european social fund in the czech republic
EUROPEAN UNION
MINISTRY OF EDUCATION, YOUTH AND SPORTS
OP Education for Competitiveness

INVESTMENTS IN EDUCATION DEVELOPMENT

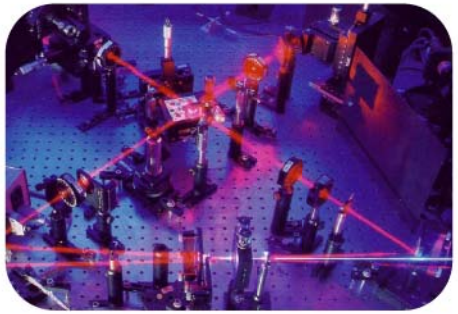
Nonclassical Light from Semiconductors

Gregor Weihs

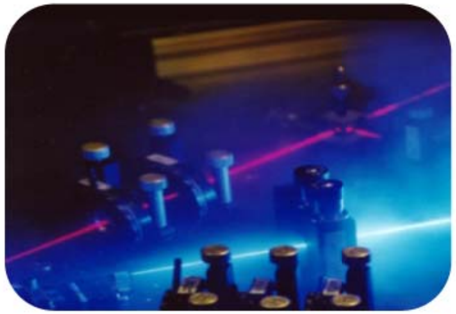
Institute for Experimental Physics - University of Innsbruck
Institute for Quantum Computing – University of Waterloo

MOTIVATION

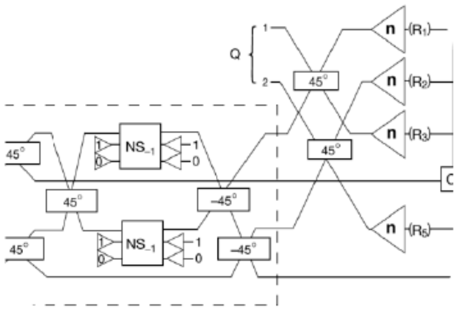
Quantum Cryptography



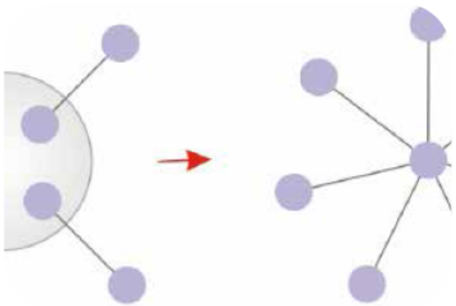
Teleportation



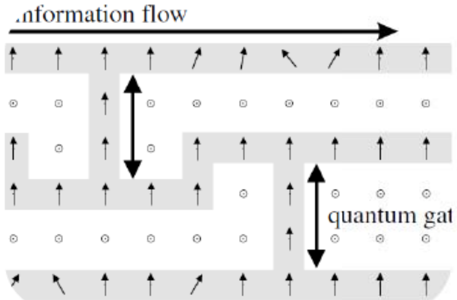
Purification



Linear Optical Quantum Computing

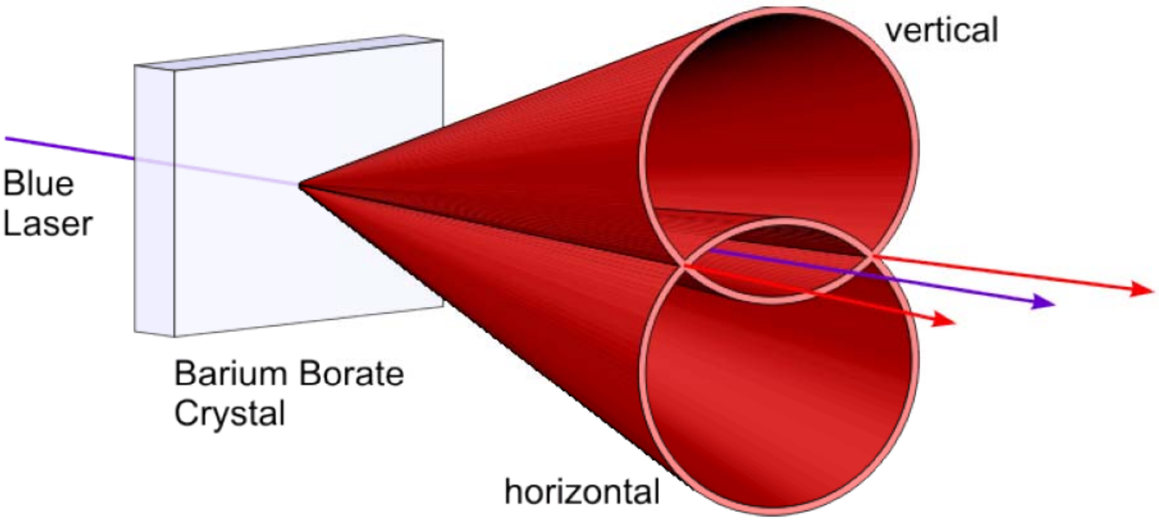


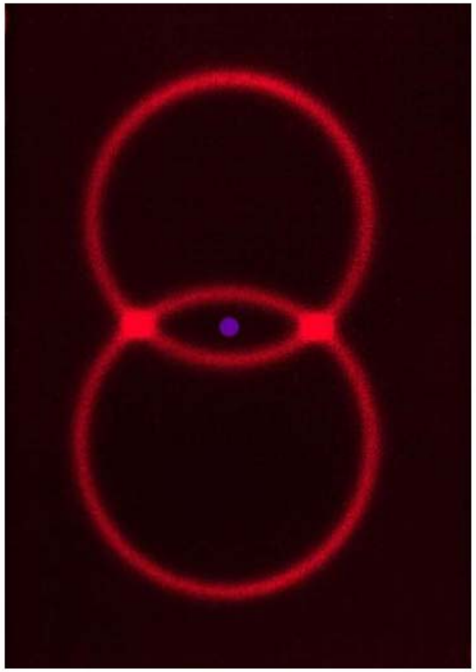
Multipartite Entanglement



Measurement-based Quantum Computing

Entangled Photon Pairs





$$|\Psi\rangle = \frac{1}{2}(|H\rangle_1 |V\rangle_2 + |V\rangle_1 |H\rangle_2)$$

- Typical conversion efficiency: 10^{-10}
- Typical detected pair rates: 20,000 for 50 mW blue laser power

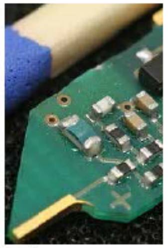
P. G. Kwiat, et al., PRL **75,** 4337 (1995).

GOALS

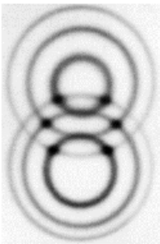
Pure, with high fidelity

Triggered, on demand

One pair at a time



Miniaturized



Maximally entangled

Integrated with laser, active and passive elements and detectors

CONTENTS

Waveguides

- Phase-matching
- Bragg-reflection waveguides
- Polarization entanglement
- Integration

Quantum dots

- Excitation mechanisms
- Coherent control
- Non-gaussian states
- Time-bin entanglement

GROUP

Waveguides
Rolf Horn, Kaisa Laiho
Thomas Günthner, Benedikt Pressl
Matthias Covi

Quantum dots
Ana Predojevic
Hari Jayakumar, Tobias Huber, Thomas Kauten
Daniel Föger, Stephanie Grabher, Lorenz Butschek

COLLABORATIONS AND FUNDING

Waveguides

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Sven Höfling, Christian Schneider
(U. Würzburg)

Stephan Reitzenstein
(TU Berlin)

Quantum dots

Helmut Ritsch
(U. Innsbruck)

Hashem Zoubi
(MPI Dresden)

G. Solomon
(NIST Gaithersburg)

Radim Filip, Miroslav Ježek
(U. Olomouc)

erc

FWF Der Wissenschaftsfonds.

CIFAR CANADIAN INSTITUTE for ADVANCED RESEARCH

CONTENTS

Waveguides

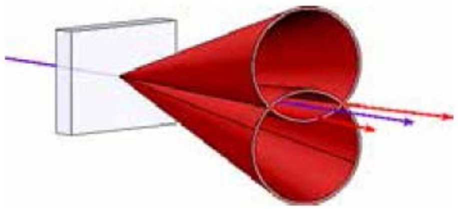
- Phase-matching
- Bragg-reflection waveguides
- Polarization entanglement
- Integration

Quantum dots

- Excitation mechanisms
- Coherent control
- Non-gaussian states
- Time-bin entanglement

SEMICONDUCTOR SOURCES FOR INTEGRATION

+



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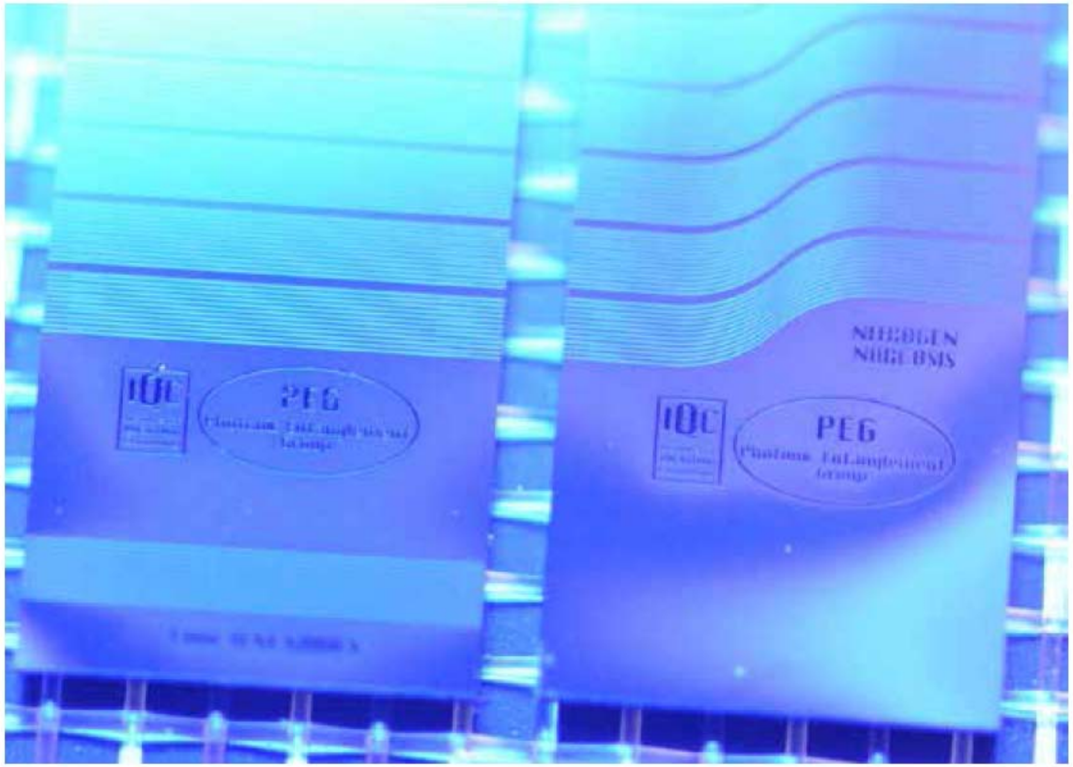
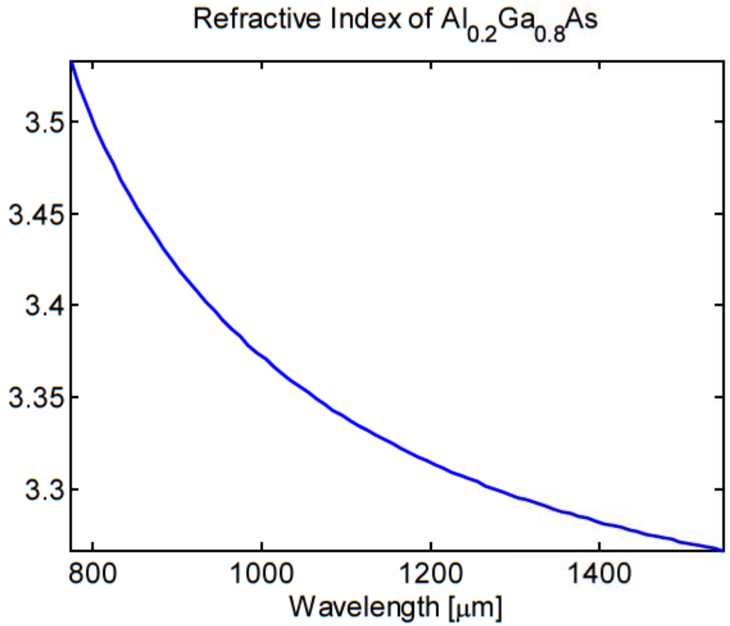
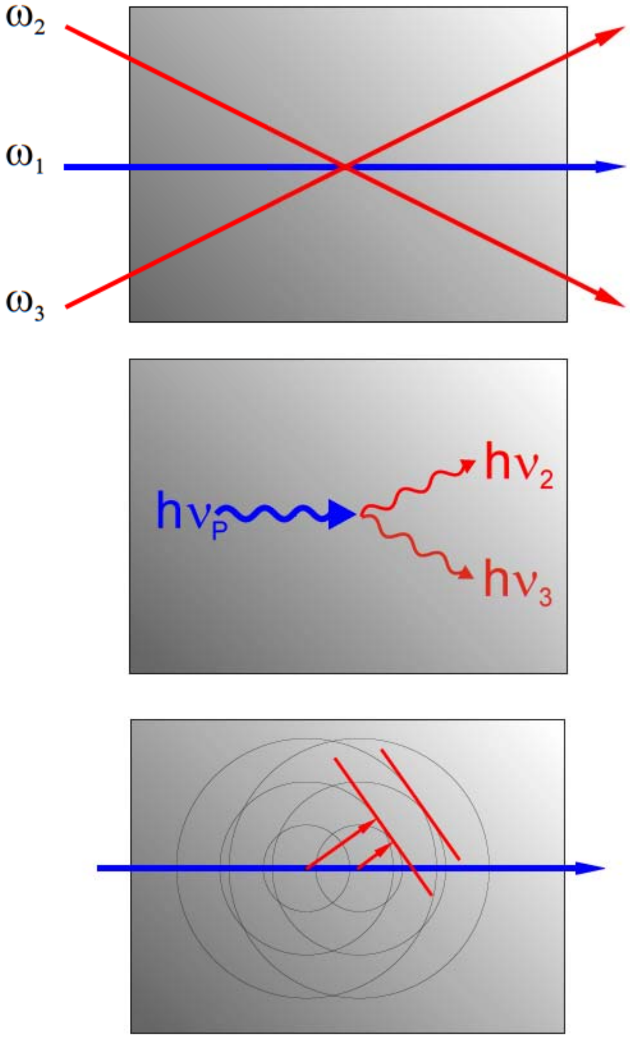


III-V Nonlinear Optics

- \+ 2^{nd} order nonlinear effects preferred
  - \+ Easy pump removal
  - \+ Linear in pump power
- \+ Zinc-blende crystals have $\chi(2)$
  - \+ GaAs, InP, AlAs, InAs
  - \+ GaAs $\chi(2)$ is **100 pm/V (!)**
- – Phase-matching difficult
  - – Large dispersion in NIR
  - – No birefringence
  - – No poling



Phase Matching



- Three waves interact
- Integration over interaction region leads to approximate momentum conservation

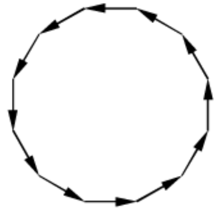
$$\hbar k_p = \hbar k_2 + \hbar k_3$$

- Vastly different frequencies experience different refractive indices

PHASE MATCHING

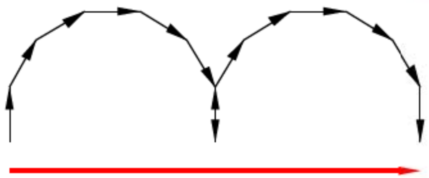
- Nonlinear conversion will only be efficient, if $\Delta k\ L \approx 0$
- Exploit birefringence
  - e.g. $n_e(\omega) = n_o(2\omega)$
  - Tune by angle, temperature, direction
  - Artificial form birefringence
- Exploit waveguide modes
- Modulate nonlinearity
  - Periodic poling

No Phase-Matching



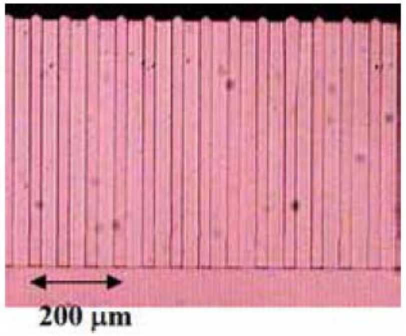
Perfect Phase-Matching

Quasi-Phase-Matching

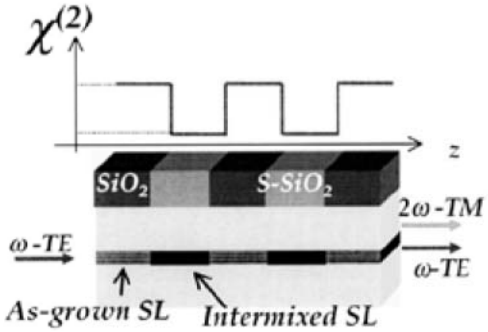


PHASE-MATCHING SOLUTIONS

- Periodic domain-inversion
- Domain disordering
- Form birefringence
- Counter-propagating
- Directional / WGM
- Waveguide modes

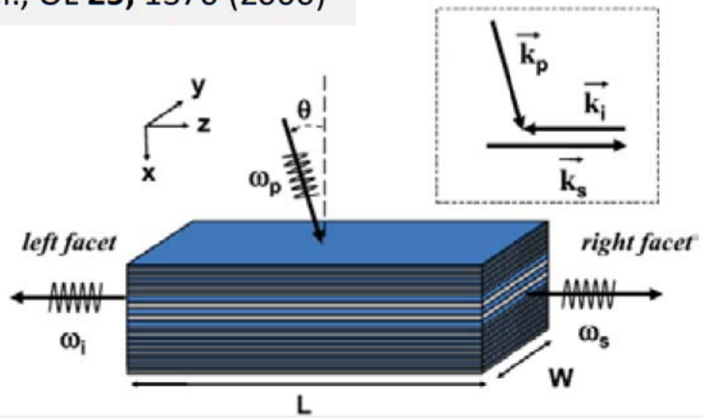


Pinguet, PhD Thesis, Stanford (2002)
Skauli et al., OL **27,** 628 (2002)



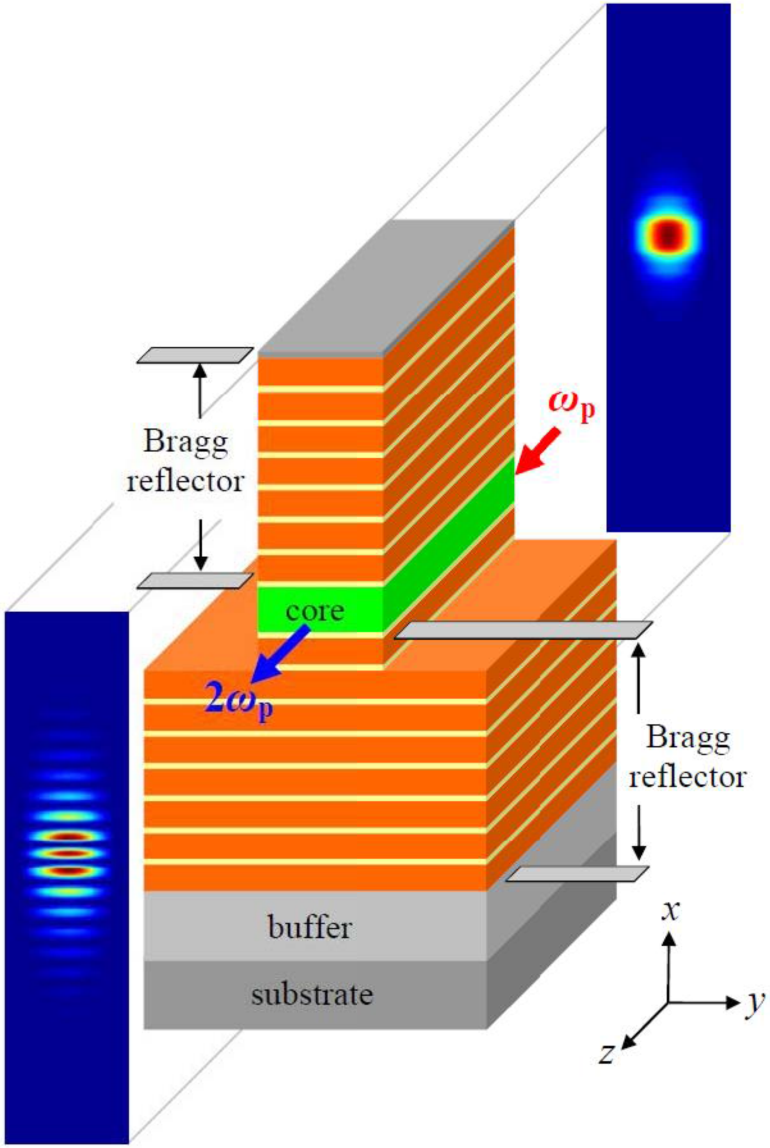
Helmy et al., OL **25,** 1370 (2000)

Ravaro et al., APL **91,** 191110 (2007)



Caillet et al., Opt. Express **18,** 9967 (2010)

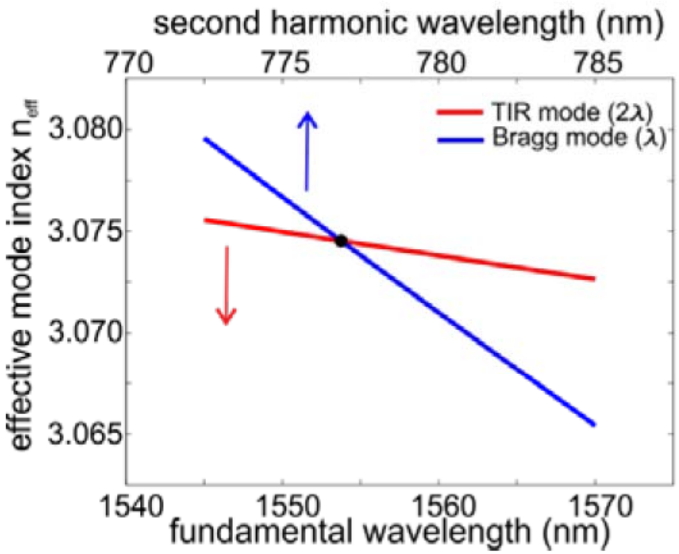
BRAGG-REFLECTION WAVEGUIDES

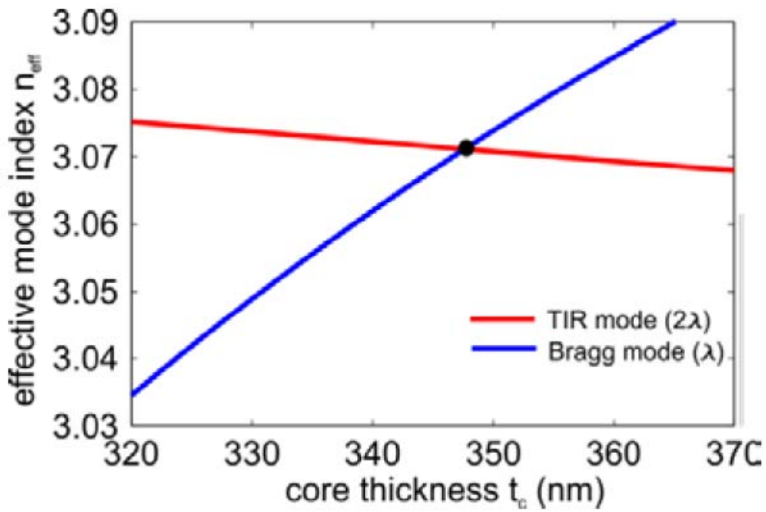


- Transverse Bragg reflector introduces additional guided mode with much lower effective index
- Bragg mode at 2ω can match regular index guided mode at ω
- No periodicity in propagation direction, i.e. no QPM

Yeh & Yariv, Opt. Comm. **19,** 427 (1976);
Helmy et al., Opt. Lett. **32,** 2399 (2007);
Abolghasem et al., IEEE Photon. Tech. Lett. **21,** 1462 (2009).

BRW PHASE-MATCHING

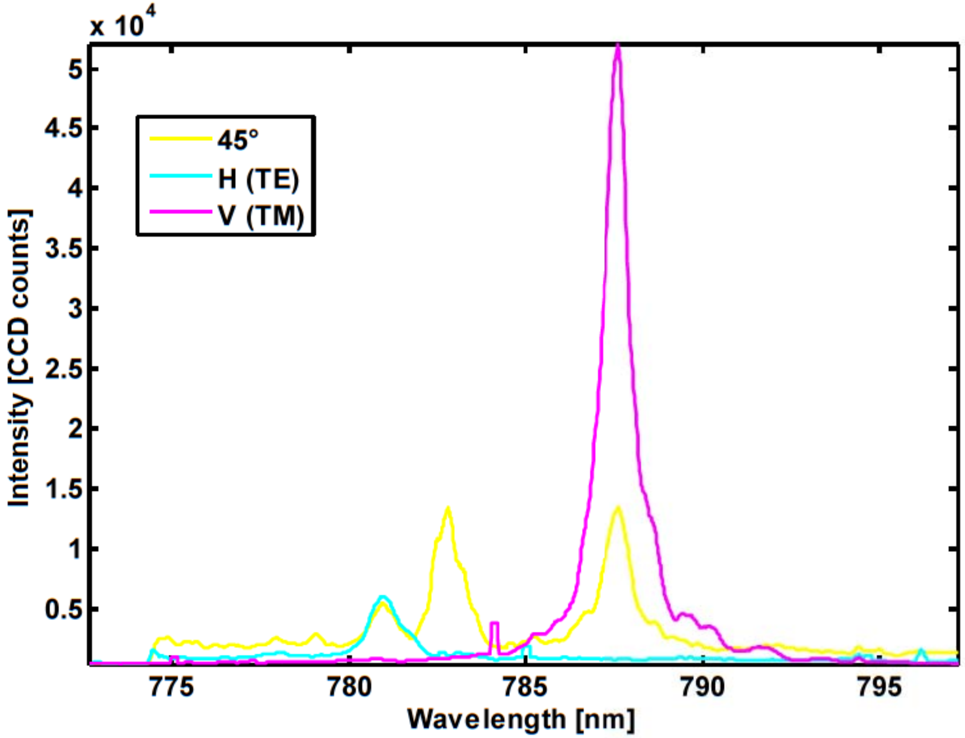




- Tuning mechanisms
  - composition, thickness, width, temperature
- Phase-matching configurations
  - Type-I: TE + TE → TM, Type-II: TE + TM → TM, Type-0: TM + TM → TM

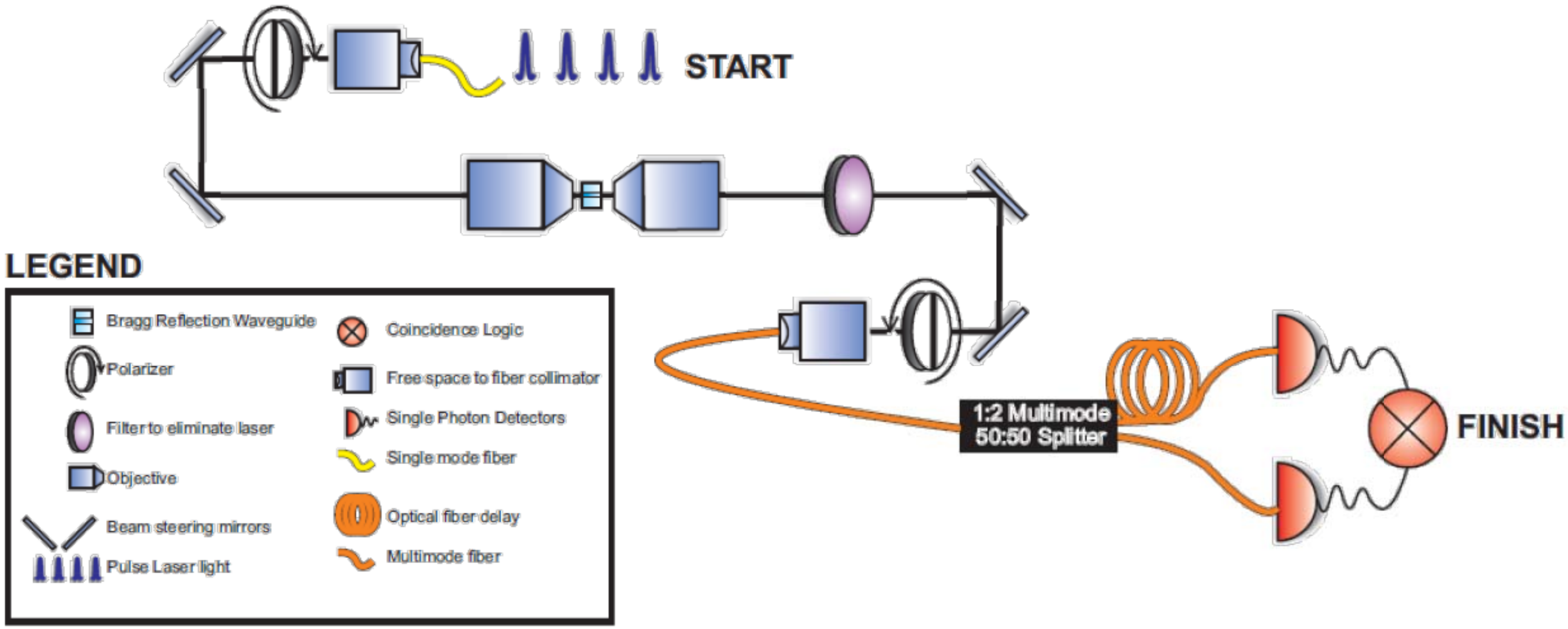
z [001]
[110]
4.4 µm
TBR
3.6 µm
ML
Core

SECOND HARMONIC GENERATION (SHG) RESULTS



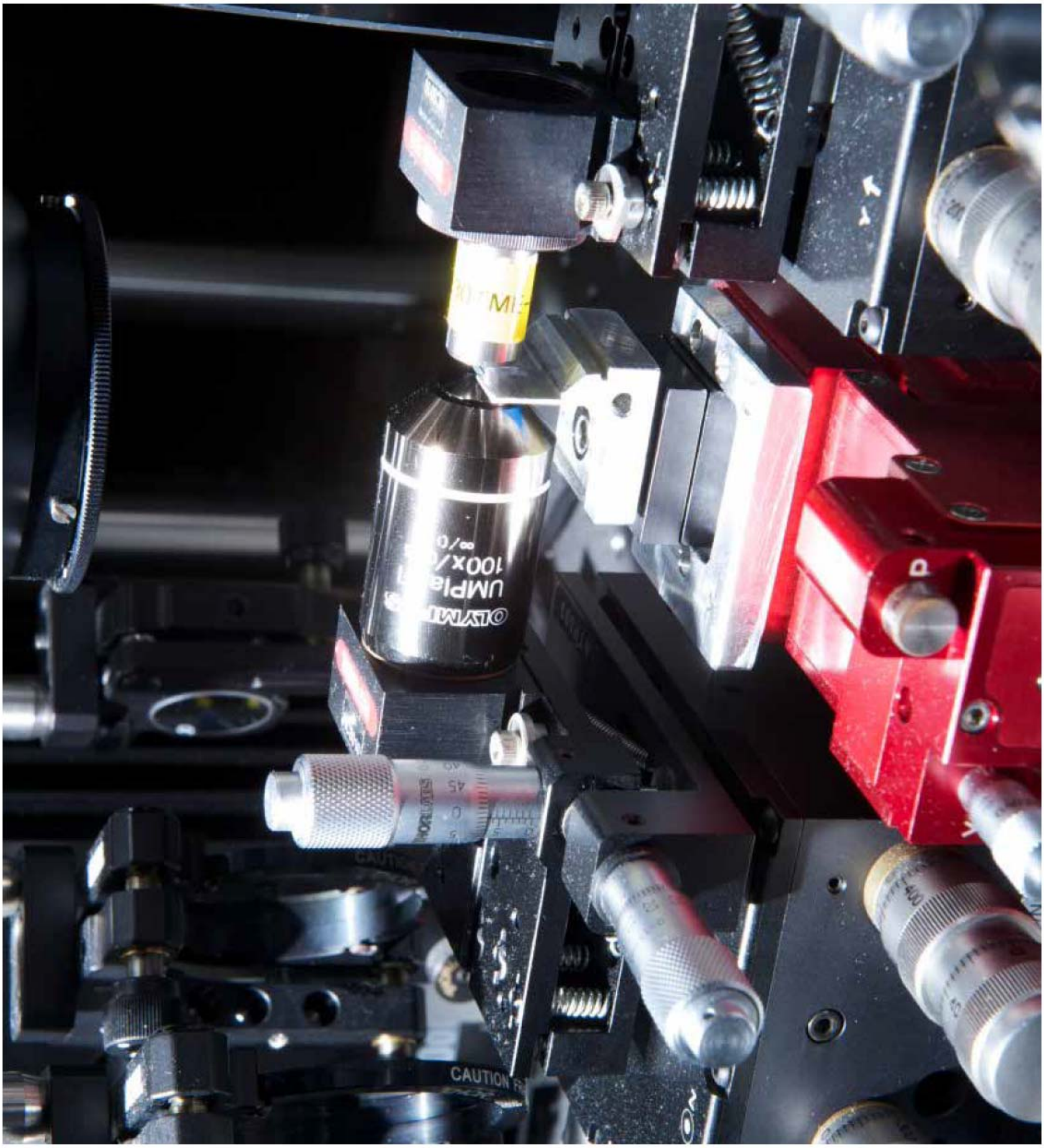
- Type-I: TE + TE ➔ TM
- Type-II: TE + TM ➔ TM
- Type-0: TM + TM ➔ TM (!!!, strongest in our sample)

EXPERIMENT

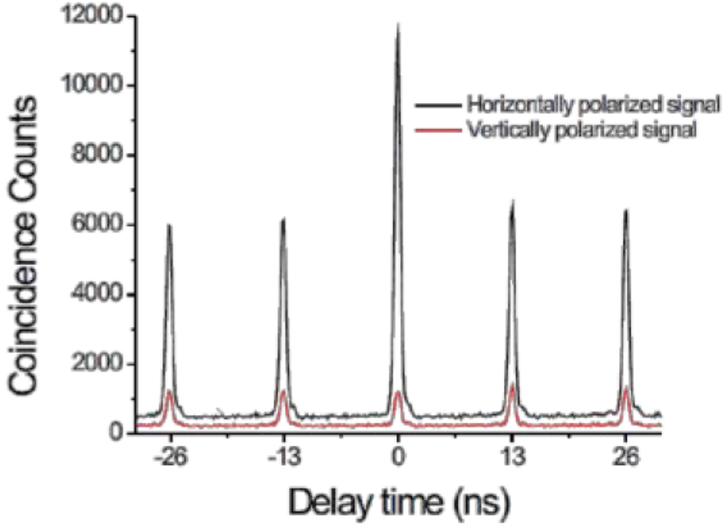


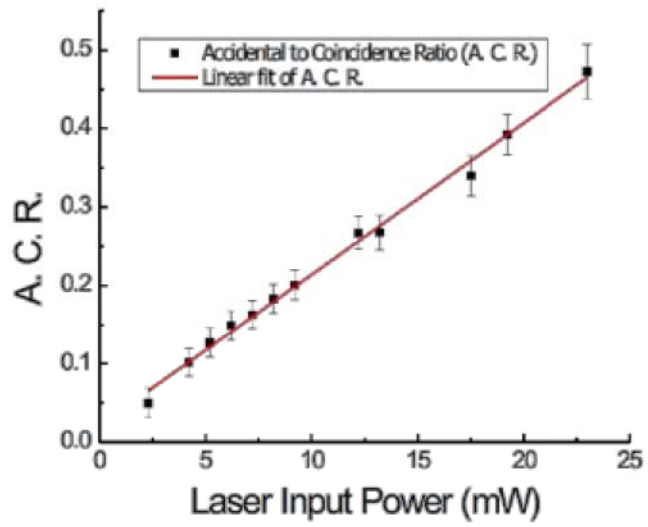
- Coupling via front- and backside imaging
- Start-stop measurement using gated InGaAs APDs

BRW: Setup



POLARIZATION AND POWER SCALING



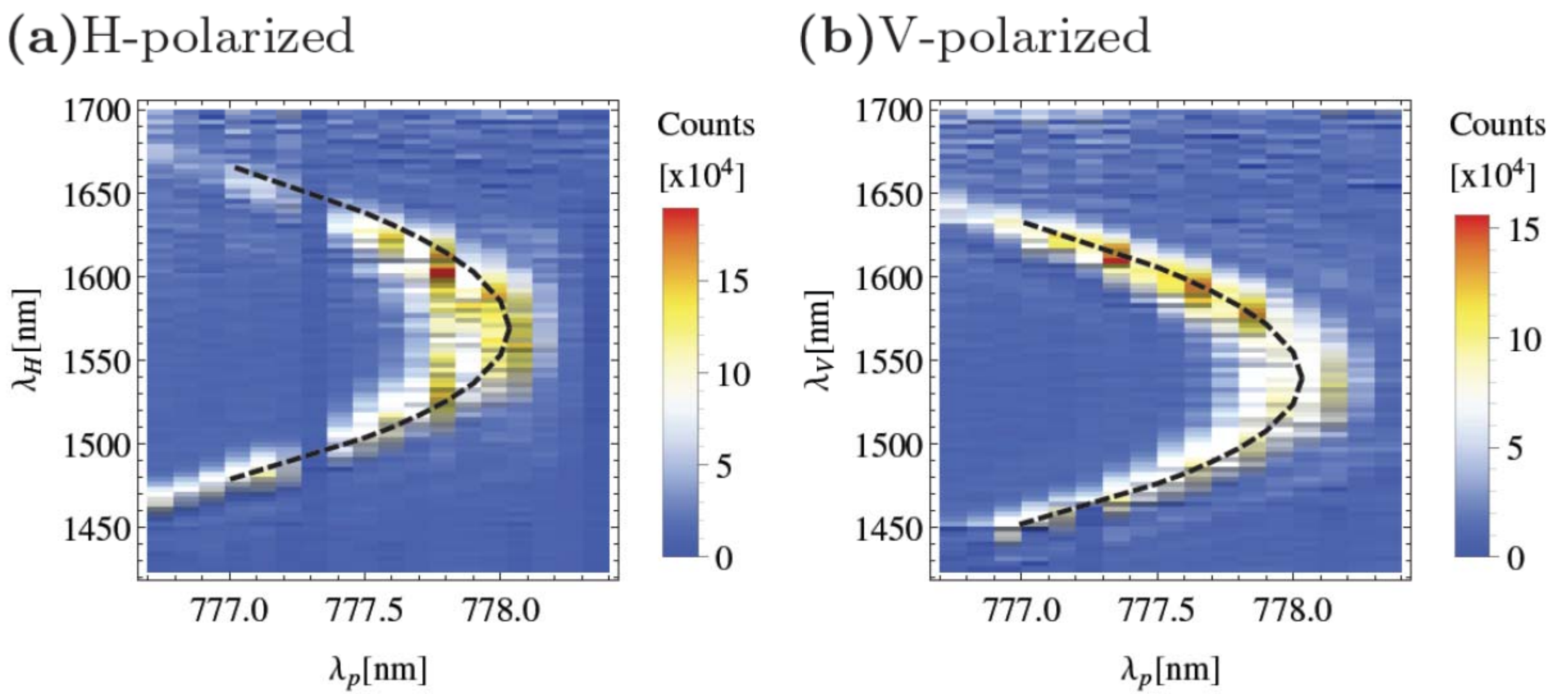


- Clear polarization signatures for various phase-matching schemes
- Expected power scaling

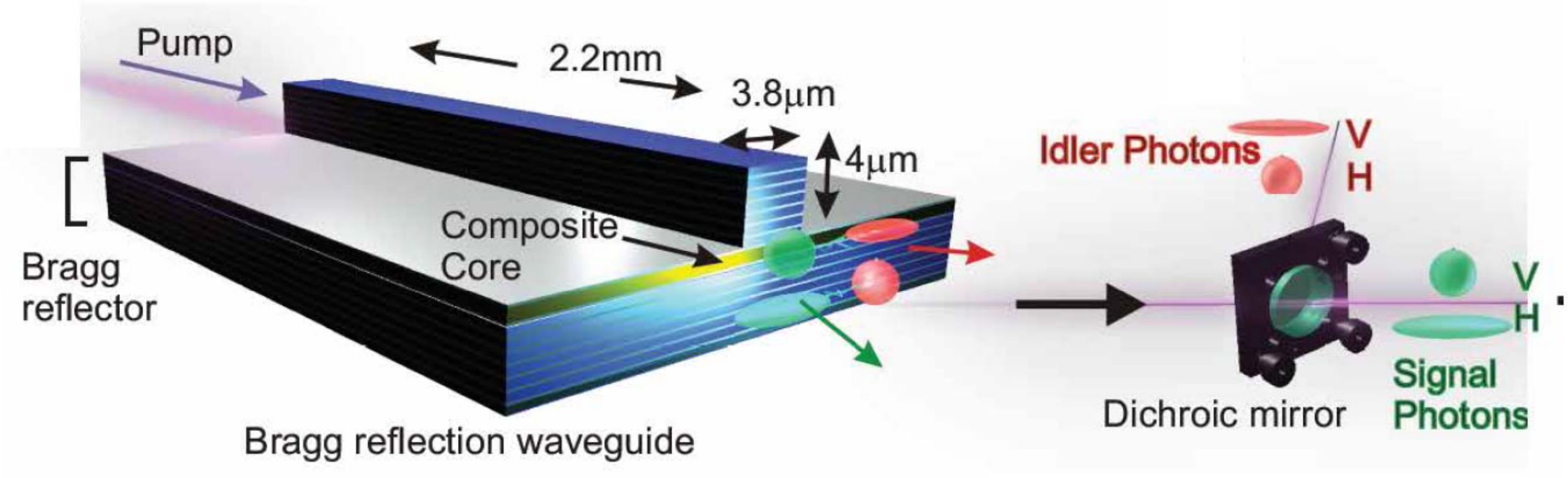
R. Horn et al., PRL **108,** 153605 (2012)

POLARIZATION ENTANGLEMENT FROM BRW

- Small birefringence for the TIR mode allows direct polarization entanglement out of the BRW around degeneracy point

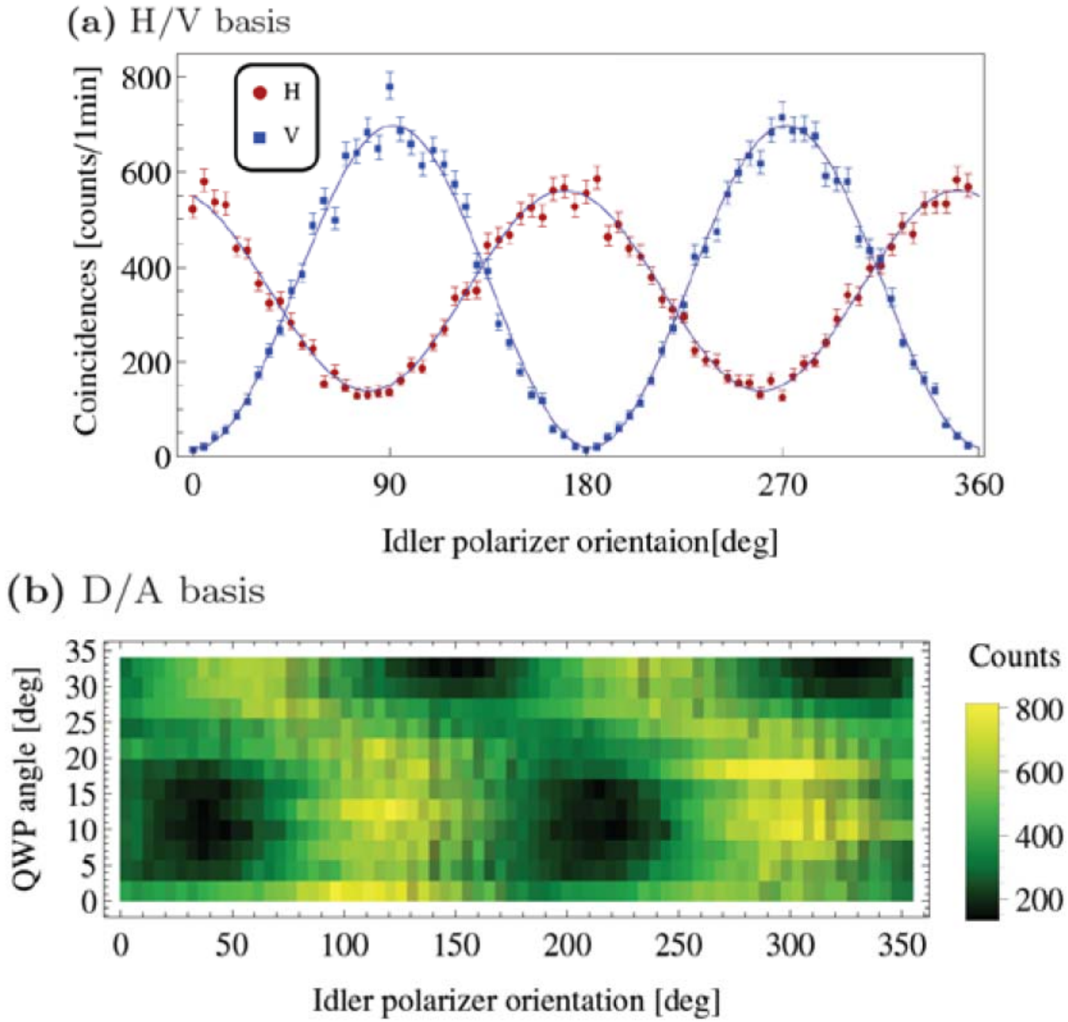


EXPERIMENT

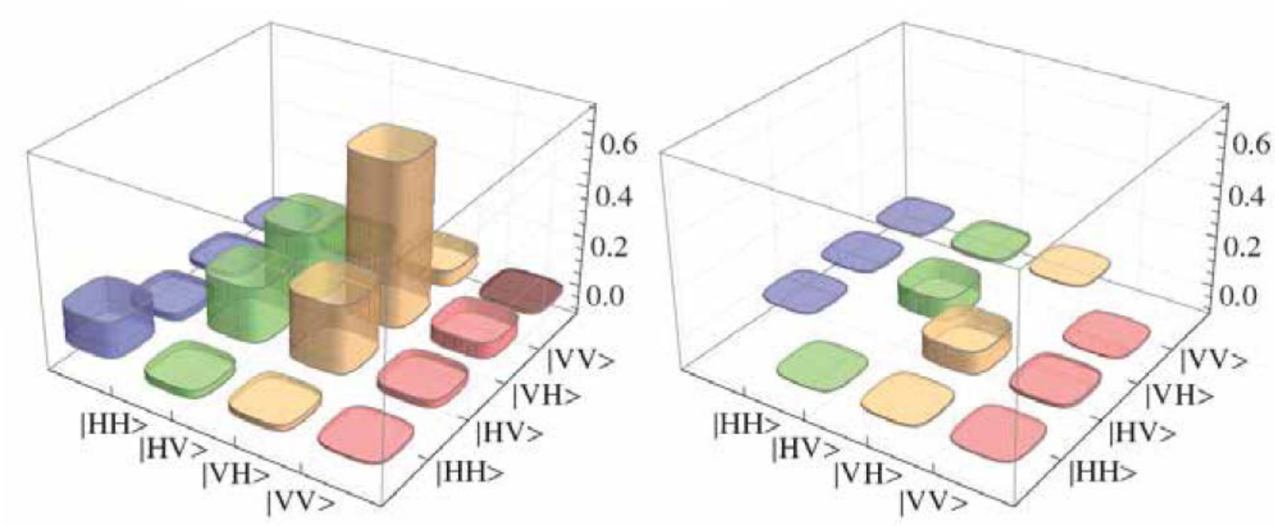


- Produce non-degenerate polarization entanglement
- Use dichroic splitter near central wavelength

Polarization entanglement



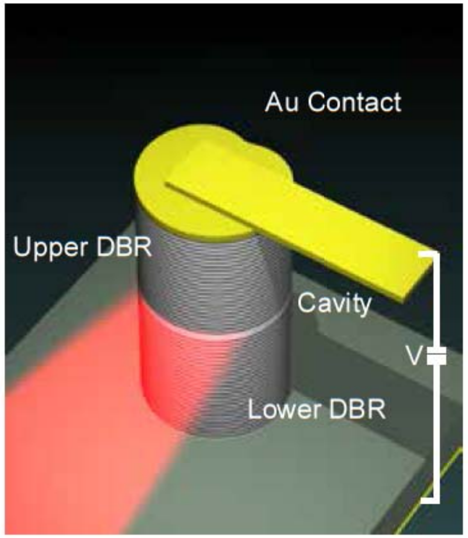
POLARIZATION ENTANGLEMENT

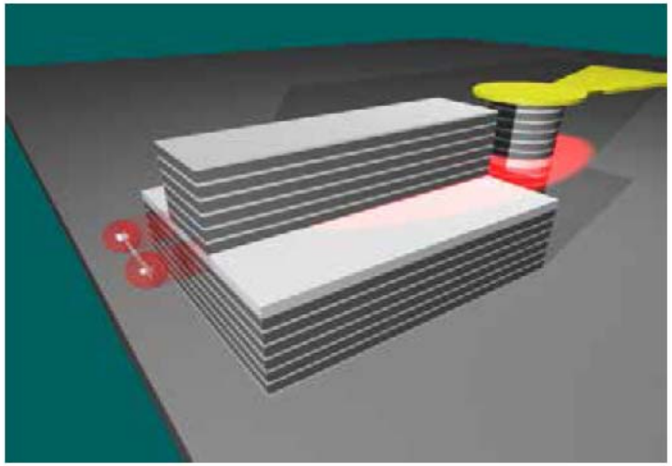


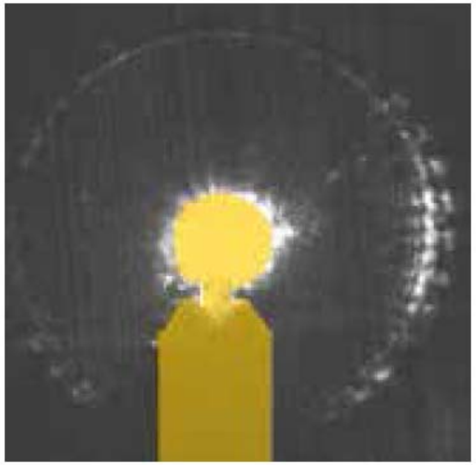
- Pronounced HH background
- Concurrence 0.52
- Fidelity to Ψ^+: 0.83

INTEGRATING A LASER ON THE CHIP

- Whispering Gallery Mode lasers
  - Limaçon shape for directed emission
  - Quantum dots or wells as gain medium
- Endfire or tunnel coupling to BRW
- Possibly internal conversion







Pictures C. Schneider, S. Reitzenstein

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- Excitation mechanisms
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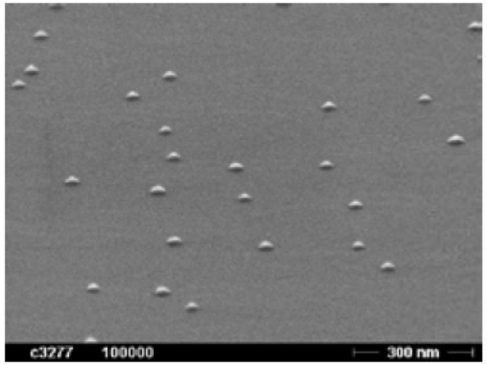
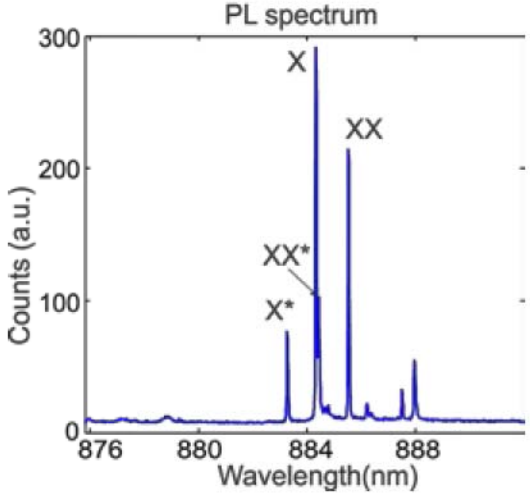
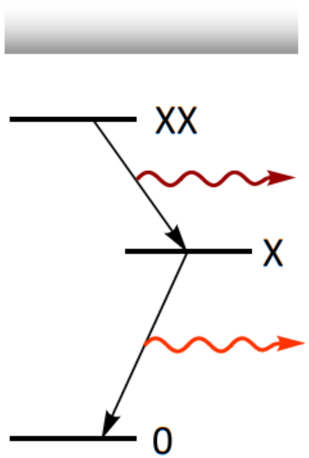
- Non-gaussian states
- Time-bin entanglement

INAS ON GAAS DOTS

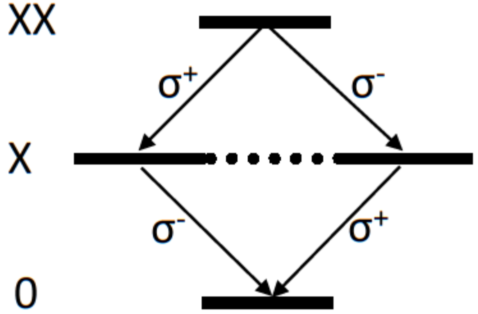
- Convenient emission wavelength
  - around 920 nm (as grown)
  - around 880 nm (annealed)
- High photon detection efficiency
- Lithographic selection possible





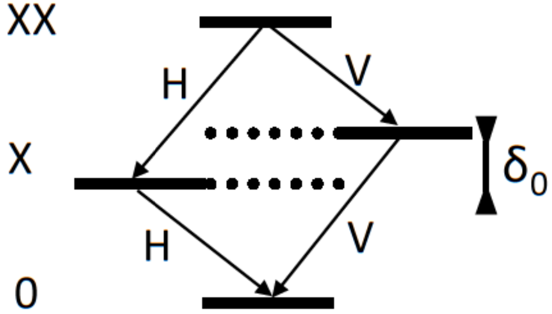


POLARIZATION ENTANGLEMENT



Perfect, Isotropic Dot

- Degenerate exciton fine structure
- Polarization entanglement
  [Benson et al. PRL **84,** 2513 (2000)]

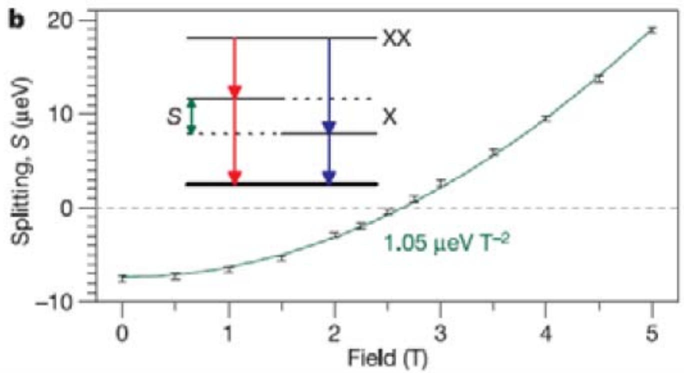


Real, Anisotropic Dot

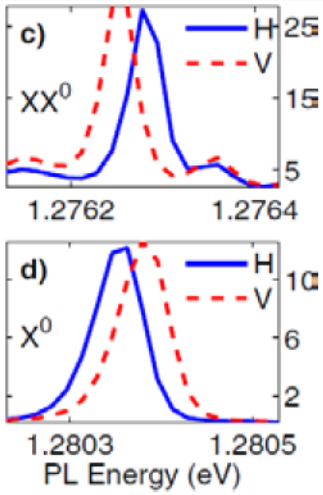
- Exciton fine structure splitting
- Two linear polarizations (aligned with dot major & minor axis)
- Polarization correlation in cascade
  [Santori et al. PRL **66,** 045308 (2002)]

Polarization Entanglement Recovery

- Removal of splitting
  - Annealing
  - Magnetic Fields
  - Electric Fields
  - Dedicated growth: Hafenbrak et al. NJP **9,** 315 (2007); Salter et al. Nature **465,** 594 (2010)
- Narrow filtering (overlapping lines)
- Dressed states
  - Jundt et al. PRL **100,** 177401 (2008).
  - Müller et al. PRL **103,** 217402 (2009)
- Removal of XX binding energy
  - Reimer et al. Nano Lett. **11,** 645 (2011)
- Photonic molecules
  - Dousse et al., Nature **466,** 217 (2010)
- Inverted pyramidal dots
  - Mohan et al., Nature Photonics **4,** 302 (2010)

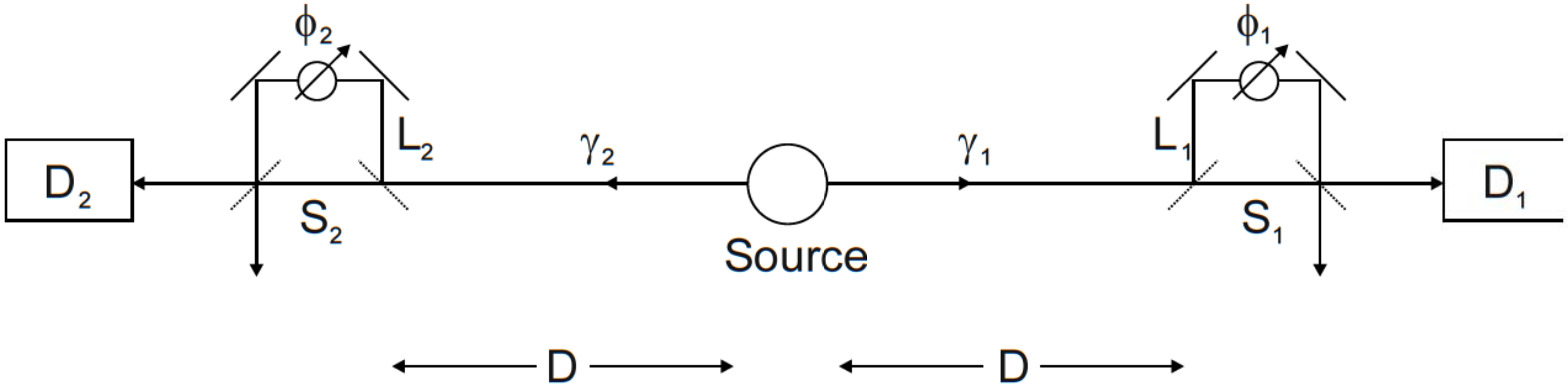


Stevenson et al., Nature **439,** 179 (2006).
Young et al., PRL **102,** 030406 (2009).



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

ENERGY-TIME-ENTANGLEMENT



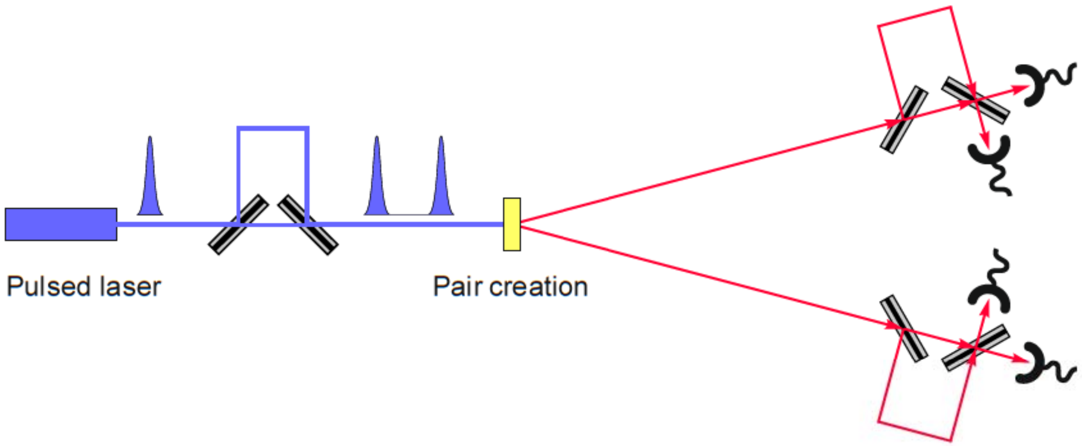
VOLUME 62, NUMBER 19 PHYSICAL REVIEW LETTERS 8 MAY 1989

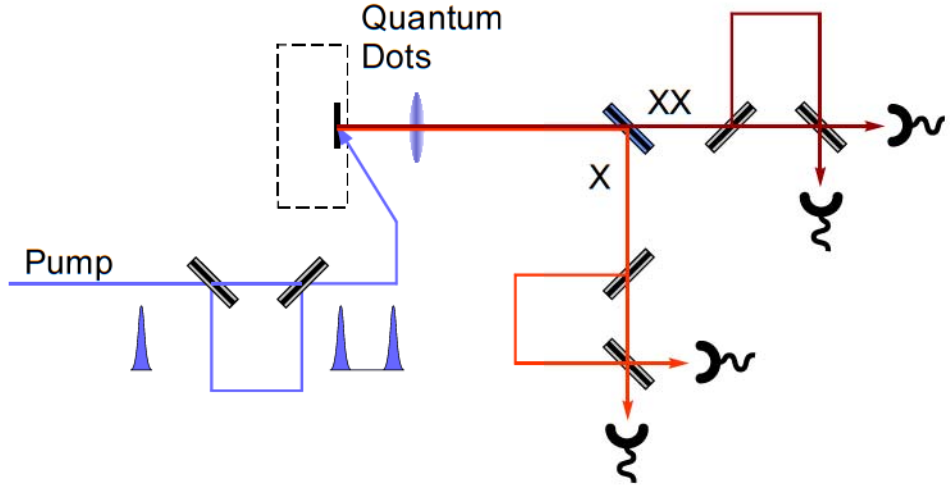
Bell Inequality for Position and Time

J. D. Franson
Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland 20707-6099
(Received 24 October 1988)

The quantum-mechanical uncertainty in the position of a particle or the time of its emission is shown to produce observable effects that are inconsistent with any local hidden-variable theory. A new experimental test of local hidden-variable theories based on optical interference is proposed.

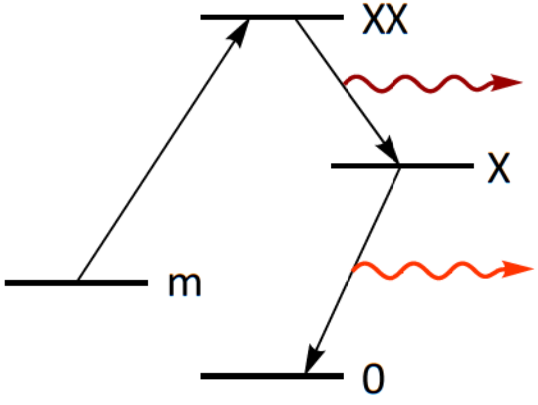
TIME-BIN ENTANGLEMENT: SPDC AND QUANTUM DOTS





TIME-BIN ENTANGLEMENT FROM QUANTUM DOTS

- Biexciton Level is not long-lived ➔ another level required



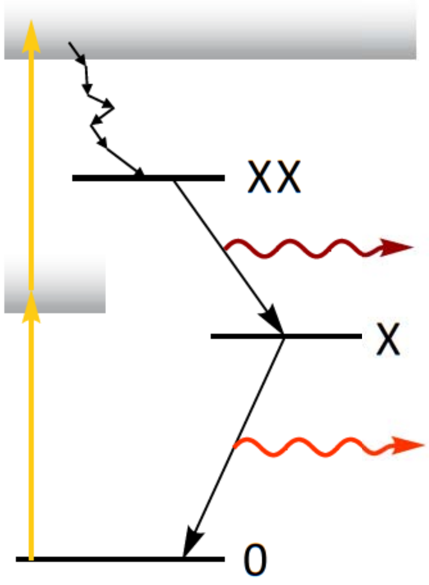
- Two coherent excitation pulses from m to XX with probabilities p_1 and p_2 will yield a state

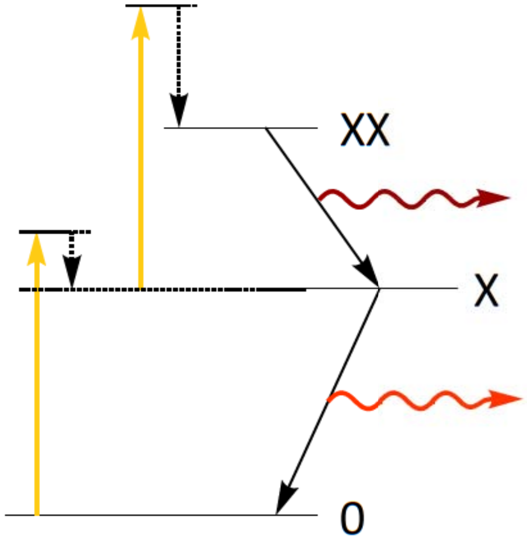
$$\sqrt{p_1}\,|\text{early}\rangle\,|\text{early}\rangle + e^{i\phi_p}\sqrt{(1-p_1)p_2}\,|\text{late}\rangle\,|\text{late}\rangle$$

- Ideally, p_1 = ½ and p_2 =1

OPTICAL EXCITATION MECHANISMS

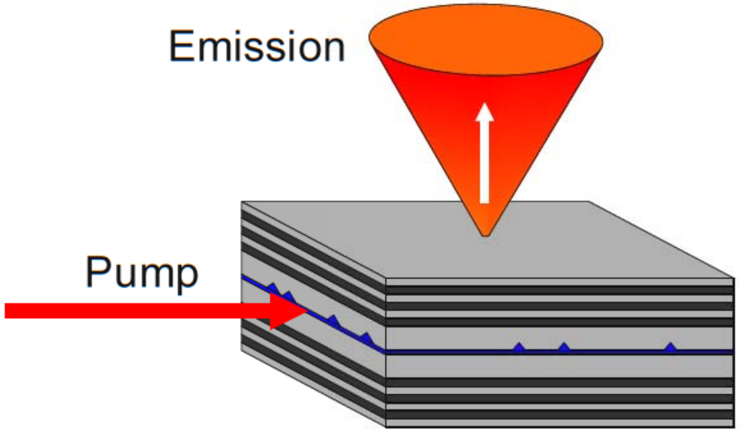
- Above-band
- Quasi-resonant
  - Excited confined states
  - LO-phonon assisted
- Single photon resonant ➔ X only
  - Adiabatic passage
    Simon et al. PRL **106,** 166801 (2011).
  - Mollow triplet photon pairs
    Ulhaq et al. Nat. Photon. **6,** 238–242 (2012)
- Two-photon resonant
  - PLE (cw): Brunner et al. PRL 73, 1138 (1994)
  - II-VI dots (huge biexciton binding)
    Flissikowski et al. PRL **92,** 227401 (2004)
  - III-V dots photocurrent:
    Stufler et al. PRB **73,** 125304 (2006)
    Boyle et al. Physica E **42,** 2485 (2010)





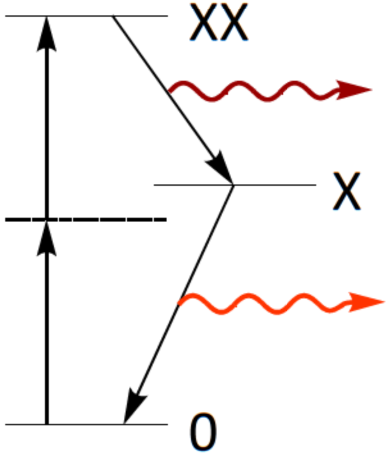
SIDE PUMPING

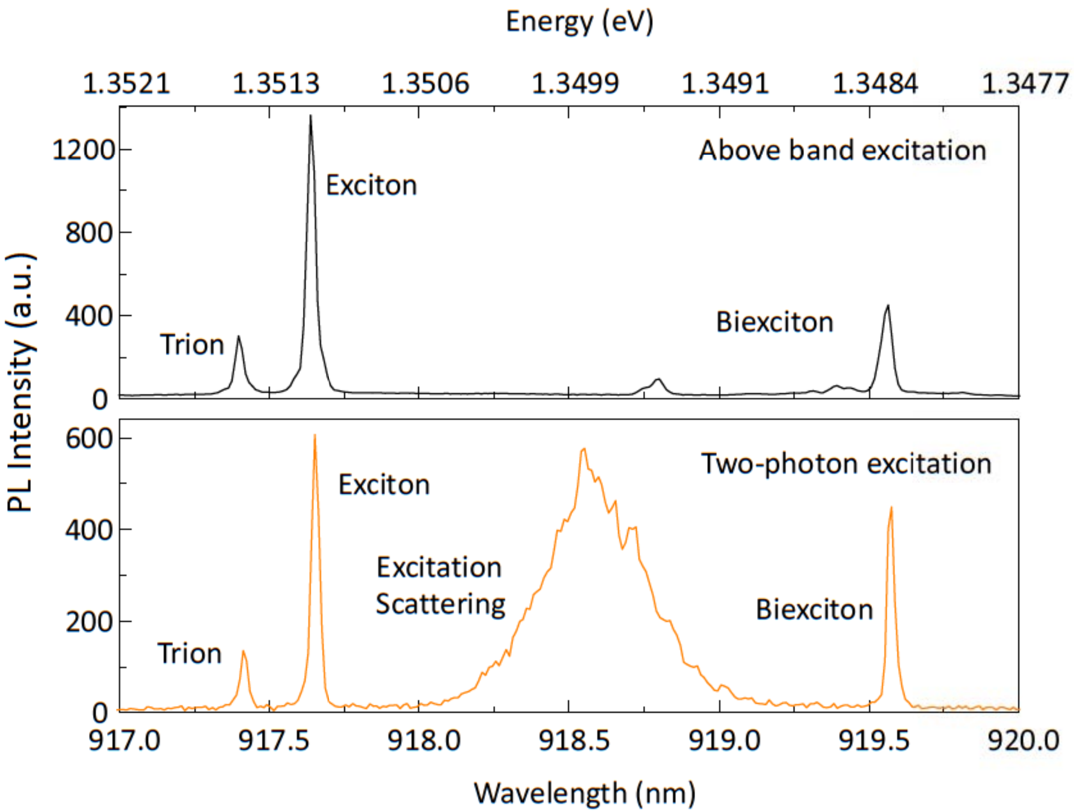
- Planar cavity acts as waveguide for pump
- No masking required
- Focusing difficult



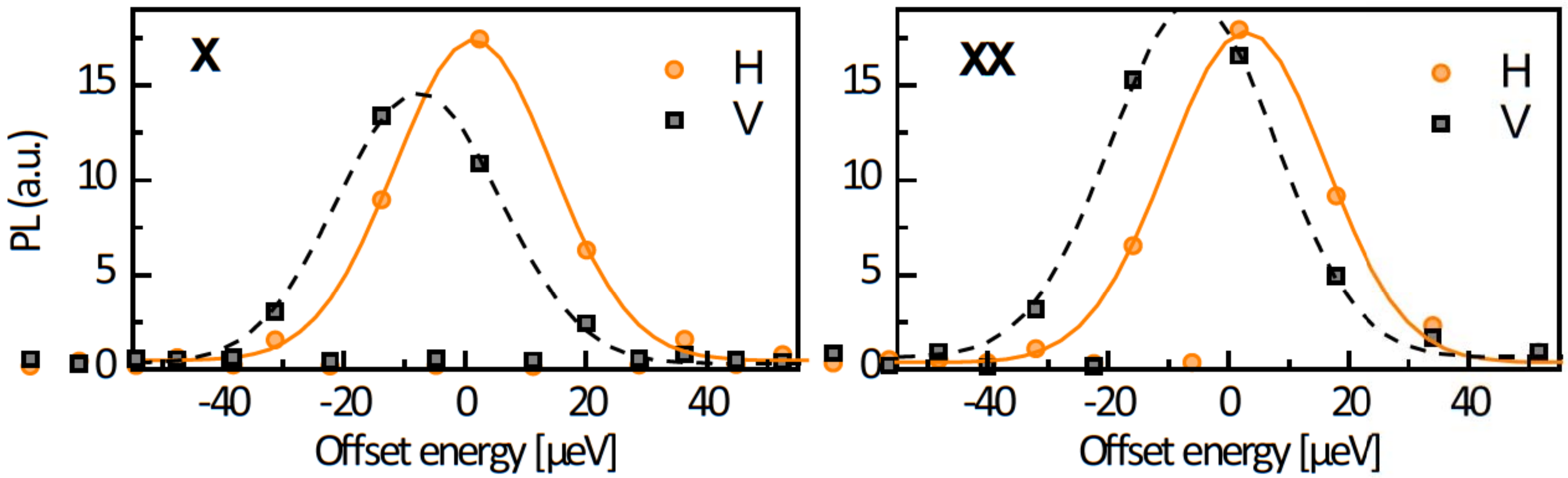
Coherent Excitation

- In order to keep the phase we need to excite coherently
- Use two-photon excitation directly to the biexciton

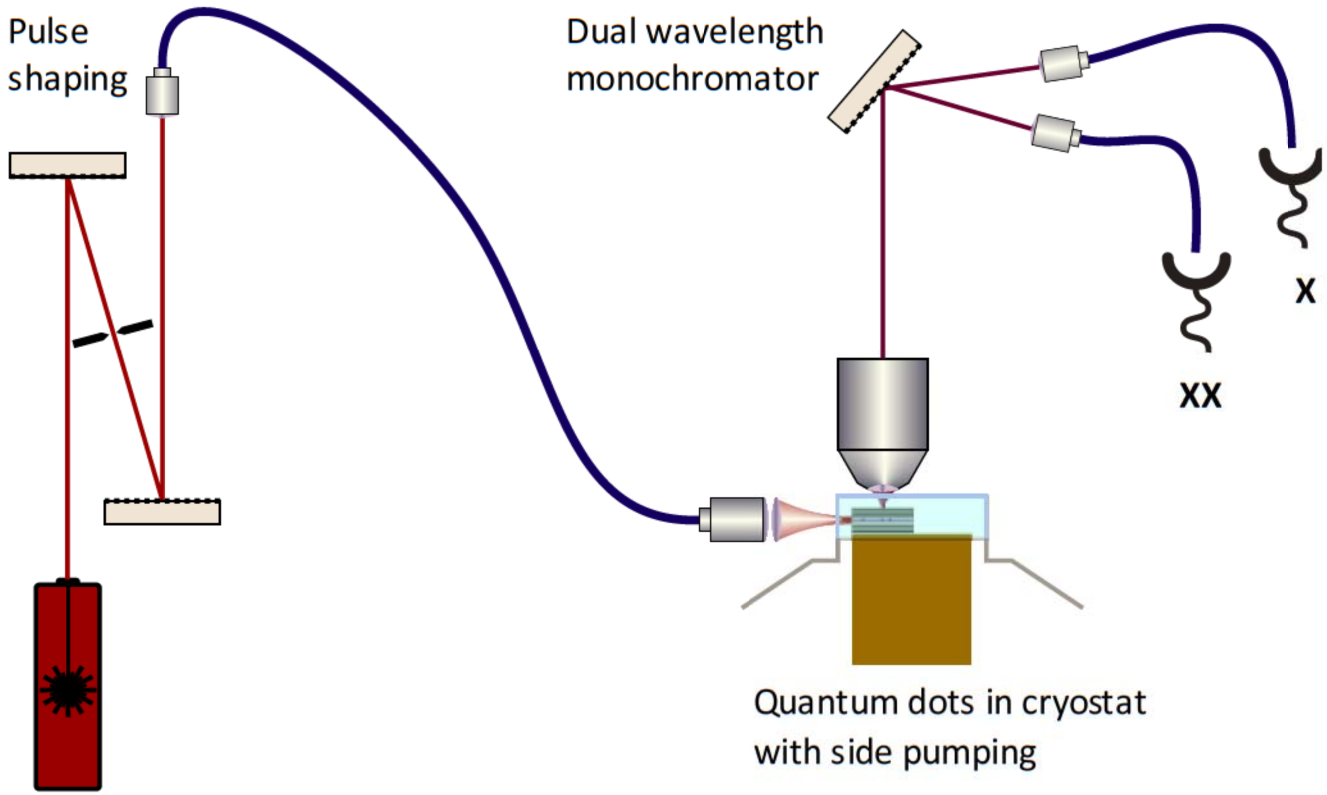




FINE STRUCTURE

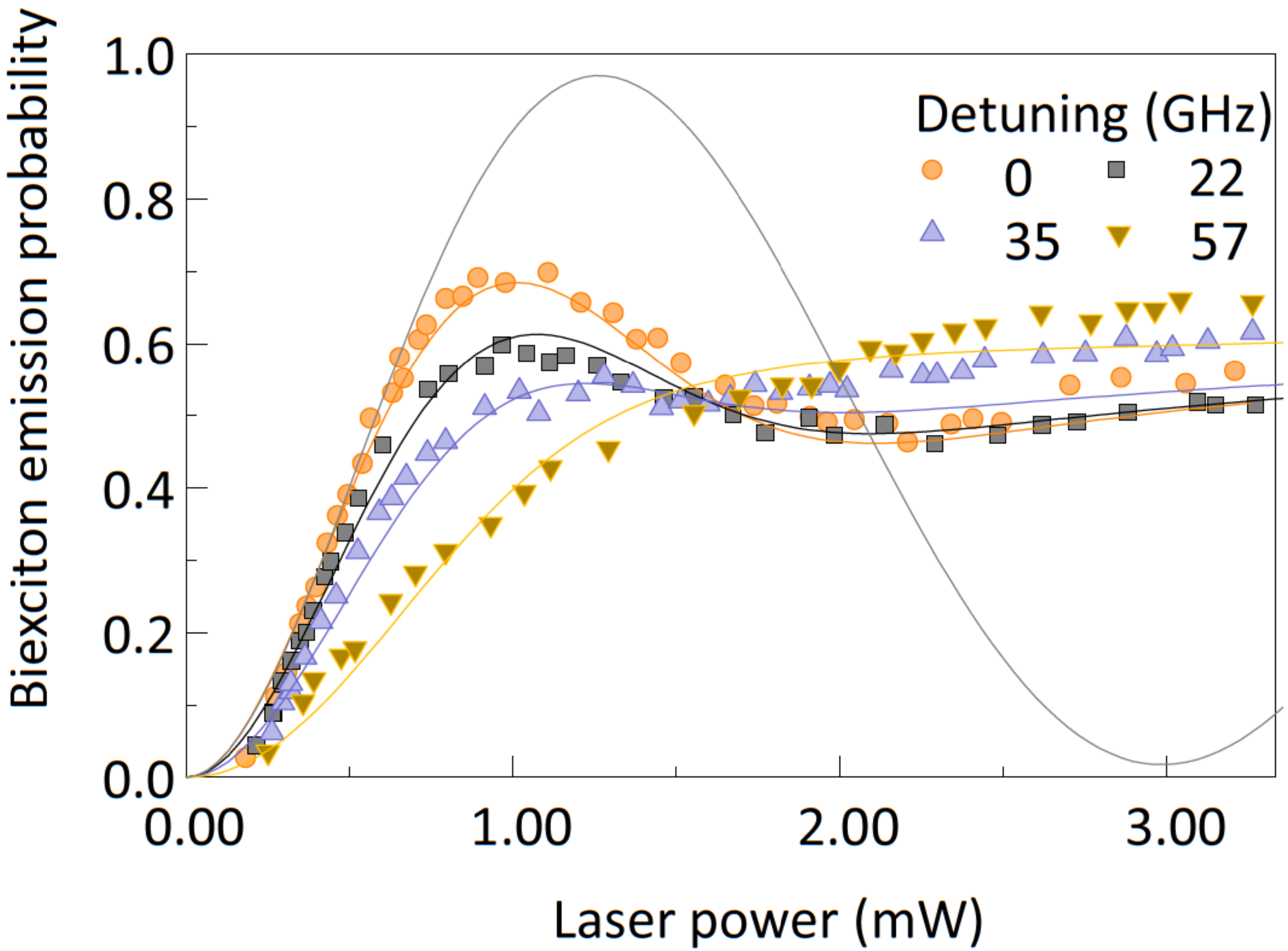


EXPERIMENT

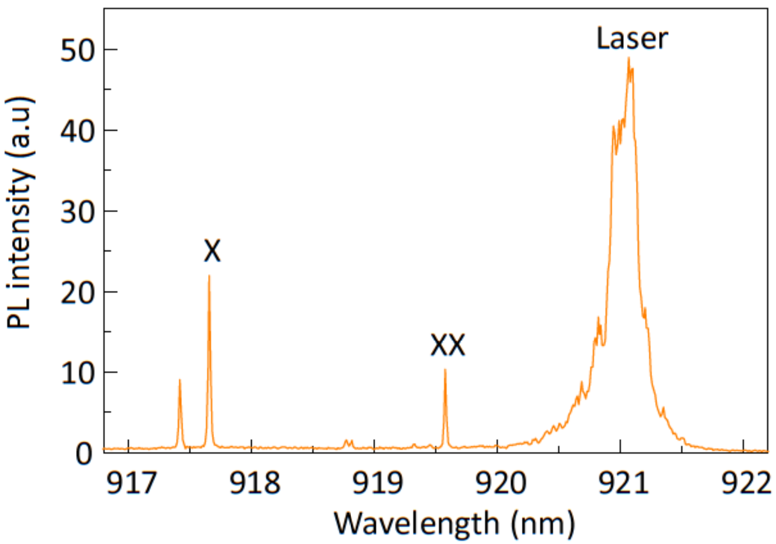


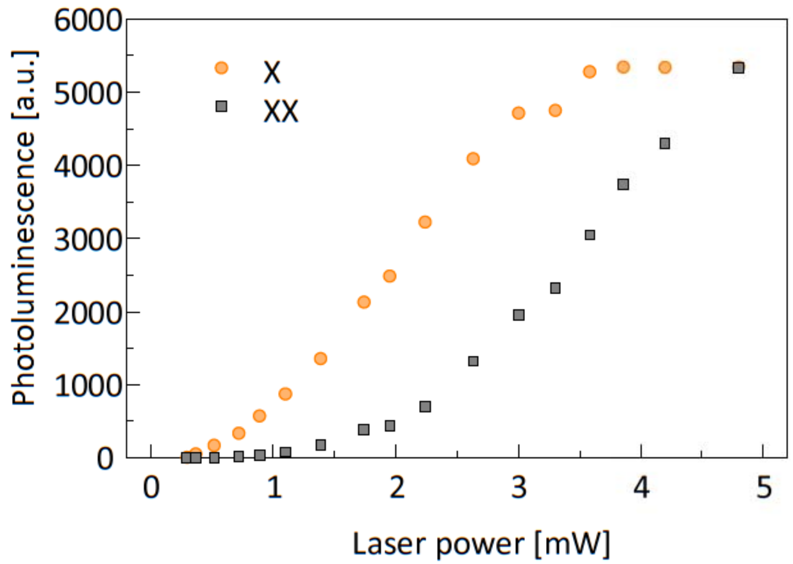
Pulse shaping
Dual wavelength monochromator
X
XX
Quantum dots in cryostat with side pumping
Ti:Sapphire laser 10 ps

Excitation Power Dependence (Rabi Oscillations)



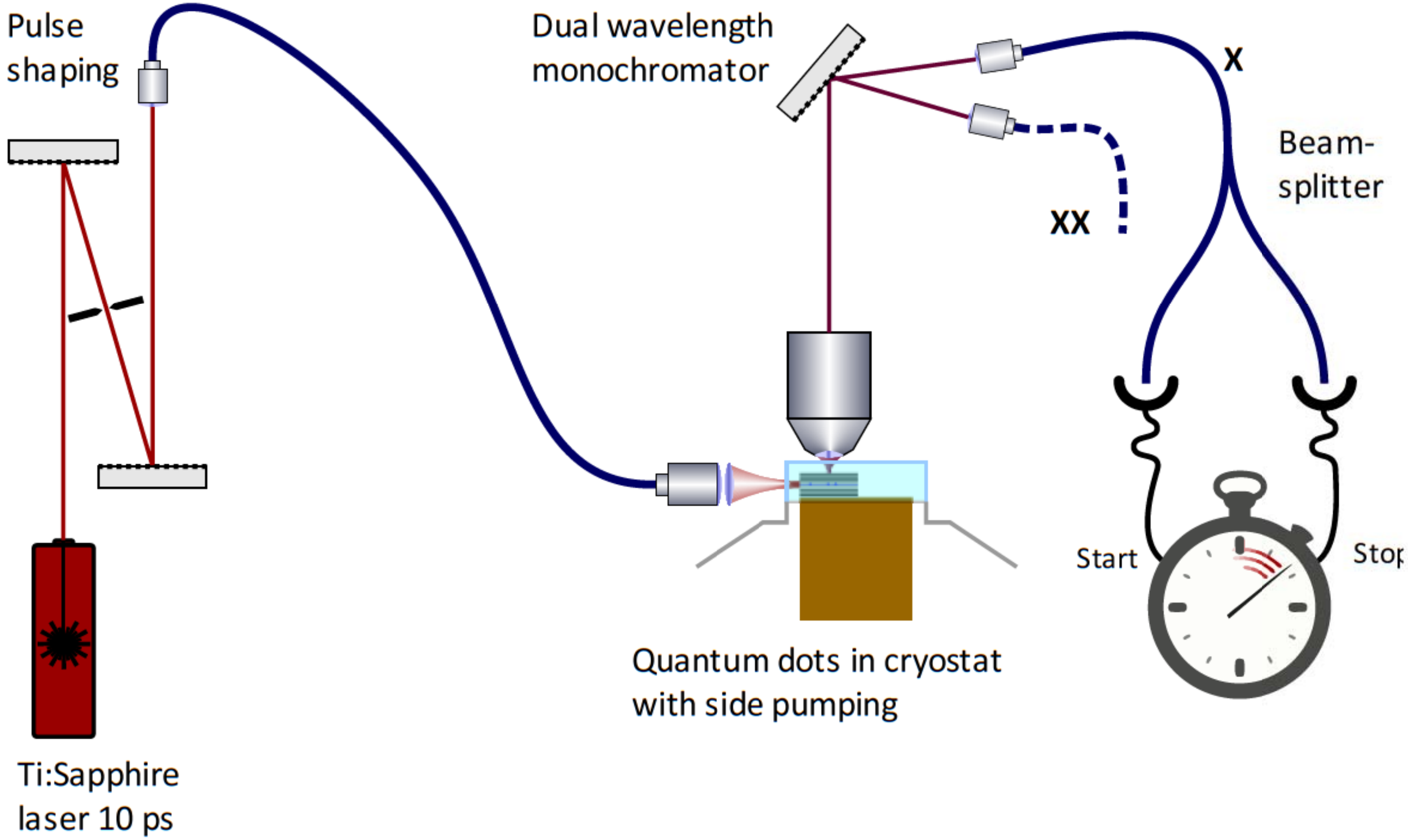
COMPARISON: INCOHERENT EXCITATION



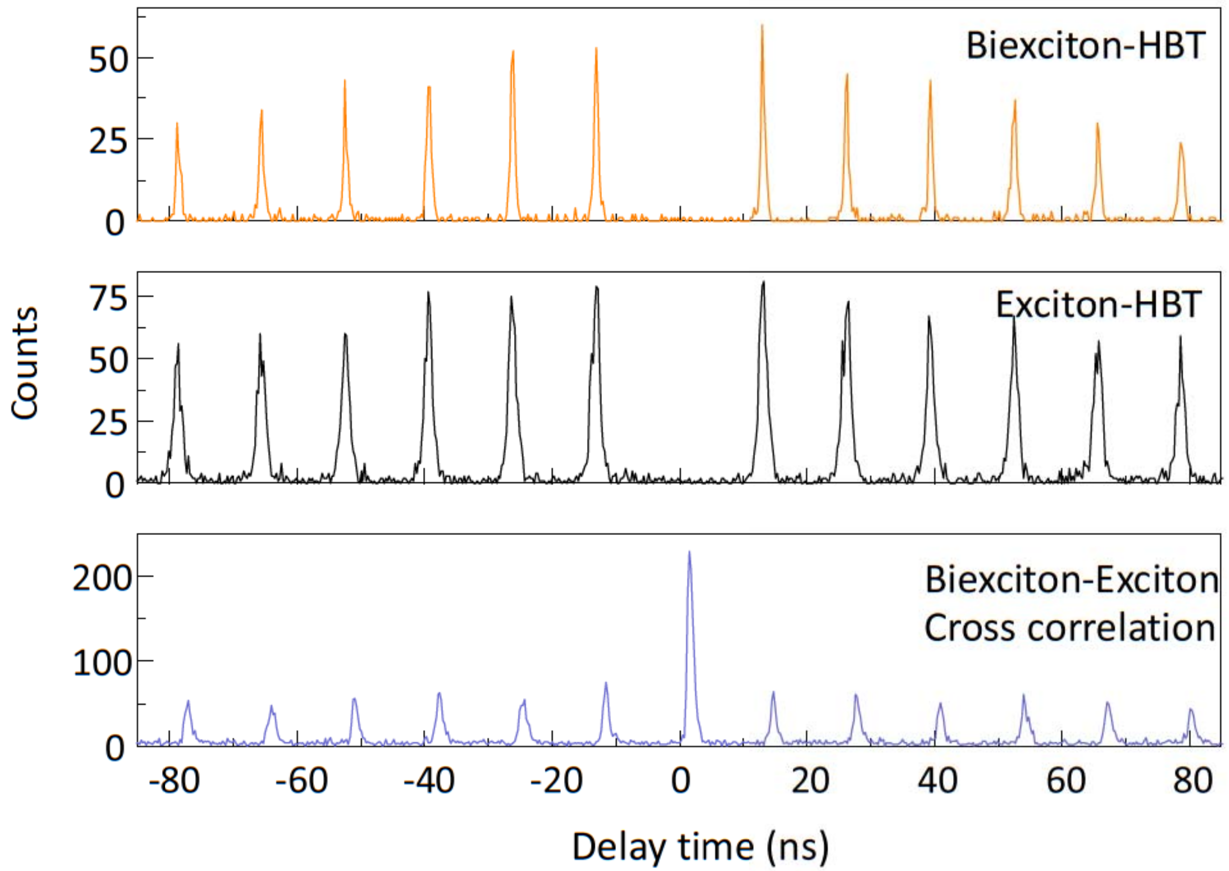


- Far red-detuned laser
- Saturation seen in exciton and (not so much in biexciton)

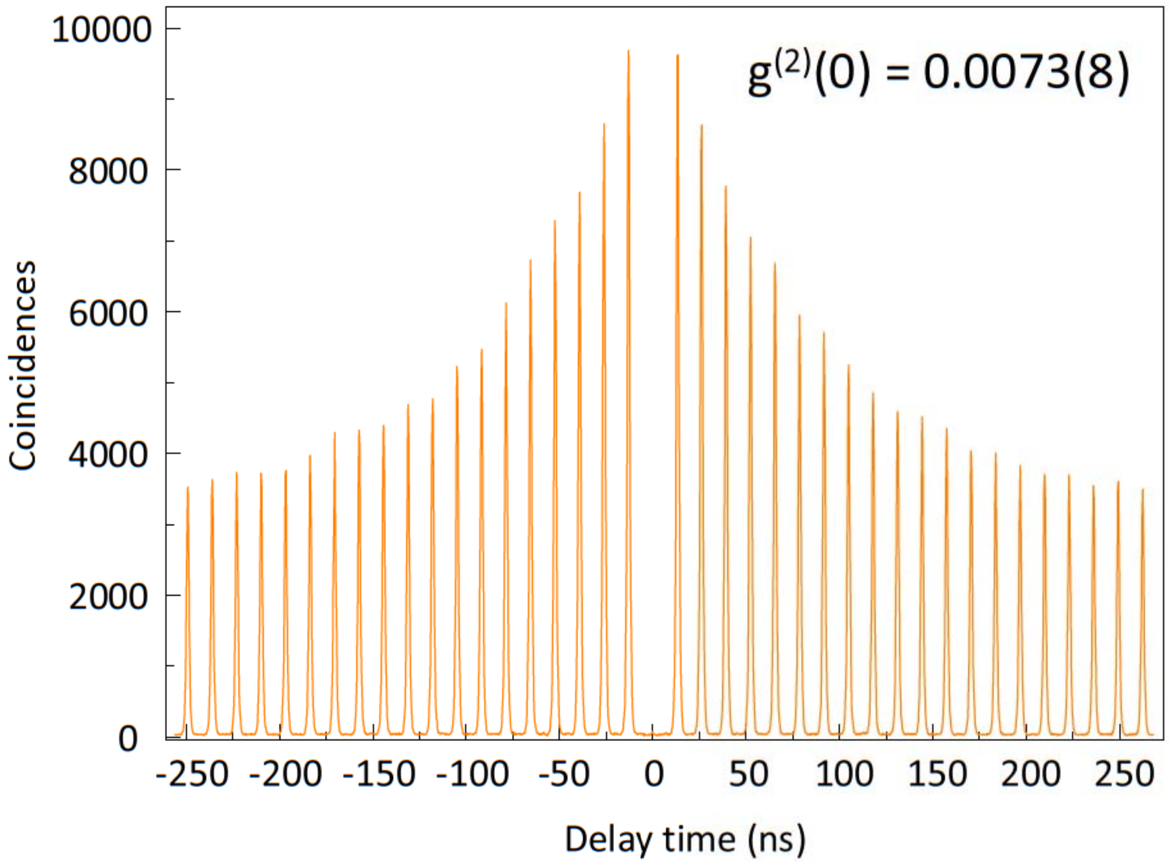
Photon Statistics (Hanbury Brown – Twiss measurment)



HANBURY-BROWN-TWISS CORRELATIONS

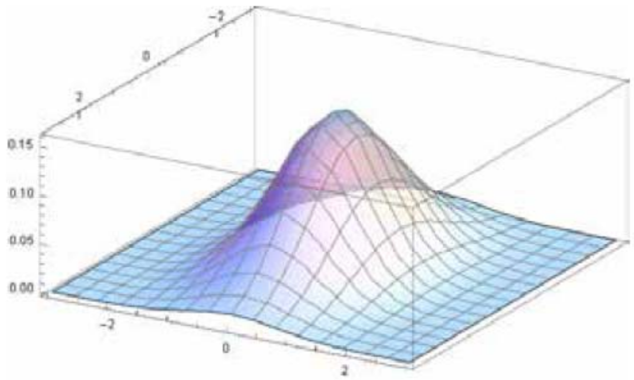


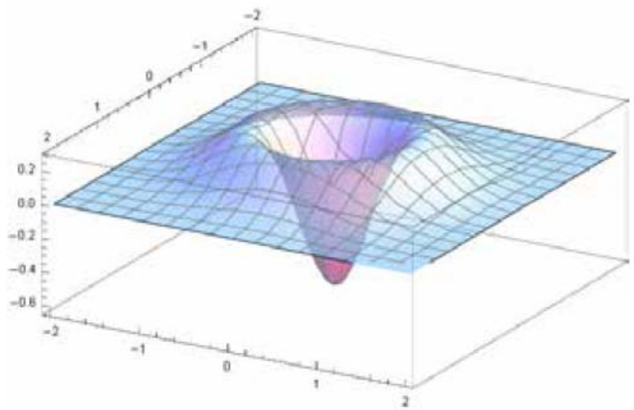
A REALLY NICE SINGLE PHOTON SOURCE ☺



H. Jayakumar et al., PRL **110,** 135505 (2013)

(NON-) GAUSSIAN STATES

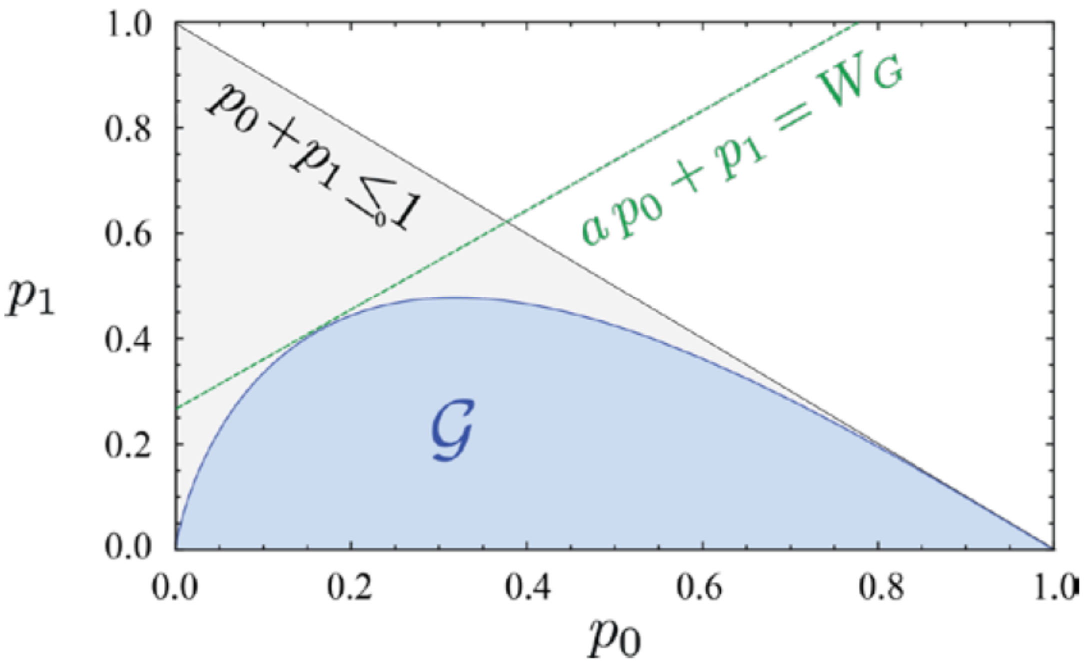




- Gaussian
  - Vacuum
  - Coherent
  - Squeezed
  - Mixtures thereof
- Non-Gaussian
  - Single photon
  - Fock states
  - Schrödinger cats
  - Photon-subtracted
  - …

Need high efficiency to measure negative Wigner function!

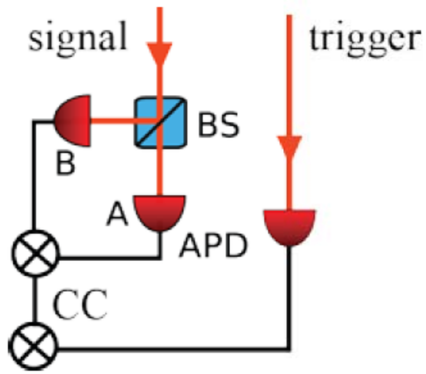
DETECTING NON-GAUSSIAN STATES OF LIGHT



$$p_0 = 1 - \frac{R_1 + R_2}{R_0}$$

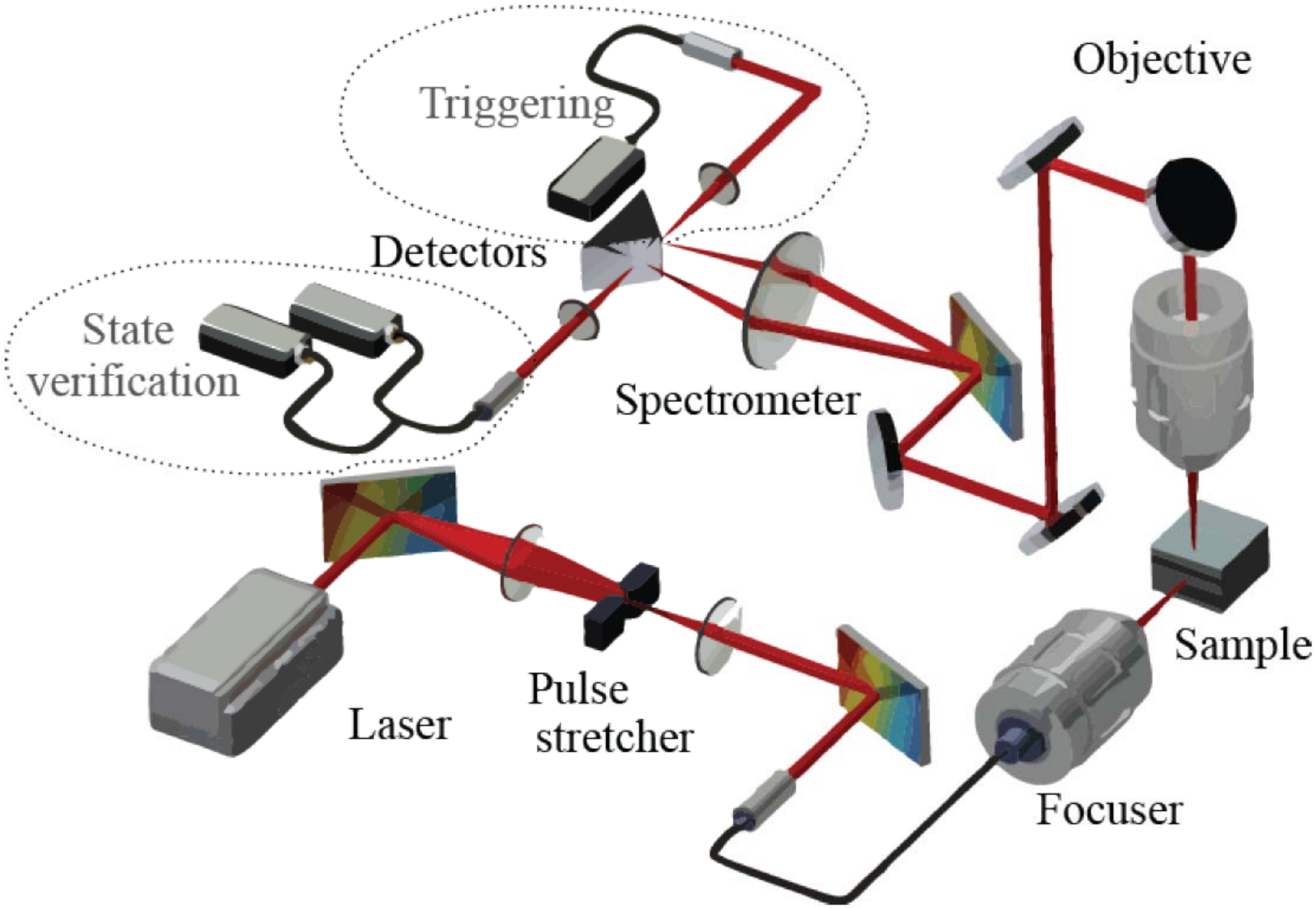
$$p_1 = \frac{R_1 - R_2}{R_0}$$

$$p_{2+} = 1 - p_0 - p_1$$

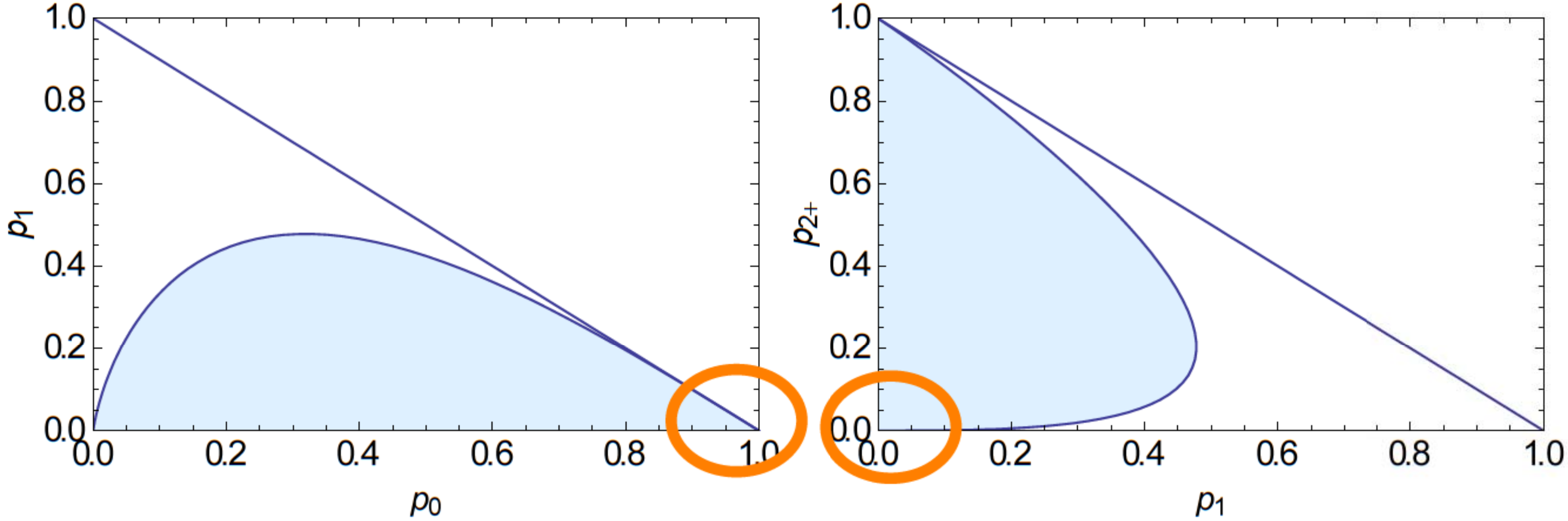


Filip & Mišta, PRL **106,** 200401 (2011)
Ježek et al., PRL **107,** 213602 (2011)

Non-gaussianity from quantum dots



Criterion at low efficiency



- Even at low efficiencies there is a sizable region of allowed non-Gaussian states
- Measurement times become very long to reduce error bars

NON-GAUSSIANITY RESULTS

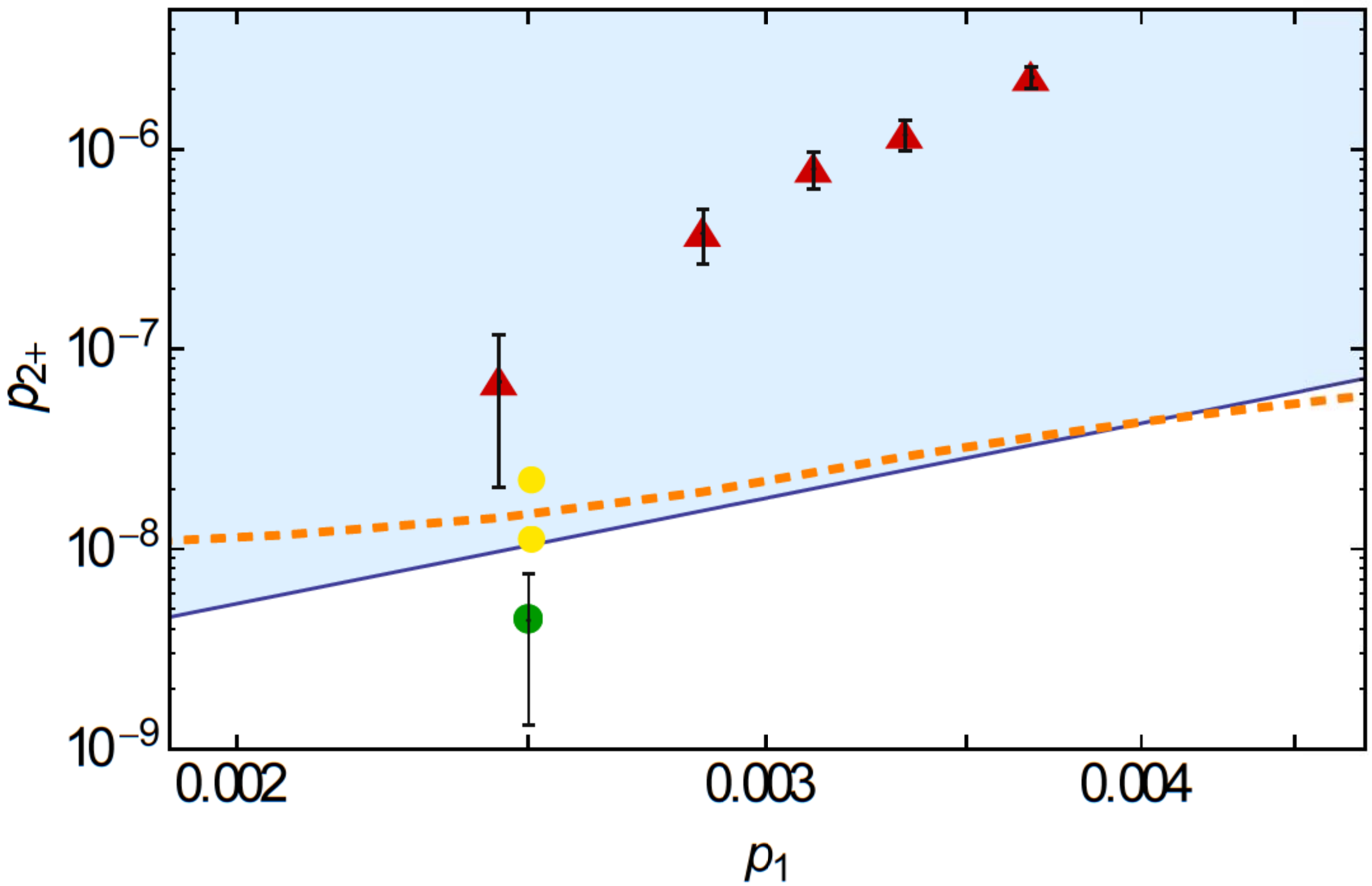
Above-band excitation

w [ns]	p_0	$10^3\ p_1$	$10^8\ p_{2+}$	$10^8\ \Delta W$
1.536	0.997553(6)	2.446(6)	6.9(49)	-5.9(49)
2.084	0.997140(7)	2.859(7)	39. (12)	-37. (12)
2.560	0.996885(7)	3.144(7)	81. (17)	-79. (17)
3.072	0.996660(7)	3.339(7)	119. (20)	-117. (20)
3.840	0.996319(8)	3.678(8)	231. (29)	-228. (29)

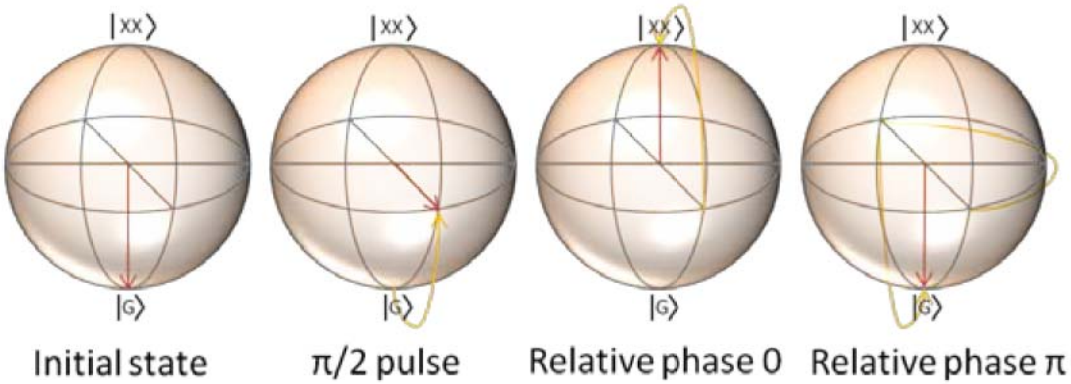
Two-photon resonant excitation

w [ns]	p_0	$10^3\ p_1$	$10^8\ p_{2+}$	$10^8\ \Delta W$
5.12	0.997498(2)	2.502(2)	0.44(31)	**0.60(31)**
10.24	0.997490(2)	2.510(2)	1.10(49)	–0.05(49)
10.50	0.997490(2)	2.510(2)	2.21(70)	–1.16(70)

Non-gaussianity results

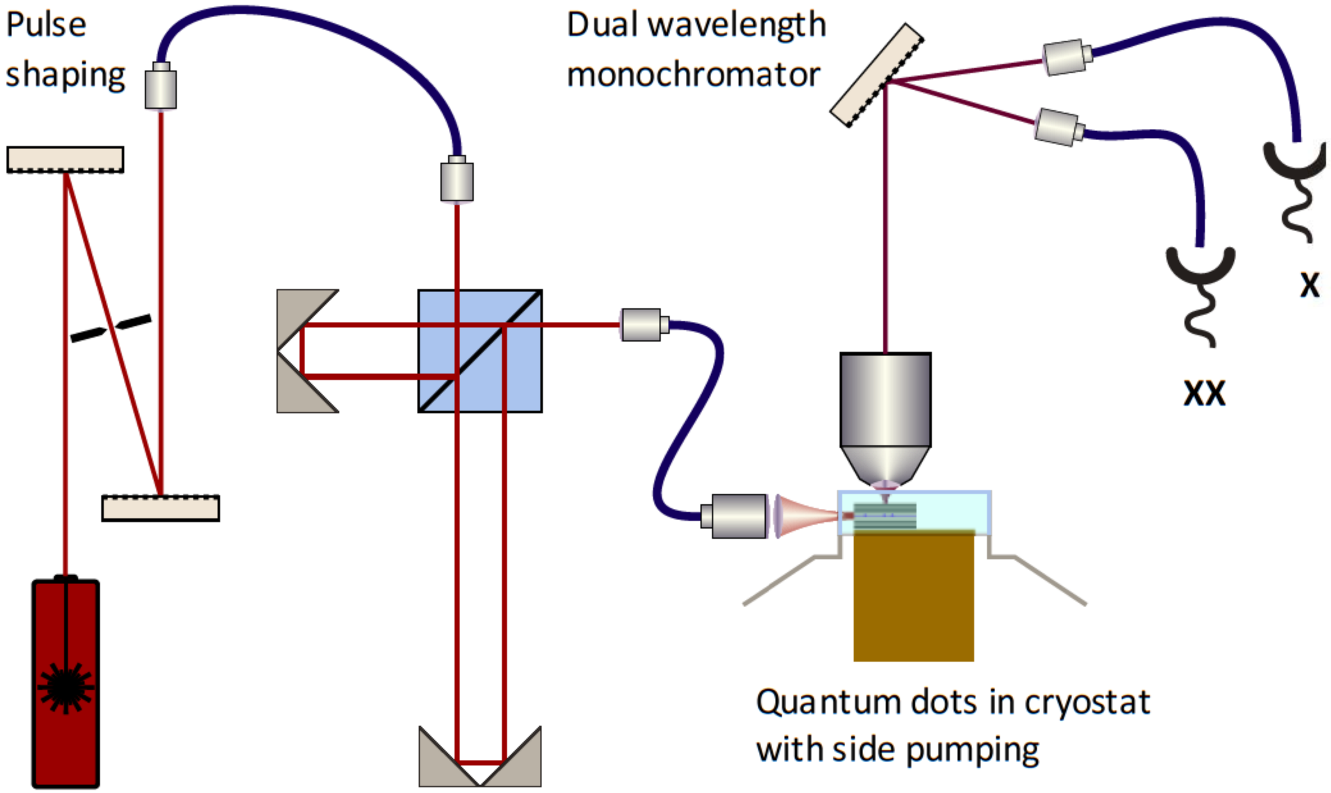


COHERENT MANIPULATION

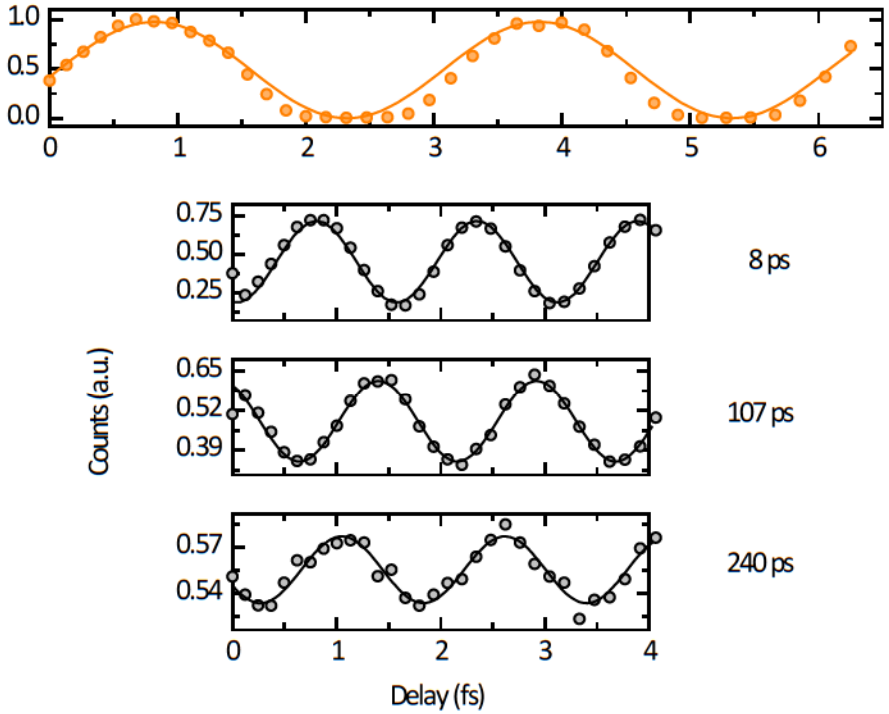


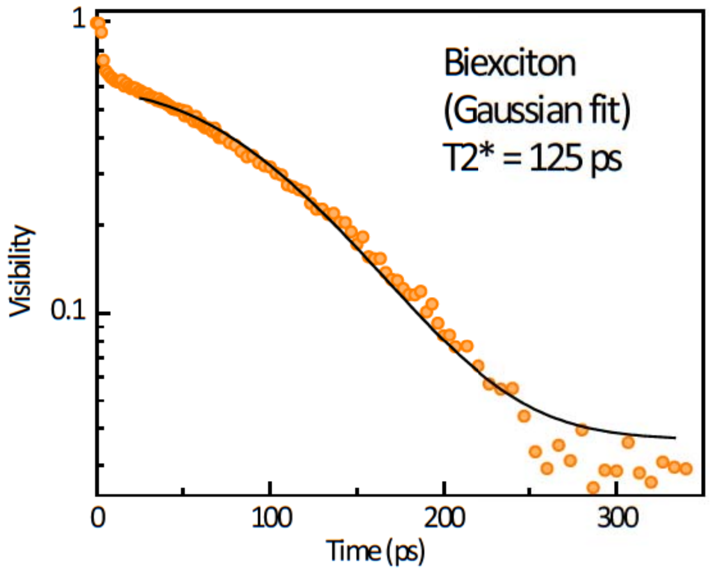
- Two-pulse coherent manipulation
- Two π/2 pulses with a fixed relative phase
- Phase of superposition state evolves along the equator.
- Ramsey interference

Ramsey Experiment



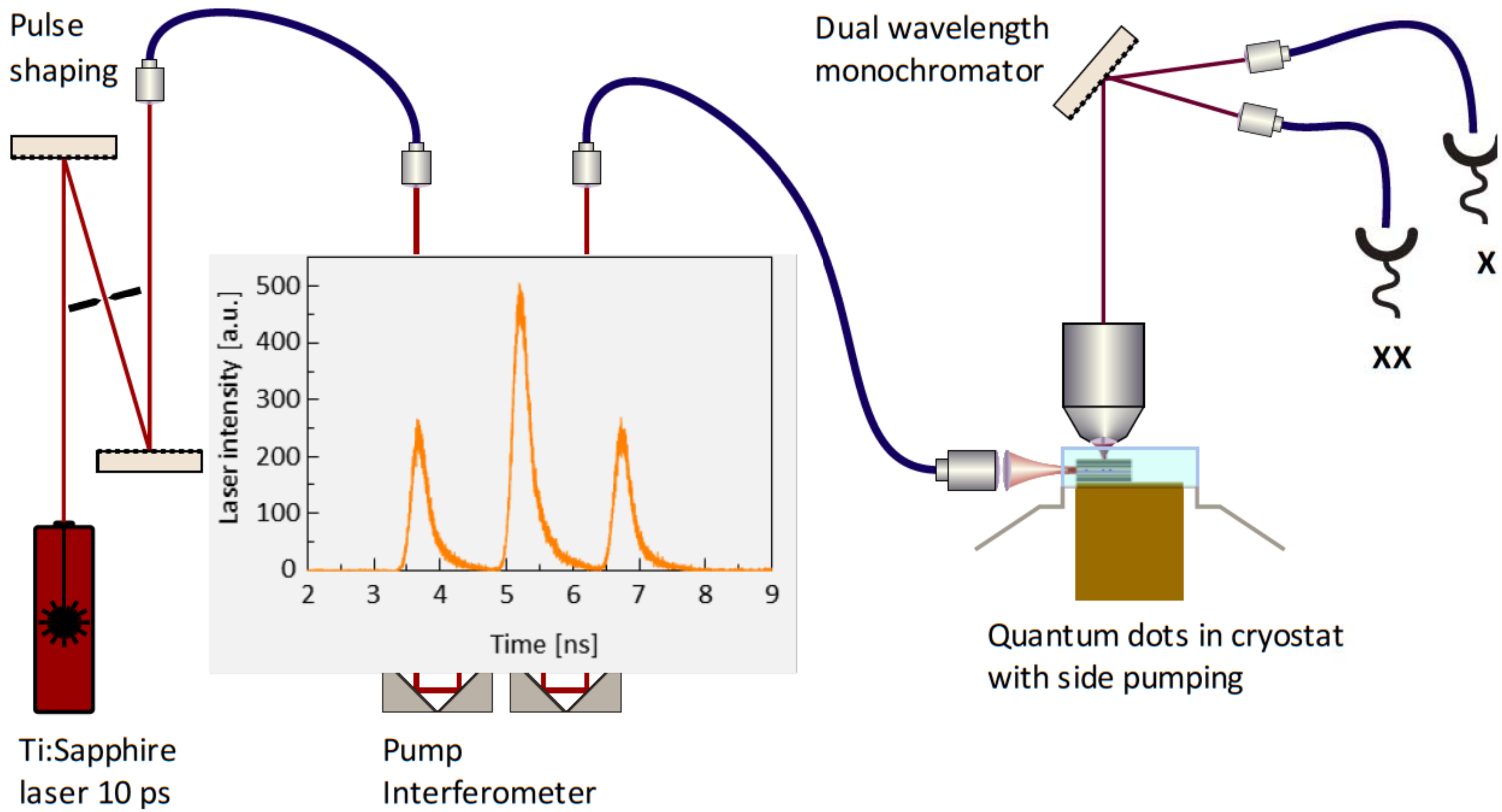
COHERENT MANIPULATION (RAMSEY INTERFERENCE)



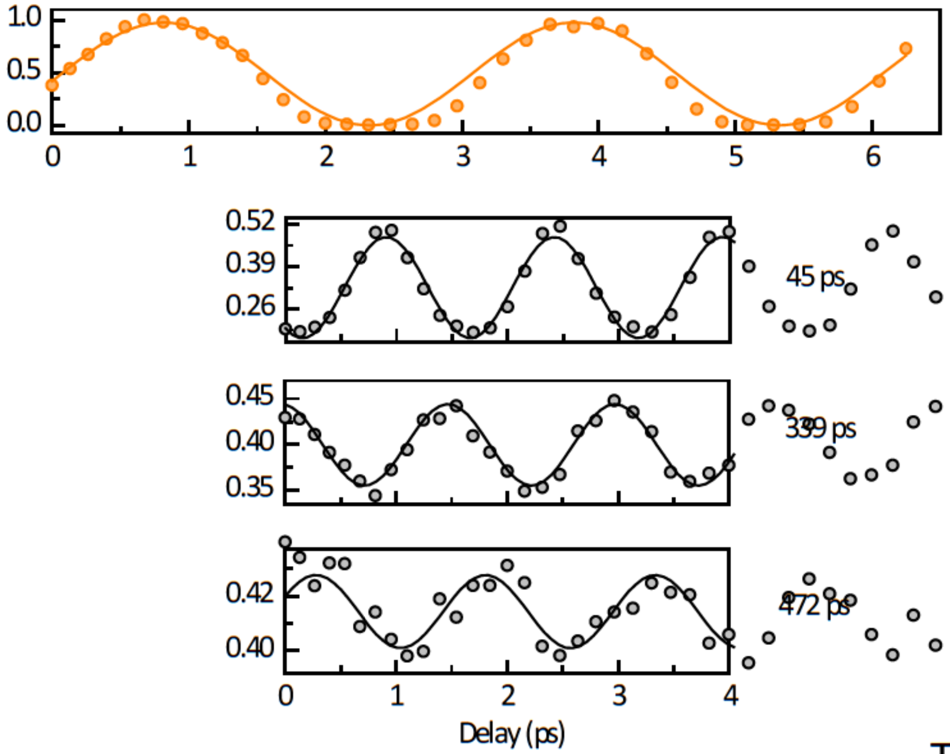


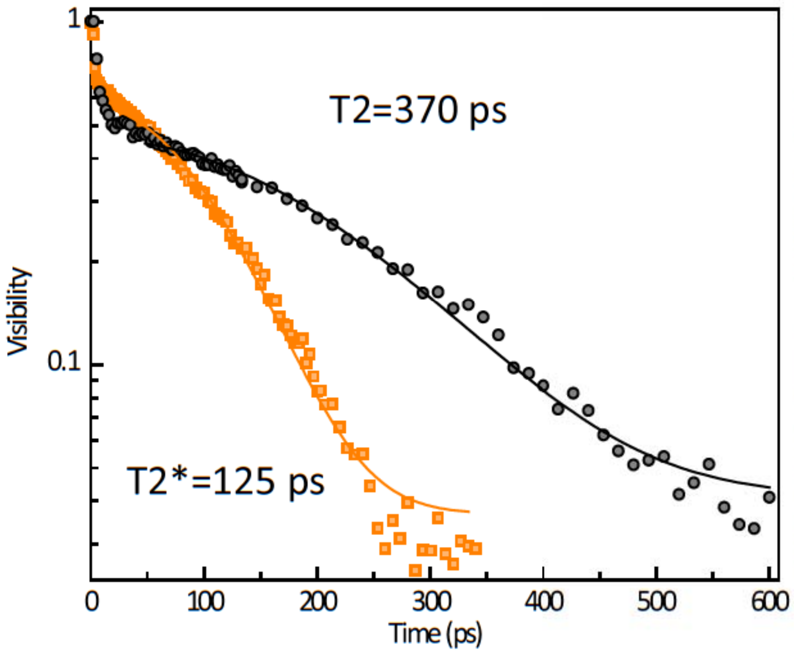
- Laser interference up to ~ 5ps
- Interference fringe frequency doubles – two-photon excitation
- Gaussian exponential – Inhomogeneous broadening

ECHO EXPERIMENT



ECHO-RAMSEY INTERFERENCE

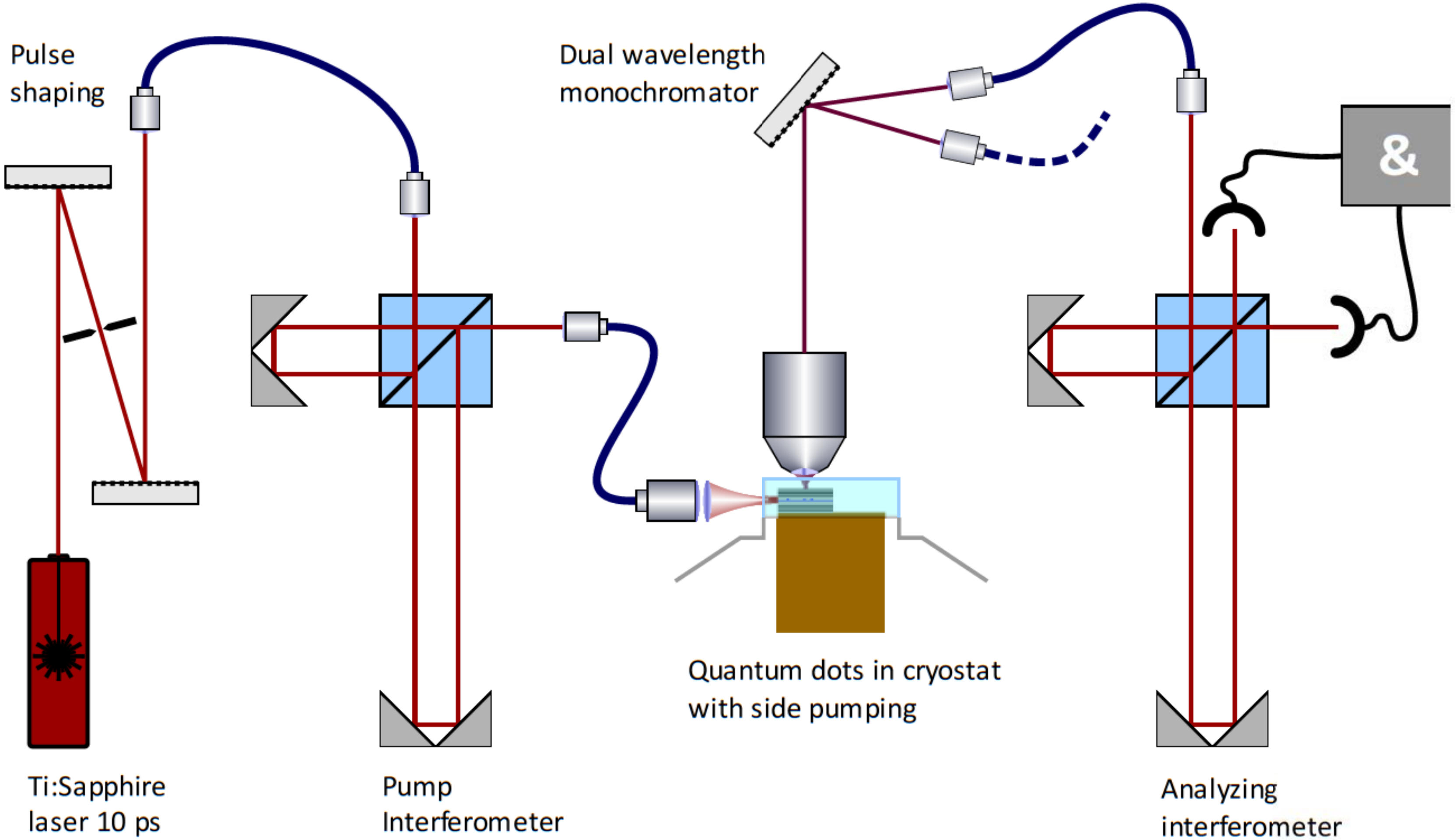




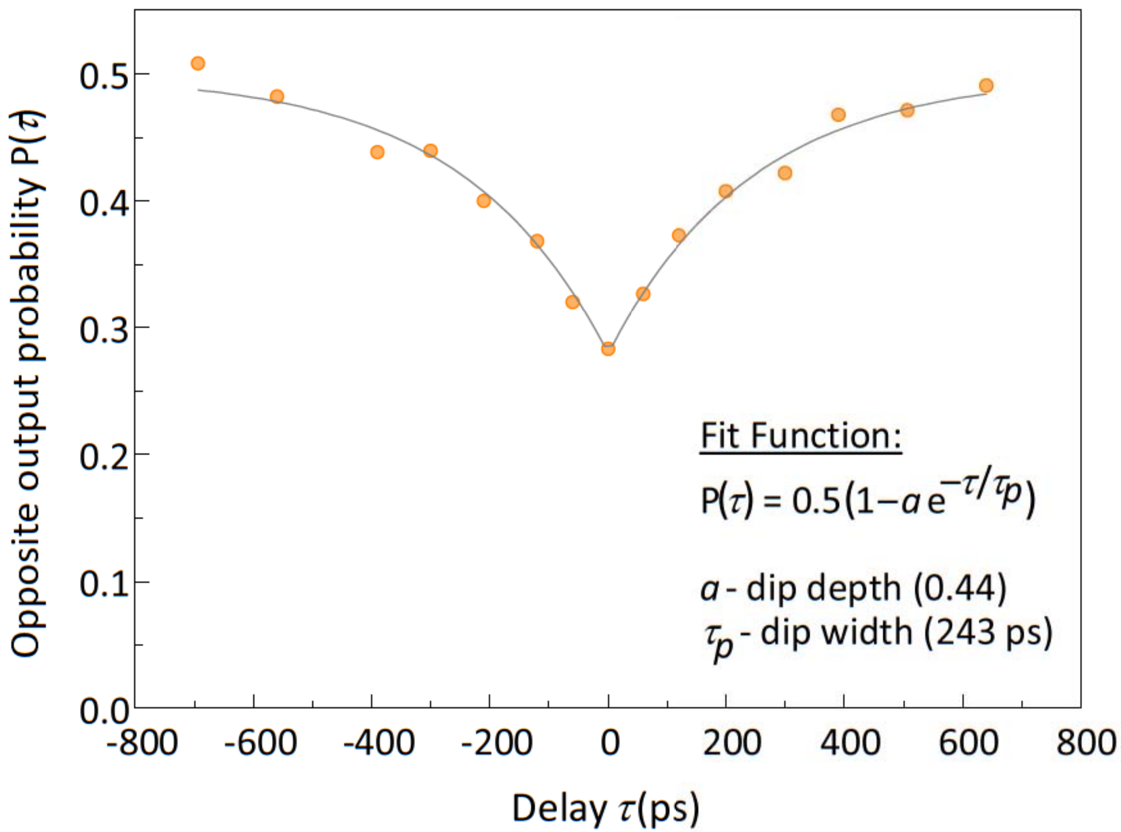
T2 – still not transform limited (810 ps)

H. Jayakumar et al., PRL **110,** 135505 (2013)

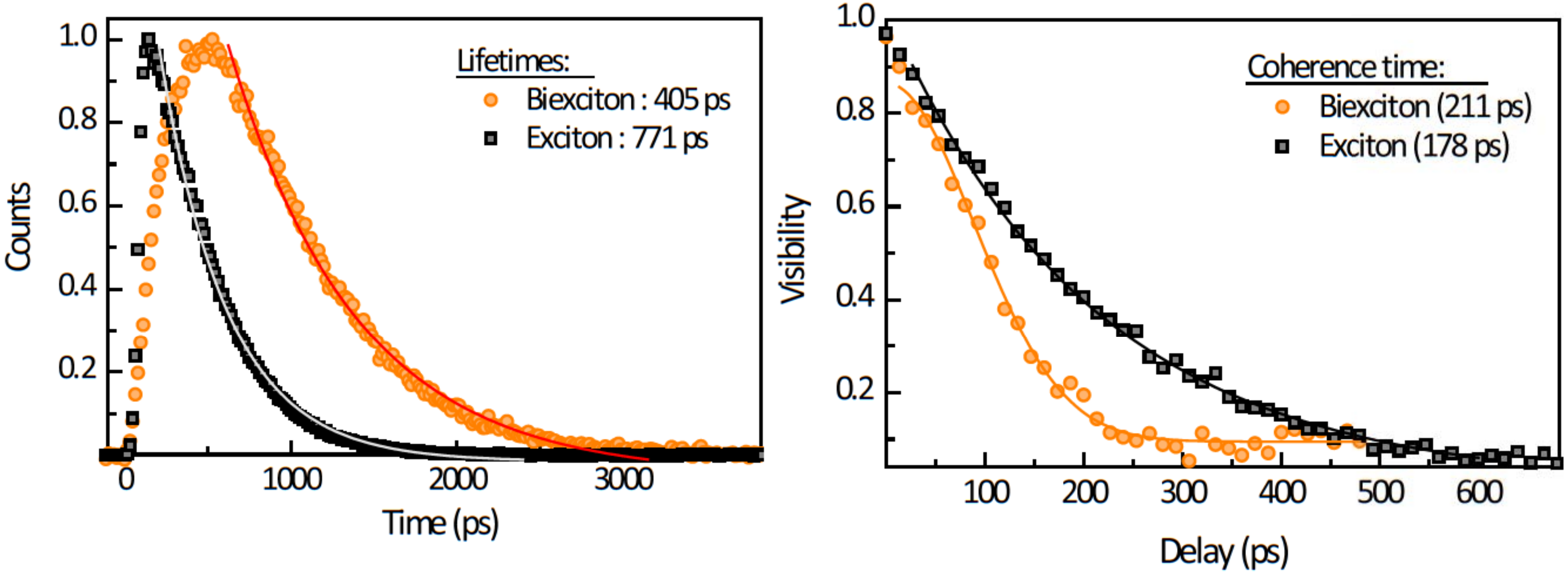
HONG-OU-MANDEL INTERFERENCE BETWEEN SUCCESSIVE PHOTONS



HONG-OU-MANDEL INTERFERENCE BETWEEN SUCCESSIVE PHOTONS



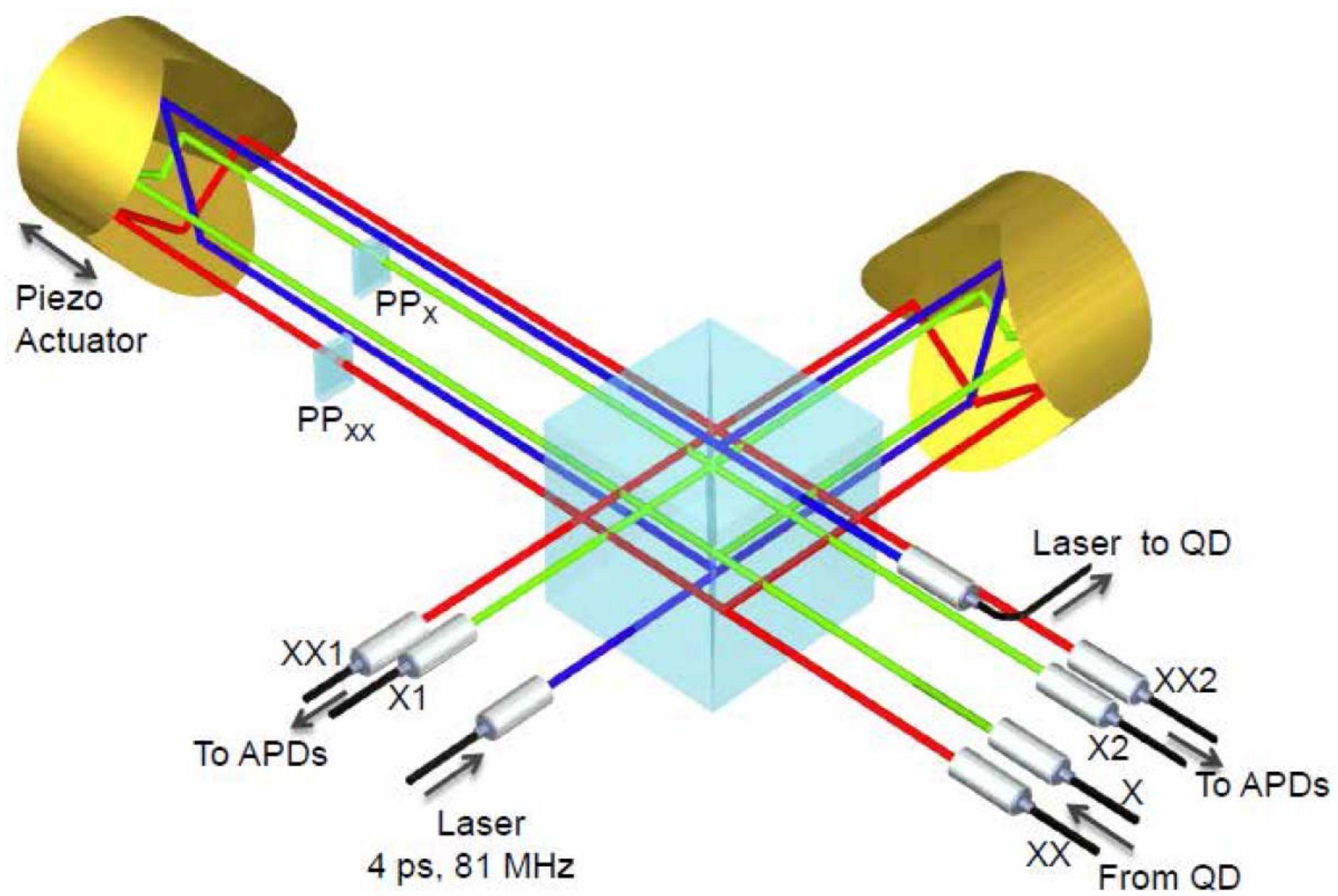
Photon characterization



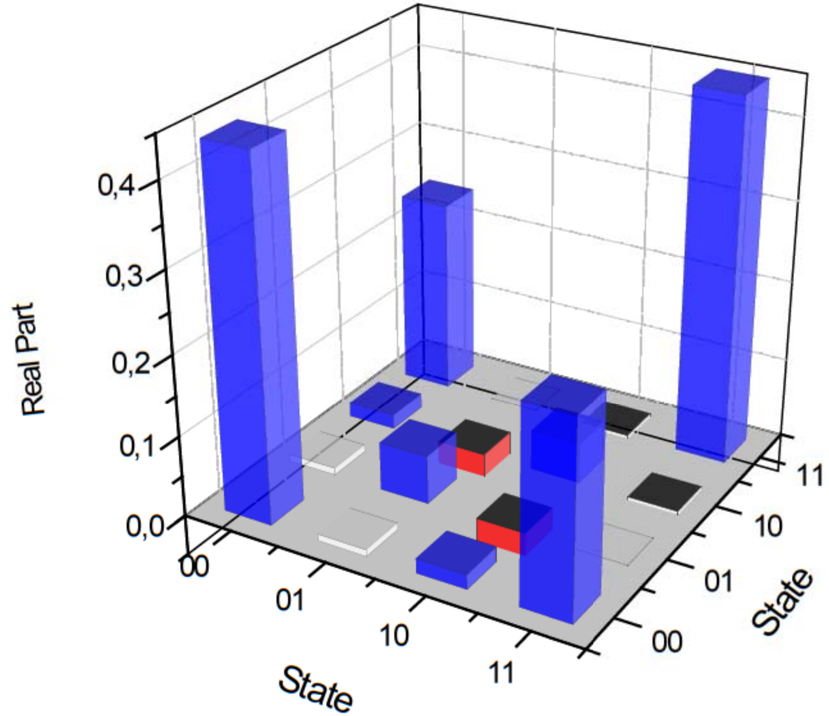
Fourier-Transform limited: Coherence time / Lifetime = 2

Measured ratios: Biexciton : 0.52
Exciton : 0.23

TIME-BIN ENTANGLEMENT



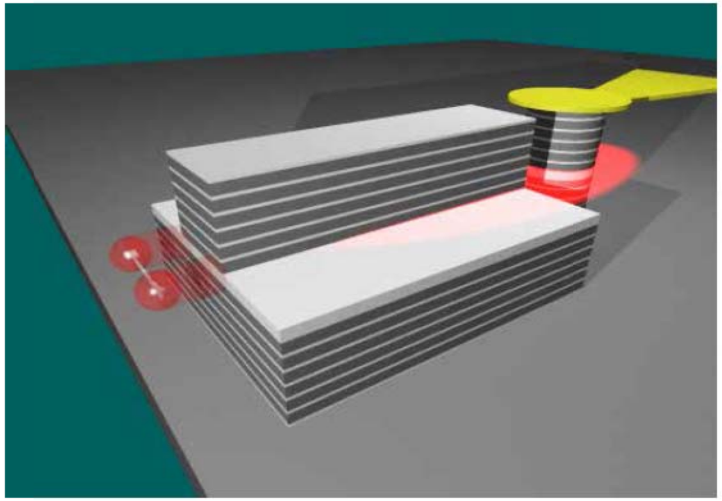
TIME-BIN ENTANGLEMENT



- So far limited entanglement: Tangle 0.17(3)
- Improve classical correlation by better time selection
- Improve two-photon interference by wavepacket shaping

CONCLUSIONS

- **Semiconductor waveguides**
  - Full integration



- **Quantum dots**
  - single photons
  - single pairs