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Direct Observation of Spontaneous Parametric Polariton Scattering

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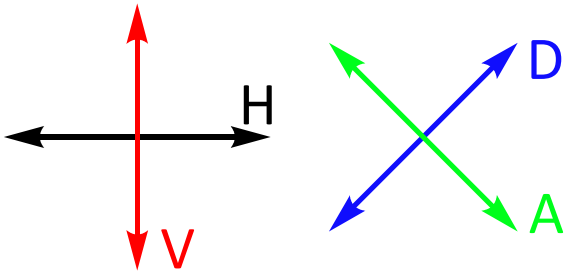
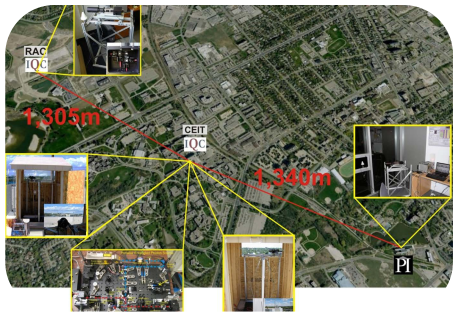
Entanglement

$$|\psi\rangle = \frac{1}{\sqrt{2}}[|\mathrm{H}\rangle_1|\mathrm{H}\rangle_2 + |\mathrm{V}\rangle_1|\mathrm{V}\rangle_2]$$

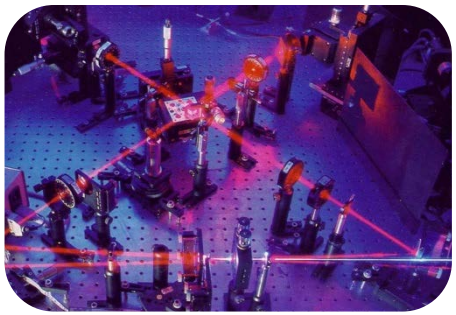
$$|\mathrm{H}\rangle|\mathrm{H}\rangle + |\mathrm{V}\rangle|\mathrm{V}\rangle = |\mathrm{D}\rangle|\mathrm{D}\rangle + |\mathrm{A}\rangle|\mathrm{A}\rangle$$



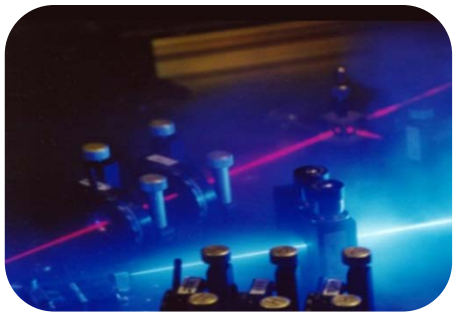
Applications of Entanglement



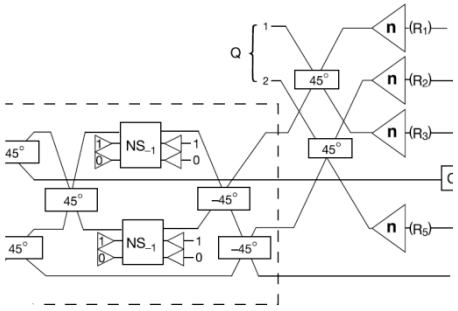
Quantum Cryptography



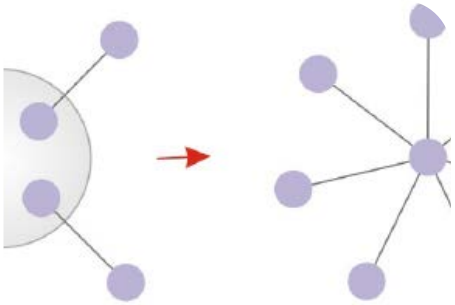
Teleportation



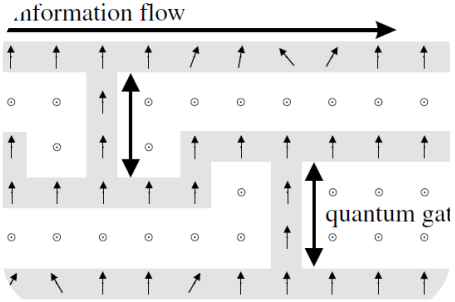
Purification



Linear Optical Quantum Computing



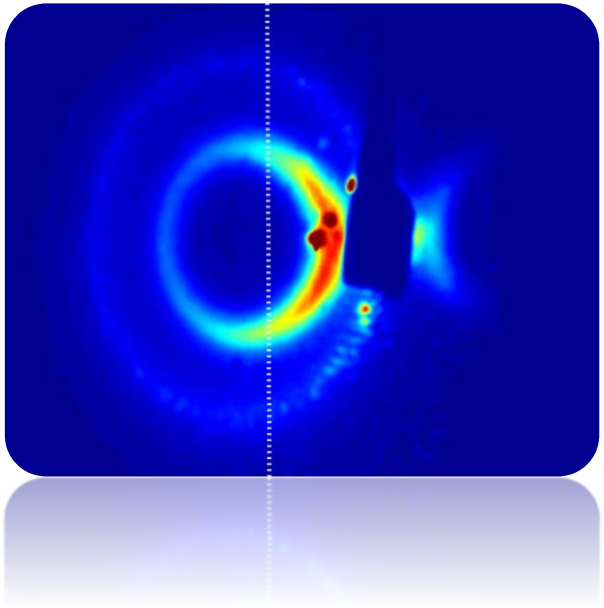
Multipartite Entanglement



Measurement-based Quantum Computing

Contents

- Entangled exciton-polaritons
- Background processes
  - Double cavity Rayleigh scattering
- Correlation measurements
- Outlook



Group

Polariton Team
Post-Doc: *Zoltán Vörös*
PhD Students: *Patrick Mai, Mathias Sassermann*
MSc Students: *Judith Wörle, Lukas Einkemmer*

Collaborations and funding

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Christian Schneider, Martin Kamp
(U. Würzburg)

Stefano Portolan
(U. Southampton)

FWF
Der Wissenschaftsfonds.

erc

ÖAW
Österreichische Akademie der Wissenschaften

CIFAR
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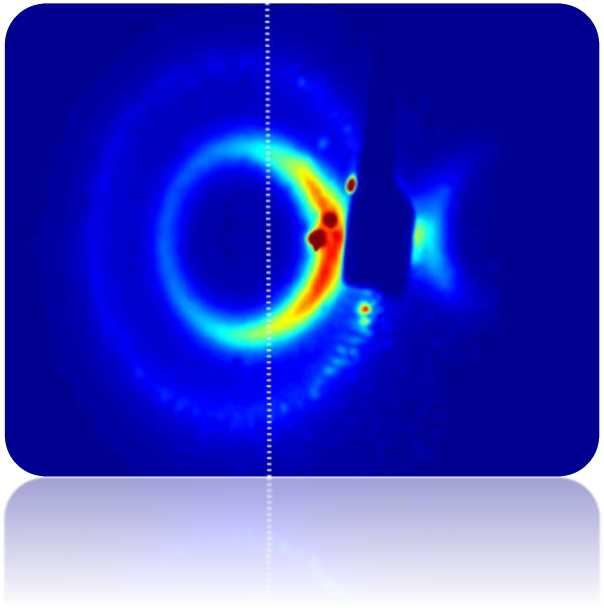
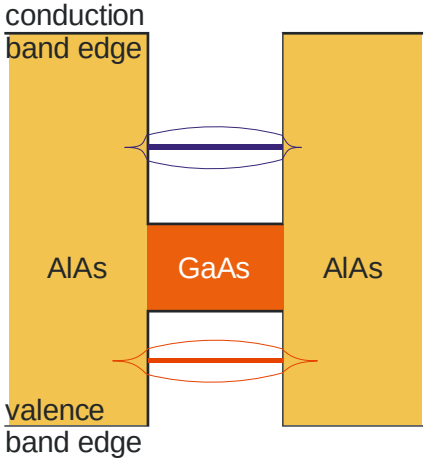
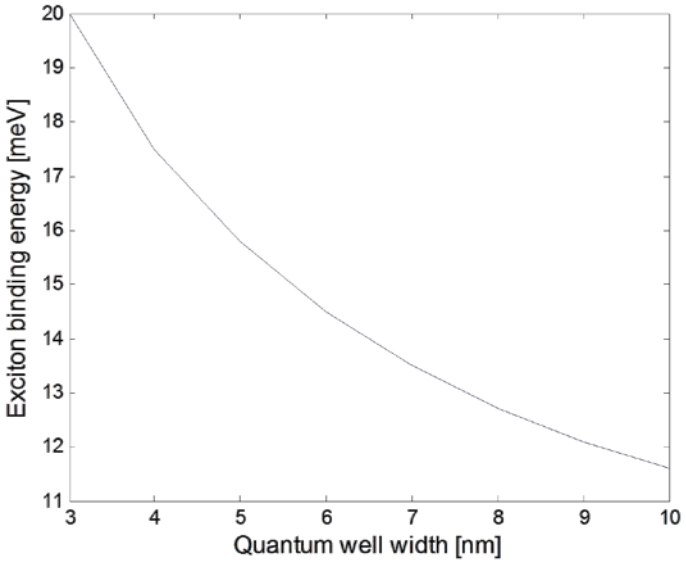


Quantum Well Excitons

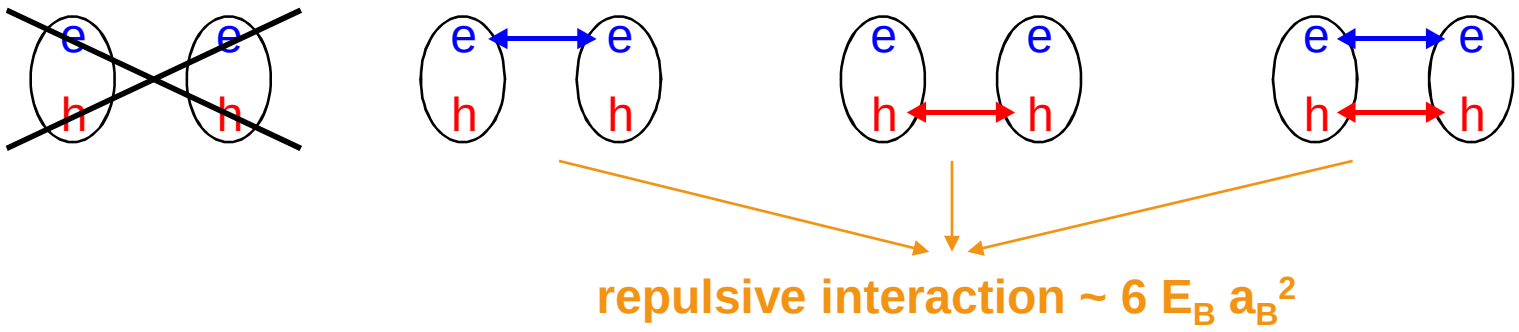
- Quantum wells increase binding energy, if width is smaller than 3D exciton Bohr-diameter
- Increased oscillator strength
- Easy integration into cavities
- Binding energies can dominate optical properties up to room temperature
- Quantum well-excitons can be excited in a spin polarized way in contrast to bulk excitons





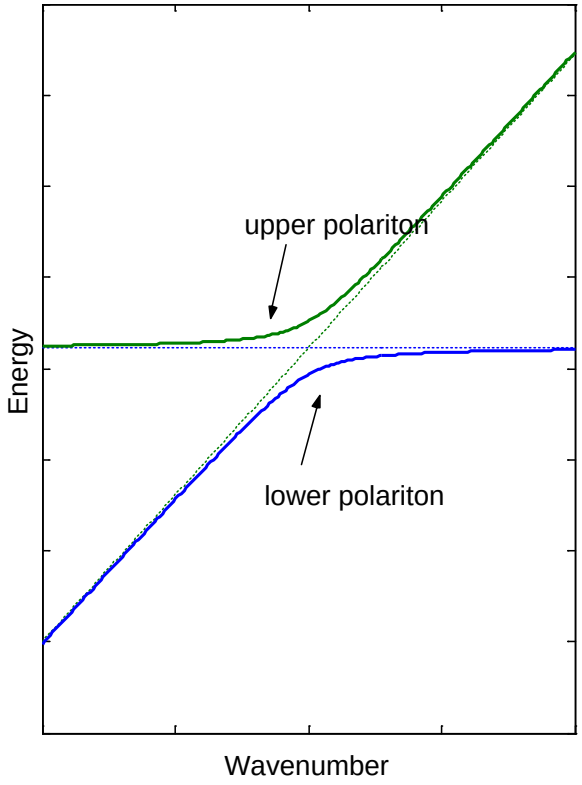
Exciton-Exciton Interaction

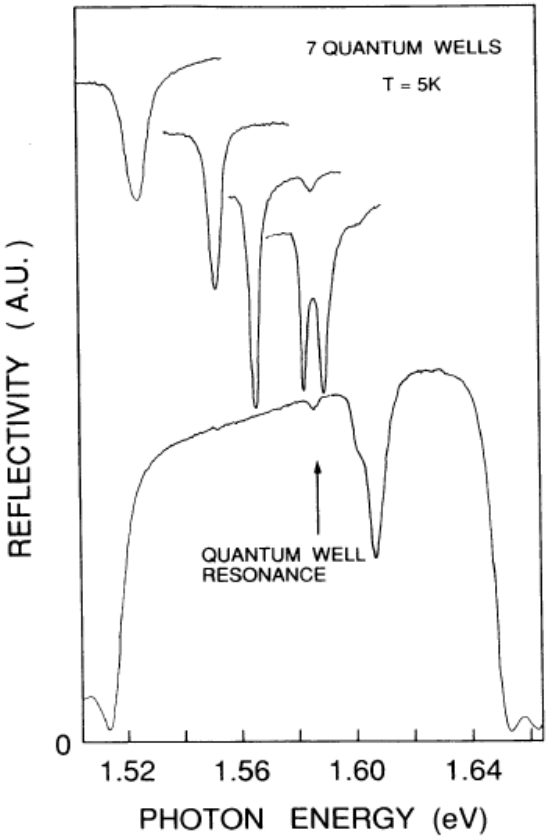
Electron and hole exchange interaction induces long-ranged repulsive interaction for same-spin excitons



Interaction strength: 6 $E_B\, a_B^2 \approx 5\times10^{-11}$ meV cm^2

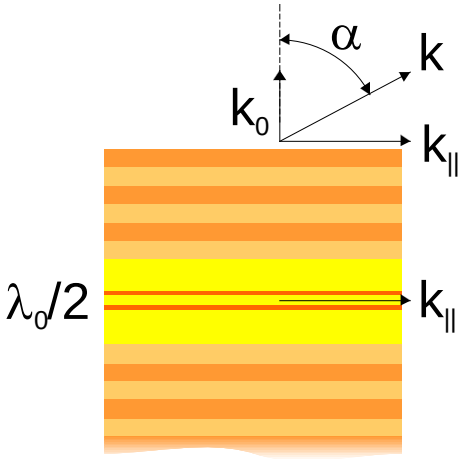
Strong Coupling of Excitons



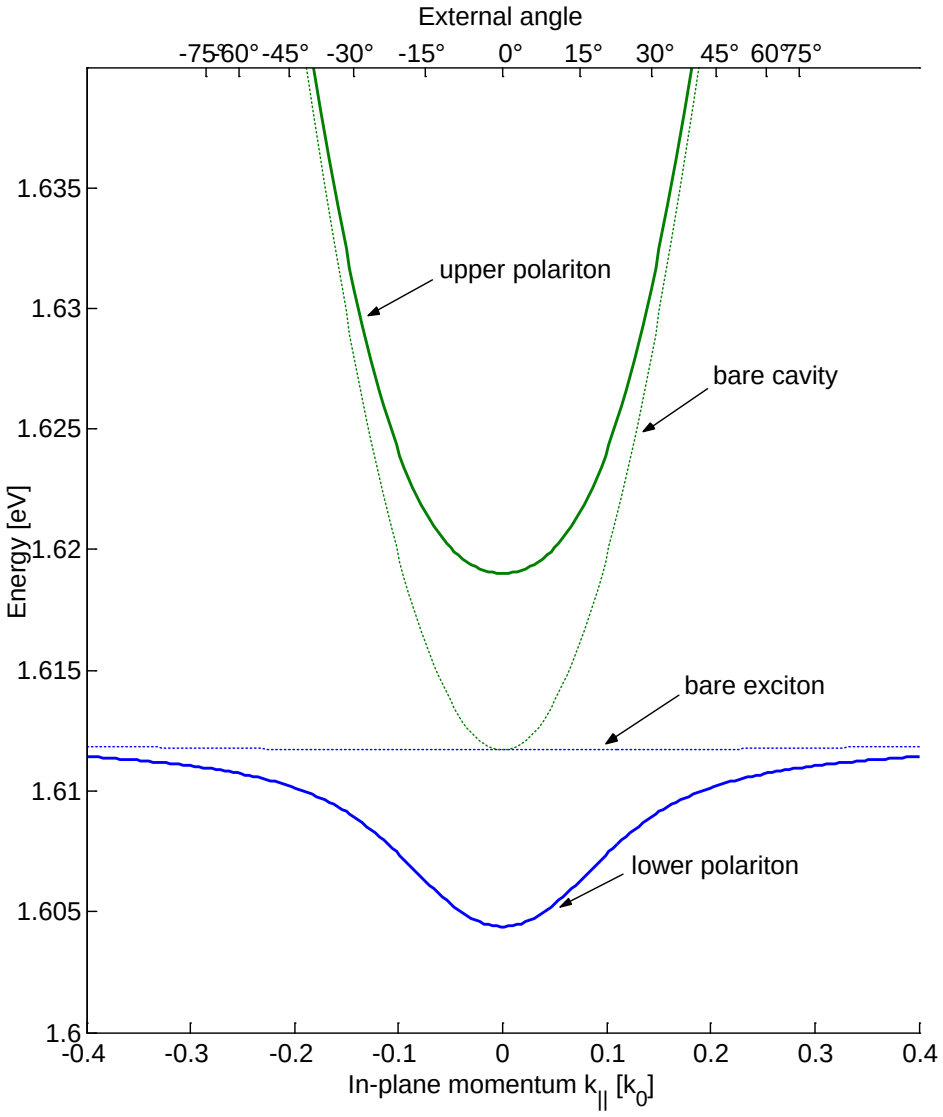


- J. J. Hopfield (1958) introduces the polariton as a quasiparticle
- C. Weisbuch et al. (1992) observe strong coupling in a GaAs/AlAs microcavity

Microcavity Exciton-Polaritons



Lower polariton effective mass is many orders of magnitude lighter than exciton mass, electron mass!



Exciton and Exciton-Polariton Scattering

- Exciton-exciton interaction strength: $6\ E_B\ a_B^2 \approx 5 \cdot 10^{-11}$ meV cm^2
- Polaritons are superpositions of excitons and photons:

$$\begin{pmatrix} b \\ a \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} p_L \\ p_U \end{pmatrix}$$

- Exciton-exciton interaction

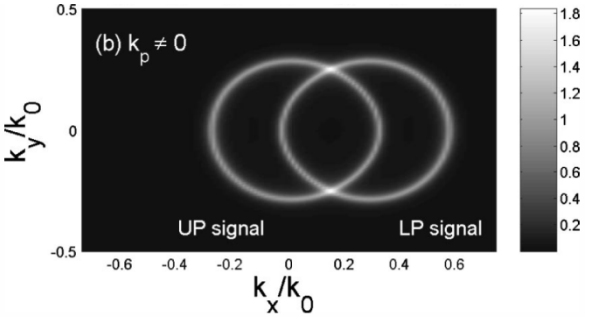
$$H_{XX} = \frac{1}{2} \sum \frac{a_B^2}{S} \frac{6e}{\epsilon a_B} b^\dagger_{\mathbf{k}+\mathbf{q}} b^\dagger_{\mathbf{k}'-\mathbf{q}} b_{\mathbf{k}} b_{\mathbf{k}'}$$

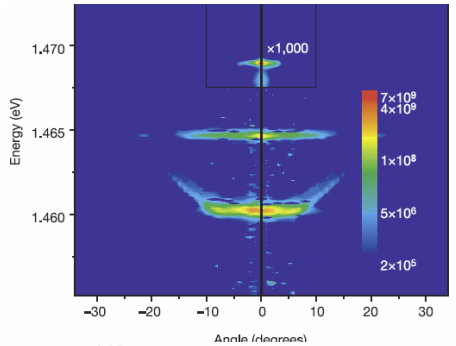
- Polariton Saturation

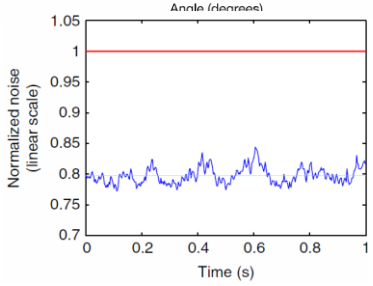
$$H_{XC}^{\text{sat}} = -\sum \frac{\hbar \Omega_R}{n_{\text{sat}} S} a^\dagger_{\mathbf{k}+\mathbf{q}} b^\dagger_{\mathbf{k}'-\mathbf{q}} b_{\mathbf{k}} b_{\mathbf{k}'}$$

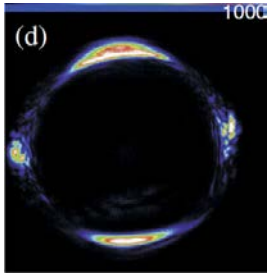
Quantum Correlations from Polariton Scattering

- Parametric oscillation
  Baumberg, et al., Phys. Rev. B **62**, R16247 (2000).
  Diederichs et al., Nature **440,** 904 (2006).
- Phase matching
  Dasbach et al. , PRB **66,** 201201(R) (2002).
  Langbein, Phys. Rev. B **70**, 205301 (2004).
- Entanglement
  Ciuti, PRB **69,** 245304 (2004).
  Savasta et al., PRL **94,** 246401 (2005).
  Portolan et al., J. Phys. **210,** 012033 (2010).
  Portolan, et al., New J. Phys. **16** (2014).
- Squeezing
  J. P. Karr, et al., Phys. Rev. A **69**, 031802 (2004).
  T. Boulier, et al., Nat Commun **5** (2014).
- Polariton-polariton correlation
  Langbein, Phys. Stat. Sol. **242,** 2260 (2005).
  Romanelli et al., PRL **98,** 106401 (2007).
  Ardizzone et al., PRB **86,** 041301 (2012).





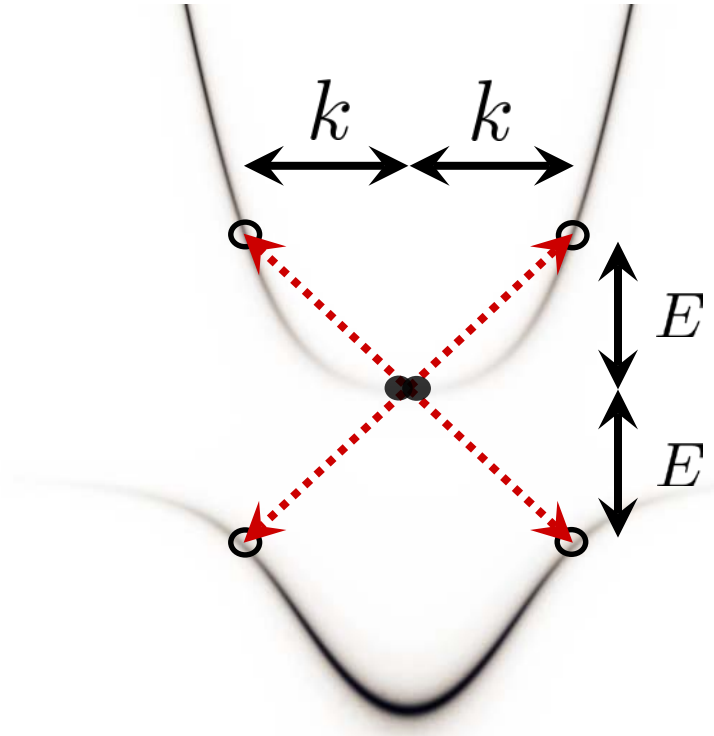




Entanglement from polariton scattering

Energy and momentum conservation in elastic scattering process

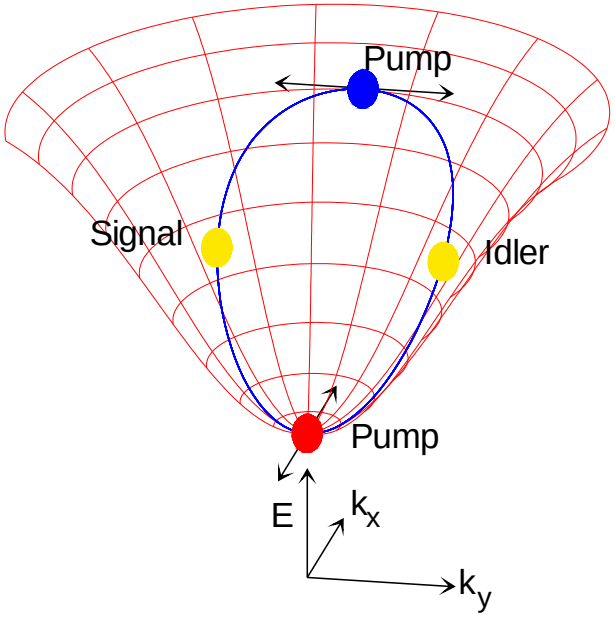
$$2k_p = k_1 + k_2$$
$$2E_p = E_1 + E_2$$

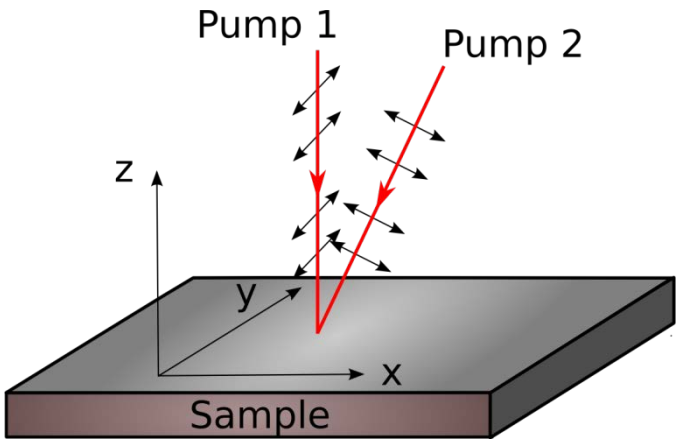


C. Ciuti, Phys. Rev. B **69** (2004)

Polarization Entanglement

- Varying the pump polarizations controls entangled state type

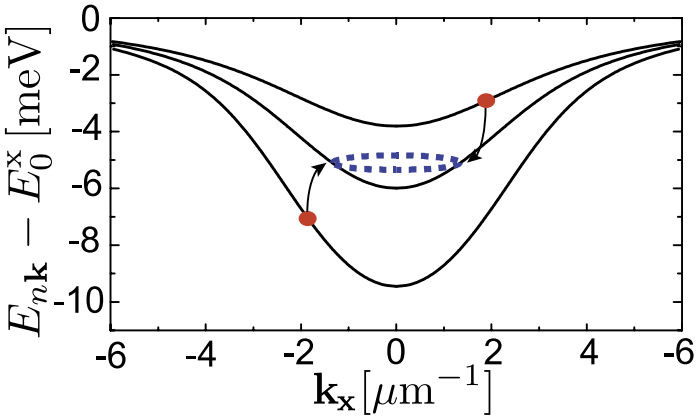


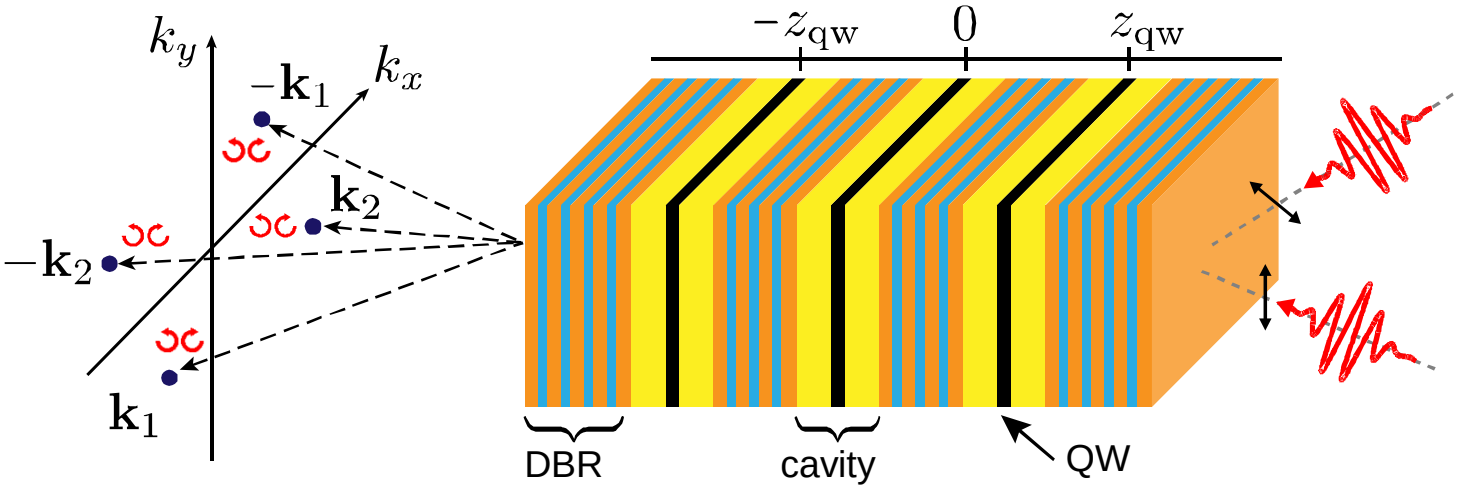


Portolan et al., J. Phys **210,** 012033 (2010).

Hyperentanglement

- Simultaneous entanglement in multiple degrees of freedom
- Use cross-polarized pumps and multiple output modes
- All branches below exciton reservoir





Portolan, et al., New J. Phys. **16,** 063030 (2014).

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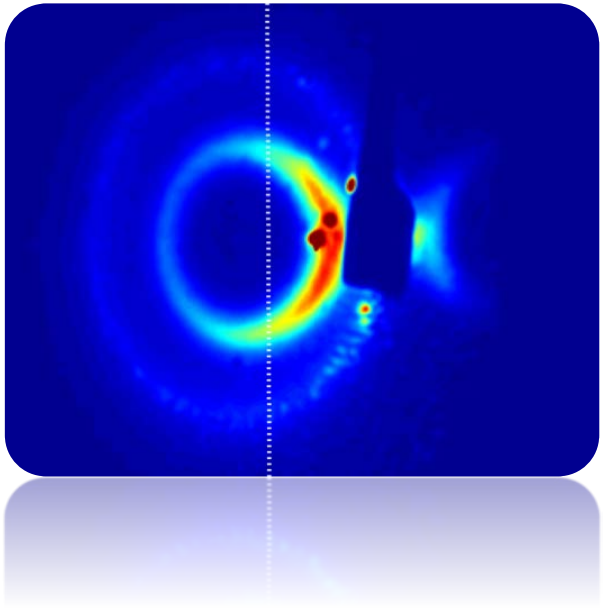


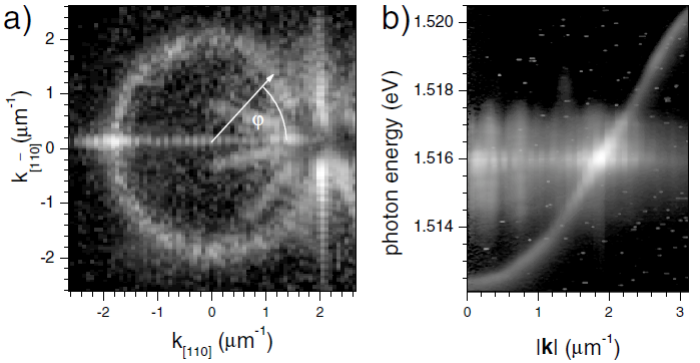
Background Mechanisms

- Incoherent Luminescence
  - ➔ slow component: time-resolve
  - ➔ fast component ???
  - ➔ avoid exciton reservoir

- Resonant Rayleigh scattering
  - ➔ non-degenerate phase-matching

- Surface Rayleigh scattering
  - ➔ transmission geometry

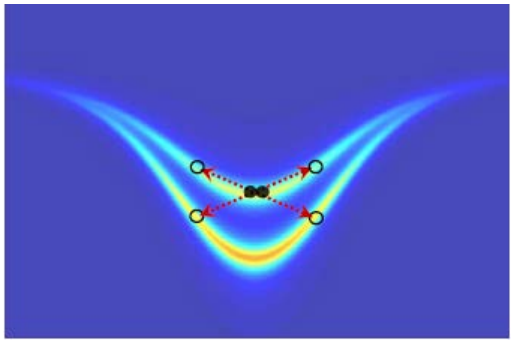
- Broadening

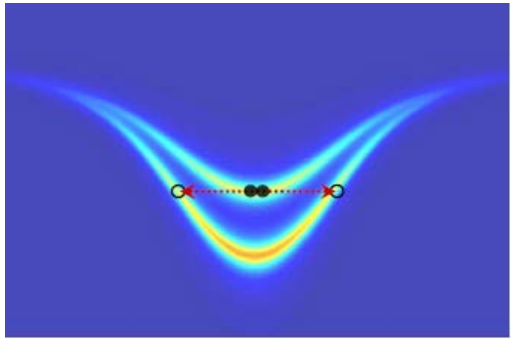


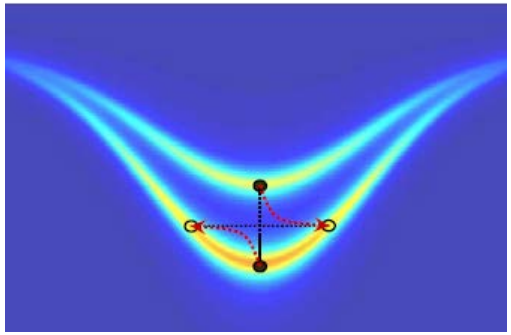
Langbein & Hvam, PRL **88**, 047401 (2002).

Double Cavity Phase Matching

- Double cavity results in two lower and two upper polariton modes
- Protection from exciton reservoir through energy barrier
- More symmetric scattering channels
- Easier handling than photonic wires

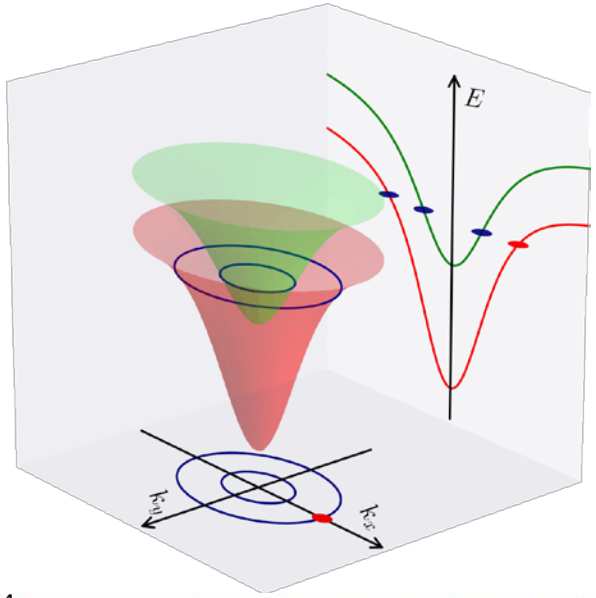


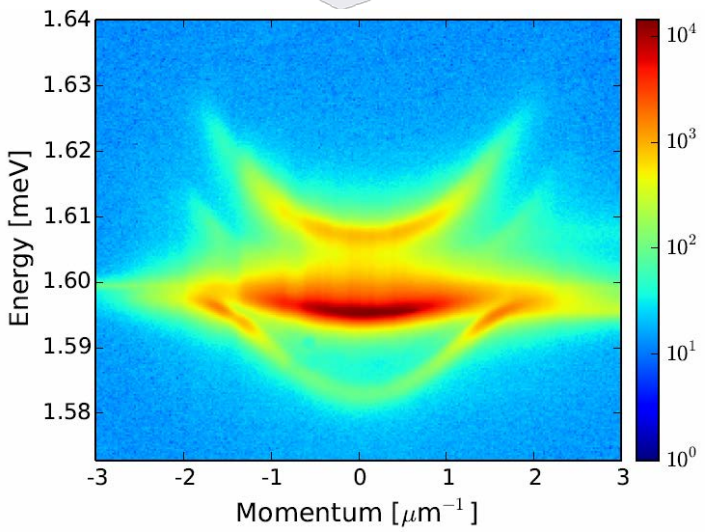


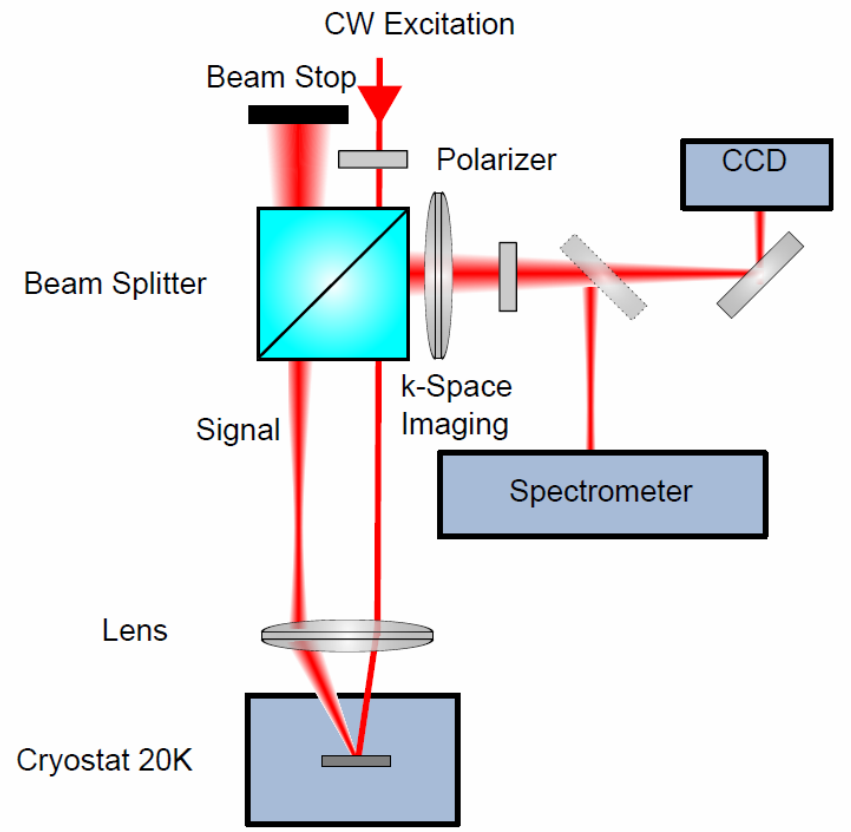


Einkemmer et al., arXiv:1305.1469.

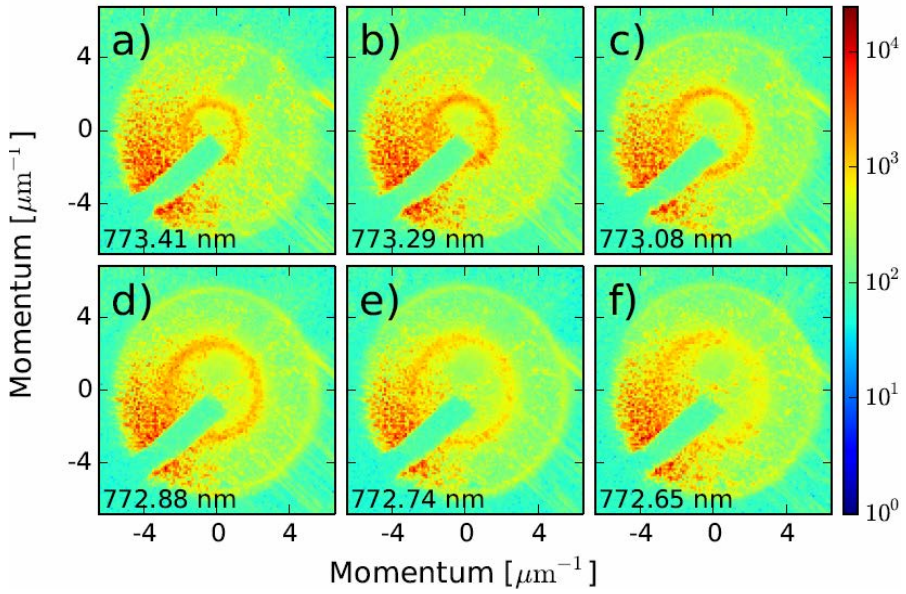
Double Cavity Raleigh Scattering

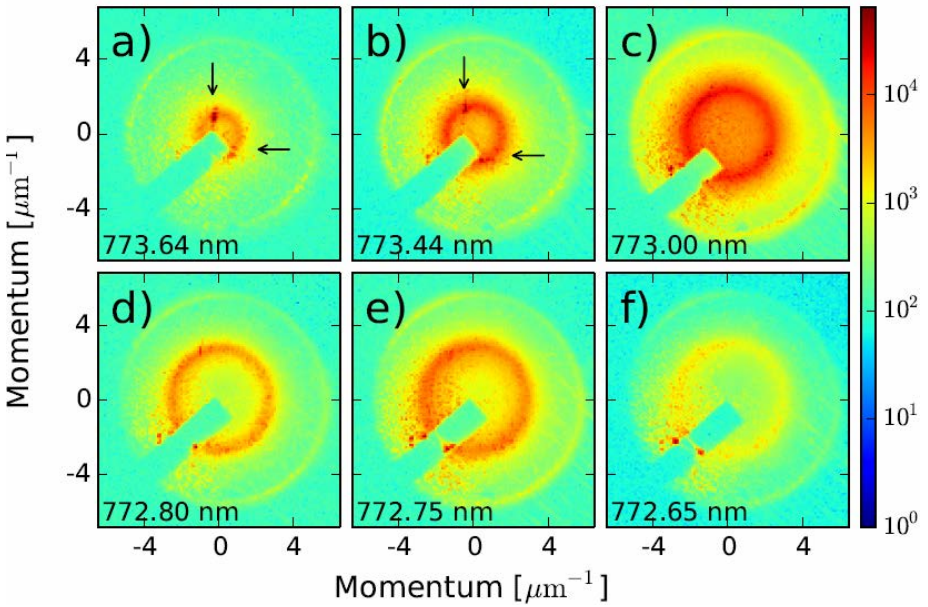


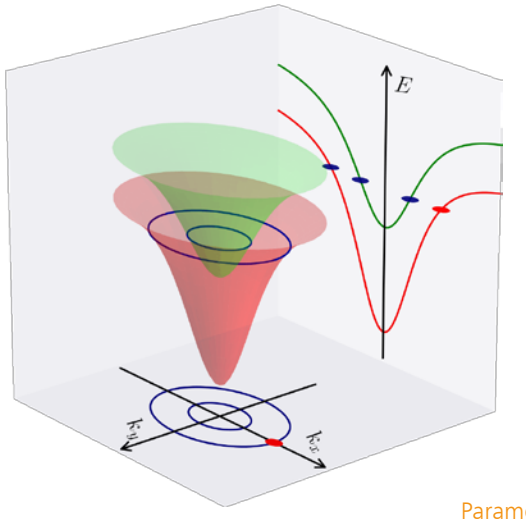




Double Cavity Raleigh Scattering







Theory: Vörös & Weihs, J. Phys. Cond. Mat. **26,** 485303 (2014).
Expt: Mai et al. arXiv:1404.7402

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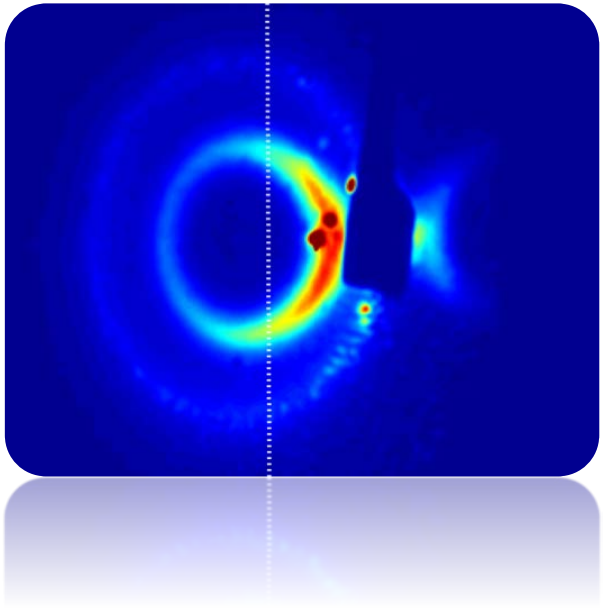
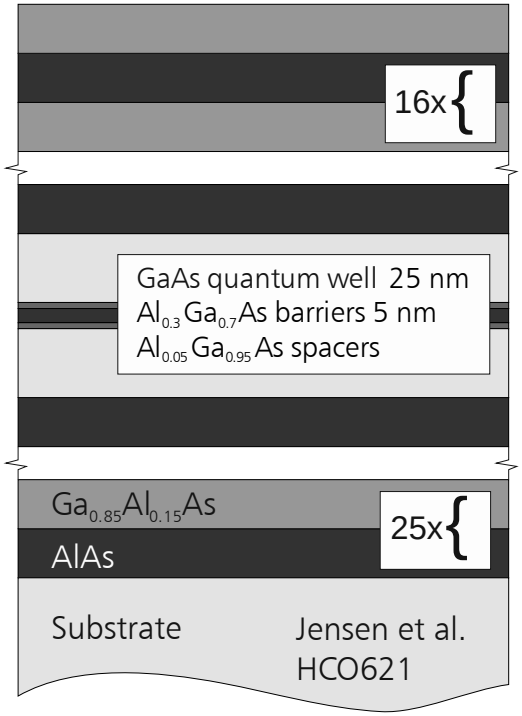
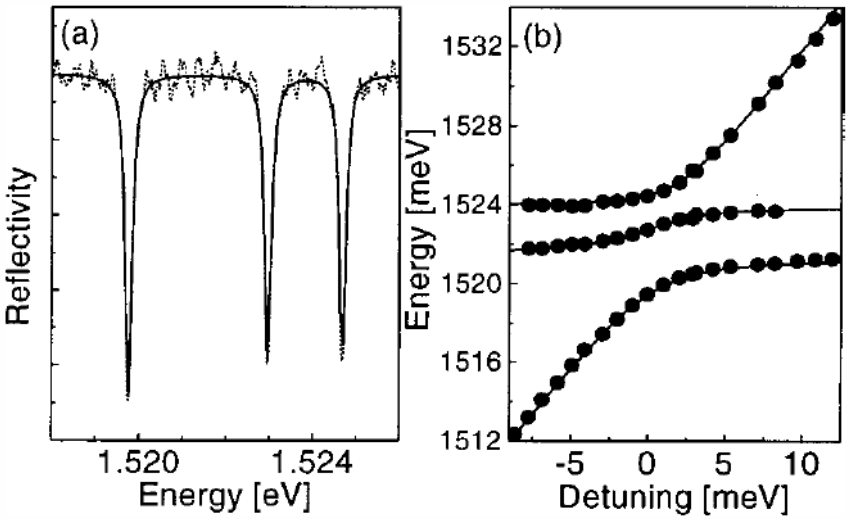


Narrow Linewidth Sample

- Wide quantum wells, soft barriers, low gap spacer
- 190 μeV polariton linewidth

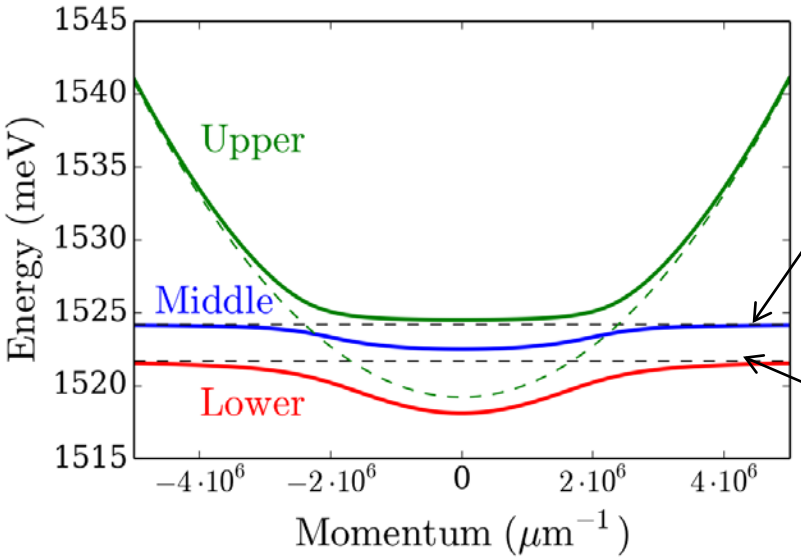


Sample c/o Wolfgang Langbein



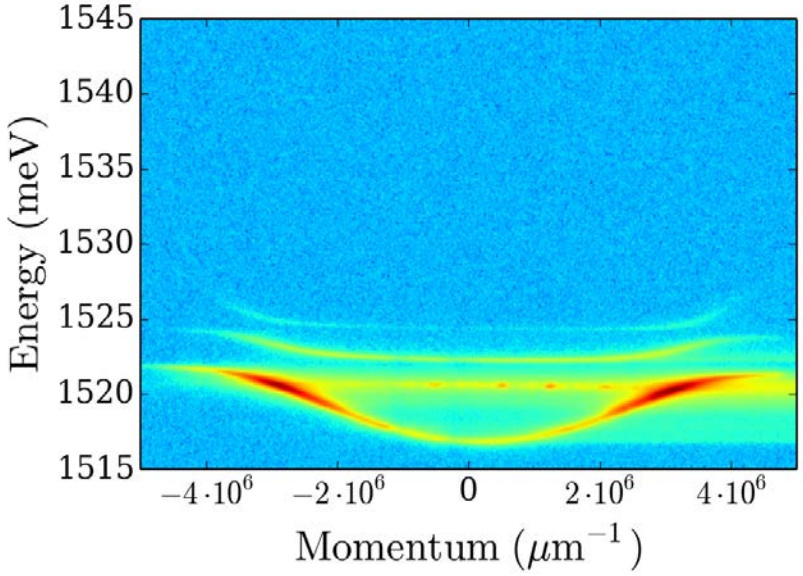
From: Jensen et al. Appl. Phys. Lett. **76,** 3262 (2000)

Angular Dispersion



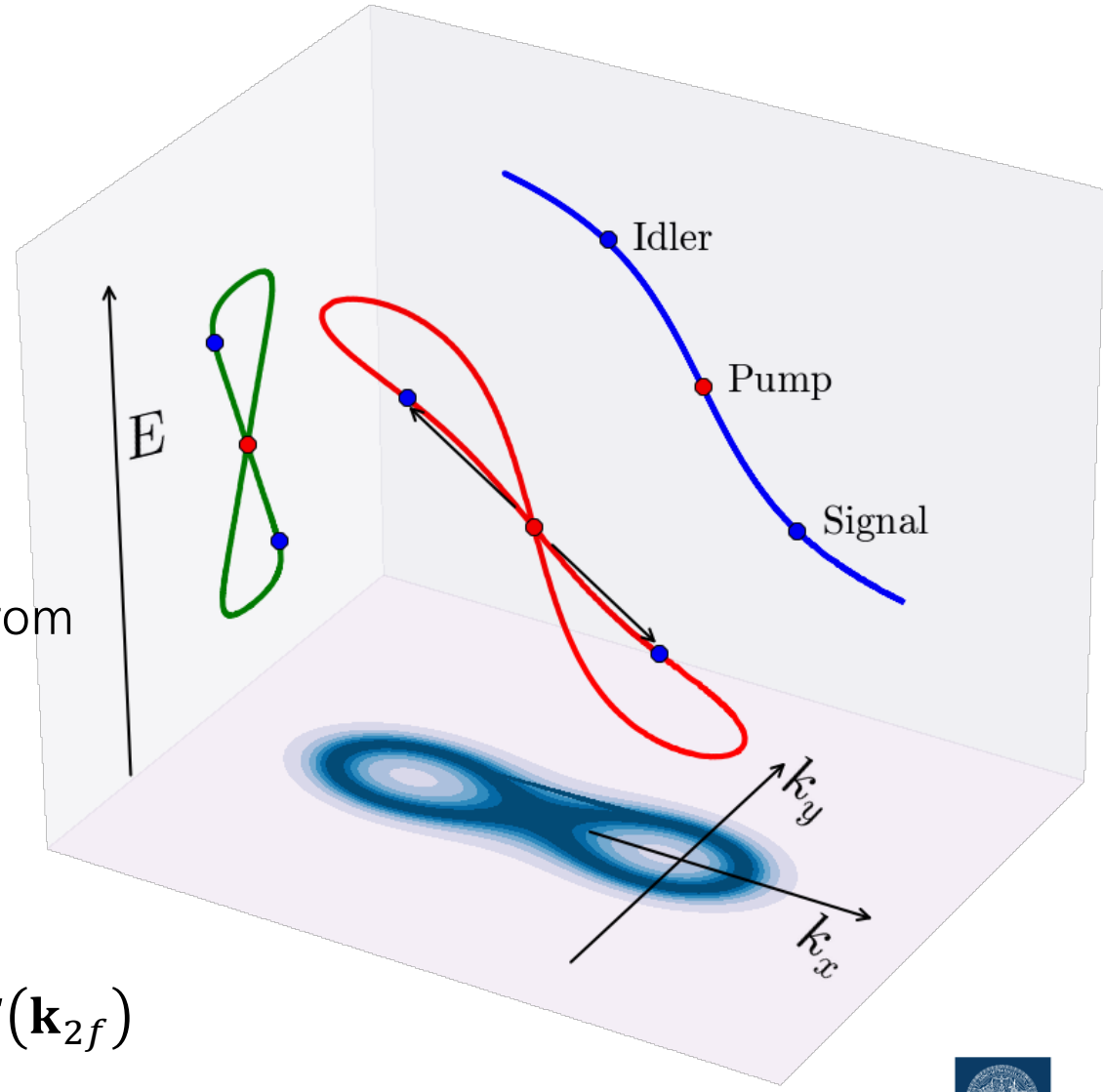
Light hole exciton

Heavy hole exciton



Planar Cavity Phase Matching

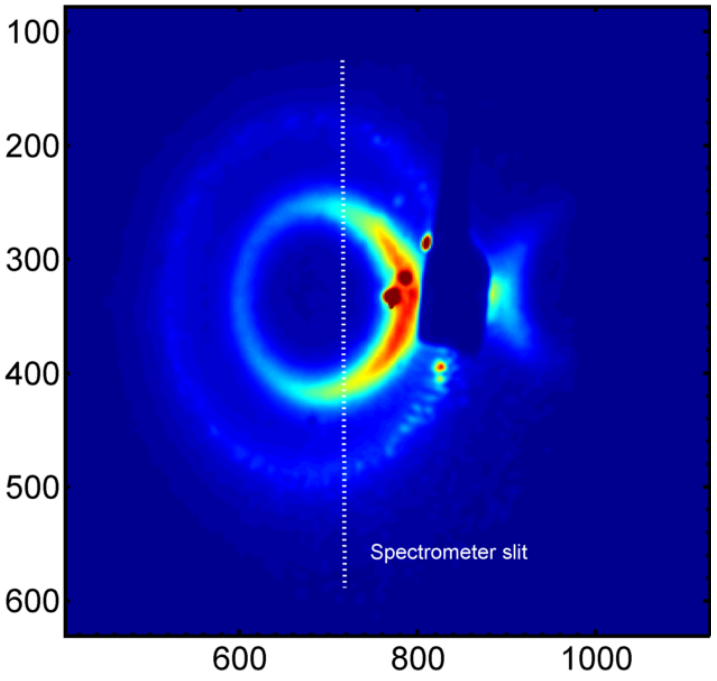
- Characteristic 8-shape
- Idler has smaller photonic component
- Signal suffers from luminescent background
- Signal and Idler immune from Rayleigh scattered pump

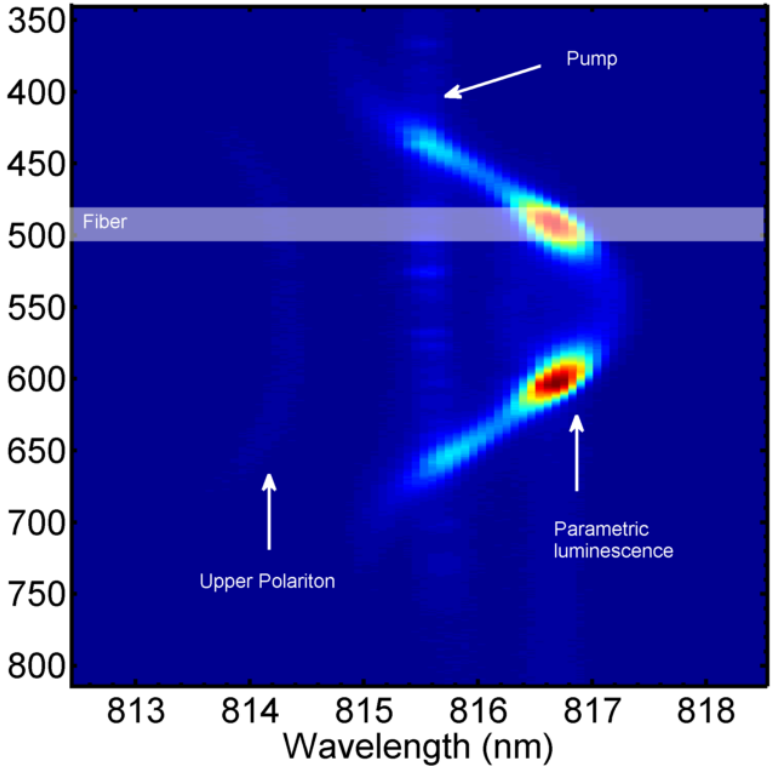


$$\mathbf{k}_{1i} + \mathbf{k}_{2i} = \mathbf{k}_{1f} + \mathbf{k}_{2f}$$

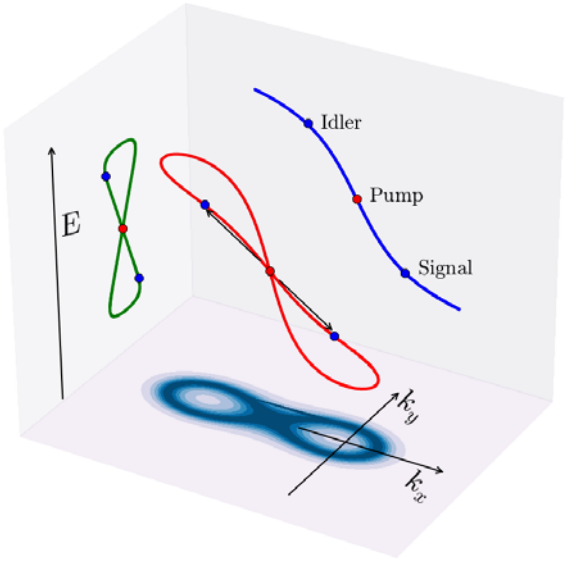
$$E(\mathbf{k}_{1i}) + E(\mathbf{k}_{2i}) = E(\mathbf{k}_{1f}) + E(\mathbf{k}_{2f})$$

Phase Matching





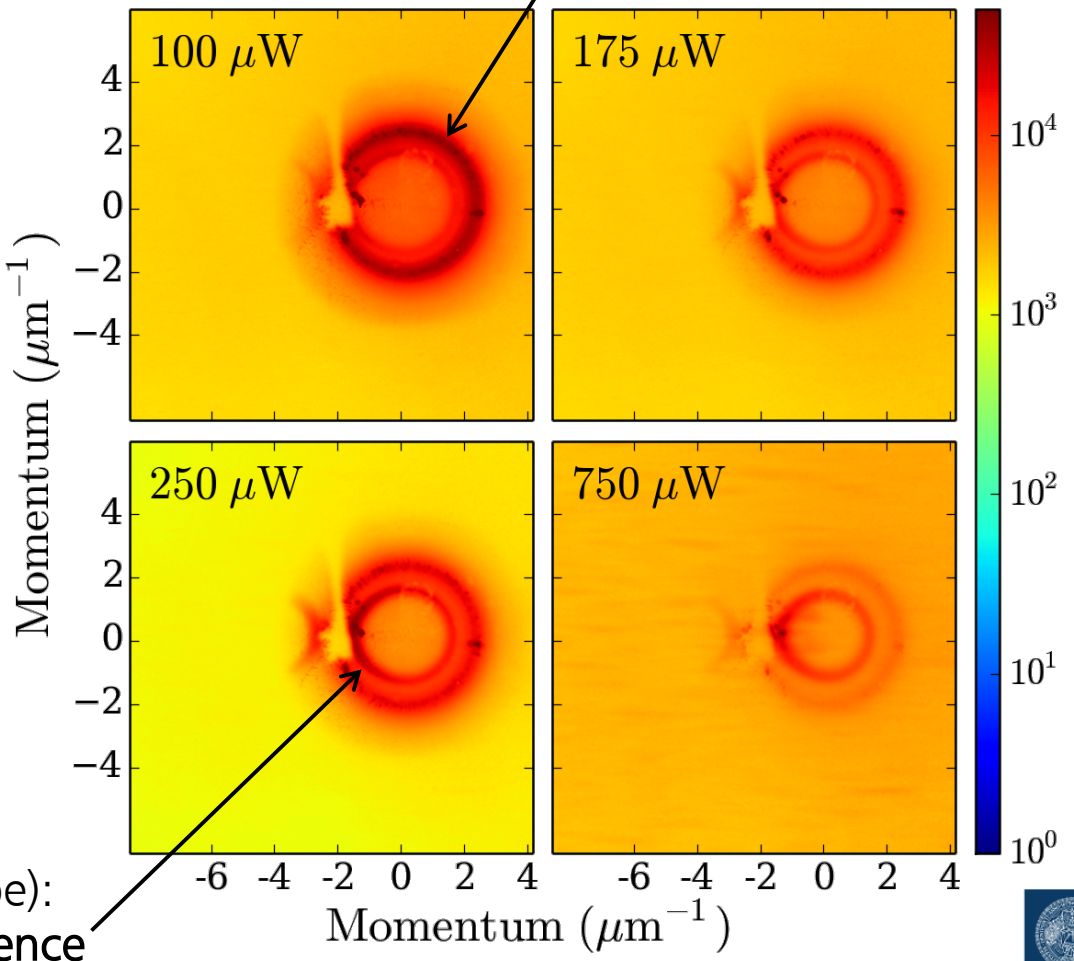
Power Dependence



Rayleigh scattering $\sim P$

Parametric scattering $\sim P^2$

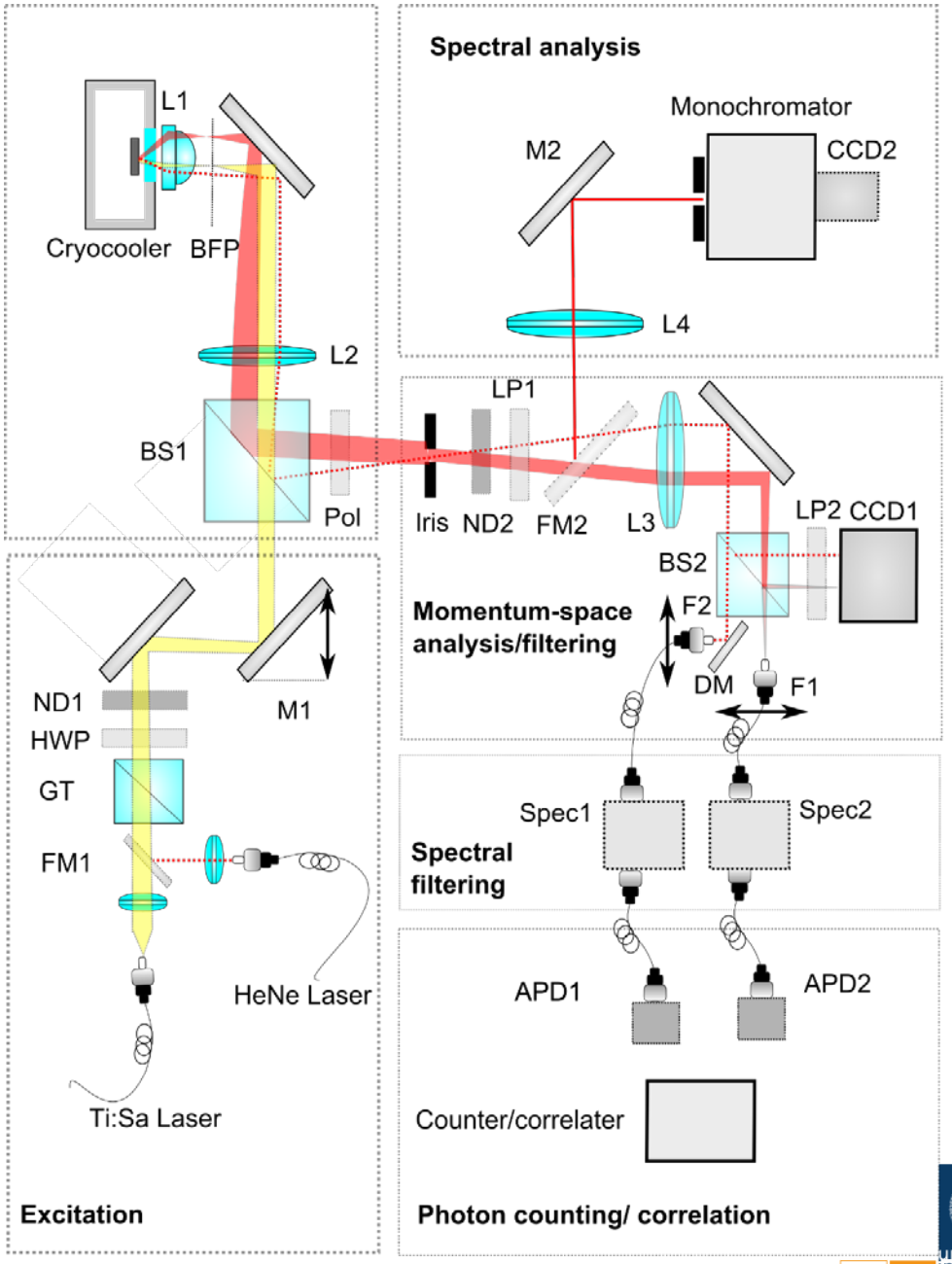
Outer ring:
Resonant Rayleigh scattering
(imperfections in DBR)



Inner "Ring" (8-shape):
Parametric luminescence

Setup

- Spatial and Momentum Filtering
  - Spectral does not improve results much
- Separate directions by mirror edge
- Use MM fibers to pick up correlated points



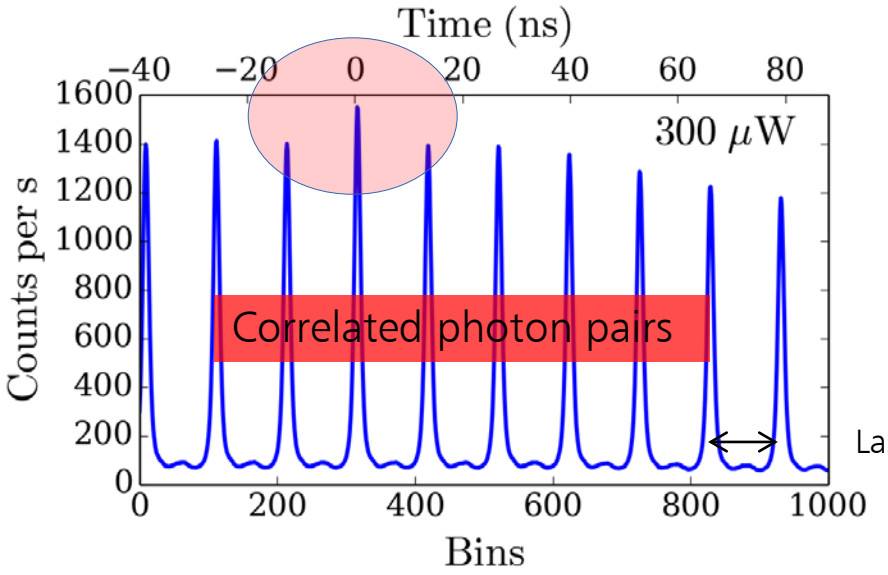
Far-field correlations

- Phase-matching

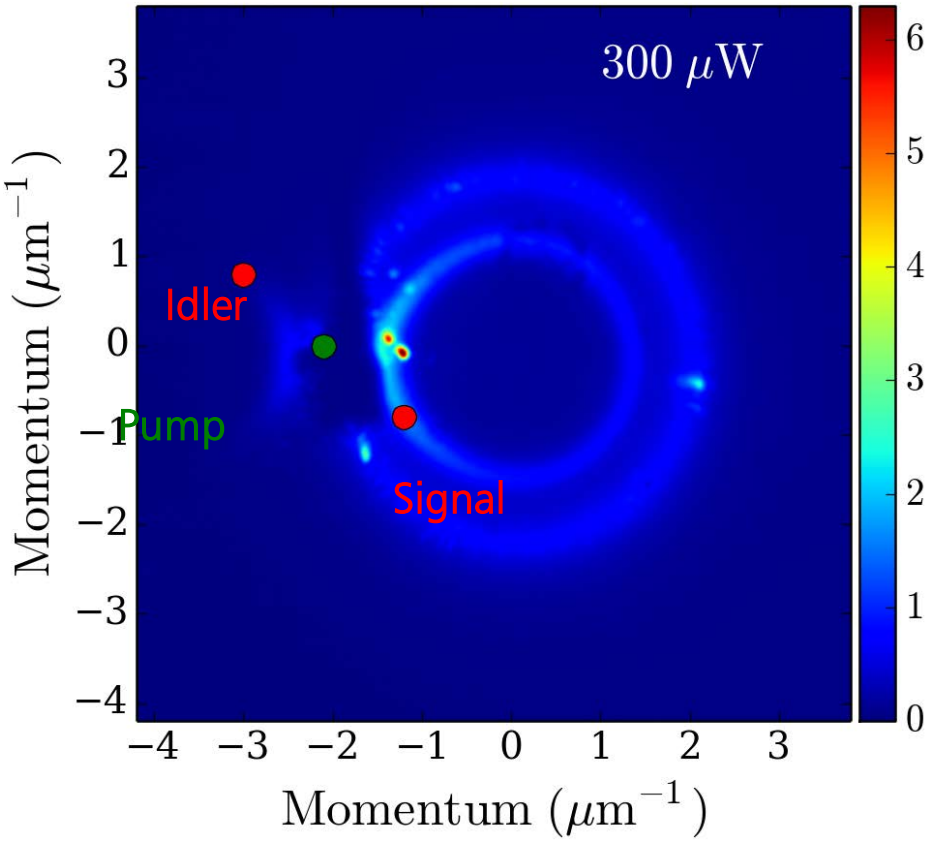
  $2\mathbf{k}_p = \mathbf{k}_s + \mathbf{k}_i$

- Bunching degree

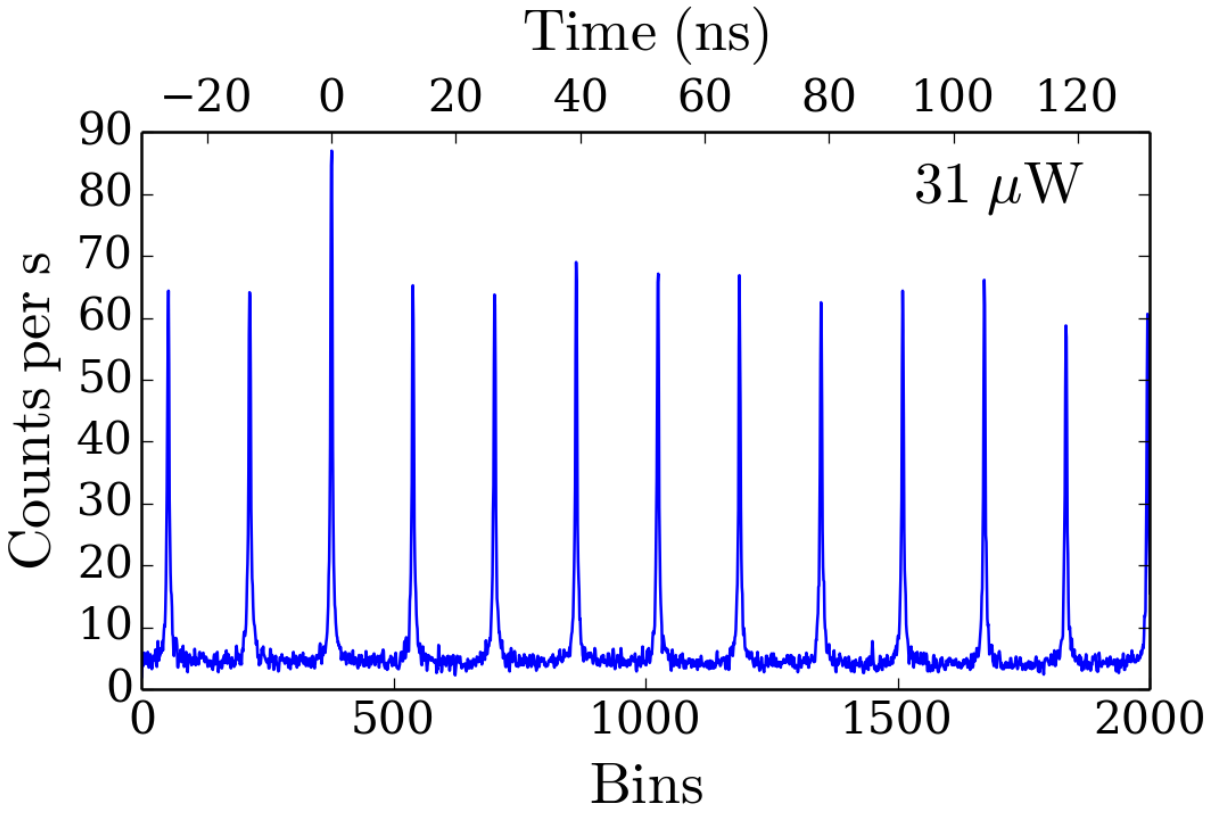
  peak at 0 delay relative to neighbours (similar to $g^{(2)}$)



Far-field image

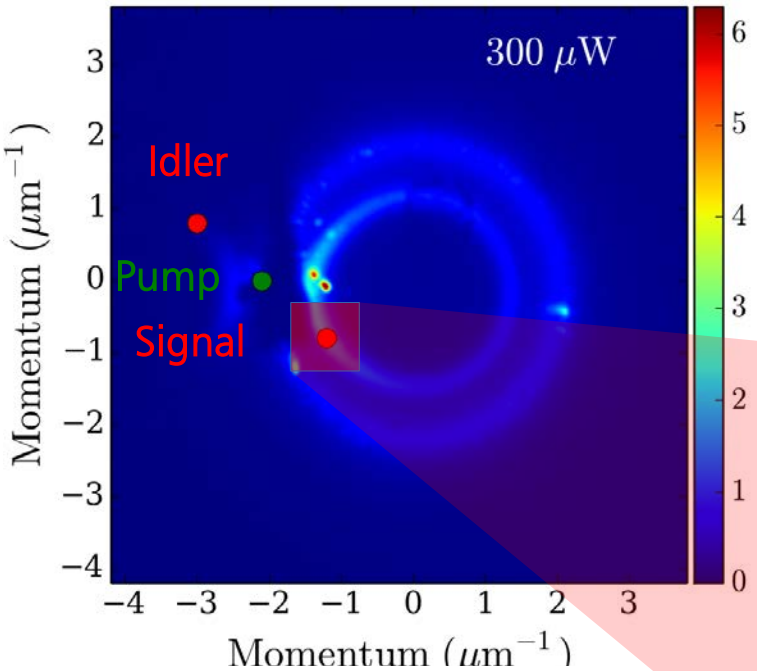


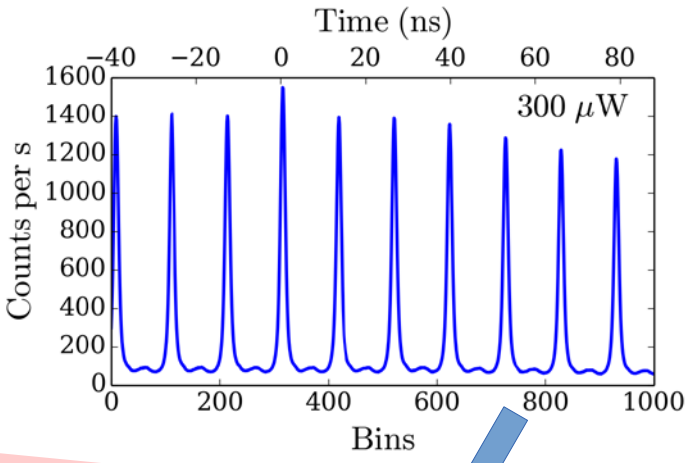
Cross-Correlation Measurments

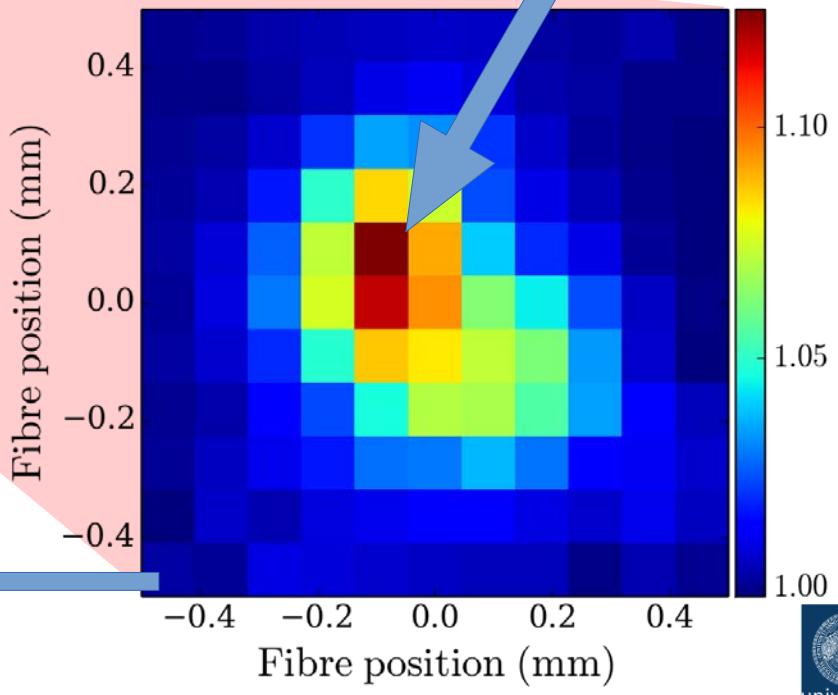


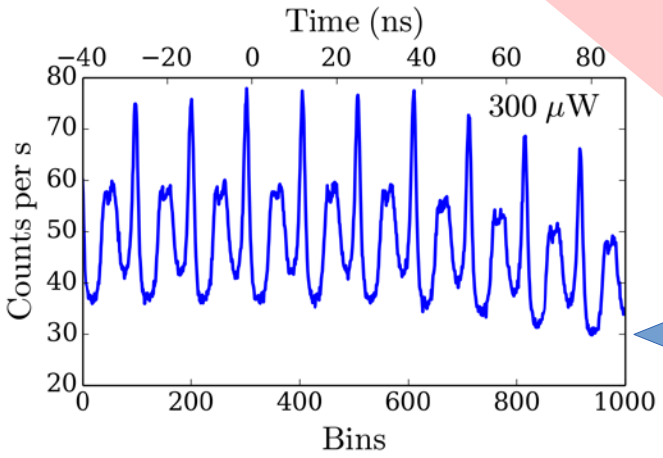
- No narrow time-filtering applied
- No narrow spectral filtering applied
- Spatial filtering in image plane improves results

Momentum Correlation

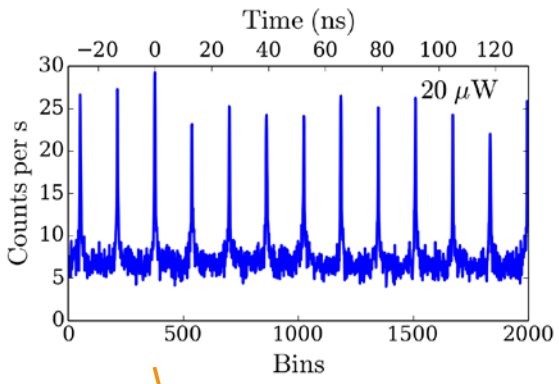


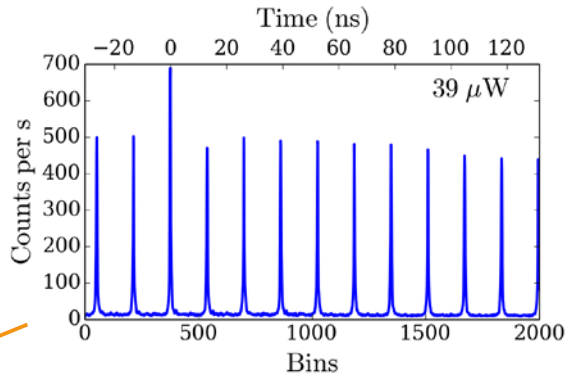


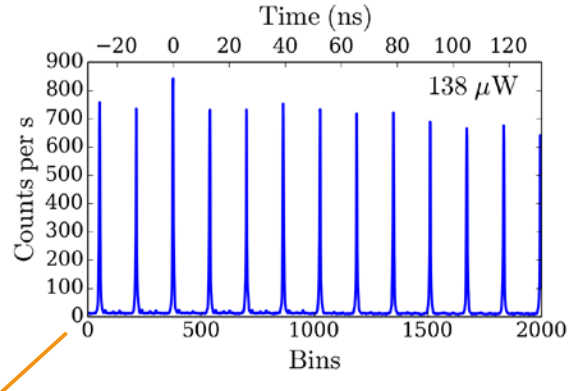


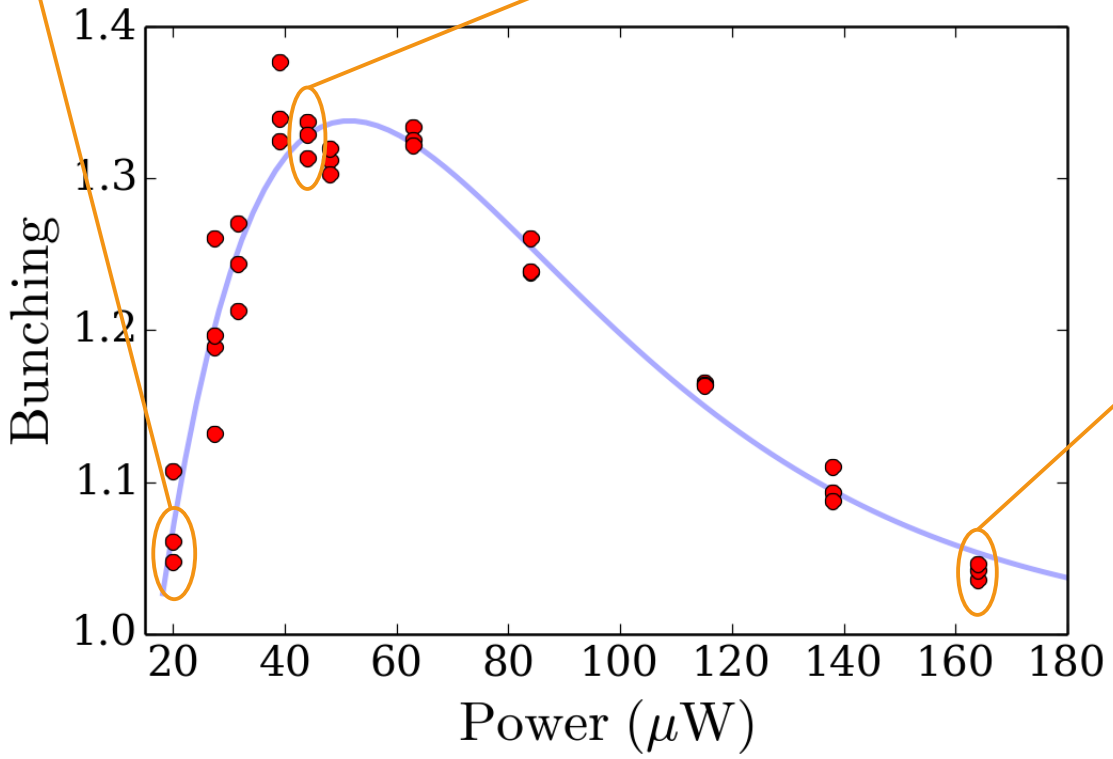


Cross-Correlation Power Dependence





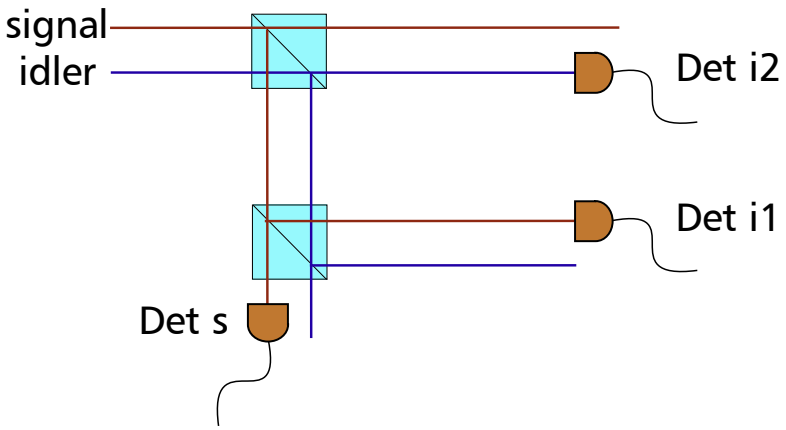


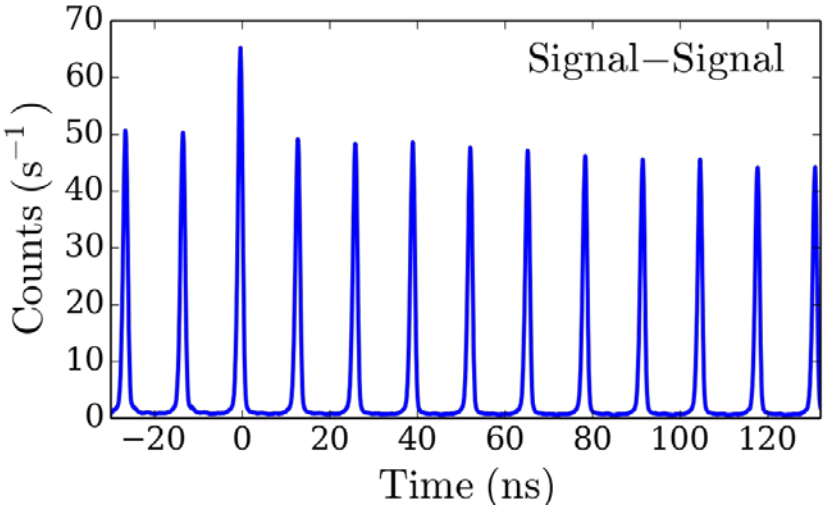


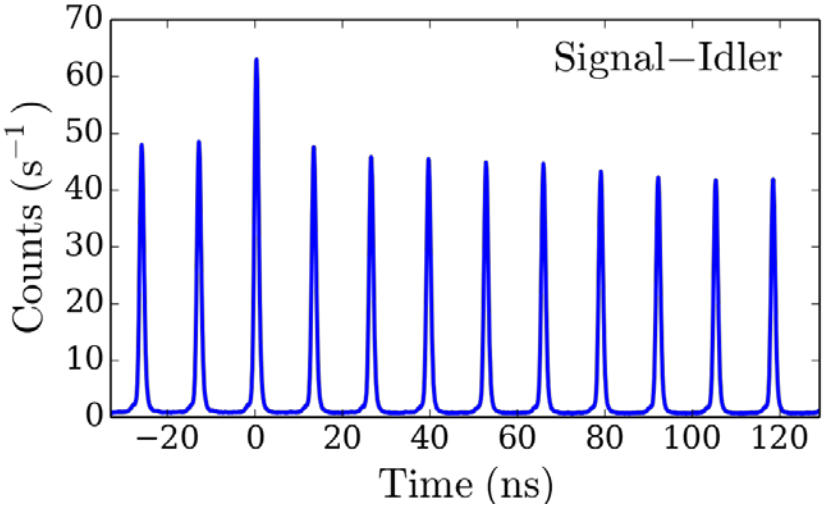
Cross-Correlation Power Dependence

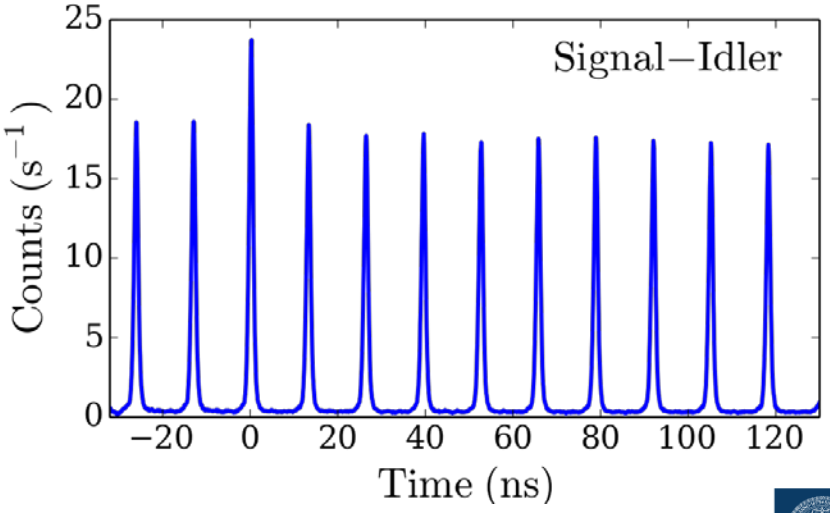
- Dark counts - **constant**
- Background – (mostly) **linear**
  - RRS
  - Phonon
  - Multiple parametric scattering
- Parametric luminescence - **quadratic**
- Dispersion renormalization
- Saturation

Cross- vs. Autocorrelation

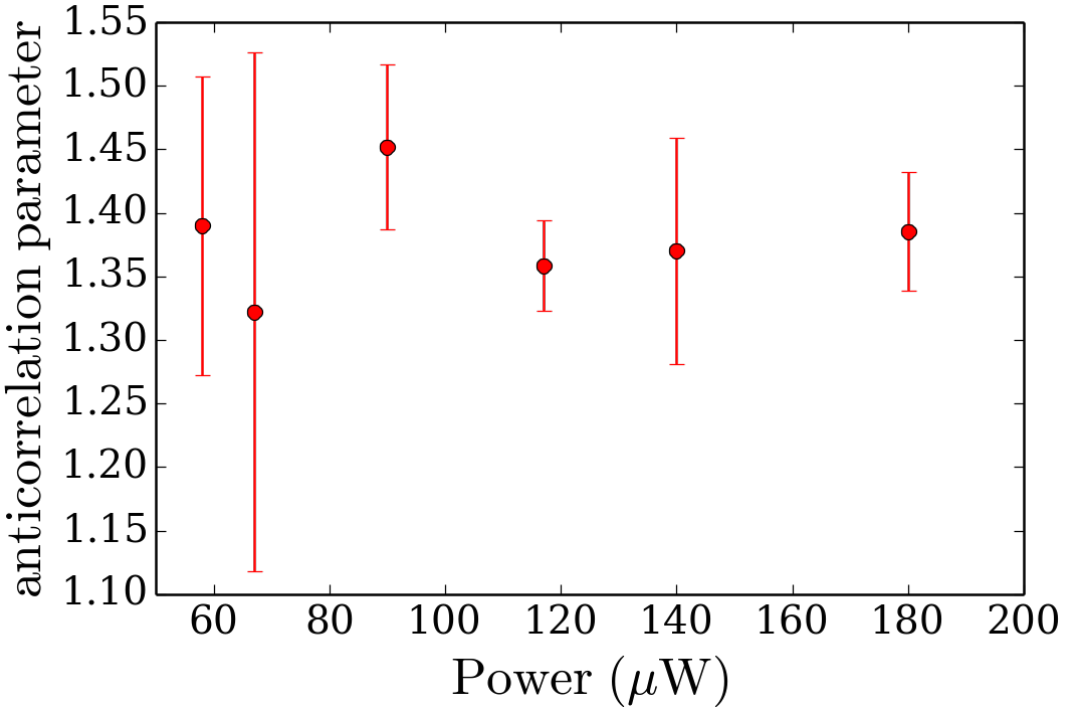








Heralding



$$\alpha = \frac{N_{si_1i_2}N_s}{N_{si_1}N_{si_2}}$$

P. Grangier et al., Europhys. Lett. **1**, 173 (1986).

Conclusions & Outlook

- Polarization currently used for pump suppression
- Improve spectral filtering
- Optimize pump pulse length
- Use inverting interferometer to superpose signal modes and idler modes respectively.