Modern technologies for quantum photonics II

Quantum photonics in multi-dimensional systems

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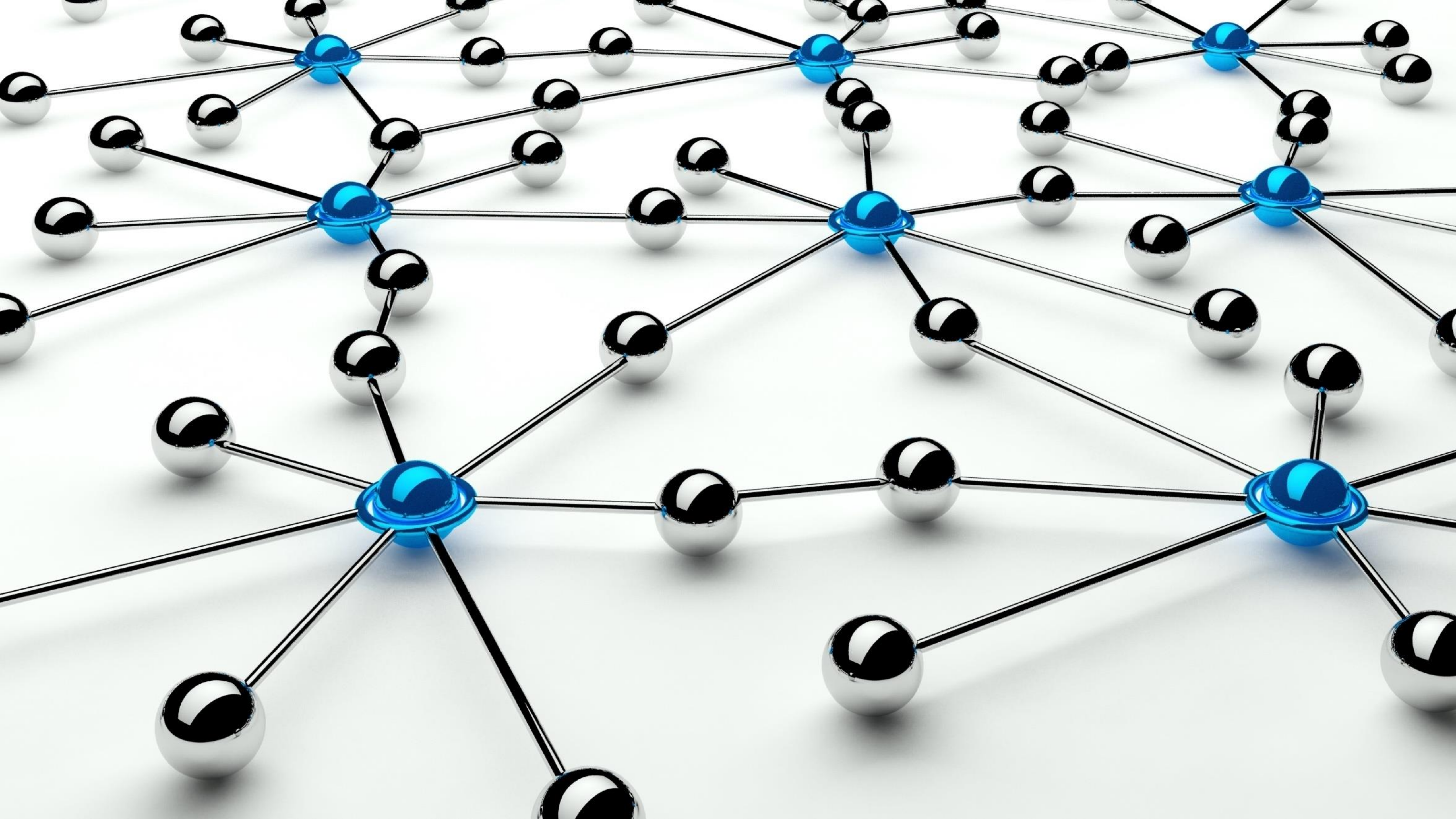
ICTP Winter College on Optics:
Quantum Photonics and Information
13/02/2020



SCALABILITY

COST

SIMPLICITY

RESOURCES

COMPATIBILITY

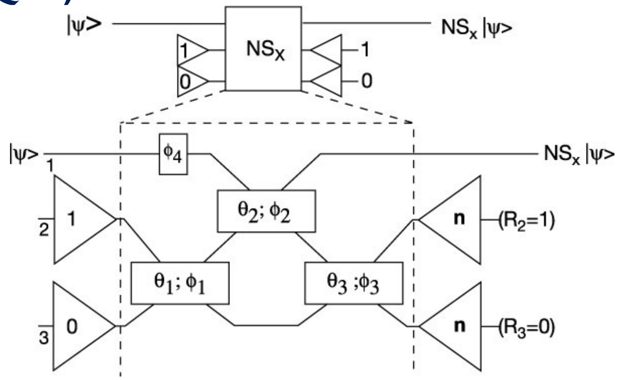
ALPHABET

RECONFIGURABILITY

Goal: to build multi-dimensional systems

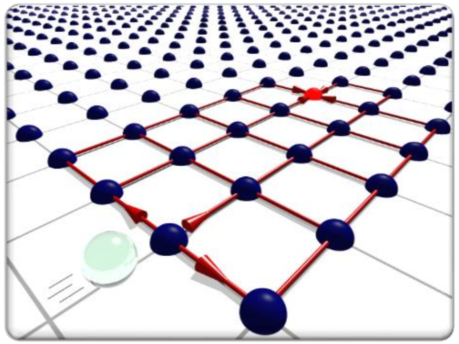
2D encoding,
many paths,
many photons

- Optical quantum computation (LOQC)



Knill, Laflamme, Milburn, Nature (2001)

- Quantum walks and quantum simulation

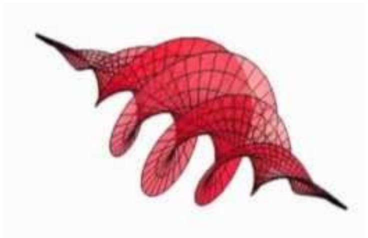


Schreiber et al., Science (2012)

few-D coin,
many positions,
few photons

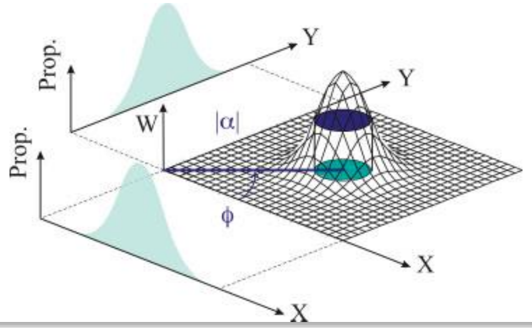
- High-dimensional information coding for quantum communication

Orbital angular momentum states

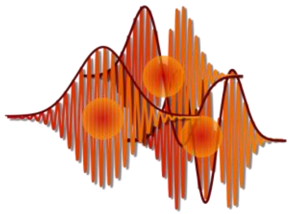


Padgett, Barnett, Boyd et al., Science (2010)

Continuous variable / Photon number states



Temporal modes of pulsed quantum states



Brecht et al., Phys. Rev. X **5**, 041017 (2015)

HD alphabet,
one channel,
few photons

Outline

Optical modes

Parametric down-conversion

Quantum pulse gate

Applications

Optical modes

Definition:

Modes are eigenfunctions of the wave equations, including boundary condtions, e.g. resonators or waveguides.

Properties:

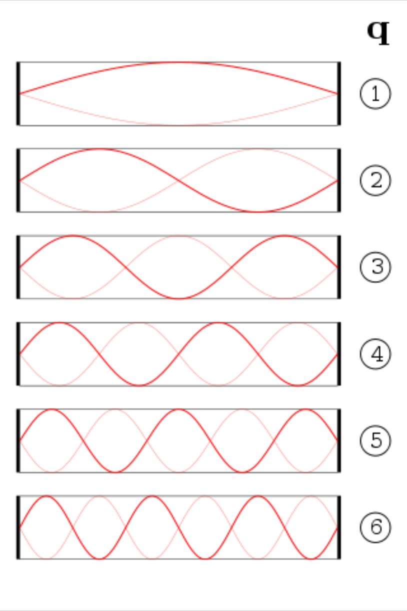
- ▶ they are orthogonal; dissimilar modes do not interfere
- ▶ within the same mode light is coherent and does interfere

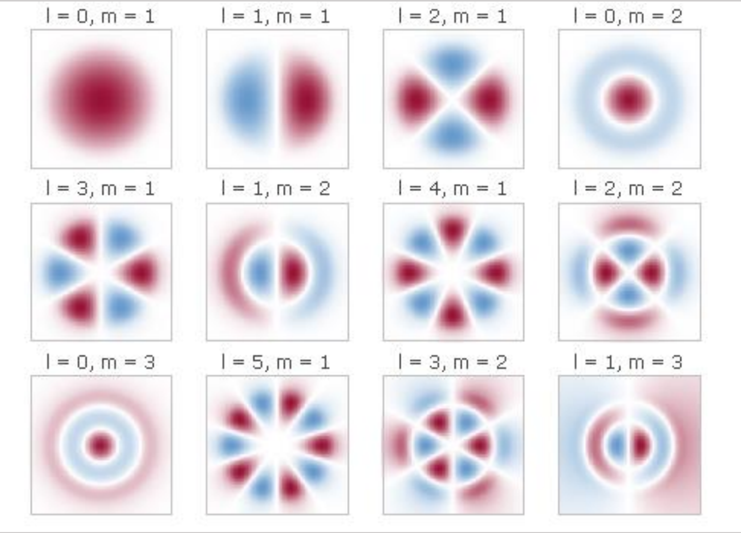
Temporal modes: in direction of propagation (time, frequency)

Spatial modes: transvers to direction of propagation (x, and $\vec{k}$)

Example: cavity modes

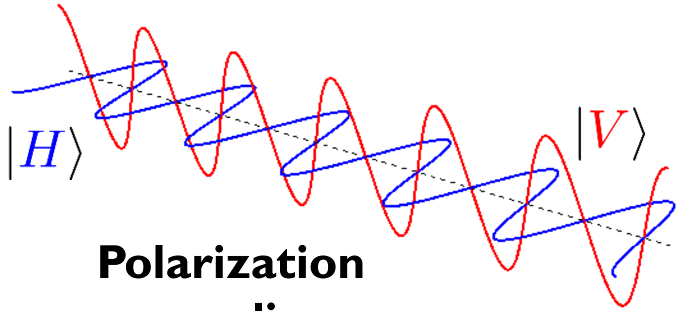
longitudinal modes





transverse modes

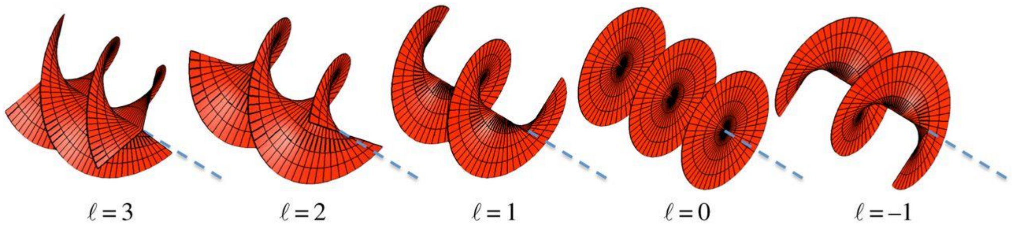
High-dimensional information encoding



Polarization encoding

$|0\rangle$ or $|1\rangle$ or $|2\rangle$ or $|3\rangle$ or $|4\rangle$ or $|5\rangle$ or $|6\rangle$ or $|7\rangle$ or $|8\rangle$

Spatial encoding

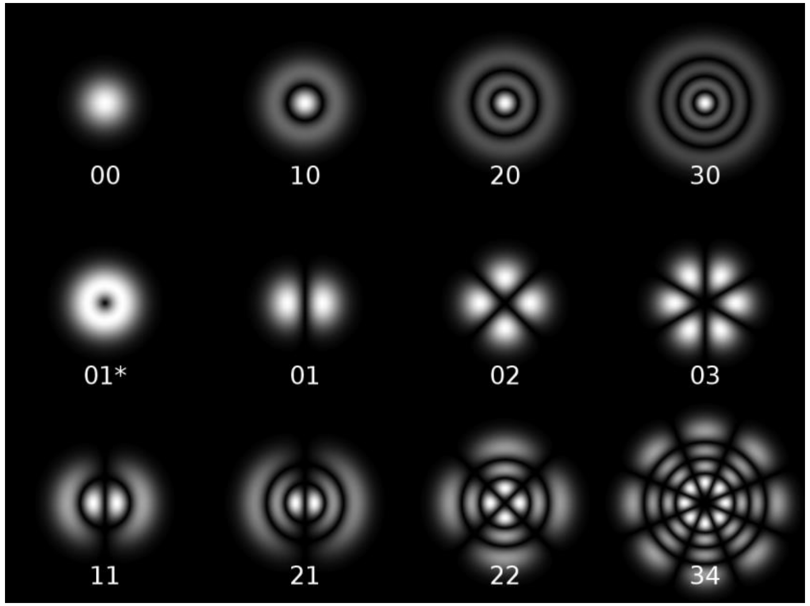


Leach et al., Science 329, 662-665 (2010)
Bent, et al, Phys. Rev. X 5, 041006 (2015)
Naidoo, et al, Nat. Photon. 10, 327 (2016)

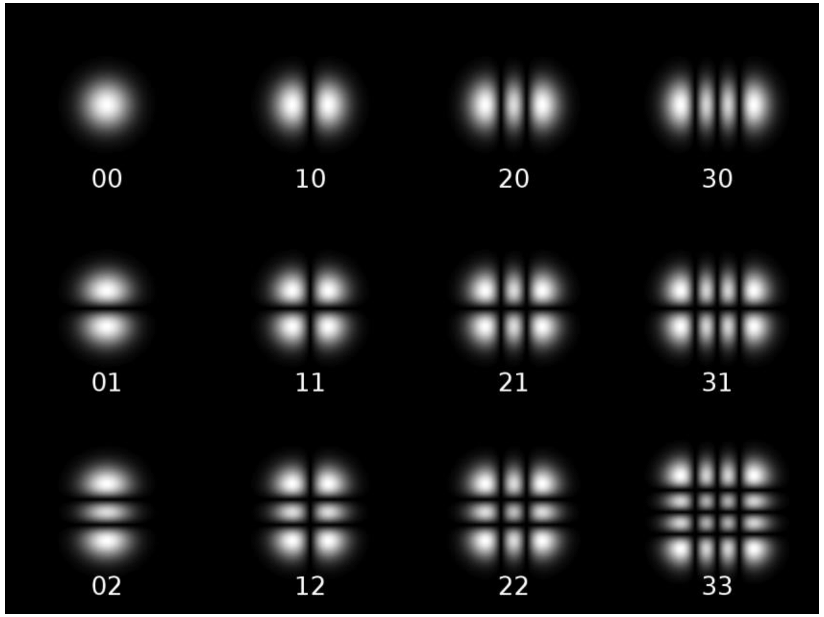
- More information encoded per photon
- Enhanced resilience to loss and noise
- High dimensional entanglement

Transverse spatial modes

- Laguerre-Gauss modes



- Hermite-Gaussian modes



Spatial modes are orthogonal

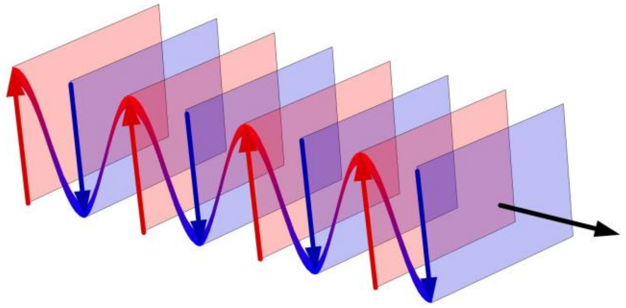
$$\int_{-\infty}^{\infty} u_n^*(x,z)\,\tilde{u}_m(x,z)\,dx = \delta_{nm}$$

$$\tilde{E}(x,y,z) = \sum_n \sum_m c_{nm}\tilde{u}_n(x,z)\tilde{u}_m(y,z)e^{-jkz}$$

Gaussian beam

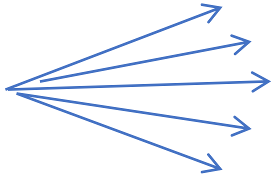
- Plane wave: single k-vector

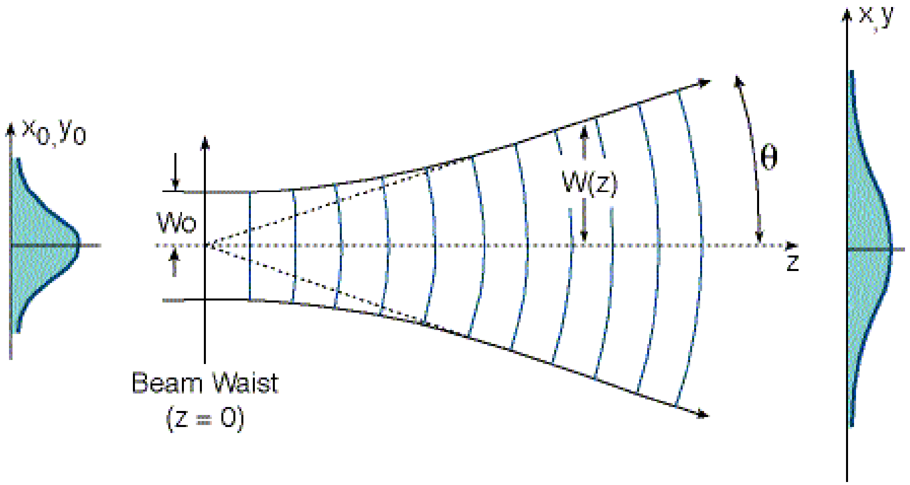
$\vec{k}$



- Gaussian beam: superpostions of wave vectors

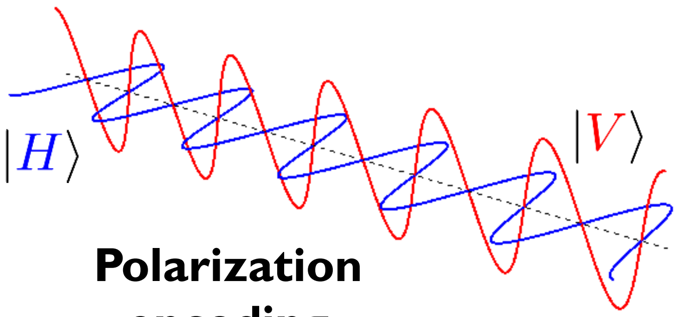
$\vec{k}$





$$E_0 \propto \int_{-\infty}^{\infty} \frac{dk_x}{2\pi} \int_{-\infty}^{\infty} \frac{dk_y}{2\pi} \exp\left(ik_x x + ik_y y + ikz - i\frac{k_x^2 + k_y^2}{2k} z - \frac{w_0^2}{4}\left(k_x^2 + k_y^2\right) \right).$$

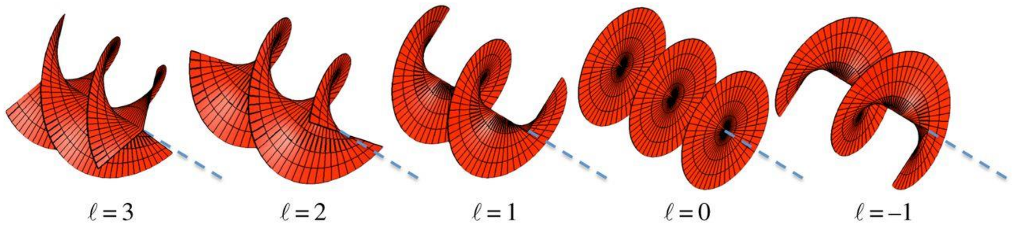
High-dimensional information encoding



Polarization encoding

$$|0\rangle \text{ or } |1\rangle \text{ or } |2\rangle \text{ or } |3\rangle \text{ or } |4\rangle \text{ or } |5\rangle \text{ or } |6\rangle \text{ or } |7\rangle \text{ or } |8\rangle$$

Spatial encoding



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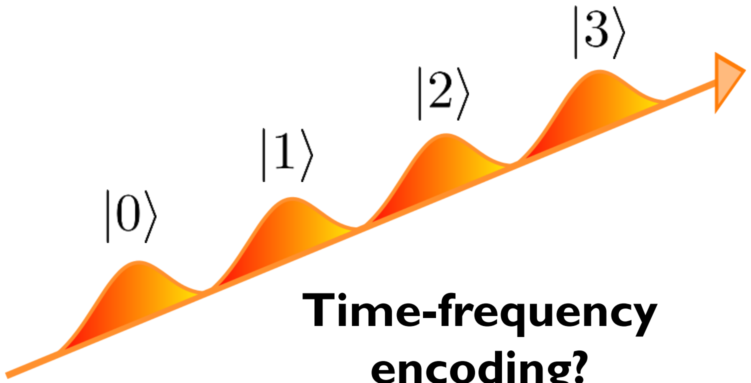


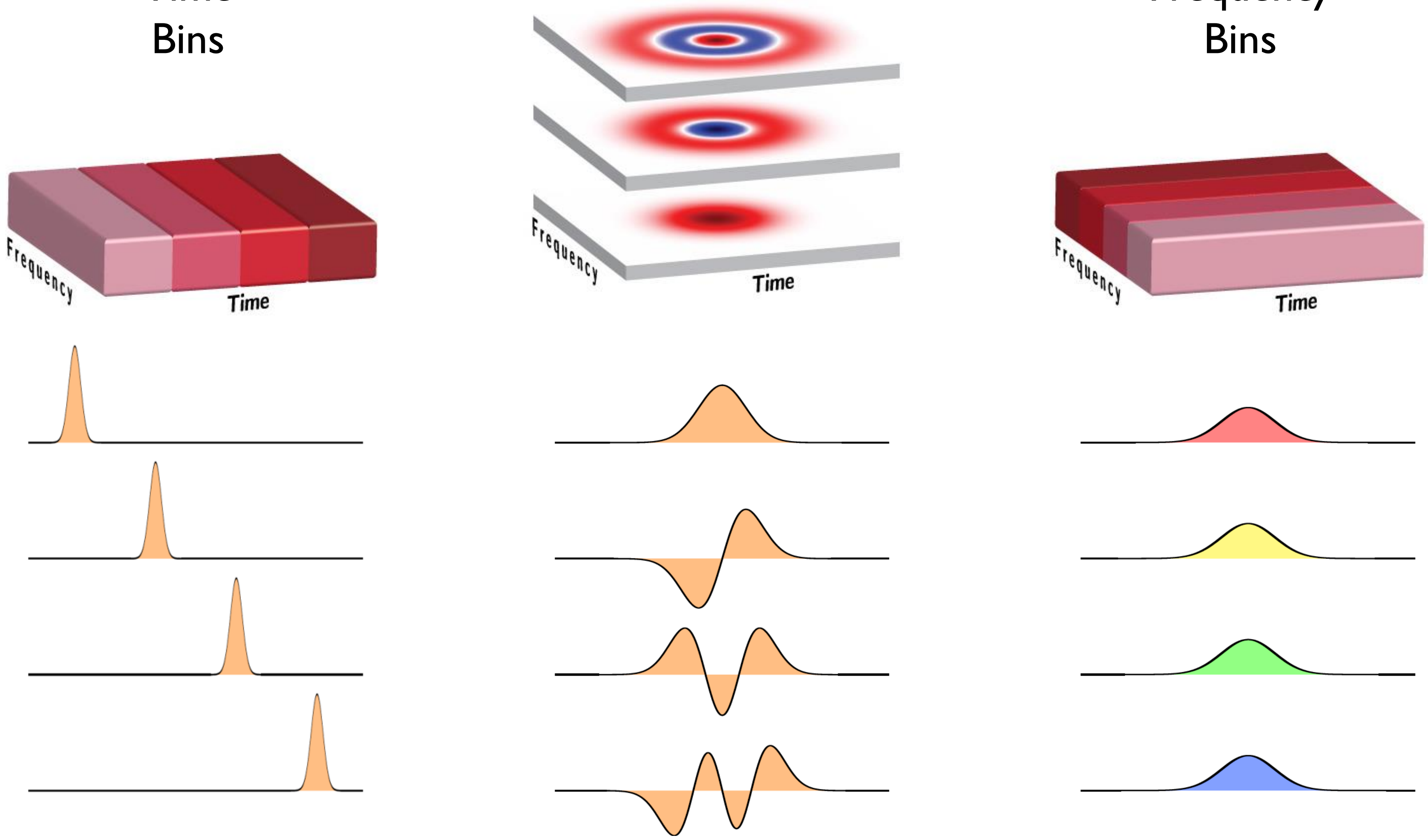
Time-frequency encoding?

Time-frequency modes

Time Bins

Pulsed Temporal Modes

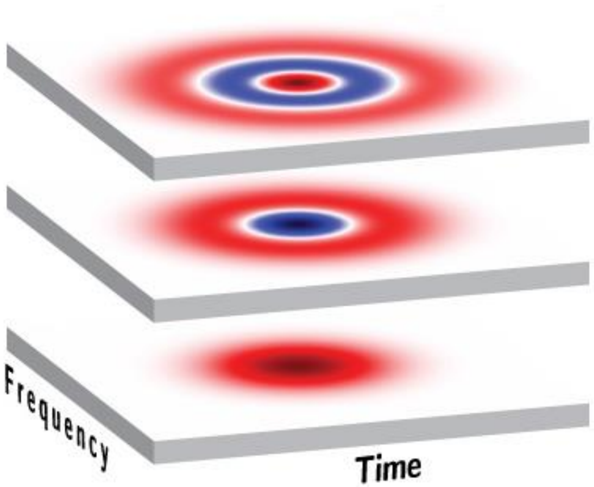
Frequency Bins

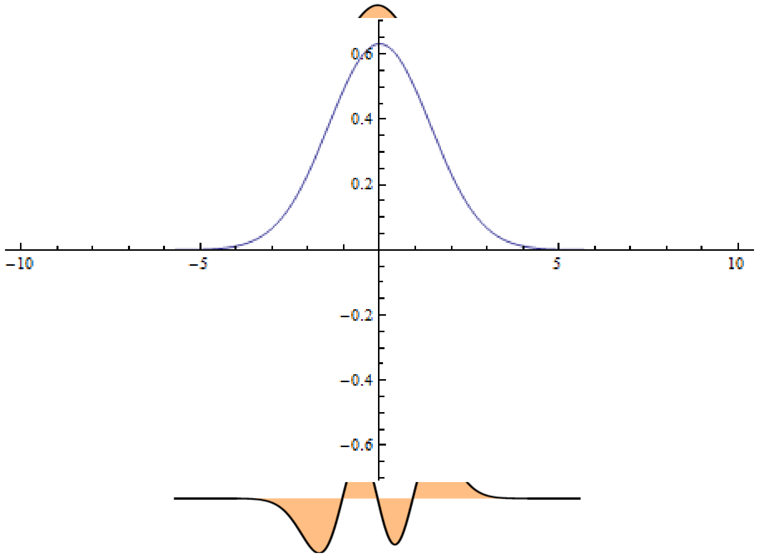


B. Brecht, D.V. Reddy, C. Silberhorn, M. G. Raymer, PRX **5** 041017 (2015)

Pulsed temporal modes

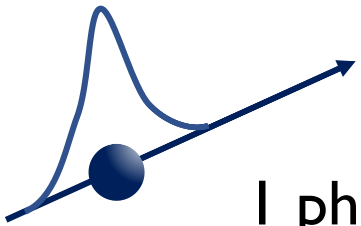
- Hermite-Gaussian envelopes in frequency and time
- Overlapping intensities but orthogonal field amplitudes
- Naturally compatible with waveguides and fibers
- Pulse and spectral width scale as $\sqrt{2n+1}$



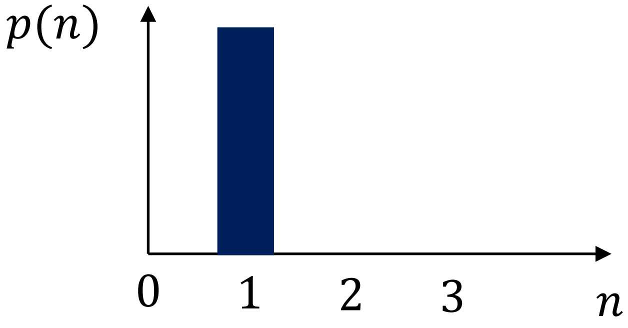


B. Brecht, D.V. Reddy, C. Silberhorn, M. G. Raymer, PRX **5** 041017 (2015)

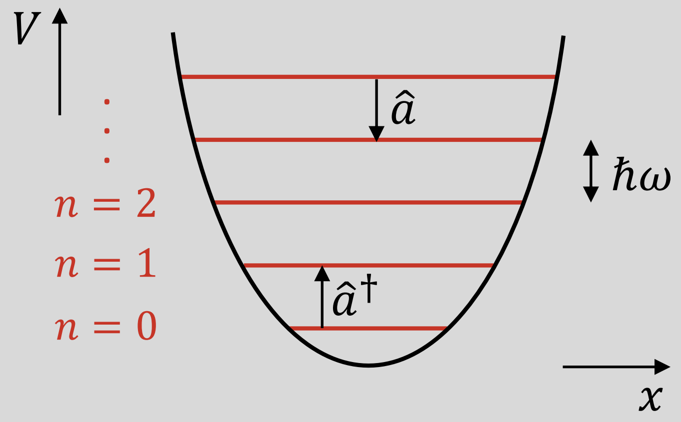
What is a single photon?



1 photon = 1 quantum



Quantisation of an optical field mode



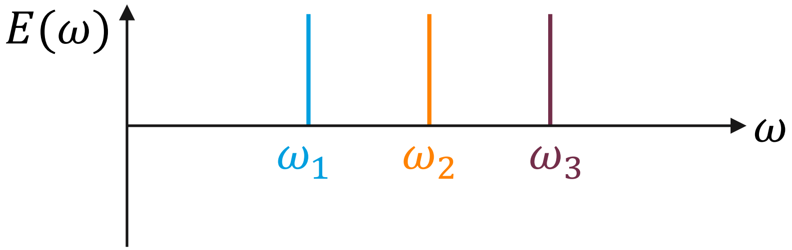
plane wave = harmonic oscillator

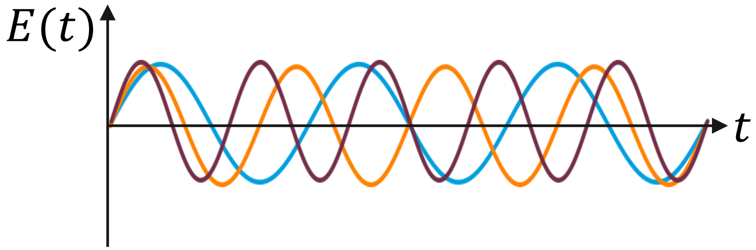
$$\hat{E} = \hat{a}e^{-i(\omega t - \vec{k}\vec{r})} + \hat{a}^\dagger e^{i(\omega t - \vec{k}\vec{r})}$$

$$|\psi\rangle = \sum_{n=0}^{\infty} c_n \frac{\left(\hat{a}^\dagger\right)^n}{\sqrt{n!}} |0\rangle$$

Pulsed temporal mode states of single photons

Monochromatic modes

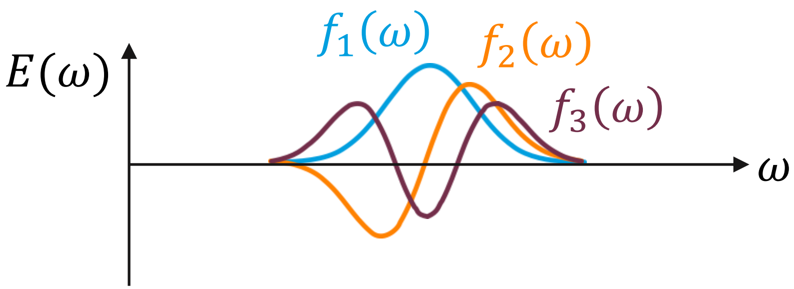


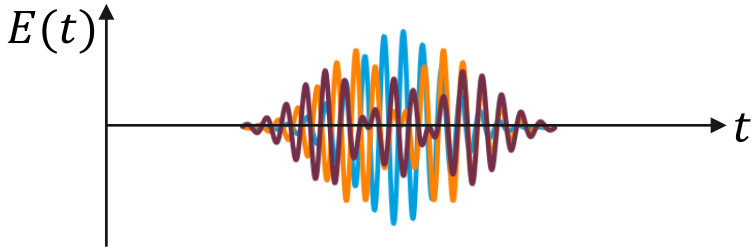


$$\left[\hat{a}(\omega_i), \hat{a}^\dagger(\omega_j)\right] = \delta(\omega_i - \omega_j)$$

State: $|\omega_j\rangle = \hat{a}^\dagger(\omega_j)|0\rangle$

Temporal modes





$$\hat{A}_j = \int d\omega\, f_j(\omega)\hat{a}(\omega)$$

$$\left[\hat{A}_i, \hat{A}_j^\dagger\right] = \delta_{ij}$$

State: $|A_j\rangle = \hat{A}^\dagger|0\rangle$

B. Brecht et al, Phys. Rev. X **5**, 041017 (2015)

Outline

Optical modes

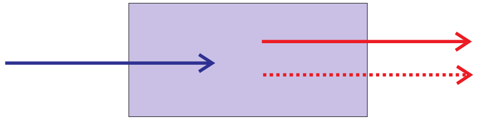
Parametric down-conversion

Quantum pulse gate

Applications

Parametric down-conversion

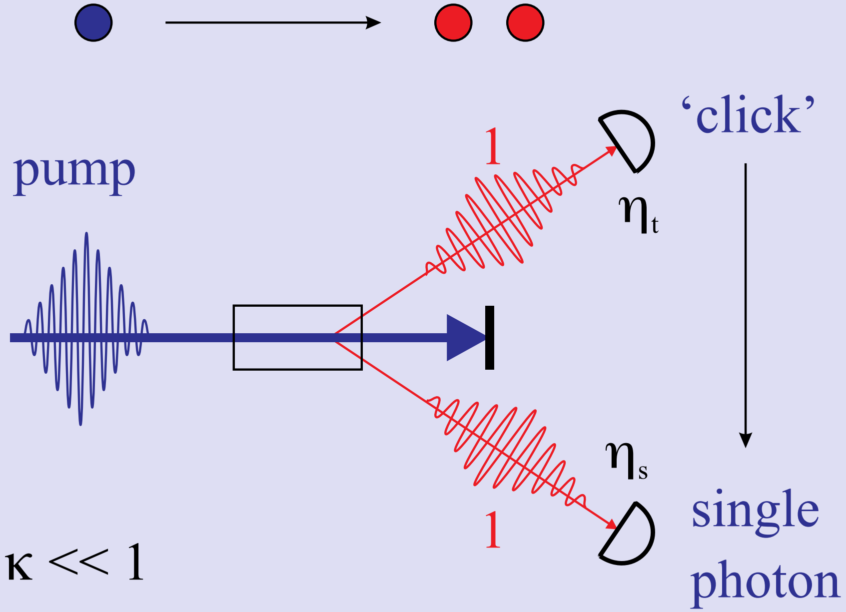
How can we generate single photons?



nonlinear medium

$$P = \varepsilon_0 \left[\chi^{(1)}\vec{E} + \chi^{(2)}\vec{E}\vec{E} + \chi^{(3)}\vec{E}\vec{E}\vec{E} + \cdots \right]$$

Parametric downconversion

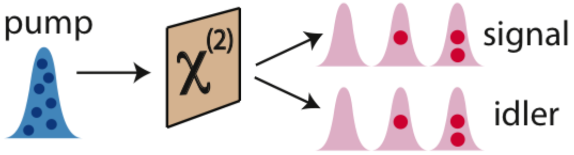


Photons are produced in pairs

$$R_s = \eta_s \cdot R, \quad R_i = \eta_i \cdot R$$
$$R_{coinc} = \eta_s \eta_i \cdot R$$

$$\eta_s = \frac{R_{coinc}}{R_i}$$

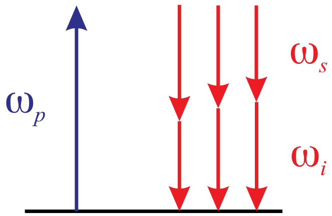
Parametric down-conversion



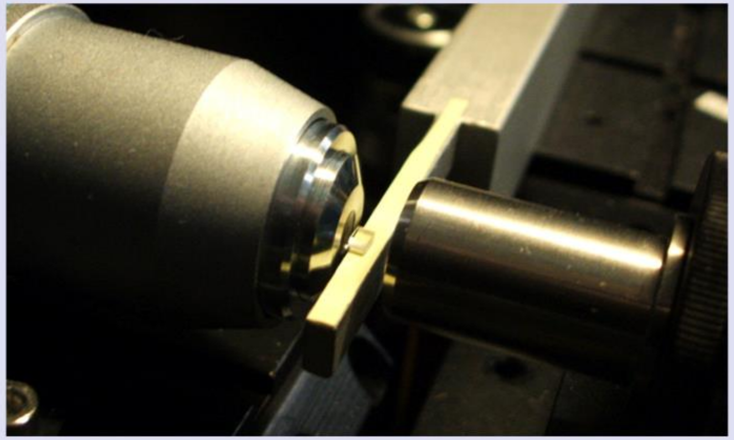
$$\hat{H} = \alpha\, a^{\dagger} b^{\dagger} + h.c.$$
$$|\psi\rangle = \sum \lambda_n |n,n\rangle$$

energy conservation

$$W_p = W_s + W_i$$

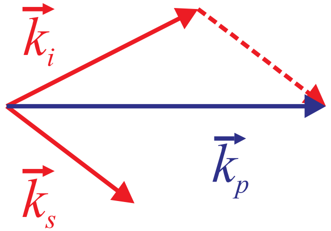


PDC in waveguides



momentum conservation

$$\vec{k}_p = \vec{k}_s + \vec{k}_i$$



Spatial k-vectors defind by guide

Parametric down-conversion

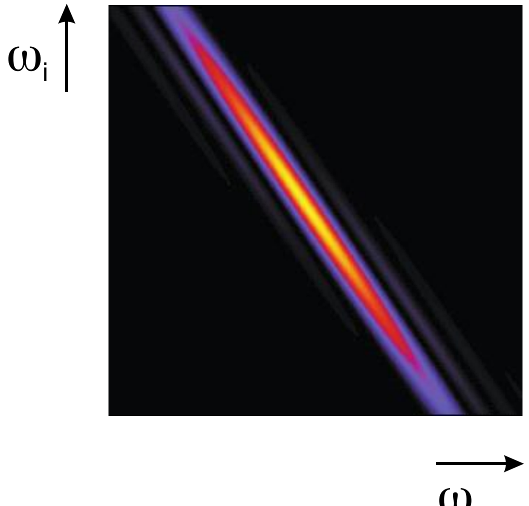
"Ideal" bi-photon state …

$$|1\rangle\,|1\rangle \;=\; \hat{A}_s^\dagger \hat{B}_i^\dagger \;|0\rangle \;=\; \iint d\omega_s\, d\omega_i\, f_A(\omega_s)\cdot g_B(\omega_i)\; \hat{a}^\dagger_{\omega_s}\; \hat{a}^\dagger_{\omega_i}\,|0\rangle$$

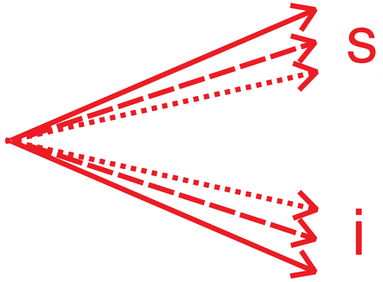
Functions $f_A(\omega_s)$ and $g_B(\omega_i)$ define **one** temporal mode each!

… but PDC is typically correlated in:

optical frequencies



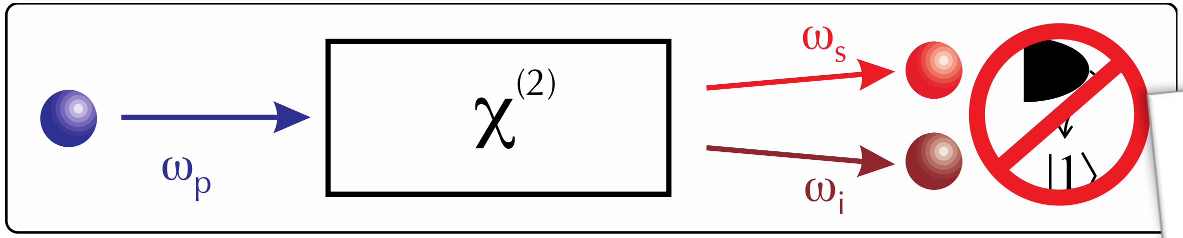
transverse momenta



No correlations for PDC in wave guides

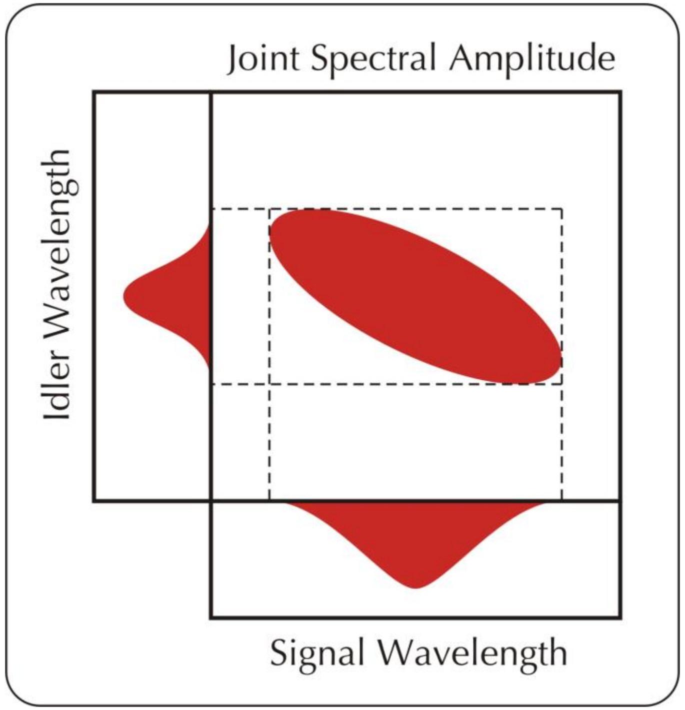
Heralding single photons

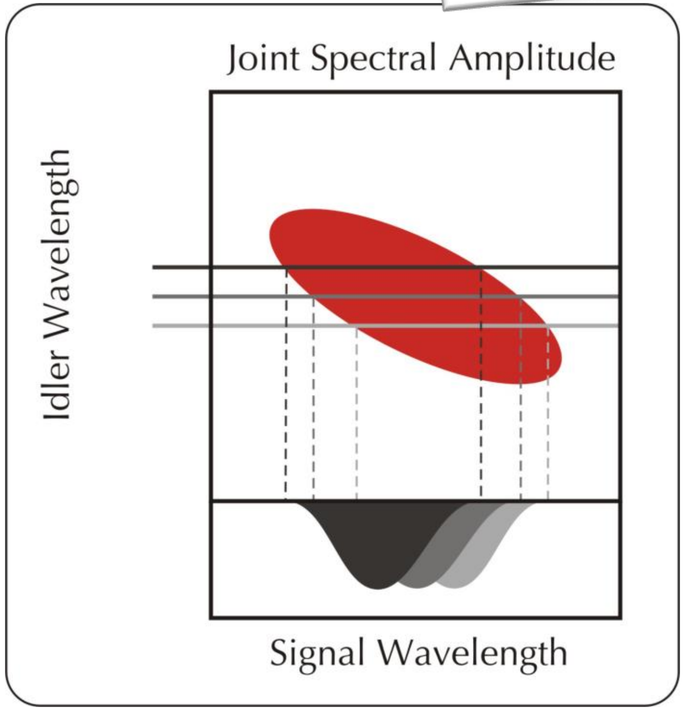
Correlated Bi-photon state



- mixed state:

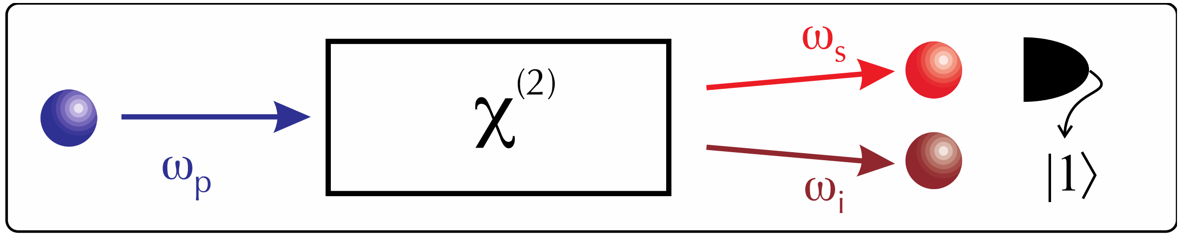
$$\hat{\rho} = \int d\omega\, p(\omega)\ \hat{a}^{\dagger}_{\omega} |0\rangle \langle 0| \hat{a}_{\omega}$$





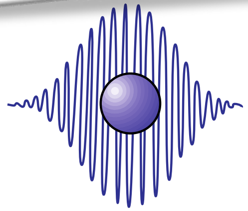
Heralding single photons

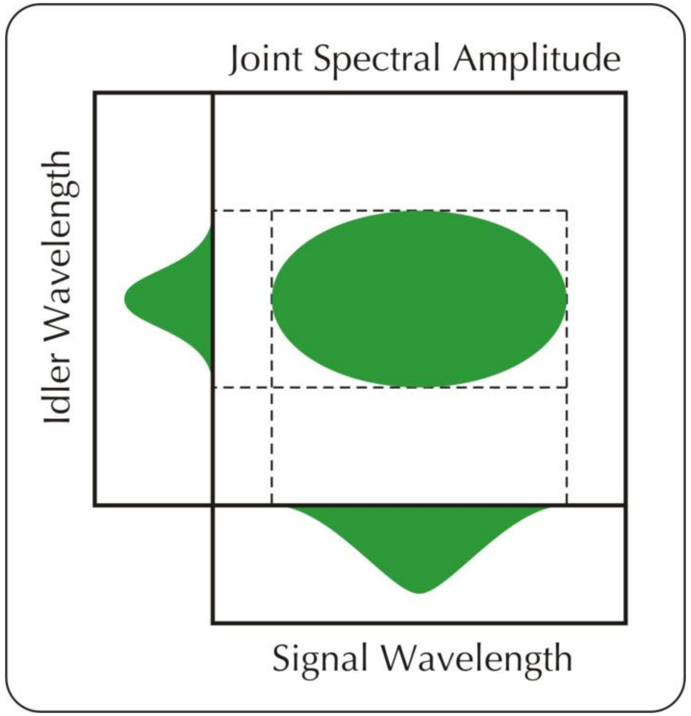
Uncorrelated Bi-photon state

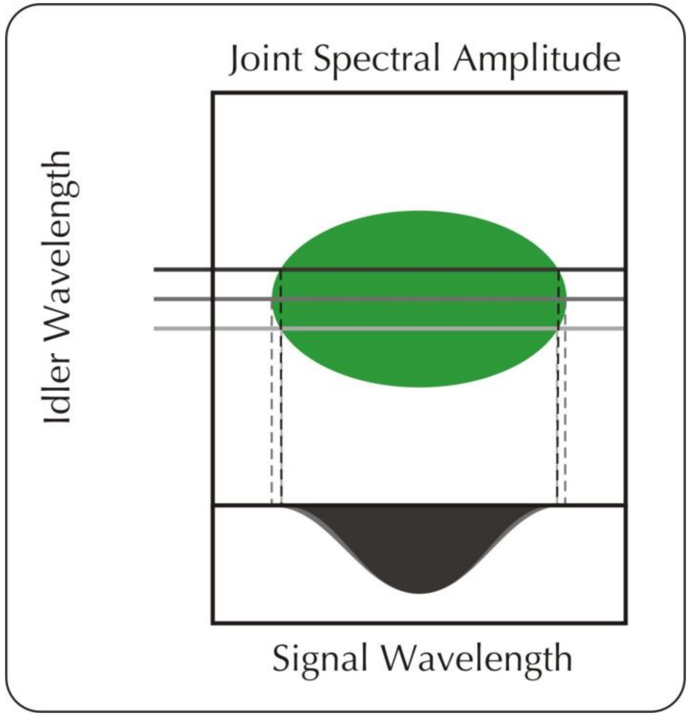


- pure state:

$$|1\rangle = \int d\omega\, f(\omega)\ \hat{a}^\dagger_\omega |0\rangle = \hat{A}^\dagger |0\rangle, \qquad \hat{\rho} = |1\rangle\langle 1|$$

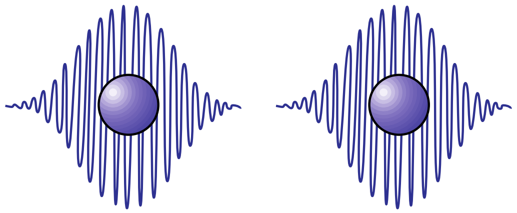


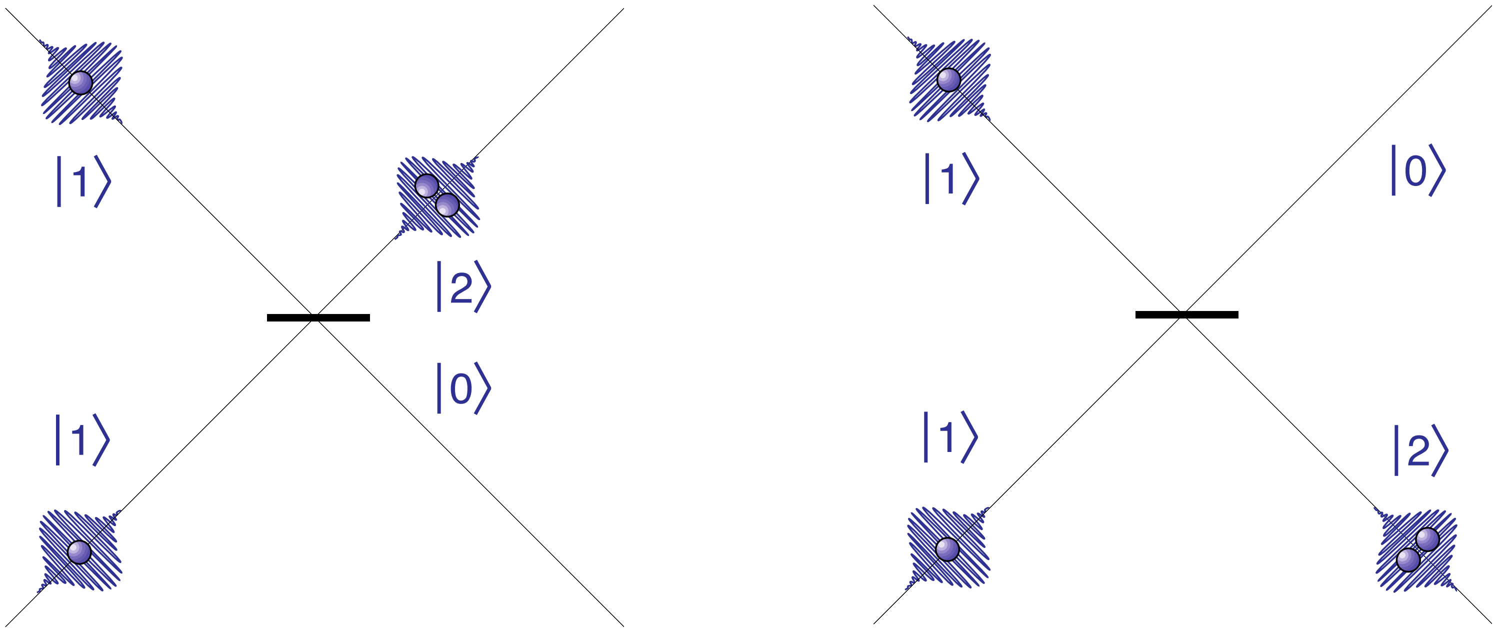




HOM interference

Pure single photons like to team up!



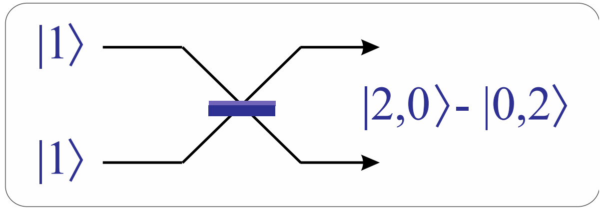


$$|1\rangle\,|1\rangle \quad \longrightarrow \quad |0\rangle\,|2\rangle - |2\rangle\,|0\rangle$$

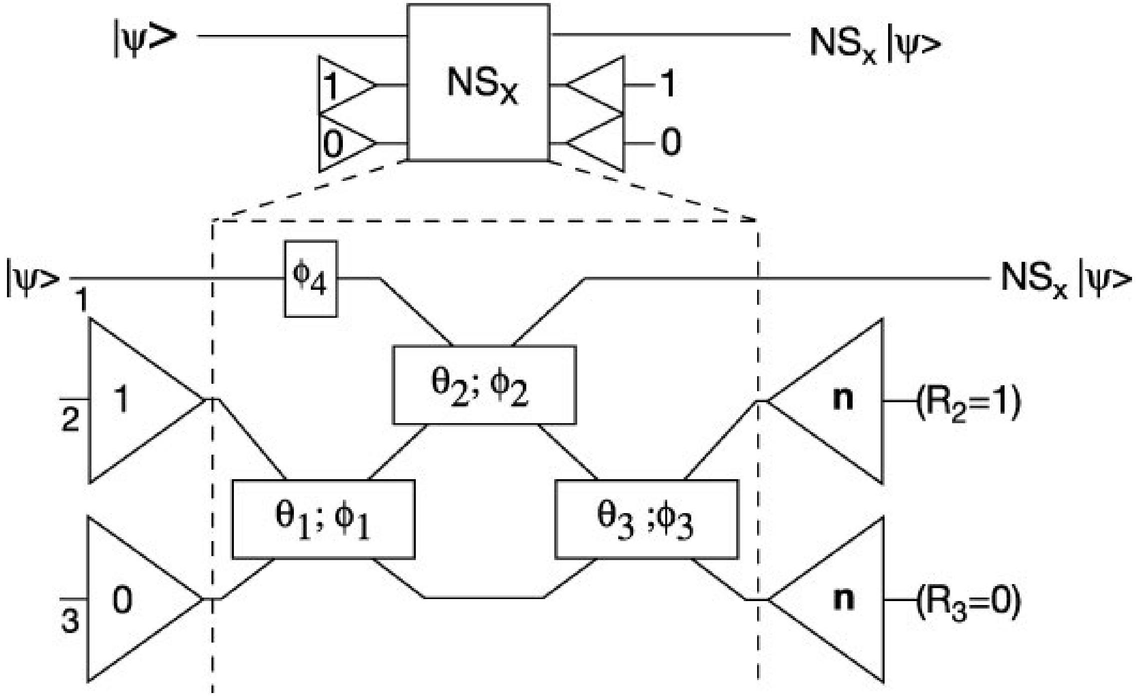
C. K. Hong, Z.Y. Ou, L. Mandel, Phys. Rev. **59**, 2044, 1987

Quantum information processing

What is HOMI good for?

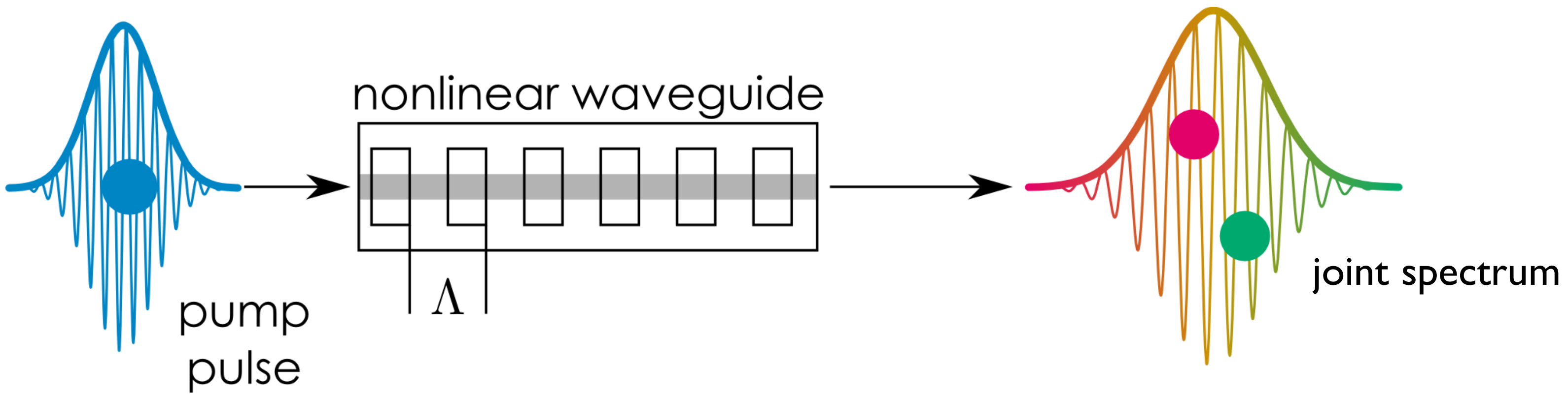


Linear optical quantum computation



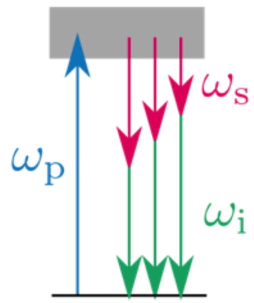
Knill, Laflamme, Milburn, Nature **409,** 46, (2001)

Guided-wave parametric down-conversion



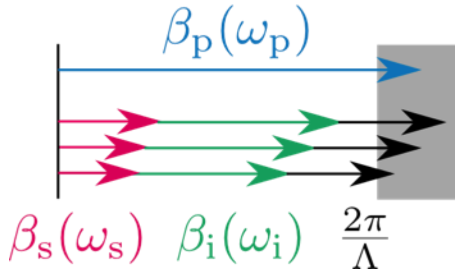
Energy conservation

$$\omega_\mathrm{p} = \omega_\mathrm{s} + \omega_\mathrm{i}$$



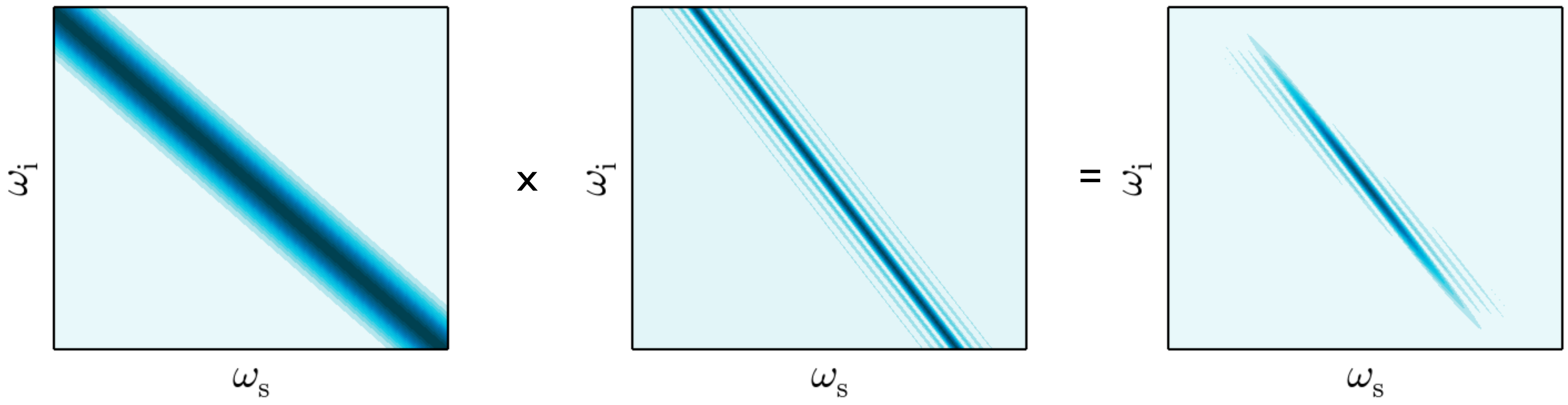
Phasematching

$$\beta_\mathrm{p} = \beta_\mathrm{s} + \beta_\mathrm{i} + \frac{2\pi}{\Lambda}$$



Guided-wave parametric down-conversion

Energy conservation $\alpha(\omega_s + \omega_i)$ × Phasematching $\phi(\omega_s, \omega_i)$ = Joint spectral amplitude (JSA) $f(\omega_s, \omega_i)$



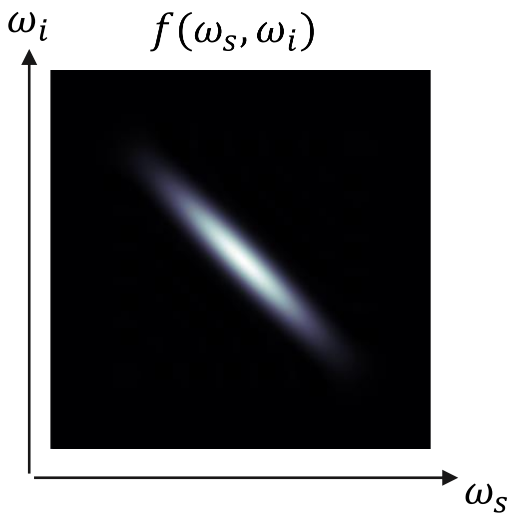
$$|\psi\rangle_{\mathrm{PDC}} = \exp\left[\mathcal{B}\int d\omega_s d\omega_i\, f(\omega_s, \omega_i)\hat{a}^\dagger(\omega_s)\hat{b}^\dagger(\omega_i) + \mathrm{h.c.}\right]|0\rangle$$

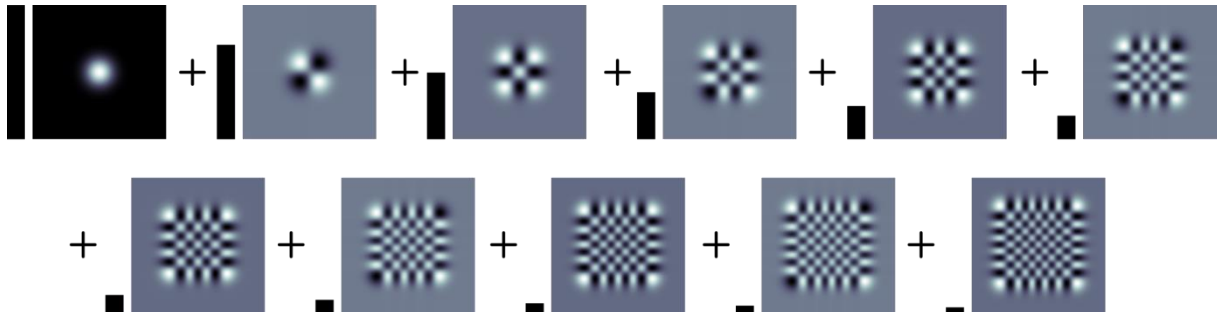
Bi-photon state (general)

$$|\Psi\rangle = |0\rangle|0\rangle + \iint d\omega_s\, d\omega_i\, f(\omega_s, \omega_i)\ \hat{a}_i^\dagger\ \hat{a}_s^\dagger\ |0\rangle \quad \neq |0\rangle|0\rangle + \kappa|1\rangle|1\rangle$$

The Schmidt decomposition

$$f(\omega_s, \omega_i) = \sum_k \sqrt{\lambda_k} g_k(\omega_s) h_k(\omega_i)$$

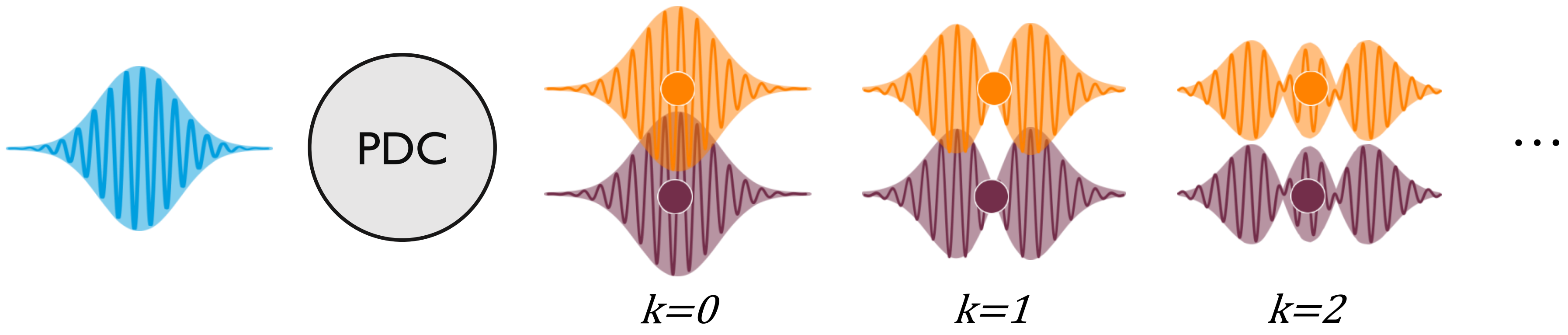




$$|\psi\rangle_{\mathrm{PDC}} = \bigotimes_k \exp\left[\theta\sqrt{\lambda_k}\hat{A}_k^\dagger \hat{B}_k^\dagger + h.c.\right]|0\rangle$$

Law, Walmsley, Eberly, Phys. Rev. Lett. **84**, 5304 (2000)

$$|\psi\rangle_{\mathrm{PDC}} = \bigotimes_k \exp\left[\theta\sqrt{\lambda_k}\hat{A}_k^\dagger\hat{B}_k^\dagger + h.c.\right]|0\rangle$$



Multimode PDC state

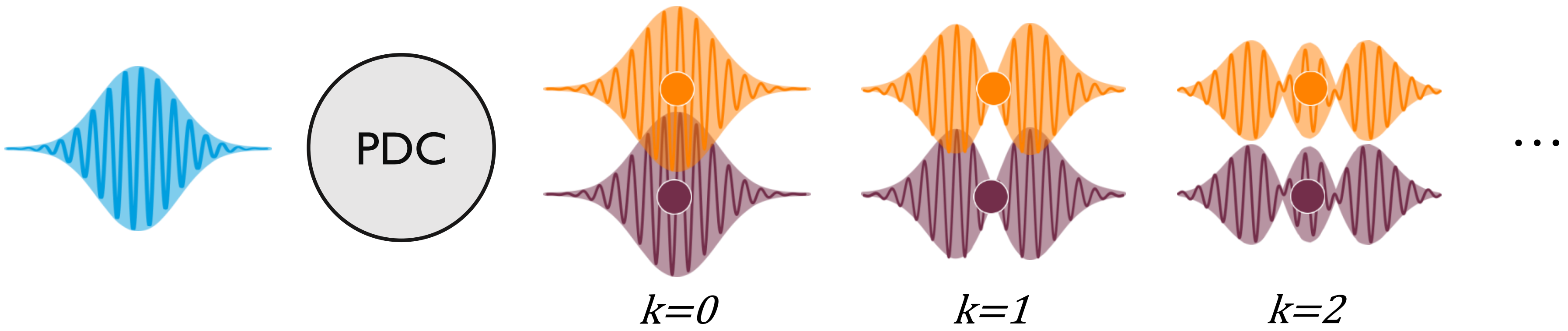
- The **effective number of modes / amount of spectral entanglement** is characterized by the Schmidt number

$$K = 1/\left(\sum_k \lambda_k^2\right)$$

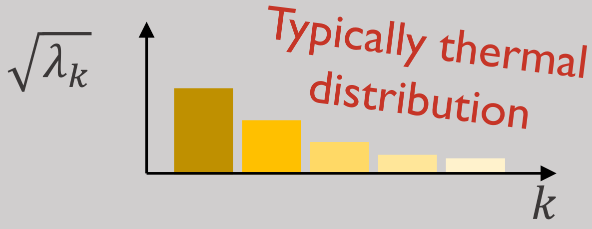
- The temporal-mode properties are encoded in the JSA of the PDC

Law, Walmsley, Eberly, Phys. Rev. Lett. **84**, 5304 (2000)

$$|\psi\rangle_{\text{PDC}} = \bigotimes_k \exp\left[\theta\sqrt{\lambda_k}\hat{A}_k^\dagger\hat{B}_k^\dagger + h.c.\right]|0\rangle$$



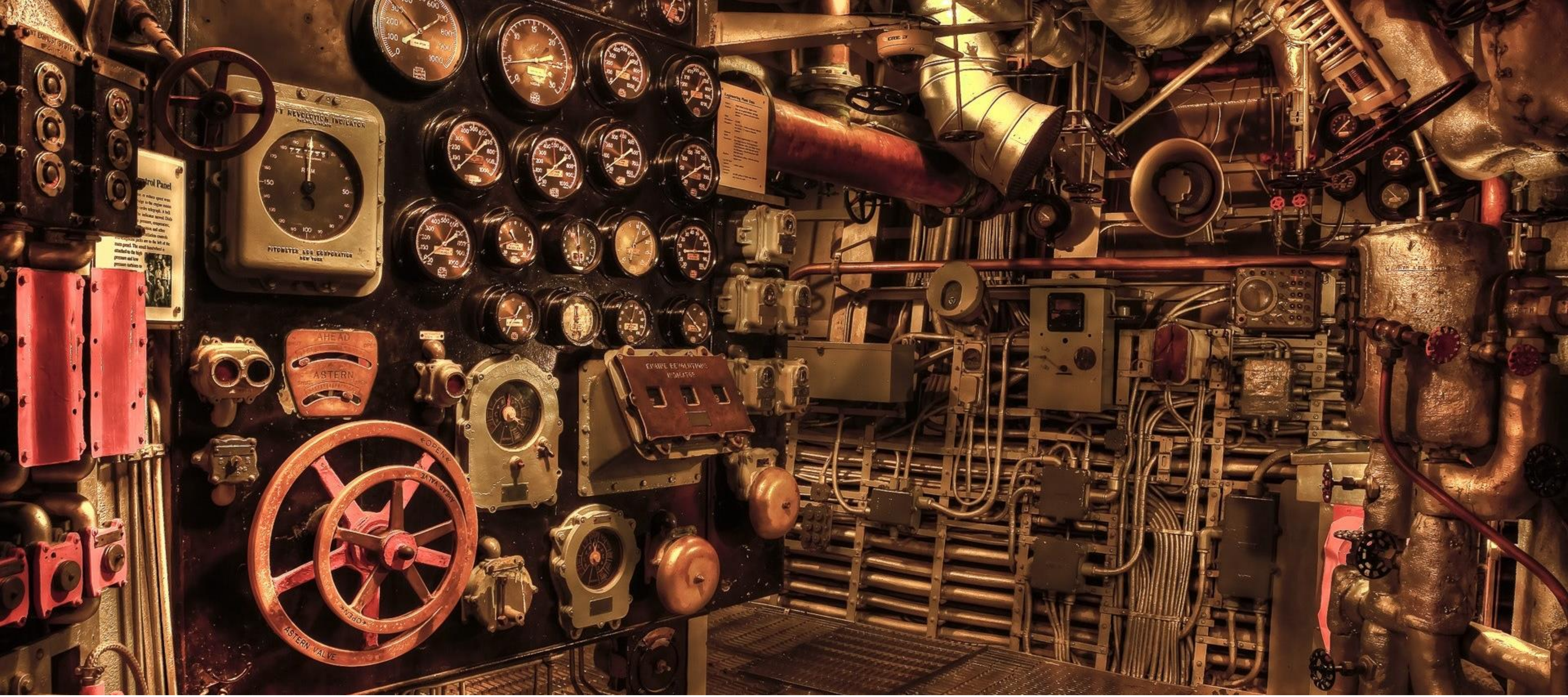
$$f(\omega_s,\omega_i) = \sum_k \sqrt{\lambda_k}\, g_k(\omega_s) h_k(\omega_i)$$



?

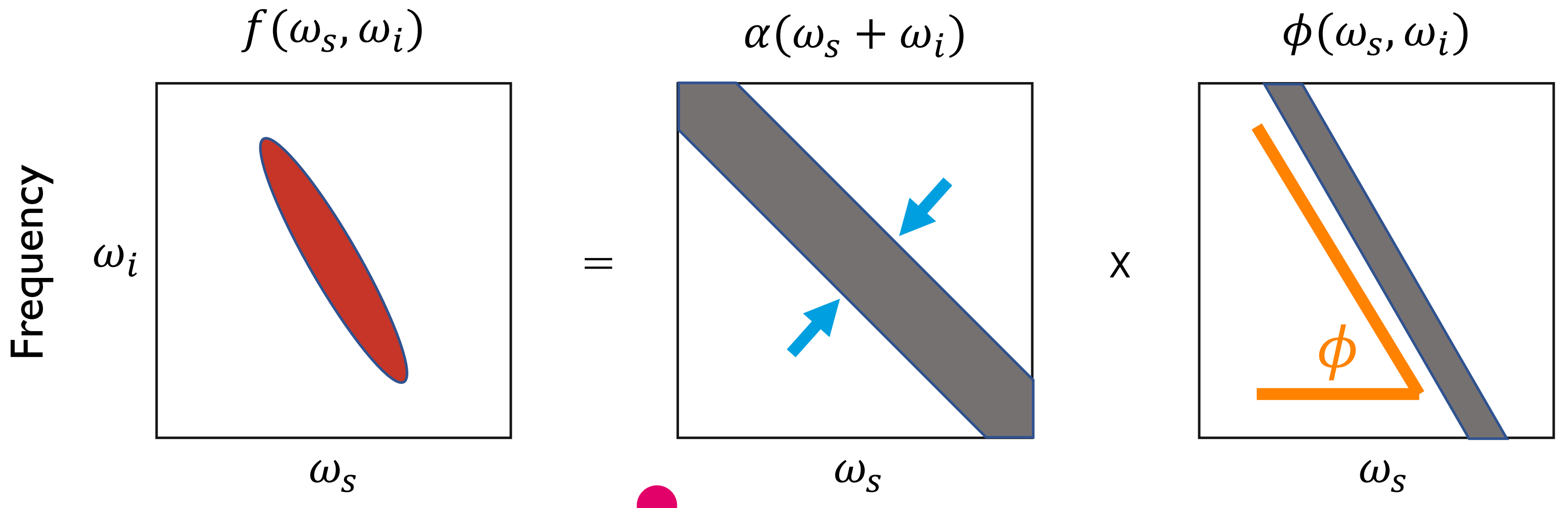
Engineered distribution

Law, Walmsley, Eberly, Phys. Rev. Lett. **84**, 5304 (2000)

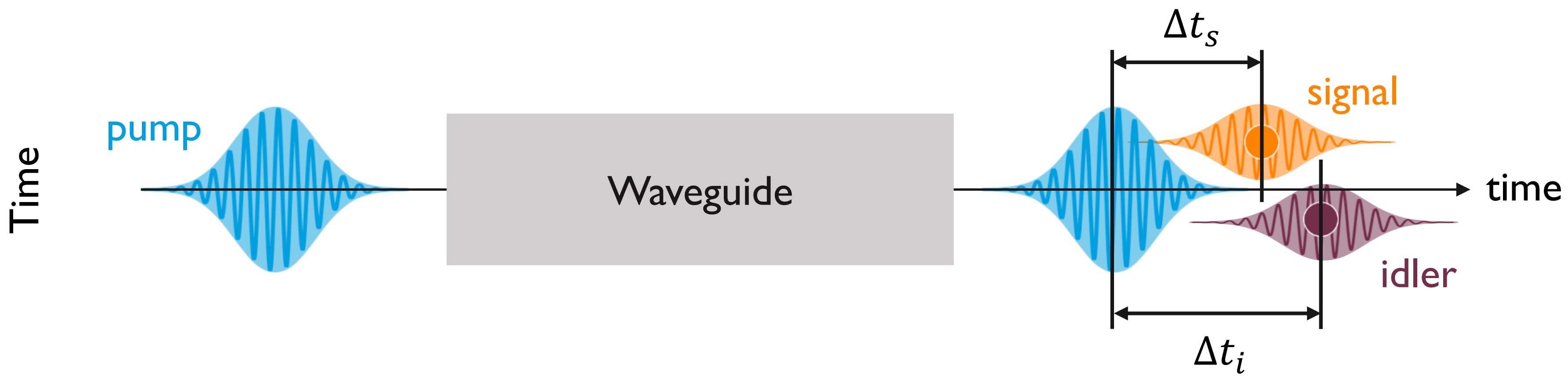


Source engineering – which knobs to turn?

Group velocity matching

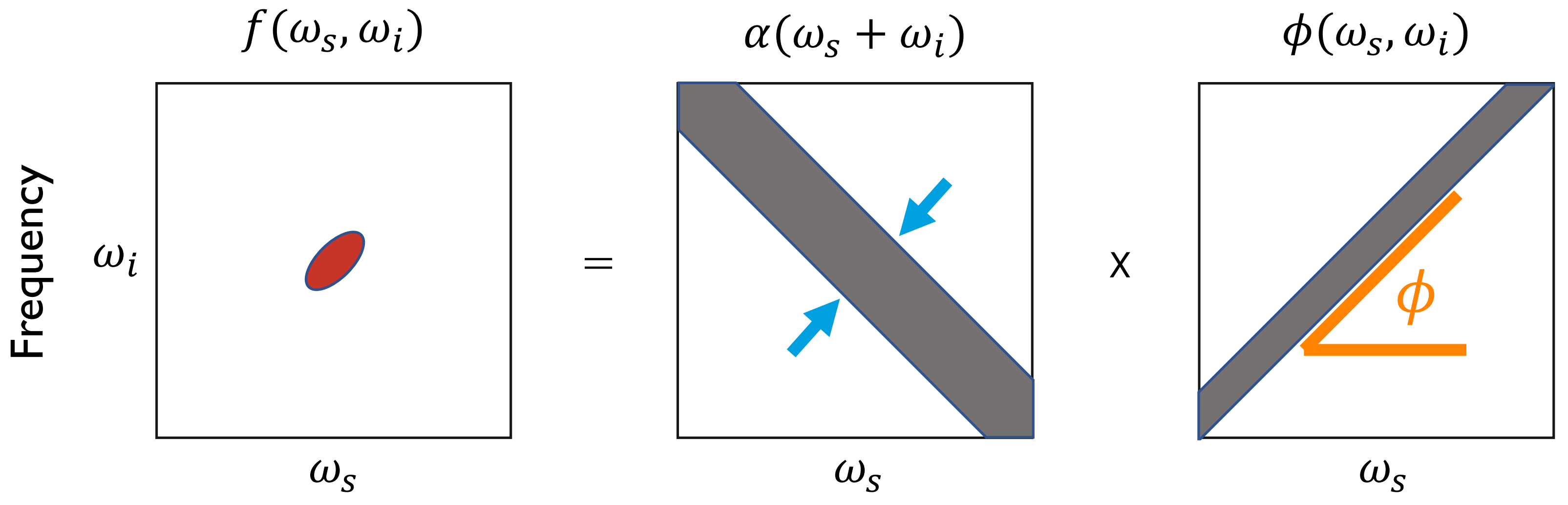


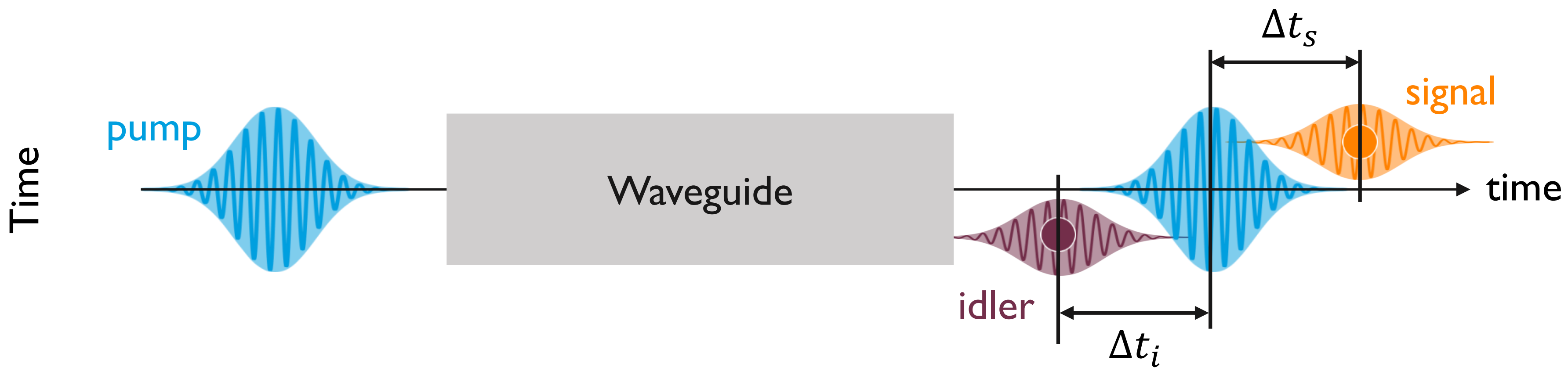
$$\tan\phi = -\frac{\left(v_s^{-1} - v_p^{-1}\right)}{\left(v_i^{-1} - v_p^{-1}\right)}$$



A. B. U'Ren et al, Las. Phys. **15**, 146-161 (2005)

Group velocity matching





Pump spectrum

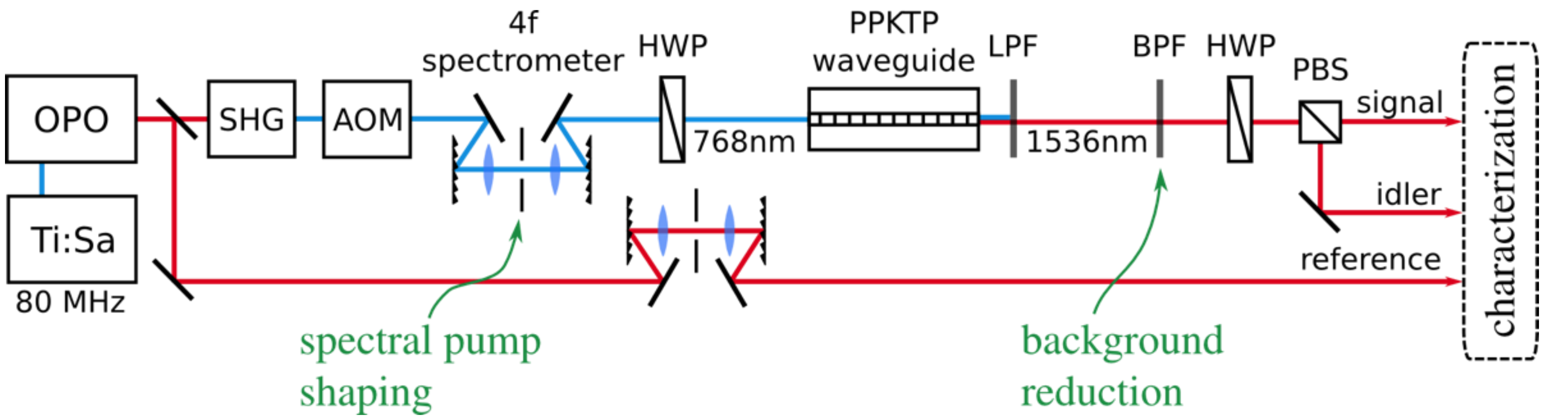
- Width
- Shape

Phasematching

- Angle
- (Pattern)

C. Silberhorn, et al, Las. Phys. **15**, 146-161 (2005)

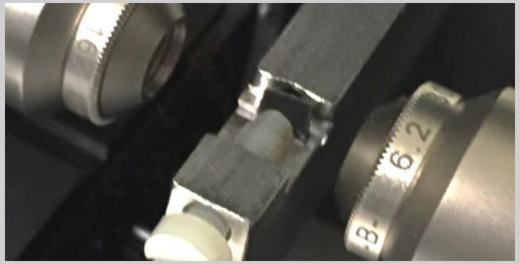
Experiment

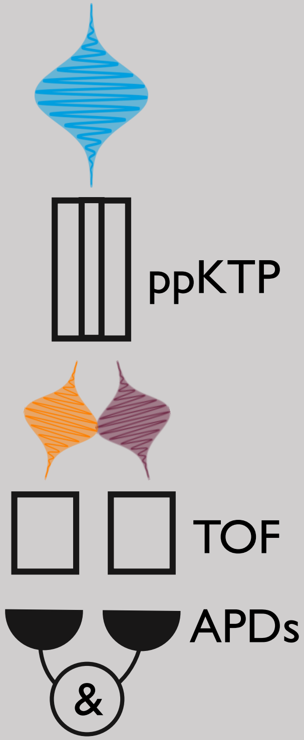


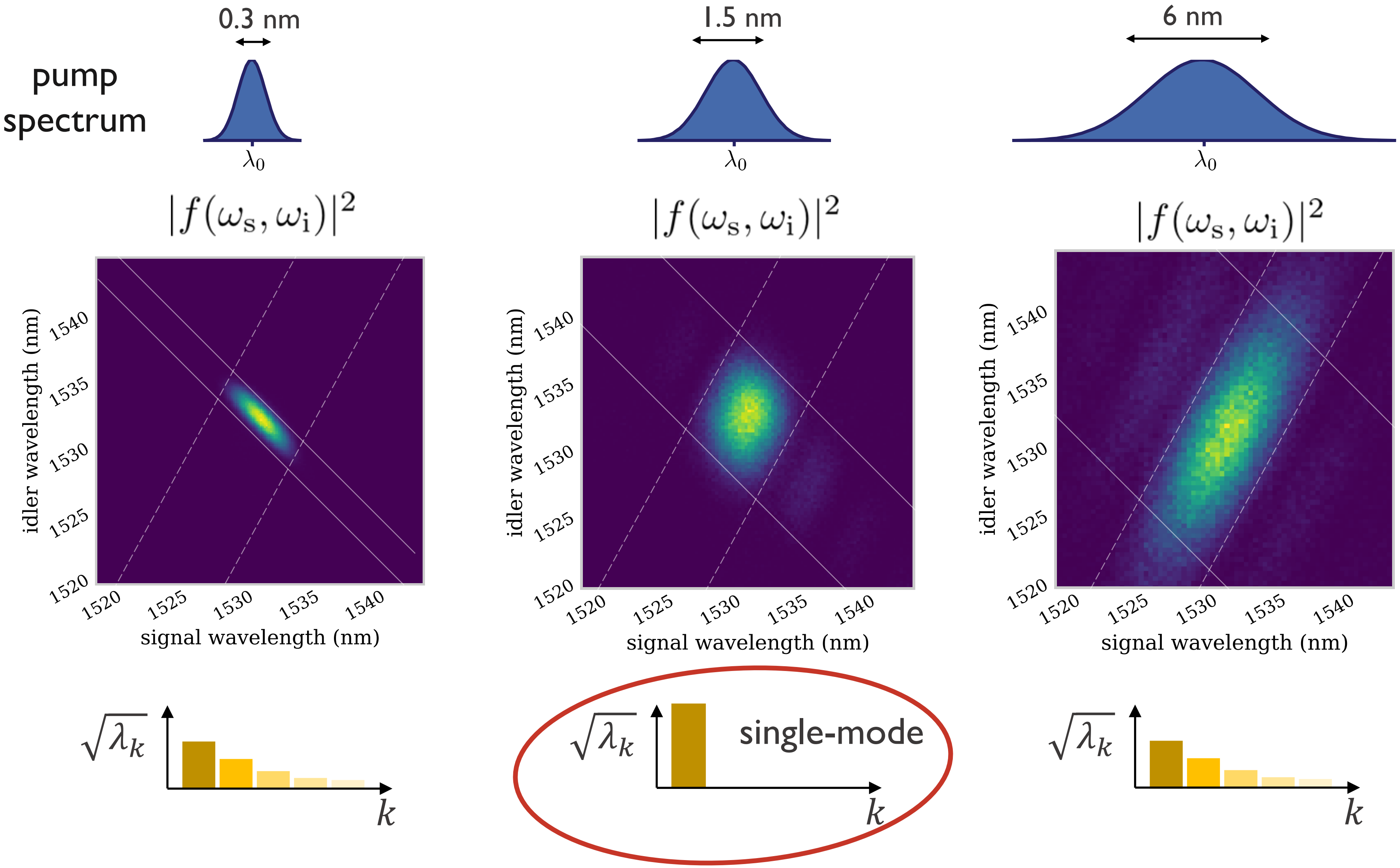
- No narrowband spectral filtering
- Coupling into single-mode fibers of up to 70% and 80%, corresponding to Klyshko efficiencies of 15.5% and 20.5%.

ppKTP waveguide

- group velocity matching at telecoms wavelengths
- high brightness
- 8mm length



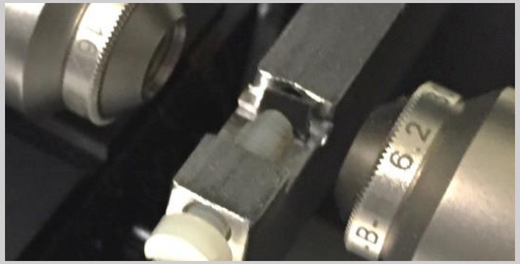


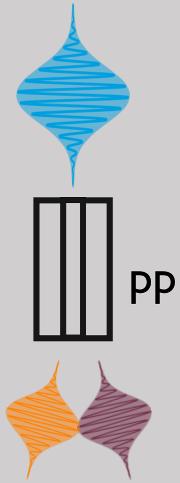


A. Eckstein et al, Phys. Rev. Lett. **106**, 013603 (2011)
G. Harder et al, Opt. Express **21**, 13975 (2013)

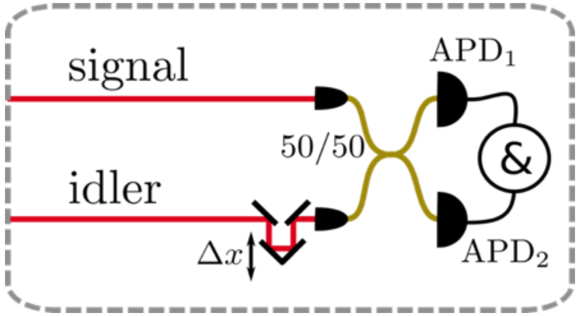
ppKTP waveguide

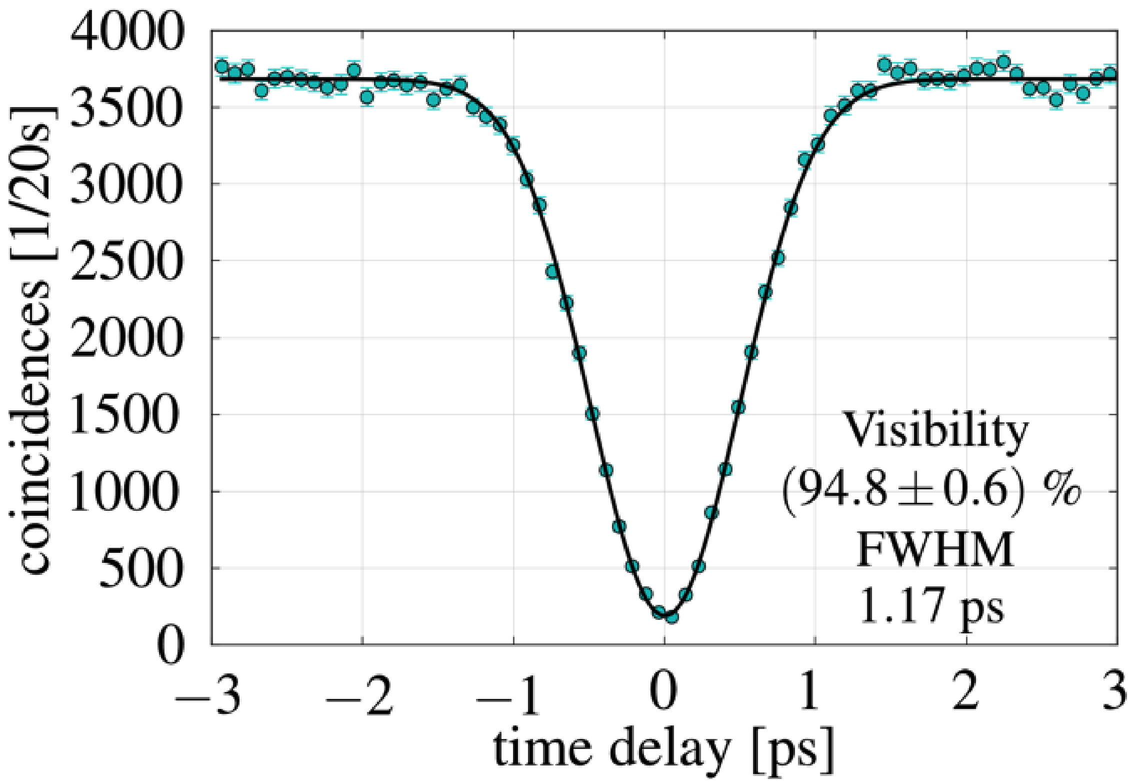
- group velocity matching at telecoms wavelengths
- high brightness
- 8mm length





signal-idler HOMI
→ indistinguishability





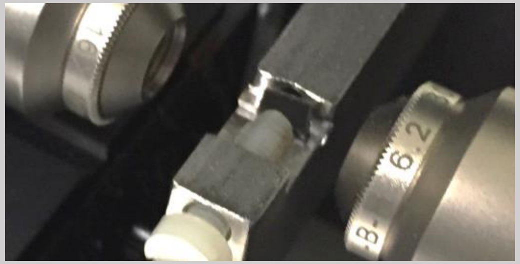
Visibility$_{dip}$ ≈ 95%

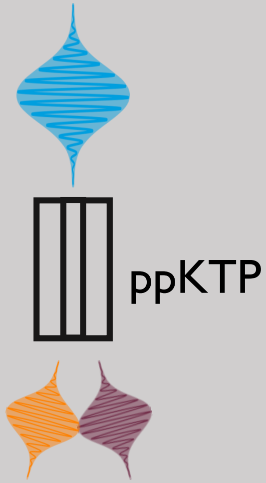
⇒ **High indistinguishability**

G. Harder et al, Opt. Express **21**, 13975 (2013)

ppKTP waveguide

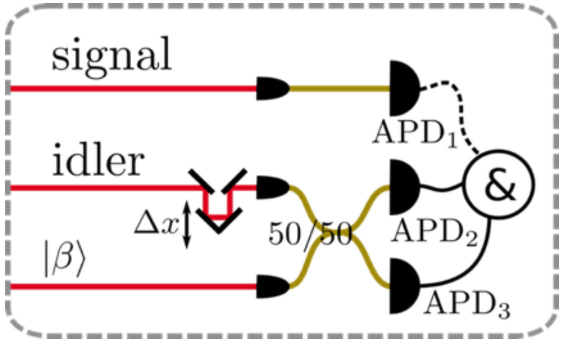
- group velocity matching at telecoms wavelengths
- high brightness
- 8mm length

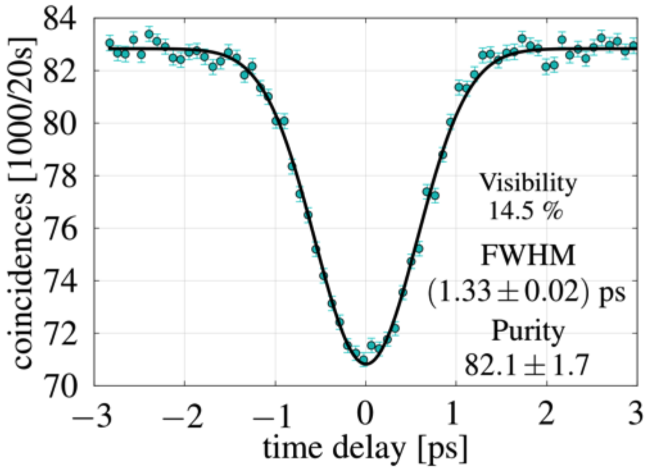


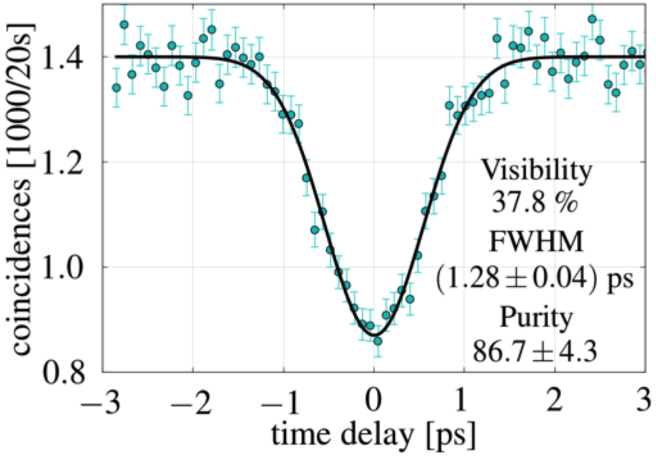


signal-reference HOMI
→ spectral purity

For decorrelated joint spectral amplitdute







Purity ≈ 85%

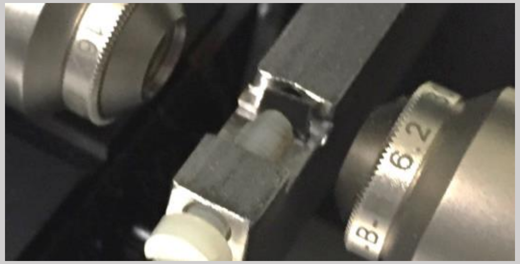
$\Rightarrow$ High decorrelation

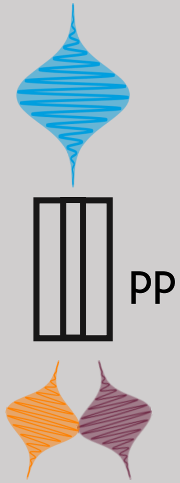
G. Harder et al, Opt. Express **21**, 13975 (2013)

For decorrelated joint spectral amplitdute

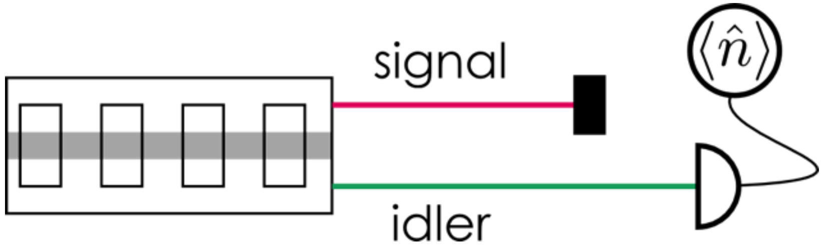
ppKTP waveguide

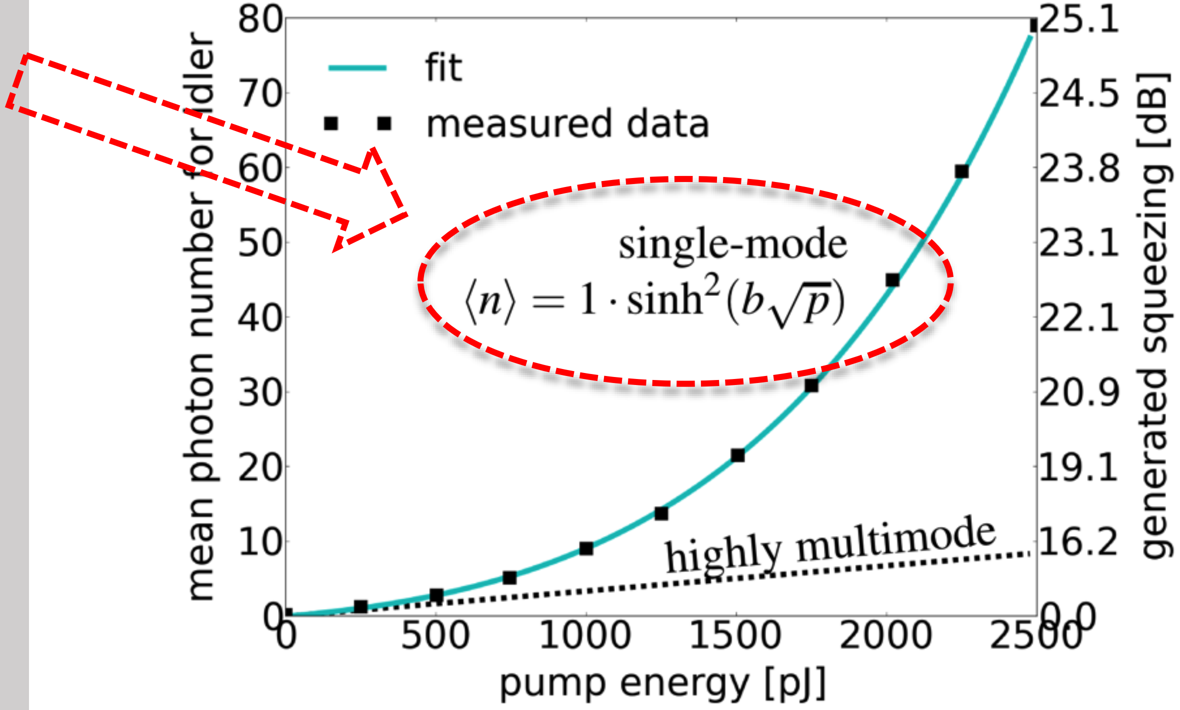
- group velocity matching at telecoms wavelengths
- high brightness
- 8mm length



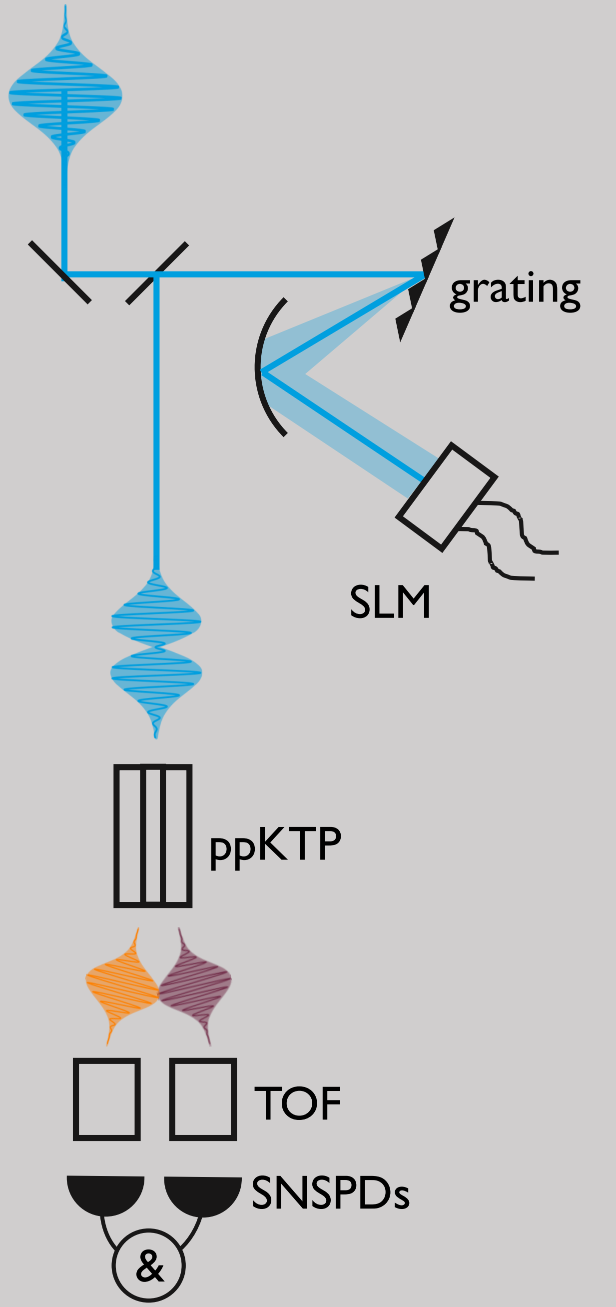


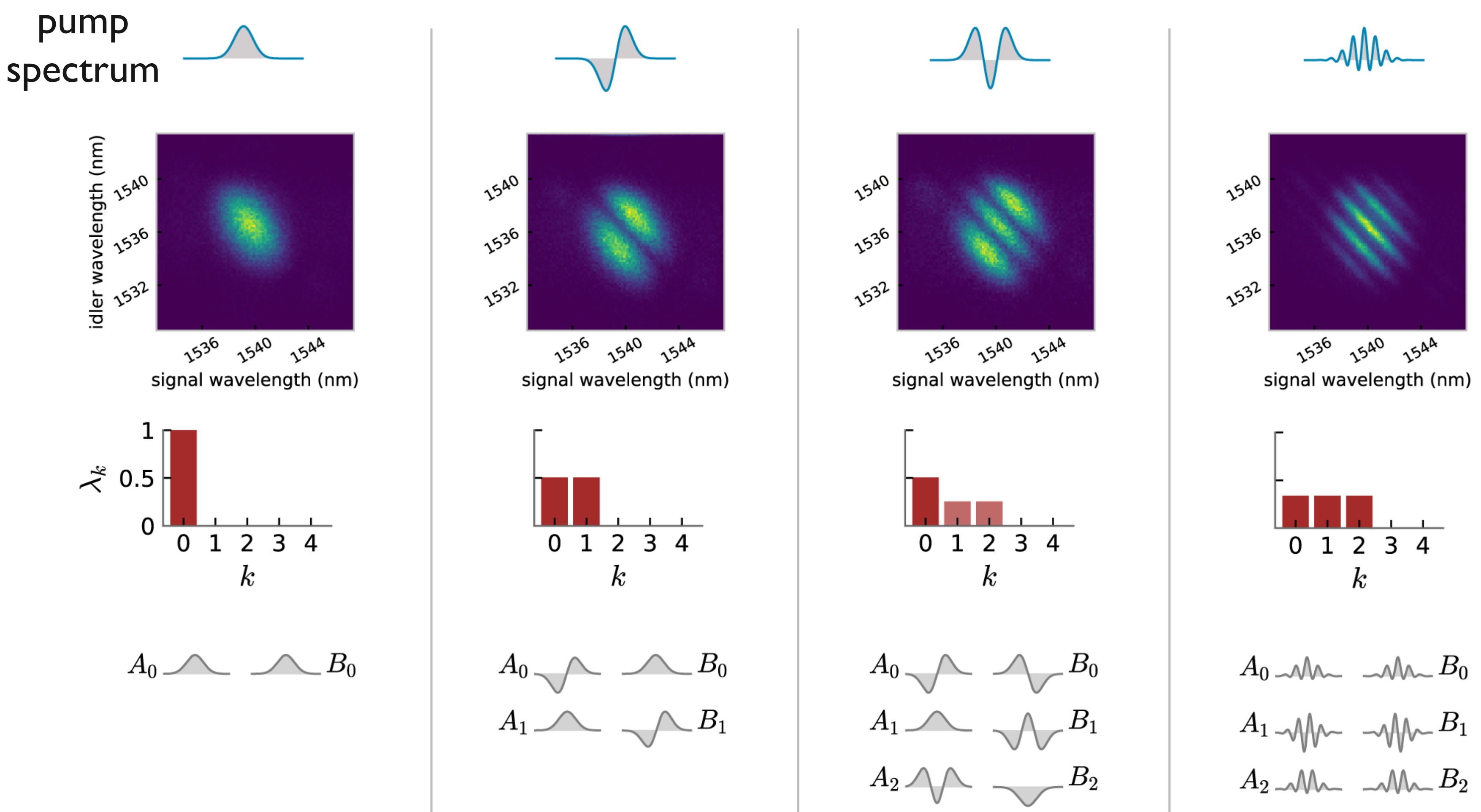
photon counting
→ source brightness





- High brightness
- Clean single-mode behaviour





Can generate user-defined temporal-mode states

B. Brecht et al, Phys. Rev. X **5**, 041017 (2015)
V. Ansari et al, Optica **5**, 534 (2018)
G. Patera et al, Eur. Phys. J. D 66:241 (2012)

Outline

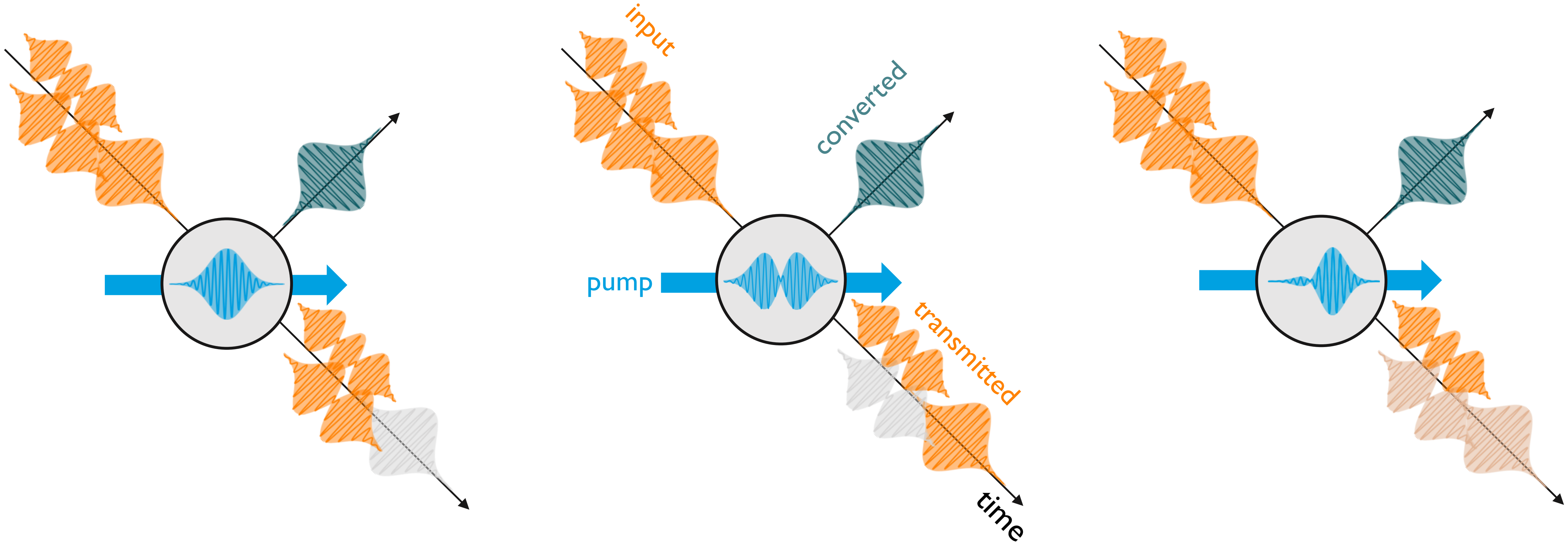
Optical modes

Parametric down-conversion

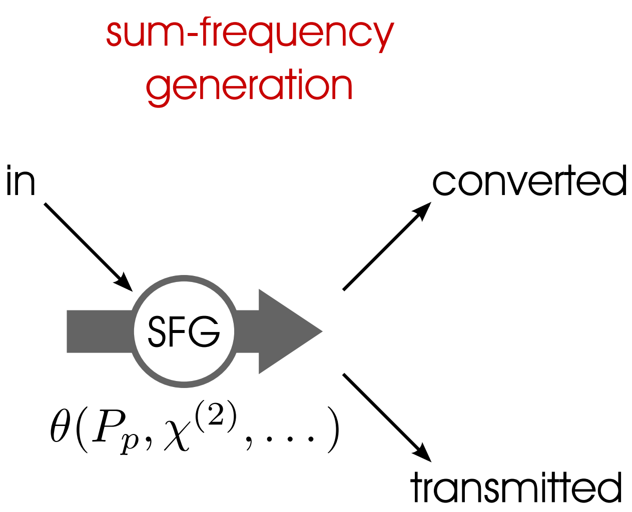
Quantum pulse gate

Applications

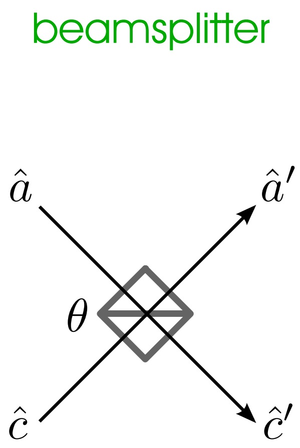
What would we like to have?



Sum-frequency generation? Maybe???



$$\hat{H}_{\mathrm{SFG}} = \theta\left(\hat{a}_{\mathrm{in}}\hat{c}^{\dagger}_{\mathrm{out}} + \mathrm{h.c.}\right)$$



$$\hat{H}_{\mathrm{BS}} = \theta\left(\hat{a}\hat{c}^{\dagger} + \hat{a}^{\dagger}\hat{c}\right)$$

Multi-mode theory for SFG

$$|\psi\rangle_{\mathrm{out}} = \mathrm{e}^{\mathrm{i}\theta \int \mathrm{d}\omega_{\mathrm{in}}\mathrm{d}\omega_{\mathrm{out}} G(\omega_{\mathrm{in}},\omega_{\mathrm{out}})\hat{a}(\omega_{\mathrm{in}})\hat{c}^{\dagger}(\omega_{\mathrm{out}}) + \mathrm{h.c.}} |\psi\rangle_{\mathrm{in}}$$

- Does this operate on one pulsed temporal mode?
- How can we define temporal modes for SFG?

Revealing the pulsed temporal modes

Starting point

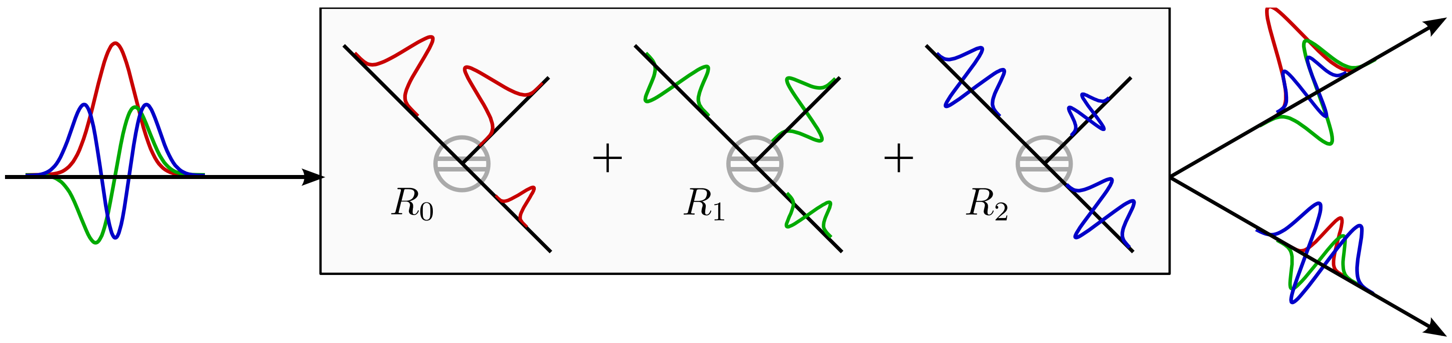
$$|\psi\rangle_{\text{out}} = \mathrm{e}^{\mathrm{i}\theta\int \mathrm{d}\omega_{\text{in}}\mathrm{d}\omega_{\text{out}}G(\omega_{\text{in}},\omega_{\text{out}})\hat{a}(\omega_{\text{in}})\hat{c}^\dagger(\omega_{\text{out}})+\text{h.c.}}\,|\psi\rangle_{\text{in}}$$

-
- some math
-

analogous to
Schmidt mode decomposition

$$|\psi\rangle_{\text{out}} = \mathrm{e}^{\mathrm{i}\sum_j \kappa_j\theta\left(\hat{A}_j\hat{C}_j^\dagger+\hat{A}_j^\dagger\hat{C}_j\right)}\,|\psi\rangle_{\text{in}}$$

Array of beamsplitters operating on pulse modes[6,7]

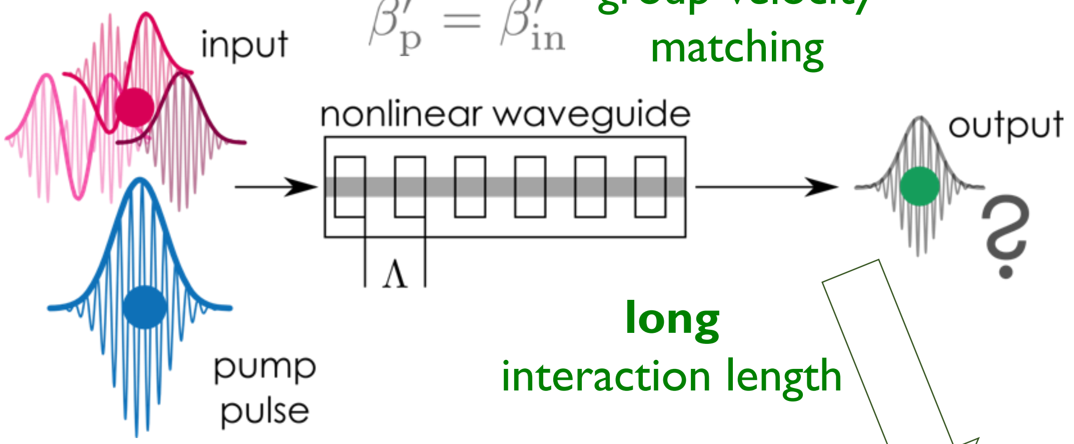


[6] M. G. Raymer et al., Opt. Comm. **283**, 747-752 (2010)
[7] A. Eckstein et al., Opt. Express **19** 13770 (2011),

The quantum pulse gate (QPG)

QPG = single TM SFG

$\beta'_{\mathrm{p}} = \beta'_{\mathrm{in}}$ group-velocity matching



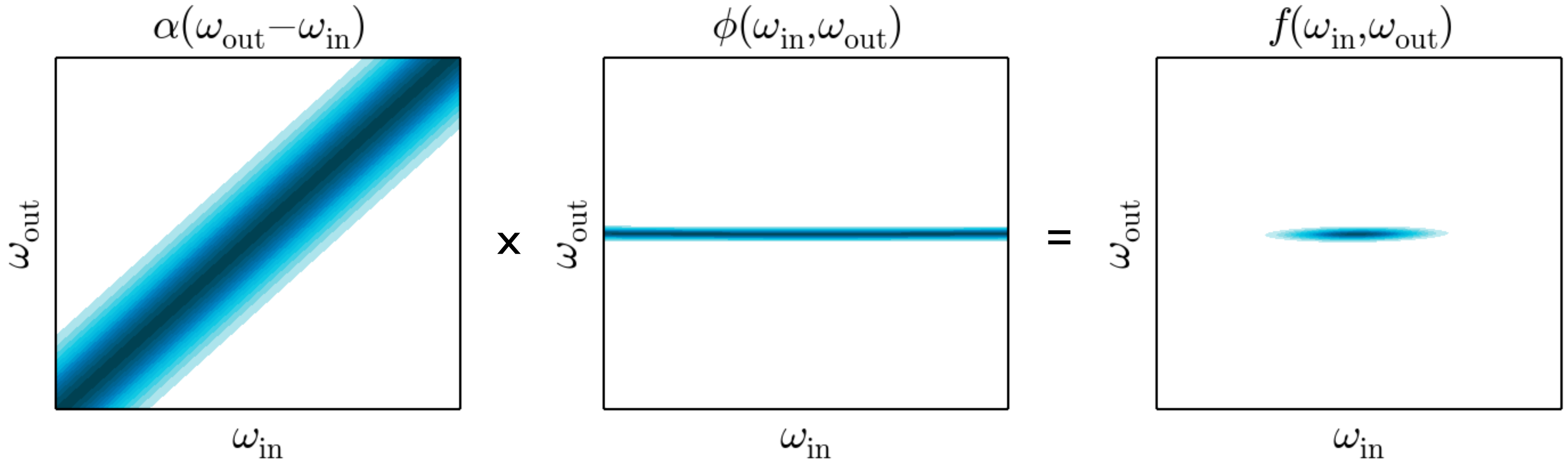
long interaction length

Energy conservation

$$\omega_{\mathrm{p}} + \omega_{\mathrm{in}} = \omega_{\mathrm{out}}$$

Phasematching

$$\beta_{\mathrm{p}} + \beta_{\mathrm{in}} + \frac{2\pi}{\Lambda} = \beta_{\mathrm{out}}$$

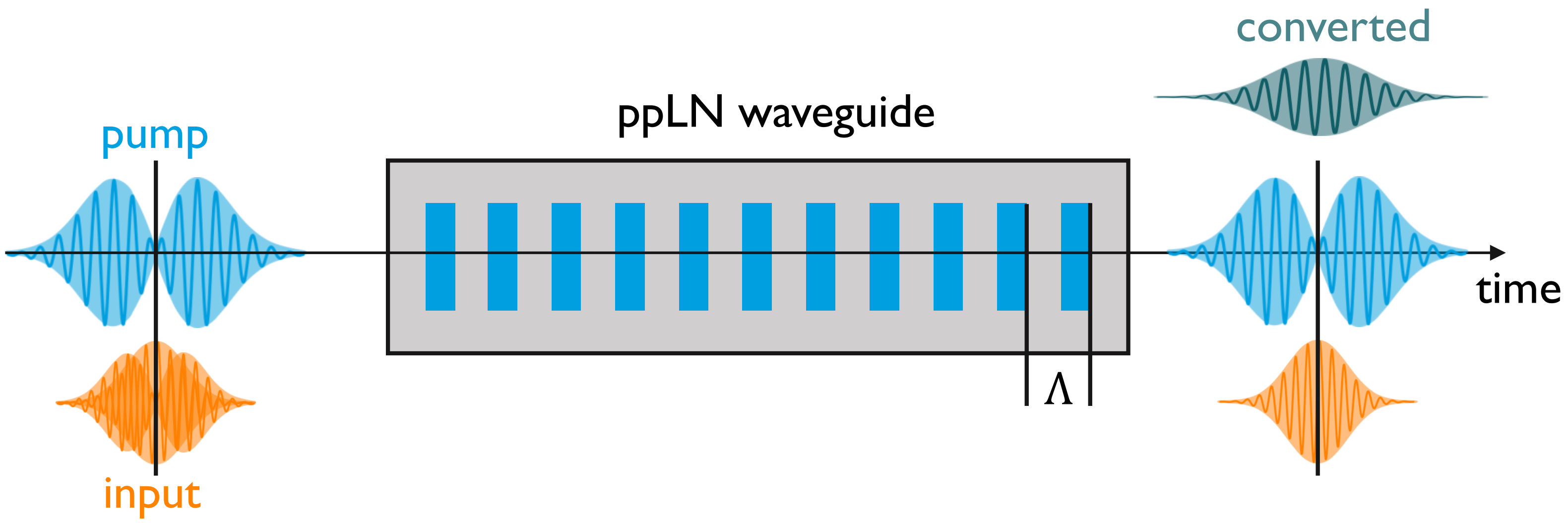


Eckstein, et al., Opt. Exp. 19, 13370 (2011)
Brecht, et al., New J. Phys. 13, 065029 (2011)

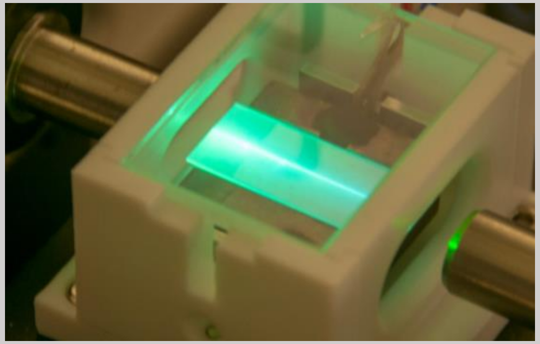
Realisation – group velocity matched sum frequency generation

$$\omega_c = \omega_p + \omega_{in}$$

$$k_c = k_p + k_{in} + \frac{2\pi}{\Lambda}$$



$$\eta_{\text{SFG}} \propto \int d\omega\, f_p(\omega) f_{in}^*(\omega)$$

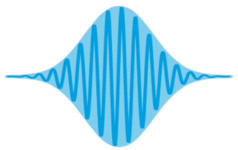


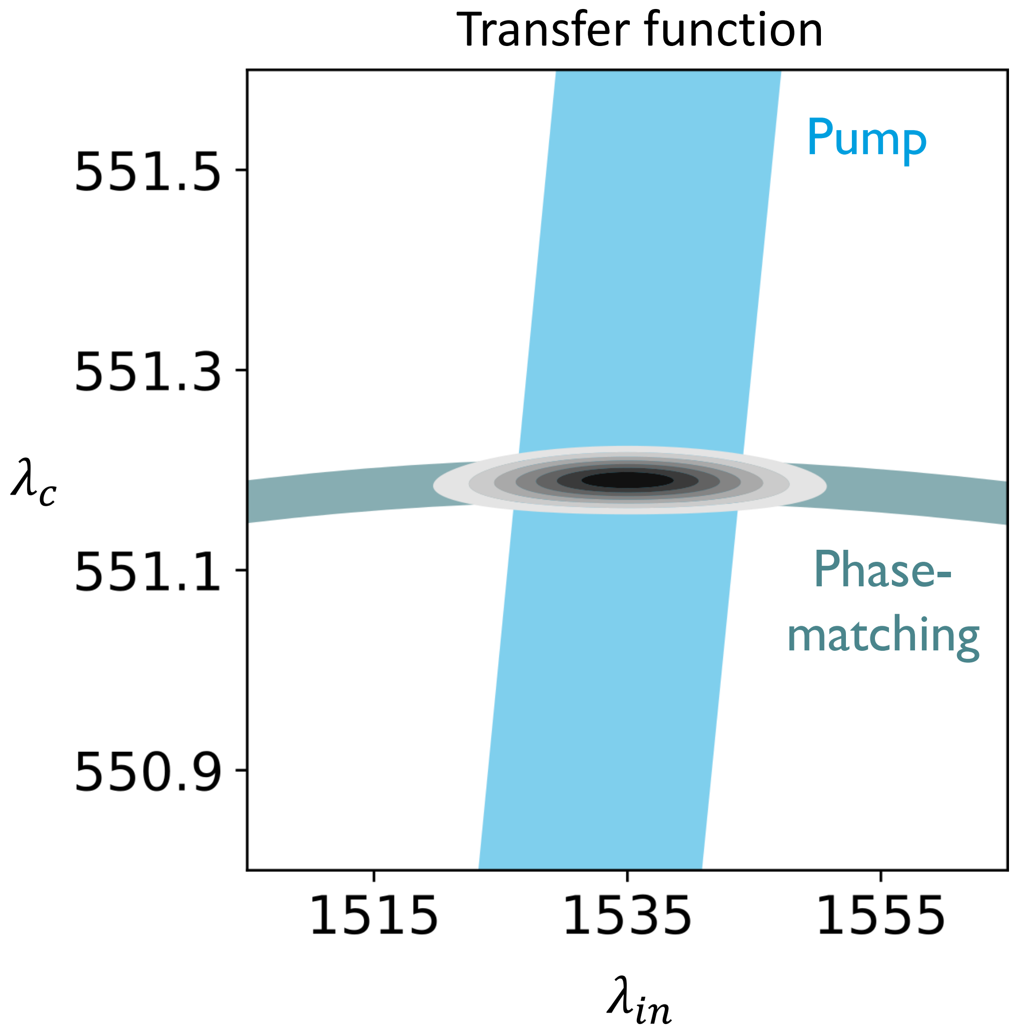
- **homebuilt** ppLN waveguide
- 4.5μm poling period
- operated at 190°C
- type II SFG
- $v_g^{(p)} = v_g^{(in)}$
- $\lambda_{in} = 1550\text{nm}$
- $\lambda_p = 860\text{nm}$

A. Eckstein et al, Opt. Exp. **19**, 13370 (2011)
B. Brecht et al, New J. Phys. **13**, 065029 (2011)

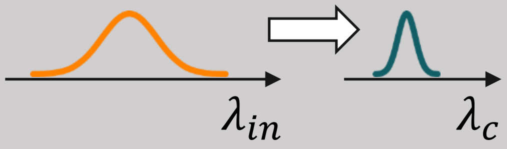
A closer look at the pulse gate operation

Pump
pulse

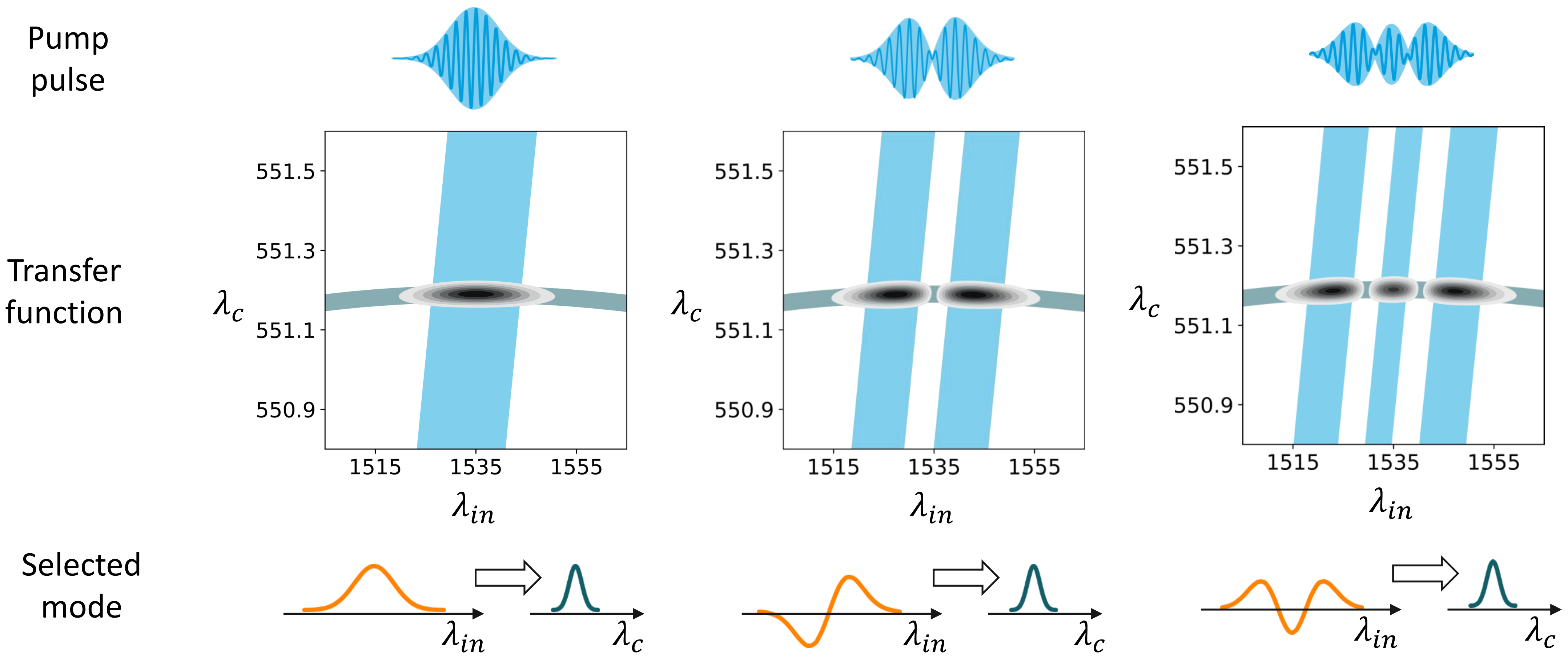




- Transfer function is product of pump and phasematching (c.f. JSA)
- Can use the Schmidt decomposition formalism
- Selected input mode defined by pump
- Converted mode defined by phasematching



A. Eckstein et al, Opt. Exp. **19**, 13370 (2011)
B. Brecht et al, New J. Phys. **13**, 065029 (2011)



$$|\psi\rangle_{out} = \exp\left[\theta \hat{A}\hat{C}^\dagger + \theta^* \hat{A}^\dagger \hat{C}\right]|\psi\rangle_{in}$$

QPG = special beam splitter for temporal modes

B. Brecht et al, New J. Phys. **13**, 065029 (2011)

A quantum pulse gate based on spectrally engineered sum frequency generation

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[1] *Max Planck Institute for the Science of Light, Günther-Scharowsky-Strasse 1, 91054 Erlangen, Germany*

ARTICLE

Received 8 Oct 2016 | Accepted 16 Dec 2016 | Published 30 Jan 2017 DOI: 10.1038/ncomms14288 OPEN

Highly efficient frequency conversion with bandwidth compression of quantum light

Markus Allgaier[1], Vahid Ansari[1], Linda Sansoni[1], Christof Eigner[1], Viktor Quiring[1], Raimund Ricken[1], Georg Harder[1], Benjamin Brecht[1,2] & Christine Silberhorn[1]

APPLIED PHYSICS LETTERS **112**, 031110 (2018)

Streak camera imaging of single photons at telecom wavelength

Markus Allgaier,[1] Vahid Ansari,[1] Christof Eigner,[1] Viktor Quiring,[1] Raimund Ricken,[1] John Matthew Donohue,[1] Thomas Czerniuk,[2] Marc Aßmann,[2] Manfred Bayer,[2] Benjamin Brecht,[1,3] and Christine Silberhorn[1]

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[2] *Experimentelle Physik II, Technische Universität Dortmund, D-44221 Dortmund, Germany*

New Journal of Physics

The open-access journal for physics

From quantum pulse gate to quantum pulse shaper—engineered frequency conversion in nonlinear optical waveguides

Benjamin Brecht[1,3], Andreas Eckstein[1,2], Andreas Christ[1,2], Hubertus Suche[1] and Christine Silberhorn[1,2]

[1] Applied Physics, University of Paderborn, Warburger Strasse 100, 33098 Paderborn, Germany

Quantum Science and Technology

PAPER

Fast time-domain measurements on telecom single photons

Markus Allgaier[1], Gesche Vigh[1], Vahid Ansari[1], Christof Eigner[1], Viktor Quiring[1], Raimund Ricken[1], Benjamin Brecht[1,2] and Christine Silberhorn[1]

RAPID COMMUNICATIONS

PHYSICAL REVIEW A **90**, 030302(R) (2014)

Demonstration of coherent time-frequency Schmidt mode selection using dispersion-engineered frequency conversion

Benjamin Brecht,[1] Andreas Eckstein,[1,2] Raimund Ricken,[1] Viktor Quiring,[1] Hubertus Suche,[1] Linda Sansoni,[1] and Christine Silberhorn[1]

[1] *Integrated Quantum Optics, Applied Physics, University of Paderborn, Warburger Strasse 100 33098, Paderborn, Germany*

[2] *Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom*

(Received 18 March 2014; published 12 September 2014)

PHYSICAL REVIEW LETTERS **120,** 213601 (2018)

Tomography and Purification of the Temporal-Mode Structure of Quantum Light

Vahid Ansari,[1,*] John M. Donohue,[1,†] Markus Allgaier,[1] Linda Sansoni,[1] Benjamin Brecht,[1,2] Jonathan Roslund,[3] Nicolas Treps,[3] Georg Harder,[1] and Christine Silberhorn[1]

[1] *Integrated Quantum Optics, Paderborn University, Warburger Strasse 100, 33098 Paderborn, Germany*

[2] *Clarendon Laboratory, Department of Physics, University of Oxford, Parks Road OX1 3PU, United Kingdom*

[3] *Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-PSL Research University, Collège de France; 4 place Jussieu, F-75252 Paris, France*

(Received 26 January 2018; published 23 May 2018)

B. Brecht et al, Phys. Rev. X 5, 041017 (2015)

Outline

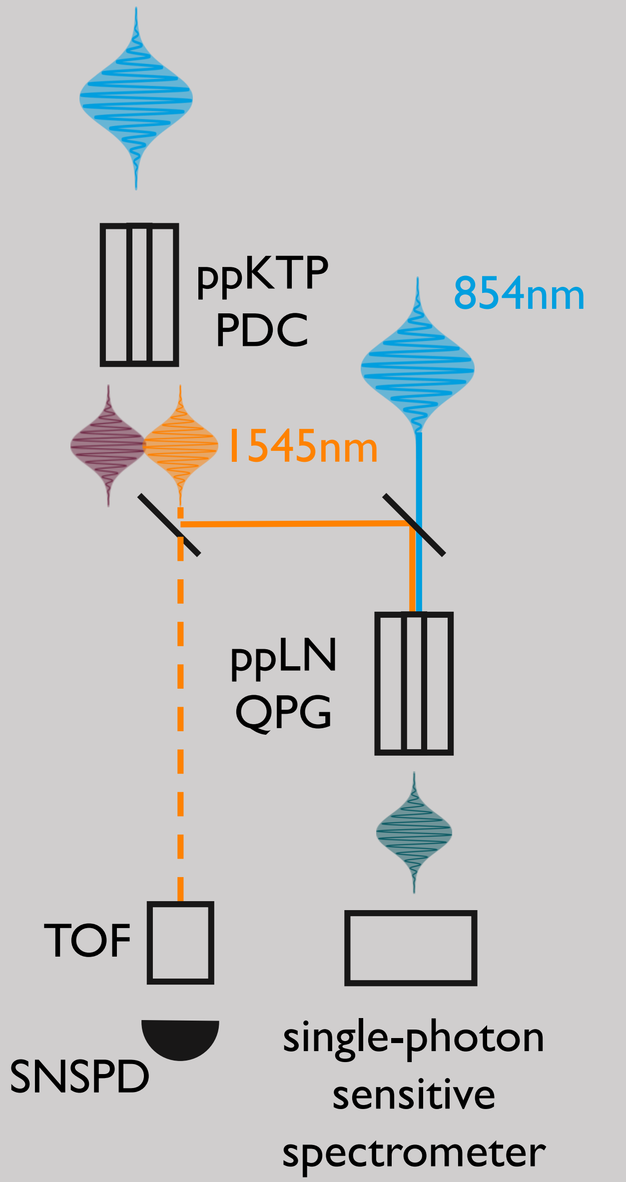
Optical modes

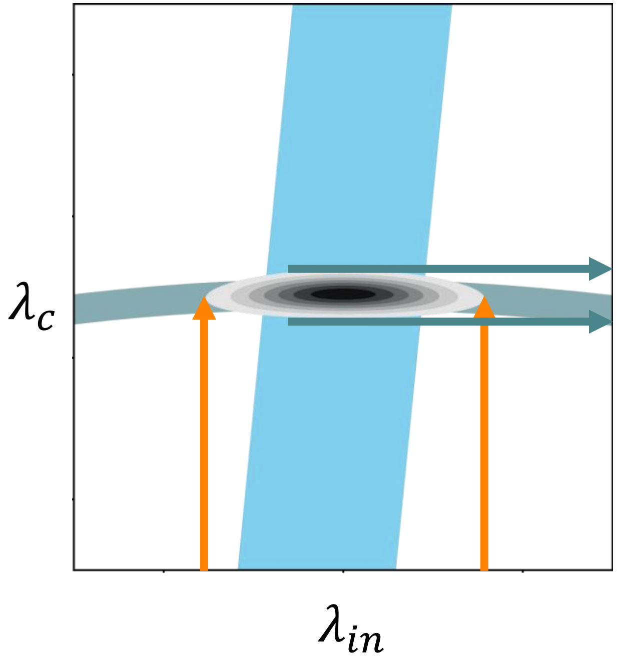
Parametric down-conversion

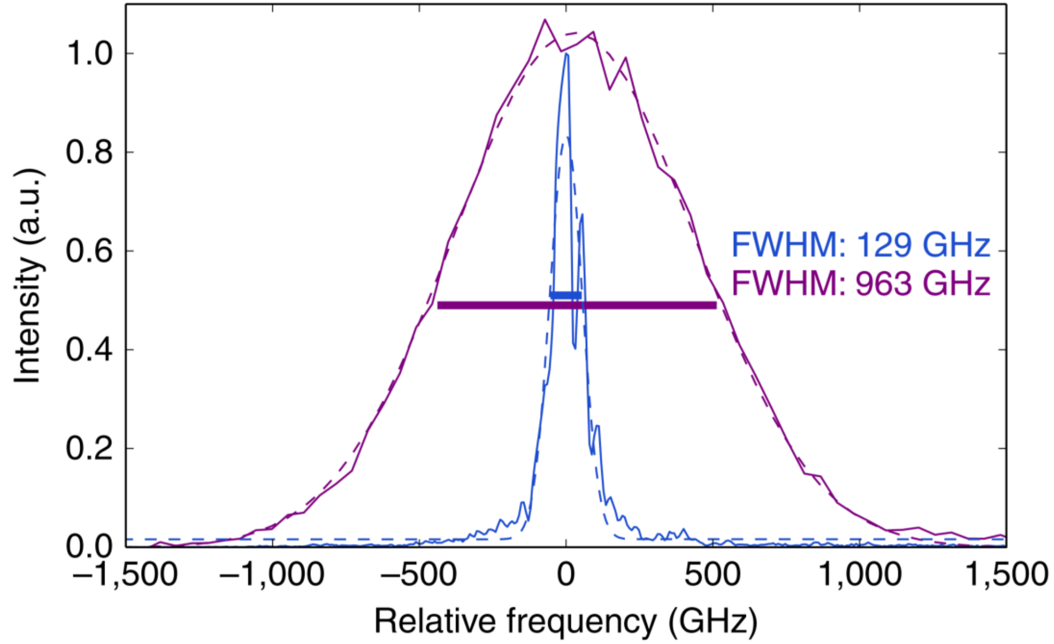
Quantum pulse gate

Applications

Time-frequency manipulations of single photons







$g_h^{(2)} = 0.32 \pm 0.01$ before and after conversion
→ **no noise**

$\frac{\Delta\omega_{in}}{\Delta\omega_c} = 7.47 \pm 0.01$ limited by $\Delta\omega_{in}$

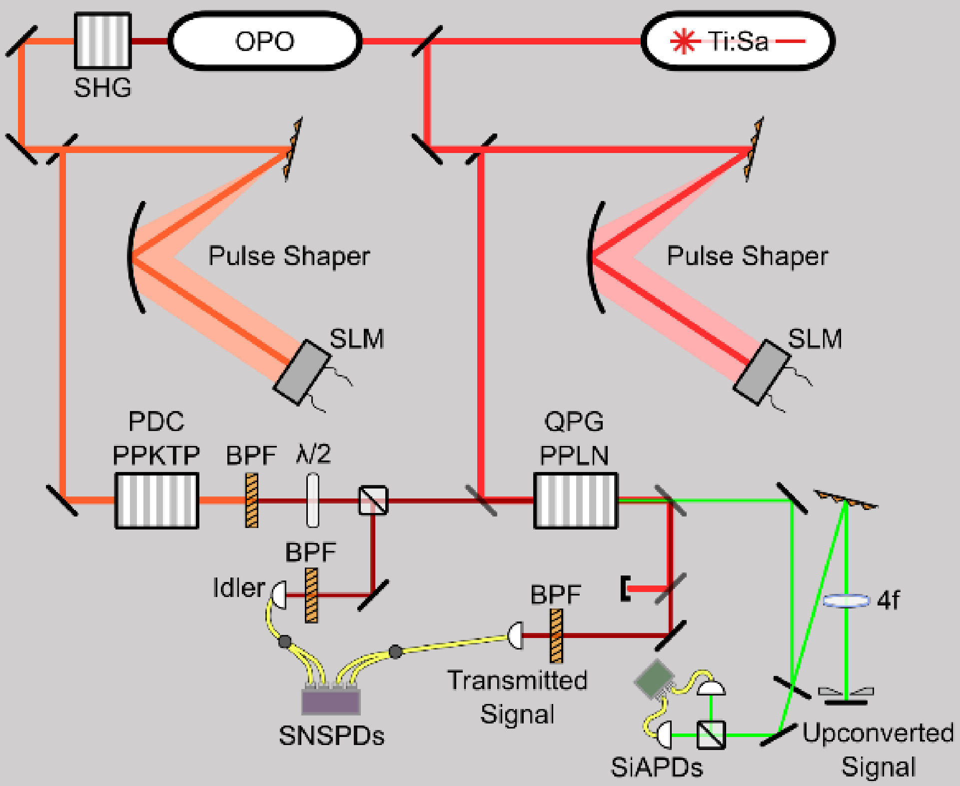
$\eta_{int} = 61.5\%$

$\eta_{ext} = 16.9\%$

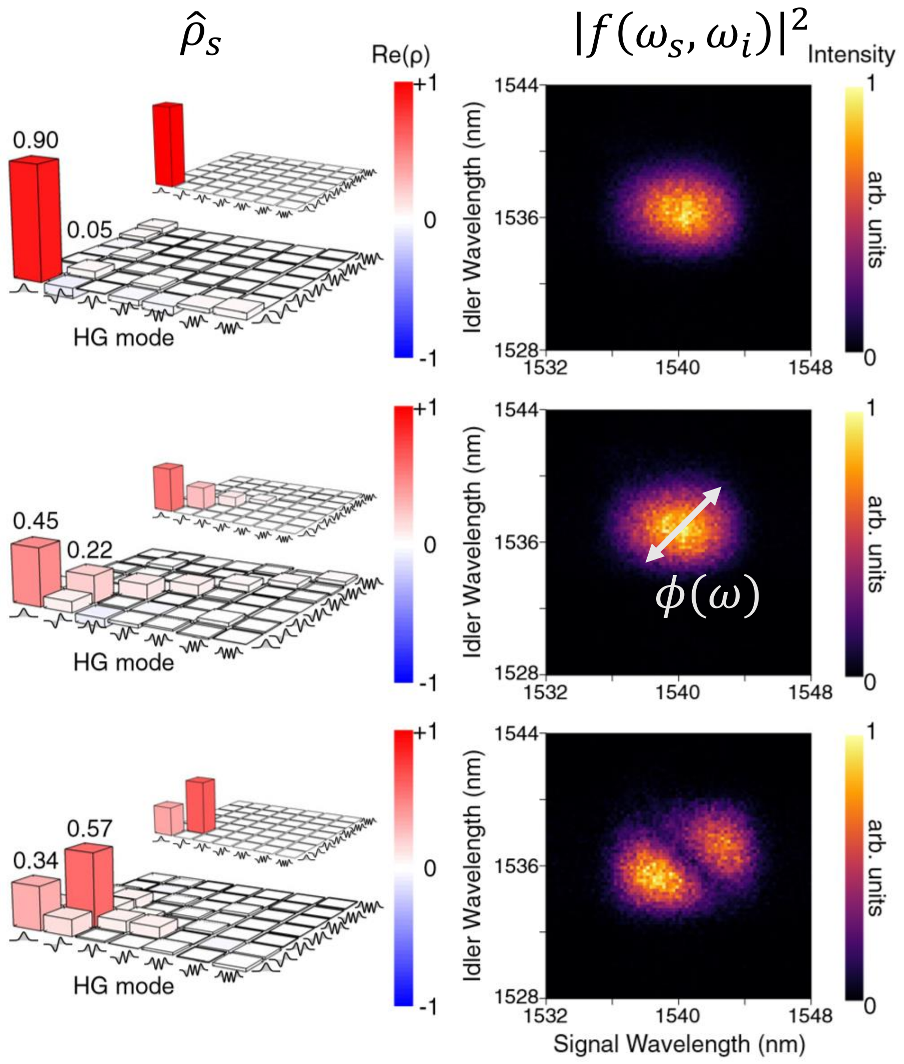
$\eta_{Filter} = 13.4\%$

M. Allgaier et al, Nat. Commun. **8**, 14288 (2017)

Tomography of PDC photons



- signal at 1540nm
- pump at 876nm
- bandwidth compression ~10
- operated at low efficiency
- $g^{(2)}$ of converted light > 1.9 → **single mode**



photon purity from

$\hat{\rho}_s$	$g^{(2)}$
89.6%	92.9%
31.7%	32.7%
53.1%	49.8%

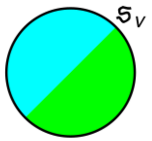
all errors <1%

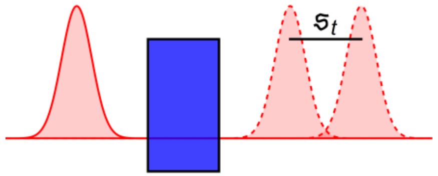
V. Ansari et al, Phys. Rev. Lett. **120**, 213601 (2018)

Time-frequency metrology at the quantum limit

Frequency

Time

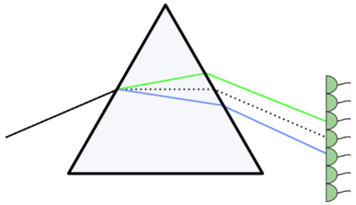


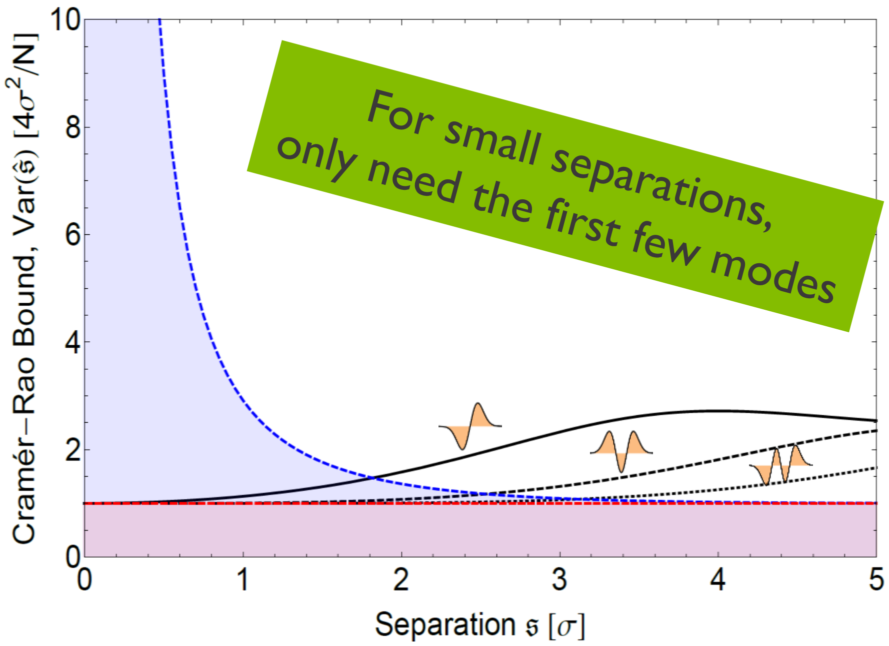


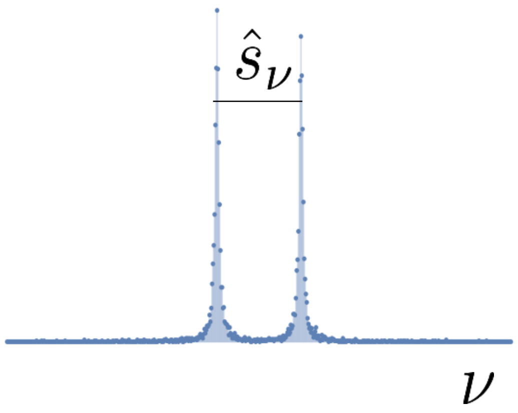
$$\mathrm{Var}(\hat{s}) \geq \frac{1}{N \int \mathrm{d}x \, \frac{1}{I(x,s)} \left(\frac{\partial I(x,s)}{\partial s} \right)^2} \geq \frac{1}{4N\sigma^2}$$

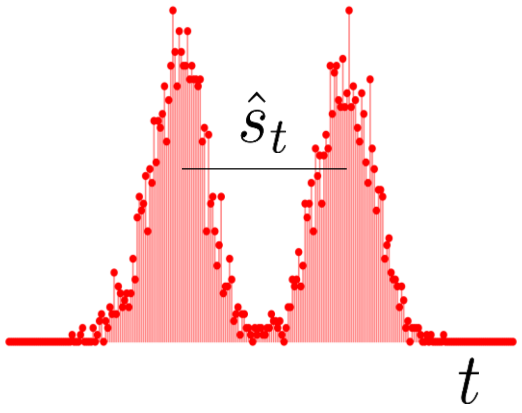
Intensity-Counting Limit

Quantum Limit





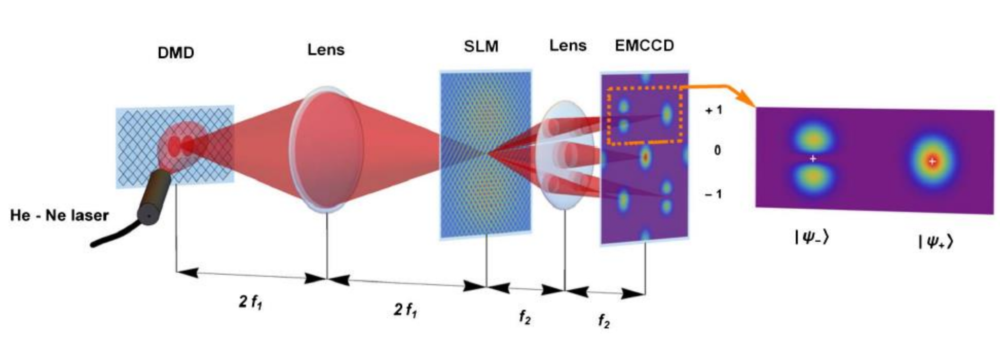




M. Tsang, R. Nair, and X.-M. Lu, Phys. Rev. X **6**, 031033 (2016)
M. Paur, B. Stoklasa, Z. Hradil, L.L. Sanchez-Soto, and J. Rehacek, Optica **3** 1144 (2016)

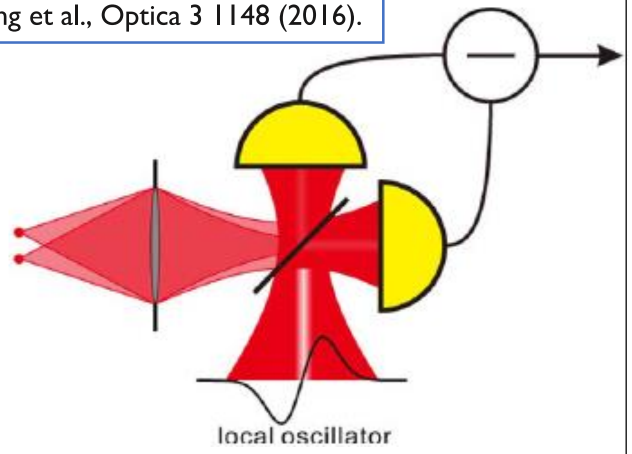
Time-frequency metrology at the quantum limit

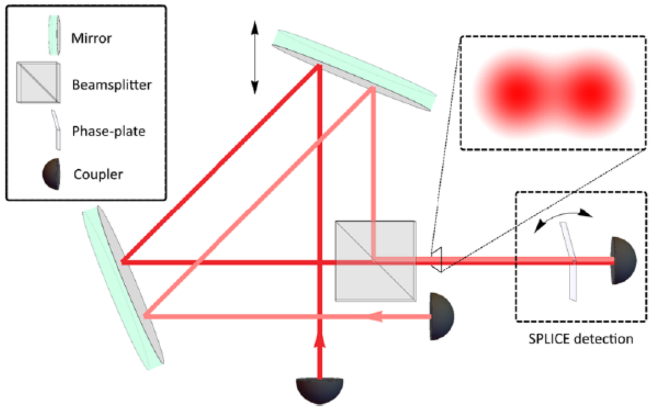
Freq



SLM Projections
M. Paur et al, Optica 3 1144 (2016)

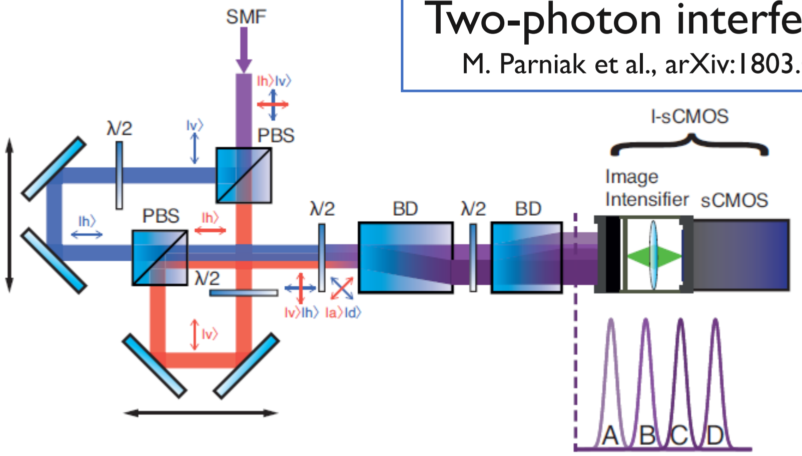
Homodyne Detection
F. Yang et al., Optica 3 1148 (2016).





Parity measurement
W.K. Tham, H. Ferretti, A.M. Steinberg, PRL 118 070801 (2016).

Two-photon interference
M. Parniak et al., arXiv:1803.07096



odes

5

M. Tsang, R. Nair,

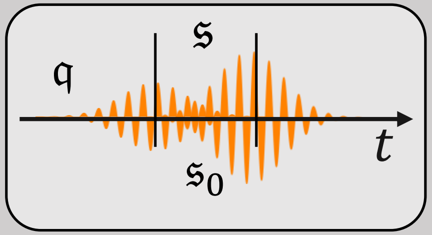
M. Paur, B. Stoklasa, Z. Hradil, L.L. Sanchez-Soto, and J. Rehacek, Optica **3** 1144 (2016)

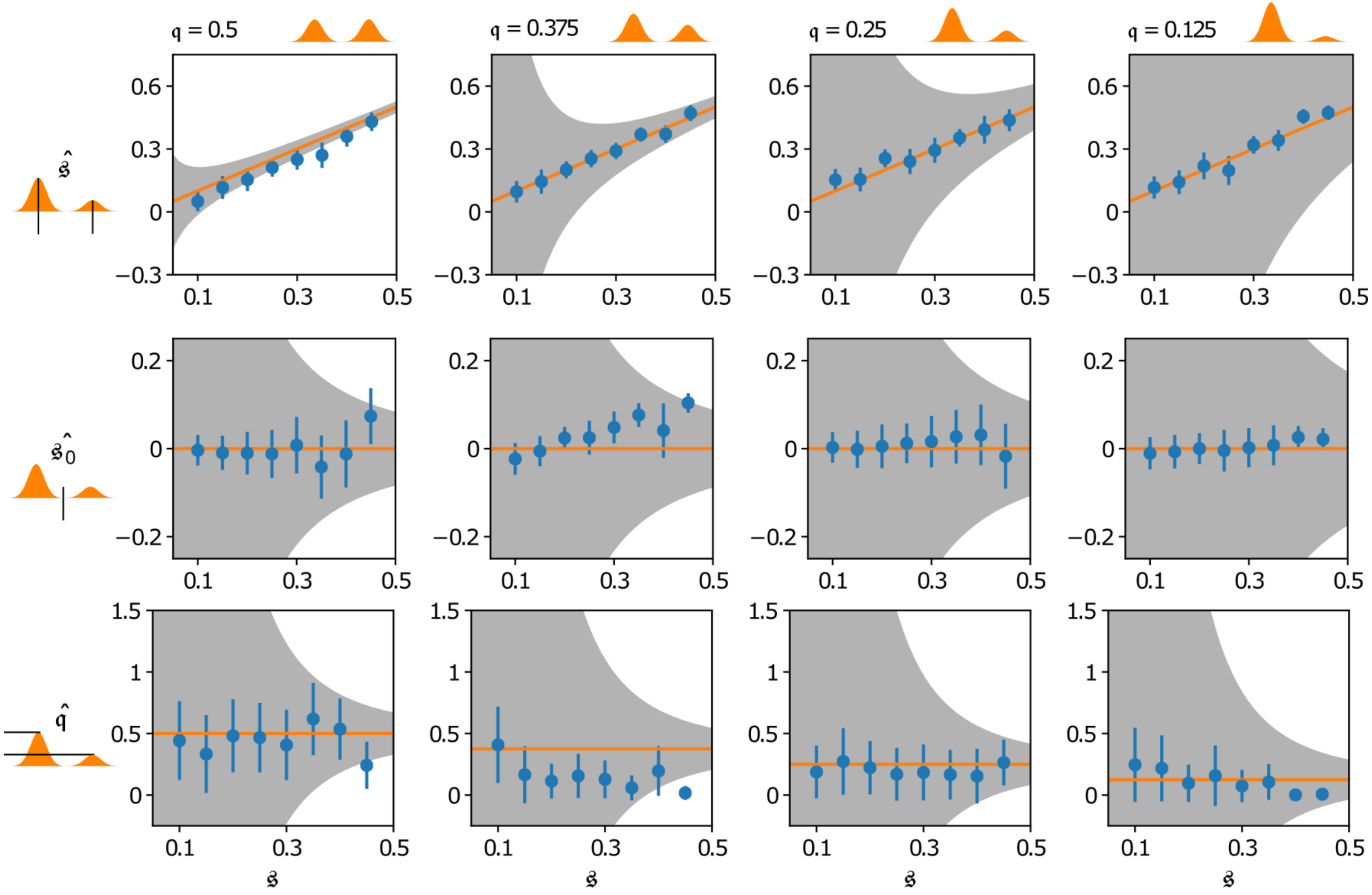
Multi-parameter estimation

- $\lambda_p = 862\text{nm}$
- $E_p = 150\text{pJ}$

- $\lambda_{in} = 1540\text{nm}$
- $\sigma_{in} = 280\text{GHz}$
- $\tau_{in} = 250\text{fs}$

- $L = 35\text{mm}$
- $T = 193^{\text{o}}\text{C}$
- $\sigma_\phi = 17\text{GHz}$

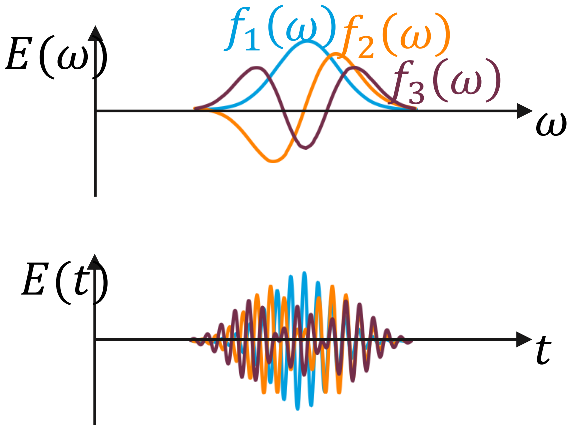




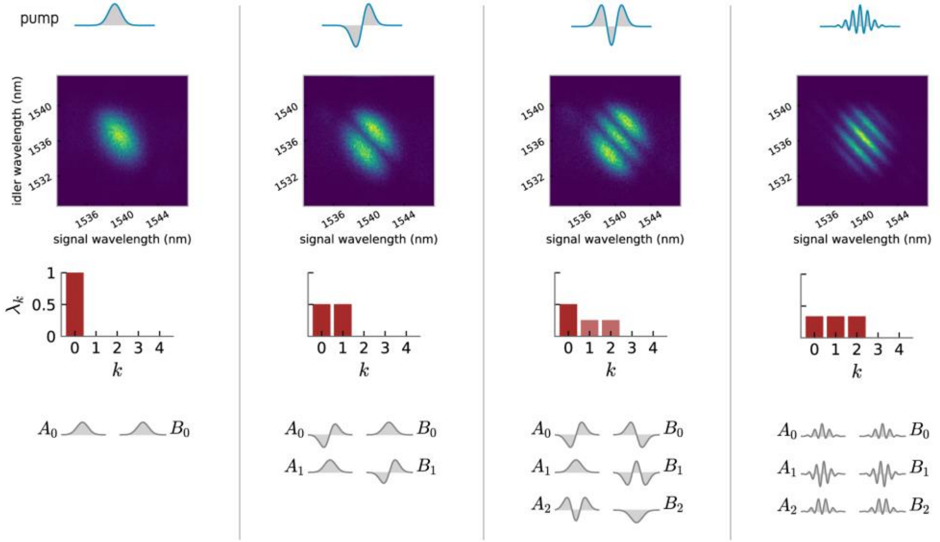
in preparation

Summary

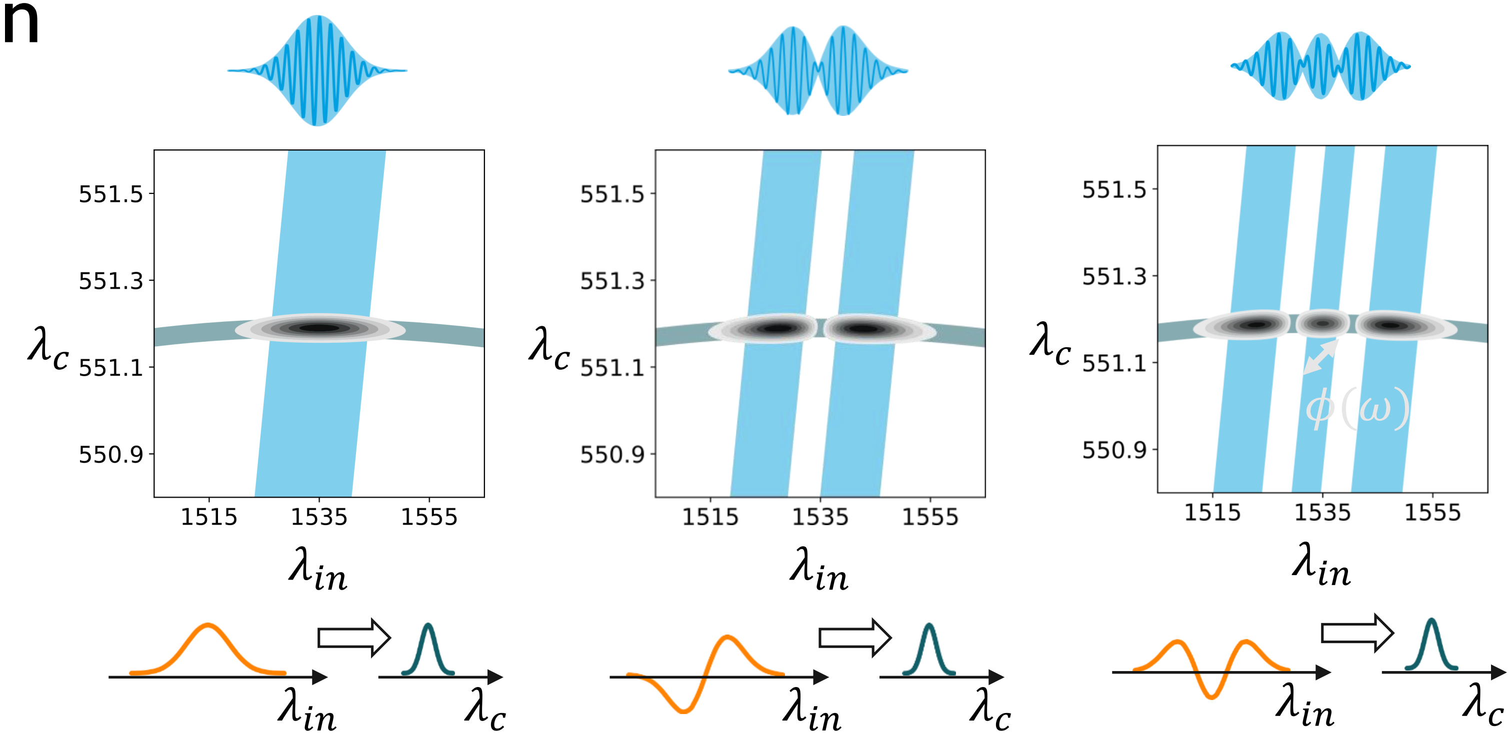
Optical modes



Parametric down-conversion



Quantum pulse gate



Applications

Thank you for your attention

Quantum Networks

Benjamin Brecht
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Michael Stefszky
Vahid Ansari
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Melanie Engelkemeier
Jano Gil Lopez
Johannes Tiedau
Nidhin Prasannan
Rene Pollmann

Technology

Christof Eigner
Laura Padberg
Felix vom Bruch
Viktor Quiring
Raimund Ricken

Devices

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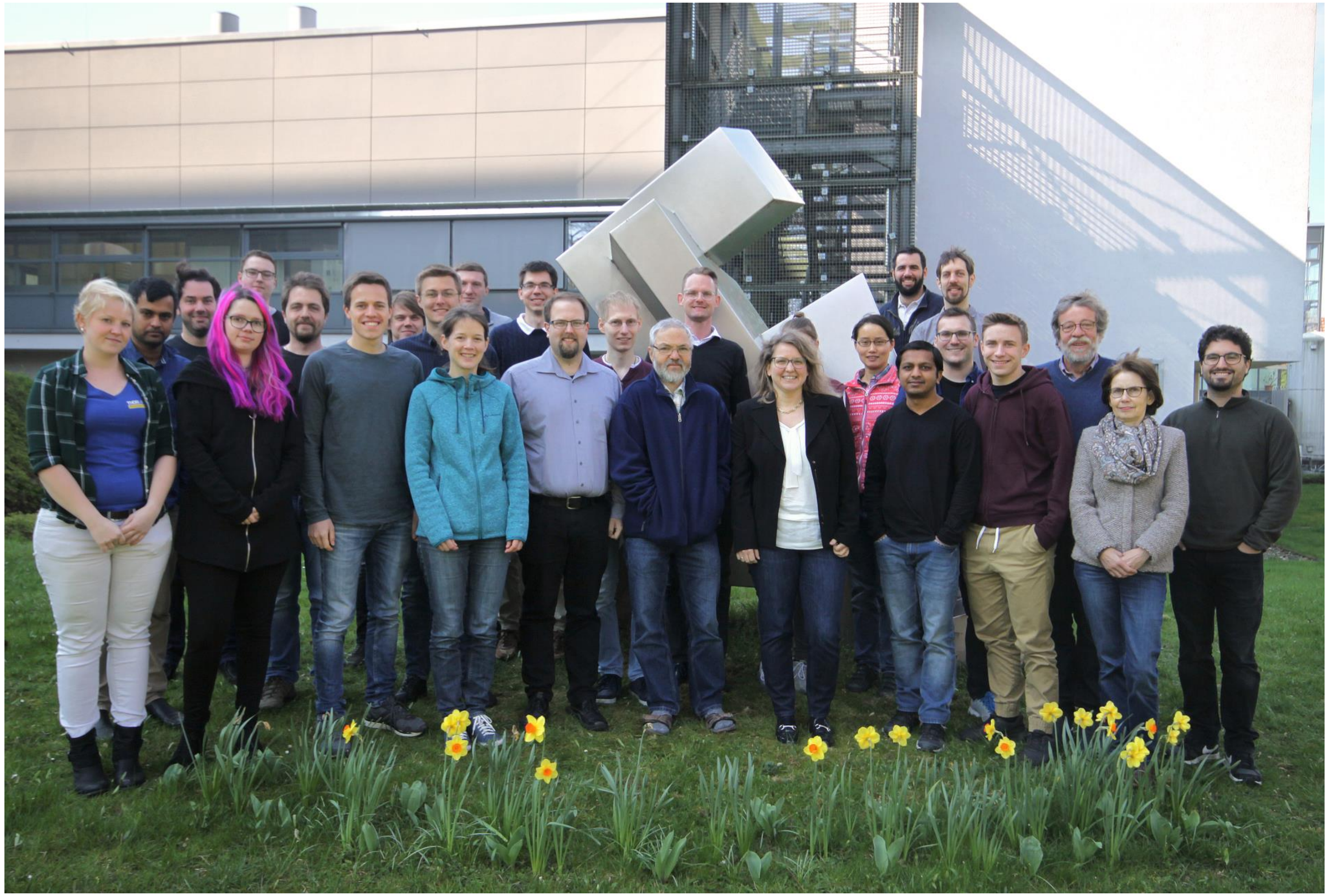
Kai-Hong Luo
Matteo Santandrea
Marcello Massaro
Sebastian Brauner
Christian Kießler



Silberhorn group

We have open positions (and candy…)

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