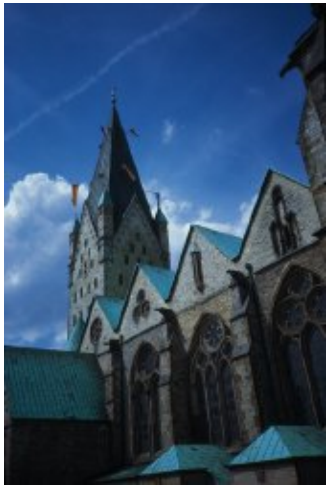
Controlling temporal modes of pulsed quantum light

Christine Silberhorn



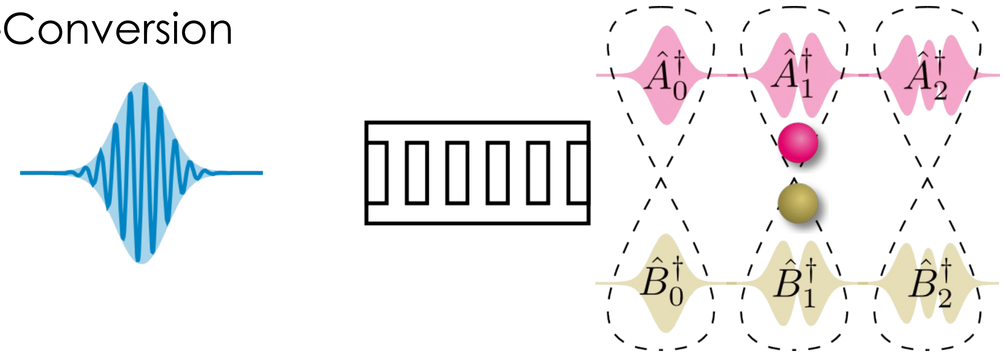
10. July 2018

Integrated Quantum Optics,
Department of Physics, University of Paderborn

CeOPP
Center for Optoelectronics and Photonics Paderborn

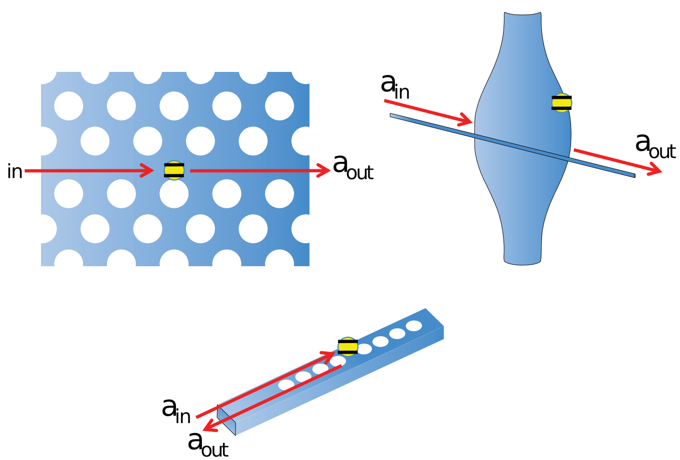
TMs in quantum optics

Parametric Down-Conversion



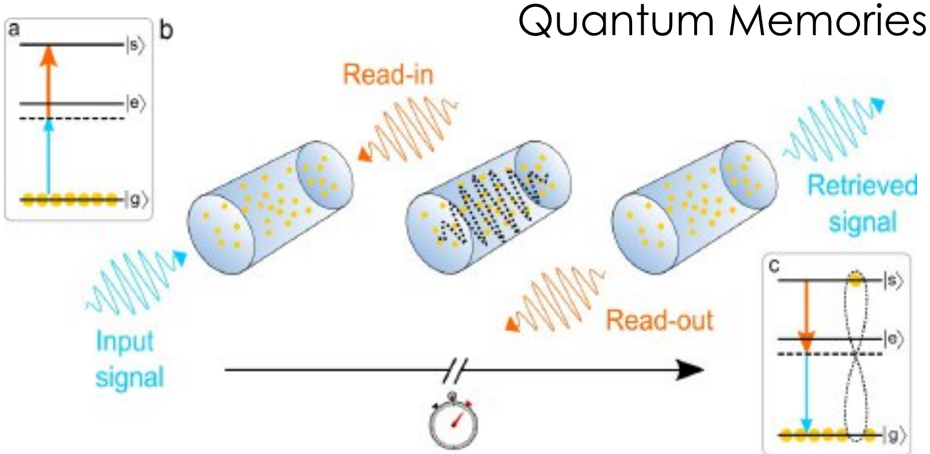
Law,, Walmsley, Eberly, Phys. Rev. Lett. 84, 5304 (2000)

Two-level non-linearities



Ralph, et al., Phys. Rev. Lett. 114, 173603 (2015)

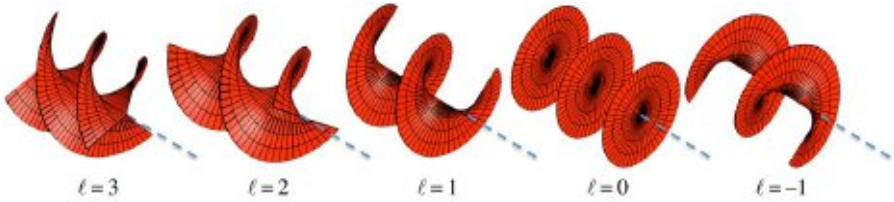
Quantum Memories



Kaczmarek, et al., arXiv:1704.00013 (2017)
Sprague et al.; Nat. Photon 8, 287-291 (2014)

Pulsed temporal modes

➢ High dimensional quantum optics



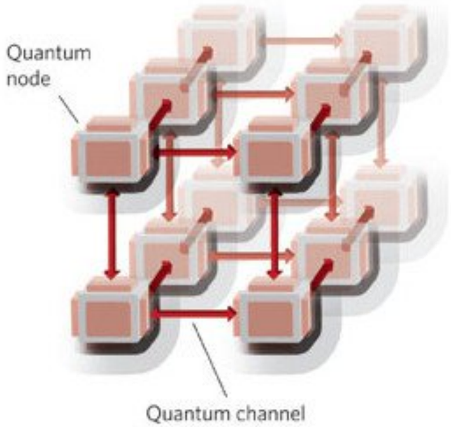
Leach et al., Science 329, 662-665 (2010)
Bent, et al, Phys. Rev. X 5, 041006 (2015)
Naidoo, et al, Nat. Photon. 10, 327 (2016)

- Increased information capacity
- Increased security of quantum communication
- High dimensional entanglement / Hilbert space

➢ Interfacing in hybrid networks

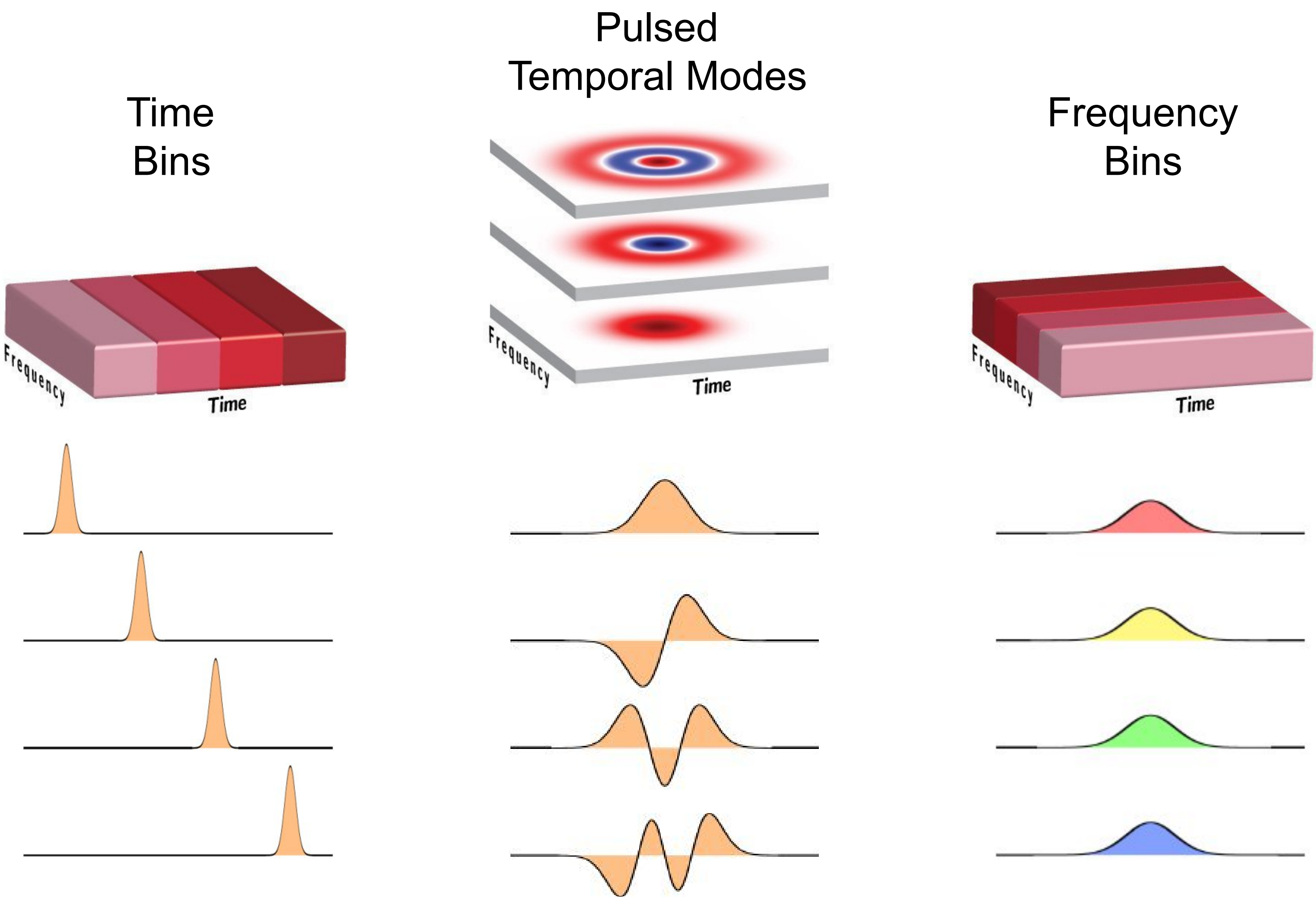
- Bandwidth compression
- Temporal mode selection for non-linear optics

Ralph, et al., Phys. Rev. Lett. 114, 173603 (2015)



Kimble; Nature **453**, 1023-1030 (2008)

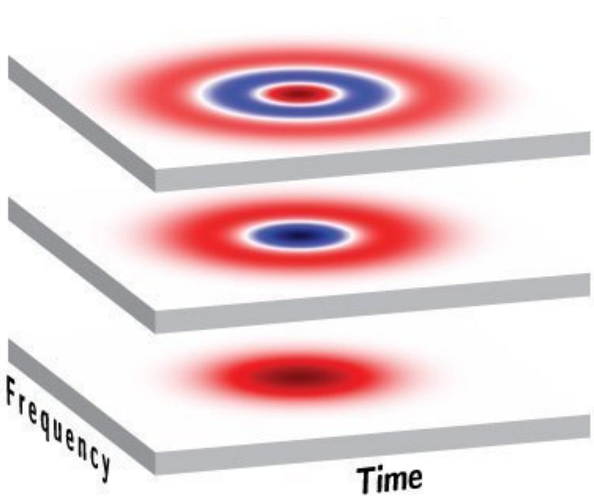
Time-Frequency Photon Encoding

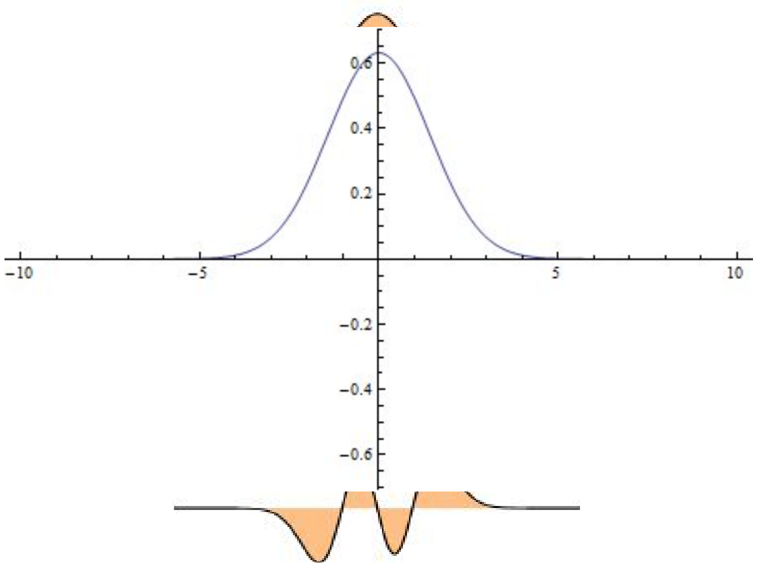


B. Brecht, D. V. Reddy, C. Silberhorn, M. G. Raymer, PRX **5** 041017 (2015)

Pulsed temporal modes

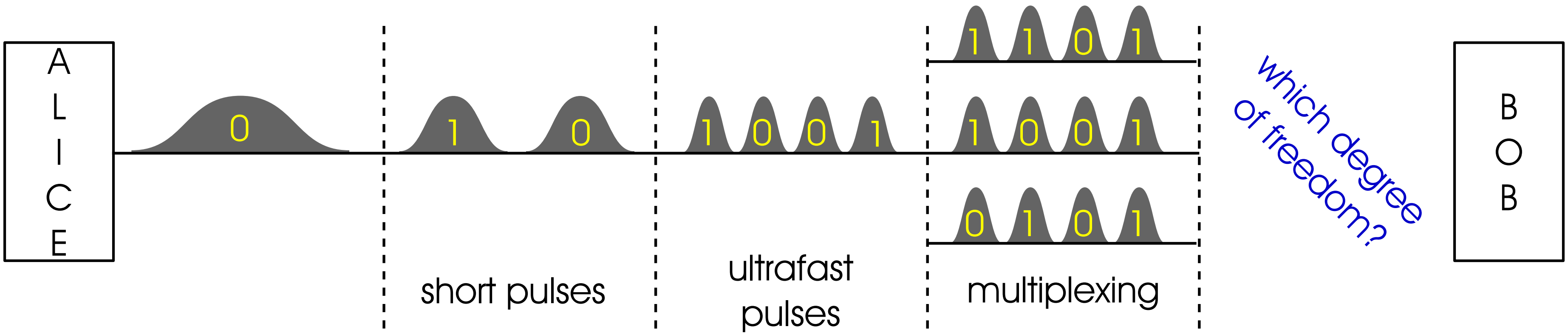
- Hermite-Gaussian envelopes in frequency and time
- Overlapping intensities but orthogonal field amplitudes
- Naturally compatible with waveguides and fibers
- Pulse and spectral width scale as sqrt(2n+1)



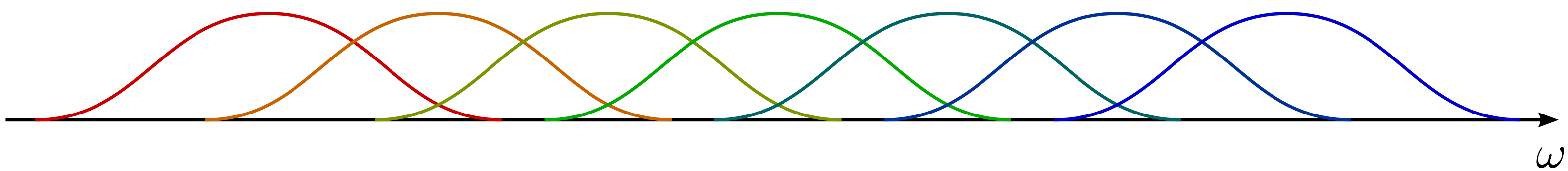


B. Brecht , D. V. Reddy, C. Silberhorn, M. G. Raymer, PRX **5**, 041017 (2015)

Quantum communication: data transmission rates



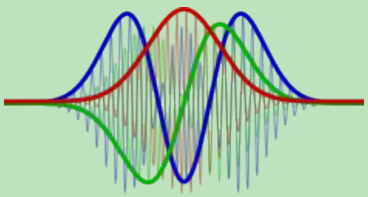
Frequency multiplexing is difficult with ultrafast pulses due to spectral overlap (C-Band 1530nm-1565nm; 10nm FWHM = 400fs)



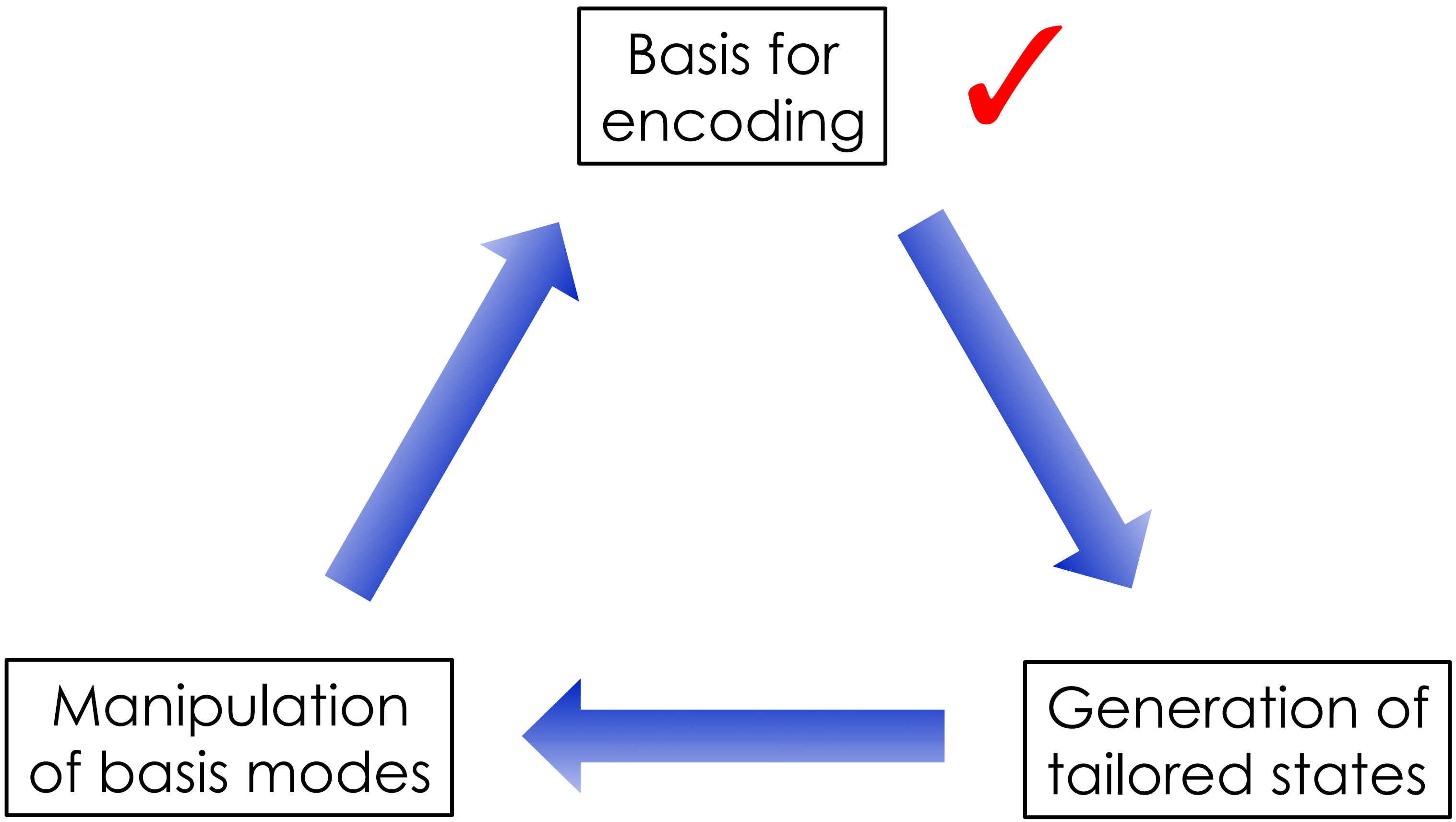
With ultrafast pulses

appealing degree of freedom: **temporal modes**

overlap in frequency and time



Requirements for high dimensional quantum coding



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

① Engineered parametric downconversion

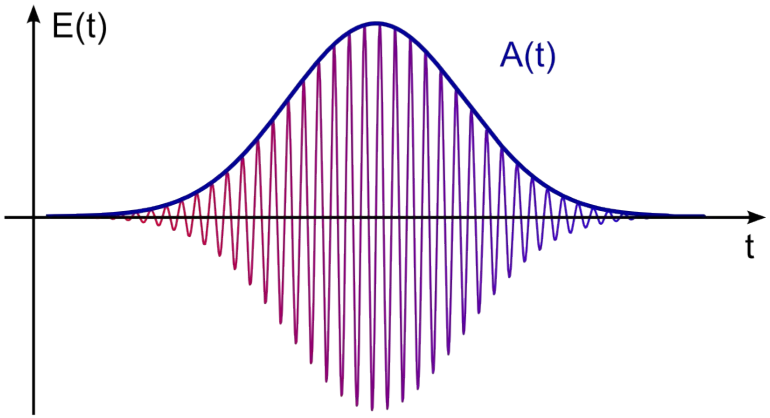
② Quantum pulse gate

③ Applications

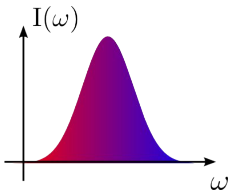
Pulsed temporal modes

Pulsed light

finite time durations
implies spectral bandwidth



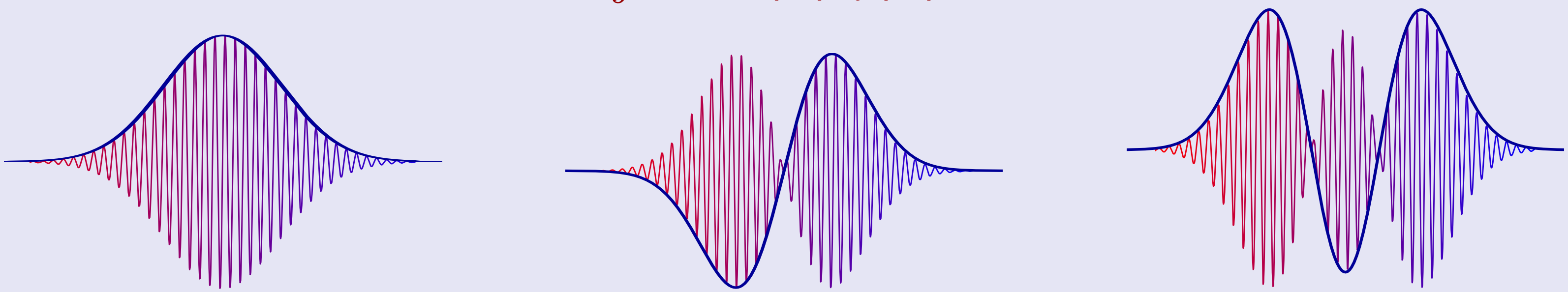
$$(\Delta t) \cdot (\Delta \omega) \geq C$$



$$E(t) = A(t) e^{i\varphi(t)} e^{i\omega_0 t} + \text{c.c.}$$

Pulse shapes

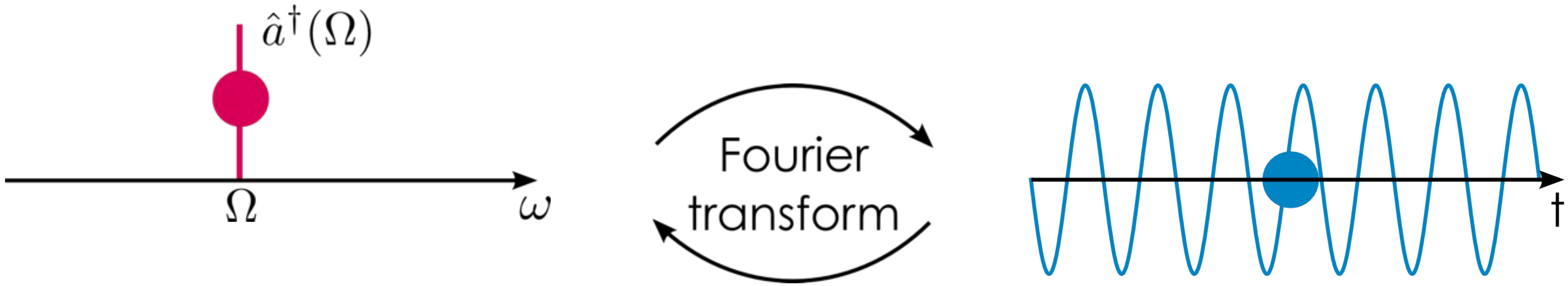
orthogonal broadband modes: $\int d\omega \; h_i(\omega) h_j(\omega) = 0, \quad i \neq j$



$E^+(t) = \int d\omega \; h_0(\omega) \; e^{i\omega t}$ $\quad$ $E^+(t) = \int d\omega \; h_1(\omega) \; e^{i\omega t}$ $\quad$ $E^+(t) = \int d\omega \; h_2(\omega) \; e^{i\omega t}$

Temporal modes of pulsed photons

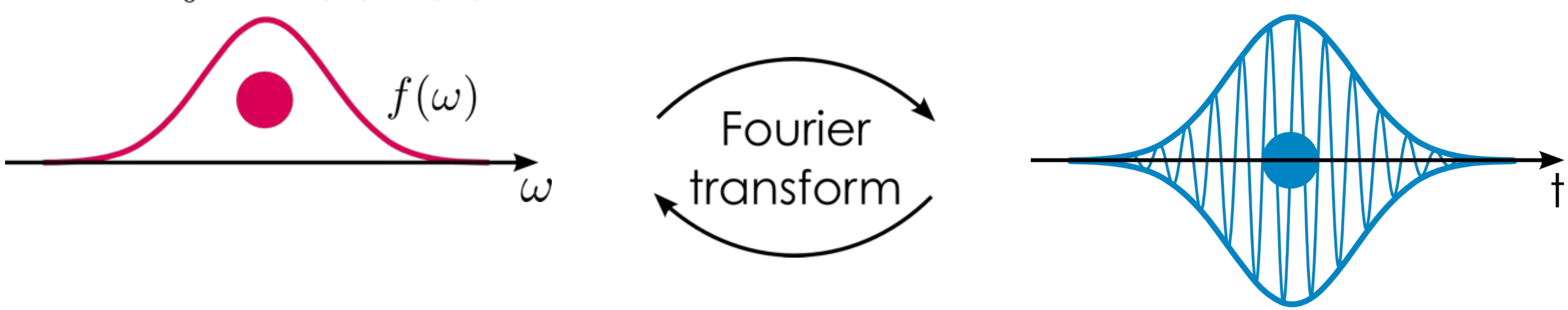
Monochromatic creation operator (bit rate = 0)



Temporal mode creation operator (bit rate = Fourier limit)

$$\hat{A}^\dagger \equiv \int d\omega \, f(\omega)\hat{a}^\dagger(\omega)$$

$\Delta\tau \, \Delta\omega \geq C$

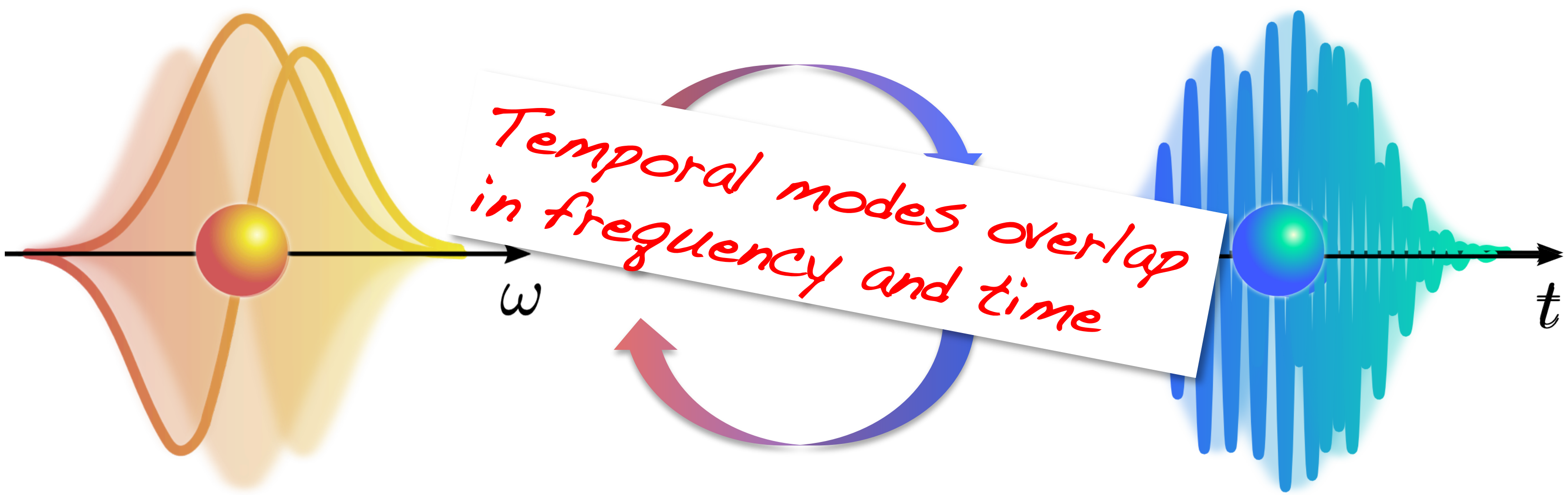


Law, et al, Phys. Rev. Lett. 84, 5304 (2000)

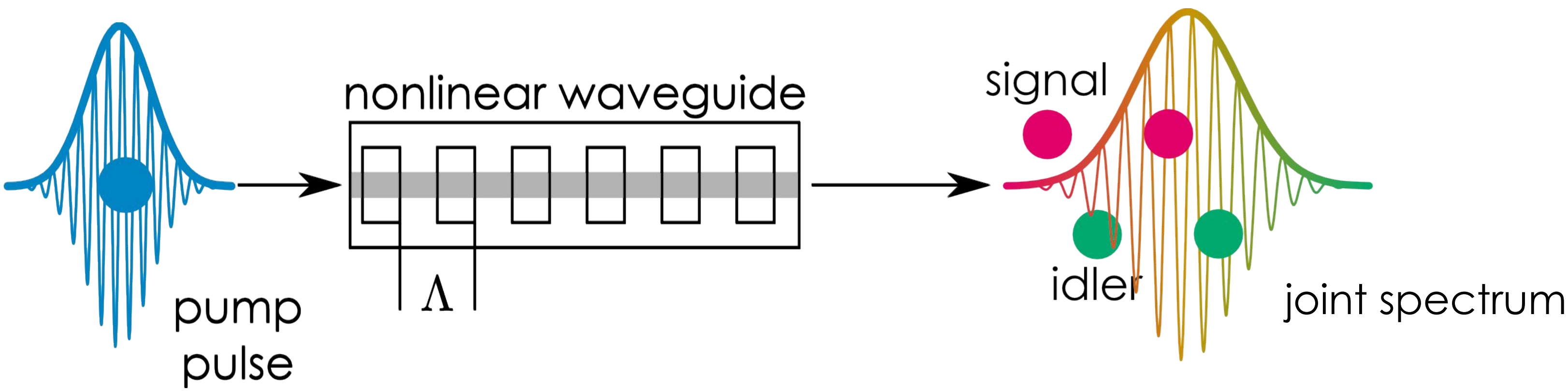
Pulsed temporal modes

$$\hat{A}^\dagger = \int d\omega\, f(\omega)\hat{a}^\dagger(\omega)$$

$$\hat{A}^\dagger = \int dt\, \tilde{f}(t)\hat{a}^\dagger(t)$$

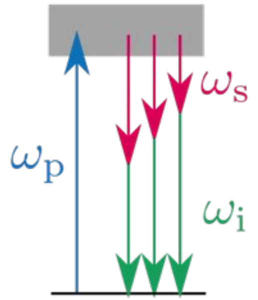


Waveguided parametric down-conversion



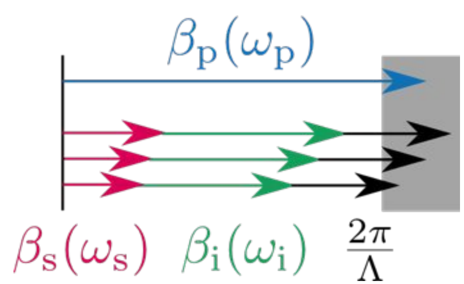
Energy conservation

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

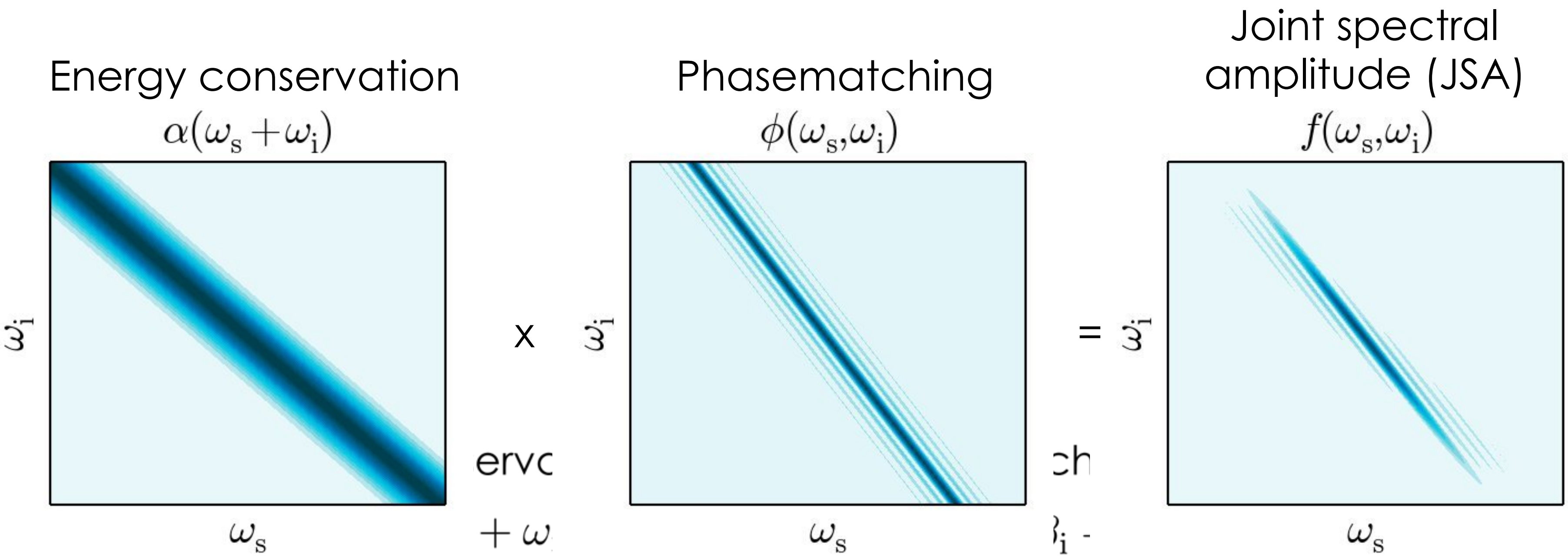


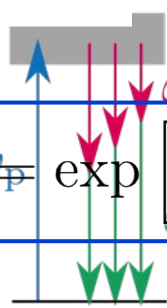
Phasematching

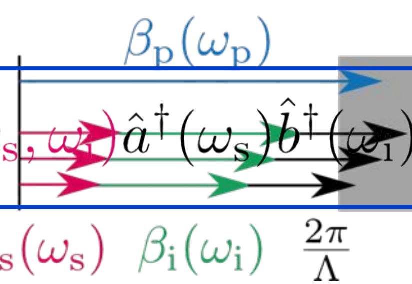
$$\beta_{\mathrm{p}} = \beta_{\mathrm{s}} + \beta_{\mathrm{i}} + \frac{2\pi}{\Lambda}$$



Waveguided parametric down-conversion







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

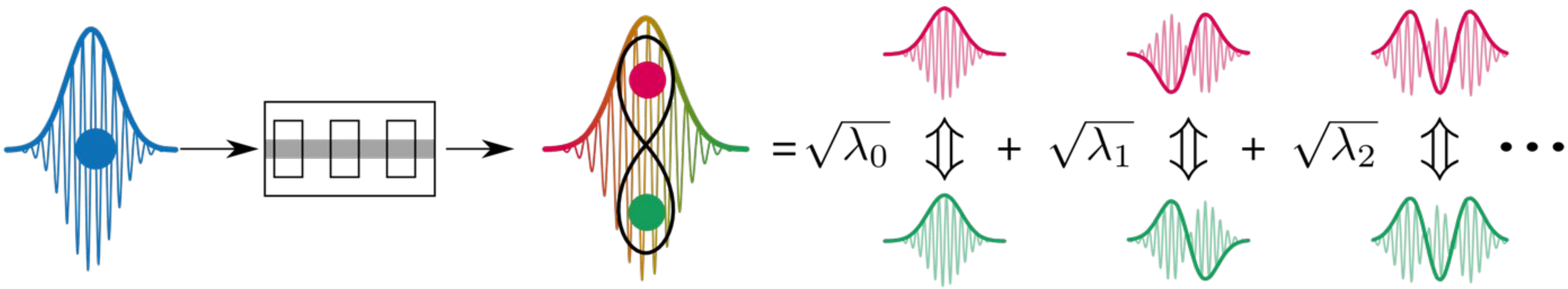
Bi-photon state (general)

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

Schmidt decomposition

$$|\psi\rangle_{\text{PDC}} = \bigotimes_k \exp\left[\mathcal{B}\sqrt{\lambda_k}\left(\hat{A}_k^\dagger \hat{B}_k^\dagger - \hat{A}_k \hat{B}_k\right)\right]|0\rangle \approx \sum_k \mathcal{B}\sqrt{\lambda_k}\hat{A}_k^\dagger \hat{B}_k^\dagger|0\rangle$$

Photon-pair approximation
-> only valid for low pump powers



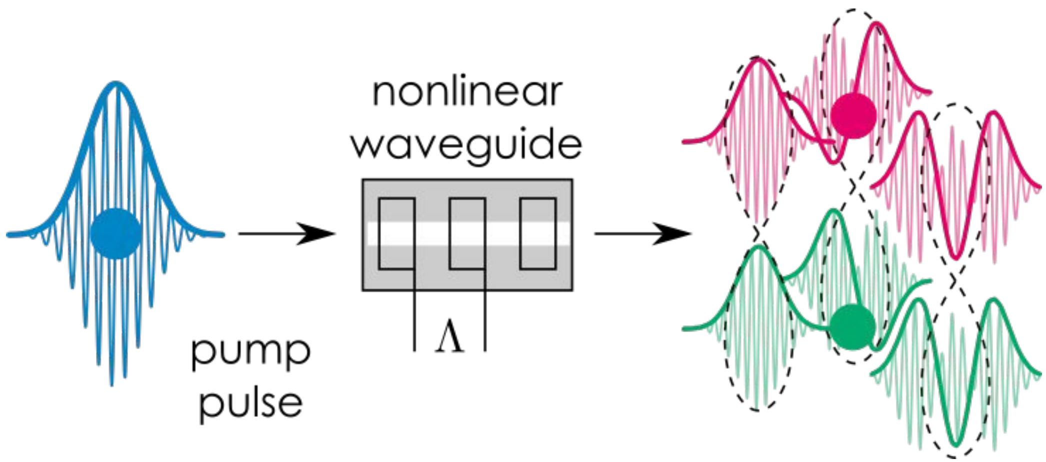
Multimode PDC state

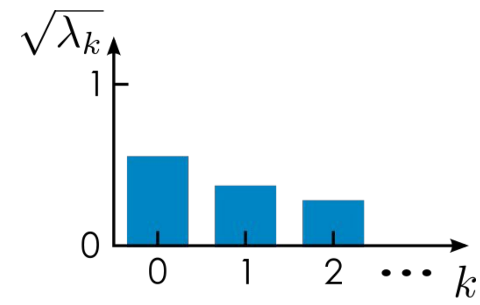
- The **effective number of modes / amount of spectral entanglement** is characterized by the Schmidt number

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

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

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





Pairs of pulsed temporal modes

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

- Generation of many pairs of pulsed photons
- Schmidt number = **effective number of modes**
  = **amount of spectral entanglement**
- Intrinsic high-dimensional structure

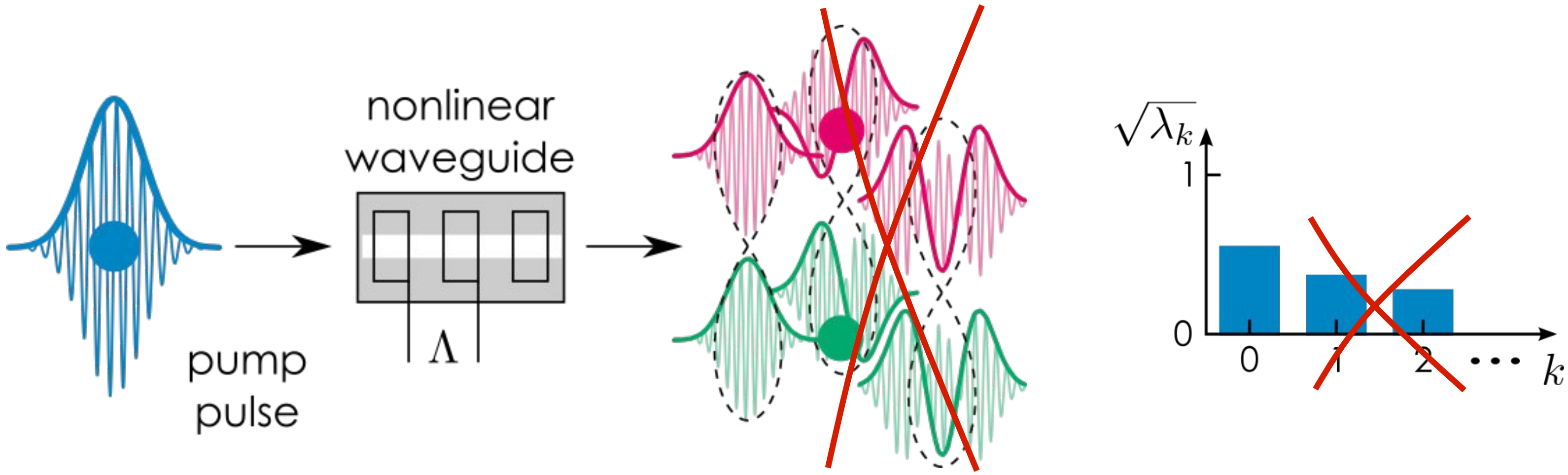
$$|\psi\rangle_{\mathrm{PDC}} \approx \sqrt{\lambda_0}\,|\;\rangle + \sqrt{\lambda_1}\,|\;\rangle + \sqrt{\lambda_2}\,|\;\rangle \ldots$$

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

Christ, et al, New J. Phys. 15, 053038 (2013)
Mauerer, et al, Phys. Rev. A 80, 053815 (2009)

Dispersion engineered parametric down-conversion

- Control of spectral correlations

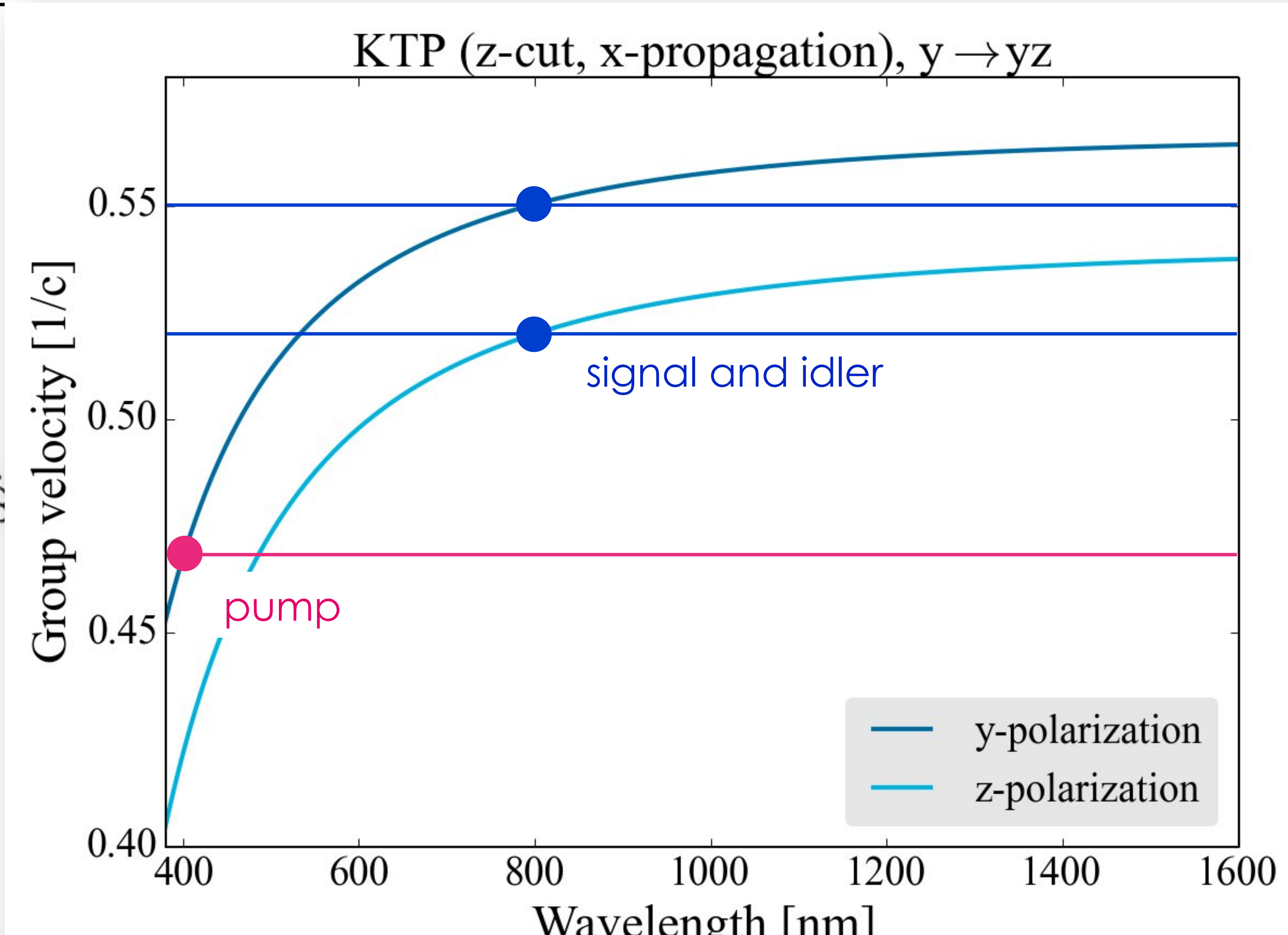


Pairs of temporal modes

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

Mosley, et al, Phys. Rev. Lett. 100, 133601 (2008)
Eckstein, et al, Phys. Rev. Lett. 106, 013603 (2011)
Harder, et al, Opt. Exp. 21, 13975 (2013)

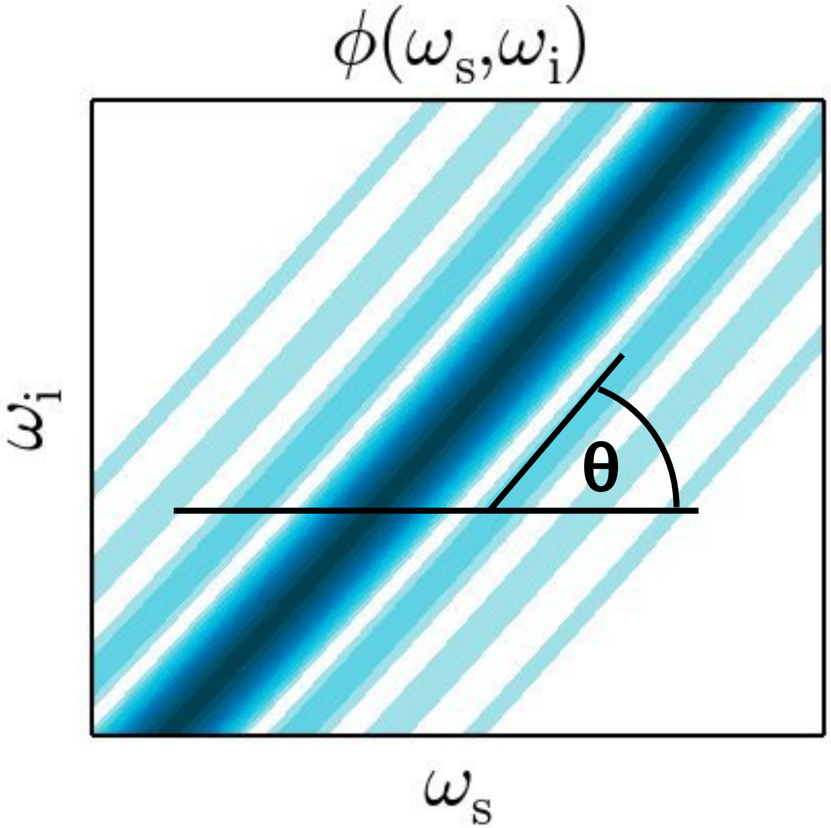
Phasematching



Brecht, et al, Phys. Status Solidi C 8, 1235 (2011)

Keller, et al, Phys. Rev. A 56, 1534 (1997)
Grice, et al, Phys. Rev. A 64, 063815 (2001)
Giovanetti, et al, Phys. Rev. A 66, 043813 (2002)
U'Ren, et al, Las. Phys. 15, 146 (2005)

Phasematching in KTP

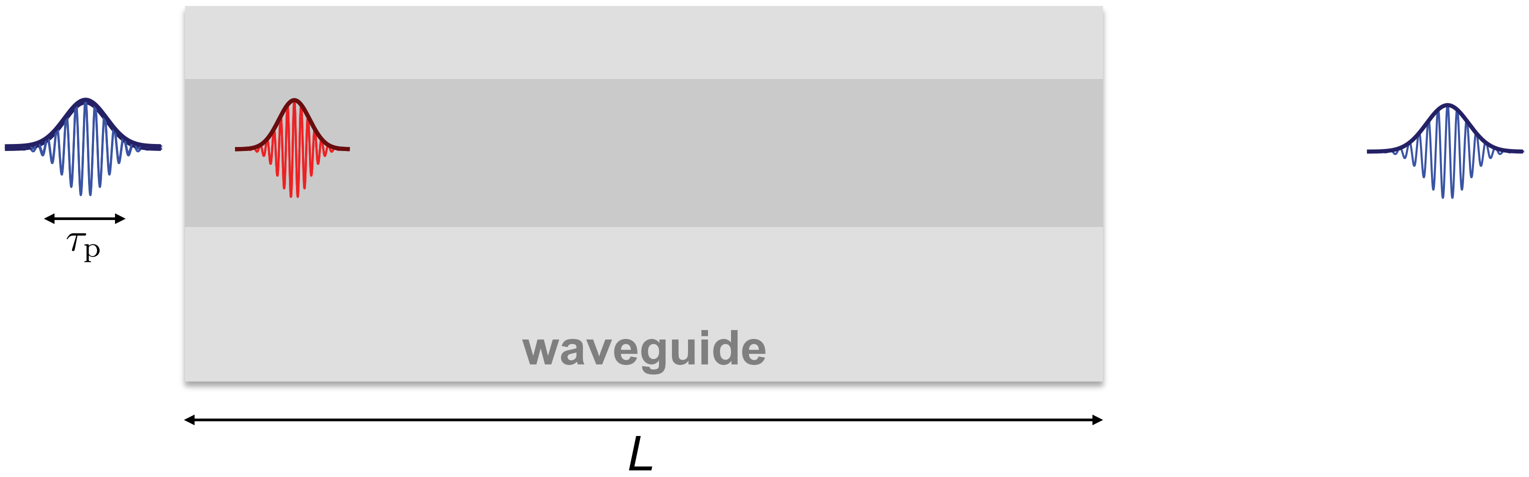


$$\theta = -\arctan\left(\frac{\beta_s' - \beta_p'}{\beta_i' - \beta_p'}\right)$$

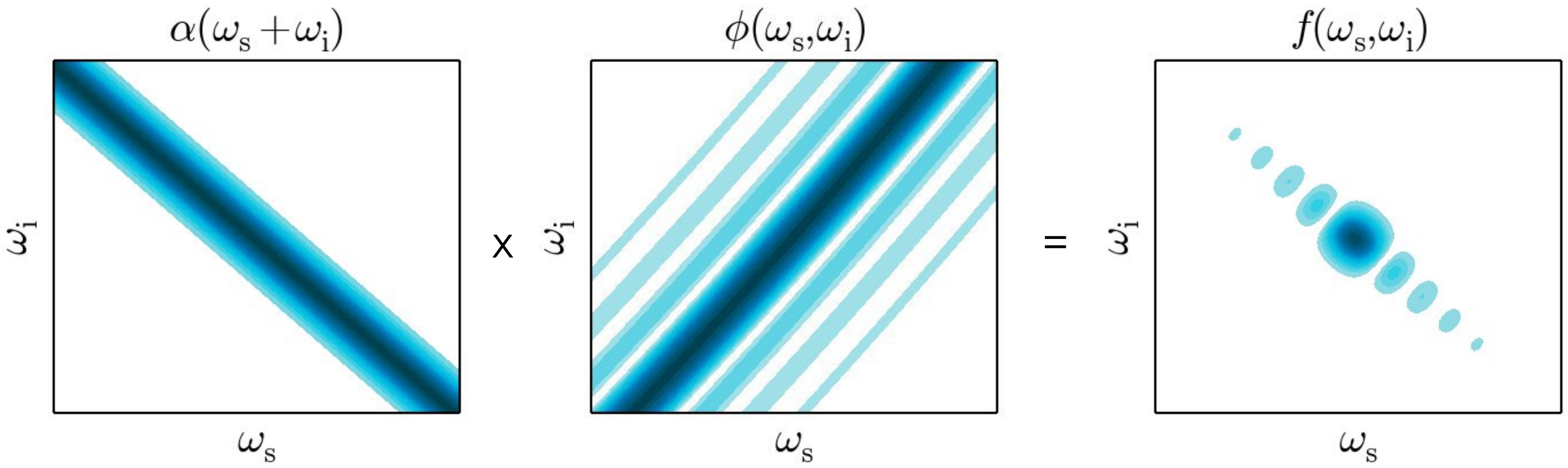
$$\theta = 59^\circ$$

Keller, et al, Phys. Rev. A 56, 1534 (1997)
Grice, et al, Phys. Rev. A 64, 063815 (2001)
Giovanetti, et al, Phys. Rev. A 66, 043813 (2002)
U'Ren, et al, Las. Phys. 15, 146 (2005)

Propagation in time



Pump envelope



narrow pump spectrum

negative correlations
$K = 1.55$

adapted pump spectrum

vanishing correlations
$K = 1.17$

broad pump spectrum

positive correlations
$K = 1.31$

Keller, et al, Phys. Rev. A 56, 1534 (1997)
Grice, et al, Phys. Rev. A 64, 063815 (2001)
Giovanetti, et al, Phys. Rev. A 66, 043813 (2002)
U'Ren, et al, Las. Phys. 15, 146 (2005)

First realization: KDP bulk crystal source at 800nm

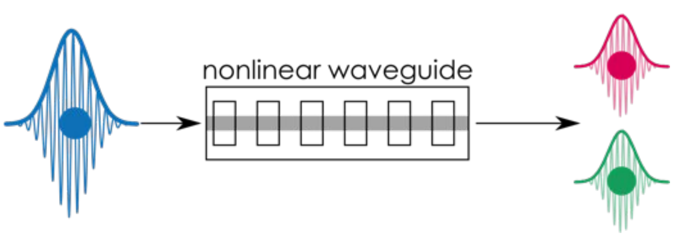
PRL **100,** 133601 (2008) PHYSICAL REVIEW LETTERS week ending 4 APRIL 2008

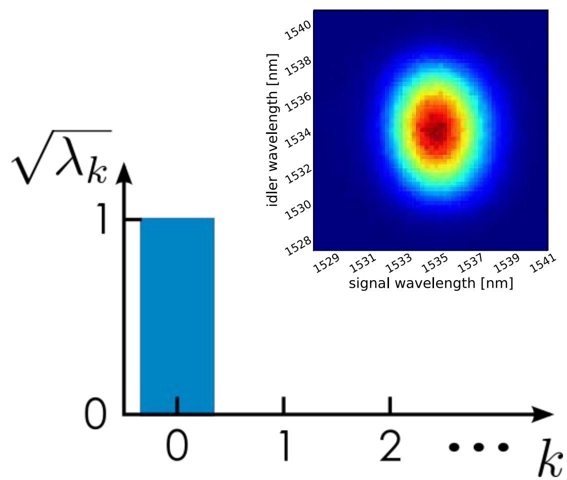
Heralded Generation of Ultrafast Single Photons in Pure Quantum States

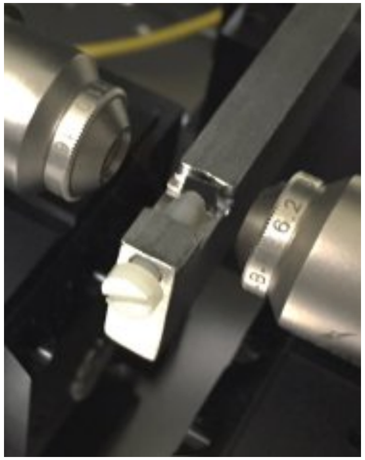
Peter J. Mosley,[1,*] Jeff S. Lundeen,[1] Brian J. Smith,[1] Piotr Wasylczyk,[1,2] Alfred B. U'Ren,[3] Christine Silberhorn,[4] and Ian A. Walmsley[1]

$$|\psi\rangle_{\mathrm{PDC}} \approx \mathcal{B}_0 \hat{A}_0^\dagger \hat{B}_0^\dagger |0\rangle$$

In waveguides: *KTP @ 1550nm*



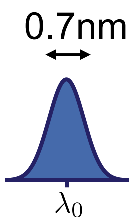




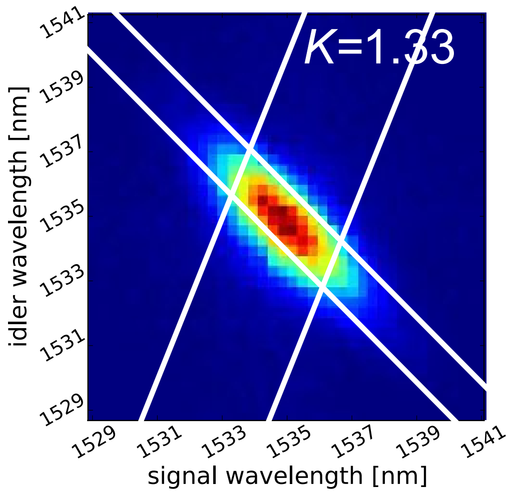
Mosley, et al, Phys. Rev. Lett. 100, 133601 (2008)
Eckstein, et al, Phys. Rev. Lett. 106, 013603 (2011)
Harder, et al, Opt. Exp. 21, 13975 (2013)

State engineering via pump shaping

pump spectrum



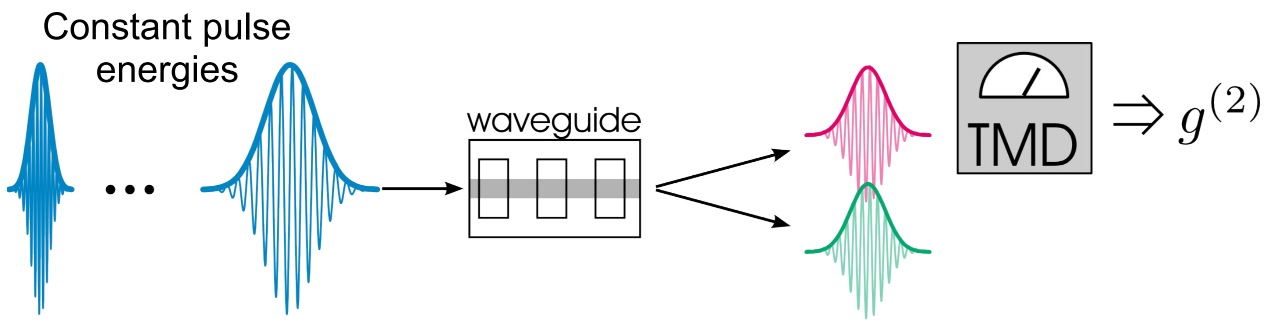
$|f(\omega_s, \omega_i)|^2$

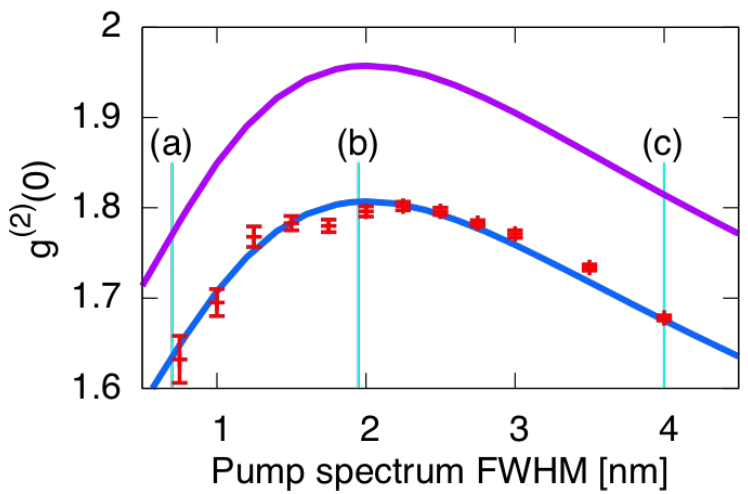


negative correlations

Avenhaus, et al, Opt. Lett. 34, 2873 (2009)
Eckstein, et al, Phys. Rev. Lett. 106, 013603 (2011)
Harder, et al, Opt. Express 21, 13975 (2013)

Multiple temporal modes



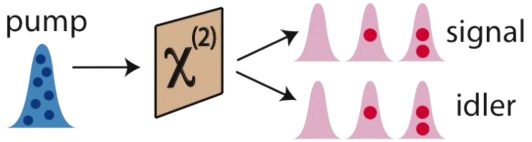


- Different pump bandwidths
- Different number of modes
- Influences photon statistics

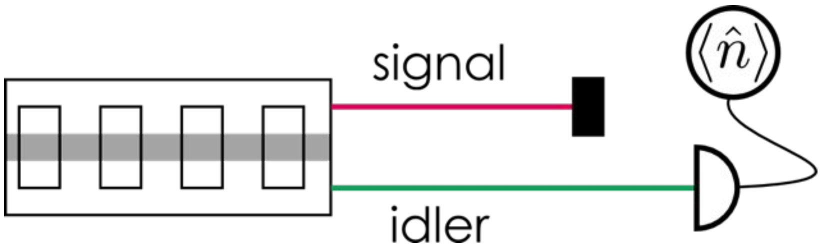
$$g^{(2)}(0) = 1 + \frac{1}{K}$$

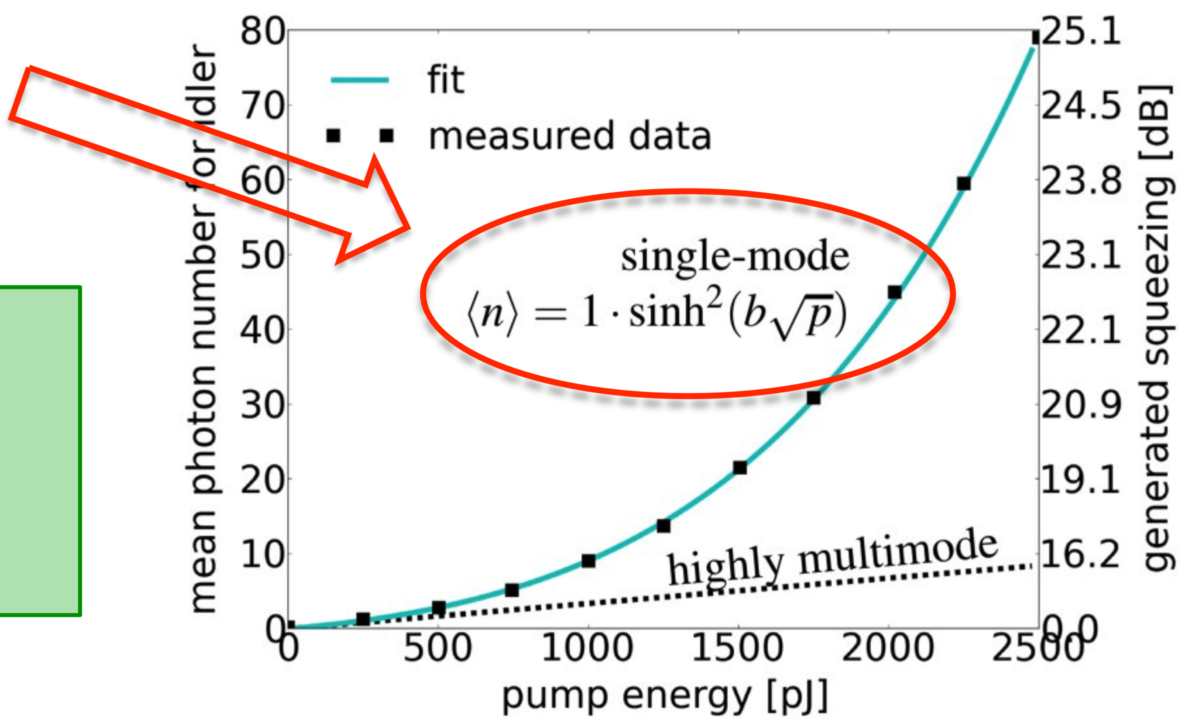
Avenhaus, et al, Opt. Lett. 34, 2873 (2009)
Eckstein, et al, Phys. Rev. Lett. 106, 013603 (2011)
Harder, et al, Opt. Express 21, 13975 (2013)

Source brightness



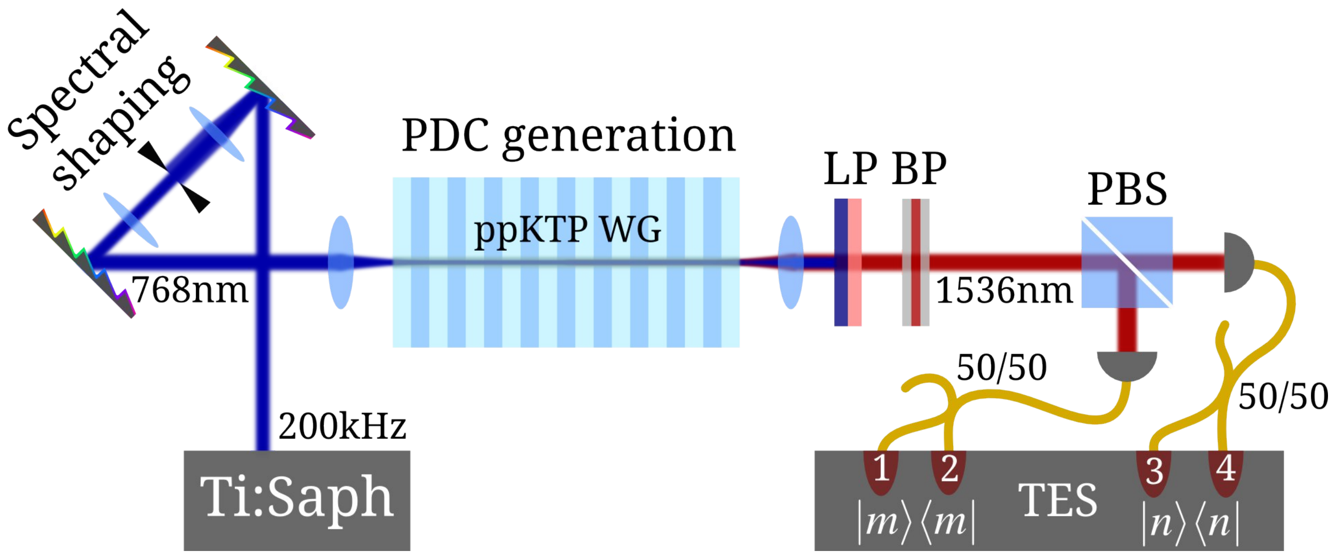
$$\hat{H} = \alpha \, a^\dagger b^\dagger + h.c.$$
$$|\psi\rangle = \sum \lambda_n |n,n\rangle$$





- High brightness
- Clean single-mode behaviour

Measuring mesoscopic photon number states



Source

- 8mm ppKTP waveguide
  → 1ps pulses
- Poling period 117 µm
- single-mode at 1536 nm

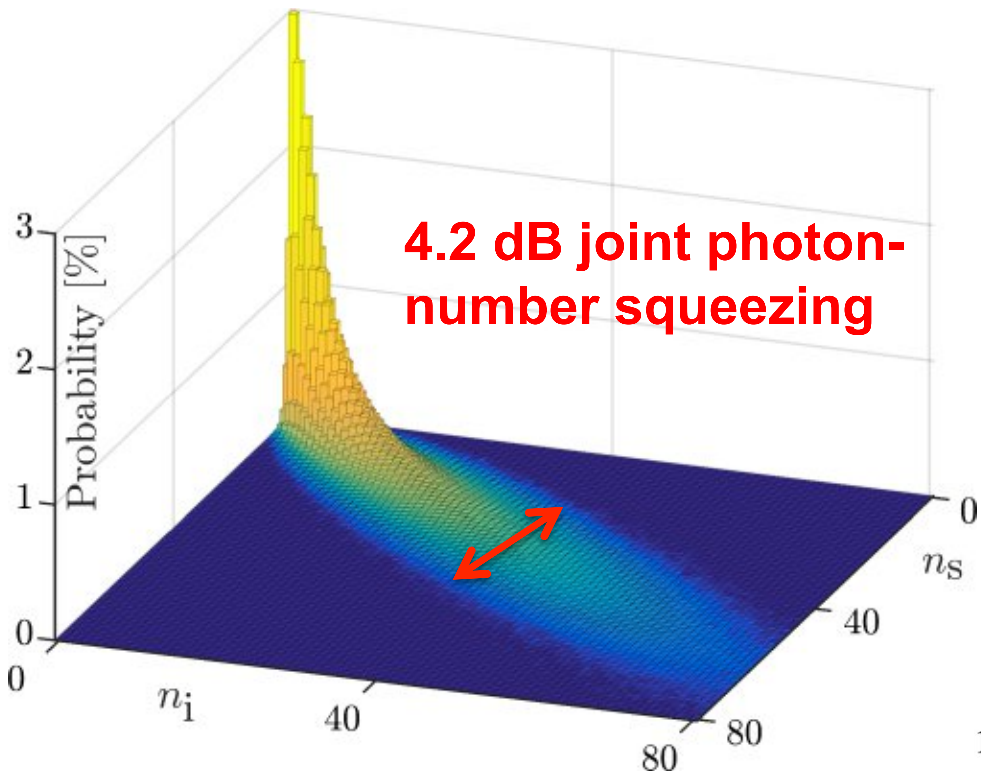
G. Harder et al., Opt. Express 21, 13975 (2013)
A. Eckstein et al., Phys. Rev. Lett. 106, 013603

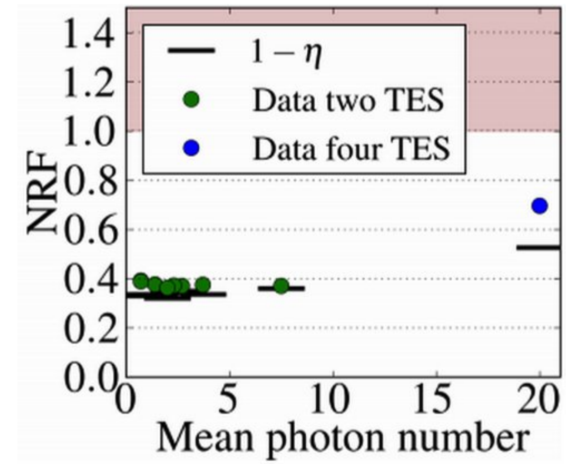
Detector

- Transition Edge Sensor with tungsten in an optical structure

A. E. Lita et al., Opt. Express 16, 3032 (2008)

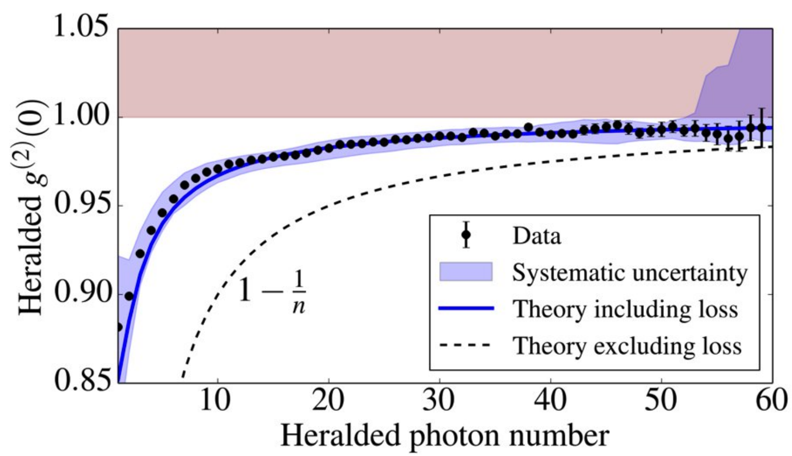
in collaboration with NIST, Boulder: Thomas Gerrits, Sea Woo Nam





- Mean photon number of **20**

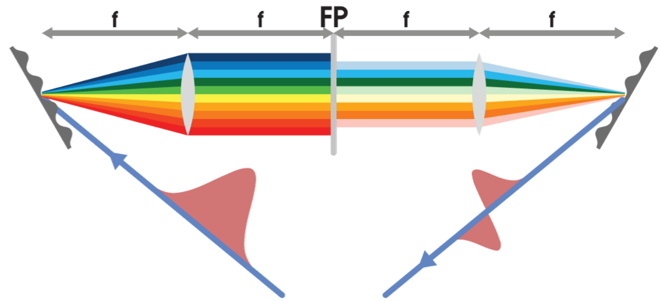
- Detection efficiencies (4 TES): 43% and 52%

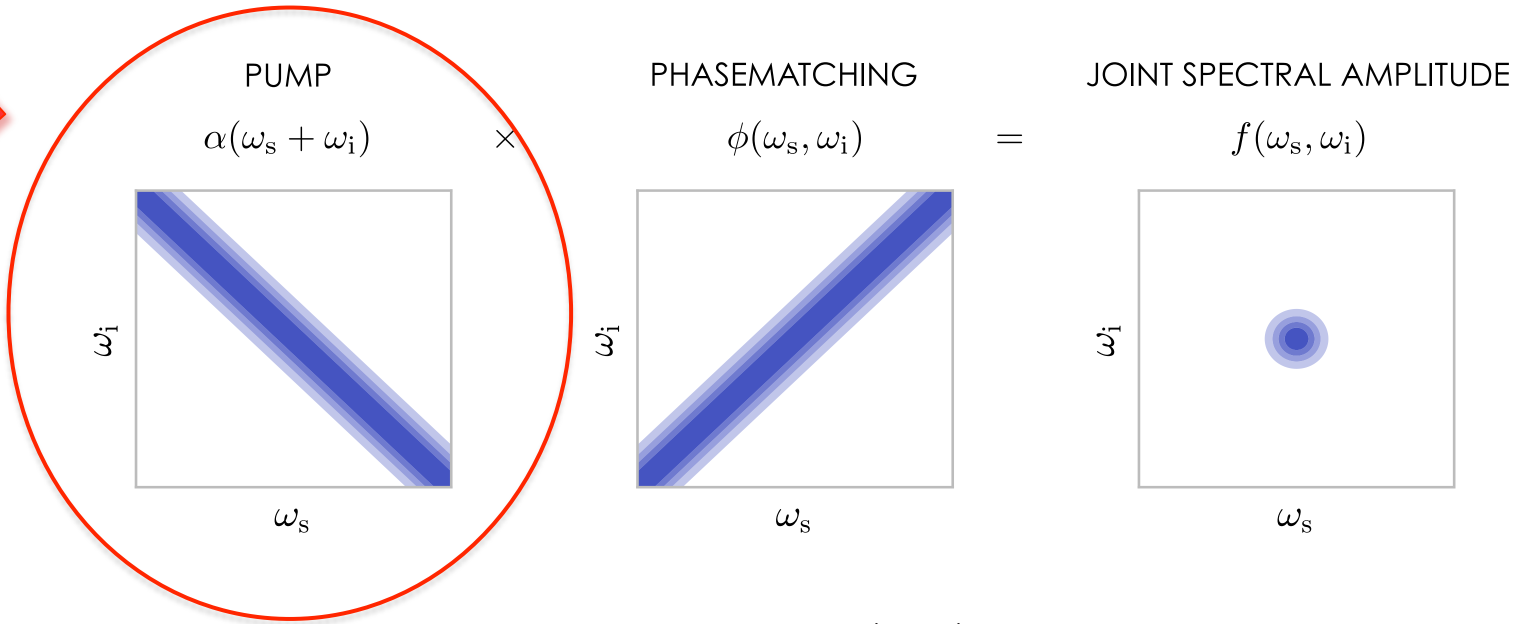


G. Harder et al., Phys. Rev. Lett. **116**, 143601 (2016)

Ultrashort pulse shaping

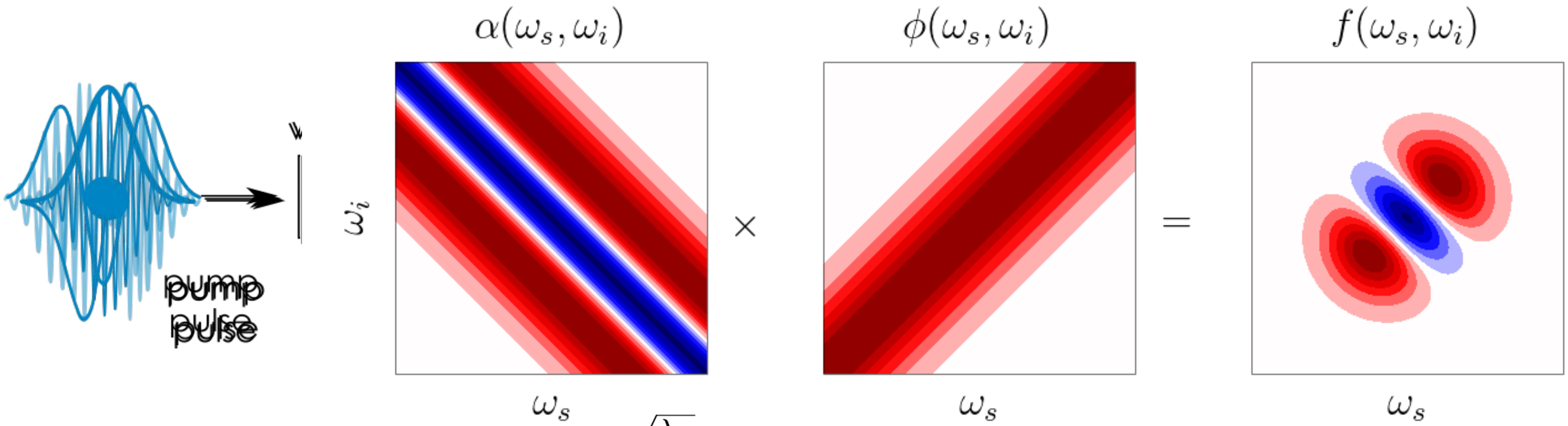
- Nonlinear waveguides
- Control of spectral correlations
  - Dispersion-free 4f setup
  - **Liquid crystal SLM**
  - Shaping spectral amplitude & phase
  - Resolutions of < 10 pm



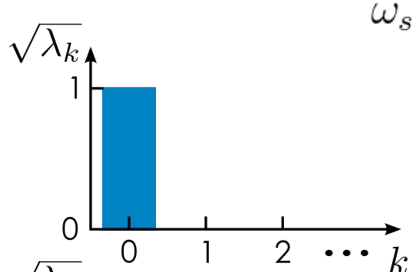


$$|\psi\rangle \approx \sum_k \sqrt{\lambda_k}\, \hat{A}_k^\dagger\, \hat{B}_k^\dagger\, |0\rangle$$

Schmidt modes with shaped pump pulses

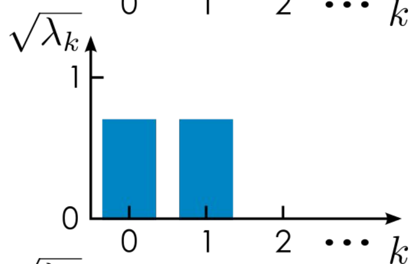


Gaussian pump



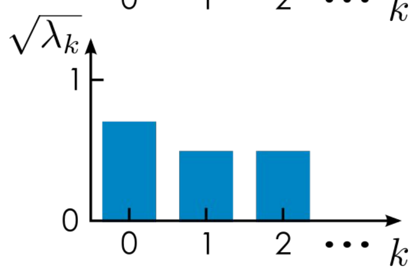
K=1

1st Hermite-Gaussian pump



K=2

2nd Hermite-Gaussian pump

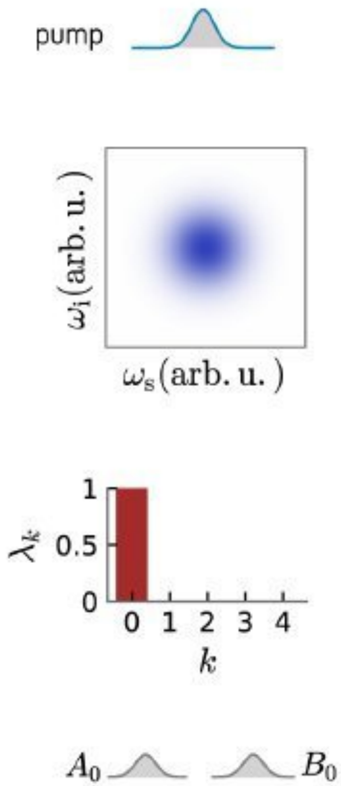


K=2.66

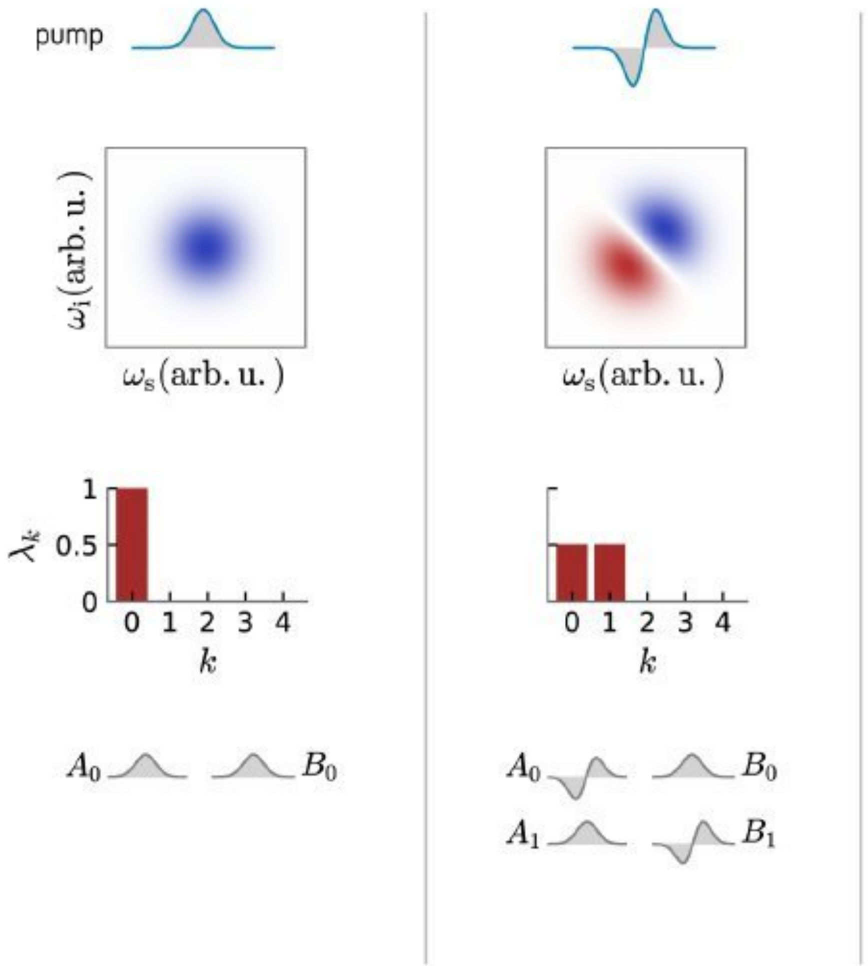
Schmidt rank = Hermite number of pump

Brecht et al.,PRX 5, 041017 (2015)

Orchestrating Schmidt modes



Brecht, et al., PRX 5, 041017 (2015)
Patera, et al, Eur. Phys. J. D 66:241 (2012)

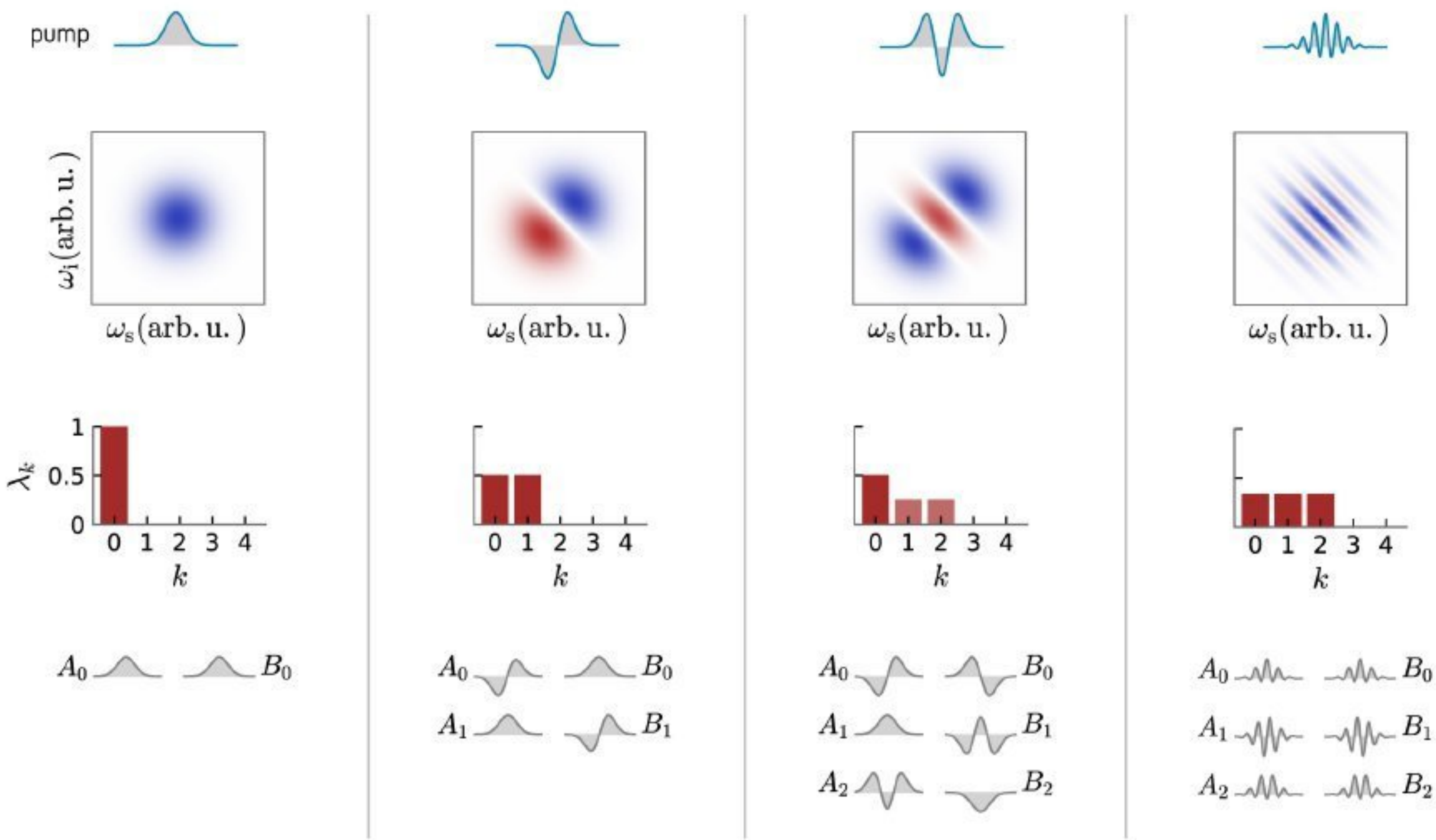


temporal-mode Bell state

$$|\psi\rangle \approx \frac{1}{\sqrt{2}}\left(|\frown_s, \sim_i\rangle + |\sim_s, \frown_i\rangle\right)$$

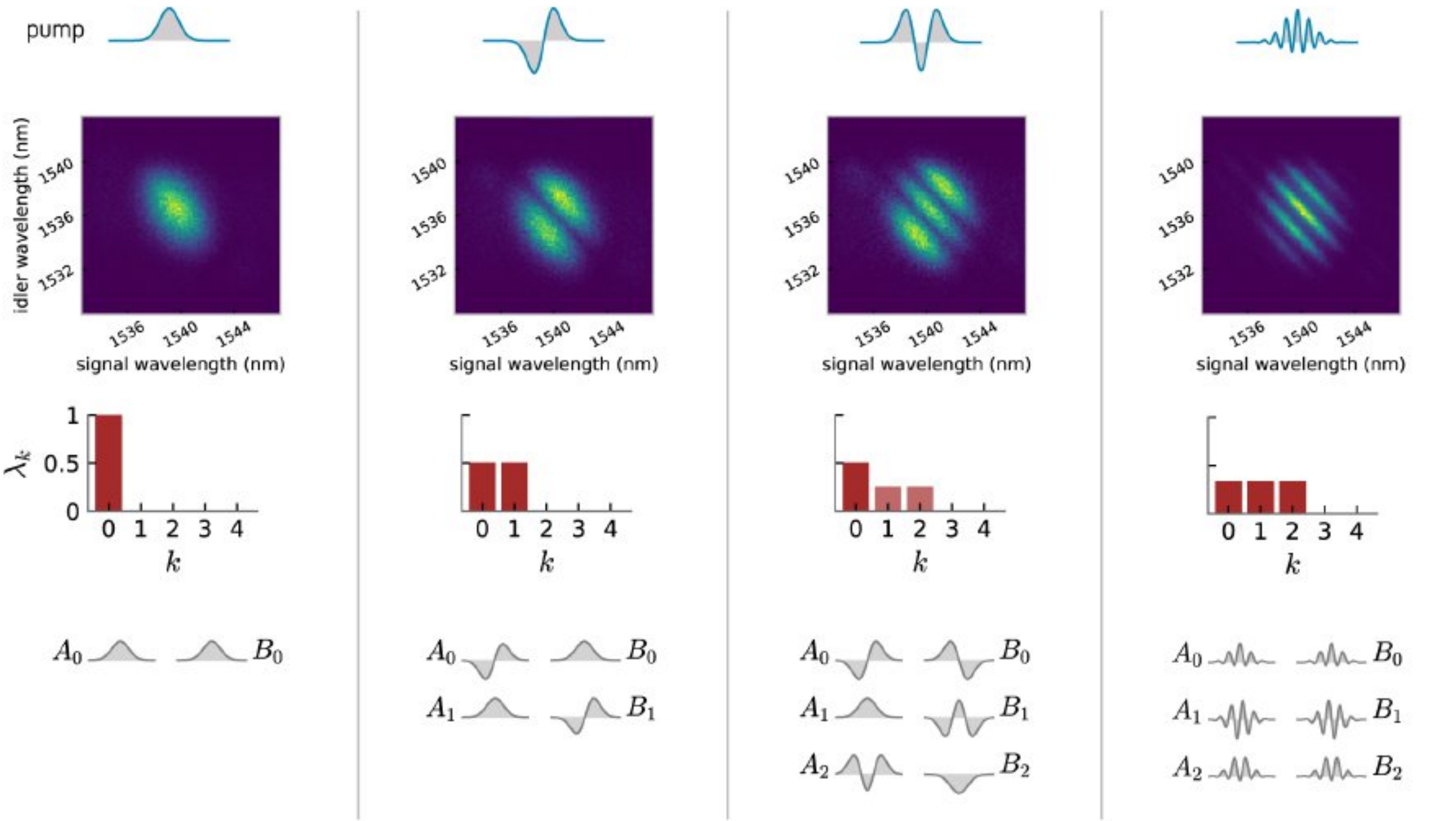
Brecht, et al., PRX 5, 041017 (2015)
Patera, et al, Eur. Phys. J. D 66:241 (2012)

Orchestrating Schmidt modes

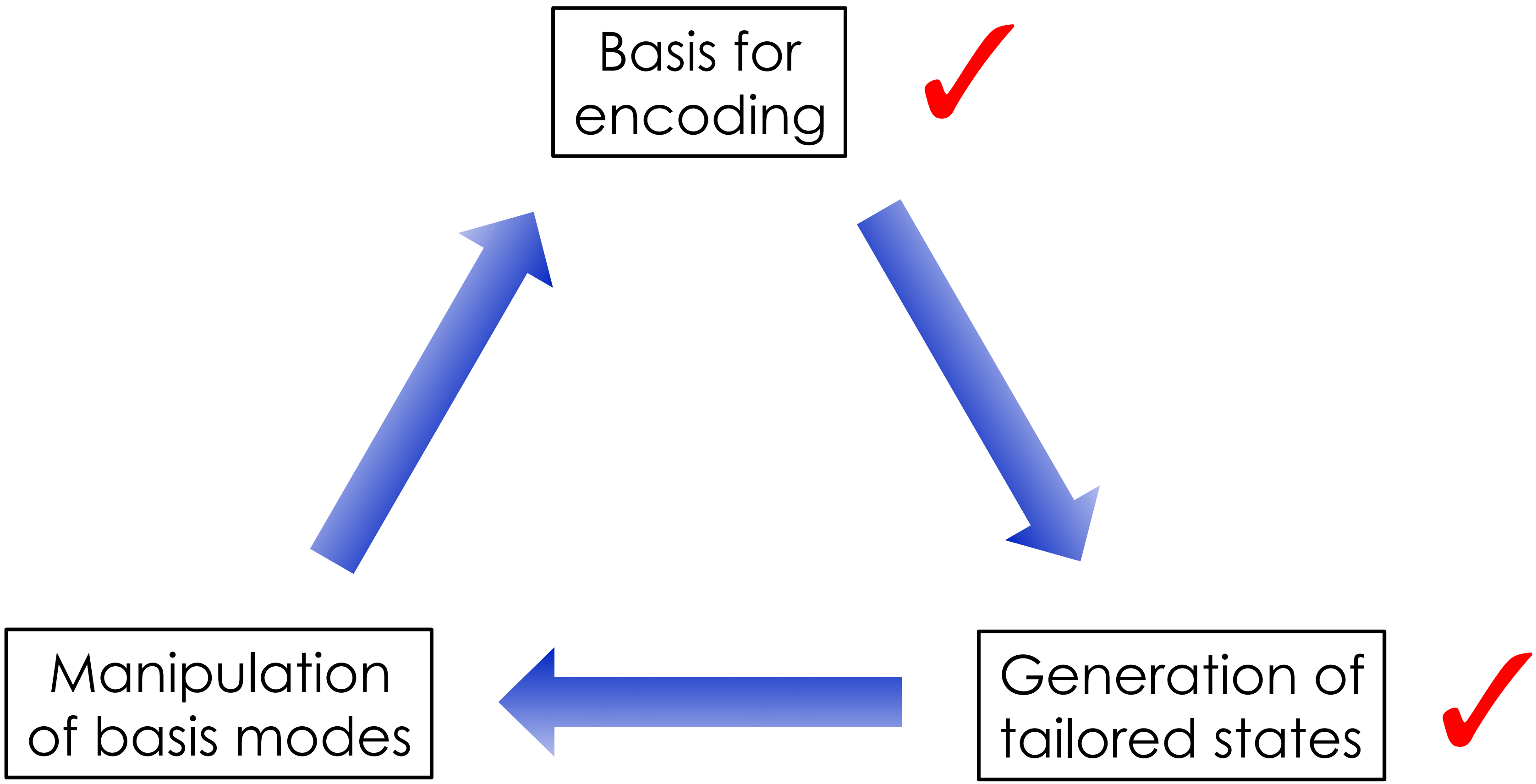


Brecht, et al., PRX 5, 041017 (2015)
Patera, et al, Eur. Phys. J. D 66:241 (2012)

Orchestrating Schmidt modes



Requirements for high dimensional quantum coding



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

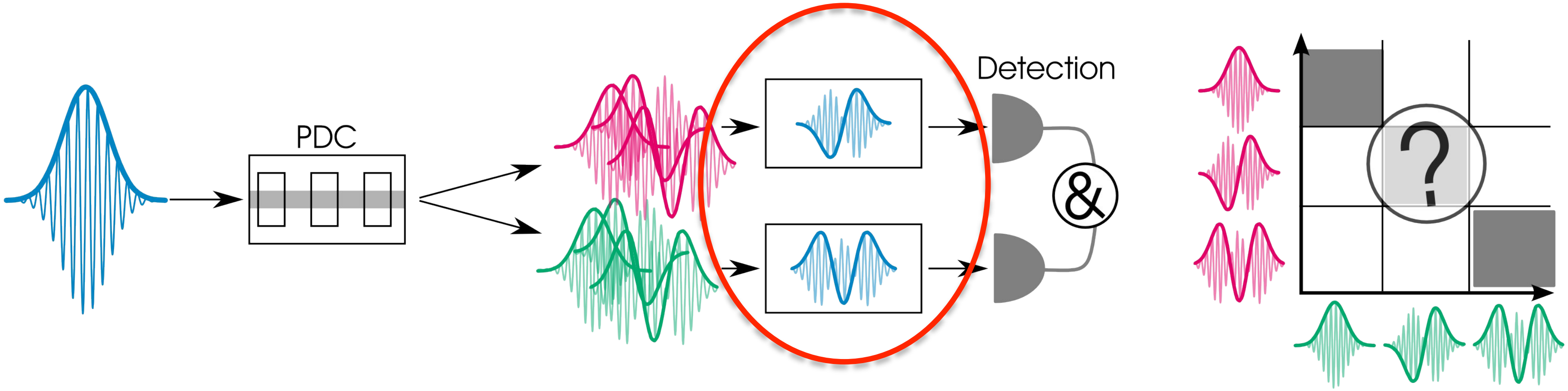
① Engineered parametric downconversion

② Quantum pulse gate

③ Applications

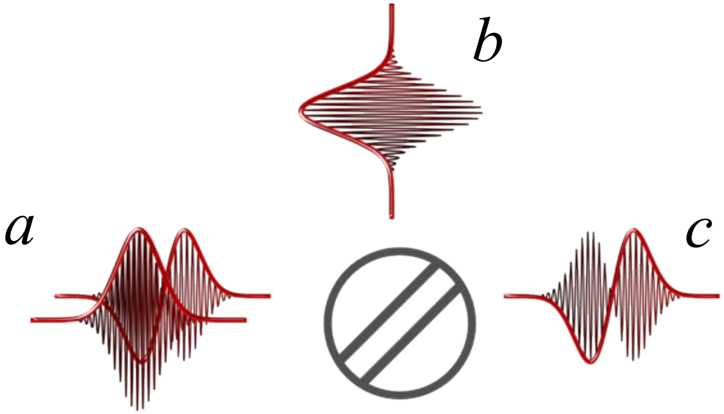
Temporal mode entanglement characterization

$$|\psi\rangle_{\mathrm{PDC}} = \bigotimes_k \exp\left[\mathcal{B}\sqrt{\lambda_k}\left(\hat{A}_k^\dagger \hat{B}_k^\dagger - \hat{A}_k \hat{B}_k\right)\right]|0\rangle \approx \sum_k \mathcal{B}\sqrt{\lambda_k}\hat{A}_k^\dagger \hat{B}_k^\dagger |0\rangle$$



How can we address / characterize temporal modes?

Separator for ultrafast modes?

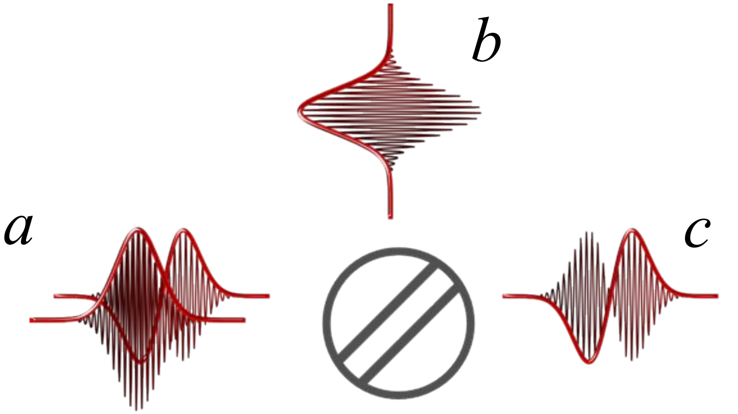


$$|\phi_0\rangle_a |\phi_1\rangle_a \rightarrow |\phi_0\rangle_b \quad |\phi_1\rangle_c$$

Requirement

Separator for ultrafast temporal pulse modes.

Separator for ultrafast modes?

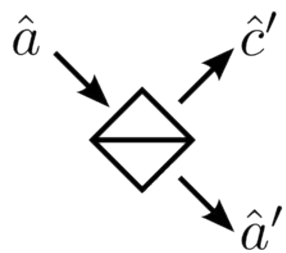


$$|\phi_0\rangle_a|\phi_1\rangle_a \to |\phi_0\rangle_b \;'\; |\phi_1\rangle_c$$

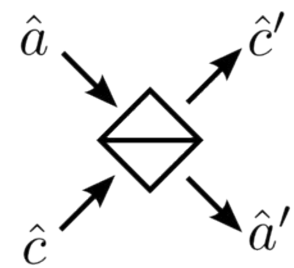
General beamsplitter

Find a process with a similar Hamiltonian

Compare with polarizing beam splitter



$$\hat{a} \to T\hat{a}' + R\hat{c}'$$



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