Quantum Frequency Conversion and Temporal-Mode Multiplexing of States of Light

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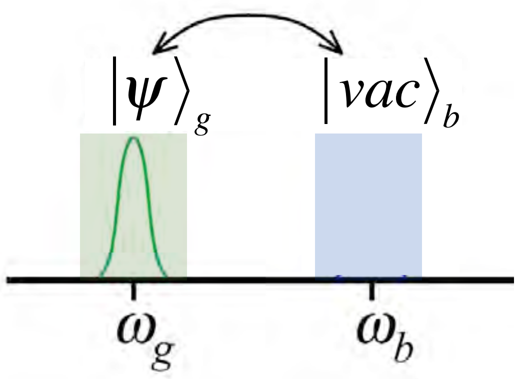
Conference on Quantum Information and Quantum Control (CQIQC-V) Toronto 2013

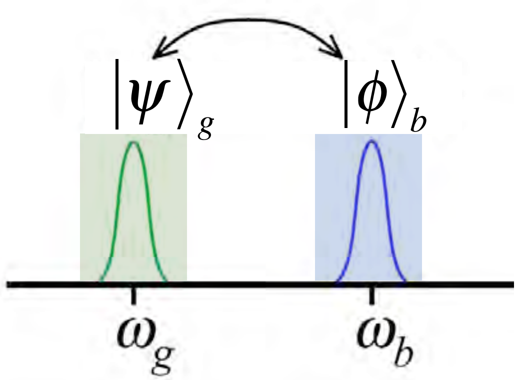
Oregon Center for Optics

Quantum Frequency Conversion (QFC):

The complete or partial exchange of quantum states between two spectral bands.



$$|\psi\rangle_g |vac\rangle_b \mapsto |vac\rangle_g |\psi\rangle_b$$



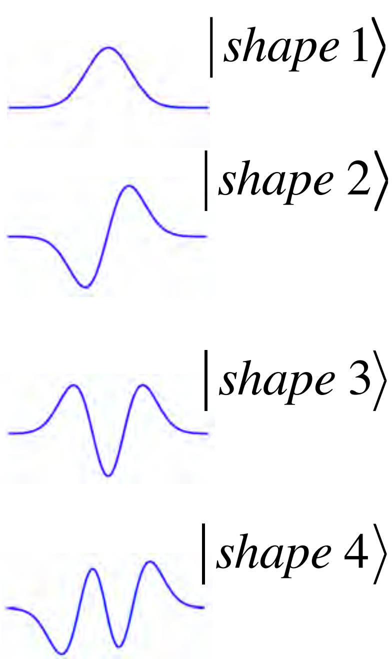
$$|\psi\rangle_g |\phi\rangle_b \mapsto \alpha|\psi\rangle_g |\phi\rangle_b + \beta|\phi\rangle_g |\psi\rangle_b$$

note: need phase coherence for the latter

Potential Uses of Single-Photon States

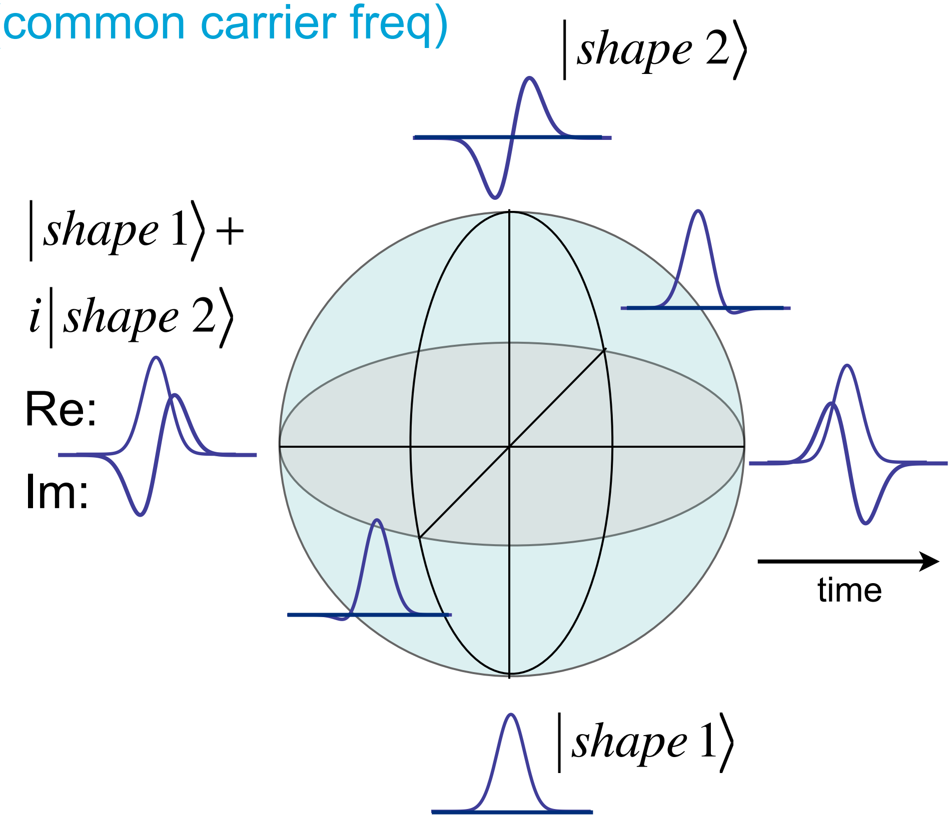
A. Many Classical Bits in Single Photon

(common carrier freq)



B. Spectral-Temporal Photonic Qubit

Bloch sphere
(common carrier freq)



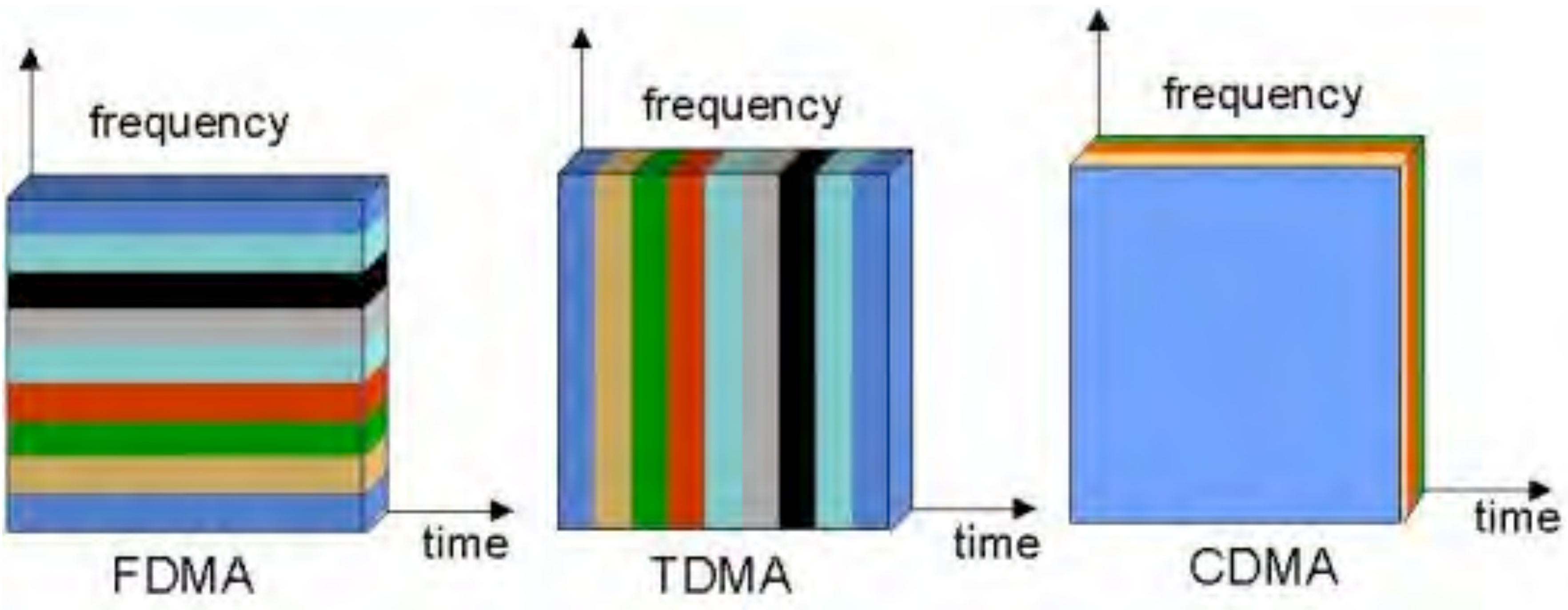
Need Pulse-Shape Multiplexing

Commonly used multiplexing schemes in radio technology

Frequency-division multiple access

Time-division multiple access

Code-division multiple access

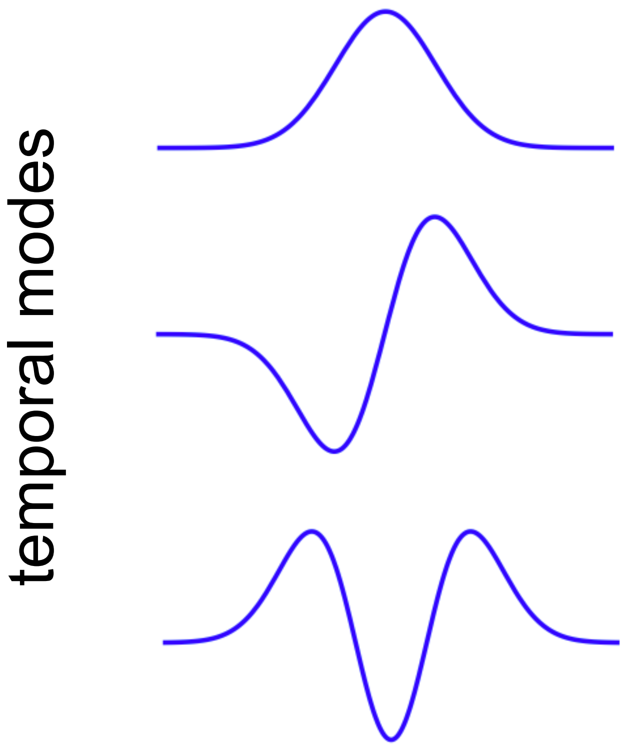


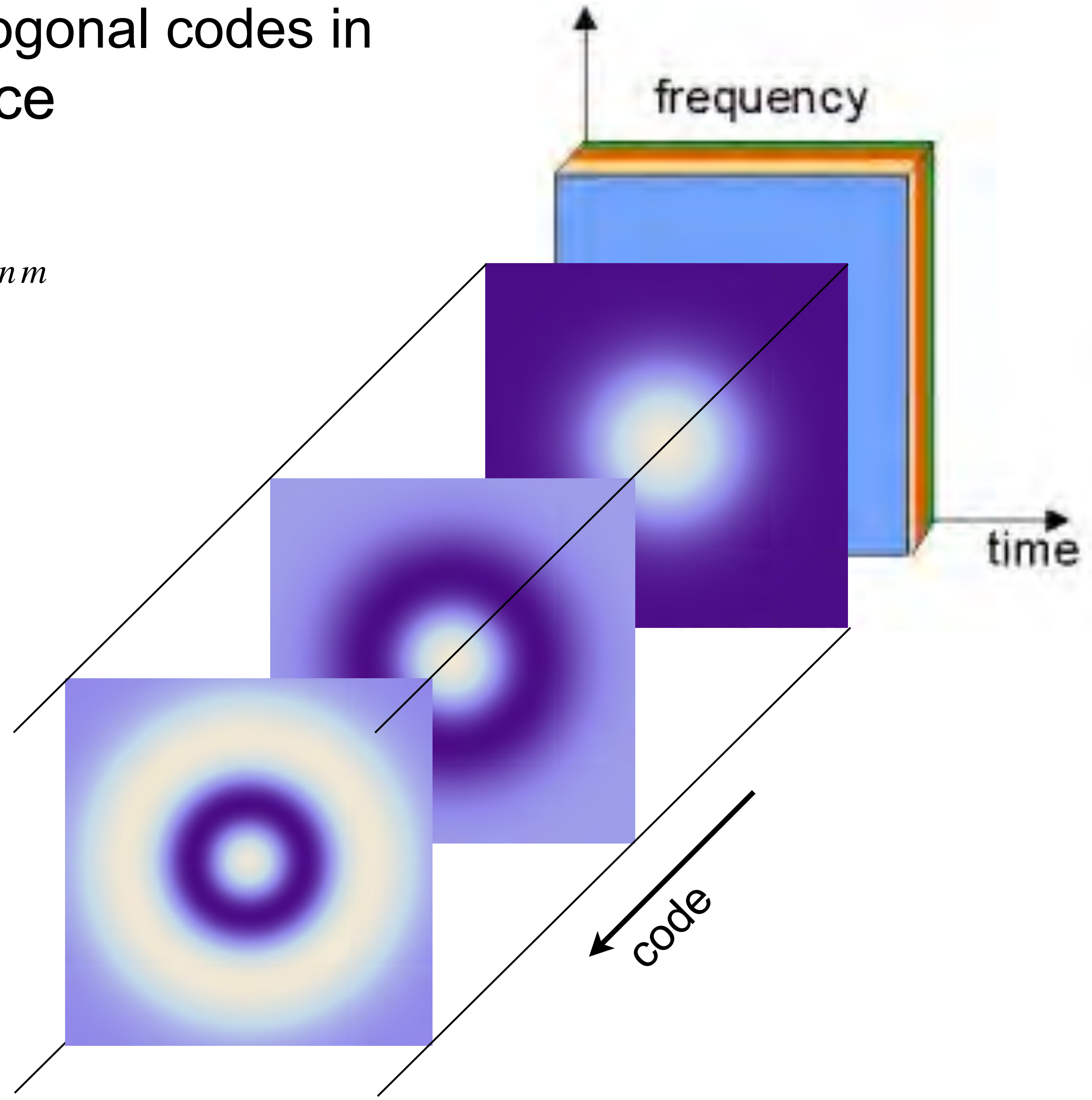
FDMA and TDMA use only time-frequency space

http://www.umtsworld.com/technology/cdmabasics.htm

CDMA uses field-orthogonal codes in code space

$$\int E_n^*(t) E_m(t) dt = \delta_{nm}$$

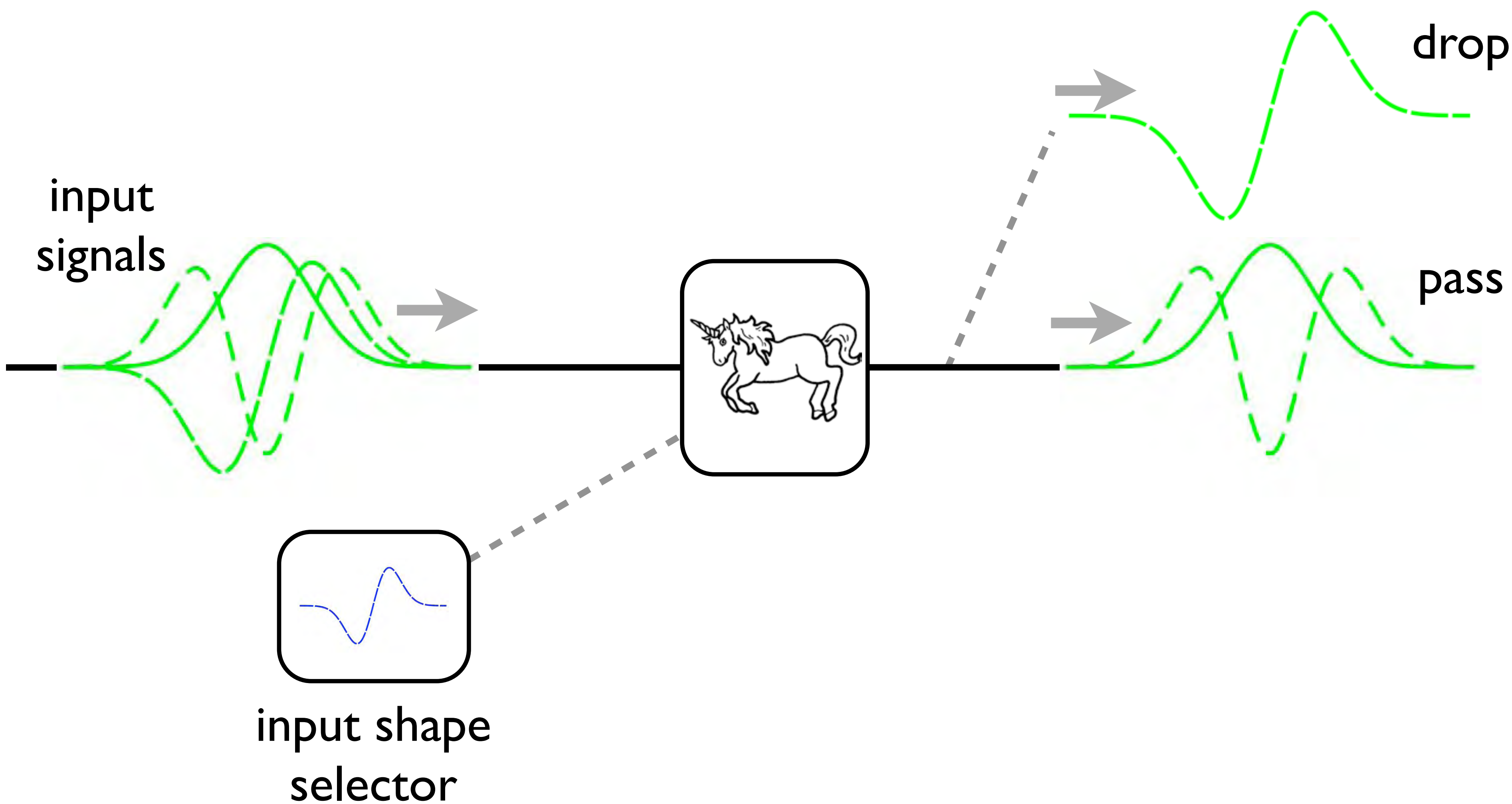




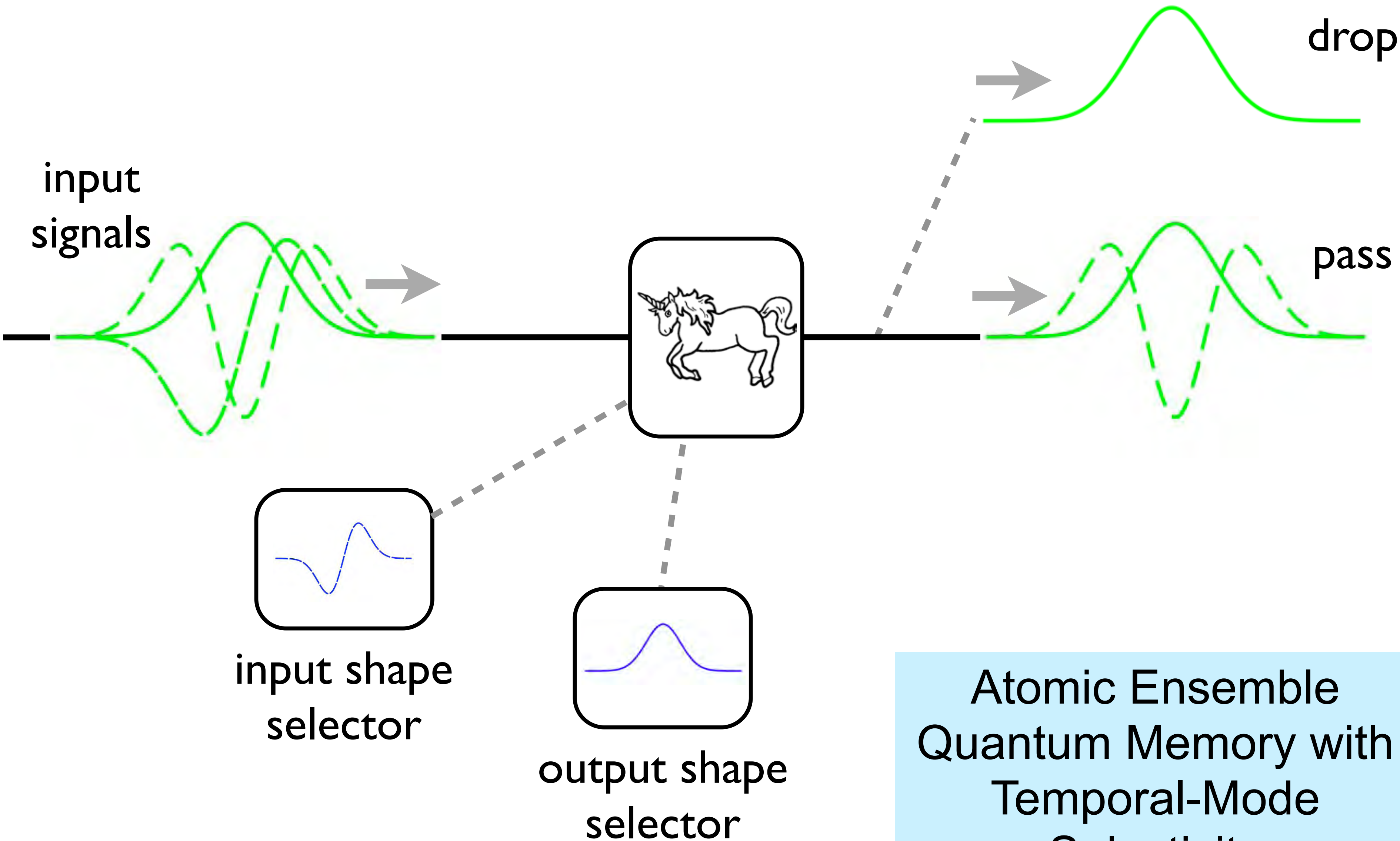
In radio, field-orthogonal codes are easily demultiplexed.
In optical, there is *NO* known method to demultiplex field-orthogonal codes.

^ efficiently

The Mythical Device



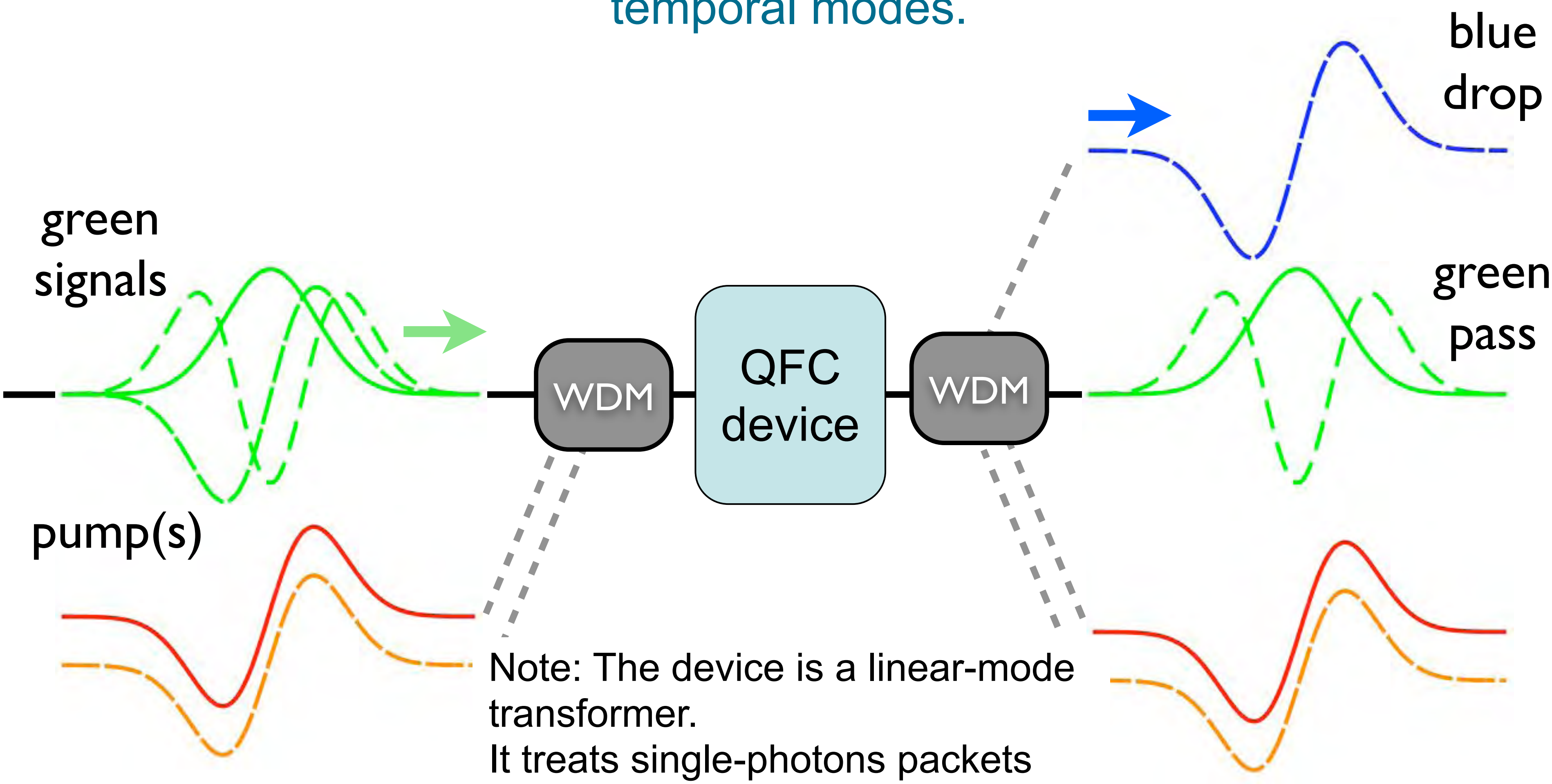
The Mythical Device with Optional Output Shape Control



Atomic Ensemble Quantum Memory with Temporal-Mode Selectivity

Nonlinear Optical Frequency Conversion:

a potential method to spatially separate field-orthogonal temporal modes.

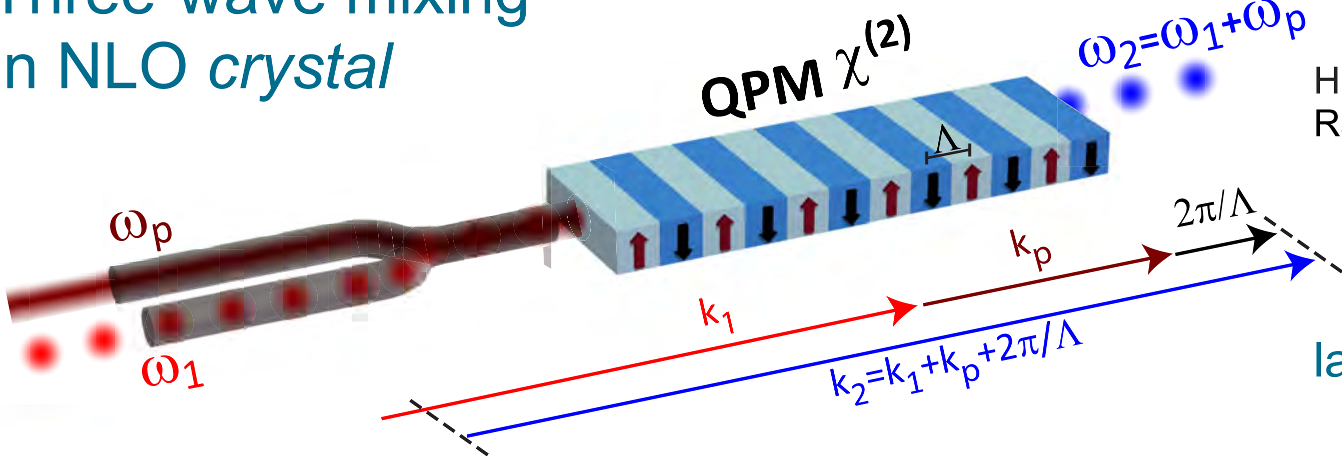


Note: The device is a linear-mode transformer.
It treats single-photons packets the same as weak classical (coherent-state) fields.

Three-wave mixing: Eckstein, Brecht, Silberhorn, Opt. Express 19, 13770 (2010)
Four-wave mixing: McKinstrie, Mejling, Raymer, Rottwitt, Phys. Rev. A 85, 053829 (2012)

Methods for Quantum Frequency Conversion

Three-wave mixing
in NLO *crystal*



Huang and Kumar, PRL (1992)
Rakher, ... Srinivasan, Nat. Photonics **4,** 786 (2010)

large frequency shift

from: MR and KS, Physics Today, **65**, 32 (2012)

Methods for Quantum Frequency Conversion

Three-wave mixing
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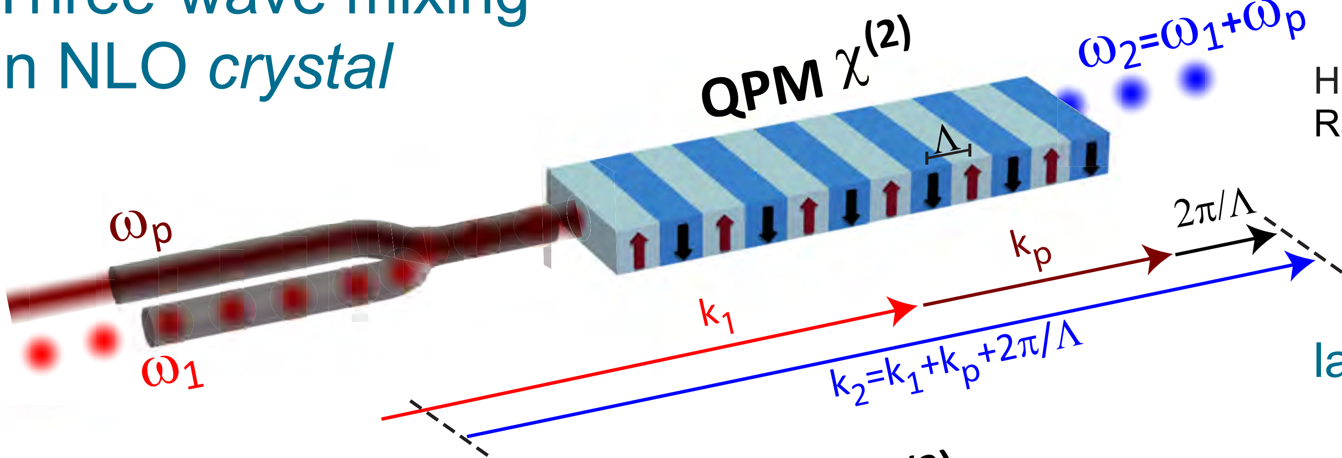
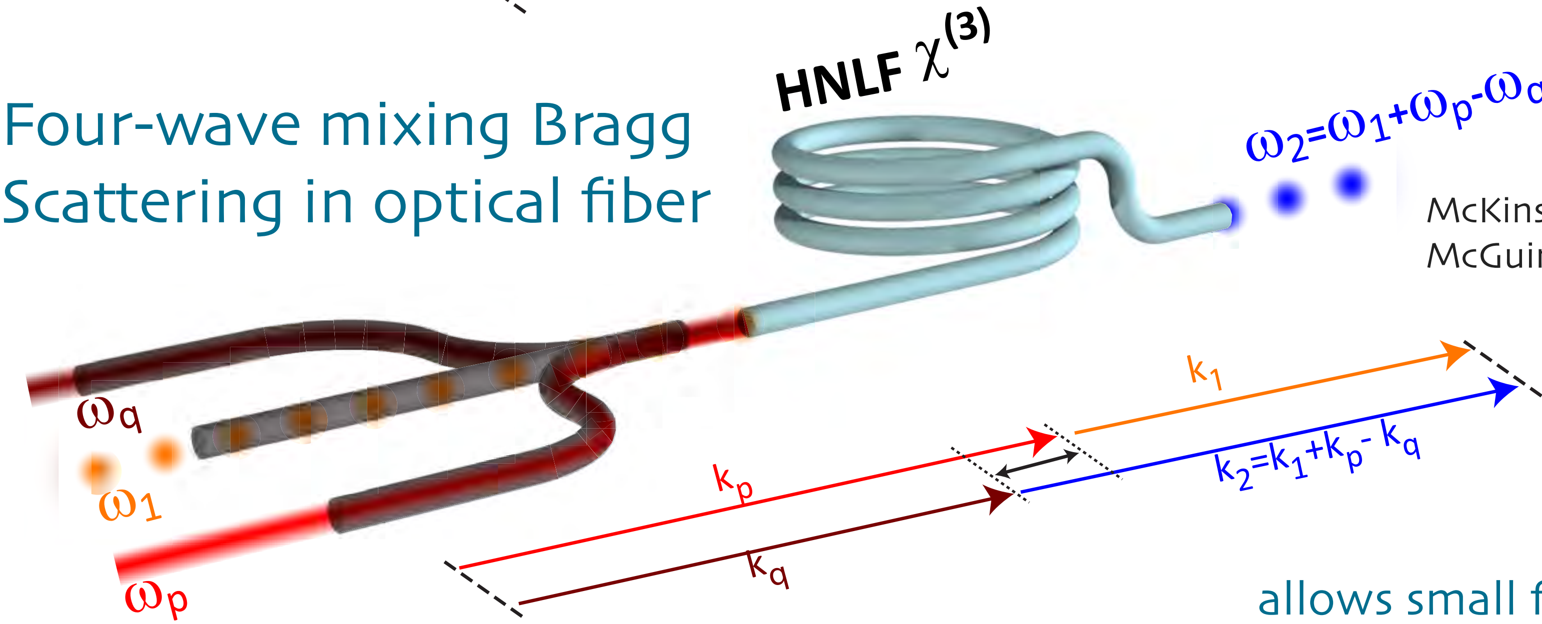


Huang and Kumar, PRL (1992)
Rakher, ... Srinivasan, Nat. Photonics **4,** 786 (2010)

large frequency shift

Four-wave mixing Bragg
Scattering in optical fiber



McKinstrie, Opt Ex (2005)
McGuinness PRL (2010)

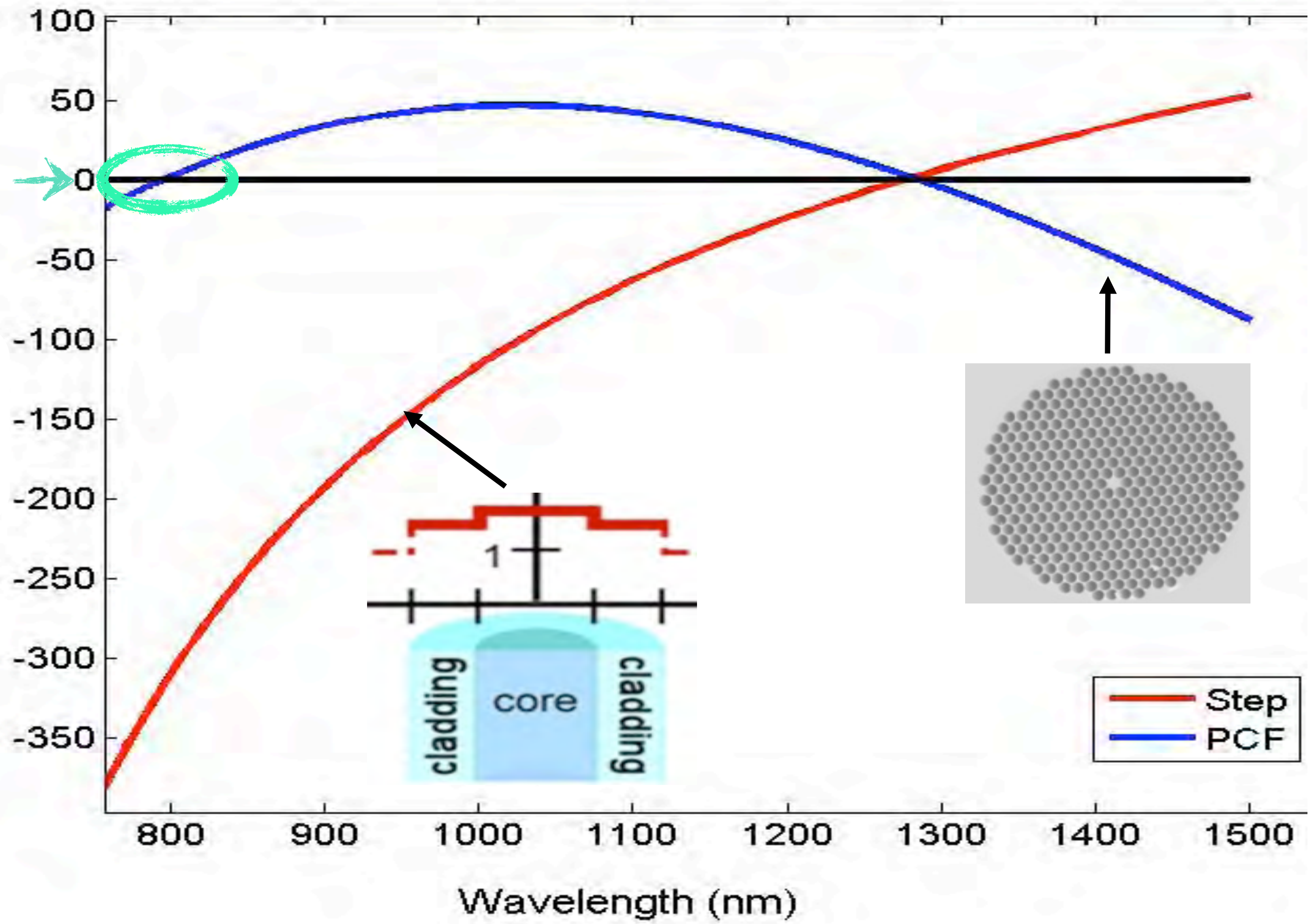
allows small frequency shift

from: MR and KS, Physics Today, **65**, 32 (2012)

EXPERIMENTS: Dispersion of Step-Index Fiber and Photonic-Crystal Fiber

Zero Dispersion

$$\frac{d}{d\lambda}\left(\frac{1}{v_g}\right)$$



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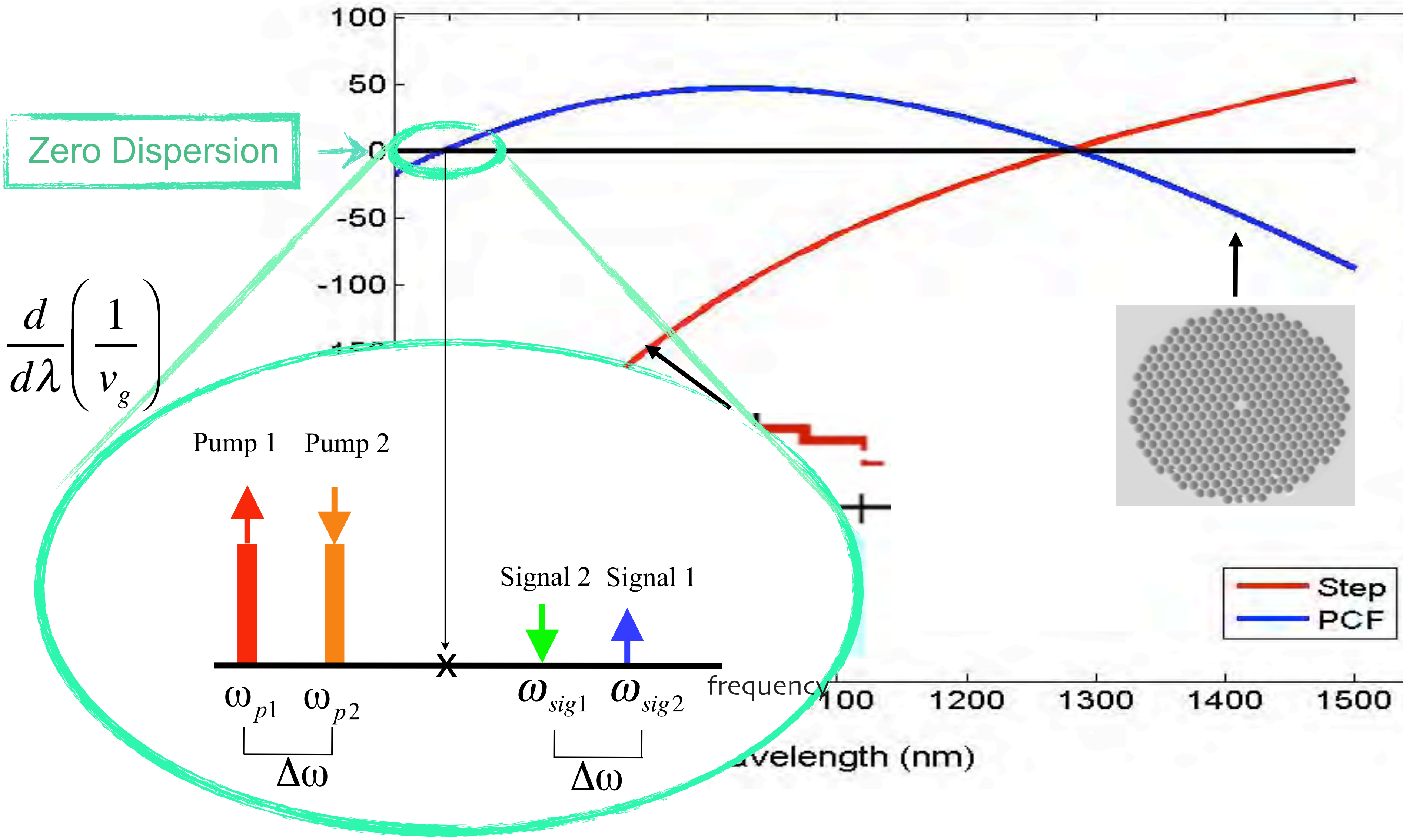
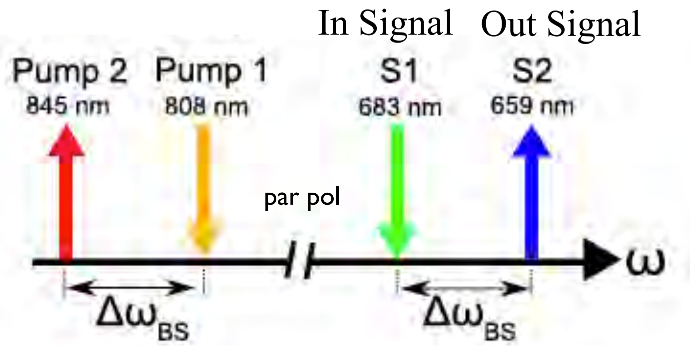
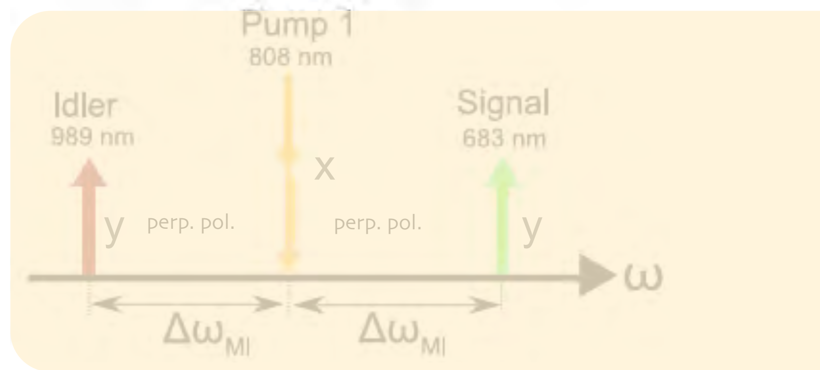
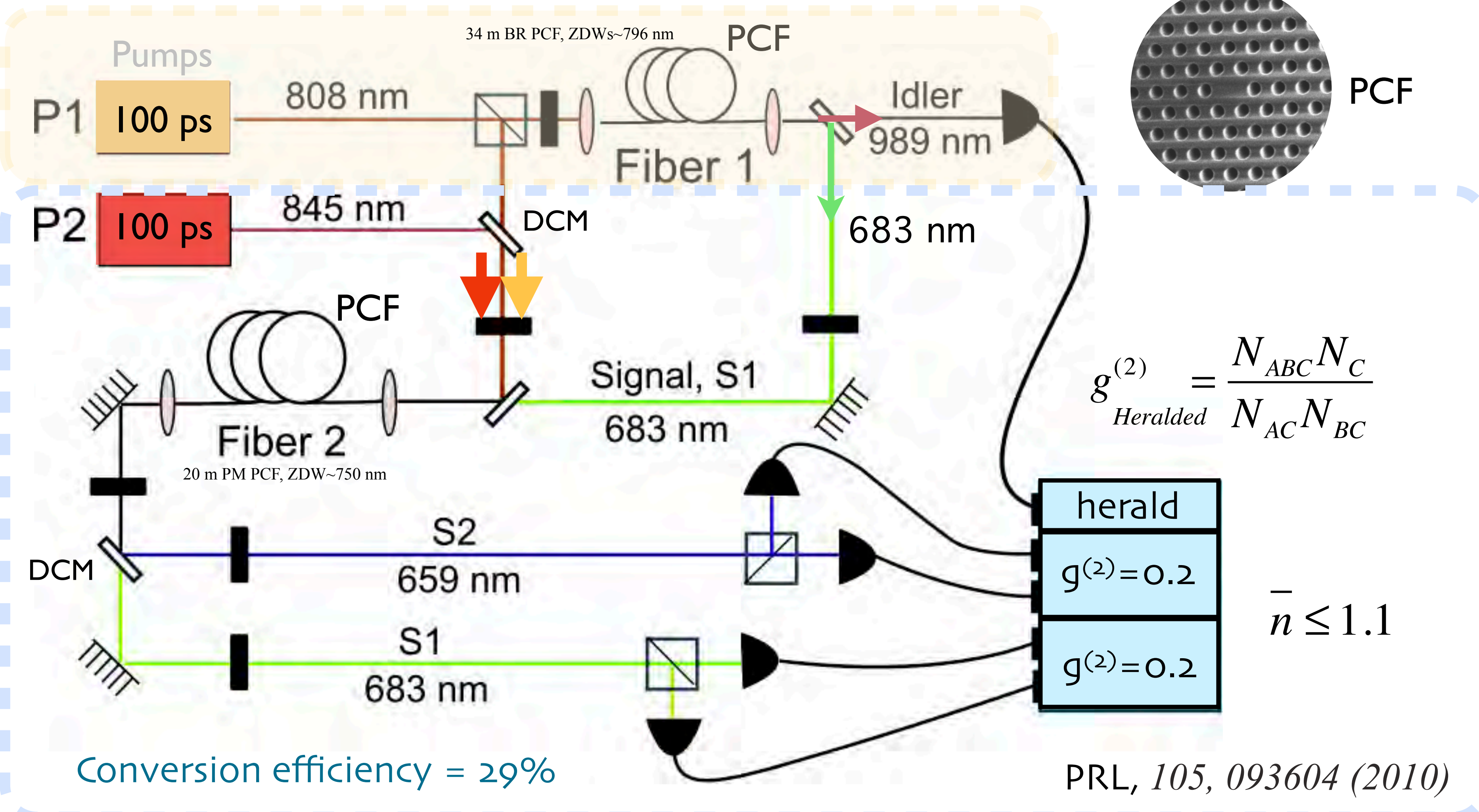


Signal 1 has same group velocity as Pump 1.
Signal 2 has same group velocity as Pump 2.

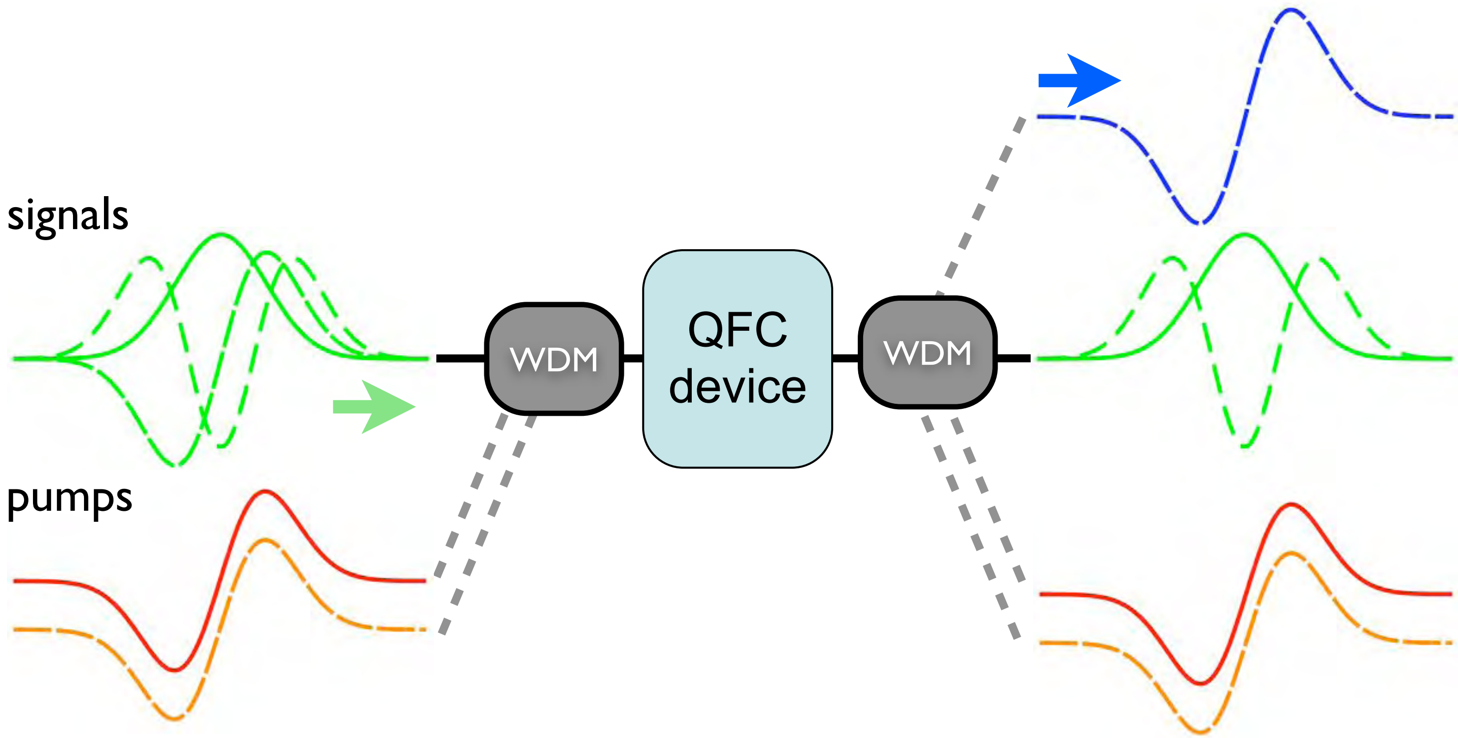
2. Conversion

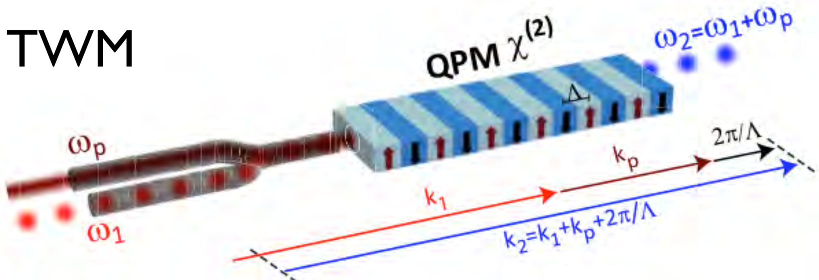


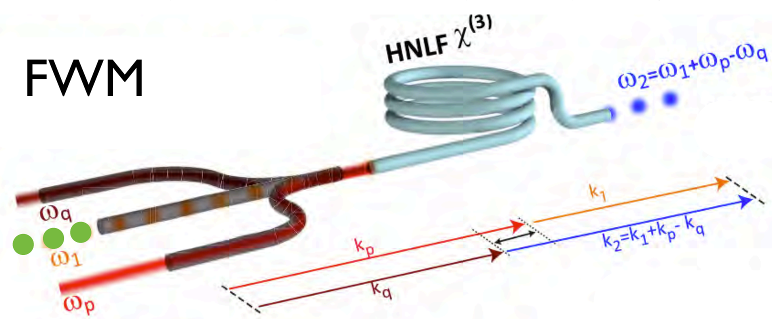




How effective can QFC be in separating field-orthogonal optical codes?







Modeling QFC by Nonlinear Wave Mixing

$$\left(\frac{\partial}{\partial z}+\frac{1}{v_g}\frac{\partial}{\partial t}\right)A_g(z,t)=i\gamma P(z,t)A_b(z,t)$$

$$\left(\frac{\partial}{\partial z}+\frac{1}{v_b}\frac{\partial}{\partial t}\right)A_b(z,t)=i\gamma P^*(z,t)A_g(z,t)$$

pump shapes

$$P_{TWM}(z,t)=A_p^*(z,t)$$

$$P_{FWM}(z,t)=A_{p1}^*(z,t)A_{p2}(z,t)$$

pump/coupling γ

The equations are linear in A_g and A_b signal field operators.
Solution:

$$\begin{pmatrix} A_g(t) \\ A_b(t) \end{pmatrix}_{OUT} = \int^t dt' \begin{pmatrix} G_{gg}(t,t') & G_{gb}(t,t') \\ G_{bg}(t,t') & G_{bb}(t,t') \end{pmatrix} \begin{pmatrix} A_g(t') \\ A_b(t') \end{pmatrix}_{IN}$$

All quantum correlations can be calculated from Green functions.

Four-wave mixing: McGuinness, MR, CM, Opt. Express 19, 17876 (2011)
Three-wave mixing: Reddy, MR, CM, AM, KR, Opt. Express 21, 13840 (2013)
Christ, Brecht, Mauerer, Silberhorn (NJP 2013)

Schmidt Mode Decomposition of the Green functions

(singular-value decomposition)

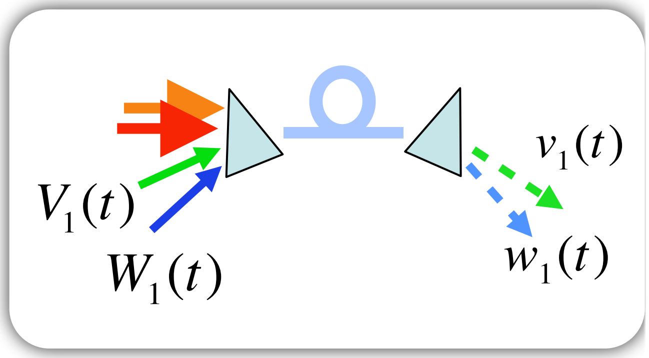
$$\begin{pmatrix} A_g(t) \\ A_b(t) \end{pmatrix}_{OUT} = \sum_n \int^t dt' \begin{pmatrix} \tau_n v_n(t) V_n^*(t') & i\rho_n v_n(t) W_n^*(t') \\ i\rho_n w_n(t) V_n^*(t') & \tau_n w_n(t) W_n^*(t') \end{pmatrix} \begin{pmatrix} A_g(t') \\ A_b(t') \end{pmatrix}_{IN}$$

with $\rho_n^2 + \tau_n^2 = 1$ ρ_n^2 **= conversion,** τ_n^2 **=nonconversion**

Temporal Schmidt modes reduce problem to low-dimensional state space:

$$if \quad \begin{pmatrix} A_g(t') \\ A_b(t') \end{pmatrix}_{IN} = \begin{pmatrix} a_g V_1(t') \\ a_b W_1(t') \end{pmatrix}$$

$$then \quad \begin{pmatrix} A_g(t) \\ A_b(t) \end{pmatrix}_{OUT} = \begin{pmatrix} (\tau_1 a_g + i\rho_1 a_b)\, v_1(t) \\ (i\rho_1 a_g + \tau_1 a_b)\, w_1(t) \end{pmatrix}$$

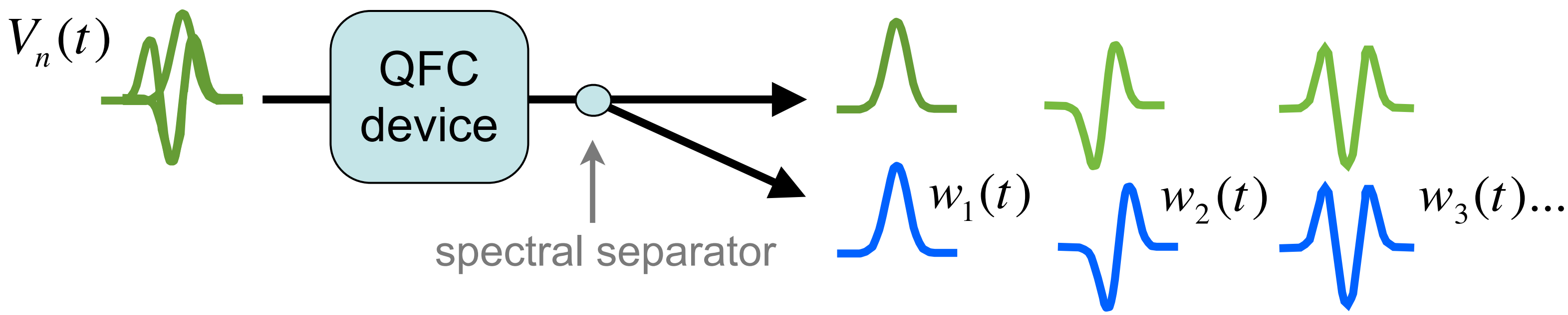


Operators undergo a pair-wise beam-splitter transformation

MR, HM, SVE, CM Opt. Commun. 238, 747 (2010)

Figure of Merit for Temporal-mode Selectivity

$$G_{bg}(t,t')=i\sum_n \rho_n\, w_n(t)\, V^*_n(t')$$



$$\eta_n = |\rho_n|^2 = \textit{conversion efficiency}$$

$$separability \equiv \frac{\eta_{Target}}{\sum_n \eta_n} \le 1$$

$$S \equiv Selectivity \equiv separability \times \eta_{Target}$$

$$S = \frac{|\eta_{Target}|^2}{\sum_n \eta_n} \le 1$$

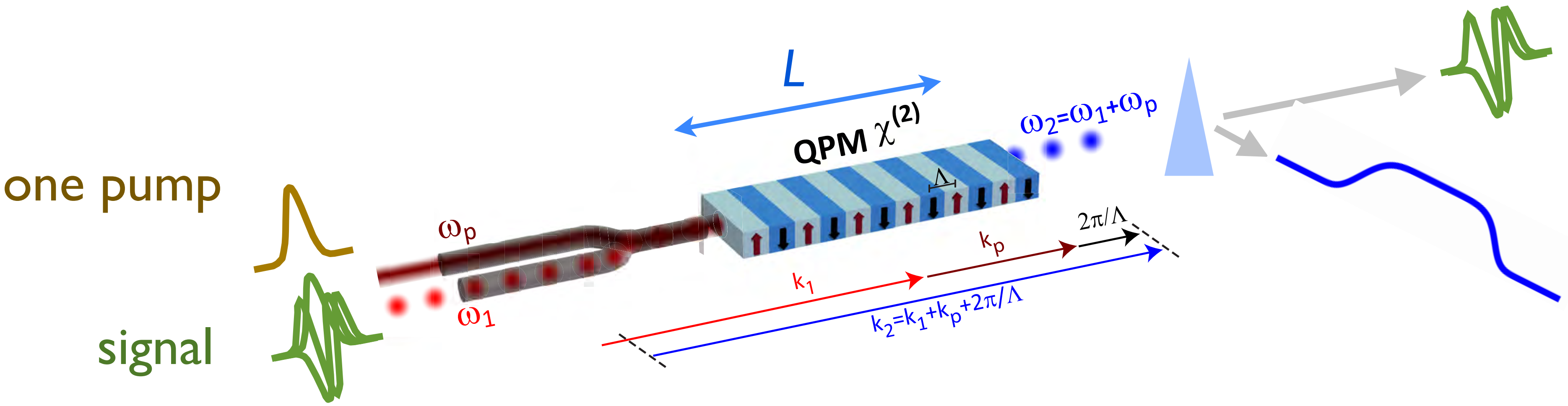
ideally: $S = 1$

Reddy, MR, CM, AM, KR,
Opt. Express 21, 13840 (2013)

Apply to three-wave mixing:

Three-wave Mixing

Optimum case: Pump velocity matches ‘green’ signal velocity. Blue is slower.



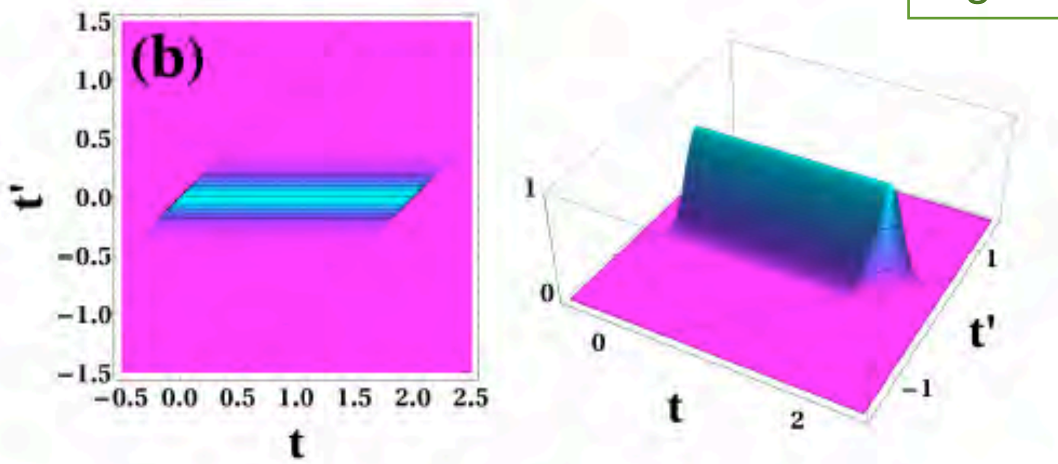
Reddy, MR, CM, LM, KR,
Opt. Express 21, 13840 (2013)

Three-wave Mixing - Low conversion efficiency

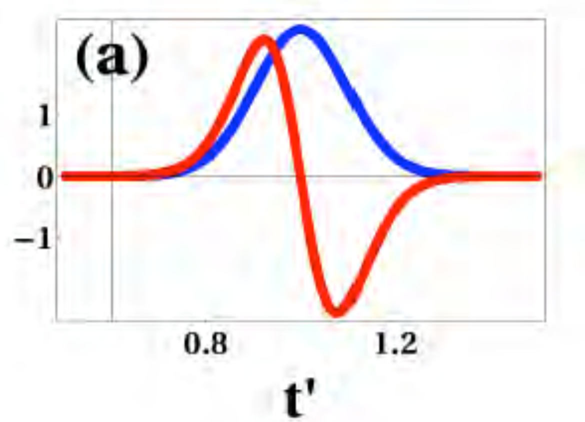
ultrashort pump pulse

Optimum case: Pump velocity matches green signal velocity

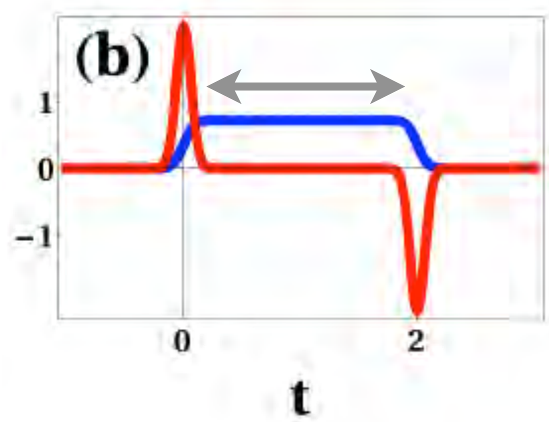
Green function



Schmidt modes: input



Schmidt modes: output

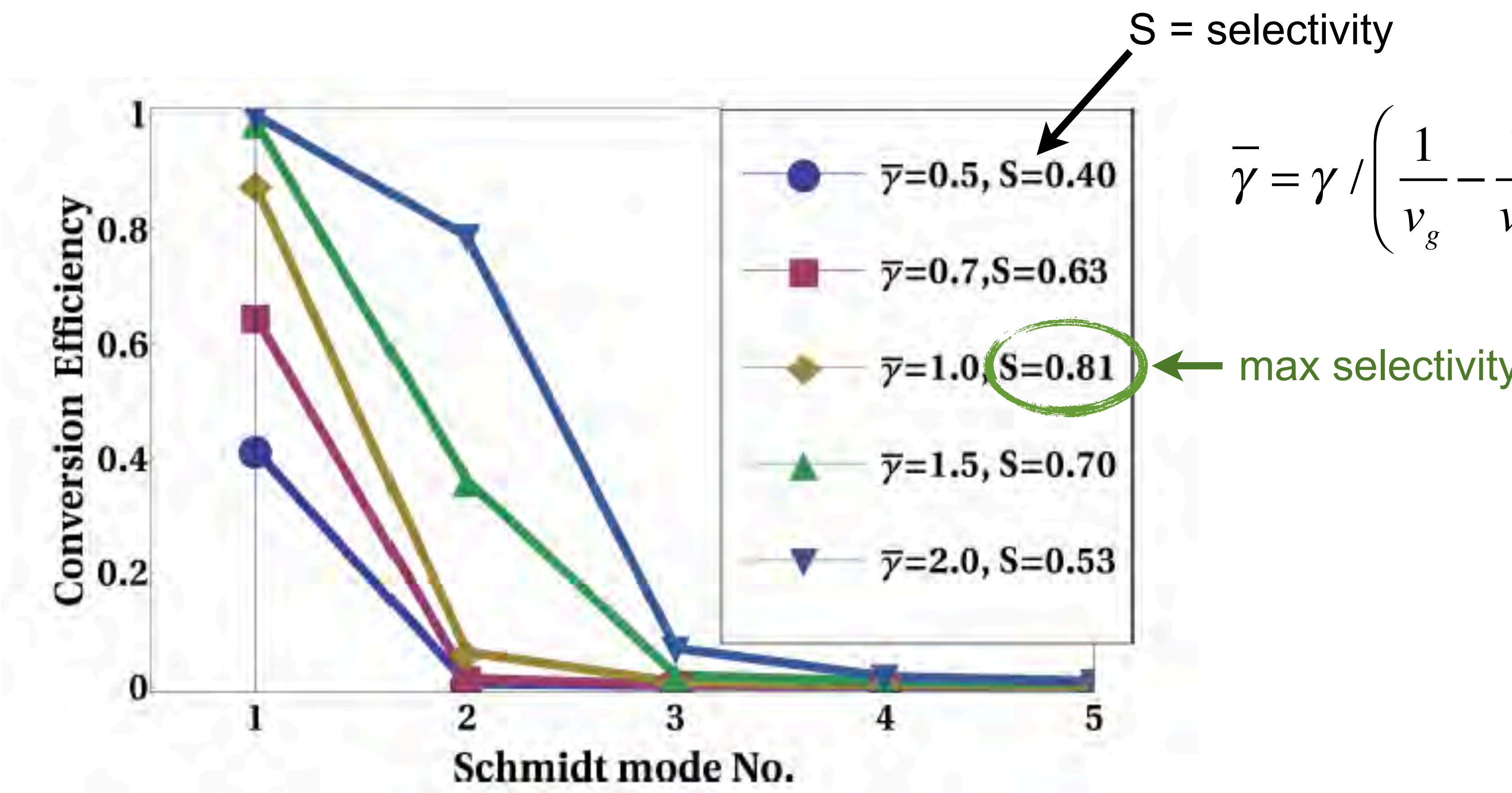


duration= $\left(\frac{1}{v_g} - \frac{1}{v_b}\right)L$

Separability is 0.94, but Selectivity is low when conversion efficiency is low.

Three-wave Mixing - High conversion efficiency ultrashort pump pulse

Optimum case: Pump velocity matches green signal velocity

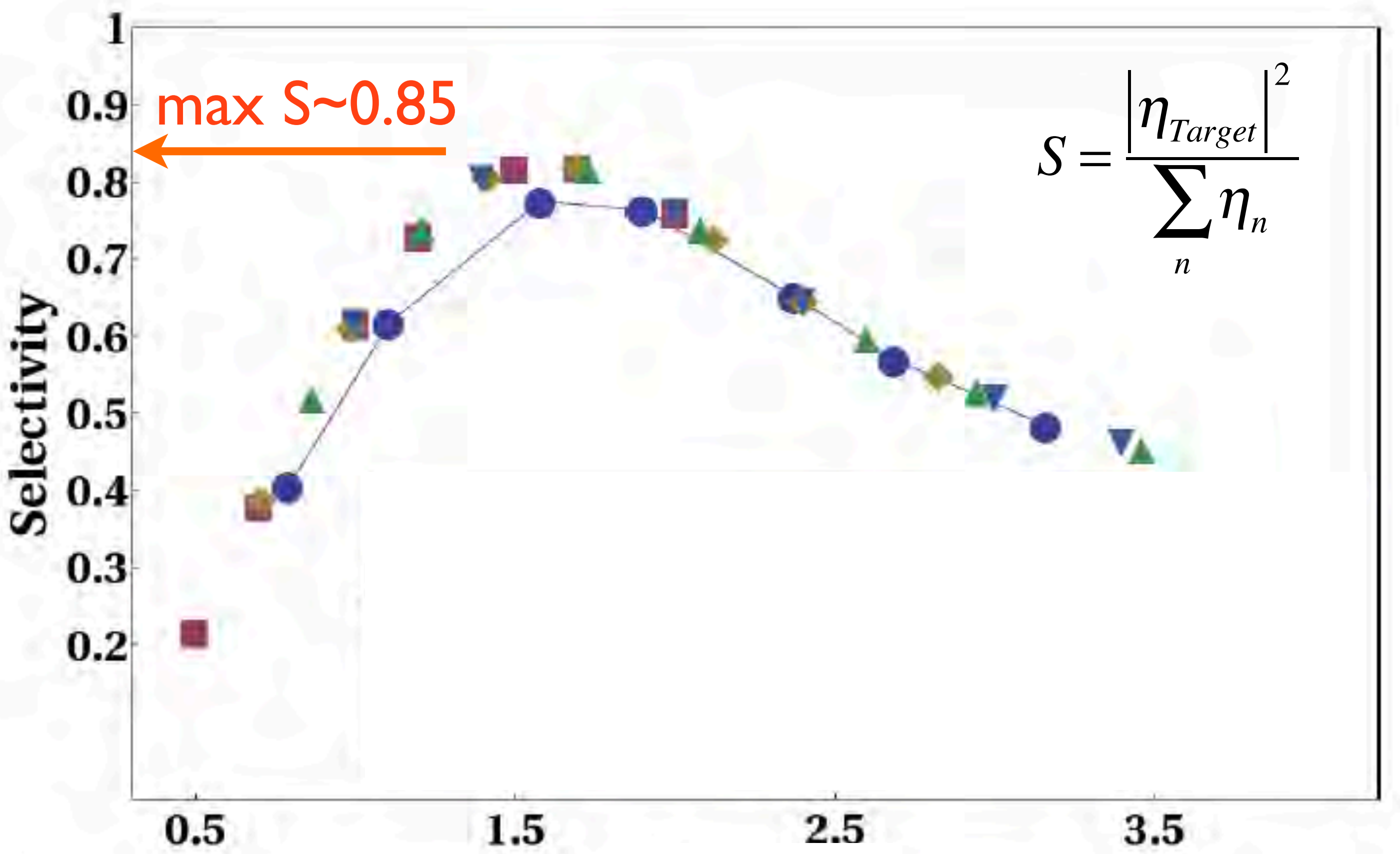


$$\bar{\gamma} = \gamma \Big/ \left(\frac{1}{v_g} - \frac{1}{v_b} \right)$$

Three-wave Mixing - High conversion efficiency

ultrashort pump pulse

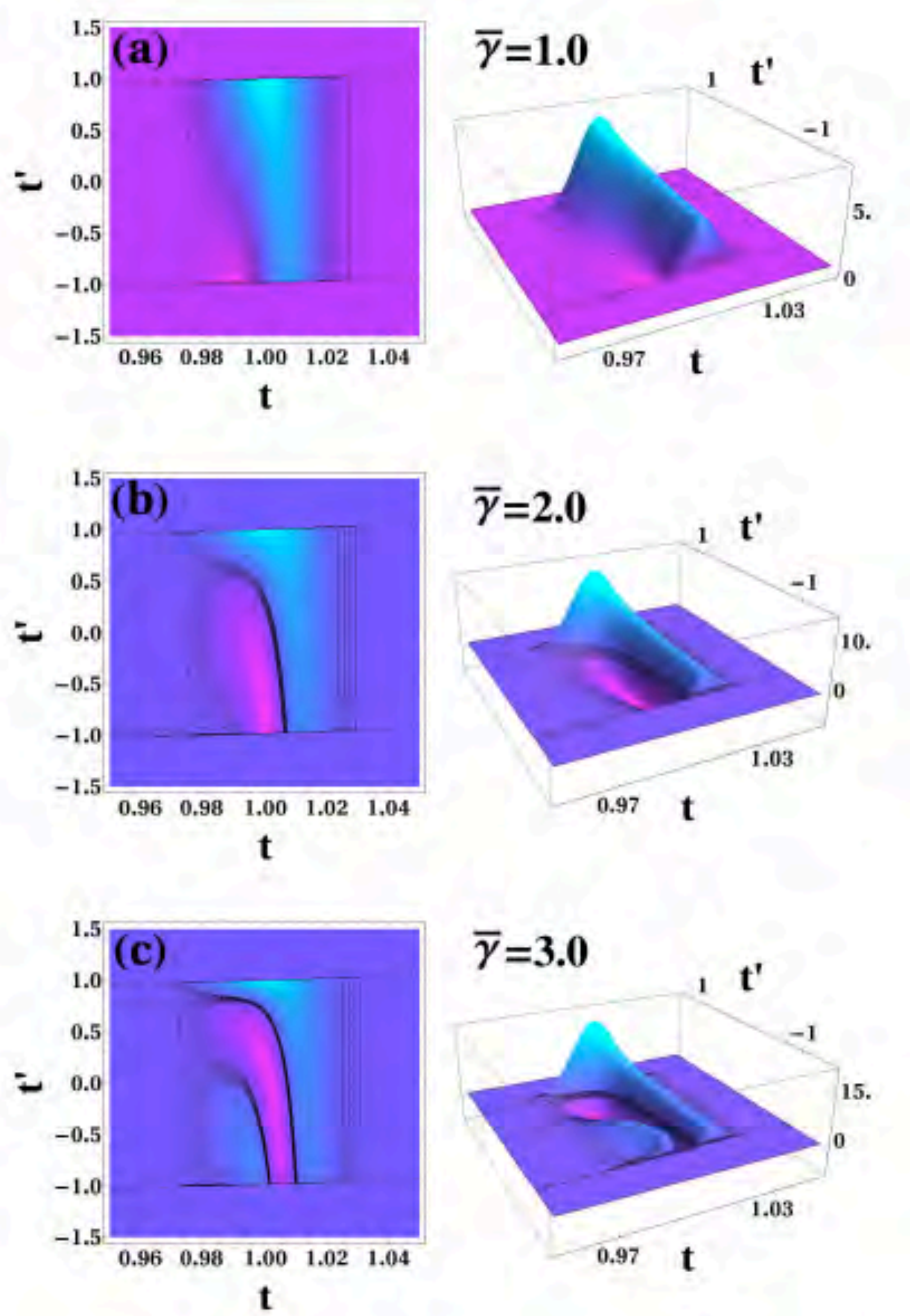
Optimum case: Pump velocity matches green signal velocity



pump strength, $\gamma \sqrt{\frac{L}{\left(\frac{1}{v_g} - \frac{1}{v_b}\right)}}$

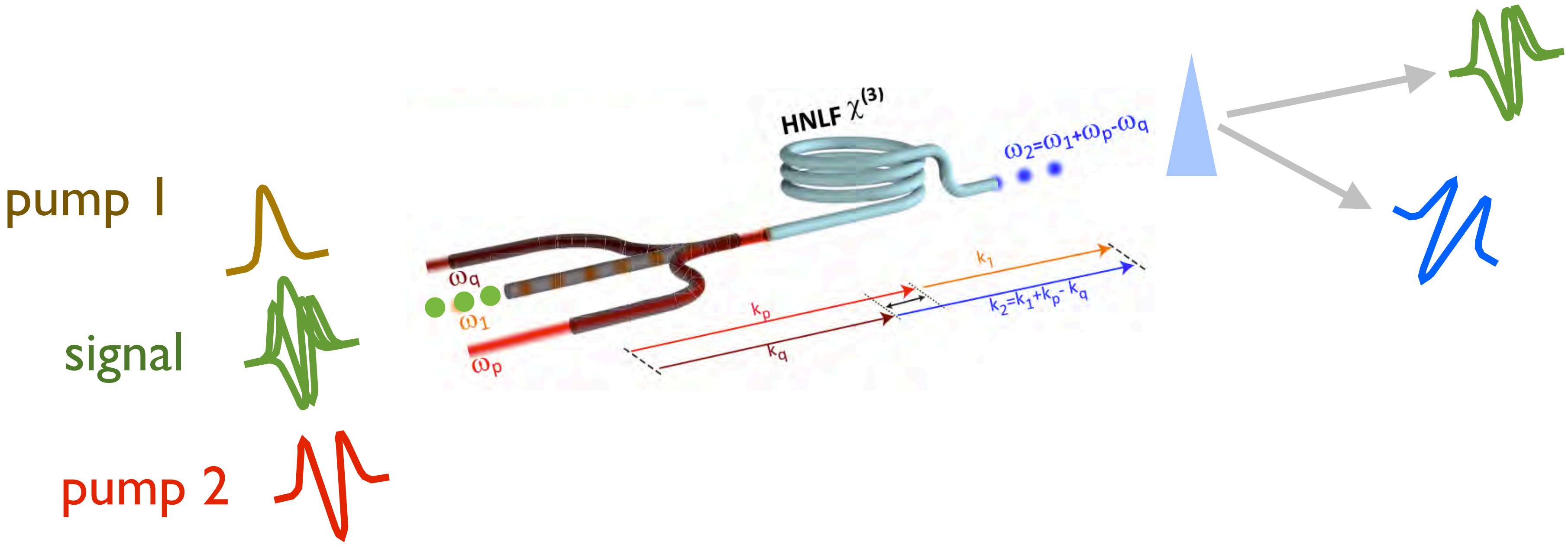
Origin of limited Selectivity: oscillations in the Green function make it non-separable.

Consequence of ‘Rabi oscillations’ between blue and green.



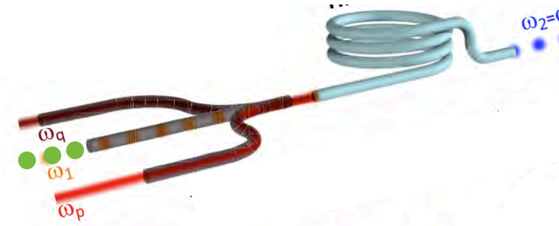
Four-wave Mixing

One pump selects the input mode shape;
Other pump determines the output mode shape.



CM, LM, MR, KR, PRA 053829 (2012)

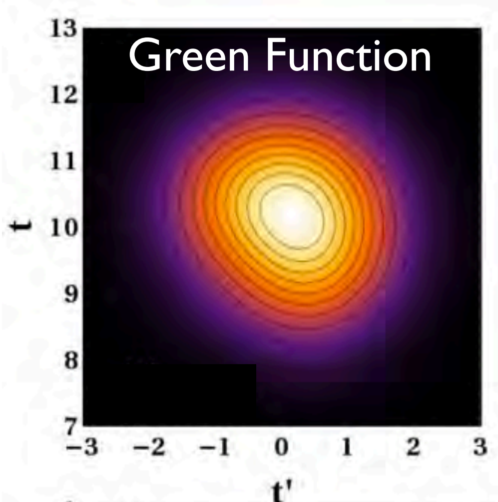
Four-Wave Mixing

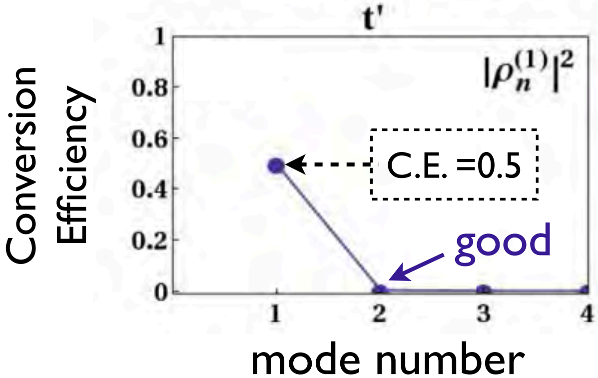


Much the same as TWM, with the shape of the medium replaced by the shape of the second pump.

Optimum case: pump 1 velocity matches green signal velocity and pump 2 matches blue signal velocity. Complete collision occurs.

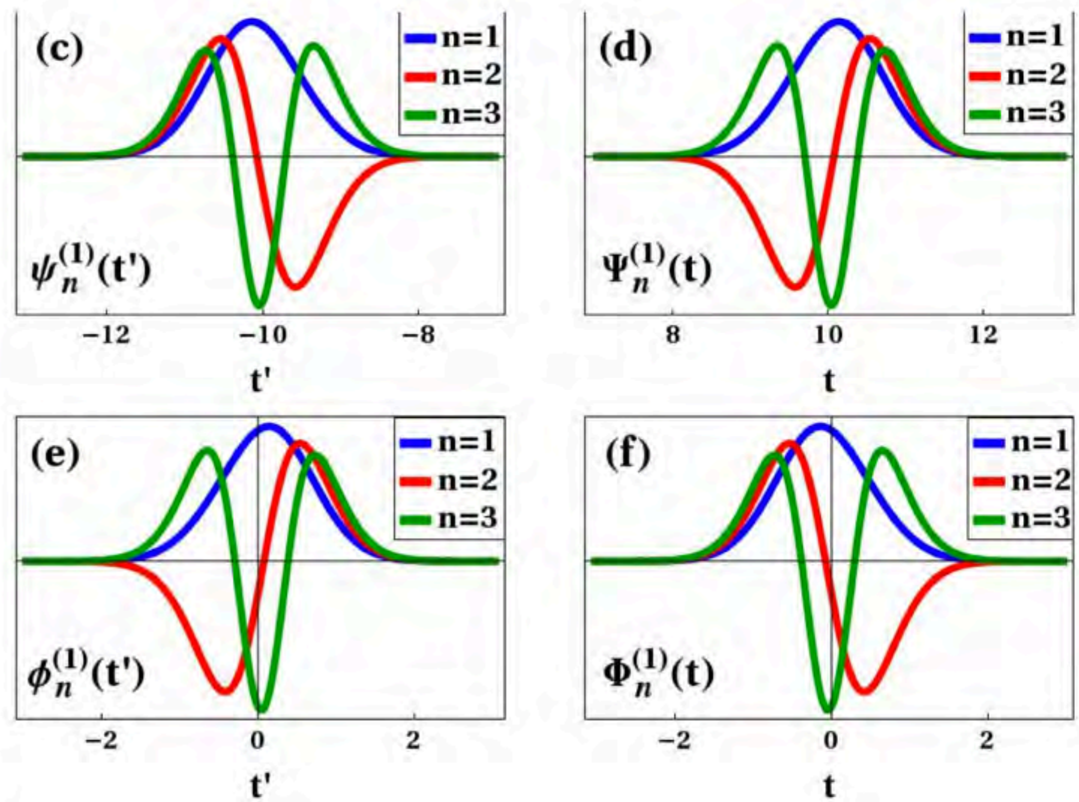
$\bar{\gamma} = 0.83$





Schmidt modes: input

Schmidt modes: output

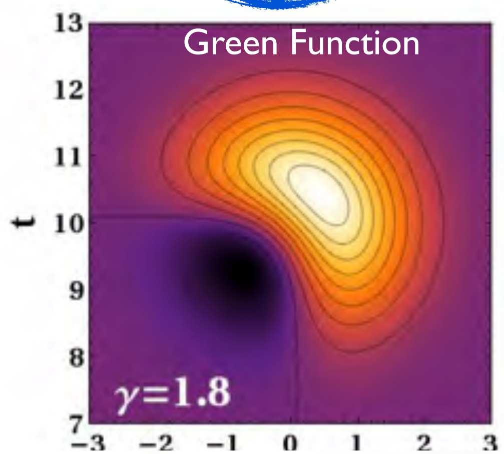


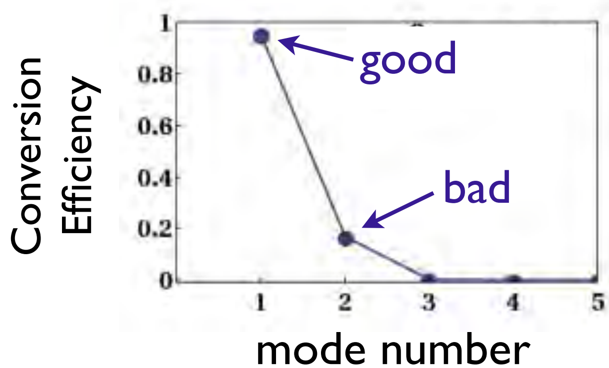
Selectivity ~ 0.5

increase $\bar{\gamma}$

Four-Wave Mixing

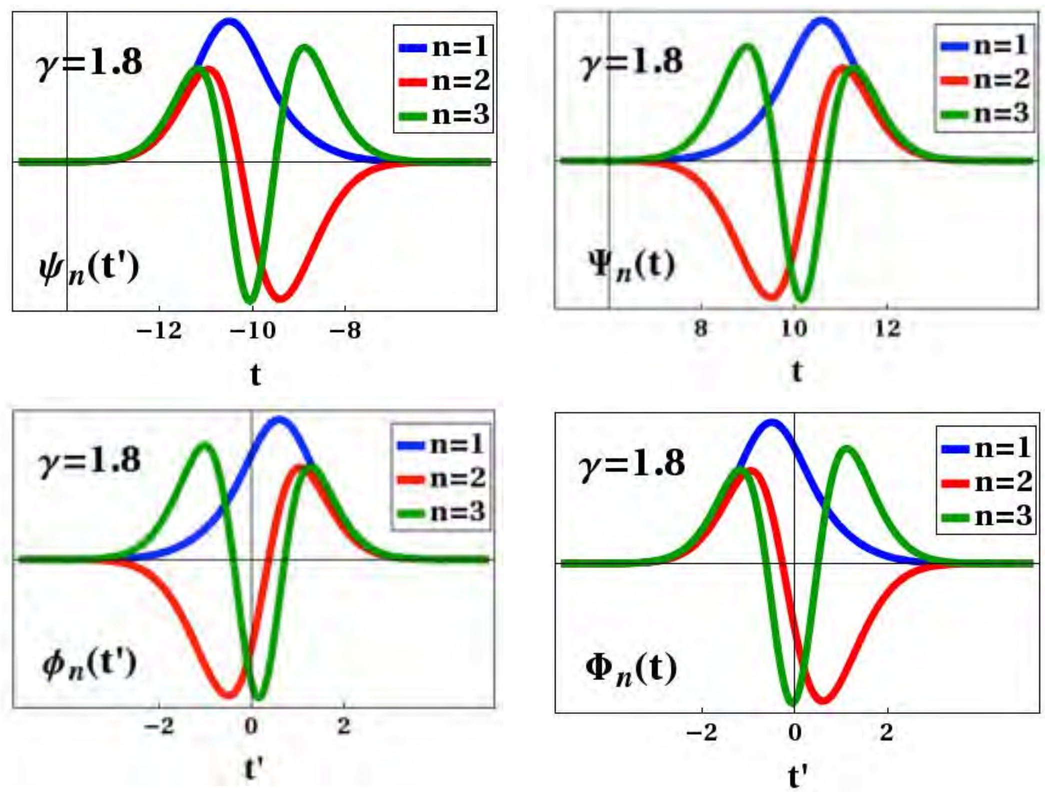
$\bar{\gamma} = 1.8$





Schmidt modes: input

Schmidt modes: output



Selectivity ~ 0.7

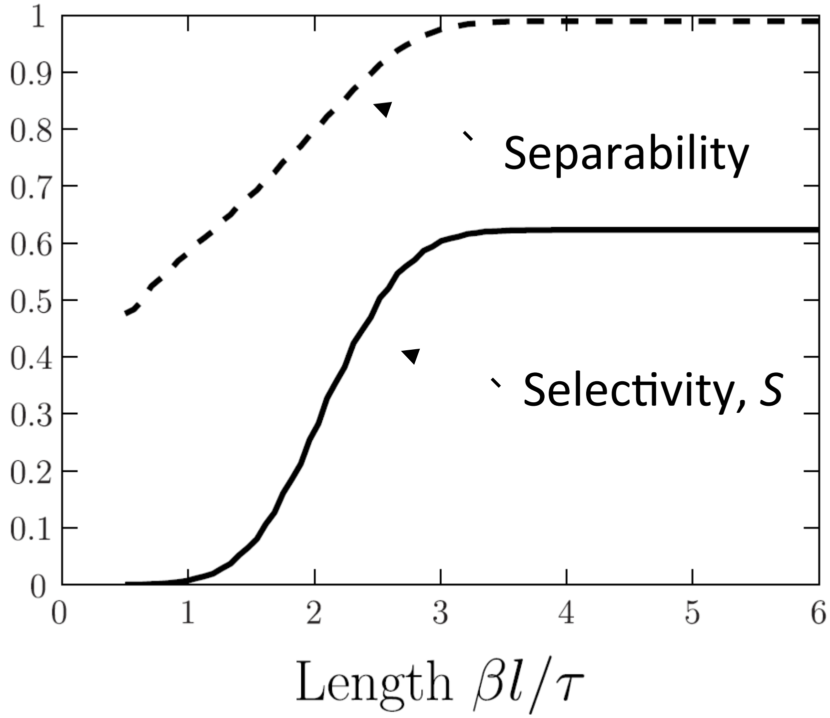
Four-Wave Mixing

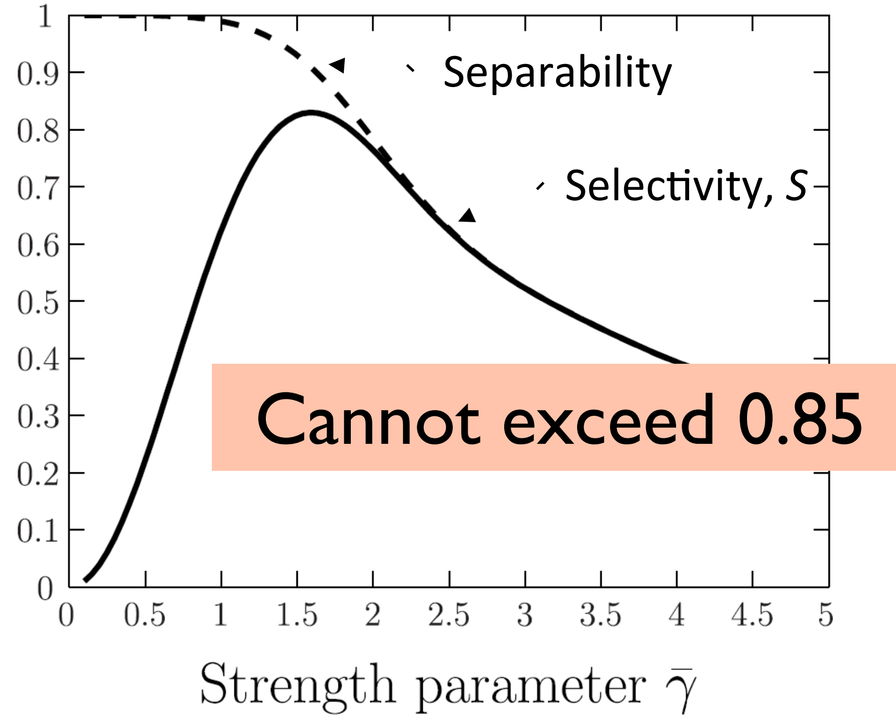
$$\eta_n = |\rho_n|^2 = conversion\ efficiency$$

$$S \equiv Selectivity \equiv separability \times \eta_{Target}$$

$$separability \equiv \frac{\eta_{Target}}{\sum_n \eta_n} \leq 1$$

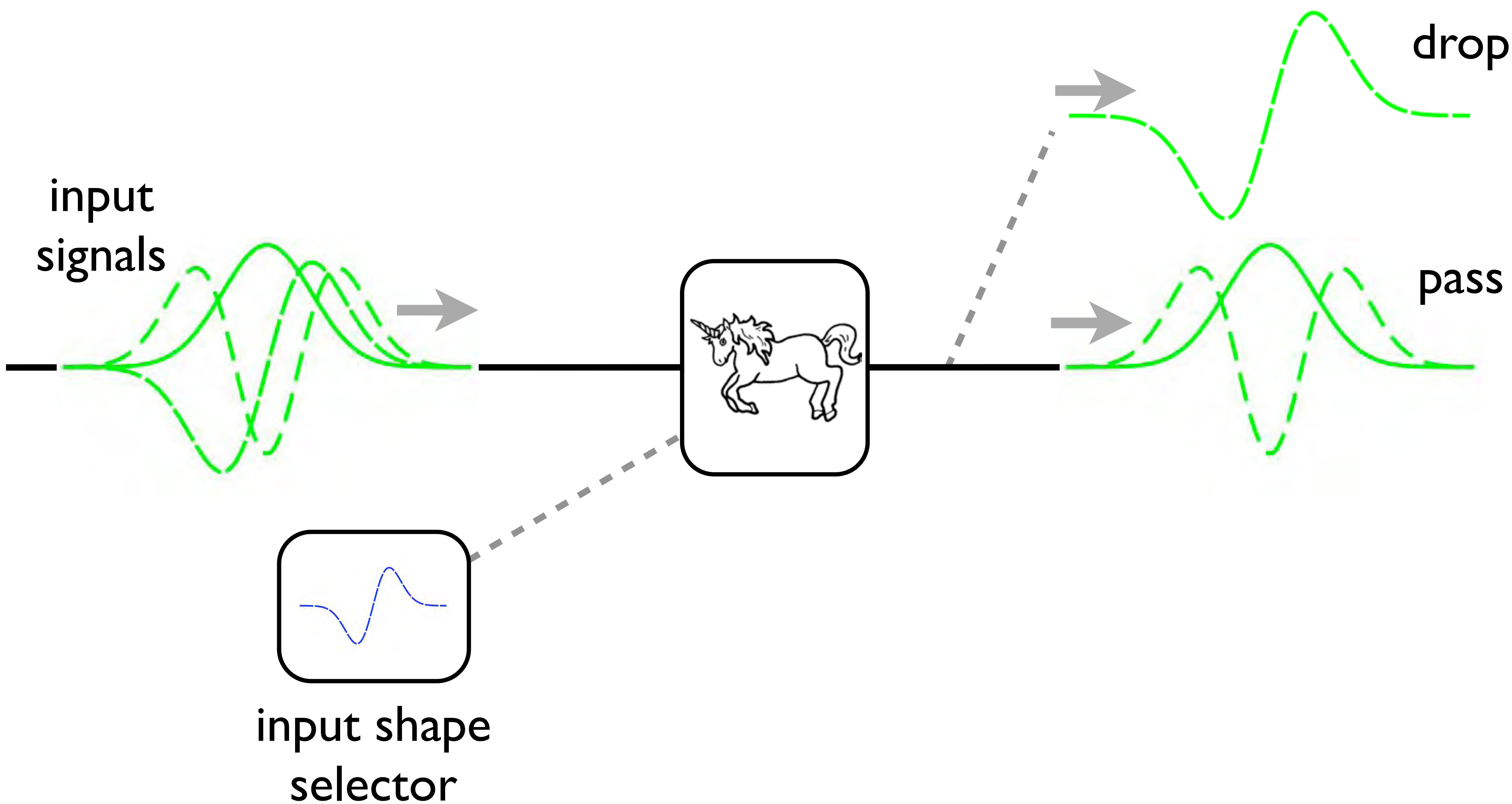
$$S = \frac{|\eta_{Target}|^2}{\sum_n \eta_n} \leq 1$$



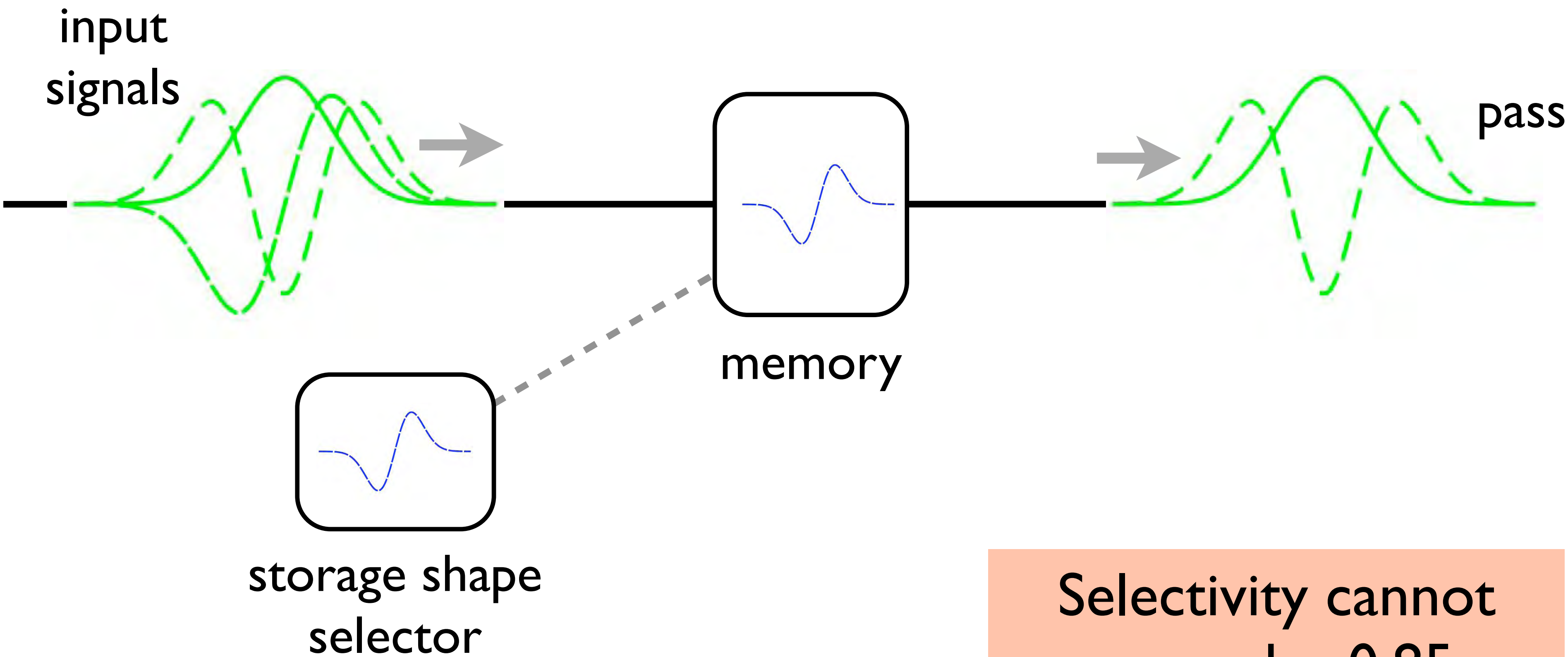


L Mejling, K Rottwitt, CM, DR, MR

Still Mythical: a drop device with 100% Selectivity



Atomic Ensemble Quantum Memory with Temporal-Mode Selectivity



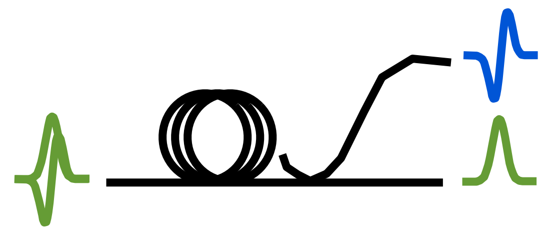
Selectivity cannot exceed ~ 0.85

J Nunn et al (2007)

"Mapping broadband single-photon wavepackets into an atomic memory," J. Nunn, I. A. Walmsley, M. G. Raymer, K. Surmacz, F. C. Waldermann, Z. Wang, and D. Jaksch, Phys. Rev. A, 75, 011401R (2007)

Quantum conversion between near-frequency channels, for Quantum Internet

Temporal-mode-selective routing, shaping of single-photon qubits. Pulse-shape-division multiplexing with temporally orthogonal codes.



Dileep Reddy, University of Oregon

C. J. McKinstrie, Bell Laboratories

Lasse Mejling and Karsten Rottwitt
Technical University of Denmark

NSF

unicorn