Нелинейная динамика фотонов в квантовой оптике

Александр Солнцев и Андрей Сухоруков

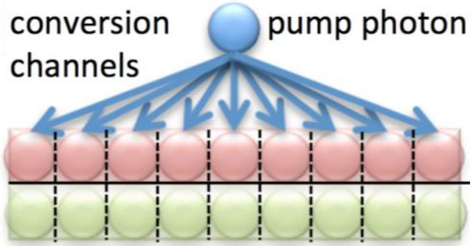
School of Mathematical and Physical Sciences
University of Technology Sydney
Sydney, Australia

Nonlinear Physics Centre,
Research School of Physics and Engineering,
Australian National University, Canberra, Australia

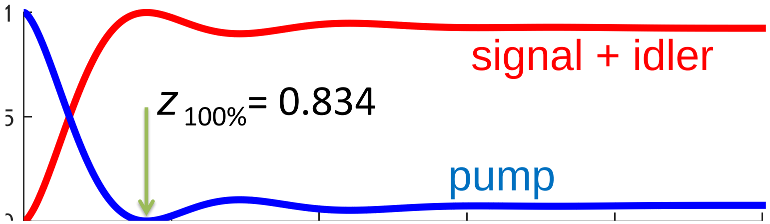
Outline

- Introduction: 1 to 2 photon conversion in nonlinear media

- Rabi oscillations – or not?
- Frequency dispersion and decay to a continuum

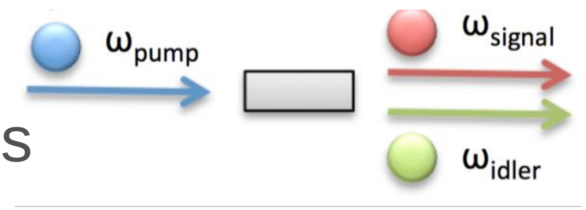


- Prediction of complete conversion
- Conclusion and outlook

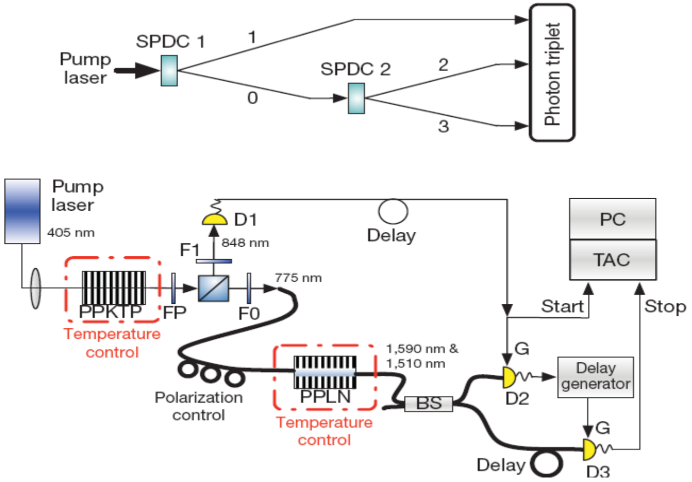


Single photon conversion

- produce heralded multi-photon entanglement
- create optically switchable quantum circuits
- implement an improved form of down-conversion with reduced higher-order effects
- generation of photon triplets

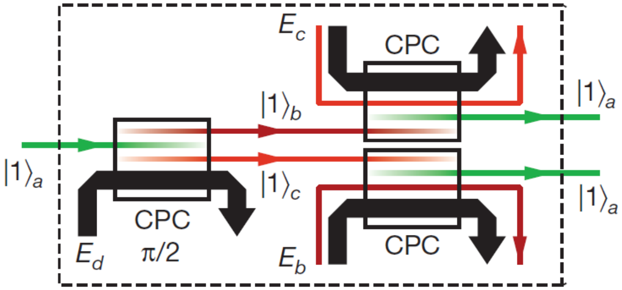


photon triplets generation



H. Hubel, D.R. Hamel, A. Fedrizzi, S. Ramelow, K.J. Resch, and T. Jennewein, Nature Photonics Lett. 466, 601-603 (2010).

deterministic photon doubling

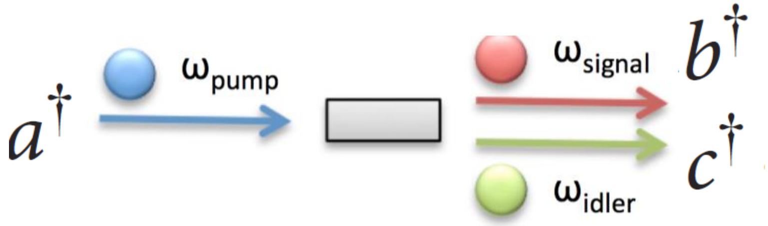


N. K. Langford, S. Ramelow, R. Prevedel, W. J. Munro, G. J. Milburn and A. Zeilinger, Nature **478**, 360-363 (2011).

doi:10.1038/nature10463

Efficient quantum computing using coherent photon conversion

N. K. Langford[1,2,3], S. Ramelow[1,2], R. Prevedel[1,4], W. J. Munro[5,6], G. J. Milburn[7,1] & A. Zeilinger[1,2]



- Effective Hamiltonian in quadratic nonlinear media $\tilde{H} = \tilde{\gamma} a b^\dagger c^\dagger + \tilde{\gamma}^* a^\dagger b c$

- Experimental realization with four-wave mixing in Kerr-type (cubic) nonlinear media

$$H = \gamma a b^\dagger c^\dagger d + \gamma^* a^\dagger b c d^\dagger$$

- The fourth wave is a high-power coherent state, providing effective quadratic nonlinearity with $\tilde{\gamma} \propto \gamma E$

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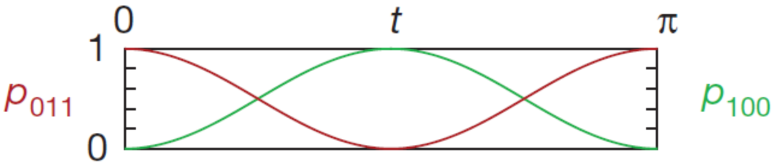
- Predict Rabi-like oscillation between single and biphoton states

$$|\psi(t)\rangle = \cos(\Gamma t)|100\rangle + i\frac{\tilde{\gamma}}{|\tilde{\gamma}|}\sin(\Gamma t)|011\rangle$$



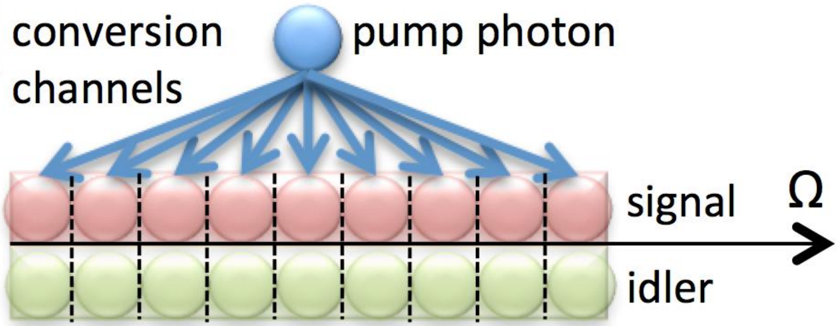
- Experimentally achieved $\Gamma t \approx 10^{-4}$

- How to improve efficiency?

- **Our work: nontrivial effect of frequency dispersion!**

One and two-photon states

pump photon converts into signal and idler photons



Conversion channels: different frequency detunings between signal and idler

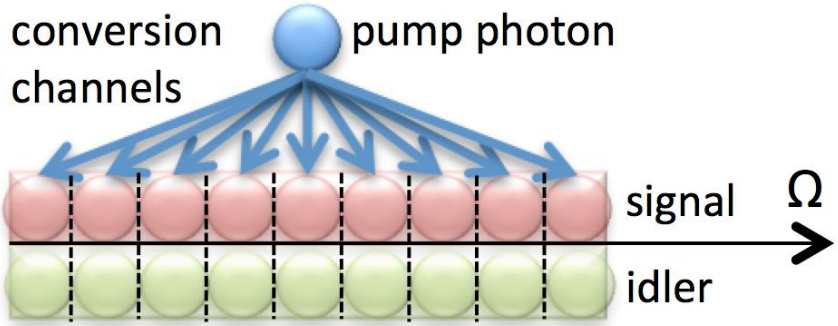
$$\omega_p \rightarrow \omega_s + \omega_i;$$

$$\omega_s = {}^{\omega_p}/_2 + \Omega; \quad \omega_i = {}^{\omega_p}/_2 - \Omega.$$

Single input photon and biphoton states

$$|\psi\rangle = U(z)a_p^{+}(\omega_p)|0\rangle + \int d\Omega V(\Omega, z)a_s^{+}(\omega_s)a_i^{+}(\omega_i)|0\rangle$$

Evolution of one and two-photon states



Single input photon and biphoton states

$$|\psi\rangle = U(z)a_p^+(\omega_p)|0\rangle + \int d\Omega V(\Omega,z)a_s^+(\omega_s)a_i^+(\omega_i)|0\rangle$$

Coupled-mode Schrödinger–like equations for pump $U(z)$ and bi-photon $V(\Omega,z)$ functions

$$\frac{dU}{dz} = -\chi\int d\Omega V(\Omega,z) + i\beta_U(\omega_p)U(z),$$

$$\frac{dV(\Omega,z)}{dz} = \chi U(z) + i\beta_V(\omega_p,\Omega)V(\Omega,z)$$

χ - nonlinear susceptibility coefficient,
β_U - the pump mode propagation constant in a single waveguide,
β_V - signal and idler mode propagation constant.

Conversion rate proportional to square root of the biphoton bandwidth!

Analogy with decay to a continuum

Vladimir M. Akulin

Coherent Dynamics of Complex Quantum Systems

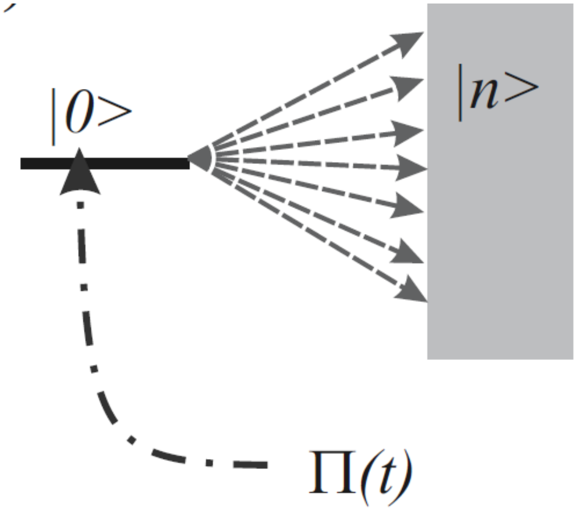
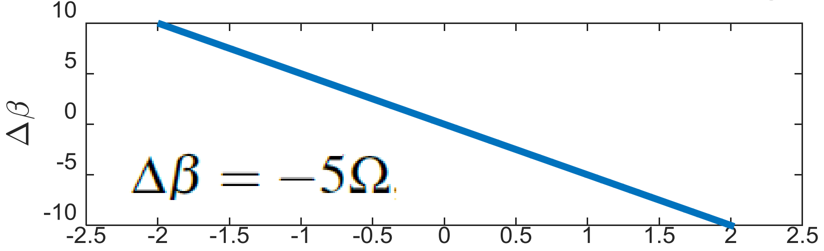
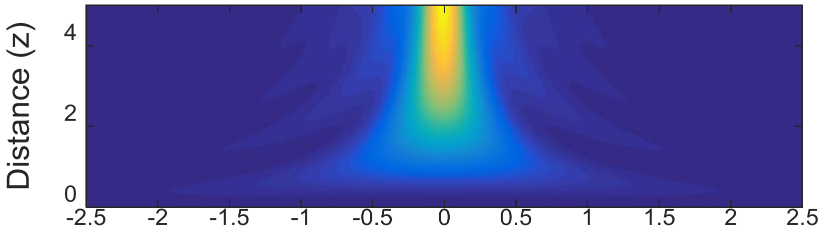


Fig. 3.5. Level–band problem.

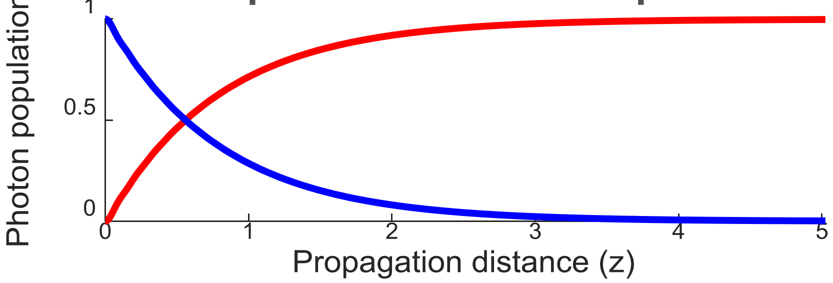
Linear dispersion $\Delta\beta = \beta_U - \beta_V$



Biphoton spectrum



One photon and biphoton

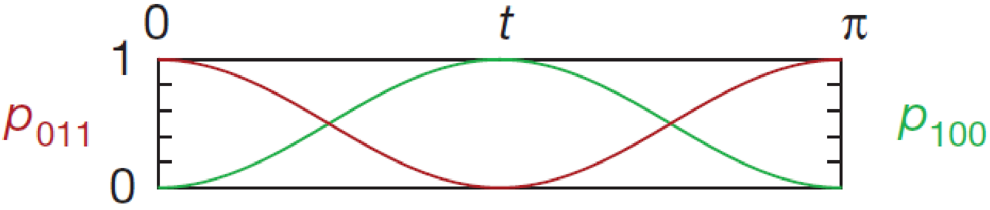


- Exponential decay of one-photon state for linear dispersion
- No Rabi oscillations!

Why no Rabi oscillations?

- Rabi oscillations predicted in N. K. Langford, S. Ramelow, R. Prevedel, W. J. Munro, G. J. Milburn and A. Zeilinger, Nature **478**, 360-363 (2011).

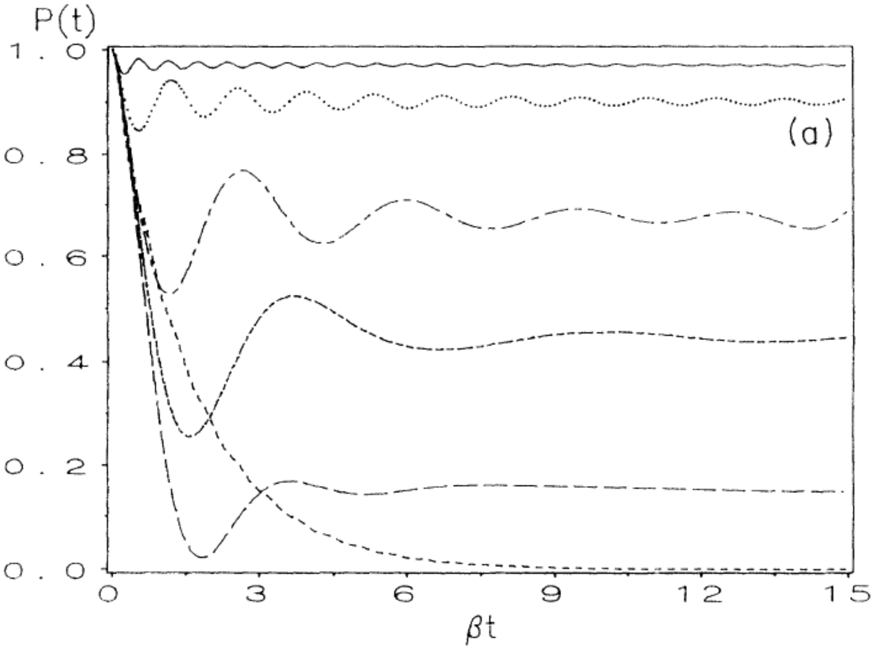
$$|\psi(t)\rangle = \cos(\Gamma t)|100\rangle + i\frac{\tilde{\gamma}}{|\tilde{\gamma}|}\sin(\Gamma t)|011\rangle$$



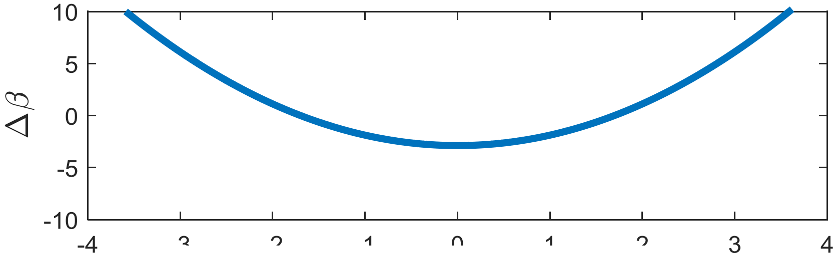
- Dispersion excluded from consideration, $\tilde{H} = \tilde{\gamma} a b^\dagger c^\dagger + \tilde{\gamma}^* a^\dagger b c$ assuming phase-matching regime
- But photon conversion is spontaneous process, goes to states both at and near phase-matching!

Making dispersion more flat: quadratic shape

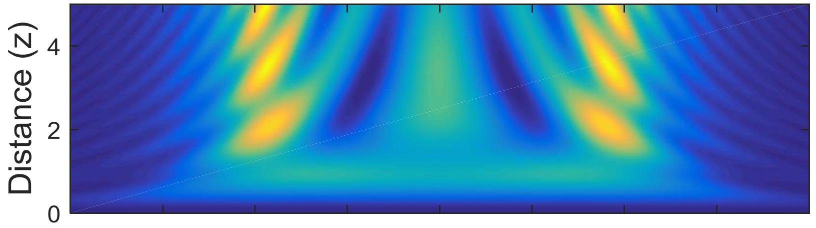
- S. John and T. Quang, “Spontaneous emission near the edge of a photonic band-gap,” Phys. Rev. A 50, 1764 (1994).



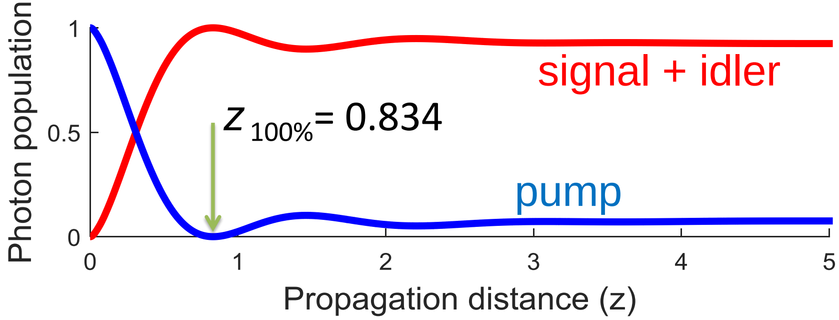
Dispersion $\Delta\beta = \Omega^2 - 2.88$



Biphoton spectrum

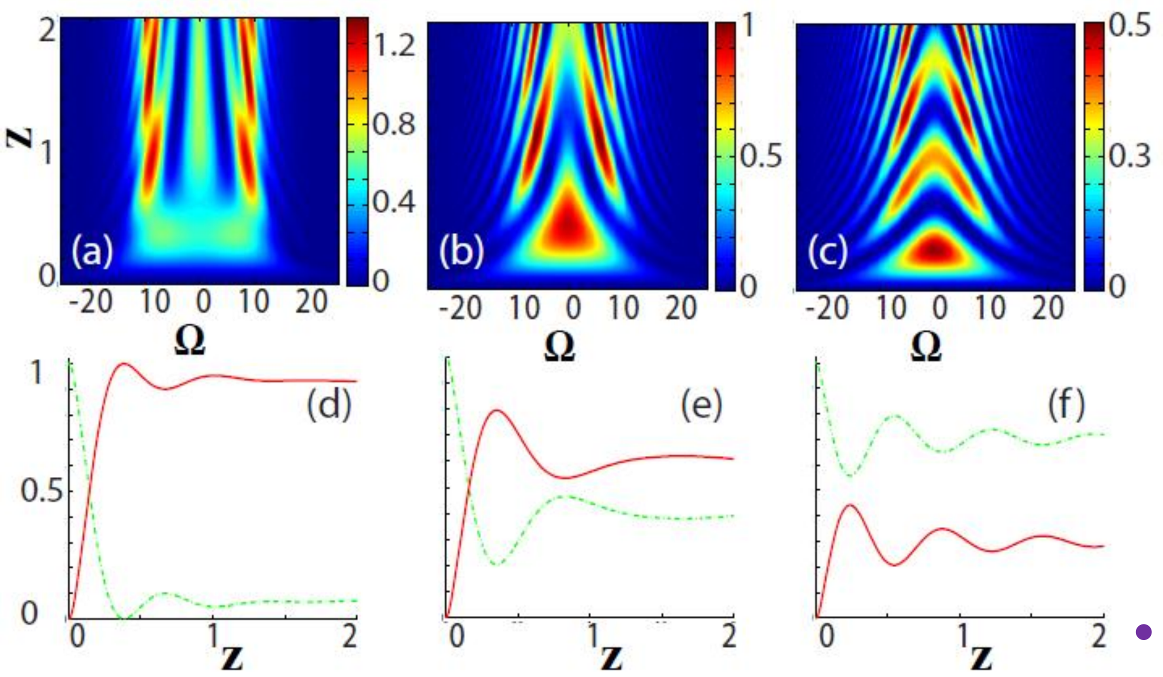


One photon and biphoton



- Identify new regime of complete conversion at finite propagation distance for optimal dispersion!

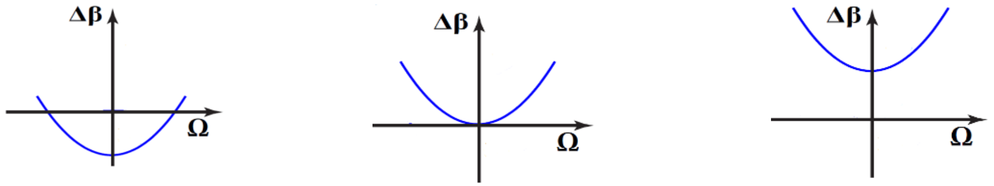
Complete photon conversion



Spectral biphoton intensity

Total single and biphoton intensities

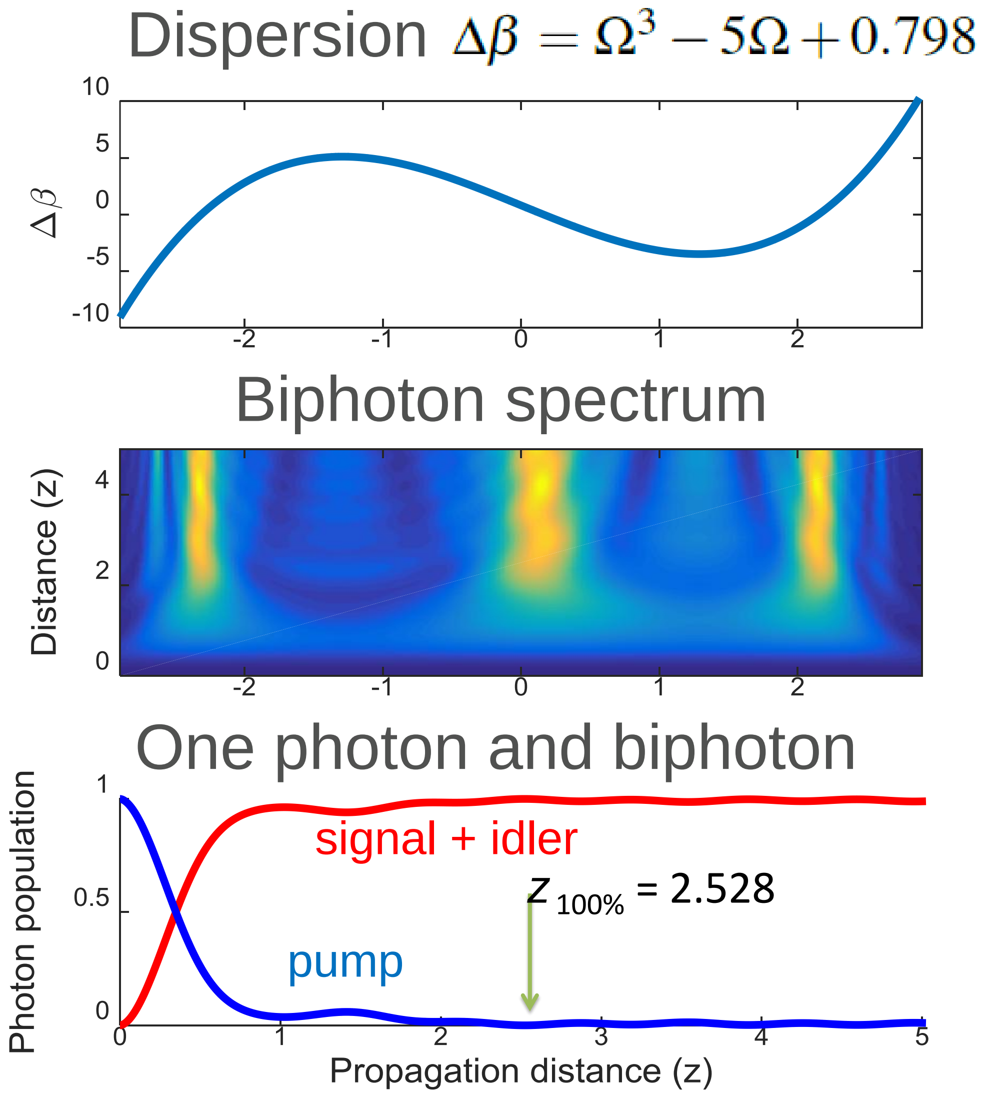
- Non-monotonious decay enables complete conversion
- Broad spectrum: nontrivial temporal correlations with ultrashort features



Different phase mismatch

Complete conversion for cubic dispersion

- Complete conversion at a particular distance
- Very high conversion at longer distances
- More robust compared to quadratic dispersion



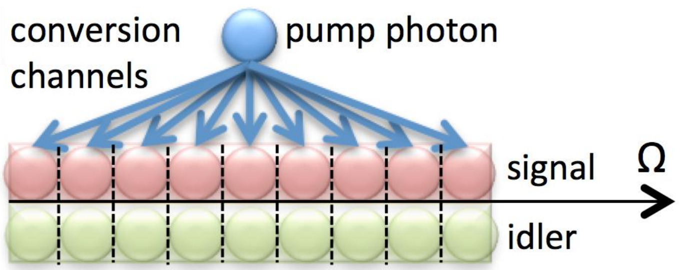
Dispersion $\Delta\beta = \Omega^3 - 5\Omega + 0.798$

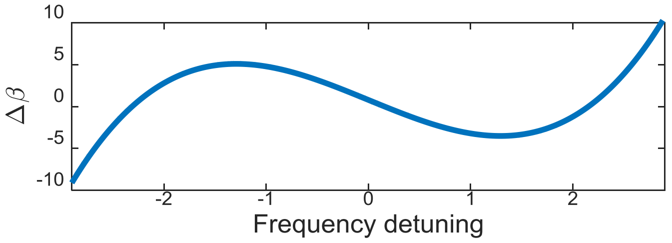
Biphoton spectrum

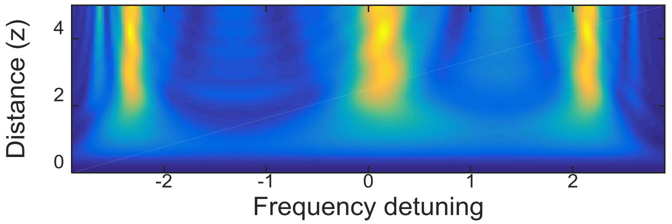
One photon and biphoton

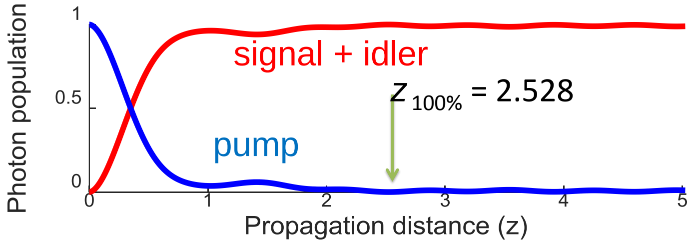
Outlook: towards complete 1 to 2 photon conversion

- Highly nonlinear fiber or waveguide
- Design for broadband phase-matching: conversion rate proportional to square root of the biphoton bandwidth
- Engineer dispersion around phase-matching: achieve complete conversion
- Next step: use broadband control laser pulses $\boldsymbol{\omega_p + \omega_c \rightarrow \omega_s + \omega_i}$
- *Antonosyan, Solntsev, Sukhorukov, Opt. Comm. 327, 22 (2014); submitted (2017)*









UTS

School of Mathematical and Physical Sciences

Технологический Университет Сиднея (UTS)
Alexander.Solntsev@uts.edu.au

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