16 June 2014, Virginia

Accessing the frequency resource of broadband bi-photons

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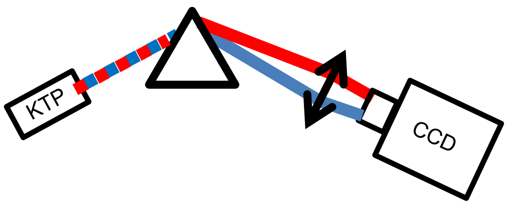
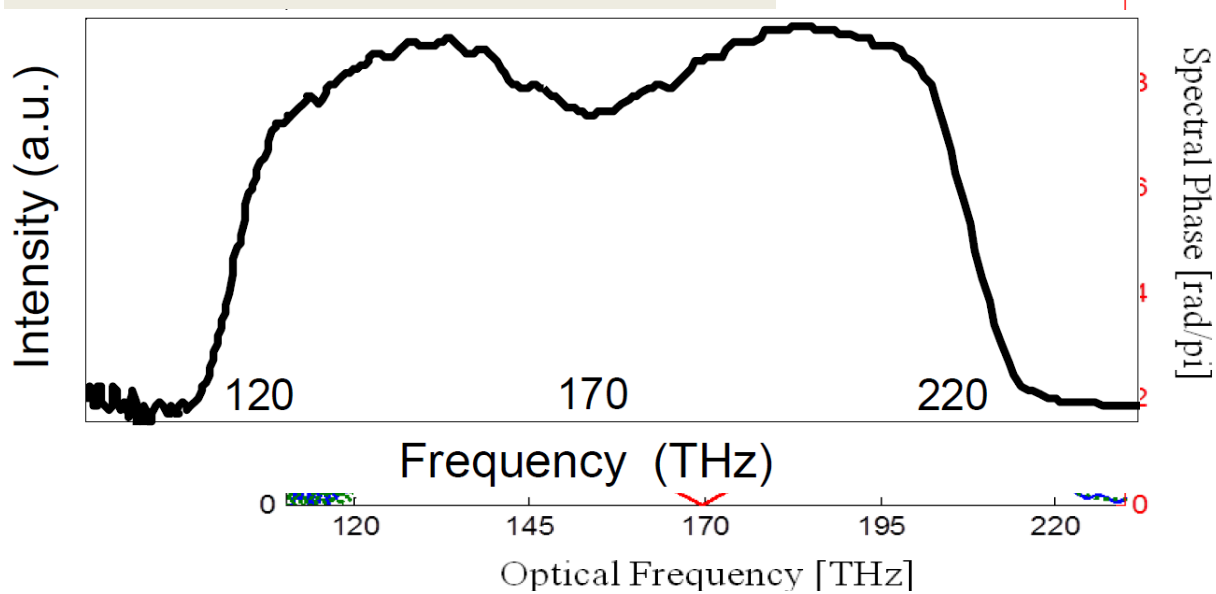
$$ ₪ ISF, EU-IRG,
Kahn Foundation

Broadband Bi-photons Full Quantum Wave Function

7 milliseconds!





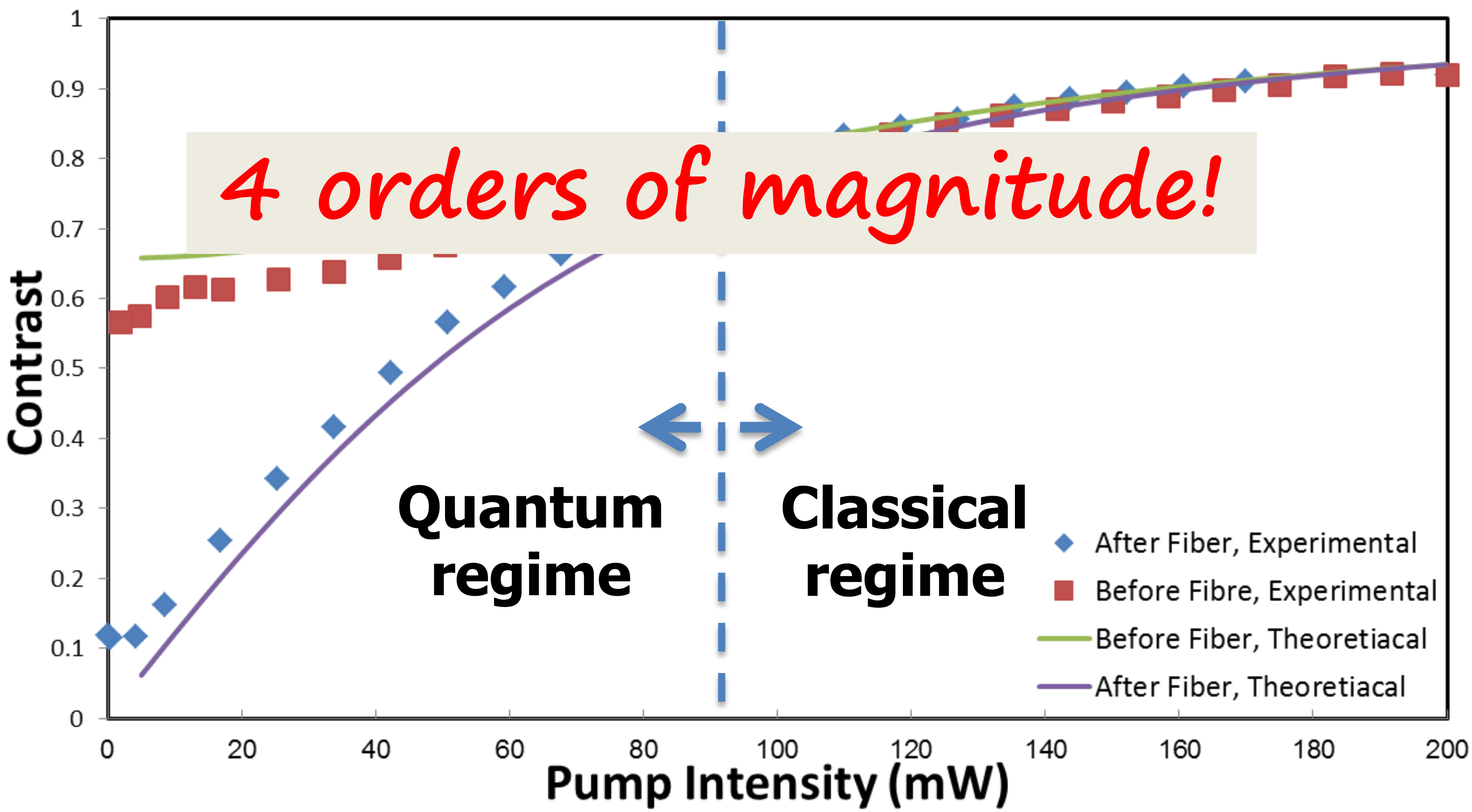
- **Amplitude**
- **Phase**
- **Purity**
- **Sum frequency Correlation**

~10^8 photons/detection-time

New J. Phys. **16, 053012 (2014)**

Classical to Quantum Transition

The contrast as a function of the attenuation.



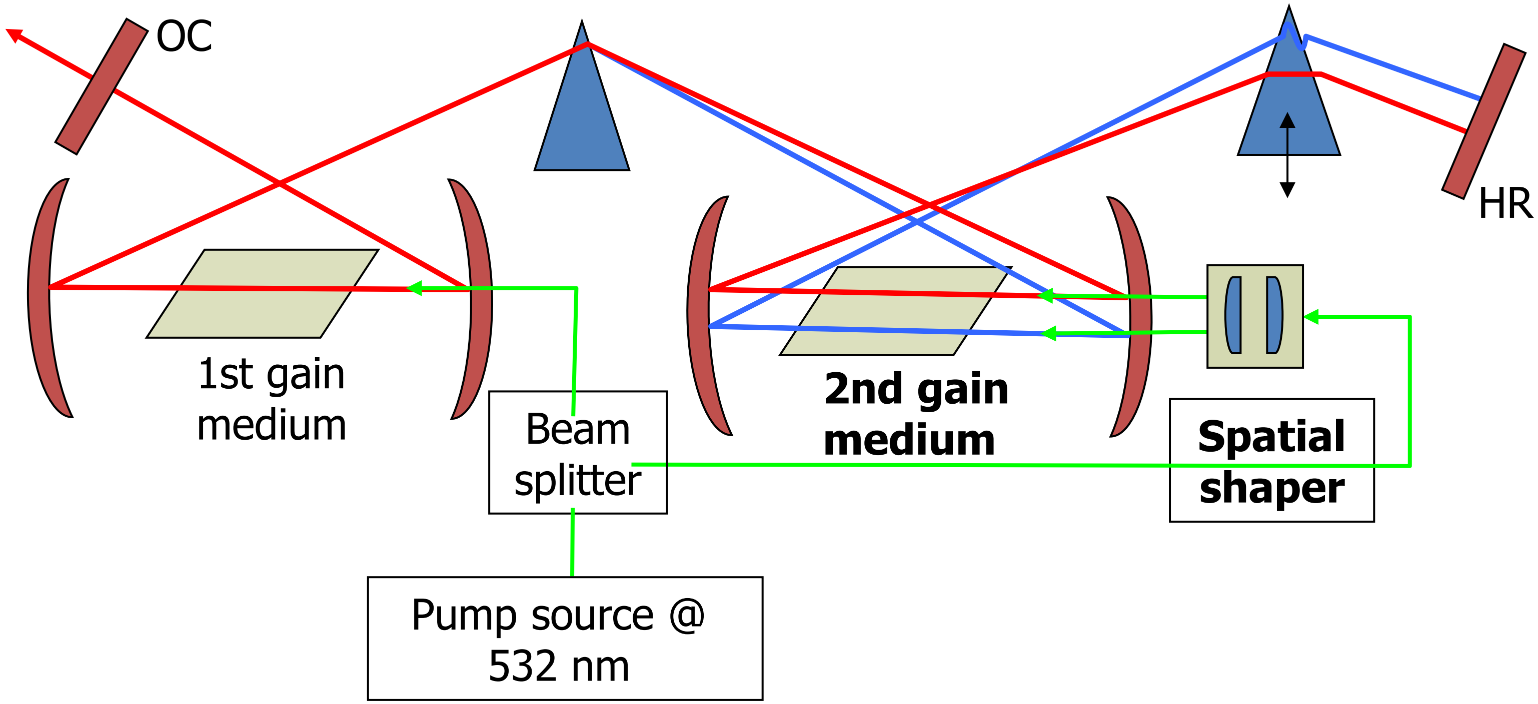
Outline

- **Time-energy entangled photons are great !**
- **Why no one uses them ?** (How to measure ?)
- Efficient measurement with a **quantum bi-photon interference**
- **Fringe contrast as a nonclassical witness**
- **The classical-to-quantum transition**
- New effects - **FWM with imaginary gain**
- (if time permits) **An efficient source of high-power broadband two-mode squeezing (OPO)**
- **Conclusions**

Group Overview

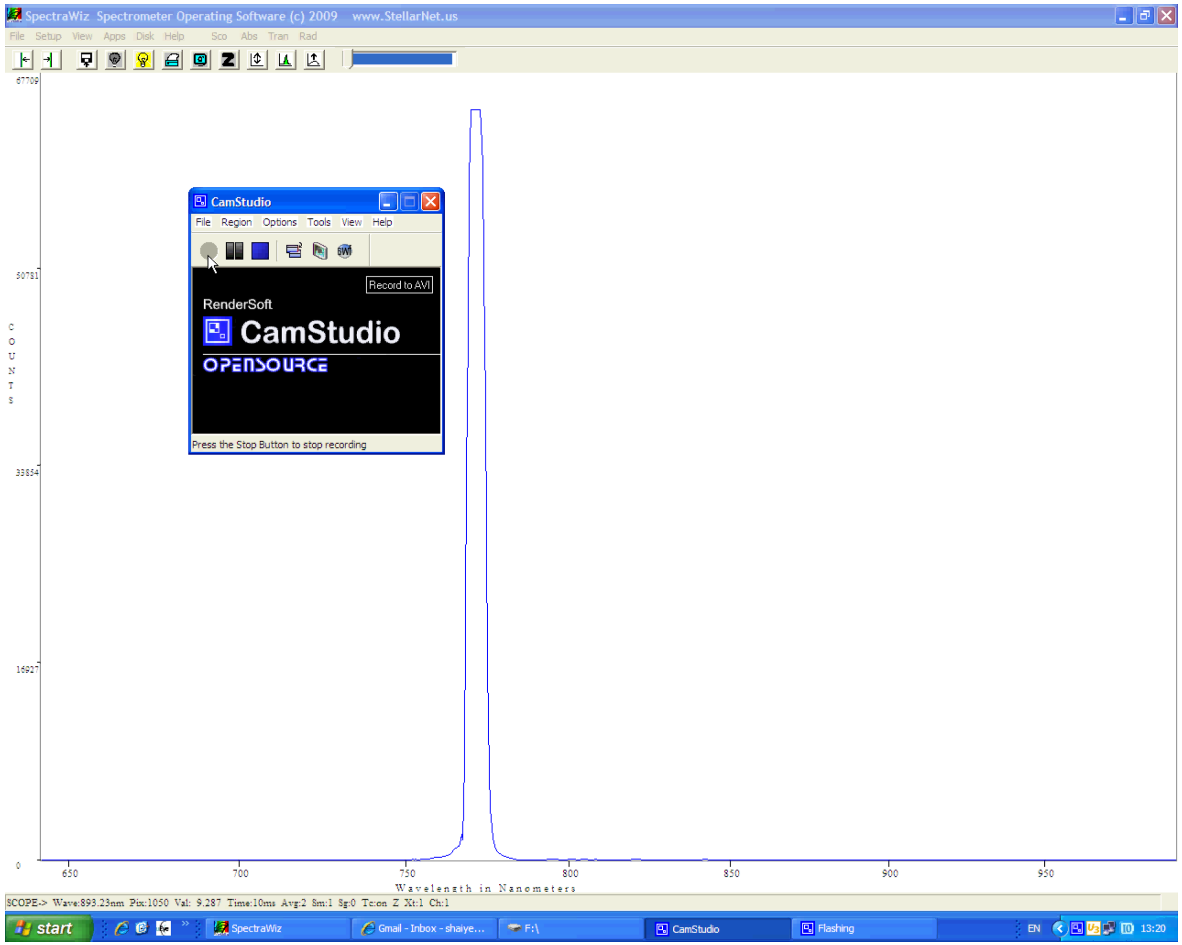
- Frequency comb sources
  - Control of mode-locking physics
  - New configurations of Kerr-lens mode locked lasers
- Precision measurements of ultrafast dynamics in molecules
- Ultra-broadband, time-energy correlated light – Sources and applications
  - Bi-photons (low power) and coherent squeezed light (high power)

Controlling the comb spectrum by Gain shaping



Spatial shape of pump = **Spectral** shape of gain

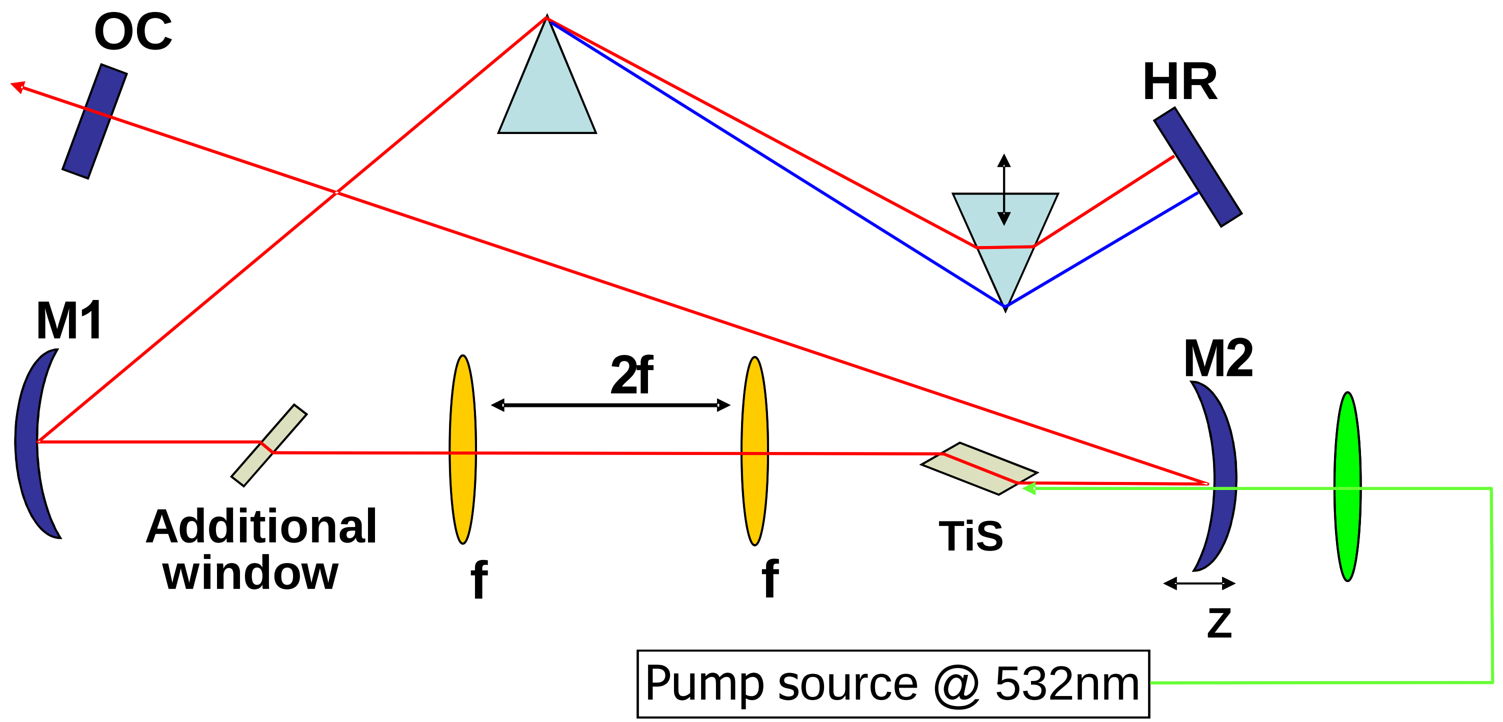
Manipulating the Mode-locking spectrum in real time



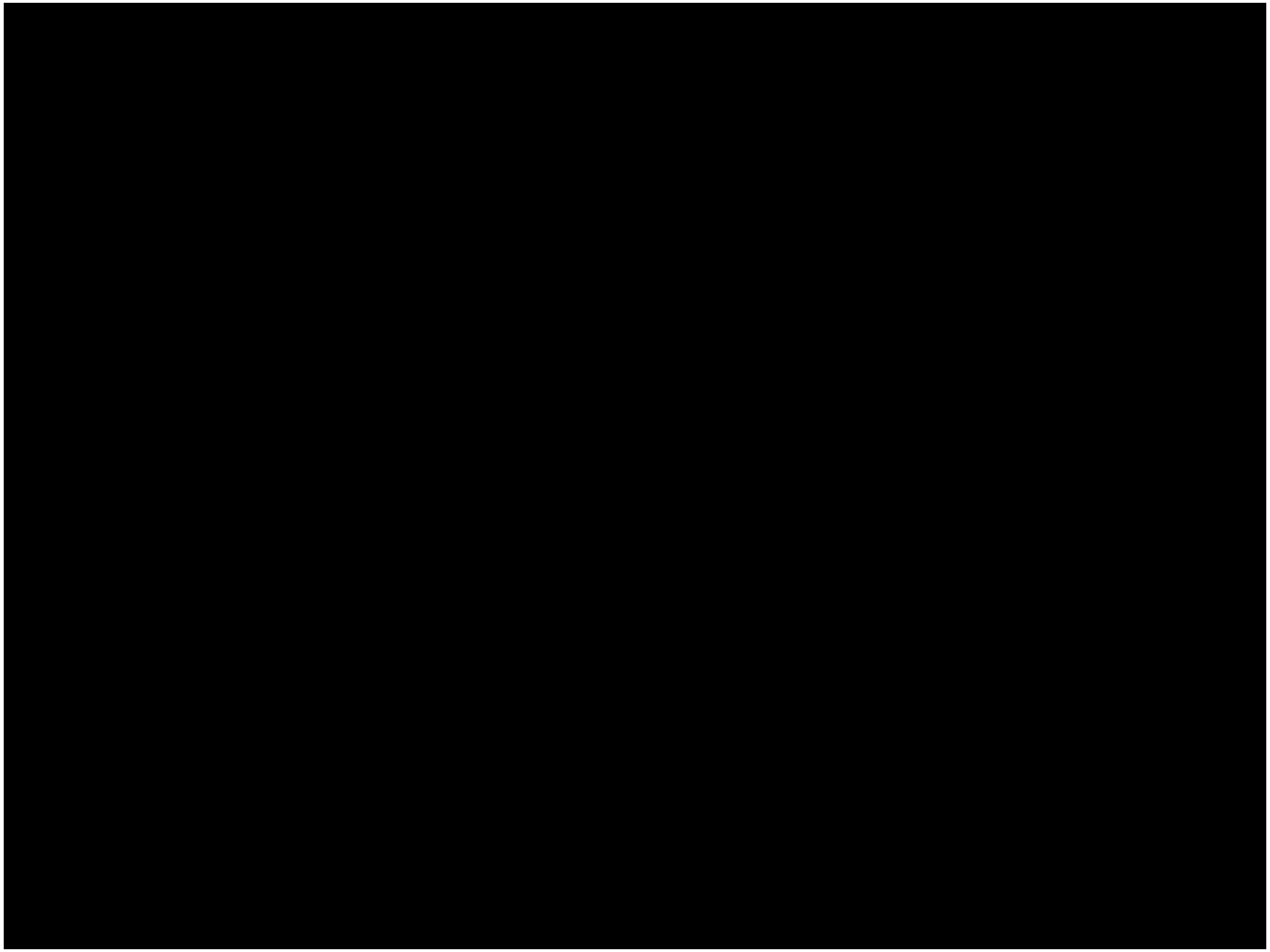
Optics Express **20**, 9991-9998 (2012),

"**Intra-cavity gain shaping of mode-locked Ti:Sapphire laser oscillations**"

Mode locking below the CW threshold

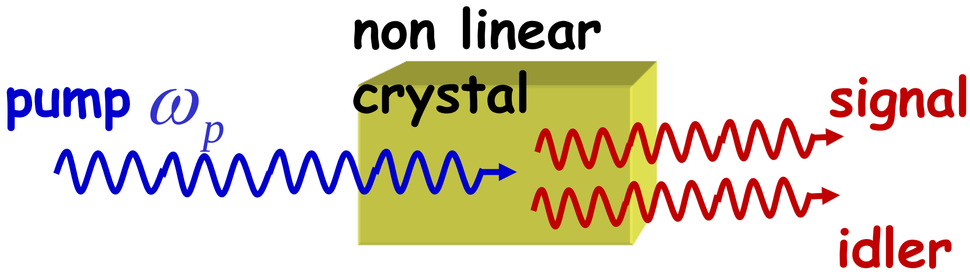


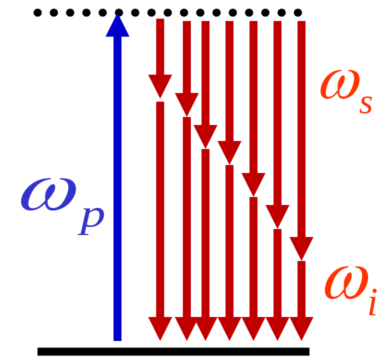
Mode locking below the CW threshold



Opt. Express **21**, 19040–19046 (2013),
"**Mode locking with enhanced nonlinearity - a detailed study**"

Time-Energy Entangled Photons

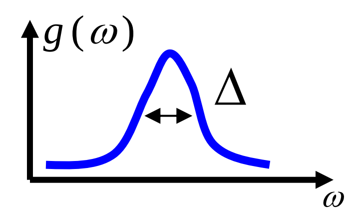




$$\omega_s + \omega_i = \omega_p \qquad\qquad \omega_s - \omega_i = ?$$

The two-photon state (monochromatic pump)

$$\left|\psi\right\rangle = \left|0\right\rangle + \varepsilon \int d\omega\, g(\omega) \left|1_{\omega_0-\omega}, 1_{\omega_0+\omega}\right\rangle$$



Entanglement

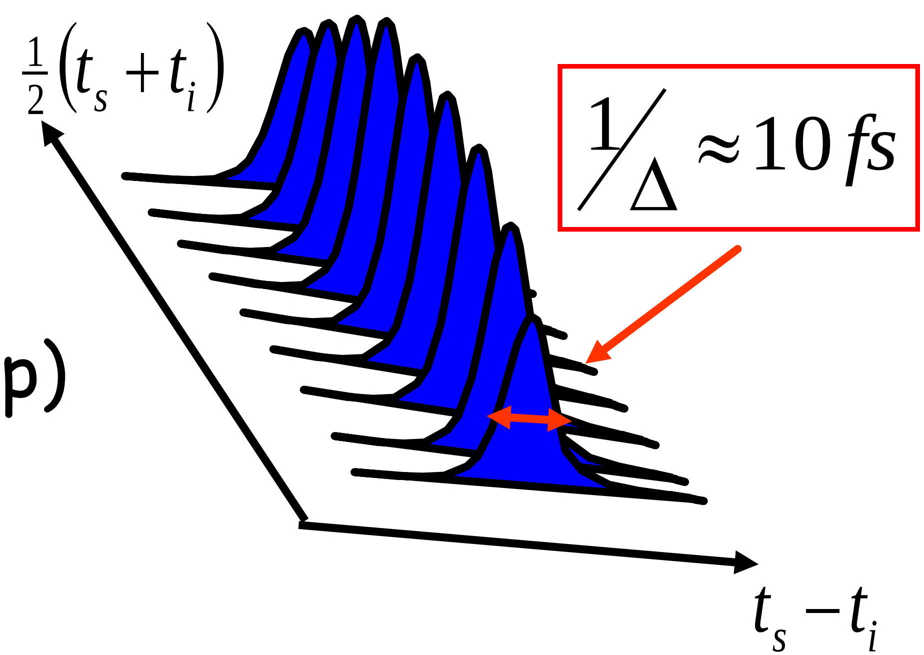
Time-Energy Correlation

$$\left|\psi\right\rangle = (1-\varepsilon)\left|0\right\rangle + \varepsilon\int d\omega\, g(\omega)\left|1_{\omega_{p/2}-\omega}, 1_{\omega_{p/2}+\omega}\right\rangle$$

uncertainty relation → $t_s + t_i = ?$ $\quad t_s - t_i \approx 1/\Delta$

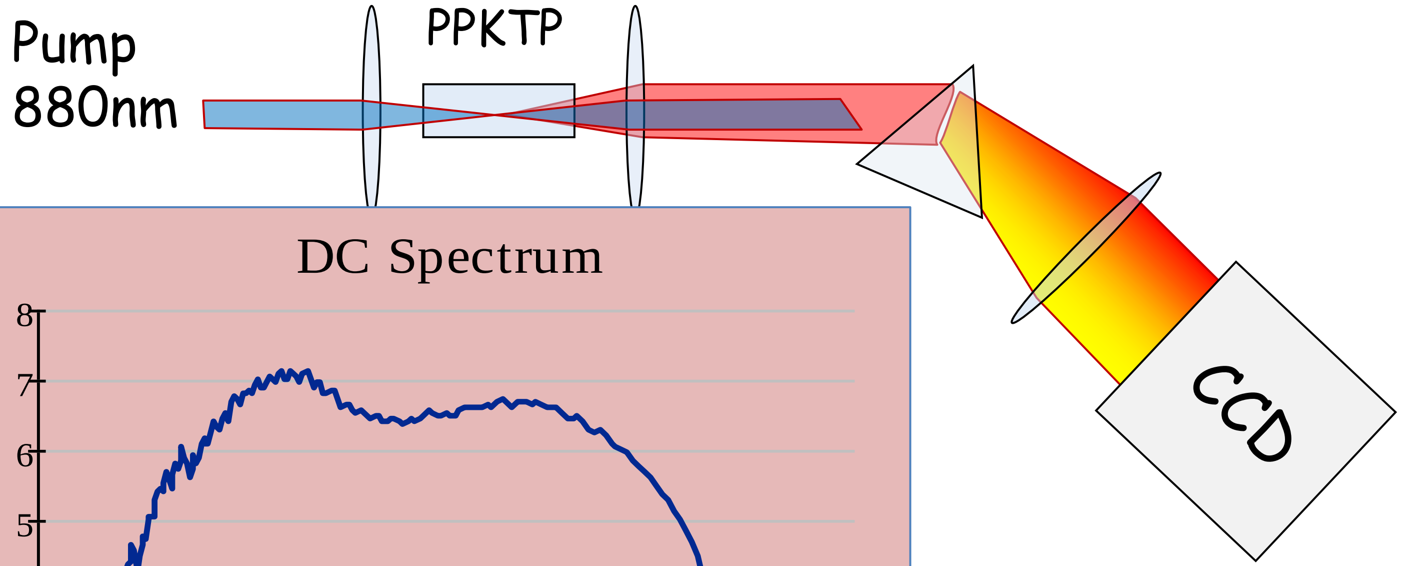
the two-photon wave function (monochromatic pump)

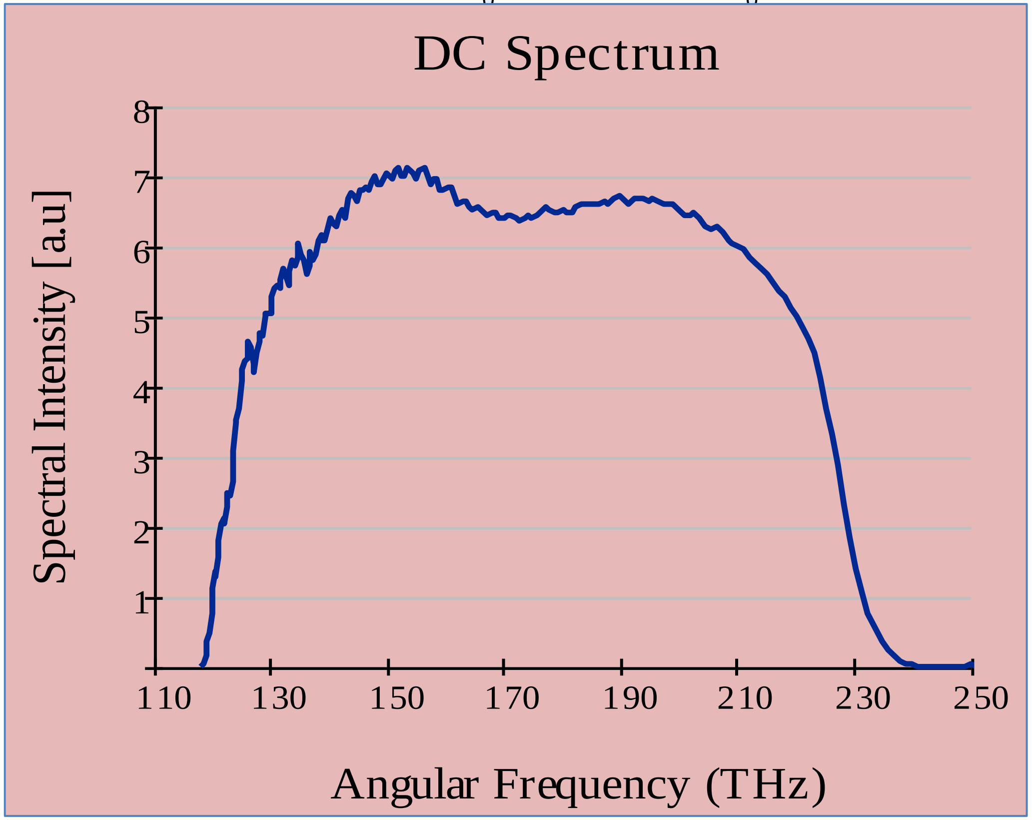
$$\Psi(t_s, t_i) \propto G(t_s - t_i)$$



Ultra-Broadband bi-Photons

Zero Dispersion !

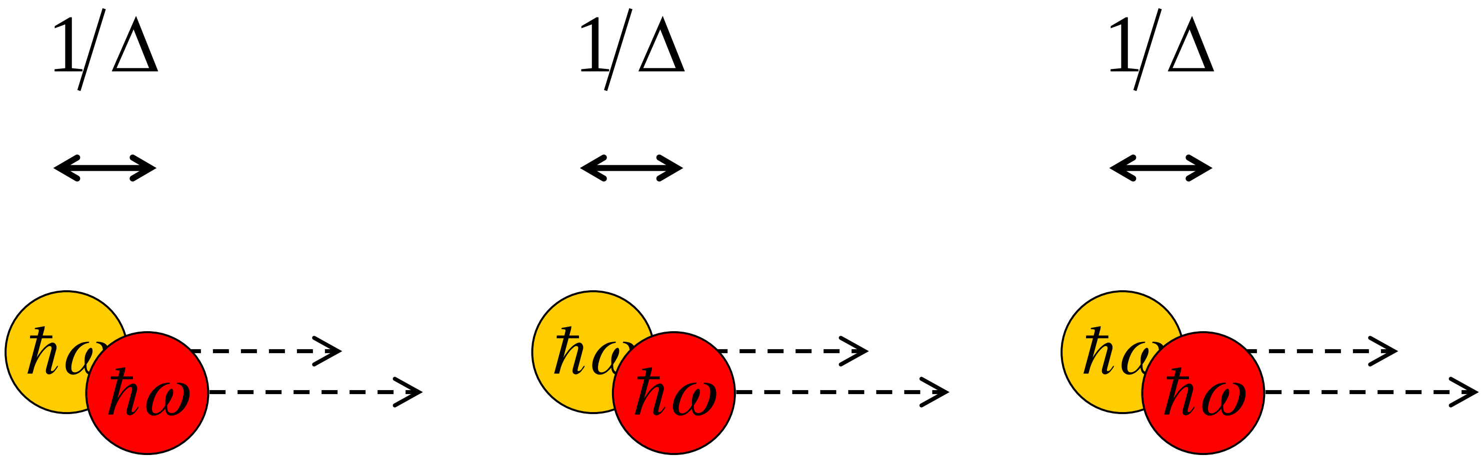




"Single cycle" bi-photons

Why ultra-broad photon pairs ?

<u>**Because there are so many of them !**</u>



$$\Phi_{\max} \approx \Delta \approx 10^{14}\, pairs/s \approx 12\,\mu W$$

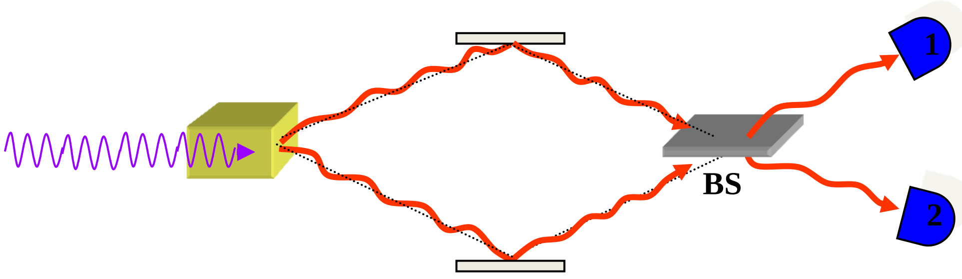
Why not?

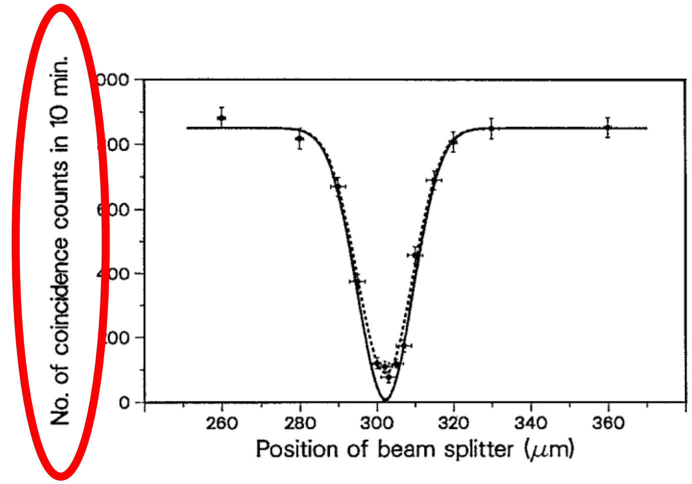
Direct detection does not work:

- Slow detectors cannot observe the sharp time-correlation
- Slow detectors = energy distinguishability

Need some other scheme

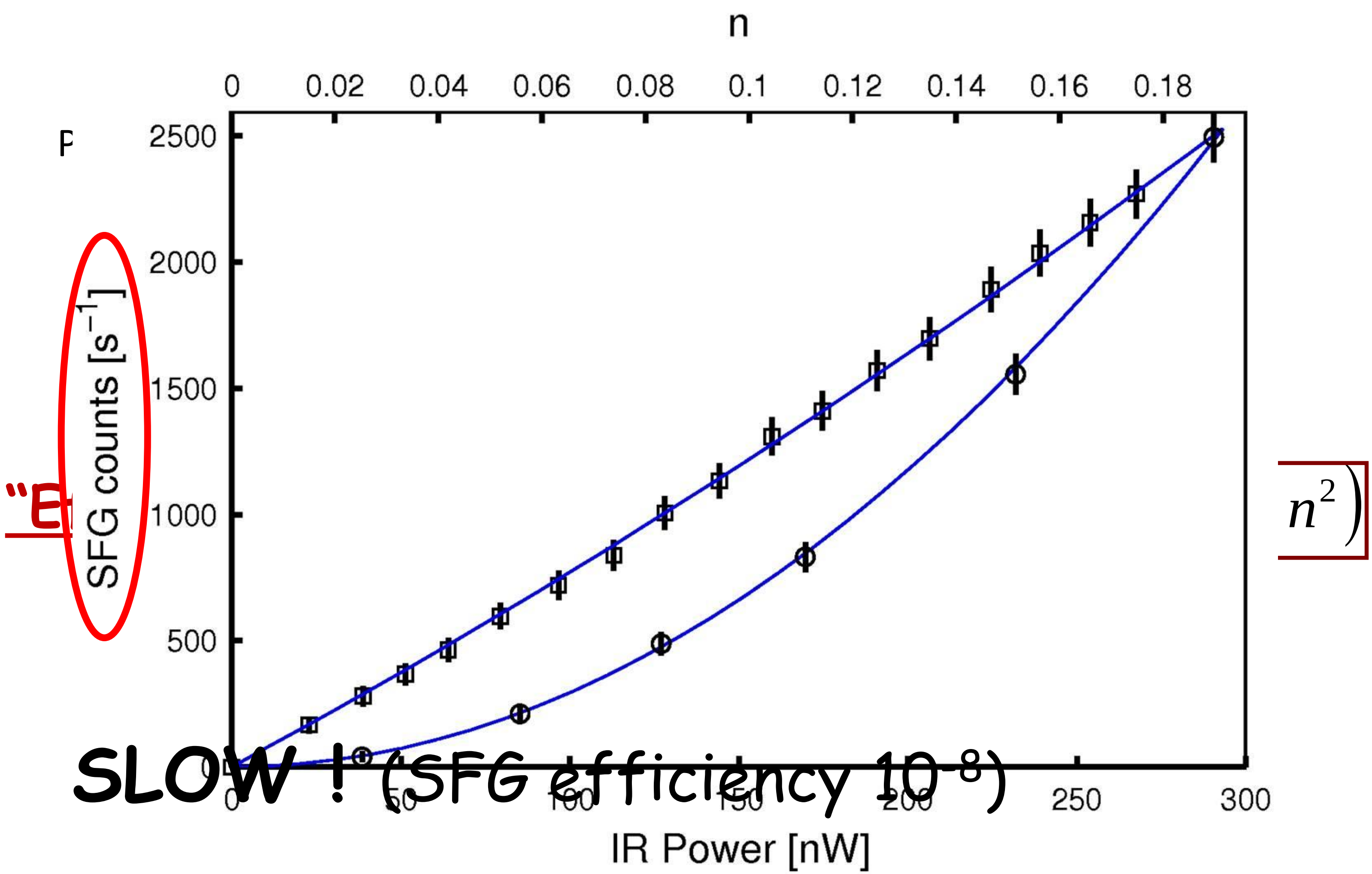
Measuring bi-photons - HOM





SLOW ! (coincidence limit <10^6 ph/s)

Measuring bi-photons - SFG

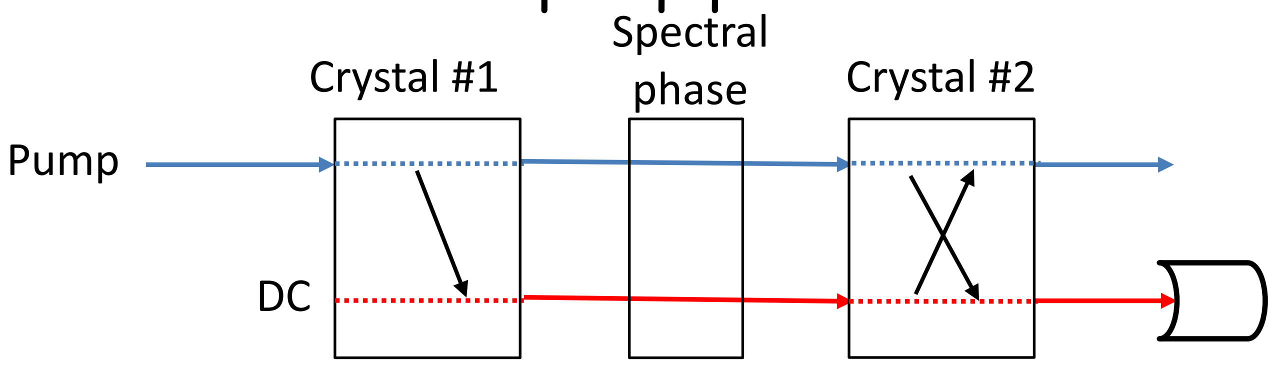


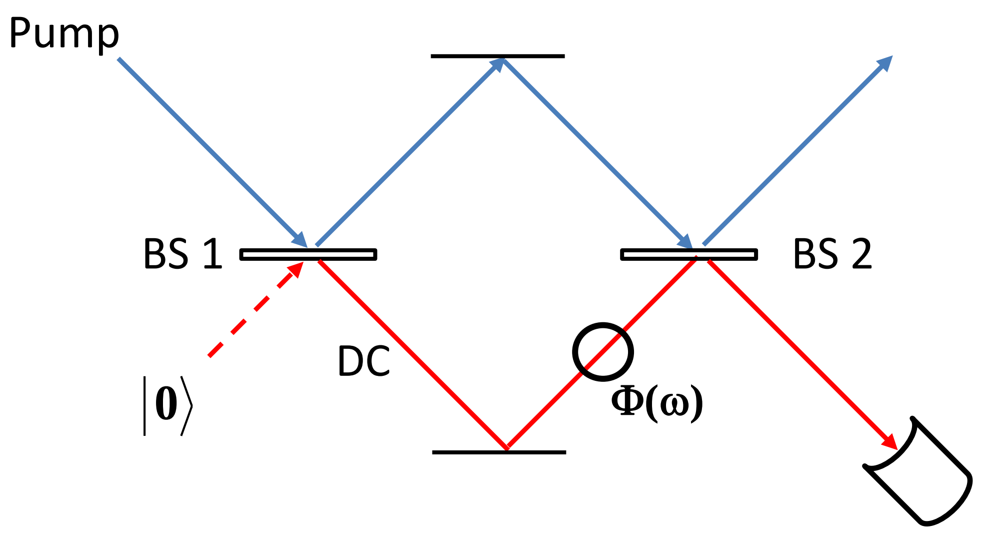
SLOW ! (SFG efficiency 10^{-8})

PRL **94**, 043602 (2005) , PRL **94**, 073601 (2005)

Quantum two-photon interference

What if we let the pump pass ?

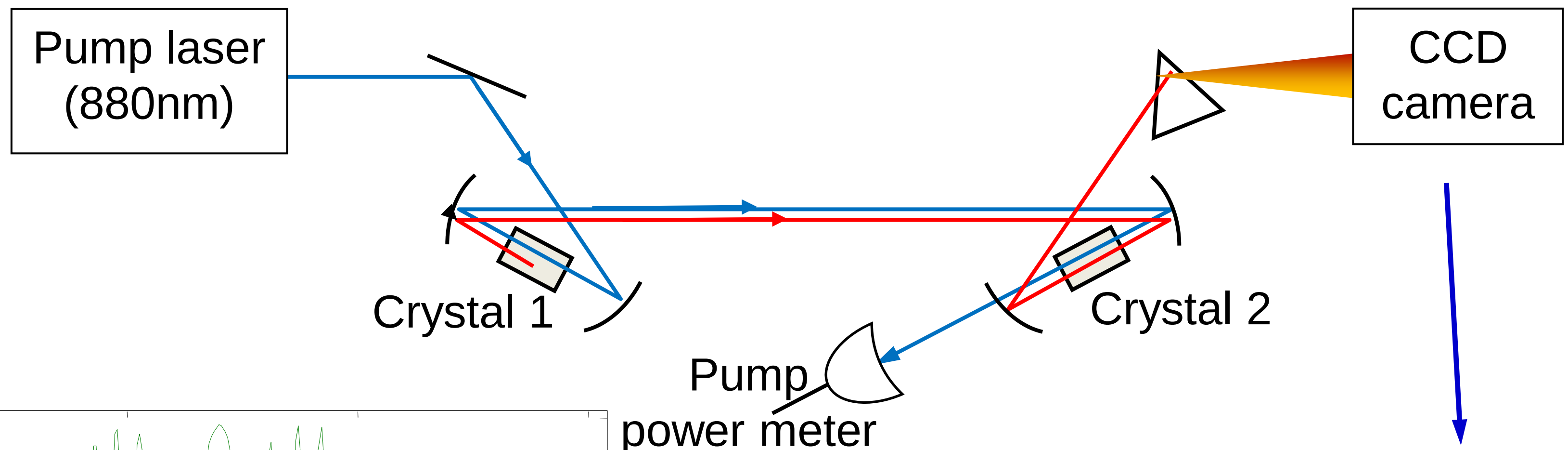


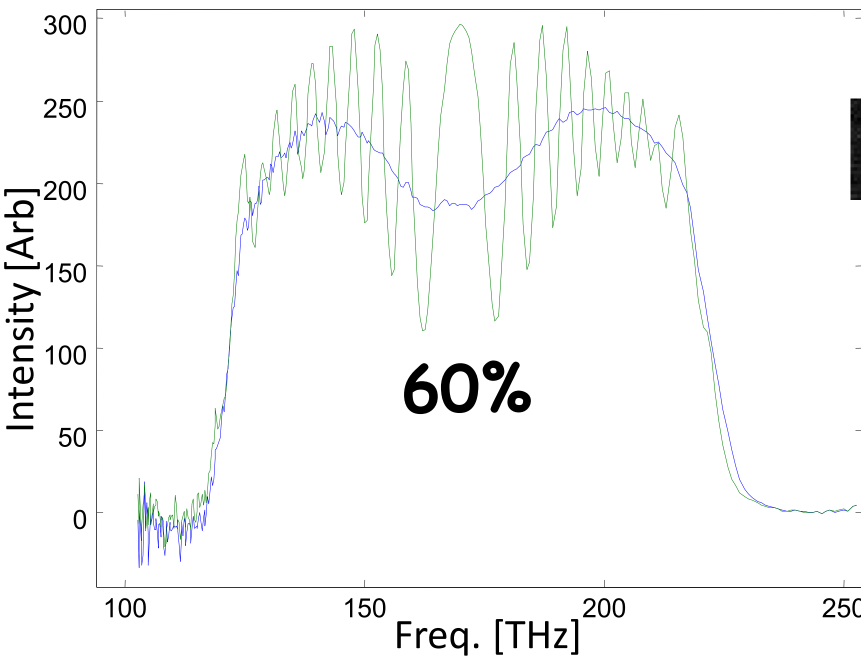


"Frustrated Two-Photon Creation via Interference" , T. J. Herzog, J. G. Rarity, H. Weinfurt & A. Zeilinger, *Phys. Rev. Lett.* **72**, 629-632 (1993).

Detection of bi-photons by attempting to annihilate them

Quantum two-photon interference





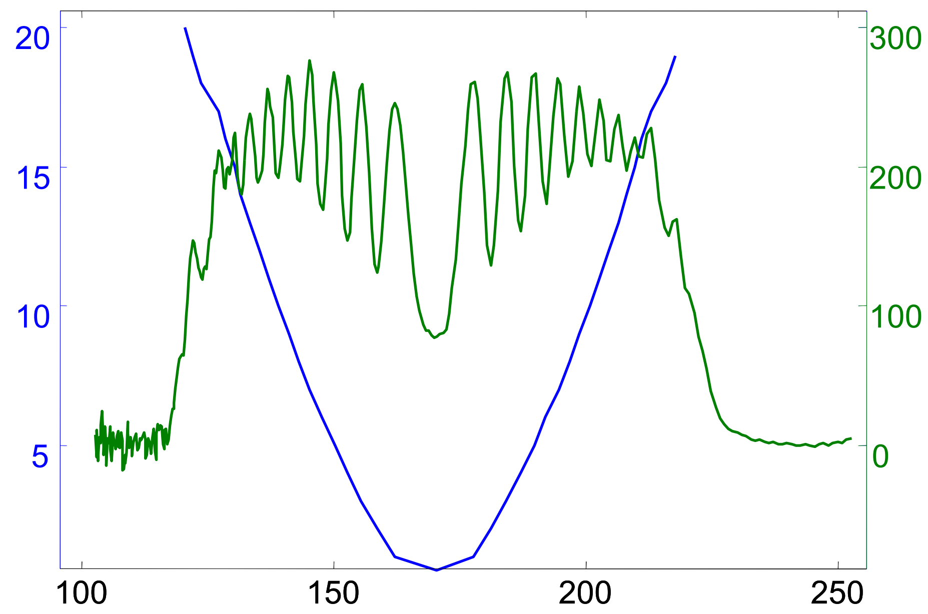
SFG efficiency = 60%

Inherent phase stability !

7ms integration time
on a simple CCD !

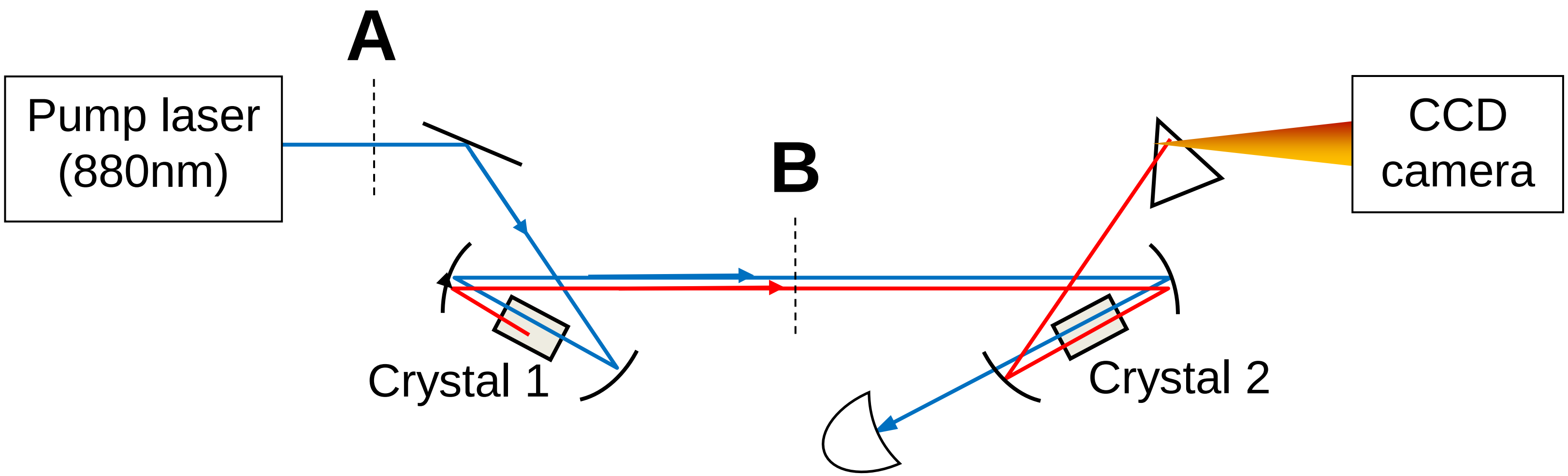
New J. Phys. 16, 053012 (2014)

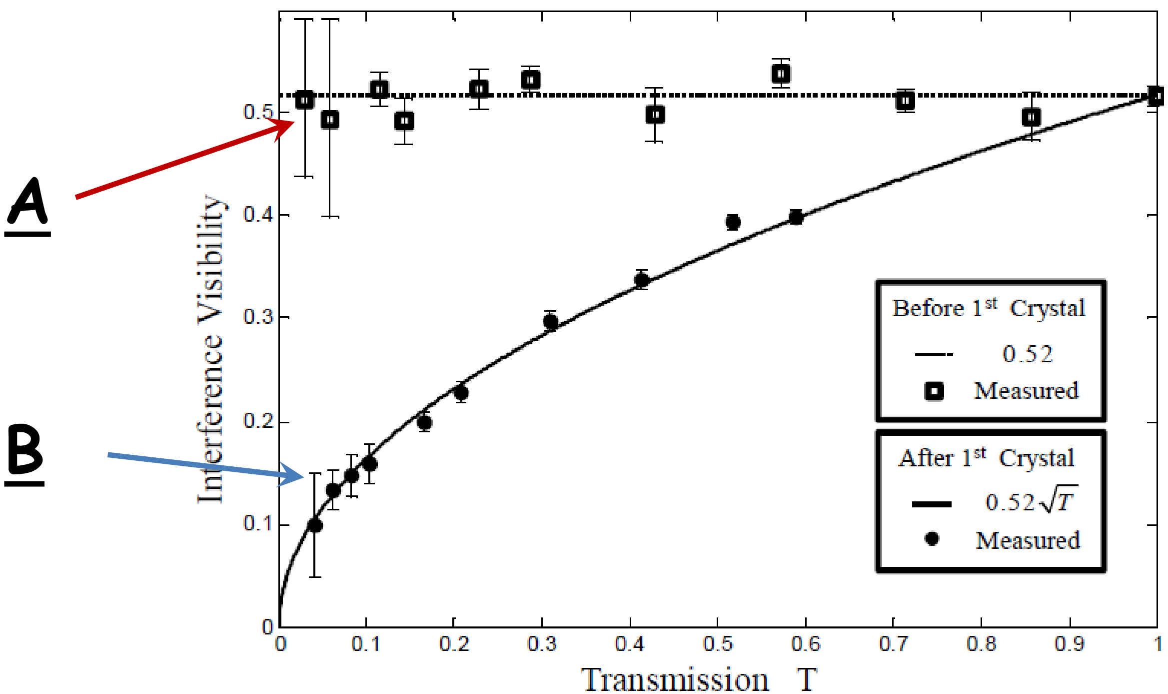
Reconstruct the spectral phase



- Phase mismatch
- Dispersion from the dielectric mirrors

What is non-classical ?

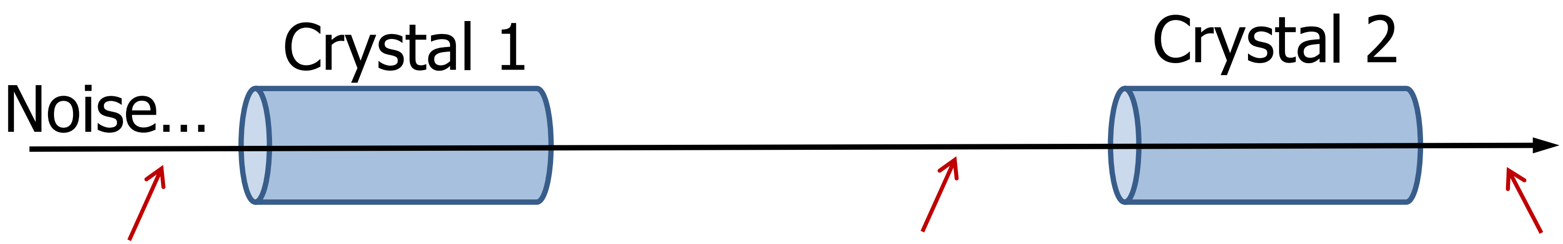




Measure of the two-photon purity

SPEED !
Full flux detected

Classical model (simplified)



$A_1(0) = n_r + i n_i$

$A_1(L) = e^{gL} n_r + i e^{-gL} n_i$

$A_2(0) = q + ip$

$A_2(L) = e^{g_2 L} q + i e^{-g_2 L} p$

$I_2 = q^2 e^{2 g_2 L} + p^2 e^{-2 g_2 L}$

$$V_{classical} = \frac{I_2^{\max} - I_2^{\min}}{I_2^{\max} - I_2^{\min}} = \frac{\left(q^2 e^{2gL} + p^2 e^{-2gL}\right) - \left(q^2 e^{-2gL} - p^2 e^{2gL}\right)}{\left(q^2 e^{2gL} + p^2 e^{-2gL}\right) + \left(q^2 e^{-2gL} + p^2 e^{2gL}\right)} = \frac{\left(q^2 - p^2\right)}{\left(q^2 + p^2\right)} \tanh(2gL)$$

$$\frac{\left(q^2 - p^2\right)}{\left(q^2 + p^2\right)} = \tanh(2 g_1 L)$$

$$V_{classical} = \tanh(2 g_1 L) \tanh(2 g_2 L)$$

$$V_{classical}^{A} \approx (2gL)^2 \propto I_P$$

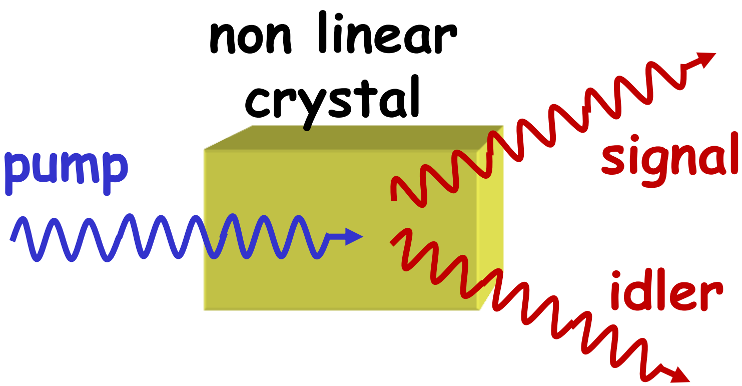
$$V_{classical}^{B} \approx (2 g_1 L)(2 g_2 L) \propto \sqrt{I_P}$$

Conclusions (so far)

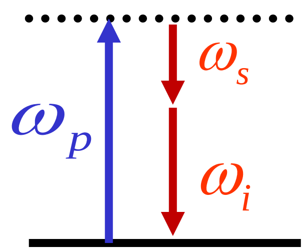
1. Bandwidth allows **ultra-high flux** of collinear **"single cycle"** bi-photons
2. The pumped crystal acts as a bi-photon detector with **near unity efficiency**.
3. **No coincidence detection** ! Standard intensity detection at the bi-photons rate
4. Comparing single photon loss with pair-wise loss verifies non-classical behavior.
5. **Speedup** ! X10^4 demonstrated, X10^8 feasible

Now to FWM…

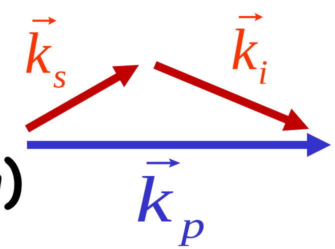
Down conversion



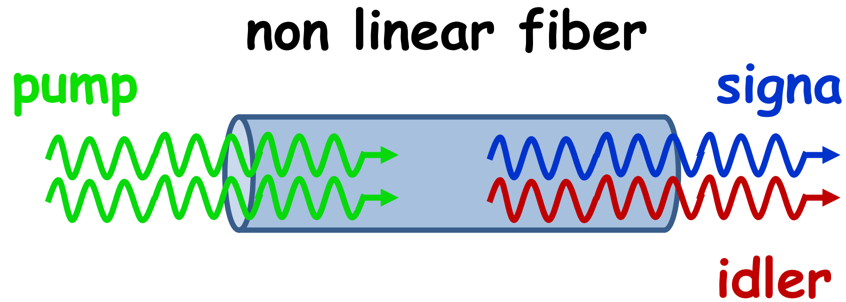
energy conservation

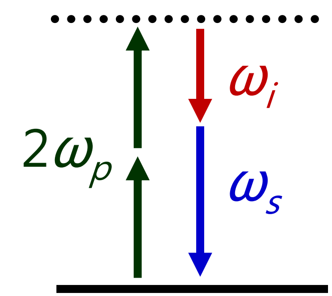


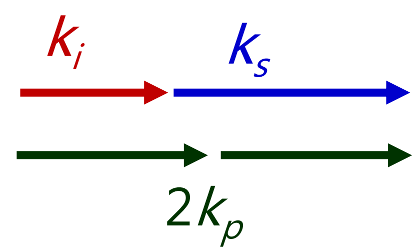
momentum conservation (phase matching)



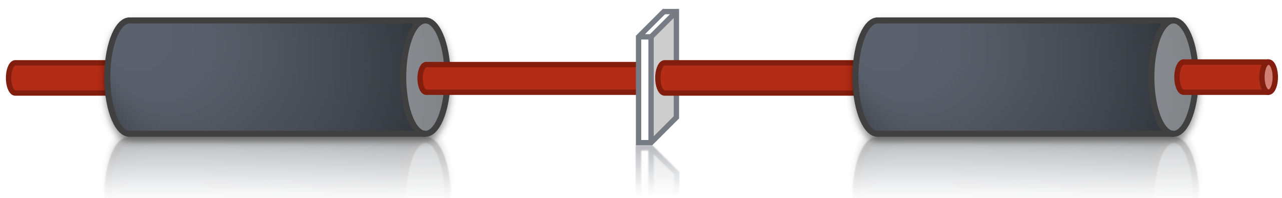
Four Waves Mixing



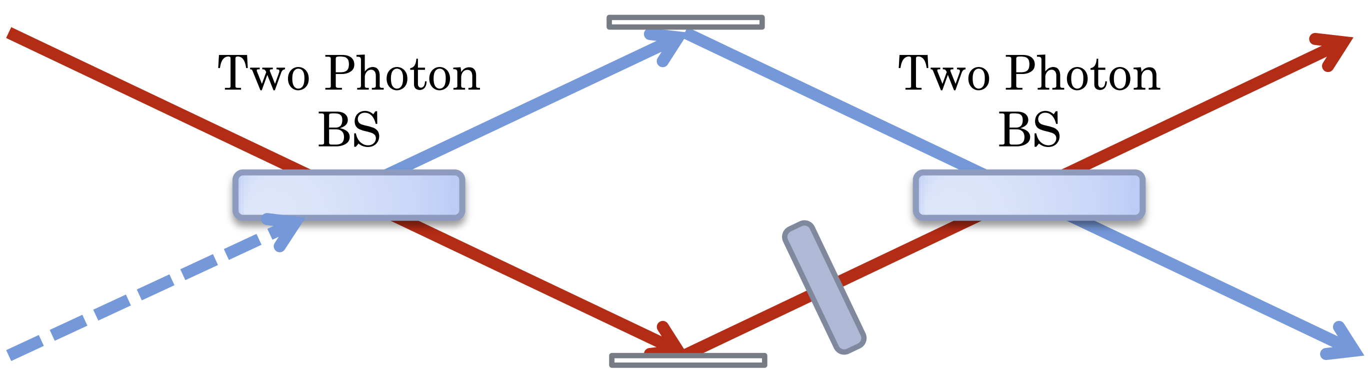




FWM concept



An equivalent Mach-Zehnder interferometer **for Bi-photons:**



FWM and TWM – Differences…

Down conversion

$$\frac{\partial}{\partial z} A_s = -i\chi A_p A_i^* e^{-i\Delta k \cdot z}$$

$$\frac{\partial}{\partial z} A_i = -i\chi A_p A_s^* e^{-i\Delta k \cdot z}$$

Four Waves Mixing

$$\frac{\partial}{\partial z} A_s = -i\gamma \left(2\left|A_p\right|^2 A_s + A_p^2 A_i^* e^{-i\Delta k \cdot z} \right)$$

$$\frac{\partial}{\partial z} A_i = -i\gamma \left(2\left|A_p\right|^2 A_i + A_p^2 A_s^* e^{-i\Delta k \cdot z} \right)$$

Rescale equations

$$B_{s,i} = A_{s,i} e^{-2i\gamma\left|A_p\right|^2 z}$$

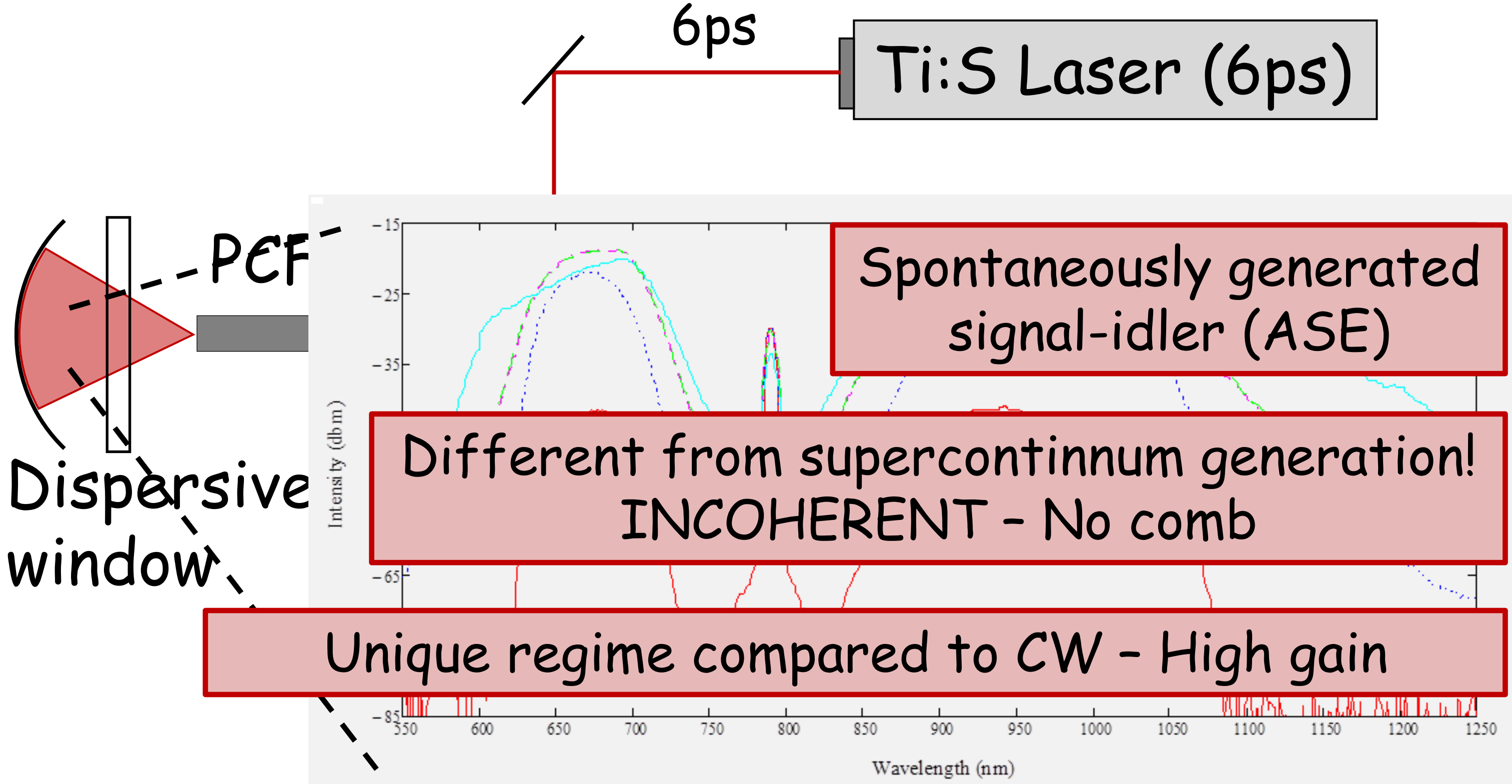
$$\frac{\partial}{\partial z} B_s = -i\gamma A_{p,0}^2 B_i^* e^{-i\left(\Delta k - 2\gamma\left|A_p\right|^2 \right) \cdot z}$$

$$\frac{\partial}{\partial z} B_i = -i\gamma A_{p,0}^2 B_s^* e^{-i\left(\Delta k - 2\gamma\left|A_p\right|^2 \right) \cdot z}$$

Generalized phase mismatch

$$\Delta\kappa = \Delta k - 2\gamma\left|A_p\right|^2$$

The Experiment



Spontaneously generated signal-idler (ASE)

Different from supercontinnum generation! INCOHERENT – No comb

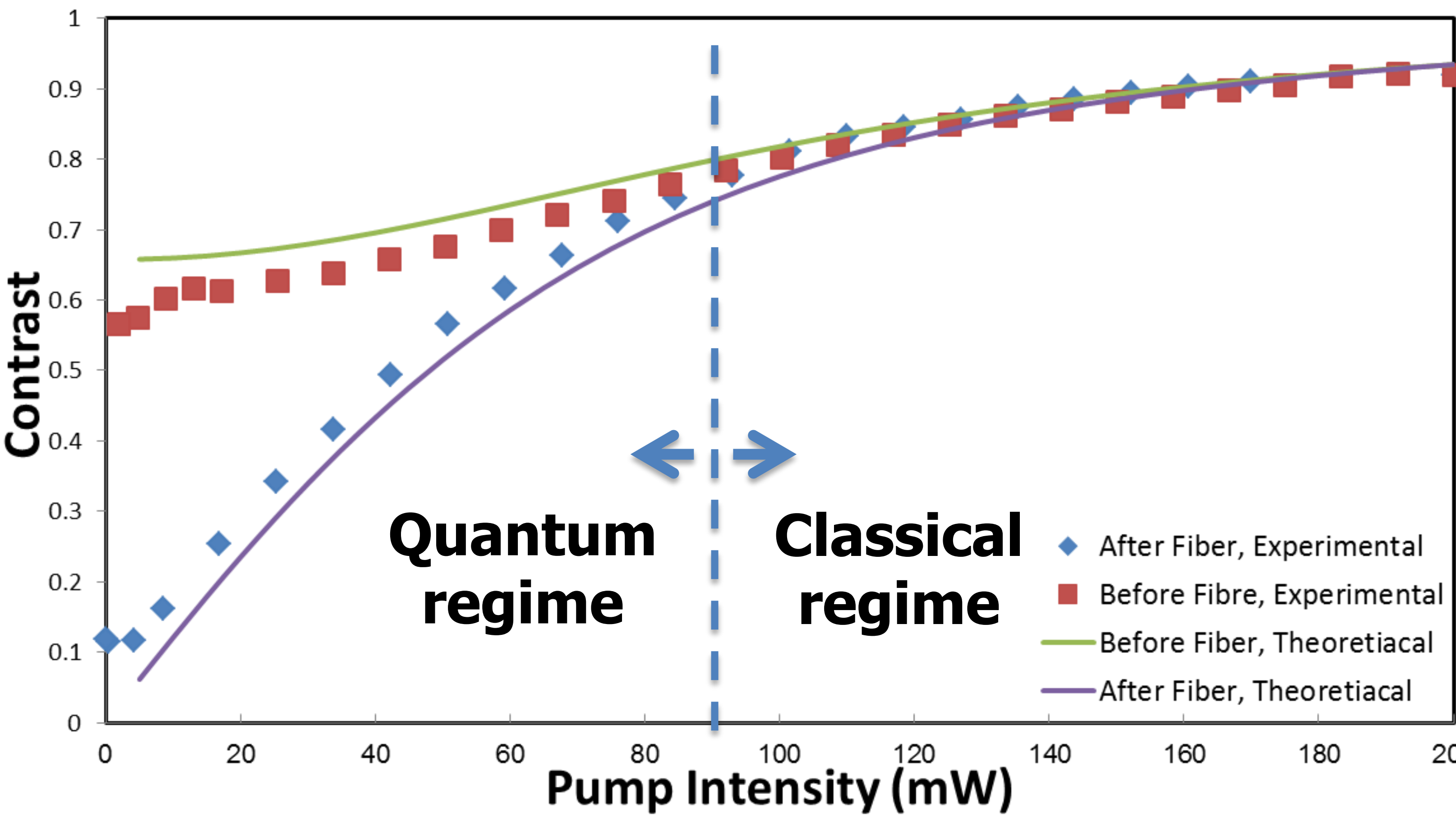
Unique regime compared to CW – High gain

Can cover the full Quantum-Classical transition

Rafi Z. Vered, Michael Rosenbluh, and Avi Pe'er, ***"Two-photon correlation of broadband-amplified spontaneous four-wave mixing"***, Phys. Rev. A **86**, 043837 (2012)

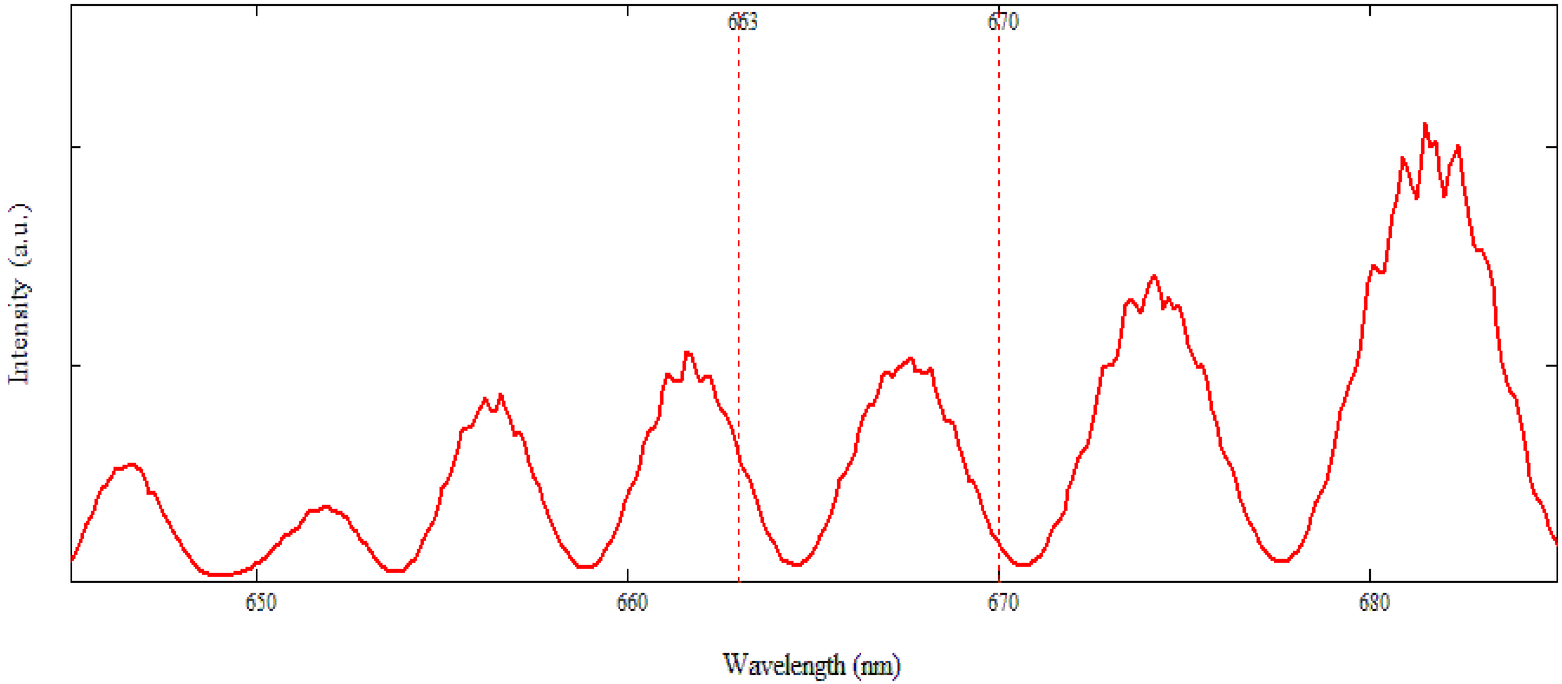
Classical-to-quantum transition

Near zero dispersion - 784nm ($\Delta k \approx 0$, real gain)



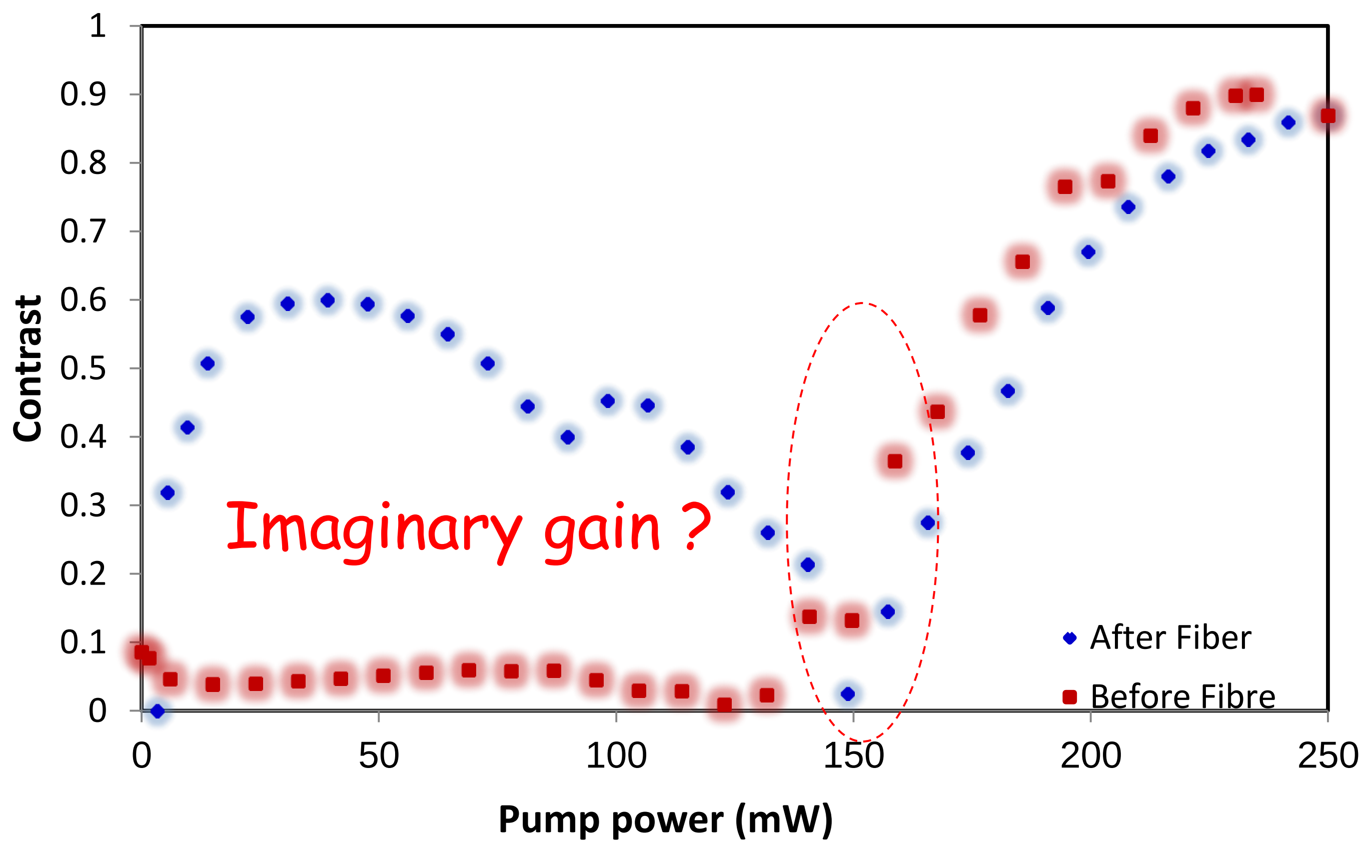
FWM – nearby pump wavelength

Shift pump - 787nm (Δk<0, threshold for gain)



Phase shift with intensity

FWM – nearby pump wavelength



Squeezing ?

FWM Gain Solution

Signal/idler solution

$$B_{s,i} = b_{s,i}^{\pm} e^{\pm g\cdot z} e^{-i\frac{\Delta q}{2}z}$$

$$I_{s,i} \propto I_P z^2 \left(\frac{Sinh[gz]}{gz} \right)^2$$

$$g = \sqrt{\gamma^2 |A_p|^4 - \frac{\Delta q^2}{4}}$$

Similar to 3-waves, but…

Generalized phase mismatch

$$\Delta q = \Delta k - 2\gamma |A_p|^2$$

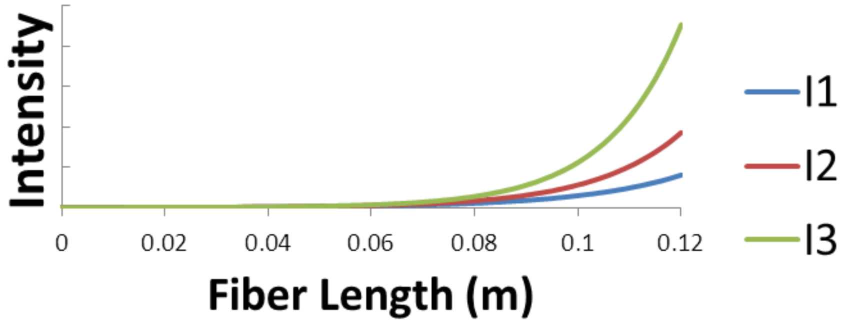
Gain can become imaginary !

Correlation ?

Imaginary gain ?

For real gain:

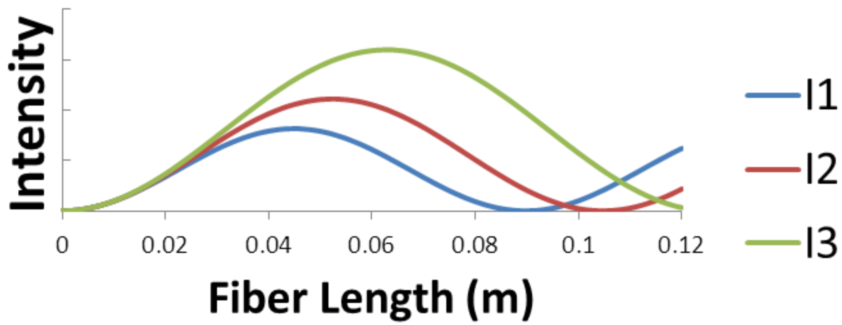
$$I_{FWM} \propto \frac{I_p^2}{g^2} sinh^2(gl)$$



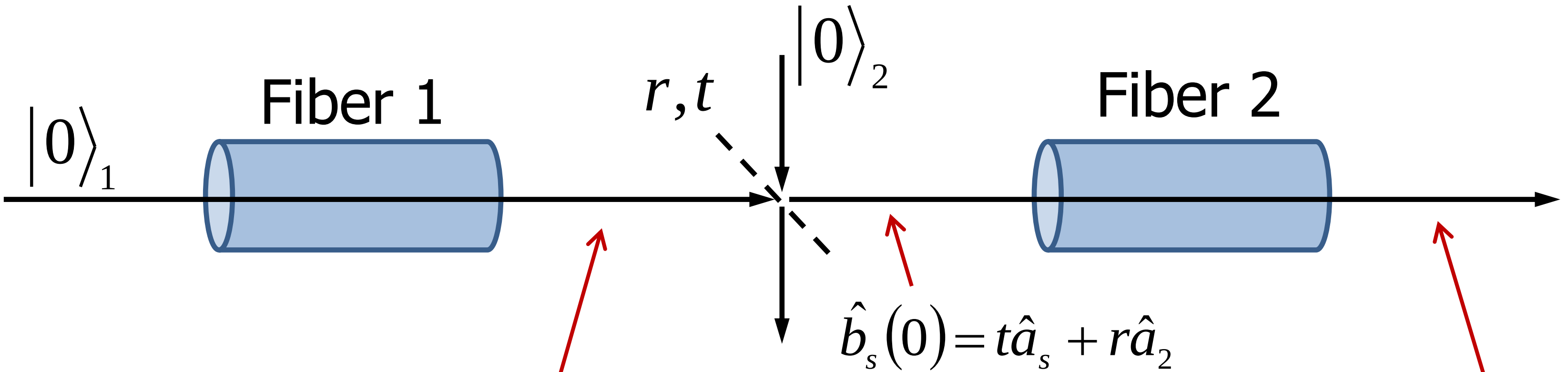
$$I_3 > I_2 > I_1$$

For imaginary gain:

$$I_{FWM} \propto l^2 I_p^2 sinc^2(|g|l)$$



Quantum model (full)



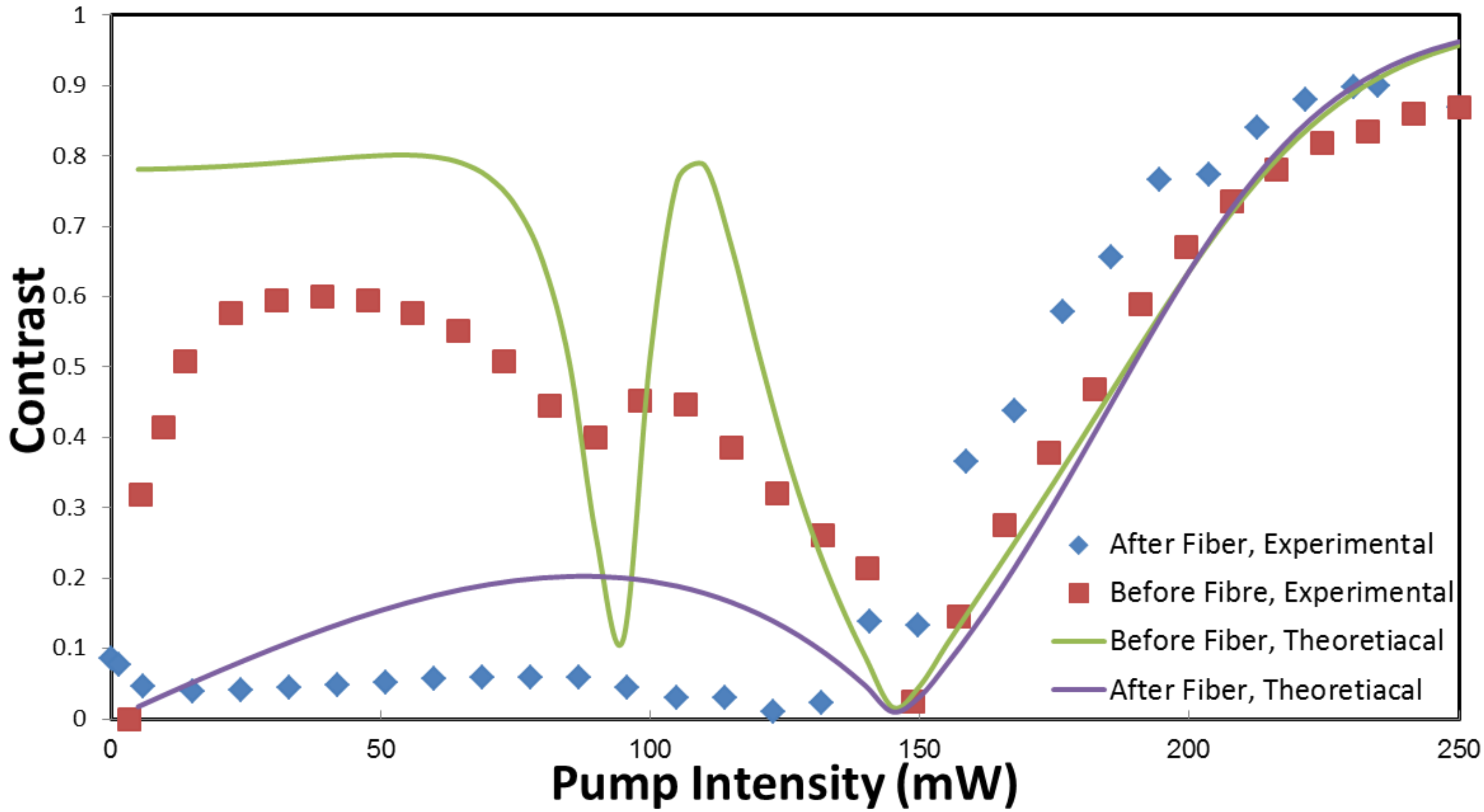
$$\hat{a}_s(L) = \left[\left(\cosh(g_1 L) + i\frac{\Delta\kappa}{2g_1}\sinh(g_1 L)\right)\hat{a}_s(0) + i\frac{\gamma|A_P|^2}{g_1}\sinh(g_1 L)\hat{a}_i^+(0)\right]$$

$$\hat{b}_s(L) = \left[\left(\cosh(g_2 L) + i\frac{\Delta\kappa}{2g_2}\sinh(g_2 L)\right)\hat{b}_s(0) + i\frac{\gamma|A_P|^2 e^{2i\varphi_P}}{g_2}\sinh(g_2 L)\hat{b}_i^+(0)\right]$$

$$N_s(\varphi_P) = {}_{1,2}\langle 0|\hat{b}_s^+\hat{b}_s|0\rangle_{1,2}$$

CW treatment
(no time dependence)

Theory vs experiment



<u>Contrast reduction ?</u>

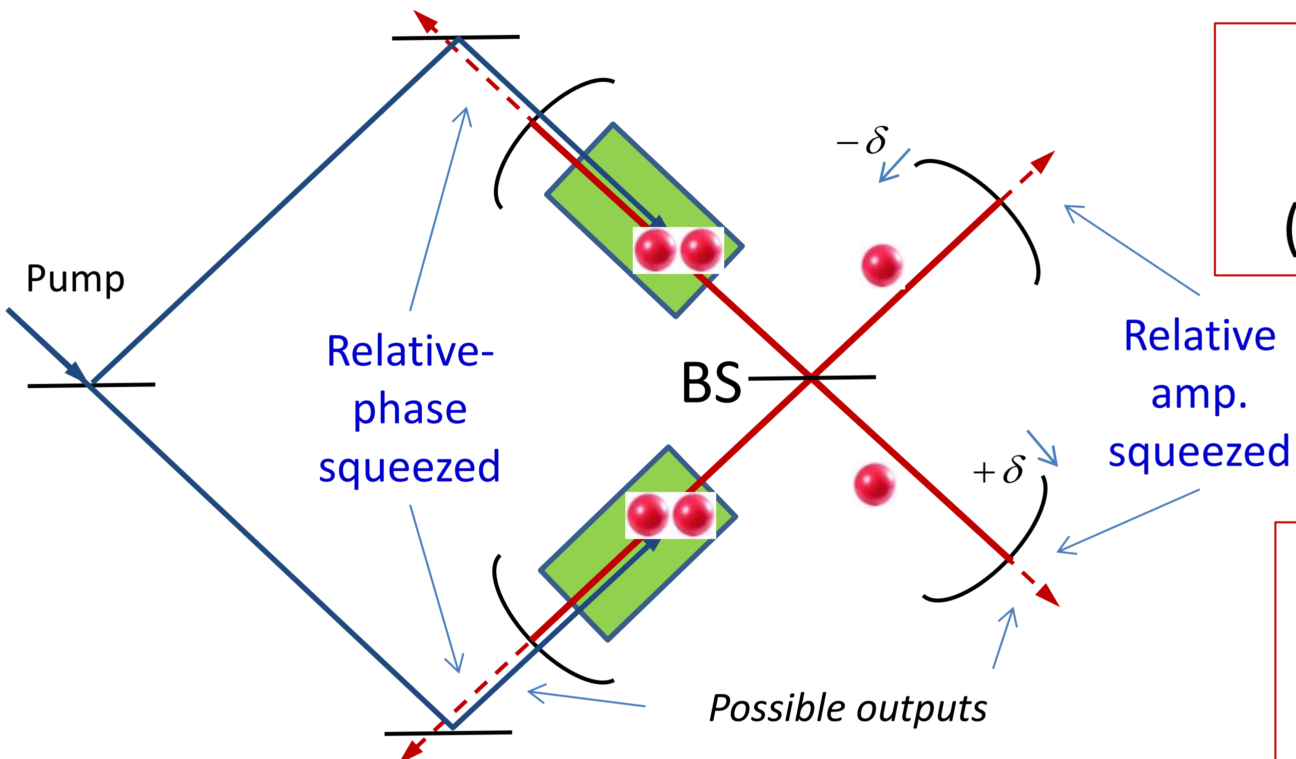
Pulse effects, Spectrometer resolution

Conclusions (II)

- Observation of the **entire classical-quantum transition** with FWM in fiber
- Span 4 orders of magnitude (and more…)
- **Bi-photon generation with imaginary gain**
- Can this be used to measure broadband (two-mode) squeezing ?

A high-power efficient source (OPO) ?

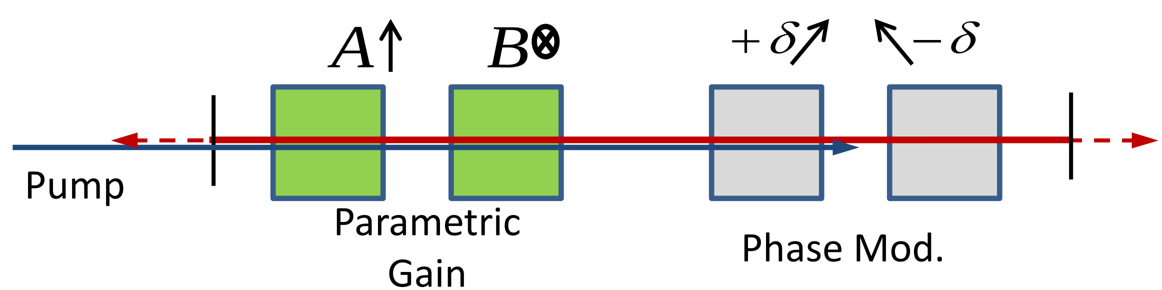
What if we introduce a (HOM) interferometer into the Source ?



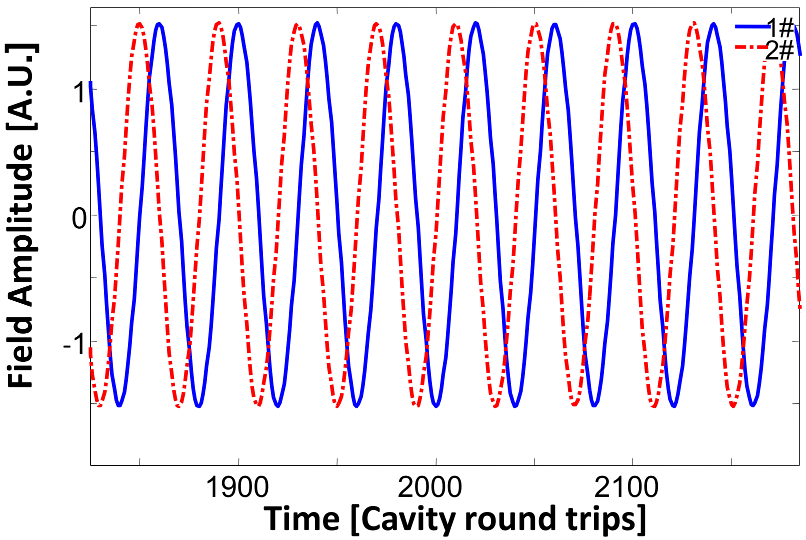
Full simulation of cavity dynamics (including vacuum)

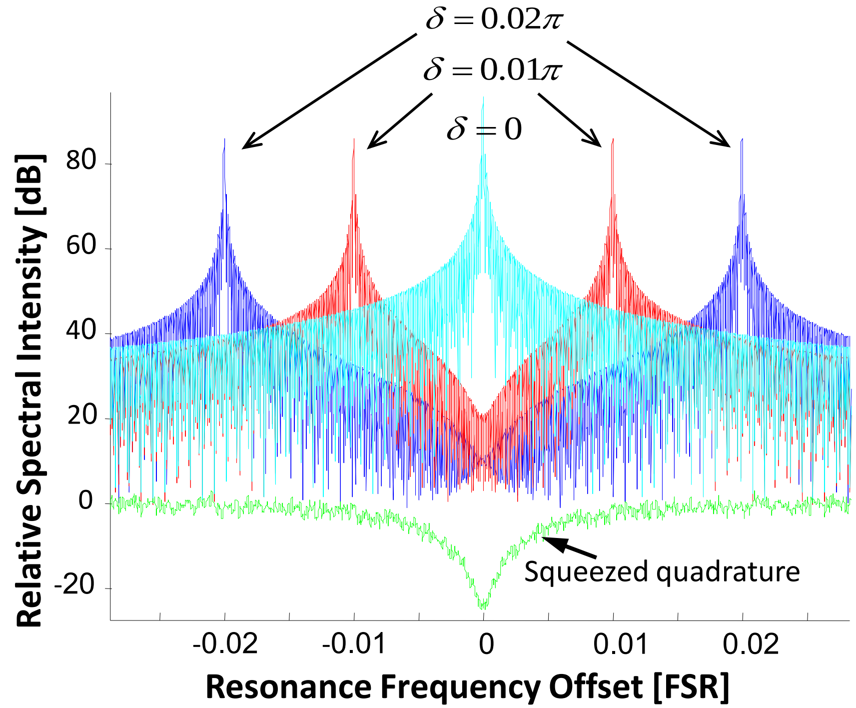
Approximate analytic models (intuition)

A simple realization:



Coupled narrowband oscillation





Quantum Beating at $\omega_{beat} = 2\delta \cdot f_{rep}$

Two-mode squeezing with arbitrary, tuned separation !

Direct electronic detection / stabilization

Coupled OPOs – Narrowband theory

Exact dynamical equation (including vacuum)

$$\tau \frac{d}{dt} A = \left[-\frac{T^2}{2} A + \left(\kappa l A_p - \tfrac{1}{2} \kappa^2 l^2 A^2 \right) A^* \right] \cos\delta + \left[\left(1 - \frac{T^2}{2} \right) B + \left(\kappa l A_p - \tfrac{1}{2} \kappa^2 l^2 B^2 \right) B^* \right] \sin\delta + T n^A(t)$$

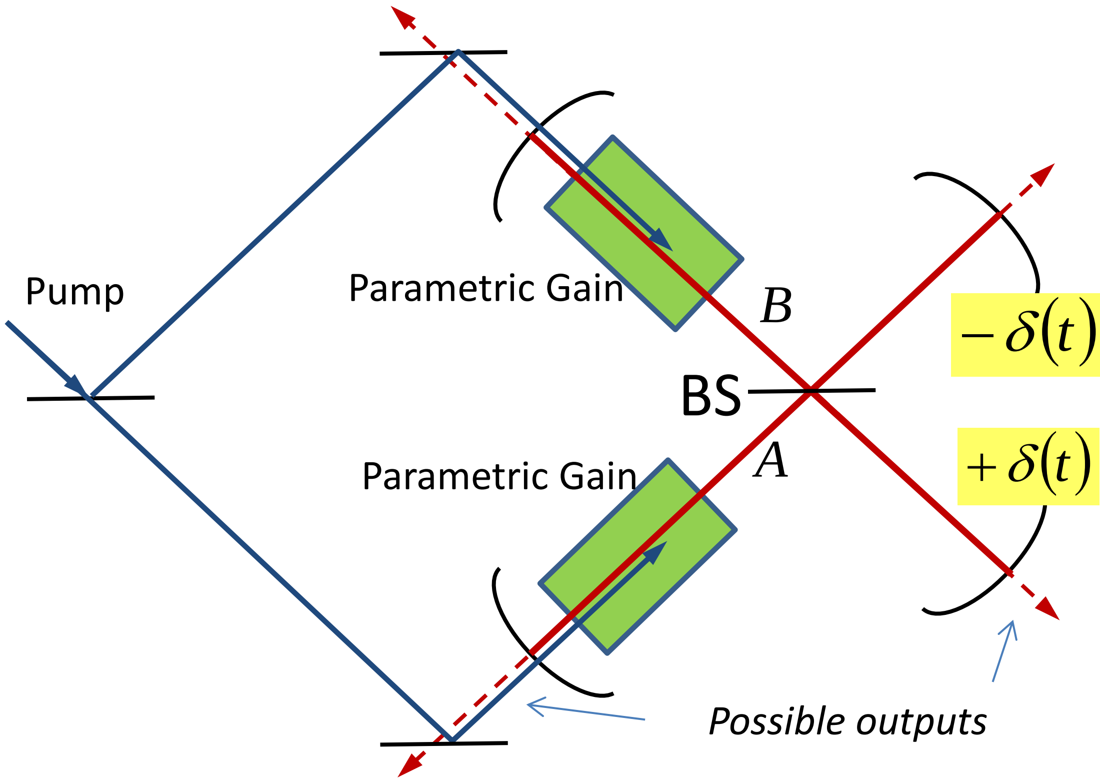
Approximate analytic model

$$\tau \frac{d}{dt} \begin{bmatrix} A \\ B \end{bmatrix} \approx \begin{bmatrix} 0 & \delta \\ \delta & 0 \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix}$$

Quantum beats

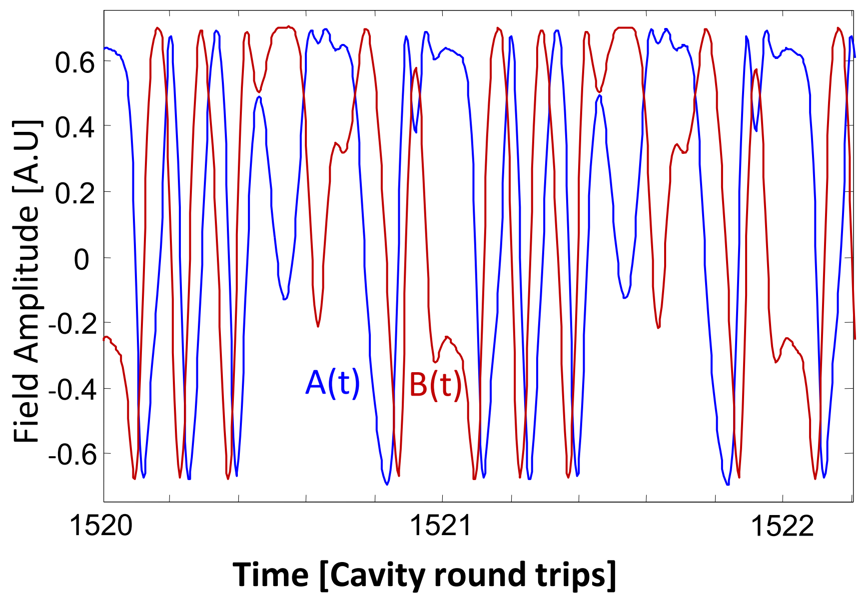
What if… (II)

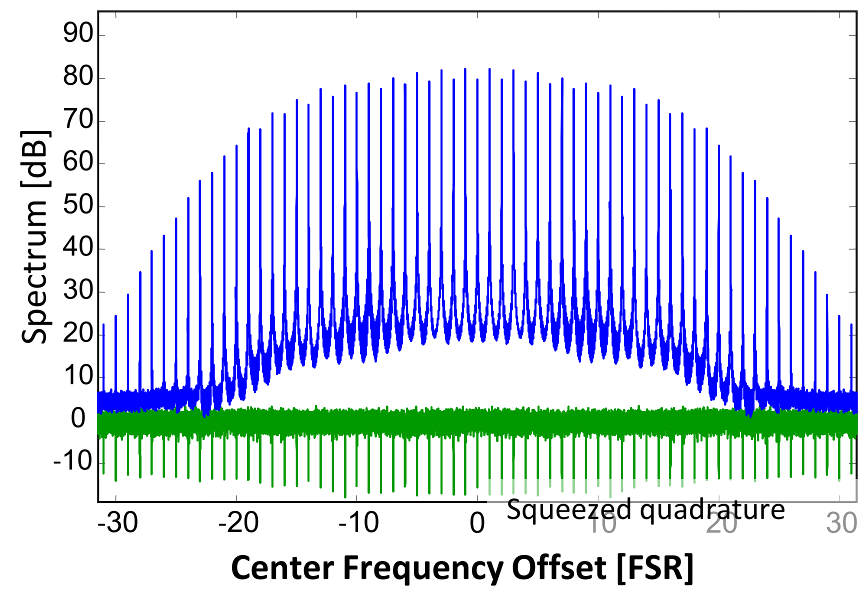
What if we <u>modulate</u> the coupling phase at the repetition rate of the cavity ?



Pairwise mode locking

Energy spread between modes - Pairwise mode locking

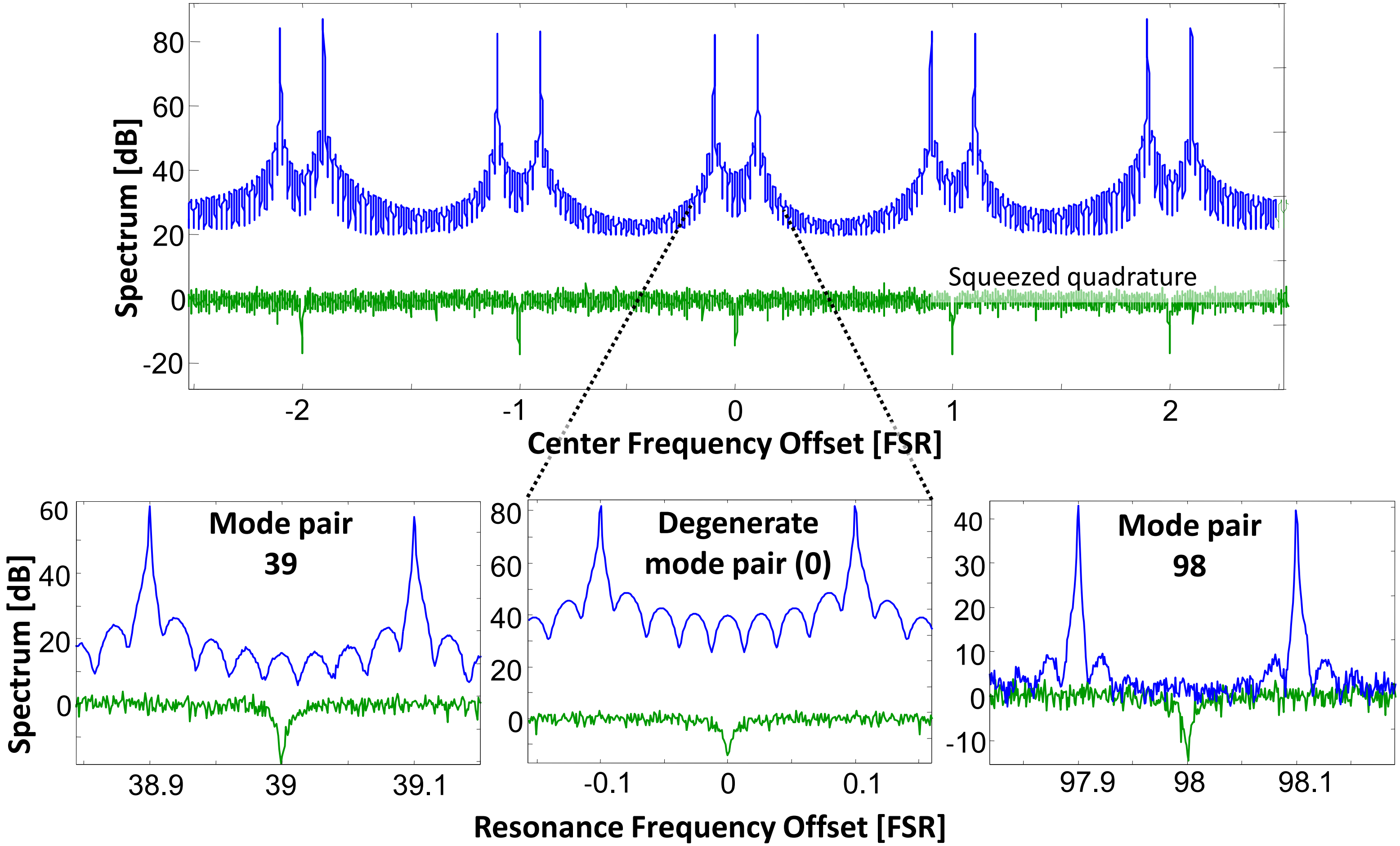




A two-photon analog for active mode locking in lasers

Quantum Frequency Comb!

Quantum two-photon comb



A Coherent Link between all pairs !

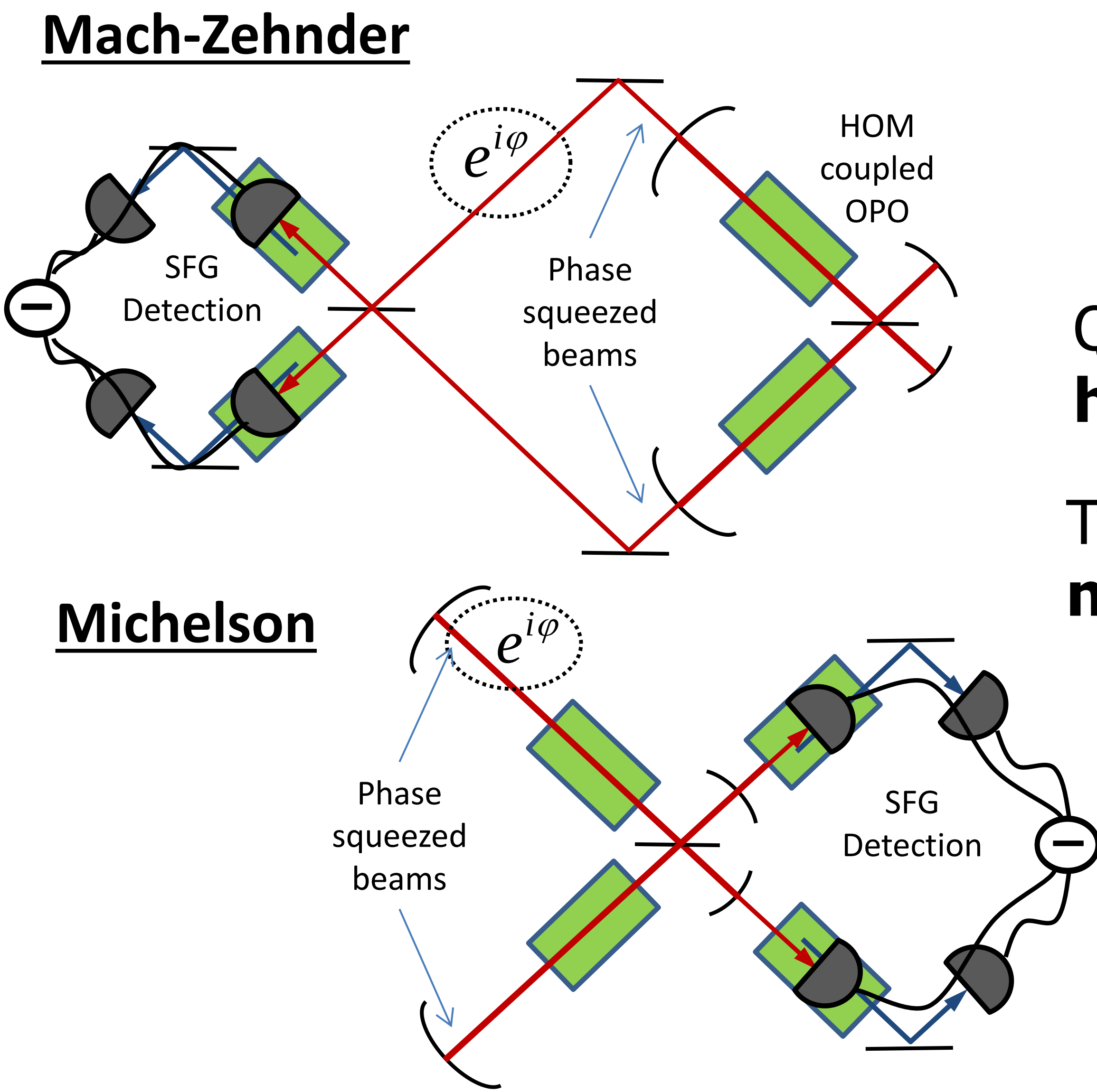
What is it good for… ?

The comb = **Coherence transfer across the spectrum** (freq. counting)

Same possibilities with broadband two-photon coherence and squeezing

- **Precision phase measurement – sub shot-noise**
- Atoms as nonlinear mixers (Kimble 1997)
- Modification of atomic natural lifetime in broadband squeezed light (Gardiner 1987)
- Classical applications (spread-spectrum optical communication…)
- What else… ?

Precision phase measurement

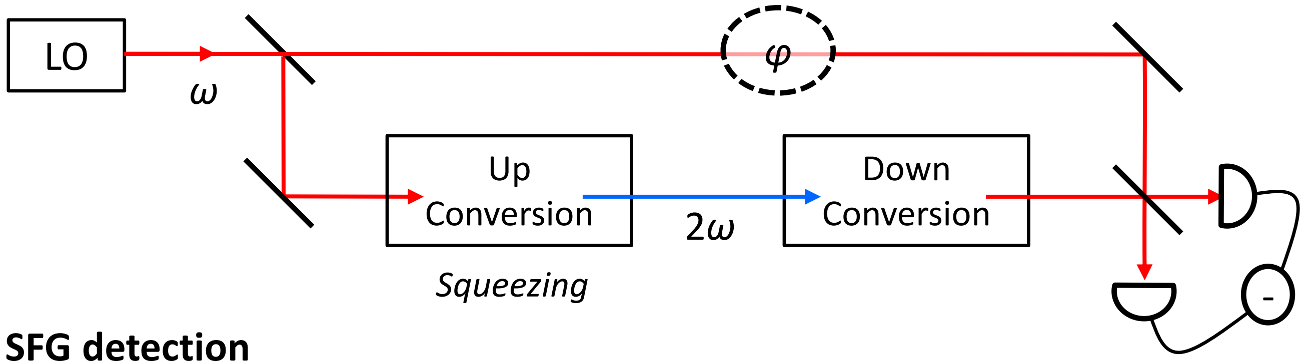


Quantum beat –
high freq. detection

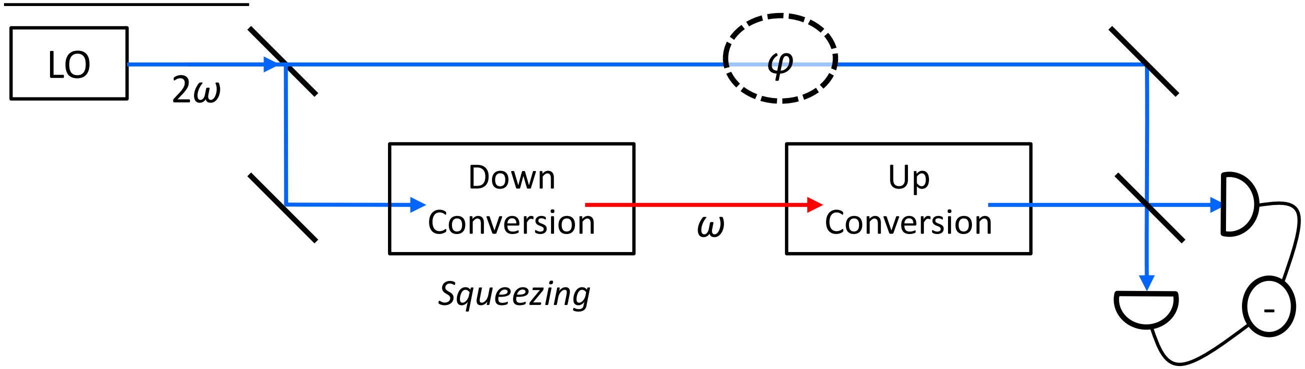
Two Squeezed beams -
no local oscillator

SFG detection of Squeezing at high-power

Homodyne detection



SFG detection



$$V_2^0 = 1 + \frac{4\nu^2(N + M - \nu^2/8)}{(1 + 3\nu^2/4)^2}$$

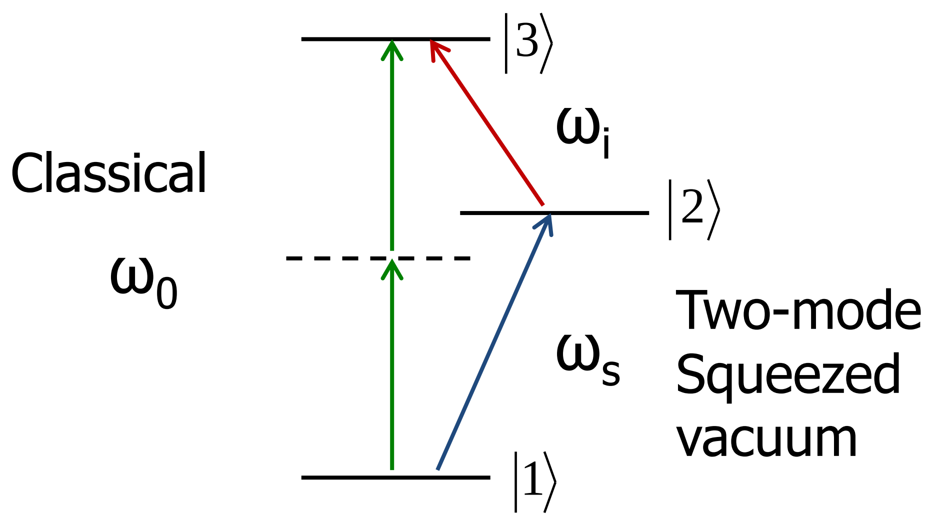
$$V_2^{\pi/2} = 1 + \frac{4\nu^2(N - M + \nu^2/8)}{(1 + \nu^2/4)^2}$$

Fully quantum analysis

Phys. Rev. A. **88**, 043808 (2013)

Atoms as nonlinear mixers

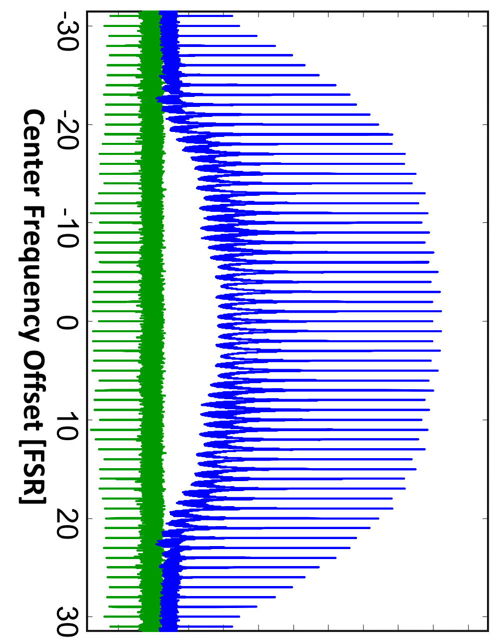
PRA 55, 1605 (1997)



Quantum interference in two-photon absorption

Two pairs coherently linked

With quantum comb



All pairs squeezed and coherently linked !

Conclusions (last)

- **HOM coupled OPOs** – A source for above threshold, high-power broadband two-mode squeezed light
- **Pairwise mode-locking** – two-photon analog of active mode-locking
- A pairwise coherent link across a broad spectrum – **Another kind of Quantum comb**
- It will be useful for something
- Experiments on the way…

Theory – Coupled OPOs - Broadband

Exact dynamical equation (including mismatch):

$$\tau\frac{d}{dt}A_t(\omega) = \left\{-\frac{T^2}{2}A_t(\omega) + \left[\kappa l A_p - \tfrac{1}{2}\kappa^2 l^2\left(1 - \tfrac{1}{3}i\Delta k l\right)\sum_\omega A_t(\omega)A_t(-\omega)\right]A_t^*(-\omega)\right\}\cos\delta$$

$$+\left\{\left(1-\frac{T^2}{2}\right)B_t(\omega) + \left[\kappa l A_p - \tfrac{1}{2}\kappa^2 l^2\left(1 - \tfrac{1}{3}i\Delta k l\right)\sum_\omega B_t(\omega)B_t(-\omega)\right]B_t^*(-\omega)\right\}\sin\delta + T n_t^A(\omega)$$

Mode locking analog (classical theory):

$$\tau\frac{d}{dt}A(\omega) = G_A A(\omega) + \frac{\delta_{AC}}{2}\left[B(\omega+\omega_r) + B(\omega-\omega_r)\right]$$

$$\tau^2\frac{d^2}{dt^2}\langle|A(\omega)|^2\rangle = [4G_A^2 - \delta_{AC}^2]\langle|A(\omega)|^2\rangle + \frac{\delta_{AC}^2}{2}\left[\langle|B(\omega+\omega_r)|^2\rangle + \langle|B(\omega-\omega_r)|^2\rangle\right]$$

$$4G_A^2\langle|A(\omega)|^2\rangle - \delta_{AC}^2\left[\langle|A(\omega)|^2\rangle - \langle|B(\omega)|^2\rangle\right] + \frac{\delta_{AC}^2}{2}\omega_r^2\frac{d^2}{d\omega^2}\langle|B(\omega)|^2\rangle = 0$$

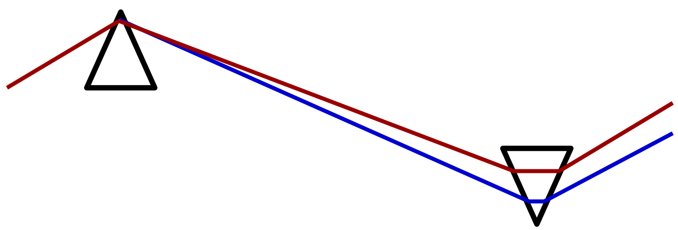
$$\frac{\delta_{AC}^2}{2}\omega_r^2\frac{d^2}{d\omega^2}\langle|A(\omega)|^2\rangle = -4G^2\langle|A(\omega)|^2\rangle$$

Gaussian spectrum $\langle|A(\omega)|^2\rangle \sim e^{-\omega^2/\Delta^2}$ $\quad \Delta^2 = \delta_{AC}\omega_r\mu,$ $\qquad G_0^2 = \delta_{AC}\,\omega_r/4\mu$

Dispersion compensation

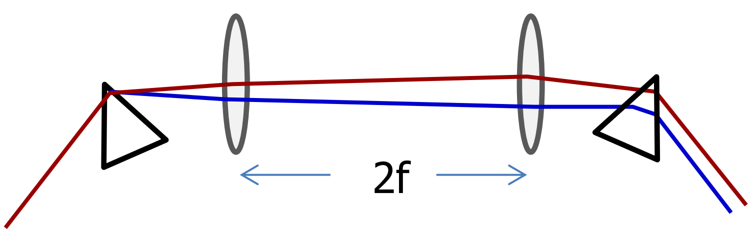
Spectral symmetry → **Only even orders important**

<u>Standard</u>



Cannot handle 4^{th} order
(need negative distance)

<u>Novel</u>



Space – material
interchanged

Telescope = negative distance