Coherence conditioned on a single photon

Kevin Resch

Department of Physics, University of Toronto

Accomplices

Jeff Lundeen

Aephraim Steinberg

$ Funding $

Photonics Research Ontario (PRO)

NSERC

Walter C. Sumner Foundation

Motivation

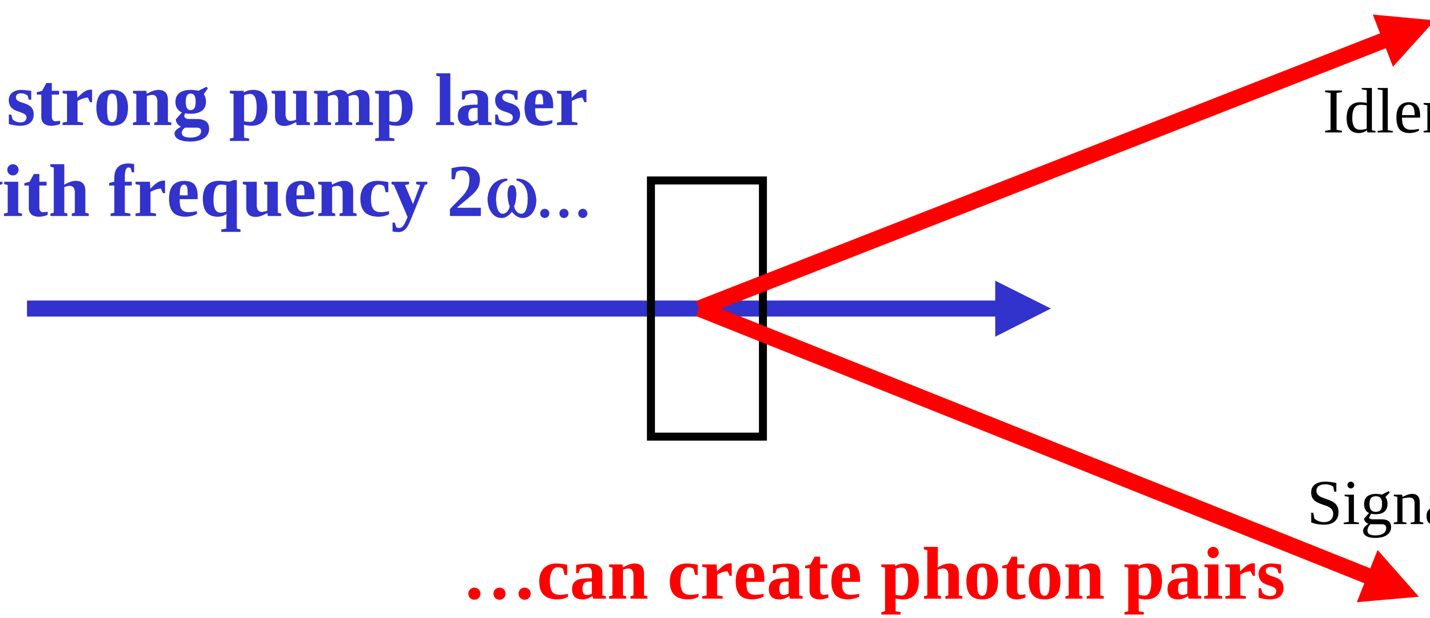
- Study interference between quantum and classical light sources

- This “conditional coherence” effect can be used to understand other Q/C interference effects

- System for state preparation originally proposed by L.Hardy and recently extended by J.Clausen et al.

Down-conversion

A strong pump laser with frequency 2ω…



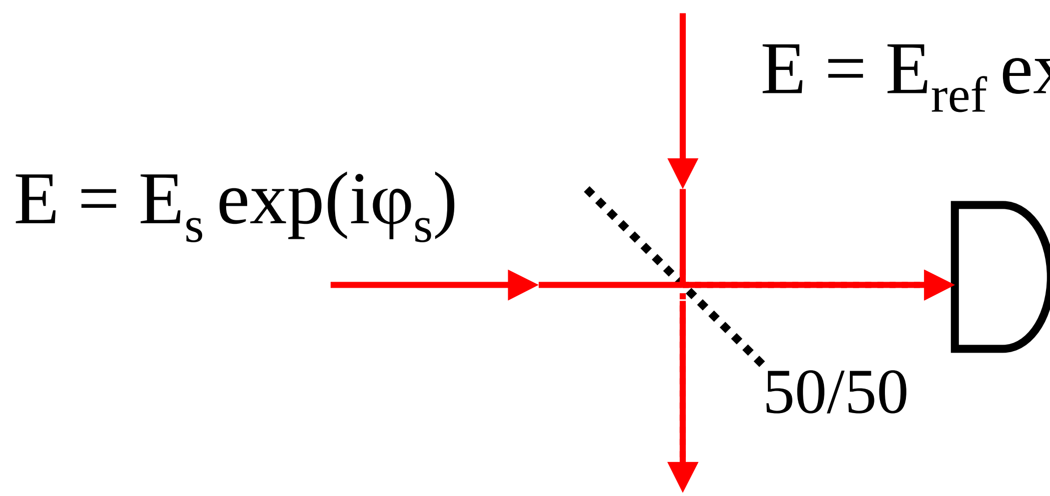
…can create photon pairs through SPDC

- Strong Correlations in energy, momentum, time, polarization, “phase”, and **photon number**

- If there is a photon in one arm, then there is also a photon in the other arm

Homodyne measurement

- Phase sensitive measurement



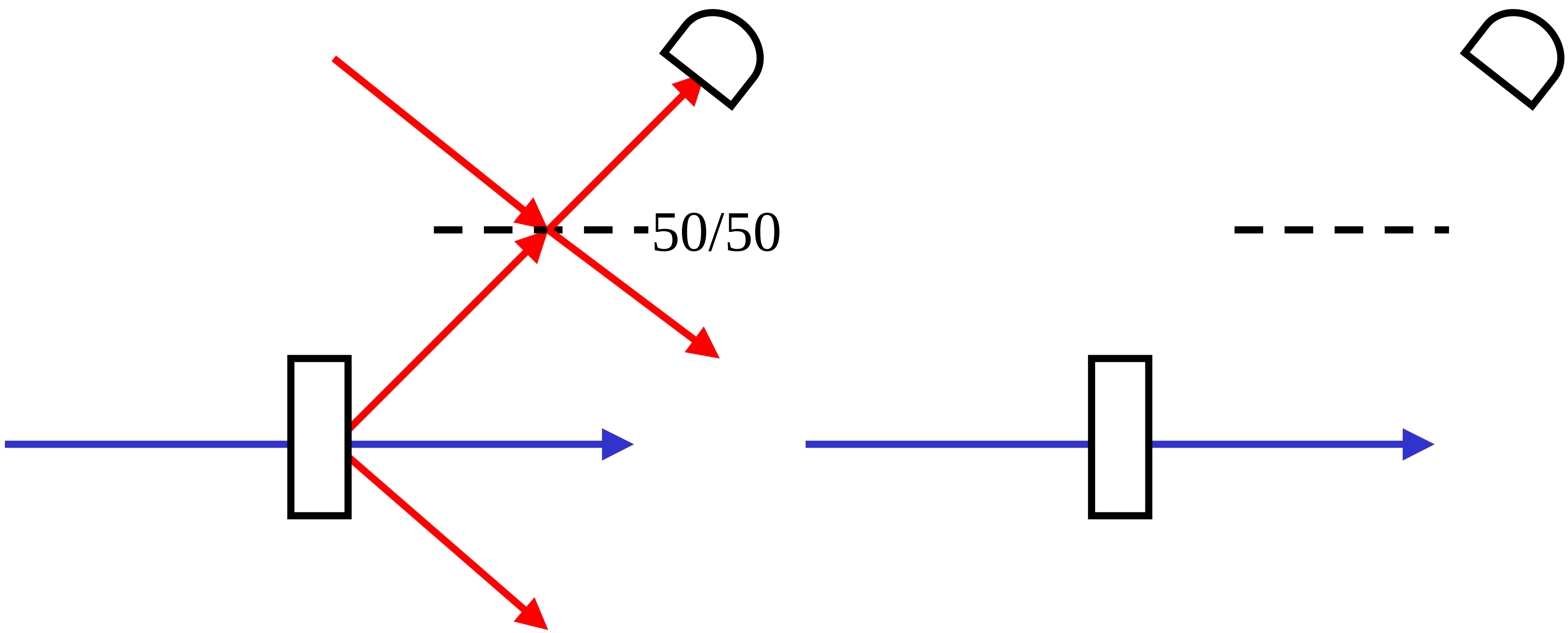
Obtain some relative phase information

- Detector response

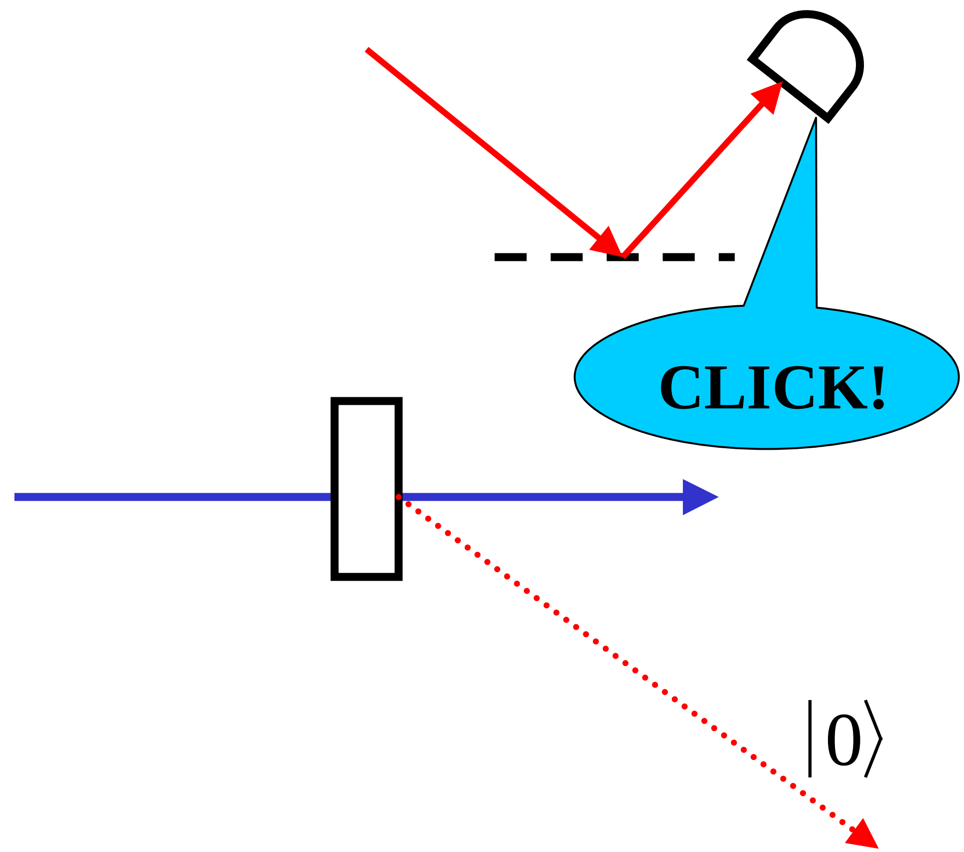
$$\propto |E_{ref}|^2 + |E_s|^2 + 2E_{ref}E_s \boxed{\sin(\varphi_{ref} - \varphi_s)}$$

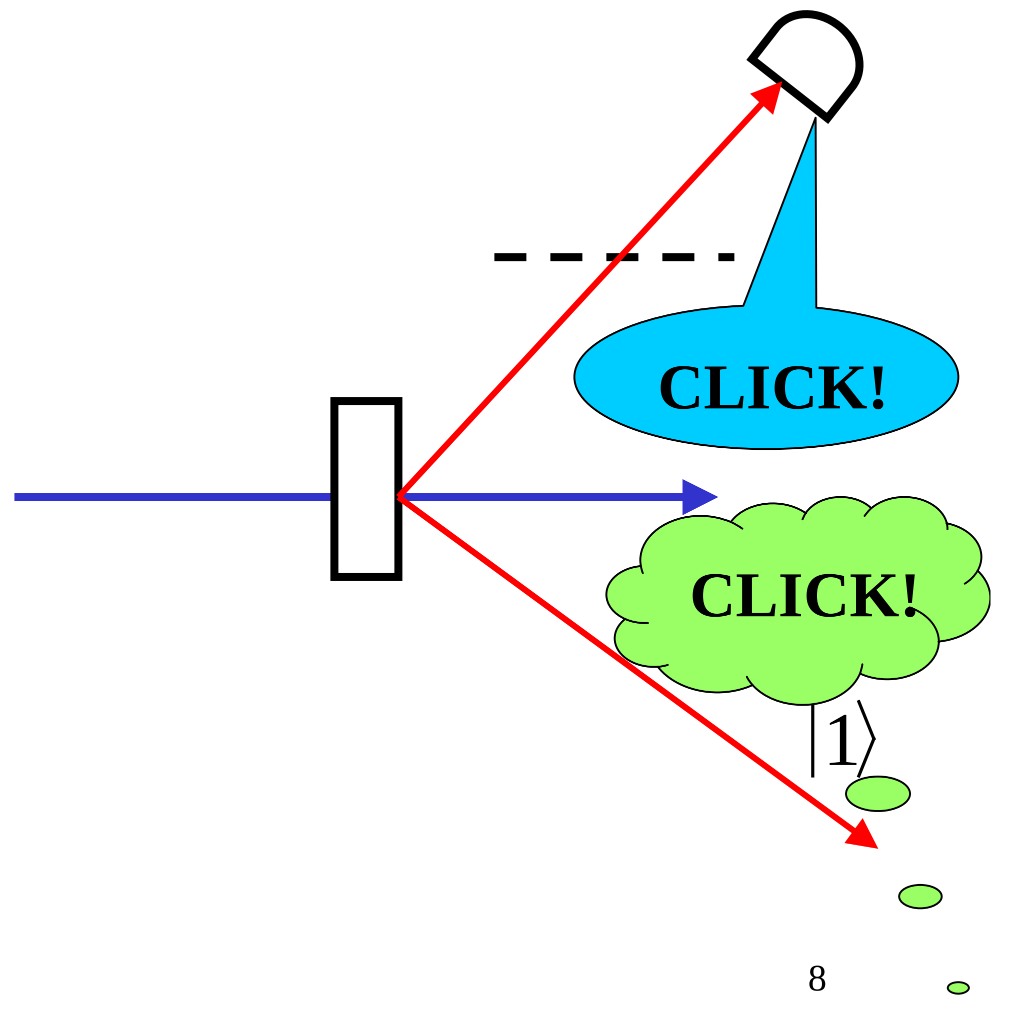
“Operational phase operator” J. W. Noh, A. Fougères, and L. Mandel 1991

Phase measurement of one down-conversion beam

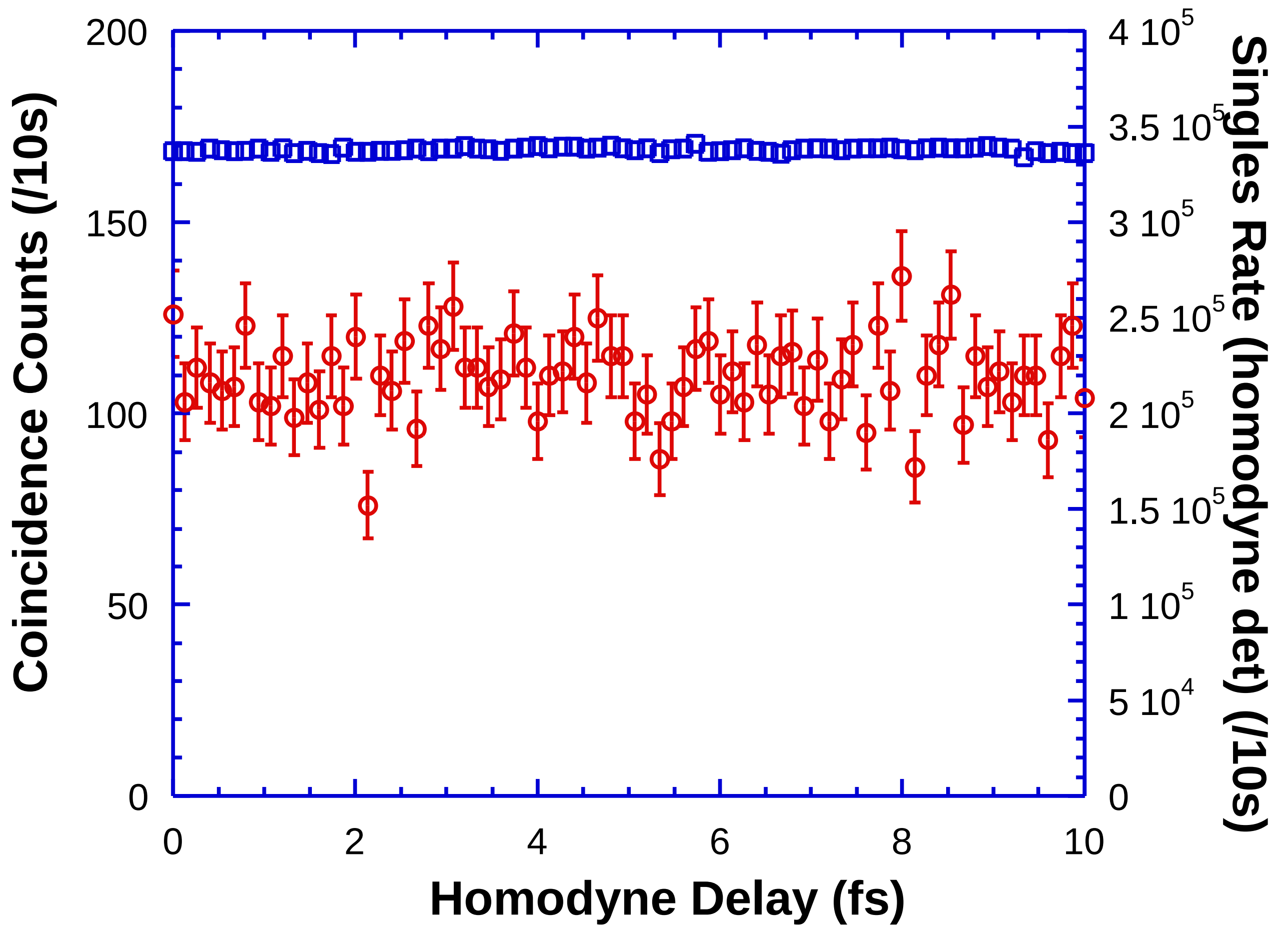


- The strong number correlations distinguishes the two paths
- $\Delta n \Delta \varphi > 1/2$ ⟶ A single photon cannot have a phase


CLICK!
$|0\rangle$


CLICK!
CLICK!
$|1\rangle$

One down-converted beam has no phase

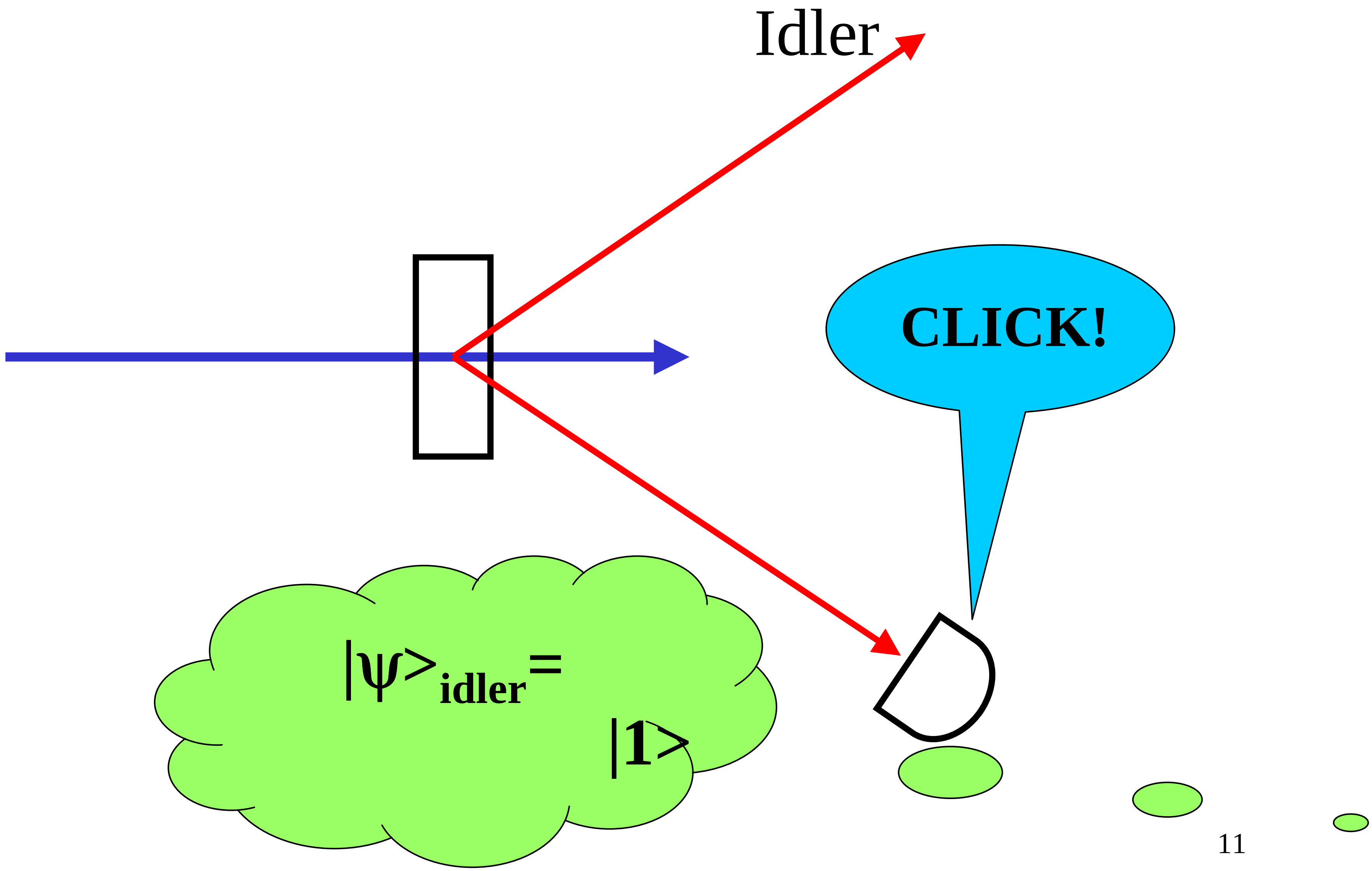


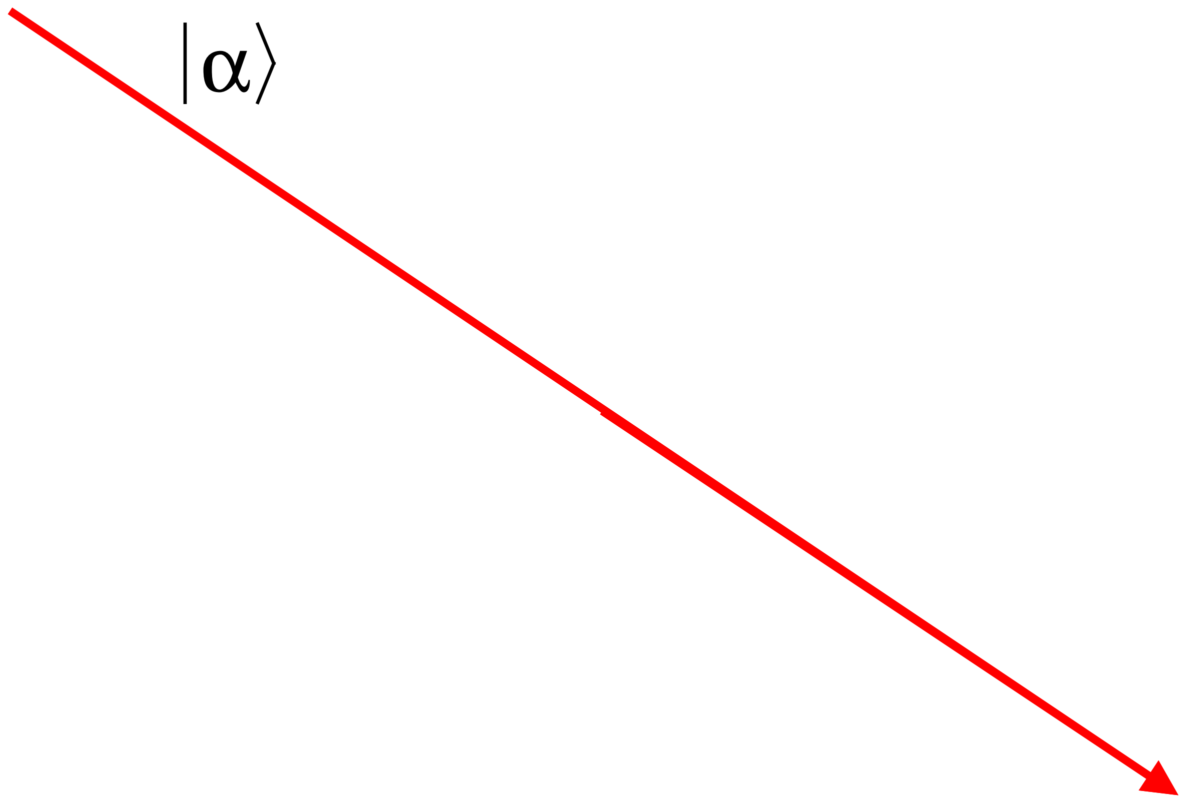
Weakening number correlations

- A coherent state, $|\alpha\rangle$, has an uncertain photon number:

$$|\alpha\rangle = \exp\left(-\frac{|\alpha|^2}{2}\right)\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}|n\rangle \approx |0\rangle + \alpha|1\rangle$$

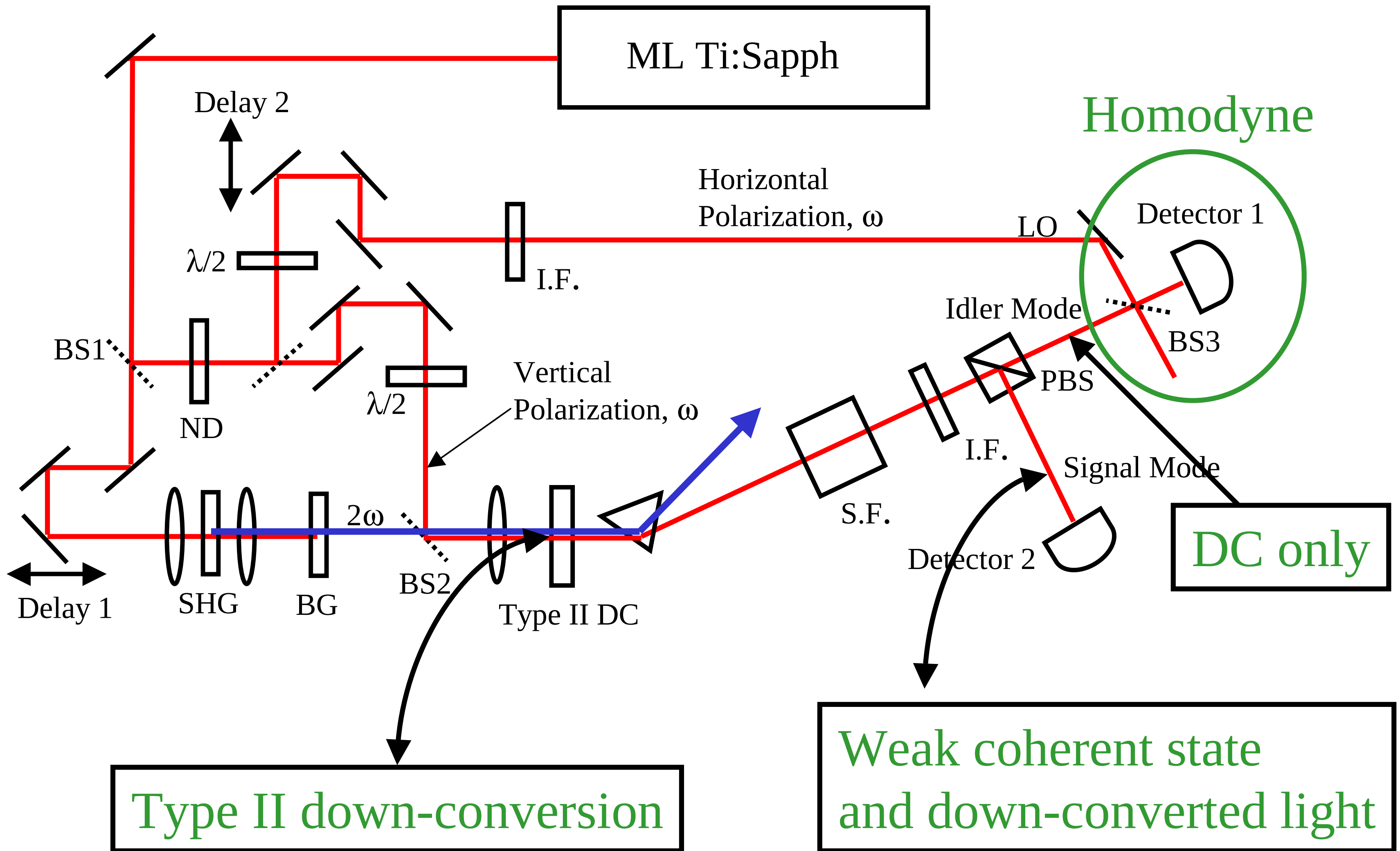
- Superposing a weak coherent state over a down-conversion beam weakens the number correlations


Idler
CLICK!
|ψ>idler=
|1>



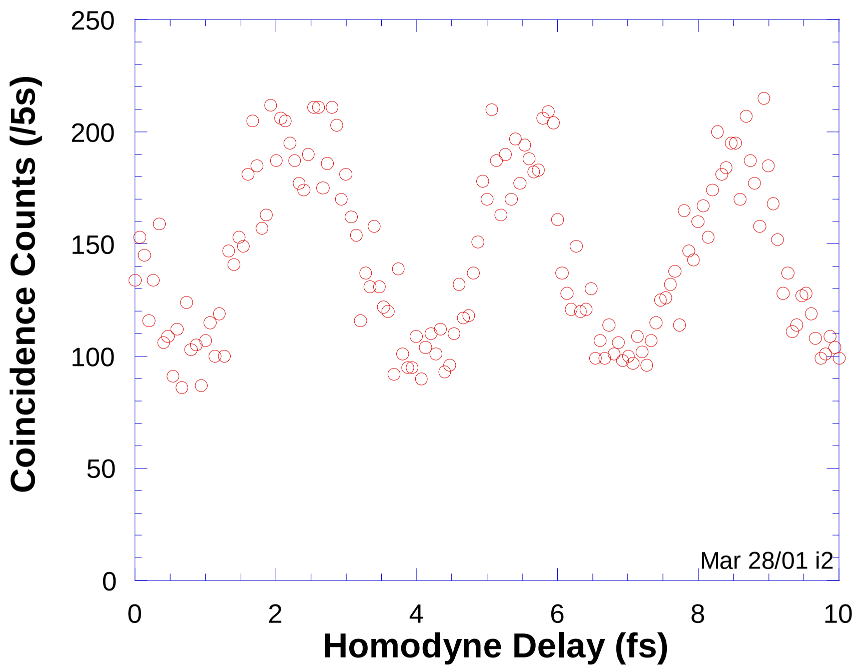
A|0>+B|1>

Experimental

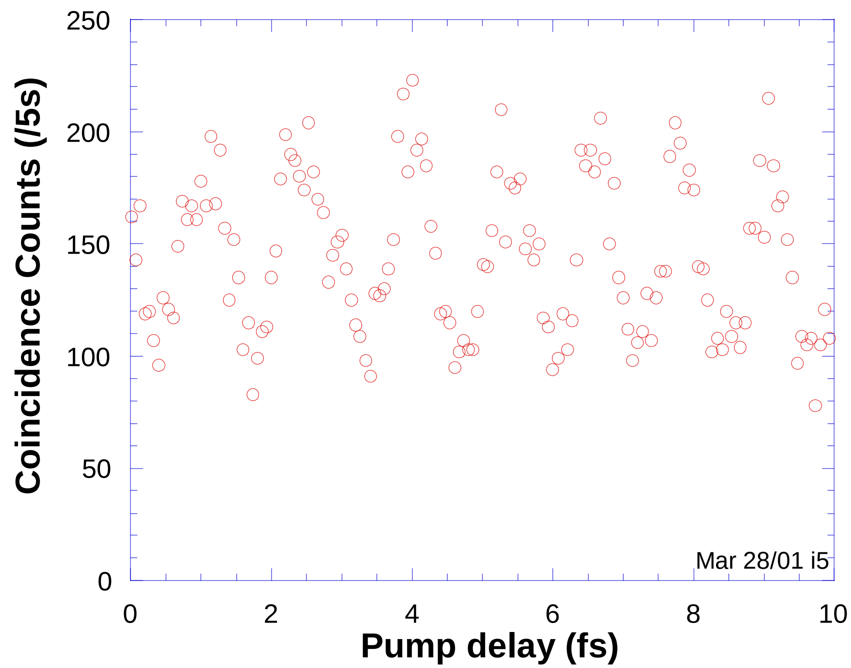


Conditional coherence

Coincidences vs. Homodyne Delay



Coincidences vs. Pump Delay



Conditional coherence (theory)

$$\left|\psi\right\rangle_{init} = \left|\alpha\right\rangle_s \left|0\right\rangle_i \left|\gamma\right\rangle_{pump}$$

No Stimulated Emission terms

$$\xrightarrow{\chi^{(2)},\Delta t} \left(\left|0\right\rangle_s + \alpha\left|1\right\rangle_s\right)\left|0\right\rangle_i - \frac{i\Delta t}{\hbar} g\gamma\left|1\right\rangle_s\left|1\right\rangle_i$$

$$= \left|0\right\rangle_s \left(\left|\mathbf{0}\right\rangle_{\mathbf{i}}\right) + \left|1\right\rangle_s \left(\alpha\left|\mathbf{0}\right\rangle_{\mathbf{i}} - \frac{\mathbf{i\Delta t}}{\hbar}\mathbf{g}\gamma\left|\mathbf{1}\right\rangle_{\mathbf{i}}\right)$$

- If $A_{DC} << A_{LO}$, then idler is conditionally in a weak coherent state
- Phase is set to difference between the pump phase and the signal coherent state

Conditional coherence (theory)

$$|\psi\rangle_{init} = |\alpha\rangle_1 |0\rangle_2 |\gamma\rangle_{pump}$$

$$\xrightarrow{\chi^{(2)},\Delta t} \left(|0\rangle_1 + \alpha|1\rangle_1\right)|0\rangle_2 - \frac{i\Delta t}{\hbar} g\gamma |1\rangle_1 |1\rangle_2$$

$$= |0\rangle_1|0\rangle_2 + \alpha|1\rangle_1|0\rangle_2 - \frac{i\Delta t}{\hbar} g\gamma |1\rangle_1|1\rangle_2$$

No Stimulated Emission terms

Conditioned on the detection of a photon in mode 1

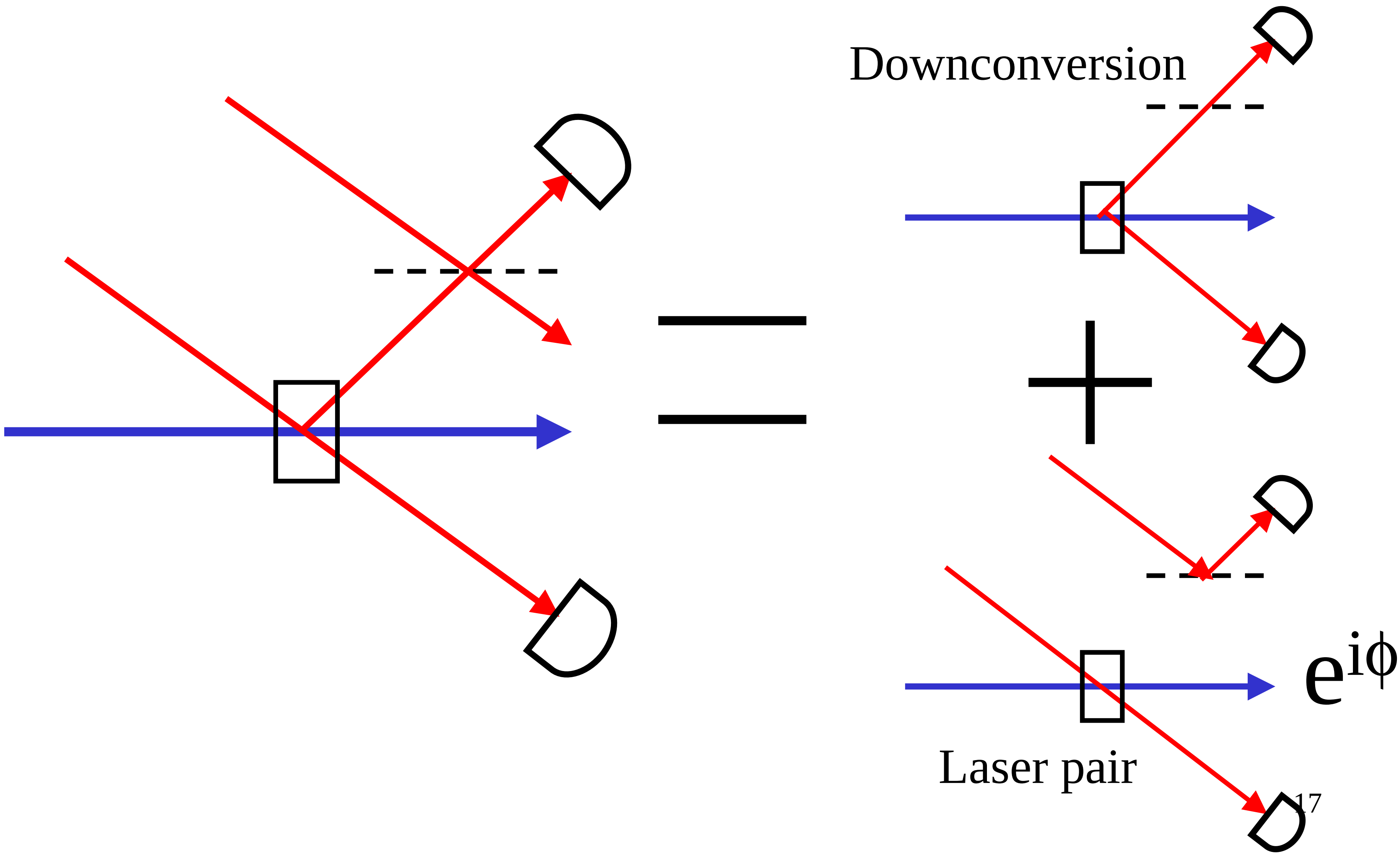
$$|\phi\rangle \approx \alpha|0\rangle_2 - \frac{i\Delta t}{\hbar} g\gamma|1\rangle_2$$

$$\approx |0\rangle_2 - \frac{i\Delta t}{\hbar} g \frac{|\gamma|}{|\alpha|} \exp i(\varphi_\gamma - \varphi_\alpha)|1\rangle_2$$

A weak C.S if small

Fixed phase

Interference between two paths



Intuitive “classical” explanation

- Down-conversion beams have a well-defined phase ***sum*** set by pump laser.

  Koashi et al. (1994) , Kuzmich et al. (2000), discussed in L.Mandel (90s)

- The weak laser interferes constructively with certain signal phases, and interferes destructively with others. This creates a correlation between the idler phase and the intensity of the light in the signal mode.

- Predicts the correlation, but the quantum effect can be stronger (higher visibility)

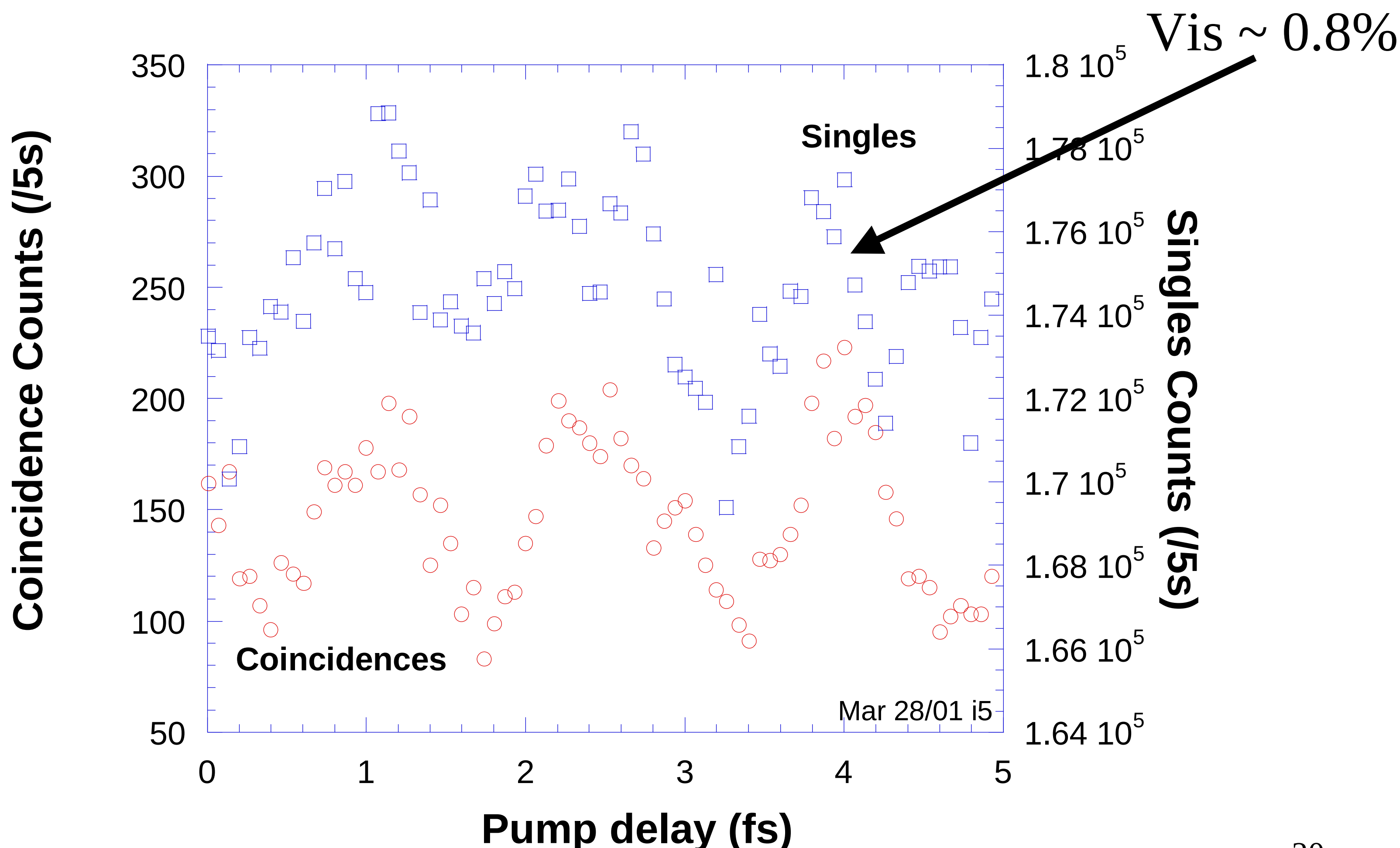
Difference-frequency generation

- Experiment looks similar to OPA, but the interference effect in coincidence rate cannot be explained by DFG

- If the signal and pump lasers are bright enough (much greater than one photon per pulse), then the light in the idler mode is *unconditionally* in a coherent state. If DFG was the cause of the effect, then the singles and coincidence visibilities would be the same.

- Expected to see some evidence of this “unconditional coherence” effect at <1.0%

Effect explainable by DFG? unconditional coherence



Classical limit – DFG

$$|\psi\rangle_{init} = |\alpha\rangle_1 |0\rangle_2 |\gamma\rangle_p$$

Take $|\gamma|$, and $|\alpha|$ to be >>1

$$H_{int} = g a_1^+ a_2^+ a_p + g^* a_1 a_2 a_p^+ \approx g\alpha^* \gamma a_2^+ + g^* \alpha \gamma^* a_2$$

$$\exp\left(-\frac{iH_{int} t}{\hbar}\right) = \exp\left(-\frac{it}{\hbar}\left(g\alpha^*\gamma a_2^+ + g^*\alpha\gamma^* a_2\right)\right)$$

➢ Define, $A = -\frac{it}{\hbar} g\alpha^* \gamma$

$$\exp\left(-\frac{iHt}{\hbar}\right) = \boxed{\exp(A a_2^+ - A^* a_2)} = \hat{A}$$

Coherent state creation operator

$$\hat{A}|0\rangle = |A\rangle = \exp\left(-\frac{|A|^2}{2}\right)\sum_n \frac{A^n}{\sqrt{n!}}|n\rangle$$

Summary

- Introducing a weak coherent state can weaken the number correlations in SPDC. The idler is collapsed to a weak coherent state conditioned on the detection of a single signal photon.

- Related to the two crystal experiment on induced coherence (Zou, Wang, Mandel 1991) → Unconditional, no "absolute" phase reference.

- "Asymmetric entanglement"

- State preparation (Hardy, Clausen)