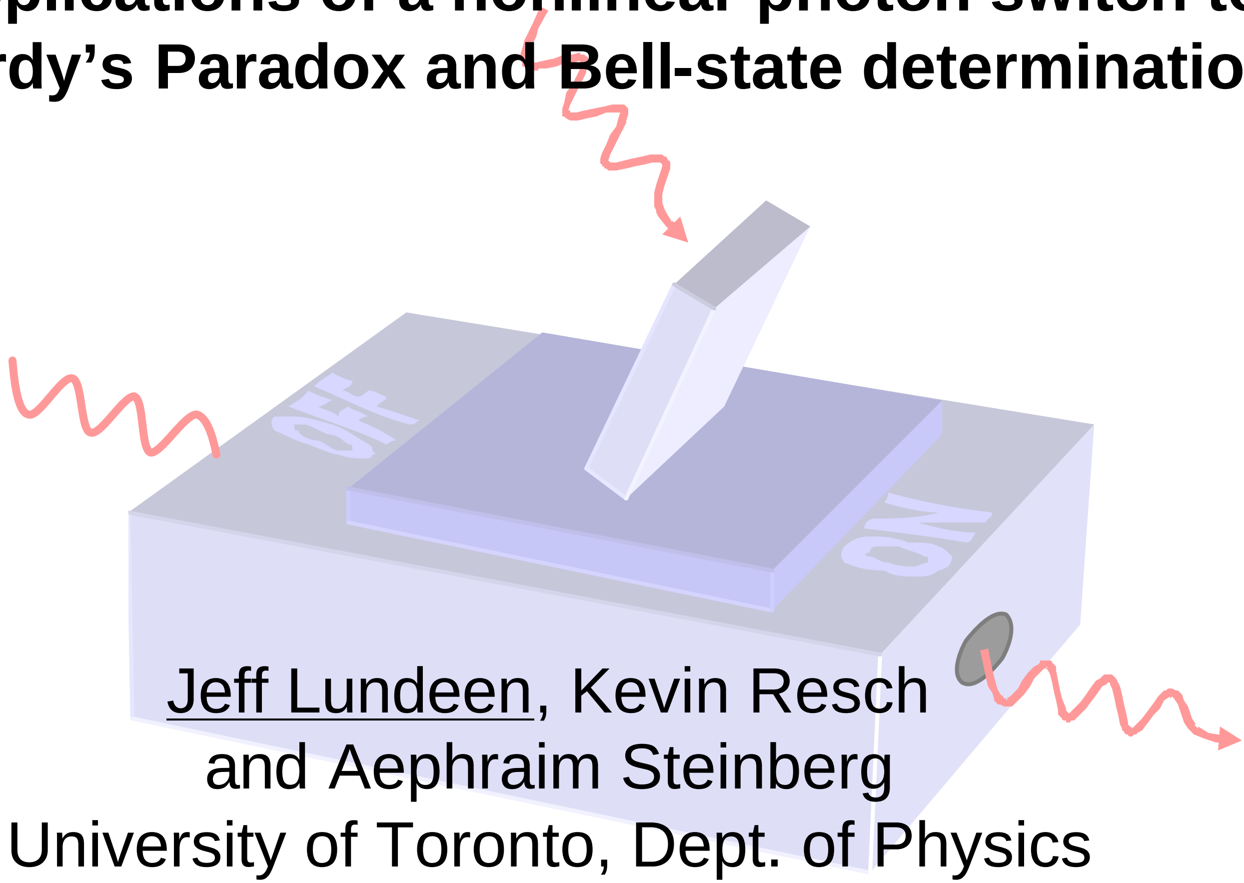
Applications of a nonlinear photon switch to Hardy's Paradox and Bell-state determination



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PQE XXXV

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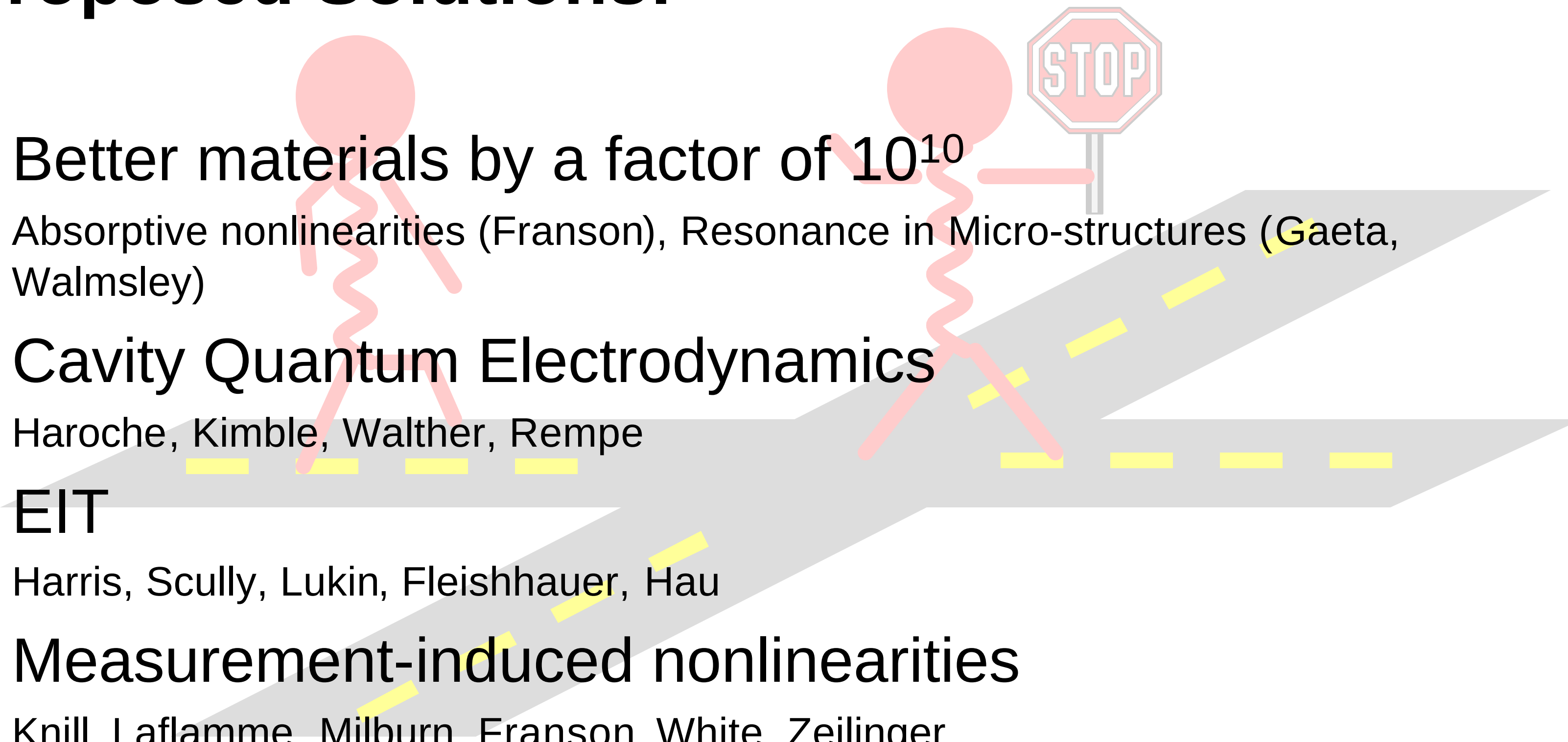
Can we construct a two-photon gate?

Photons do not naturally interact: Great for transmission. Not so great for calculation.

Proposed Solutions:



- Better materials by a factor of 10^{10}

  Absorptive nonlinearities (Franson), Resonance in Micro-structures (Gaeta, Walmsley)

- Cavity Quantum Electrodynamics

  Haroche, Kimble, Walther, Rempe

- EIT

  Harris, Scully, Lukin, Fleishhauer, Hau

- Measurement-induced nonlinearities

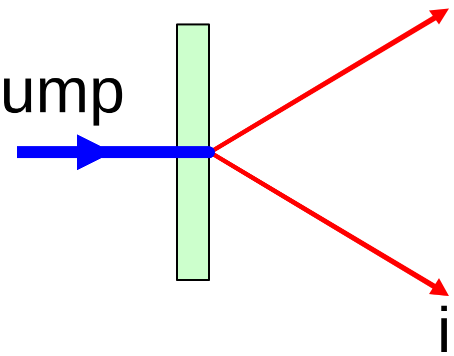
  Knill, Laflamme, Milburn, Franson, White, Zeilinger

- Interference-enhanced nonlinearities

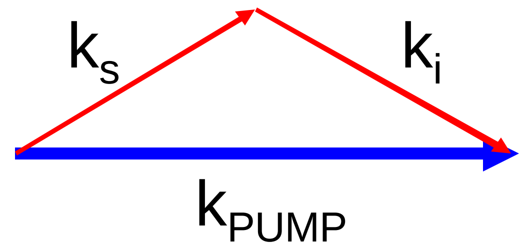
  Exchange effects in atomic clouds (Franson), $\chi^{(2)}$ with interference (Steinberg)

Spontaneous Parametric Downconversion

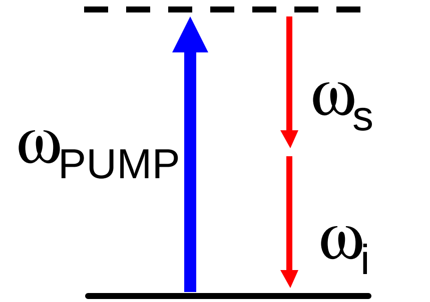
Downconversion



Momentum is conserved..



..as well as energy

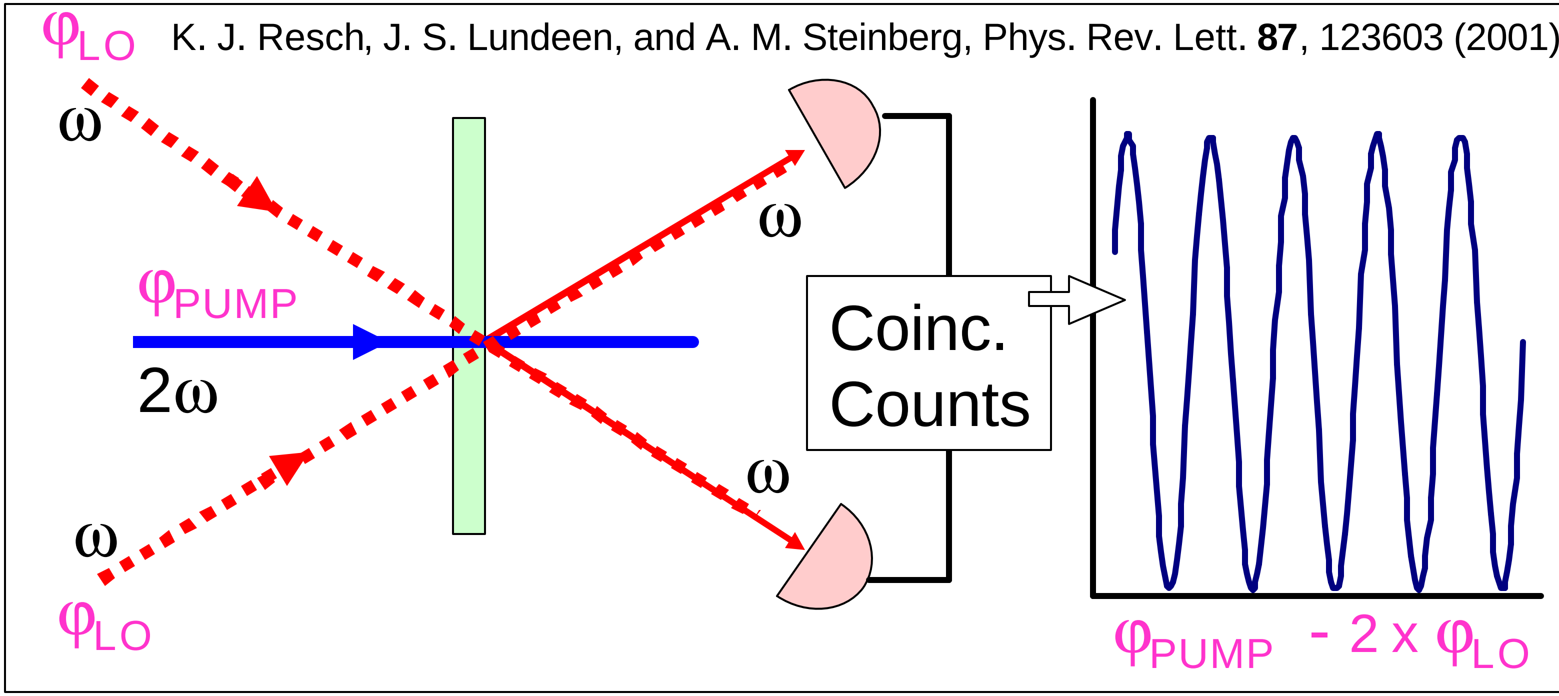


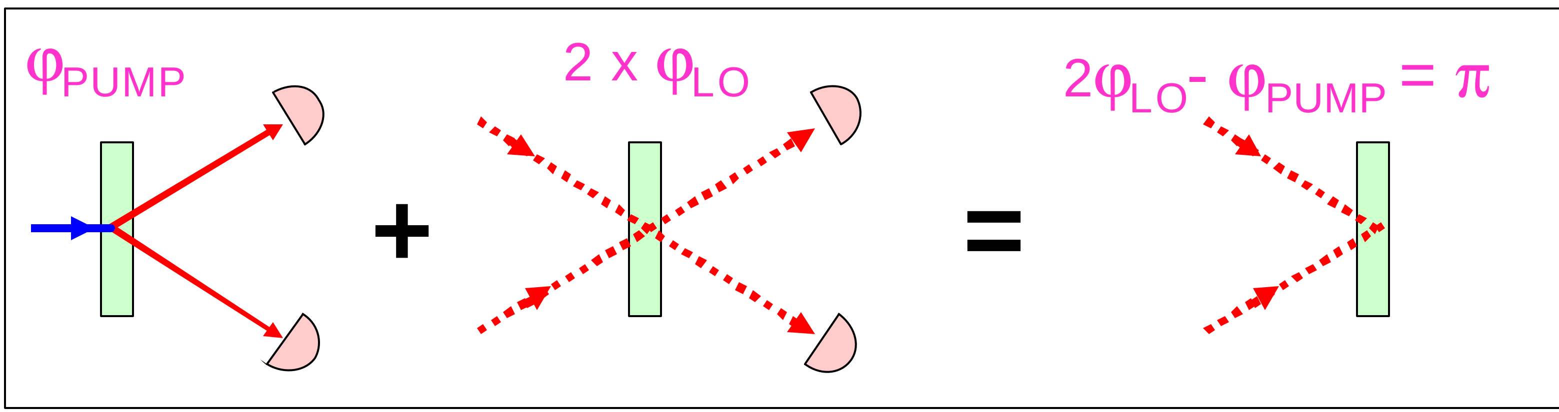
$$\varphi_{PUMP} = \varphi_s + \varphi_i$$

- A pump photon is spontaneously converted into two lower frequency photons in a material with a nonzero $\chi^{(2)}$

The Switch

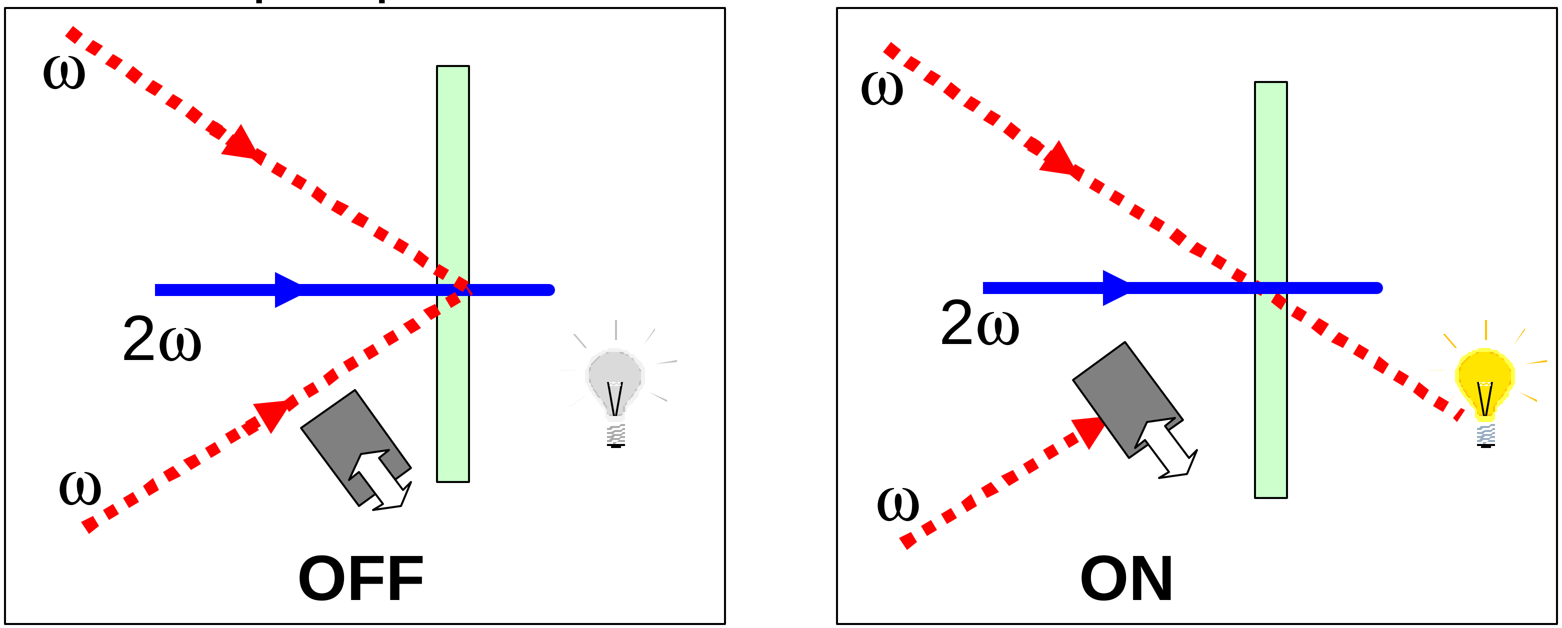
K. J. Resch, J. S. Lundeen, and A. M. Steinberg, Phys. Rev. Lett. **87**, 123603 (2001).





The Absorptive Gate

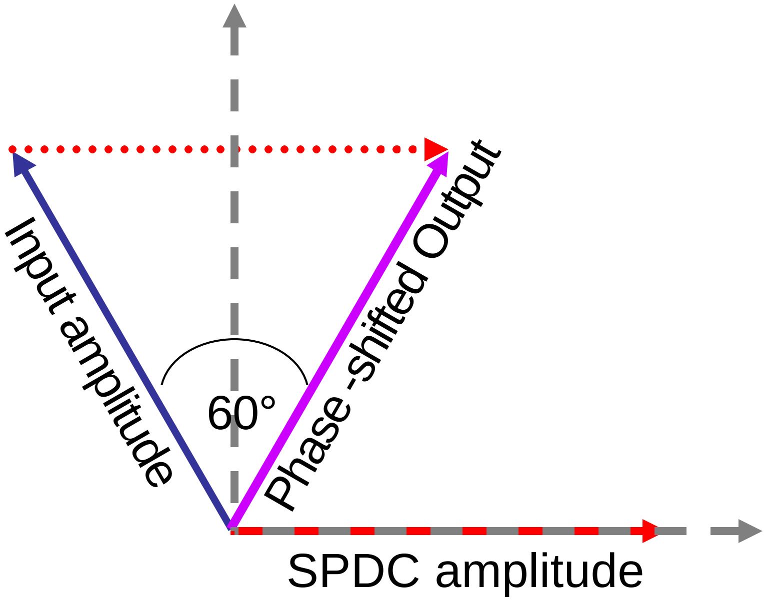
- Phase chosen so that all photon pairs are “absorbed” into the pump beam



- On average < 1 photon per pulse
- One photon controls the transmission of the other beam
- The blue pump beam acts as a catalyst increasing SHG by a factor of 10^{10}

The Phase Gate

- Set two-photon amplitudes so that they add up to give a phase-shifted output



a|00⟩ + ß|10⟩ + ?|01⟩ +d|11⟩

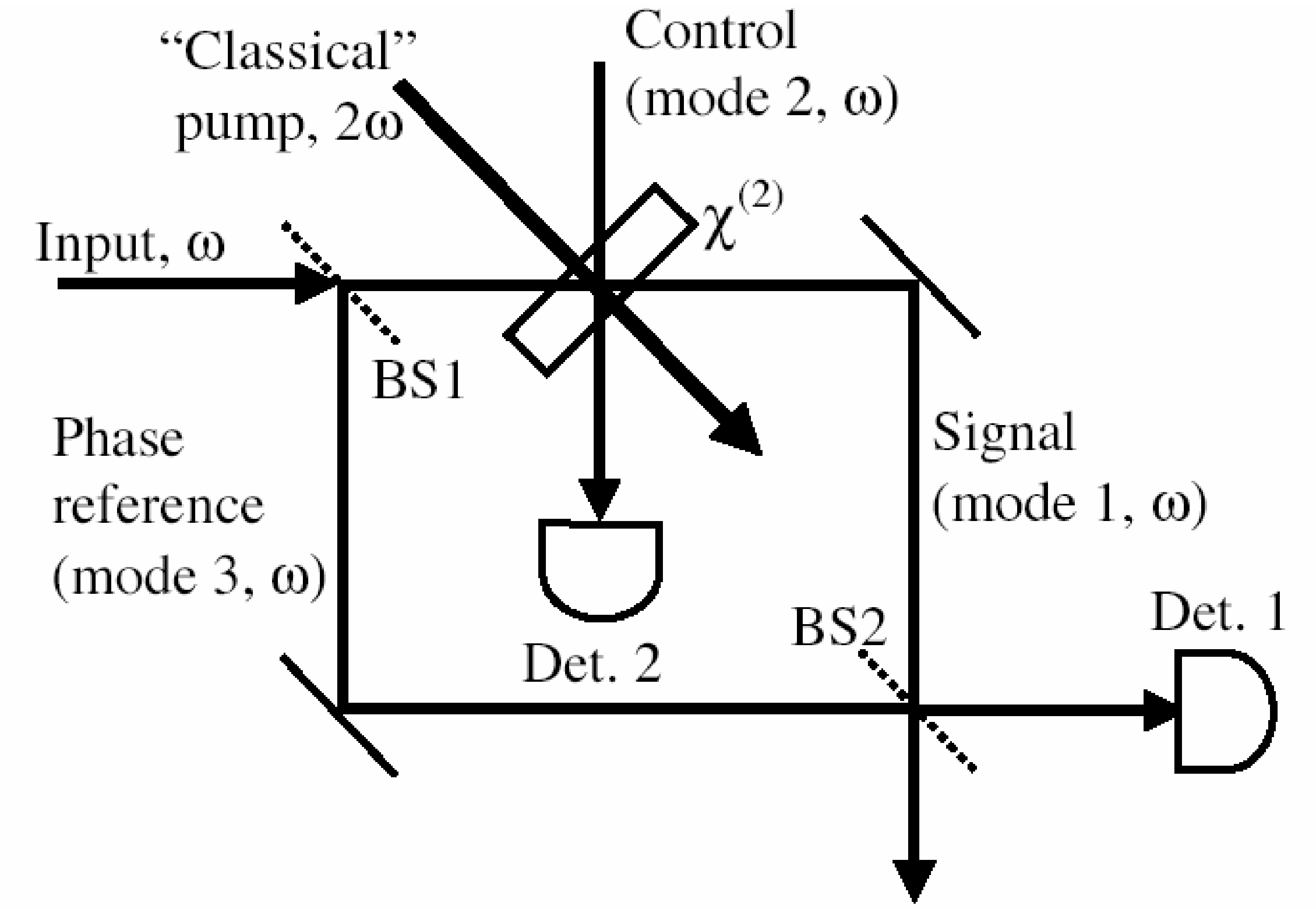
⇓

a|00⟩ + ß|10⟩ + ?|01⟩ +d$e^{ip/3}$|11⟩

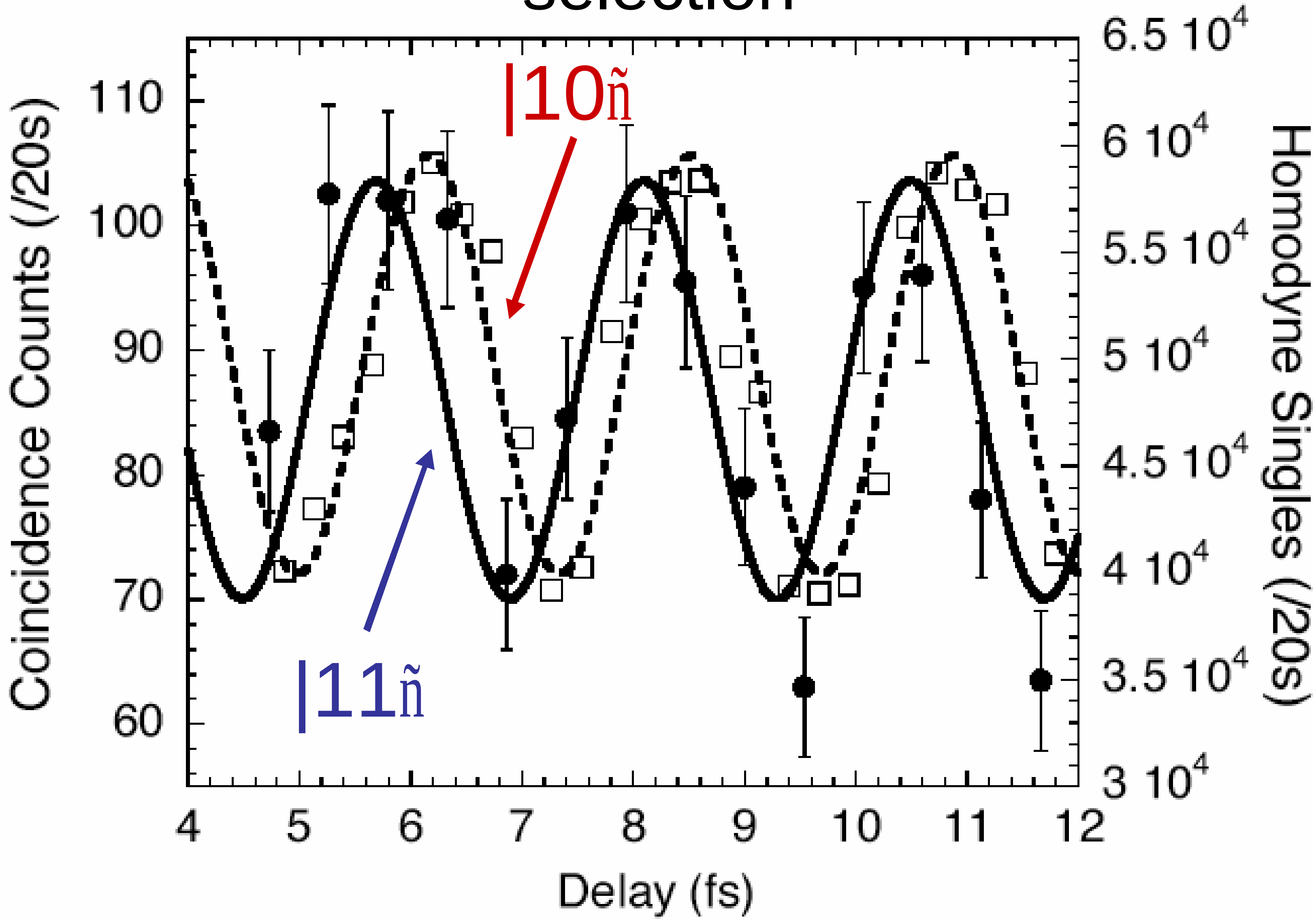
Resch et al, Phys. Rev. Lett. 89, 037914 (2002)

Measurement of Phase-shift

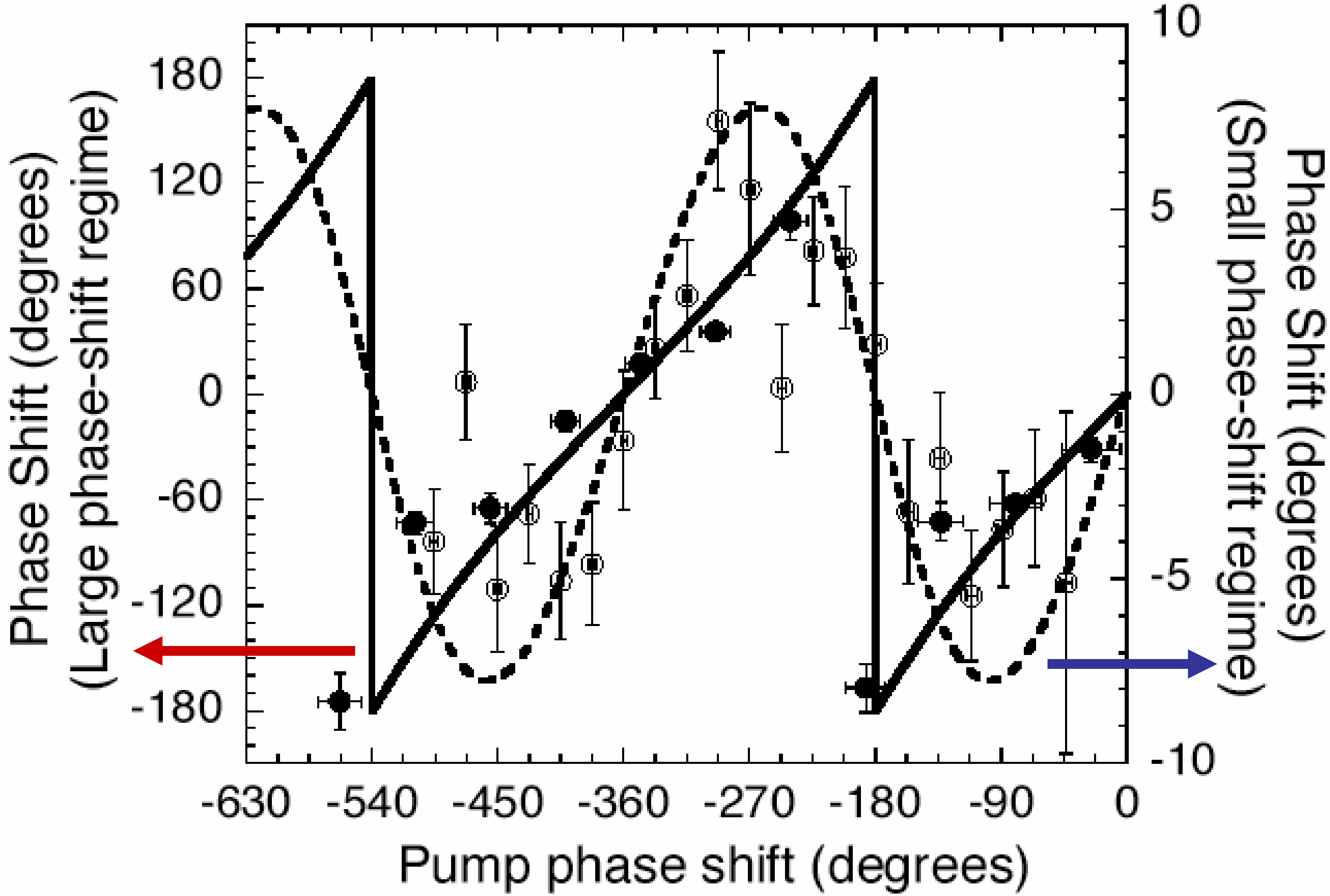
- Turn one of the input beams into a Mach-Zehnder and insert gate in one arm



Interference Fringes with and without Post-selection



Variable Phase-Shifts

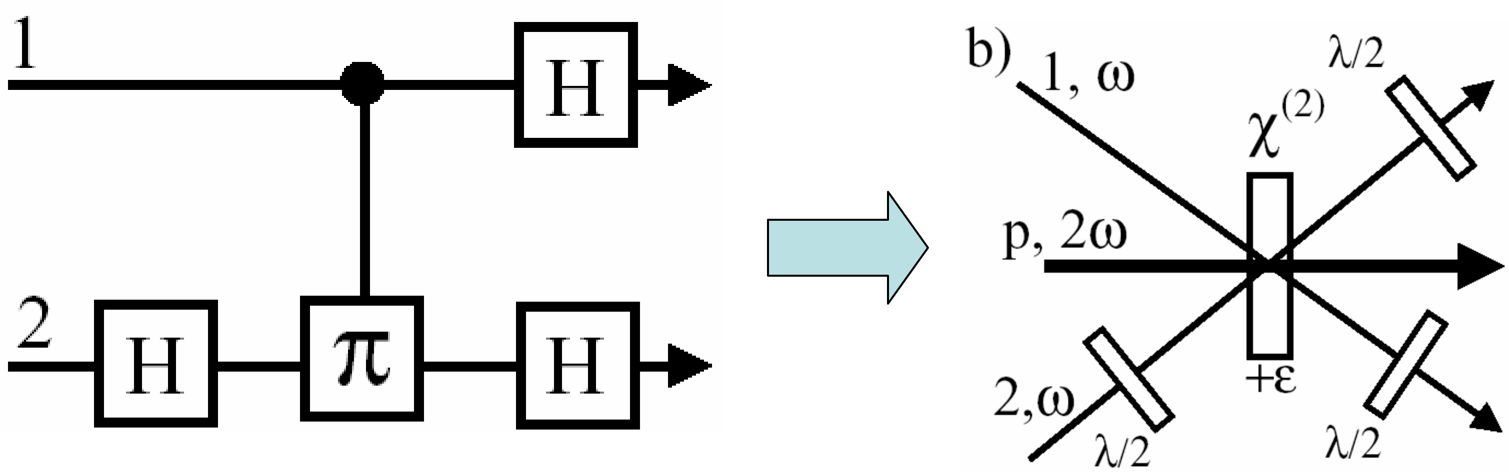


Caveats

- Typically, optical quantum computing uses single photons
- Single-photons do not have a well defined phase
- Both the absorptive gate and the phase gate rely on interference and hence require input beams with a well defined phase
- In practice: Input beams = weak coherent states or SPDC beams
- Concept: We can't know in advance whether the input beams contain a photon or not

Bell-state Analyzer

- Impossible to measure all four Bell-states with linear-optics



- Converts each Bell-state to a different basis state (i.e. |?ñ **?** |HHñ)

- Insert interference-based phase-gate in place of CPHASE

- Works for Dense-Coding (send 2 bits with one photon)

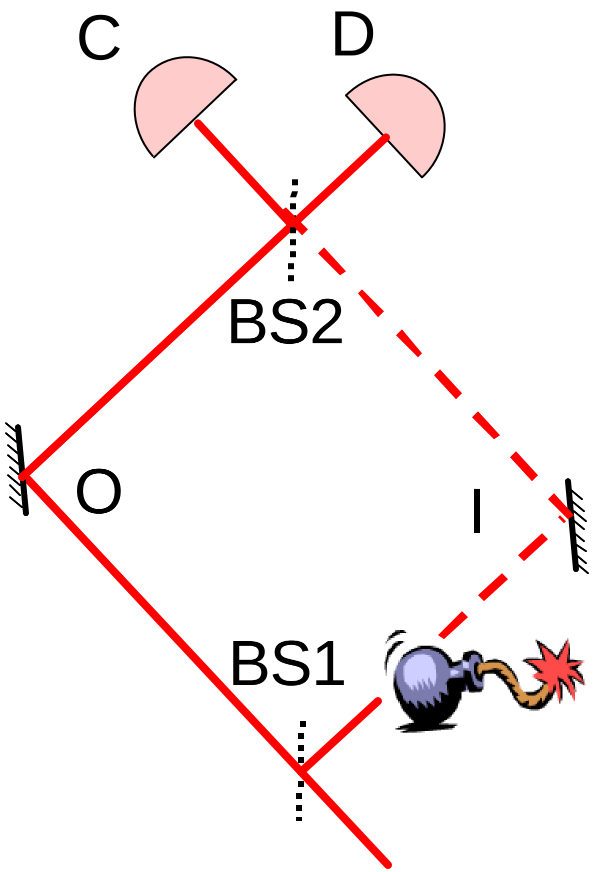
- Doesn't work for Teleportation

$$|0\rangle - \varepsilon\,|\psi^-\rangle \longrightarrow |0\rangle + \varepsilon\,|H\rangle_1\,|H\rangle_2$$
$$|0\rangle - \varepsilon\,|\psi^+\rangle \longrightarrow |0\rangle + \varepsilon\,|H\rangle_1\,|V\rangle_2$$
$$|0\rangle - \varepsilon\,|\phi^-\rangle \longrightarrow |0\rangle + \varepsilon\,|V\rangle_1\,|H\rangle_2$$
$$|0\rangle - \varepsilon\,|\phi^+\rangle \longrightarrow |0\rangle + \varepsilon\,|V\rangle_1\,|V\rangle_2$$

Resch and Al, in *The Physics of Communication*, Proc. XXII Solvay Conf. on Physics, Antoniou, Sadovnichy, and Walther eds., World Scientific (2003), pp 437-451.

Interaction-Free Measurement

A. C. Elitzur, and L. Vaidman, Found. Phys. **23**, 987 (1993)



Bomb Absent:

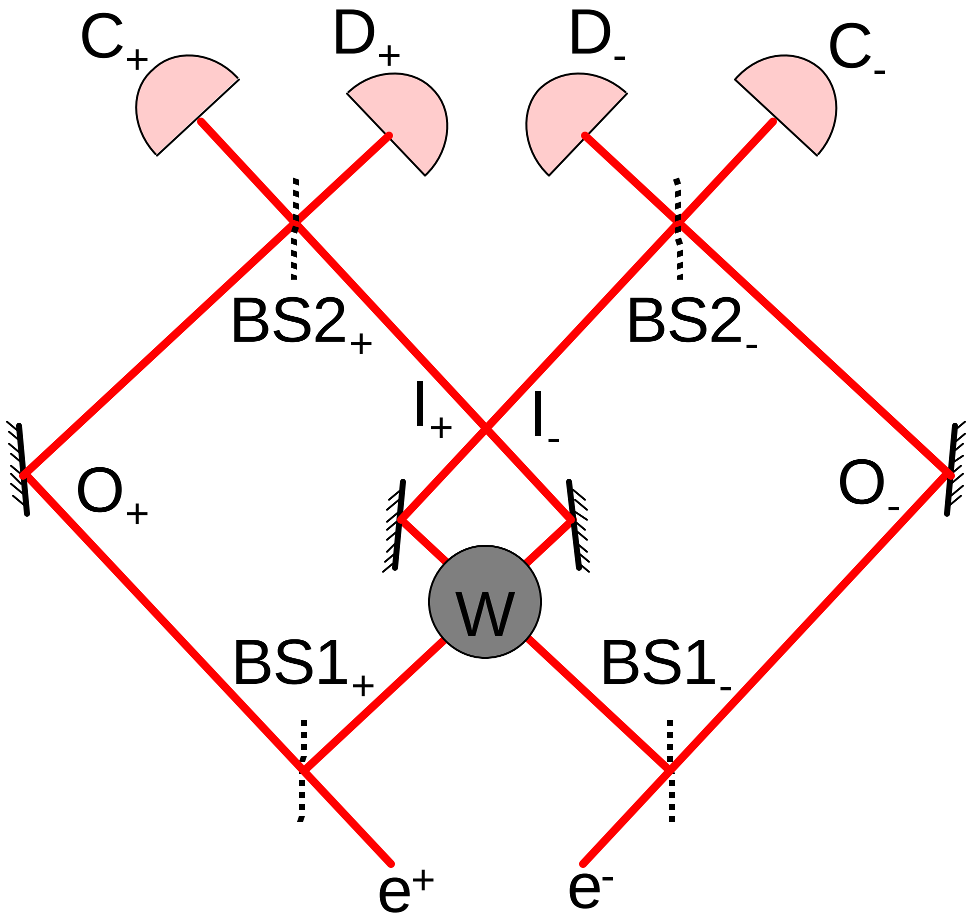
Only detector C fires

Bomb Present:

Detector	**Prob.**	**Result**
C	¼	None
D	¼	Present
Neither	½	Bang

Hardy's Paradox

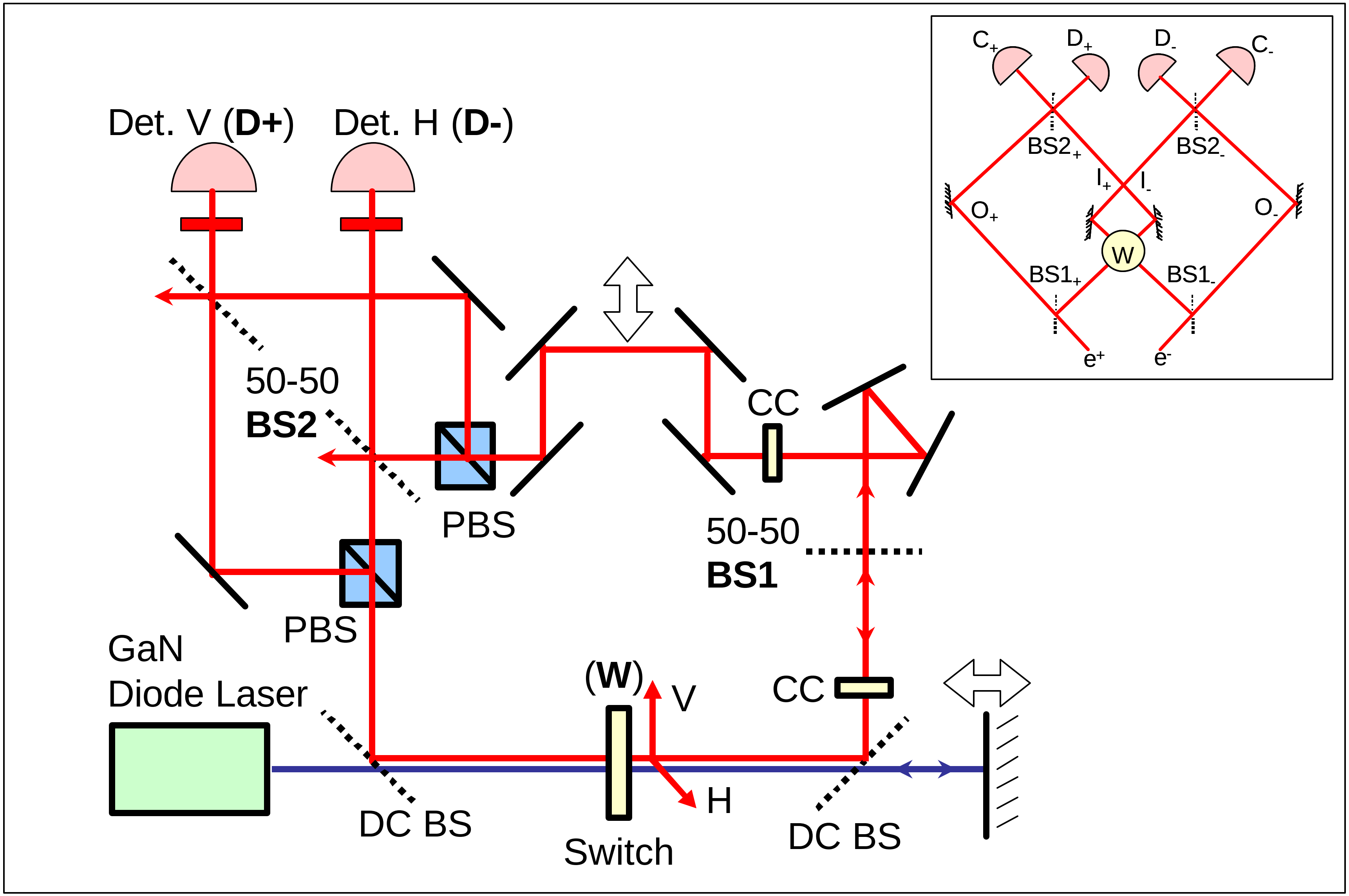
L. Hardy, Phys. Rev. Lett. **68**, 2981 (1992)



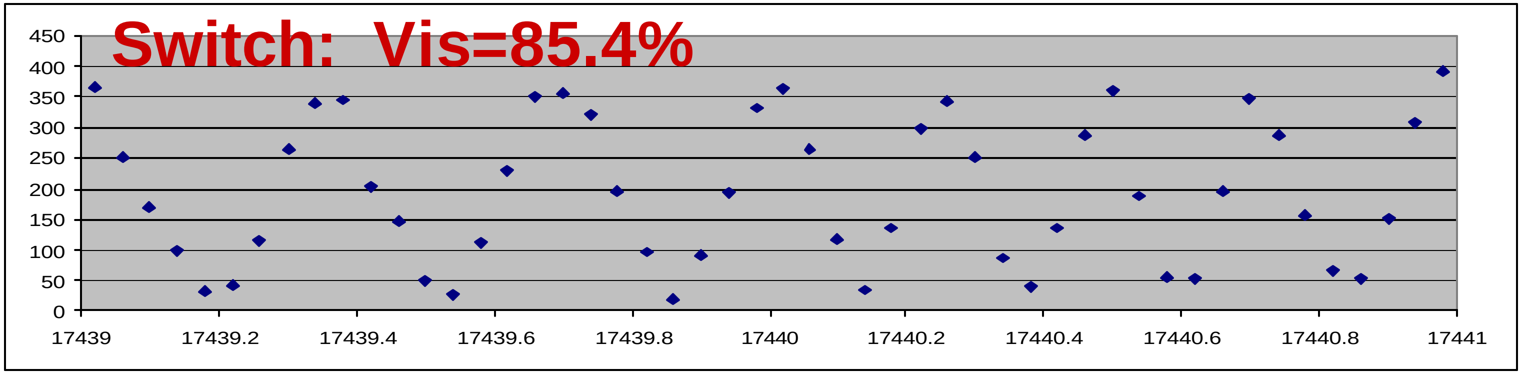
Outcome	Prob
D_+ and C_-	1/16
D_- and C_+	1/16
C_+ and C_-	9/16
D_+ and D_-	1/16
Explosion	4/16

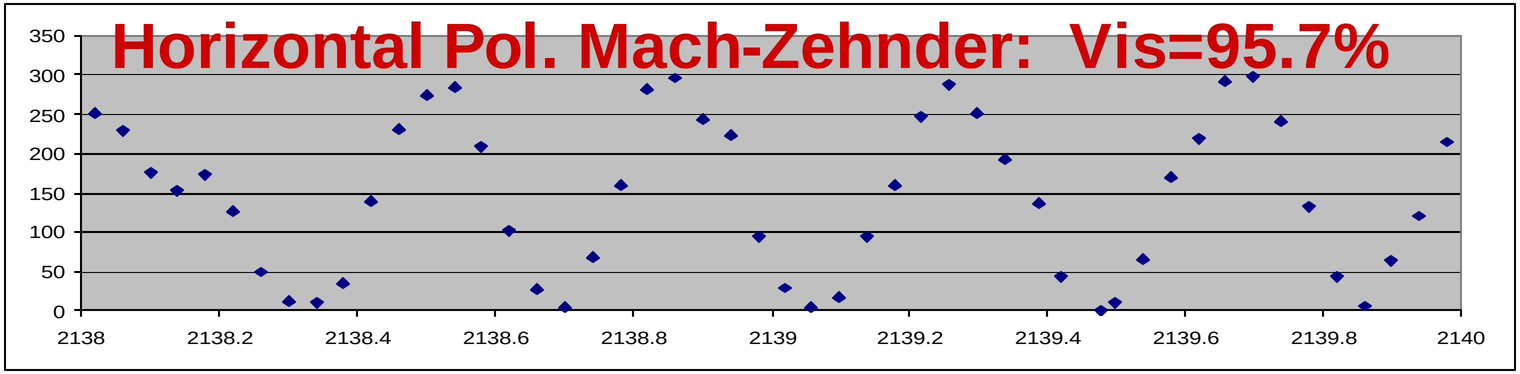
- Can we talk about the past in postselected QM?
- How should we interpret indirect quantum measurements?

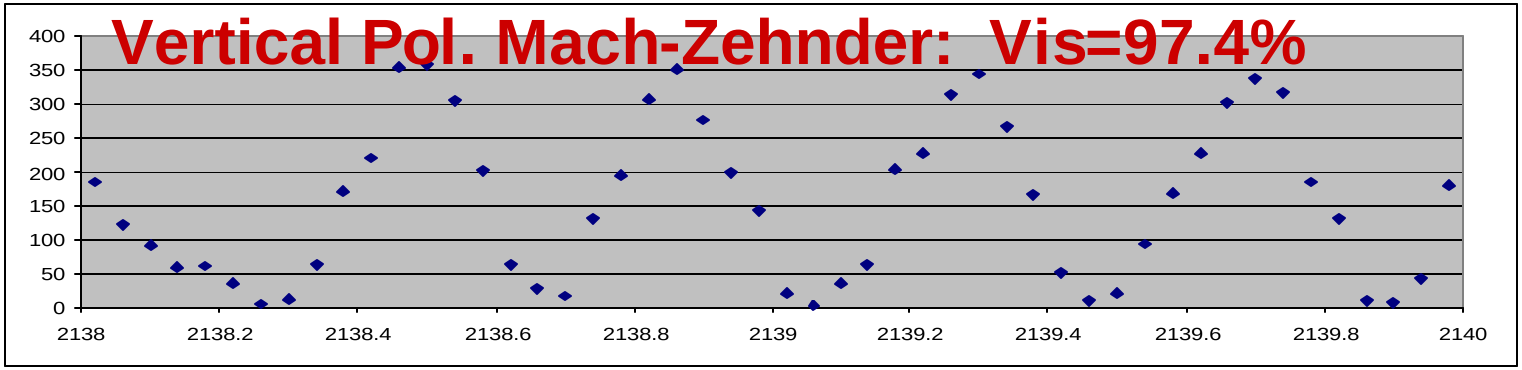
Experimental Setup



Experimental Data







Experimental Data

Testing IFM+

If D+ clicks Þ

Photon is in arm I-	96%
Photon is in arm O-	4%

Testing IFM-

If D- clicks Þ

Photon is in arm I+	97%
Photon is in arm O+	3%

Testing Switch

Rate of photon pairs in I+ and I-
= 10.4 ± 0.33/5s

The Paradox

Rate of D+ and D- coincidences
= 7.28 ± 0.41/5s

Weak Measurements

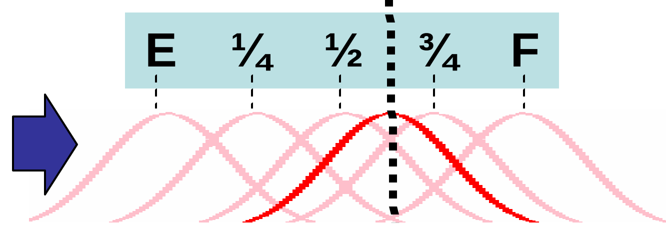
Aharonov, Albert,&Vaidman , PRL 60, 1351 ('88)

Measurement	**Pointer Position Uncertainty**
Ideal	Dirac Delta
Real	Width << Change in Position
Weak	Width >> Change in Position

Average position of pointer:

Pointer(X) = $\exp[-(X - gA_W)^2 / \Delta X]$

$$A_W = \frac{\langle\phi|A|\psi\rangle}{\langle\phi|\psi\rangle}$$



$\Delta X \Delta P \geq h/2\pi$

⇒ small disturbance

⇒ little system – pointer entanglement

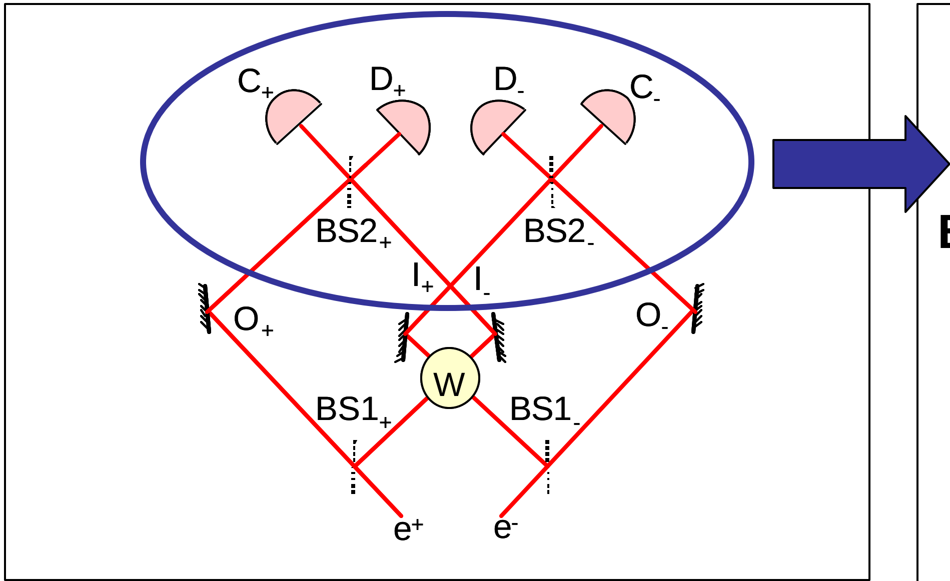
⇒ simultaneous measurement of different weak values

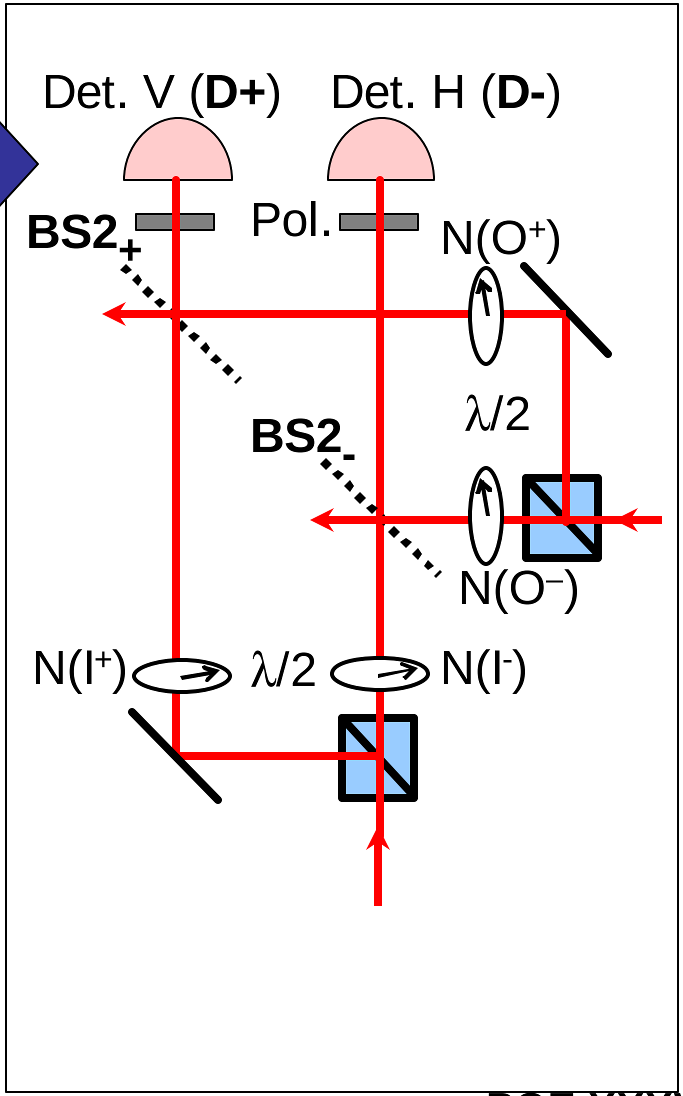
⇒ useful for investigating post-selected systems: Hardy's Paradox

Weak Measurements in Hardy's Paradox

Y. Aharanov, A. Botero, S. Popescu, B. Reznik, J. Tollaksen, Phys. Lett. A 301, 130 (2001)

Resch &Steinberg, PRL 92,130402 (2004)





# In Arm	N(I-)	N(O−)	
N(I+)	0	1	1
N(O+)	1	-1	0
	1	0	

Conclusions

- Interference-enhanced $\chi^{(2)}$ nonlinearities can be used to make absorptive and phase gates

- The phase-gate can be used to make a Bell-state analyzer useful for Dense-coding

- A single-photon level switch allows photons to annihilate each other with a high efficiency in Hardy's Paradox

- We are now experimenting with weak measurements in Hardy's Paradox.