THE AUSTRALIAN NATIONAL UNIVERSITY

2004 Quantum Optics Group

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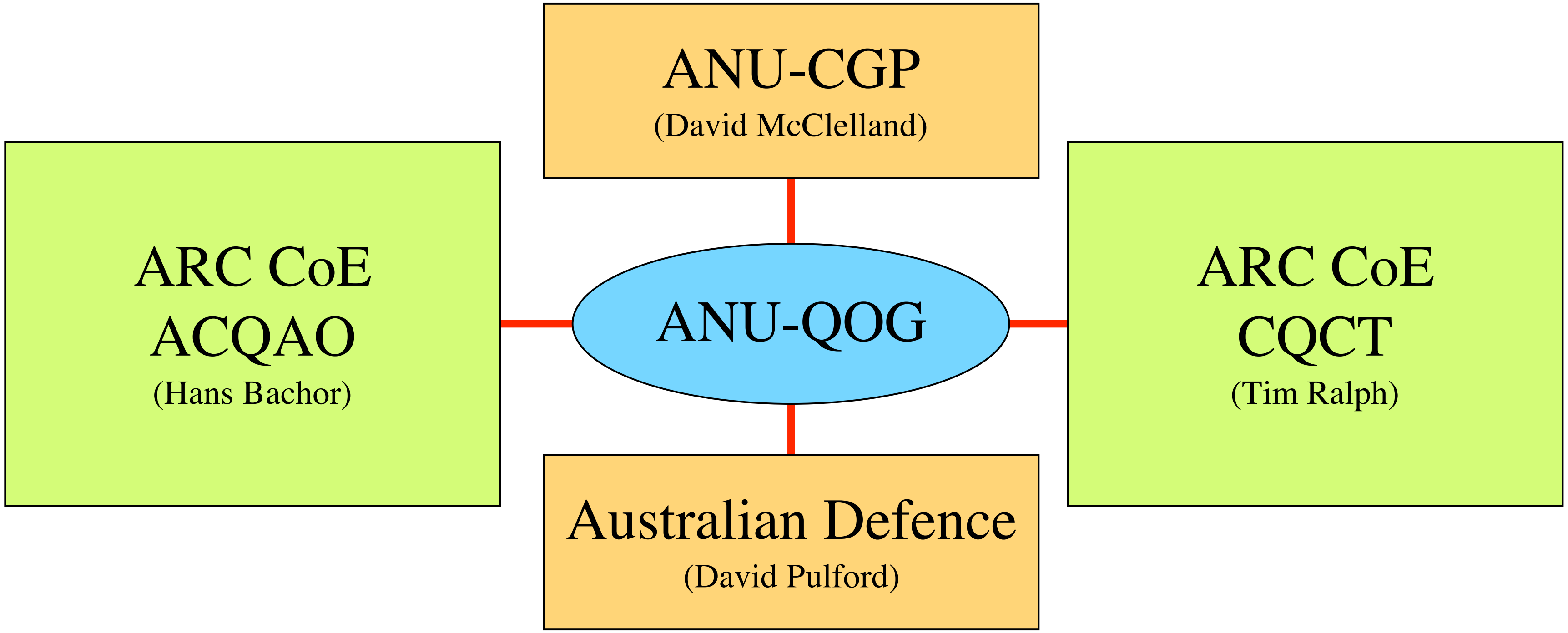
ANU QUANTUM OPTICS

Papers and Projects in 2004



- 12 Refereed articles in 2003
- 10 Refereed articles in 2004

- Tripartite quantum state sharing
  - Phys. Rev. Lett. 92, 177903 (2004).
- Squeezing in the audio gravitational-wave detection band
  - Phys. Rev. Lett. 93, 161105 (2004).
- Quantum cryptography without switching
  - Phys.Rev. Lett. 93, 170504 (2004).

Our presentation

- Ping Koy:
  - Audio frequency squeezing experiment.

McKenzie, Grosse, Bowen, Gray, McClelland and Lam, *Phys*. *Rev*. *Lett*. **93**, 161105 (2004)

- Ping Koy:
  - Quantum cryptography theory

Weedbrook, Lance, Bowen, Symul, Ralph and Lam, *Phys*. *Rev*. *Lett*., **93**, 170504 (2004)

- Thomas:
  - Quantum cryptography experiment.

Could we have another *Phys*. *Rev*. *Lett*. Please?

Audio Freq. Sqz for Grav. Wave Detection

Kirk McKenzie`*, Nicolai Grosse*, Warwick Bowen*, Stanley Whitcomb†,
Malcolm Gray`, David McClelland` and Ping Koy Lam`*

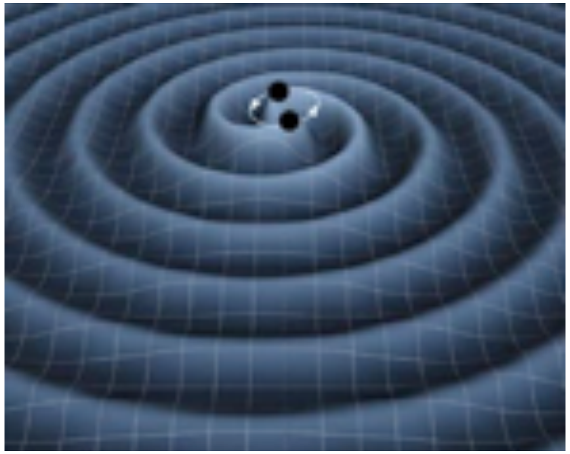
`The Center for Gravitational Physics

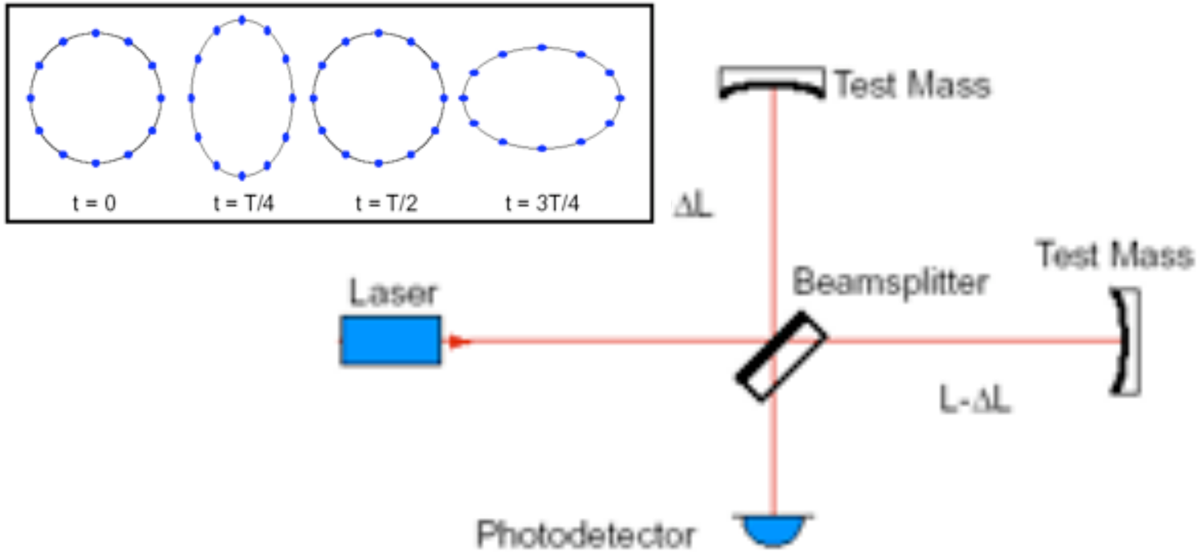
*The Quantum Optics Group

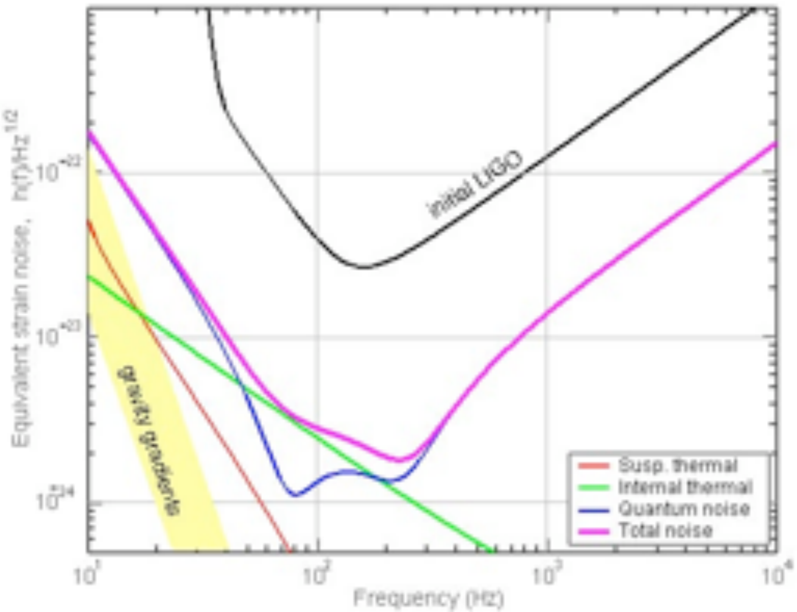
†Californian Institute of Technology

Gravitational Waves

Black Hole Binary &
Ripples in Space-Time





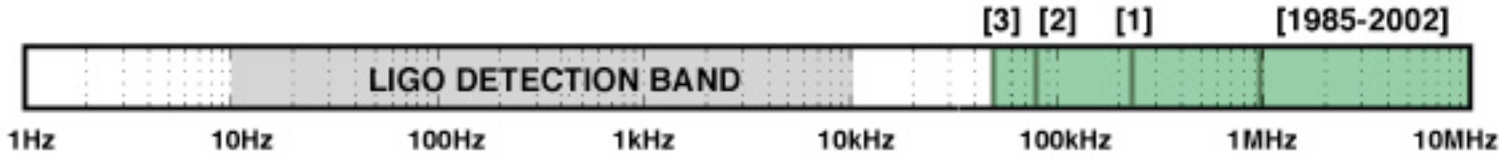


Techniques for reducing optical noise

- Nonlinear / quantum technique
- Common mode rejection technique
- Active feedback control technique
- Passive environmental stabilization technique

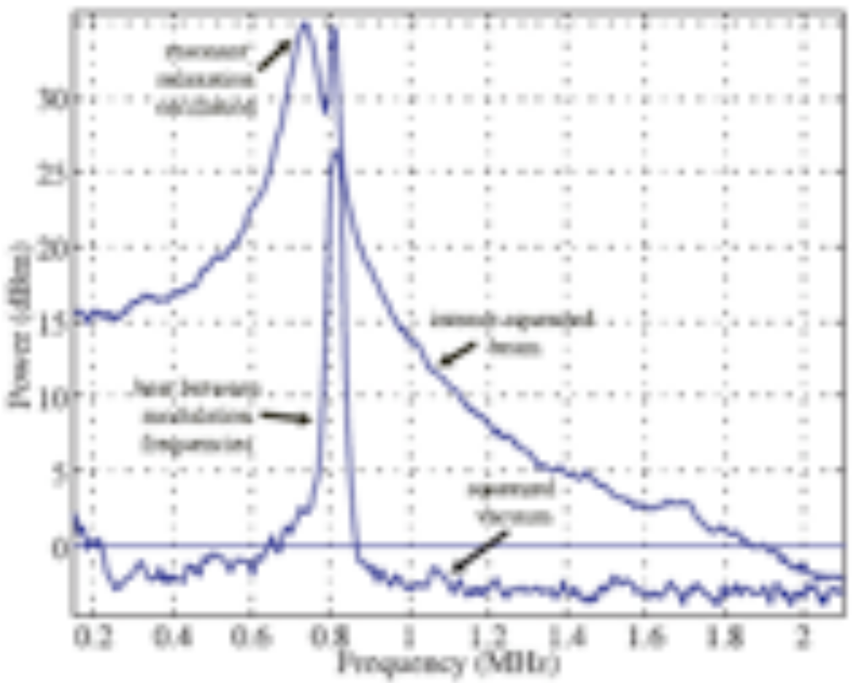
- Resonant relaxation oscillation noise
- Laser phase noise
- Photo-refractive noise (phase matching)
- Photo-expansive noise (heating)
- Pump noise (green light)
- Seed noise (IR light)
- Quantum noise
- Acousto-optic noise
- Electro-optic noise
- Electrical noise (power supplies)
- Cross talk (lack of balancing, polarization extinction)
- Beam pointing noise
- Detector noise
- Resonator noise (detuning)
- Compound cavity/ Intra-cavity noise

Previous Low Frequency Results



- Recent CW LF Results include
  - 220kHz -W.P. Bowen *et al*. [1]
  - 80kHz - R. Schnabel *et al*. [2]
  - 50kHz - J. Laurat *et al*. [3]

All experiments rely mostly on common mode noise cancellation!



[1] W.P. Bowen *et al*. J. Opt. B **4** 421 (2002)
[2] R. Schnabel *et al*. arXiv quant-ph/0402064 (2004)
[3] J. Laurat *et al* arXiv:quant-ph/0403224 (2004)

OPA/OPO Theory II

The variances in the frequency domain for the OPA/OPO output are;

$$V_{OUT}^{\pm}(\omega) = C_s V_s^{\pm}(\omega) + C_l V_l^{\pm}(\omega) + C_v^{\pm}(\omega) V_v^{\pm}(\omega) + \alpha^2 \left(C_p V_p^{\pm}(\omega) + C_{\Delta}^{\pm} V_{\Delta}^{-}(\omega) \right)$$

↑	↑	↑	↑	↑
Seed	Loss	Vacuum	Pump	Detuning
(f < 2MHz)			(f < 2MHz)	(f < 50kHz)

For below threshold OPO $\alpha = 0$ and $V_s^{\pm} = 1$;

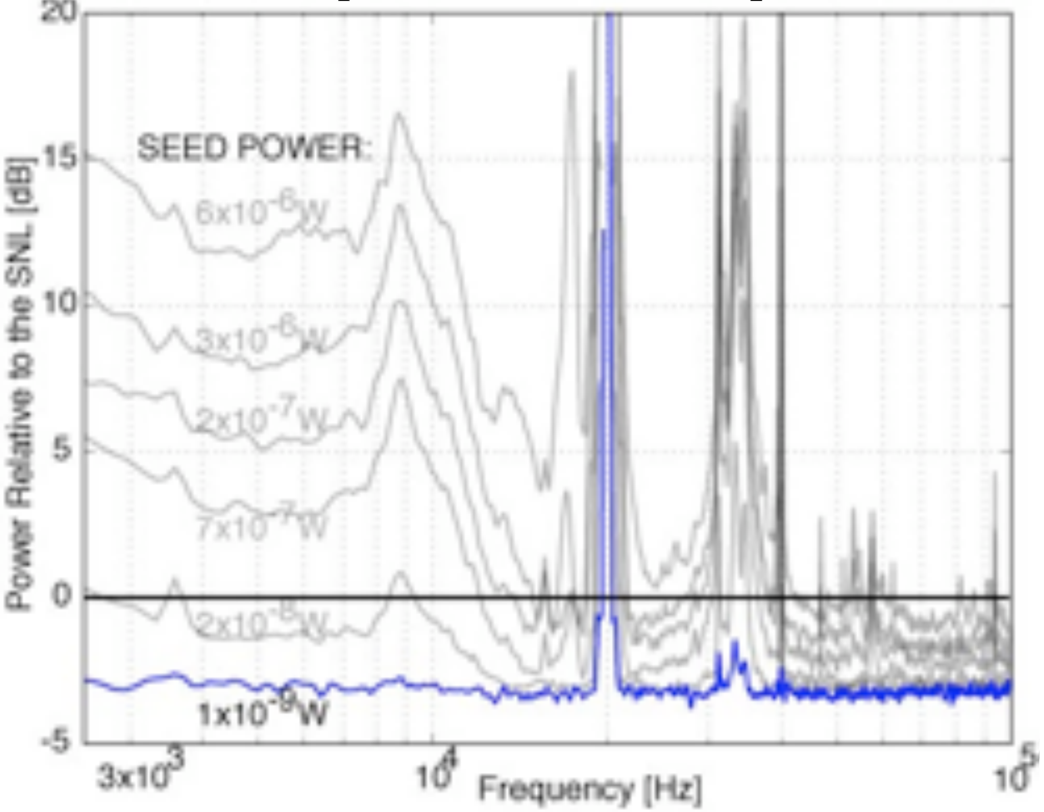
$$V_{OPO}^{\pm}(\omega) = C_s + C_l + C_v^{\pm}(\omega)$$

OPO is immune to laser noise, pump noise and detuning noise!

No one really have experimentally done an OPO squeezing experiment properly!

OPA Squeezed Quadrature Spectrum

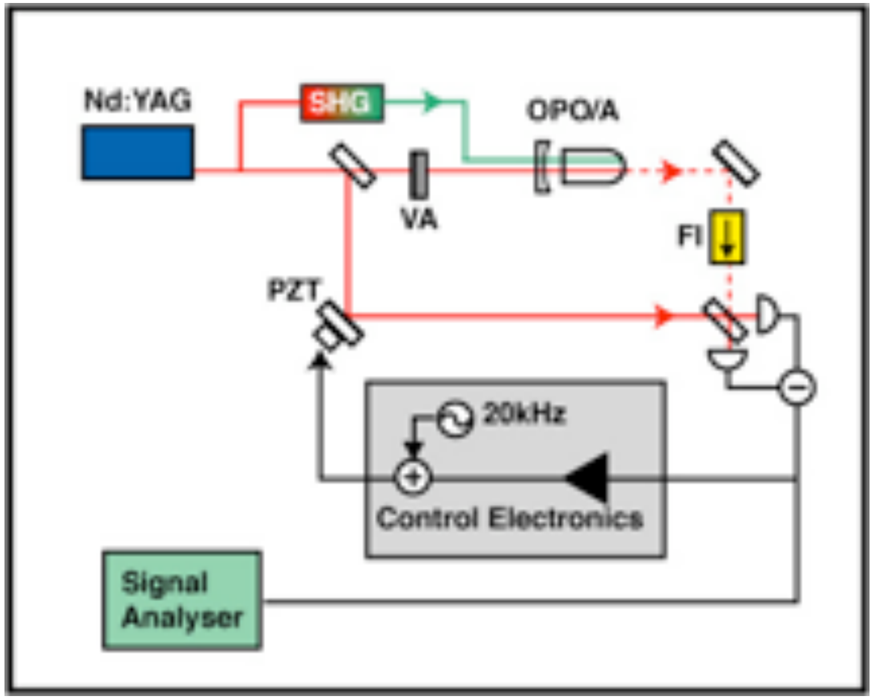
Locked Squeezed Quadrature Spectrum

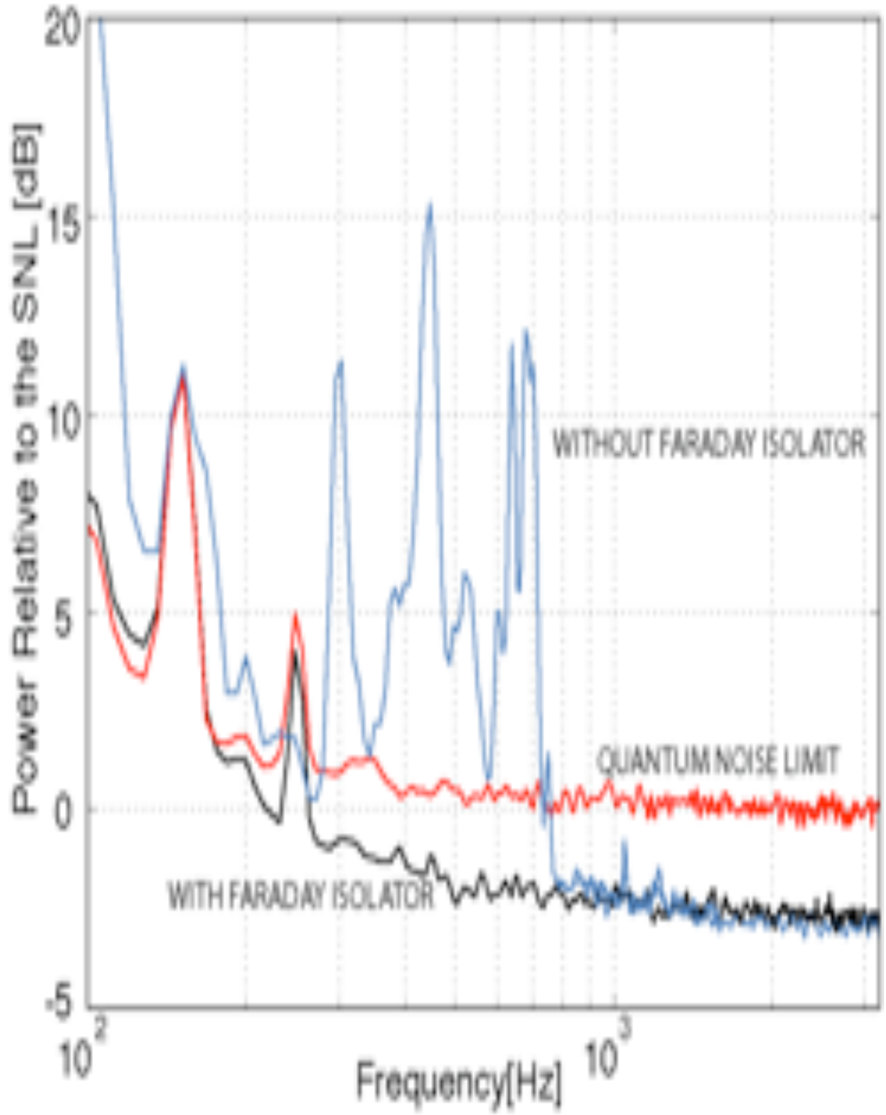


RBW = 128Hz, RMS averages = 1000, Electronic noise (at -12dB) subtracted from all traces

OPO Squeezing Without/With Isolator

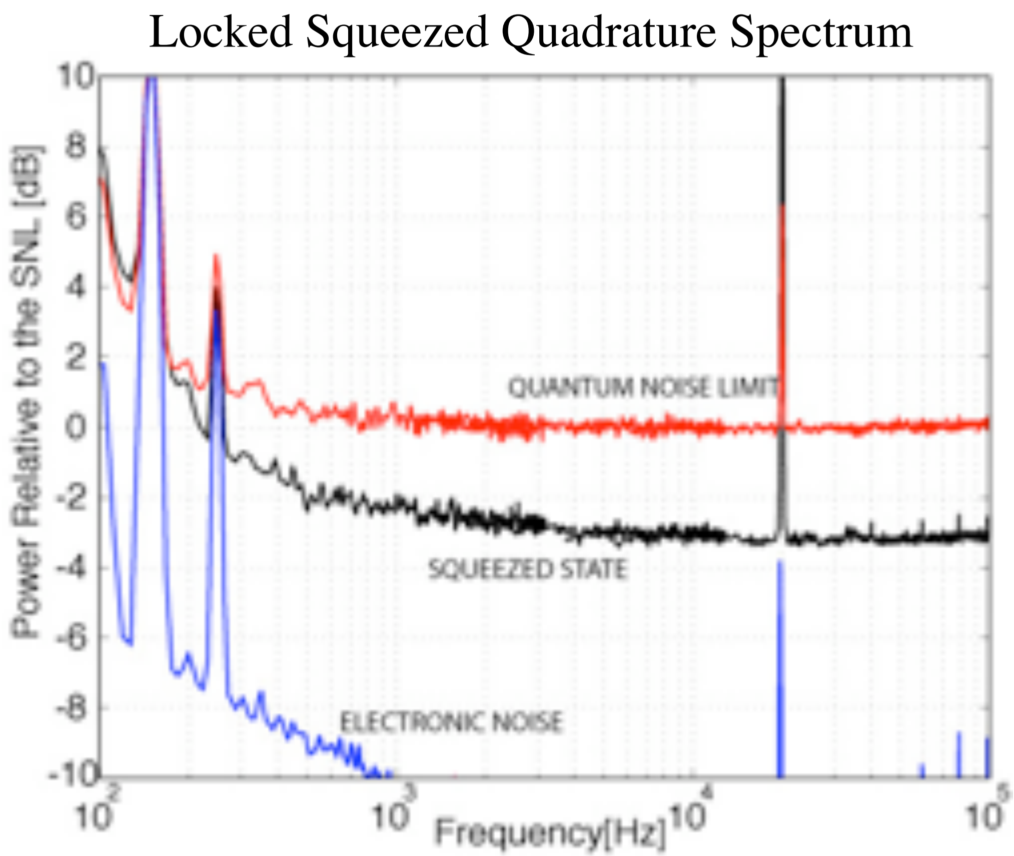
Experiment Schematic





RBW = 8Hz, No.RMS ave = 400 without isolator, 500 for QNL and with Isolator. Electronic noise (not shown) was not subtracted

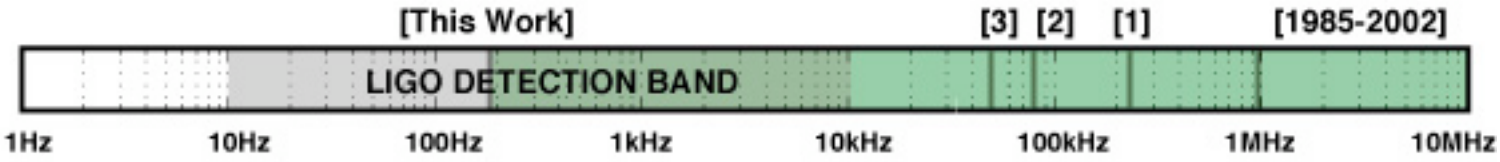
OPO Squeezed Quadrature Spectrum



From 100Hz-3.2kHz: RBW = 8Hz, no. RMS ave = 500
From 1.6kHz-12.8kH: RBW = 32Hz, no. RMS ave = 1000
From 3.8kHz-100kHz: RBW = 128Hz, no. RMS ave = 2000

Phys. Rev. Lett. 93, 161105 (2004)

Conclusions & Future Work



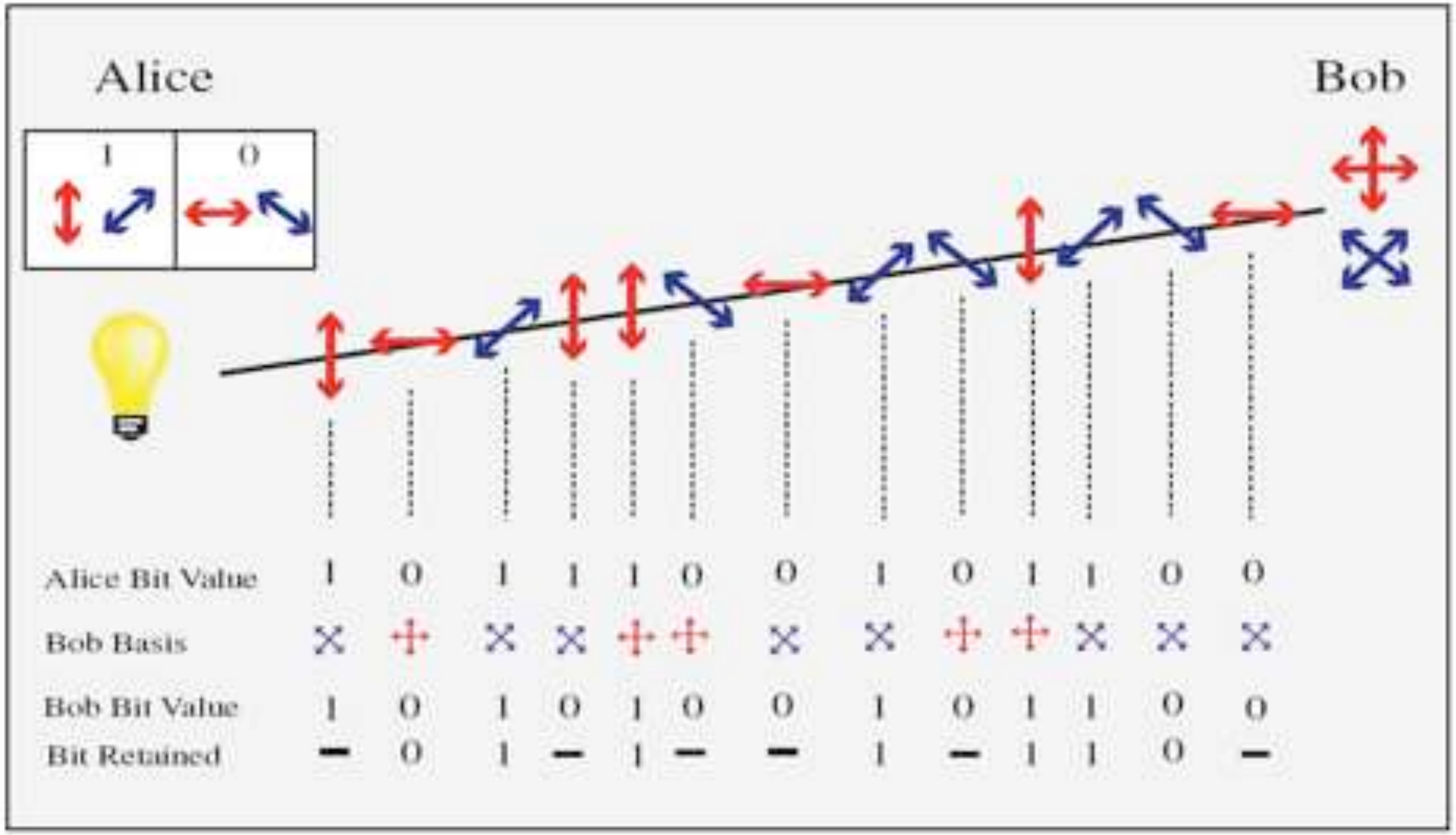
Conclusions

- Need to get rid of almost all IR photon to get real OPO!
- 200Hz Squeezing.
- Noise locking technique to lock a squeezed vacuum.

Future Work

- To get down to 10Hz in squeezing
  - Photo-thermal analysis, line-noise subtraction, more advanced locking loops.
- To get 10 dB squeezing
  - New GrIIRA free crystals
  - Increase OPO escape efficiency
  - Increase observable universal by a factor of ~36.

The BB84 Protocol



[Bennett and Brassard, *Proceedings IEEE.*, (1984)]

What do we need to implement quantum cryptography?
What role does quantum mechanics play?

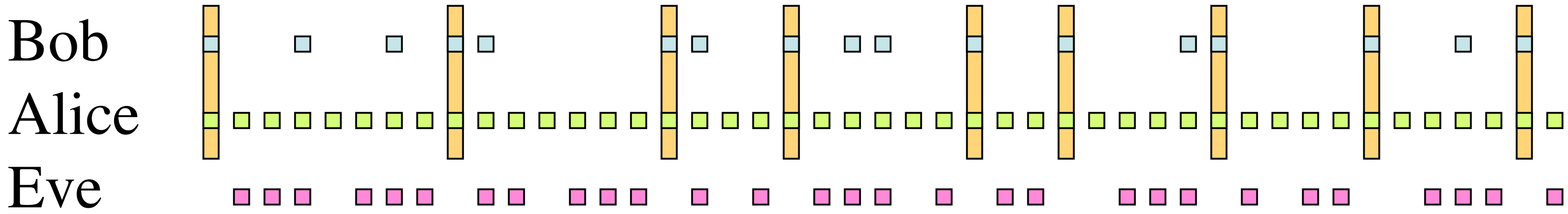
Necessary ingredients for QKD

- Single photons...
- Qubits...
- Squeezing...
- Quantum correlations (sub-quantum noise correlations)...
- Entanglement...
- Alice and Bob share more information than Eve ($I_{AB} > I_{AE}$)...
- Bob needs to randomly switch measurement basis...

None of the above!

Really necessary ingredients for QKD

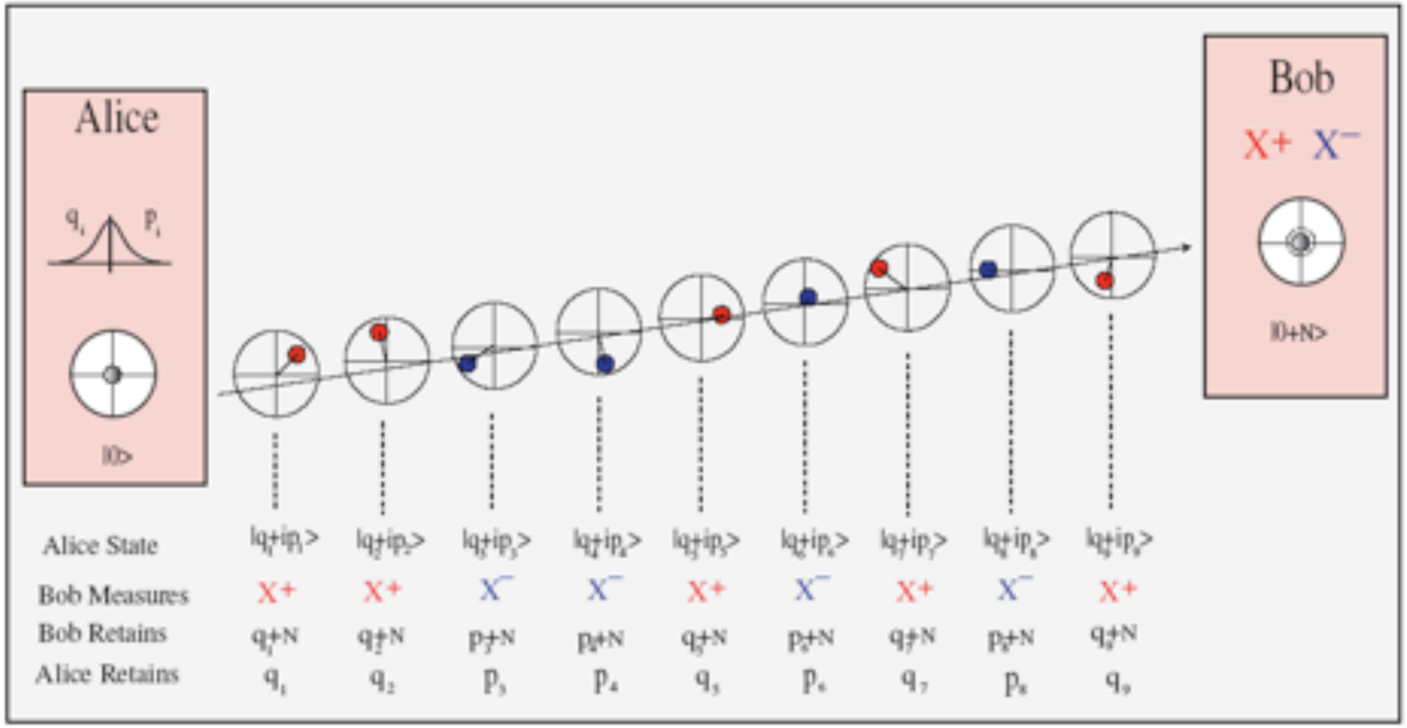
- We only need 2 things
- Differential correlations
  - Alice and Bob shares different information from Alice and Eve



- Known bounds
  - Heisenberg uncertainty, no-cloning limit, Shannon, entropy, etc.
  - There exist classical information protocols to distill secret key, amplify privacy, reconcile data remotely.

A great number of QKD proposals are overkills!

Continuous Variable Quantum Cryptography



- No need single photon, squeezing, entanglement... Just coherent states

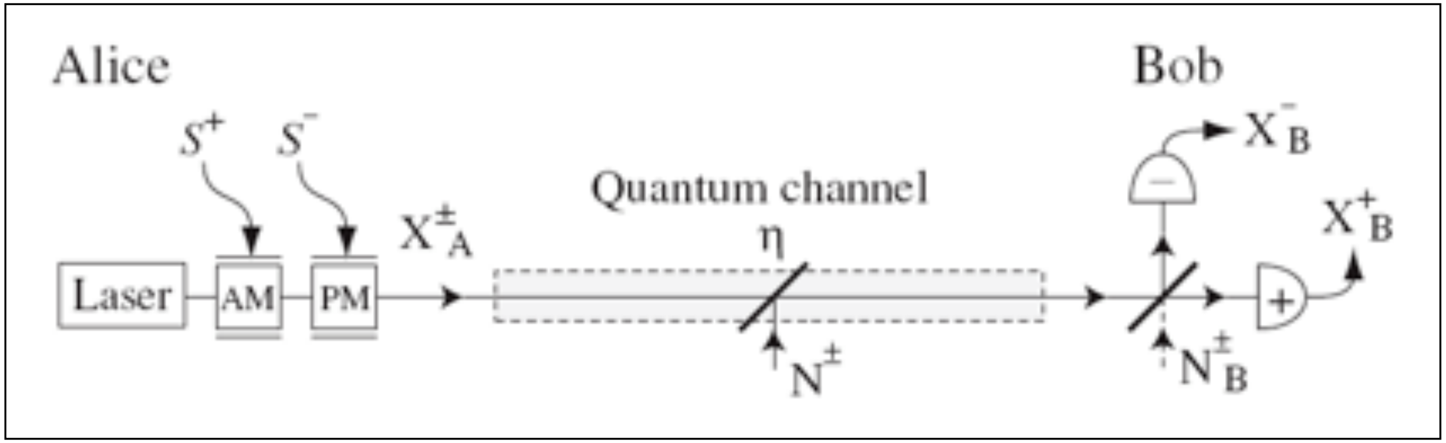
[Grosshans and Grangier, *Phys*. *Rev*. *Lett*. **88**, 57902 (2002)]

[C. Silberhorn et al., *Phys*. *Rev*. *Lett*. (2002)]

- No need to switch measurement basis

[Weedbrook, Lance, Bowen, Symul, Ralph and Lam, *Phys*. *Rev*. *Lett*., **93**, 170504 (2004)]

Quantum Cryptography without Switching

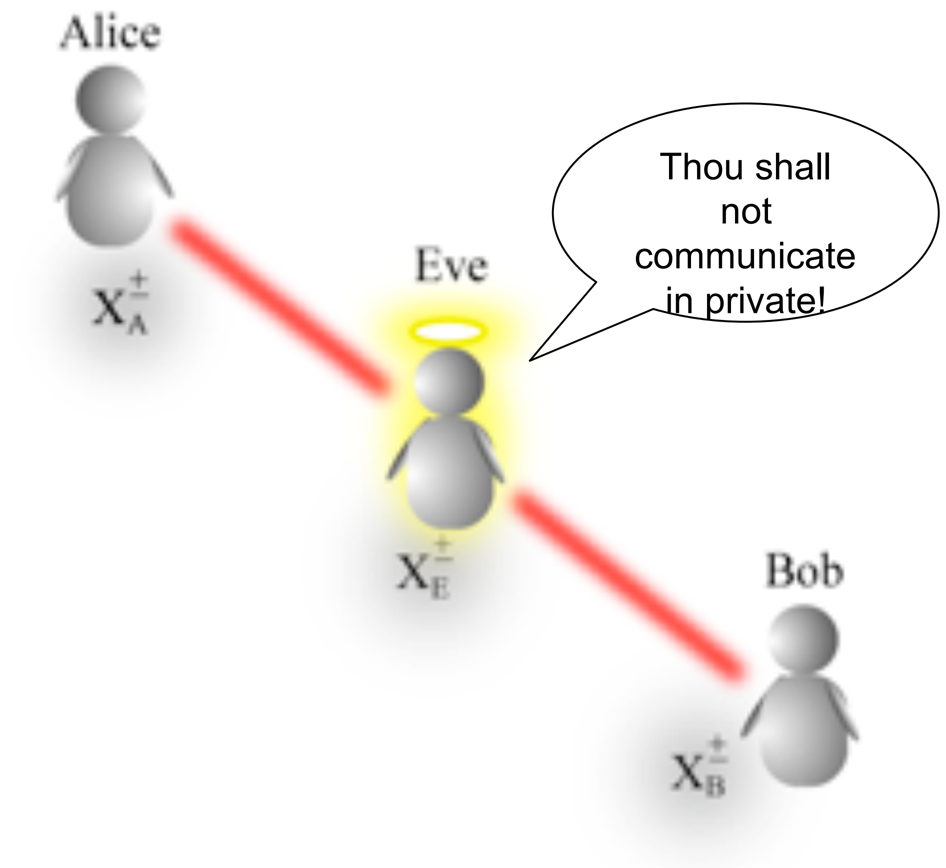


The Simultaneous Quadrature Measurement (SQM) Protocol.

- Alice: Encodes random numbers on both non-commuting quadratures on a coherent state.
- Alice: Transmits the coherent states.
- Bob: Measures both quadratures simultaneously.
- Analyse SQM protocol in the context of Grosshans and Grangier reverse reconciliation protocol.

G&G Reverse Reconciliation (GGRR)

- Direct reconciliation
  - Bob tries to guess what Alice has sent.
  - Loss 50% => Eve has the upper hand.
- Reverse reconciliation
  - Alice tries to guess what Bob has measured.
  - Loss of any amount still has Alice knowing more than Eve.



Secret Key Rate

$$\hat{X}^{\pm}_{E|B} = \hat{X}^{\pm}_{B} - \alpha\hat{X}^{\pm}_{E}$$
$$\hat{X}^{\mp}_{A|B} = \hat{X}^{\mp}_{B} - \beta\hat{X}^{\mp}_{A}$$

$$I = \frac{1}{2}\log_2\left(1 + S/N\right)$$

$$[\hat{X}^{+}_{E|B}, \hat{X}^{-}_{A|B}] = [\hat{X}^{+}_{B}, \hat{X}^{-}_{B}] = 2i$$

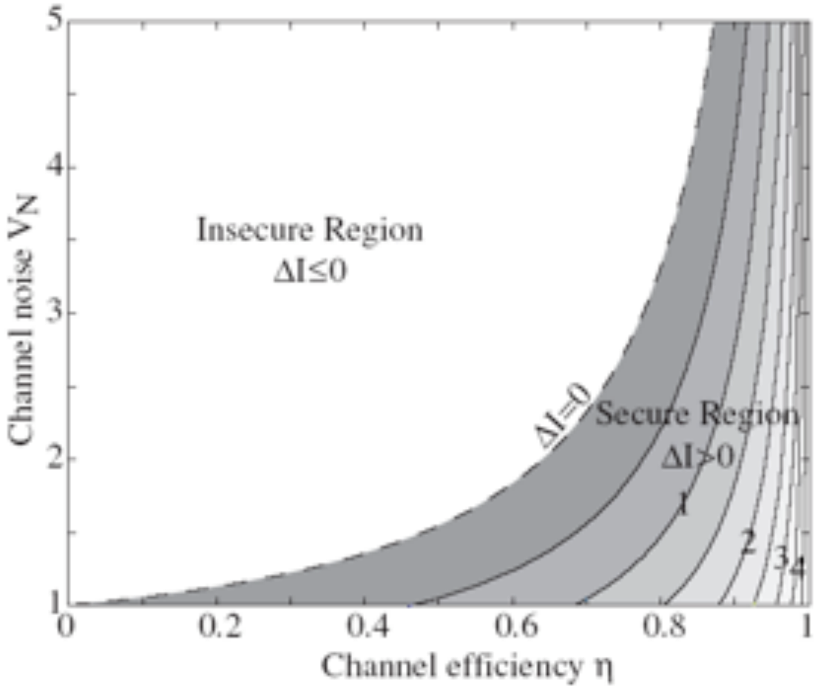
$$\begin{aligned} \Delta I &= \Delta I^{+} + \Delta I^{-} \\ &= (I^{+}_{BA} - I^{+}_{BE}) + (I^{-}_{BA} - I^{-}_{BE}) \end{aligned}$$

$$\Delta \mathrm{I} = \frac{1}{2}\log_2\left(\frac{V^{+}_{E|B}V^{-}_{E|B}}{V^{+}_{A|B}V^{-}_{A|B}}\right)$$

Eve's Conditional Variance

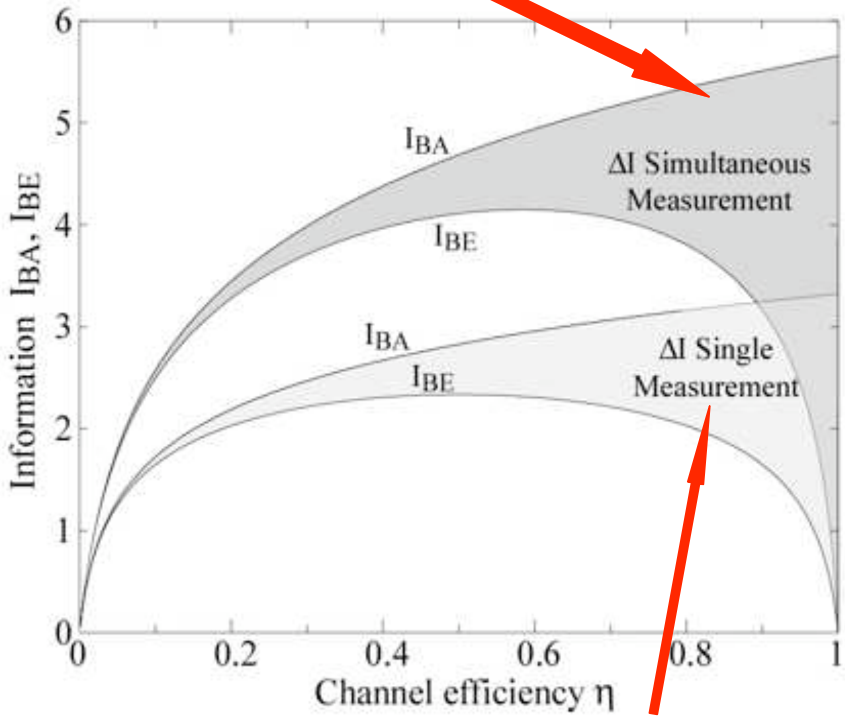
Alice's Conditional Variance

The SQM Protocol - Results



$$\Delta \mathrm{I} \geq \log_2\left(\frac{(\frac{\eta}{V_A}+(1-\eta)V_N)^{-1}+1}{\eta+(1-\eta)V_N+1}\right)$$

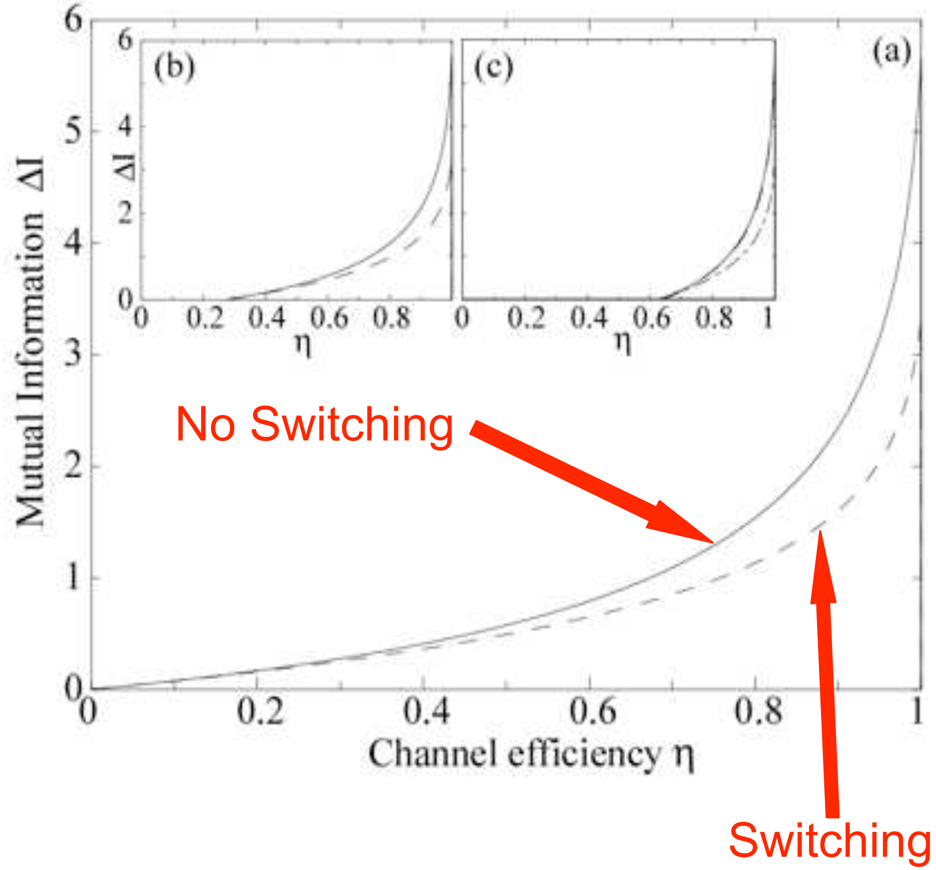
No Switching



Switching

$$\Delta I = I_{BA} - I_{BE}$$

The SQM Protocol - Results



- Experimentally a lot simpler
  - The process of switching in continuous variables, limits the bandwidth in the cryptographic protocols.
- Applicable to all existing CVQC.

Virtual entanglement