Proof-of-principle demonstration of QKD immune to detector attacks

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in the maritime environment

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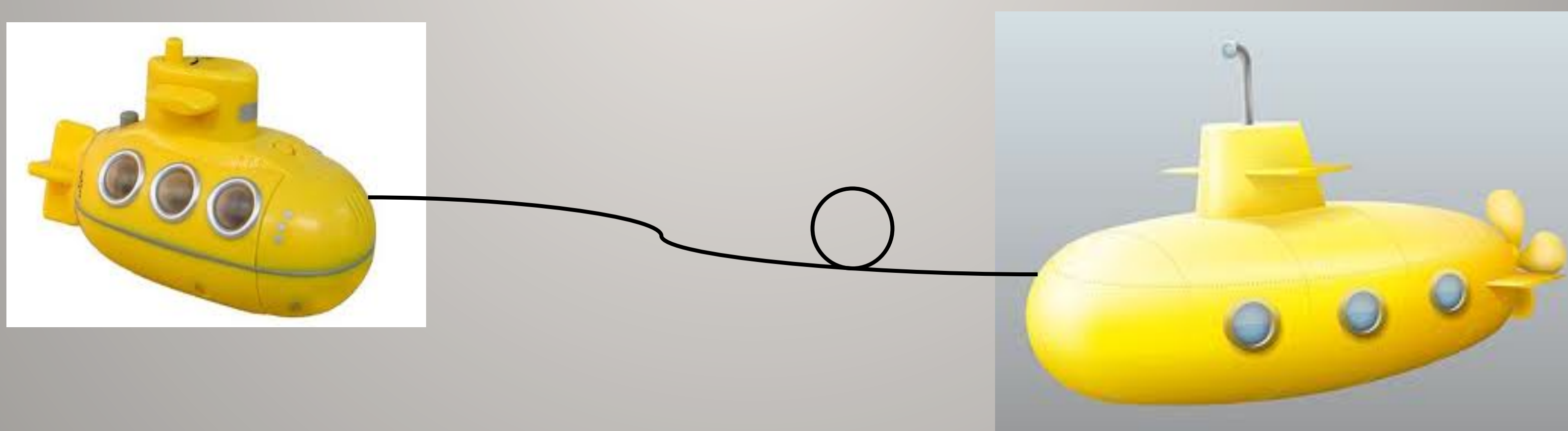
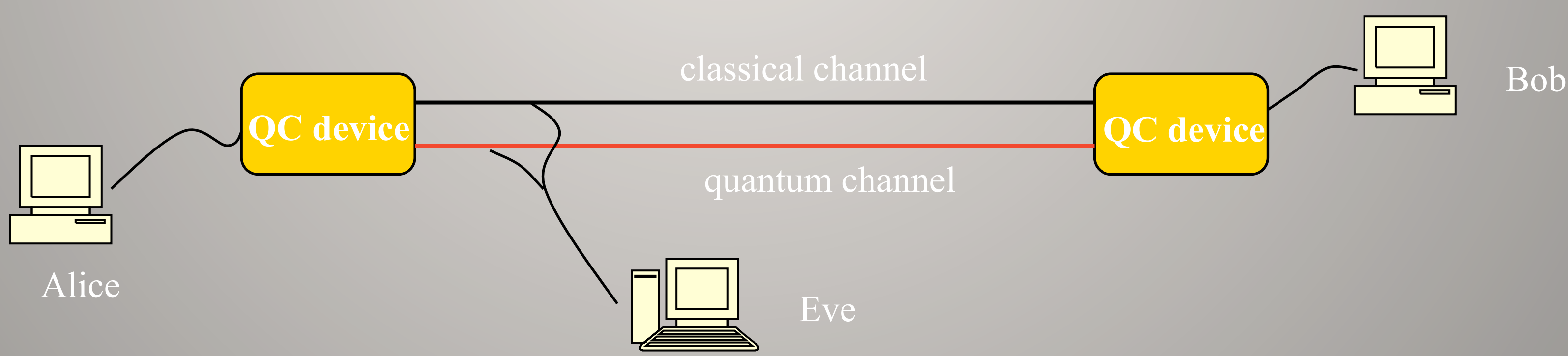


Quantum key distribution

- Information-theoretic security proven (even assuming imperfect devices)
- Impressive experimental progress since 1989
    - more than 100 km distance (fiber and free-space)
    - trusted-node networks (BBN-DARPA, SECOQC, Tokio, Swiss)
    - commercial devices (idQuantique, MagiQ)



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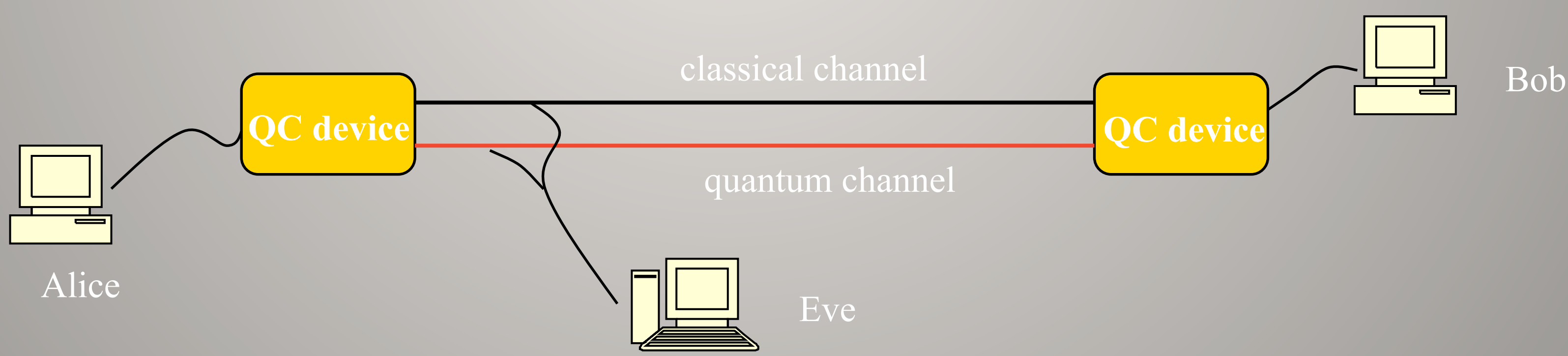
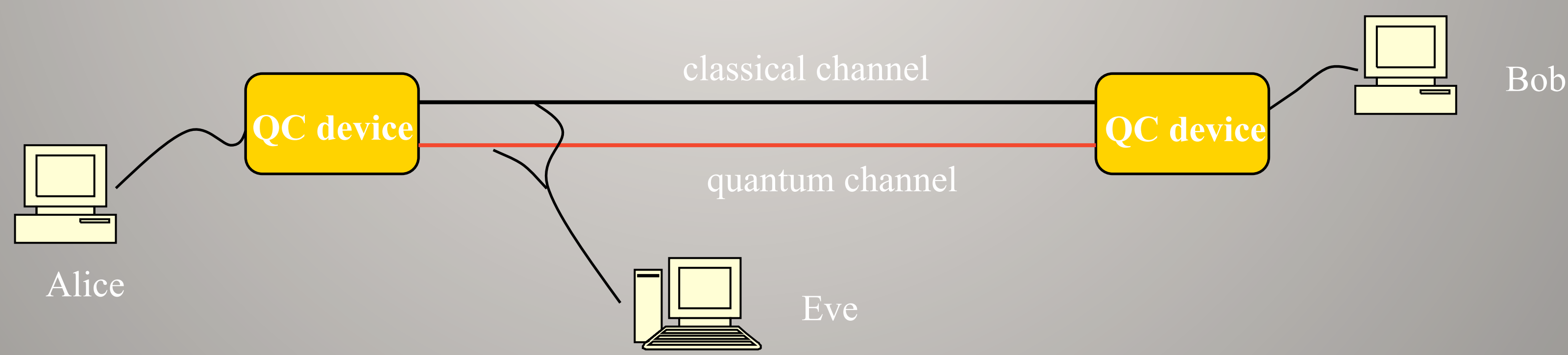
BUT



Outline

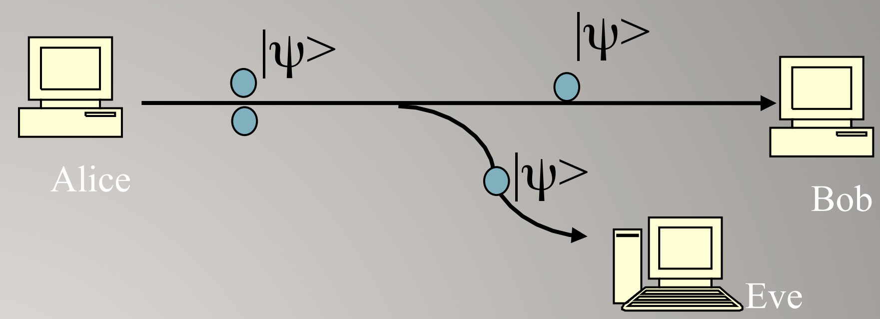
- Side-channel attacks
- Measurement-device independent (MDI) QKD
    - the protocol
    - proof-of-principle demonstration
- Conclusion



Side-channel attacks

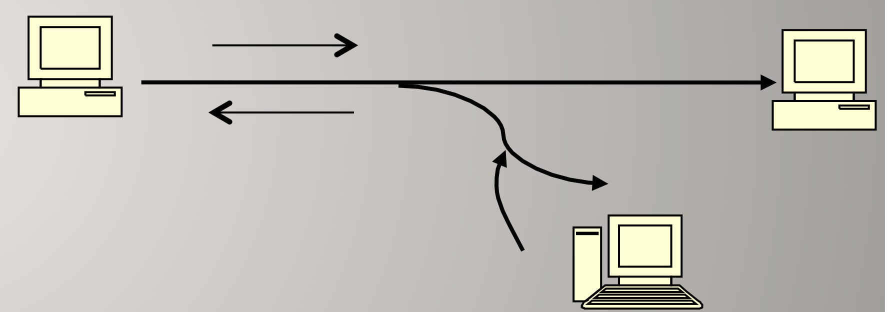
- **Photon number splitting**

  Counter measure: decoy state protocol



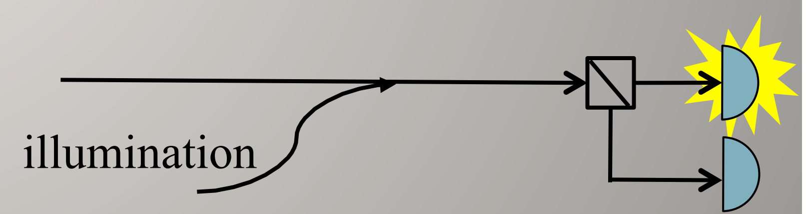
- **Trojan Horse attacks**

  Counter measure: optical isolator



- **Remote controlling detectors**

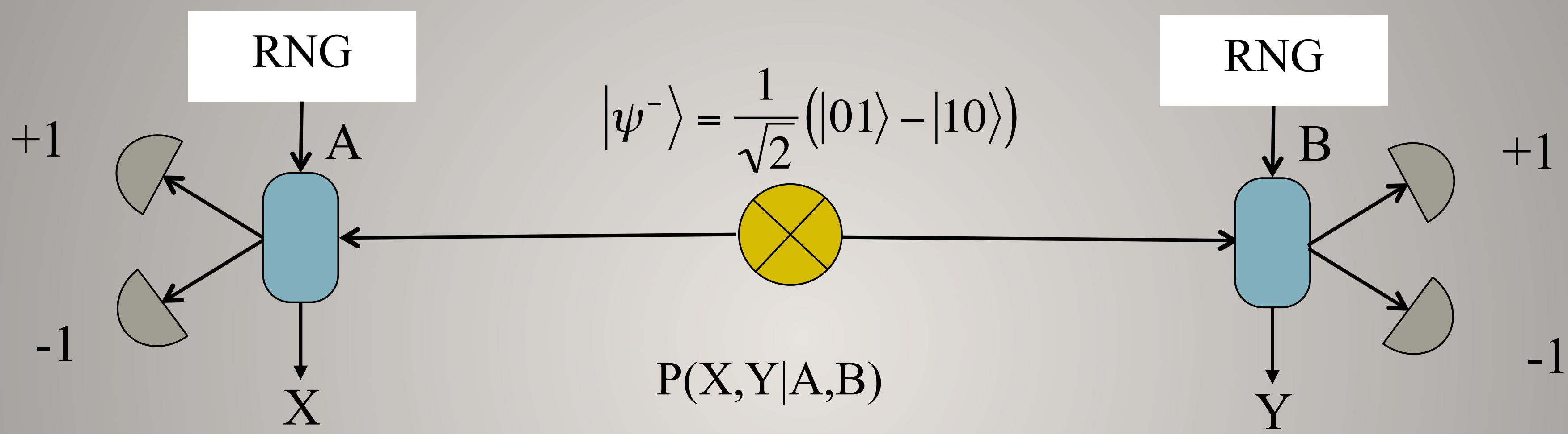
  Counter measure: robust detectors



Can we devise (& implement) a protocol that is robust wrt to <u>any side-channel attack</u> (known or yet-to-be discovered)??

Brassard *et al*, PRL 85, 1330 (2002); Gisin et al, PRA 73, 022320 (2006), Lydersen, Nature Phot. **4**, 686 (2010)

Device independent QKD



- requires generation of entangled photons, and projections onto qubit states

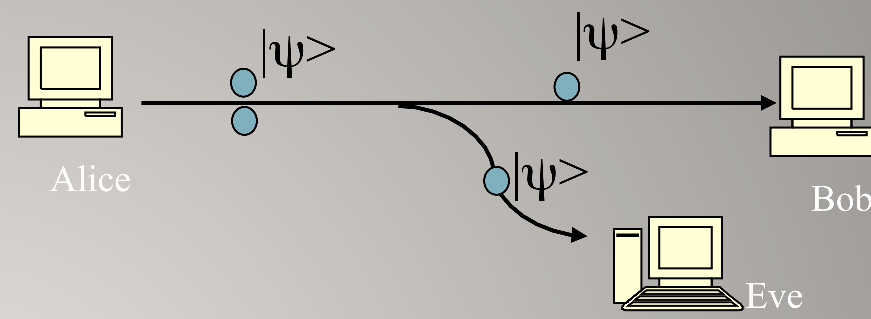
- sifting, error correction and privacy amplification allows distributing secret keys

- currently infeasible (detection loophole needs to be closed)

Side-channel attacks

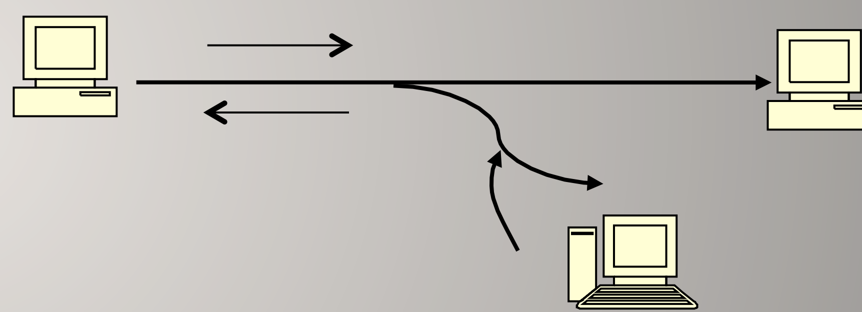
- Photon number splitting

Counter measure: decoy state protocol



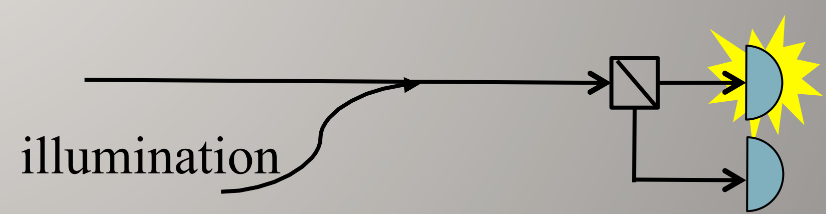
- Trojan Horse attacks

Counter measure: optical isolator



- remote controlling detectors

Counter measure: robust detectors



Can we devise (& implement) a protocol that is robust wrt to <u>any detector attacks</u>?

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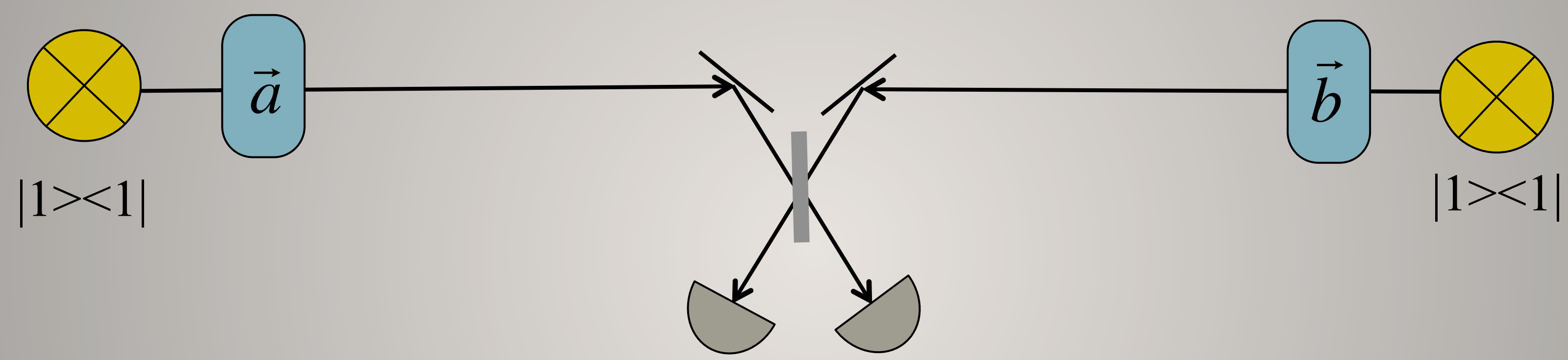
QKD using time-reversed entanglement

$$|\psi^-\rangle = \frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right) = \frac{1}{\sqrt{2}}\left(|+-\rangle - |-+\rangle\right)$$

$\vec{\alpha}, \vec{\beta} \in [|0>, |1>, |+>, |->]$



- requires generation of qubit states, and projection onto entangled states

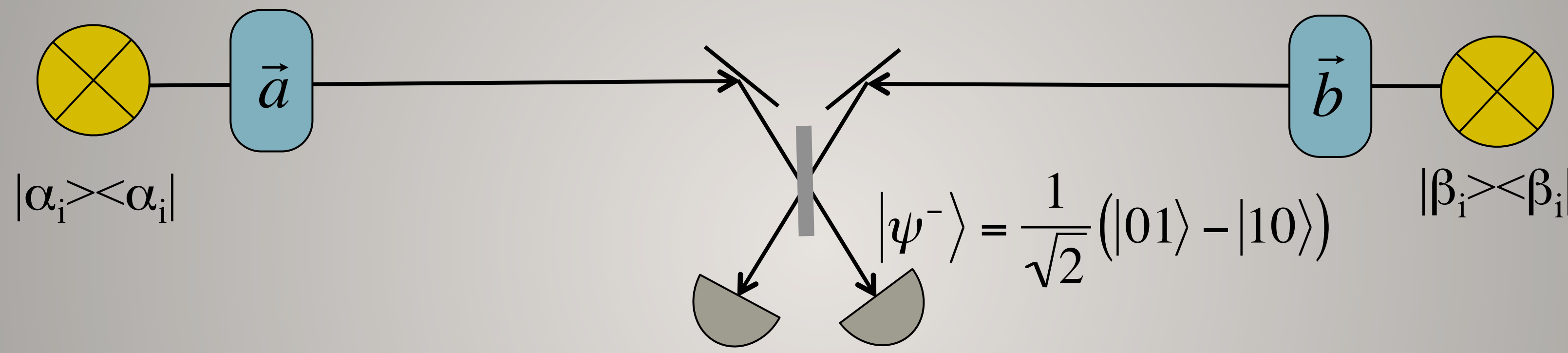
- sifting (*x-key*, *z-key*), bit flip at Bob's, EC and PA allows distributing secret keys

- de-correlates detection pattern from key bit -> immune to any detector attack

- currently difficult to implement (single photon sources)

Measurement Device Independent - QKD

$\vec{\alpha}, \vec{\beta} \in [|0\rangle, |1\rangle, |+\rangle, |-\rangle]$



- requires generation of qubit (signal&decoy) states and proj. onto entangled states

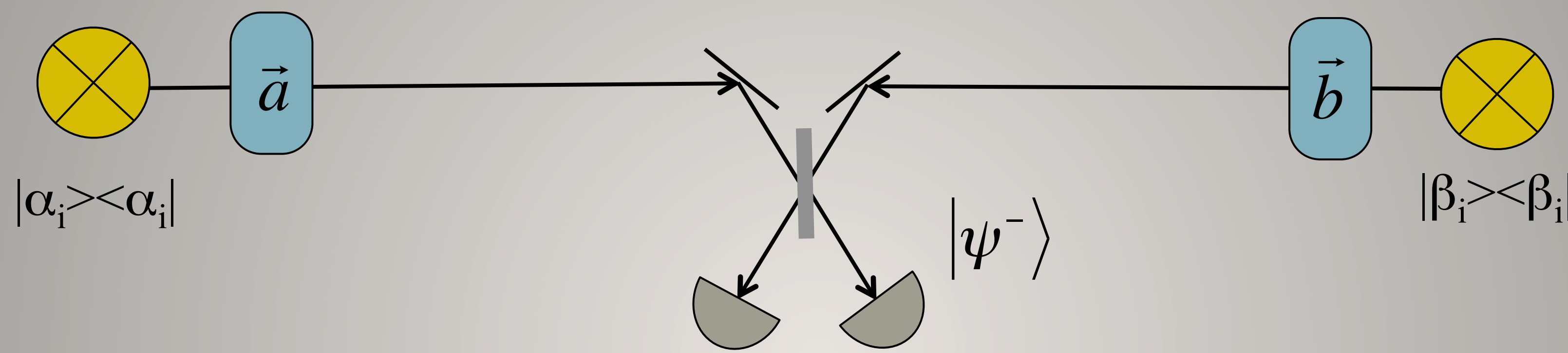
- sifting (*x-key, z-key*), bit flip at Bob's, EC and PA allows distributing secret keys

- de-correlates detection pattern from key bit -> immune to any detector attack

- should be feasible with existing technology

Lo et al. PRL **108**, 130503 (2012) (see also Braunstein et al, PRL 108, 130502 (2012)).

Decoy states in MDI-QKD



- allows overcoming threat of PNS attacks

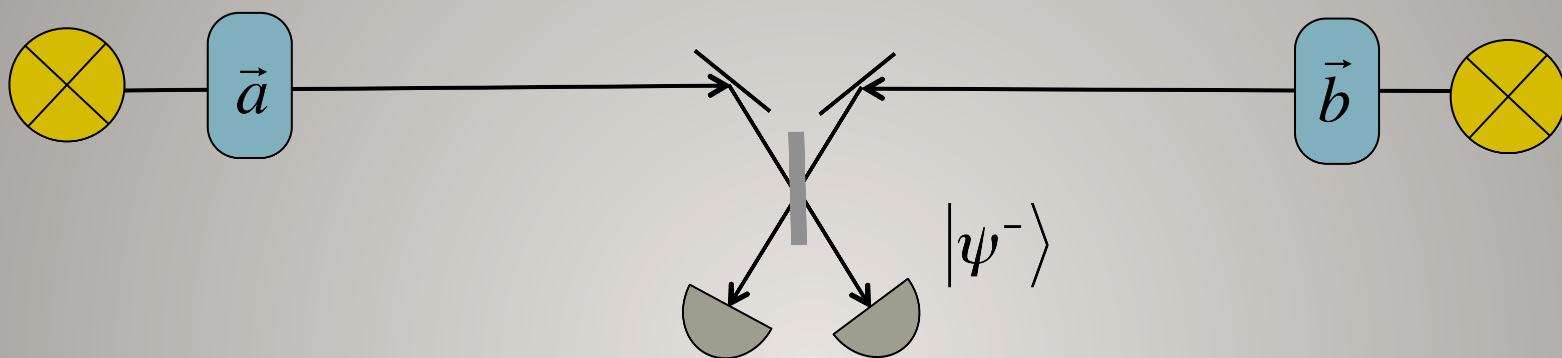
- random variation between 3 different mean numbers of photons per qubit carrier allows assessing Q^x_{11}, Q^z_{11}, e^x_{11}, and e^z_{11} ($\rho=\Sigma P(n)|n\rangle\langle n|$)

- secret key is distilled from *z-key* (using *x-key to* assess I(A;E))

$Q^z_\mu := Q^z_{\mu_A \mu_B}$

$$R = Q^z_{11} \{1 - h_2(e^x_{11})\} - Q^z_\mu \, f \, h_2(e^z_\mu)$$

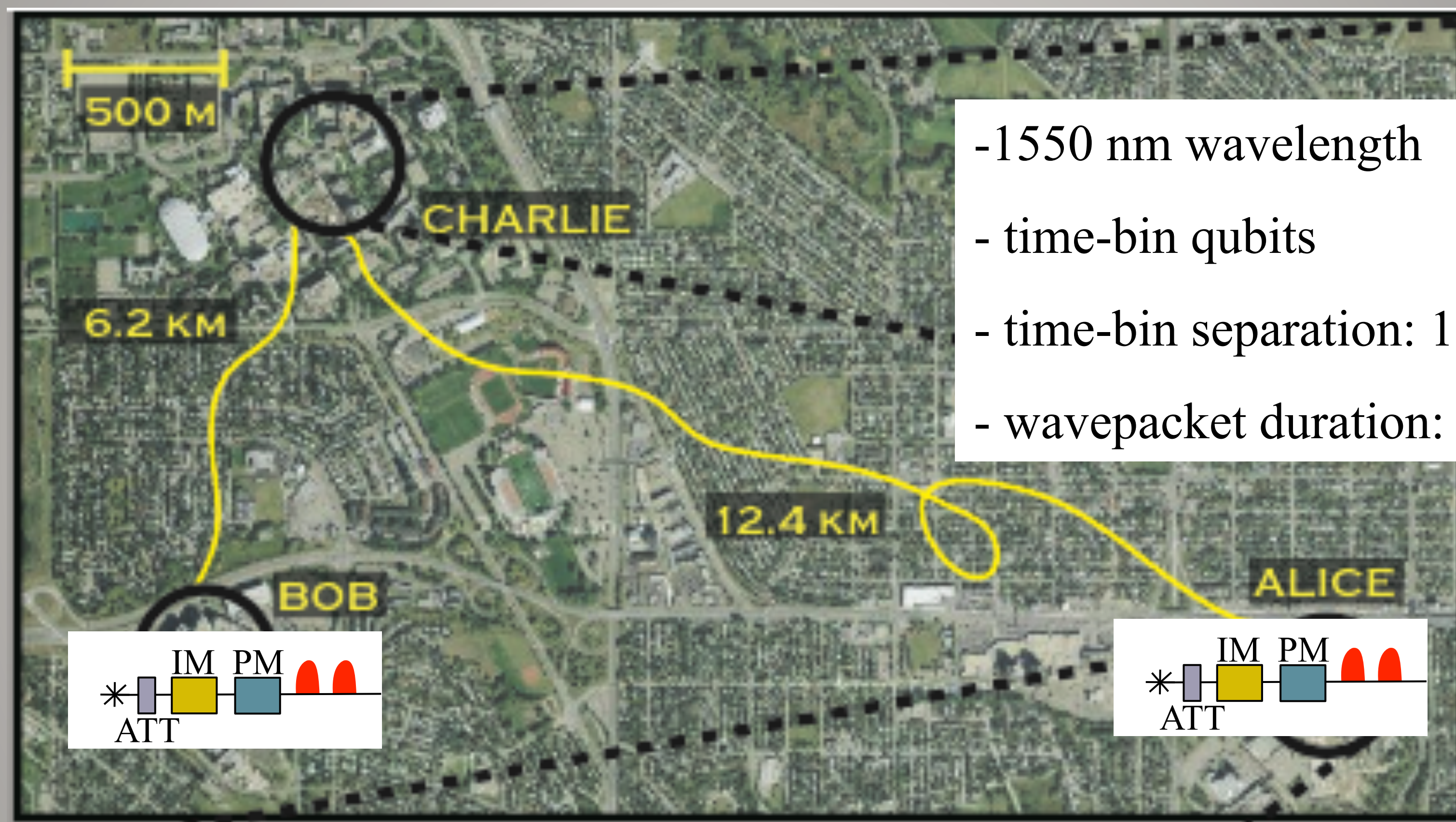
Bell-state measurement



- requires indistinguishable photons
    - spatial mode
    - temporal mode
    - spectrum
    - polarization
- needed for MDI-QKD, quantum repeater, quantum networks, LOQC

note: as difficult for attenuated laser pulses as for photons from photon pairs

Generic setup



-1550 nm wavelength

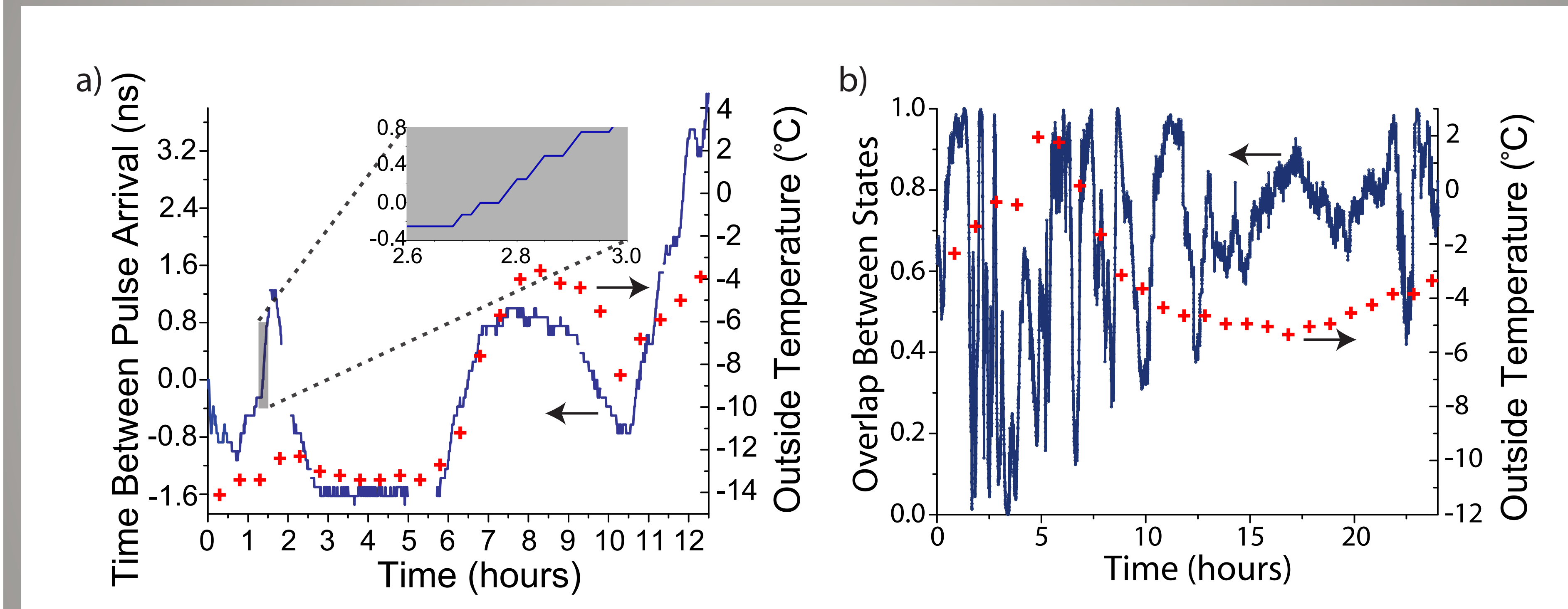
- time-bin qubits

- time-bin separation: 1.4 ns

- wavepacket duration: 500 ps

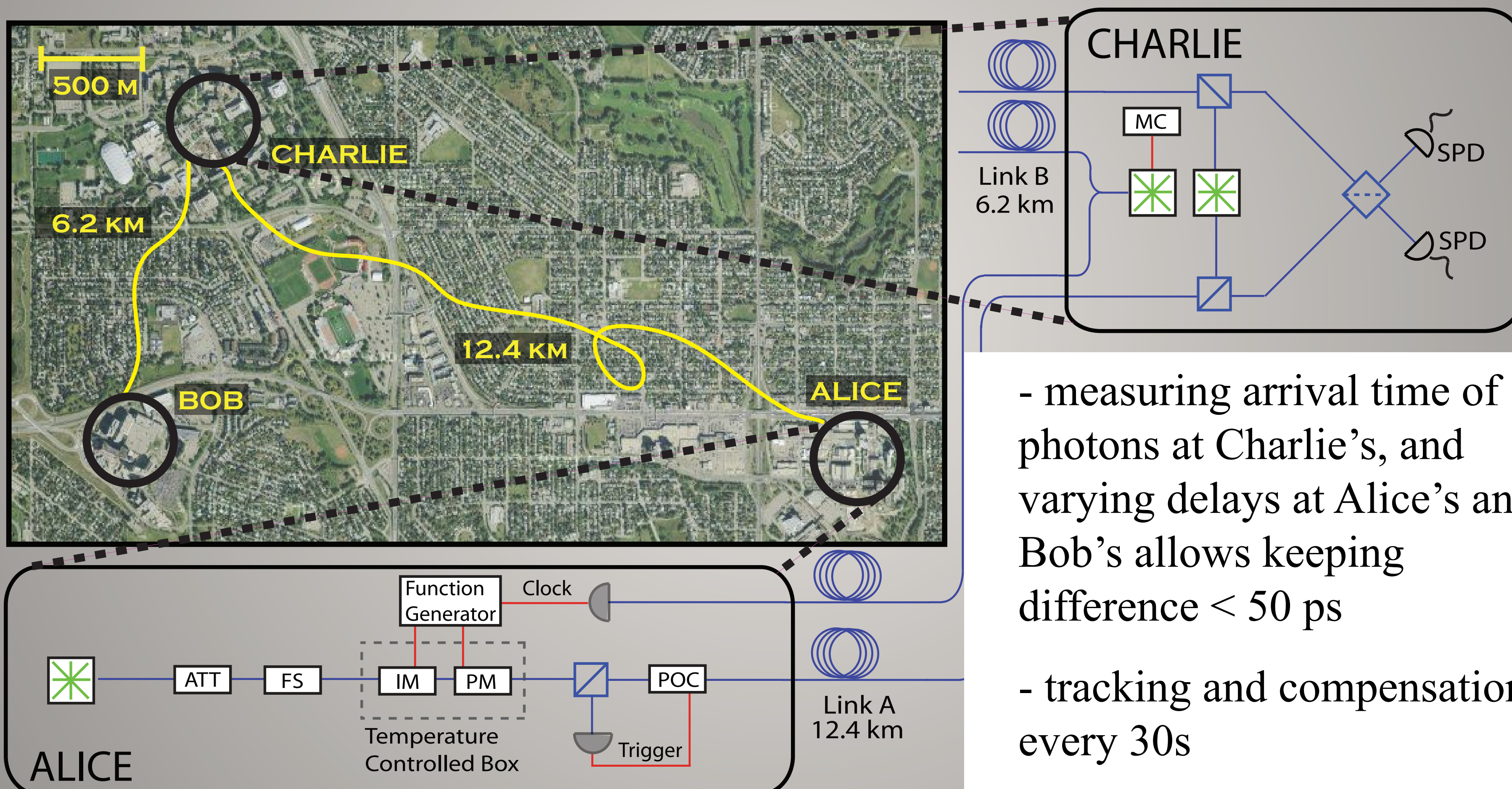
and measurements in the lab with fibre on spools

Environment-induced fluctuations



plus frequency drift of Alice's with respect to Bob's laser of up to 20 MHz/hour

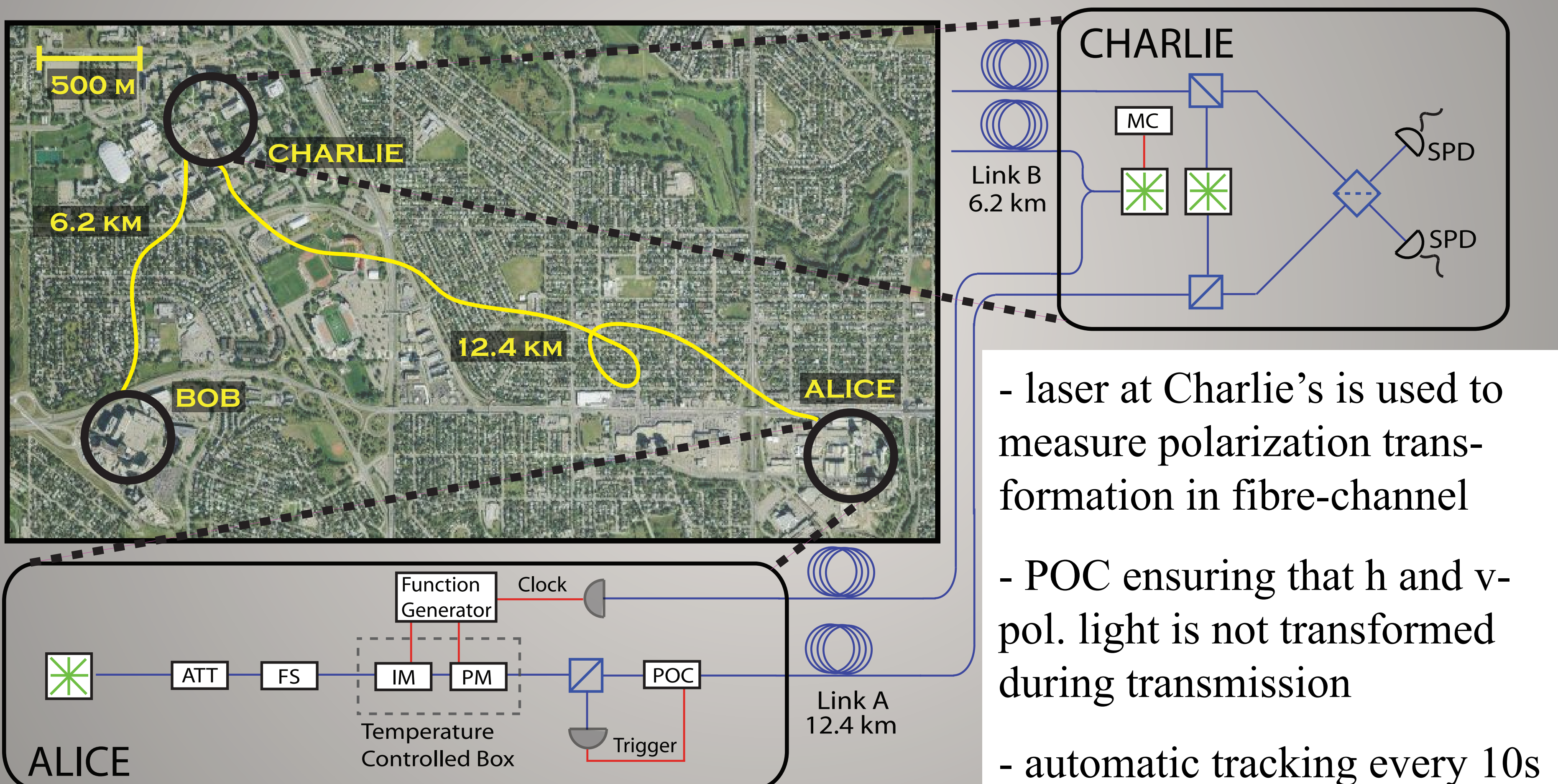
Feedback systems – arrival time



- measuring arrival time of photons at Charlie's, and varying delays at Alice's and Bob's allows keeping difference < 50 ps

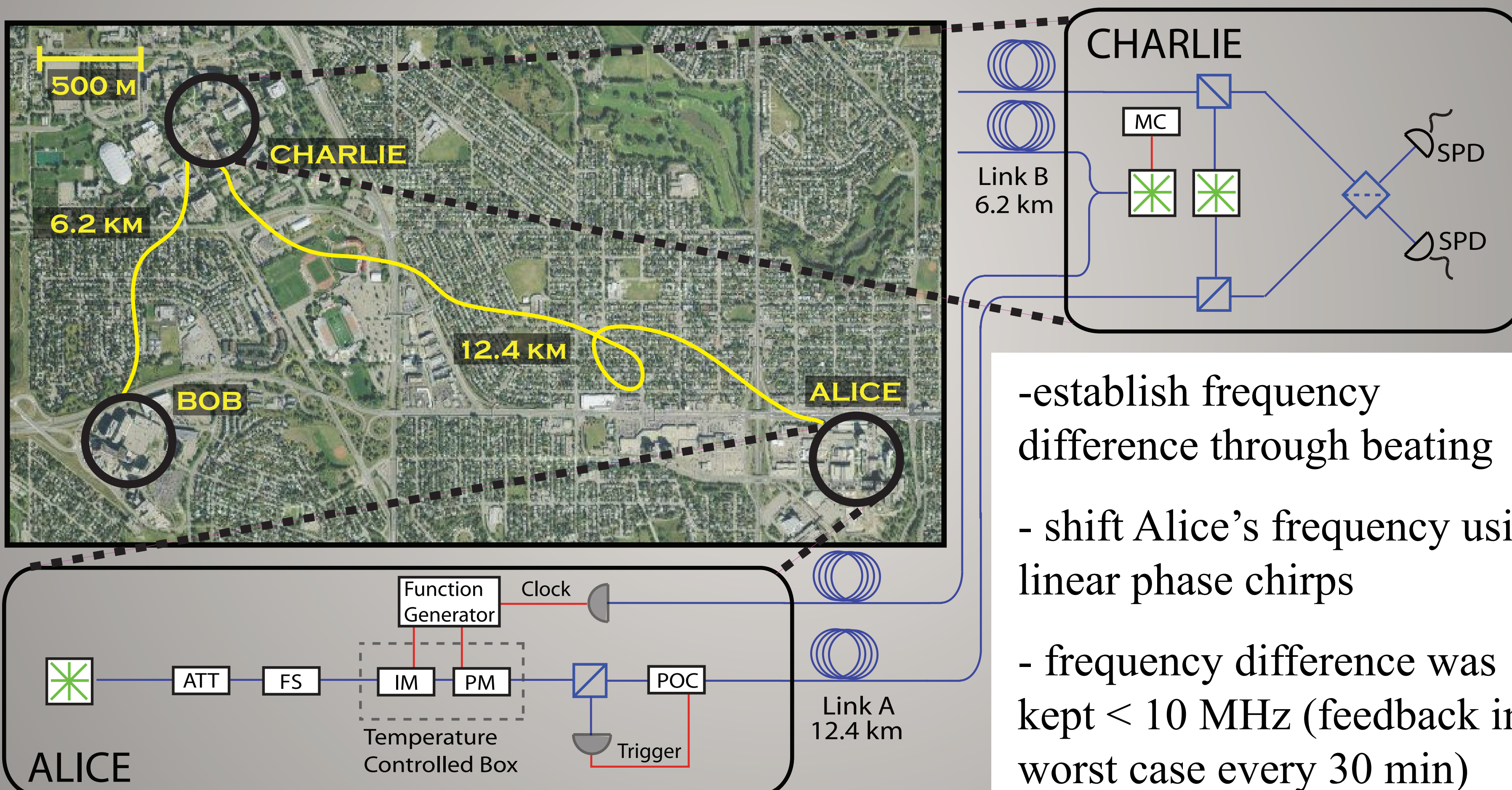
- tracking and compensation every 30s

Feedback systems – polarization



- laser at Charlie's is used to measure polarization transformation in fibre-channel
- POC ensuring that h and v-pol. light is not transformed during transmission
- automatic tracking every 10s

Feedback systems – frequency (spectrum)

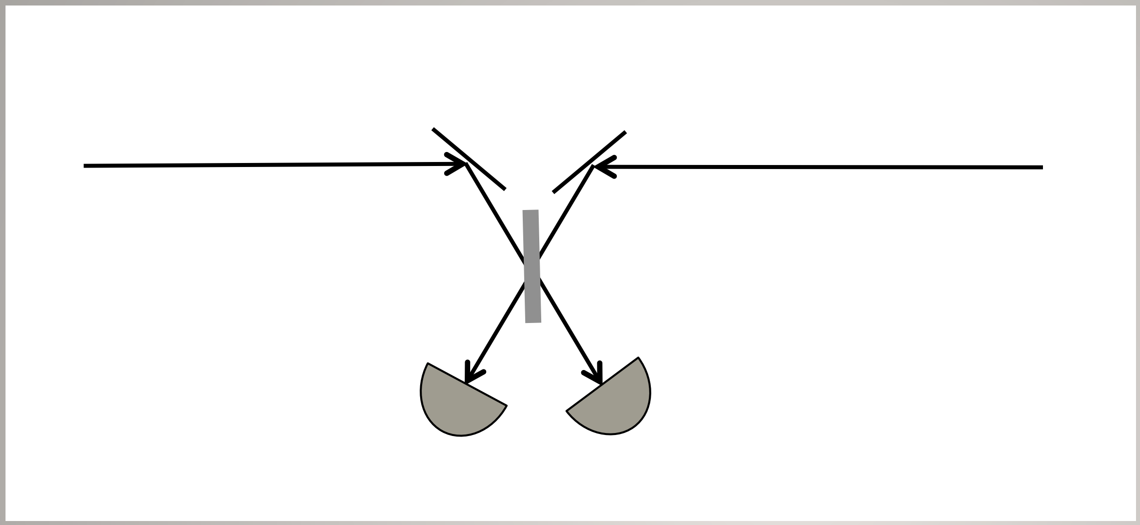


-establish frequency difference through beating

- shift Alice's frequency using linear phase chirps

- frequency difference was kept < 10 MHz (feedback in worst case every 30 min)

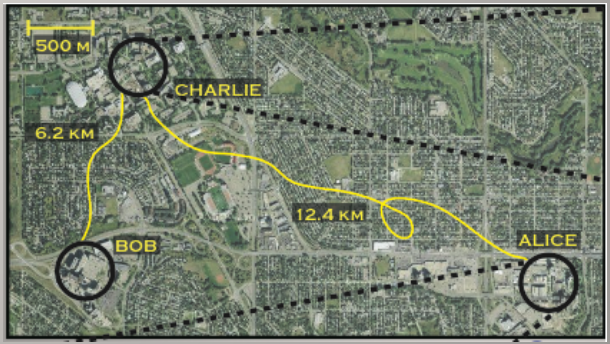
Feedback systems - performance



Indistinguishability assessed via HOM dip:

V_{HOM}=47±1% (V_{max}=50%)

(measurement with classical light is sufficient!)



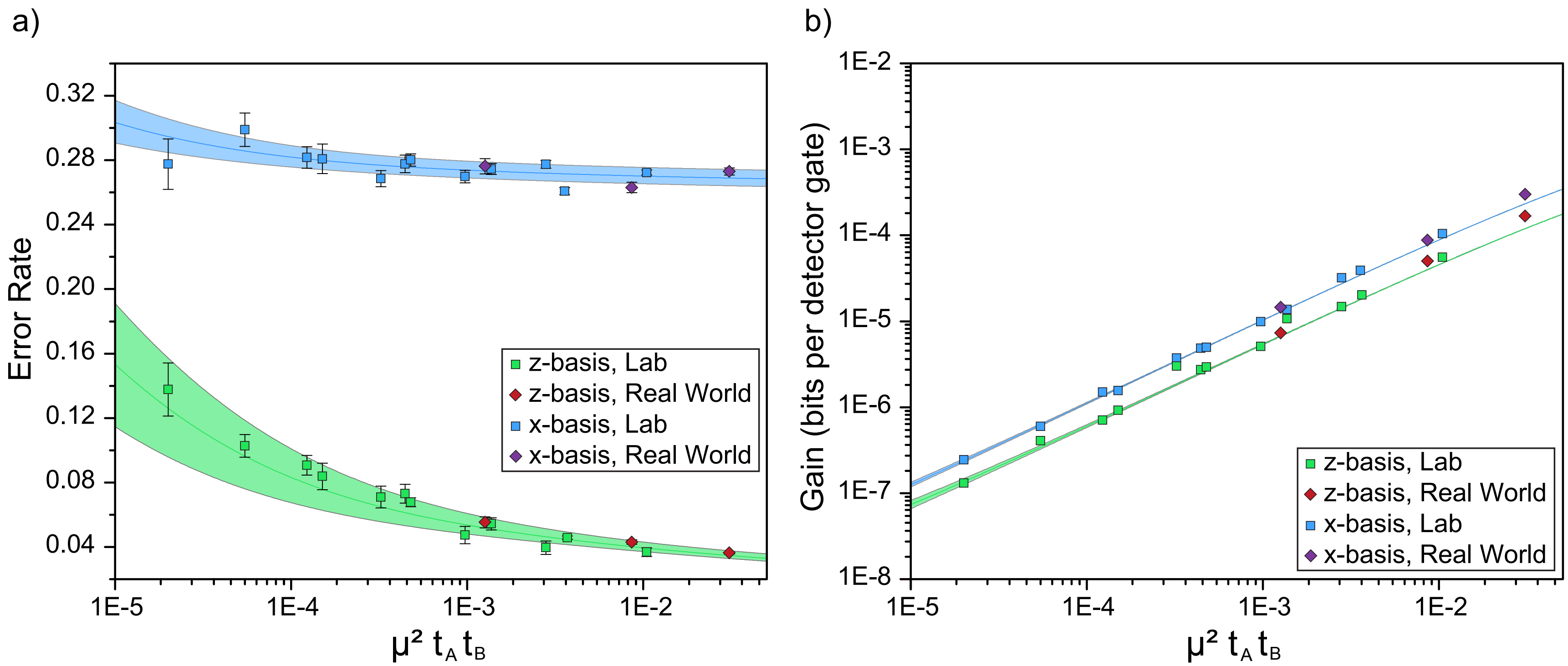
Measurements

- Generate all 8 combinations of states with Alice and Bob using the same basis (x or z)
- $\mu \in [0.1, 0.25, 0.5]$; $\mu_A = \mu_B$
- various distances (loss), inside and outside lab; $l_A = l_B$
- measure error rates and gains

ℓ_A [km]	l_A [dB]	ℓ_B [km]	l_B [dB]	total loss l [dB]
30.98	6.8	11.75	6.8	13.6
40.80	9.1	40.77	9.1	18.2
51.43	11.3	32.19	11.3	22.7
61.15	13.7	42.80	13.6	27.2
12.4	4.5	6.2	4.5	9.0

Real-world measurements

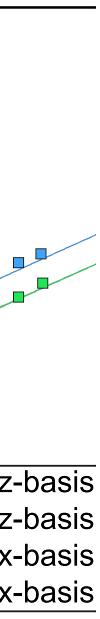
Results

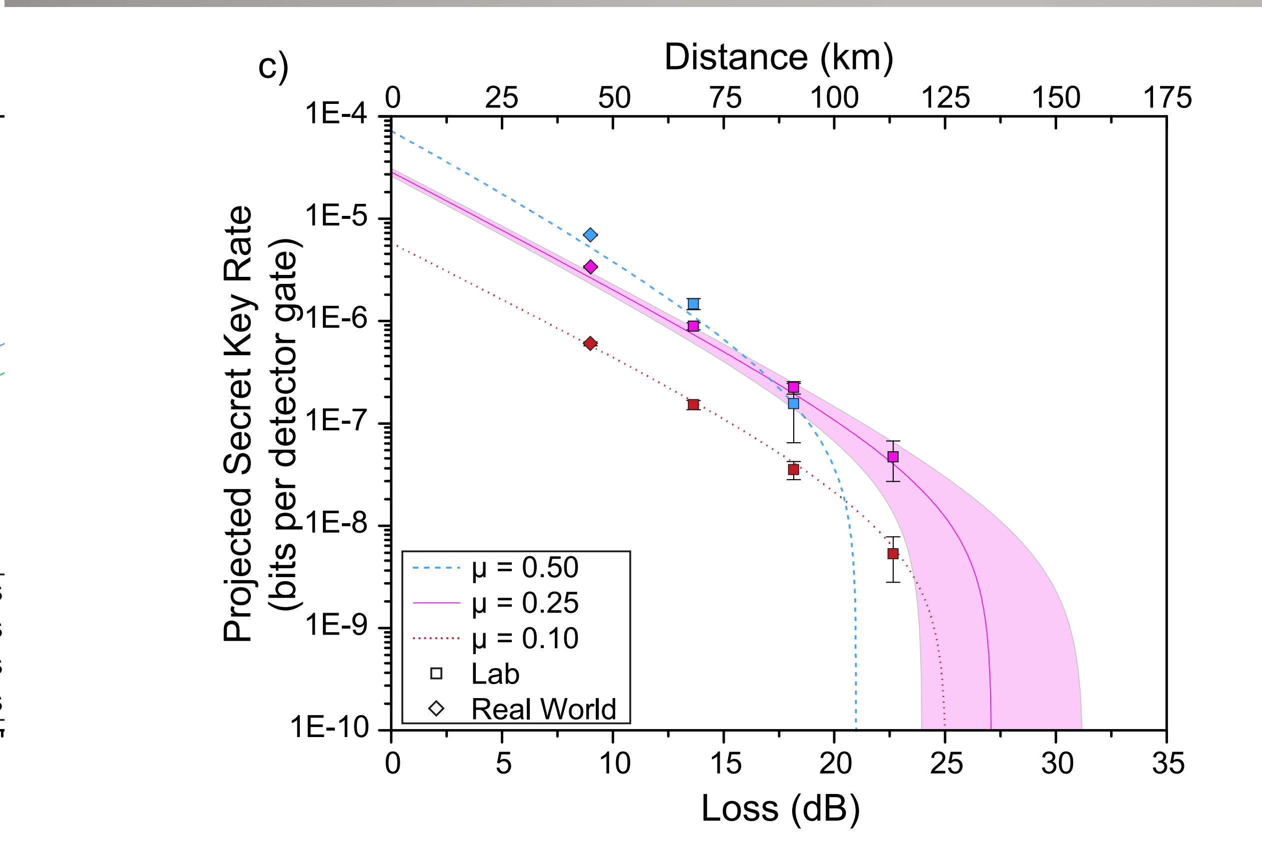


Simulations using independently established parameters and assuming ≤ 2 photons behind BS describe observed error rates and gains over >3 orders of magnitude, and in and out-of lab

-> we understand the imperfections (state preparation, detector noise) that affect the measurable quantities

Results





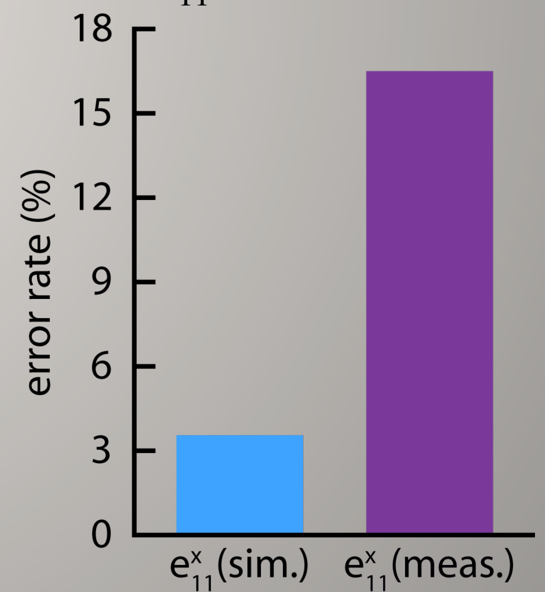
Measured: Q^x_μ, Q^z_μ, e^x_μ, e^z_μ

Estimated: Q^z_{11}, e^x_{11}

- model allows estimating $R= Q^z_{11}\,\{1-h_2(e^x_{11})\} - Q^z_\mu\, h_2(e^z_\mu)$
- but decoy state method needed for actual key distribution
- QKD up to ~125 km assuming efficient decoy state method

More recent results

- 3-value decoy state method has recently been proposed
- requires measuring 7 combinations of different mean photon numbers
- tests over 2x30 km fibre spools yield first results
- discrepancy between simulated and measured e^x_{11} currently large
    - μ_d, μ_s not yet optimized to yield good (upper) bound on e^x_{11}
    - state generation currently not perfect
- work in progress

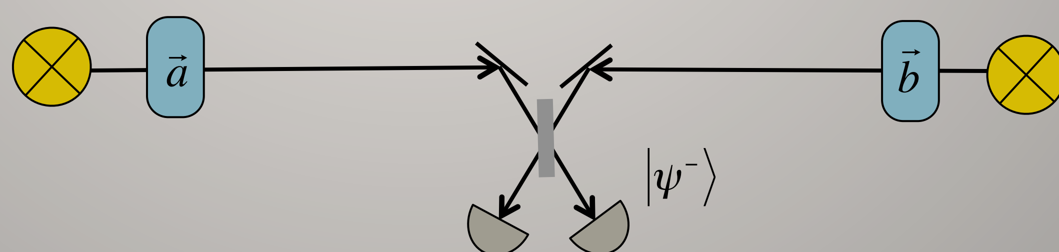


X.-B. Wang, arXiv:1207.0392, similar work by T. Ferreira da Silva et al., arXiv:1207.6345

QC2 Lab

Conclusion

- MDI-QKD protocol removes detector side-channels
- technology is sufficiently mature to implement protocol
- more (straightforward) work require to build complete system
- efficiency of decoy-state protocol can probably be improved
- two-photon interference over real-world optical fibers also removes obstacle for quantum repeaters



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