Implementation of an attack scheme on a practical QKD system

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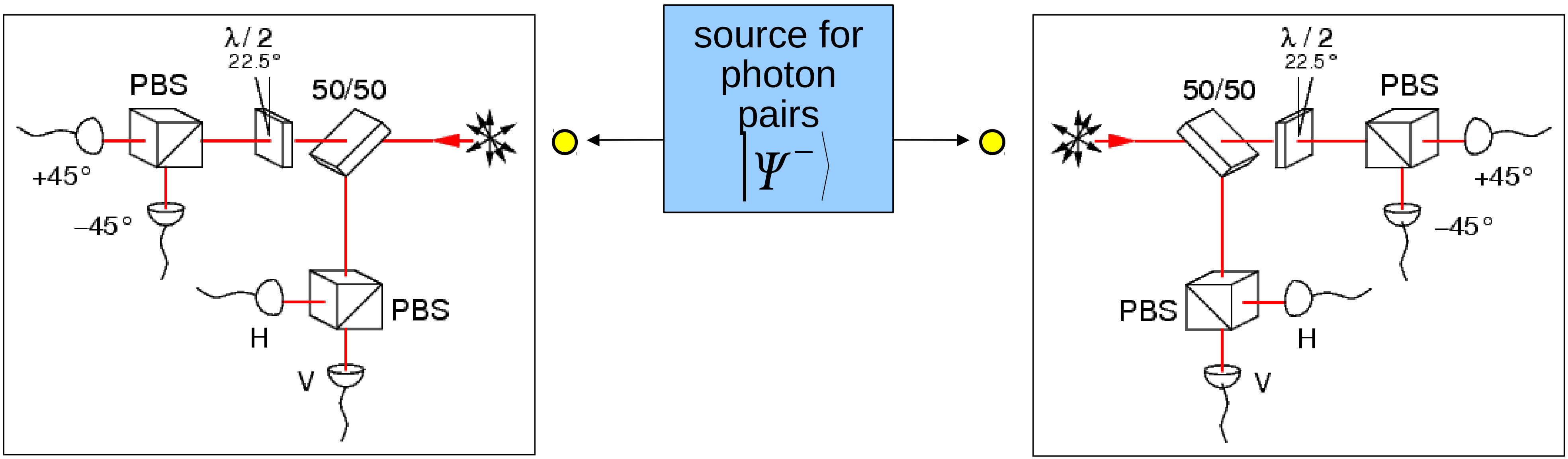
Overview

- Our BB92 QKD implementation
- Older attacks
- Photodetector vulnerability
- Practical attack on BBM92 for a fiber channel
- 'Faking' the violation of a Bell test

QKD with photon pairs: BBM92

Quantum correlations & measurements on both sides



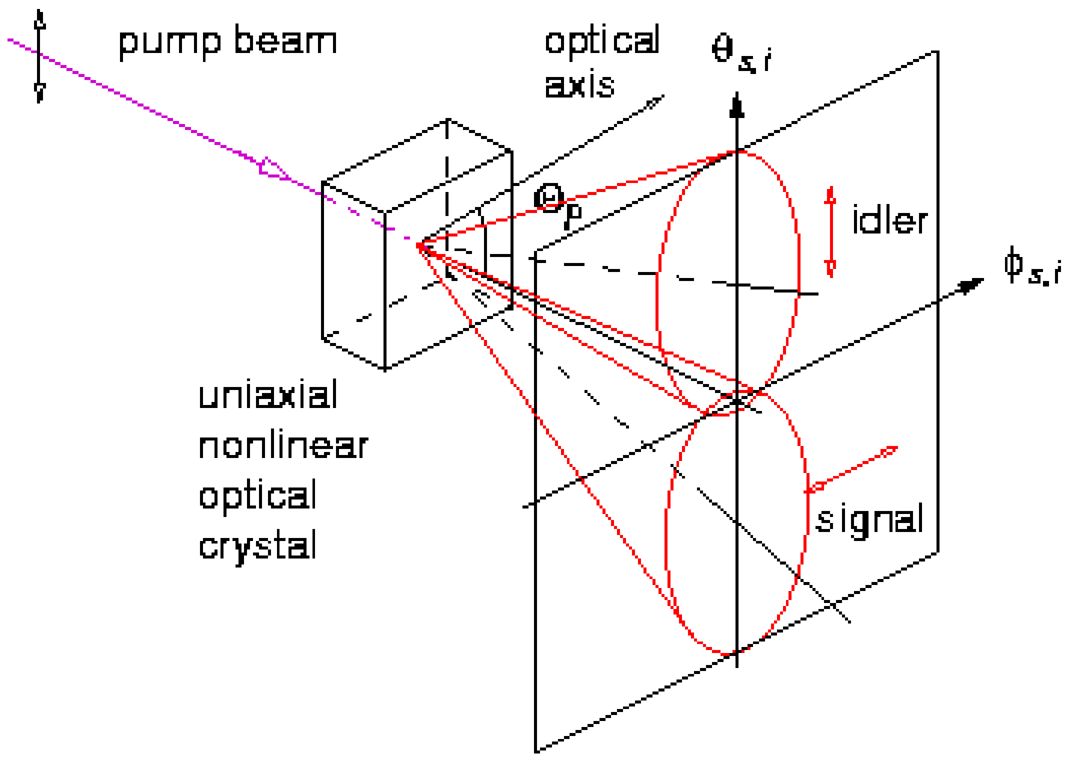
public discussion (sifting, key gen / state estimation)

error correction, privacy amplification

- like BB84, but no trusted random numbers for key
- direct use of quantum randomness for measurement basis

Entangled Photon Source

- Use non-collinear type-II parametric down conversion



two indistinguishable decay paths lead to

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)$$

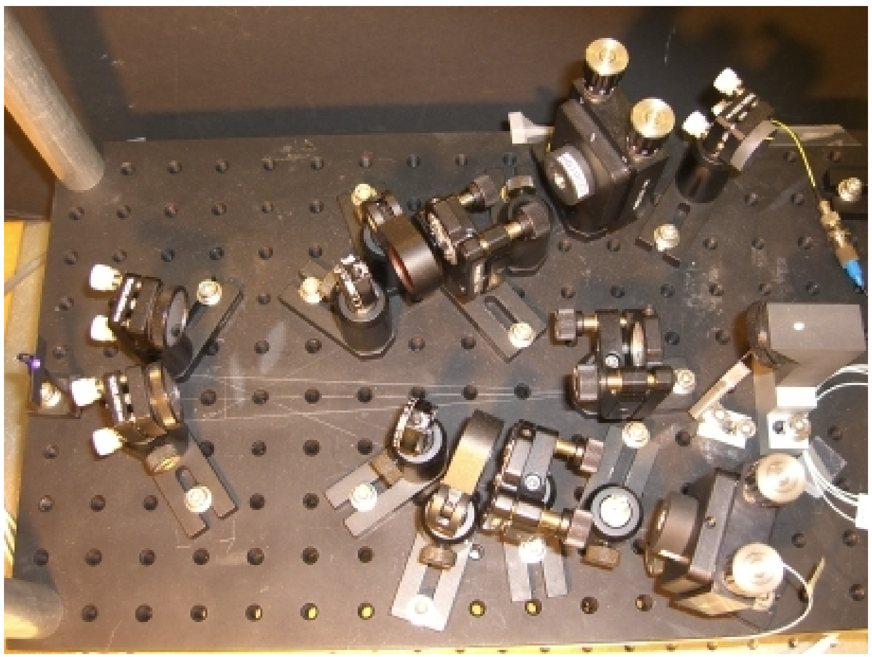
*P.G. Kwiat et al., PRL **75**, 4337 (1995)*

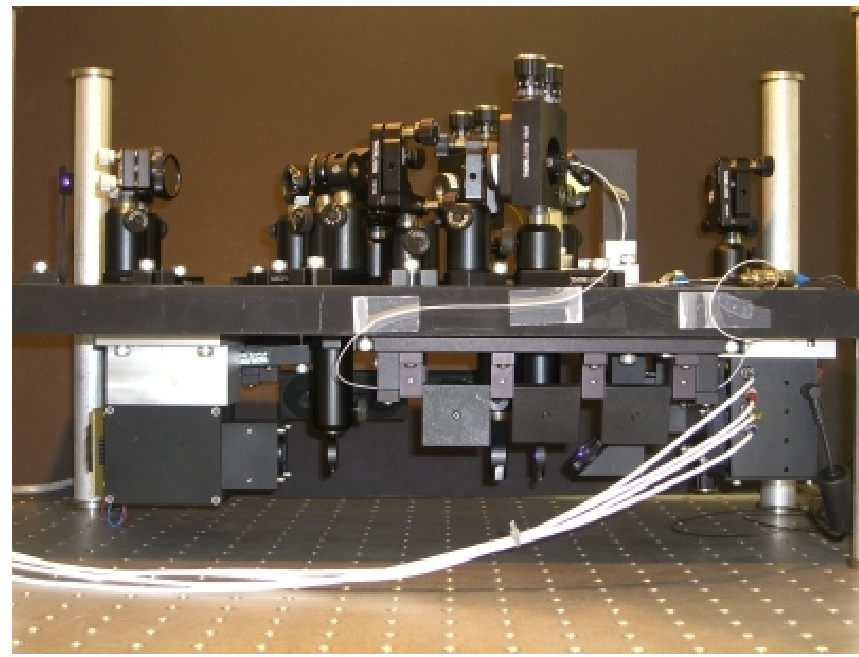
- Collect polarization-entangled photon pairs into single spatial modes (e.g. optical fibers) for good transmission

*C.K., M.O., H.W., PRA **64**, 023802 (2001)*

Practical Pair Source

Diode-laser pumped non-collinear type-II PDC in BBO

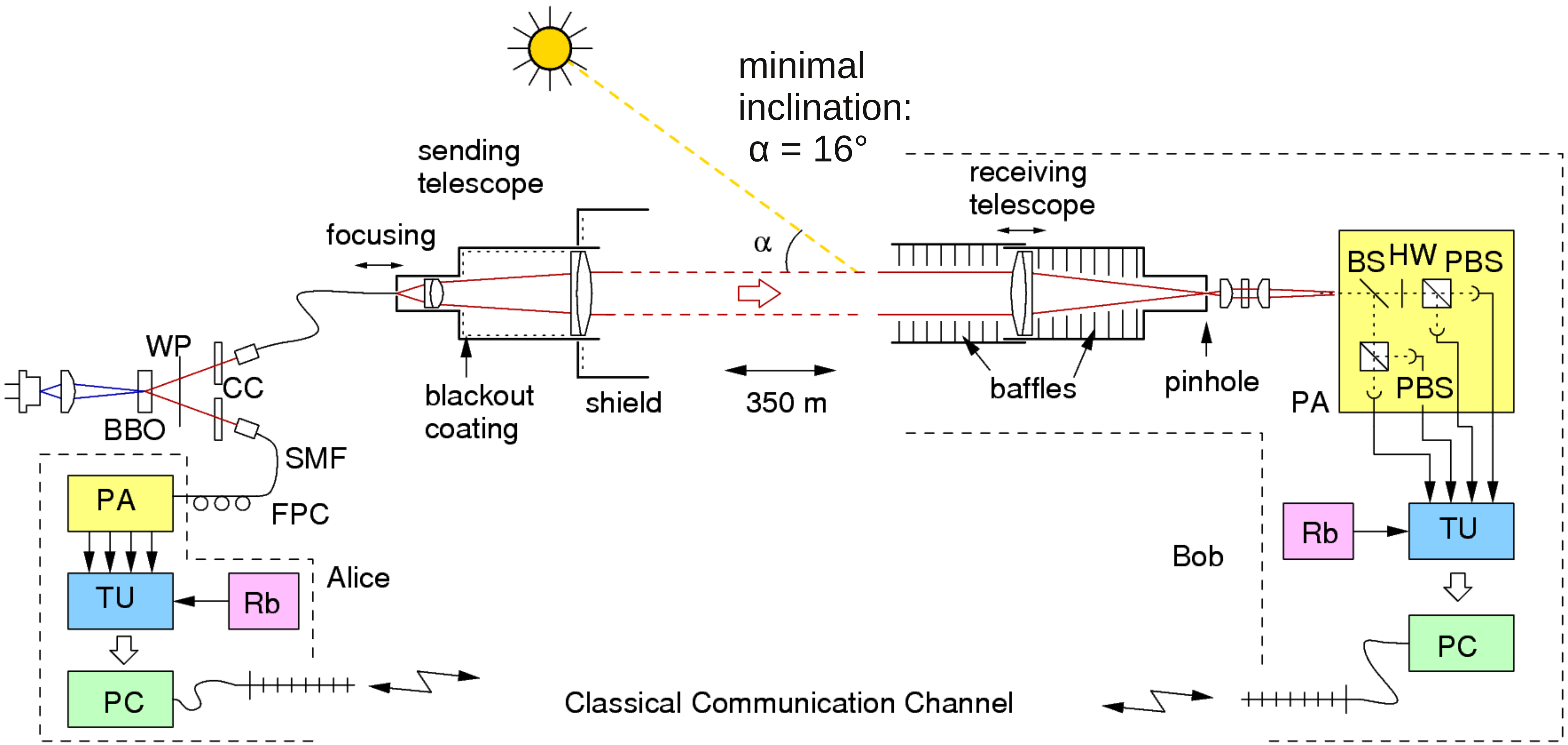




- 24,000 s^{-1} detected pairs from 40 mW pump @ 407nm in single mode fibers, 24 % pair/single ratio (2mm BBO)
- polarization correlation visibility in 45° basis: 92%
- optical bandwidth 6.5 nm FWHM around 810nm / 818 nm
- small footprint, works in outdoor conditions

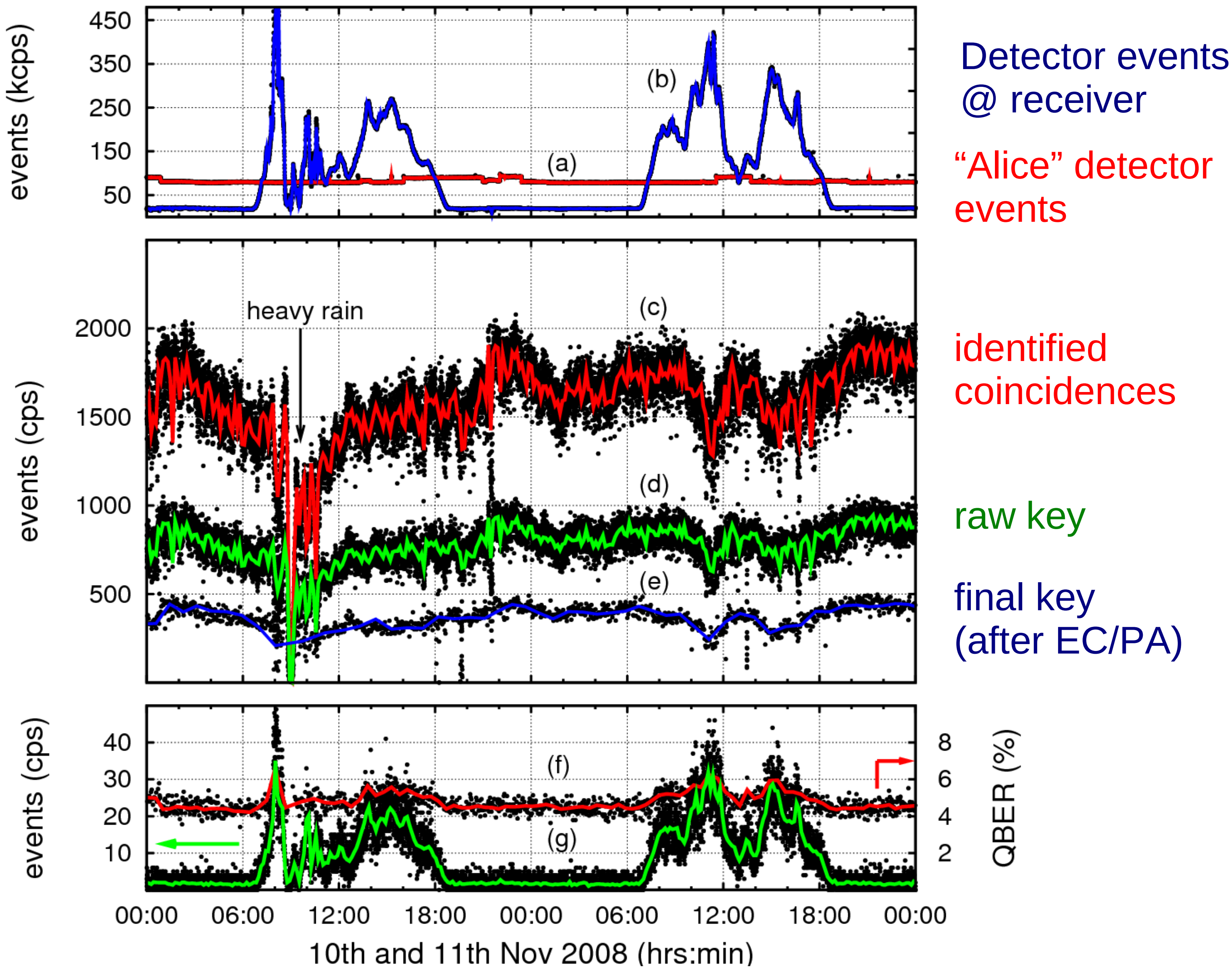
Our reference QKD system

free space link, works even in daylight



- polarization encoding, cw pair source, wavelength 810±3nm
  timestamping photoevents

Typical performance

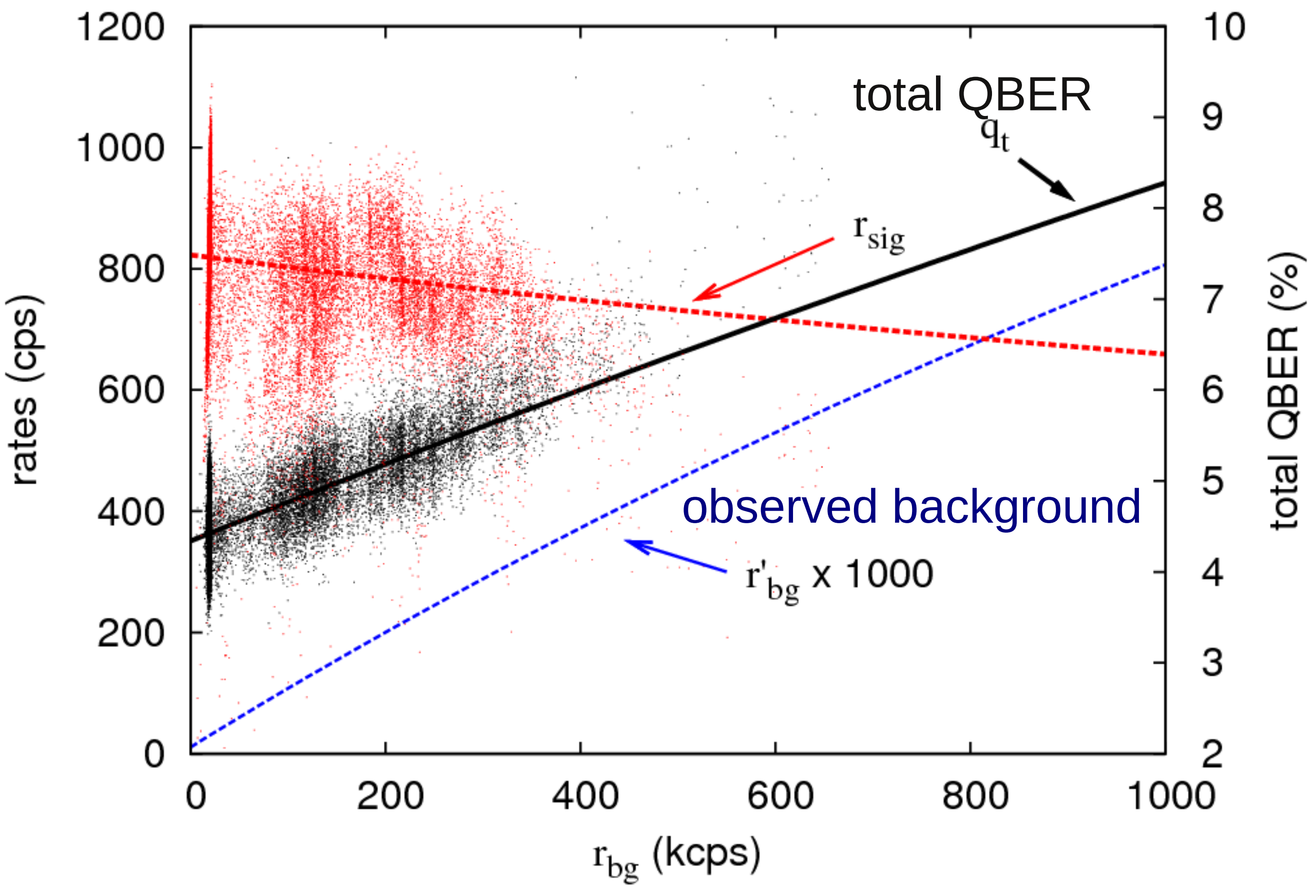


- optical BW: 6.7 nm FWHM
- coincidence time 2 ns
- receiver telescope: 100 µrad
- continuous operation over 4 days

*M. P. Peloso, I. Gerhardt, C. Ho, A. Lamas-Linares, C.K., NJP **11**, 045007 (2009)*

Detector saturation in daylight

Detector saturation and QBER



Background rate (uncorrected for detector saturation)

- main limit is detector saturation, not QBER due to accidental coincidences
- similar for high bit rate systems

Field usage, open source

PDC pair source & sender

- System gets simpler and more robust, low power consumption (<65W)

receiving side

- Software is open source (GPLv2): http://code.google.com/p/qcrypto

  Open hardware under way

Various practical attacks...

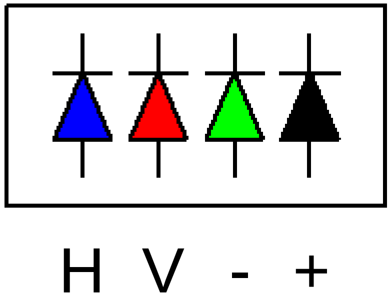
- Too large Hilbert space in practical BB84 -
  not only multi-photon problems

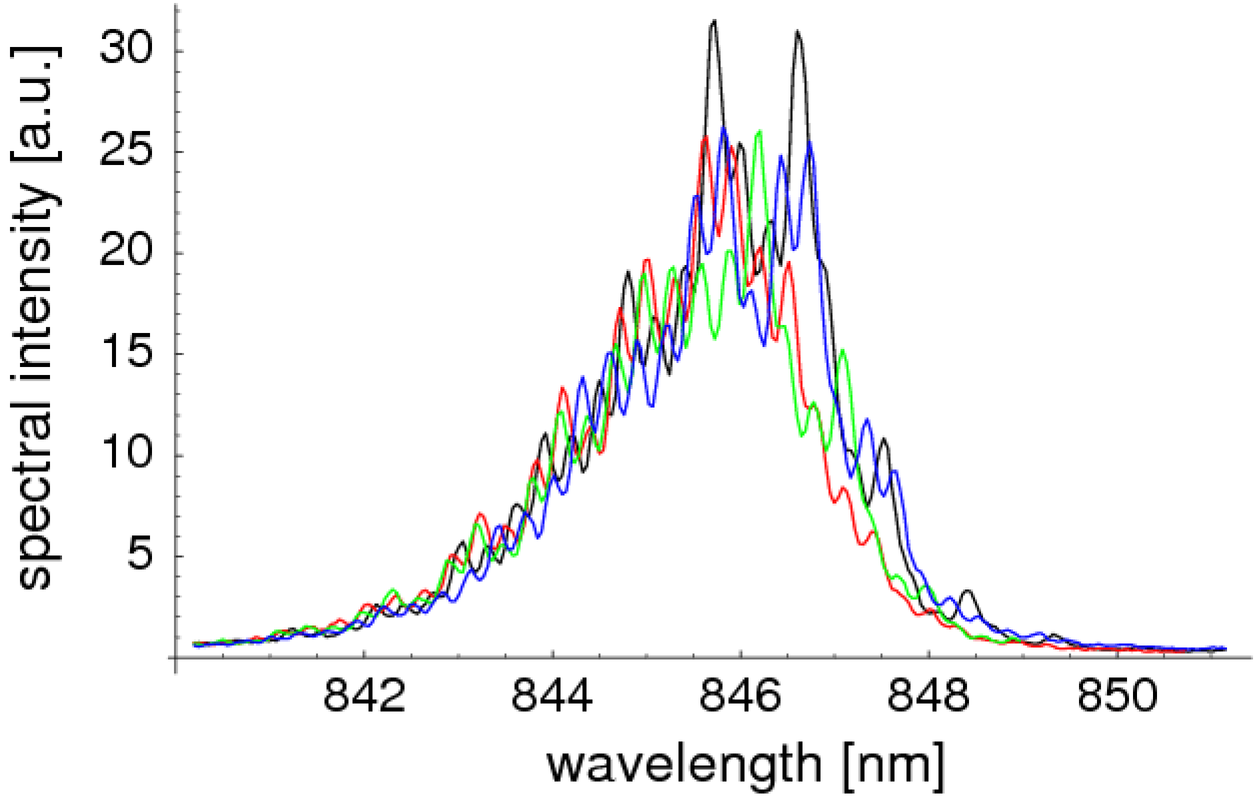
- Leaking of timing information in classical communication

- Active detector attack

BB84: Spectral backdoor

Don't measure polarization, but e.g. color:
The Hilbert Space in your system is larger than it appears

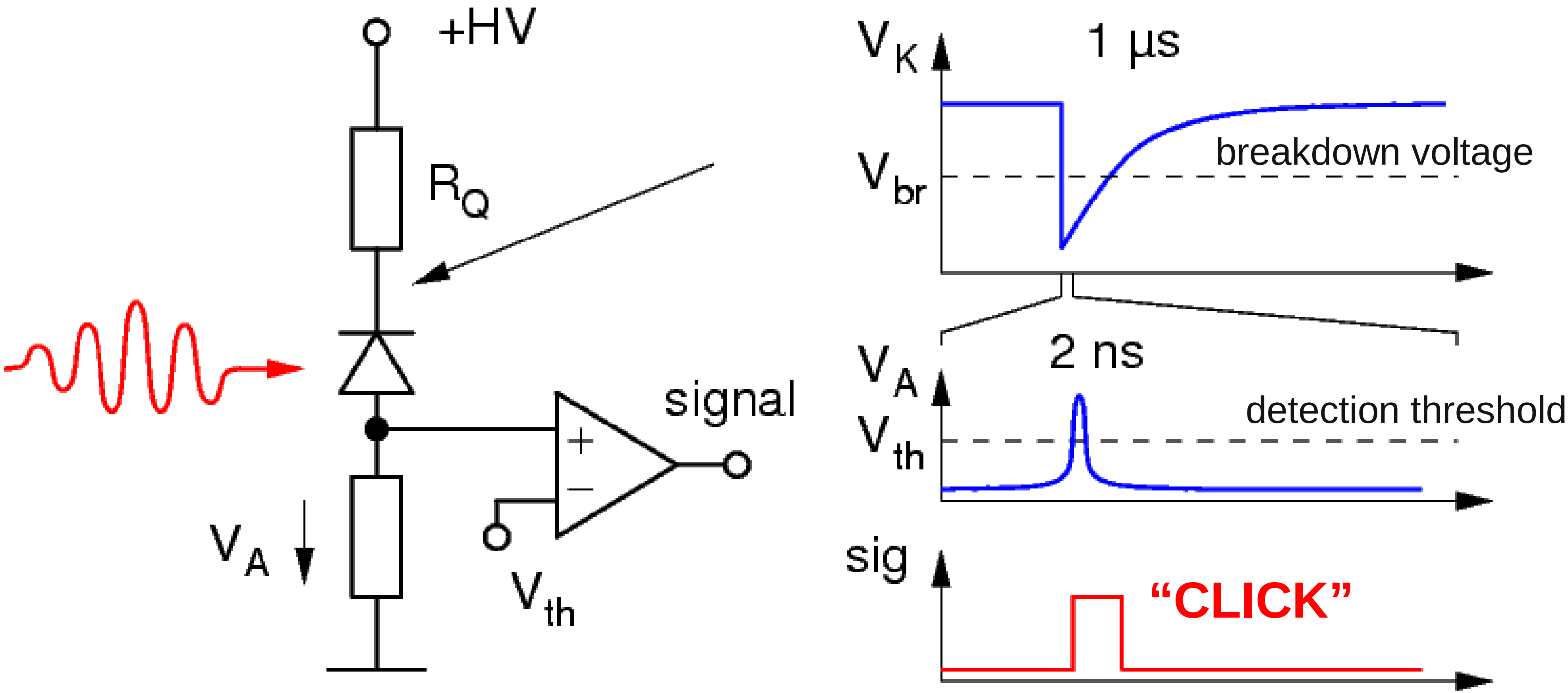




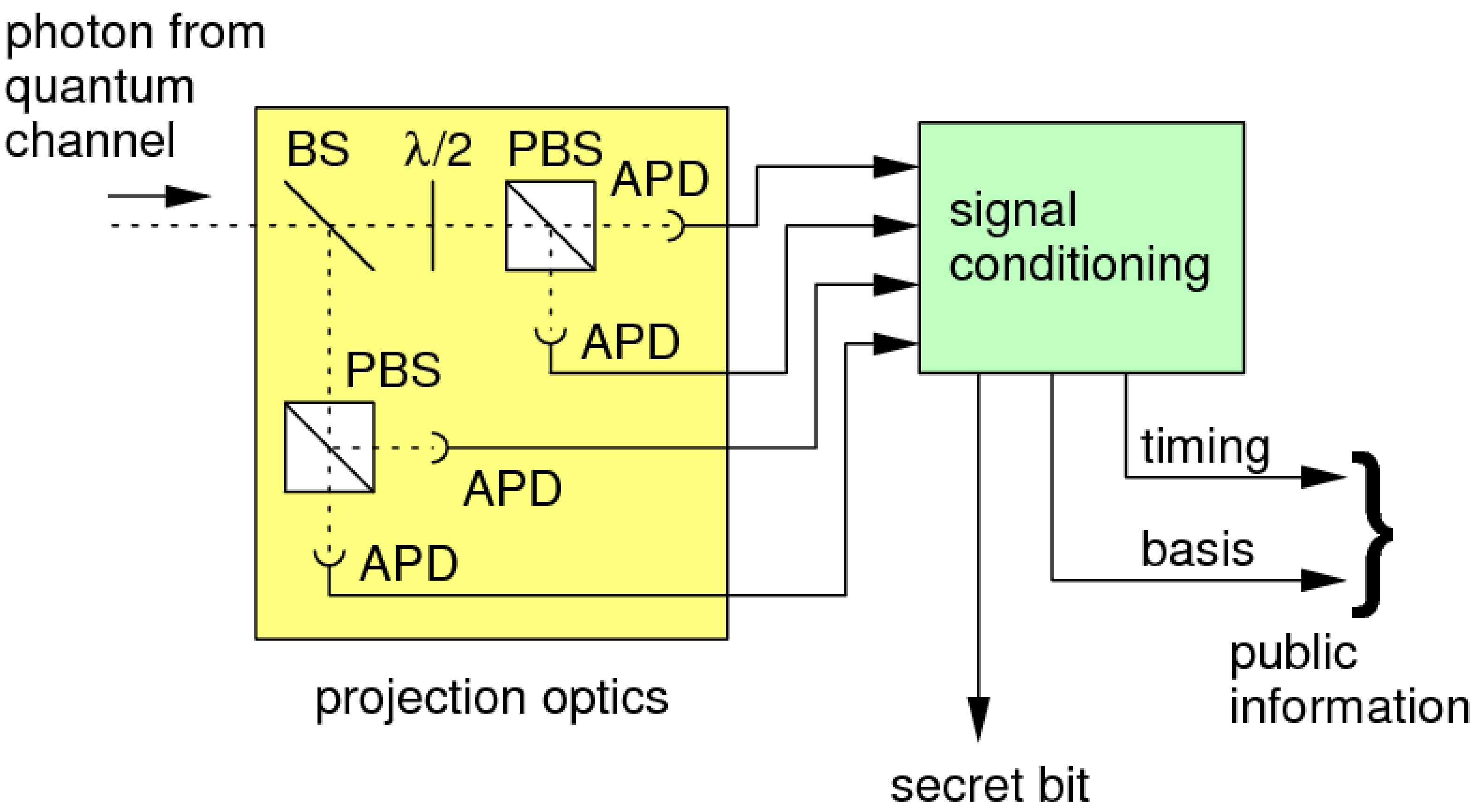
asymptotic
average
information
leakage: <2%

Basic photodetector operation

Avalanche photodiodes (APD) are common "single photon" detectors

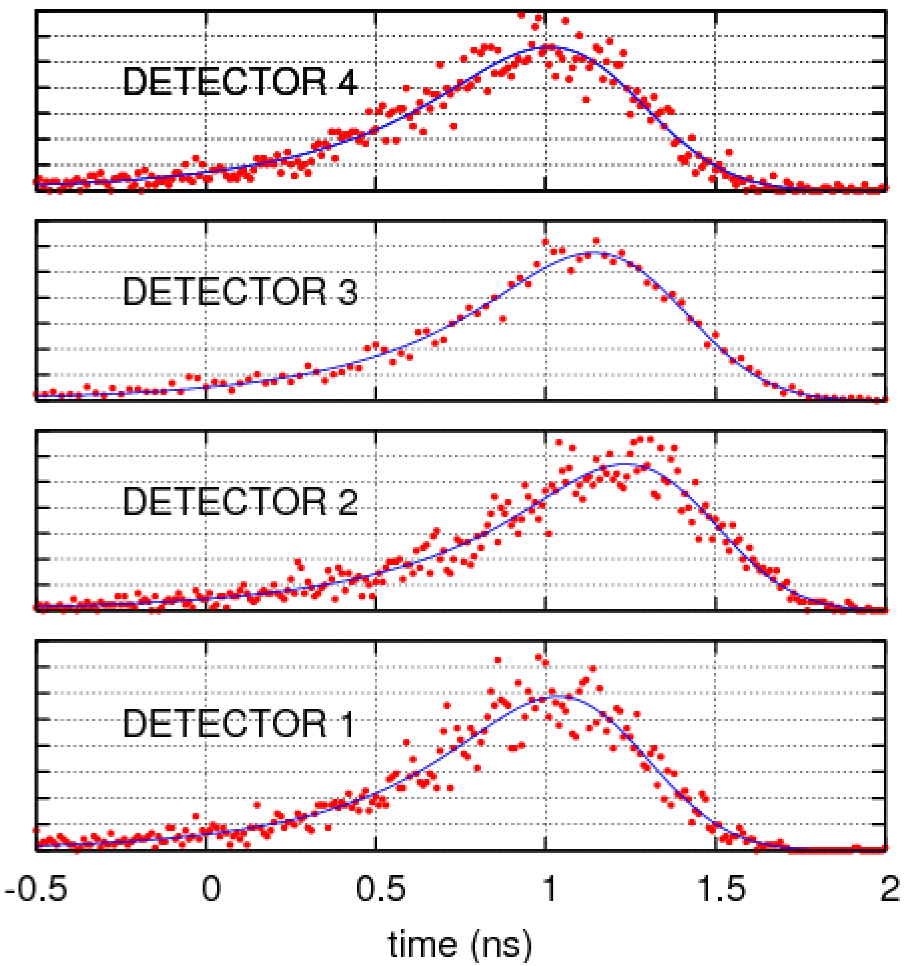


Timing channel attack I

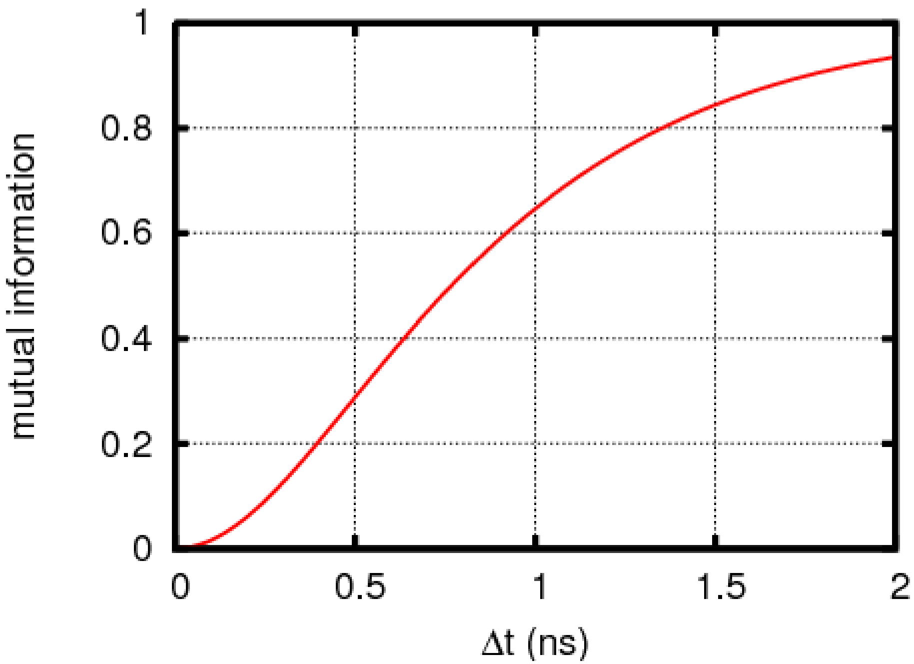


Timing channel attack II

Classical timing information carries fingerprint of detectors:



small detector imbalances may tell Eve a lot!

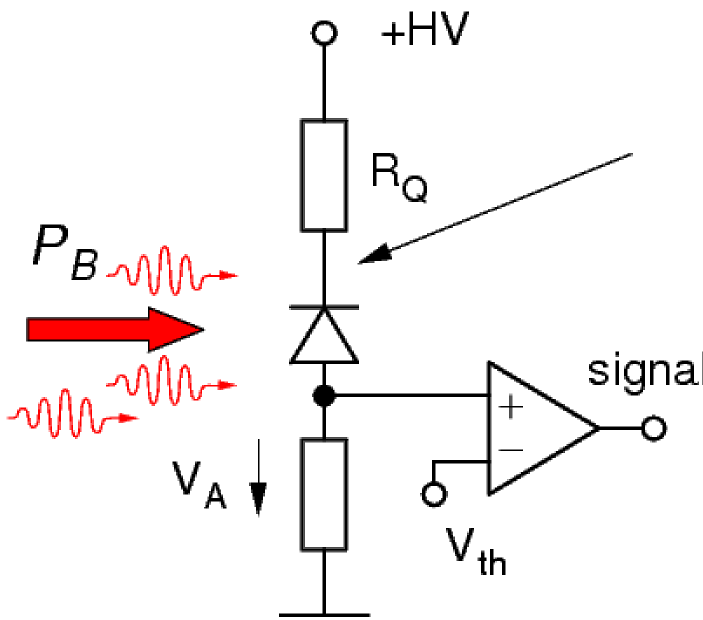


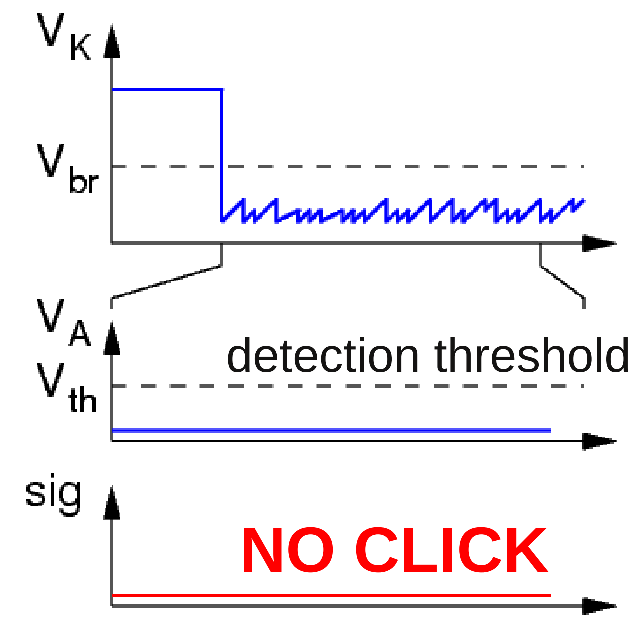
ALL, CK, Optics Express ***15****, 9388 (2007)*

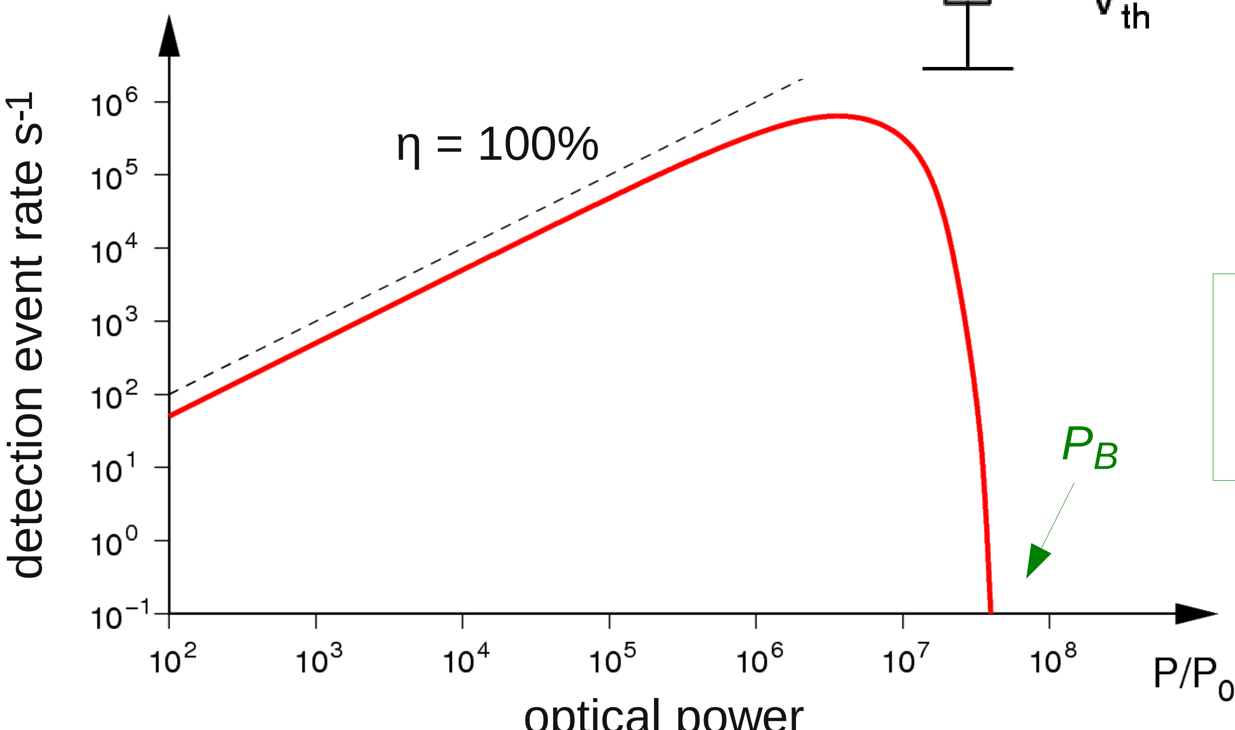
APD detector vulnerability I

Basic Problem:

APD saturate and can be blinded



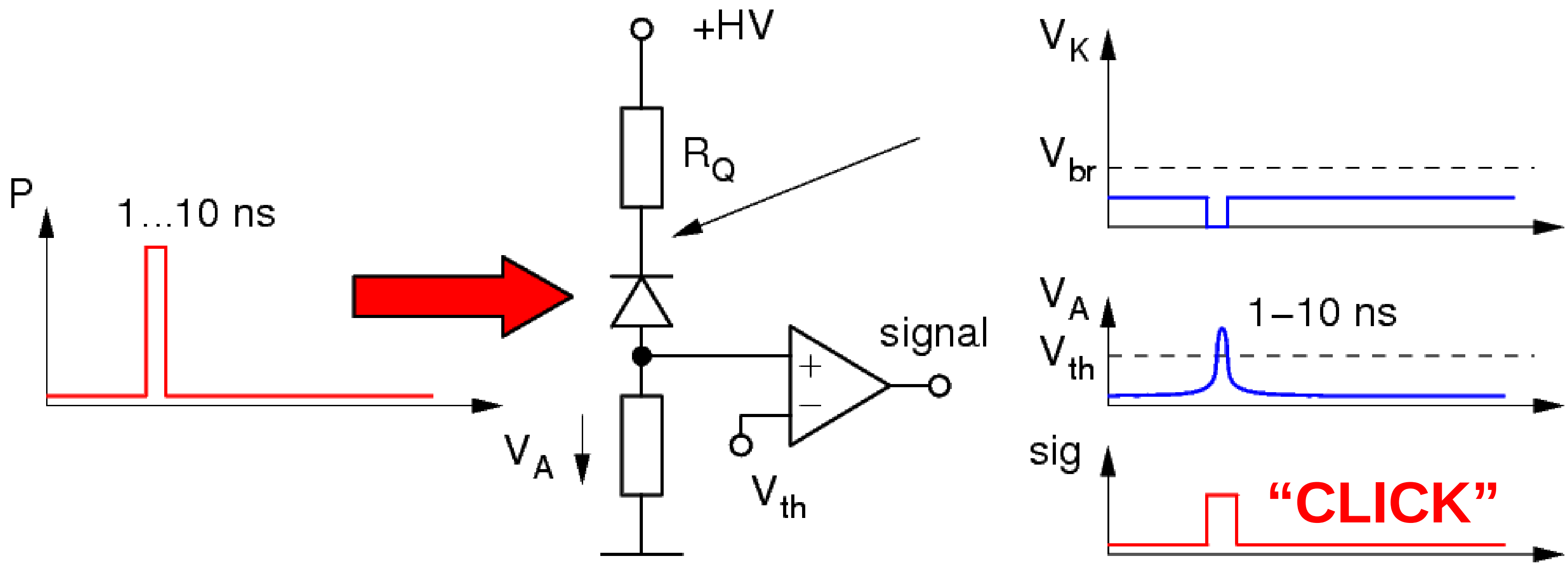




blinding power P_B: 1..10 pW (corresponding to 10^6-10^7 events / sec)

APD vulnerability II

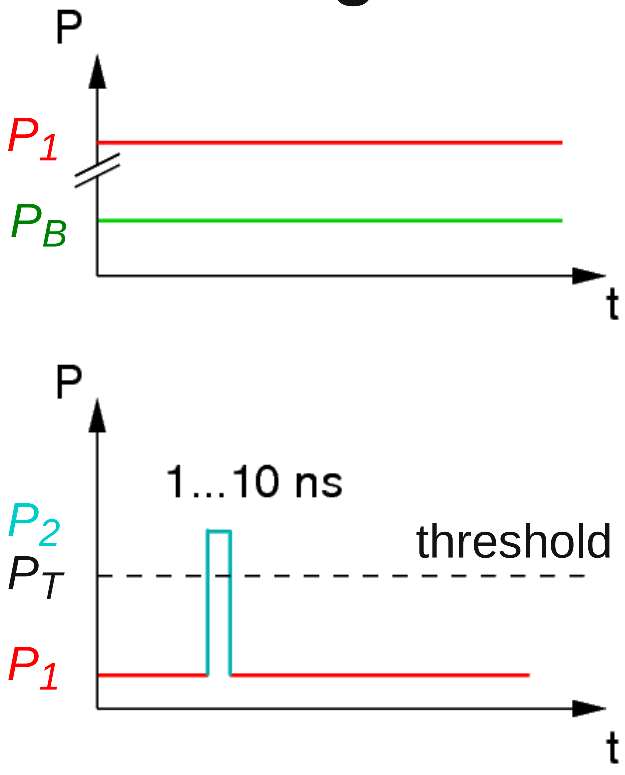
...and forced to give a signal by bright light pulses:



Avalanche diode operates in PIN / normal amplification regime

Hijacking one detector...

Combined to attack scheme by sending 'fake states' of classical light:



- Detector is quiet

  blinding level $P_1 > P_B$ (few pW)

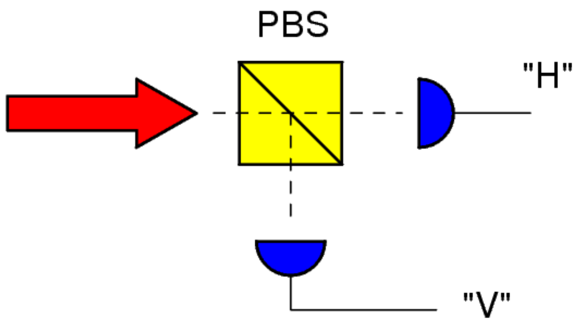
- Detector can be forced to a click at well-defined time

  $P_2 > P_T$ (few mW)

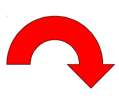
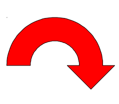
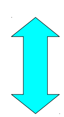
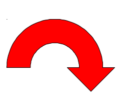
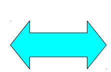
*Fake state attack : Vadim Makarov, NJP **11**, 065003 (2009)*

Hijacking the 'measurement'

- This works with detector pairs as well:



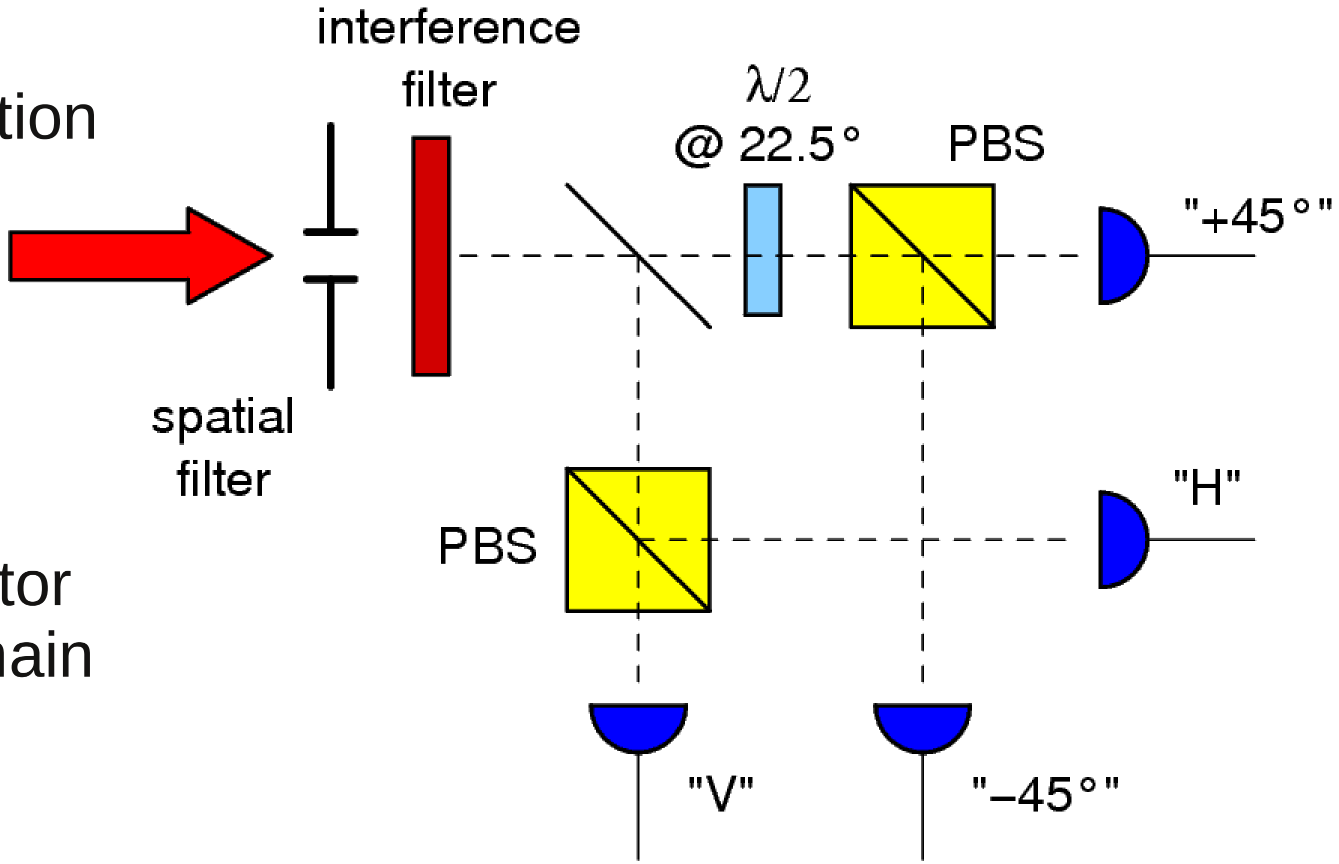
Choose unpolarized / circularly polarized P_1 and different linear polarizations to fake a 'click'

Light:	**"H" detector:**	**"V" detector:**
 $>2\ P_B$	no click	no click
 + 	click	no click
 + 	no click	click

Why stop at two....

Control of a passive base choice QKD detector:

- Choose σ+ polarization for blinding

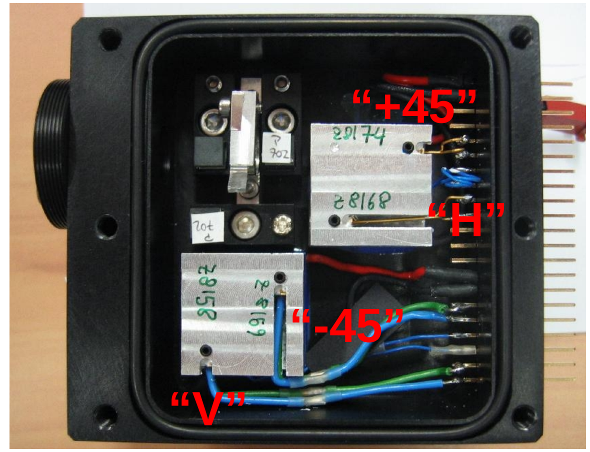


- Choose power for each fake pulse such that one detector fires, the others remain below threshold

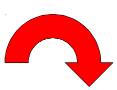
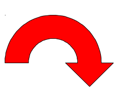
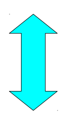
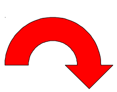
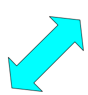
- Eve now has complete control over this detection scheme....

Four detector attack

"faked state"

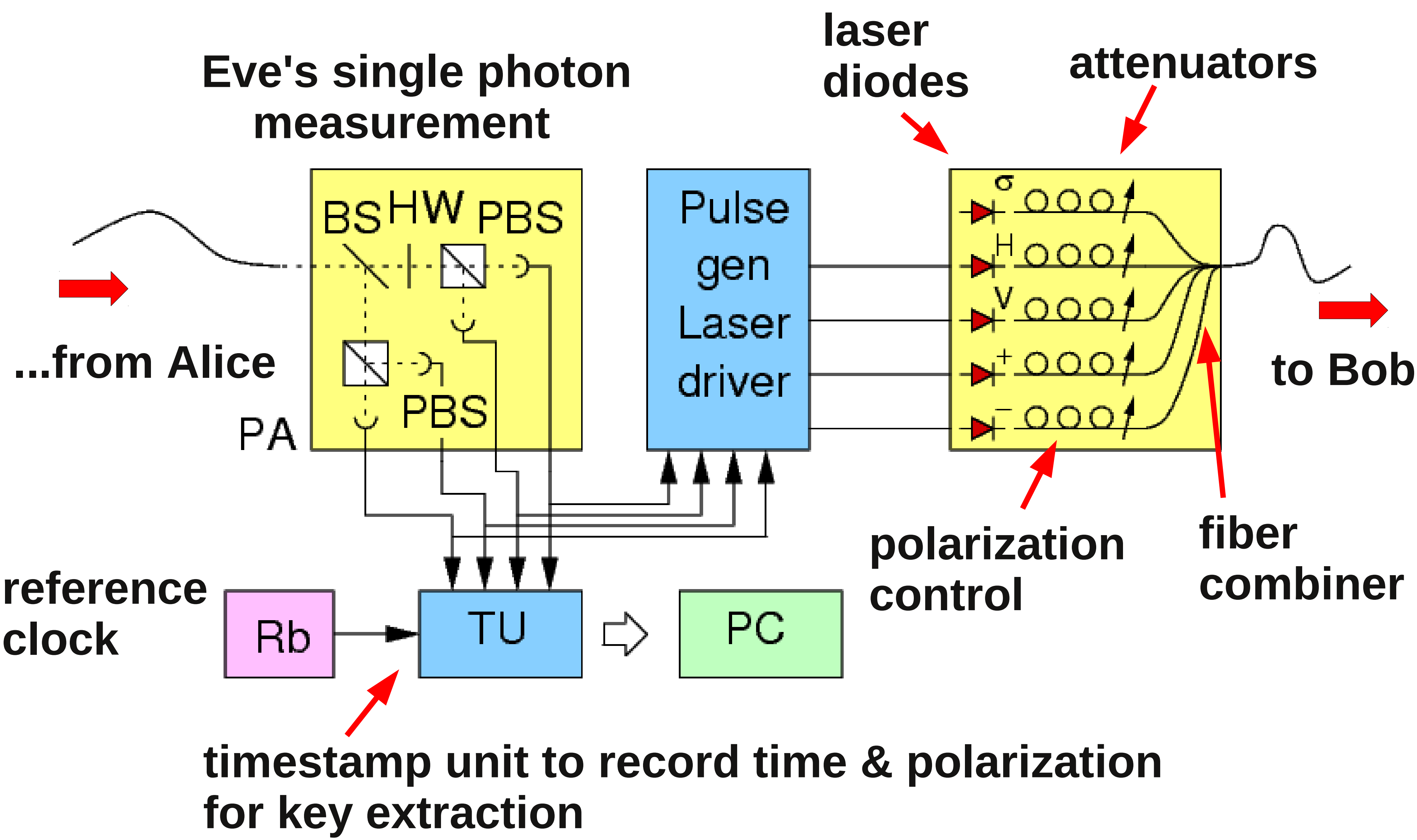


our polarization detector

Light:		"H"	"V"	"+45"	"-45"
	>4 P_B	no click	no click	no click	no click
	+ 	click	no click	no click	no click
	+ 	no click	no click	click	no click

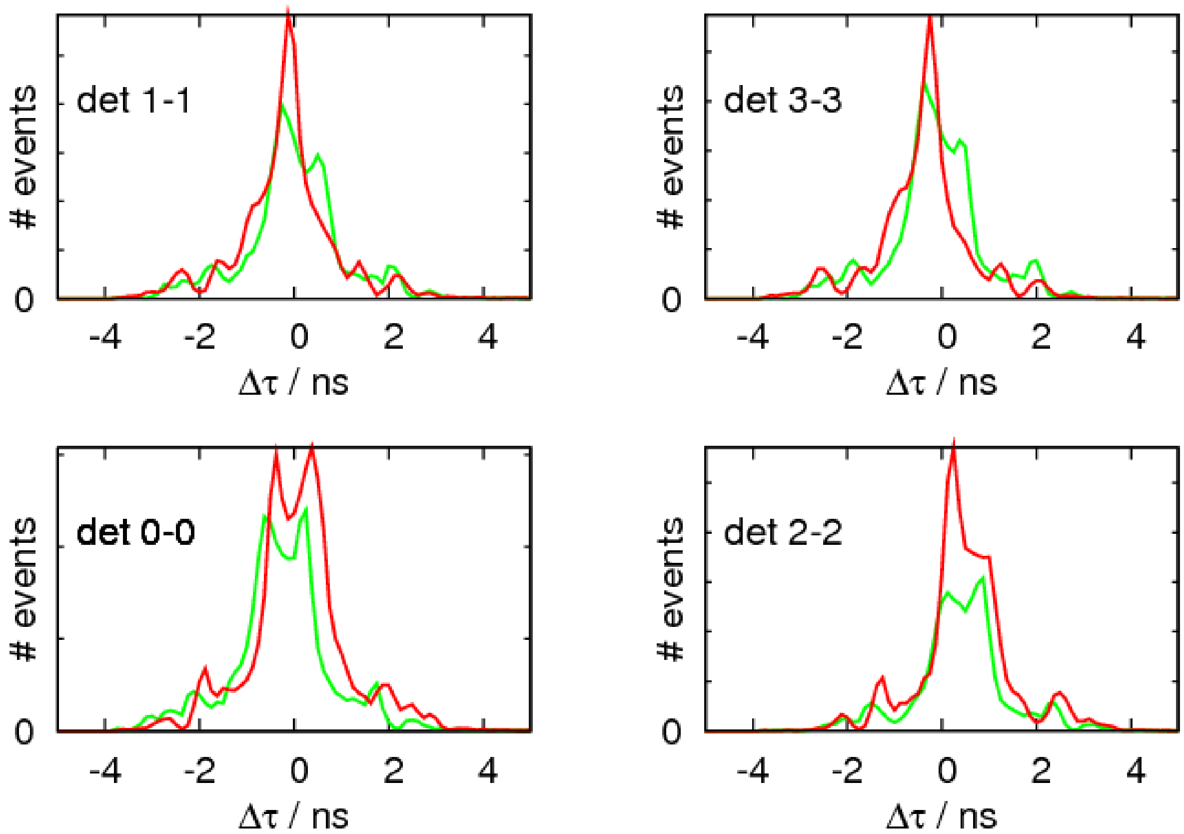
- Choose pulse amplitudes above +45 threshold, but below H/V threshold -- ideally 1- √2/2 margin for P_2

Eve's intercept-resend kit



Eve's insertion timing

Coincidence timing histograms of a working system



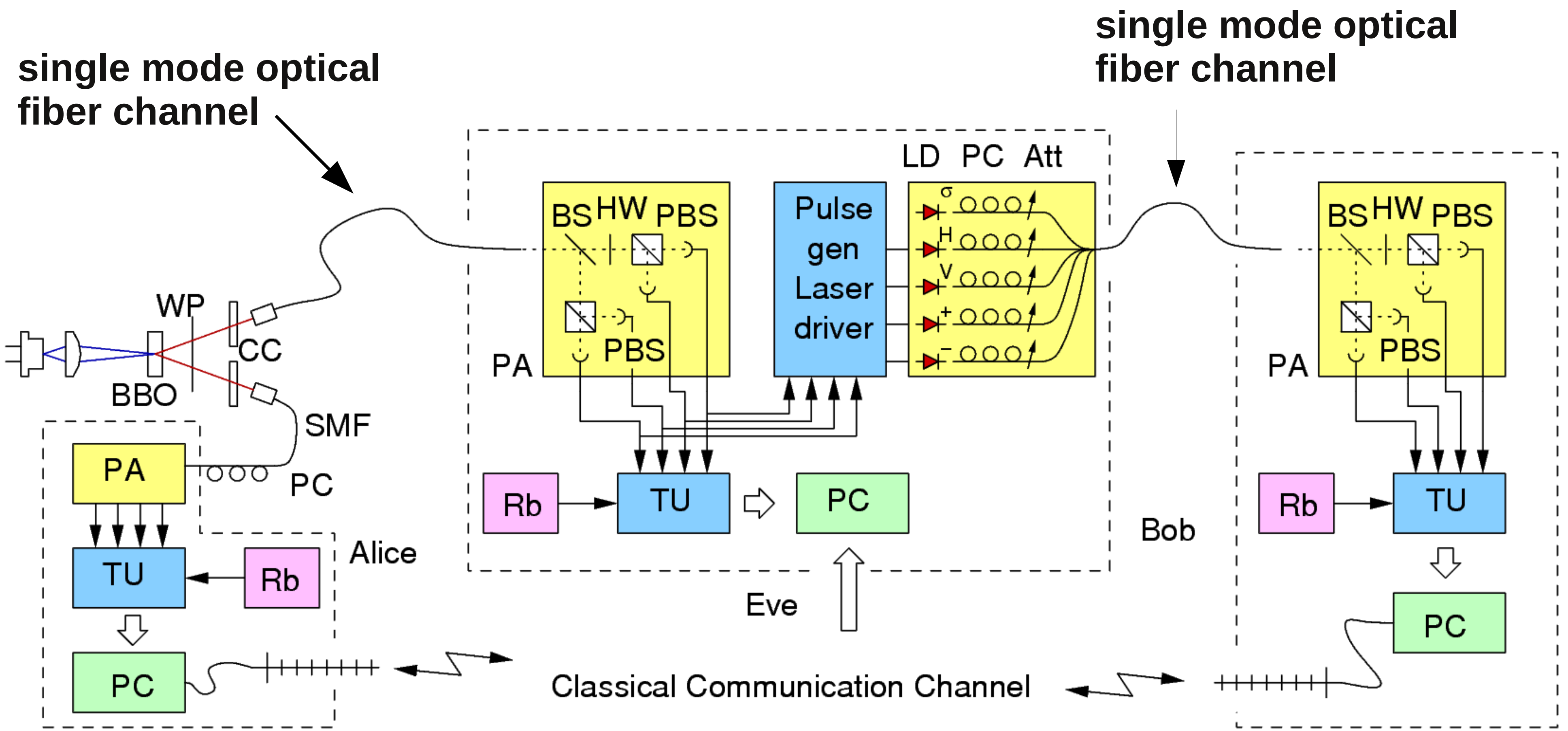
without Eve intercept

with Eve intercept

No resolvable influence on detector signal timing (<100 ps jitter)

Insertion delay ~10 nsec

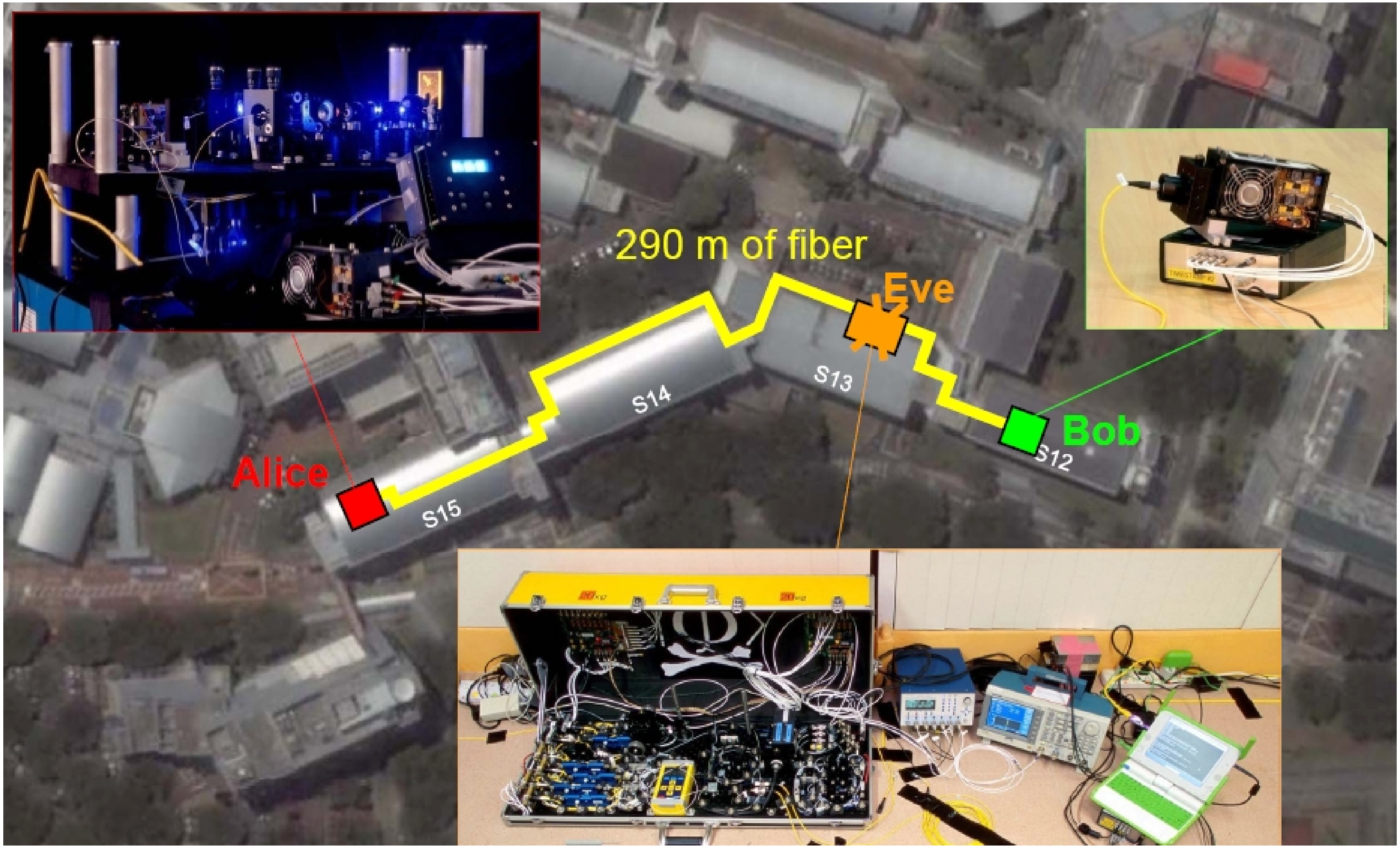
Full intercept/resent scheme



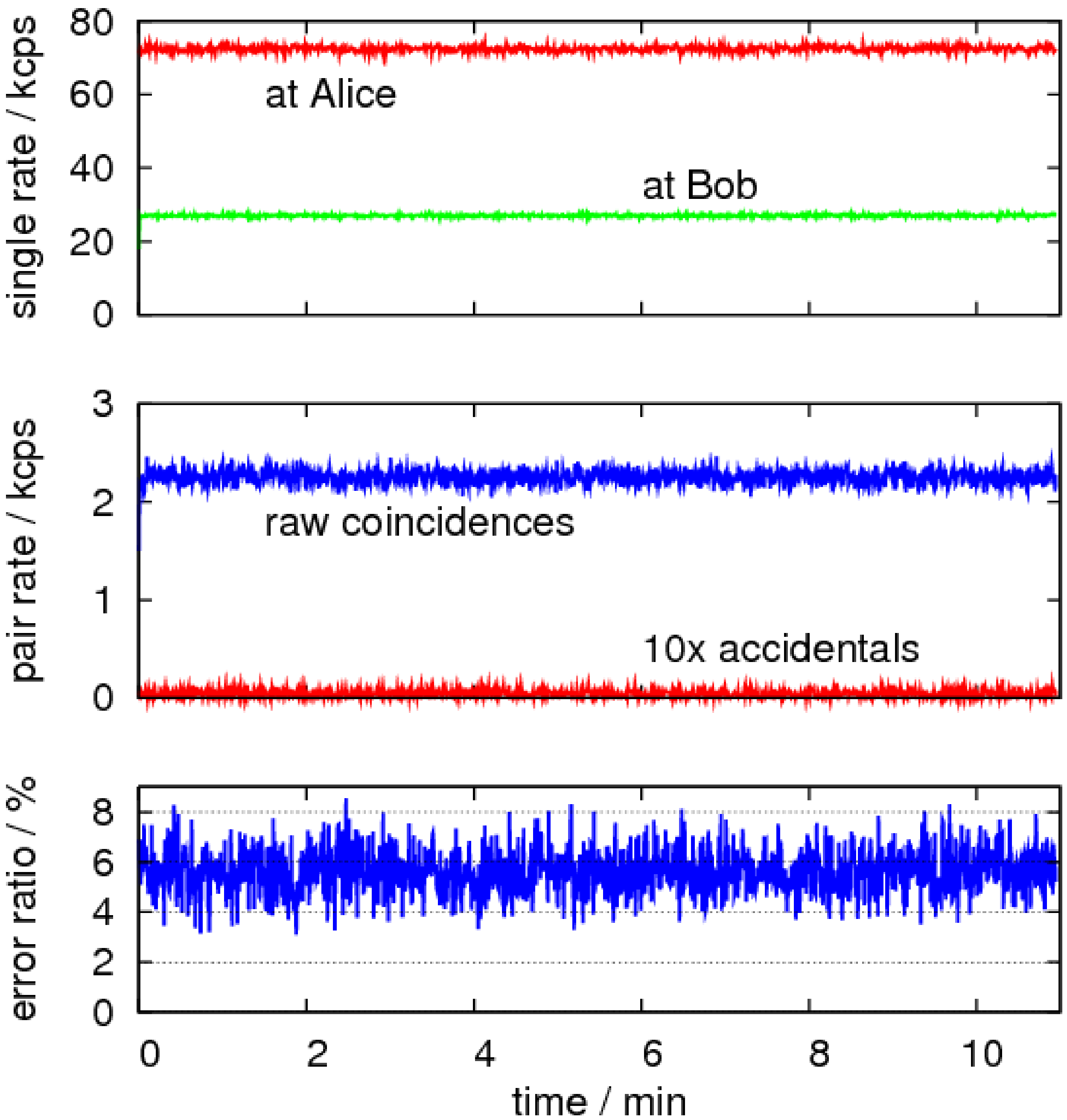
(wireless LAN)

Layout of the plot

"Realistic" fiber link across the Science faculty @ NUS



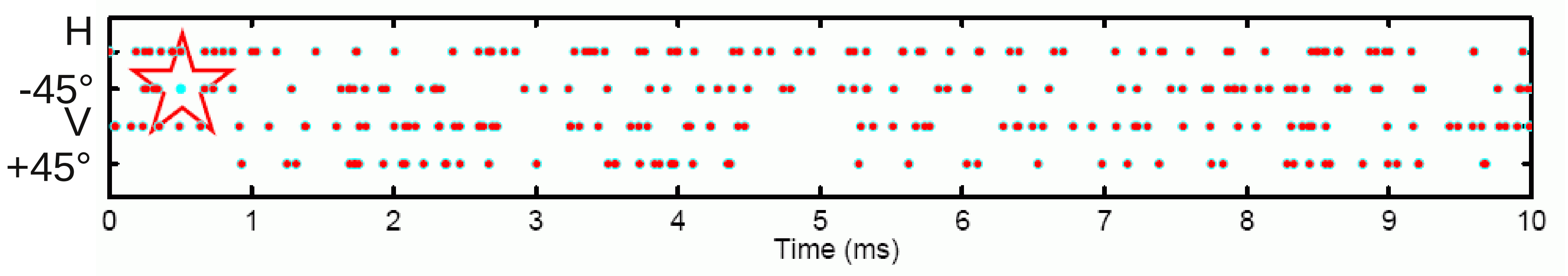
Results for Alice & Bob



- reasonable photo detection rates on both sides (includes transmission loss)
- reasonable pair rate and raw key rate around 1.1 kcps
- no spurious pulses
- reasonable error ratio for this source allows to extract 500 bits/sec key after PA / EC

Attack Results I

A real-time display of events between Eve and Bob:



- About 97%-99% of Eve clicks are transferred to Bob
- Eve can identify successful detections by Bob from timing information (classical channel intercept)
- Eve knows correctly identified pairs due to losses (classical channel intercept)
- Eve knows all detector outcomes of Bob

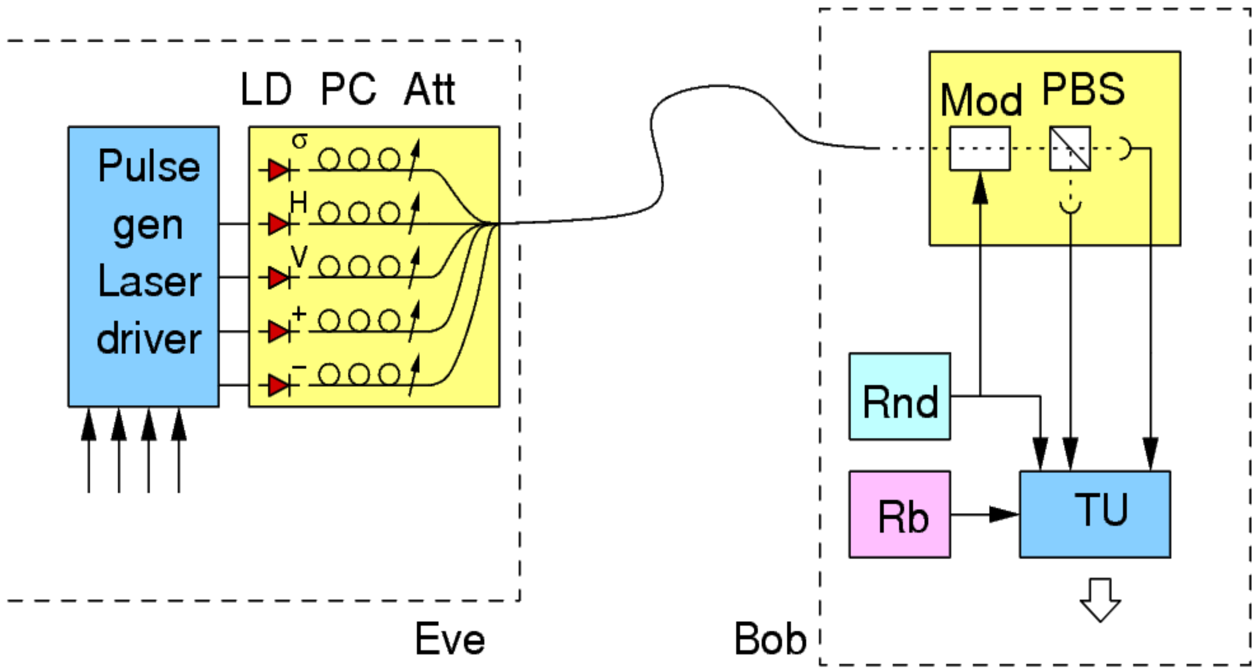
Attack Results II

- Correlation between Eve and Bob's result (the hijacked receiver) is 100%

630,106	0	0	0
0	841,072	0	0
0	0	1,116,070	0
0	0	0	1,026,603

- Eve has Bob's complete raw key
- By eavesdropping the classical communication in error correction/privacy amplification, Eve can reconstruct the secret key

Does active base choice help?

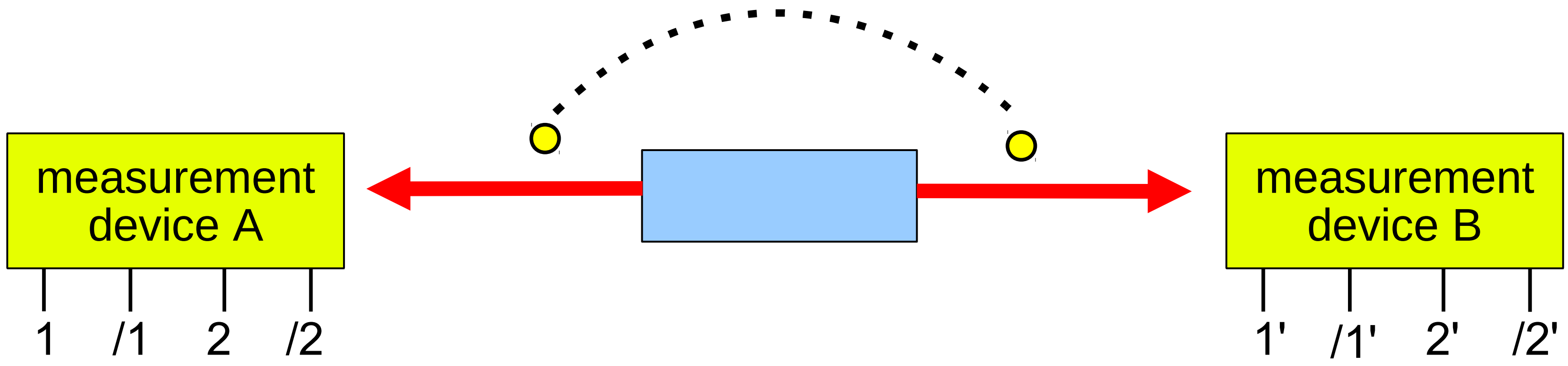


- Correlation between Eve's command and Bob results is 100%
- Bob's probability of getting Eve's base choice correct is 50%

Presence of Eve looks like 50% loss (no big help)

Do other protocols help?

Device-independent / Ekert-91 protocol idea



For proper settings 1, 2, 1', 2' and state $|\Psi^-\rangle$ $S = \pm 2\sqrt{2}$

- Estimate quantitatively the knowledge of Eve of raw key between A and B from S:

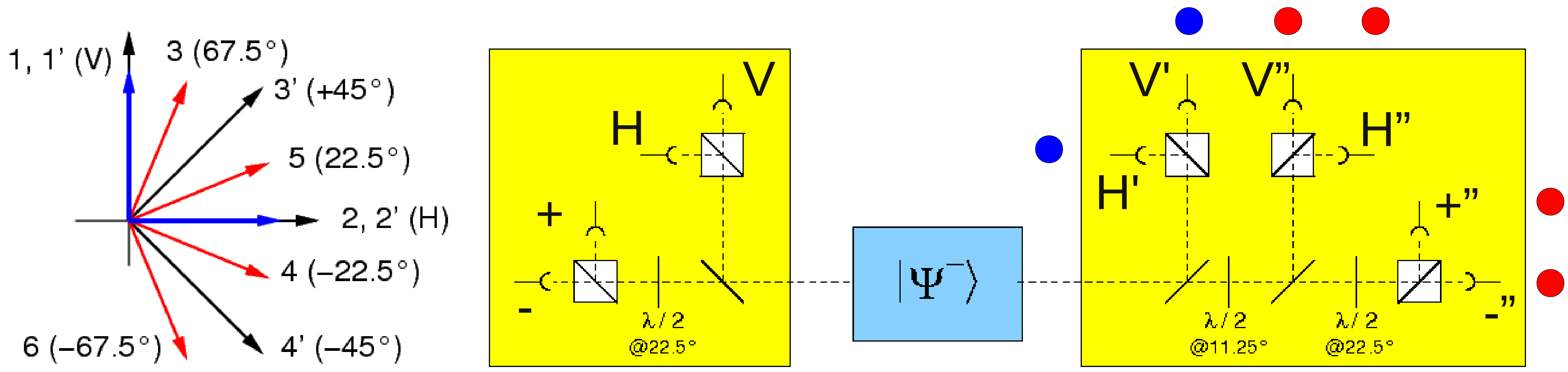
$$I_E(S) = h\left(1 + \frac{\sqrt{S^2/4 - 1}}{2}\right)$$

- No fingerprint problems of photons due to side channels

A. Acin, N. Brunner, N. Gisin,S. Massar, S. Pironio, V. Scarani, PRL 98, 230501 (2007)

Implementation (partial?)

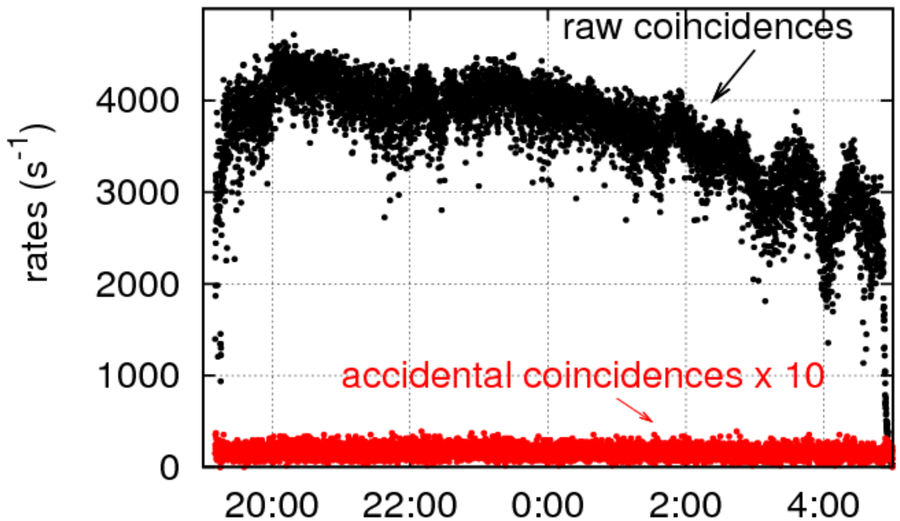
- use almost same kit:

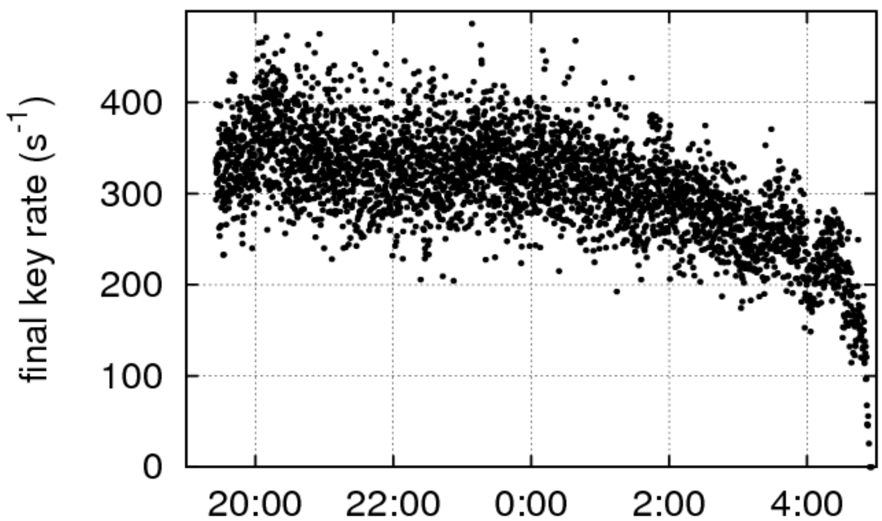


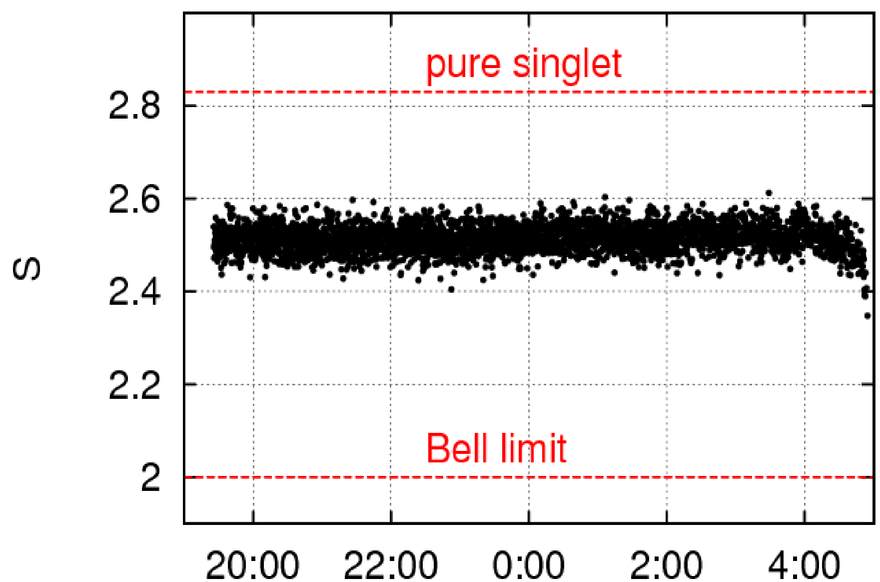
- {H,V; H',V'} coincidences → key generation
- {H,V,+,-;H”,V”,+”,-”} coincidences → CHSH Bell test
- low QBER with existing simple source

Practical E91 Key Generation

Key generation results:





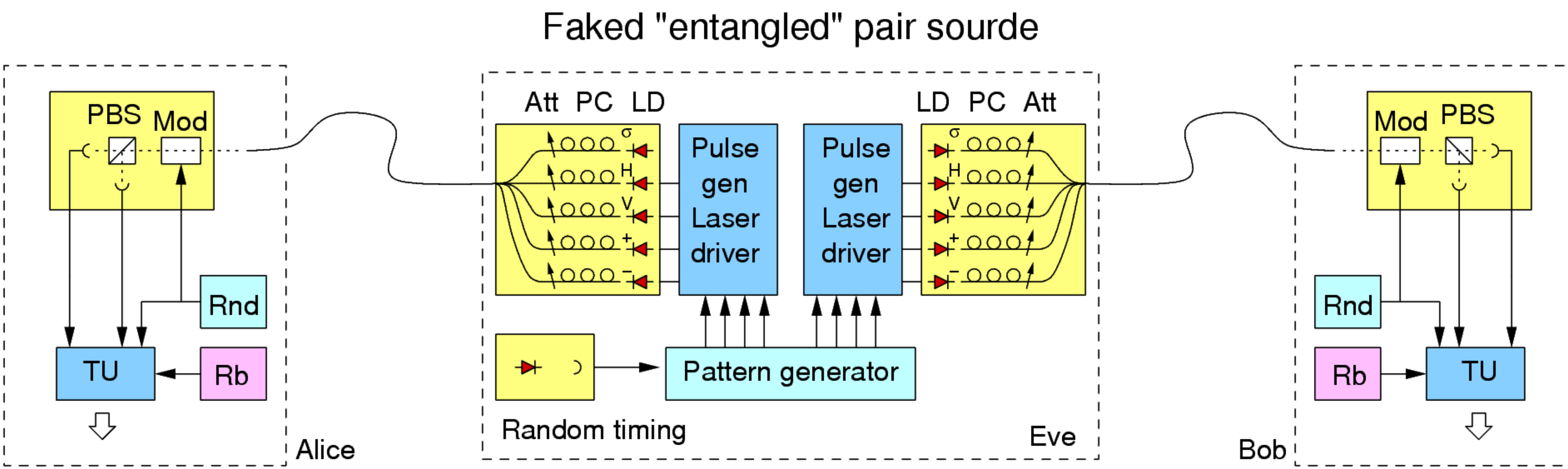


- continuous operation at night
  final key after EC/PA: 10^7 bits

A. Ling, M. Peloso, I. Marcikic, A. Lamas-Linares, V. Scarani, C.K., Phys. Rev. A ***78****, 020301(2008)*

Faking Violation of a Bell ineq

(core part of device-independent QKD protocol)



- Alice & Bob will see “programmed” correlations in 25% of the cases (base match on both sides), rest nothing
- Alice and Bob cannot distinguish from lossy line....
- We programmed (and found) CHSH results from S = -4 .... 4 with active choice

What is going on??

How can device-independent break down?

- Losses in CHSH are removed by post-selecting pair observations using a fair sampling assumption

- Current pair sources (η = 70%) and detectors (η = 50% for non-cryogenic ones)

- Eve hides behind losses of transmission line. Best guess: optical fiber and ideal (η = 100%) detectors, active base choice: At 0.2dB/km@1550nm, T = 25% for *dist* = 30 km

- Only very short distances possible with current detectors

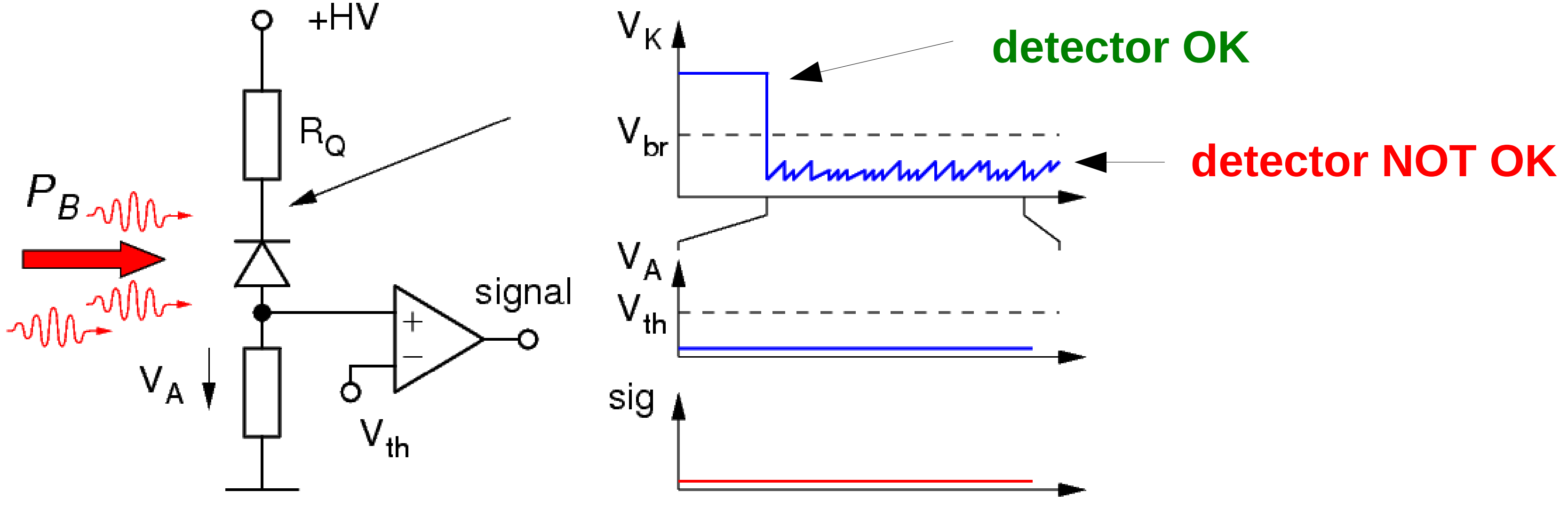
Can this be fixed ?

Yes, of course.

- Monitor total intensity with a separate, non-saturable photodetector (PIN diode)

  Blinding power and bright pulses are much brighter than usual photon signal

- Monitor the state of APD's by looking at their voltage, asserting 'detector readiness'



Is this a “good” fix....?

...of a “Bad Implementation” ??

- Are there detectors / detector concepts which are not susceptible to such or similar attacks?
- Do we have other practical attacks?
- Will all practical implementations always be potentially bad implementations of a theoretically secure protocol?
- Let's leave Hilbert space and have independent challenge/assessments of security claims
- What do we offer in comparison to classical key exchange devices like tamper-safe devices? Is QKD just an elegant version of such a device?

Valerio Scarani, C.K., arxiv:0906.4547

Thank You!

Team members NTNU Trondheim
Vadim Makarov
Qin Liu
Johannes Skaar

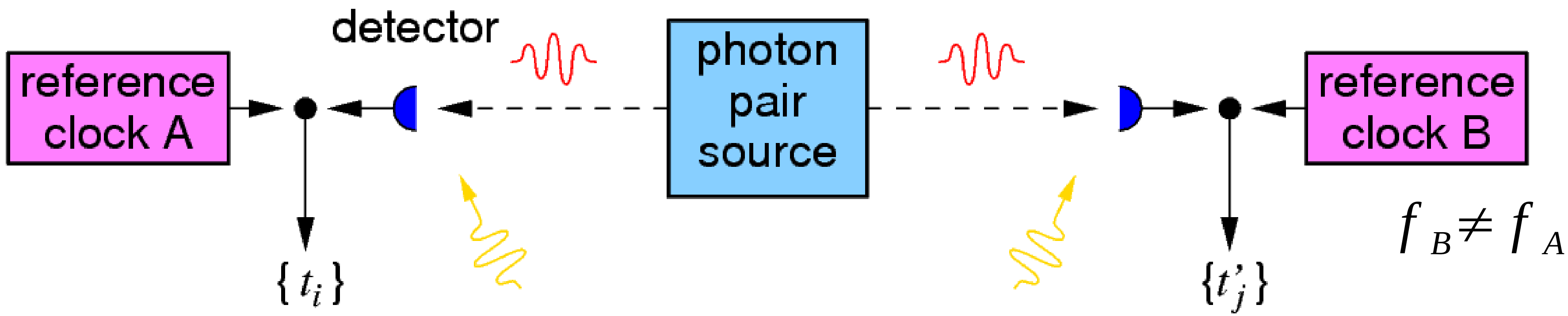
Team members CQT Singapore
Ilja Gerhardt
Matt Peloso
Caleb Ho
Antia Lamas-Linares
Valerio Scarani
C.K.

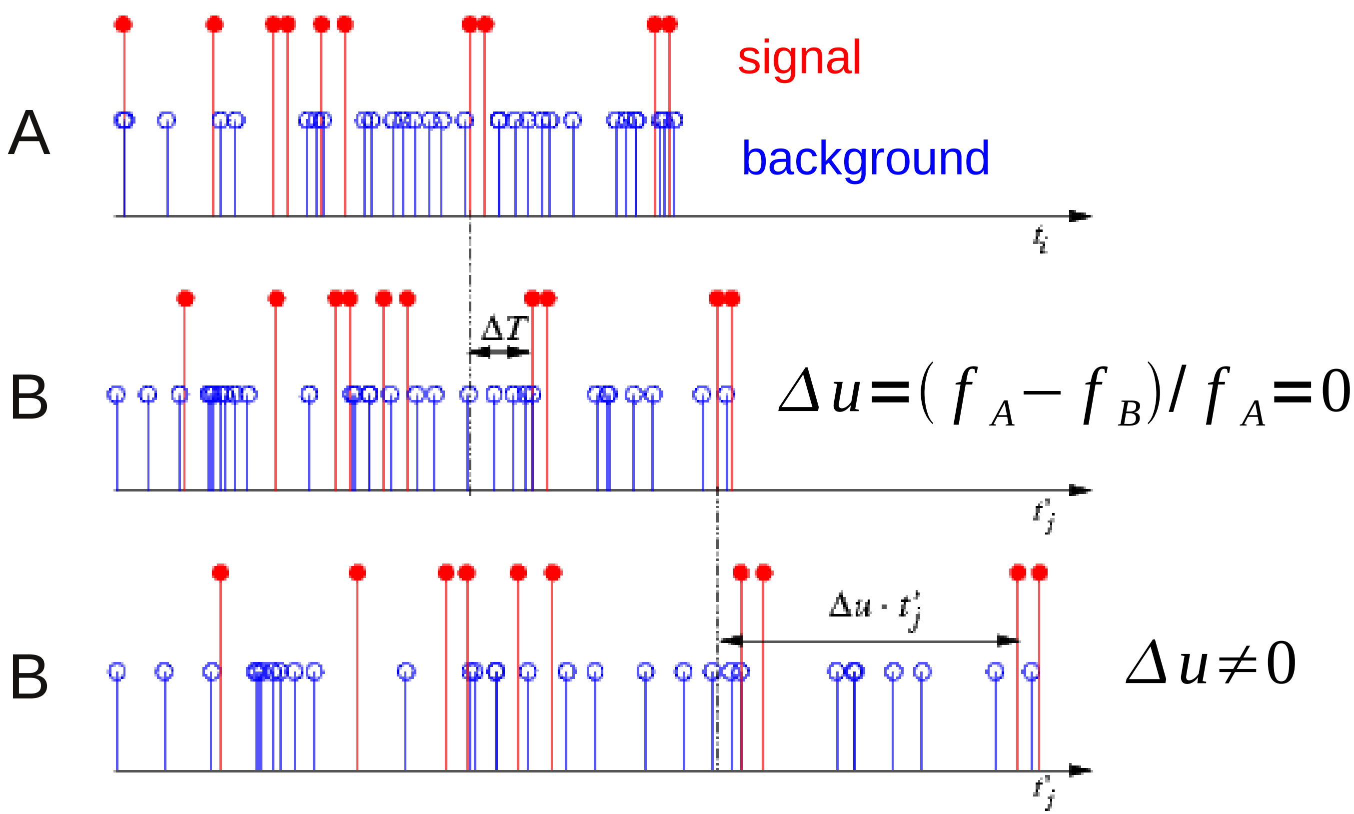
Group:
http://www.qolah.org

CQT Graduate program:
http://cqtphd.quantumlah.org

Clock synchronization I

No dedicated hardware, use correlations in SPDC

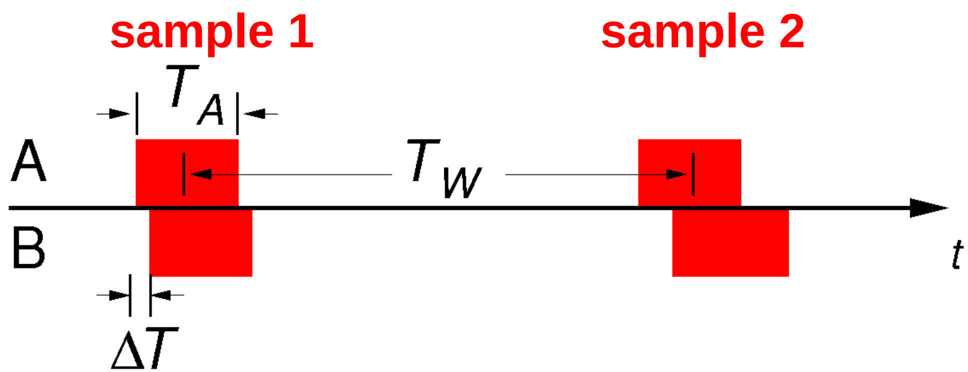




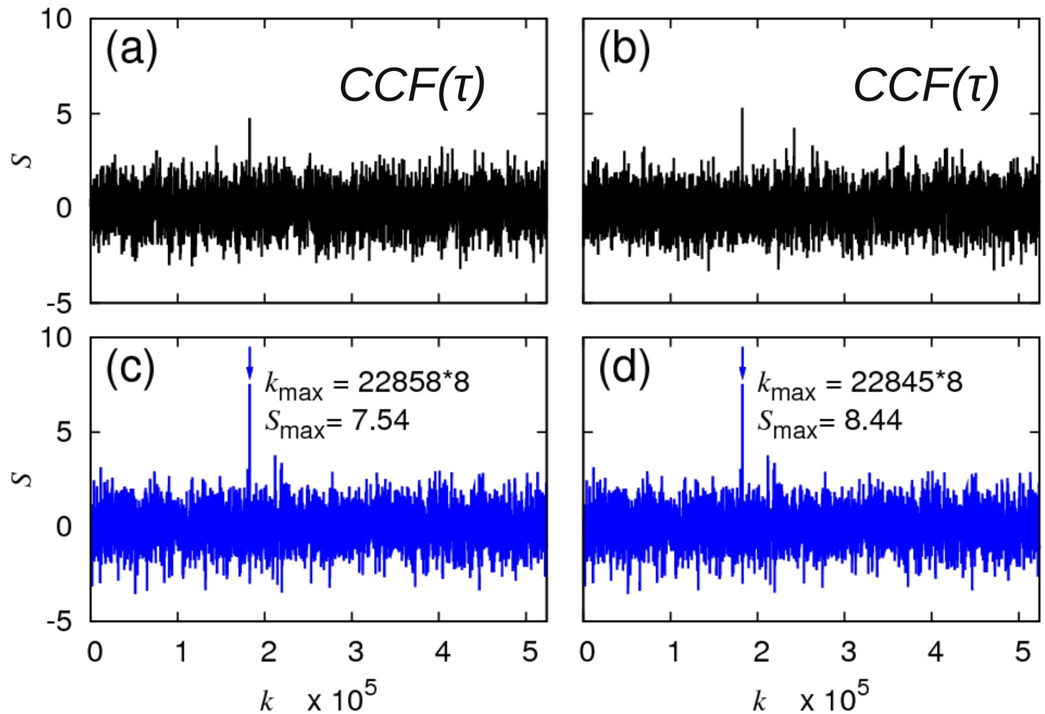
- find ΔT to 10^{-9} accuracy via tiered CCF
- Δu and ΔT unknown

Clock synchronization II

- Step 1: Find “coarse” time difference in short interval via peak in cross-correlation function



sample detection events over two short periodes 1 and 2



find timing difference ΔT in both intervals with coarse timing resolution δT

typical values:

ΔT_A = 250 ms
δT = 2...20 μs

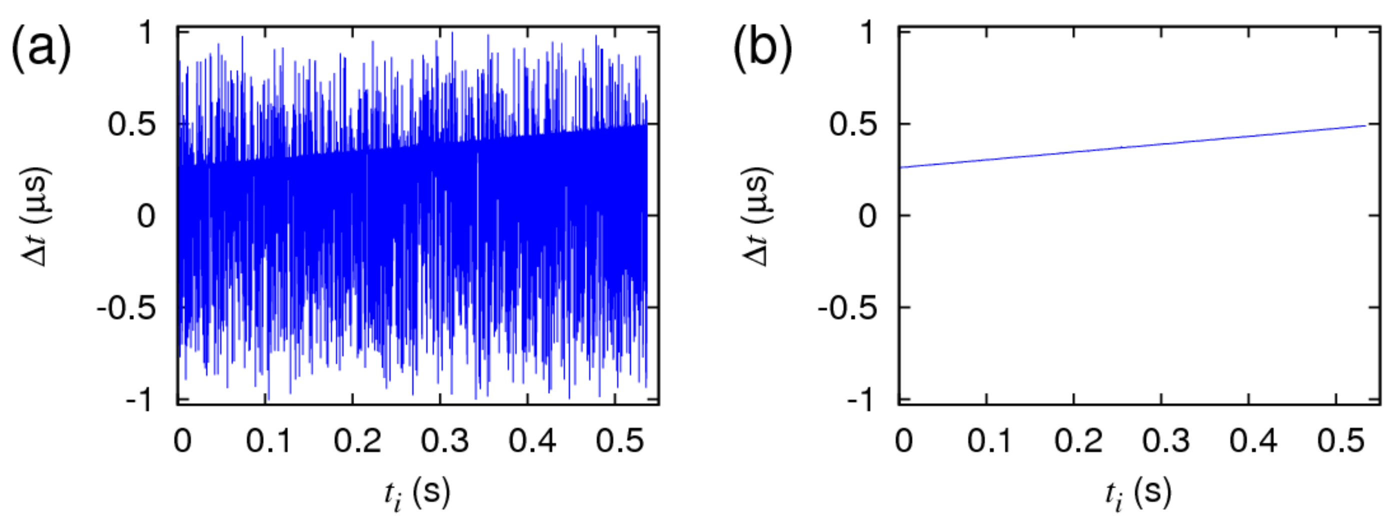
need δT = 2 ns

Clock synchronization III

- Step 2: Follow short timing differences in large intervals δt

Take time differences Δt of pairs in time intervals δT...

....and remove neighbors with too different Δt



- Step 3: Extract fine time offset part ΔT and relative frequency difference Δu from residual difference distribution

Works for $\delta T/\Delta T = 10^{-9}$, $\Delta u = 10^{-4}$, up to *Sig/BG* = 1/100

C. Ho, A. Lamas-Linares, C. Kurtsiefer, NJP ***11****, 045011 (2009)*

Very gory details

open code under GPL:
http://code.google.com/p/qcrypto/