Remote clock synchronization with entangled photon pairs

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SPIE 2019
Thurs, 15 Aug
11:10am – 11:30am

Timing Consistency

Cloud computing

- Between globally distributed, multi-versioned databases
- Sub-millisecond accuracy

Financial Markets

- Between buyers and sellers
- Sub-millisecond accuracy

Global Positioning

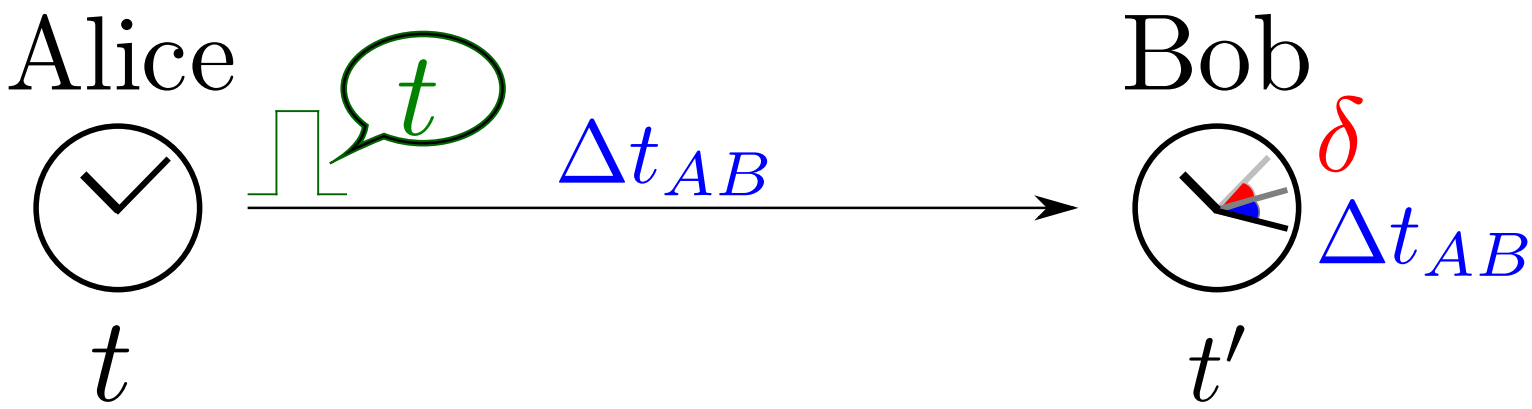
- Between satellites and receivers
- Few nanosecond accuracy

Synchronization of Remote Clocks

Distribution of Time and Frequency

Time Distribution

One-Way Synchronization



$$\Delta t_{AB} = \frac{\text{Distance}}{c_n}$$

$$\delta = t' - t - \Delta t_{AB}$$

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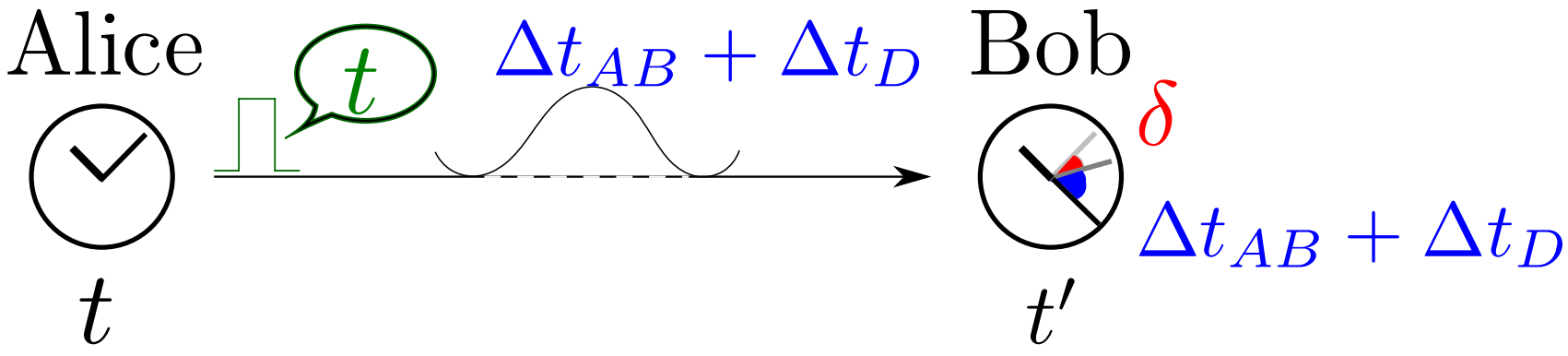
[1] arXiv:1710.05798 (2017)

[2] e.g. Global Navigation Satelite Systems

One-way Synchronization

Cannot Detect Delays



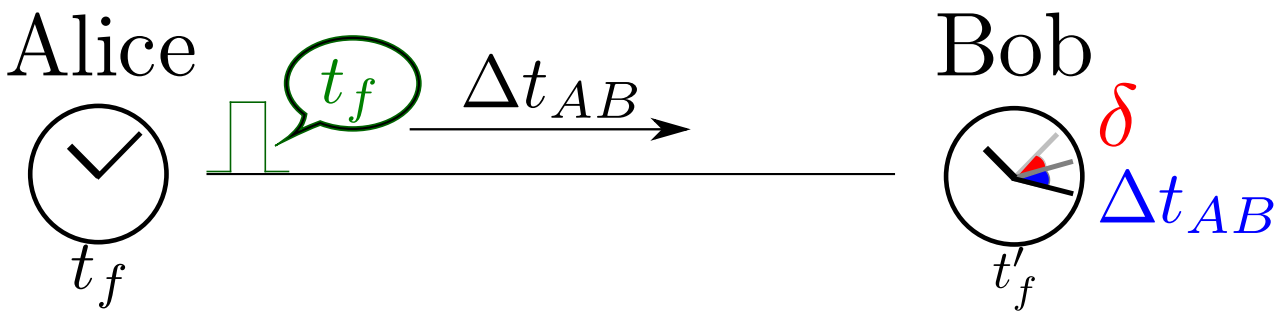
Bob unaware of additional delay $\rightarrow$ wrong δ

Cannot be prevented by Authentication or Cryptography!

Security requires trusted value of t_{AB}

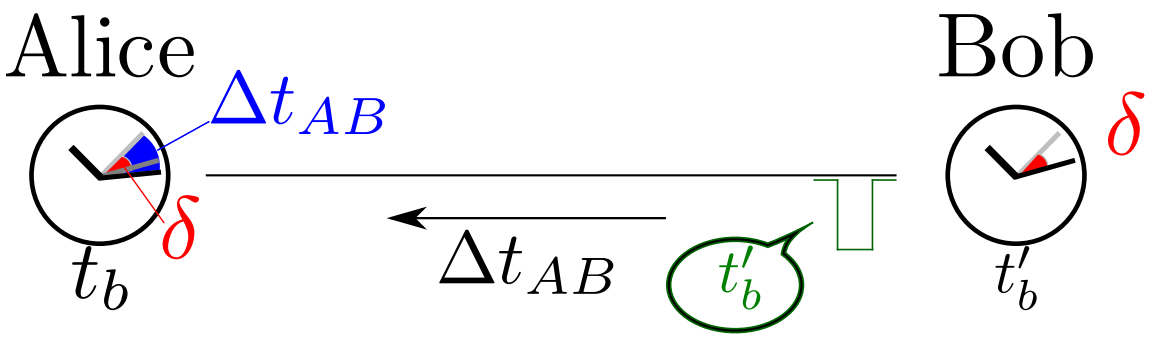
Distance-Independent Clock Synchronization

Forward



$$t'_f - t_f = \Delta t_{AB} + \delta$$

Backward

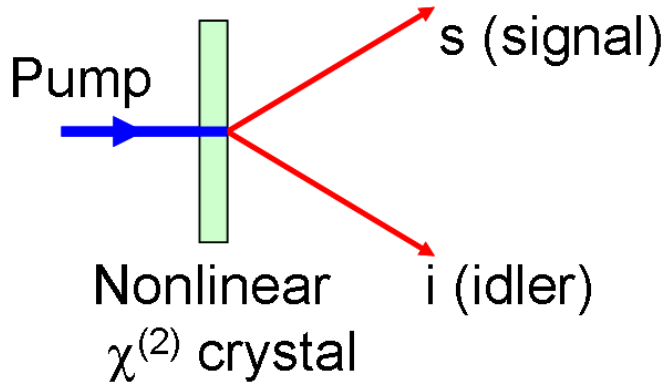


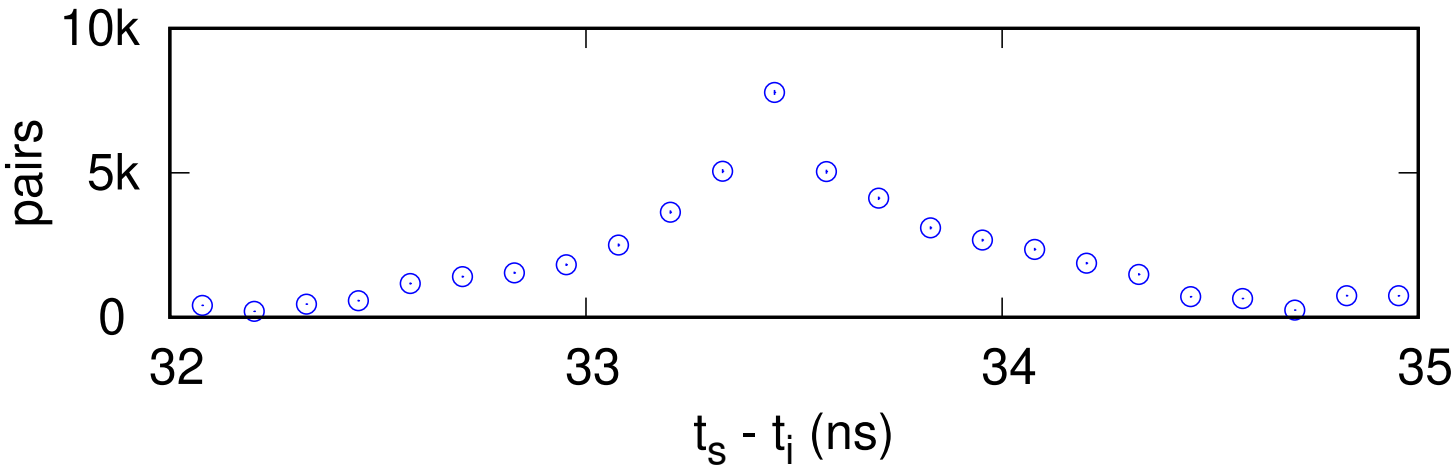
$$t_b - t'_b = \Delta t_{AB} - \delta$$

$$\delta = \frac{(t'_f - t_f) - (t_b - t'_b)}{2} \quad \text{independent of } \Delta t_{AB}$$

[1] e.g. Network Time Protocol

Time-Correlated Photon Pairs from SPDC

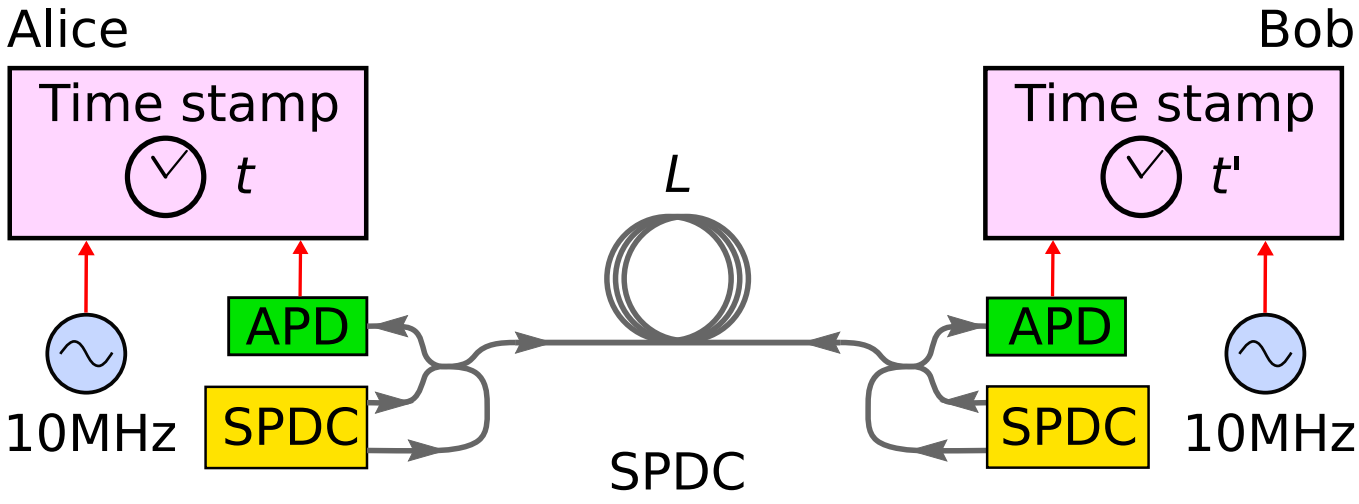


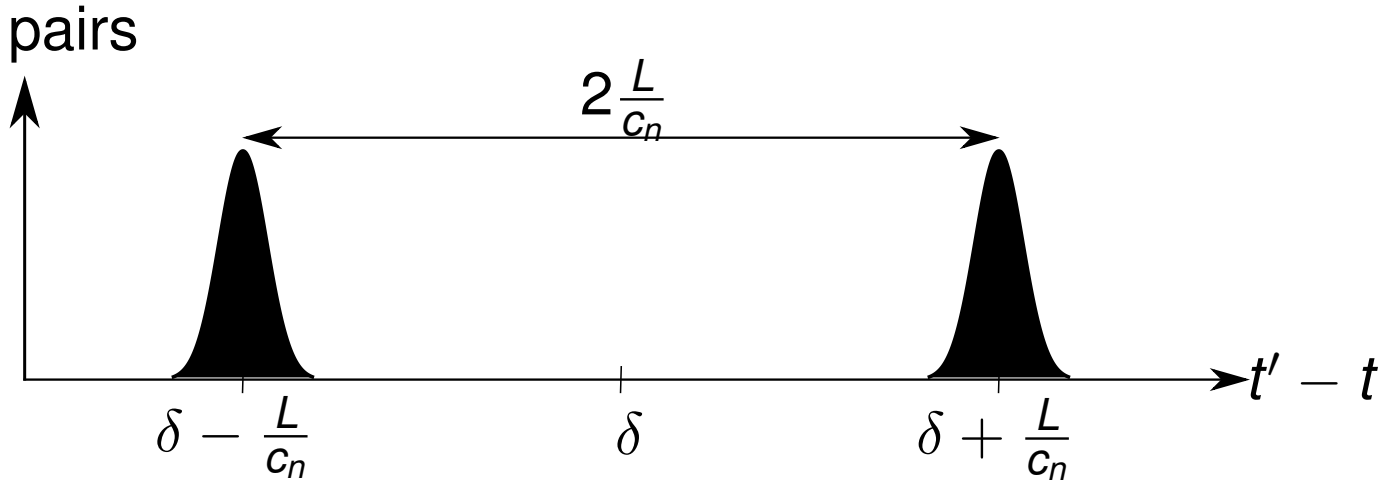


[1] Spontaneous Parametric Down-Conversion

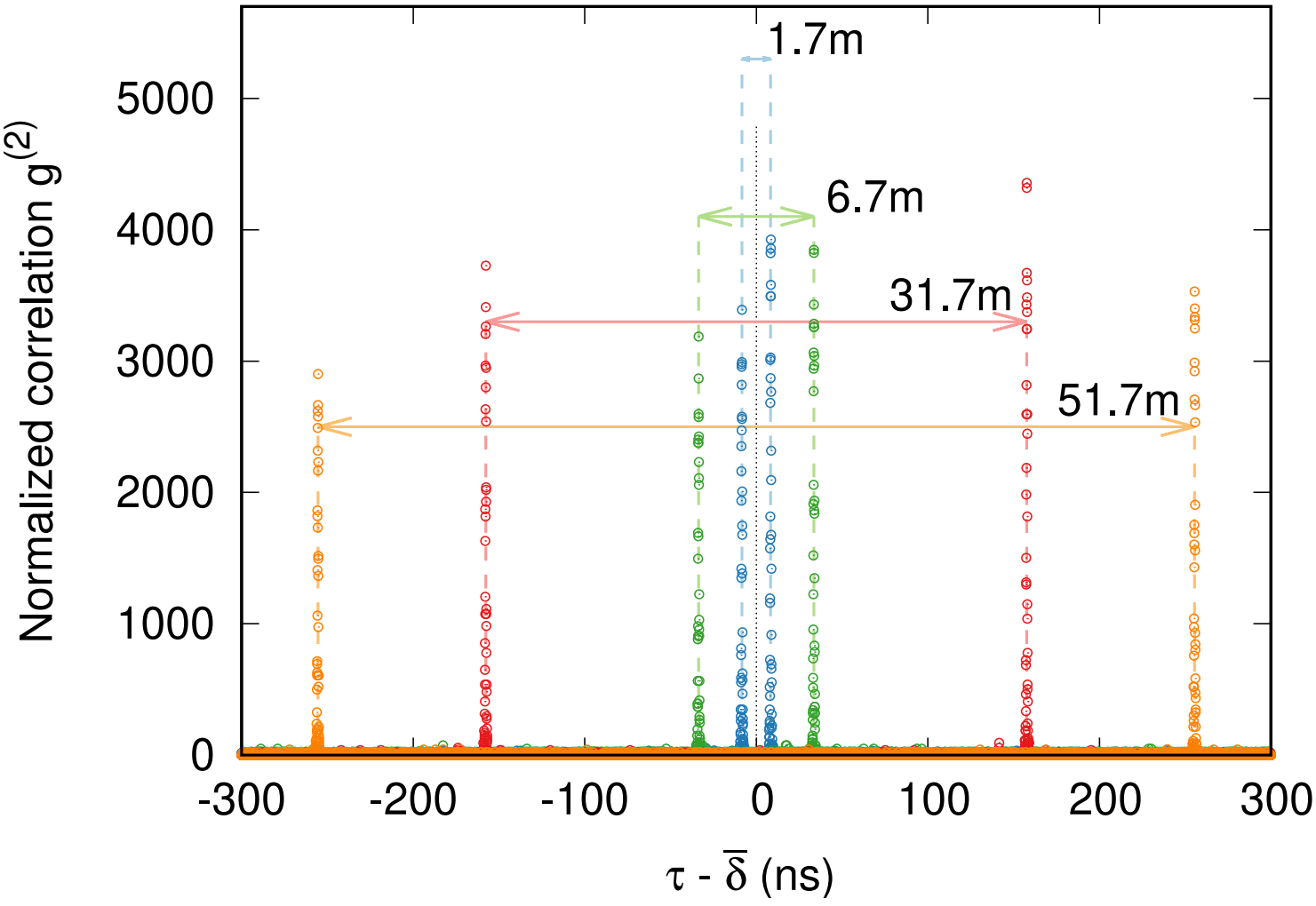
[2] New J. Phys. 11, 045011 (2009)

Symmetric Clock Synchronization with SPDC

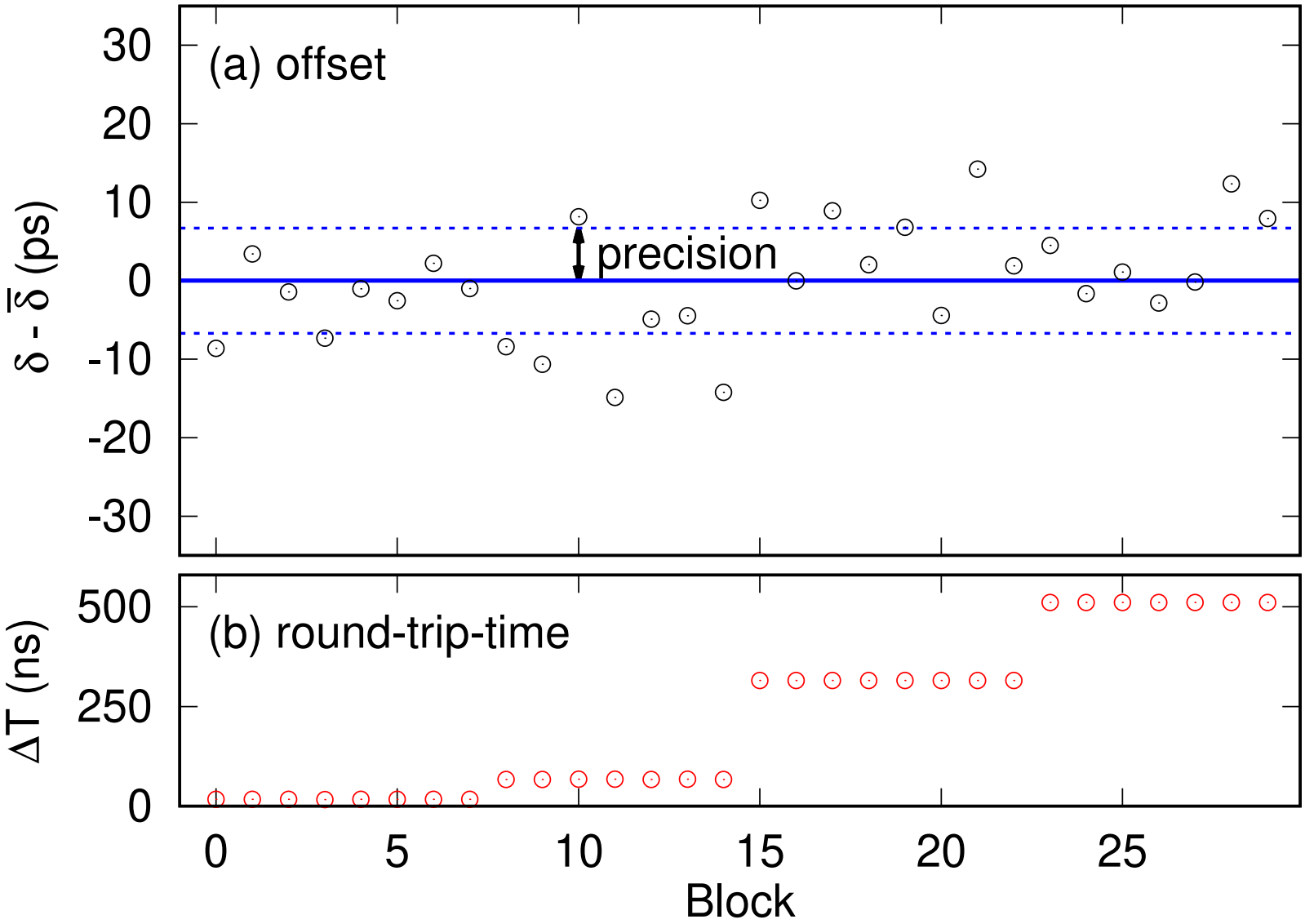


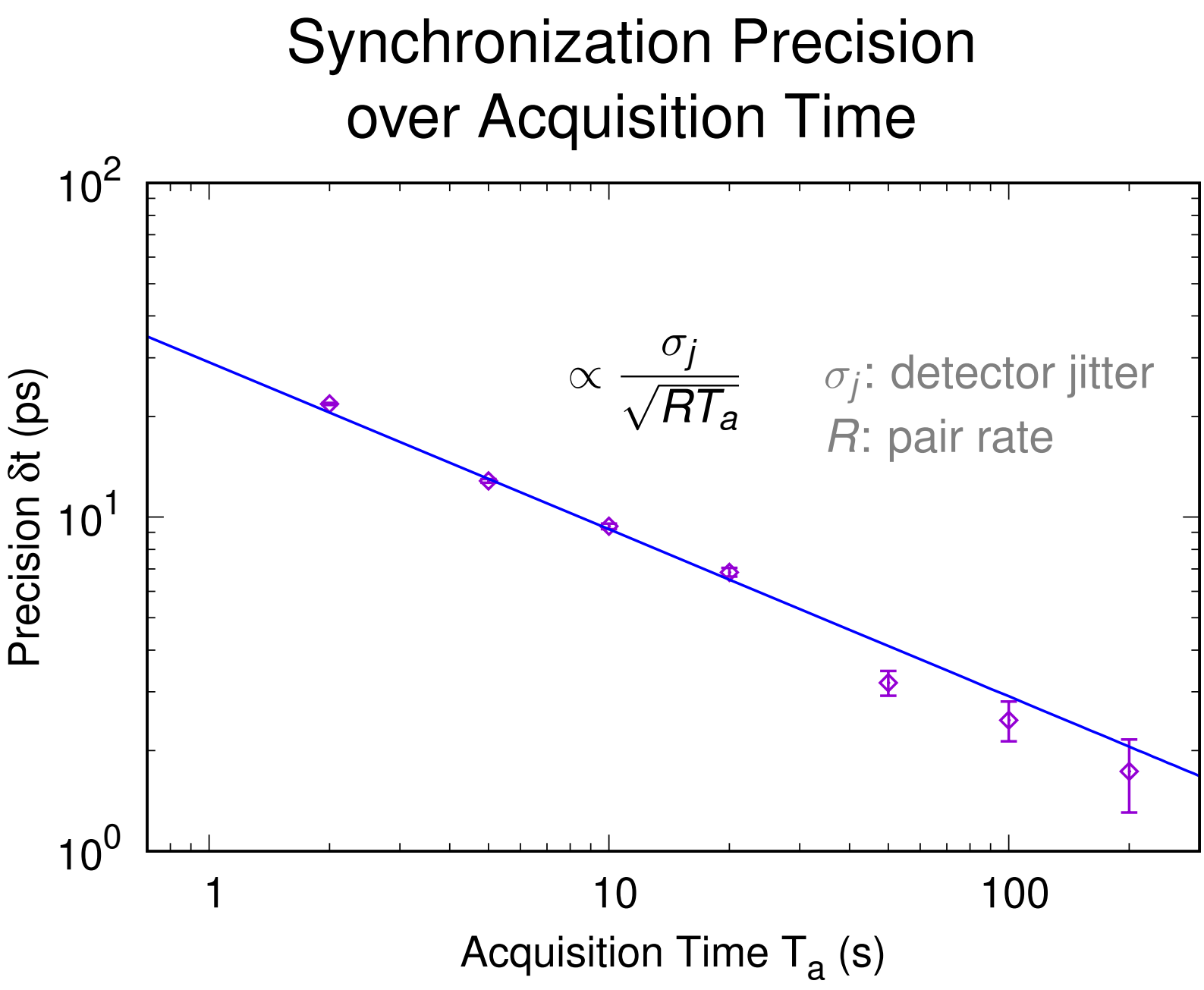


Constant δ, Varying L
Common Frequency Reference

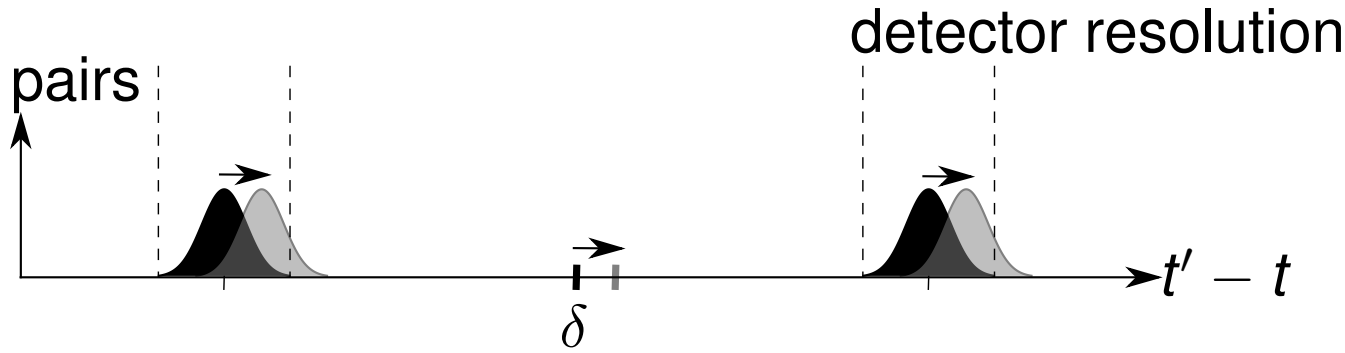


Clock Synchronization Independent of Distance

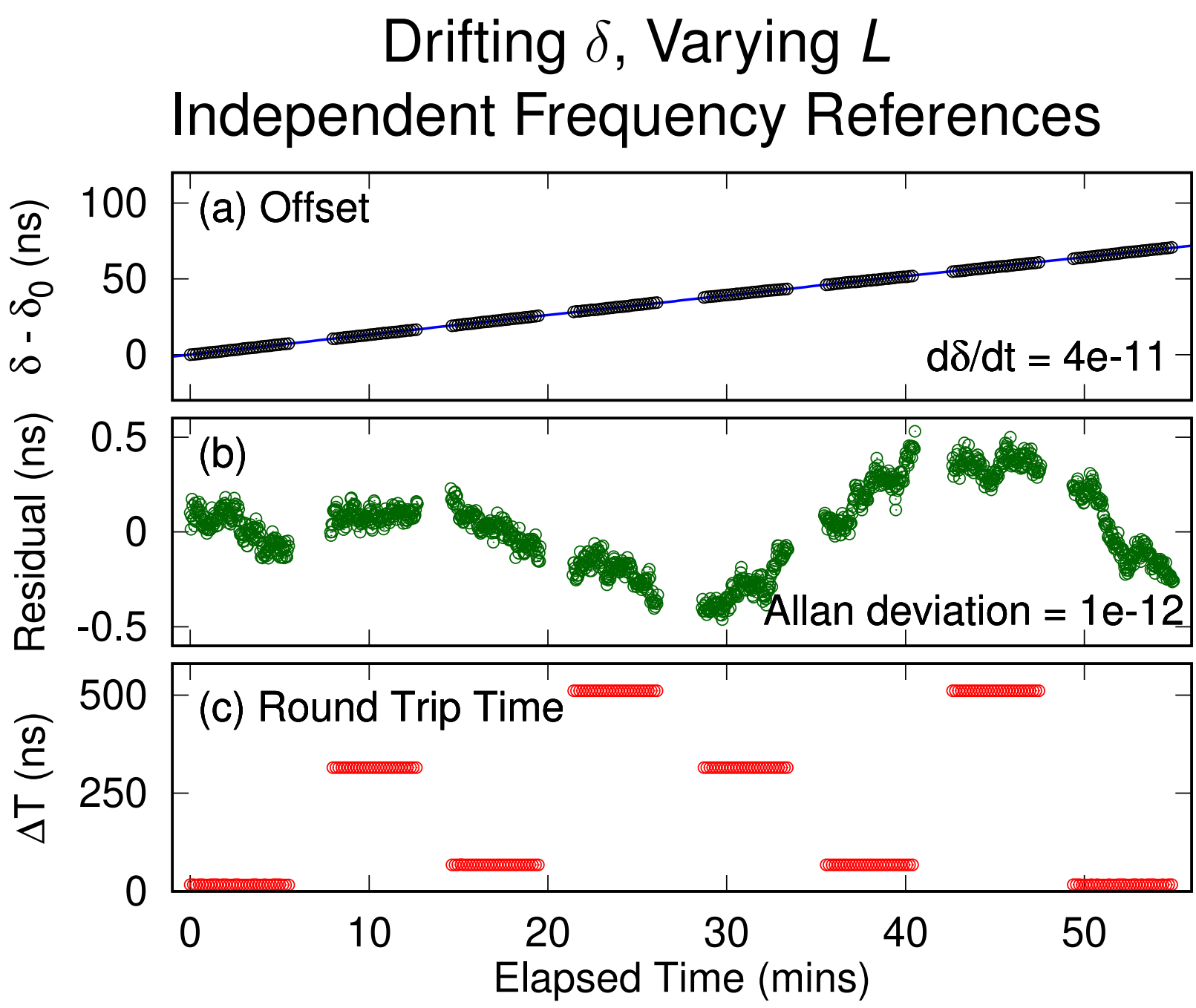



Synchronization Precision
over Acquisition Time
10^2
10^1
10^0
Precision δt (ps)
1
10
100
Acquisition Time T_a (s)
$\propto \frac{\sigma_j}{\sqrt{RT_a}}$
σ_j: detector jitter
R: pair rate

With Independent Frequency References
the Clock offset δ drifts with time

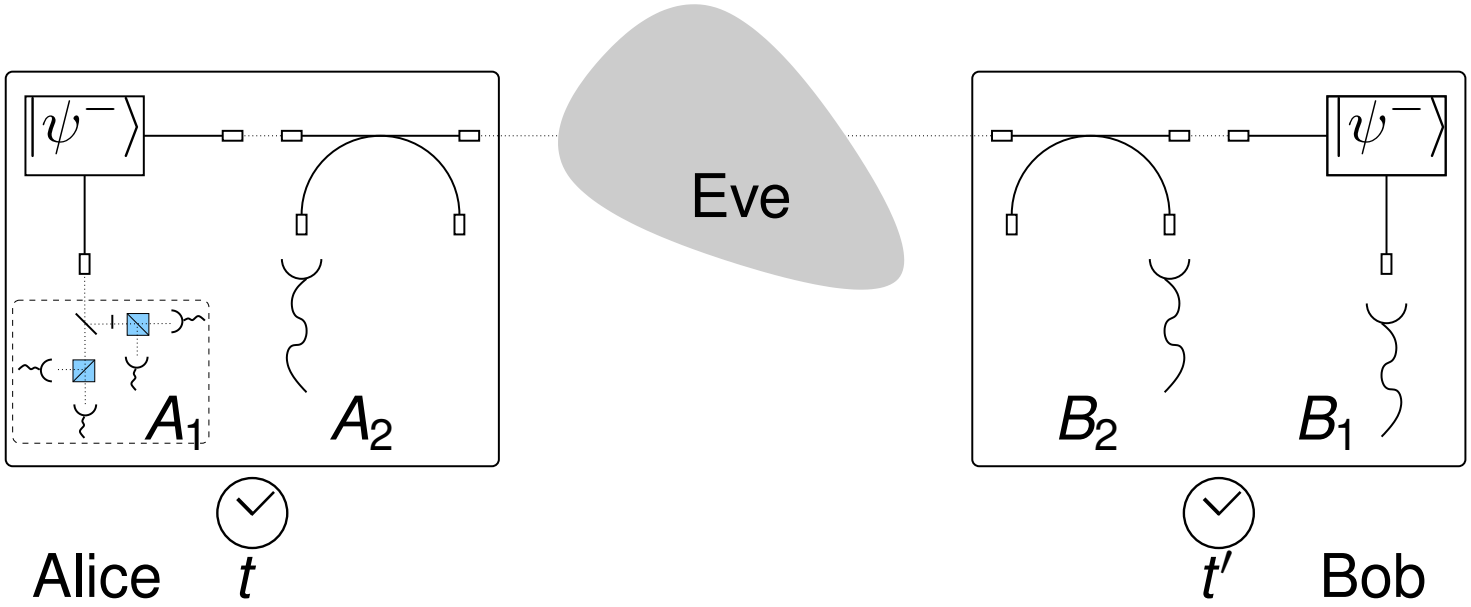


	precision	$<$	peak drift	$<$	detector resolution
for 2 sec:	20 ps	$<$	100 ps	$<$	600 ps


Drifting δ, Varying L
Independent Frequency References
(a) Offset
dδ/dt = 4e-11
δ - δ0 (ns)
100
50
0
(b)
Allan deviation = 1e-12
Residual (ns)
0.5
0
-0.5
(c) Round Trip Time
ΔT (ns)
500
250
0
0
10
20
30
40
50
Elapsed Time (mins)

Signal Verification

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



Violation of Bell's Inequality:

Ensures photons detected are part of the same entangled pair

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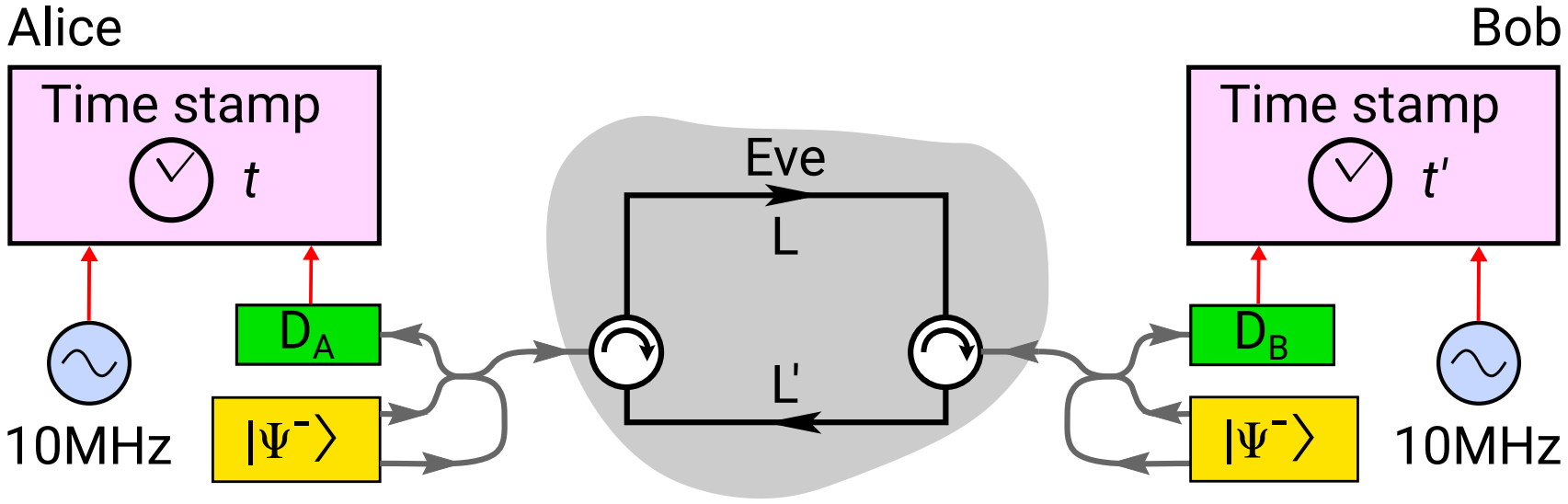
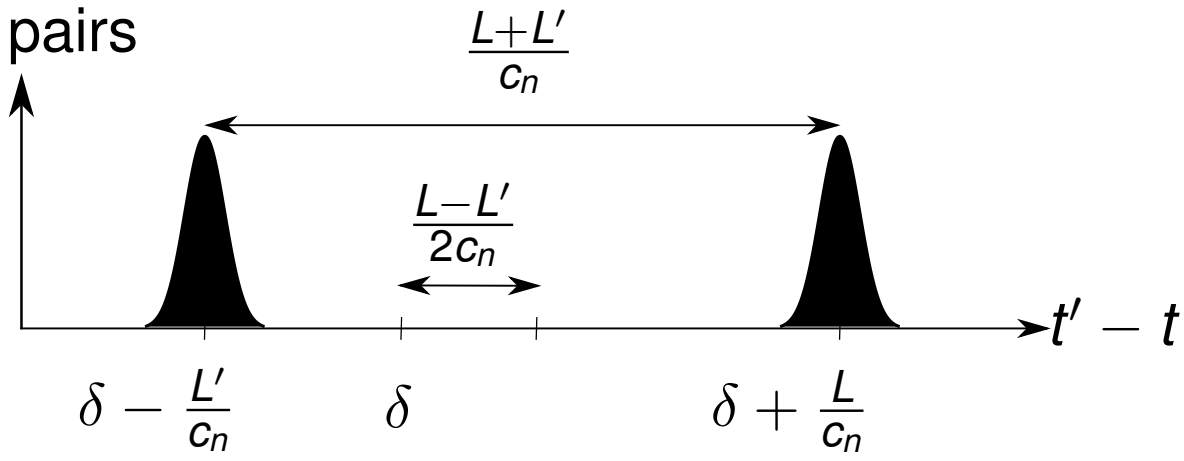
[1] Monogamy of entanglement: Phys. Lett. A 360, 249 (2006).

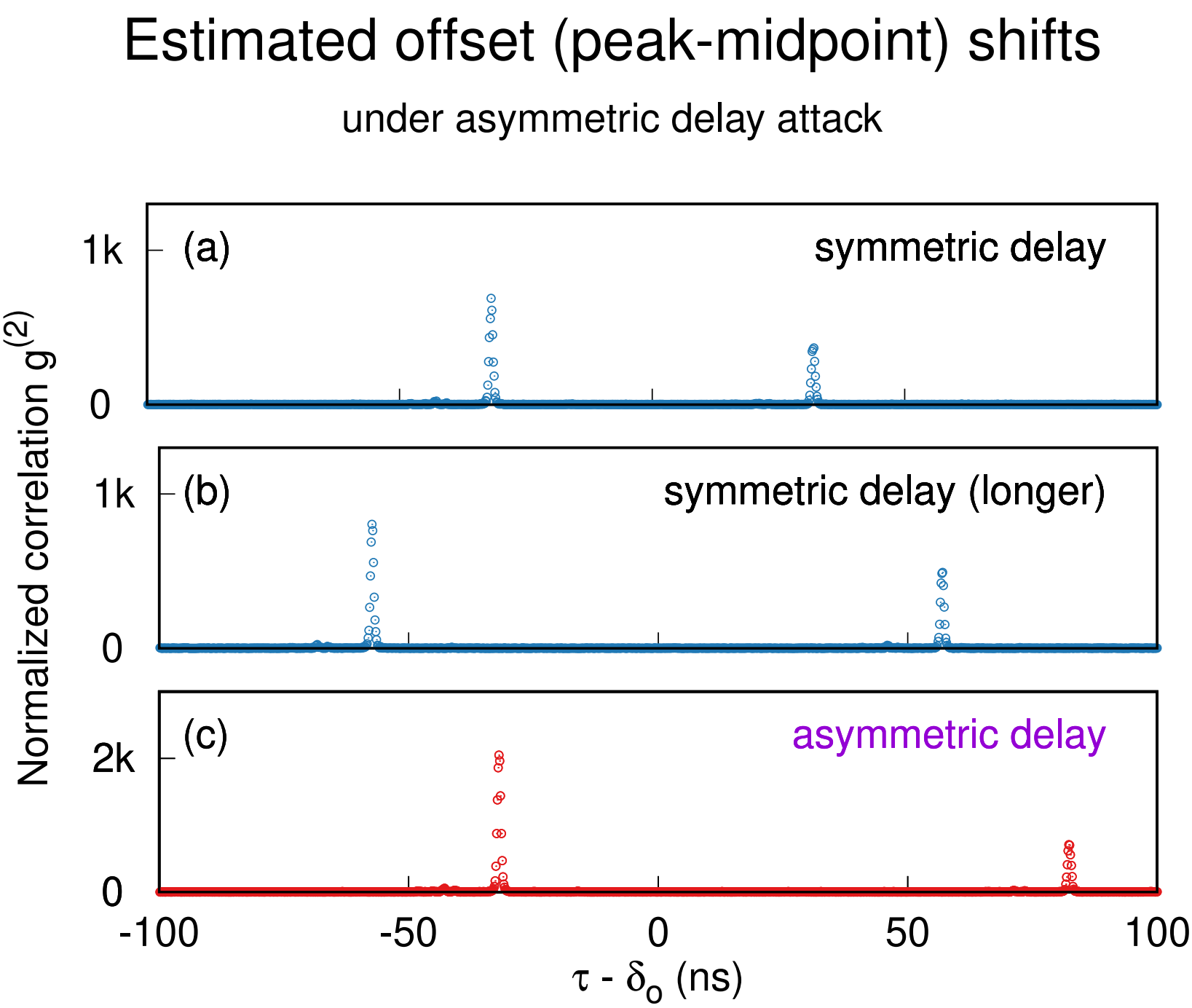
[2] No-cloning theorem: Nature 299, 802 (1982).

Asymmetric Delay Attack





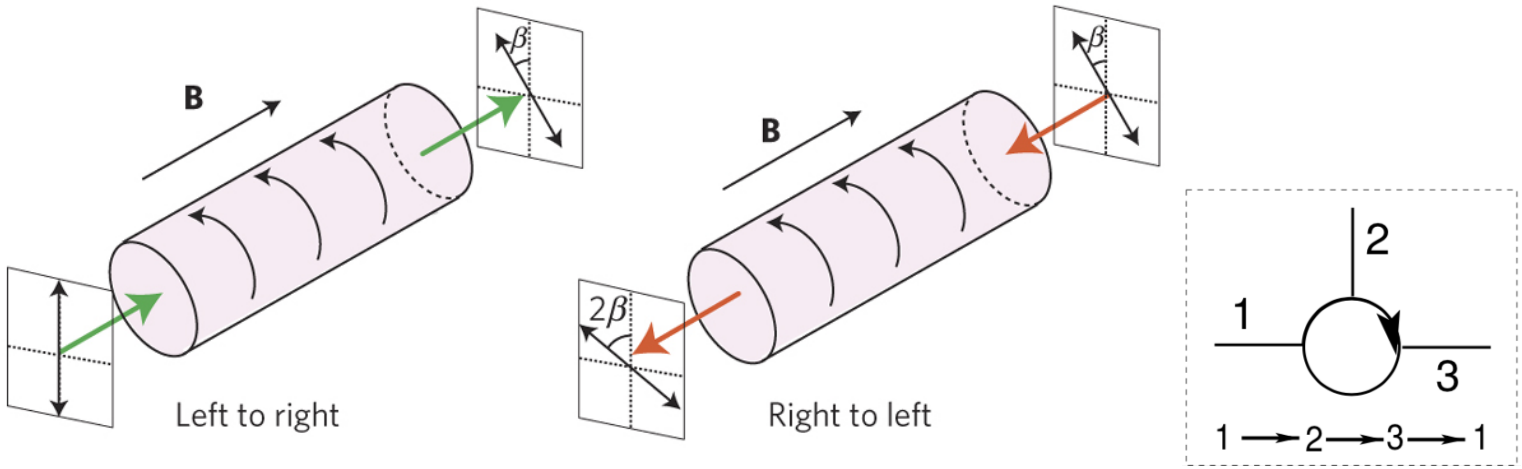
$\delta \neq$ midpoint between two coincidence peaks


Estimated offset (peak-midpoint) shifts
under asymmetric delay attack
Normalized correlation g(2)
1k
0
(a)
symmetric delay
1k
0
(b)
symmetric delay (longer)
2k
0
(c)
asymmetric delay
-100
-50
0
50
100
τ - δo (ns)

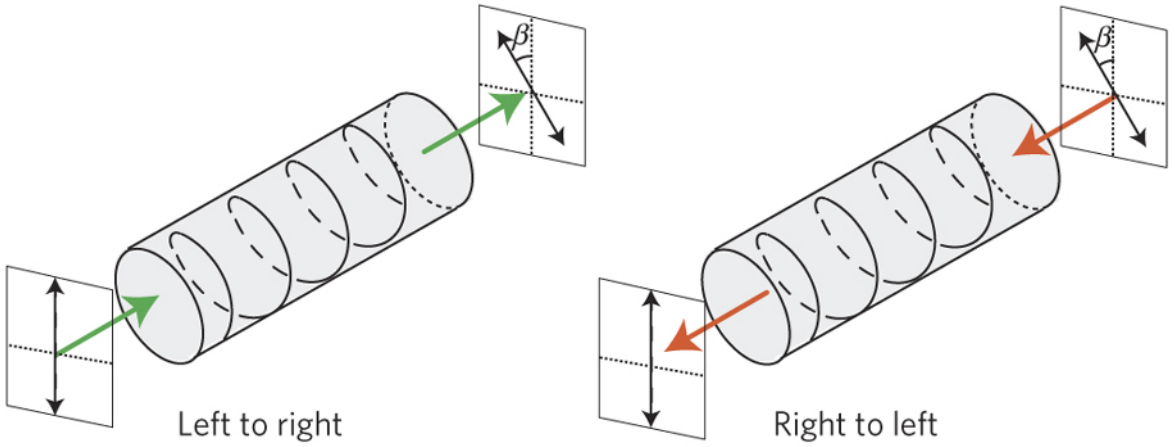
Creating Channel Asymmetry

with Faraday Rotation (FR)

NOT time-reversible (*FR in circulators*)

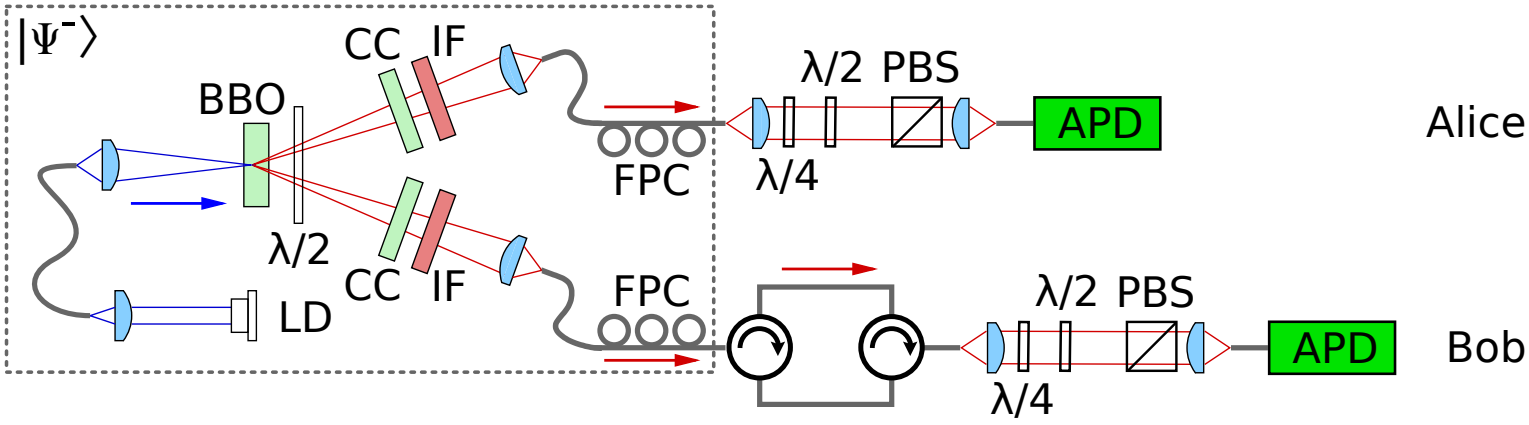


Time-reversible (*e.g. waveplates*)



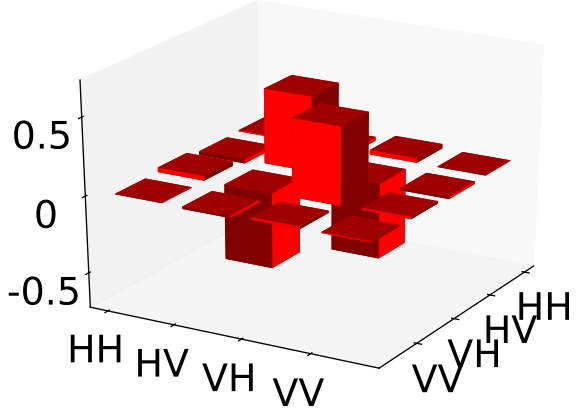
[1] Image Credit: FOSCO

Can we detect Faraday Rotation in Circulators?

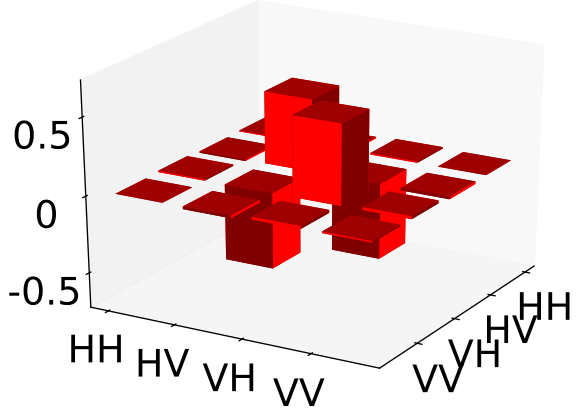


$n \times 180^{o}$ rotation: $|\psi\rangle_B \rightarrow \pm|\psi\rangle_B \quad \left|\Psi^-_{AB}\right\rangle \rightarrow \pm\left|\Psi^-_{AB}\right\rangle$

No Circulator



Circulators in Channel



Summary

Synchronization with time-correlated photons[1]

- Independent of clock separation
- Intrinsic clock instabilities can be resolved

Security with polarization-entanglement

- Enables signal verification

Ongoing research

- Detecting circulator-based asymmetric delay attacks[2]
- e.g. cyclic evolution of quantum state $\rightarrow$ Berry phase[3]

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[1] Appl. Phys. Lett. 114, 101102 (2019)
[2] arXiv:1907.09661 (2019)
[3] arXiv:1808.09019 (2018)