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Entanglement-based High-Dimensional Quantum Key Distribution

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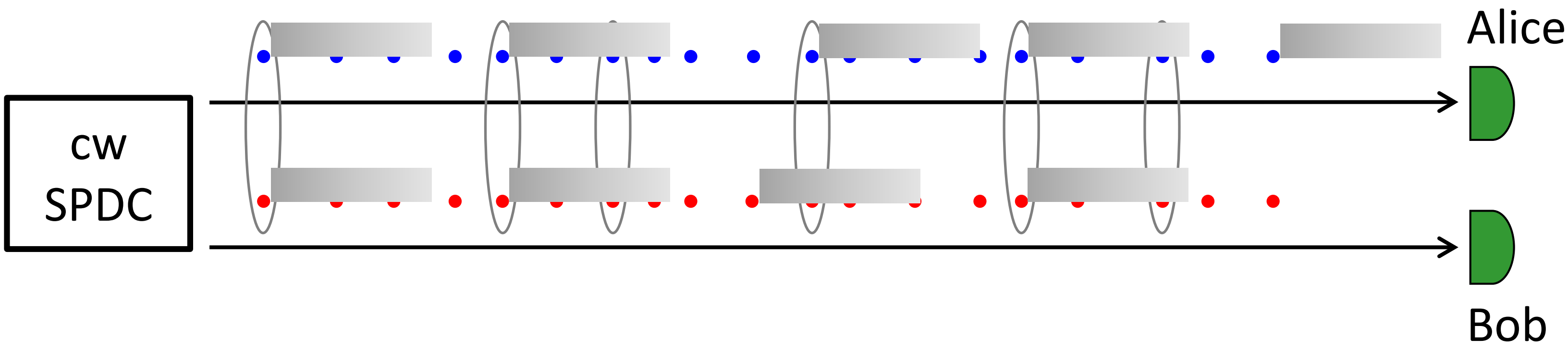
MIT, NIST, JPL

OPTICAL AND QUANTUM COMMUNICATIONS GROUP

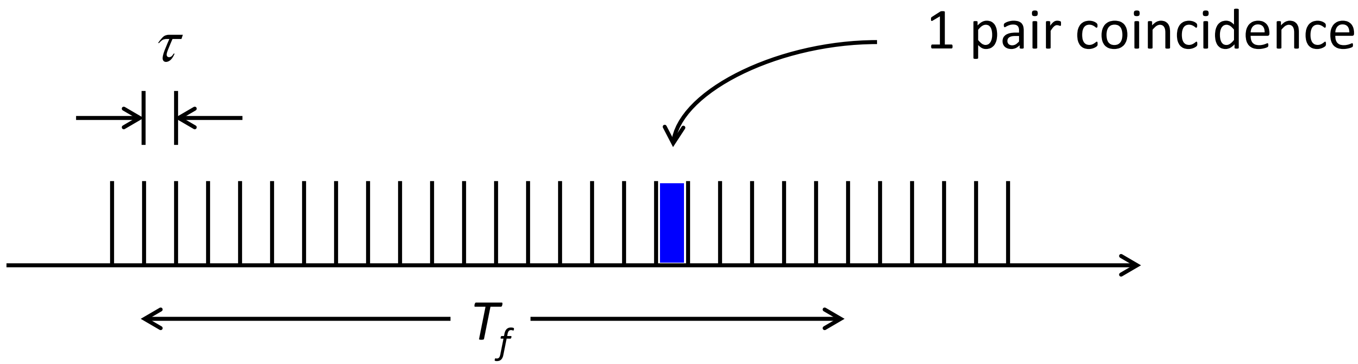
Motivation for high-dimensional encoding



- QKD typically operates under "photon-starved" conditions
  - component loss + propagation losses
  - long recovery times for detection system
  - low flux at receivers; few detected coincidences
  - $\Rightarrow$ many empty time periods between detection events

- High-dimensional encoding
  - maximize throughput with limited number of detection events
  - pack more bits per coincidence detection (multiple bits per photon)

Multiple-bit time-of-arrival encoding



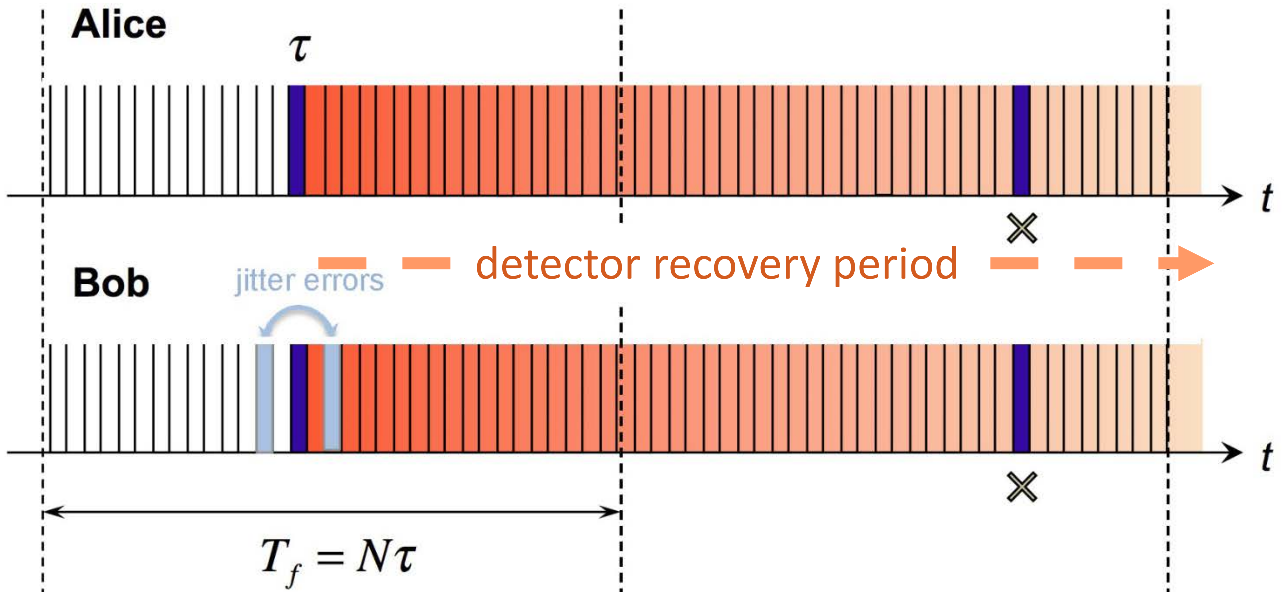
T_f/τ : N bins per frame

T_f = 10 ns, τ = 1 ps, N = 10^4 (~13 bits/photon-pair)
Potential raw key rates = 1.3 Gbps
(0.1 Gbps with binary encoding)

- Continuous-time encoding
- Discrete-energy measurement (photon counting)

Initial concept and demonstration of large alphabet encoding:
John Howell *et al*., PRL **98**, 060503 (2007)

HDQKD (time-of-arrival encoding)



- Time-energy entangled-photon source
  - high flux + single spatial mode + high entanglement quality
- WSi superconducting nanowire single-photon detectors
  - high efficiency + short reset time + low timing jitter
- Efficient error correction and privacy amplification
  - Multi-layer low-density parity check designed for HD encoding
- Security check against collective attacks
  - dispersive optics or Franson interferometer

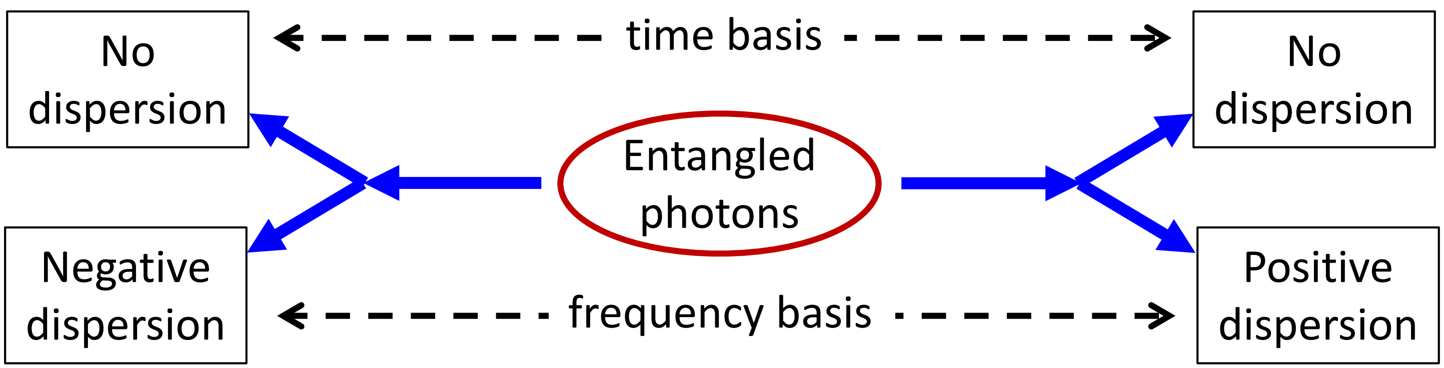
Security of HDQKD based on time-energy entanglement

Apply security analysis technique for CVQKD to HDQKD:

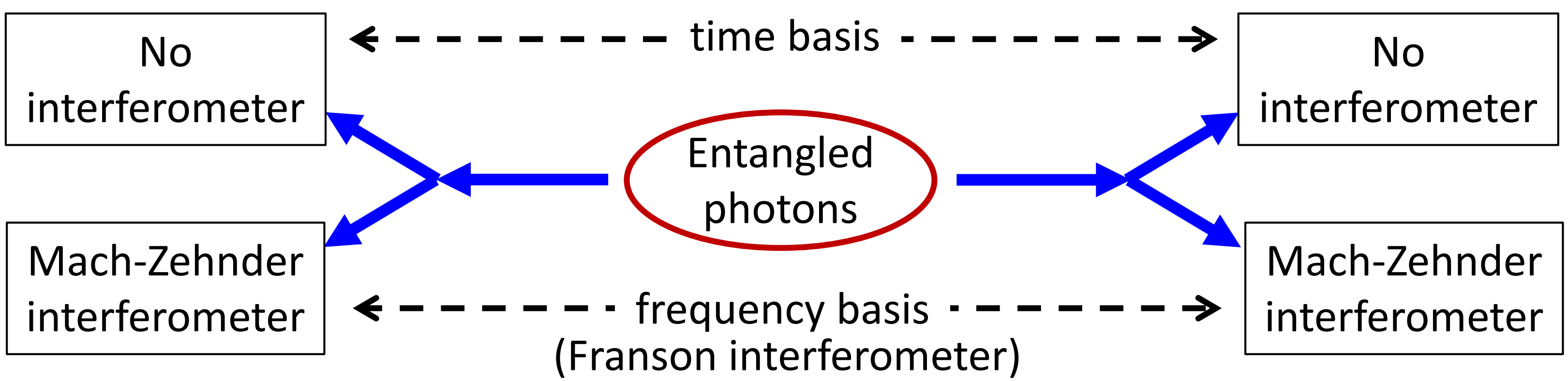
Continuous time (arrivals) and frequency (detunings) as conjugate bases

Relate measurements to time-frequency covariance matrix (TFCM)

Dispersive optics   Mower *et al.*, PRA **87,** 062322 (2013)

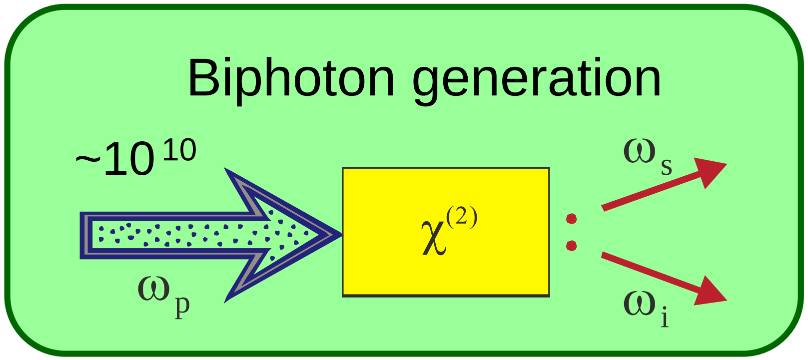


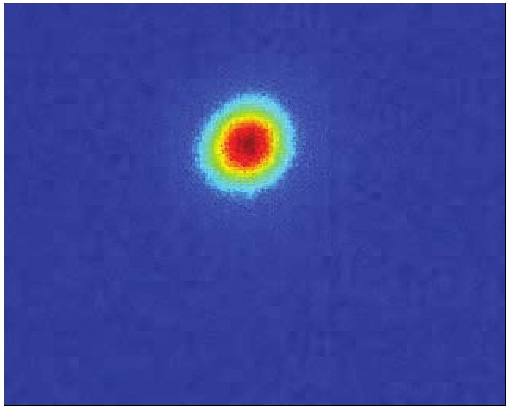
Franson interferometer   Zhang *et al.*, PRL **112,** 120506 (2014)

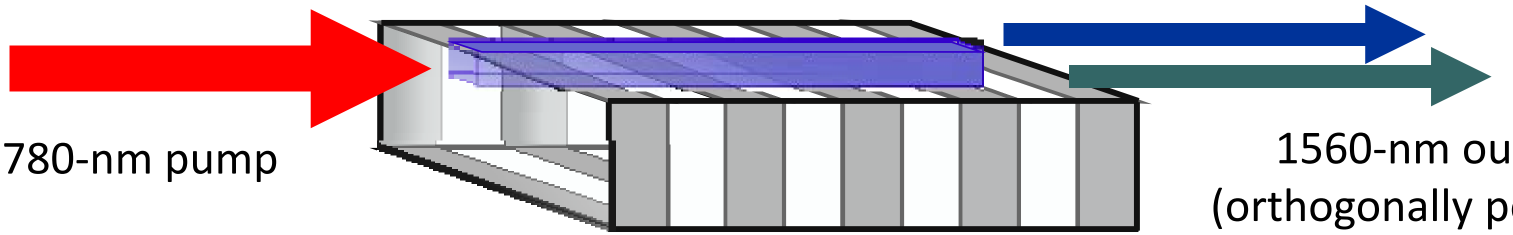


Time-energy entangled-photon source

Spontaneous parametric downconversion (SPDC)





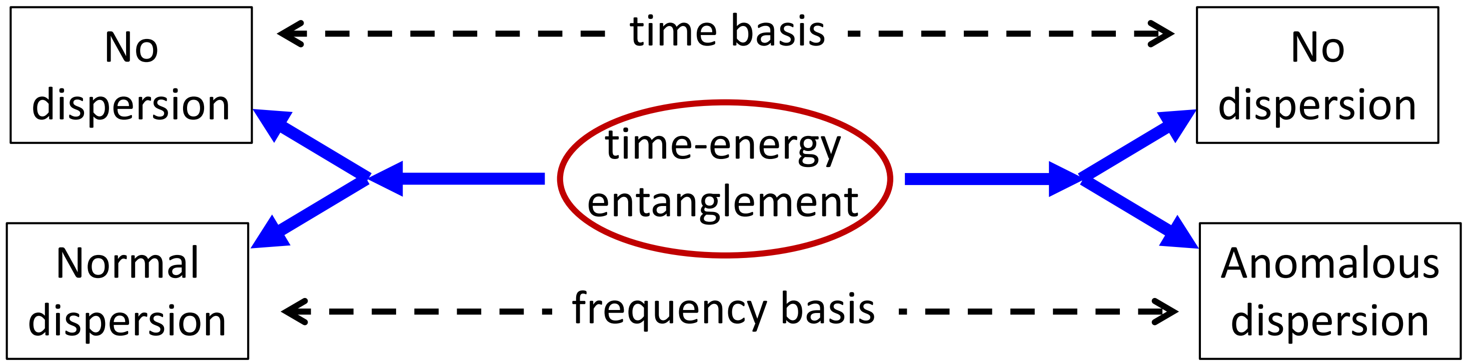


Type-II phase-matched PPKTP waveguide

- Efficient generation: 10^7 pairs/s/nm/mW (1.6 nm bandwidth)
- High extraction efficiency (~80%) into single-mode fibers
- Naturally time-energy entangled; very little fluorescence

Zhong *et al*., Opt. Express **28,** 26868 (2012)

Dispersive-optics QKD protocol



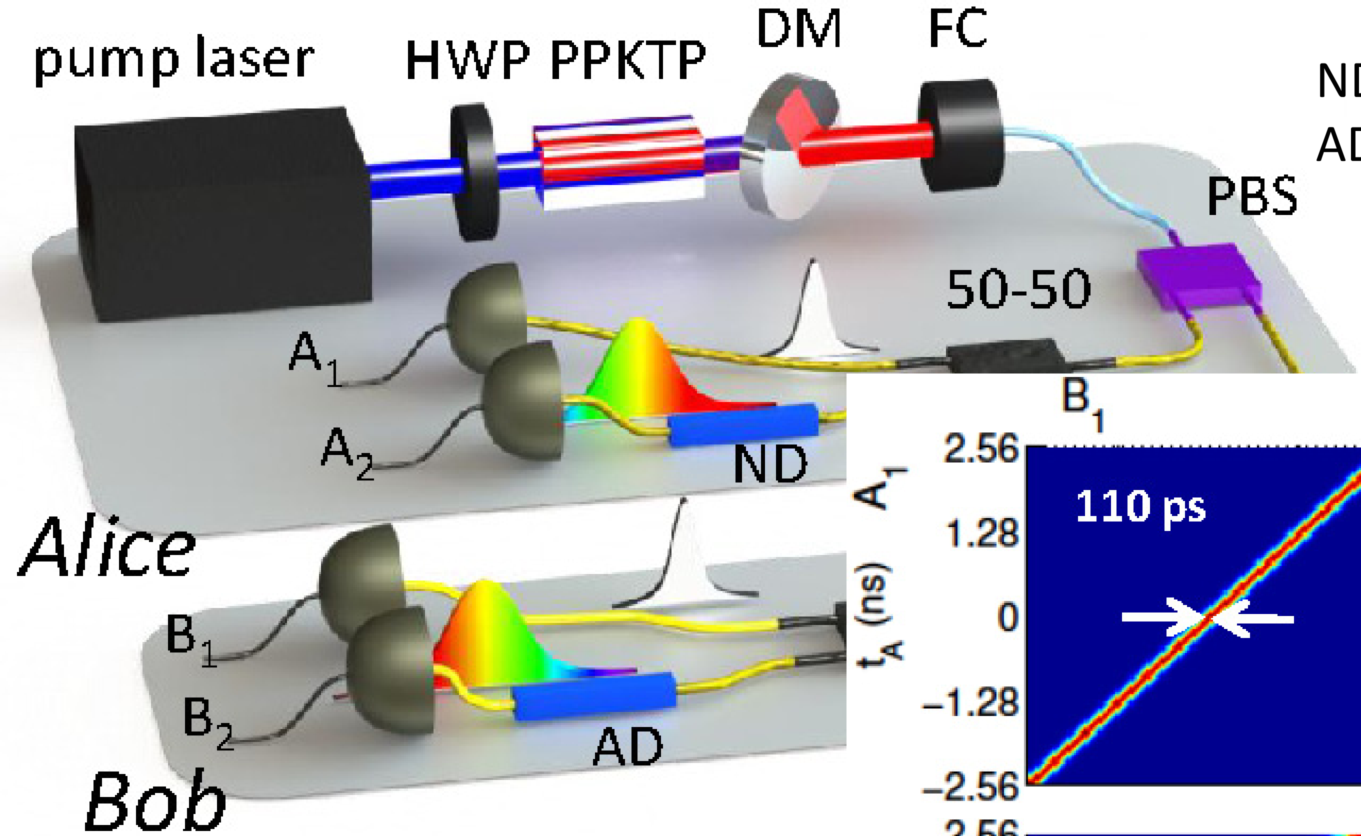
Nonlocal cancellation of dispersion: J. D. Franson, PRA (1992)

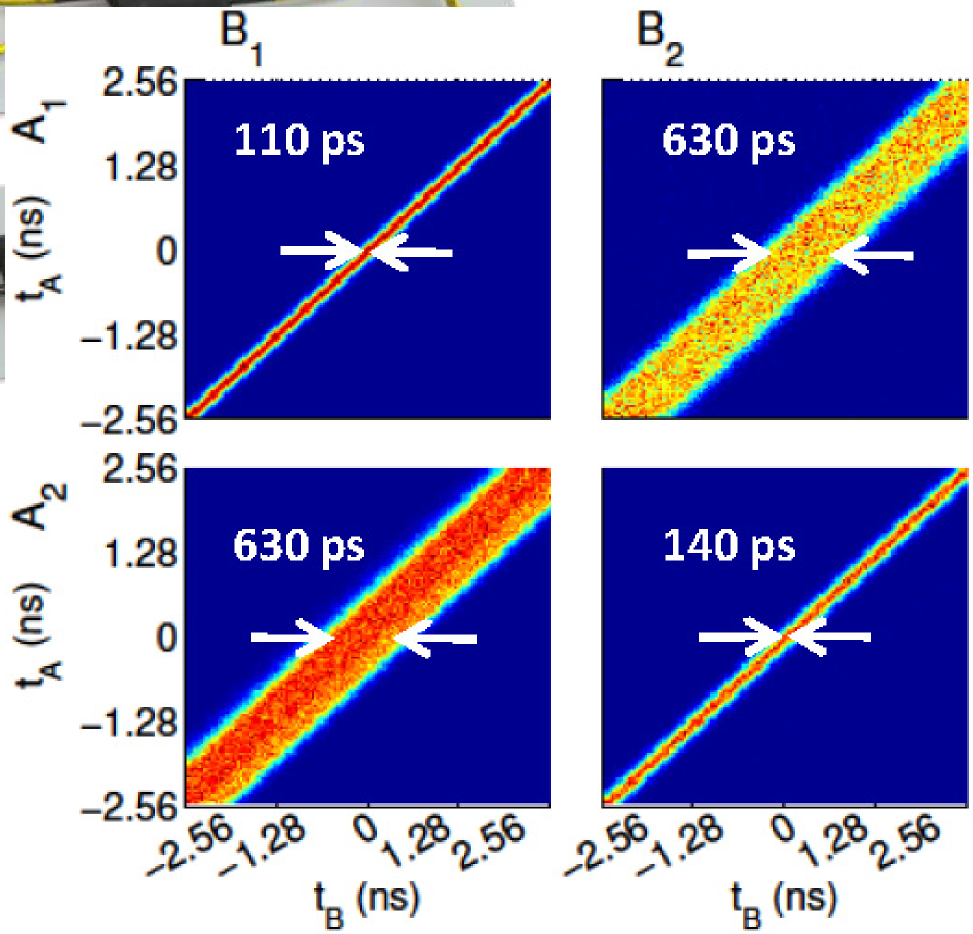
- Dispersive-optics QKD (DO-QKD)
  - two dispersive conjugate measurement bases
  - correct bases yield narrow time coincidence for key generation
  - security check: correct bases, timing errors indicate eavesdropping
  - choose frame size and bin duration in software; adjust dynamically
  - retain frames with 1 detection event by Alice and Bob
  - apply error correction and privacy amplification, finite key correction
  - obtainsecure key capacity and secure key rate

Mower, Zhang, Desjardins, Lee, Shapiro, Englund, PRA **87,** 062322 (2013)

Dispersive optics HDQKD experimental demonstration

ND: normal dispersion
AD: anomalous dispersion





6 WSi SNSPDs:
~100 ps jitter
~1 MHz max count rate
~80-90% efficiency

DOQKD secure key capacity > 3 bpc

$$r = \beta I(A;B) - \chi(A;E) - \Delta_{FK}$$

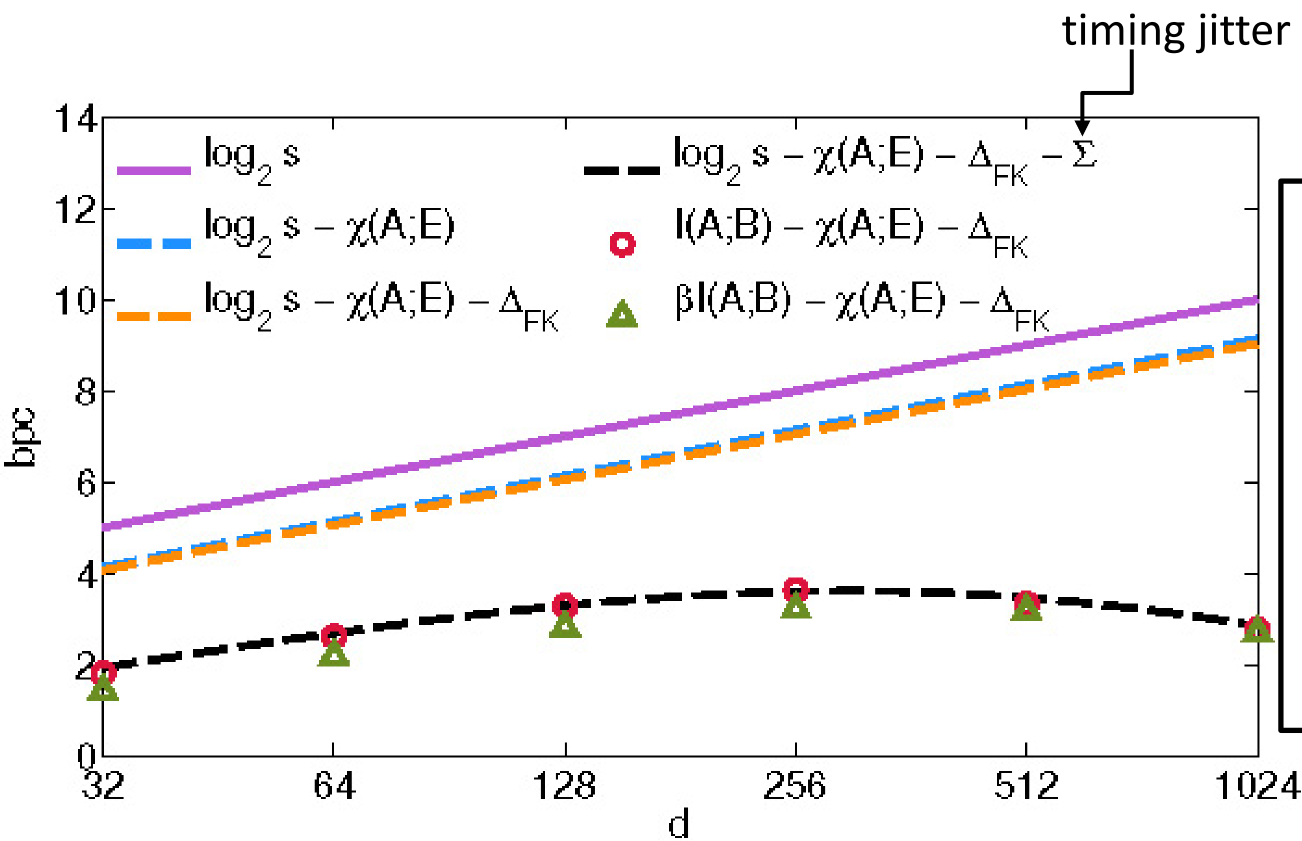
Secure key capacity

Reconciliation efficiency

Mutual information between Alice, Bob

Alice, Eve shared Holevo information

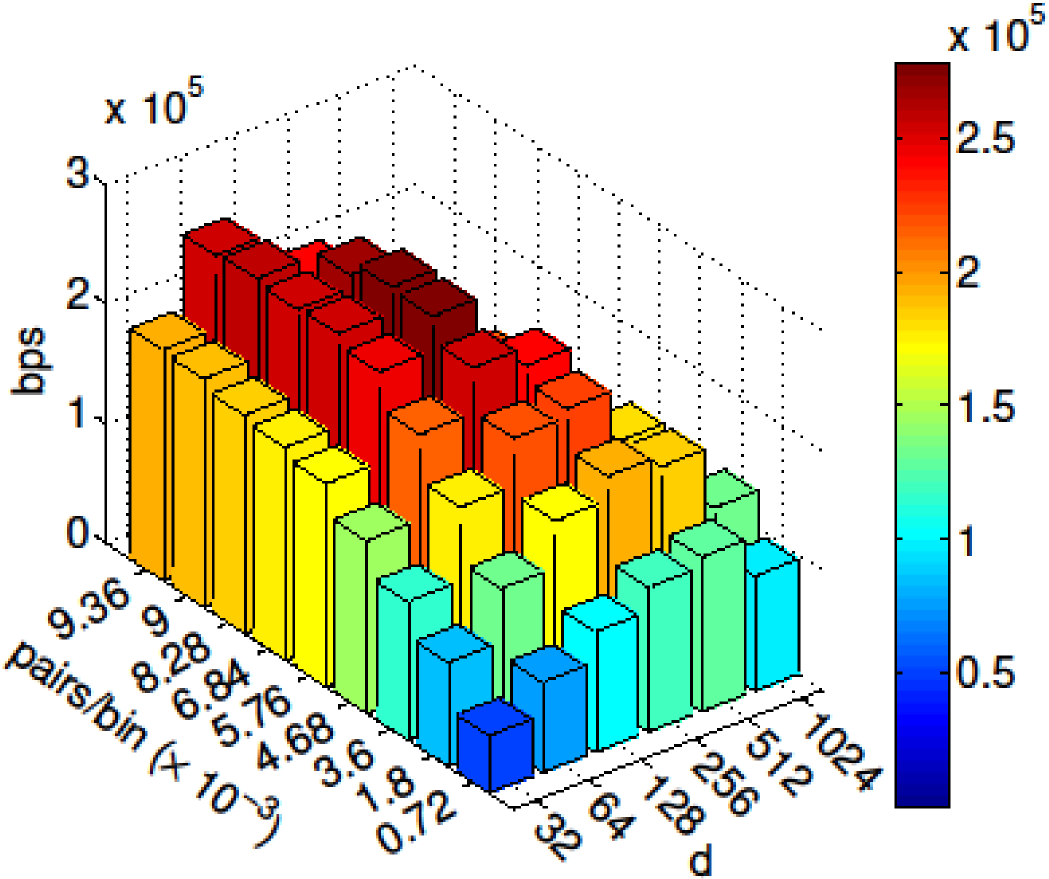
Finite-key corrections



Parameters:

- pair generation rate ~9 MHz
- detector jitter 100 ps
- bin duration 80 ps
- propagation loss 0.2 dB/km
- detector efficiency 90%
- Alice's system efficiency 10%
- Bob's system efficiency 7%
- dark count rate 1 kHz

Secure key rate > 270 kbps



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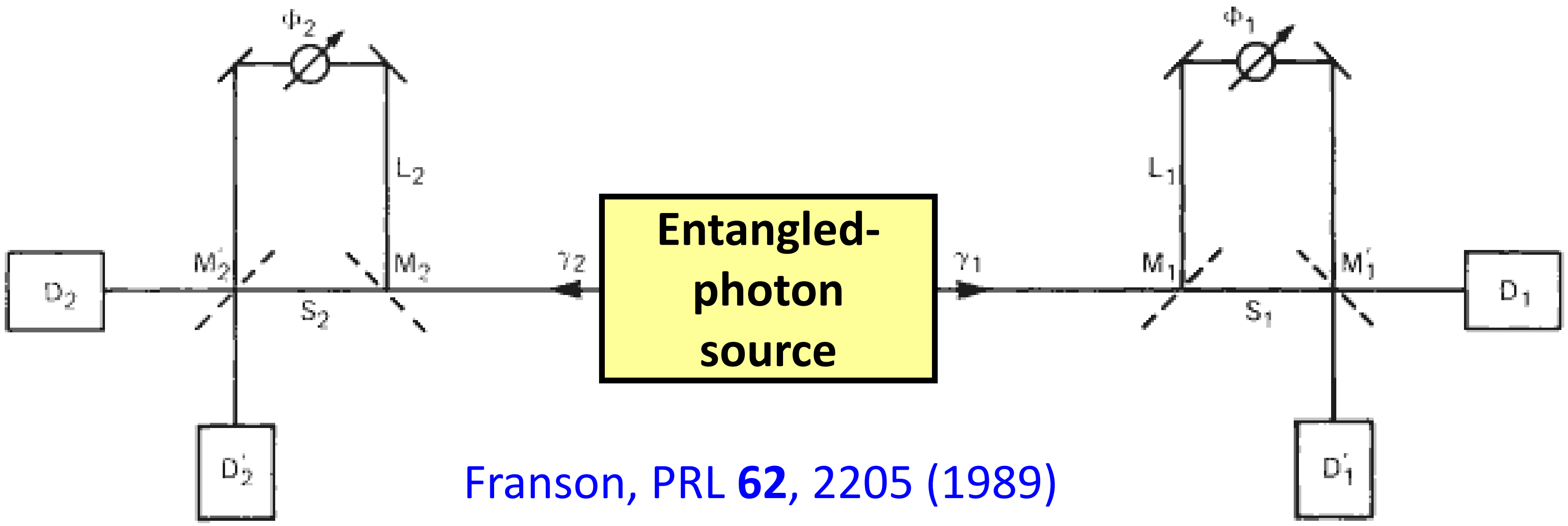
Maximum throughput does not occur where key capacity is maximum

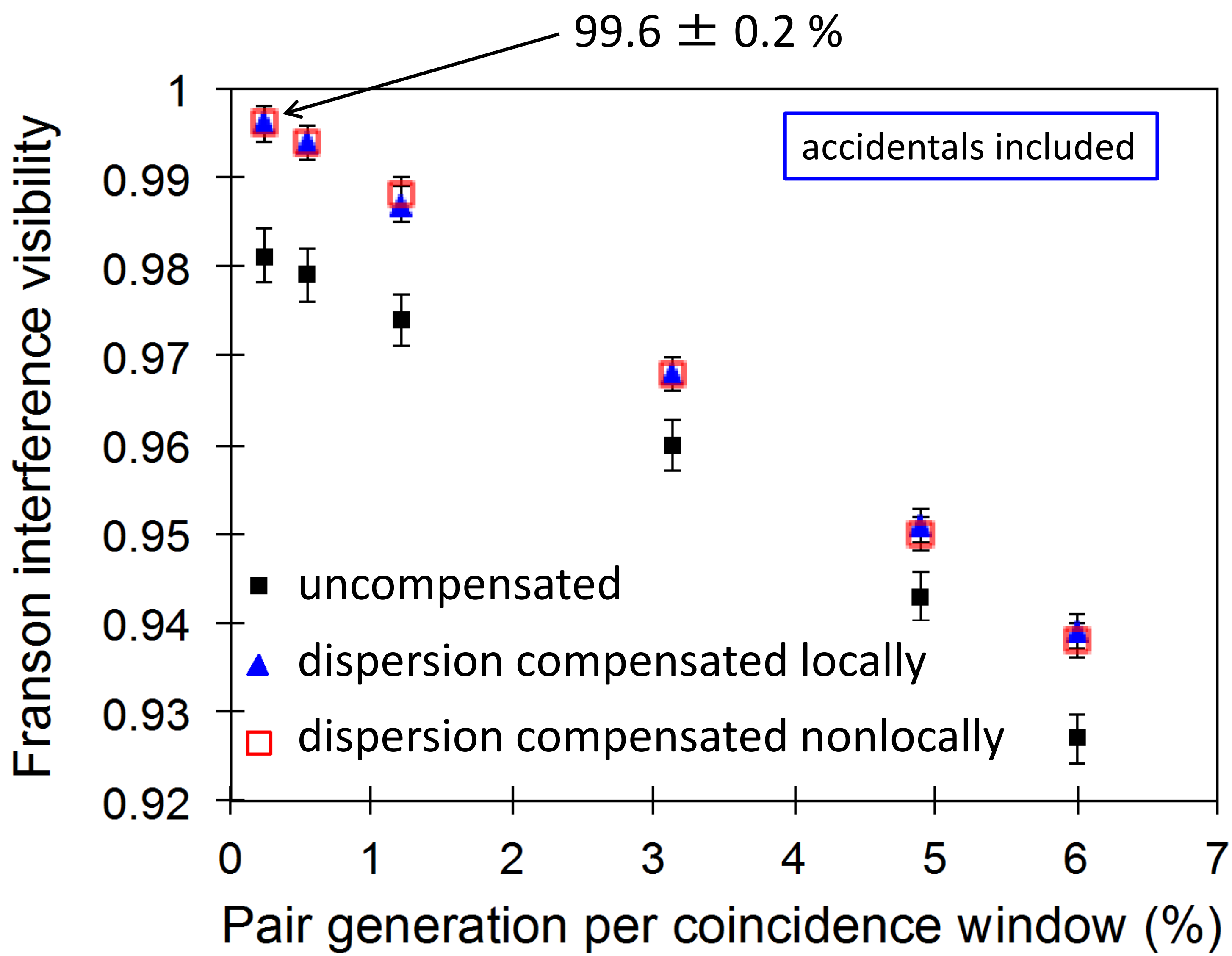
Security based on high-visibility Franson interferometer



Franson, PRL **62**, 2205 (1989)

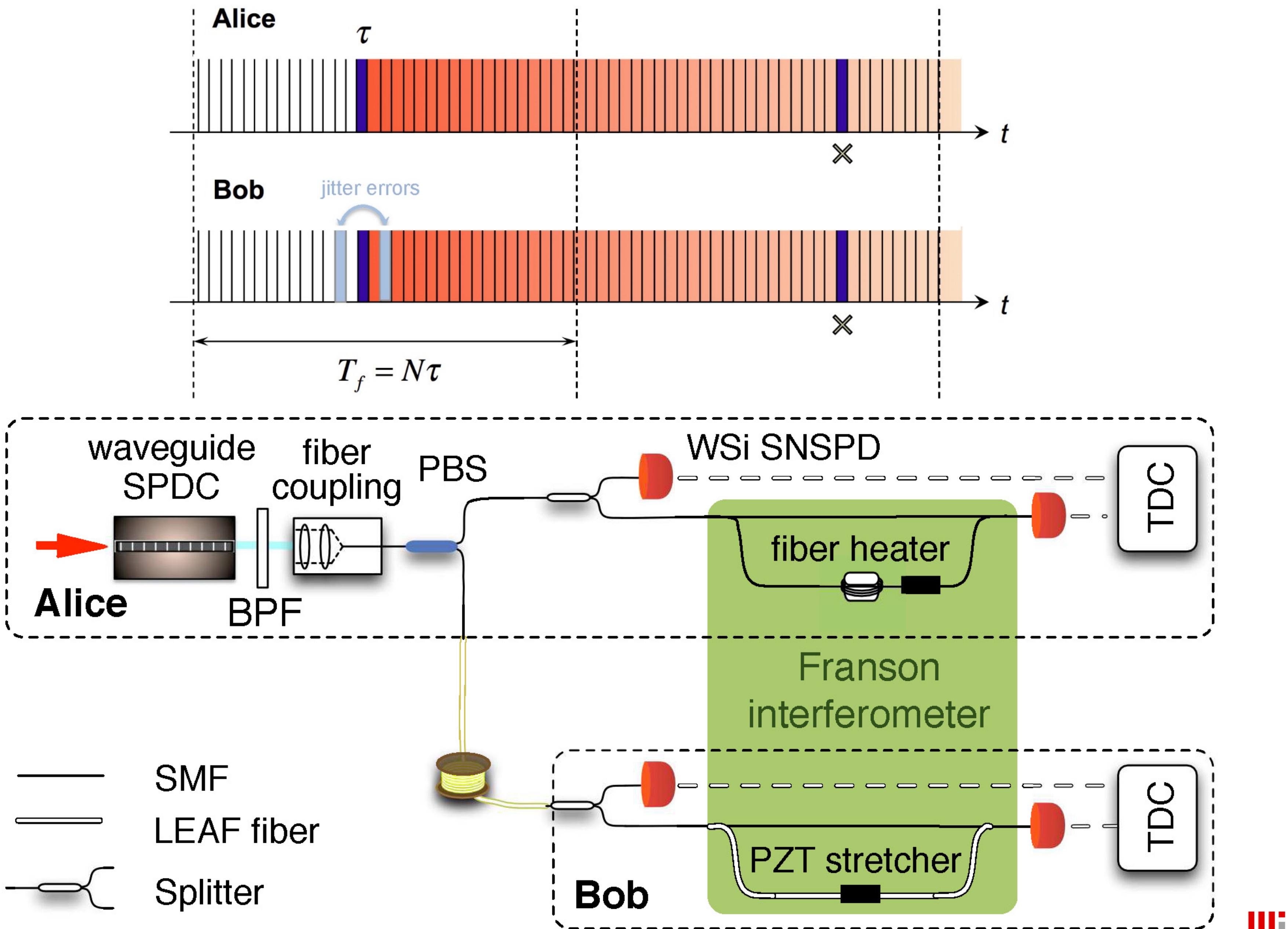
- Franson interferometer measures quality of time-energy (or time-bin) entanglement and its frequency correlation
  - frequency correlation degradation ε ➔ $V_{\text{Franson}} \leq 1 - \varepsilon$
- High visibility => small amount of frequency disturbance (by Eve)
  - Franson measurements bound Eve's Holevo information
  - visibility limited by multi-pair emission and differential dispersion between long and short paths of each arm

Dispersion-compensated Franson measurements

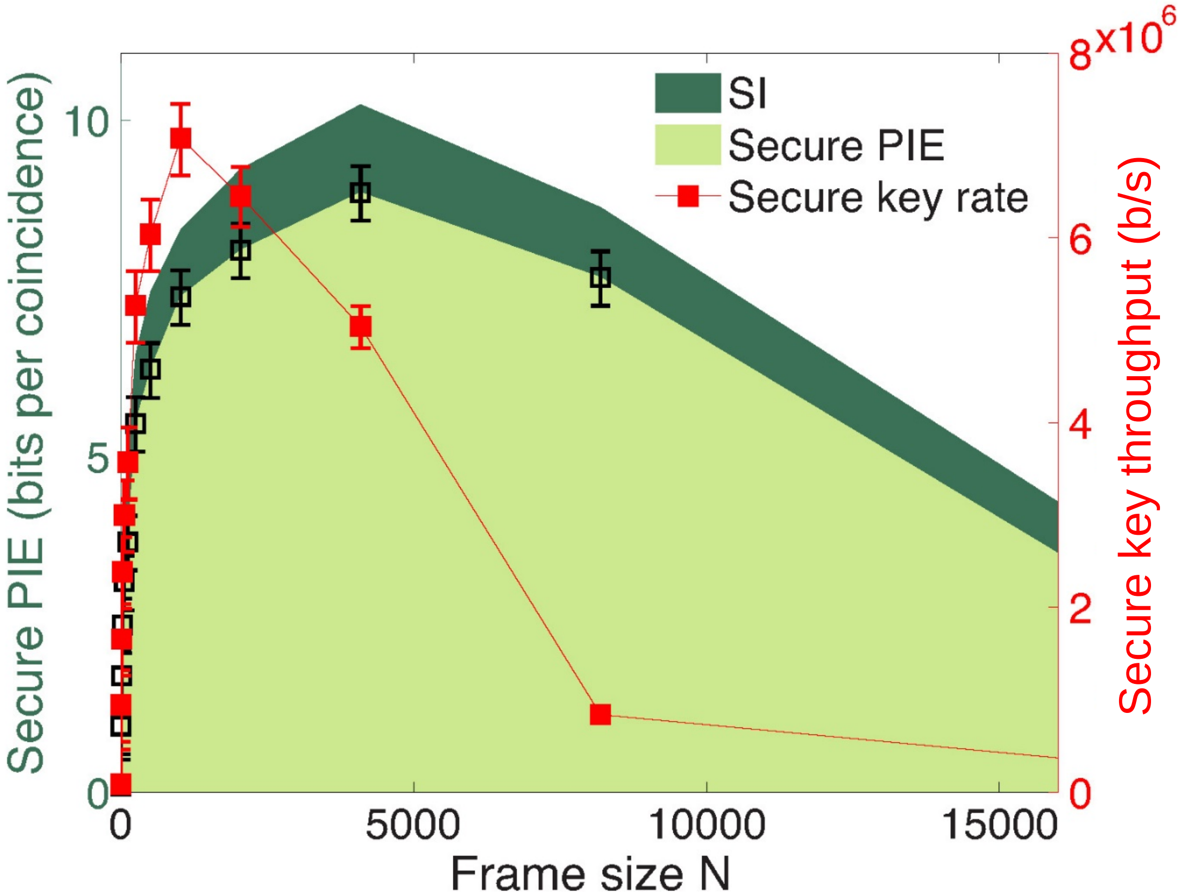


PRA **88,** 020103(R) (2013)

HDQKD with Franson security check



Franson-based HDQKD results



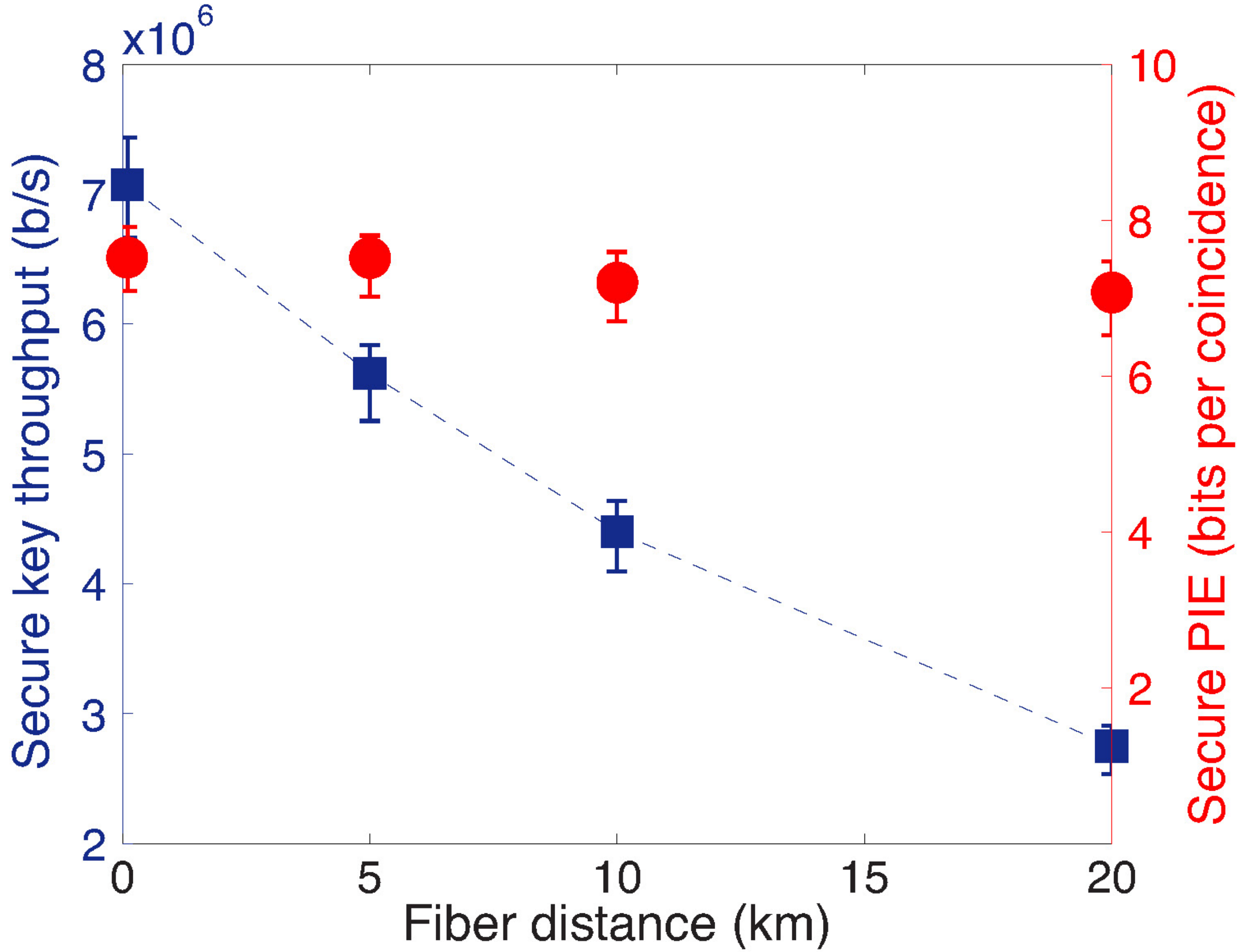
Franson visibility measurements bound Eve's Holevo information

HDQKD Improvement
500x throughput

Comparison with BBM92 [Treiber *et al.*, New J. Phys. **11,** 045013 (2009)]

	BBM92	Franson HDQKD
Secure bits/coincidence	0.35	7.5
Secure key rate	14.5 kbps	7.1 Mbps

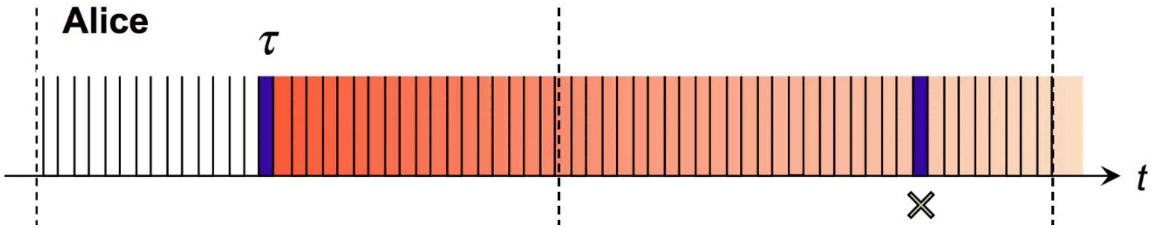
Franson HDQKD results versus distance



Secure PIE stays unaffected: 7.1 bits per coincidence

Secure key rate drops due to fiber loss

Summary



- Entanglement-based QKD with high dimensional encoding
  - multiple bits per coincidence
  - efficient error correction and privacy amplification
  - high flux single-spatial-mode PPKTP waveguide source
  - efficient WSi superconducting nanowire single photon detectors
  - security checks tightly bound Eve's Holevo information
- HDQKD security protocols
  - dispersive optics (oppositely chirped fiber Bragg gratings)
  - single Franson interferometer that does not degrade with loss
- High secure key capacity and throughput
  - dispersive optics: > 3 bpc, > 270 kbps
  - Franson: > 7 bpc, > 7 Mbps

Team members and funding

- Personnel
  - Tian Zhong, Catherine Lee, Zheshen Zhang, Hongchao Zhou, Jake Mower, Greg Steinbrecher, Ligong Wang, Xiaolong Hu, Greg Wornell, Jeff Shapiro, Dirk Englund, *MIT*
  - Rob Horansky, Varun Verma, Adriana Lita, Alessandro Restelli, Josh Bienfang, Richard Mirin, Thomas Gerrits, Sae Woo Nam, *NIST*
  - Francesco Marsili, Matt Shaw, *JPL*
- Funding
  - DARPA Information in a Photon, Columbia Optics and Quantum Electronics IGERT, NASA