Experimental Twin-Field Quantum Key Distribution over 1000 km Fiber Distance

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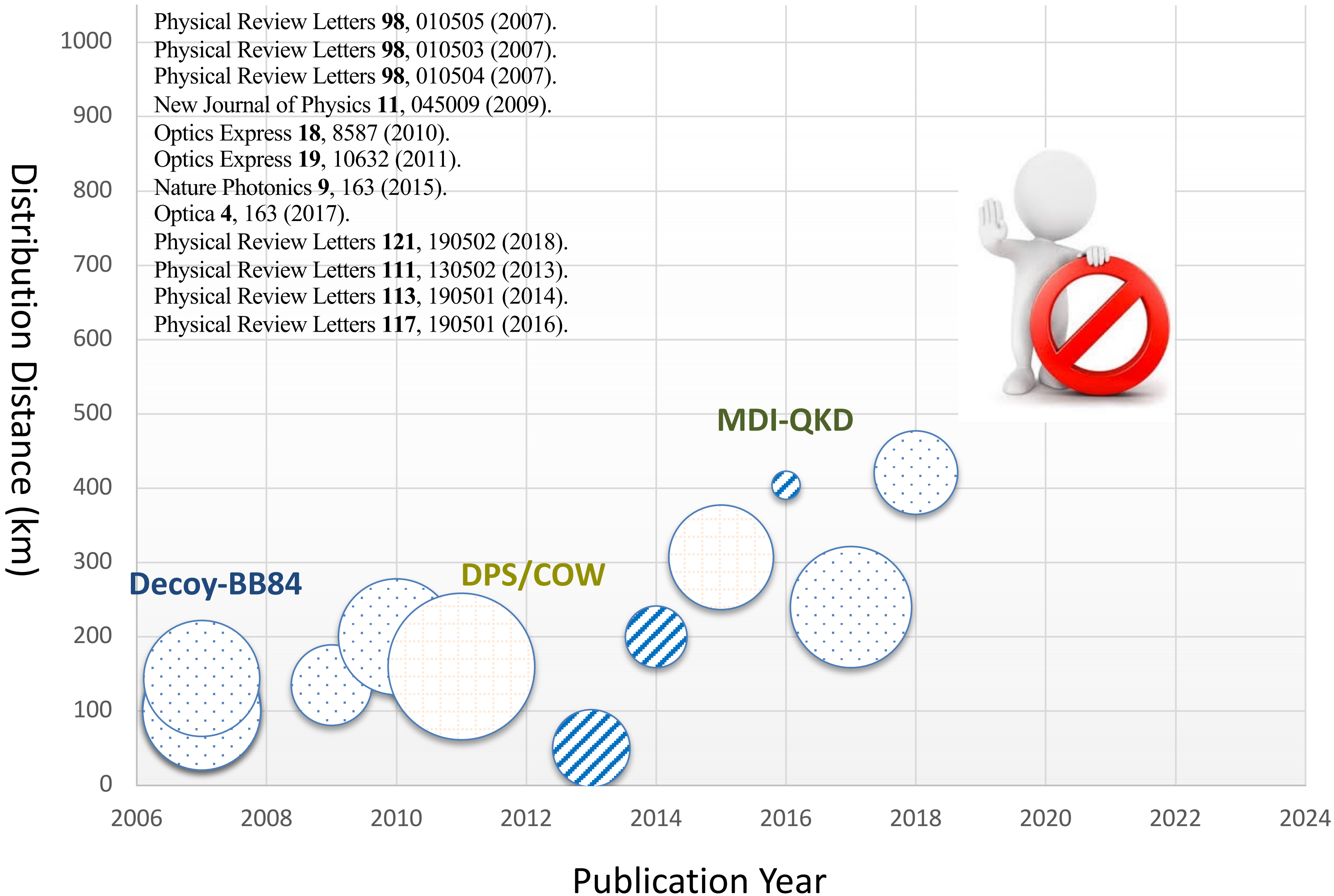
Quick Introduction: Twin-Field (TF-) QKD

Status of QKD (before TF-QKD) Systems

Limited distribution distance in QKD systems



Twin-Field QKD (TF-QKD)

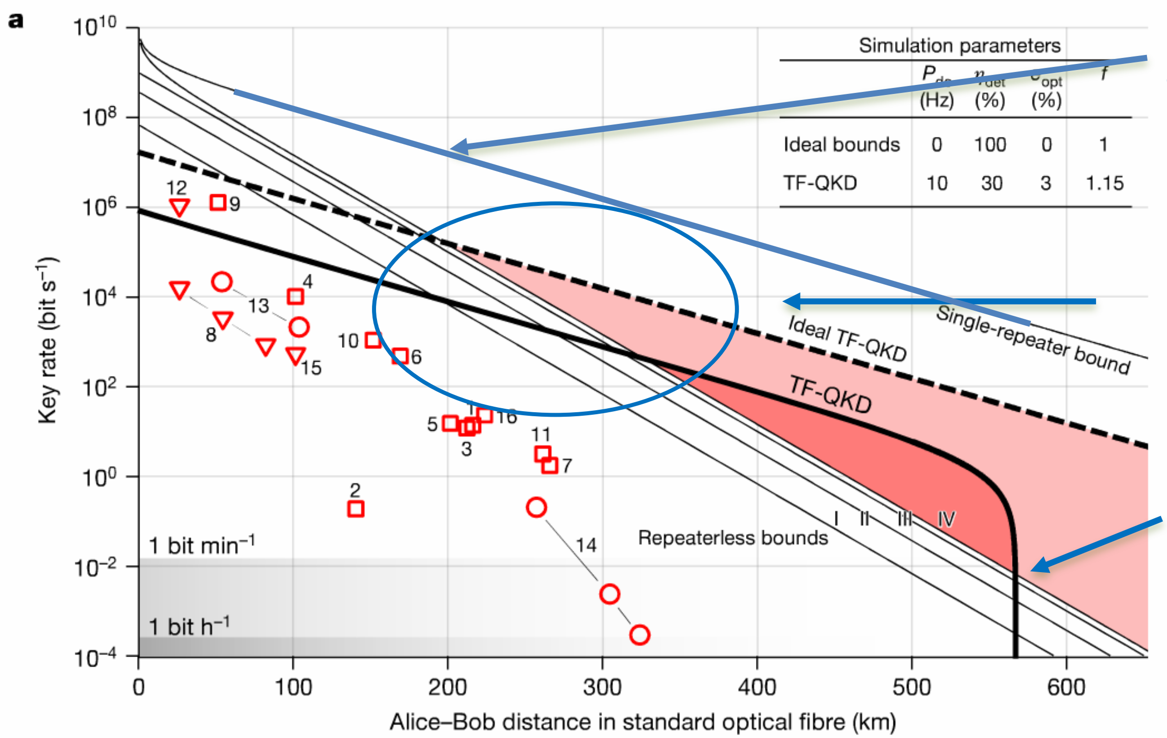
Proposed in 2018, "greatly extending the range of secure quantum communications", and "feasible with current technology".

Longer Distance

Higher Key Rate

Traditional protocol: $R \propto \eta$

TF-QKD protocol: $R \propto \sqrt{\eta}$



Key rate resembles that of a single quantum repeater

Overcomes the repeaterless secure key rate bounds

Promises ultra-long distribution distance

Lucamarini, et.al., *Nature* **557,** 400–403 (2018).

Status of QKD (before TF-QKD) Systems

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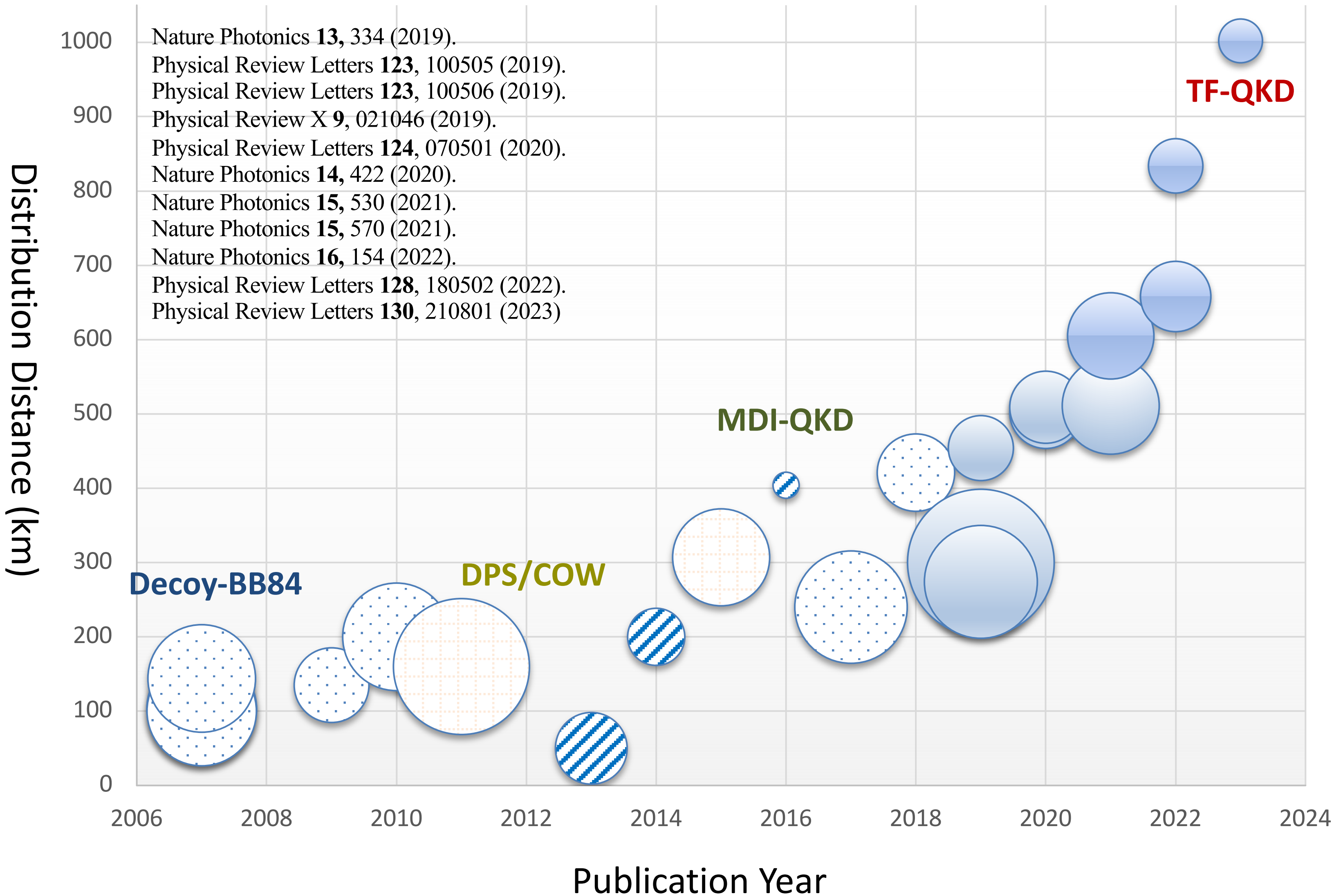
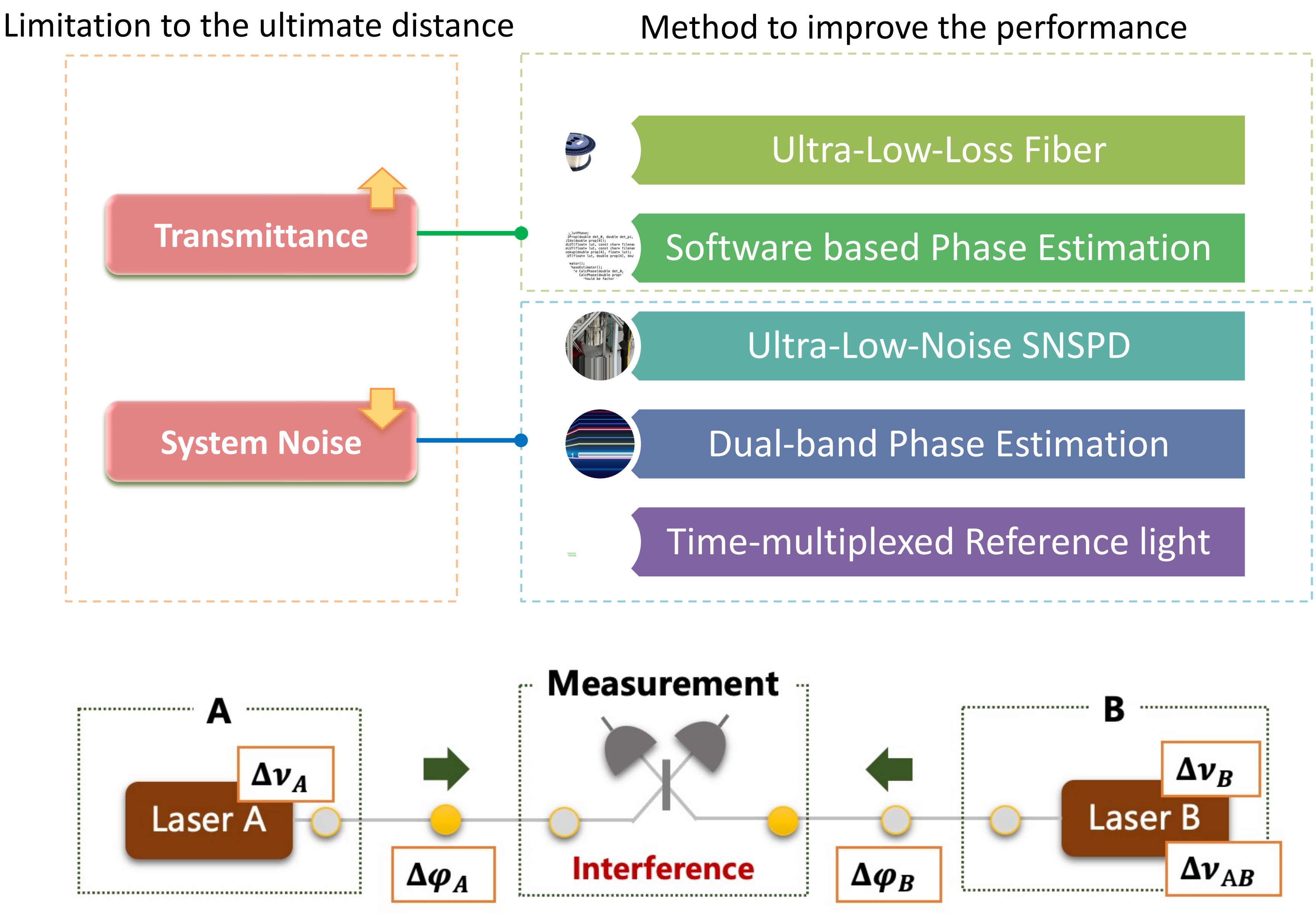


Enhancing the TF-QKD distribution distance

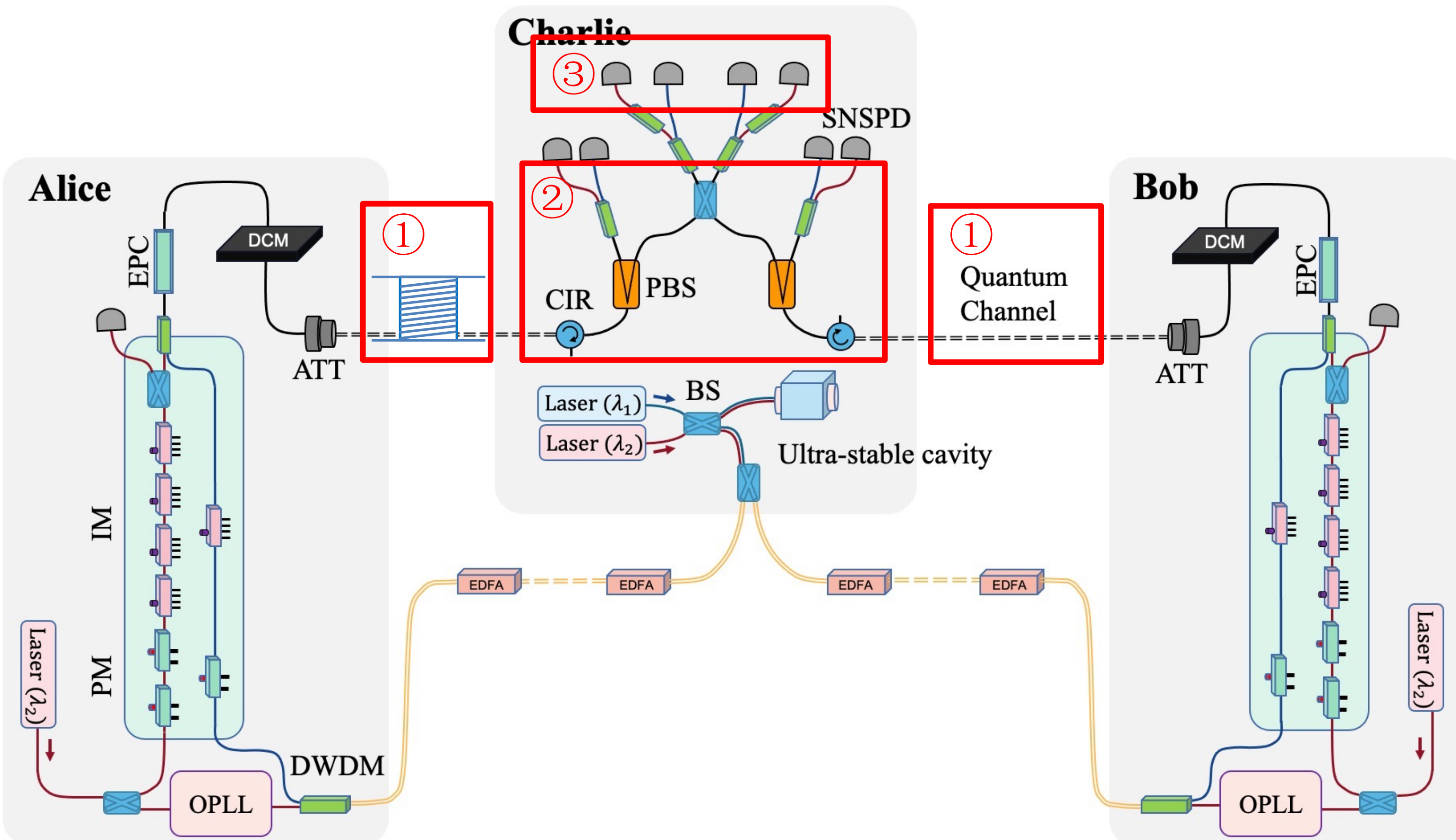
Key to realize long-distance TF-QKD



Experimental Setup - Transmittance

Transmittance

① **Fiber loss**: Ultra-Low-Loss Fiber
② **Optical loss**: Software based Phase Estimation, do not need active modulators
③ **Detection efficiency**: High efficiency Superconducting Nanowire SPD (SNSPD)



Ultra-Low-Loss Fiber

Transmittance → Ultra-Low-Loss Fiber

- “**Pure Silica Core**” technology: reducing the doped Ge in the core,
- **Decreased the fictive temperature** in the manufacturing process.
- **Large effective area** (~125 μm^2 effective area), reducing nonlinear effect in transmission.

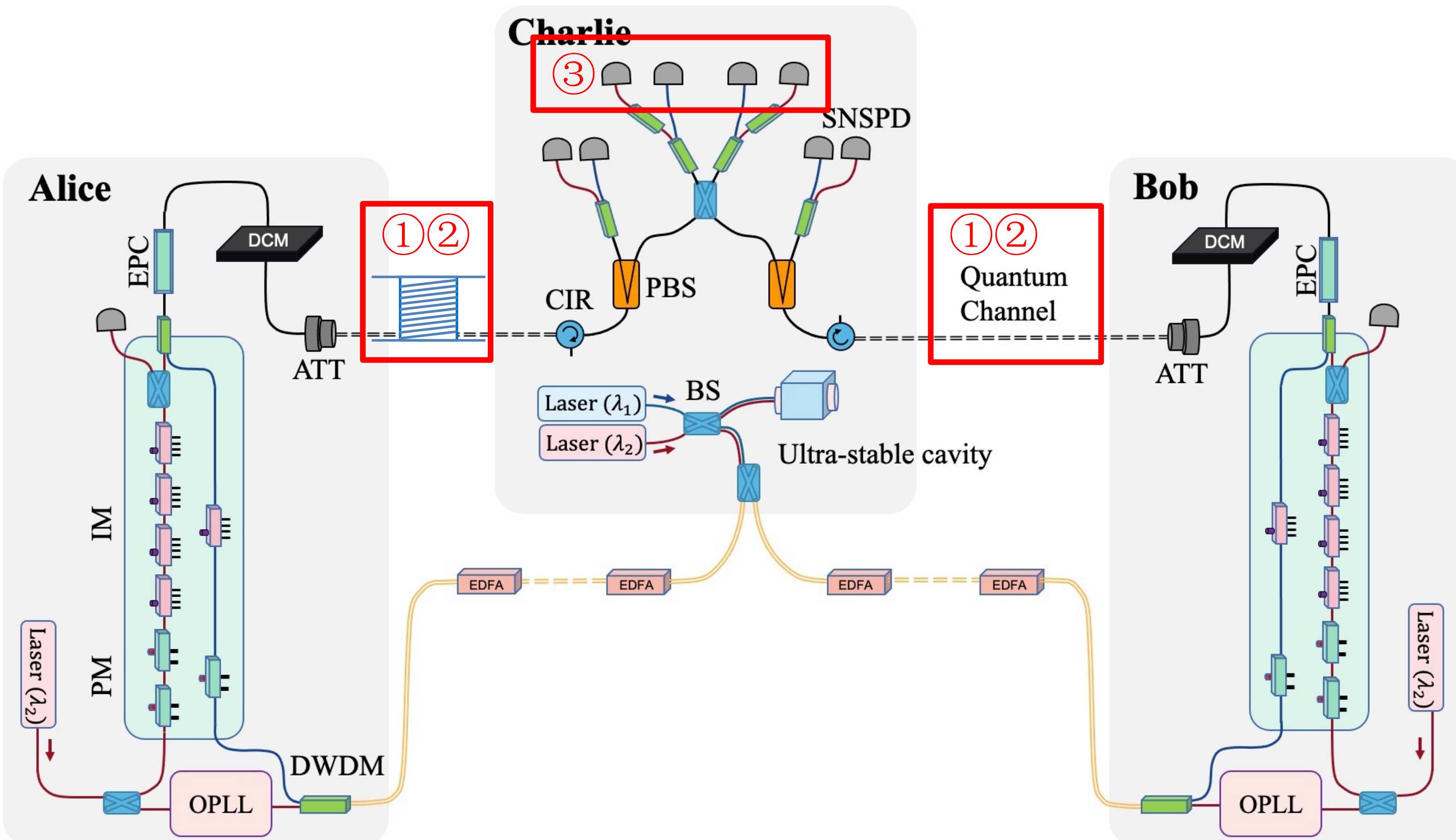
YOFC

Fiber Type	Single Mode Fiber	Commercial Ultra-Low-Loss	Ultra-Low-Loss Fiber
Attenuation	<0.2 dB/km	<0.165 dB/km	~0.157 dB/km
Atten. 1000 km	200 dB	165 dB	156.5 dB
			

Experimental Setup – System Noise

System Noise

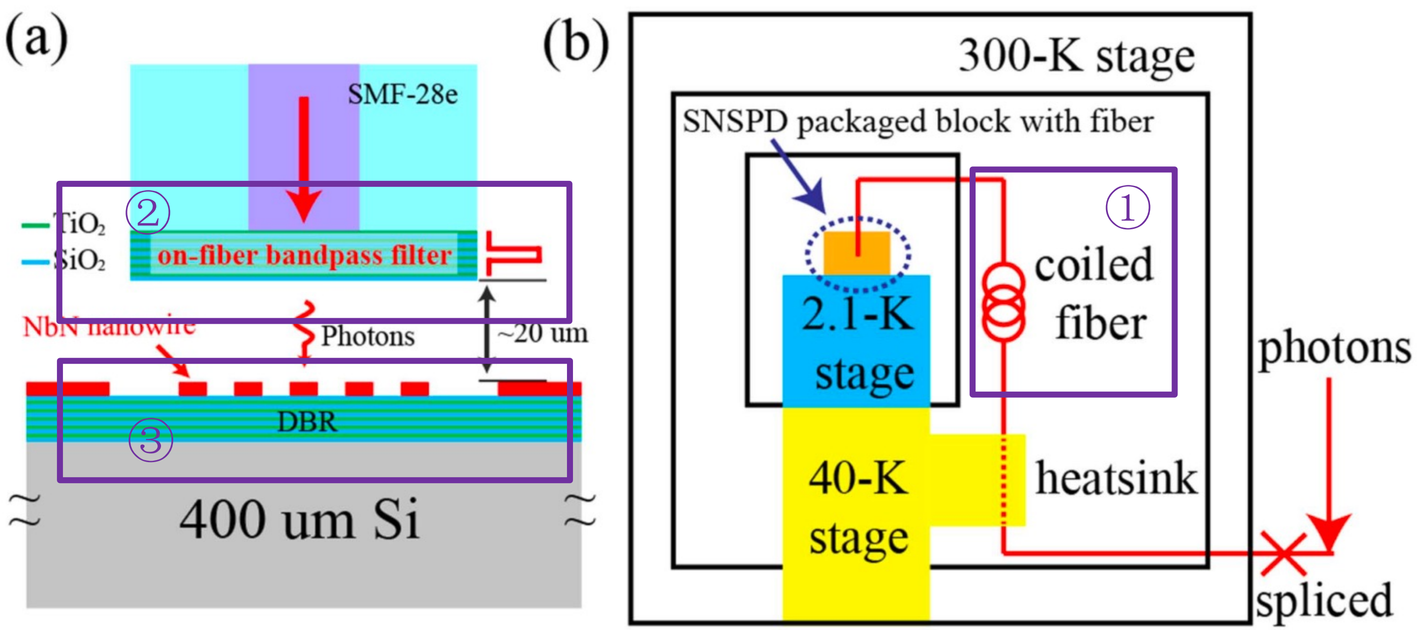
① **Re-Rayleigh Scattering**: Dual-band Phase Estimation
② **Raman Scattering**: Time-multiplexed Reference light
③ **Dark Counts**: Ultra-Low-Noise SNSPD



Ultra-Low-Noise SNSPD

System Noise → Ultra-Low-Noise SNSPD

① **Coiling the fiber**: Filtering long-wavelength (> 2 µm) noise photons,
② **Bandpass filter (BPF)** at 2.2 K: Filtering other blackbody photons.
BPF: centered at 1550 nm, 5 nm bandwidth, 85% transmittance.
③ **DBR based optical cavity**: enhancing the detection efficiency.



W. Zhang, et. al., Supercond. Sci. Technol. 31, 035012 (2018).
W. Zhang, et. al., Sci. China Phys. Mech. Astron. 60, 120314 (2017).

Ultra-Low-Noise SNSPD

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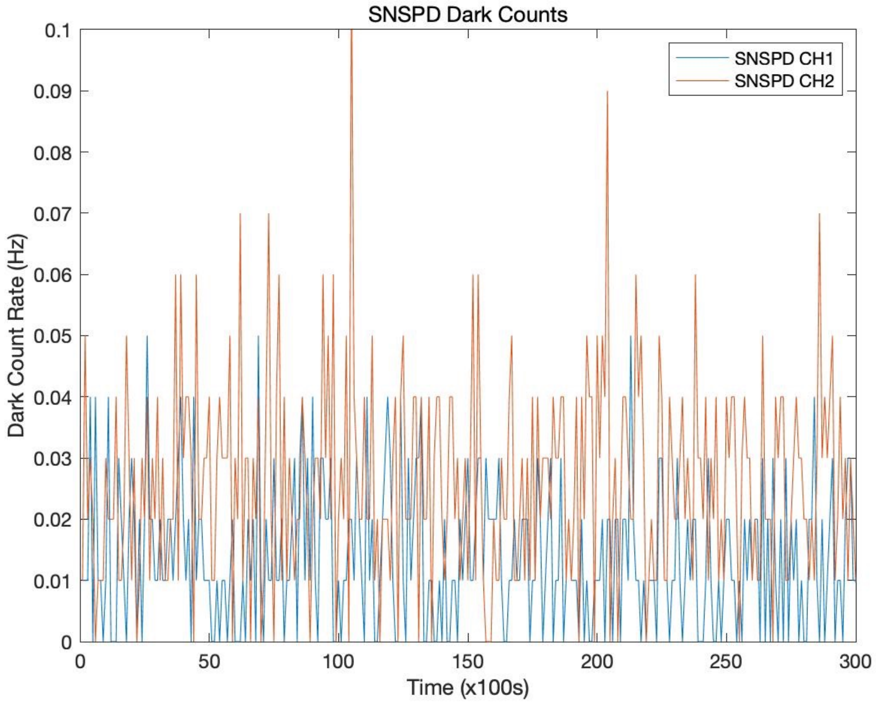
Channel	Efficiency
Ch 1	≈60%
Ch 2	

Channel	Dark Count Rate
Ch 1	0.014 Hz
Ch 2	0.026 Hz

Note: the DCR fluctuates during the experiment



TFQKD Requires a Phase Reference Pulse

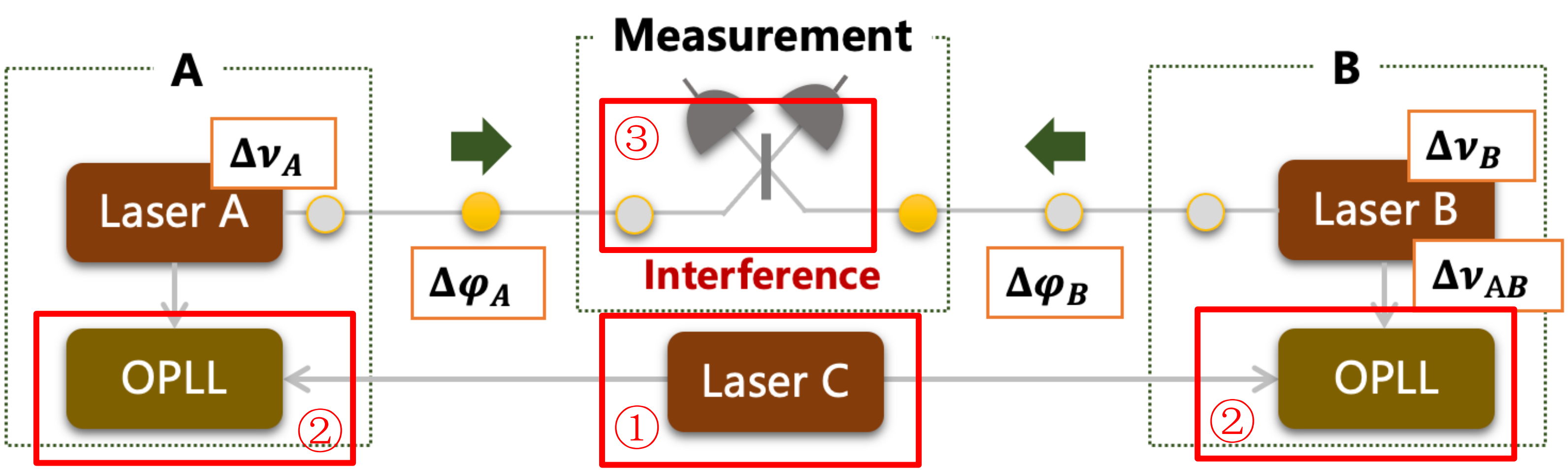
- **Single Photon Interference** with **Independent Lasers**

$$\delta_{\mathrm{ba}} = \frac{2\pi}{s}(\Delta\nu L + \nu\Delta L)$$

Wavelength difference (A/B)

Fiber length difference (A/B)

① **Ultra-stable Laser**: Stable wavelength reference.
② **Optical Phase-Locked Loop (OPLL)**: Locking λ of independent lasers.
③ **Phase Reference Pulse**: Compensate phase fluctuation in the quantum channel.



Re-Rayleigh Scattering Noise in Fiber

System Noise → Re-Rayleigh Scattering

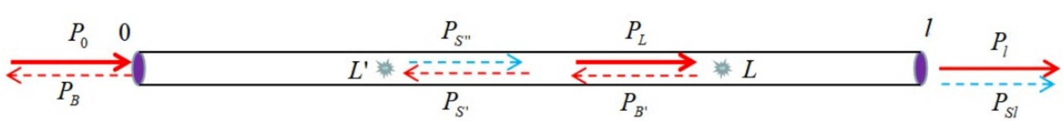
$$P_{srs} = \frac{1}{2}P_{Sl} = \frac{P_0 S^2}{4\alpha} e^{-\alpha l}[l + \frac{e^{-2\alpha l}}{2\alpha} - \frac{1}{2\alpha}]$$

① **Time-Multiplexing**: A direct way to multiplex the phase reference light (same path, same λ)
② **Re-Rayleigh Scattering Noise**: Will result in ~10 Hz Noise, thus limit the distribution distance to 600 ~ 700 km.

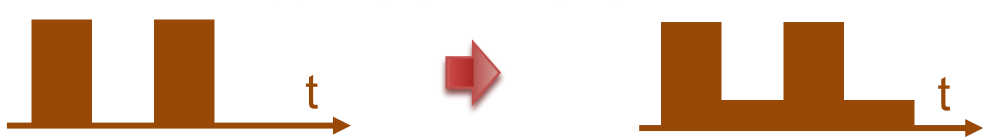
Table： Parameters

α = −0.168dB/km
S = 3.919×10^{-5}
Ref = ~2 MHz
Noise ≈ 14 cps (@650km)

(a) Rayleigh scattering in optical fiber



(b) Re-Rayleigh scattering in optical fiber



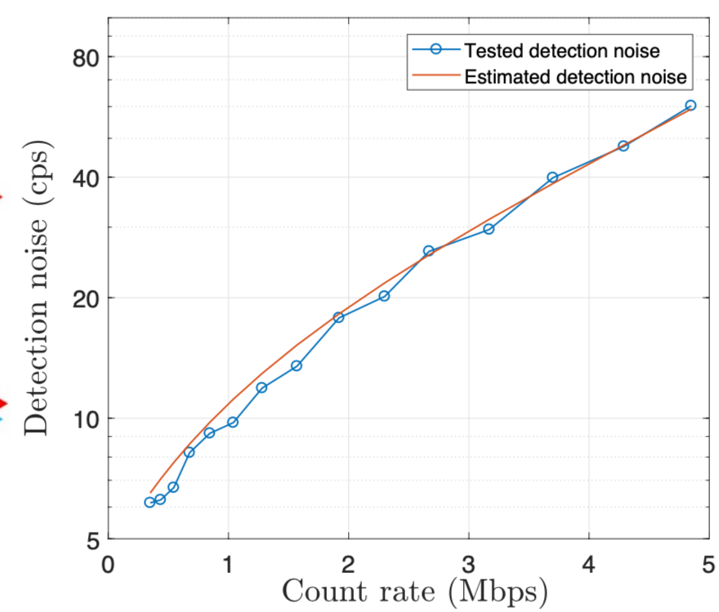


Figure: Re-Rayleigh Scattering (500 km)

Dual-band stabilization

- **Dual-band stabilization** avoid the Re-Rayleigh Scattering noise

① **Strong Phase Reference**(λ_1): Reduce the phase drift to ~1/1000.
② **Dim Phase Reference**($\lambda_2 = \lambda_s$): Stabilize the phase drift with lower intensity.
③ **WDM**: Filtering out Re-Rayleigh Scattering Noise of Strong Phase Reference

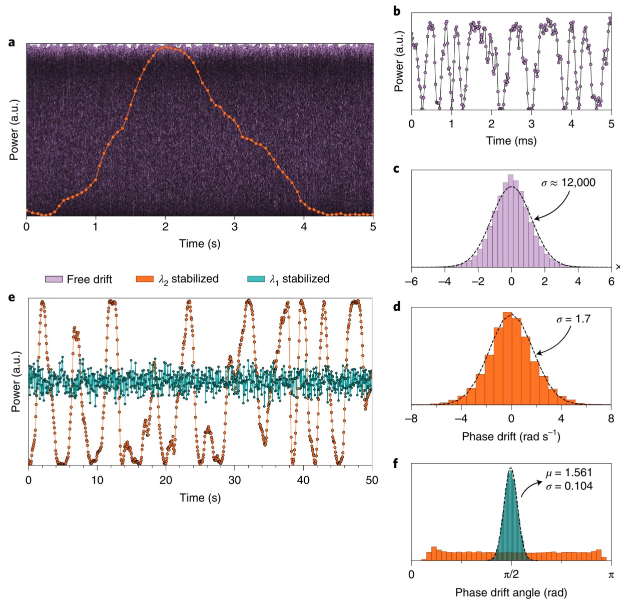


Figure: Dual-band phase stabilization

Pittaluga, M., et. al. *Nature Photonics* **15,** 530–535 (2021).

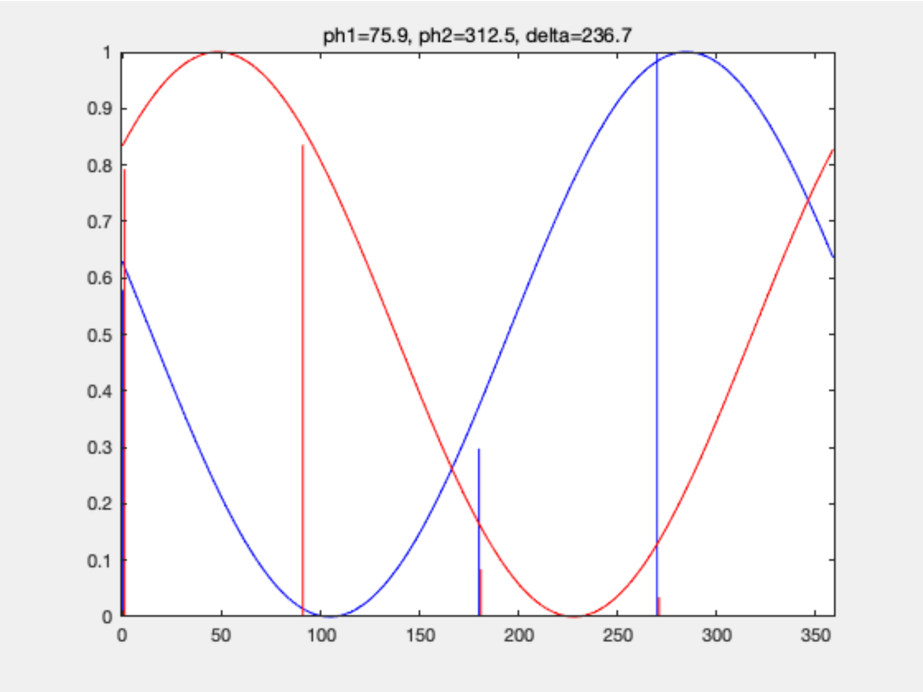


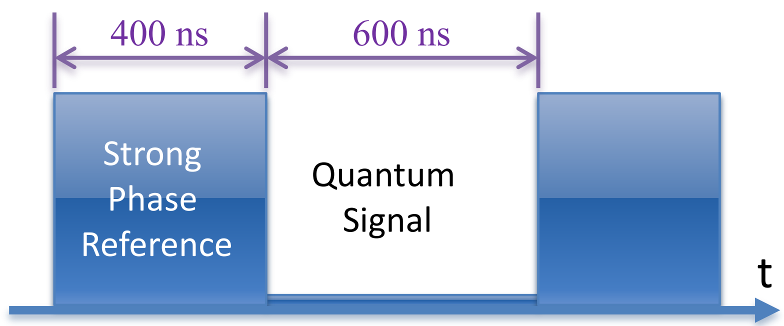
Figure: Phase Drift during 200 ms, λ_1=1550 nm and λ_2=1548 nm.

Dual-band stabilization

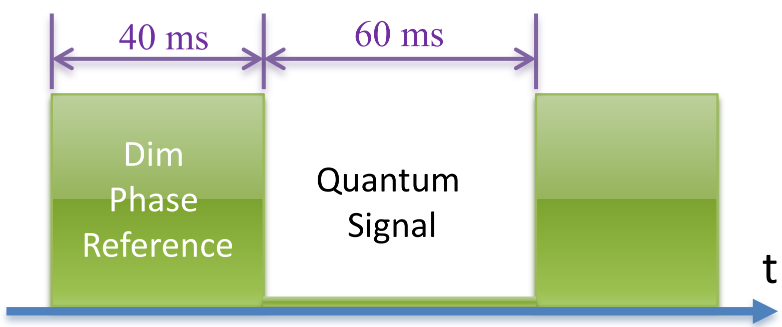
System Noise — Raman Scattering

- The main source of noise at the extreme distance.

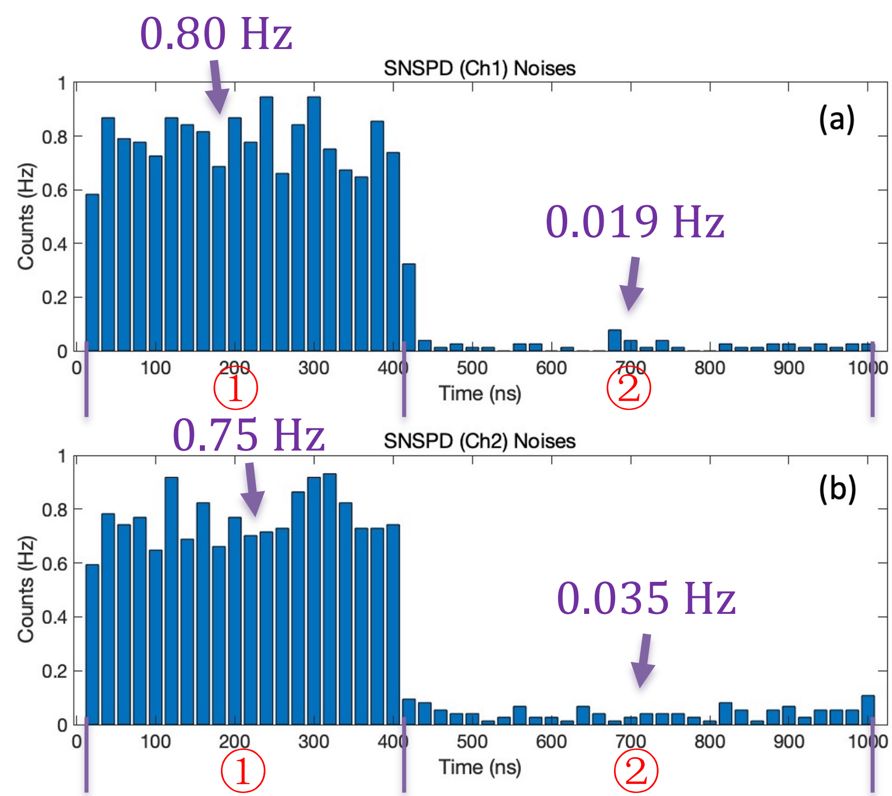
① **WDM**: cannot filter Raman noise at the same wavelength ($\lambda_s \leftarrow \lambda_1$).
② **TDM:** Time multiplexing Strong Phase Reference with quantum signal.



Strong Phase Reference: λ_1=1548.51 nm



Dim Phase Reference: λ_2=λ_s=1550.12 nm



Dual-band stabilization with data processing

- Avoid the loss induced by Phase Modulator at Charlie

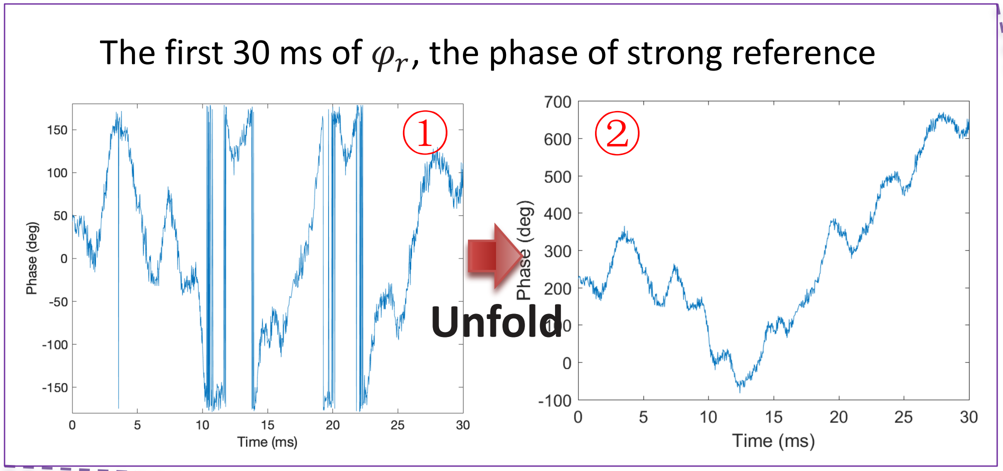
① **Calculate φ_r** using MinErr Model with 4 state sent.

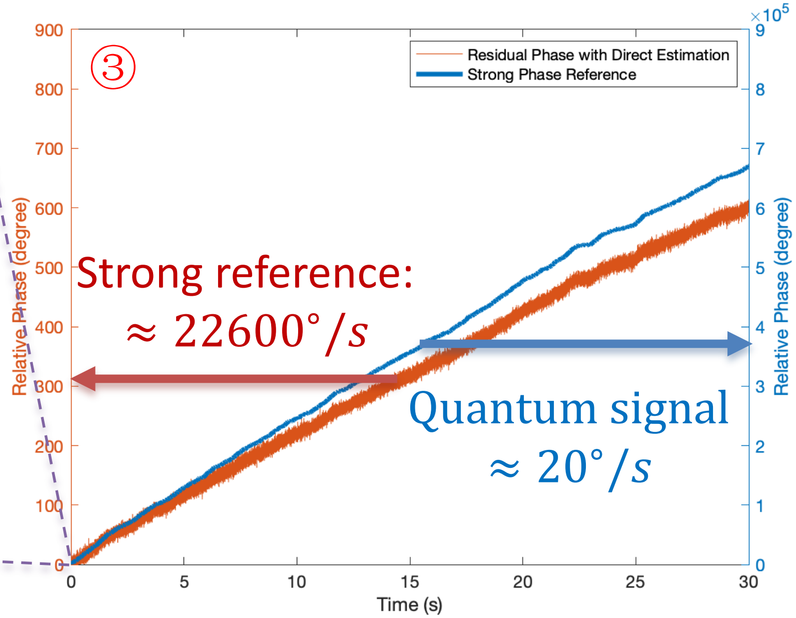
$$Err(\Delta\varphi) = \sum_i p_i \cdot (1 - \cos((\Delta\theta_i + \Delta\varphi)/2)^2)^2 \quad \text{where } \Delta\theta_i = \{0, \pi/2, \pi, 3\pi/2\}$$

② **Unfold φ_r** assuming phase changes continuously: $\Delta\phi_i - \Delta\phi_{i-1} < 180°$.

③ **Direct Estimate φ_s** using φ_r: $\phi_s(t) = \phi_r(t) + \phi_s(0) - \phi_r(0)$.

The residual phase is **reduced** by more than **1000 times** compared with free drift, similar to the reported hardware-based dual-band compensation.





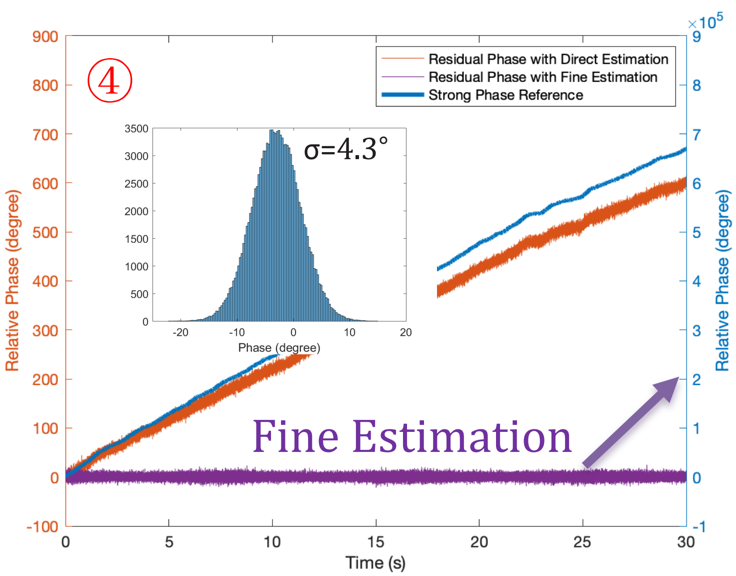
Dual-band stabilization with data processing

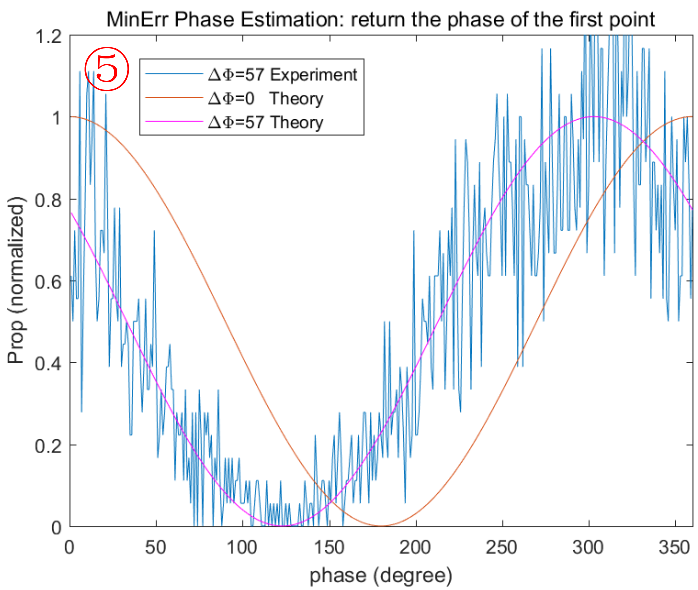
- Avoid the loss induced by Phase Modulator at Charlie

④ **Fine Estimate $\boldsymbol{\varphi_s}$** using $\boldsymbol{\varphi_r}$: $\phi_s(t) = \phi_r(t) \times \lambda_2/\lambda_1 + \phi_s(0) - \phi_r(0).$
Results in a more precise estimation of Std=4.3° in the 30 s test.
⑤ Determine the **initial phase difference**, using MinErr Model with 4 state sent:

$$Err(\Delta\varphi') = \sum_i n_i \cdot (1 - \cos((\Delta\theta_i + \Delta\varphi')/2)^2)^2$$

where n_i the count of dim reference detections with phase difference between strong reference $\Delta\theta_i$.





TF-QKD Feedback System

- Signal arrival time feedback using strong reference

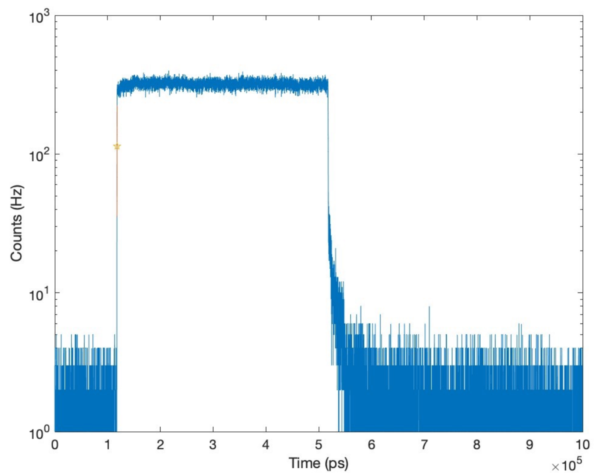


Figure: The rising edge of strong reference

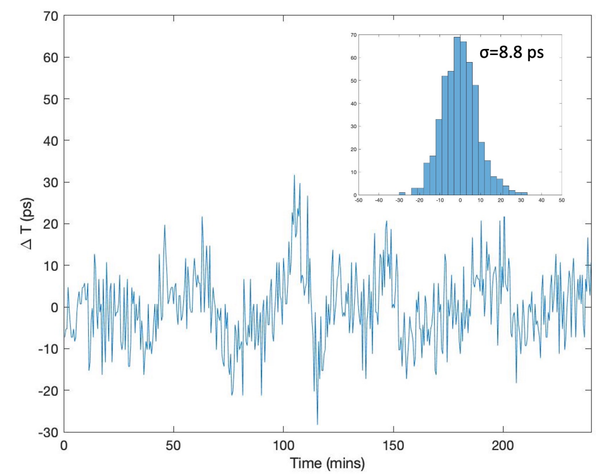


Figure: Relative delay between λ_1 and λ_2

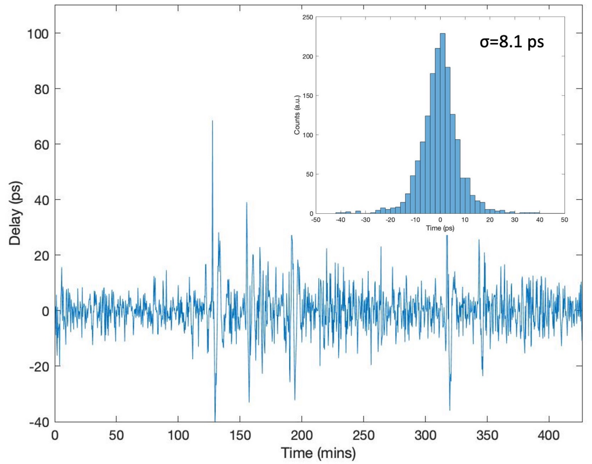


Figure: Measured delay with feedback on

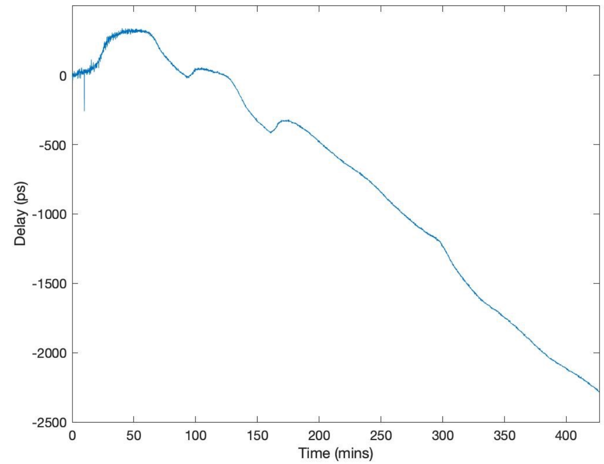


Figure: Measured delay with feedback off

TF-QKD Feedback System

- Two Wavelength Polarization Feedback

① Adjusted polarization of λ_1 to target value, e.g., 100 kHz at the monitor port,
② Minimize detected count rate of λ_2 at the monitor port,
③ If the λ_1 counts is higher than expect range, e.g., 75k~300 kHz, the first step starts again,
④ Repeating ①~③, till λ_2 falls in the target value, e.g., 100 Hz,
⑤ Repeat ①~ ④ when either λ_1 or λ_2 count rate reaches the limit of expected range.

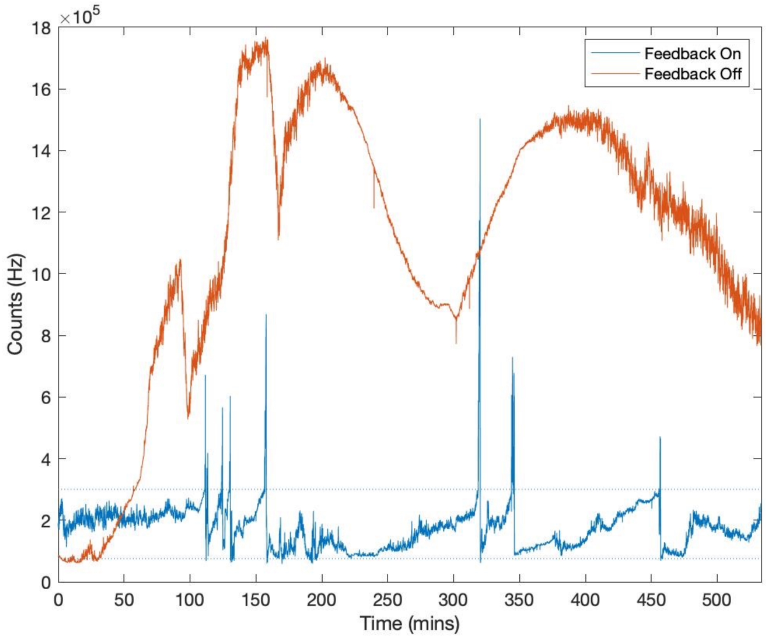


Figure: Measured polarization drift of λ_1

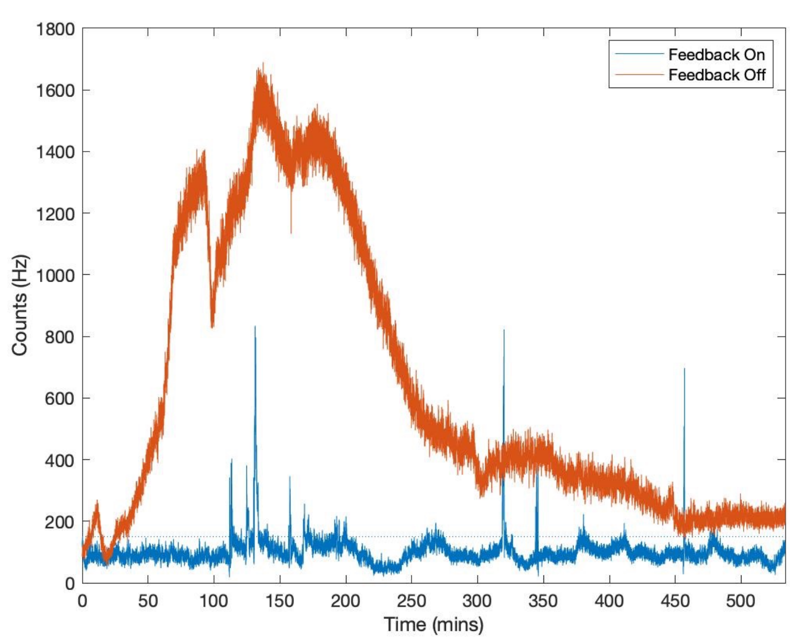


Figure: Measured polarization drift of λ_2

TF-QKD Feedback System

- Local Intensity Feedback

① Fraction of the signal is directed to monitor SNSPDs before attenuation.
② PID algorithm is used to feedback the bias of the intensity modulators.

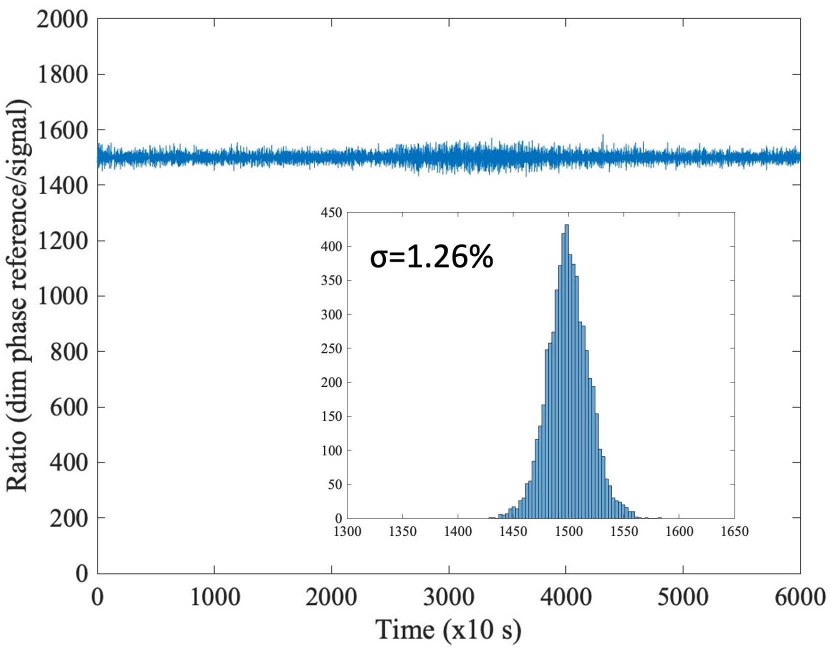


Figure: Measured ratio between the "dim phase reference" and quantum signal.

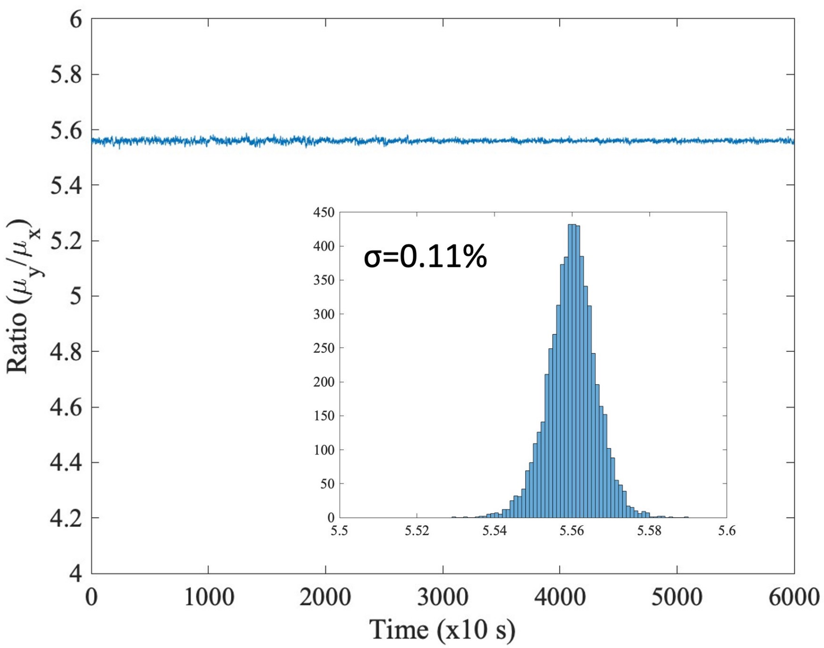


Figure: Measured ratio between μ_y and μ_x decoy states.

TF-QKD System & Performance

Total Noise: 5.4×10^{-12}

SNSPD Efficiency: ~60%
Dark Count: **~0.02 Hz**

Loss: 156.5 dB (0.157dB/km)

Data Window: 200 ps

Re-Rayleigh Scattering +
Raman Scattering: **<0.01 Hz**

Strong Ref.: ~300 kHz

Dim Ref.: ~1 kHz

Frequency: 1 GHz
Effective: 351 MHz

Relative Drift <0.1 Hz

Ultra-stable Laser<0.1 Hz

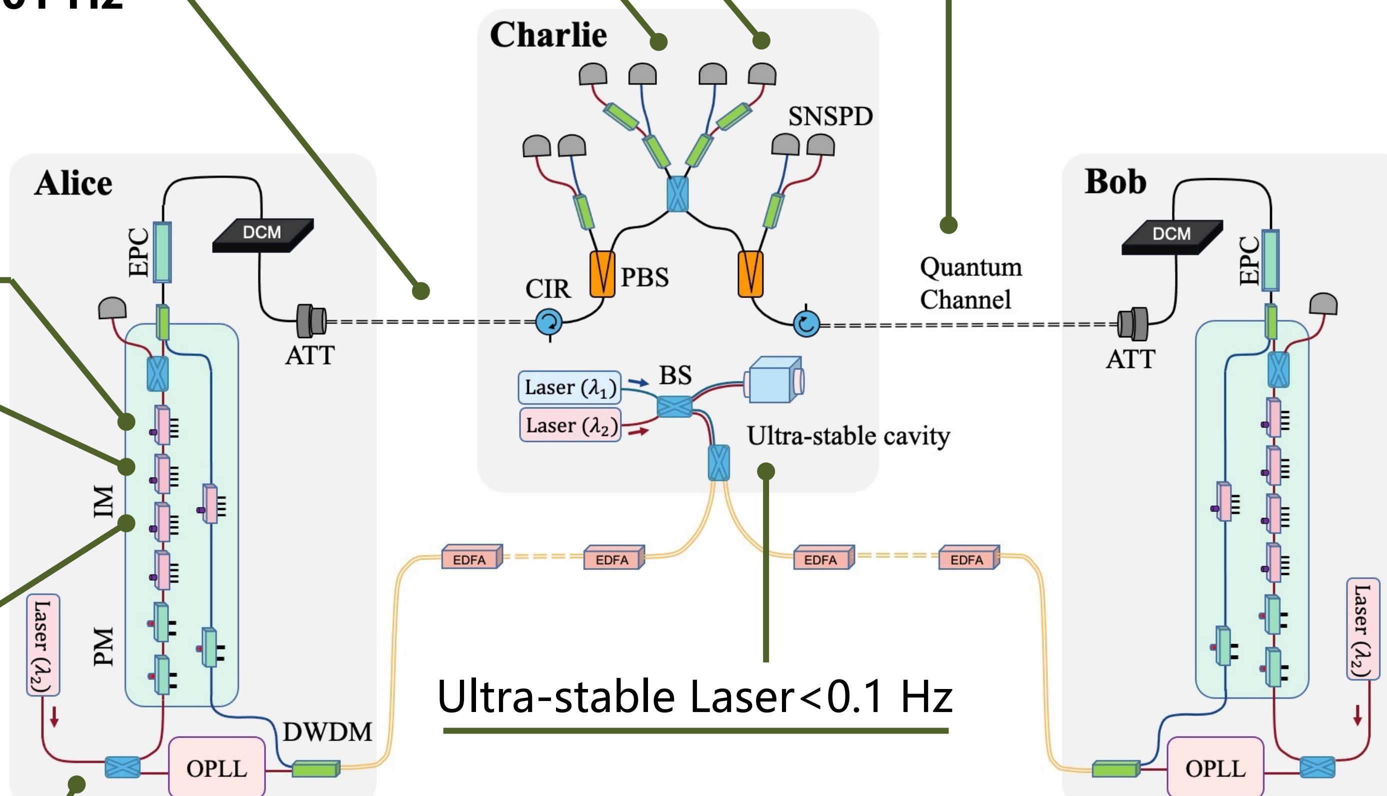
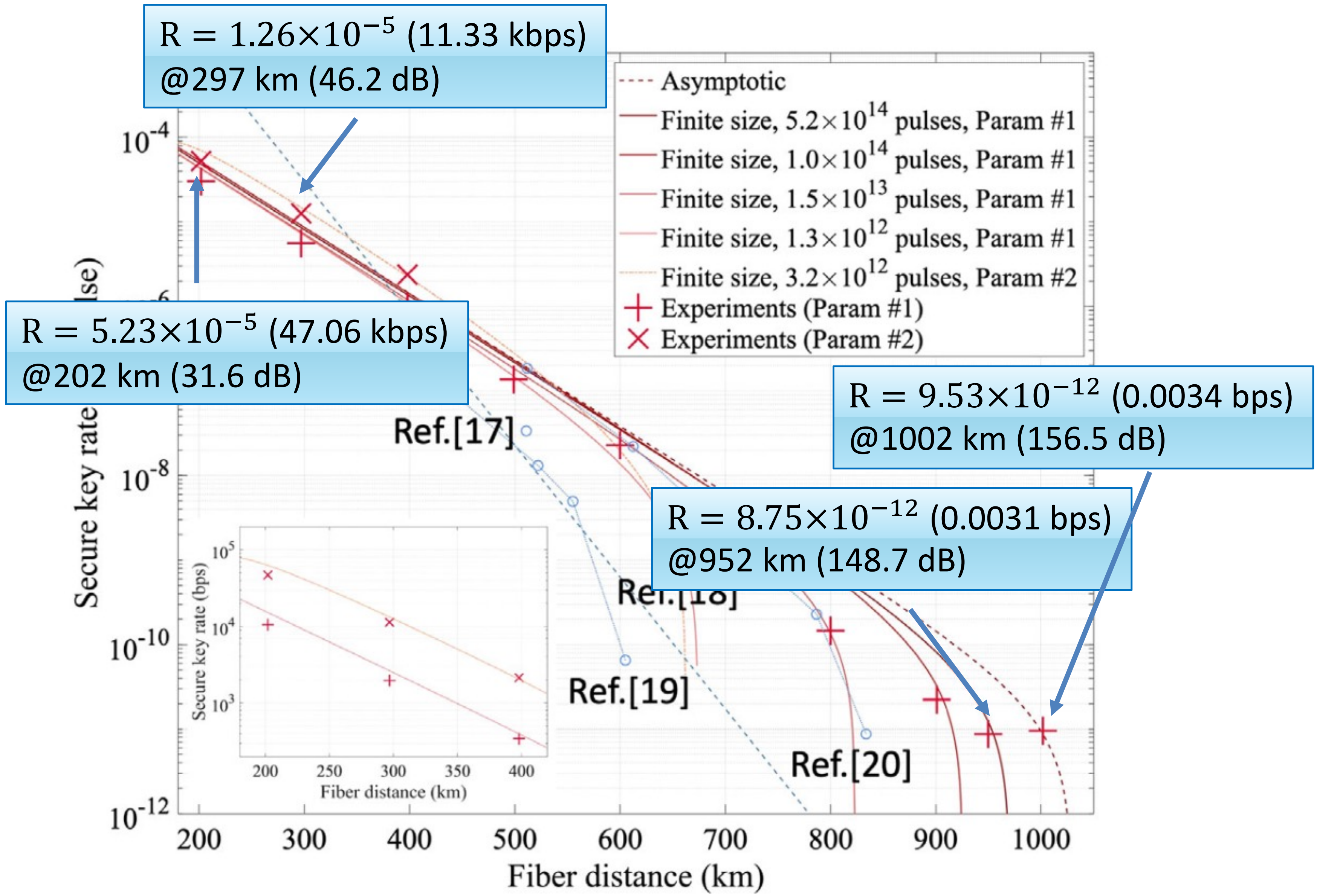


Figure: SNS-TF-QKD Setup

1002 km SNS-TF-QKD experimental result



Physical Review Letters **130**, 210801 (2023).

Contributed

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Theory:

Cong Jiang, Xiang-Bin Wang

Low-Noise SNSPD:

Weijun Zhang, Jia-Min Xiong, Cheng-Jun Zhang, Hao Li, Lixing You

Low-Loss Fiber:

Rui-Chun Wang, Jun Wu

National Key R&D Program of China

NSFC

Key R&D Plan of Shandong Province

Taishan Scholar Program of Shandong Province

Thank you!