Quantum Technologies for S.I.I. Telescopes

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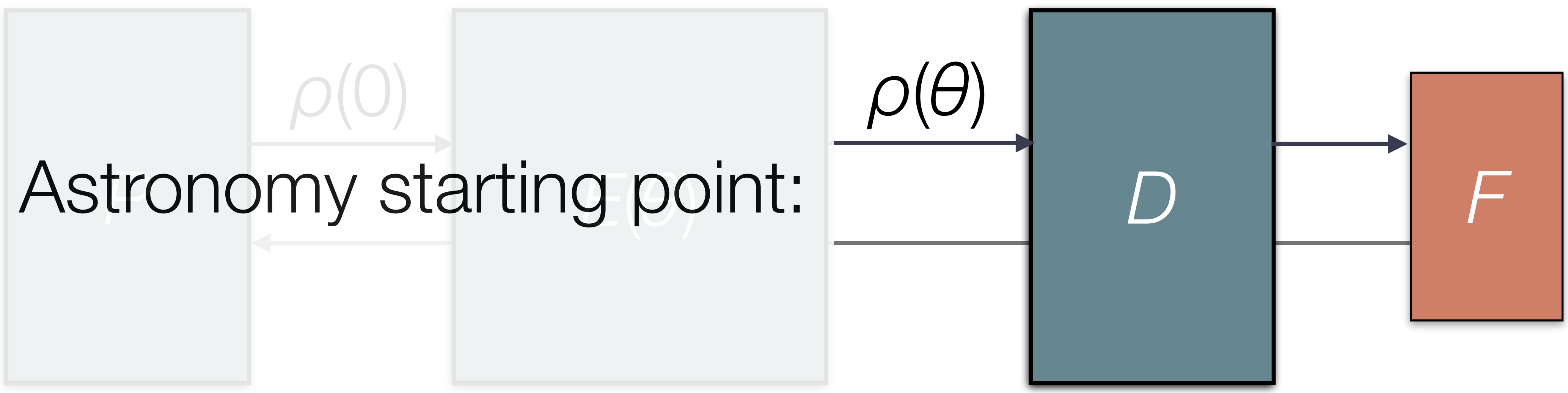
Quantum Technologies for SII Telescopes (and beyond)

- Quantum metrology
- Optimal imaging using amplitude and intensity interferometry
- Quantum networks, entanglement distribution, clock synchronisation, and all that…

Quantum Metrology

Any measurement can be thought of as a three-part process: *Prepare*, *Evolve*, *Detect*. (+ *Feedback*).

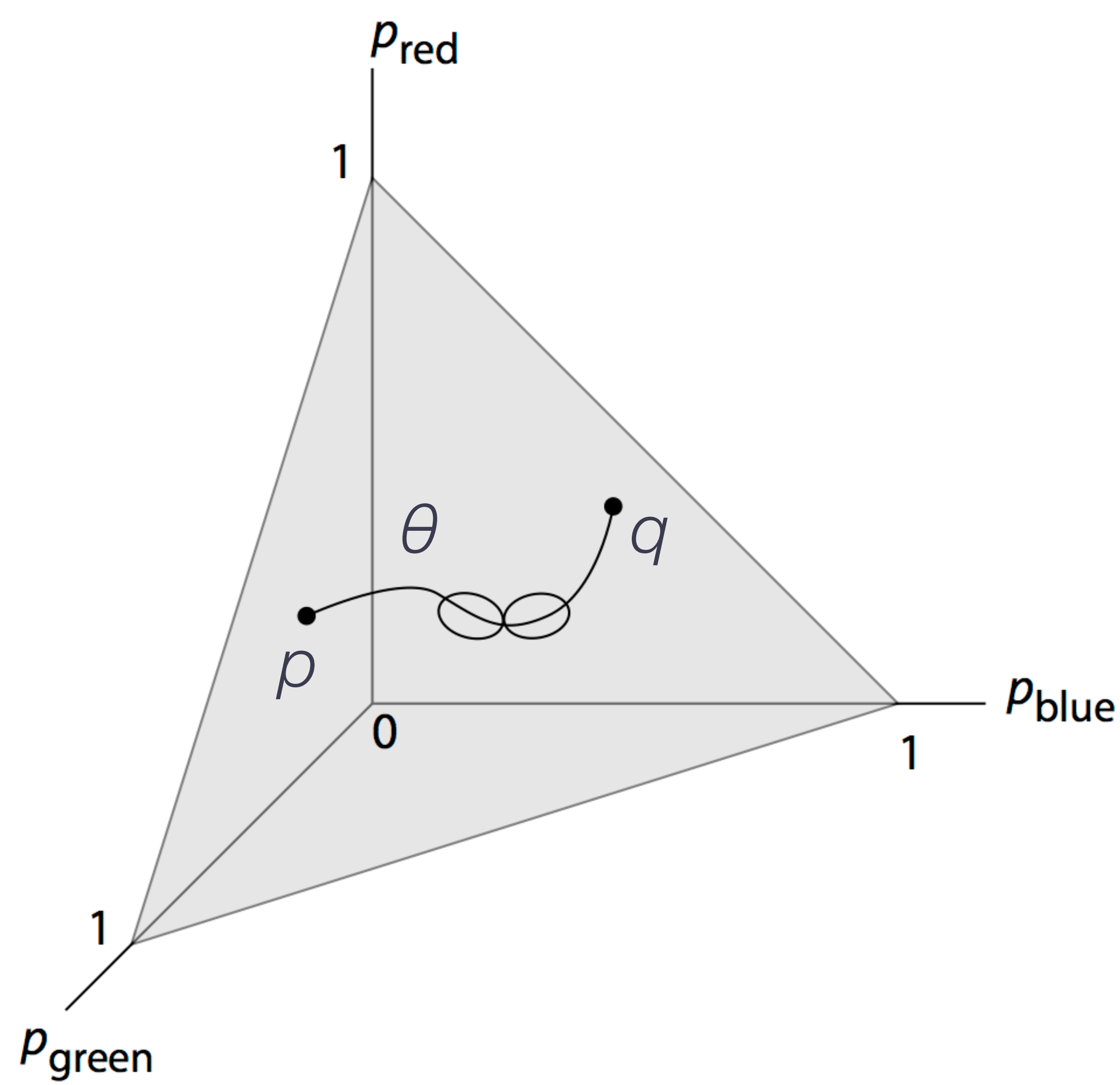


Astronomy starting point:

A big movement of the outcome distribution will give a more precise measurement.

The probabilities of the measurement outcomes depend on the quantity *θ*, otherwise our measurement does not say anything about *θ*.

We can mathematically define a distance along the path *θ* and ask the question: How often do I need to measure in order to distinguish between *p* and *q*?



The Fisher information measures the movement of the probability distributions.

Ronald A. Fisher
(1890 – 1962)

The Fisher information I is the amount of information about a quantity θ that is contained in a single measurement.

It is a *statistical* quantity that tells us something about the distinguishability of probability distributions.

The precision of the measurement procedure is determined by the Fisher information.

Calyampudi Rao (1920 – 2023)

Harald Cramér (1893 – 1985)

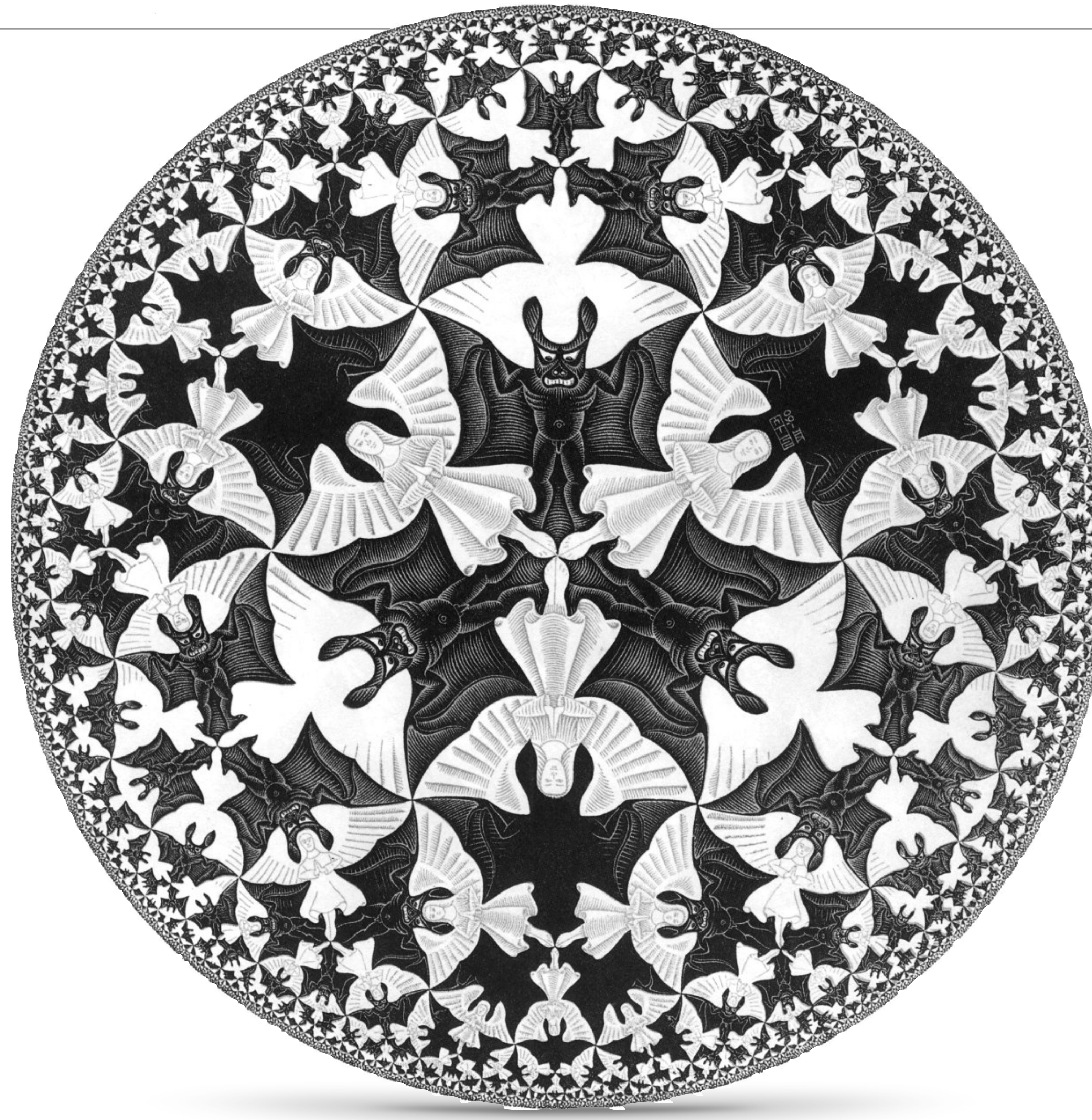
The Cramér-Rao result:

The Mean Square Error $(\delta\theta)^2$ is bounded by the inverse of the Fisher information:

$$(\delta\theta)^2 \geq \frac{1}{NI(\theta)}$$

where N is the number if independent measurements.

The space of probability distributions is highly curved, much like this Escher drawing.



The Fisher information is the metric in the curved space of probability distributions.

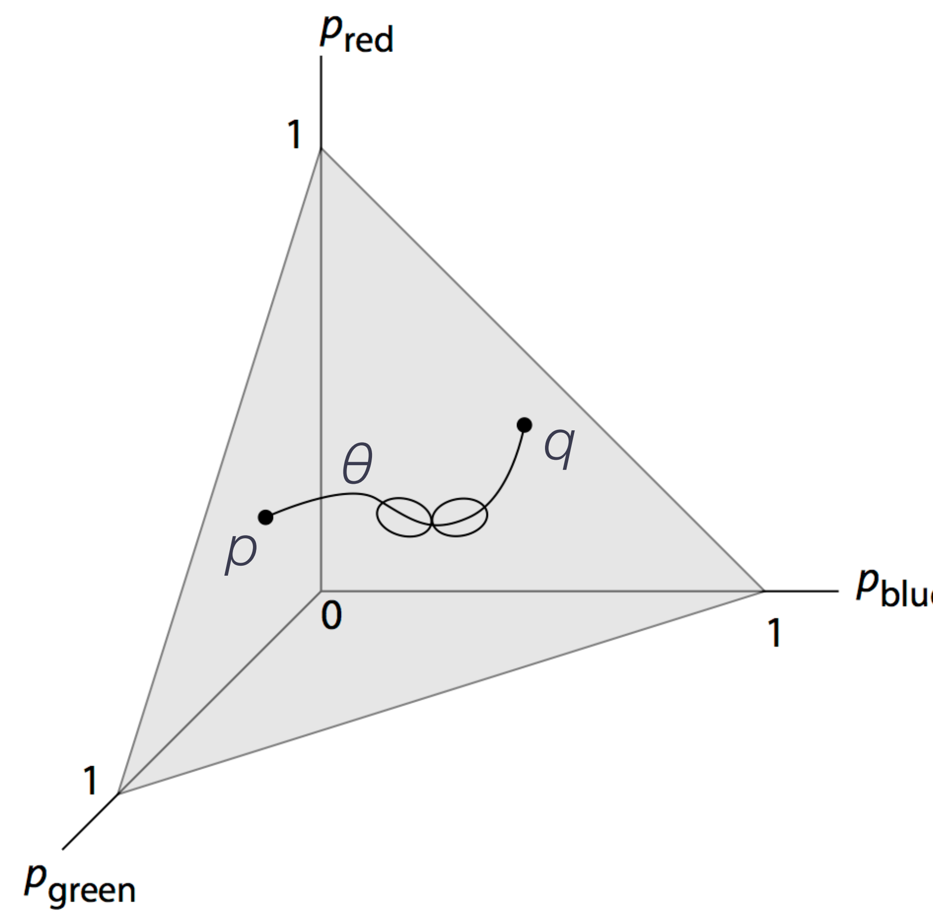
- The *statistical distance* in the probability space:

$$ds^2 = \sum_{\mathbf{x}} \frac{dp(\mathbf{x}|\theta)^2}{p(\mathbf{x}|\theta)}$$

- The threshold for distinguishing the probability distributions is:

$$N\delta s^2 \geq 1$$

- The Fisher information *I* is the speed squared along the curve (with *θ* playing the role of proper time).

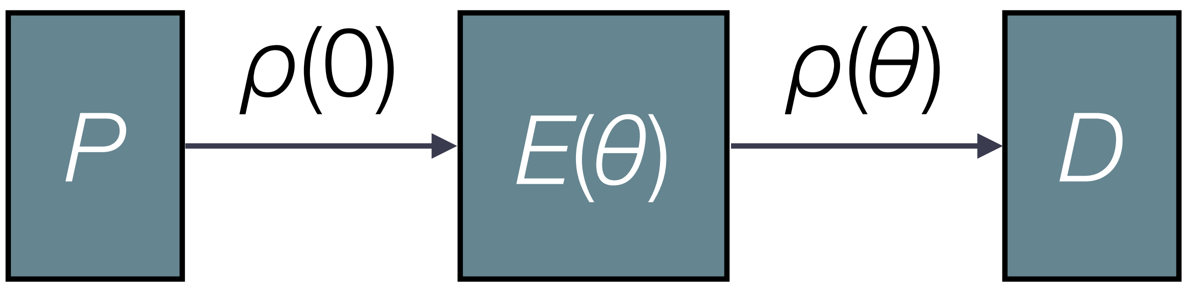


$$\boxed{I(\theta) = \left(\frac{ds}{d\theta}\right)^2}$$

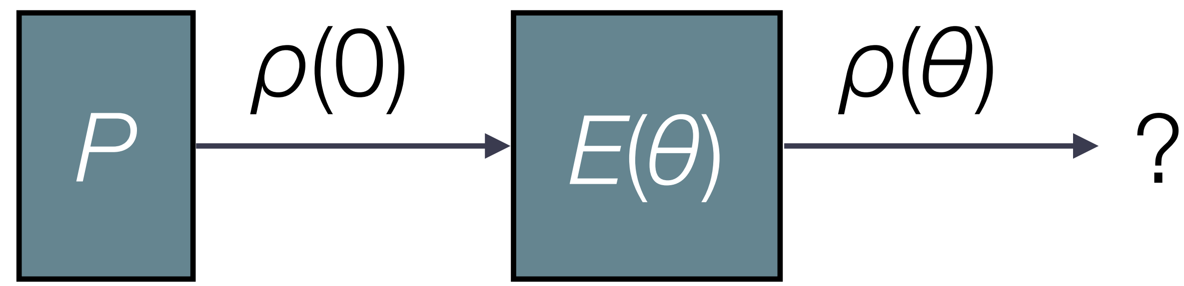
Example:
“*A stopped clock gives the right time twice a day*.”

- The probability distribution of the measurement (i.e., time readout) does not depend on time (here $\theta = t$).
- Therefore, $ds/d\theta = 0$, and the Fisher information is zero.
- Conclusion: a stopped clock cannot be used to tell time accurately!

The difference between classical & *quantum* Fisher information is measurement optimality.



- We have a probability distribution from the measurement procedure.
- The Fisher information is based directly on this distribution.



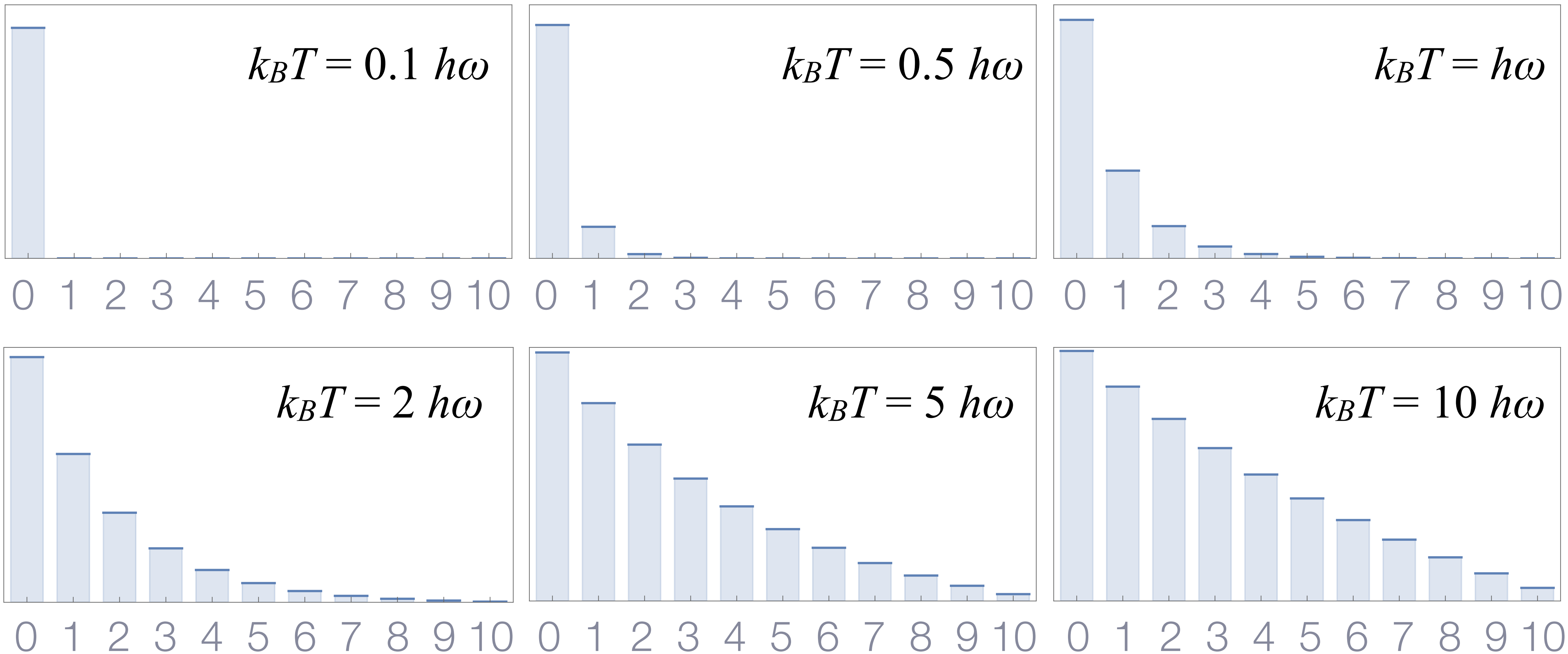
- Optimise over all possible quantum measurements.
- What is the maximum Fisher information?
- This is called the *quantum Fisher information*.

Both classical and quantum Fisher information can be used for classical *and* quantum experiments!

Classical Fisher information:
what we have in our experiment

Quantum Fisher information:
what Nature allows us to extract
(can be calculated from the quantum state directly)

Astronomy: What are we dealing with?
Probabilities of photon numbers in thermal states

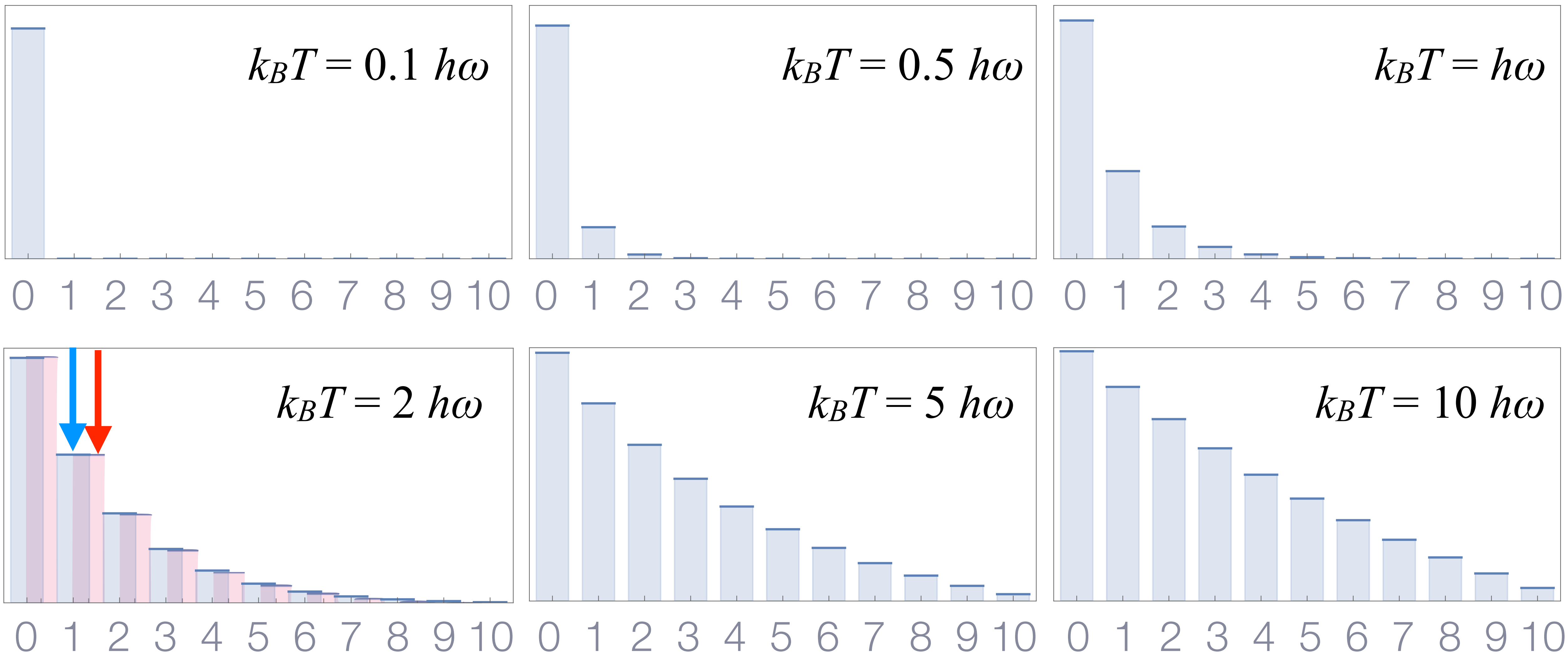


Intensity interferometry

Amplitude interferometry

Single mode
in the receiver

The effect of multiple modes on $g^{(2)}$



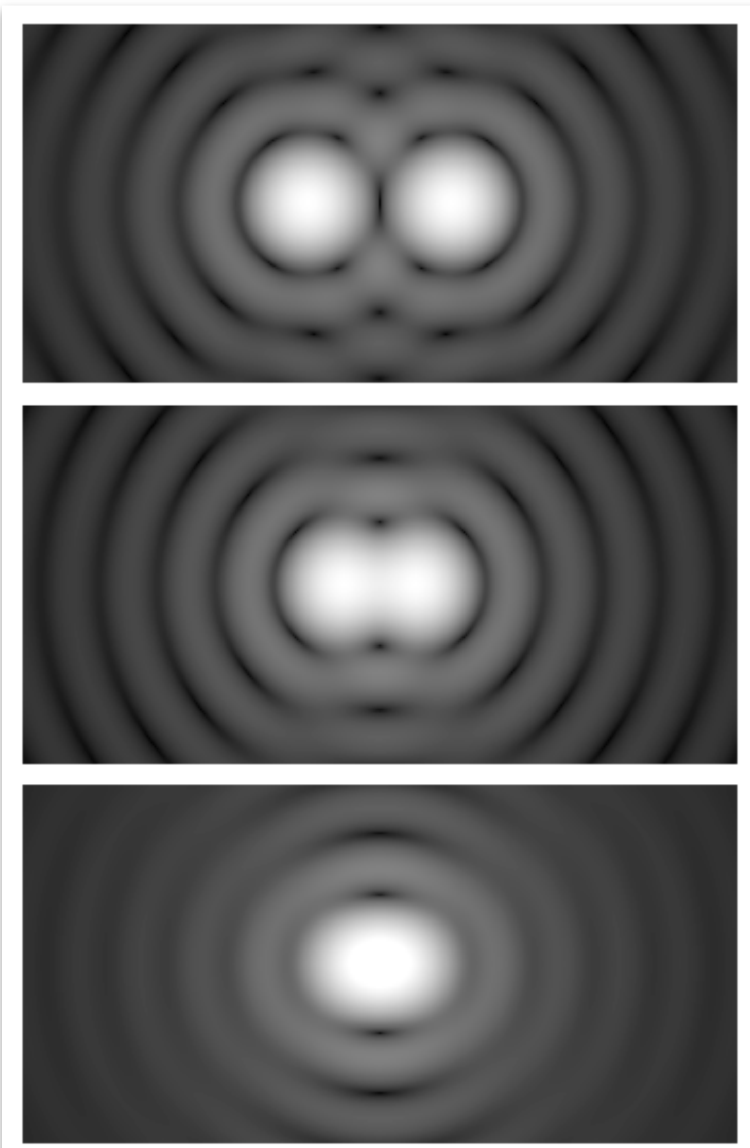
- two photons from different modes also trigger the two-photon detection signature → reduced $g^{(2)}$.

Main question: what is the best instrument to extract spatial information from thermal sources?

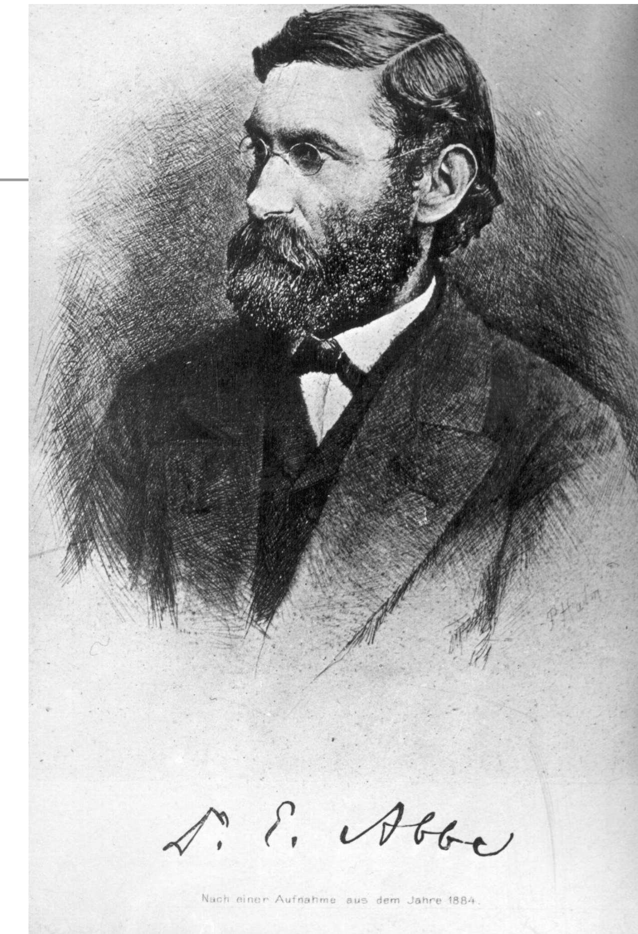
- We need to design instruments that measure the observables that are optimal, i.e., approach the *quantum* Fisher information.
- Compare the classical and quantum Fisher information for amplitude interferometry with single-photon states;
- Compare this with the Fisher information for intensity interferometry (i.e., two-photons);
- What about higher order correlation functions?

The Abbe diffraction limit

Minimum resolvable distance between two dots.



Not optimal!
(CFI < QFI)



1840 – 1905

co-worker
of
Carl Zeiss

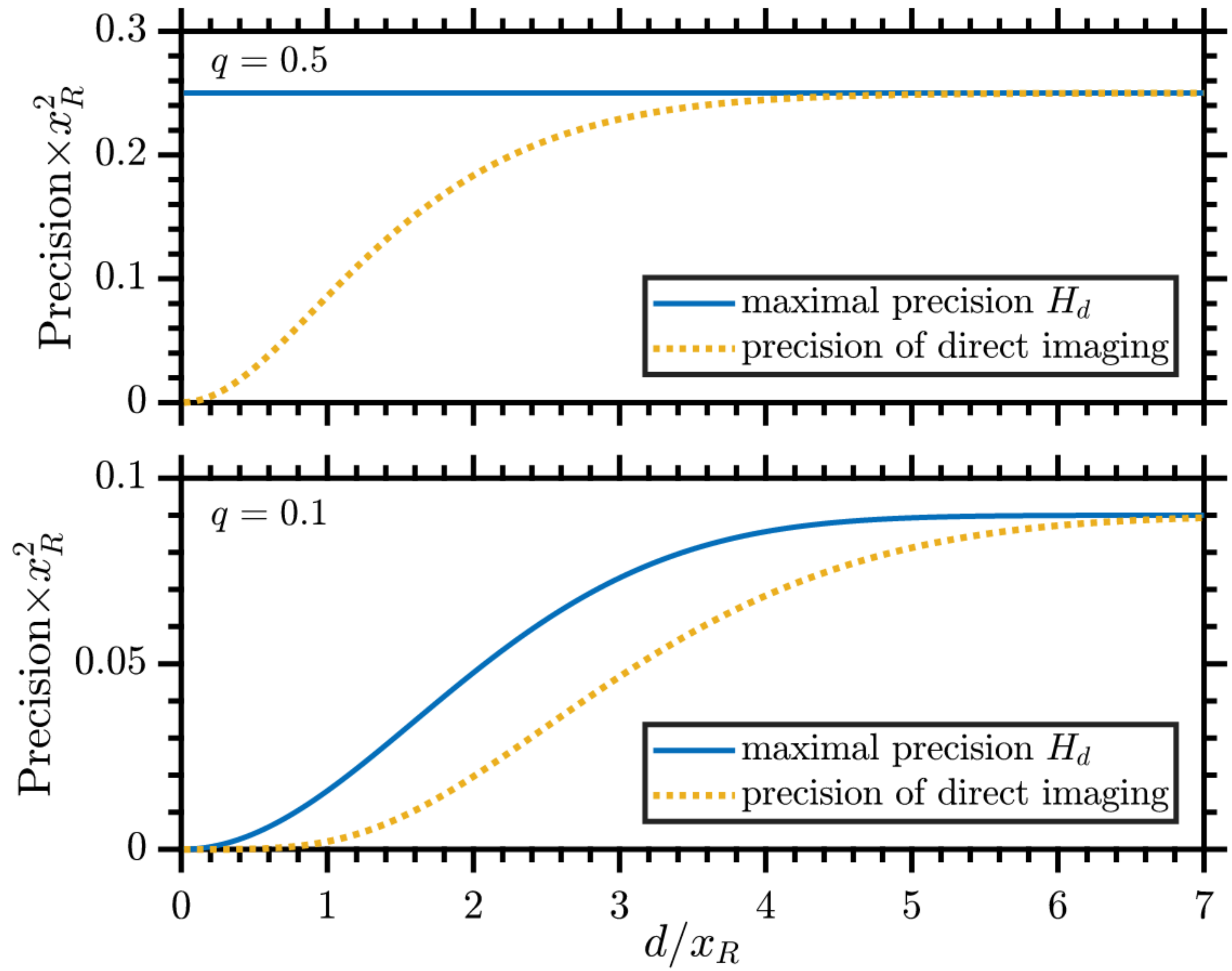
We can construct an interferometer that beats the Abbe limit—if we can find the right observable.

- In principle, we can measure *any* separation $s > 0$, even if it is much smaller than the Abbe limit.
- For small s: $\psi(x \pm \frac{1}{2}s) \simeq \psi(x) \pm \dfrac{s}{2}\dfrac{\partial\psi(x)}{\partial x}$
- Derivatives of Gaussians generate orthonormal functions.

Nair & Tsang, *Phys. Rev. Lett.*, **117**, 190801 (2016).

“Unlimited” super resolution?

- Sadly, no.
- This argument requires that the two sources are *exactly* equal in brightness.
- Here, *q* is the fraction of a single source’s intensity.



Large baseline telescopes with single-photons

Consider single-photon imaging

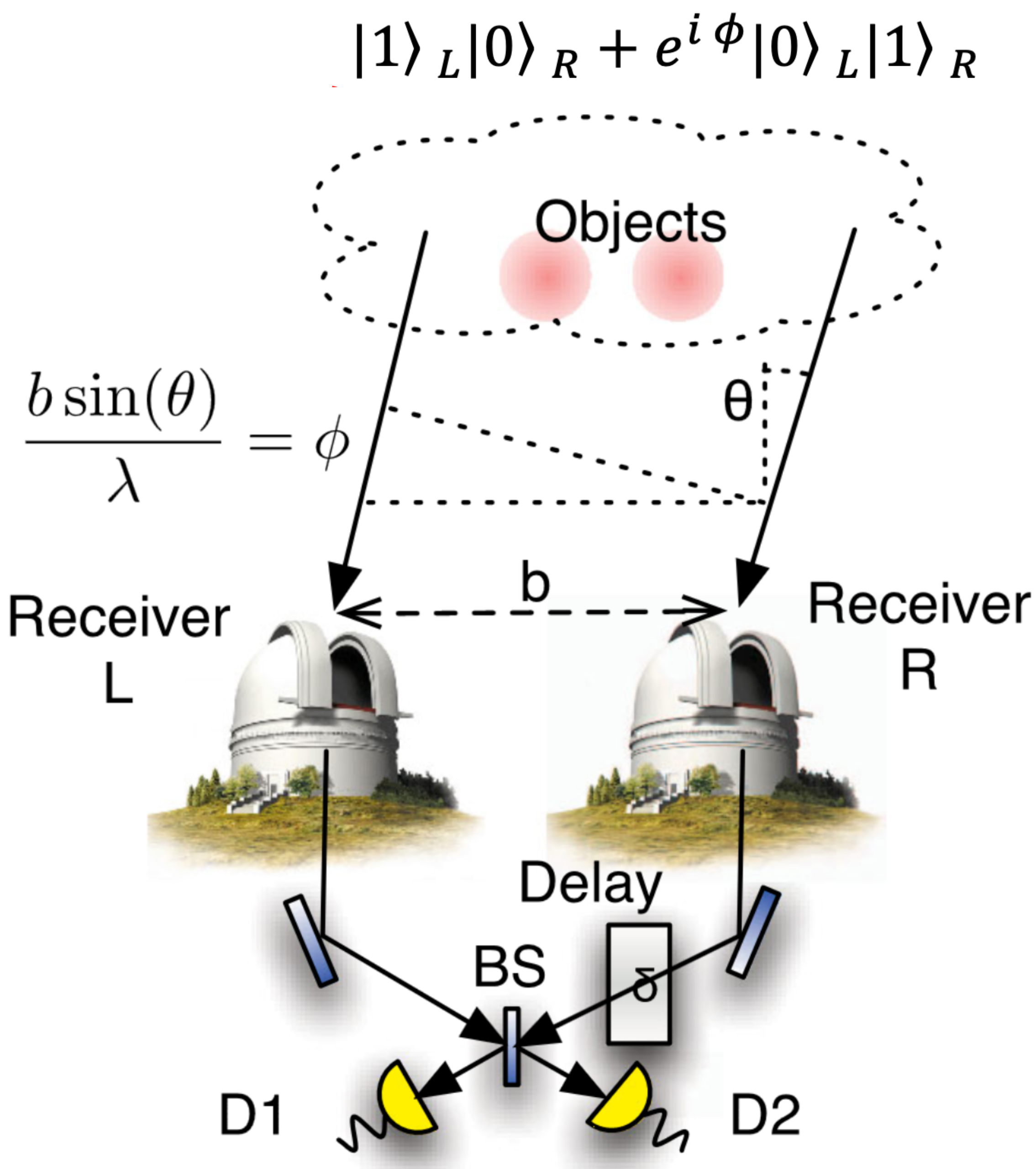
$$\rho = \frac{1}{\mathcal{Z}} \sum_{n=0}^{\infty} \mathrm{e}^{-n\hbar\omega/k_{\mathrm{B}}T} \left|n\right\rangle \left\langle n\right| \approx (1-\epsilon)\left|0\right\rangle \left\langle 0\right| + \epsilon \left|1\right\rangle \left\langle 1\right|$$

- We neglect higher-order terms in the photon number expansion of the single mode thermal state.

- Due to transverse coherence, a single photon will be in a superposition of going to two telescopes:

$$|1\rangle_L |0\rangle_R + e^{i\phi} |0\rangle_L |1\rangle_R$$

Measuring the position of a thermal point source, one photon at a time



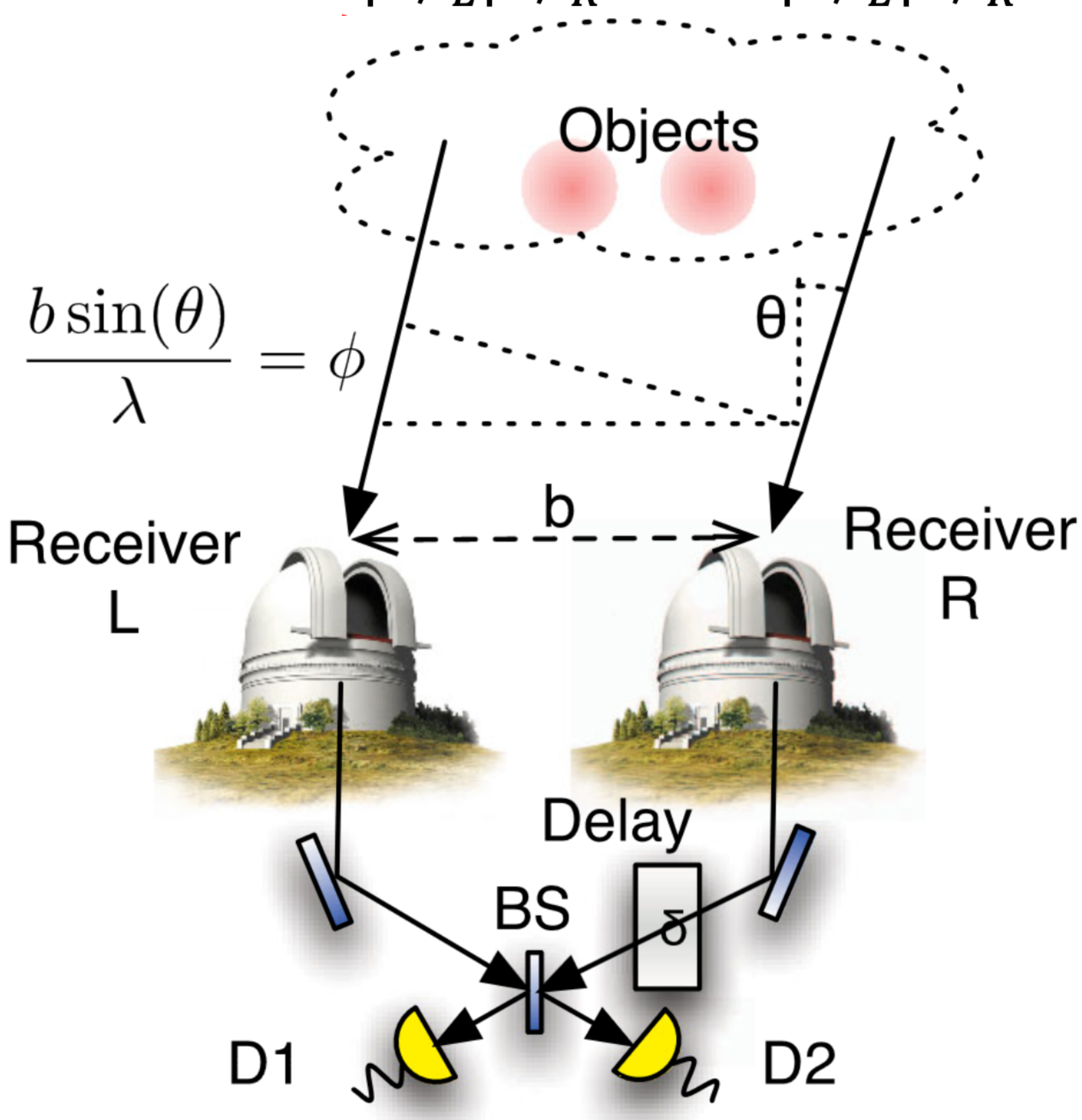
$I_Q(\varphi) = 1$

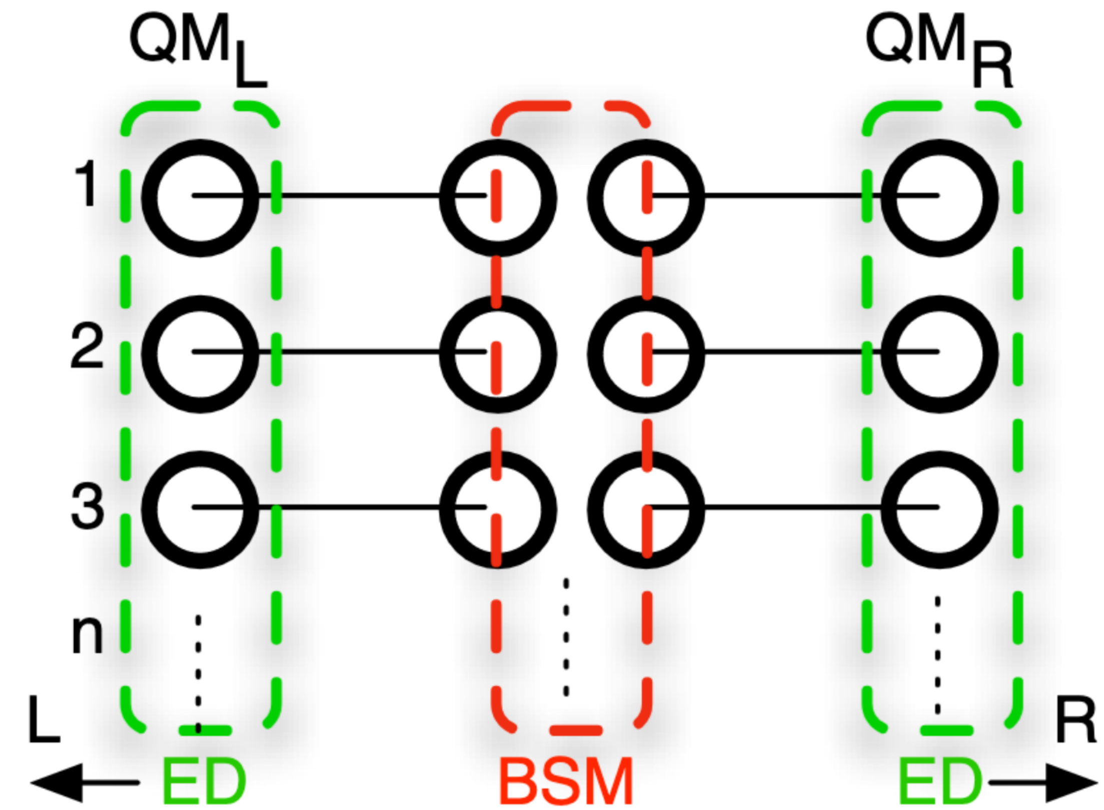
- If the single photon can interfere with itself on a 50:50 beam splitter, the classical Fisher information is also 1.
- Large baseline = photon loss

Gottesman, Jennewein & Croke, *Phys. Rev. Lett.* **109**, 070503 (2012).

Quantum Telescopes using Quantum Repeaters

$|1\rangle_L|0\rangle_R + e^{i\phi}|0\rangle_L|1\rangle_R$

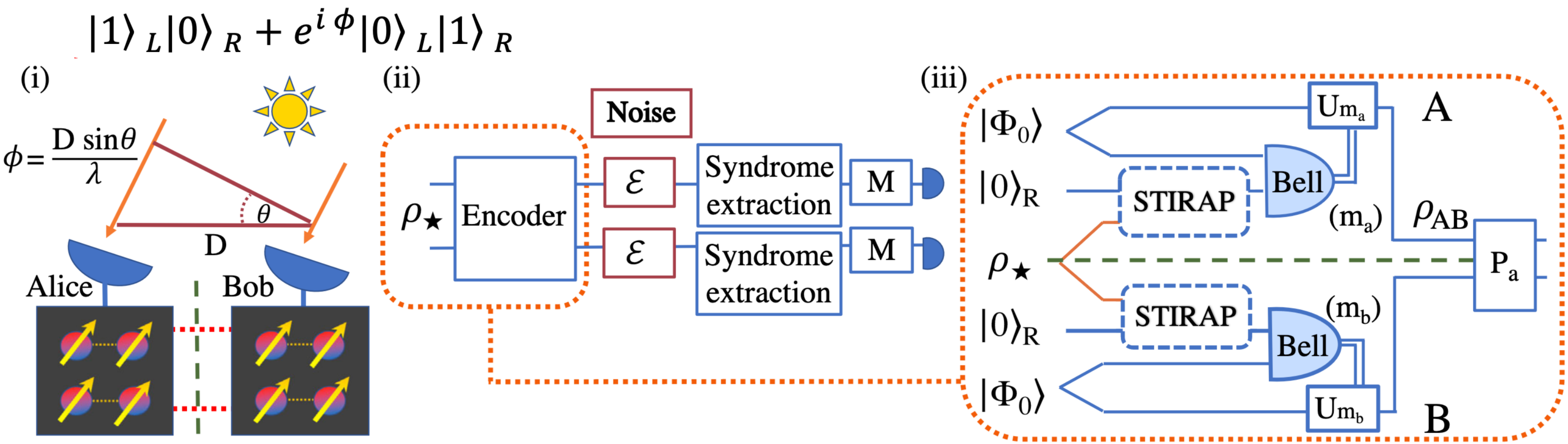




requires quantum memories

Gottesman, Jennewein & Croke, *Phys. Rev. Lett.* **109**, 070503 (2012).

Quantum Imaging using Quantum Error Correction

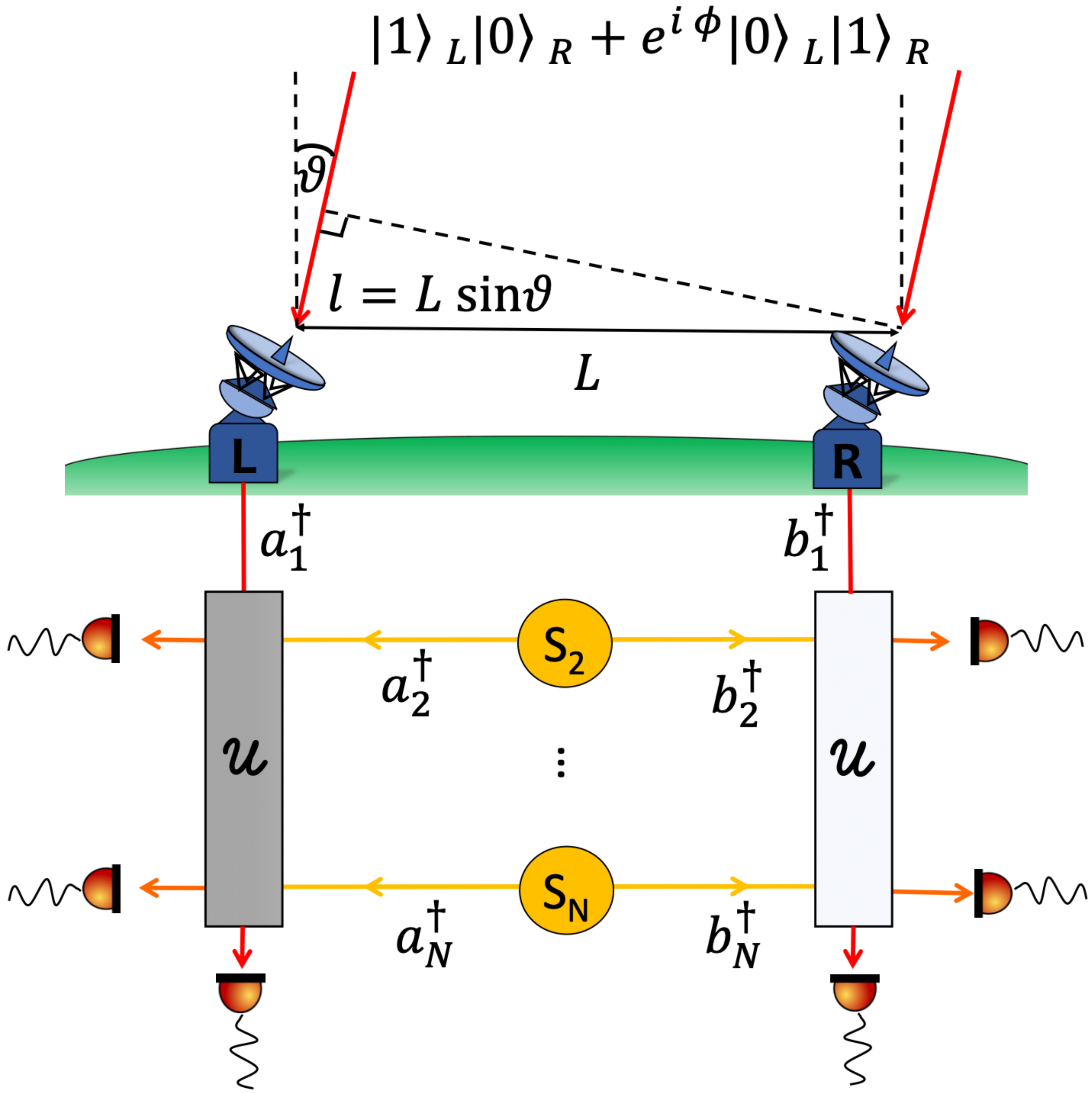


Coherent capture of a photon into a non-radiative atomic state using STIRAP to avoid optical decay

QEC designed for dephasing and amplitude damping protects the phase φ

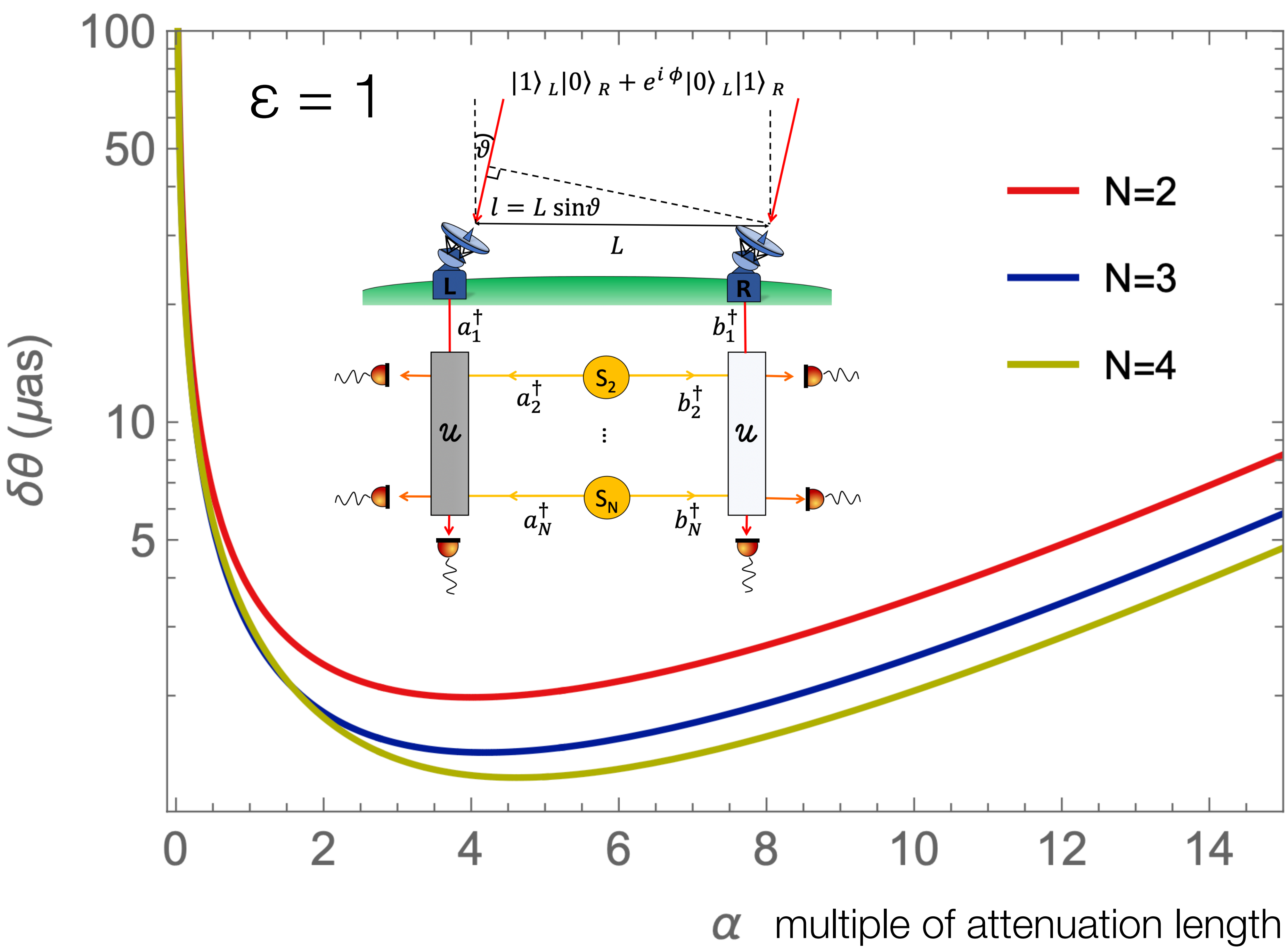
Huang, Brennan & Ouyang, *Phys. Rev. Lett.* **129**, 210502 (2022).

How can we create large baseline telescopes without quantum repeaters, memories and QEC?



M. Marchese & P. Kok, *Phys. Rev. Lett.* **130**, 160801 (2023).

Resolution for 2, 3, 4 photons against baseline αL_0

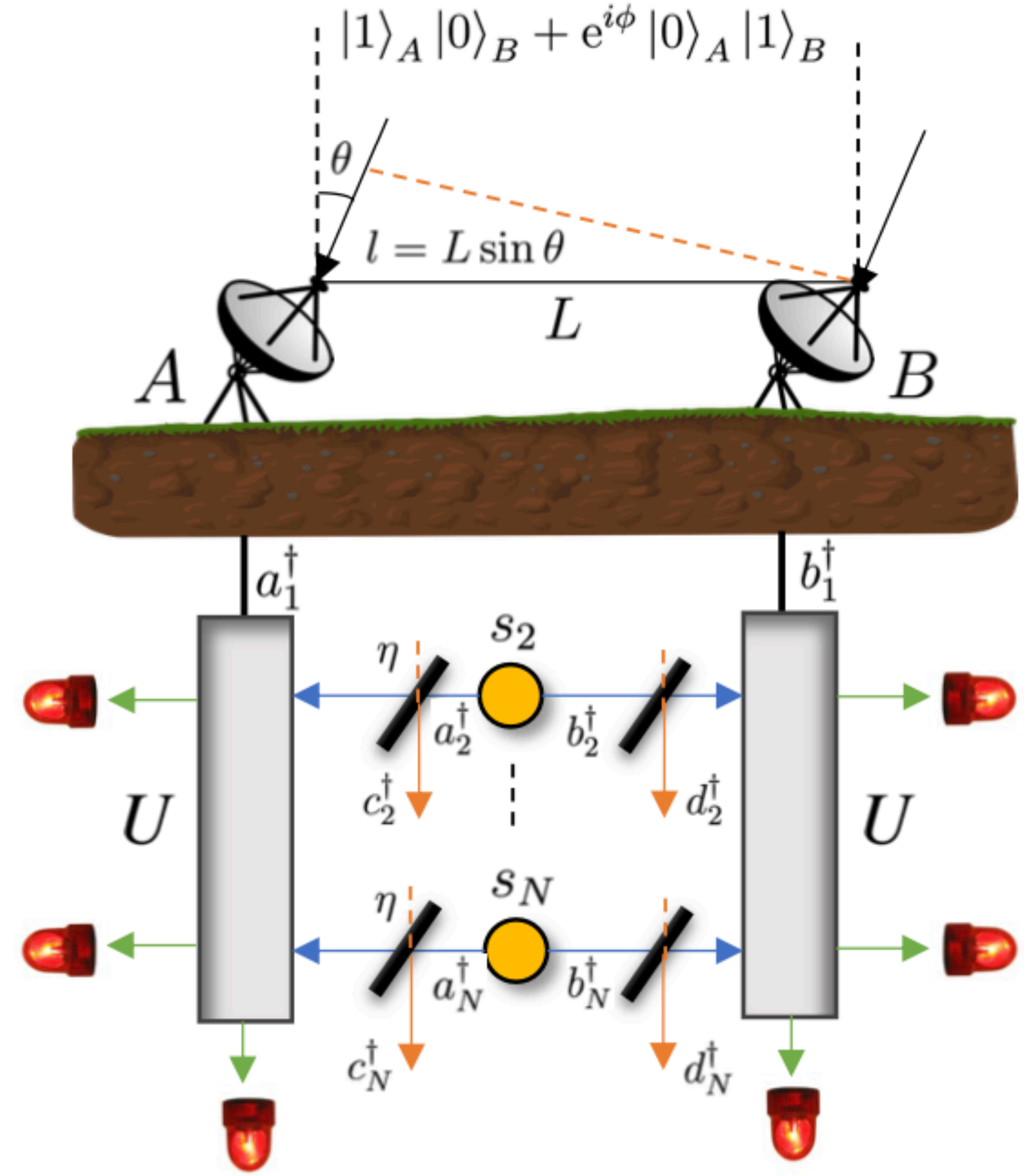


lower is better

M. Marchese & P. Kok, *Phys. Rev. Lett.* **130**, 160801 (2023);

What about low ε and partially distinguishable photons?

ε	N; $\mathscr{I}$%	$\delta\theta_{\min}(\mu\text{as})$	α_{opt}
	2; 100	2.030	4
0.99	3; 96	1.468	4.192
	3; 50	2.033	4.098
	3; 25	2.830	4.050
	2; 100	3.999	4
0.5	3; 96	2.3030	4.8911
	3; 50	3.1456	4.7868
	3; 25	4.2040	4.4409
	2; 100	19.980	4
0.01	3; 96	34.272	2.0732
	3; 50	43.449	2.0621
	3; 25	57.230	2.1542

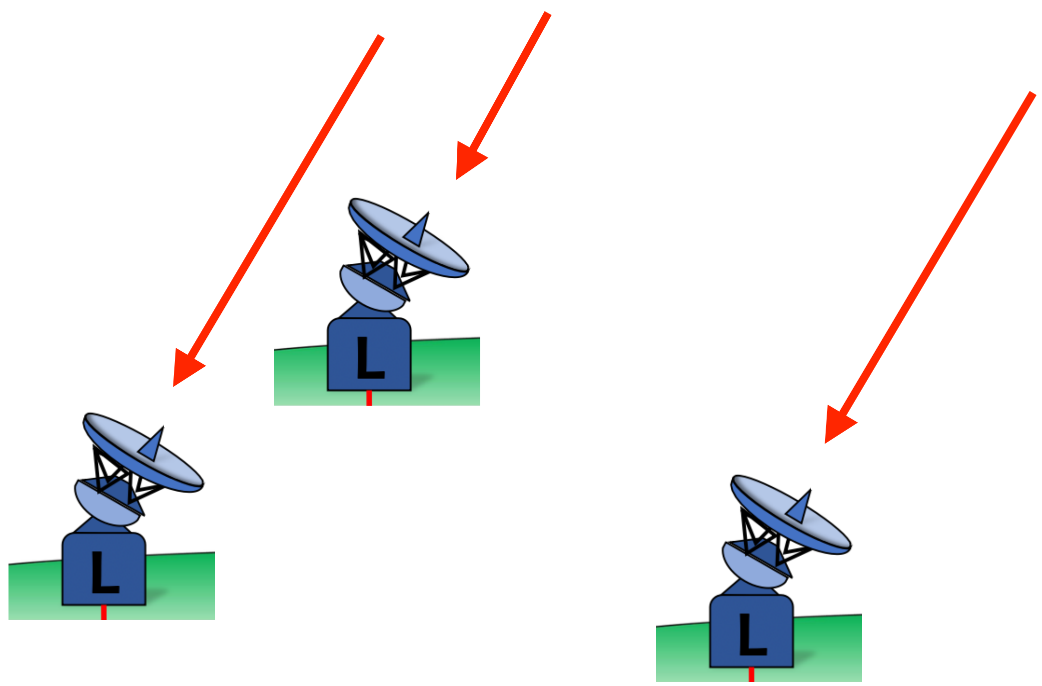


S. Modak & P. Kok, *Phys. Rev. A.* **111**, 043701 (2025).

2D positioning in the sky

- We need at least three telescopes to estimate two angles.

$$|1,0,0\rangle + e^{i\phi_1}\,|0,1,0\rangle + e^{i\phi_2}\,|0,0,1\rangle$$



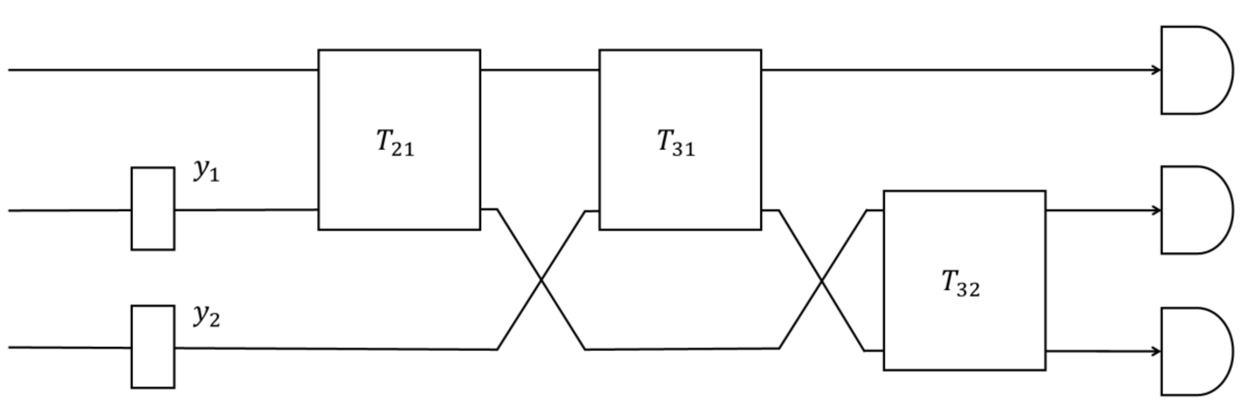
- The multi-parameter quantum Cramér-Rao bound is generally not saturable due to incompatibility of the optimal measurements for ϕ_1 and ϕ_2.

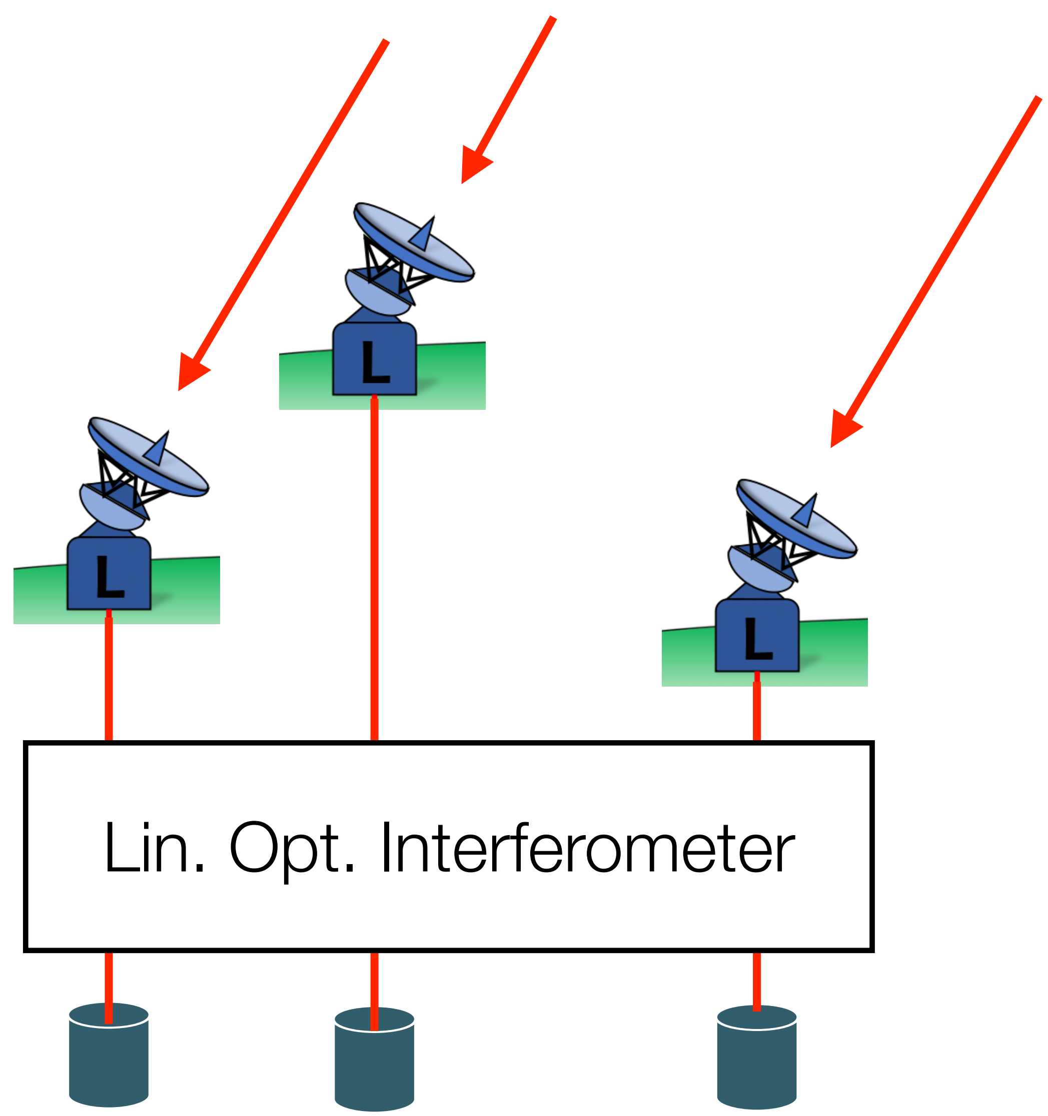
A. Cullen, C Morrison & P. Kok, *in preparation* (2025).

Sending / teleporting the star photon into a three-mode interferometer is optimal.

- For a single photon, the 2D position maps onto two relative phases in a three-mode interferometer.
- We optimised the interferometer over the classical Fisher info., and found it equal to the QFI matrix.
- Hence, this method is optimal.

$$|1,0,0\rangle + e^{i\phi_1}|0,1,0\rangle + e^{i\phi_2}|0,0,1\rangle$$



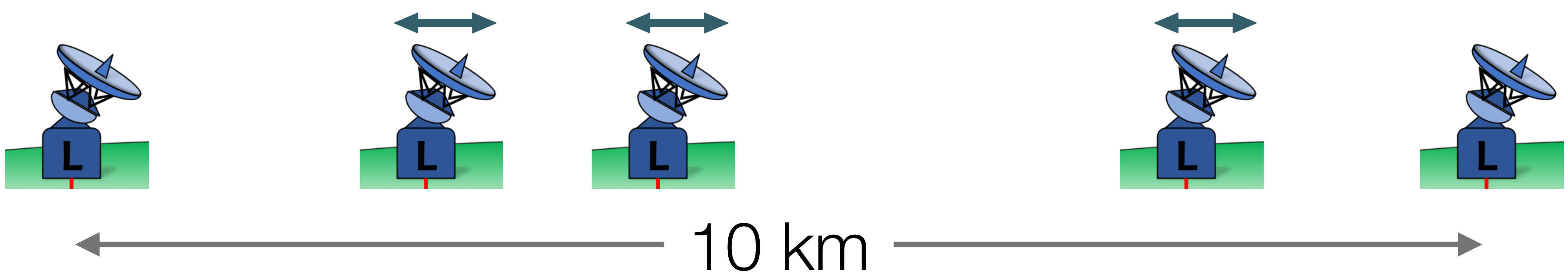


A. Cullen, C Morrison & P. Kok, *in preparation* (2025).

Quantum Fisher information
for intensity interferometry

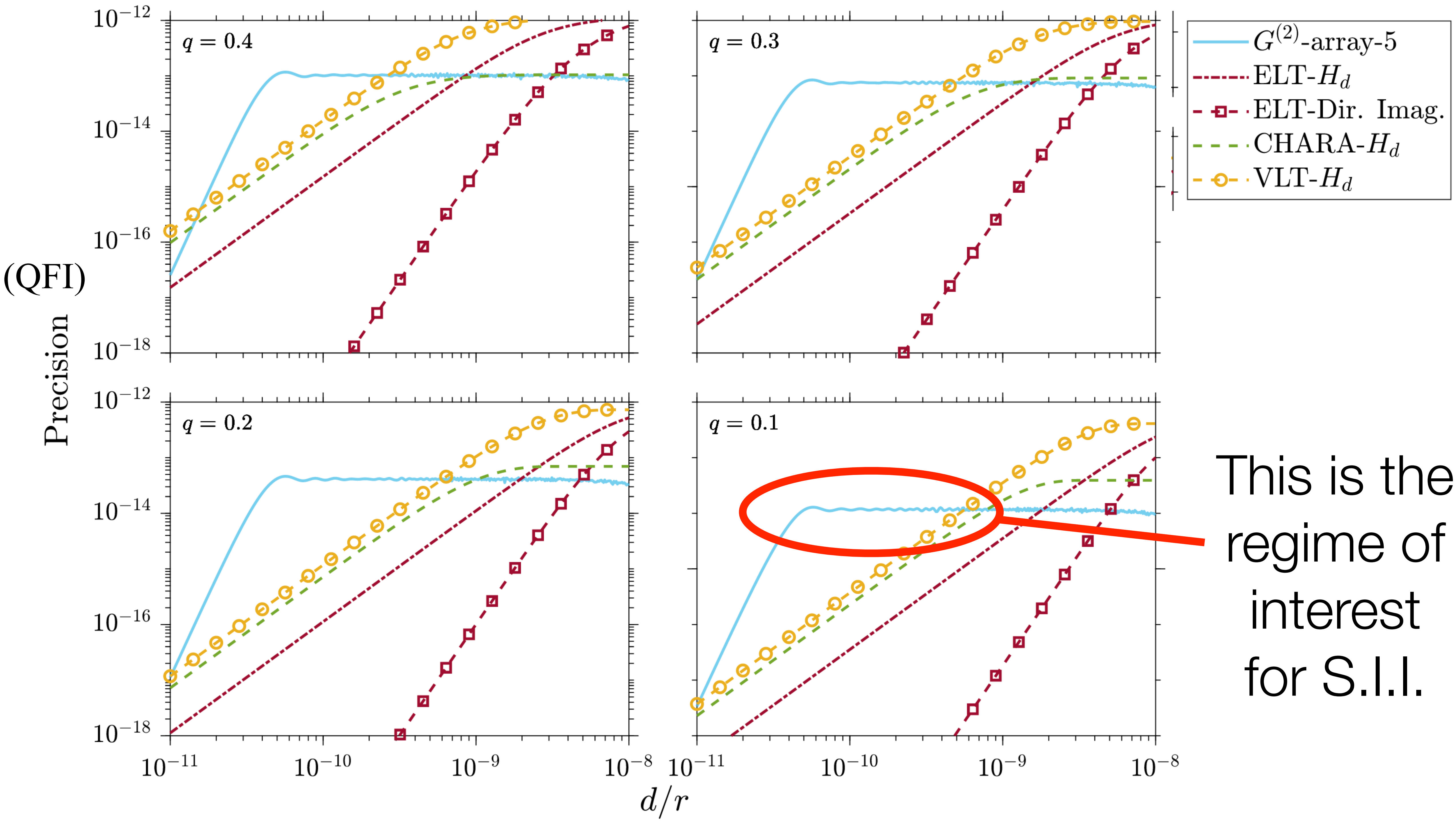
Classical Fisher information for measuring source separation

- N=100 10 m telescopes at D different positions (no AO)
- Max baseline of 10 km, groups of 5 detectors at 20 locations
- source brightness ratio is q = 0.2.



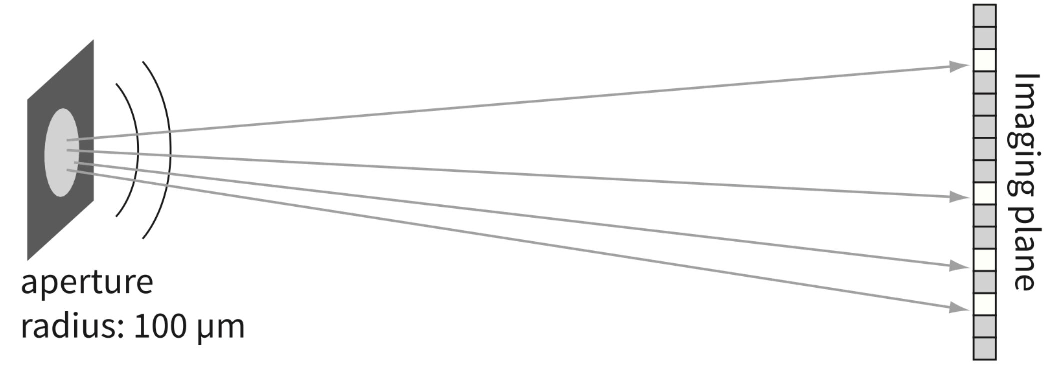
Bojer *et al.*, *New Journal of Physics* **24**, 043026 (2022).

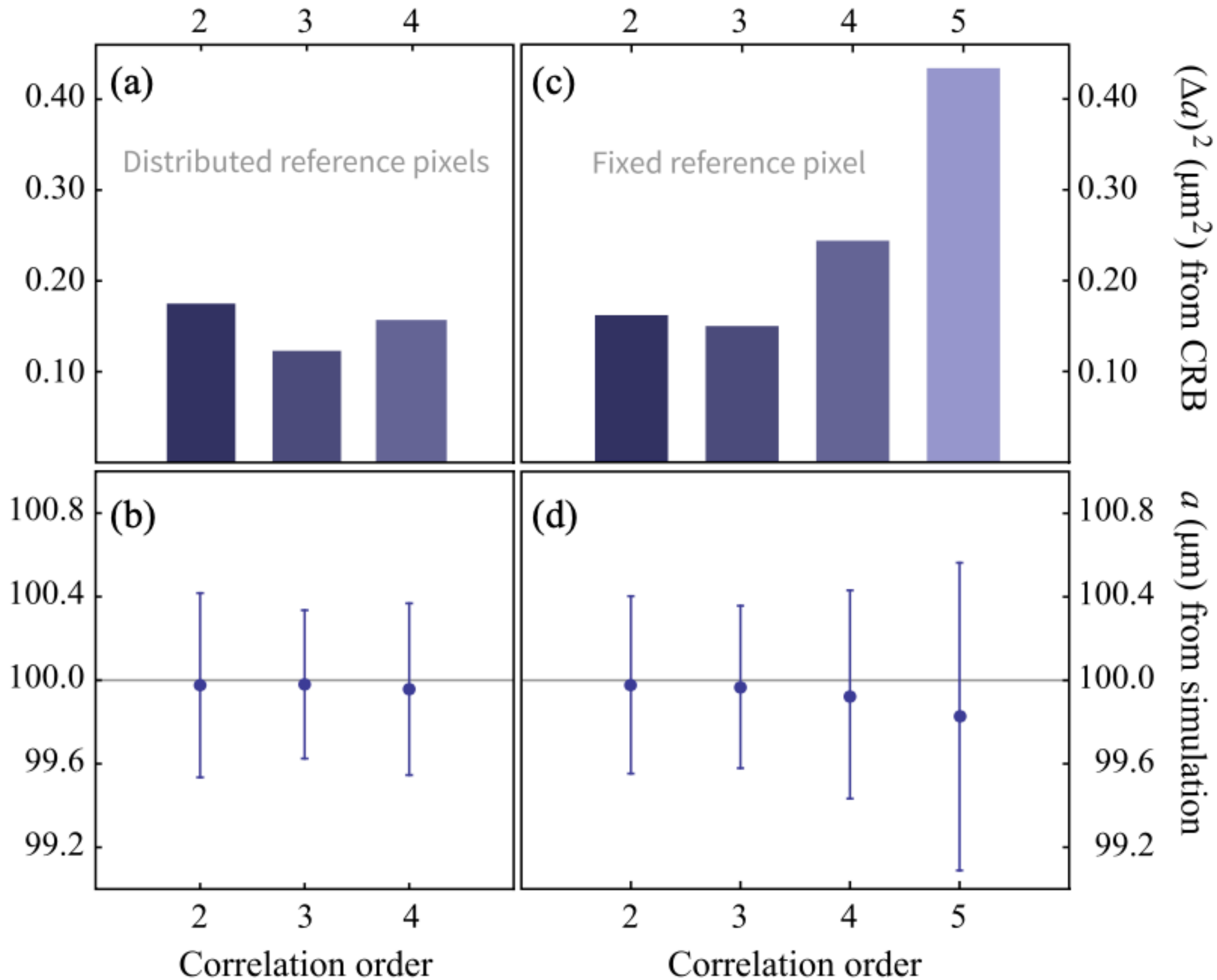
A comparison of intensity interferometry to large baseline astronomical telescopes



Bojer *et al*., *New Journal of Physics* **24**, 043026 (2022).

Higher-order correlations



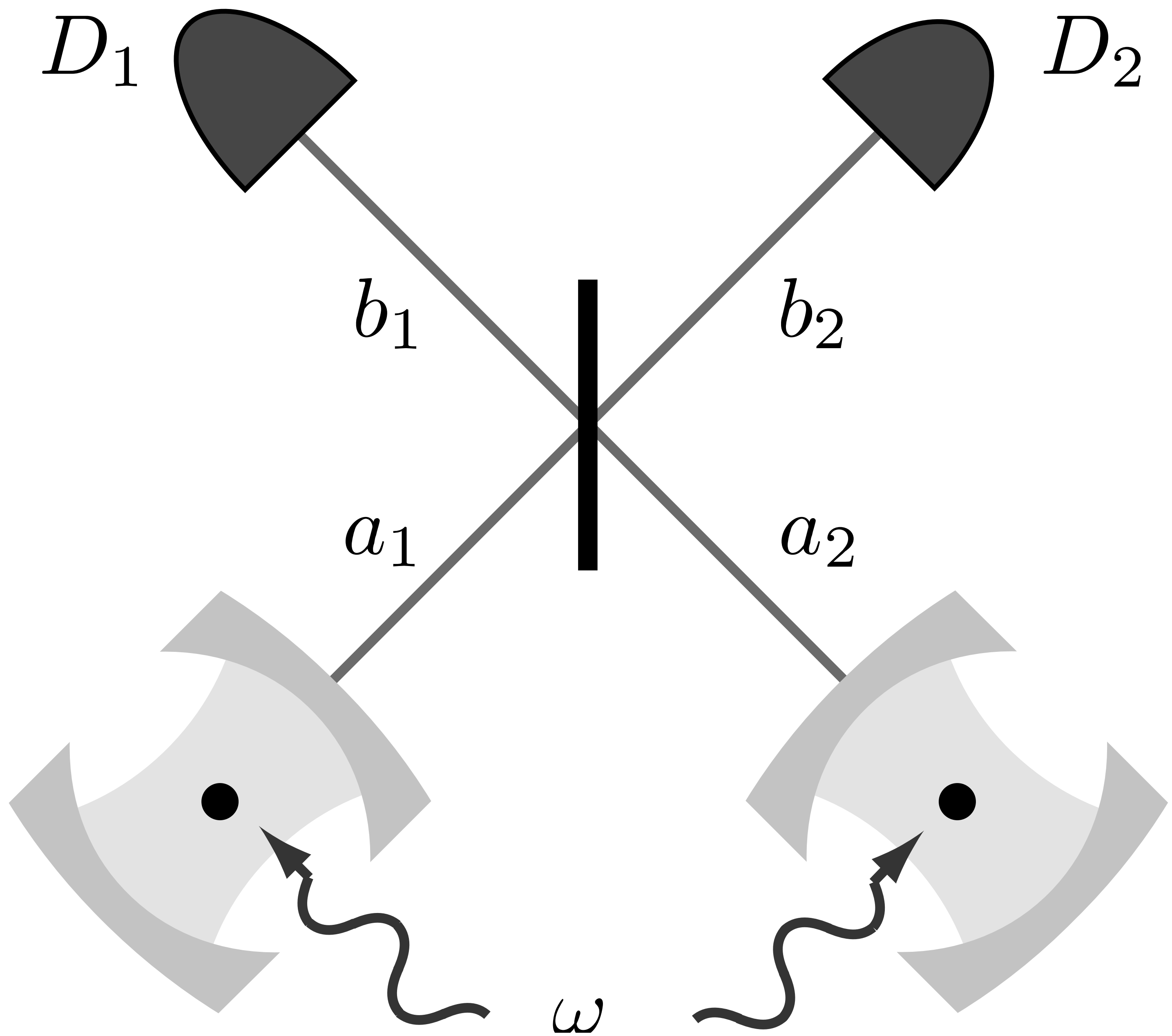


Pearce *et al.*, *Phys. Rev. A* **92**, 043831 (2015).

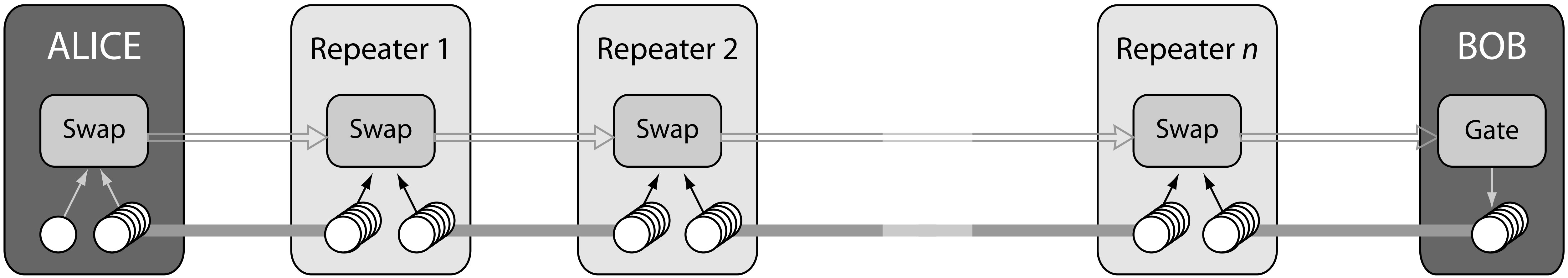
Going beyond…

Constructing a Quantum Repeater Network

Entanglement through path erasure



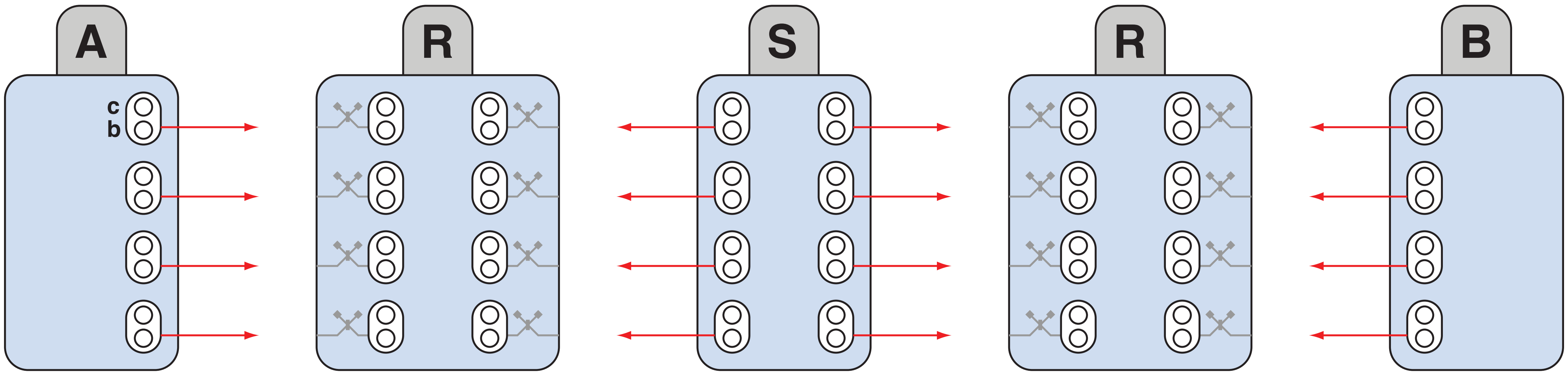
Repeaters for quantum communication



- High secret bit rate at large distances
- Low complexity at the stations
- Minimal classical communication between stations.

The Repeater Protocol: Step 1

1)



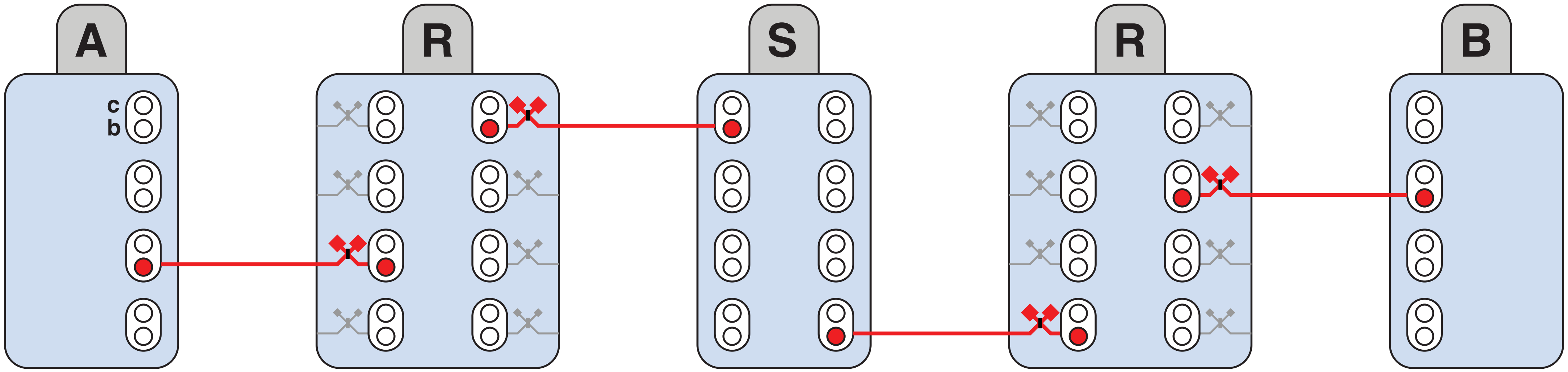
- The sender stations **S** (and in this case Alice and Bob) send photons to the receiver stations in **two** rounds to attempt a double-heralding entanglement preparation.

- Locally in both the **S** and **R** stations, the photons are entangled with a solid state system that holds two qubits; a client (**c**) and a broker (**b**).

Vinay and Kok, arXiv:1607.08140 (2016).

The Repeater Protocol: Step 2

2)

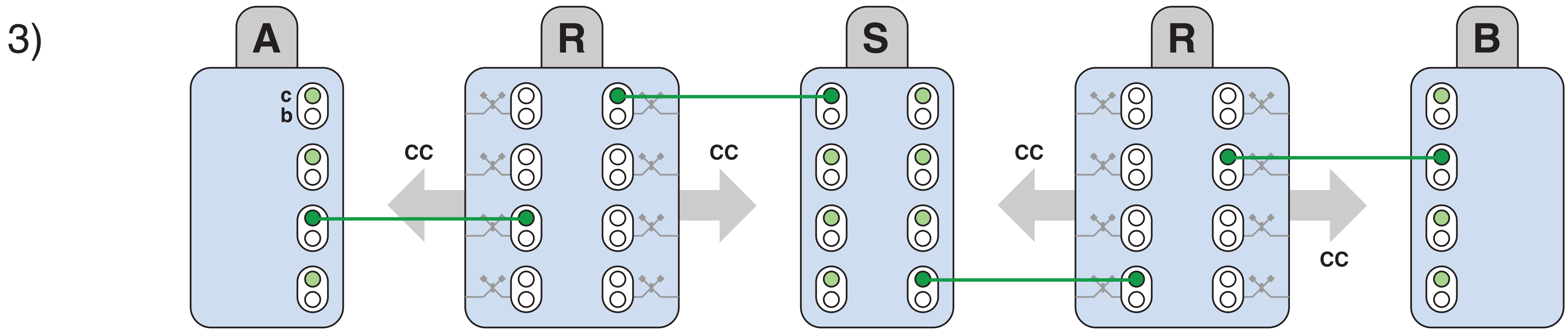


- The **R** stations determine which of their qubits have been successfully entangled with qubits in the **S** stations.

- The **S** stations do not know which entanglement procedures have been successful at this point.

Vinay and Kok, arXiv:1607.08140 (2016).

The Repeater Protocol: Step 3



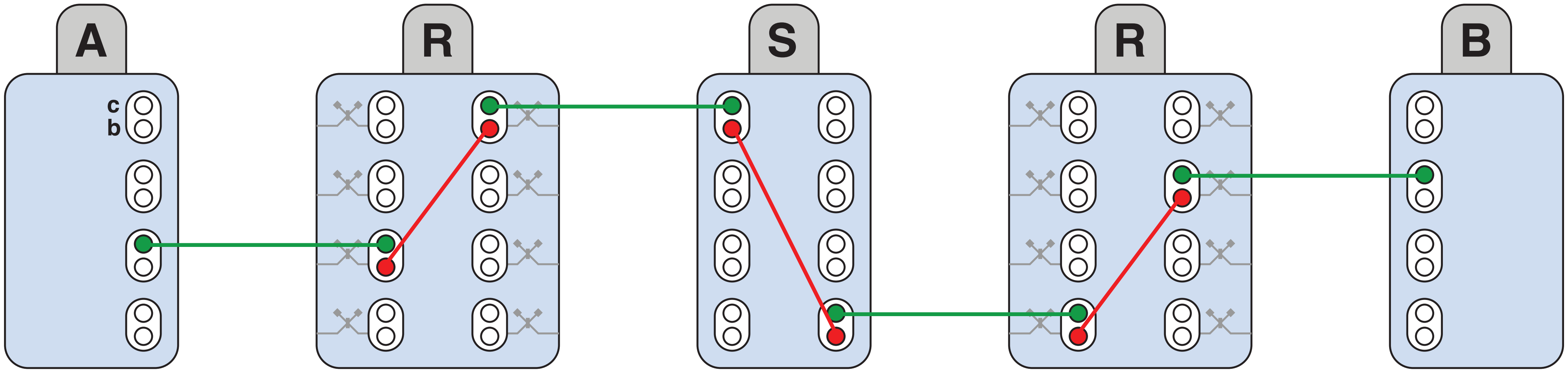
- Immediately after the double-heralding protocol, both the **R** and **S** stations map the broker qubits to the client qubits, which have much longer coherence time. The **S** stations are still flying blind.

- The R stations send a message to the *nearest* **S** stations about which of their qubits are entangled.

Vinay and Kok, arXiv:1607.08140 (2016).

The Repeater Protocol: Step 4

4)

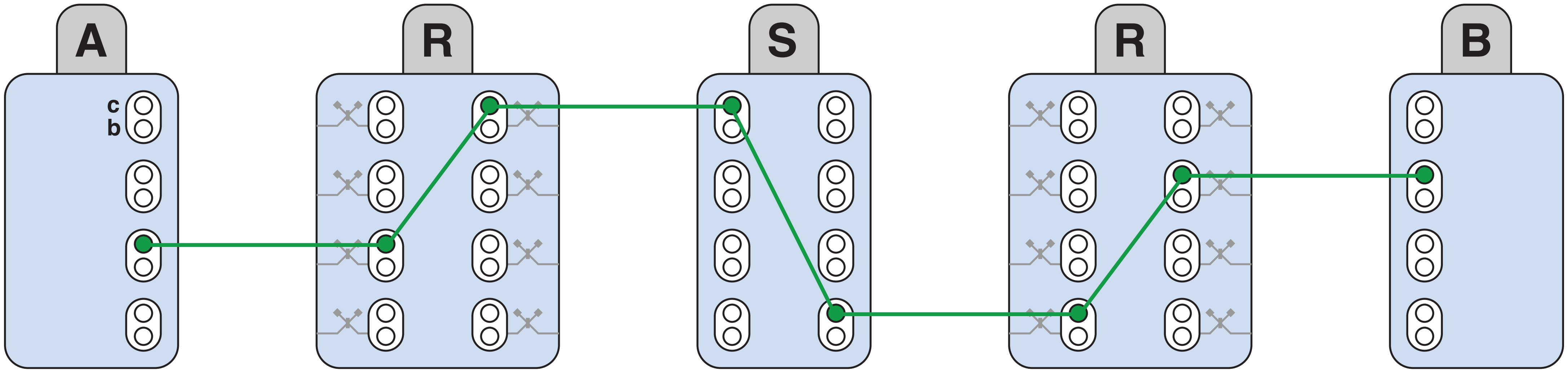


- After this short-range classical communication, both the **S** and **R** stations can now entangle the qubits that would complete the chain.
- By using the broker qubits, double-heralding is effectively nearly always successful.

Vinay and Kok, arXiv:1607.08140 (2016).

The Repeater Protocol: Step 5

5)

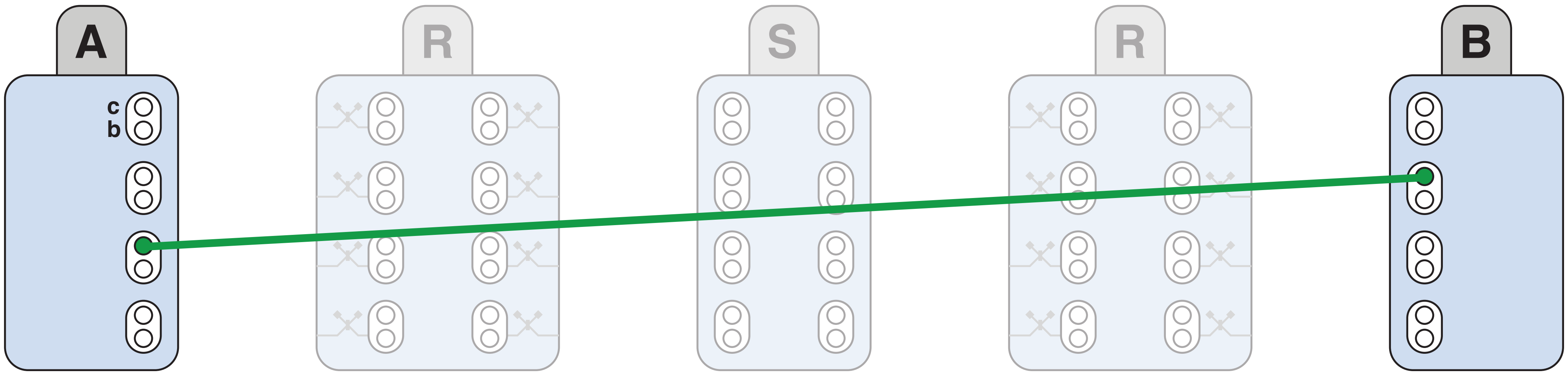


- Local deterministic CNOT operators on the two-qubit solid state systems will now create the complete chain.

Vinay and Kok, arXiv:1607.08140 (2016).

The Repeater Protocol: Step 6

6)



- All the **R** and **S** stations measure their qubits in such a way that takes them out of the linear cluster chain, effectively performing entanglement swapping.
- Alice and Bob now hold a maximally entangled state, provided the learn about the classical Pauli by-products generated in the qubit measurements.

Vinay and Kok, arXiv:1607.08140 (2016).

Distillation

- We have two pairs of imperfect entanglement in the state

$$\rho_W(x) = x \left|\Psi^+\right\rangle \left\langle\Psi^+\right| + \frac{1-x}{4}\, \mathbb{1}_4 .$$

Vinay and Kok, arXiv:1607.08140 (2016).

Distillation

- Create entanglement between A_1 and A_2, as well as B_1 and B_2 via double-heralding.

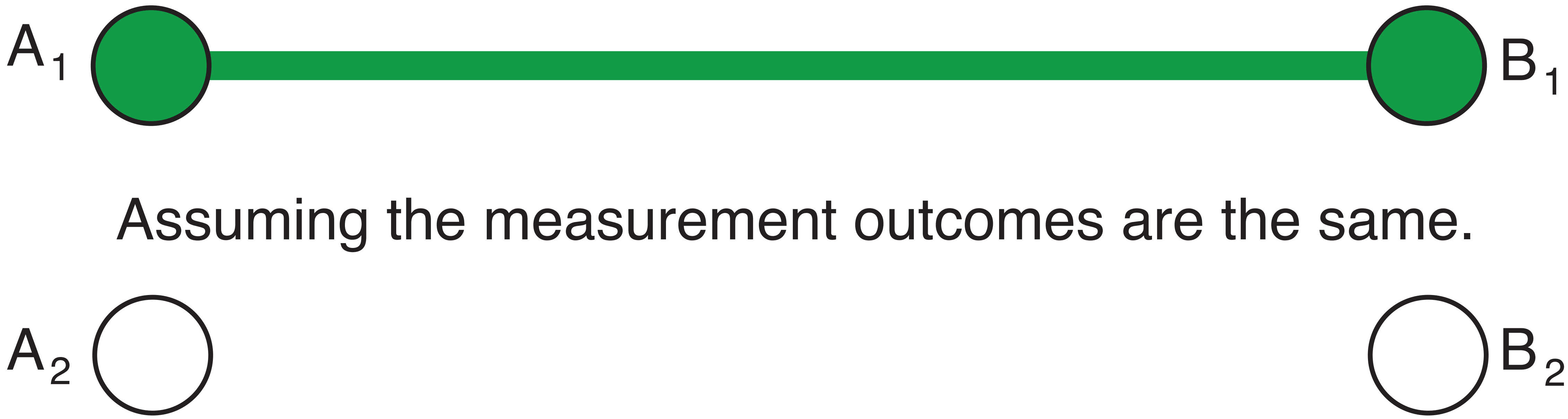
Vinay and Kok, arXiv:1607.08140 (2016).

Distillation

- Measure the target qubits A_2 and B_2.

Vinay and Kok, arXiv:1607.08140 (2016).

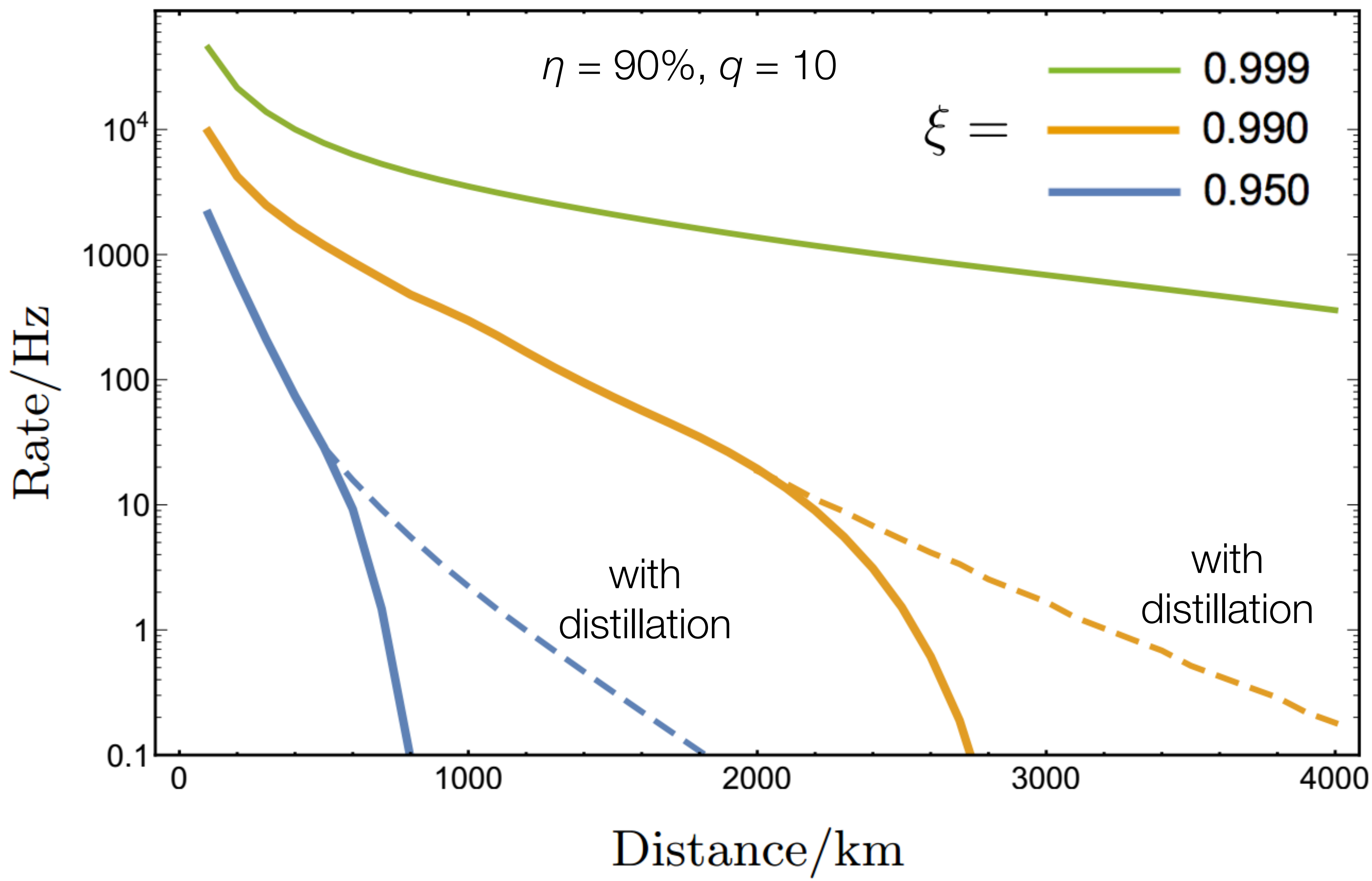
Distillation



- If the measurement outcomes are identical, then the pair A_1-B_1 is projected onto a maximally entangled state.
- This requires classical communication. Alice and Bob can *assume* all distillation works, and sort out the successful from the unsuccessful distillation in post-selection.

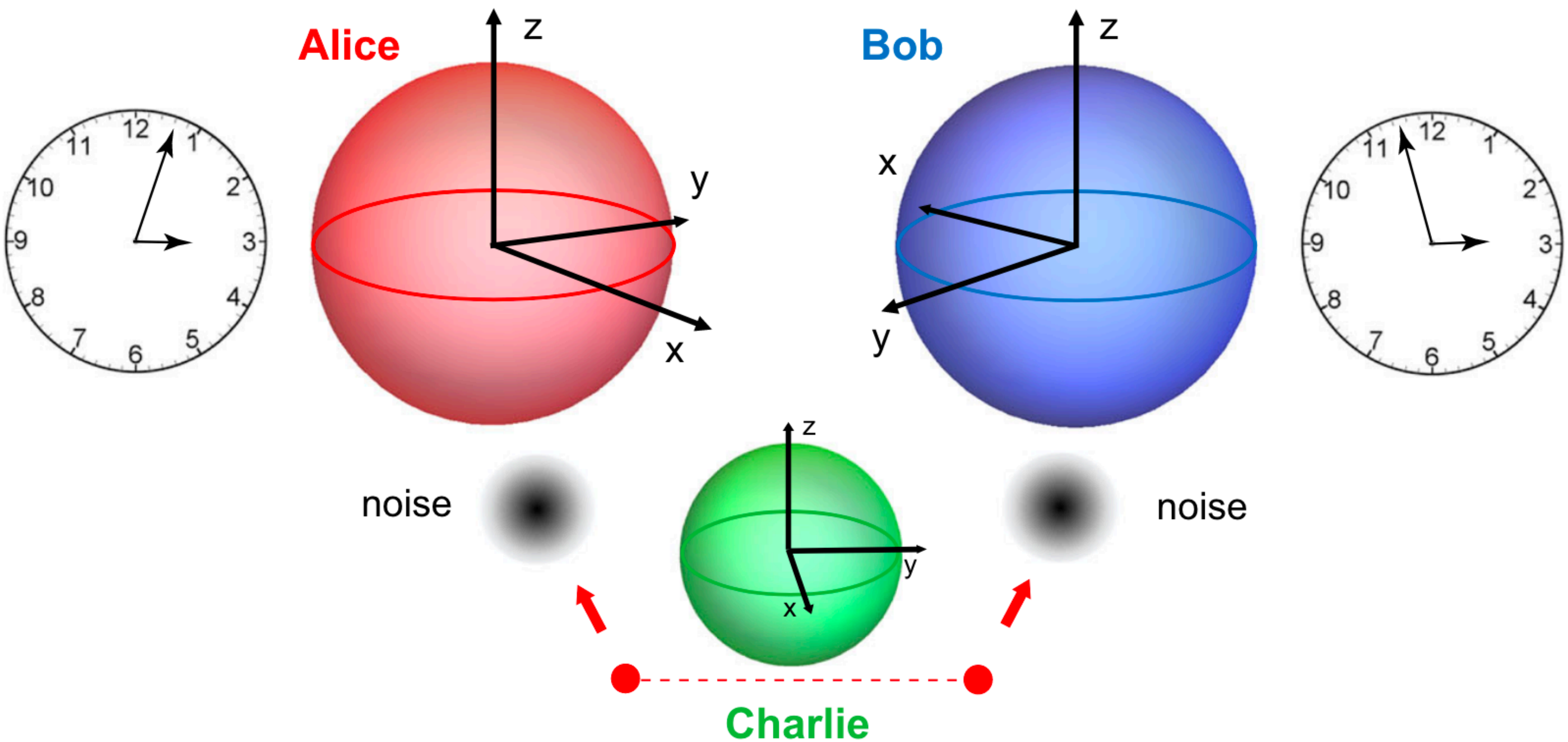
Vinay and Kok, arXiv:1607.08140 (2016).

The optimised range of the repeater protocol



Vinay and Kok, arXiv:1607.08140 (2016).

Quantum clock synchronisation



- We can use entanglement not only to synchronise clocks, but also to establish a common reference frame.

Ilo-Okeke et al, npj Quant. Inf. **4**, 40 (2018).

Conclusions

- We can rigorously compare the performance of astronomical instruments and their optimal operation in terms of the quantum and classical Fisher information.

- Quantum techniques allow us to go well beyond traditional imaging techniques, but at the cost of the complexity of the quantum instruments.

- Dramatic improvements are possible when quantum memories, repeaters and error correction become available.