Satellite-based quantum key distribution in the presence of bypass channels

QCrypt 2023

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August 2023

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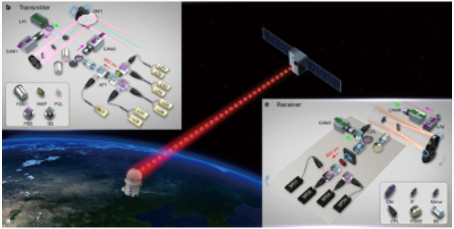
arXiv:2212.04807

Background and motivation

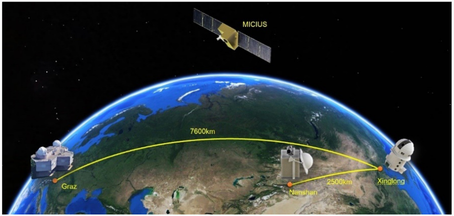
Satellite based QKD

As a solution to achieve very long distance QKD, and overcome fundamental bounds without repeaters, significant effort has been devoted to satellite QKD:

[Nature **549**, 43 (2017)]



[PRL **120**, 030501 (2018)]



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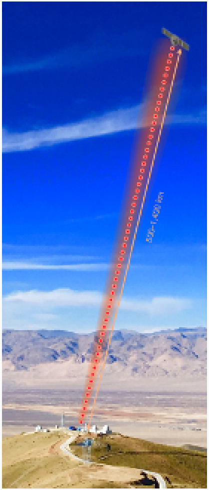

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- Very expensive
- Limited availability (For LEO satellites roughly 5mins to exchange keys)
- Only night operation
- Highly weather dependent
- Requirement of large ground station telescopes (order of 1m diameter)

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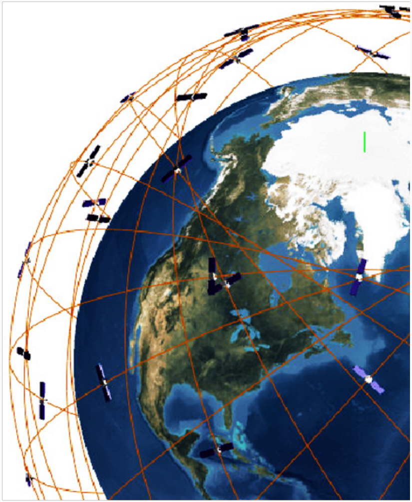

What can we do?

With such challenges, how can we hope to do any better in space? Lets consider relevant eavesdropping models...

Goal of QKD

We are looking for **shared, private randomness**:

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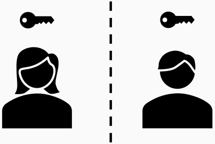
Alice and Bob hold the same key



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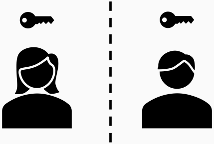
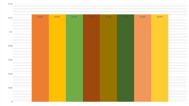


Private randomness

The key is unpredictable to any third party/eavesdropper



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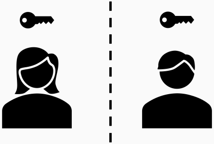

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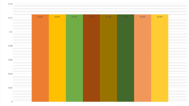

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Given some basic and necessary assumptions on Eve, and experimental observations, prove the above properties

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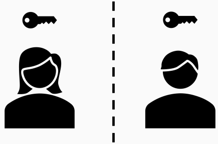

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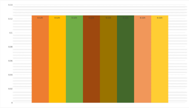

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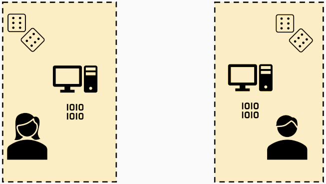
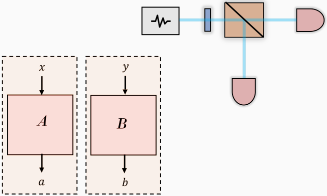
Let us examine the different eavesdropping assumptions and restrictions commonly encountered in QKD...

Common eavesdropping assumptions in QKD

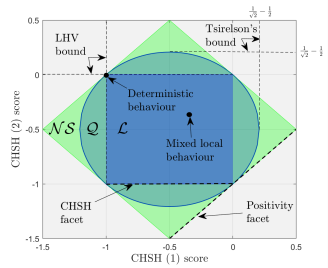
Secure lab and user assumptions



Eve's control over the devices



Fundamental physics governing an all powerful Eve



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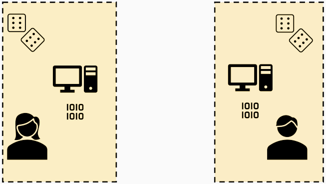

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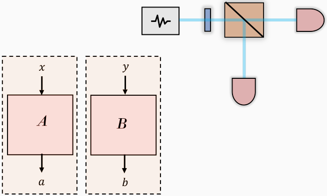

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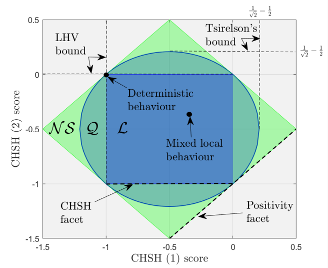
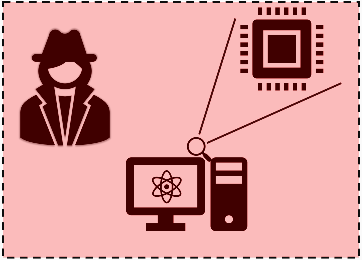


Underlying assumption:
Eve still has access to the **entire channel**, and **unlimited computational resources**. Is this always realistic?

Additional eavesdropping restrictions in QKD

Current literature has explored making QKD more practical by imposing well justified *restrictions* on Eve:

Computational assumptions on Eve



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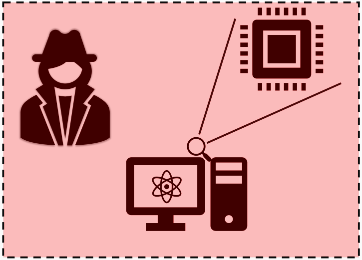

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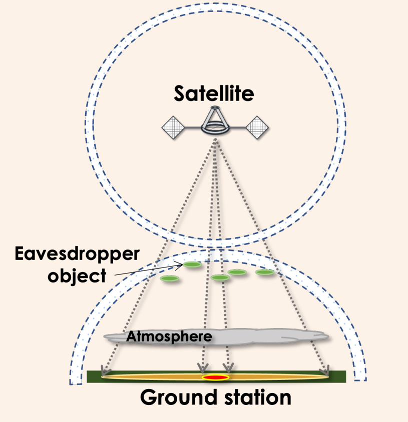
Restrictions on Eve in satellite QKD



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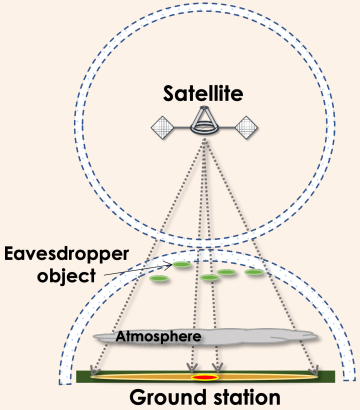

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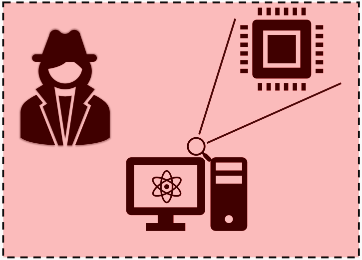

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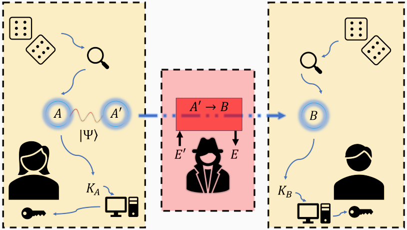
Depart from an all powerful Eve

Satellite QKD with restricted eavesdropping: this work

Restricted versus unrestricted eavesdropping

Unrestricted eavesdropping:
Eve has complete access to the channel



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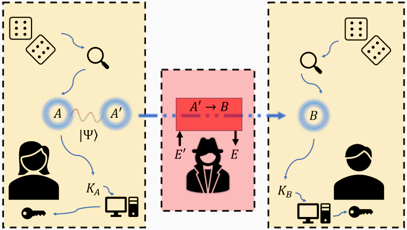

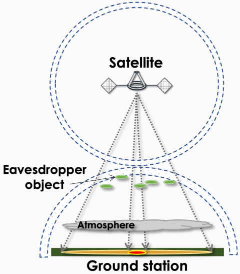

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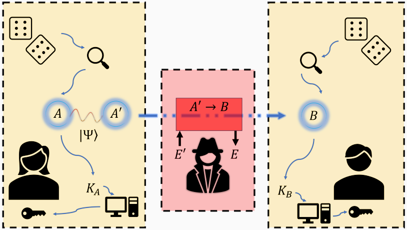

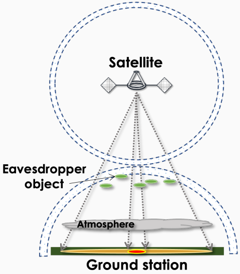

Implications for satellite QKD:

- Eve can collect Alice's signal in full, and send anything to Bob
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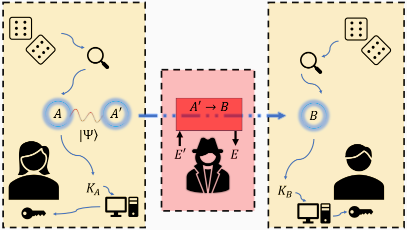

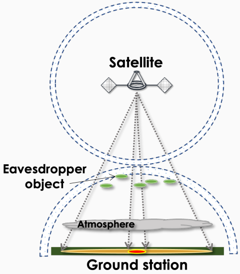

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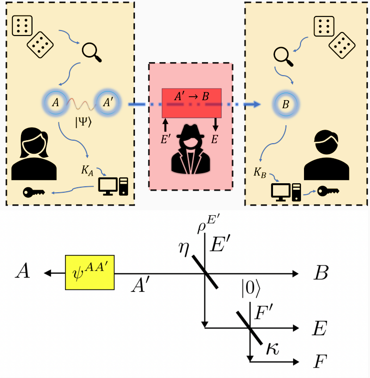
Can we relax this for line of sight satellite links? Could we monitor the link, alerting us to eavesdropping objects?

Existing Satellite QKD Eavesdropping model: wiretap channel



[Phys. Rev. Applied **14** 024044 2020], [Entropy **21** 397 2019], [Phys. Rev. Applied **16** 2021]

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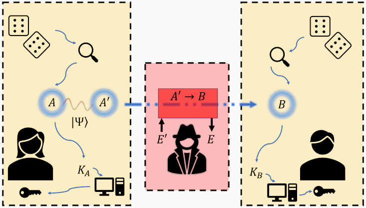

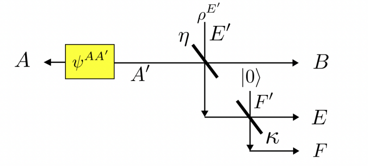

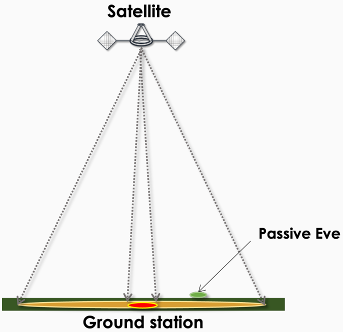

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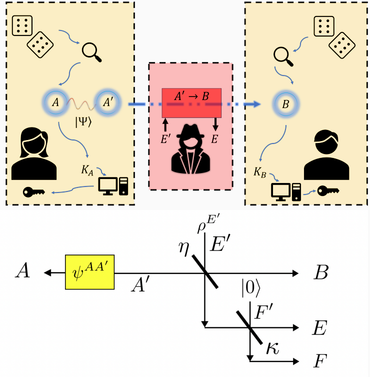

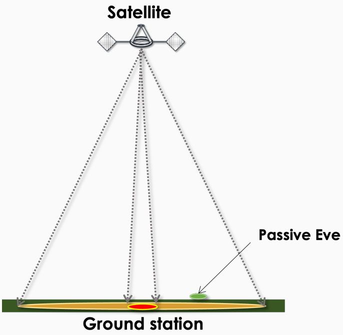

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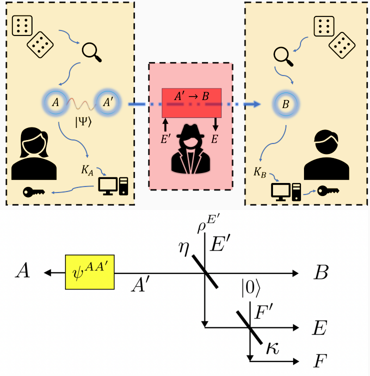

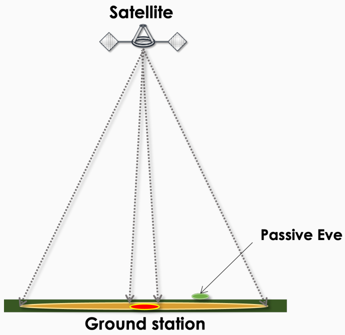

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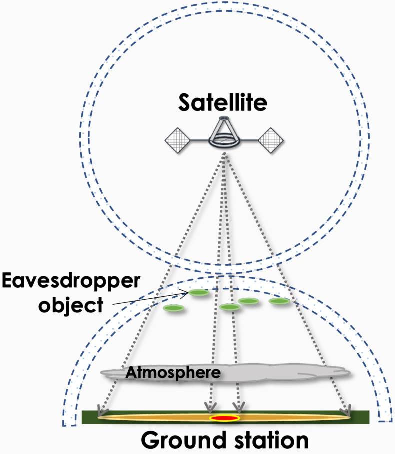
Key goal:
To provide a **generic framework** for restricted Eavesdropping with **verifiable assumptions**

Restricted versus unrestricted eavesdropping



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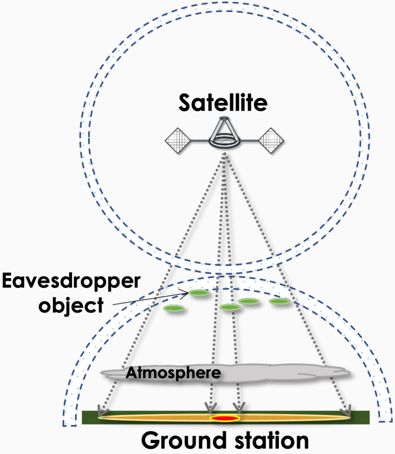

Monitoring possibilities:

With detection systems, such as LIDAR, Alice and Bob can possibly rule out the presence of eavesdropping objects of a certain size

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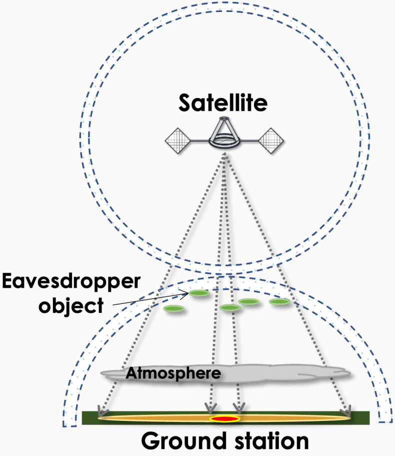

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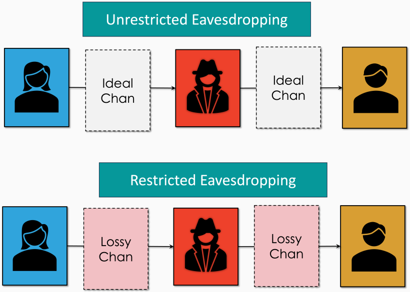

Implication:

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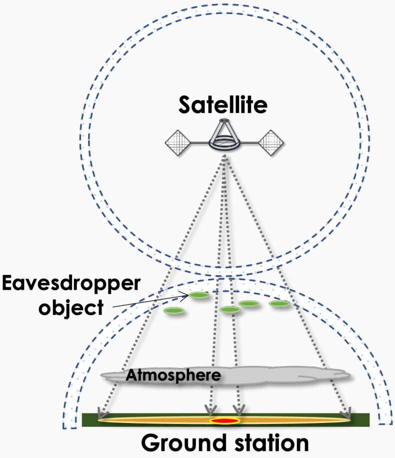

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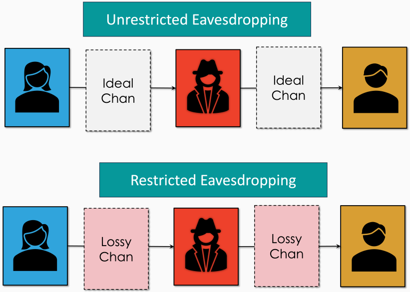

Implication:

→Limit size of Eve's object

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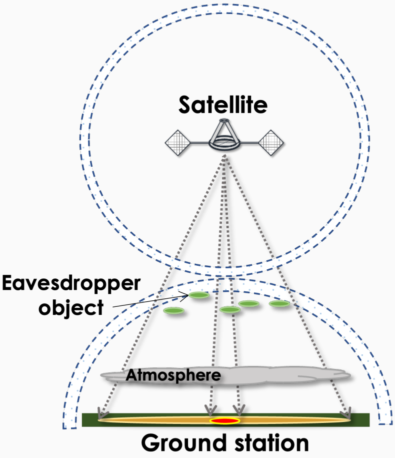

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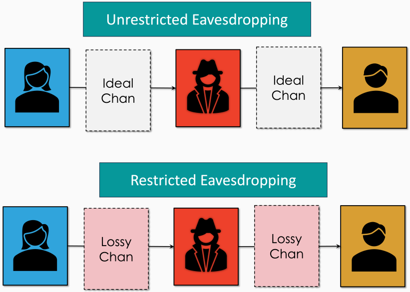
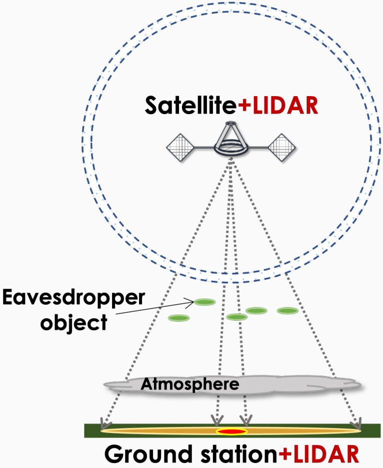
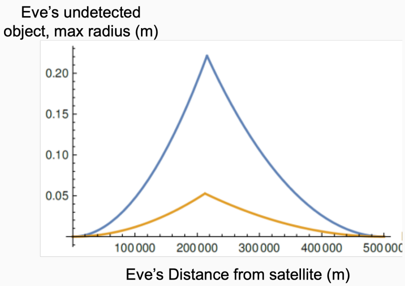


Implication:

$\rightarrow$Limit size of Eve's object$\rightarrow$ limit Eve's collection and resend efficiency, i.e. *ideal channels are replaced with lossy channels*

Monitoring example using LIDAR





LIDAR with 1W, 4W, Tx power and telescope diameter 30cm, 100cm, for Alice (satellite) and Bob (ground station) resp. LEO satellite altitude 500km.

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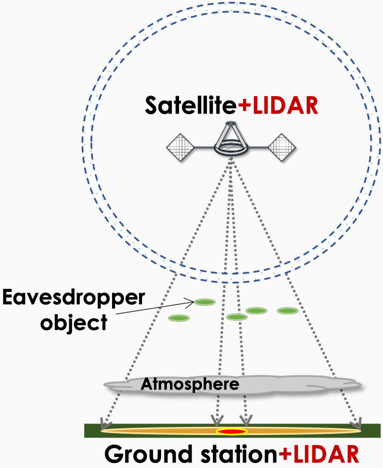

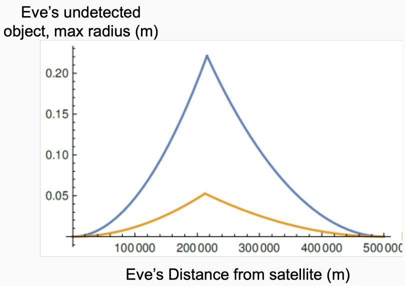

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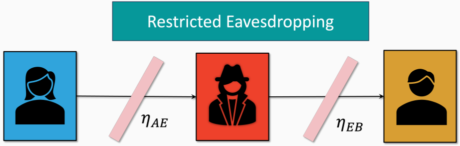
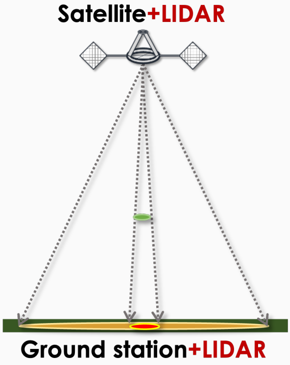
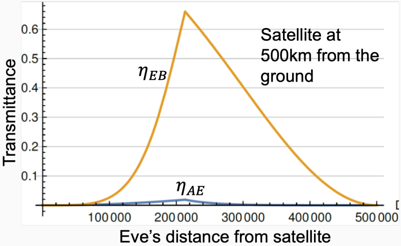
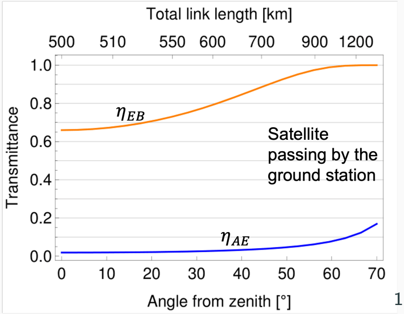
Eve’s collection and resend capabilities

Continuing the LIDAR example, preliminary calculations suggest:



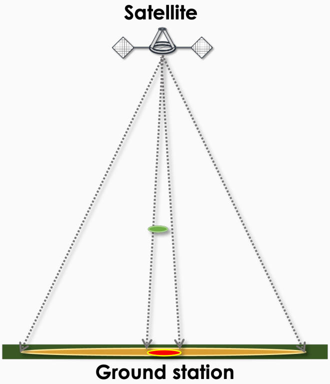






A new QKD scenario

What about signal that does not reach Eve, but might still find its way to Bob?



A general model

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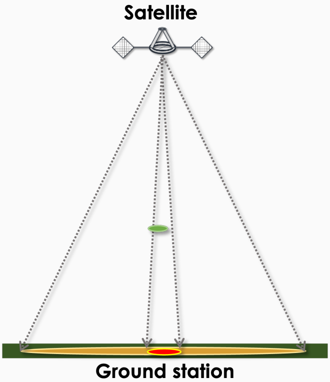


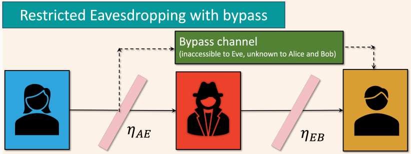
Regardless of the monitoring technique, bounds on η_{AE}, η_{EB} result in a new QKD model which is interesting in its own right...

Satellite QKD with bypass channels

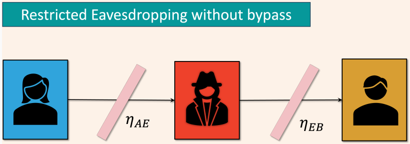
Different models

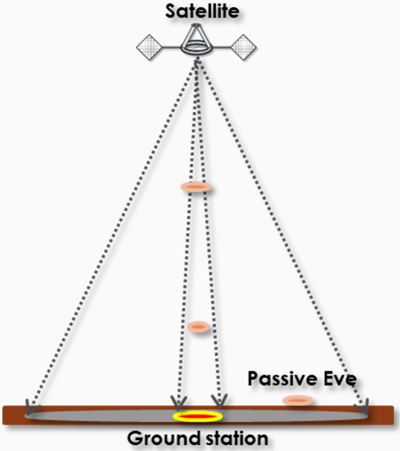
In principle, some signals that reach Bob may **bypass** Eve, but Alice and Bob are unable to fully characterise it either. Assume Alice and Bob have characterised η_{AE}, η_{EB} by some means; we are then left with two case:

Scenario (a):



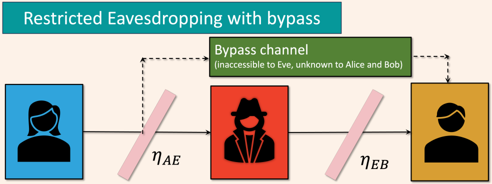
Scenario (b):



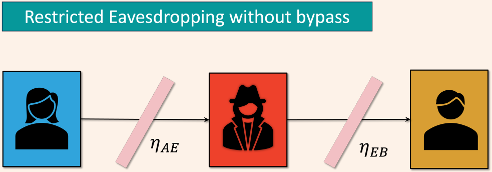


Different models: key rate comparison

Scenario (a):



Scenario (b):



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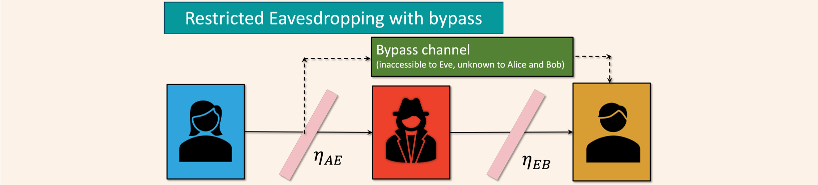

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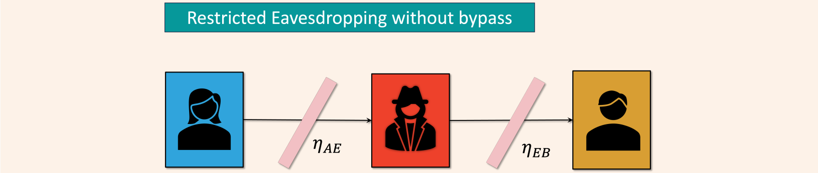

Theorem 1

For a fixed set of observables, secret key rate (b) $\geq$ secret key rate (a).

Why? Attacks in (b) can be viewed as a subset of those in (a).

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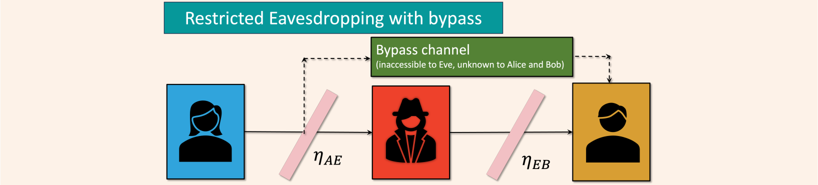
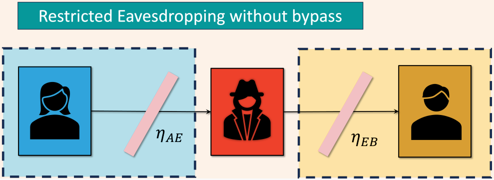


Scenario (b):

Extended Alice and Bob box: easy to compute upper bound



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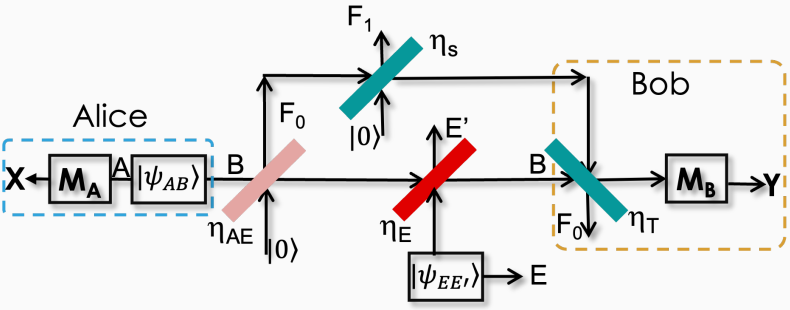
Implications on key rates

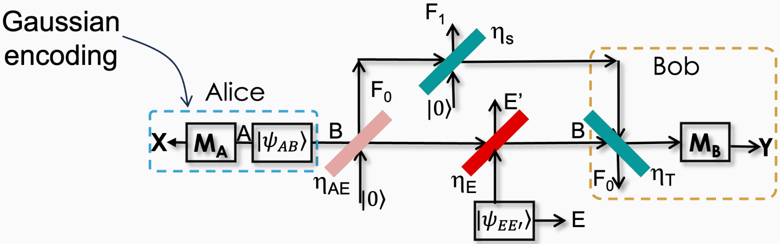
CV-QKD setup



We work out the key rate for a CV-QKD system with:

- Lossy bypass channel, $\eta_{EB} = 1$

CV-QKD setup



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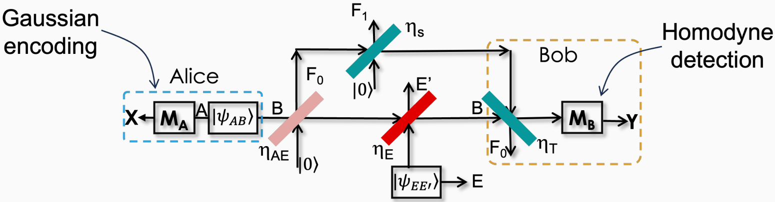

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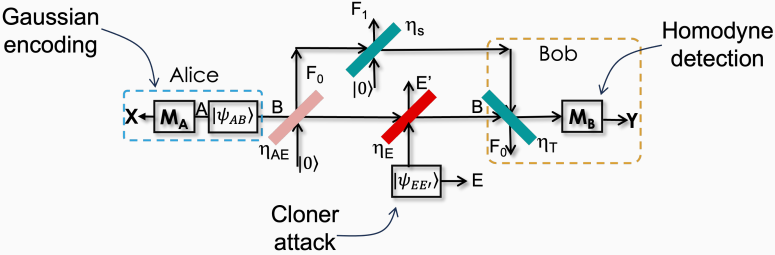

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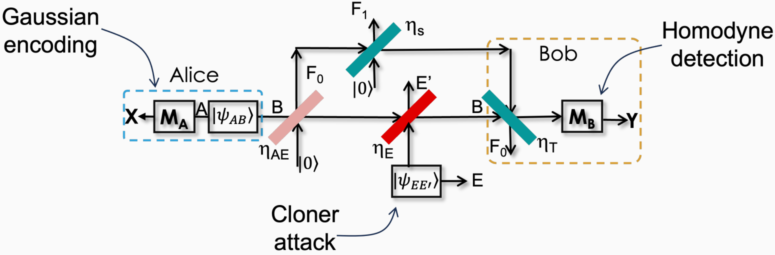

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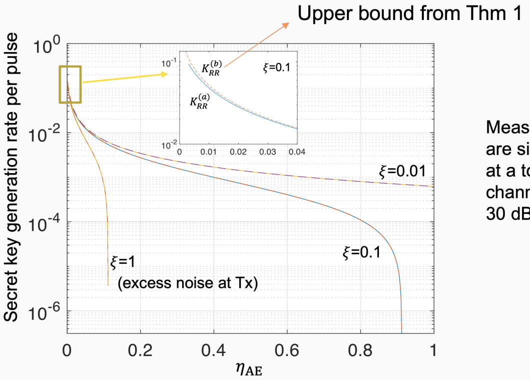
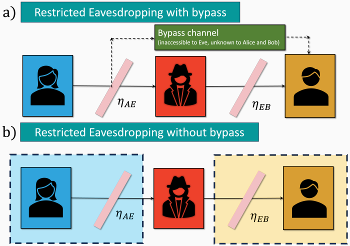
Recall: bypass is uncharacterised $\rightarrow$ minimise key rate over feasible set

Generic upper bound:
scenario (b)

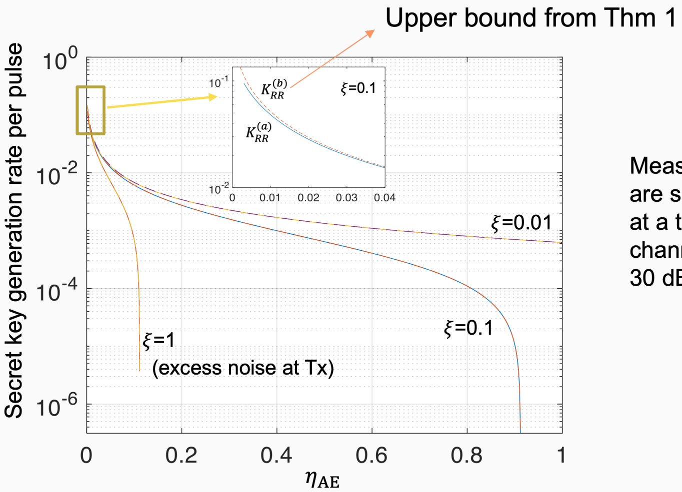


Measured data are simulated at a total channel loss of 30 dB; $\eta_{EB} = 1$



Lower bound from the bypass model:
scenario (a)

CV-QKD results



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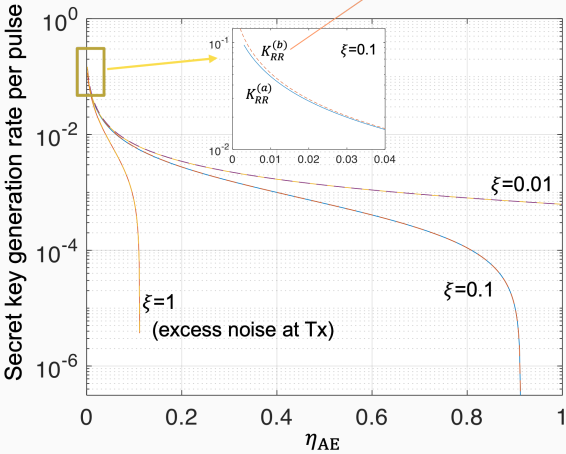
- **Reverse reconciliation:** Lower bound is very close to upper bound; optimum is achieved when bypass is lossless and noiseless

CV-QKD results

Upper bound from Thm 1



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- **Reverse reconciliation:** Lower bound is very close to upper bound; optimum is achieved when bypass is lossless and noiseless
- **Direct reconciliation:** advantage only at very lower η_{AE}

DV-QKD setup

We also consider BB84 with single photons and phase-randomnised weak coherent pulses

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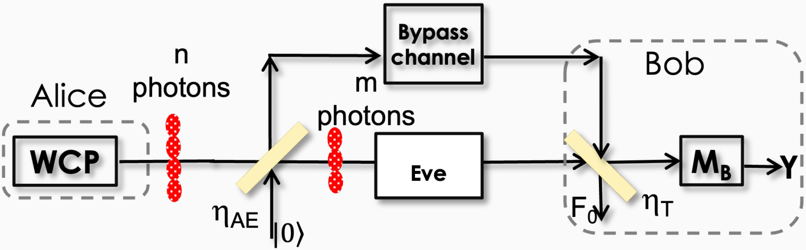
→ *photon number channel*



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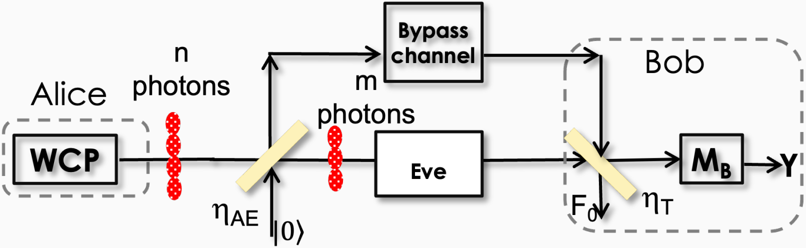

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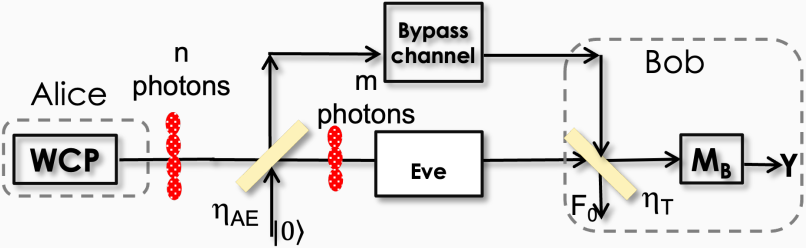
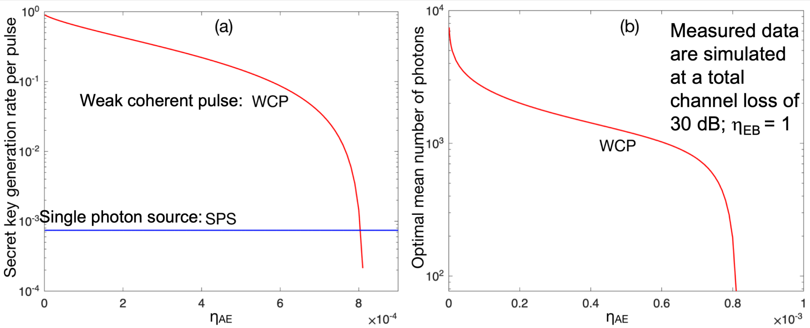


- Secret key bits are obtained when Alice sends exactly one photon
- With a bypass channel we can get detection at Bob with no photon going through Eve

DV-QKD results

Phase randomised WCP offers advantage at lower η_{AE}

We can capitalise on cases where no photon has gone through Eve



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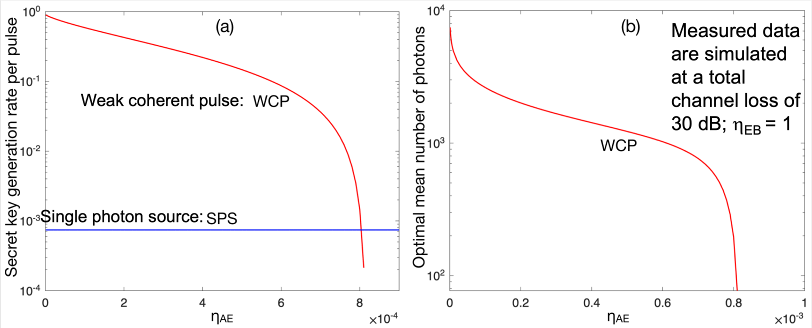

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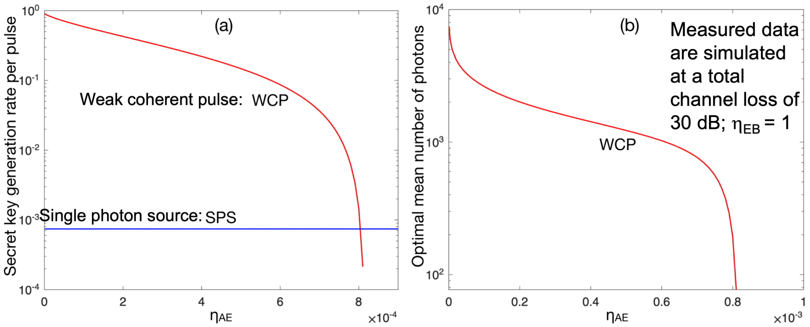

- Single photon BB84 *is not* optimal in the bypass model $\rightarrow$ eavesdropping restrictions influence best choice of protocol
- Behaviour we would expect to see in wiretap channel

DV-QKD numerical approach

Ongoing investigation$\rightarrow$ application of numerical security proofs (Winick *et al.*, [Quantum **2**, 77 (2018)]) to this problem.

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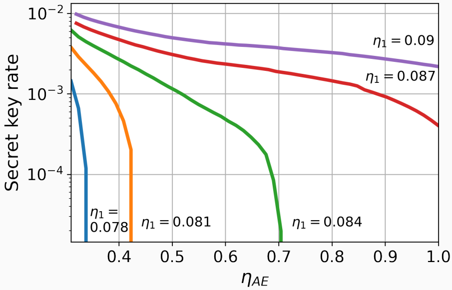
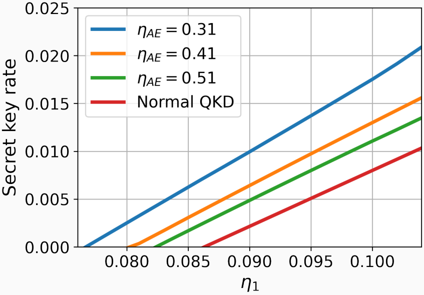
As an example for SPS: bypass channels can improve robustness to a detector efficiency mismatch at the receiver





η_1 = Bob's detector efficiency mismatch, $\eta_T \approx \eta_{AE}$, $\eta_S = 1$.

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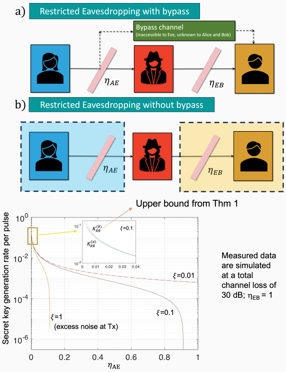

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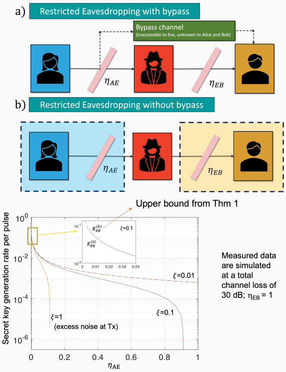

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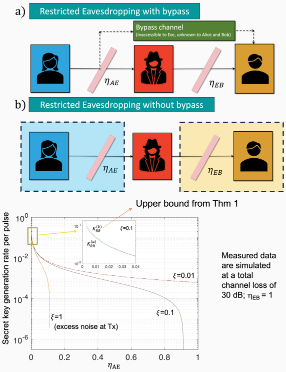

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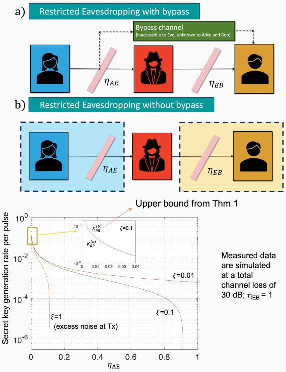

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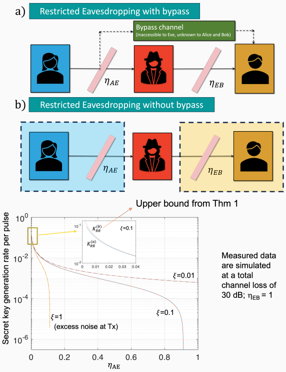

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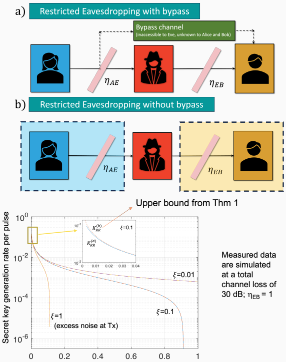

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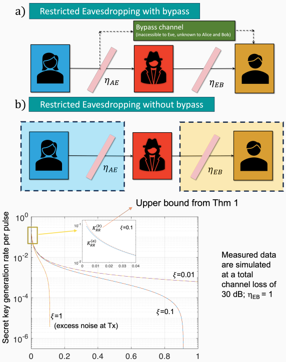

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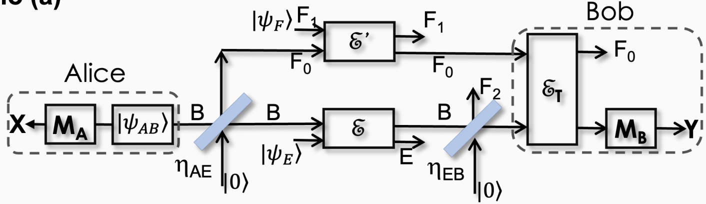
Thank you for your attention! arXiv:2212.04807

Bonus slides

Generic model for QKD with bypass

Scenario (a)



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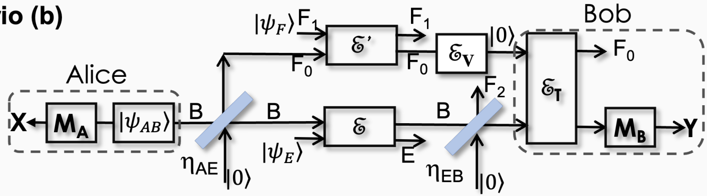
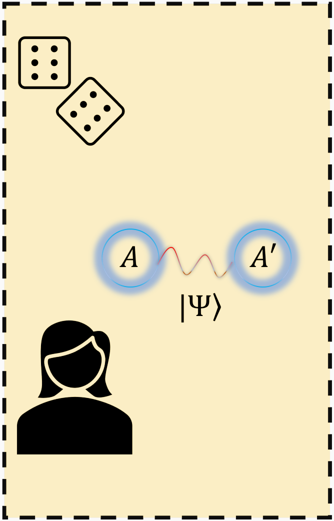


Standard QKD scenario



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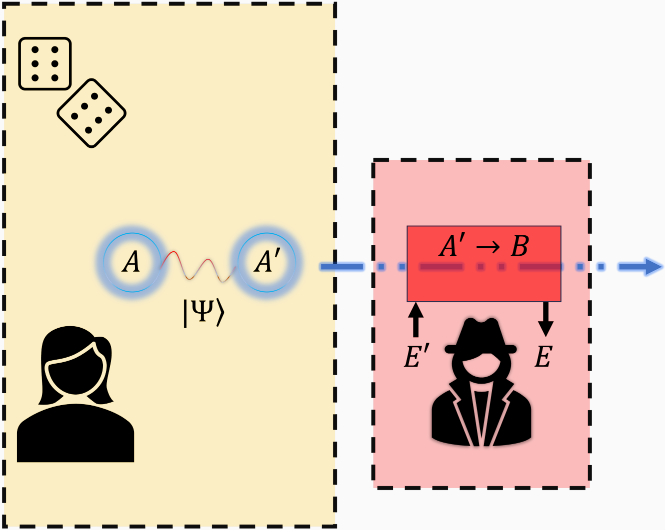

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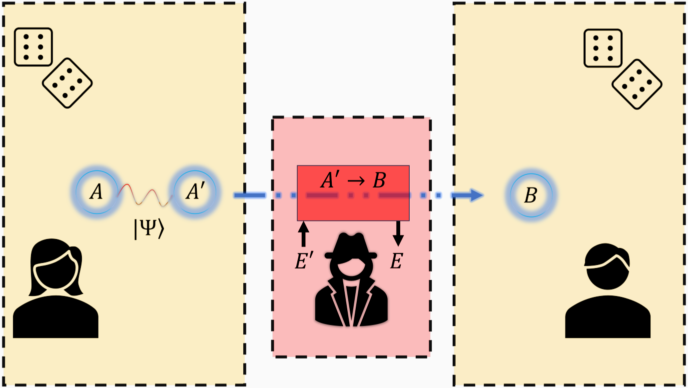

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