Quantum repeaters in space

Carlo Liorni, Hermann Kampermann, Dagmar Bruß
Institut für Theoretische Physik III, Heinrich-Heine-Universität, Düsseldorf 40225, Germany
carlo.liorni@hhu.de

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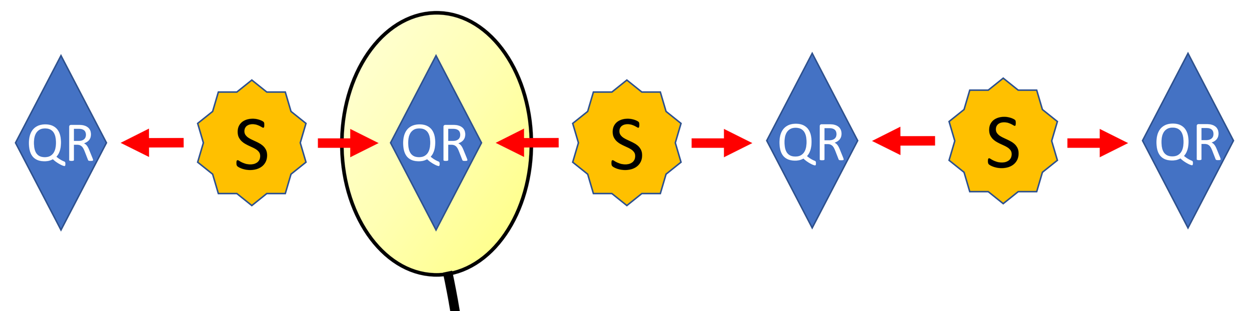
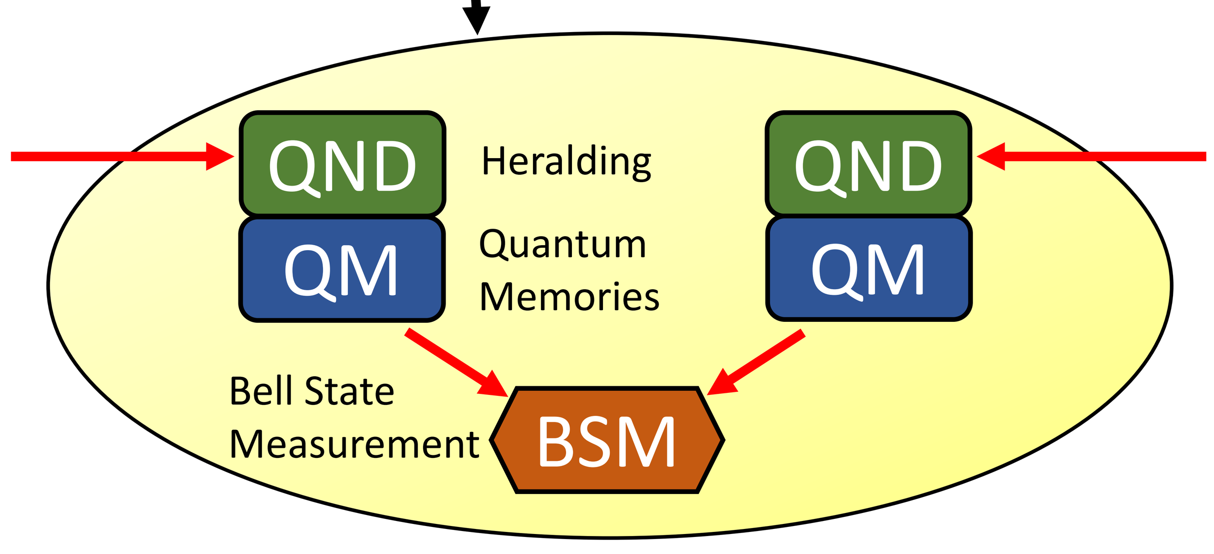
Introduction

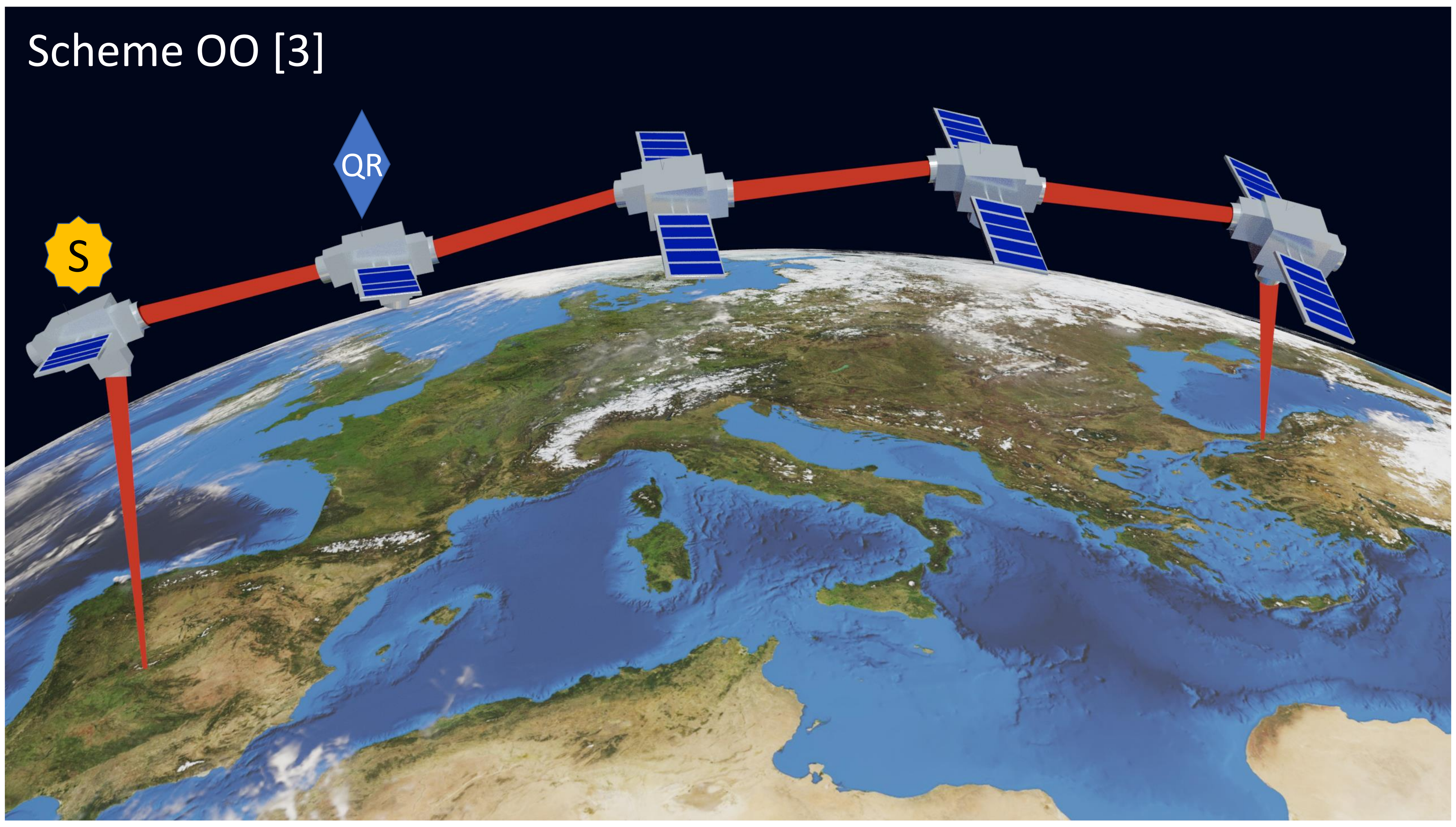
- **Losses** in optical fibres hinder the **direct transmission** of **quantum signals**
- Quantum Repeaters (**QR**s) [1] can solve the problem
- **Satellite links** can bridge long distances [2]
- With satellites, **few** QRs are sufficient to reach **global distances**
- **Orbiting repeater** stations greatly improve the **performance**, **reliability** and **flexibility** and seem **feasible**

Quantum repeaters



Entanglement Swapping (ES)

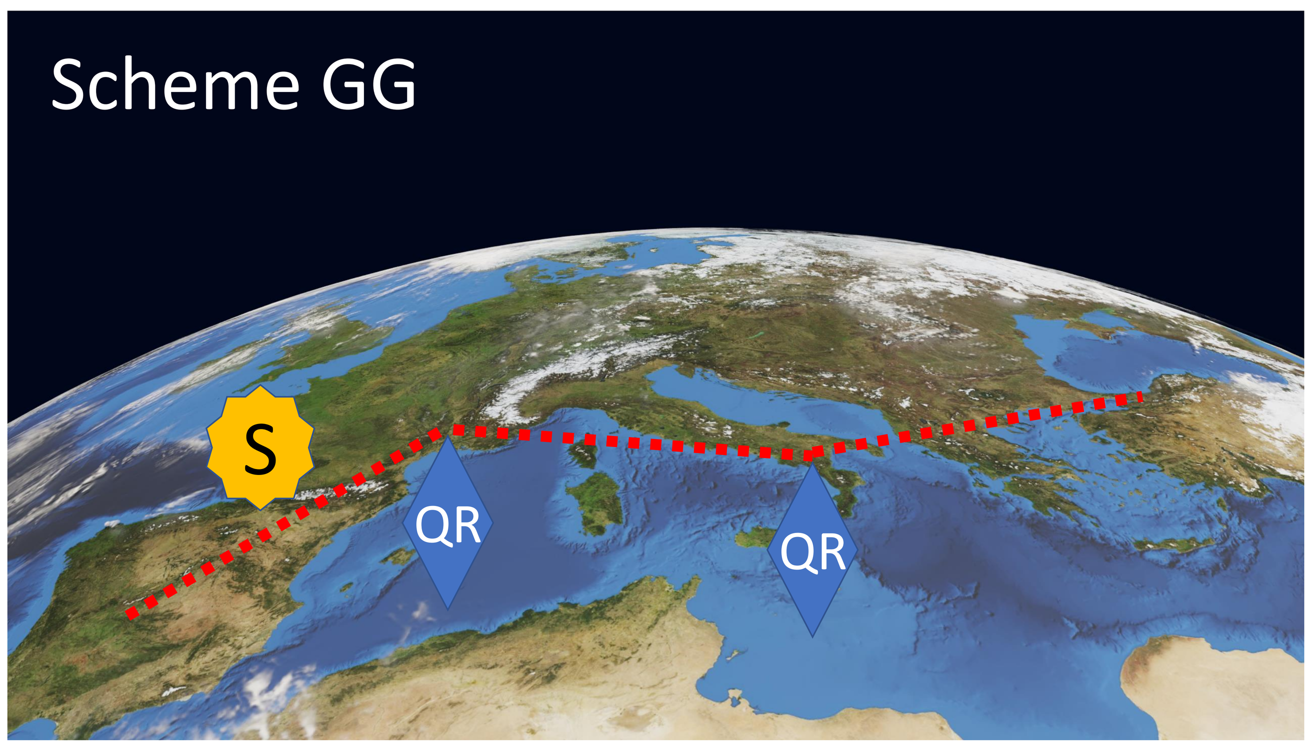


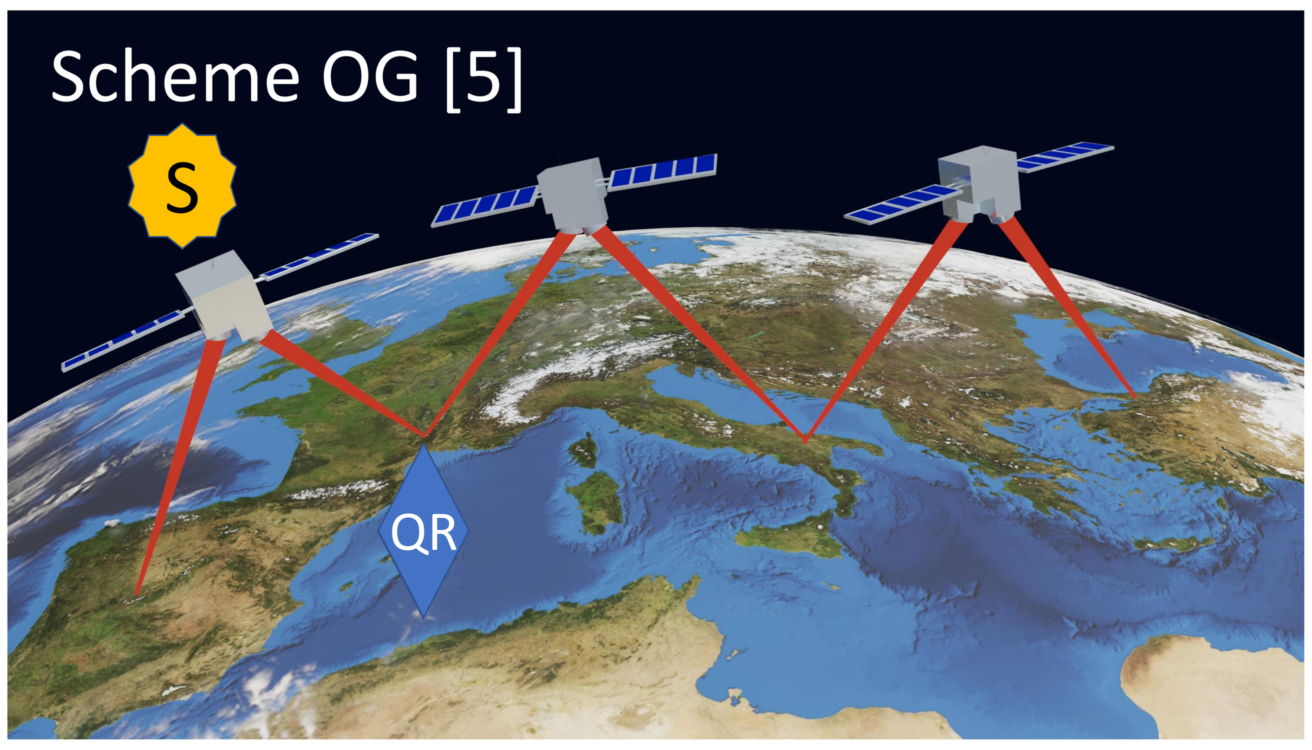


Standard **QR** chain configuration [1] (in optical fibres). Divide the link in 2^n elementary links.

S produces and sends **pairs of entangled photons** to the adjacent QRs [4].

Entanglement sources (**S**) on satellites: substitute fibre links with **satellite double down-links** [2,5] or **inter-satellite** links [3]





Secret Key Rate

BB84 protocol, measurement on the entangled pairs shared at the end points

$$R_{QKD}^{BB84} = R_{rep}\, P_{click}\, R_{sift}\, r_{\infty}^{BB84}$$

$$R_{rep} = \frac{1}{T_0} P_0\, P_{QND}^2\, P_W^2 \left(\frac{2}{3} P_{ES}\, P_R^2\right)^n$$

$$P_{click} = \eta_d^2$$

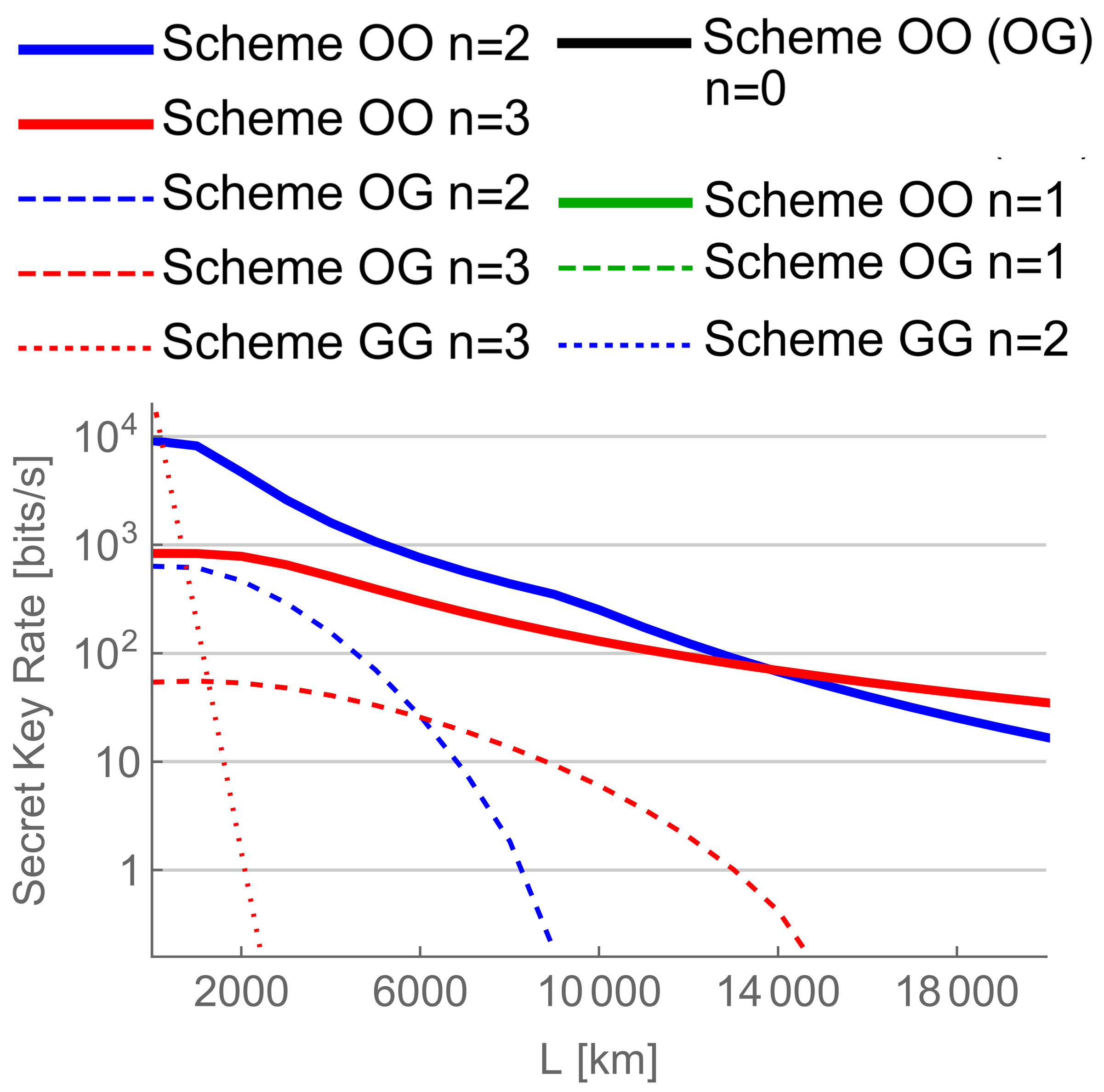
$$r_{\infty}^{BB84} = 1 - h(e_Z) - h(e_X)$$

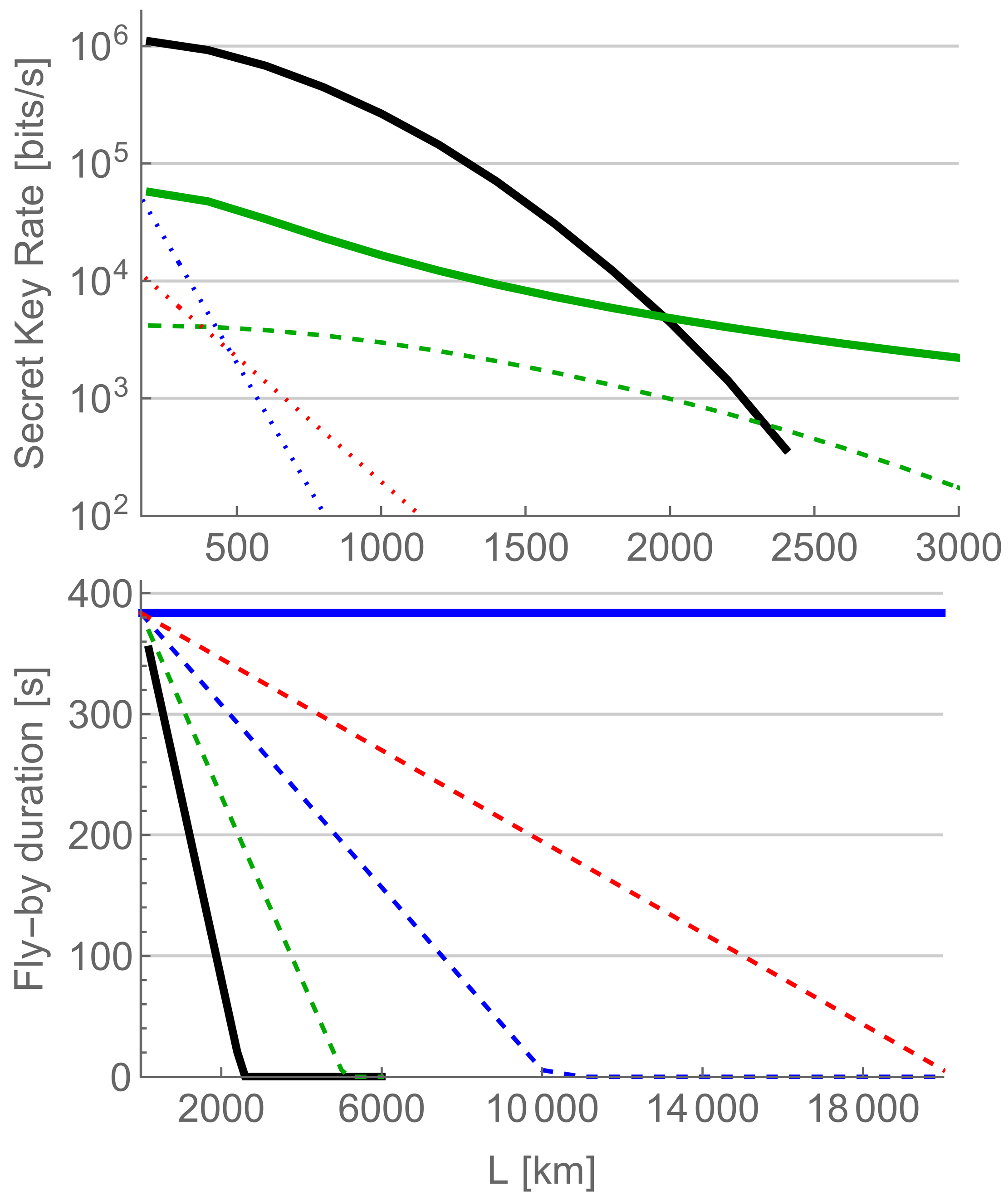
- T_0 elementary time [6]
- P_0 transmittance elem. link
- P_{QND} heralding efficiency
- P_W QM write probability
- P_{ES} ES success probability
- P_R QM read probability
- η_d detection efficiency

QR analysis of [7], added **inefficiencies**, **probabilistic** ES and **no Entanglement Distillation** (ED) [8].

The **error rate** e_Z (e_X) in the Z (X) basis is monitored in the final measurements of the quantum states at the end points, h is the binary entropy.

Results





Advantages of scheme OO over OG

- Much less weather dependent, requires good weather conditions only at the end points
- Potential almost world-wide coverage with few satellites
- Easy trans-oceanic links (very difficult in OG)
- Longer fly-by duration

Parameters

- Ultra low-loss fibres (attenuation α=0.17 dB/km)
- Imperfect Gaussian beams with quality factor M^2
- We assumed long coherence times of the memories
- Included mixing with environmental photons

R_s	20 MHz	Repetition rate of the source
$R_s^{n=0}$	1 GHz	Repetition rate of the source
P_{QND}	0.5	QND measurement efficiency
P_W	0.9	Memory writing efficiency
P_R	0.9	Memory reading efficiency
η_d	0.9	Detector efficiency
P_{dark}	10^{-5}	Dark click probability
h	500 km	Altitude circular orbits
W_0	0.25 m	Initial beam width
R_{OO}	0.5 m	Receiver radius OO
R_{OG}	0.5 m	Receiver radius OG
λ	580 nm	Wavelength, OO and OG
M^2	3	Quality factor
F_0	0.98	Initial pair Fidelity

[1] H.-J. Briegel et al, PRL 81, 5932 (1998).
[2] J. Yin et al., Science 356, 1140-1144 (2017).
[3] C. Liorni et al., arXiv:2005.10146 (2020).
[4] Then entanglement is swapped in a hierarchical way, until the ends are reached.
[5] K. Boone et al., PRA 91, 052325 (2015).
[6] Here, inverse of the source rep. rate (20MHz).
[7] S. Abruzzo et al., PRA 87, 052315 (2013).
[8] We consider high fidelity elementary pairs (F=0.98), which might require one round of ED.

[3]