Challenges and solutions for physically secure, space-based global quantum communications

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Joint Lab Integrated Quantum Sensors
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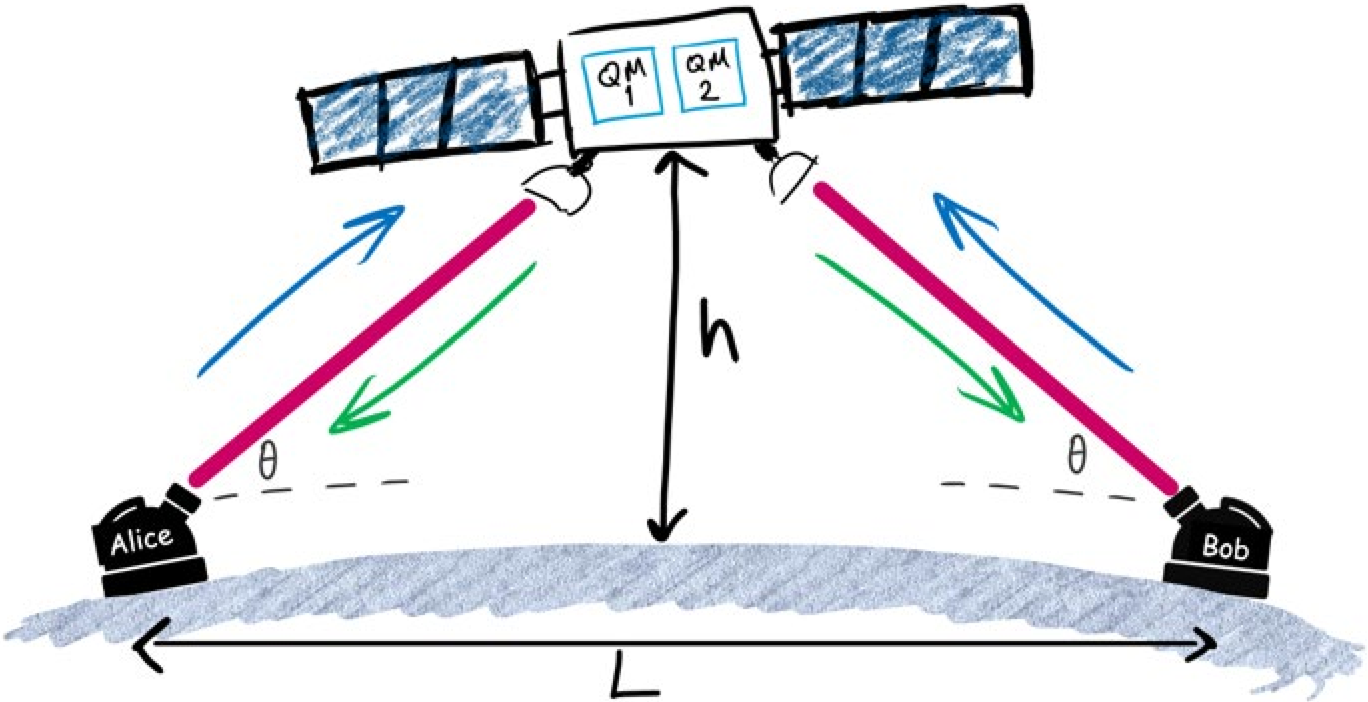
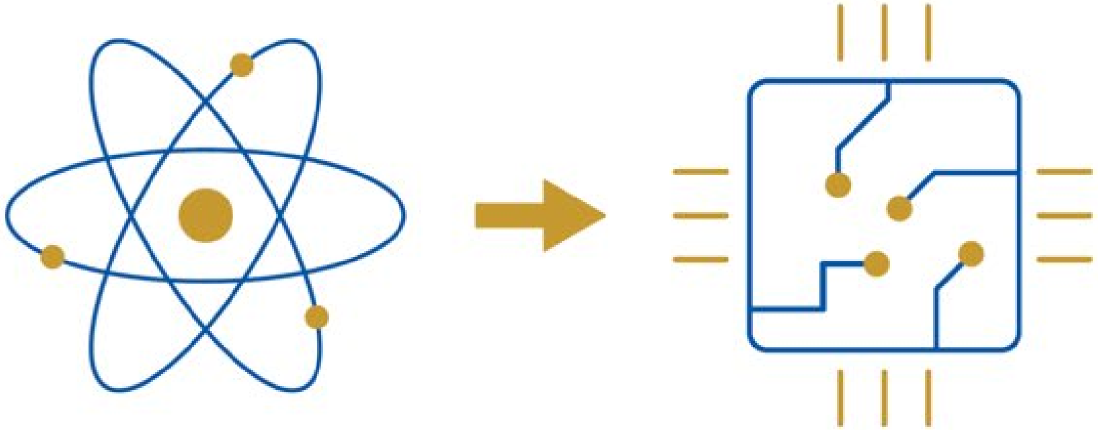
http://iqs.berlin



OPTIMO I & II, *Optical Memories in Orbit* Phase I & II, DLR
QSPACE, Maria Skłodowska-Curie Individual Fellowship, EC

Joint Lab Integrated Quantum Sensors

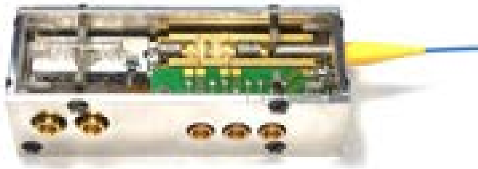


Goal: Development of compact and robust atom-based sensor technologies

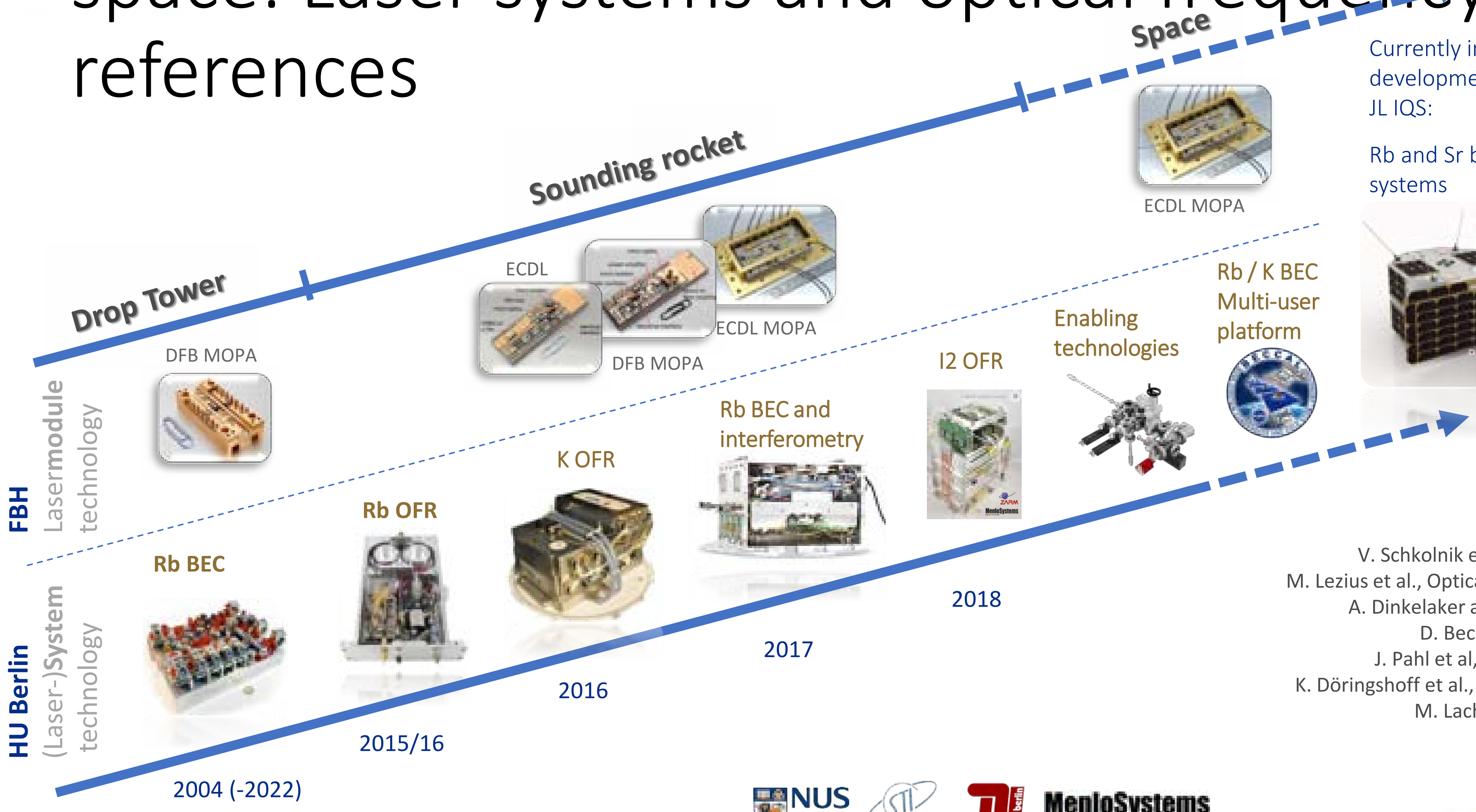
Joint Lab Integrated Quantum Sensors (Est. 2019)

Led by Dr. Markus Krutzik

Humboldt-Universität zu Berlin & Ferdinand-Braun-Institute
www.qt-berlin.de



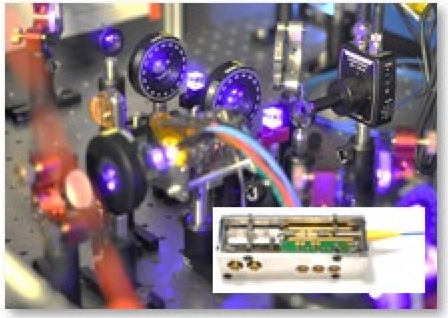
Enabling technologies for quantum sensors in space: Laser systems and optical frequency references



V. Schkolnik et al., Applied Phyics B 122, (2016), p.1-8
M. Lezius et al., Optica Vol. 3, Issue 12, (2016), pp. 1381-1387
A. Dinkelaker at al. Appl. Opt. 56 (2017), p. 1388–1396
D. Becker et al, Nature 562 (2018), p. 391–395
J. Pahl et al, Applied Optics 58 (2019), p. 5456-5464
K. Döringshoff et al., Phys. Rev. Applied 11 (2019), p. 054068
M. Lachmann et al, Nat comm 12, (2021), 1317

Rb: Rubidium, K: Potassium, I2:Iodine
BEC: Bose-Einstein condensate
OFR: Optical frequency reference

R&D Joint Lab Integrated Quantum Sensors



Rubidium vapor cell based optical frequency references and clocks

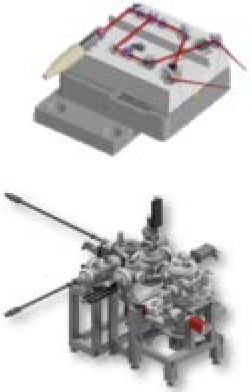
- 5S→5P, 5S→5D, 5S→6P
- Integrated sensor heads
- Micro-fabricated vapor cells
- Stand-alone systems

Strontium beam Ramsey-Bordé (RB) interferometer *and* miniaturized **cold Strontium** optical lattice clock

- Compact source cells and int. optics
- Diode laser based systems
- Stand-alone systems

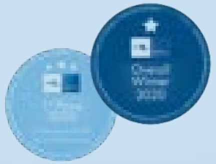
Miniaturized hybrid traps for **Rubidium BEC** and integrated Physics packages

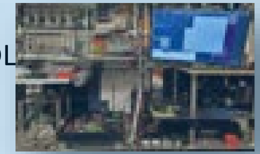
- Free-space optical systems for atomic manipulation in UHV; adhesive qual.
- AM of functional ceramics and metal components for HV/UHV



Atomic **Quantum Memories**

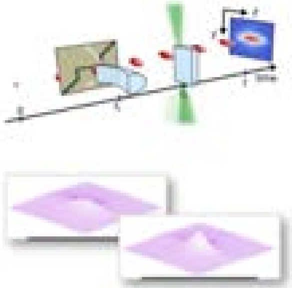
- Applications of quantum memories in space
- Rb Bose-Einstein condensates for high performance memories
- 19'' rack Cs warm vapor demonstrator (together with DL –OS/ TUB)
- EIT enhanced velocimetry





Rubidium BEC interferometry in µg within QUANTUS collaboration led by LU Hannover

- Time-domain atom optics
- Waveguide interferometry
- Fundamental physics tests
- Laser system development

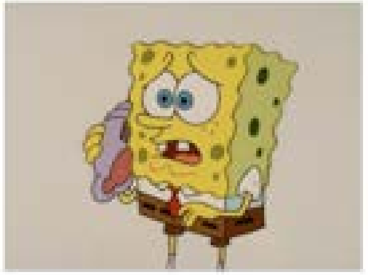


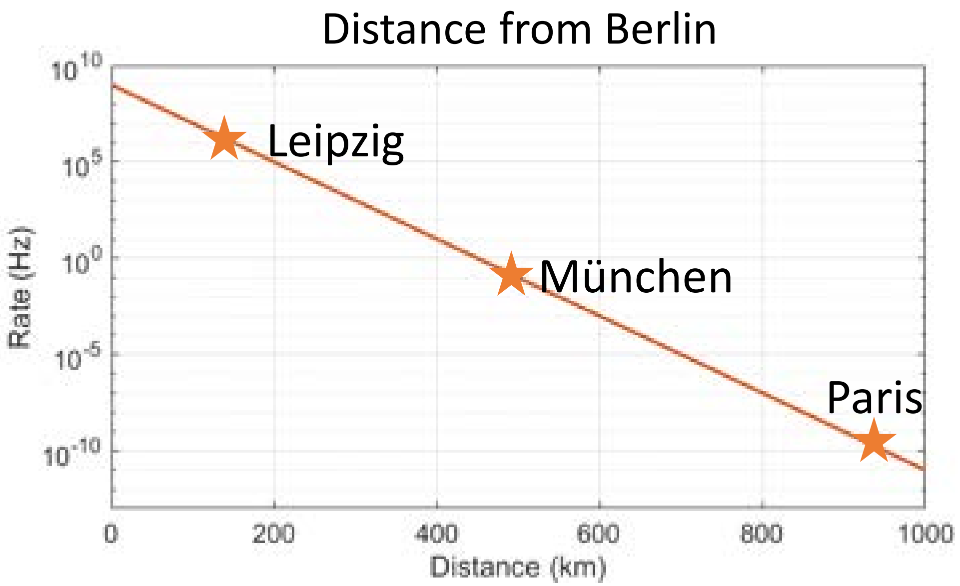
Funding:

Quantum communications

Transfer of a quantum state between two (or more) parties.

⟵ $|\psi\rangle$ ⟶





Quantum state is usually encoded in different degrees of freedom of photons.
Loss in optical fibers limits the transmission range to around few hundred kms.

Example: attenuation of 1550 nm photons is 0.2 dB/km (~5%)
With 1 GHz source, T > 300 years to receive a single photon at 1000 km distance

A solution: Optical repeaters in classical communication.
No-cloning theorem* precludes their use in quantum communication.

*D. Dieks, Phys. Lett. A. **92**, 271 (1982) & W. K. Wootters and W. H. Zurek, Nature, **299**, 802 (1982)

Quantum repeaters

Idea: divide the communication length into 2^n smaller segments, create entanglement between neighbouring nodes and then extend it via entanglement swapping operations over the whole link.

(n: nesting level)

H. J. Briegel, W. Dur, J. I. Cirac, P. Zoller, PRL **81**, 5932 (1998)

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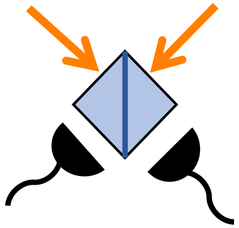

«Entanglement swapping»

H. J. Briegel, W. Dur, J. I. Cirac, P. Zoller, PRL **81**, 5932 (1998)

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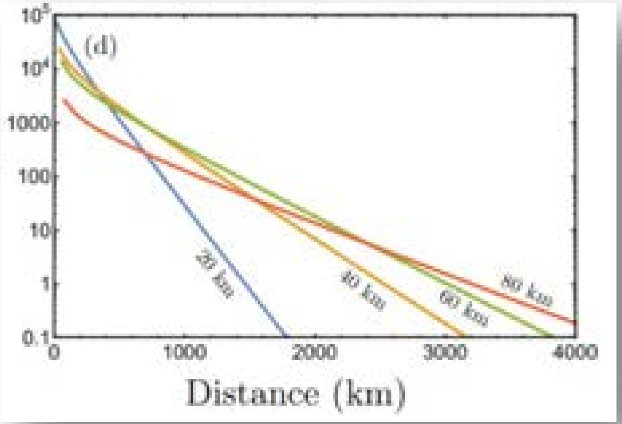
Longest range ground-based Q-rep has a predicted range of ~4000 km*



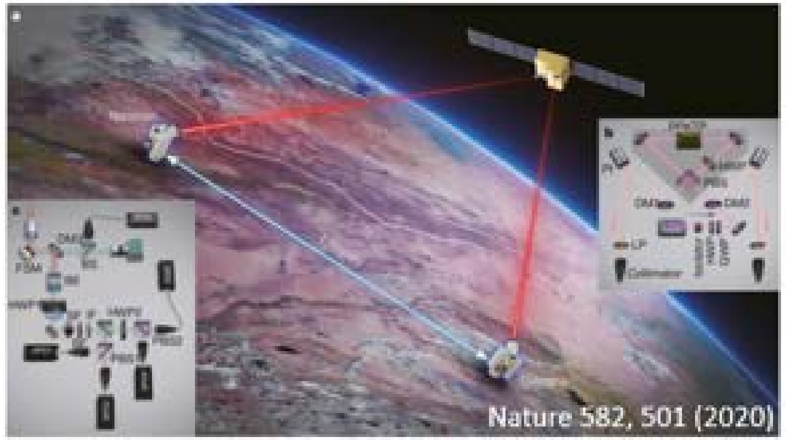
S.E. Vinay and P. Kok, PRA **95**, 052336 (2017)

*except those based on QEC (one needs quantum processors for EC every 1-2 km)

L.-M.Duan, M.D. Lukin, I.Cirac and P. Zoller, Nature **414**, 413 (2001)

C. Simon, H. de Riedmatten, M. Afzelius, N. Sangouard, H. Zbinden and N. Gisin, Phys. Rev. Lett. **98**, 190503 (2007)

Space-based quantum communications

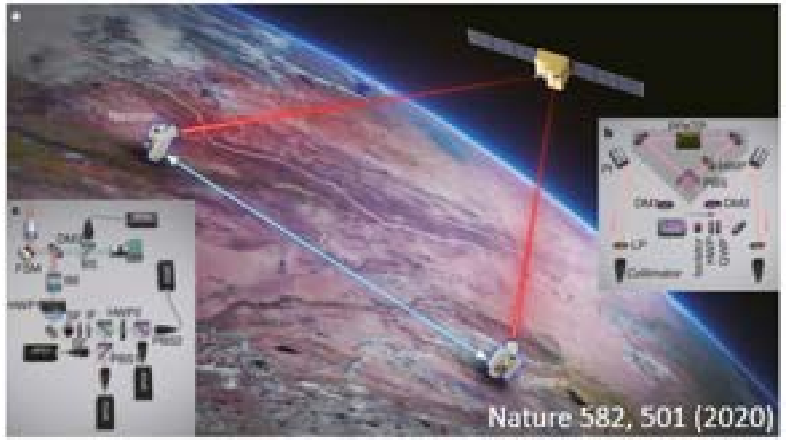


Nature 582, 501 (2020)

Direct communication is limited with the line-of-sight distance of the satellite (~2000 km for LEO, 1/3rd of Earth surface for GEO)

A network of satellites is needed for global coverage!
(with integrated ground links)

Space-based quantum communications



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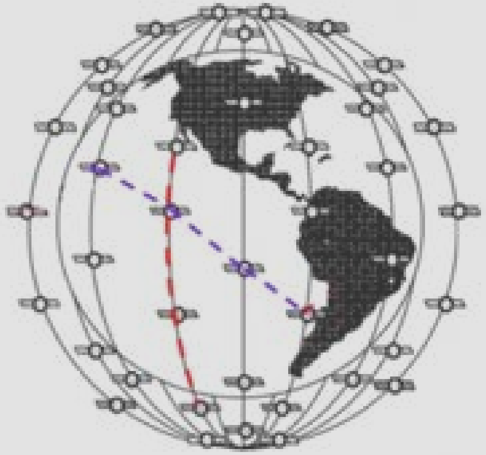
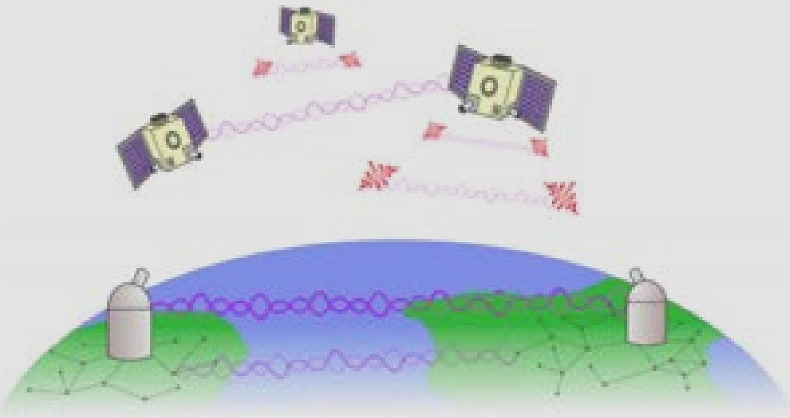
Satellite quantum network proposals without memories



T. Vergoossen et. al., Acta Astronautica **173**, 164 (2020)



S. Khatri et. al., npj Quant. Inf. **7**, 4 (2021)

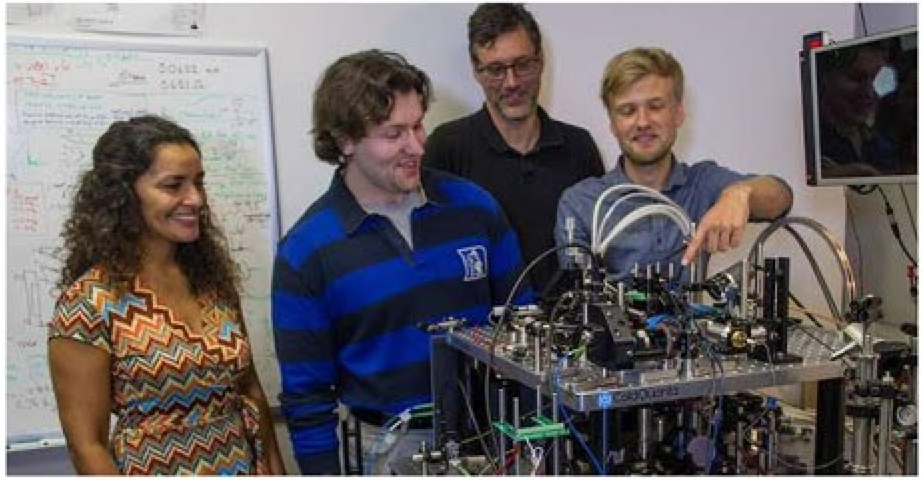
Interlude – atomic physics in space

Tremendous progress in space-based atomic physics experiments in recent years.

OCTOBER 12, 2016

New instrument on ISS to study ultra-cold quantum gases

by Tomasz Nowakowski, Astrowatch.net, Astrowatch.net

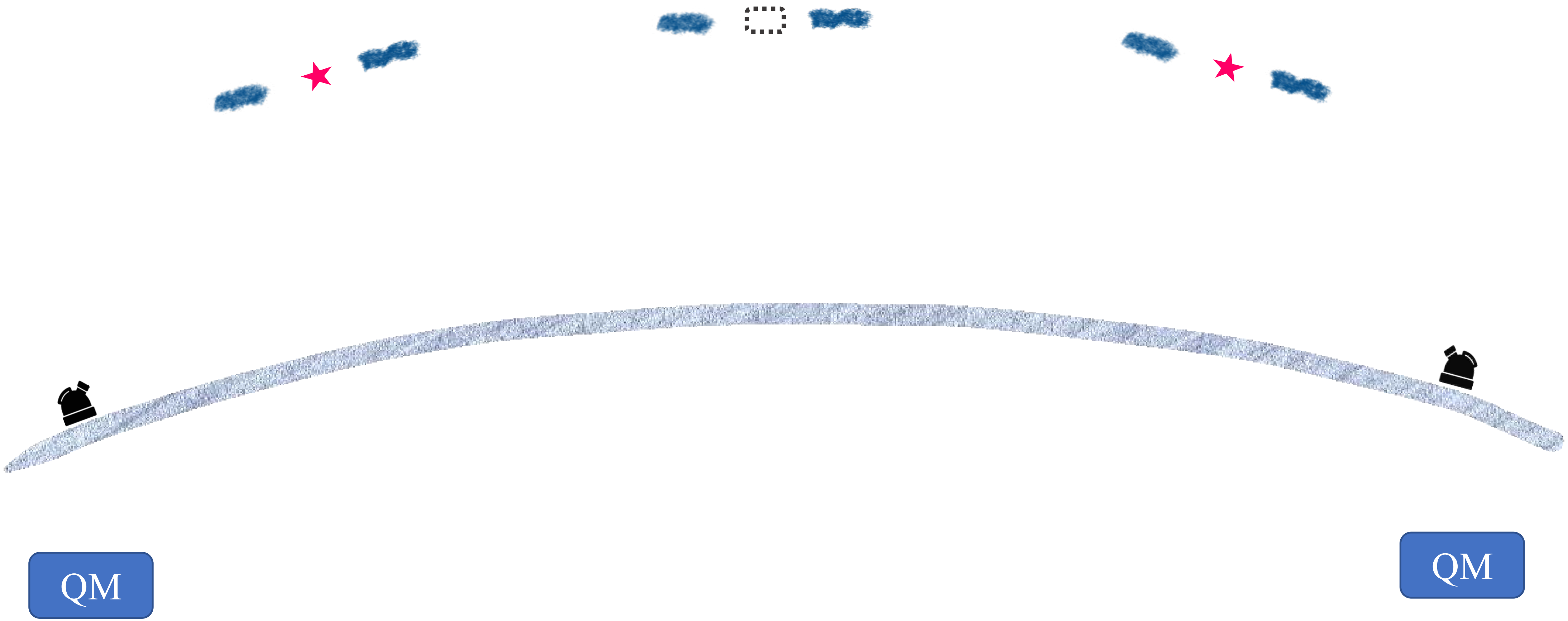


Credit: Astrowatch.net

A new science instrument, slated to be installed onboard the International Space Station (ISS) in late 2017, is expected to yield interesting results regarding quantum phenomena. The Cold Atom Laboratory, or CAL, will study degenerate quantum gases in the microgravity environment of the orbital outpost.

Astronaut C. Koch helps installing the Cold Atom Laboratory on board ISS.
https://directory.eoportal.org/web/eoportal/satellite-missions/i/iss-cal

Space-based quantum repeater



M.G. *et. al.*, npj Quant. Inf. **7**, 128 (2021)

Space-based quantum repeater

Entanglement distribution time:

$$T_{\mathrm{tot}}^{\mathrm{QND}} = \left[R_{\mathrm{s}} \eta_{\mathrm{s}} P_0^{\mathrm{avg}} \eta_{\mathrm{q}}^2 \eta_{\mathrm{w}}^2 \left(\frac{2}{3} \frac{\eta_{\mathrm{r}}^2 \eta_{\mathrm{d}}^2}{2} \right)^n \right]^{-1}$$

R_S : source repetition rate

$\eta_{\mathrm{s,q,w,r,d}}$: source, QND, memory write, read and detection efficiency

P_0^{avg}: average two-photon transmission

n: nesting level ($L = 2^n \times L_0$)

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Space-based DLCZ protocol with single mode memories

Space-based DLCZ protocol with multimode (N=100) memories

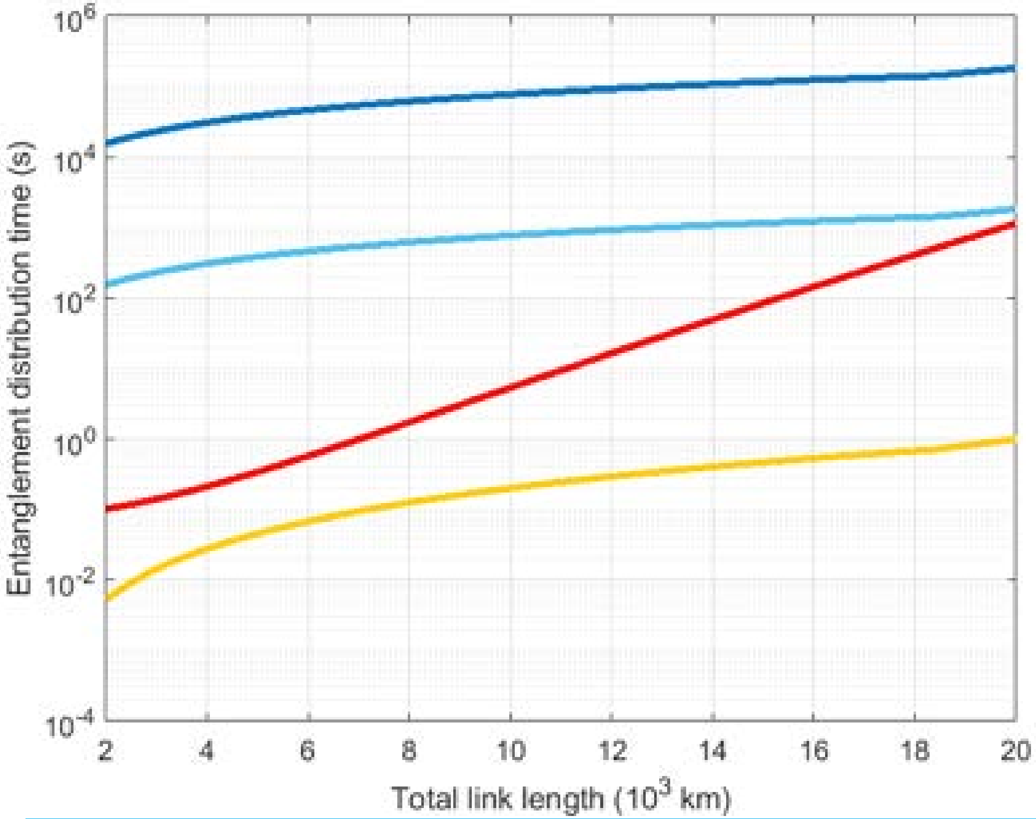
Hybrid ground-space QND protocol

Space-based QND protocol

Sender telescope: 15 cm
Receiver telescope: 50 cm
Memory efficiency: 0.9
Beam divergence: 5 μrad
Nesting level, n = 3

h=400 km
R_S : 20 MHz
$\eta_s = 1$
$\eta_q = 0.5$
L: varied

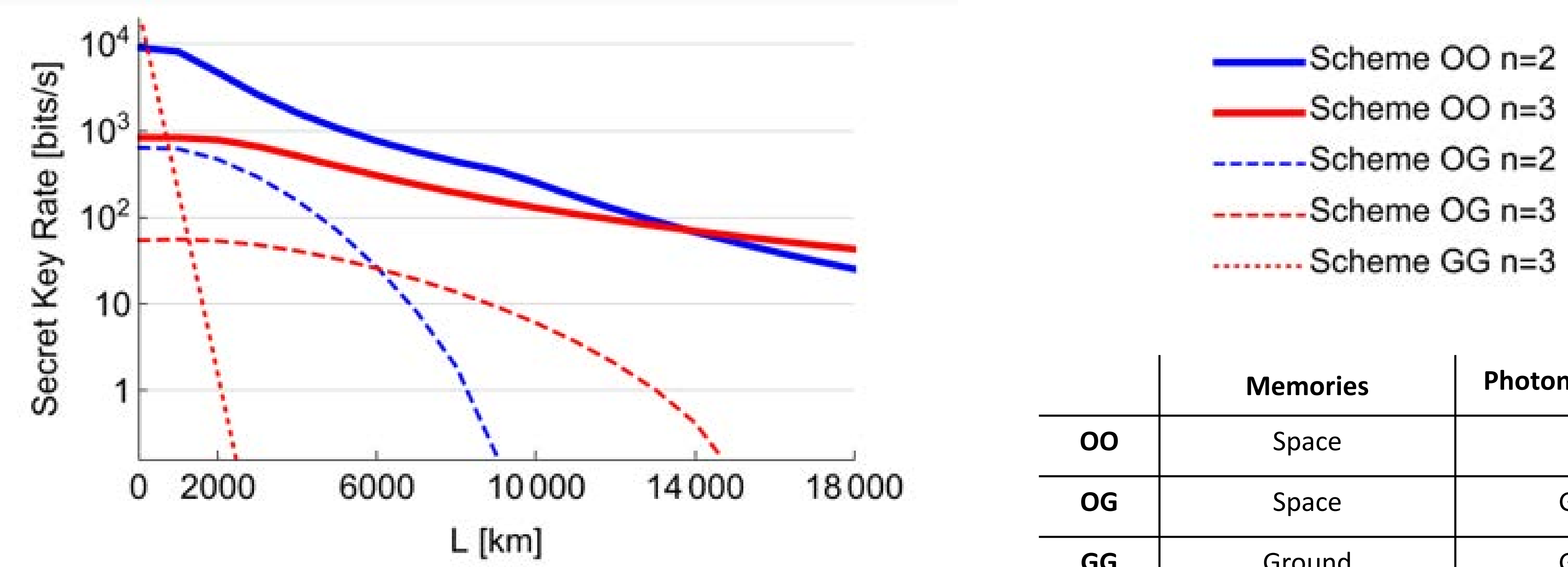
M.G. *et. al.*, npj Quant. Inf. **7**, 128 (2021)



Almost three orders of magnitude higher key rates for truly global distances!

Comparison with ground based-QR

Parallel work by the group of Prof. Dagmar Bruß from Düsseldorf



	Memories	Photon pair sources
OO	Space	Space
OG	Space	Ground
GG	Ground	Ground

C. Liorni, H. Kampermann and D. Bruß, New J. Phys **23**, 053021 (2021)

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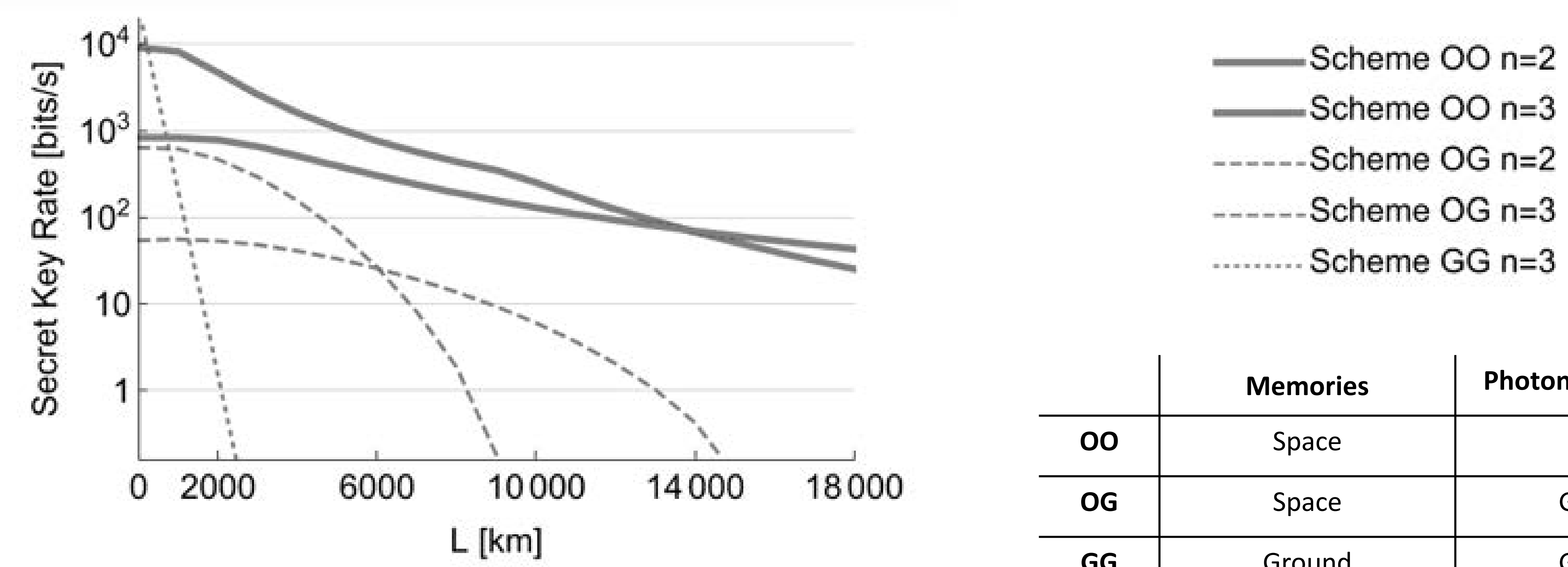

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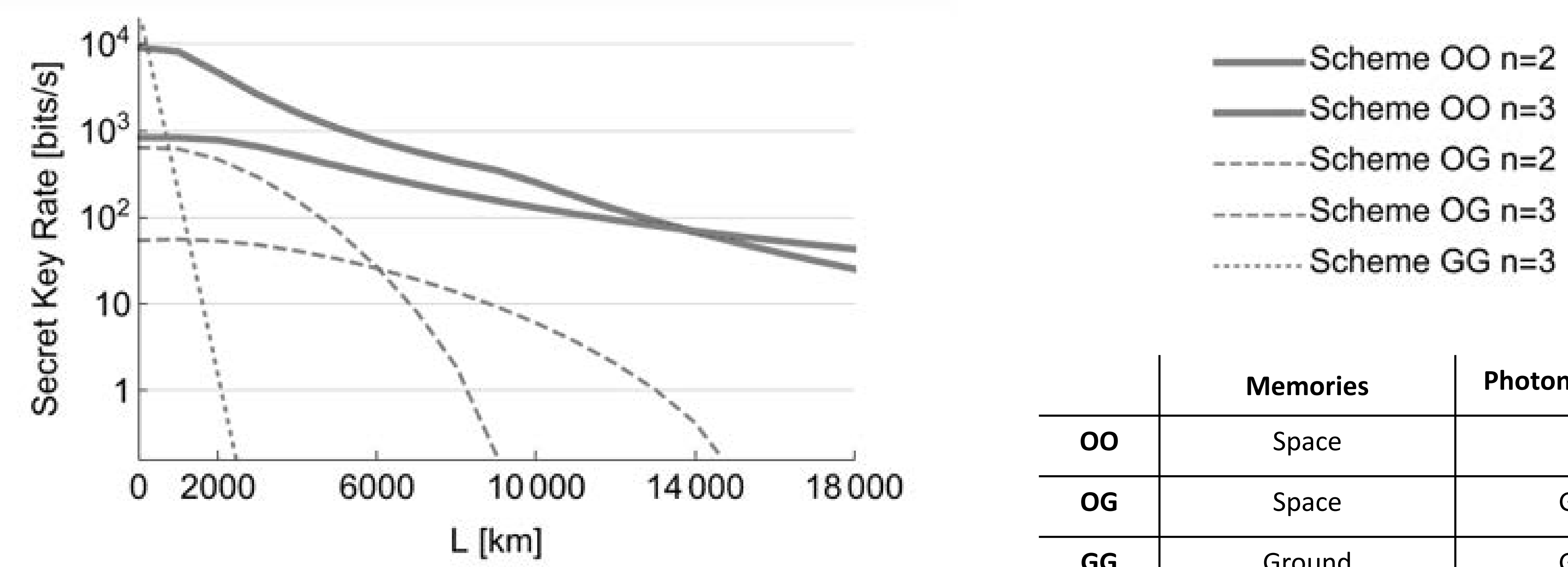

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C. Liorni, H. Kampermann and D. Bruß, New J. Phys **23**, 053021 (2021)

Outlook – experimental activities

Setting up an experiment at the HU Berlin based a Rb BEC for long storage times (OPTIMO-II).

Team: Dr. Elisa Da Ros, Dr. Victoria Henderson, Oliver Anton, MG and Markus Krutzik

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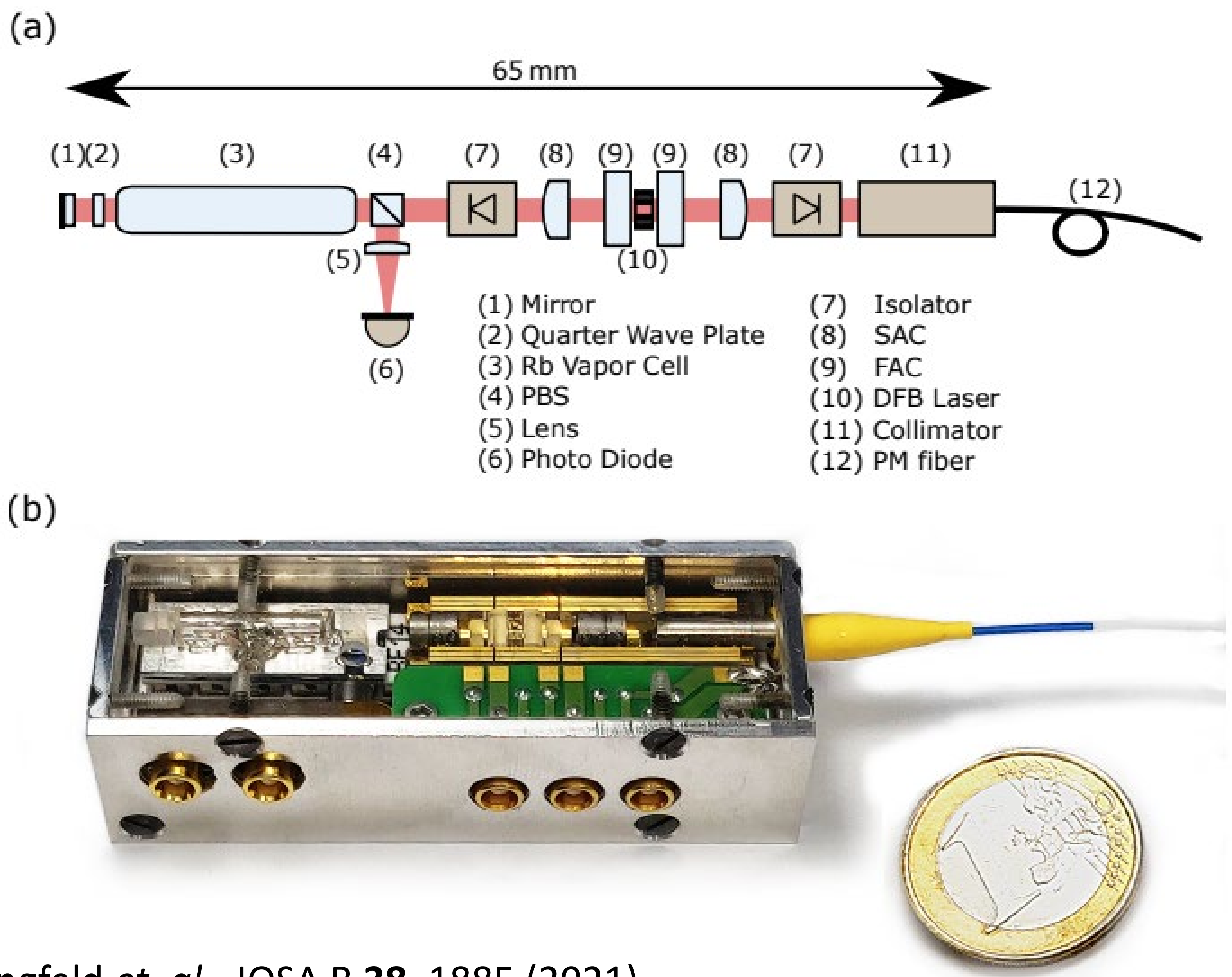
QuMSeC

Joint project with Prof. Janik Wolters from DLR/TU Berlin on portable, warm vapour memories.

Team: Martin Jutisz, MG, and Markus Krutzik

Overall Winner 2020

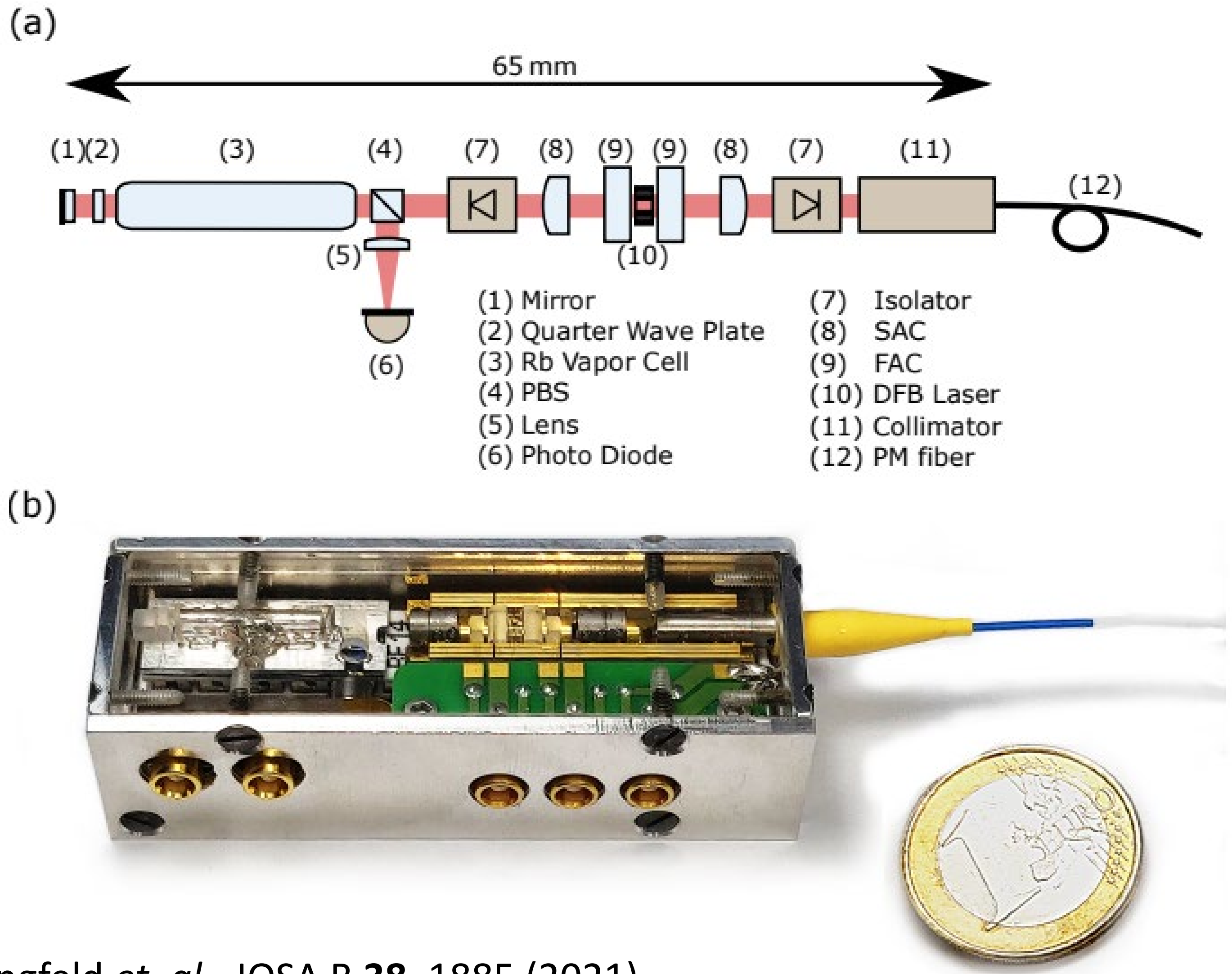
Outlook – experimental activities

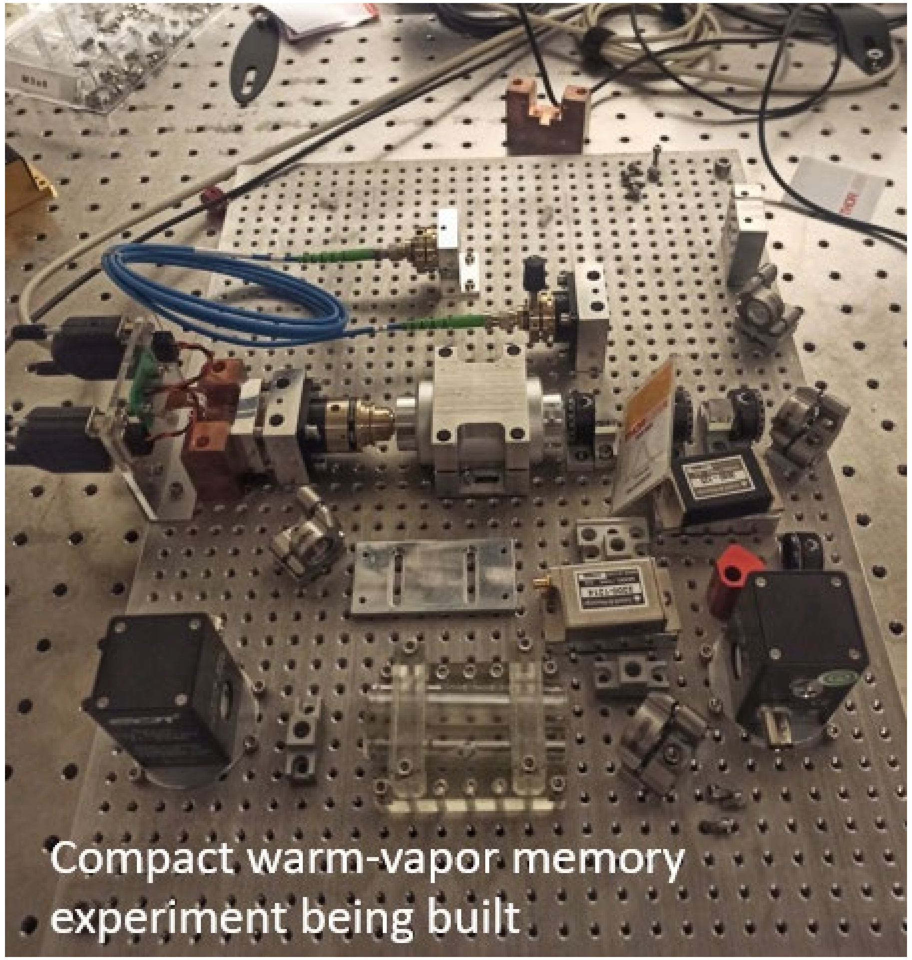


One of our ongoing activities:
Miniaturized warm-vapour atomic frequency reference based on Rb gas

A. Strangfeld *et. al.*, JOSA B **38**, 1885 (2021)

Outlook – experimental activities



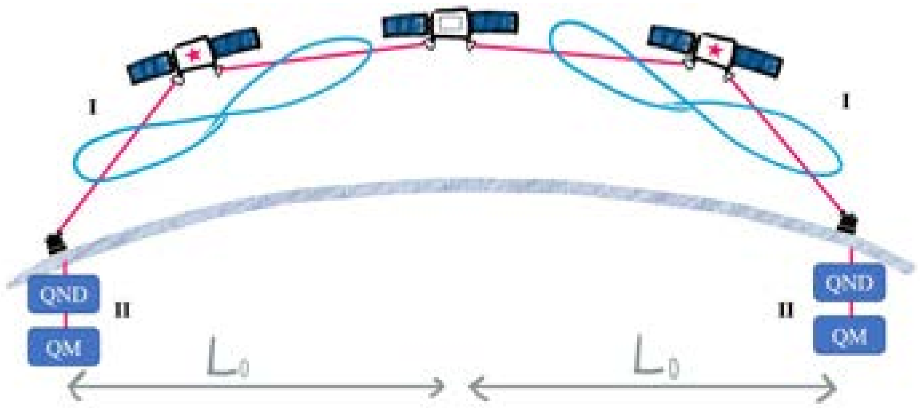


A. Strangfeld *et. al.*, JOSA B **38**, 1885 (2021)

Summary and conclusions

Motivations:

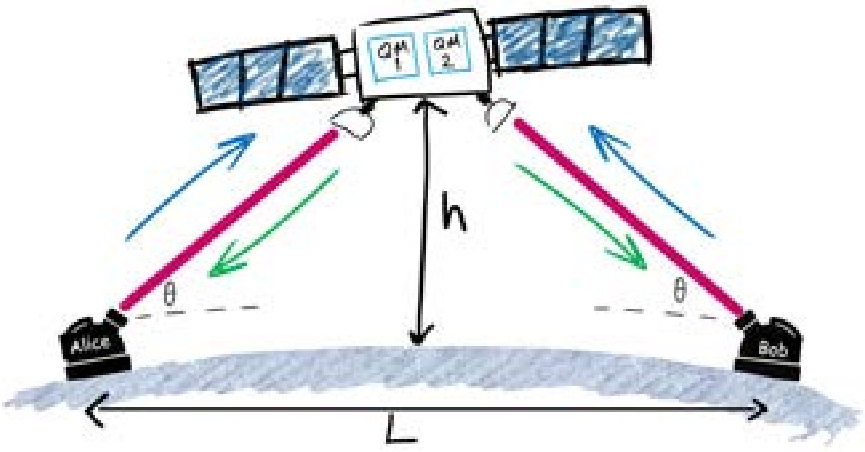
1: Reaching global distances is difficult even with (land-based) quantum repeaters
2: Atomic physics experiments in space are no longer a dream!



We extended the earlier space-ground repeater schemes and showed that space-based repeaters offer faster entanglement distribution times across the globe.

See also: C. Liorni, H. Kampermann and D. Bruß, New J. Phys. **23** 053021 (2021)

We quantified the advantage that memories would bring in space-based MA-QKD schemes.



Quantum memories will be crucial for **untrusted** global space quantum networks.

Acknowledgements

We acknowledge the support by the German Space Agency DLR with funds provided by the Federal Ministry of Economics and Technology (BMWi) under grant numbers 50WM1958 (OPTIMO), 50WM2055 (OPTIMO-2) and 50RP2090 (QuMSeC). MG acknowledges the European Union Horizon 2020 R&I programme Marie Skłodowska- Curie grant No. 894590 (QSPACE).