In-field entanglement distribution over a 96 km-long submarine optical fibre

Sören Wengerowsky,
Siddarth Koduru Joshi,
Fabian Steinlechner,
Julien R. Zichi,
Sergiy M. Dobrovolskiy,
René van der Molen,
Johannes W. N. Los,
Val Zwiller,
Marijn A. M. Versteegh,
Alberto Mura,
Davide Calonico,
Massimo Inguscio,
Hannes Hübel,
Anton Zeilinger,
André Xuereb,
Rupert Ursin

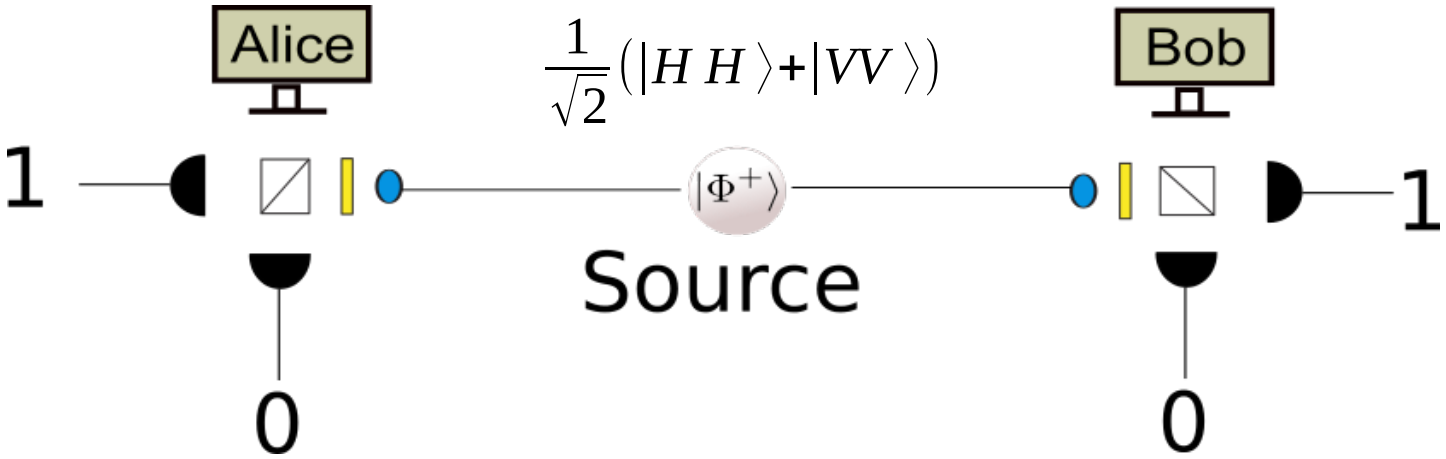
ÖAW AUSTRIAN ACADEMY OF SCIENCES

IQI Vienna

Soeren.Wengerowsky@oeaw.ac.at

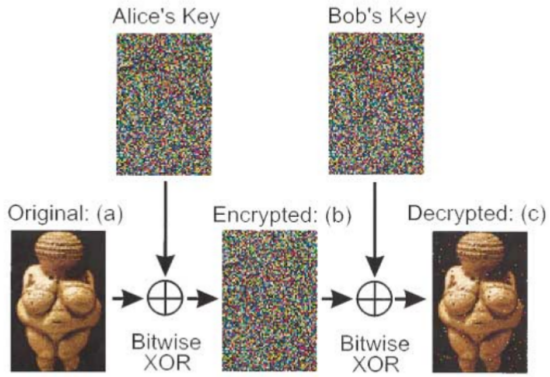
Entanglement makes QKD easy …

- Entanglement-based QKD:
  - Local results are objectively **random**
  - Outcomes are **correlated** → raw Key
  - No RNG needed, neither at the sender, nor at the receiver.



Ekert. A., Phys. Rev. Lett. 67, pp. 661-663 (1991)

Jennewein, T., et al. Phys. Rev. Lett. 84.20 (2000)
Naik DS, et al. Physical Review Letters 84(20):4733–4736.
Tittel W. et al. Physical Review Letters 84(20):4737–4740.



Overview

Optical Fiber

Author	Deg. of Freedom	Distance Alice - Bob	Channel length	
Hübel et al. 2007	Polarization	Lab	100 km	Asym.
Salart et al. 2008	Energy-Time	18 km	35 km	Sym.
Treiber et al. 2009	Polarization	~ 10 km	16 km	Asym.
Inagaki et al. 2013	Time-Bin	Lab	300 km	Sym.
Valivarthi et al. 2016	Time-Bin	16 km		Teleportation
Sun et al. 2016	Polarization	30 km		Teleportation
Sun et al. 2017	Time-Bin	12.5 km	100 km	Ent. Swap

Free Space

Ursin et al. 2007	Polarization	144 km	144 km	Asym.
Scheidl et al. 2009	Polarization	144 km (Source-Bob)	288 km	Sym.
Yin et al. 2017	Polarization	1200 km	1600 – 2400 km	Sym. Satellite
Yin et al. 2017	Polarization	1000 km	530 – 1000 km	Asym. Satellite

Overview

Optical Fiber

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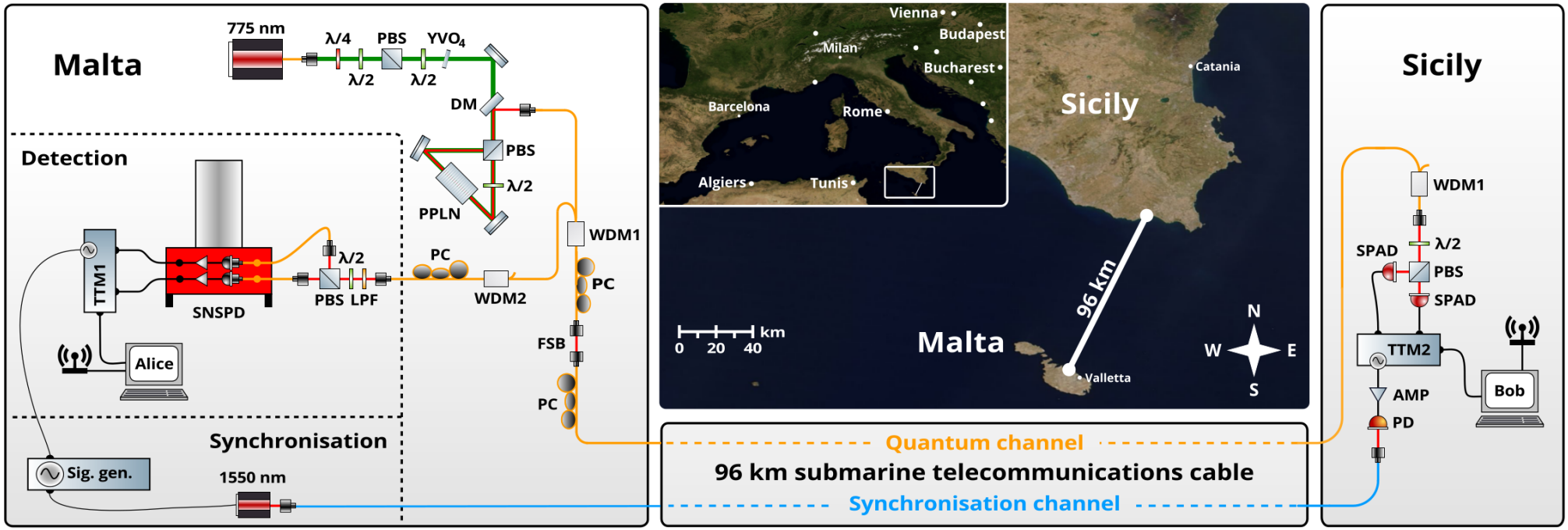
Sun et al. 2017	Time-Bin	12.5 km	100 km	Ent. Swap
This Work	Polarization	94.2 km	96 km	Asym.
This Work	Polarization	Lab	192 km	Asym.

Ding et al., "Polarization variations in installed fibers and their influence on quantum key distribution systems," Opt. Express 25, 27923-27936 (2017)

The Fiber Cable

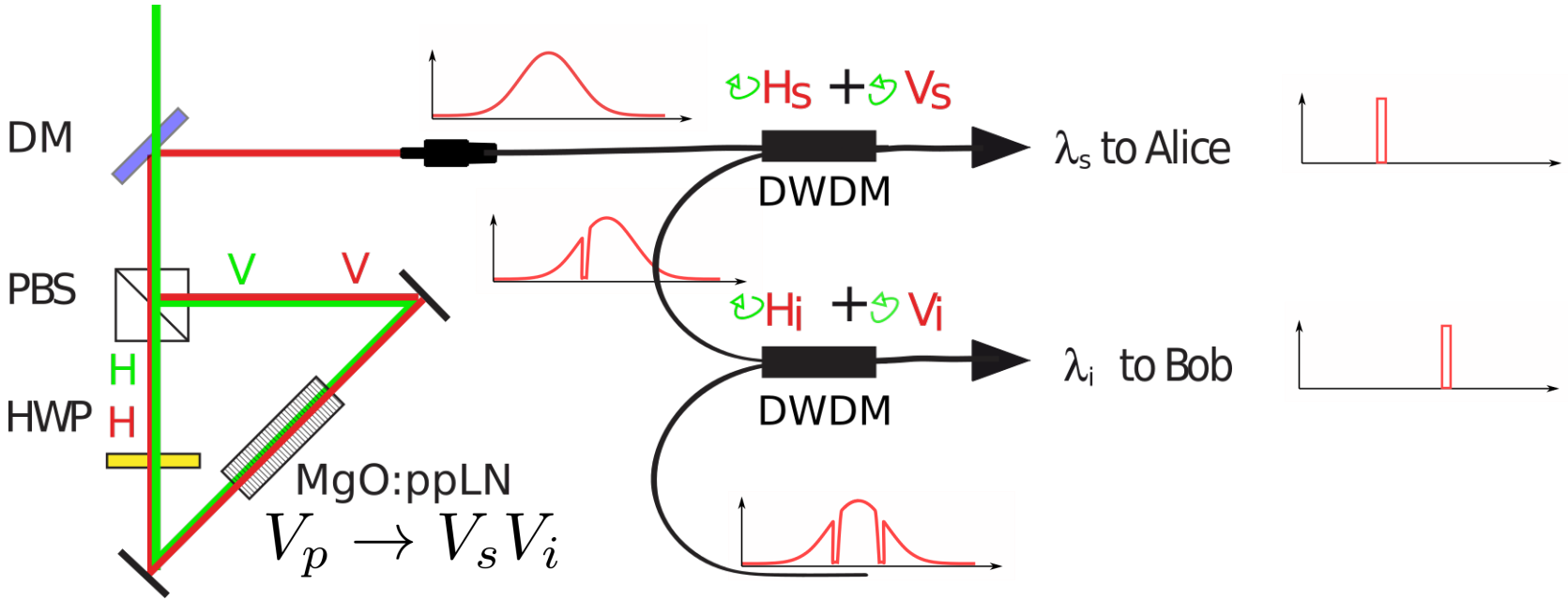
- 24 strands
- Deployed on ocean floor, partially buried
- NZDSF (“Corning Leaf”)
  Dispersion: 6 ps/(nm*km)
- 4 Fibers are transmitting live internet data
- 2 Dark Fibers were used by us.

Setup



-22 dB attenuation

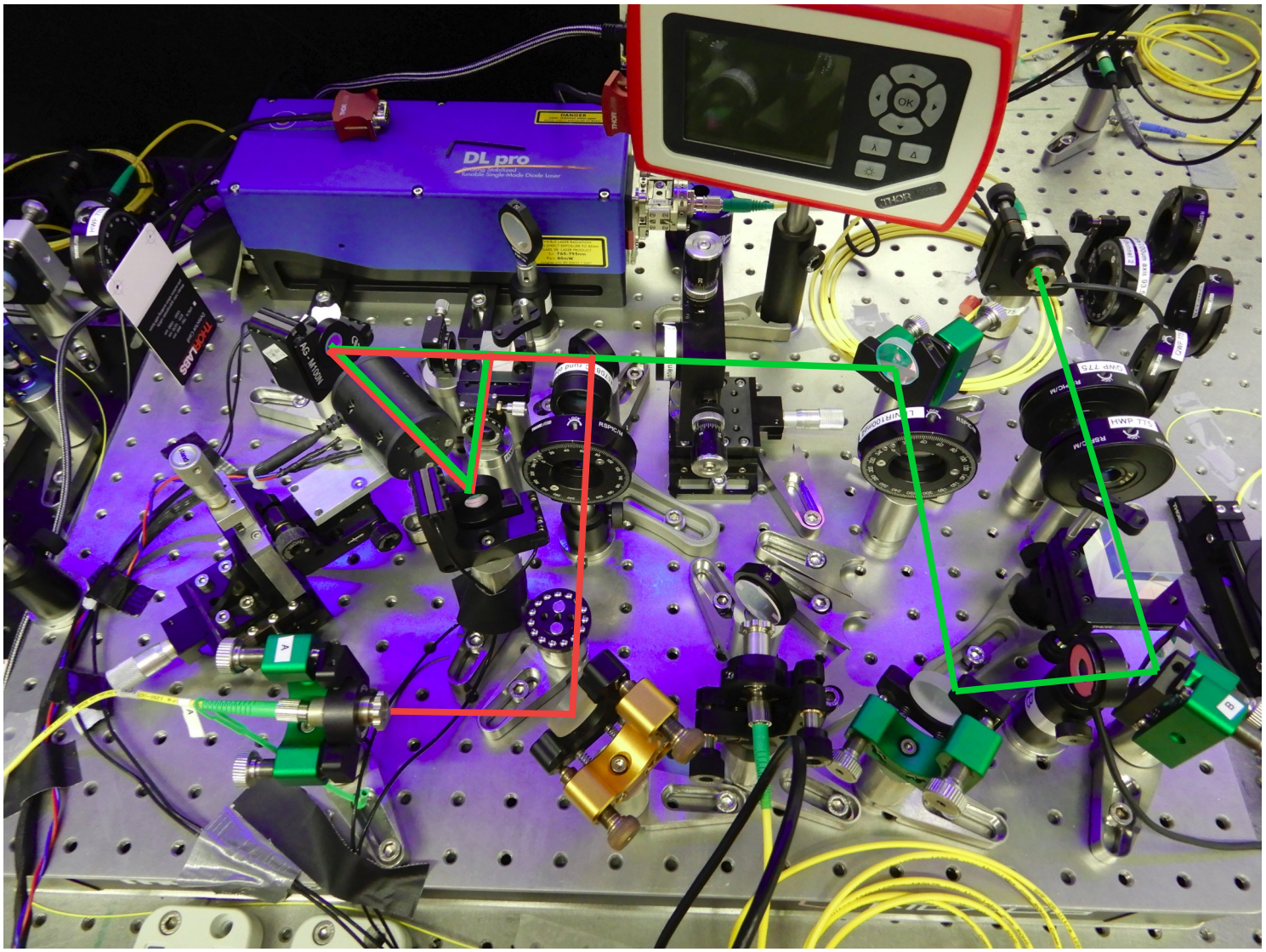
Type – 0 Sagnac Source



$$|\Phi\rangle = |\circlearrowright\rangle + e^{i\varphi}|\circlearrowleft\rangle$$

$$|\Phi^+\rangle = |H_s H_i\rangle + |V_s V_i\rangle$$

T. Kim, M. Fiorentino, and F. N. C. Wong, Phys. Rev.A73, 012316 (2006)


DL pro
OK

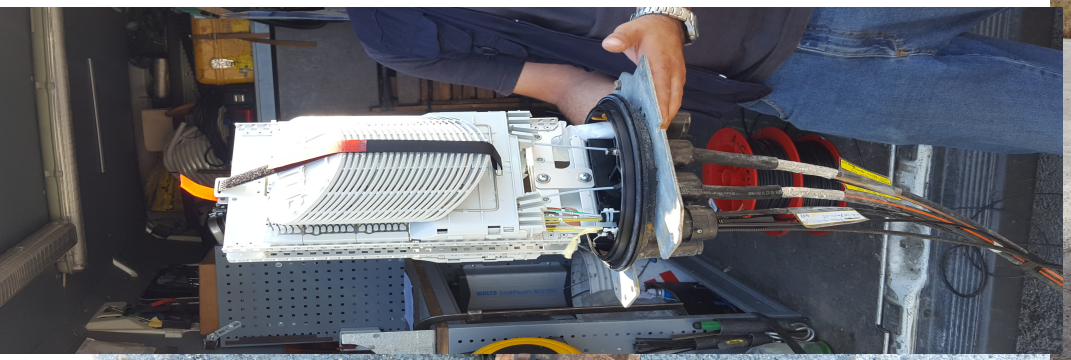
Malta

- Melita Datacenter

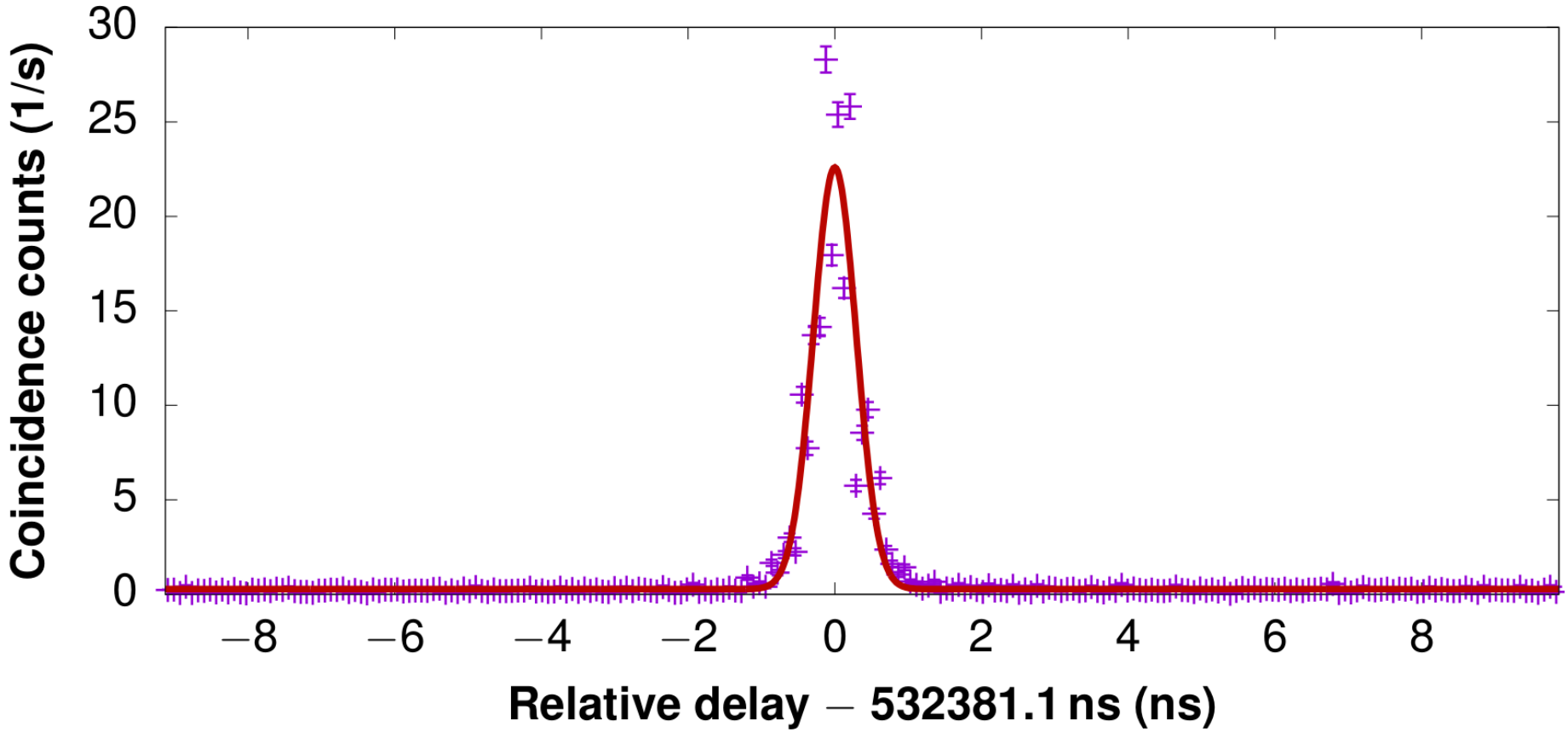
Soeren.Wengerowsky@oeaw.ac.at

Pozzallo / Sicily

- Access through a manhole
- Receiver in a car



Cross-correlation

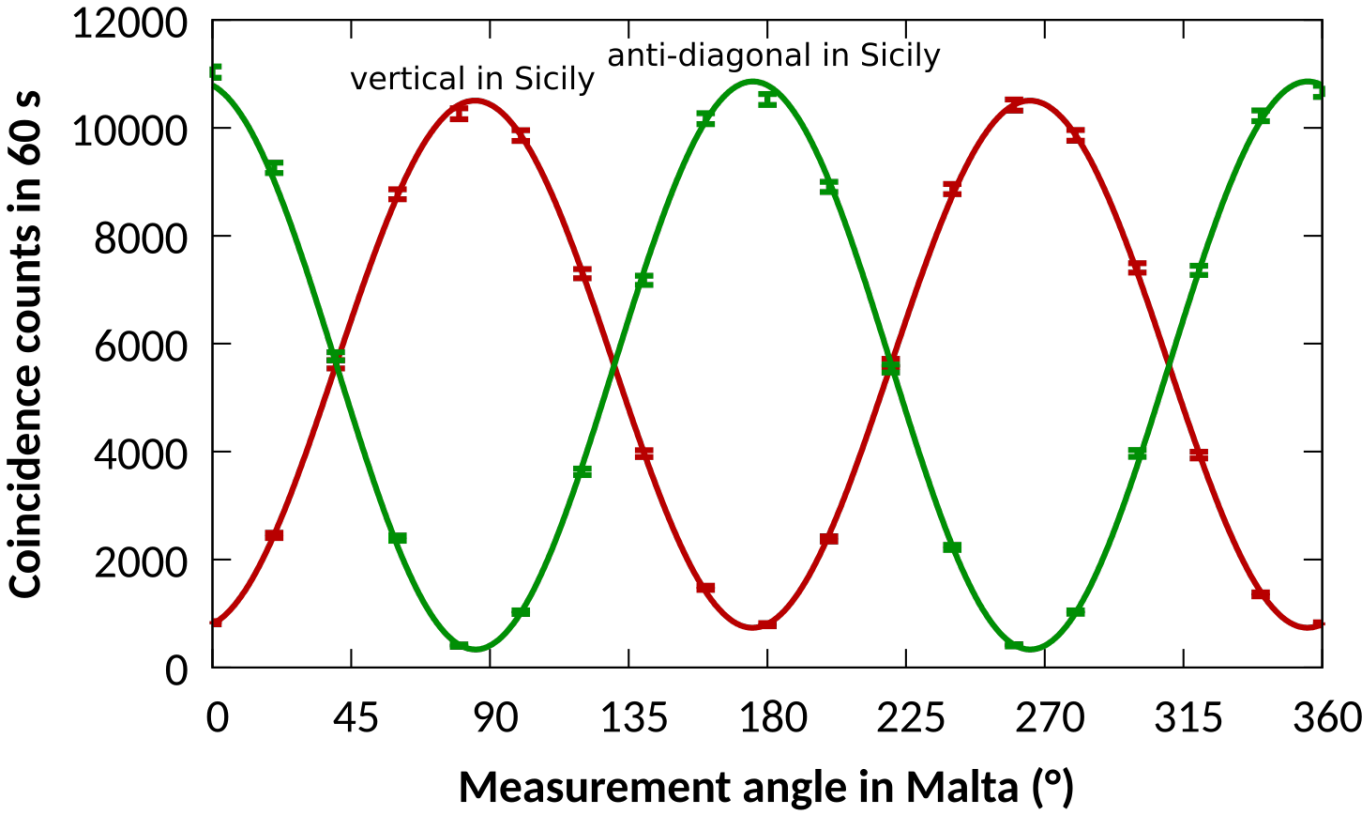


Integration time: 60 seconds, scaled to Hz

The FWHM ~ 0.7 ns (Gaussian)

- timing uncertainty of the SPADs in Sicily (approx. 450 ps)
- the dispersion of the fiber link (approx. 380 ps)
- other effects e.g. jitter of the time-bins in the time-tagging units (approx. 180 ps).

Visibility

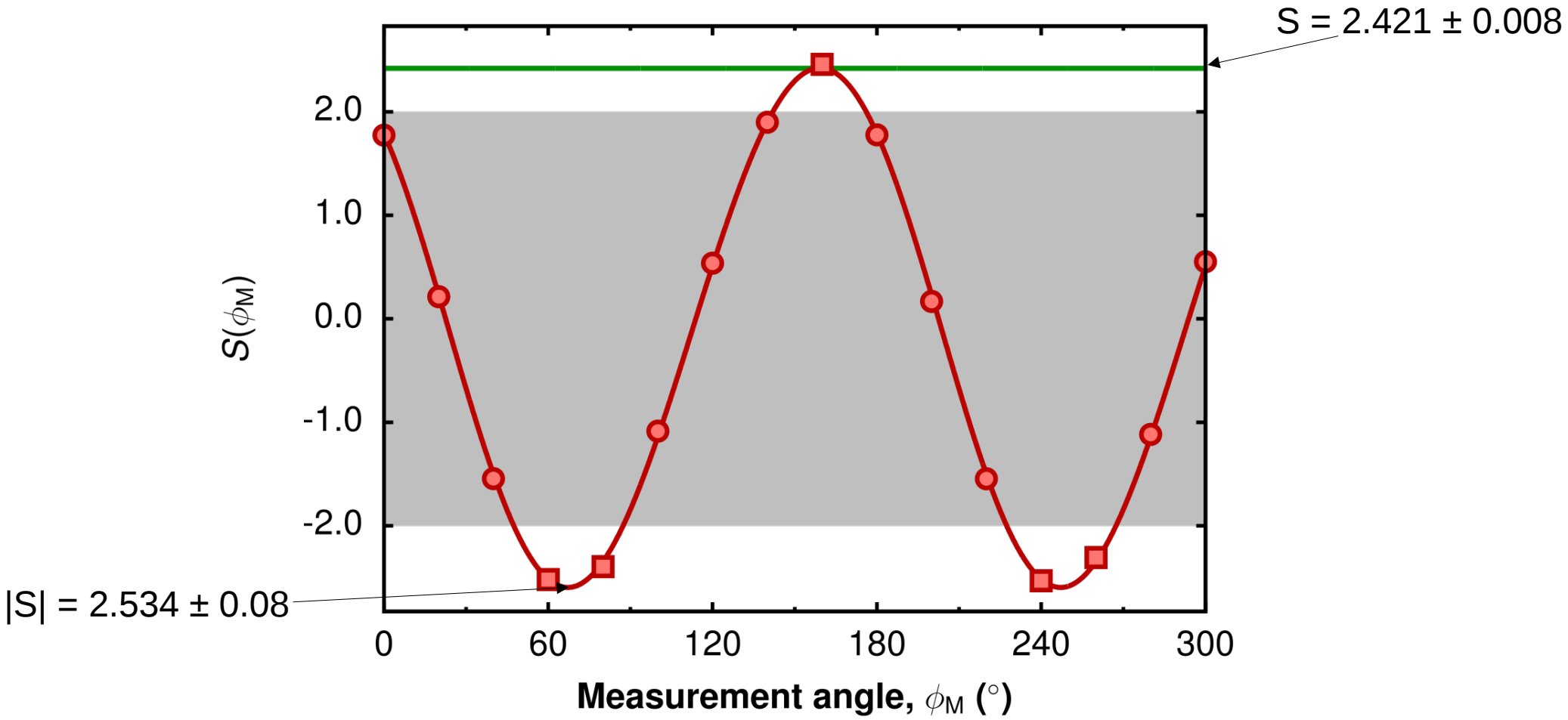


Results:

- Visibility:
  - HV: 86.8+- 0.8%
  - DA: 94.1+- 0.2%
- Coincidence rate ~ 250 Hz
- => Secure Key rate ~ 30 Hz

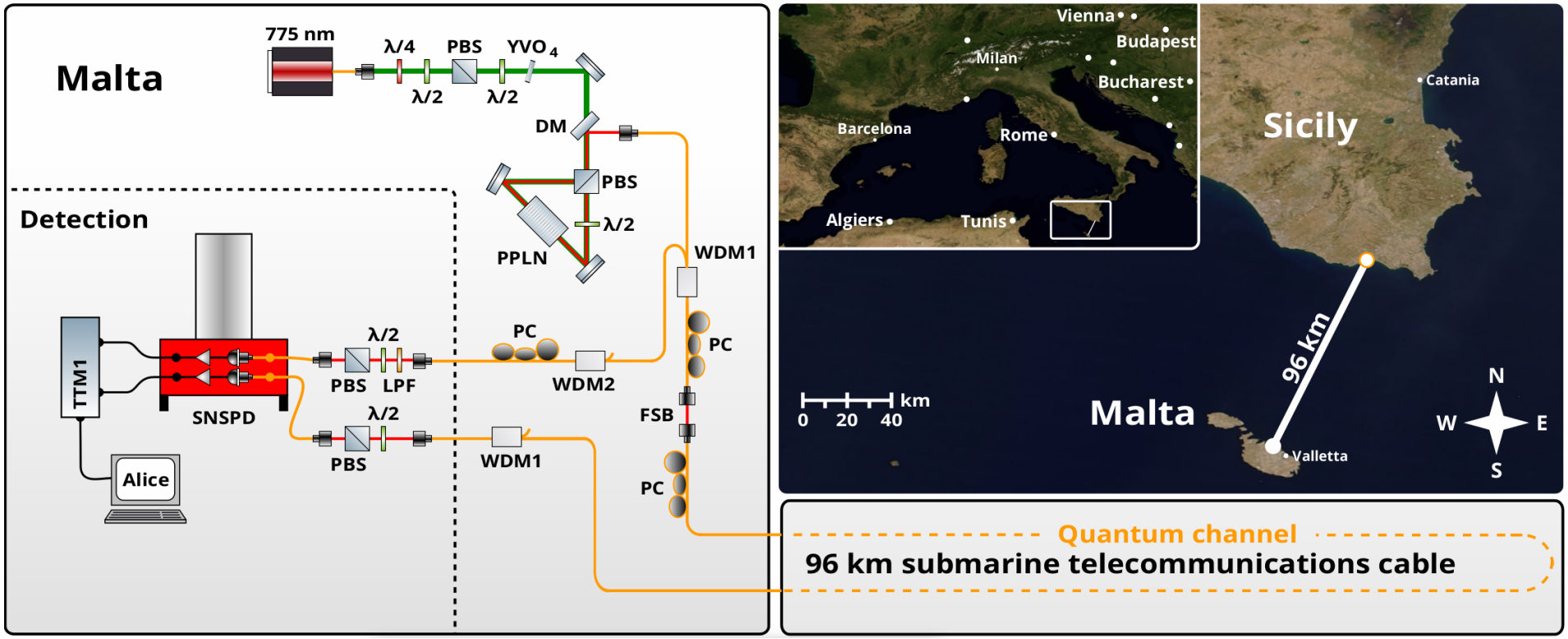
X. Ma, C.-H. F Fung, and H.-K. Lo Physical Review A 76.1 (2007): 012307.

CHSH Violation



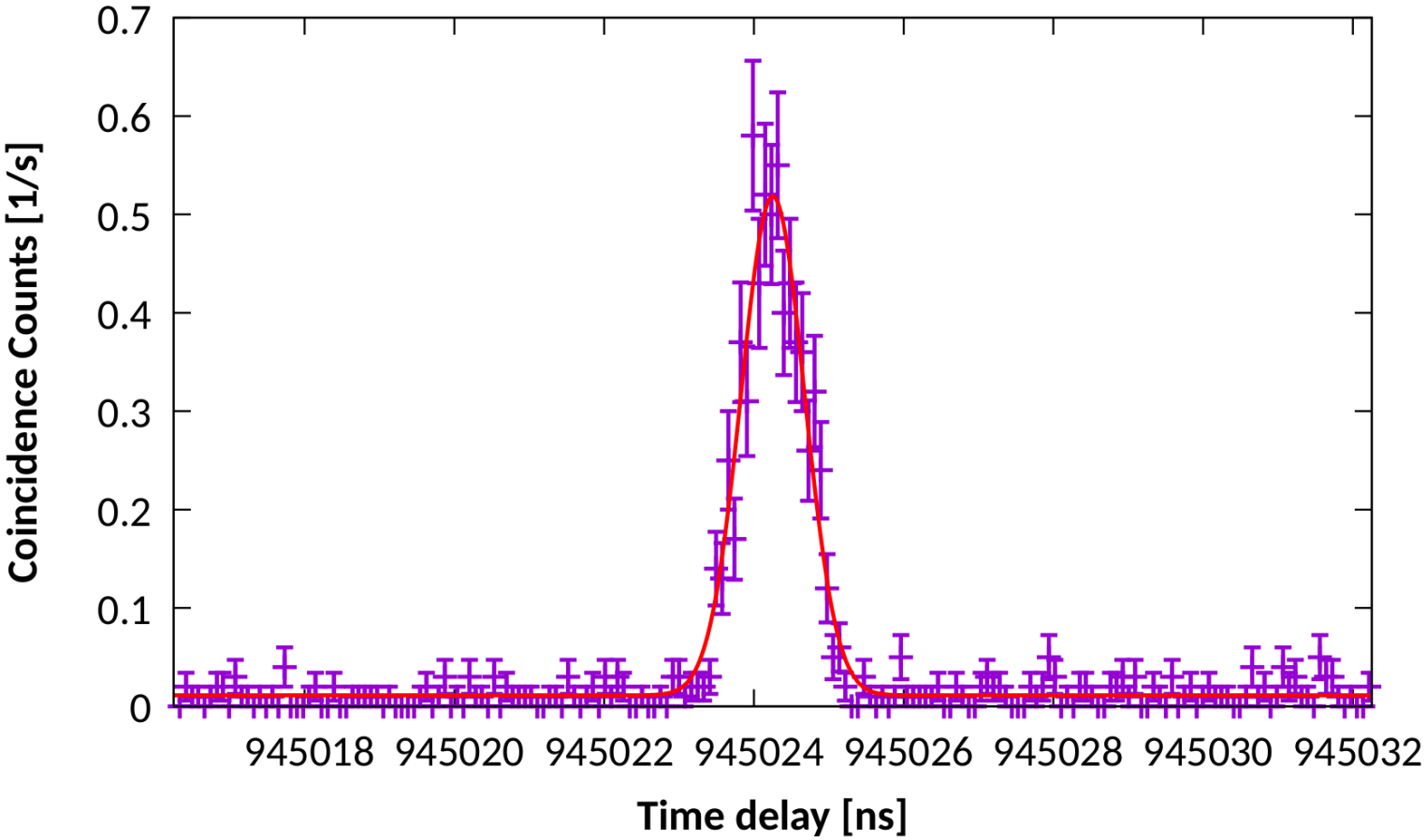
CHSH quantity $S(\varphi_M)$ as a function of the measurement angle for the analyser in Malta, φ_M

Malta → Malta



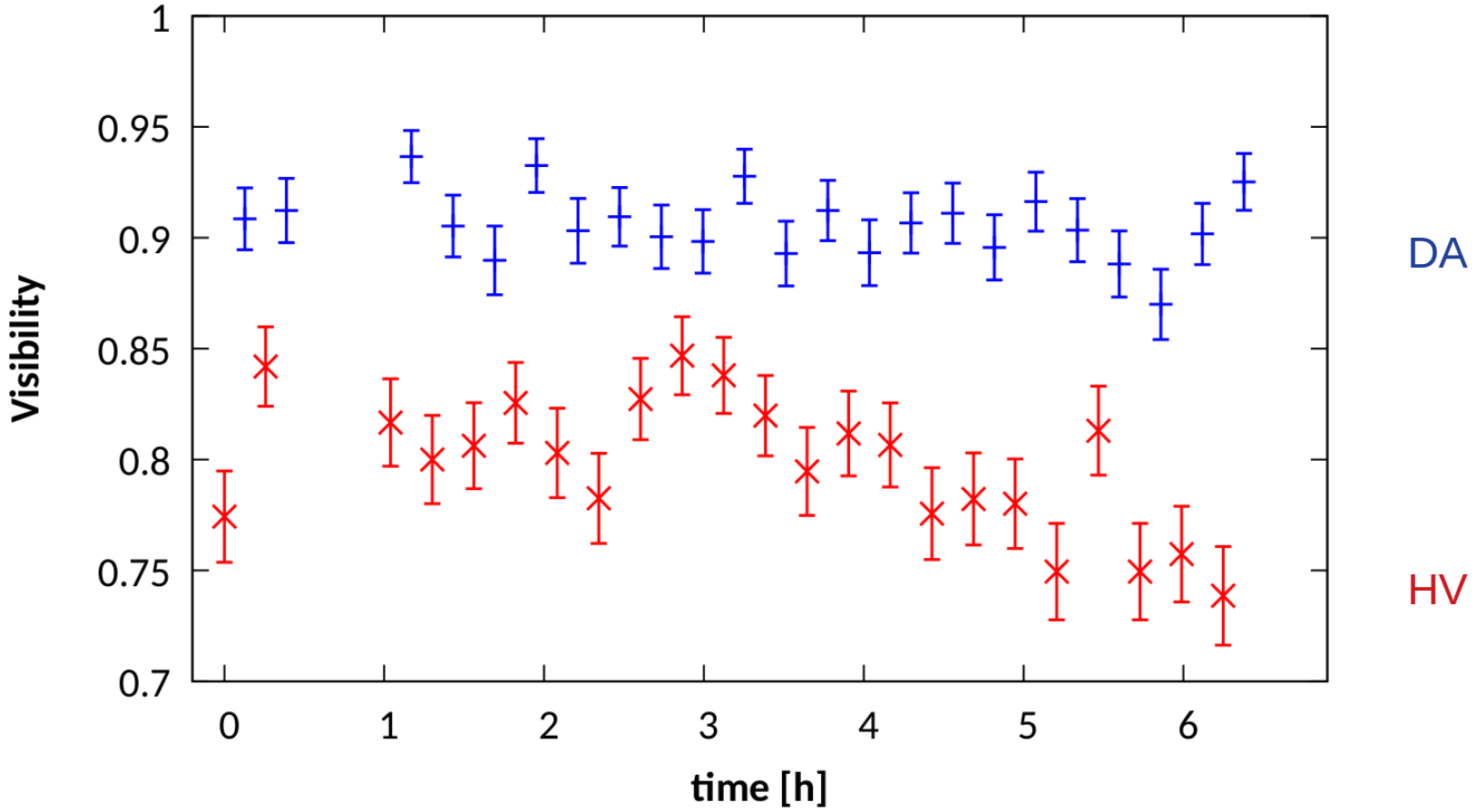
-48 dB attenuation

Cross-correlation



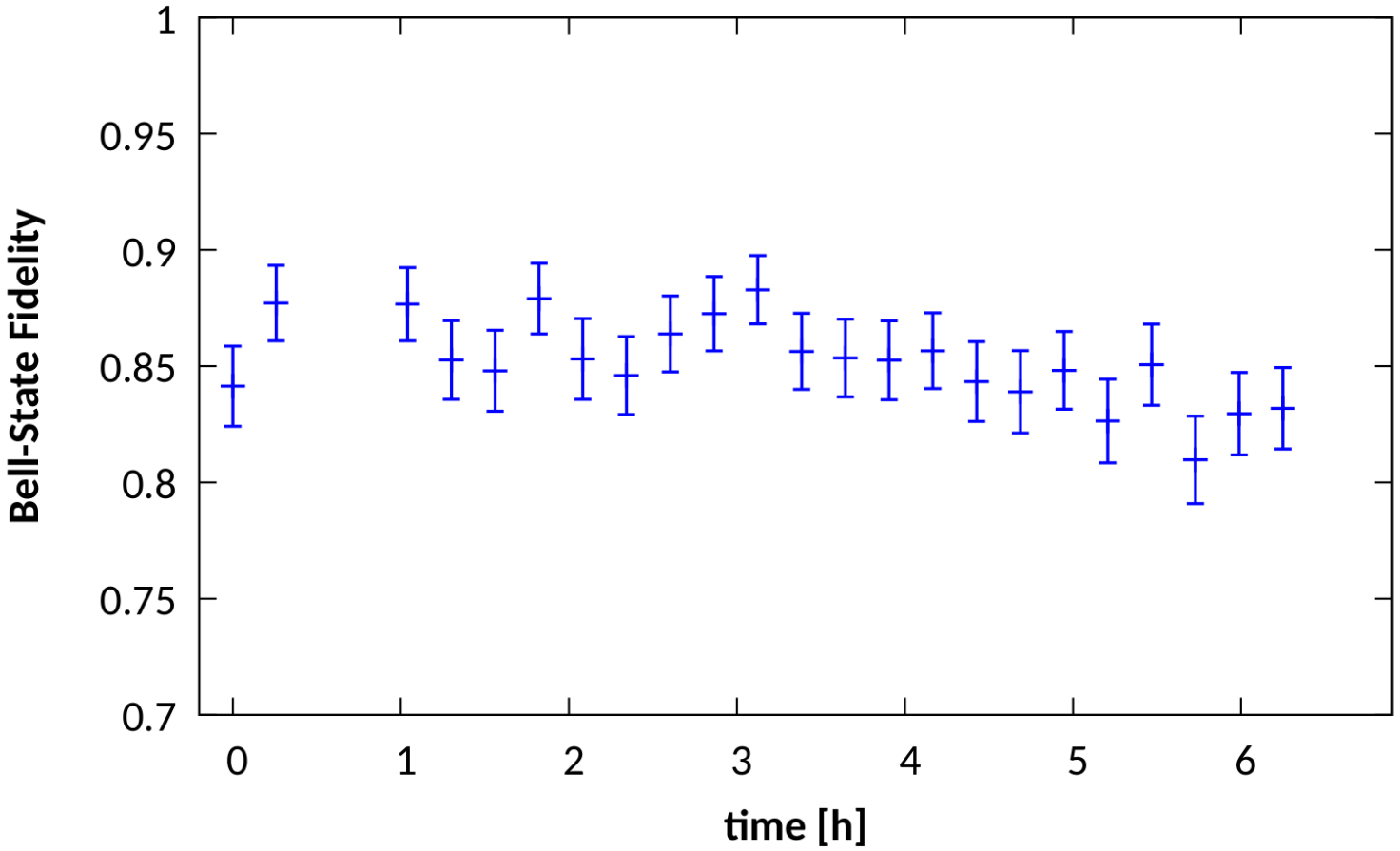
- 100 seconds integration time (~ 3.8 Hz)
- Fit: FWHM of 820 +- 20 ps
- ~760 ps chromatic dispersion
- FWHM of local measurement of the source and detectors: ~ 250 +- 20 ps
- Distance compared to OTDR measurement – off by ~ 200 m

Visibility vs. time



- Polarisation entanglement maintained over night, no significant drift over night
- Most symmetric values measured (not in graph): HV: 85 +- 2 %
  DA: 86 +- 2 %
- Possible secret key rate: 0.4 Hz

Visibility vs. time



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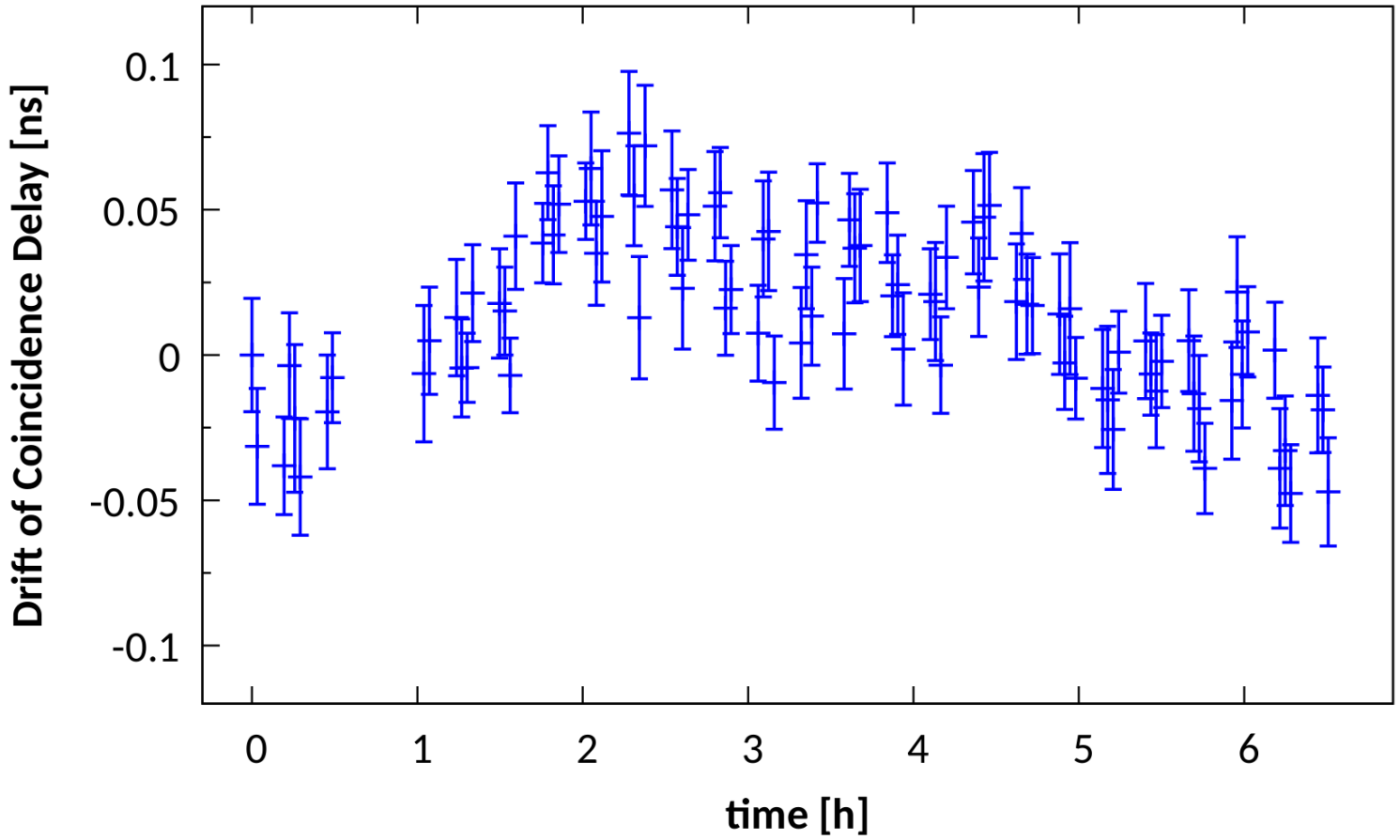
Drift of Coincidence Peak



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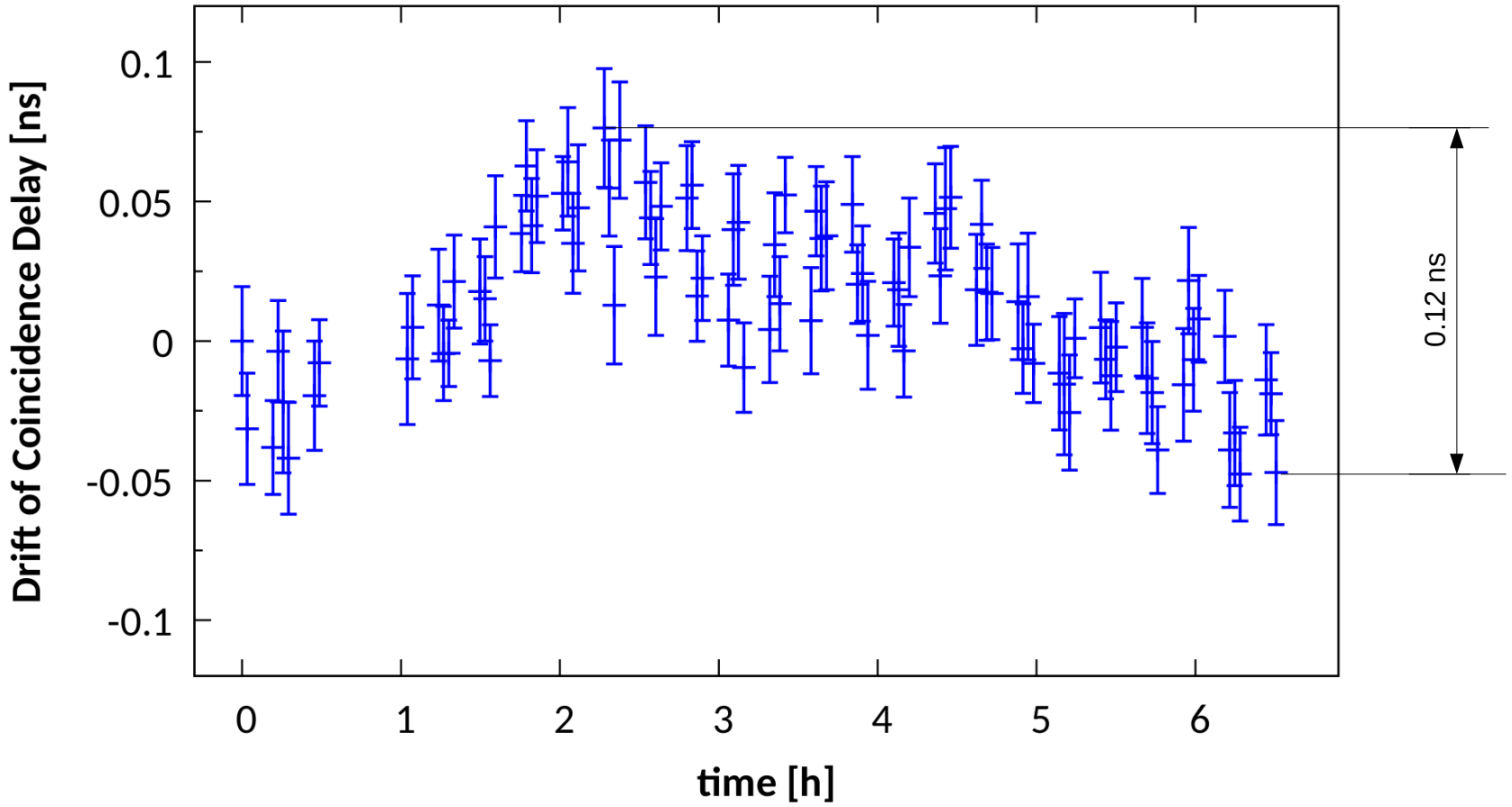


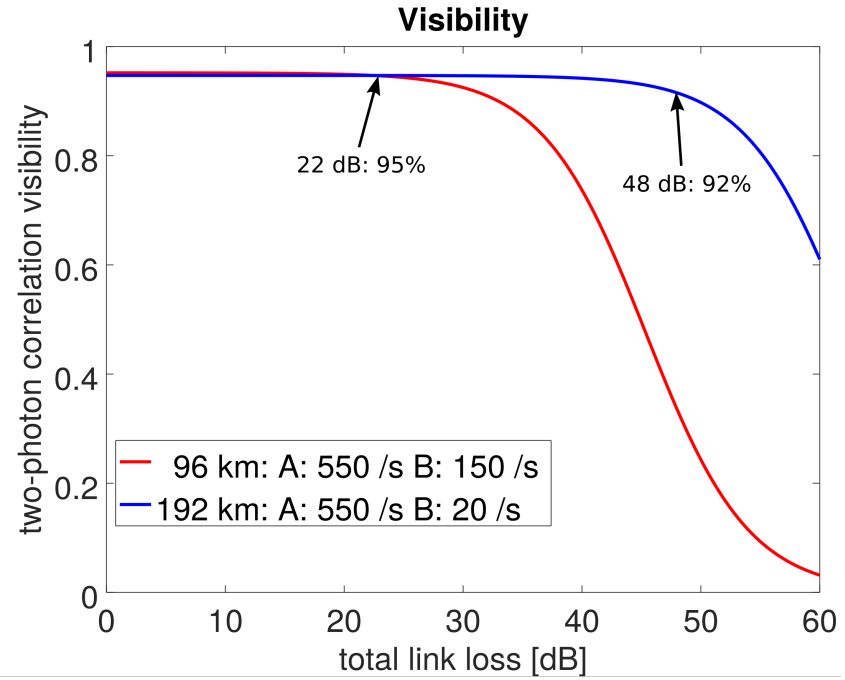
$$\frac{d(nL)}{dT} = L \underbrace{\frac{dn}{dT}}_{6.6*10^{-6}} + n \underbrace{\frac{dL}{dT}}_{5.6*10^{-7}}$$

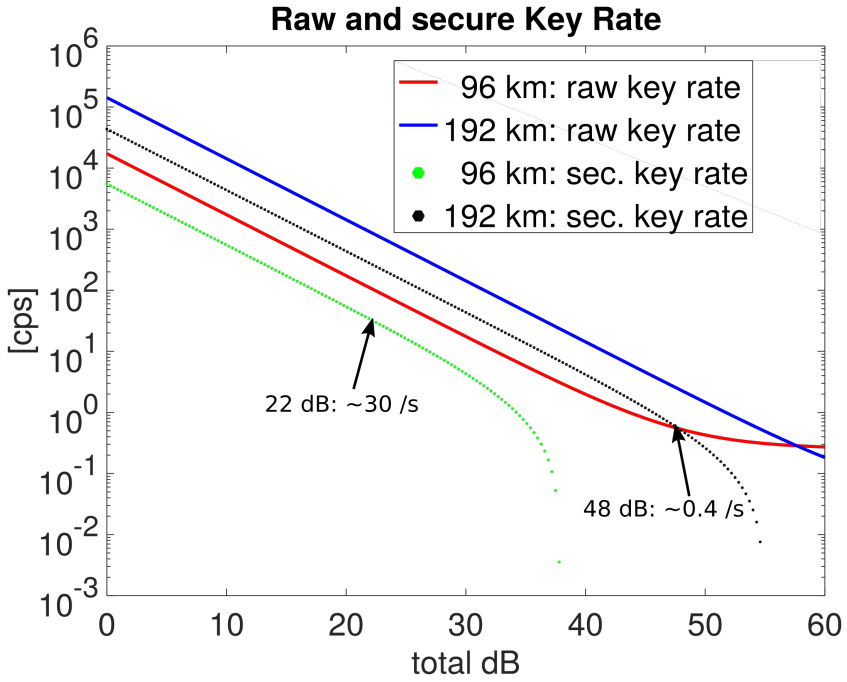
- change of refractive index dominates
- Temperature change: < 30 mK
- length change ~ 3 mm

Link Budget

- Accidental coincidences deteriorate the visibility
- Detectors in Sicily: 10% and 3% efficiency (~550 and ~150 dark counts)
- SNSPD in Malta: ~60% (~550 dark counts)
- Bob SNSPD for 192 km Experiment: 12% Efficiency and 20 dark counts.

- Next Steps:
  - Dispersion Compensation
  - Detectors with less timing uncertainty





Ma X, Fung CHF, Lo HK (2007) Physical Review A 76(1):012307

Thanks

More Details?
ArXiv: 1803.00583

Questions?
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Questions or suggestions?
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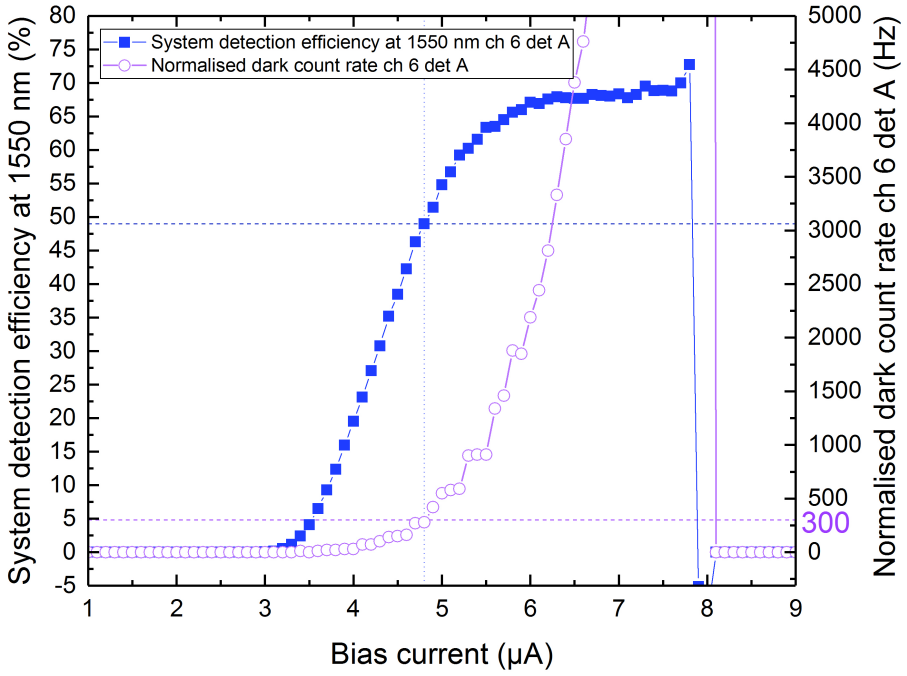
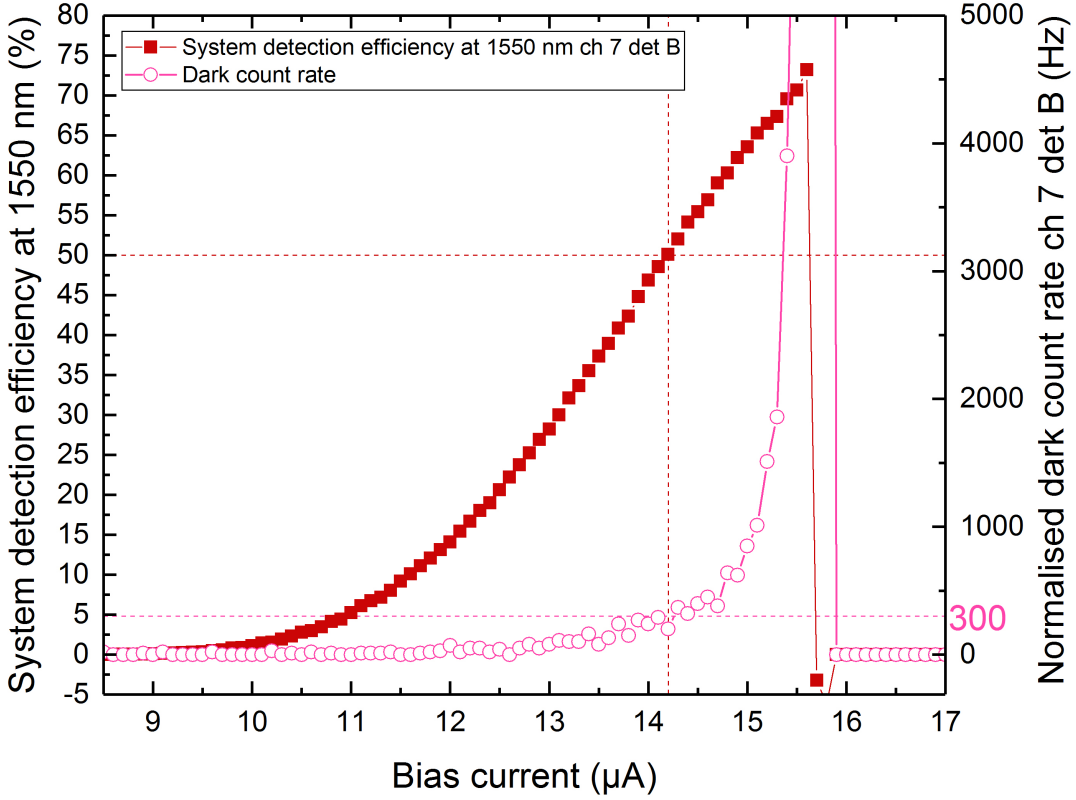
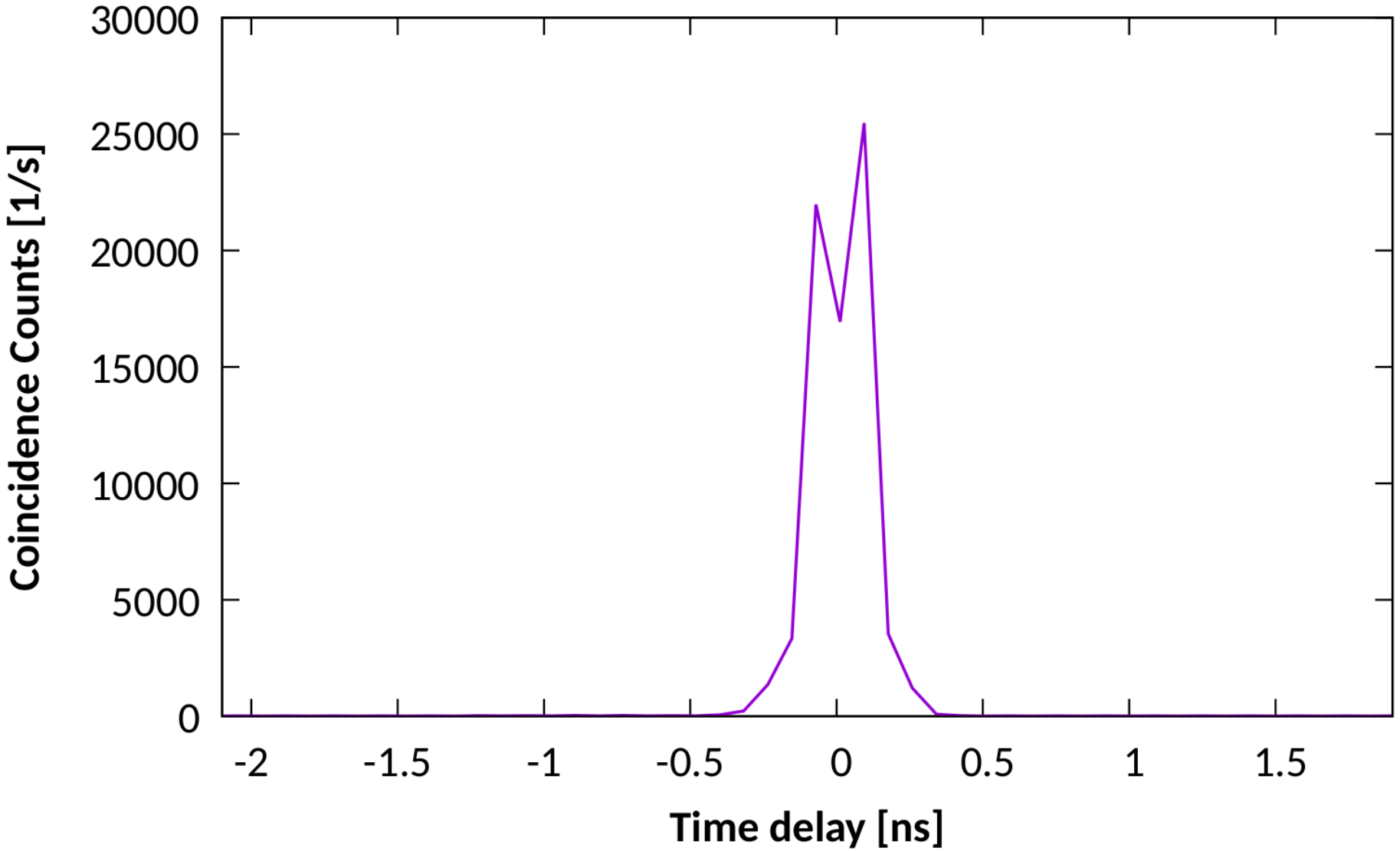
ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN
FWF
esa
FFG
IQI Vienna

SNSPD dark counts

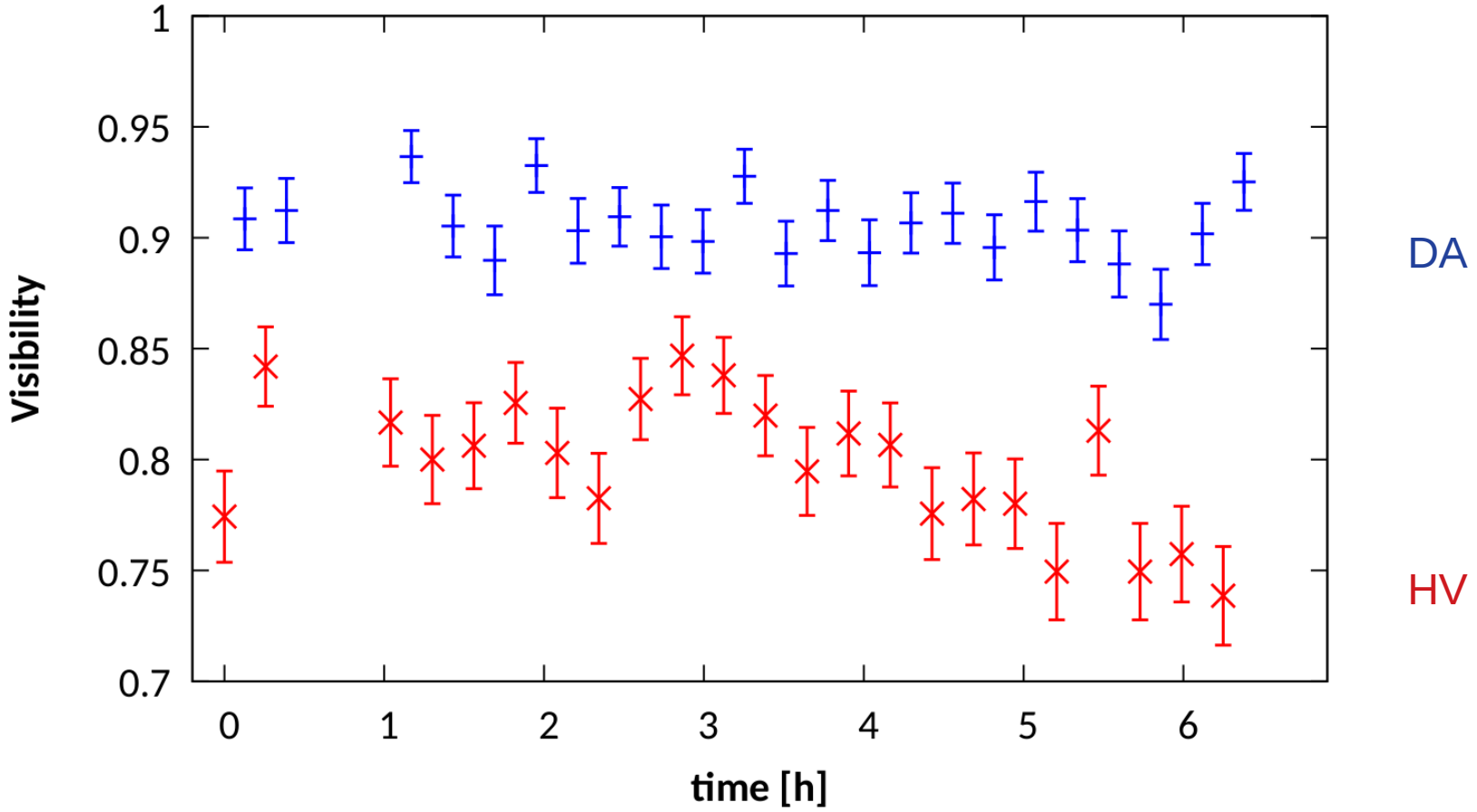




Source and SNSPDs locally



Visibility vs. time



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- Best values measured (not in graph): HV: 85 +- 2 %
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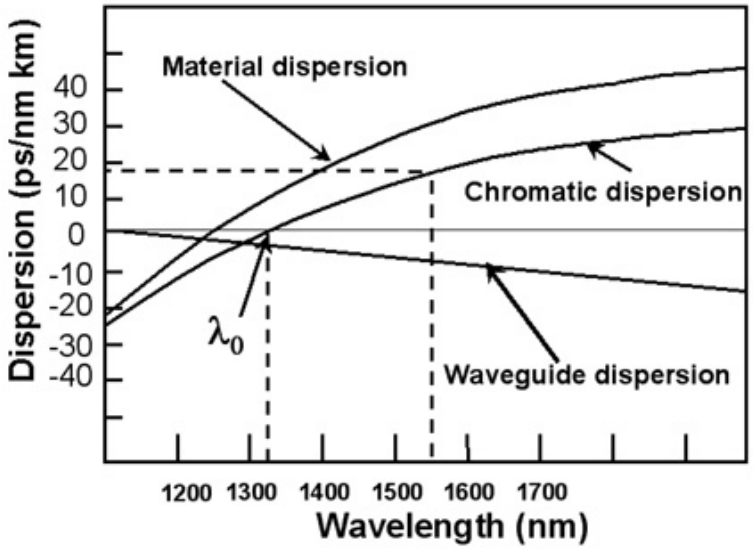
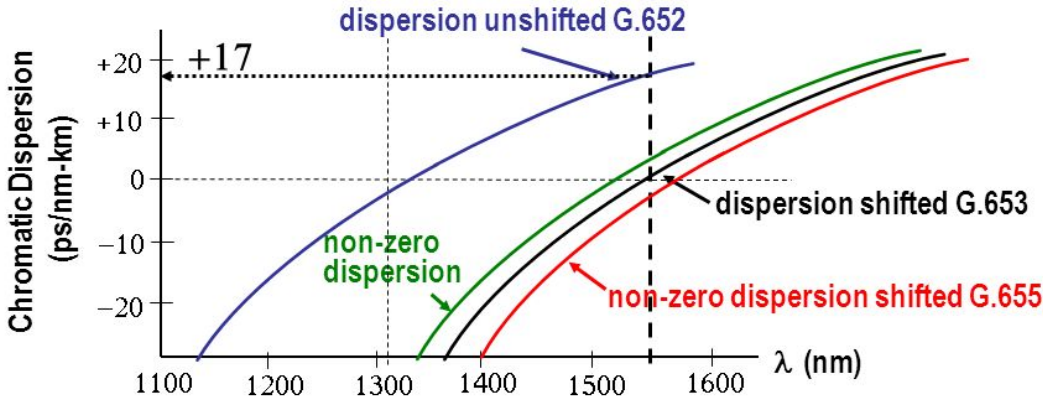
Dispersion



$$D = \frac{-1}{c\,\lambda}\,\lambda^2\,\frac{d^2 n_{eff}(\lambda)}{d\,\lambda^2}$$



- “Corning Leaf” (Malta-Sicily): 4.5 – 6 ps/(nm*km)
- SMF28: 17 ps/(nm*km)

Yariv, Yeh: Photonics, 6th Ed. 2009, Oxford University Press

http://slideplayer.com/slide/6926786/

- Accidental coincidences deteriorate the visibility
- Detectors in Sicily: 10% and 3% efficiency (~550 and ~150 dark counts)
- SNSPD in Malta: 55% and 60% (~550 dark counts)
- SNSPD for 192 km Experiment: 10% Efficiency and 20 dark counts.

- Next Steps:
  - Dispersion Compensation
  - Detectors with less timing uncertainty