MPQ LMU
MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK
LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

xqp HARALD WEINFURTER
EXPERIMENTAL QUANTUM PHYSICS

Event-Ready loophole free Bell Test
using
Heralded Atom-Atom Entanglement

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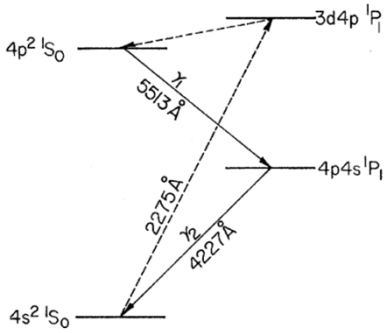
ENB-ExQM, EU-QWAD, BMBF-Q-Com-Q, NIM, DFG

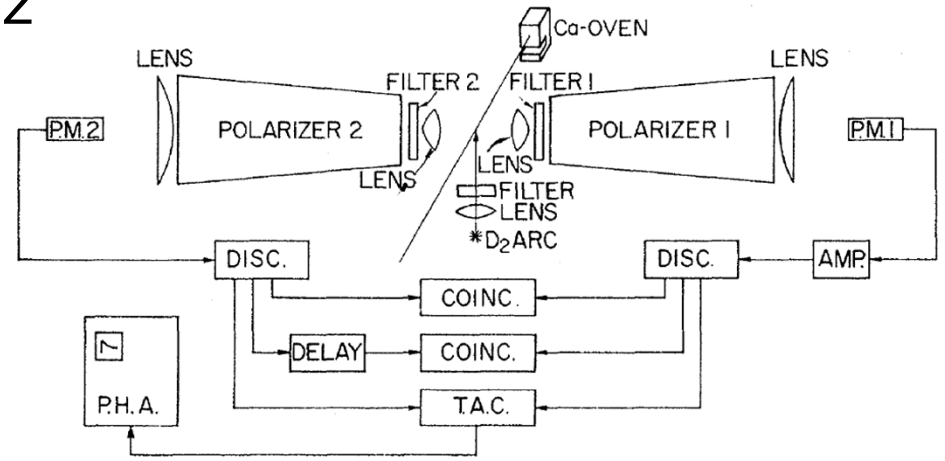
Overview

- Atom-Atom-Entanglement
  - atom-photon entanglement + entanglement swapping
  - fast and efficient state detection
- loophole free Bell-test
  - device independence – random numbers
- DI key distribution
- quantum repeater

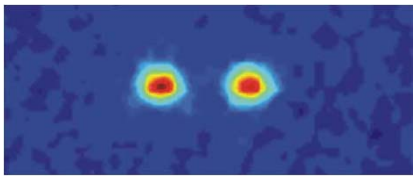
experimental tests

- Freedman, Clauser 1972





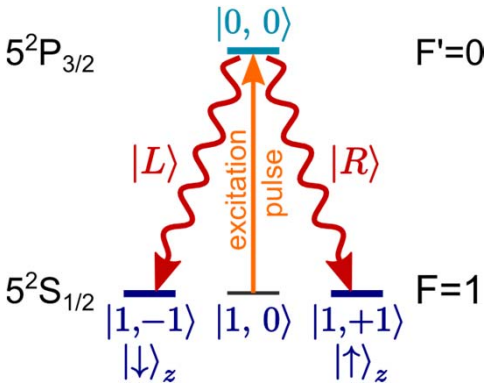
- loopholes: detection, locality
  - Rowe et al. 2000 (Ch. Roos et al. 2004): efficient detection of 2 entangled ions

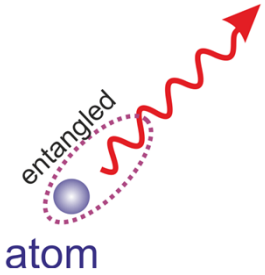


  - Weihs et al. 1998: independent observers

starting point

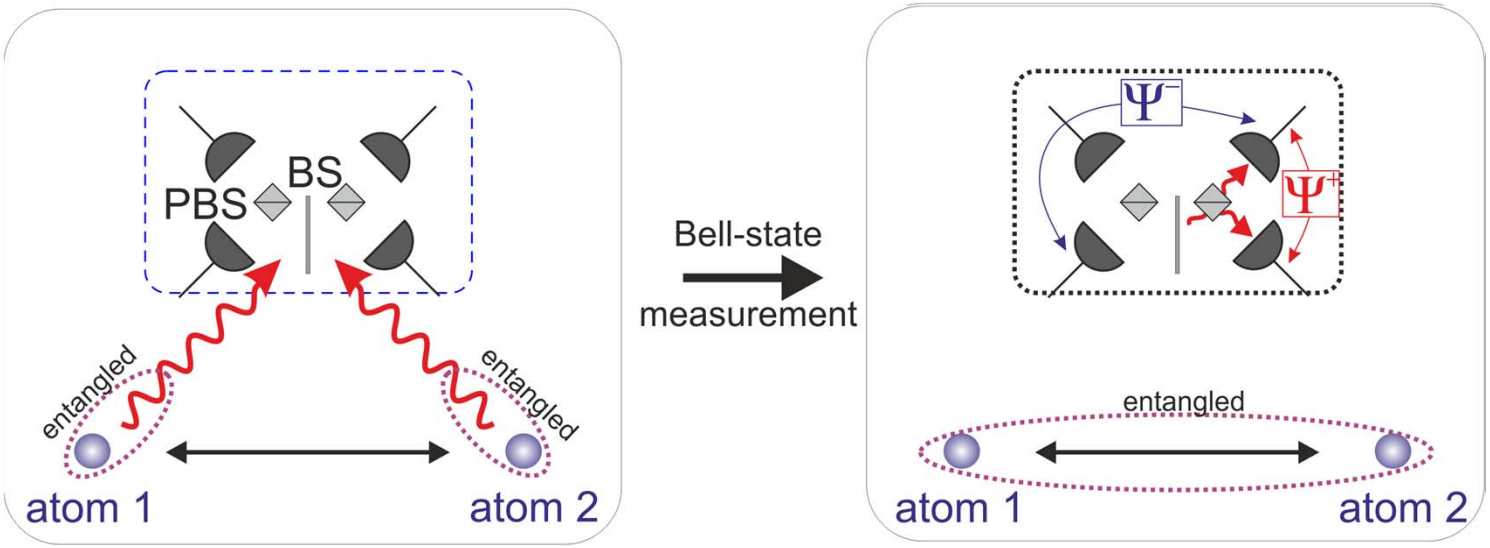
^{85}Rb





$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\rangle_z |L\rangle + |\uparrow\rangle_z |R\rangle\right)$$

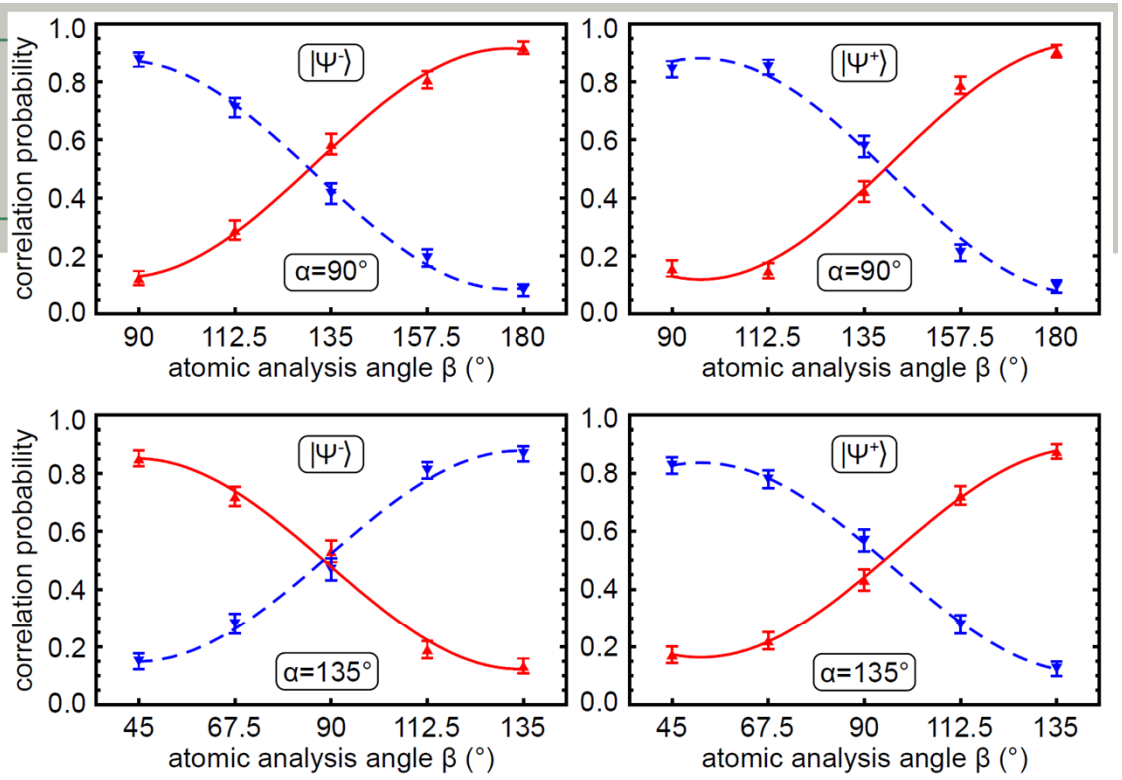
starting point



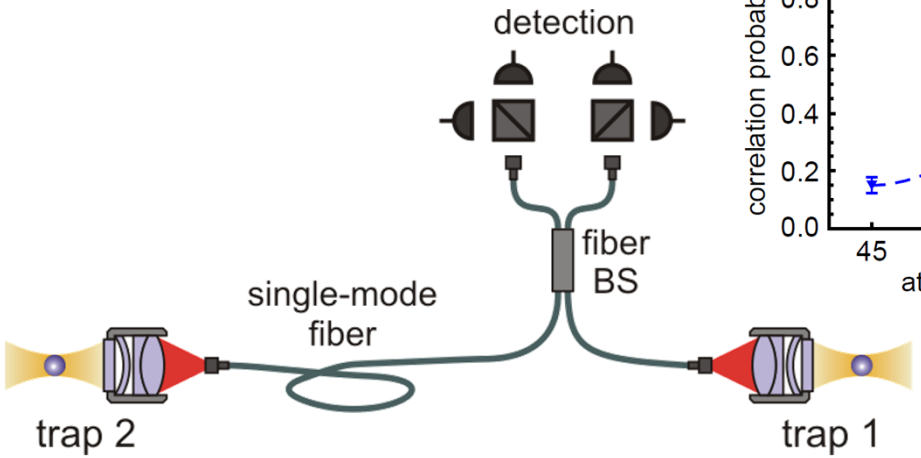
- entanglement between separated atoms
- heralded
  → "event ready" Bell test

M. Zukowski, A. Zeilinger, M.A. Horne, A. K. Ekert, Phys. Rev. Lett. 71, 4287 (1993)

Bell experiment over 20 m



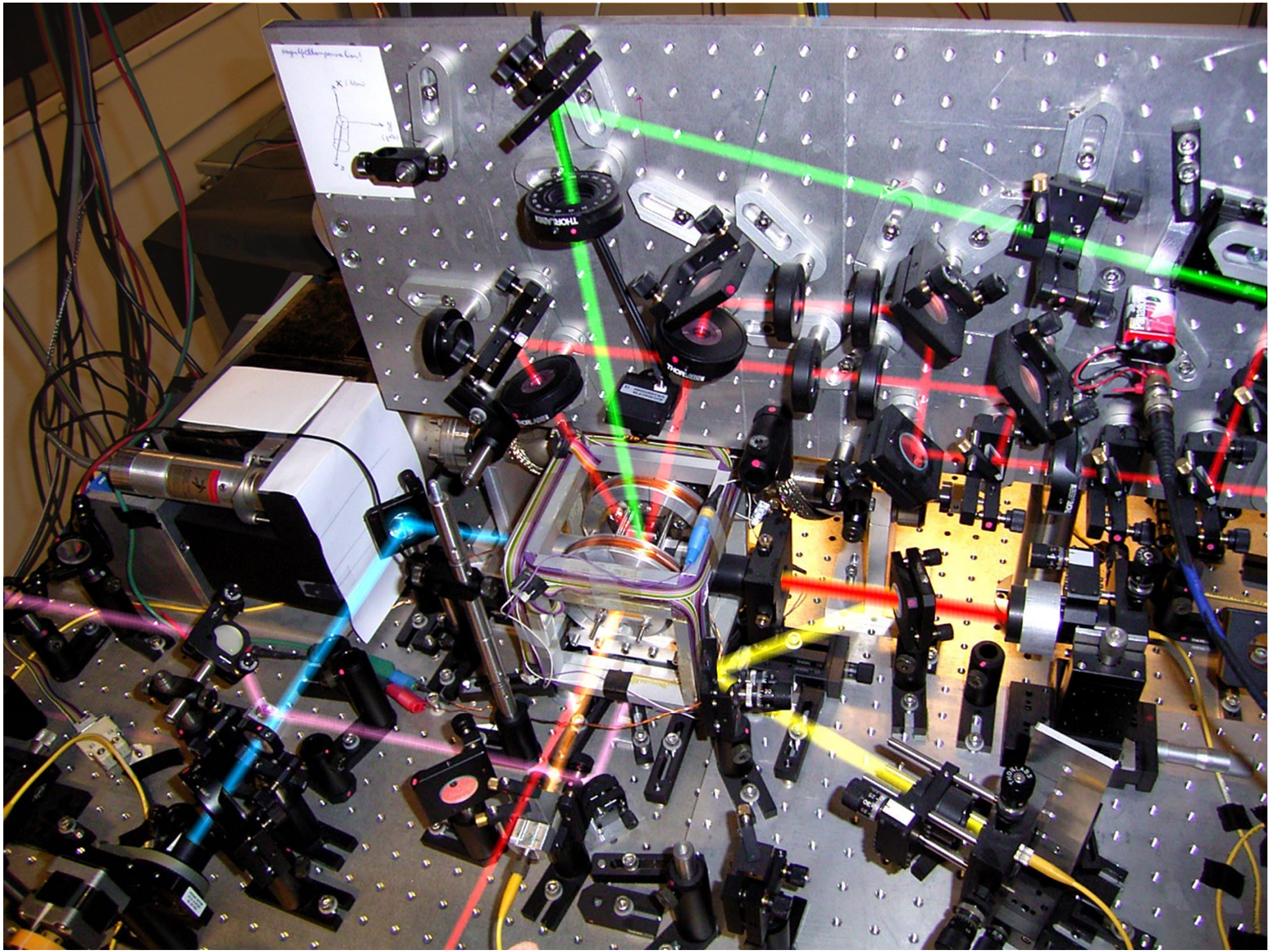
- atom-atom entanglement



- measure $p_{//}$, $p_{\perp}$ (rate 1/40s)
- vis 72%...81%
- evaluation of Bell-inequality: $S = 2.19 \pm 0.09$

→ atoms separated by 20 m
→ perfect "detection"

J. Hofmann, et al., Science **337**, 6090 (2012)

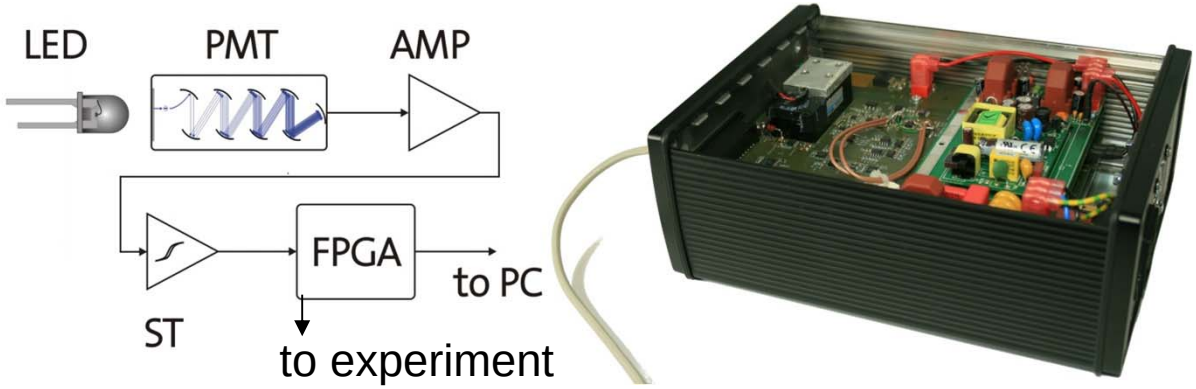


independent observer

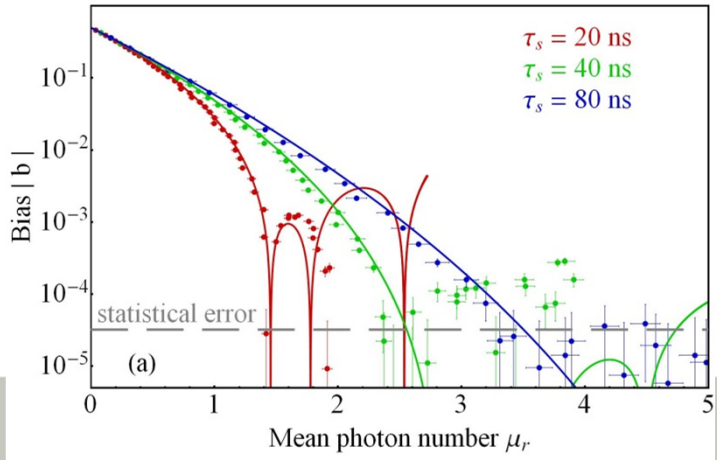
- quantum random number
- fast state-selective ionisation of the atoms

Quantum Random Numbers

- detect photons
  → random telegraph signal
    → sample periodically



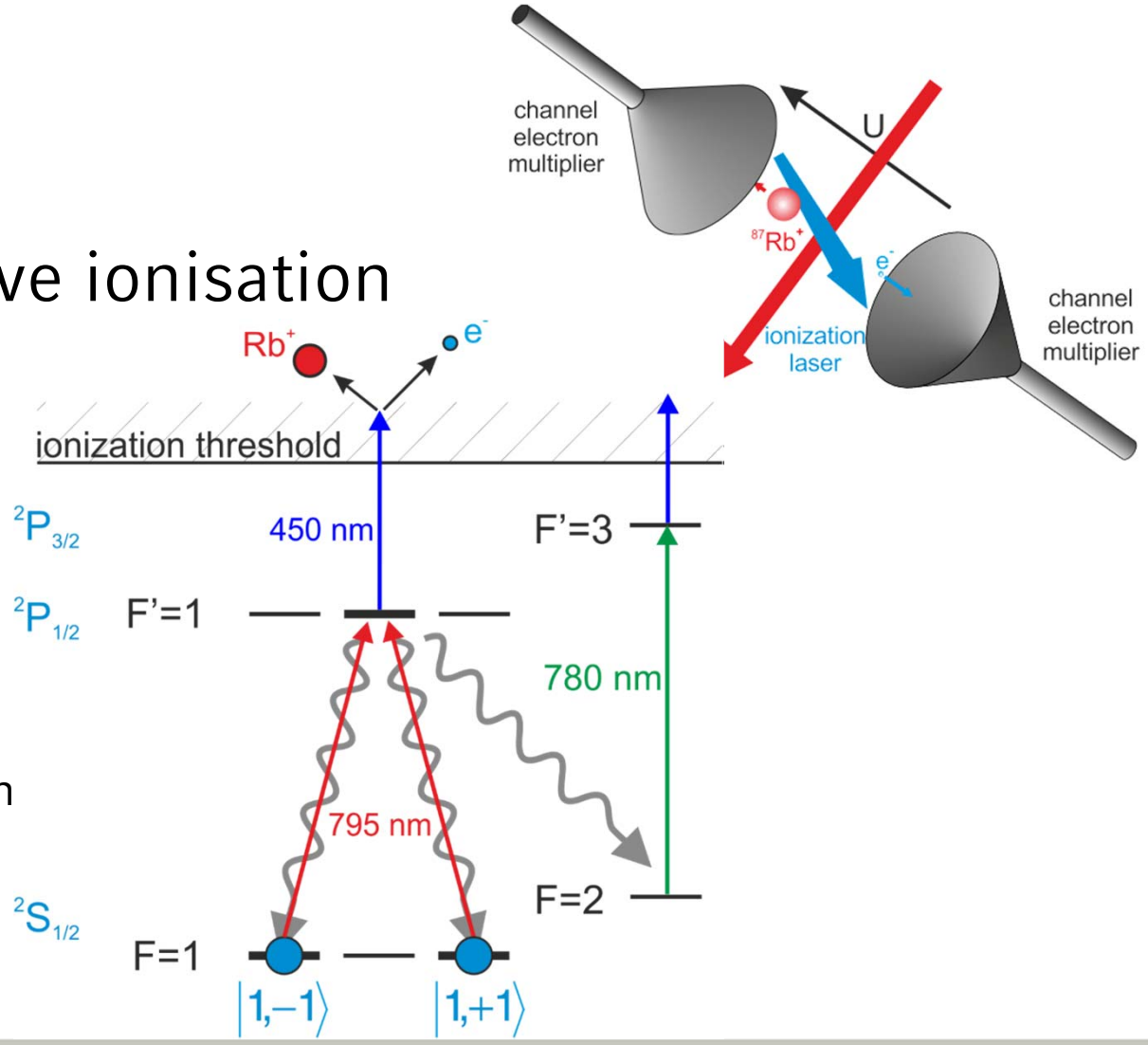
- no bias – no postprocessing
- 50 MHz



M. Fürst et al., Optics Express 18, 13029 (2010)

fast atomic state analysis

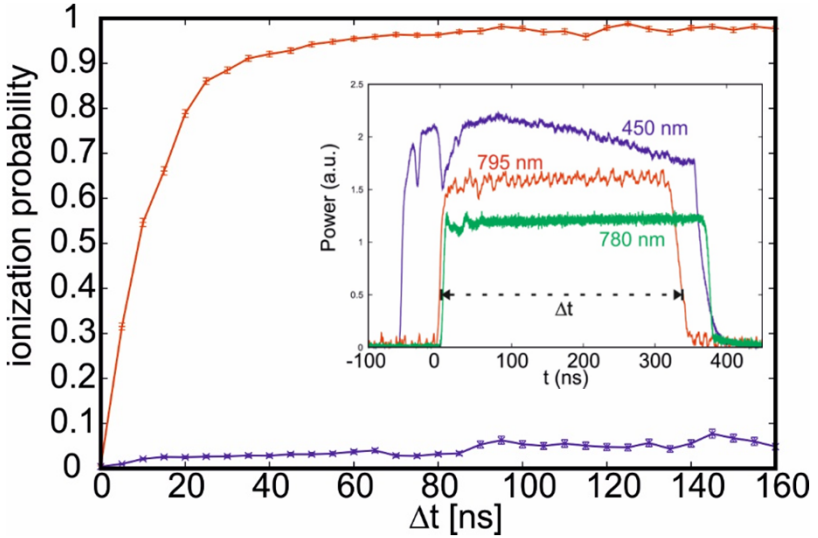
- state selective ionisation

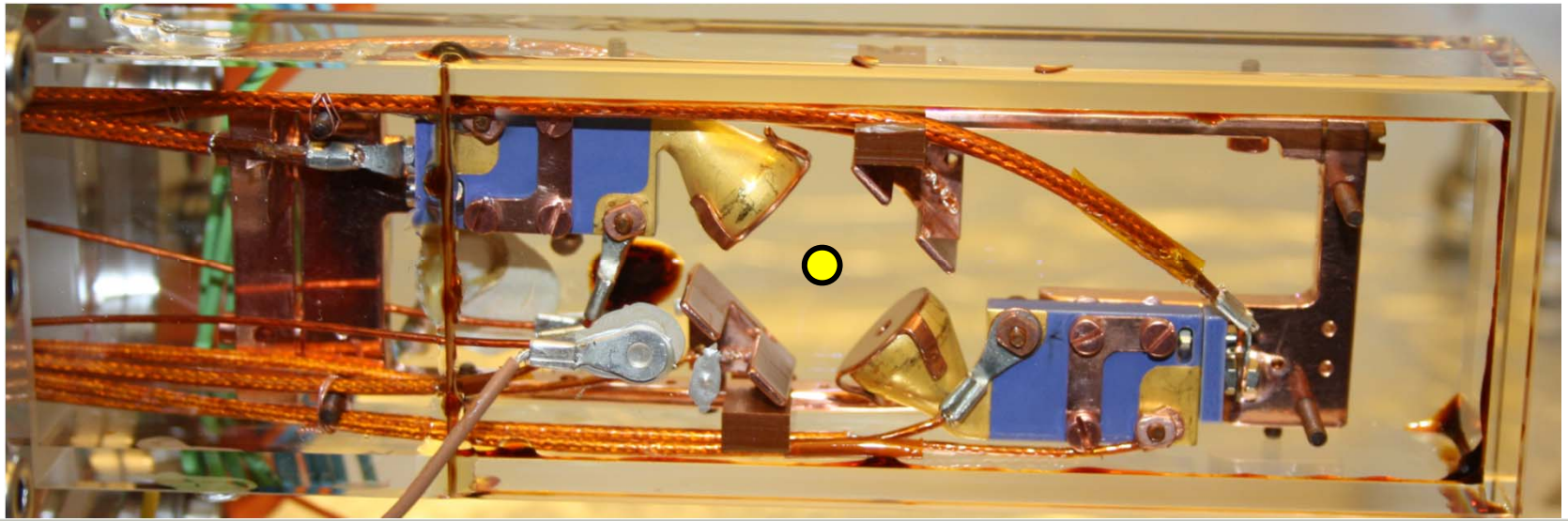


bright / dark state
depending on polarization

fast atomic state analysis

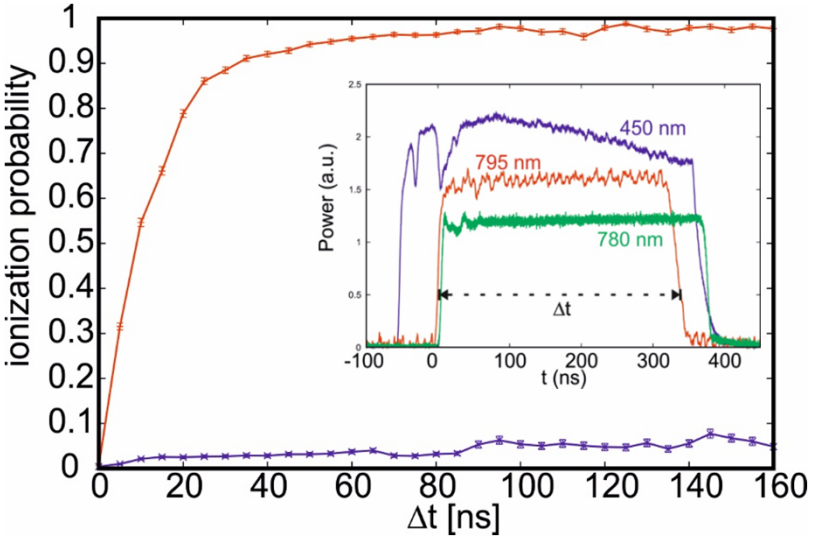
- ionisation
  - t = ~130 ns
  - F = 0.965

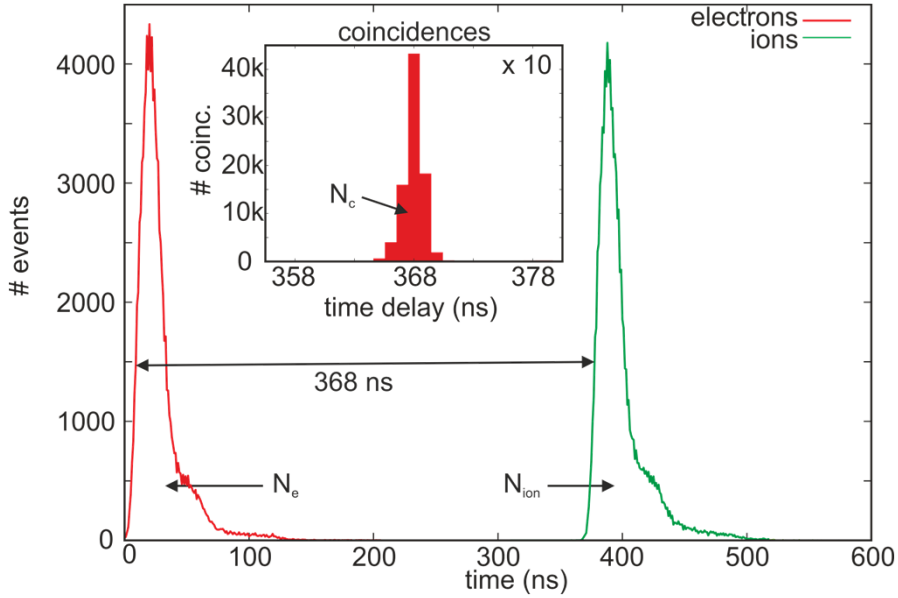




fast single atom state analysis

- ionisation
  - t = ~130 ns
  - F = 0.965

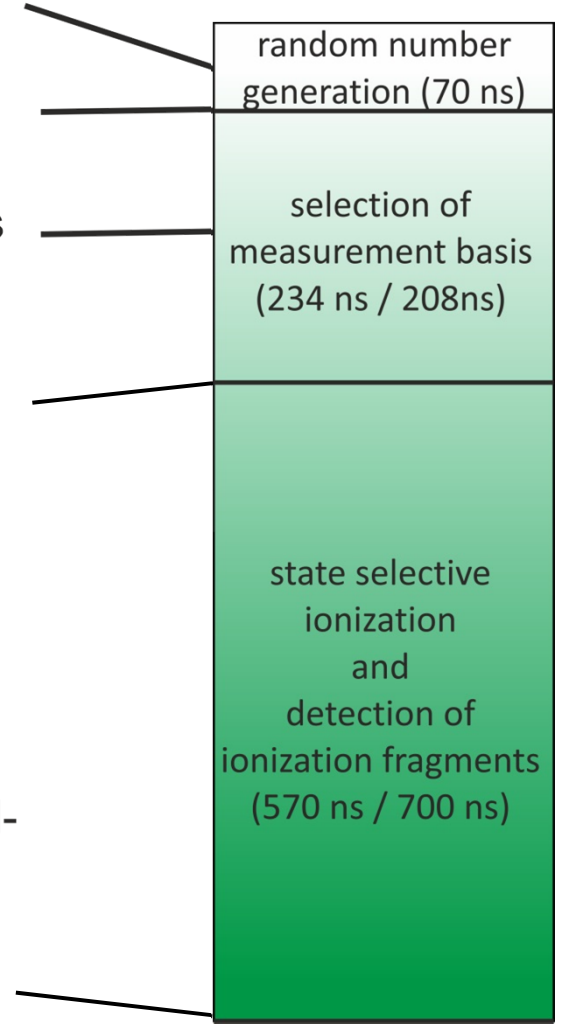




- efficiency
  - flight time 368 ns
  - N_i = 100391
    N_e = 98515
    N_c = 88326
  - η=0.988 ± 0.005

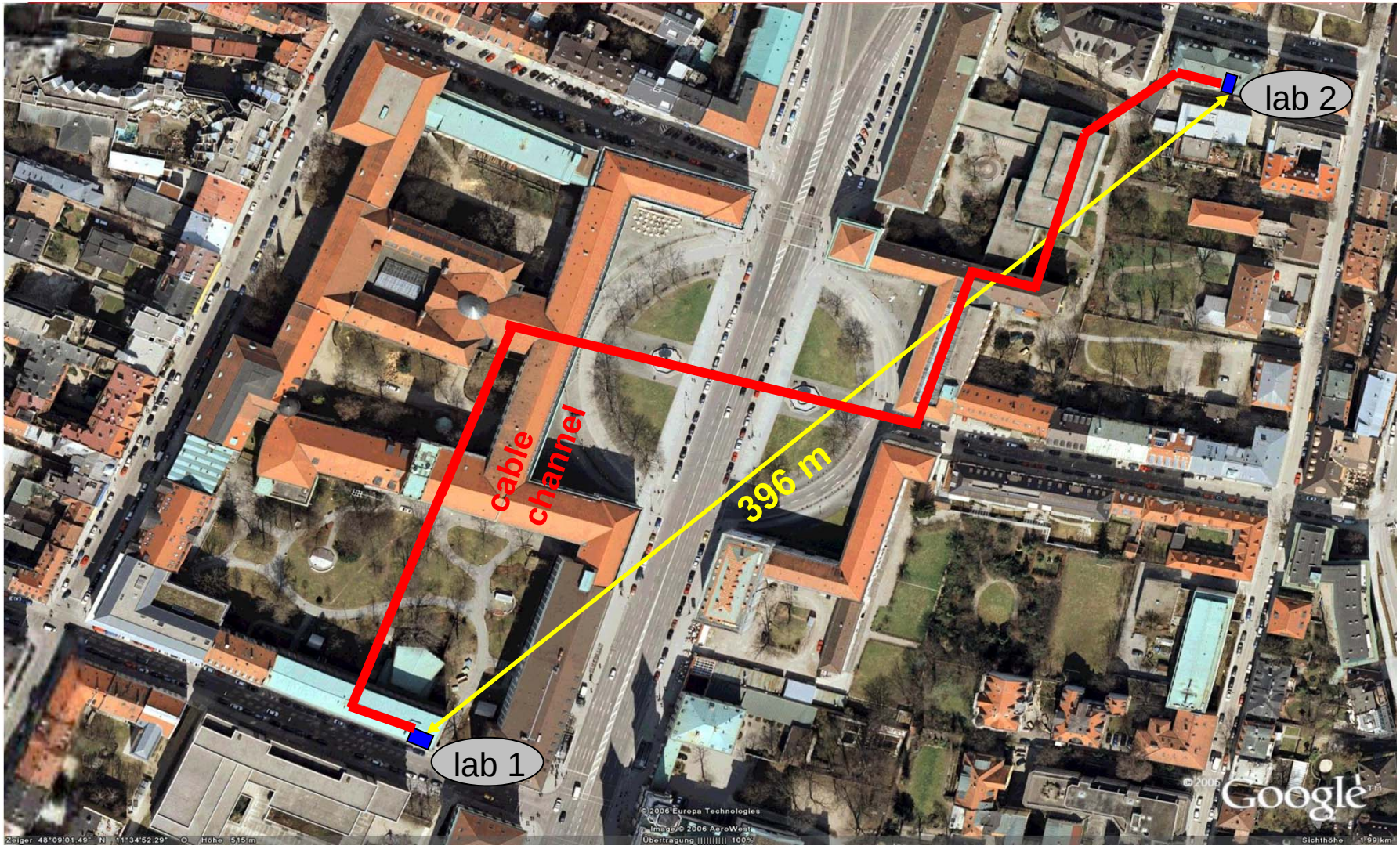
time budget

- random number generation via photon counting
- trigger from Bell state measurement
- selection of measurement basis with fast AOMs
- state selective ionization
- time of flight of ionization fragments to detectors
- buildup of avalanche in channel-electron multiplier
- detection logic outputs result

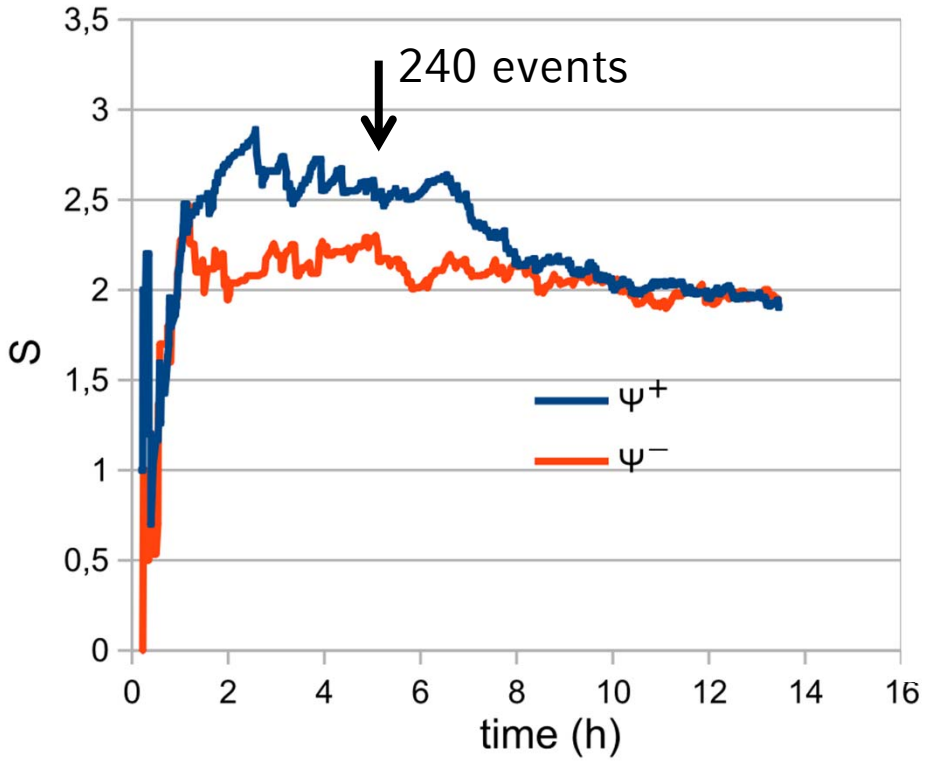


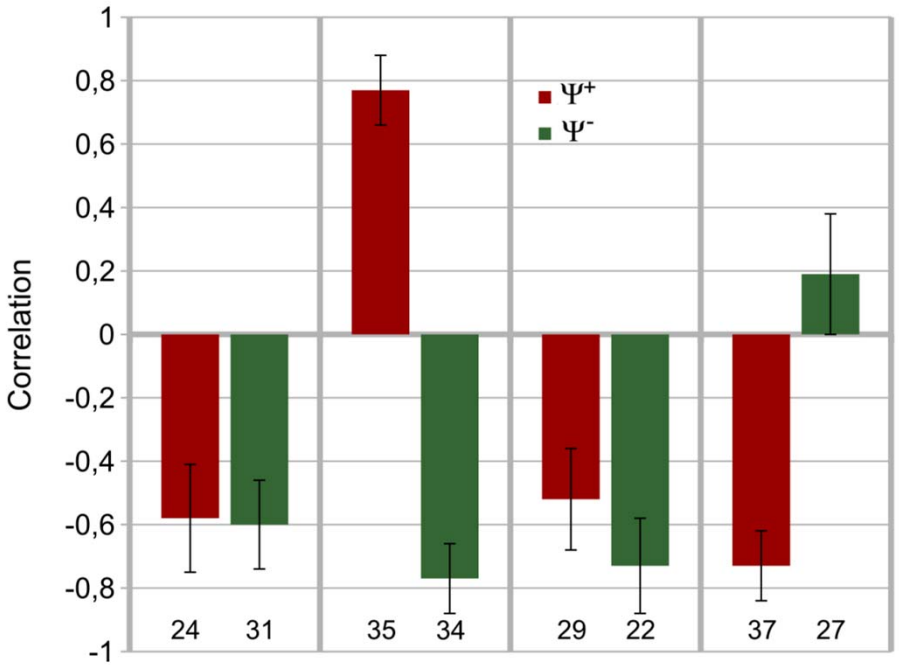
$t < 1\ \mu s$

University of Munich LMU



Nov 27th



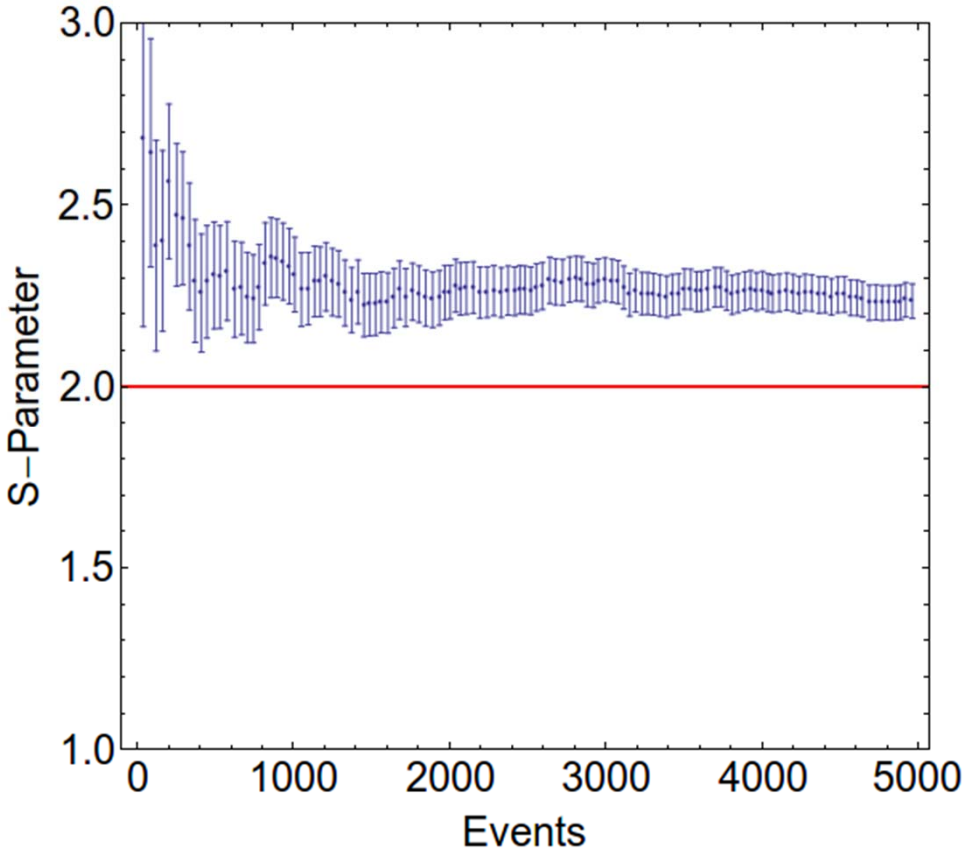


- "stable" for few hours with S>2

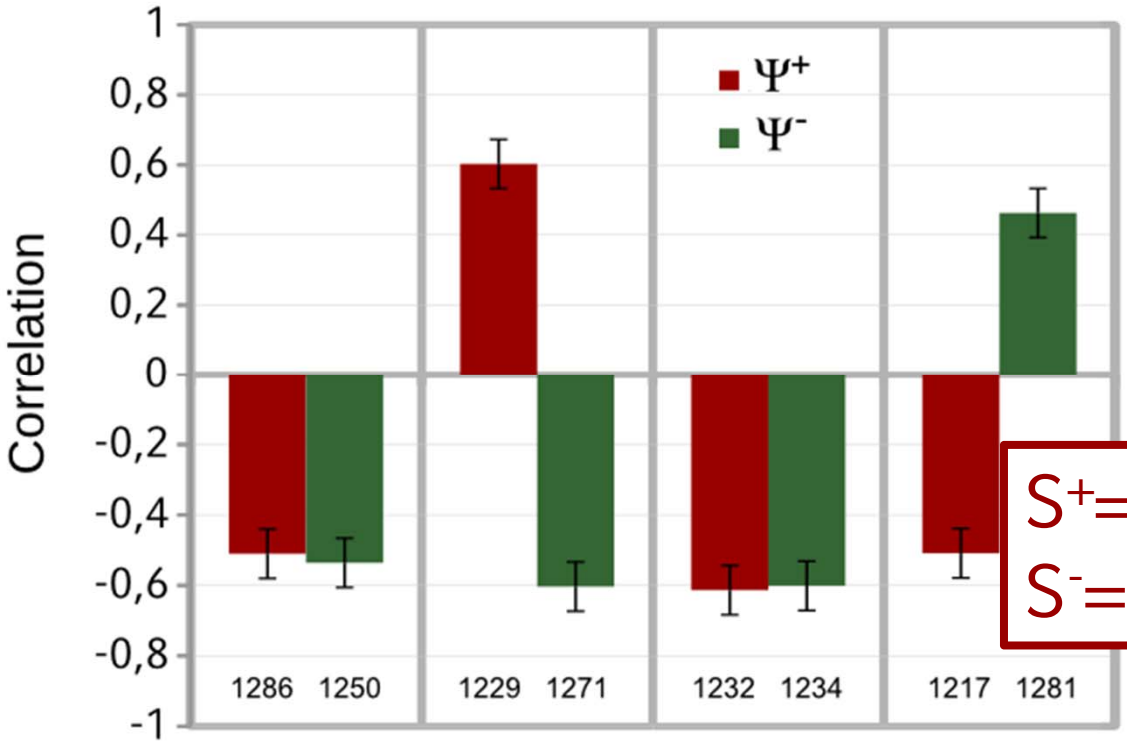
$S^{+}=2.60 \pm 0.28$

$S^{-}=2.28 \pm 0.30$

15.-20. April



- goal 10.000 events
  - stable for 5 days; maintainance every day



$S^{+}=2.24 \pm 0.047$
$S^{-}=2.20 \pm 0.047$

hypothesis test: "LHV correct"
p-value: $P_m=7.1\cdot10^{-10}$ / $P_g=6.8\cdot10^{-11}$

public observers

watch the events coming in

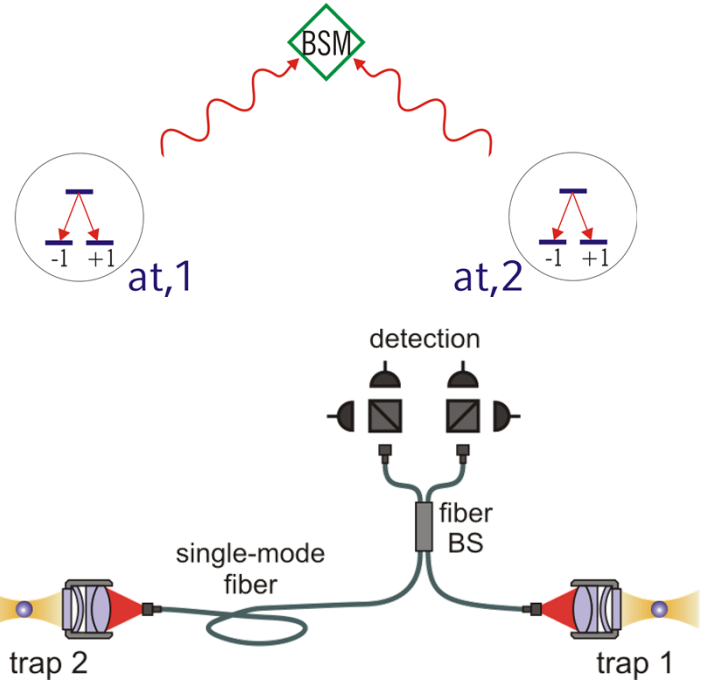
http://bellexp.quantum.physik.uni-muenchen.de/

to get informed about the next run:

@munichbellexp

Summary

- Atom-Atom entanglement
- Atom-Atom Bell test:
  - event-ready
  - no detection loophole
  - space-like separated observers



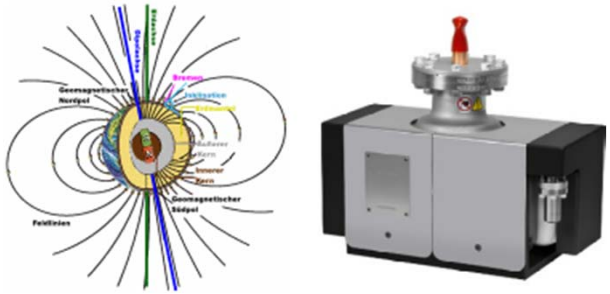
$S = 2.24 \pm 0.047$

@munichbellexp

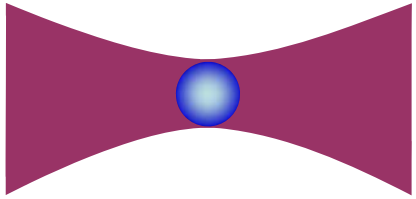
- DI QKD - quantum repeater

"CHALLENGES"

magnetic fields



dipole trap



limits to visibility

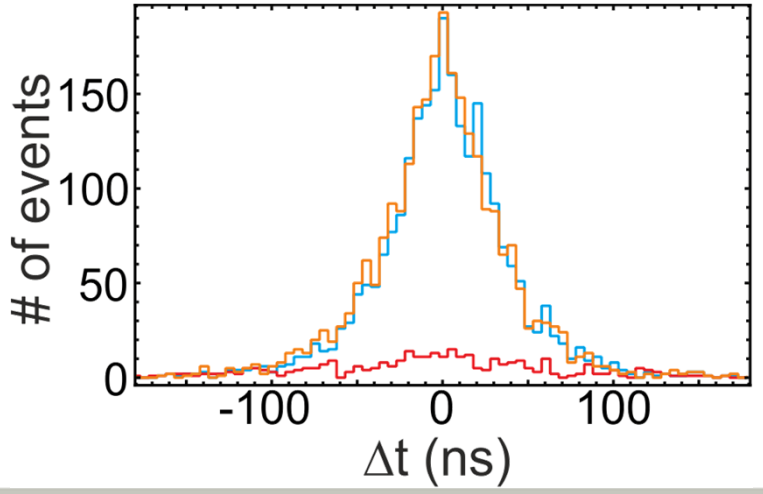
limits to visibility

- two photon interference
  - two photon emission from one atom ($g^{(2)}(0) = 0.0078$!)

total Vis<80%

  - (I) different atomic states
  - (II or III) first emission changes temporal mode overlap

⇨ Vis = 0.922



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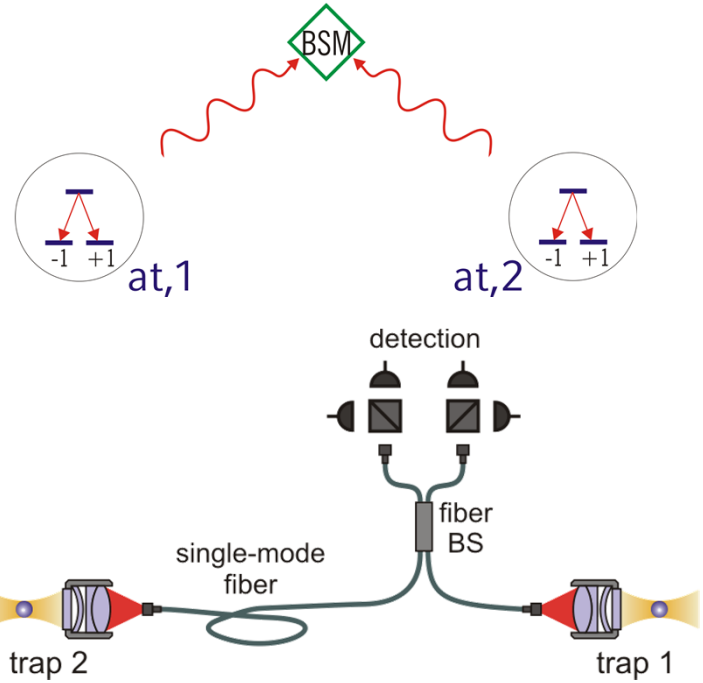

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- DI QKD - quantum repeater