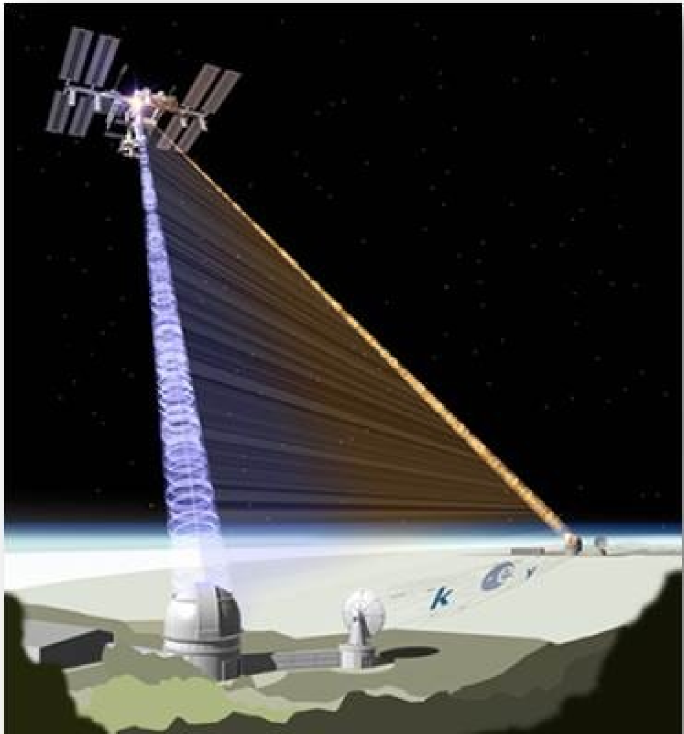
Entanglement, loop holes & quantum optics in space

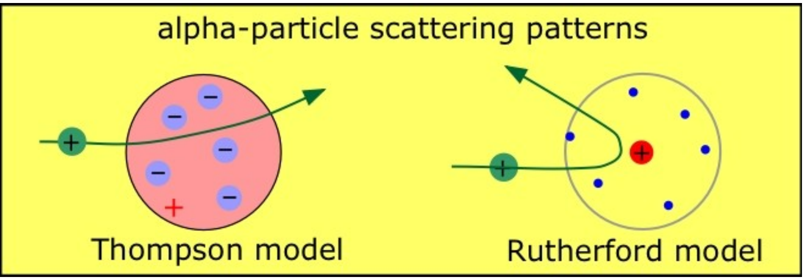
Rainer Kaltenbaek*

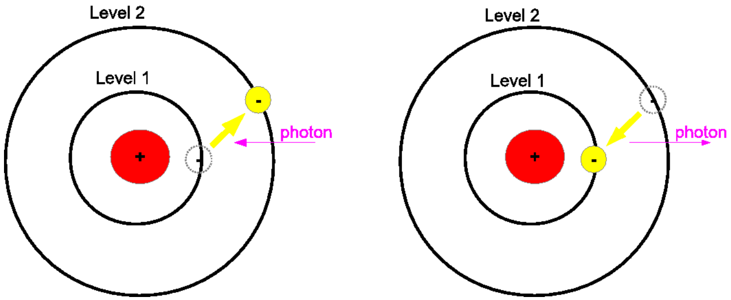
*Aspelmeyer group
Vienna Center for Quantum Science and Technology
Faculty of Physics, University of Vienna, Austria

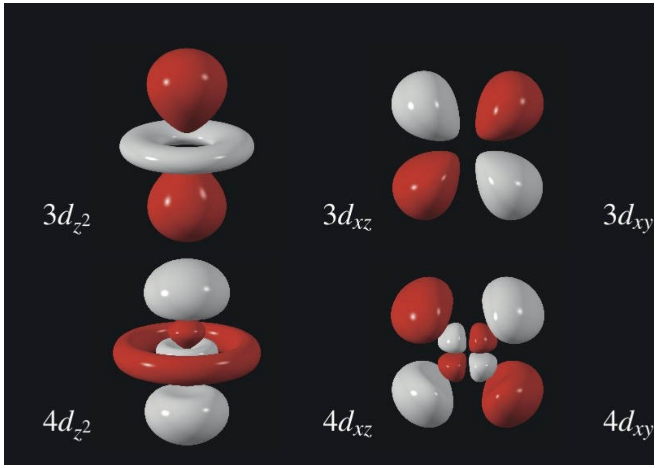


“Common sense”, “reality”, or
why it may hard to write about quantum physics

The atom and “reality”

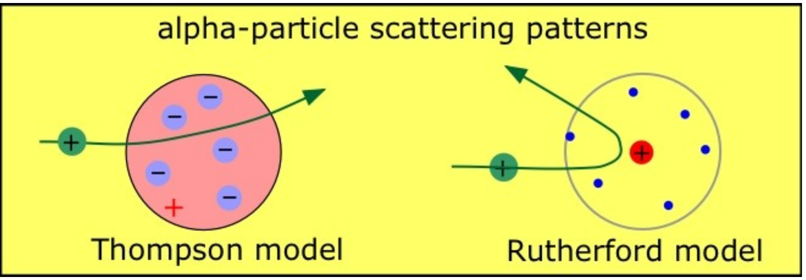


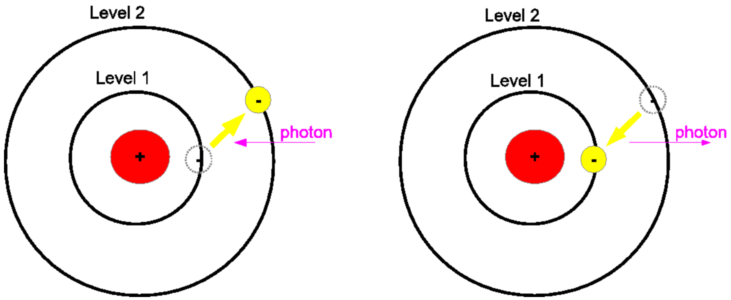


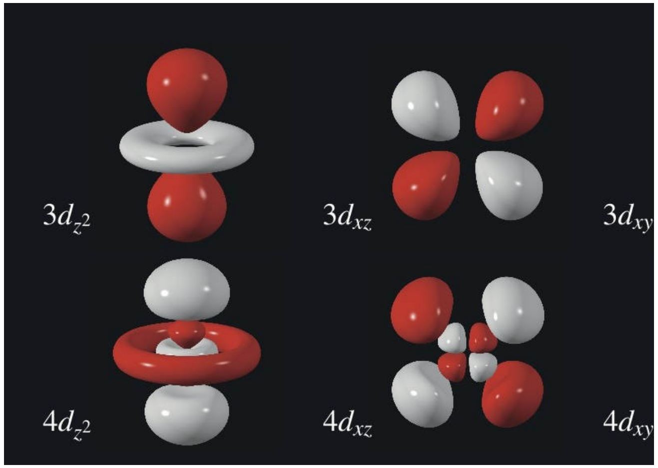


Journalist:
“so, Mr. Pauli, what does an electron look like?“

The atom and “reality”



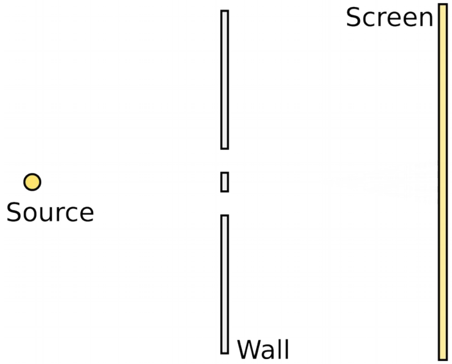




Journalist:
“so, Mr. Pauli, what does an electron look like?“

Pauli: “**an electron does not look like**“

Double slits & “reality”



So, dear Niels, which slit does the particle go through?

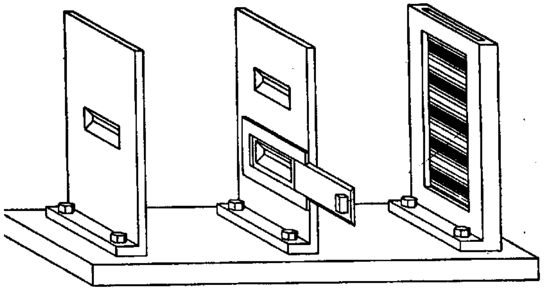


Fig. 4

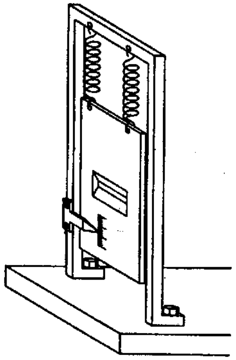
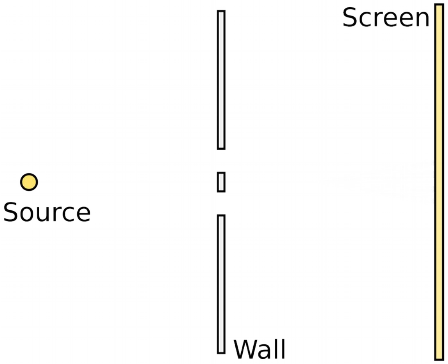


Fig. 5

Double slits & “reality”

VCQ
Vienna Center for Quantum Science and Technology



So, dear Niels, which slit does the particle go through?

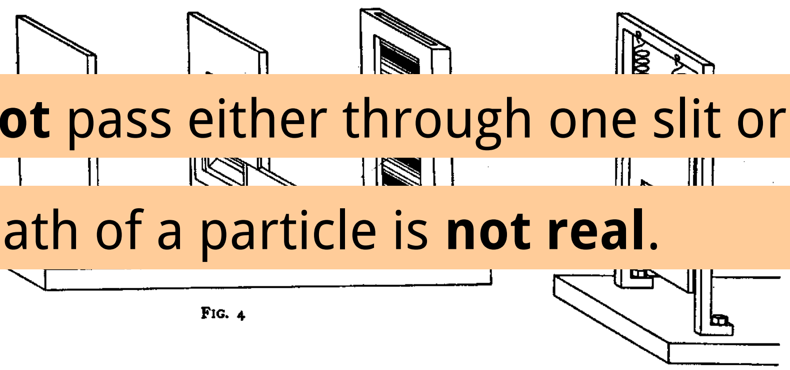
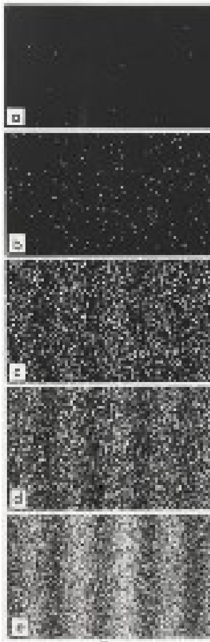


FIG. 4

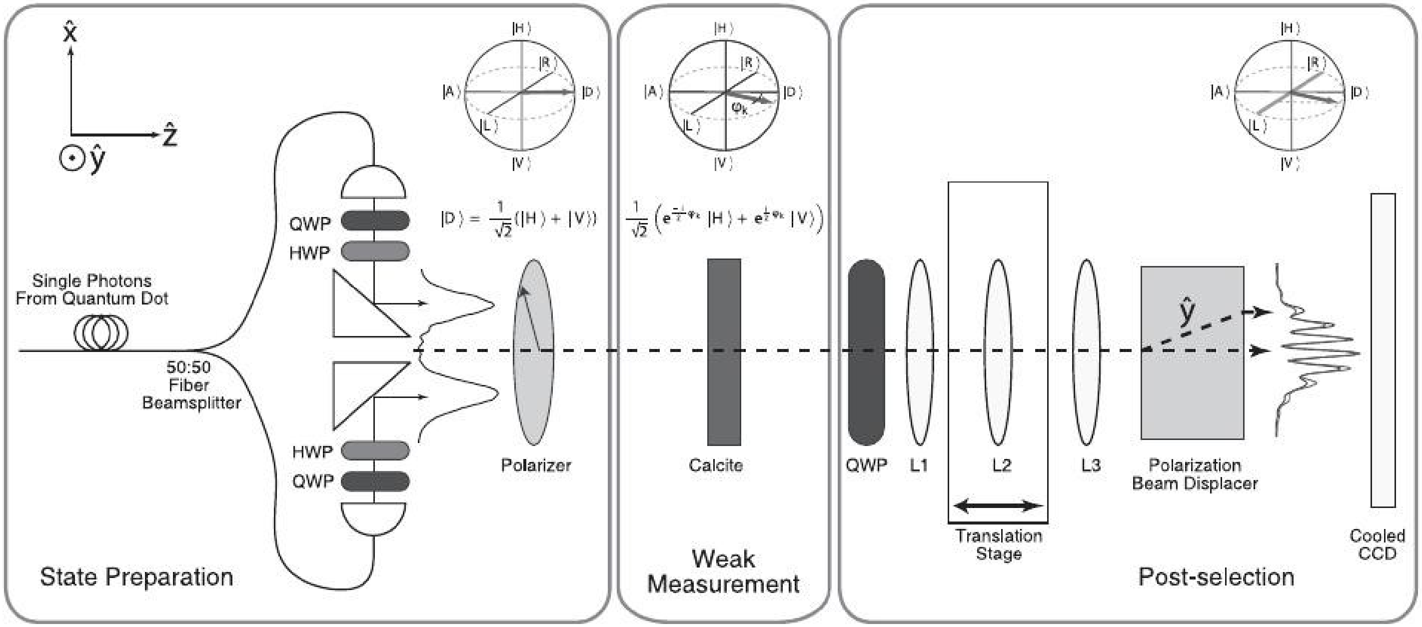
FIG. 5

A particle **does not** pass either through one slit or the other

The path of a particle is **not real**.

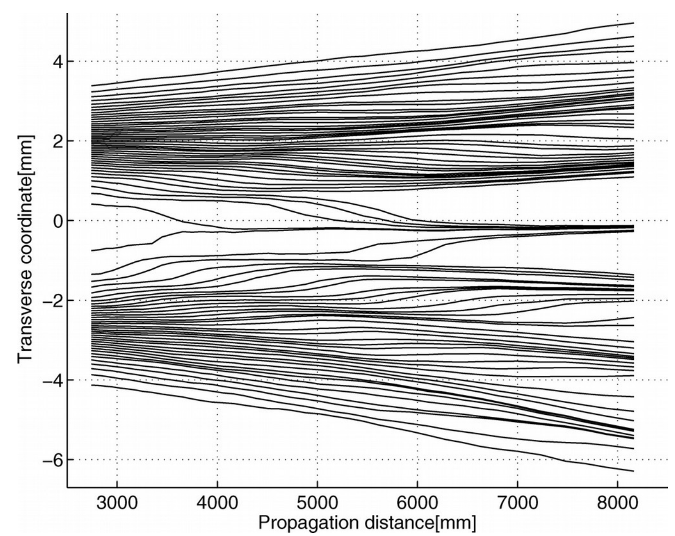


But what about that trajectory experiment?

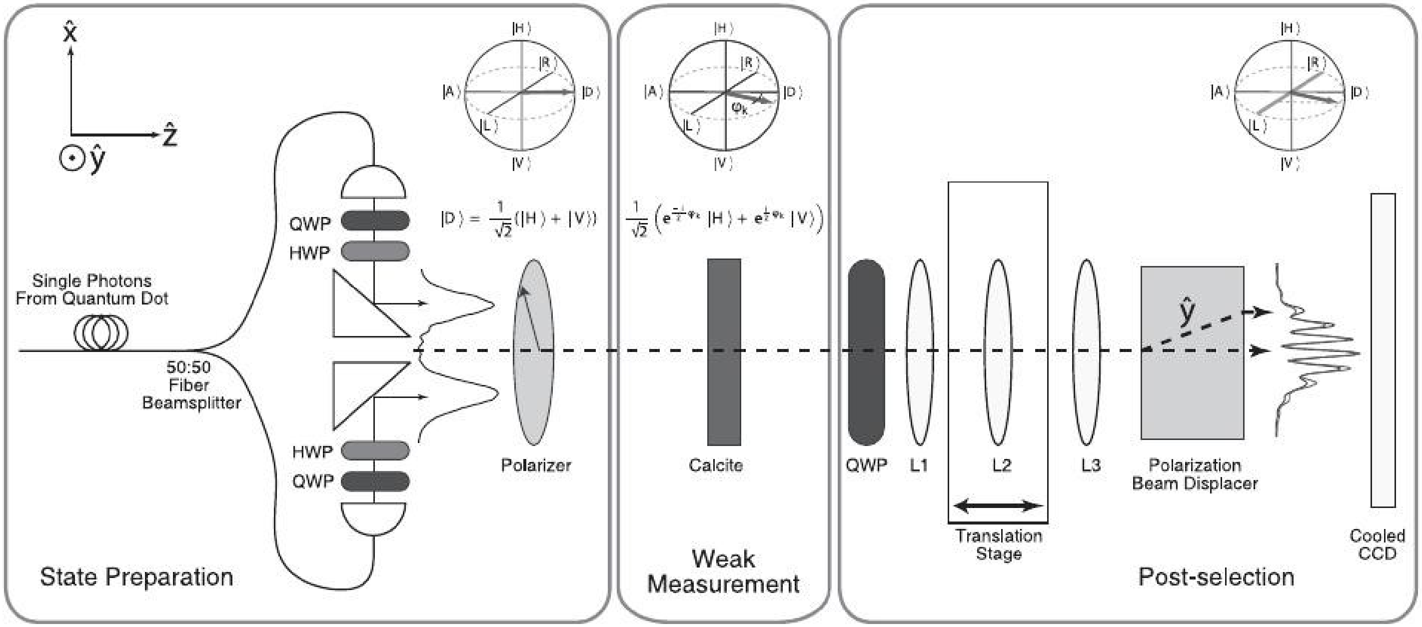


A. Steinberg's group: S. Kocsis et al., Science **332**, 1170 (2011)

double-slit interference + weak measurement of ensemble momentum at various distances
→ reconstructed "ensemble particle trajectories"

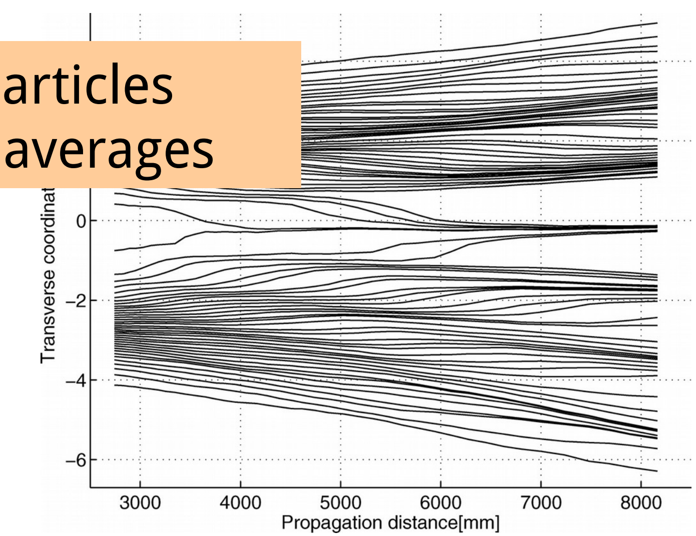


But what about that trajectory experiment?



A. Steinberg's group
1170 (2011)

double-slit interference + weak measurement of
ensemble momentum at various distances
→ reconstructed "ensemble particle trajectories"



No information about single particles
Only about means of ensemble averages

But ...

what's really happening?

... answering a question with a question

what do you mean by "really"?

Entanglement and what people call “non-locality”

Classical “non-locality” at the airport

Adam

Eve

Classical “non-locality” at the airport

Adam

Eve

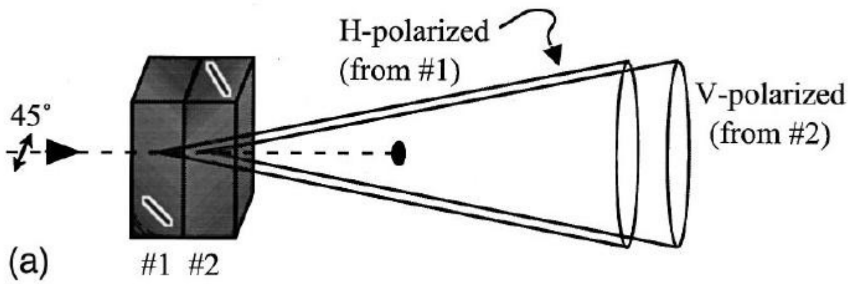
later at home

No interaction
No “spooky action at a distance”

But that's just classical correlations
and no entanglement...

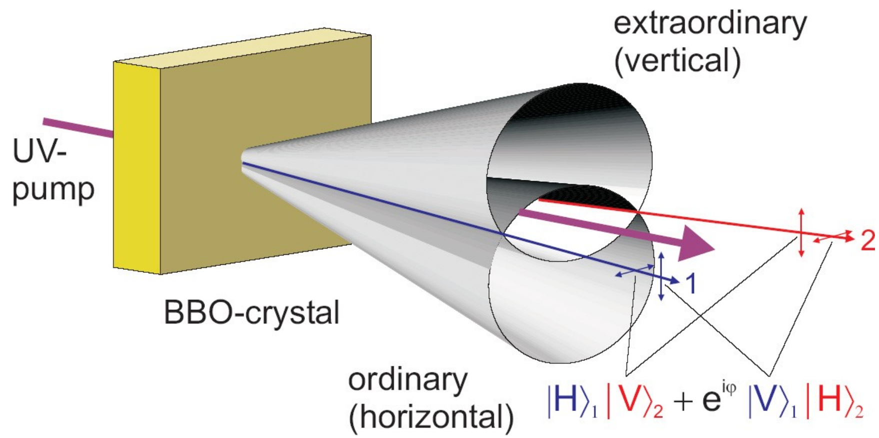
spontaneous parametric down conversion (SPDC)

Type I

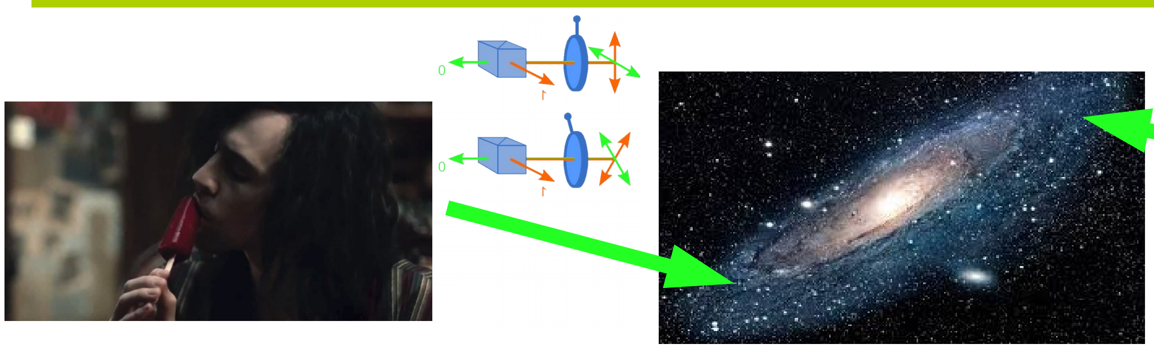


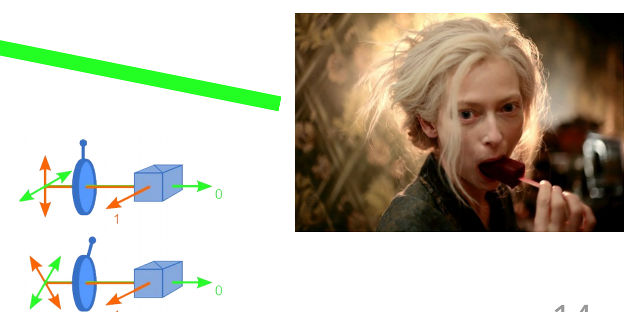
$$|H\rangle_1|H\rangle_2 + e^{i\phi}|V\rangle_1|V\rangle_2$$

Type II



The photons are not “both H” or “both V”
Their polarization is **undefined**

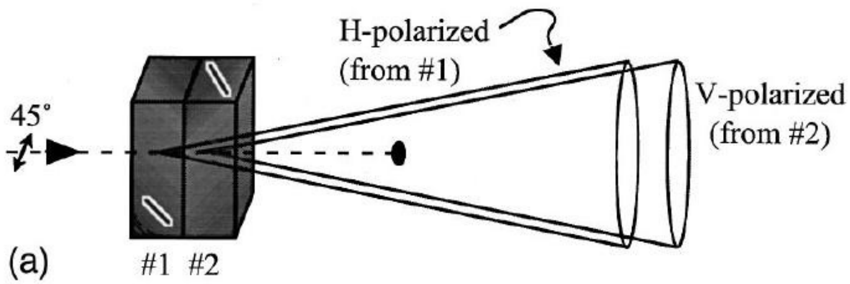




Entanglement – with photons

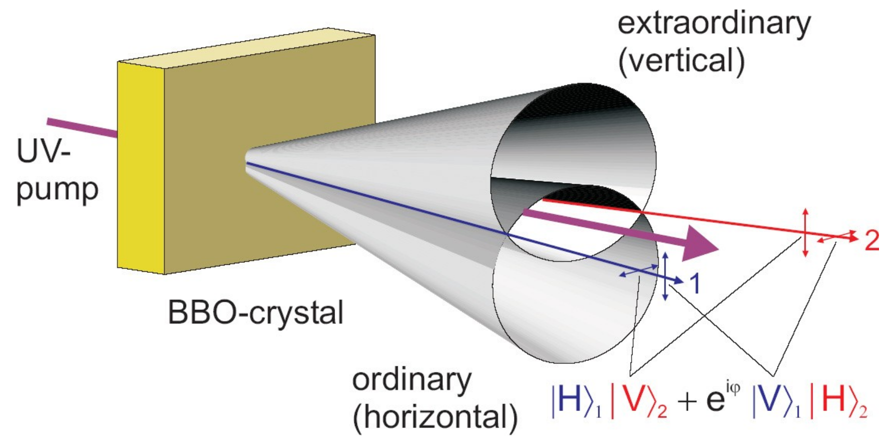
Two ways to get entangled photons using spontaneous parametric down conversion (SPDC)

Type I



$$|H\rangle_1|H\rangle_2 + e^{i\phi}|V\rangle_1|V\rangle_2$$

Type II



Perfect correlations, for any two **identical** measurements

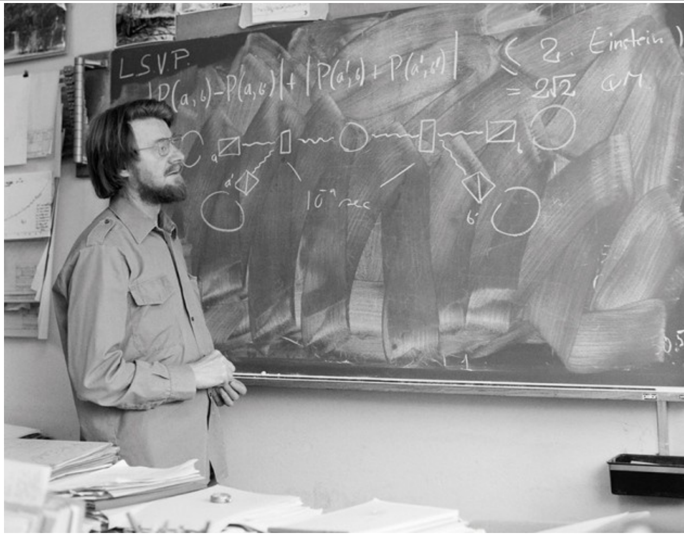
That's what Einstein called

“spooky action at a distance”

... but “really”

it's just updating one's knowledge

Local realism and Bell's theorem



Bell – **any** theory fulfilling both:

- **Locality** (no communication/actions/influences faster than light)
- **Reality** (measurement outcomes predefined by “hidden variables”)

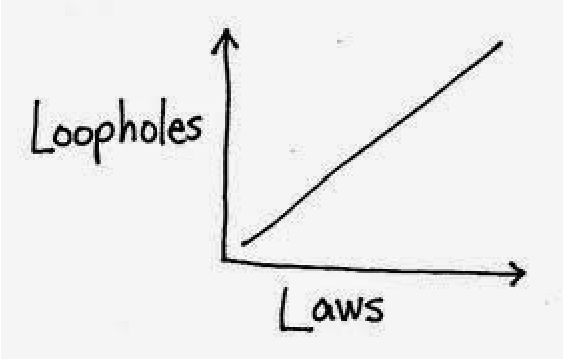
fulfils Bell's inequality

Quantum theory violates Bell's Inequality

Loopholes

Bell's inequality **cannot** be tested experimentally
→ CHSH inequality (1969) & CH inequality (1974)

→ experiments violate Bell-type inequalities

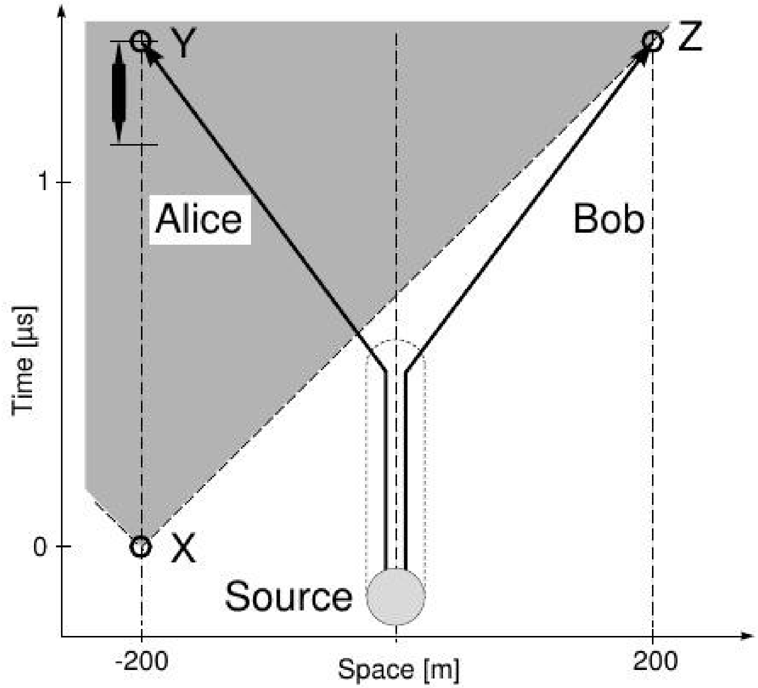


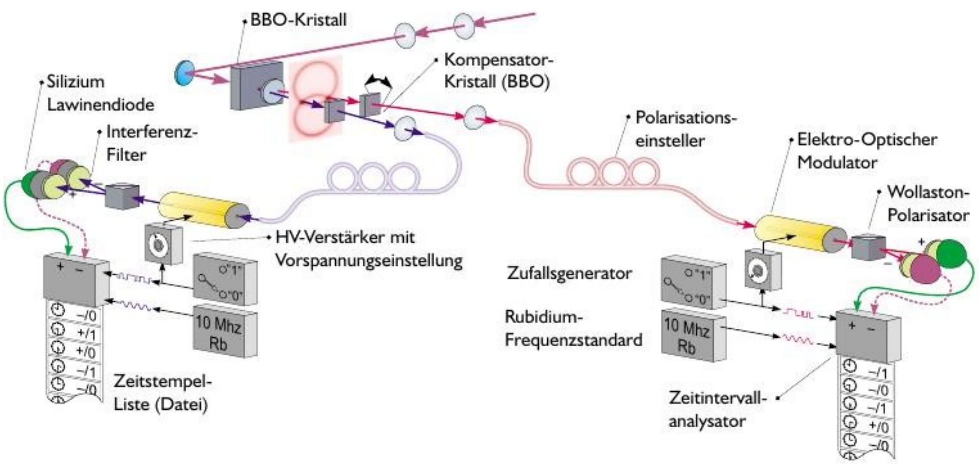
Experimental imperfections require additional assumptions

- finite detection & collection efficiency
  → **detection loophole**
- measurement settings chosen randomly
  → **locality loophole**
  → **freedom-of-choice loophole**

Closing the locality loophole

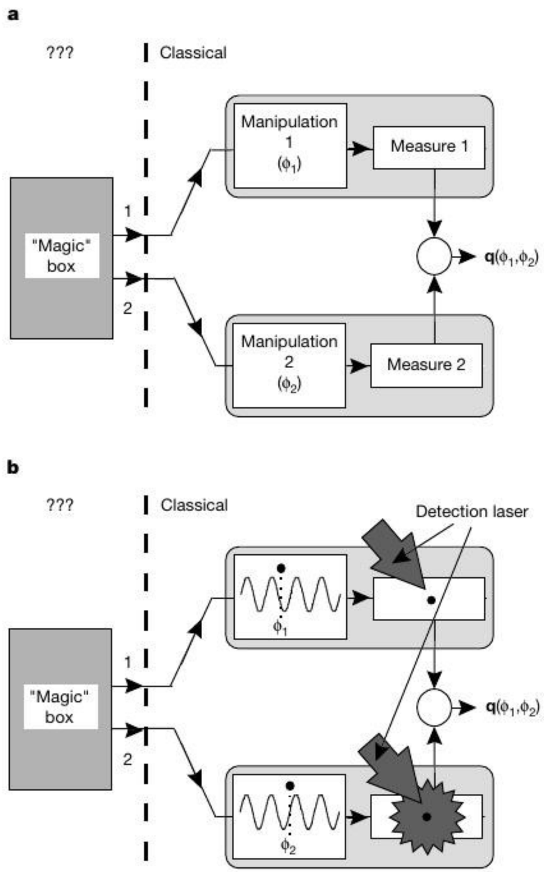
Zeilinger group: G. Weihs et al., PRL **81**, 5039 (1998)

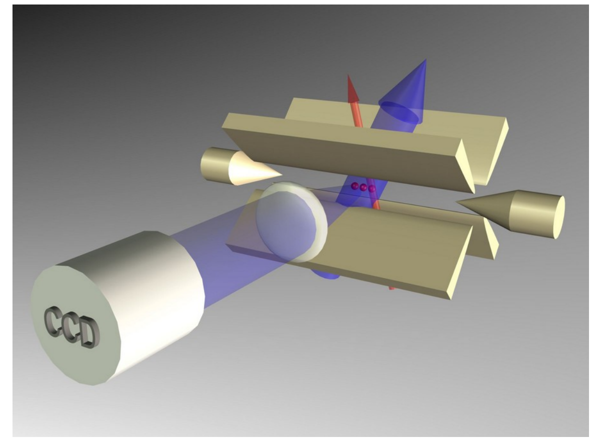




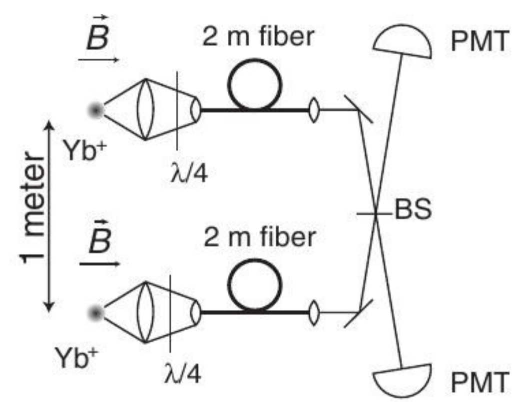
Closing the detection loophole – with ions

Wineland group: M. A. Rowe et al., Nature **409**, 791 (2001)





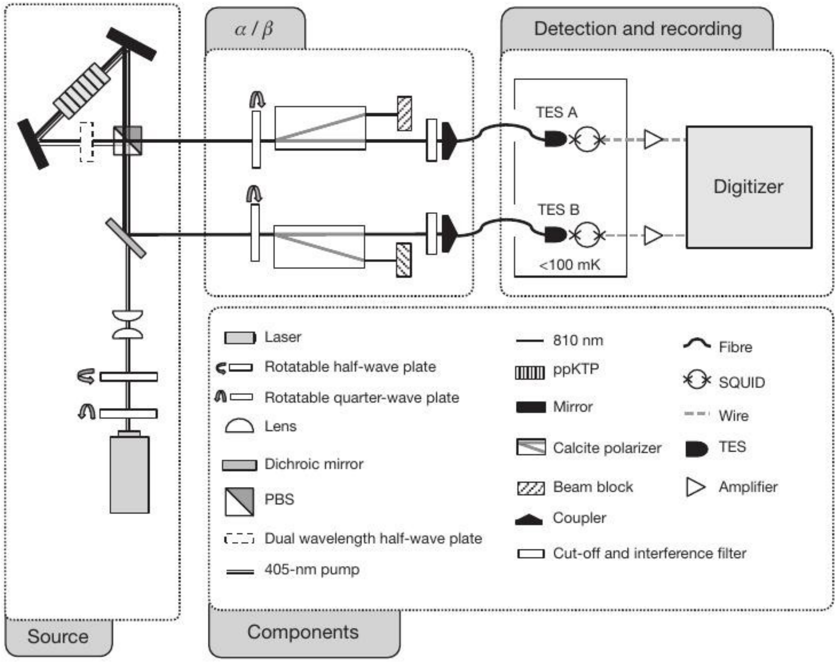
(Blatt group)

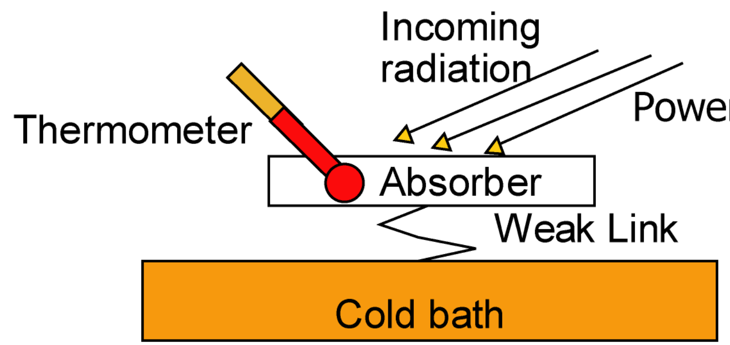


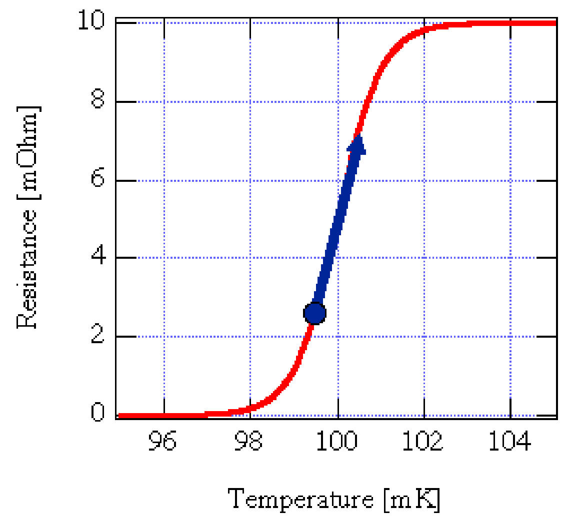
Monroe group: D. N. Matsukevich et al., PRL **100**, 150404 (2008)

Closing the detection loophole – with photons

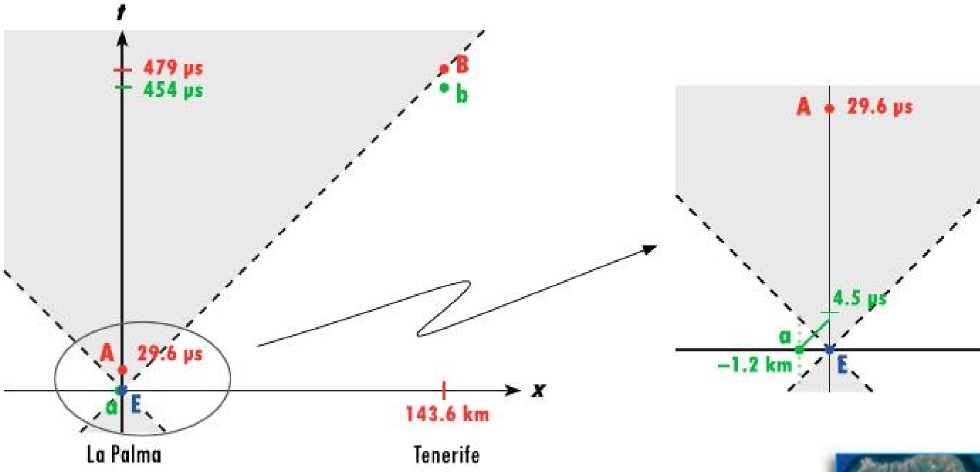
Zeilinger group: M. Giustina et al., Nature **497**, 227 (2013)





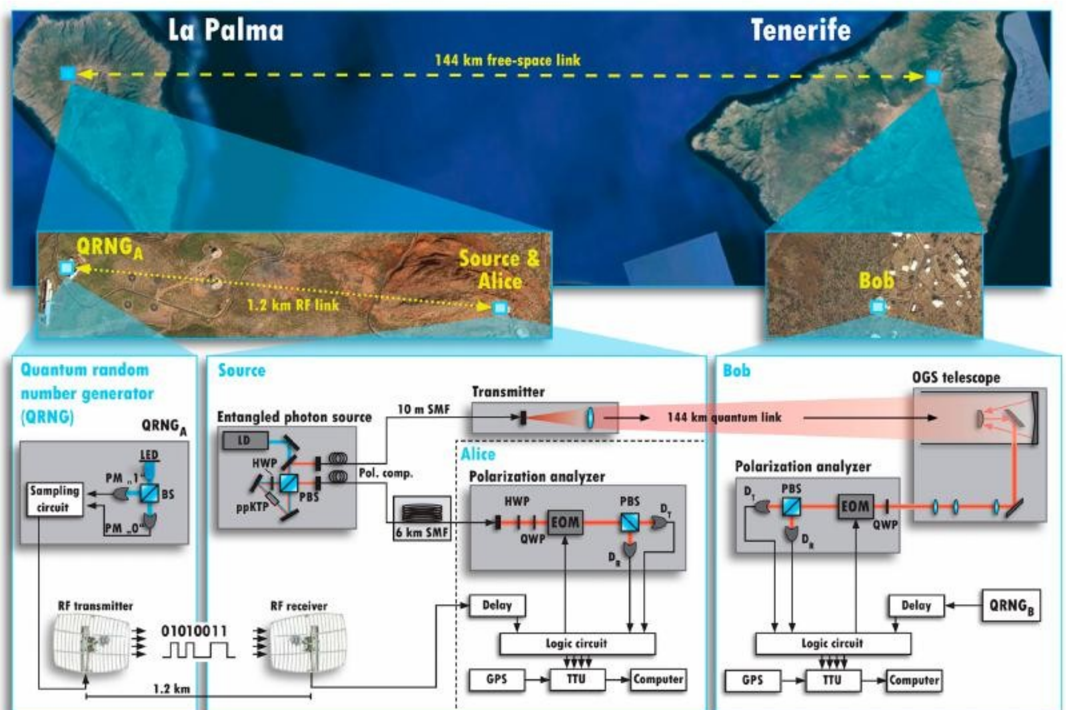


Closing the freedom-of-choice loophole



Source event & choice of settings independent

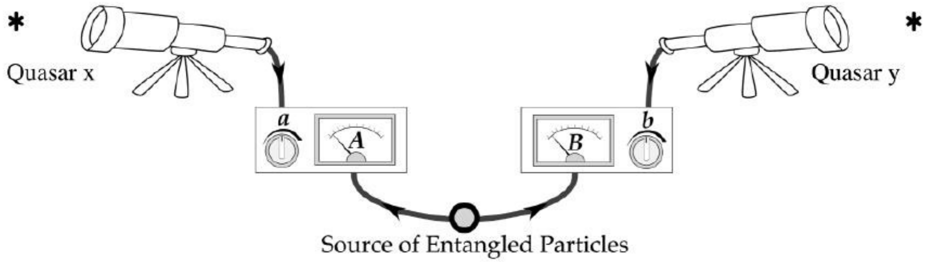
Zeilinger group: T. Scheidl, R. Ursin et al. PNAS **107**, 19708 (2010)

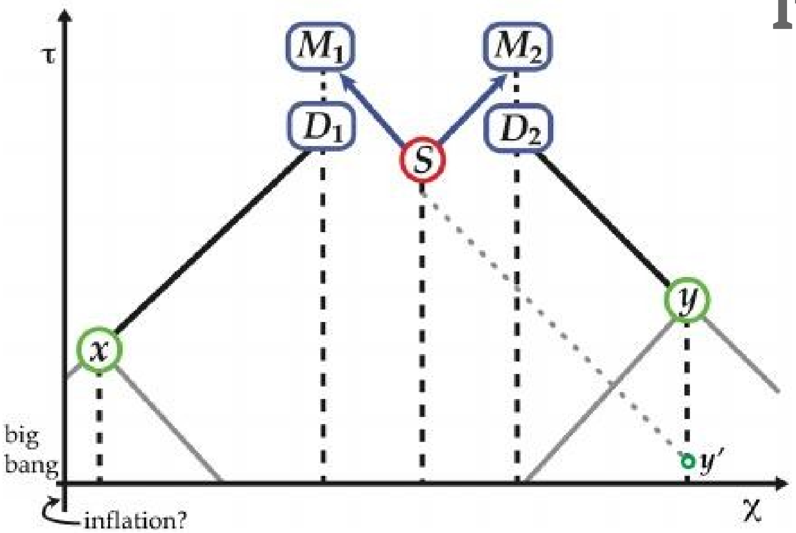


Distances comparable to ISS-ground distance

Even more freedom of choice?

Base choice of settings on distant quasars
J. Gallicchio, A. S. Friedman & D. I. Kaiser, PRL **112**, 110405 (2014)





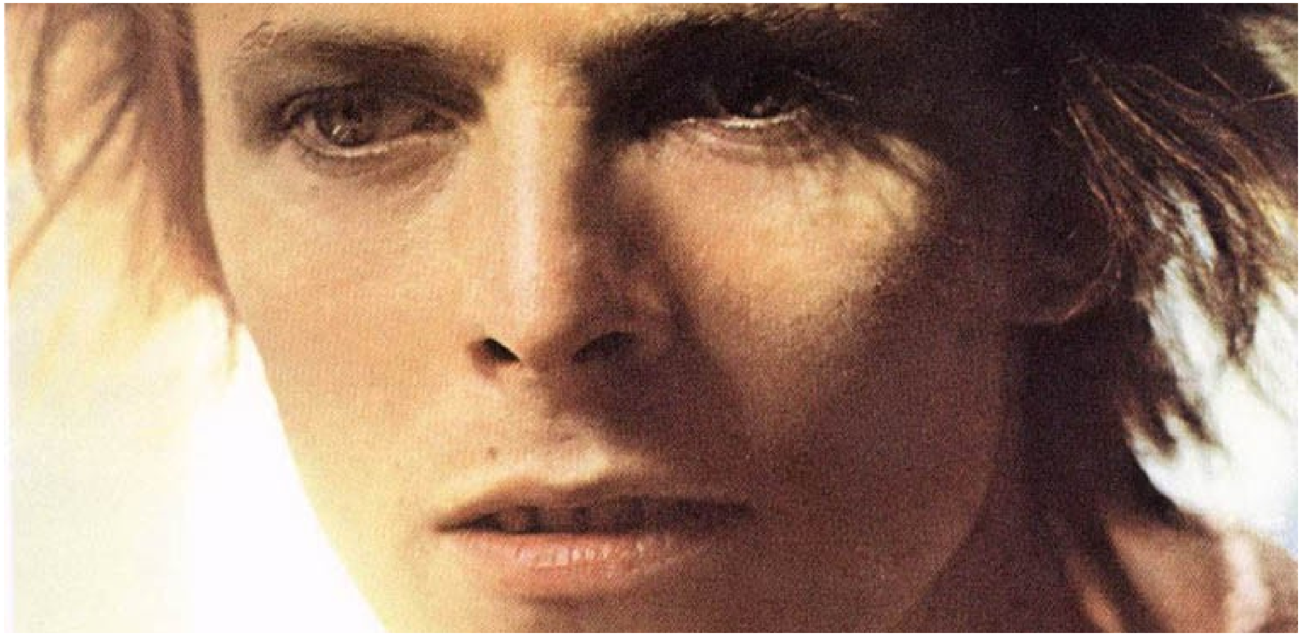
If there's a conspiracy,

it's as old as the universe

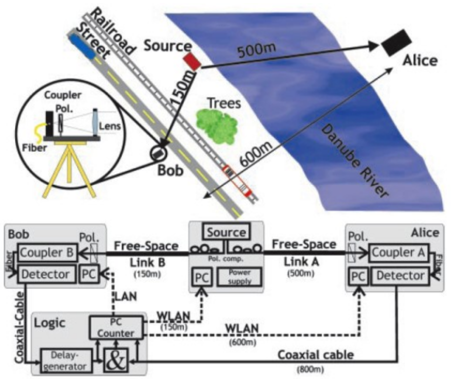
or really damn clever...

Is it time...

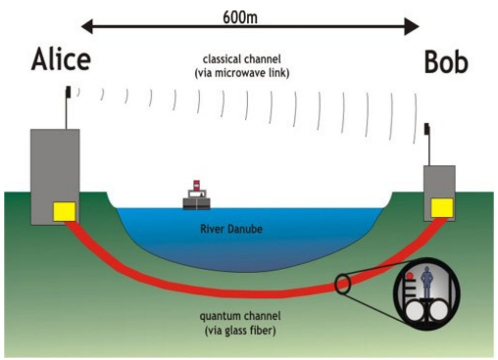
to go to space?



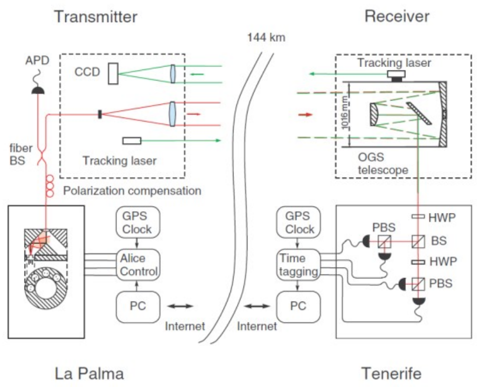
Towards space I/II



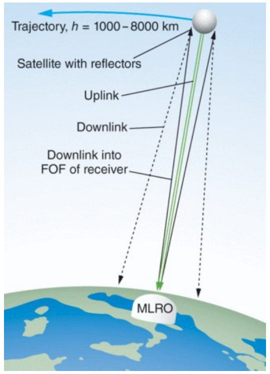
M. Aspelmeyer et al,
Science **301**, 621-623 (2003)



R. Ursin et al,
Nature **430**, 849 (2004)

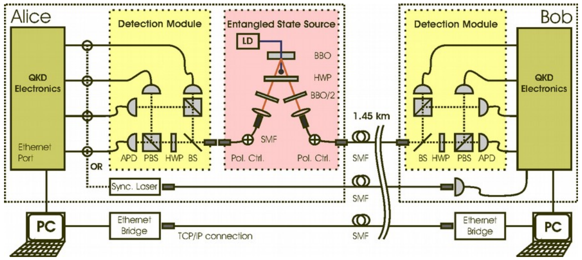


T. Schmitt-Manderbach et al,
PRL **98**, 010504 (2007)

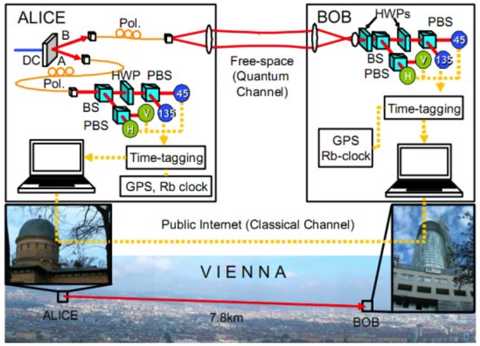


P. Villoresi et al,
NJP **10** 033038 (2008)

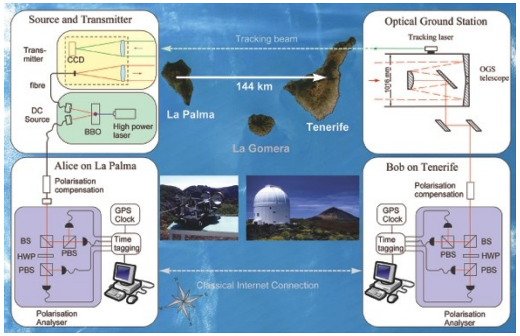
Real World Quantum Communication History



A. Poppe et al,
Opt. Exp. **12**, 3865-3871 (2004)

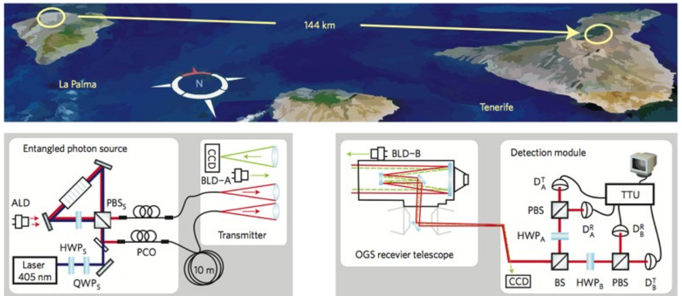


K. Resch et al,
Opt. Exp. **13**, 202-209 (2005)

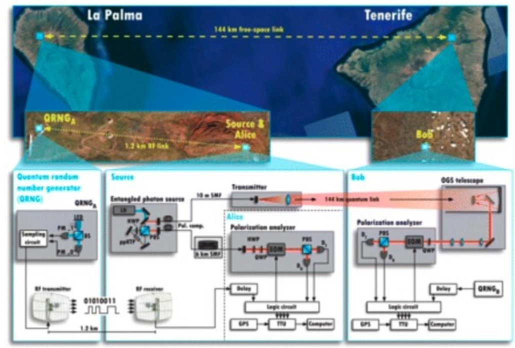


R. Ursin et al,
Nature Phys. **3**, 481 - 486 (2007)

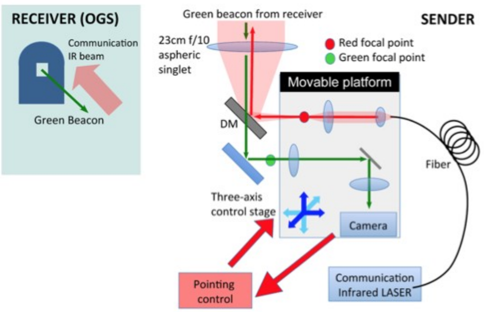
Towards space II/II



A. Fedrizzi et al. Nature Phys. **5**, 389 (2009)

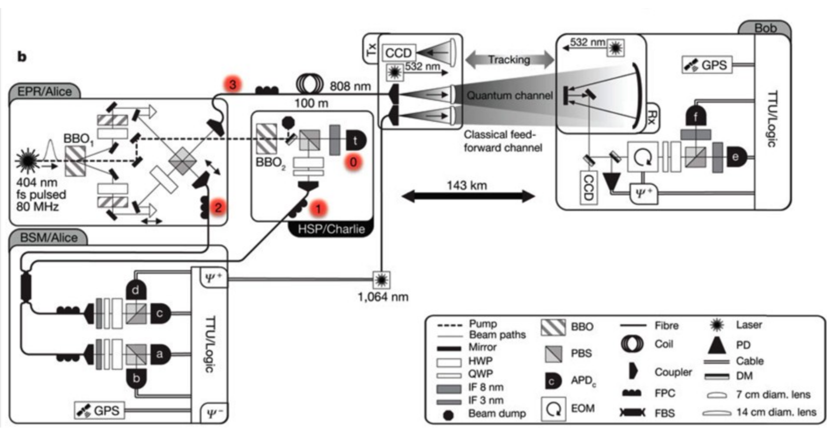


T. Scheidl, et al PNAS, **107**, 19708 (2010)

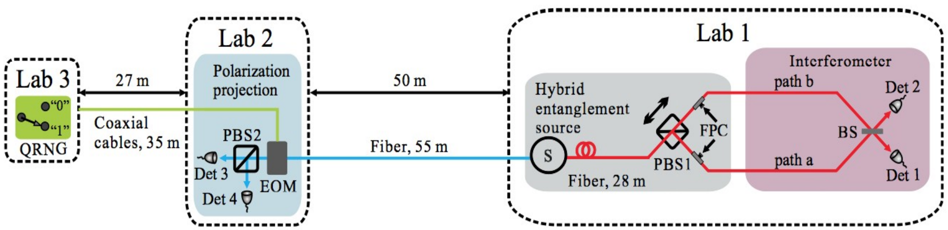


I. Capraro, et al PRL **109**, 200502 (2012)

Real World Quantum Communication History

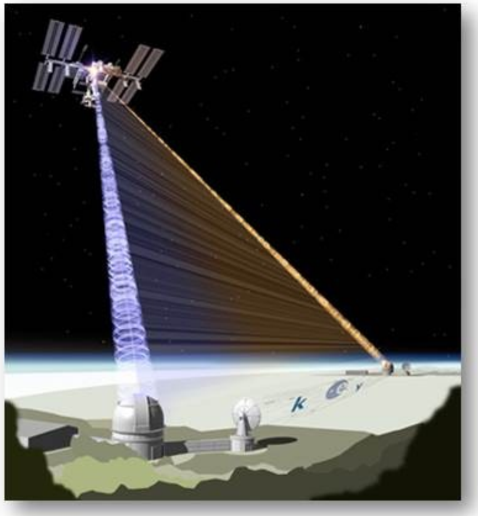


X.-S. Ma, et al, Nature **489**, 269 (2012)

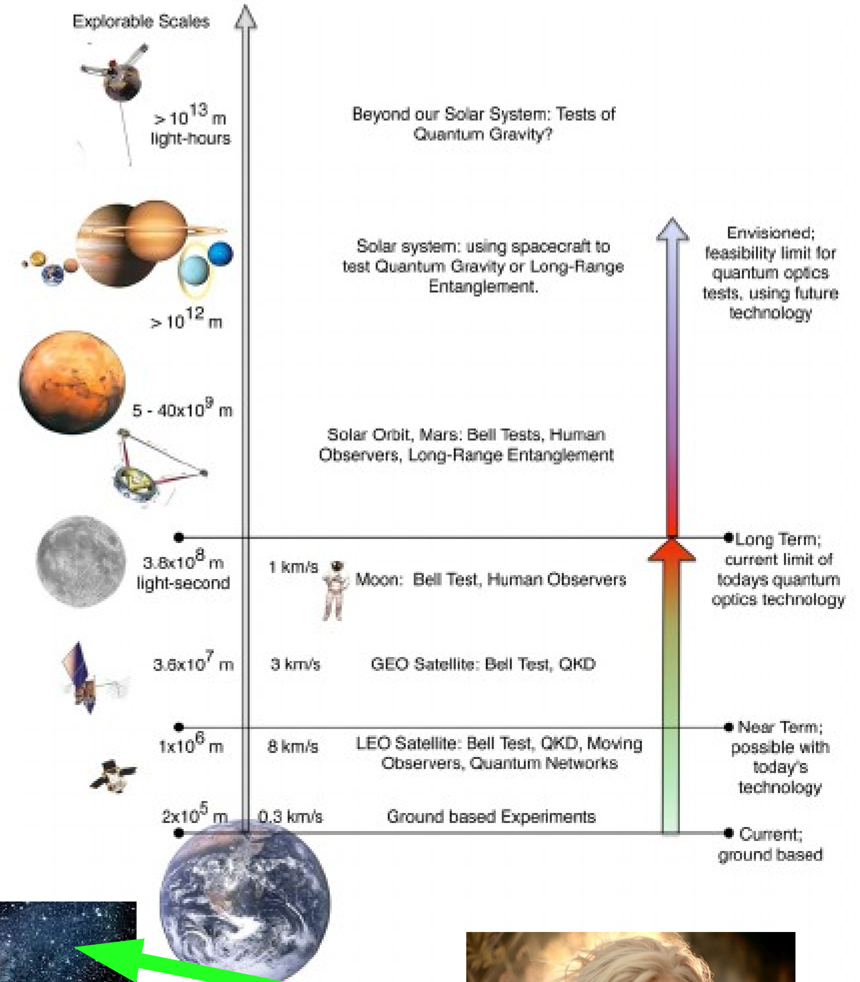


X.-S. Ma et al. PNAS **110**, 1221 (2013)

Why space?

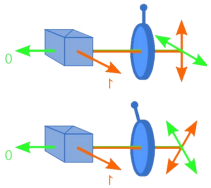


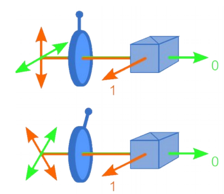
- large distances
- Bell tests with large relative velocities



- Far-off dreams for

  the future



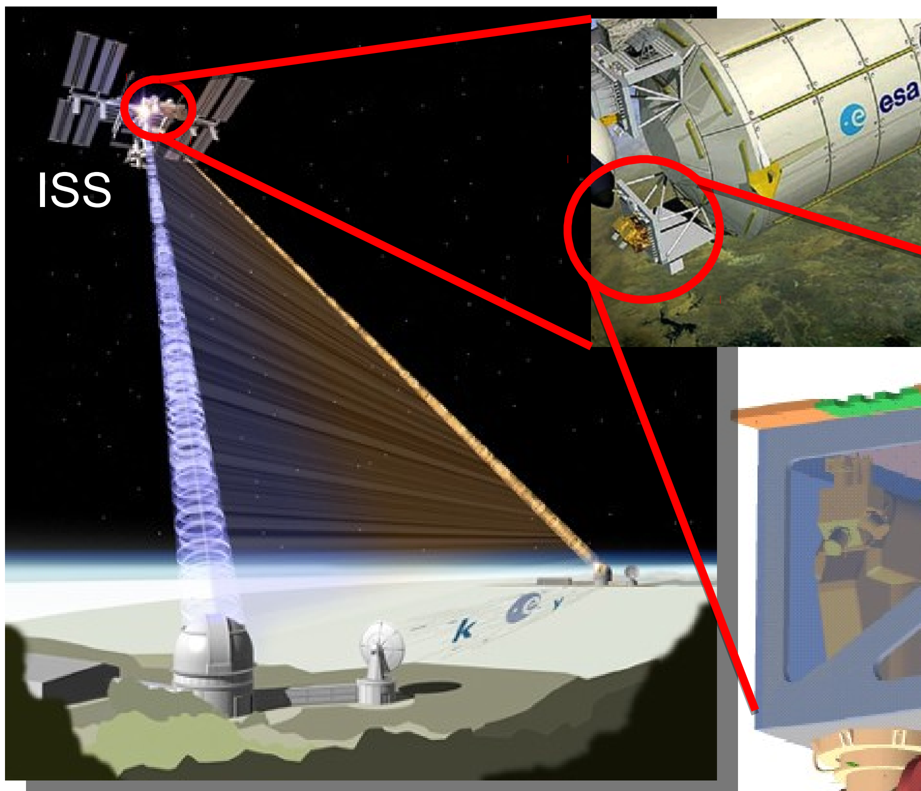


Dual-downlink (Space-QUEST proposal – for ISS)

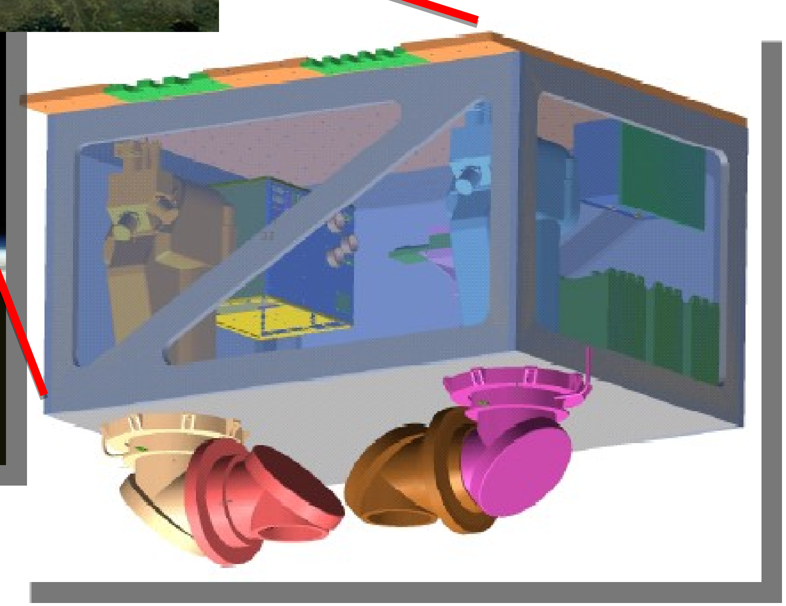
Simultaneous
optical downlink:
1400 km separation.

ISS Requirements:

- Mass: 90 kg
- Power: 250 W
- Volume:1 m3



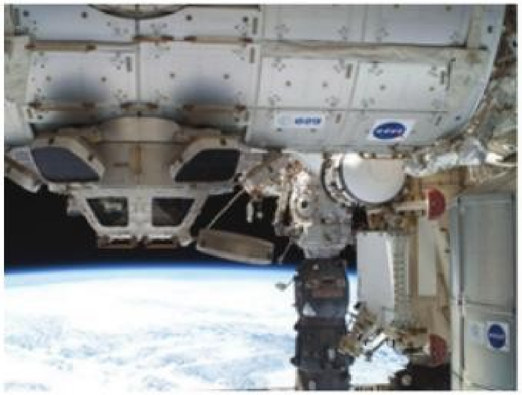
Enangled photon source

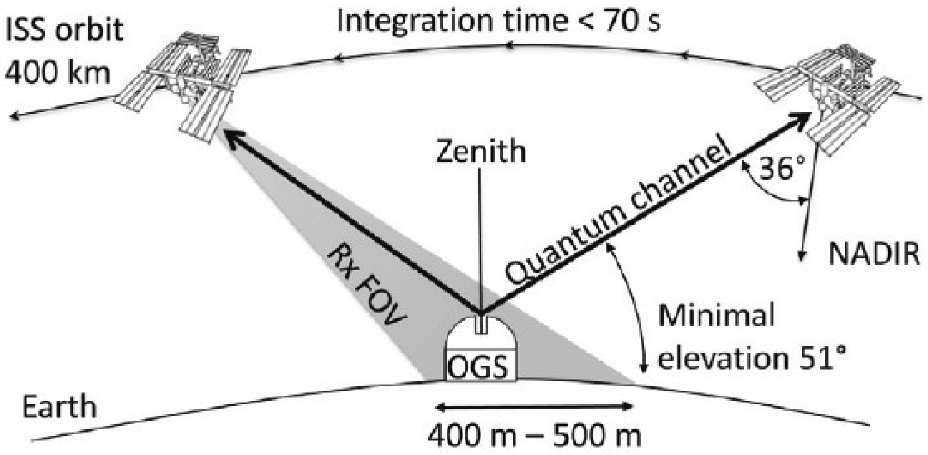


R. Ursin et al., Europhysics News,
26-29, 40–40 (3) (2009)

Options for Bell-type experiments in space

Single-uplink (ISS)



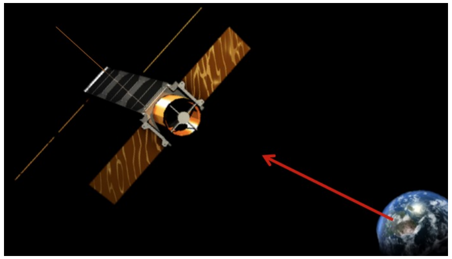


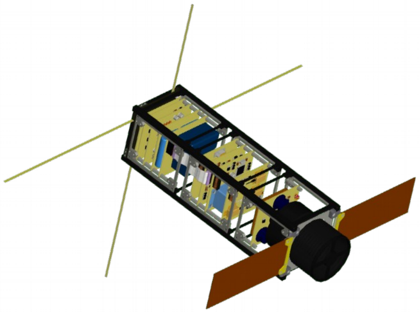
Using a motorized photo-lens-pod (existing) and a dedicated quantum detector as “camera”.

T. Scheidl, E. Wille, and R. Ursin, New Journal of Physics, **15**, 043008 (2013)

Options for Bell-type experiments in space

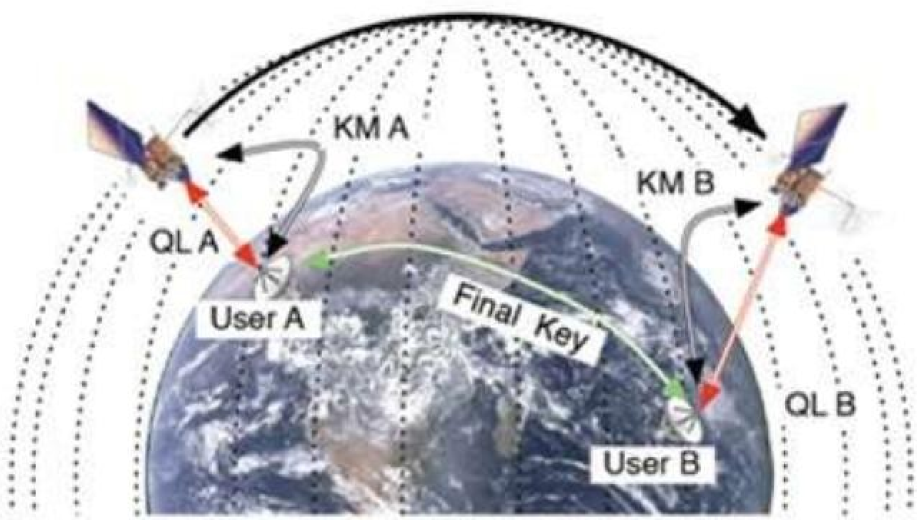
Single-uplink (CubeSat)





20x20x40 cm (!)
9 cm telescope
PAT control

R. Ursin et al., in preparation



Orbit schematic from QEYSSAt mission overview

Conclusions & outlook

- Microscopic systems do not “look like”
- There's no “non-locality”
- The air is getting really thin for loopholes & local realism
- Space: new opportunities for quantum technology

  & for testing quantum physics
- Various options for space experiments (dual down link, single up link, CubeSat, ...)

Thanks

Vienna Center for Quantum Science and Technology

Thanks to Rupert Ursin for the space-related things

!THANK YOU!

Thanks for funding:

APART
Austrian Program for Advanced Research and Technology

Österreichische Akademie der Wissenschaften

Marie Curie FP7-PEOPLE-2010-RG
STREP MINOS
ERC Starting Grant

FWF
START
P15939
L426

ASAP project
Nr. 3589434
FFG