Workshop on Quantum Nonlocality, Causal Structures and Device-Independent Quantum Information

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In Search of Superluminal Quantum Communications: preliminary measurements.

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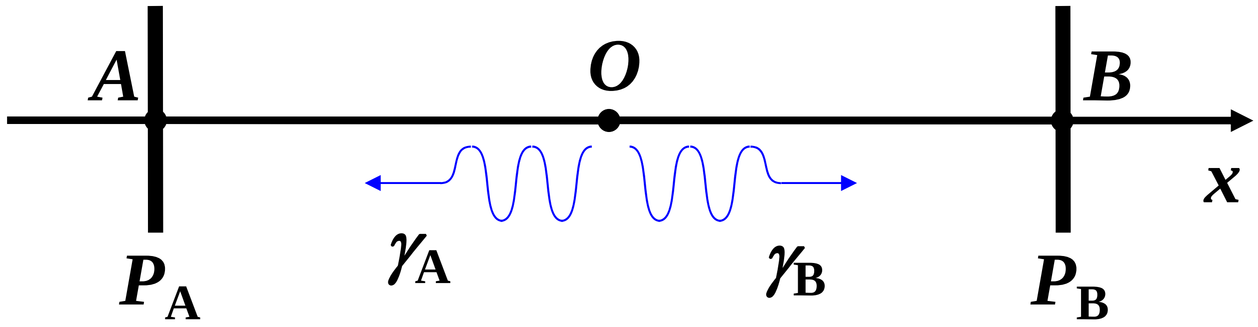
The EPR Paradox (Einstein, Podolski, Rosen)



γ_A and γ_B: photons emitted at point O in the entangled state

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|HH\rangle + e^{i\phi}|VV\rangle\right)$$

H,V = horizontal and vertical polarization.

QUANTUM MECHANICS IS NON LOCAL: a measurement of polarization of photon γ_A at point A leads to the collapse of state $|\psi\rangle$ and sets the polarization of photon γ_B at point B even for "space like" events (Action at a distance ?).

Local Interpretations of *QM*

- Local variables

The entangled state $|\psi\rangle$ is a statistical collection of states as well as for thermodynamic systems. At the creation time each photon is in a well defined polarization state with a given probability.

Bell inequality (1964)
Aspect experiment (1982)

$\Rightarrow$ **Local variables alone cannot explain experimental results; We need "something more"**

- Superluminal communications (Bell[1], Eberhard[2], Bohm and Hiley[3])

The wave function collapse occurs locally and propagates at a distance through superluminal messengers (**tachyons**).

$\vec{v} = \vec{\beta}c$: velocity of *PF* with respect to the laboratory.

$V_t = \beta_t c$: tachyon's velocity in the *PF*.

Causal paradoxes? $\rightarrow$ No, if a tachyons preferred frame (*PF*) exists.

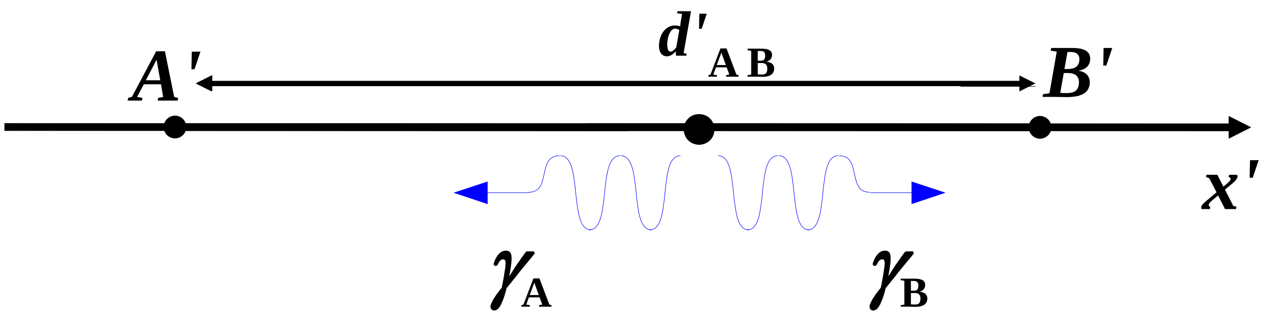
if the model is correct then superluminal messages will ...

Is the model against relativity? ... point of view, absolutely no !

J. D. Bancal, S. Pironio, A. Acín, Y. C. Liang, V. Scarani and N. Gisin, 2012 Nat. Phys. 8 867
T. J. Barnea, J. D. Bancal, Y. C. Liang and N. Gisin, 2013 Phys. Rev. A 88 022123
B. Cocciaro, 2018 Physics Essays 31 531-547. arXiv:1209.3685
B. Cocciaro, 2015 Journal of Physics: Conference Series **626** 012054

1: J. S. Bell in P. C. W. Davies and J. R. Brown, "The Ghost in the Atom", Cambridge University Press (1986)
2: P. H. Eberhard, *A realistic model for Quantum Theory with a locality property*, in W. Shommers (Ed.), "Quantum Theories and Pictures of Reality", W. Schommers, ed., Springer Verlag, Berlin (1989).
- *Restoring Locality with Faster-Than-Light Velocities*, Lawrence Berkeley Lab., LBL-34575, (Aug. 1993).
3: D. Bohm and B. J. Hiley, "The undivided universe", Routledge (1993)

Ideal Experiment in the *PF* *S'*

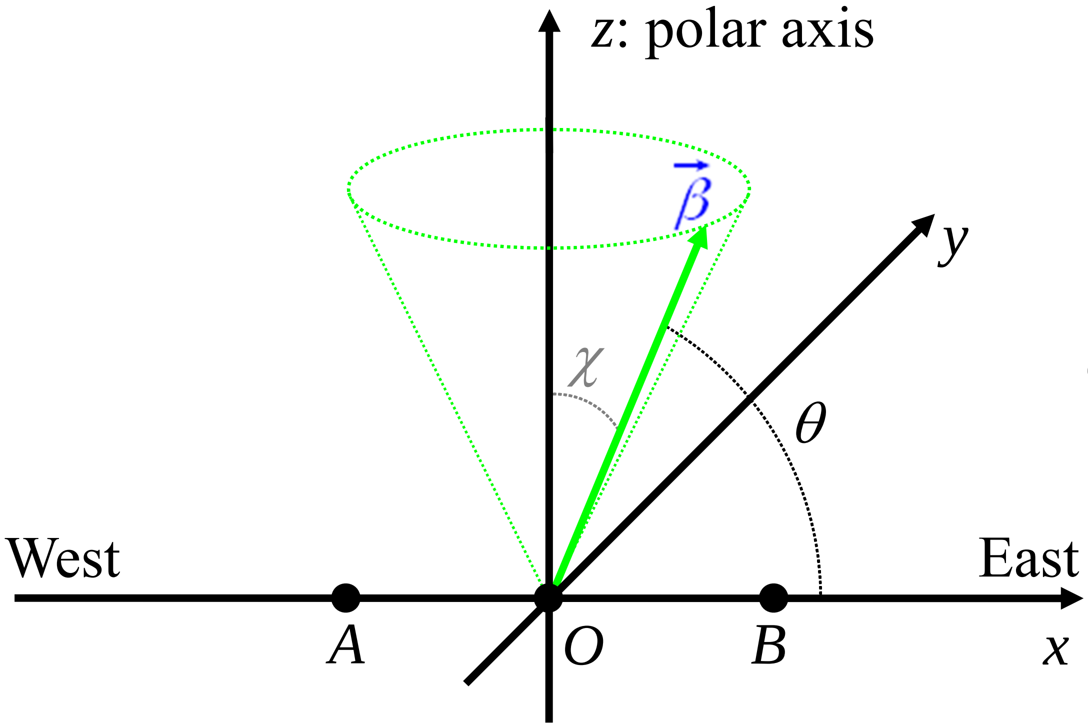


$$|\Delta t'| \quad > \; 0$$

No quantum communication occurs if

$$\beta_t < \beta_{t,\,max} = d'_{AB} \,/\, |c\Delta t'|$$

Actual Experiment on the Earth Frame



$\vec{V} = \vec{\beta}\, c$: velocity of the *PF*.

O: source of the entangled photons

$OA = OB \quad \Rightarrow \quad \Delta t = 0$

Lorentz transformations: $\Delta t' = \gamma (\Delta t - \vec{\beta} \cdot \overrightarrow{AB} / c)$

$\Rightarrow \quad \Delta t' = 0$ if $\Delta t = 0$ and $\vec{\beta} \cdot \overrightarrow{AB} = 0$

Quantum communication does not occur if $\beta_t < \beta_{t,\,max}$

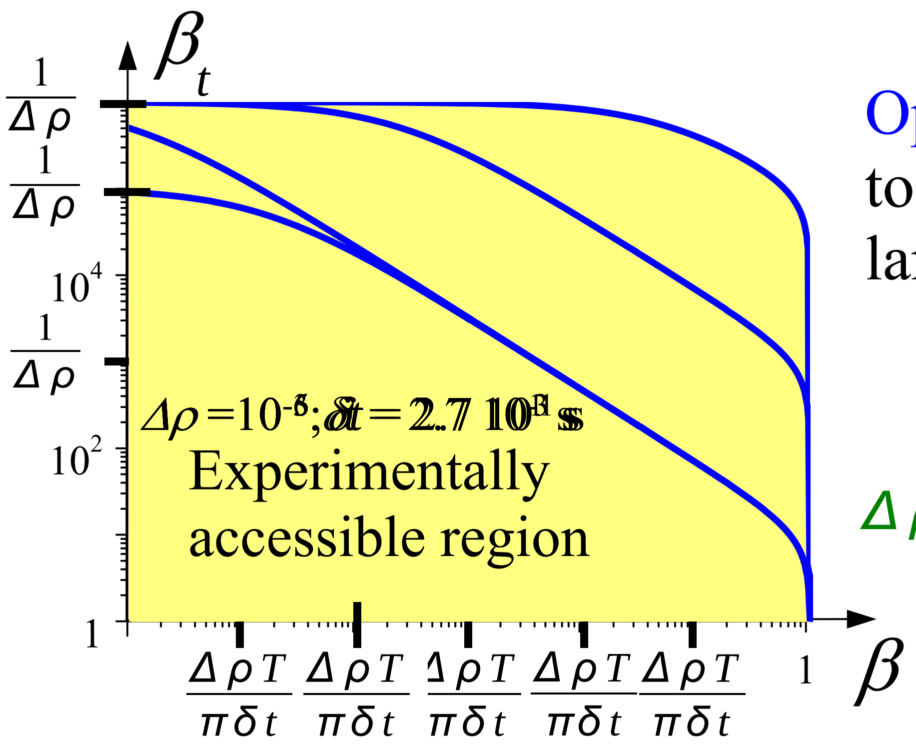
$$\beta_{t,\max} = \sqrt{1 + \frac{(1-\beta^2)[1-(\Delta\rho)^2]}{\left[\Delta\rho + \beta \sin\left(\frac{\pi}{T}\delta t\right)\right]^2}}$$

$\beta_{t,\,max} = d'_{AB} / |c\Delta t'|$

D. Salart et al., Nature **454** (2008) 861.

$\Delta\rho = \dfrac{\Delta d}{d_{AB}} \ll 1$ (Δd = uncertainty on the optical paths equality), δt = acquisition time ($\delta t \ll T$),

$\beta = V/c$ = preferred frame velocity, T = sidereal day,

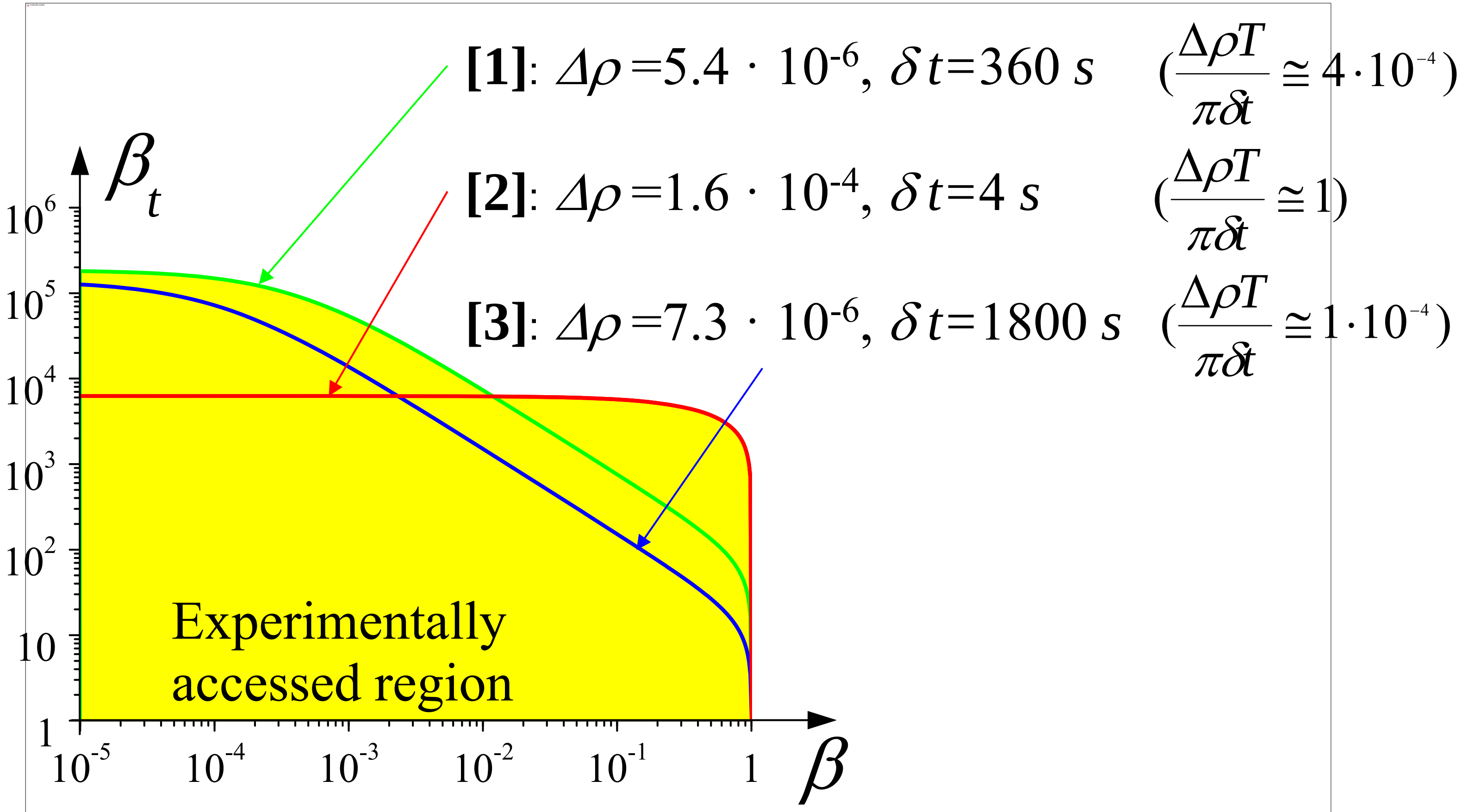


Optimal experimental conditions to have an accessible region as large as possible:

$\Downarrow$ $\qquad\qquad$ $\Downarrow$

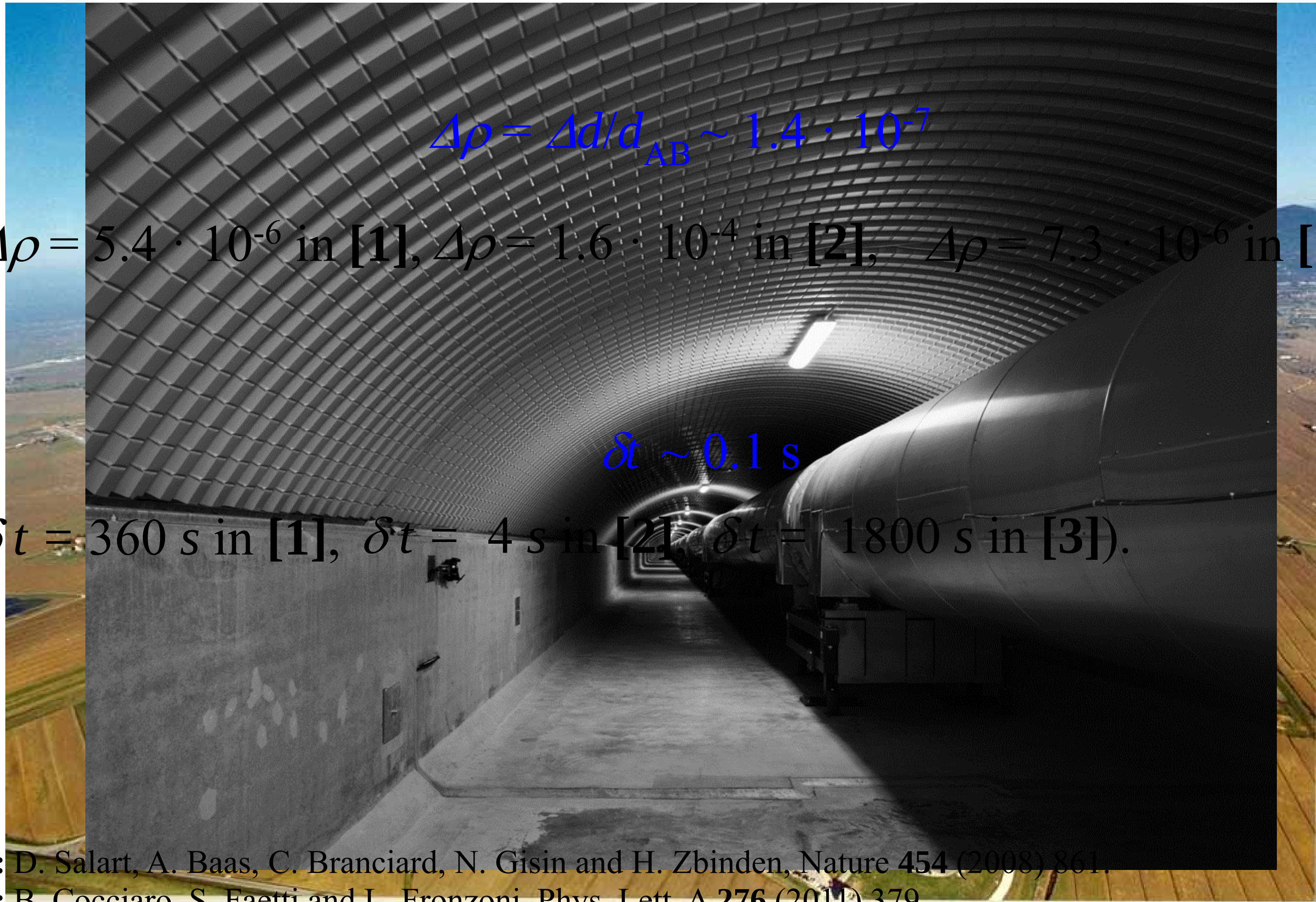
$\Delta\rho \to 0$ $\qquad\qquad$ $\dfrac{\Delta\rho\, T}{\pi\,\delta t} > 1 \Rightarrow \delta t < \dfrac{\Delta\rho}{\pi} T$

Previous experimental results



[1]: D. Salart, A. Baas, C. Branciard, N. Gisin and H. Zbinden, Nature **454** (2008) 861.
[2]: B. Cocciaro, S. Faetti and L. Fronzoni, Phys. Lett. A **276** (2011) 379.
[3]: J. Yin, Y. Cao, H. L. Yong, J. G. Ren, H. Liang, S. K. Liao, F. Zhou, C. Liu, Y. P. Wu, G. S. Pan, L. Li, N. L. Liu, Q. Zhang, C. Z. Peng and J. W. Pan, 2013 Phys. Rev. Lett. **110** (26) 260407

A new improved experiment
(EGO - Virgo)



$\Delta\rho = \Delta d/d_{AB} \sim 1.4 \cdot 10^{-7}$

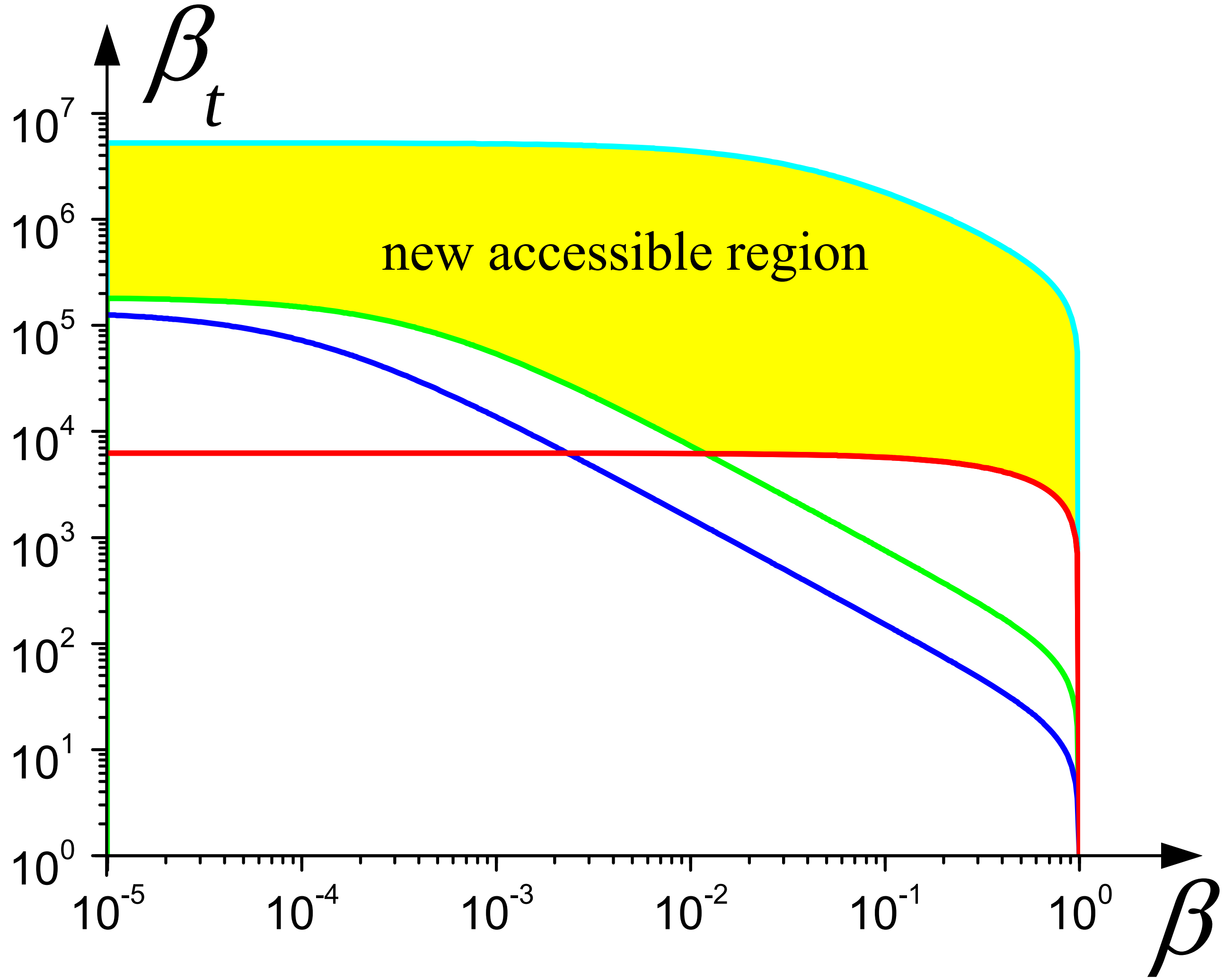
($\Delta\rho = 5.4 \cdot 10^{-6}$ in **[1]**, $\Delta\rho = 1.6 \cdot 10^{-4}$ in **[2]**, $\Delta\rho = 7.3 \cdot 10^{-6}$ in **[3]**).

$\delta t \sim 0.1$ s

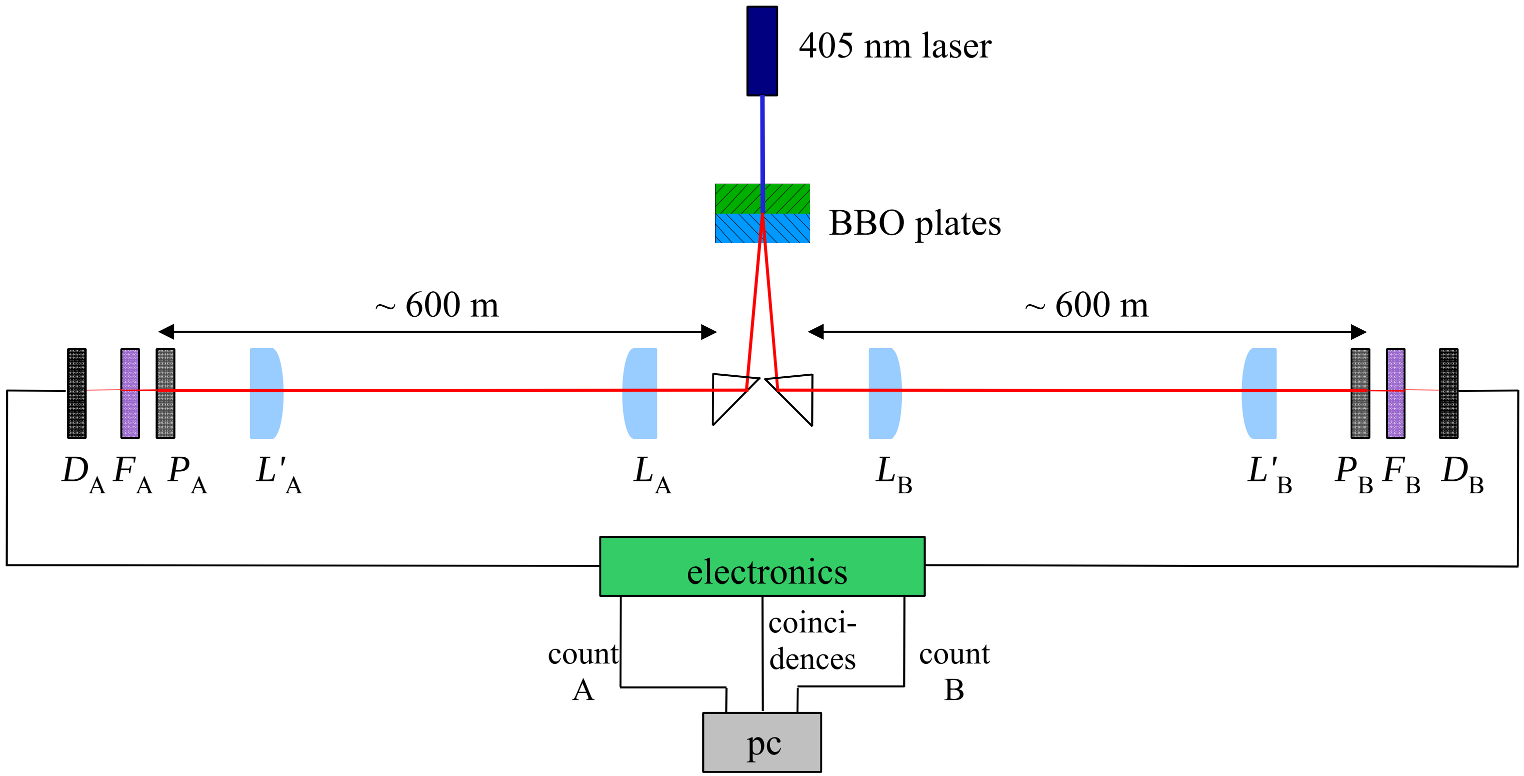
(δt = 360 *s* in **[1]**, δt = 4 s in **[2]**, δt = 1800 *s* in **[3]**).

[1]: D. Salart, A. Baas, C. Branciard, N. Gisin and H. Zbinden, Nature **454** (2008) 861.
[2]: B. Cocciaro, S. Faetti and L. Fronzoni, Phys. Lett. A **276** (2011) 379.
[3]: J. Yin, Y. Cao, H. L. Yong, J. G. Ren, H. Liang, S. K. Liao, F. Zhou, C. Liu, Y. P. Wu, G. S. Pan, L. Li, N. L. Liu, Q. Zhang, C. Z. Peng and J. W. Pan, 2013 Phys. Rev. Lett. **110** (26) 260407

Expected Experimental Results



Schematic view of the experimental apparatus



L_A, L'_A, L_B, L'_B = achromatic lenses with focal length f = 6 m and diameter ϕ = 10 cm;
P_A, P_B = polarizing plates (thickness=220 μm);
F_A, F_B = bandpass optical filters ($\Delta\lambda$ = 10 nm);
D_A, D_B = Detectors (avalanche photodiodes + electronics).

Main features of the new experiment:

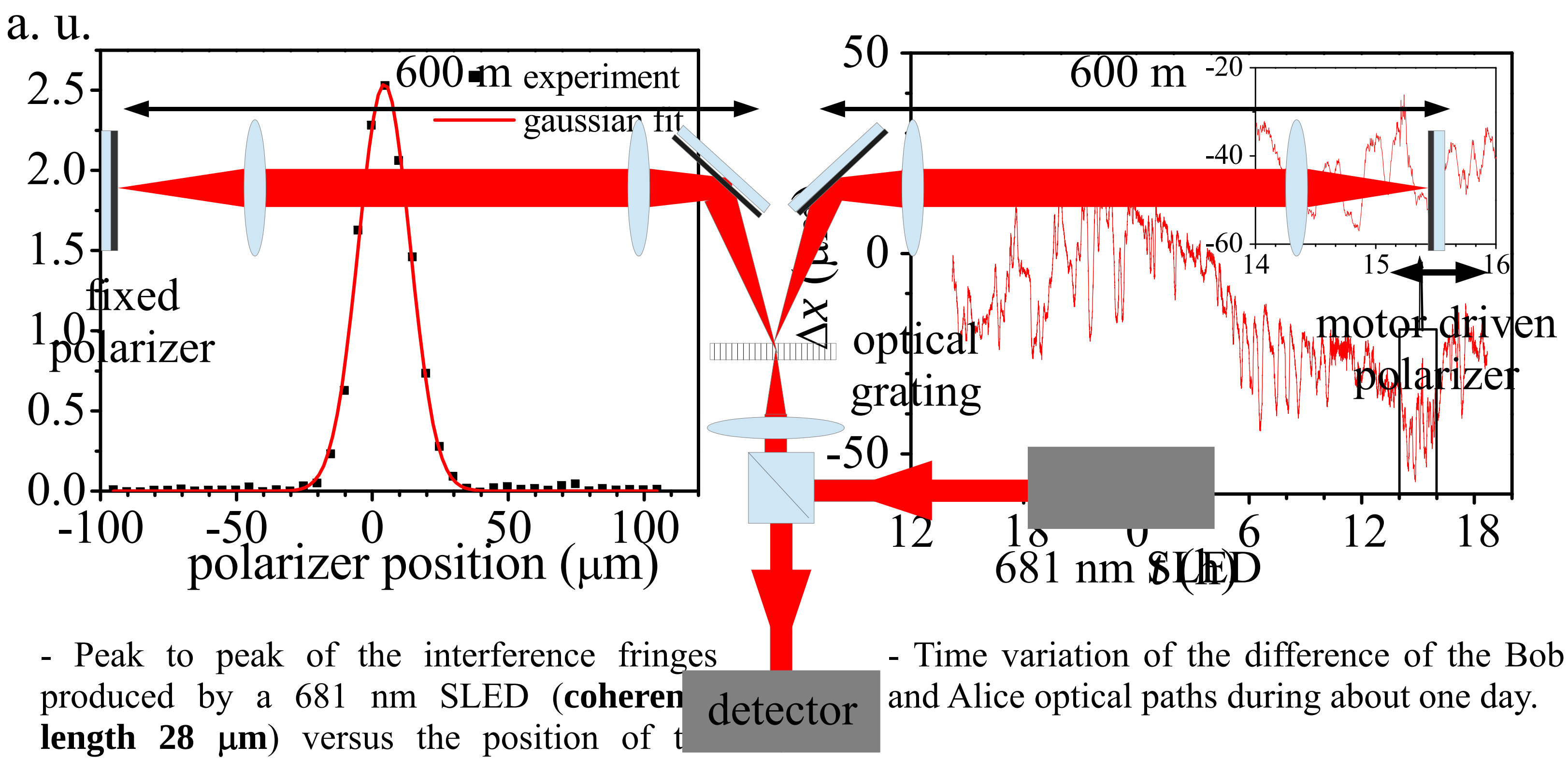
1 – small uncertainty on the equality of the optical paths (Δd < 30 µm):

* interferometric method to equalize the optical paths;

* interferometric feed-back to maintain the paths equality during a sidereal day;

Preliminary interferometric measurements over 120 m paths

Simplified scheme of the interferometric apparatus



- Peak to peak of the interference fringes produced by a 681 nm SLED (**coheren** **length 28 µm**) versus the position of t motor moved polarizer. The maximum corresponds to the equality of the optical paths in the interferometer.

- Time variation of the difference of the Bob and Alice optical paths during about one day.

Main features of the new experiment:

2 - large number of coincidences/s $\Rightarrow \delta t < 0.1$ s:

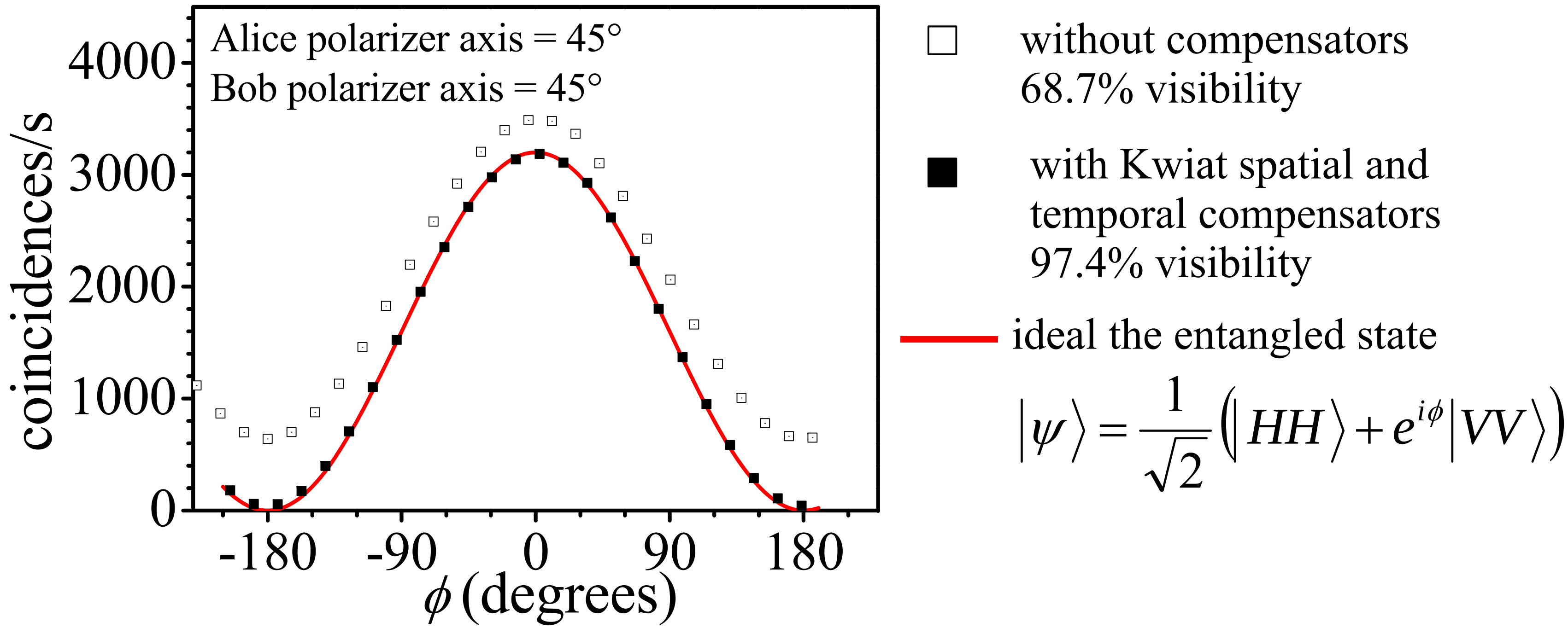
* high power pump laser beam (210 mW at 406.3 nm);

* detection of entangled photons over a large solid angle (aperture 0.7 °);

* negligible photon losses along the paths (~ 600 m) by a suitable optical design.

3 – high fidelity of the entangled state (~98%):

* use of the method developed by the Kwiat group [R. Rangarajan, M. Goggin and P. Kwiat, Optics Express, **17** 18920 (2009)] to compensate the dephasing due to the large detection solid angle and the 167 μm coherence length of the pump laser.



$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|HH\rangle + e^{i\phi}|VV\rangle\right)$$

Drawbacks:

1 – wander and beam spot size variations due to air turbulence:

Images of an expanded (5 cm diameter) HeNe laser beam at various distances from the laser source

Drawbacks:

2 – air dispersion $\Rightarrow$ uncertainty on the optical paths of the entangled photons:

$$\Delta d = (\partial n/\partial \lambda)\ \Delta\lambda\ d \sim 40\ \mu\text{m}$$

n = air refractive index[1]
$\Delta\lambda$ = width of the interference optical filters (10 nm)
d = photons path lenght (~ 600 m)

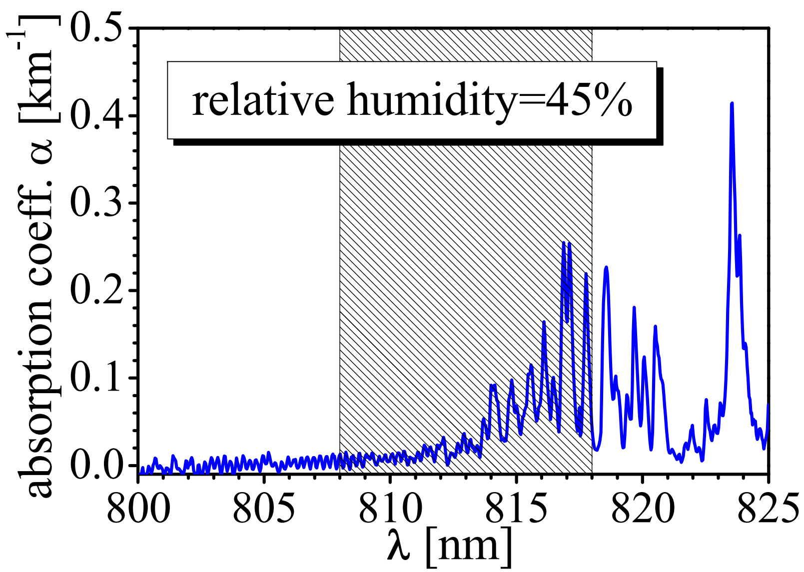
$\Downarrow$

negligible with respect to our main uncertainty due to the finite thickness of the polarizing layers (~220 μm)

1: P. E. Ciddor *Appl. Opt.* 35, 1566–1573 (1996) and http://emtoolbox.nist.gov/Wavelength/Ciddor.asp

Drawbacks:

3 – air absorption of entangled photons at 813 nm



The absorption peaks in the figure are due to H_20. From integration of the absorption spectrum in the 808-818 nm interval (bandwidth of our filters) we get the fraction of absorbed entangled photons at 600 m:

$$\Delta n/n = 2.4\%$$

For a 100% relative humidity we extimate

$$\Delta n/n = 5.3\%$$

⇓

Air absorption doesn't represent an important drawback for our experiment.

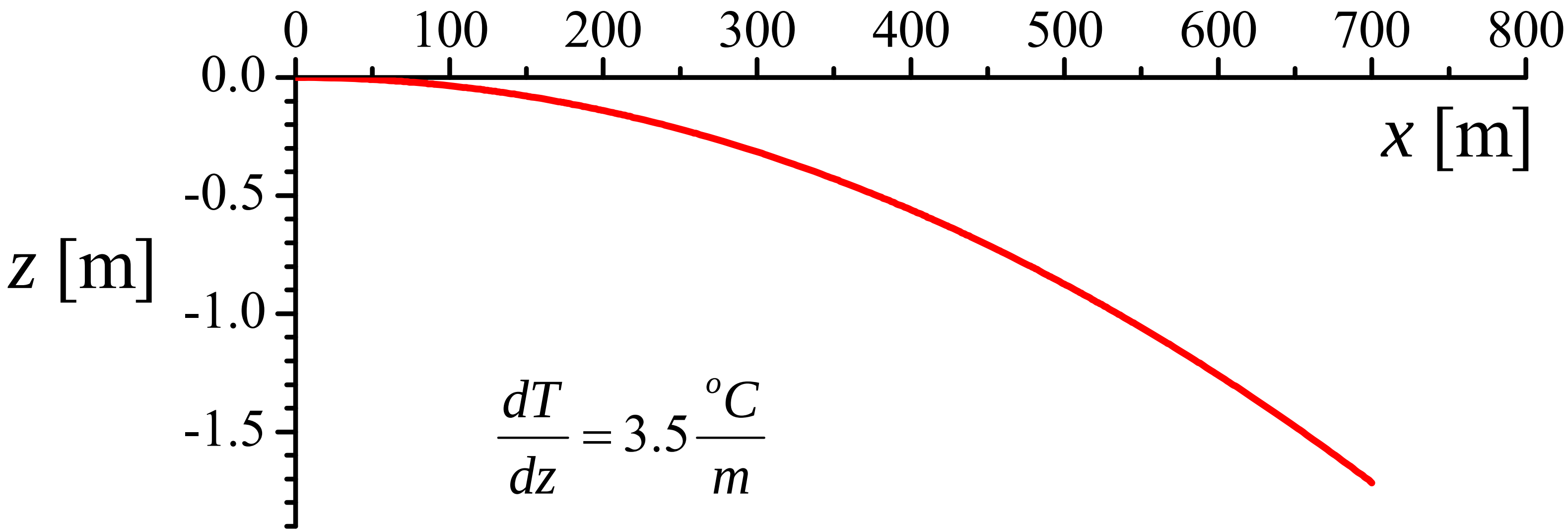
An unexpected drawback:

Vertical displacement of the optical beams due to the temperature gradient produced by sunlight on the top of the EGO gallery (up to 1.2 m at a distance of 600 m!)

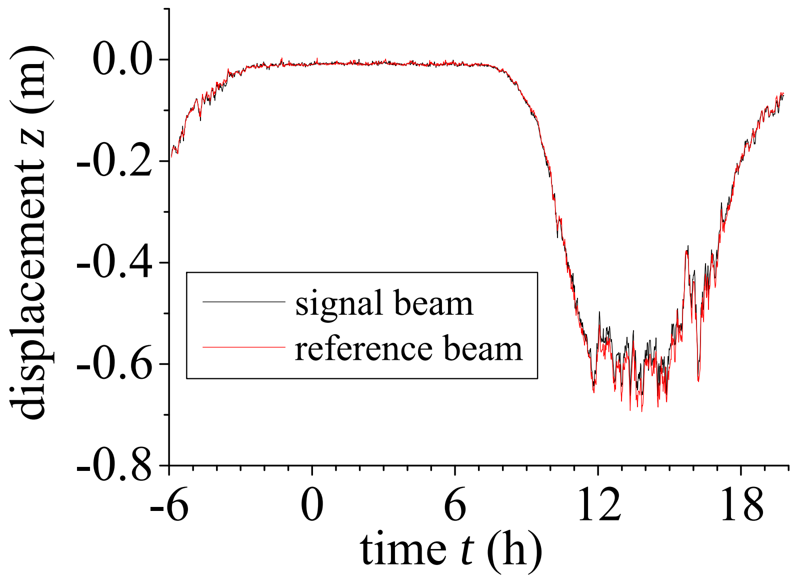
Theoretical predictions for the vertical beam displacement, z, versus the horizontal beam displacement, x, along the EGO gallery:

$$z(x) = \frac{a}{2} x^2$$

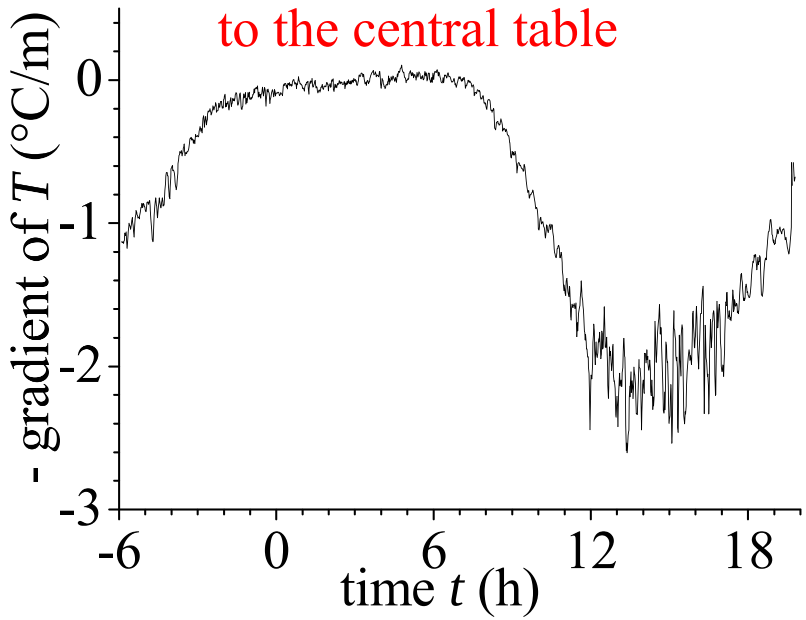
where $a = \frac{d \ln[n(T)]}{dT} \frac{dT}{dz} \cong -10^{-6} \frac{dT}{dz}$

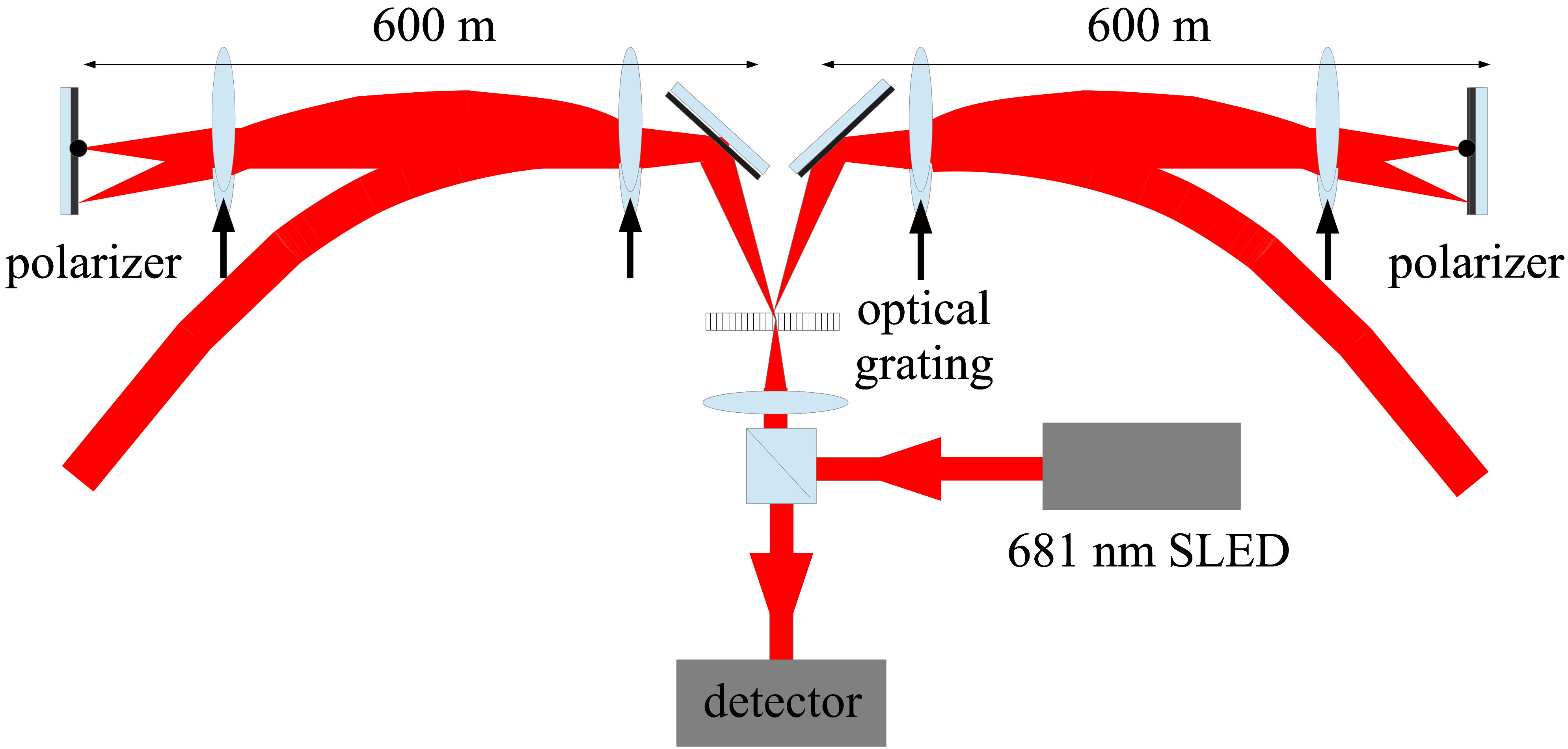


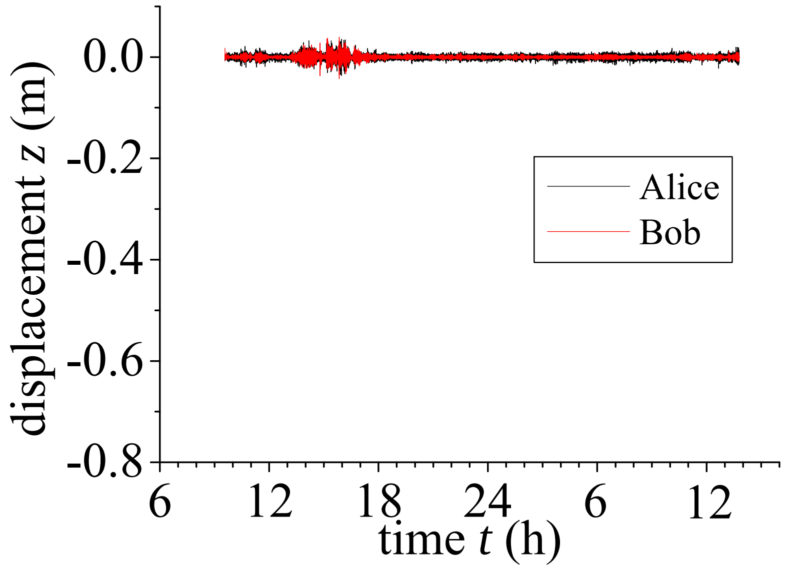
$$\frac{dT}{dz} = 3.5 \frac{^oC}{m}$$



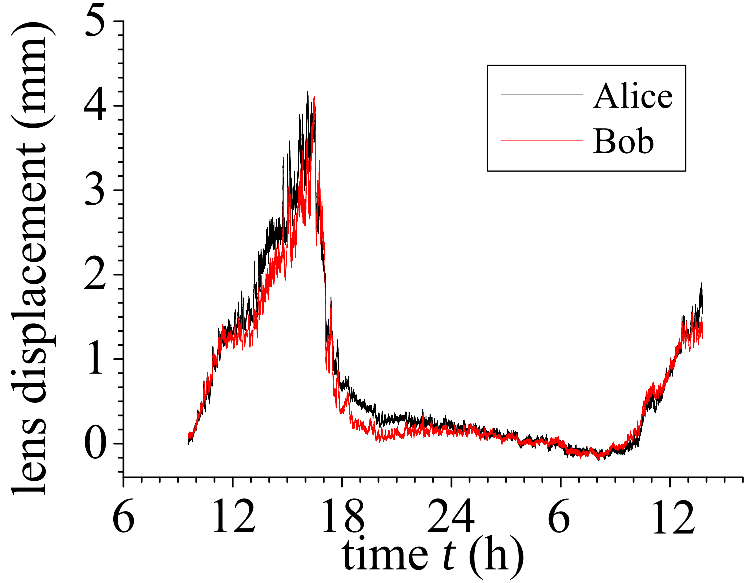
temperature gradient close to the central table




600 m
600 m
polarizer
polarizer
optical
grating
681 nm SLED
detector



0.0
-0.2
-0.4
-0.6
-0.8
displacement z (m)
6
12
18
24
6
12
time t (h)
Alice
Bob



5
4
3
2
1
0
lens displacement (mm)
6
12
18
24
6
12
time t (h)
Alice
Bob

Thank you very much

winter: T=5 C (41 F)

summer: T=35 C (95 F)