# Constraining the correlation distance in quantum measurements from the Moon

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- Reminder of Bell inequalities - The latest test
- Spatio-temporal dependance of correlations?
- Lunar and other tests

updates and developments at
http://luth7.obspm.fr/~schneider/qm.html

# Reminder: rules of Quantum Physics

**R0** An experiment can be divided into an apparatus and a system

State

**R1** Every system *S* is described by a Hilbert space *Hilb.*

For *S = (S1, S2)* , $Hilb = Hilb1 \otimes Hilb2$

**R2** A system can be in different states, discribed by $\Psi \in Hilb$

For *S = (S1, S2)* , $\Psi = \Psi 1 \otimes \Psi 2$

**R3** A system usually evolves according to the equation $-i\hbar\, d\Psi/dt = H\Psi$

Observable

**R4** Experiments lead to observables described by $A \in Herm(Hilb)$

**R5** Only possible results of measurements of *A* are proper values $a_i$ $A\Psi_i = a_i \Psi_i$

**R6** Results of measurements are random with probabilities $p_i = |<\Psi|\Psi_i>|^2$

**R7** After a measurement the system is in a state $\Psi_i$

# Comment on rules of Quantum Physics

- The mathematics of rules: no problem, universal consensus
- The rules also contain words from plain language:

  «  apparatus », « experiment », « measurement », « observable », « result »

  These common-language, unavoidable, words are the source of controversies in the understanding of quantum physics.

# A problem with quantum rules

Question: what is the meaning of superposed states?

Let $|+/-x\rangle$ be the eigenstate of $\sigma_x$ for the proper value +/-1/2

$$|+/- x\rangle = (|+y\rangle +/- |-y\rangle)/\sqrt{2}$$

The measurement of $\sigma_y$ gives +1/2 or -1/2 with probability 50%

==> Two possible views (or « interpretations »):

1/ $|+x\rangle$ « has » no definite value of $\sigma_y$ prior to measurement (QM)

2/ $|+x\rangle$ « has » a definite value of $\sigma_y$ but it is unknown.

A complete description of the state $|+x\rangle$ then requires extra « hidden » parameters .

(similar e.g. to positions and velocities of individual molecules of a gaz with temperature *T* )

# A problem with quantum rules

Hidden parameters $\lambda$ with distribution probability $\rho(\lambda)$

$|x\rangle \longrightarrow |x,\lambda\rangle$

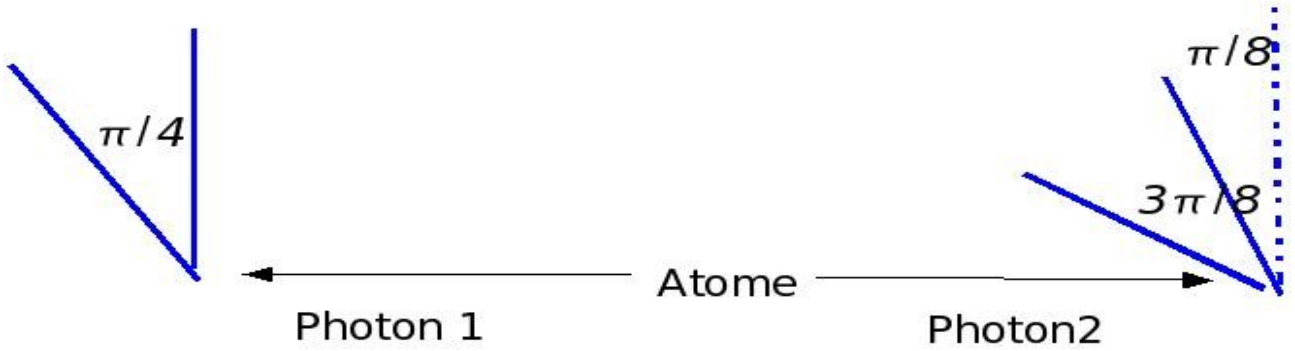
# Bell theorem

Consider then a 0 spin system decaying into 2 spin ½ systems 1 and 2 (inspired by Einstein-Podolski-Rosen paradox EPR)

Conservation of spin ==> in any direction *a*,

$$(\sigma_a)_2 = -(\sigma_a)_1$$

# Bell theorem (2)




4 statistical correlations:

$$C(0,\pi/8), C(0,3\pi/8), C(\pi/4,\pi/8), C(\pi/4,3\pi/8)$$

- Suppose $\lambda$ attached to 1 and 2 (local hidden variables)

  Prediction from local hidden (Bell theorem)

  $$C(0,\pi/8)-C(0,3\pi/8)+C(\pi/4,\pi/8)-C(\pi/4,3\pi/8)<2$$

  **whatever** $p(\lambda)$

- Prediction from standard MQ :

$$C(0,\pi/8)-C(0,3\pi/8)+C(\pi/4,\pi/8)-C(\pi/4,3\pi/8)=2\sqrt{2}$$

# Bell theorem (3)

- Other possibility: non-local hidden parameters
- A physical model (Bohm, Vigier et al ~'60):
  - Waves are « real physical objects »
  - Quantum system made of/embedded in a « subquatum », chaotic, medium in which  hidden parameters propagate at a speed >>> c.
  - These hidden parameters behave as « effective » non local parameters
  - Then possible to reconcile these hidden parameters with prediction of standard QM

# Bell theorem (4)

- QM ==> Instantaneous statistical correlation at a distance

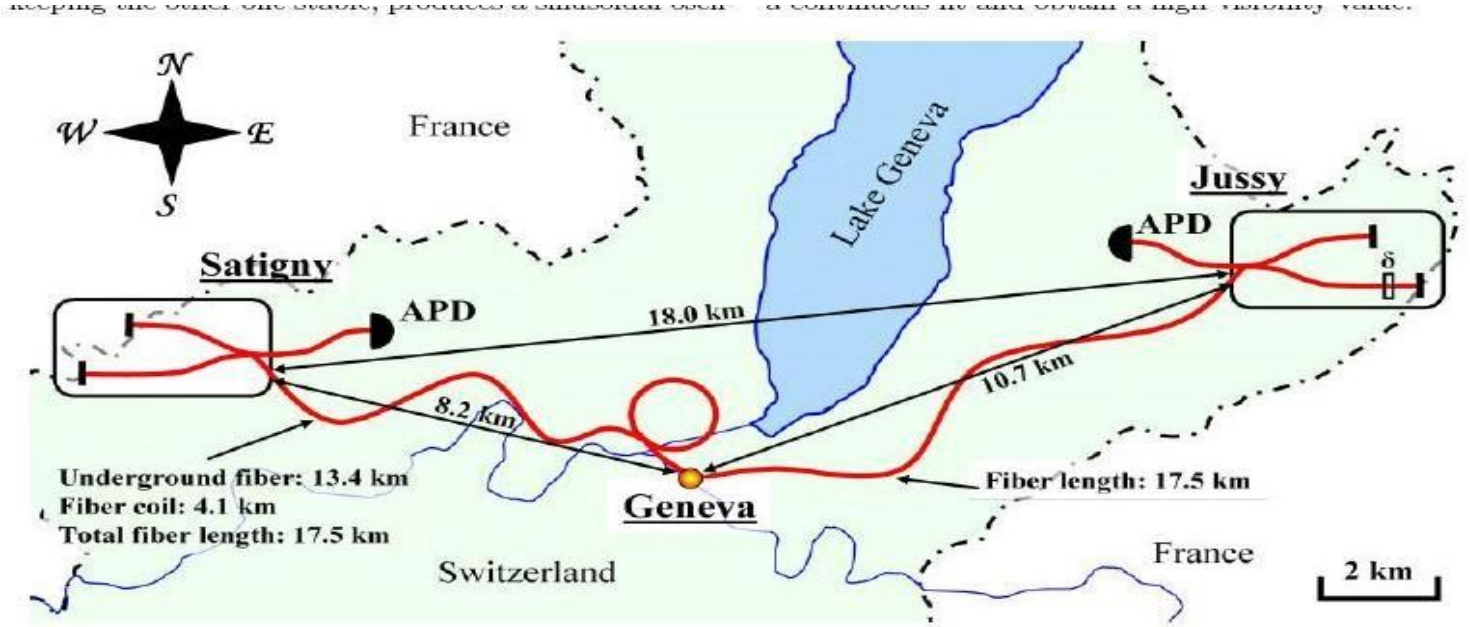
  **whatever the distance between detectors**

  (propagation speed V infinite)

- Experiment confirms prediction of standard QM

  Tested until 18 km between 2 detectors (V > $10^7 c$ )

Gisin et al 2007



# Spatio-temporal dependance of correlations ? (1)

Questions:

- Does the correlation distance D go until infinity ?

  (even beyond the cosmological horizon ? )
- Is the « correlation speed » V necessarily infinite ?

Standard QM: **YES**

B.-V's or other theories answer: ??

4 possibilities:

- D infinite, V infinite (standard QM)
- D infinite, V finite (« dynamic correlation »)
- D finite, V infinite (« static correlation »)
- D finite, V finite (« dynamic correlation »)

# What distance $D_o$ and speed V of correlation?

- Play only with *G*, *h*, *c*

$$D=\sqrt{\frac{Gh}{c^3}}=10^{-33}cm \qquad V=c$$

- Play also with $m_Q$ (quark mass, Higgs mass...)

$$D=\sqrt{\frac{Gh}{c^3}}\left(\frac{Gm_Q^2}{hc}\right)^N=10^{-33-39N}cm \qquad V=\left(\frac{Gm_Q^2}{hc}\right)^N c=10^{-39N}c$$

- Play with non standard phenomena
  - « 5th force »: *D ~1 cm – 1 m*
  - MOND (dark matter): *D ~ 1 Mpc*
  - Cosmological constant *D = 10 Gpc*

Conclusion: no obvious prediction

# A test

Idea: measure $D_o$ and $V$

e.g. $C(\theta,\theta',D)=C_o(D_o/D)^{-n}$ or $C(\theta,\theta',D)=C_o(1-e^{-D/D_o})$

(e.g. Introduce a dissipative term in Schröd. eq.: $d\psi/dt=iH\psi+[\rho,H]$ )

==> Extend as much as possible the distance of measurement of correlations

e.g.: **Earth-Moon distance** (18 km ---> 400.000 km)

==> Put the (orientable) polarizers and detectors on the Moon

Put the laser source on the Earth and point it toward the Moon..

Remark: influence of gravitational waves background negligeable (Raynaud, Lamine et al. GRG 36, 2271, 2004)

# A fundamental question

Suppose mirror on the Moon and detectors on Earth
Easier to do than to put detectors and
tunable polarizers on the Moon

MQ: Correl. distance = distance between detectors D1
BV: Correl. distance = distance of propagation D2?

Question:

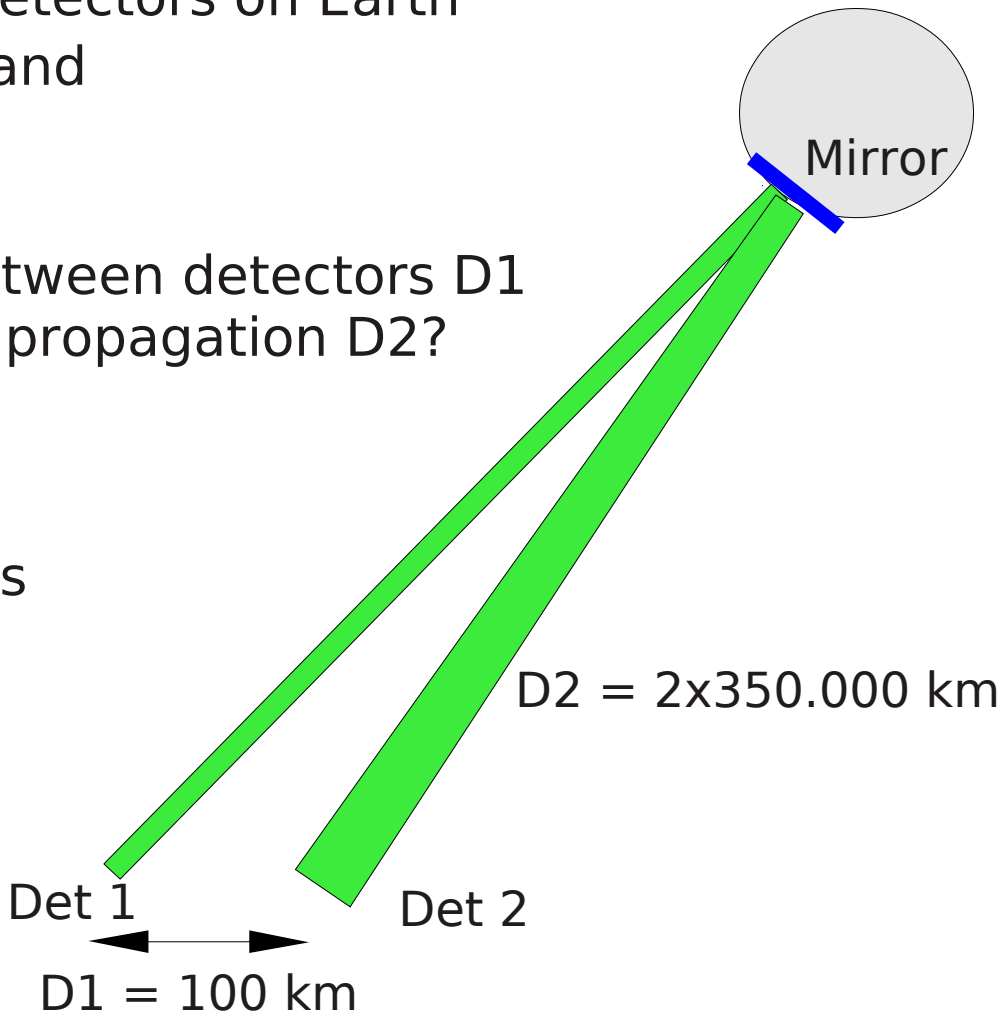
System = 2 photons
Apparatus = mirrors +detectors

or

System = 2 photons + mirrors
Apparatus = detectors

==>

Root of concept of measurement.

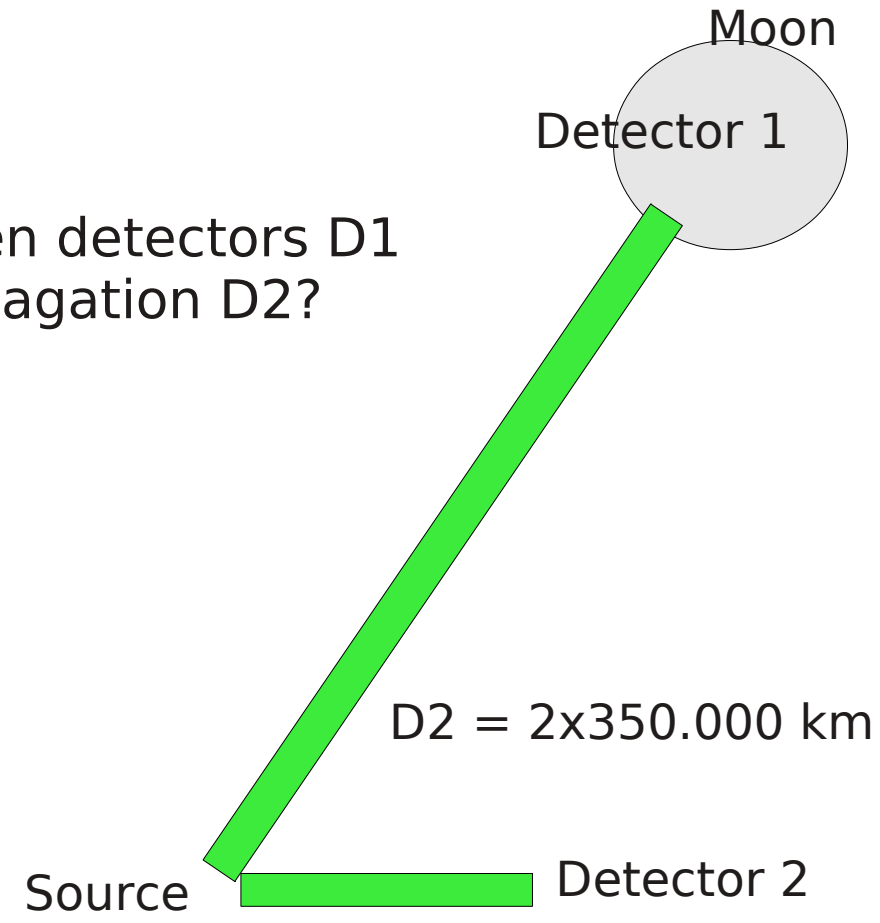



Strict QM: measurement = appearance of a number on a display

Naive view: measurement = system-apparatus interaction

# A fundamental question

Put detectors and
tunable polarizers on the Moon

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# An Earth-Moon laser

Mirror deposited on the Moon by Apollo


- The Apache Point Observatory's 3.5 meter telescope
  - Southern NM (Sunspot)
  - 9,200 ft (2800 m) elevation
  - Great "seeing": 1 arcsec

# Toward a real implementation


DOCUMENT

document title/ titre du document

**DIRECTORATE OF HUMAN SPACEFLIGHT**

**ESA FIRST LUNAR LANDER: REQUEST FOR INFORMATION**

See also: Science from the Moon (Burns et al) arXiv:0909.1509

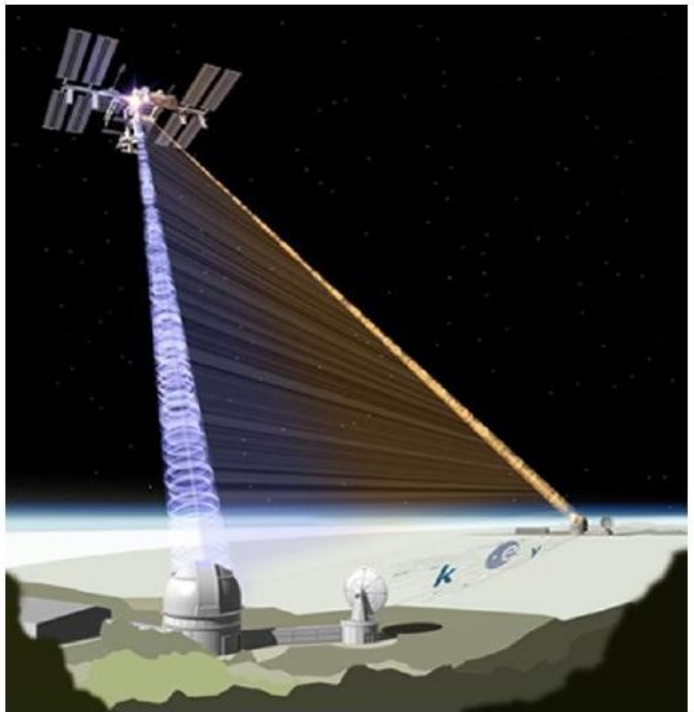
# Prospects for a Lunar Base

- Prerequisite to establish a permanent Lunar base: **Water**

  Permanent at the frozen polar regions (T= 100 K) ?
  Natural sources:
  - Bombardement by comets
  - H+ in stellar wind + O in lunar rocks --> H20 ==> $10^{7\text{-}8}$ tons
  - Check underway after NASA/LCROSS crash on the Moon (12 Oct)
- Plans to to establish a permanent Lunar base:
  - Under study: European Lunar Lander (ESA, Astrium/DLR)
  - Preparation: European, NASA « Lunar Science Institutes »
  - 23 October 2009: ESA+EU Ministerial Conference in Prague to establish « a policy in the field of exploration of our solar system, going back to the Moon ».

# Other possibilities

- ISS: projet Space-QUEST (Ursin et al. 2008)



Problems:

- less room than on Moon
- distance = 400 km instead of 400.000 km
- duration of individual experiments:
  a few minutes/hour
- 400 km experiments will certainly become possible on Earth thanks to progress in fiber optics

- Planet Mars (Kaltenbaek 2003): very futuristic
- LISA? (5 million km) See poster by Acef et al. for LISA lasers
- **Transfer correlated quantum states in free boxes at the edge of he Solar System**:
  no technological possibility forseen