Title: Local and Nonlocal Quantum Tests

Date: Jul 20, 2006 05:15 PM

URL: http://pirsa.org/06070055

Abstract:

Local and Nonlocal Quantum Tests

Conference in Honour of

Abner Shimony

Perimeter Institute

July 20, 2006

4π Spinor Rotation

Rauch, Z, Badurek, Wilfing, Bauspiess, Bonse 1975

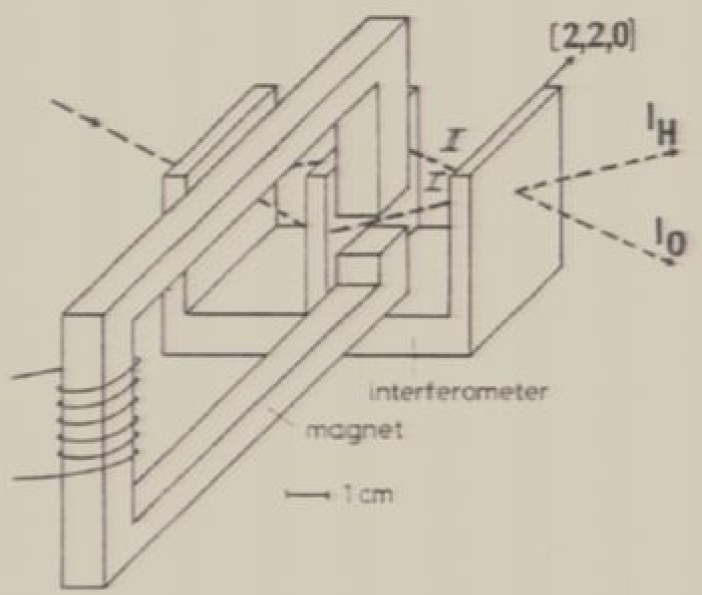


Fig. 1. Sketch of the experimental setup.

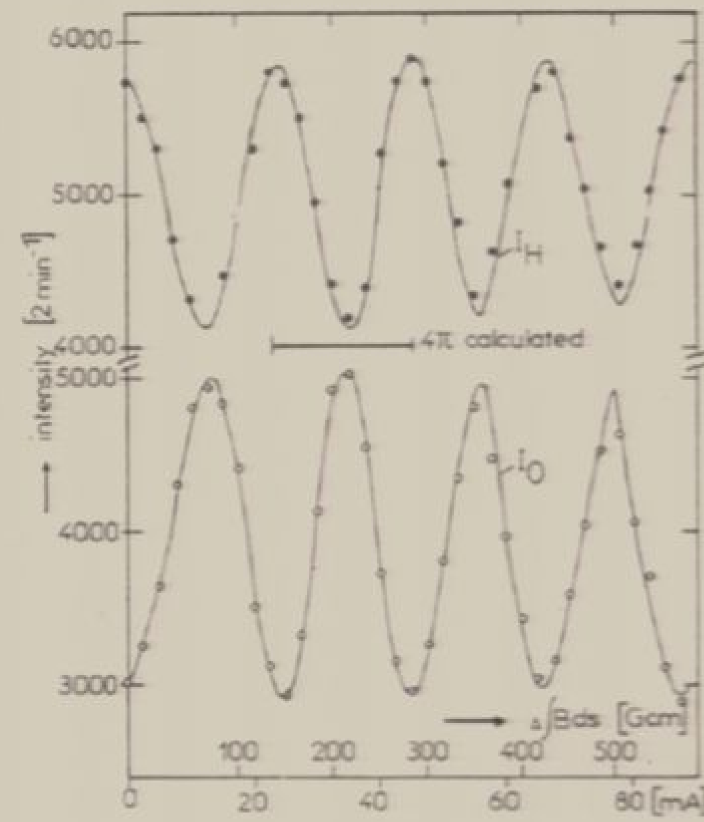


Fig. 2. Observed intensity oscillations of the 0- and H-beam as a function of the difference of the magnetic field action on beam I and II ($\Delta\int B ds = \int B_z ds$ (path I) $- \int B_z ds$ (path II)).

Horne and Shimony ca 1975 Electron Interferometry

Nonlinear Schrödinger Equation

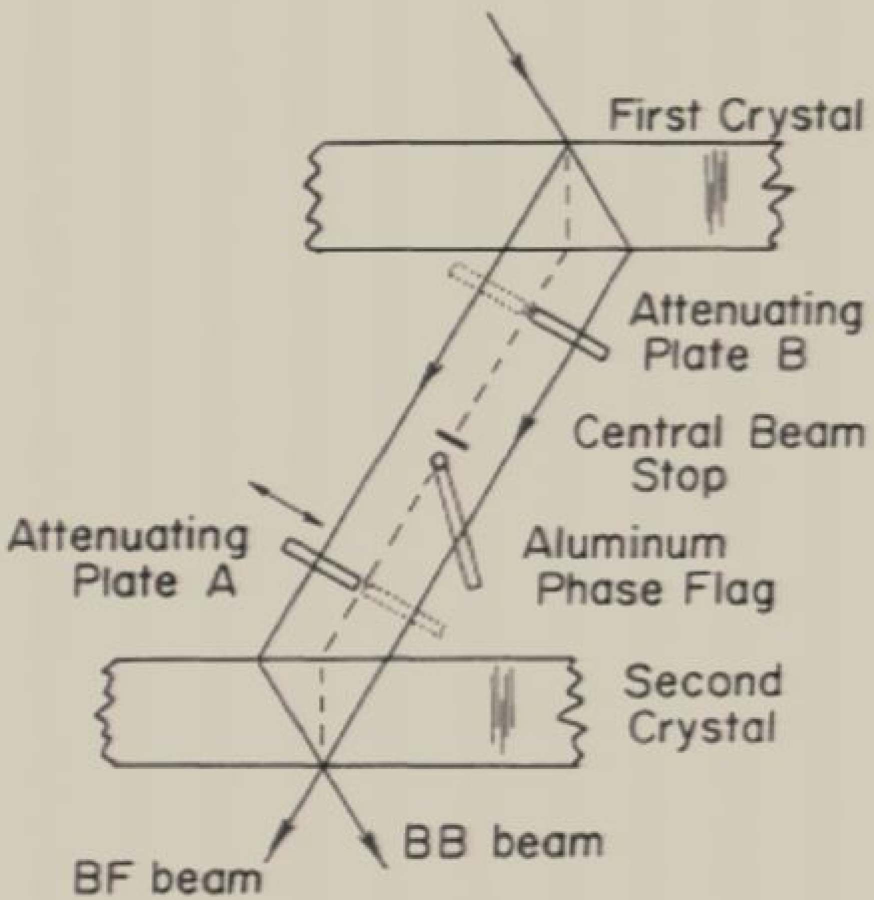
I. Bialynicki-Birula and J. Mycielski 1975

$$\left(-\frac{\hbar}{2m}\nabla^2 + V(\vec{r},t) + F\left(\left|\psi(\vec{r},t)\right|^2\right)\right)\psi(\vec{r},t) = i\hbar\frac{\partial}{\partial t}\psi(\vec{r},t)$$

$$F\left(\left|\psi\right|^2\right) = -\underline{b}\ln\left(\underline{a}^n\left|\psi\right|^2\right)$$

- Limits Wave Packets from Spreading
- Separability of Non-interacting Sbsystems

An amplitude-dependent Phase



Clifford G. Shull, MIT, Cambridge, Massachusetts, USA, receives one half of the 1994 Nobel Prize in Physics for development of the neutron diffraction technique.

Proposal: Shimony 1979

Experiment: Shull, Atwood, Arthur, Horne 1980

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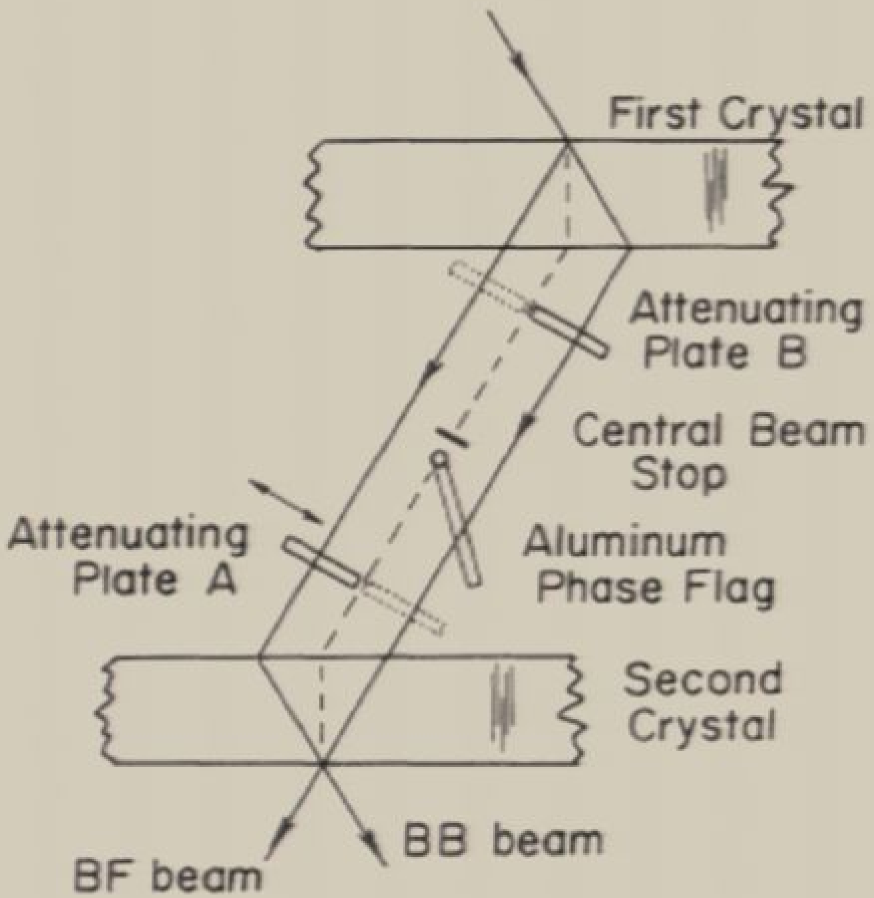

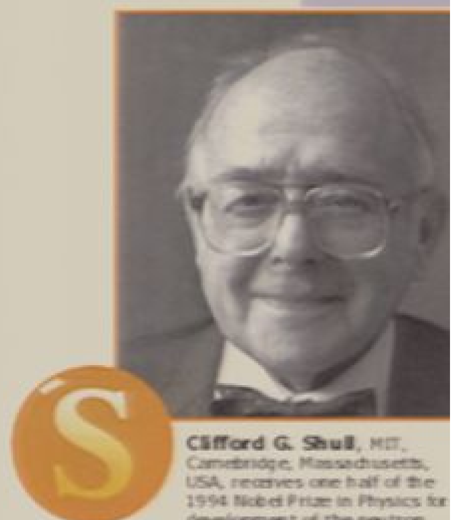

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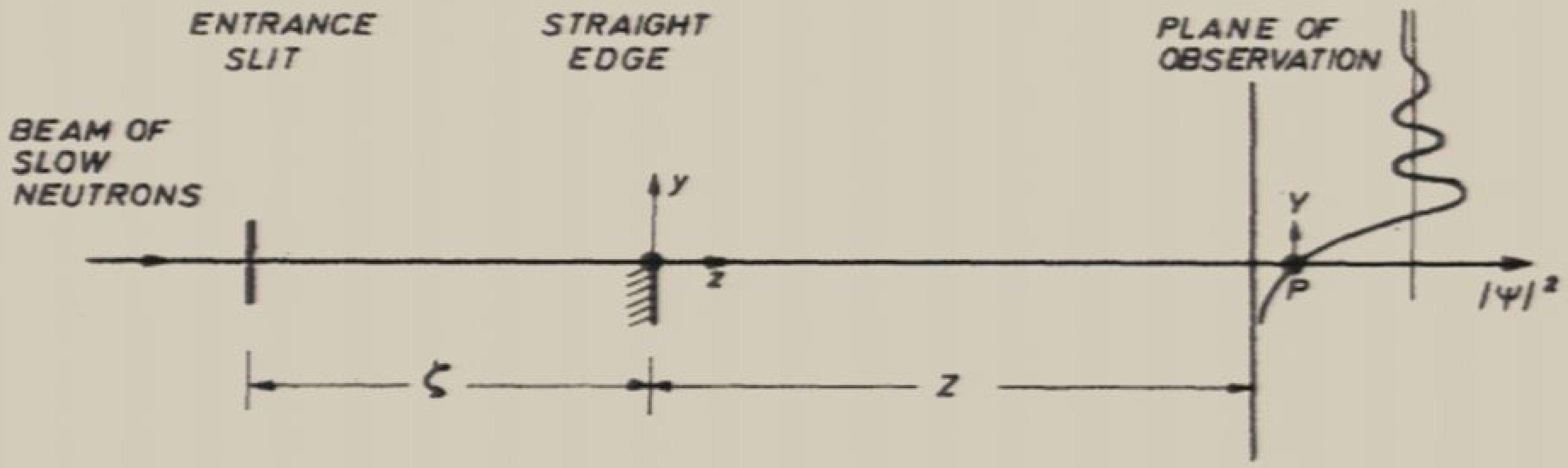
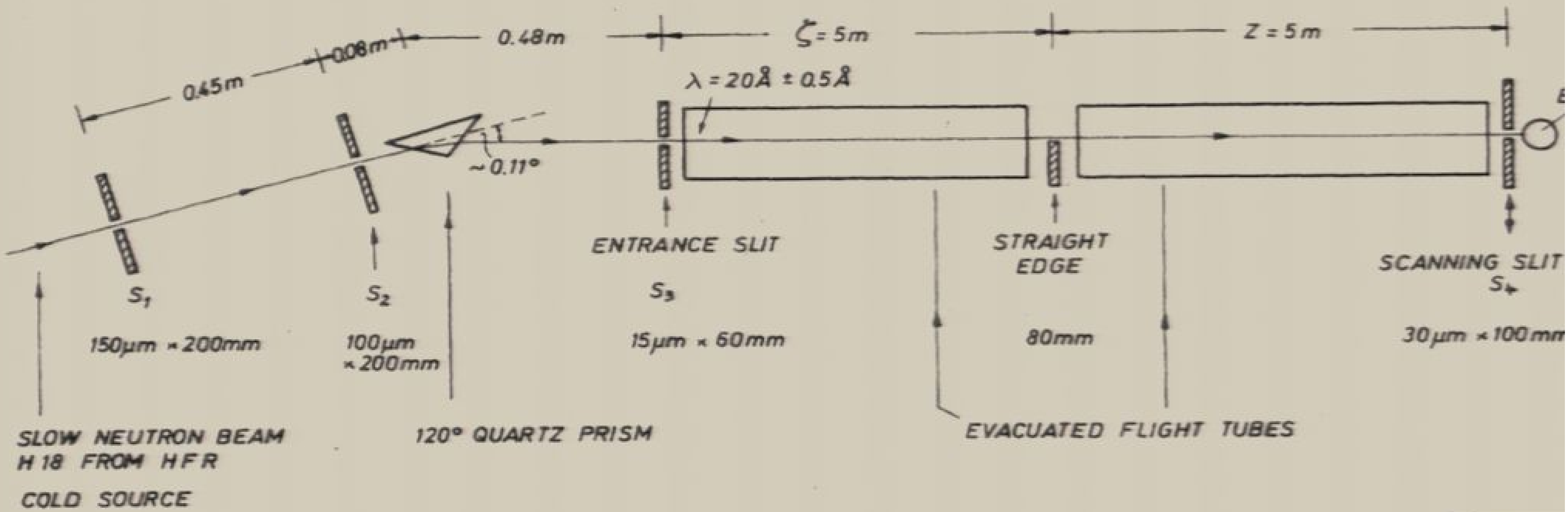
Neutron Free-Space Propagation Experiment

Gähler, Klein, Z 1981



Fresnel Diffraction at Absorbing Edge

The Experiment at
Institute Laue-Langevin Grenoble

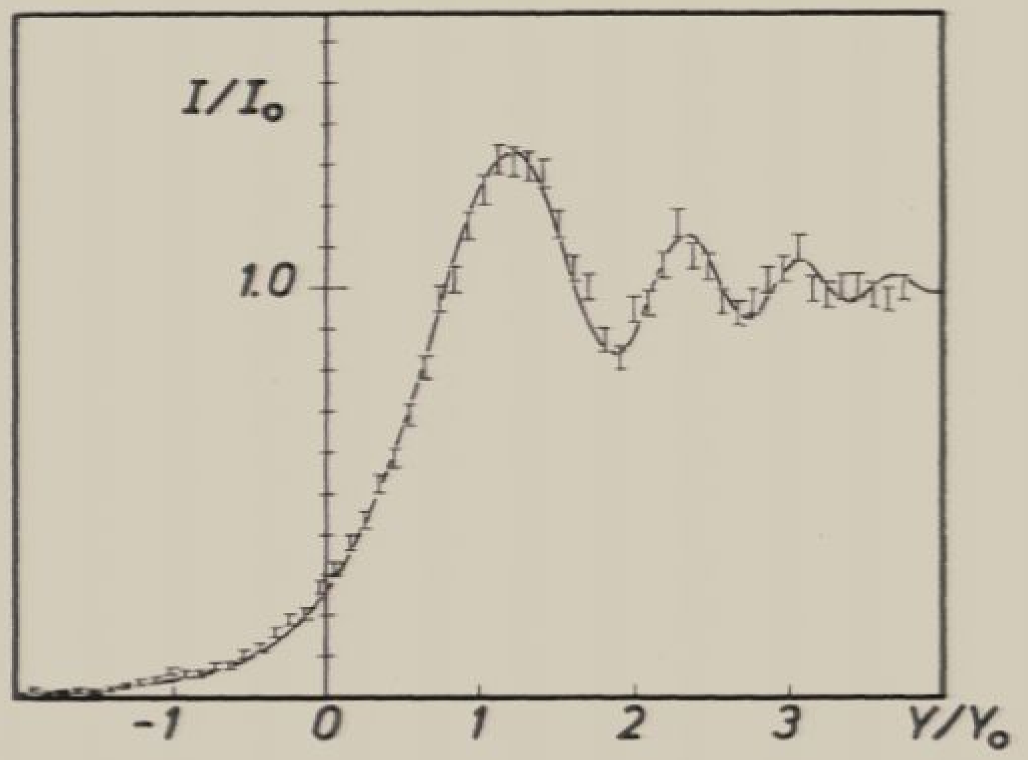


Cold Neutrons:

$\lambda = 2$ nm

$v = 200$ m/s

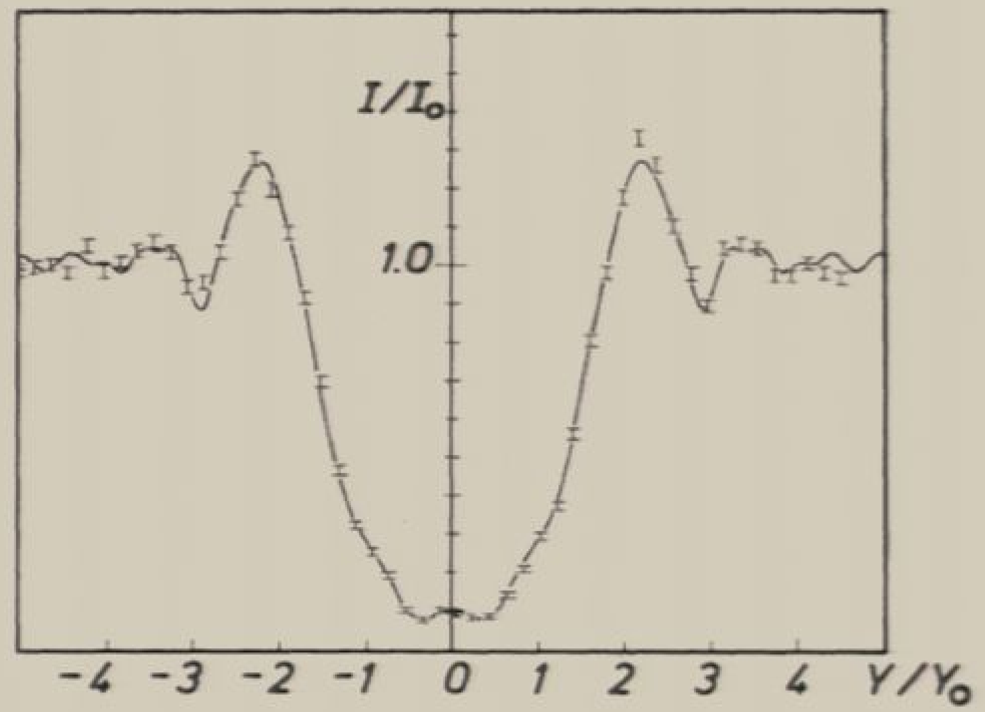
Experimental Result



$b < 3.10^{-15}$ eV

Electron
Wave packet
 > 3mm

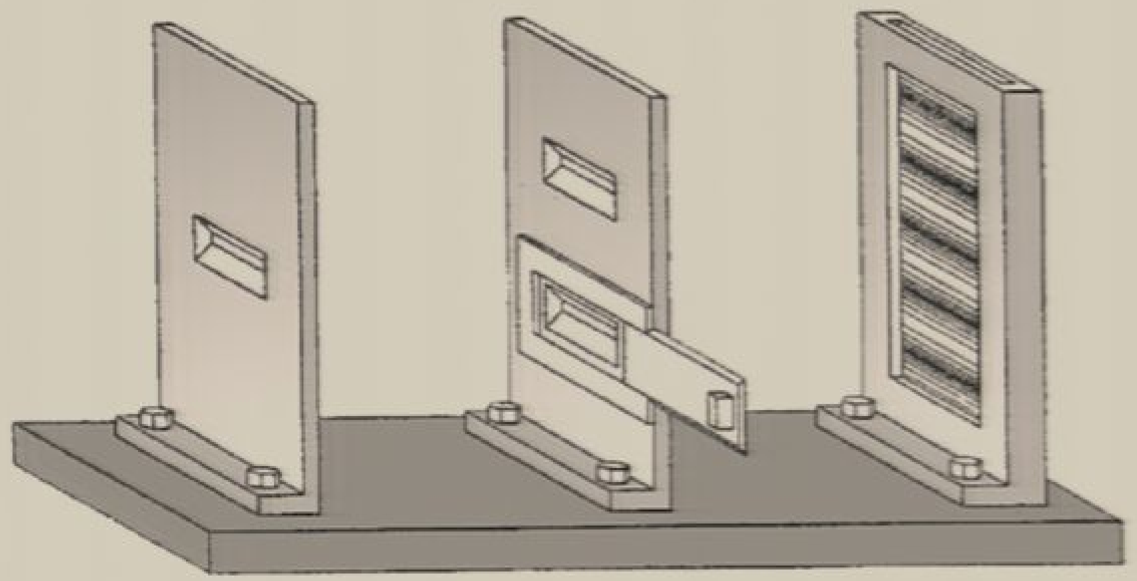
Diffraction at an Absorbing Wire

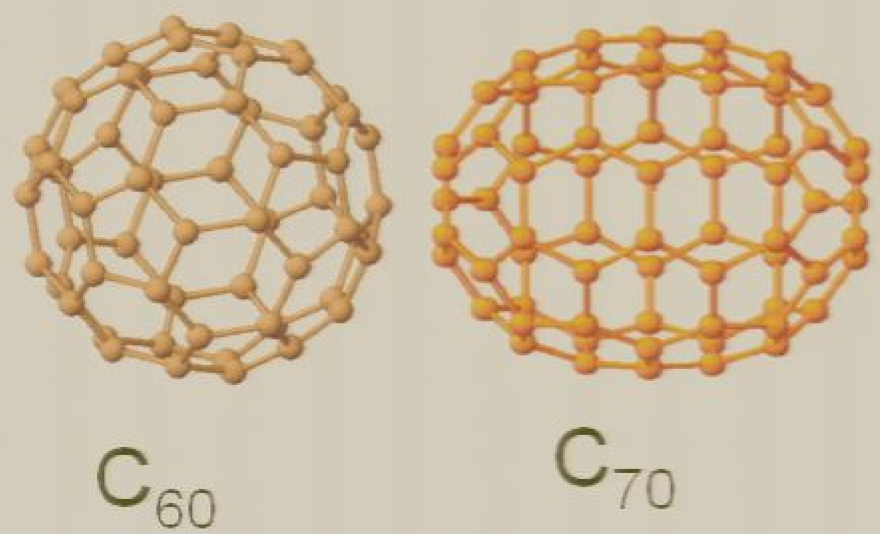


Poisson's Spot for Neutrons

Arago

Matter-Wave Interferences

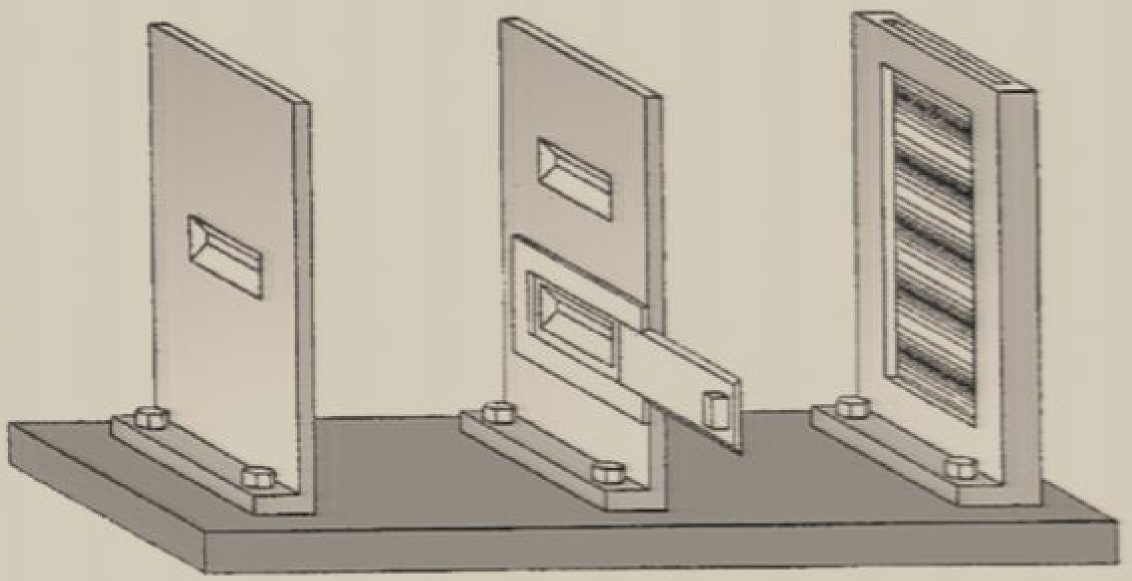


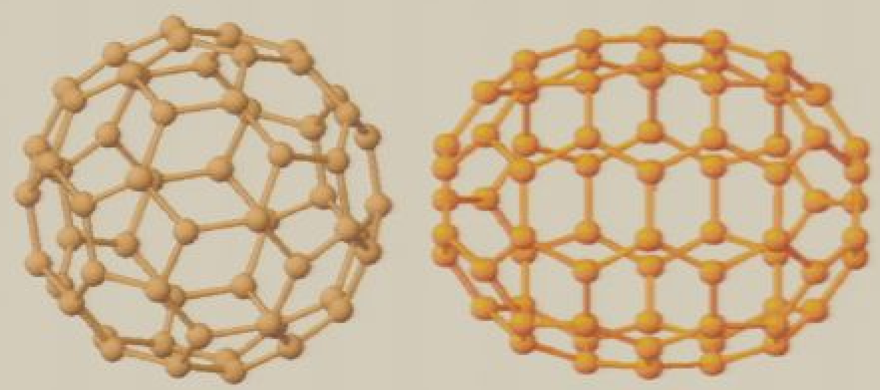


Matter-Wave Interferences

- Electrons, Neutrons, Atoms, Small Molecules
  ......

- Is there a Limit?





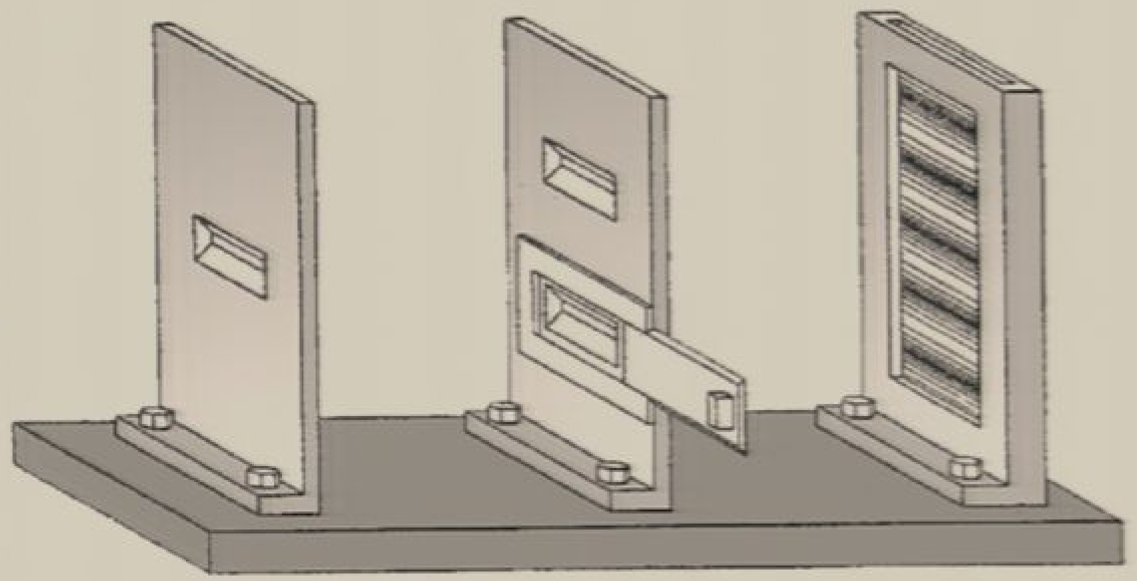
C_{60} C_{70}

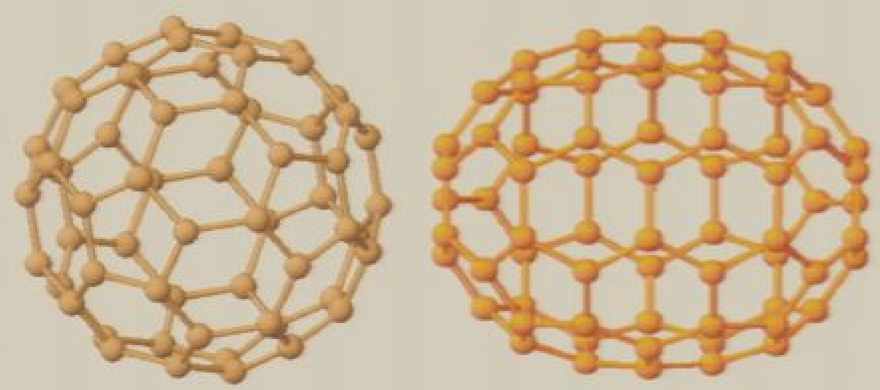
Matter-Wave Interferences

- Electrons, Neutrons, Atoms, Small Molecules
  ......

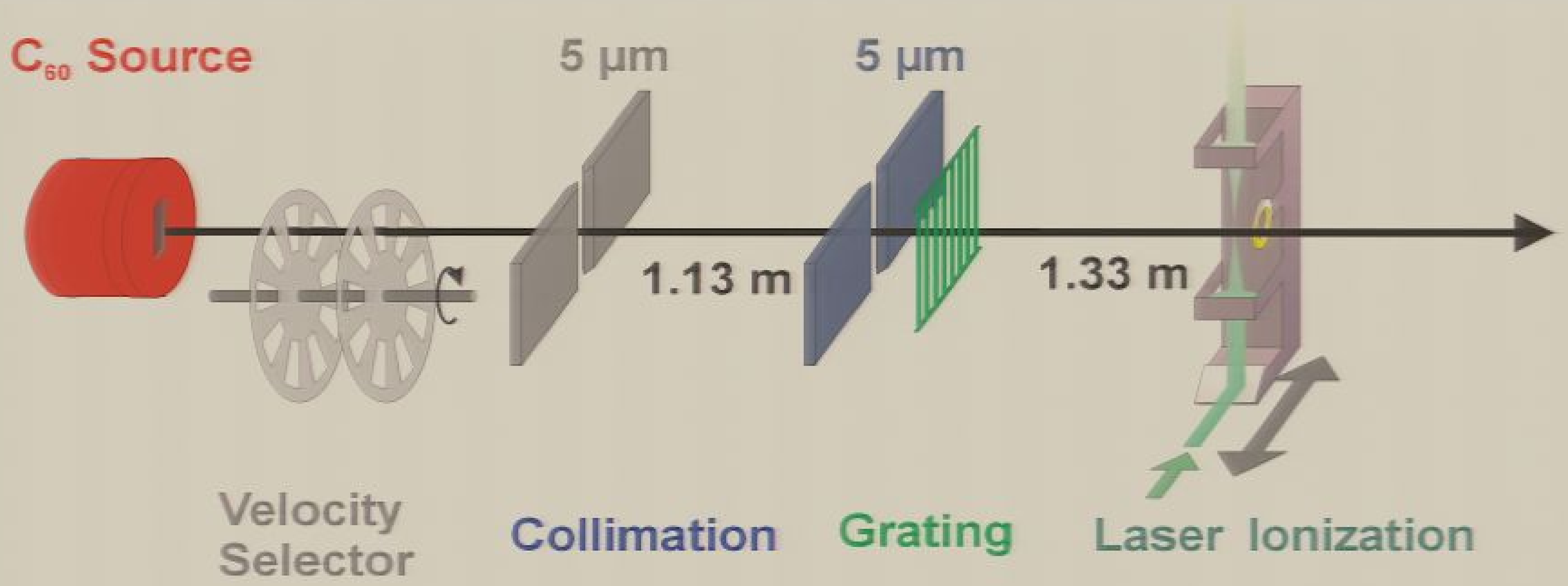
- Is there a Limit?

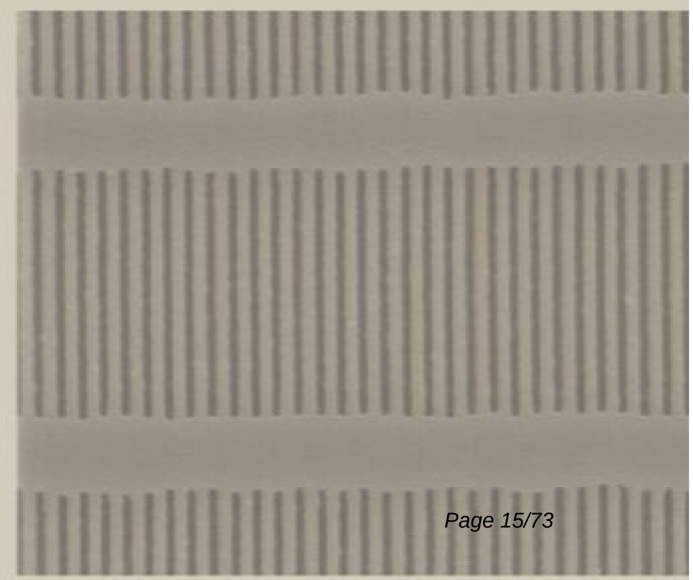
  Mass? Complexity? Temperature?



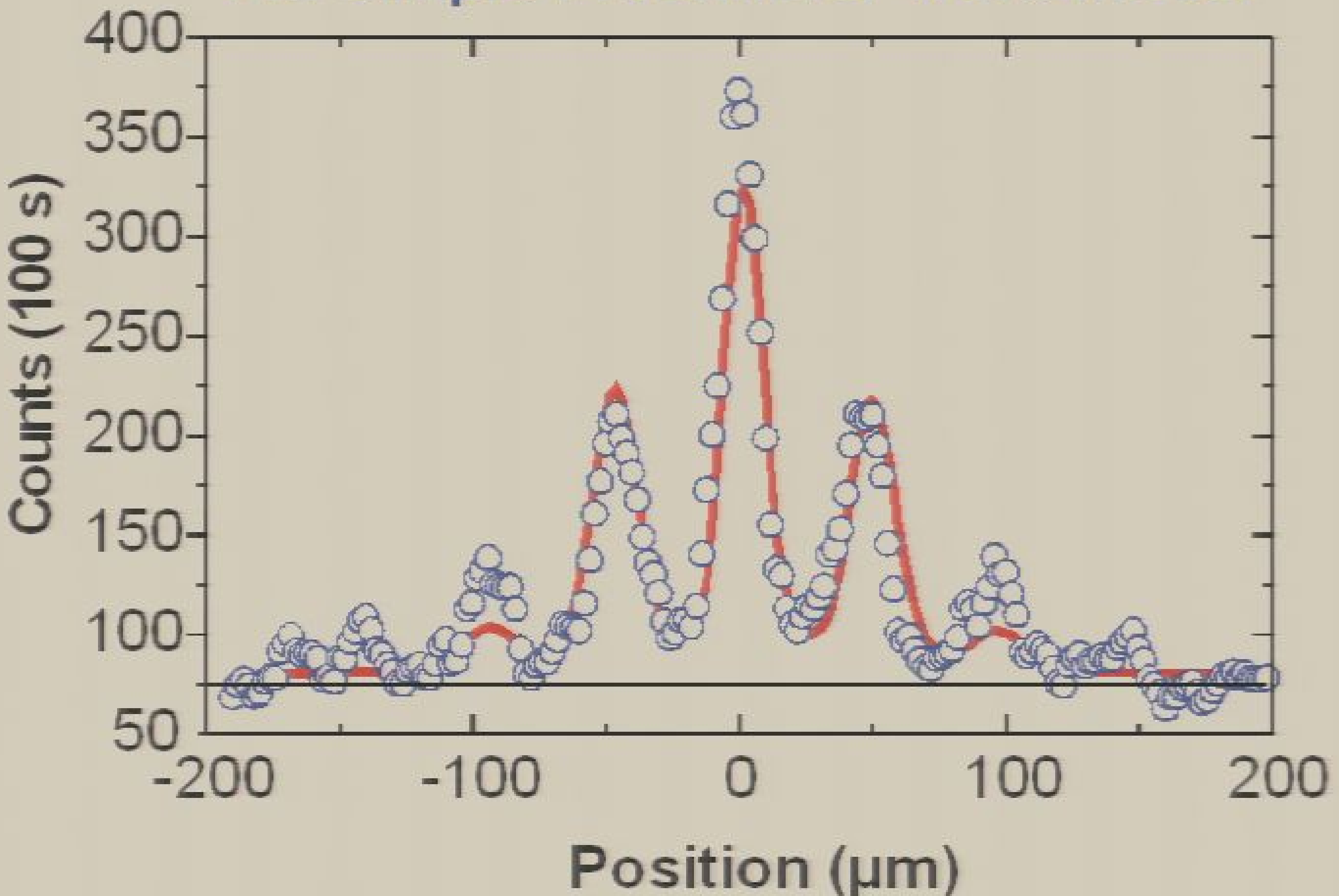


C_{60} C_{70}

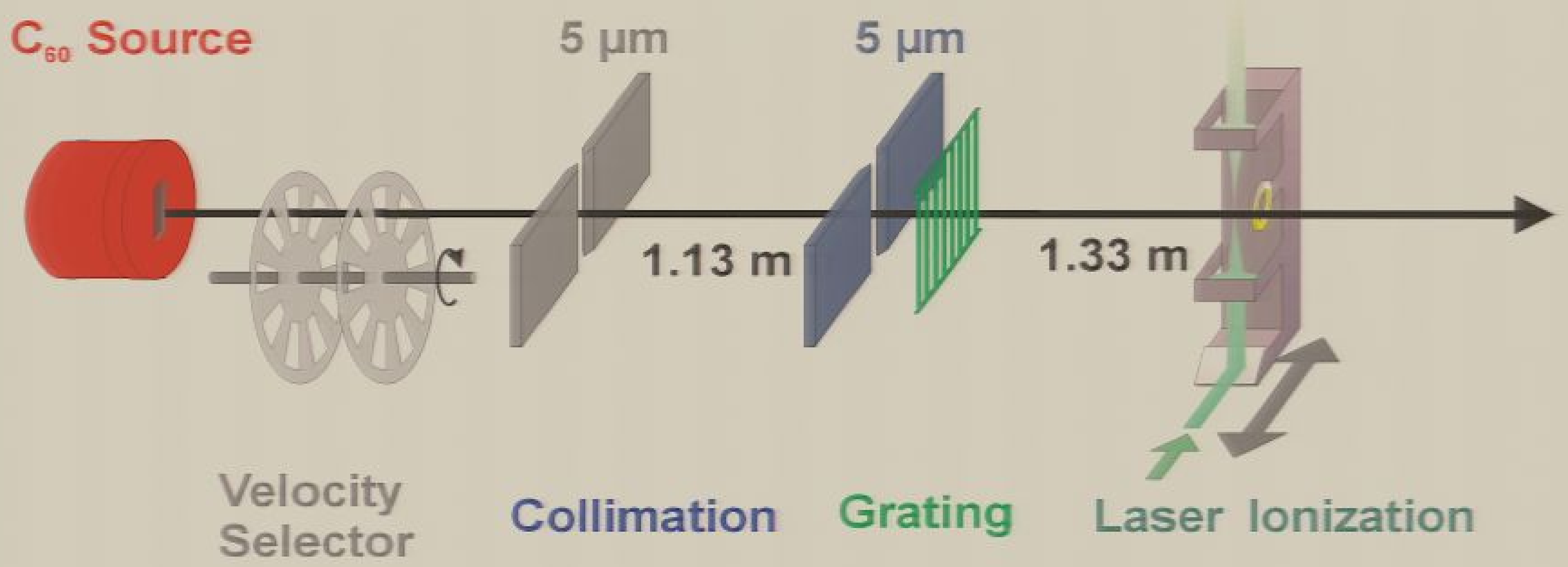

C_{60} Source
5 μm
5 μm
1.13 m
1.33 m
Velocity Selector
Collimation
Grating
Laser Ionization



Fit: simple Fraunhofer wave model



Casimir Interaction



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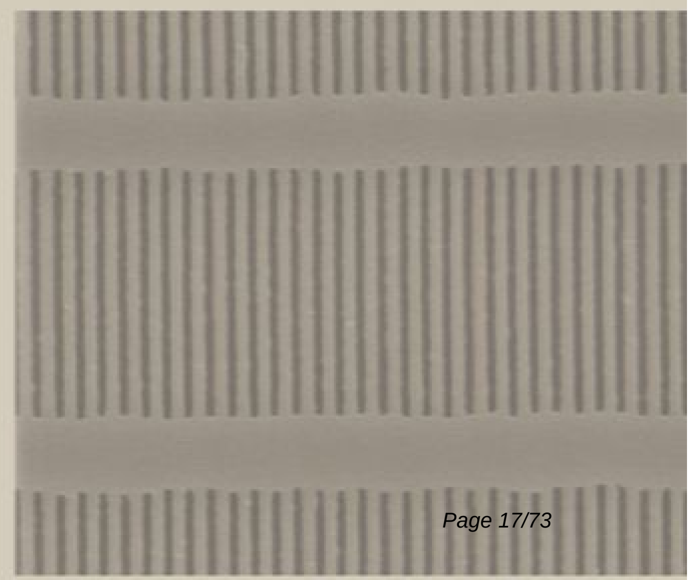

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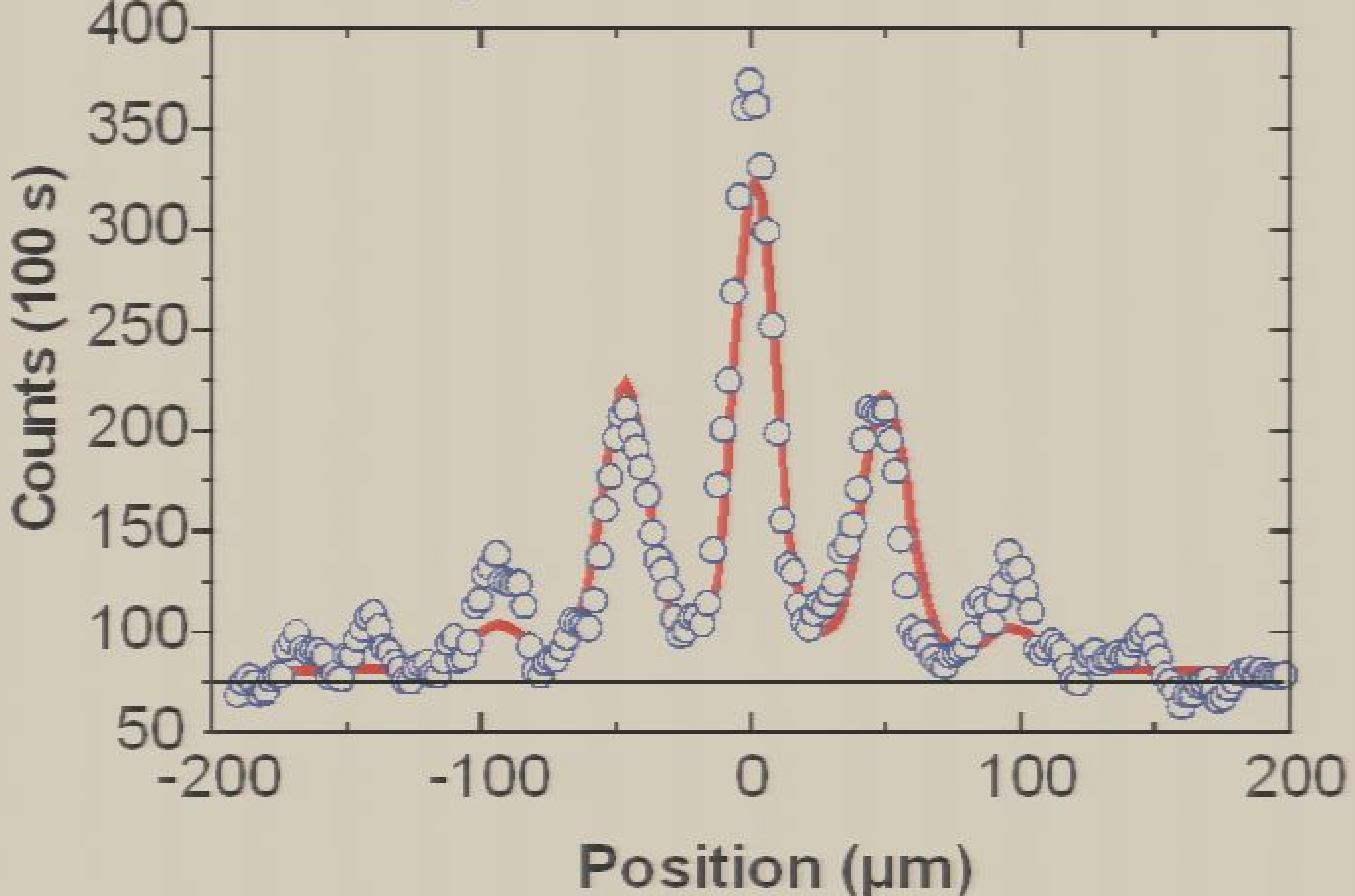
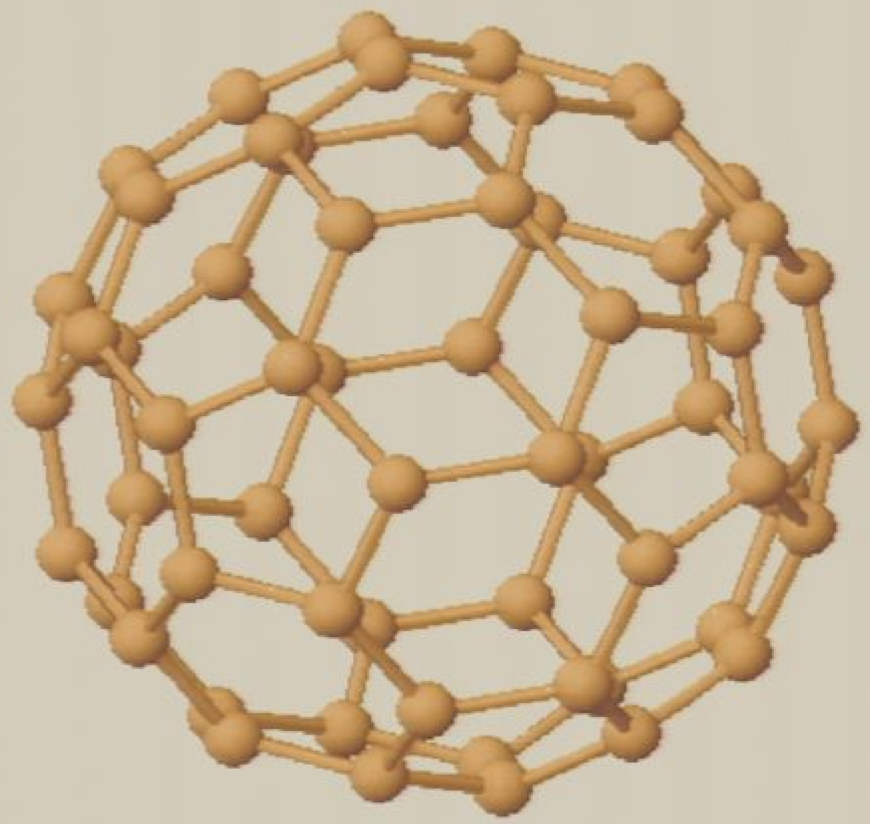


Casimir Interaction

The Scale

$T \approx 900$ K

$$\lambda_{deBroglie} \approx 3 \,.\, 10^{-12}\text{ m} = 3 \,.\, 10^{-2}\text{ Å}$$



λ_{dB}

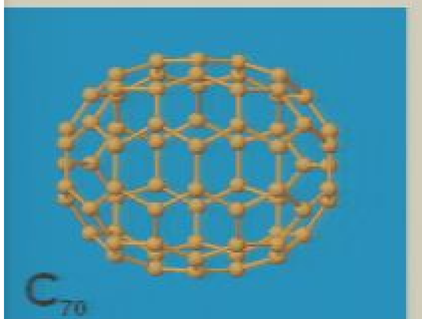
Diameter:

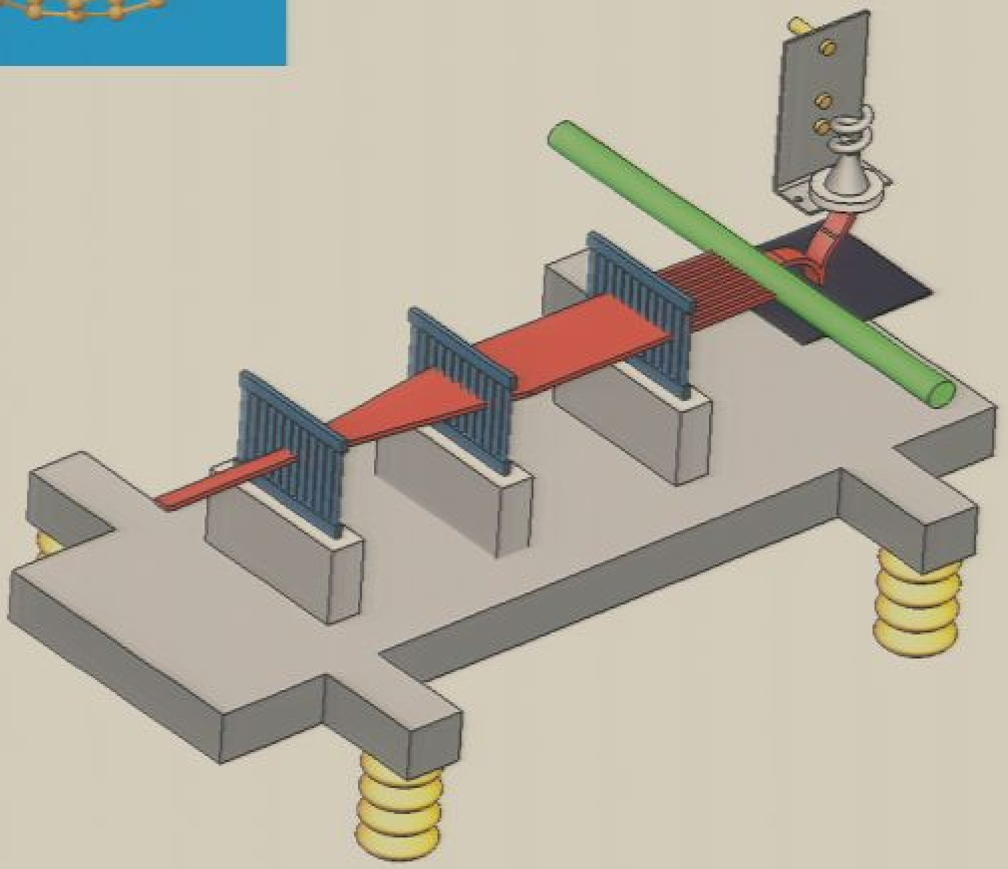
$D \approx 10^{-9}$ m = 10 Å

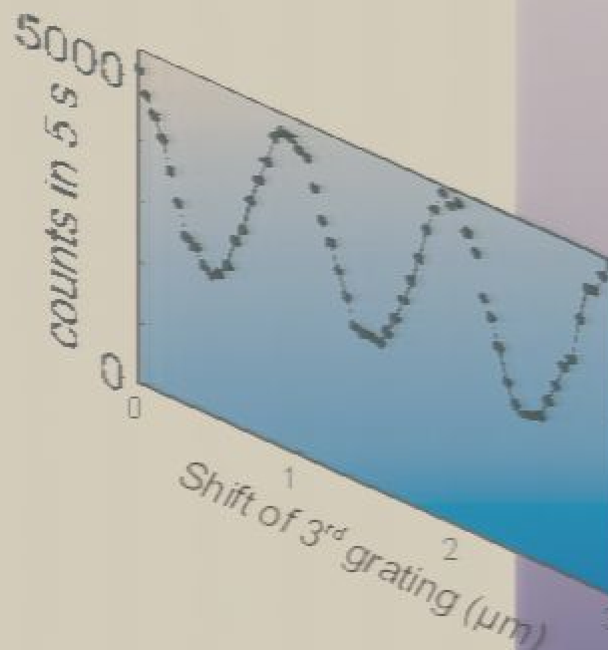
$$\boxed{\lambda_{dB} \ll D}$$

Coherence Length:

2 - 5 λ_{dB} !







Visibility:

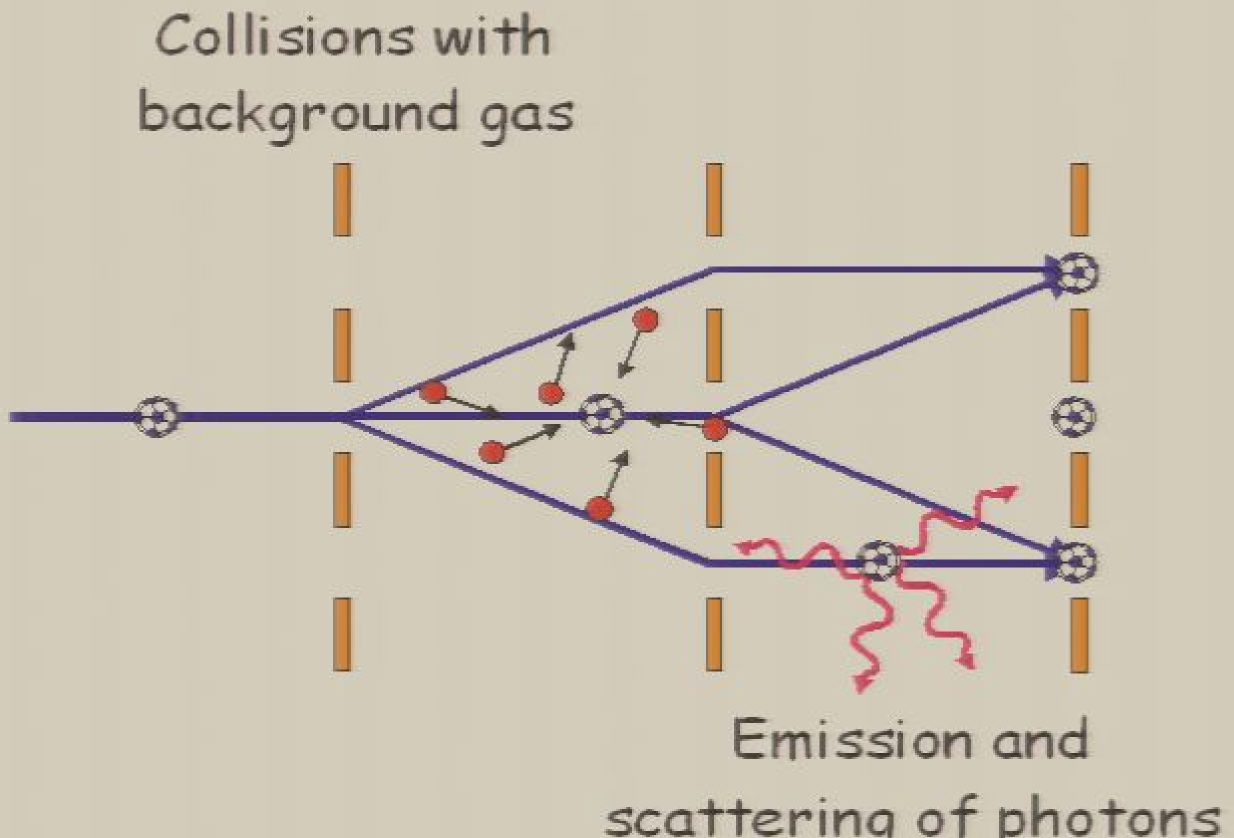
$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

Hackermüller et al. Phys. Rev. Lett. 88, 100404 (2002).

Where is the Limit ?

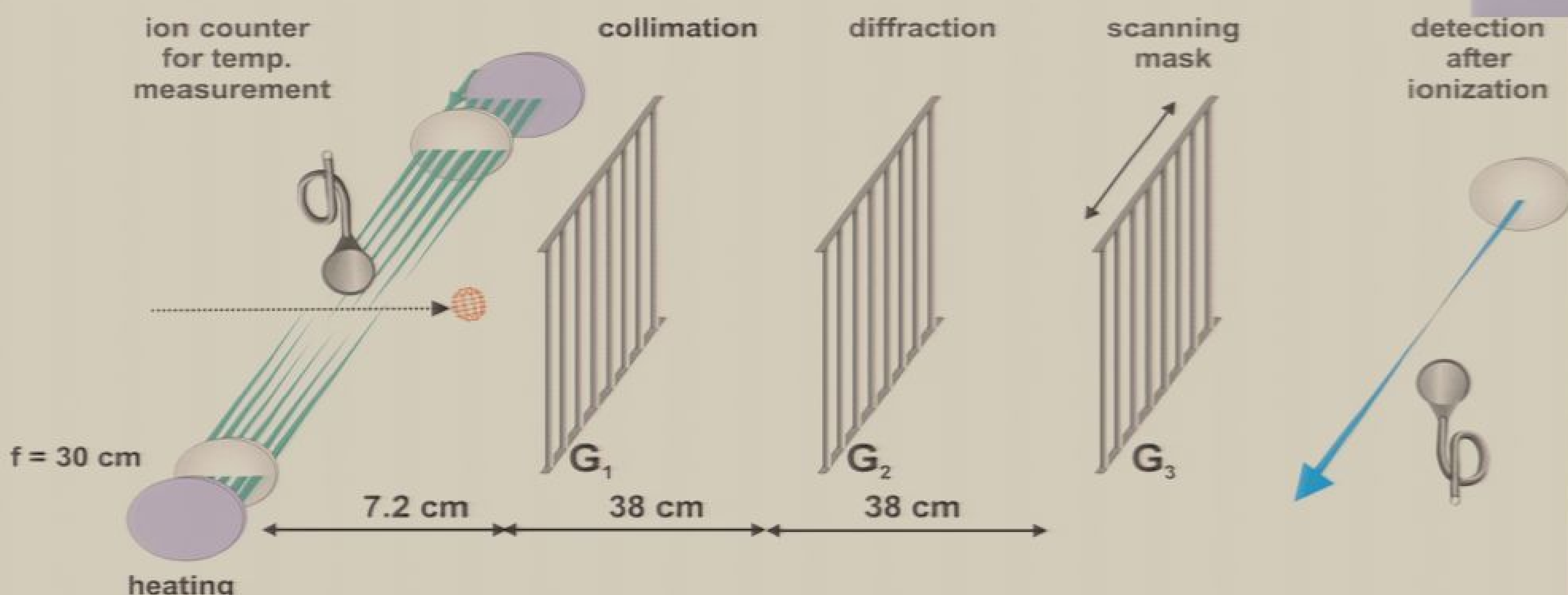
Collisional or Thermal Decoherence

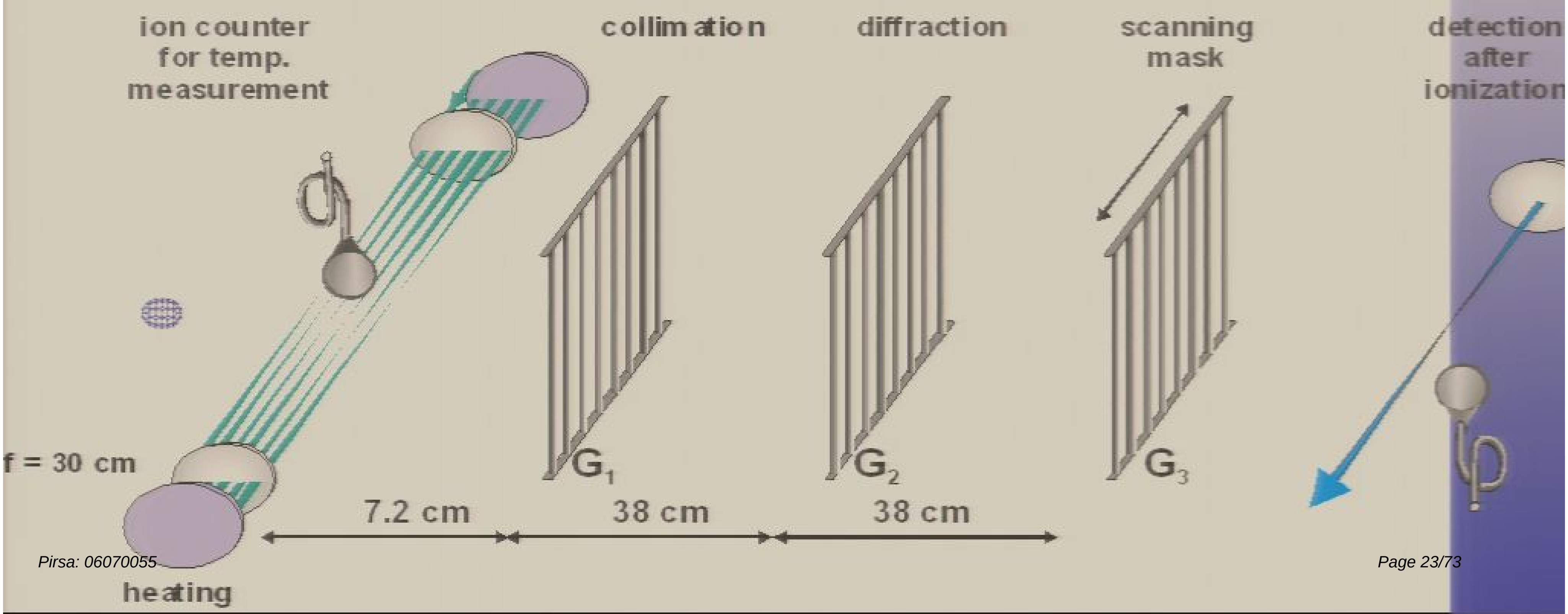
Transition to Classical Dynamics



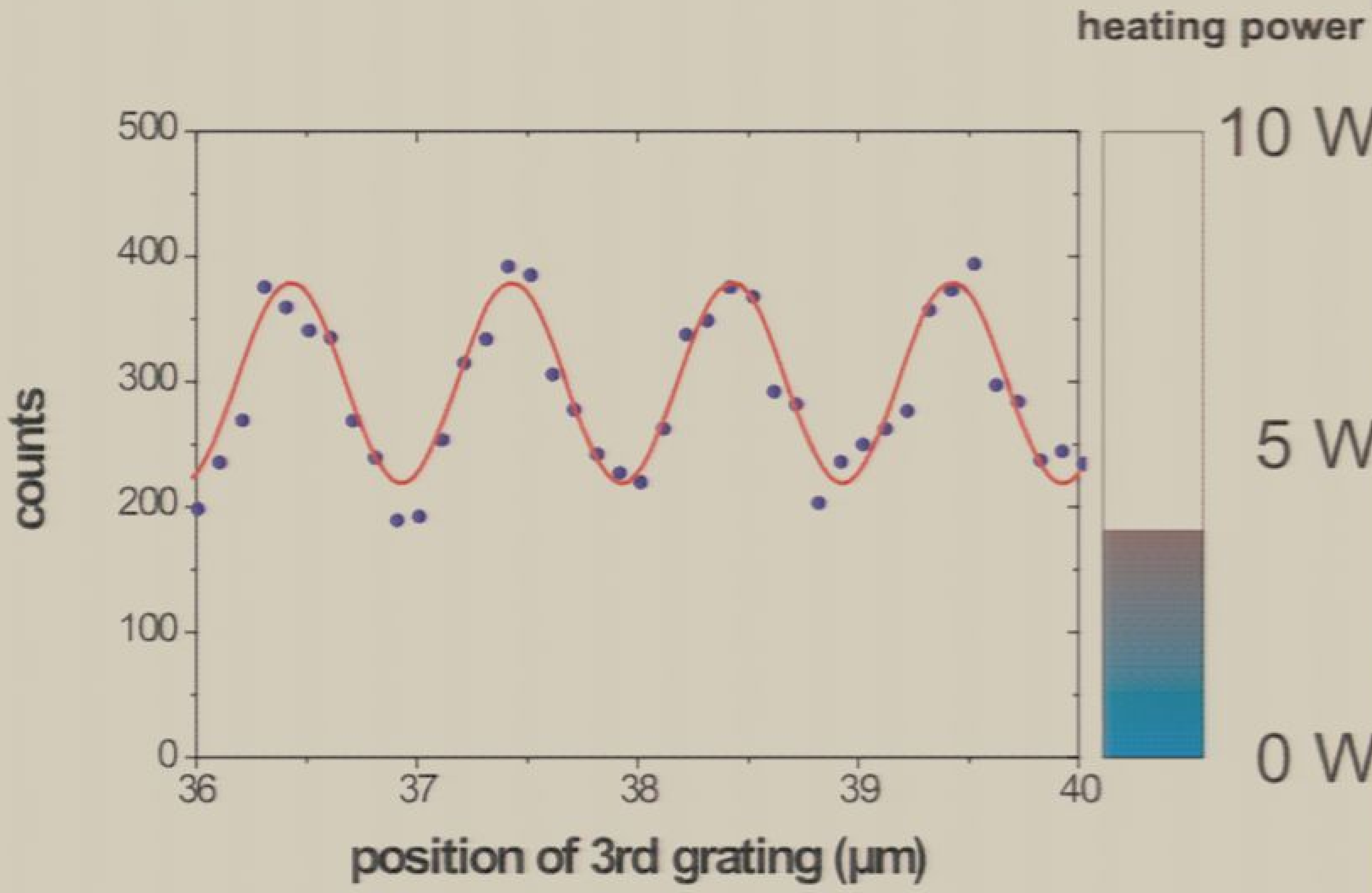
Decoherence by Emission of Thermal Radiation

Where are the Boundaries of the Quantum World?

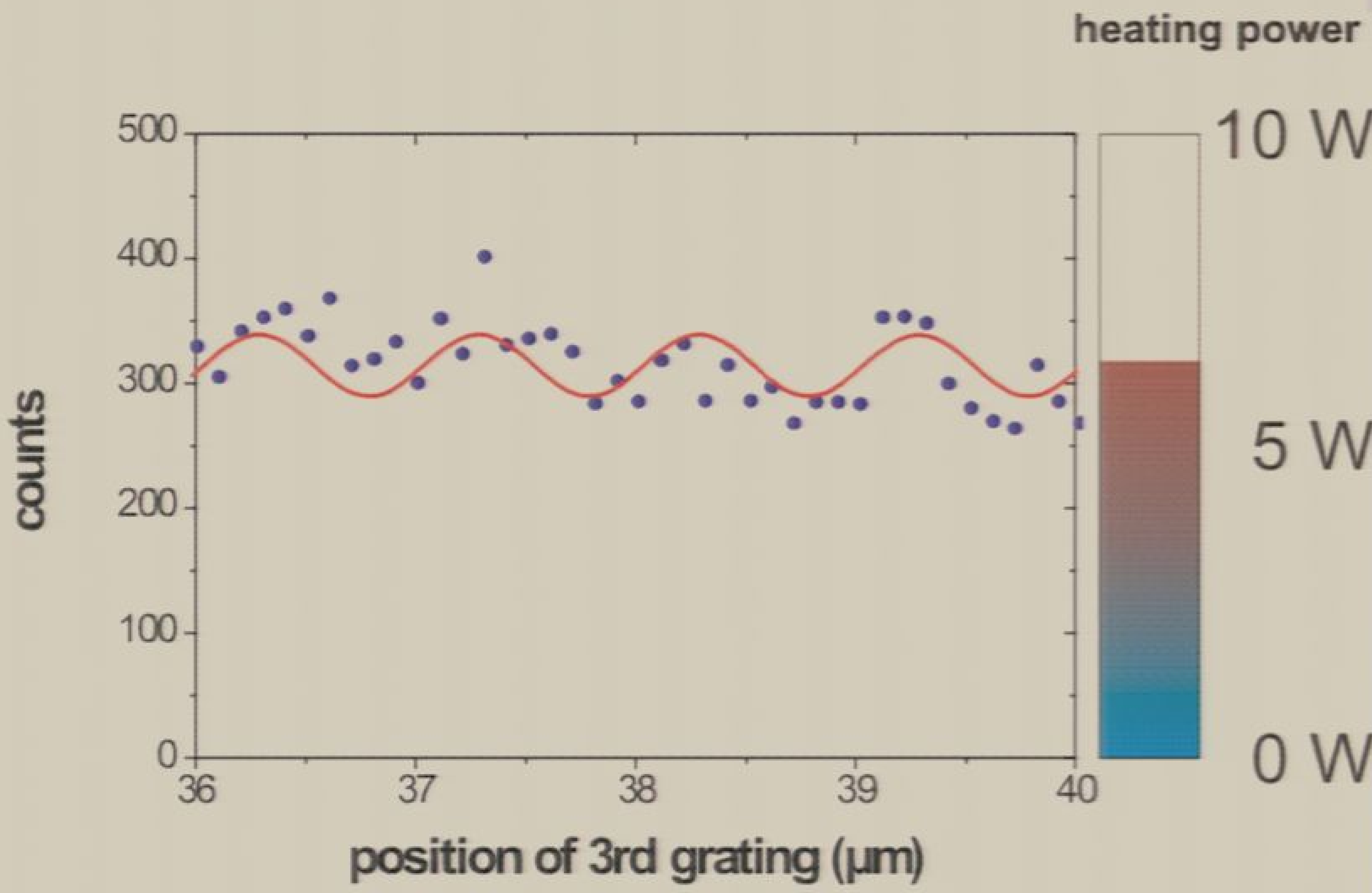




ion counter
for temp.
measurement
collimation
diffraction
scanning
mask
detection
after
ionization
f = 30 cm
G$_1$
G$_2$
G$_3$
7.2 cm
38 cm
38 cm
heating



heating power
10 W
5 W
0 W
counts
500
400
300
200
100
0
36
37
38
39
40
position of 3rd grating (µm)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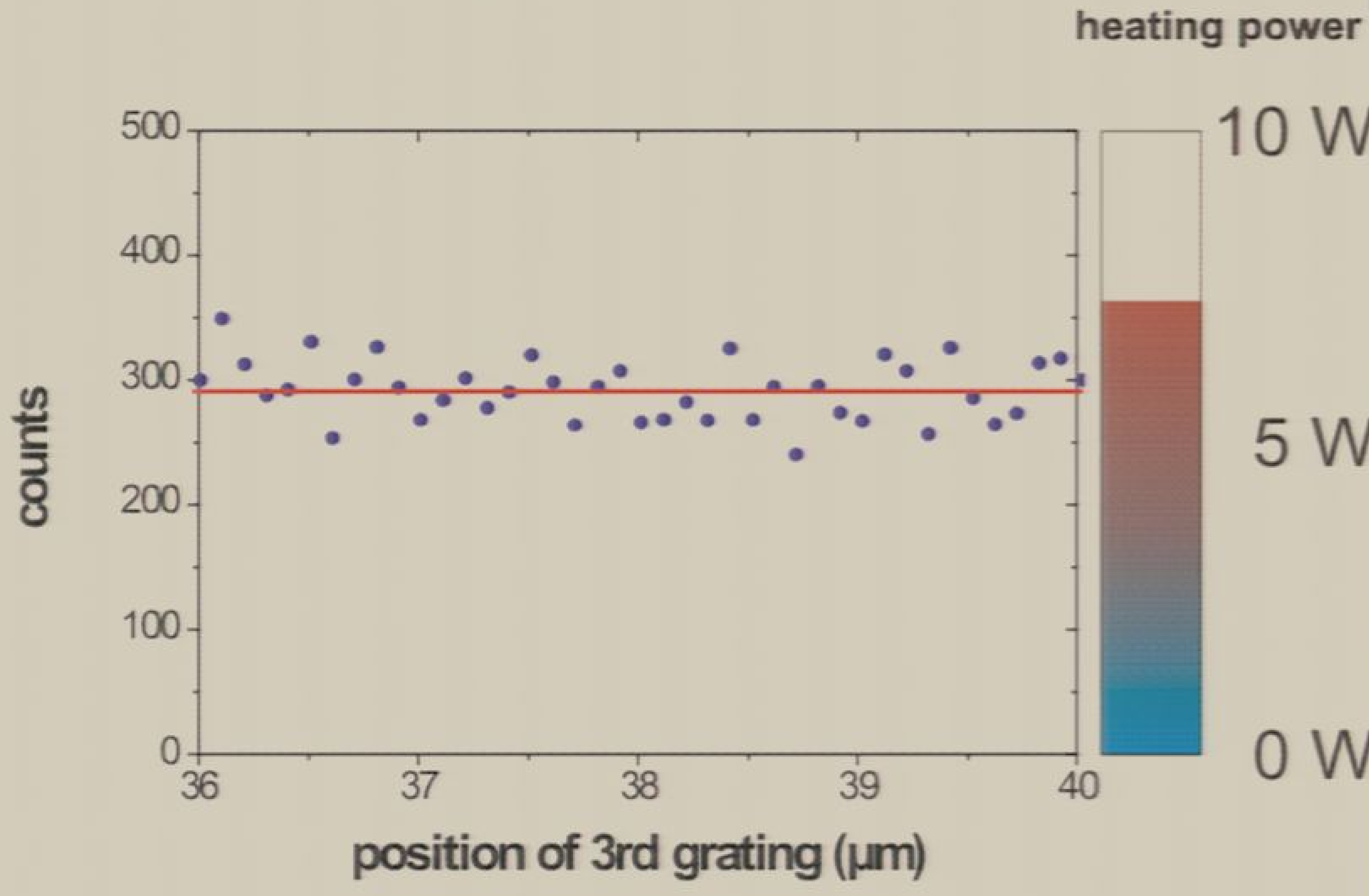
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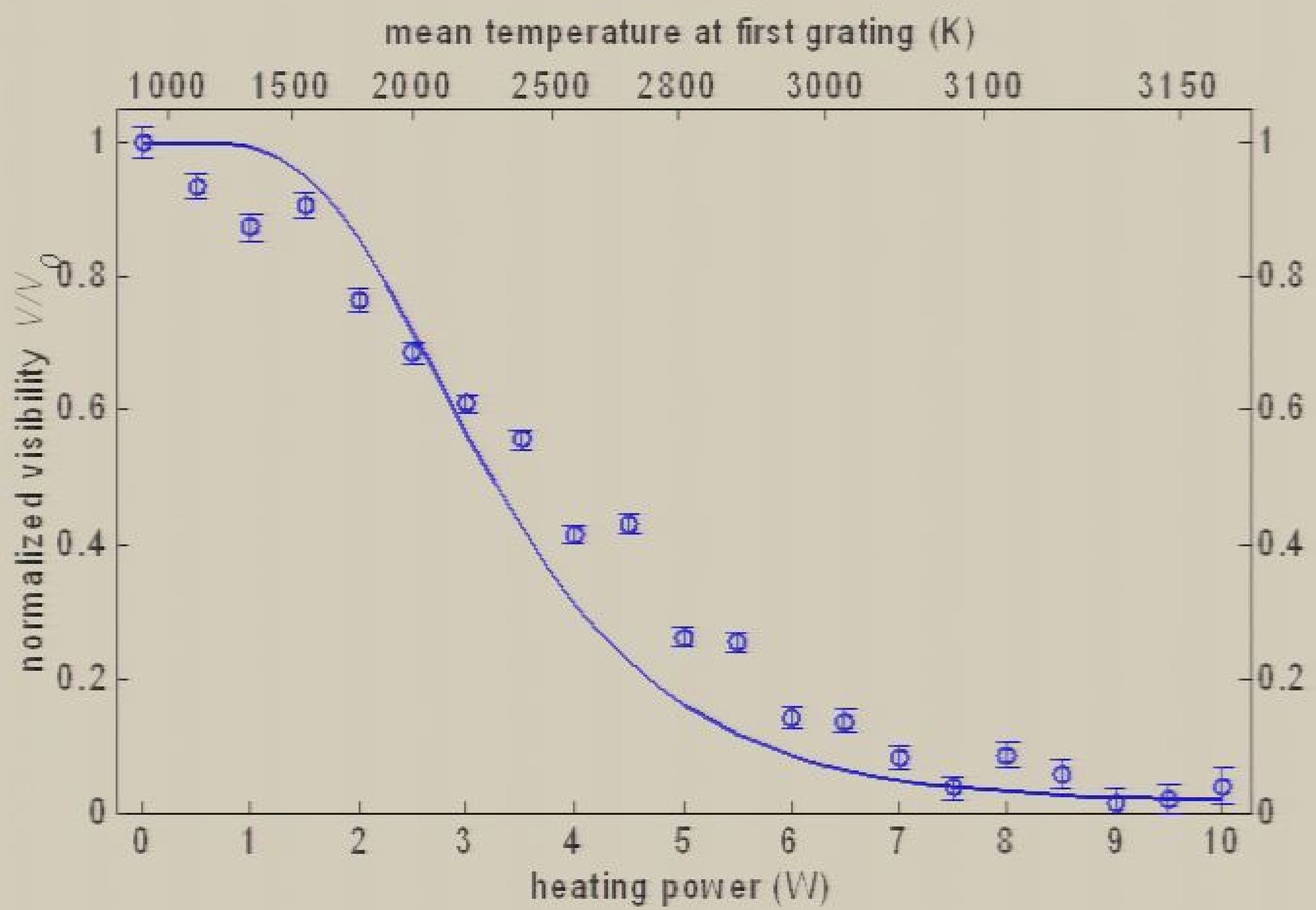
Thermal Decoherence of C_{70}

Comparison between Experiment & Theory



v = 200 m/s, 16 heating beams

L. Hackermüller, K. Hornberger, B. Brezger, A. Z., Markus Arndt: Nature 2005

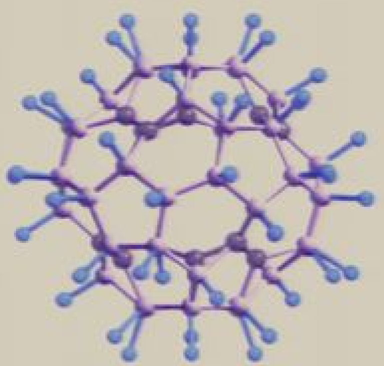
Are there Macroscopic Limits for Matter Waves?

Mass? Complexity?

Next Step:

$C_{254}H_{377}N_{65}O_{76}S_6$

Present Record:

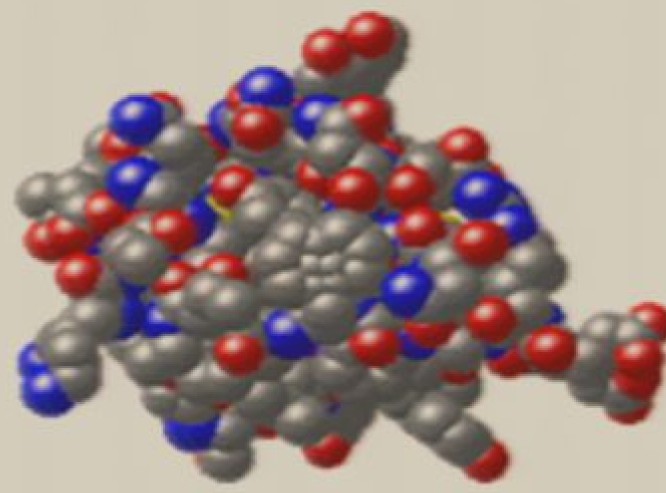


$C_{60}\,F_{48}$

(1632 Da)

108 Atoms in

a single Object !

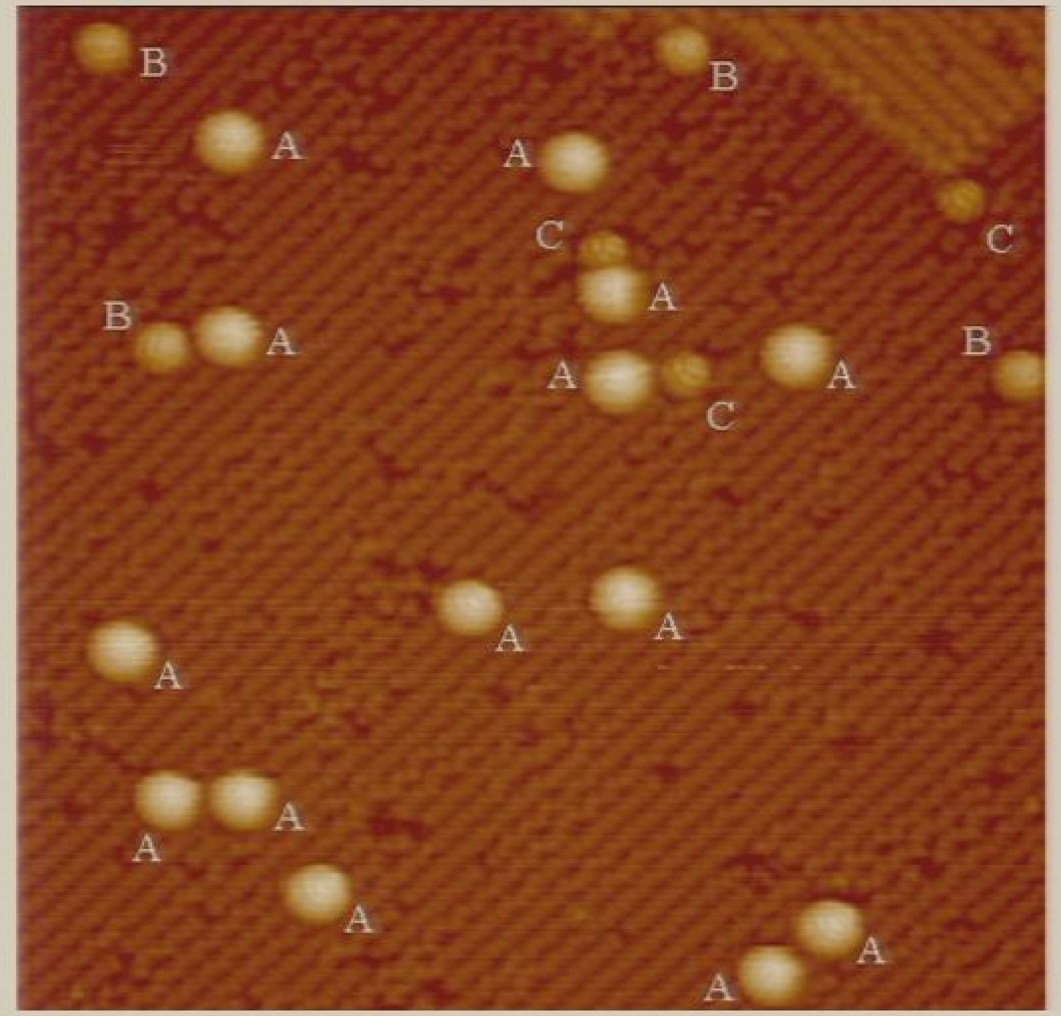


Insulin
(~ 6 kDa)

Our Prediction:

No Decoherence up to
Mass of small Viruses

Fullerenes as Classical Objects



Niels Bohr:

Experimenter decides

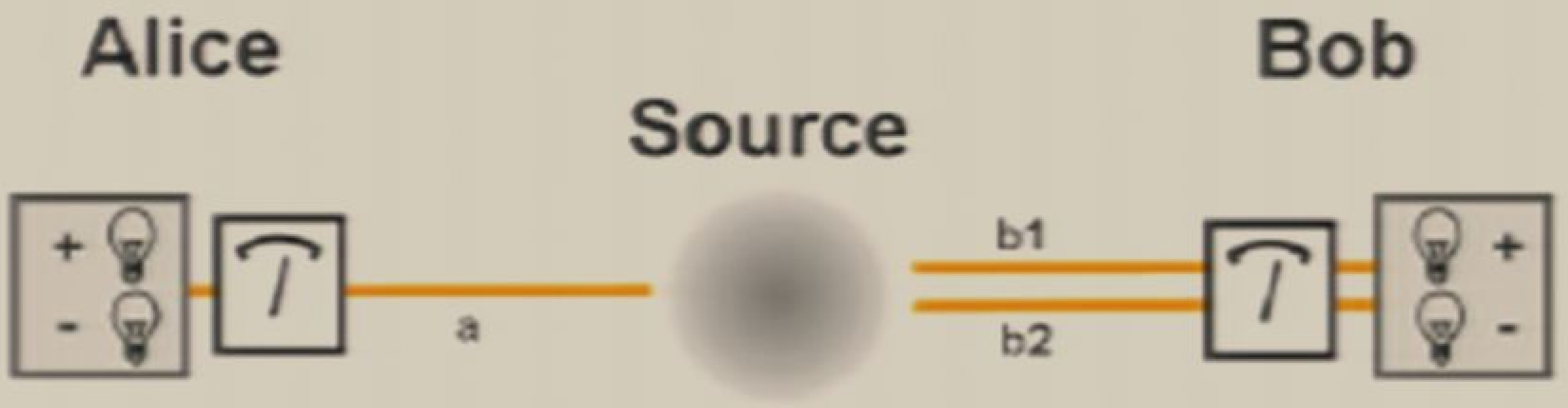
… by choice of
Apparatus

Entanglement itself as an EPR Element of Reality

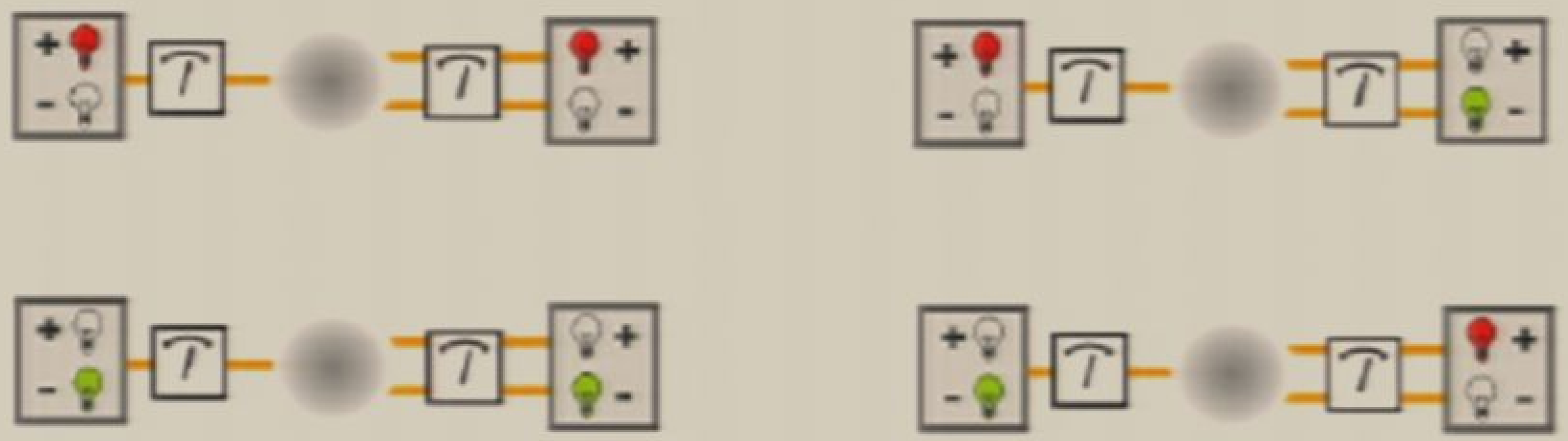
Walther, Resch, Brukner, Z PRL 2006

$$|\Phi^-\rangle_{a,b} = \frac{1}{\sqrt{2}}(|H\rangle_a|\phi^-\rangle_{b_1,b_2} - |V\rangle_a|\psi^+\rangle_{b_1,b_2})$$

- A nonproperty of individuals as element of Reality
- GHZ State RRR + LLL


Alice
Source
Bob
+
-
a
b1
b2
+
-

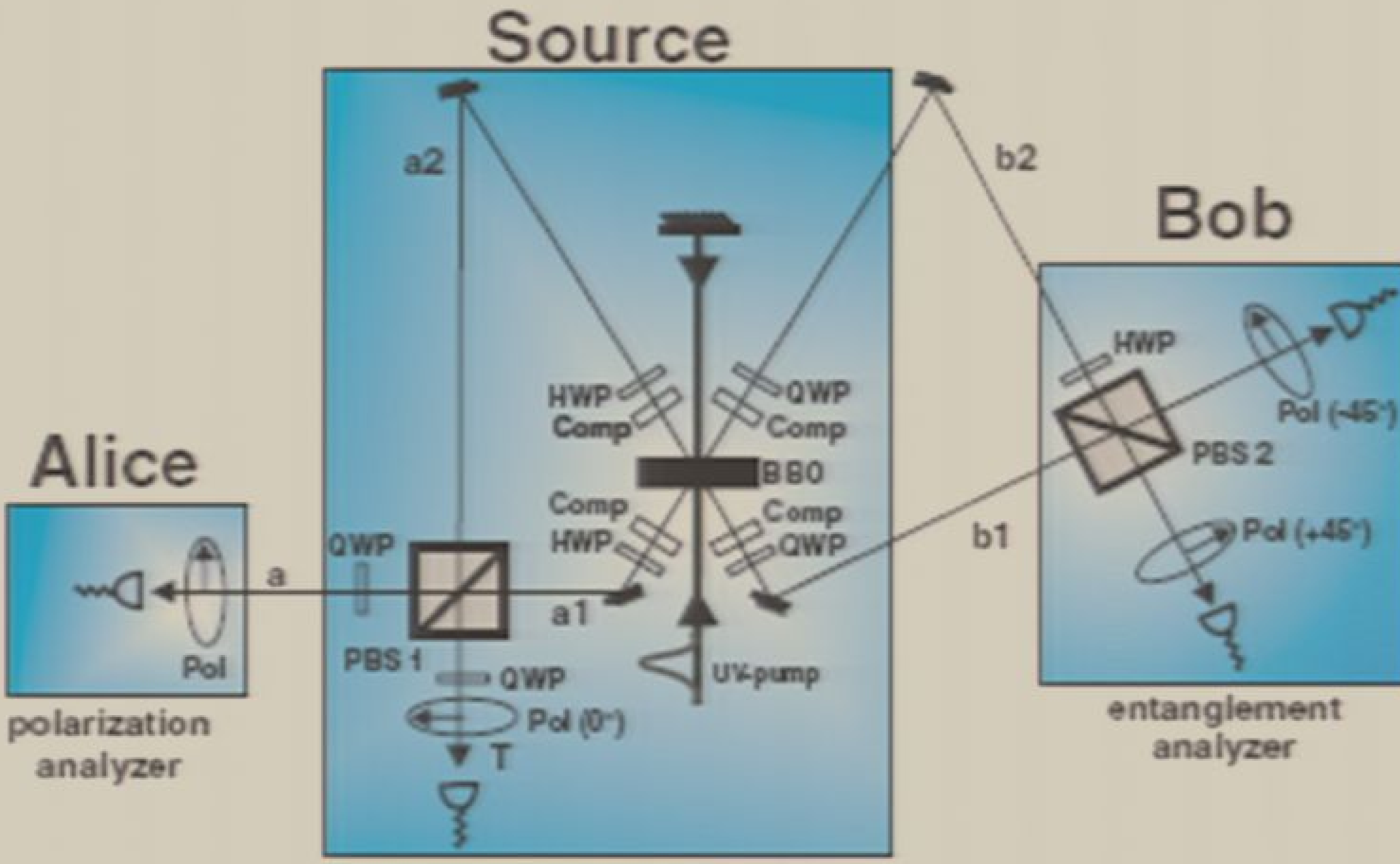
Perfect Correlations



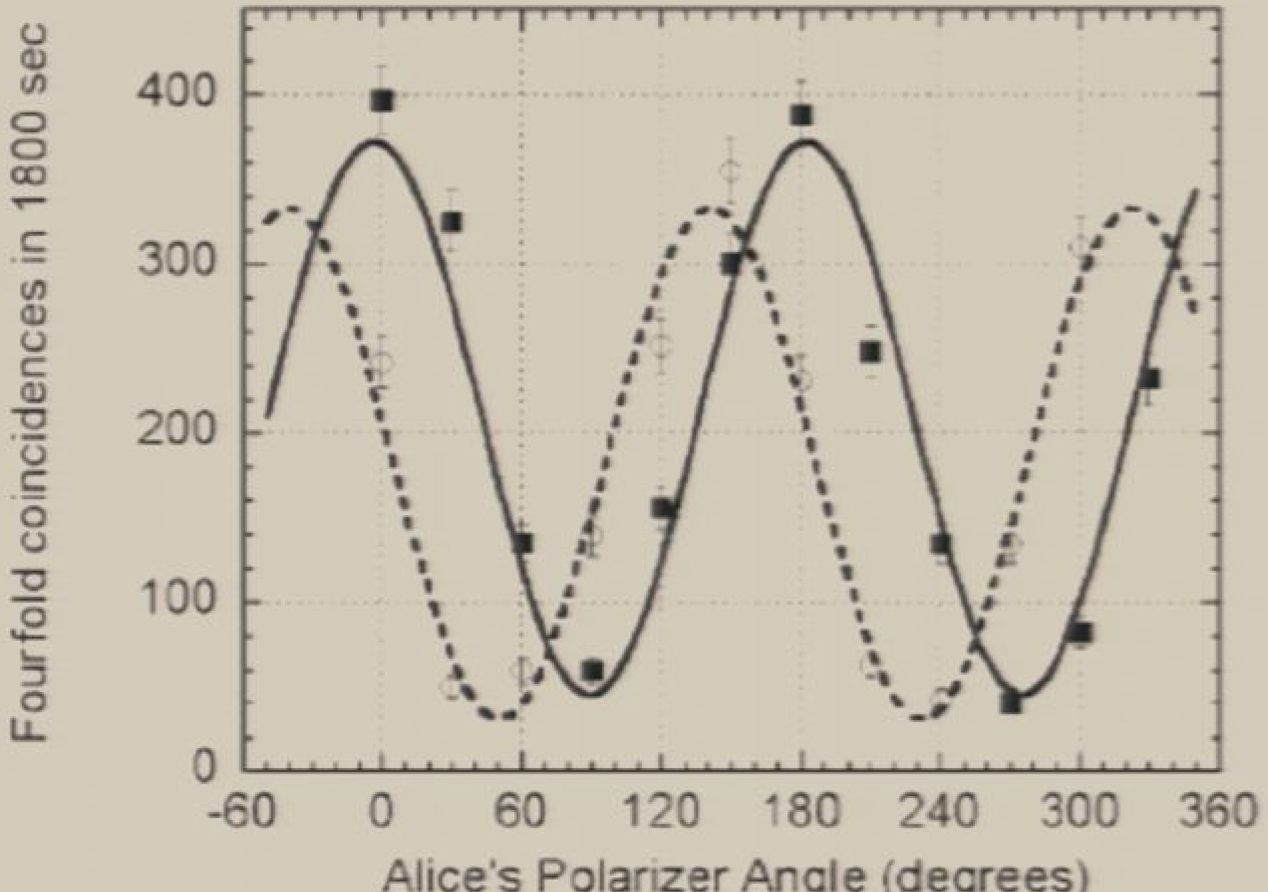
CHSH Violation ?

Superposition $\Phi^{+} + \Psi^{+}$

The Experiment



Superposition



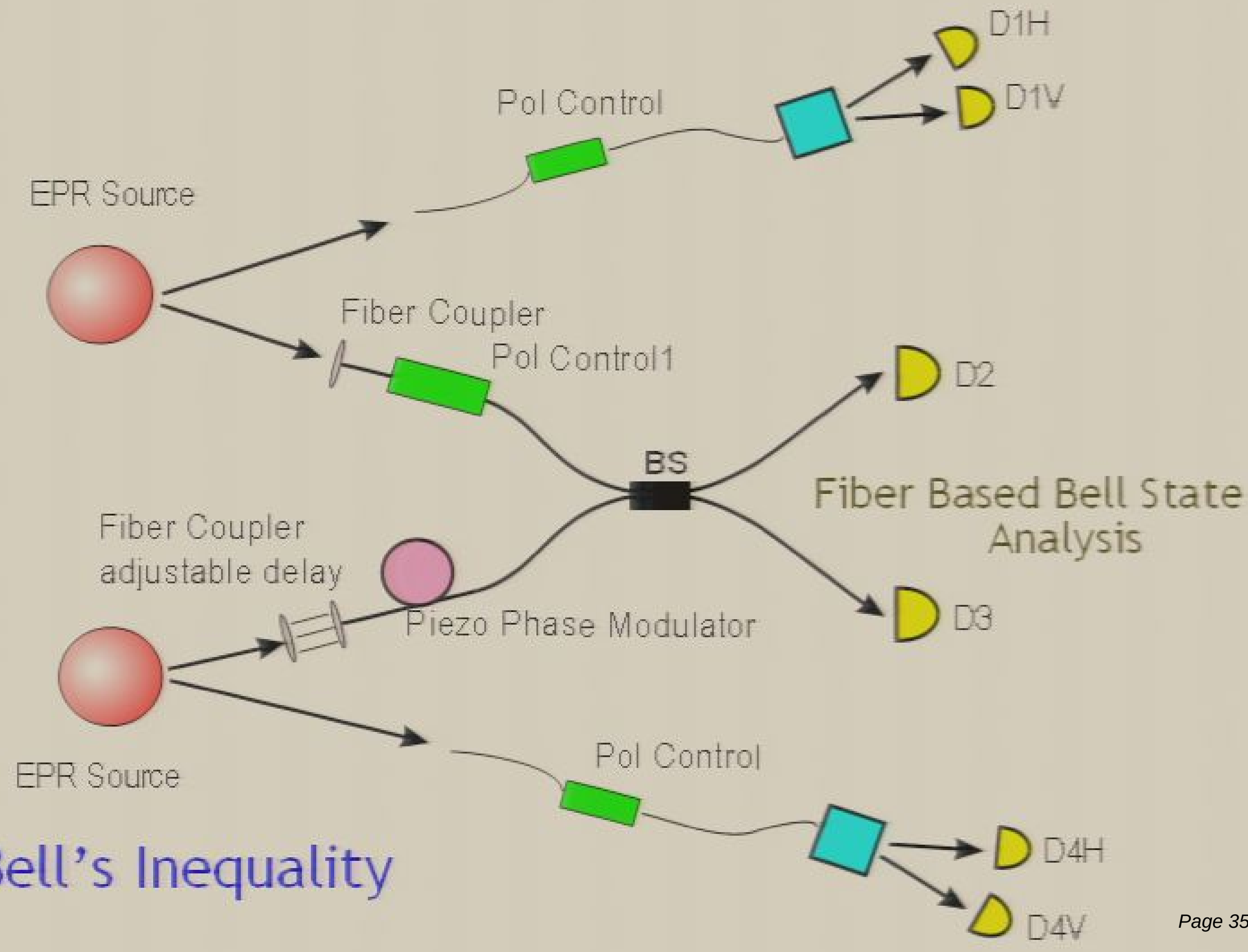
Full: Φ^+

Empty:

Superposition $\Phi^+ + \Psi^+$

Entanglement Swapping

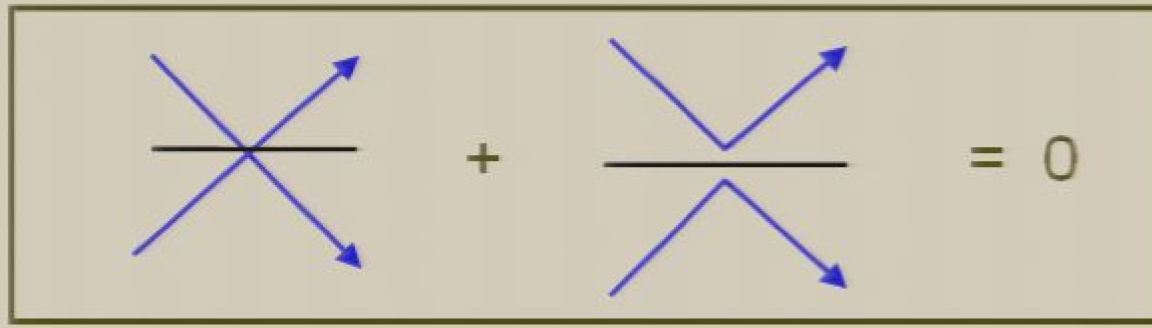
J.-W. Pan et al., Phys. Rev. Lett. **86**, 4435 (2001)
T. Jennewein et al., Phys. Rev. Lett. **88**, 017903 (2002)

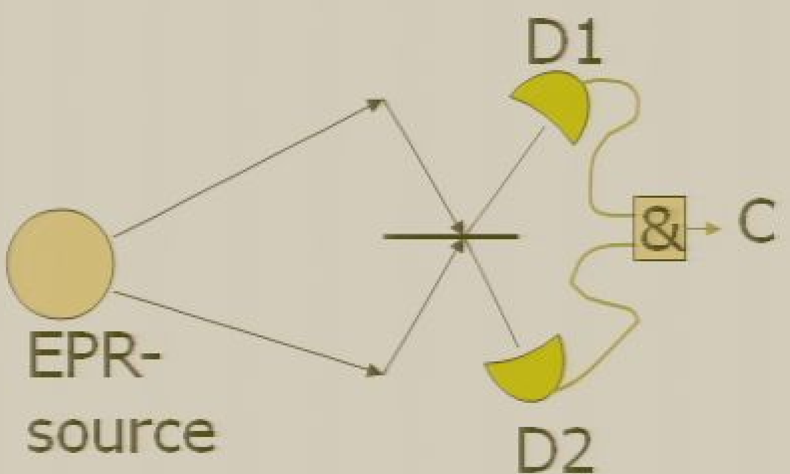


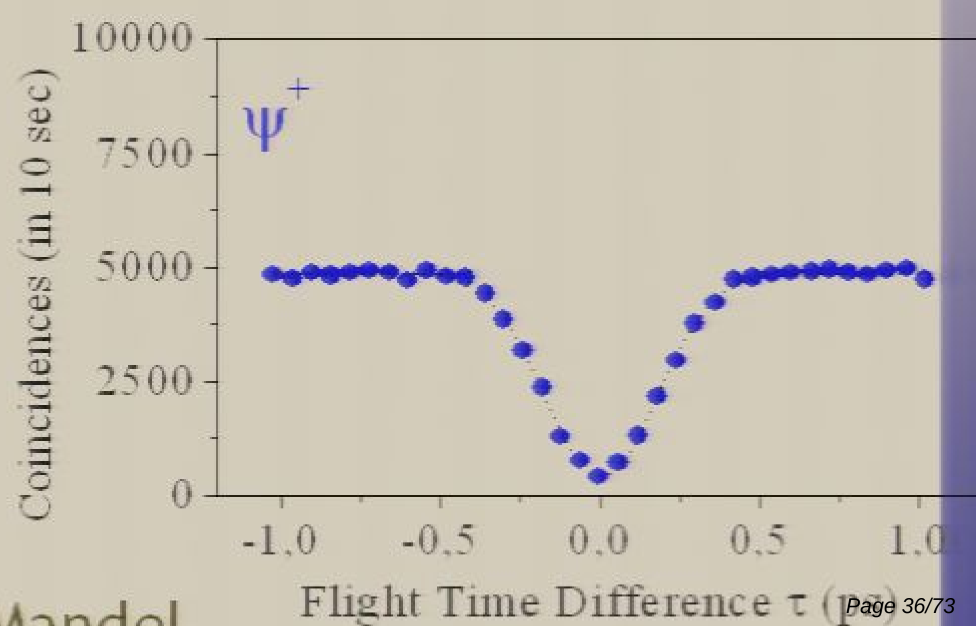
Violation of Bell's Inequality

Bosonic States

$$\left|\psi^{+}\right\rangle = \frac{1}{\sqrt{2}}\left\{\left|1\right\rangle\left|0\right\rangle + \left|0\right\rangle\left|1\right\rangle\right\}$$



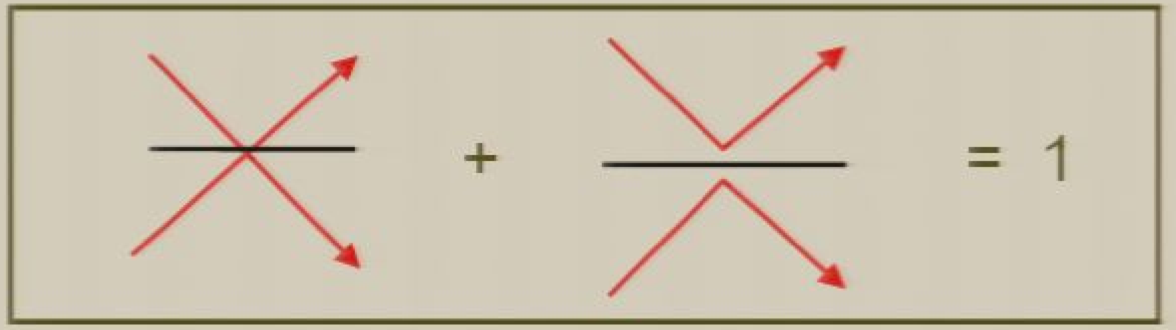


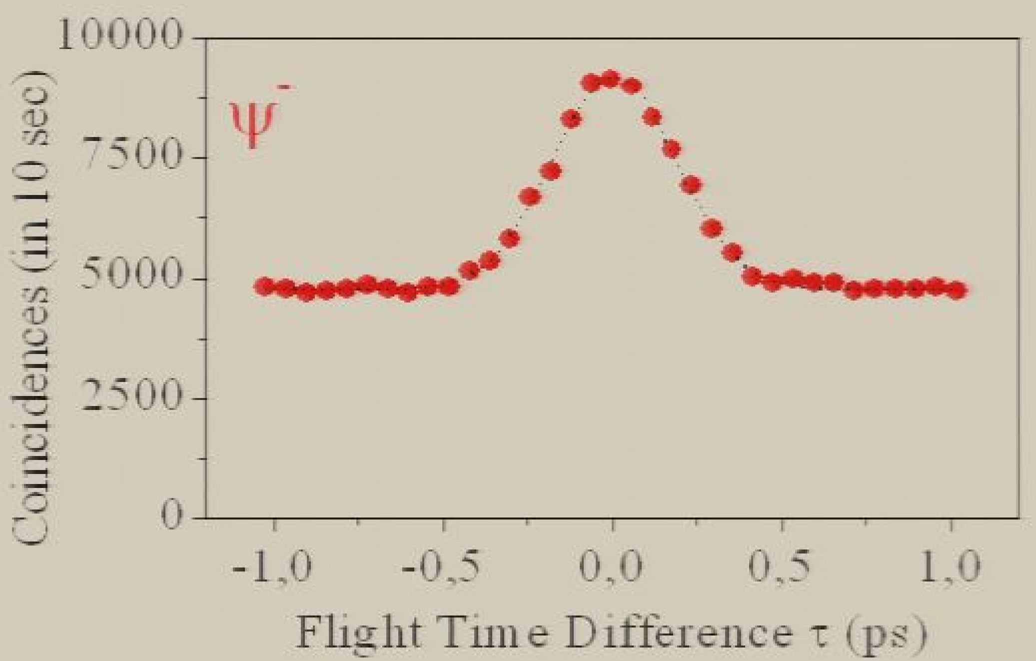


Hong, Ou Mandel

Fermionic States

$$\left|\psi^-\right\rangle = \frac{1}{\sqrt{2}}\left\{\left|1\right\rangle\left|0\right\rangle - \left|0\right\rangle\left|1\right\rangle\right\}$$





Bosonic States

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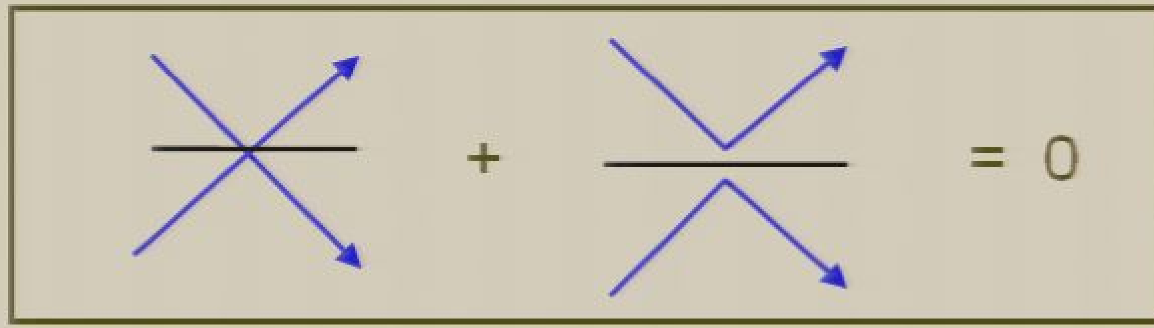
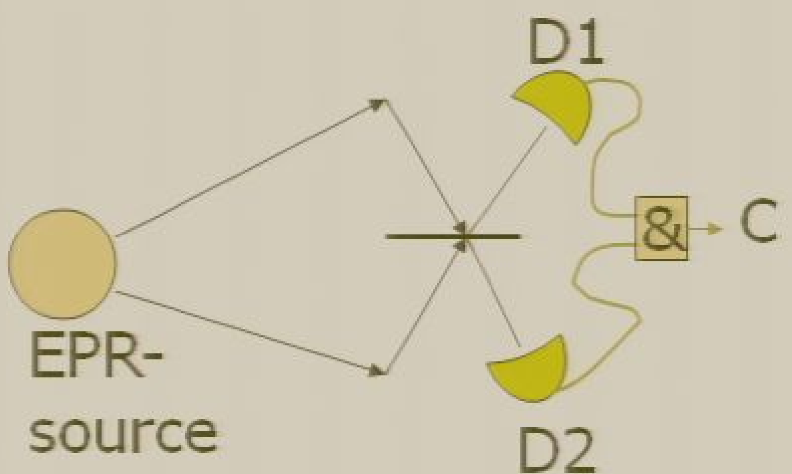
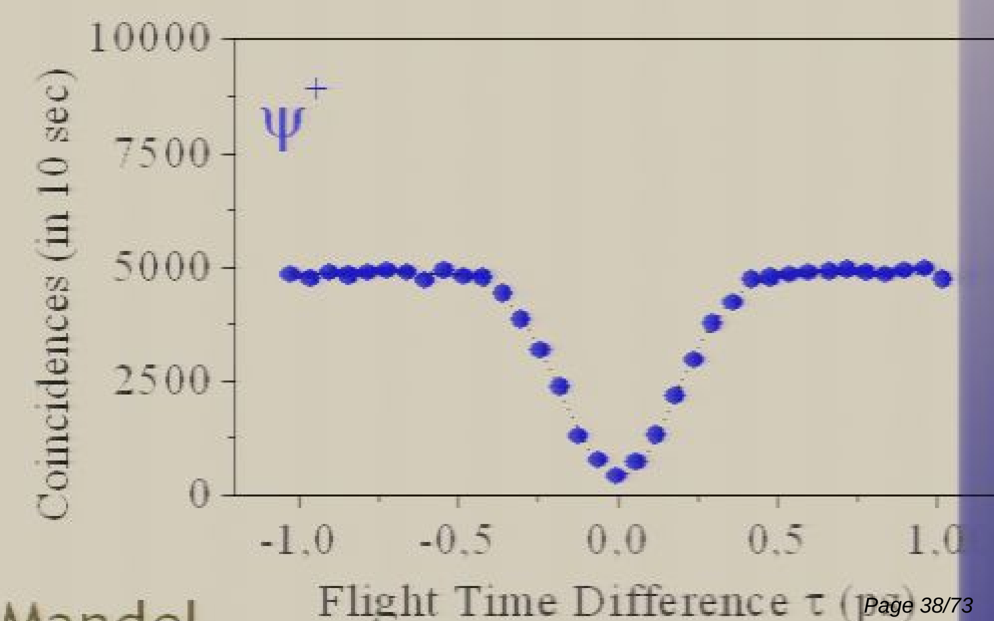
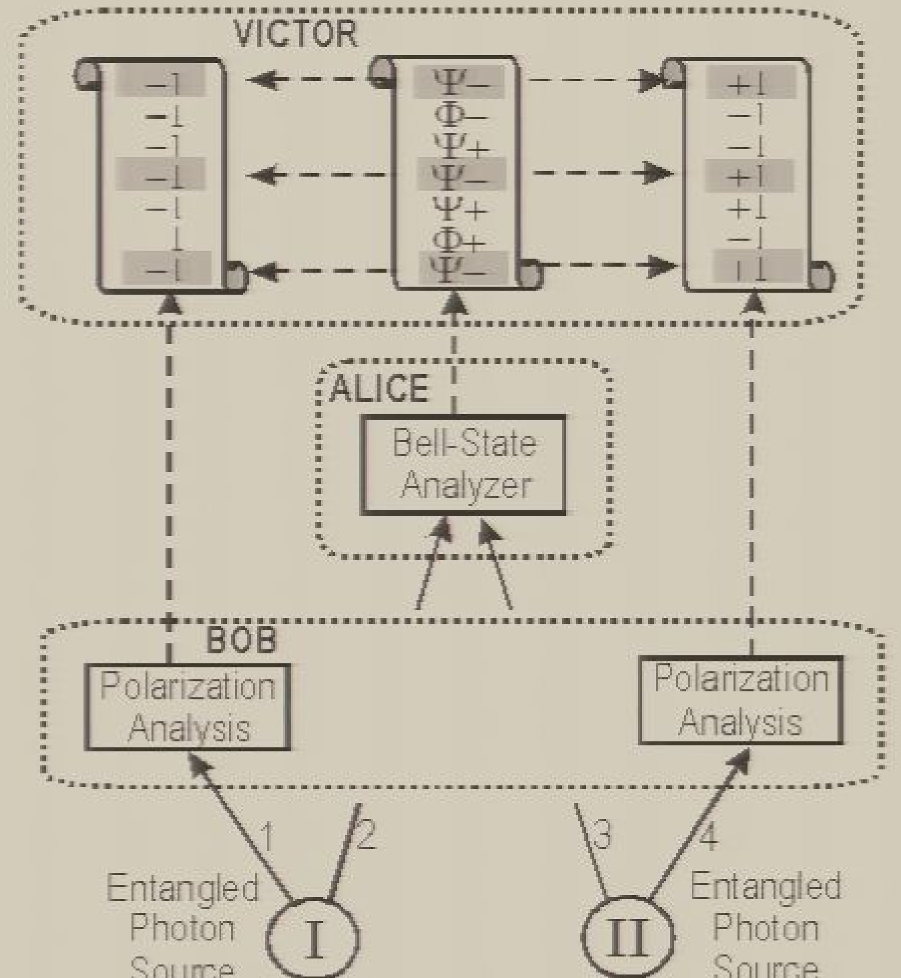






Hong, Ou Mandel

Delayed – Choice Teleportation of an Entangled Photon



Photon 1 and 4 Become Entangled after their Registration!

Relational Bits!

Proposal: Asher Peres 2001

Experiment:

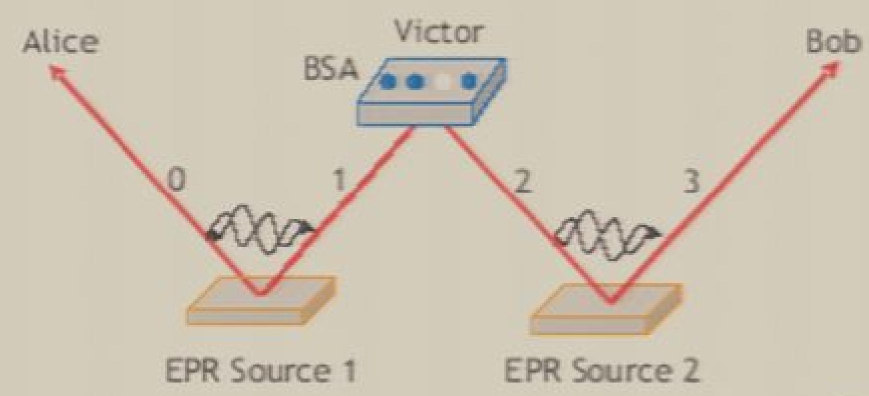
T. Jennewein, G. Weihs, J.W. Pan, A.Z.

Experimental Nonlocality Proof of Quantum Teleportation and Entanglement Swapping:

PRL 88 (2002) 17903

Fully Independent Sources for Quantum Repeaters

- 2 independent fs pump lasers
- 2 separated downconversion setups
- time-synchronization of sources to approx. 280 fs (not necessary in principle!)
- approx. 160 4-folds in 900 sec.



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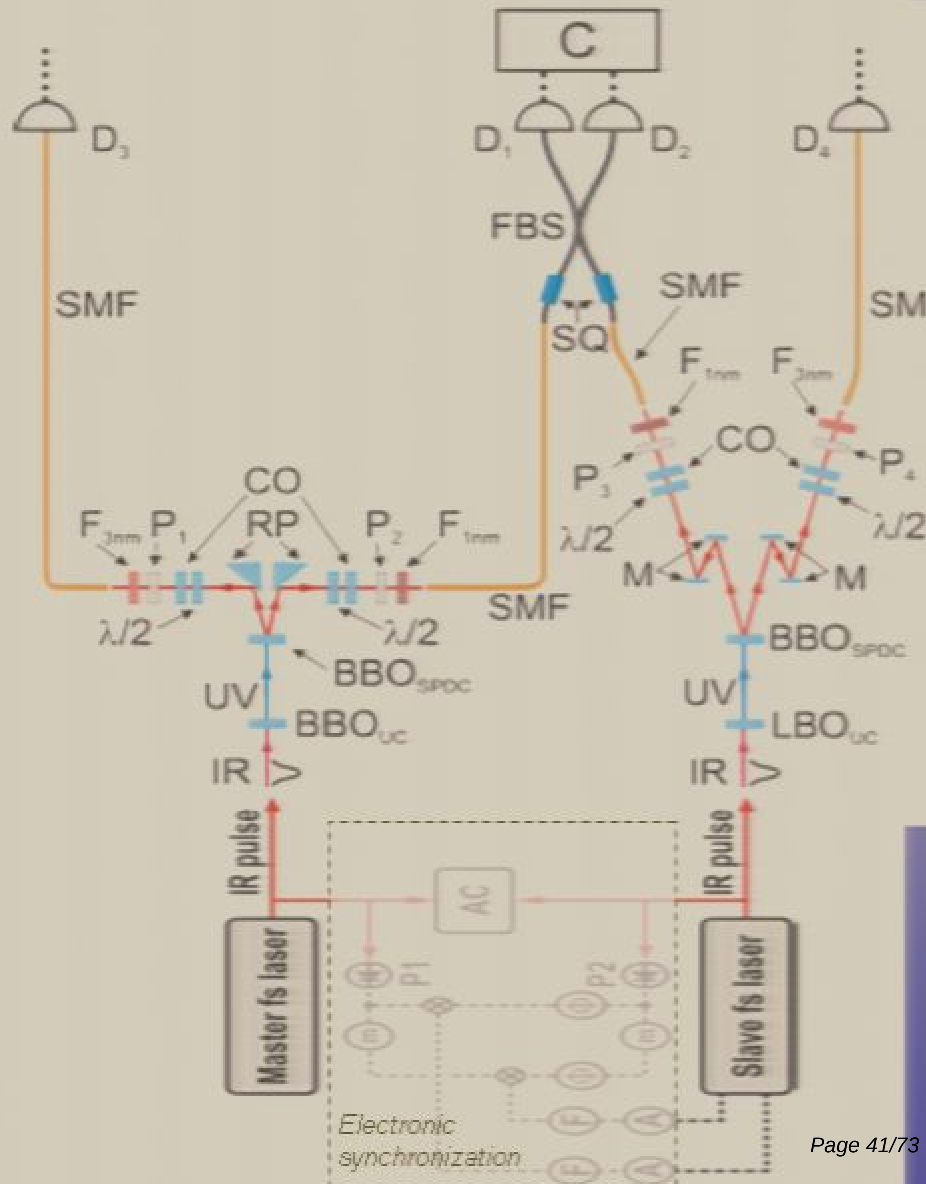
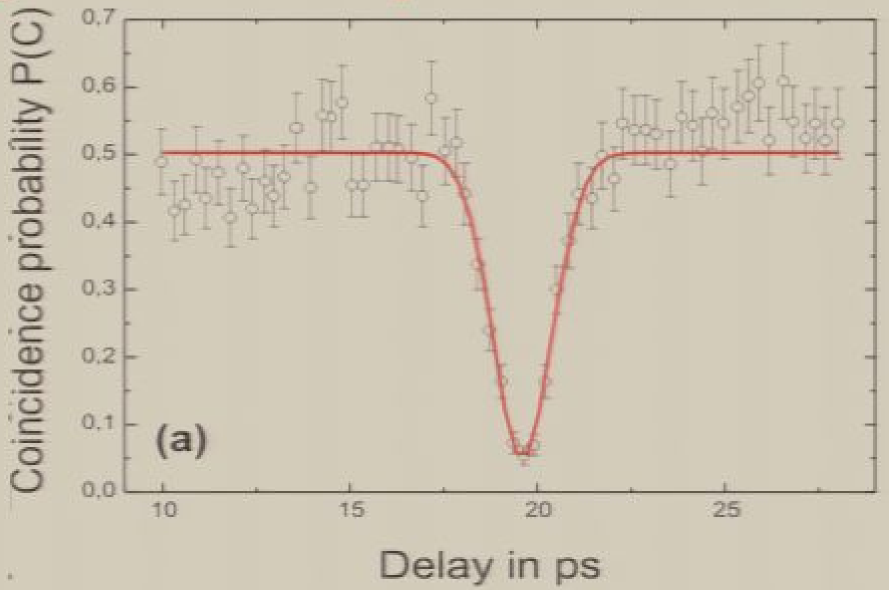
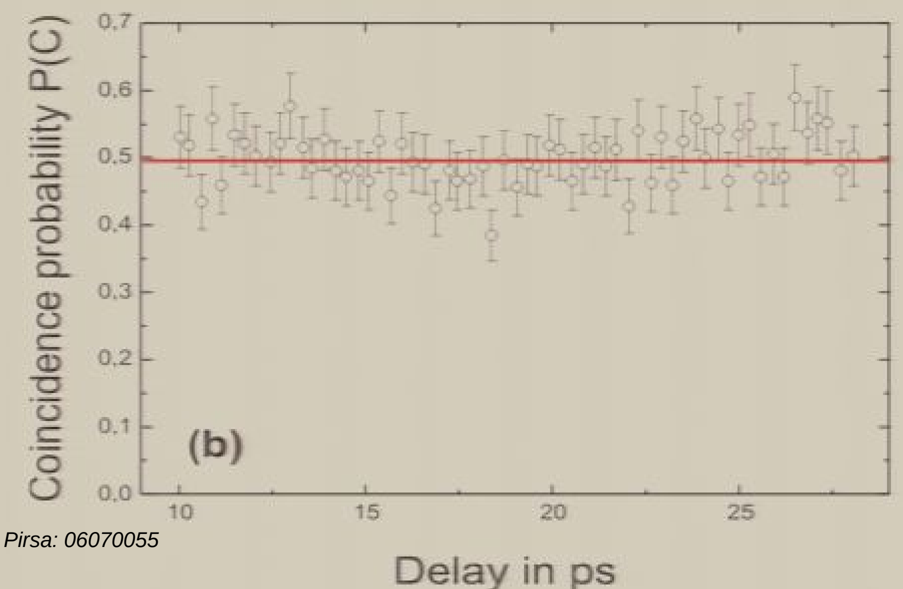
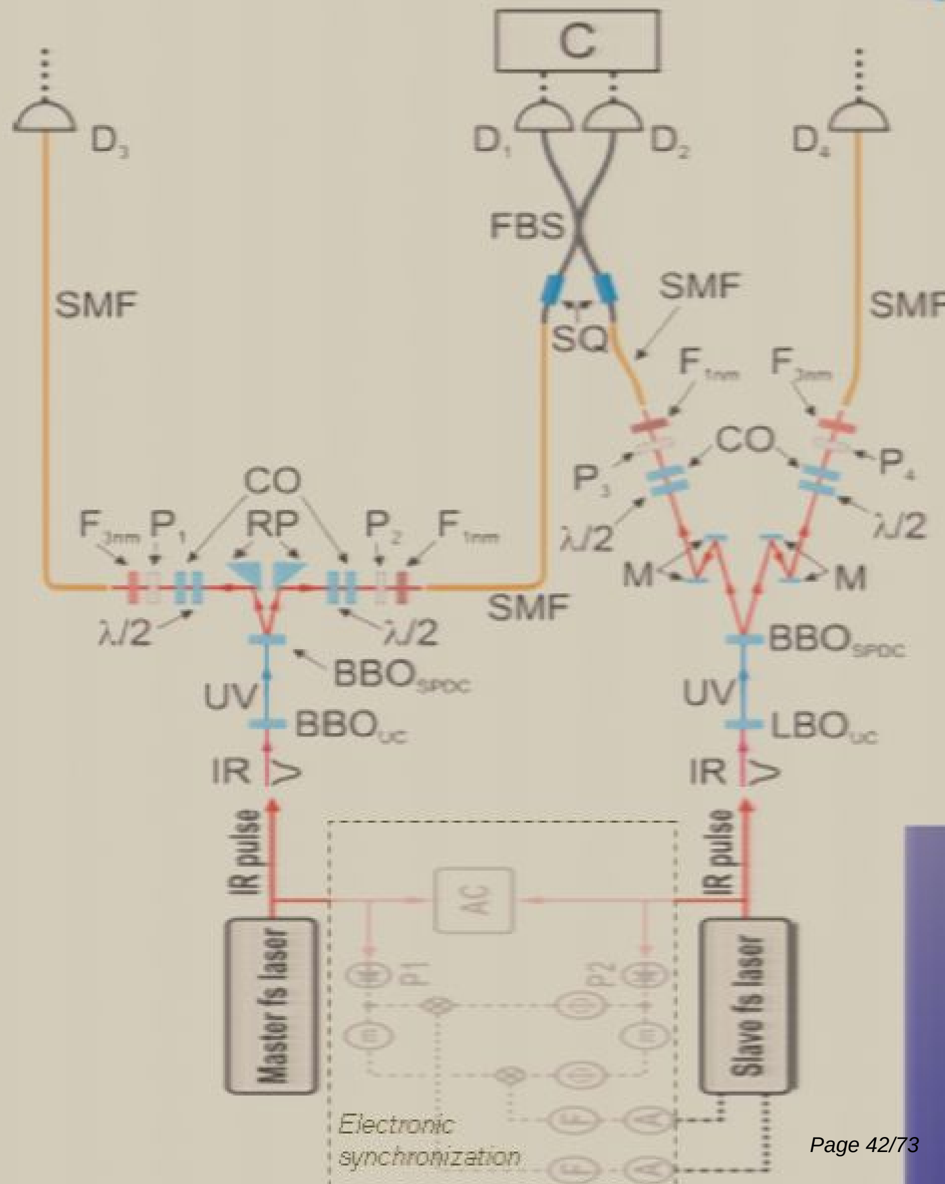


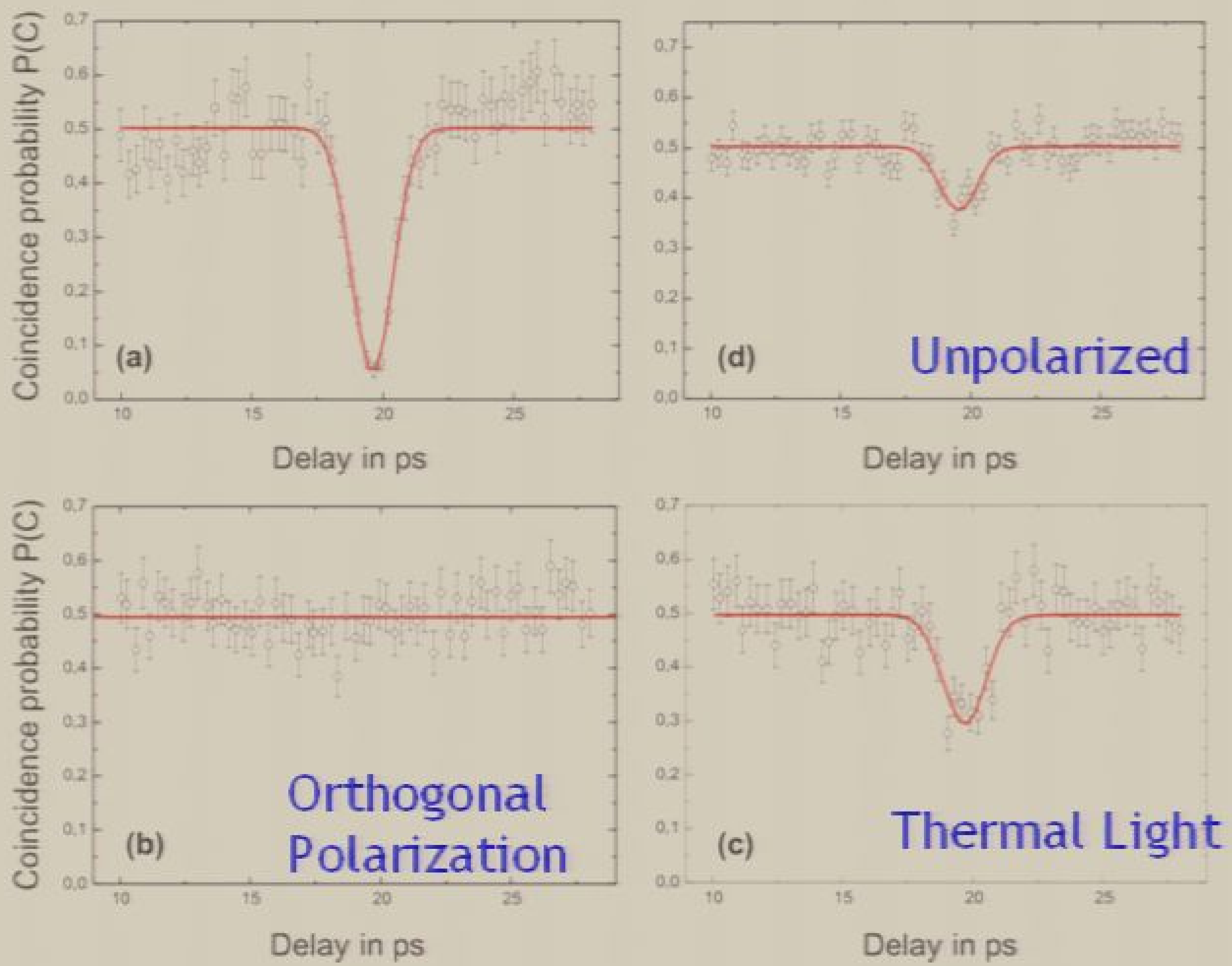
Fully Independent Sources for Quantum Repeaters







Independent-Photon Interference



Kaltenbaeck, Blauensteiner, Aspelmeyer, Zukowski, Z., 2005

Testing Non-local HV Theories

A.J. Leggett, Found Phys. 33, 1469 (2003)

CNLHV

Crypto-Nonlocal Hidden Variable Theories

- All predictions for individual photons ✓
- All experiments on pairs so far:
  - Perfect correlations ✓
  - Correlations in a plane on Poincaré Sphere ✓

What about non-local realistic models?

$A_1 = \pm 1$, $A_2 = \pm 1$

$B_1 = \pm 1$, $B_2 = \pm 1$

(A) Measurement outcomes are determined by pre-existing properties of particles independent of the measurement (realism).

(B) Physical states are statistical mixtures of subensembles with definite polarisation

(C) polarisation is defined such that expectation values taken for each subensemble obey Malus' Law.

A.J. Leggett, Found Phys. 33, 1469 (2003)

Aspelmeyer, Paterek, Gröblacher, Brukner, Zukowski, Z (2006)

What about non-local realistic models?

- **Non-local** dependence: A=A(a,**b**,**B**), B=B(b,**a**,**A**)
- Obey no-signaling condition
- Can explain results of all known Bell-experiments

A.J. Leggett, Found Phys. 33, 1469 (2003)
Aspelmeyer, Paterek, Gröblacher, Brukner, Zukowski, Z (2006)

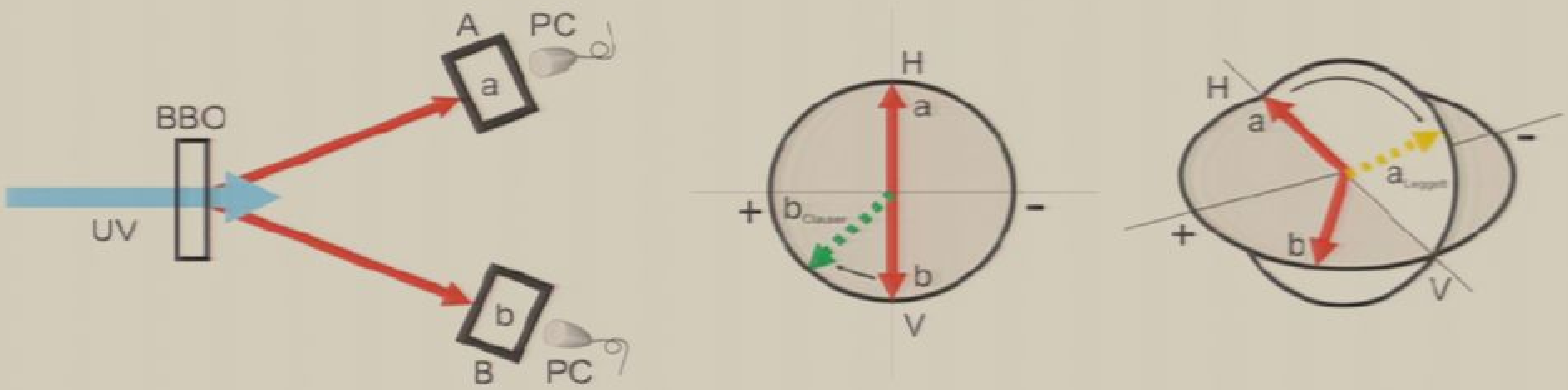
General Non-Local Theory:

$$A = A(\lambda, \vec{u}, \vec{a}, \eta)$$

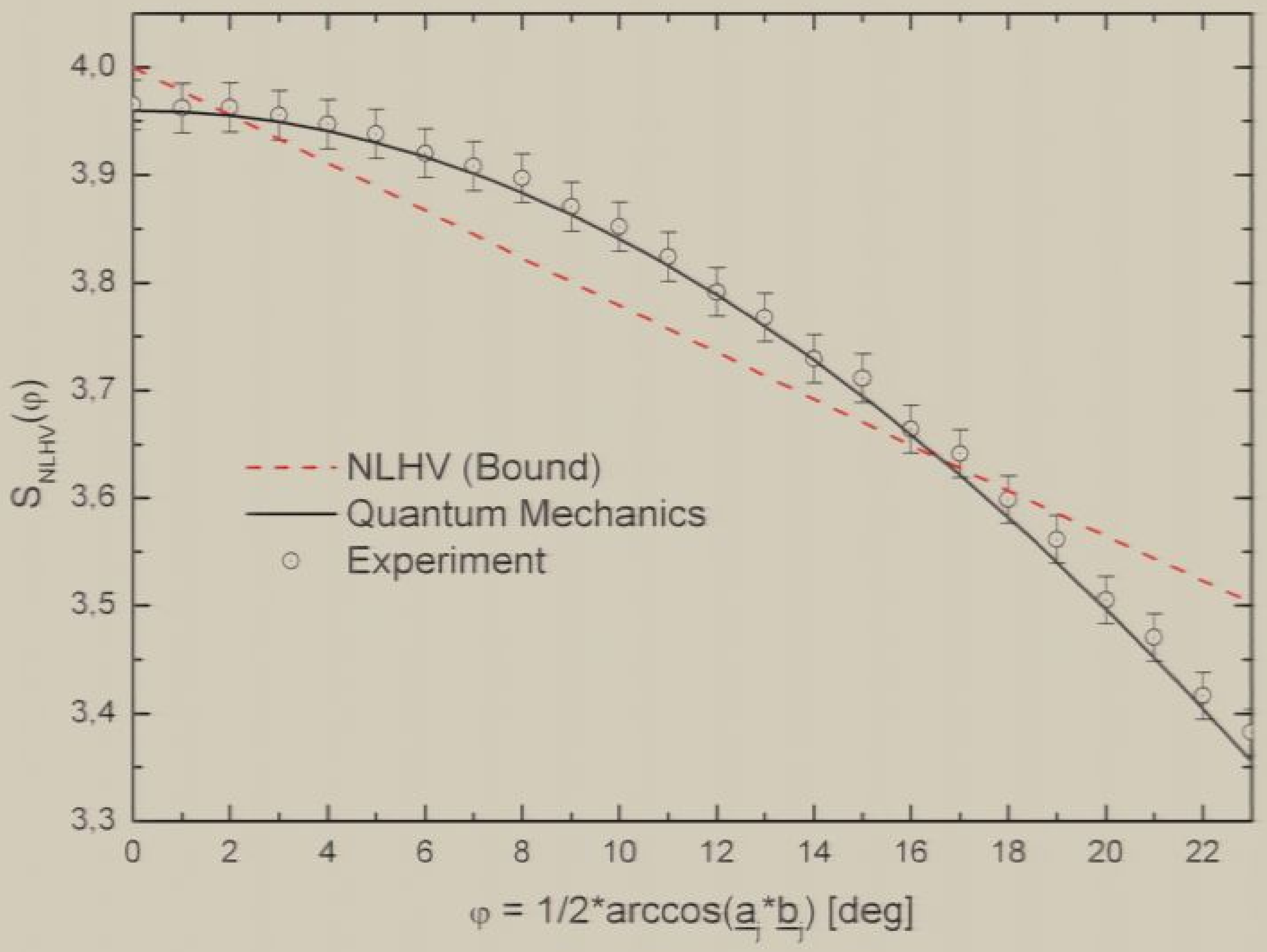
Malus' Law Requirement:

$$\overline{A}(\vec{u}) = \int d\lambda \rho_{\vec{u}}(\lambda) A(\lambda, \vec{u}, \vec{a}, \eta) = \vec{u} \cdot \vec{a}$$

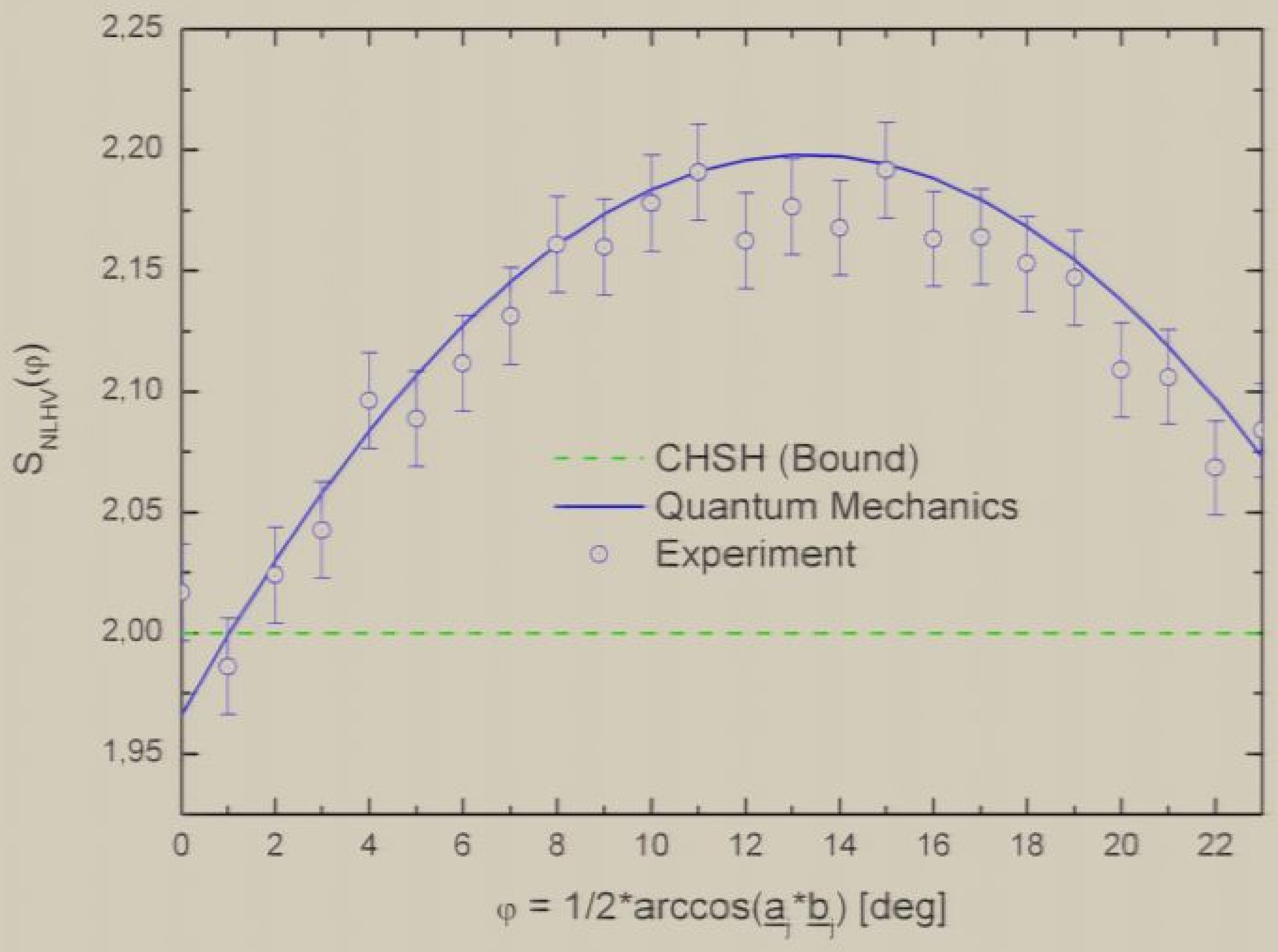
Experimental Tests of Local and Non-local hidden variable theories



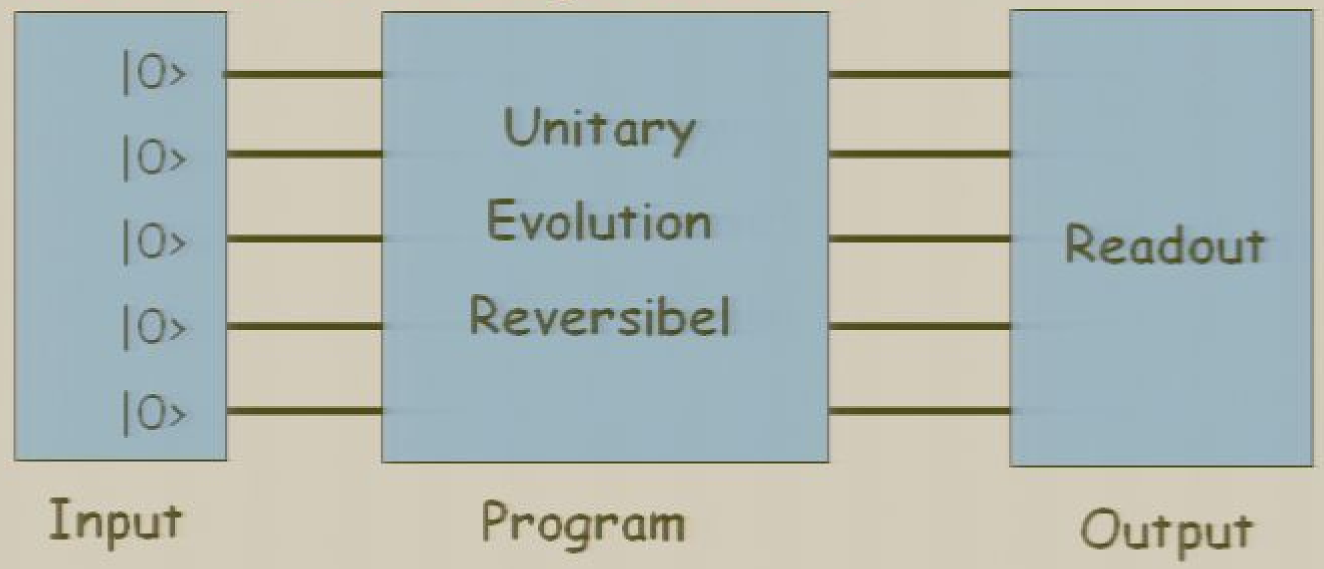
Wu, Shaknov 1950
Kocher, Commins 1967
Freedman, Clauser 1972
Aspect, Grangier ... 1982
Weihs ... 1998
Aspelmeyer, Paterek, Gröblacher, Brukner, Zukowski, Z. (2006)



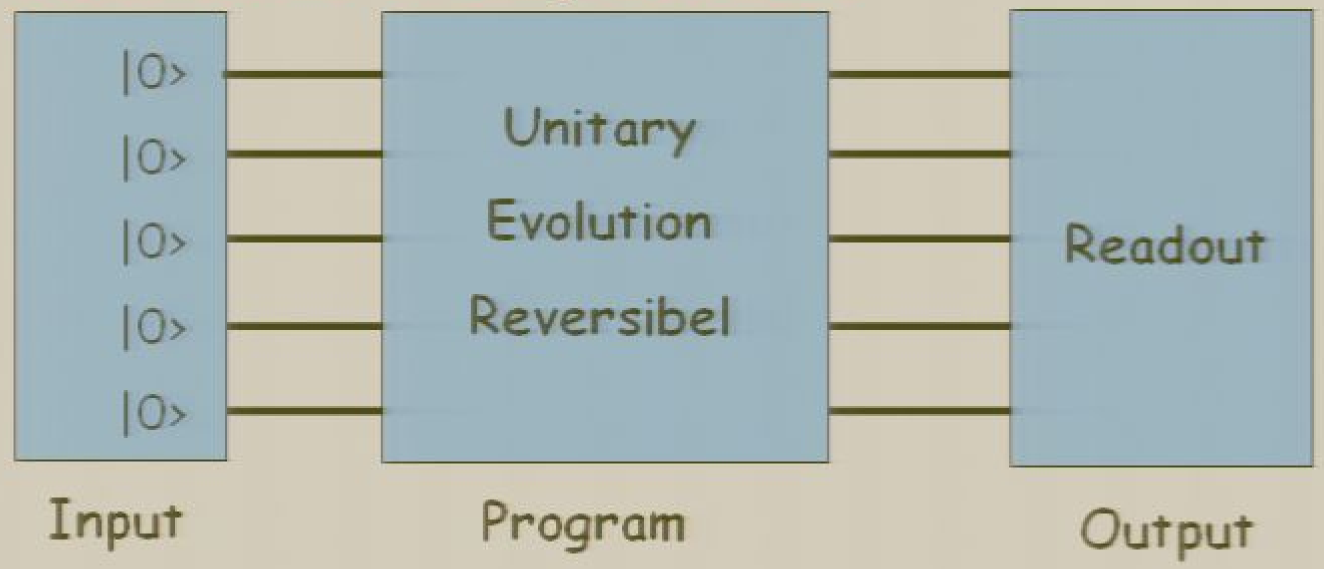
$S_{NLHV}(\varphi)$
NLHV (Bound)
Quantum Mechanics
Experiment
φ = 1/2*arccos($\underline{a}_j$*$\underline{b}_j$) [deg]


CHSH (Bound)
Quantum Mechanics
Experiment
$S_{NLHV}(\varphi)$
φ = 1/2*arccos($\underline{a}_j$*$\underline{b}_j$) [deg]
2,25
2,20
2,15
2,10
2,05
2,00
1,95
0 2 4 6 8 10 12 14 16 18 20 22

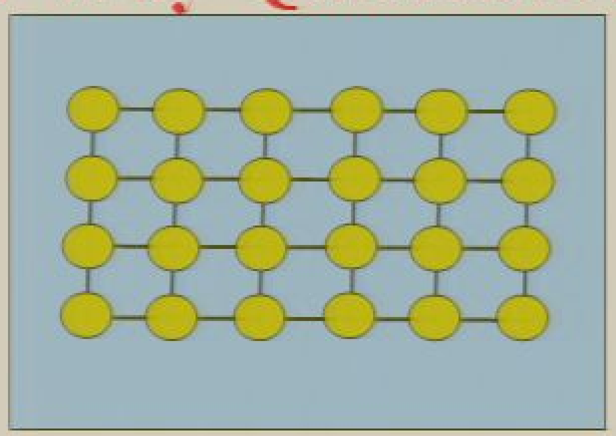
Standard Quantum Computation



Standard Quantum Computation



One-Way Quantum Computation



Cluster State

Program:
Measurement
Sequence

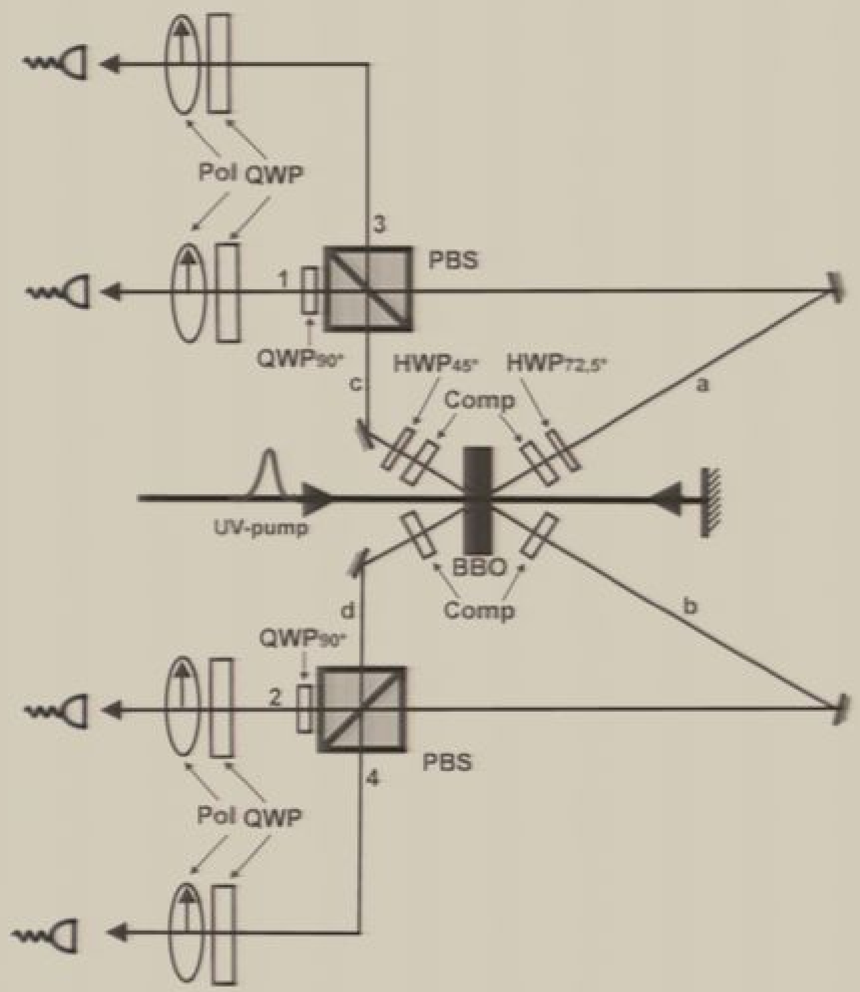
Infinite Library
Jorge Louis Borges

Linear Optics:
Knill, Laflamme, Milburn
Nature 409, 176 (2001)

Proposal:
Raussendorf & Briegel
PRL 86, 5188 (2001)

Experiment:
Walther et al.
Nature 434, 169 (2005)

The Cluster State Machine



Walther et al., Nature 434, 169 (2005)

Reality vs. Information

University Vienna

The Experimentalist Interrogates Nature
Asking Questions.
From the Answers we Construct Reality.

What is the Relation
between Material Existence and Knowledge,
between Reality and Information?

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All Information is Classical

Bohr (1948):

„However far the (quantum) phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms.“

Quantum Information is only the Representation of Classical Information in a Quantum Formalism

Information Content of a Quantum System

University Vienna

The Information Content Scales with the Size of the System.

Feynman:

„It always bothers me that ... it takes a computing machine an infinite numer of logical operations to figure out what goes on in no matter how tiny a region of space ... Why should it take an infinite amount of logic to figure out what one tiny piece of space-time is going to do?"

Large Systems... Huge Number of Bits
Huge Amount of Information

The most elementary system represents the truth value of one proposition only

The Most Elementary System ... One Bit

Less is not Possible!

A. Z.: *A Foundational Principle of Quantum Mechanics* Found. Phys. (**1998**) 29, 631.

The Most Elementary System ... One Bit

Less is not Possible!

C. Brukner and A. Zeilinger, Phys. Rev. Lett. 83, (1999) 3354-3356
C. Brukner and A. Zeilinger, *von Weizsäcker Festschrift*, 2003

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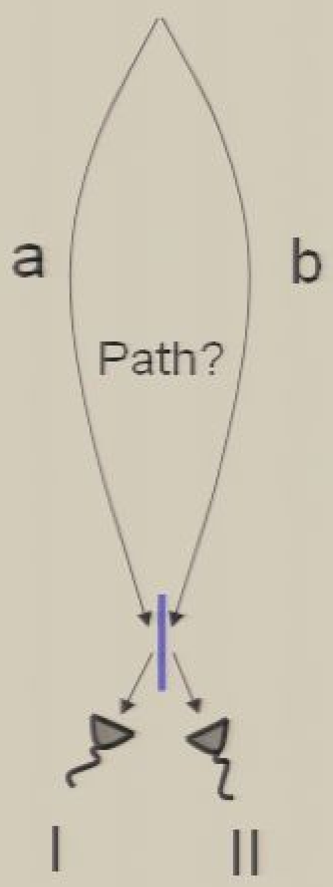
Complementarity



1 Bit of Information

Either:
Used for Which-Path Information

→ No Information Available to Determine if Detector I or II will fire.

Or:
1 Bit of Information about Detector I or II

→ No Which-Path a or b Information

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Randomness

Answer to One Question
Well-Defined
e.g. Path Information

→ No Info left to decide what to do at the Beam Splitter

→ „Clicks“ at Detectors I and II Irreducibly Random

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Entanglement

2 Elementary Systems → 2 Bits of Information

Classically: Each Bit represents a Possible Result for Each System Separately.

Quantum: Both Bits Only Represent How Measurement Results on the Two Systems Relate to Each Other.

FAQs:

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Qu.: What is the Quantum State ?
A.: Just a representation of Information.

Qu.: Information about what?
A.: About results of observation, i.e. features of a classical apparatus.

Qu.: Information what for?
To calculate probabilities of future events, i.e. future features of classical apparatus.

There is no more!

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FAQs 2:

Qu.: What about the Measurement Problem?
A.: There is no Measurement Problem!

Qu.: How come?
A.: It is most natural to change our representation of information, i.e. the quantum state, when our knowledge changes because of new information.

„The act of recording ... Is not a physical but rather, so to say, a mathematical process. With a sudden change of our knowledge also the mathematical representation of our knowledge undergoes of course a sudden change."
Heisenberg Feb 2, 1960

Quantum Physics: Unification of Information and Reality

University Vienna

We must only admit concepts which can be operationally verified

It is impossible to operationally verify any distinction between reality and information

Reality = Information
Information = Reality

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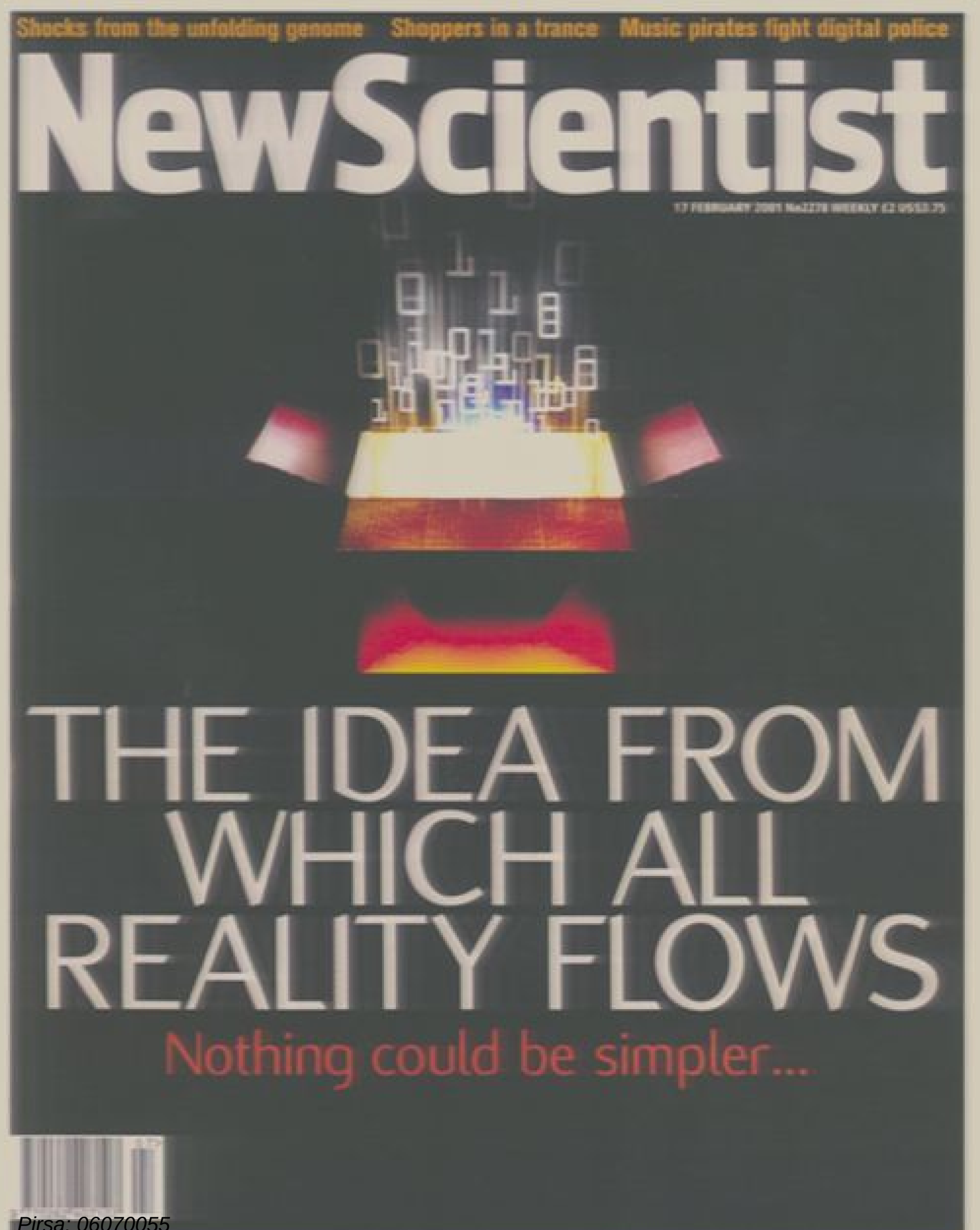

„In the beginning was the bit"

Hans Christian von Baeyer

17. Feb. 2001

445. Proposal for Einstein's Membership in the Prussian Academy of Sciences[1]

Berlin, 12. Juni 1913.

Die unterzeichneten Mitglieder der Akademie beehren sich, die Erwählung des ordentlichen Professors der theoretischen Physik an der eidgenössischen technischen Hochschule in Zürich, Dr. Albert Einstein, zum ordentlichen Mitglied der Akademie, mit einem besonderen persönlichen Gehalt <zu-nächst> von <6000> 12000 M., zu beantragen.[2]

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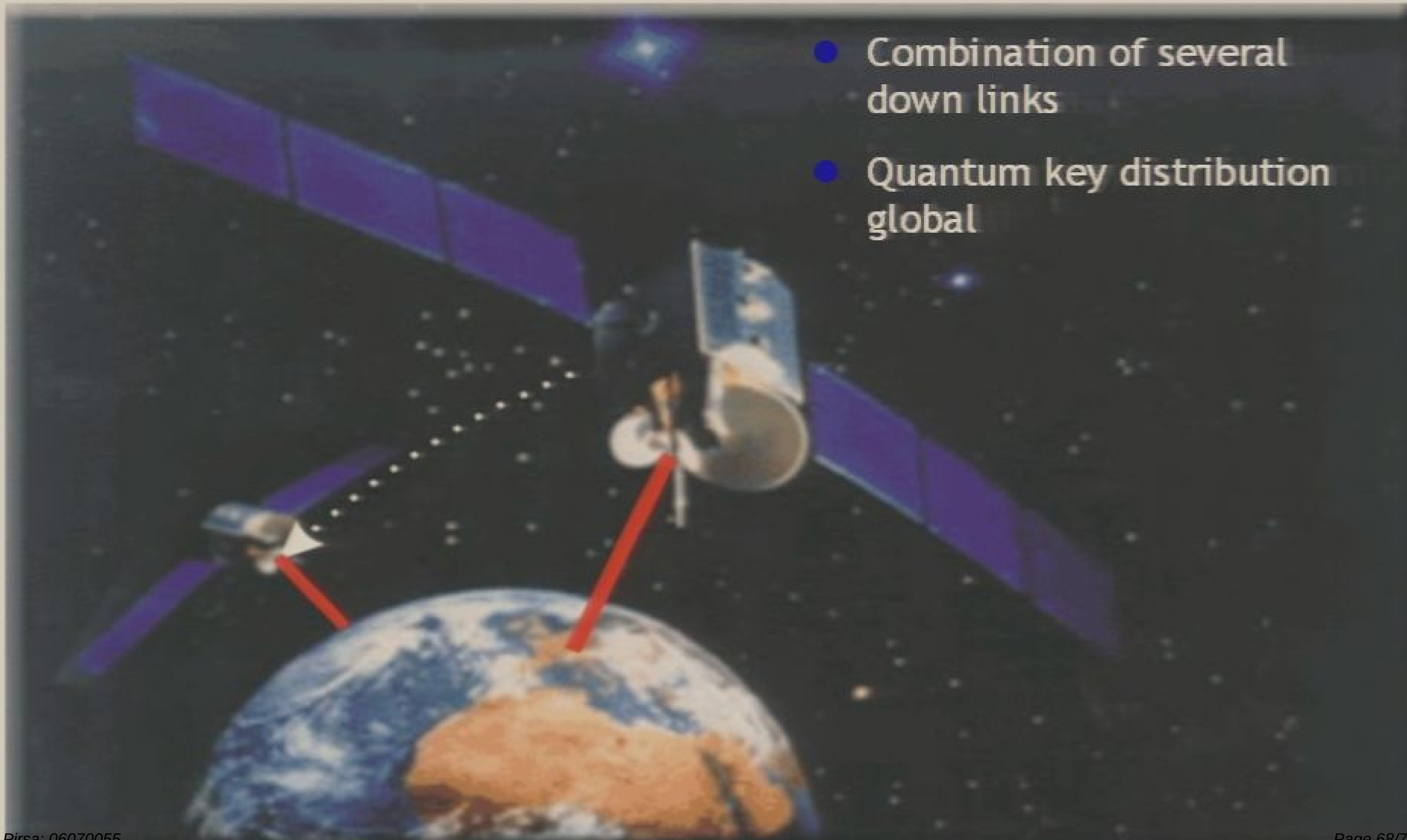
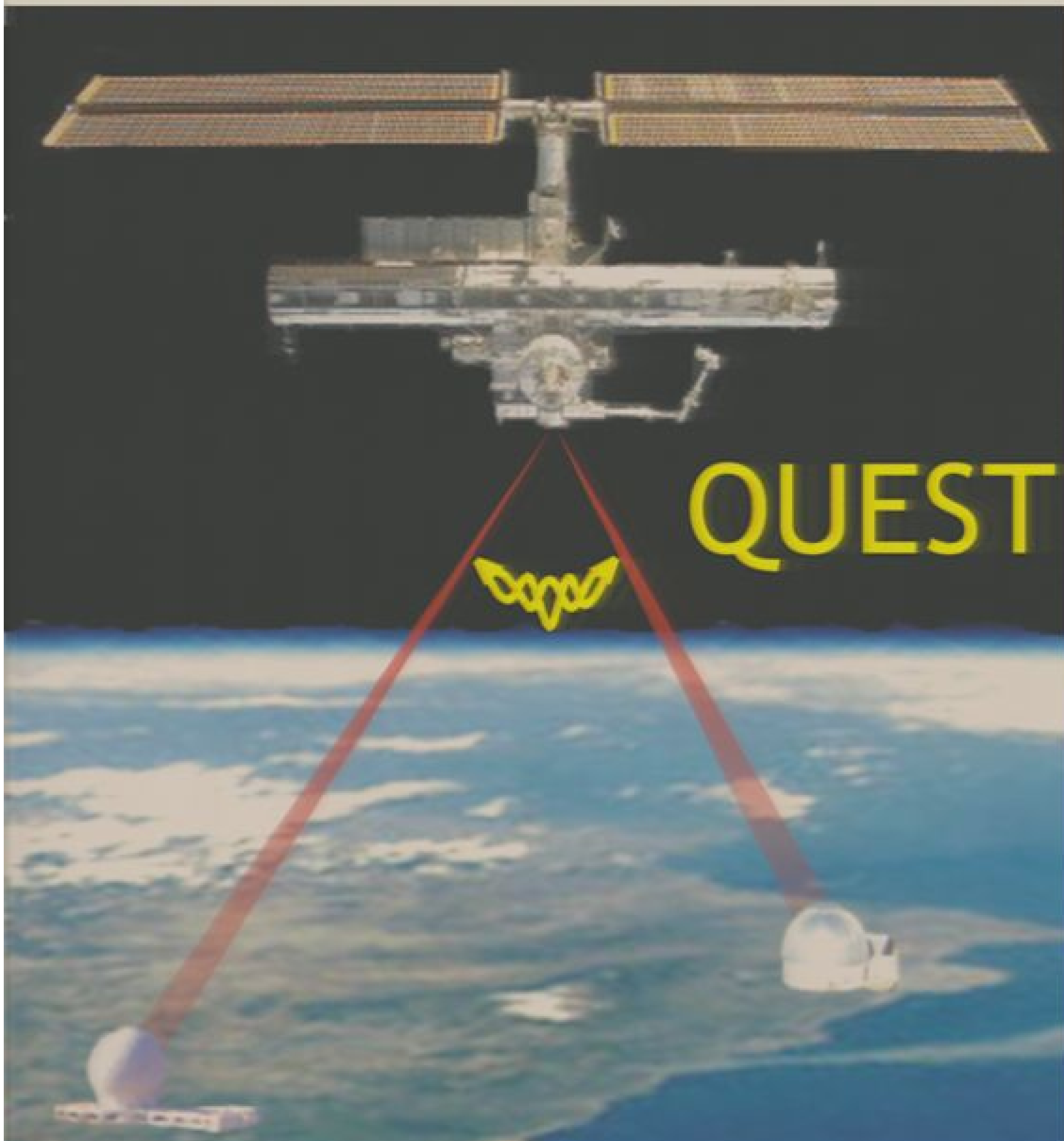
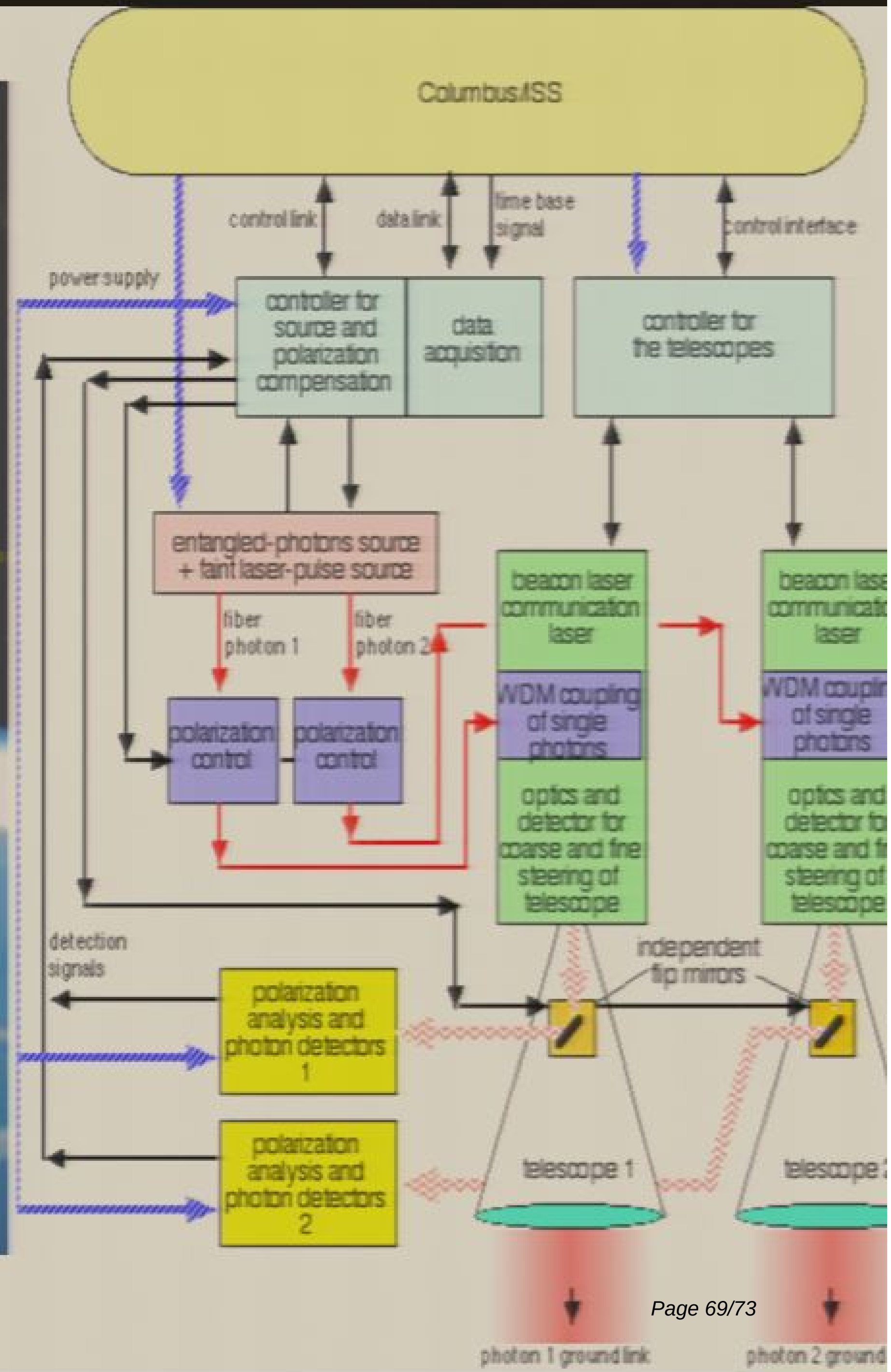
in bemerkenswerter Weise Stellung genommen hätte. Daß er in seinen Spekulationen gelegentlich auch einmal über das Ziel hinausgeschossen haben mag, wie z. B. in seiner Hypothese der Lichtquanten, wird man ihm nicht allzuschwer anrechnen dürfen; denn ohne einmal ein Risiko zu wagen, läßt sich auch in der exaktesten Naturwissenschaft keine wirkliche Neuerung einfüh-


Combination of several down links
Quantum key distribution global


QUEST


Columbus/ISS
control link
data link
time base signal
control interface
power supply
controller for source and polarization compensation
data acquisition
controller for the telescopes
entangled-photons source + faint laser-pulse source
fiber photon 1
fiber photon 2
polarization control
polarization control
beacon laser communication laser
WDM coupling of single photons
optics and detector for coarse and fine steering of telescope
detection signals
independent flip mirrors
polarization analysis and photon detectors 1
polarization analysis and photon detectors 2
telescope 1
photon 1 ground link

WANTED

Erwin Schrödinger

DEAD AND ALIVE

Ende der Bildschirmpräsentation. Zum Beenden klicken.

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS