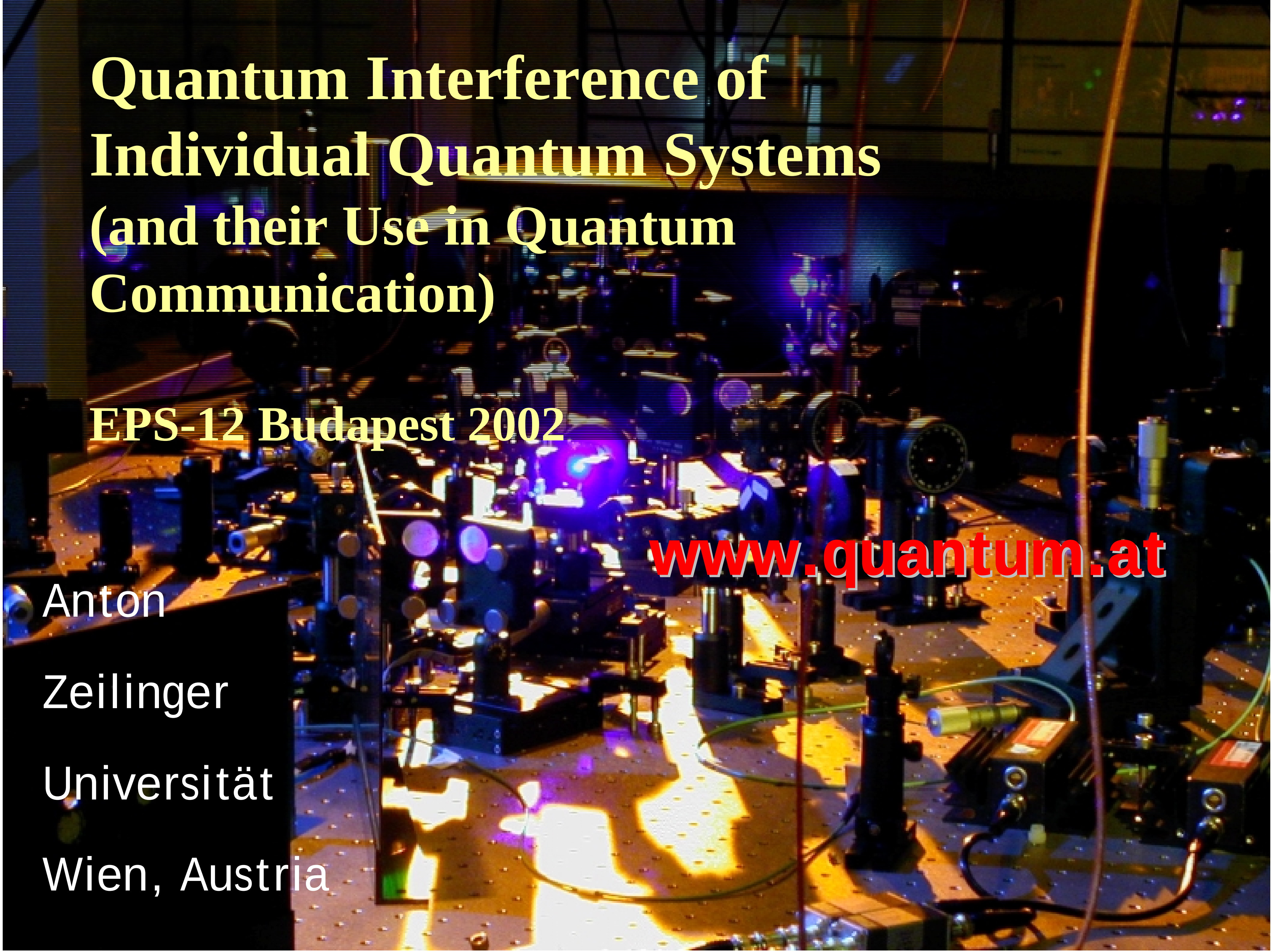
Quantum Interference of Individual Quantum Systems (and their Use in Quantum Communication)

EPS-12 Budapest 2002

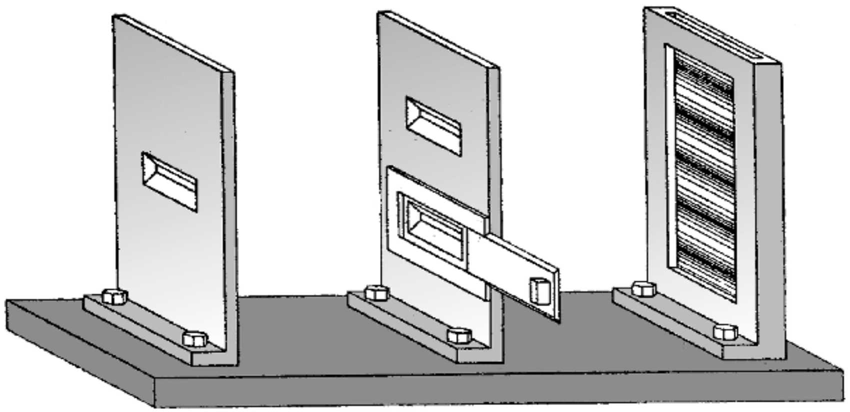


www.quantum.at

Anton Zeilinger
Universität Wien, Austria

Steps in Individual Quantum Systems Experimentation

- 1. First Demonstrations of Feasibility
- 2. Realization of Historic Gedanken Experiments



- 3. New unforeseen Possibilities
- 4. Ideas for New Information Technology
- 5. Exploring the Limits

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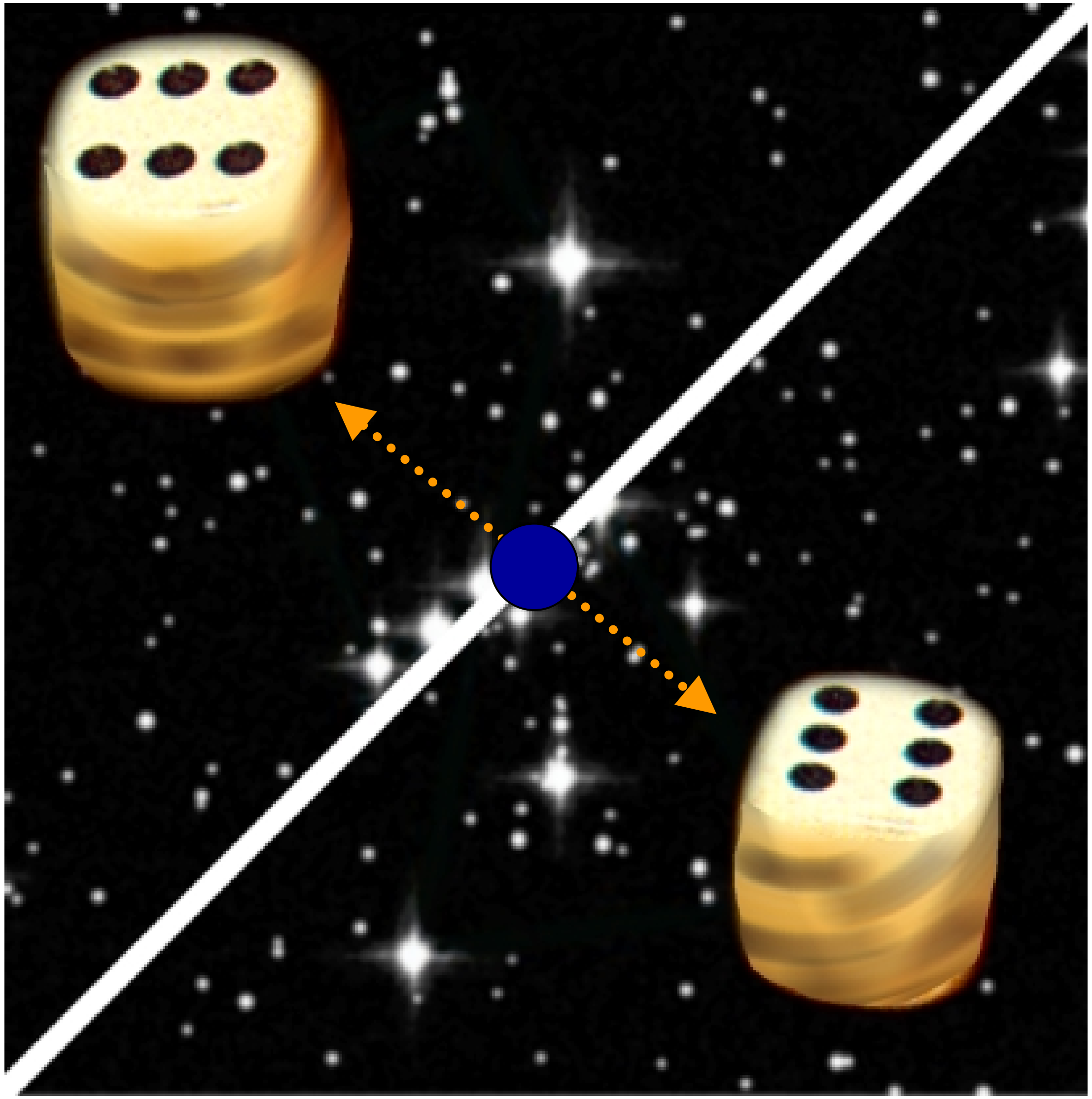
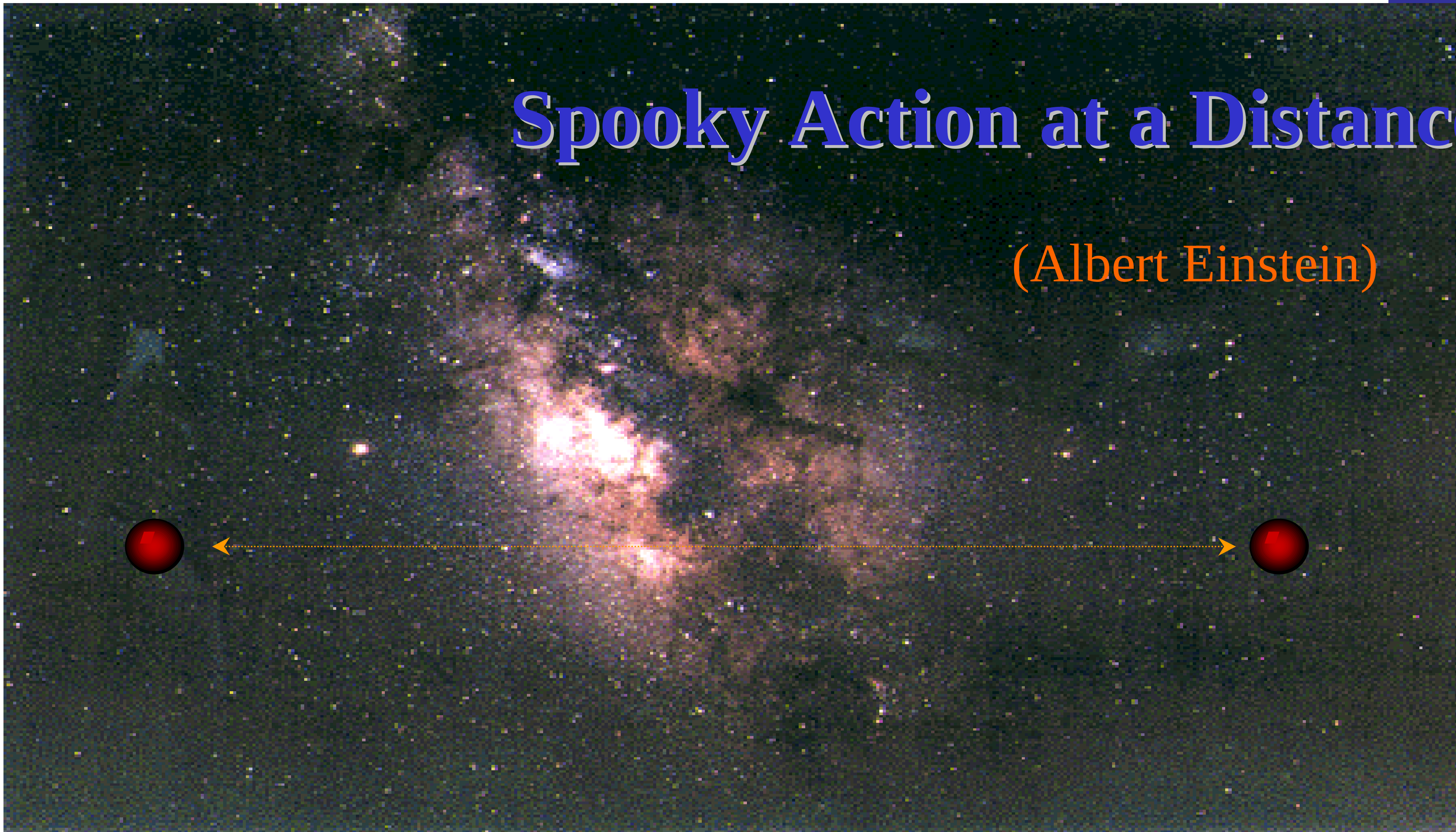
Entanglement

The Essence of Quantum Physics



E. Schrödinger (1935)

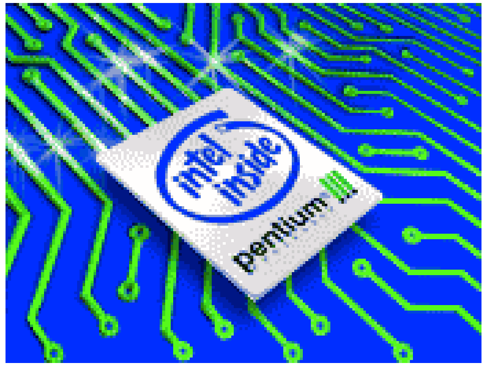
Entanglement



Quantum Information Applications

Moores Law: Exponential Increase of Transistors on a Chip

Year:	Elektrons/Bit:
now	~100
+ 10	~10
+ 20	~1



The Age of Quantum Information Applications Begins

⇒ Quantum Computer
Quantum Communication
Quantum Teleportation

Entanglement and Quantum Communication

- Quantum Cryptography
- Quantum Dense Coding
- Quantum Teleportation
- Entanglement Swapping
- Teleportation of Entanglement

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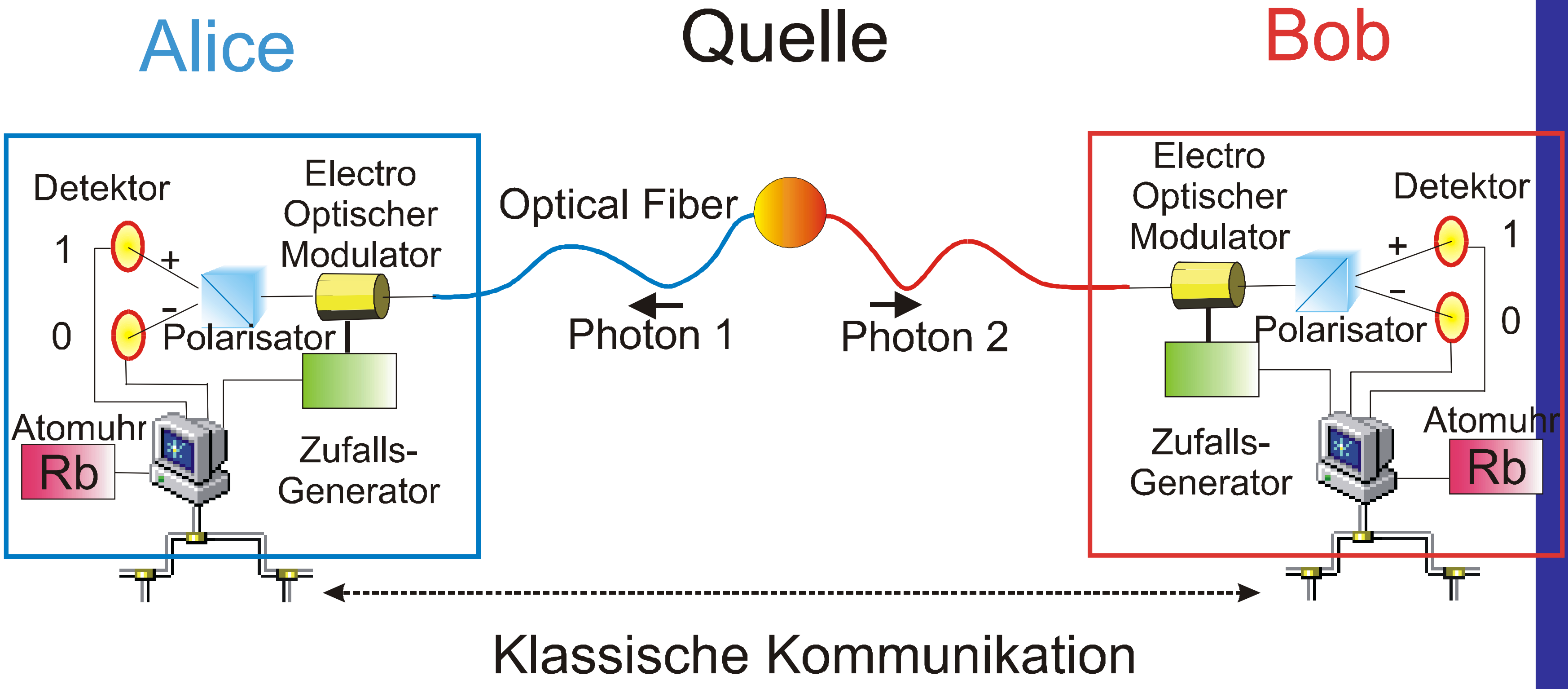
Quantum Cryptography

Experimental Arrangement

T. Jennewein et al. PRL 84 (2000) 4279



Quantum Cryptography

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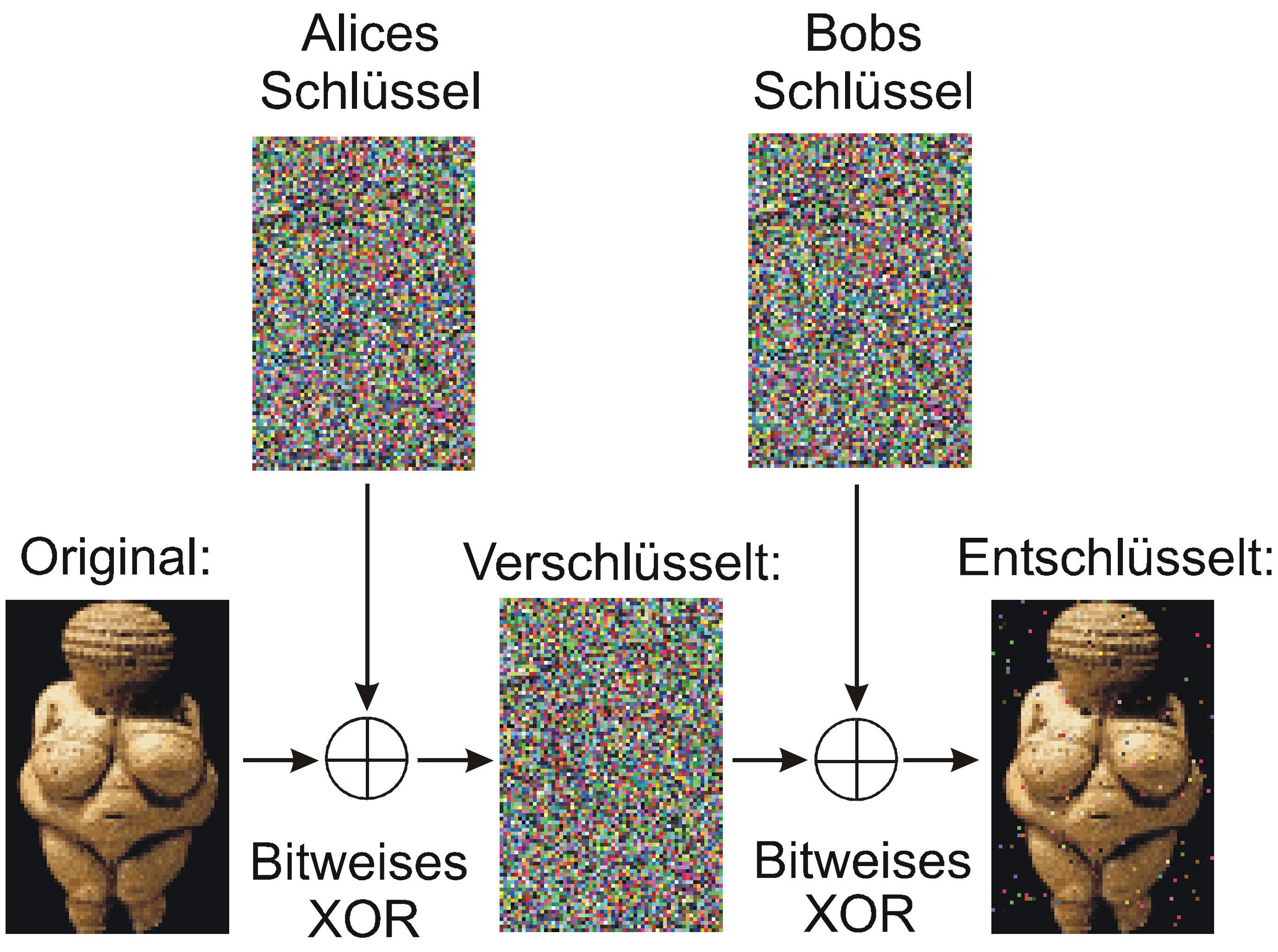
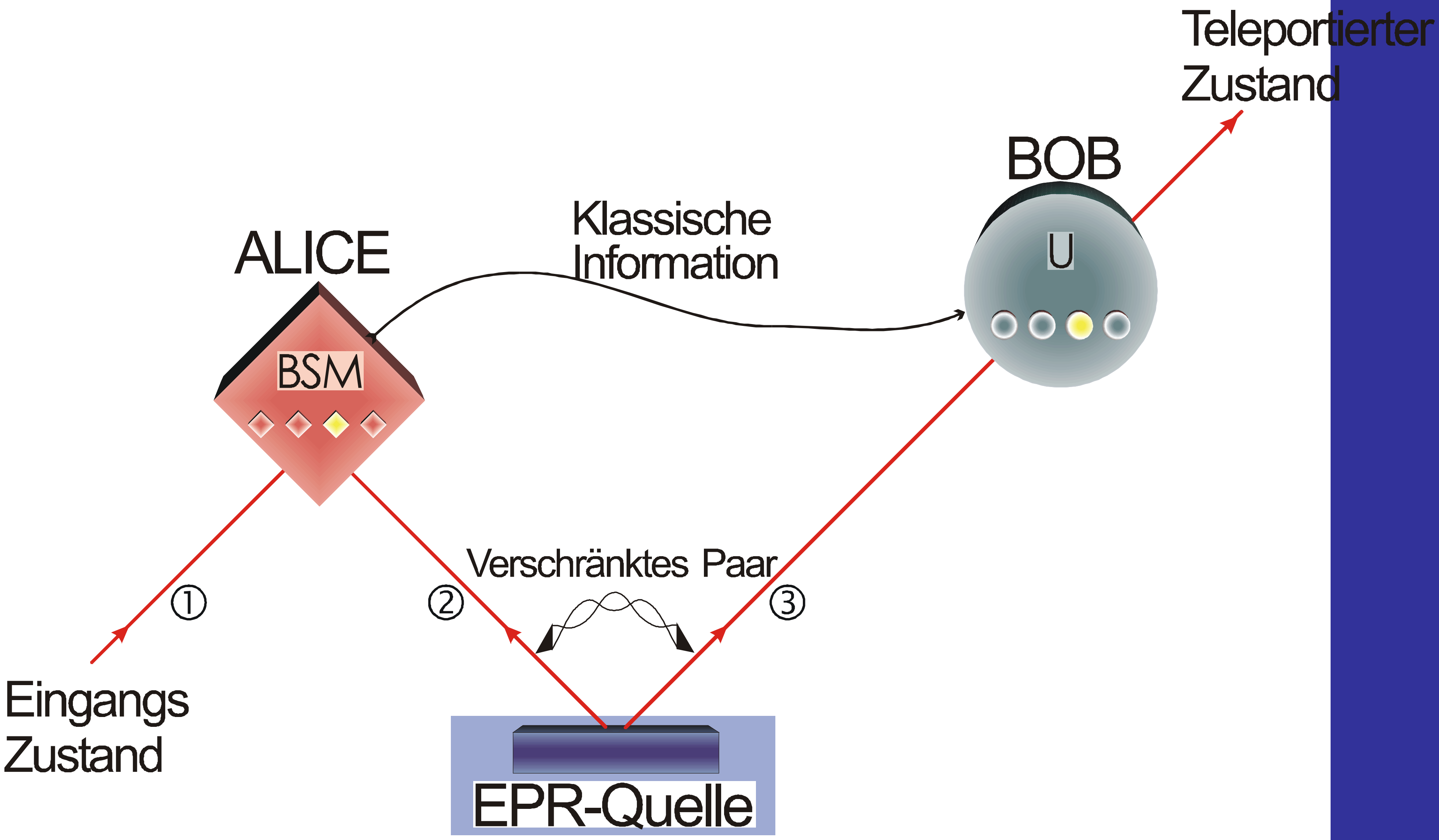
Encoding a Secret Message



Schlüssel: 51840 Bit, Bit Fehlter Wahrsch. 0.4 %

Quantum Teleportation



Recent Results:

Quantum Teleportation of an Entangled Photon

- Quantum Repeaters for Long-Distance Quantum Communication

Experimental Qutrit (and QuNit) Entanglement

- Quantum Communication with Higher Alphabets

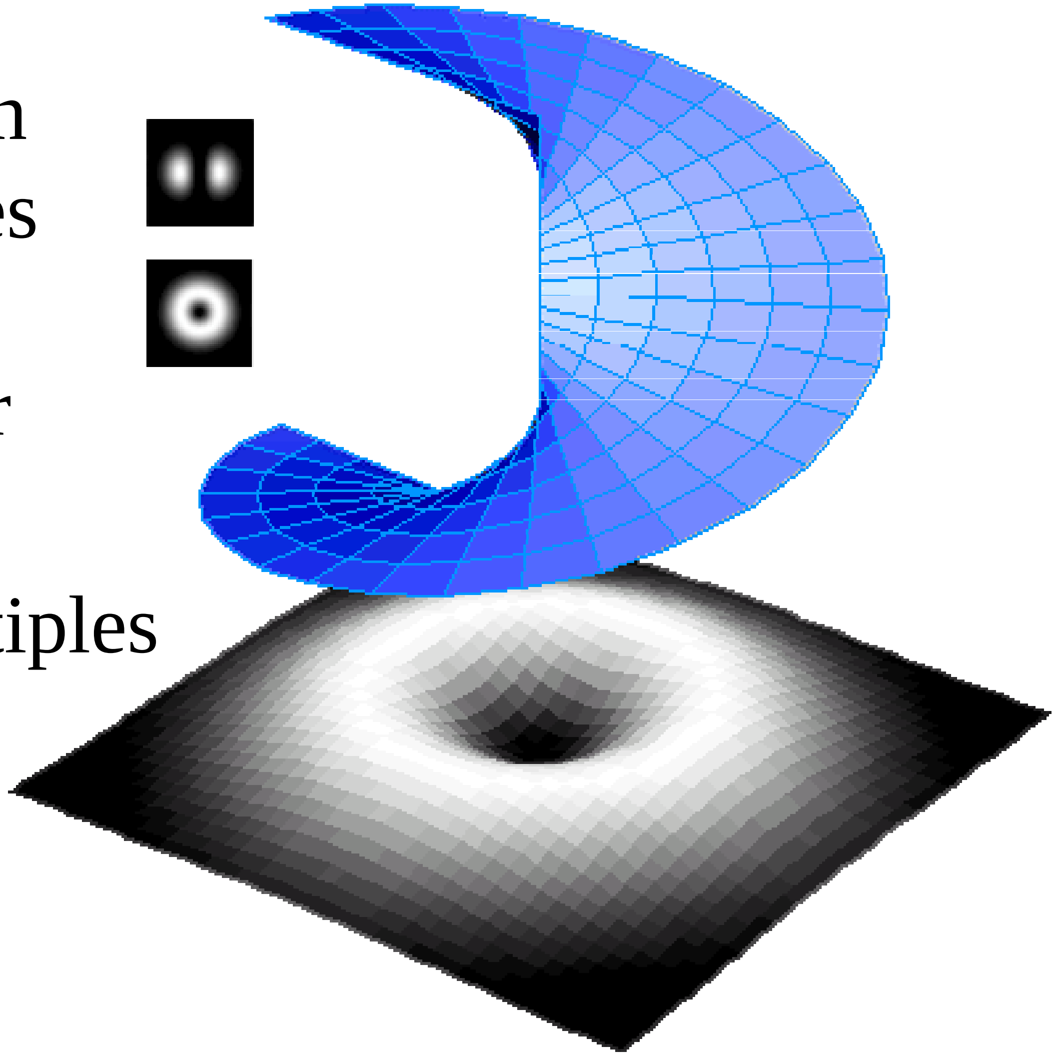
Entanglement in Systems of Dimension >2

- Photon External Angular Momentum
- Bell Test for N = 3 i.e. Qutrits

Alois Mair, Alipasha Vaziri, Gregor Weihs

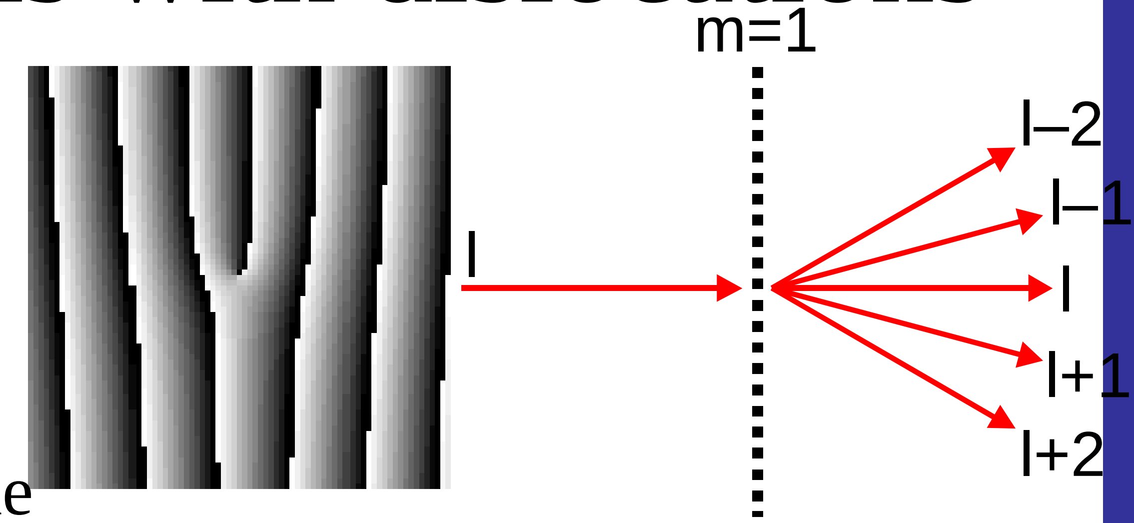
External angular momentum of photons

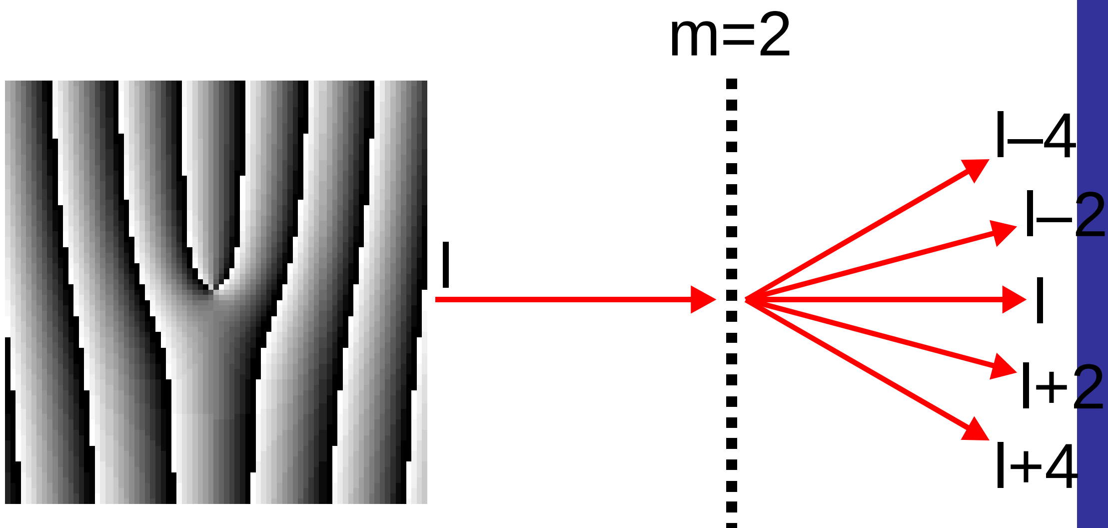
- Laguerre-Gaussian “Doughnut” modes possess external („orbital“) angular momentum.
- Quantized in Multiples of $\hbar$



Holograms with dislocations

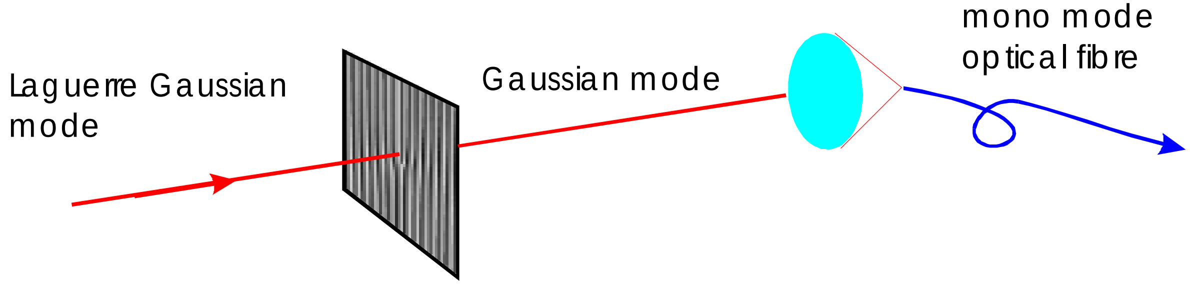
- Diffraction at a dislocation with multiplicity m into the n-th order will change the LG mode index by **n x m**
- Appropriate Blazing can transfer nearly 100% into the first order

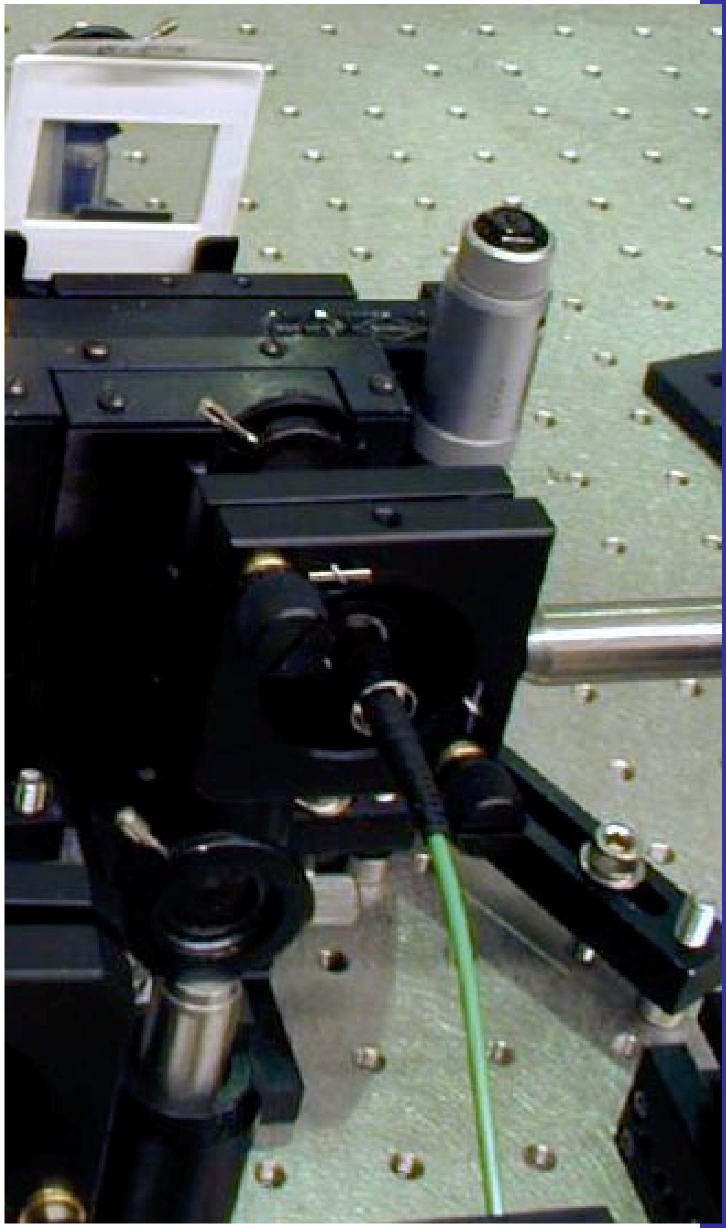




Projection onto the Gaussian Mode

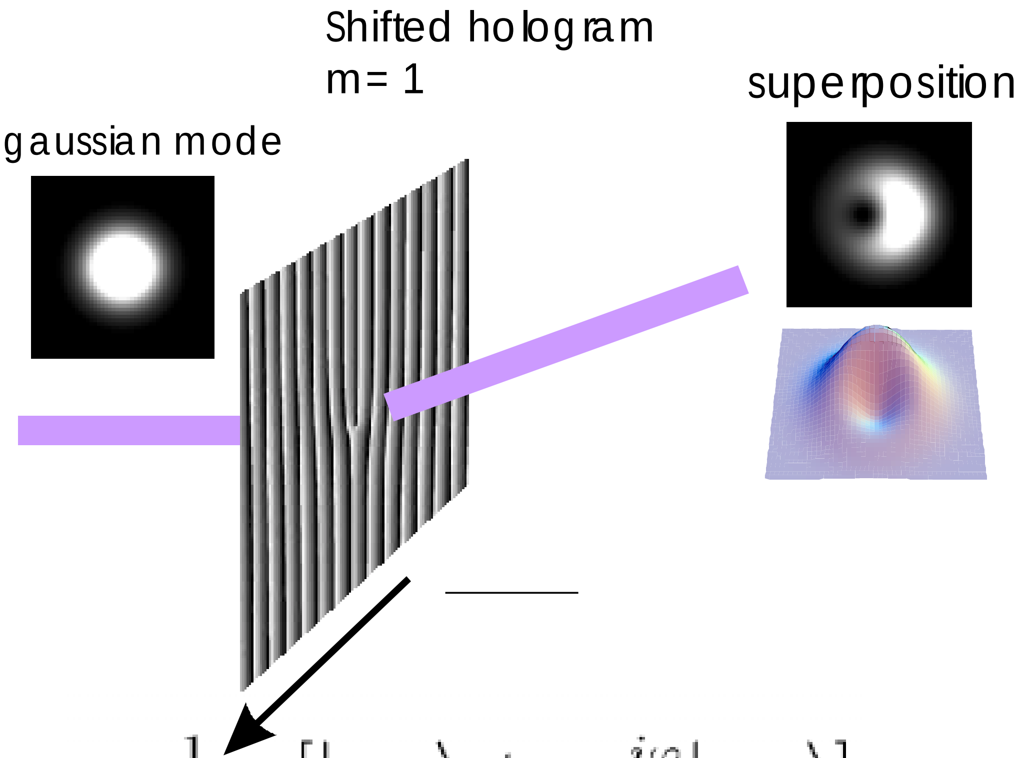
- Fiber mode is approximately Gaussian
- All other modes cannot propagate inside fiber
- Together with the hologram we can project onto **any** LG mode



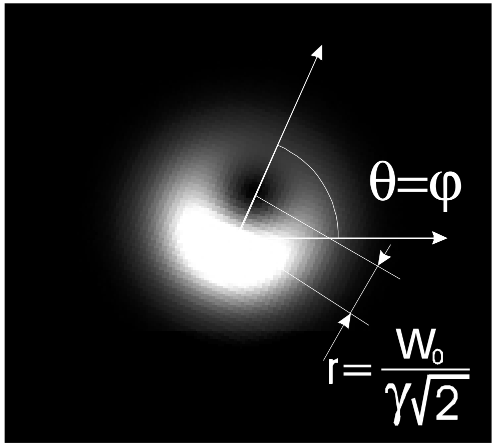


Measurement of Superpositions of Doughnut Modes

University Vienna



$$\frac{1}{\sqrt{1+\gamma^2}}\left[|u_{00}\rangle + \gamma e^{i\varphi}|u_{01}\rangle\right]$$



Superposition!

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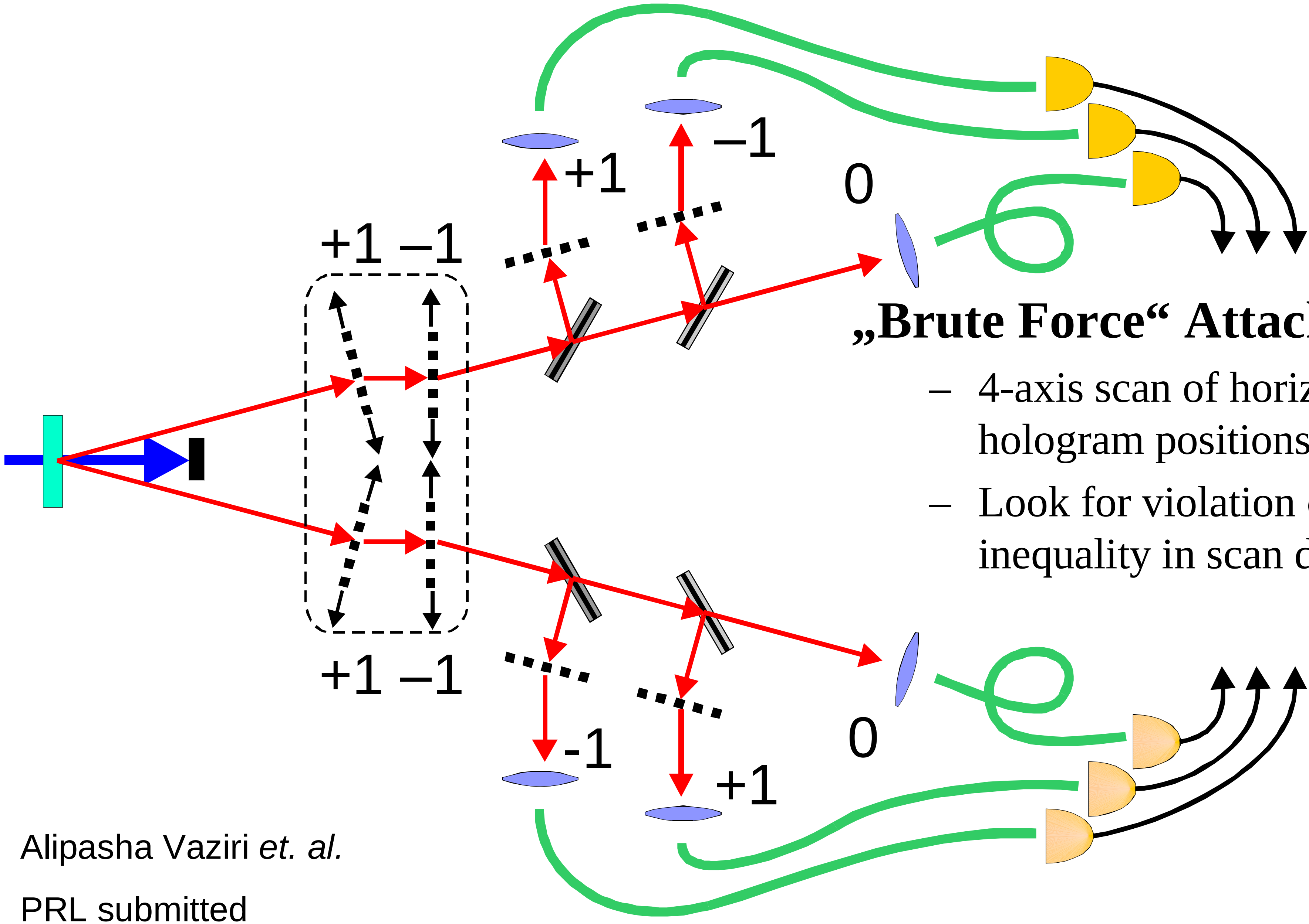
Experimental Qutrit Bell Test



„Brute Force“ Attack

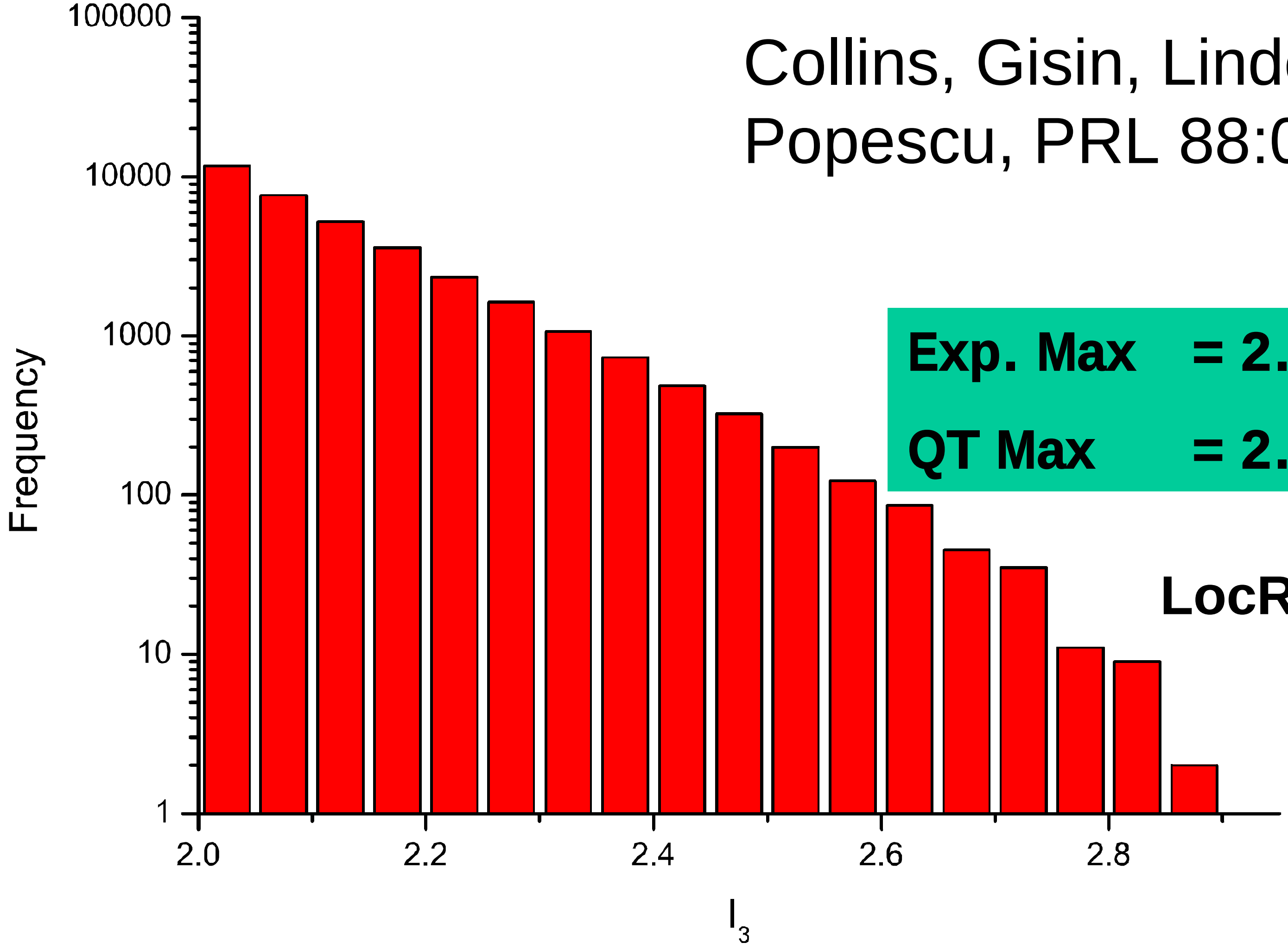
- 4-axis scan of horizontal hologram positions
- Look for violation of qutrit inequality in scan data

Alipasha Vaziri *et. al.*

PRL submitted

Experimental violation of a qutrit Bell inequality

University Vienna



Collins, Gisin, Linden, Massar, Popescu, PRL 88:040404, 2002

Exp. Max = 2.90 ± 0.05

QT Max = 2.87

LocReal Max = 2

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Quantum Nature of Qubit Teleportation

- Bell Inequality Violation in Entanglement Swapping

Thomas Jennewein, Gregor Weihs, Jian-Wei Pan

Long-Distance Teleportation

Quantum Repeater

Teleportation of Entanglement

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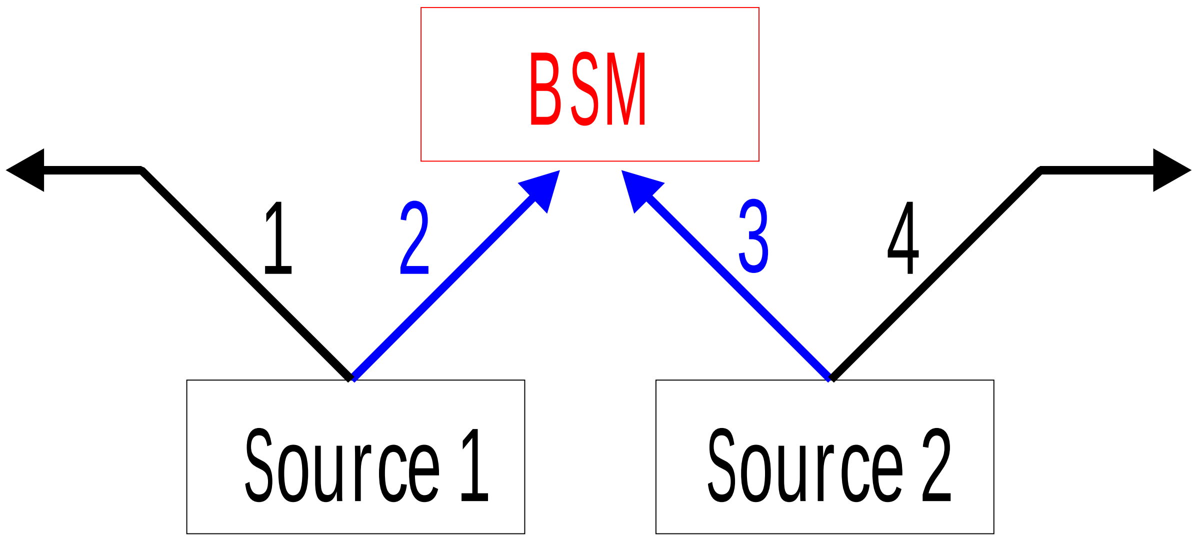
Start with 2 Independent Pairs



Photon 2 is Teleported to Photon 4

Photon 3 is Teleported to Photon 1

Experimental Arrangement

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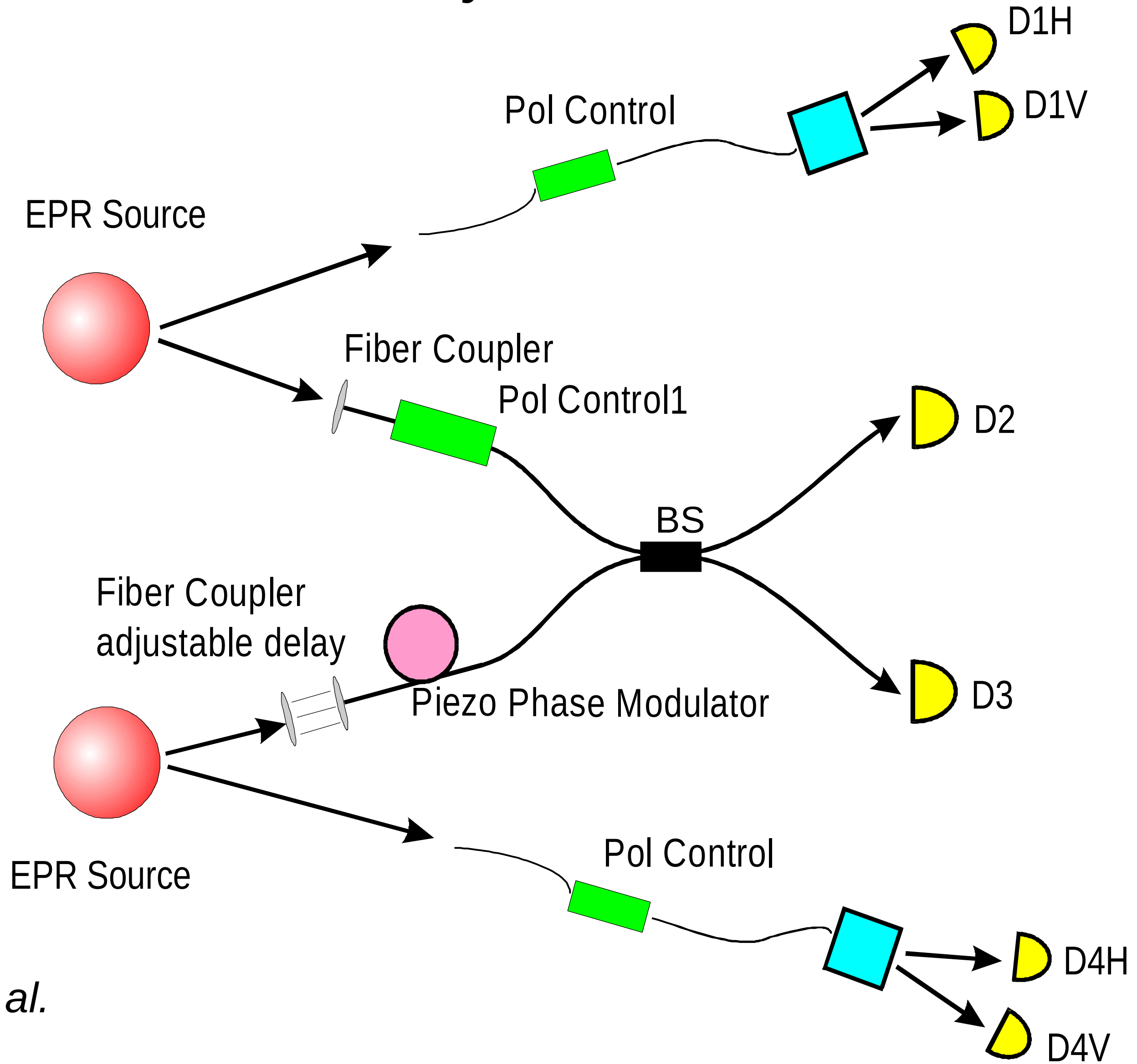
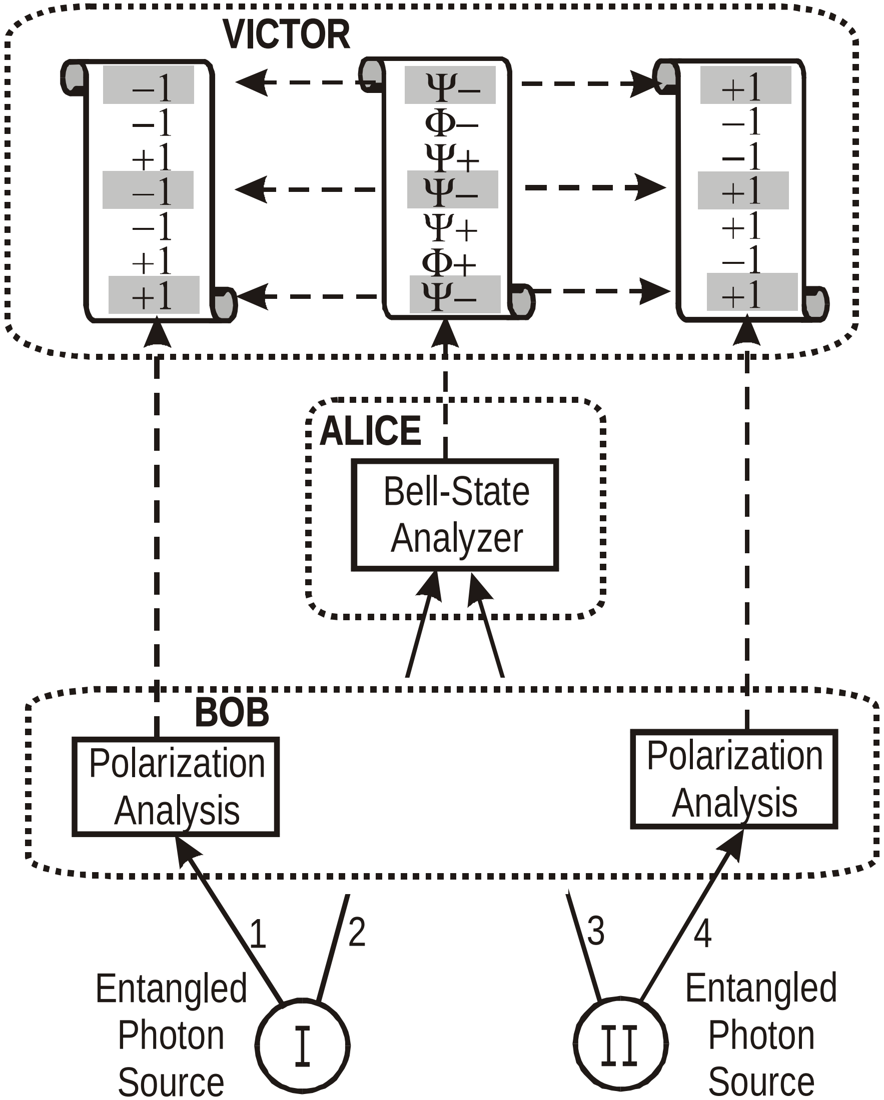
Fiber Based Bell State Analysis



Thomas Jennewein *et. al.*

PRL 88 (2002) 17903

Delayed – Choice Teleportation



Photon 1 and 4 Become Entangled after They Became Registered!

Relational Bits!

Testing Bell's Inequality with Teleported Entanglement

$$S(\alpha,\alpha',\beta,\beta') =$$

$$= \left|E(\alpha,\beta) - E(\alpha,\beta')\right| + \left|E(\alpha',\beta) + E(\alpha',\beta')\right| \leq 2$$

Experimentally

$$S(0°,45°,22.5°,67.5°) =$$

$$= \left|0.6281 - (+0.6766)\right| + \left|-0.5748 - 0.5407\right| =$$

$$= 2.420 \pm 0.091 \not\leq 2$$

Matter-Wave Interferences

- Electrons
- Neutrons
- Atoms
- Small Molecules

- Is there a Limit?
- Mass?
- Complexity?
- Temperature?

Macromolecule Interference

- New Dimensions – New Physics
- Nanoscale Lithography
- Quantum Interference for Biological Macromolecules
- Transition to Classical Objects?
- Decoherence Studies

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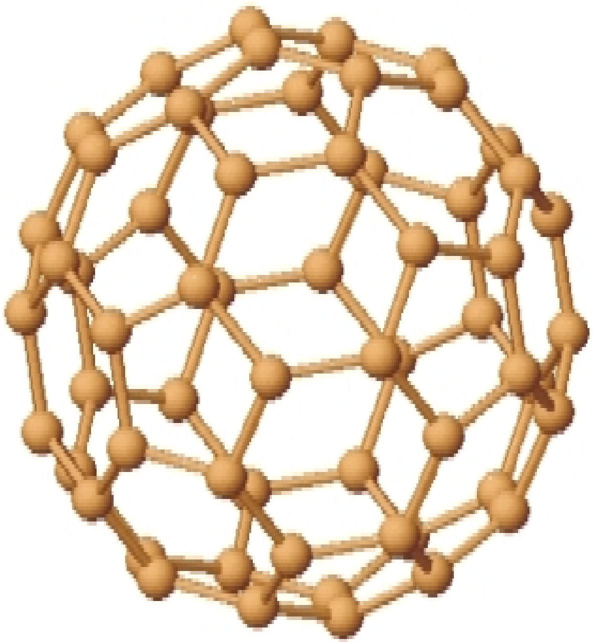
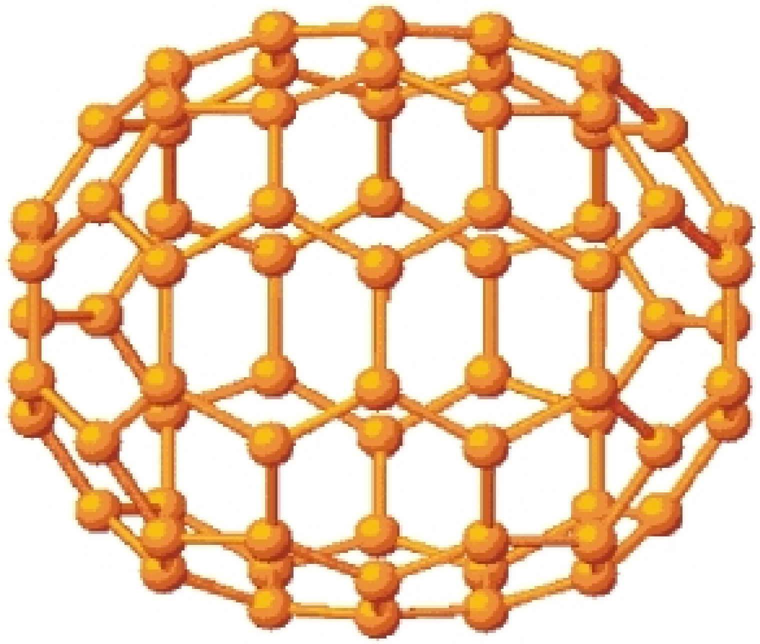
Fullerene Interference



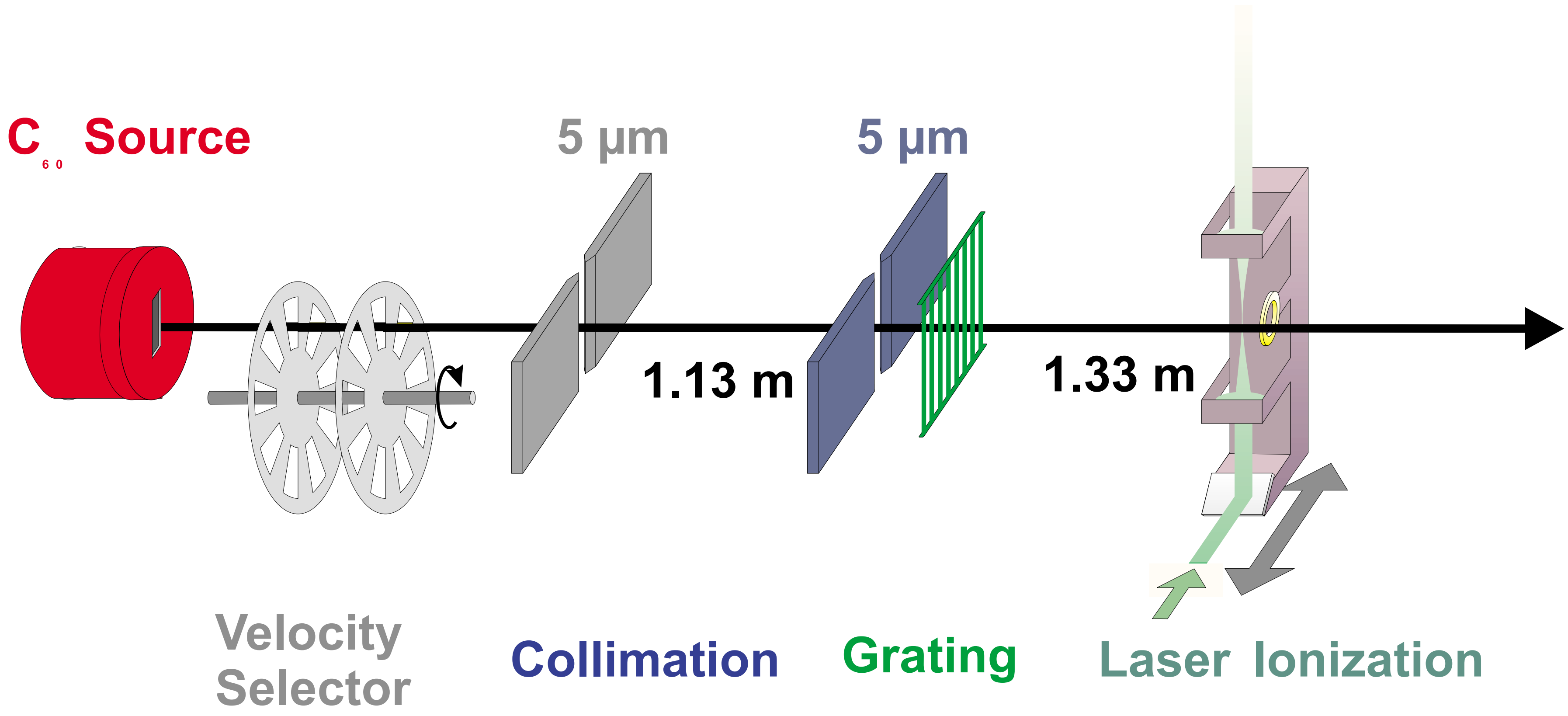
C_{60}



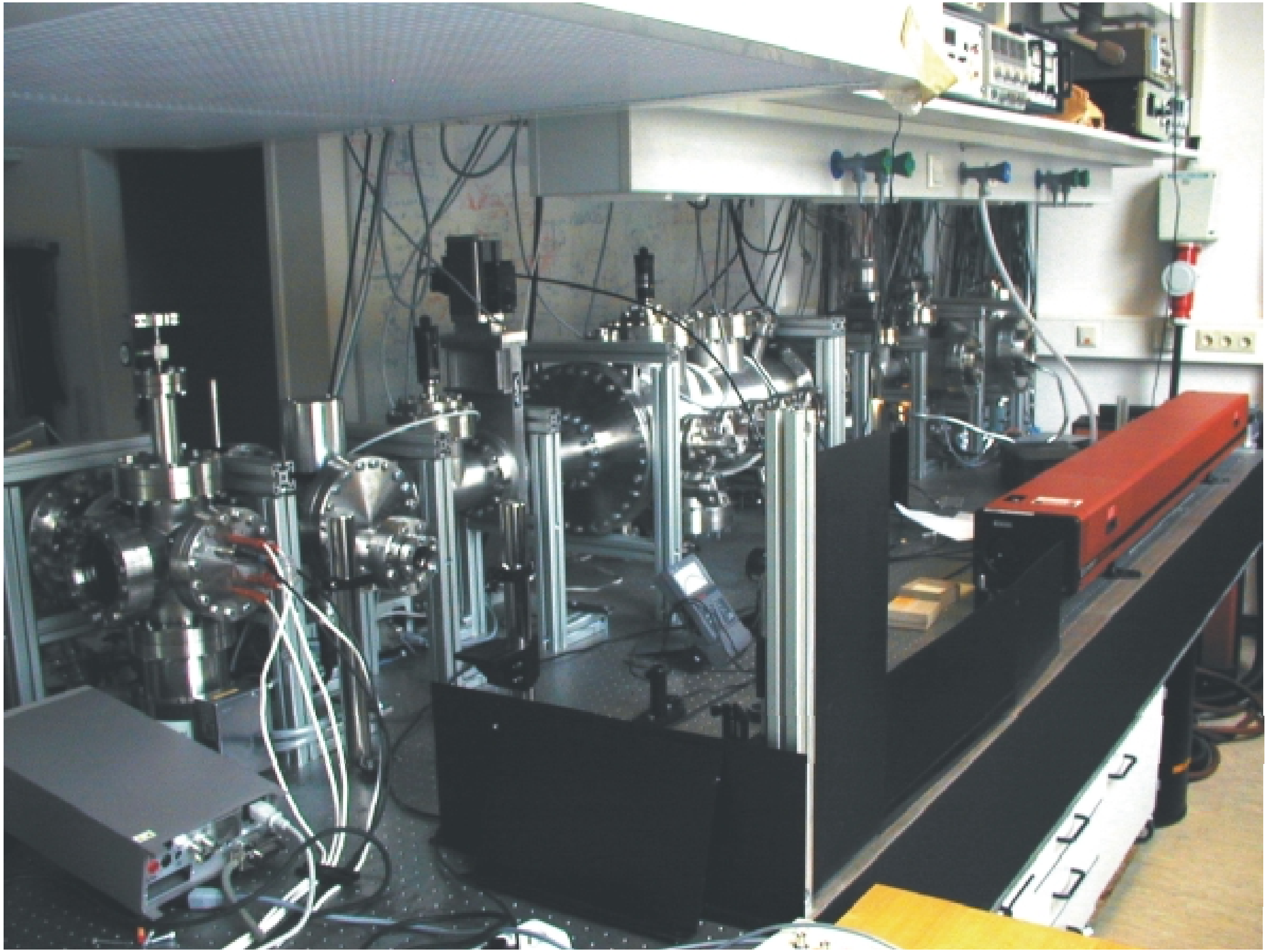
C_{70}

M. Arndt et. al. **Nature 401**, 680-682, 14. October 1999

Experimental Setup



The Laboratory



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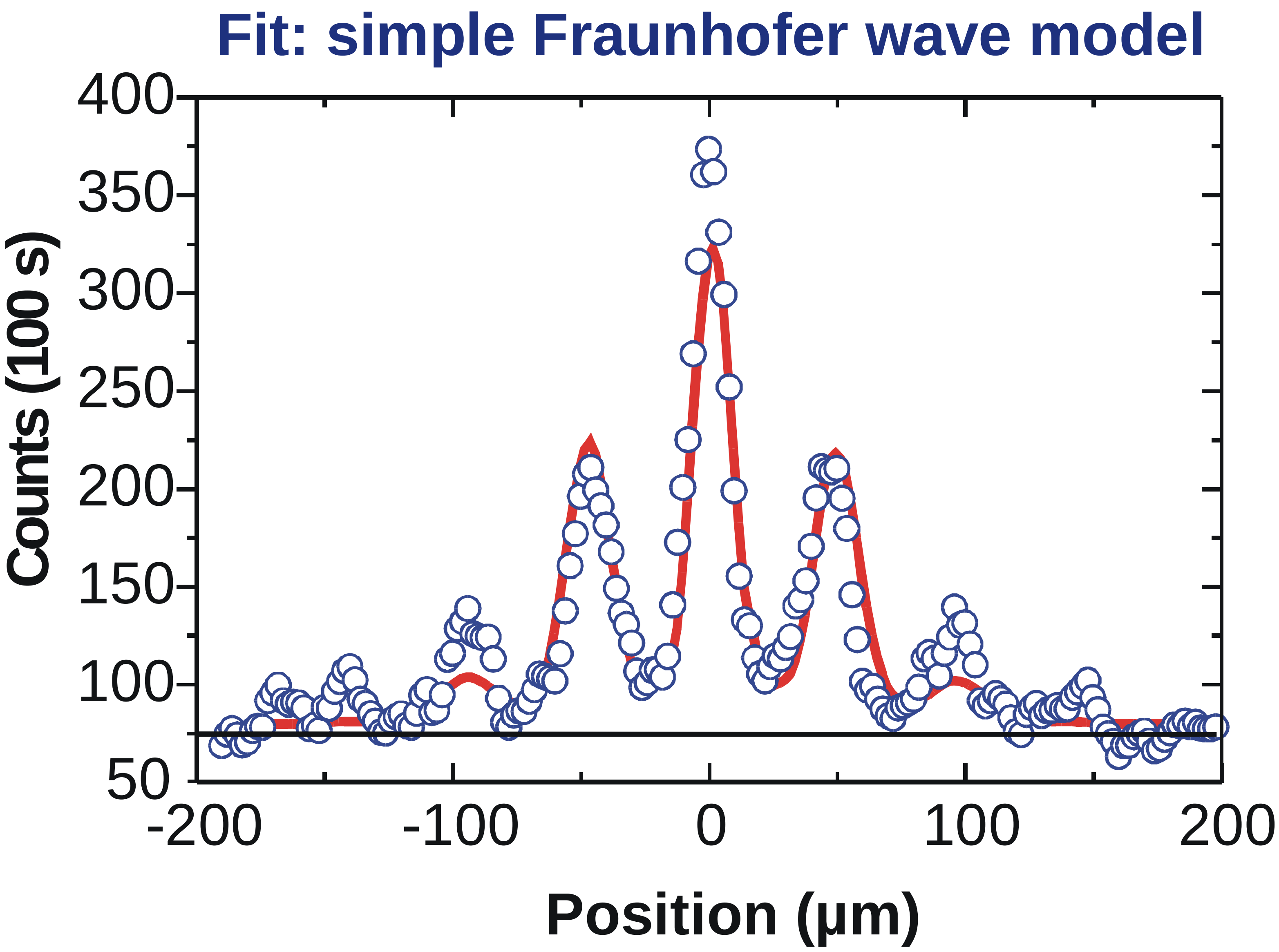
Fullerene Interference Pattern



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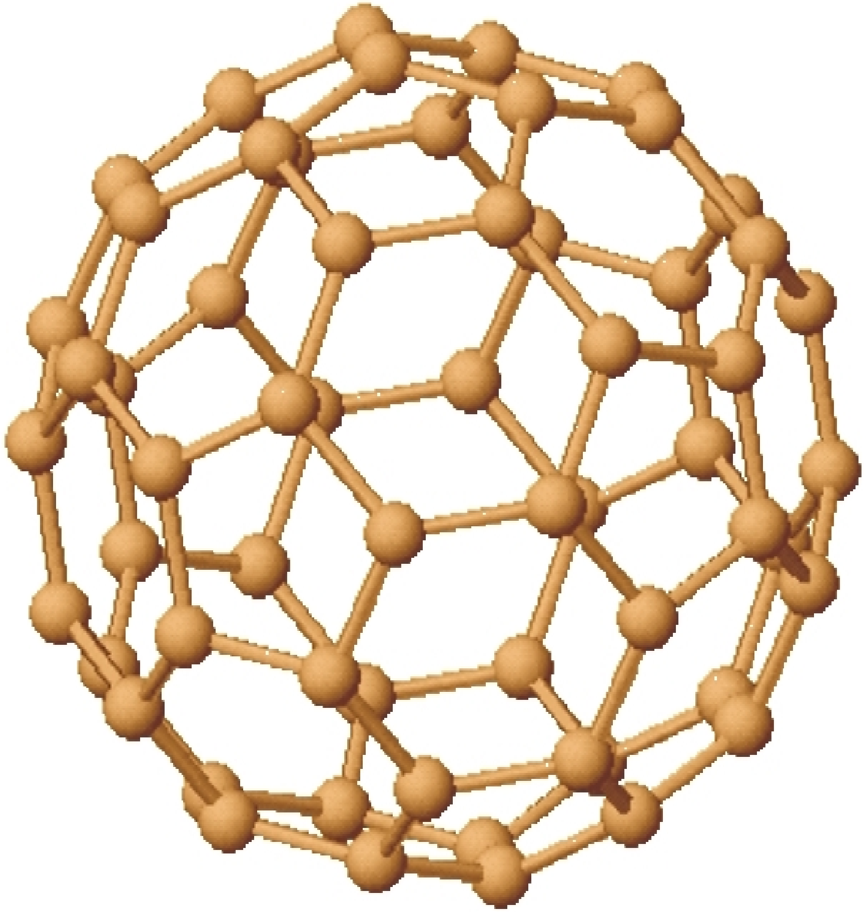
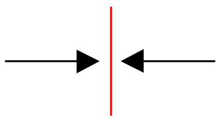
The Scale





$\lambda_{dB} \approx 3 \times 10^{-12}$ m

Diameter:
$C_{60} \approx 10^{-9}$ m

$\lambda_{dB} \ll D$

Coherence Length:
2 - 5 λ_{dB} !

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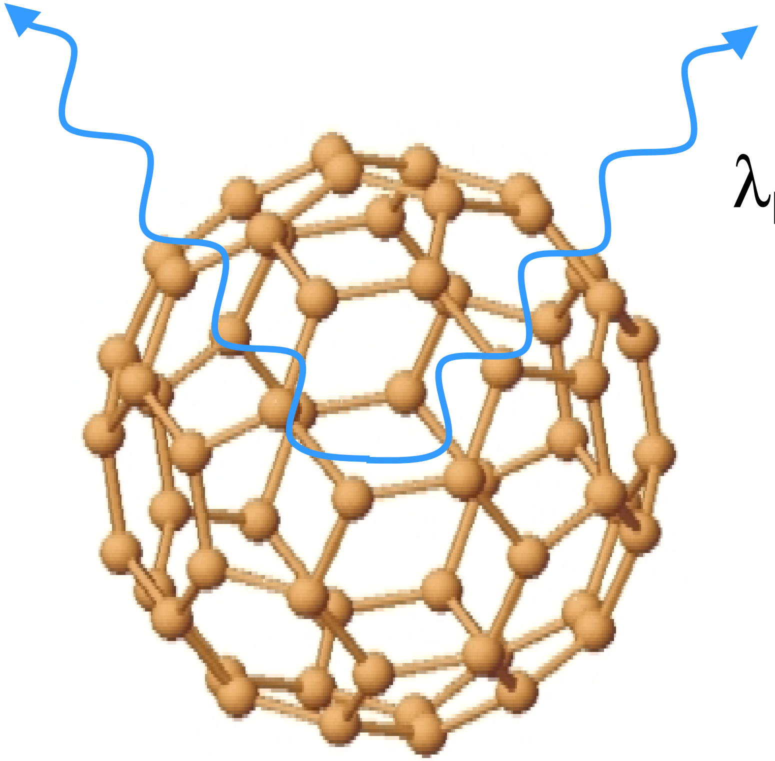
No Decoherence

T ≈ 900K

Many Internal Degrees of Freedom Excited!



λ_{Photon}

Single-Molecule Interference

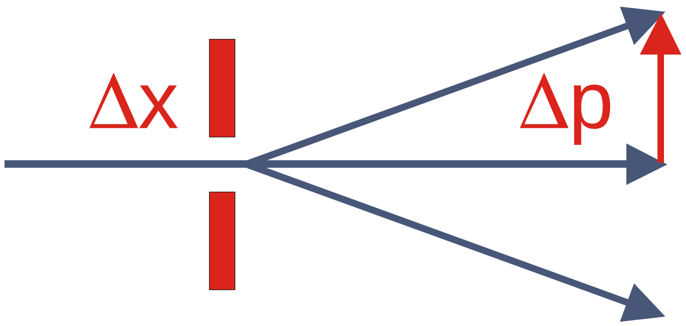
Why do we see Interference?

$\lambda_{Photon} >> $ Path Separation

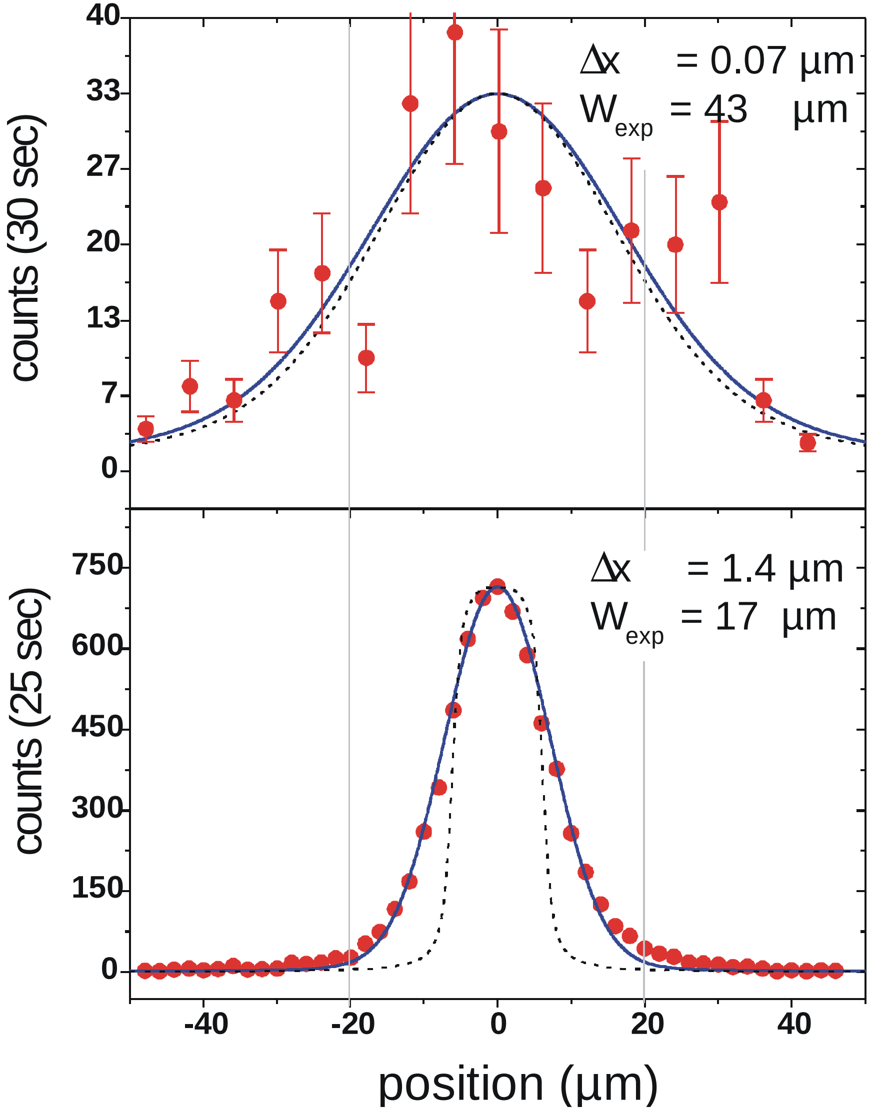
No Which-Path Information in Environment

Heisenberg Uncertainty for Macromolecules

- Measurement by Diffraction at a Narrow Slit
- Prepares Coherent Wave Fronts



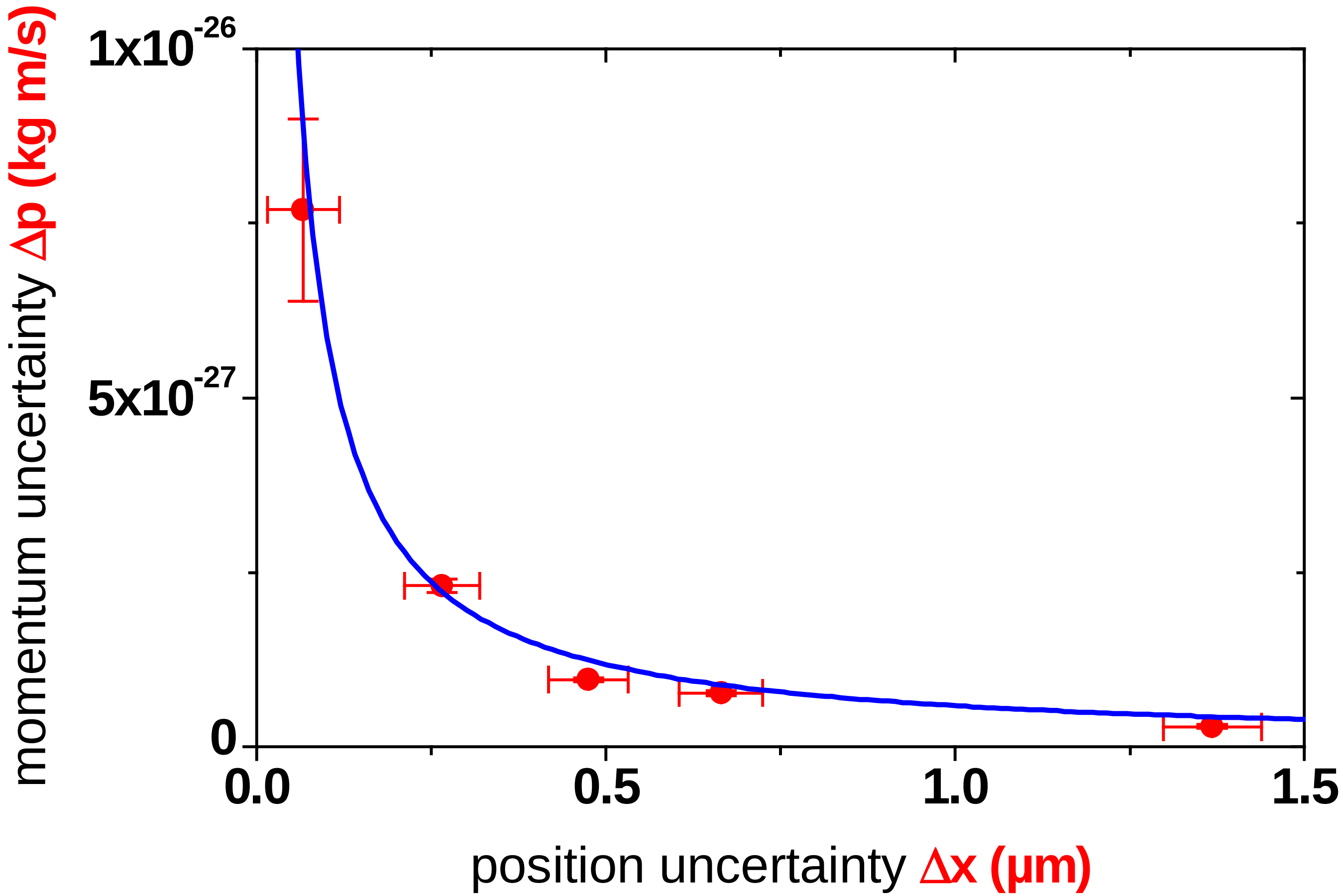
Experimental Results



Smaller Slit Width

Larger Momentum Spread

Heisenberg Uncertainty

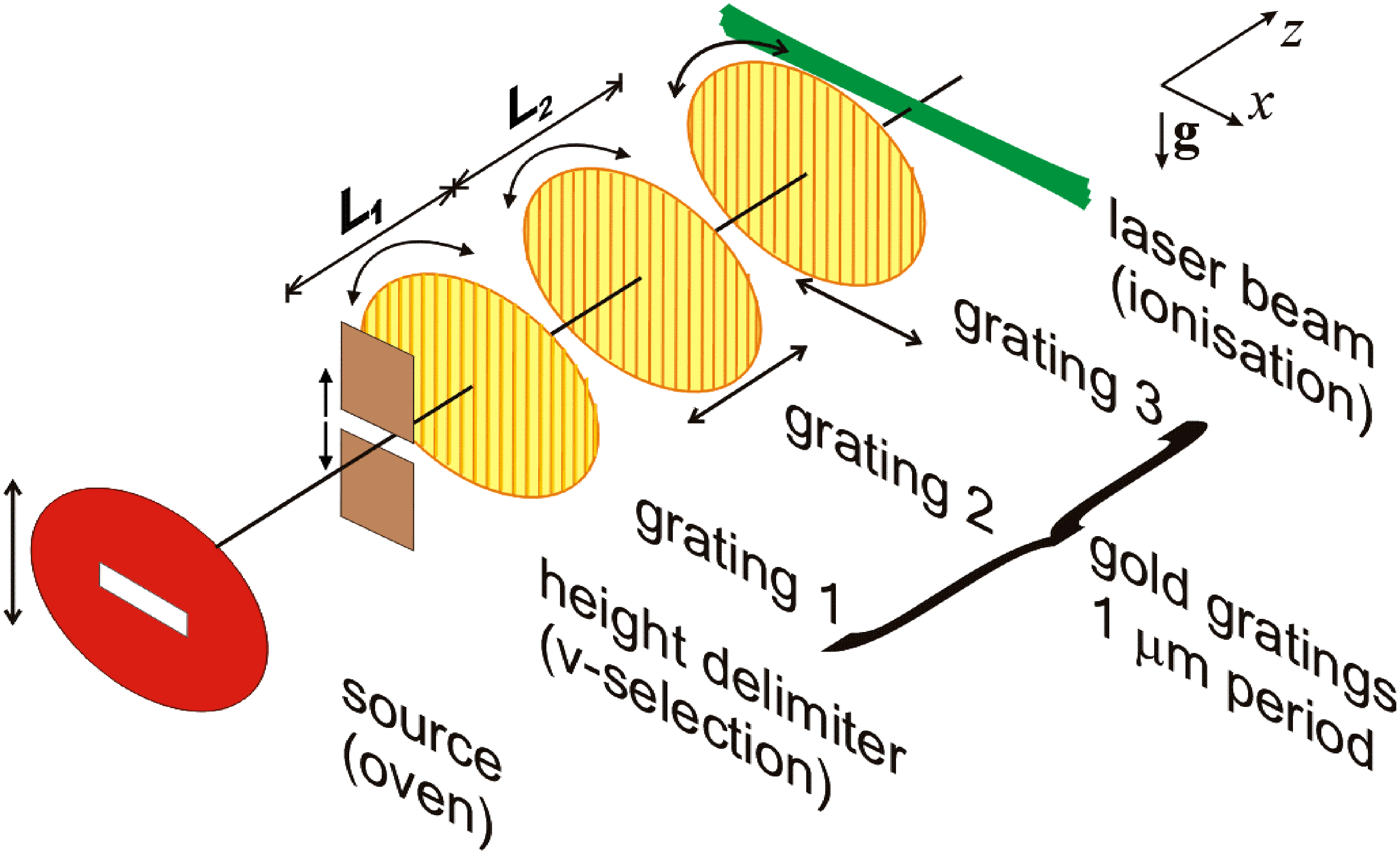


Talbot-Lau Interferometer

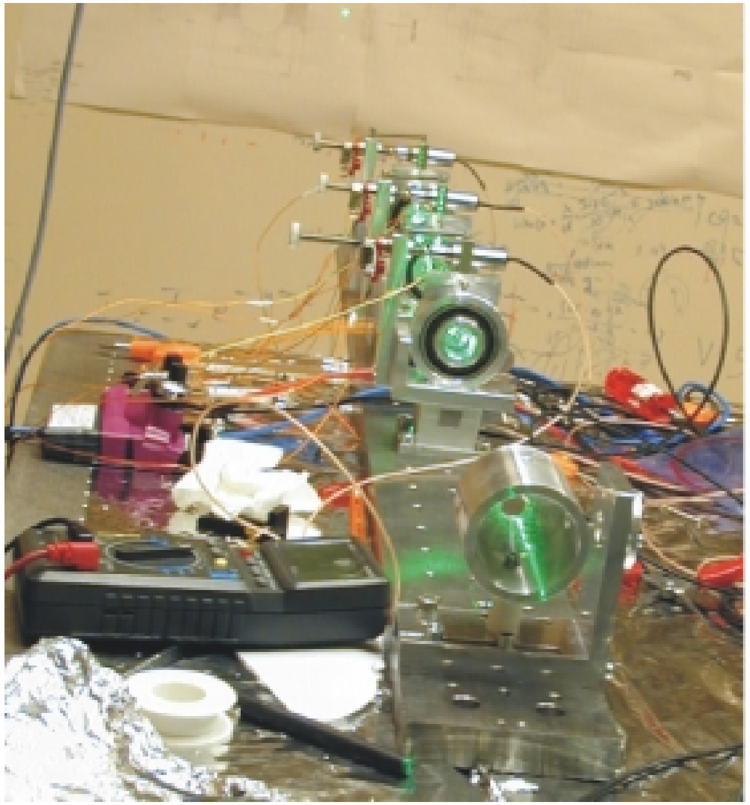
Near-Field interferometer for macromolecules

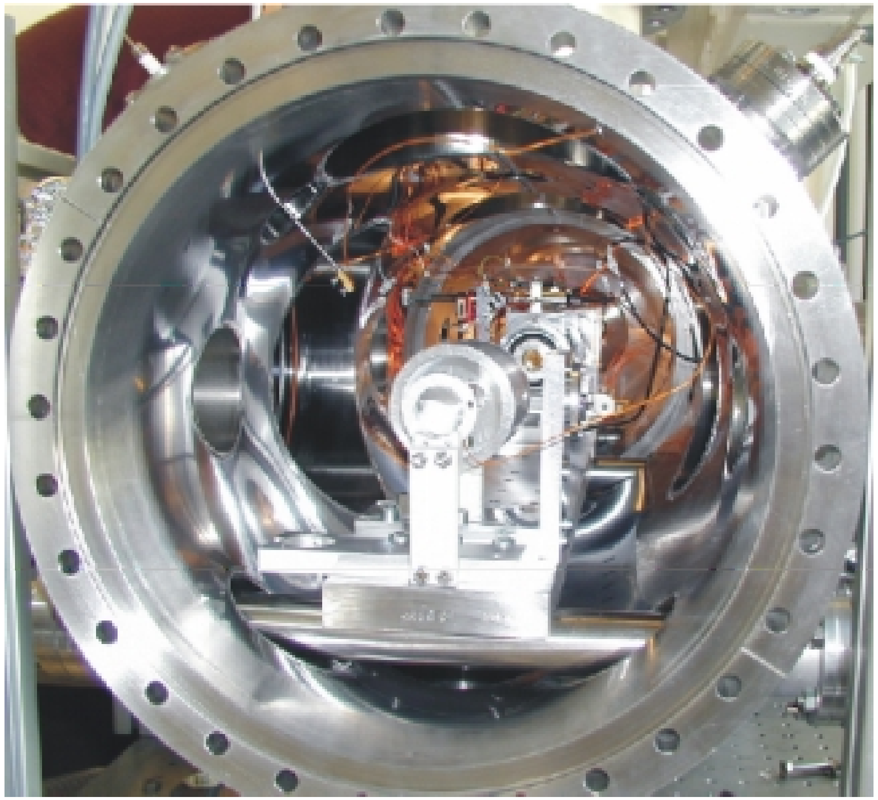
- **Decoherence studies**
- **Study influence of**
  - **van der Waals interactions**
  - **Collisions with rest gas**
- **Best choice for even larger macromolecules**
- **Scaling ~ sqrt (M)**

Talbot-Lau Interferometer



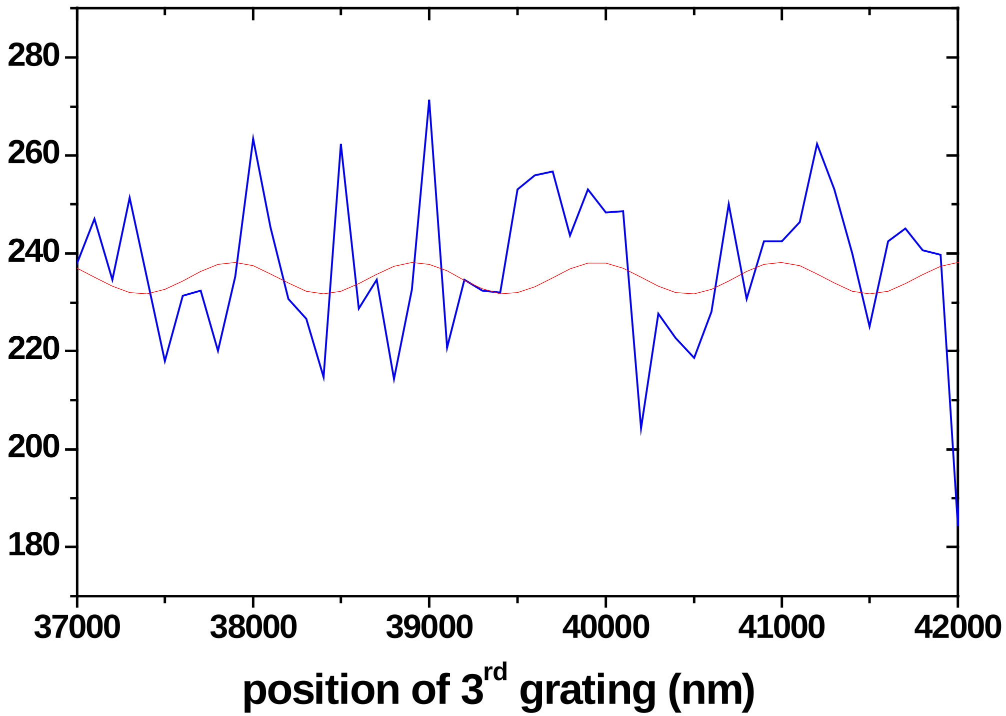
The Interferometer Setup



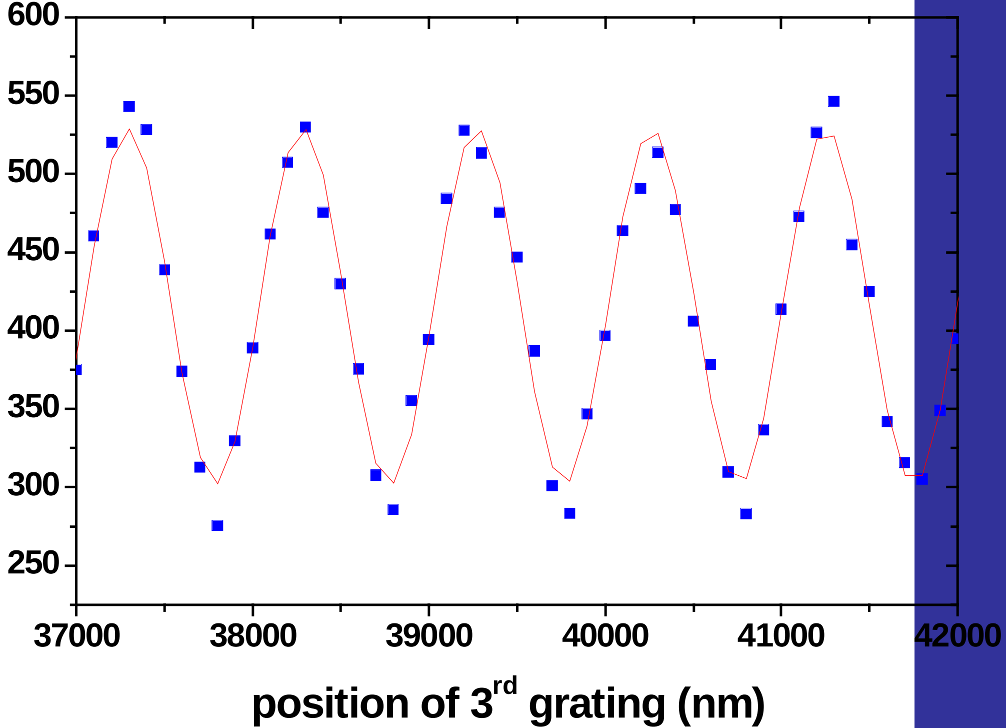


Interference Fringes

Optical table: down



Vibration isolation active!



Interference Fringe Contrast

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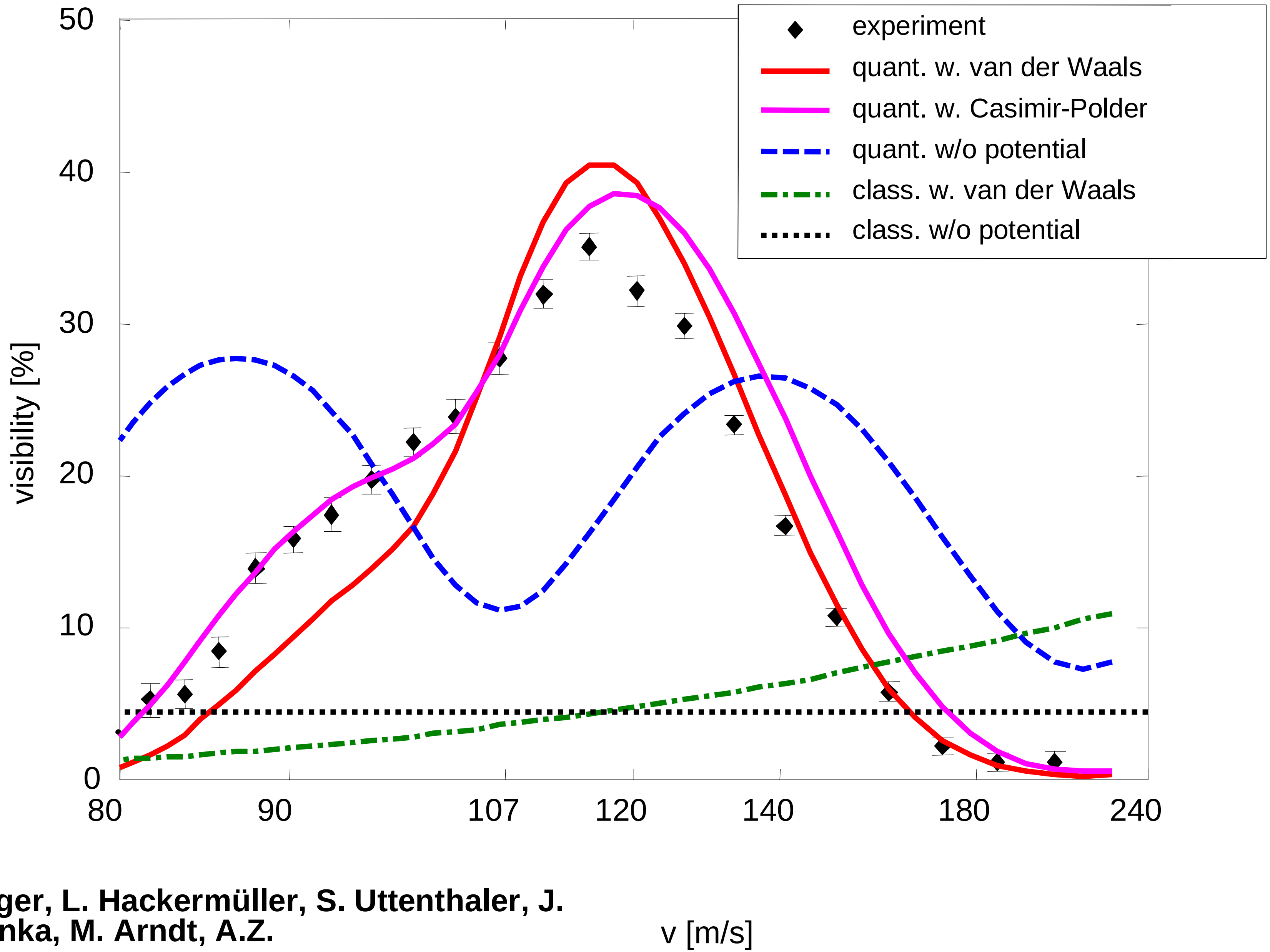

B. Brezger, L. Hackermüller, S. Uttenthaler, J. Petschinka, M. Arndt, A.Z.

Phys. Rev. Lett. 88, 100404 (2002).

Where is the Limit ?

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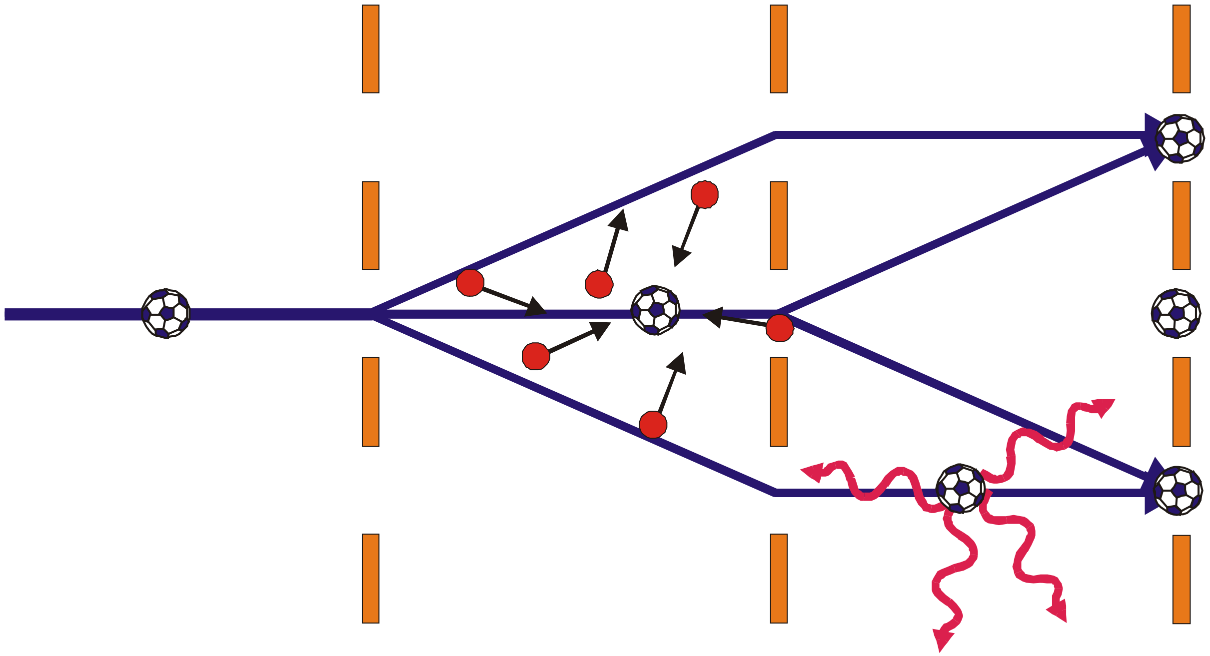
Collisional or Thermal Decoherence

Collisions with background gas



Emission and scattering of photons

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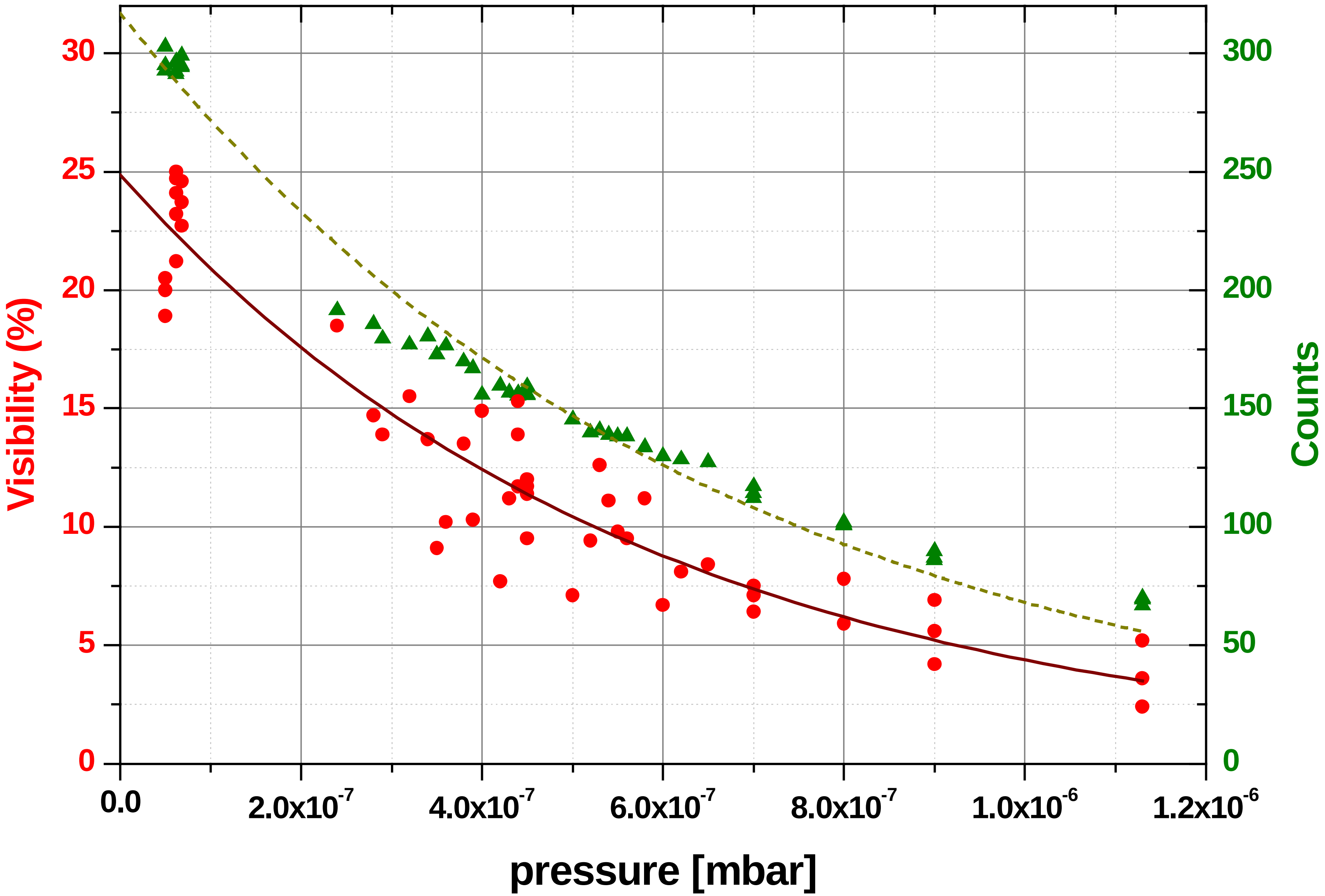
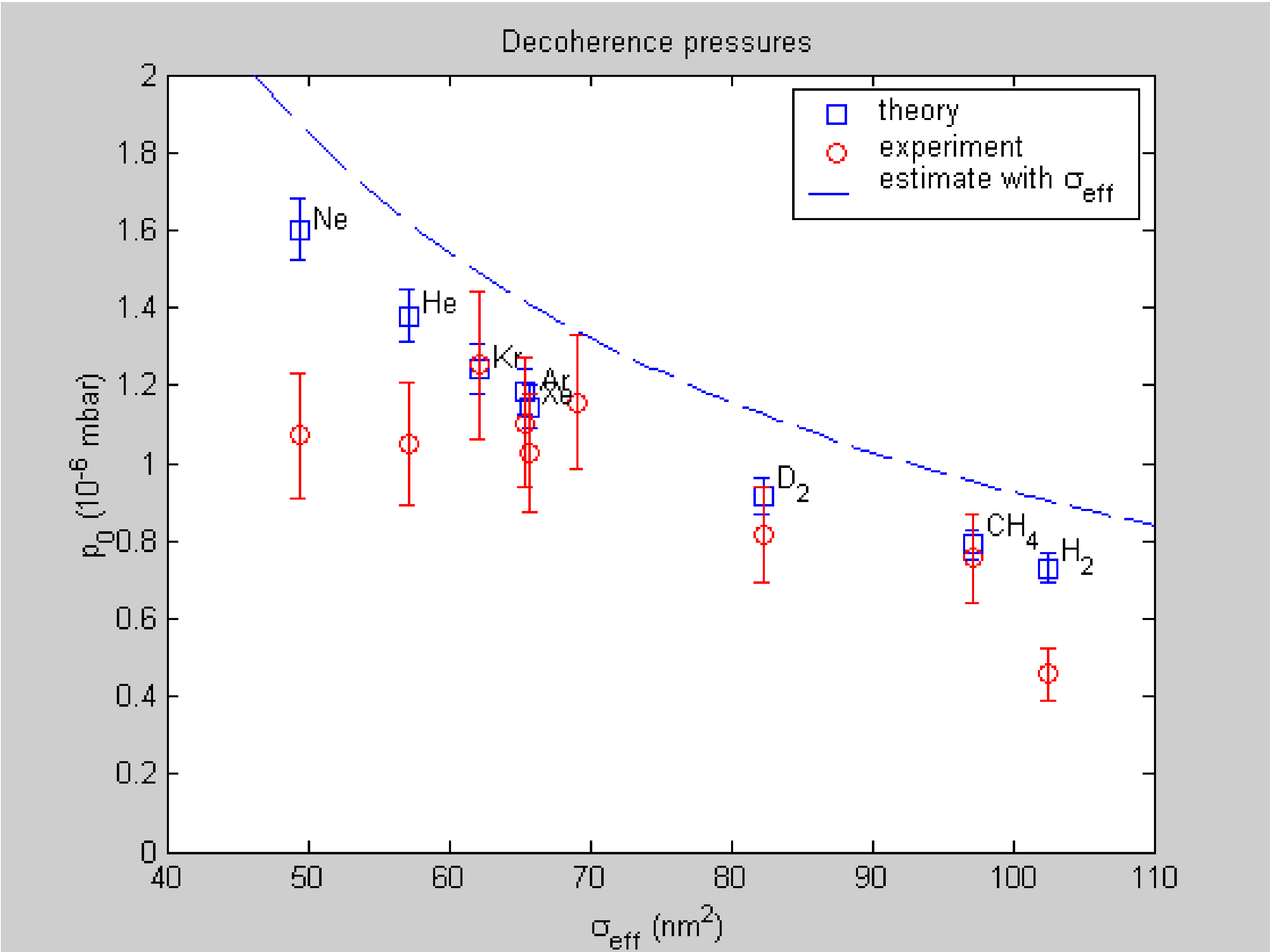
Collisional Decoherence



Collisional Decoherence



Thermal Decoherence by Photon Emission

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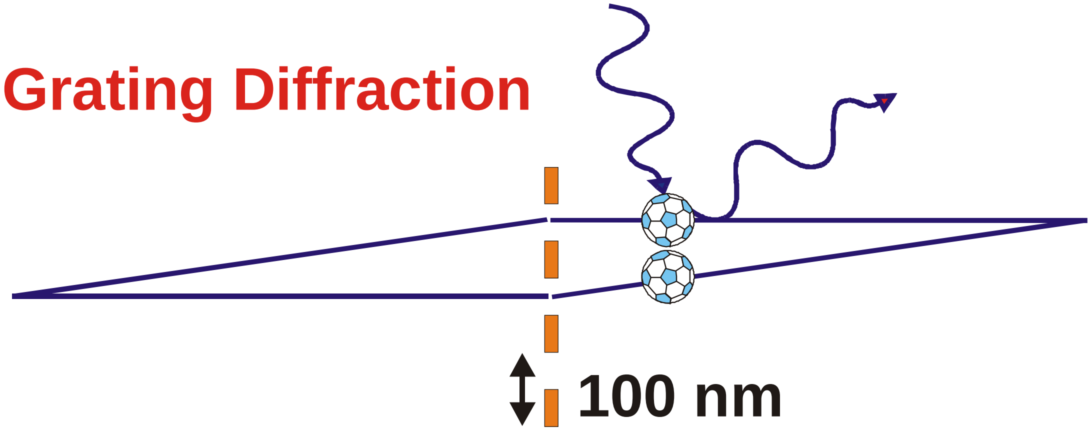
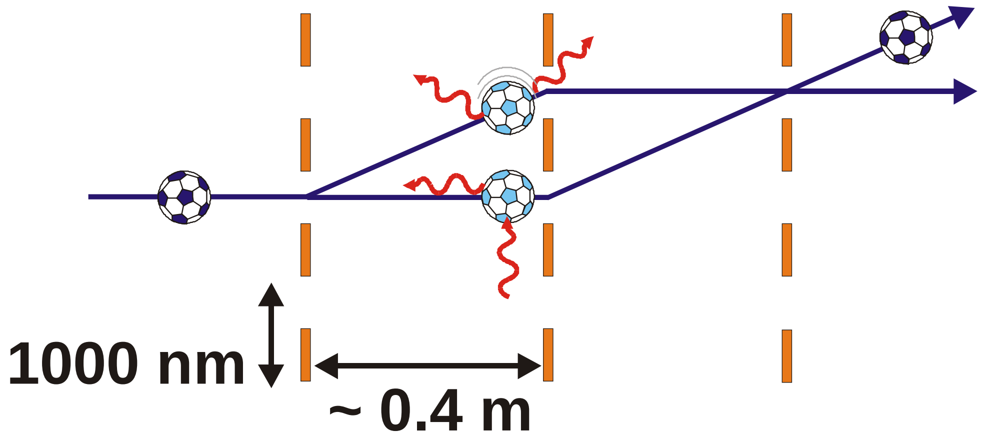
Grating Diffraction



Up to

T ~ 3000 K!

Talbot-Lau Interferometry



Thermal Decoherence by Photon Emission

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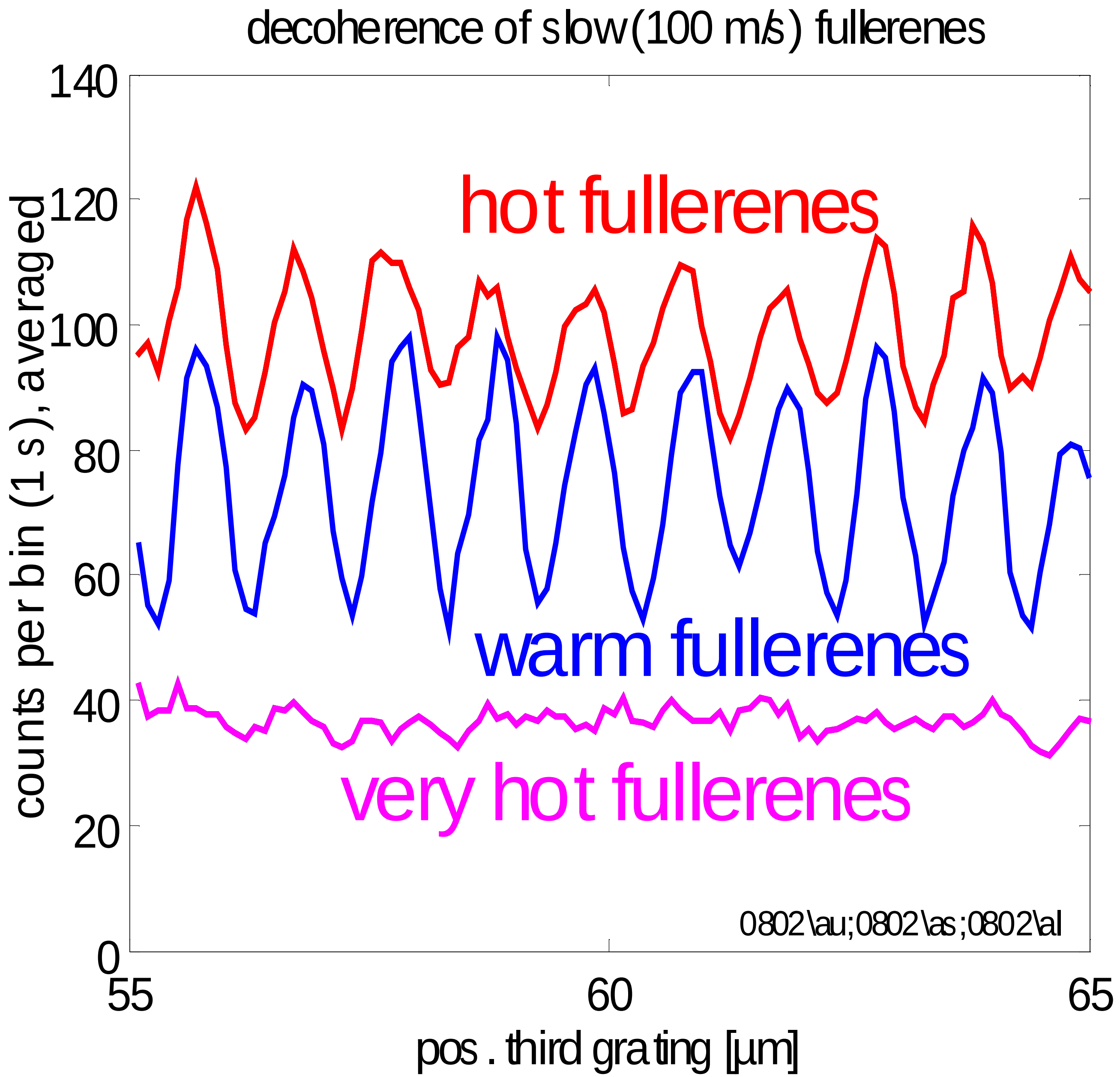

Biomolecule Interference

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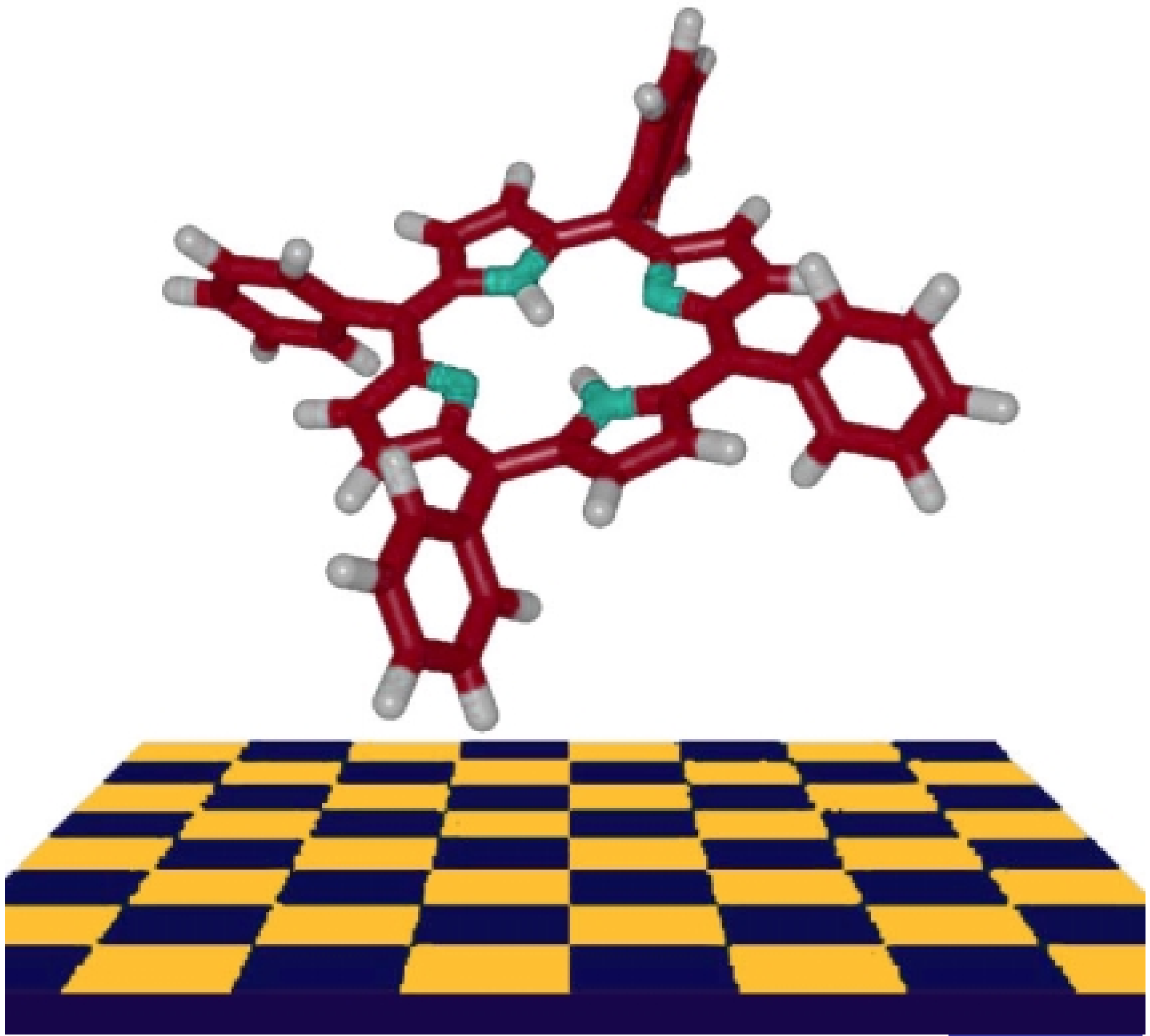
Porphyrin

A = 614 amu

- **Meta-Tetraphenyl-Porphyrin**
- **Formula: $C_{44}H_{30}N_4$ (TPP)**
- **Mass: 614 amu**
- **Planar central structure**
- **Tilted phenyl rings**
- **228 vibrational modes!**



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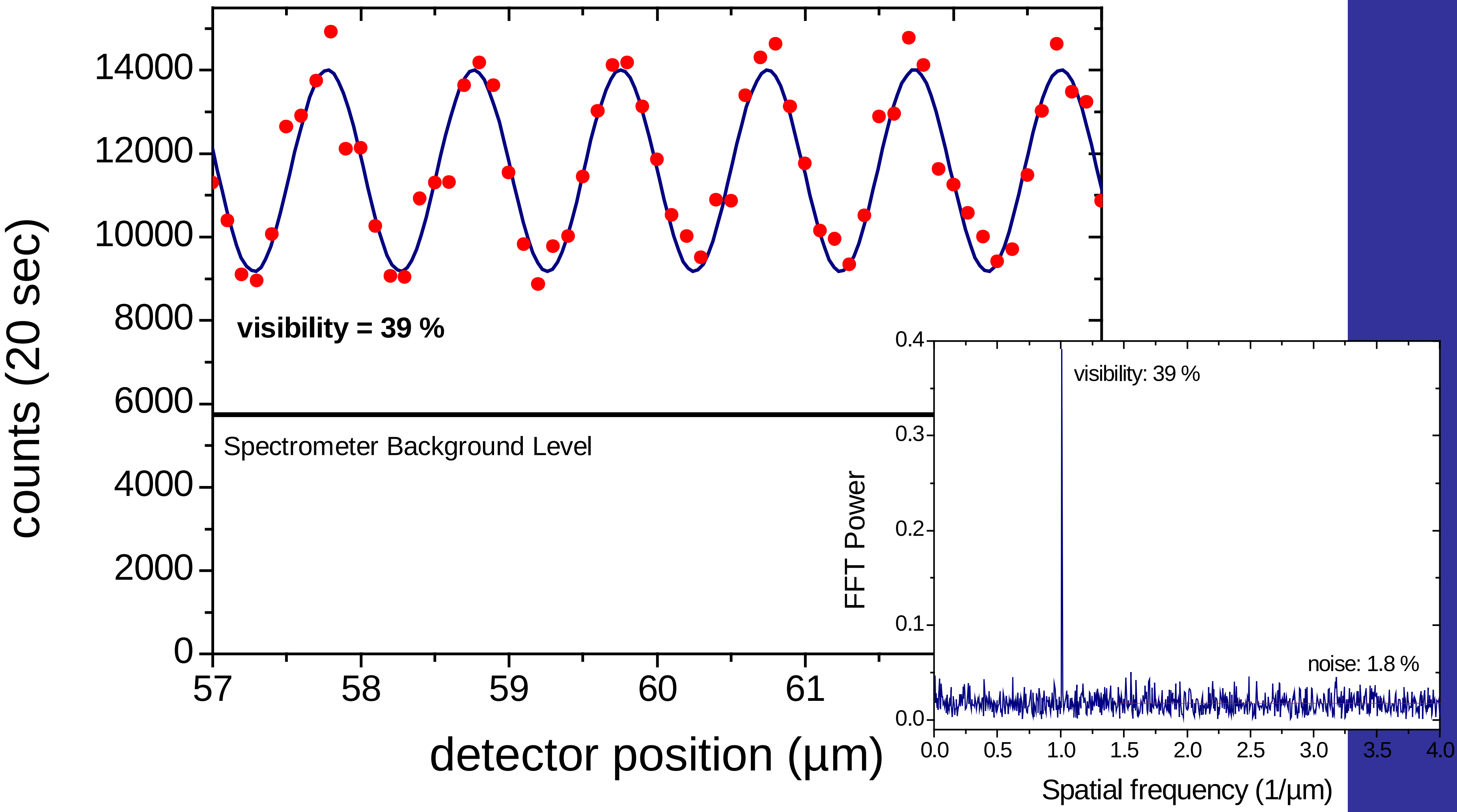
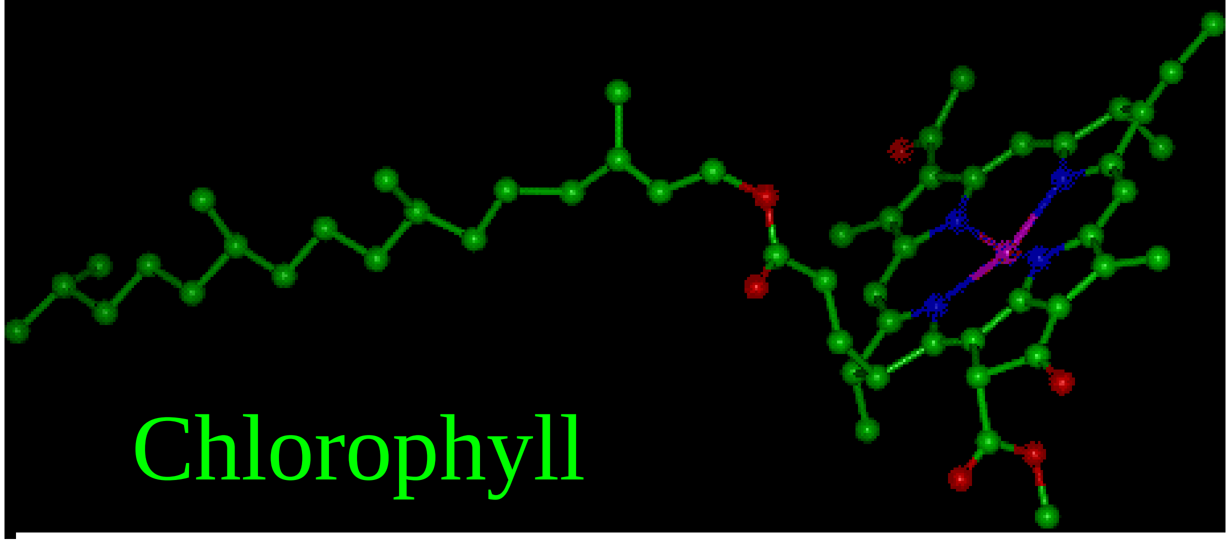
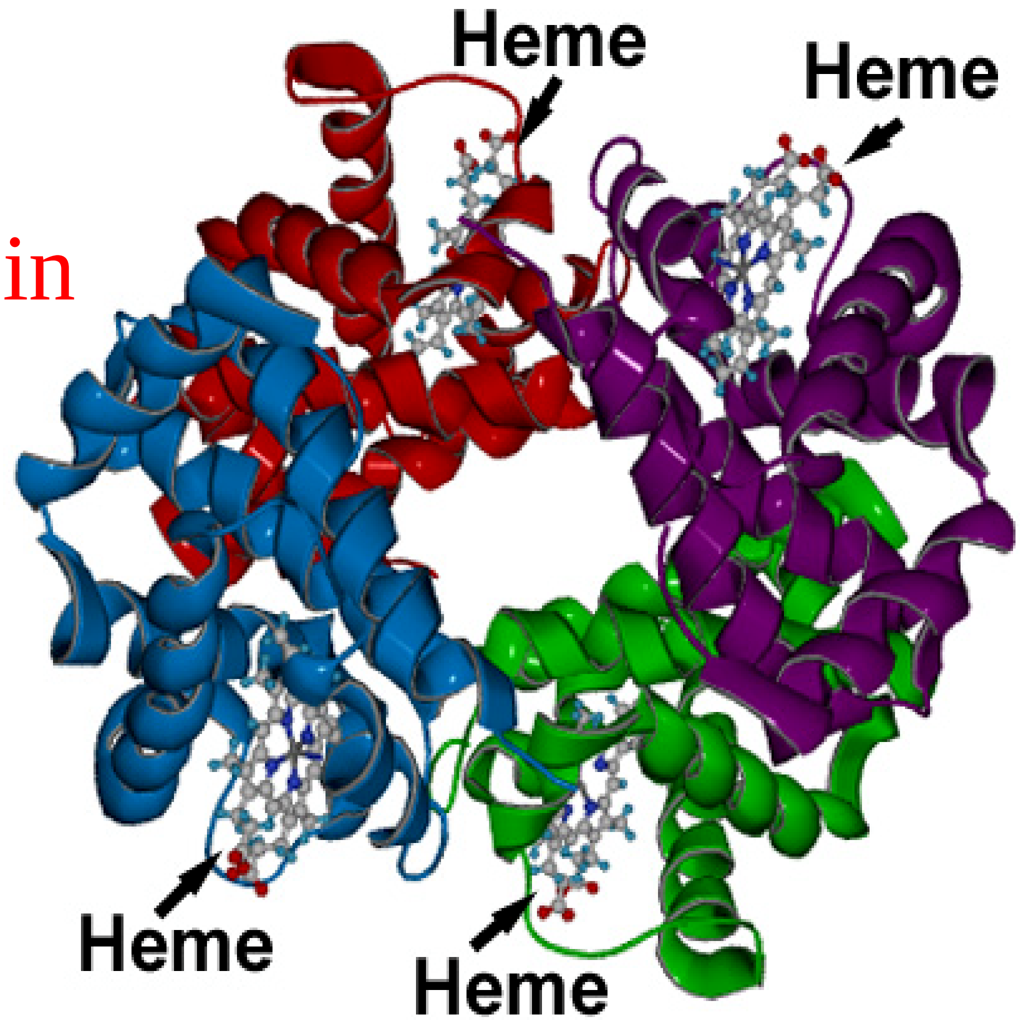
Porphyrin Interference

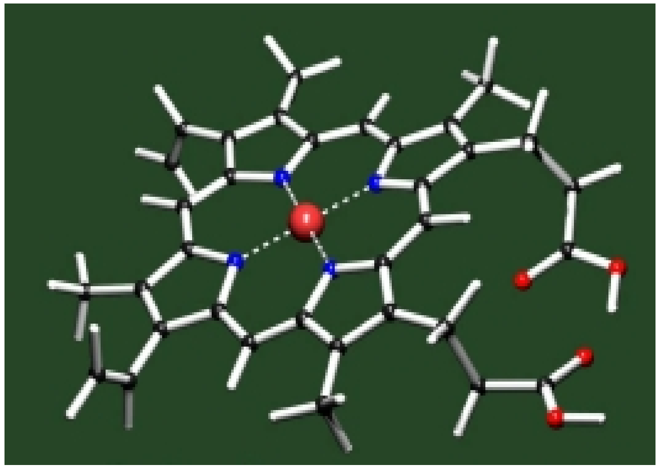


The Role of Porphyrin



Hemoglobin





Heme

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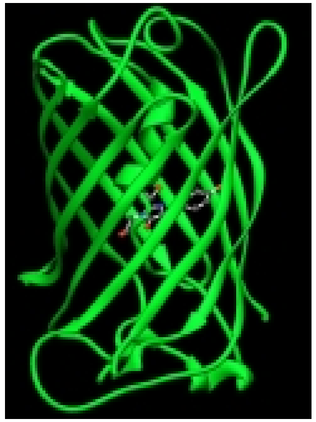
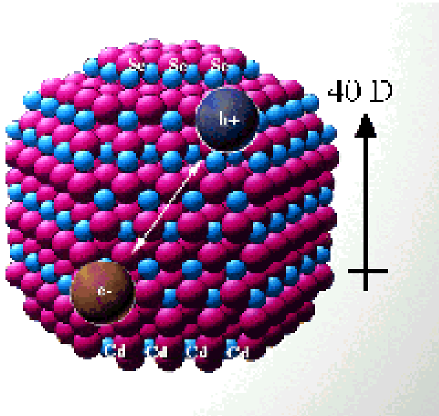
Are there Limits for Macroscopic Matter Waves?

Mass?

Complexity?

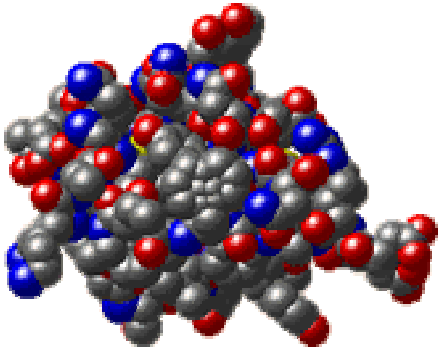


GFP
(~ 27 kDa)



CdSe nanocrystal
(> 10 kDa)

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



Insulin
(~ 6 kDa)

The Molecule Group

University Vienna

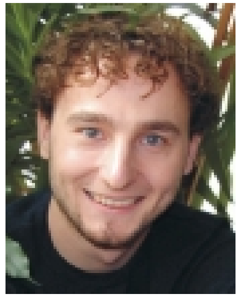
Keller

Nairz

Arndt

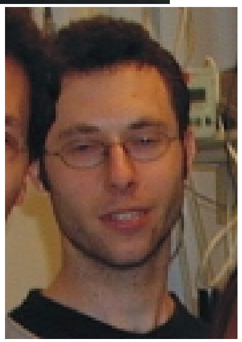
?

Stibor



Voss-Andreae

Hornberger



v.d. Zouw

Petschinka

Hackermüller

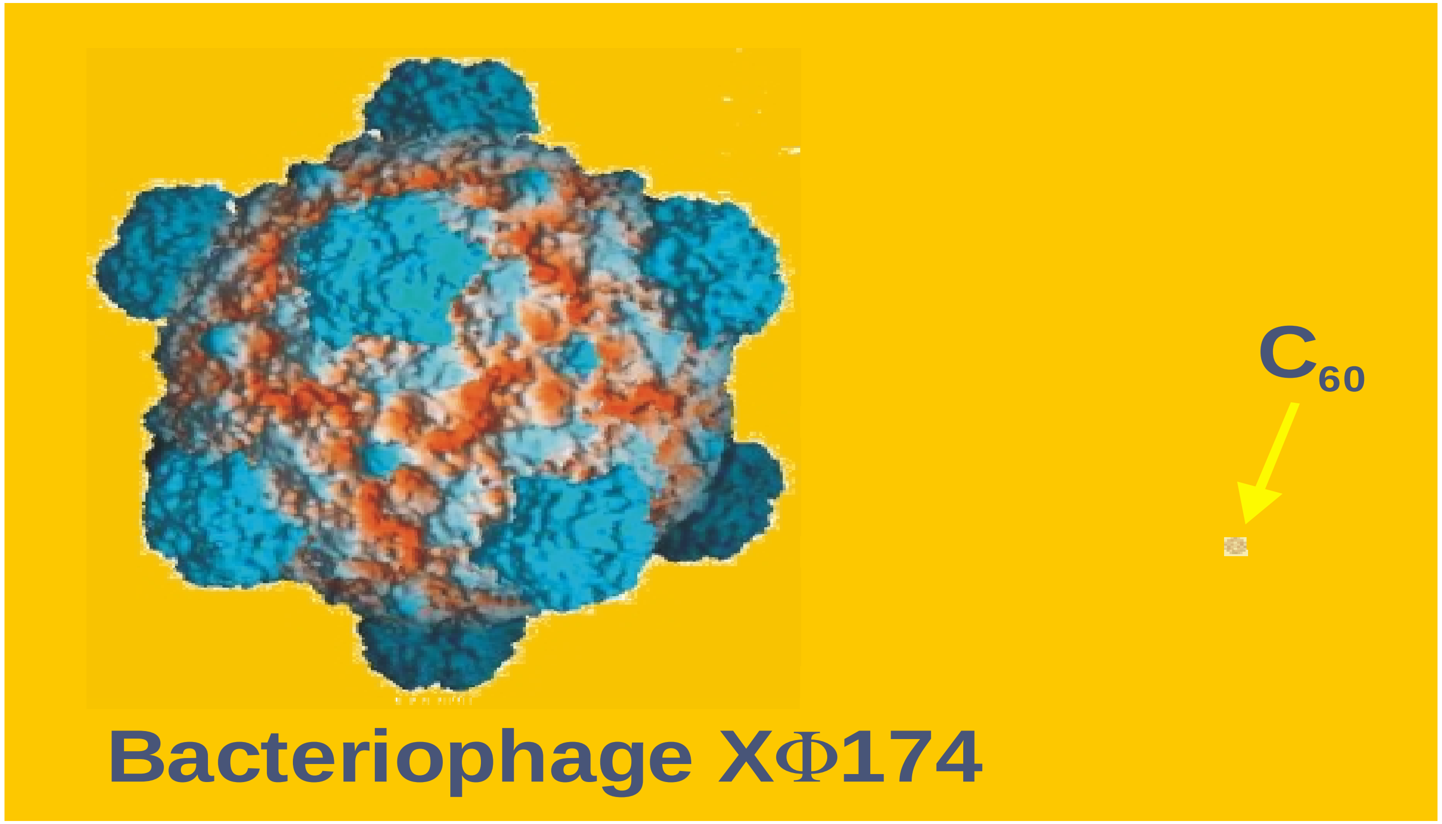
Brezger

Uttenthaler

Reiger

Our Phantasy ???

University Vienna



WANTED

Erwin Schrödinger

DEAD AND ALIVE


USE BOTH EXITS
WHEN LEAVING
THE
PARKING STRUCTURE