Title: Nanoparticle interferometry: experimental tests of the quantum superposition principle at high mass and complexity.

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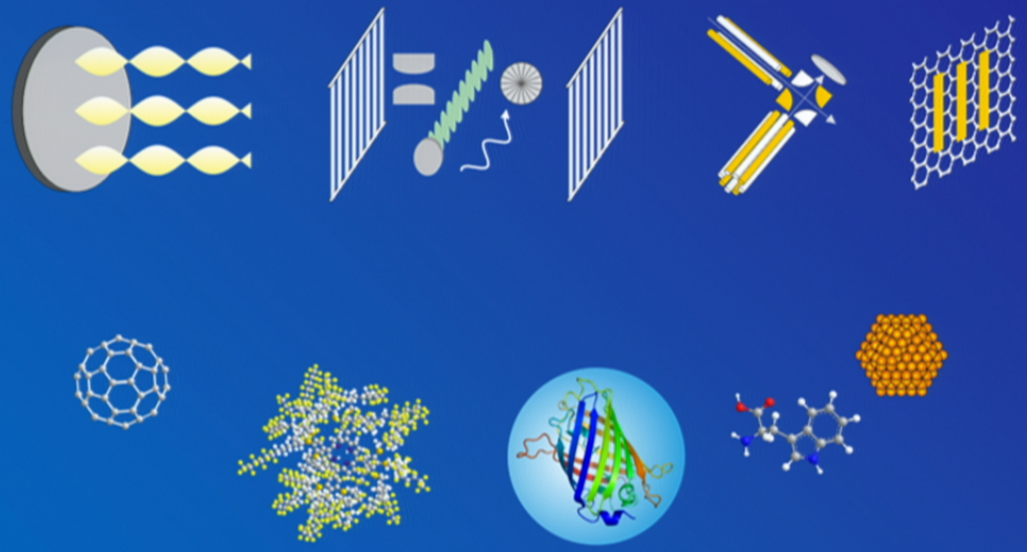
URL: http://pirsa.org/13050067

Abstract:

Nanoparticle interferometry



Experimental tests of the quantum superposition principle

Markus Arndt
University of Vienna, Quantum Nanophysics Group
www.quantumnano.at

Quantum physics is everywhere in our life !

- **Chemistry:**
  Stability of matter

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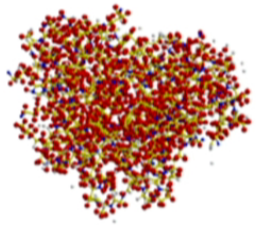
- **Chemistry:**
  Stability of matter
- **Medical tomography:**
  Nuclear spin in magnetic imaging
- **Photovoltaics:**
  Photo effect: light comes in packets
- **Laser:**
  Bose statistics
- **Clocks & GPS :**
  Atomic quantum states
- **Medical sciences:**
  Wave nature of neutrons in protein crystallography



Why does quantum physics still surprise us?

Everyday world	Quantum world
Objects always in defined states	Quantum superpositions
Subjective chance	Objective randomness
All interactions are local	Information can be non-local
Reality	Potentiality ?

The Quantum Superposition Principle is …
A Basis for Emergent Quantum Technologies

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- **Matter-wave based Quantum Sensors**
  - **Electron:** ultra-weak magnetic fields, surface structures, SQUIDS
  - **Atoms:** gravity, geodesy & navigation, test of GRT
  - **Molecules:** metrology on (bio)molecules and nanoparticles

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- **Q-Computers & Q-Simulators, Q-Cryptography, …**
  - "Quantum bit $\alpha|0\rangle + \beta|1\rangle$" rather than "classical bits 0 or 1"
    → expect enormous speed-up caused by quantum superposition
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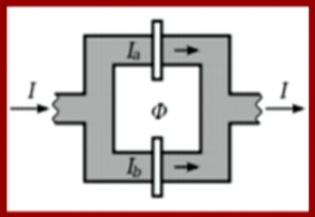
- **Quantum effects in biology?**
  - Information processing (magnetic orientation of birds, sense of smell..)
  - Models for solar energy harvesting?

How macroscopic can a quantum system be?

- # Electrons: $< 10^{14}$
- Temp.: 1 mK ... K



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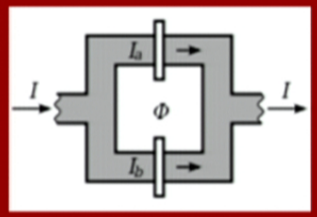

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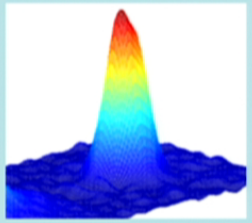
- λ_{dB} : single atoms

  unless entangled ...



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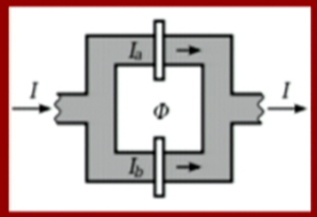

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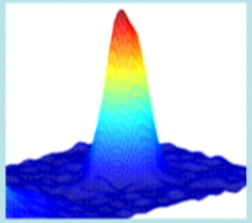

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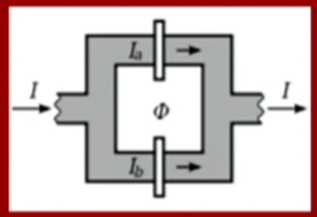

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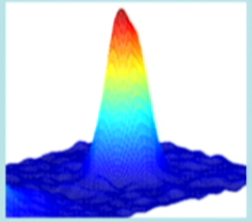

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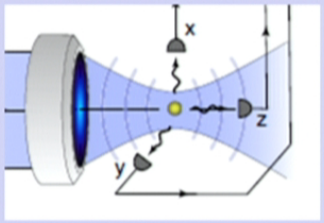

Nanospheres
(not yet quantum)

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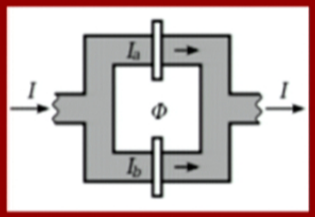

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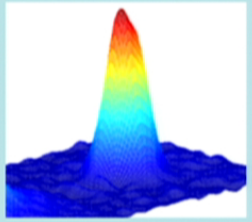

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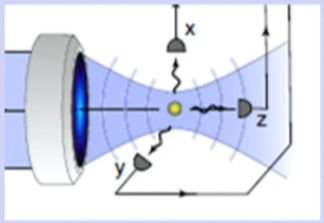

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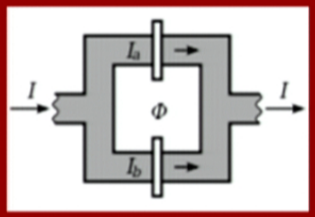

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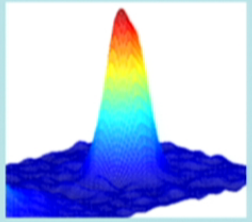

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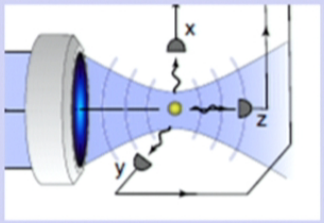

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- High mass: pg ...ng
- Temp.: µK ... mK

Nano-Oscillators

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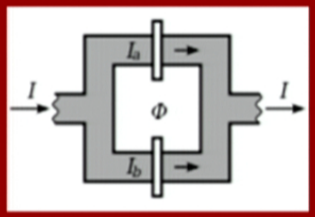

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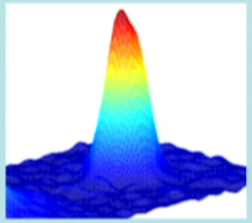

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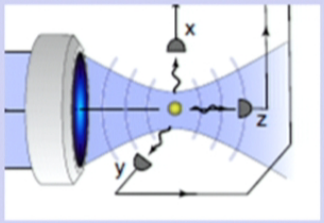
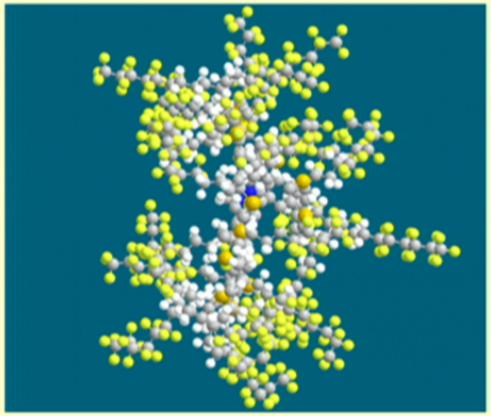


Nanospheres
(not yet quantum)

- High mass: pg ...ng
- Temp.: µK ... mK

Nano-Oscillators

- # of Atoms: 1 ... 10^3... 10^6
- Temp.: 4 K .. 1000 K
- λ_{dB}: entire complex



Macromolecules

Today !!

So far: Schrödinger's wave equation … holds all tests

$$i\hbar \frac{\partial \psi}{\partial t} = H\,\psi$$

It is not „written in stone“

Erwin Schrödinger‘s grave in Alpbach

I'm inclined to put my money on the idea that if you push quantum mechanics hard enough it will break down and something else will take over – something we can't envisage at the moment.

Sir Anthony Leggett
cited in New Scientsts 2010

Matter waves physics – "the heart of quantum physics"
Illustrates many relevant quantum effects

Louis de Broglie

$$\lambda_{\mathrm{dB}} = \frac{h}{m \cdot \mathrm{v}}$$

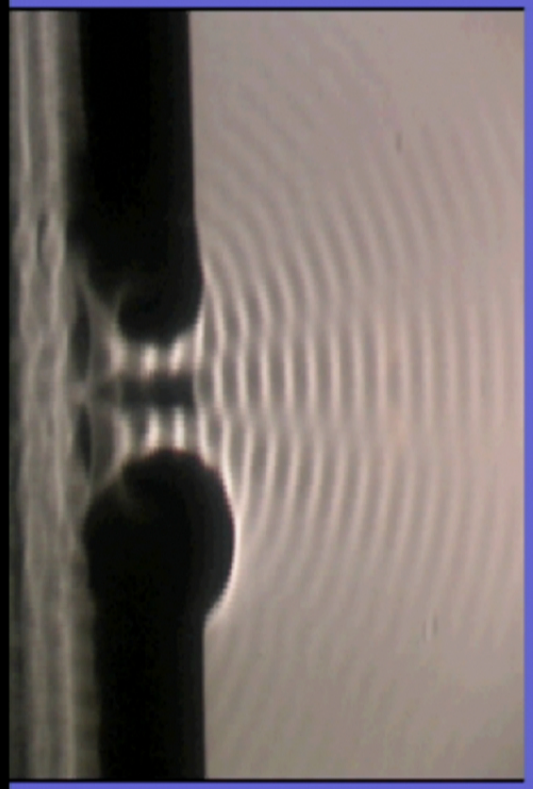
Erwin Schrödinger

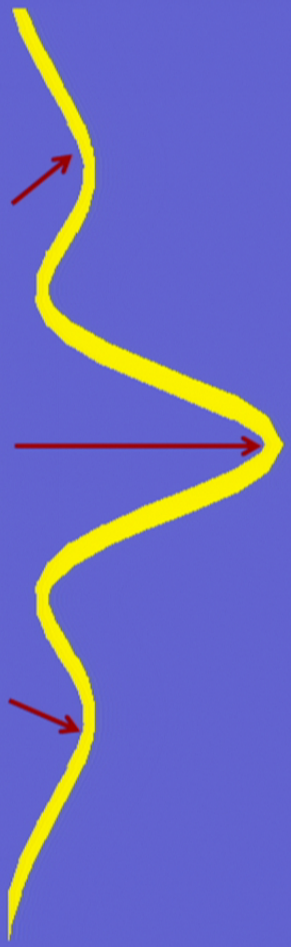
Formalization

Davisson/Germer/Thomson

Experimental verification

The „smoking gun“ of wave phenomena: Interference





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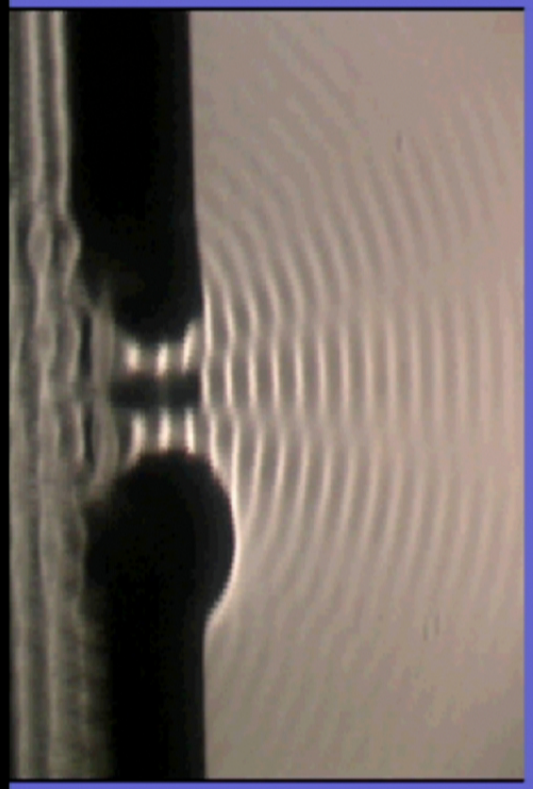
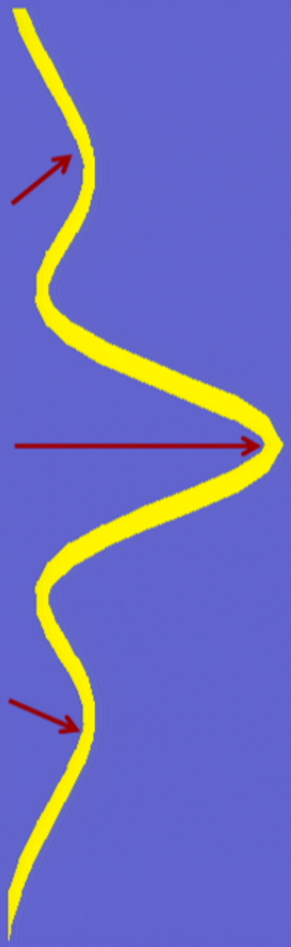
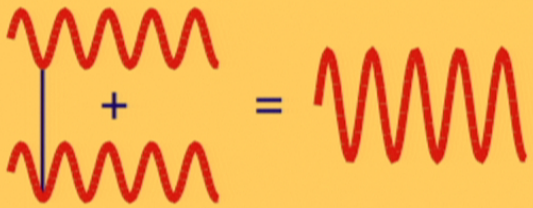
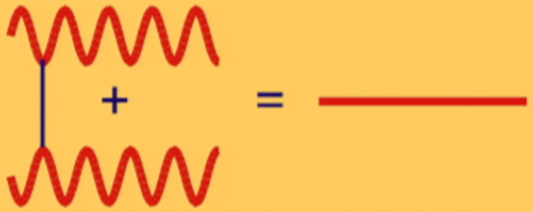




Maximum on Maximum
→ Amplification

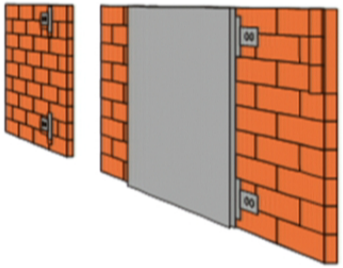


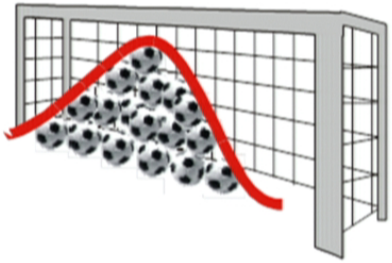
Maximum on Trough
→ Cancellation



When particles "are" waves …
Would you expect this: Quantum Soccer

$$\lambda_{\mathrm{dB}} = \frac{h}{m \cdot \mathrm{v}}$$





Left gate open:
→ single peak distribution in the goal!
→ Broader than expected because of quantum wave effect

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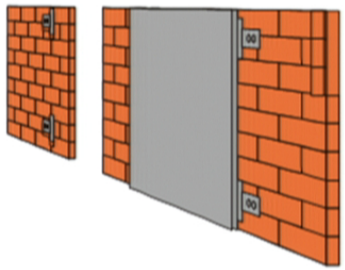

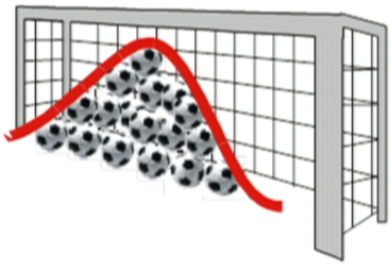

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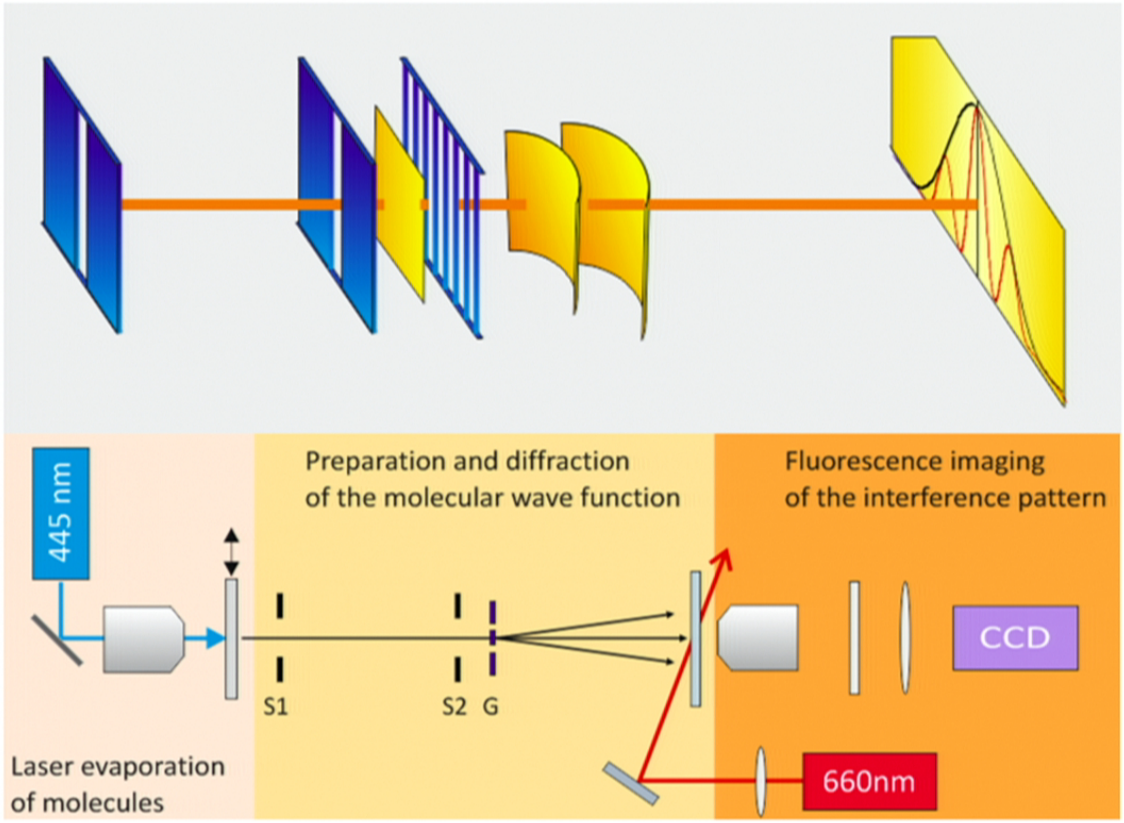
Visualizing Quantum Superposition in the laboratory

Seeing the quantum wave nature of with single-molecule sensitivity



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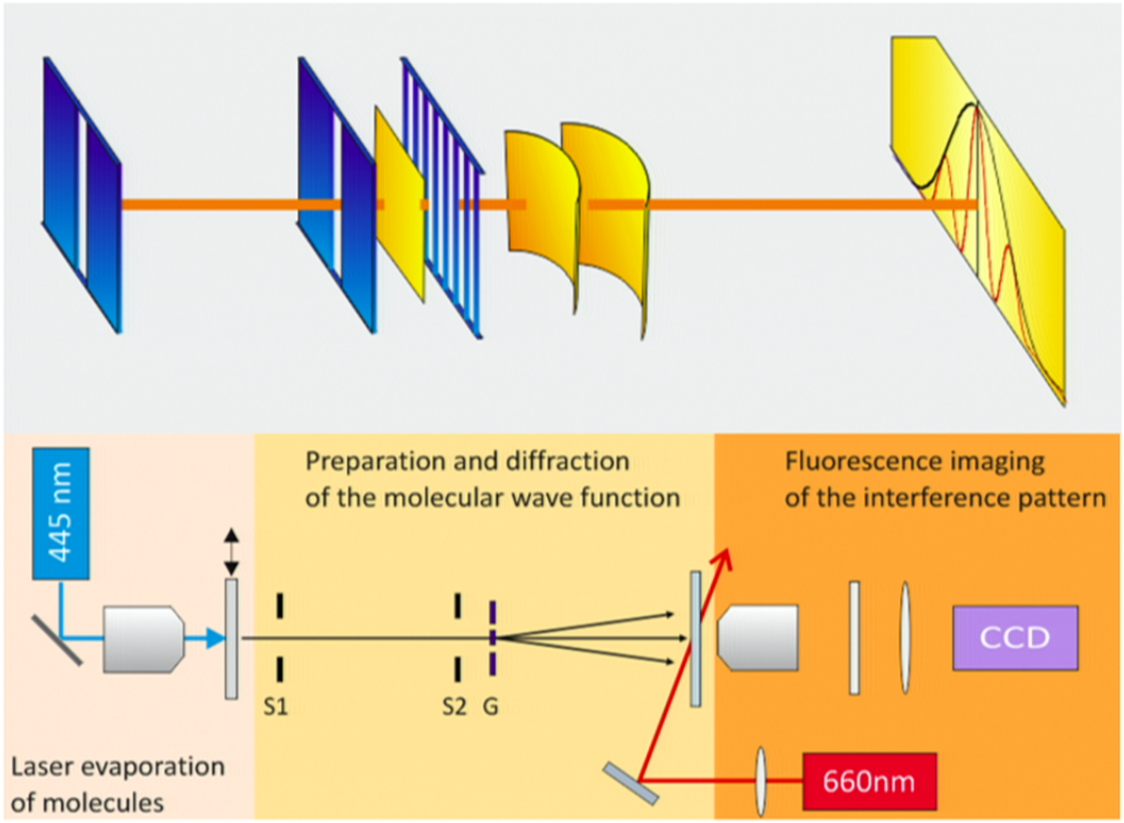

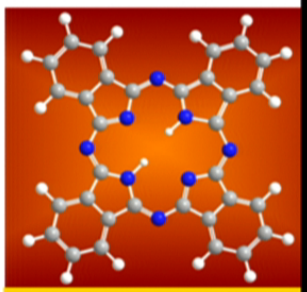

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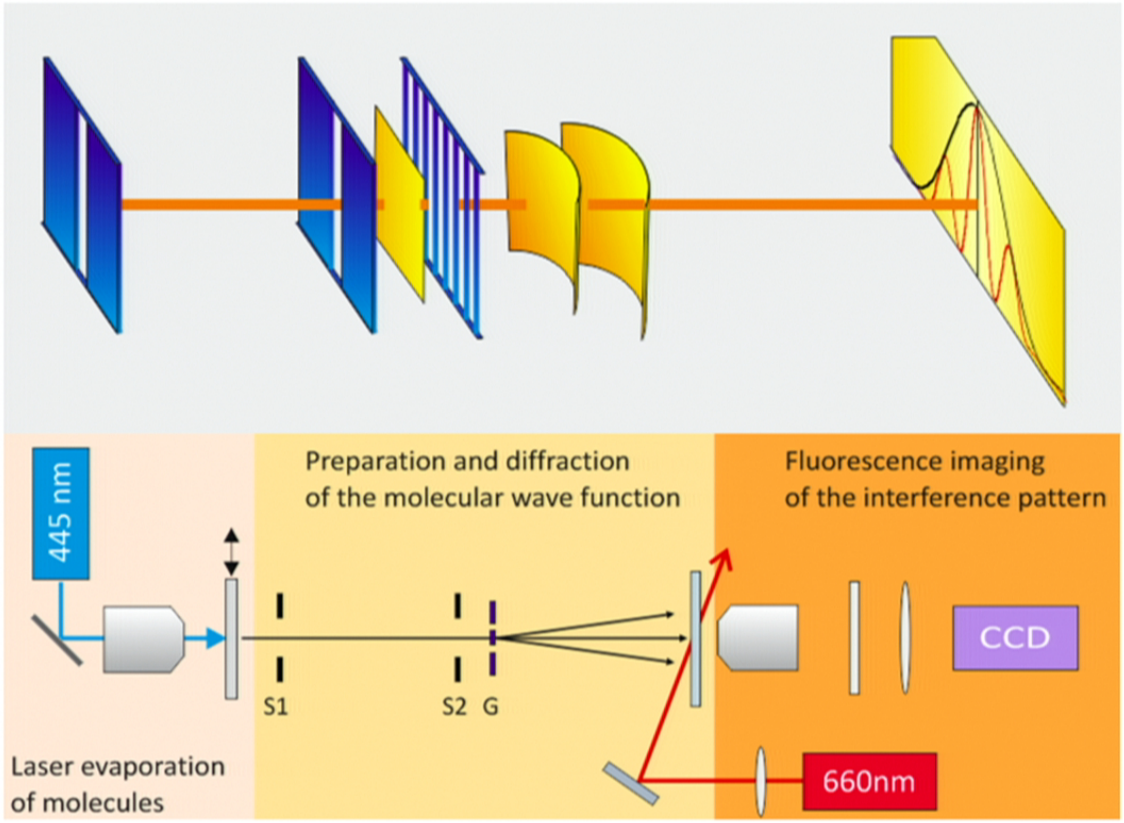

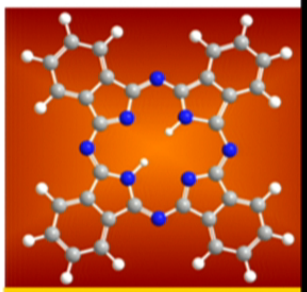

Phthalocyanine

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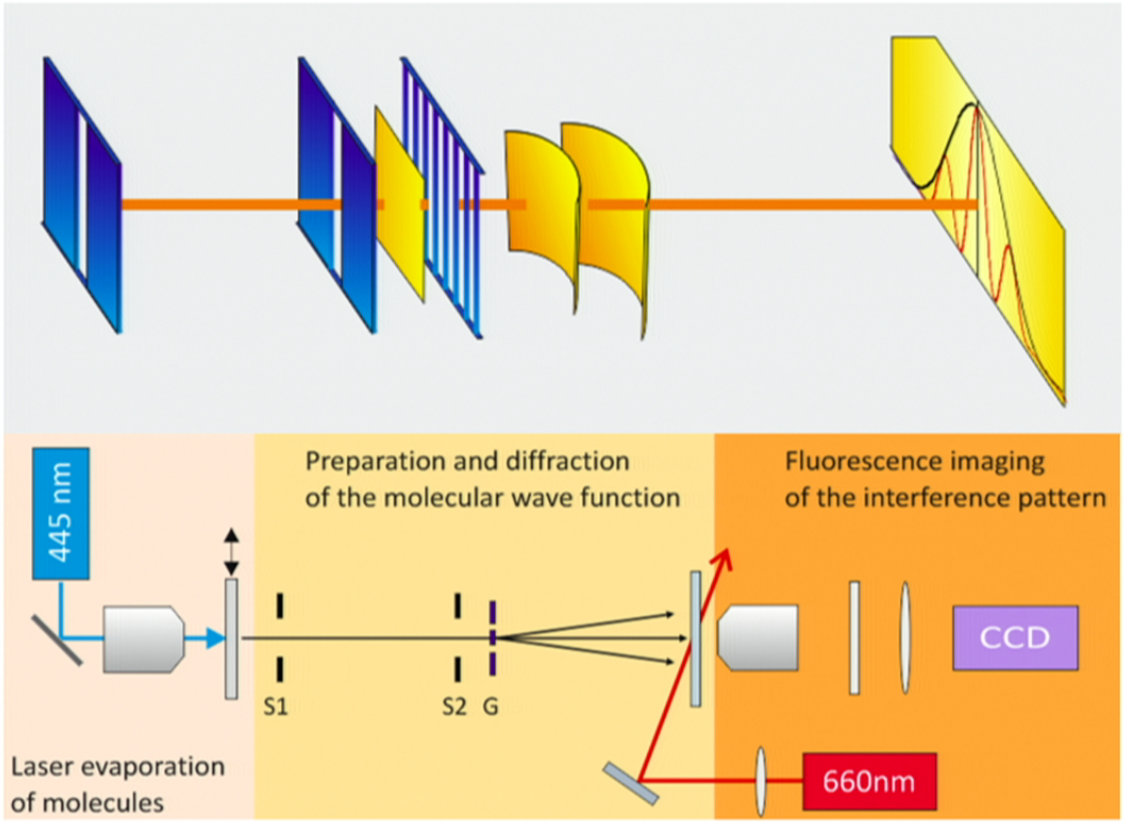

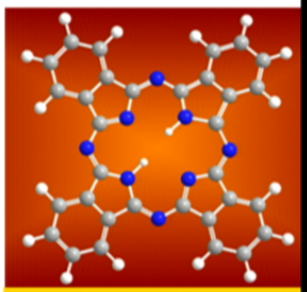

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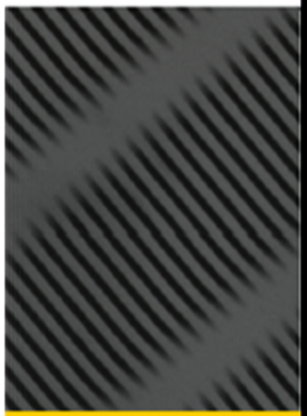
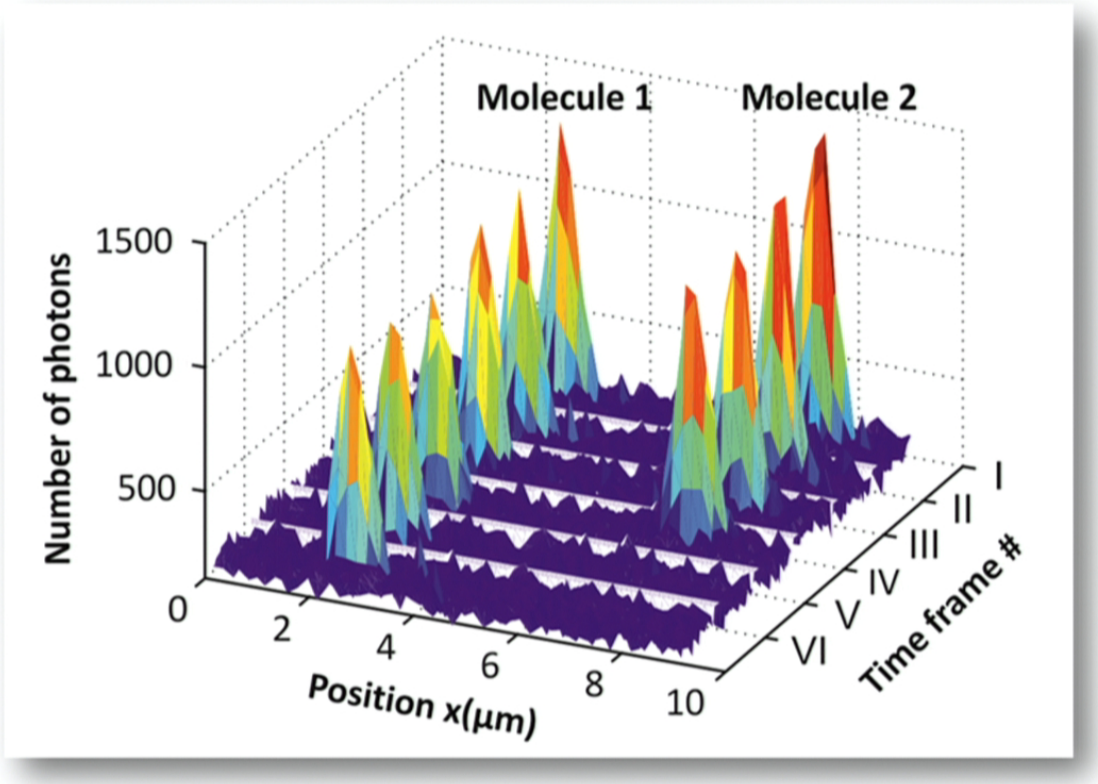


Nanograting, SiN
d=100 nm,
s=50 nm. t=10 nm

Single molecule fluorescence: molecule localization with 10 nm accuracy



Evaporation: 445 nm, 100 mW
Detection: 661 nm, 50 mW, EMCCD

Abrupt bleaching from one frame to the next indicates single molecules

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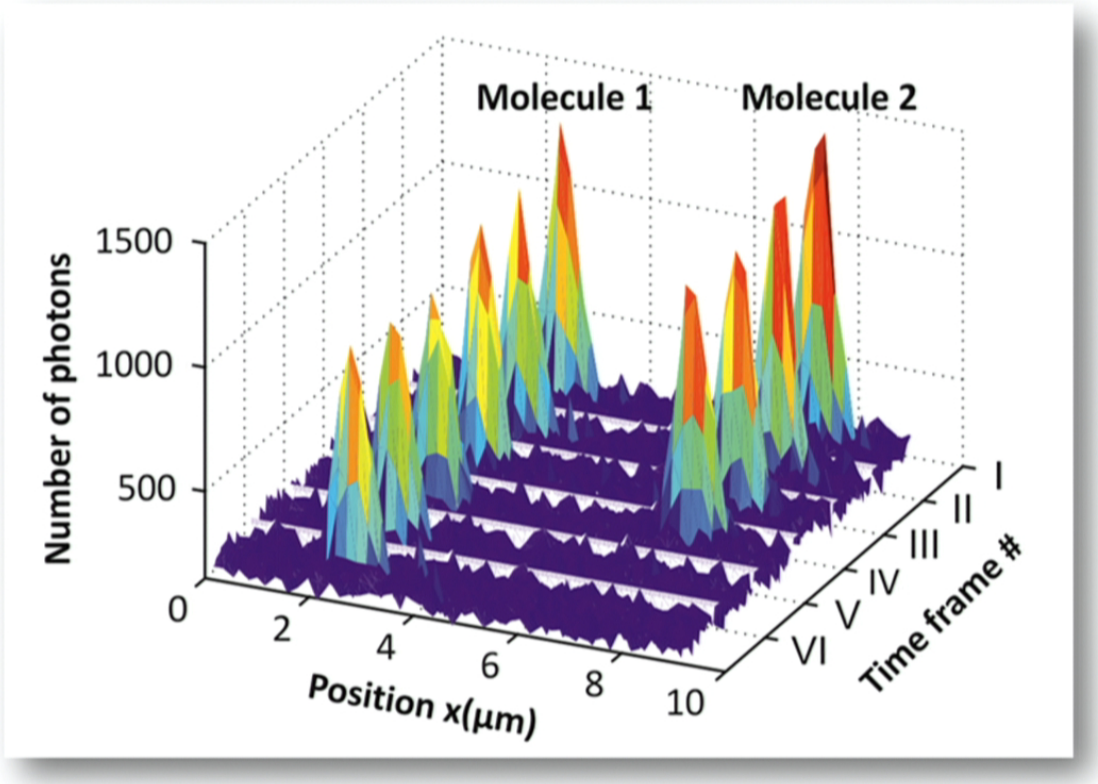

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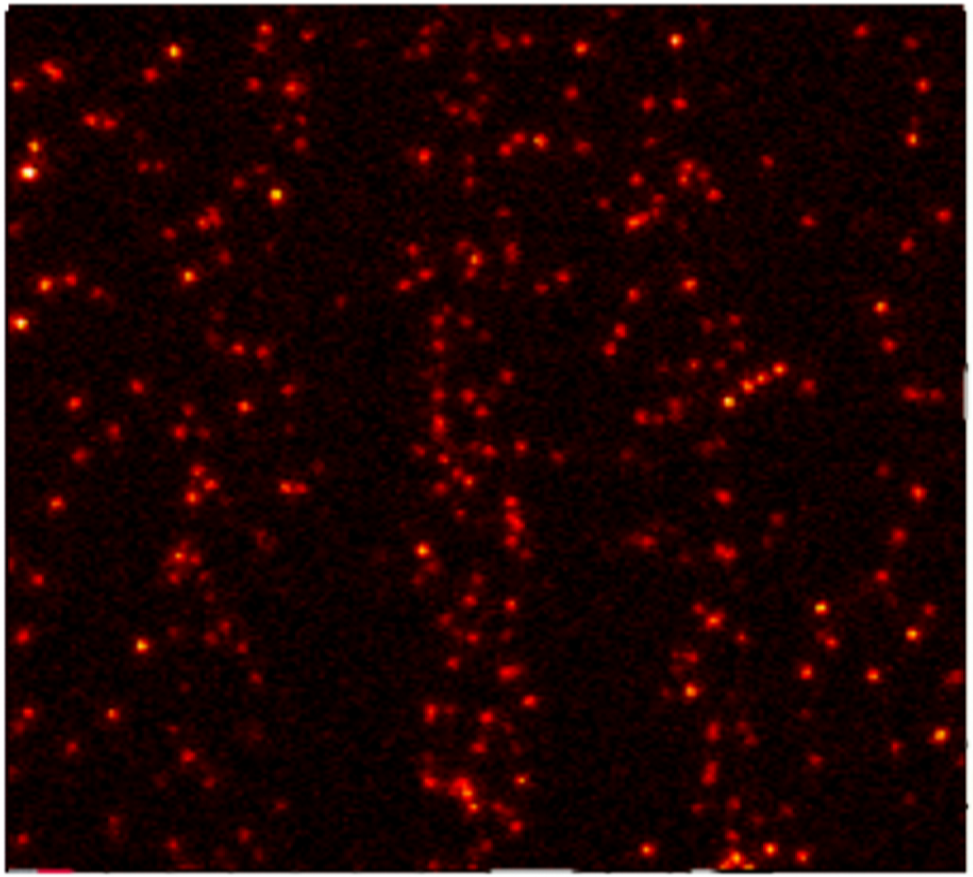
Delocalized propagation & localized detection
Determinism & Objective randomness
Wave & Particle



Juffmann et al. Nature Nanotechnology 2012, DOI: 10.1038/NNANO.2012.34

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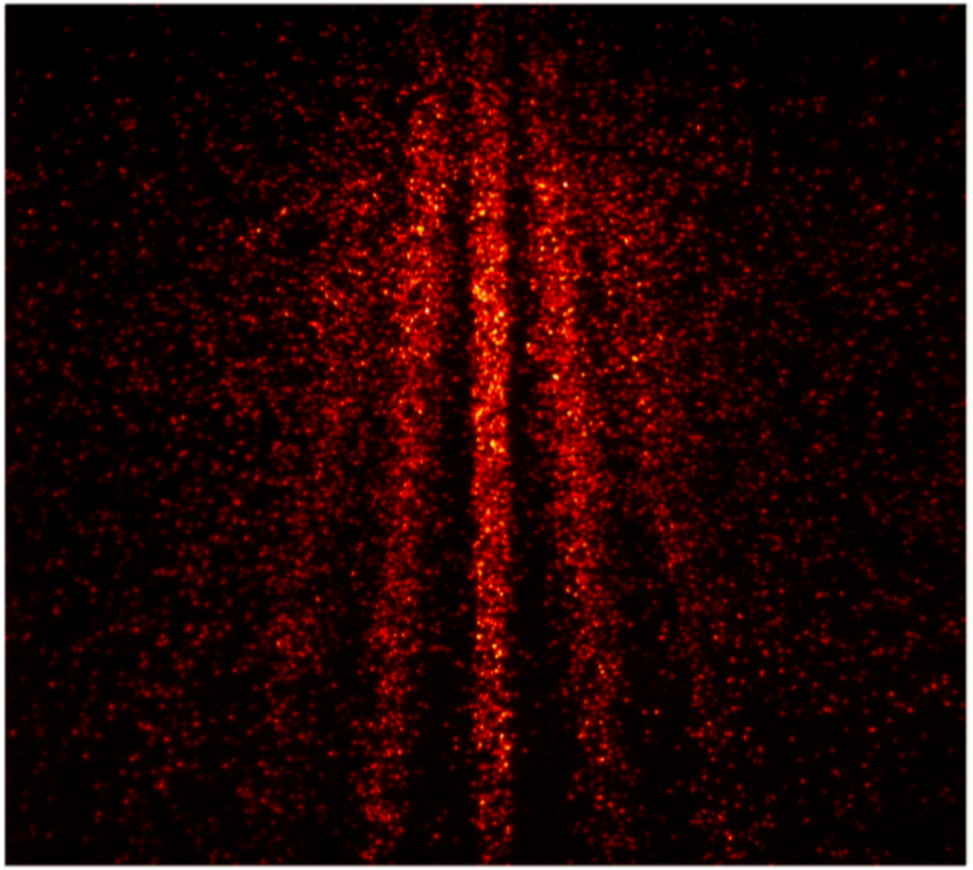

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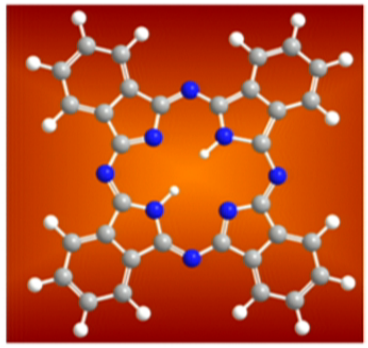
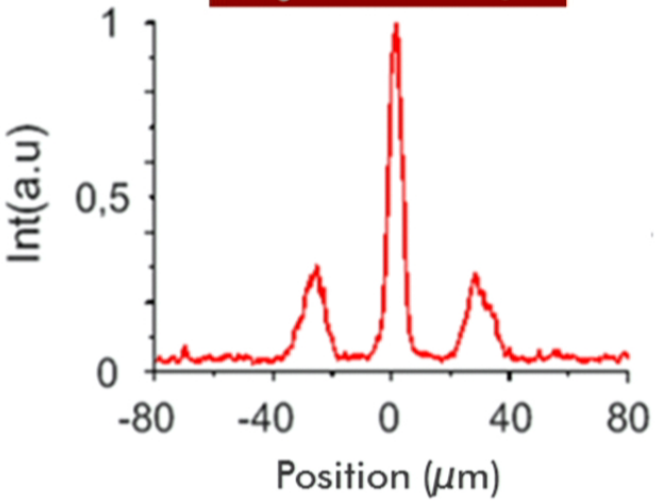
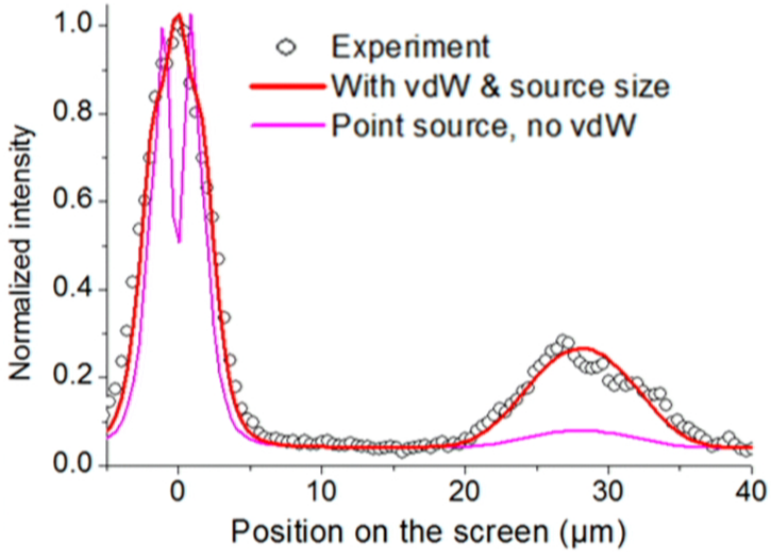
The role of intramolecular quantum fluctuations and vdW forces





PcH_2: $C_{32}H_{18}N_8$
N=58, m=514



Locality / Non-Locality / Reality

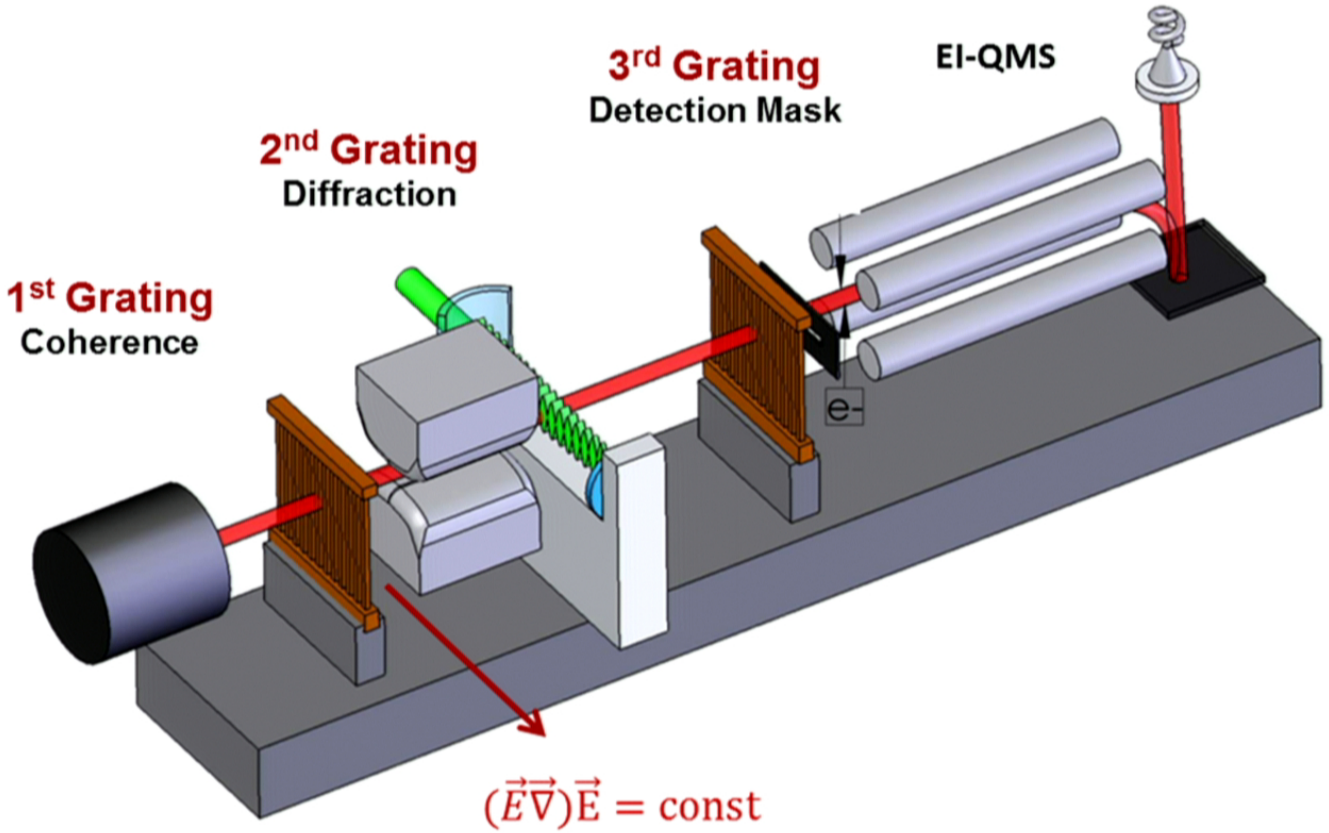
- **Each molecule interferes with itself: requires delocalization**
  - Molecular Diameter $\simeq$ 2 nm,
  - Molecular de Broglie wavelength $\lambda \simeq$ 5 pm
  - Almost all molecules „of the same kind" are still clearly distinguishable: Hundreds of different vibrational states, rotation, spin, hyperfine…

- **Even delocalized molecules interact with a local environment**
  - the full molecular mass, polarizability and dipole moment are required at every instant of interaction, even when the interaction is delocalized

    The internal molecular properties are never ‚smeared' out.

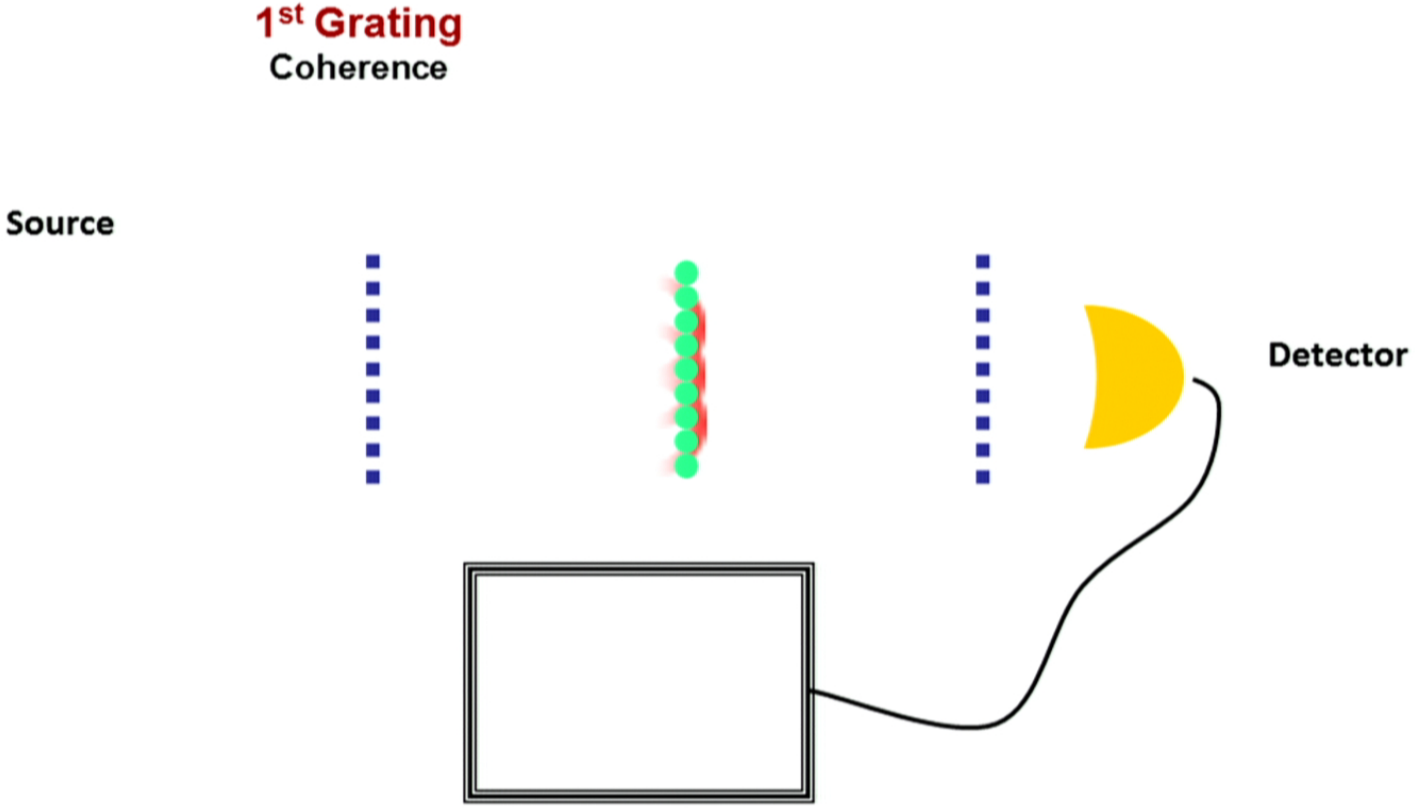
How to see quantum delocalization for even larger molecules ?

Optomechanical forces
Diffraction of matter at standing light waves



Gerlich et al. Nature Physics 3, 711 (2007)

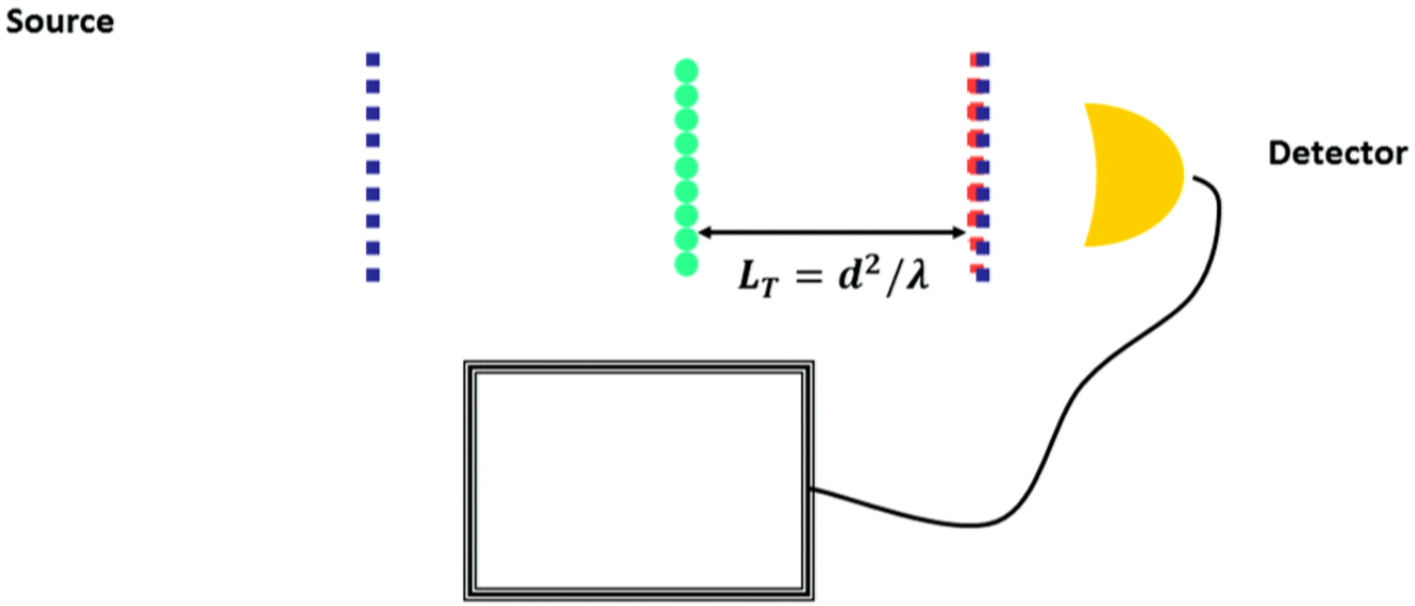
Kapitza-Dirac-Talbot-Lau interferometry



Kapitza-Dirac-Talbot-Lau interferometry

1st Grating Coherence

2nd Grating Diffraction



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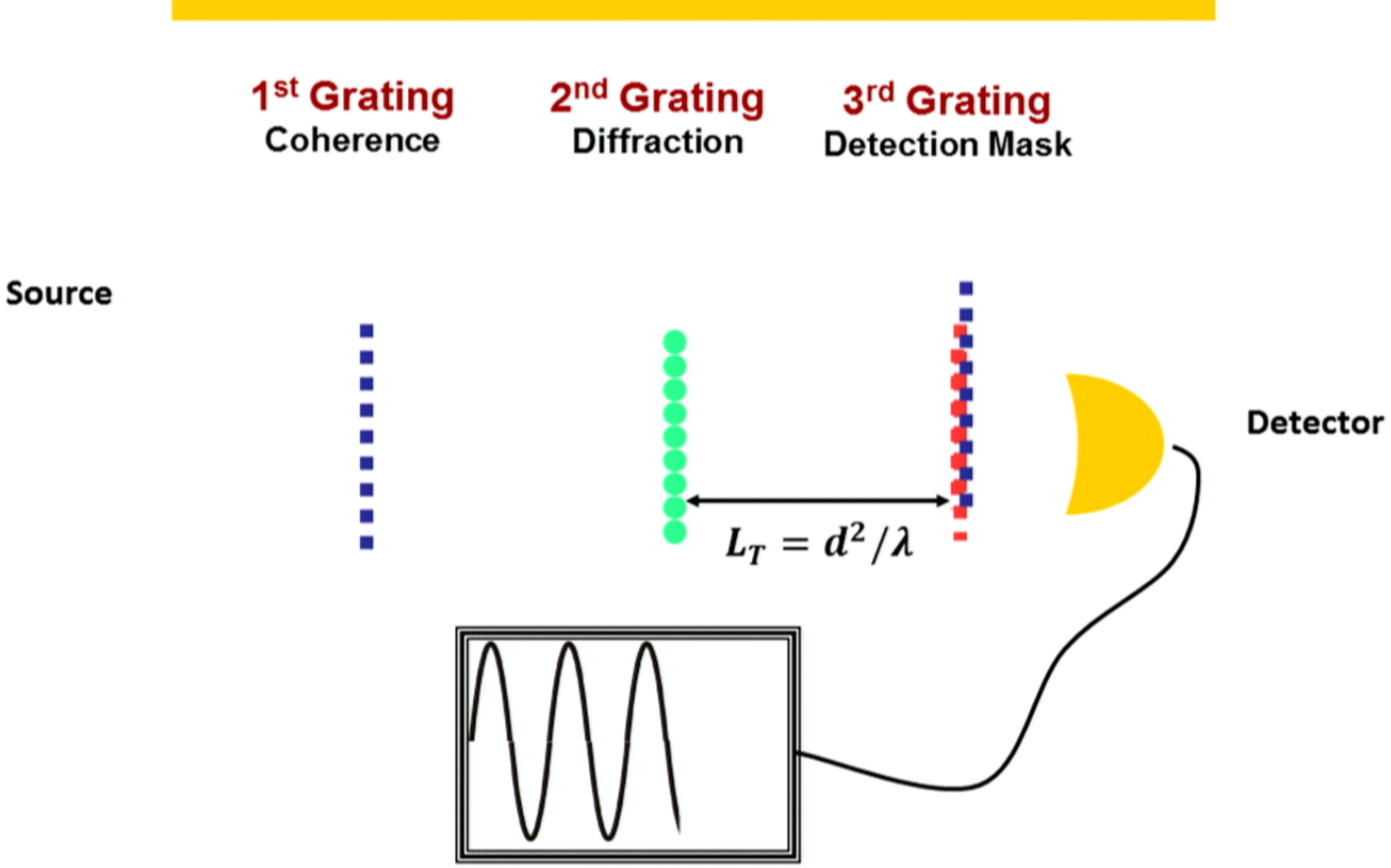
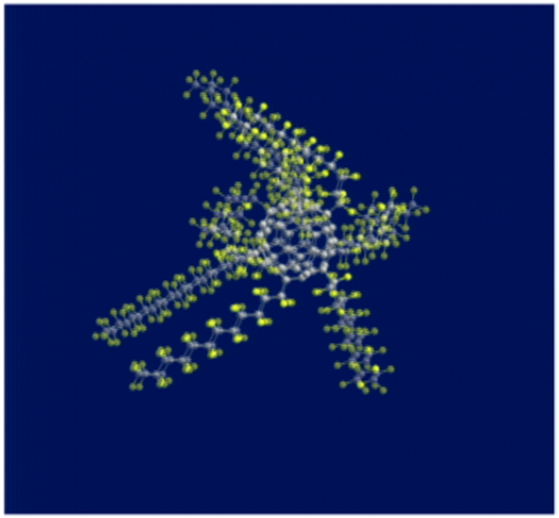


Nature Physics 3, 711 (2007)

Quantum Delocalization & Interference of „Molecular Octpusses“

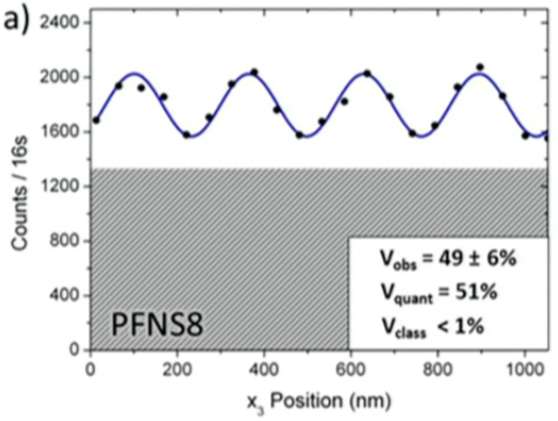
Nature Communications 2, 263 (2011).

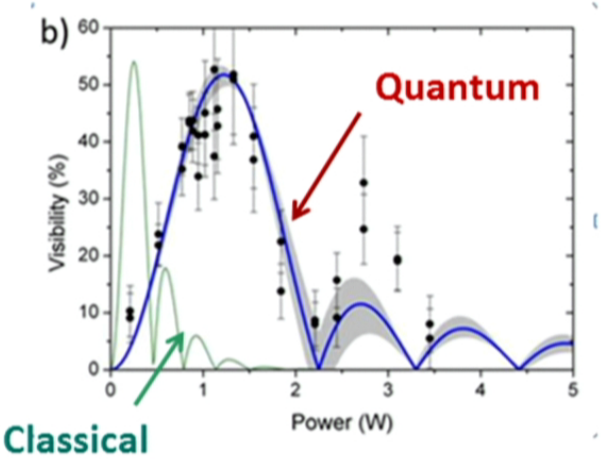
PFNS8: 5672 amu, 356 atoms



$C_{60}[C_{12}F_{25}]_8$

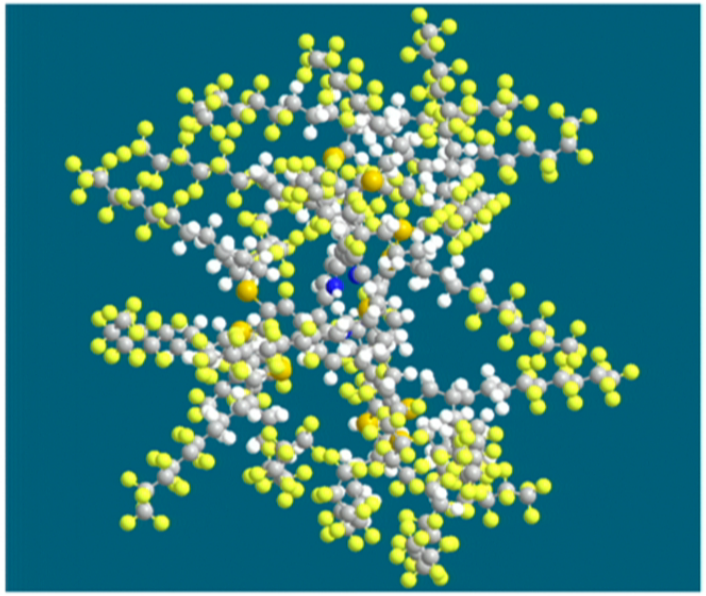
High-contrast interferogram

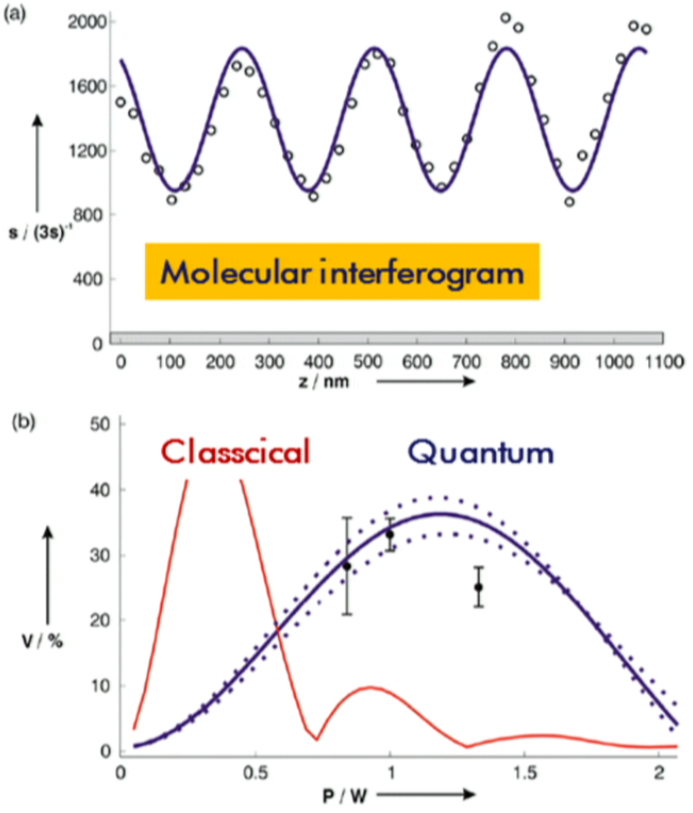




Current Record in Complex Quantum Delocalization & Interference

$C_{284}H_{190}F_{320}N_4S_{12}$
m=10,123 amu, N > 800 Atoms

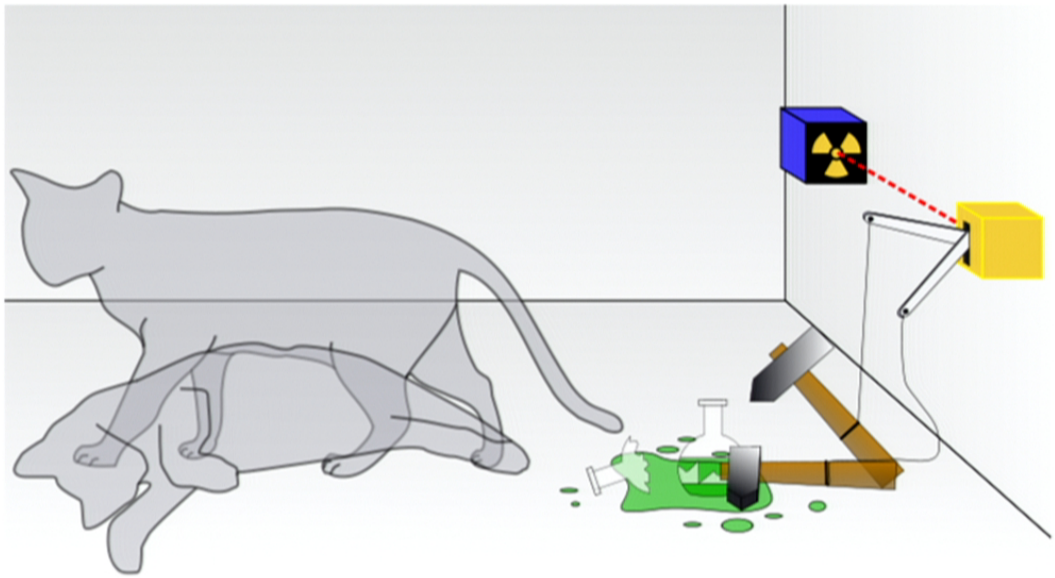




Eibenberger, Gerlich, Arndt, Mayor, Tüxen, subm. to **Phys. Chem. Chem. Phys. (2013)**

Does a Quantum Octopus qualify as a Schrödinger cat ?

- A Schrödinger cat is an illustration for something that…
  - is ‚classical': complex, macroscopic and evtl. warm
  - is simultaneoulsy in two unambiguously discernible states
  - Symbolizes quantum entanglement



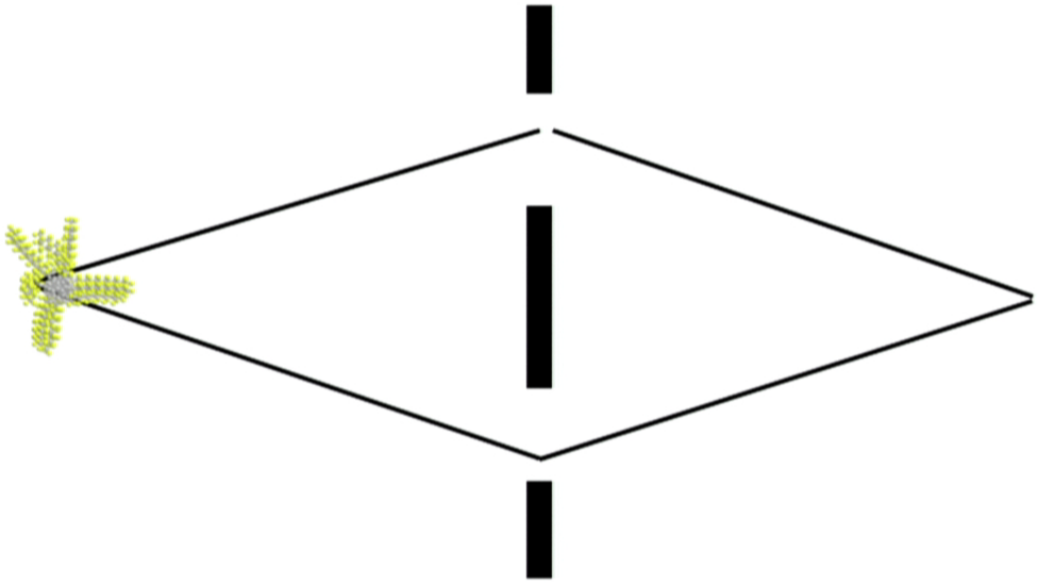
E. Schrödinger
Die gegenwärtige Situation in der Quantenmechanik, Naturwissenschaften, 23 (1935)

Image: Wikipedia

Does a Molecular Octopus qualify as a Schrödinger cat ?

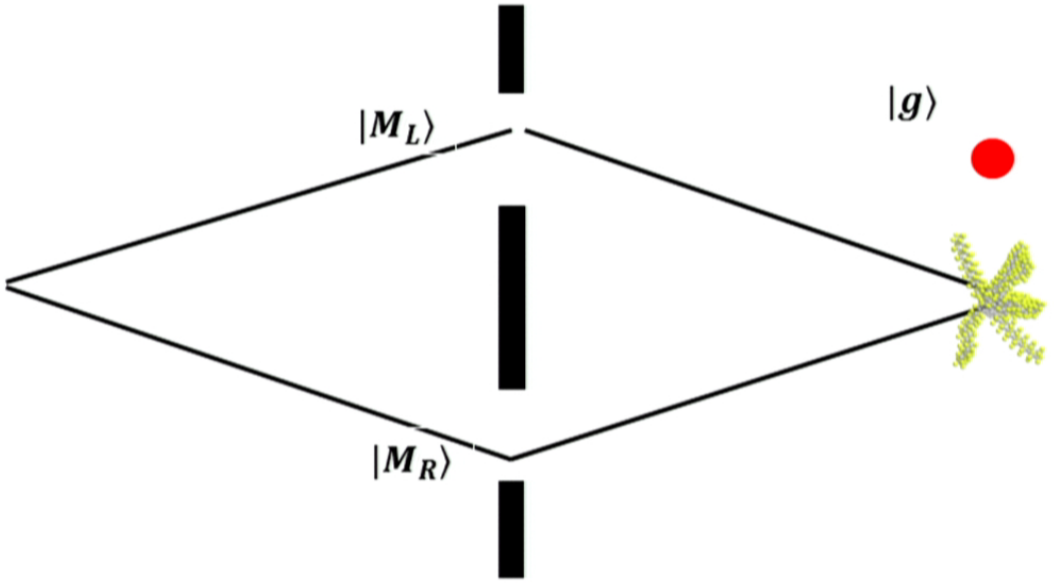
The Quantum Octopus and its brothers

- More than 800 atoms
- Even hotter than any living cat (500 K)
- Can be brought into superpositions of two or more position states
- Delocalization over 100 times the size of the molecule



Does a Quantum Octopus qualify as a Schrödinger cat ?

- **Schrödinger cat:**
  - Entanglement between macroscopic (classical) + microscopic (quantum) object
- **„Octopus“:**
  - Does not need entanglement to get in a quantum superposition
  - Does get entangled in collisional decoherence → unobserved Bell state



$$|\psi\rangle = \frac{1}{\sqrt{2}}[|M_L\rangle + |M_R\rangle] \otimes |g\rangle \xrightarrow{collision} \frac{1}{\sqrt{2}}[|M_L{}'\rangle|g_L\rangle + |M_R{}'\rangle|g_R\rangle]$$

Why don't we see quantum effects in our daily life?

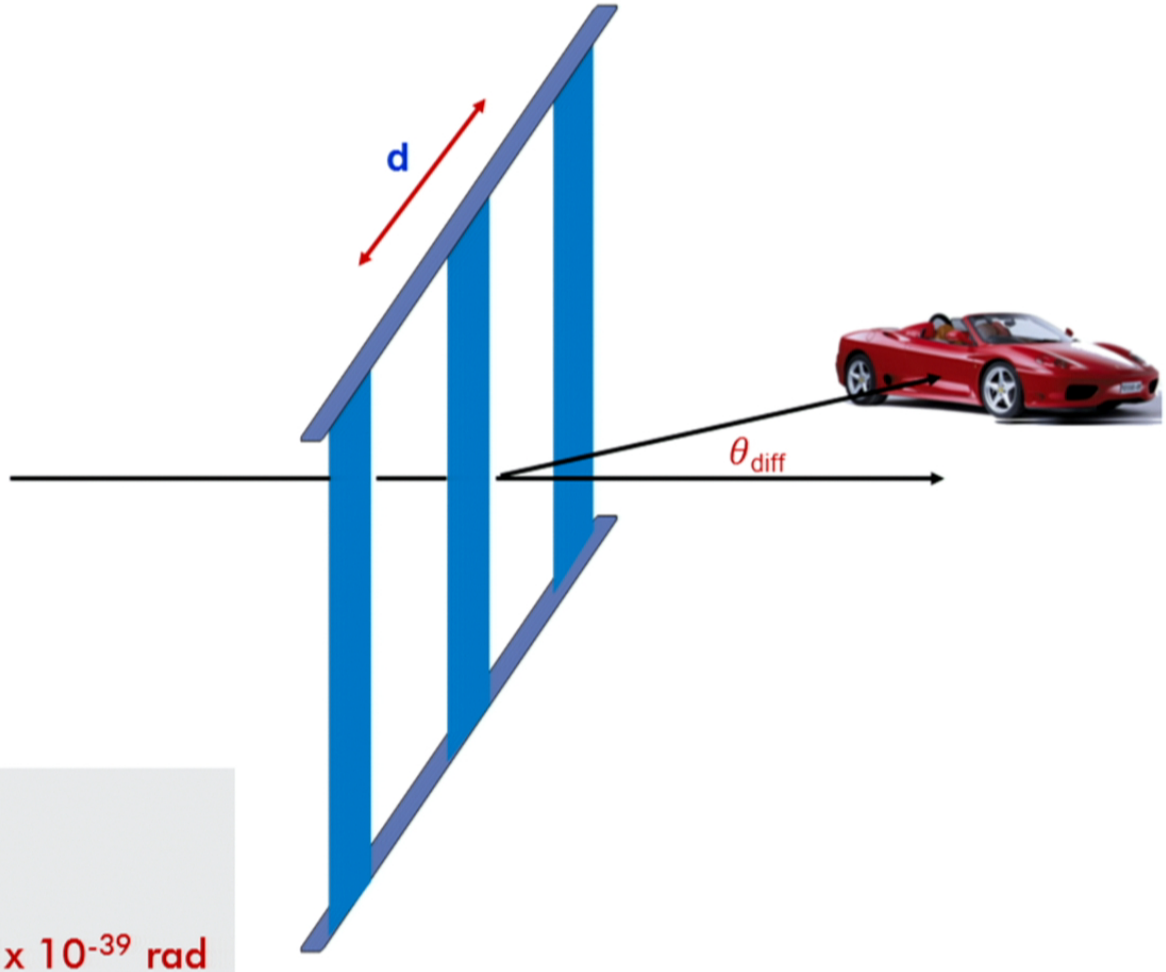
1. Kinematics

2. Decoherence

3. Phase averaging : scrambling of Q-waves by noise

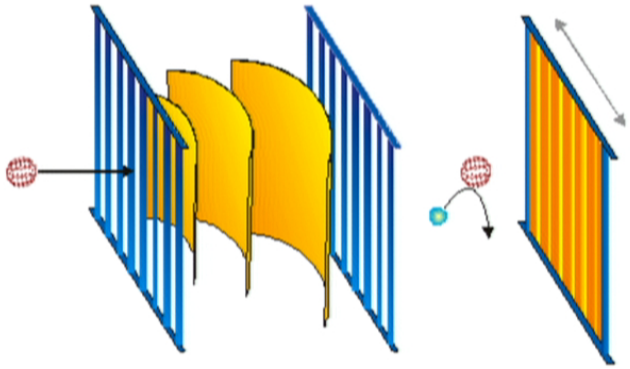
4. May quantum mechanics not be valid for massive bodies?

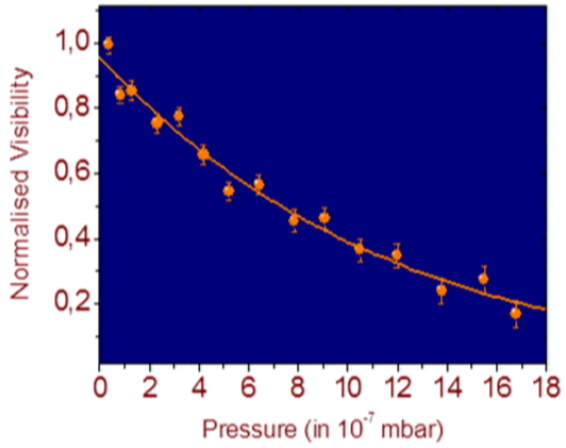
Kinematics: A car is just too massive



v =300 km/h
m=1000 kg
d = 2 m
$\theta_{diff} = \lambda_{dB}/d = 4 \times 10^{-39}$ rad

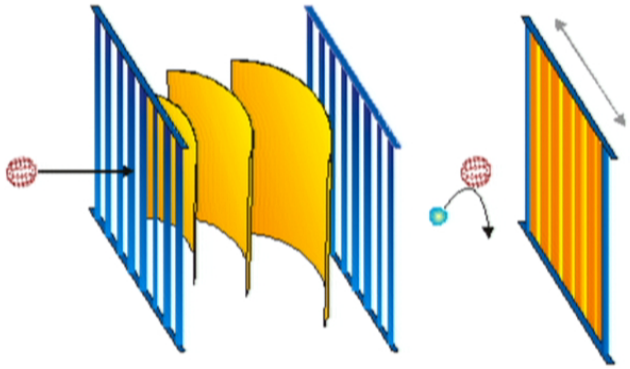
Collisions

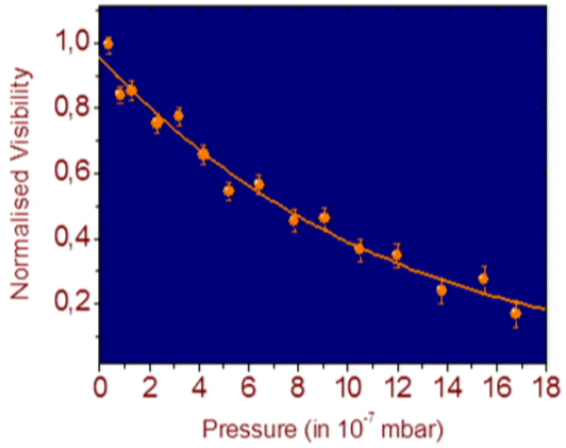




Phys. Rev. Lett. 90, 160401 (2003).

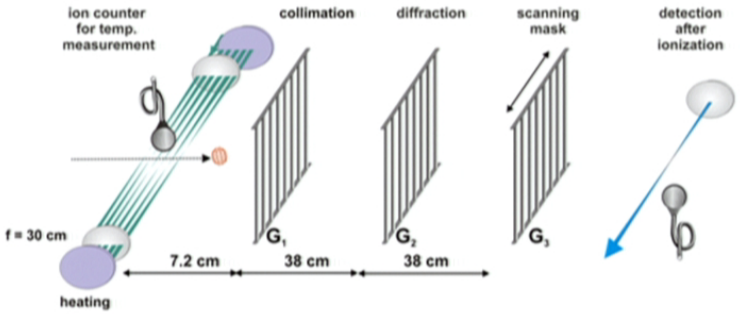
Collisions

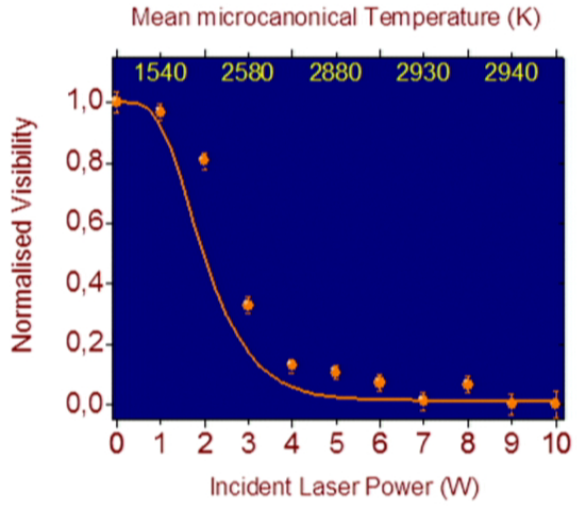




Phys. Rev. Lett. 90, 160401 (2003).

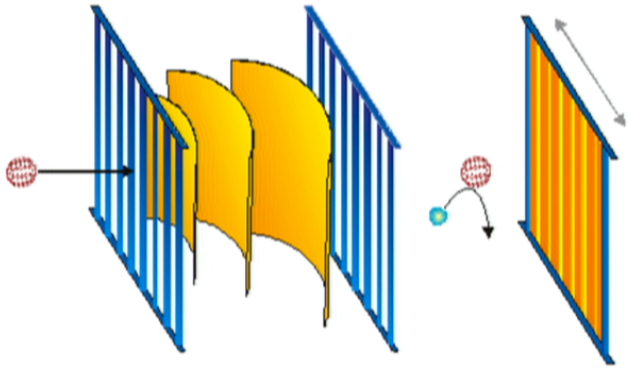
Thermal photons

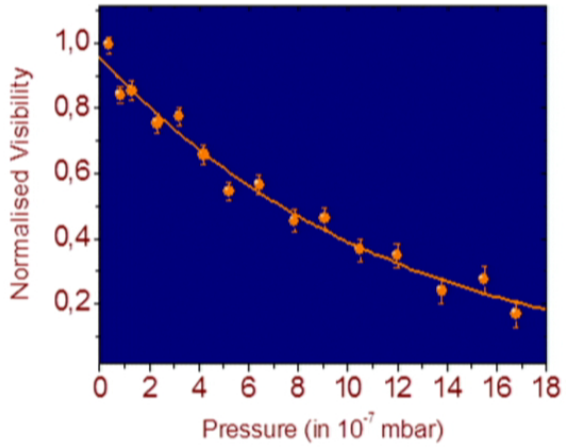




NATURE, 427, 711–714 (2004).

Collisions





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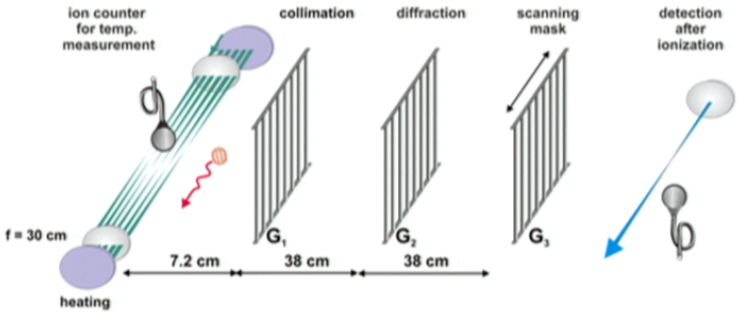

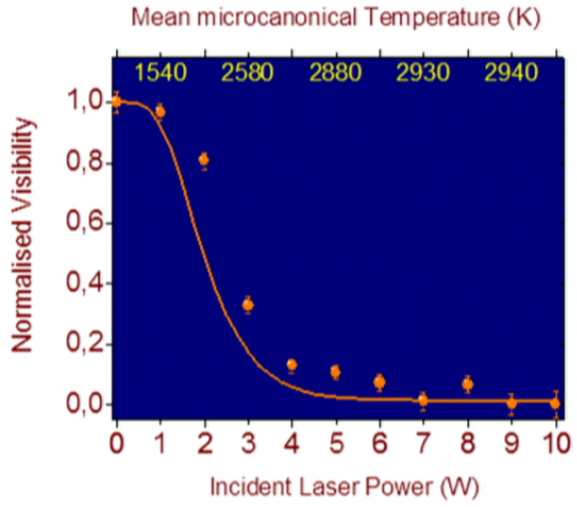

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Quantum physics is precise

but quantum objects are also easily perturbed :

How can we utilize quantum wave effects to measure tiny forces?

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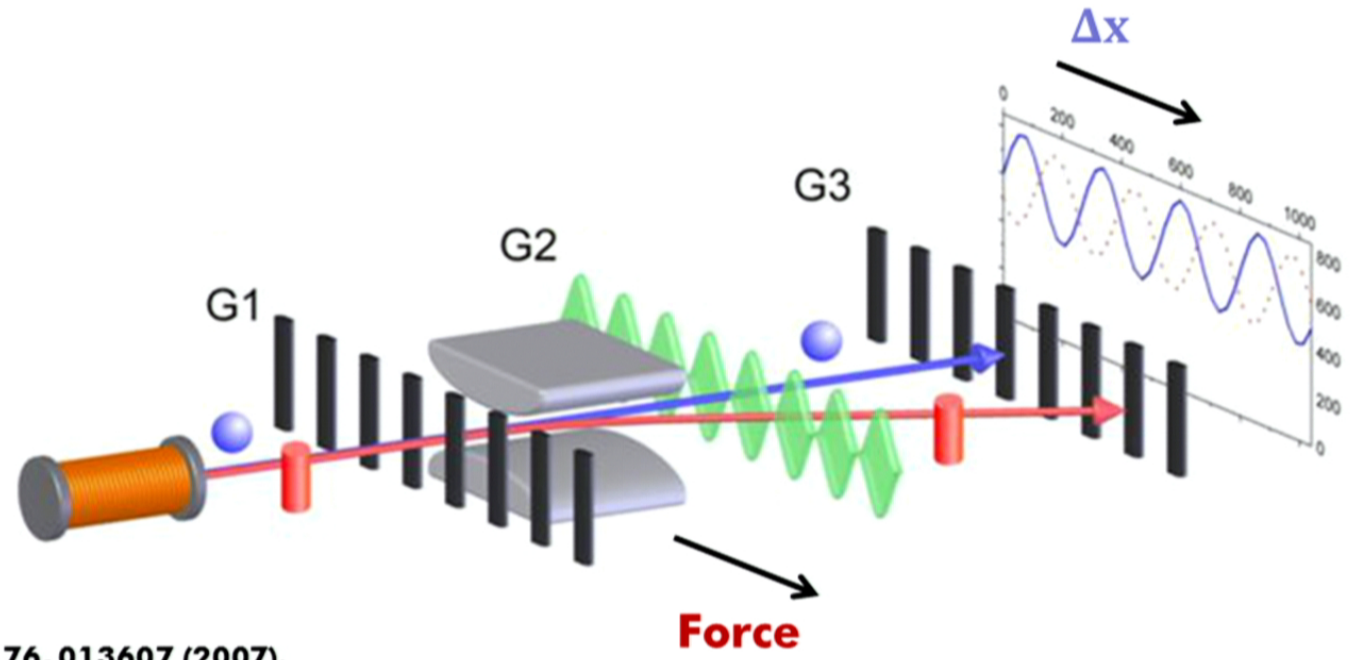
How can we utilize quantum wave effects to measure tiny forces?

Influence of external and inertial forces „F“



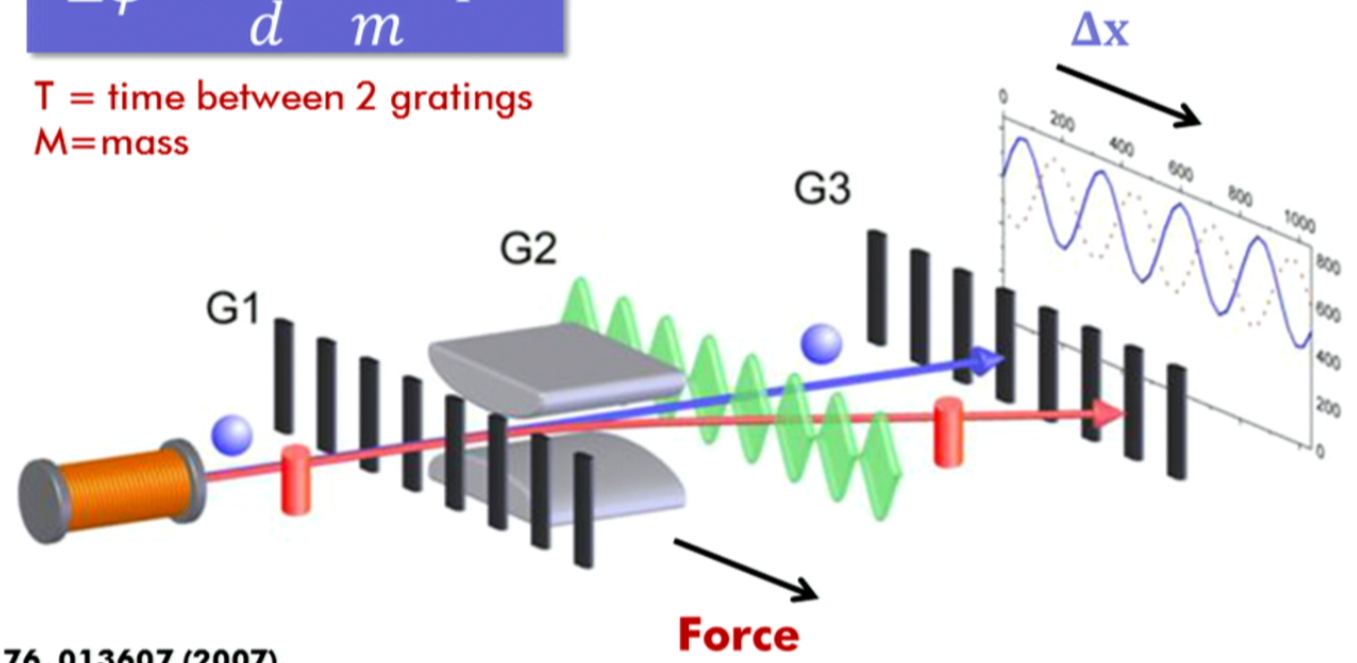
PRA 76, 013607 (2007).
Angew. Chem. Int. Ed. 47, 6195 (2008)
Chem. Comm. 46, 4145 (2010) ...

Influence of external and inertial forces „F“

Quantum fringe is shifted by:

$$\Delta\phi \propto \frac{2\pi}{d} \cdot \frac{F}{m} \cdot T^2$$

T = time between 2 gratings
M=mass



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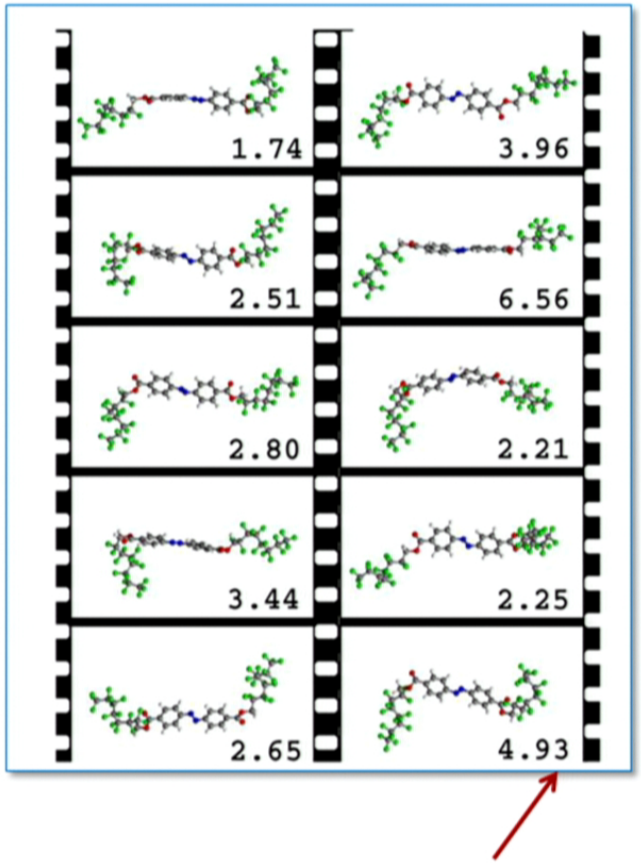
Angew. Chem. Int. Ed. 47, 6195 (2008)
Chem. Comm. 46, 4145 (2010) ...

‚Seeing without looking‘:
The influence of internal states on the Q-delocalized molecule

Azobenzene derivative:

- No static dipole moment
- Many different conformations
- Dynamics on the ps-scale

- **Result 1:**
  High-contrast de Broglie interference
- **Result 2:**
  Dynamic dipole moments μ influential



Phys. Rev. A 81, 031604(R) (2010)

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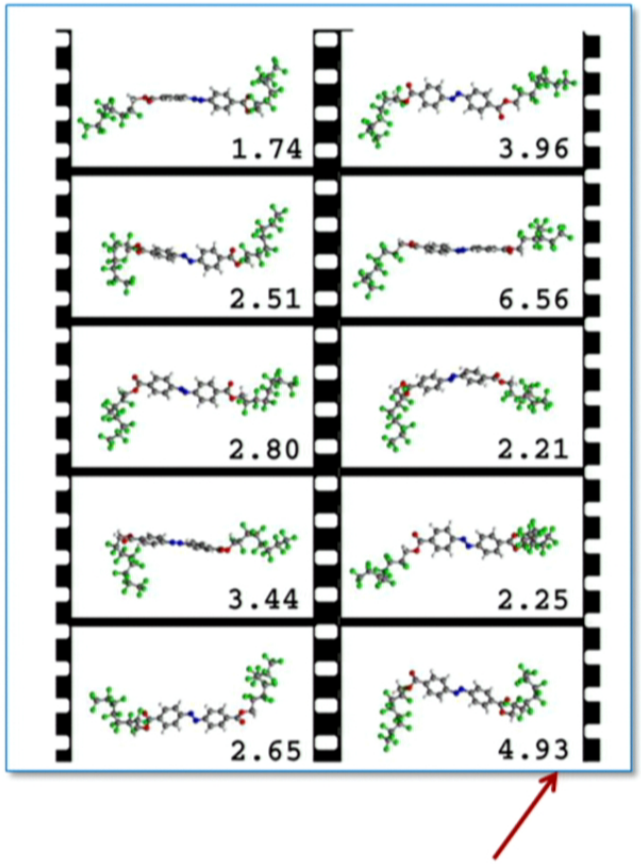
$$\chi = \alpha_{stat} + \langle \mu_z^2 \rangle / (k_B T)$$

$$\boldsymbol{F} \propto \chi \cdot (\boldsymbol{E} \cdot \boldsymbol{\nabla})\mathbf{E}/\mathrm{m}v^2$$



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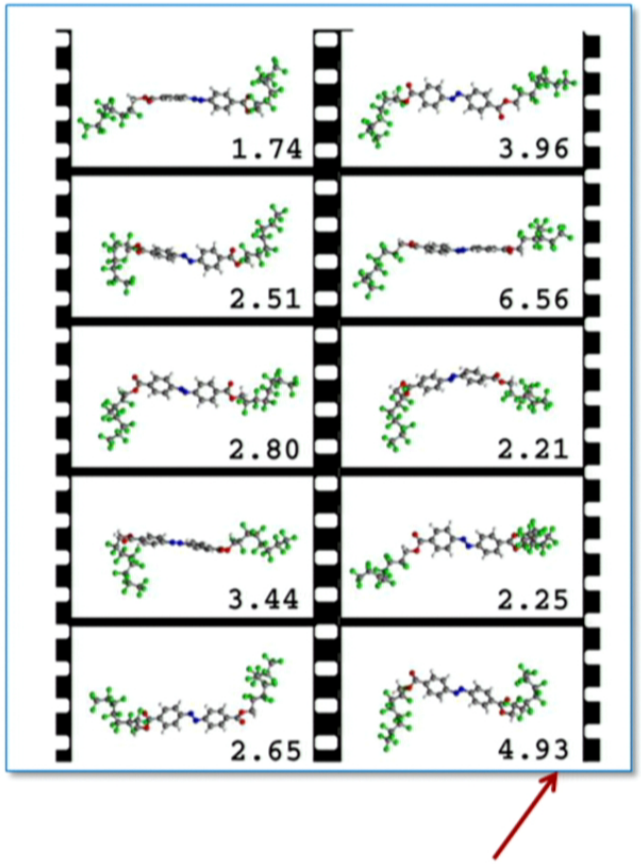

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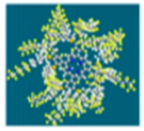


Towards quantum interferometry of biomolecules in biomimetic environments

Idea:

Quantum interferogramms are free-flying nanorulers for precision metrology.

Compare:

- Unsolvated molecules
- Molecules in hydrate and salt shell

Learn:

Absorption σ_{abs},

Collision cross sections σ_{coll},

Polarizability α,

Electrical & mag. dipole d, μ,

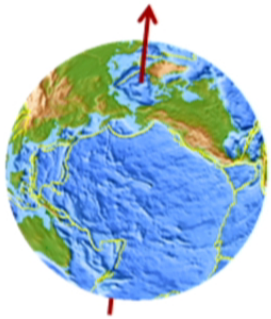
Photoisomerization behavior …

Does it matter that we live on Earth ?

Acceleration of the interferometer during particle flight
→ Shift of the interference fringe Δx

Shifts are velocity (time) dependent Δx (v,t):

$$\boldsymbol{F} = m \cdot \boldsymbol{a}, \quad \boldsymbol{\phi} \propto \boldsymbol{F}$$



Earth's rotation

$$a_{coriolis} = 2\, v \times \Omega$$

$$\Delta\phi \propto \frac{4\pi}{d} \cdot v \times \Omega \cdot T^2$$

With: Ω= 72 µrad/s = once / day

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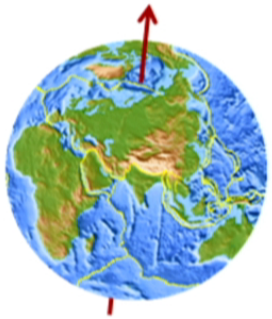

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Earth's gravity

$$a_{gravity} = g = 9.81\ m/s^2$$

$$\Delta\phi \propto \frac{2\pi}{d} \cdot g \cdot T^2$$

Possible limitations to quantum delocalization ?

Spontaneous Localization

- **Ghirardi, Rimini, Weber:** Phys. Rev. D 34, 470 (1986).
- **Pearle:** Phys. Rev. A 39, 2277 (1989).
- **Adler et al. :** Science 325, 275 (2009).
- **Bassi et al.** Reviews of Modern Physics 85, 471 (2013).
- **Bedingham,** Foundations of Physics 41, 686 (2010).
- **Nimmrichter & Hornberger:** Phys. Rev. Lett. **110**, 160403 (2013).

Gravity related effects

- **Gravitational waves (Reynaud et al.):**
  Gen. Rel. Grav. 36 (2004), 2271
- **Space-time flucutations (Wang et al.):**
  Class. Quant. Grav. L59, 23 (2006)
- **Newton-Schrödinger equation (Giulini):**
  Class. Quant. Grav. 28: 195026 (2011)
- **Objective collapse of the wave function (Penrose / Diosi):**
  Gen. Rel. Grav., 28, 581 (1996)

Pulsed interferometry in the time domain

Convert Talbot length to Talbot time

$$L_T = \frac{d^2}{\lambda} = \frac{d^2}{h} \cdot m \cdot v \quad \Rightarrow \quad T_T = \frac{L_T}{v} = \frac{d^2}{h} \cdot m$$

All particles of mass *m* have the same talbot time

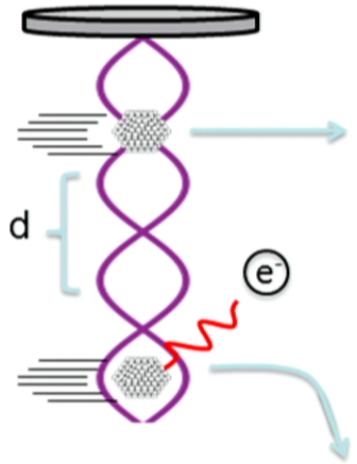
Idea: Pulsed laser light gratings

- Ionizing: absorptive
- In addition: dipole phase grating

Realization: F2 excimer laser

$$d = \frac{\lambda_{laser}}{2} = \frac{157\,nm}{2} = 78{,}5\ nm$$

$$\Rightarrow \quad T_T = 15\ \mathrm{ns} \cdot m\ [\mathrm{amu}]$$



Cahn et.al., *PRL* **79** (1997) Reiger, et al. Opt. Comm. (2006) Nimmrichter et.al., *NJP* **13** (2011)

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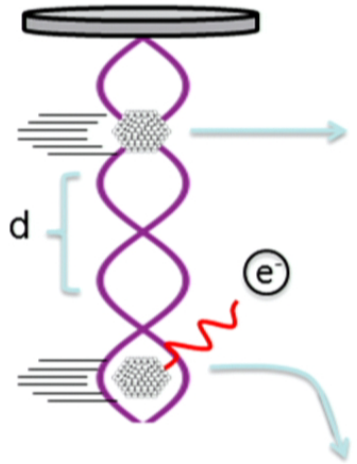

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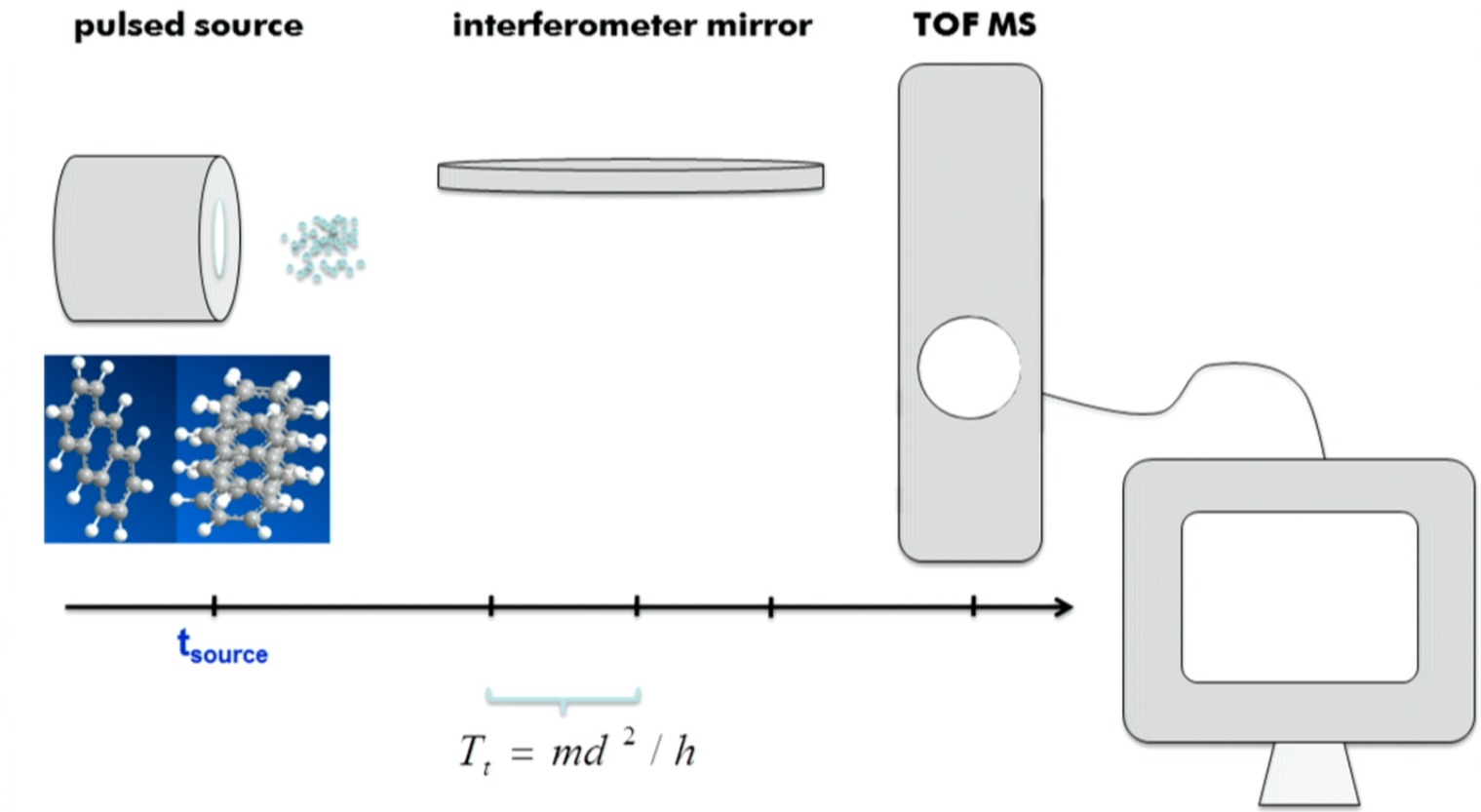
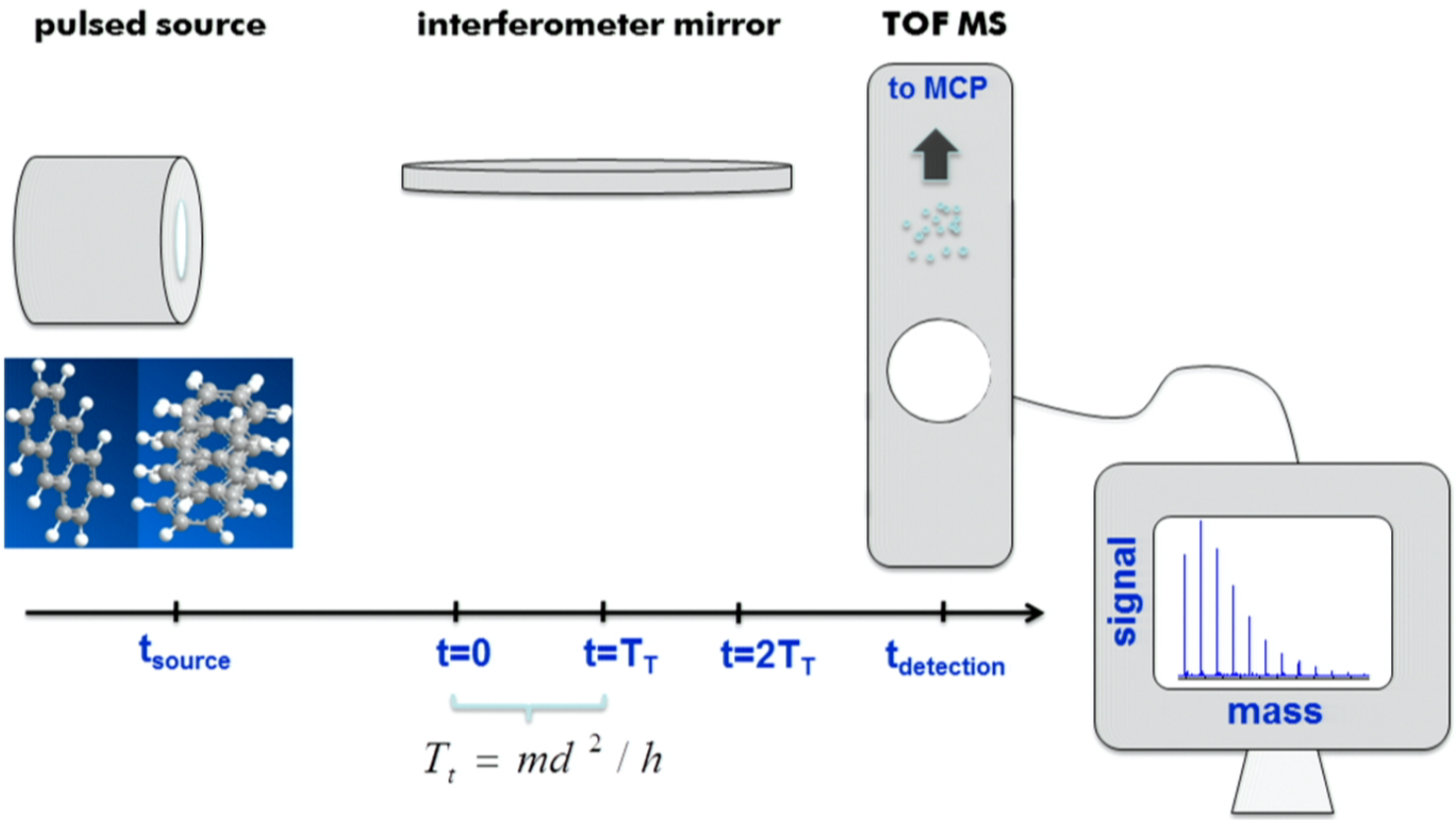
Cluster interferometry in time with ionizing laser gratings



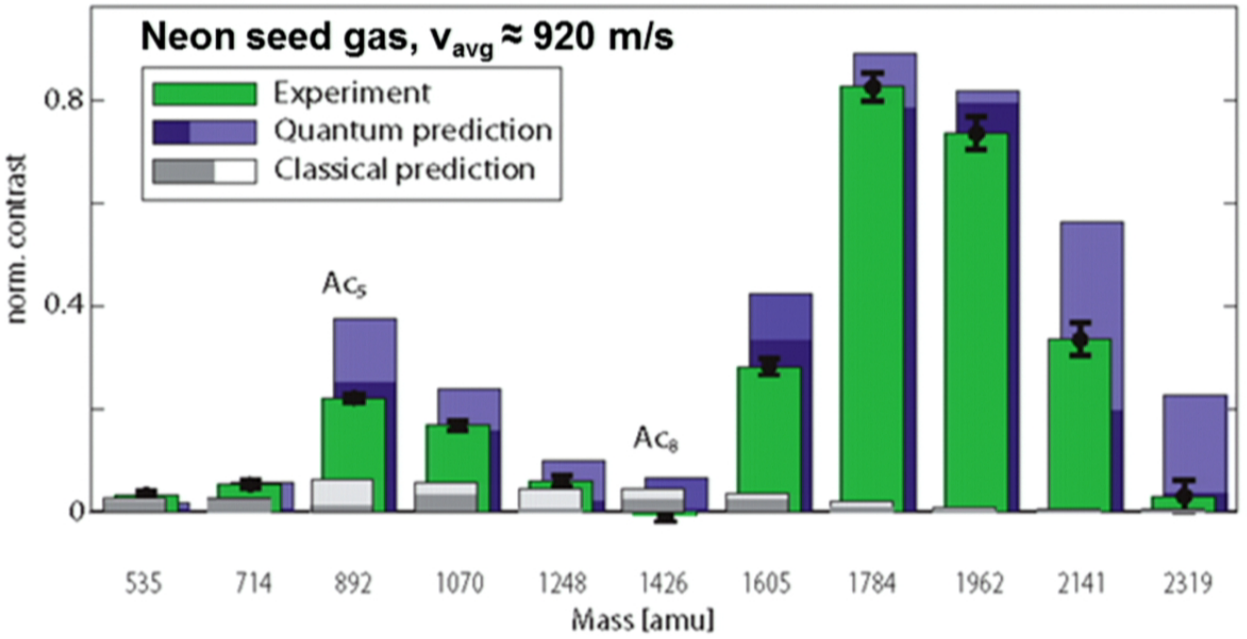
Pulsed Anthracene clusters	3 x 157 nm, τ = 6 ns F_2 excimer laser	157 nm, SPI

Cluster interferometry in time with ionizing laser gratings



Pulsed Anthracene clusters	3 x 157 nm, τ = 6 ns F_2 excimer laser	157 nm, SPI

Test 1: Anthracene cluster interference: OTIMA experiment vs. theory



- Good agreement with quantum theory within experimental uncertainties
- Clearly non-classical

Haslinger et. al. *Nature Physics*, doi:10.1038/nphys2542 (2013)

A zoo of organic clusters showing quantum interference

A tool for high-mass Quantum Interference
$\Rightarrow$ in microgravity or with stable levitation

A tool for high-mass Quantum Interference
⇒ in microgravity or with stable levitation

- Talbot-length: $L = g^2/\lambda$
- Smallest laser grating period : $g = \lambda/2 = 100\ \mathrm{nm}$
  (limits: a) existing lasers & b) $\lambda \gg D_{\mathrm{particle}}$)
- High mass and T=10 K $\rightarrow v = \sqrt{2kT/m}$
  - $m = \mathbf{10^6}$ amu → v= 0.4 m/s → $\lambda_{dB} = 1\ \mathrm{pm}$
  - $m = \mathbf{10^{10}}$ amu → v = 2.5 mm/s → $\lambda_{dB} = 15\ \mathrm{fm}$
- Existing Vienna OTIMA interferometer can cope with 200 fm.
  Can be stretched by 10x to apparatus size of L=0.5 m
- Time of flight :
  - 30 ms for 10^6 amu ⇒ OK on earth
  - **3 sec for 10^8 amu** → still OK in **drop tower** or **parabolic flight**
  - 300 s for 10^{10} amu ⇒ would work in microgravity

A tool for high-mass Quantum Interference
⇒ in microgravity or with stable levitation

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- Existing Vienna OTIMA interferometer can cope with 200 fm.
  Can be stretched by 10x to apparatus size of L=0.5 m
- Time of flight :
  - 30 ms for 10^6 amu ⇒ OK on earth
  - **3 sec for 10^8 amu** → still OK in **drop tower** or **parabolic flight**
  - 300 s for 10^{10} amu ⇒ would work in microgravity

A tool for high-mass Quantum Interference ⇒ in microgravity or with stable levitation

- Talbot-length: $L = g^2/\lambda$
- Smallest laser grating period : $g = \lambda/2 = 100\ \mathrm{nm}$
  (limits: a) existing lasers & b) $\lambda \gg D_{\mathrm{particle}}$)
- High mass and T=10 K $\rightarrow v = \sqrt{2kT/m}$
  - $m = \mathbf{10^6}$ amu → v= 0.4 m/s → $\lambda_{dB} = 1\ \mathrm{pm}$
  - $m = \mathbf{10^{10}}$ amu → v = 2.5 mm/s → $\lambda_{dB} = 15\ \mathrm{fm}$
- Existing Vienna OTIMA interferometer can cope with 200 fm.
  Can be stretched by 10x to apparatus size of L=0.5 m
- Time of flight :
  - 30 ms for 10^6 amu ⇒ OK on earth
  - **3 sec for 10^8 amu** → still OK in **drop tower** or **parabolic flight**
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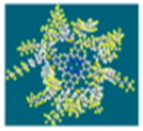
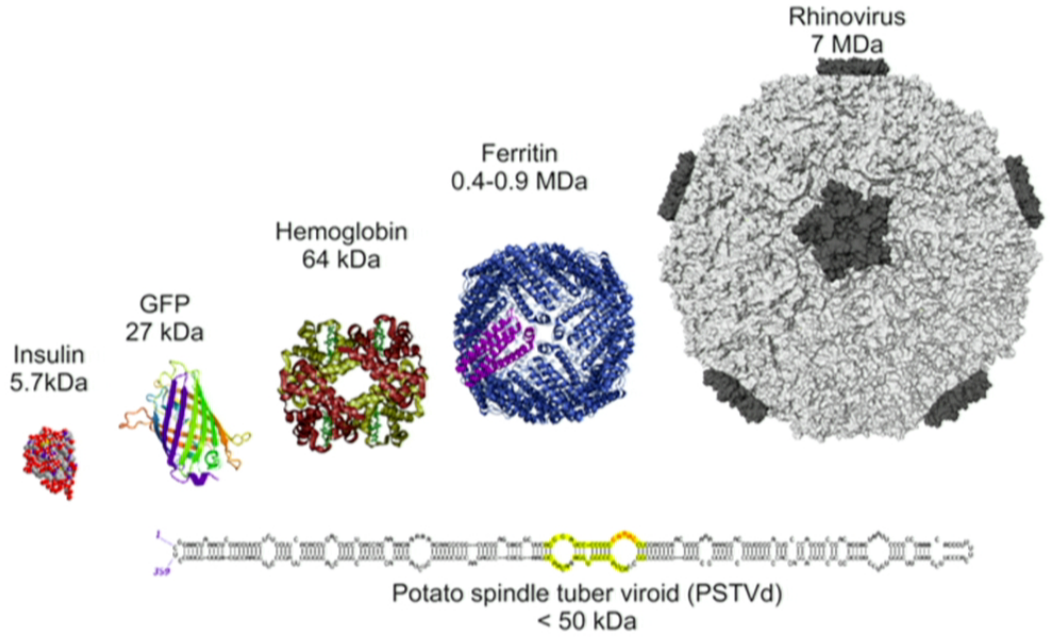


Prospects: large biomolecules !?



Require one of these ...

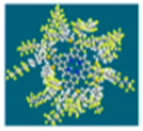
- New ionization techniques for biomolecules
- 1-photon isomerization gratings
- 1-photon fragmentation gratings
- Thermal gratings with detector responsive to internal energy

On the testability of CSL alternatives to QM

CSL assumes an extension of the Schrödinger equation by a non-linear term (the collapse)

HOWEVER:

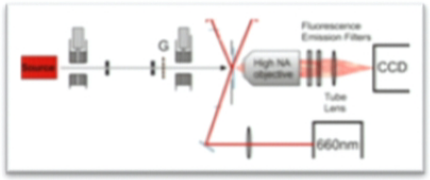
- **Same functional form as quantum decoherence by unkown particles → How could we ever distinguish**
  - **Quantum decoherence, which avoids genuine „reality“**
  - **CSL collapse which ‚almost‘ generates reality?**



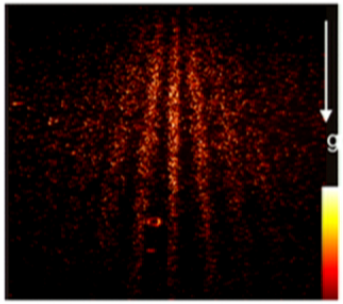
Summary and Outlook

GROUP: **Markus Arndt**

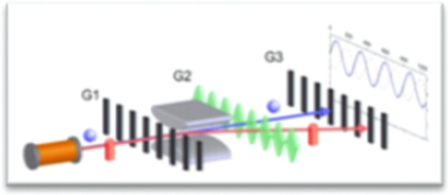
New methods for Far-Field Intererometry



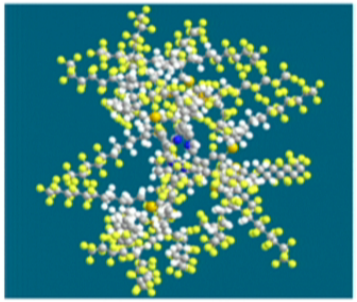
Juffmann et al.
Nature Nanotechn. (2011)



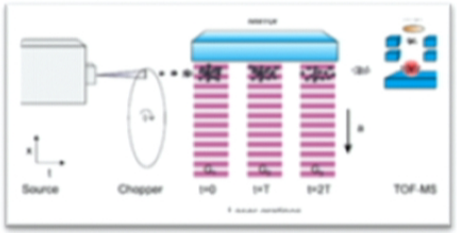
Highest Mass & Complexity In Quantum Interference



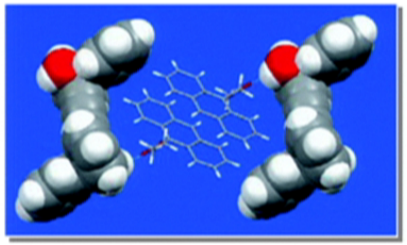
Gerlich et al. **Nature Communs. 2011**
Eibenberger et al. **PCCP (2012)**



An Ionizing Interferometer in the Time Domain



Haslinger et al.
Nature Phys. (2013)



Team 2012