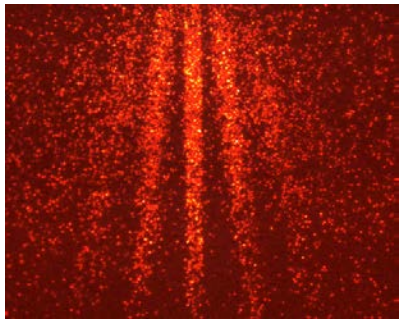
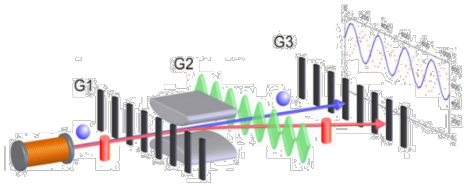
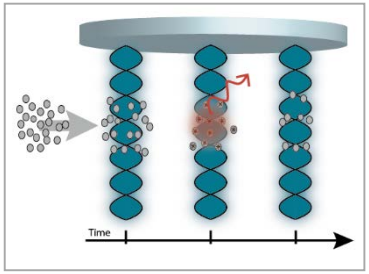
Experiments to Probe Quantum Linearity at the interface to Gravity & Complexity

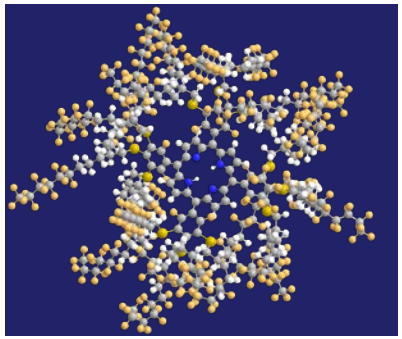


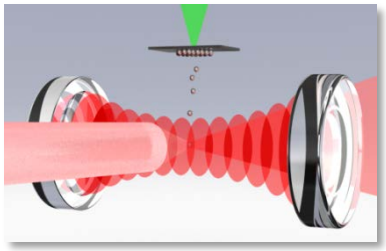


KDTL-Interferometry

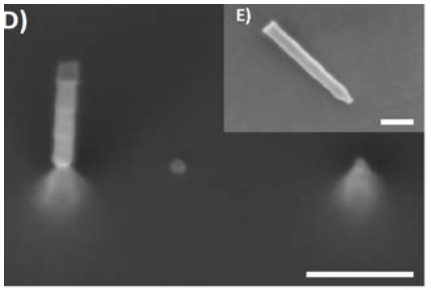


OTIMA-Interferometry





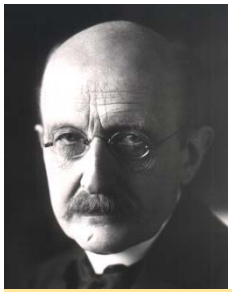
Cavity Cooling of Silicon



Rotating nanorods

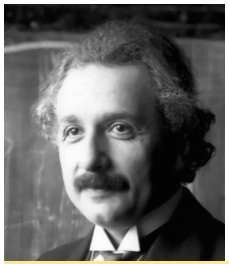
Markus Arndt
Universität Wien, Quantum Nanophysics Group
www.quantumnano.at

The origin of matter-wave physics



Quantum relation for light: $E = h \cdot \nu$

Max Planck, 1900



Special theory of relativity: $E = mc^2$ & Lorentz transformation

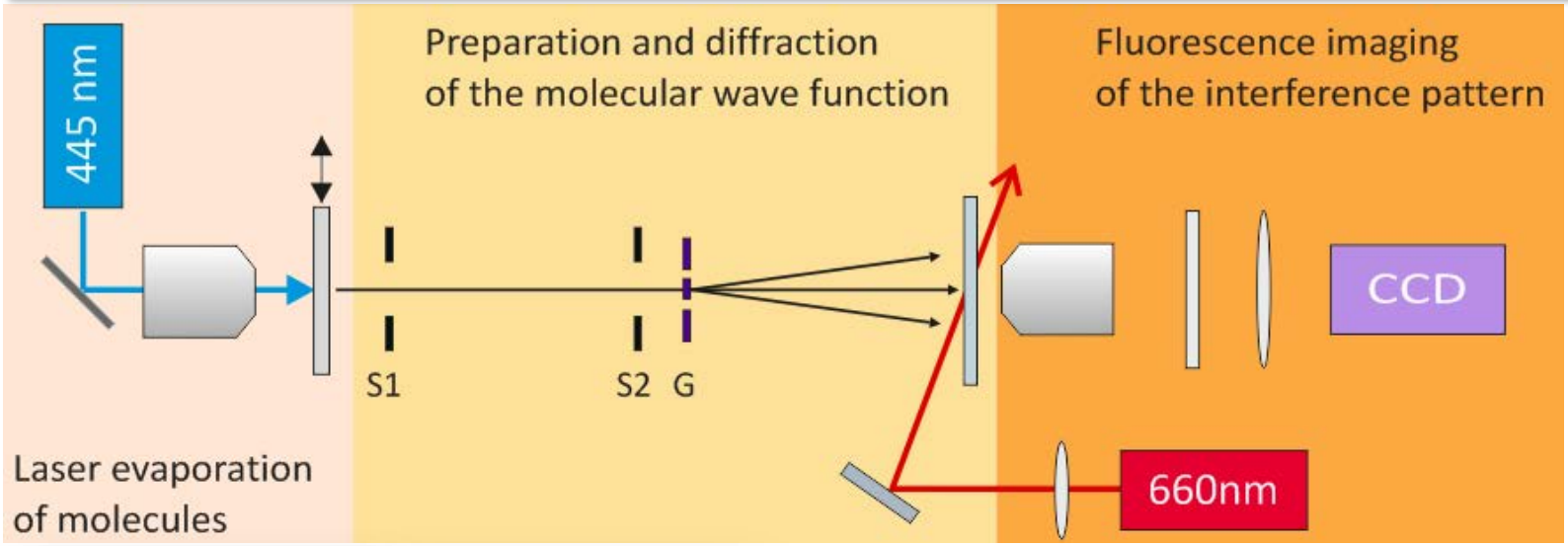
Albert Einstein, 1905

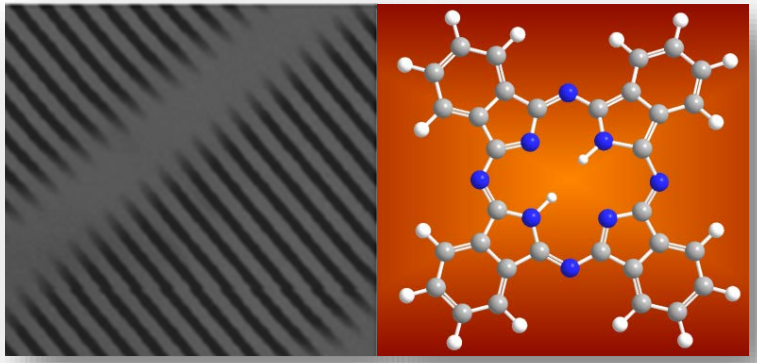
Matter waves: combining both theories → $\lambda = h/mv$

"An observer for whom a portion of matter is in steady motion […] will constantly see the internal periodical phenomenon in phase with with a wave […] By means of these new ideas, it will […] probably be possible to solve almost all the problems brought up by quanta."

L. de Broglie, 1923

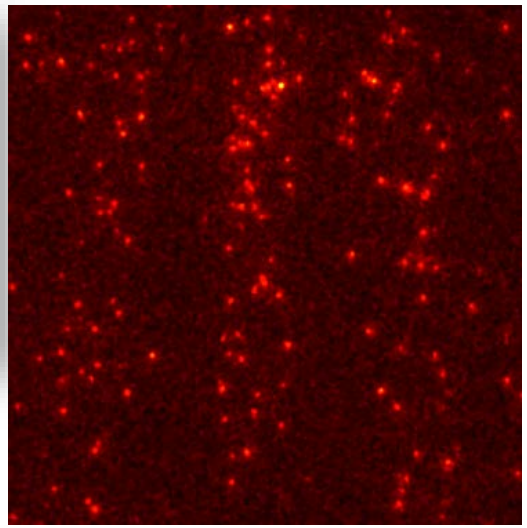
Visualizing Matter-Waves in single molecule diffraction
Here: Gravity is ‚only'a parameter

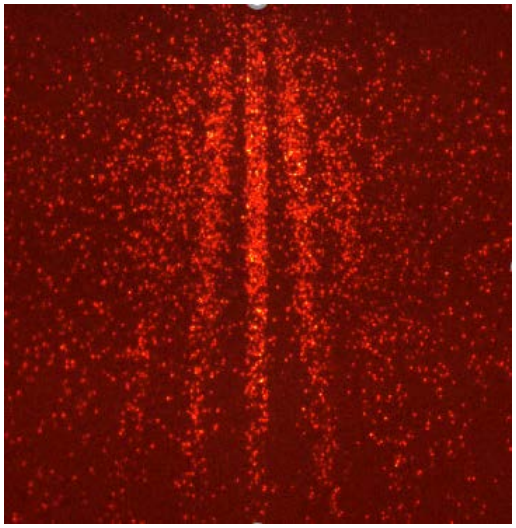




SiN Nanograting
d=100 nm, s=50 nm,
t=10 nm

Phthalocyanin
m=514 amu
$\lambda_{dB} = 5$ pm



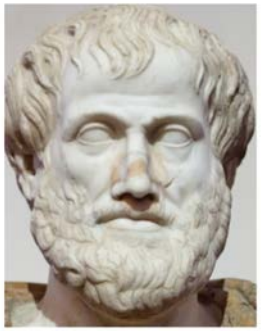


T. Juffmann, et al. **Nature Nano 7, 297 (2012)** & Brandt et al. **Nature Nano 10, 845-848 (2015).**

Our daily prejudices originate in Aristotle‘s ‚Sentence of non-contradiction‘

Aristotle, Metaphysica IV, 3 - 6, 8 (384 - 322 B.C.)

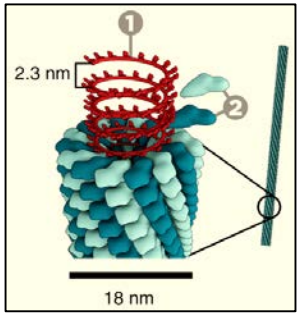
- … the same attribute **cannot** at the same time **belong and not belong** to the same subject … !
- … it is **impossible** for any one to believe the same thing **to be** and **not to be**
- … this at least is obviously true, that the word **'be' or 'not be' has a definite meaning …“**

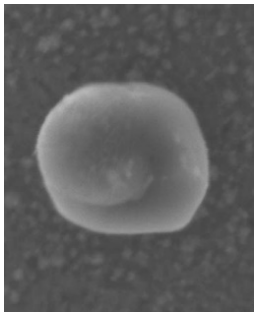


Why are quantum phenomena observed in the microscopic world, but rarely in our daily lives ?

What does gravity or the fabric of space-time have to do with it?

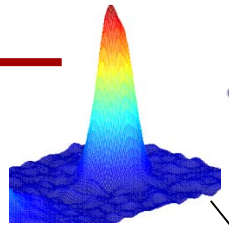
Pushing quantum experiments to a classical limit

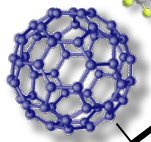


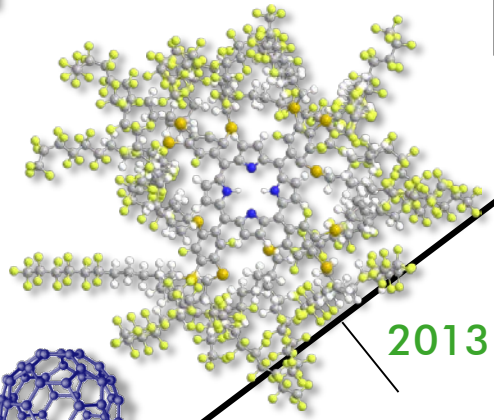


- Many atoms: 10^2-10^9
- Ultra-cold: 1 pK .. 1 μK
- Binding: neV

→ λ_{dB} : single atoms







GOAL:
m > 10^7-10^{10} amu

2013 m > 10.000 amu
810 atoms

1999 C_{60} & C_{70}

1995 BEC

Pritchard, MIT
Bordé, Paris

90's I_2, Na_2, He_2

80's Na, SF_6

1936 Neutron

1930 He atoms & H_2

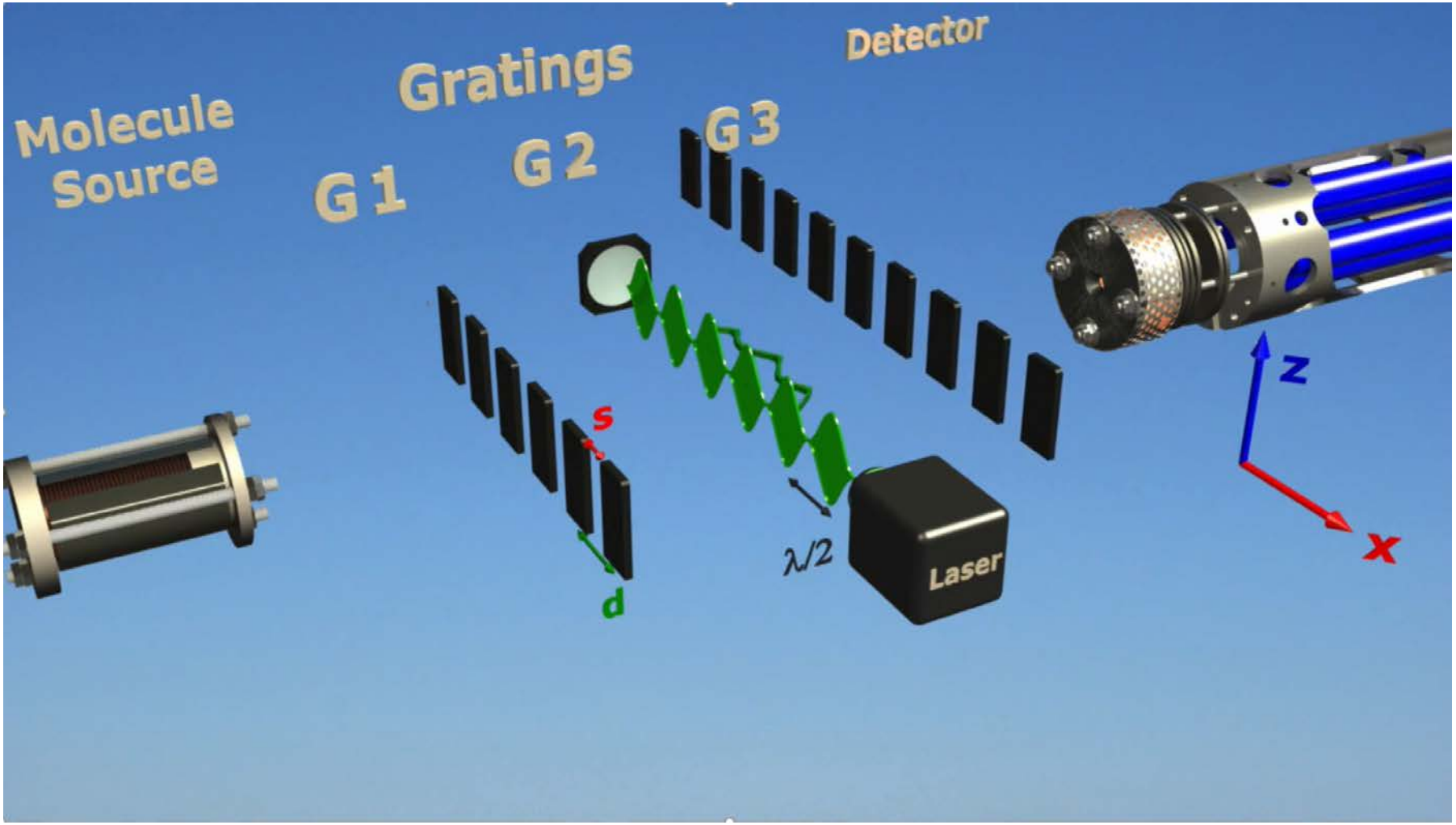
1927 Electron

1923 De Broglie hypothesis

- Many atoms: 10^2-10^6 ?
- Hot !: 4 K .. 1000 K
- Binding: 1..10 eV

→ λ_{dB}: entire complex

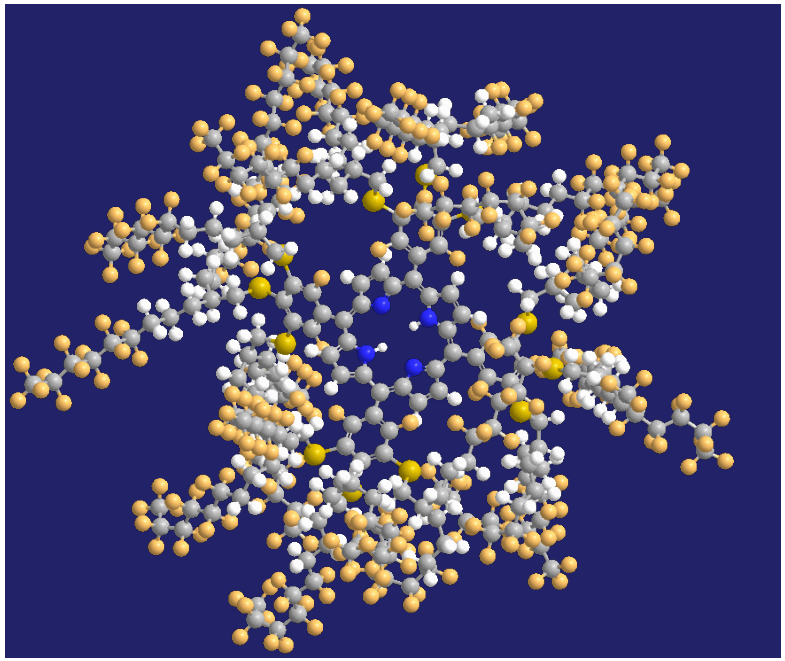
Kapitza-Dirac Talbot Lau Interferometer (KDTLI)
A tool for exploring high mass matter-waves



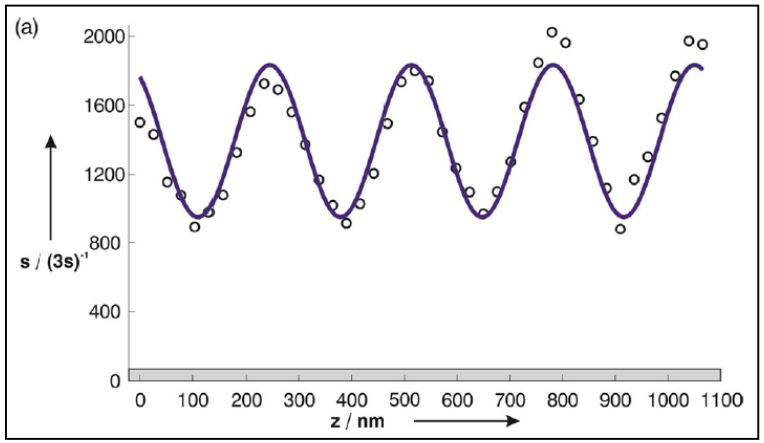
S. Gerlich, et al. **Nature Physics 3, 711 (2007).**
L. Mairhofer, S. Eibenberger, J.P. Cotter, M. Romirer, A. Shayeghi, M. Arndt, **Angew. Chem. Int. Ed. 56, 10947 (2017).**

Highest mass in matter-wave interference so far…

$C_{284}H_{190}F_{320}N_4S_{12}$
m=10‘123 amu, N = 810 Atoms



Molecular interferogram



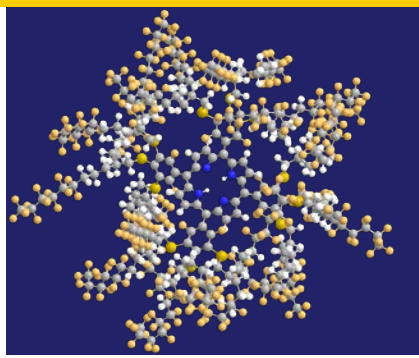
Also here:

- Gravity is used to sort the molecular velocities
- The grating slits are aligned with gravity
  → no gravitational phase shift

De Broglie wavelengths $\lambda_{dB} \simeq 300$ fm

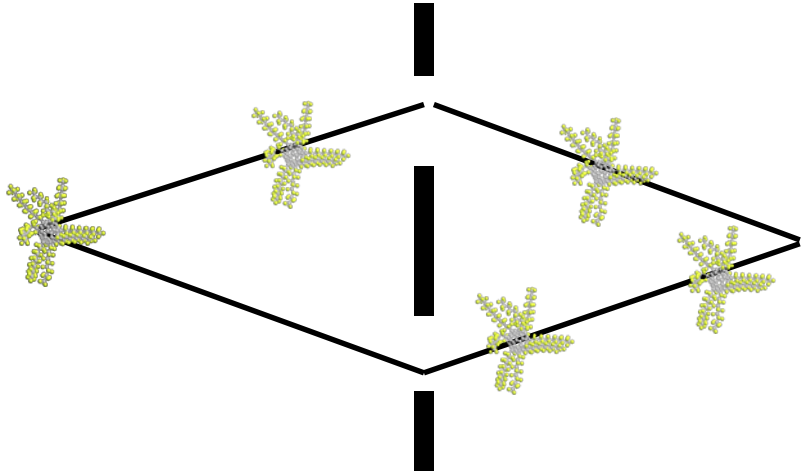
S. Gerlich, S. Eibenberger, M. Tomandl, S. Nimmrichter, K. Hornberger, P. Fagan, J. Tüxen, M. Mayor, M. Arndt, **Nature Comm. 2, 263 (2011)**
S. Eibenberger, S. Gerlich, M. Arndt, M. Mayor, J. Tüxen, **Phys. Chem. Chem. Phys. 15, 14696 (2013).**

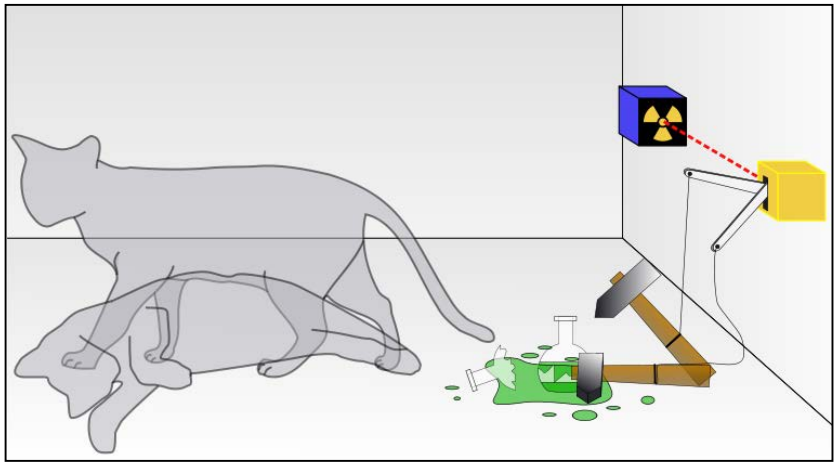
A Macromolecule as Schrödinger‘s cat ?



TPPF20

- Contains 810 atoms (like a small BEC)
- Contains one biodye (porpyhrin) in its center
- Is hotter than any living cat (500 K)
- Propagates in a superposition of multiple position states separated by 100× the molecular diameter





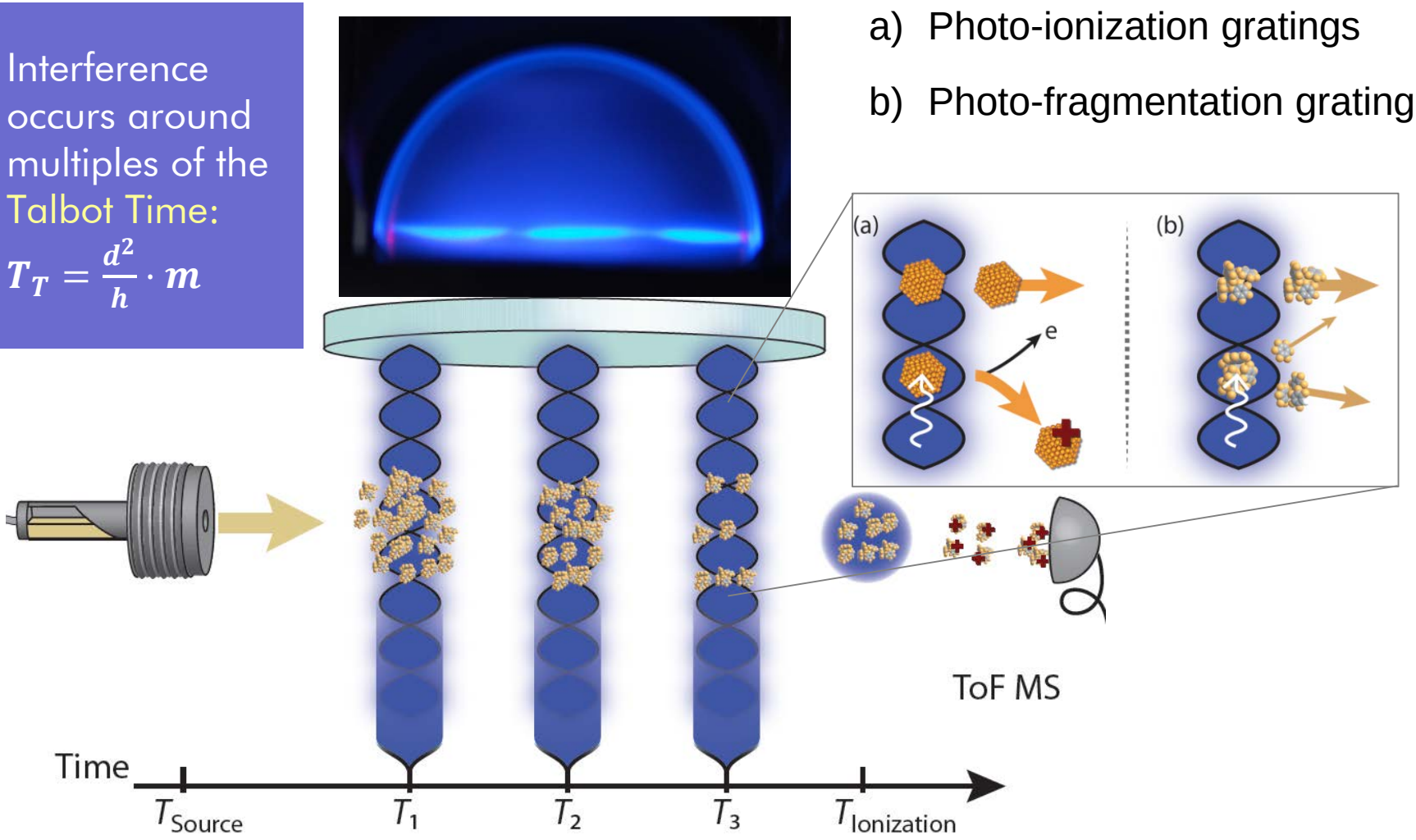
OTIMA: A near-field Interferometer with optical gratings for pulsed beams of molecular clusters and nanoparticles

Interference occurs around multiples of the Talbot Time:

$$T_T = \frac{d^2}{h} \cdot m$$

a) Photo-ionization gratings

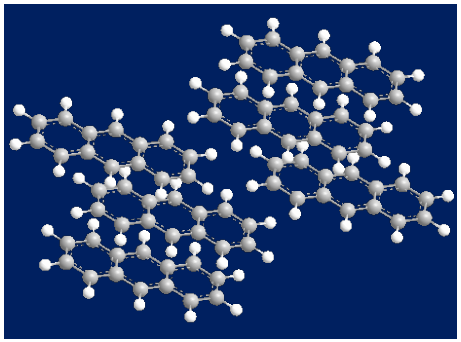
b) Photo-fragmentation gratings

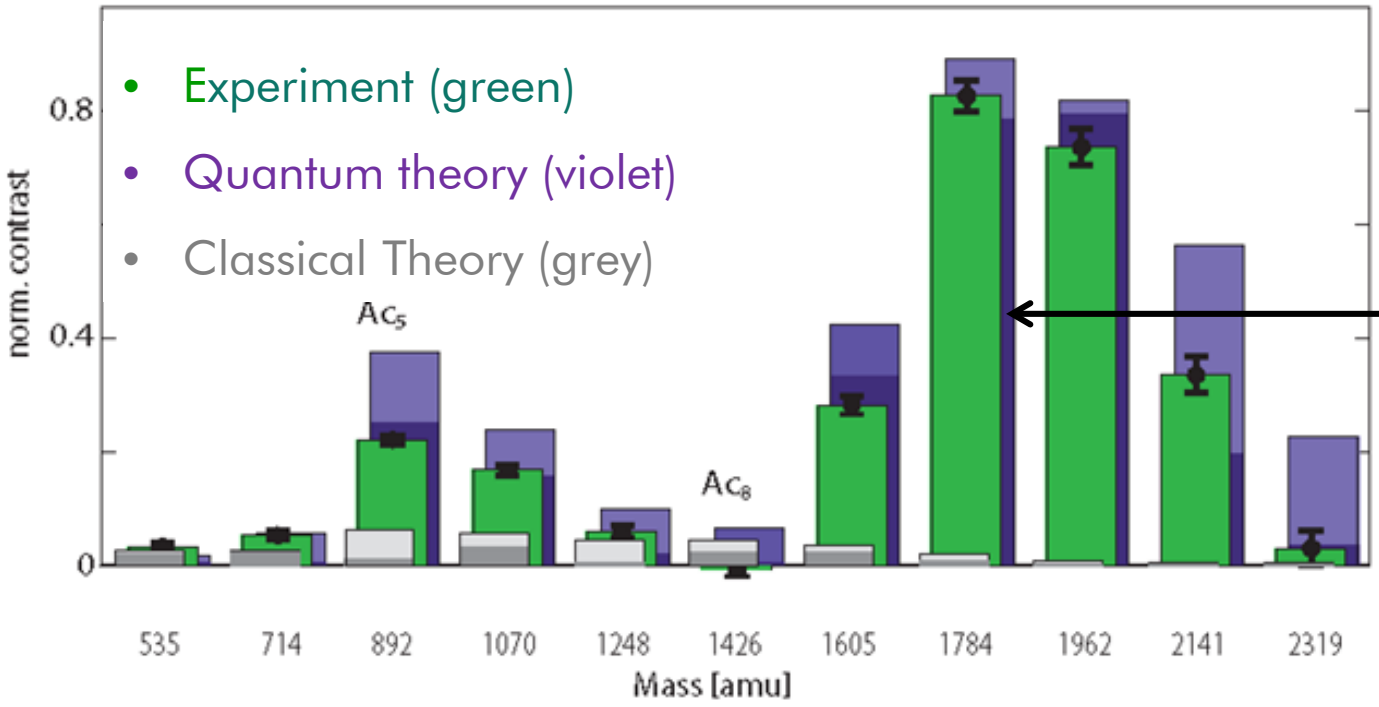


P. Haslinger, N. Dörre, P. Geyer, J. Rodewald, S. Nimmrichter, M. Arndt, **Nature Physics 9 ,144–148** (2013)

N. Dörre et al. **Phys. Rev. Lett., 113 (2014) 233001.**

Quantum interference of Anthracene clusters
Mass-dependent transmission



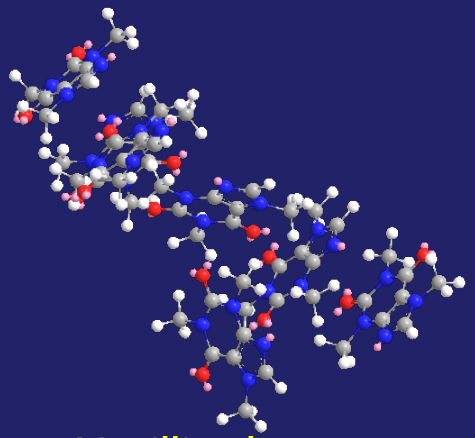


$\lambda_{dB} \simeq 200$ fm

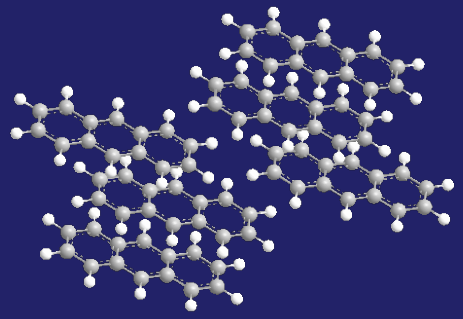
Supersonic cluster expansion and ToF selection
→ Constant particle velocity
→ De Broglie wavelength $\lambda_{dB} \propto 1/m$

P. Haslinger, N.Dörre, P. Geyer, J. Rodewald, S. Nimmrichter, and M. Arndt,
A universal matter-wave interferometer with optical ionization gratings in the time domain, Nature Physics 9, 144–148 (2013).

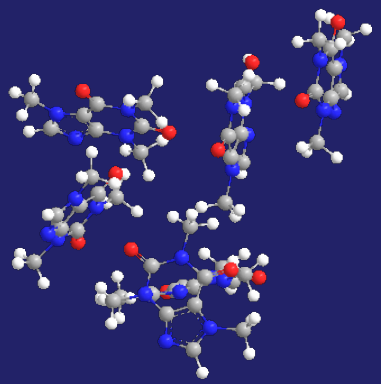
Quantum interference observed in OTIMA interferometry !



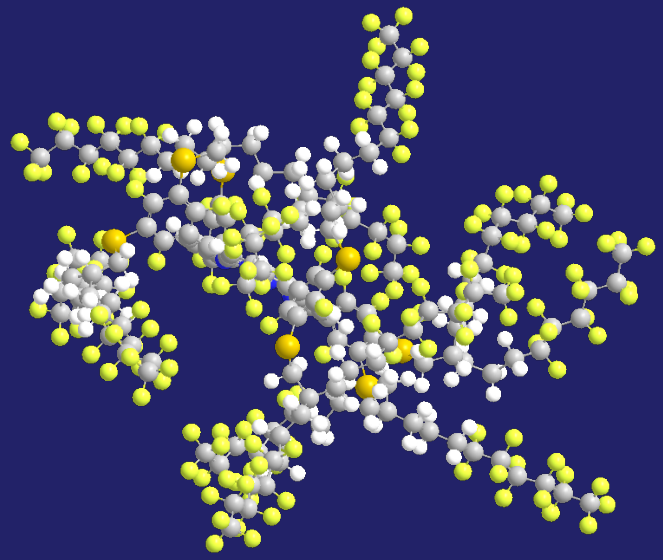
Vanillin cluster
(n=2…15)



Anthracene cluster
(n=3…12)

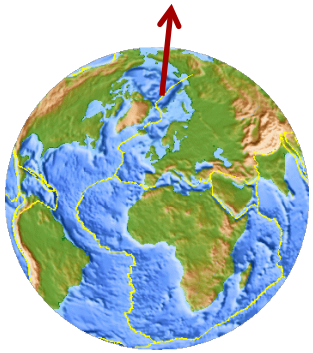


Caffein cluster
(n=3…12)



Pefluoroalkyl-functionalized
Tetraphenlyporphyrin, 6308 amu

Does it matter that we work on Earth ?



- Any **constant acceleration a** of the particle leads to a **fringe shift:**

$$\Delta x_F = a\,T^2 = a\,L^2/v^2$$

→ Averaging over velocities reduces the interference contrast

Earth's gravity: $a = g$

$$\Delta x_{\mathrm{grav}} = g\left(\frac{L}{v}\right)^2$$

Can be compensated for in time-domain interferometry

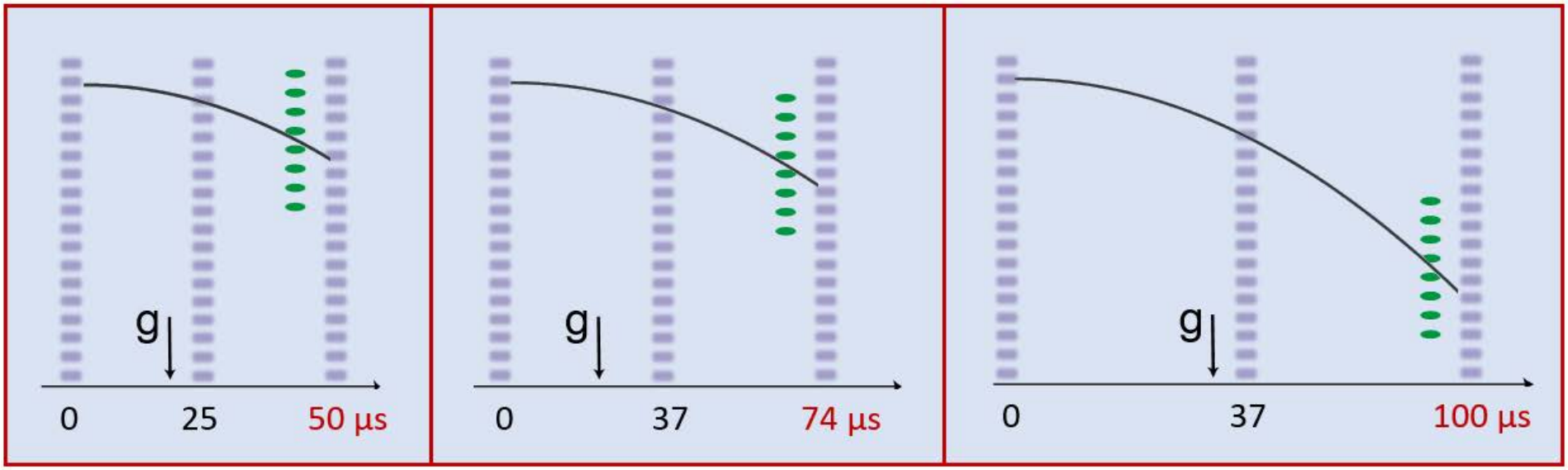
Earth's rotation: $a = 2\,v \times \Omega$

$$\Delta x_{\mathrm{rot}} = 2\vec{v} \times \vec{\Omega}\left(\frac{L}{v}\right)^2$$

Dispersive effect even in time-domain interferometry

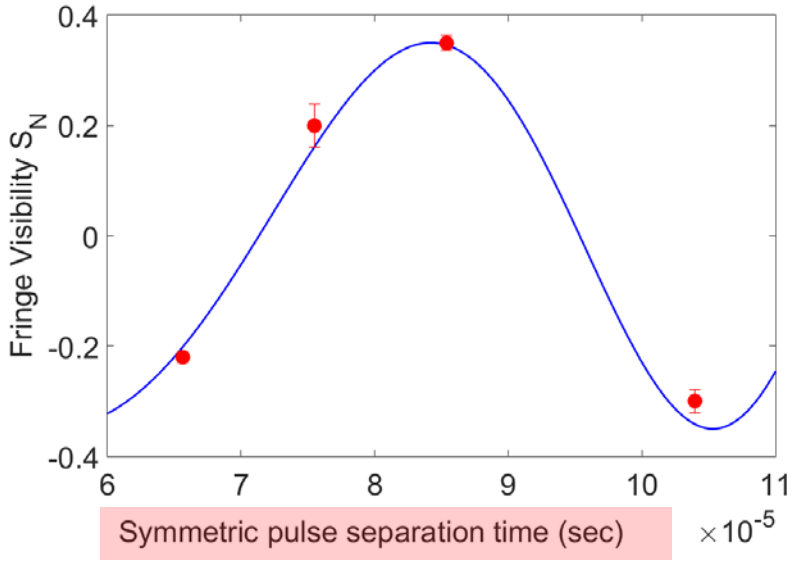
- In our interferometers even relative height differences of ΔH =30 pm between two interferometer arms are measurable, because of the gravitational phase shift

A molecular interference pattern as a nanoruler to measure free fall
Here: scanning the grating separation in OTIMA interferometry



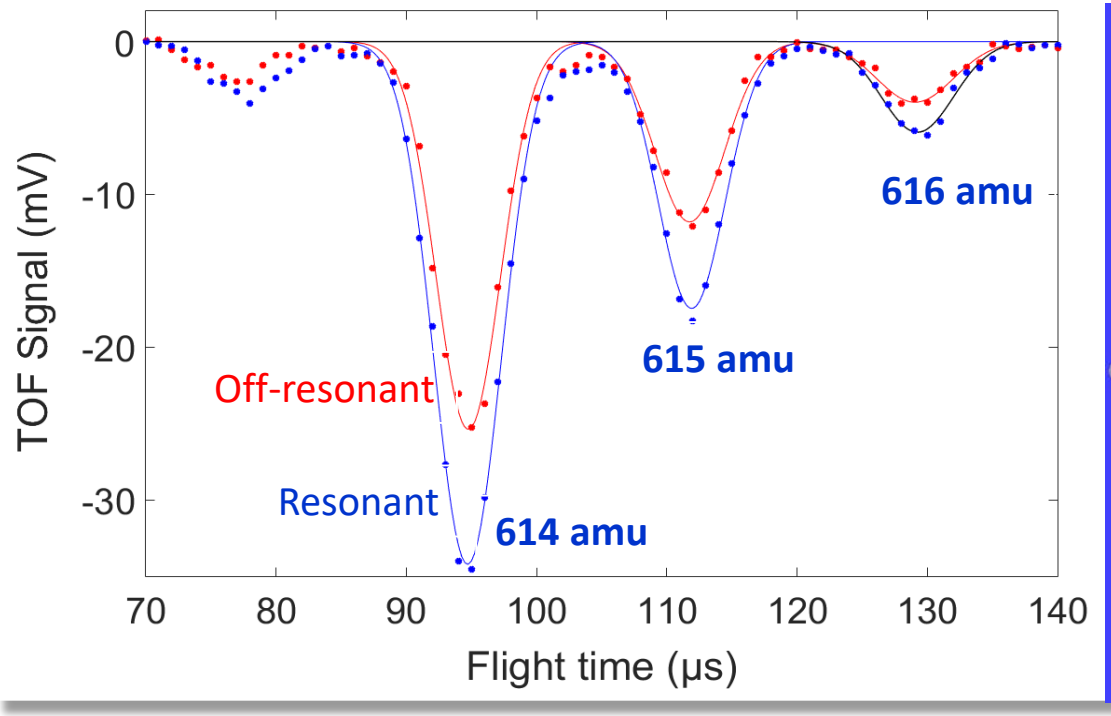
Symmetrically stretching the interferometer in time:

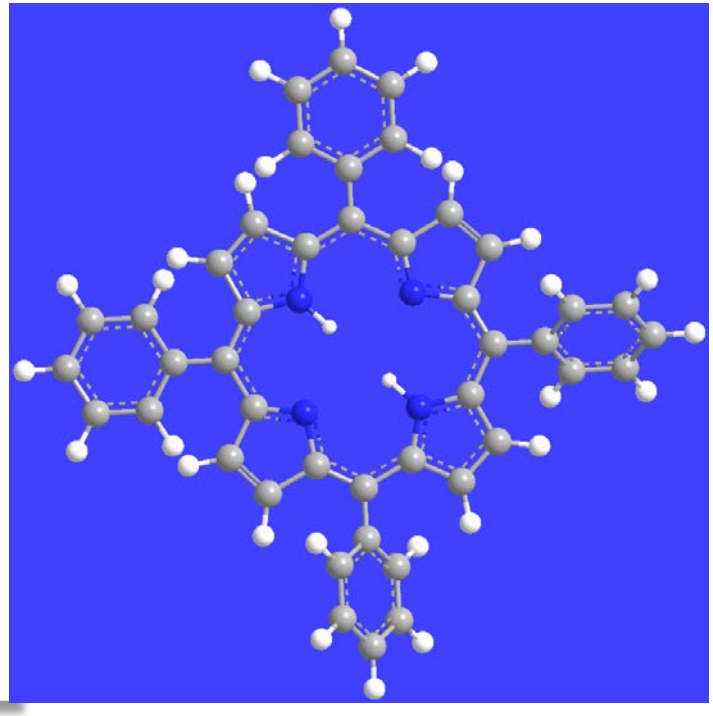
→ Gravitational acceleration "g"



Isotope-selective interference in free fall: the case of TPP

Fixed Talbot length. Varying isotopes = varying the isospin-mass ratio.





- **Isotopically pure bosonic TPP:** >50%
- Fermion with **one ^{13}C:** 30 %
- Boson with **two ^{13}C atoms:** 7%
- Fermion with **three ^{13}C atoms:** 1%.

- **Proof of principle:** $\eta = 1$ %
- Future with T_{flight} = 100 ms → $\eta = 10^{-8}$
- **What can we learn from it ?**

Rodewald J, et al. **New J. Phys. 20, 033016 (2018).**

Could there be any non-standard coupling of a delocalized quantum object with gravity ?

1) Angular Momentum ?

- Multiple isospin ratios in the same beam → tested here
- Structure has angular momentum → tested here
- Delocalized aromatic systems → tested here

2) Vibrational superposition in free fall

3) Chirality ?

4) Other forms of energy than rest mass?

- Binding energy & thermal energy > 10 keV in 10^7 amu virus

Do gravitational or cosmological perturbations impose any limits to free matter-wave evolution ??

- **Gravitational wave background:** contrast falls $\propto \exp\left[-\left(\frac{mv^2 \sin \alpha_{split}}{\omega_{GW}}\right)^2\right]$

  Reynaud group: Phys. Rev. Lett. 96 (2006). & Gen. Rel. Grav. 36, 2271 (2004)

- **Gravity induced dephasing of clocks:** dephasing rate $\propto \sqrt{N_{osc}} \cdot \Delta x \cdot T\ [K]$

  Brukner group: Nature Comm. 2, 505 (2011), Nat. Phys. 11 668 (2015).

- **State diffusion on space-time fluctuations:** dephasing $\propto m^2$

  C. Wang et al.: Class. Quantum Grav. 23, L59 (2006).

- **Low-mass, strongly coupling Dark Matter:** decoherence $\propto m^2$

  J. Riedel, I. Yavin: Phys. Rev. D 96, (2017).

- **Continous Spontaneous Localization:** rate $\propto m^2$

  Ghirardi, Rimini, Weber, Pearl: Phys. Rev. D 34, 470 (1986)

- **Gravity-induced collapse of the wave function:** rate $\propto m^2$

  Diosi/Penrose: Phys. Lett. 105 A, 199 (1984), Gen. Rel. Grav. 28, 581 (1996)

- **Newton-Schrödinger equation:** effects grow $\propto m^2$

  Giulini et al. Class. Quant. Grav. 25, 154010 (2008)

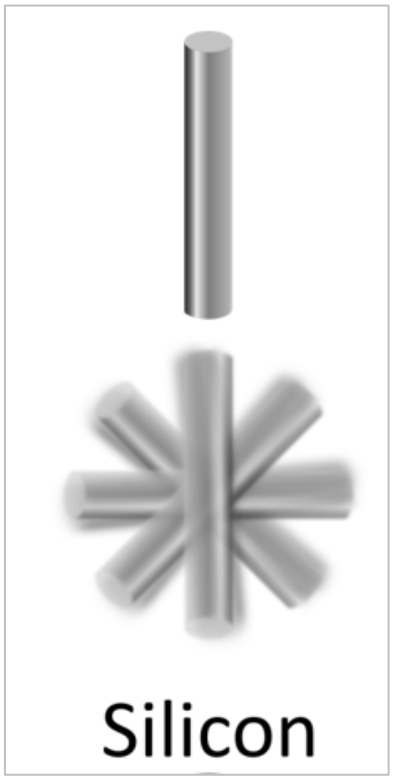
GRT

Q-G

DM

G-induced Non-linear QM

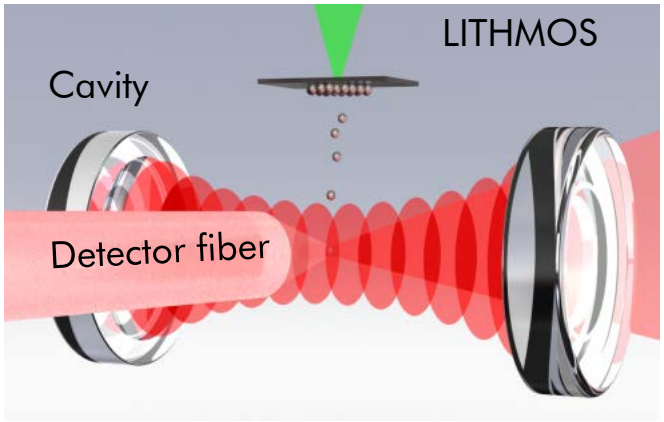
The next step in High-mass Quantum Interference
1. Towards de Broglie intererence of 10^7 amu
2. Rotational states interference

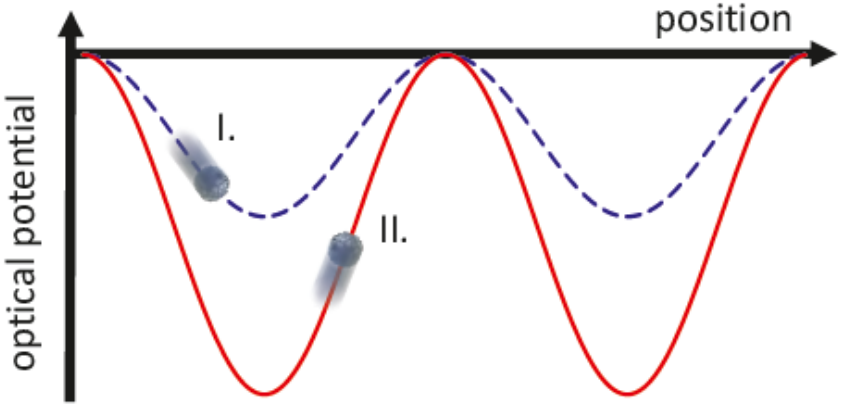


- Talbot-length: $L_T = d^2/\lambda_{dB}$, Talbot time: $T_T = m \cdot d^2/h$
- Optical grating period : $\mathrm{d} = \lambda_L/2 \simeq 106.5\ \mathrm{nm}$
- High mass and $\boldsymbol{T = 10\ K}$ $\rightarrow \mathrm{v} = \sqrt{2k_B T/m}$
  - $\boldsymbol{m = 10^6}$ amu $\rightarrow$ v= 0.4 m/s $\rightarrow \lambda_{dB} = 1\ \mathrm{p}m$
  - $\boldsymbol{m = 1010}$ amu $\rightarrow$ v = 2.5 mm/s $\rightarrow \lambda_{dB} = 15$ fm
    $\rightarrow$ Compatible with our interferometers
- But: The coherence times are challenging
  - 300 ms for 10^7 amu $\Rightarrow$ OK in a fountain in the Lab
  - 3 s for 10^8 amu $\Rightarrow$ OK in a drop tower or mine shaft
  - 300 s for 10^{10} amu $\Rightarrow$ requires satellite or phase-stable levitation
- Collimation < 1 mrad $\rightarrow$ T < 10 μK to stay on the detector

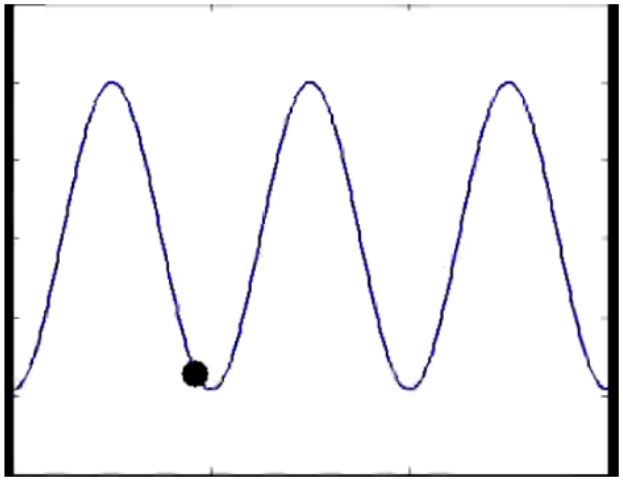
How to cool the linear motion of nanoparticles ?

Silicon nanoparticles in a high finesse cavity





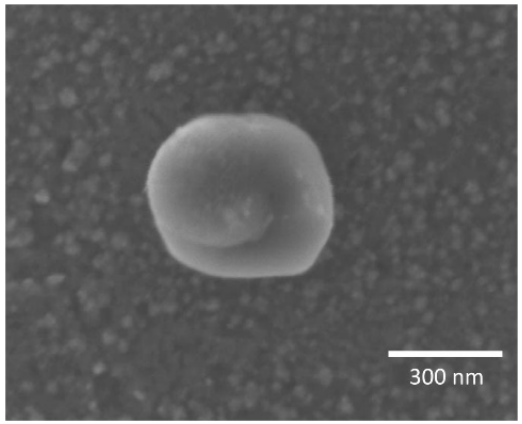
- Laser red-detuned to cavity
- Incident particle = refractive index
  → stretches the optical path length
- More light enters
  → stronger dipole potential
- Delayed response by cavity
  → Sisyphus effect.

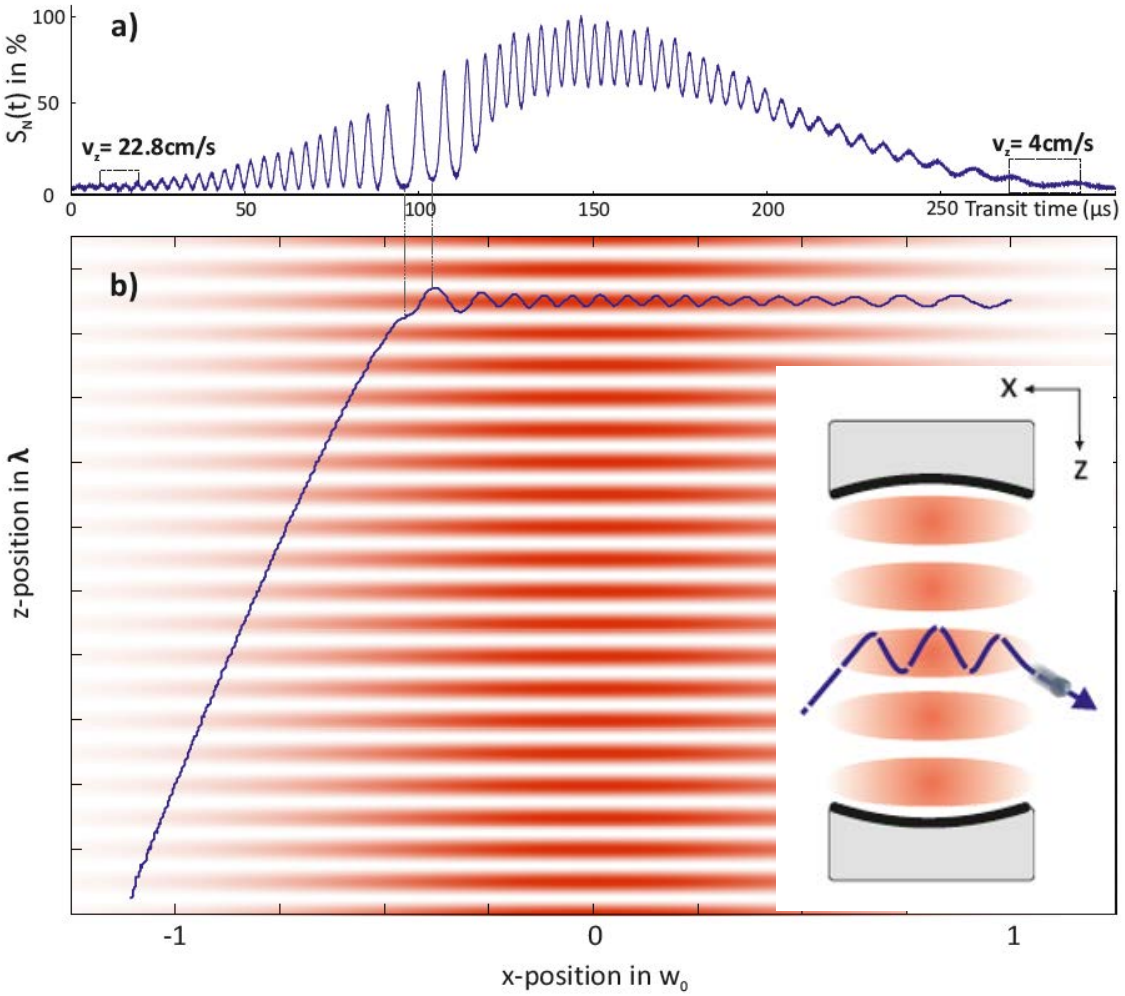


Cavity cooling of 10^{10} amu Si nanoparticles from 23 cm/s → 4 cm/s

Cavity cooling:

$$E_{\text{in}}^{T} = 30\times\ E_{\text{out}}^{T}$$





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Do gravitational or cosmological perturbations impose any limits to free matter-wave evolution ??

- **Gravitational wave background:** contrast falls $\propto \exp\left[-\left(\frac{mv^2 \sin \alpha_{split}}{\omega_{GW}}\right)^2\right]$
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- **Gravity induced dephasing of clocks:** dephasing rate $\propto \sqrt{N_{osc}} \cdot \Delta x \cdot T\ [K]$
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- **State diffusion on space-time fluctuations:** dephasing $\propto m^2$
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- **Low-mass, strongly coupling Dark Matter:** decoherence $\propto m^2$
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- **Continous Spontaneous Localization:** rate $\propto m^2$
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- **Gravity-induced collapse of the wave function:** rate $\propto m^2$
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- **Newton-Schrödinger equation:** effects grow $\propto m^2$
  Giulini et al. Class. Quant. Grav. 25, 154010 (2008)

GRT

Q-G

DM

G-induced Non-linear QM

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European Research Council

Team today:

Far-field:
- Christian Brand
- Stephan Troyer

OTIMA
- Georg Richter
- Philip Rieser
- Armin Shayeghi

CAVITY
- Stefan Kuhn

Bio Sources
- Moritz Kriegleder
- Philipp Geyer
- Philipp Rieser
- Maxime Debiossac

LUMI
- Yaakov Fein
- Philipp Geyer
- Lukas Mairhofer
- Stefan Gerlich

THEORY
- Filip Kialka

Former coworkers:

Far-field:
- Thomas Juffmann
- Cristian Knobloch
- Michele Sclafani

OTIMA
- Nadine Dörre
- Andrea Grimaldi
- Philipp Haslinger
- Jonas Rodewald

Bio Sources
- Ugur Sezer
- Maxime Debiossac

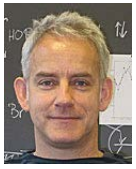
CAVITY
- Peter Asenbaum
- James Millen
- Franz Wieser

KDTLI
- Sandra Eibenberger
- Joe Cotter
- Hendrik Ulbricht
- Lucia Hackermüler
- Lukas Mairhofer

THEORY
- Stefan Nimmrichter

Collaborations

Klaus Hornberger



Marcel Mayor

Ori Cheshnovsky

Valentin Köhler

Angelo Bassi

Fernando Patolsky

Michael Trupke

Benjamin Stickler