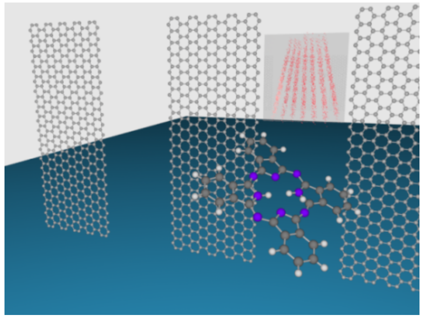
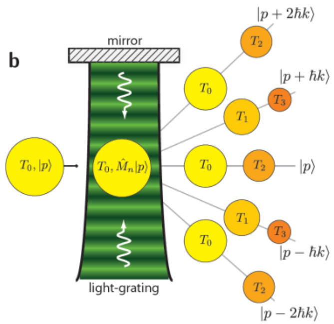
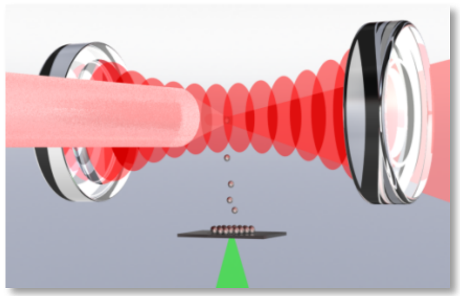
An introduction to matter wave interferometry with Atoms, molecules and nanoparticles







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

Why matter-waves in the 21st century ? (1)

1. Atoms

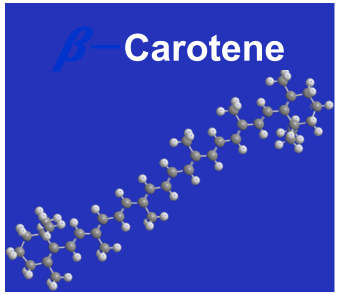
- Fundamental physics
  - Tests of the equivalence principle
  - Precision measurements of fundamental constants α, G, ...
  - Tests of general relativity (red shift)
  - Search for forces on small length scales (5th forces, higher dimensions)
  - Search for gravity waves

- Inertial navigation
  - Gain independence from GPS

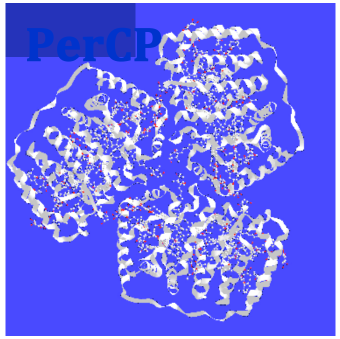
- Geodesy
  - Search for natural resources
  - Determine geological water tables
  - Seismic monitoring

Why matter-waves in the 21st century ? (2)

2. Biomolecules & Nanoparticles



- **Small biomolecules**
  - Quantum assisted **measurements** of $\alpha, \chi_{el}, d, \chi_{mag}, \mu, \sigma_{opt}$?
  - Can we realize „Schrödinger‘s cat“ in a **biomimetic environment**?
  - Complexity → New **decoherence** mechanisms ?

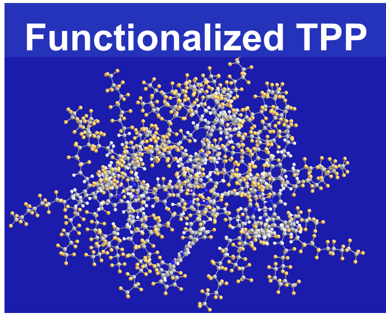


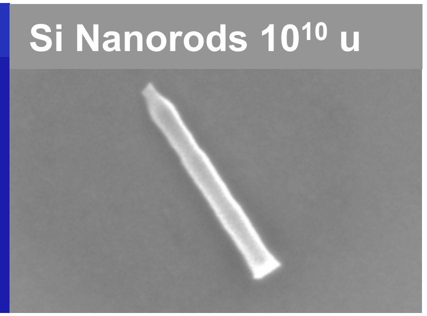
- **Large biomolecules**
  - Can we delocalize large bionanomatter, such as **DNA, proteins**… ?
  - Is quantum delocalization compatible with **biological functionality** ?

- **Nanoparticles (**OTIMA → see Jonas Rodewald‘s talk**)**
  - Are there any **mass limits** to quantum superpositions ?
  - Can we find indications for spontaneous **collapse** models ?
  - **Future:** Can **gravitational modifications of QM** be explored ?

See also:

- Kaltenbaek et al. (MAQRO),
- Bateman, Ulbricht et al.,
- Ghirardi, Bassi, Giulini, …





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Diffraction “of atoms” & “at atoms”

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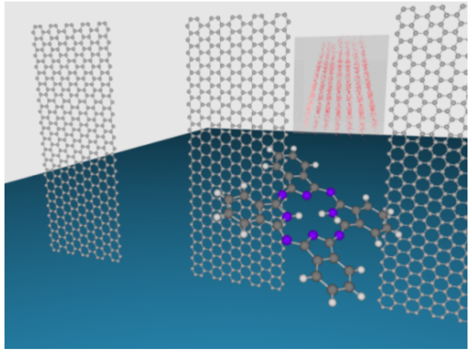
Brand et al. **(2015)**



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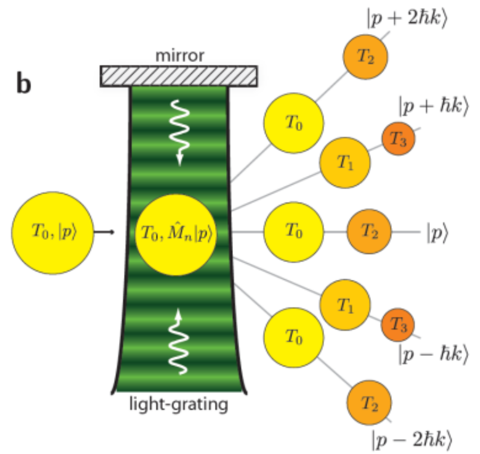

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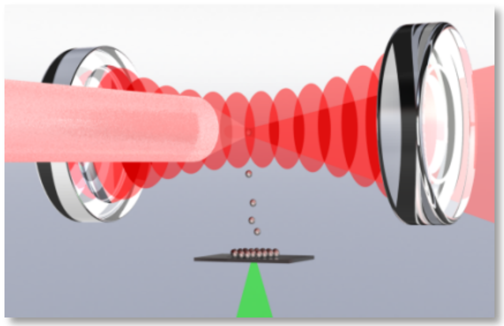
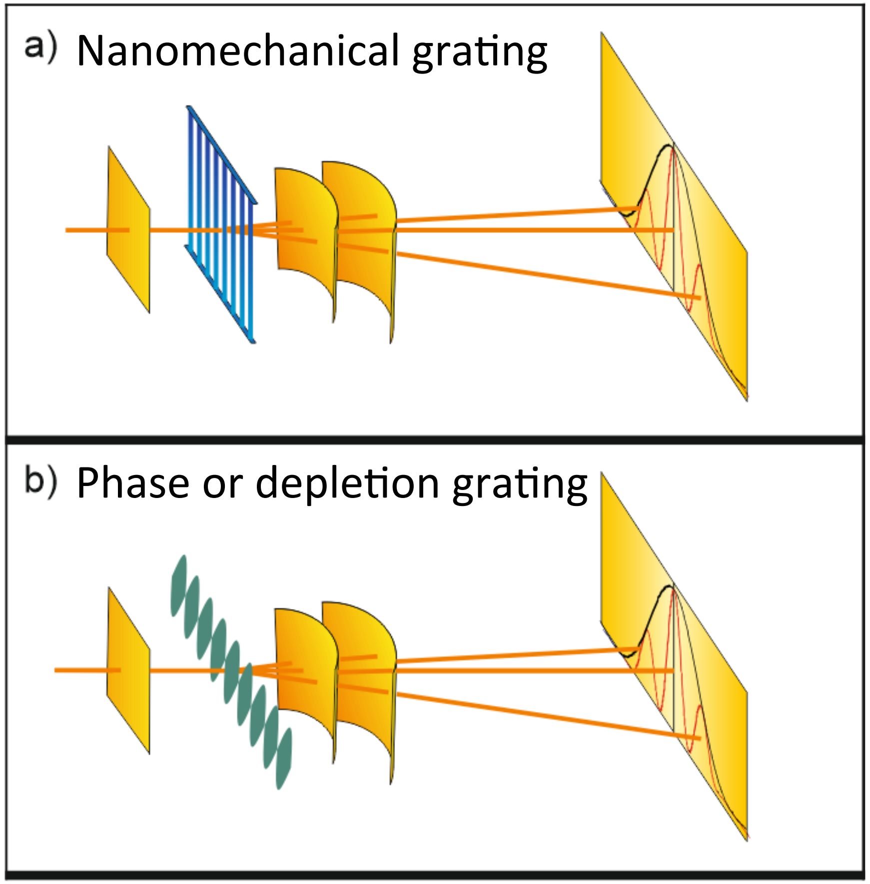


Typical beam splitters for atoms

Wave-front beam splitters

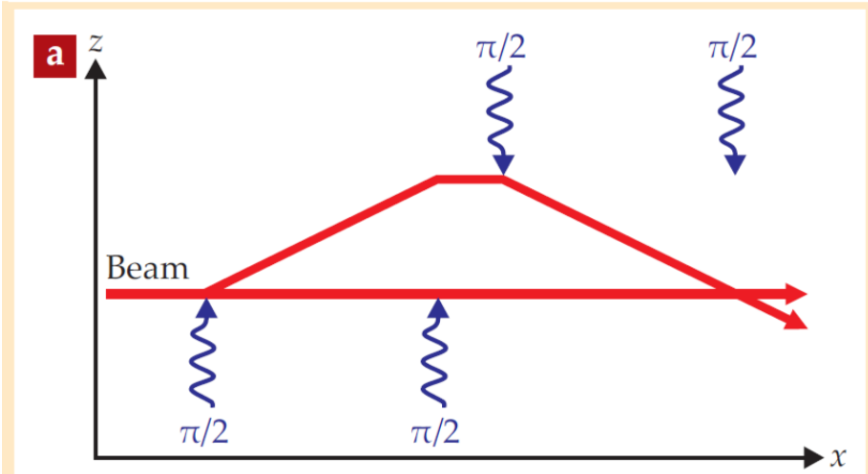


Rabi frequency: $\Omega = d_A E_L / \hbar$ → Beam splitter = ¼ Rabi cycle: $\int \Omega \, d\tau = \pi/2$

Some prototypical Atom Interferometers

Ramsey-Bordé interferometer

- $4\times\pi/2$ – Pulses
- $|g\rangle \rightarrow \propto |g,\boldsymbol{p}_0\rangle + e^{i\phi}|e,\boldsymbol{p}_0+\hbar\boldsymbol{k}\rangle$



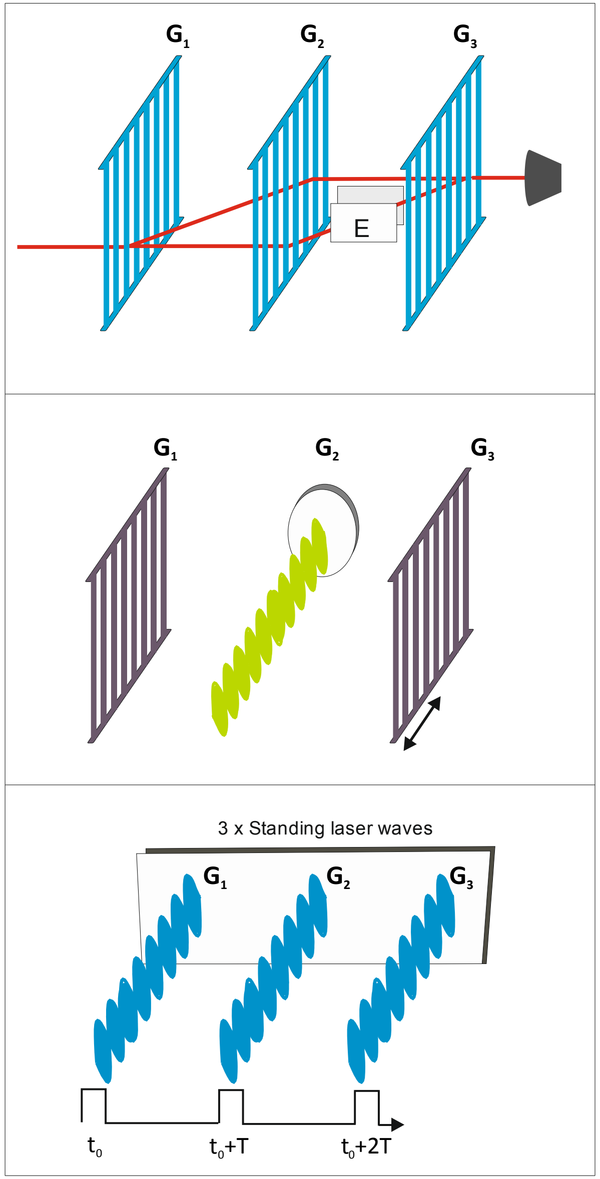
M. Arndt, **Phys. Today, 67** 30-36 (2014) .

„Universal“ Interfeormeters use wave-front beam splitters

1. **Nanomechanical beam splitters**
2. **Optical Phase Gratings**
3. **Optical Depletion Gratings**

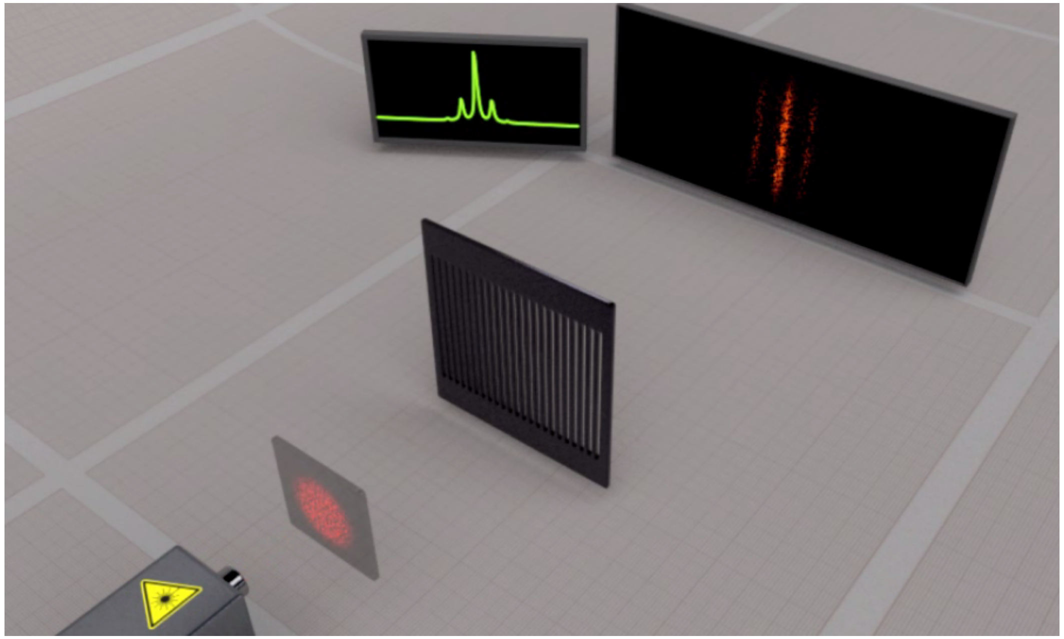
Far-field:
Mach-Zehnder Interferometry

Near-field:
Talbot-Lau Interferometry

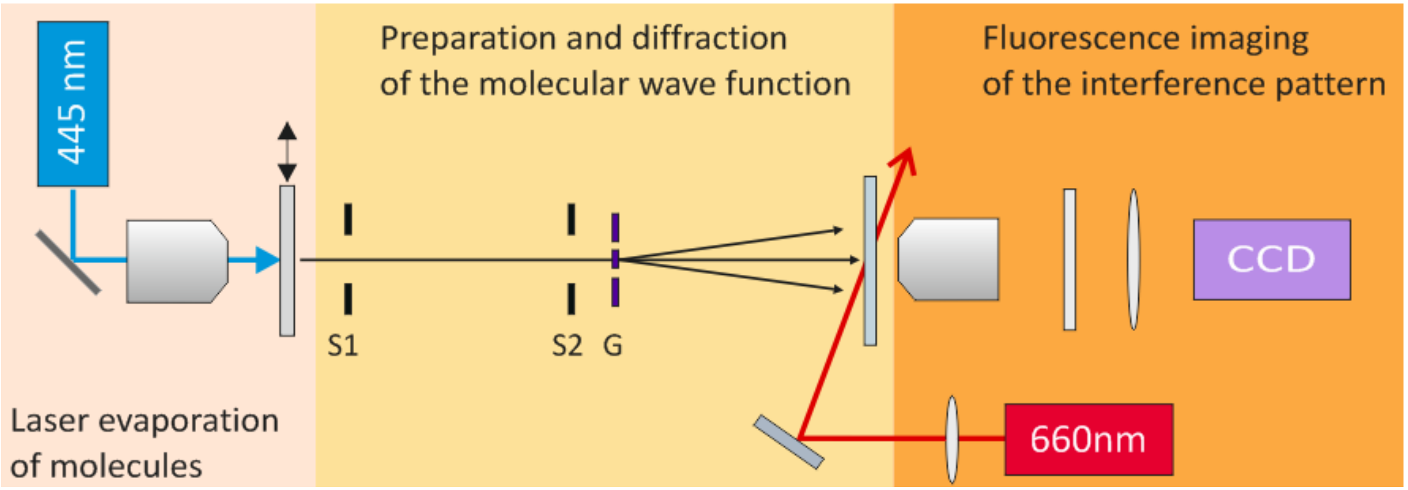


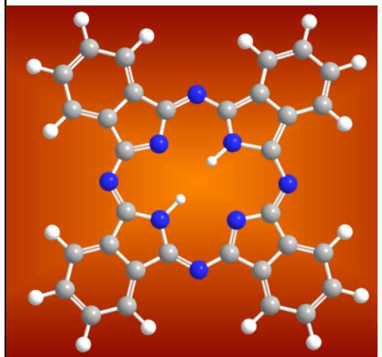
Single Molecule Diffraction at a Nanograting

Gratings by
O. Cheshnovsky
Tel Aviv Univ.



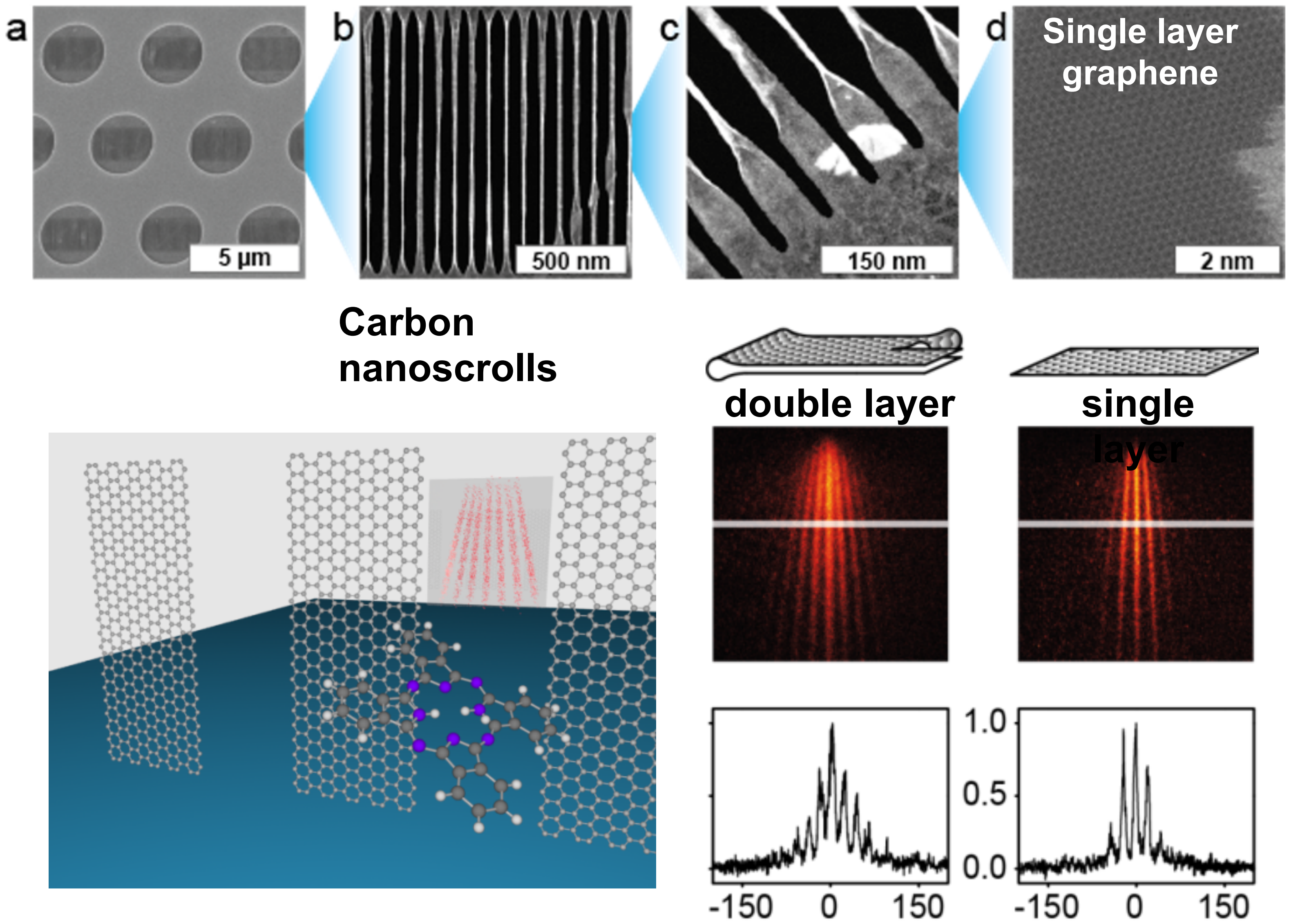
$m = 514$ amu
$v = 100 m/s$
$\lambda_{dB} = 5$ pm





Phthalocyanin

The thinnest conceivable diffraction element?
Single layer graphene!



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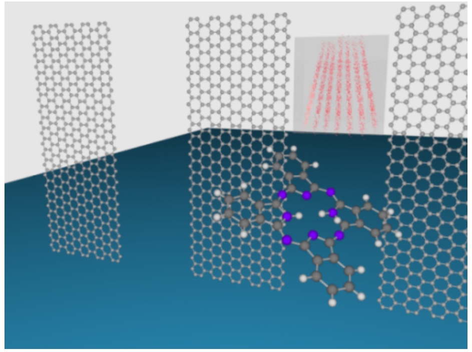

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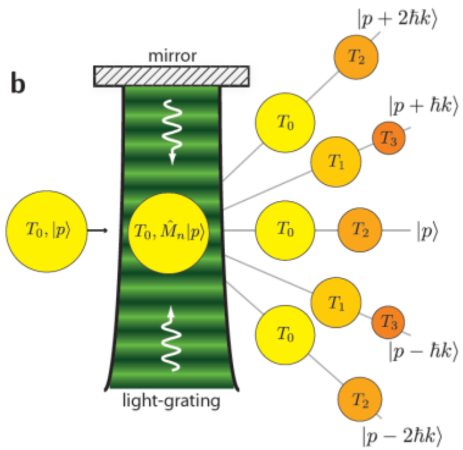

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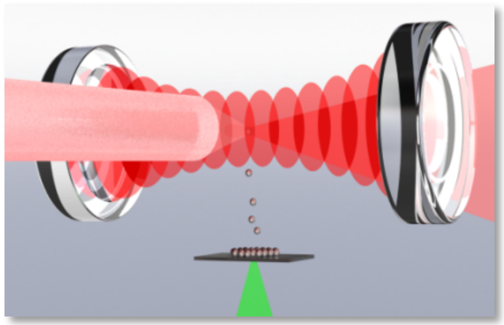
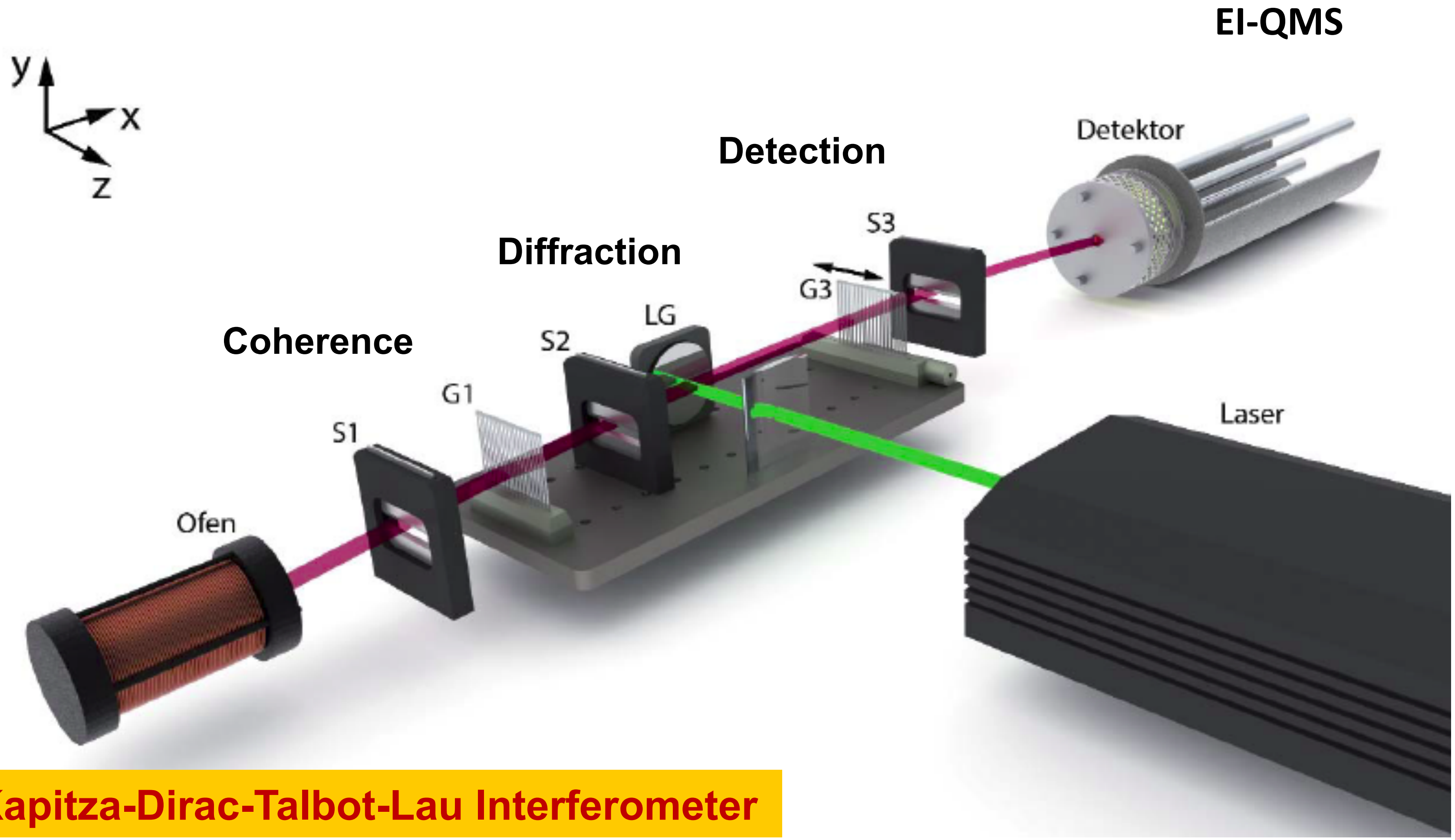


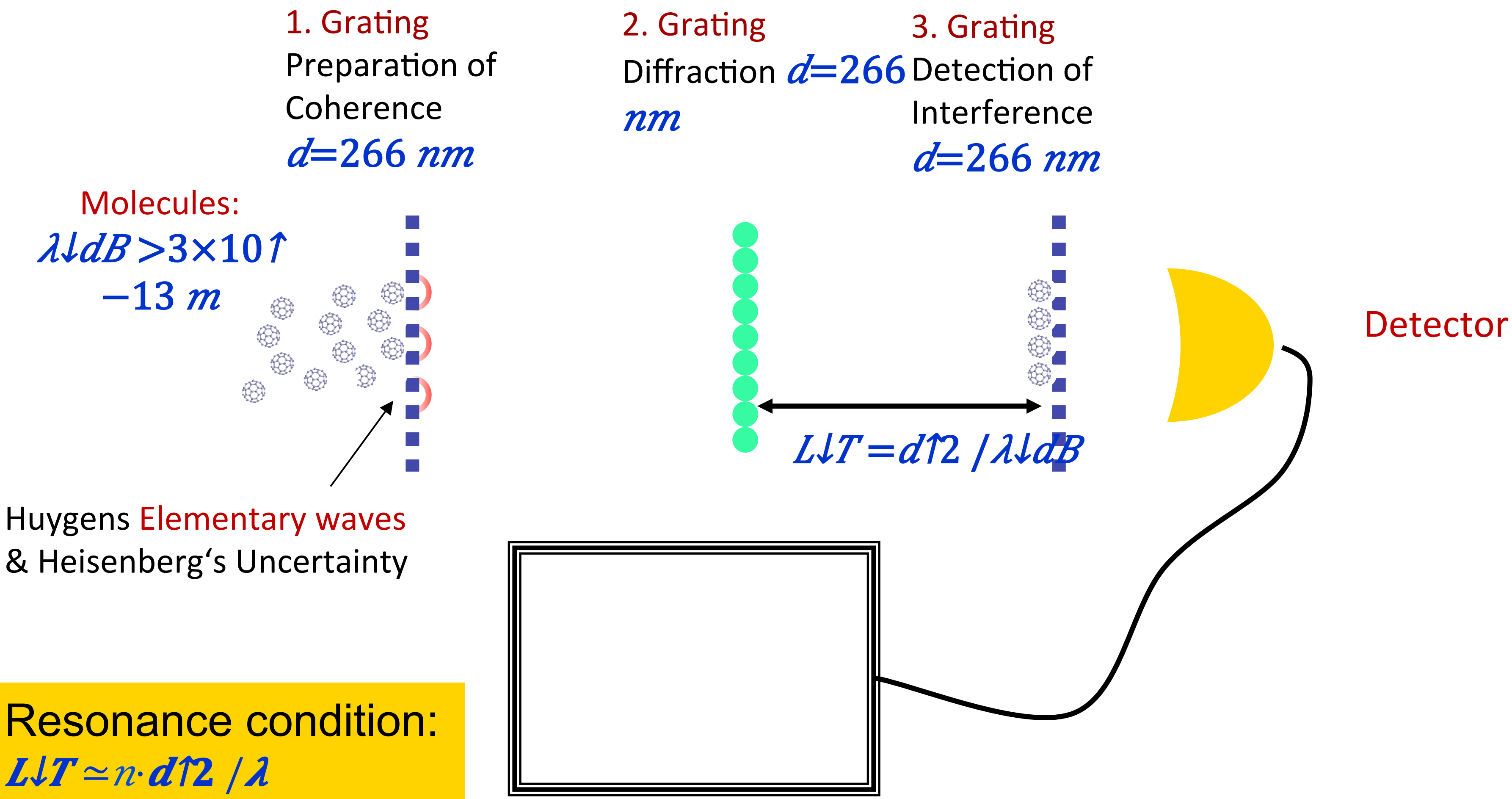
3-Grating Interferometer for Quantum Physics with Massive Molecules



Kapitza-Dirac-Talbot-Lau Interferometer

S. Gerlich, L. Hackermüller, K. Hornberger, A. Stibor, H. Ulbricht, M. Gring, F. Goldfarb, T. Savas, M. Müri, M. Mayor & M. Arndt
Nature Physics 3, 711-715 (2007)

Kapitza-Dirac-Talbot-Lau Interferometry:
Coherent self-imaging with incoherent particle sources



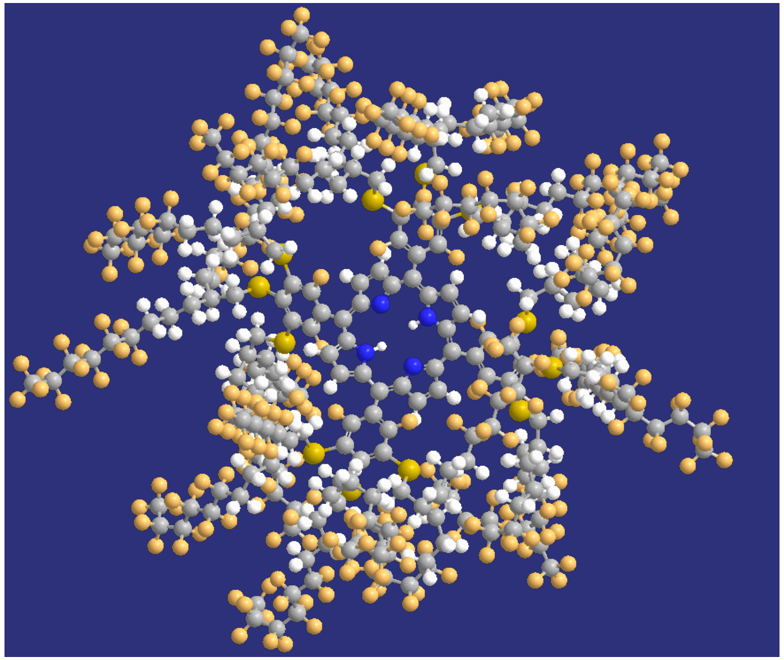
Resonance condition:

$L_T \simeq n\cdot d^2/\lambda$

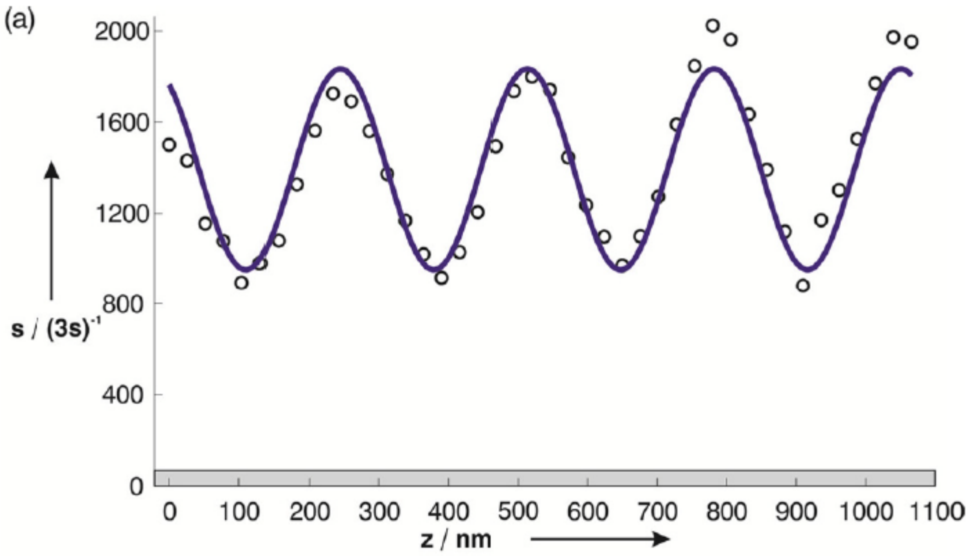
The most massive molecule that showed Quantum Delocalization & Interference, so far…

$C_{284}H_{190}F_{320}N_4S_{12}$

m=10,123 amu, N > 800 Atoms

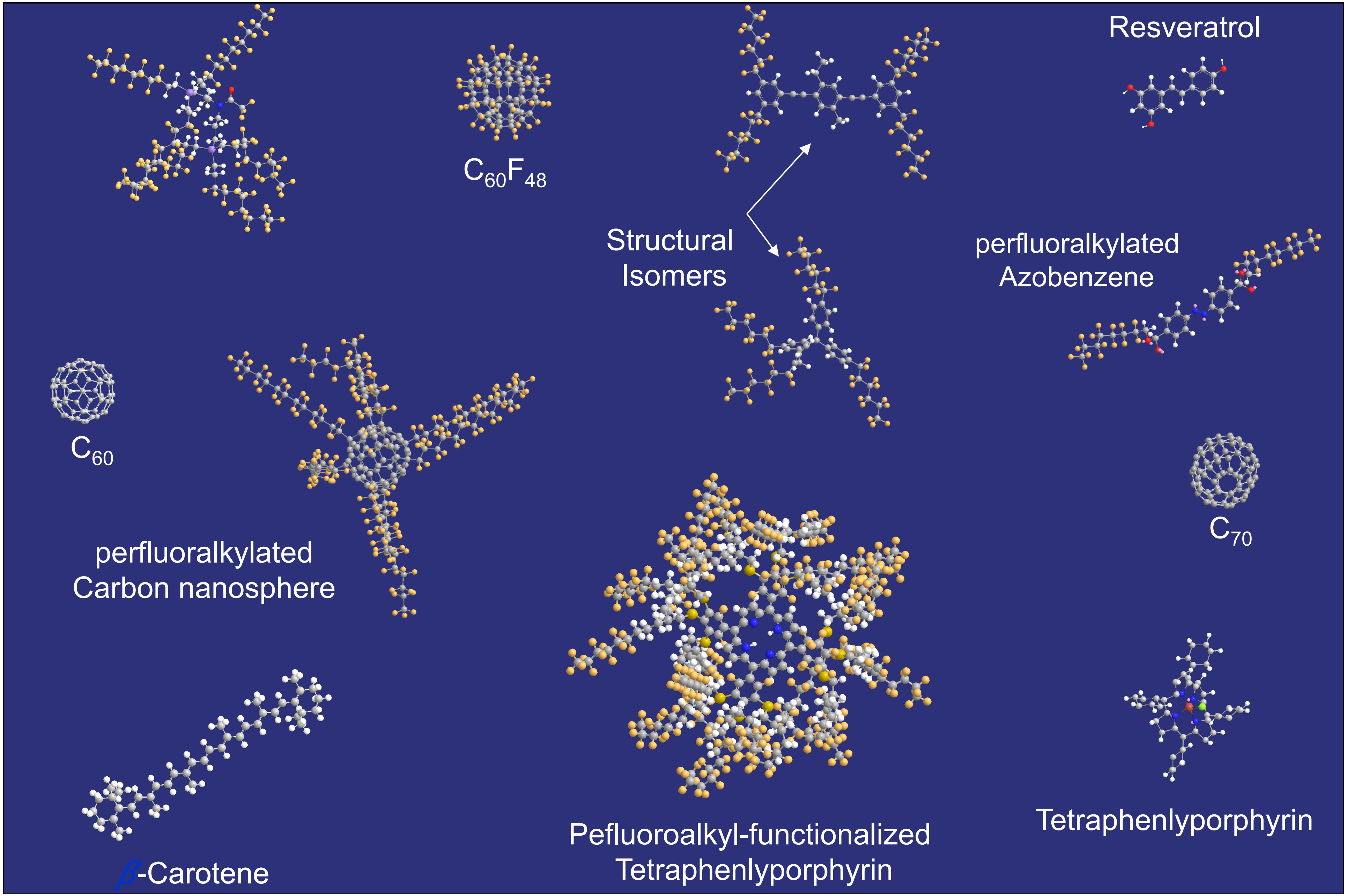


Molecular Interferogram

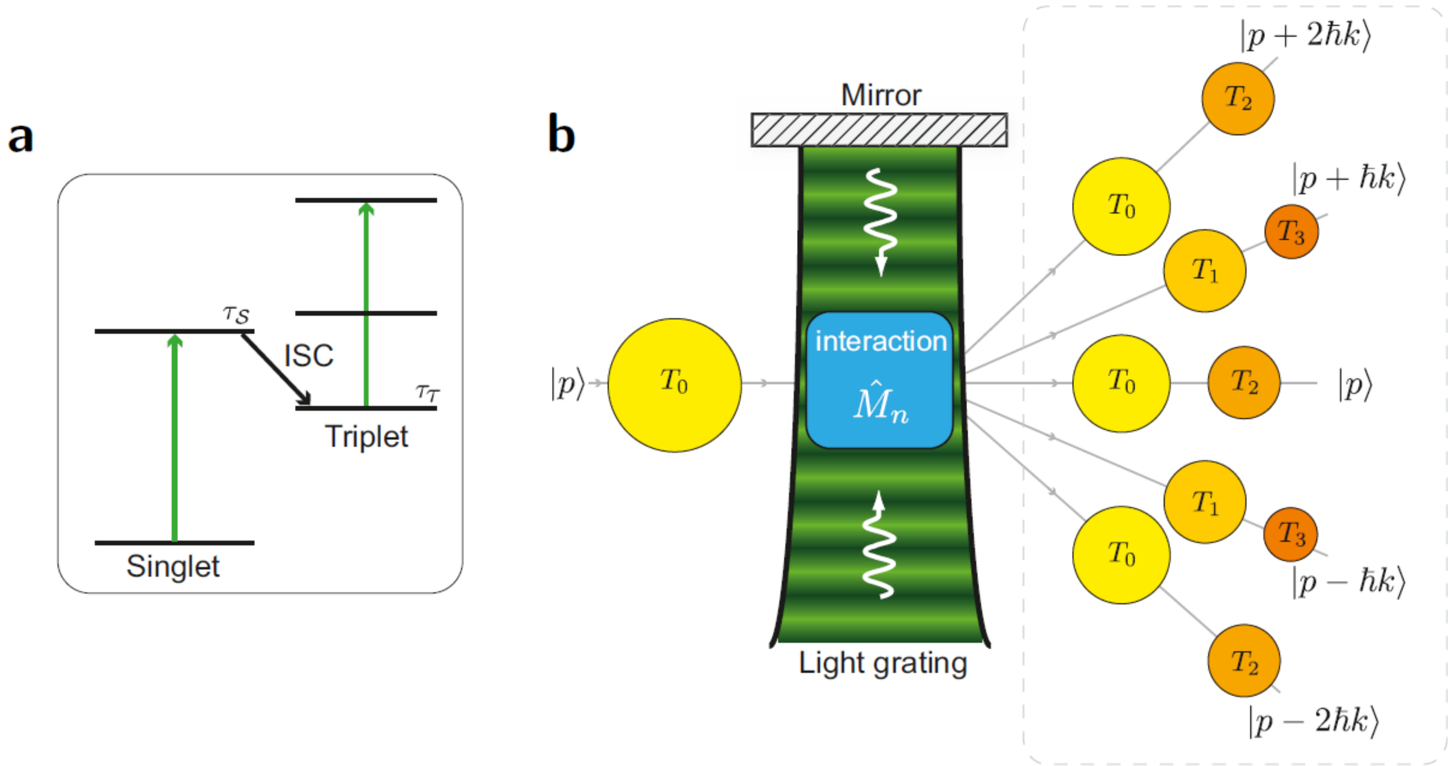


- Gerlich et al. Nature Commun. 2, 263 (2011).
- Eibenberger et al., Phys. Chem. Chem. Phys. 15, 14696 (2013)

We have seen Quantum Interference with these molecules in our KDTL interferometer !

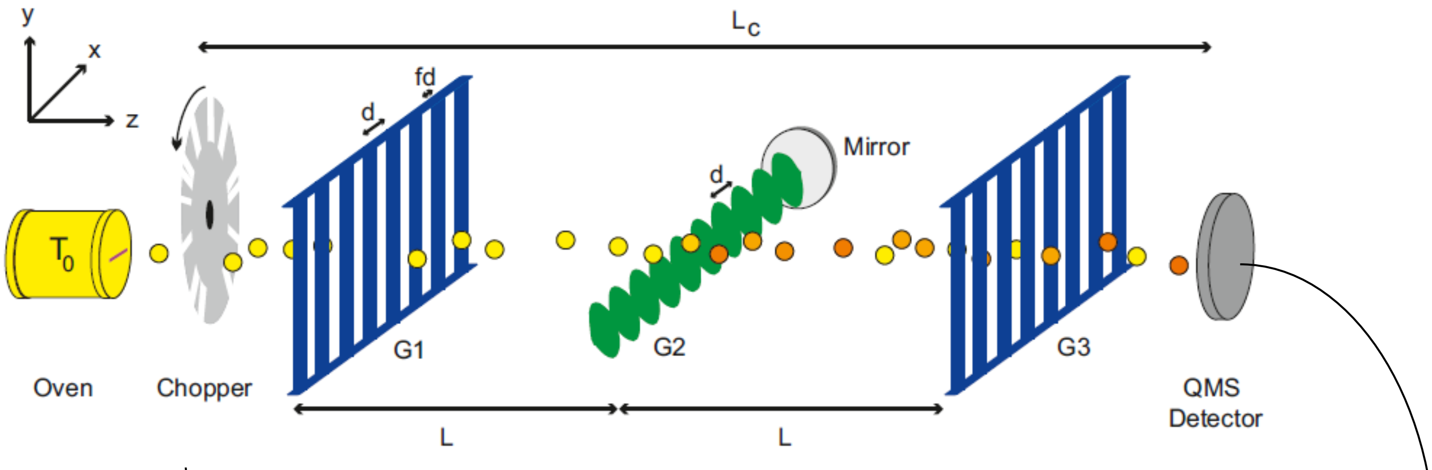


Three beam splitting mechanisms in a phase grating with absorption

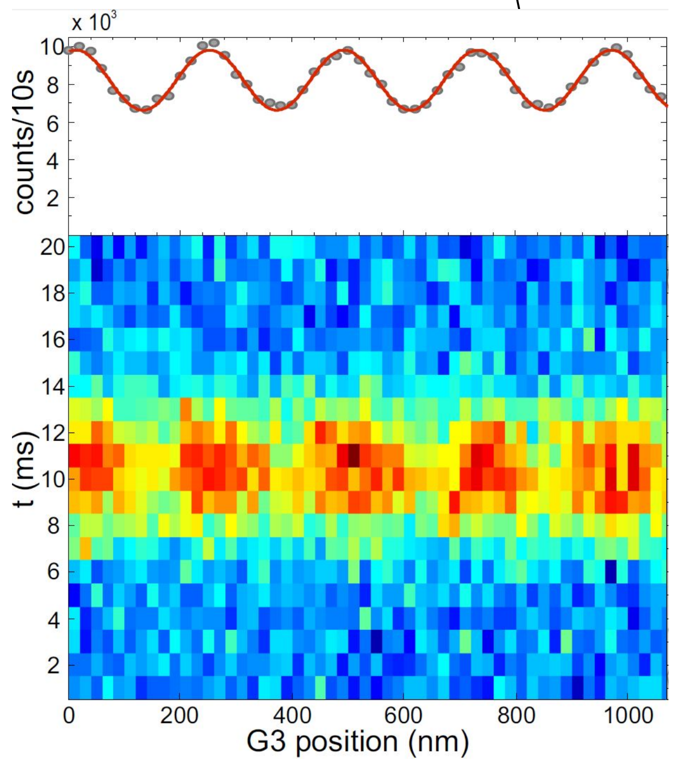


1. Periodic matter-phase modulation via the dipole force
2. Coherent single-photon recoil beam splitting
3. Measurement-induced grating: Photo-depletion & heating

Time resolved detection of the molecular interference pattern



- The chopper wheel contains a **pseudo-random sequence of openings**
- Convolution of the molecular arrival time distribution with the chopper function allows to retrieve the true **velocity distribution with 2% resolution.**

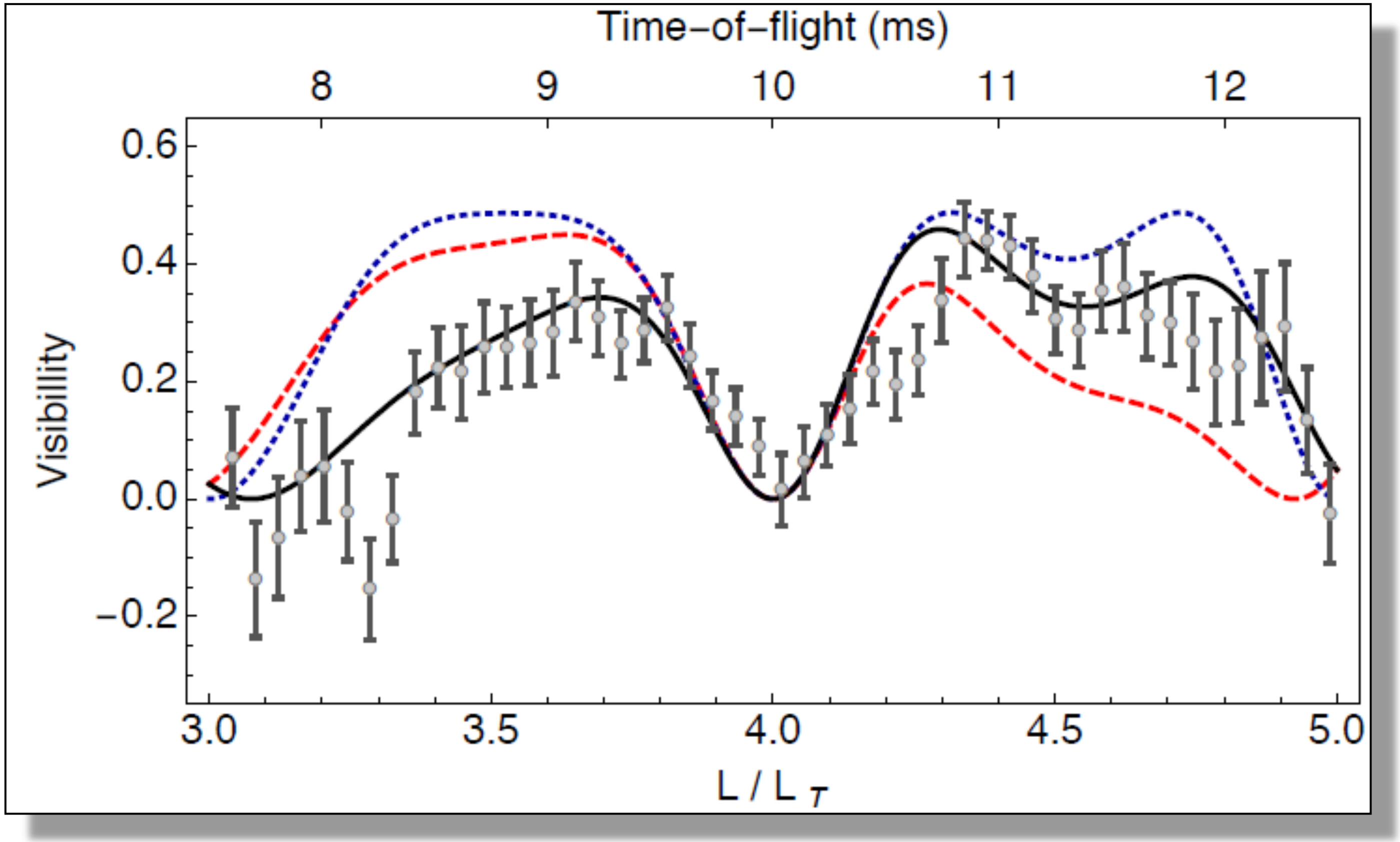


Fringe visibility vs. Scaled Talbot length (Molecular flight time)

Blue: Quantum prediction pure phase grating

Red: Absorption assumed to be a random walk

Black: Quantum model with coherent absorption



J. P. Cotter, S. Eibenberger, L. Mairhofer, X. Cheng, P. Asenbaum, M. Arndt, K. Walter, S. Nimmrichter, and K. Hornberger, submitted (2015).

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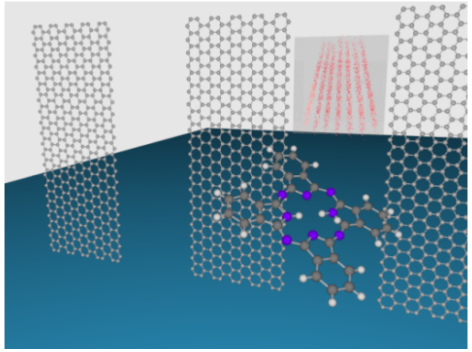

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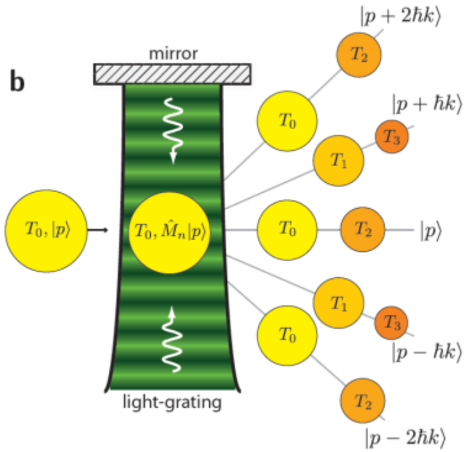

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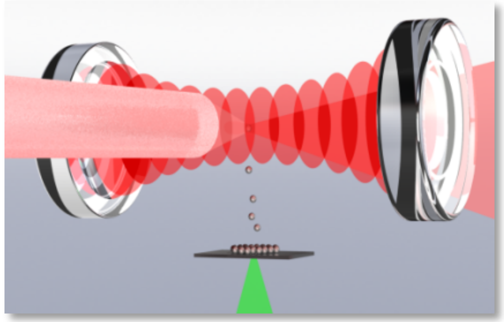
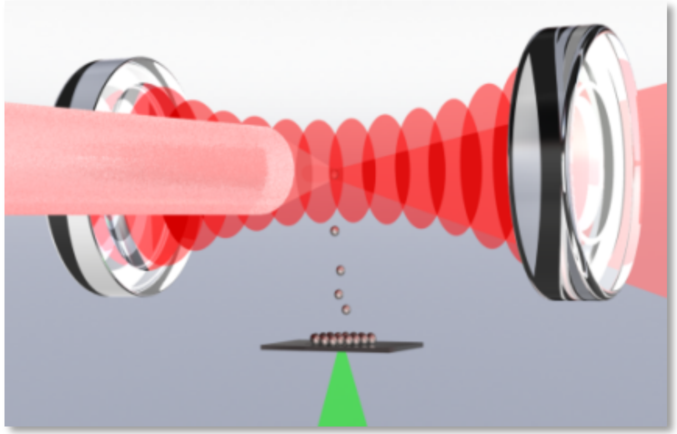


Experimental Setup for Cavity cooling

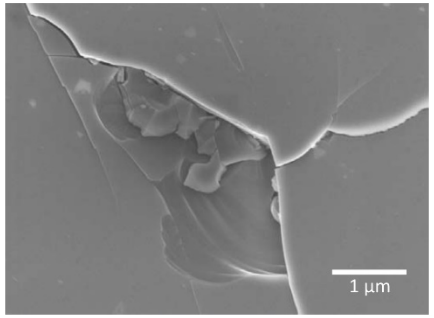
- Slowing laser: λ= 1560 nm,
  red detuned against cavity resonance
- Cavity finesse: F = 3×10^5
- Cavity power: P= 100 – 400 W



Particle Generation & Launch:

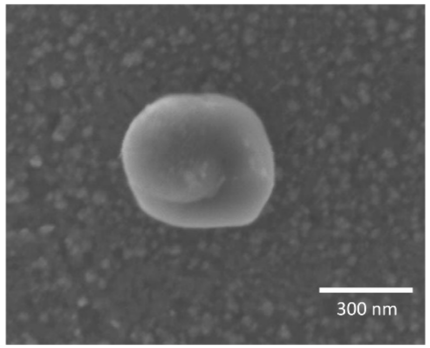
a) Laser **I**nduced **TH**er**MO**mechanical **S**tress

LITHMOS: E=3-5 mJ, τ=8 ns, λ= 532nm

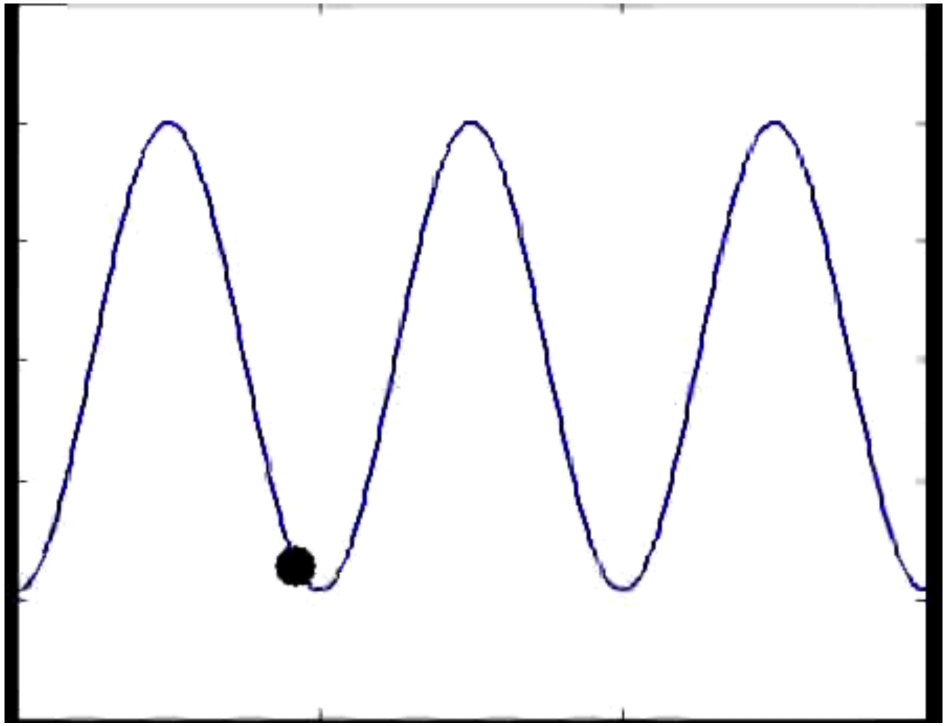


b) Silicon nanoball:

m=10^{10} amu, v $\simeq$0.2 ...10 m/s



Dielectric nanoparticle in a high-finesse blue-detuned IR cavity



See also Theory:

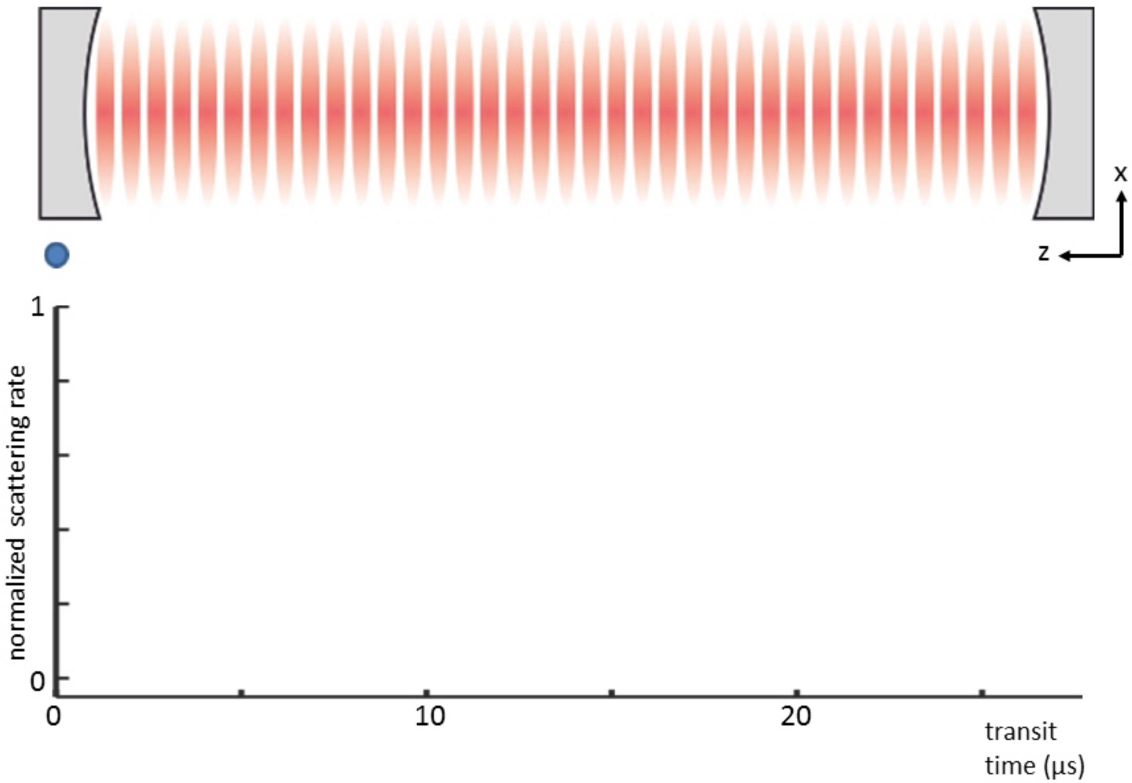
P. Horak et al. : Phys. Rev. Lett. 79, 4974 - 4977 (1997).

V. Vuletic et al. : Phys. Rev. Lett. 84, 3787 - 3790 (2000).

Nanoparticle experiments:

N. Kiesel et al. Proc. Natl. Acad. Sci. USA **110**, 14180 (2013).

How to detect the motion of the particle?
Monitoring the scattered light under 90°

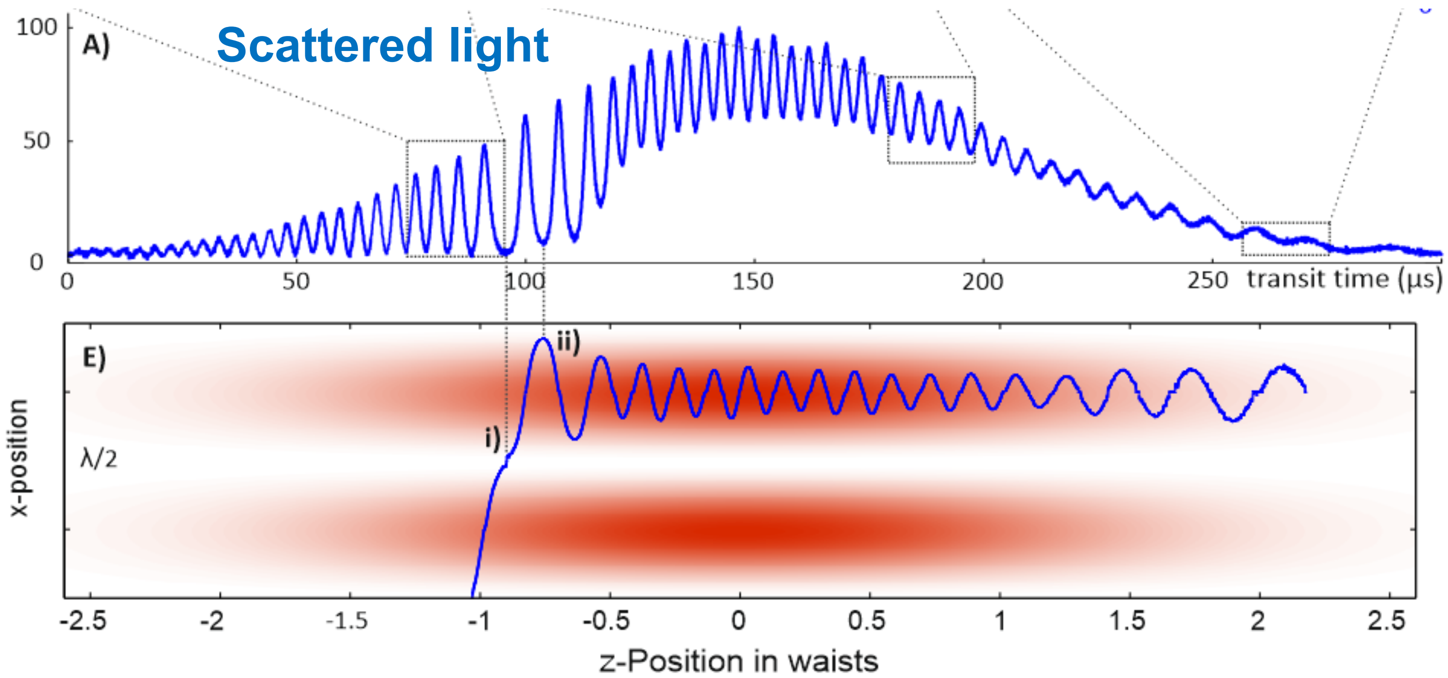


Cavity cooling of a nanoparticle in high vacuum

A particle is transversally slowed from 23 cm/s to 4 cm/s

i) Last run over the standing wave

ii) First reflection by optical potential



P. Asenbaum, S. Kuhn, U. Sezer, S. Nimmrichter, M. Arndt, **Nature Comm. 4, 2743 (2013).**

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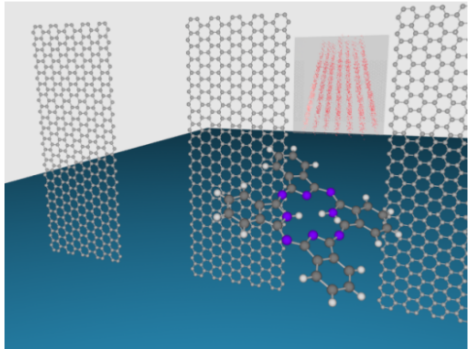

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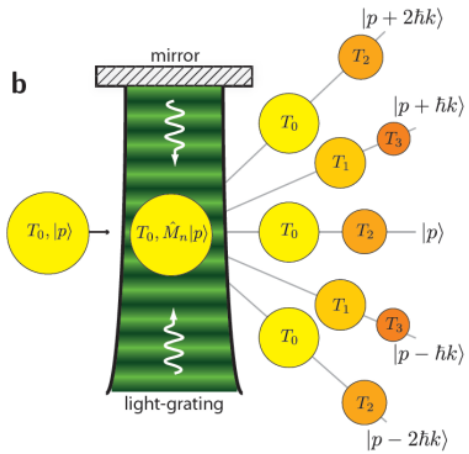

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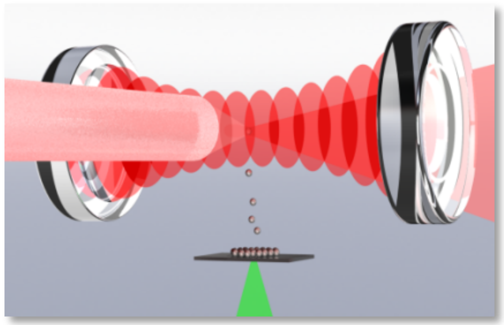
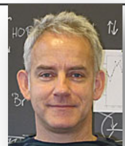


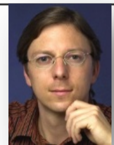
Danke !

QNP Team 2014
Univ. Vienna

European Research Council
Established by the European Commission

Adv. Grant: PROBIOTIQUS


Marcel Mayor
Univ. Basel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Ori Cheshnovsky
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Uzi Even
Tel Aviv Univ.


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