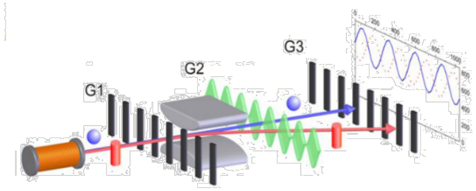
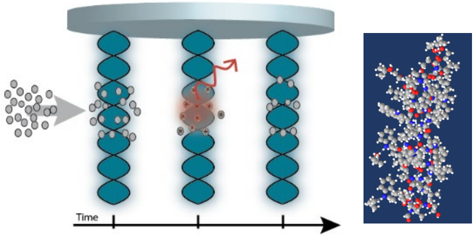
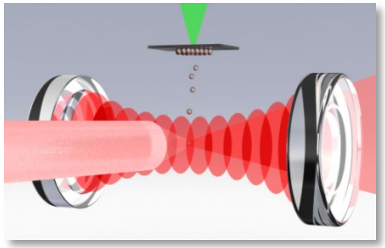
Universal Matter-Wave Interferometry
& Gravitational Physics



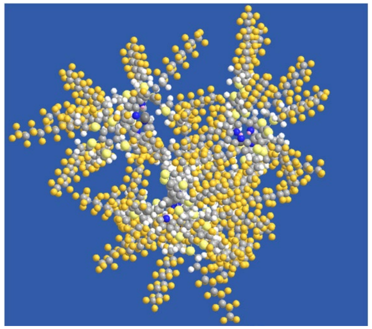
LUMI-Interferometry

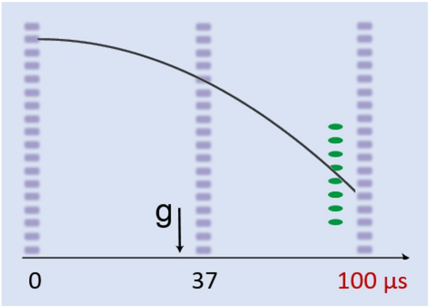


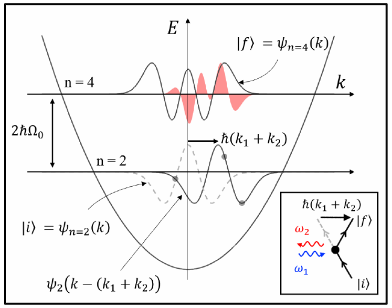
OTIMA-Interferometry



Trapped Particles







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www.quantumnano.at

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ComplexQuantumSystems

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- Armin Shayeghi

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- Stefan Putz

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- Aljosha Vukovic

Bio-beams/SNWDs
- Marcel Strauß
- Martin Mauser
- Julia Salapa
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- Philipp Geyer

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- Moritz Kriegleder
- Ugur Sezer

THEORY
- Stefan Nimmrichter

Collaborations

Duisburg: Theory
Klaus Hornberger, Benjamin Stickler

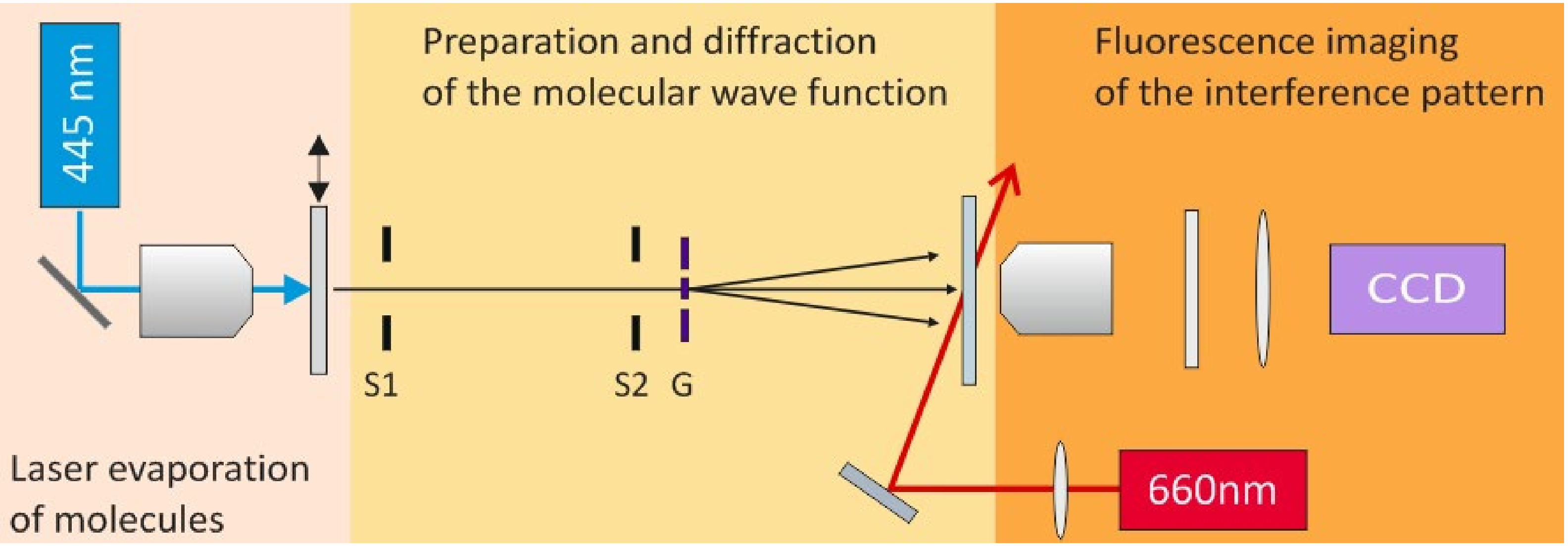
Basel: Chemistry
Marcel Mayor, Valentin Köhler

Tel Aviv: Nanofabrication & Imaging
Ori Cheshnovsky, Fernando Patolsky

Uni Wien: Micro-mirror fabrication
Michael Trupke, Georg Wachter

Kapitza-Dirac Blockade
Wayne Cheng-Wei Huang, Göttingen
Herman Batelaan, Lincoln/Nebraska

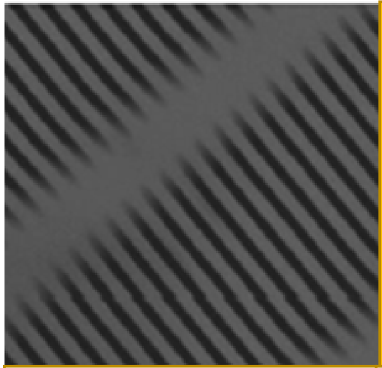
1. The trivial aspect of gravity in molecule diffraction
Free fall & Gravitational velocity selection

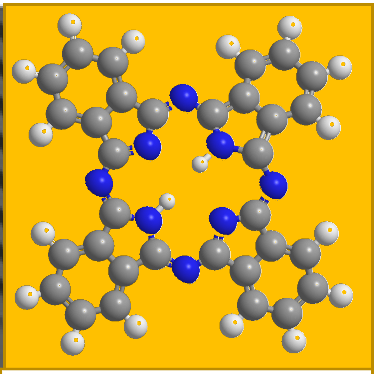


Laser evaporation of molecules

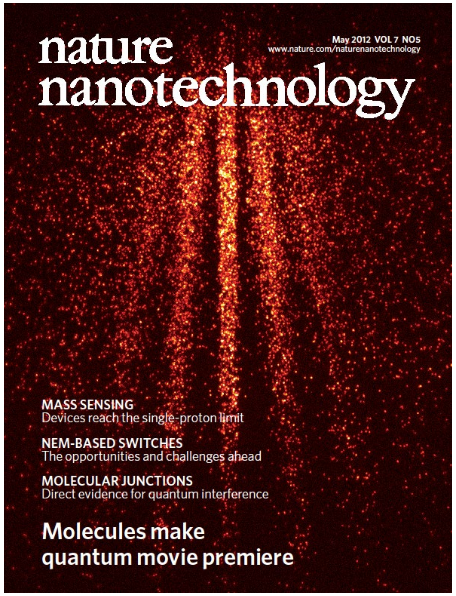
Preparation and diffraction of the molecular wave function

Fluorescence imaging of the interference pattern





SiN Nanograting	Phthalocyanin
d=100 nm	$m = 514$ amu
s=50 nm	$v = 100$ m/s
t=10 nm	$\lambda_{dB} = 5$ pm



nature nanotechnology

May 2012 VOL 7 NO5
www.nature.com/naturenanotechnology

MASS SENSING
Devices reach the single-proton limit

NEM-BASED SWITCHES
The opportunities and challenges ahead

MOLECULAR JUNCTIONS
Direct evidence for quantum interference

Molecules make quantum movie premiere

T. Juffmann, A. Milic, M. Müllneritsch, P. Asenbaum, A. Tsukernik, J. Tüxen, M. Mayor, O. Cheshnovsky, M. Arndt, **Nature Nano. 7, 297 (2012)**

2. A long-term research programme: Dephasing by stochastic gravitational wave background ?

- Matter-wave interference contrast reduced by stochastic gravitational wave background

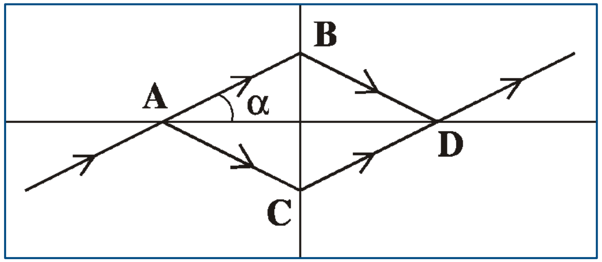
$$V = \exp\left(\frac{i\Delta\varphi^2}{2}\right) \cdot V_0$$

with an rms phase perturbation

$$\Delta\varphi^2 = \int_0 \frac{d\omega}{2\pi} S_h[\omega] \cdot A[\omega] \cdot F[\omega]$$

where

$$A[\omega] = 16 \cdot \Omega^2 \sin^2(\alpha) \cdot (1 - \cos(\omega\tau))^2 / \omega^2$$



- $S_h[\omega]$ = gravitational strain noise
- $F[\omega]$ = filter function
- $A\,[\omega]$ = apparatus function

- Quadratic in kinetic energy $\Omega^2 = E_{kin}^2/\hbar^2$

- Too small for cold-atom & high-mass interferometry (by many orders of magnitude)

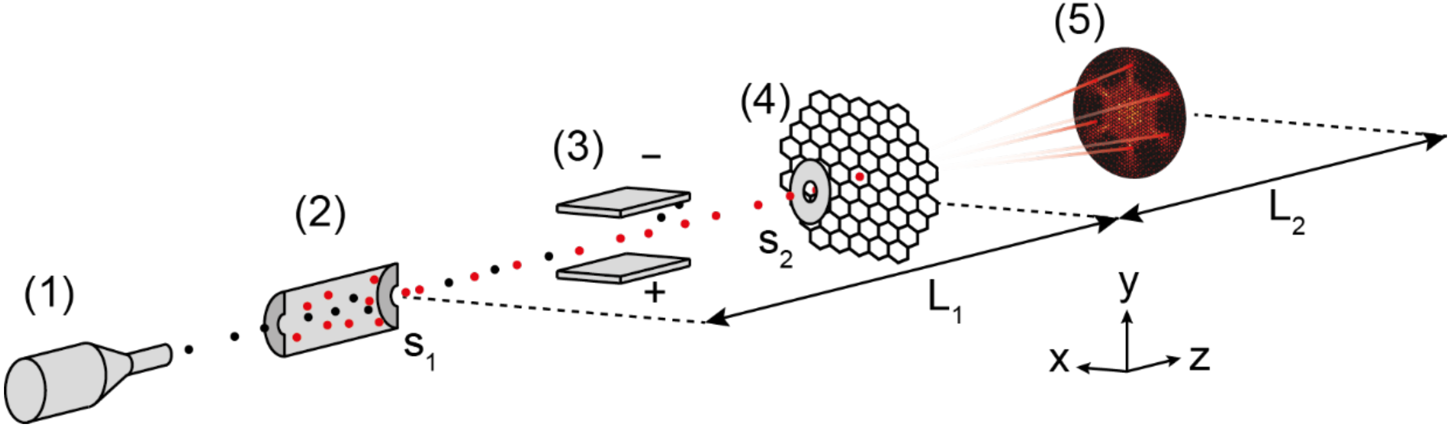
- **But**: for any experimentally accessible λ_{dB} the lightest mass serves the purpose best

$$E_{kin} = \frac{p^2}{2m} = \frac{h^2}{2m\lambda_{dB}^2}$$

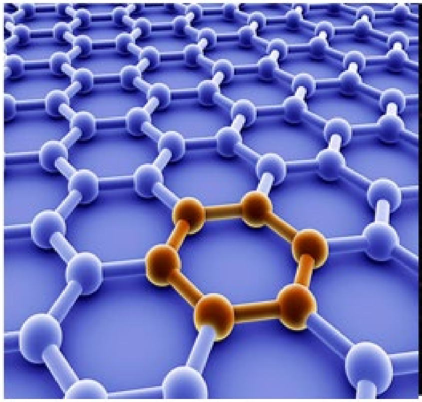
B. Lamine, R. Hervé, A. Lambrecht, and S. Reynaud, *Ultimate decoherence border for matter-wave interferometry*, **Phys. Rev. Lett. 96, 050405 (2006).**

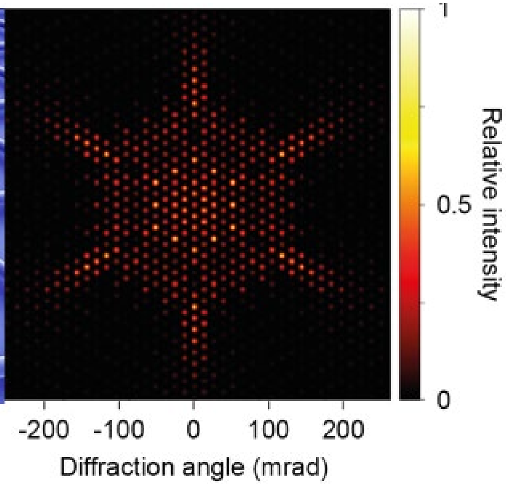
Is it possible to generate wide angle beam splitter for superfast atoms?

Christian Brand,
now DLR Ulm



- Hydrogen atoms
- E = 80 eV
- v = 124 km/s
- $\lambda_{dB} = 3.4$ pm
- Graphene lattice: d=2.46 Å





C. Brand, M. Debiossac, T. Susi, F. Aguillon, J. Kotakoski, P. Roncin, and M. Arndt
Coherent diffraction of hydrogen through the 246 pm lattice of graphene, to appear in **New J. Phys. 21, 033004 (2019).**

Currently still a thought experiment …

For atoms with $E = 80$ eV transmitted in the grey area

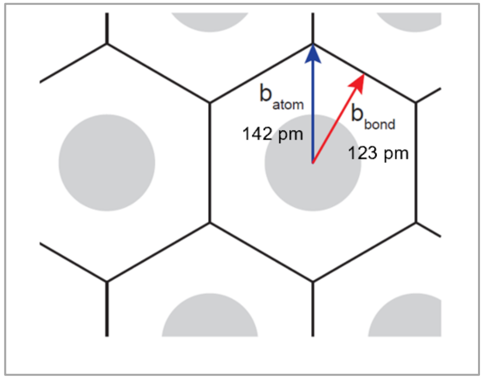
- Δp to carbon mesh < intrinsic momentum uncertainty
- 8-10% of atoms diffract coherently up < 50 mrad (4th order)
- In $\tau = 100$ ms: 2700 m flight distance, 5 cm falling height
- Coherent beam splitting of 135 m conceivable (?!!)

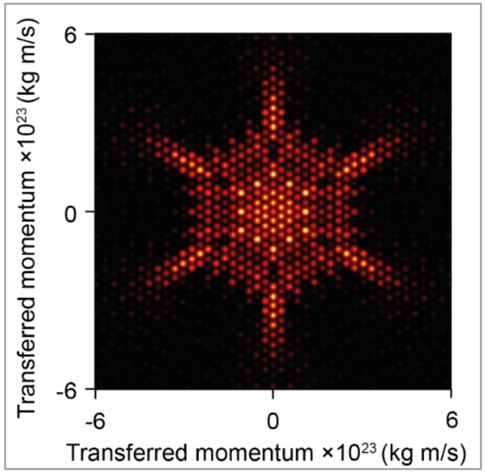
Thought experiment:

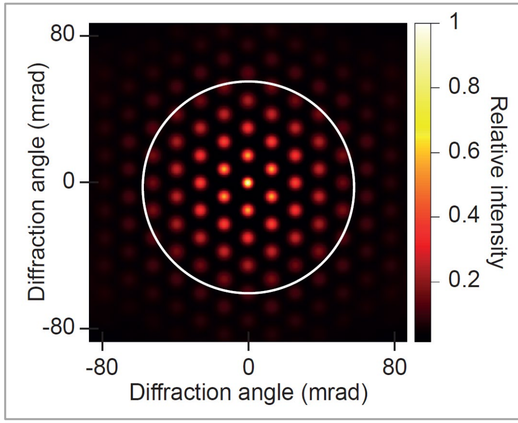
- M= 1 amu, $v = 10^5$ m/s → $\lambda = 4$ pm
- $d = 2.4 \times 10^{-10}\, m, \alpha \simeq 10\ \mathrm{mrad}, L = 4000\ \mathrm{m}$,

$\rightarrow E = 80\ \mathrm{eV},\ A = 10\ \mathrm{m}^2, \tau = 10^{-2}\ s$

Feasible in the long run ?







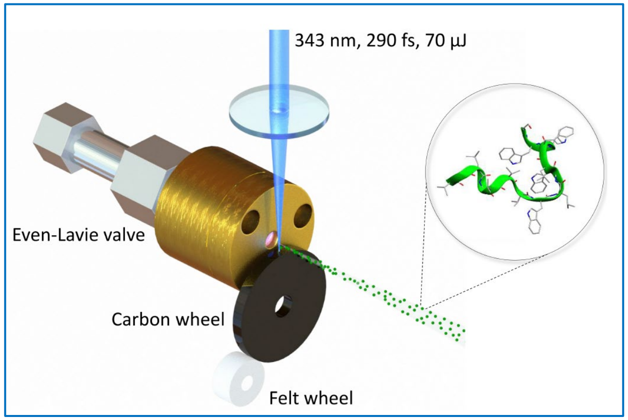
C. Brand, M. Debiossac, T. Susi, F. Aguillon, J. Kotakoski, P. Roncin, and M. Arndt
Coherent diffraction of hydrogen through the 246 pm lattice of graphene, to appear in **New J. Phys. 21, 033004 (2019).**

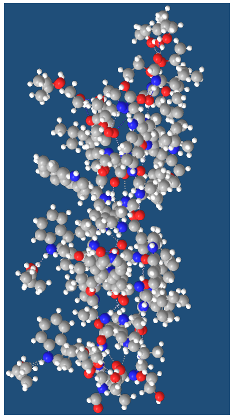
A weak equivalence demonstrator in OTIMA interferometry

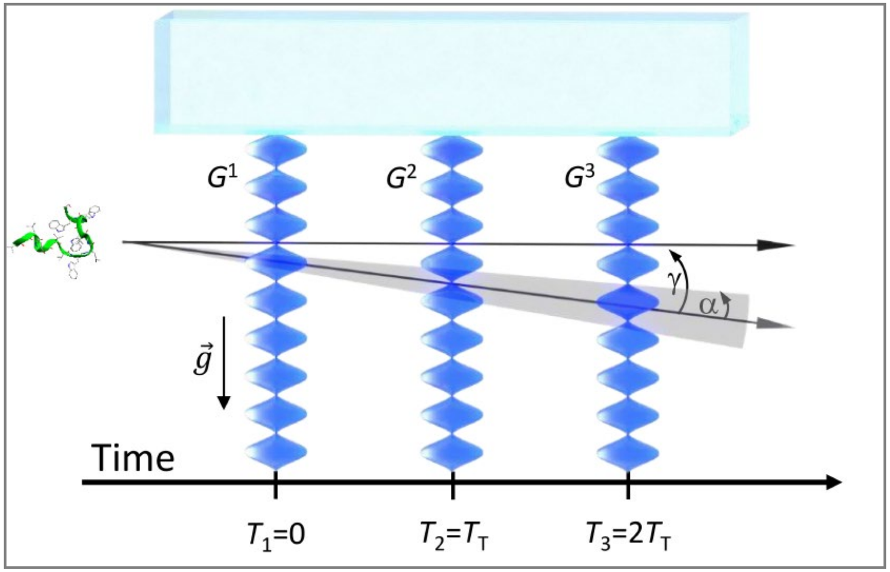
Near field OTIMA interferometry
The quantum wave nature of antibiotic polypeptides

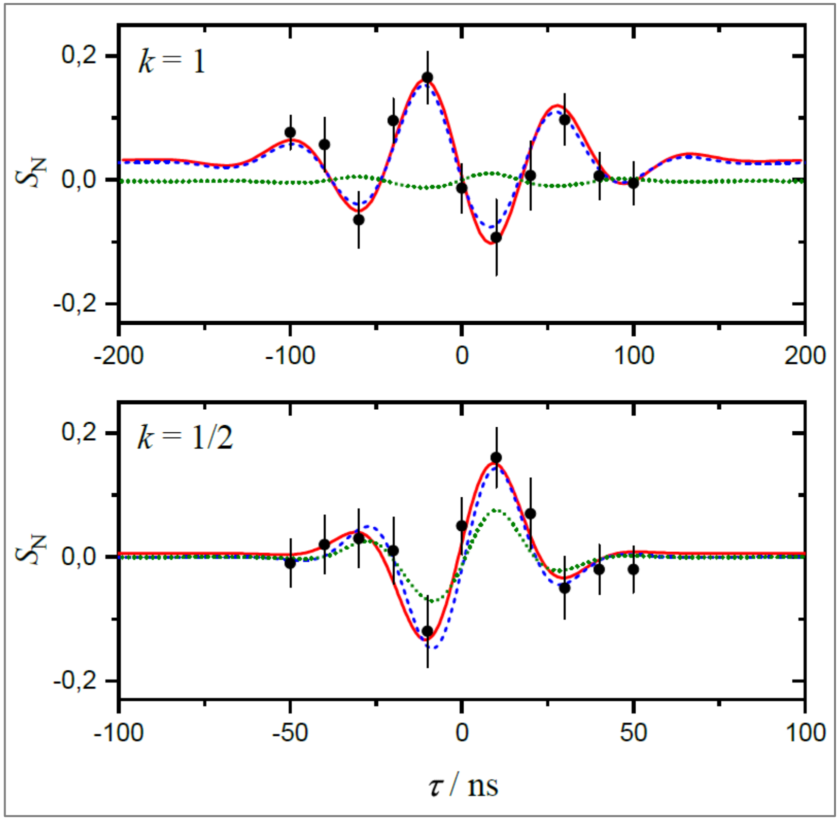
A. Shayeghi

P. Rieser



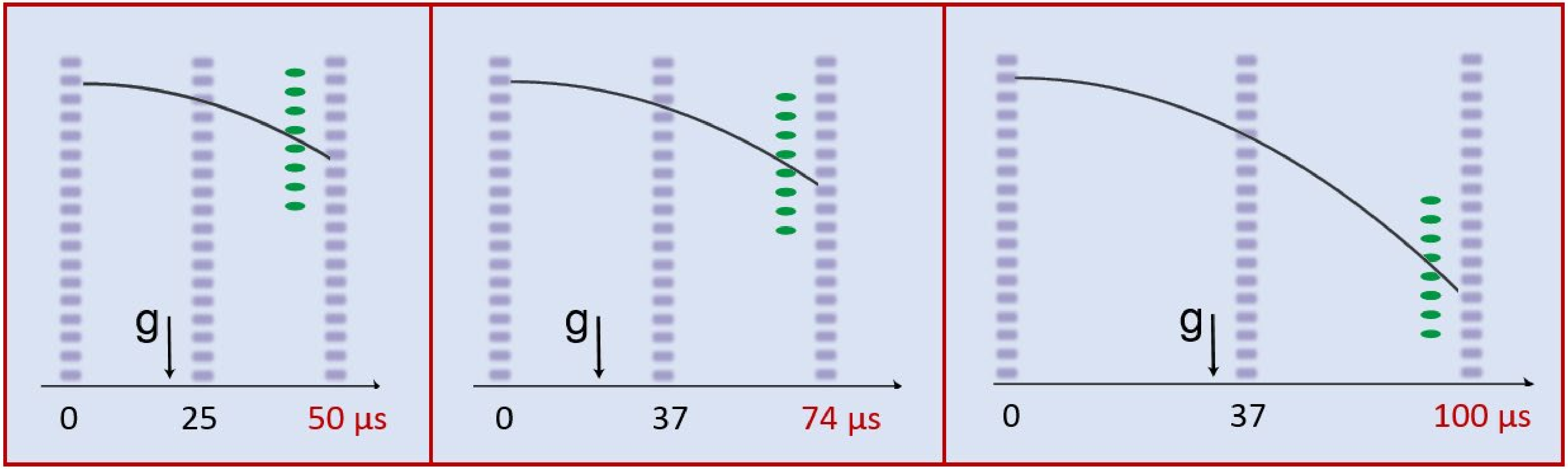






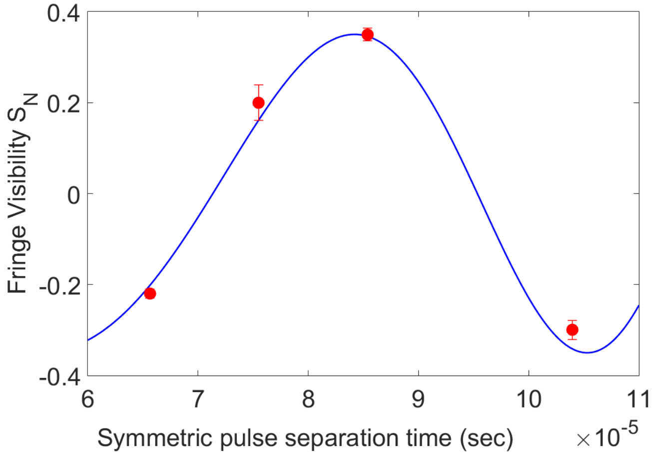
A. Shayeghi, P. Rieser, G. Richter, U. Sezer, J.H. Rodewald, P. Geyer, T.J. Martinez, and M. Arndt,
Matter-wave interference of a native polypeptide, **Nat. Communs. 11, 1447 (2020).**

3. Molecular interference patterns as nanorulers to measure free fall: The OTIMA version of „COW“ interferometry



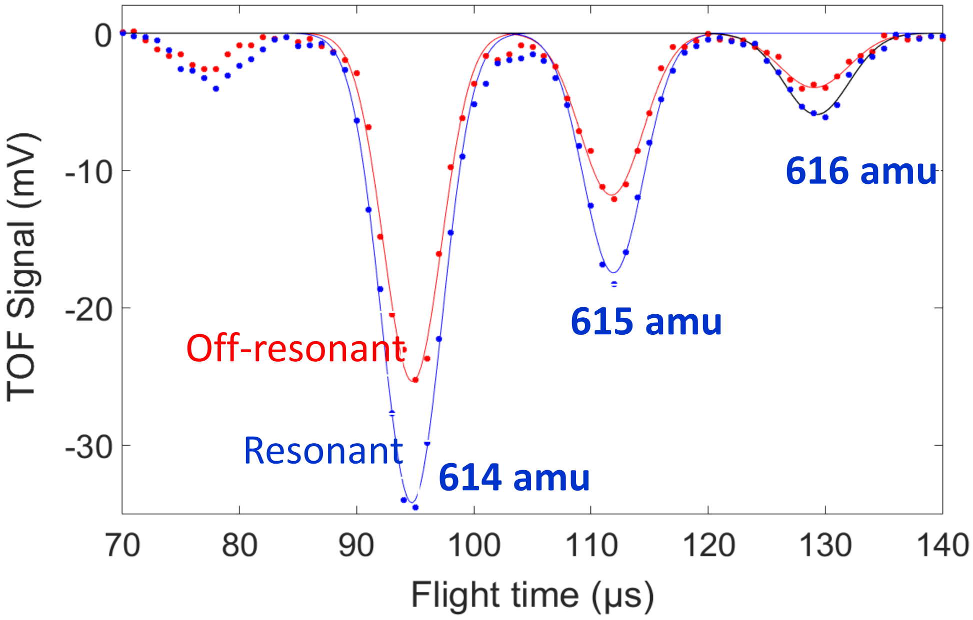
Symmetrically stretching the interferometer in time:

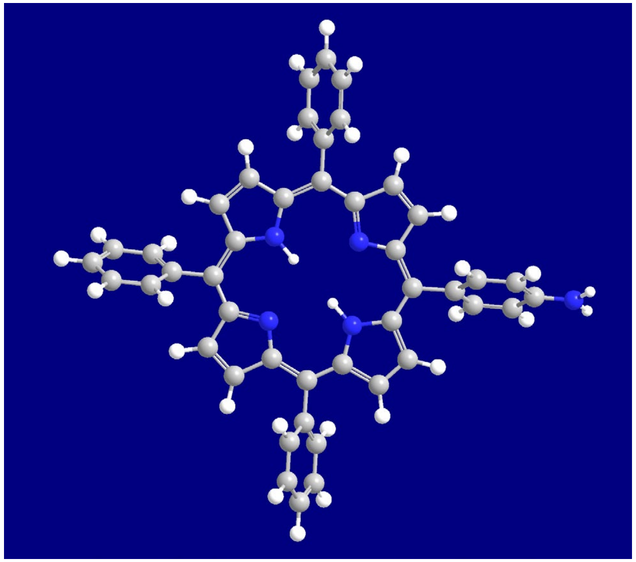
→ Gravitational acceleration “g”



J. Rodewald, N. Dörre, A. Grimaldi, P. Geyer, L. Felix, M. Mayor, A. Shayeghi, and M. Arndt,
Isotope-selective high-order interferometry with large organic molecules in free fall, **New J. Phys. 20, 033016 (2018).**

Isotope-selective interference in free fall: Comparison of tetraphenylporphyrin isotopes





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

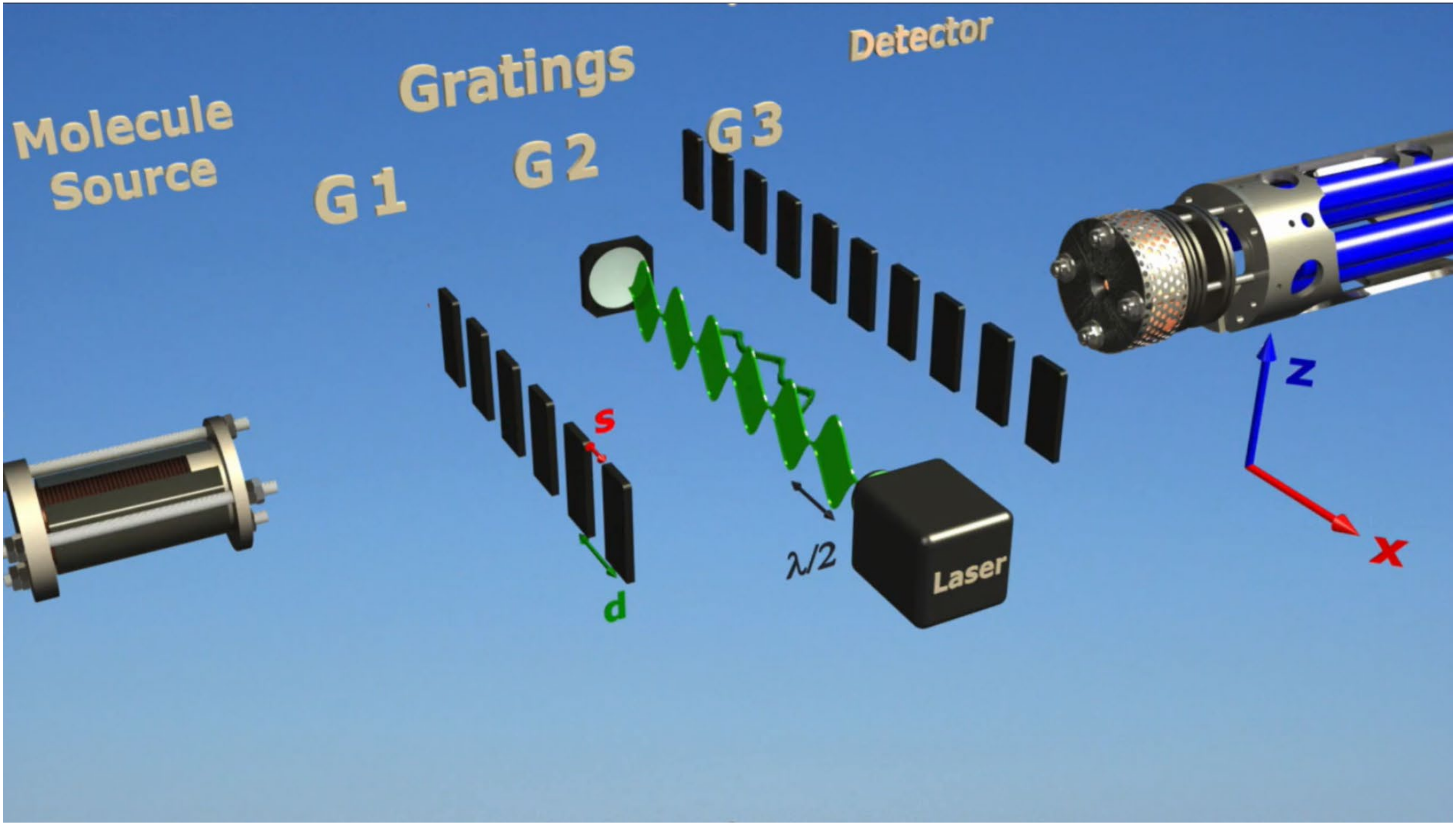
- **Proof of principle:** $\eta \coloneqq \Delta g/g < 1\ \%$
- Future T_{flight} = 1 s → $\eta < 10^{-8}$
- **What can we learn from**
  - Ferromagnets & Superconductors?
  - High internal ring currents?
  - High internal energy?

J. Rodewald, N. Dörre, A. Grimaldi, P. Geyer, L. Felix, M. Mayor, A. Shayeghi, and M. Arndt, *Isotope-selective high-order interferometry with large organic molecules in free fall,* **New J. Phys. 20, 033016 (2018).**

Long Base Line
Universal Matter-Wave
Interferometry

LUMI 1.0 & upgrades

Long-Baseline Universal Matter-Wave Interferometry : **KDTLI / LUMI 1.0**



First L = 0.2 m interferometer: Gerlich et al. **Nature Physics 3, 711 (2007)**
First L = 2.0 m interferometer: Y. Y. Fein, P. Geyer, P. Zwick, F. Kiałka, S. Pedalino, M. Mayor, S. Gerlich & M. Arndt, **Nature Physics 15, 1242 (2019).**

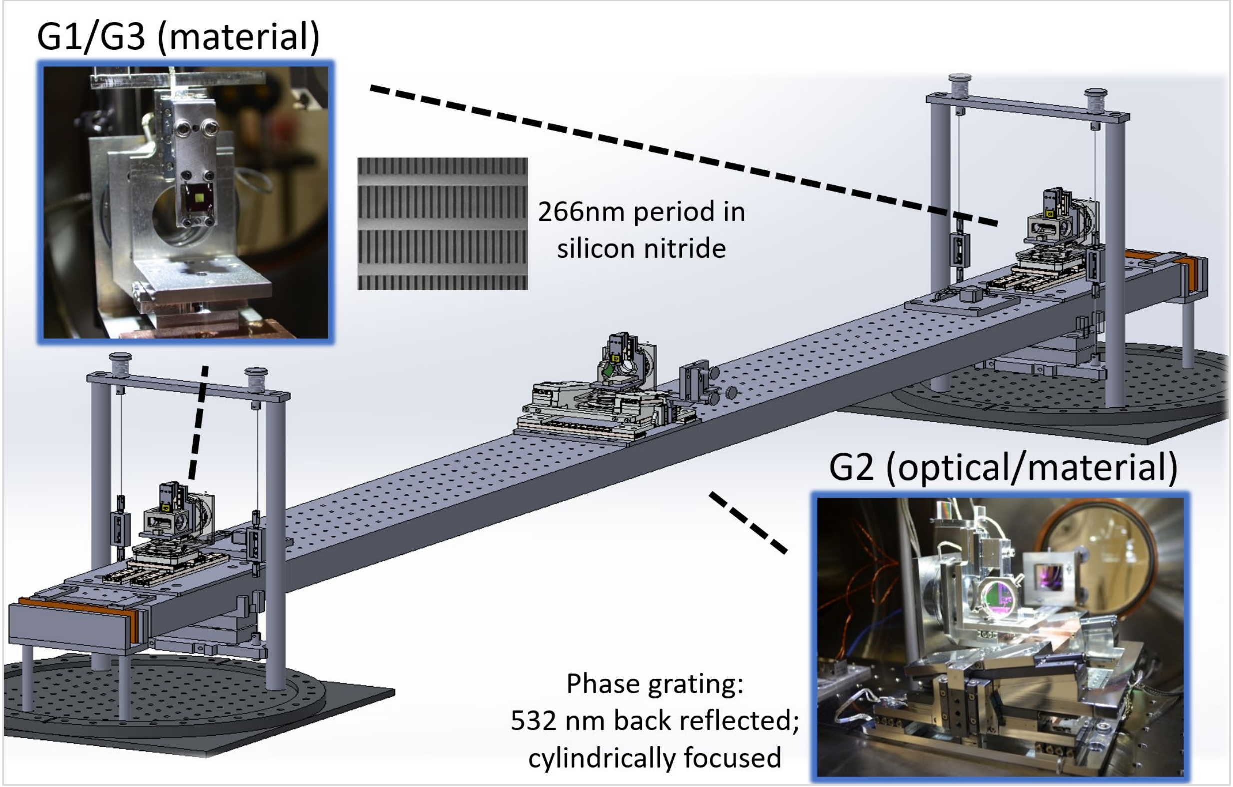
Long Base-line Universal Matter-Wave Interferometer: **LUMI**

1 - 100th order interference observed with:

- **Atoms:** Cs, Ba, Sr
- **Molecules:** C_{60}, Anthracene, Rubrene, …
- **Tripeptides:** e.g. Ala-Trp-Ala
- **Macromolecules:** >25 kDa

Design specifications:

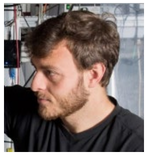
- **Wavelength** : $\lambda_{dB} < 50$ fm
- **Mass (@ 300 m/s):** $M > 3 \times 10^4$ amu
- **External force** : $F < 10^{-26}$ N


G1/G3 (material)

266nm period in silicon nitride

G2 (optical/material)

Phase grating:
532 nm back reflected;
cylindrically focused


Y. Y. Fein

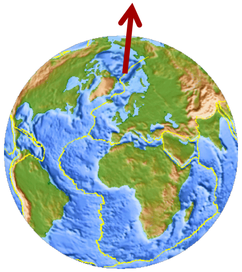

P. Geyer


S. Pedalino


S. Gerlich

Y. Y. Fein, P. Geyer, P. Zwick, F. Kiałka, S. Pedalino, M. Mayor, **S. Gerlich** & M. Arndt, **Nature Physics 15, 1242 (2019).**

4. Fringe shifts caused by gravity and Earth‘s rotation



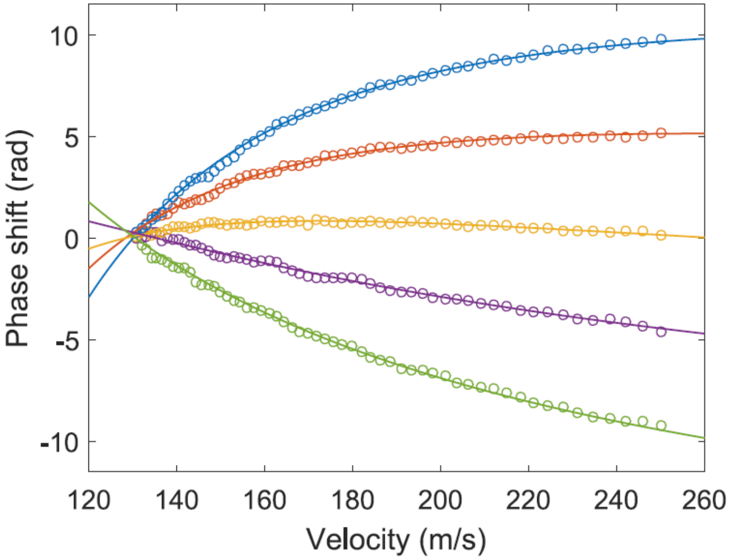
- In Talbot-Lau interferometry, the acceleration a yields a fringe phase shift $\Delta\phi = k_d a T^2$
- The flight time between the gratings is velocity dependent: $T = L/v$
- Averaging over a class of velocities reduces the interference contrast

Earth‘s rotation: $\boldsymbol{a} = 2\,\mathrm{v} \times \boldsymbol{\Omega}$

Earth‘s gravity: $\boldsymbol{a} = \boldsymbol{g} \cdot \vartheta_{roll}$

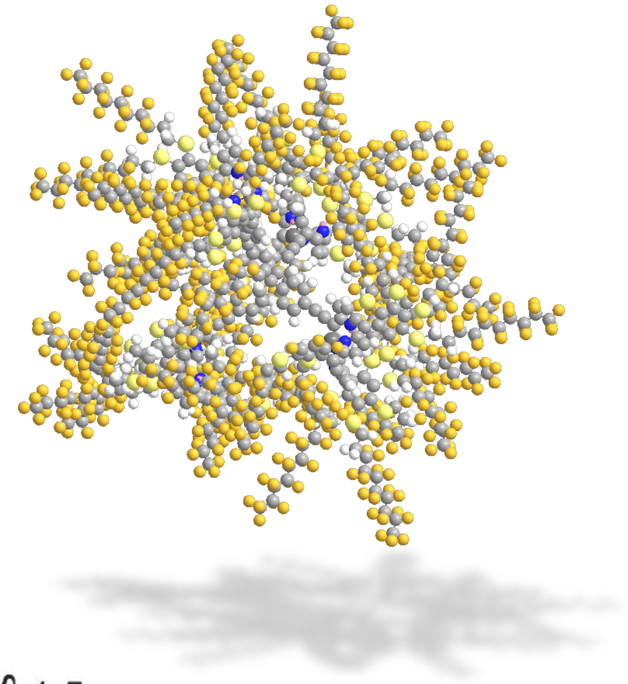
One can **compensate Coriolis & Gravity** acceleration by rolling the gratings by the angle:

$$\vartheta_{roll} = -\Omega_E v_p / g$$



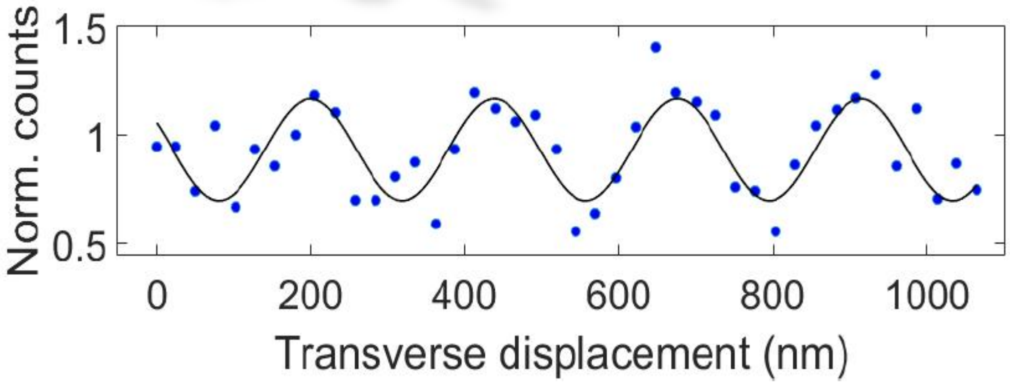
Y.Y. Fein, F. Kiałka, P. Geyer, S. Gerlich, and M. Arndt,
Coriolis compensation via gravity in a matter-wave interferometer, **New J. Phys. 22, 033013 (2020).**

Quantum Wave Nature of the most massive molecular family



Perfluoroalkyl-functionalized Oligo-Porphyrines

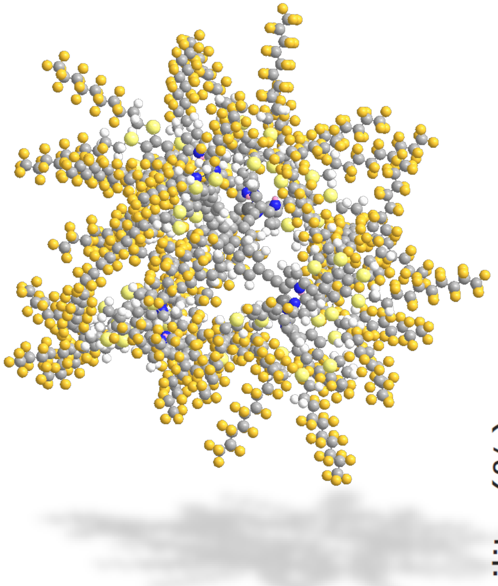
- m ≃ 25000 - 28000 amu
- $N \simeq$ 1800 - 2000 Atoms per molecule
- $C_{715}H_{260}F_{908}N_{16}S_{53}Zn_4$
- Velocity: $\mathrm{v} = 300$ m/s
- Molecular diameter: $D = 50$ Å
- Billions of structural Isomers / Conformers
- De Broglie Wavelength $\lambda_{dB} = 50 - 60$ fm



The interference pattern emerging when G3 is moved.

Y. Y. Fein, P. Geyer, P. Zwick, F. Kiałka, S. Pedalino, M. Mayor, **S. Gerlich** & M. Arndt, **Nature Physics 15, 1242 (2019).**

Matter-wave fringe visibility allows distinguishing Classical from Quantum Phenomena

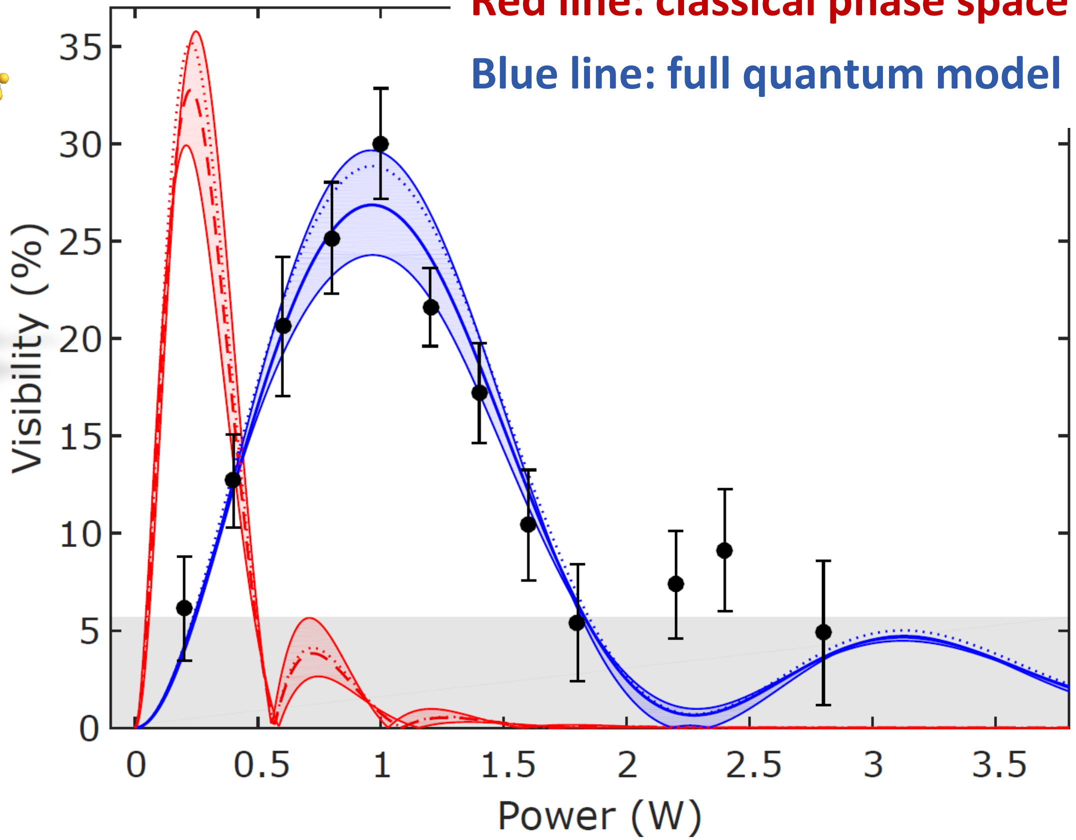


- m > 25000 amu
- N ≃ 2000 atoms

Black circles: Experiment

Red line: classical phase space evolution

Blue line: full quantum model

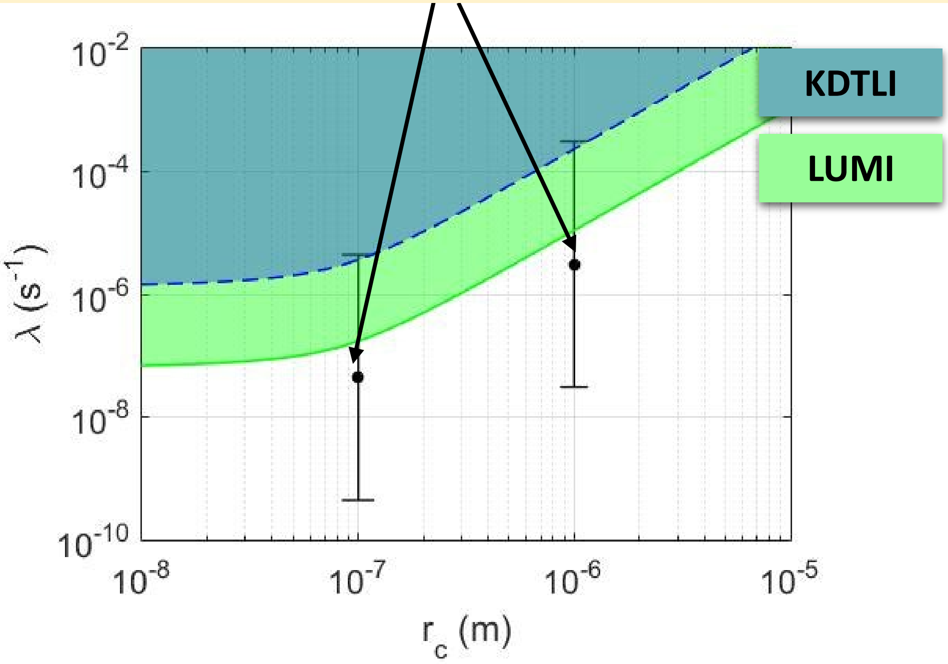


Y. Y. Fein, P. Geyer, P. Zwick, F. Kiałka, S. Pedalino, M. Mayor, S. Gerlich & M. Arndt, **Nature Physics 15, 1242 (2019).**

Interferometric bounds on Continuous Spontaneous Localization (CSL)

- CSL models assume a stochastic perturbation (by an unknown agent) which collapses the wave function at rate λ_c to a Gaussian state of width r_c.
- The collapse rate is predicted to scale like: $\lambda_c \propto m^2$
- If collapse occurred more often than expected, coherence would be lost.

Prediction by S. Adler, J. Phys. A, 40 2935 (2007)



LUMI sets currently the strongest interferometric bound on collapse models for $r_c \in [10 - 1000]\ nm$

Y. Y. Fein, P. Geyer, P. Zwick, F. Kiałka, S. Pedalino, M. Mayor, S. Gerlich & M. Arndt, **Nature Physics 15, 1242 (2019).**

5. Quantum Macroscopicity

by **S. Nimmrichter & K. Hornberger** Phys. Rev. Lett. 110, 160403 (2013)

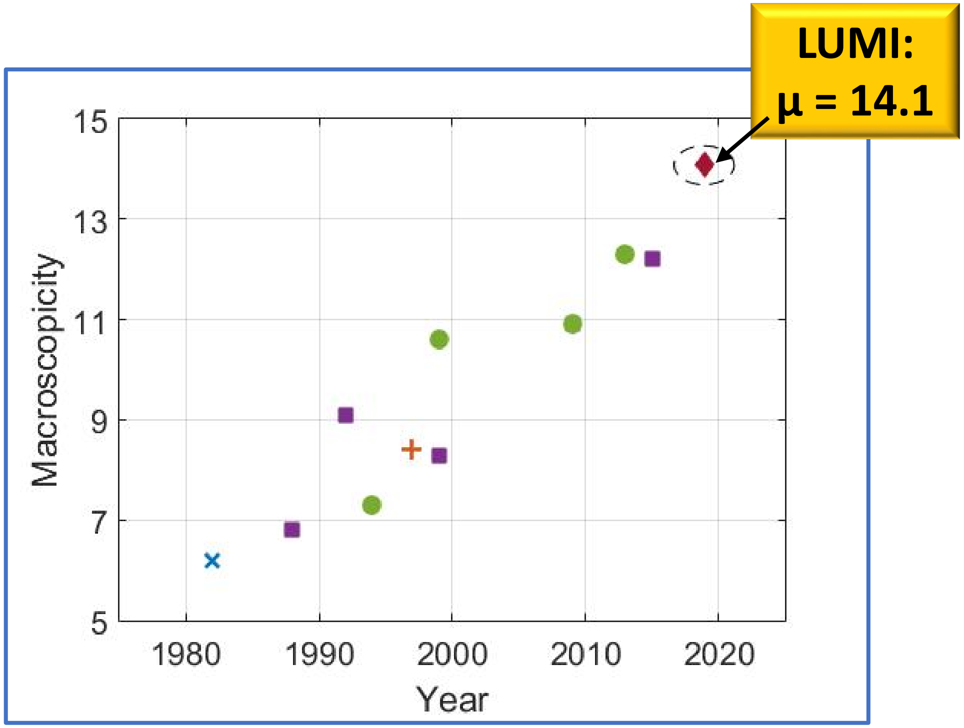
Quantum Macroscopicity $\mu \propto m^2$
measures how well
an experiment can **exclude**
a generic set of
Non-linear Extensions to
Quantum Mechanics

$$\mu = \log_{10}\left(\frac{1}{\ln(V/V_0)}\left(\frac{m}{m_e}\right)^2\frac{\tau}{1\,sec}\right)$$

What does μ=14 signify ?
To achieve the same bounds on QM an **electron interferometer** would need to maintain coherence (at equalt contrast and integration time) for over **80 million years** !

Previous macroscopicites for

- **Neutrons** : **x**
- **Atom** : ■
- **Molecules** : ●



LUMI:
μ = 14.1

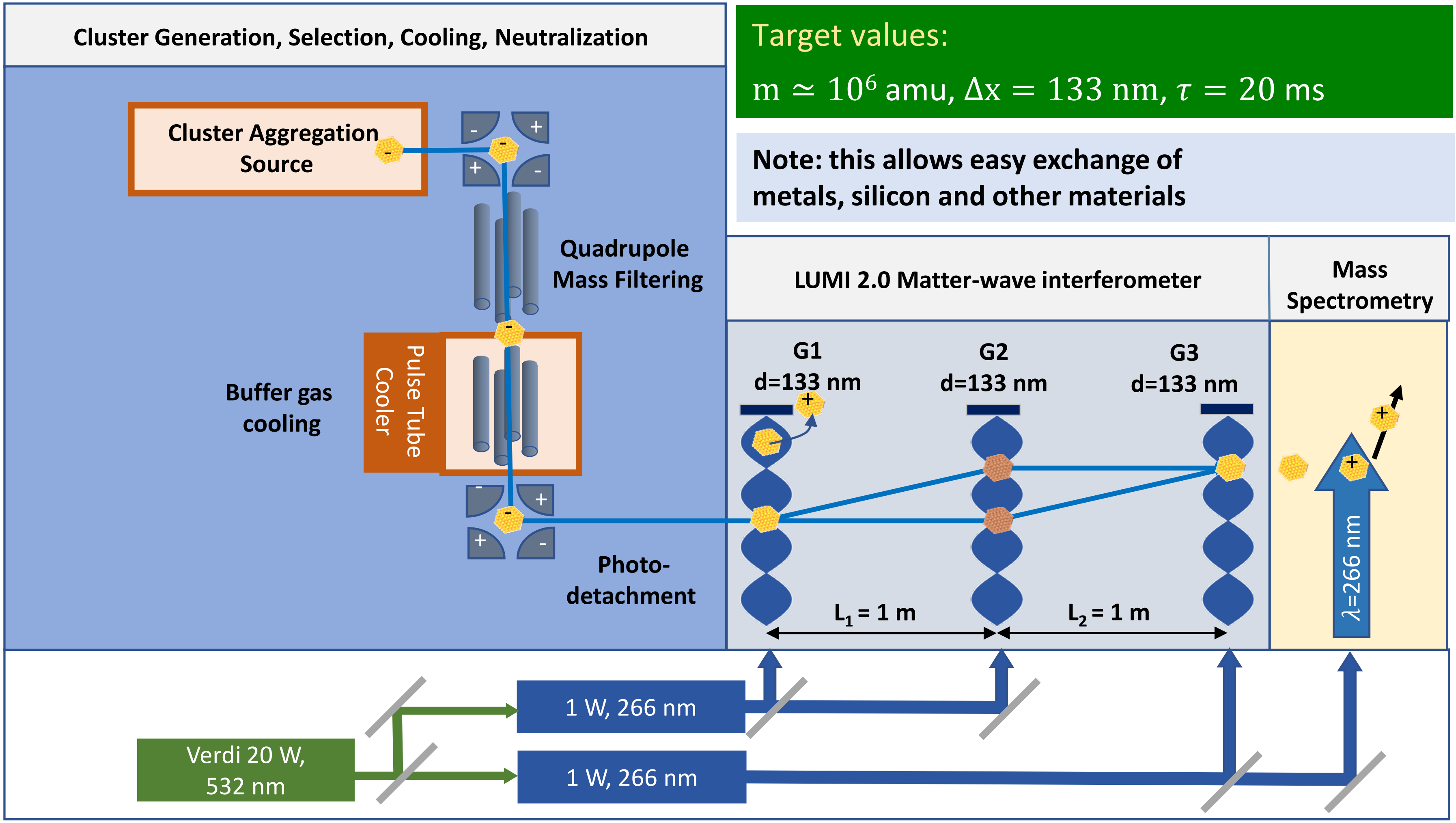
Y. Y. Fein, P. Geyer, P. Zwick, F. Kiałka, S. Pedalino, M. Mayor, S. Gerlich & M. Arndt, Nature Physics 15, 1242 (2019).

6. Work in progress: Interferometry with Large Metal Clusters: LUMI 2.0

Target values:

$m \simeq 10^6$ amu, $\Delta x = 133$ nm, $\tau = 20$ ms

Note: this allows easy exchange of metals, silicon and other materials



Cluster Generation, Selection, Cooling, Neutralization

Cluster Aggregation Source

Quadrupole Mass Filtering

Buffer gas cooling

Pulse Tube Cooler

Photo-detachment

LUMI 2.0 Matter-wave interferometer

Mass Spectrometry

1 W, 266 nm

1 W, 266 nm

Verdi 20 W, 532 nm

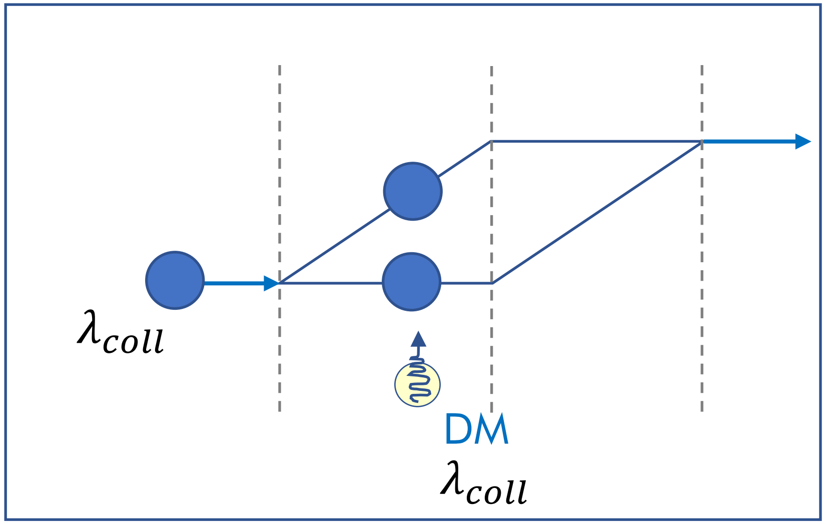
Proposed upgrade to: $m \simeq 10^8$ amu, $\Delta x = 80$ nm, $\tau = 2$ s in a tower on Earth

E. Reiger, et al., *Exploration of gold nanoparticle beams for matter-wave interferometry*, **Opt Commun 264, 326 (2006).**

F. Kiałka et al, *Concepts for long-baseline high-mass matter-wave interferometry*, **Phys. Scr. 94, 034001 (2018).**

7. Low-energy dark matter: Why matter-waves may be favourable

- An interferometer with widely separated arms is sensitive to decoherence by small momentum transfer in collision with dark matter.
- Prepare widely separated quantum states (Schrödinger Cat, Matter-Wave) If λ_{dB} (DM) < wave-packet separation of P1→ „wich-path information“
- If coherent scattering, d.h transverse coherence of DM > colliding matter particle: collision cross section $\boldsymbol{\sigma_{coll} \propto m^2}$ … increases with mass.



Watch out for daily and annually varying decohence caused by the motion of the Earth and the sun.

LUMI 3.0 target at QNP @ UNIVIE
$M = 5 \times 10^5$ amu, $\tau > 0.02$ s, $\Delta V/V < 1\%$

LUMI 4.0 perspectives for QNP@UNIVIE
$M = 5 \times 10^7$ amu, $\tau > 1$ s, $\Delta V/V < 1\%$

C.J. Riedel, *Decoherence from classically undetectable sources: Standard quantum limit for diffusion*, **Phys. Rev. A 92, (2015)**
C.J. Riedel, and **I. Yavin,** *Decoherence as a way to measure extremely soft collisions with dark matter*, **Physical Review D 96, 023007 (2017).**

Towards high-mass quantum states

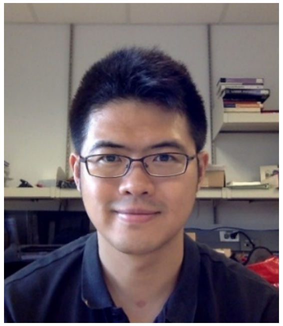
Cold source &

large coherent momentum transfer

8. Inelastic Kapitza-Dirac scattering & KD-blockade

The goal is to prepare …

- Very large Schrödinger Cat states of massive particles
- Very Large Momentum Transfer Beam Splitters
- Nano-mechanical number states
- Nano-mechanical 2-level systems



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(Univ. of Göttingen)

The method shall be universal and applicable to

- Trapped electrons
- Trapped atoms, trapped macromolecules & nanoparticles

Herman Batelaan
(Lincoln, Nebraska)

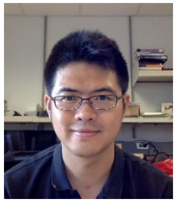
Solution

- Couple light & momentum and avoid internal states
  Inelastic Kapitza Dirac scattering

- Suppress undesired transitions by amplitude interference
  Kapitza-Dirac blockade

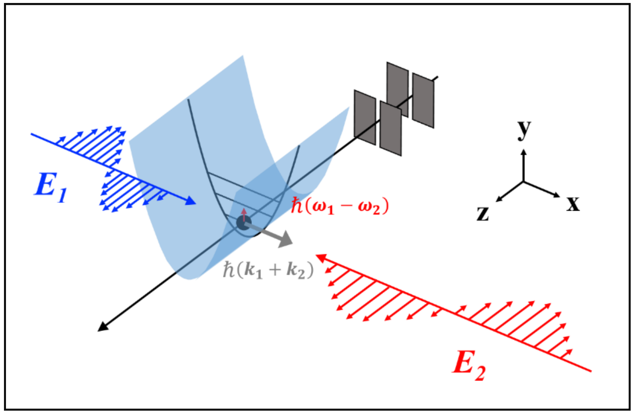
Wayne Cheng-Wei Huang, Herman Batelaan & Markus Arndt, ***Phys. Rev. Lett. (2021)*** *, arXiv:2011.12881v2*
Kapitza-Dirac blockade: A universal tool for the deterministic preparation of non-Gaussian oscillator states

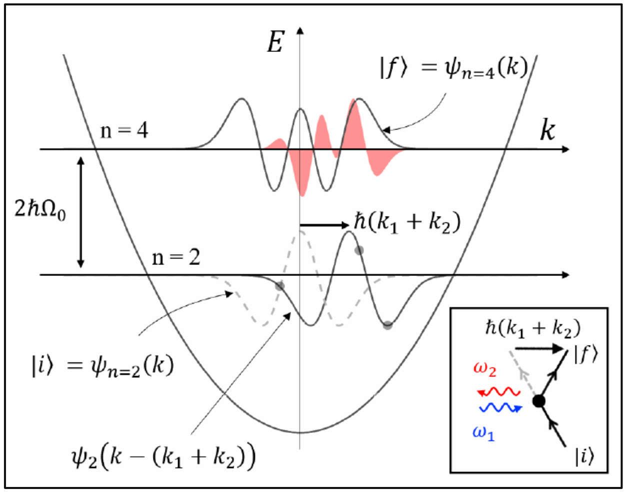
Kapitza-Dirac blockade:
A universal tool for selective state preparation



Wayne Huang

- Massive particle in 1D trap:
  - Optical tweezer
  - Electrodynamical trap …
- Population of ground state:
  - Collimated beam
  - Ground state cooling (see Aspelmeyer talk)
- Coherent state transfer by Kapitza-Dirac scattering:
  - 2 counter-propagating laser beams:
    - Equal polarization, far-off resonance
    - Detuned by twice the harmonic oscillator frequency
  - Acting on
    - Charged Particles: Ponderomotive potential
    - Polarizable particles: Dipole potential
- Kapitza-Dirac Blockade:
  - Energy and momentum conservation
  - Destructive Interference of scattering amplitudes confines state transfer to the desired levels





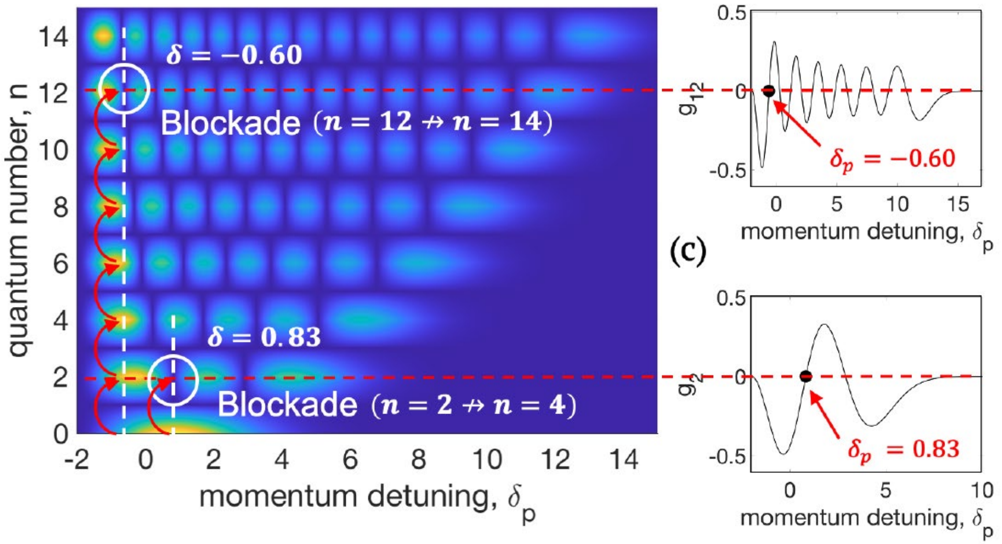
Wayne Cheng-Wei Huang, Herman Batelaan & Markus Arndt, ***Phys. Rev. Lett. (2021)***, *arXiv:2011.12881v2*

Kapitza-Dirac blockade: A universal tool for the deterministic preparation of non-Gaussian oscillator states

Kapitza-Dirac Blockade: Transition amplitudes $g_n(\eta)$ vanish at certain values of the Lamb Dicke parameter (momentum detuning)

$$g_n(\eta) \equiv \langle n+2|\cos((k_1+k_2)x)|n\rangle = -\sqrt{\frac{n!}{(n+2)!}}\eta^2 L_n^{(2)}(\eta^2)e^{-\eta^2/2}$$

$$\eta \equiv (k_1+k_2)x_0$$



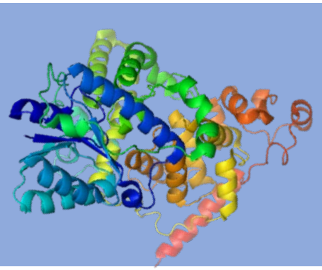
- Momentum splitting up to $\Delta p \simeq 1000\ \hbar k$ for electron & nanoparticle interferometry
- Rapid expansion of the wave function: macroscopic cat of massive particles
- $\Delta x \simeq 400\ nm$ in 30 ms for m=10^6 amu
- Can be tested with macromolecule interferometry

Wayne Cheng-Wei Huang, Herman Batelaan & Markus Arndt, ***Phys. Rev. Lett.* (2021)** , *arXiv:2011.12881v2*
Kapitza-Dirac blockade: A universal tool for the deterministic preparation of non-Gaussian oscillator states

Summary & Outlook in to the Prospects of Universal matter-wave interferometry

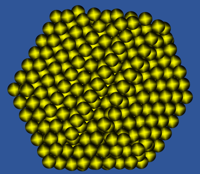
Large Biomolecules: 1 kDa - 10 MDa

Interface to Chemistry & Biology,
Quantum-enhanced metrology



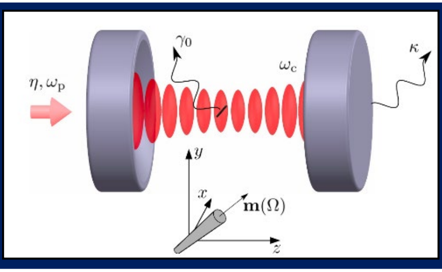
Lage Metal Clusters: 0.1 - 100 MDa

Wave function Collapse, Decoherence,
Search for light dark matter



Dielectric Nanoparticles: 1 - 100 MDa

Rotational Cooling &
KD Blockade for non-trivial quantum states



Thank you for your Attention ☺