Progress at LUMI: The Long-baseline Universal Matter-wave Interferometer

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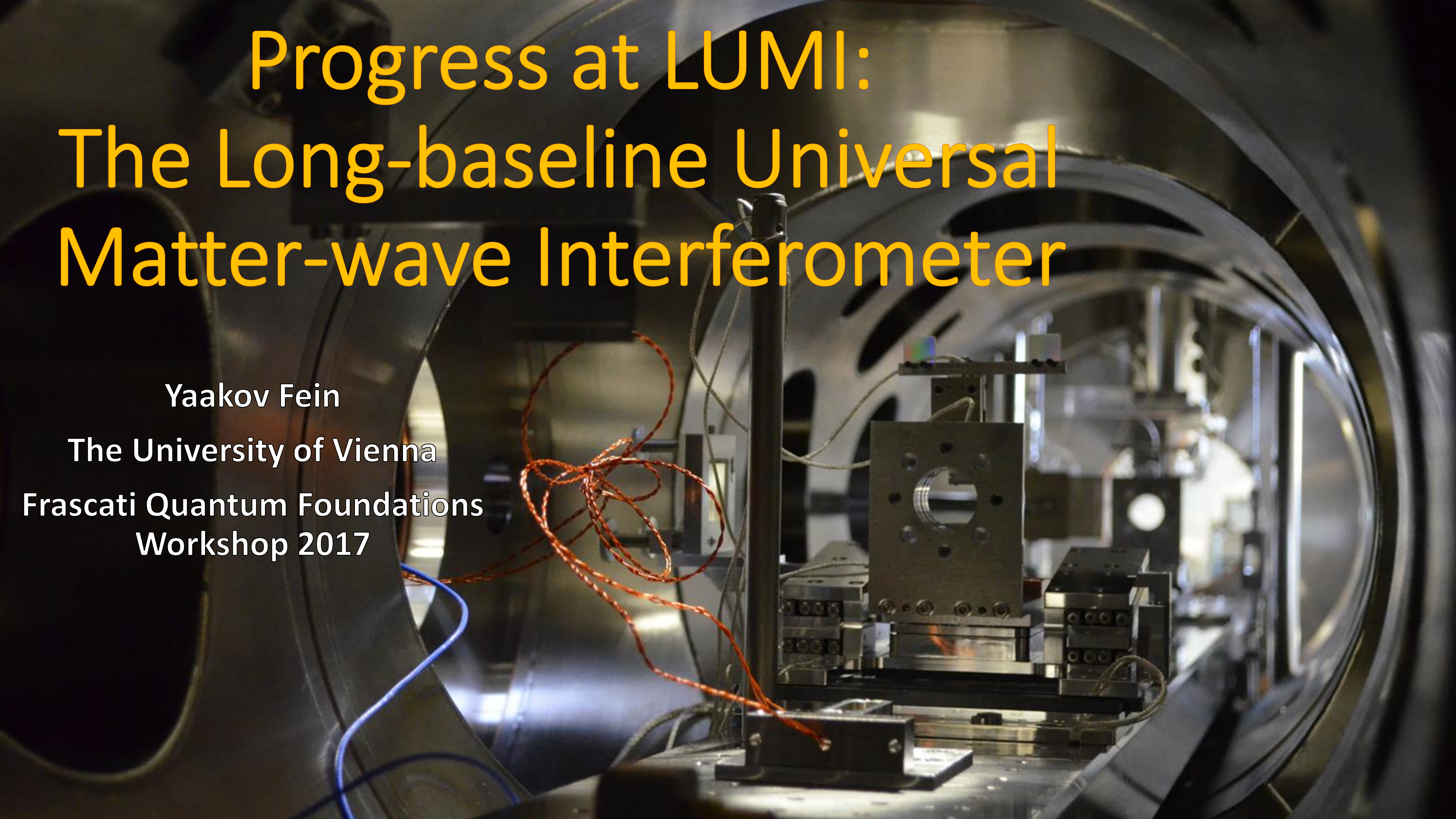
Frascati Quantum Foundations Workshop 2017



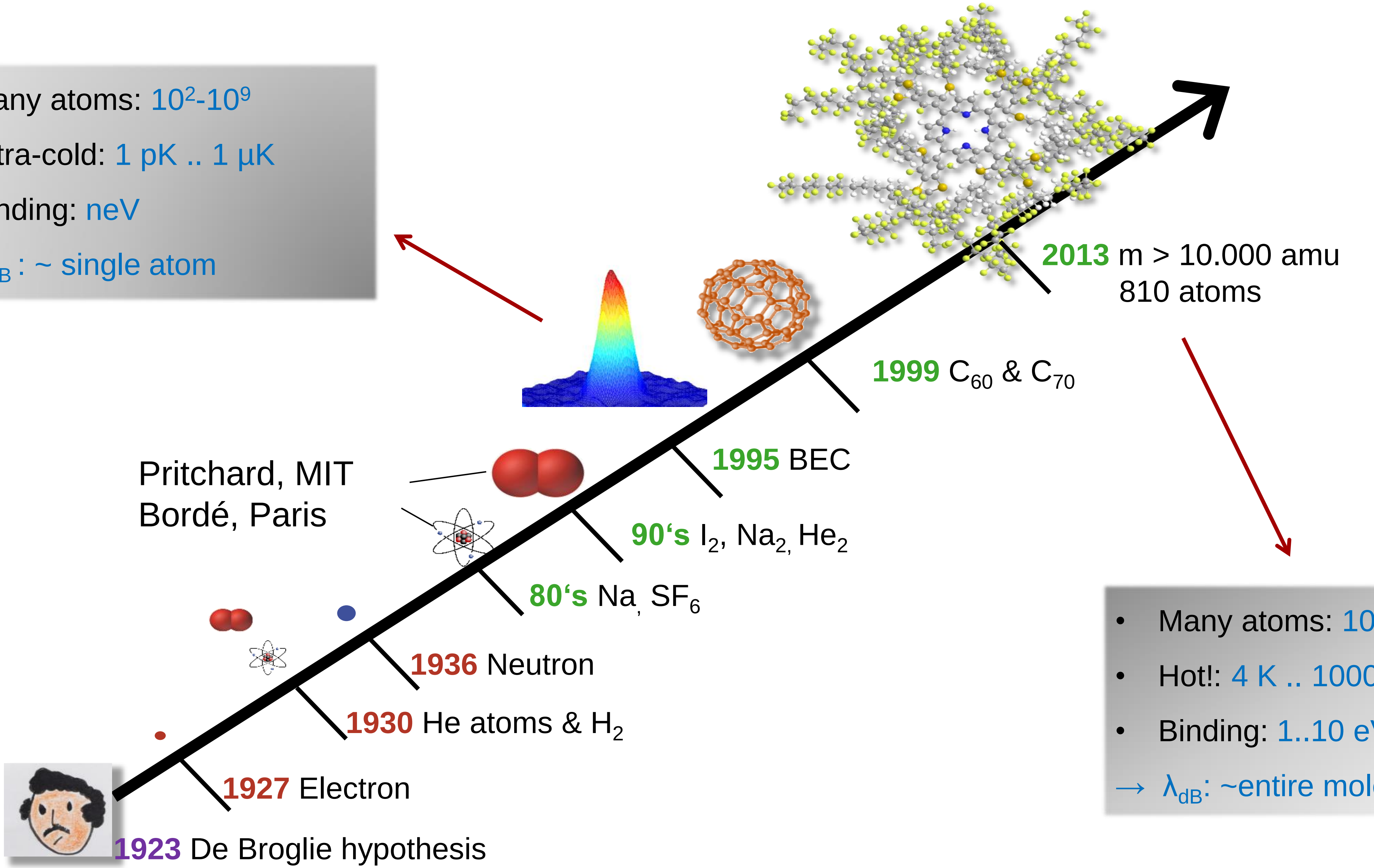
Outline

- Motivations behind molecular interferometry
- Summary of Arndt group work and various interferometer schemes
- Detailed discussion of LUMI: its motivations, challenges, and current status
- Connection to collapse models

Matter-wave Interferometry: From e^- to $C_{284}H_{190}F_{320}N_4S_{12}$

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

→ λ_{dB} : ~ single atom



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

→ λ_{dB}: ~entire molecule

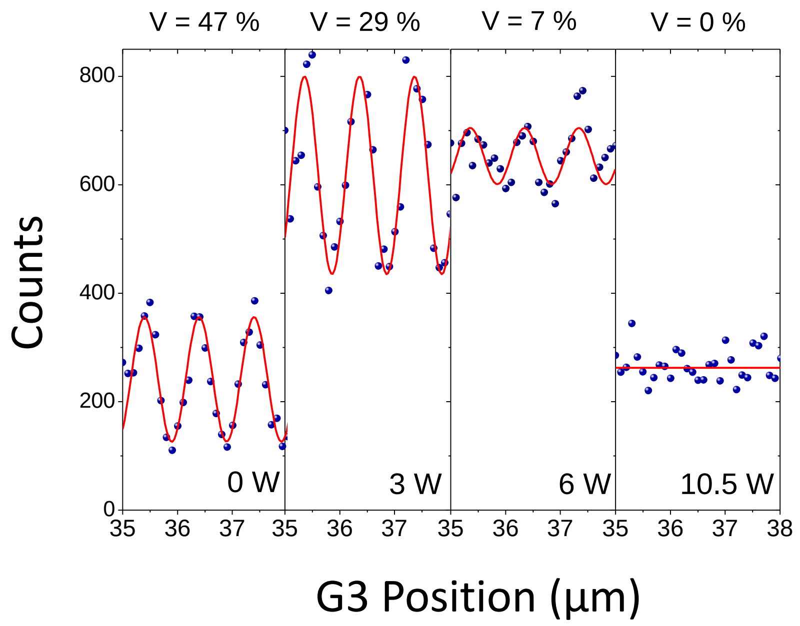
Why Molecule Interferometry?

Fundamental Studies

- Bottom-up approach to tests of quantum-classical transition
- **Direct** test of quantum superposition
- Tests of **Decoherence**: thermal, collisional, internal-clock decoherence?
- Search for gravitational waves, dark matter?

Quantum-assisted Metrology

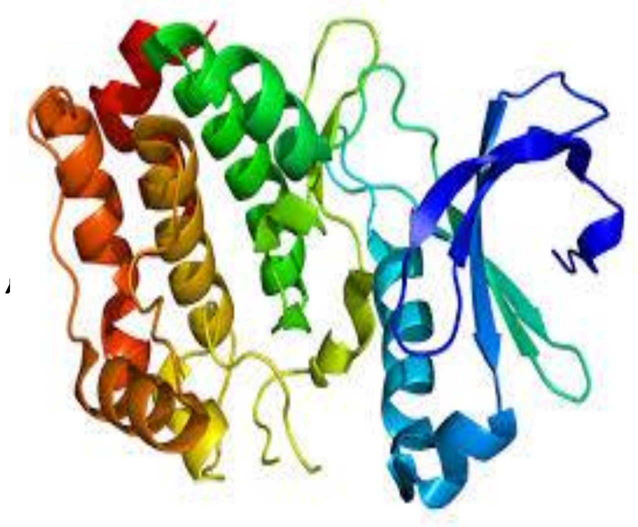
- Optical: absorption and photo-isomerization
- Electric: Polarizability and dipole moment
- Magnetic: aromaticity, excited-state dynamics



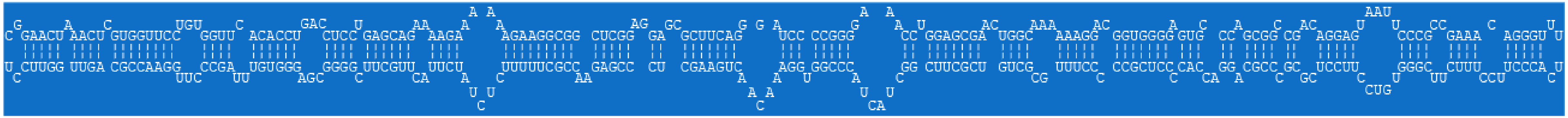
But Why Biomolecules?

Perhaps not molecule-of-choice for mass-record attempts, BUT much to be studied...

- Evolution has created **vast library of nanoparticles** to choose from
- Decoherence due to high **natural complexity**
- Interference dependence on hydration? Schrödinger cat in „natural“ environment
- Can we interfere **proteins, DNA, viroids**?
  - Does quantum delocalization preserve biological function?
  - Can we use it as a tool to learn about protein conformation?
- Will require development of beam sources, manipulation, cooling, and detection methods

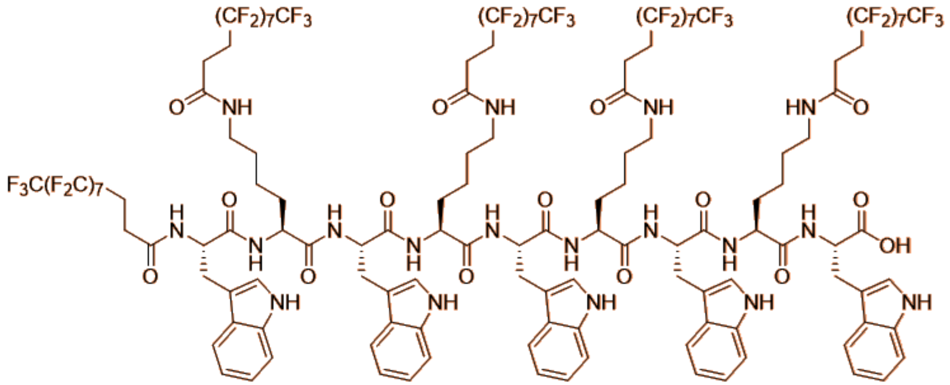


Some Intriguing Candidates



Viroids: Discovered 1971 by Theodor O. Diener

- **Self-replicating** RNA strands
- Smallest infectious agents in biology
- 70,000 amu, several hundred nucleotides per molecule
- NOTE: „Real“ viruses probably ruled out by thermal emission decoherence



Artificial Proteins:

- Laser desorption/post-ionization of functionalized 30-Amino acid peptide @ 12,300 amu

What Scheme to Use?

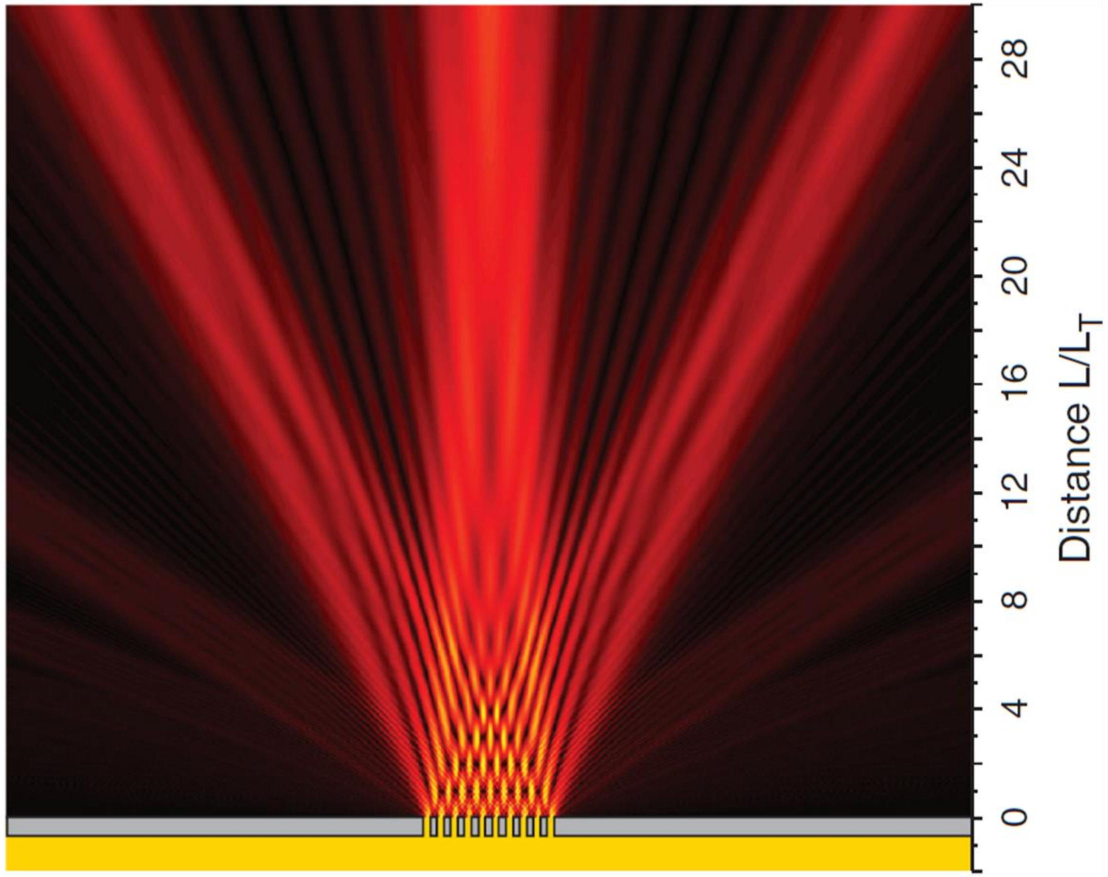
Far Field

- Easy interferometer requirements, tight **source** and **detection** requirements
- Length scale $\propto \frac{1}{m}$

  → Limited to smaller molecules

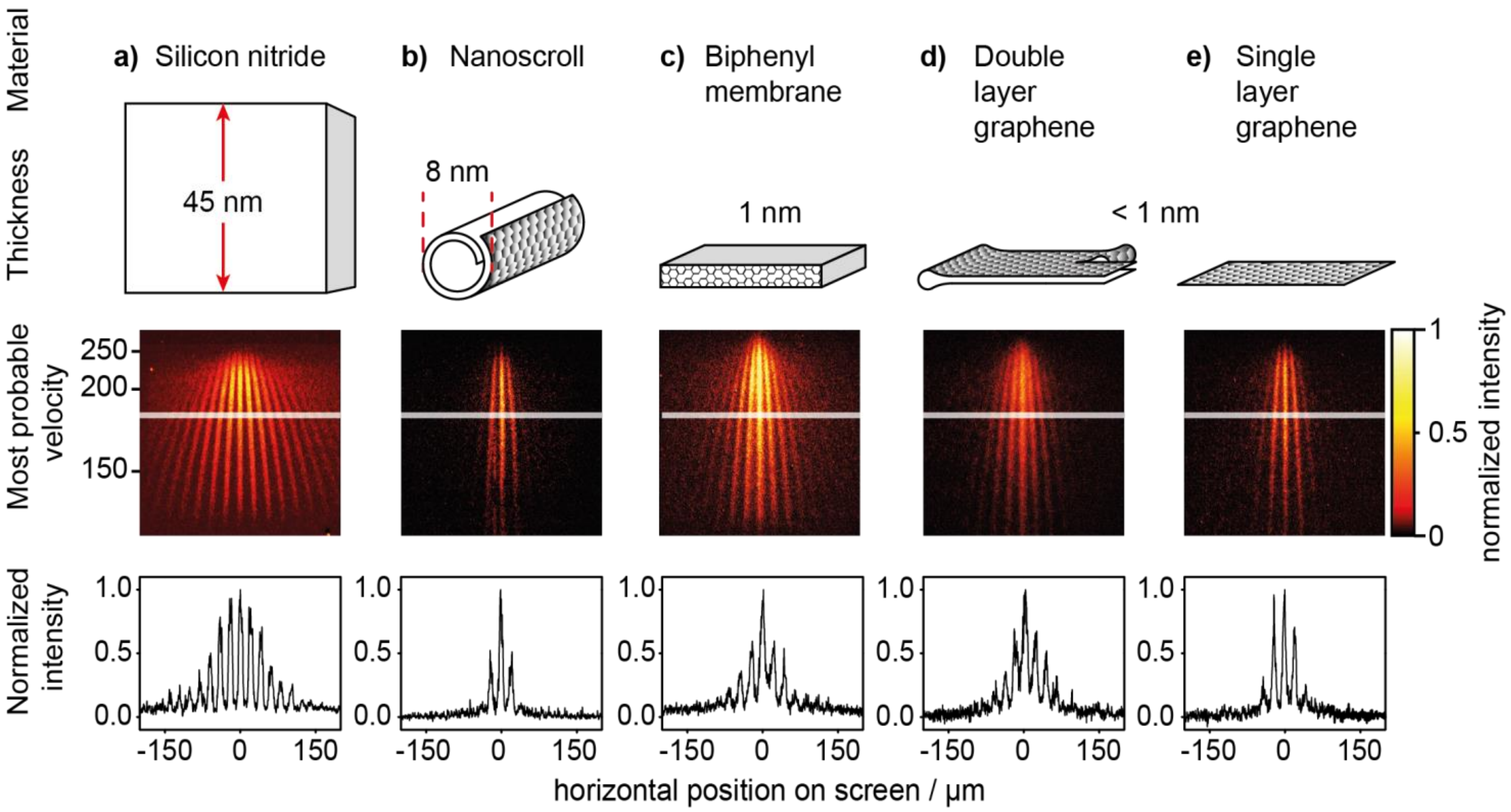
Near Field

- Stricter interferometer requirements (grating alignment, period matching, etc.)
- BUT, robust to fast and uncollimated beams
- Talbot length $L_T = d^2/\lambda_{DB}$ → length scale $\propto \frac{1}{\sqrt{m}}$



Conclusion: Depends what you want to study... But for high mass/complexity, **near field** is the way forward with technology at hand

Far Field Diffraction

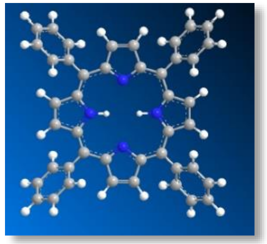


Ch. Brand, M. Sclafani,Ch. Knobloch, Y. Lilach, Th. Juffmann, J Kotakoski, C. Mangler, A. Winter, A. Turchanin, J. Meyer, O. Cheshnovsky, M. Arndt

Role of the Dipole Moment

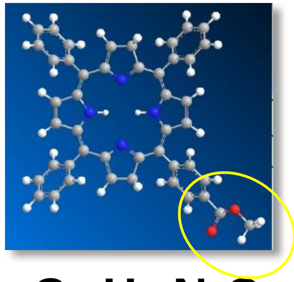
Diffraction of porphyrin derivatives at 20nm thick carbon grating

Non-polar TPP



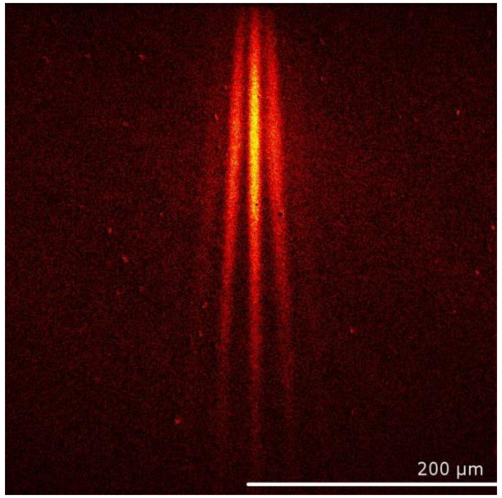
$C_{44}H_{30}N_4$

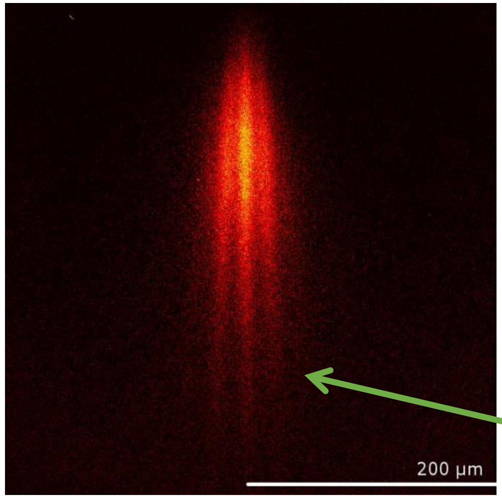
Polar Metoxy-TPP



$C_{46}H_{32}N_4O_2$

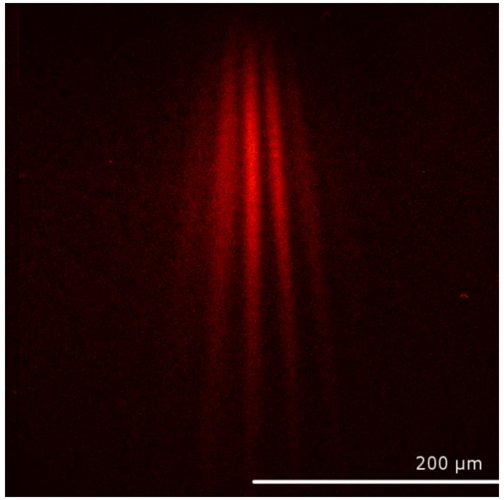
Normal Incidence
$\theta = 0°$

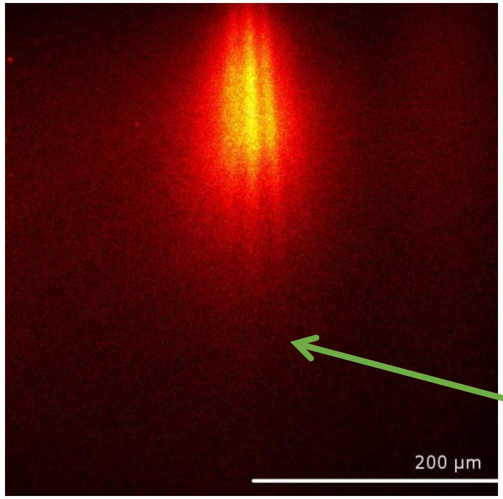




Interference preserved

Oblique Incidence
$\theta = 40°$

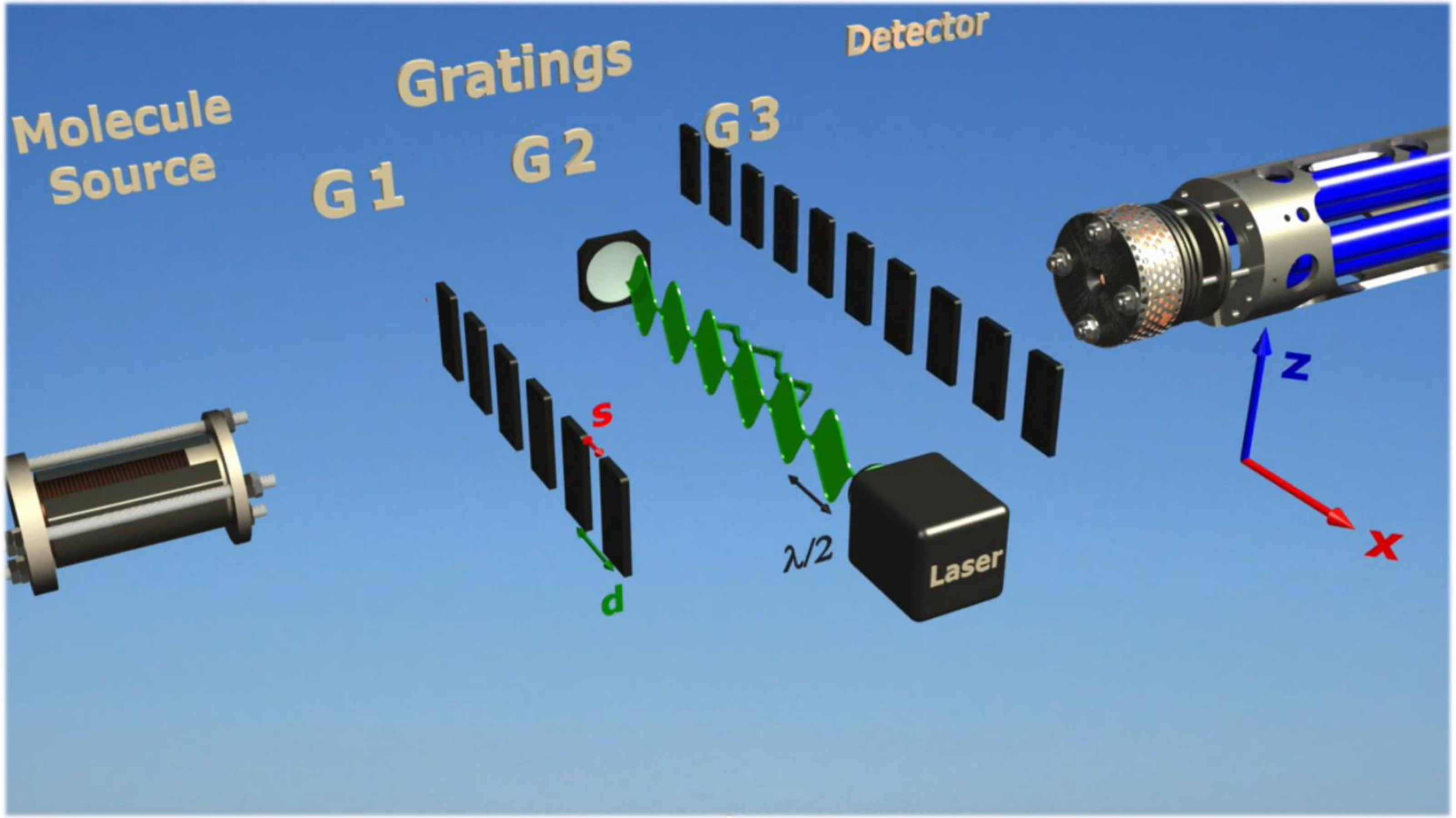




Interference destroyed

The KDTL Interferometer

- Molecule source: typically thermal
- **G1** prepares transverse coherence, **G2** diffracts, **G3** acts as mask
- **G2** is optical **phase** grating, **G1 and G3** material gratings, periods matched 1:1
- Detector behind G3, typically QMS
- Self-image imprinted on molecules via **Talbot-Lau effect**

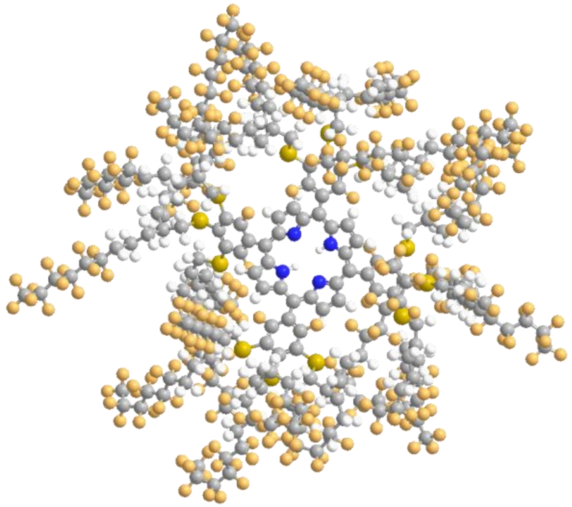


Results from KDTLI

- **Largest molecule** to show interference to date:

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

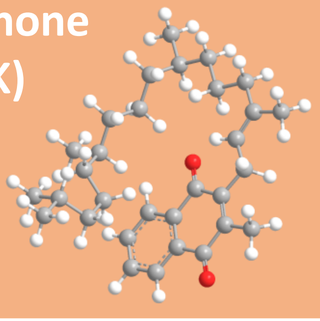
  - 10,123 amu
  - >800 atoms



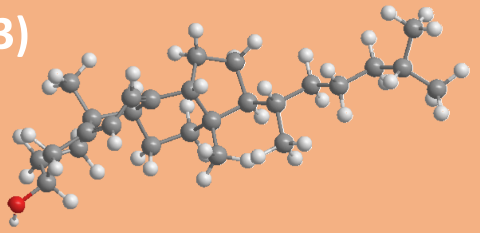
$C_{284}H_{190}F_{320}N_4S_{12}$

- Interference with **vitamins**

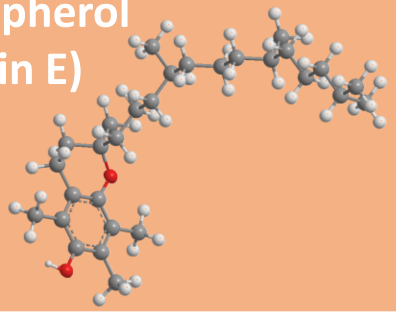
Phylloquinone (Vitamin K)



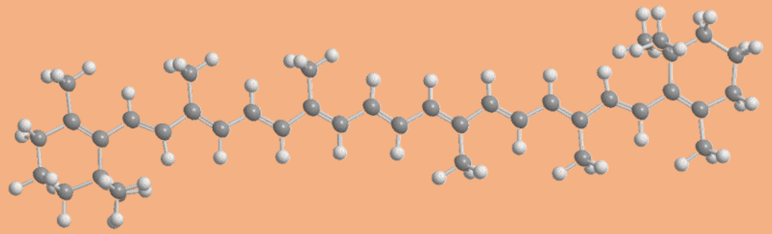
7-Dehydrocholesterol (Provitamin D3)

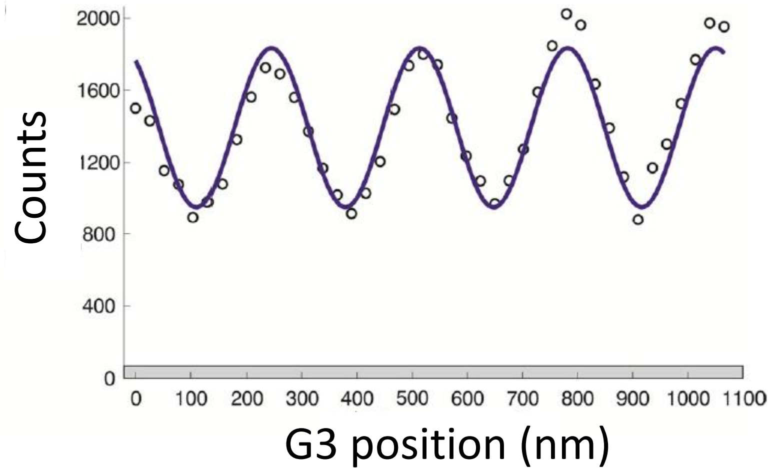


α-Tocopherol (Vitamin E)



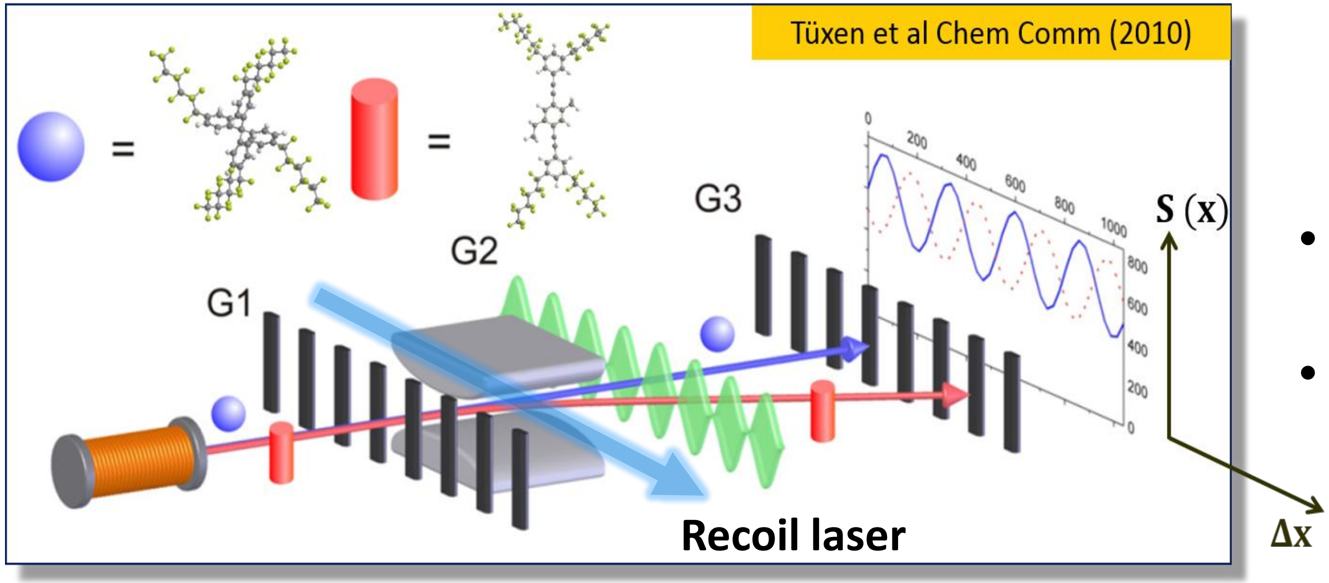
β-carotene (Provitamin A)





Metrology in KDTLI:

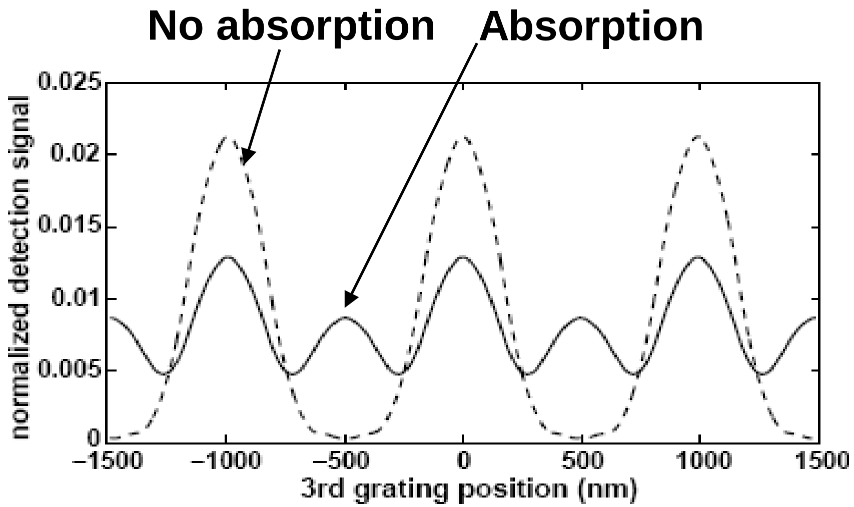
Electric Deflection, Absolute Cross Sections



$$\Delta x \propto \frac{\chi}{m} \cdot \frac{(\boldsymbol{E}\boldsymbol{\nabla})\boldsymbol{E}}{\mathrm{v}^2} \propto \frac{2\pi}{d} \cdot \frac{F}{m} \cdot T^2$$

- Electric field gives fringe shift prop. to polarizability α
- Quantum advantage: resolution better than 10nm

- Loss in visibility due to absorption yields absolute cross sections
- $\sigma_{C70} = 1.97(6) \times 10^{-21}\, m^2$
- Works for extremely dilute beams
  - $< n >_{absorption} \ll 1/molecule$



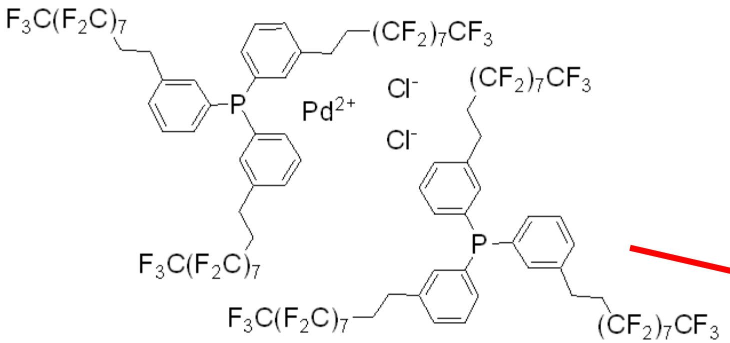
S. Nimmrichter, K. Hornberger, H. Ulbricht, M. Arndt, **Phys. Rev. A** 78, 063607 **(2008).**
S. Eibenberger, X. Cheng, J. P. Cotter, and M. Arndt, **Phys. Rev. Lett**. 112, 250402 **(2014).**

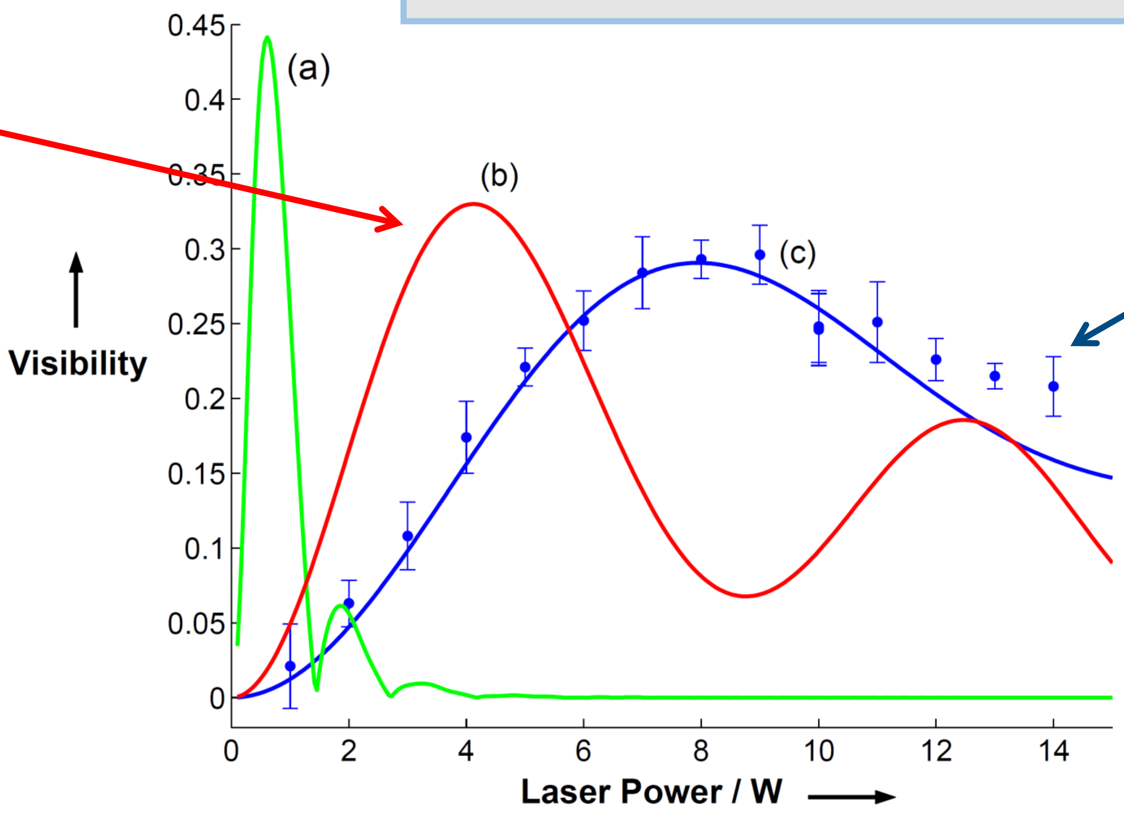
Metrology in KDTLI: *Particle identification*

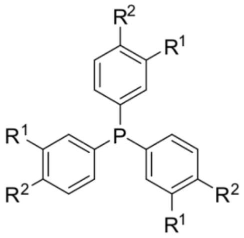
Green: Classical theory

Red: Quantum theory: intact molecule

Blue: Quantum theory: 1600 amu fragment







Angew. Chem. Int. Ed. 47, 6195 (2008).

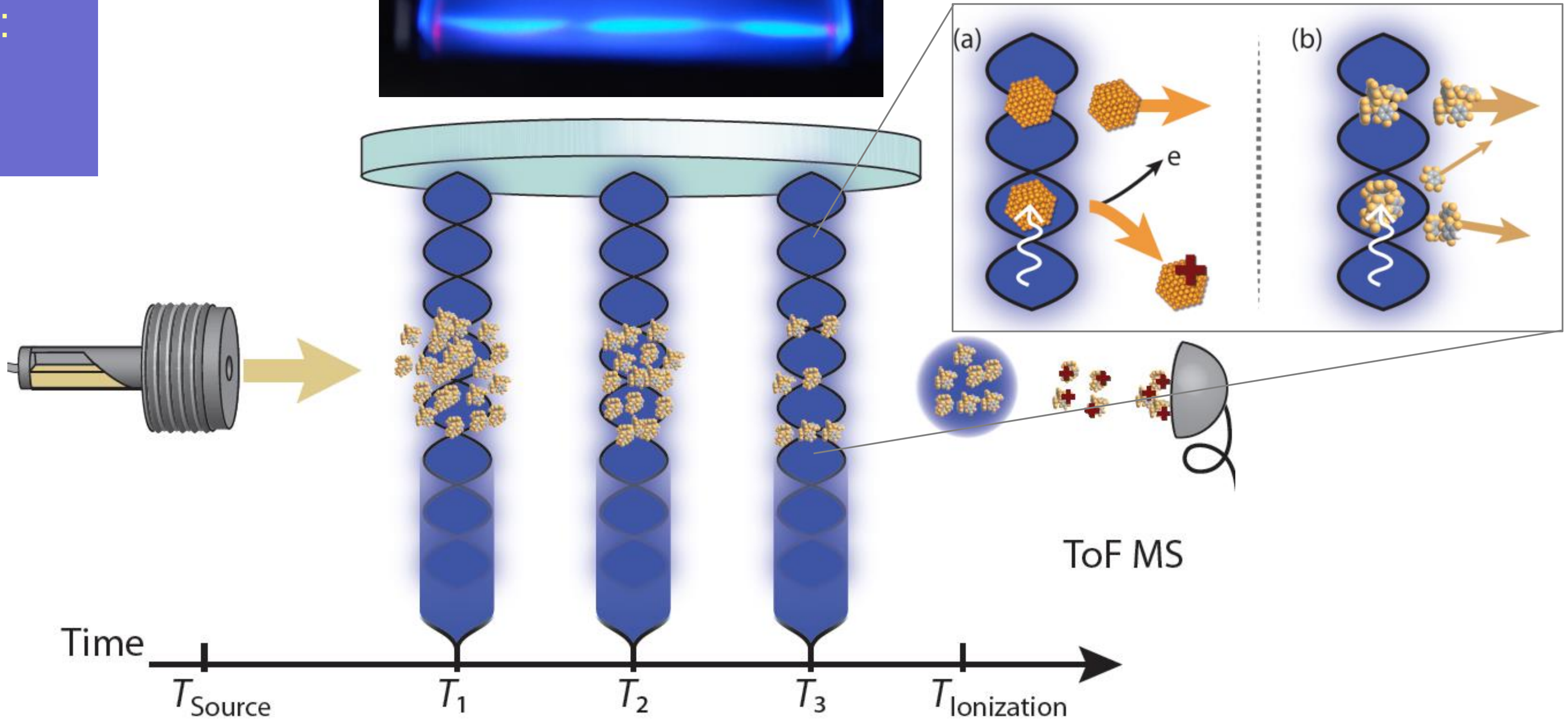
OTIMA: A near-field Interferometer with optical gratings
for pulsed beams of molecular clusters and nanoparticles

Interference occurs around multiples of the Talbot Time:

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

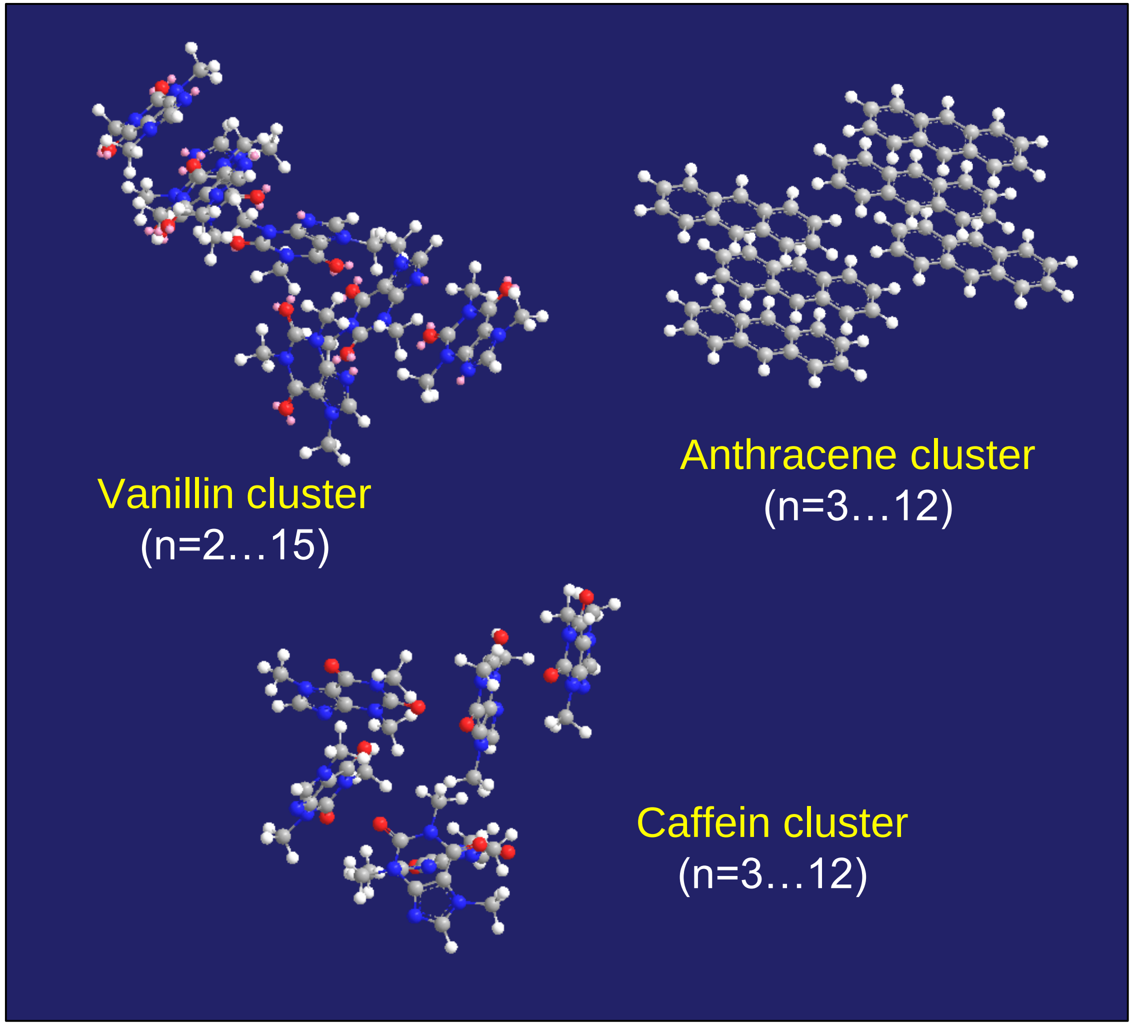
a) Photo-ionization gratings

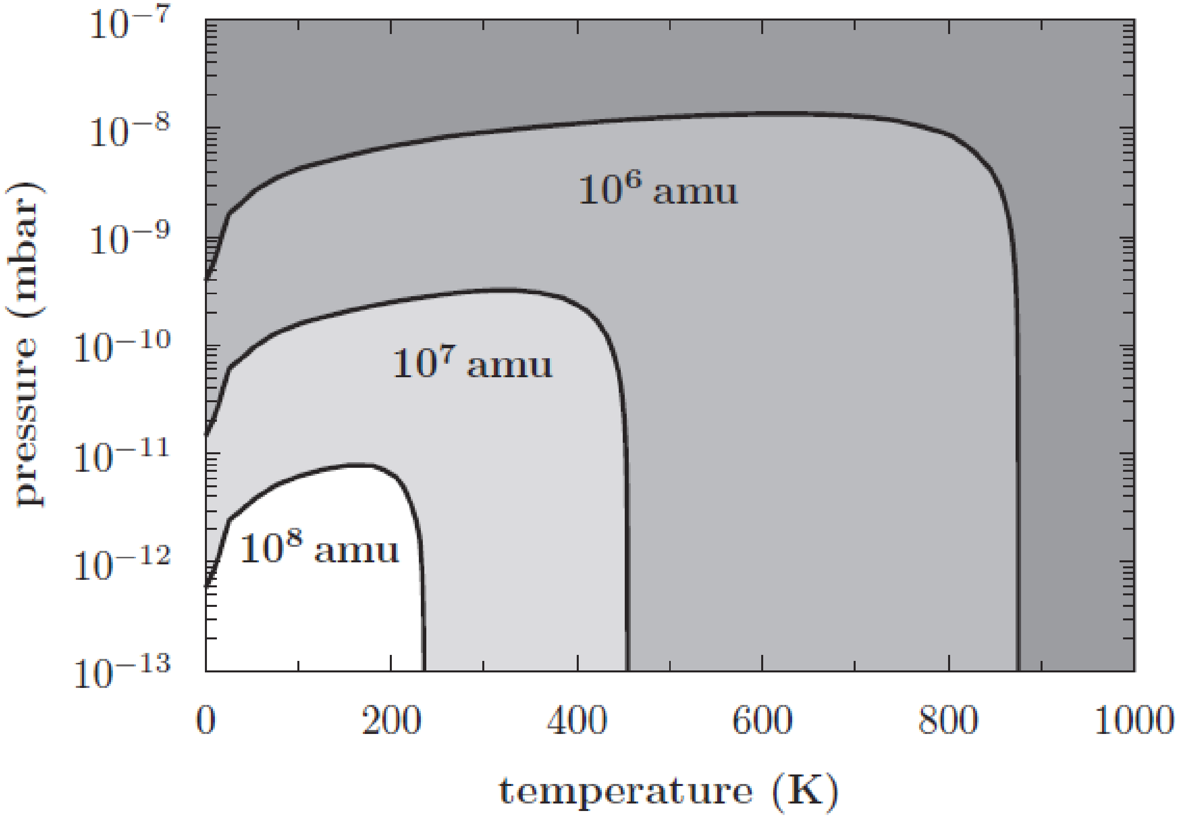
b) Photo-fragmentation gratings



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.**

Interference at OTIMA

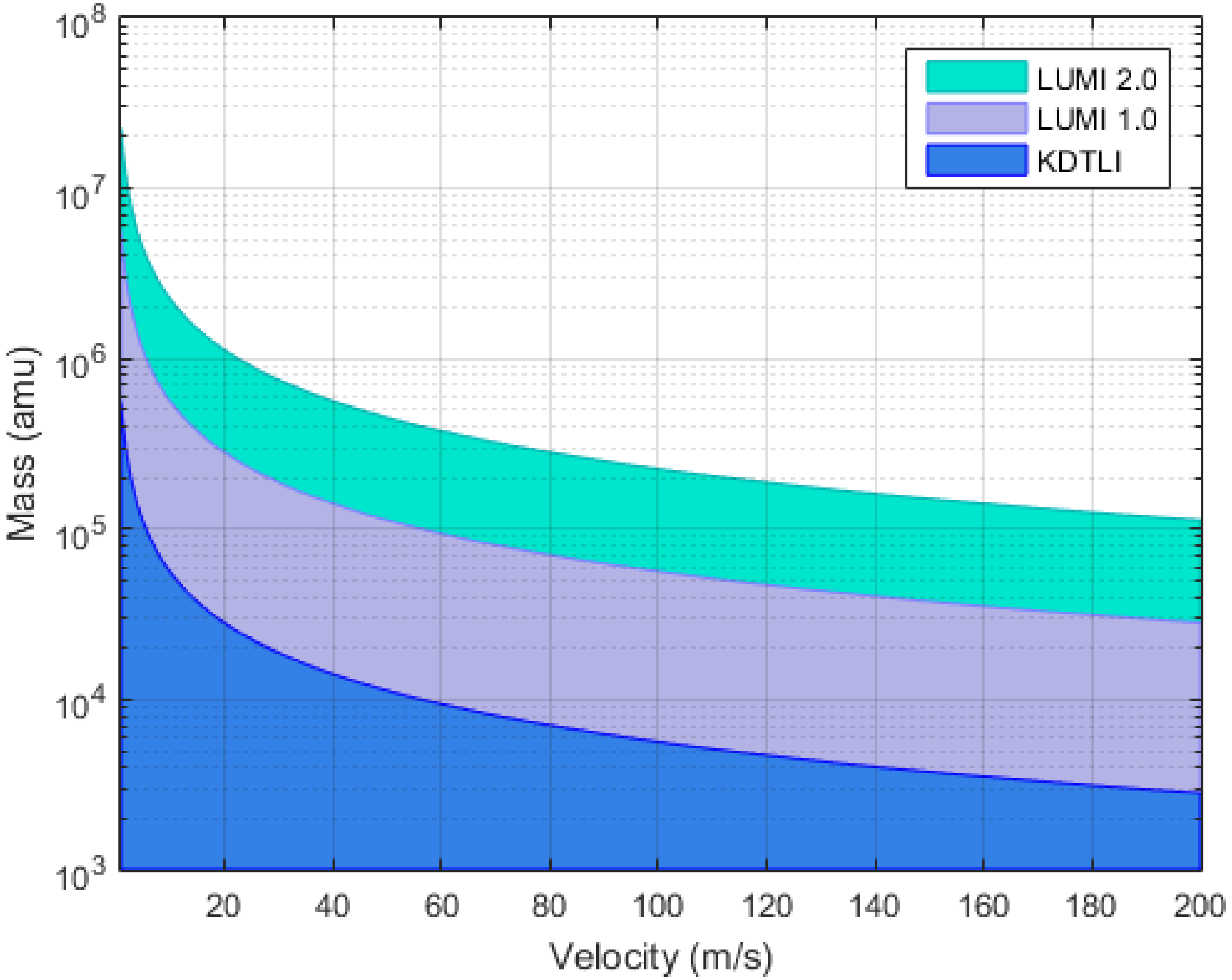




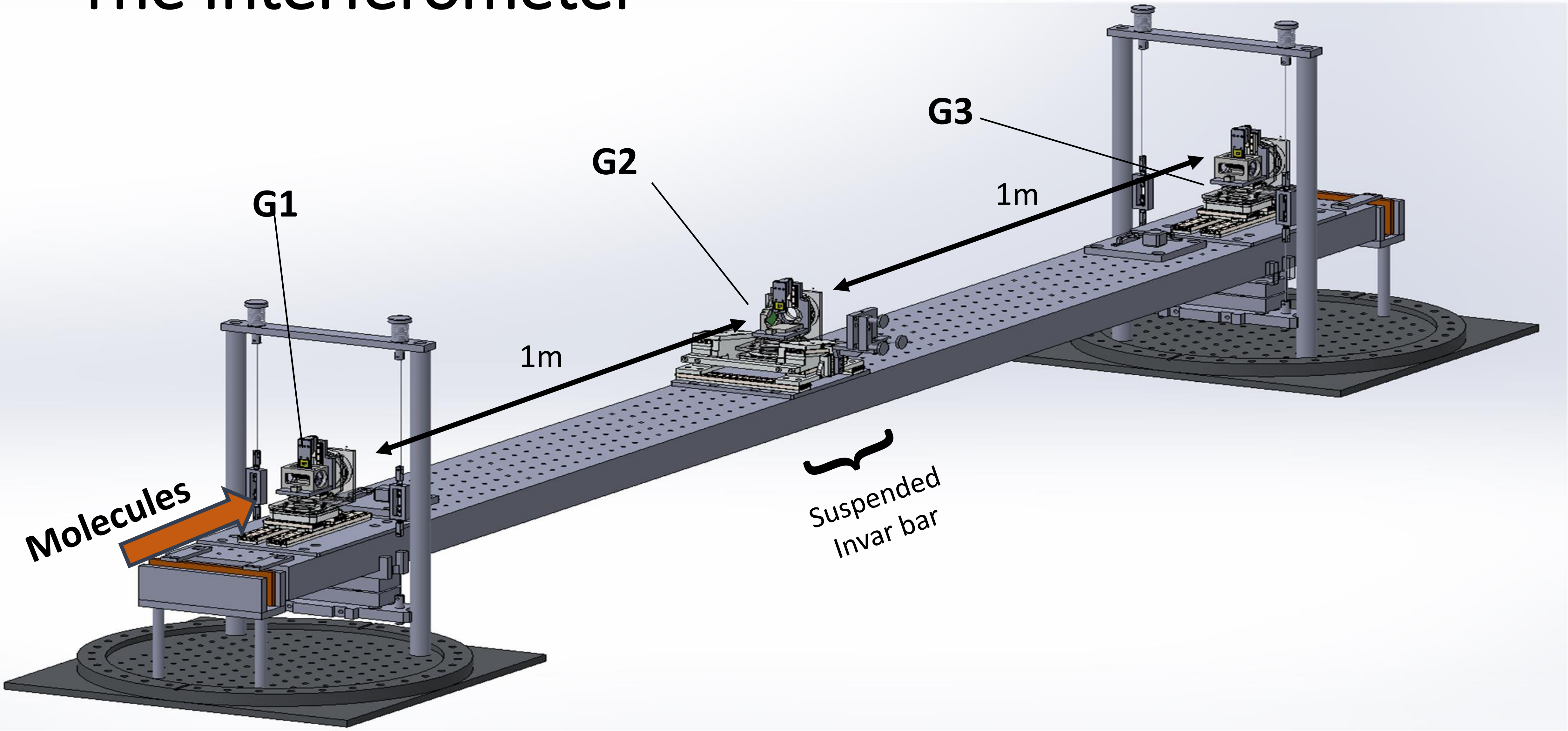
Nimmrichter et al. Physical Review A **83**, 043621 (2011)

Why LUMI?

- LUMI 1.0: KDTLI scheme
    - 1 m long arms
    - Accepts up to 100,000 amu
    - Higher mass -> more complex molecules
    - 100x metrology **sensitivity**



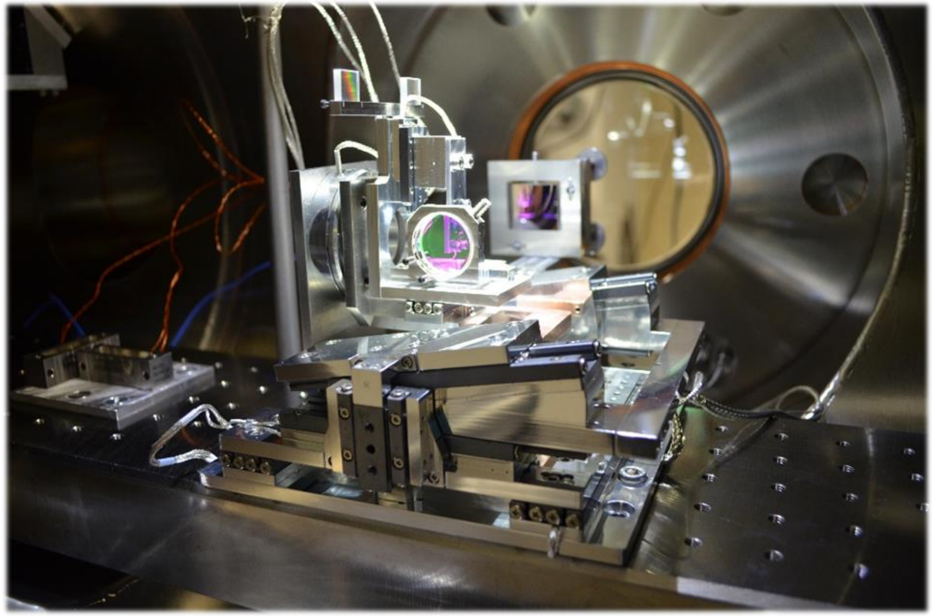
The Interferometer

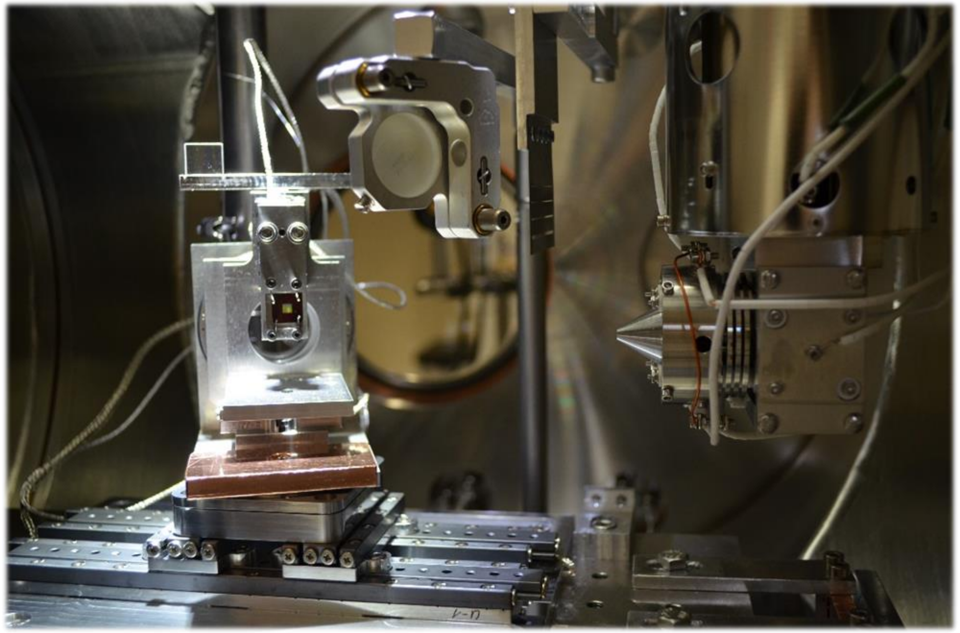


Universal?

- Nanometer repositionable piezos: near full degree of freedom for gratings
- In-vacuum exchange between material and optical gratings
- Easily exchangeable source/detector

→ Can accept large range of sources and detectors



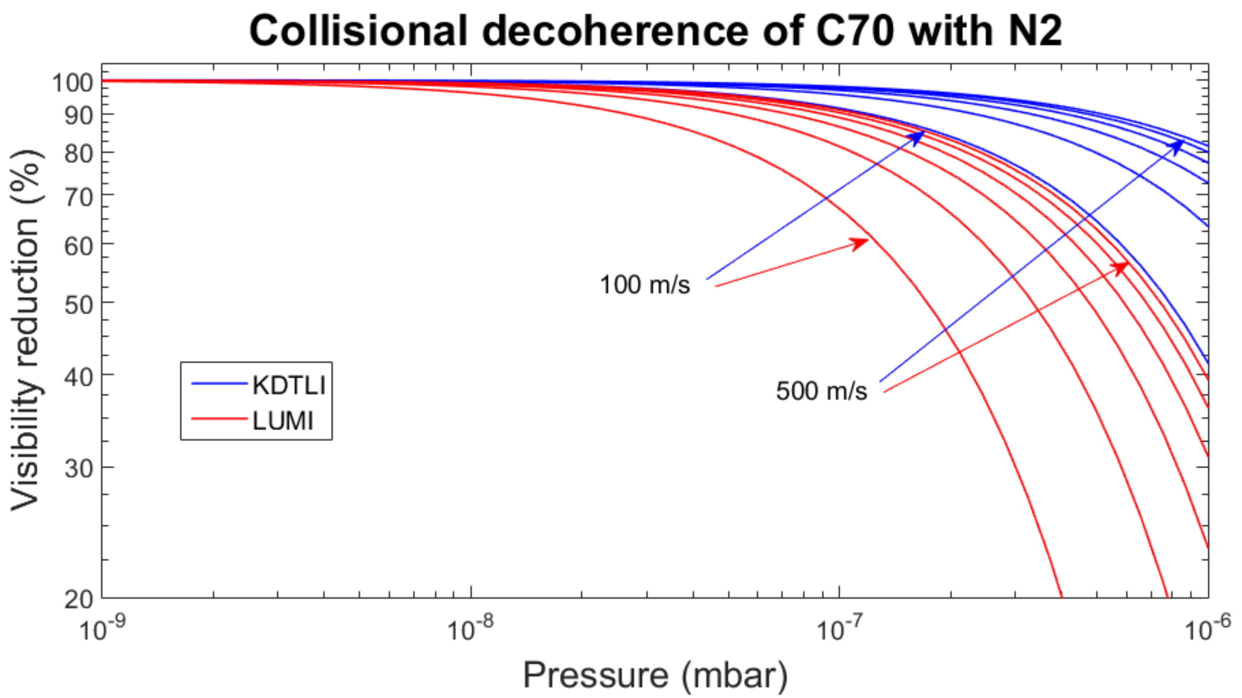


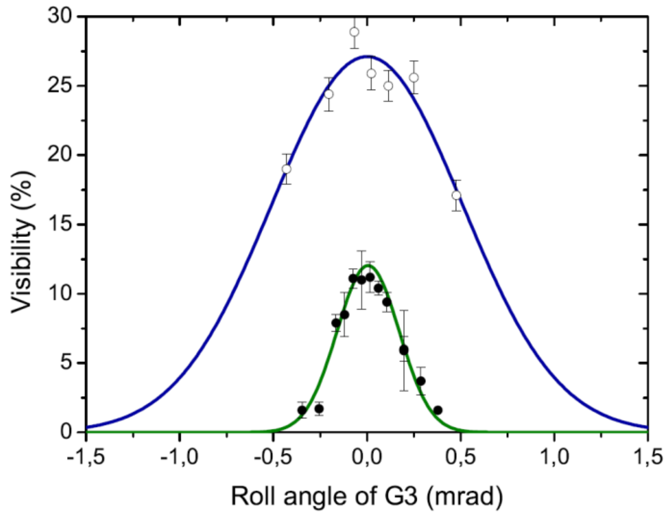
Challenges: *Part I*

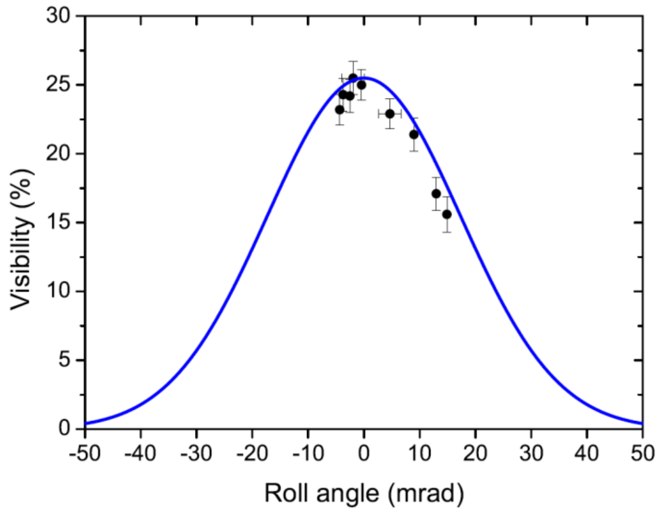
- **Collisional decoherence**
  - For given mean free path, longer length → more collisions
  - Require $< 10^{-8}$mbar
- **Counts/Detection**
  - Geometric: Drops as $1/r^2$ from point-like source
  - Low detection efficiency for large molecules
- **Tighter Alignment Criteria**
  - Visibility loss due to **common roll**

$$\propto \exp\left[-8\left(\frac{g\sin(\gamma_{roll})\pi\sigma_v \boldsymbol{L}^2}{d v_z^3}\right)^2\right]$$

→ Sub-mrad, along with **relative roll**



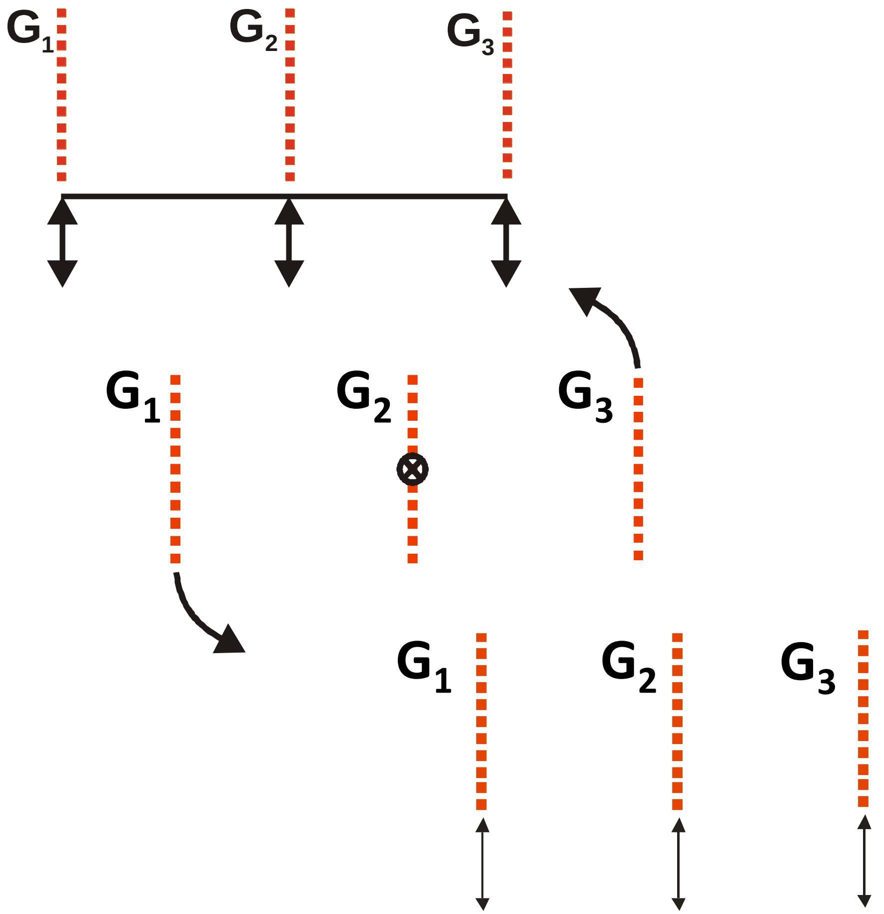


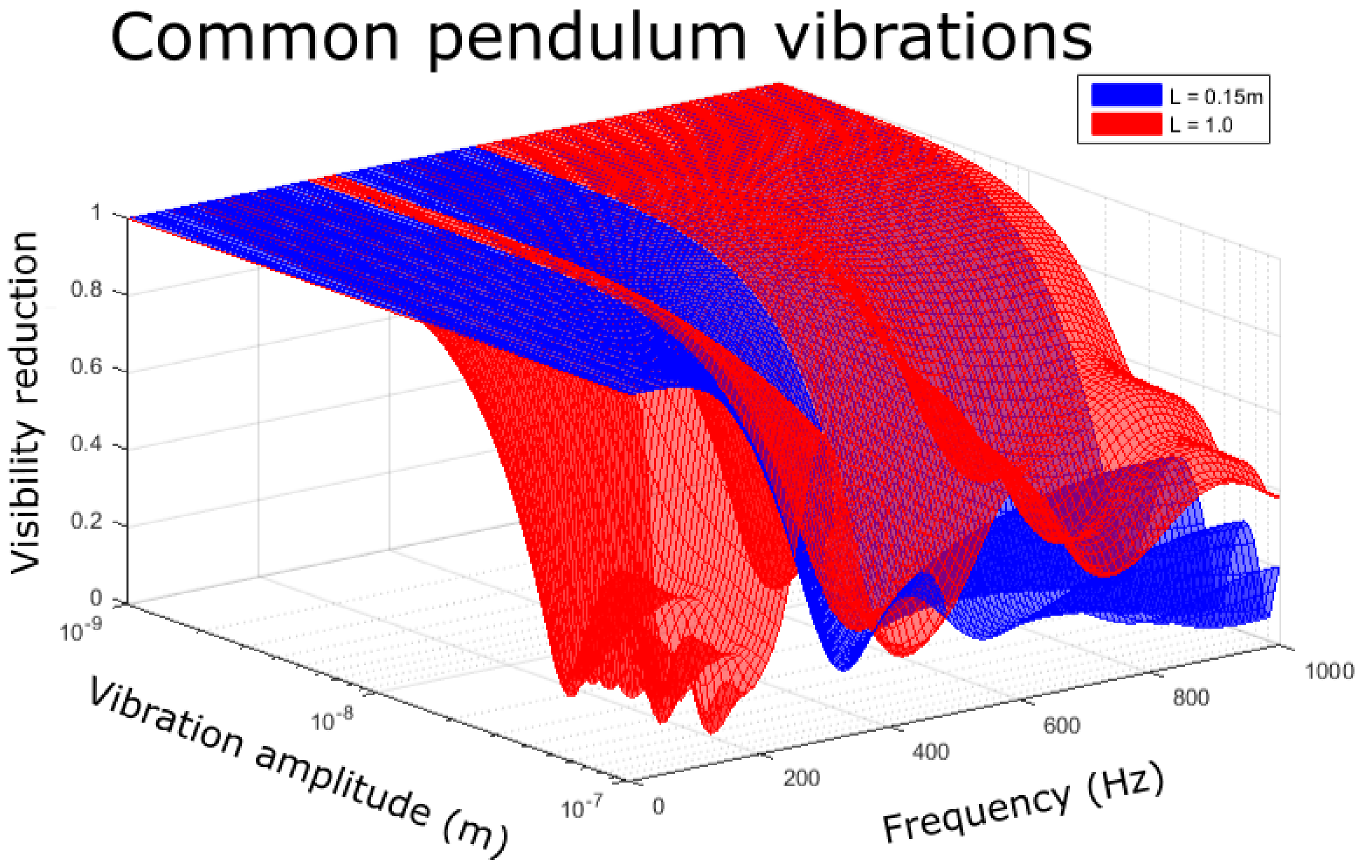


Challenges: *Part II*

Vibrations

- Phase shift: $\Delta\varphi = \frac{2\pi}{d}\left[x_1(t) - 2x_2(t) + x_{3(t)}\right]$





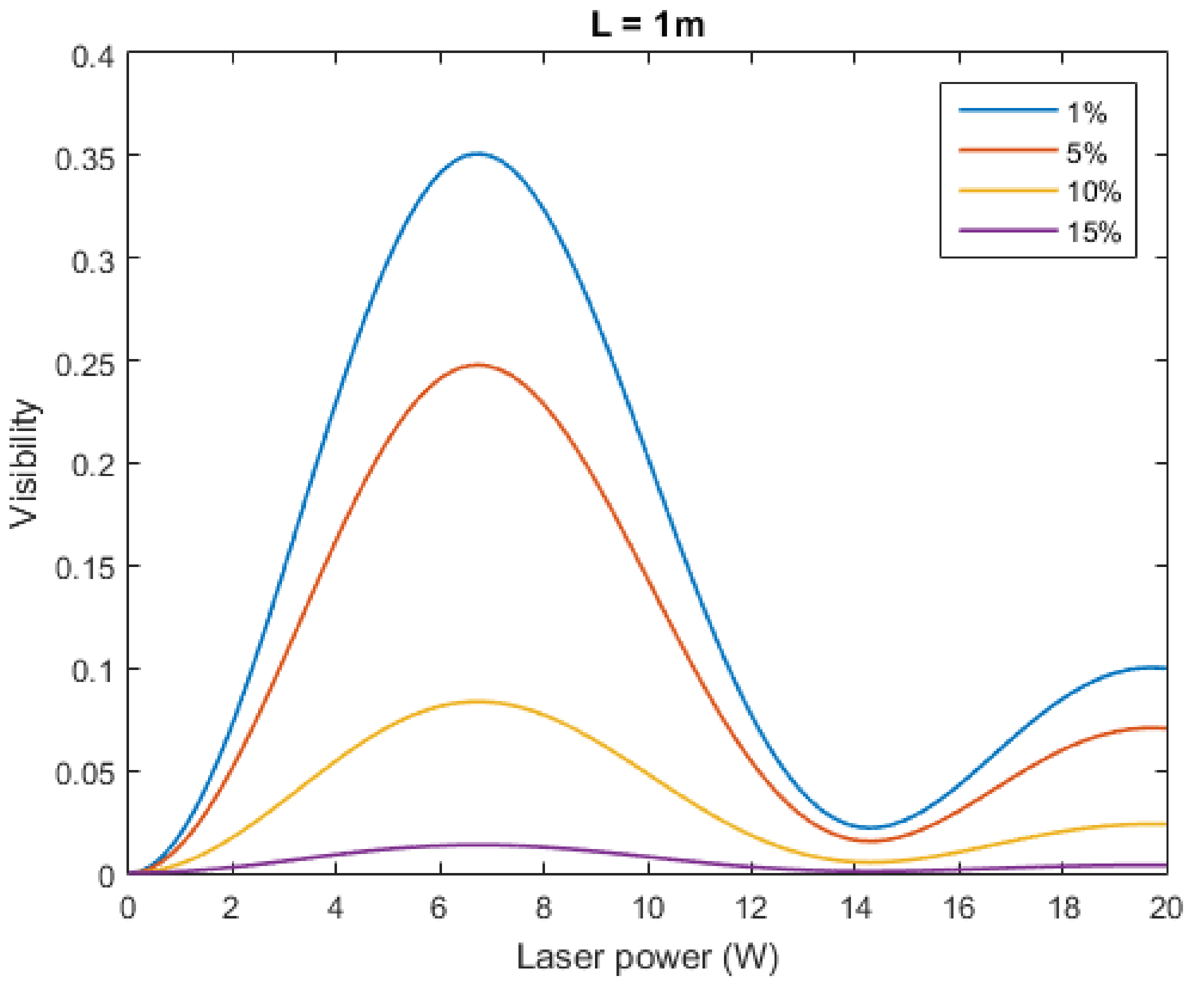
Challenges: *Part III*

Coriolis shifts

- $\Delta\Phi_{\text{rot}} = \frac{2\pi}{d} \cdot 2\vec{v} \times \vec{\Omega}_E \left(\frac{\boldsymbol{L}}{v}\right)^2$
- 10x the distance means 100x the deflection
- Visibility reduction:

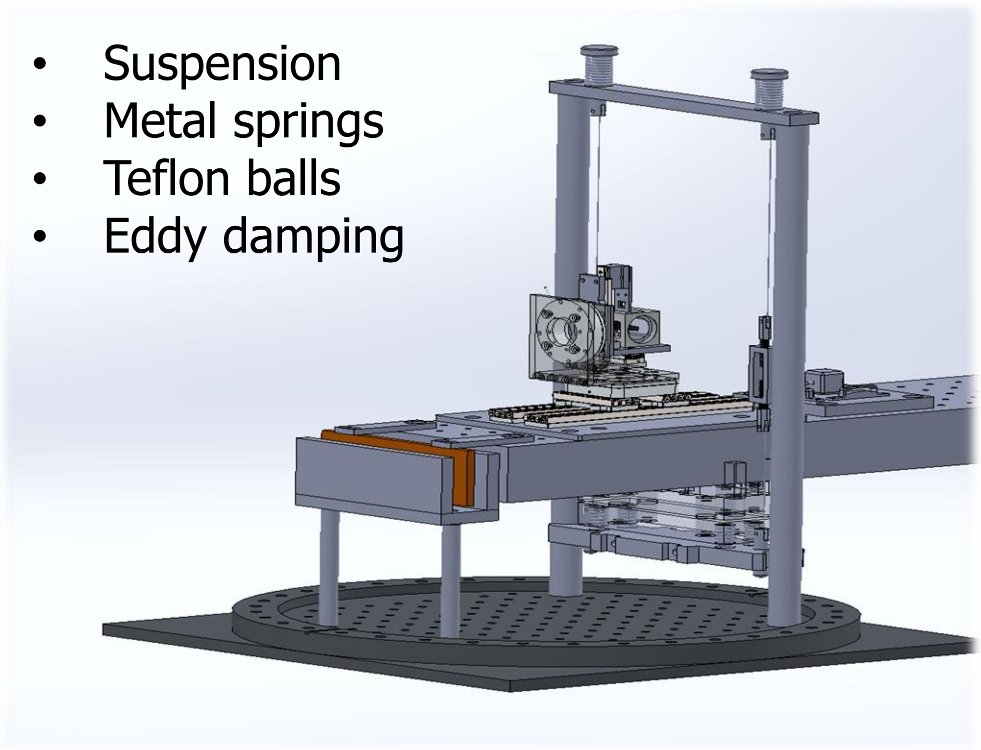
$$\exp\left[-8\left(\frac{\Omega_E \pi \sigma_v \boldsymbol{L}^2}{d v_z^2}\right)^2\right]$$

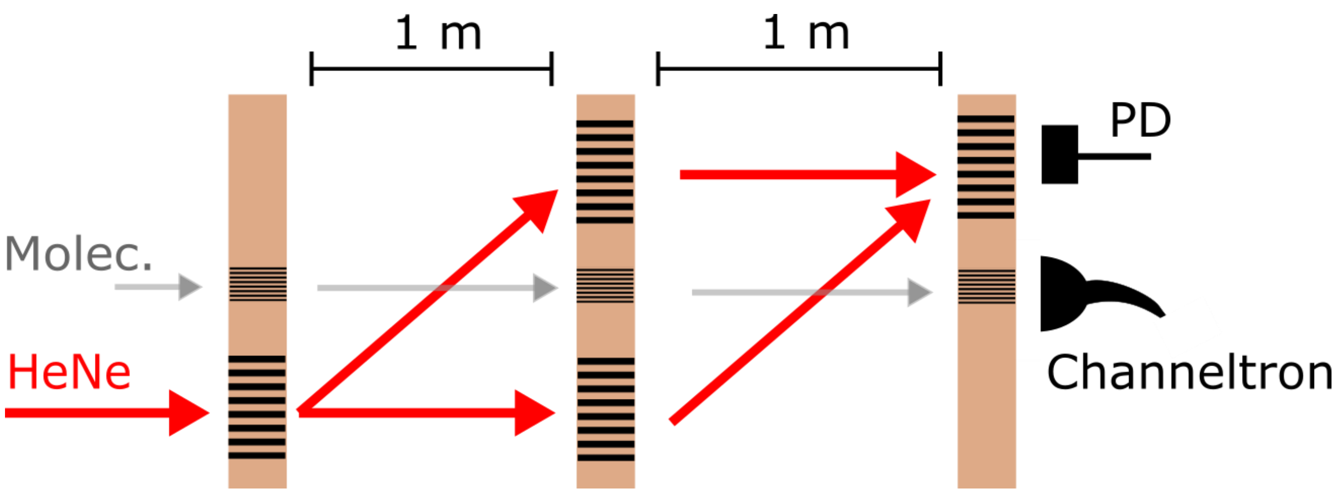
- Critical for initial alignment

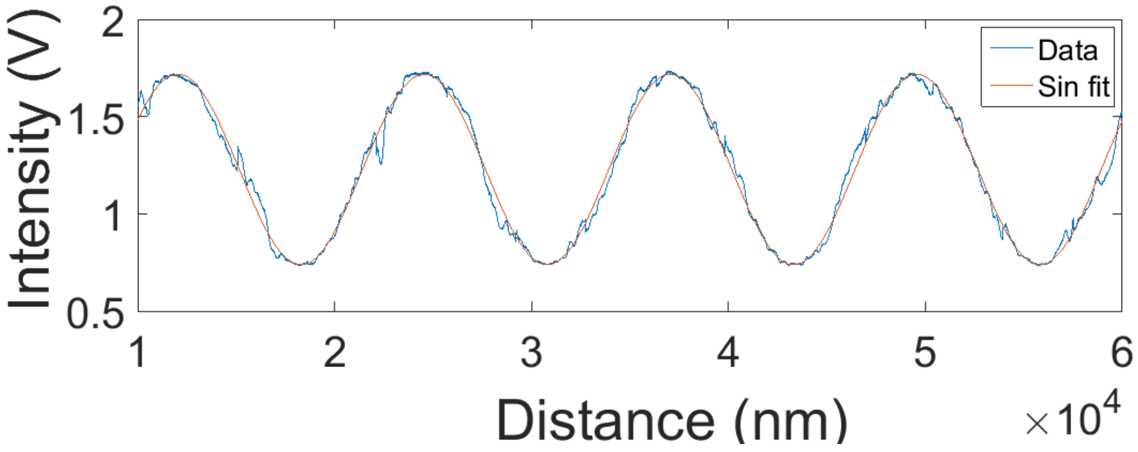


Vibration Isolation

- **Feedback:** accelerometer, optical Mach Zehnder
- Multi-stage **passive isolation**



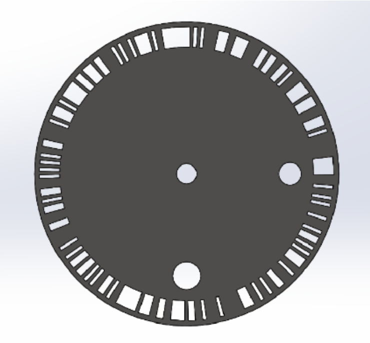


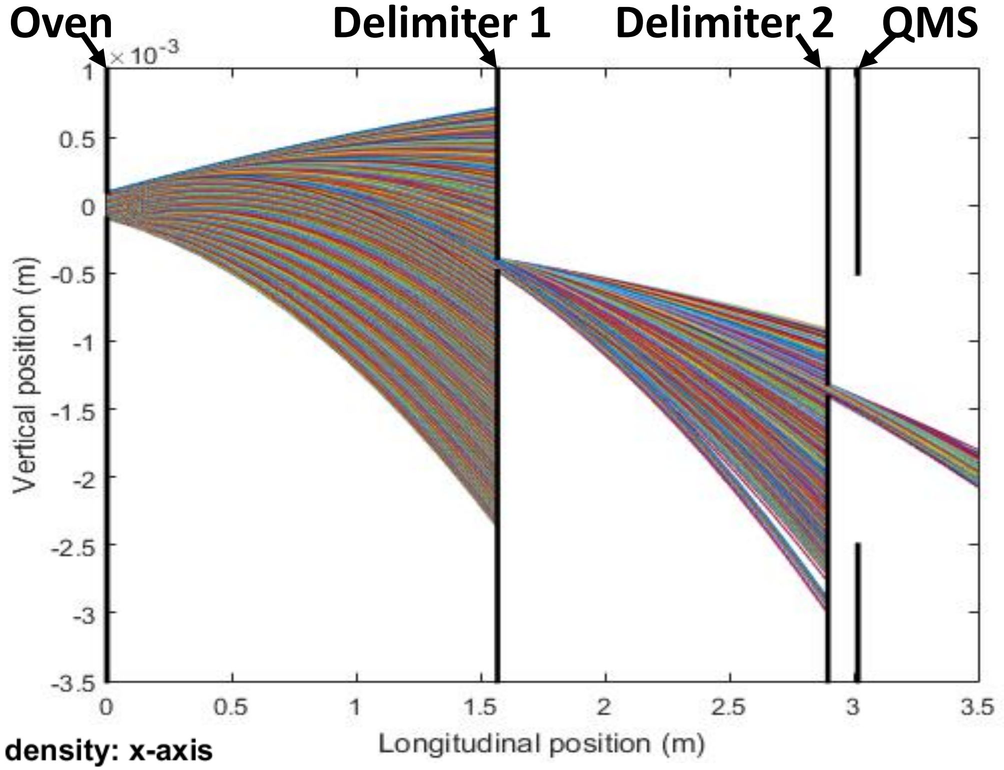


Coriolis Compensation

Approach 1: **Confine velocity spread**

- **Passive: slits**
  - Delimiter slits defining parabolas
  - Challenge: counts, selectivity
- **Active: Chopper**
  - Pseudo-random chopper + cross-correlation
  - Must be better than 1%
  - Challenge: vibrations, counts



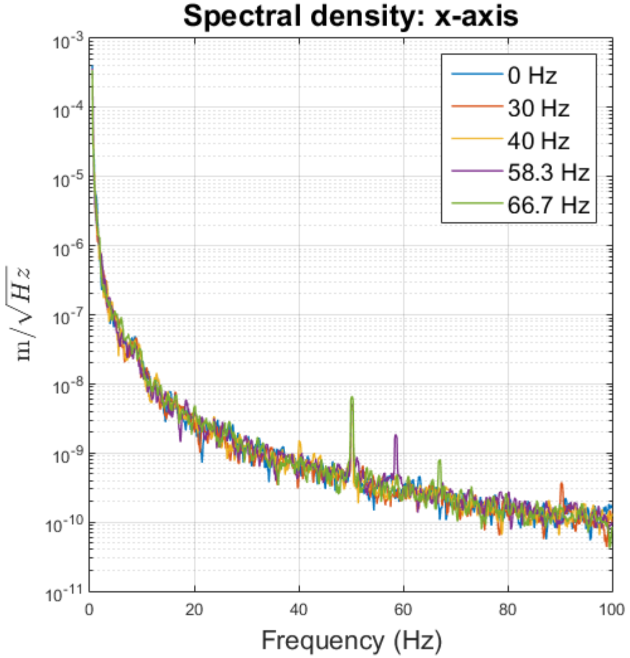


Approach 2: **Active rotation compensation**

- „Counter-rotate“ interferometer at ω_{Earth}
- Challenge: vibrations, counts

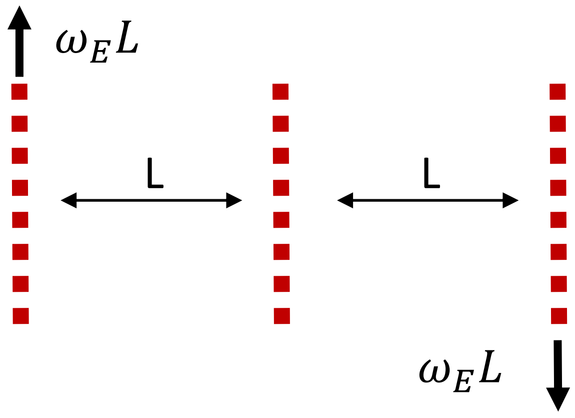
Approach 3: **Passive compensation**

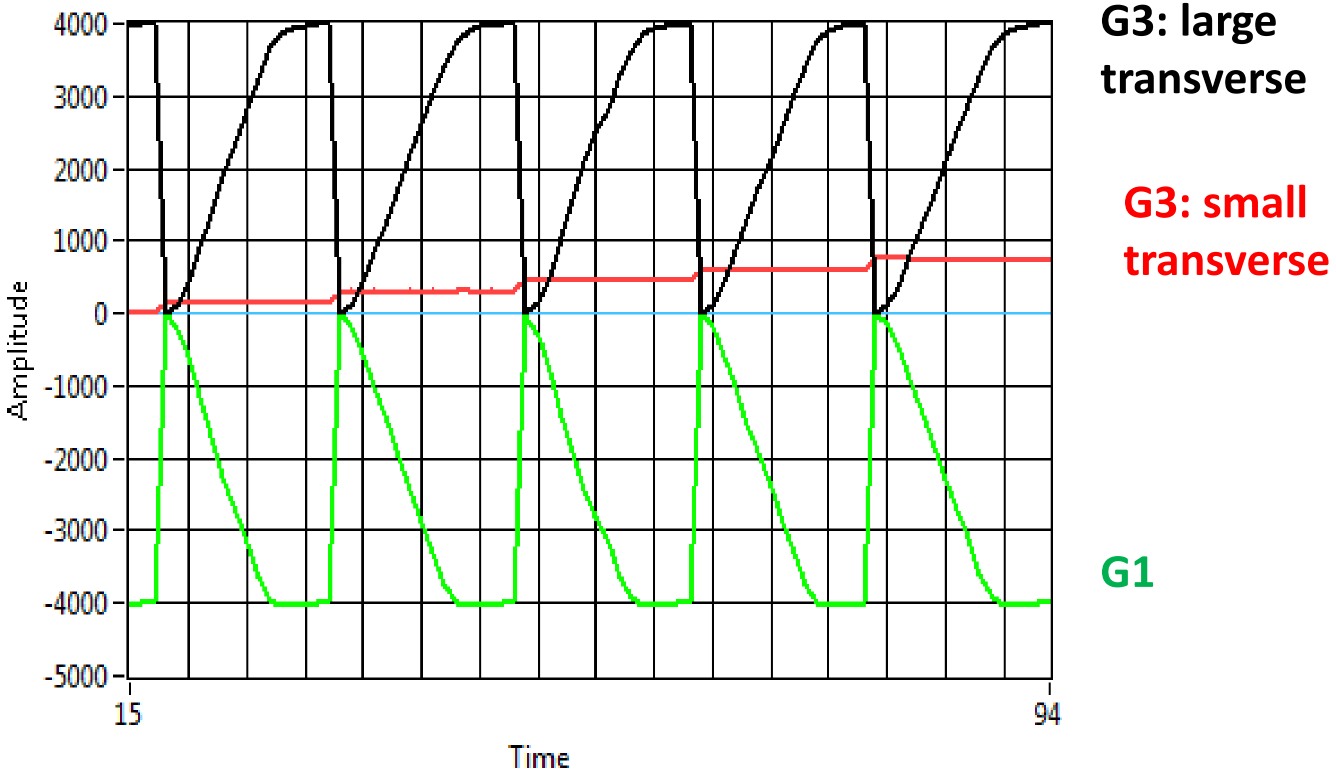
- Use interferometer scheme that passively compensates Coriolis, e.g. **4-grating scheme**
- Challenge: Increased complexity, alignment criteria, counts



Active Coriolis Compensation

- Scan 2 outer gratings transversely to cancel ω_{Earth}
- Technically challenging: slip stick motors limit range, G1 partially coated with C60, induced vibrations...





Current Experimental Status

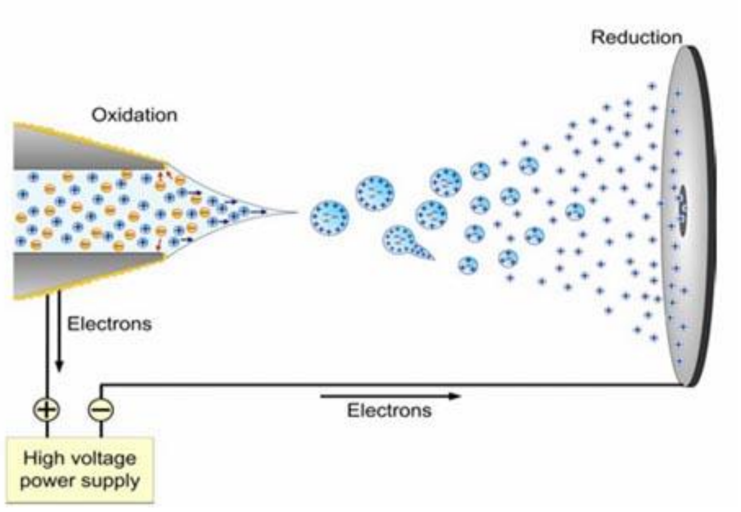
- Interferometer built (version LUMI 1.0) and pre-aligned to within 1mrad
- Aligning with C60 from thermal source and QMS detection with active Coriolis compensation
- **Hints of first signal!** But still to be confirmed and optimized...

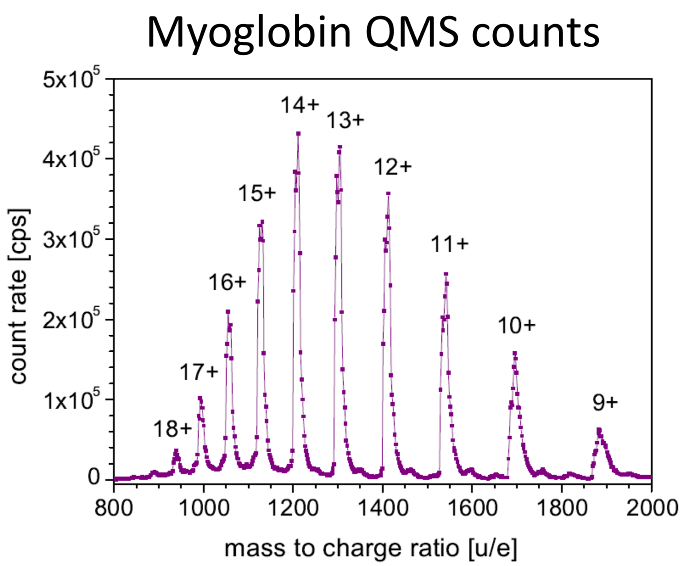
Very Near Future...

- 532 nm cavity for photoionization enhanced detection
- New detector chamber to accomodate TOF and fluorescence detection

What is missing for high-mass?
Part I: **Sources**

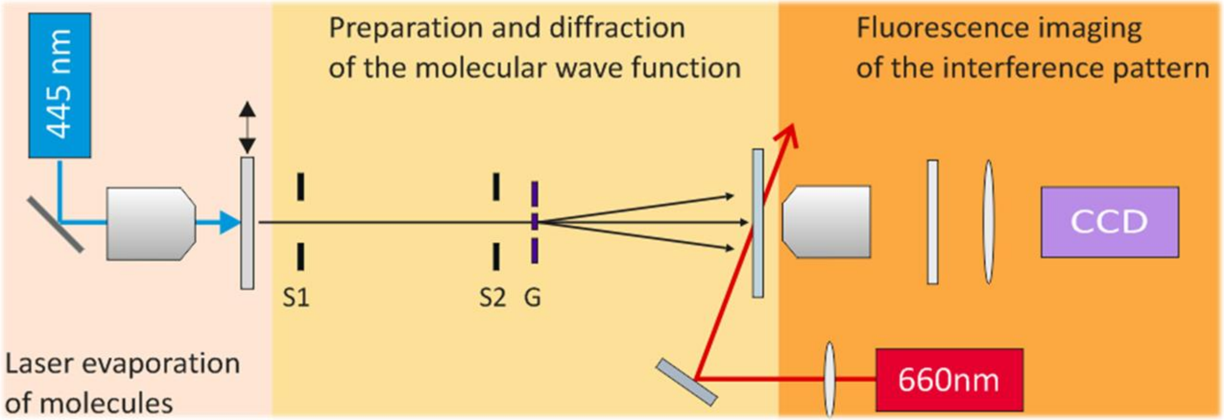
- Thermal (oven)
  - Pros: Simple, up to 10kamu range
  - Cons: Complex biomolecules do not survive intact (fragment, denature...)
  - Perfluoroalkyl tagging enhances thermal beams of polypeptides
- Electro-spray ionisation (ESI)
  - Pros: Consistent beams of large organic molecules
  - Cons: Neutralization is difficult
- Pulsed laser desorption + seed gas
  - In testing at OTIMA
- Metal cluster source
  - Pros: Continous spectrum of high masses, intense beam
  - Cons: High polarizability plus intense beam = non-suitable for material gratings

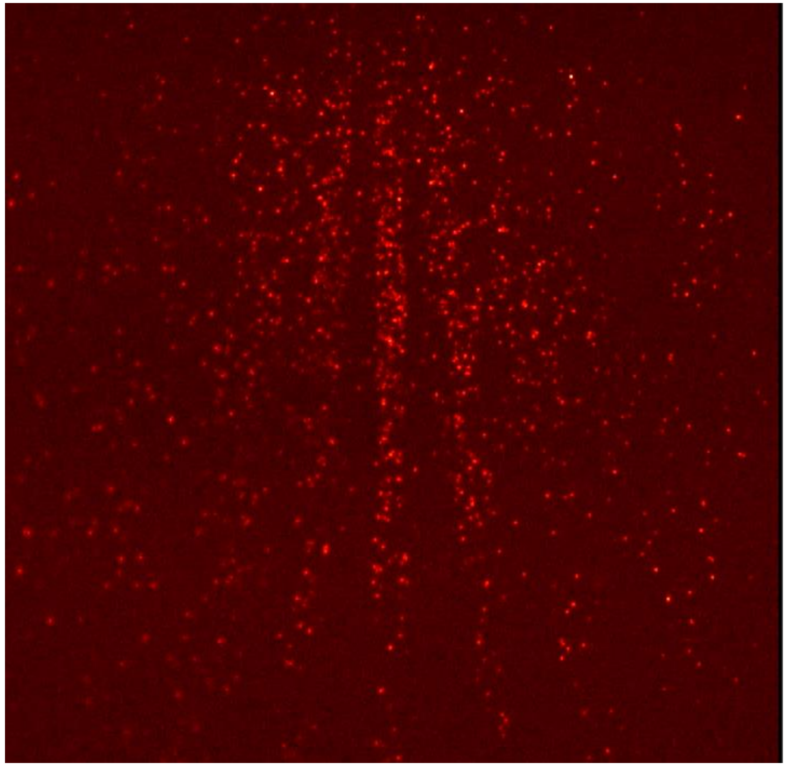




What is missing for high-mass?
Part 2: **Detectors**

- Quadrupole Mass Spectrometer (QMS)
  - Pros: Simplest, up to 35,000 amu (16,000 with in-house components)
  - Cons: Mass limited, low efficiency of e-impact ionization
  - Photo-ionization can be used for some molecules
- Fluorescence detection
  - Pros: Single-molecule resolution, free velocity selection, no inherent mass limit
  - Cons: Slower readout, fluorescence properties in vacuum?





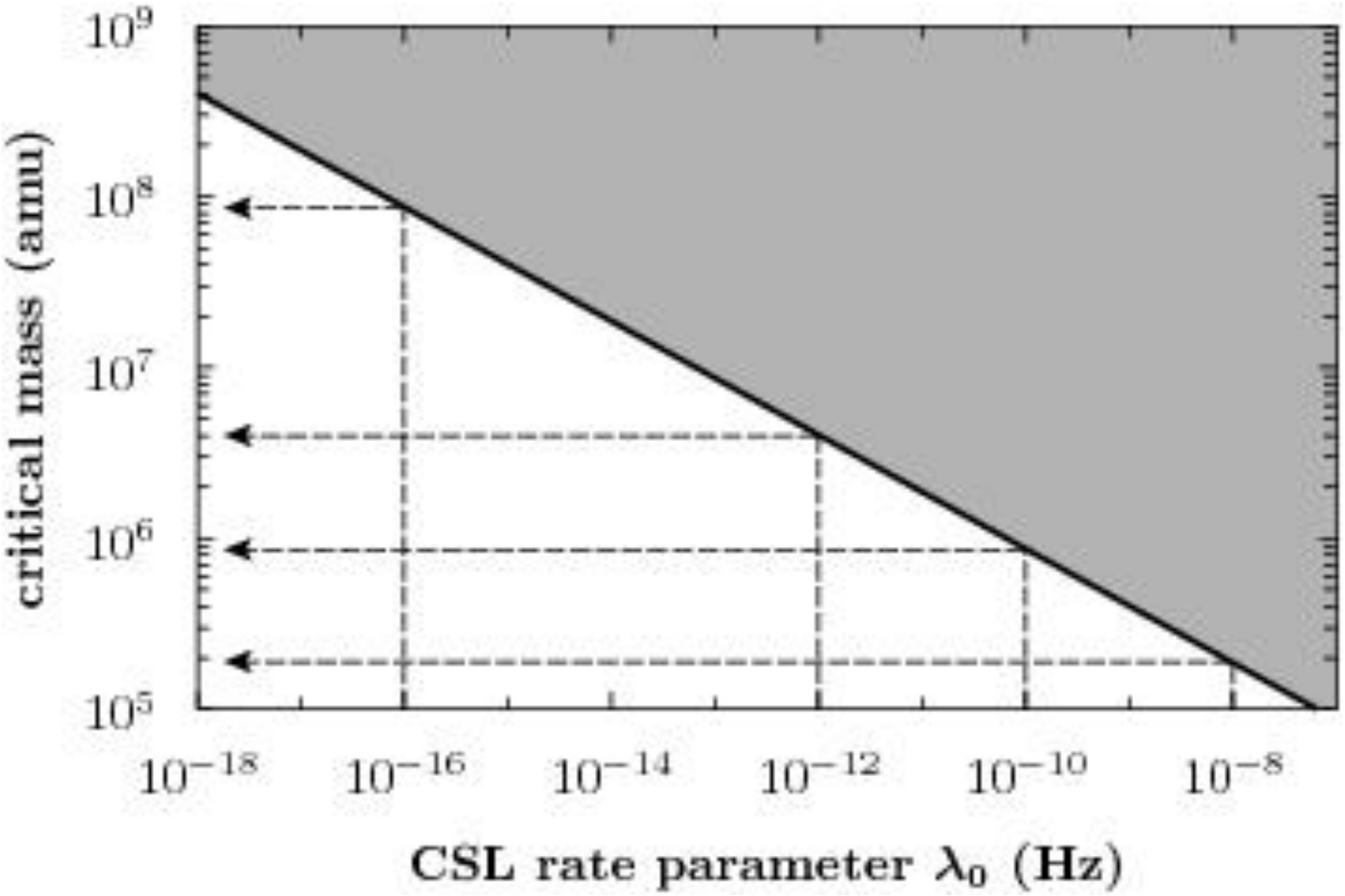
Juffmann et al., Nature Nanotechnology 7, 297 (2012)

Spontaneous Collapse Theories

- Proving high-mass interference confines SCL parameters
- KDTLI 2013 experiment (Eibenberger et al.) best limit from matter-wave interferometry:

$$\lambda > 10^{-6}\, s^{-1}$$
for $r_c = 10^{-8}\, m$

- Given $\Gamma = \lambda n^2 N$, LUMI can strengthen λ limit by an **order of magnitude**

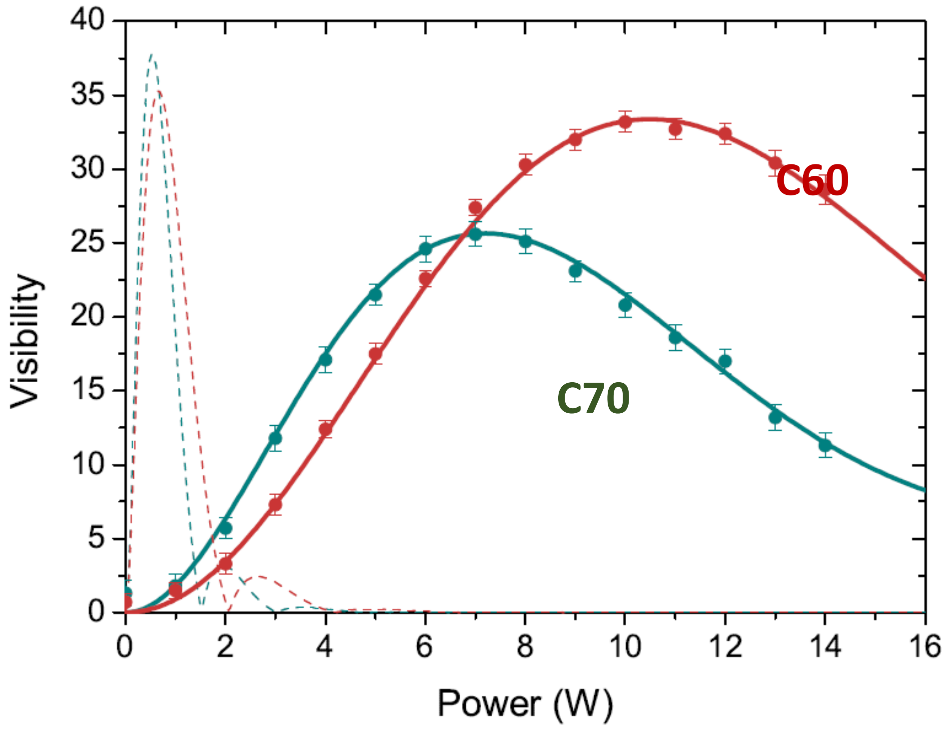


Nimmrichter et al. Phys. Rev. A 83, 043621 (2011).
Toros and Bassi arXiv:1601.02931 (2016)

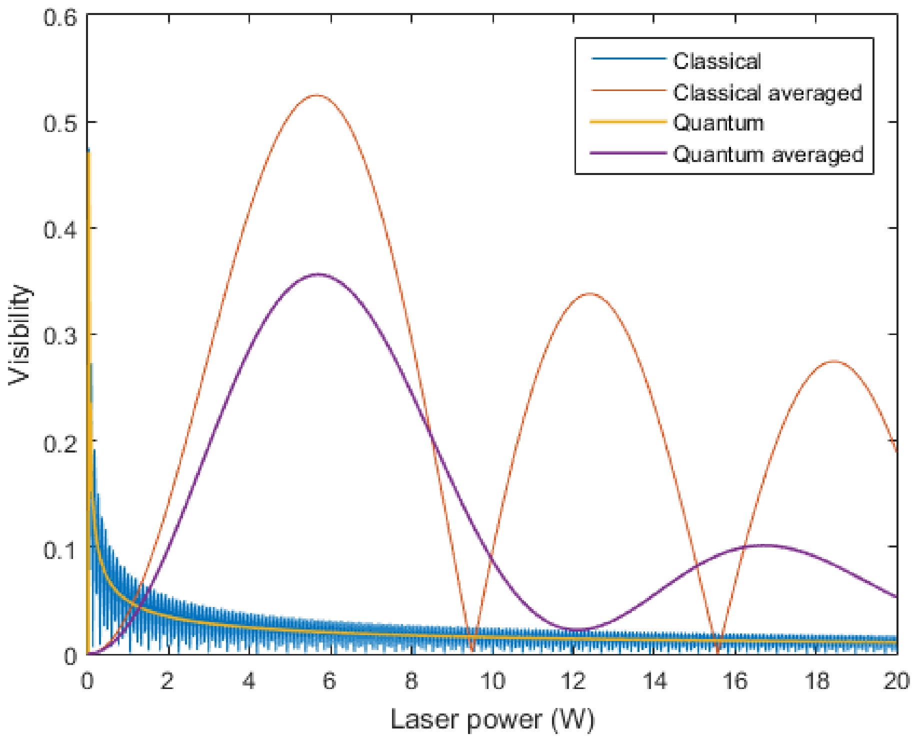
Confirming Quantumness

- Must prove „quantumness“ of fringes for superposition claim
- Compare theory and experimental visibility as function of G2 laser power (phase)
- In LUMI, classical visibility strongly suppressed for small molecules

KDTLI, C60 and C70 (Exp. and theory)



LUMI, C60 (theory)



Limits of Bounds

Matter-wave interferometry cannot compete with current bounds, but still important:

- Limits set by matter-wave interf. less sensitive to model parameters
  - e.g. Colored noise may affect X-ray bounds [1]
  - CSL nearly ruled out, but dCSL, cCSL still open: all addressed by matter-wave interferometry
- Collapse rate λ excluded at noise correlation length $r_c \approx 10^{-7} - 10^{-8}$ m → possibly more relevant?

1. Toros and Bassi arXiv:1601.02931 (2016)

Macroscopicity parameter

- Introduced in 2013 as experimental measure of macroscopicity
- $\mu > 0$ for e$^-$ superposed for > 1 second

$$\mu = \log_{10}\left[\frac{\tau_e}{1\ s}\right] \approx \log_{10}\left[\frac{1}{\ln(f)}\left(\frac{M}{m_e}\right)^2\left(\frac{t}{1\ s}\right)\right]$$

- LUMI advantage: 10x longer flight time for *same molecules* as KDTLI yields larger μ
- LUMI @ 10^5 amu: $\boldsymbol{\mu = 15.5}$

Conceivable experiments	$\boldsymbol{\mu}$
Oscillating micromembrane	11.5
Hypothetical large SQUID	14.5
Talbot-Lau interference [29] at 10^5 amu	14.5
Satellite atom (Cs) interferometer [45]	14.5
Oscillating micromirror [30]	19.0
Nanosphere interference [46]	20.5
Talbot-Lau interference [29] at 10^8 amu	23.3
Schrödinger gedanken experiment	~ 57

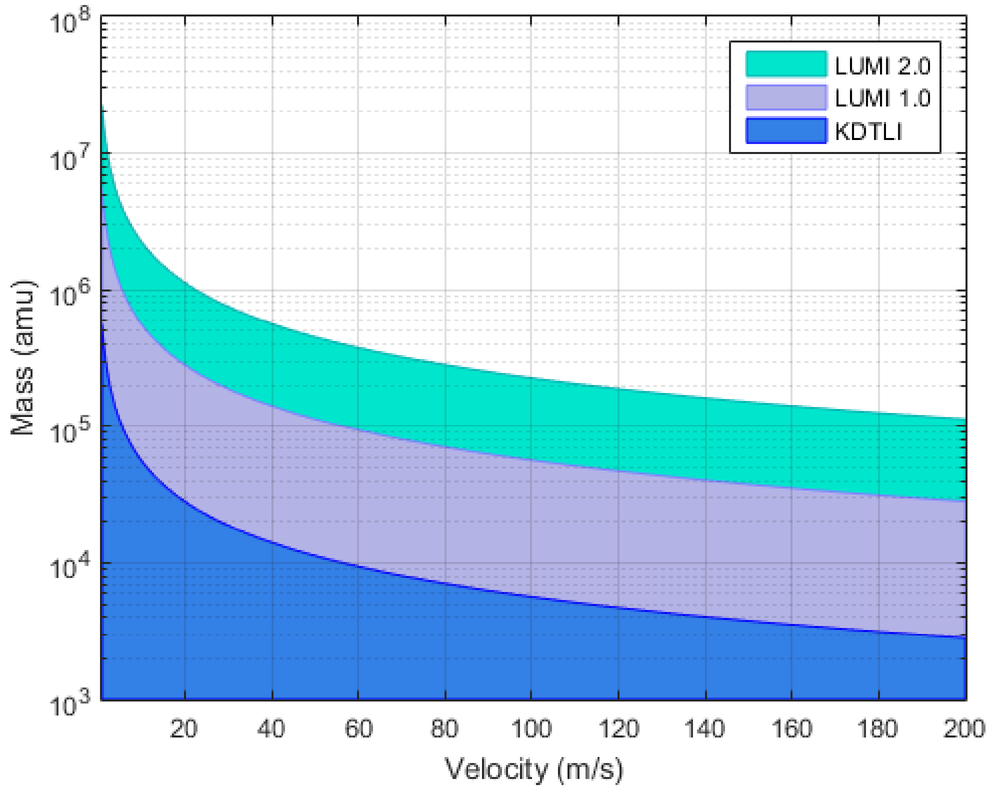
Nimmrichter and Hornberger Phys. Rev. Lett. 110, 160403 (2013).

LUMI 2.0: All Optical

- 3x optical depletion gratings
- UV light means shorter period: 133nm
- Talbot length for given mass 4x shorter

→ 4x higher mass!

- Optical gratings more robust to „dirty“ sources



- BUT, UV cavities difficult, sources and detector technologies in development...

Much to be done!

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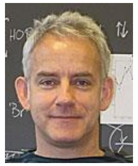
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Thermal Self-Decoherence

A first estimate (only correct to „zeroth“ order)

Radiated optical Power (Stefan-Boltzmann, modified by Kolodney)

$$P = \varepsilon \cdot A \cdot \sigma_{SB} \cdot T^4 \quad \text{with: } \varepsilon = 4.5(\pm 2.0) \cdot 10^{-5}$$

$$A = 4\pi r^2 = 1.5 \text{ nm}^2$$

T=900 K

P ~ 15 eV/s ~ 0.1 eV/ 6ms (TOF)

At most: 1 photon at λ=10µm

- **Abbé's theory of microscopy: no information available**
- **Interference maintained !**

T=2000 K

P ~ 382 eV/s ~ 2.3 eV/ 6 ms (TOF)

~ 1 photon @ λ= 0,5 µm

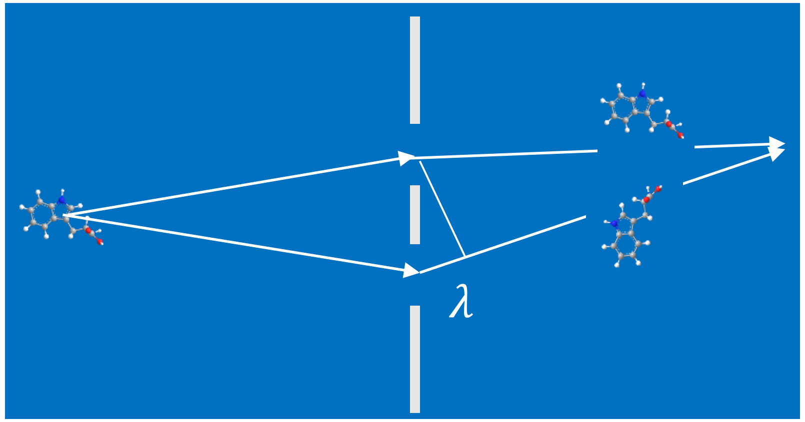
~ 20 photons @ λ=10 µm

- **Photon reveals position information !**
- **Loss of fringe contrase !**

Can Internal Clocks Influence Matter-wave Interferometry?

A rotating polar molecule resembles a „the hand of a clock "

- After it passes the double slit and arrives at the first diffraction order, will it arrive in a superposition of clock states, since it travelled along 2 paths of different length?
- Will this lead to destructive interference when the phase shift is π?



The experimental answer:

- Diffraction of polar molecules at optical gratings has not shown any major decoherence.
- Compare: moment of inertia $I = 10^{-42} kg\ m^2, T = 600\ K \ \rightarrow \nu_{rot} = \sqrt{\frac{2k_B T}{I}} = \mathbf{2 \times 10^{10}}$ **Hz**
  → Path length difference = 5 pm crossed with 100 m/s → 50 fs time lag → hardly any rotation

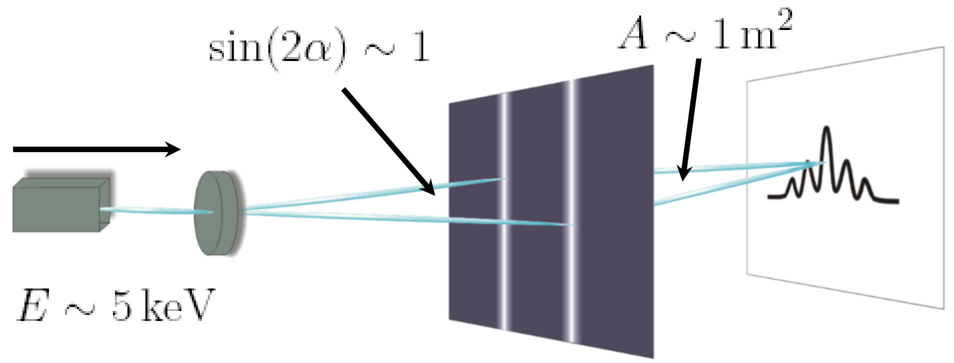
More fundamentally:

- Interference always occurs at the **same time in both arms** → **always the same clock settings !**
- The longer path length is compensated for by a higher velocity in the coherent wave packet

Gravitational wave limits to matter wave interferometry?

$$\Delta\varphi^2 \sim \Omega^2 \sin^2(2\alpha)\, S_h \tau$$

One could reach $\Delta\varphi^2 \simeq 1$ for the following parameters, where $\Omega_{\text{mat}} = \frac{\text{mv}^2}{2\hbar}$ and $\tau = 1s$



B. Lamine, Eur. Phys. J. D 20, 165 (2002)
B. Lamine PhD thesis, ENS

Even ambitious near-future high-mass interference experiments will be limited to

- M=10^6 amu, v=20 m/s → $\lambda = 20$ fm
- E=2 eV ≪ *5000 eV*
- With existing beam splitters, the area will be $A = 0.25\ \mu m \times 1\ m = 2.5 \times 10^{-7}\ m^2 \ll 1\ m^2$
  → Still too insensitive to the direct gravitational wave background

Any chances in the future? No simple solution …

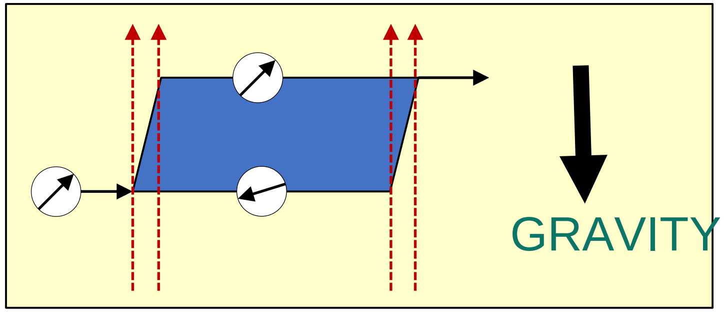
- Either much improved signal to noise, and boost in phase sensitivity (evtl. 1000x)
- Novel coherent beam splitters (x10-100 ?) and then coherent angle amplification to 1rad ?
- Space experiment with longer arm length (1000 m ?)

NOTE: An experiment of this sensitivity must be operated in space!
Otherwise overwhelmed by gravity, tides, Earth rotation, seismic …


nature physics
ARTICLES
PUBLISHED ONLINE: 15 JUNE 2015 | DOI: 10.1038/NPHYS3366

Universal decoherence due to gravitational time dilation

Igor Pikovski[1,2,3,4]*, Magdalena Zych[1,2,5], Fabio Costa[1,2,5] and Časlav Brukner[1,2]

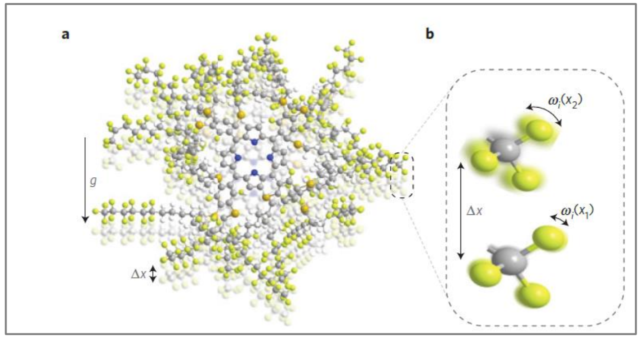


For Atoms one expects first destructive interference for

- Optical clock $\omega = 10^{15}\ s^{-1}$ (Sr clock in prep. by J. Hogan/Stanford)
- Beam separation of $h = 1m$ (0.5 m realized by Kasevich/Stanford, but not phase stable)
- Separation time $\mathrm{T} = 10\ s$ (> 1sec Kasevich/Stanford, QUANTUS coll. /Hannover/Bremen)

However: high phase resolution in atom interferometry could probably see the effect already for h=0.1 m and T=1s if the phase stability can be ensured. Sr-clock in atom interferometry, still to be demonstrated. → hard but conceivable test.

For Macromolecules (our group in Vienna)



- For $N = 810$ oscillators at temperature $T = 600K$ in superposition size $\Delta x = 10^{-6}\ m$

$$\tau_{dec} = \sqrt{\frac{2}{N}} \cdot \frac{\hbar c^2}{k_B T\ g\ \Delta x} = 8.8 \times 10^6\ \mathrm{s}$$

- **With currently known technology: Impossible to test**

Neither on Earth because of gravity (free fall) nor off-Earth since this effect requires gravity
In addition: unfavorable N-scaling