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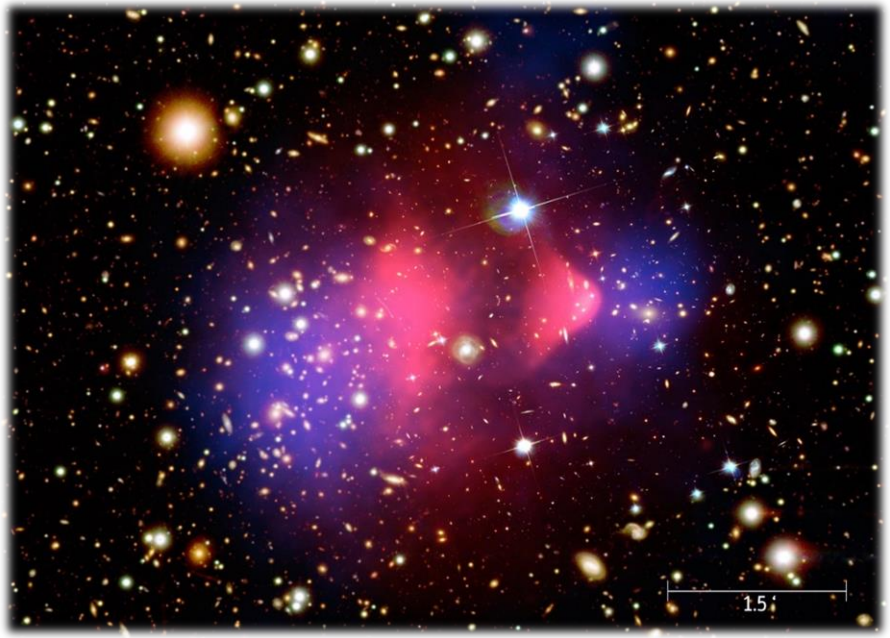
Searching for light DM with molecular matter-waves

Armin Shayeghi, Philipp Rieser & Markus Arndt

Vienna Center for Quantum Science and Technology (VCQ)
University of Vienna
Faculty of Physics

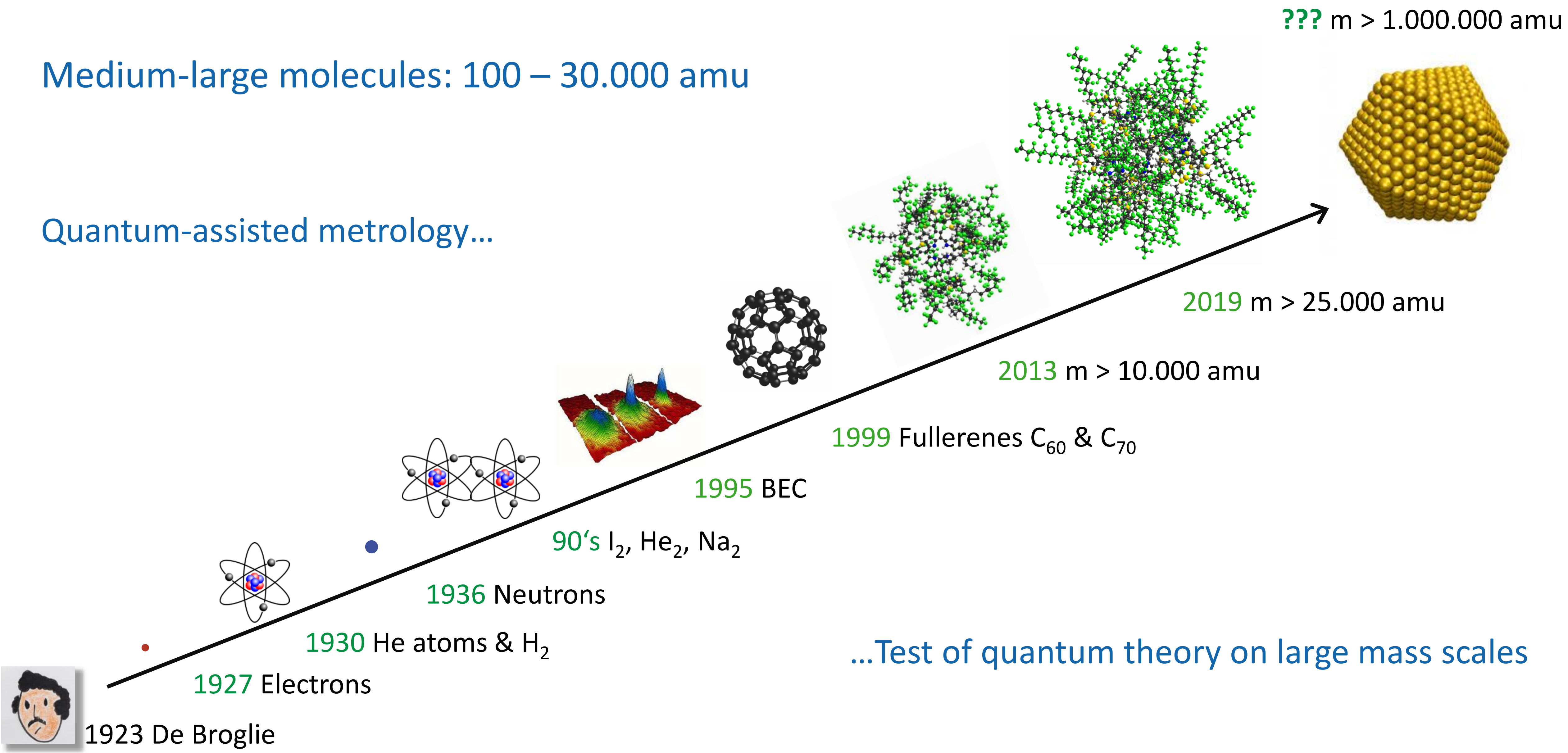
erc FWF Der Wissenschaftsfonds. VCQ



The quantum wave nature of massive matter

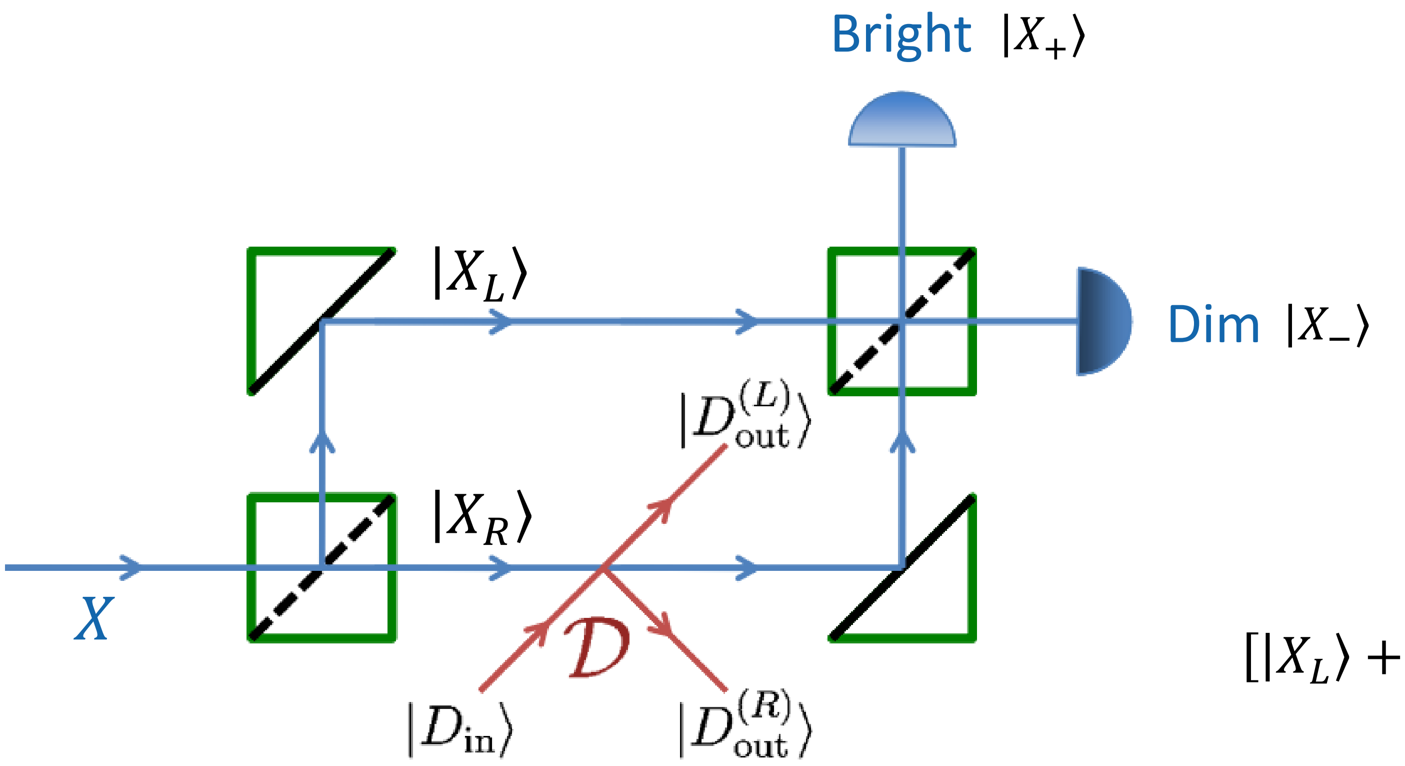
Medium-large molecules: 100 – 30.000 amu

Quantum-assisted metrology…



…Test of quantum theory on large mass scales

Decoherence detection: *J. Riedel*



Mach-Zehnder Interferometer

Measure X in the basis

$$\{|X_\pm\rangle = |X_L\rangle \pm |X_R\rangle\}$$

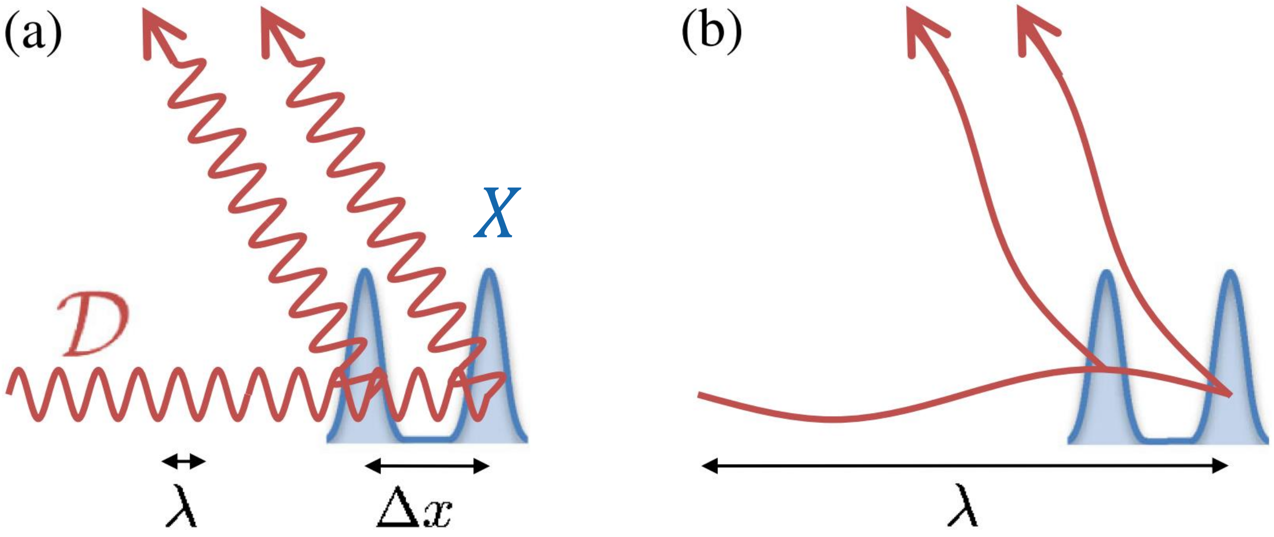
$$[|X_L\rangle + |X_R\rangle]|D_\emptyset\rangle \rightarrow [|X_L\rangle + |X_R\rangle]|D_\emptyset\rangle$$ no event

$$[|X_L\rangle + |X_R\rangle]|D_{\text{in}}\rangle \rightarrow |X_L\rangle|D_{\text{out}}^L\rangle + |X_R\rangle|D_{\text{out}}^R\rangle$$ event

$$\langle D_{\text{out}}^L|D_{\text{out}}^R\rangle \approx 0$$ „which-path“ information!

J. Riedel, *Phys. Rev. D* **88**, 116005 (2013); E. Joos and H. D. Zeh, *Z. Phys. B* **59**, 223 (1985).

DM with different de Broglie wavelengths



$\gamma = \langle D^L_{\text{out}} | D^R_{\text{out}} \rangle \approx 0$

Single event sufficient

$\gamma = \langle D^L_{\text{out}} | D^R_{\text{out}} \rangle^n \approx 0$

Many events required

State of X after τ in basis $\{|X_L\rangle, |X_R\rangle\}$

$$\rho_X = \frac{1}{2}\begin{pmatrix} 1 & \gamma \\ \gamma^* & 1 \end{pmatrix}$$

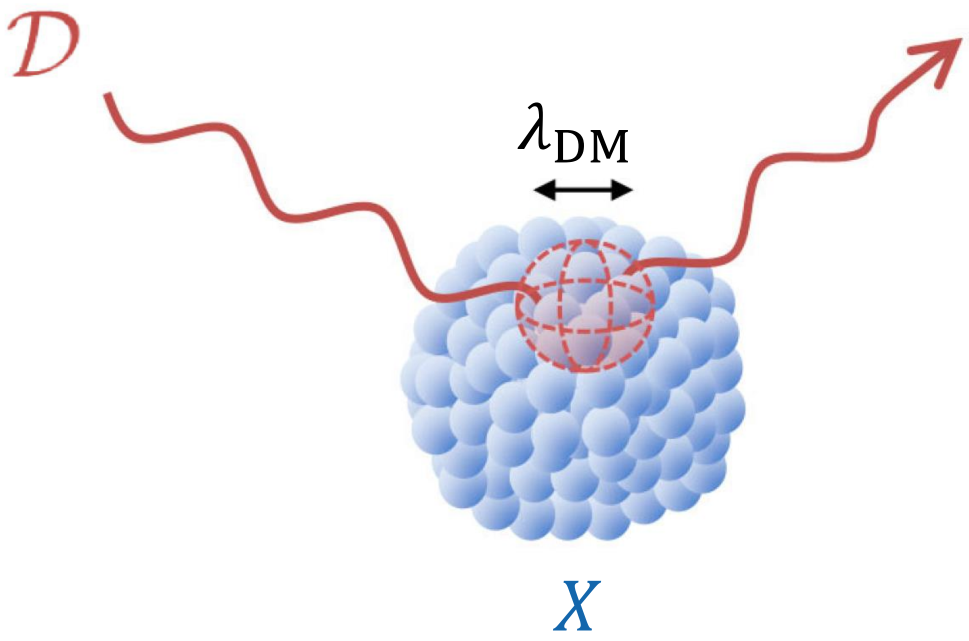
$$\gamma = \langle D^L_{\text{out}} | D^R_{\text{out}} \rangle$$

$$= e^{-\left[\int_0^\tau dt\, \Gamma(\Delta\vec{x})\right]}$$

$$= e^{-s_{\text{DM}} + i\phi_{\text{DM}}}$$

J. Riedel, *Phys. Rev. D* **88**, 116005 (2013); E. Joos and H. D. Zeh, *Z. Phys. B* **59**, 223 (1985).

Coherent elastic scattering



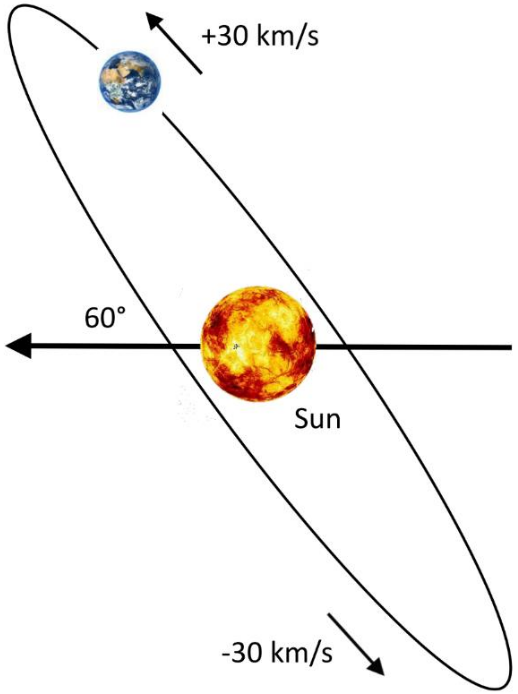
$$V_{\mathrm{coh}} = \frac{4}{3}\pi\left(\frac{\lambda_{\mathrm{DM}}}{2}\right)^3 \qquad V_X < V_{\mathrm{coh}} \rightarrow \sigma_{\mathrm{eff}} \approx N_X^2 \sigma$$

enhancement to spin-independent scattering cross section!

- sub-MeV DM is ghostly
- At least two ways of increasing likelyhood:
  1. Increase τ by lengthening interferometer/slowing down X.
  2. Superpose large clusters made of *N* atoms!
- λ_{DM}: larger than atomic spacing but smaller than wave function spread
- nucleons contribute coherently to amplitude of same out-state.
- DM does not ‘‘know’’ which nucleon it has scattered from and nucleons recoil together uniformly

J. Riedel, *Phys. Rev. D* **88**, 116005 (2013).

Annual fluctuations

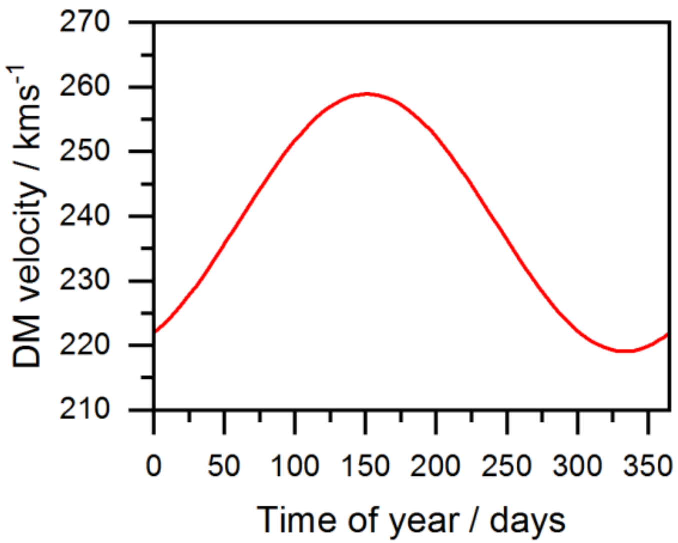


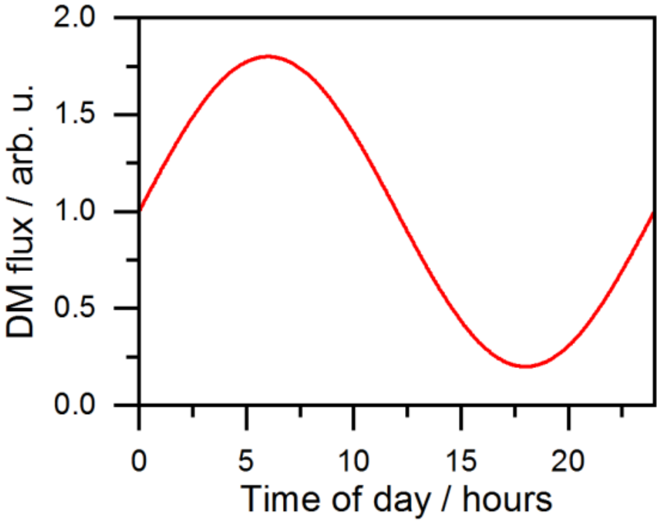
$v_{DM} = 240$ km/s

$\rho_{DM} = 0.4$ GeV/cm³

$v_s = 30$ km/s

$t_0 = 151^{st}$ day





$$v_e(t) = v_{DM} + v_s \cos(60°)\cos(\omega(t - t_0))$$

$$j = v_{DM}\frac{\rho_{DM}}{m_{DM}} \qquad \Gamma \propto \sigma j$$

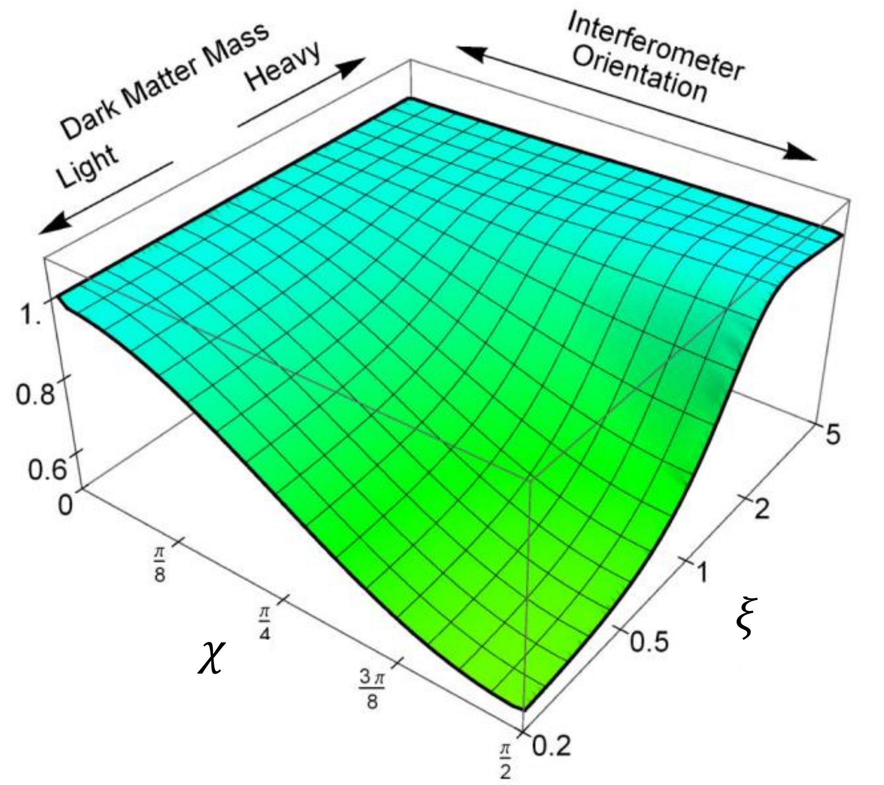
$\sigma \geq 10^{-29}$ cm² attenuation length in lead: 1m

$\geq 10^{-31}$ cm² underground laboratory 2000 m

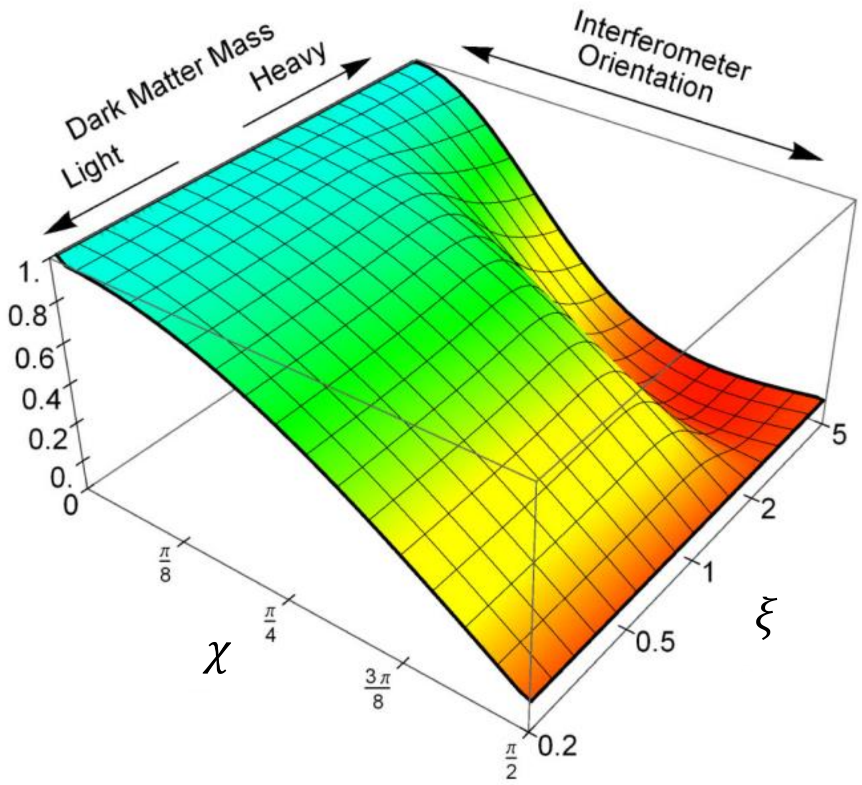
$\geq 10^{-35}$ cm² “earth” as a giant windscreen

Visibility of the dark matter wind

$$\frac{\Gamma_{\mathrm{Re}}(\Delta\vec{x})}{\Gamma_{\mathrm{Re}}(\Delta\vec{x})^{\chi=0}}$$



Decoherence rate



Phase shift

$$\frac{\Gamma_{\mathrm{Im}}(\Delta\vec{x})}{\Gamma_{\mathrm{Im}}(\Delta\vec{x})^{\chi=0}}$$

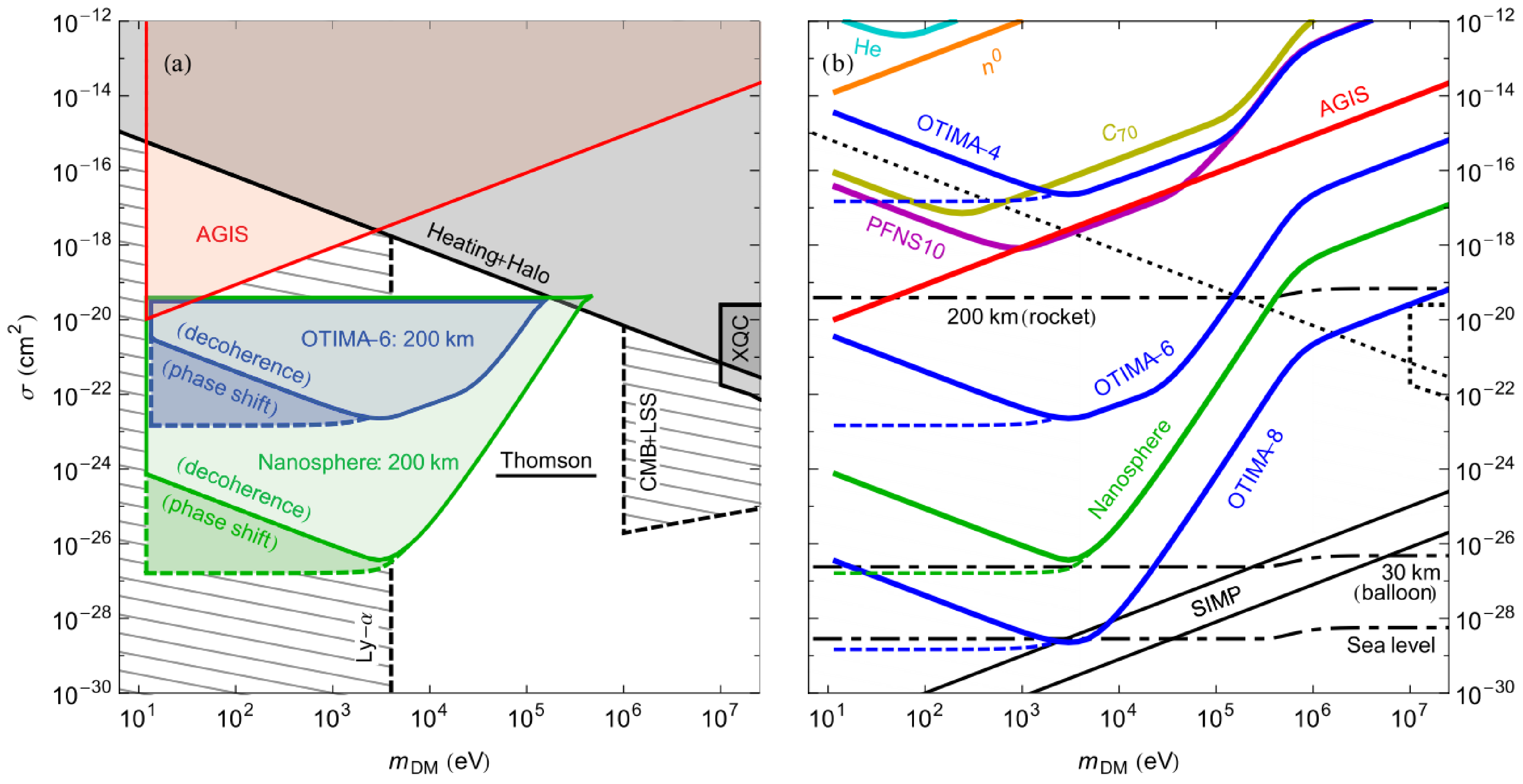
$$\xi = \frac{\Delta x}{\lambda_{\mathrm{DM}}}$$

χ = angle between $\vec{v}_{\mathrm{e}}$ and displacement $\Delta\vec{x}$

For small $\Gamma_{\mathrm{Re}}(\Delta\vec{x})$, state not decohered.
Position-dependent phase/coherent classical force.

J. Riedel, *Phys. Rev. D* **88**, 116005 (2013).

Sensitivity of existing and proposed experiments



$$|\gamma| = \frac{1}{e}$$

$$\chi = 0$$

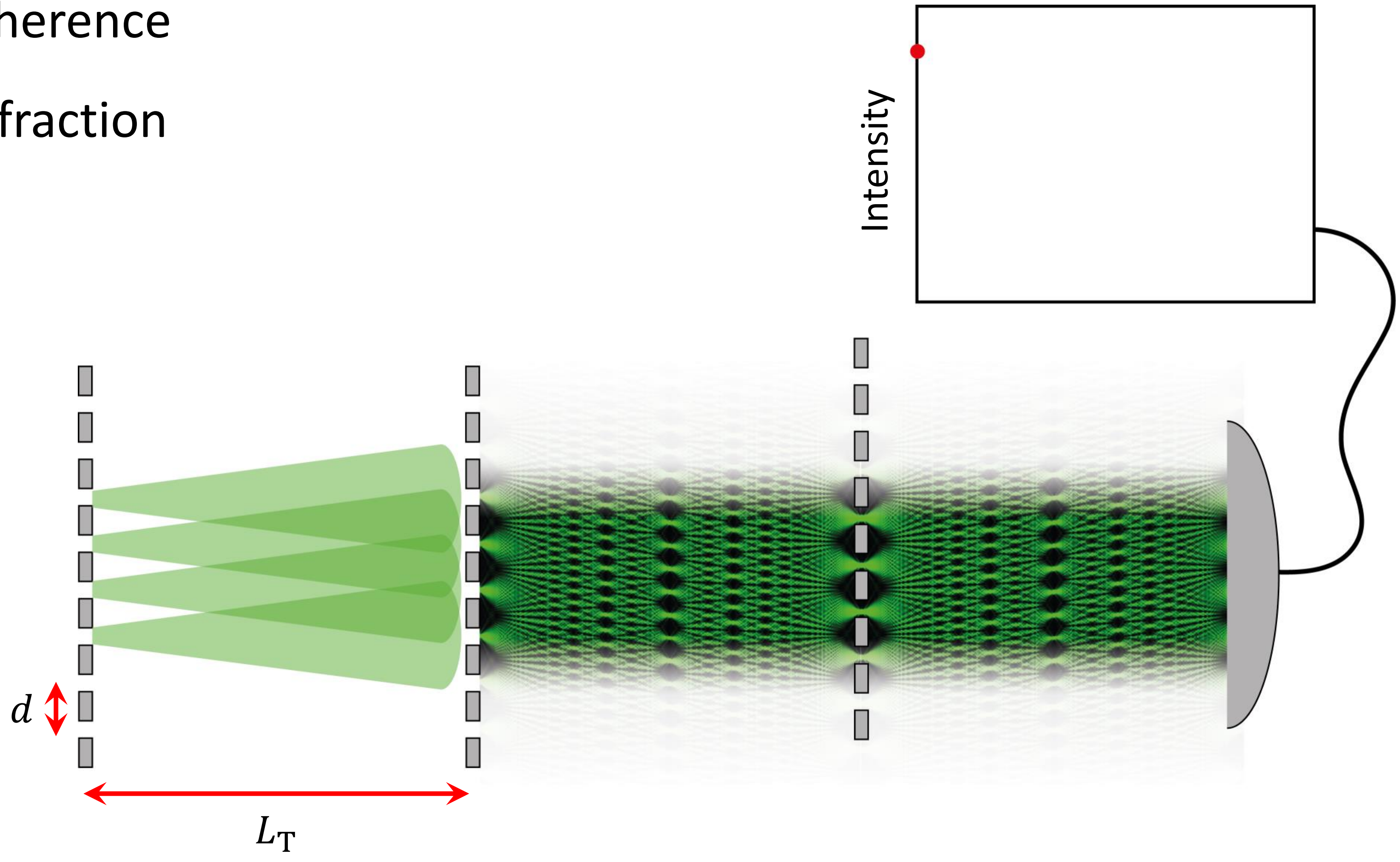
J. Riedel, *Phys. Rev. D* **88**, 116005 (2013).

Talbot-Lau Interferometry

1. Grating: Coherence

2. Grating: Diffraction

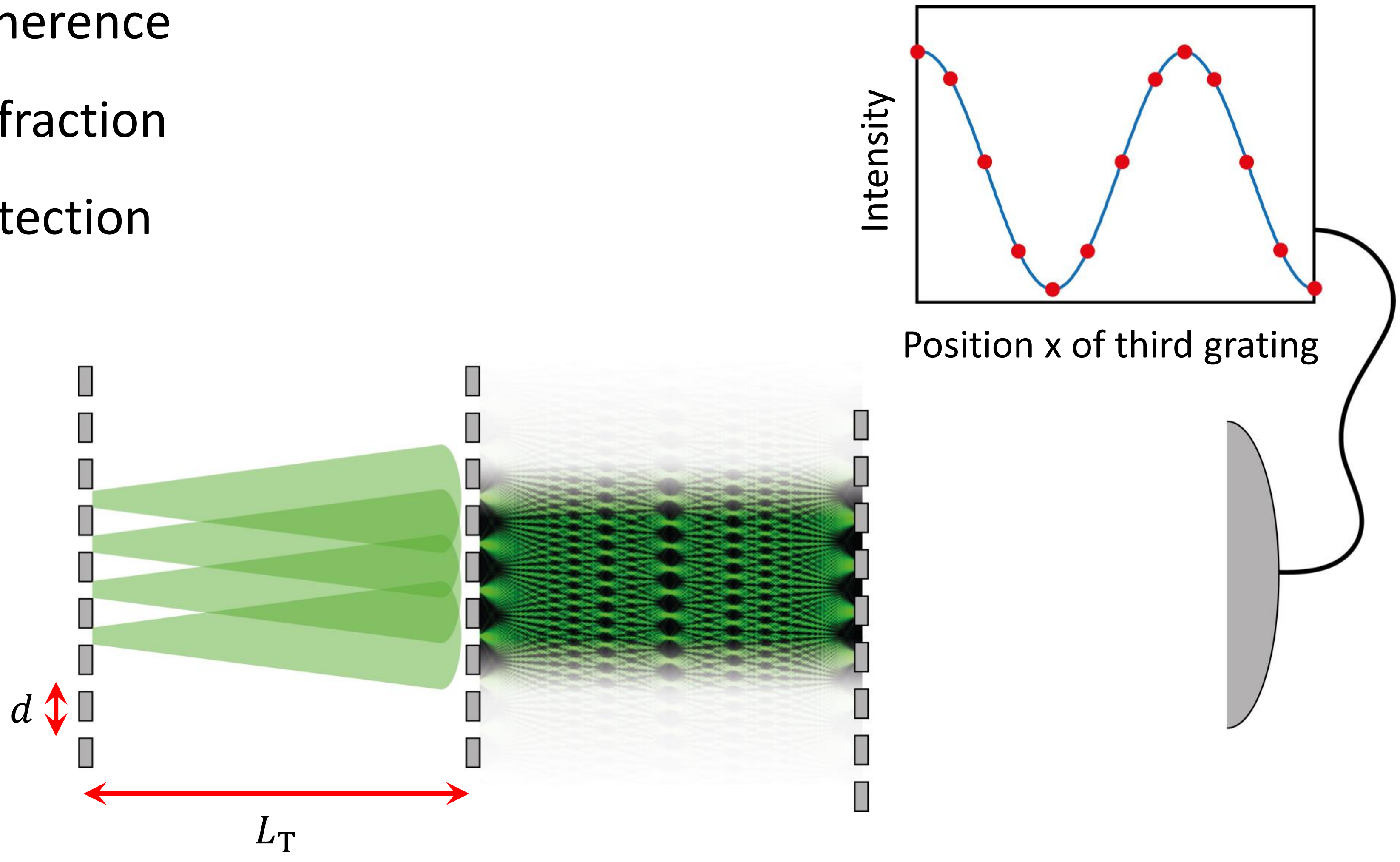
$$L_T = \frac{d^2}{\lambda_{dB}}$$



Talbot-Lau Interferometry

1. Grating: Coherence
2. Grating: Diffraction
3. Grating: Detection

$$L_\mathrm{T} = \frac{d^2}{\lambda_\mathrm{dB}}$$



Time-domain Talbot-Lau interferometry

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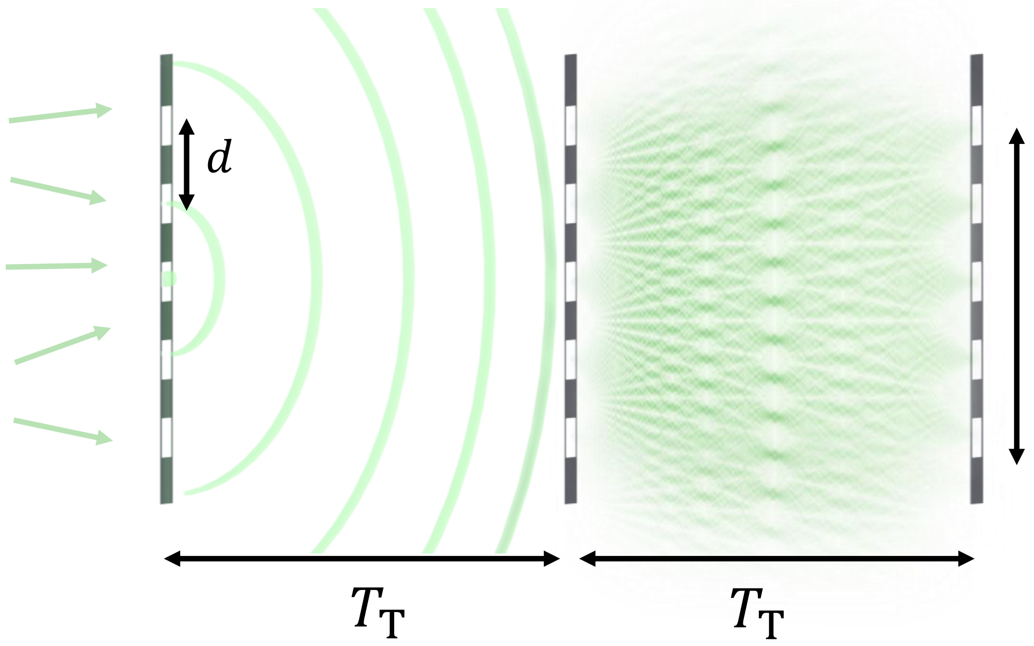


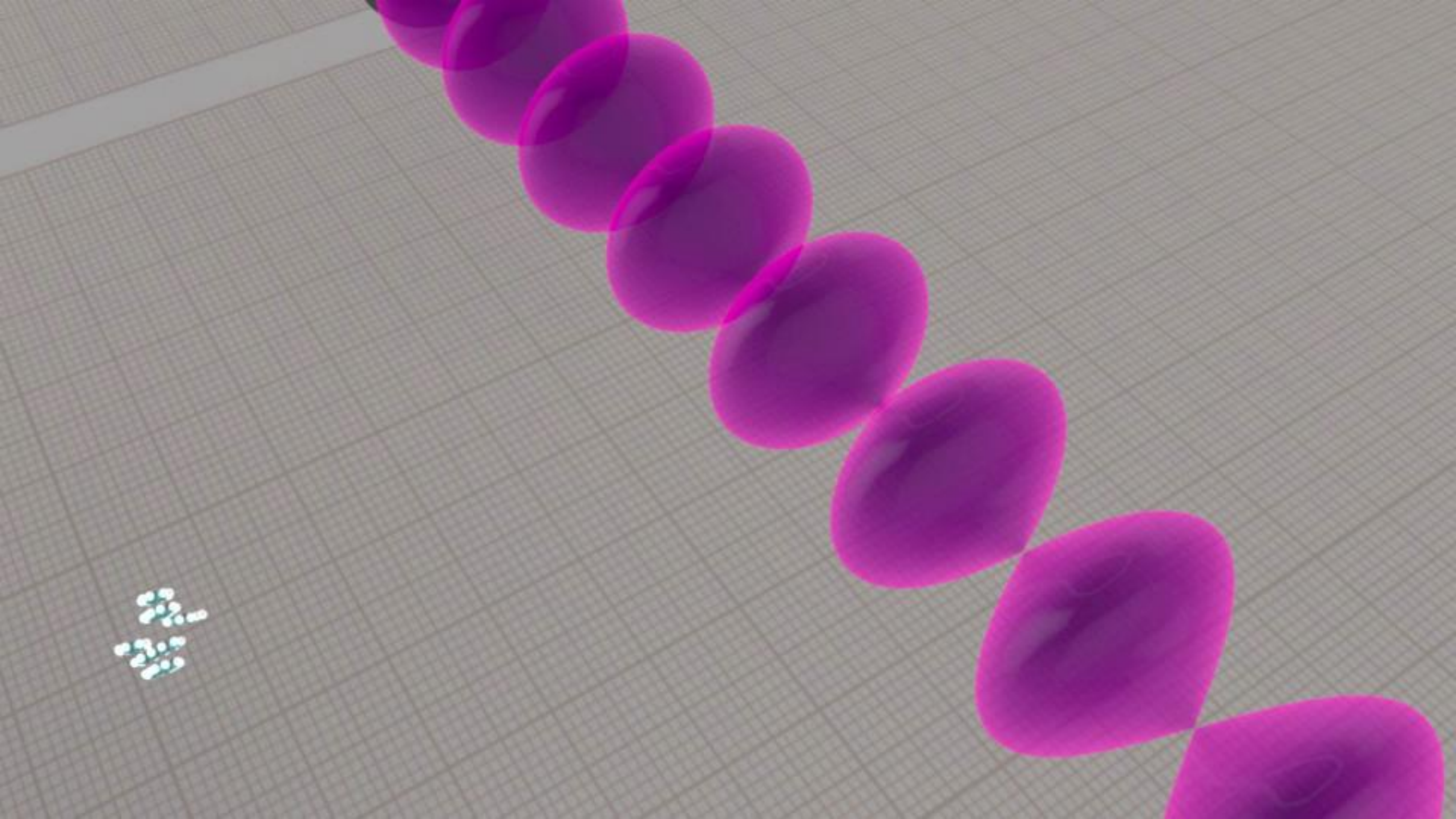
All particles with the same mass:

- contribute to the same interference pattern
- at a certain time
- regardless of their velocity
- No clogging

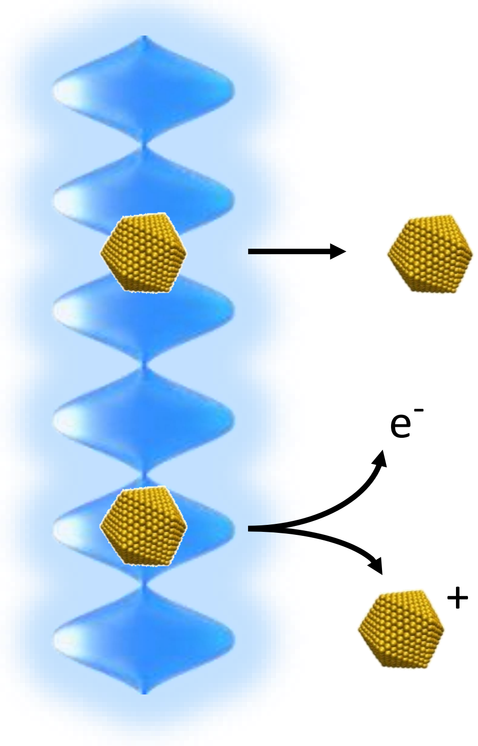
How to implement?

Pulsed VUV standing waves

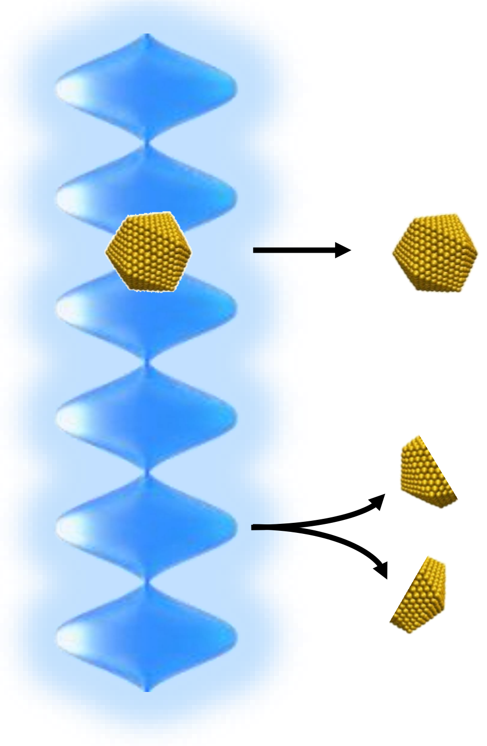
$$L_{\mathrm{T}} = \frac{d^2}{\lambda_{\mathrm{dB}}} \xrightarrow[\frac{L_{\mathrm{T}}}{v}]{\text{time-domain}} T_{\mathrm{T}} = \frac{md^2}{h}$$



Photodepletion gratings



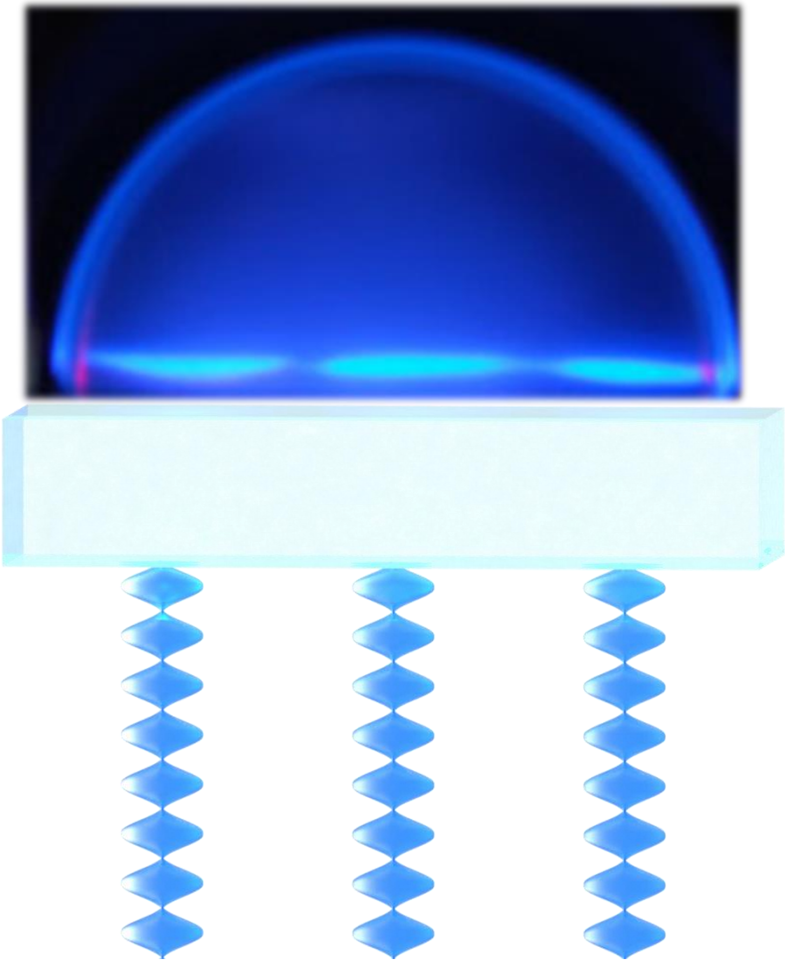
ionization gratings



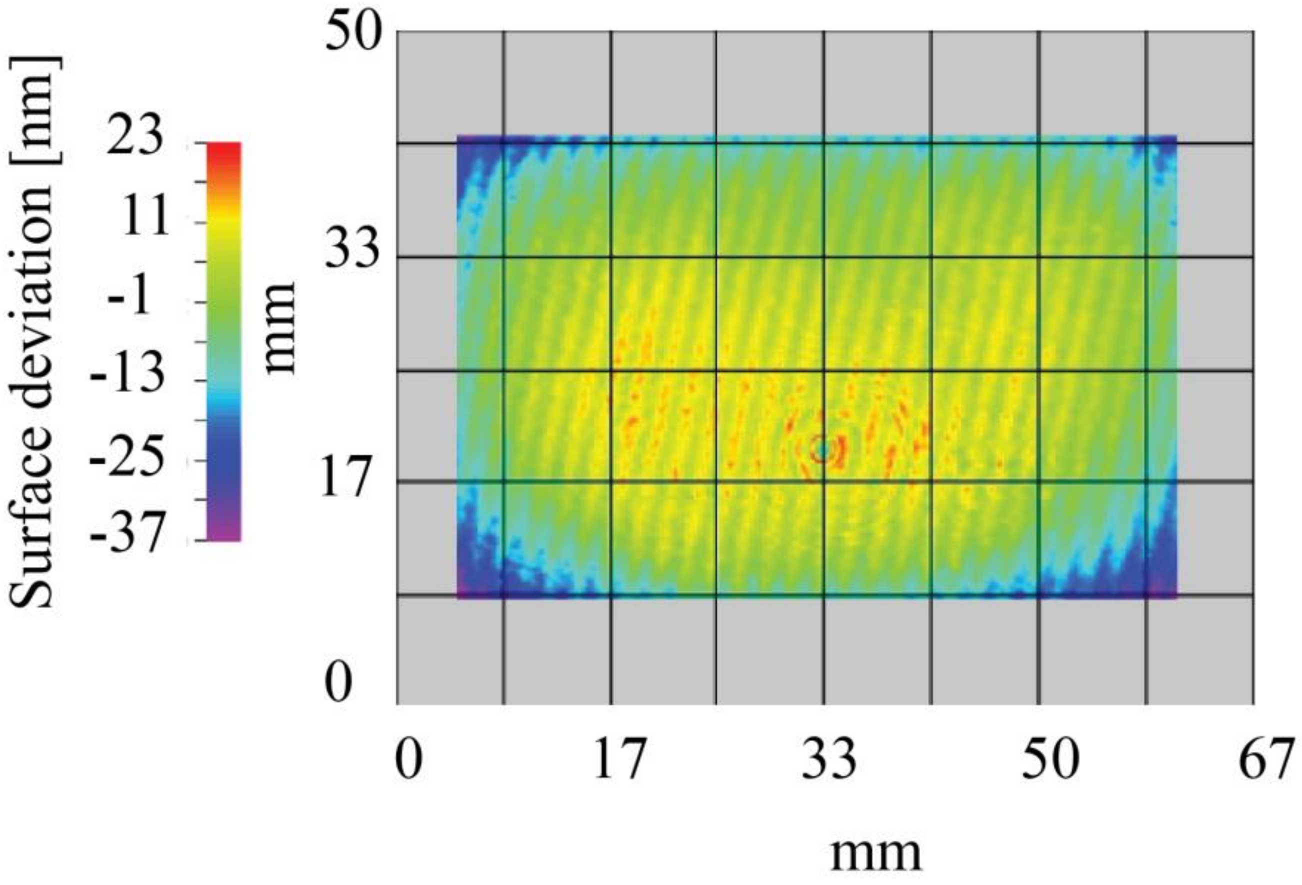
fragmentation gratings

P.Haslinger, N. Dörre, P. Geyer, J. Rodewald, S. Nimmrichter and M. Arndt, ***Nat. Phys.* 9,** 144–148 (2013).
N. Dörre, J. Rodewald, P. Geyer, B. v. Issendorff, P. Haslinger and M. Arndt, ***Phys. Rev. Lett.* 113,** 233001 (2014).

VUV mirror

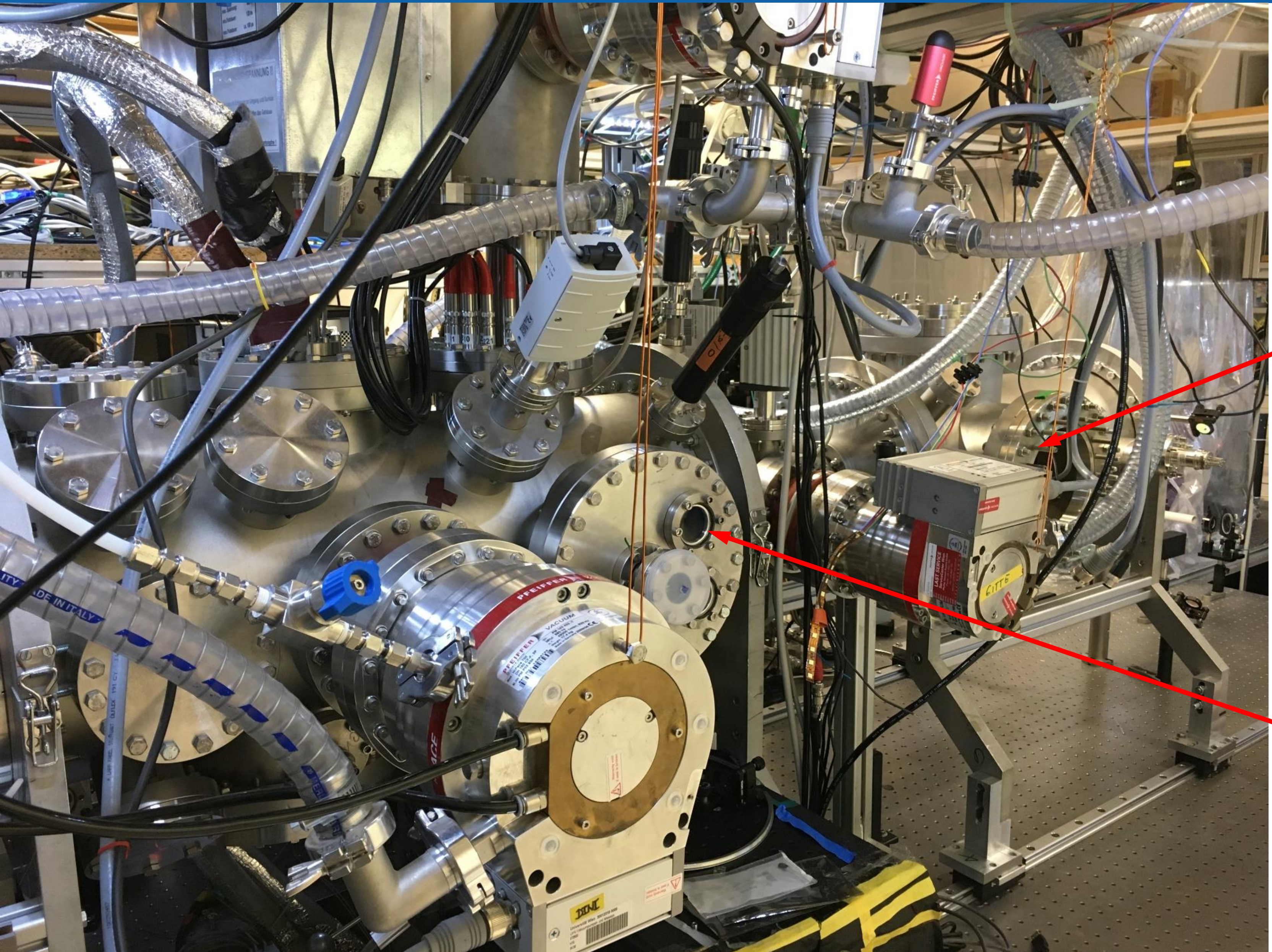


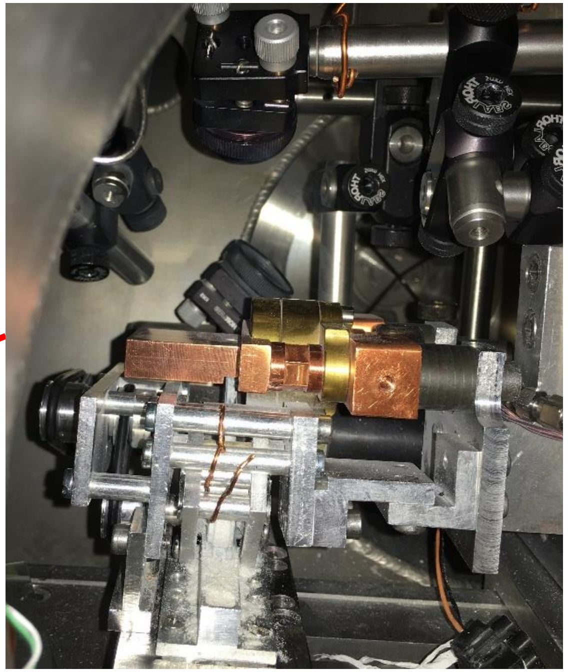
$$\Delta\phi = \frac{2\pi}{d}(\Delta x_1 - 2\Delta x_2 + \Delta x_3)$$

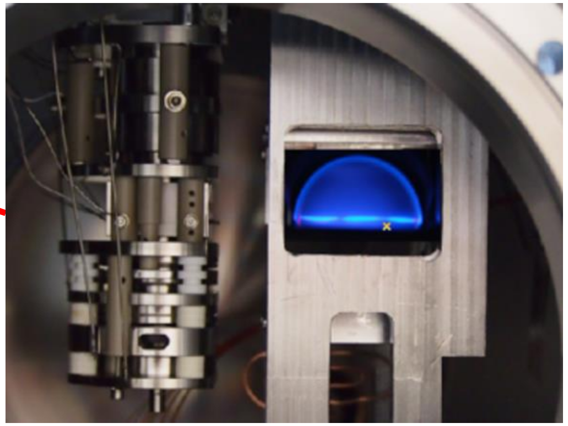


ZYGO interfereomery, LaserOptik Garbsen

OTIMA





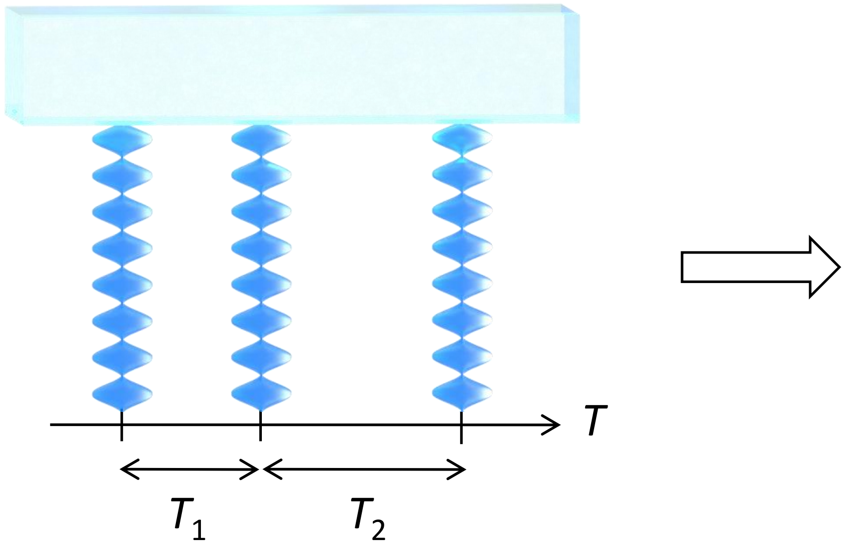


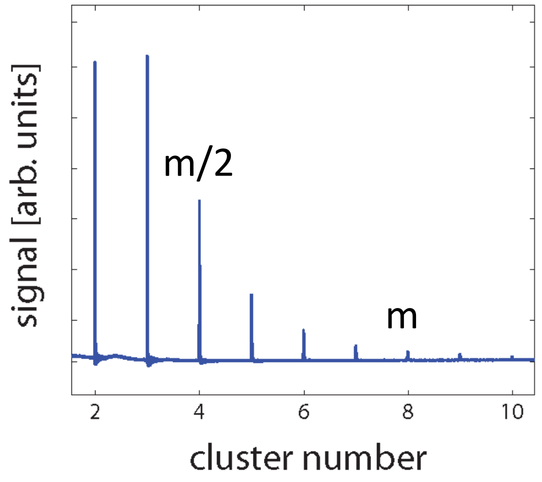
Quantum interference: mass spectrometry

Off-resonant:

$$T_1 + 100\ \text{ns} = T_2$$

Tiny mismatch destroys interference



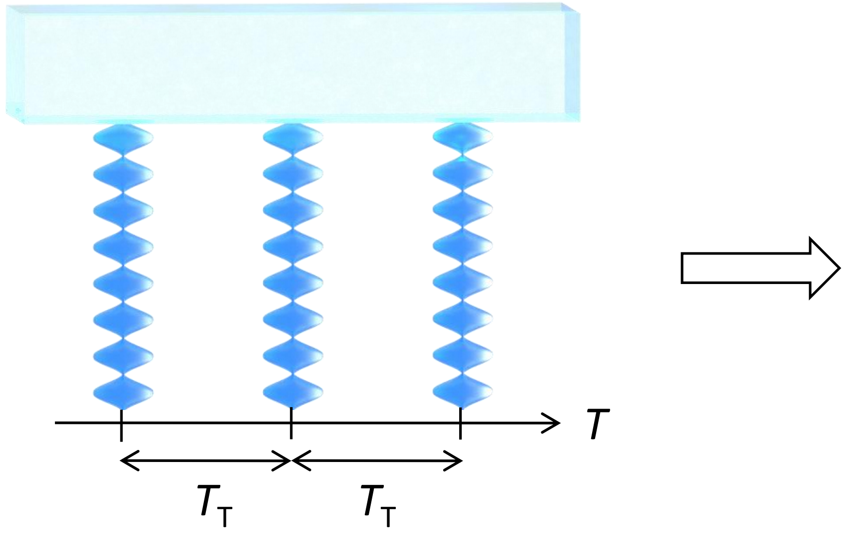


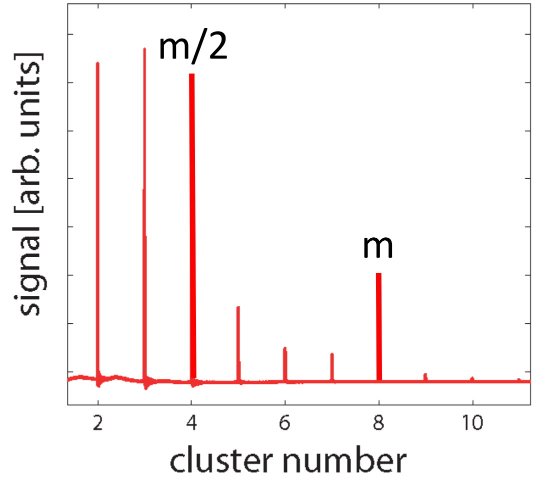
$$S_N = \frac{S_{res} - S_{off}}{S_{off}}$$

Resonant (for mass m):

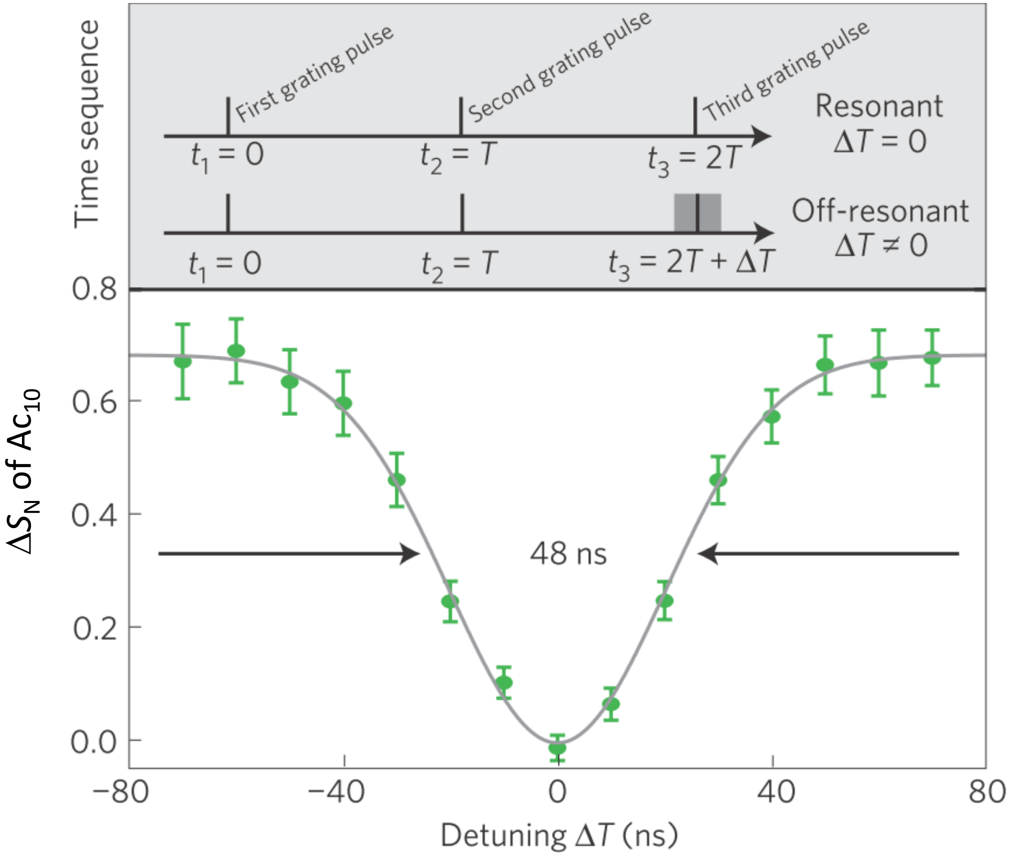
$$T_1 = T_2 = T_T(m)$$

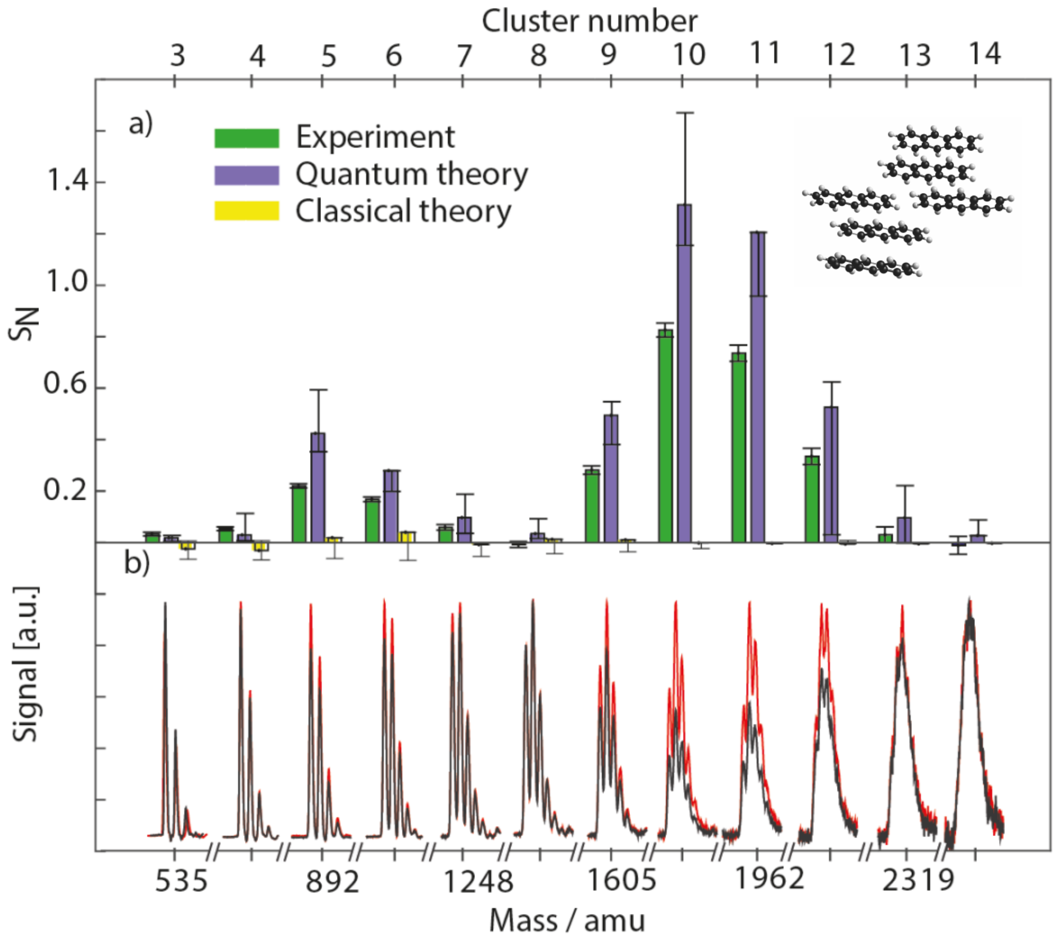
Interference modulates transmission





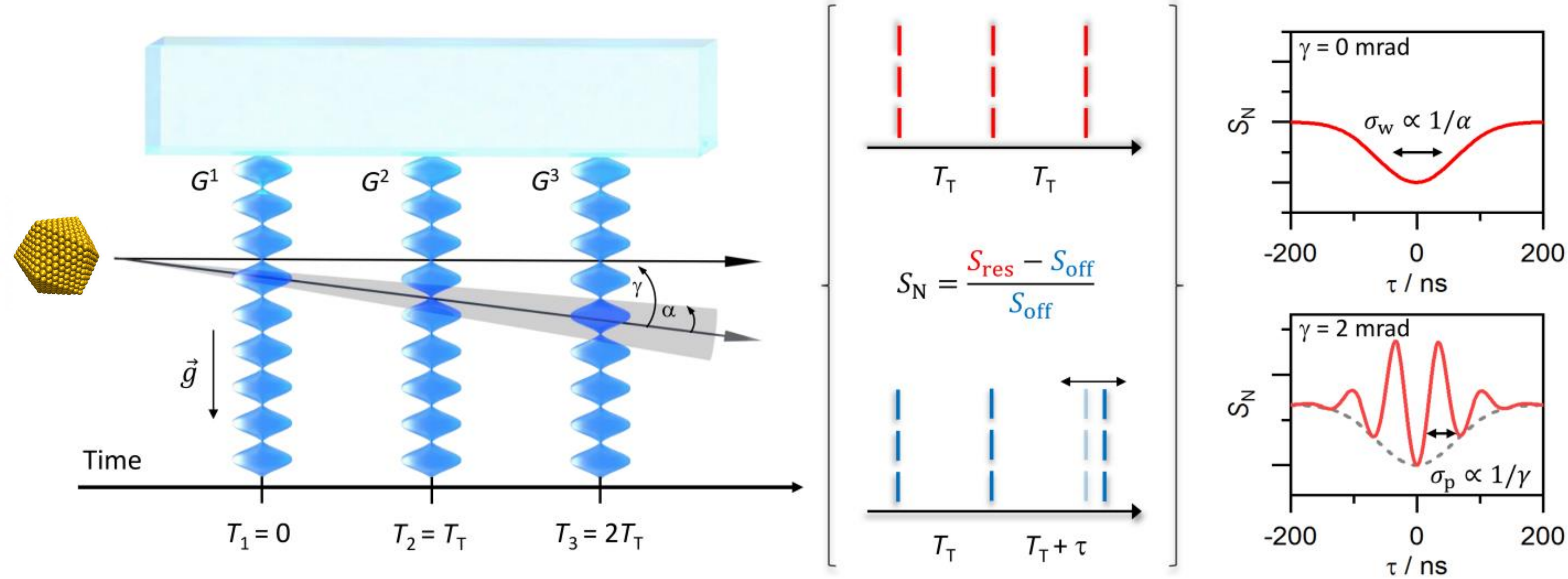
Interference of organic clusters



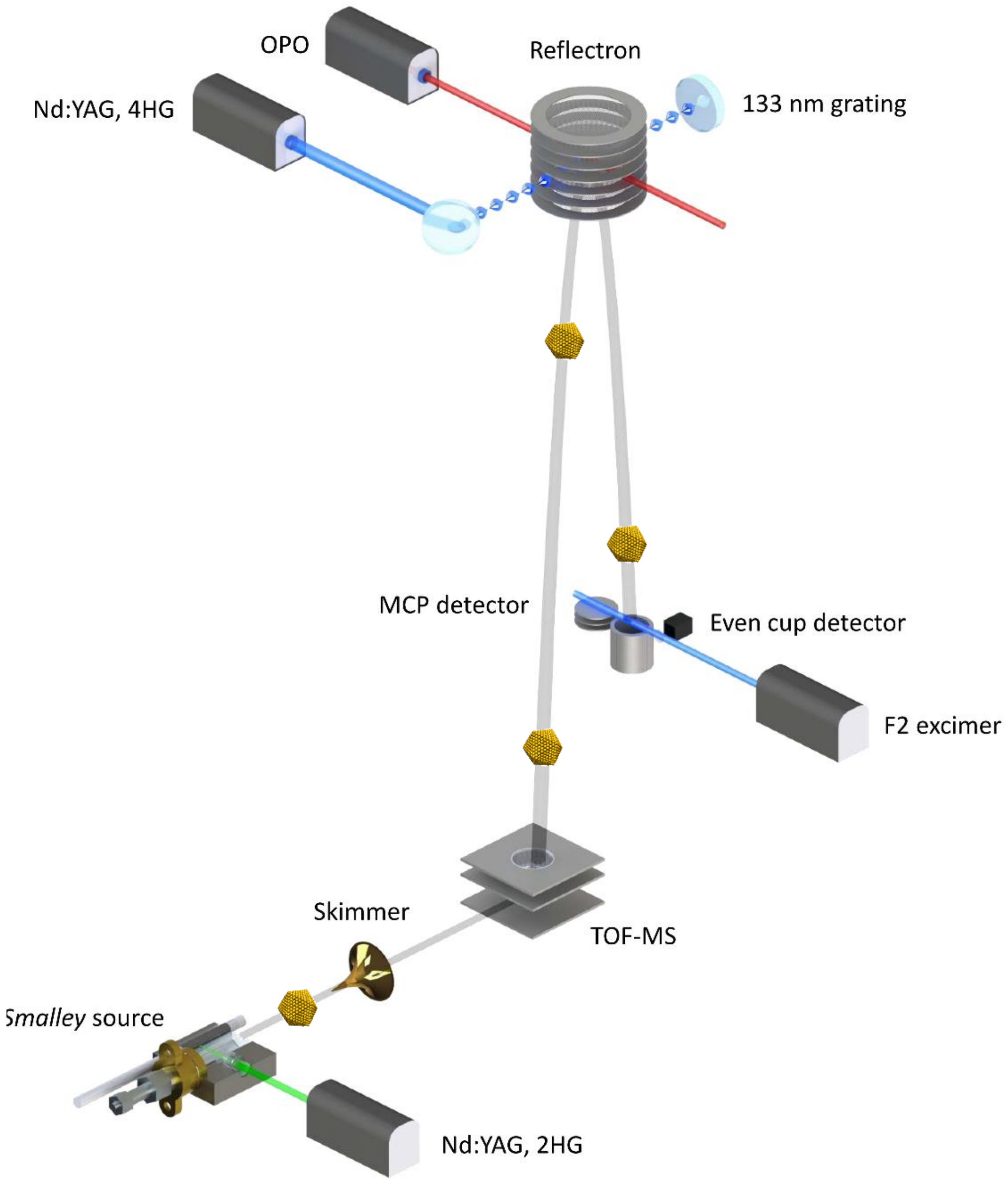


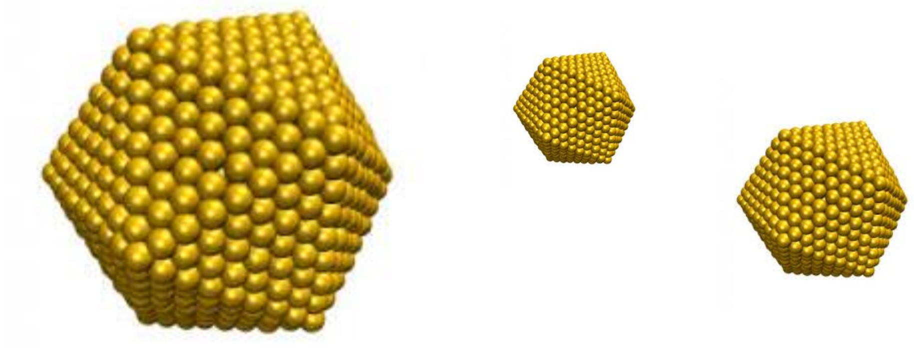
P.Haslinger, N. Dörre, P. Geyer, J. Rodewald, S. Nimmrichter and M. Arndt, ***Nat. Phys.* 9,** 144–148 (2013).
J. Rodewald, PhD thesis (2017).

Imprinting spatial fringes



Ongoing concept study: OTIMA-2





- Source of high-mass metal cluster anions

  Smalley, Magnetron, ESI?
- Deceleration in a reflectron TOF-MS
- Photodetachment
- Interferometry at low velocities
- Detection after free-fall

$$T_T = \frac{md^2}{h} \approx 15 \text{ ms @ } 157 \text{ nm for } 10^6 \text{ amu}$$

Acknowledgements

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VIENNA SCIENTIFIC CLUSTER

VCQ

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