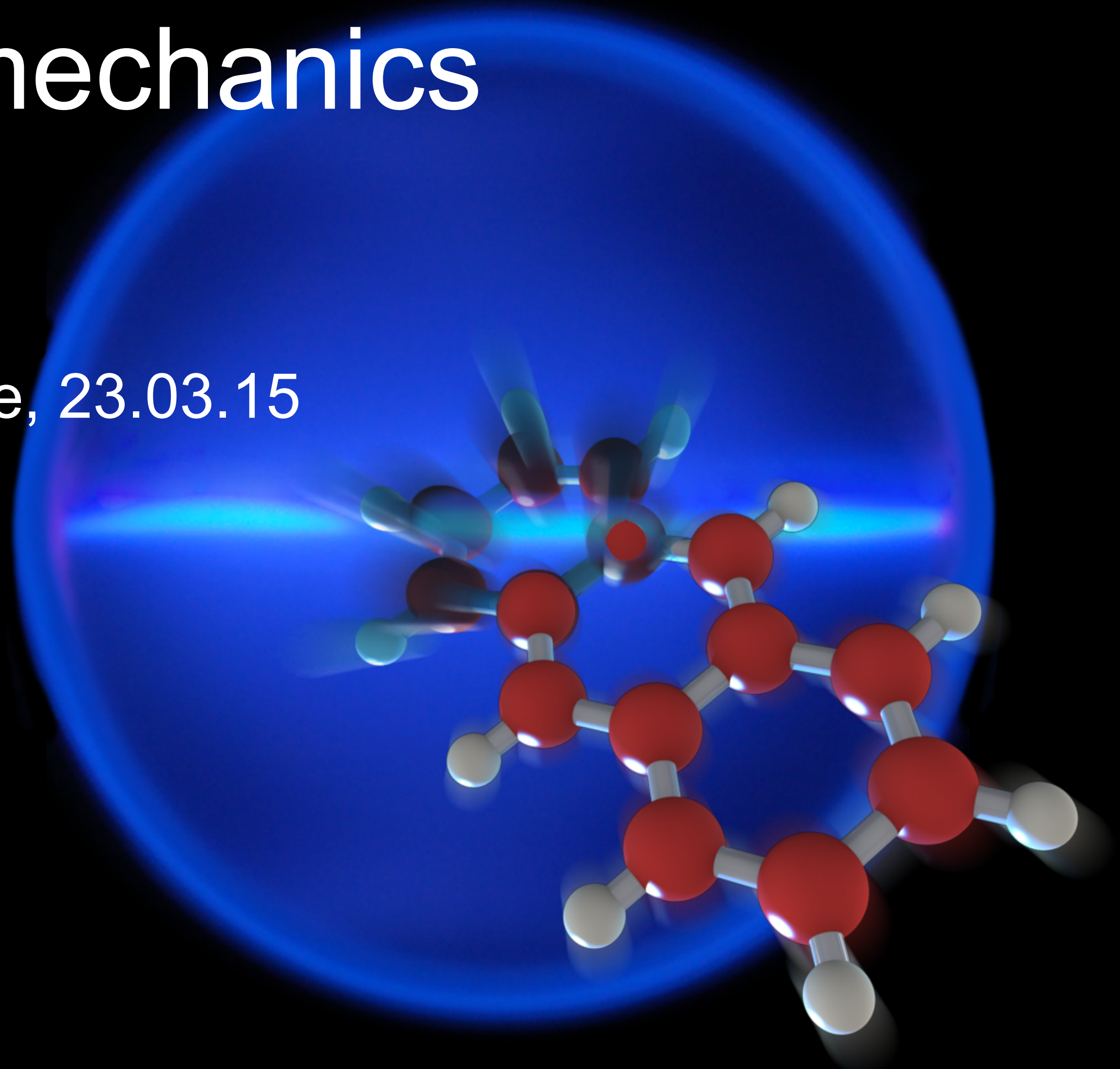
A matter-wave interferometer for testing the limits of quantum mechanics

Jonas Rodewald, Erice, 23.03.15

universität wien

CoQuS
ComplexQuantumSystems

VCQ
Vienna Center for Quantum
Science and Technology

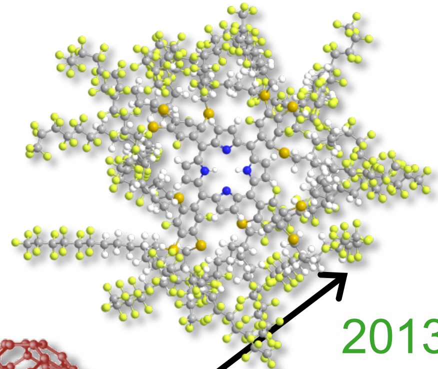


Motivation

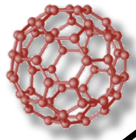
- test of quantum theory on large mass scales
- study of novel decoherence effects
- study of collaps models
- development of new grating types for matter-wave interferometry
- precision measurements of nanoparticle properties

matter-waves timeline

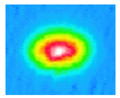
$$\lambda_{dB} = \frac{h}{m \cdot v_z}$$



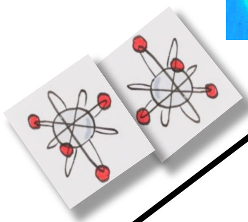
2013 m > 10.000 amu
810 atoms



1999 Fullerenes C_{60} & C_{70}

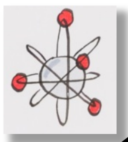


1995 BEC



90's I_2, He_2, Na_2

1936 Neutrons

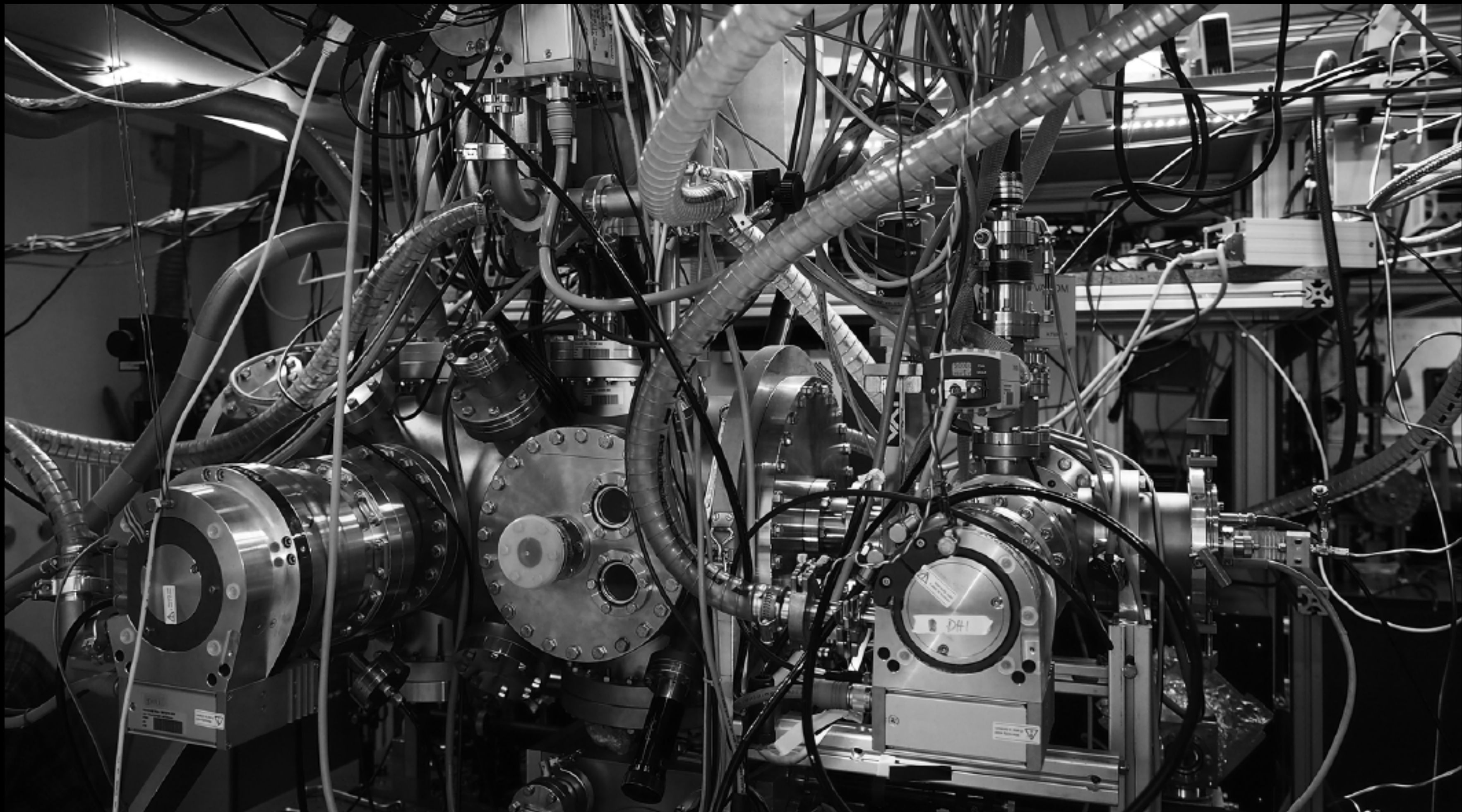


1930 He atoms & H_2

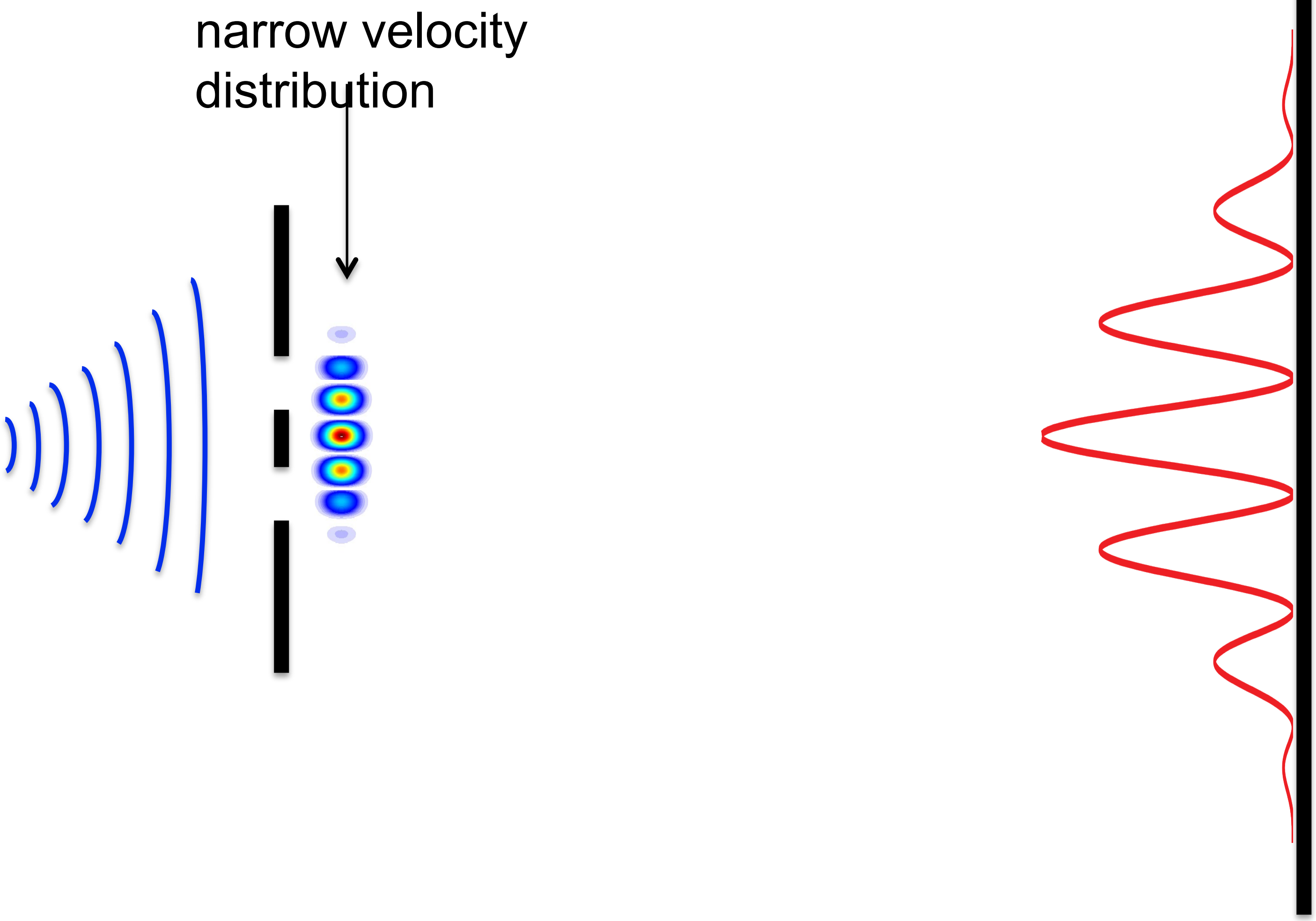
1927 Electrons

1923 De Broglie hypothesis

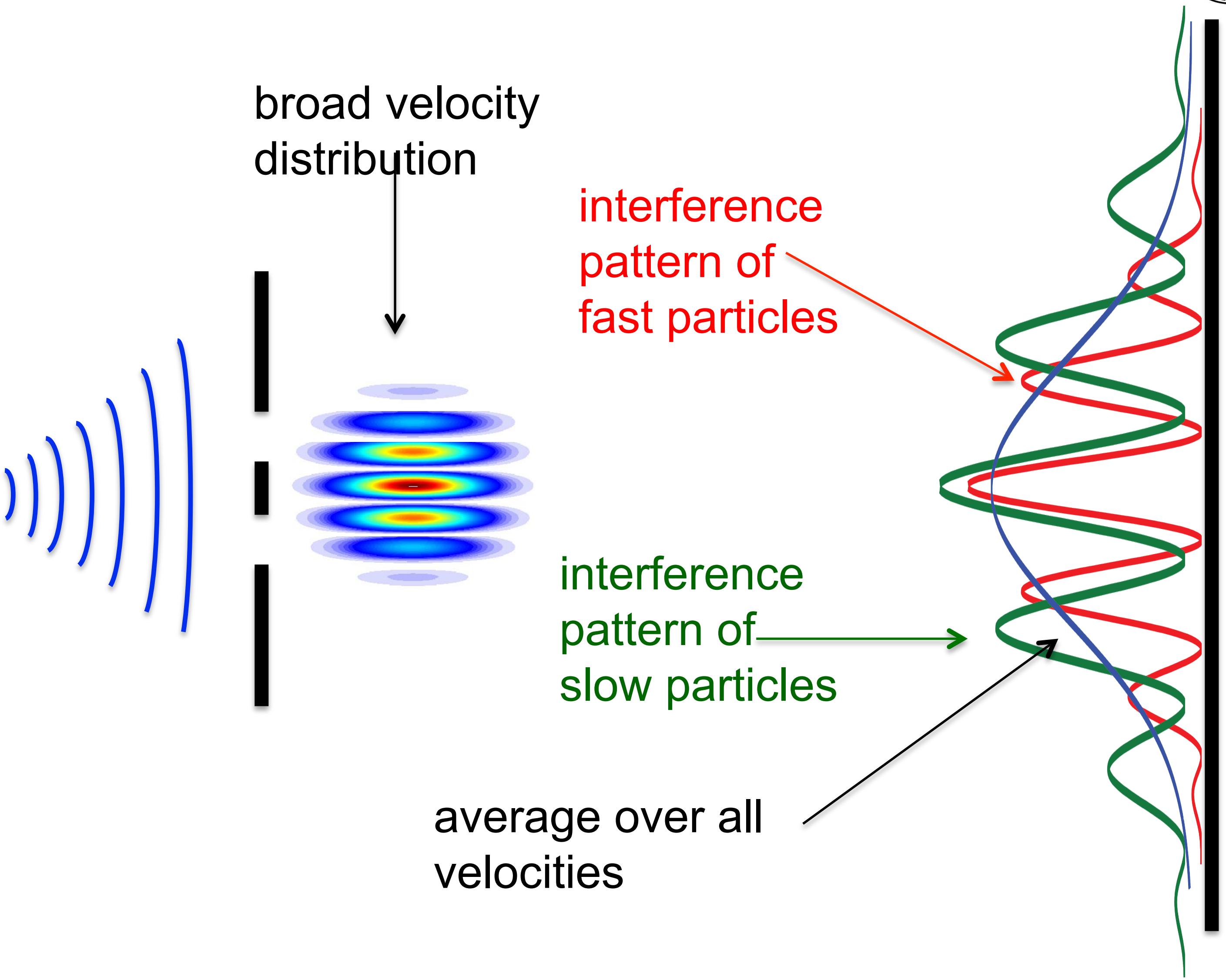
the machine



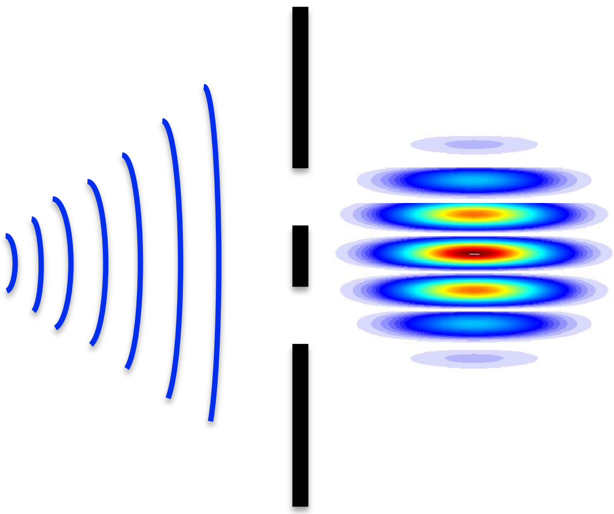
the time-domain idea



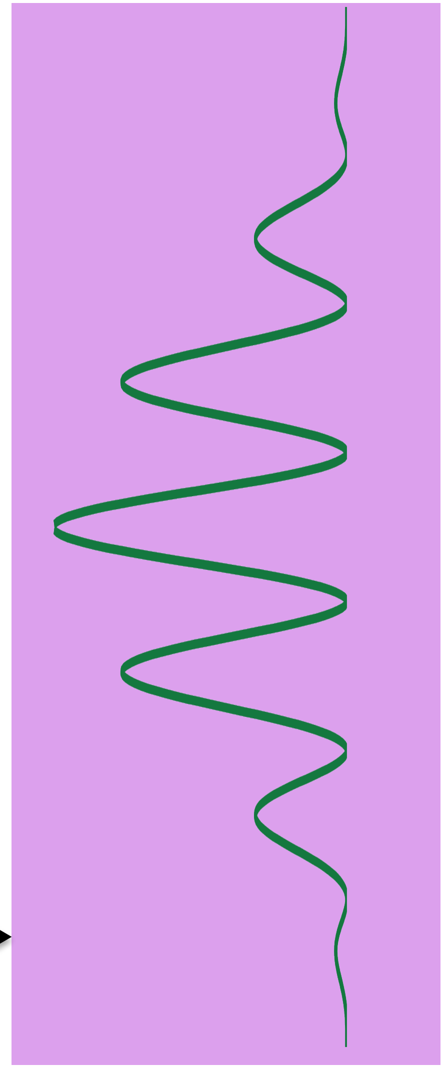
the time-domain idea



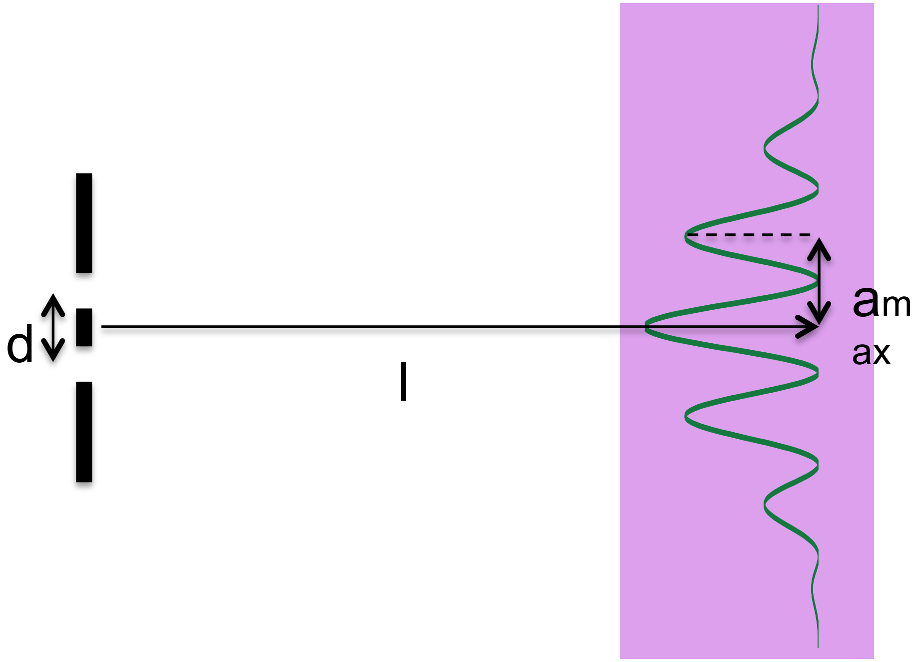
the time-domain idea



detect interference at an instant in time and over large region of space



the time-domain idea



$$a_{max} = \lambda_{dB}\, l/d$$

$$a_{max} = h/mv\, l/d$$

$$a_{max} = h/m\, t/d$$

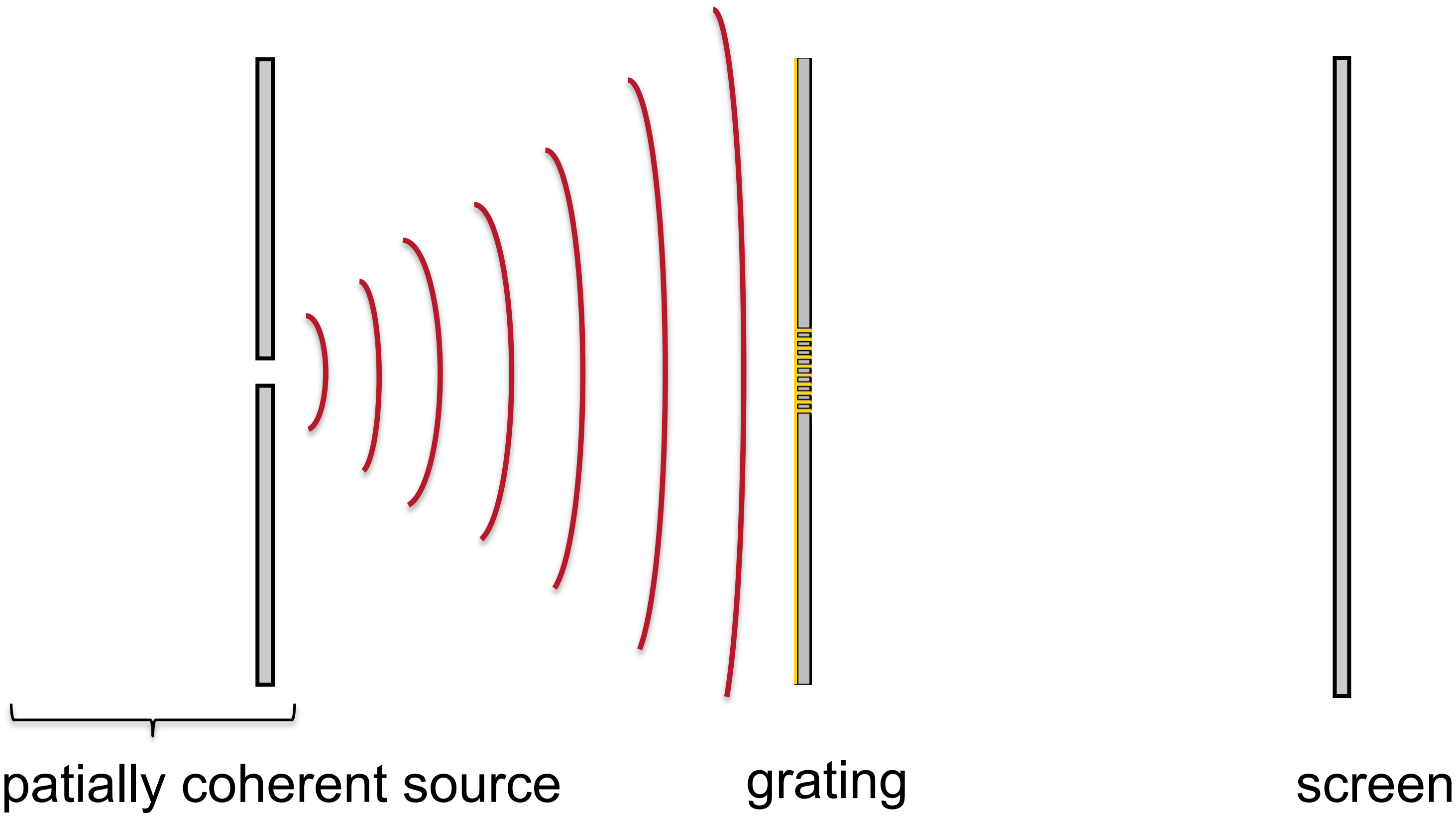
all particles with the same mass

....contribute to the same interference pattern

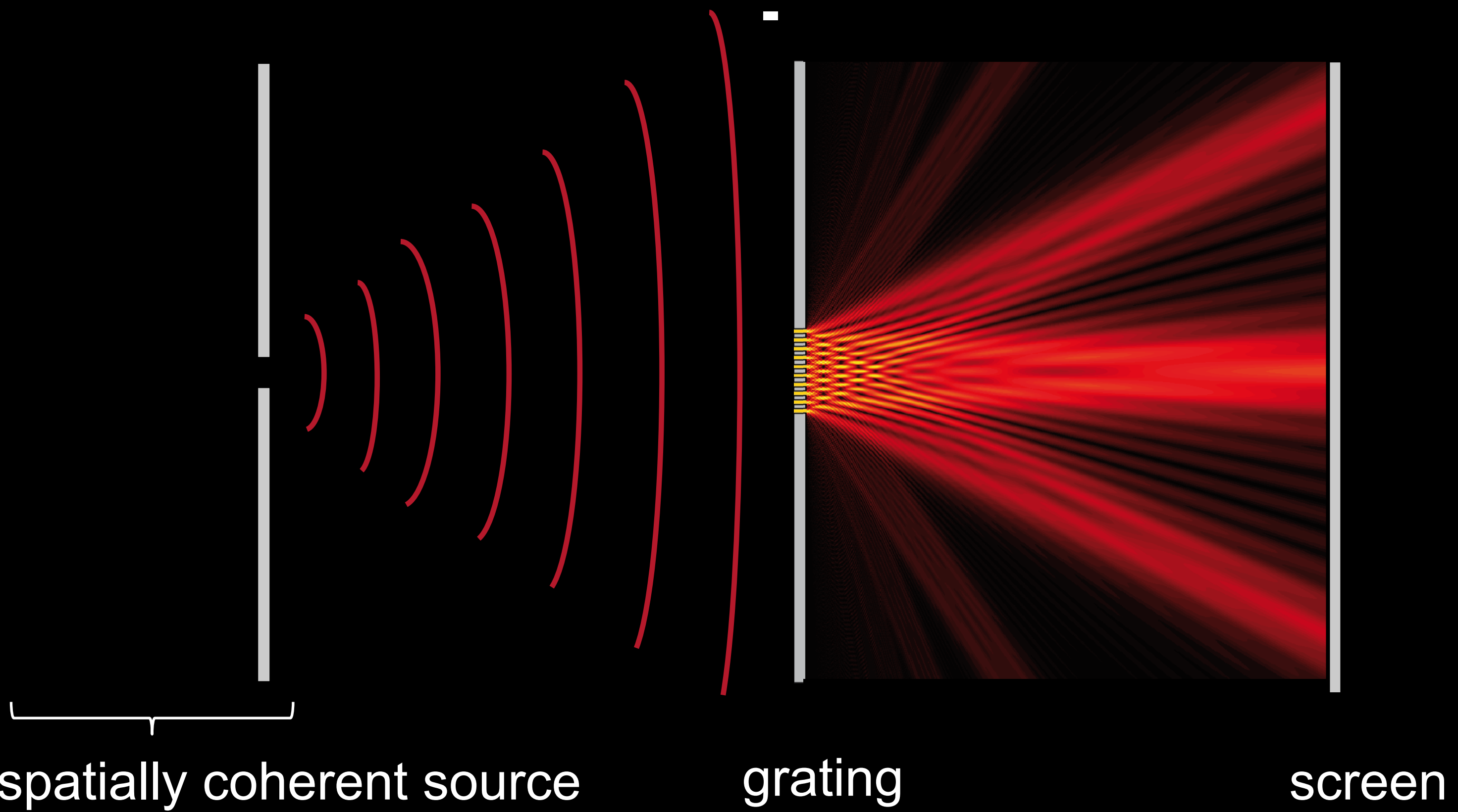
....at a certain time

....regardless of their velocity

introduction

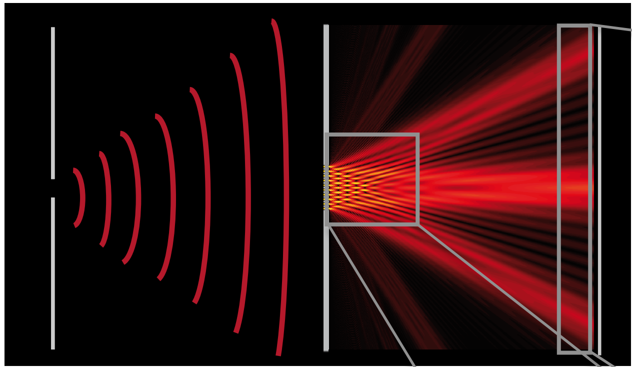


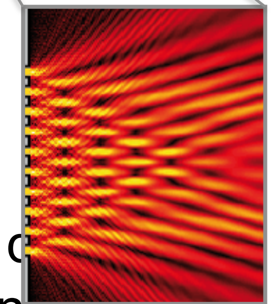
introduction



Hornberger et.al., *Rev. Mod. Phys.* (20

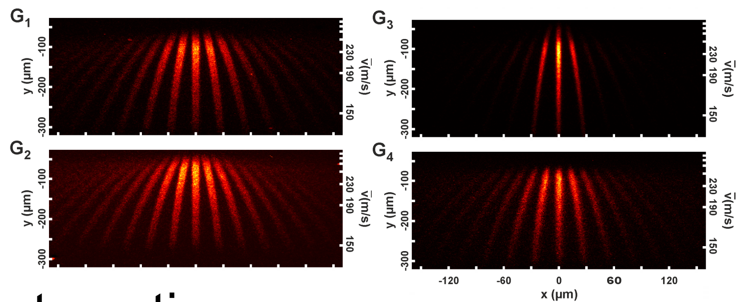
introduction





far-field diffraction:

- very quantum!
- easy to resolve diffraction p
- setup rel. easy to align and
- BUT: required distances/c
  result in low signal

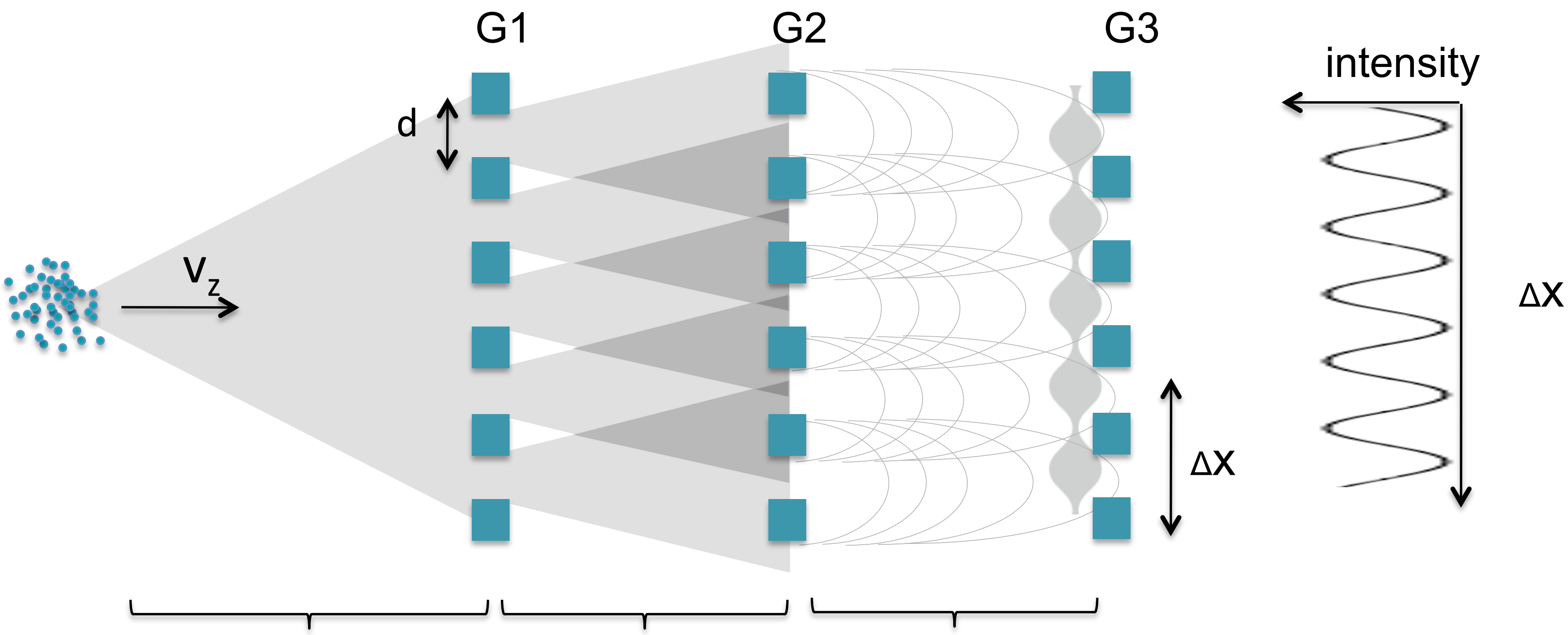


Arndt et. al, *Nature* **401**, (1999)
Juffmann et. al *Nature Nanotech*

near-field interference:

- very quantum!
  (if you know what you're c
- challenging to align, prone to many sources of dephasing/decoherence
  → sensitive detector of small forces and interactions
- favorable mass-scaling
  → capable tool for high-mass interferometry

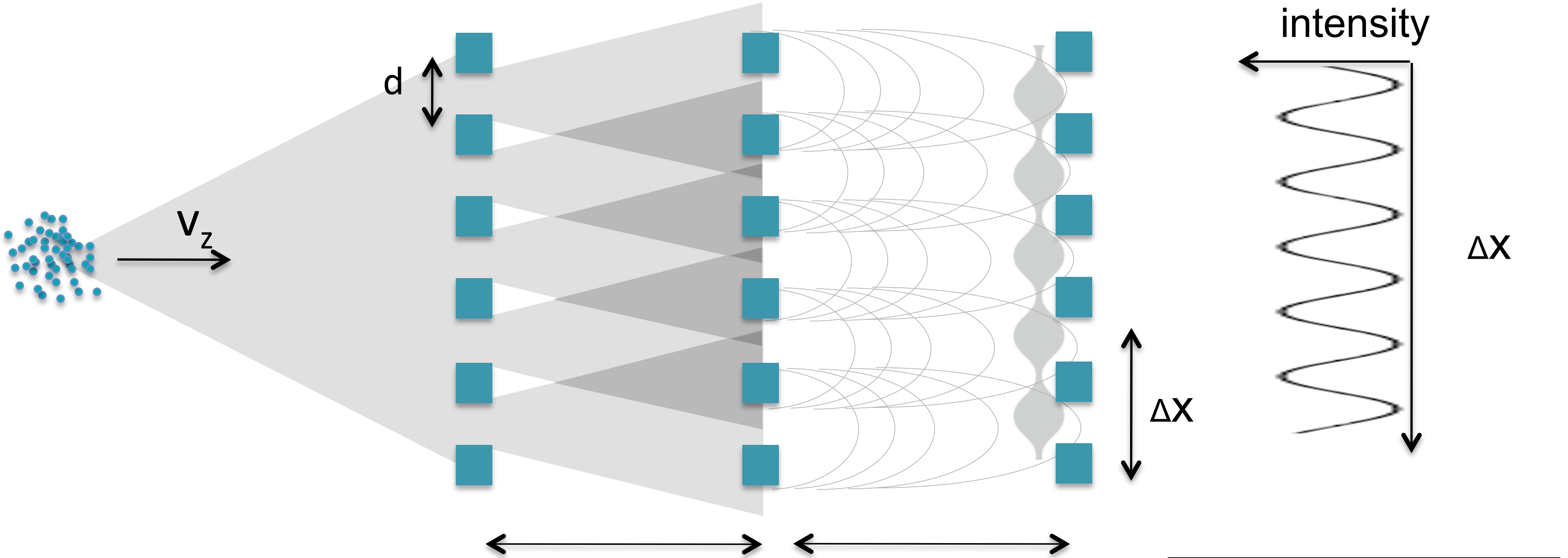
The Talbot Lau interferometer (TLI)



incoherent matter waves | preparation of transversal coherence | diffraction | detection by shift of G3

Talbot, *Philos. Mag*. **9** (1836)   Lau, *Ann. Phys.* **2** (1948)   Brezger et.al., *PRL* **88** (2002)
Hornberger et.al., *Rev. Mod. Phys.* (2011)

The Talbot Lau interferometer (TLI)



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

$$\lambda_{dB} = \frac{h}{m \cdot v_z}$$

Brezger et.al., *PRL* **88** (2002)   Hornberger et.al., *Rev. Mod. Phys.* (2011)

TLI in the time-domain

transition to time-domain

$$L_t = \frac{d^2}{\lambda_{dB}} \quad \longrightarrow \quad T_t = \frac{md^2}{h}$$

all particles with the same mass

....contribute to the same interference pattern

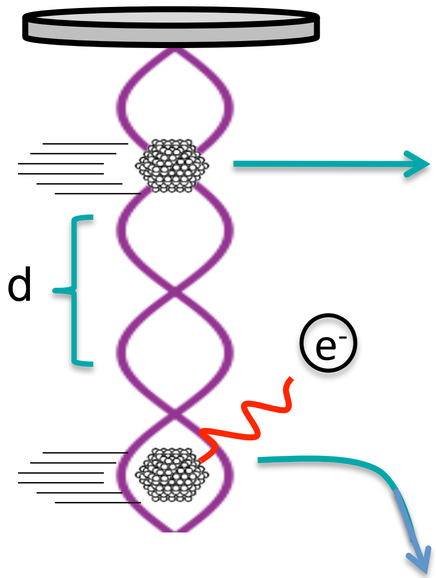
....at a certain time

....regardless of their velocity

how to implement?

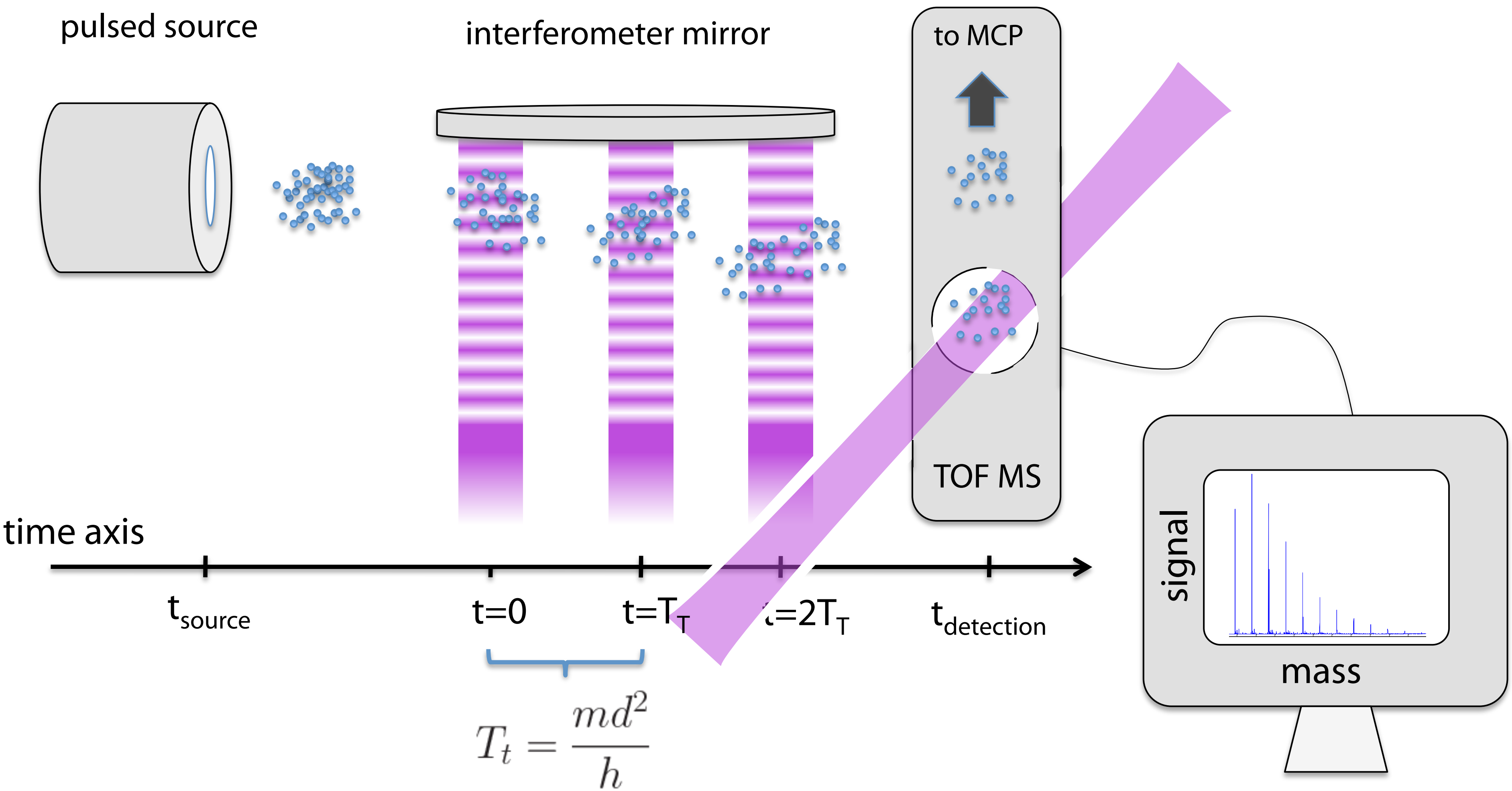
-pulsed standing laser waves as periodic depletion masks

$$d = \frac{\lambda_{laser}}{2} = \frac{157nm}{2} = 78{,}5\ nm$$



Cahn et.al., *PRL* **79** (1997) Nimmrichter et.al., *NJP* **13** (2011)

Experimental protocol

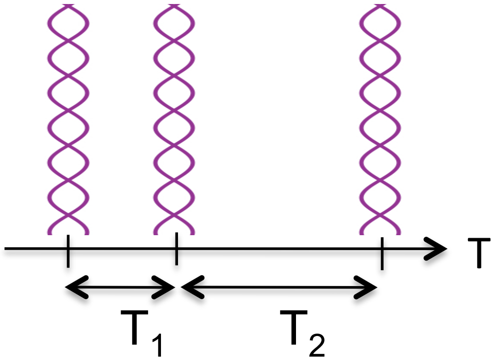


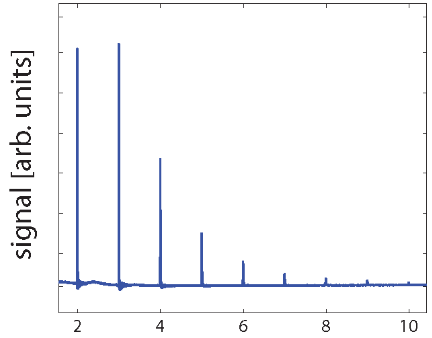
Haslinger et. al. *Nature Physics*

Detection of interference

TL-off-resonant

$$T_1 + 200ns = T_2$$

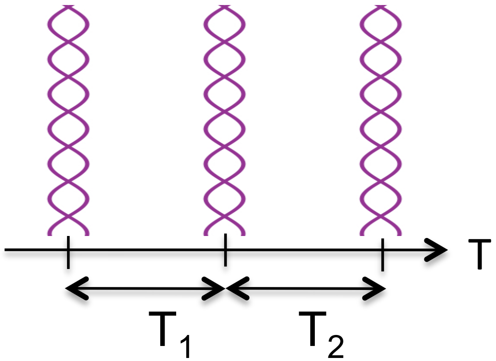


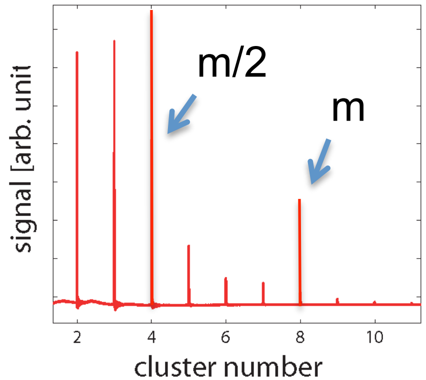


record the mass spectrum

TL-resonant
for mass m

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

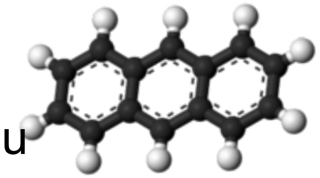




Haslinger et. al. *Nature Physics*

Interference of anthracene clusters

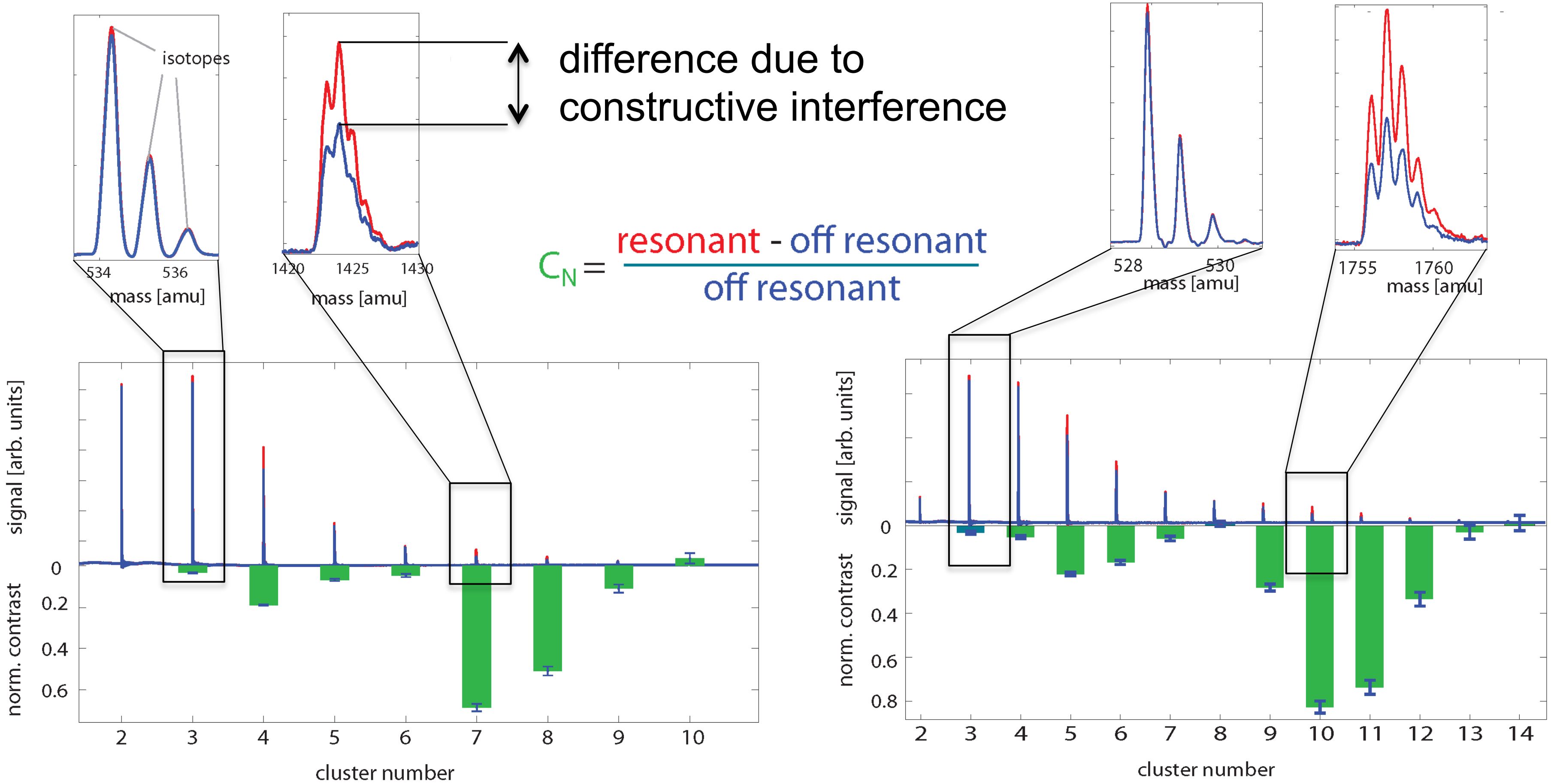
$C_{14}H_{10}$
m = 178 amu



neon seedgas, v_{avg} ≈920m/s

$$T_t = \frac{md^2}{h}$$

argon seedgas, v_{avg} ≈700m/s



Haslinger et. al. *Nature Physics*

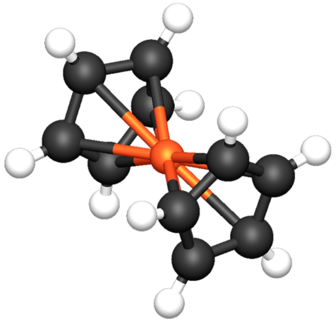
the others

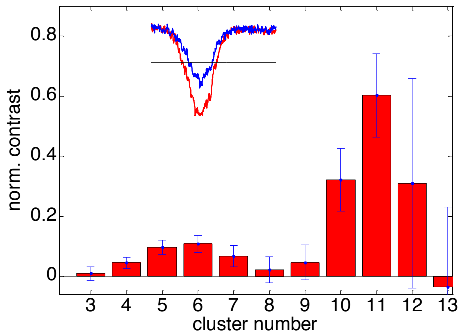
ferrocene

$Fe(C_5H_5)_2$

m = 186 amu

1973

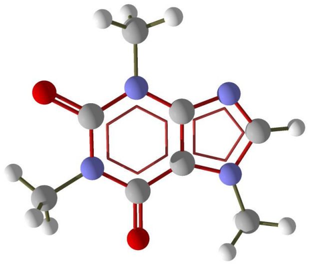


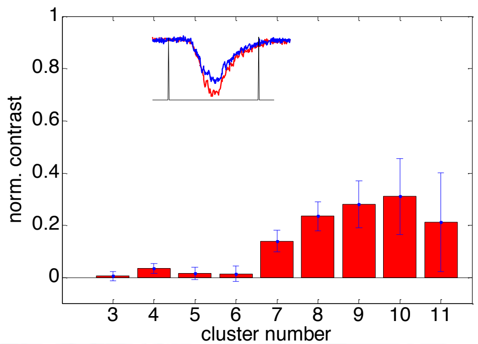


coffein

$C_8H_{10}N_4O_2$

m = 194 amu

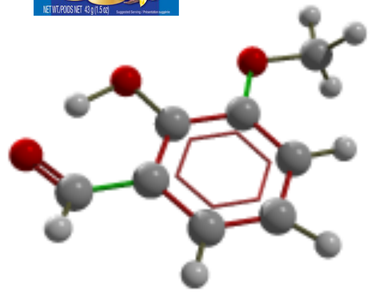


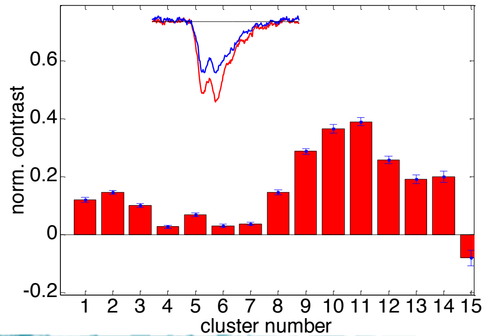


vanillin

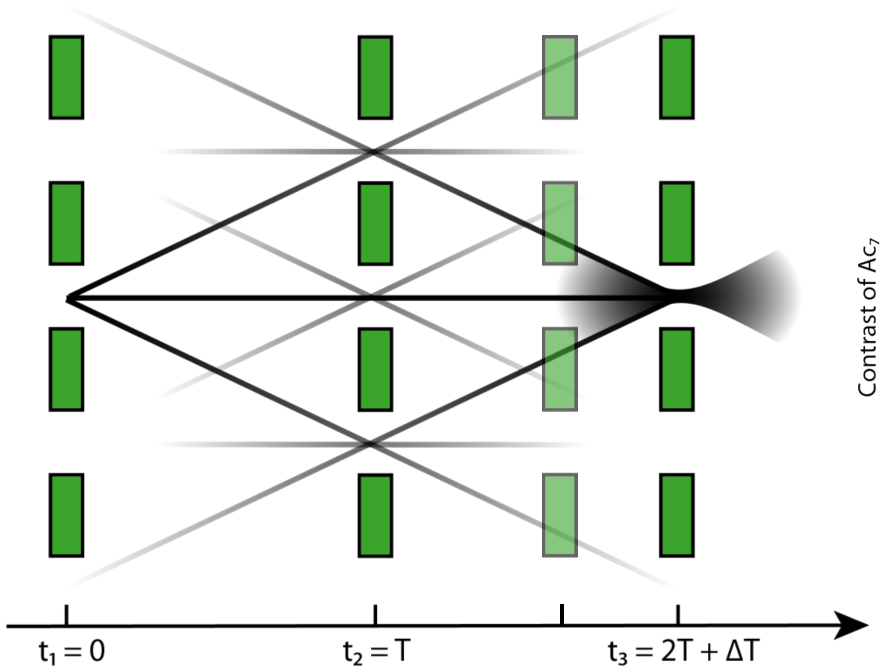
$C_8H_8O_3$

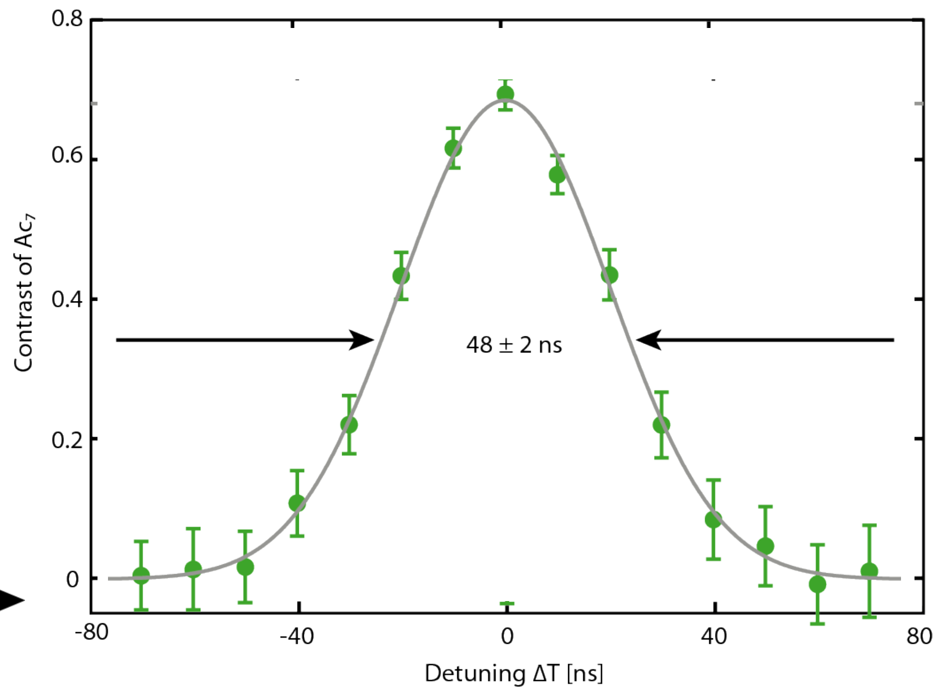
m = 152 amu





..and how long does the interference pattern exist?



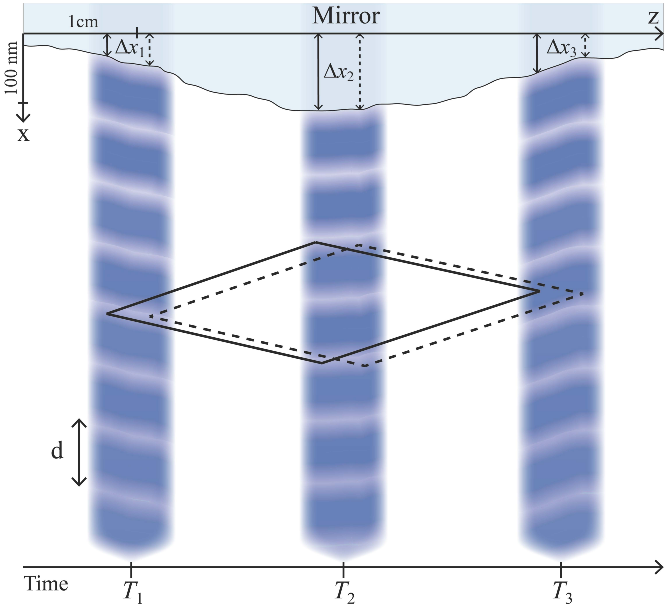


Haslinger et. al. *Nature Physics*

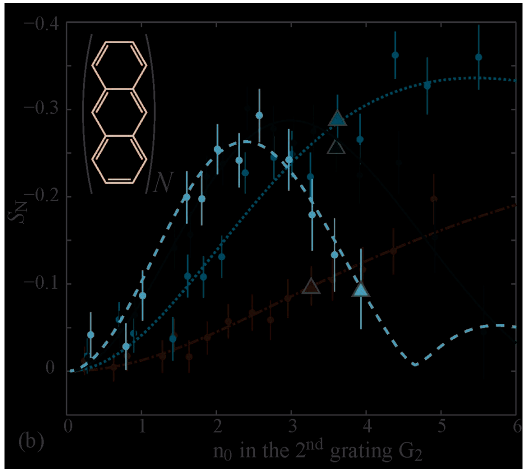
...including the imperfections

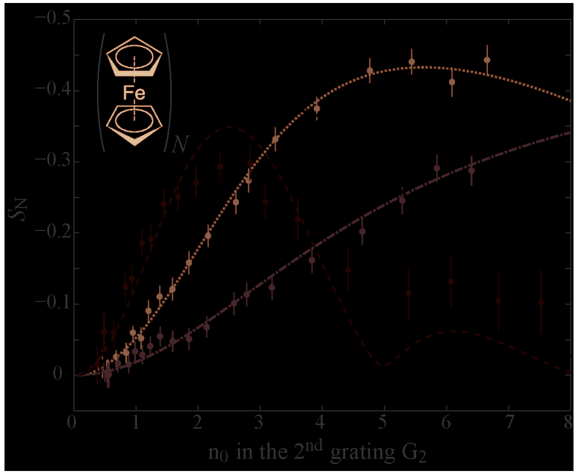
theory must include imperfections:

- limited long. coh of the garting lasers
- non-flatness of the mirrorsurface
- non-perfect mirror reflectivity



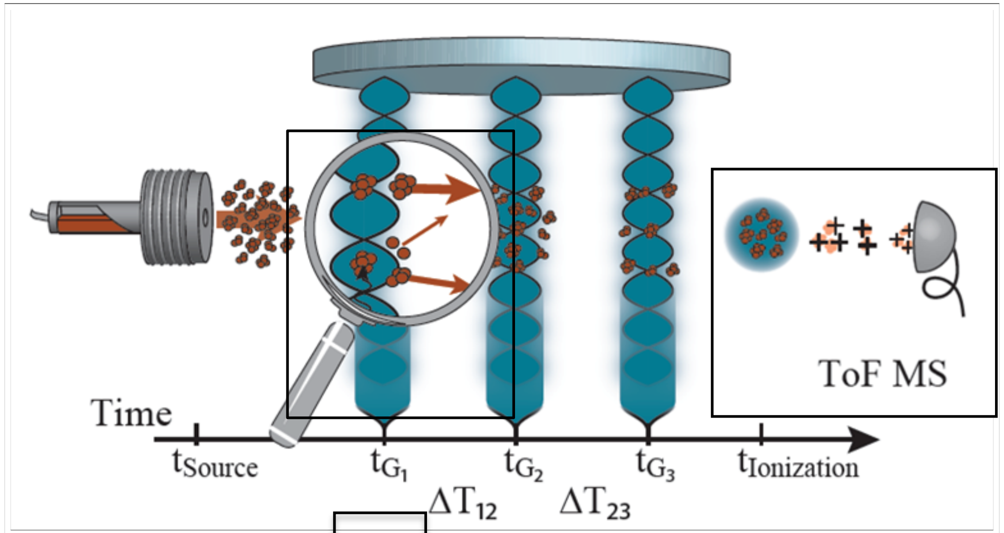
contrast vs. laser power in center gratin



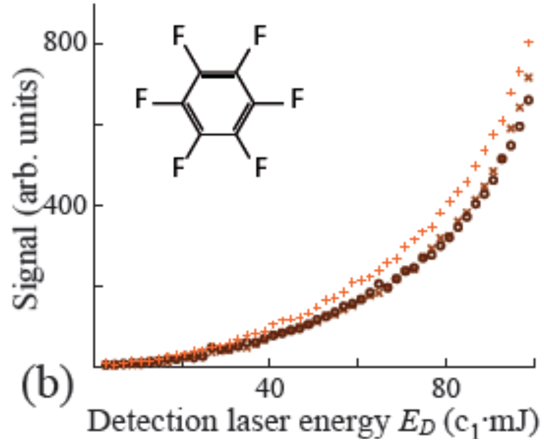


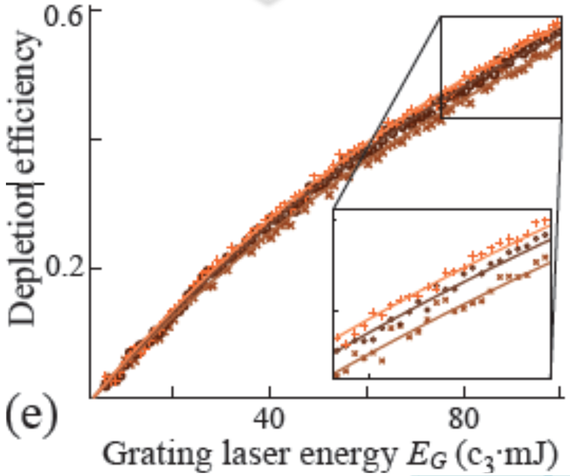
Dörre et.al. JOSA B, **32**

Fragmentation gratings



multiphoton ionization @ in the detector:



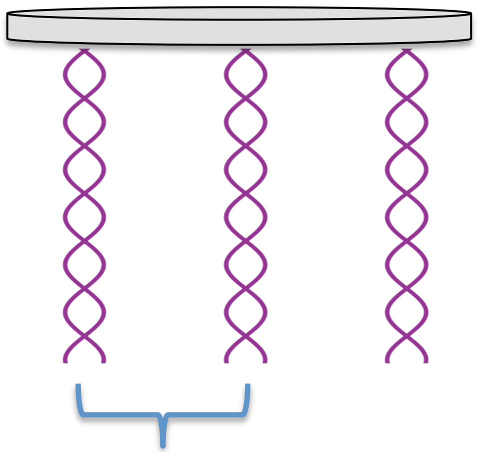


→ single photon „destruction“ mechanism in the

→ photofragmentation enables implementation o

Dörre et. al. *PRL* **113** (

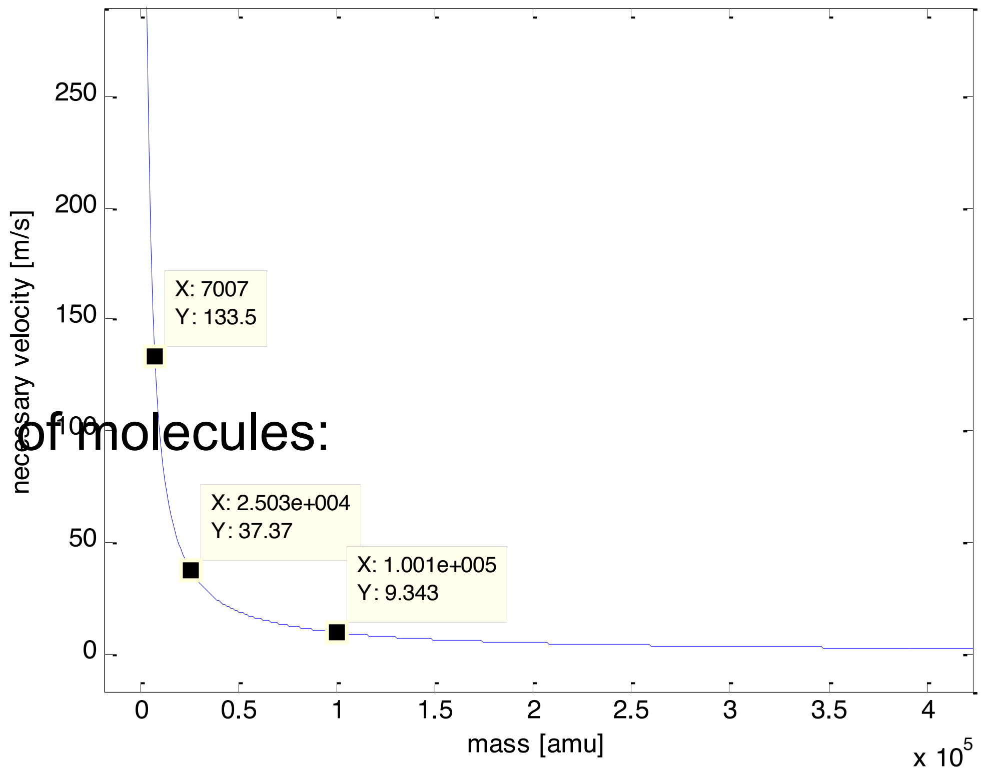
scaling up the mass: what do we nee



$s \approx 1.5\,cm$

$v = 1/m \quad sh/d^2$

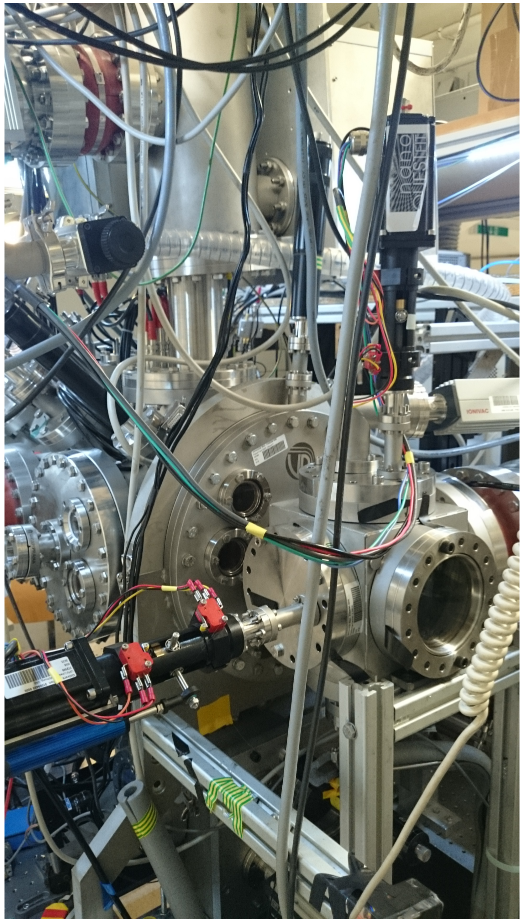
requires average velocity of

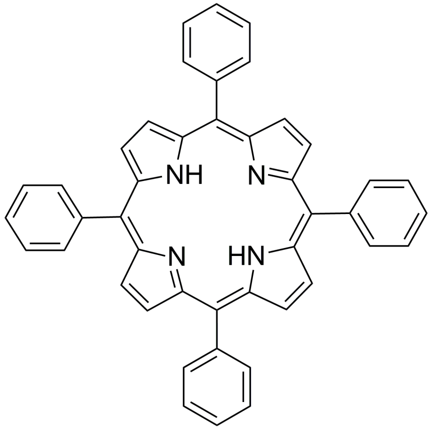


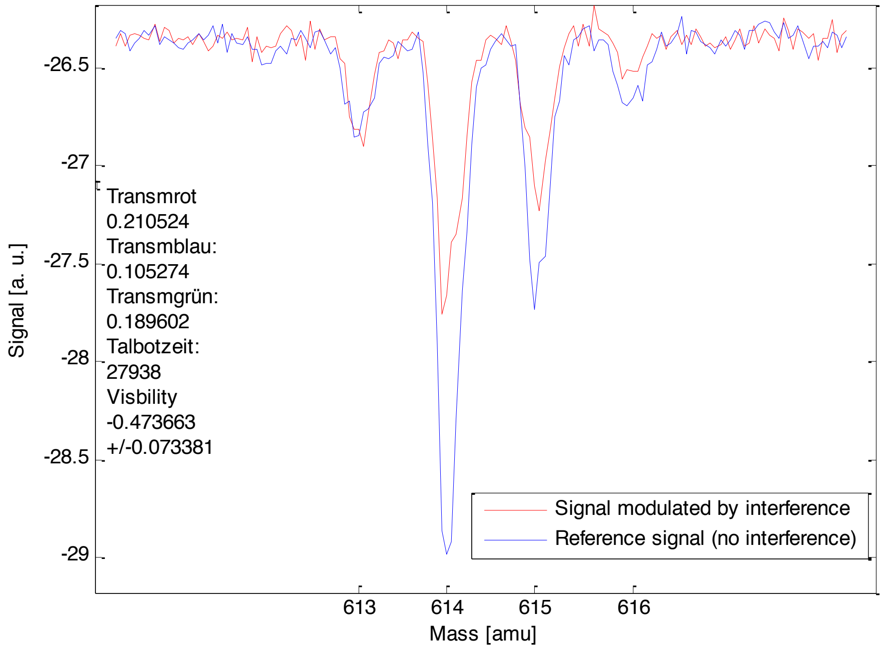
This is possible with laser evaporation of molecules:

Sezer et al, Journal of Mass Spectrometry **50**, (2015)
Felix et al, Eur. J. Org. Chem. **10** (2014)
Schmid et al J. Am. Soc. Mass Spectrom. **24**, (2013)

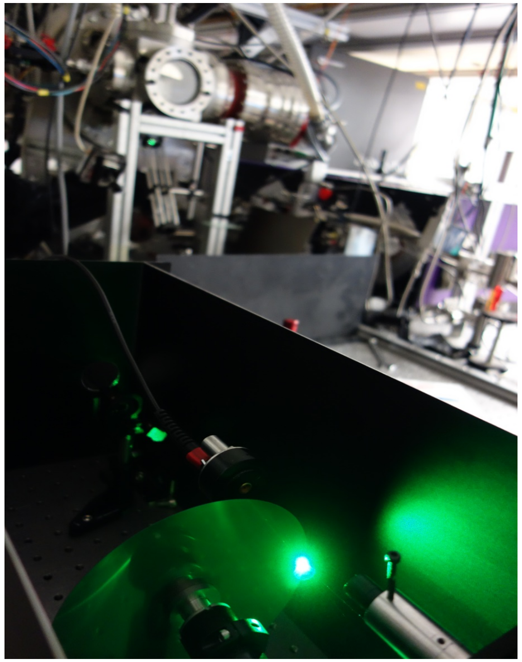
work in progress: TPP



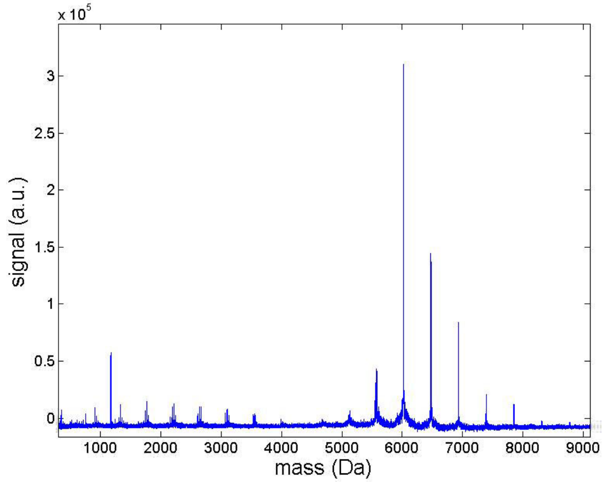


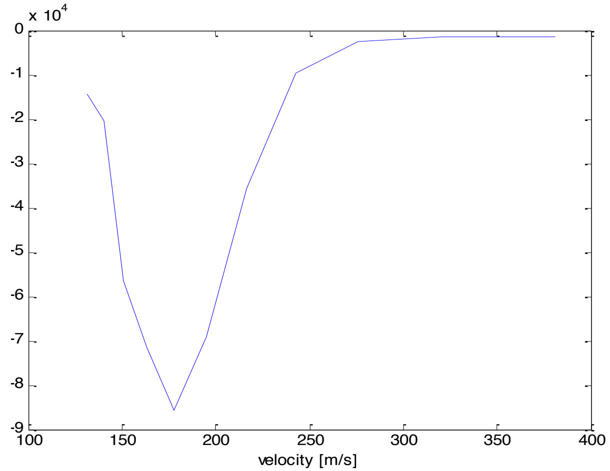


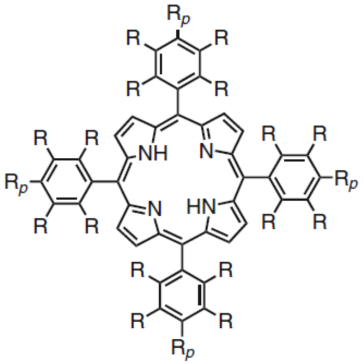
work in progress: 7.000-100.000amu



TPPF(20-x+17x),







$R^1 = F$

$R^2 = -S-CH_2CH_2-C_8F_{17}$

$R^3 = -S-CH_2-CH(CH_2CH_2C_6F_{13})_2$

(1) TPPF84: $R = R^1$; $R_p = R^2$

(2) TPPF120: $R = R^1$; $R_p = R^3$

(3) TPPF(20-x+17x): $R = R^1$ or R^2; $R_p = R^2$

(4) TPPF(20-x+26x): $R = R^1$ or R^3; $R_p = R^3$

molecules can readily be scaled up

25.000amu→66.000amu→ 100.000amu

macroscopicity?

PRL **110**, 160403 (2013) PHYSICAL REVIEW LETTERS week ending 19 APRIL 2013

Macroscopicity of Mechanical Quantum Superposition States

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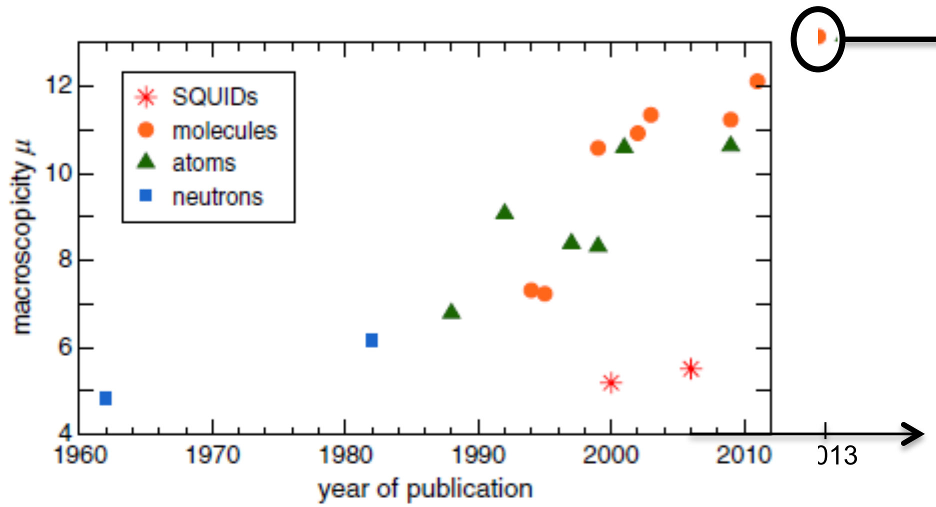
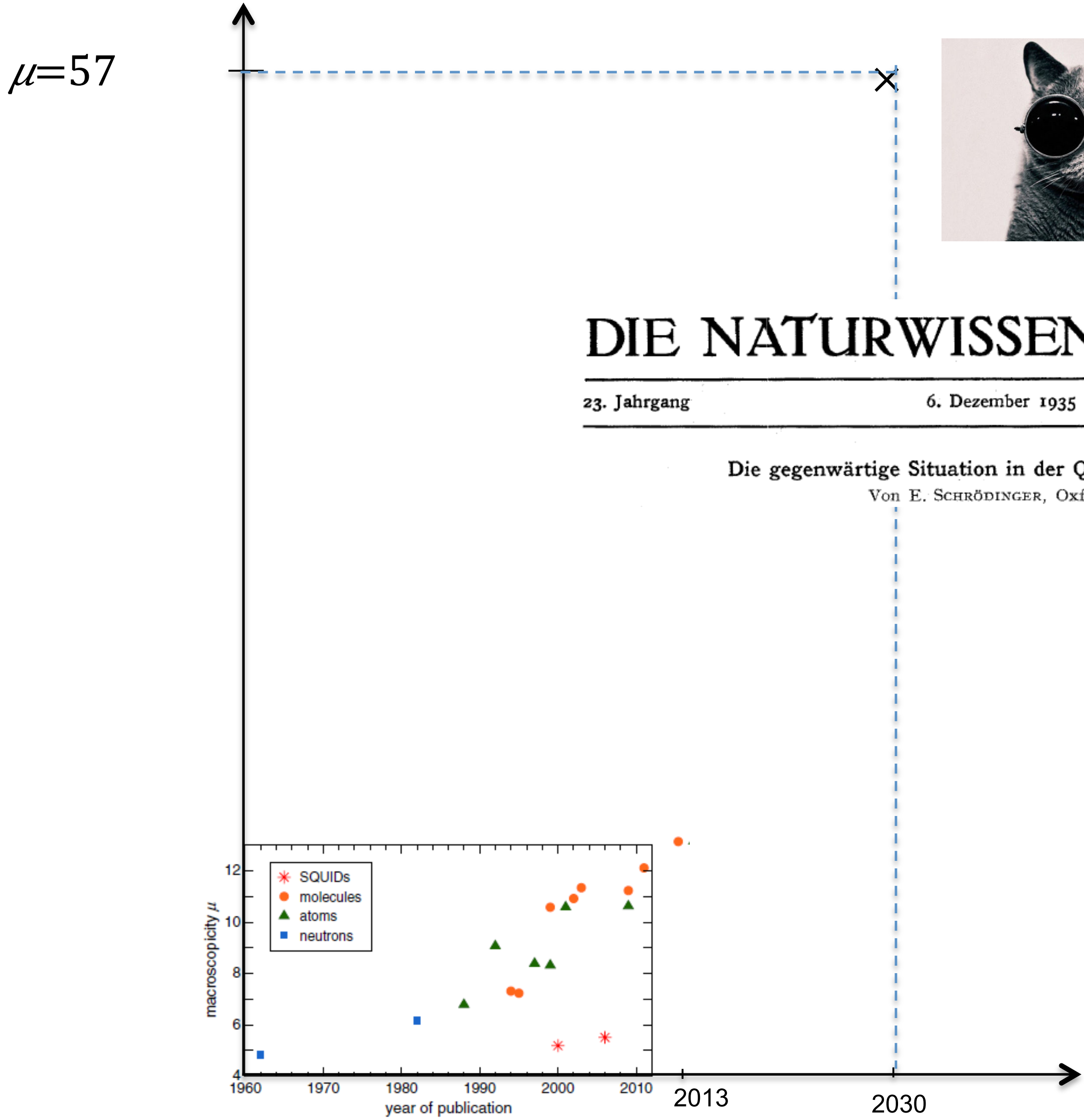
(Received 15 May 2012; revised manuscript received 25 February 2013; published 18 April 2013)

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



Eibenberger et. al. Phys. Chem. Chem. Phys. **15** (2013)

macroscopicity!!!



DIE NATURWISSENSCHAFTEN

23. Jahrgang | 6. Dezember 1935 | Heft 49

Die gegenwärtige Situation in der Quantenmechanik.

Von E. Schrödinger, Oxford.

outlook

-absence of dispersive Grating/wall interaction
→high interference contrast expected for masses even beyond 10^6 amu

mass	Talbot time	required velocity	required vacuua	gravitational deflection
10^6 amu	15 ms	1.3 m/s	10^{-9} mbar	4.5 mm
10^7 amu	150 ms	13 cm/s	10^{-11} mbar	45 cm
10^8 amu	1.5 s	1.3 cm/s	10^{-12} mbar	45 m

cooling and/or trapping necessary

managable

requires a vertical interferometer and/or no gravity

thanks for your attention!

special thanks to:

Markus Arndt

Nadine Dörre

Philipp Geyer

Ugur Sezer

Philipp Haslinger

(now at Berkley)

universität wien

CoQuS ComplexQuantumSystems

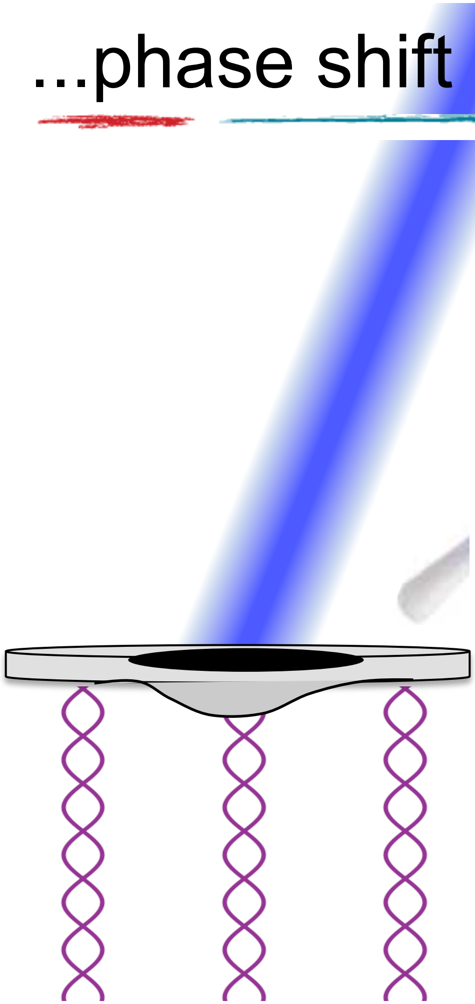
QuaBioS

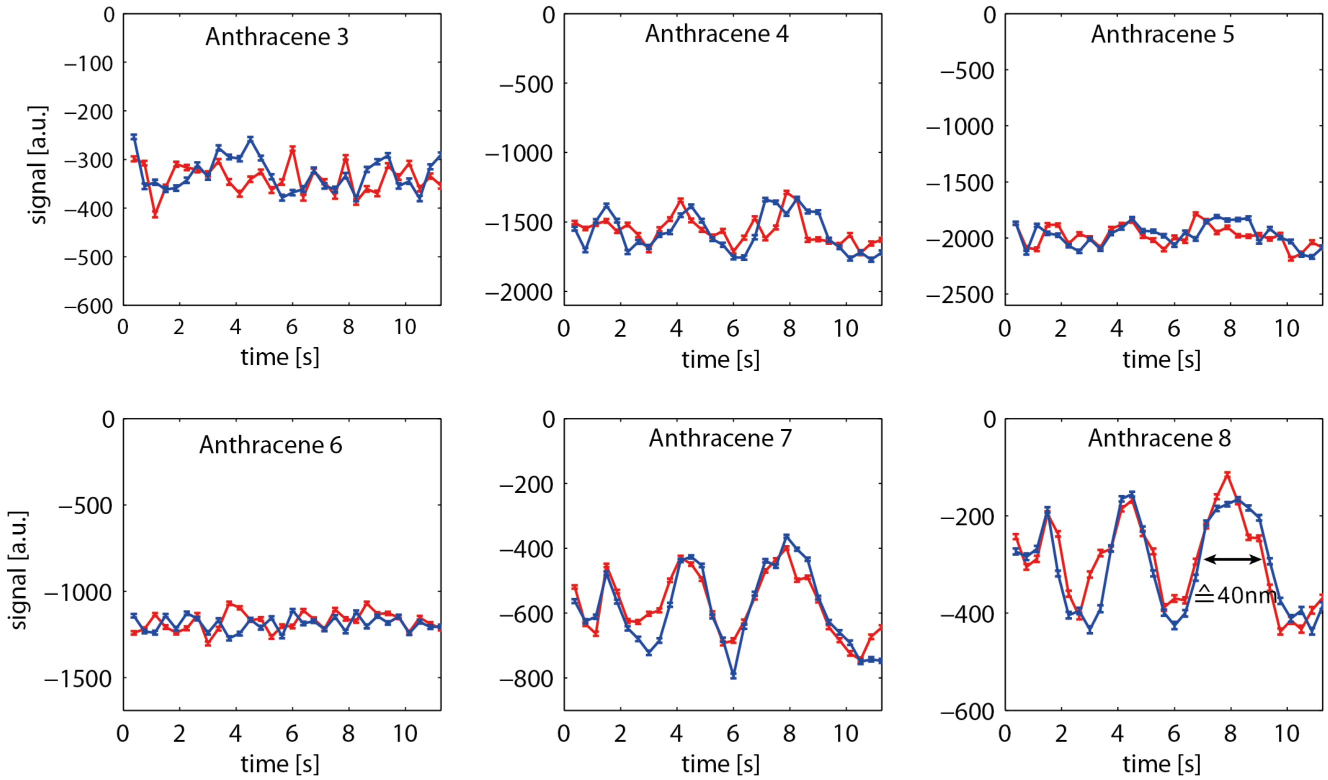
nano QUESTFIT

erc

FWF Der Wissenschaftsfonds.

...phase shift by mirror heating





effective interferometer phase scan

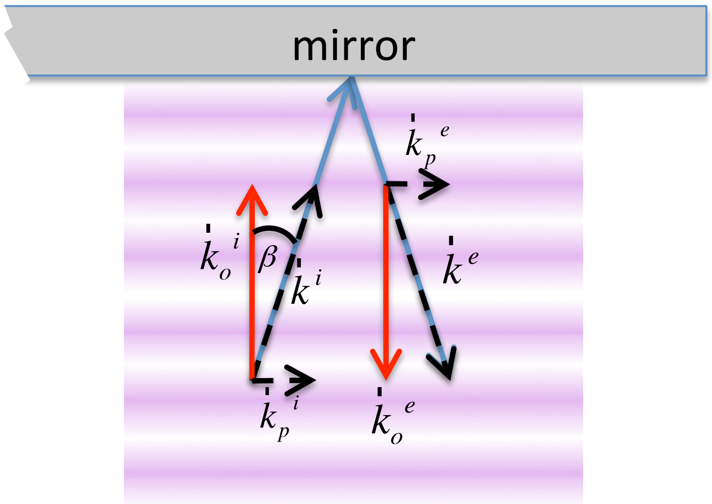
small angle (few mrad) in G2

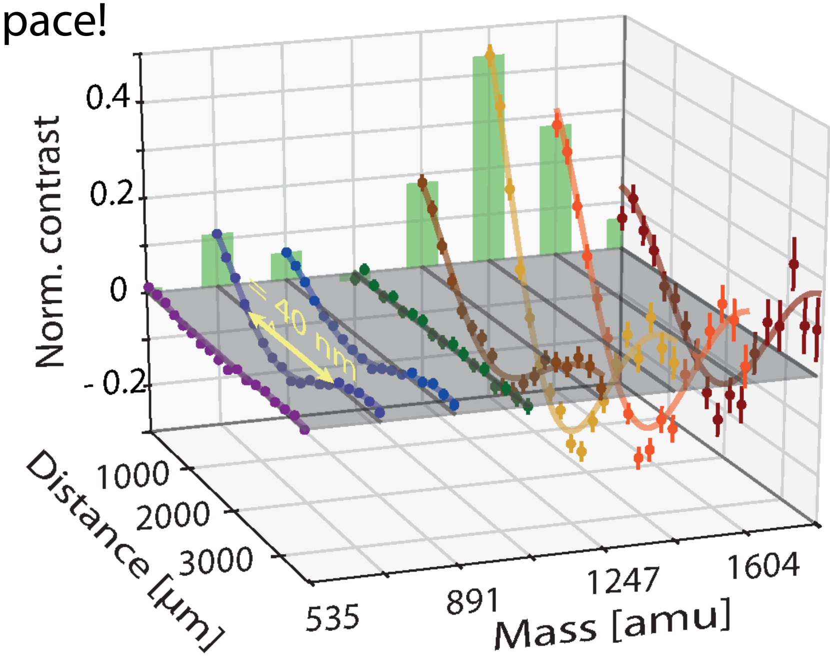
→k-vector orth. to mirror surface smaller, grating period longer, but only few pm

→accumulation of an effective G2-phase over the distance mirror-cluster beam

→scan of this distancecorresponds to phase scan

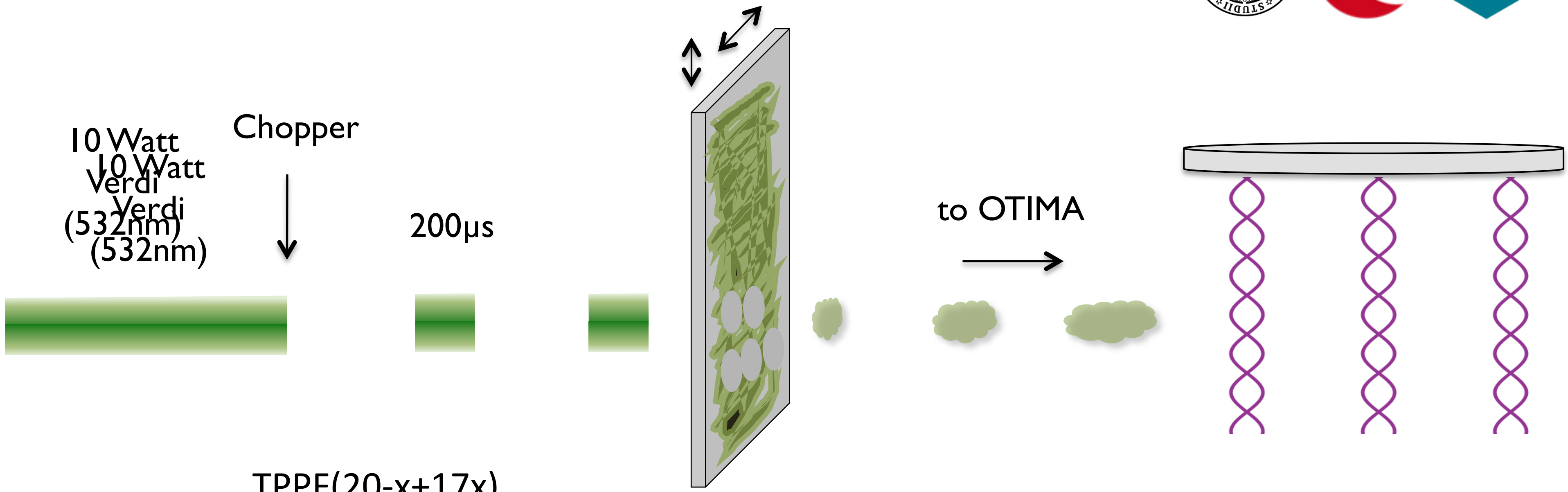
→ mapping of the interference pattern in space!



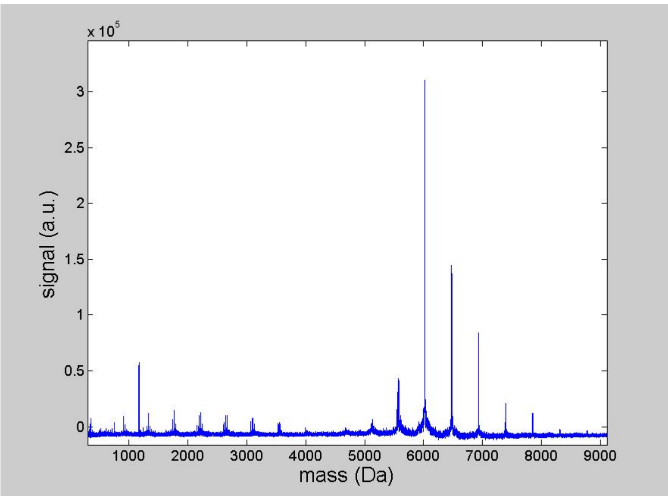


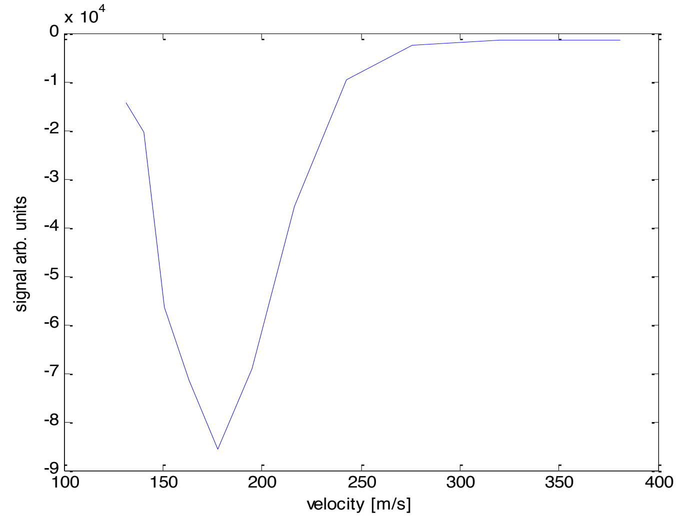
Haslinger et. al. *Nature Physics*, **doi:10.1038/nphys2542** (2013)

work in progress...



TPPF(20-x+17x),





Outlook

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plans for 2013/2014:

- test of novel grating types — e.g. multiphoton gratings, fragmentation gratings
- new particle sources — e.g. Laser heating source, atom source, metal cluster source
- optical alignment of molecules — (e.g. ß-Carotene) during flight through gratings
- time-resolved particle metrology — e.g. measurment of optical polarizability
- absolute absorption spectroscopy — based on a TLI setup (Nimmrichter et. al. 2008)

plans for 2015/2016:

- Slow and/or cool particles (e.g. with buffergas, Ionoptics)
  - → increase of the interfering mass
  - → test of Quantum mechancics new mass/complexity scales

...and other clusters!

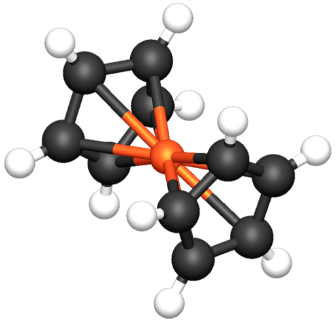
clusters of the following molecules have interfered in the OTIMA recently:

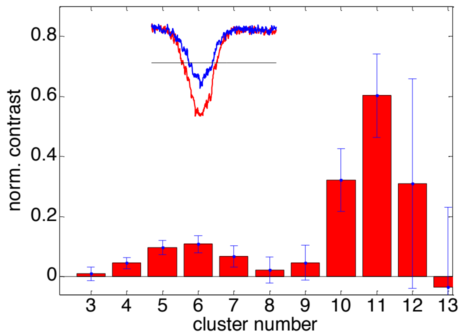
ferrocene

$Fe(C_5H_5)_2$

m = 186 amu

1973

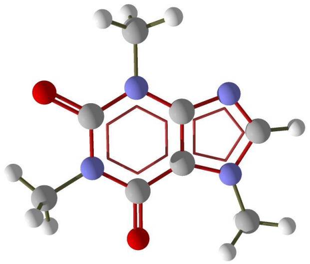


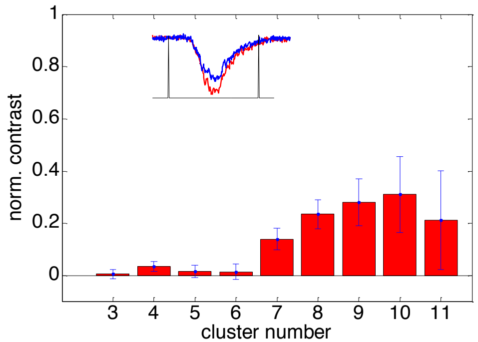


coffein

$C_8H_{10}N_4O_2$

m = 194 amu

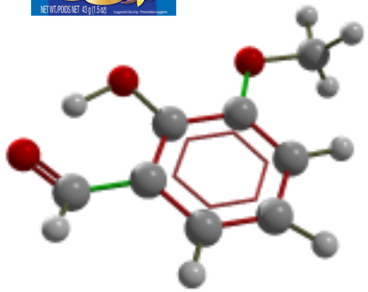


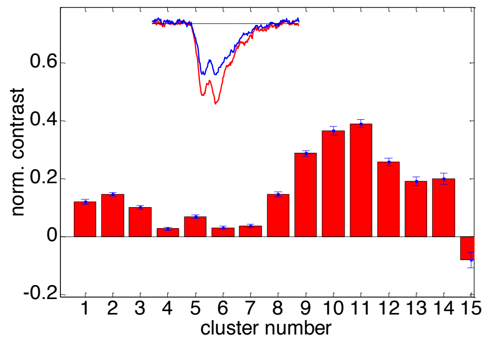


vanillin

$C_8H_8O_3$

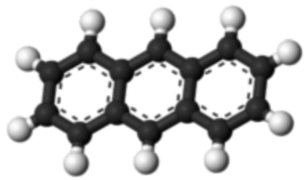
m = 152 amu

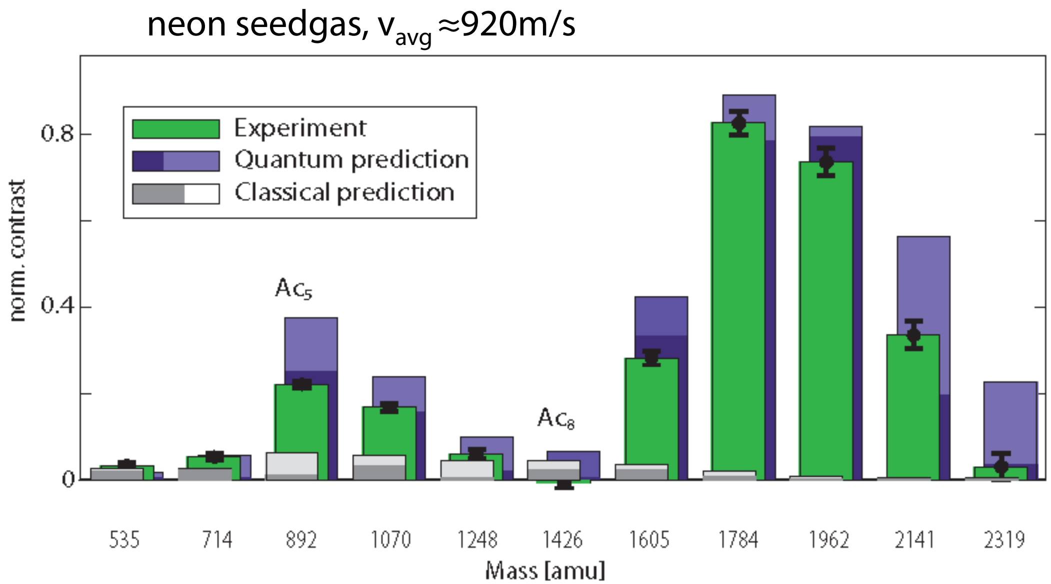


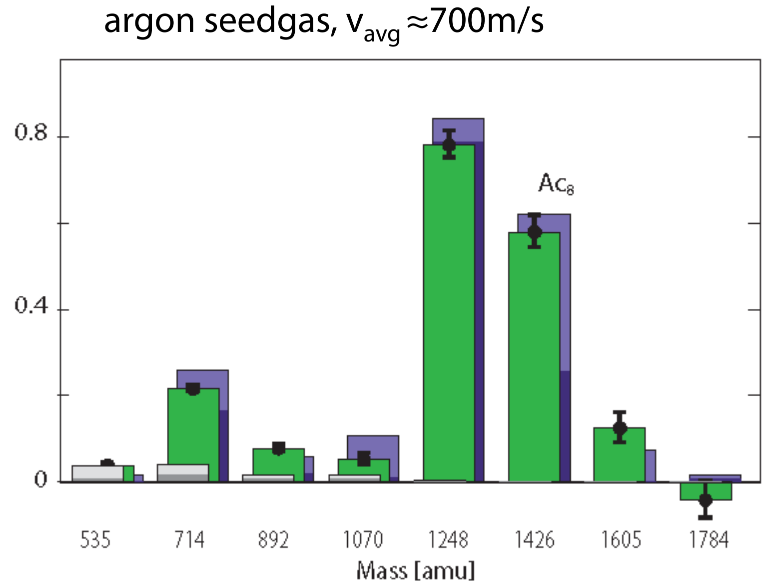


Interference of anthracene clusters: theory

$C_{14}H_{10}$
m = 178 amu







- good agreement of the data with quantum mechanics
- resulting uncertainty (light purple areas) due to insufficiently well known particle properties
- strong deviation from the classical expectation

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effective interferometer phase scan

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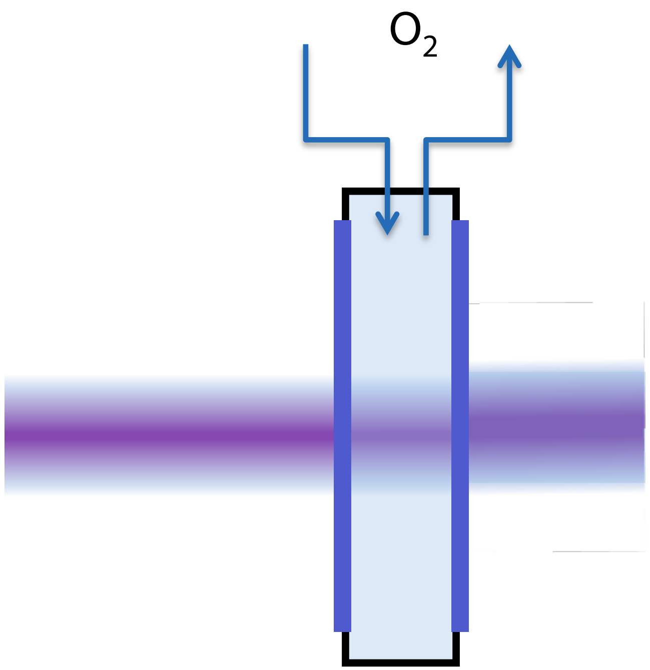

Summary

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-cluster interference in the time-domain

-versatile ionization gratings

-favorable mass scalability

→new interferometer well suited for

high contrast quantum experiments with large range of massive particles

thanks for your attention!

special thanks to

Markus Arndt
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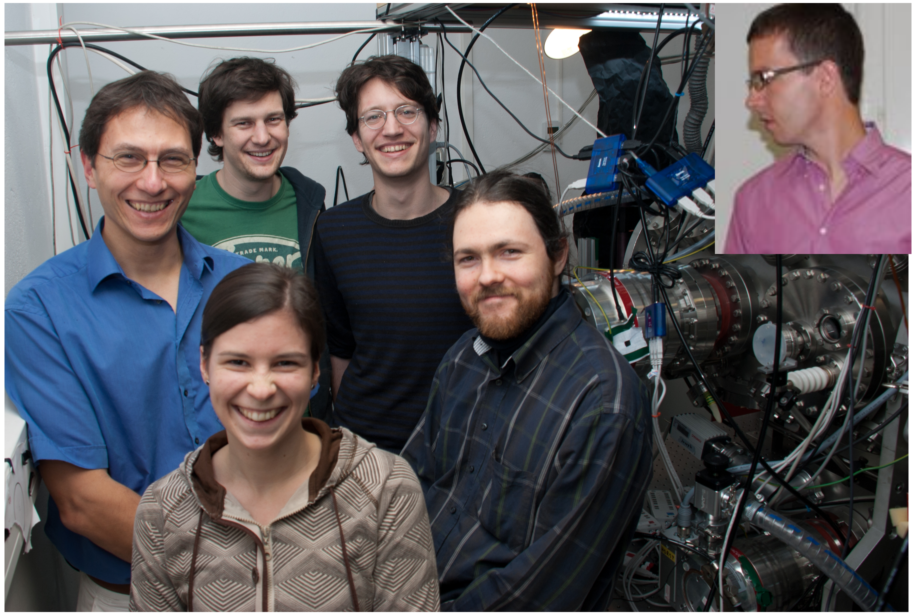
Philipp Geyer
Stefan Nimmrichter (Theory)



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FWF