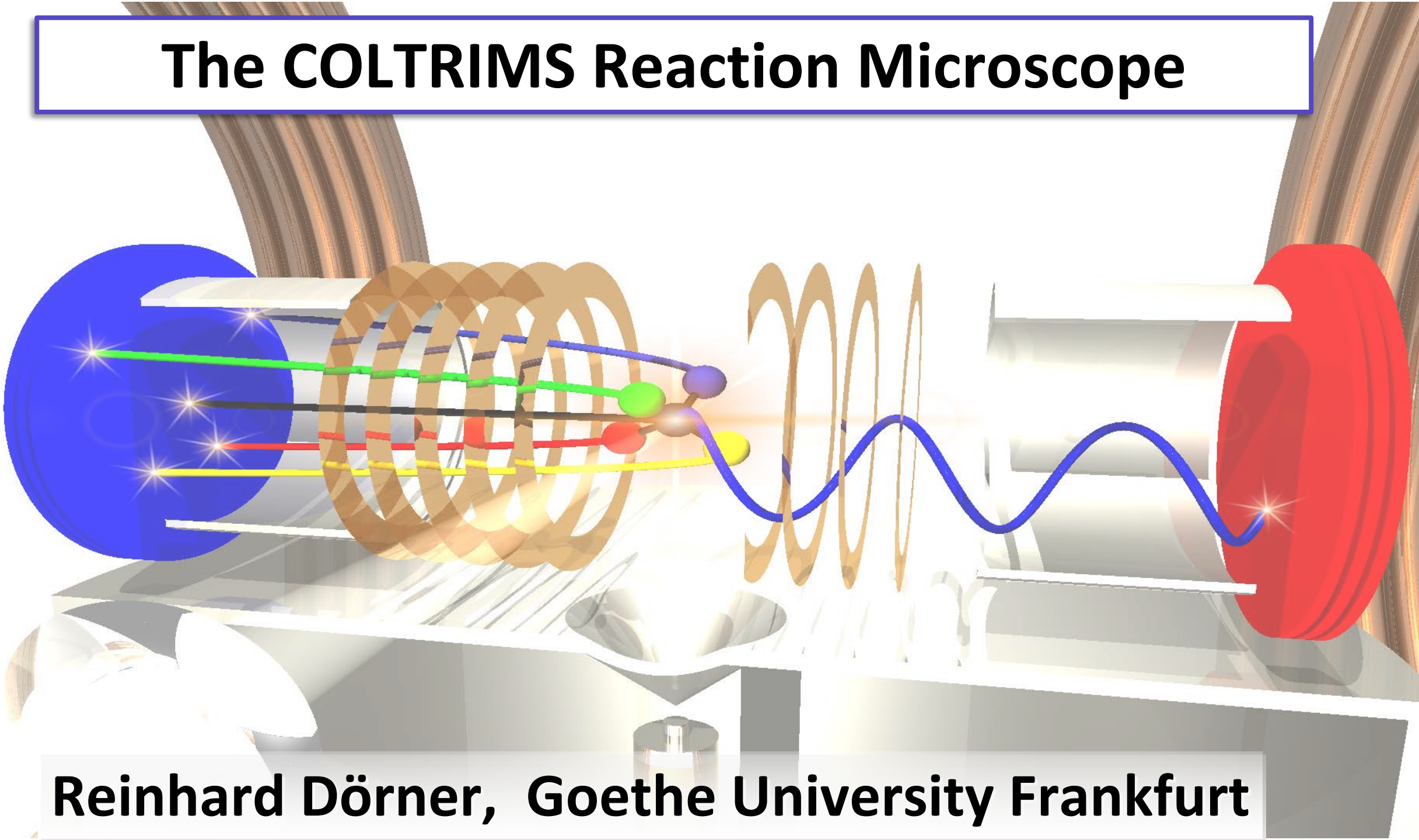
The COLTRIMS Reaction Microscope

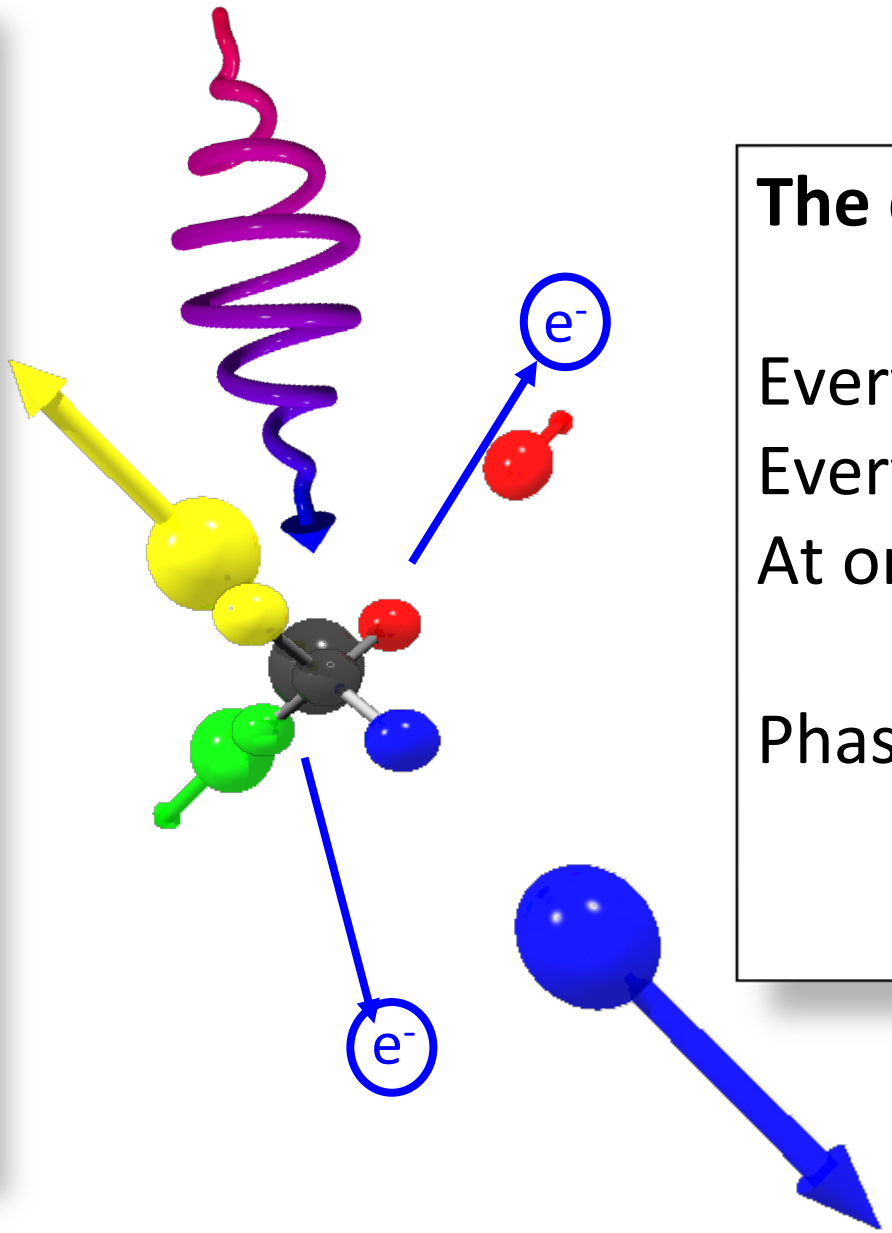


Reinhard Dörner, Goethe University Frankfurt

Quantum Challenge:

$$\Psi\left(\overrightarrow{R_i}, \overrightarrow{r_j}, t\right)$$

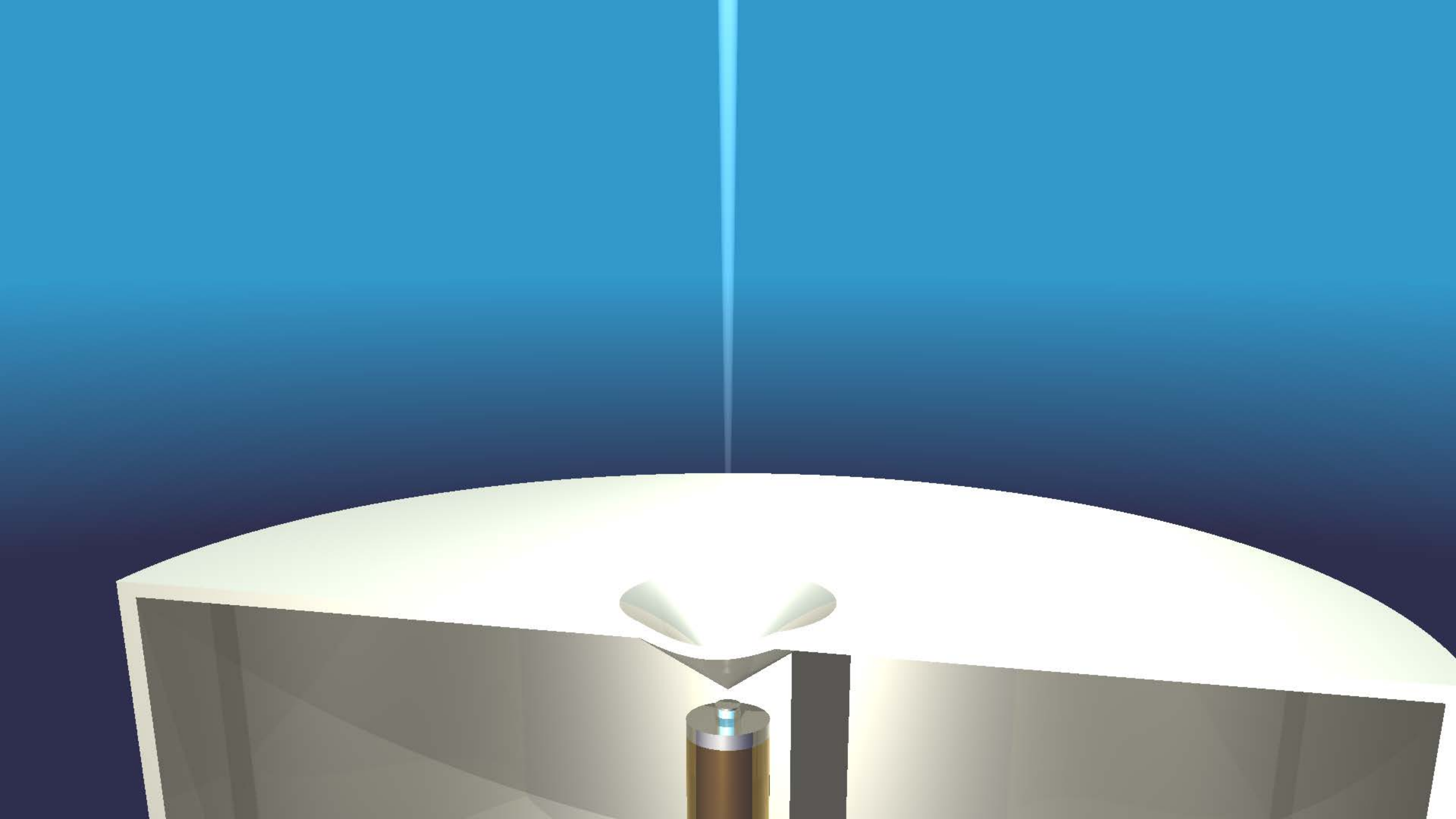
- Superposition Principle (Interferences)
- Entanglement
- Quantum delocalization
- Ultrafast time scales

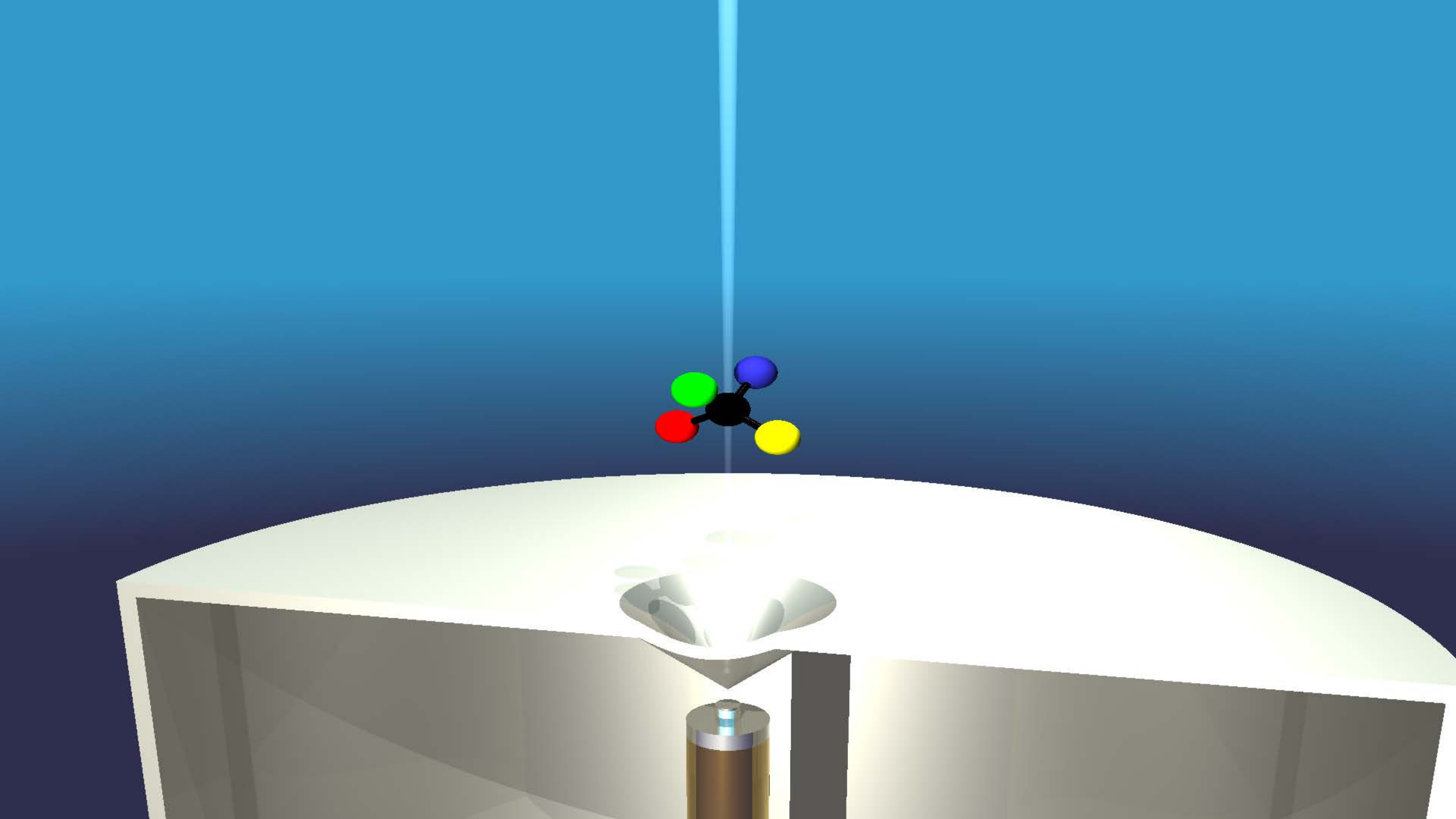


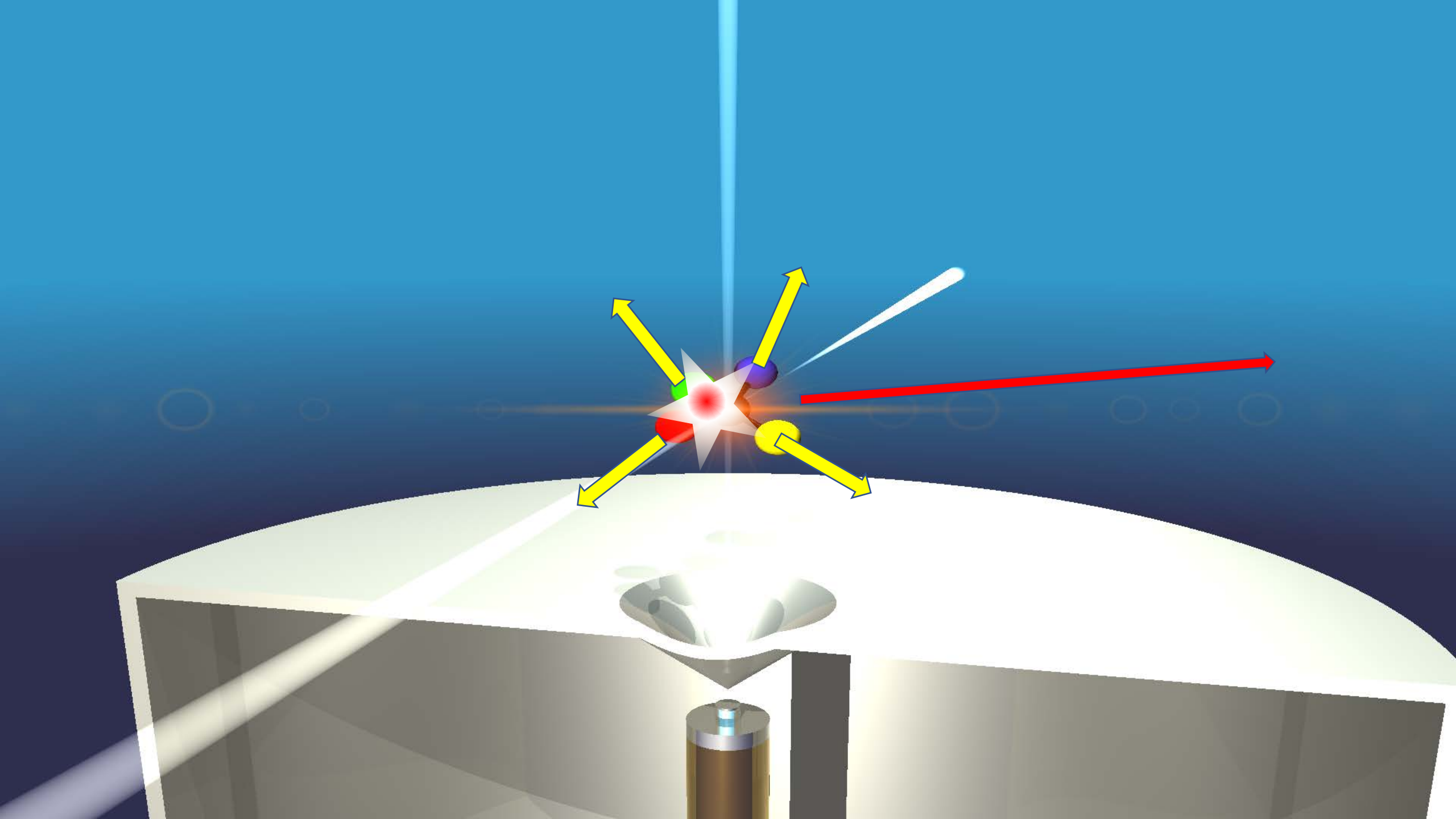
The detection challenge

Everything (e^-,ions)
Everyhwere (4π)
At once (coincidence)

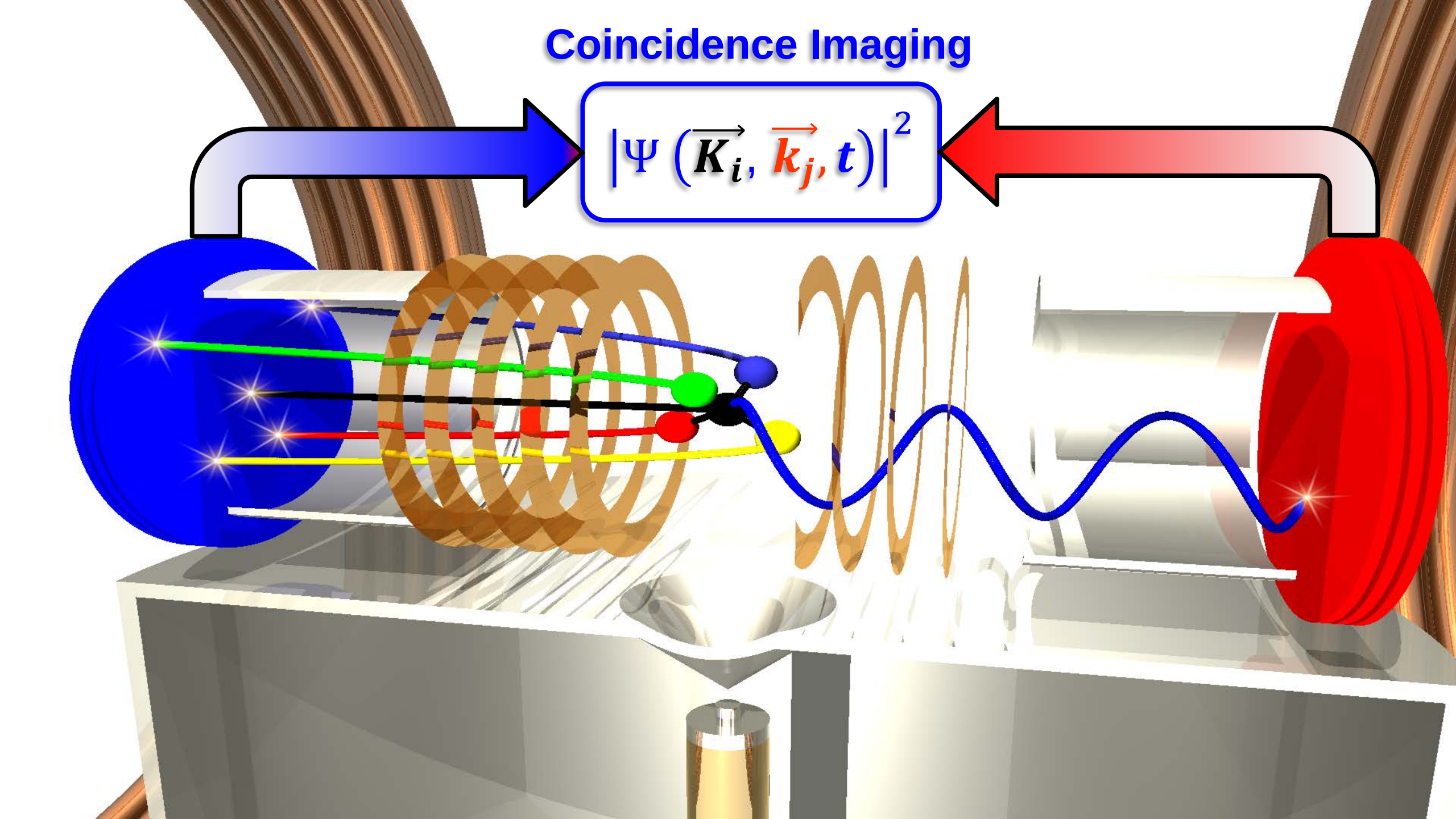
Phases





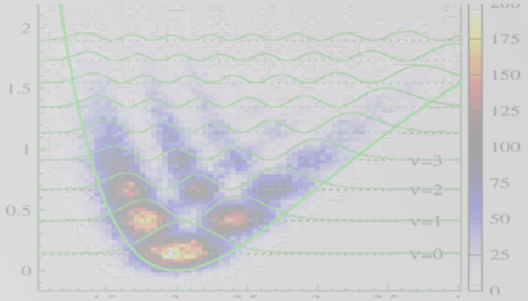


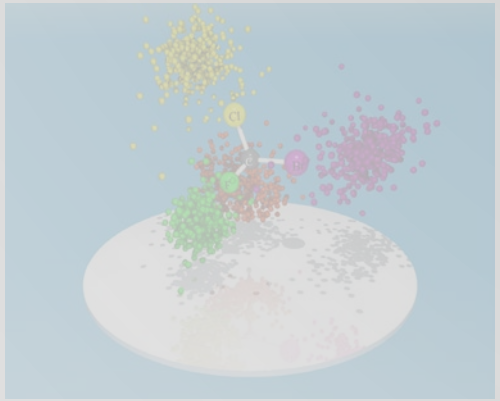
Coincidence Imaging

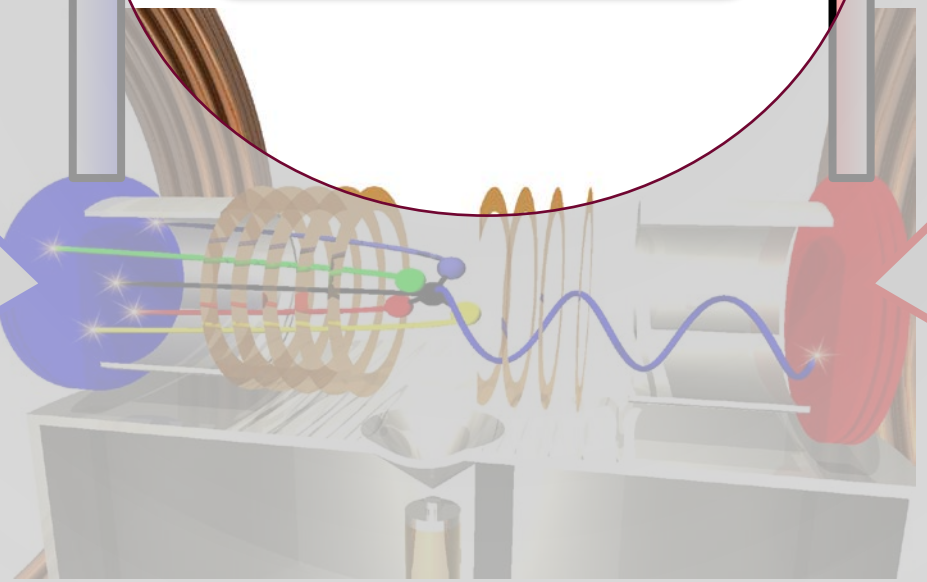


$$|\Psi(\vec{R_i}, \vec{r_j}, t)|^2$$

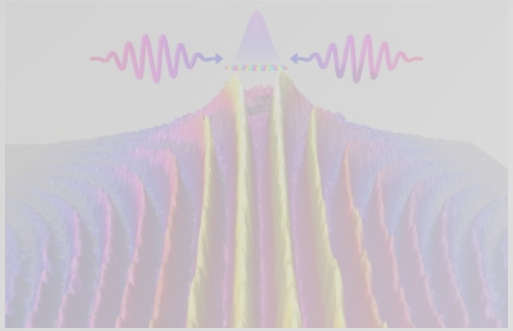
Coulomb Explosion Imaging

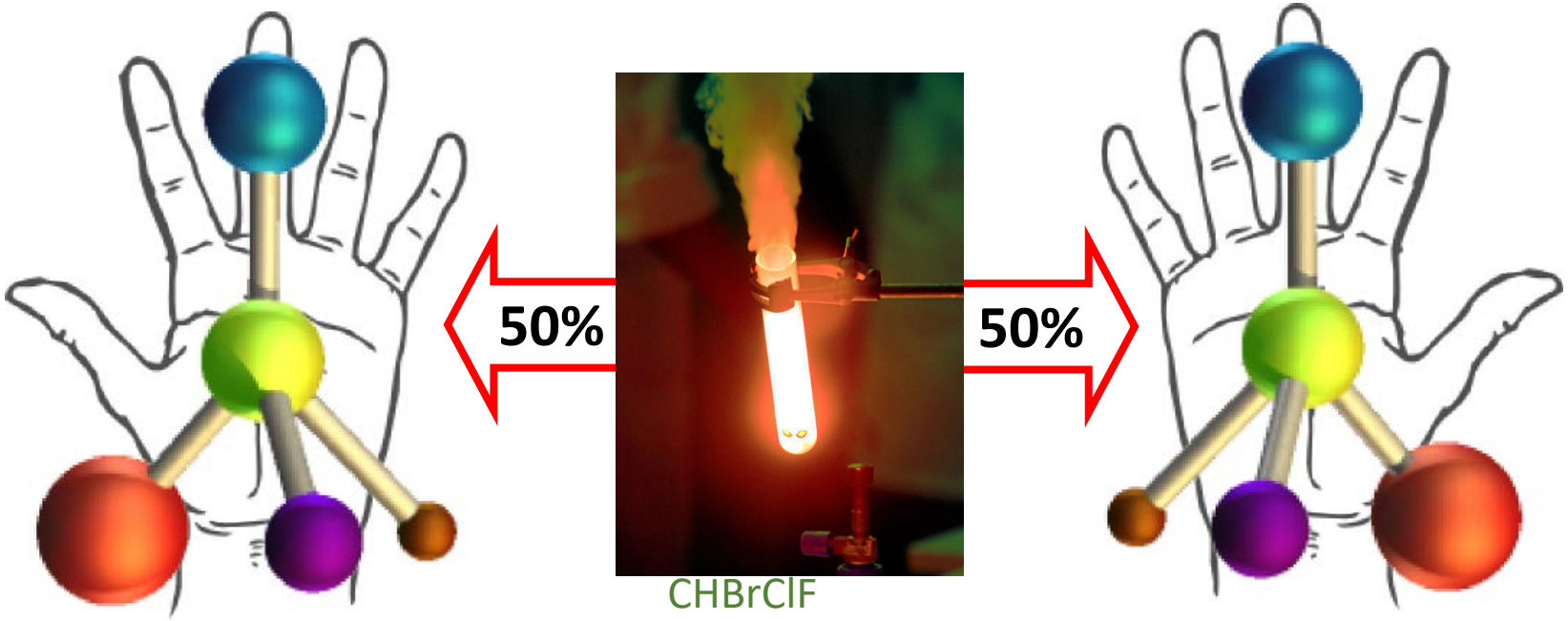


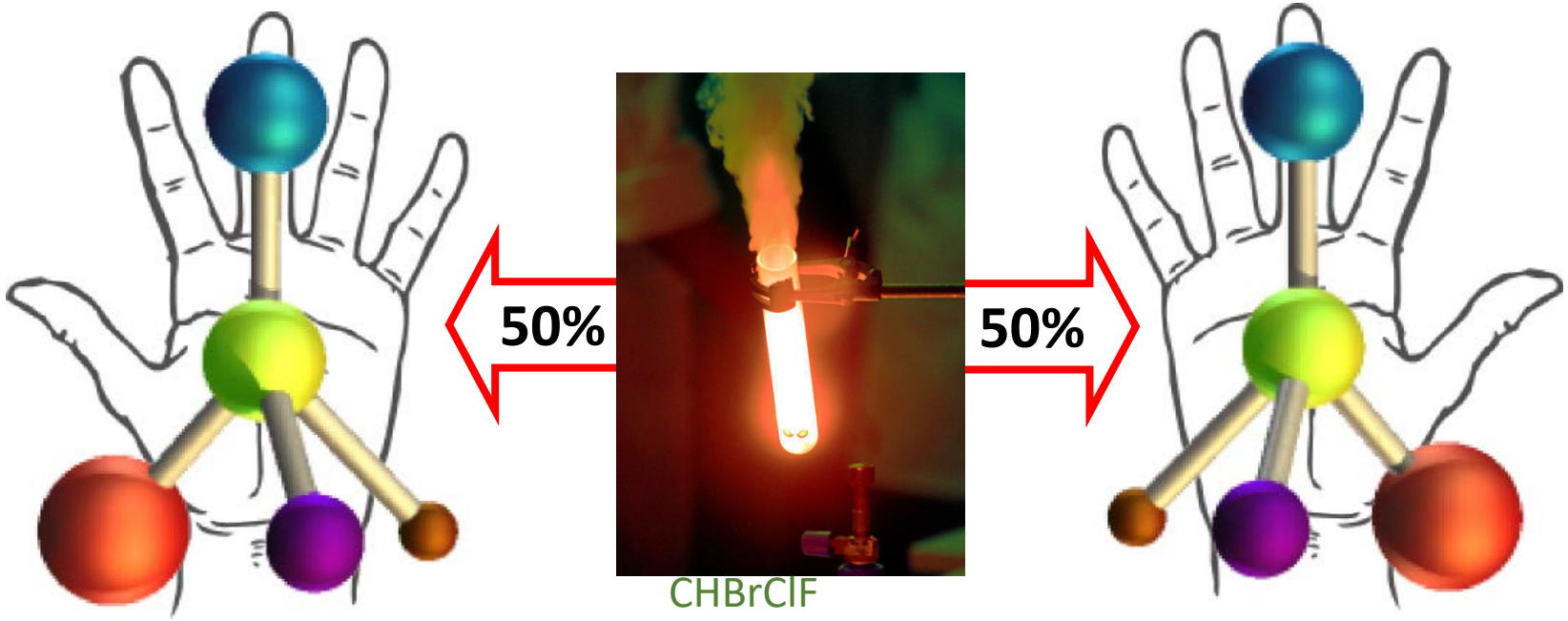




- Zeptoseconds
- Entanglement
- Ultrafast Kapitza Dirac Effect

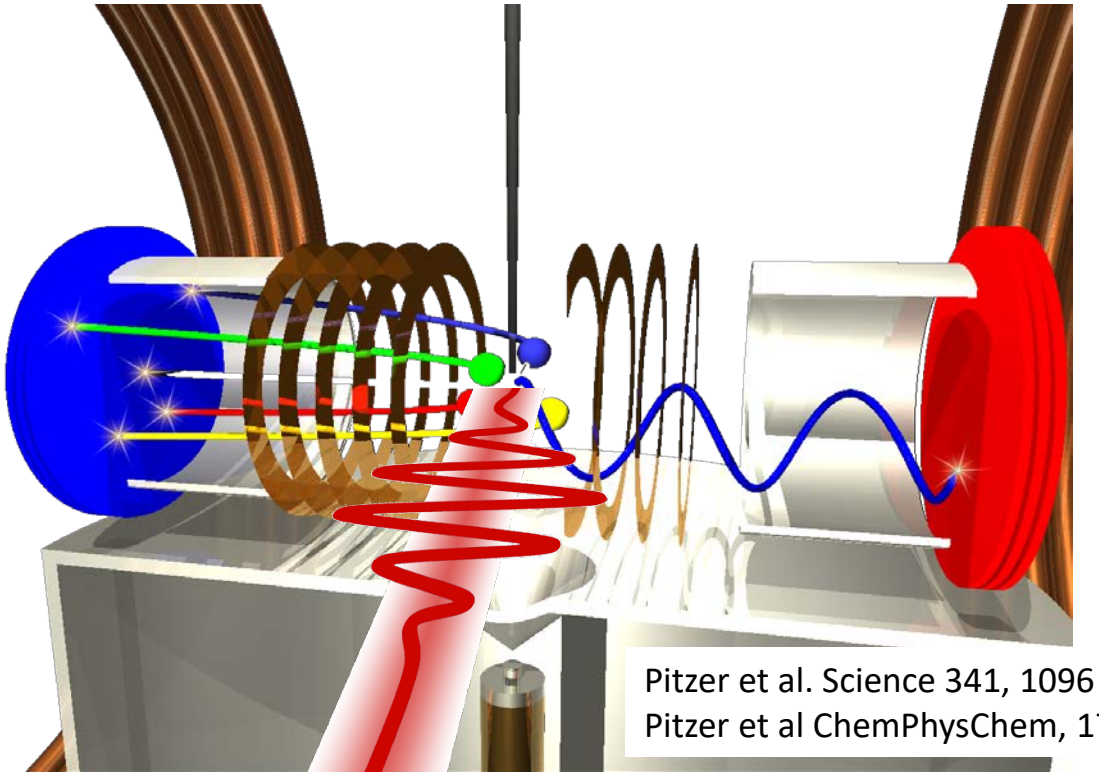



50%
50%
CHBrClF

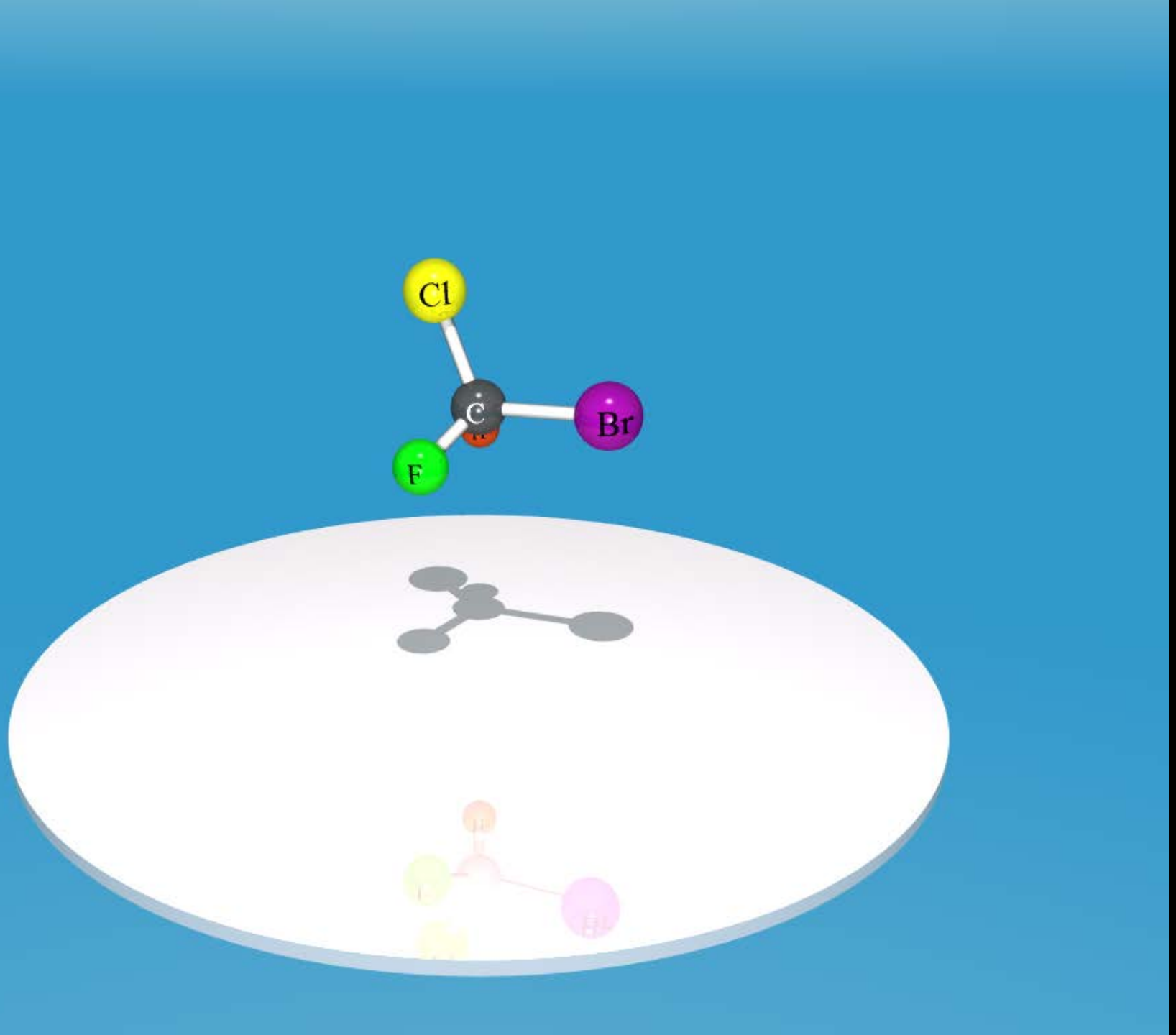


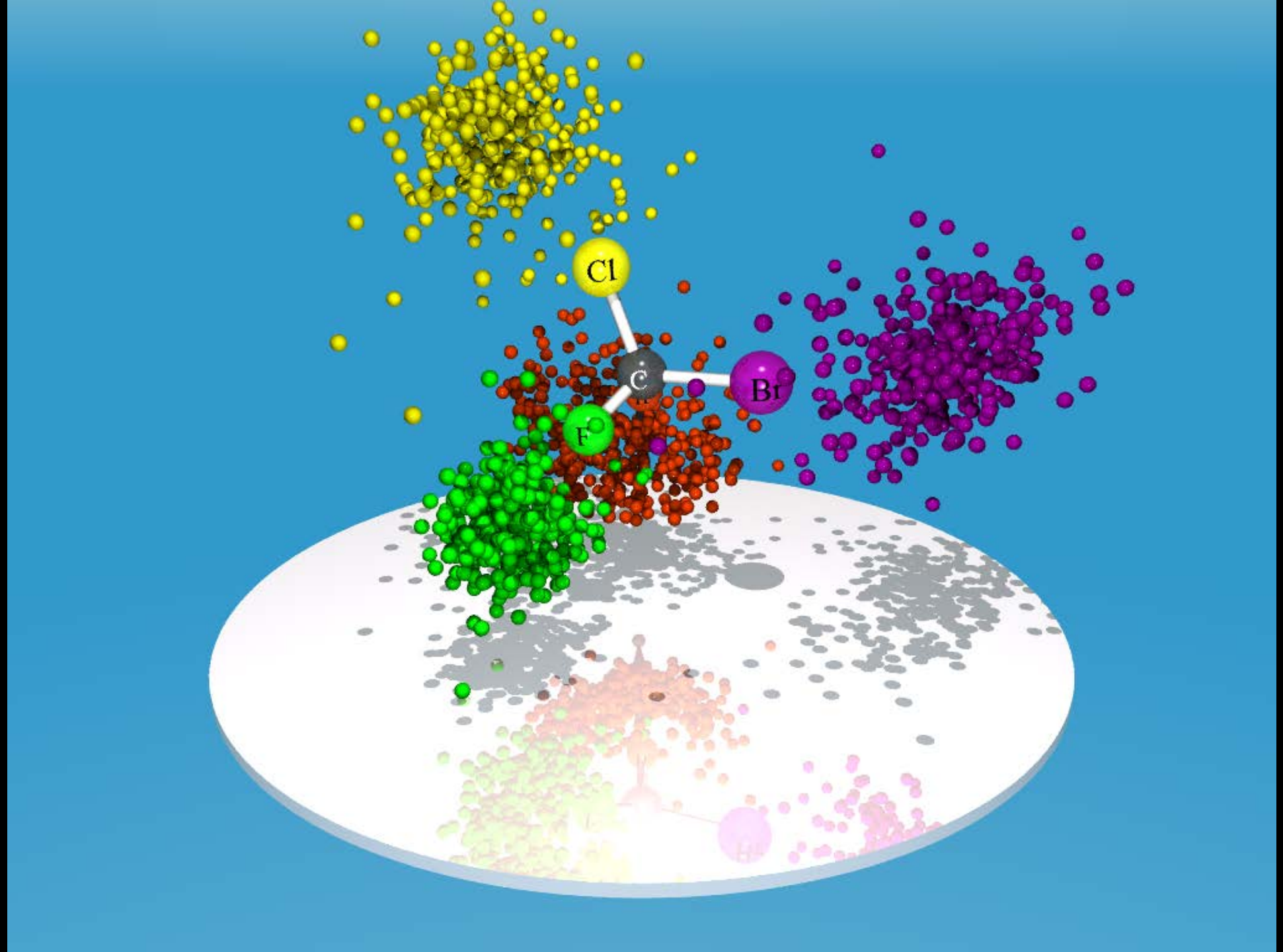
CHBrClF

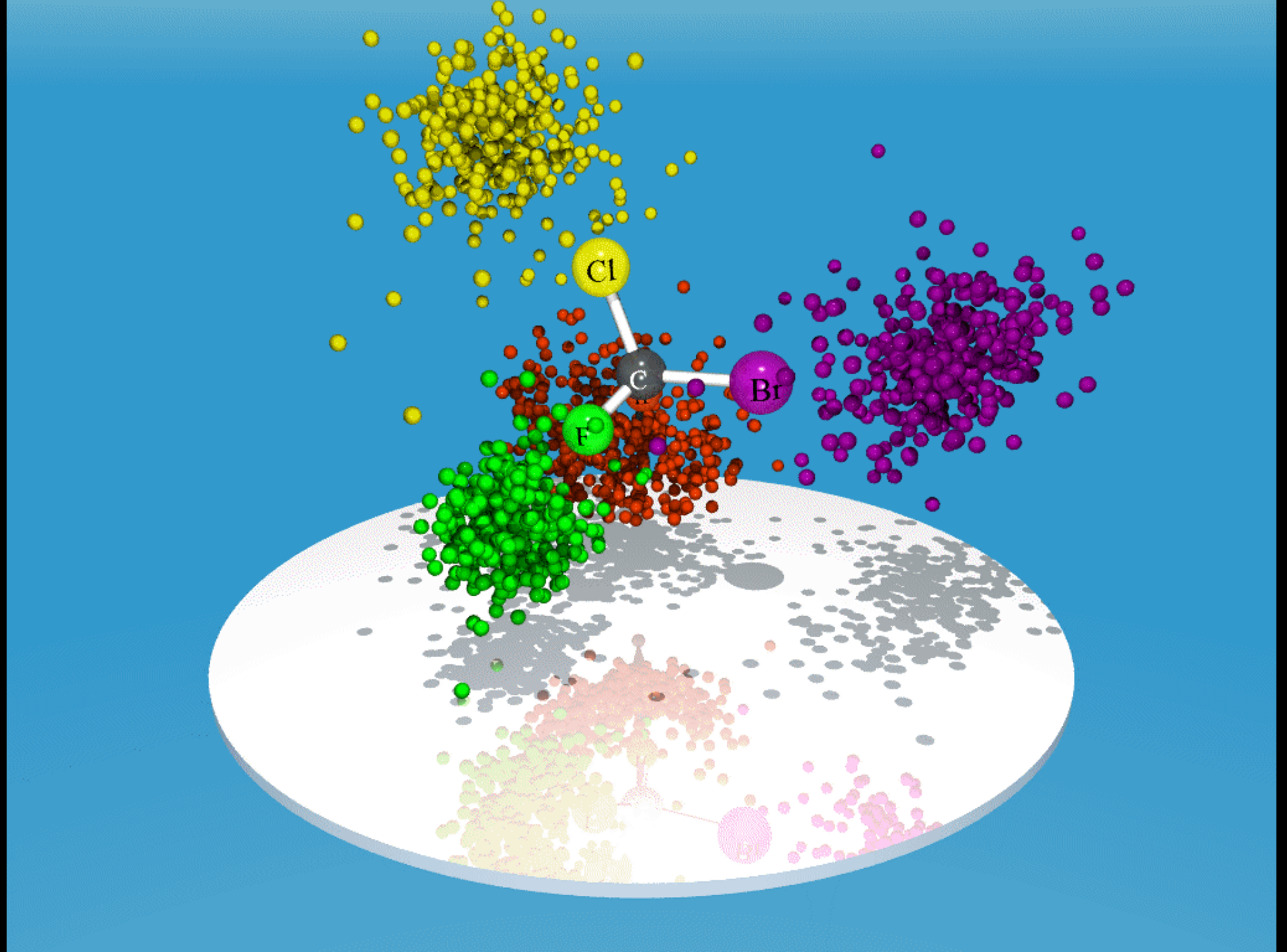
Martin Pitzer

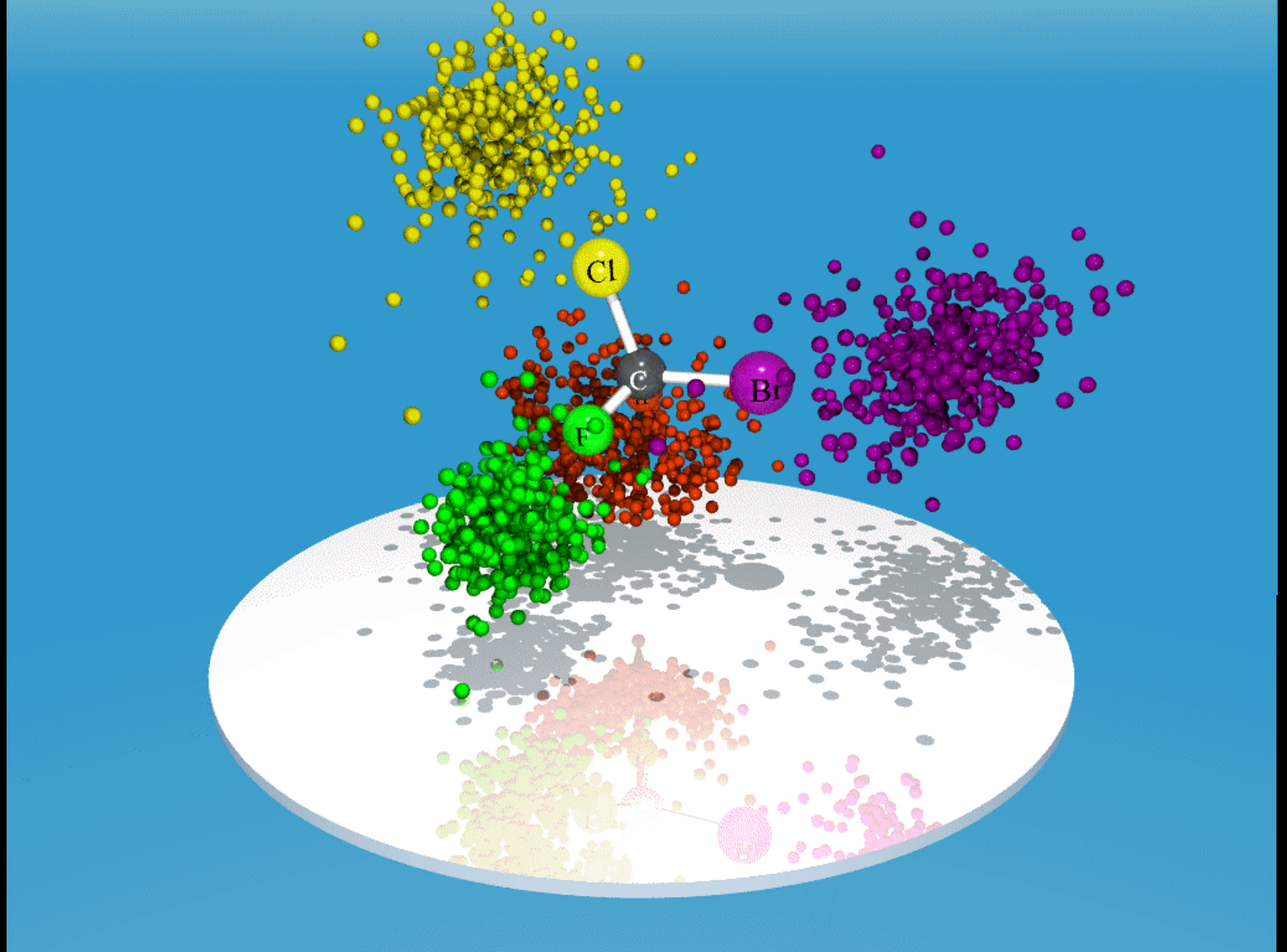


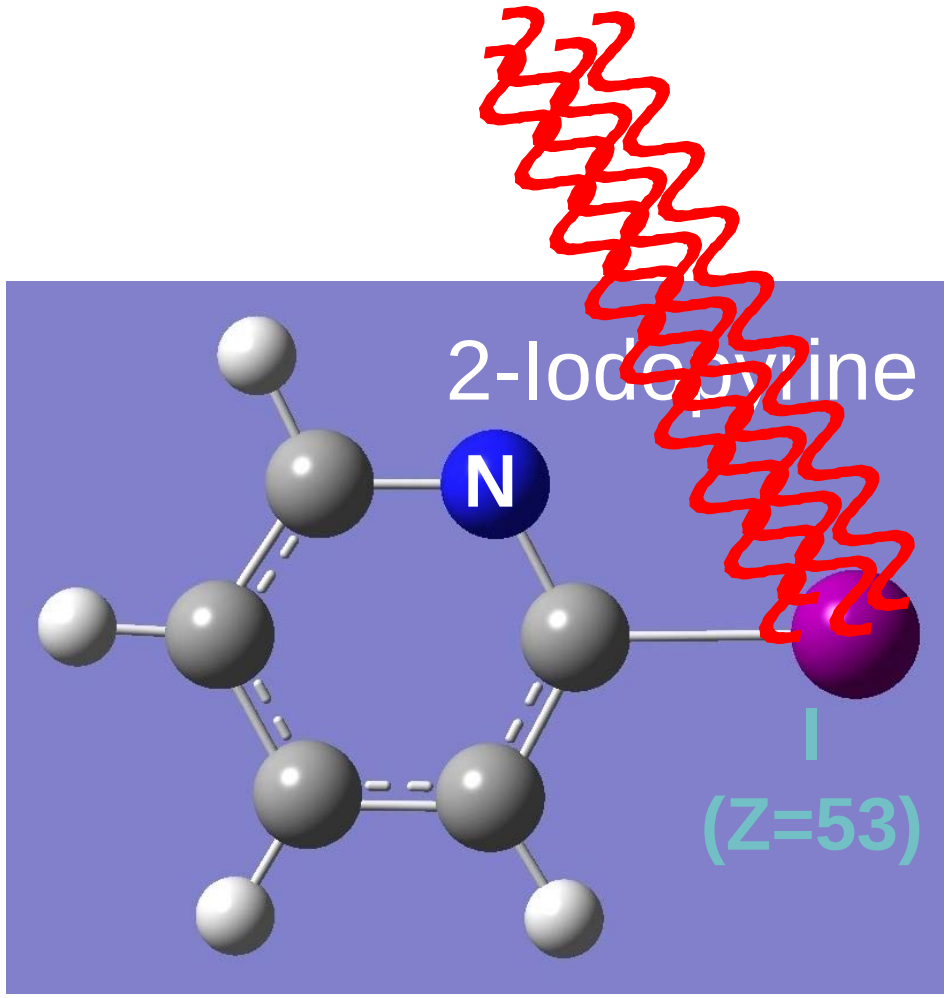
Pitzer et al. Science 341, 1096 (2013)
Pitzer et al ChemPhysChem, 17, 2465 (2016)


Cl
C
Br
F

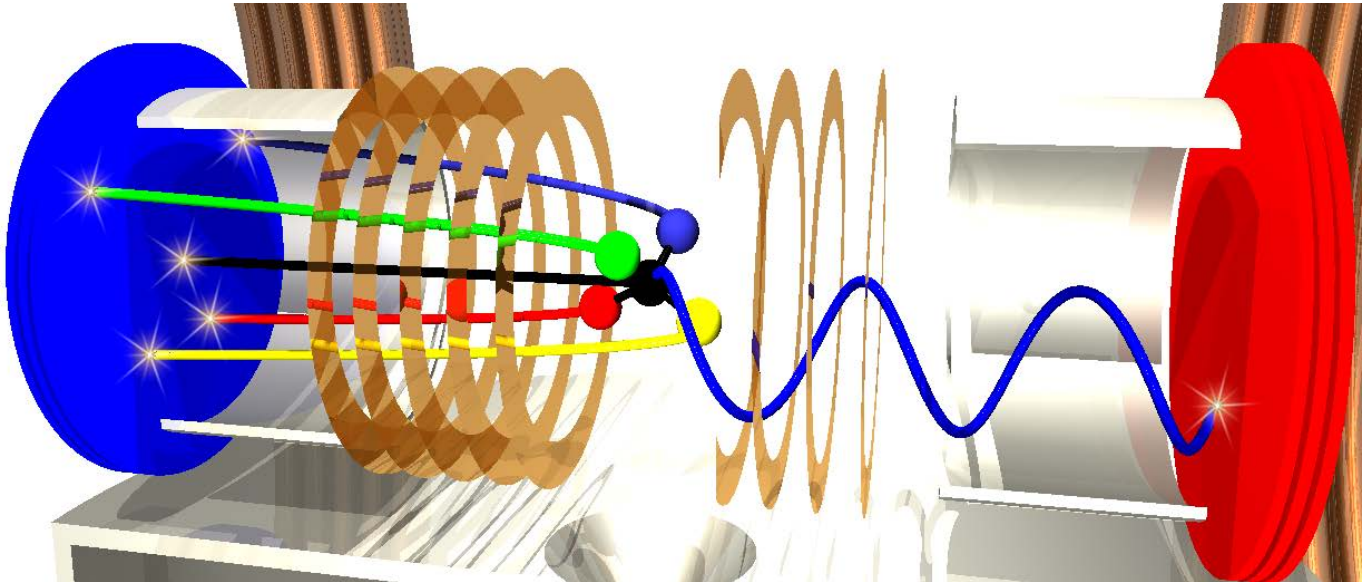

Cl
C
Br
F


Cl
C
Br
F


Cl
C
Br
F

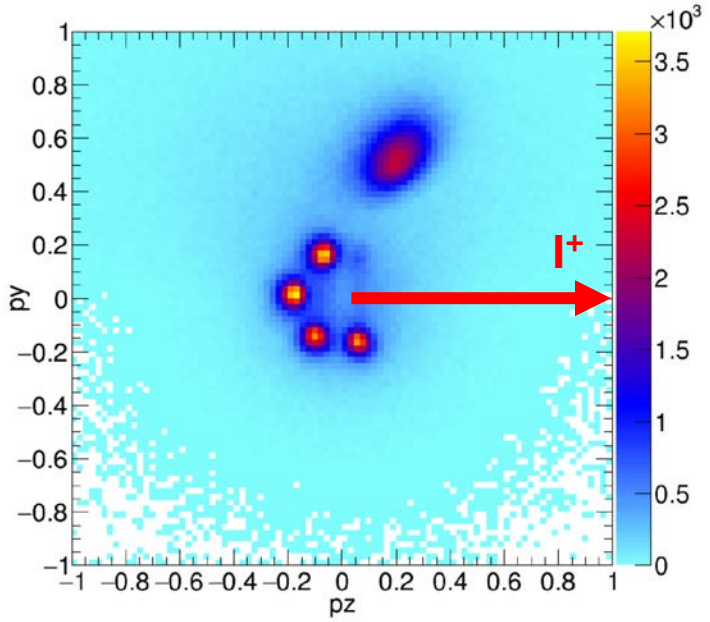


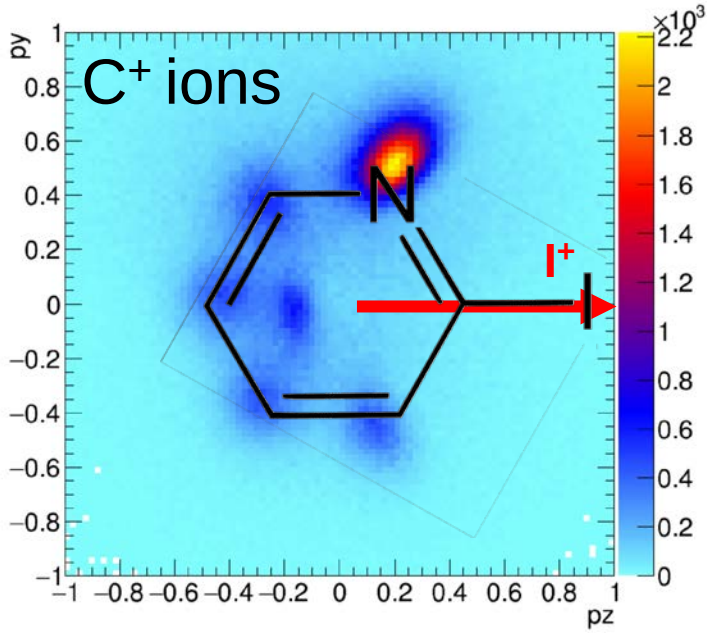
$$\Psi\left(\vec{R}_i, \vec{r}_j, t\right)$$



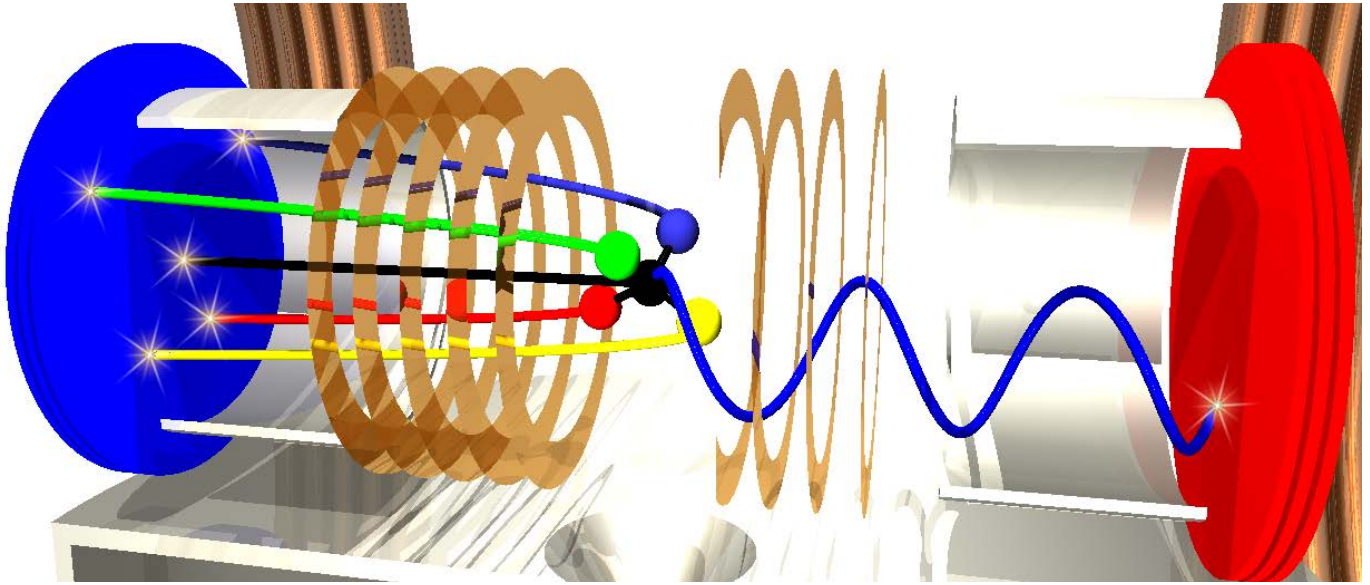
Nature Physics 18, 423–428 (2022)
Rebecca Boll, …. Till Jahnke

H^+ ions in the I^+ / N^+ frame



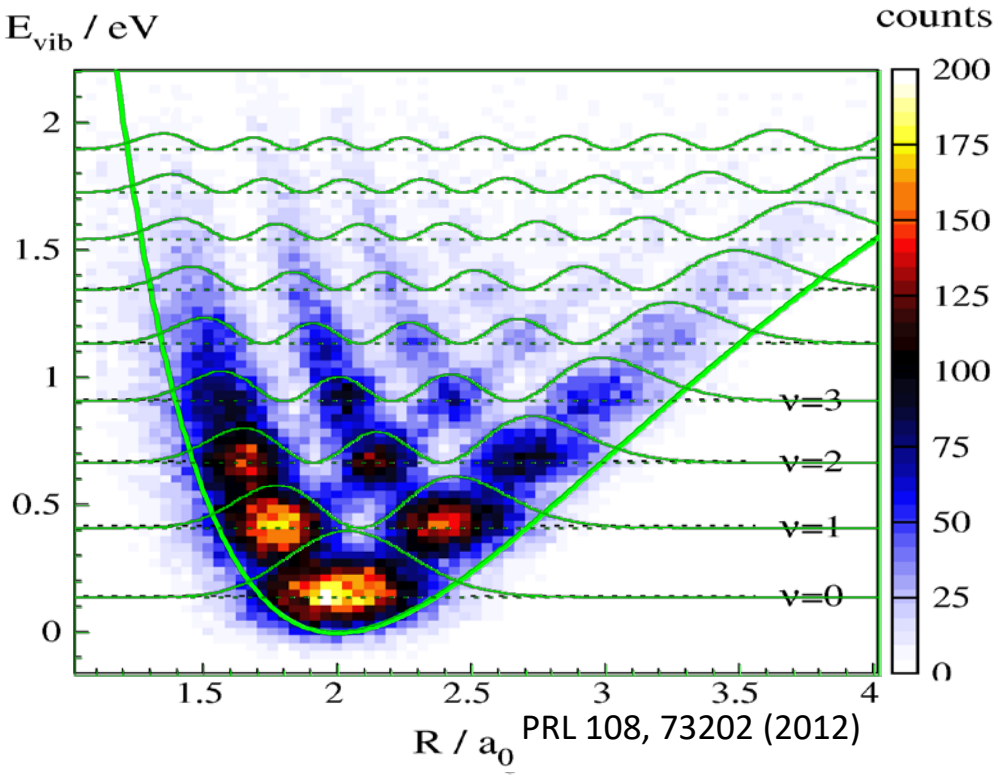


$$\Psi\left(\overrightarrow{R_i}, \overrightarrow{r_j}, t\right)$$



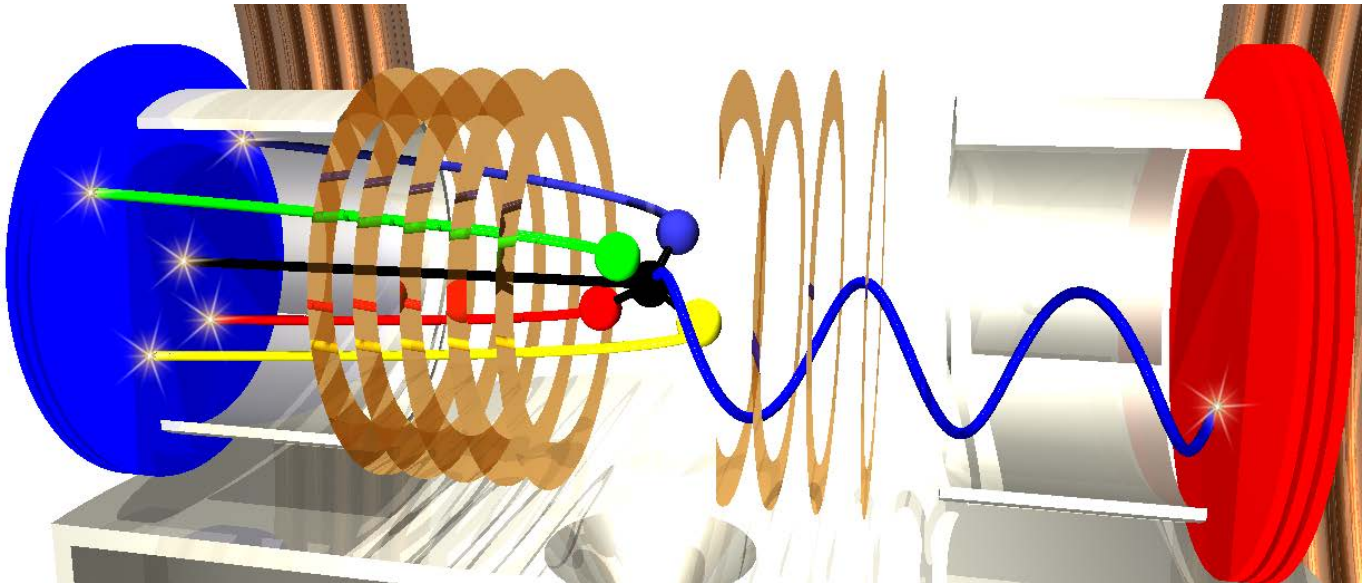
Nature Physics 18, 423–428 (2022)
Rebecca Boll, …. Till Jahnke

H_2^+



PRL 108, 73202 (2012)

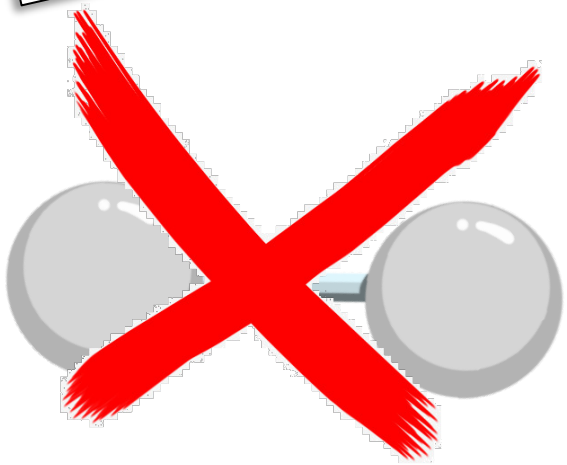
$$\Psi\left(\vec{R}_i, \vec{r}_j, t\right)$$



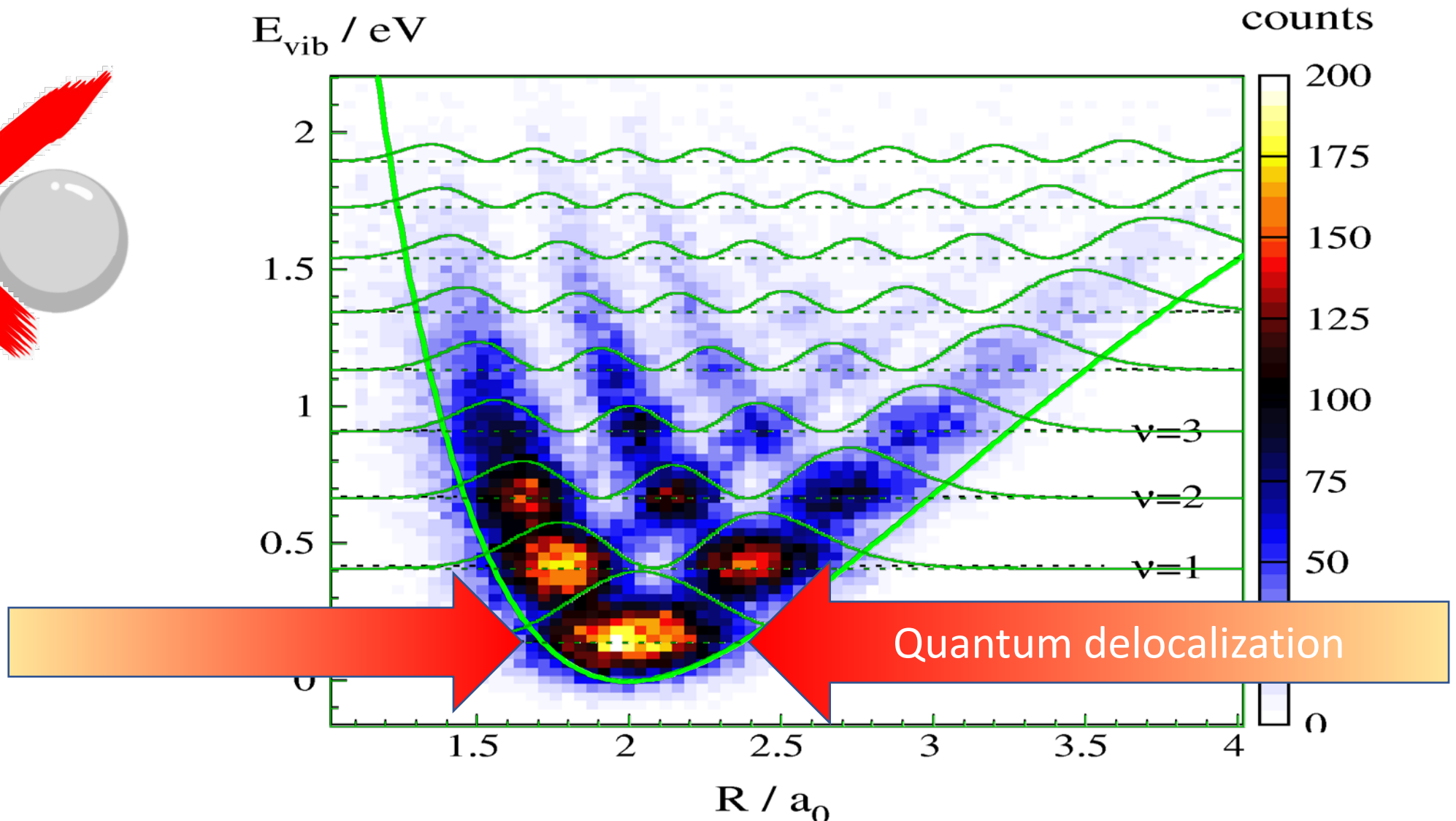
„Spatial Imaging at the quantum limit“
L. Schmidt et al
PRL 108, 73202 (2012)

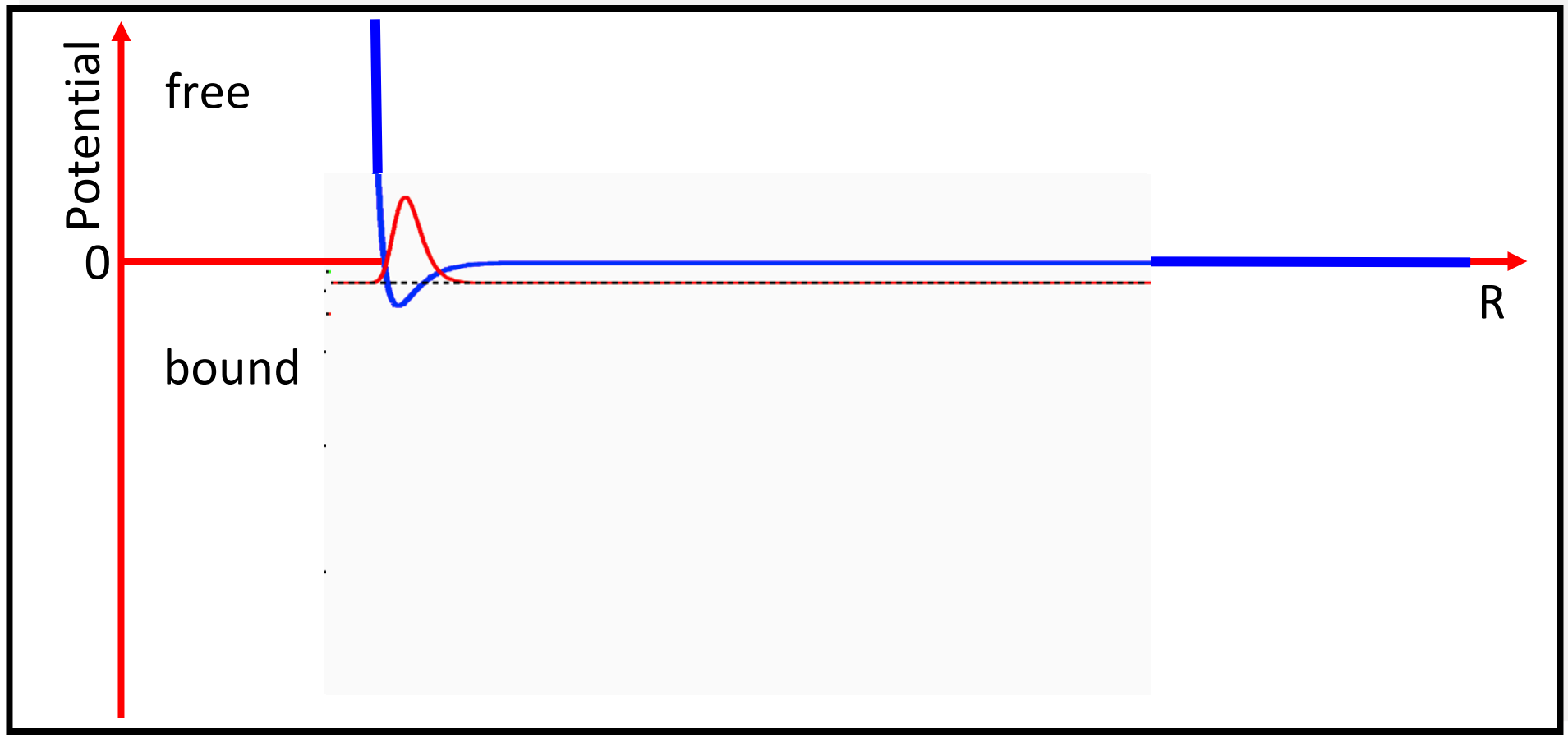
Lothar Schmidt

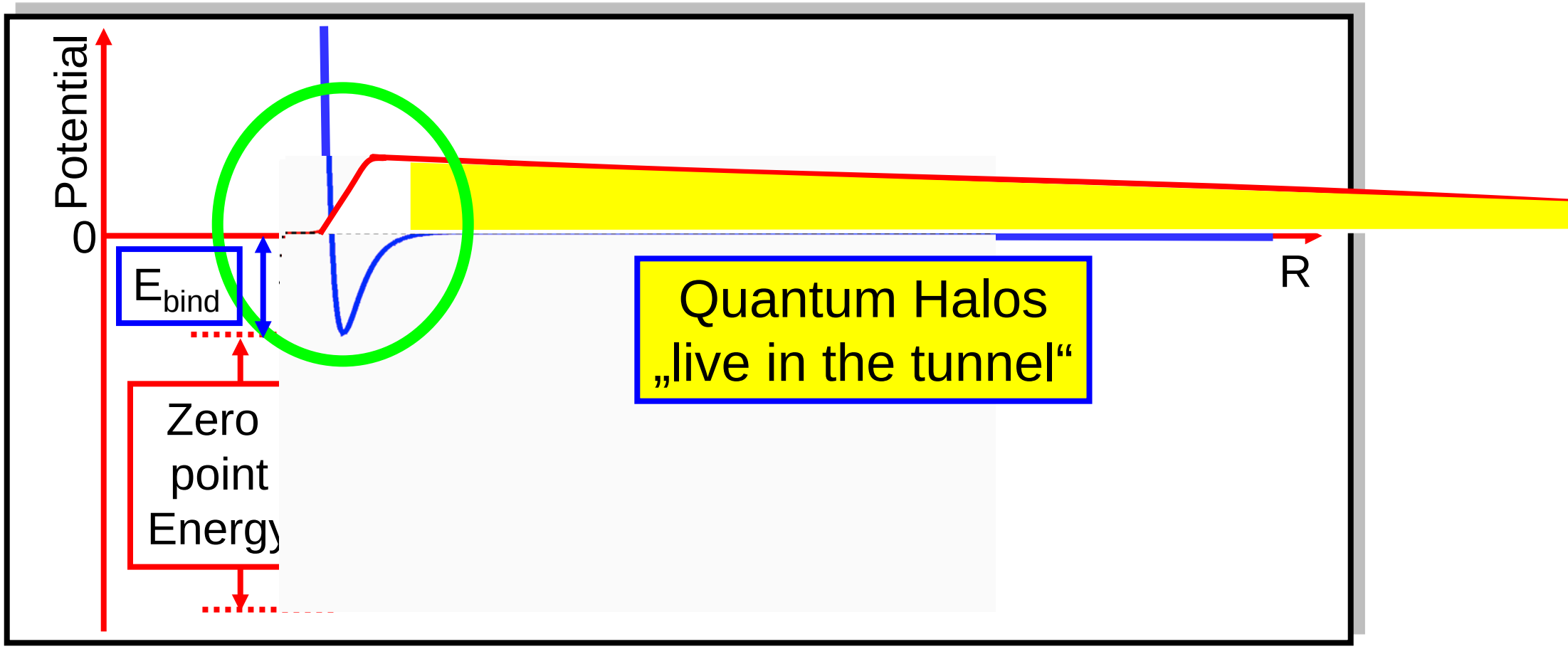
Quantum Challenge:
1. Delocalization

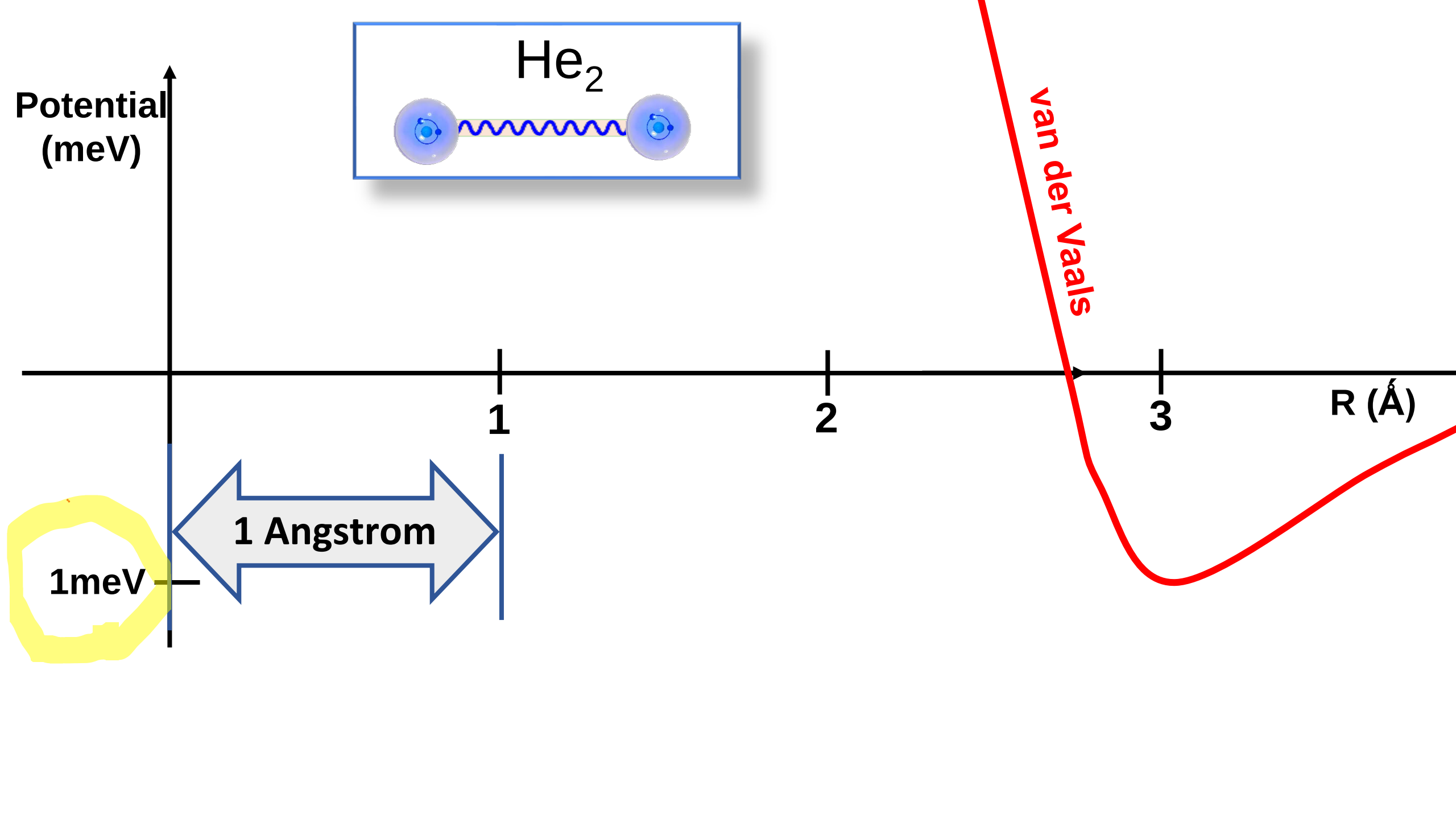


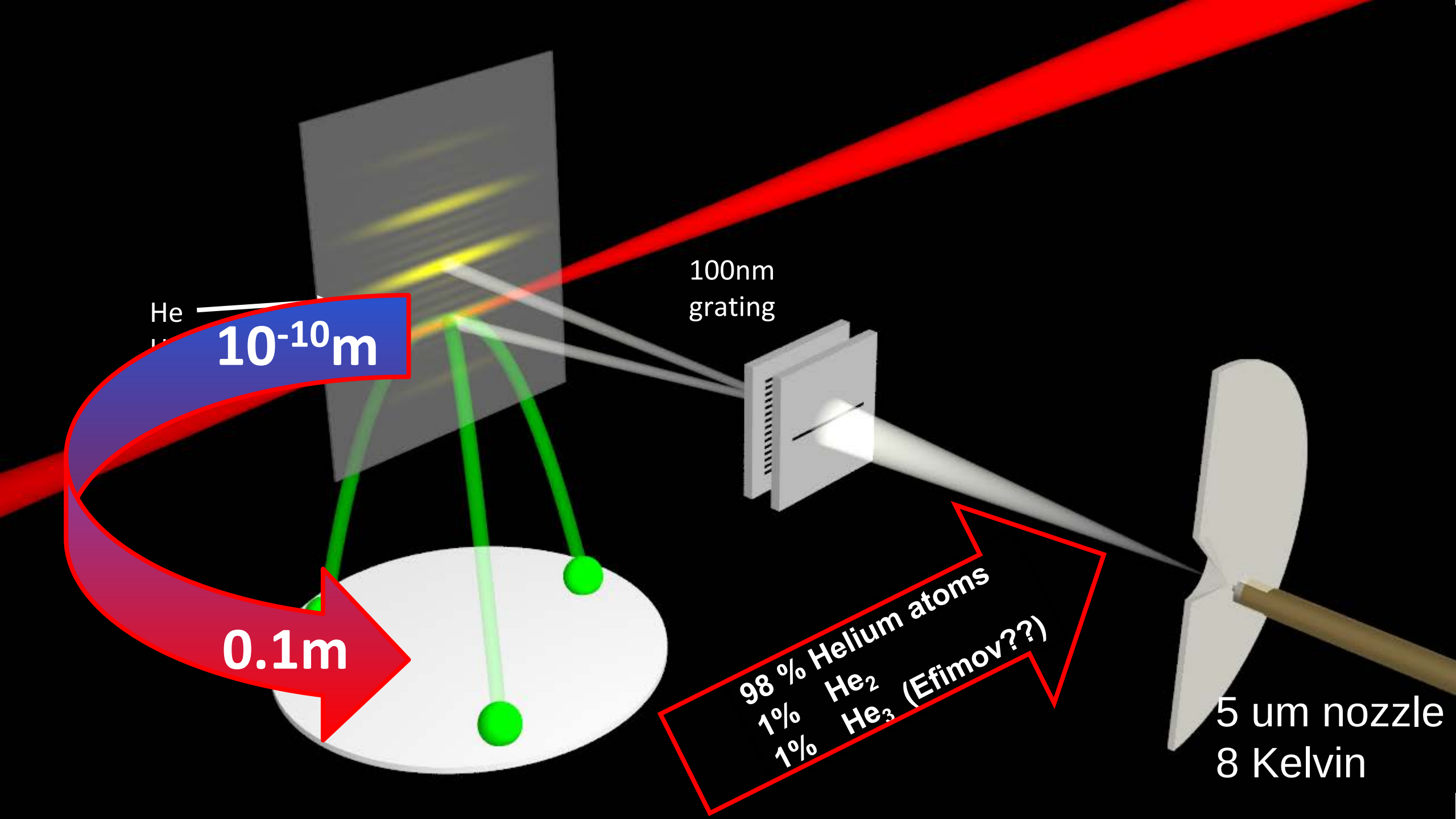
$$\Psi\left(\overrightarrow{R_i}, \overrightarrow{r_j}, t\right)$$

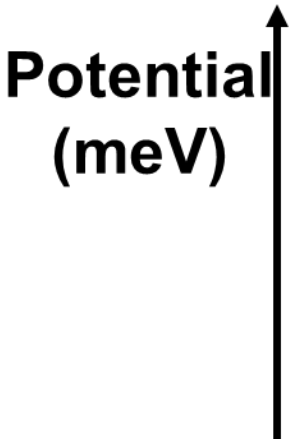


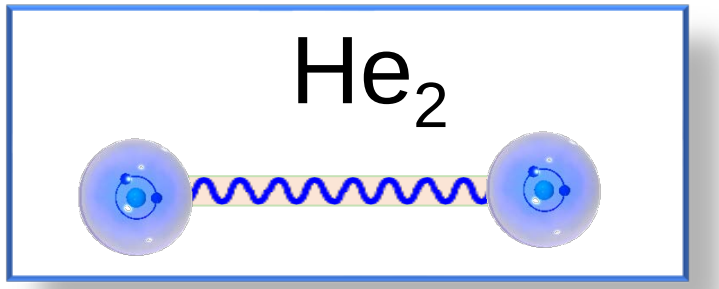

Potential
free
0
bound
R

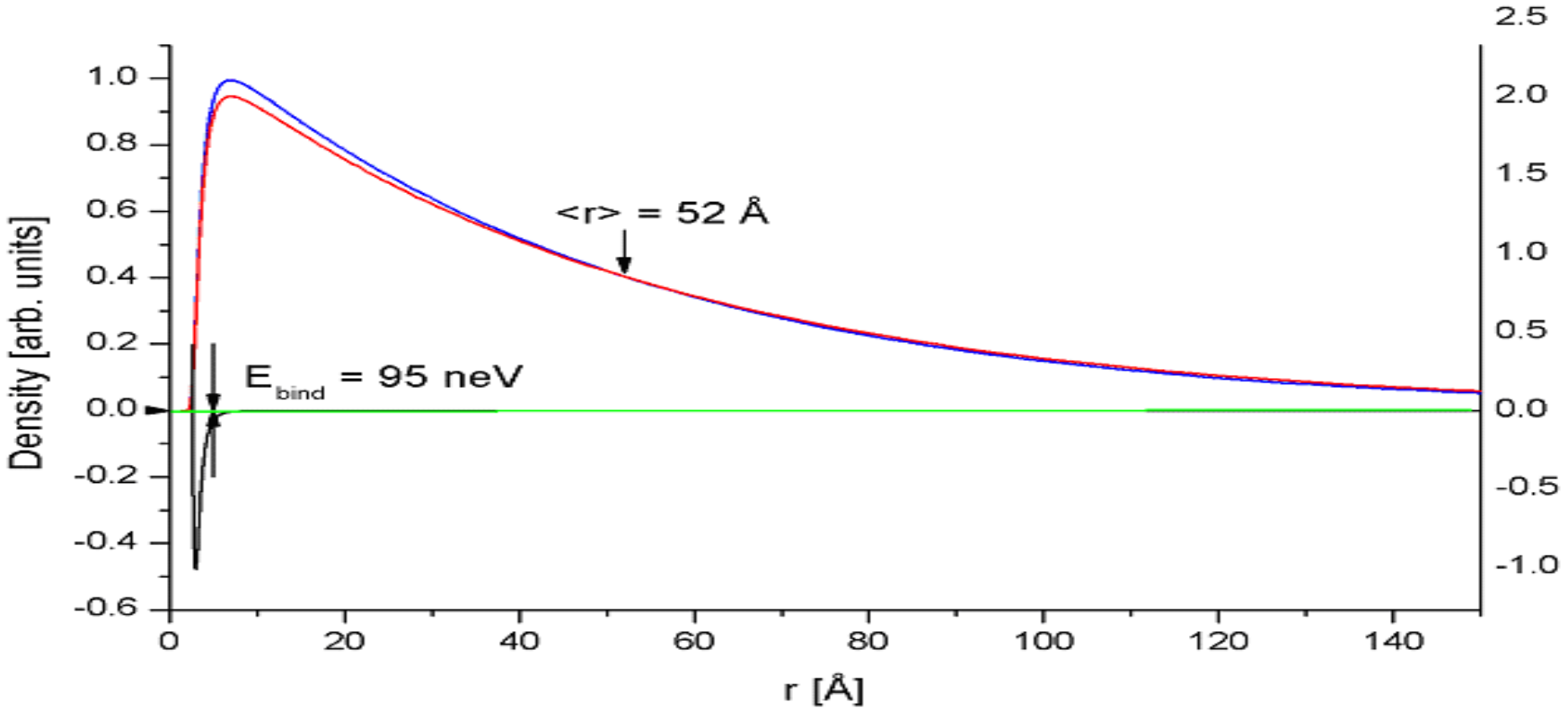

Potential
0
E_{bind}
Zero
point
Energy
R
Quantum Halos
„live in the tunnel“

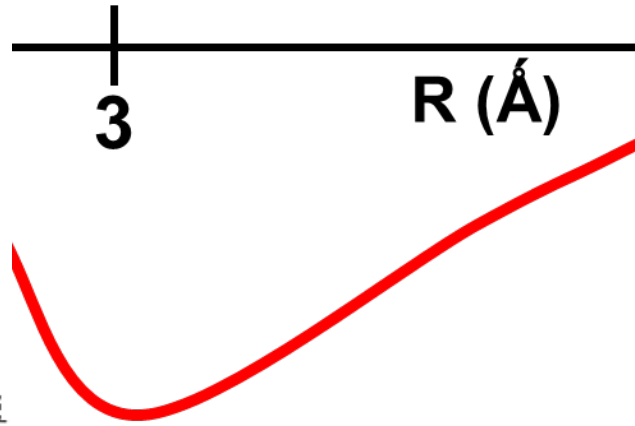

He_2
Potential (meV)
van der Vaals
1
2
3
R (Å)
1 Angstrom
1meV


He
10^{-10}m
0.1m
100nm
grating
98 % Helium atoms
1% He_2
1% He_3 (Efimov??)
5 um nozzle
8 Kelvin

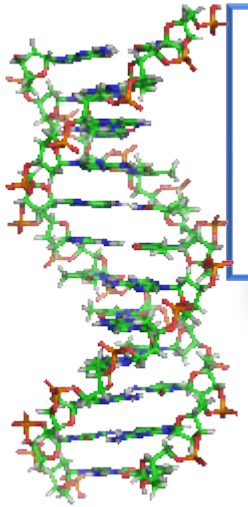


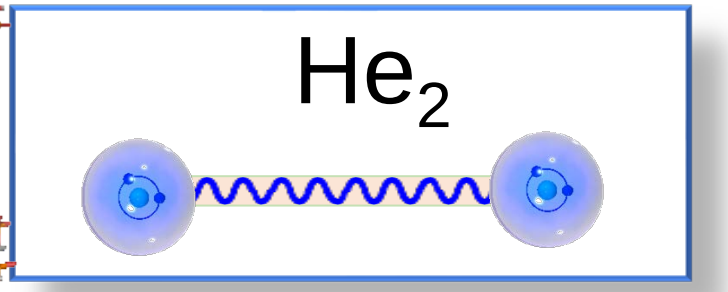






Zeller et al. PNAS 113 (2016) 14651





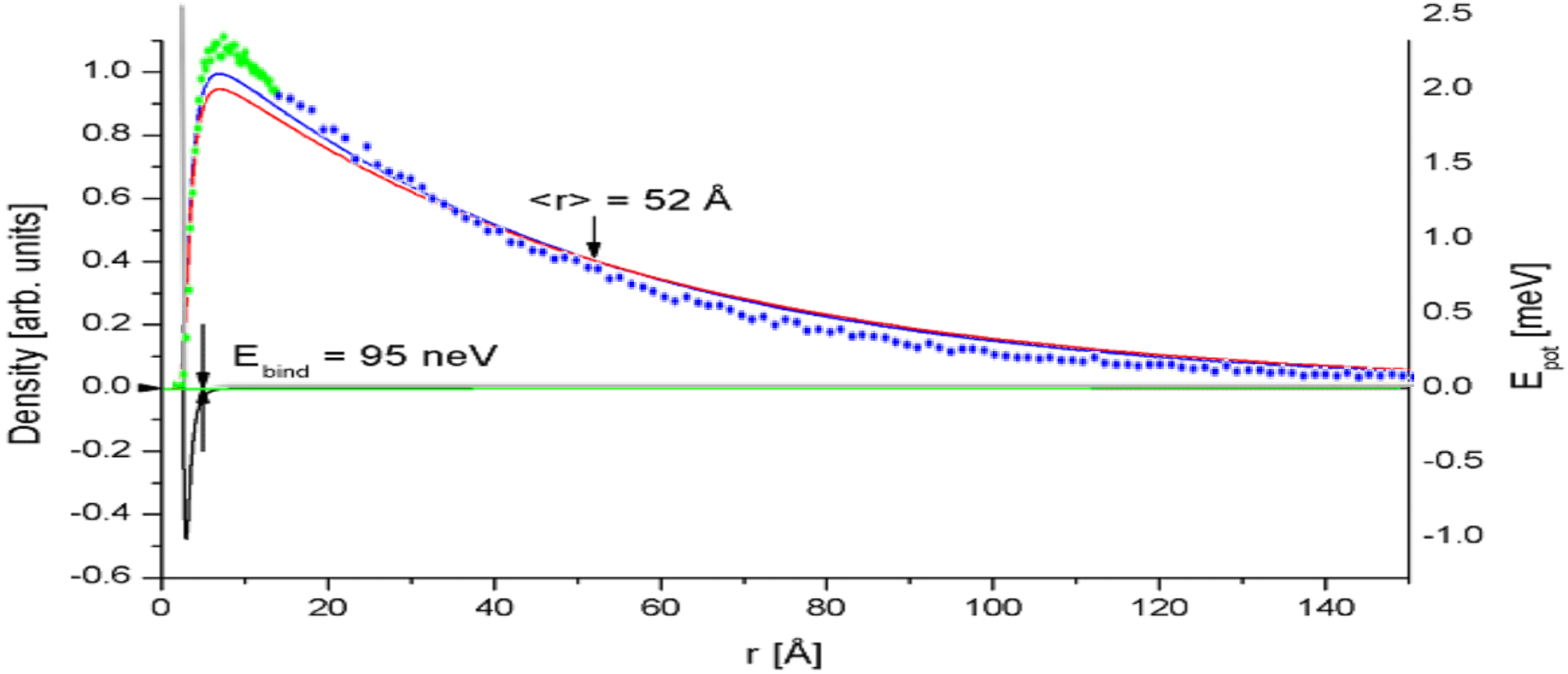
<R> = 52A

E_{bind}= 50…164 neV

0.9 10^{-3} cm^{-1}

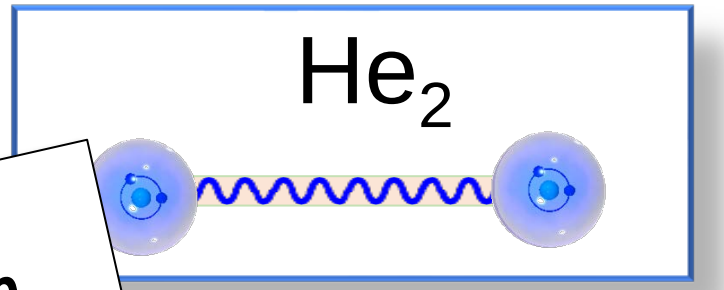
1,3mK

10^{-9} kJ/mol



Jörg Voigtsberger
Stefan Zeller

Zeller et al. PNAS 113 (2016) 14651



Quantum Challenge:
1. **Delocalization**
2. **Tunneling**

<R> = 52A

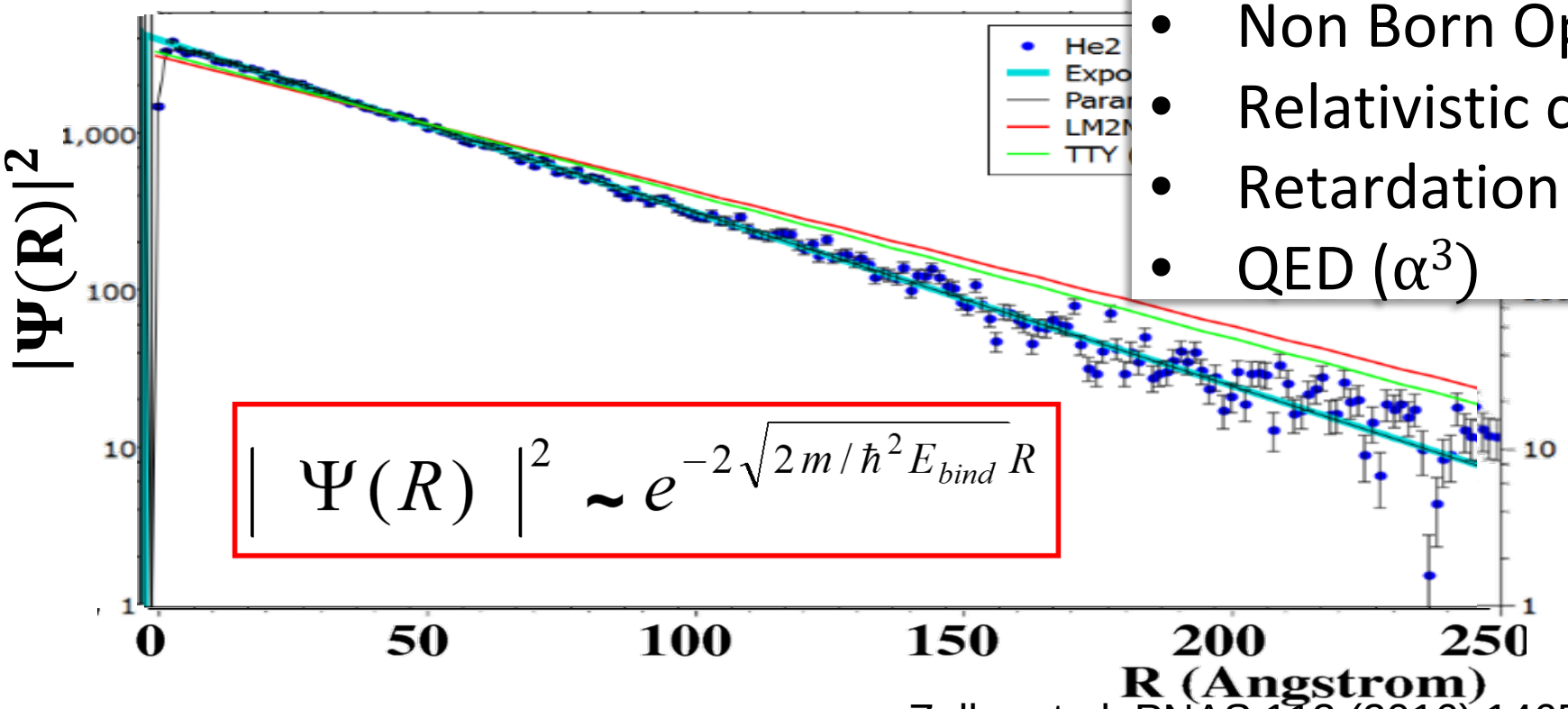
E_{bind}= 151.9 ± 13.3 neV

0.9 10^{-3} cm^{-1}

1,3mK

10^{-9} kJ/mol

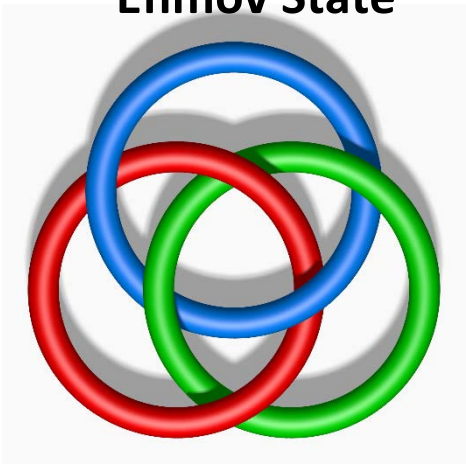
- Non Born Oppenheimer
- Relativistic corrections (α^2)
- Retardation
- QED (α^3)



Zeller et al. PNAS 113 (2016) 14651

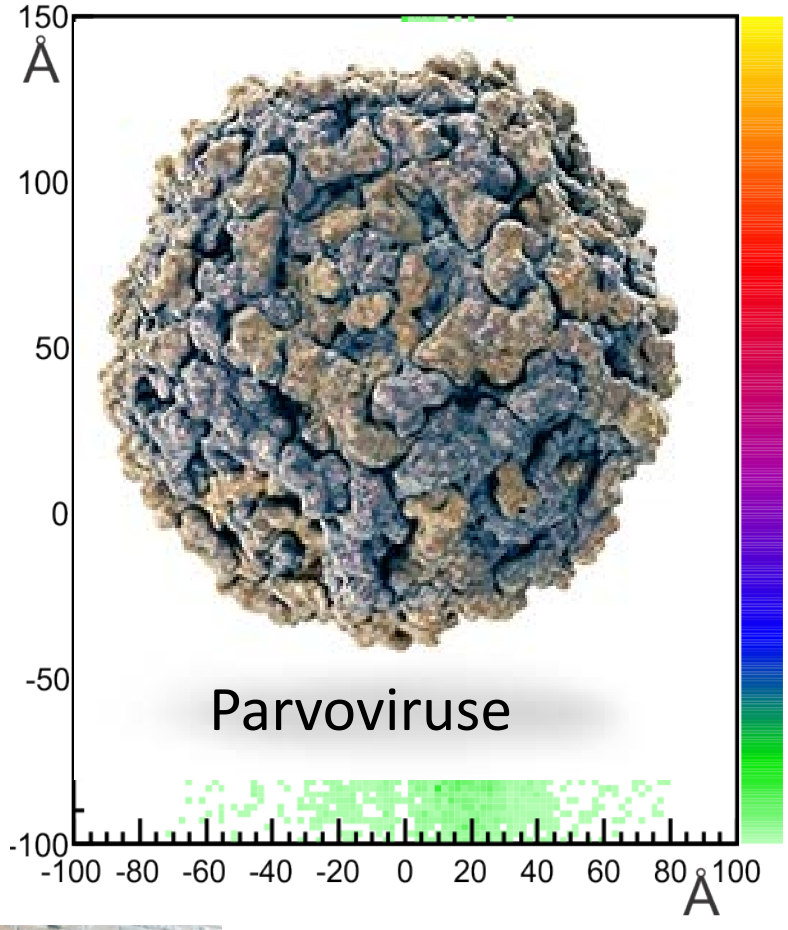
He_3 Trimer

Efimov State

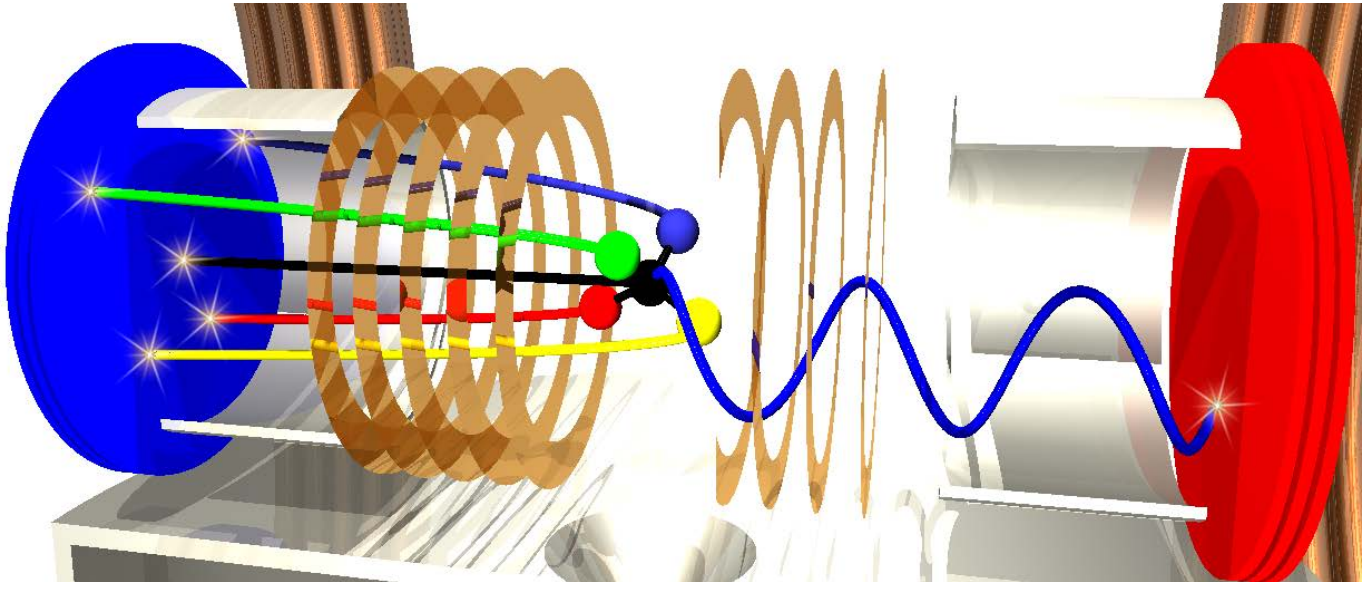


Vitali Efimov (1970).
Physics Lett. B **33**: 563 (1970).

Efimov State of He_3



$$\Psi\left(\vec{R_i}, \vec{r_j}, t\right)$$



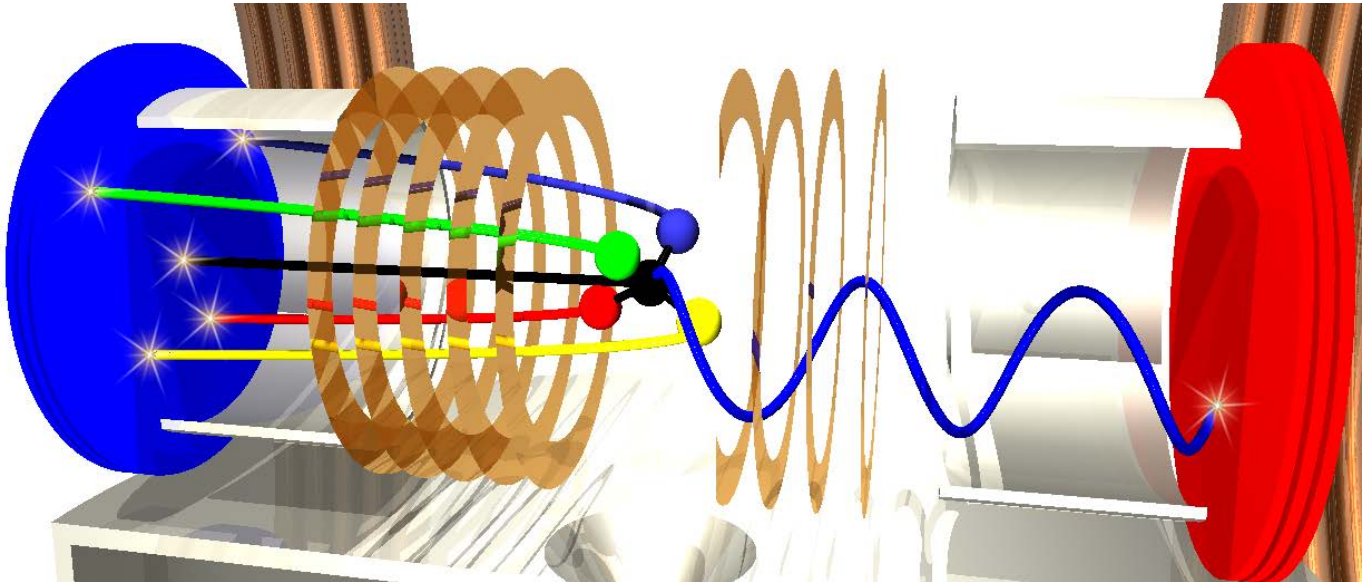
Kunitski et al. Science, 348 (2015) 551

$$\Psi\left(\vec{R}_i, \vec{r}_j, t\right)$$

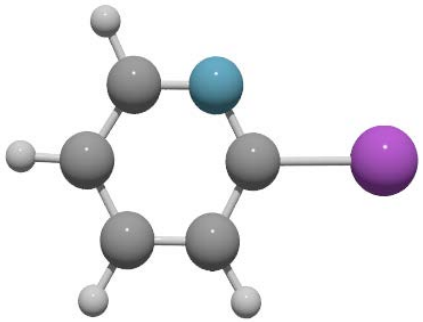
Quantum Challenge:

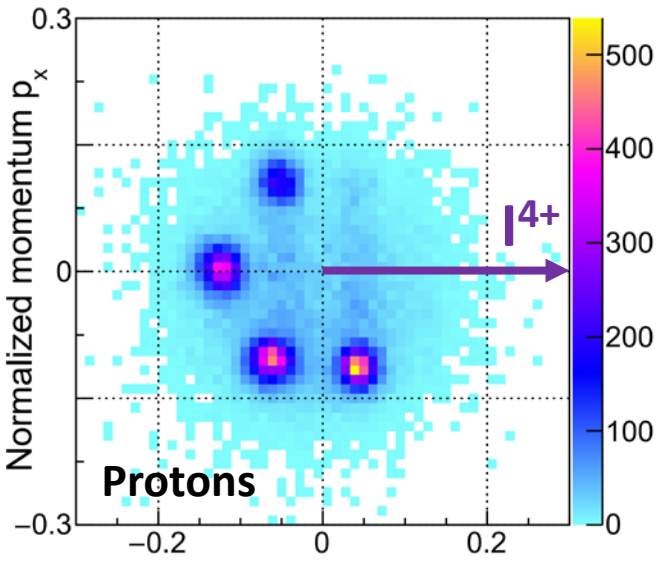
1. Delocalization
2. Tunneling

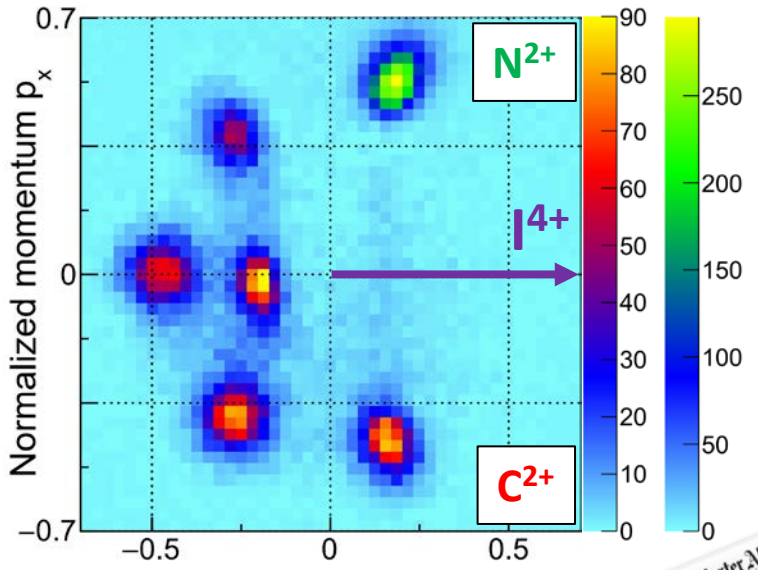
3. Correlated Quantum Fluctuations



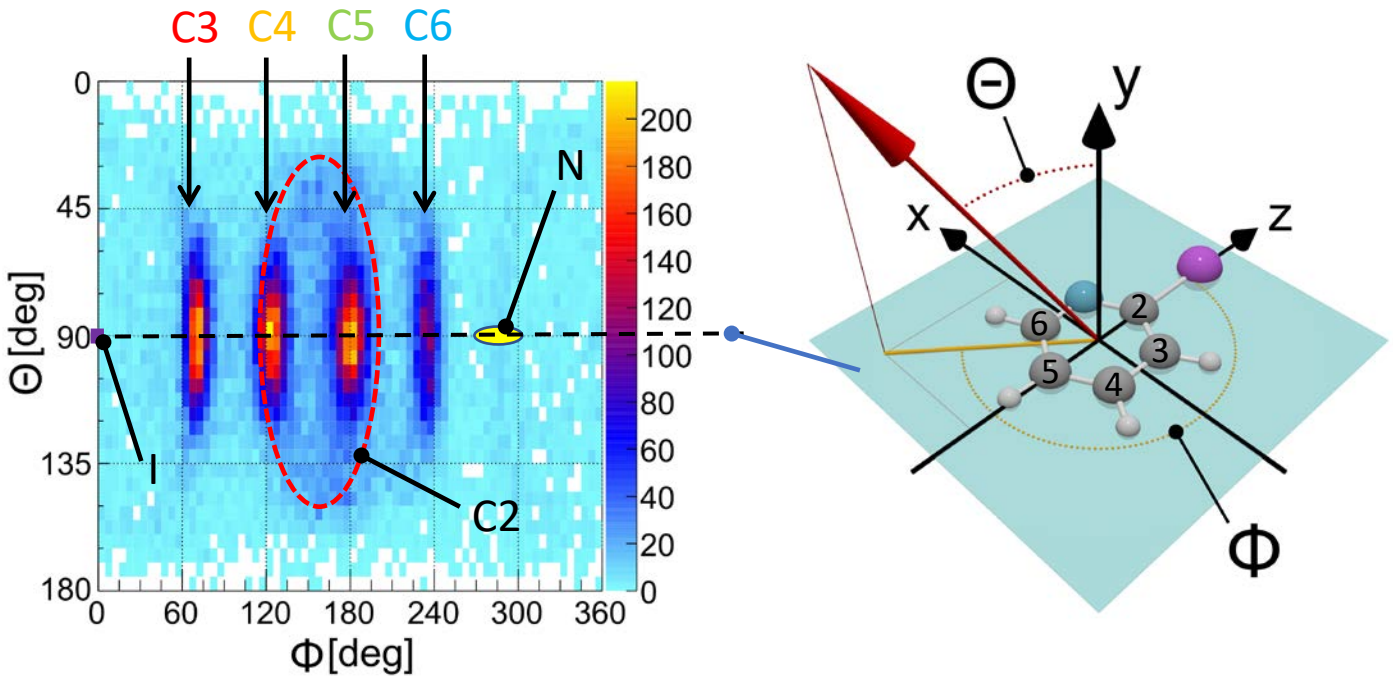
Coulomb Explosion Imaging of C_5H_4NI



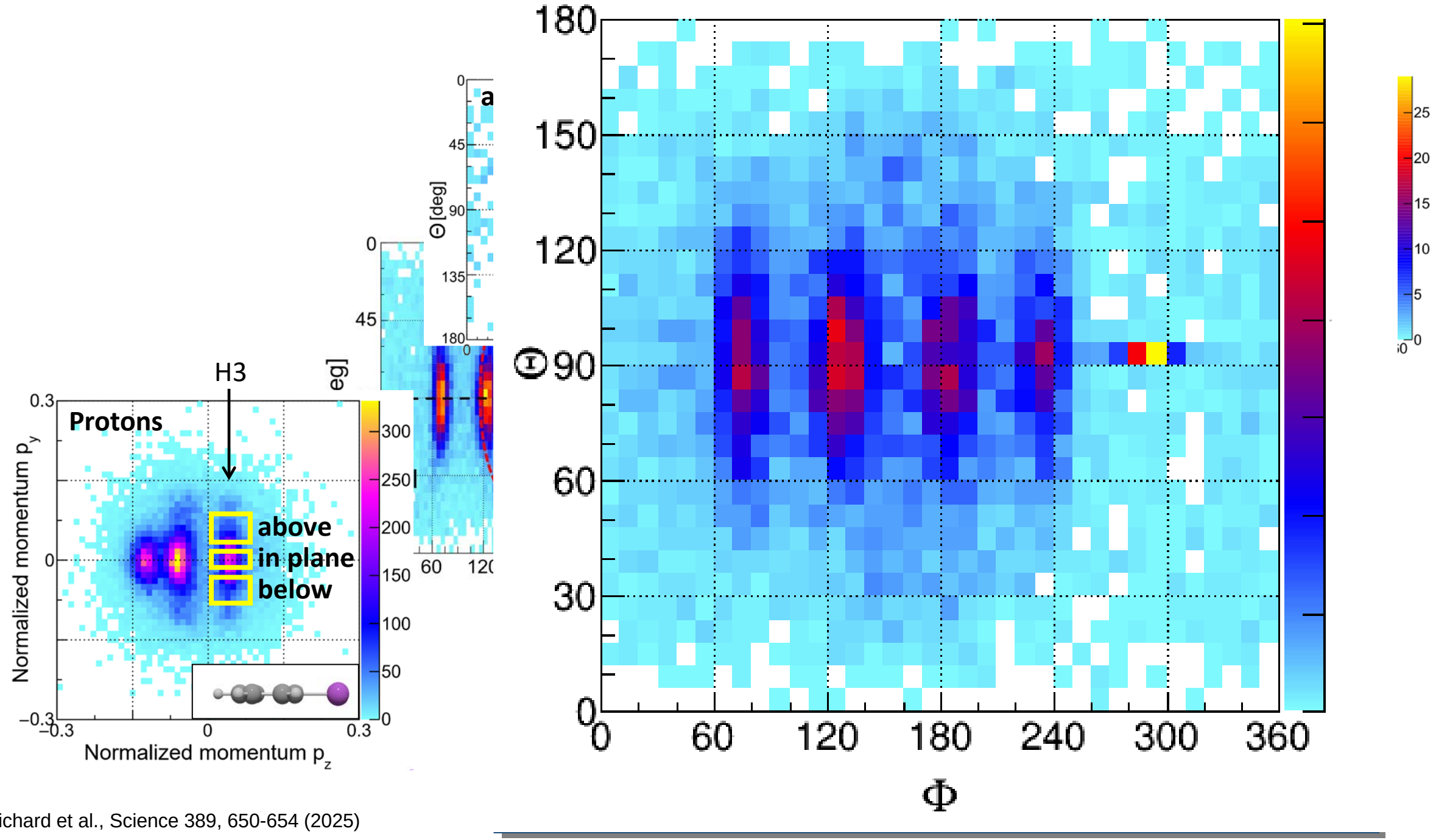




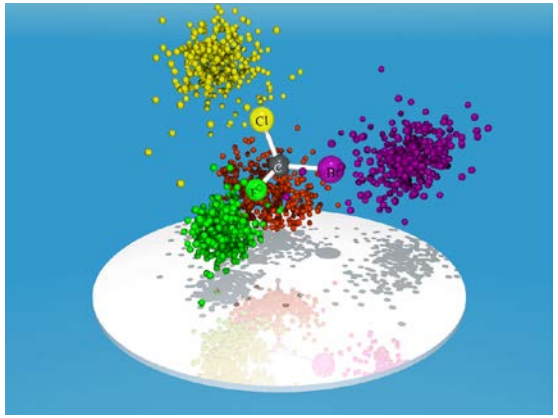
B. Richard et al., Science 389, 650-654 (2025)

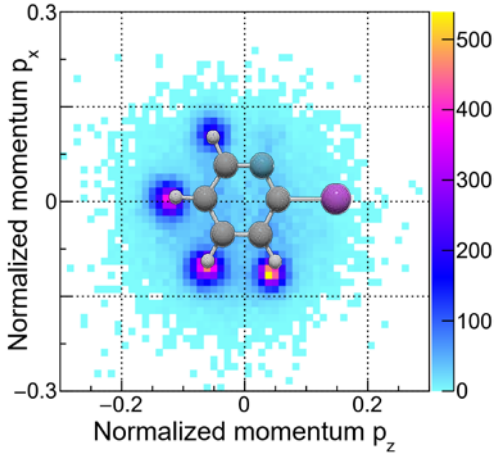


B. Richard et al., Science 389, 650-654 (2025)

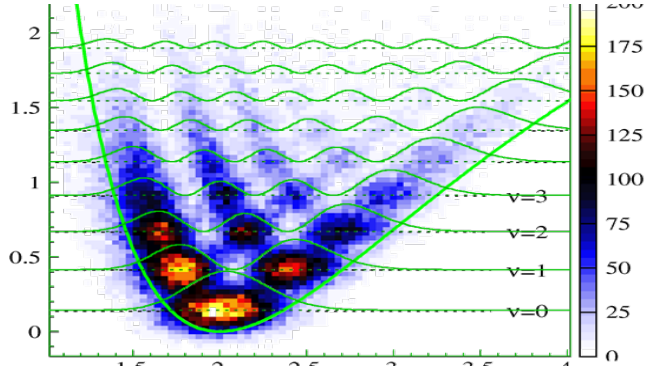


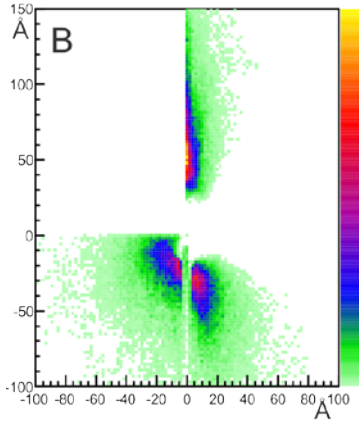
B. Richard et al., Science 389, 650-654 (2025)

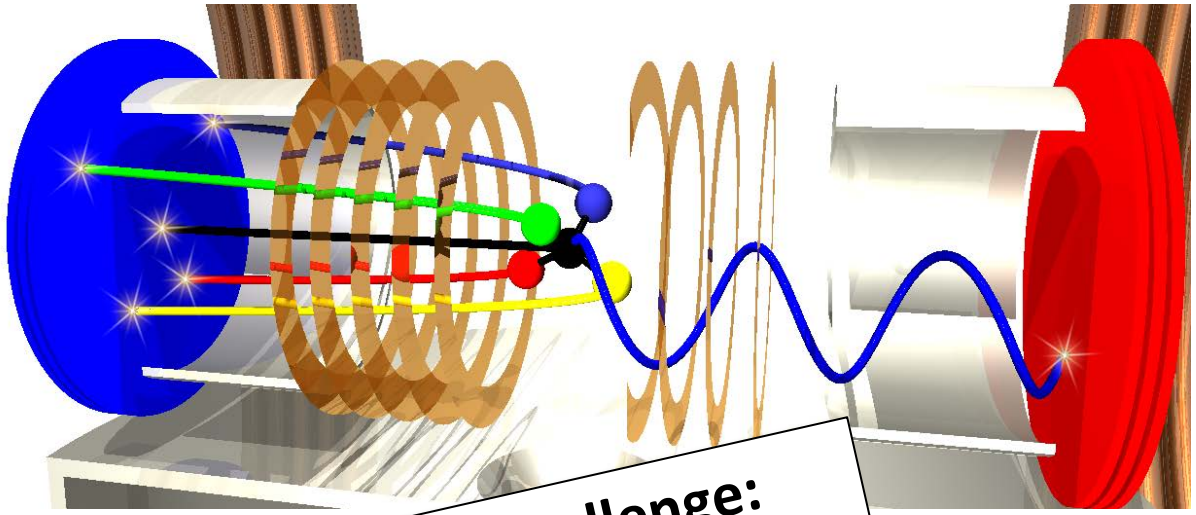


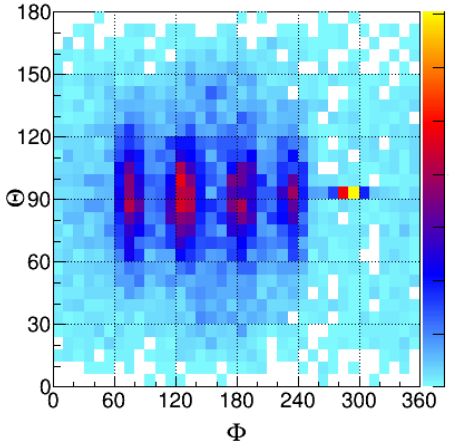


$$\Psi\left(\overrightarrow{R_i}, \overrightarrow{r_j}, t\right)$$





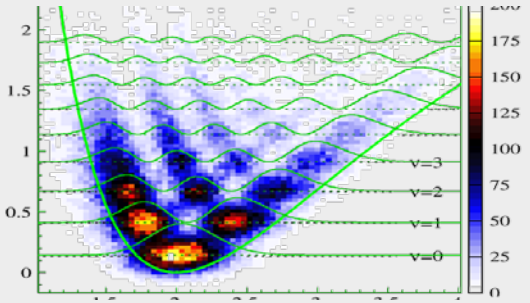


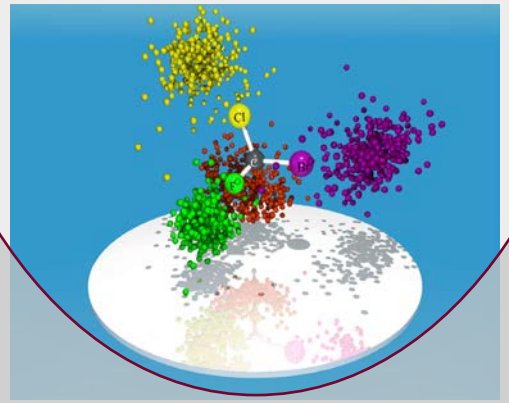


Quantum Challenge:

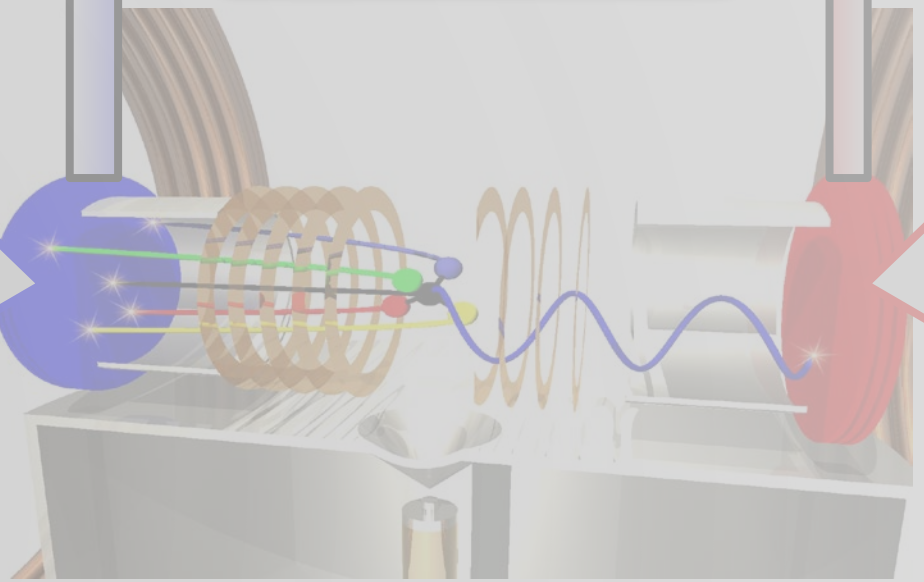
1. **Delocalization**
2. **Tunneling**
3. **Zeropoint motion**

Coulomb Explosion Imaging

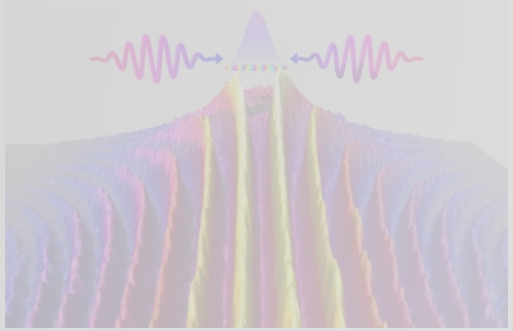




$|\Psi(\vec{R_i}, \vec{r_j}, t)|^2$



- Zeptoseconds
- Entanglement
- Ultrafast Kapitza Dirac Effect



15 fs
H_2
vibrates

50as
electron
crosses
H-atom

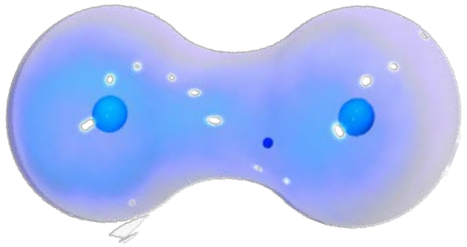
230zs
photon
crosses
H_2 HOMO

1000 fs 100fs 10fs

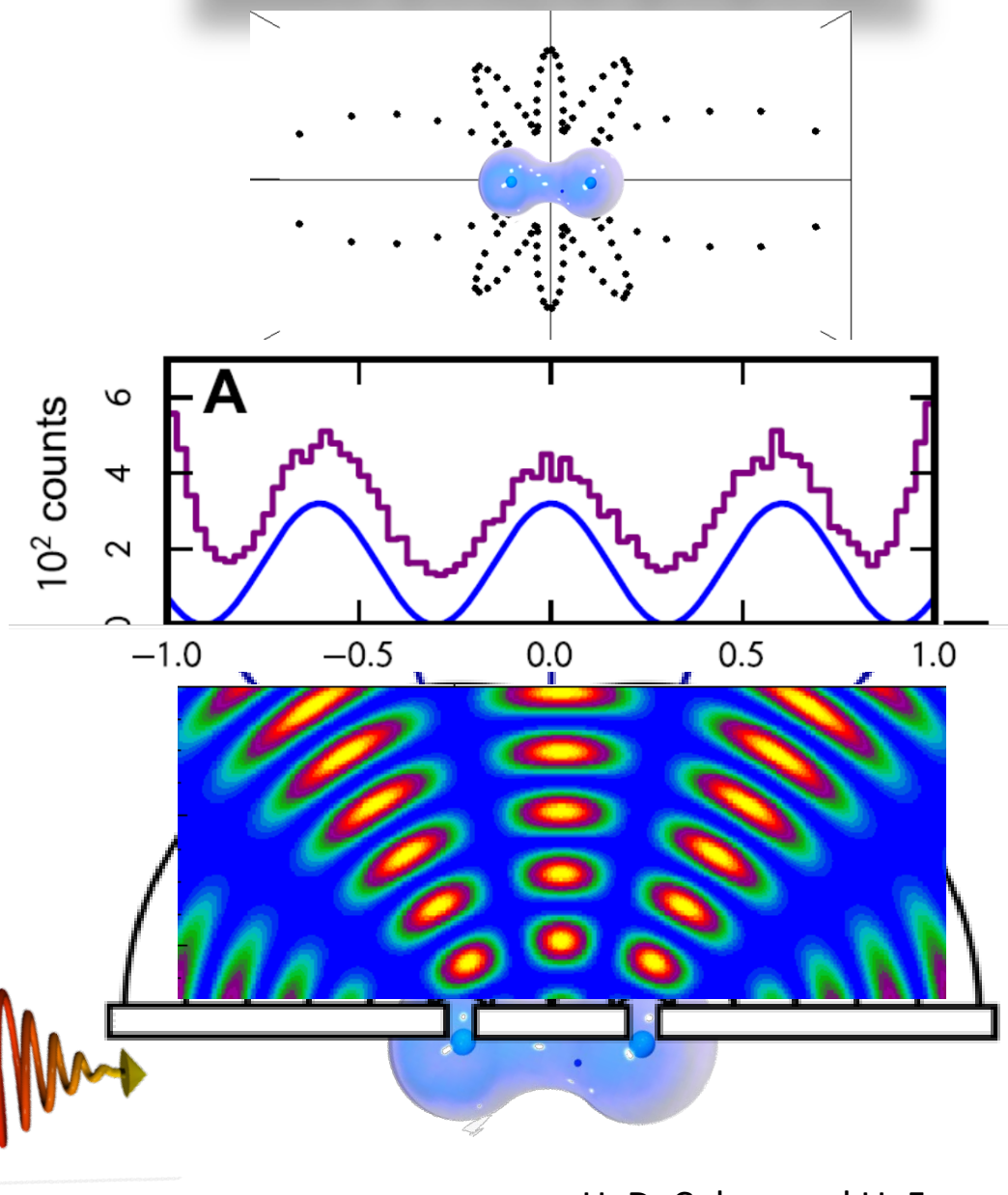
Nuclei
(vibration)

Electrons
(charge migration,
Photoionization)

Photons
Correlations
zepto



800eV $\gamma + H_2 \rightarrow p + p + 2e^-$

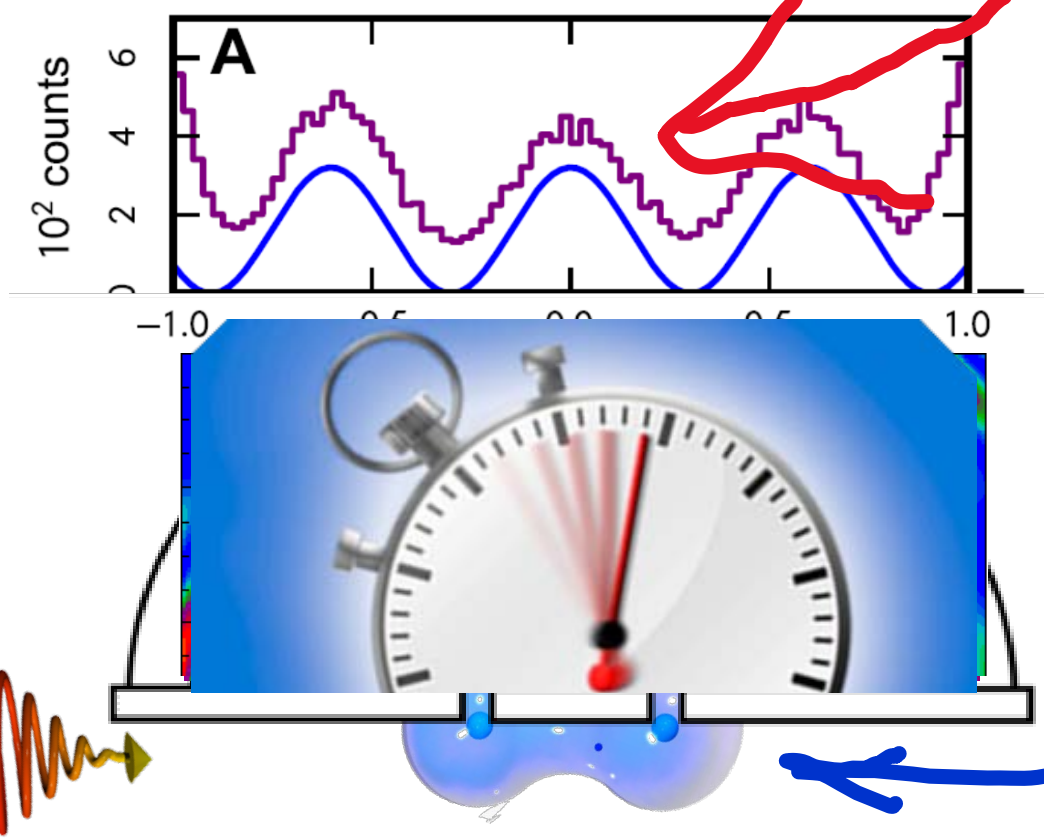


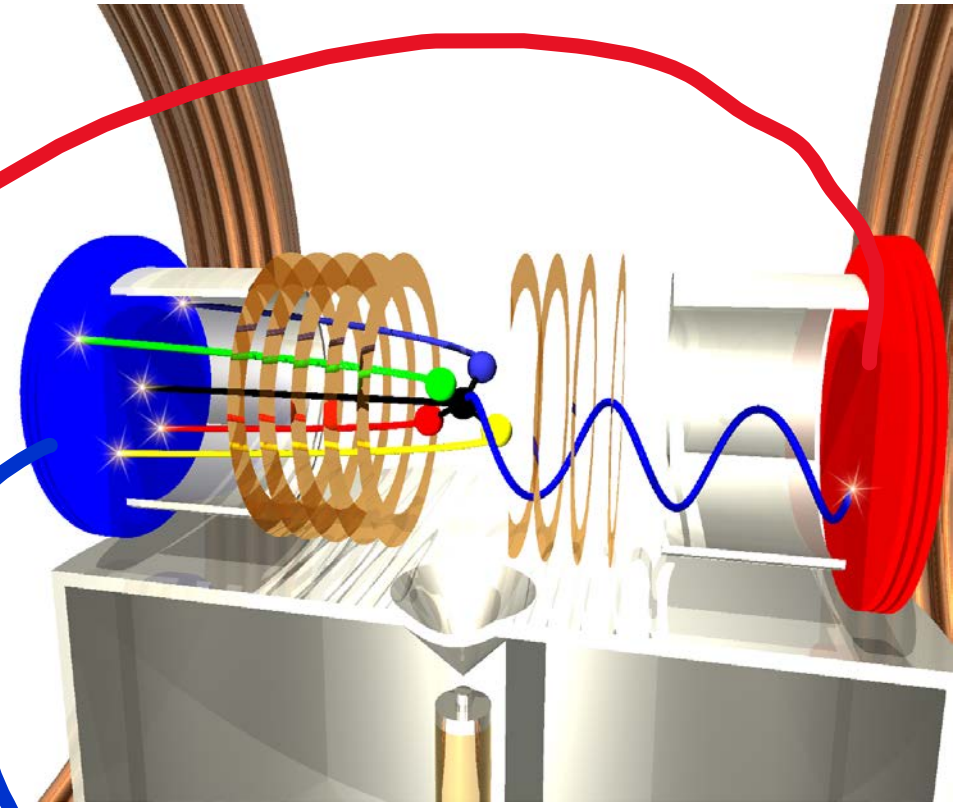
Grundmann et al. Science 370 339 (2020)

H. D. Cohen and U. Fano, Phys.Rev.150, 30 (1966)

800eV $\gamma + H_2 \rightarrow p + p + 2e^-$

Read hands of the clock



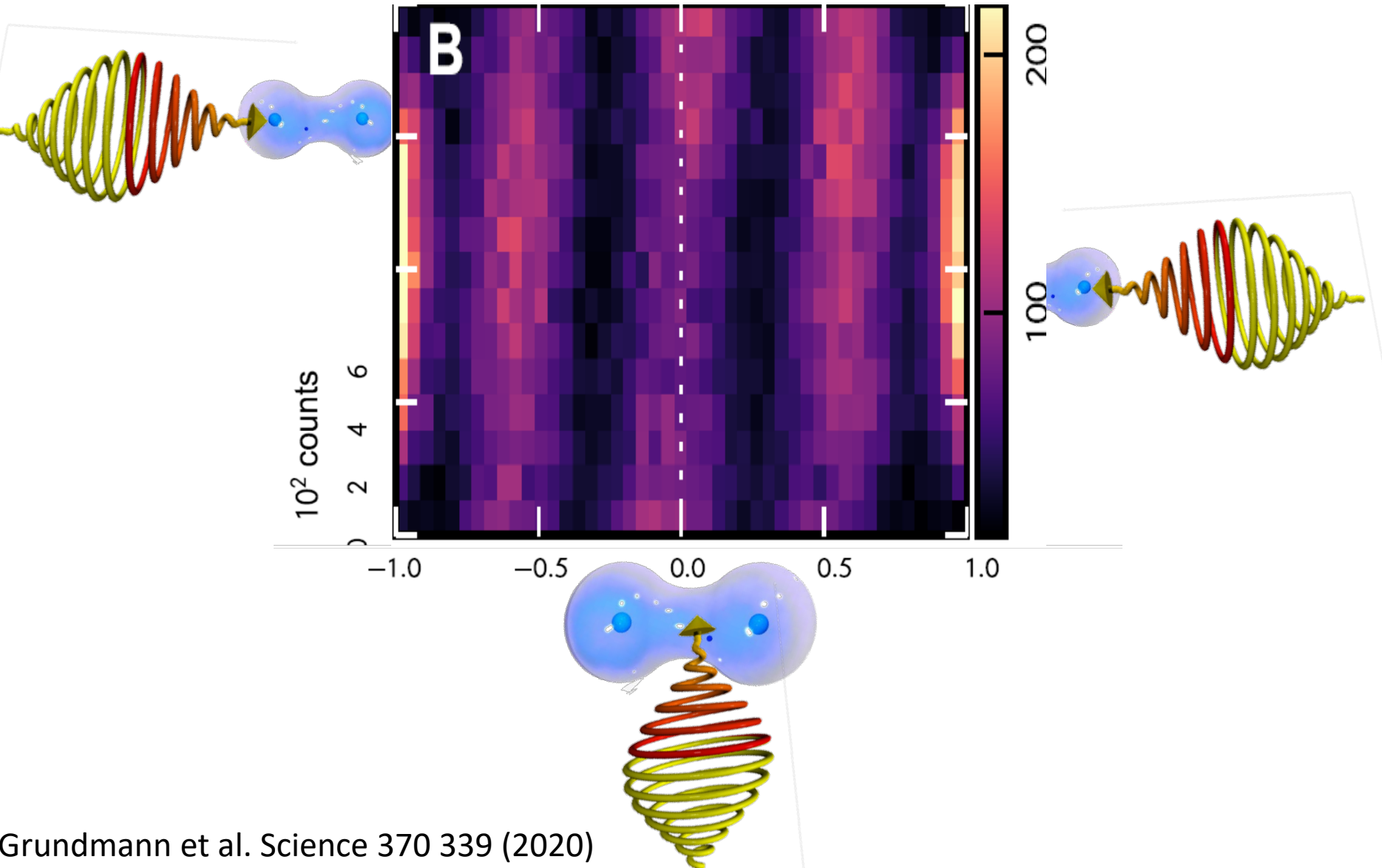


Fix the clockface

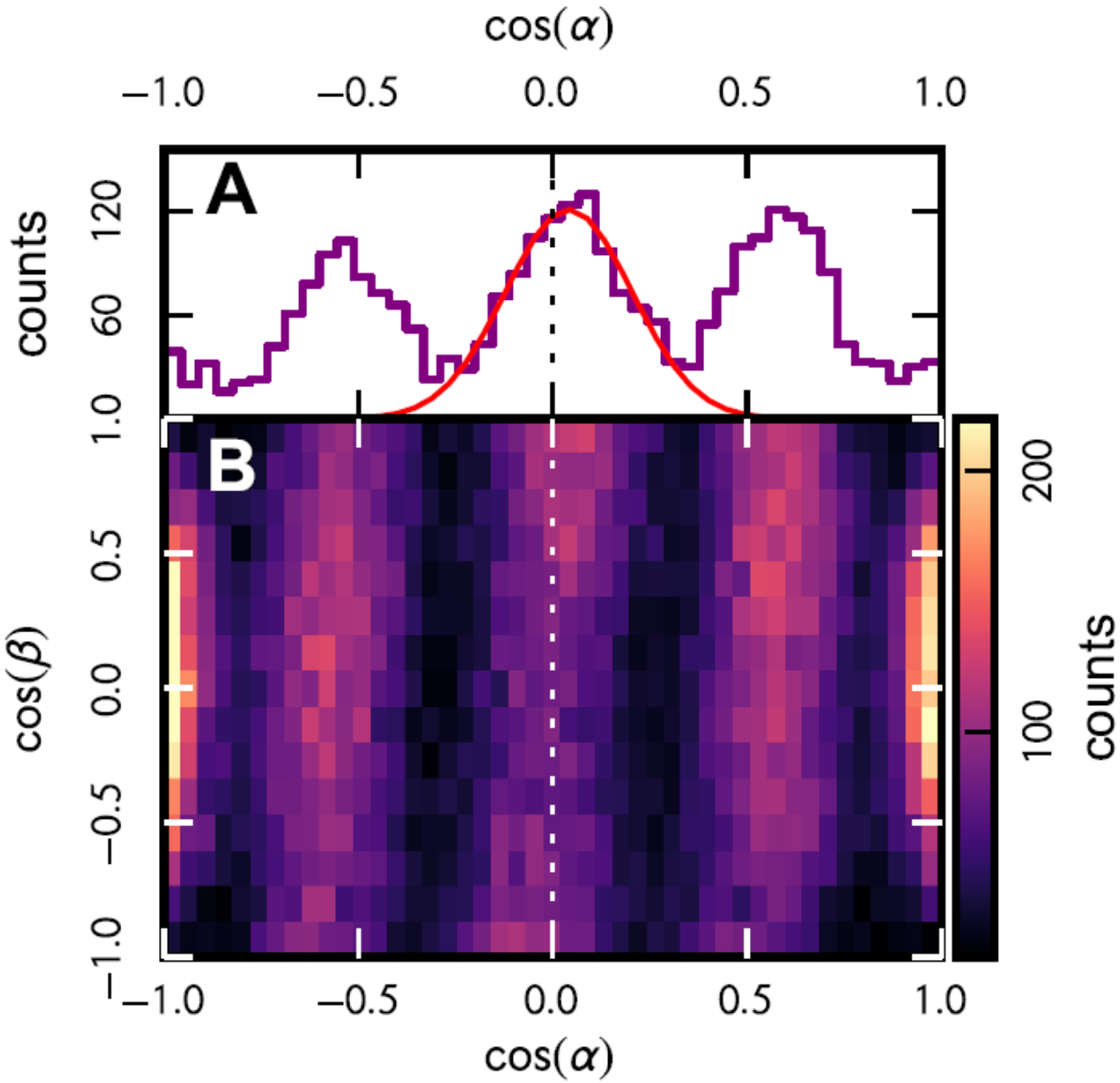
Grundmann et al. Science 370 339 (2020)

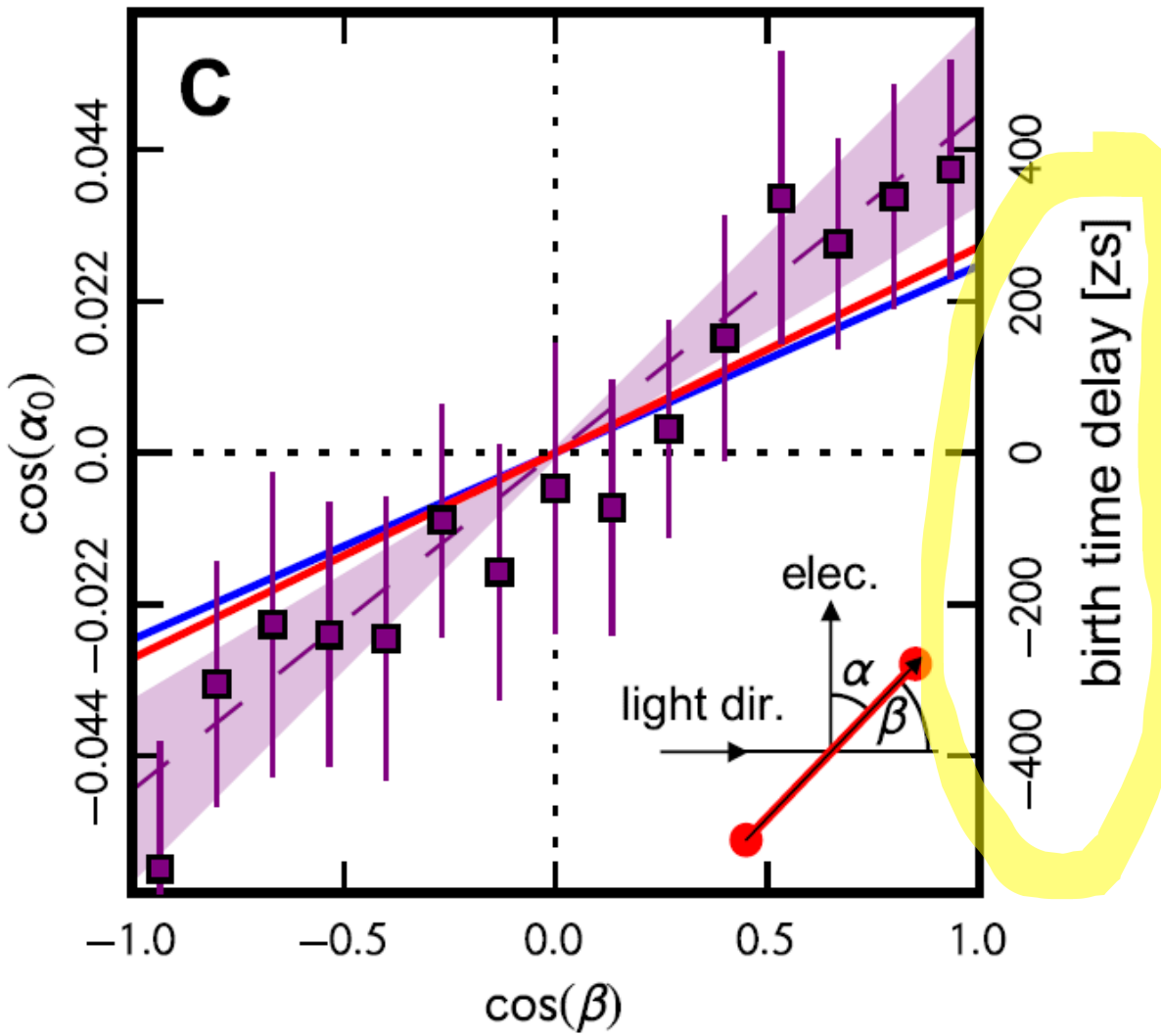
H. D. Cohen and U. Fano, Phys.Rev.150, 30 (1966)

800eV $\gamma + H_2 \rightarrow p + p + 2e^-$



Grundmann et al. Science 370 339 (2020)

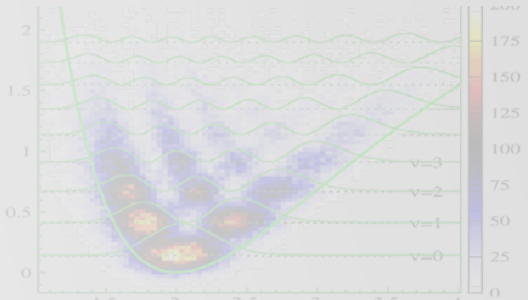


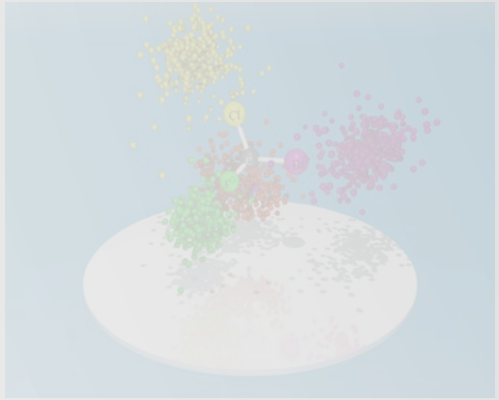


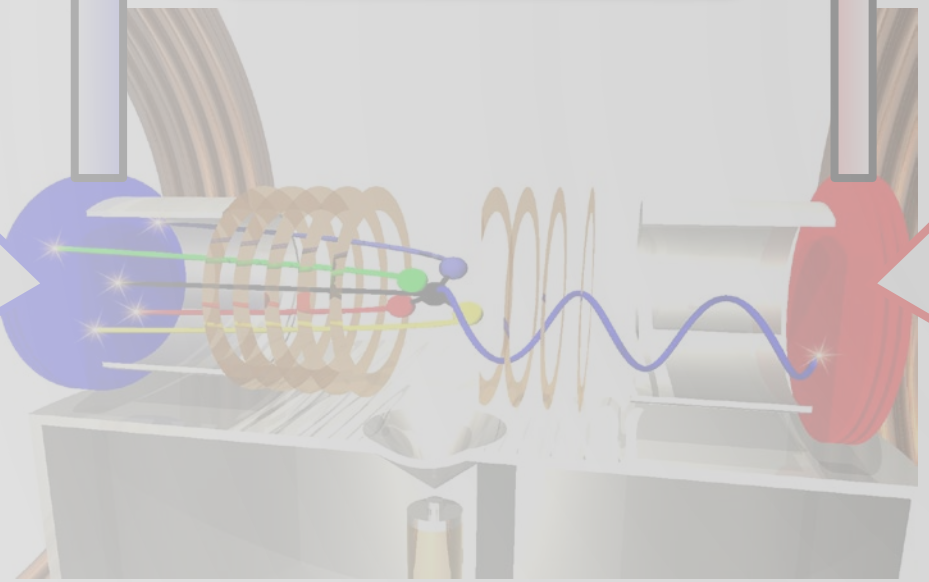
Grundmann et al. Science 370 339 (2020)

$$|\Psi(\vec{R_i}, \vec{r_j}, t)|^2$$

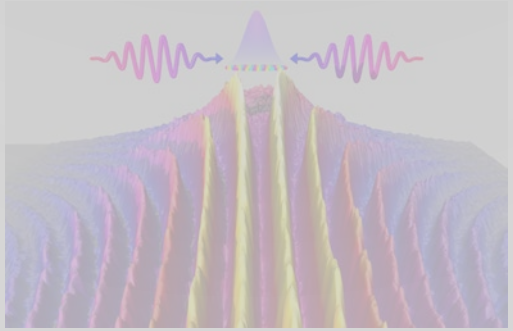
Coulomb Explosion Imaging

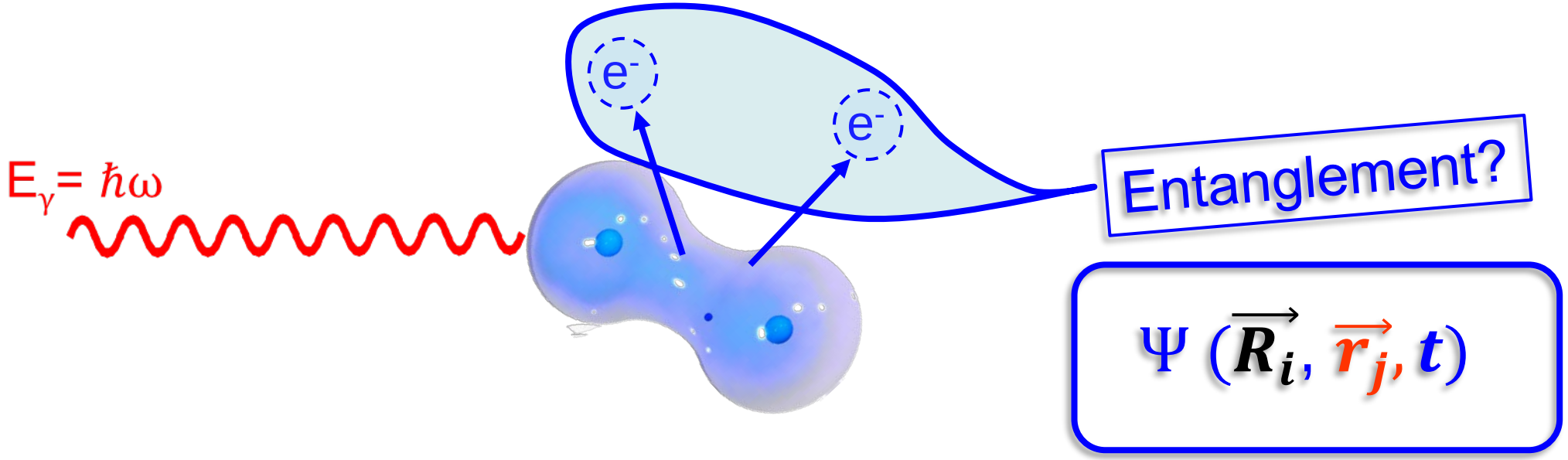






- **Zeptoseconds**
- **Entanglement**
- **Ultrafast Kapitza Dirac Effect**





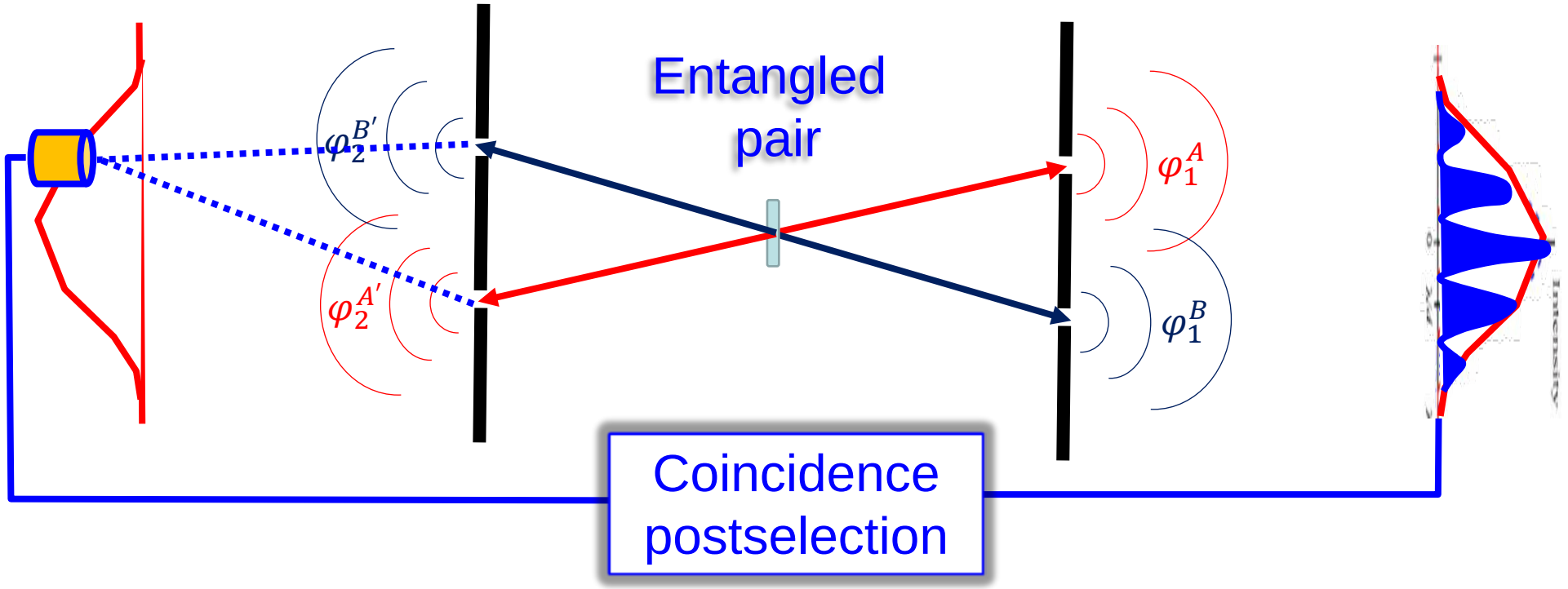
VOLUME 62, NUMBER 19 PHYSICAL REVIEW LETTERS 8 MAY 1989

Two-Particle Interferometry

Michael A. Horne
Department of Physics, Stonehill College, North Easton, Massachusetts 02356

Abner Shimony
Departments of Philosophy and Physics, Boston University, Boston, Massachusetts 02215

Anton Zeilinger
Atominstitut der Österreichischen Universitäten, Schüttelstrasse 115, A-1020 Vienna, Austria
and Physik Department E21, Technische Universität München, D-8046 Garching, Federal Republic of Germany
(Received 30 January 1989)



VOLUME 62, NUMBER 19 PHYSICAL REVIEW LETTERS 8 MAY 1989

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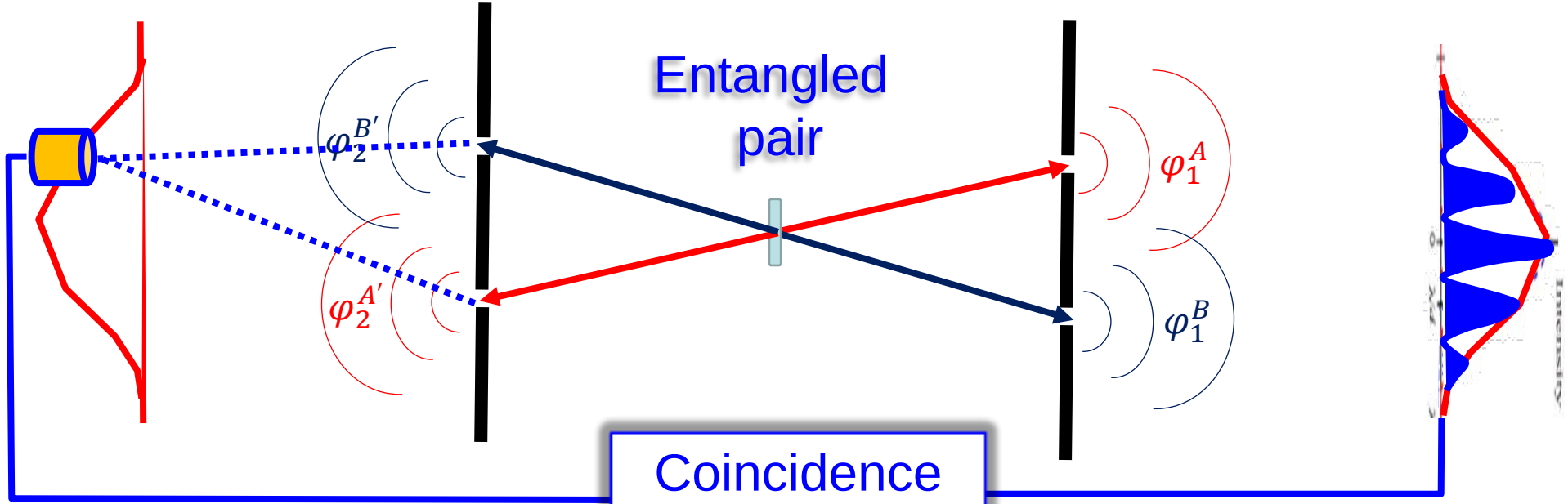
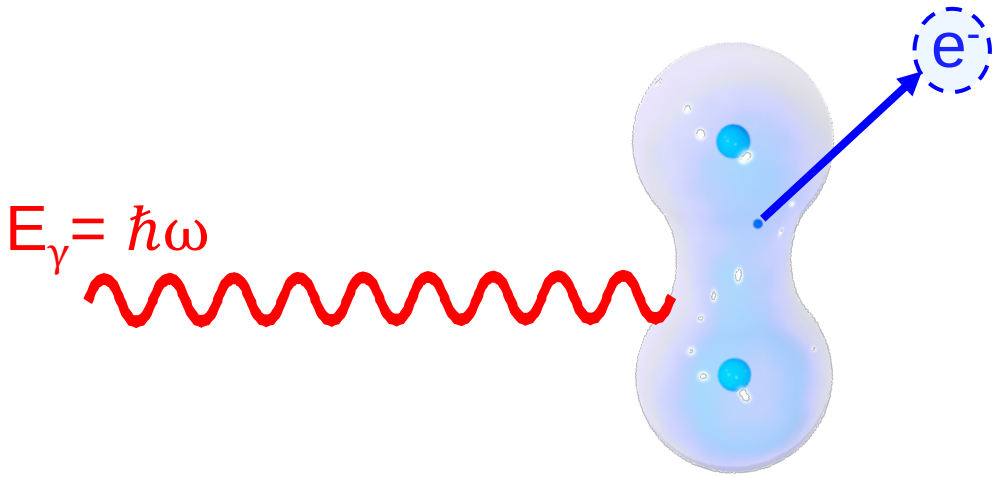
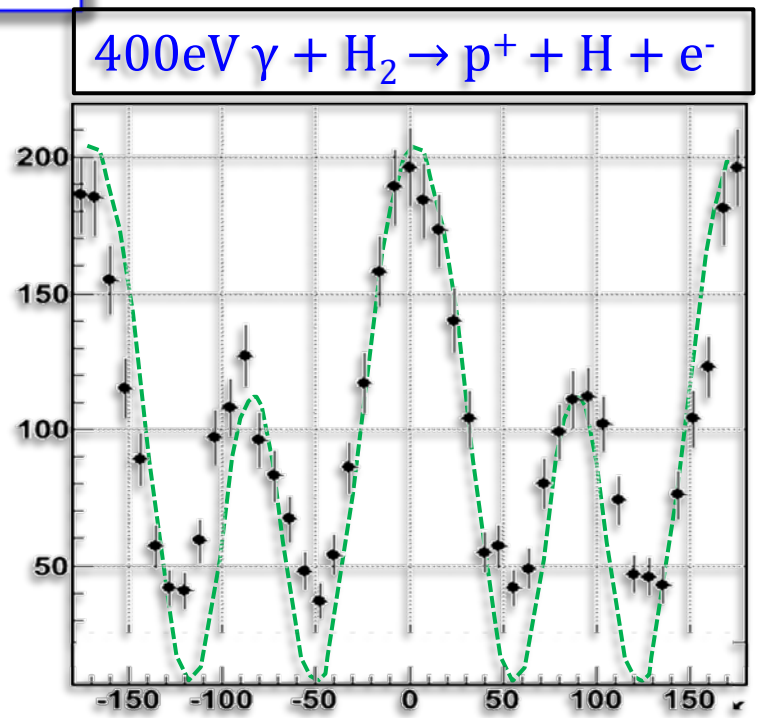
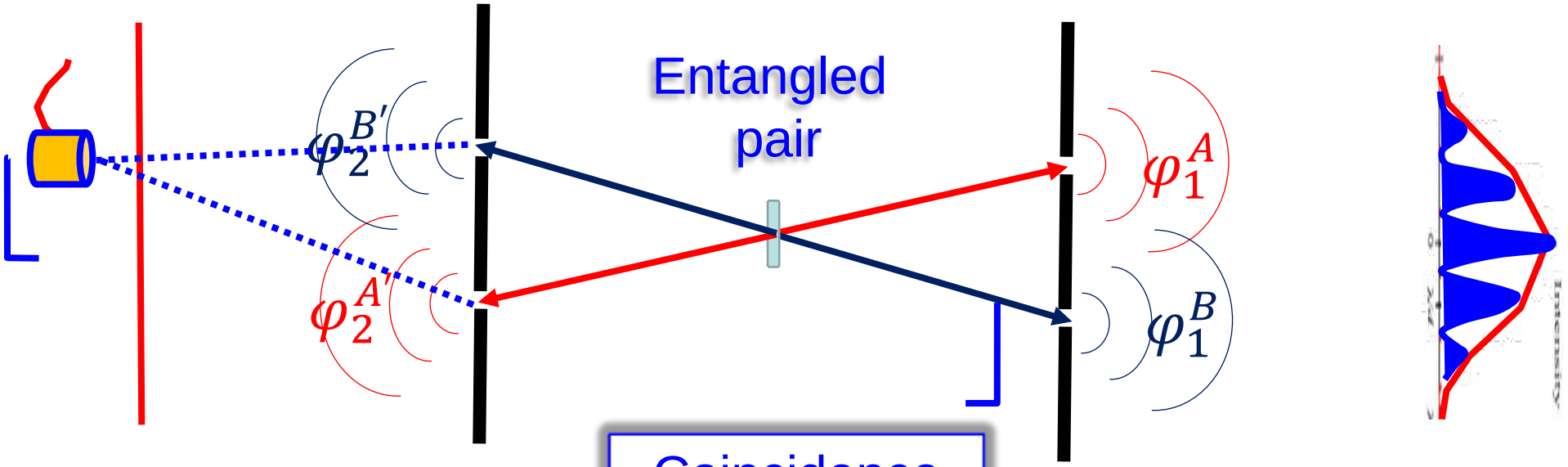


Coincidence
postselection

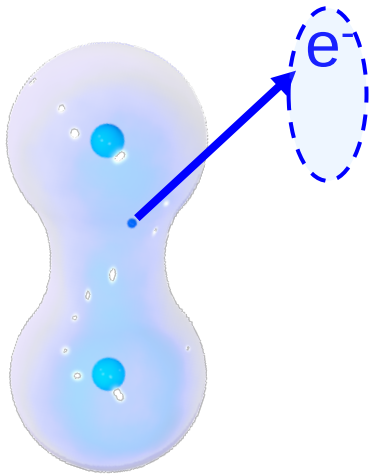


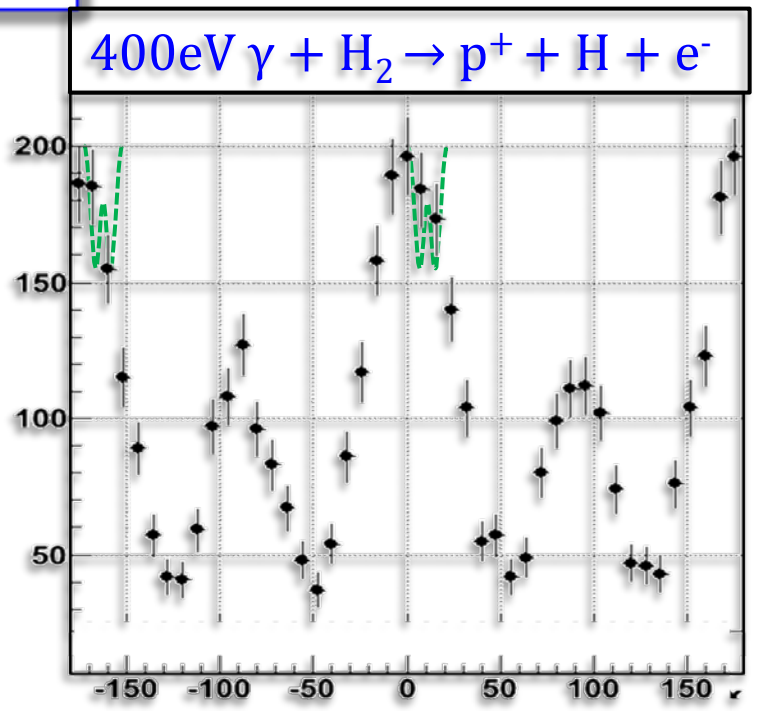




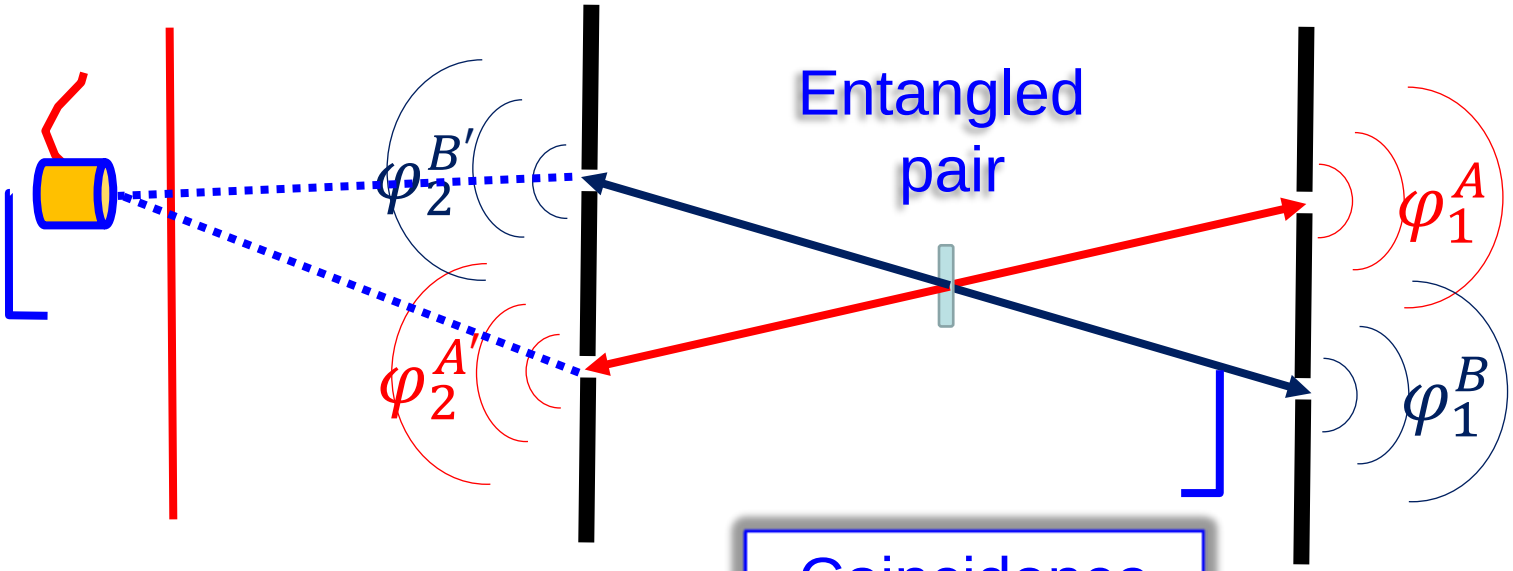
Coincidence
postselection

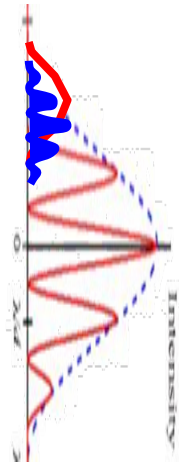
$E_\gamma = \hbar\omega$



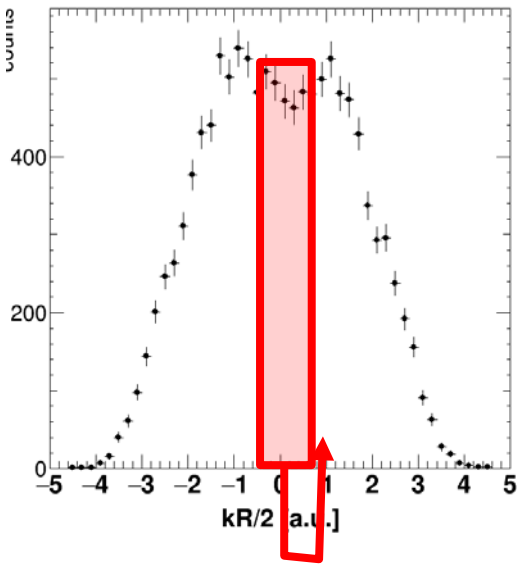


H.D. Cohen, U. Fano, Phys. Rev. 150 30 (1966)
M. Walter and J. S. Briggs, J. Phys. B 32 , 2487 (1999)

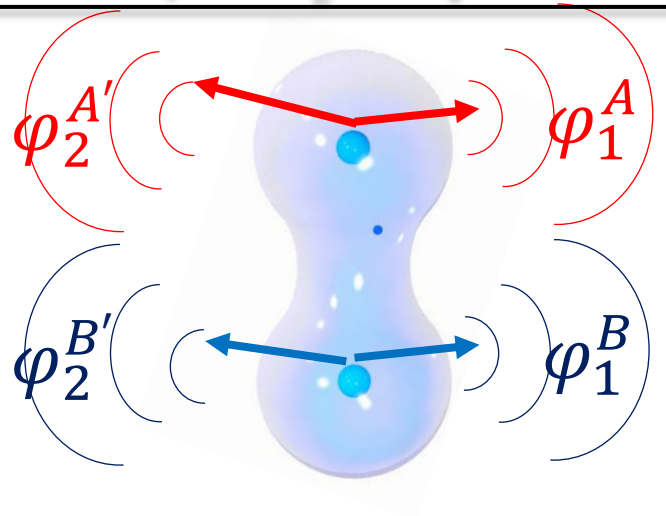


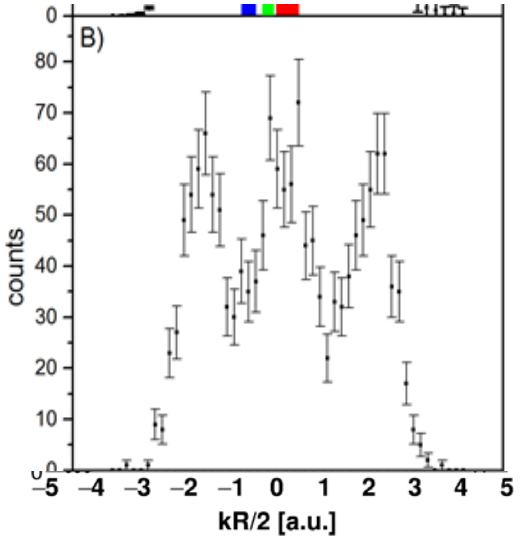


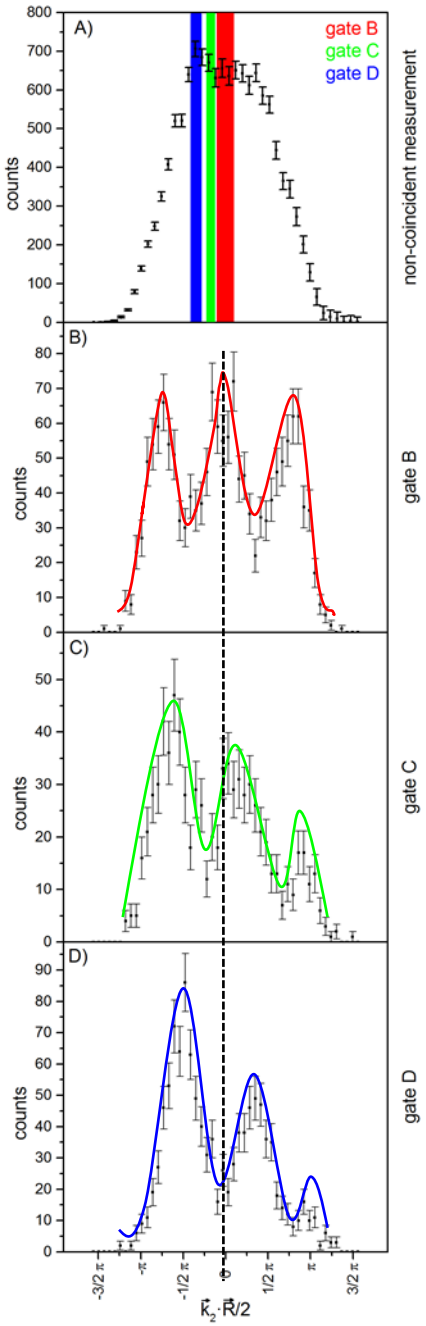
Coincidence
postselection

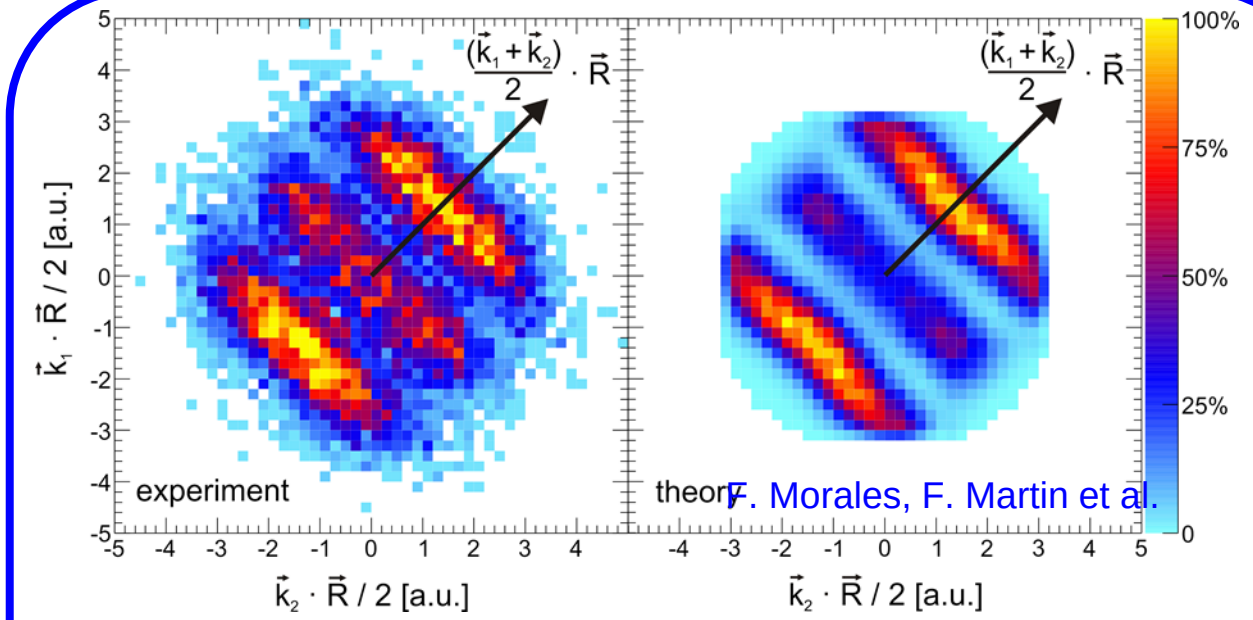


$400\text{eV}\ \gamma + H_2 \rightarrow 2p^+ + 2e^-$





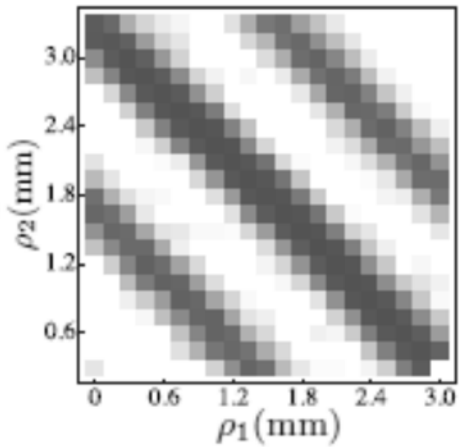




F. Morales, F. Martin et al.

Electron pairs from H_2 double ionization

photon pairs two-particle interference



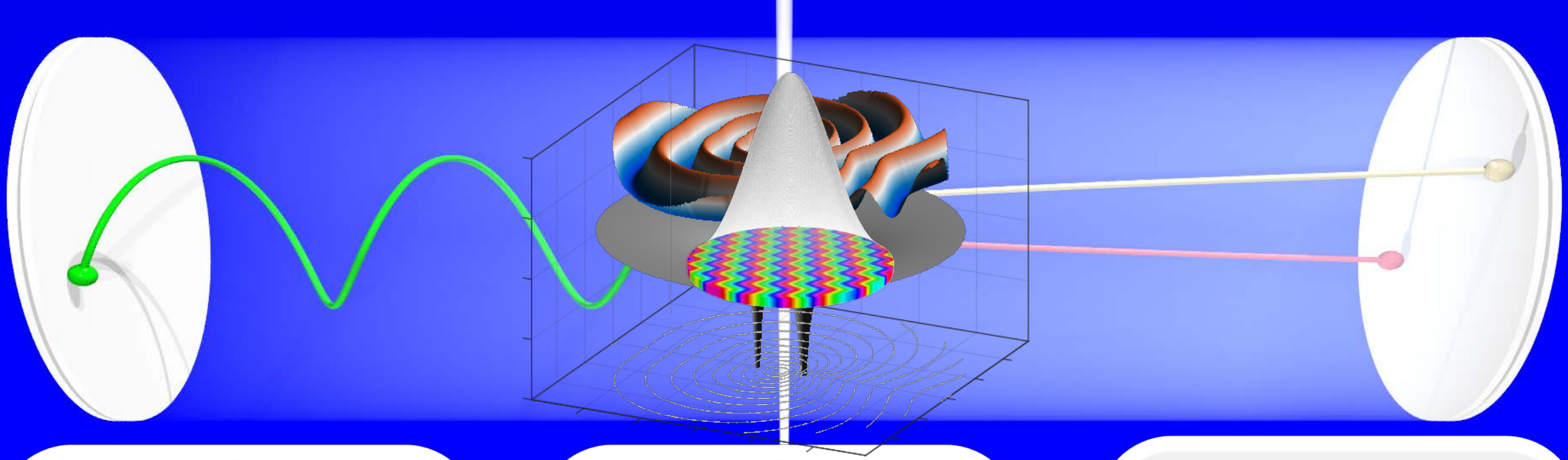
PRA 86, 032332 (2012)
M. A. D. Carvalho et al.

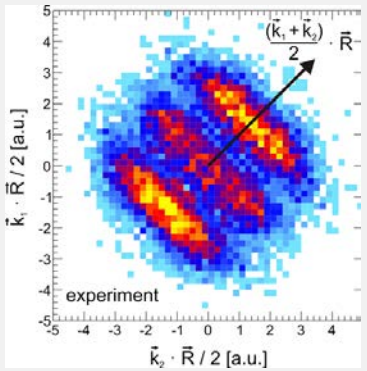
M. Waitz, et al. PRL: 117, 083002 (2016)

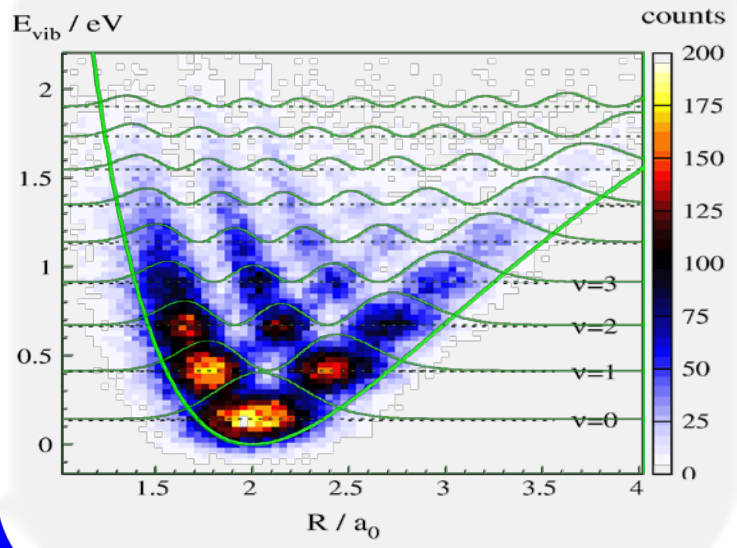
Quantum Challenge:

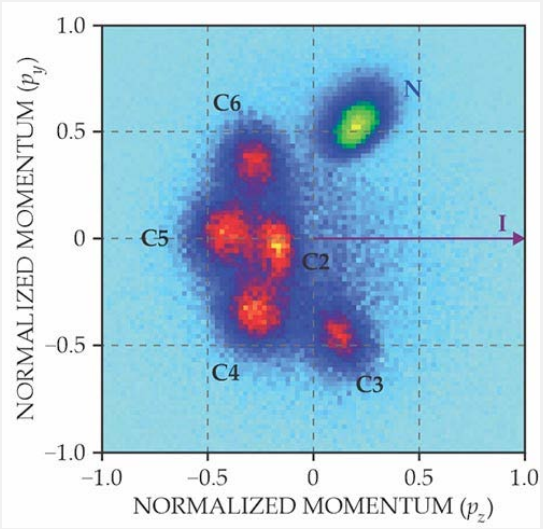
1. Delocalization
2. Tunneling
3. Zeropoint motion
4. Zepto Timescales
5. Entanglement

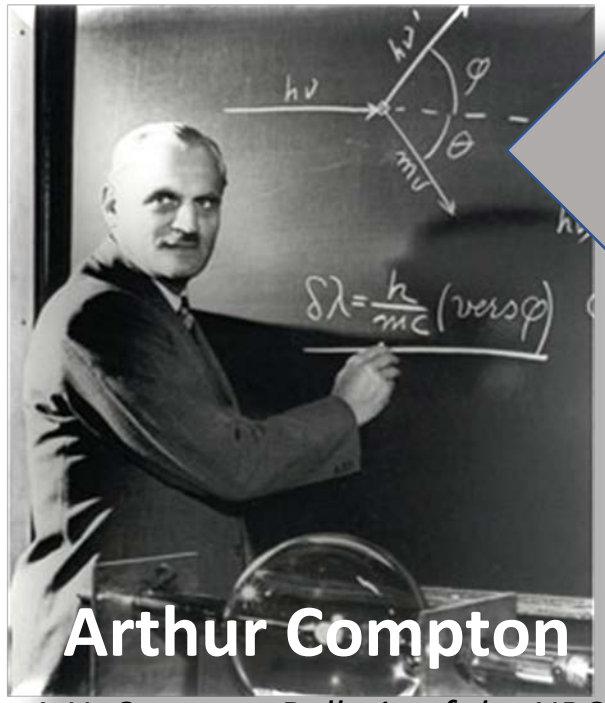
$$\Psi\left(\overrightarrow{K_i}, \overrightarrow{k_j}, t\right)$$




$\frac{(\vec{k}_1+\vec{k}_2)}{2}\cdot\vec{R}$
$\vec{k}_1\cdot\vec{R}/2$ [a.u.]
experiment
$\vec{k}_2\cdot\vec{R}/2$ [a.u.]


E_{vib} / eV
counts
v=3
v=2
v=1
v=0
R / a_0

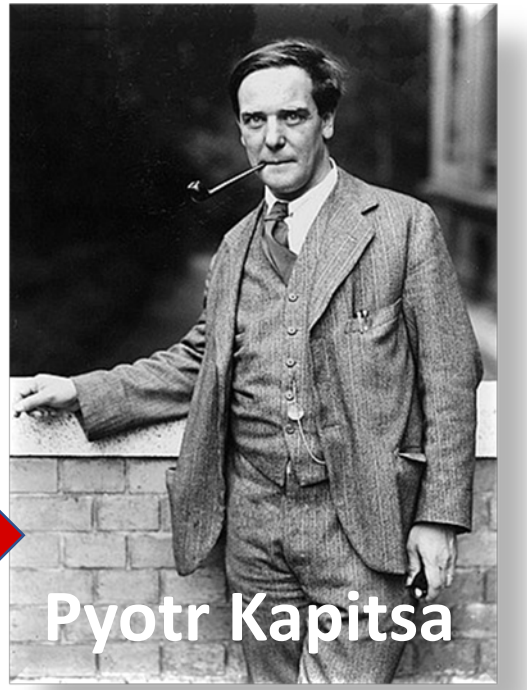

C6
N
C5
C2
I
C4
C3
NORMALIZED MOMENTUM (p_y)
NORMALIZED MOMENTUM (p_z)

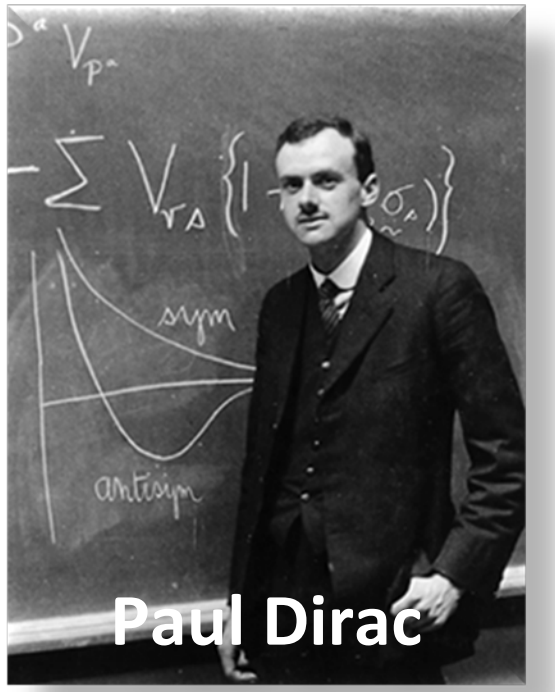


Compton Scattering

A.H. Compton Bulletin of the NRC No. 20 Vol. 4, Pt. 2 (1922)

Stimulated Compton Scattering



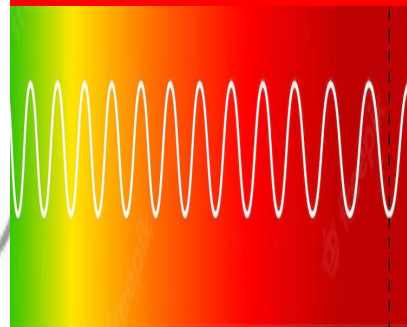


*P.L. Kapitza and P.A.M. Dirac Proc. Camb. Phil. Soc. **29** (2): 297 (1933)*

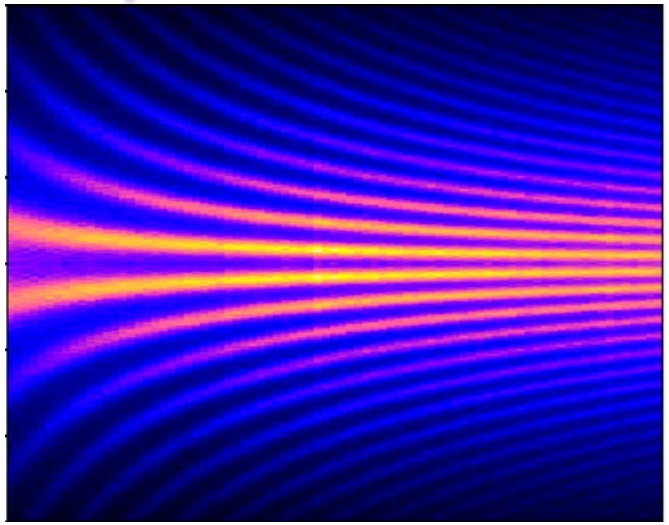
$\lambda = 0.03\text{nm}$
$E_\gamma = 40\ \text{keV}$
$k_\gamma = 12\ a.u.$

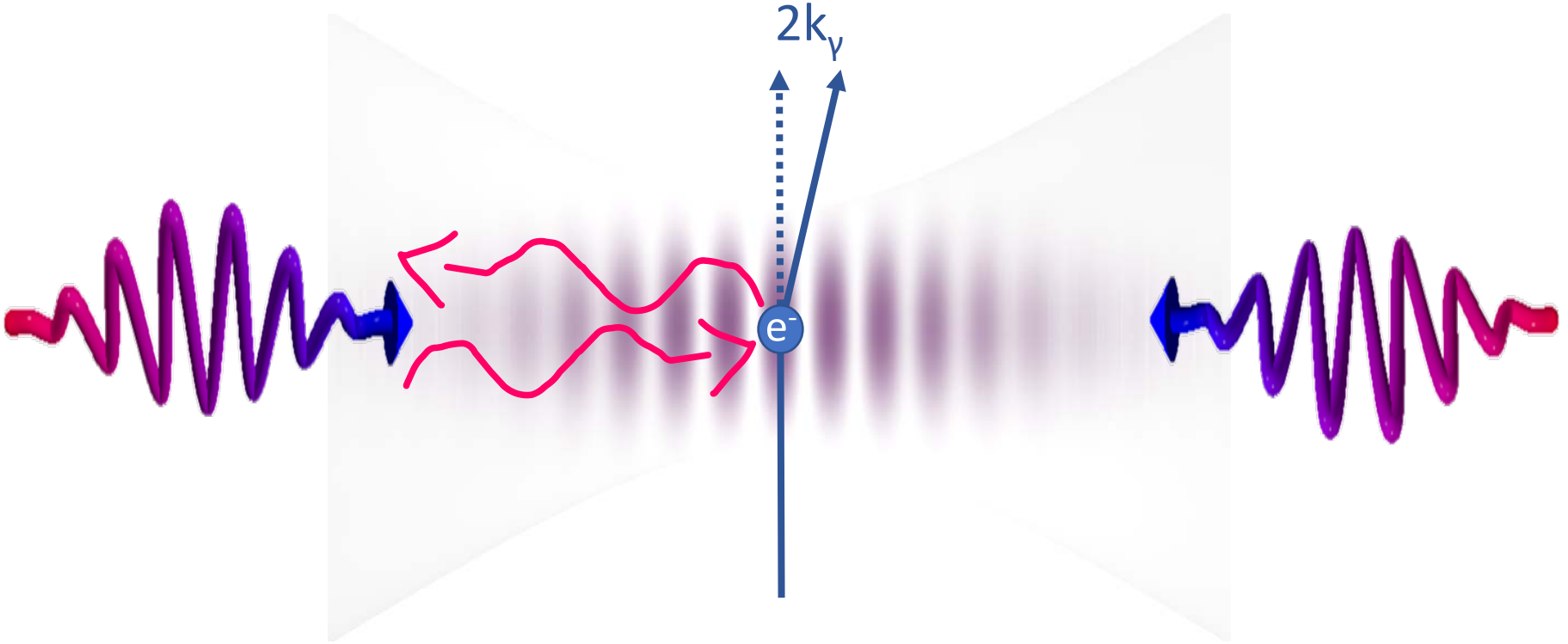
$$k_\gamma = \frac{E_\gamma}{c}$$

$\lambda = 800\text{nm}$
$E_\gamma = 1.5\ \text{eV}$
$k_\gamma = 4\ 10^{-4}\ a.u.$

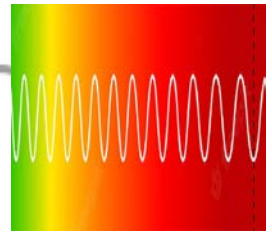


Stimulated Compton Scattering Kapitza Dirac Effect

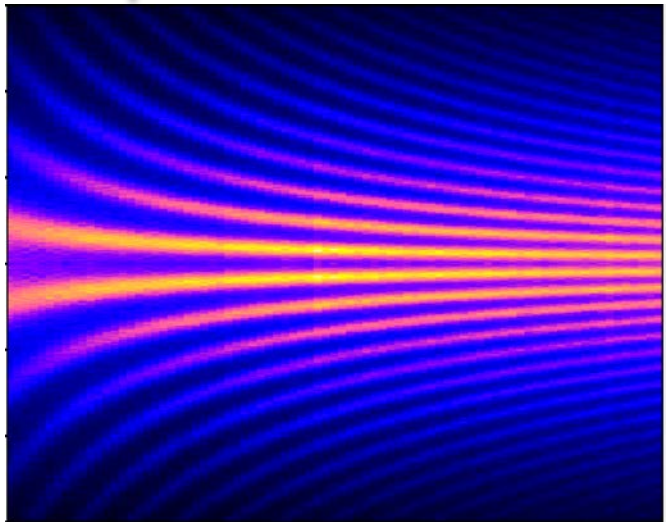


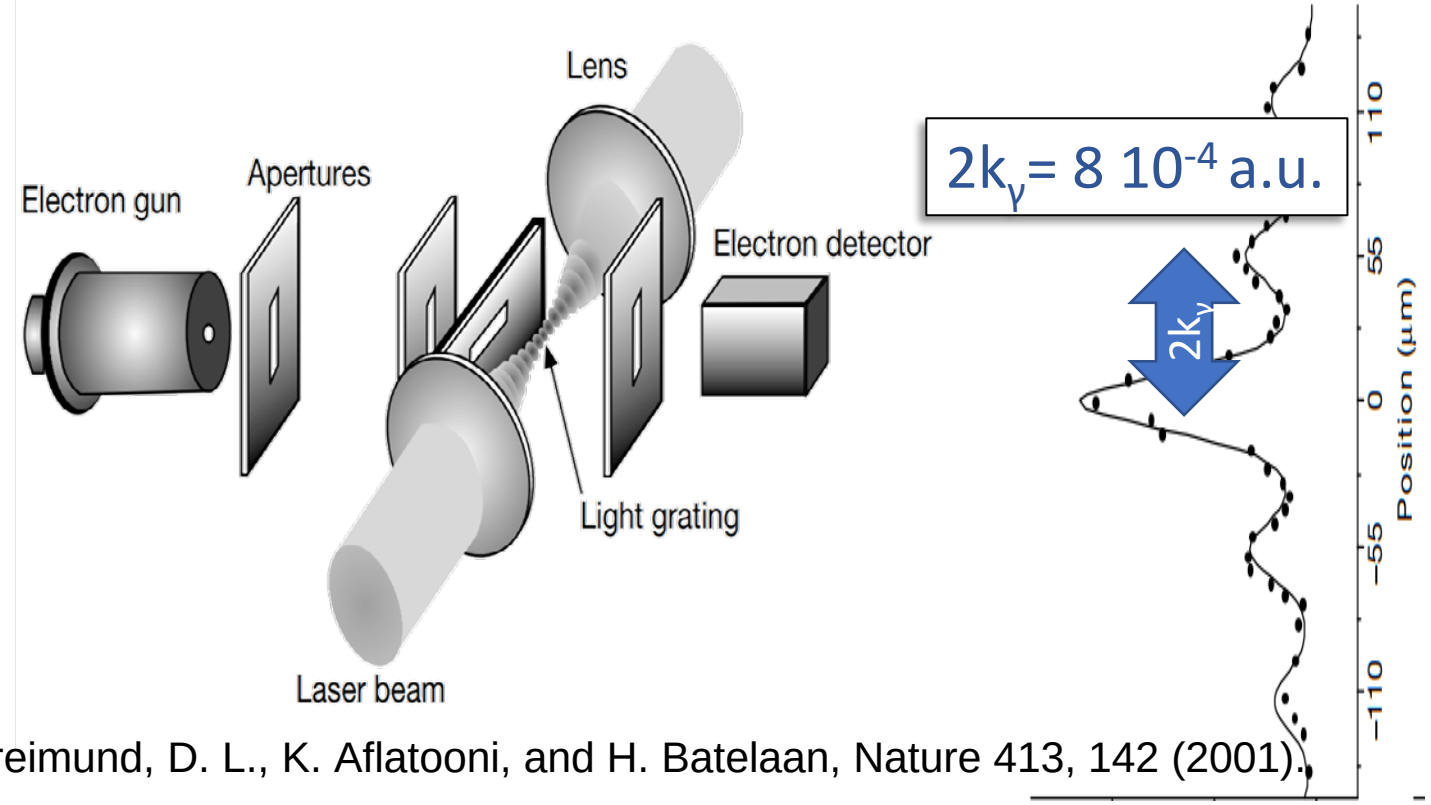


$$k_\gamma = \frac{E_\gamma}{c}$$



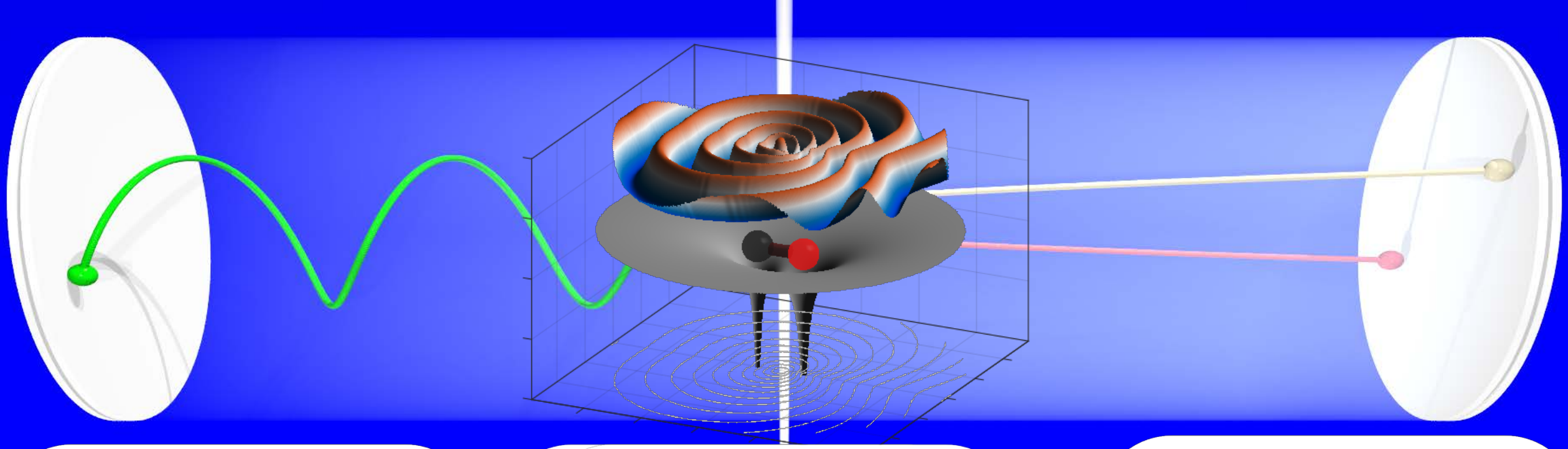
Stimulated Compton Scattering Kapitza Dirac Effect

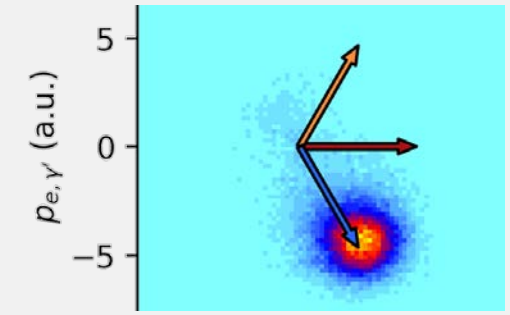


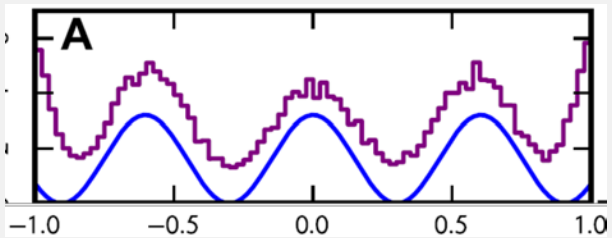


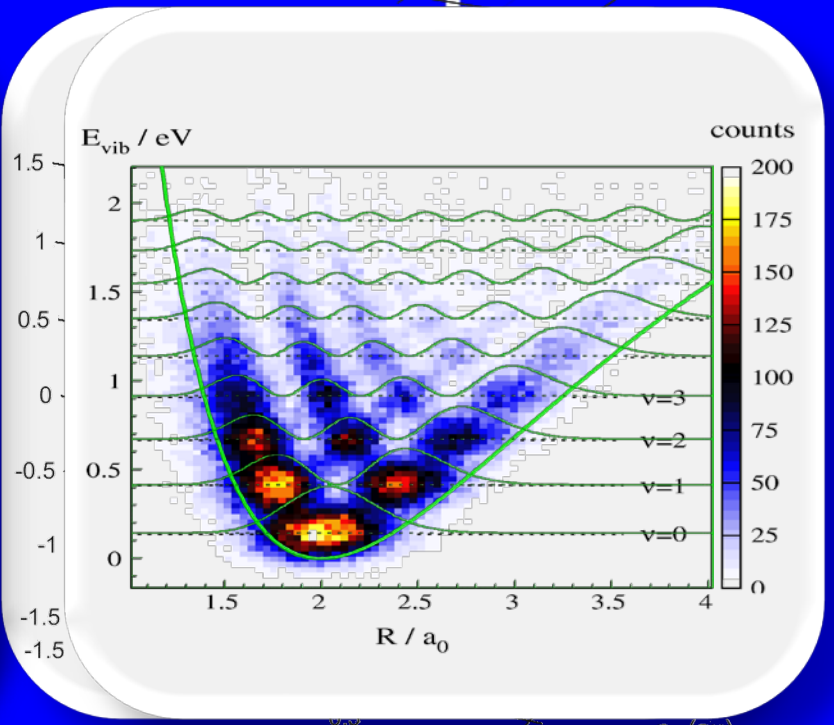
Freimund, D. L., K. Aflatooni, and H. Batelaan, Nature 413, 142 (2001).

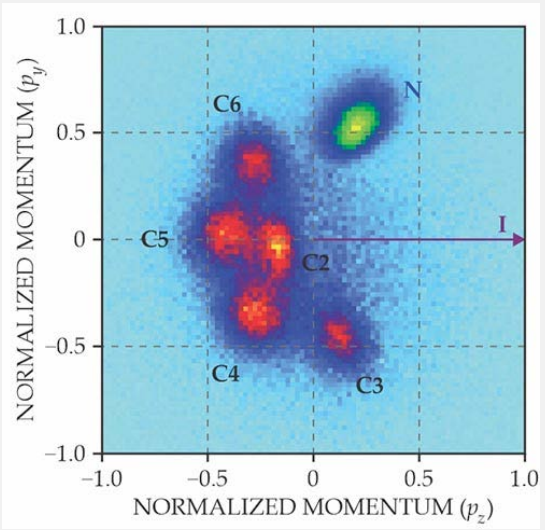
$$k_\gamma = \frac{E_\gamma}{c}$$

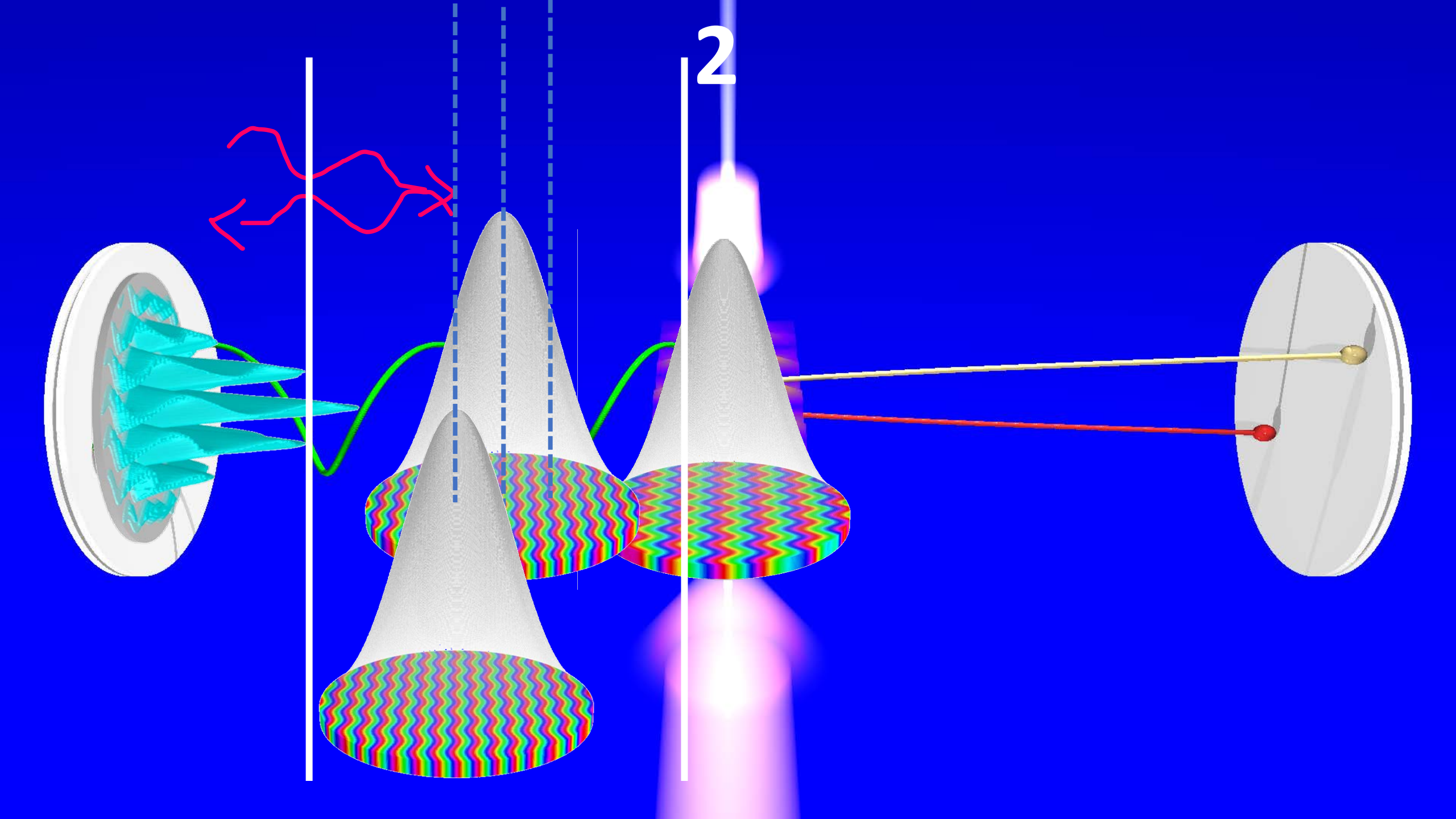



5
0
−5
$p_{e,y'}$ (a.u.)


A
−1.0
−0.5
0.0
0.5
1.0

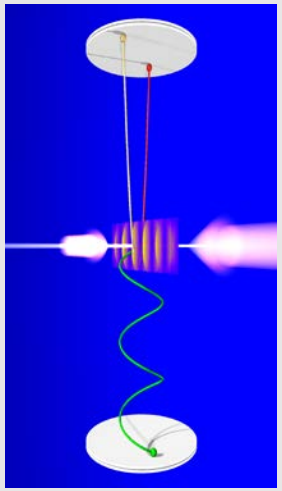

E_{vib} / eV
counts
200
175
150
125
100
75
50
25
0
v=3
v=2
v=1
v=0
1.5
2
2.5
3
3.5
4
R / a_0


1.0
0.5
0
−0.5
−1.0
NORMALIZED MOMENTUM (p_y)
C6
N
C5
I
C2
C4
C3
−1.0
−0.5
0
0.5
1.0
NORMALIZED MOMENTUM (p_z)


2

Pump:

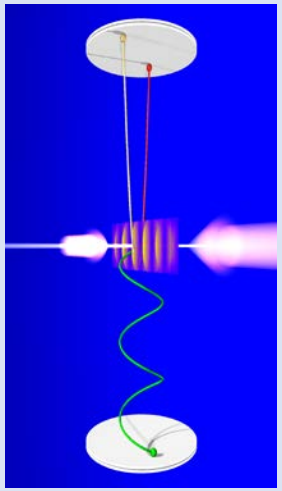
Ionization of Xe
800nm
standing wave

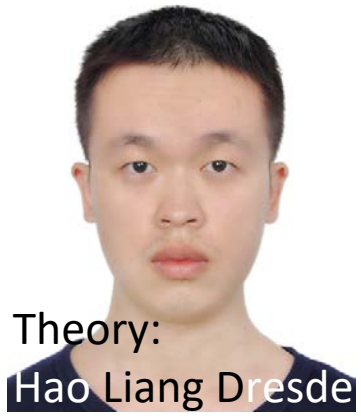


Delay (0-100 ps)

Probe:

800nm
standing wave
(weaker,
no ionization)

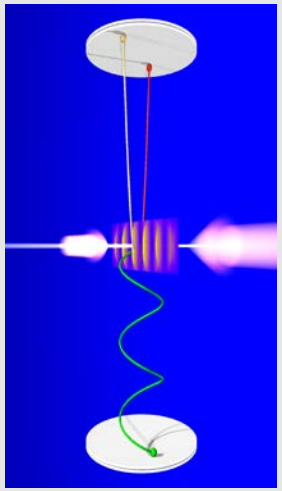




K. Lin et al Science 6690, 1467 (2024)

Pump:

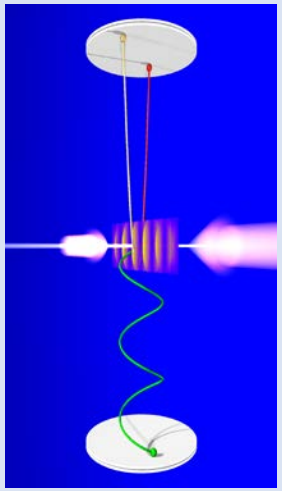
Ionization of Xe
800nm
standing wave

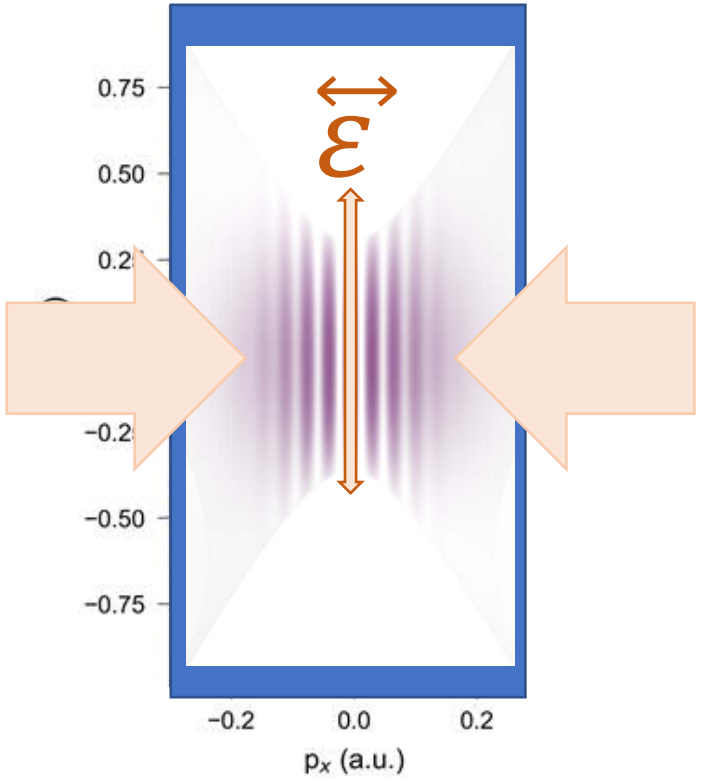


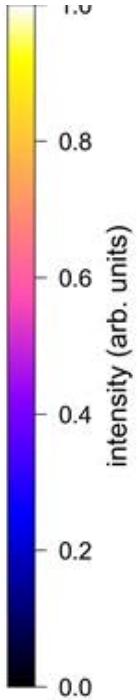
Delay (0-100 ps)

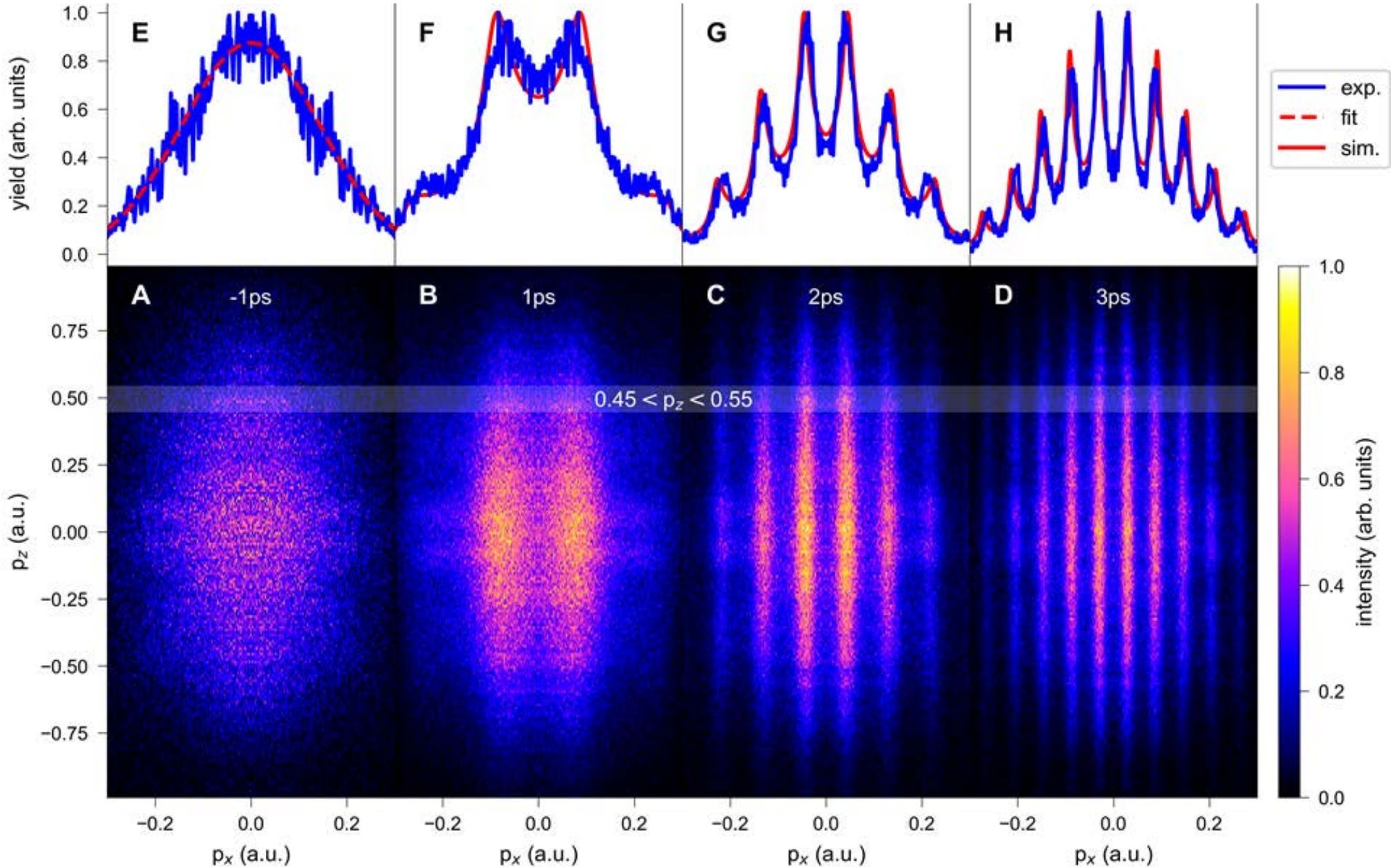
Probe:

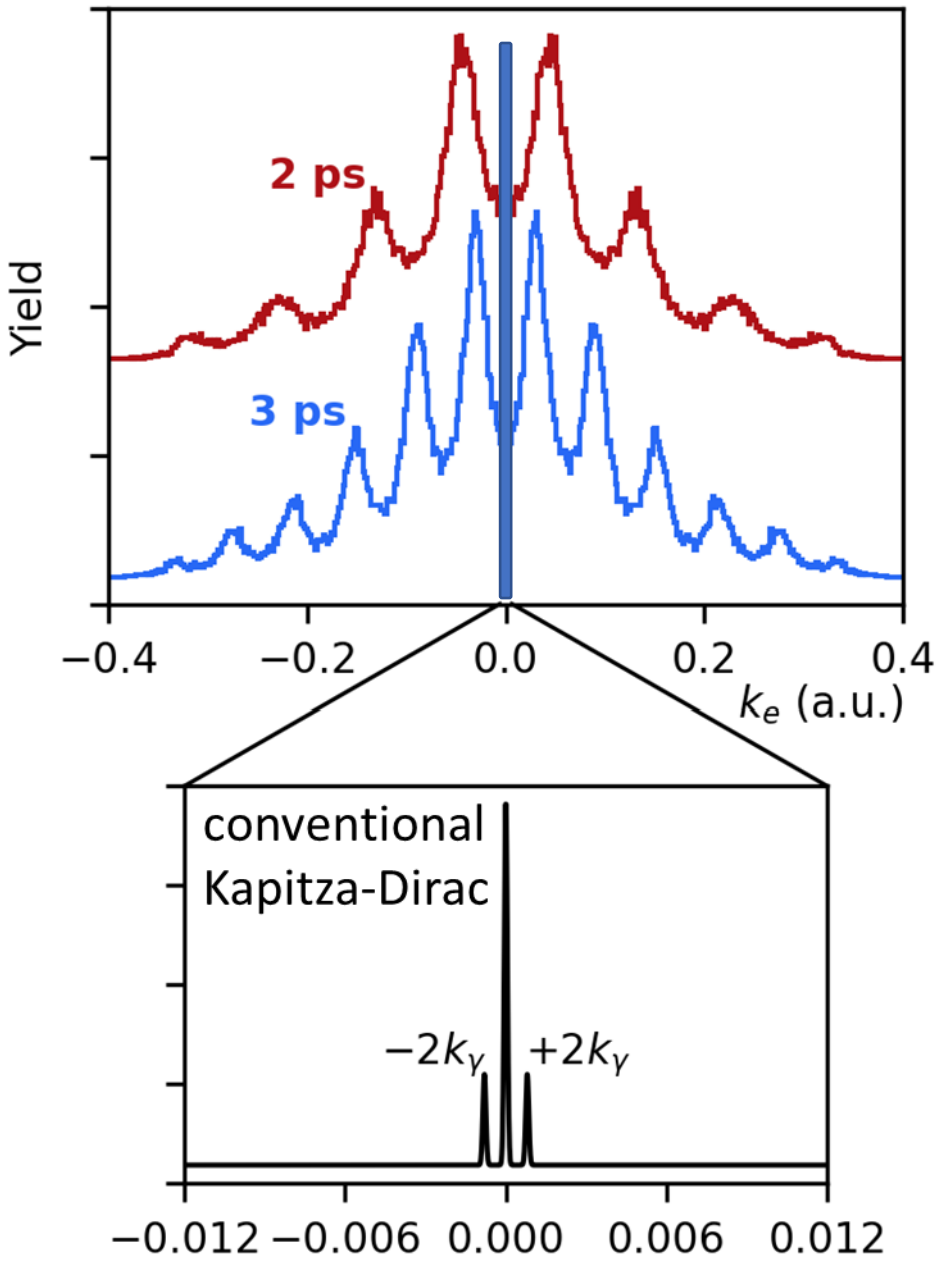
800nm
standing wave
(weaker,
no ionization)

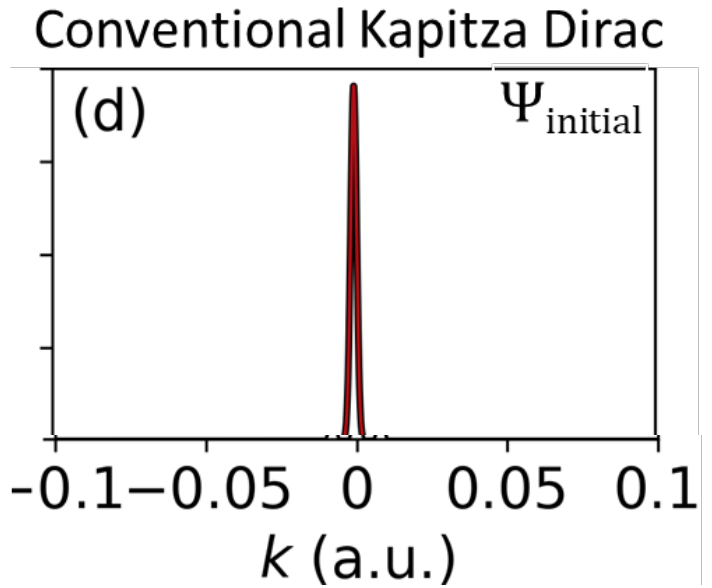




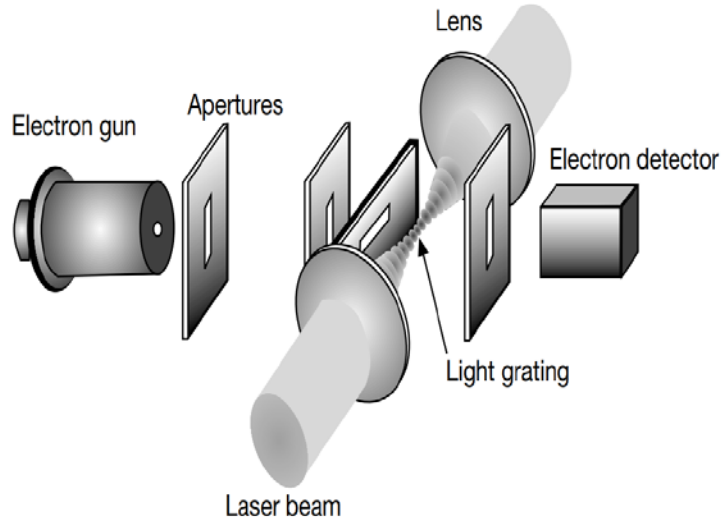


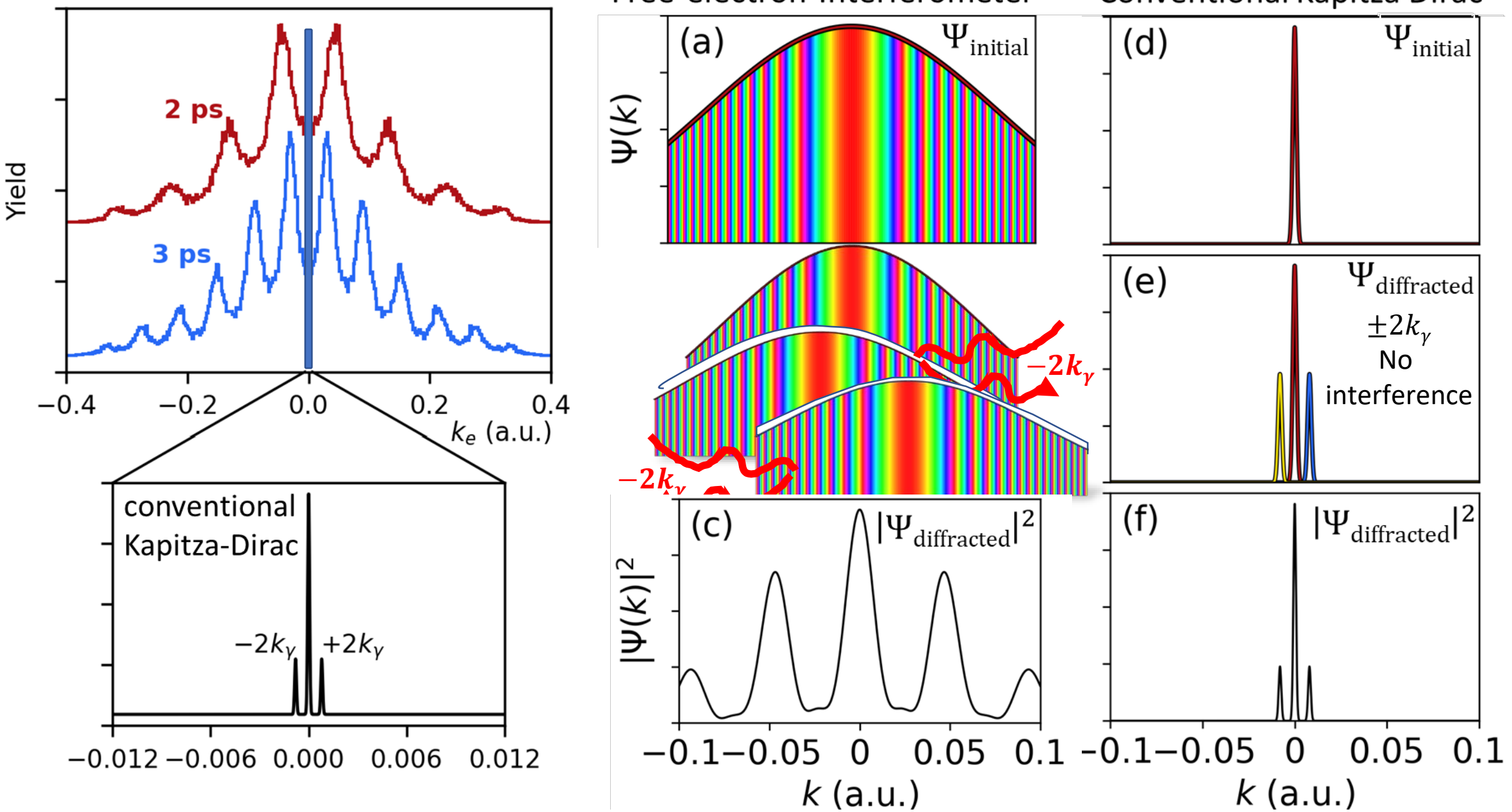

E
F
G
H
yield (arb. units)
1.0
0.8
0.6
0.4
0.2
0.0
exp.
fit
sim.
A
-1ps
B
1ps
C
2ps
D
3ps
0.45 < p_z < 0.55
p_z (a.u.)
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−0.2
0.0
0.2
p_x (a.u.)
intensity (arb. units)
1.0
0.8
0.6
0.4
0.2
0.0

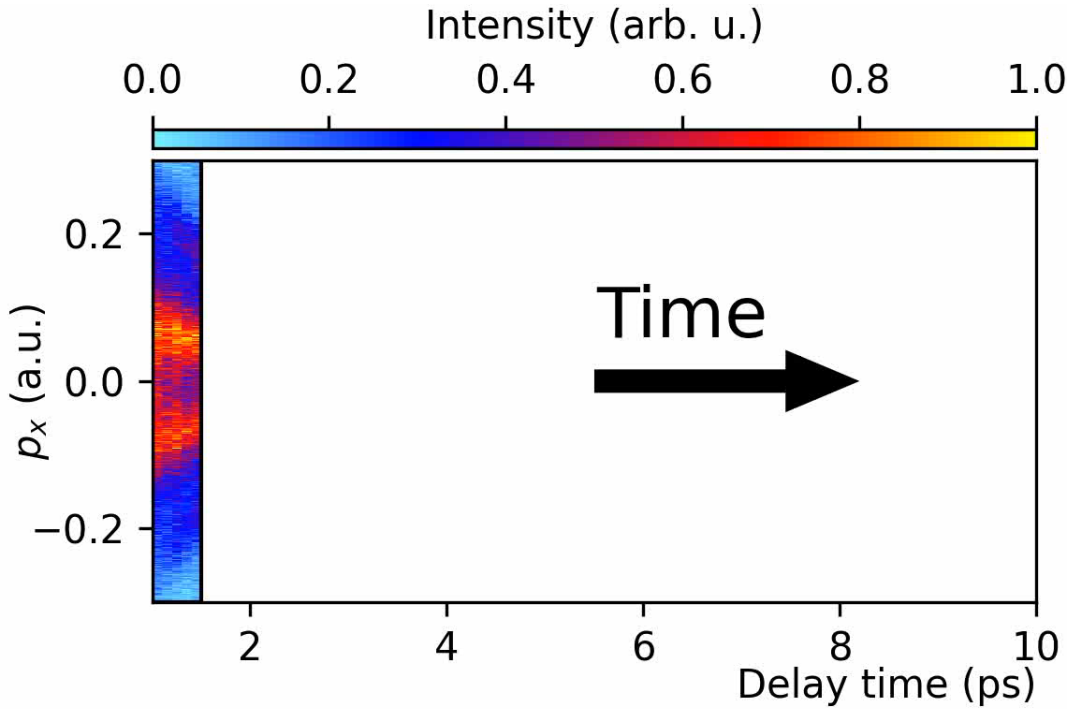


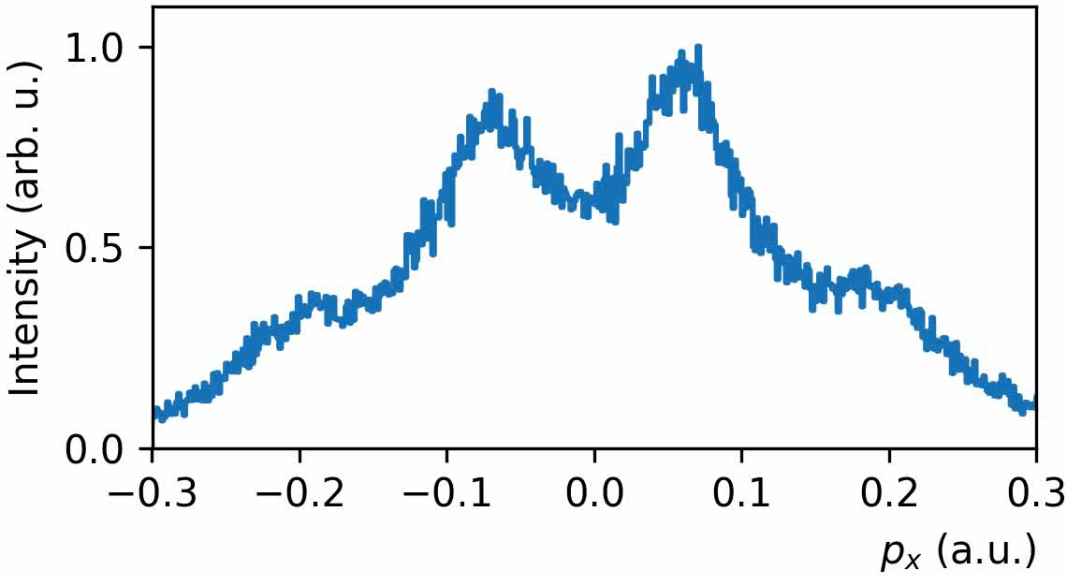


- Position: Plane wave
- Momentum: δ




Free-electron-Interferometer
Conventional Kapitza Dirac
Yield
2 ps
3 ps
−0.4
−0.2
0.0
0.2
0.4
k_e (a.u.)
conventional
Kapitza-Dirac
$-2k_\gamma$
$+2k_\gamma$
−0.012
−0.006
0.000
0.006
0.012
(a)
Ψ_{initial}
$\psi(k)$
$-2k_\gamma$
$-2k_\gamma$
(d)
Ψ_{initial}
(e)
$\Psi_{\text{diffracted}}$
$\pm 2k_\gamma$
No
interference
(c)
$|\Psi_{\text{diffracted}}|^2$
$|\Psi(k)|^2$
−0.1
−0.05
0
0.05
0.1
k (a.u.)
(f)
$|\Psi_{\text{diffracted}}|^2$
−0.1
−0.05
0
0.05
0.1
k (a.u.)





$$\Psi_1(k,t) \propto e^{\frac{ik^2}{2}t}$$

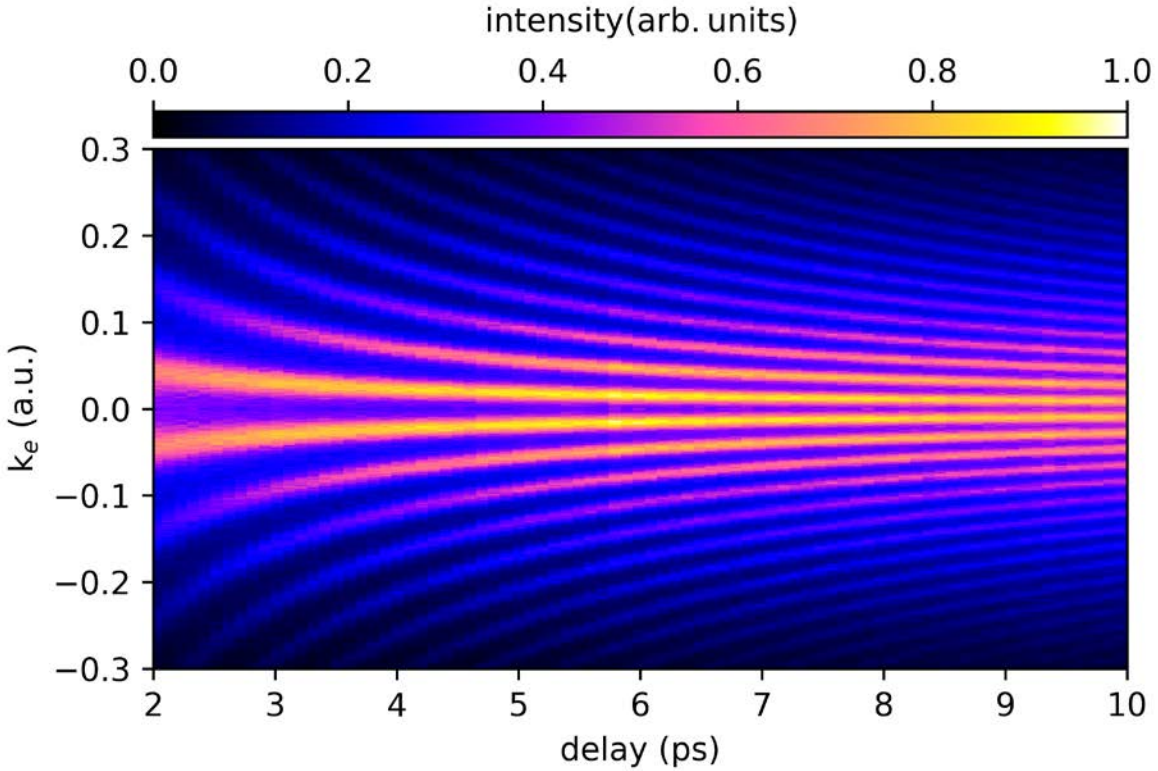
$$\Psi_2(k,t) \propto e^{\frac{i(k-2k_\gamma)^2}{2}t}$$

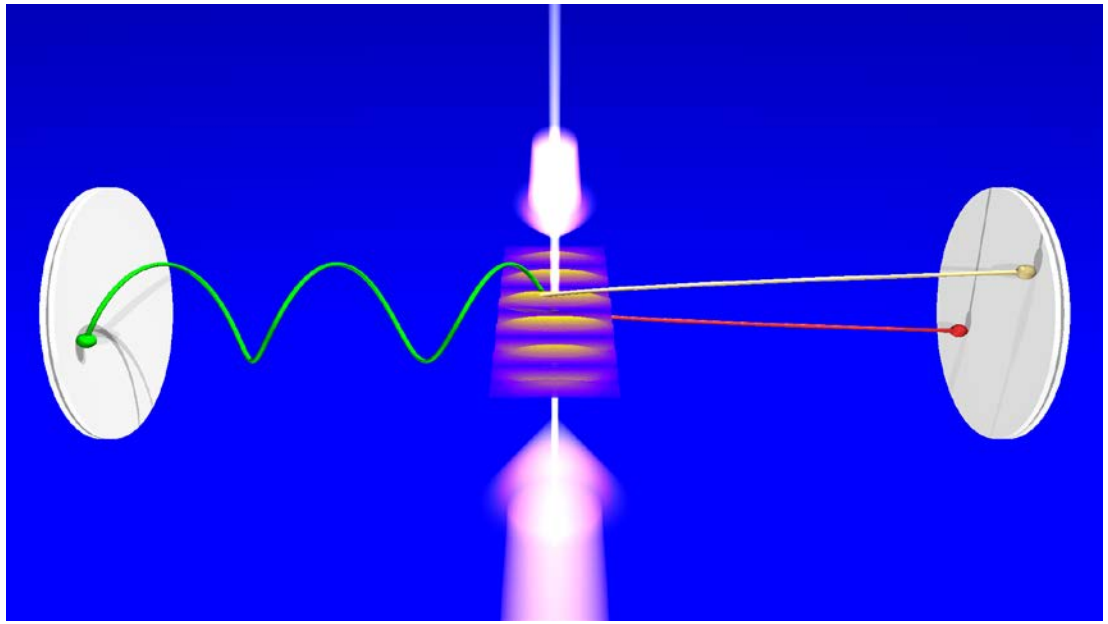
$$\Psi_3(k,t) \propto e^{\frac{i(k+2k_\gamma)^2}{2}t}$$

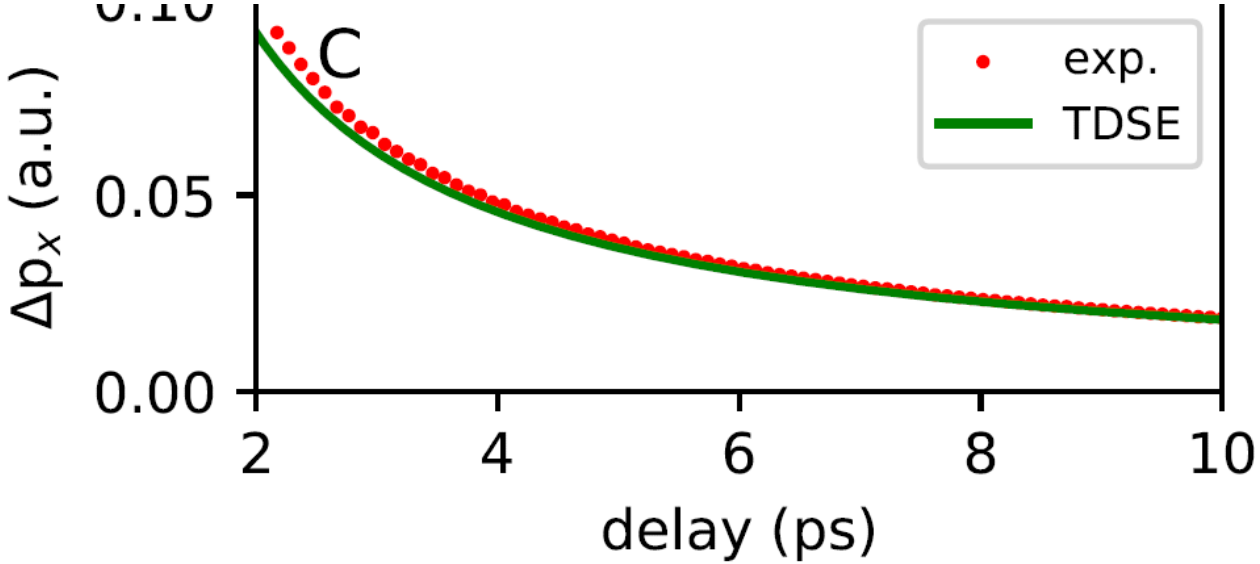
$$|\Psi_1(k,t) + \Psi_2(k,t) + \Psi_3(k,t)|^2$$

$$\propto \cos^2(\boldsymbol{k}\, k_\gamma\, t) + \ldots$$

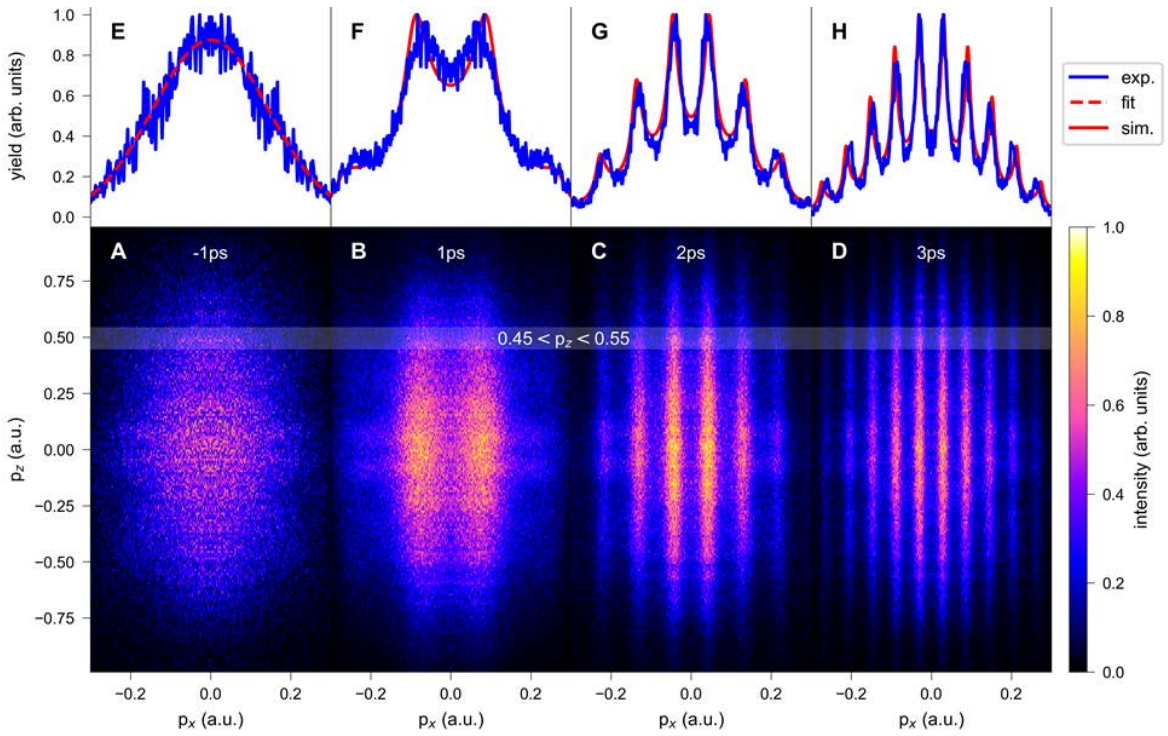
Fringe spacing 1/t

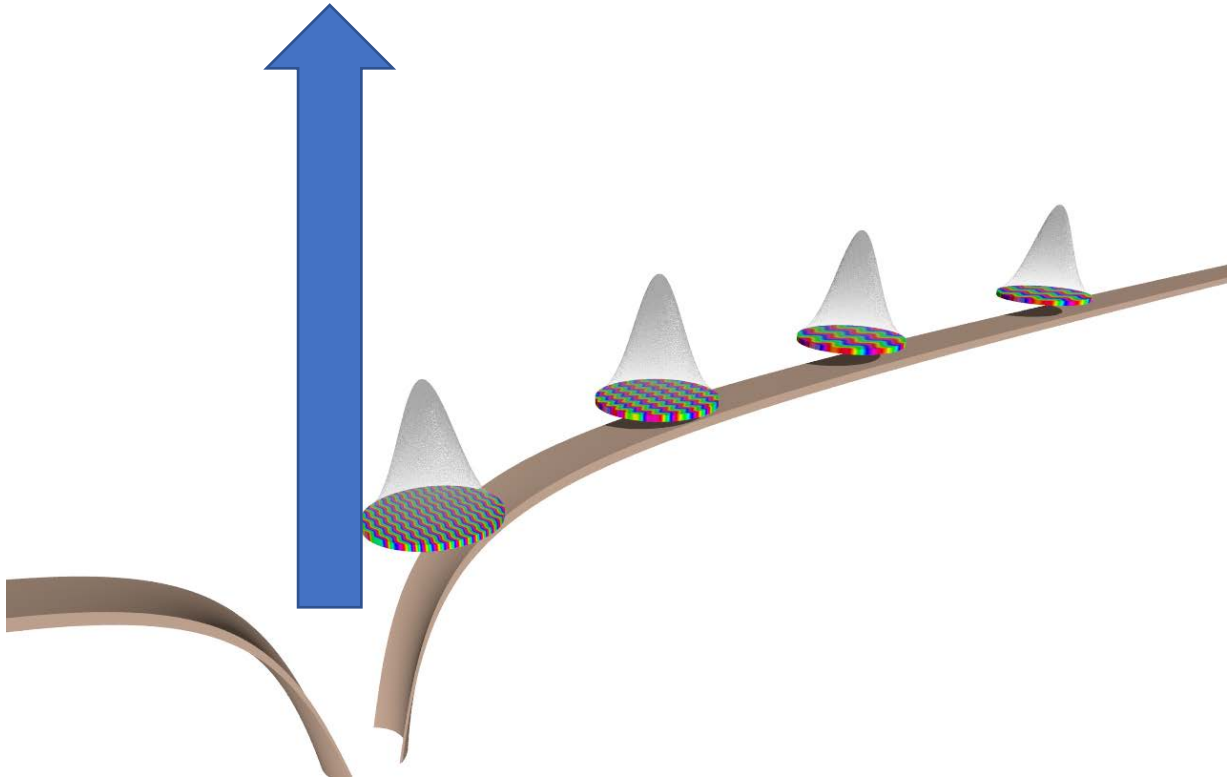






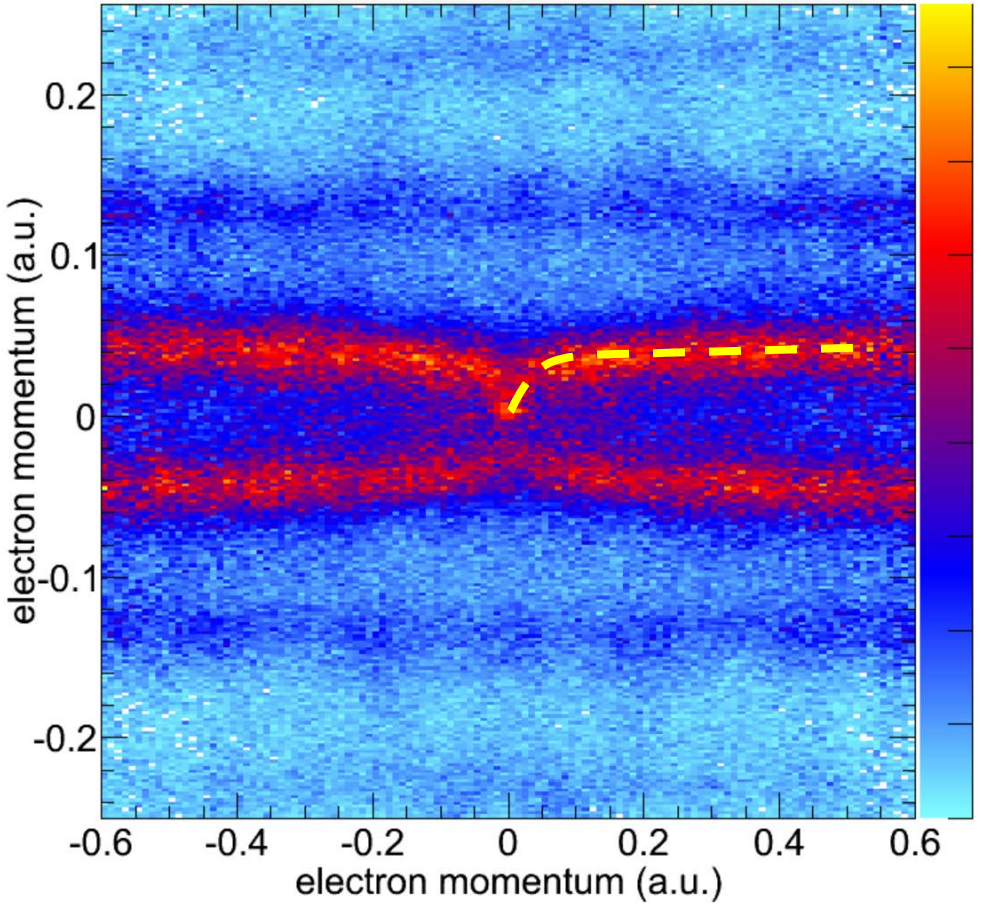
Phase of a **freely** propagating electron

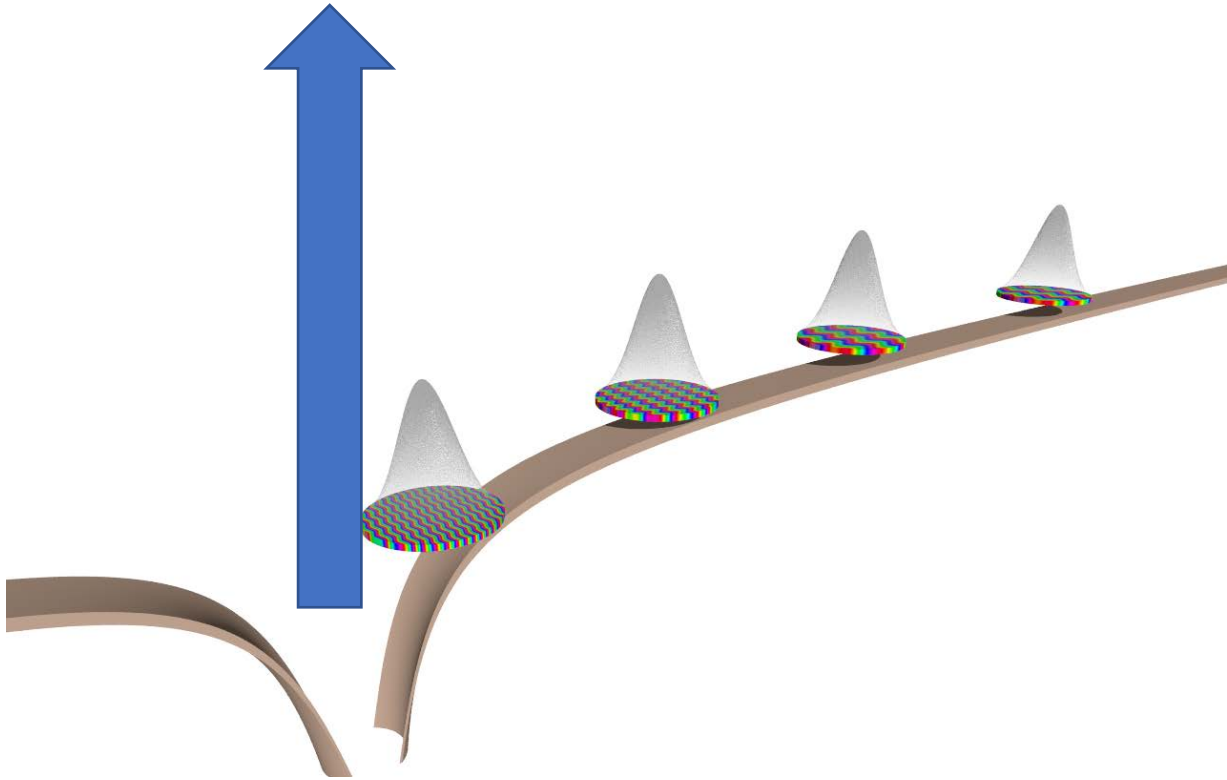




Phase of a **freely** propagating electron

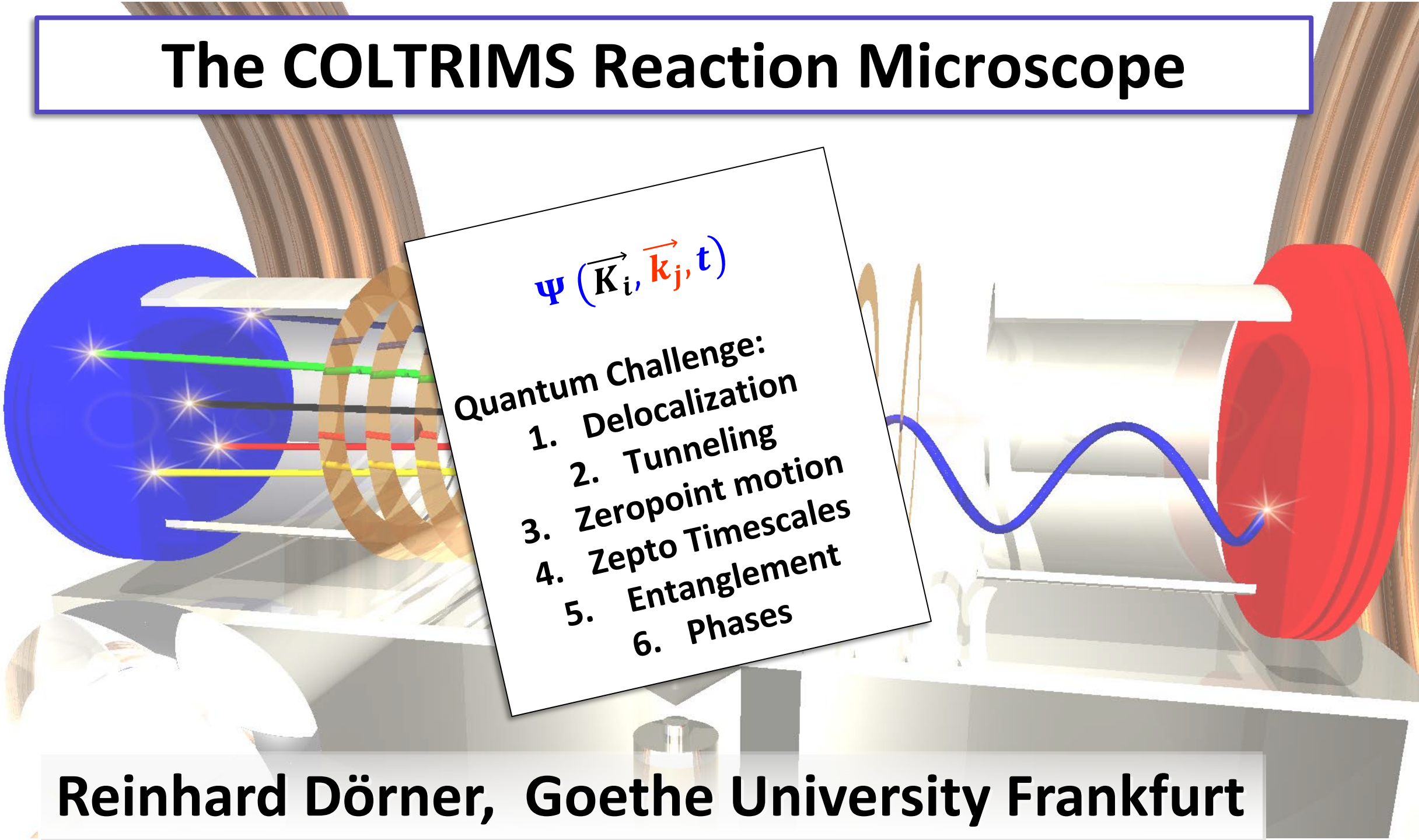
Phase of an electron climbing up a Potential





Phase of a ~~freely~~ propagating electron

The COLTRIMS Reaction Microscope



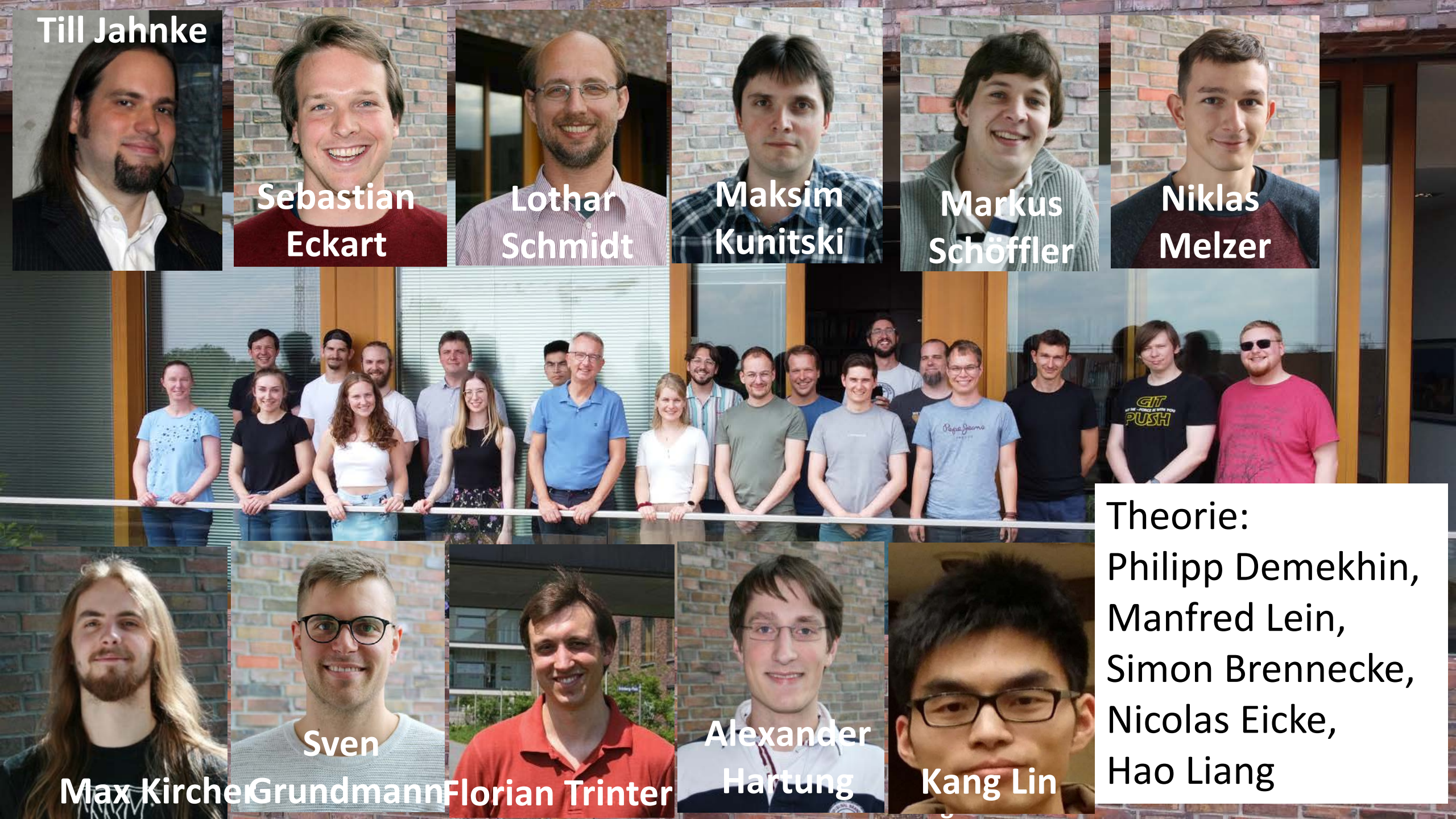
$\Psi\left(\vec{K}_i, \vec{k}_j, t\right)$

Quantum Challenge:

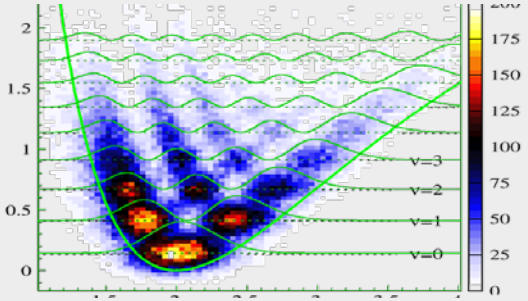
1. Delocalization
2. Tunneling
3. Zeropoint motion
4. Zepto Timescales
5. Entanglement
6. Phases

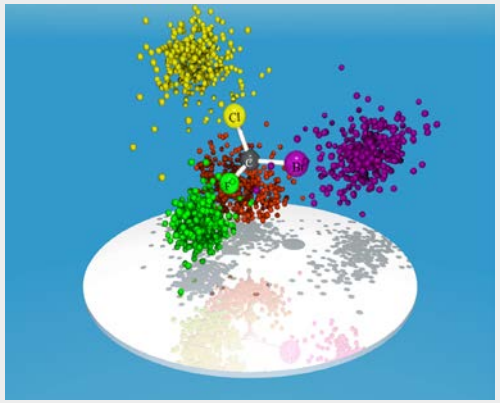
Reinhard Dörner, Goethe University Frankfurt


GIT
PUSH

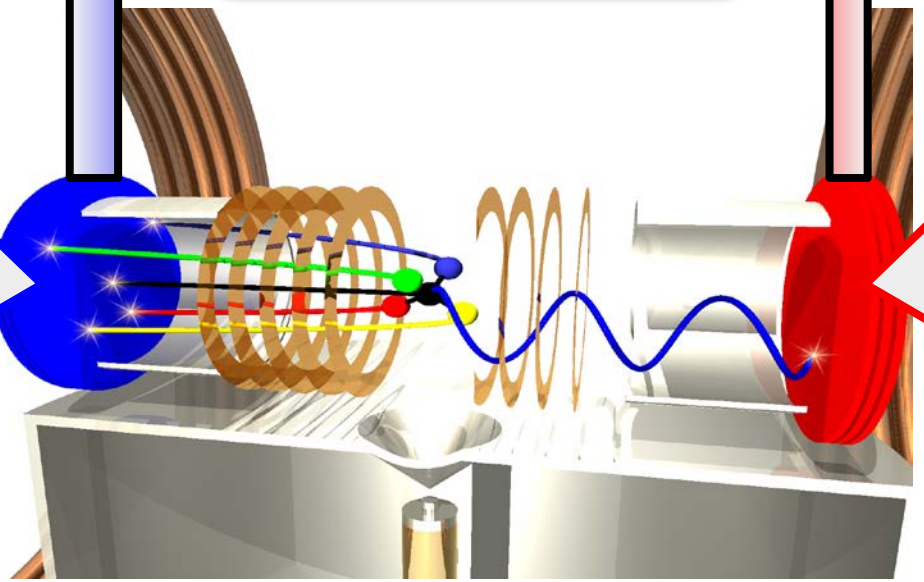

Till Jahnke
Sebastian Eckart
Lothar Schmidt
Maksim Kunitski
Markus Schöffler
Niklas Melzer
Max Kircher
Sven Grundmann
Florian Trinter
Alexander Hartung
Kang Lin
Theorie:
Philipp Demekhin,
Manfred Lein,
Simon Brennecke,
Nicolas Eicke,
Hao Liang

Coulomb Explosion Imaging





$|\Psi(\vec{R_i}, \vec{r_j}, t)|^2$



- Zeptoseconds
- Entanglement
- Ultrafast Kapitza Dirac Effect