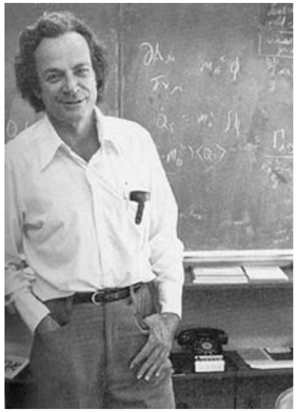
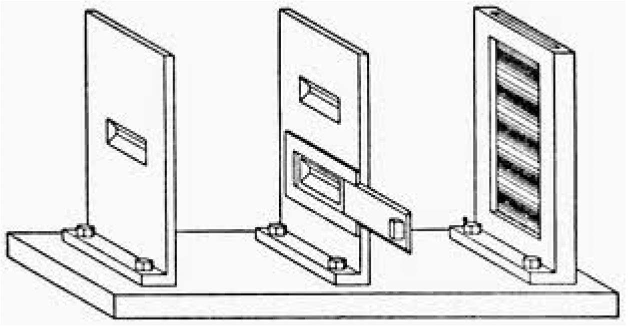
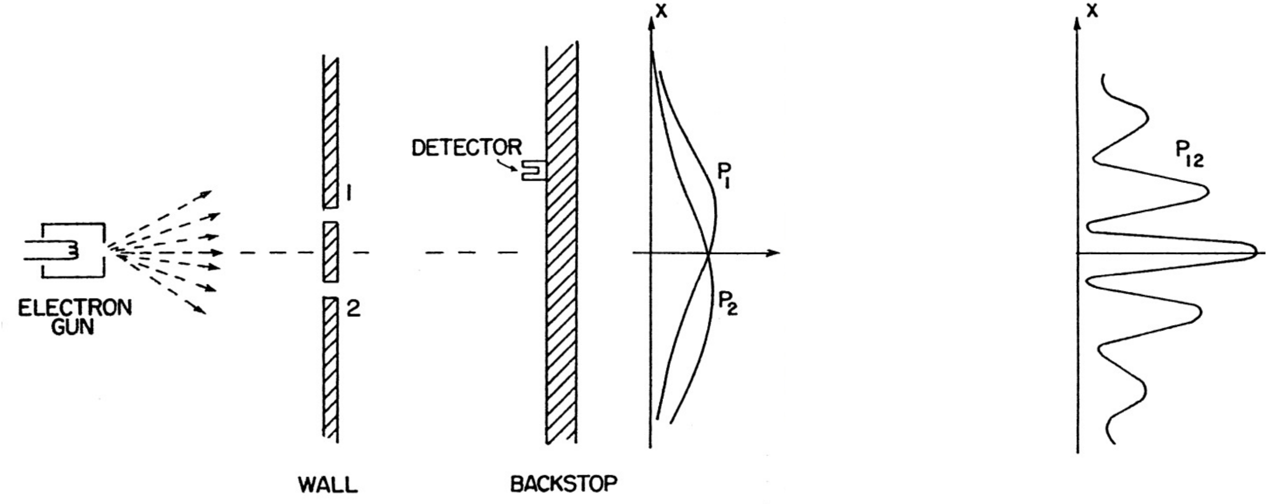


Controlled double slit diffraction

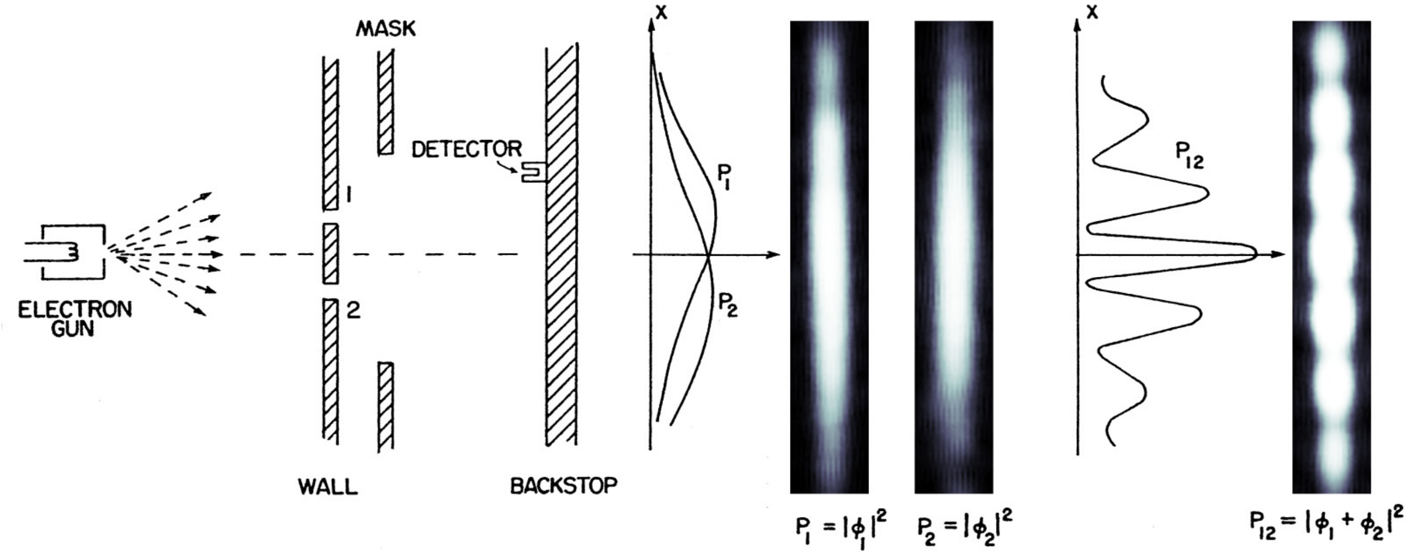


Herman Batelaan

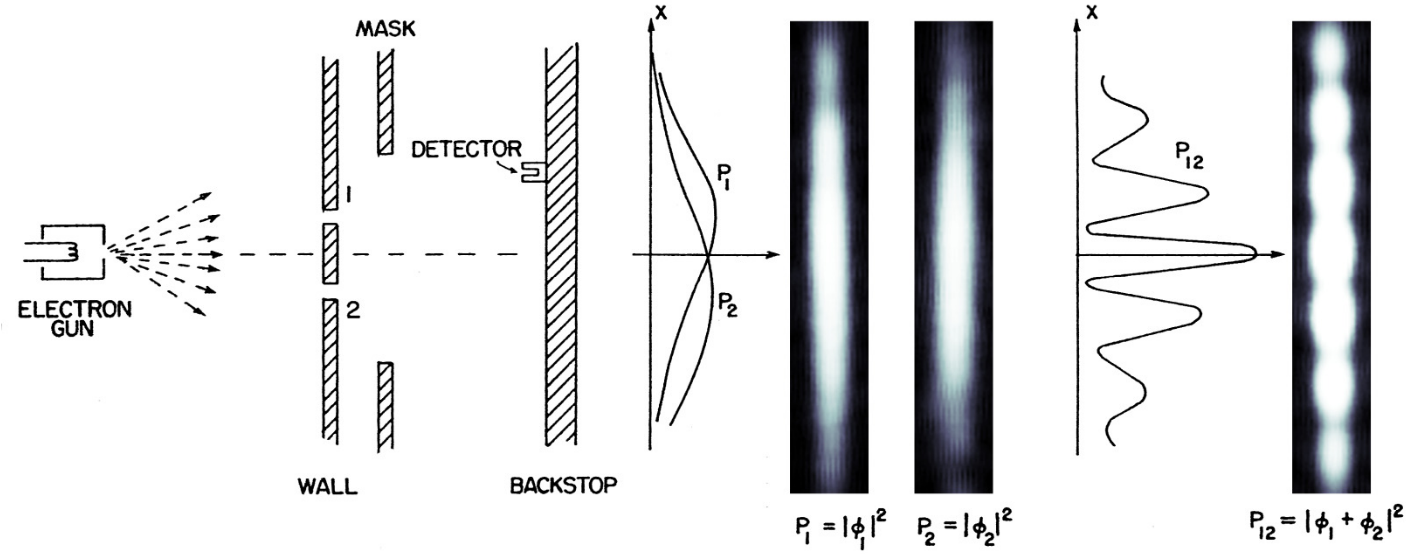


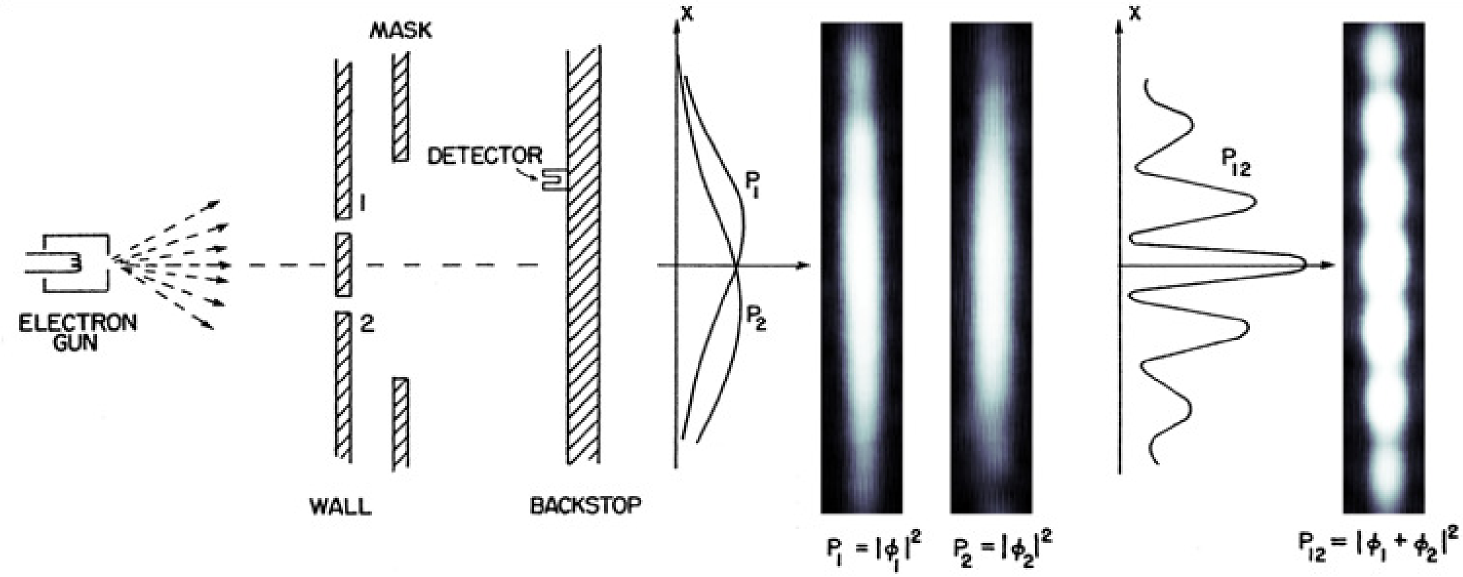
From: Feynman Lectures of Physics,
Vol III, Chapter 1.

“We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the only mystery….”

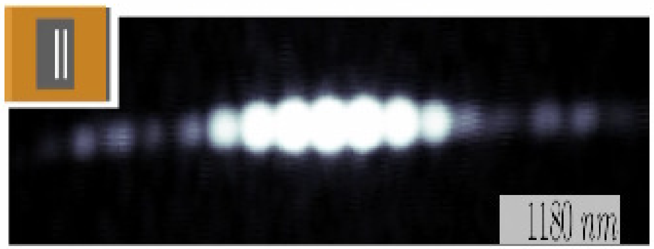


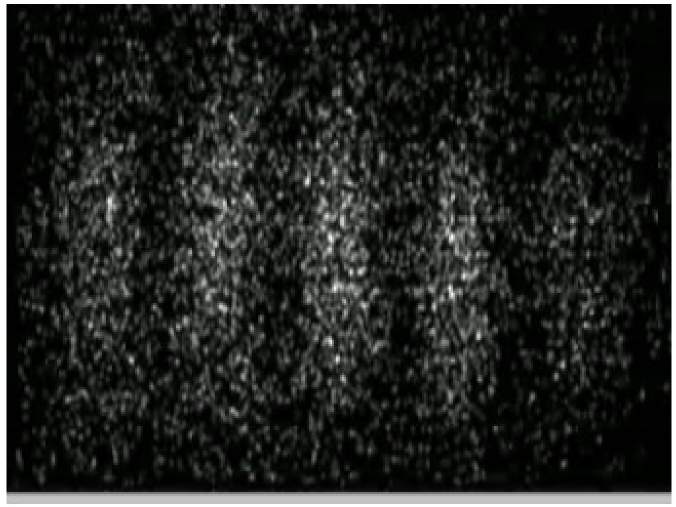
Motivated by outreach for highschool educational movie.
Damian Pope from Perimeter Institute.


MASK
DETECTOR
1
2
ELECTRON
GUN
WALL
BACKSTOP
x
P1
P2
P12
P1 = |φ1|^2
P2 = |φ2|^2
P12 = |φ1 + φ2|^2

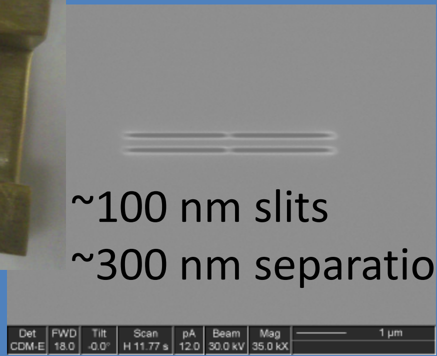


"We should say right away that you should not try to set up this experiment. This experiment has never been done in just this way. The trouble is that the apparatus would have to be made on an impossibly small scale to show the effects we are interested in.“[1]



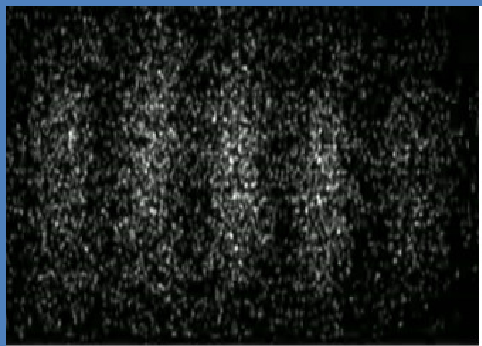


Double slit electron interference



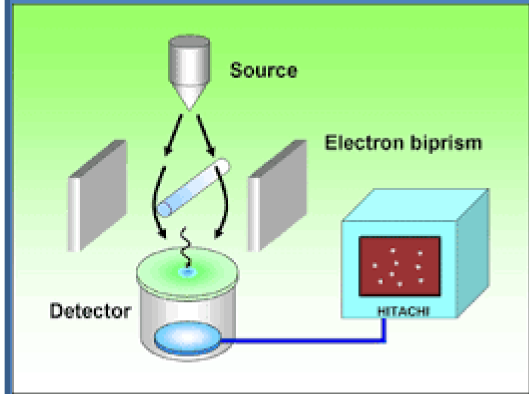
~100 nm slits
~300 nm separation

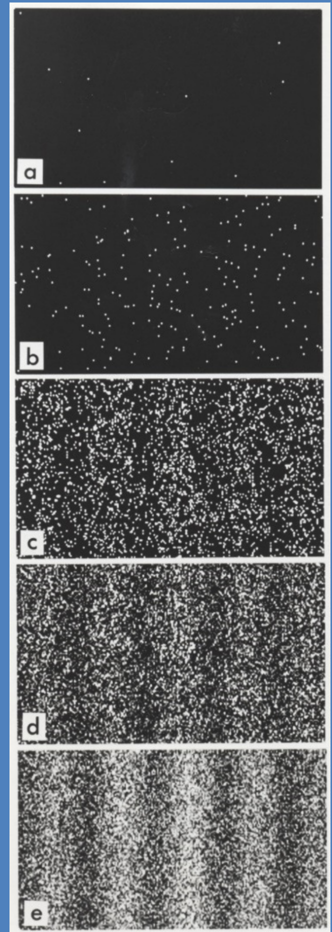
Roger Bach



R. Bach, D. Pope, S. H. Liou, H. Batelaan, New.J.Phys. 15 033018 (2013)

Biprism electron interference

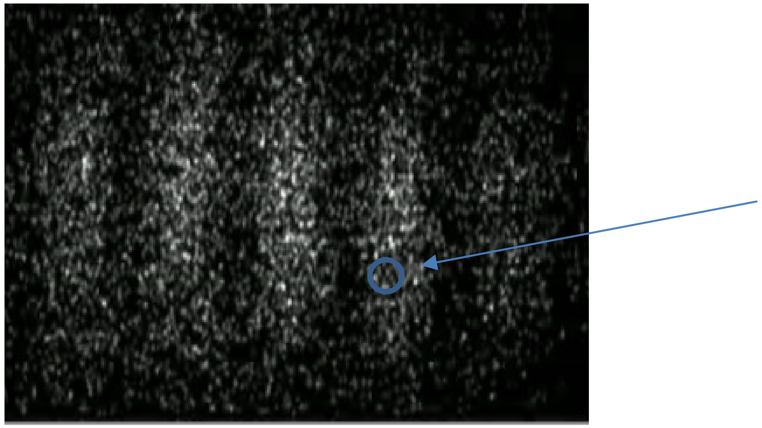




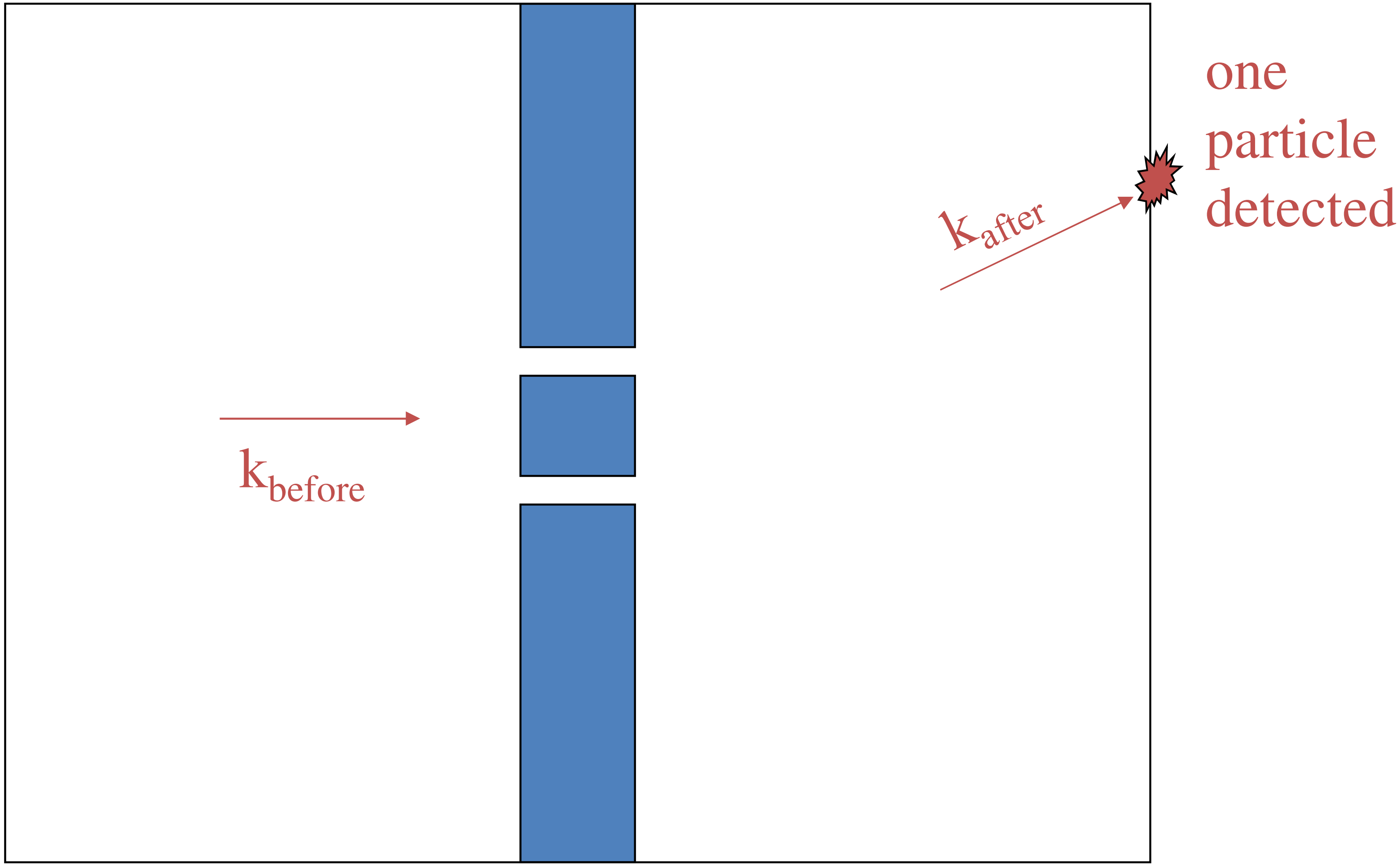
Akira Tonomura

A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki and H. Ezawa. 1989. Demonstration of single-electron build-up of an interference pattern. *American Journal of Physics.* **57.** 117-120.

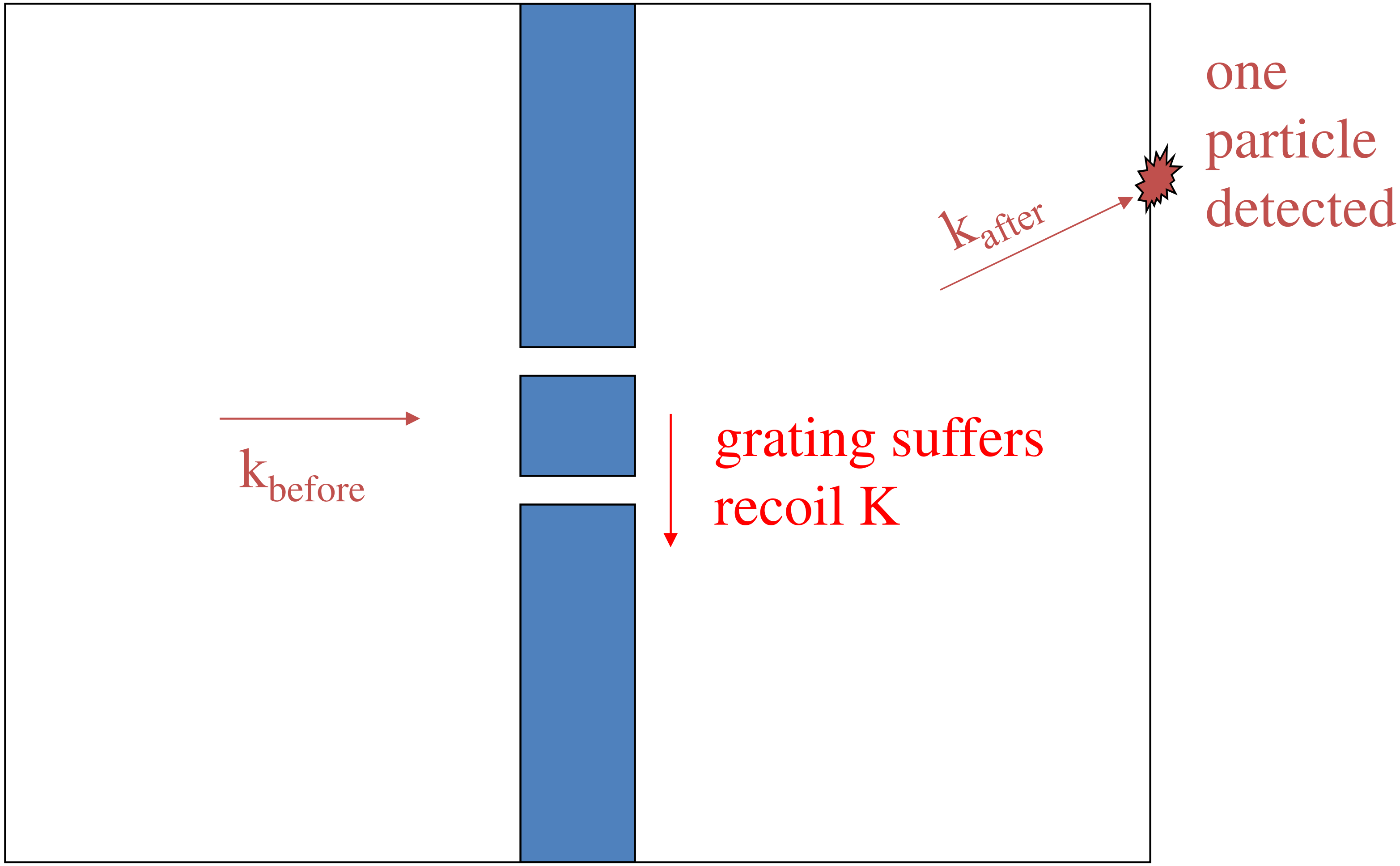
Let’s stop the experiment after the first electron has landed



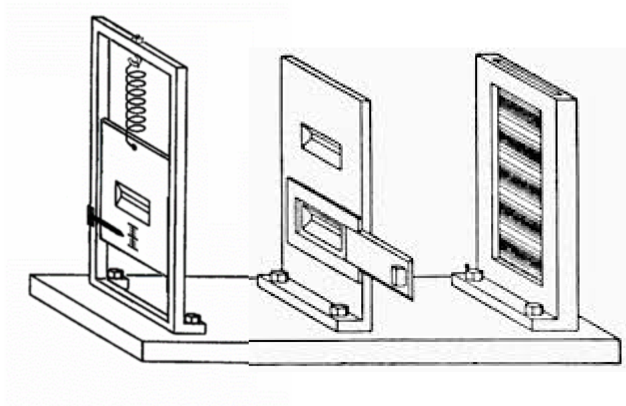
This is where it happened to land in our experiment



Is momentum conserved?

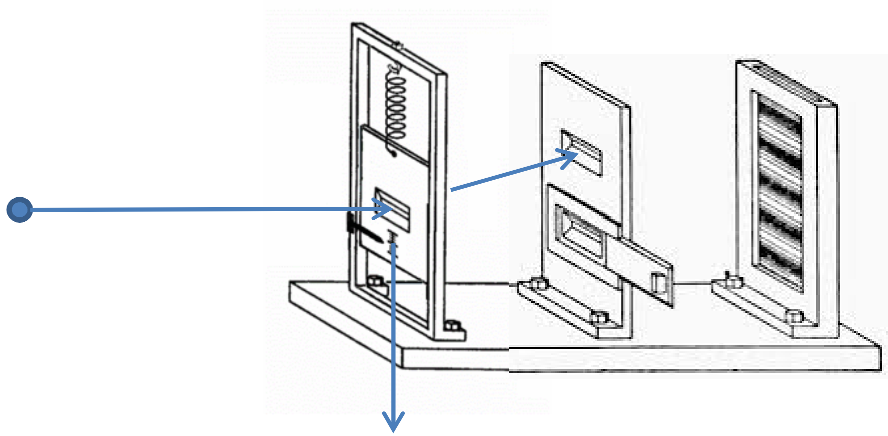


Momentum conservation…Is this what happens?



Einstein: measure the recoil of the first collimating slit and then we know which slit the particle went through and still have the interference pattern.

Einstein-Bohr dialogue



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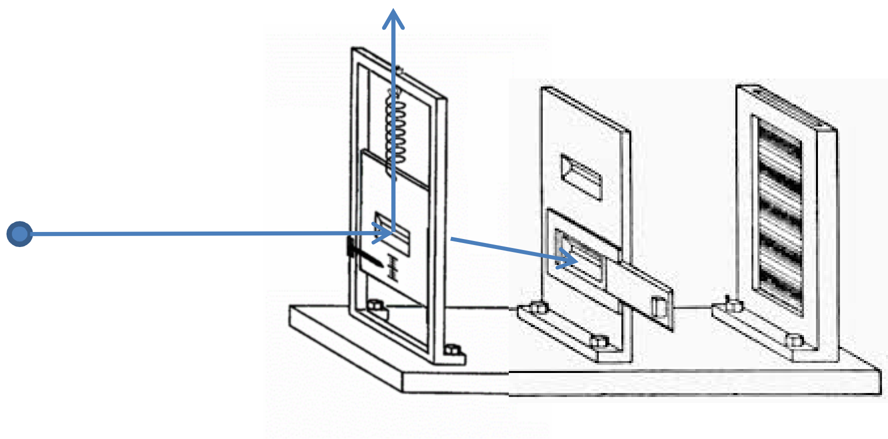

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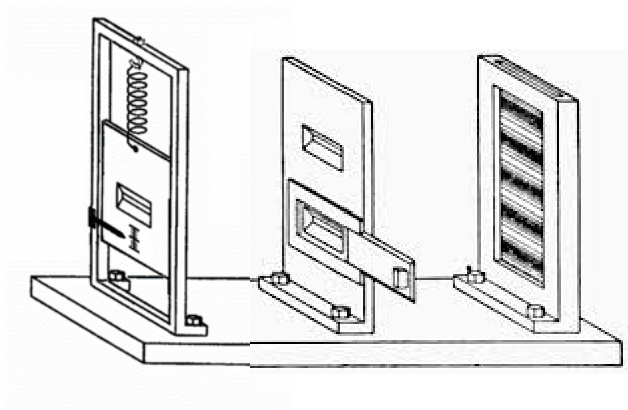
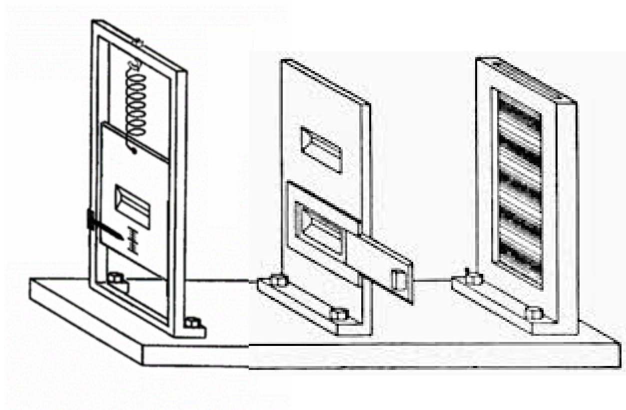


Einstein-Bohr dialogue

Einstein: measure the recoil of the first collimating slit and then we know which slit the particle went through and still have the interference pattern.

Bohr: $\Delta x \Delta p \geq \mathrm{h}$

Know the position of slit only up to Δx.
Not good enough to determine which slit…



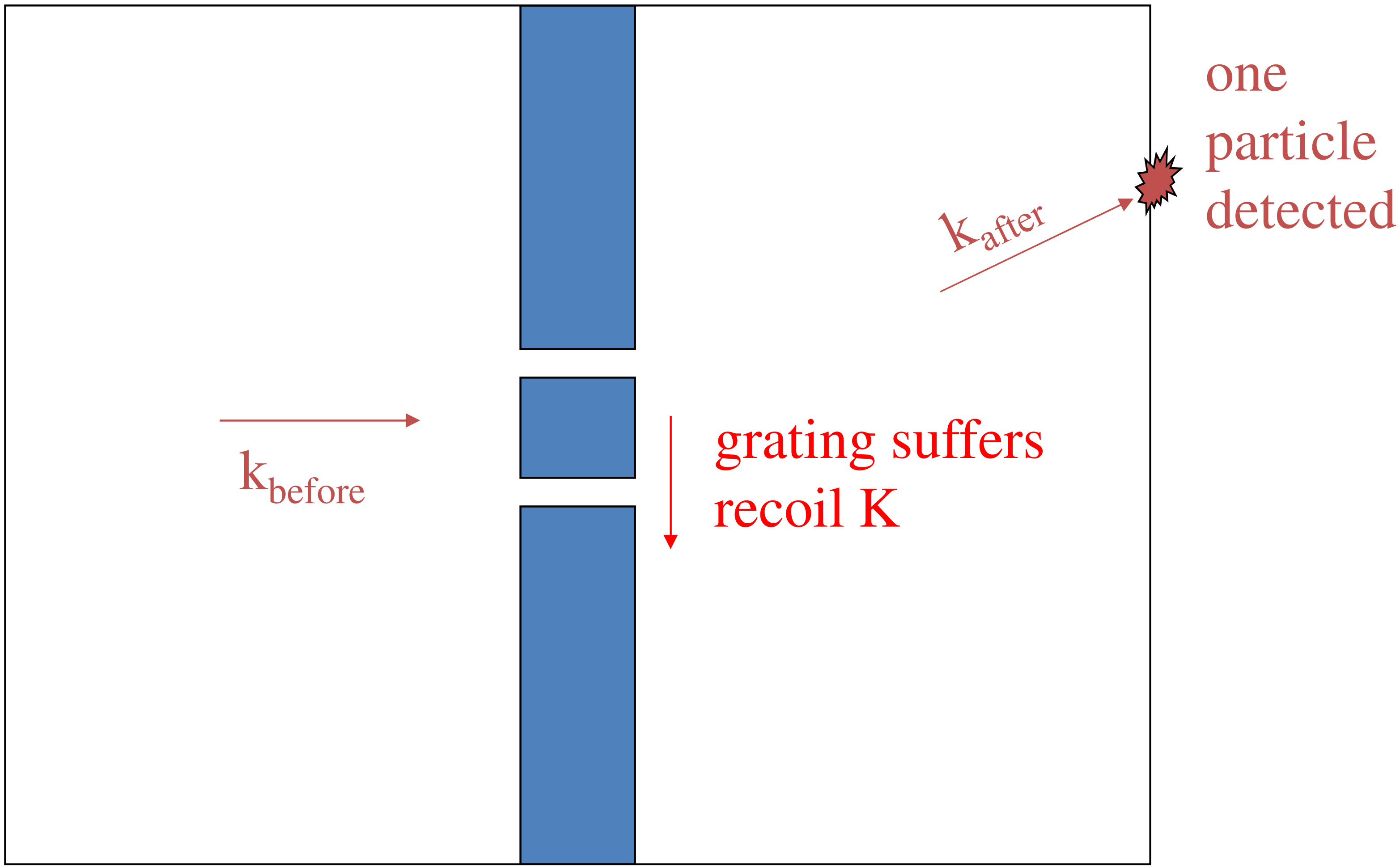
Einstein-Bohr dialogue

Einstein: measure the recoil of the first collimating slit and then we know which slit the particle went through and still have the interference pattern.

Bohr: $\Delta x \Delta p \geq \mathrm{h}$

Know the position of slit only up to $\Delta x = hbar/\Delta p$. Not good enough to determine which slit…

But both assume momentum exchange between electron and slit, as do Wooters and Zurek in their analysis decades later



What interaction caused the momentum exchange between the electron and the grating?

Answers:

1. “Electrons reflect from the bar edges”

2. “Phonons are excited in the grating”

3. “Vacuum field photons scatter the electrons and the grating imposes boundary conditions on that field”

4. “The electron’s field acts on the grating which back-acts on the electron”

5. “This is not a question one should ask”

6. “I calculated this, but never published it”

Comments:

1. “What about neutrons or photons?”

Answers:

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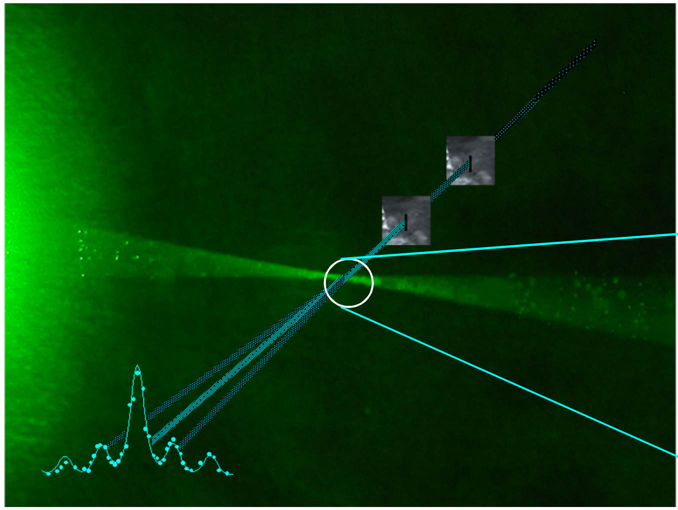
6. “I calculated this, but never published it”

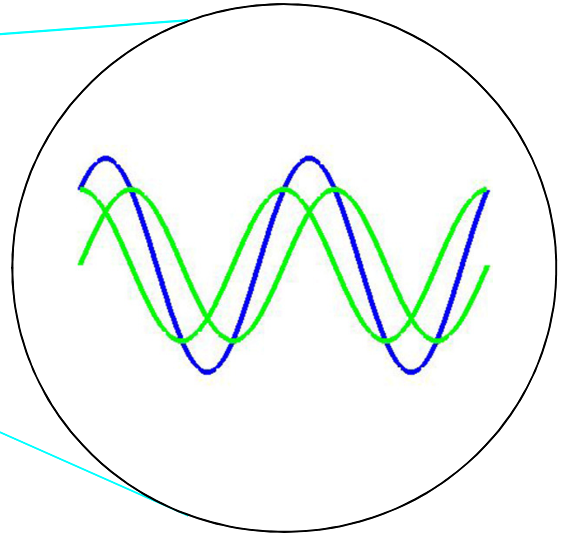
Comments: Feynman: no one has ever come up with a mechanism to explain double slit diffraction

1. “What about neutrons or photons?”

Example of diffraction



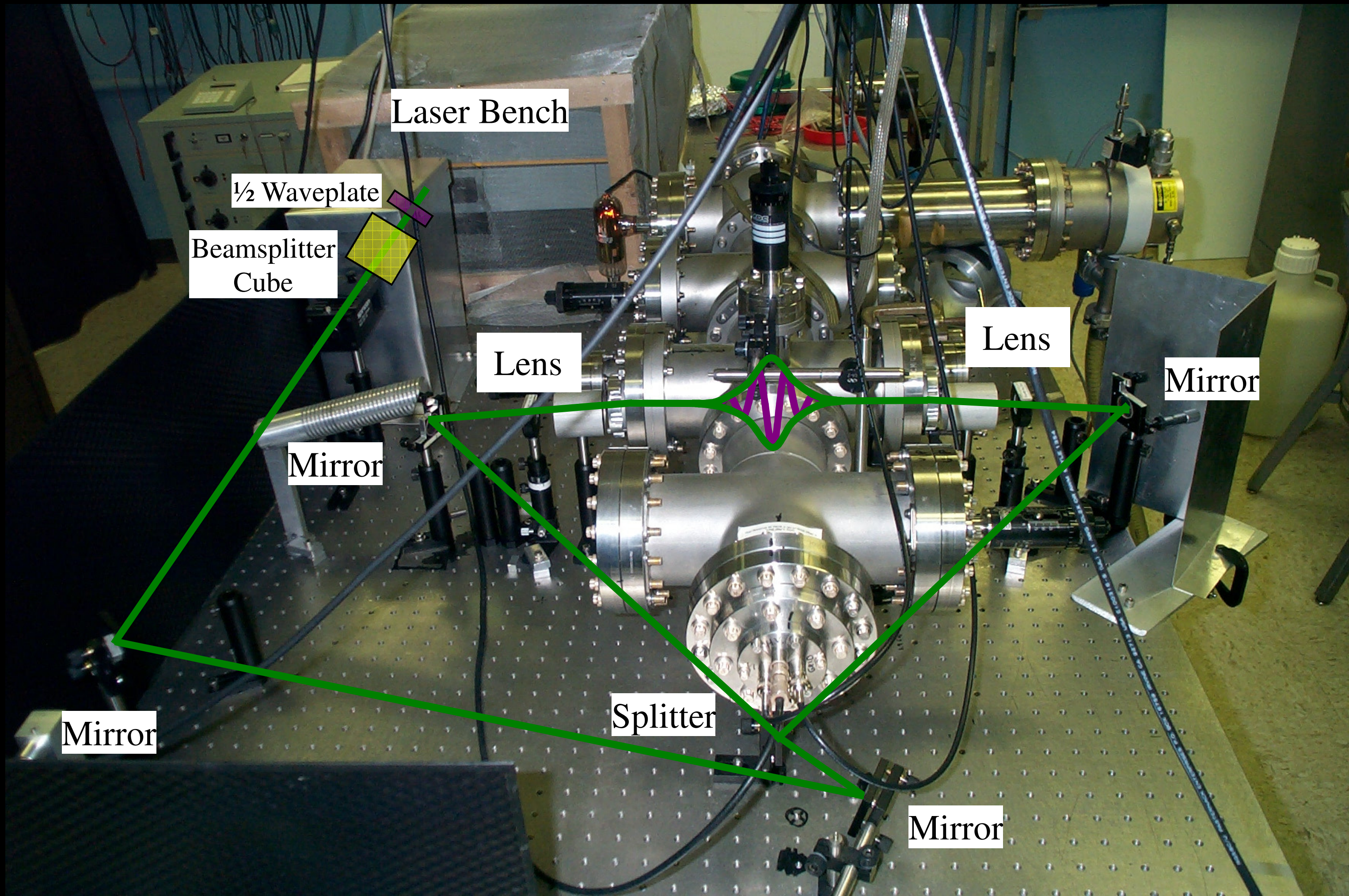
Think of..



Electrons diffracted by
a light grating

standing wave of light=grating!

Experimental Setup

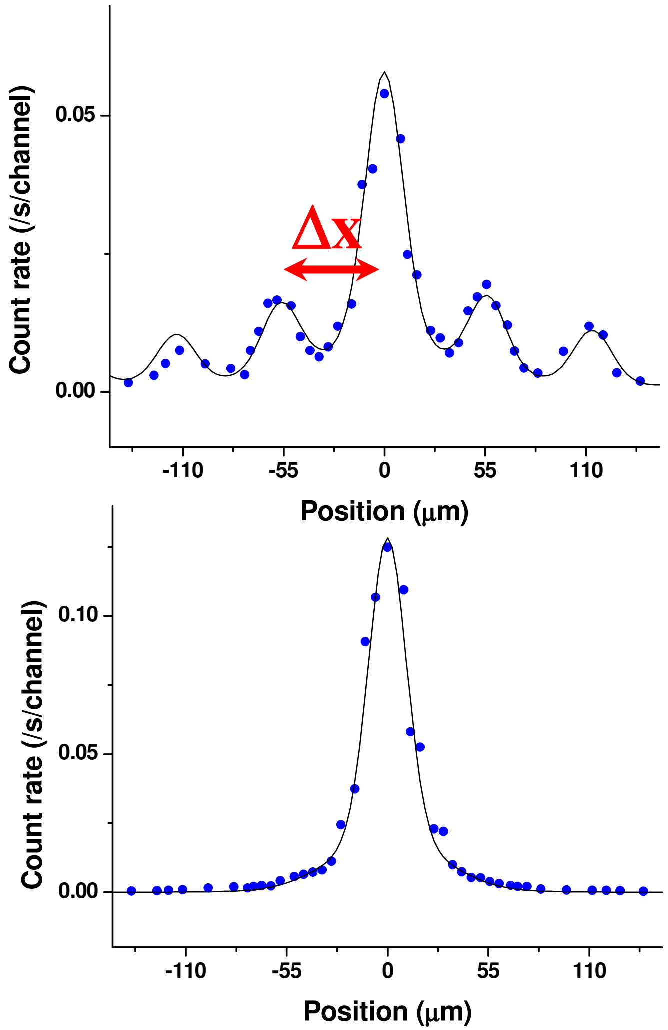


The Kapitza-Dirac Effect

$\color{red}{\Delta x} = L\,\Delta\theta =$

$= L\,\lambda_{dB}/d =$

$= 55\ \mu m$



Laser on

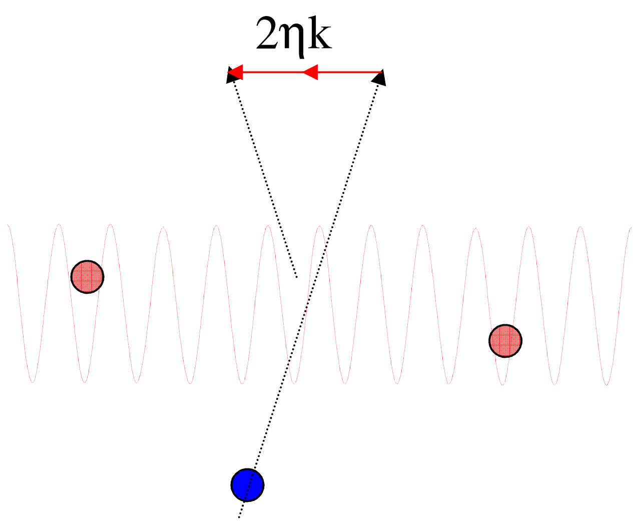
Laser off

Daniel Freimund

D. L. Freimund, K. Aflatooni, and H. Batelaan, Nature 413, 142-143 (2001)

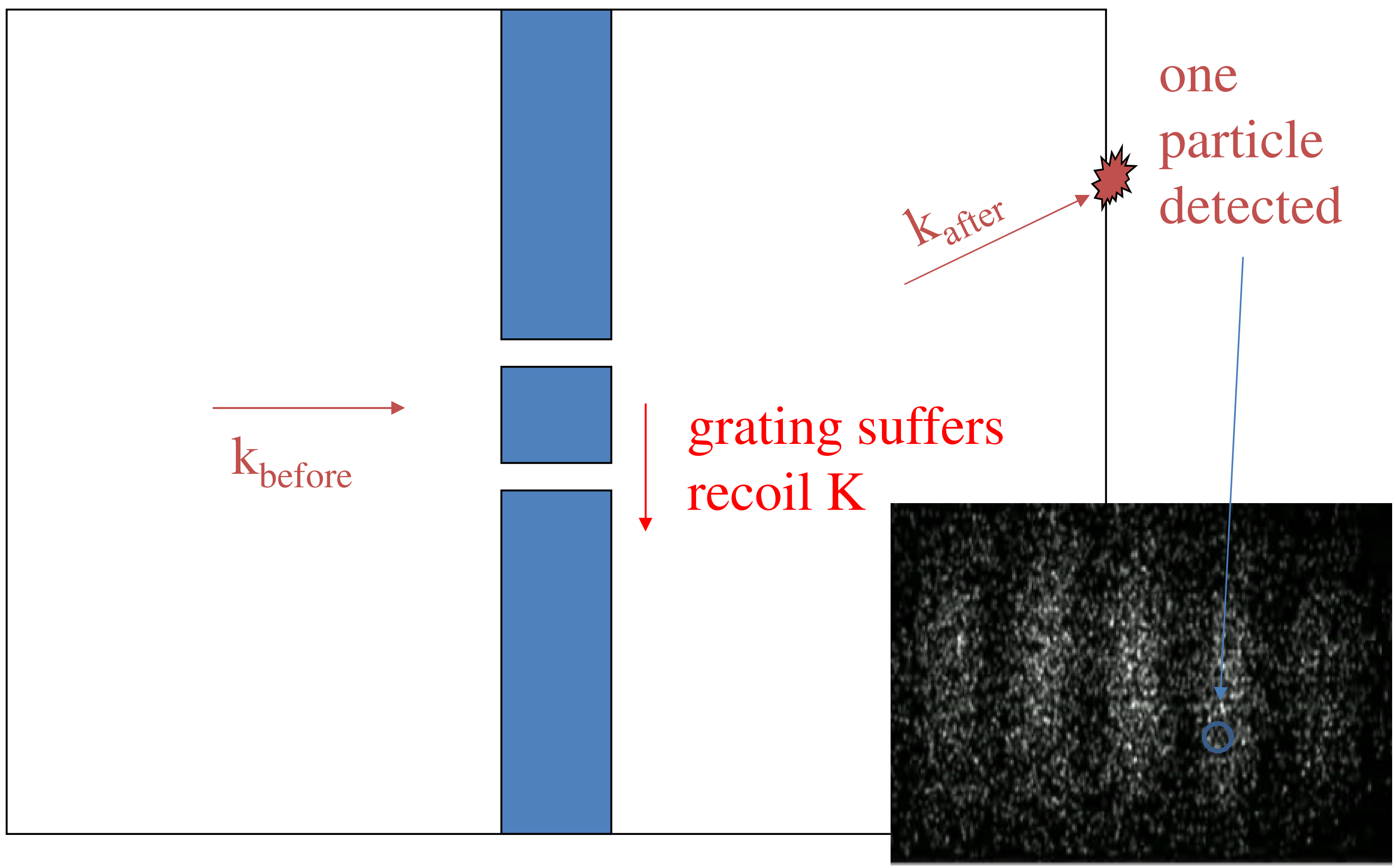
What interaction caused the momentum exchange between the electron and the grating?

What interaction caused the momentum exchange between the electron and the grating?



Stimulated Compton scattering
For this case we can answer the question!
So let's ask it for the double slit too.

H. Batelaan. Rev. of Mod. Phys. 79, 929 (2007)



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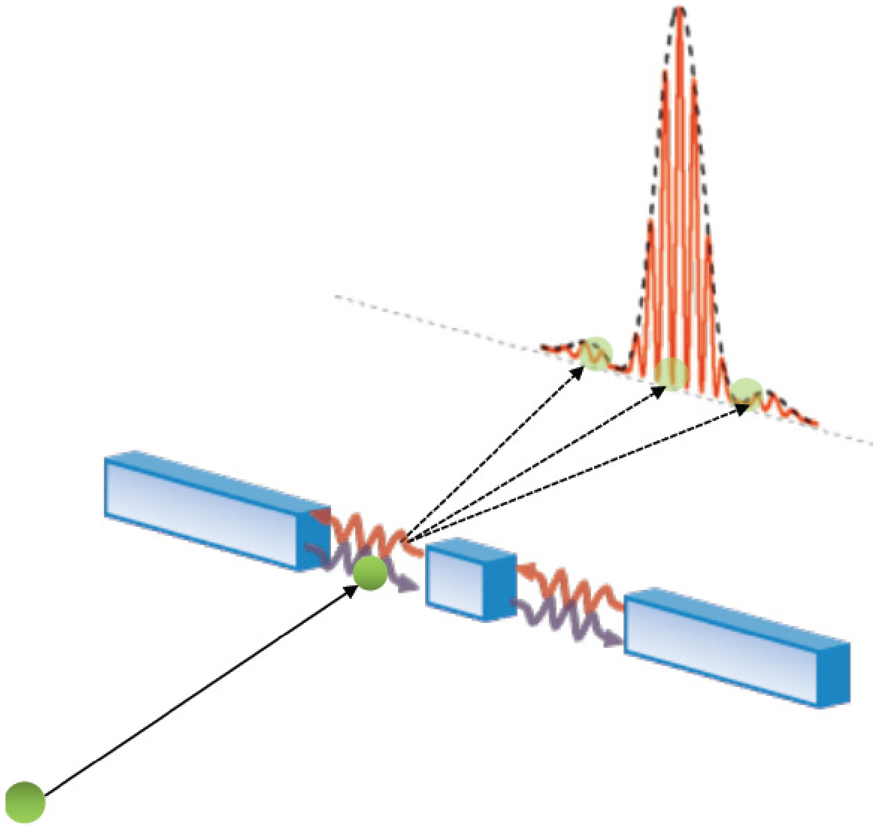
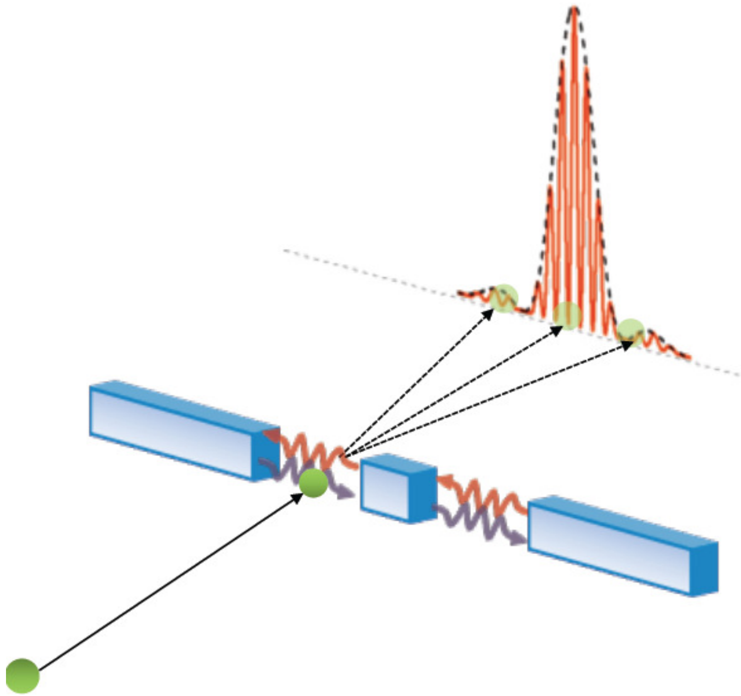


Is electron diffraction a vacuum-field effect?

Stochastic Electrodynamics: Double Slit Electron Diffraction
from de la Pena and Cetto “The Emergent Quantum” (2014)



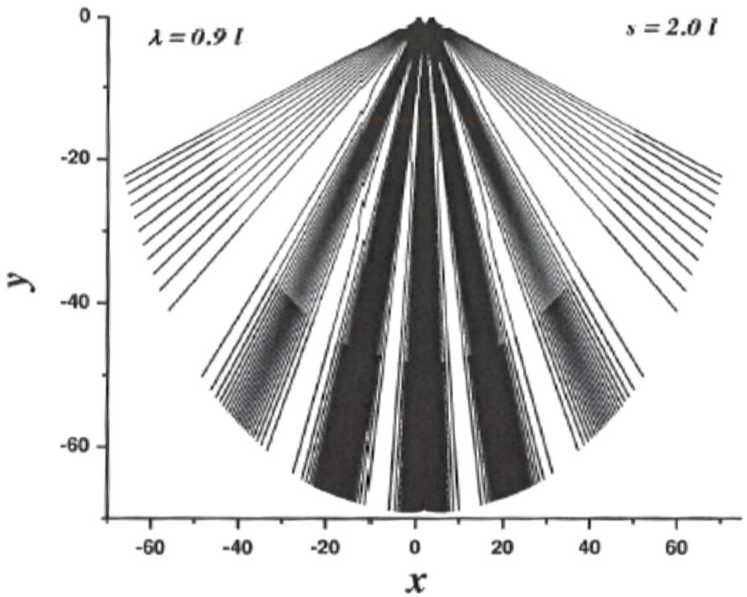
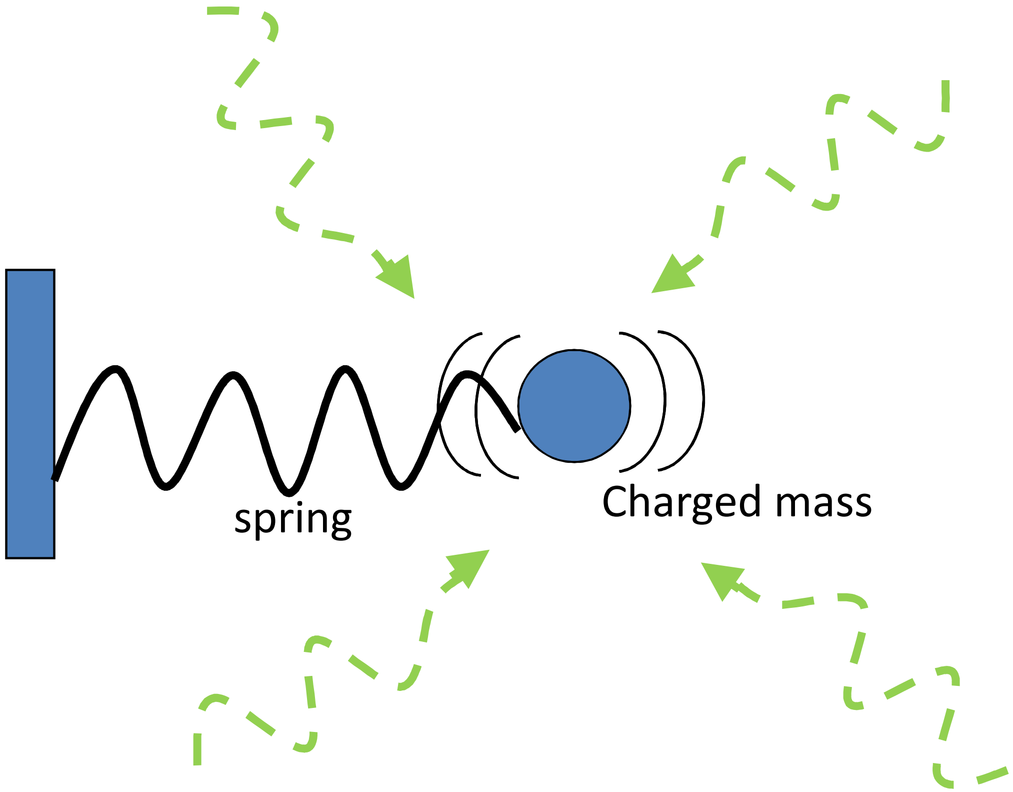


Fig. 9.2 Trajectories followed by electrons in a realistic simulation of a two-slit experiment. The particles are uniformly distributed in the beam behind the slits. The diffracted modes of the field have momentum p_B and the momentum of the particles is p, with $p = p_B$. Figure courtesy of J. Avendaño, adapted from Avendaño and de la Peña (2010)

First an "easier" toy system first : The Harmonic Oscillator



Following Boyer's work

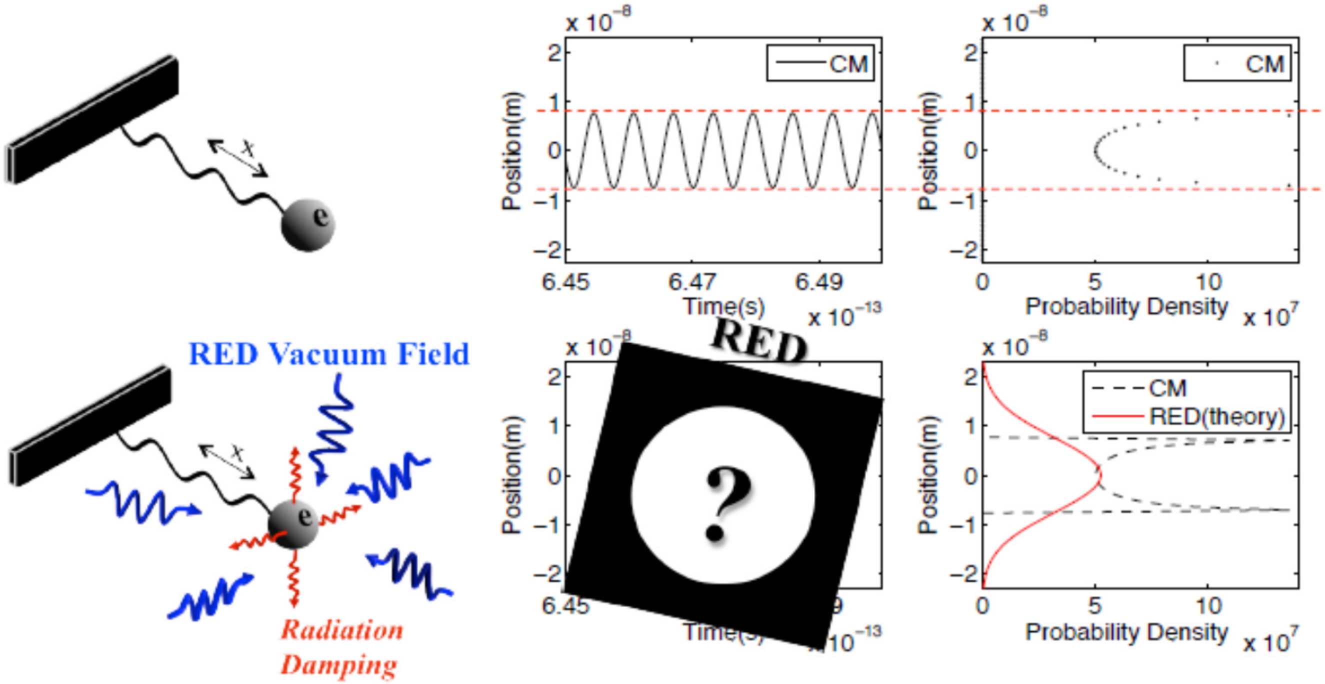
The Classical Harmonic Oscillator in the vacuum

$$m\Gamma \dddot{x} \cong -m\omega_0^2 \Gamma \dot{x}$$

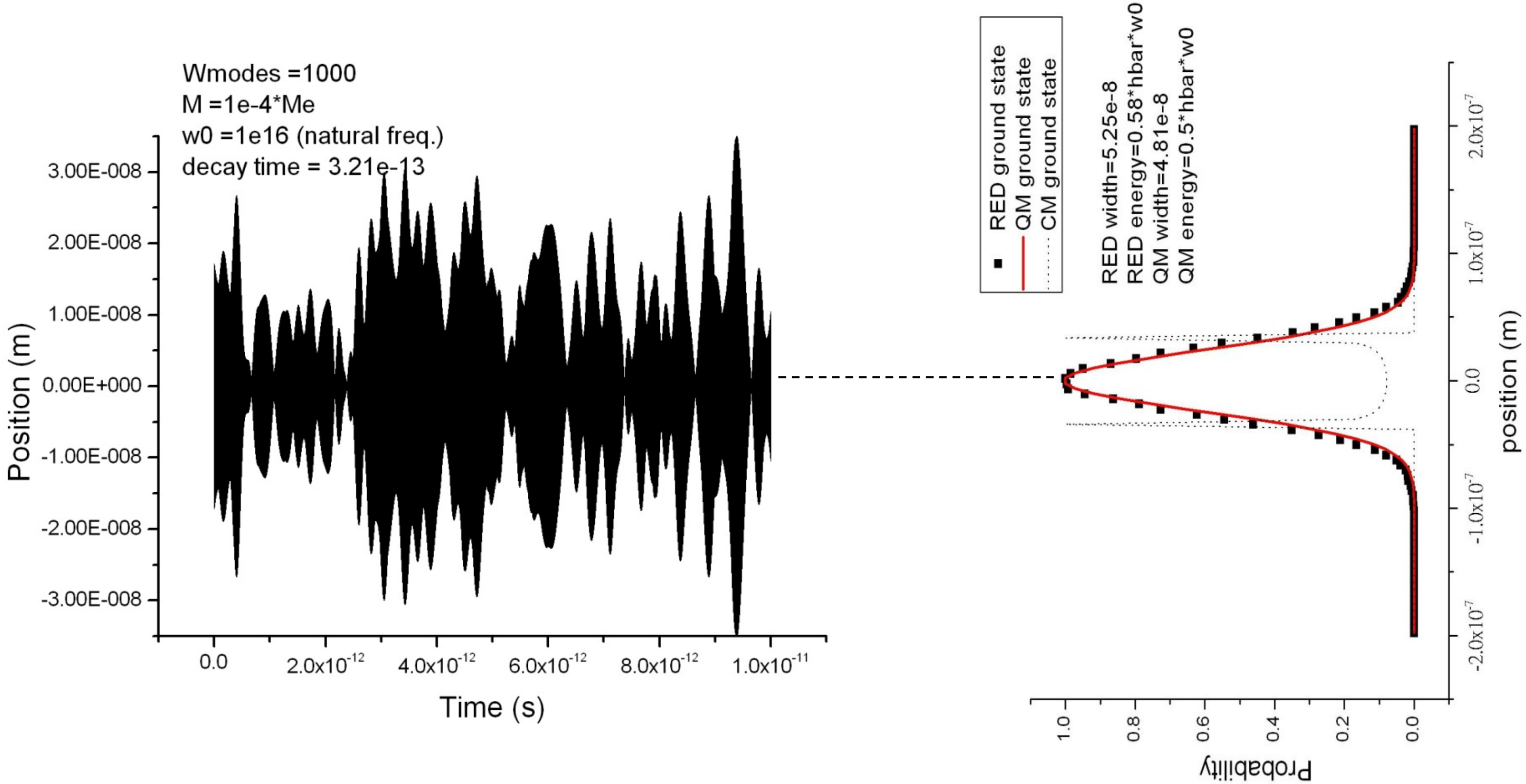
$$m\ddot{x} \cong -m\omega_0^2 x - m\omega_0^2 \Gamma \dot{x} + eE_{zp,x}(0,t)$$

Harmonic socillator | **Radiation damping** | **Vacuum field**

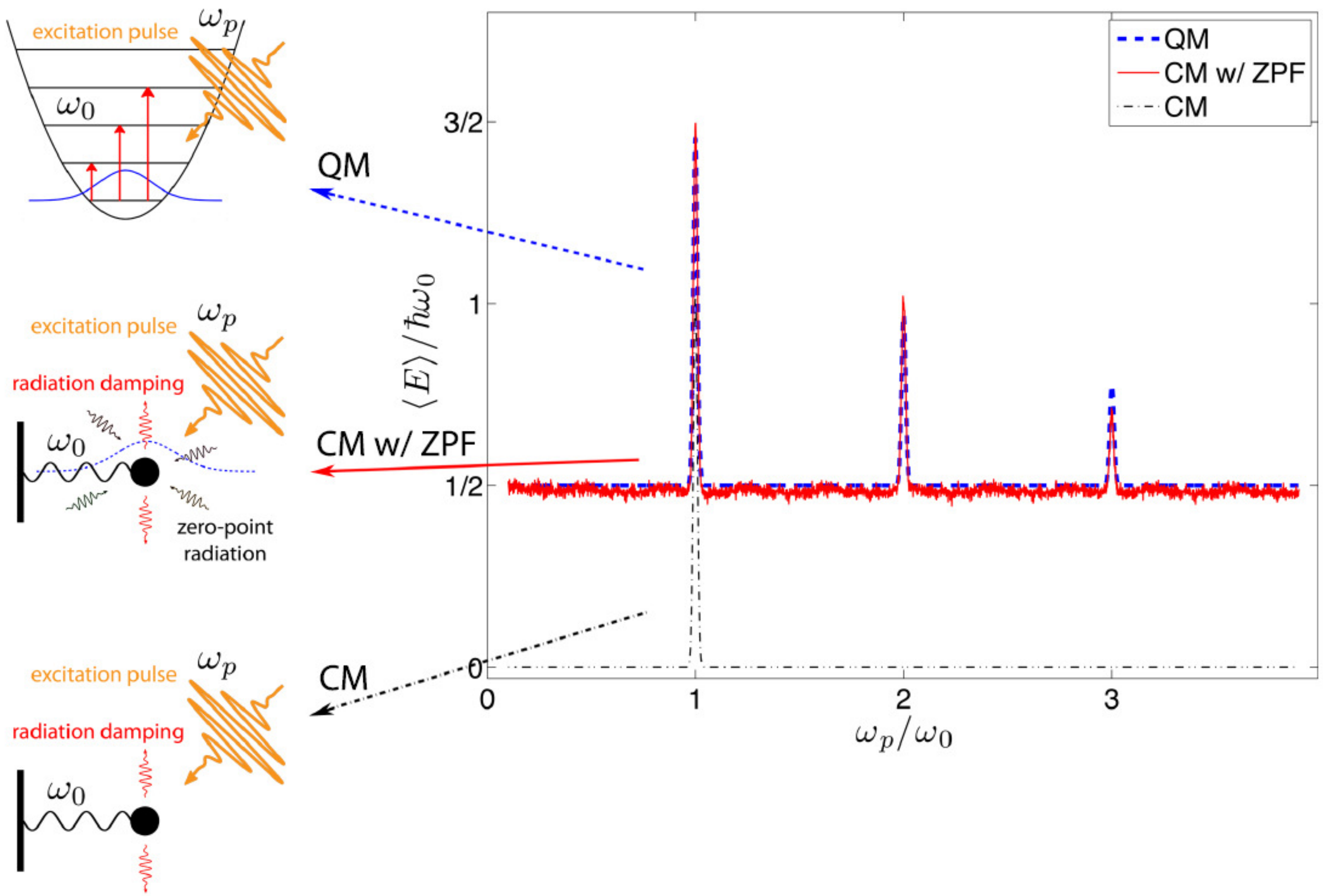
For Analytical Derivation See
T. H. Boyer Phys. Rev. D 11 , 790 (1975)


x
e
RED Vacuum Field
Radiation Damping
x 10^{-8}
Position(m)
CM
Time(s)
x 10^{-13}
Probability Density
x 10^{7}
RED
?
RED(theory)

The Harmonic Oscillator….verification

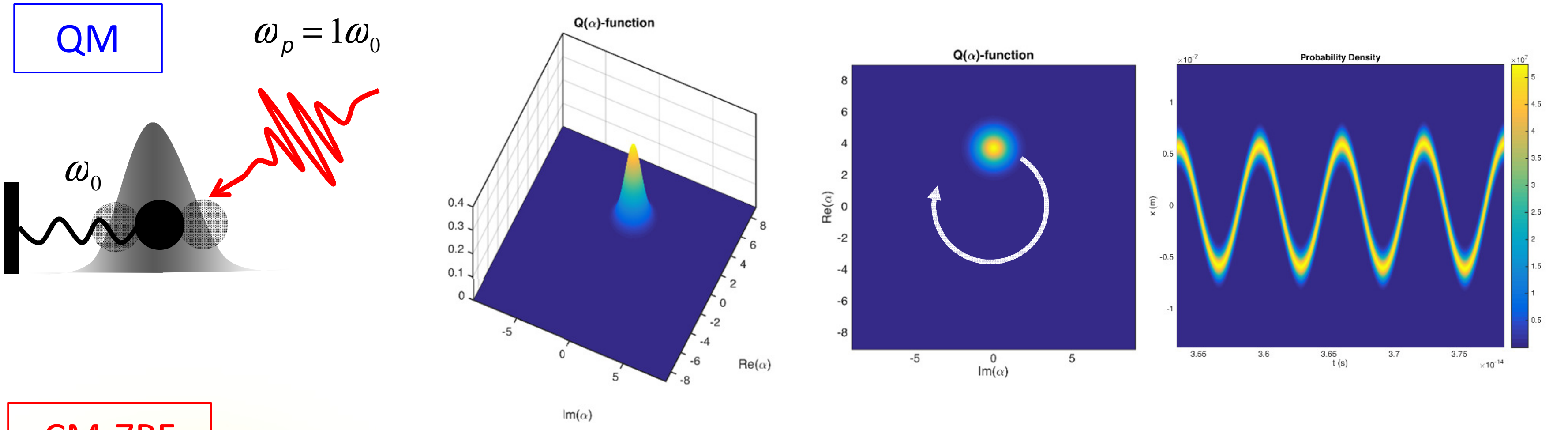


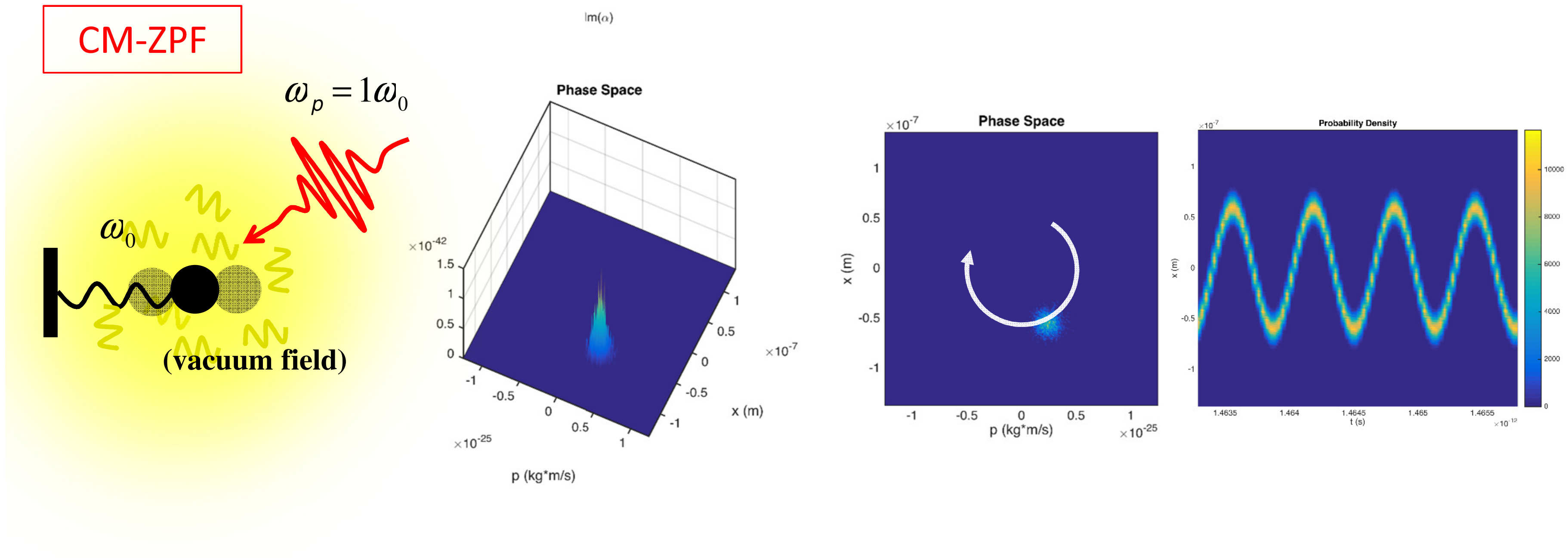
And that we can understand….



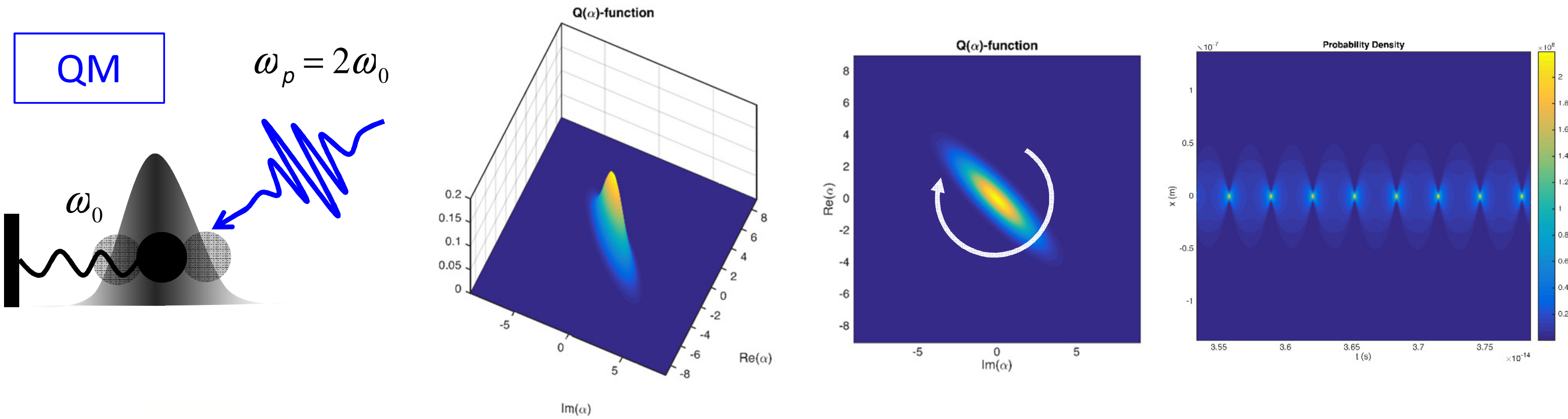
Wayne Huang and Herman Batelaan, Found. of Phys. 2015

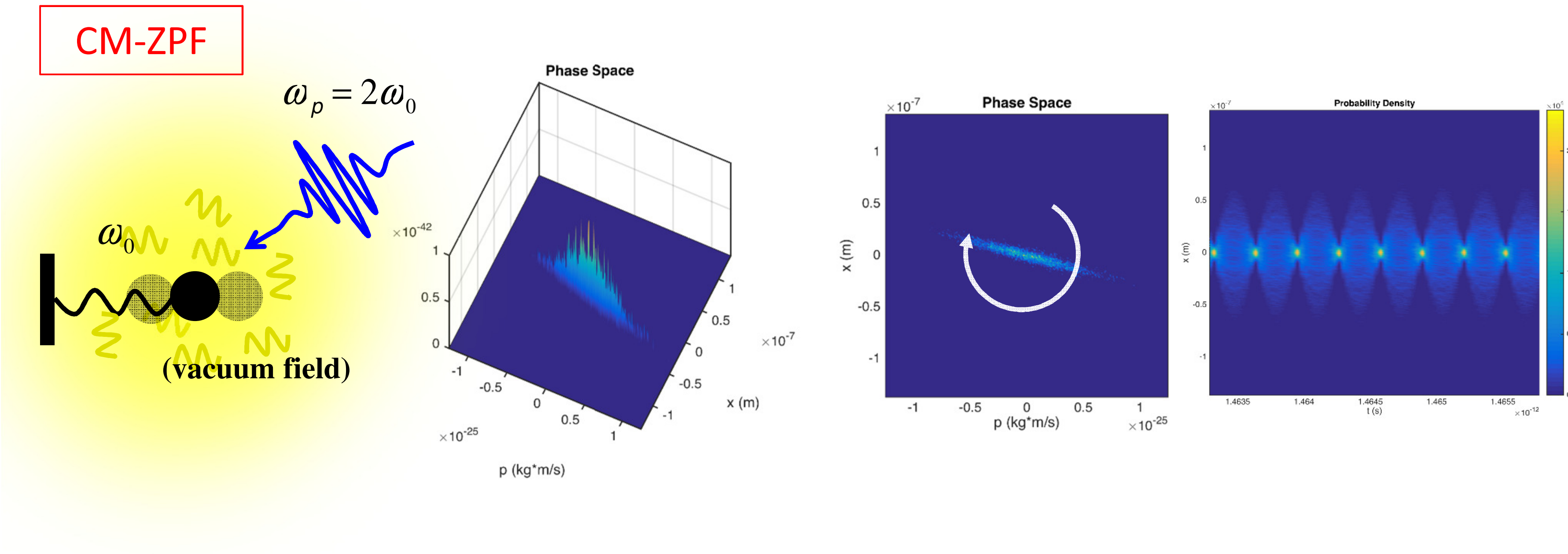
Coherent state





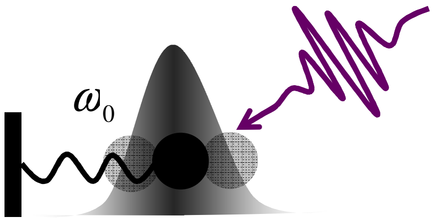
Squeezed Vacuum State

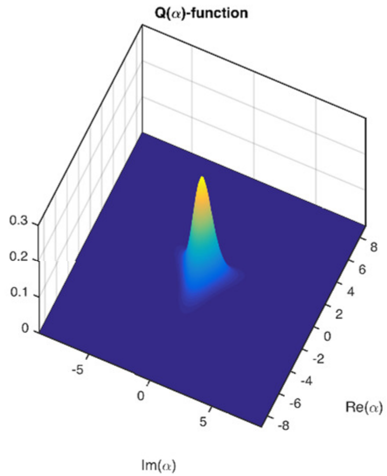


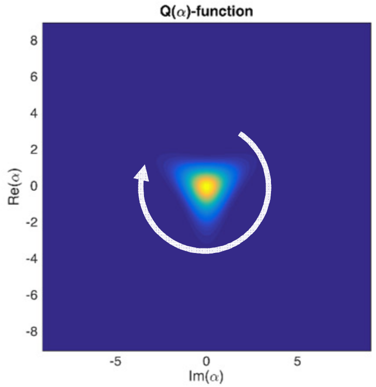


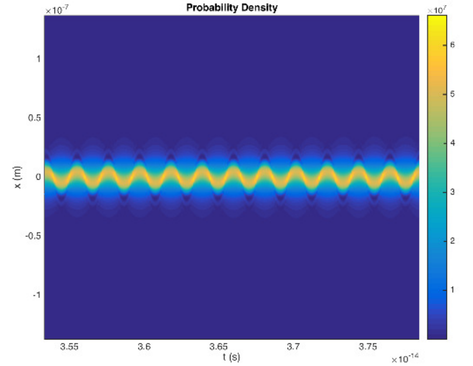
$\chi^{(3)}$-Squeezed State

QM

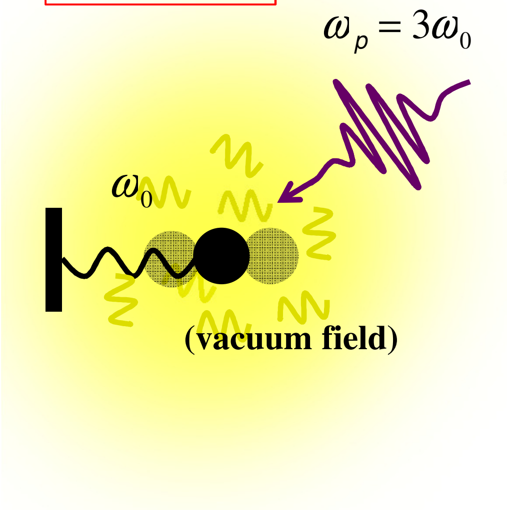


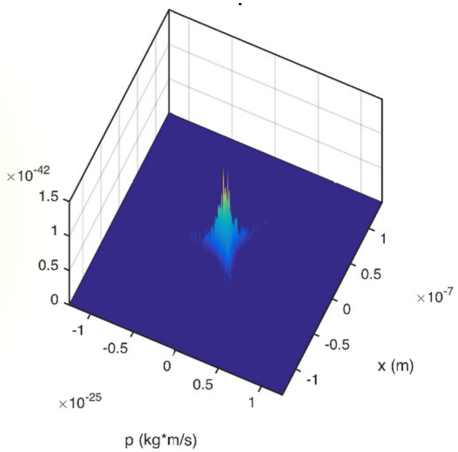


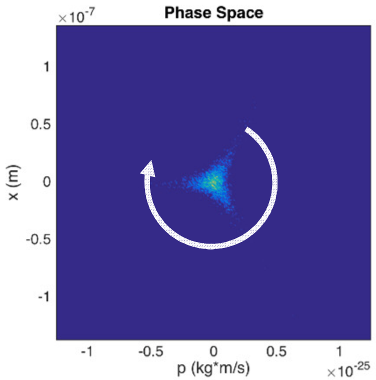


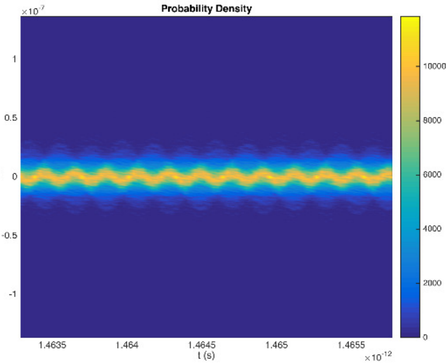


CM-ZPF



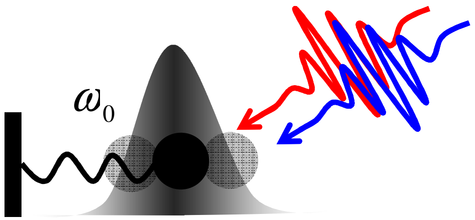


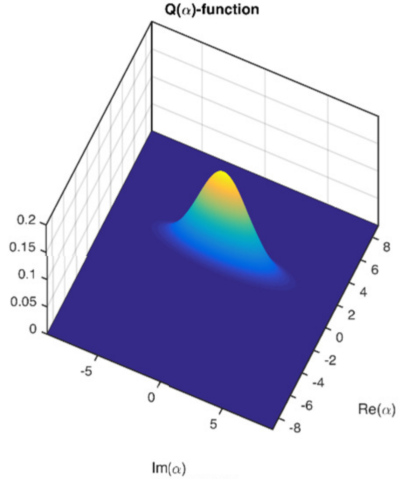


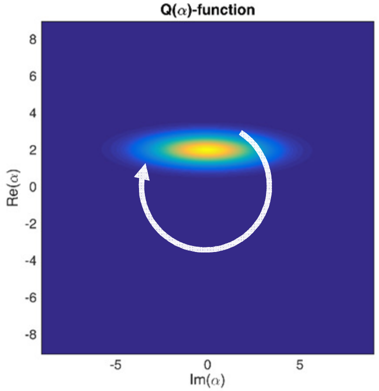


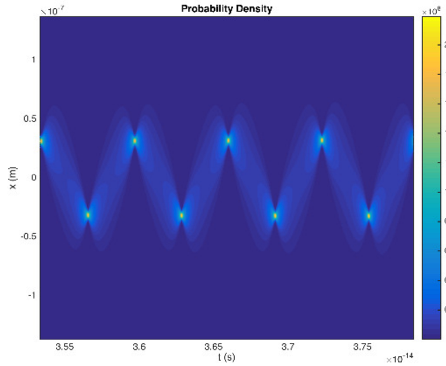
Amplitude-Squeezed State

QM

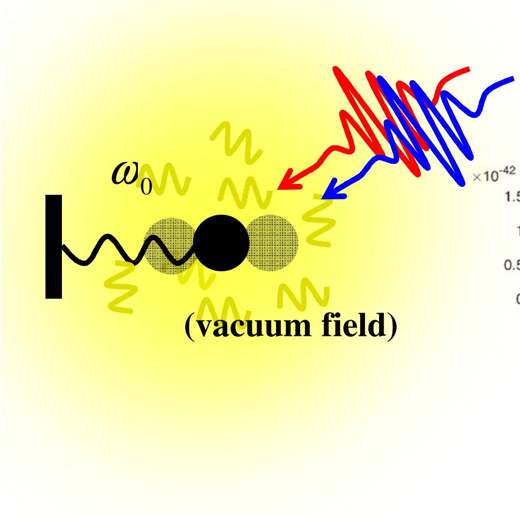


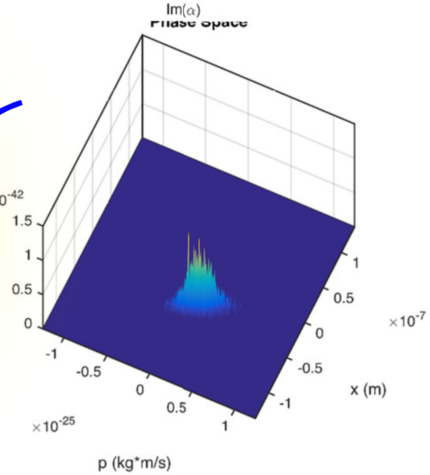


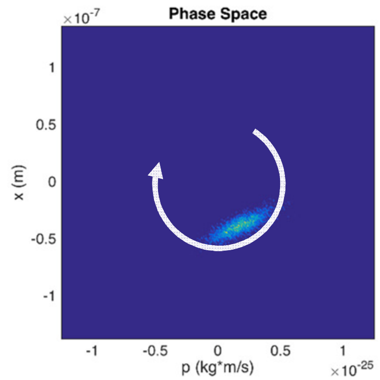


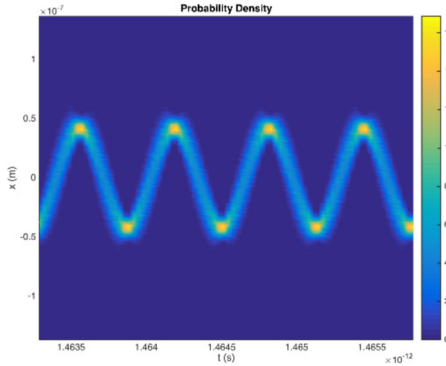


CM-ZPF



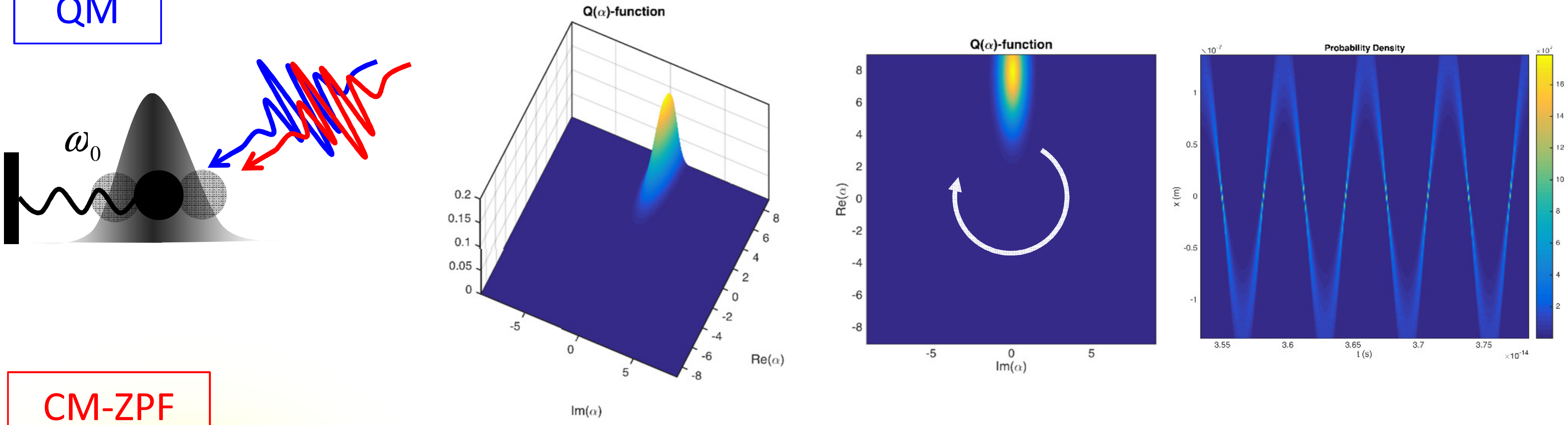




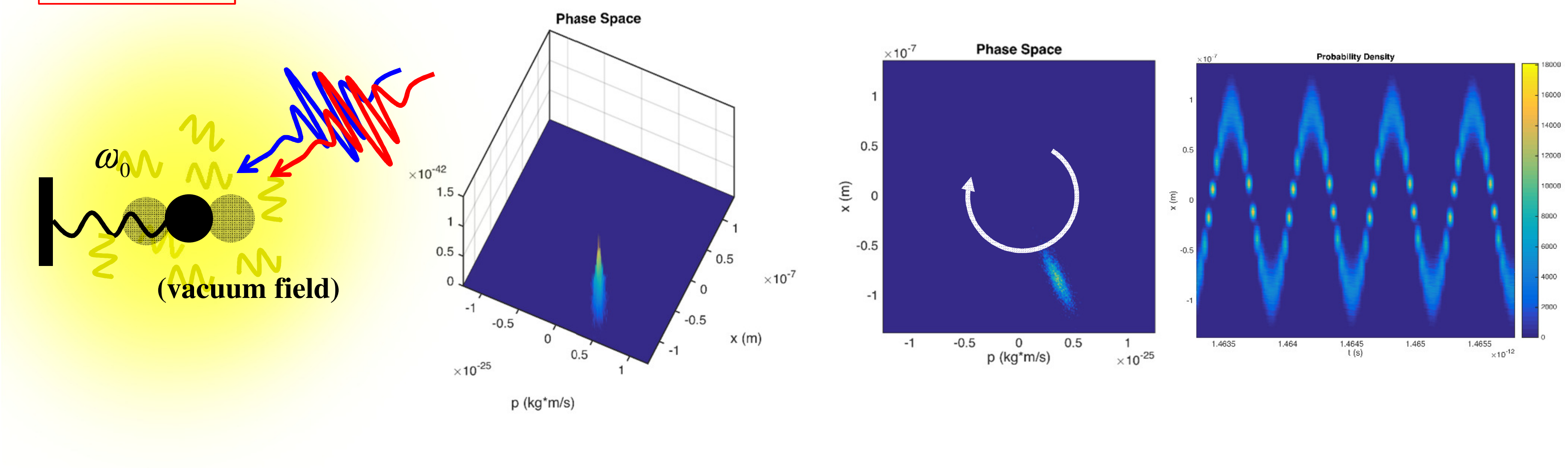


Phase-Squeezed State

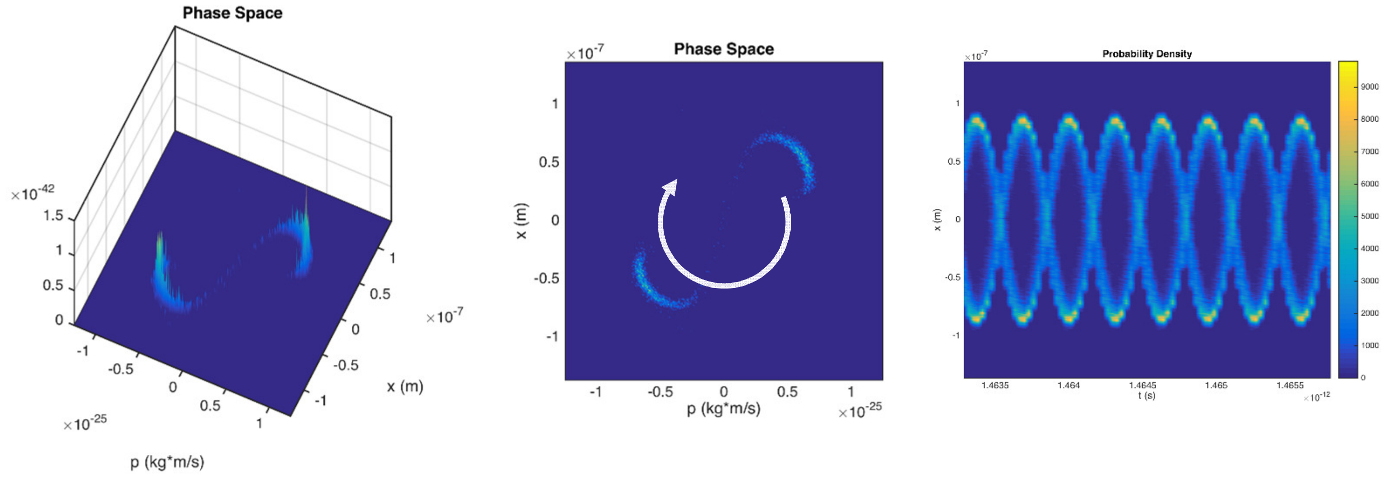
QM

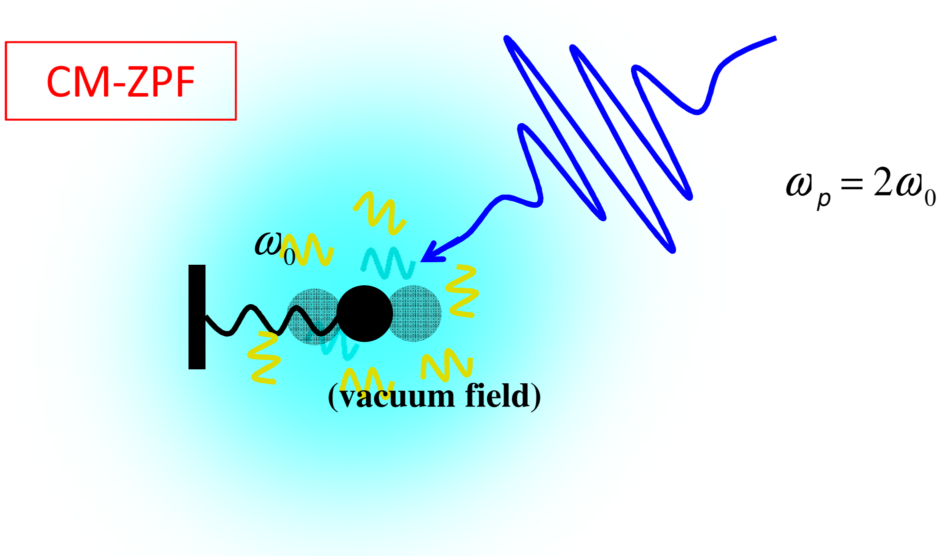


CM-ZPF



“ Schrödinger Cat State? ”





Quantum-Classical Correspondence in Heisenberg Picture

Classical Mechanics

$$m\frac{d^2}{dt^2}x(t) = -m\omega_0^2 x + qE_p(x,t)$$

where $E_p(x,t) = -\frac{\partial}{\partial t}A_p(x,t)$

Quantum Mechanics

$$\hat{H} = \left(\frac{m\omega_0^2}{2}\hat{x}^2 + \frac{\hat{p}^2}{2m}\right) - \frac{q}{2m}\left(2A_p\hat{p} - qA_p^2\right)$$

$$\begin{cases} i\hbar\frac{d}{dt}\hat{x}(t) = \left[\hat{x}(t), \hat{H}\right] \\ i\hbar\frac{d}{dt}\hat{p}(t) = \left[\hat{p}(t), \hat{H}\right] \end{cases}$$

$$\langle \Delta E(t) \rangle = \frac{m\omega_0^2}{2}\langle x^2(t) \rangle + \frac{1}{2m}\langle p^2(t) \rangle$$

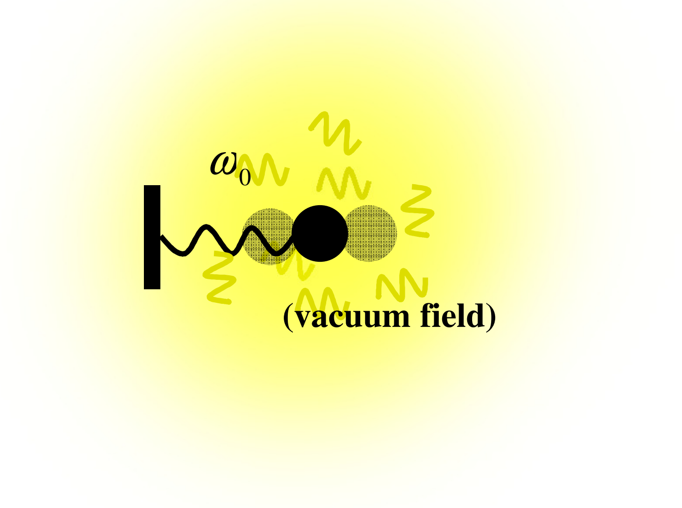
$$\langle \Delta E(t) \rangle = \frac{m\omega_0^2}{2}\langle 0|\hat{x}^2(t)|0\rangle + \frac{1}{2m}\langle 0|\hat{p}^2(t)|0\rangle$$

Classical Mechanics with Zero-Point Field (CM-ZPF)

$$m\ddot{x} = -m\omega_0^2 x - m\Gamma\omega_0^2 \dot{x} + qE_{vac,x}(t)$$

$$\vec{E}_{vac}(t) = \sum_{\vec{k},\lambda} \sqrt{\frac{\hbar\omega}{\varepsilon_0 V}} \cos\left(\omega t + \tilde{\theta}_{\vec{k},\lambda}\right) \vec{\xi}_{\vec{k},\lambda}$$

1. 2.

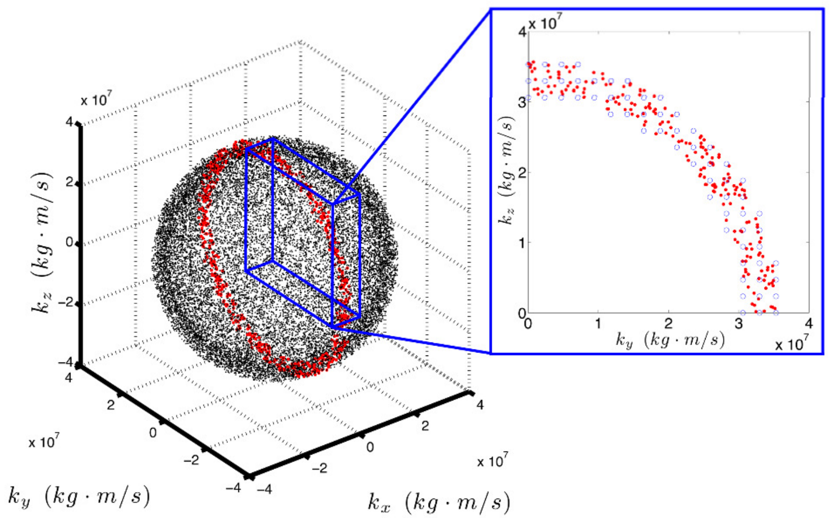


Features of the vacuum field:

1. Lorentz invariant radiation spectrum
2. Isotropic

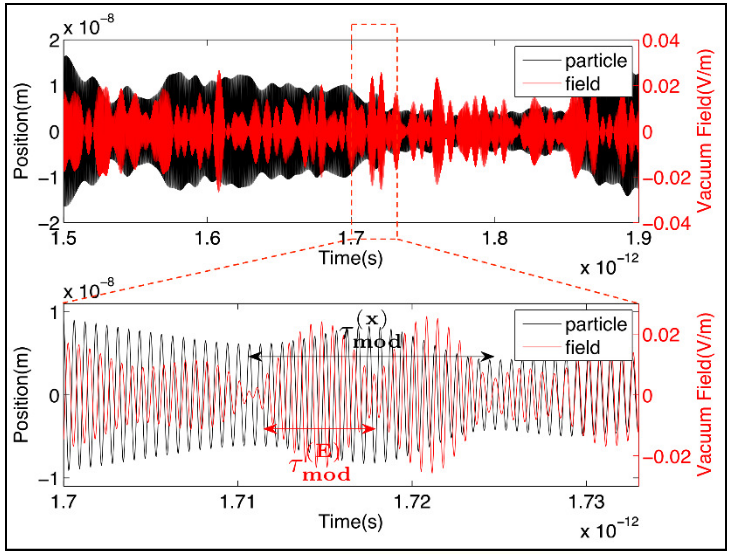
*ZPF = vacuum field

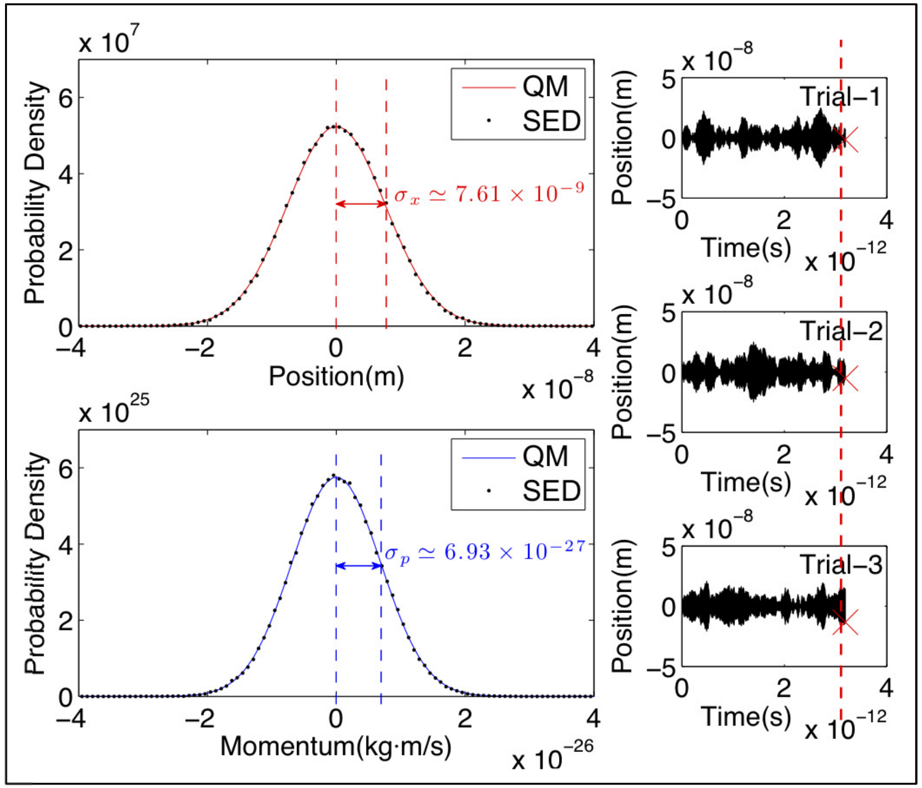
wave-vector space

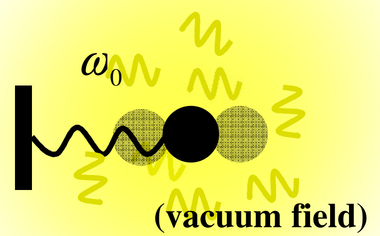


Heisenberg Minimum Uncertainty

$$\sigma_x \sigma_p = \hbar / 2$$







*stochastic electrodynamics (SED) = CM-ZPF

[ref] J. Comp. Methods Phys. 2013, 308538 (2013)
[ref] Found. Phys. (DOI) 10.1007/s10701-015-9866-9 (2015)

Agreement in Analytical Solutions

For $\chi^{(1)}$-interaction:

$$\rightarrow \begin{cases} \langle \Delta E \rangle_{QM} = \dfrac{\pi}{2} \dfrac{(qA\tau)^2}{m} \left(\dfrac{\omega_0}{\omega_p} \right) \cos^2(\theta_p) \exp\left[-2 \left(\dfrac{\omega_p - \omega_0}{2/\tau} \right)^2 \right] \\ \langle \Delta E \rangle_{CM-ZPF} = \dfrac{\pi}{2} \dfrac{(qA\tau)^2}{m} \cos^2(\theta_p) \exp\left[-2 \left(\dfrac{\omega_p - \omega_0}{2/\tau} \right)^2 \right] \end{cases}$$

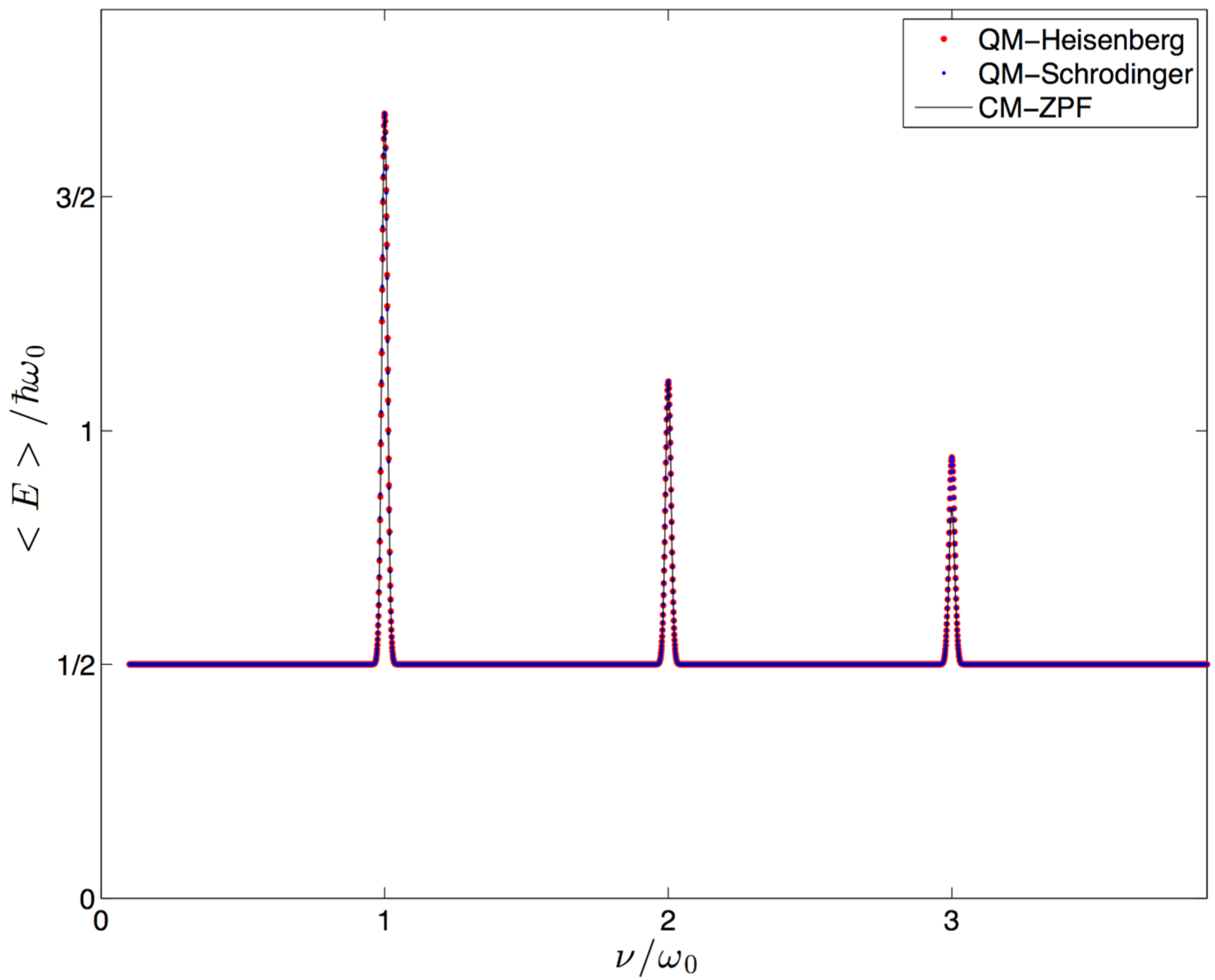
For $\chi^{(2)}$-interaction:

$$\rightarrow \begin{cases} \langle \Delta E \rangle_{QM} = \dfrac{\pi}{2} \dfrac{(qA\tau)^2}{m} \left[\left(\dfrac{\hbar\omega_p}{mc^2} \right) \sin^2(\theta_p) \right] \cos^2(\theta_p) \exp\left[-2 \left(\dfrac{\omega_p - 2\omega_0}{2/\tau} \right)^2 \right] \\ \langle \Delta E \rangle_{CM-ZPF} = \dfrac{\pi}{4} \dfrac{(qA\tau)^2}{m} \left(\dfrac{\omega_p}{\omega_0} \right) \left[\left(\dfrac{\hbar\omega_p}{mc^2} \right) \sin^2(\theta_p) \right] \cos^2(\theta_p) \exp\left[-2 \left(\dfrac{\omega_p - 2\omega_0}{2/\tau} \right)^2 \right] \end{cases}$$

For $\chi^{(3)}$-interaction:

$$\rightarrow \begin{cases} \langle \Delta E \rangle_{QM} = \dfrac{48\pi}{16^2} \dfrac{(qA\tau)^2}{m} \left(\dfrac{\omega_p}{\omega_0} \right) \left[\left(\dfrac{\hbar\omega_p}{mc^2} \right) \sin^2(\theta_p) \right]^2 \cos^2(\theta_p) \exp\left[-2 \left(\dfrac{\omega_p - 3\omega_0}{2/\tau} \right)^2 \right] \\ \langle \Delta E \rangle_{CM-ZPF} = \dfrac{12\pi}{16^2} \dfrac{(qA\tau)^2}{m} \left(\dfrac{\omega_p}{\omega_0} \right)^2 \left[\left(\dfrac{\hbar\omega_p}{mc^2} \right) \sin^2(\theta_p) \right]^2 \cos^2(\theta_p) \exp\left[-2 \left(\dfrac{\omega_p - 3\omega_0}{2/\tau} \right)^2 \right] \end{cases}$$

Comparison between QM and CM-ZPF



Do not have answer (yet).
In communication with
Jaime Avendano…

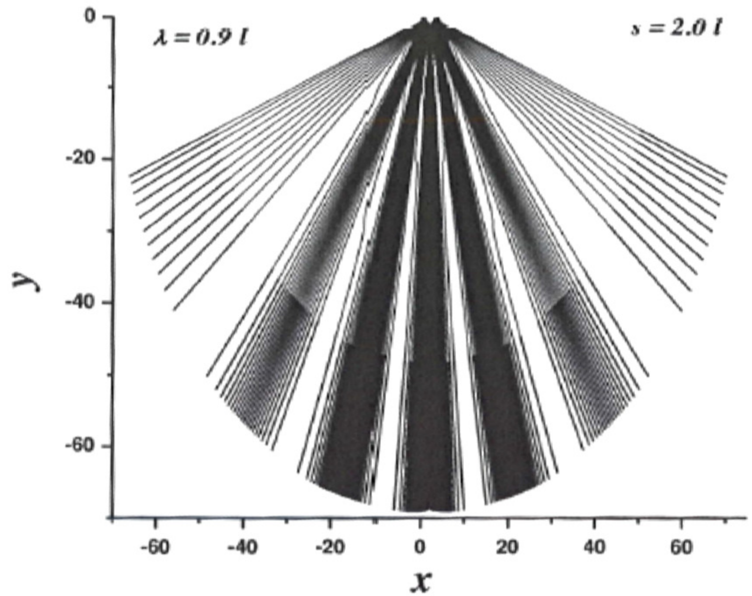
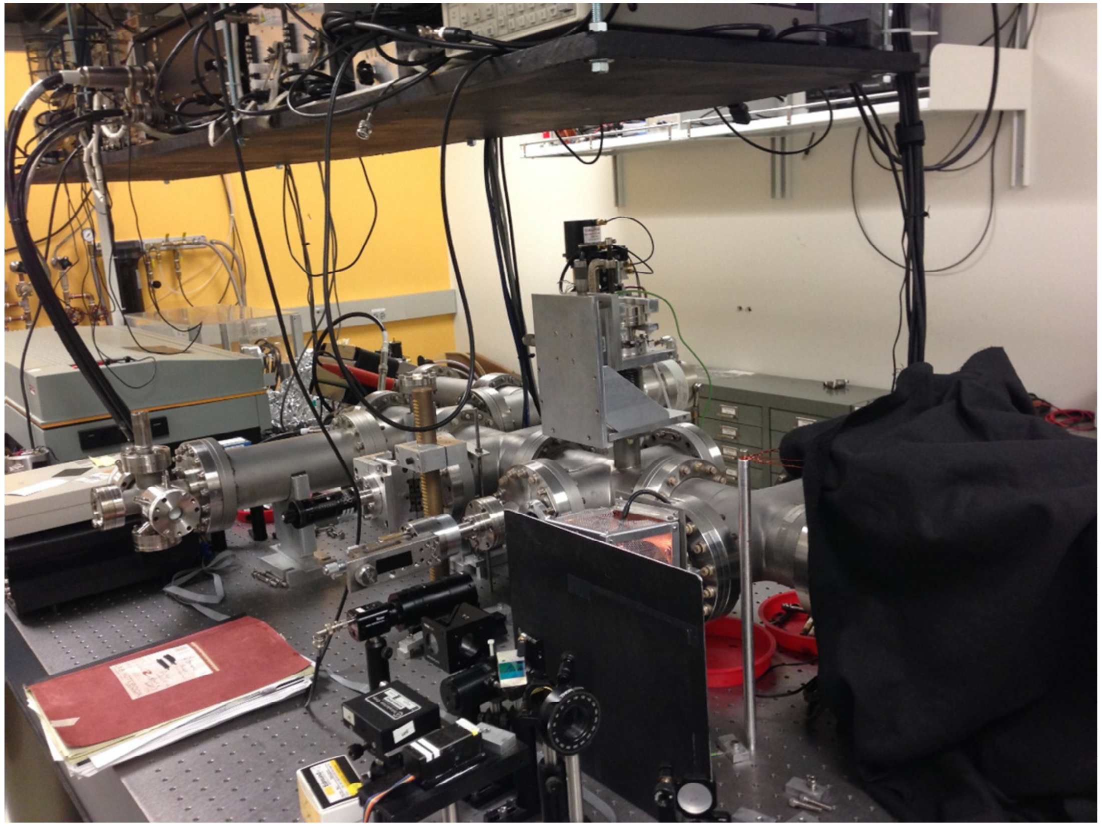


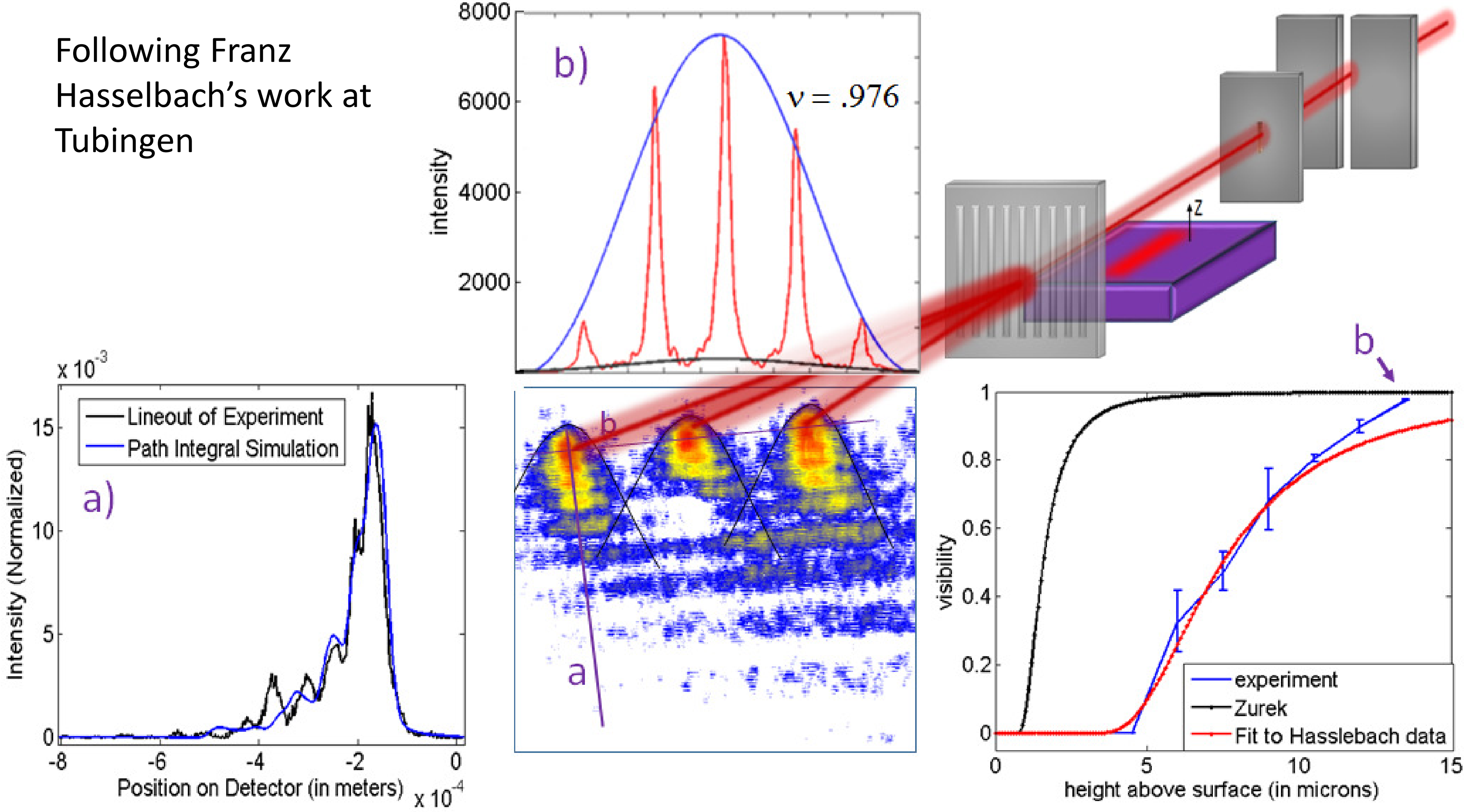
Fig. 9.2 Trajectories followed by electrons in a realistic simulation of a two-slit experiment. The particles are uniformly distributed in the beam behind the slits. The diffracted modes of the field have momentum p_B and the momentum of the particles is p, with $p = p_B$. Figure courtesy of J. Avendaño, adapted from Avendaño and de la Peña (2010)

Maybe a related experiment…



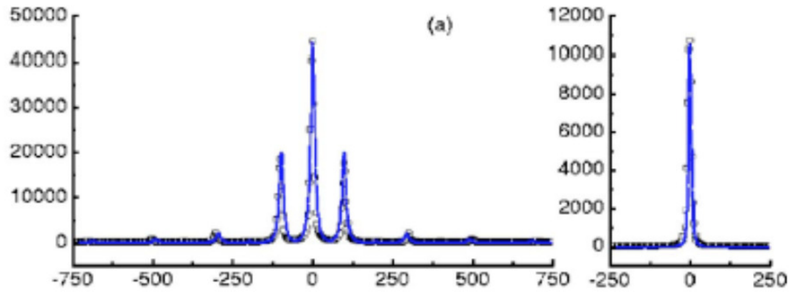
Measure decoherence.

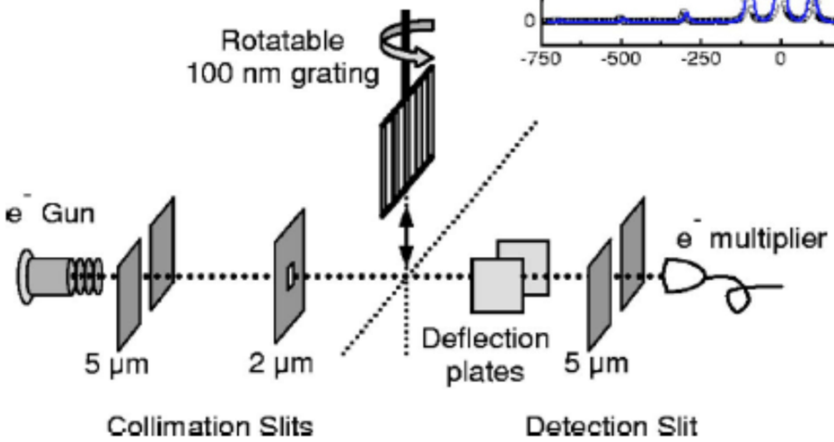
Following Franz Hasselbach's work at Tubingen

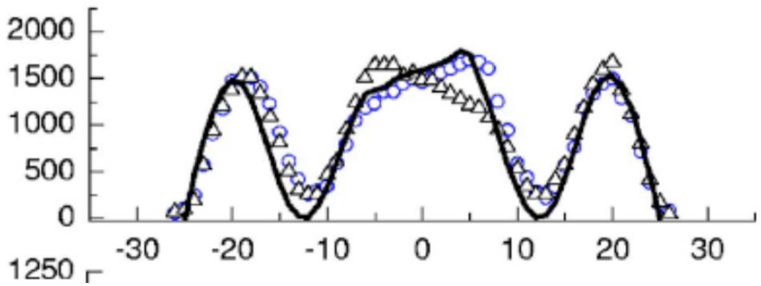


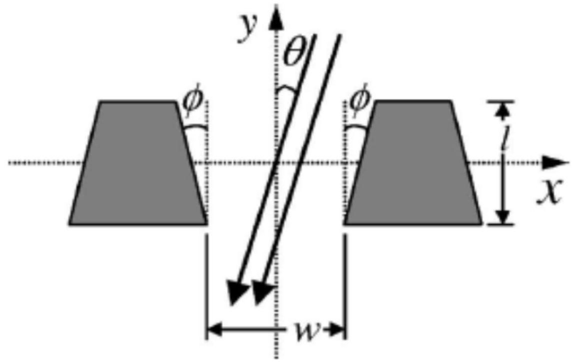
And another related experiment:

Measure image charge









Size image is 0.7 e

J. Appl. Phys. **100**, 074322 (2006)

For decoherence experiment:

1. Compare gold to Si surface

2. Try different electron energies (500 to 1500 eV)

3. Purpose to study vacuum field noise explanation of decoherence (Levinson J.Phys.A 37 3003 2004)

For image charge experiment:

1. Image charge is simplest vacuum QED effect (Larry Spruch, Peter Milonni

2. Purpose see relativistic corrections (retardation).

Back to the doube slit. Answers:

1. "Electrons reflect from the bar edges"

2. "Phonons are excited in the grating"

3. "Vacuum field photons scatter the electrons and the grating imposes boundary conditions on that field"

4. "The electron's field acts on the grating which back-acts on the electron"

5. "This is not a question one should ask"

6. "I calculated this, but never published it"

Comments:

1. "What about neutrons or photons?"

Back to the doube slit. Answers:

1. “Electrons reflect from the bar edges”

2. “Phon

Prepare grating in excited phonon state

3. “Vacuum field photons scatter the electrons and the grating imposes boundary conditions on that field”

4. “The electron’s field acts on the grating which back-acts on the electron”

5. “This is not a question one should ask”

6. “I calculated this, but never published it”

Comments:

1. “What about neutrons or photons?”

Back to the doube slit. Answers:

1. “Electrons reflect from the bar edges”

2. “Phon

Prepare grating in excited phonon state

3. “Vacu … grating imposes boundary conditions on that field

Change coating of grating

4. “The electron’s field acts on the grating which back-acts on the electron”

5. “This is not a question one should ask”

6. “I calculated this, but never published it”

Comments:

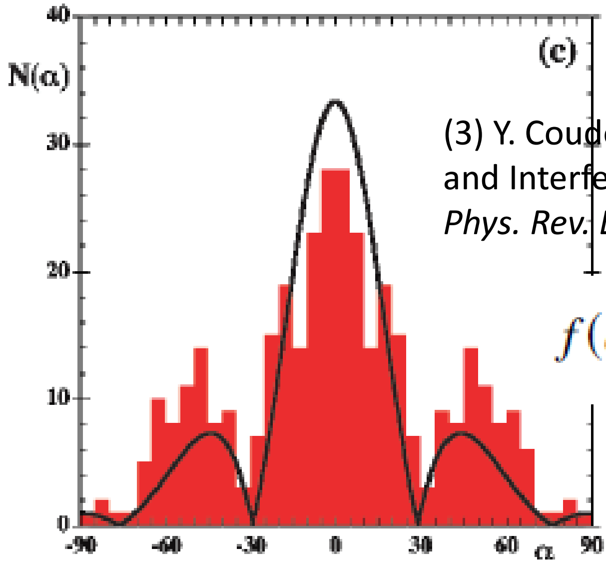
1. “What about neutrons or photons?”

Acknowledgement

- Peter Milonni
- Federico Capasso
- Holland Computing Center (HCC) of University of Nebraska
- eXtreme Science and Engineering Discovery Environment (XSEDE)
- David Pritchard (nanogratings for charged particle)
- Alex Cronin (idea image charge measurments)

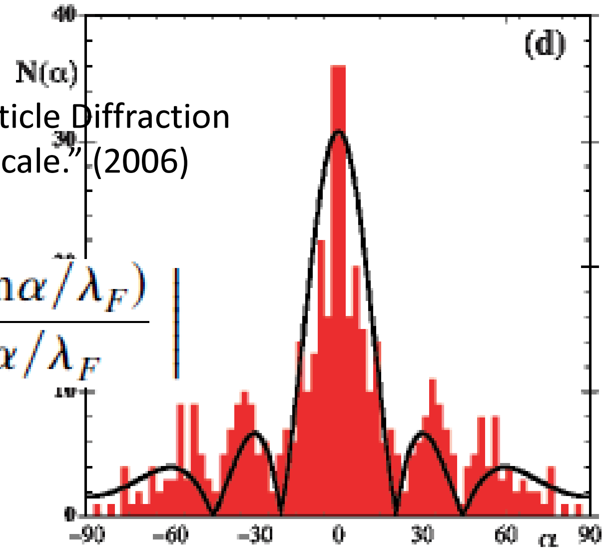
Our research Group

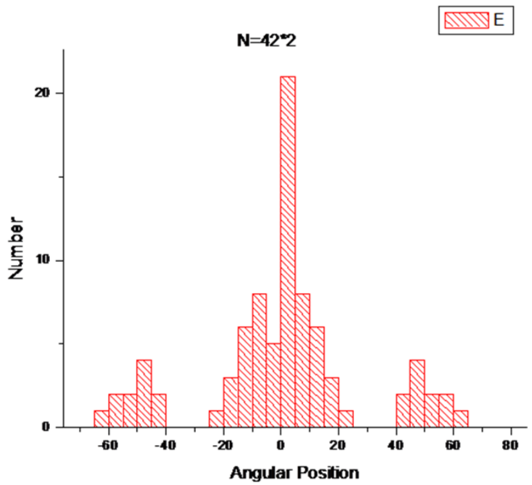
It diffracts!

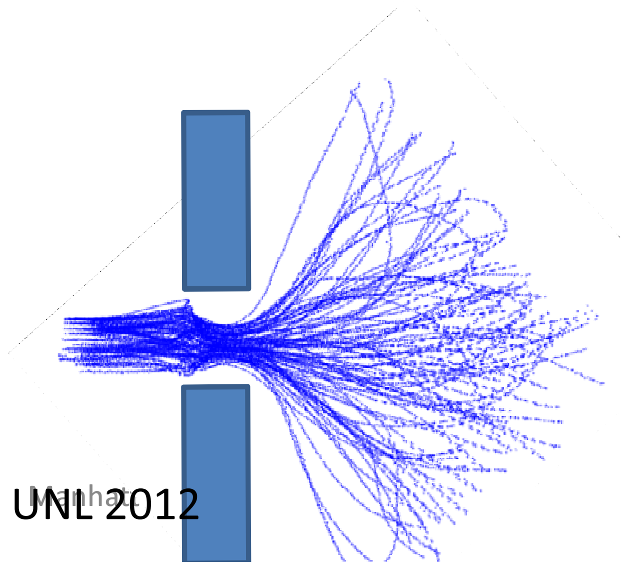


(3) Y. Couder and E. Fort "Single-Particle Diffraction and Interference at a Macroscopic Scale." (2006) *Phys. Rev. Lett.* **97** 154101

$$f(\alpha) = A \left| \frac{\sin(\pi L \sin\alpha / \lambda_F)}{\pi L \sin\alpha / \lambda_F} \right|$$







UNL 2012

Eric Jones

Double slit

Also done in Paris by Couder group