Non-sequential double ionization: The phase space perspective

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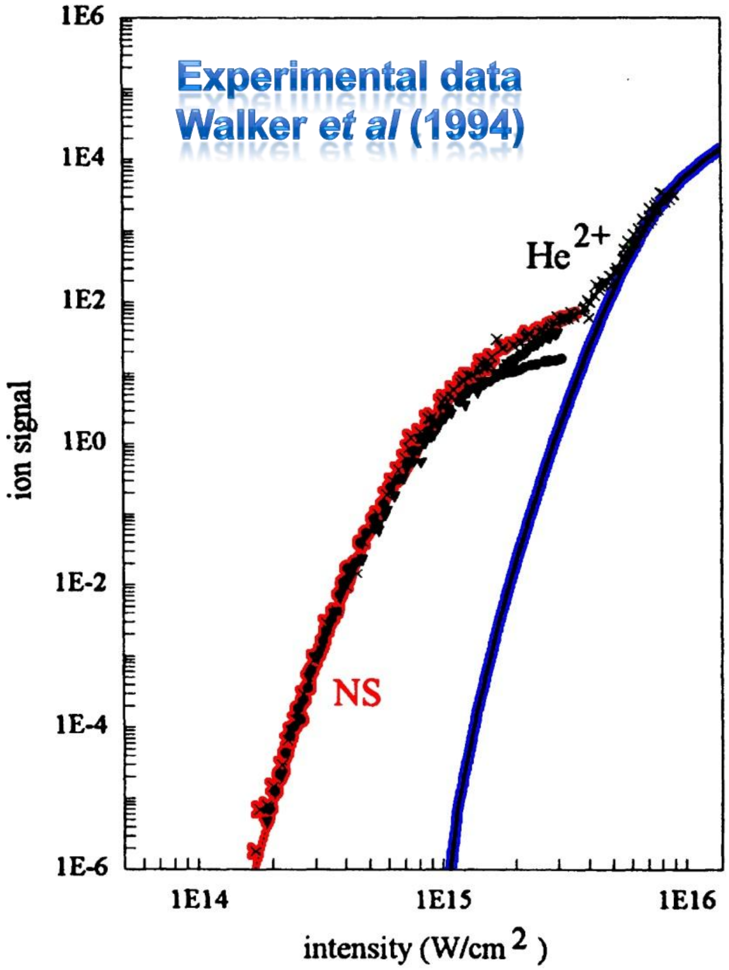
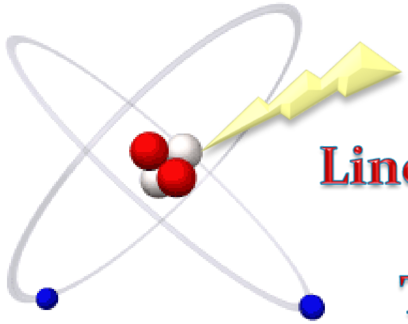
Financial support:

PICS

Double ionization: the puzzling *knee*-shape





Linear polarization
$\lambda = 780$ nm
T = 100 fs (10^{-13} s)

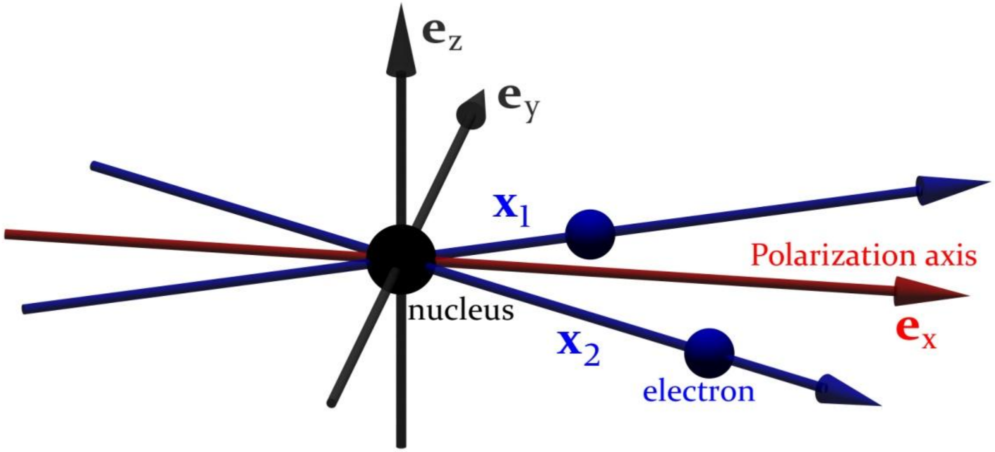
- Double Ionization
  - SDI

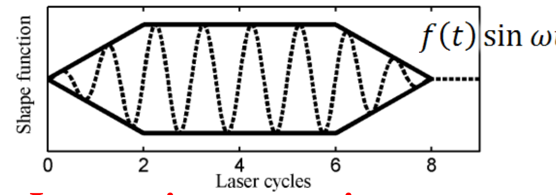
$$\mathrm{He} \rightarrow \mathrm{He}^{+} + e^{-} \rightarrow \mathrm{He}^{2+} + 2e^{-}$$

  - NSDI

$$\mathrm{He} \rightarrow \mathrm{He}^{2+} + 2e^{-}$$

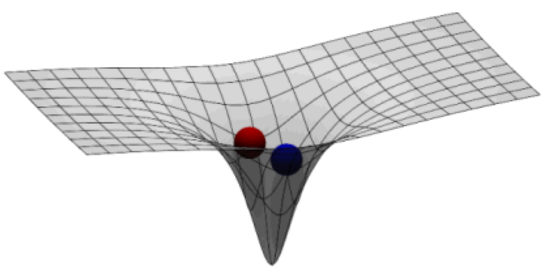
Classical model





- Laser interaction
  - dipole approximation
- Linear polarization (LP)
  - 1D model ↔ 2.5 d.o.f.
- Circular or elliptic polarization (CP/EP)
  - 2D model ↔ 4.5 d.o.f.

- Kinetic energy

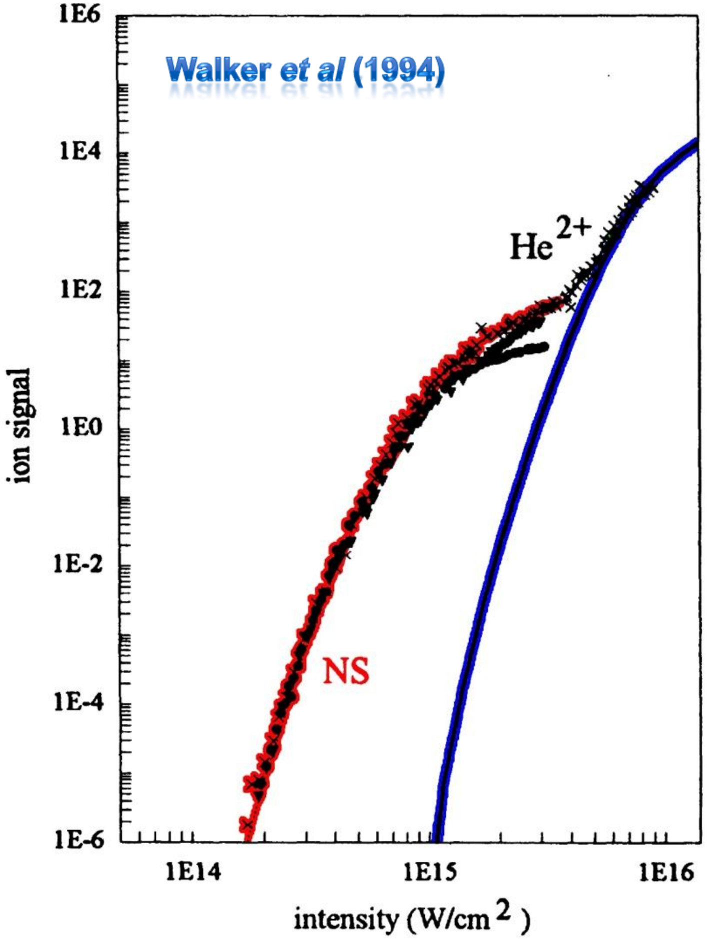


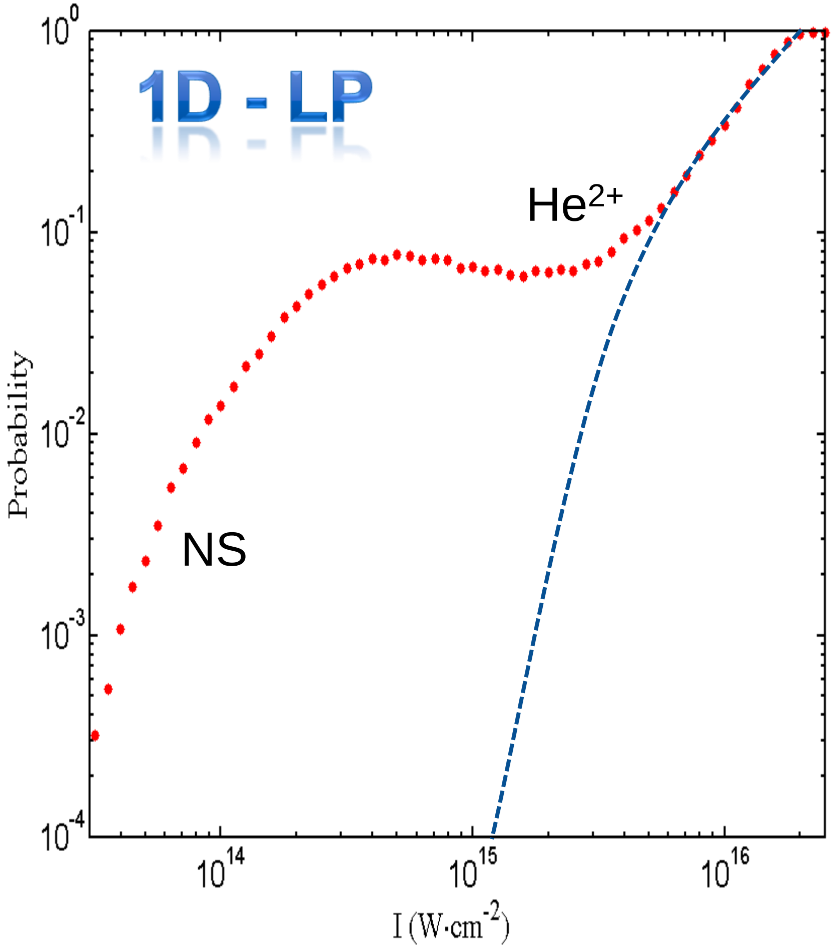
- Soft coulomb potential

J. Javanainen, J. H. Eberly and Q. Su, Phys. Rev. A 38, 3430 (1988)

$$H(\boldsymbol{x}_1, \boldsymbol{x}_2, \boldsymbol{p}_1, \boldsymbol{p}_2, t) = \frac{\|\boldsymbol{p}_1\|^2}{2} + \frac{\|\boldsymbol{p}_2\|^2}{2} + (\boldsymbol{x}_1 + \boldsymbol{x}_2) \cdot \boldsymbol{E}(t) f(t)$$
$$+ \frac{1}{\sqrt{\|\boldsymbol{x}_1 - \boldsymbol{x}_2\|^2 + b^2}} - \frac{2}{\sqrt{\|\boldsymbol{x}_1\|^2 + a^2}} - \frac{2}{\sqrt{\|\boldsymbol{x}_2\|^2 + a^2}}$$

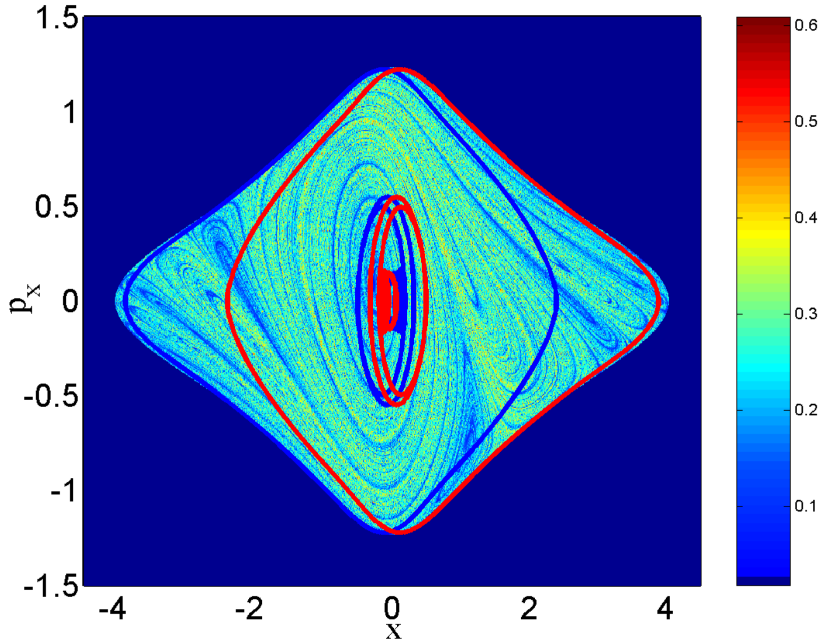
Numerical experiment: the knee



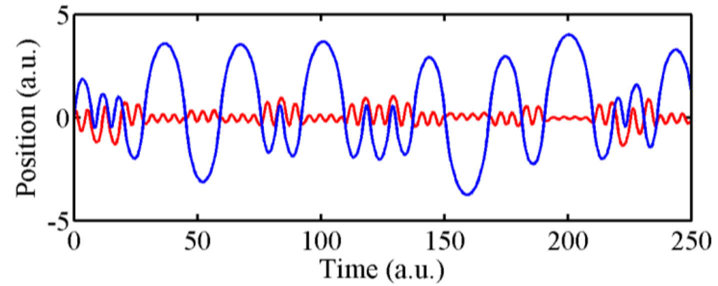


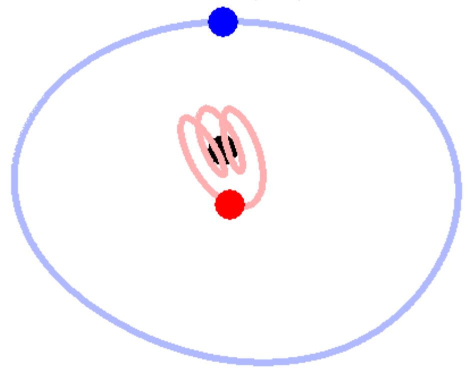
Free field motion $(E_0 = 0)$

- Finite time Lyapunov indicator



- Distance to periodic orbits





- Chaotic motion organized by hyperbolic periodic orbits
- At any time it defines an inner and an outer electron

Reduced models for inner and outer electrons

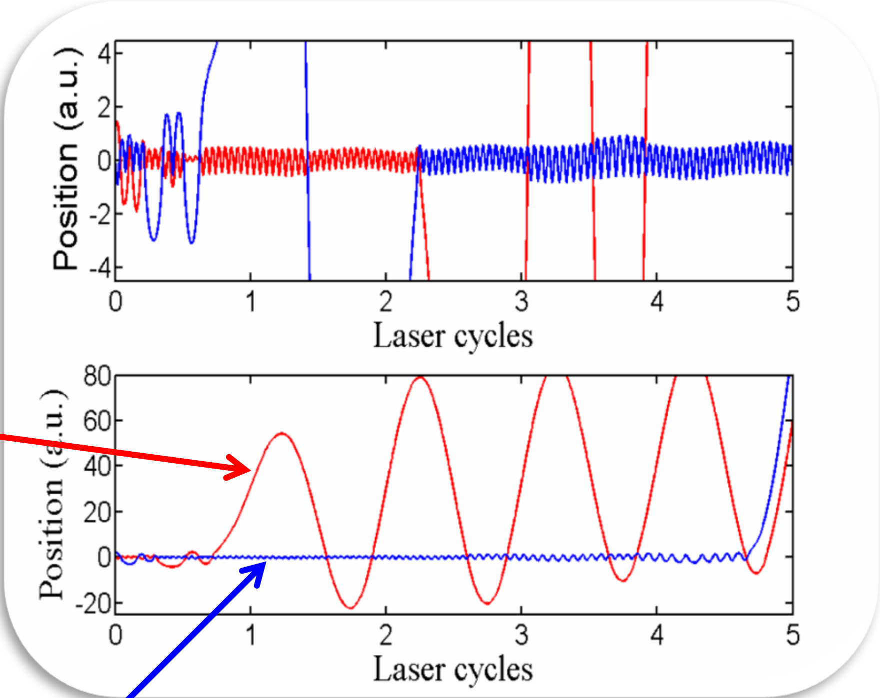
- Outer electron
  - Effective Hamiltonian

$$H^{(1)}(x, p_x, t) = \frac{p_x^2}{2} + xE_0 f(t) \sin \omega t$$

  - Maximum return energy

$$\mathcal{E}_{max} = \kappa \frac{E_0^2}{4\omega^2} \text{ with } \kappa \approx 3.17$$

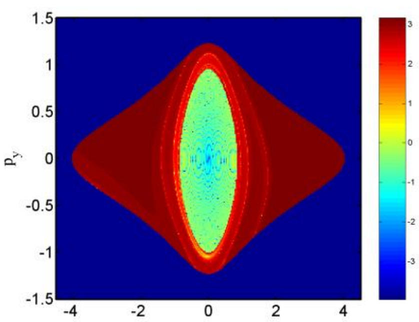
  - 3 step model (Corkum 1993)
    1. ionization
    2. return to the core
    3. collision with the core electron

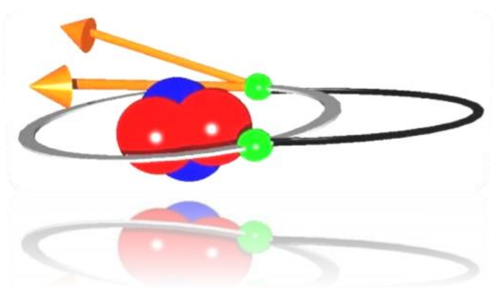


- Inner electron
  - Effective Hamiltonian

$$H^{(2)}(y, p_y, t) = \frac{p_y^2}{2} - \frac{2}{\sqrt{y^2+1}} + yE_0 f(t) \sin \omega t$$

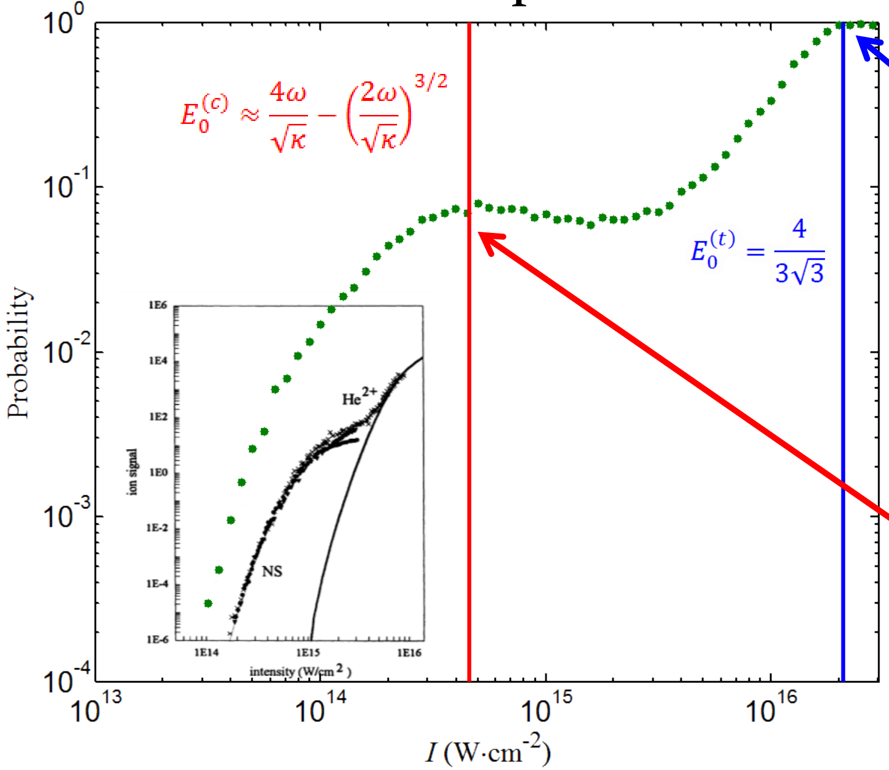
  - Laminar plot



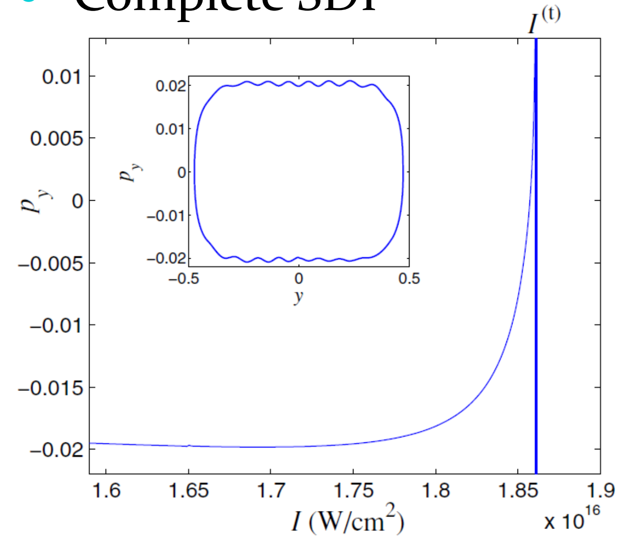


Double ionization: What is under the knee ?

- Double ionization: separate NSDI and SDI components.



- Complete SDI

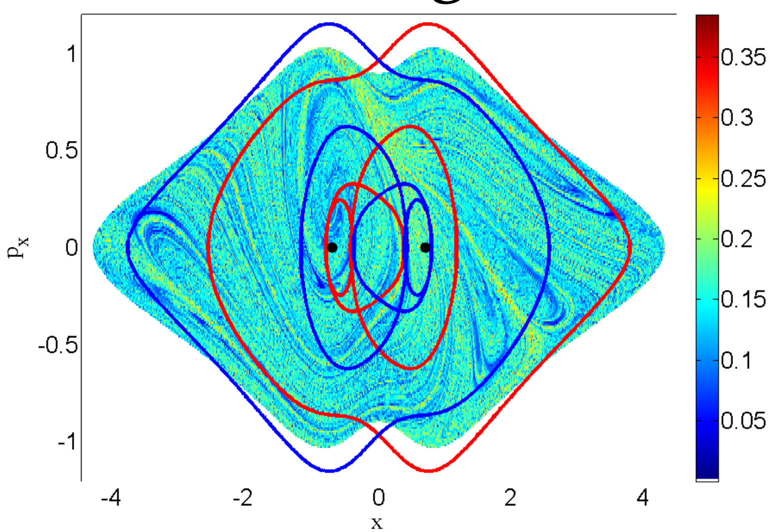


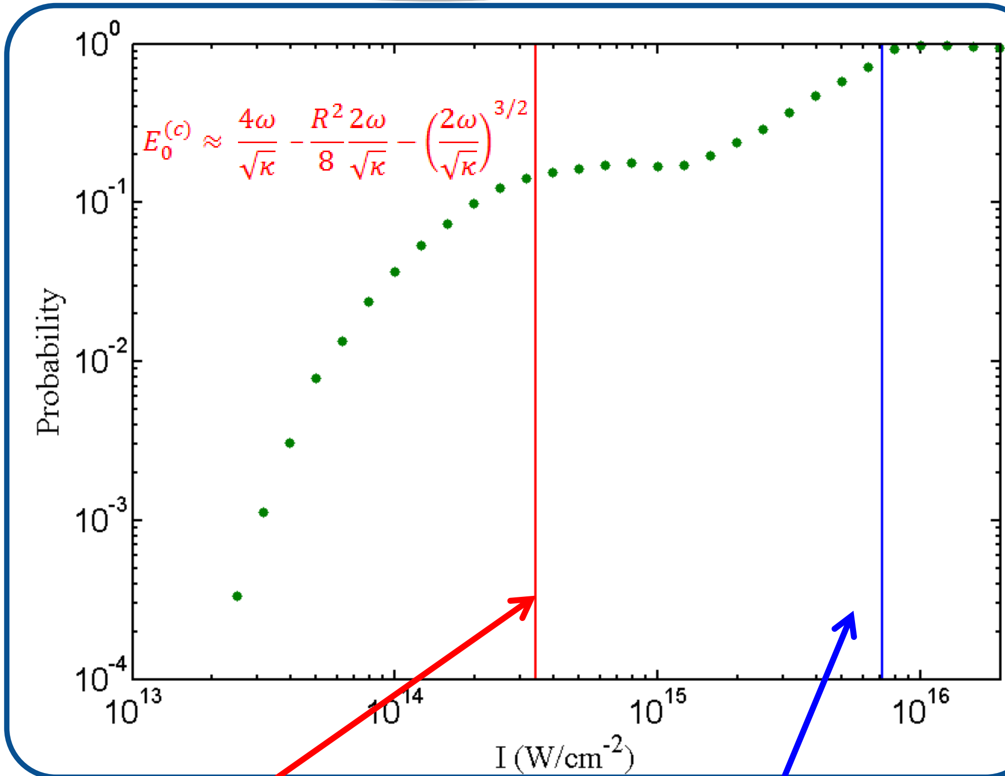
- Maximum NSDI
  - Equal sharing relation

F. Mauger, C. Chandre and T. Uzer, PRL 102, 173002 (2009); JPB 42 (2009)

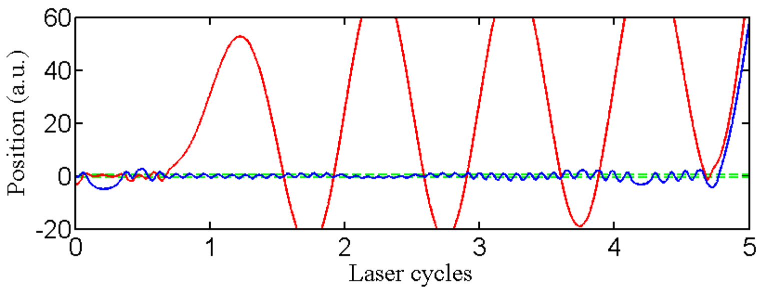
1D H_2 Molecule

- Free field organization



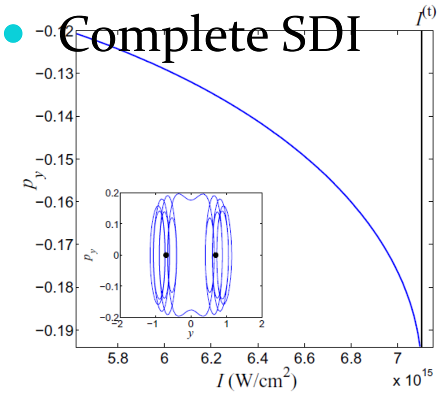


- NSDI



- Maximum NSDI
  - Equal sharing relation

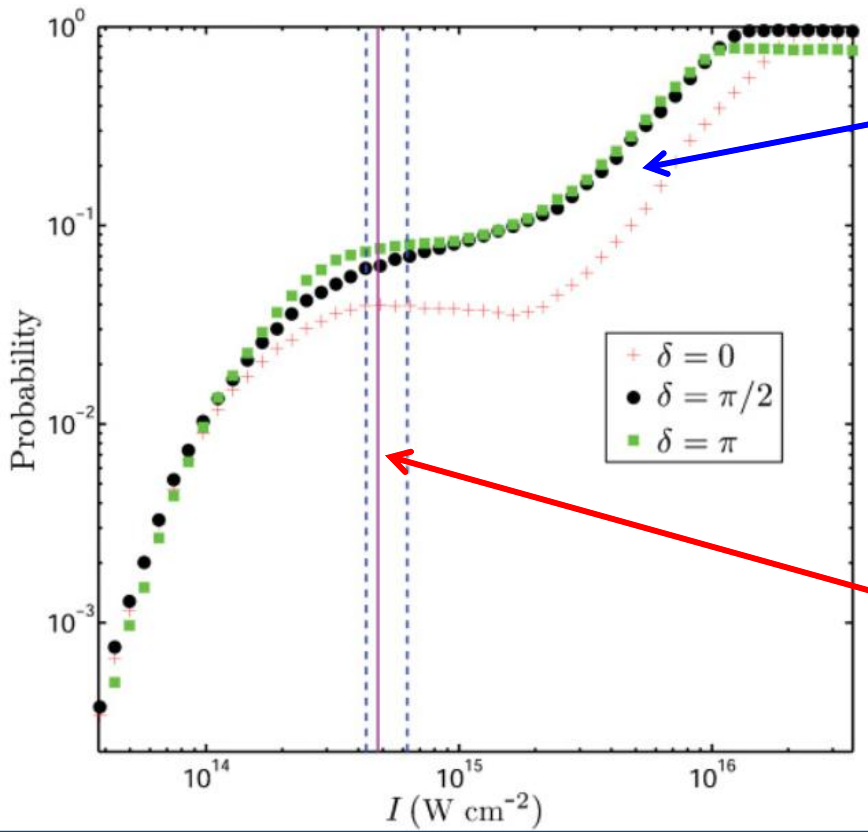
- Complete SDI



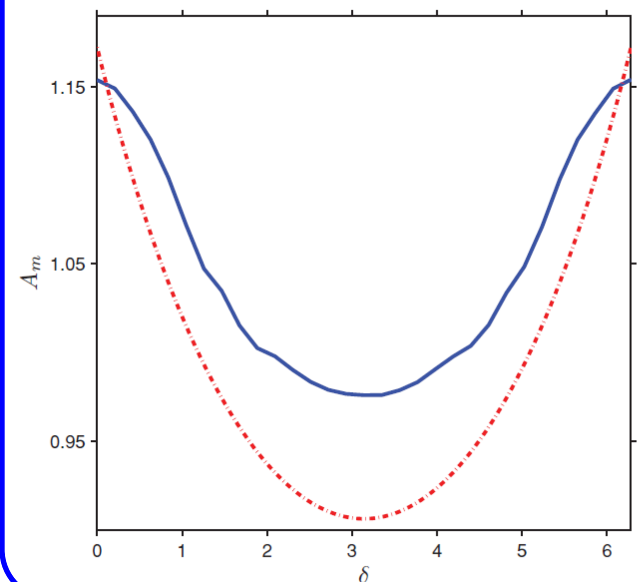
F. Mauger, C. Chandre and T. Uzer, Chem. Phys. 366, p. 64-70 (2009)

Double ionization: Controlling the knee ?

- Two color laser.



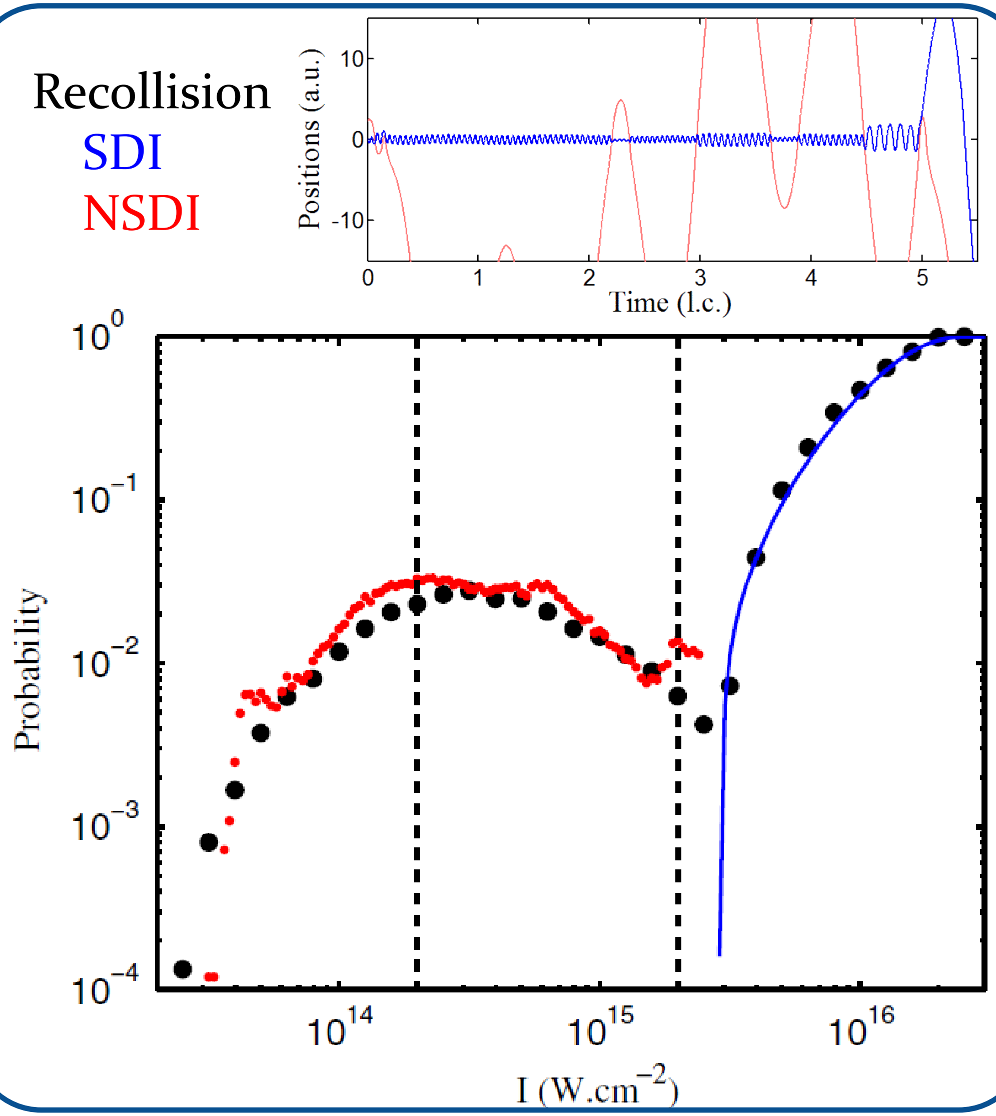
- Double ionization yield
  - Strongly sensitive to the phase lag



- Maximum NSDI
  - Weakly sensitive to the phase lag

A. Kamor, F. Mauger, C. Chandre and T. Uzer, PRE 83, 036211 (2011).

Road map for NSDI



- Kicked rotator Hamiltonian

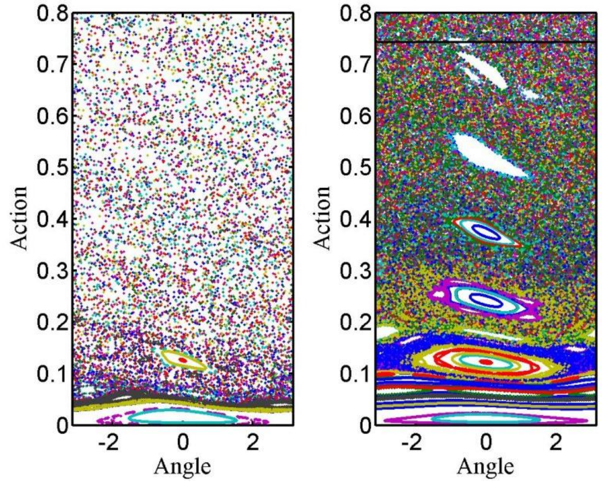
$$H_m(\varphi, A, t) = H_0(A) + \varepsilon A \cos\varphi \sum_{n=1}^{N} \delta(t - nT)$$

$$H_0(A) = -2 + \sqrt{2}\frac{e^{aA} - 1}{a}, \partial_A H_0 = \omega_0(A) = \sqrt{2}e^{aA}$$

- Symplectic map

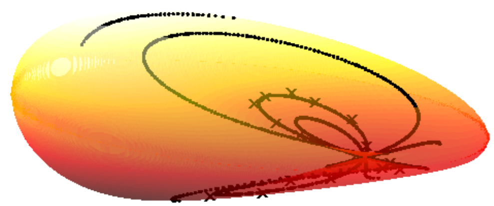
$$A_{n+1} = \frac{A_n}{1 - \epsilon \sin\varphi_n}$$
$$\varphi_{n+1} = \varphi_n + \omega_0(A_{n+1})T + \epsilon\cos\varphi_n$$

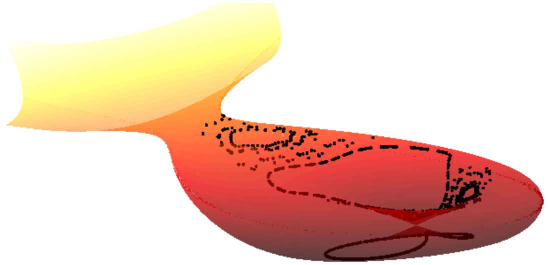
- Phase portraits



F. Mauger, C. Chandre and T. Uzer, PRL 104, 043005 (2010); PRA … (2010)

Conclusion





- Organizing structures in phase space
  - ➢ inner/outer electrons
  - ➢ reduced models
    - ⇨ equal sharing relation
    - ⇨ predictions on the knee

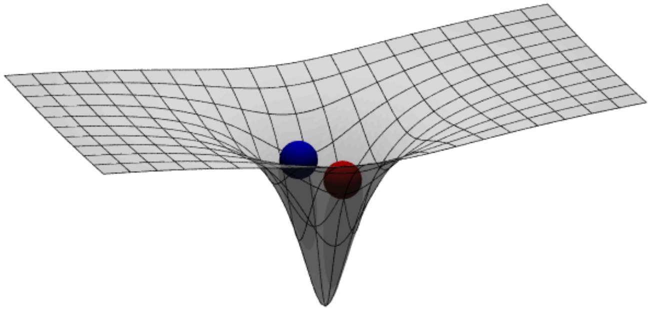
- NSDI
  - ➢ Analysis of recollision process
  - ➢ Symplectic map for recollision dynamics
  - ➢ Decomposition of the knee

- Selected references: F. Mauger, C. Chandre and T. Uzer
  1. Physical Review Letters - 102, 173002 (2009); Journal of Physics B – 42, 165602 (2009)
  2. Chemical Physics – 366, 64 (2009)
  3. Physical Review Letters – 104, 043005 (2010); Physical Review A – 81, 063425 (2010)

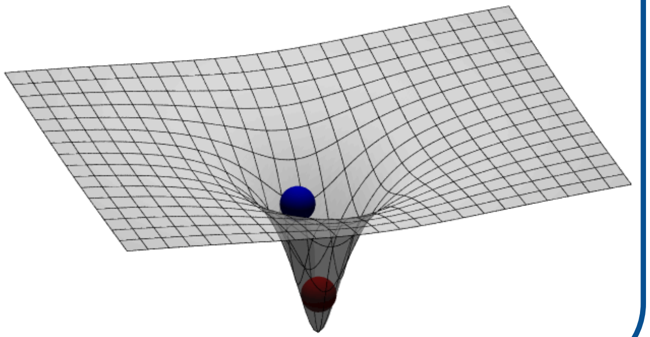
- Related works:
  - J. Javanainen, J. H. Eberly and Q. Su, Physical Review A - 38, 3430 (1988)
  - P. B. Corkum, Physical Review Letters – 71, 1994 (1993)

Recollision with circular polarization?

- Linear polarization



- Circular polarization



"only a slight ellipticity of the laser polarization will ensure that the electron never returns to the environment of the ion"
P. B. Corkum, PRL 71, 1994 (1993)

"circular polarization suppresses the enhancement."
D.N. Fittinghoff et al., PRA 49, 2174 (1994)

"enhanced double ionization for circular polarization contradicts simple rescattering theories"
G. D. Gillen et al., PRA 64, 043413 (2001)

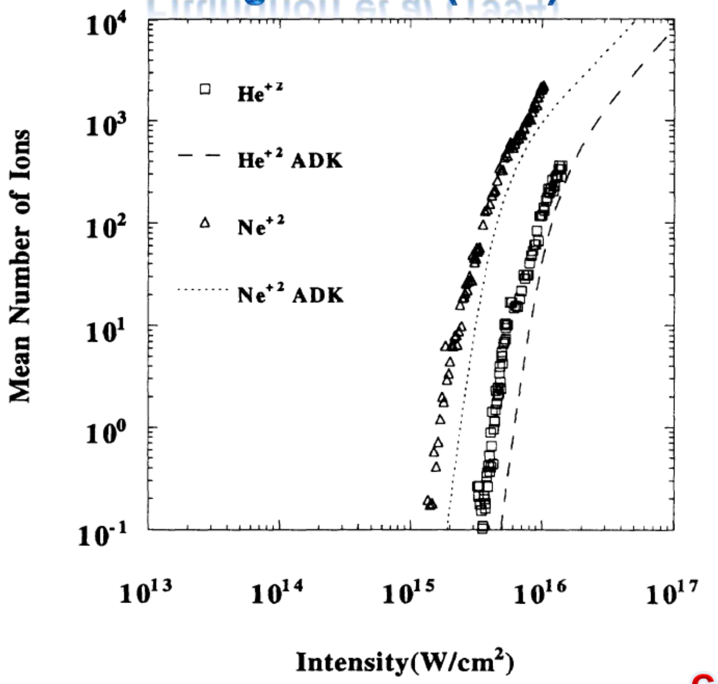
"For a laser field with circular polarization and already a field with significant elliptical polarization (...) the recollision mechanism will lose its significance."
W. Becker and H. Rottke, Cont. Phys. 49, 199-223 (2008)

"If the polarization is circular, then as soon as any portion of the wavepacket emerges from the atom (...) the motion ensures that the wavepacket never returns to the ion of its birth"
P.B. Corkum, Physics Today (March 2011)

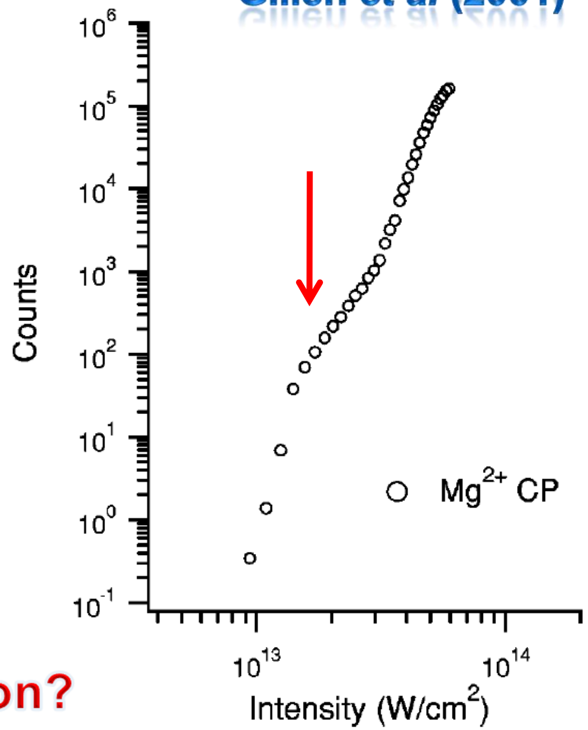
Recollision with circular polarization?

Experimental results (CP)

Fittinghoff *et al* (1994)



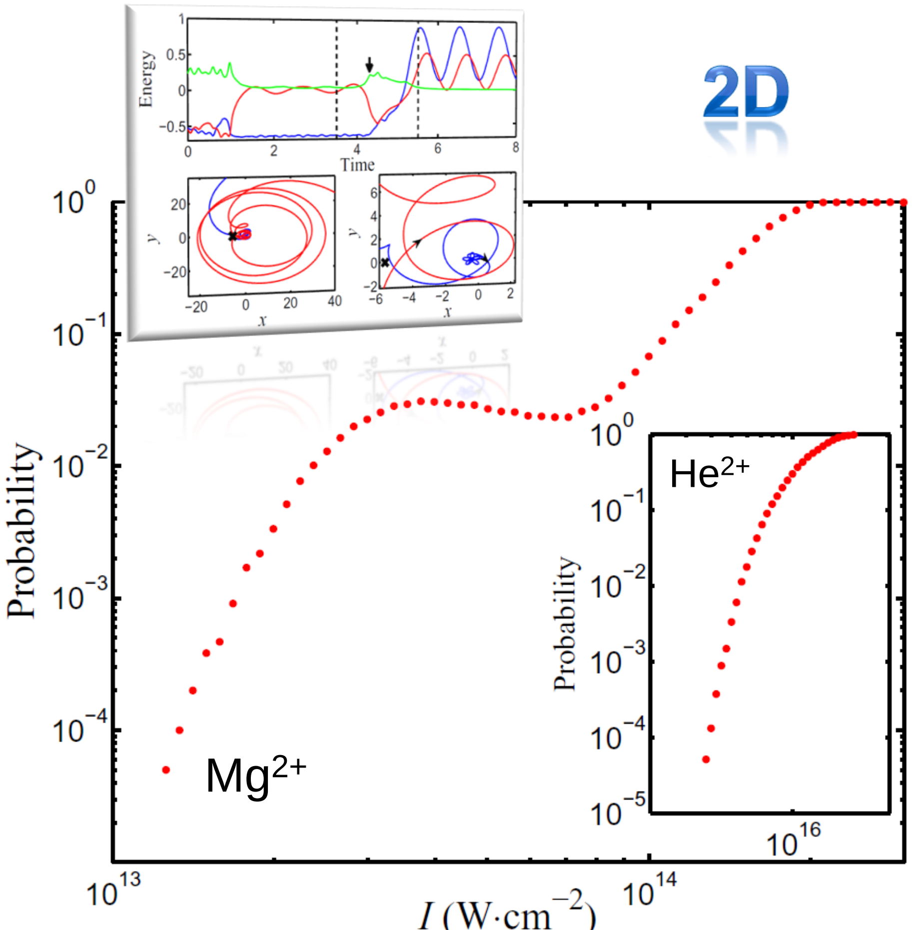
Gillen *et al* (2001)



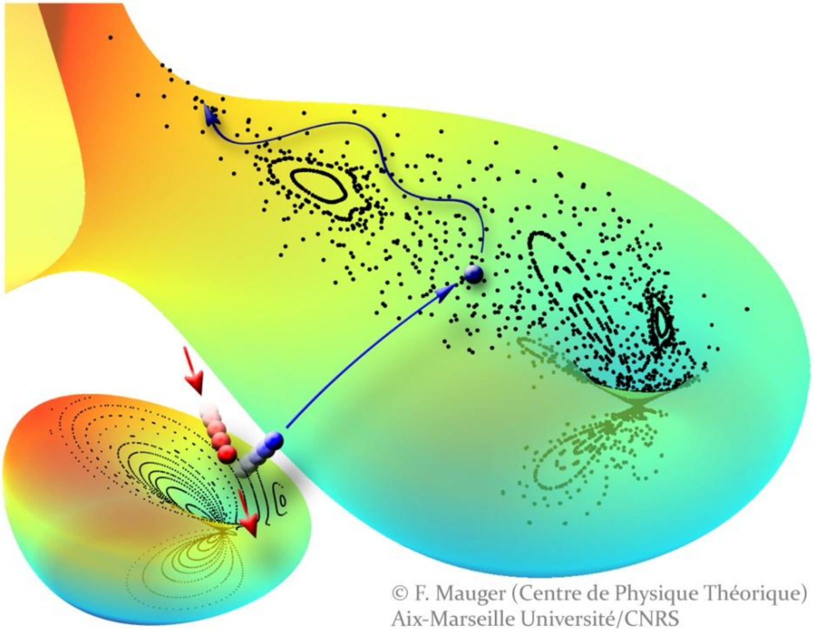
contradiction?

NSDI with circular polarization ?

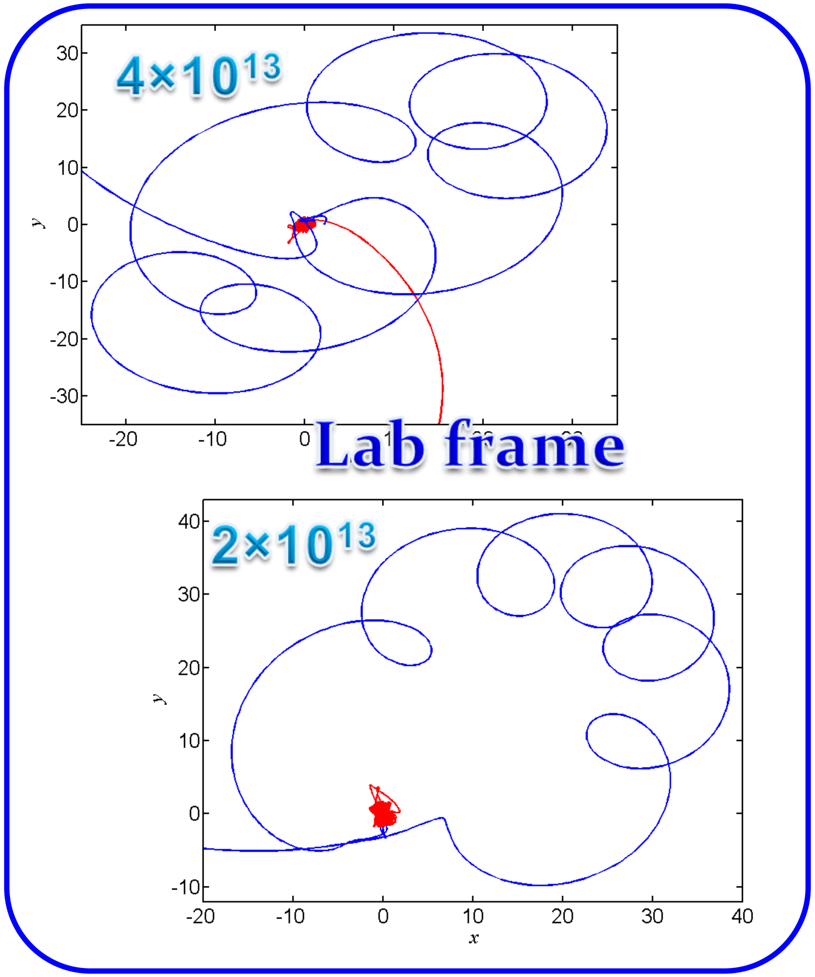
- Numerical simulations (CP)

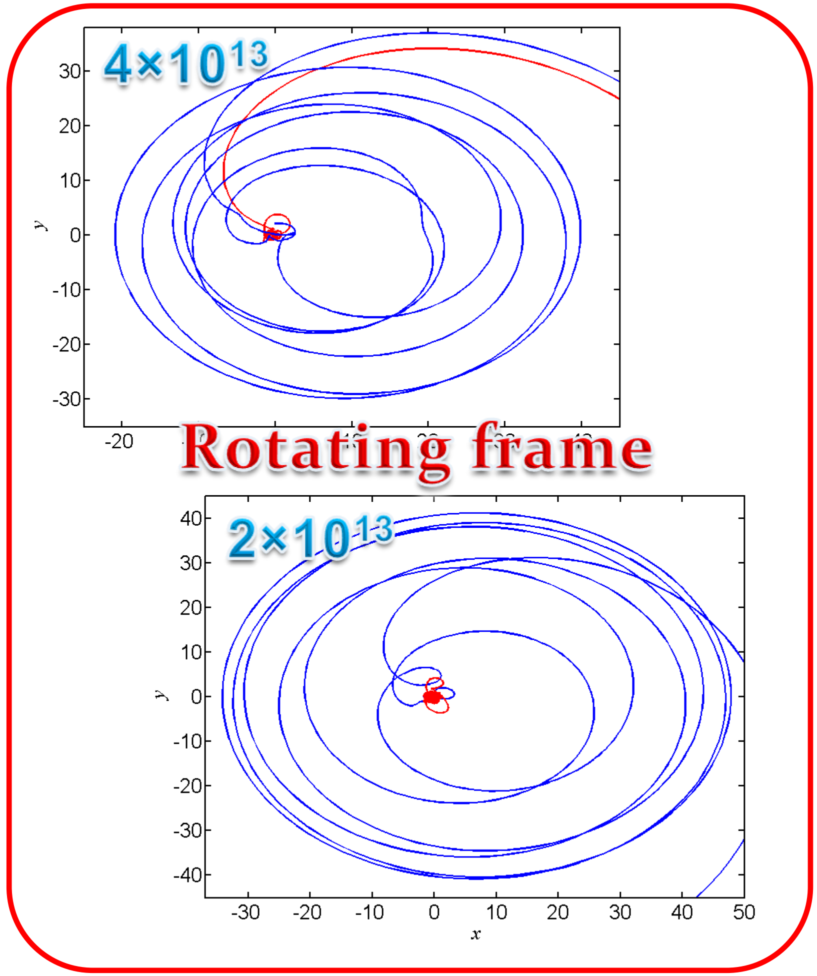


- We observe a knee shape with Mg and no knee for He
  - Significant amount of recollision for Mg.
  - For He, recollision suppressed because of initial conditions.

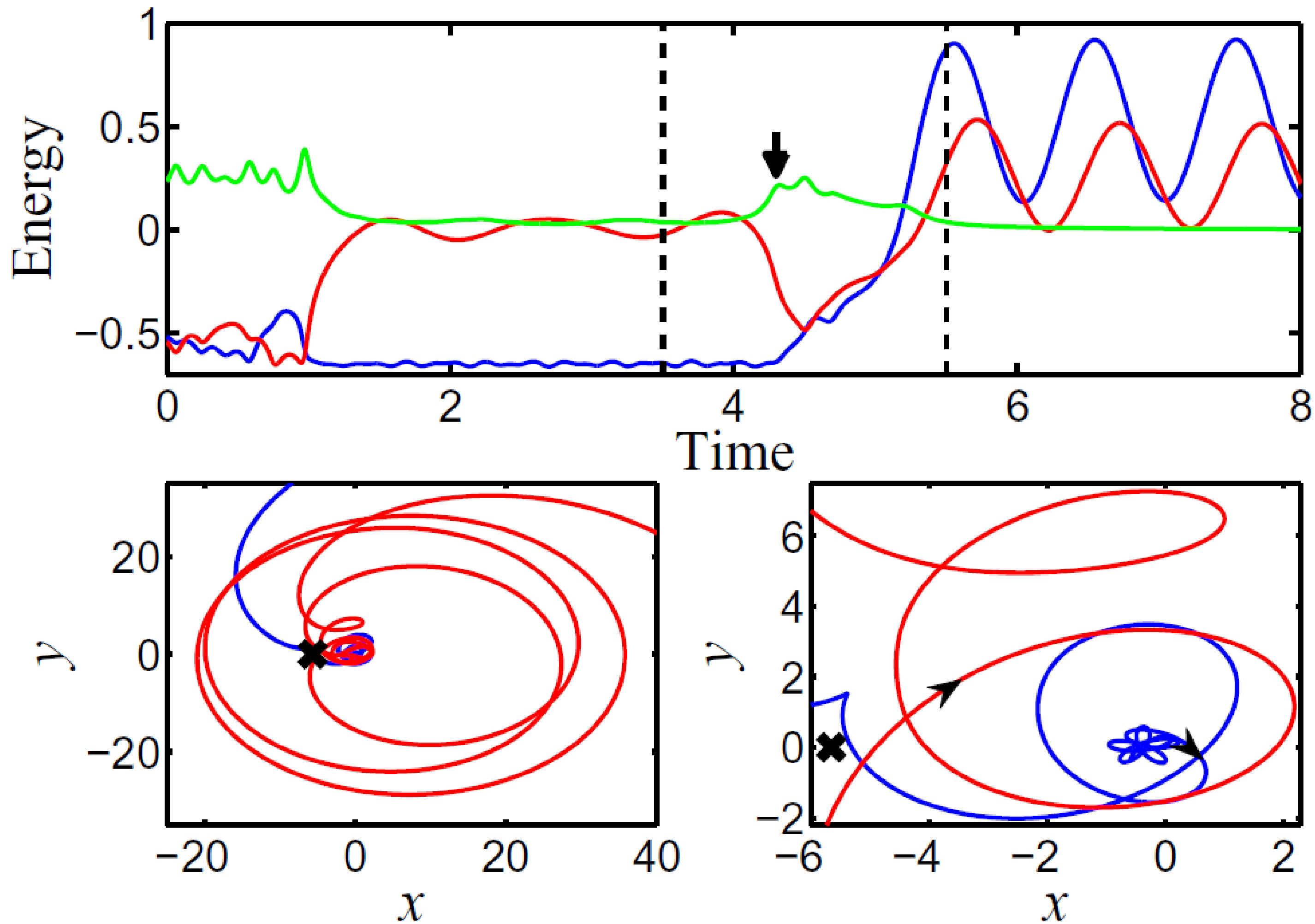


Rotating frame





Double ionization sample



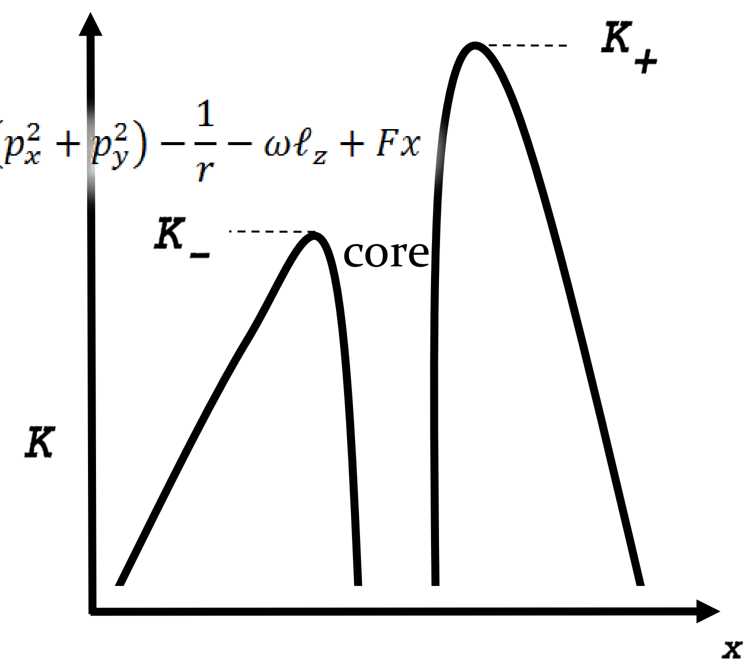
VOLUME 74, NUMBER 10 PHYSICAL REVIEW LETTERS 6 MARCH 1995

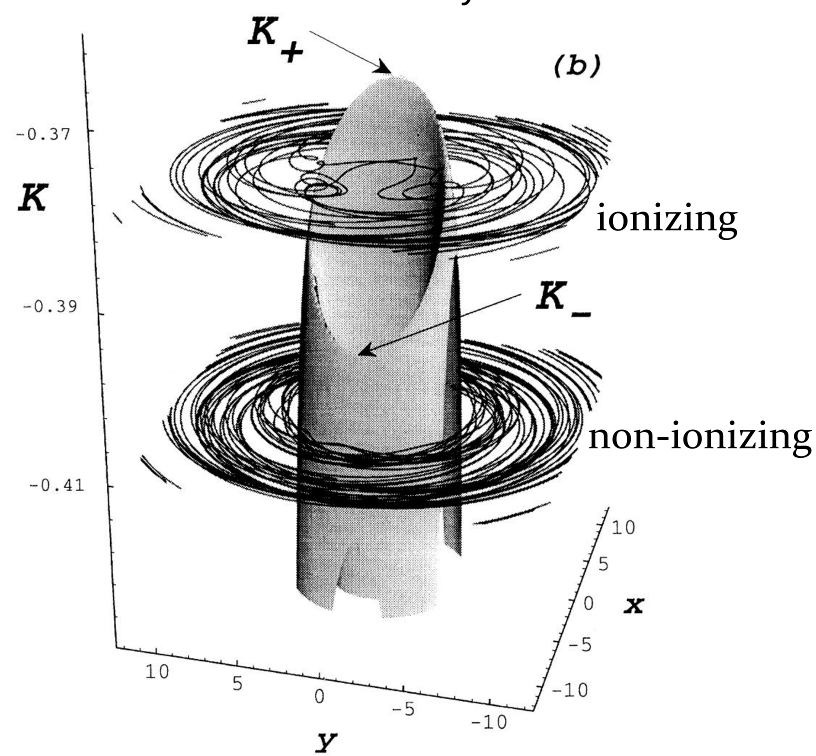
Ionization Mechanism of Rydberg Atoms in a Circularly Polarized Microwave Field

David Farrelly, Turgay Uzer

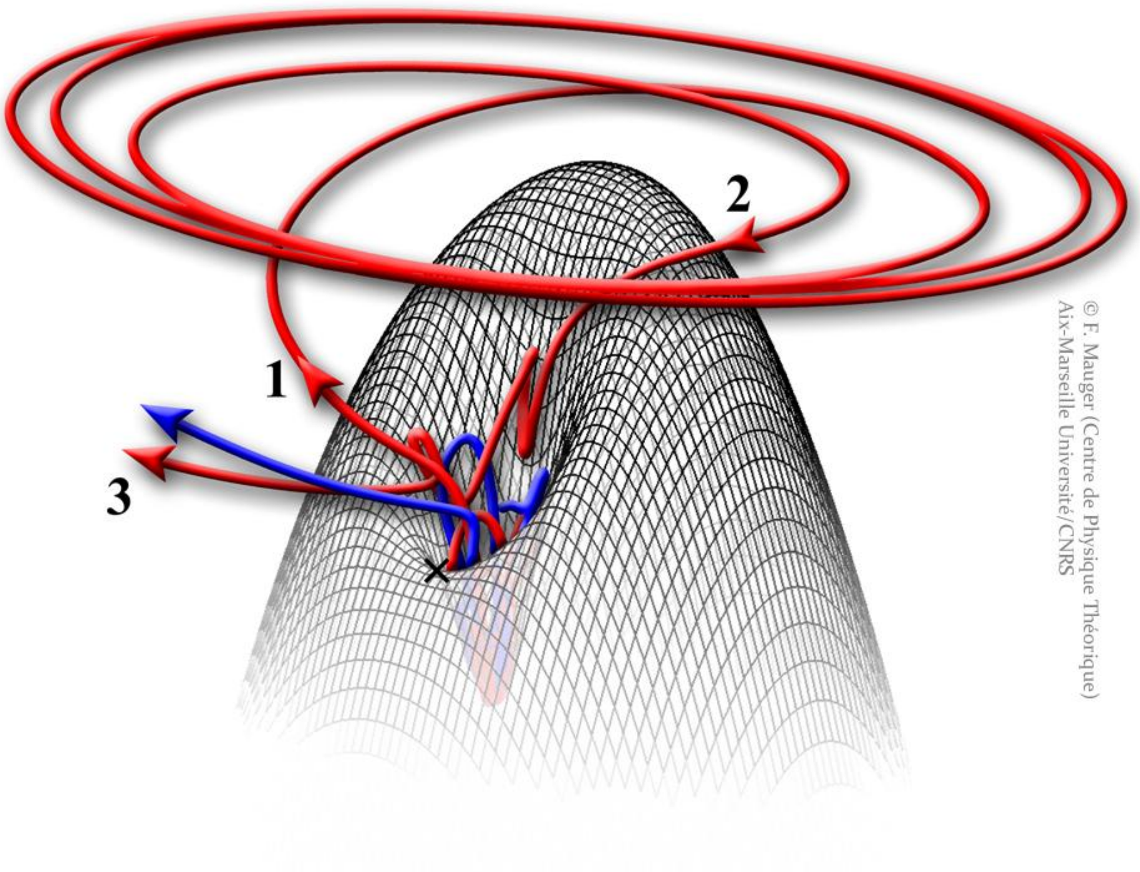
Placing a hydrogen atom in a circularly polarized microwave field exposes it to velocity-dependent forces that open new routes to chaotic ionization, access to which is controlled by the details of state preparation.

$$K = \frac{1}{2}\left(p_x^2 + p_y^2\right) - \frac{1}{r} - \omega \ell_z + Fx$$





Recollision dynamics with CP field



- Inner electron in the rotating frame

$$K = \frac{\|\boldsymbol{p}\|^2}{2} - \frac{2}{\sqrt{\|\boldsymbol{r}\|^2 + a^2}} - \omega \ell_z + E_0 x$$

- Saddle point condition

$$x = x^*, y = 0, p_x = 0, p_y = \omega x^*$$

$$\omega^2 x^* - E_0 - \frac{2x^*}{\left(x^{*2} + a^2\right)^{3/2}} = 0$$

- Periodic orbit family

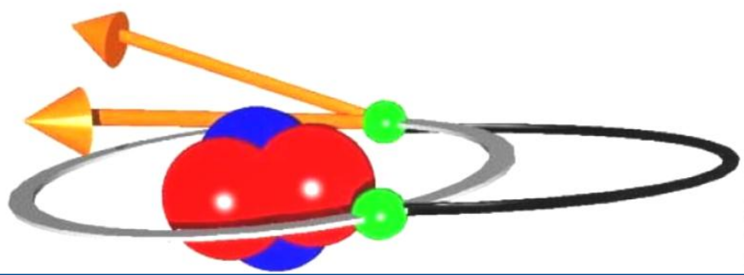
$$\rho(t) = \| \tilde{\boldsymbol{r}}_0 + \tilde{\boldsymbol{p}}_0 t \|$$

$$\tilde{\boldsymbol{r}}_0 = \boldsymbol{r}_0 - \begin{pmatrix} \frac{E_0}{\omega^2} \\ 0 \end{pmatrix}$$

$$\tilde{\boldsymbol{p}}_0 = \boldsymbol{p}_0 - \begin{pmatrix} 0 \\ \frac{E_0}{\omega} \end{pmatrix}$$

F. Mauger, C. Chandre and T. Uzer, PRL 105, 083002 (2010)

Conclusion



- LP
  - ➢ inner/outer electrons
  - ➢ reduced models
    ⇨ predictions on the knee
  - ➢ symplectic map for recollision dynamics
- CP
  - ➢ knee for CP (agreement with experiments)
  - ➢ conditions for knee in CP
  - ➢ recollision scenario MAY apply

- Our publications: F. Mauger, C. Chandre and T. Uzer
  1. Physical Review Letters - 102, 173002 (2009); Journal of Physics B – 42, 165602 (2009)
  2. Chemical Physics – 366, 64 (2009)
  3. Physical Review Letters – 104, 043005 (2010); Physical Review A - 81, 063425 (2010)
  4. Physical Review Letters – 105, 083002 (2010)
- Related theoretical works:
  - X. Wang and J. H. Eberly, Physical Review Letters – 103, 103007 (2009)
  - X. Wang and J. H. Eberly, Physical Review Letters – 105, 083001 (2010)