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Ultrafast Nano-Optics

Carrier-envelope phase effects on the strong-field photoemission of electrons from sharp metallic tips

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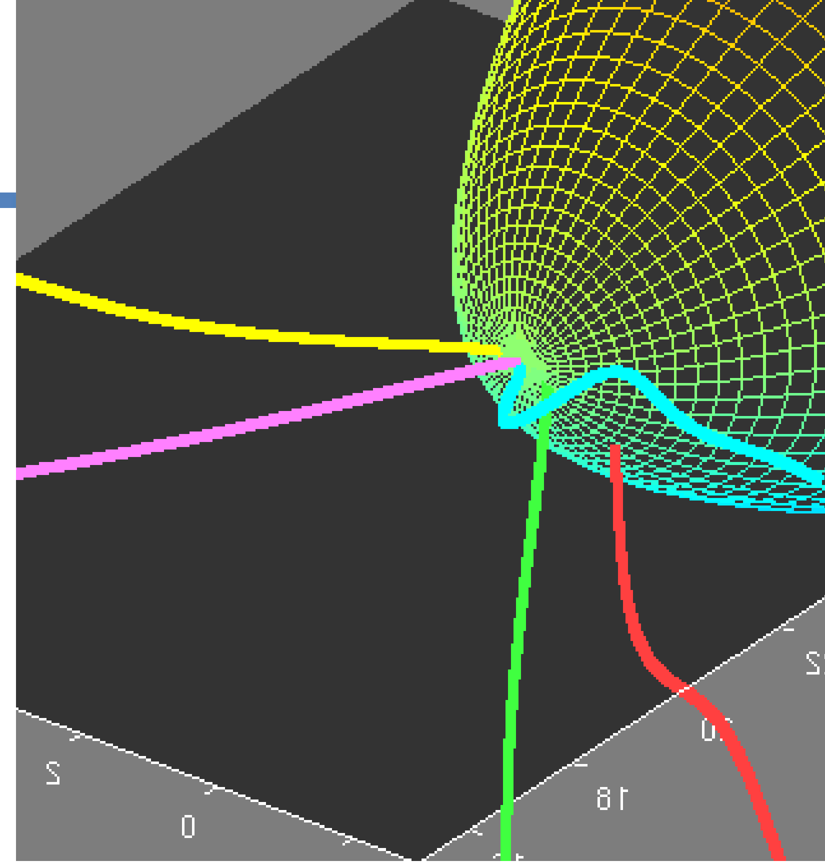
IFN-CNR, Dipartimento di Fisica, Politecnico di Milano, Italy

Ultrafast Nano-Optics

Outline



- Strong-field phenomena around metallic nanostructures:
  - Emission
  - Acceleration in the near field
- Strong-field regime
- Methods: experimental and numerical
- Experimental observation of CEP-effect on acceleration
- New control mechanisms for electron motion

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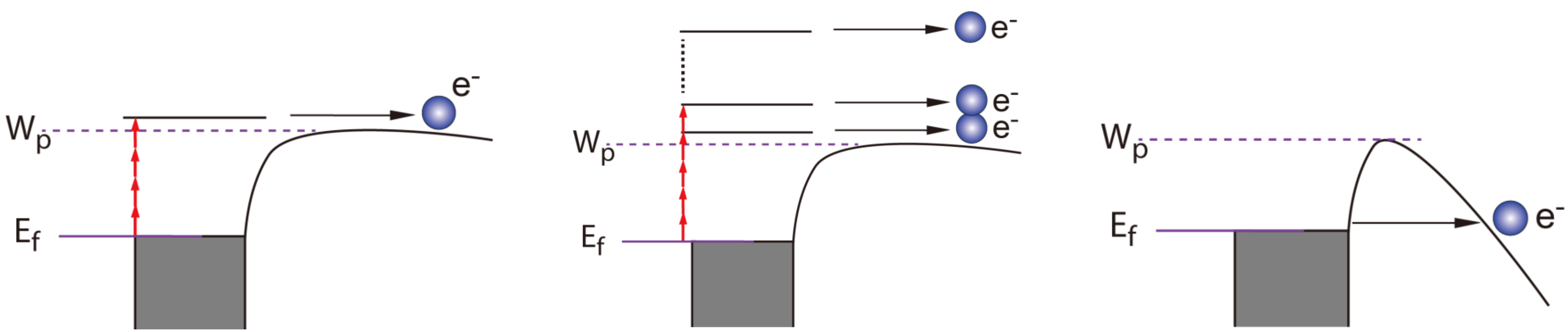
Strong-field phenomena

Observation of strong-field effects with metal nanostructures:

- High harmonic generation
- Attosecond pulses and x-ray radiation
- Electron emission from metal nanostructures



MPI (Multi-Photon Ionisation) | ATI (Above-Threshold Ionisation) | Strong-field Photoemission

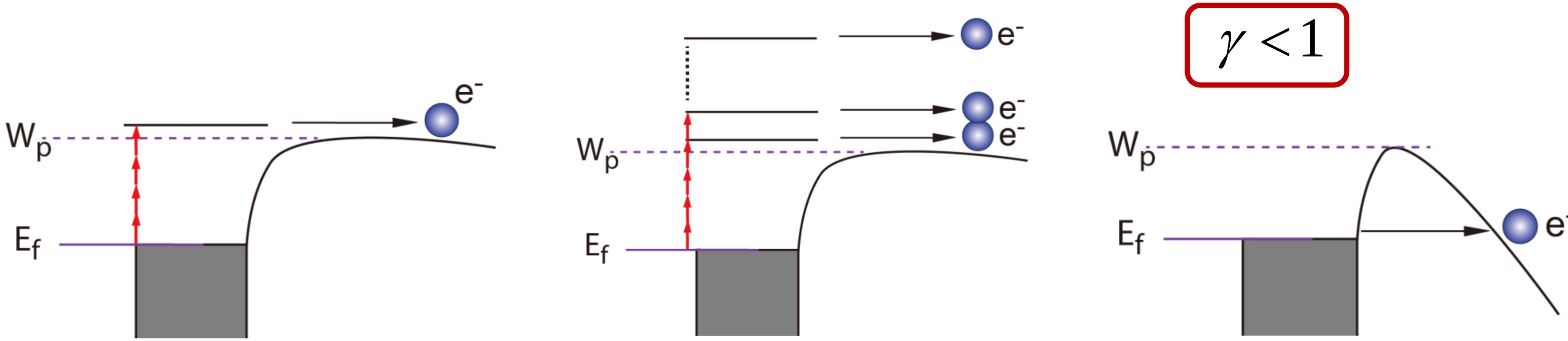
C. Ropers et al., PRL **98**, 043907 (2007), R. Bormann et al., PRL **105**, 147601 (2010)
G. Herink et al., Nature **483**, 190 (2012), D.J. Park et al., Phys. Rev. Lett. **109**, 244803 (2012)
M. Krüger et al., Nature **475**, 78 (2011), M. Schenk et al., Phys. Rev. Lett. **105**, 257601 (2010)

Strong-field phenomena

Characterization: Keldysh parameter $$\gamma = \frac{\omega\sqrt{2m_e\Phi}}{e \cdot f \cdot E_0}$$

Transition ATI $\Rightarrow$ Strong-field photoemission

$$\gamma < 1$$



MPI
(Multi-Photon
Ionisation)

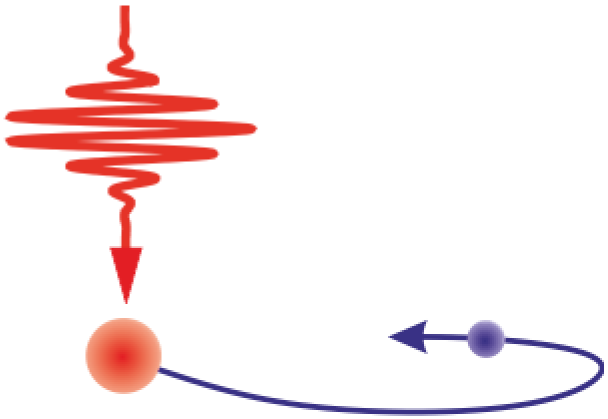
ATI
(Above-Threshold
Ionisation)

Strong-field
Photoemission

L.V. Keldysh, Soviet Physics Jetp-Ussr **20**, 1307 (1965)

Atomic system vs. nanostructures

Emission:
Similar to atomic systems



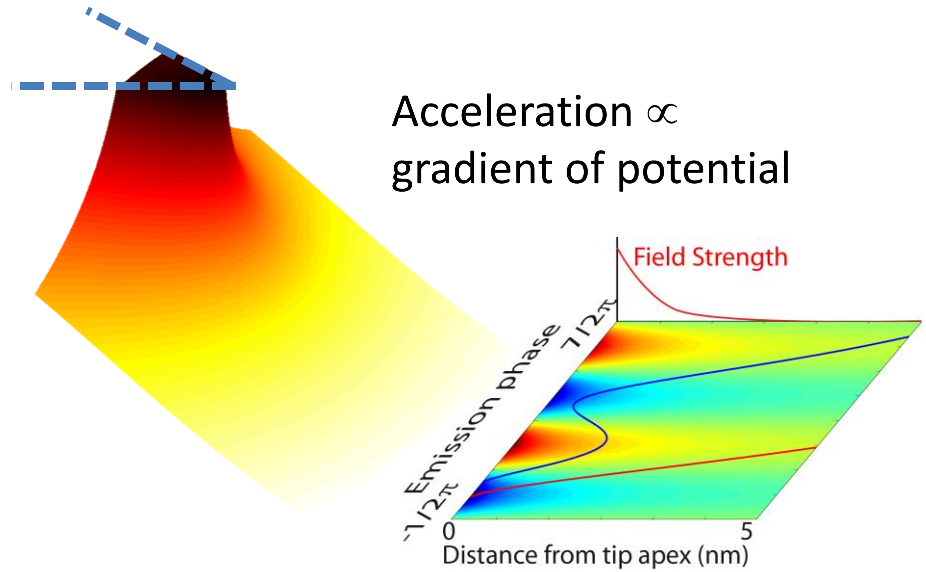
New phenomena discovered:

- High harmonic generation
- Attosecond generation

CEP control required

Difference:
Electron motion in the near field

Acceleration ∝ gradient of potential



New phenomena in strong near field:

- Suppression of quiver motion

⇒ Sub-cycle electrons

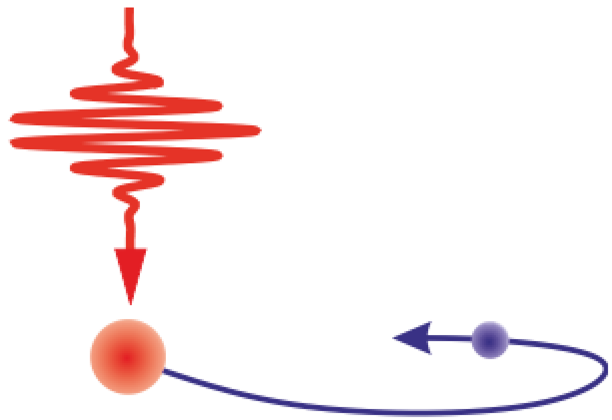
Atomic system vs. nanostructures

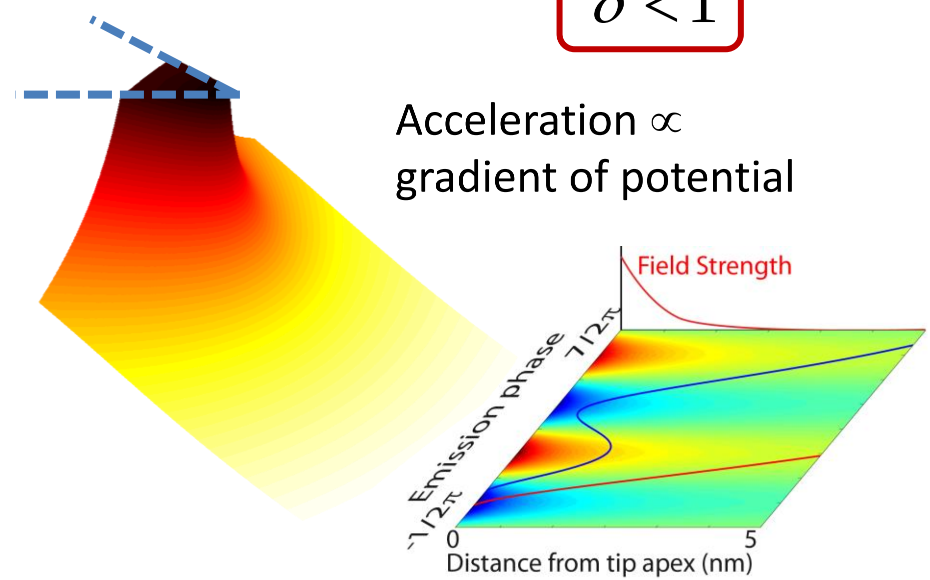
Characterization: Spatial adiabaticity parameter

$$\delta = \frac{l_F}{l_q}; \quad l_q = \frac{e \cdot f \cdot E_0}{m_e \omega^2}$$

Sharp metal structures ⇒ short near-field decay length

$$\delta < 1$$



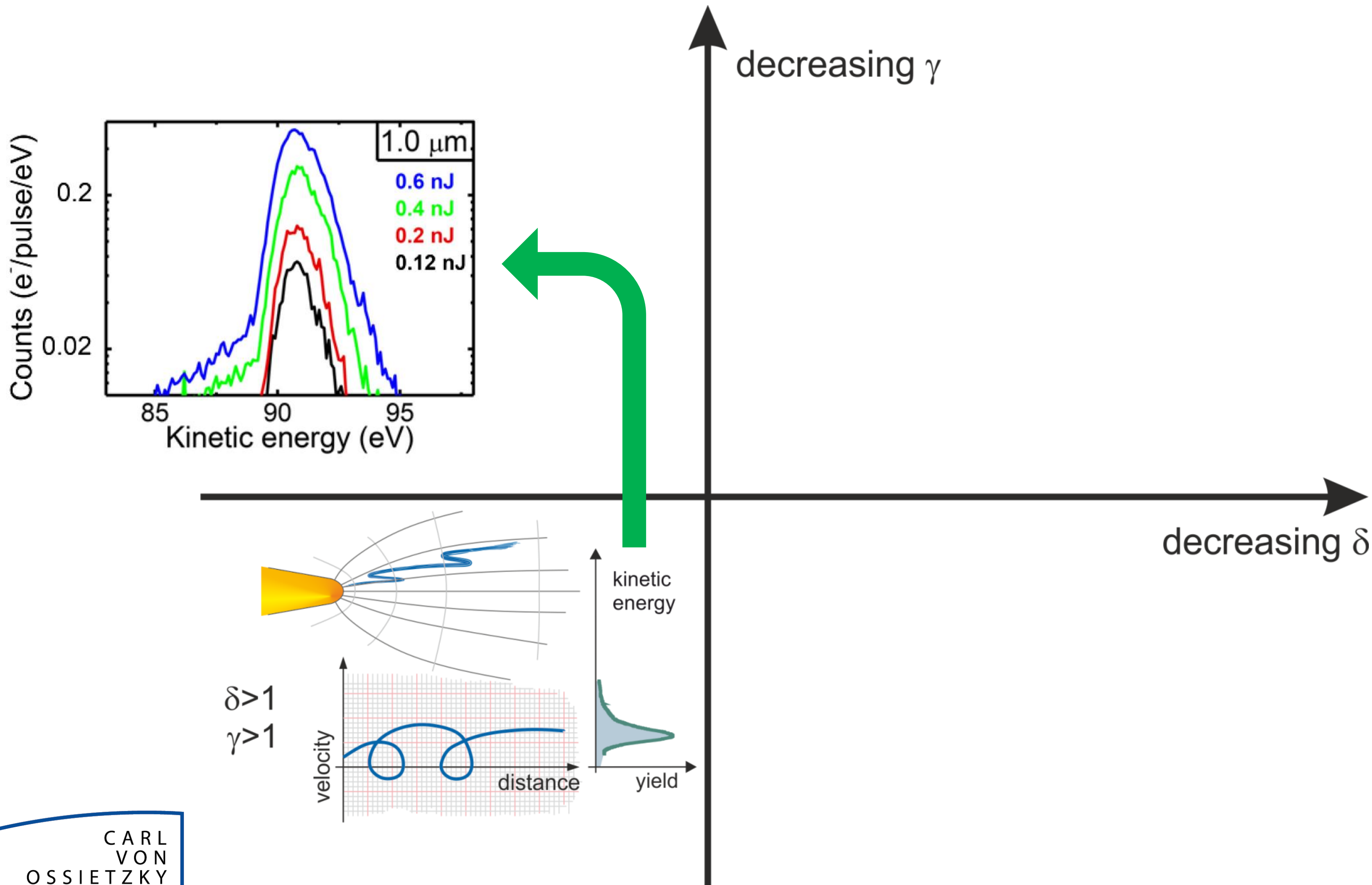


Acceleration ∝ gradient of potential

G. Herink et al., Nature **483**, 190 (2012), D.J. Park et al., Phys. Rev. Lett. **109**, 244803 (2012)

Ultrafast Nano-Optics

Four regimes of photoemission



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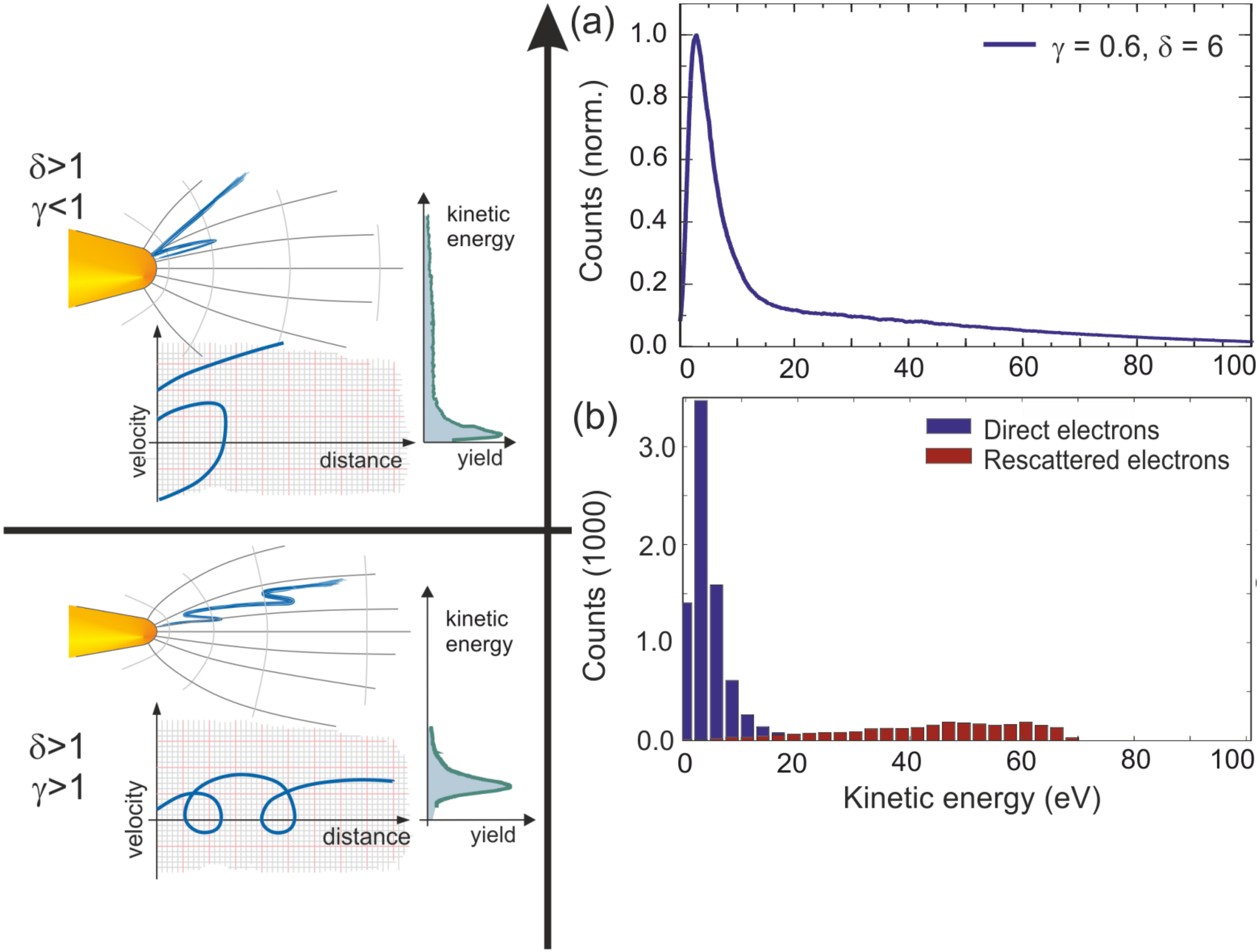
Four regimes of photoemission

Ultrafast Nano-Optics



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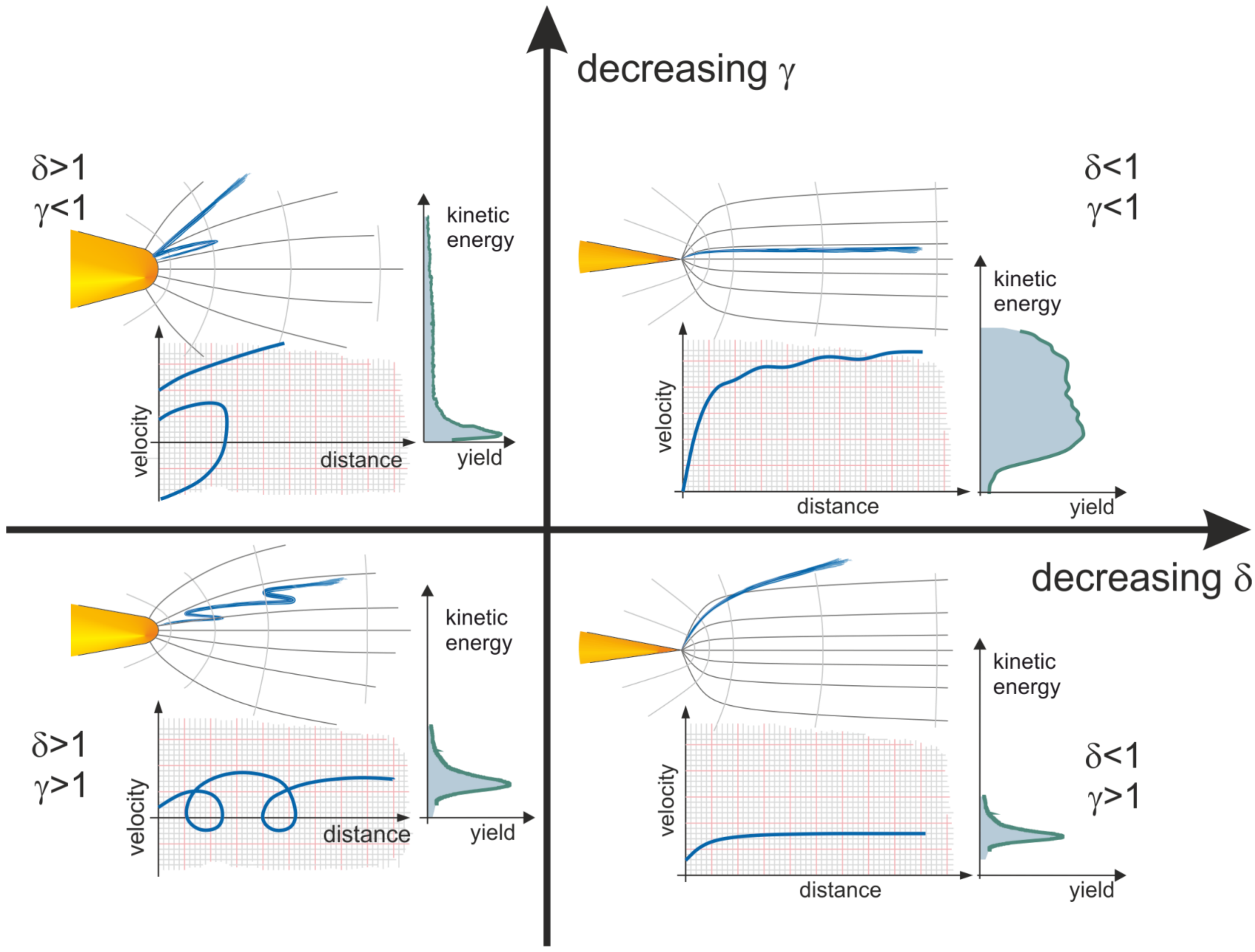
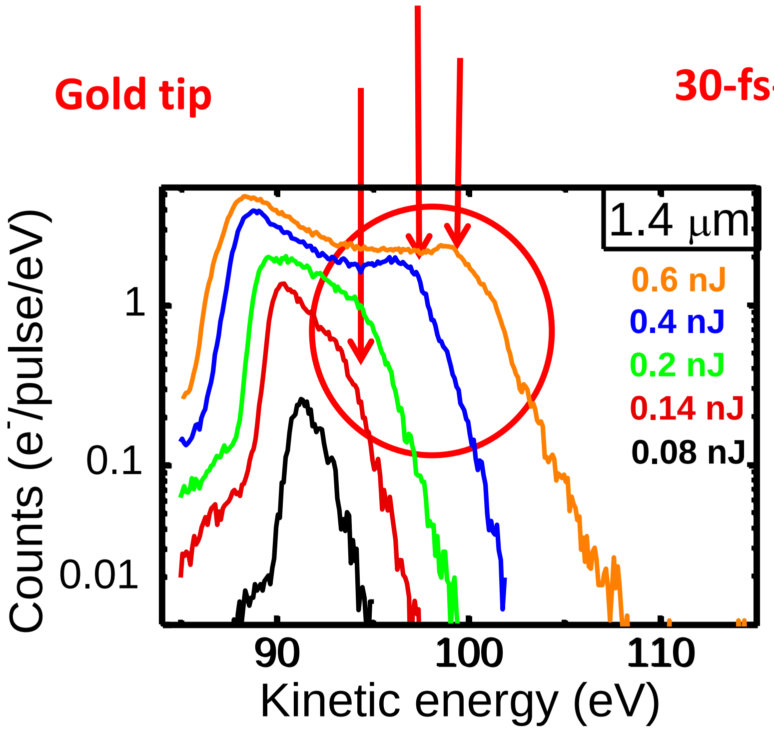
Four regimes of photoemission

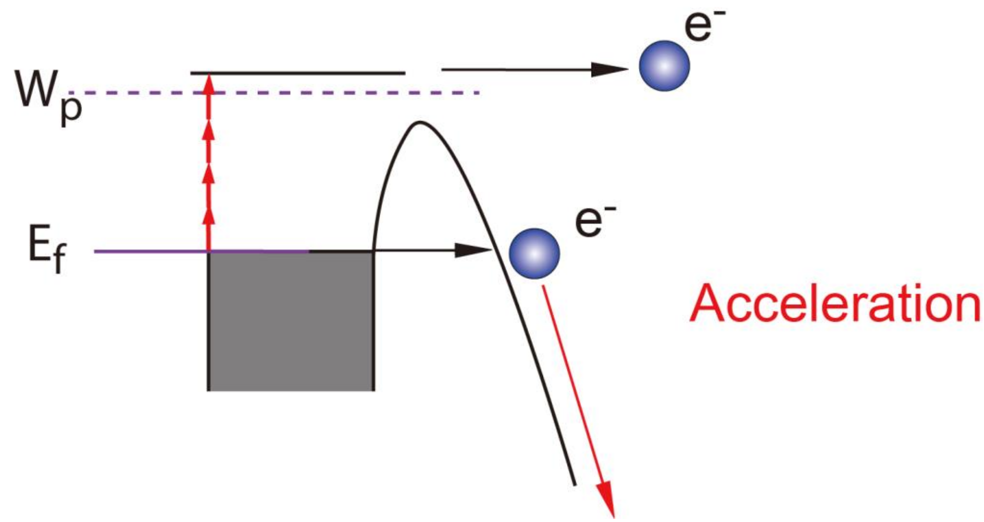


Regime: $\gamma<1$, $\delta<1$

Gold tip

30-fs-pulses at 1.4 µm





$$E_{loc} \leq 25 \text{ V/nm}, \quad f = 9 \quad \text{at 0.6nJ}$$

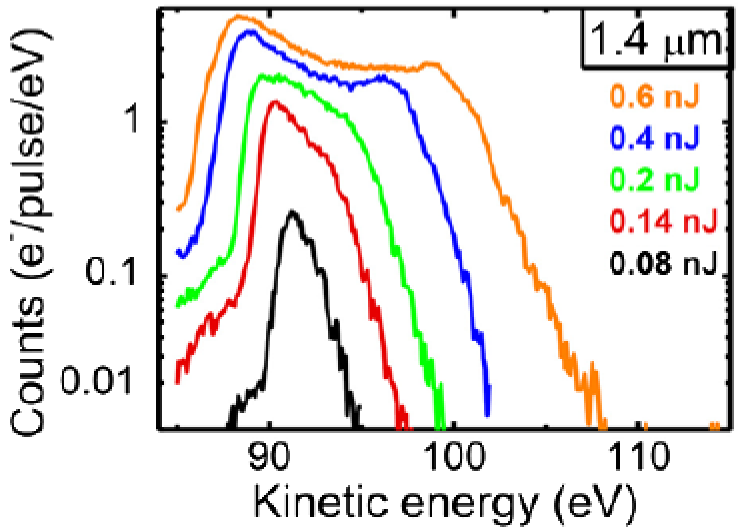
$$E_{loc} \leq 9.3 \text{ V/nm}, \quad f = 9 \quad \text{at 0.08nJ}$$

Emergence of a pronounced plateau

$\Rightarrow$ Signature of strong-field acceleration

Ultrafast Nano-Optics

Regime: $\gamma<1$, $\delta<1$



- Strong-field-induced tunneling
- Acceleration within one half cycle

⇒ Sub-cycle electrons form a plateau

New sub-cycle regime

⇒ unique to nanostructures

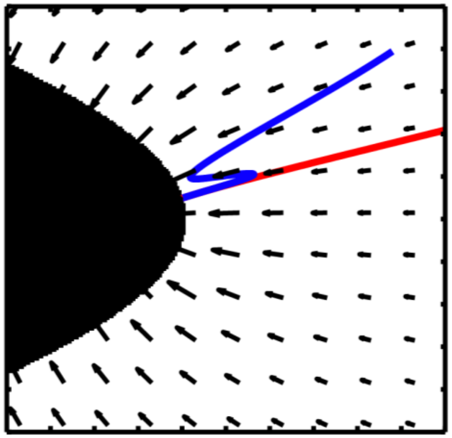
- Recollisions are suppressed
- Electrons follow field lines

⇒ Fundamentally different electron dynamics

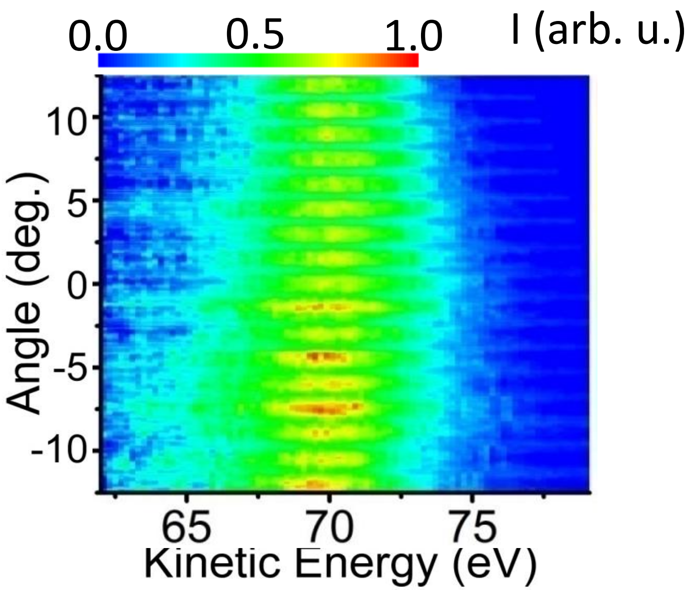
First experiments in sub-cycle regime performed only recently:

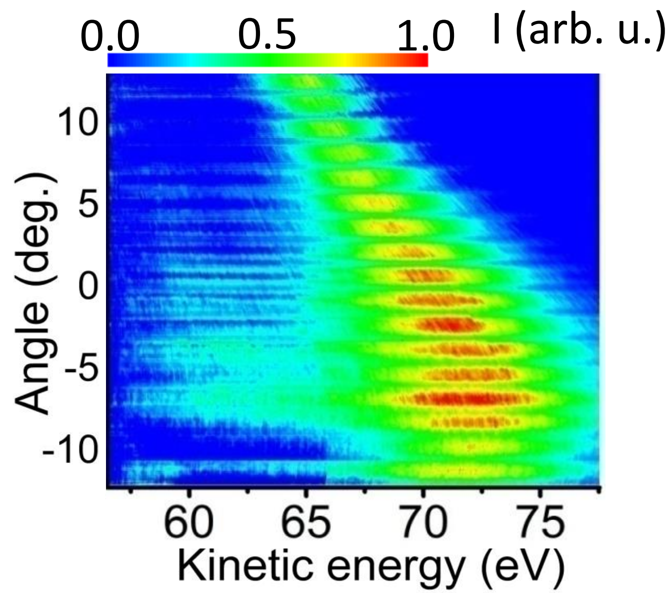
G. Herink, D.R. Solli, M. Gulde, and C. Ropers, Nature **483**, 190 (2012)
D.J. Park, P. Piglosiewicz, ..., C. Lienau, Phys. Rev. Lett. **109**, 244803 (2012)
S.V. Yalunin, G. Herink, …, P. Hommelhoff, …, C. Ropers, Ann. Phys. **525**, L12 (2013)
D.J. Park, P. Piglosiewicz, …, P. Groß, and C. Lienau, Ann. Phys. **525**, 135 (2013)
B. Piglosiewicz, …, P. Groß, C. Cerullo, and C. Lienau, Nature Photon. **9**, 37 (2014)

Angle-resolved energy spectra



Emission cone narrowing of the fastest electrons from >30° down to 12°



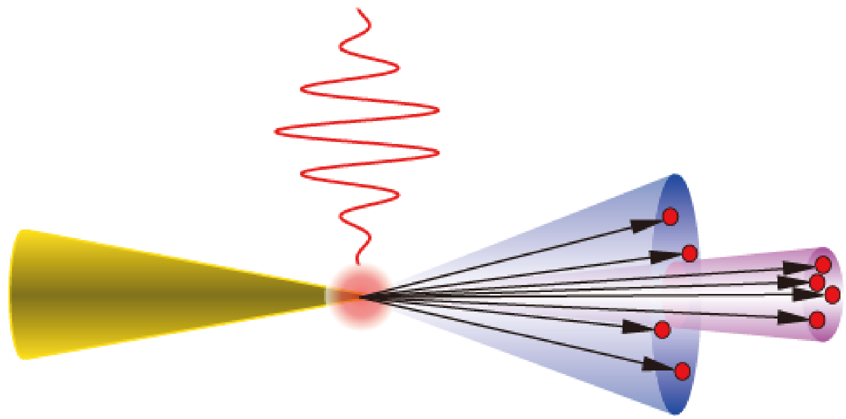


D.J. Park et al., Phys. Rev. Lett. **109**, 244803 (2012)

Control of electron motion

Steering effect of the fastest electrons

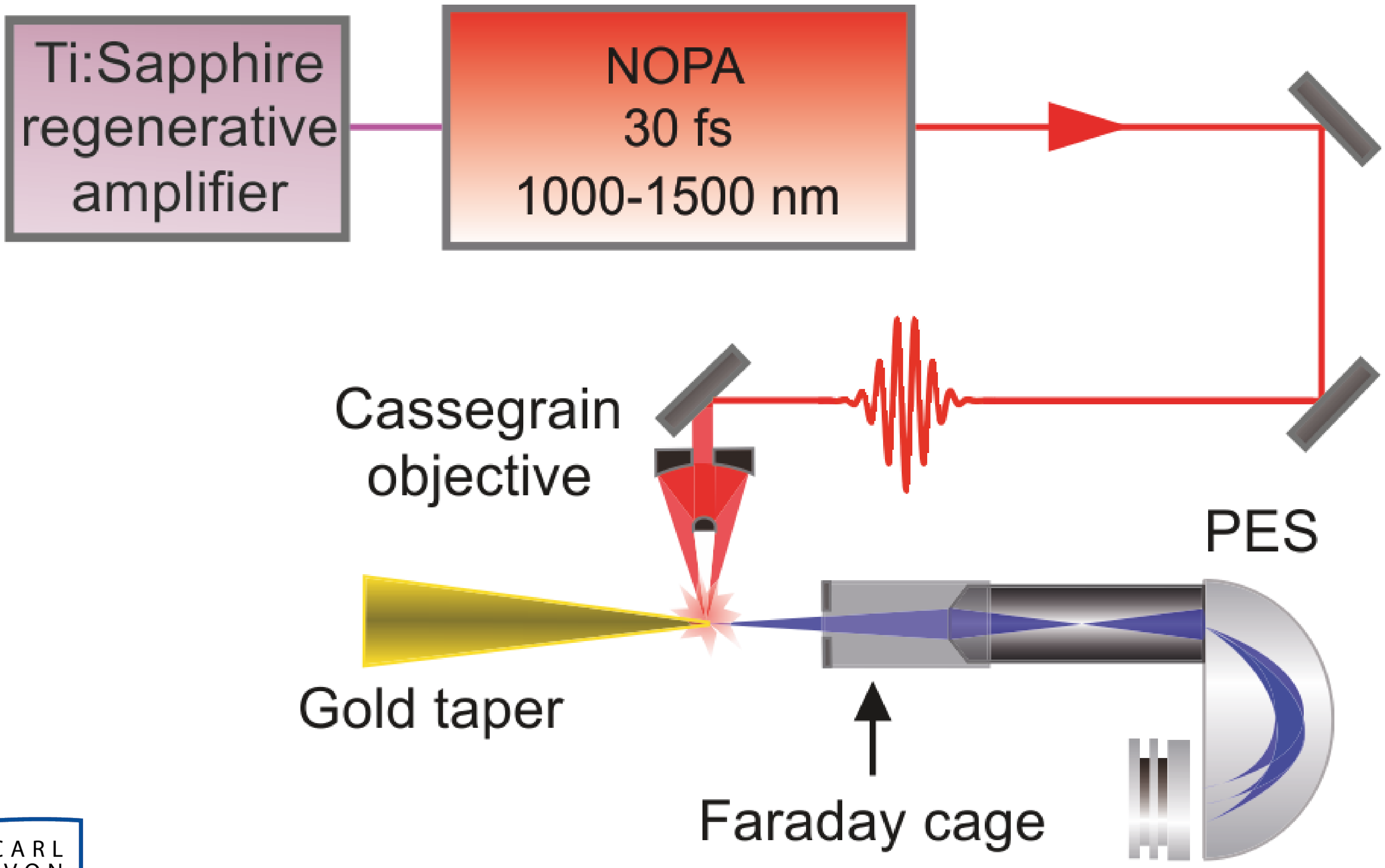
⇒ a new control handle via the spatial field distribution



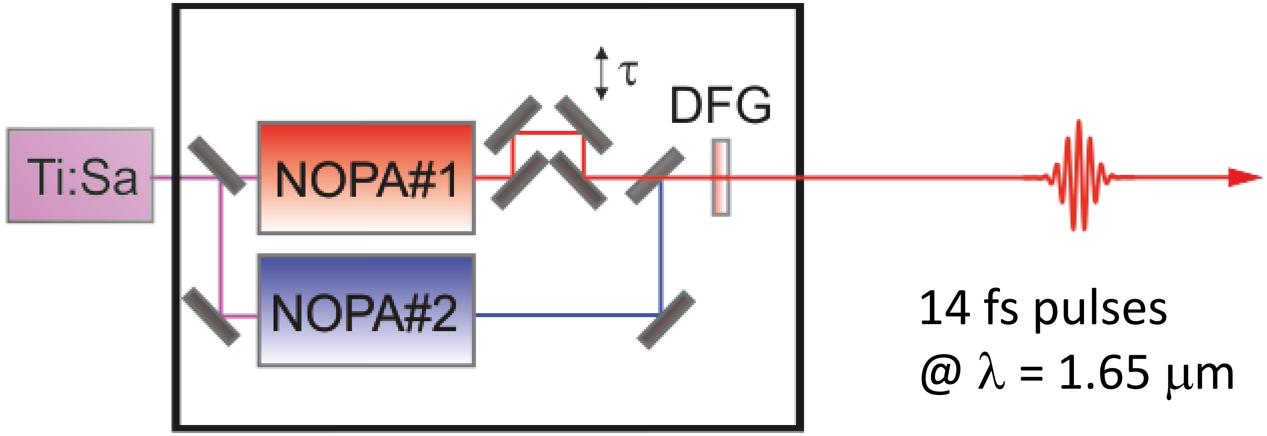
Control via the temporal field distribution, too?

⇒ study the influence of carrier-envelope phase

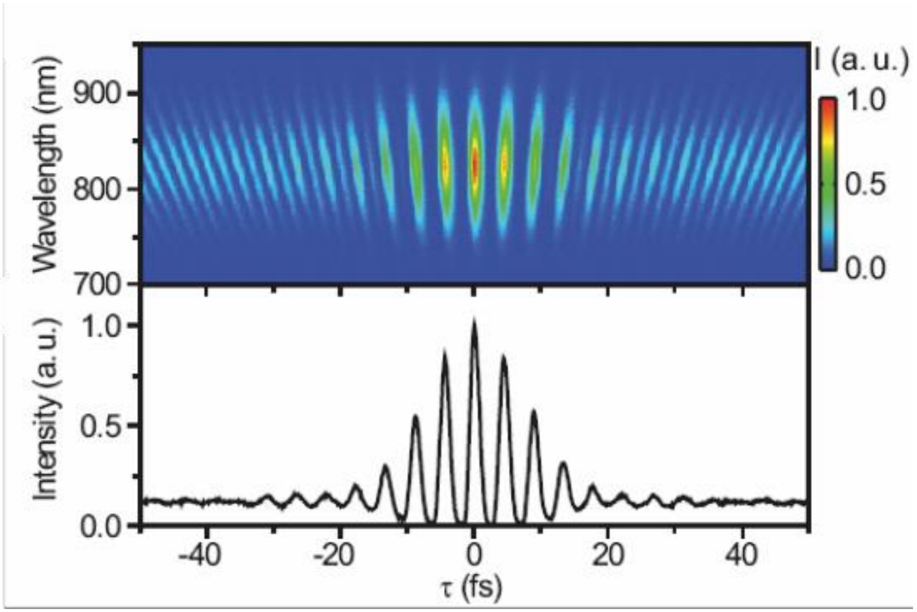
Experimental setup



Experimental setup



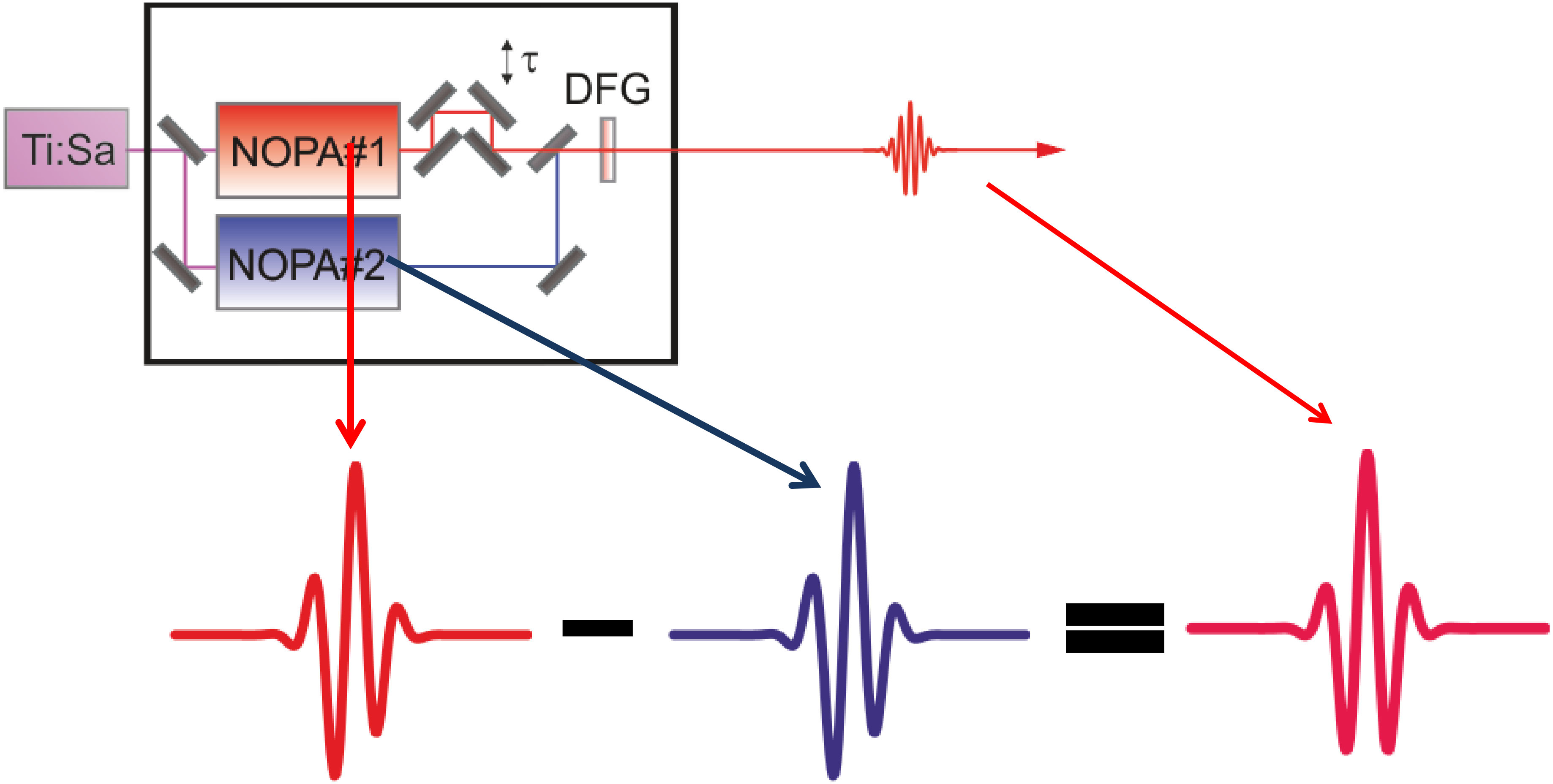
14 fs pulses
@ λ = 1.65 μm



- Center wavelength: 1.65 μm
- Pulse duration: 14 fs

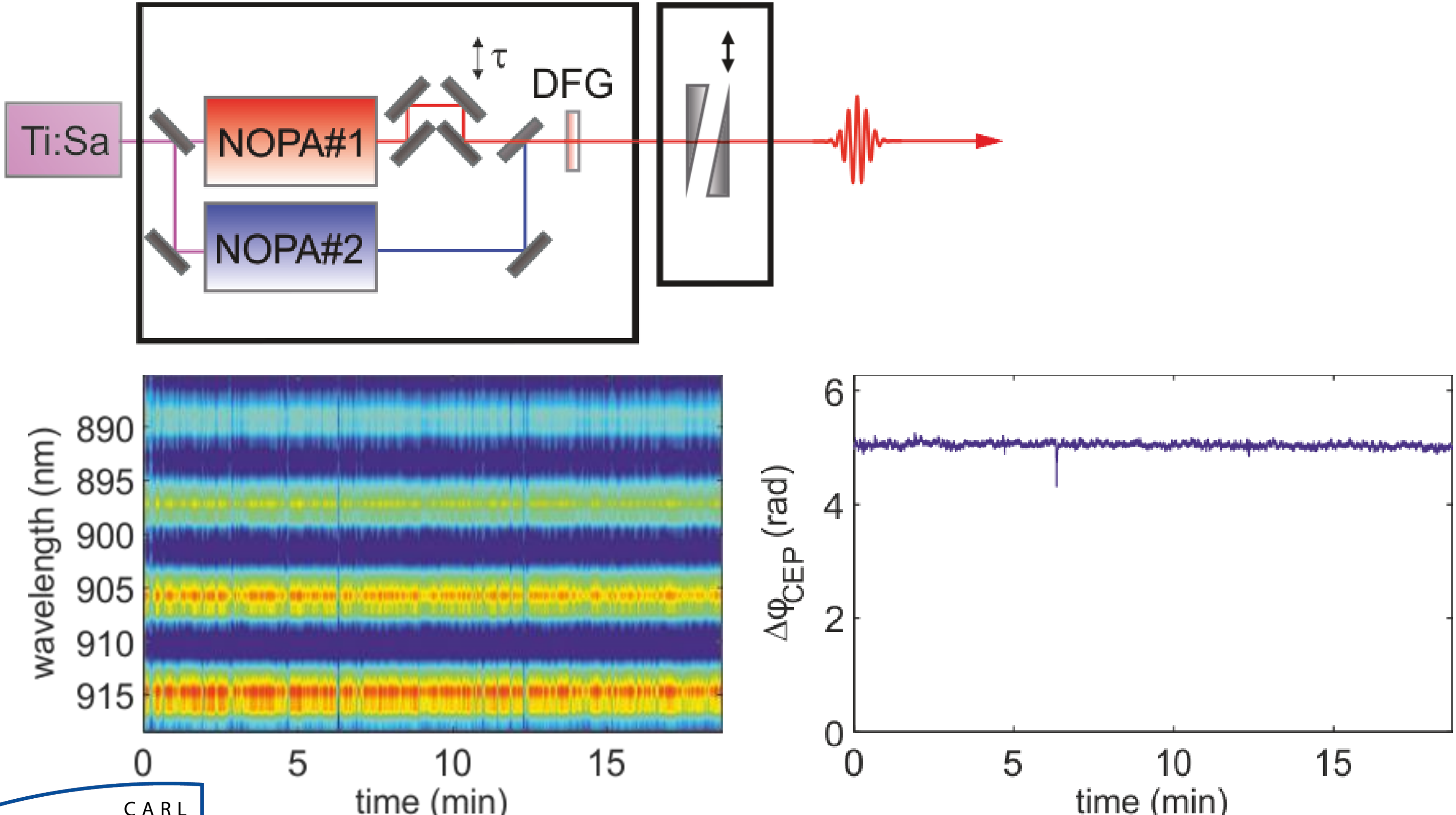
Manzoni et al., Opt. Lett. **29**, 2668 (2004); Cerullo et al., Laser Photonics Rev. **5**, 323 (2011)

Experimental setup



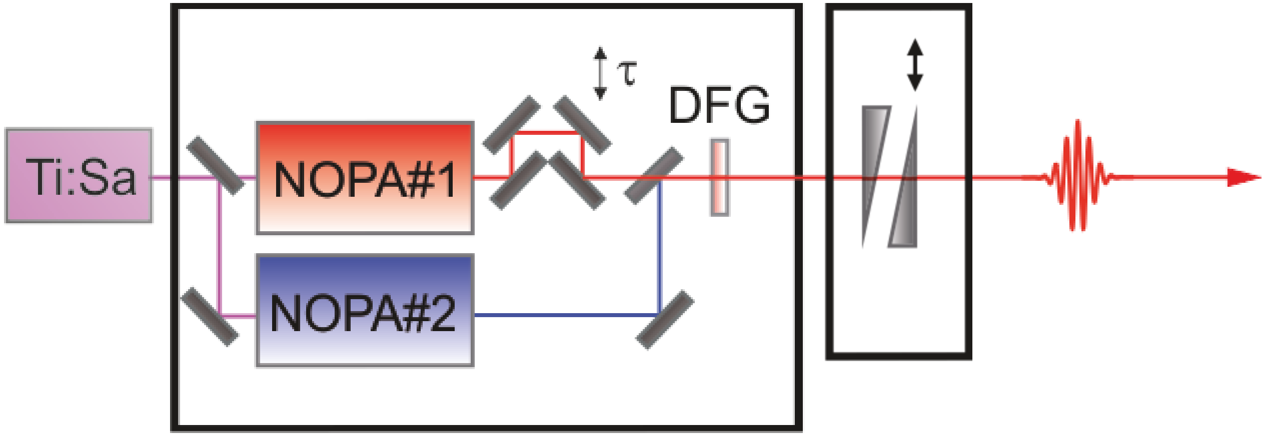
Manzoni et al., Opt. Lett. **29**, 2668 (2004); Cerullo et al., Laser Photonics Rev. **5**, 323 (2011)

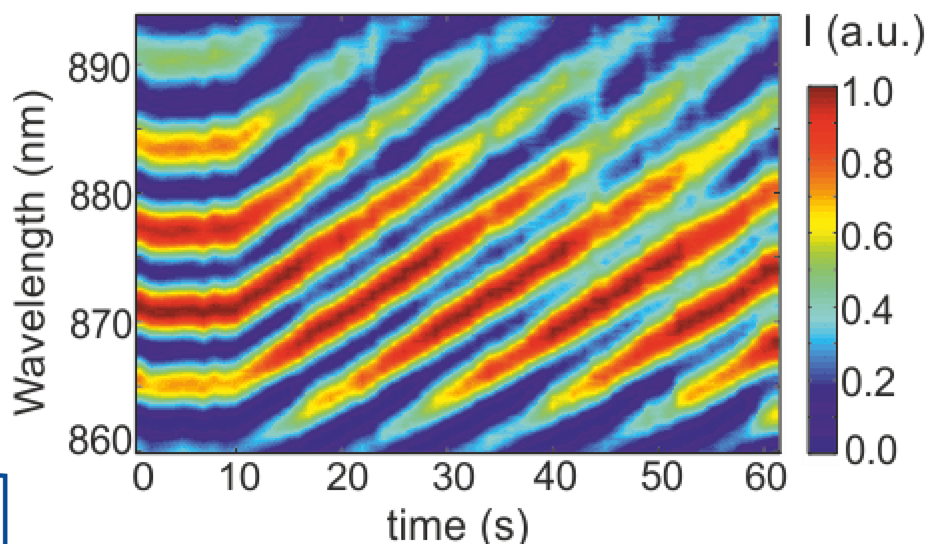
Experimental setup



Manzoni et al., Opt. Lett. **29**, 2668 (2004); Cerullo et al., Laser Photonics Rev. **5**, 323 (2011)

Experimental setup



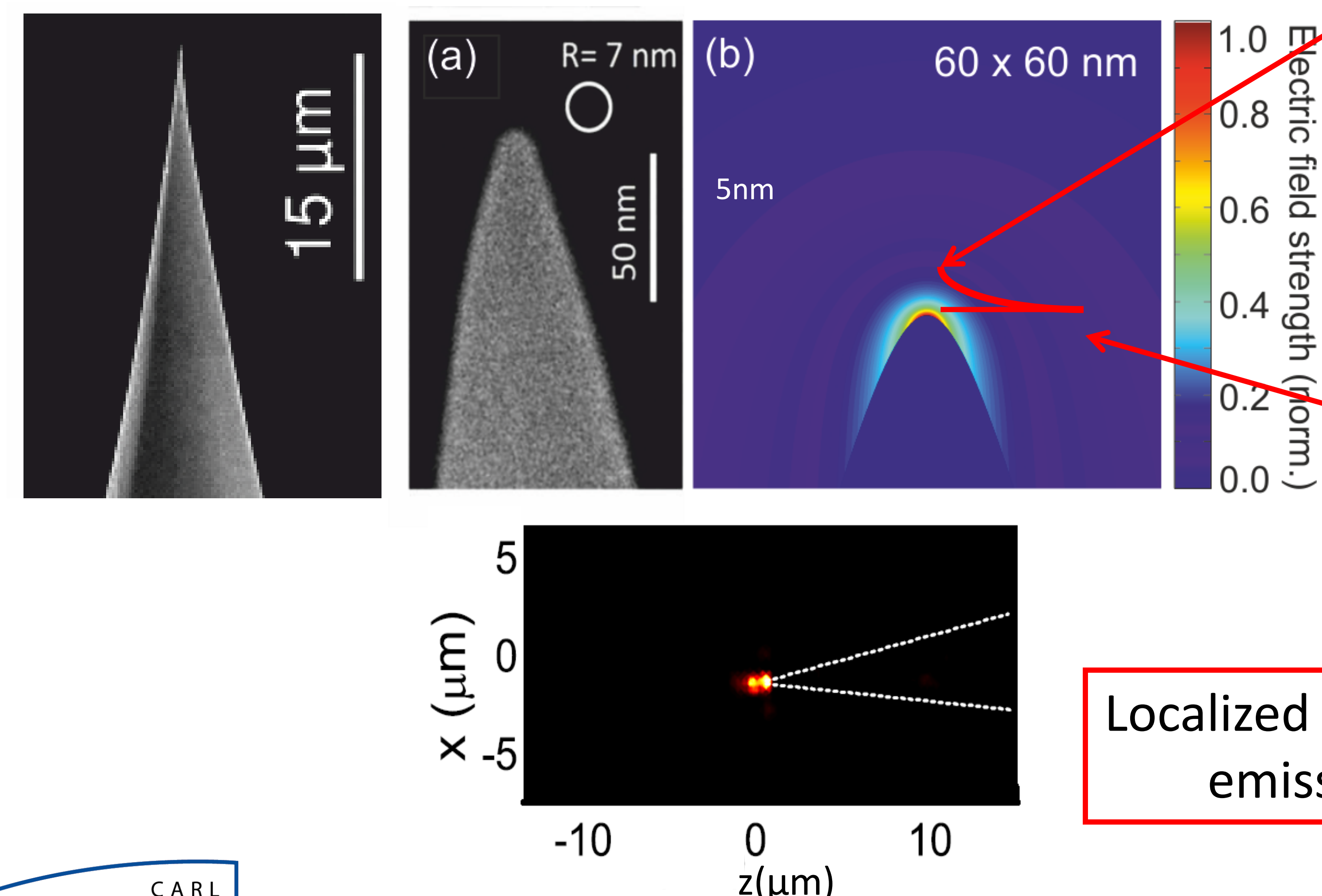


- Passive CEP stability: <50 mrad over 20 min
- CEP control: 8.8π linear shift

Manzoni et al., Opt. Lett. **29**, 2668 (2004); Cerullo et al., Laser Photonics Rev. **5**, 323 (2011)

Ultrafast Nano-Optics

Nanotips for electron emission



Field enhance-ment: $f = 9$

Decay length: $L_f = 1.7$ nm

Localized electron emission

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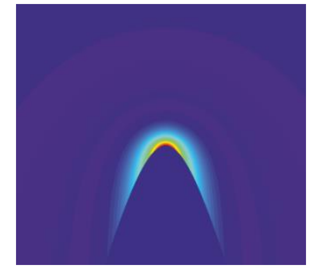
C. Ropers et al., PRL **98**, 043907 (2007), R. Bormann et al., PRL **105**, 147601 (2010)

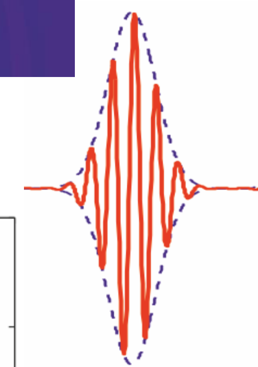
Numerical model

Spatio-temporal **electric field distribution**

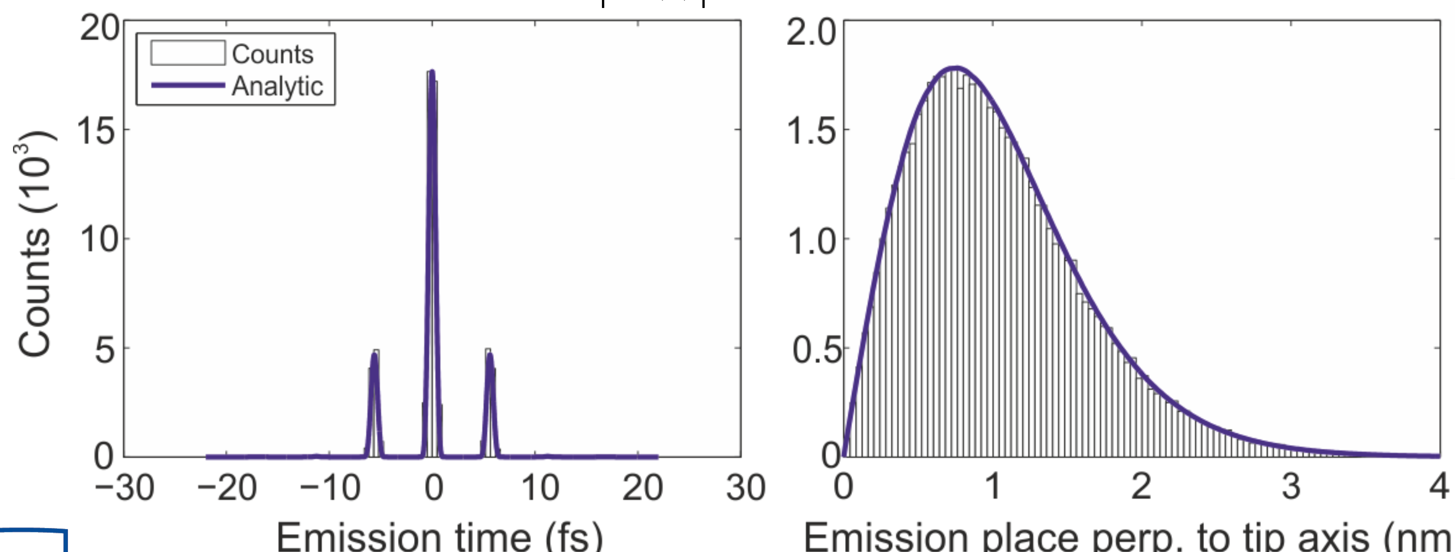
$$\vec{E}\left(\vec{r},t\right)=E_0\left(\vec{r}\right)\exp(-2\sqrt{\ln 2}t^2/\tau^2)\cos(\omega t)$$



Fowler-Nordheim tunneling describes emission probability



$$J(t)\propto\Theta(E(t))\left|E(t)\right|^2\exp\left(\frac{-4\sqrt{2m}\Phi^{3/2}}{3\hbar e\left|E(t)\right|}\right)$$



N. Behr and M.B. Raschke, J. Phys. Chem. C **112**, 3766 (2008)
G. Herink *et al.*, Nature **483**, 190 (2012)

Numerical model

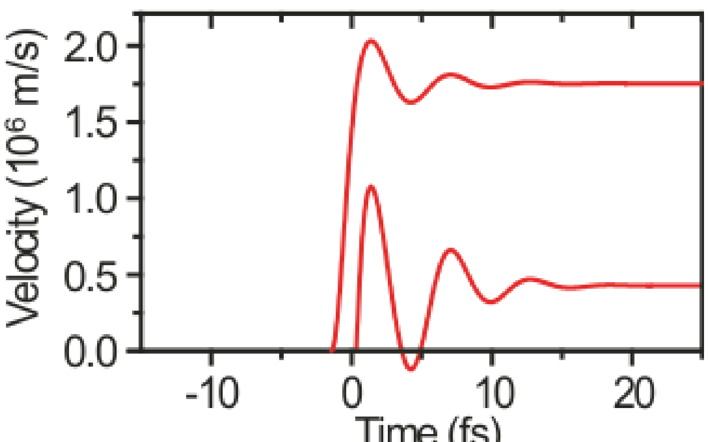
Classical equation of motion for the released electron, in temporally and spatially varying electric field

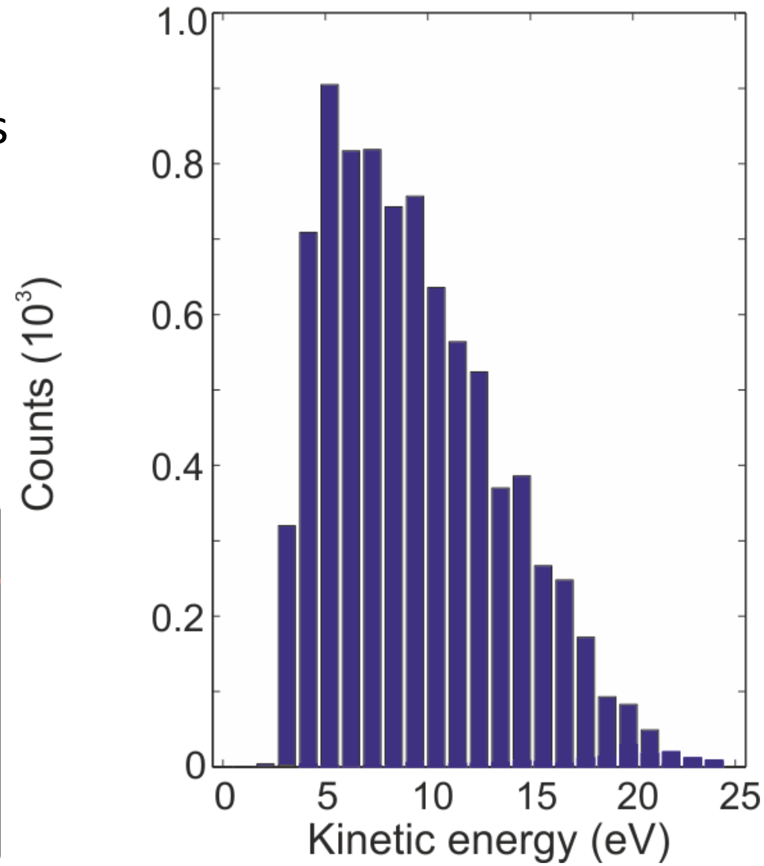
$$m\ddot{\vec{r}} = -e\vec{E}(\vec{r},t)$$

Rescattering with the tip: 100% elastic collisions

Electron motion per emission site and time

$\Rightarrow$ (angle-resolved) kinetic energy spectra





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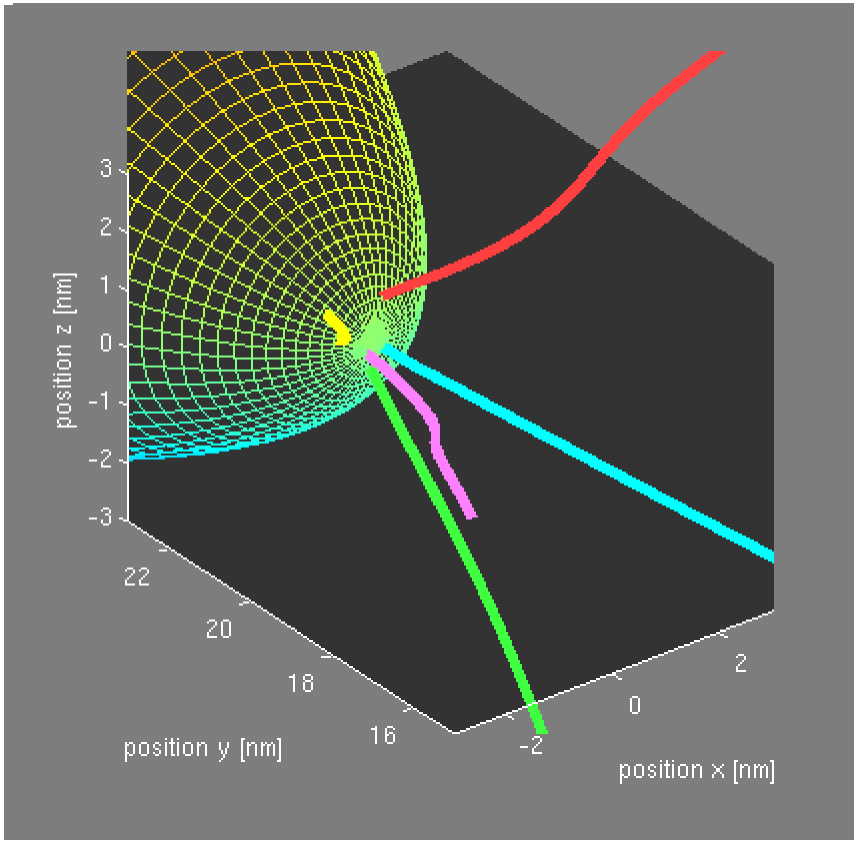
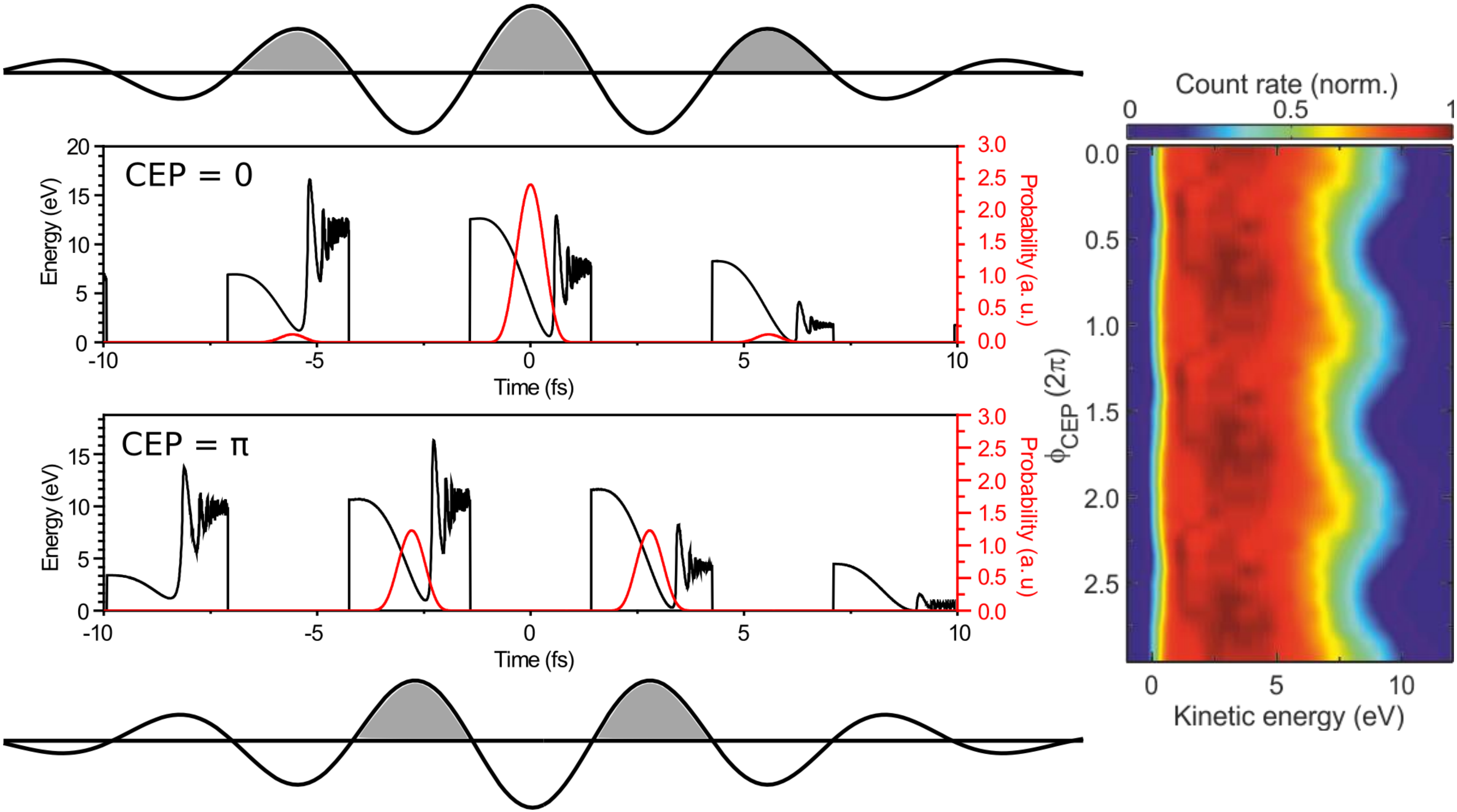


Consider **charged particle effects**

$\Rightarrow$ Requires fully three-dimensional trajectory calculations

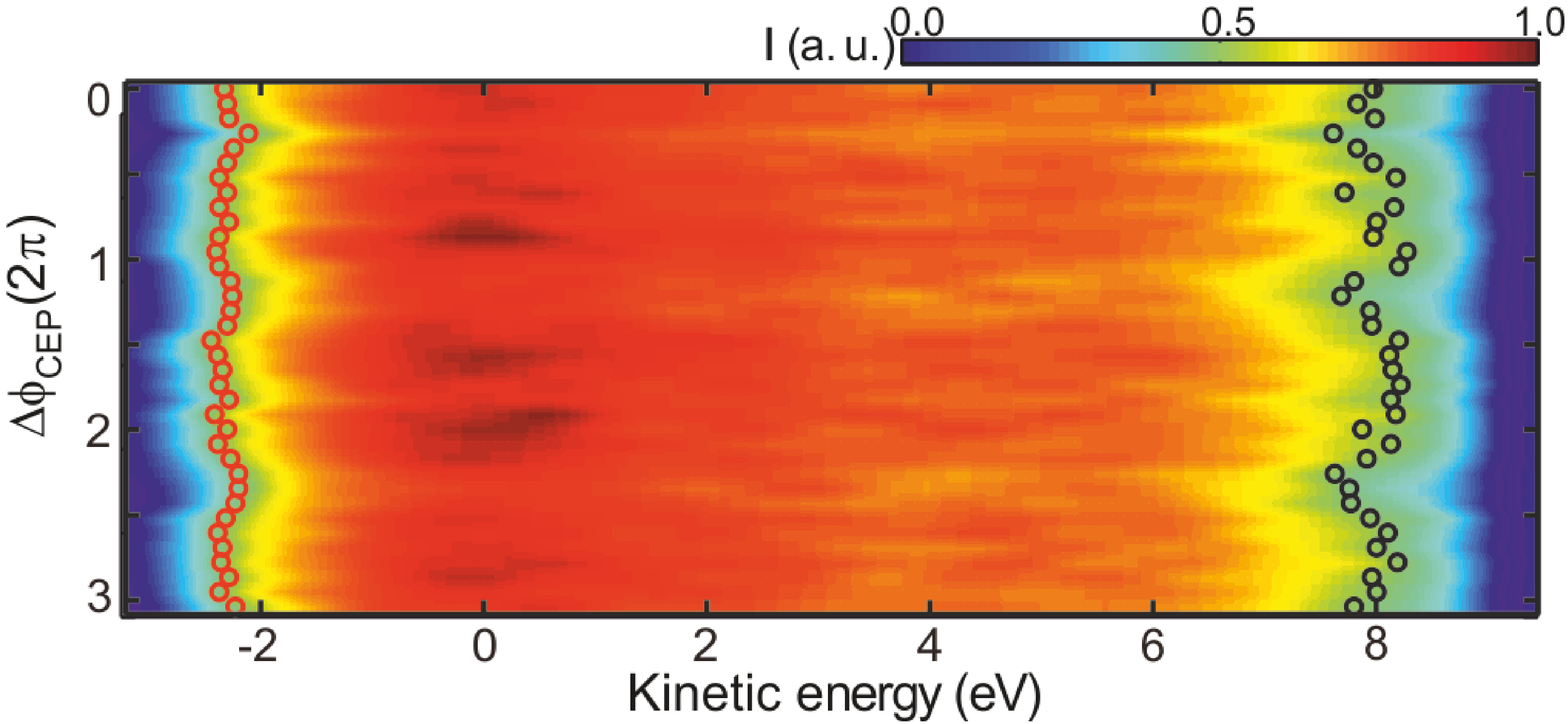
B. Piglosiewicz et al., Nature Photon. **9**, 37 (2014)
B. Piglosiewicz et al., Quantum Matter (2014)

CEP dependence: expectation



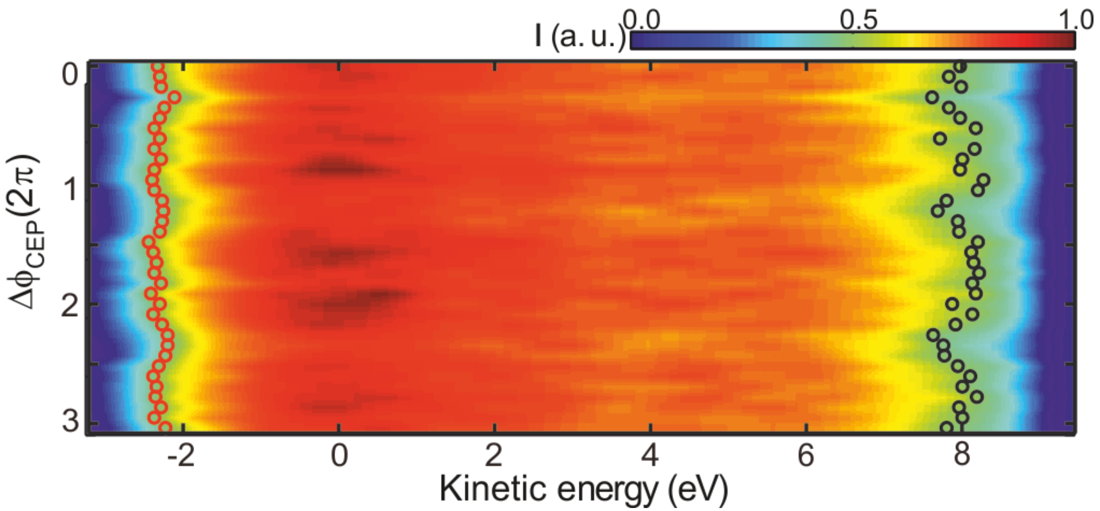
B. Piglosiewicz et al., Nature Photon. **9**, 37 (2014)

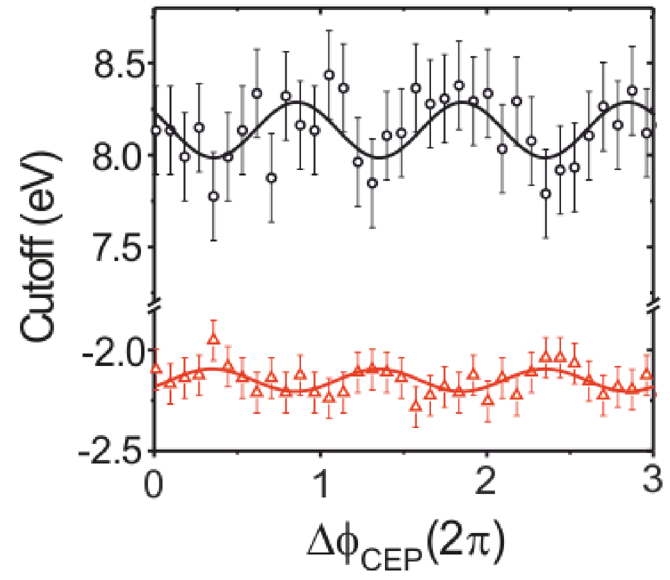
CEP dependence: measurement



B. Piglosiewicz et al., Nature Photon. **9**, 37 (2014)

CEP dependence: measurement





First observation of CEP effect

from metallic nanostructures in strong-field regime

New control mechanism on sub-femtosecond electron motion

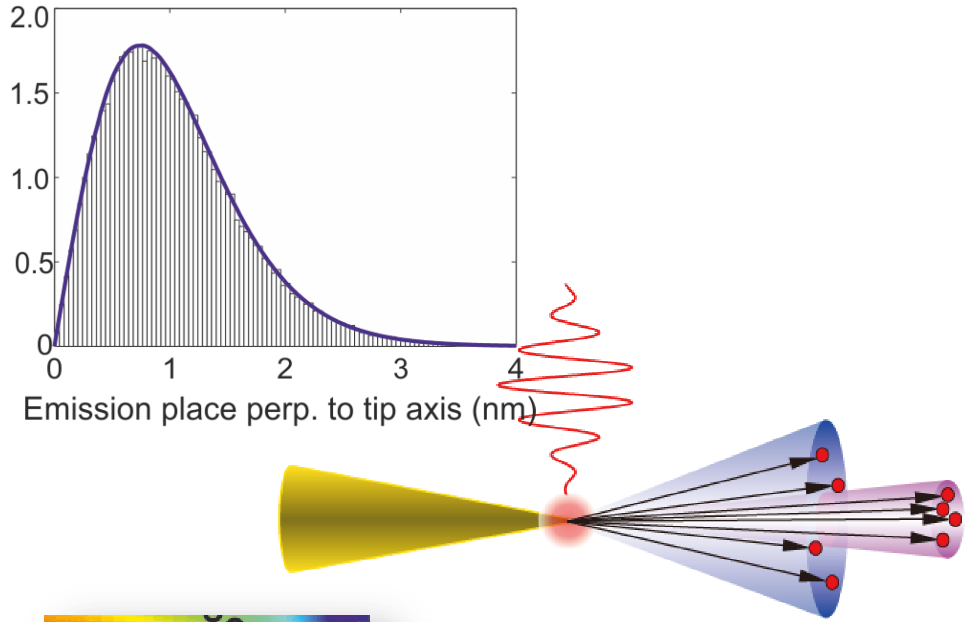
B. Piglosiewicz et al., Nature Photon. **9**, 37 (2014)

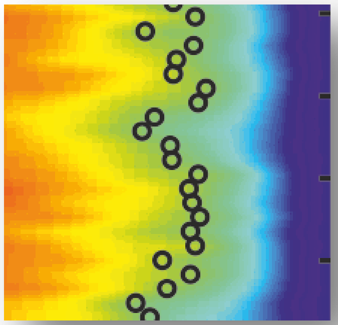
New electron source

1. Controlled emission
   ⇒ few-nm area

2. Spatial motion control
   ⇒ order of nanometers

3. Temporal control
   ⇒ sub-femtosecond

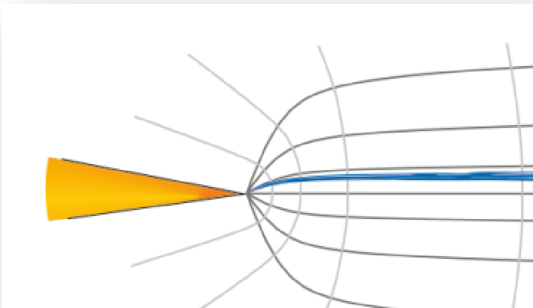




⇒ A new class of electron source

⇒ Towards attosecond control and electron streaking

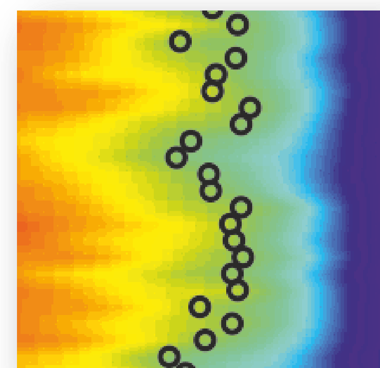
Summary



Strong-field emission and accelertation of electrons: unique to nanostructures

Control of electron motion

- Steering along field lines:
  Control via nanostructure shape
- Velocity change through the laser field phase:
  Control via temporal field



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