# Photoemission from metal nanotips studied and controlled with femtosecond laser pulses

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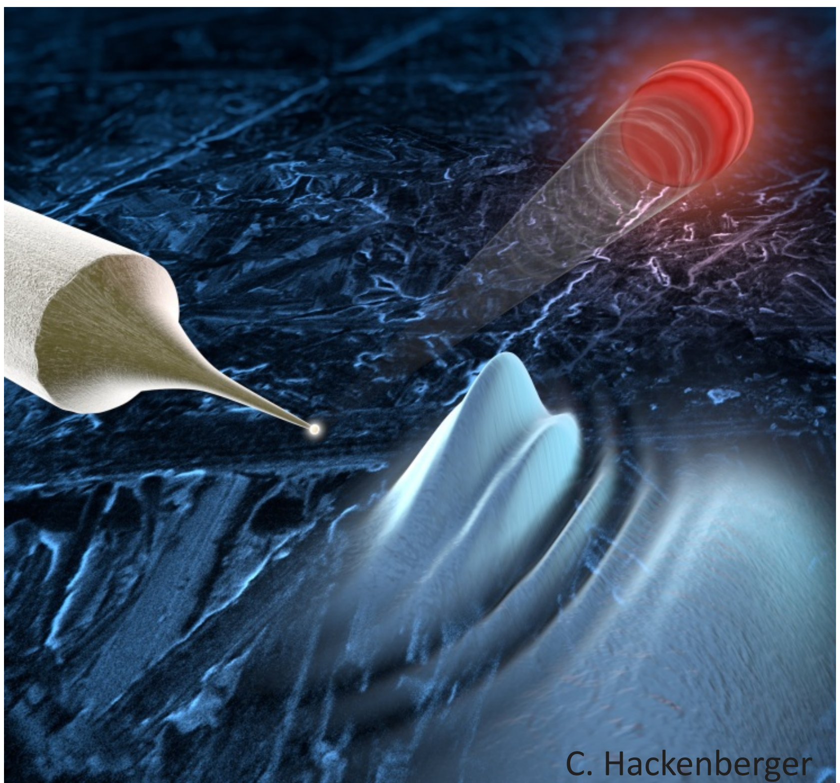
2) Weizmann Institute of Science
3) Ludwig-Maximilians-Universität München
4) Technische Universität Wien

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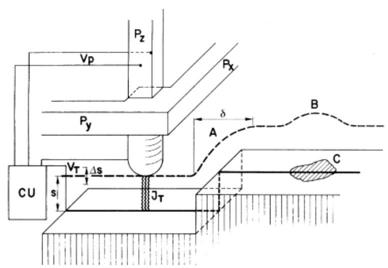
Gordon and Betty MOORE FOUNDATION

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

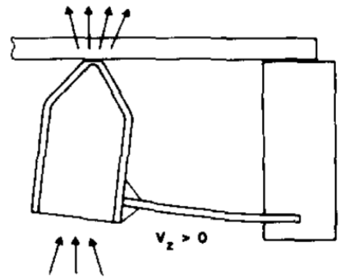
# Introduction

**In scanning probe microscopy:**



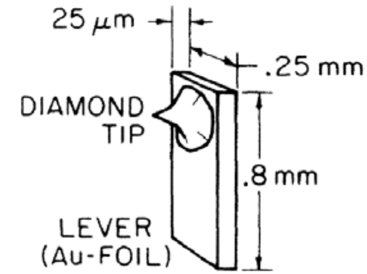

STM

G. Binning et al.,
Appl. Phys. Lett. **40**, 178 (1982).




SNOM

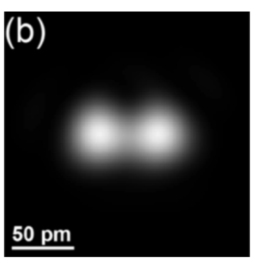
D. Pohl et al.,
Appl. Phys. Lett.**44**, 651 (1984).




AFM

G. Binning et al.,
PRL **56**, 930 (1986).

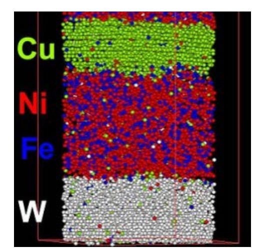
**As a source of electrons:**




TEM

R. Erni et al., PRL **102**, 096101 (2009).

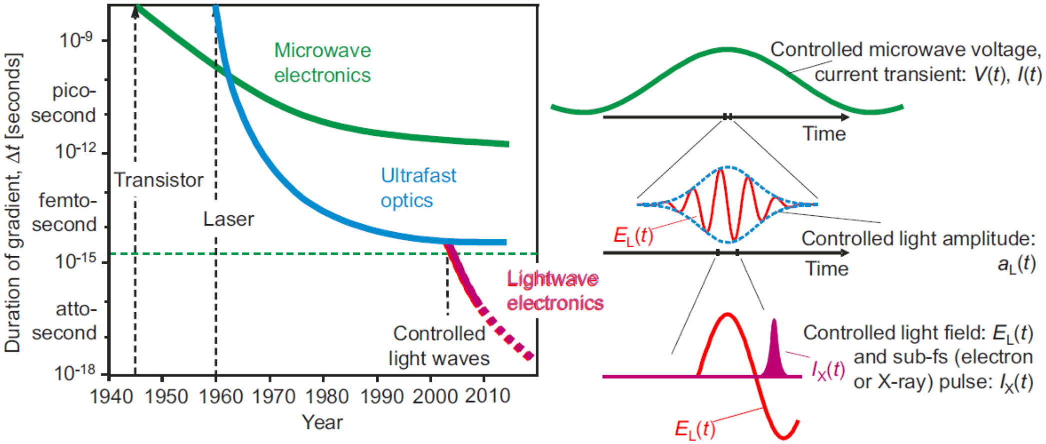
**In material science:**




APT

E. Müller et al., Rev. Sci. Instrum. **39**, 83 (1968).
picture from wikipedia

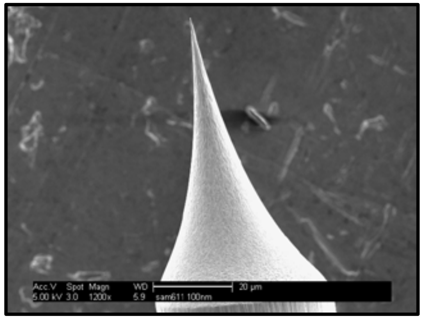
# Introduction




F. Krausz, Rev. Mod. Phys. **81**, 163 (2009).

-> Study of light-matter interaction at (sub-)fs timescales

**Favorable properties of sharp metal tips:**

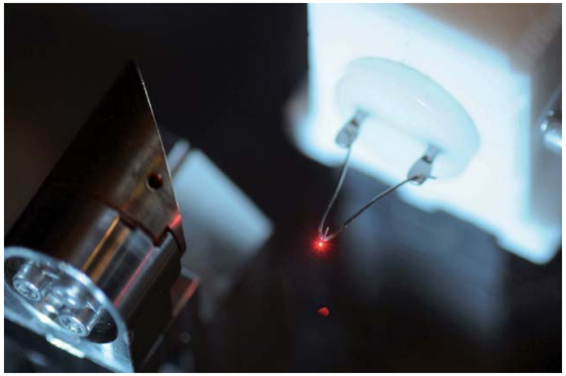


- Apex controllable to the atomic level
- Small scale
  - -> Field enhancement
  - -> Small active area, i.e. small emission spot
- Coherence of electron emission
- Readily fabricable from many materials

# Outline


**Toolbox**

- Fabrication and characterization of metal nanotips & setup
- Femtosecond lasers



**Light-matter interaction**

- Optical near fields at metal tips
- Photoemission regimes from metal tips
- Control of emitted electron‘s motion

# Outline

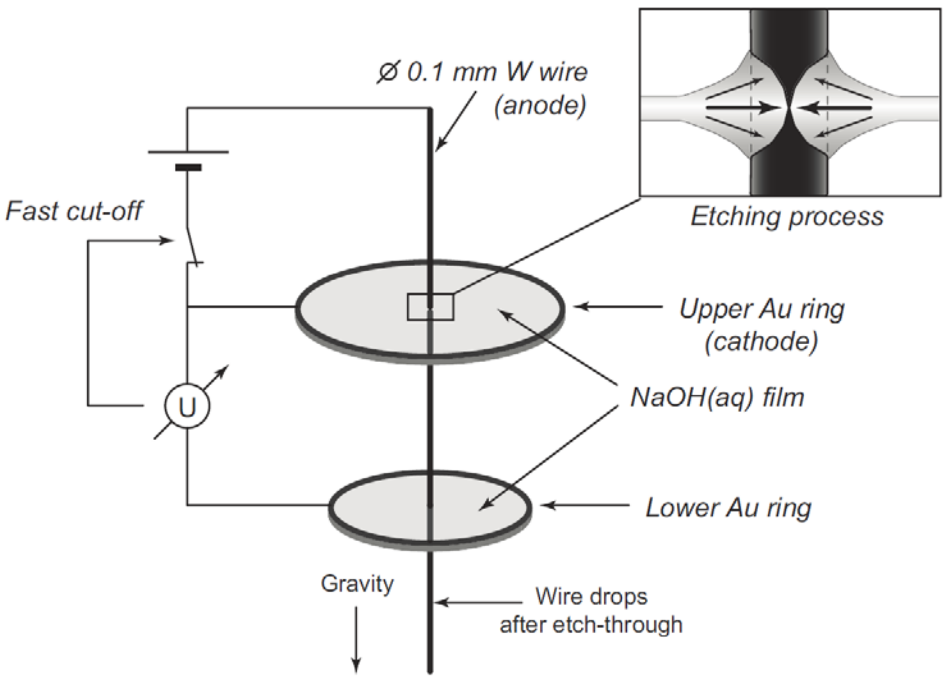
**Toolbox**

- Fabrication and characterization of metal nanotips & setup
- Femtosecond lasers

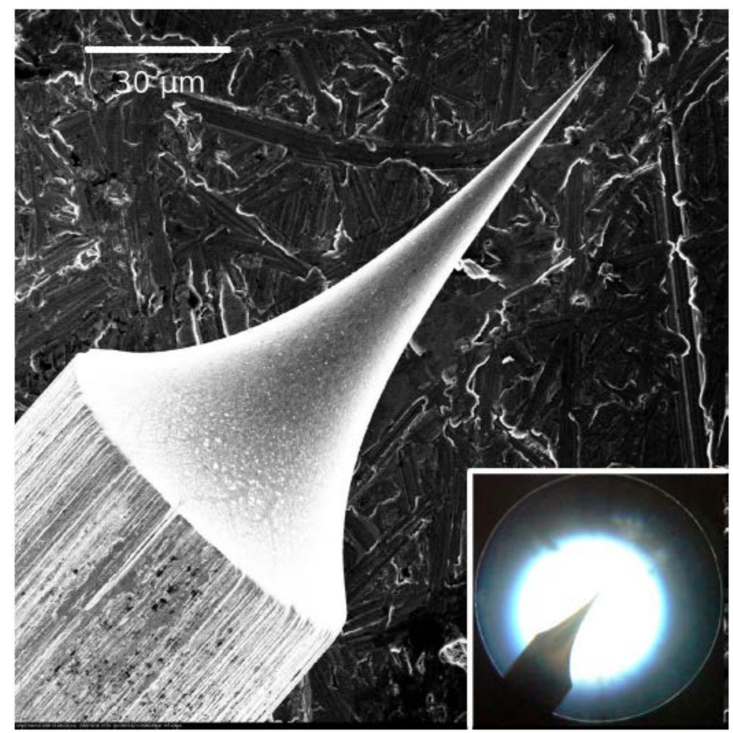
# Fabrication of sharp nanotips

**Electrochemical etching of tips**

e.g. Nakamura et al., Rev. Sci. Instrum. **70**, 3373 (1999).




**SEM and optical image of a tungsten tip**

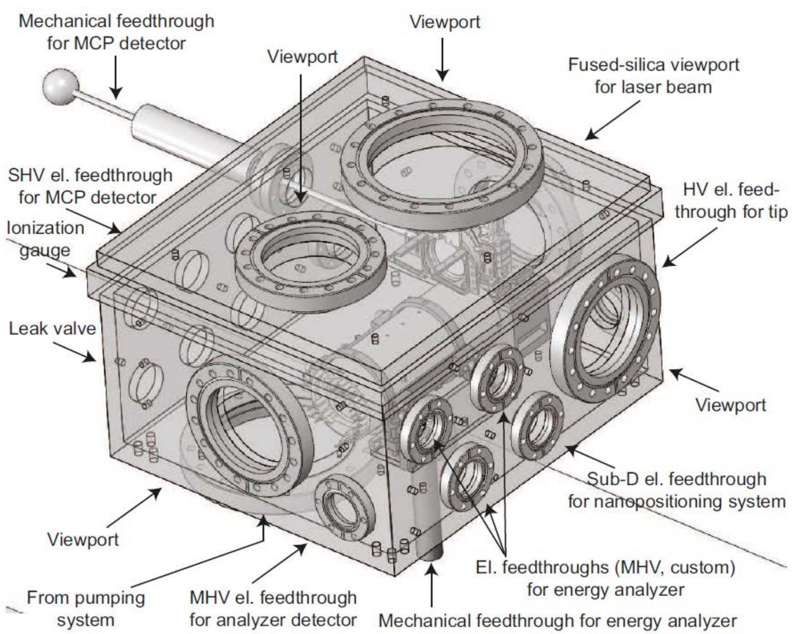



M. Krüger, PhD thesis (2013).

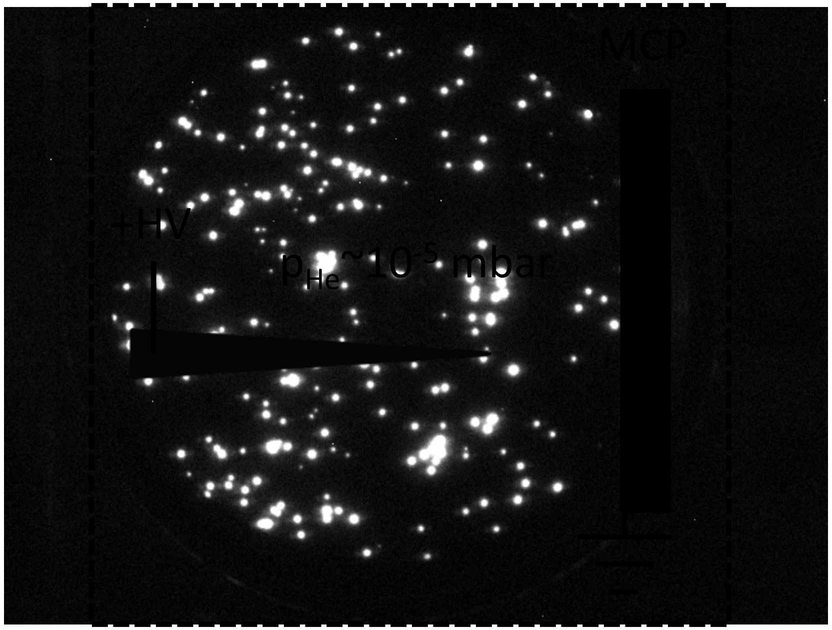
# In-situ characterization (**F**ield **I**on **M**icroscope)

E. Müller, Z. Phys. **131**, 136 (1951).

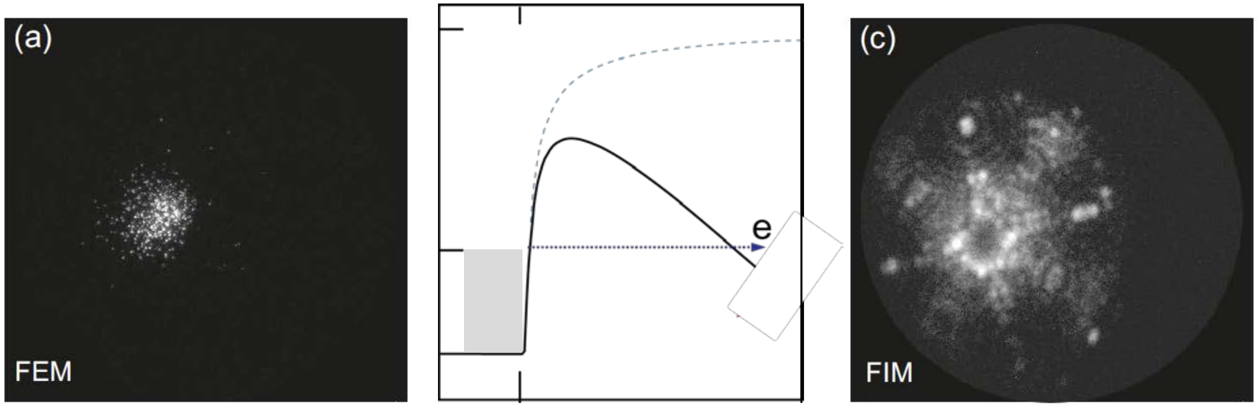
**UHV chamber (~5 $10^{-10}$ mbar)**




**FIM movie**




**Observations from a clean W(310) tip**



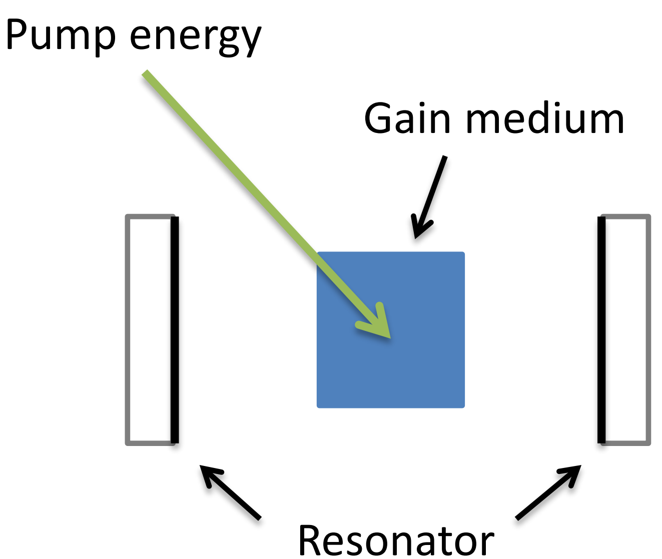

M. Krüger, PhD thesis (2013).

# Femtosecond lasers

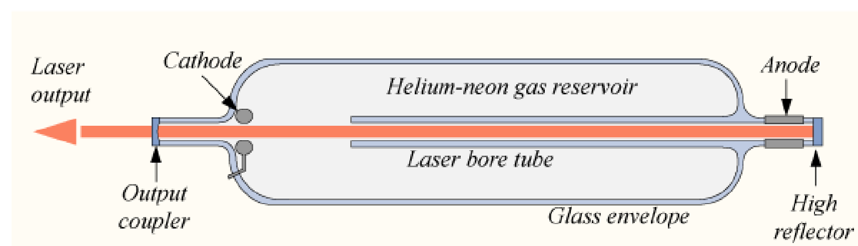
**Favorable properties:**

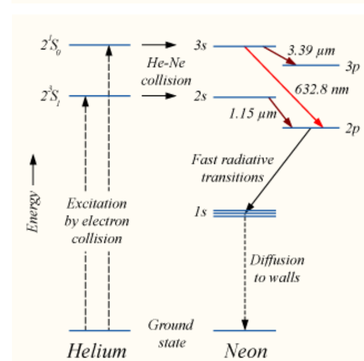
- Reach high peak electric fields with low thermal load
- Temporal resolution on electronic timescale
  - -> Resolve emission/excitation process
  - -> Limit electron emission time

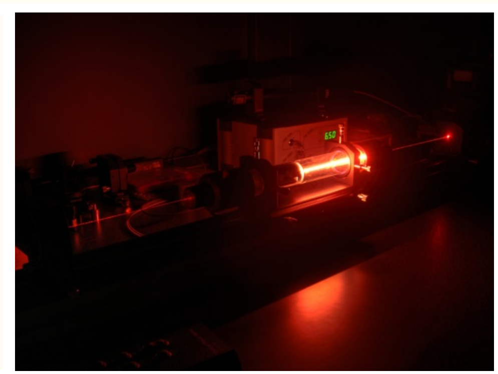
**Laser principles:**




e.g. HeNe laser (wikipedia.org)

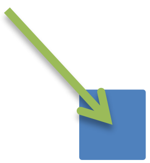


# Femtosecond lasers

<u>Broadband gain</u> medium:
Ti:Sapphire



P. Moulton, JOSA B **3**, 125 (1986).

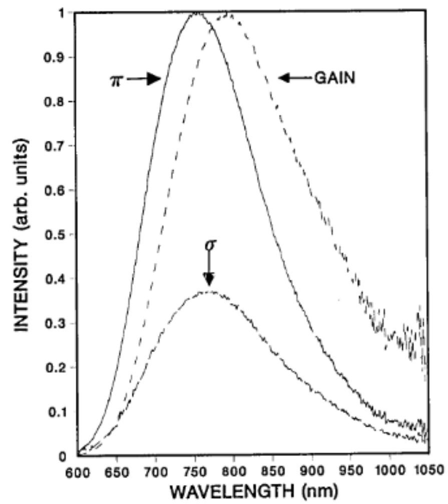
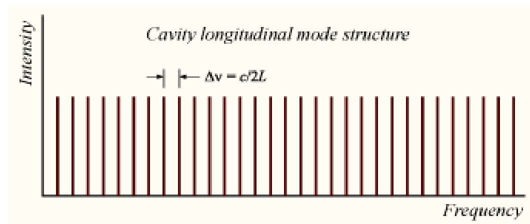
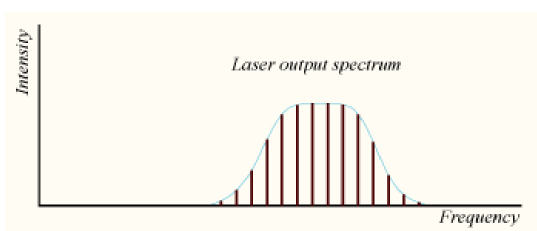



Fig. 2. Polarized fluorescence spectra and calculated gain line shape for Ti:$Al_2O_3$.

Longitudinal modes




wikipedia.org



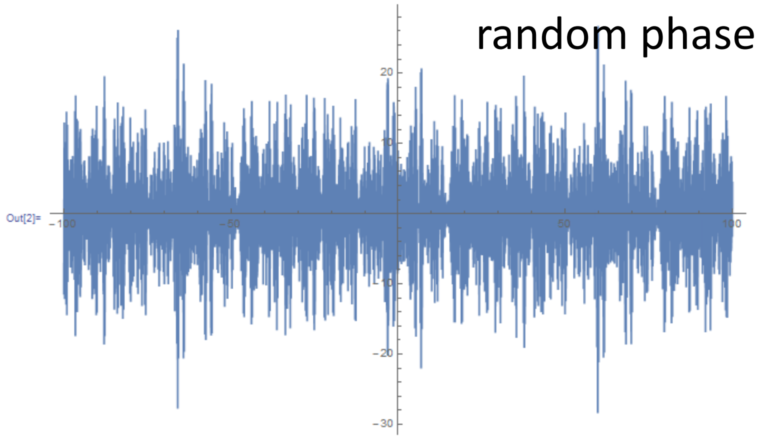

wikipedia.org

-> Hundreds of thousands of longitudinal modes

# Mode locking

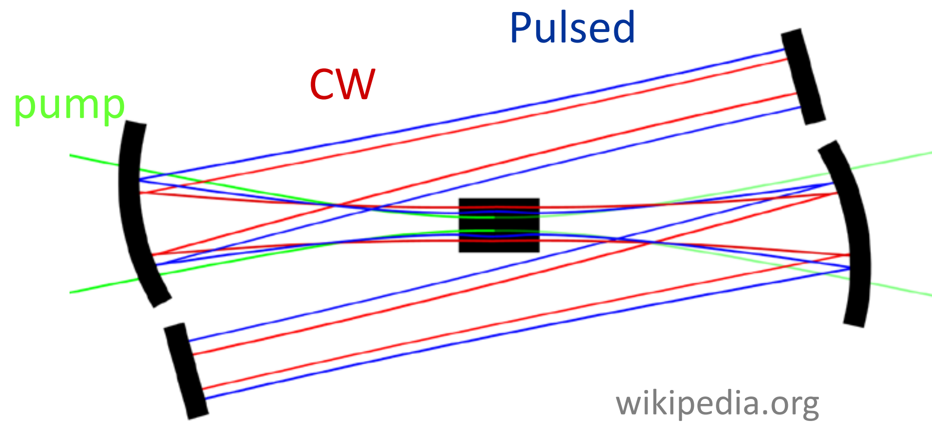
**General idea**

```
In[1]:= TotalField = Sum[Cos[(20 + 0.1 * i) * x + RandomReal[] * 2 * Pi], {i, 100}];
        Plot[TotalField, {x, -100, 100}, PlotRange → All]
```




**Soft Kerr lens mode locking**

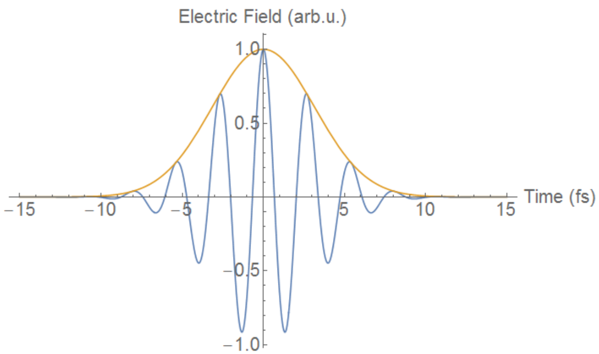
Kerr effect: $n = n_0 + n_2 I$

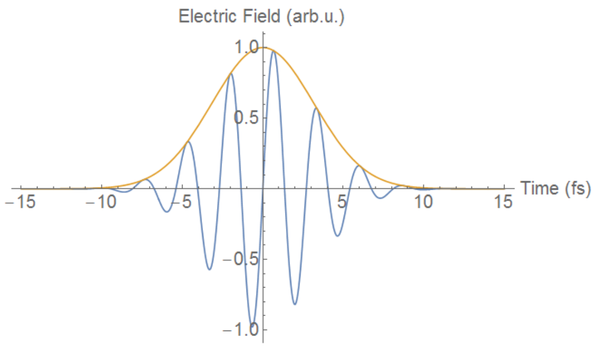



wikipedia.org

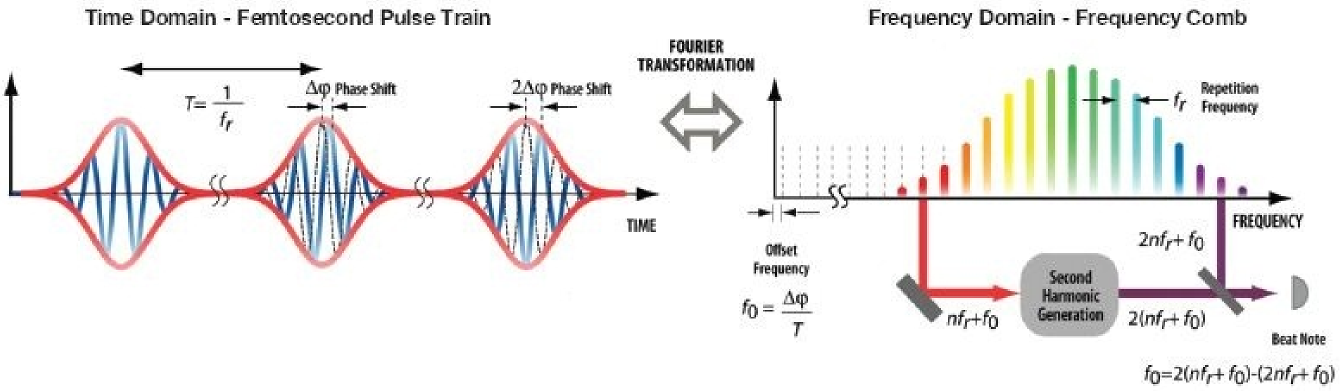
# CEP control

**Would like direct control over electric field:**



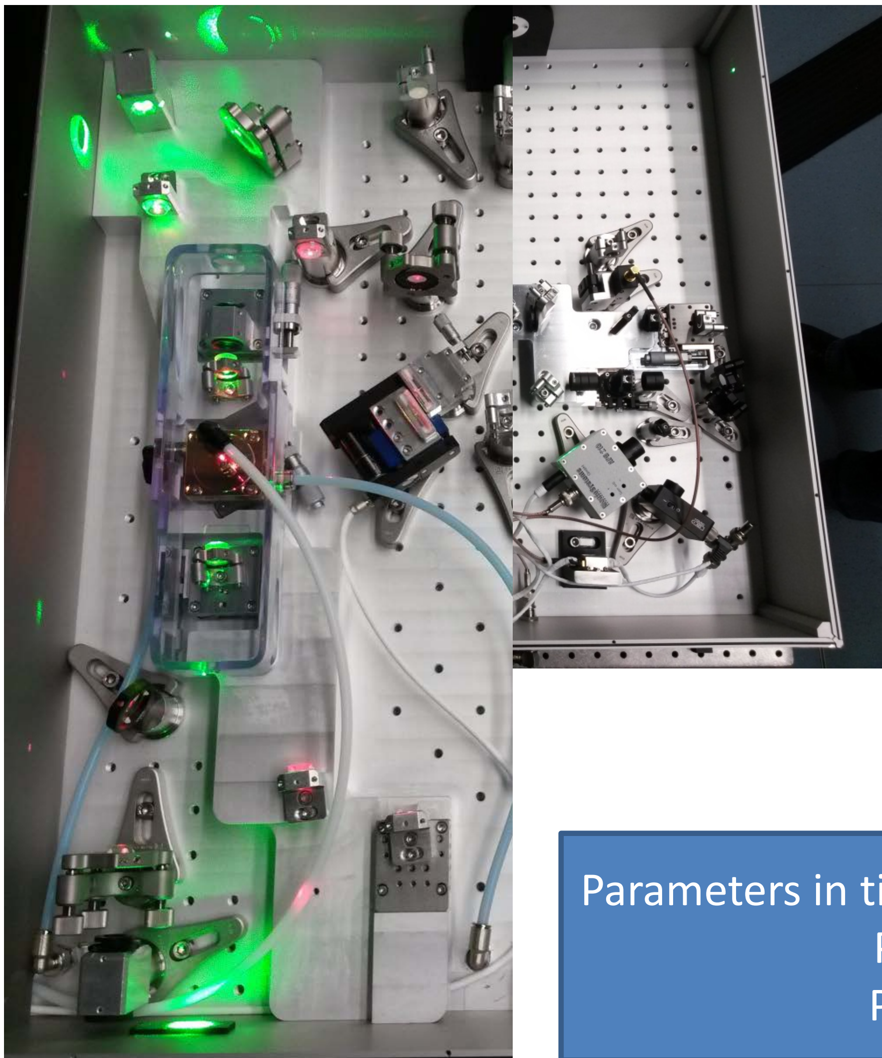

**Solution: Frequency comb with $f_0$=0**



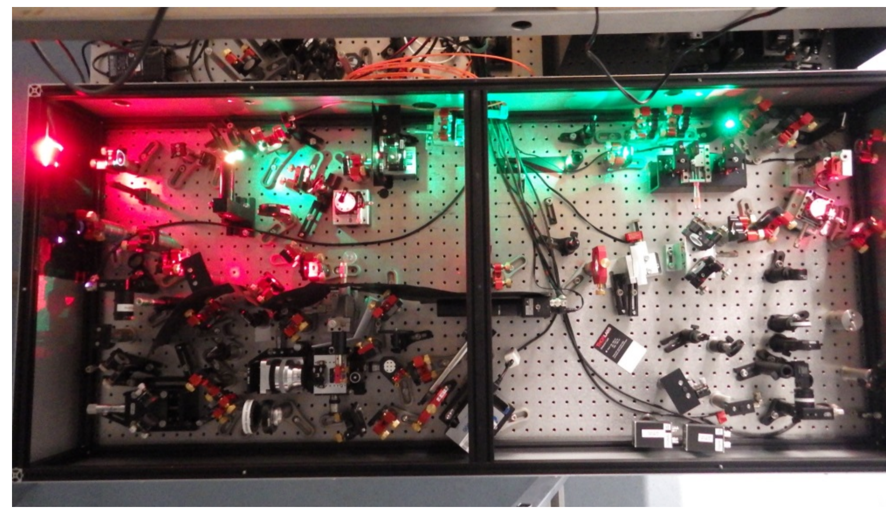

Nobel prize 2005

# Examples and parameters

5 fs, 800 nm, CEP-stable



10 fs, 2 um, CEP-stable



C. Homann et al., Optics Letters **37**, 1673 (2012).

Parameters in tip experiments:

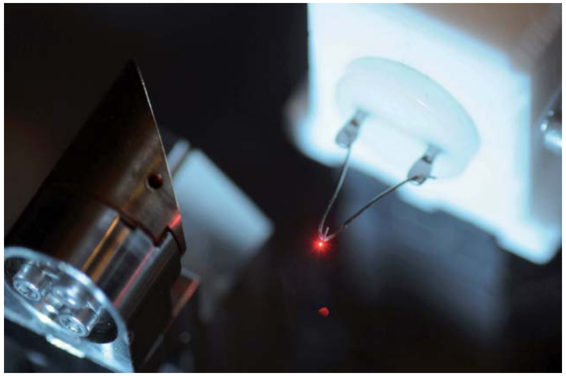
Peak intensities up to ~$10^{14}$ W/cm²

Peak electric fields up to ~$10^{10}$ V/m

# Part II

**Light-matter interaction**

- Optical near fields at metal tips
- Photoemission regimes from metal tips
- Control of emitted electron‘s motion



# Near fields

**Whole research field in itself:**
Nanooptics, optical antennas (antenna resonances, plasmonic effects, … )

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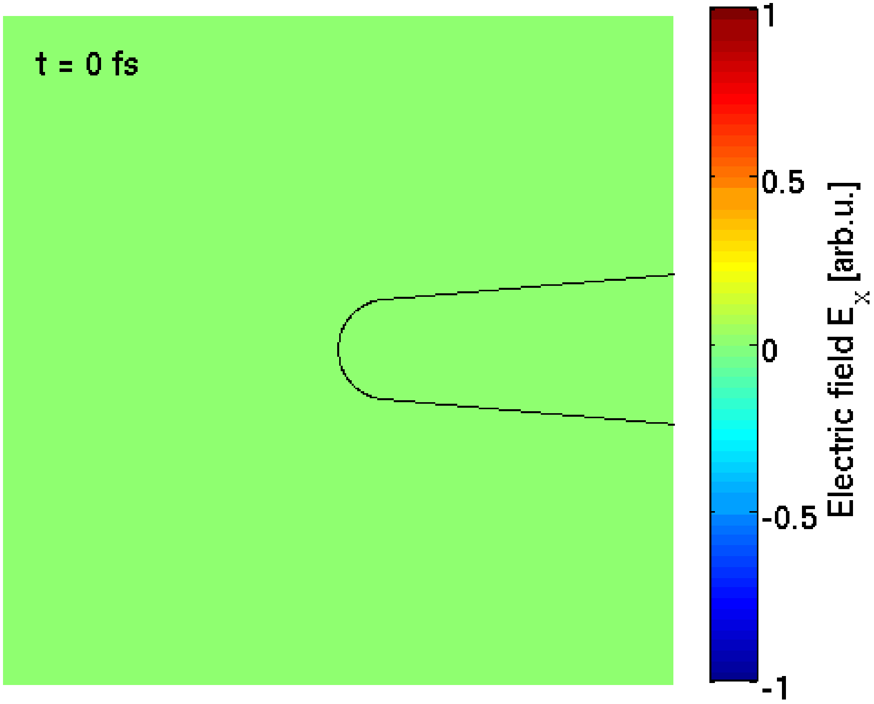



W tip, r=30 nm, 5°, 800 nm, 5 fs

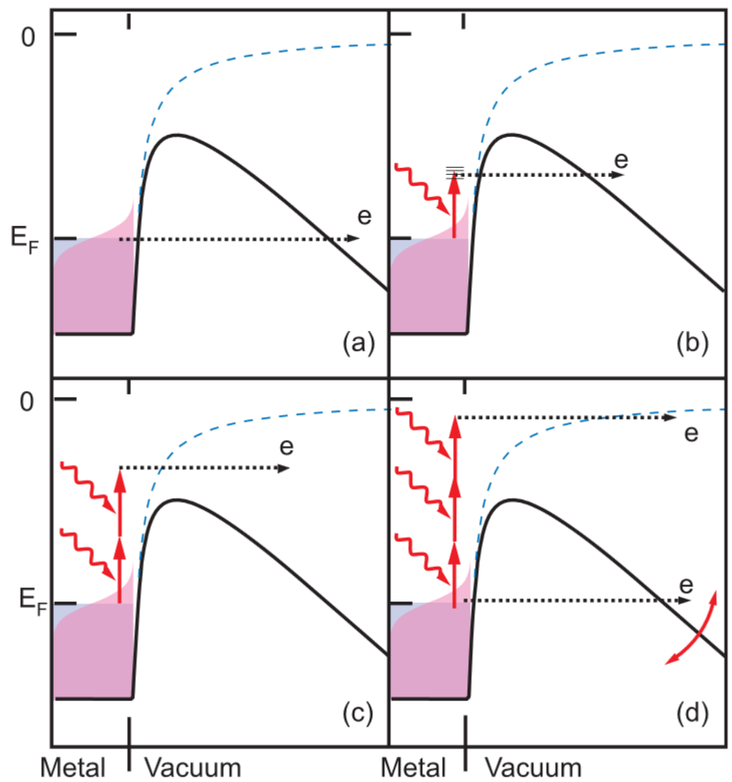
Here: Similar to lightning-rod effect, very flat response in frequency

# Mechanisms of electron emission at metal tips

DC Field Emission

Multiphoton Photoemission

Schenk et al., PRL **105**, 257601 (2010).
Kealhofer et al., PRB **86**, 035405 (2012).




Photofield emission

Hommelhoff et al., PRL **96**, 077401 (2006).

Also: (transient) thermally enhanced field emission

Kealhofer et al. PRB **86**, 035405 (2012).
Herink et al., NJP **16**, 123005 (2014).
Yanagisawa et al., PRL **107**, 087601 (2011).

Above-threshold Photoemission

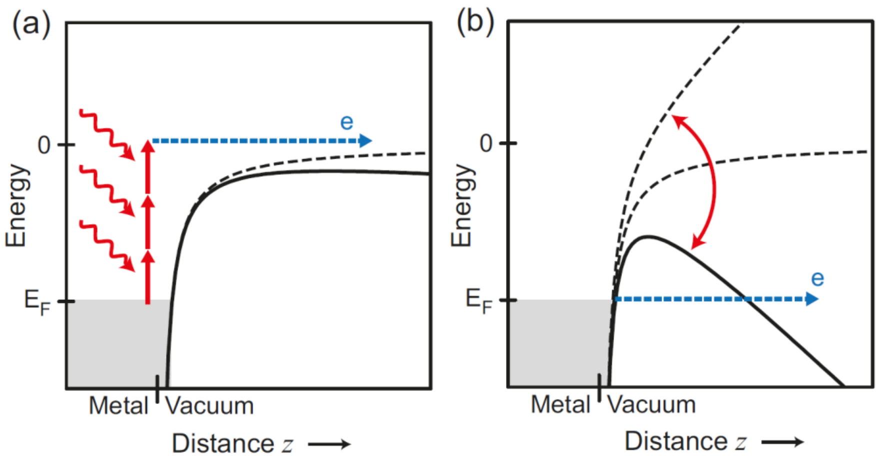
Schenk et al., PRL **105**, 257601 (2010).
Bormann et al., PRL **105**, 147601 (2010).

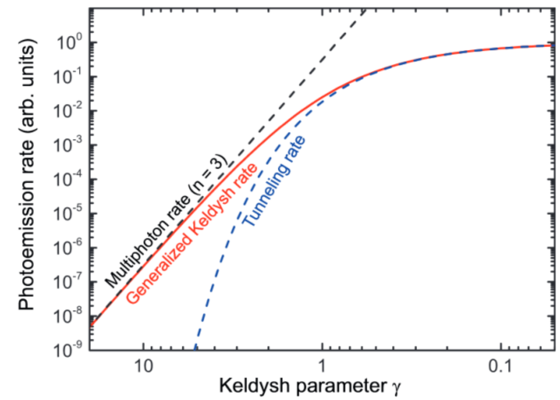
Optical tunelling

Piglosiewicz et al., Nat. Photon. **8**, 37 (2014).
Bormann et al., PRL **105**, 147601 (2010).

Kealhofer et al. PRB **86** 035405 (2012).

# Keldysh theory

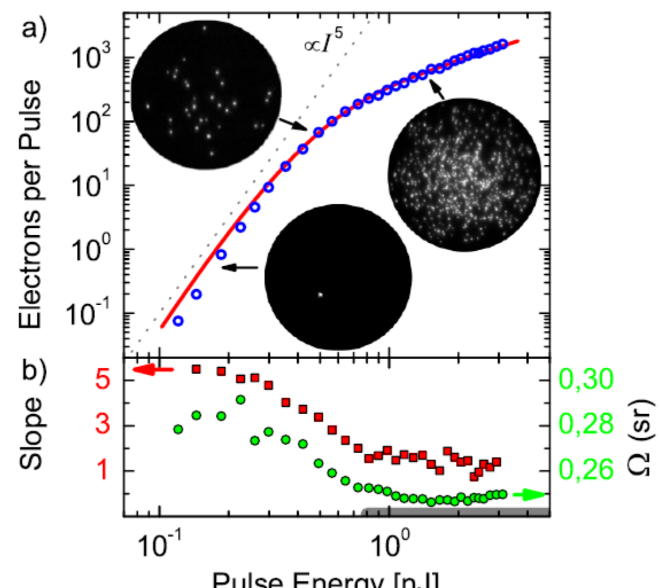



Electron emission rate: $P(\gamma) \propto \exp\left\{-\frac{2\phi}{\hbar\omega}\left[\left(1+\frac{1}{2\gamma^2}\right)\right.\right.$

Keldysh parameter: $\gamma = \sqrt{\frac{\phi}{2U}}$

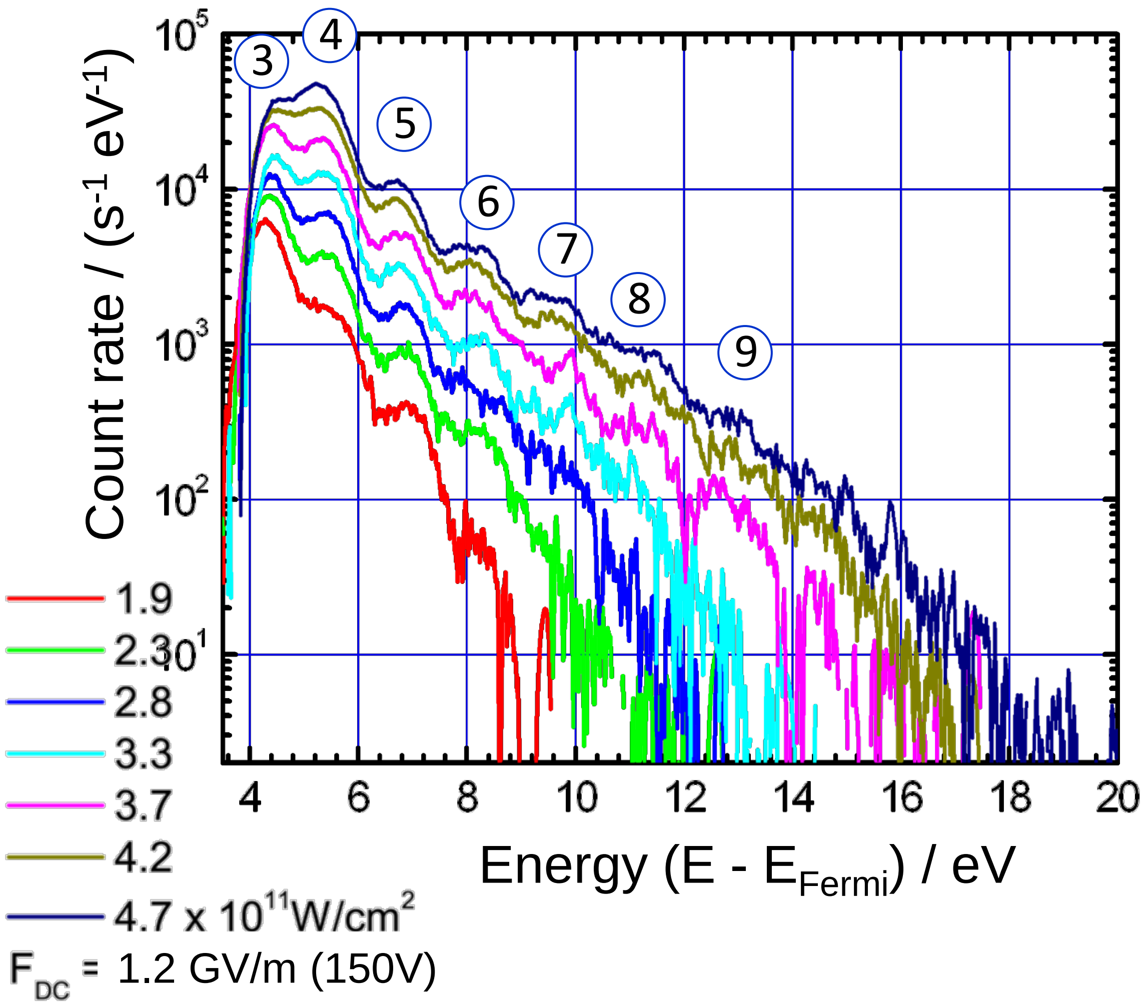
Ponderomotive energy: $U_\mathrm{p} = \frac{1}{2}m\left\langle v(t)^2\right\rangle$

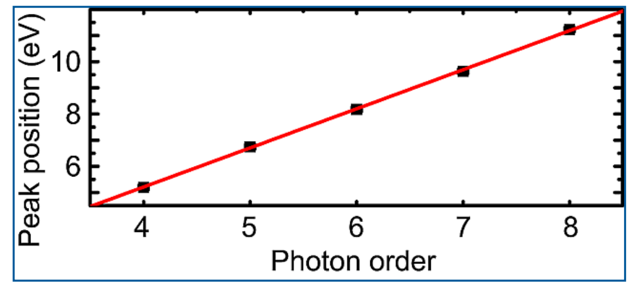


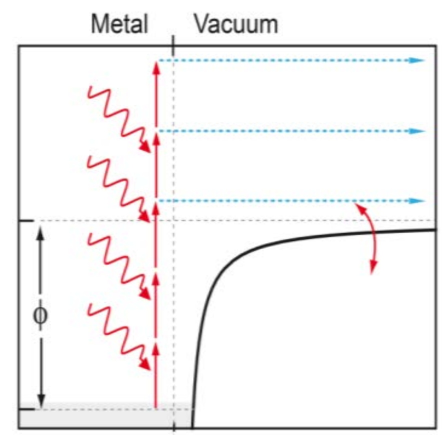

M. Krüger, PhD thesis (2013).

Bormann et al., PRL **105**, 147601 (2010).

# Above-threshold photoemission



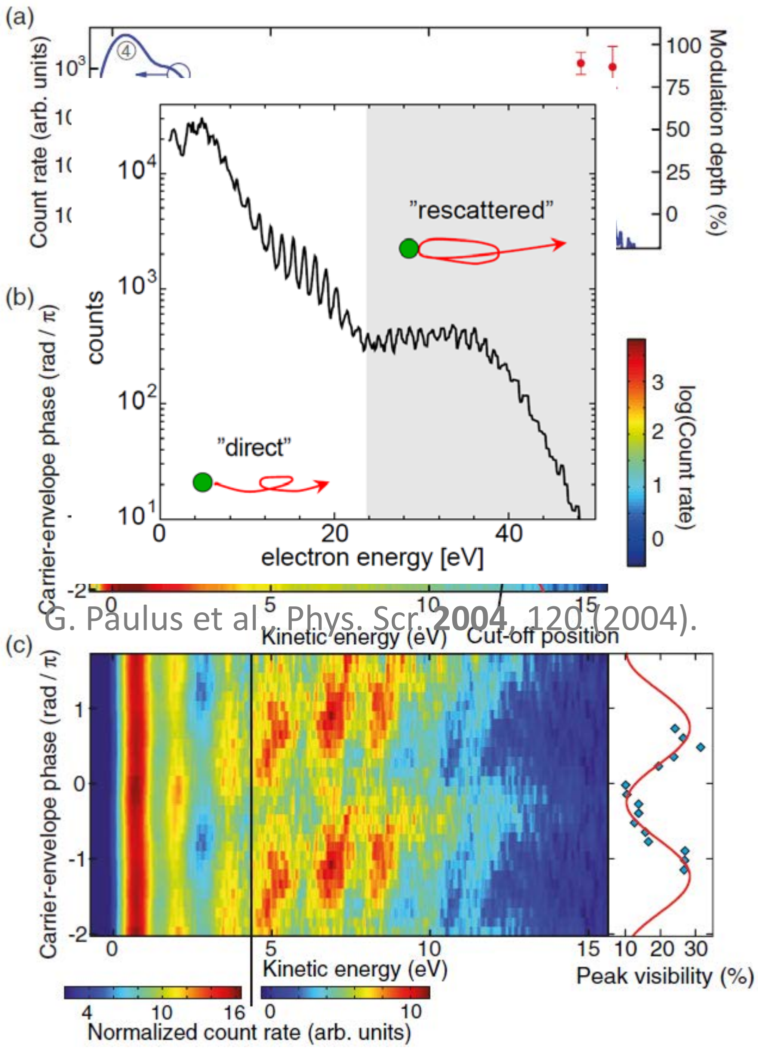



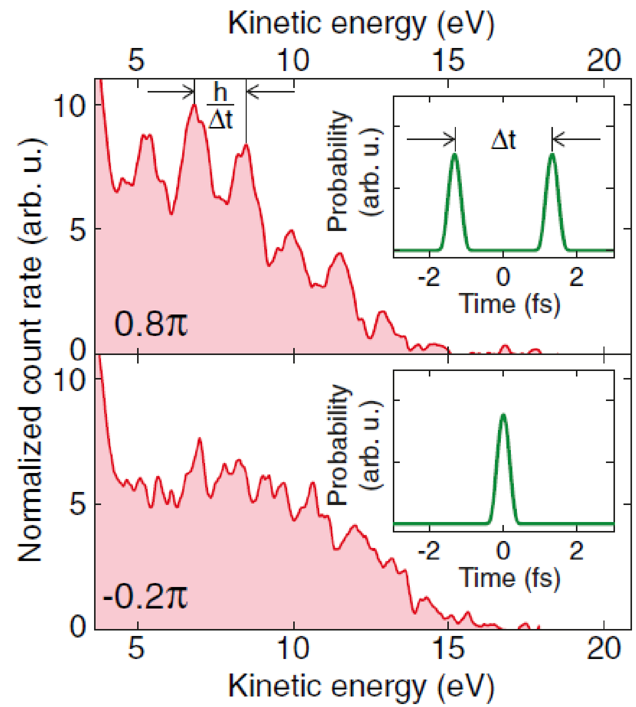

Clear peaks because of single nanoemitter

M. Schenk, M. Krüger, P. Hommelhoff, PRL **105**, 257601 (2010).

# Carrier-envelope phase effects



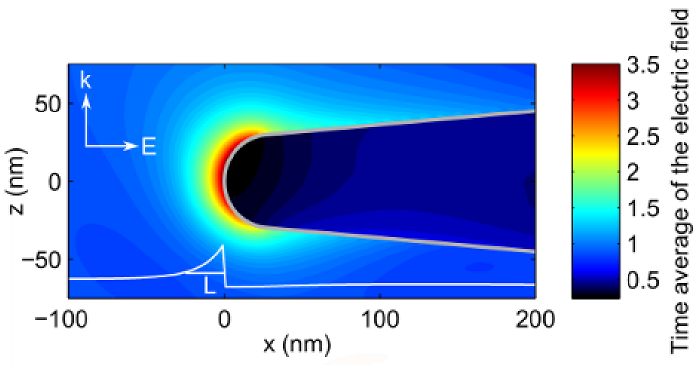

G. Paulus et al., Phys. Scr. **2004**, 120 (2004).

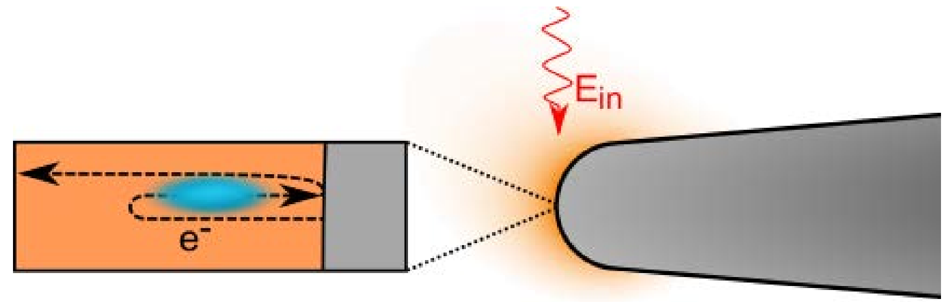



M. Krueger et al., Nature **475**, 78 (2011).

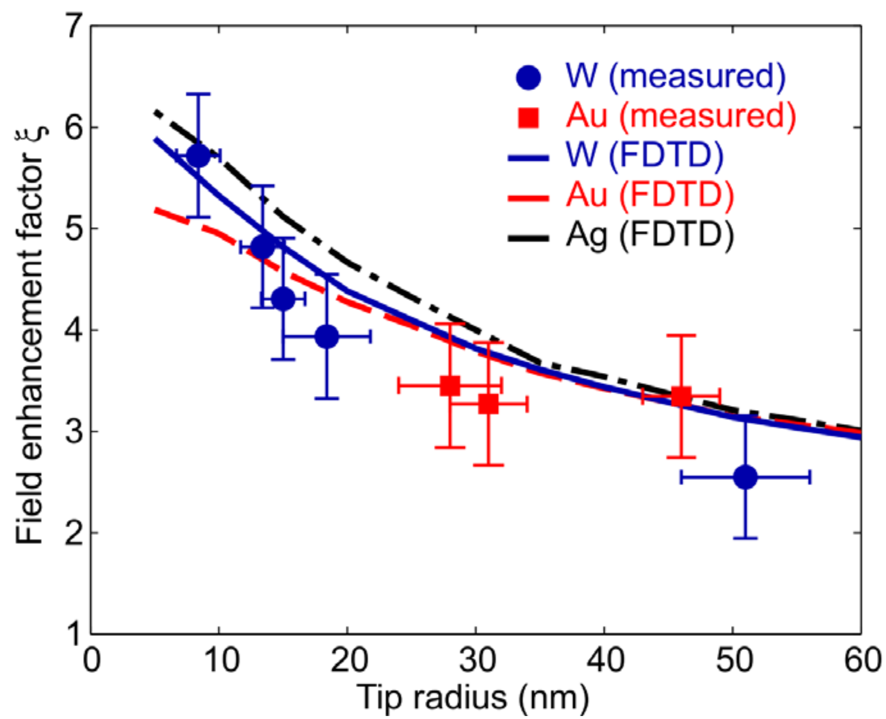
M. Krueger et al., J.Phys.B. **45**, 074006 (2012) .

# Near-fields revisited



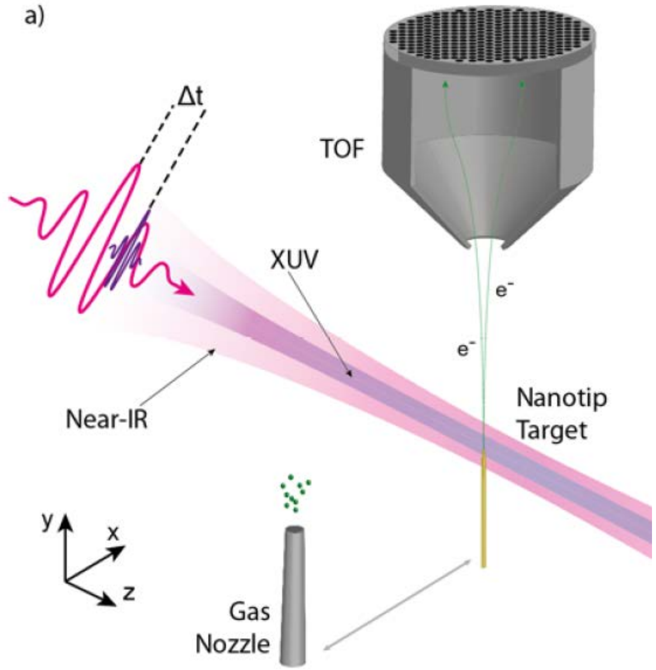

- Good agreement between measurement and simulation
- Field enhancement factors between 6 and 2 for 5 nm to 50 nm tips
- Little difference between tungsten and gold tips

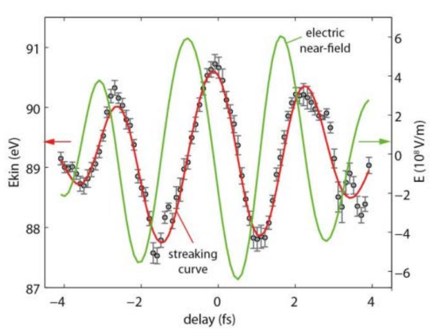



S. Thomas et al., Nano Lett. **13**, 4790-4794 (2013).
M. Krüger et al., J. Phys. B **47**, 124022 (2014).

# Near-fields revisited II

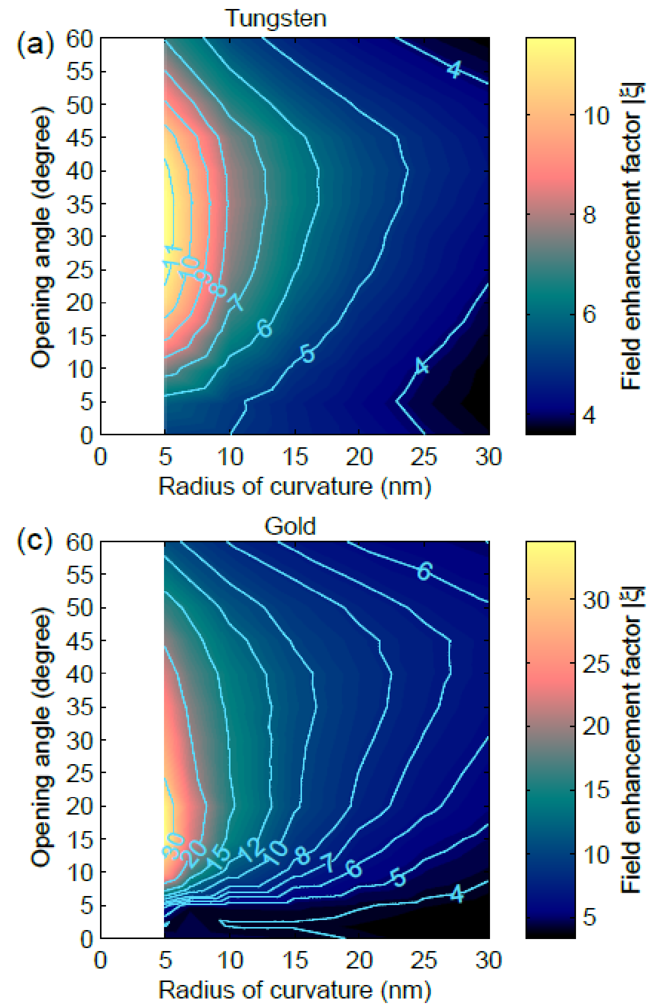
## Attosecond streaking of near fields



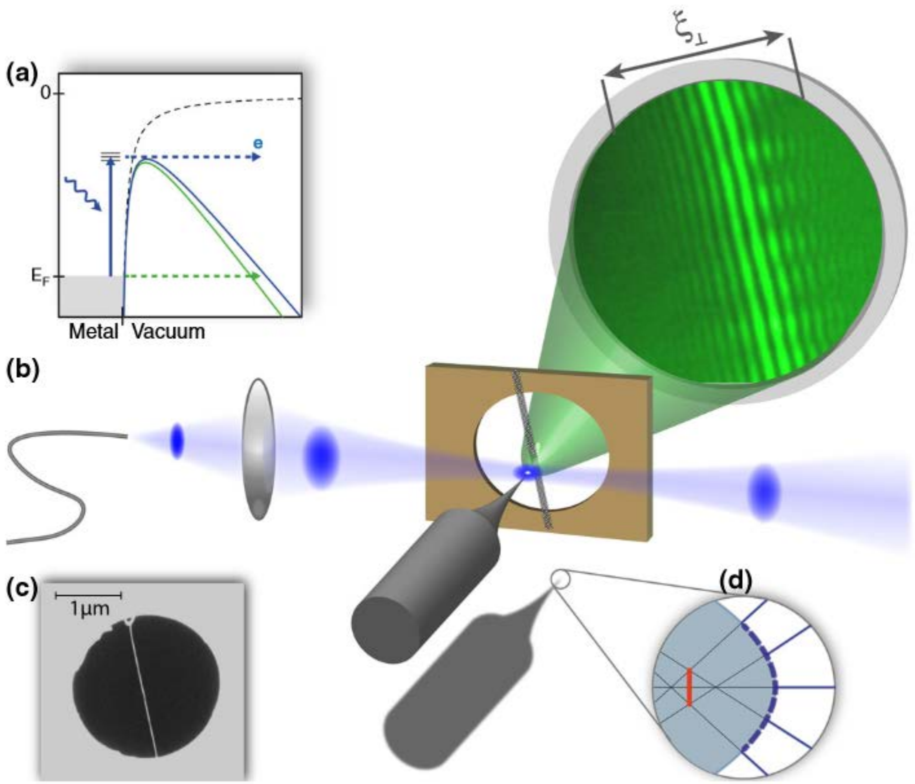

B. Förg et al., http://arxiv.org/abs/1508.05611

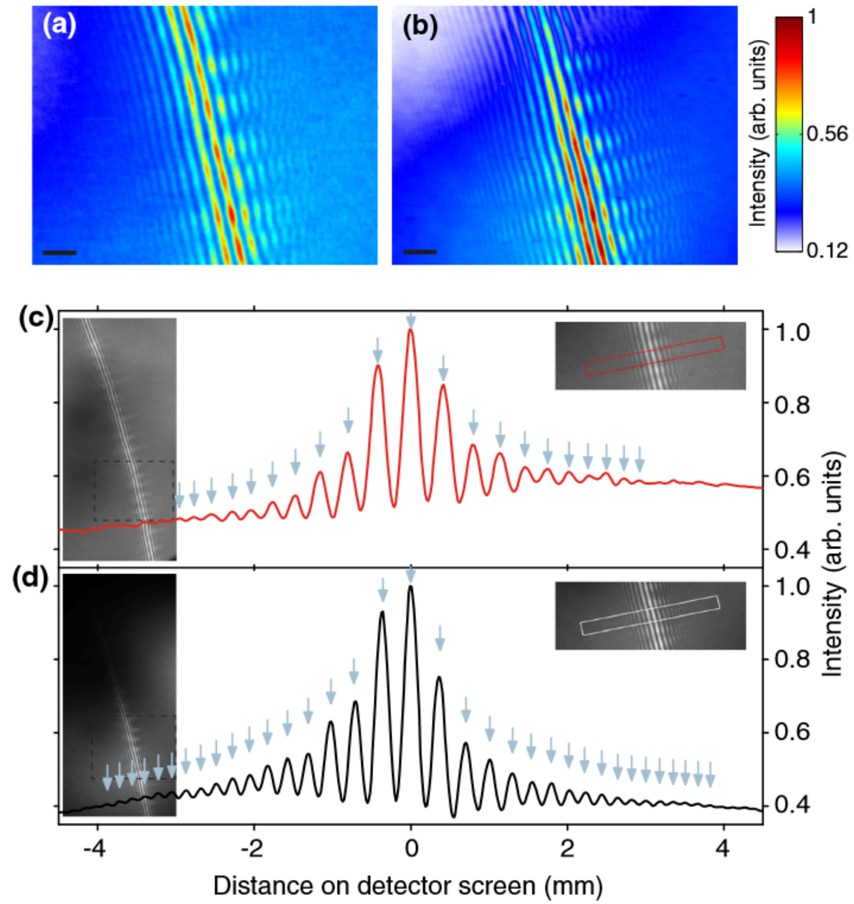
## Larger opening angles (simulation)




S. Thomas et al., New J. Phys. **17**, 063010 (2015).

# Transverse coherence of photoemission




Effective source radius: r <=0.80 nm (laser-triggered), r <=0.55 nm (DC)

D. Ehberger et al., PRL **114**, 227601 (2015).

# Summary

- Metal nanotips present a well-controlled nanoscale system for studies of light-matter interaction at high fields. It is a very promising source for electron pulses with superb coherence and femtosecond duration.
- Photoemission has many different regimes, depending on materials and laser parameters. Above-threshold photoemission can be coherently controlled in a two-color scheme.
- Electron propagation after emission is sensitive to the precise form of the laser field. Using rescattered electrons as a messenger, near fields can be sampled on the 1 nm scale.