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New frontiers for control schemes

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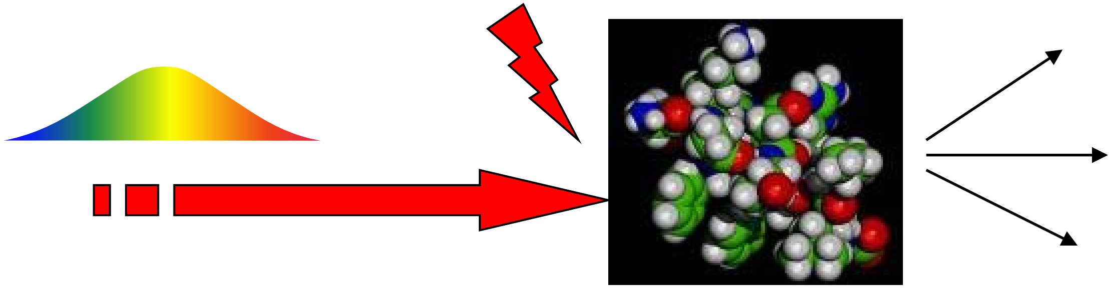
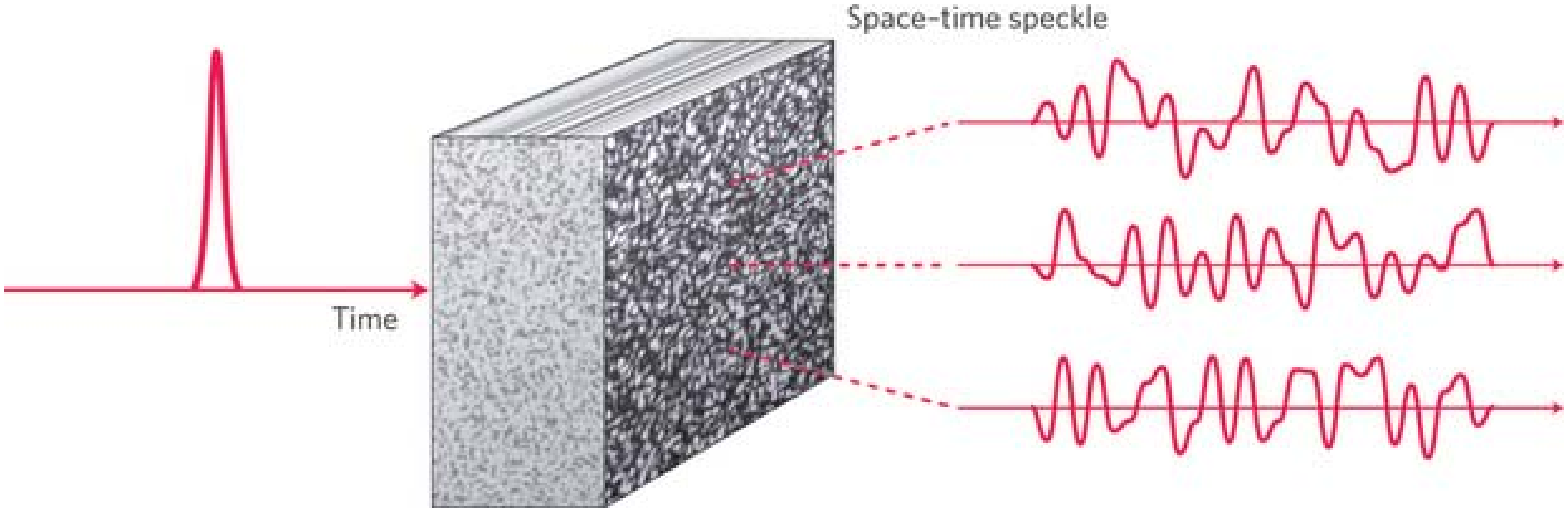
Coherent control



- Coherent control has been introduced in the mid 80’s with the goal of controlling outcome of chemical reaction. It has been extended to many systems

➢ **Two directions:**
  ➢ Control of scattering light
  ➢ Strong Field interaction with a single nanotip (only part of the talk is on the website)

Control of scattering light

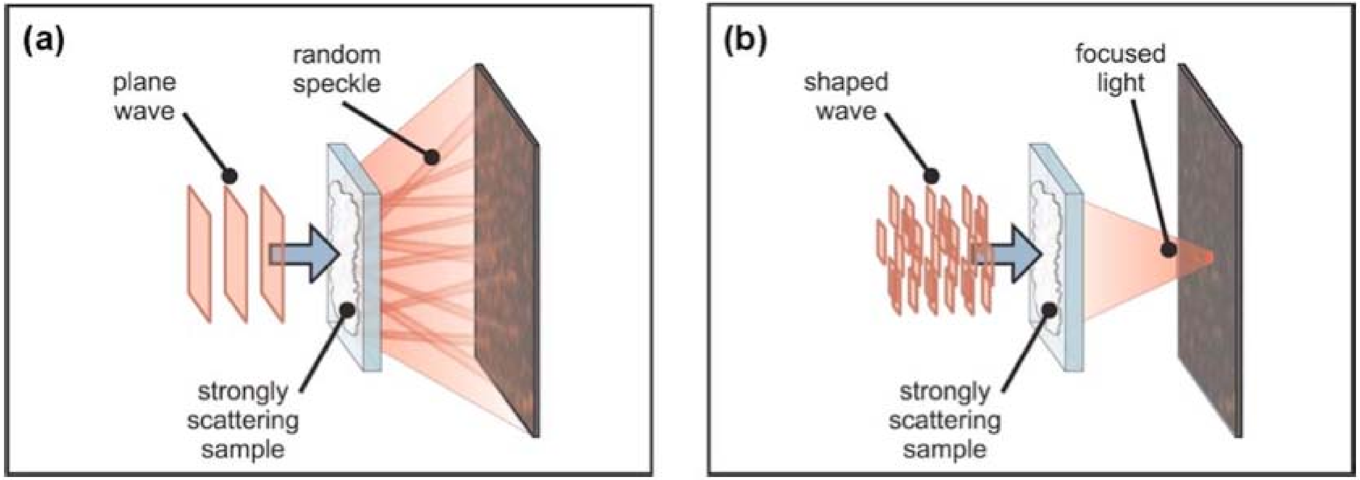


Weiner , Nature Photonics 5, 332–334 (2011)

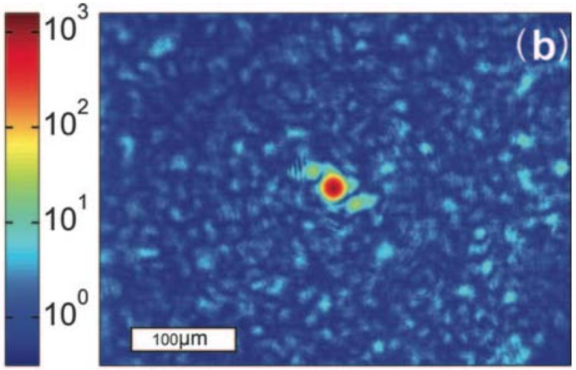
Starting with cw laser and adaptative optics

- Spatial phase-shaping of incident c.w. wavefront

I. Vellekoop and A. Mosk, Opt. Lett. **32**, p.2309 (2007)

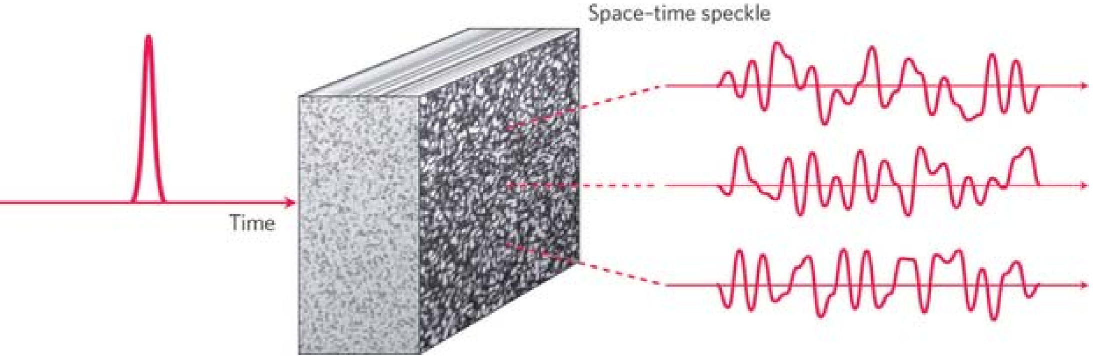


Inverts scattering process to form spatial focus



Popoff, S. et al. *Measuring the transmission matrix in optics: an approach to the study and control of light propagation in disordered media*. ***Phys Rev Lett 104, 100601 (2010).***

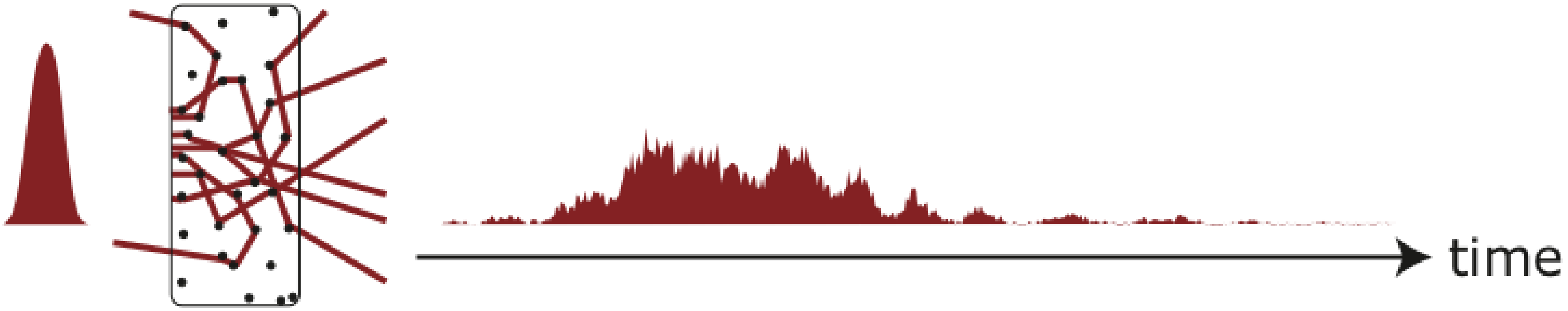
Popoff, S., et al. *Image transmission through an opaque material.* ***Nat Commun 1, (2010)***



What's happen in the case of broadband pulse?

- Scattering process dispersive
  - Each frequency will lead to a different speckle pattern (overall image contrast reduced)
  - Complex spatio-temporal coupling through the medium.
  - Spatio-spectral resolution required to study individual speckle fields

- Temporally stretched with characteristic Thouless time
  - Formation of 'temporal speckle field'



Very active field

- Aulbach et al, Phys. Rev. Lett. 106, 103901 (2011),

Control of Light Transmission through Opaque Scattering Media in Space and Time

- Katz et al , Nature Photonics 5, 372–377 (2011) ,

Focusing and compression of ultrashort pulses through scattering media.

- McCabe et al, Nature Communications 2, 447 (2011)

Spatio-temporal focusing of an ultrafast pulse through a multiply scattering medium

- *Tajalli et al, JOSA B , 29 (2012)*

Characterization of the femtosecond speckle field of a multiply scattering medium via spatio-spectral interferometry

- Katz et al. , Nature Photonics **6**, 549-553 (2012)

Looking around corners and through thin turbid layers in real time with scattered incoherent light

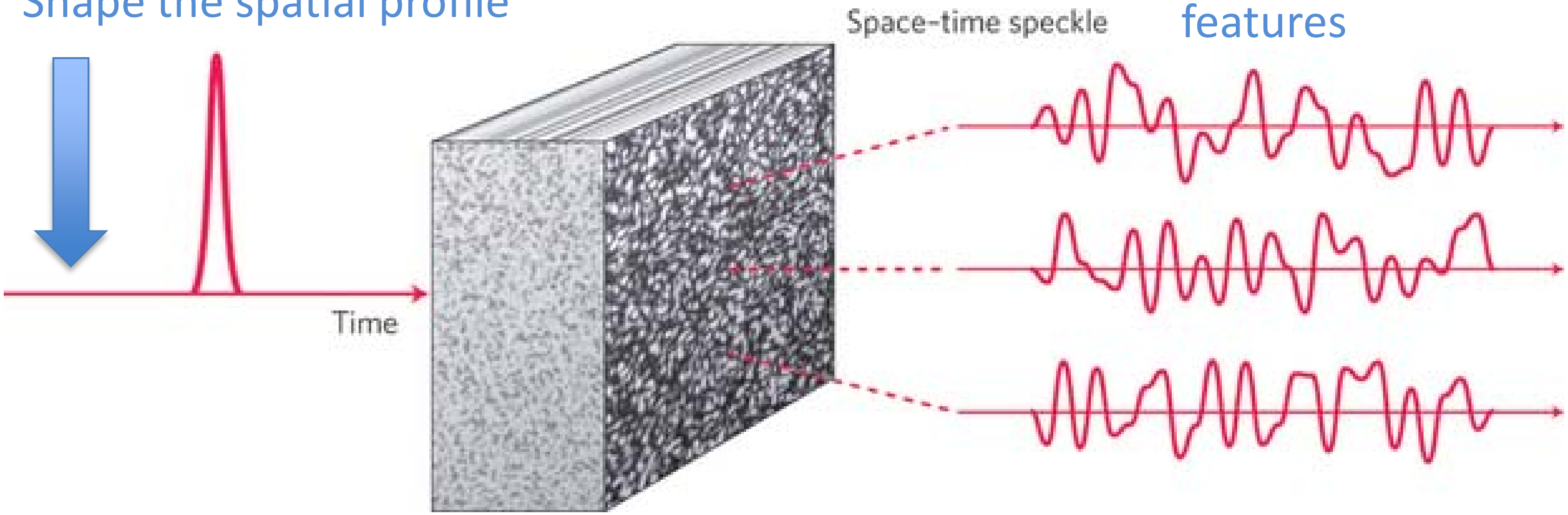
To control the temporal feature by controlling the spatial parameters

- Katz et al , Nature Photonics 5, 372–377 (2011)

Focusing and compression of ultrashort pulses through scattering media.

Shape the spatial profile

Control the temporal features

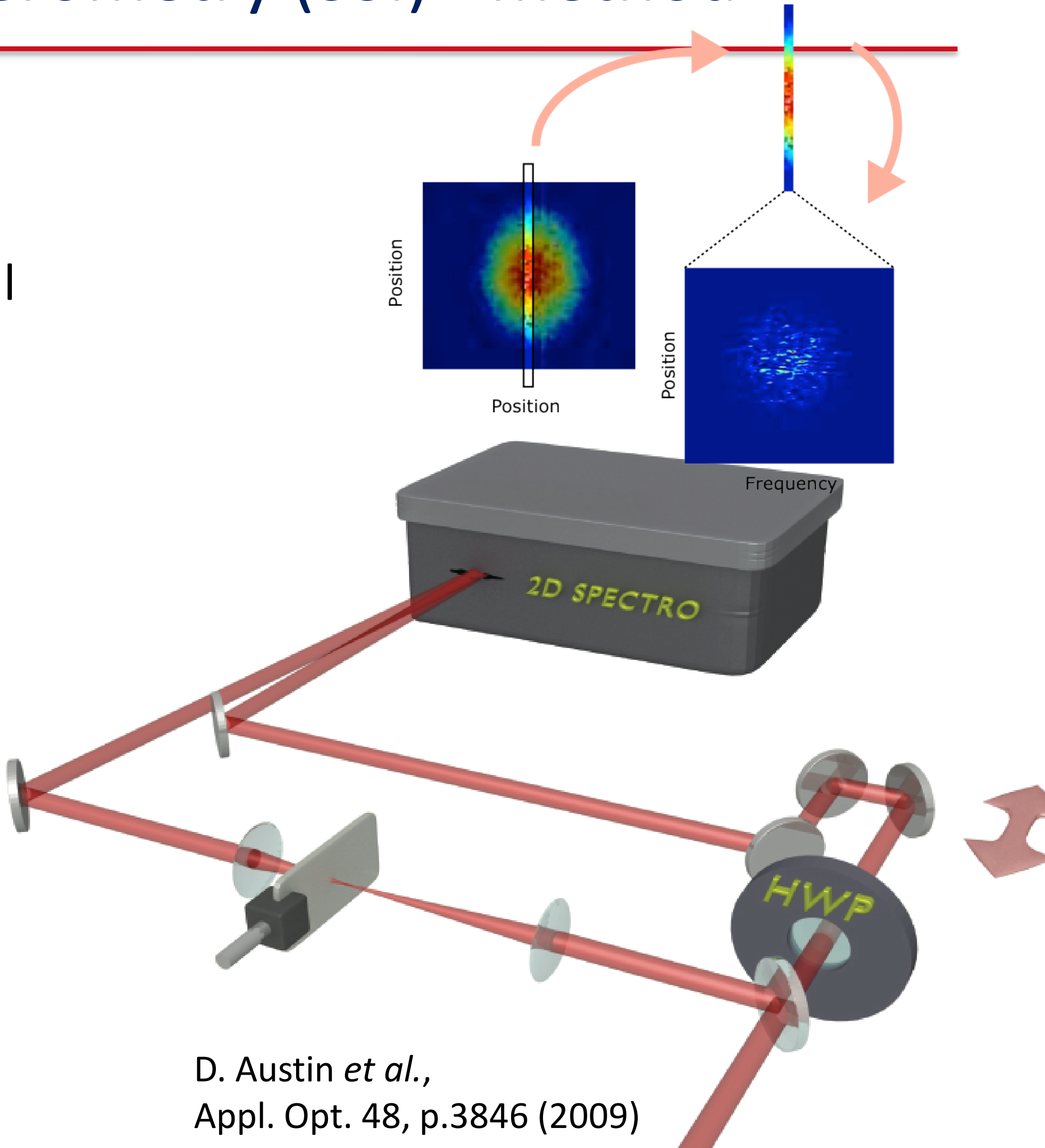


McCabe et al, Nature Communications 2, 447 (2011)
Spatio-temporal focusing of an ultrafast pulse through a multiply scattering medium

⇨ Control the position by controlling spectral parameters

Spatially and spectrally resolved interferometry (SSI) - method

- The ultrashort pulse is focused onto a thin scattering ZnO layer leading to a complex spatio-temporal speckle.
- The spatio-temporal speckle is reimaged onto 2D spectrometer and interfers with a reference beam.
- This causes interferences. The spatial and spectral periods are determined by the relative delay and angle of the two beams



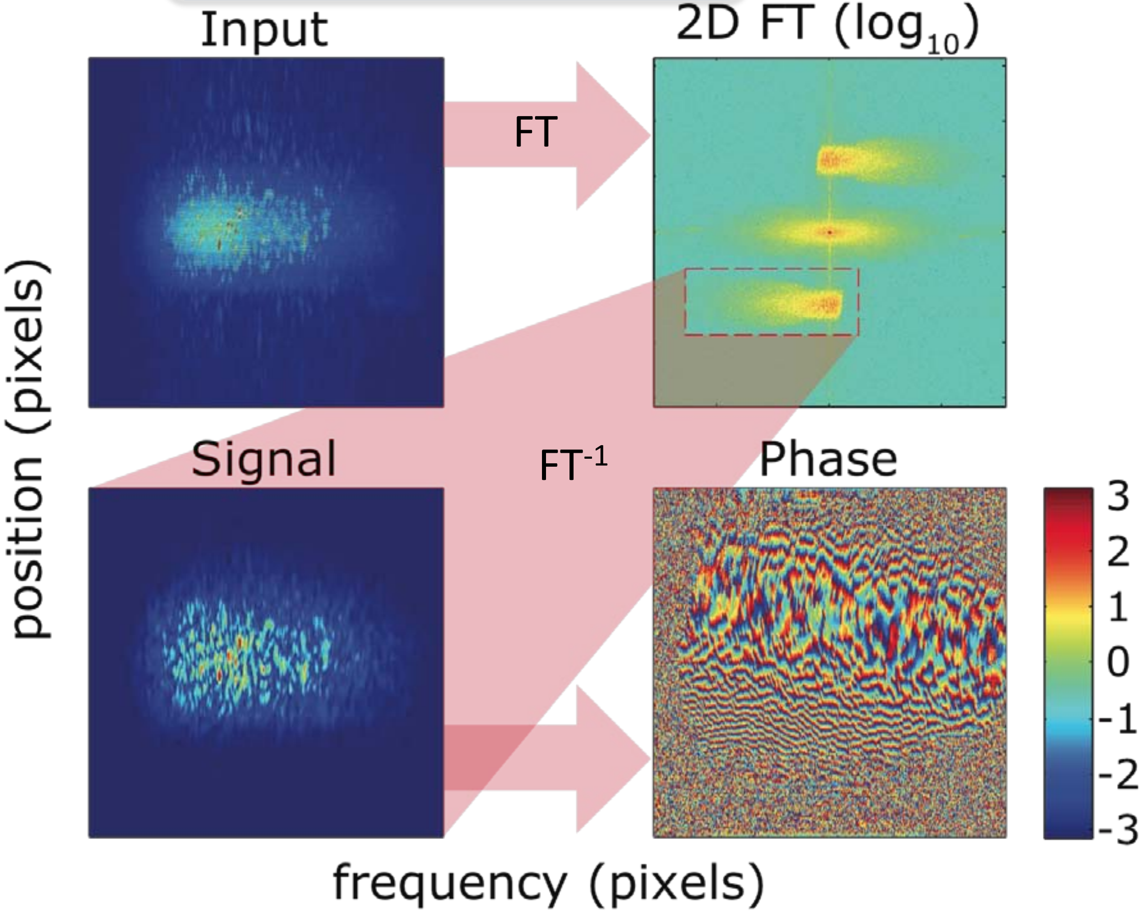
D. Austin *et al.*,
Appl. Opt. 48, p.3846 (2009)

Spatially and spectrally resolved interferometry (SSI) - extraction

$$\begin{aligned} S(x,\omega) &= | A_s(\omega,y)e^{i\phi_s(\omega,y)} + A_r(\omega,y)e^{i[\phi_r(\omega,y)+\omega\tau+k_y y]} |^2 \\ &= | A_s(\omega,y)|^2 + | A_r(\omega,y)|^2 \\ &+ | A_s(\omega,y)|| A_r(\omega,y)| \cos\boxed{[\phi_s(\omega,y)-\phi_r(\omega,y)-\omega\tau-k_y y]}. \end{aligned}$$

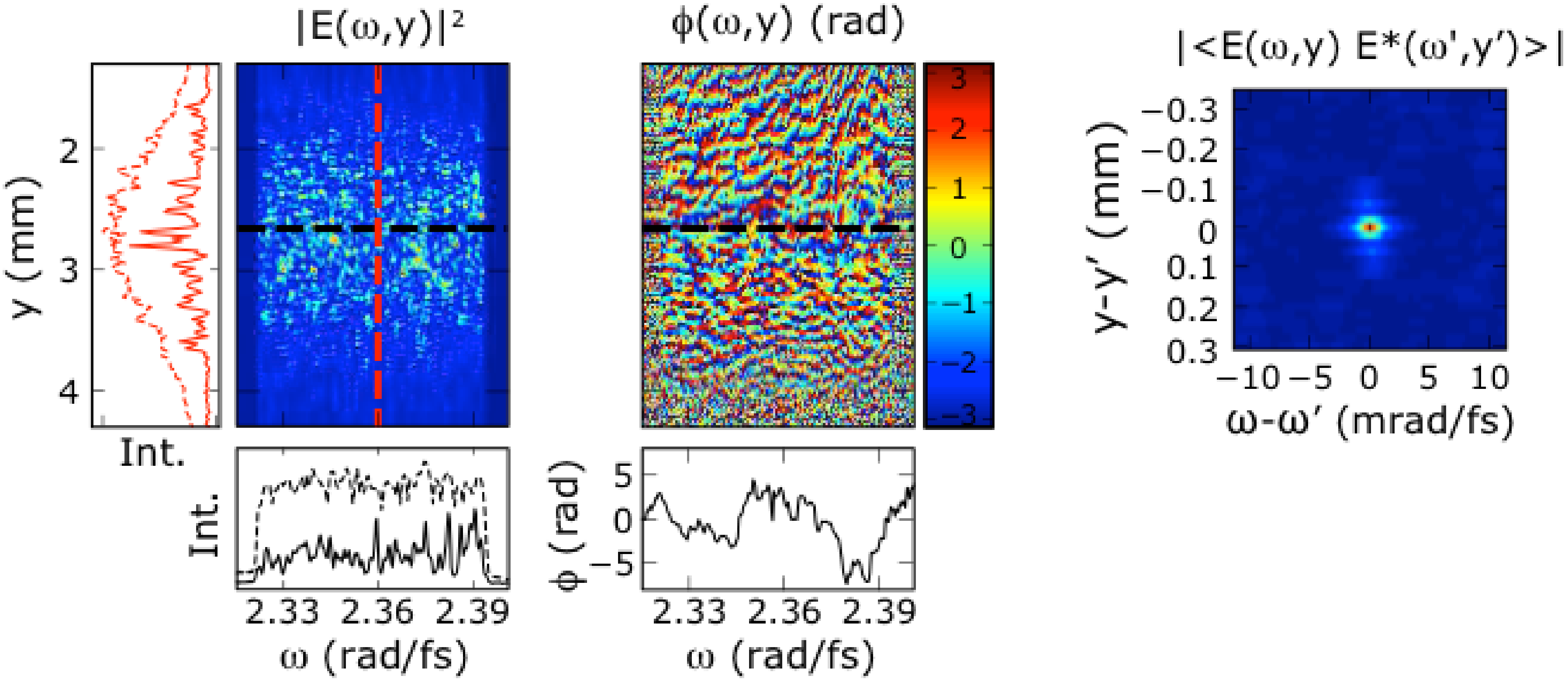
- The fringes are additionnally modulated by the relative phase between the two beams.

- FT along both spatial & spectral axes / a.c. filtering/ inverse F.T.



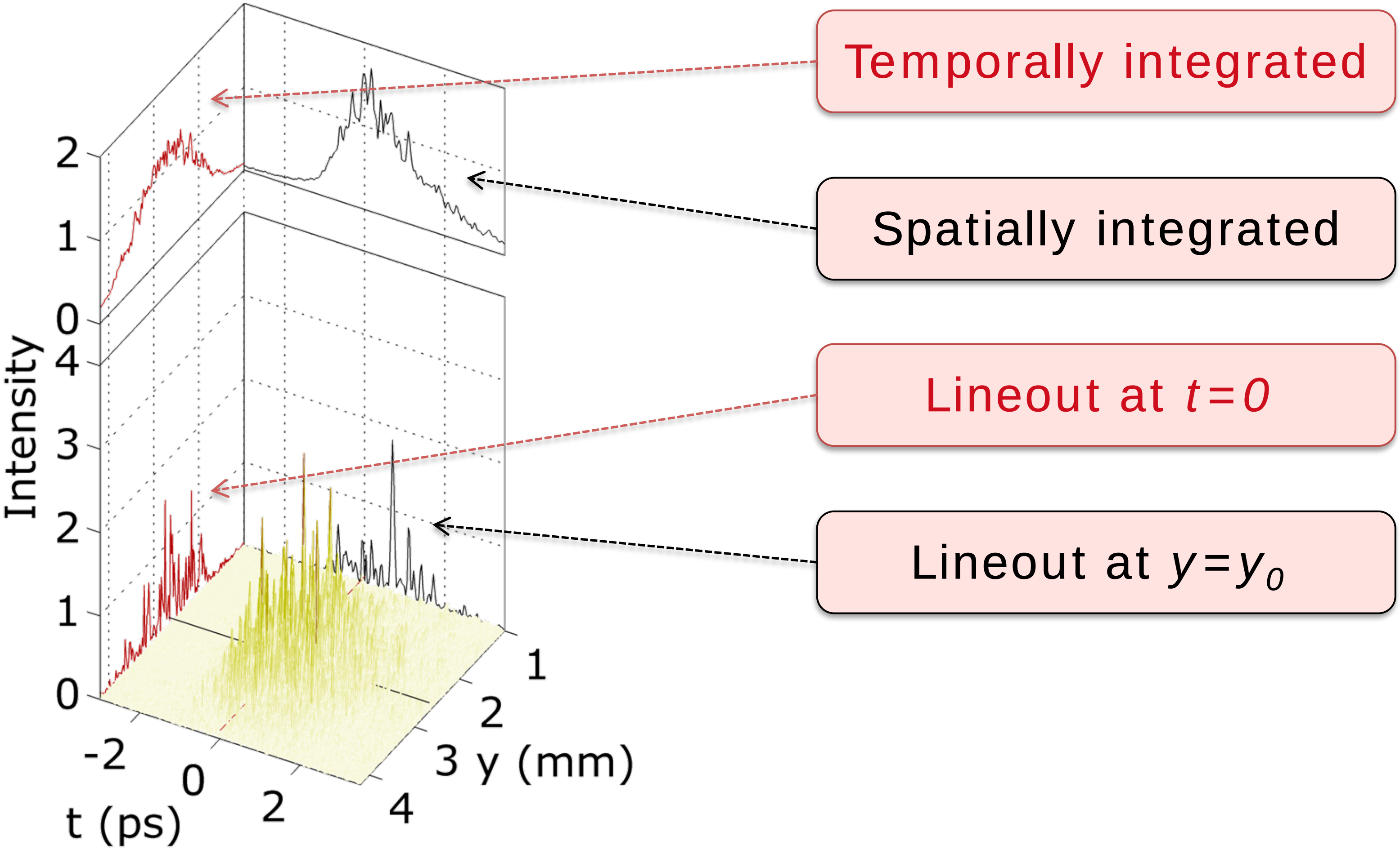
Spectral measurements

- Reconstruct spatio-spectral intensity and phase
  - No large-scale spatial or spectral correlations
  - Autocorrelation function retrieves speckle grain size (50µm) and medium bandwidth (2.55 mrad/fs)



Temporal focussing - results

- Measure unshaped spatio-temporal speckle field $E(y,t)$

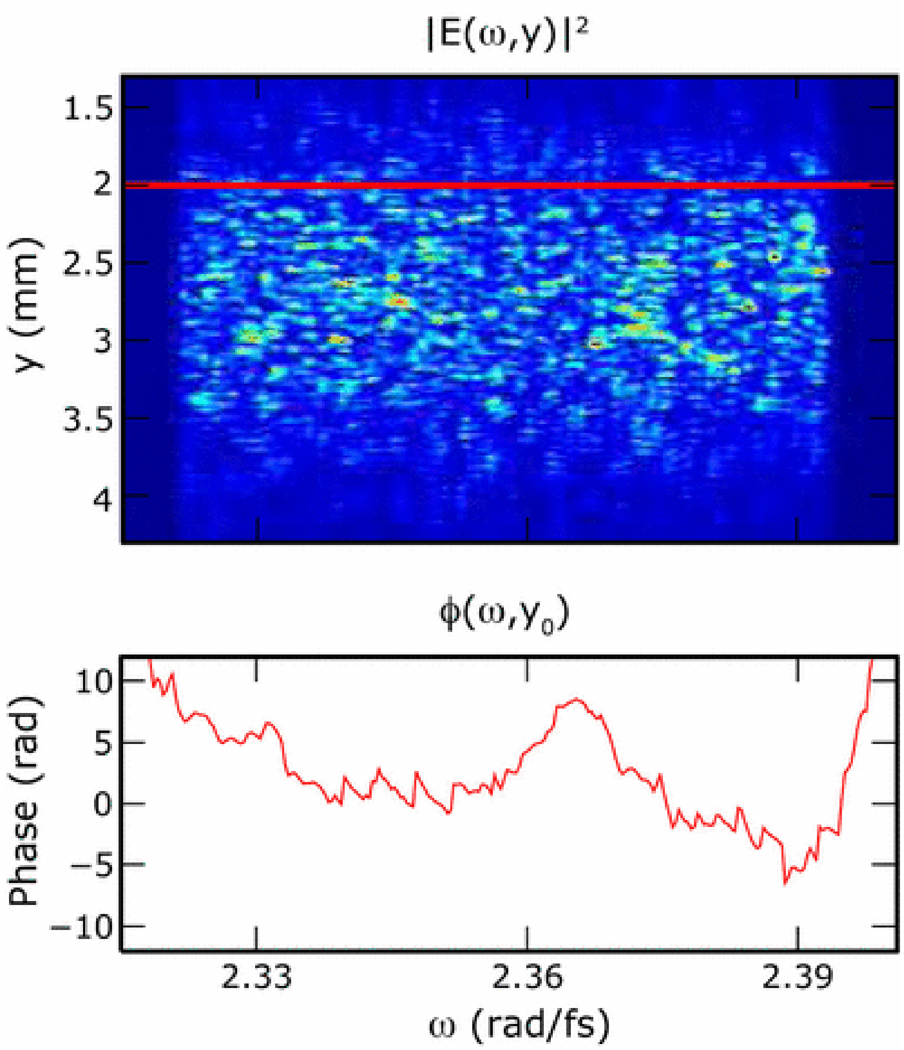


Spatial resolution of spectral phase

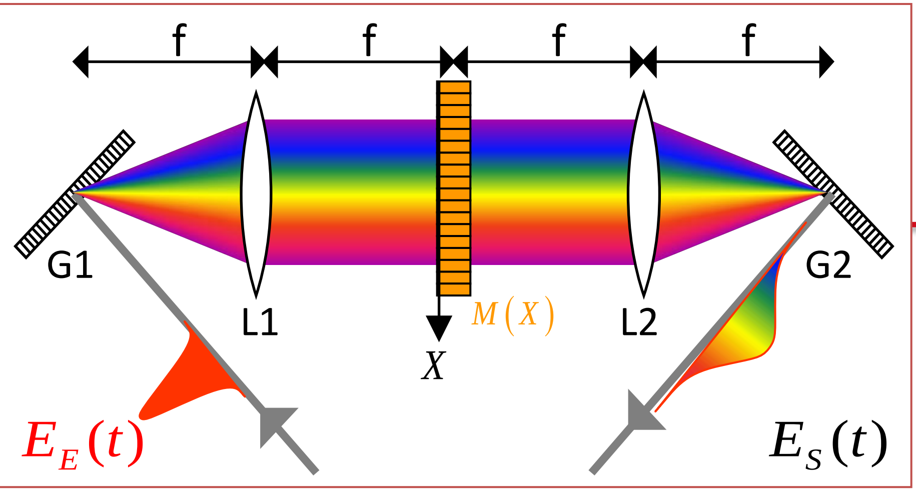
- Phase correlations over extent of speckle grain only

- In contrast to many control experiments, spatial resolution essential (spatially averaged phase meaningless!)

EXPERIMENT: Active control of speckle temporal field



Experiment:

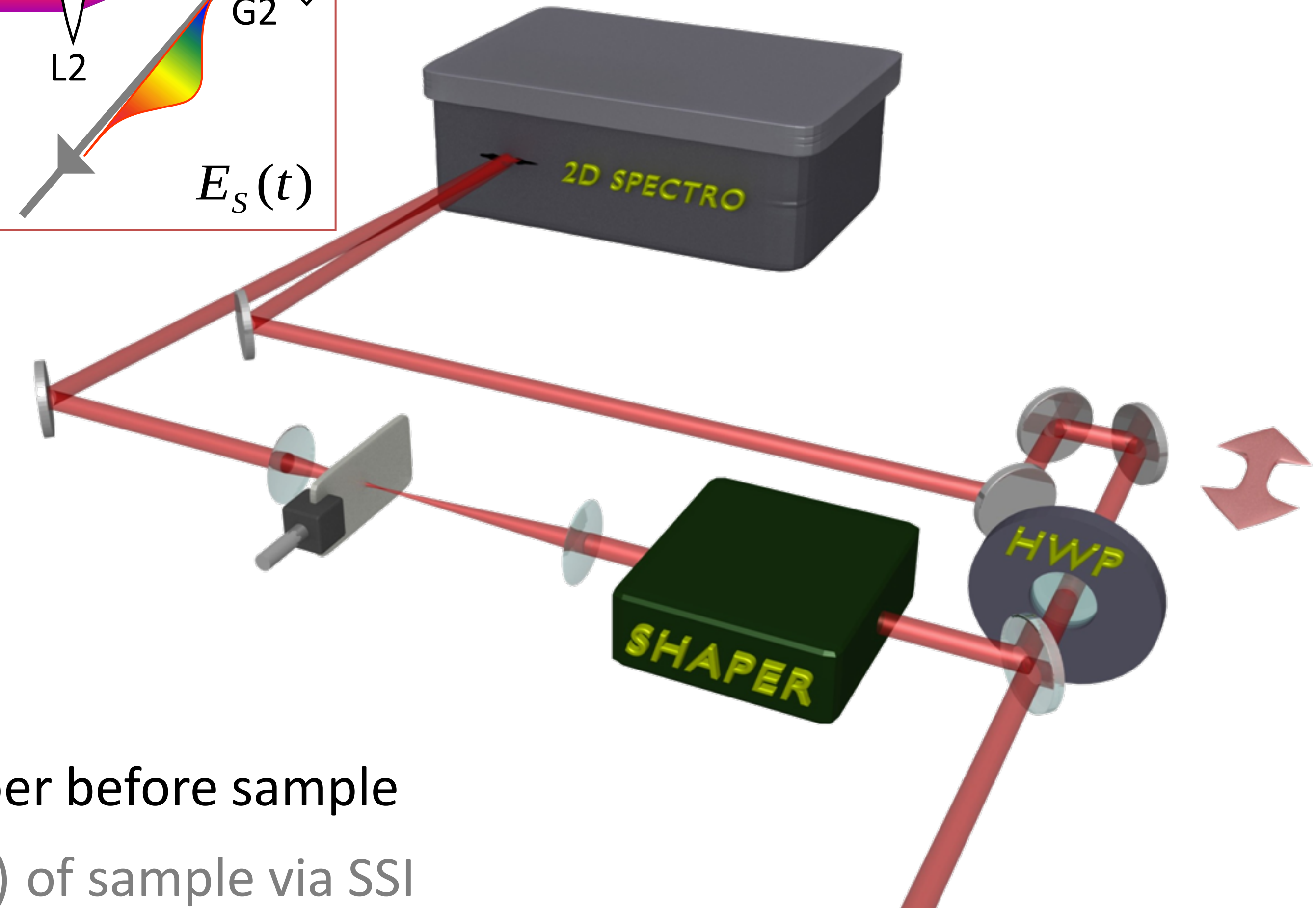


Folded 4f line

640 pixels over 30nm

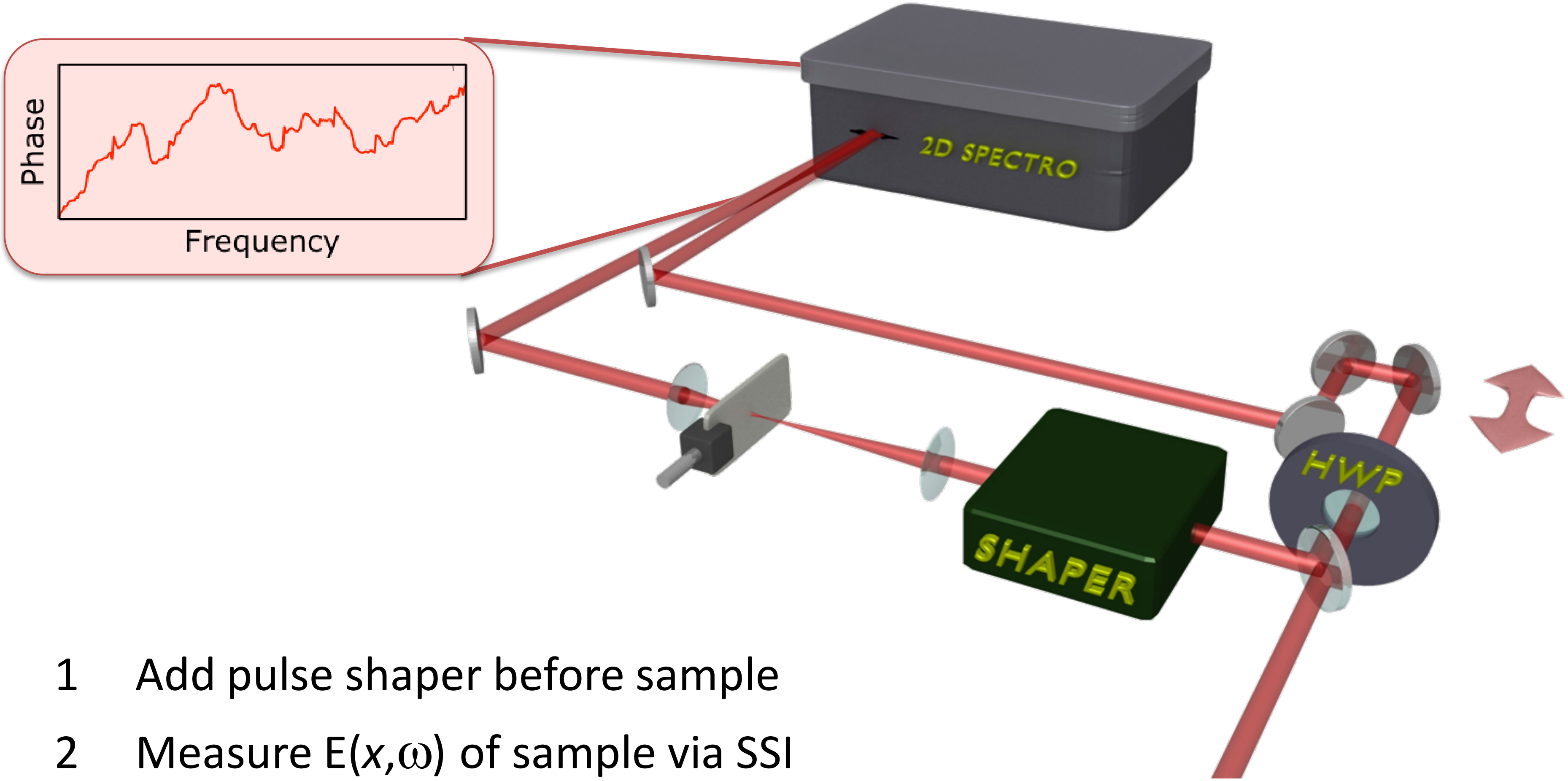
0.06nm resolution

23ps shaping window



1. Add pulse shaper before sample
2. Measure $E(x,\omega)$ of sample via SSI
3. Choose spatial ‘slice’ y_0 + programme $\varphi(x_0,\omega)$ into shaper

Experiment: speckle phase compensation & temporal focussing

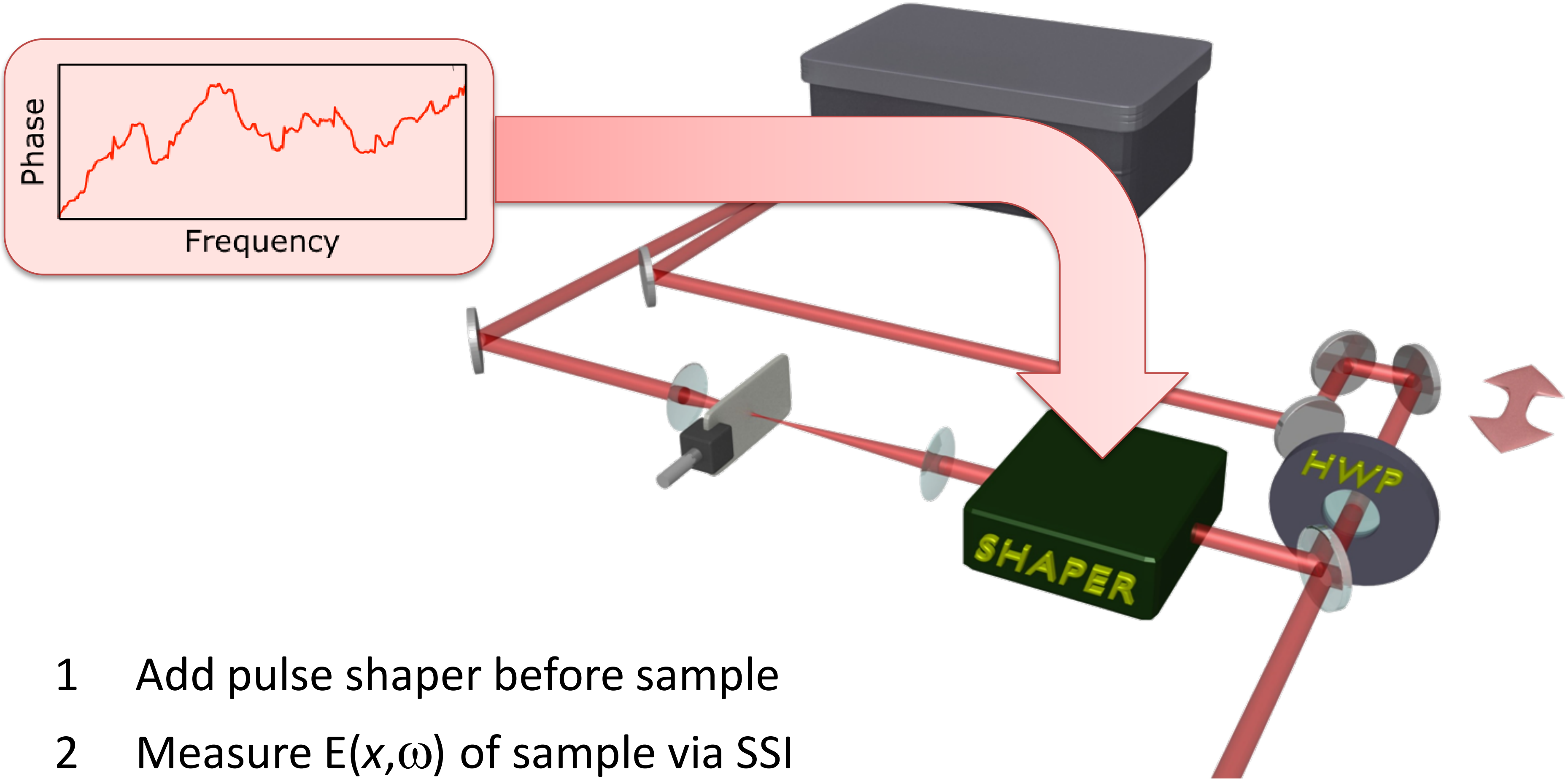


1 Add pulse shaper before sample

2 Measure E(x,ω) of sample via SSI

3 Choose spatial ‘slice’ y_0 + programme $\varphi(x_0,\omega)$ into shaper

Experiment: speckle phase compensation & temporal focussing



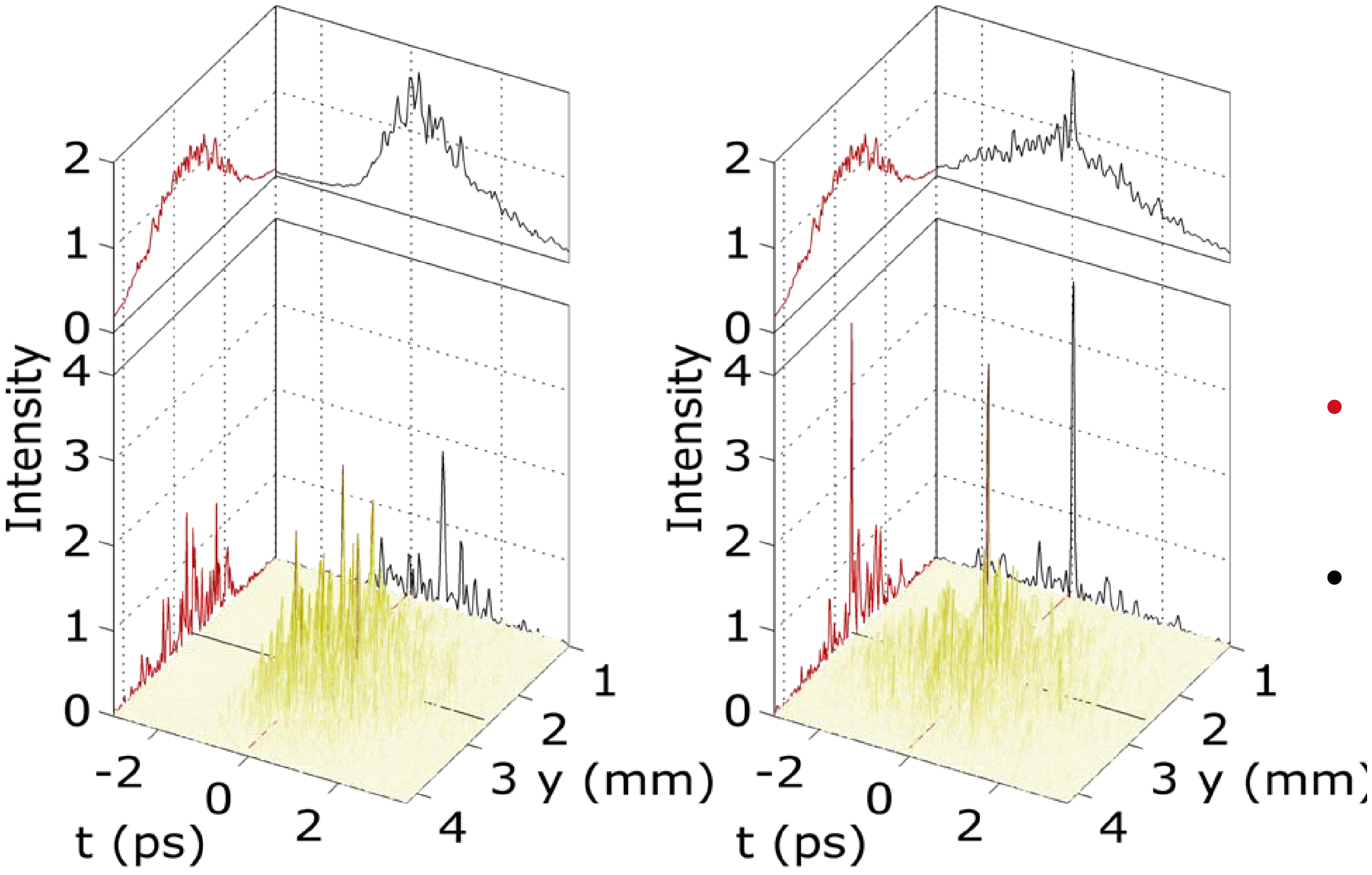
1 Add pulse shaper before sample

2 Measure E(x,ω) of sample via SSI

3 Choose spatial 'slice' y_0 + programme $\varphi(x_0,\omega)$ into shaper

Temporal focussing - results

- Phase compensation → emergence of intense peak



- Spatially localized to 30µm. No spatial redistribution (biological samples)
- Temporally focused to 59fs
- Contrast ratio of 15 relative to unshaped background

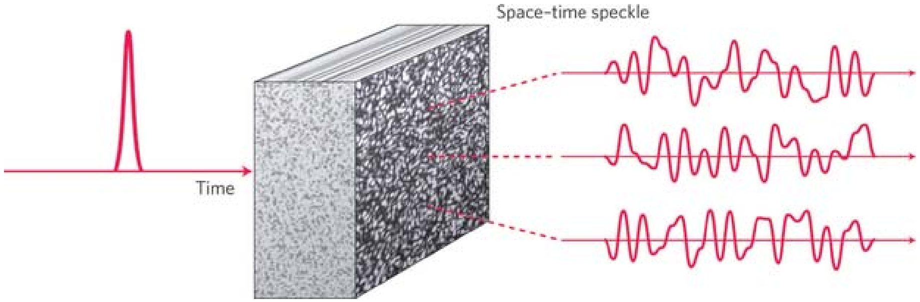
Conclusion 1

- In general : Space-time coupling limits the control of the interaction of the shaped pulse with the system.

- However in scattering media, strong coupling of space and time adds new control parameters with a high dynamic range.

The complexity of the system determines the quality of the control.

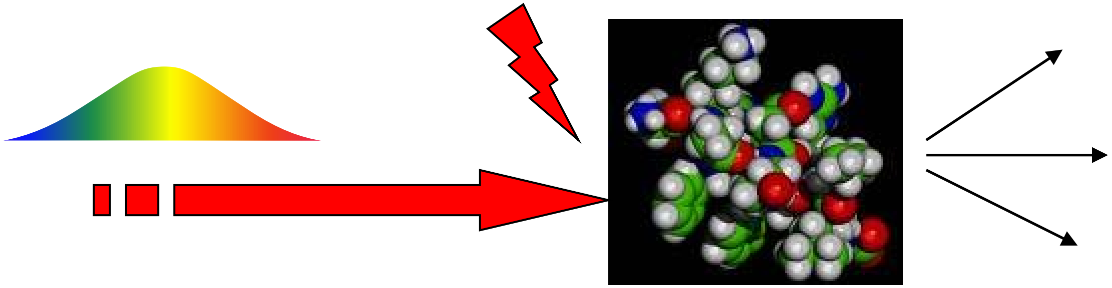
New type of pulse shaping : Temporal/spectral basis



McCabe et al, Nature Communications 2, 447 (2011)

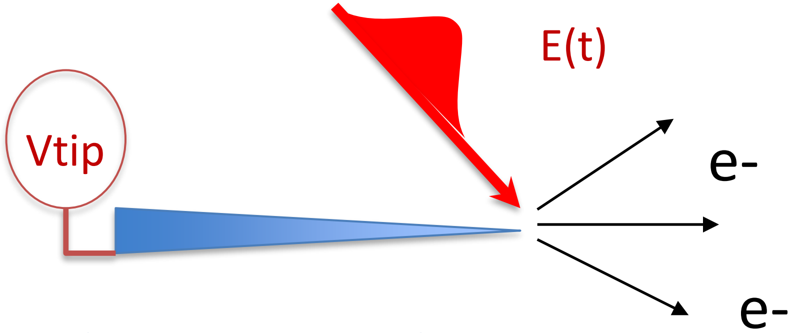
To go further :
-3D measurement for vortices
-Extension to quantum light using the spatio-temporal coupling

Coherent control



- ➢ **Two directions:**
  - ➢ Control of scattering light in open-loop control
  - ➢ Strong Field interaction with a nanotip (Preliminary studies)

Interaction of a single nanotip with ultrashort laser pulses



External fields:

-Ultrashort laser pulses

- DC field

Local intensity enhancement

Sub-wavelength confinement of optical field/plasmonic effects

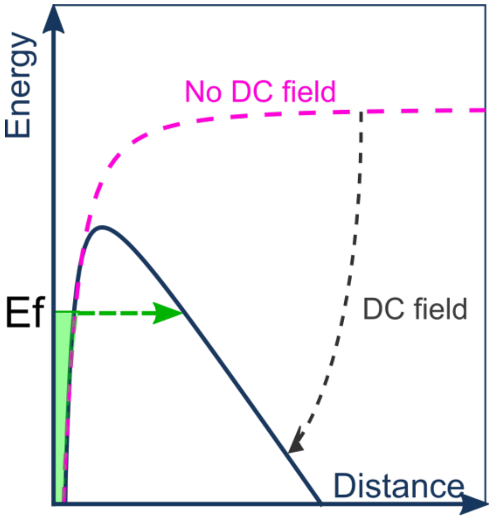
Nanostructures design adds new degrees of control

Motivations:

- Ultrashort nanometric electron sources (high temporal coherence +high spatial coherence) for holographic electron microscopy
- Strong-field physics on single objects (ATP peaks, CEP effects…)
- Interresting source for electron quantum optics

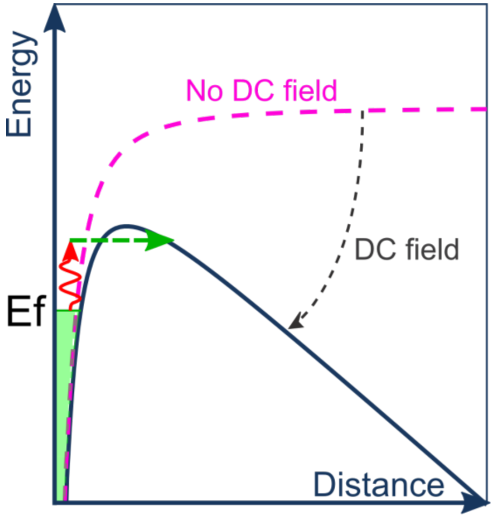
Physical mechanisms for laser-induced field emission

Cold Field Emission



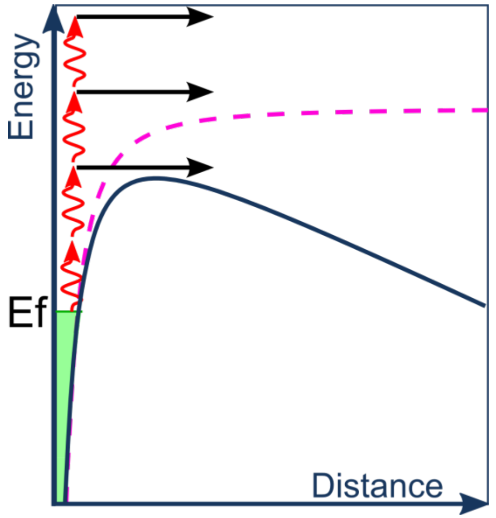
- DC applied to the tip
- Electrons can tunnel through the potential barrier
- Used in e- microscopy

Photofield Emission



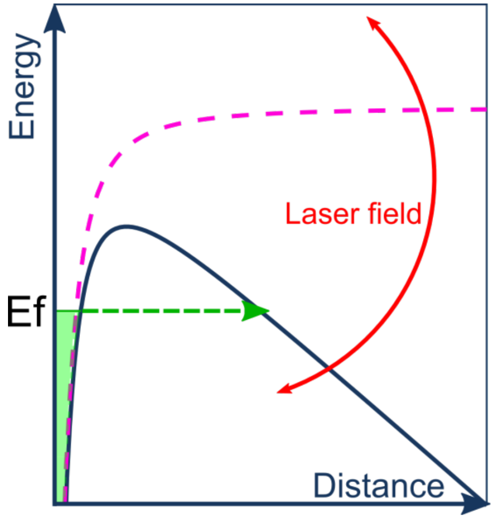
- Smaller DC applied to the tip
- Short laser pulse focused on the tip
- Electrons can absorb a photon and then tunnel through the potential

Multiphotonic regime



- Electrons can absorb more photons than necessary (ATP)
- Electrons are emitted with larger energy

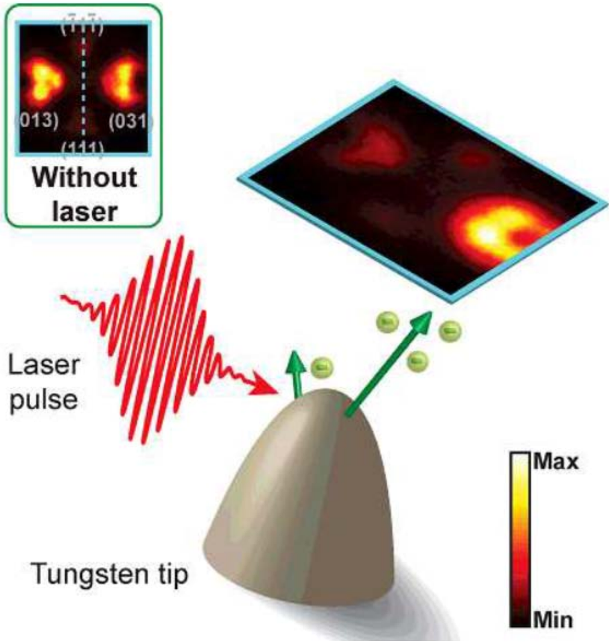
Optical tunneling regime

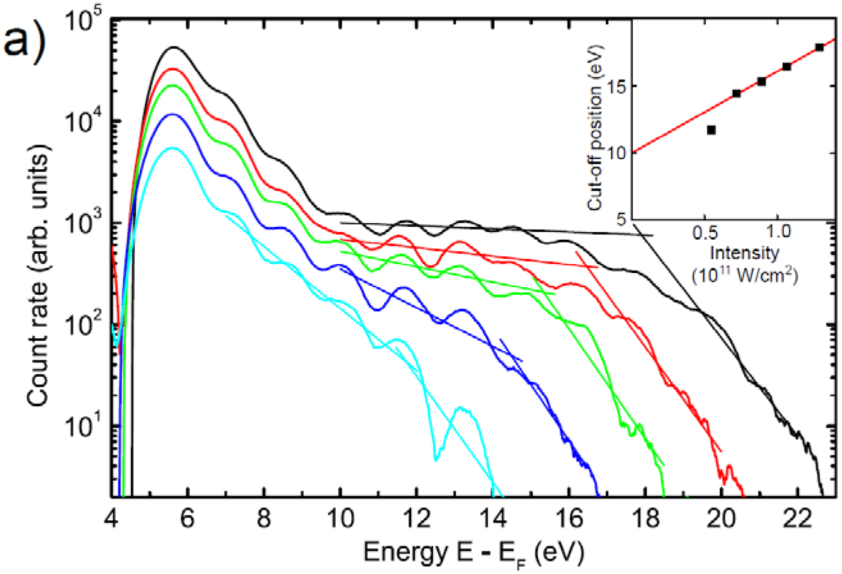


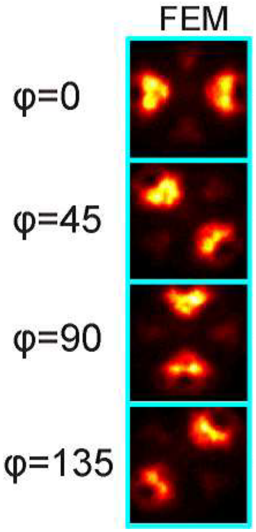
- The laser E-field is dominant, driving the electrons motion
- Recollision

Several works on metallic tips (W, Au, HfC …)

- **On Tungsten tip**
  - to study quantum properties of these ultrashort electron sources (Lougowski PRA2011)
  - to control the electron emission site by the control of the polarization (Yanagisawa PRL 2009)
  - To observe strong –field signature and CEP effects(Kruger Nature 2011)

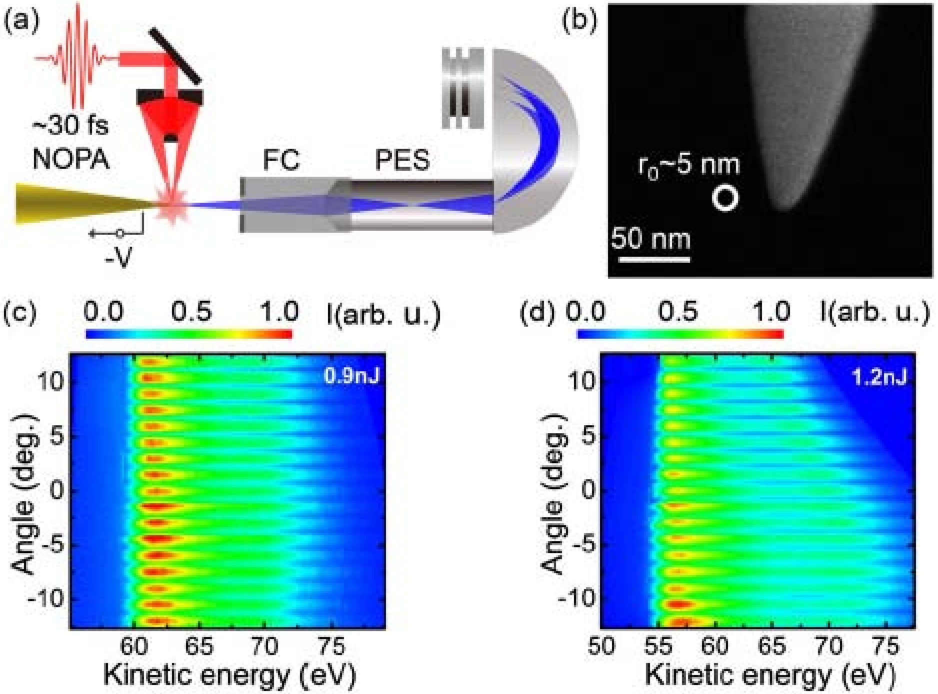


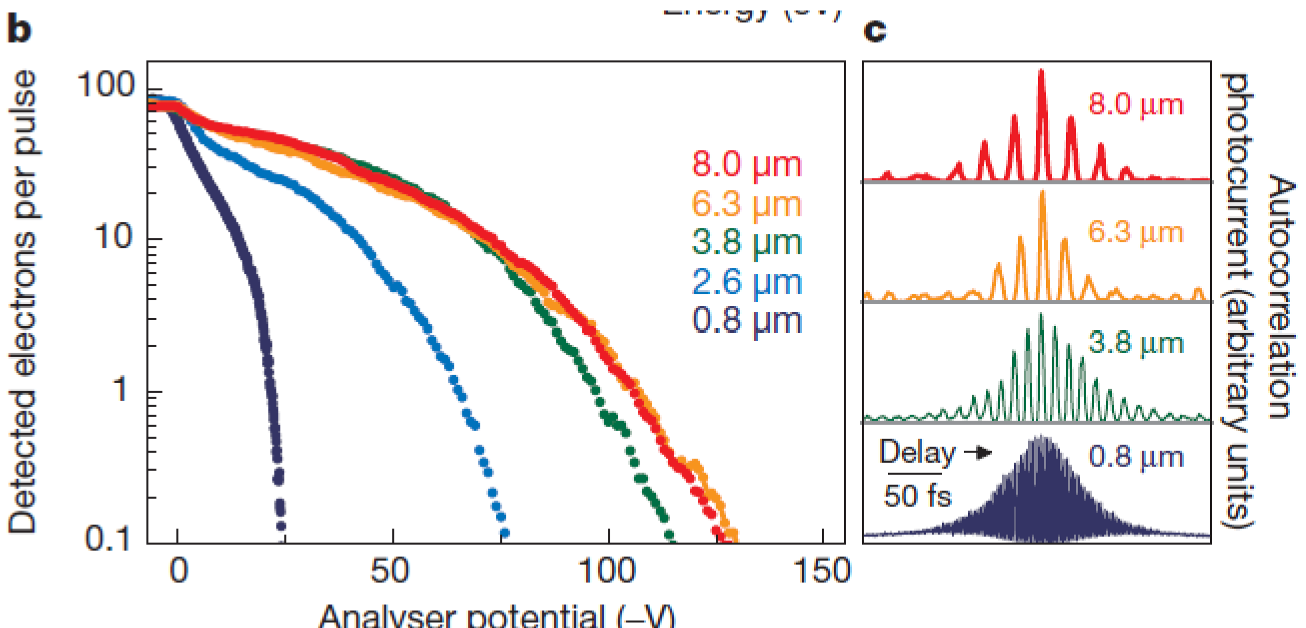




Several works on metallic tips (W, Au, HfC …)

- **On Gold tip** to study strong field phenomena
  - as a fonction of the laser wavelength (Herink Nature 2012) : They observe different regimes depending if the electrons escape the nanolocal field.
  - With angle resolved electron spectrometer (Park PRL 2012)

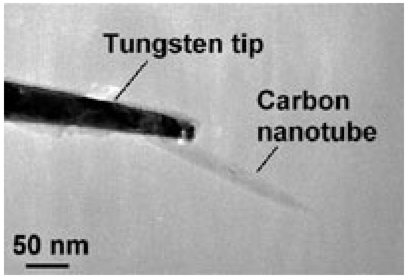




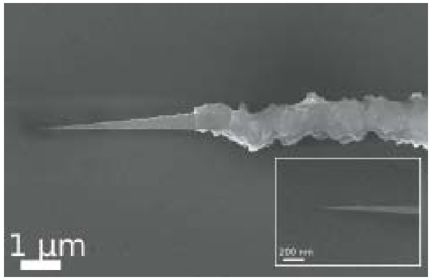
Carbon Cone motivations

Electron microscopy

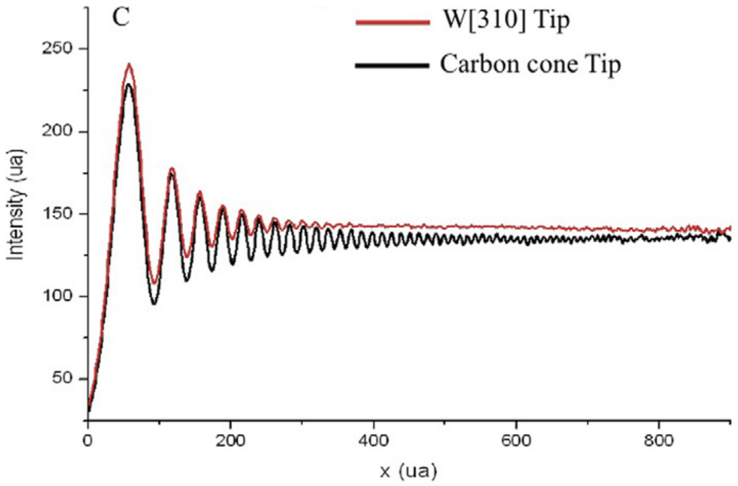
Carbon nanotubes (CNT)-based Carbon Cones as new candidates for Cold Field Emission Gun



De Jonge et al.
Nature 2002



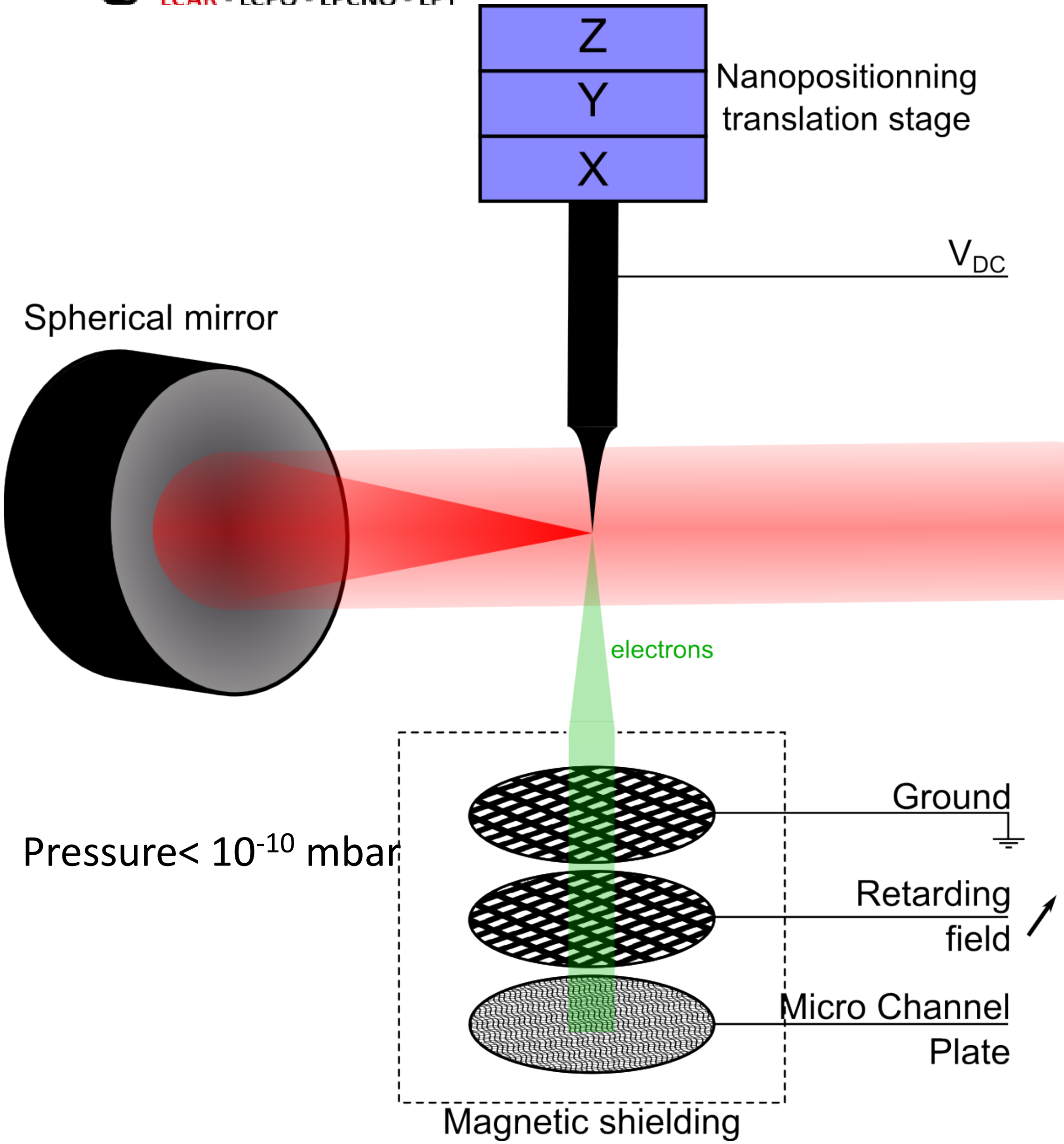
Houdellier et al. **(CEMES)**
Carbon 2012



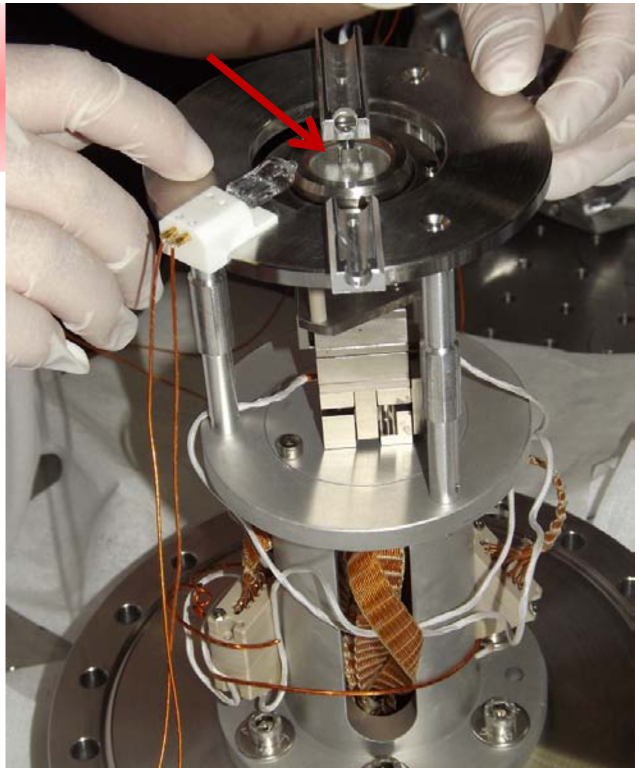
- **Main advantages:**
- High Brigtness and reliable source for electron microscopy (optimized geometrical shape)
- High robustness. Higher damage threshold
- High thermal conductivity
- Properties can be modified by adding dopants and filled species
- **Our Goal** : Exploring laser induced field emission with this new nano-object

Experimental set-up

- 20 fs laser pulses at 800 nm with 80 MHz repetition rate focused on a few µm
- Nanotip mounted on a 3D nanopositionning translation stage
- Retarded Field Spectrometer (resolution $dE/E \sim 10^{-3}$)

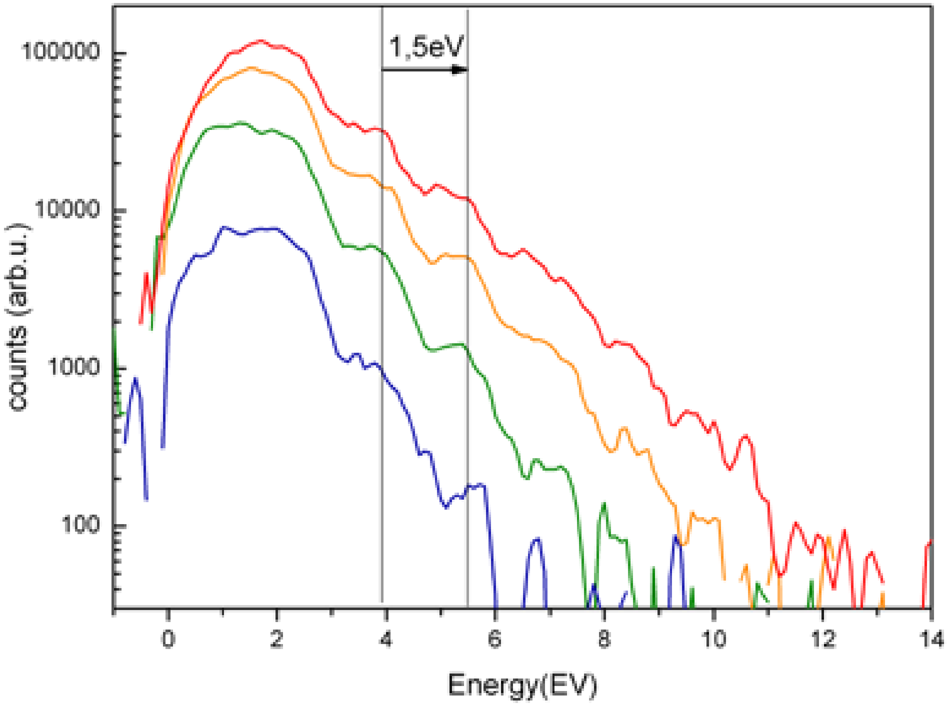


Pressure< 10^{-10} mbar



Tests performed on Tungsten tip

Experimental photoelectron spectra for a W tip



DC field = 40 V **(~0.05GV/m)**

Laser Power between 30 and 60 mW
Focus size= 4 µm
Laser Field**~ 2 GV/m**

Tip radius~ **120 nm** (Can be determined by Fowler-Nordheim theory)

- Observation of Above Threshold Photoemission similar to Hommelhoff's results (see Review article NJP 2012)

Preliminary Results

-First observation of laser-induced emission from a carbon cone.

-Very efficient source : our detection set-up saturates at 50mW laser power (Vtip= 30V)

-Highly non linear process

-Highly sensitive to the polarization of the laser

Thanks to

- B. Chalopin (Ass. Prof), M. Bionta (phD), P. Kluepfel (post-doc), A. Tajalli(phD), D. McCabe(Post-doc)

- **Electron Detection (LCAR) :** P. Moretto-Capelle, J-P Champeaux
- **CNT synthesis (CEMES):** A. Masseboeuf, M. Monthioux

- **Oxford** : D. Austin, B. Smith, I. Walmsley
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