Elettra Sincrotrone Trieste

# Chemical and magnetic imaging with x-ray photoemission electron microscopy (XPEEM)

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# Why do we need photoelectron microscopy?

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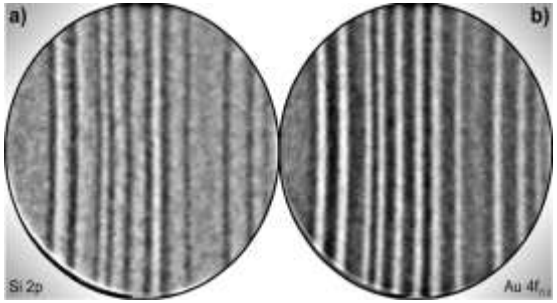
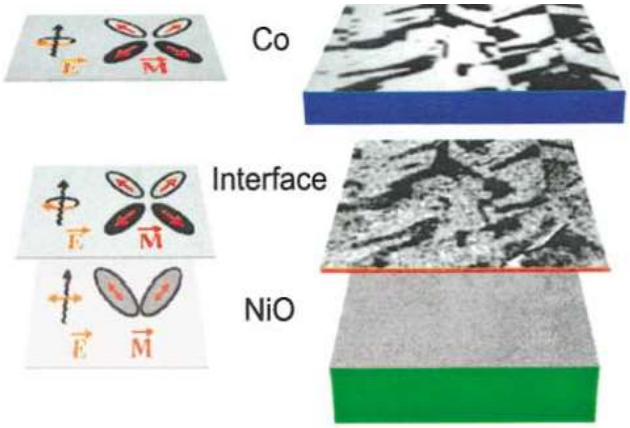
- To combine SPECTROSCOPY and MICROSCOPY to characterise the structural, chemical and magnetic properties of surfaces, interfaces and thin films
- Applications in diverse fields such as surface science, catalysis, material science, magnetism but also geology, soil sciences, biology and medicine.

Surface Science



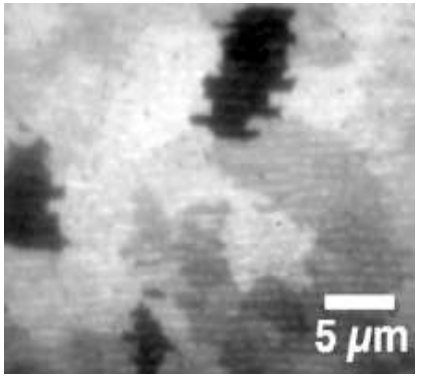

DOI: 10.1103/PhysRevLett.86.5088

Magnetism




DOI: 10.1103/PhysRevLett.87.247201

Biology




PRL **98,** 268102 (2007)

# Outline

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- Synchrotron radiation and x-ray spectro-microscopy: basics
- Cathode lens microscopy: methods
- Applications
  - Chemical imaging of micro- structured materials
  - Graphene research.
  - Biology
  - Magnetism
  - Time-resolved XPEEM

# Why does PEEM need synchrotron radiation?

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- High intensity of SR makes measurements faster
- Tuneability – very broad and continuous spectral range from IR to hard X-Rays
- Narrow angular collimation
- Coherence!
- High degree of polarization
- Pulsed time structure of SR – This adds time resolution to photoelectron spectroscopy!
- Quantitative control on SR parameters allows spectroscopy:
    - Absorption Spectroscopy (XAS and variants)
    - Photoemission Spectroscopies (XPS, UPS, ARPES, ARUPS)

$$J = f(h\nu, \varepsilon, \Theta, \Phi; E^{e}_{kin}, \sigma, \theta_e, \varphi_e)$$

# Cathode lens microscopy methods

PEEM, LEEM, SPELEEM, AC-PEEM/LEEM

# PEEM basics

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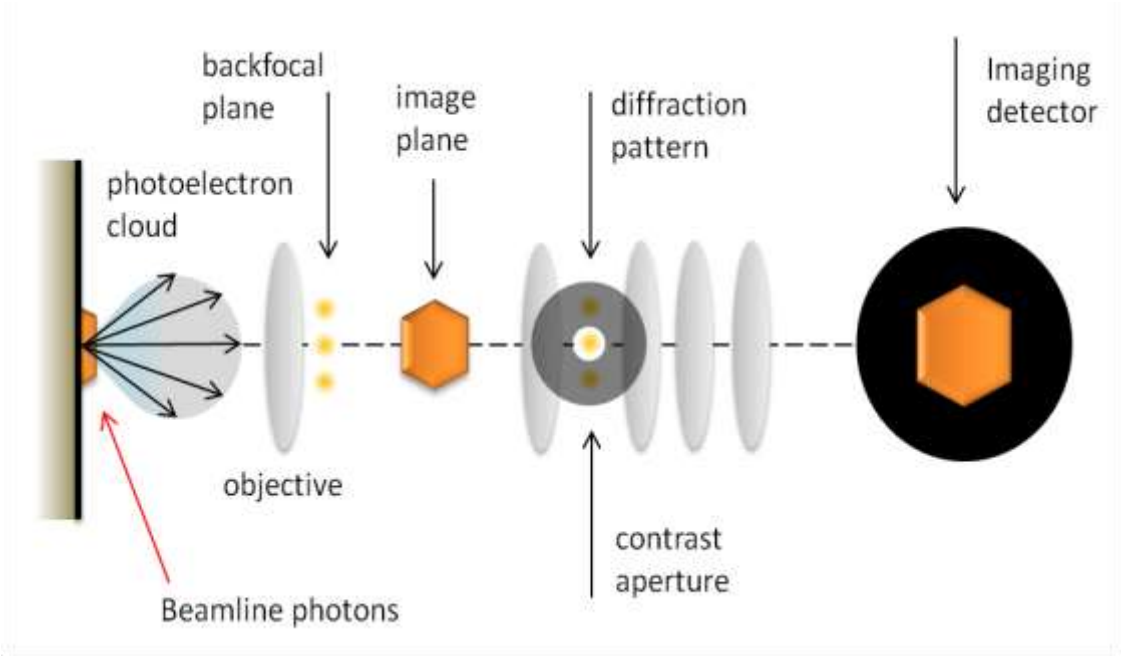


- Direct imaging, parallel detection
- Lateral resolution determined by electron optics: with AC, few nm possible
- Elemental sensitivity (XAS)
- Spectroscopic ability (energy filter)
- $P_{max} < 5 \cdot 10^{-5}$ mbar

PEEM is a full-field technique. The microscope images a restricted portion of the specimen area illuminated by x-ray beam. Photoemitted electrons are collected at the same time by the optics setup, which produces a magnified image of the surface. The key element of the microscope is the objective lens, also known as cathode or immersion lens, of which the sample is part

# Cathode lens operation principle

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1. In emission microscopy $\theta$ (emission angle) is large. Electron lenses can accept only small $\theta$ because of large chromatic and spherical aberrations

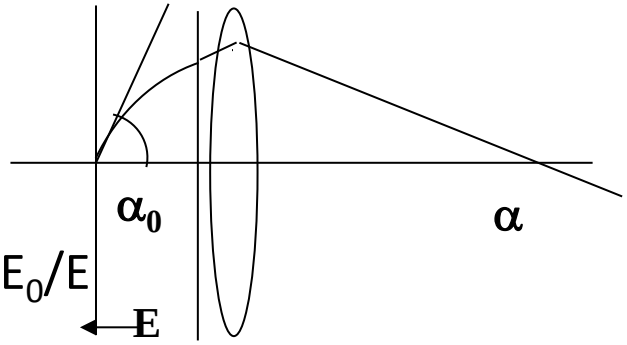
2. Solution of problem: accelerate electrons to high energy before lens → Immersion objective lens or cathode lens

$n \sin\theta = \text{const}$

$n \sim \sqrt{E}$

$\theta \rightarrow \alpha$

$\sin\alpha / \sin\alpha_0 = \sqrt{E_0/E}$

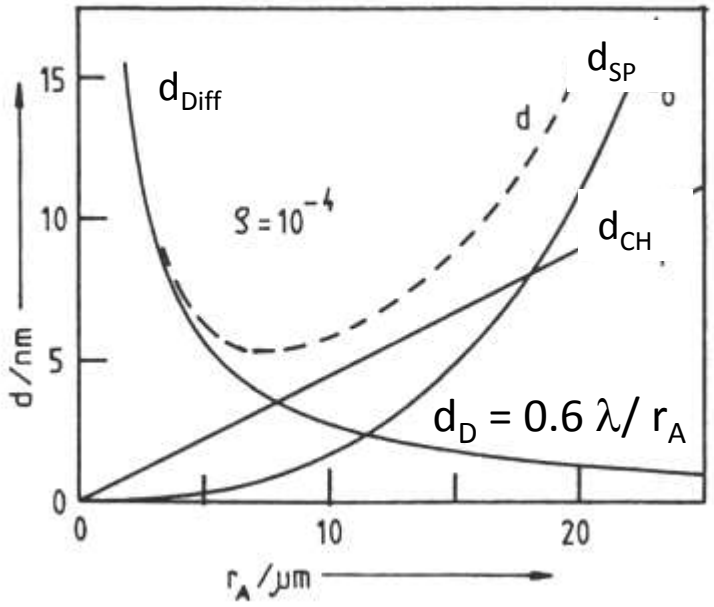



Example for E = 20000 eV:

| $E_0$ | 2 eV | 200 eV |
|---|---|---|
| $\alpha$ for $\alpha_0 = 45^o$ | $0.4^o$ | $4.5^o$ |

3. The aberrations of the objective lens and the contrast aperture size determine the lateral resolution

$$d = \sqrt{d_{SP}^2 + d_{CH}^2 + d_D^2}$$



# The different types of PEEM measurements

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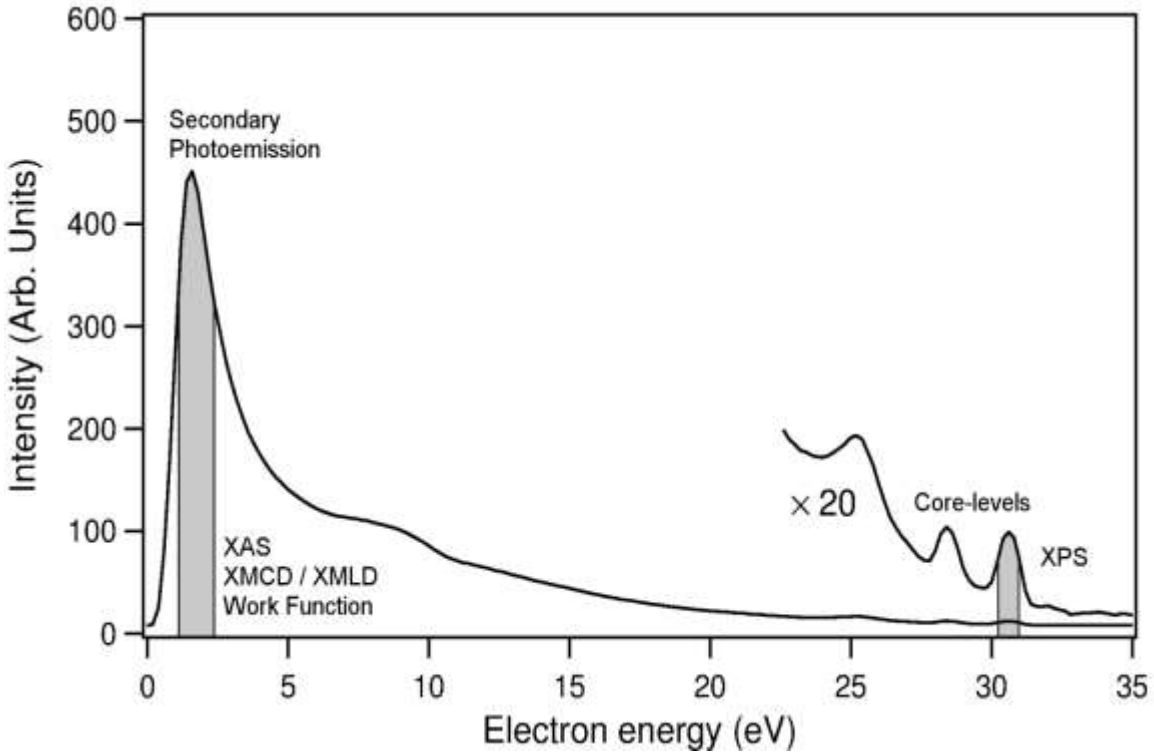
| PEEM | Probe | Measurement |
|---|---|---|
| • threshold microscopy | Hg lamp | photoelectrons |
| • Laterally resolved XPS, micro-spectroscopy | X-ray | core levels or VB ph.el. |
| • Laterally resolved UPS, microprobe ARUPS /ARPES | X-rays, He lamp | VB photoelectrons |
| • Auger Spectroscopy | X-ray, or electrons | secondary electrons |
| • XAS-PEEM (XMC/LD-PEEM) | X rays | secondary electrons |




Require energy filter

# Simple PEEM instruments

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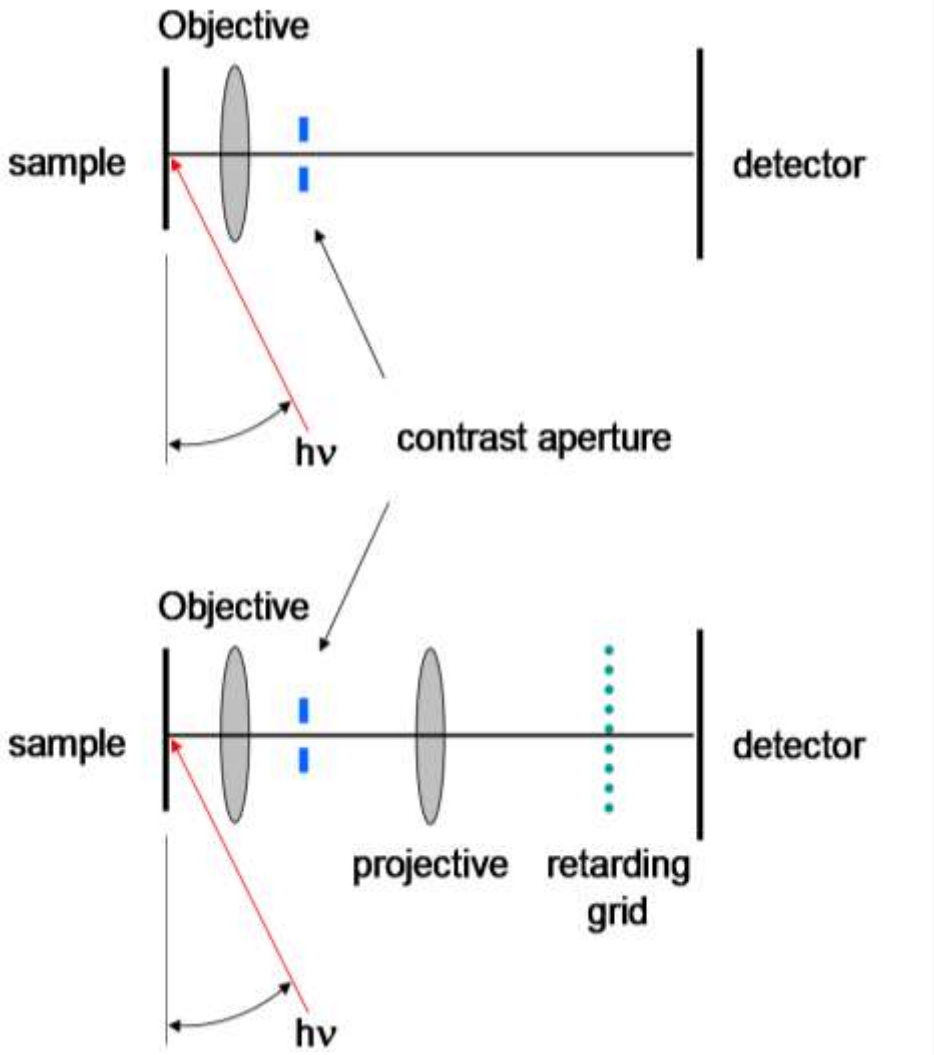


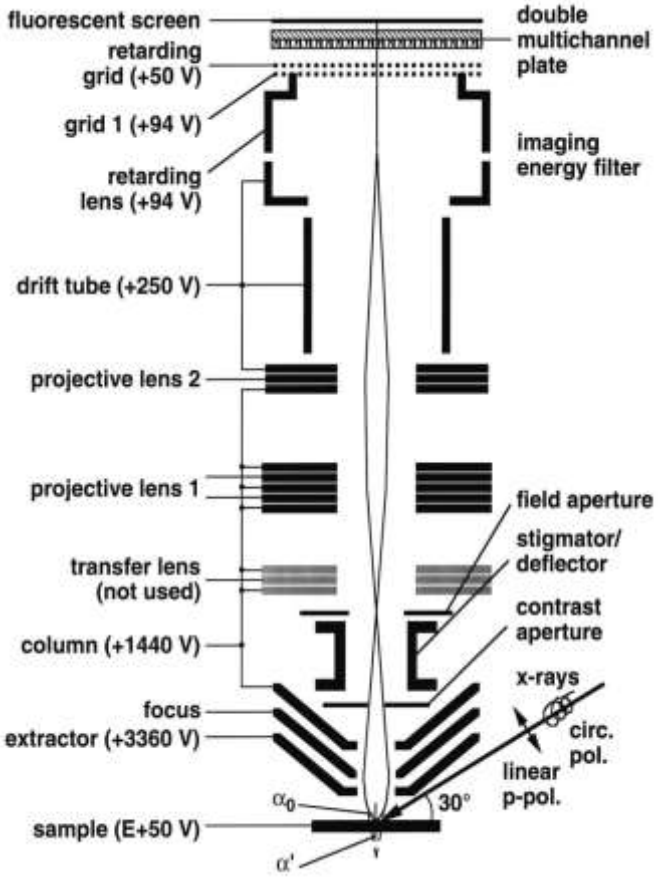

# PEEM instrments with energy filter: NanoESCA

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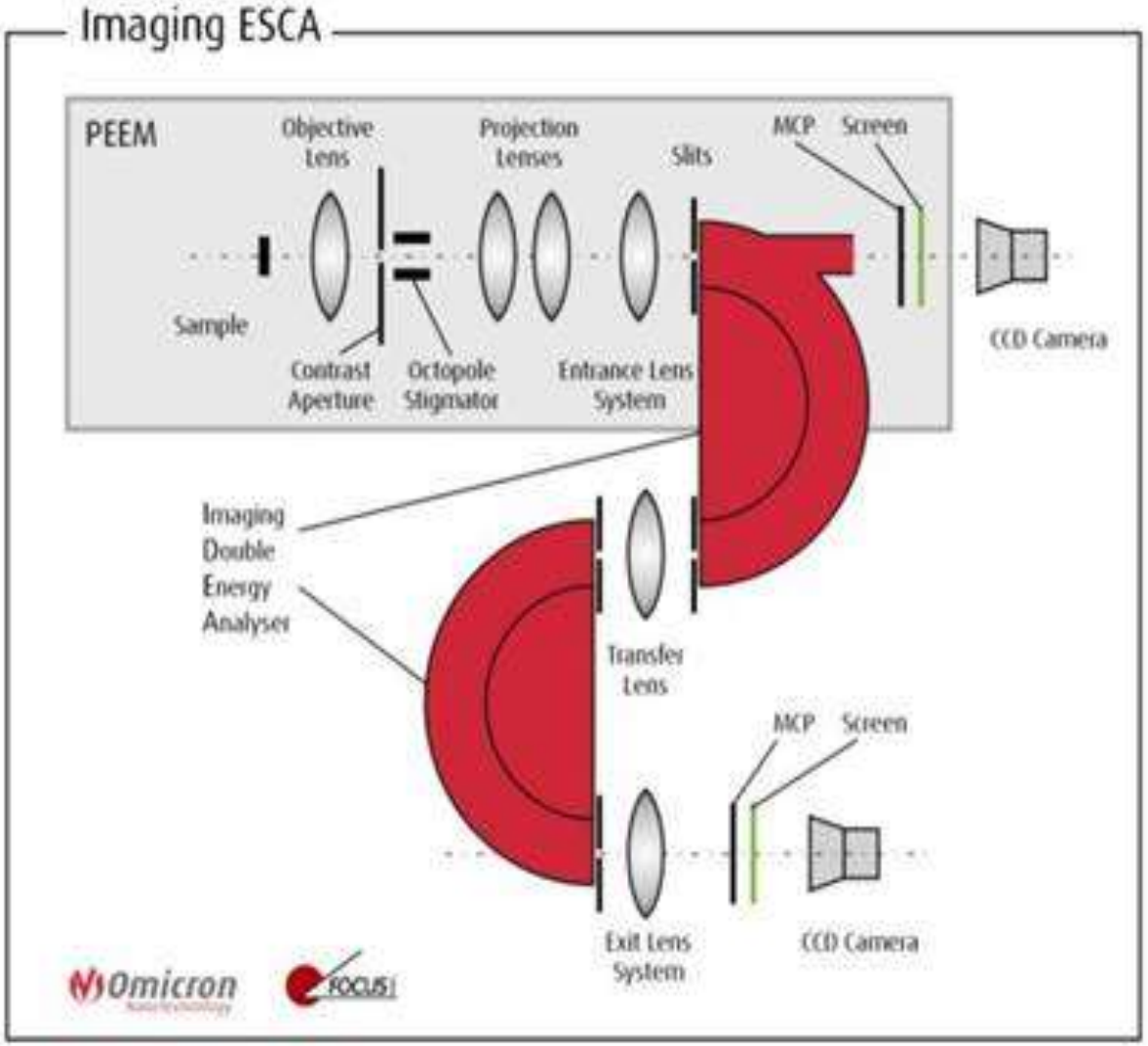

# Image contrast in LEEM

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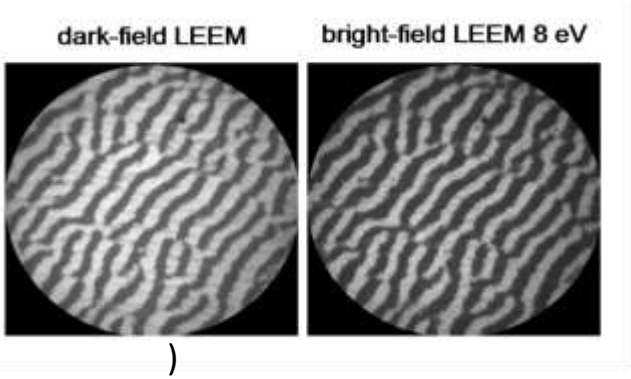
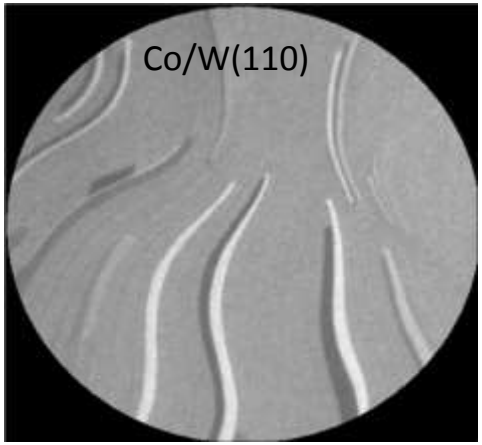
Different contrast mechanisms are available for strucutre characterization

## SURFACE STRUCTURE

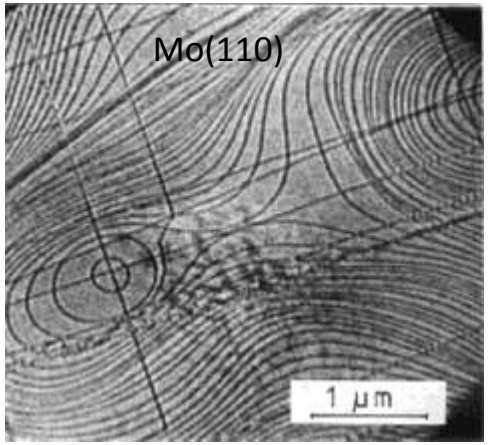



)

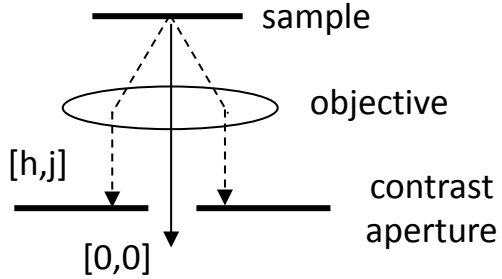
## FILM THICKNESS



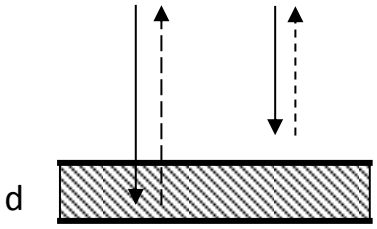

## STEP MORPHOLOGY



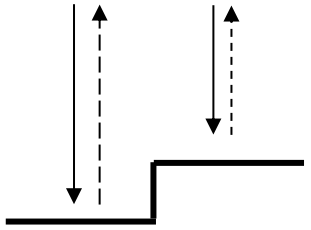

## diffraction contrast




## quantum size contrast




## geometric phase contrast



# SPELEEM = LEEM + PEEM

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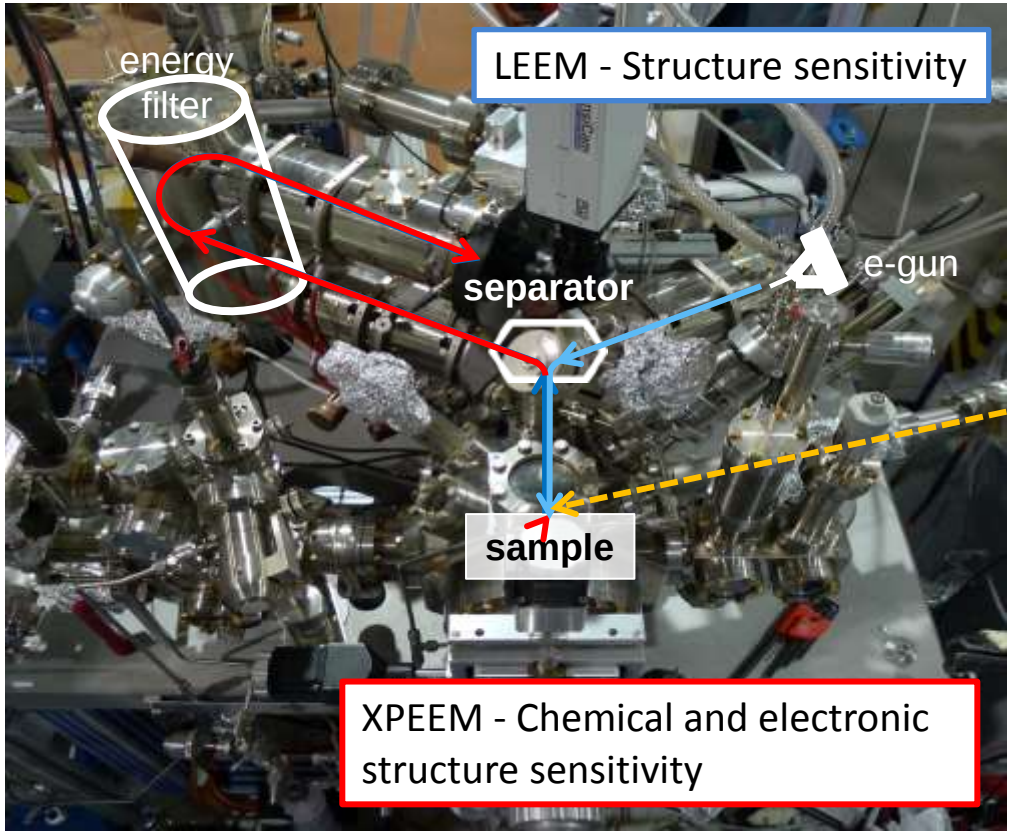
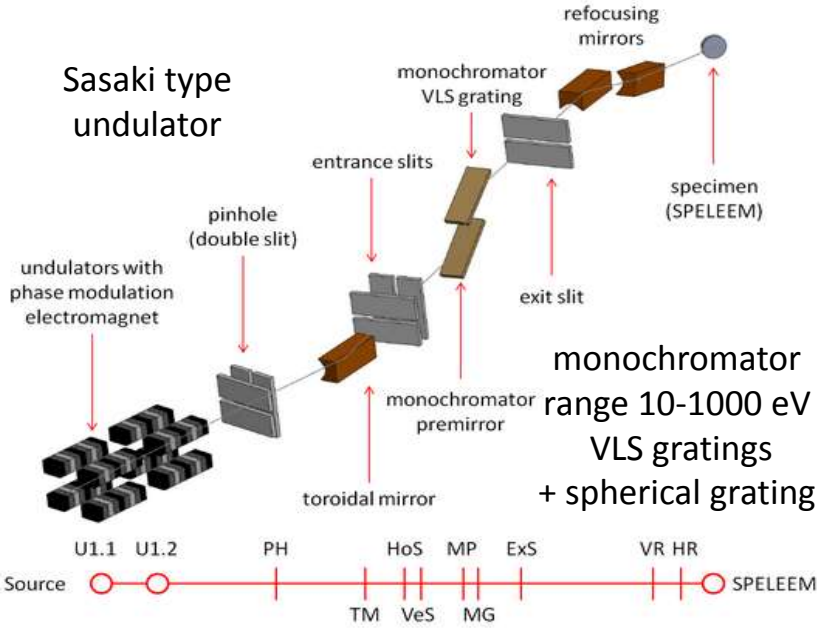



## The Nanospectroscopy beamline@Elettra

Flux on the sample: $10^{13}$ph/sec (microspot)
intermediate energy resolution.




**Applications**:
characterization of materials at microscopic level, magnetic imaging of micro-structures
Imaging of dynamical processes


A. Locatelli, L. Aballe, T.O. Menteş, M. Kiskinova, E. Bauer, Surf. Interface Anal. 38, 1554-1557 (2006)

T. O. Menteş, G. Zamborlini, A. Sala, A. Locatelli; Beilstein J. Nanotechnol. 5, 1873–1886 (2014)

# SPELEEM many methods analysis

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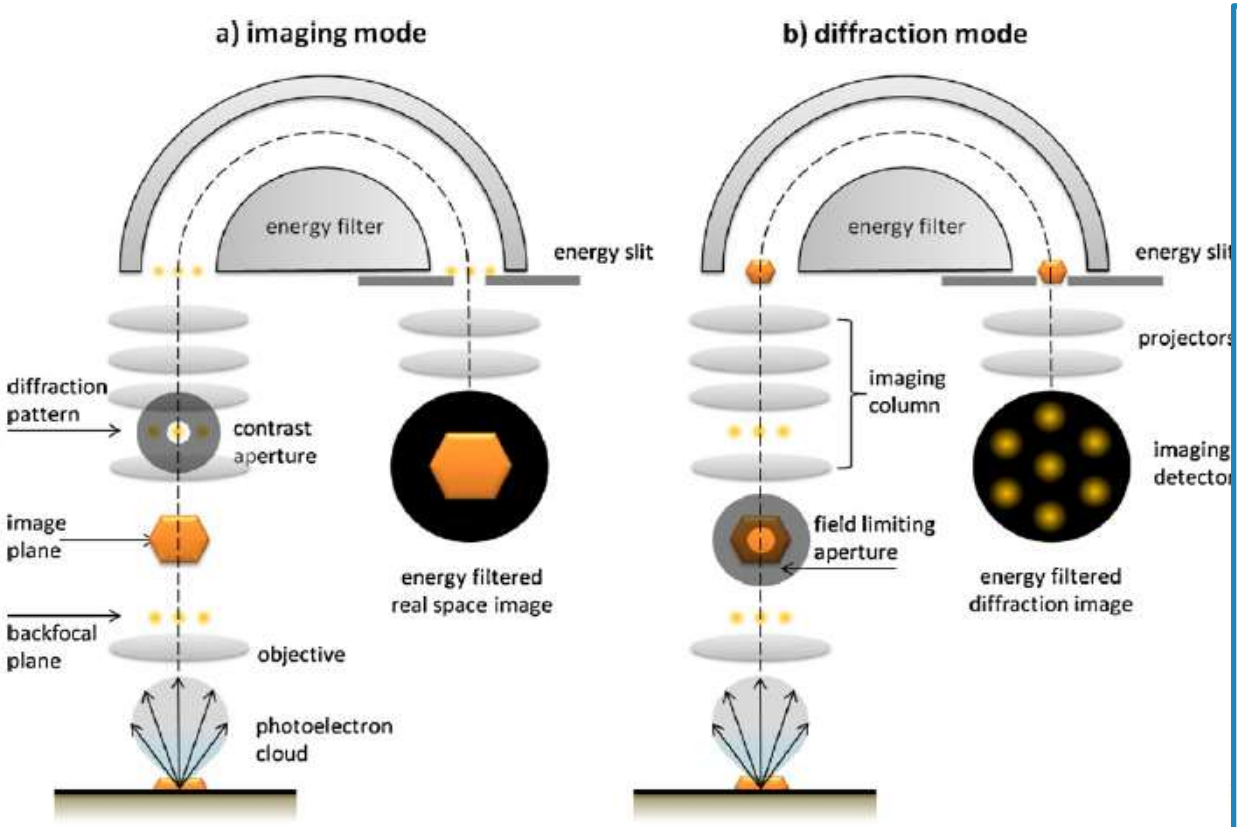
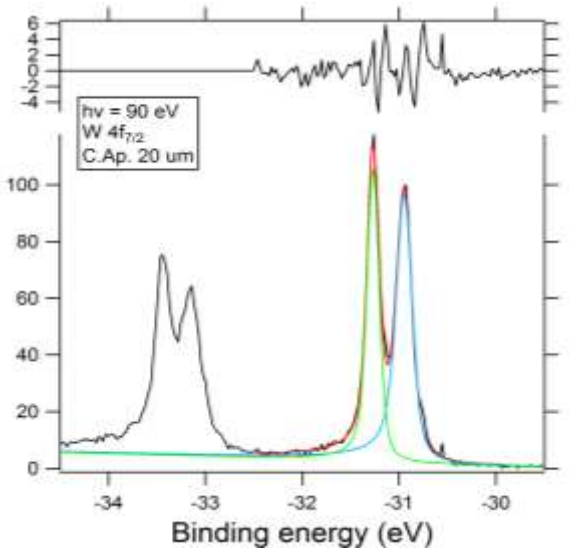
Spectroscopic imaging
XAS-PEEM / XPEEM / LEEM

microprobe-diffraction
ARPES / LEED

microprobe-spectroscopy
XPS




T. O. Menteş et al.
Beilstein J. Nanotechnol. 5, 1873–1886 (2014).

*energy resolution*
**µXPS** : 0.11 eV

*spatial resolution*
**LEEM** : 10 nm
**XPEEM** : 25 nm

*energy resolution*
**XPEEM** : 0.3 eV

*Limited: to 2 microns in dia.*
*angular resolution*
**transfer width**: 0.01 $Å^{-1}$

# SPELEEM summary

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**Performance**: lateral resolution in imaging: 10nm (LEEM)
30 nm (XPEEM)
energy resolution: 0.3 eV (0.1 eV muXPS)

**Key feature**: multi-method instrument to the study of surfaces and interfaces offering *imaging* and *diffraction* techniques.

**Probe**: *low energy e-* (0-500 eV) ⟷ structure sensitivity
*soft X-rays* (50-1000 eV) ⟷ chemical state, magnetic state, electronic struct.

**Applications**: *characterization* of materials at microscopic level
*magnetic imaging* of microstrucutres
*dynamical processes*

# Correction of spherical and chromatic aberrations

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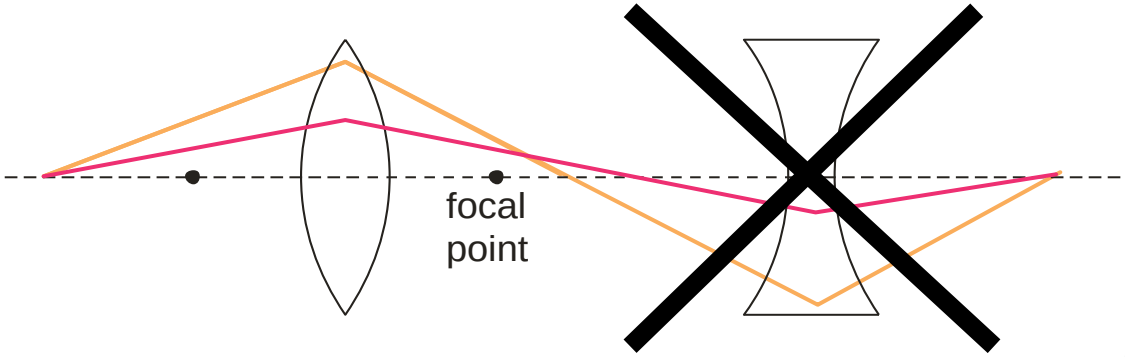
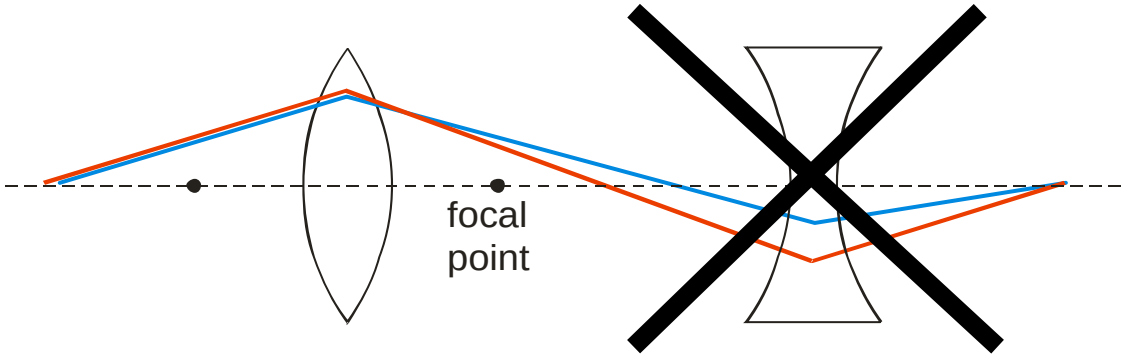
## Electron optics

Round **convex** lenses

Round **concave** lenses

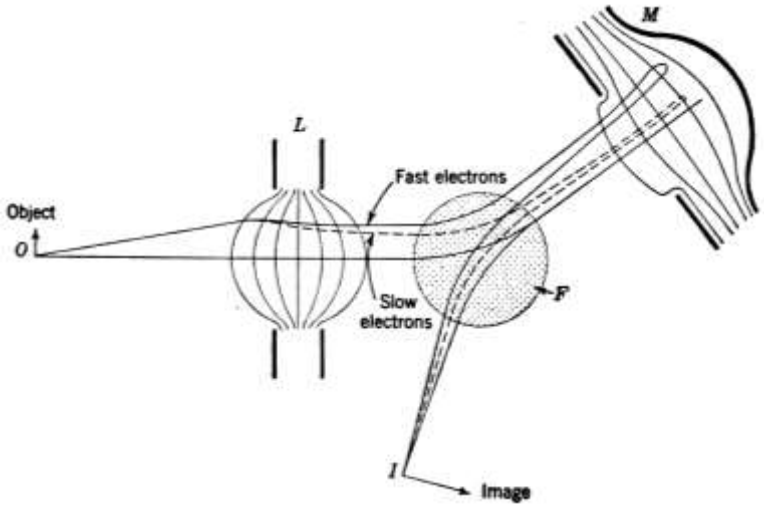



Spherical aberration




Chromatic aberration

## Electron Mirror




V.K. Zworykin et al, Electron Optics and the Electron Microscope, John Wiley, New York 1945

# The SMART AC microscope: calculation

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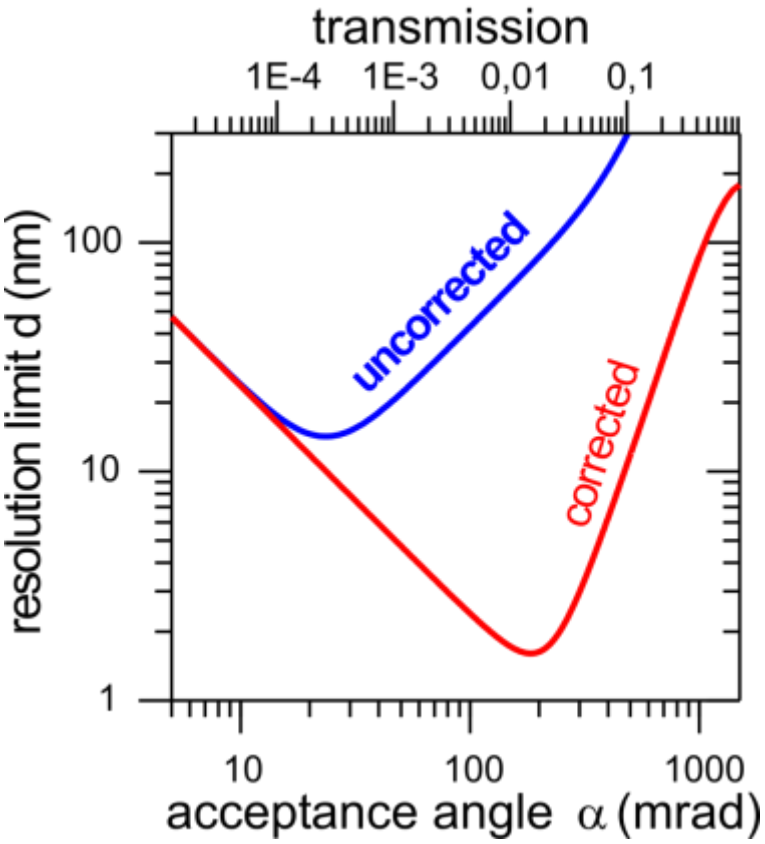
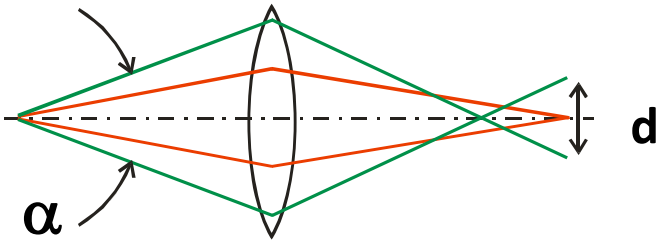
Simultaneous improvement in
Transmission and Resolution!!!



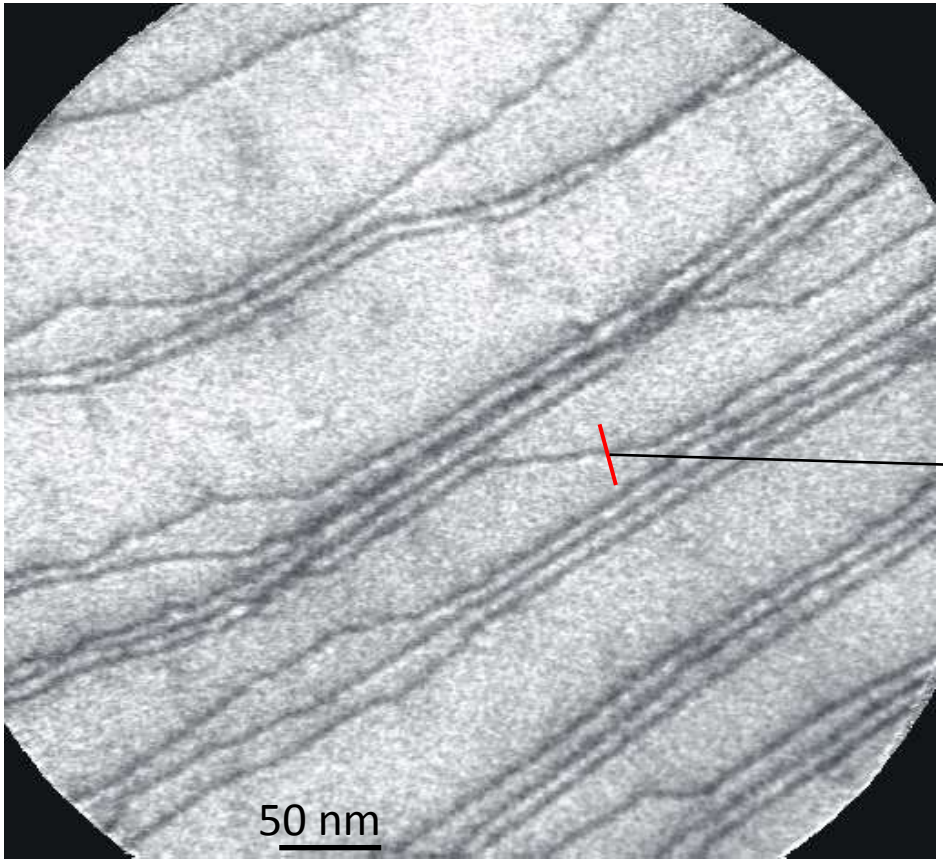



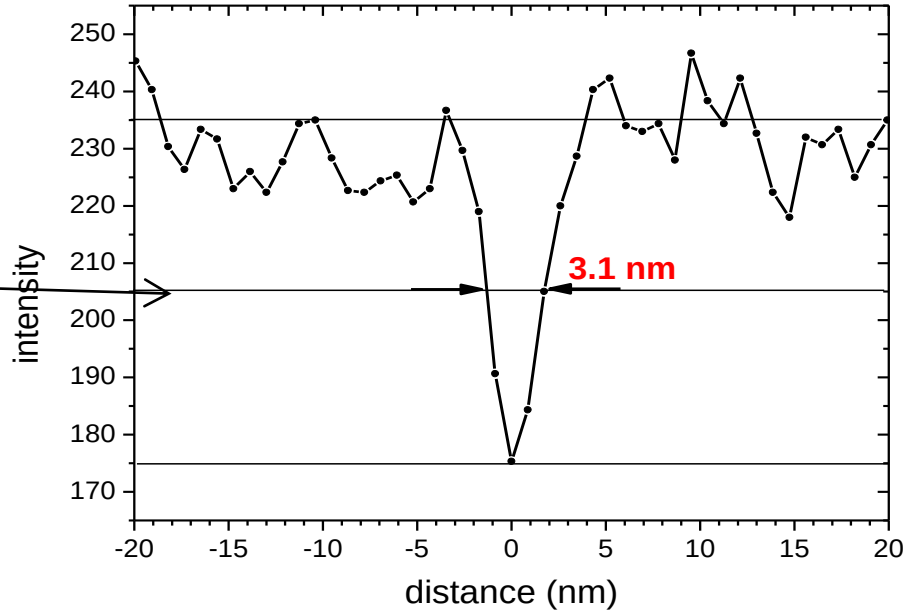

| Resolution limit | without correction | with correction |
|---|---|---|
| Spherical | $\alpha^3 + \ldots$ | $\alpha^5$ |
| Chromatic | $\Delta E\ \alpha + \ldots$ | $\Delta E\ \alpha^2 + \Delta E^2\ \alpha$ |
| Diffraction | $1/\alpha$ | $1/\alpha$ |

D. Preikszas, H. Rose, J. Electr. Micr. 1 (1997) 1
Th. Schmidt, D. Preikszas, H. Rose et al., Surf.Rev.Lett 9 (2002) 223

# First results of the SMART microscope @BESSY

**Atomic steps on Au(111)**,
LEEM 16 eV, FoV = 444 nm x 444 nm
(18.09.06)




Courtesy of Th. Schmidt et al.; 5th Int. Conf. LEEM/PEEM, Himeji, 15.-19. Oct. 2006

# Lateral resolution limitations: space charge

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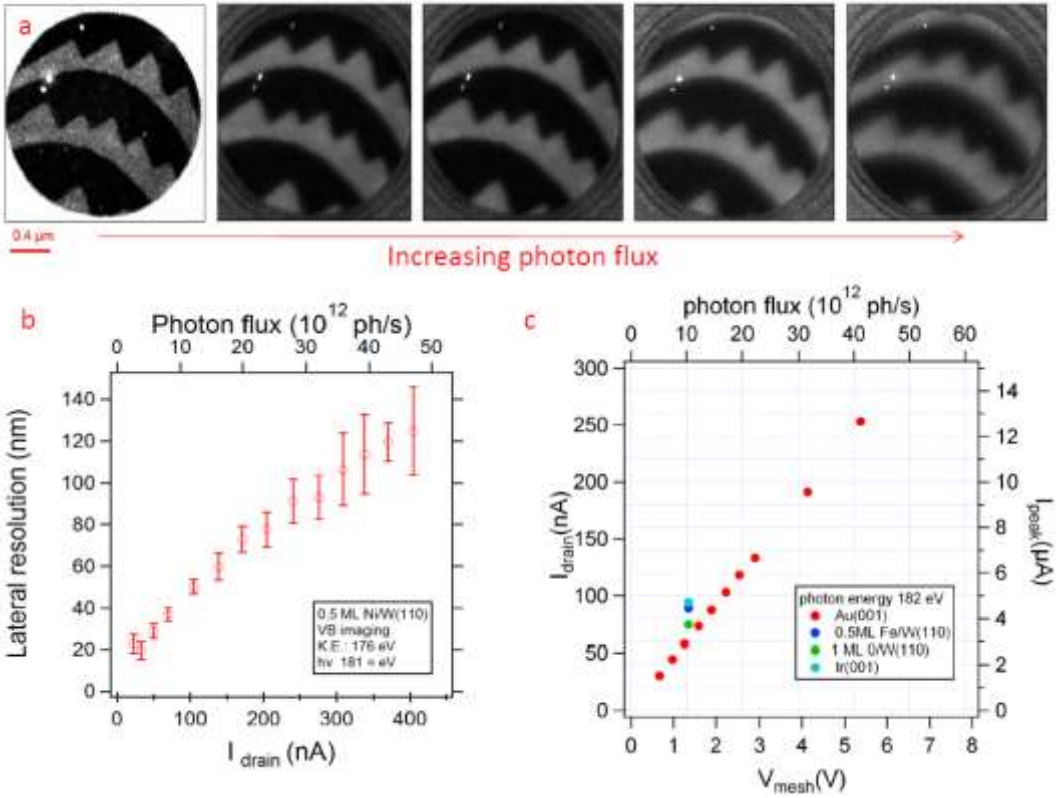
Ni/W(100) hv = 181 eV



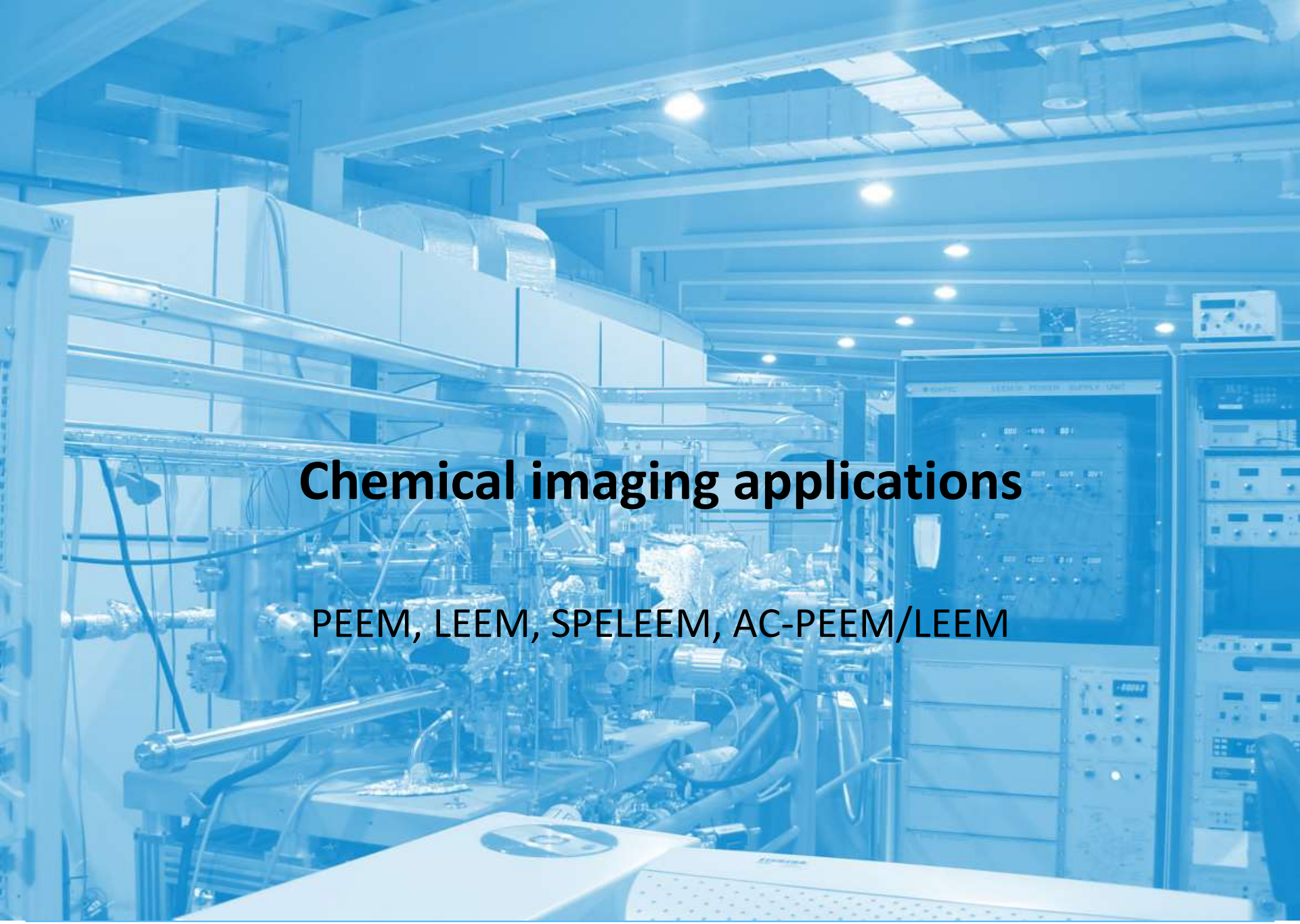

**photocurrent estimate for SPELEEM@Elettra; Au/W(110)**

- 440 bunches
  rev. frequency: 1.157 MHz
  bunch length: 42 ps (2GeV)
- 1 $10^{13}$ ph./s on sample =
  = 20000 ph./bunch
- Total photoionization yield: about 2% photons result in a photoemission event
- $I_{peak} \approx 400\ e^-/\ 42$ ps
  ≈ 1.5µA vs 20 nA (LEEM)

13 pA/µm$^2$ versus 20 nA/µm$^2$

1. Image blur can be observed with SR but only under very high photon fluxes. Must Keep into account in beamline design. No space charge in LEEM
2. Both the lateral and energy resolution are strongly degraded by Boersch and Loeffler effects occurring in the first part of optical path.

Ultramicroscopy **111**, 1447 (2011).



# Chemical imaging applications

PEEM, LEEM, SPELEEM, AC-PEEM/LEEM

# Au/$TiO_2$(110): controlling growth by vacancies

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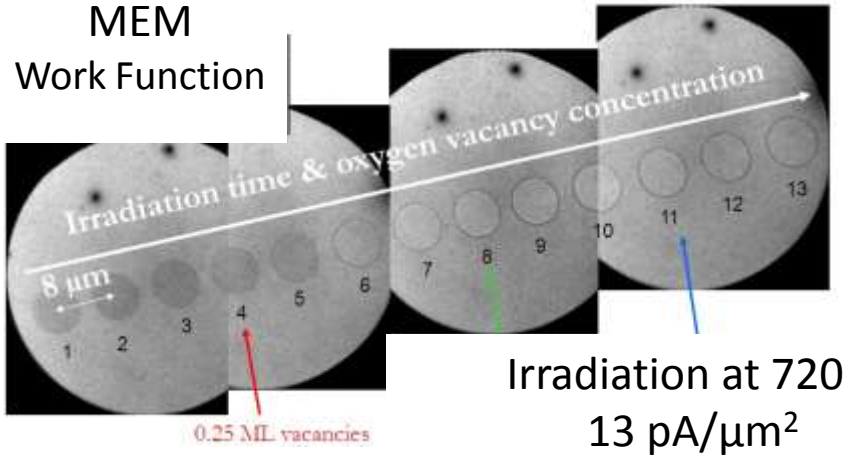
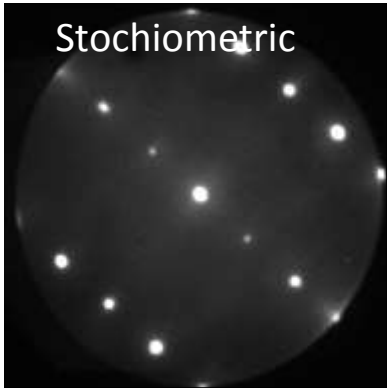
## Creation of ordered oxygen vacancies

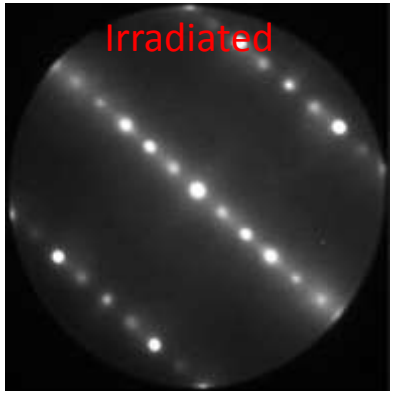
MEM
Work Function




Irradiation at 720 K
13 pA/µm²

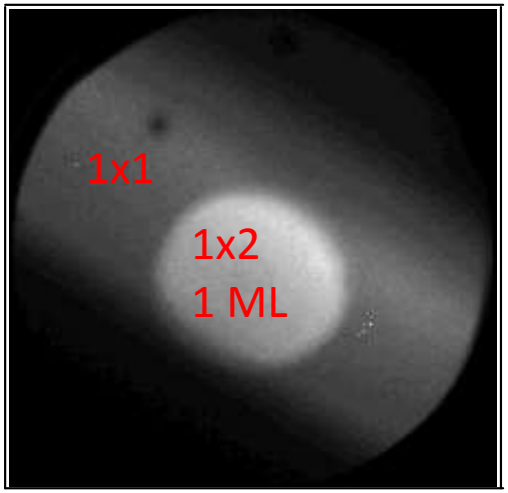



(1x1)



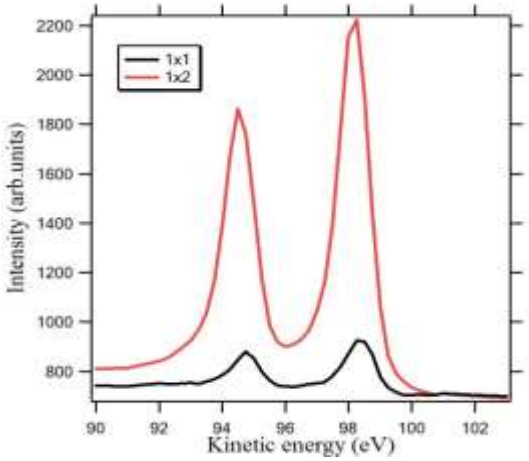

(1x2)

## Au growth on $TiO_2$(110)




XPEEM
@ Au 4f

µ-LE
struc




µ-XPS

# Surface Oxygen on Ag : *e-beam "Lithography"*

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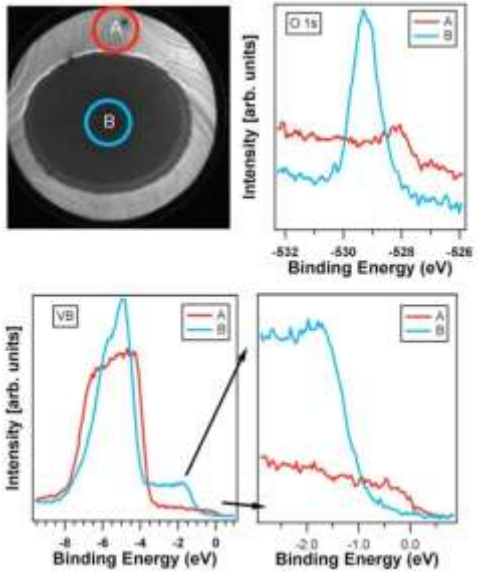
Full oxidation of Ag using $NO_2$ does not occur:

$$NO_2 \rightarrow NO_{ad} + O_{ad}$$

Instead: e-beam (60 eV) stimulated desorption of $NO_{ad}$ works at RT!

Low T: $NO_{ad}$ stays, prevents oxidation.

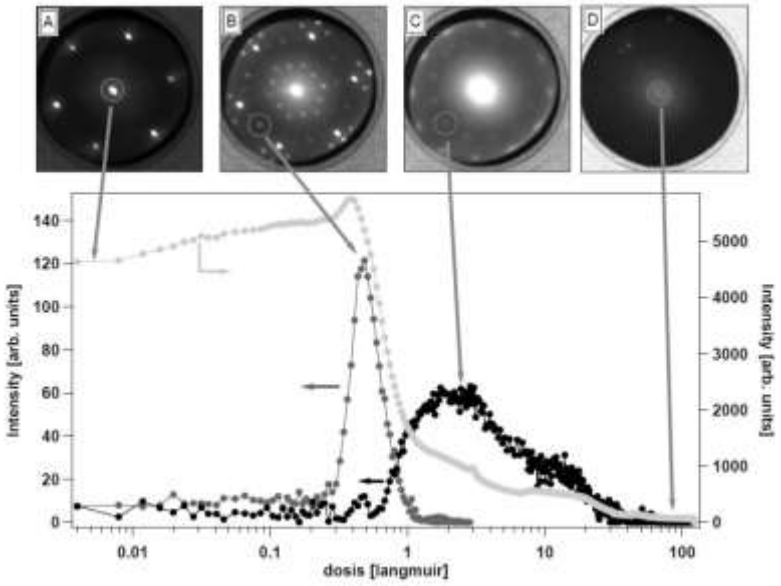
High T: $NO_{ad}$ desorbs, but $Ag_2O$ unstable.




A: metallic Ag
B: $Ag_2O$

S. Günther *et al.*, *App. Phys. Lett.* 93, 233117 (2008).

LEED reveals path towards $Ag_2O$ under e-beam




S. Günther *et al.*, *Chem. Phys. Chem.* 2010.

# Surface Oxygen on Ag : *photon-beam "Lithography"*

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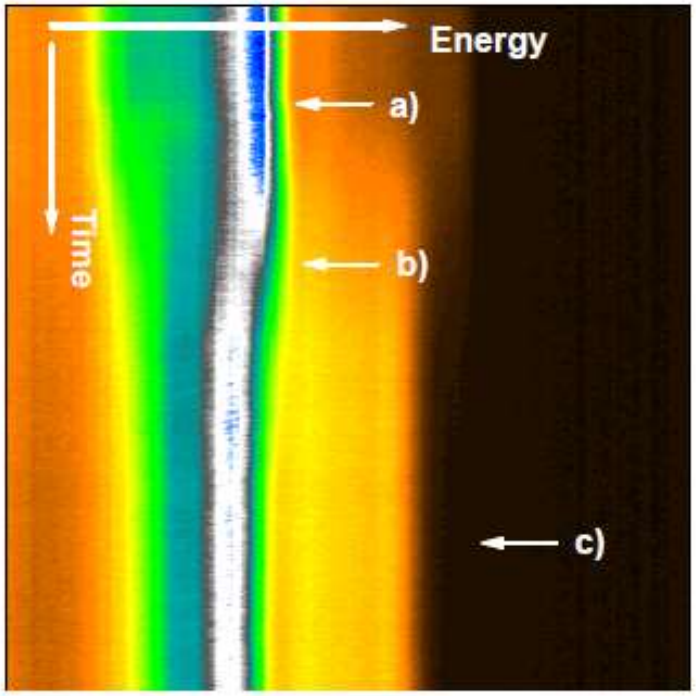
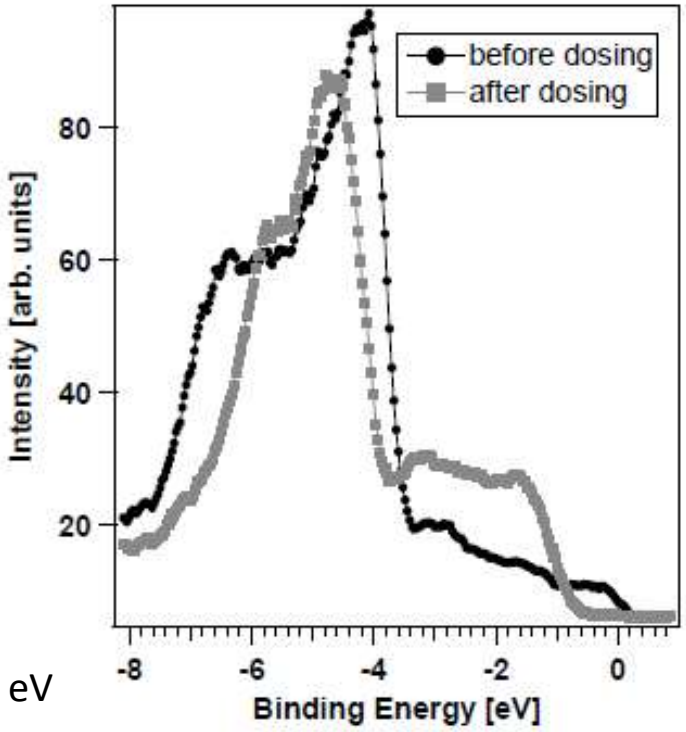
MEM 28 µm x 350 µm; after 130 L $NO_2$;

hv = 40 eV




-9 eV

4 eV




(a) Start of NO2 adsorption, *t = 0 s,*

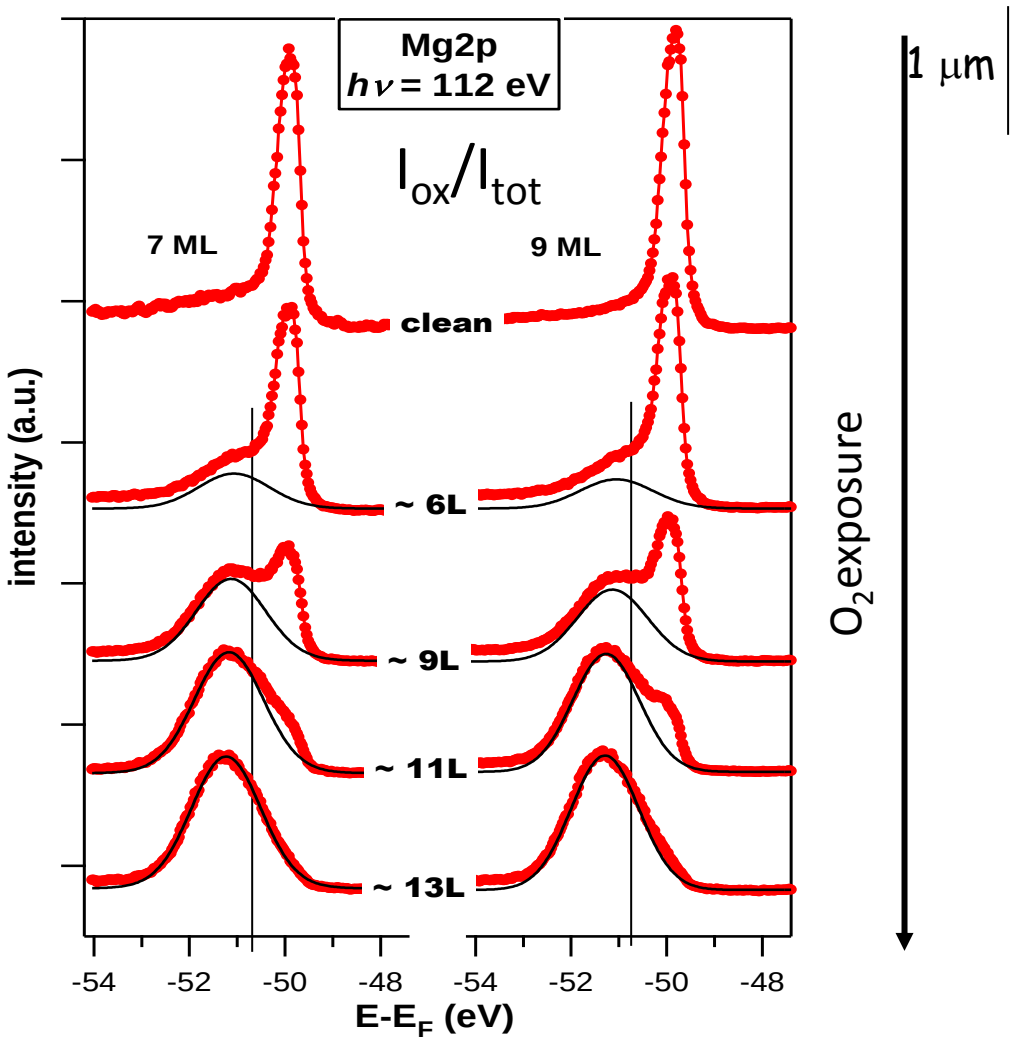
*(b) t = 210 s, p($NO_2$) =1.8×$10^{-7}$ mbar, 17 L $NO_2$,*

*(c) t = 540 s, p($NO_2$) =2.5×$10^{-7}$ mbar, 67 L $NO_2$.*

S. Günther *et al.*, *Chem. Phys. Chem.* 2010.

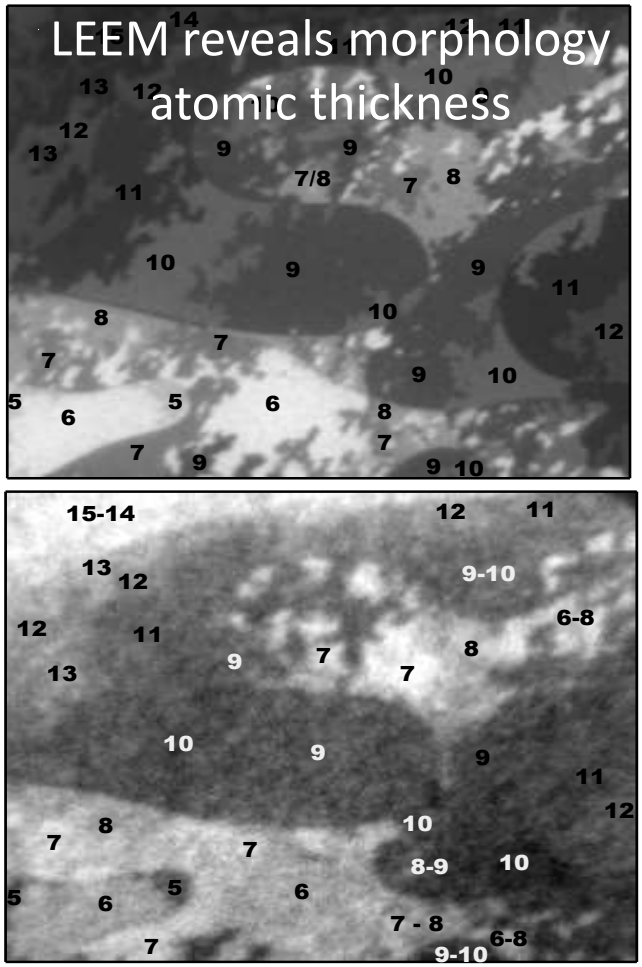
# Thickness dependent reactivity in Mg

Elettra Sincrotrone Trieste







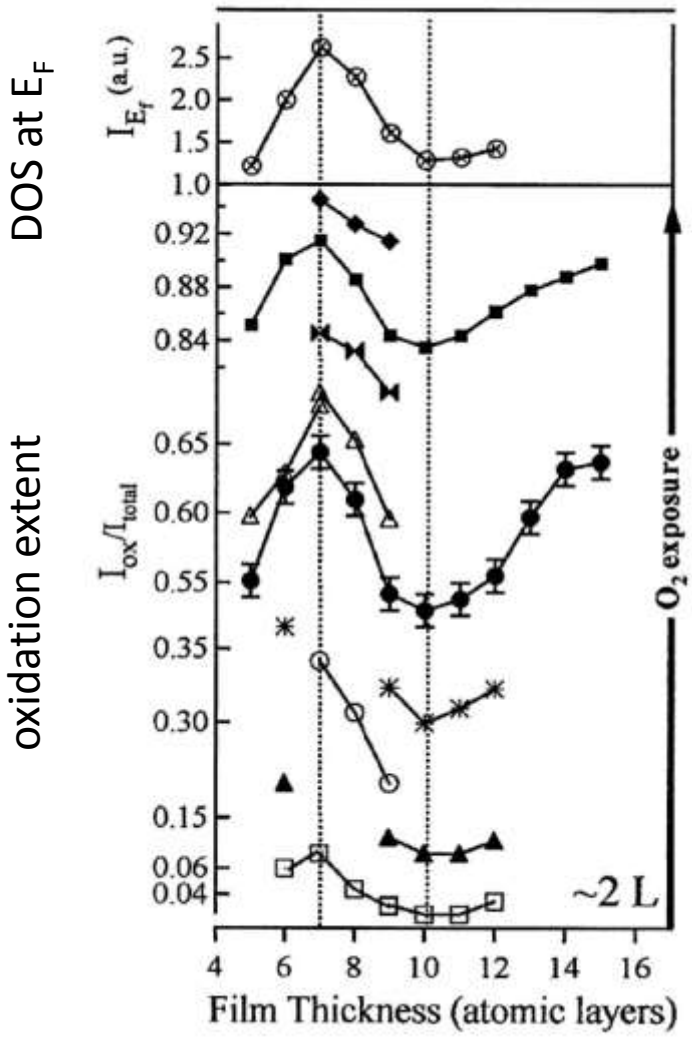



Oxide component reveals chemistry!

L. Aballe *et al.*, Phys. Rev. Lett. **93**, 196103 (2004)

# Oxidation of Mg film and QWR

Elettra Sincrotrone Trieste




FACTS

- ✓ Strong variations in the oxidation extent are correleted to thickness and to the density of states at $E_F$
- ✓ XPEEM is a powerful technique for correlating chemistry and electronic structure information

SIGNIFICANCE OF THE EXPERIMENTS

- ✓ Control on film thickness enables modifying the molecule-surface interaction
- ✓ Theoretical explanation: Decay length of QWS into vacuum is critical: it reproduces peak of reactivity in experimental data. See Binggeli and M. Altarelli, Phys.Rev.Lett. 96, 036805 (2005)

L. Aballe *et al.*, Phys. Rev. Lett. 93, 196103 (2004)

# Spatio-temporal patterns in surface chemical reactions

Elettra Sincrotrone Trieste

VOLUME 65, NUMBER 24 PHYSICAL REVIEW LETTERS 10 DECEMBER 1990

**Spatiotemporal Concentration Patterns in a Surface Reaction: Propagating and Standing Waves, Rotating Spirals, and Turbulence**

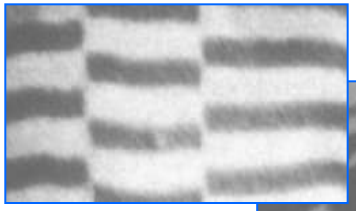
S. Jakubith, H. H. Rotermund, W. Engel, A. von Oertzen, and G. Ertl
*Fritz-Haber-Institut der Max-Planck-Gesellschaft, Faradayweg 4-6, D-1000 Berlin 33, Germany*
(Received 25 June 1990)

Belousov-Zabatinski reaction (solution of, acidified bromate, malonic acid, ceric salt)

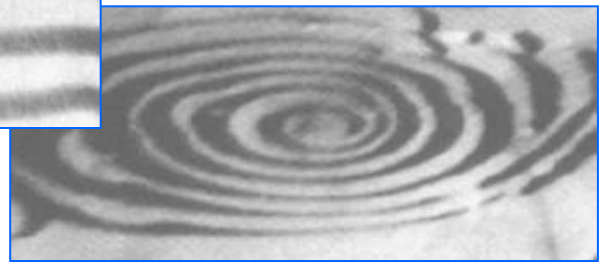
Pattern formation
in surface chemical reactions

oscillatory oxidation of carbon monoxide on a Pt(110) surface

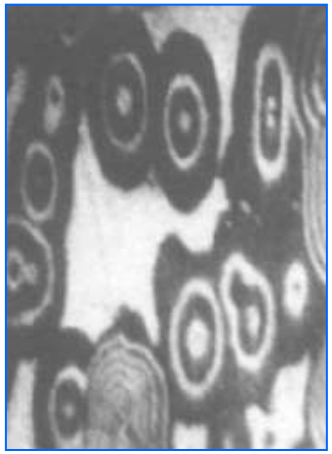
standing fronts



rotating spirals



target waves



Jakubith *et al.*, PRL 65, 3013 (1990)

See also: W. Engel, *et al.*, Ultramicroscopy **36**, 148–153 (1991).

# Reaction diffusion patterns: NO+$H_2$ /Rh(110)

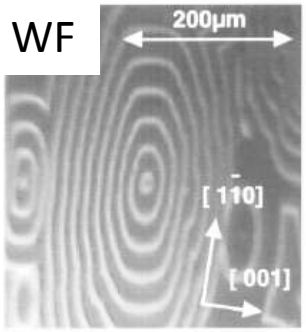
Elettra Sincrotrone Trieste

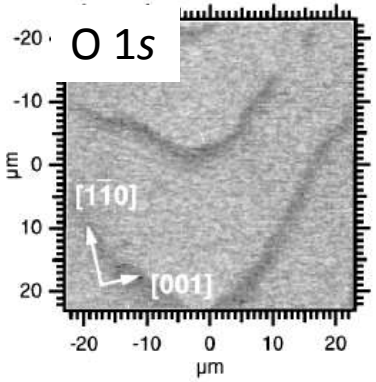
**First quantitative measurements of concentration profiles by SPEM**

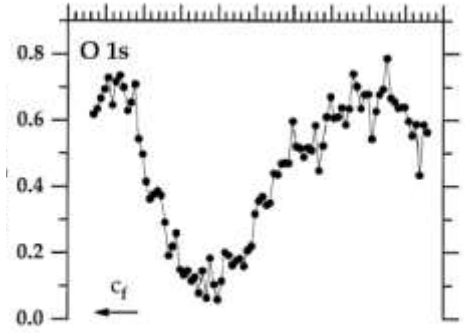
Schaak et al

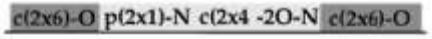
Phys. Rev. Lett. **83**, 1882 (1999)

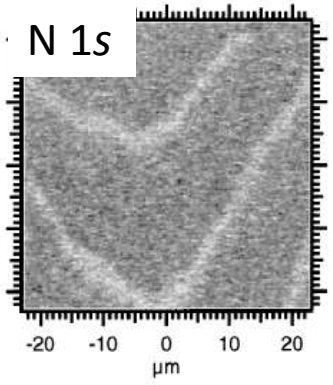
$$H_2 + 2^* \leftrightarrow 2H_{ad},$$
$$NO + * \leftrightarrow NO_{ad},$$
$$NO_{ad} + * \rightarrow N_{ad} + O_{ad},$$
$$2N_{ad} \rightarrow N_2 + 2^*,$$
$$O_{ad} + 2H_{ad} \rightarrow H_2O + 3^*,$$

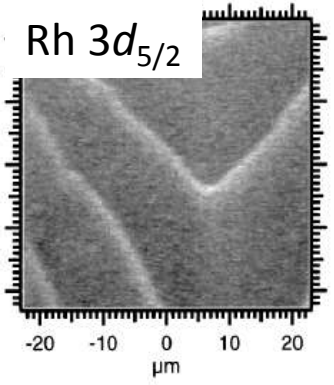


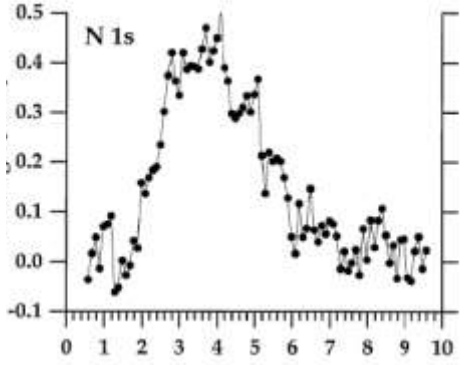



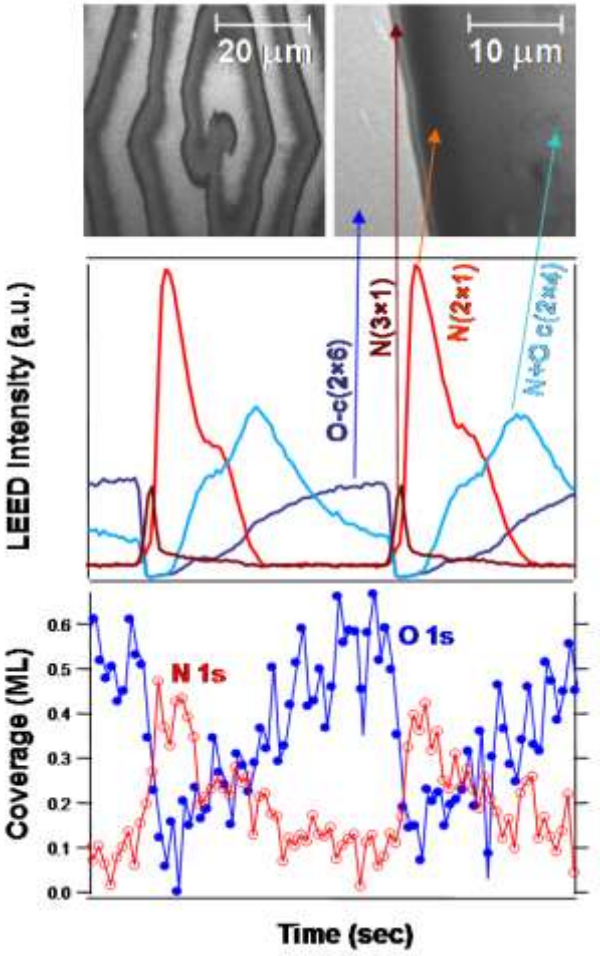




**LEEM, micro-LEED**

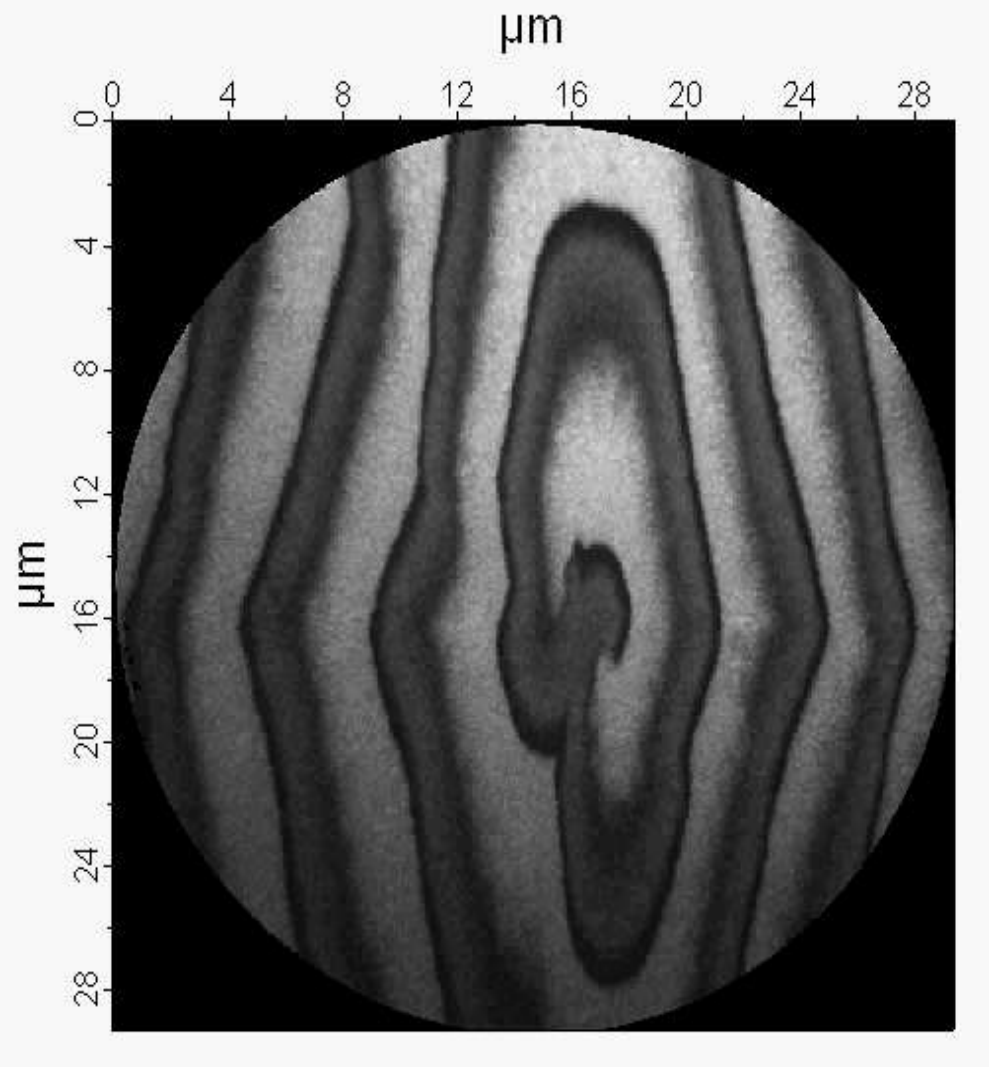
Th. Schmidt *et al.*,

Chem. Phys. Lett. 318, 549 (2000)



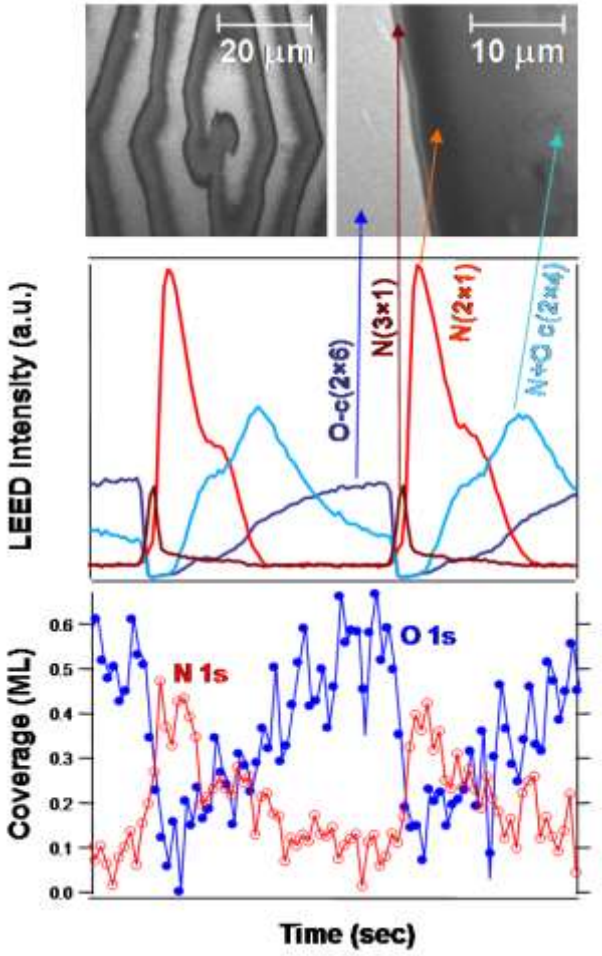
# Reaction diffusion patterns: NO+$H_2$ /Rh(110)

Elettra Sincrotrone Trieste




**LEEM, micro-LEED**

Th. Schmidt *et al.*,
Chem. Phys. Lett. 318, 549 (2000)

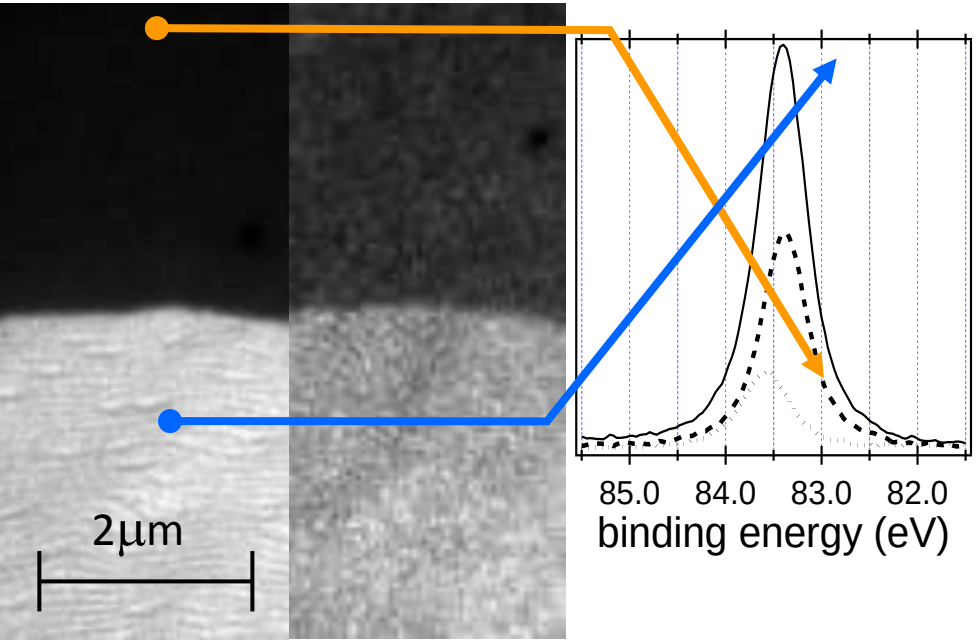


# Reactive phase-separation processes

Elettra Sincrotrone Trieste

H2+O2/Au/Rh(110)

Spectroscopic determination of reaction inducedredistribution




LEEM

XPEEM

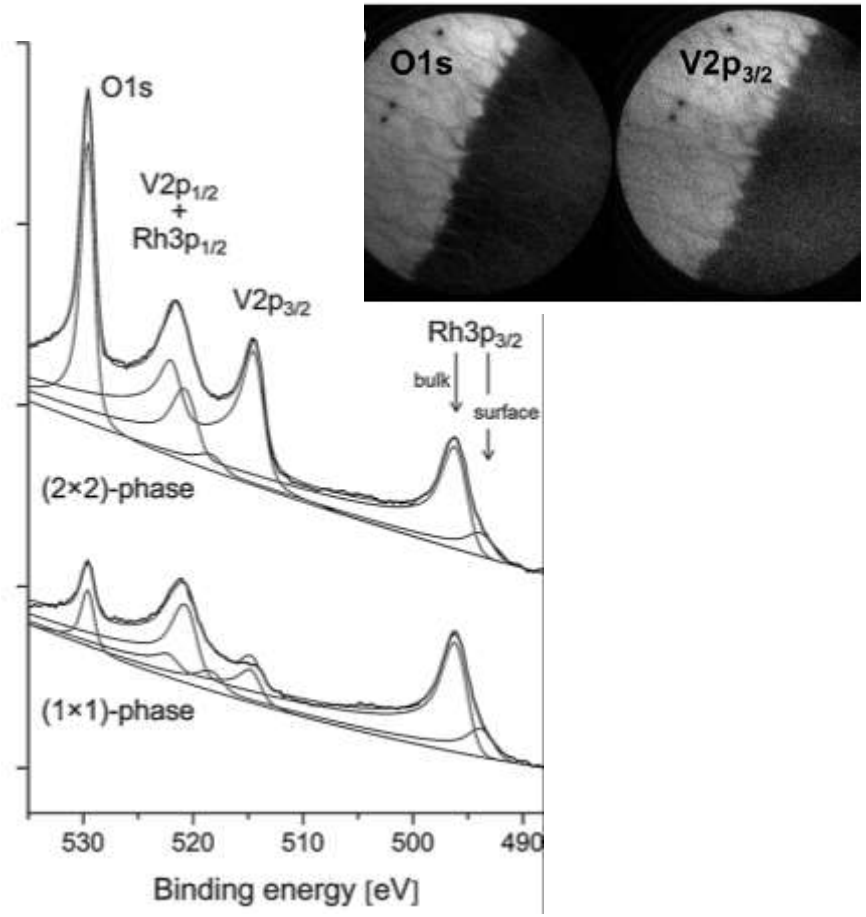
Au 4f $_{7/2}$

Surface Science 566–568 (2004) 1130–1136

J. AM. CHEM. SOC. 2005, *127*, 2351−2357

V/Rh(110) during water formation reaction

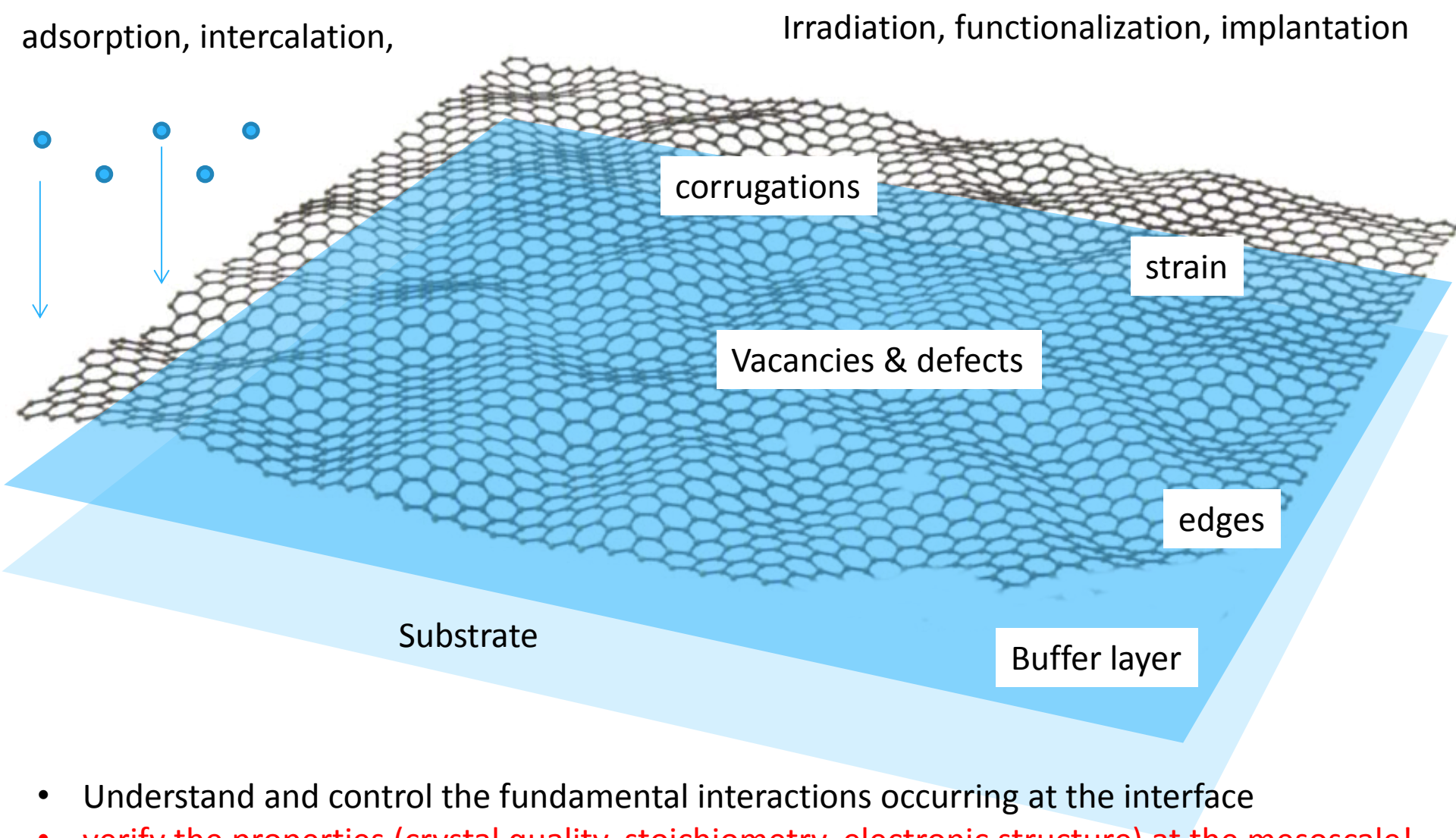
Spectroscopic determination of the oxidation state




F. Lovis et al., *J. Phys. Chem. C* **115,** 19149 (2011)

# The complexity of the metal-graphene interface

Elettra Sincrotrone Trieste




- Understand and control the fundamental interactions occurring at the interface
- verify the properties (crystal quality, stoichiometry, electronic structure) at the mesoscale!

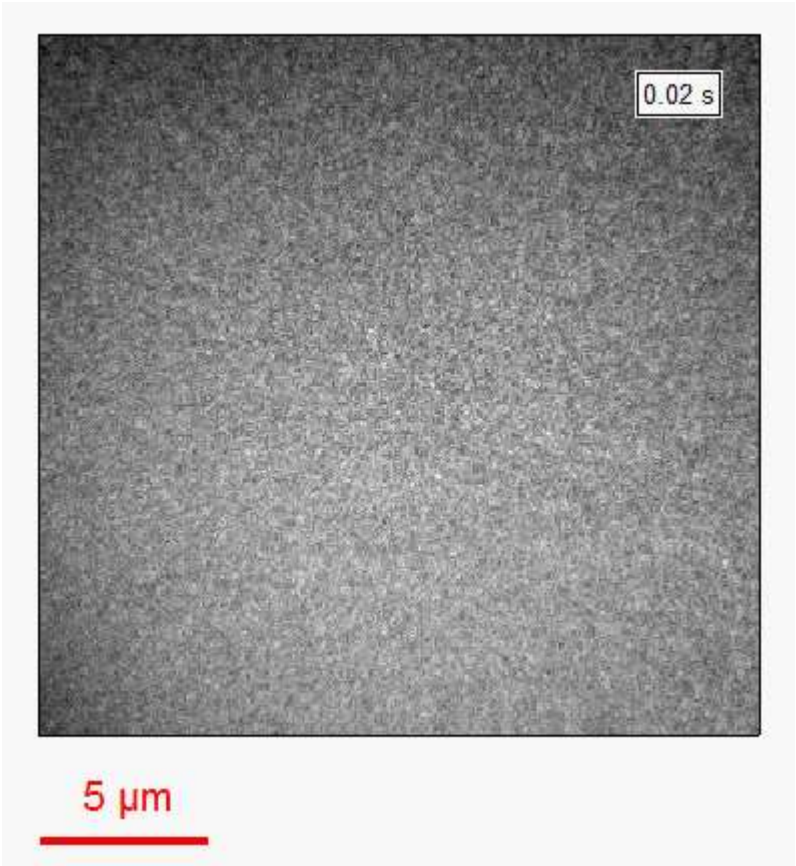
# XPEEM studies of graphene

- Effect of substrate' symmetry
  - The complex structure of g/Ir(100)
- Buffers
  - Au Intercalation
  - Carbides in graphene on Ni(111)
- Irradiation/implantation
  - Low energy N+ ion irradiation of g/Ir(111)
  - Irradiation with noble gases of g/Ir(100)

# High temperatrue graphene growth on Ir(100)

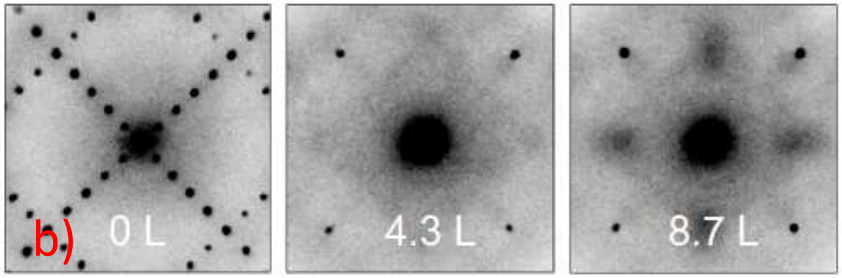
Elettra Sincrotrone Trieste

LEEM imaging

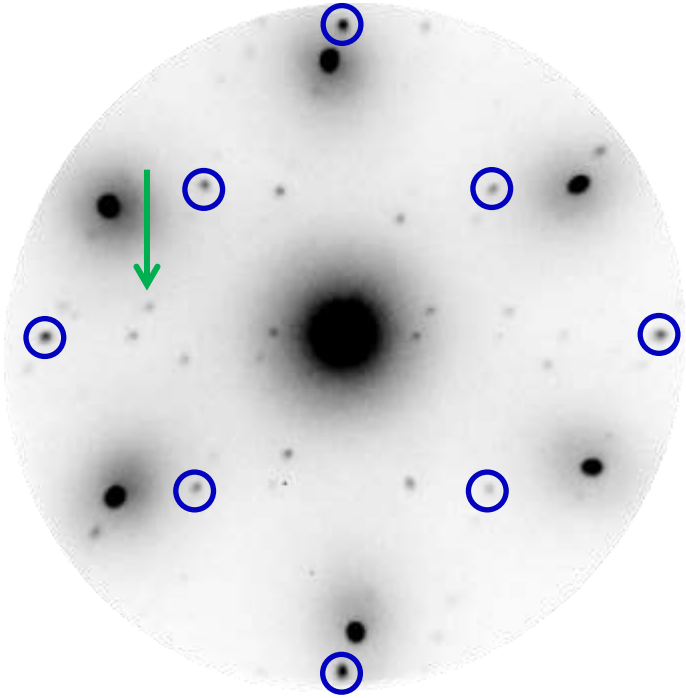



T > 800 C;P=2·10$^{-8}$ mbar ethylene

microprobe-LEED: Ir



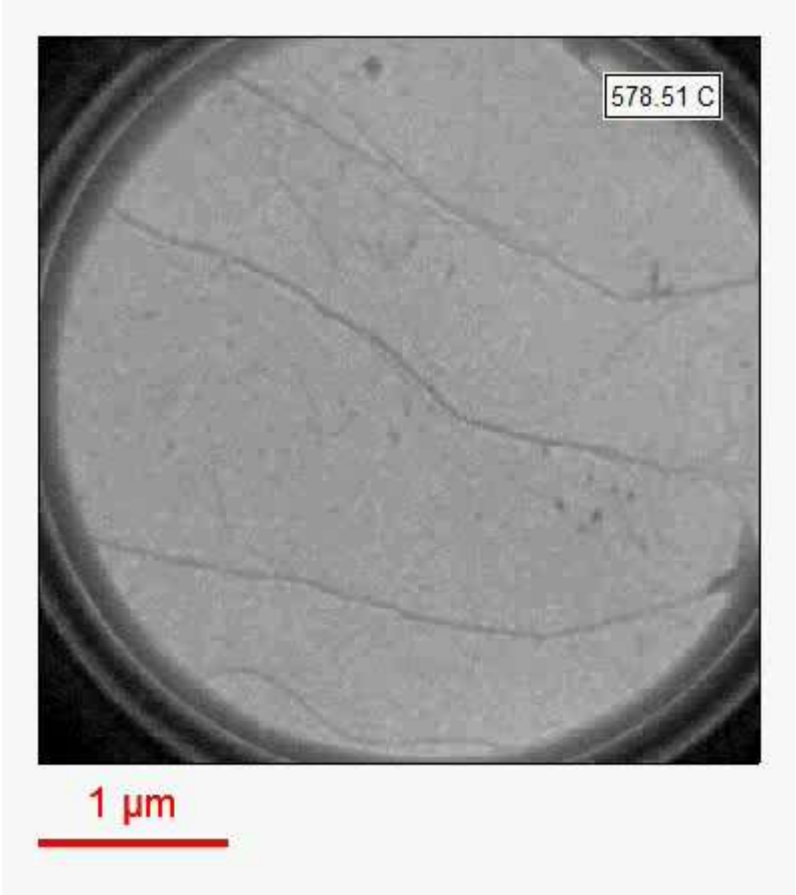

microprobe-LEED: graphene



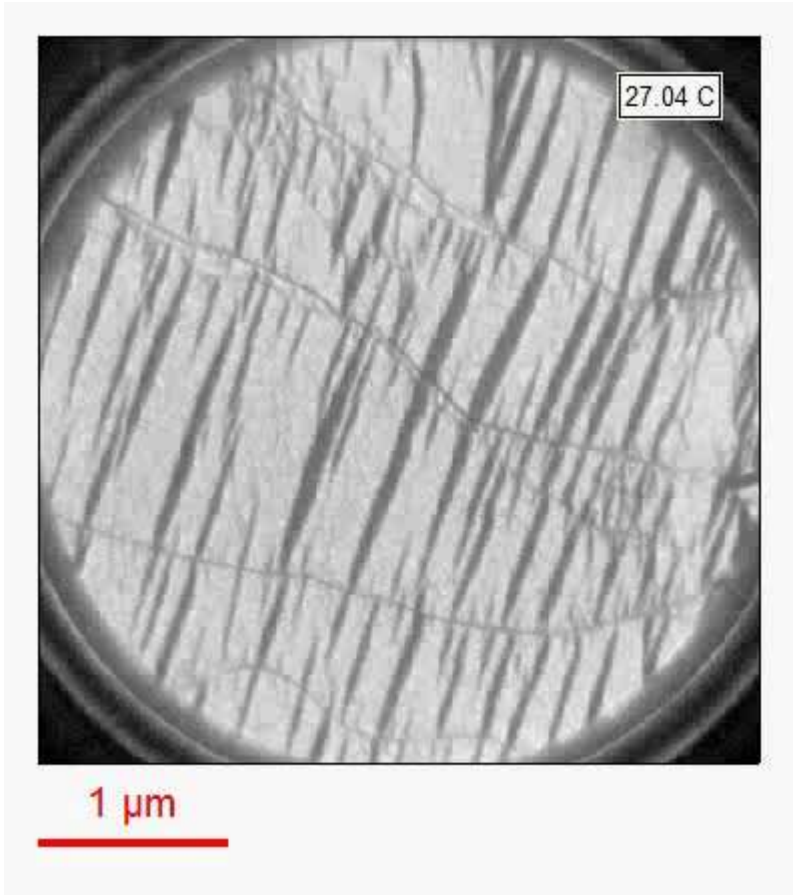
# Reversible graphene phase transformation

Elettra Sincrotrone Trieste

Upon cooling a distinct graphene phase nucleates forming dark stripes



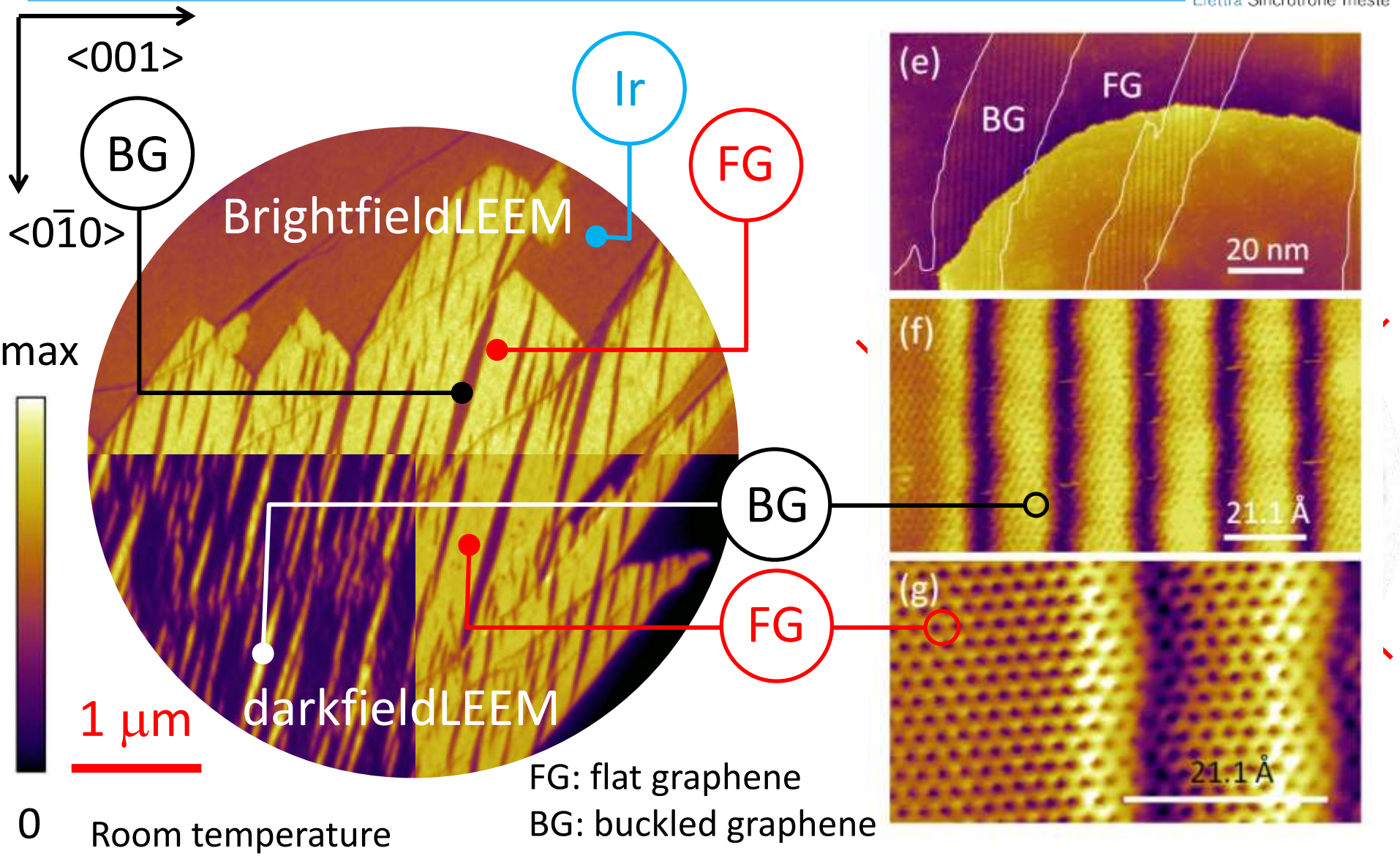

The stripes disappear when annealing the sample to high temperature.




Fov 4 µm, S.V. 13 eV

# Graphene/Ir(100): strucutre of FG and BG

Elettra Sincrotrone Trieste



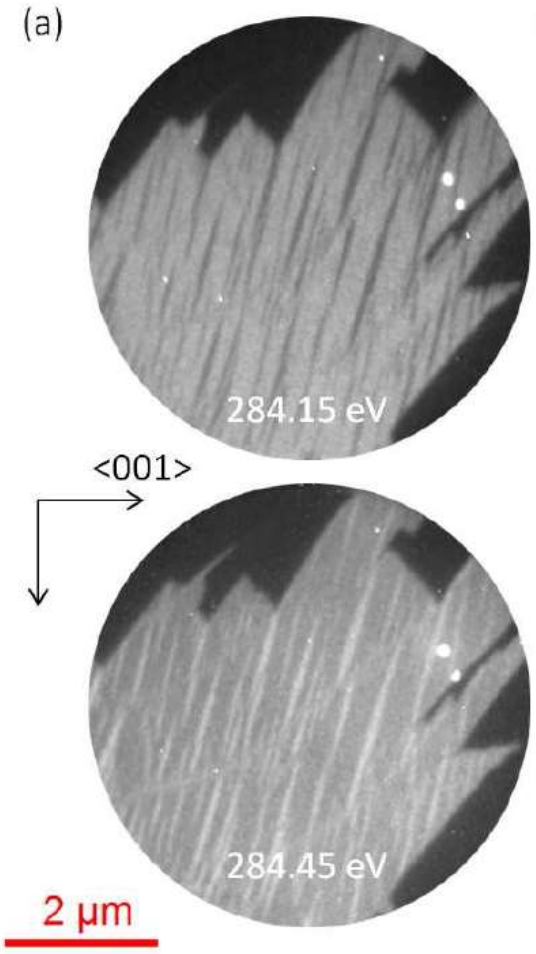

FG: flat graphene
BG: buckled graphene

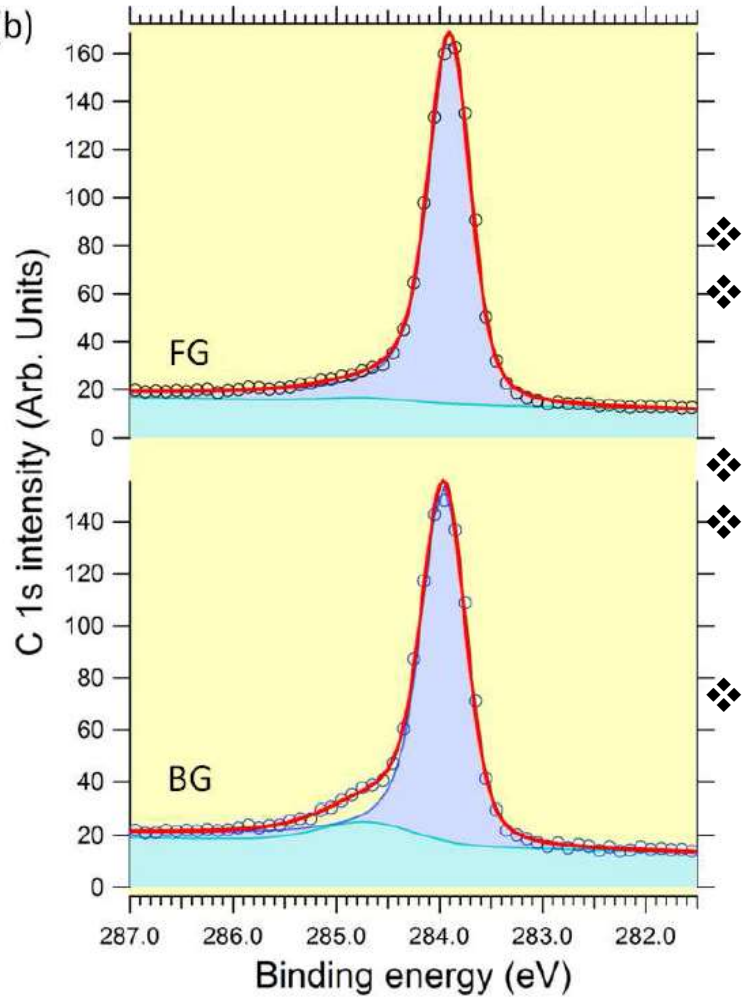

A. Locatelli et al; ACS Nano, ACS Nano, 7, 6955–6963 (2013)

# Buckled graphene unit cell by ab-initio

Elettra Sincrotrone Trieste

## buckled graphene unit cell




## Buckled Graphene

Exceptionally large buckling

GGA:

- Min Ir-C distance of 1.9 Å
- Max Ir-C distance of 4.0 Å

DFT-D:

- Min Ir-C distance of 2.1 Å
- Max Ir-C distance of 3.7 Å

- 18 atoms over 160 (i.e. 11%) are **chemisorbed**, the others are physisorbed

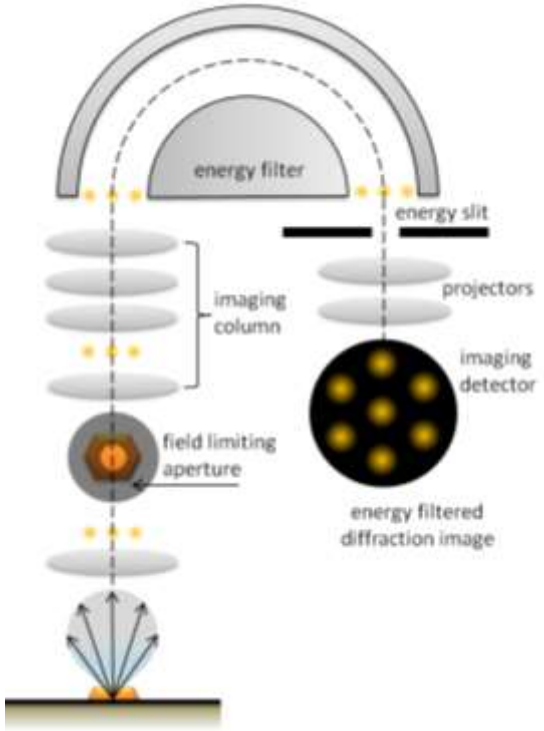
**Buckled graphene shows regular one-dimensional ripples with periodicity of 2.1nm**.

# Electronic structure: graphene doping

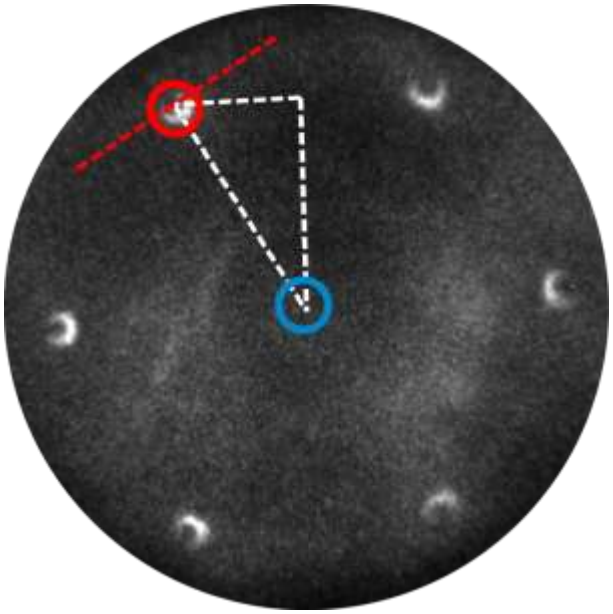
Elettra Sincrotrone Trieste

what is the difference in electronic structure between FG and BG?
do they both show the same Dirac-like dispersion?

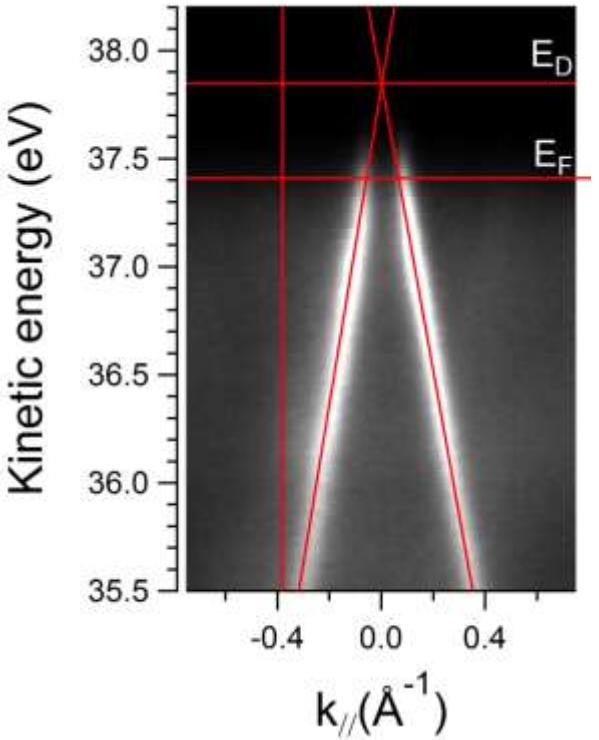
Diffraction Imaging




measurements limited to 2 um in dia.



μ-ARPES at $E_F$




$E_D$ = 0.42 eV

# Different character of FG and BG



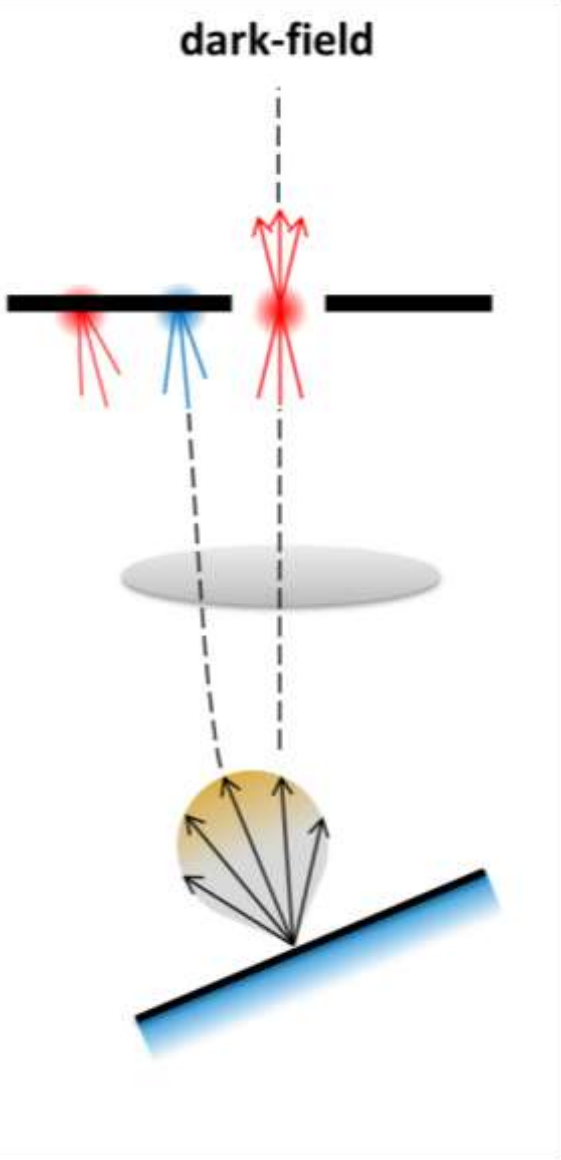
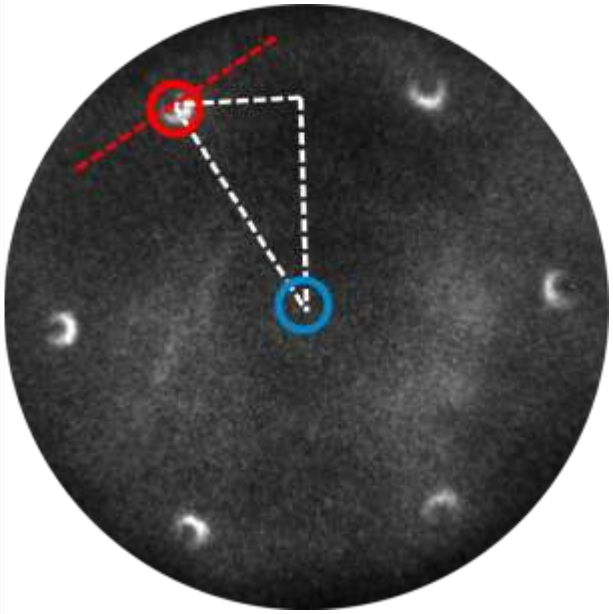
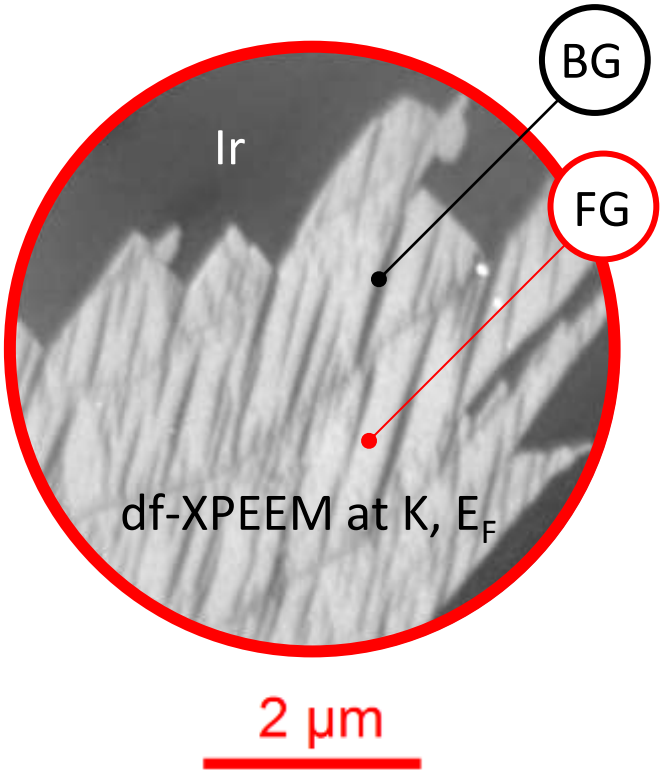



Image intensity proportional to local DOS!



μ-ARPES at $E_F$




**FG:** high DOS at K → Dirac cones intact
**BG** hybridized, metalllic-like DOS

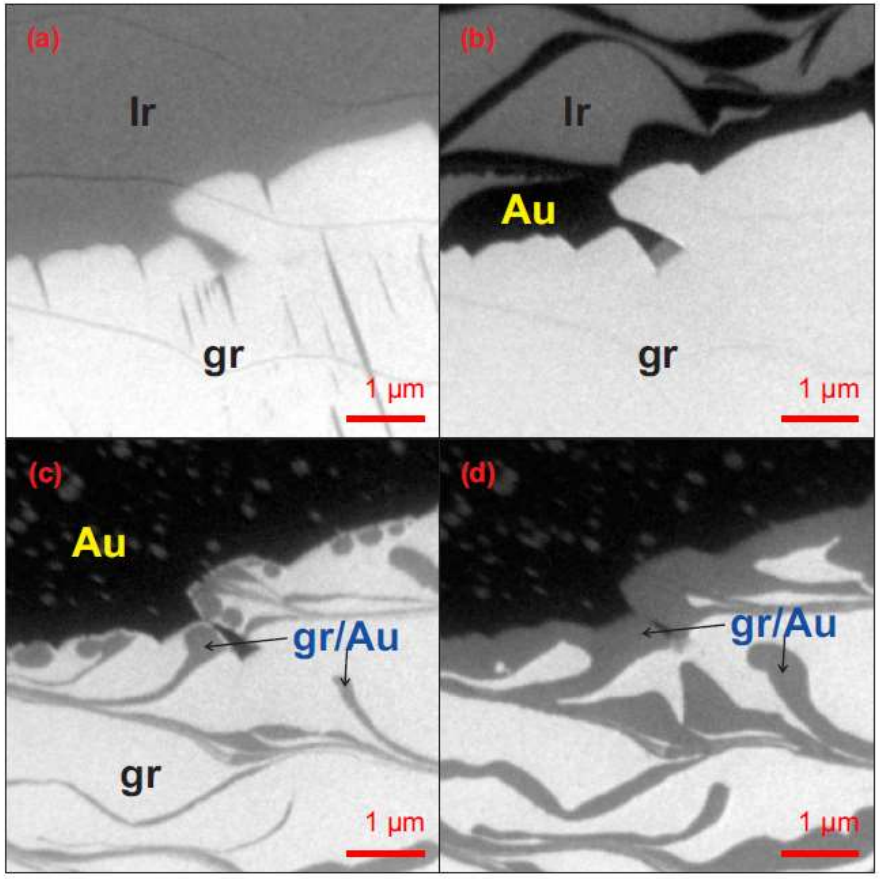
**Decoupling graphene from substrate:**

- **Intercalated Au/g/Ir(100)**
- **Switchable formation of carbides in g/Ni(111)**

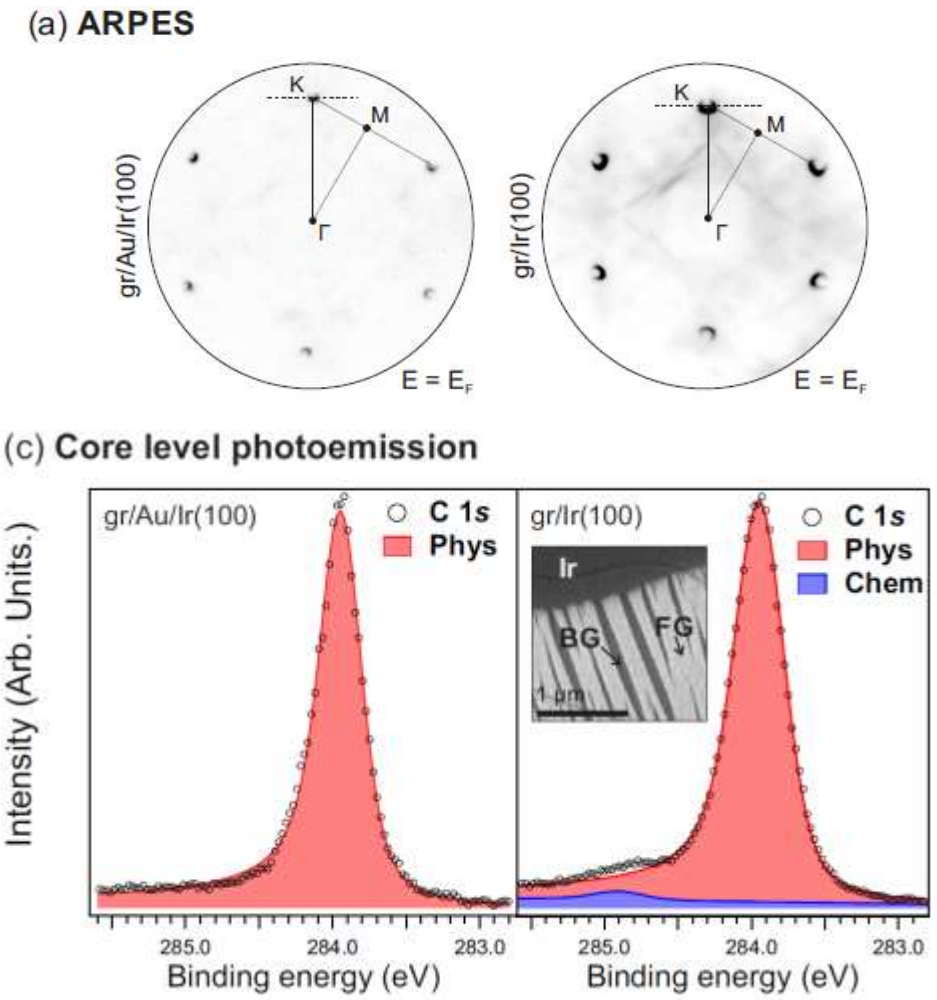
# Tuning the interaction by Au intercalation

Elettra Sincrotrone Trieste

Real time LEEM imaging during Au intercalation at 600 °C



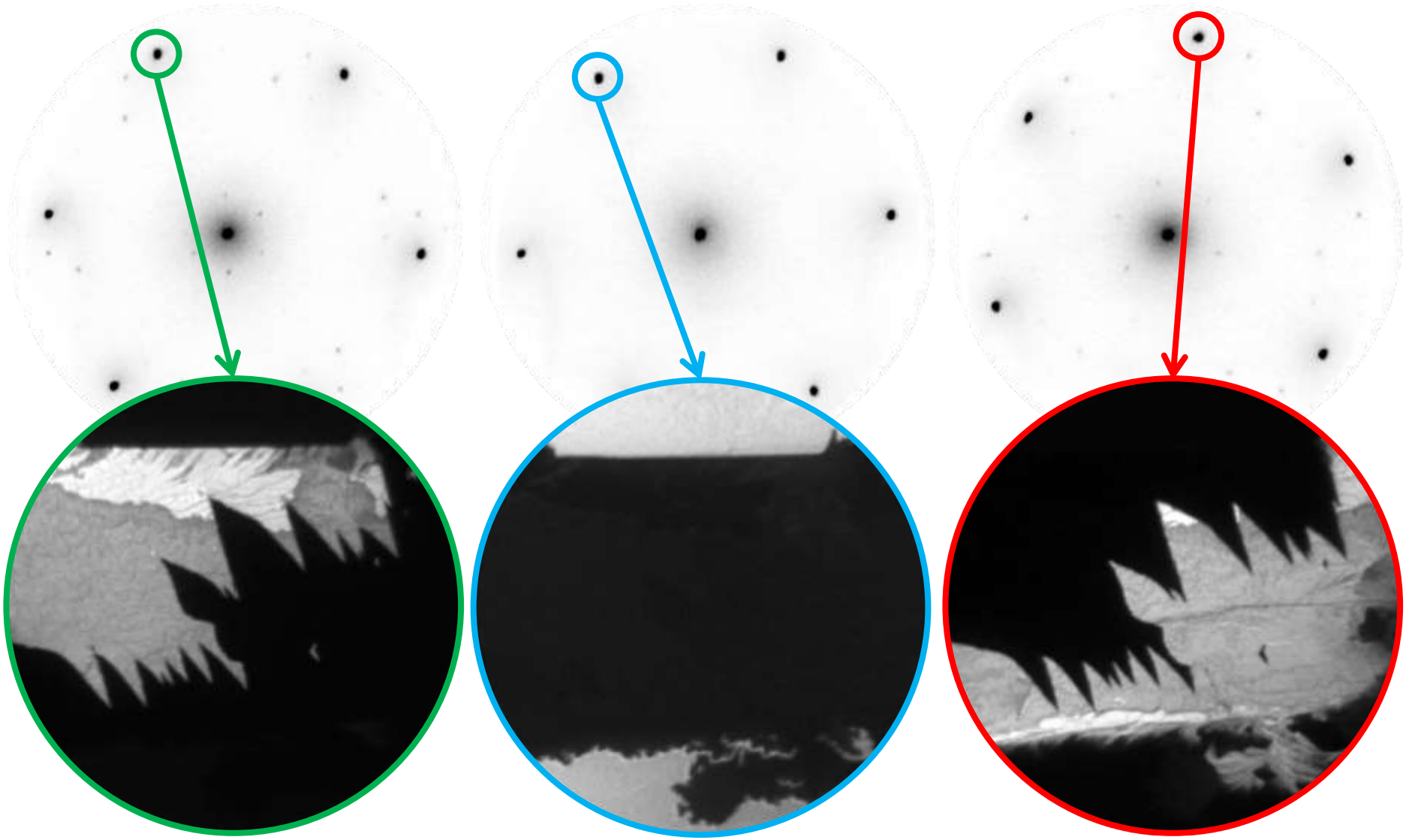

Electonic structure by microprobe ARPES



# Identifying crystal grains in graphene/Ni(111)

Elettra Sincrotrone Trieste

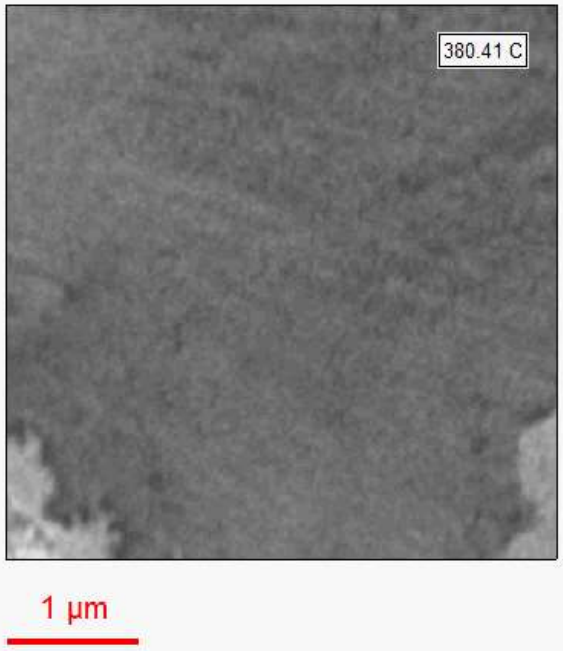
rotated graphene (+17) epitaxial graphene rotated graphene (-17)



# Formation/dissolution of carbides under rg/Ni(111)

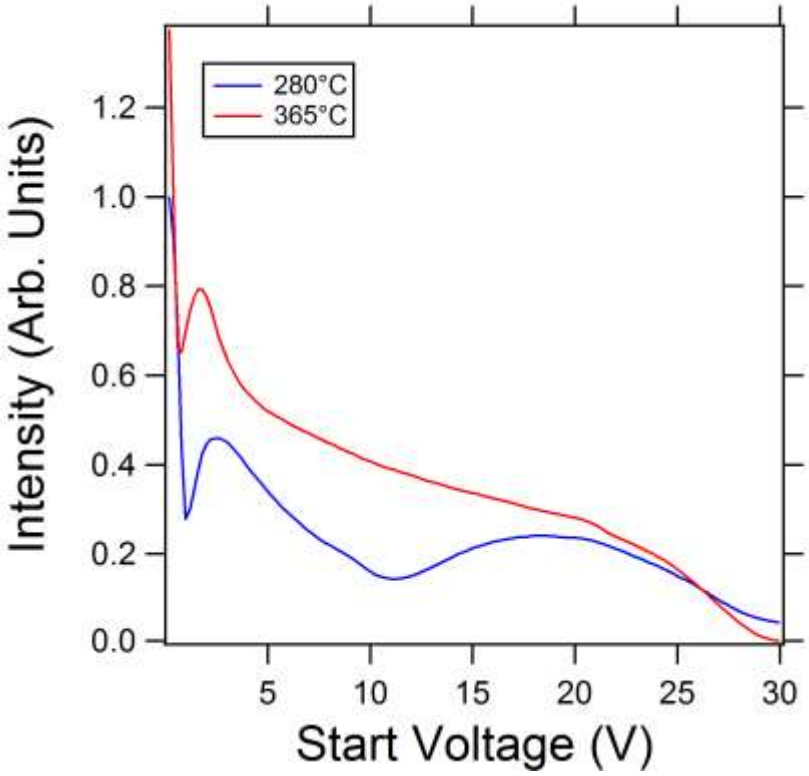
Elettra Sincrotrone Trieste

**1: carbide nucleation**




The Ni-carbide nucleates exclusively under rotated graphene, starting at temperatures below 340°C

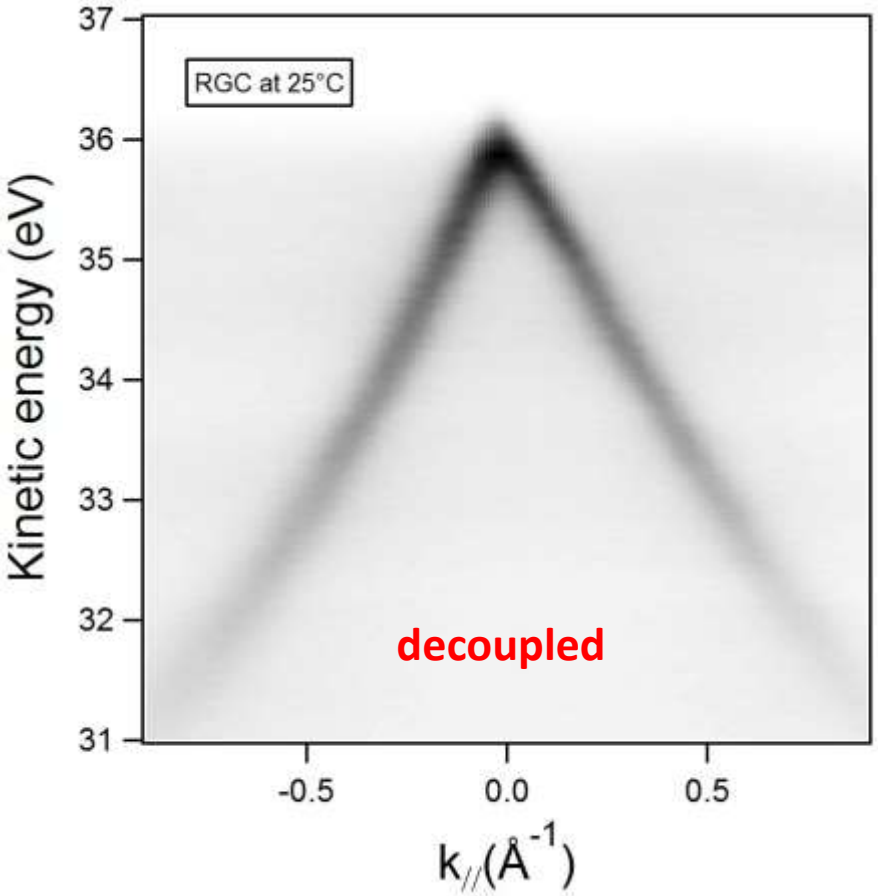
**Different electron reflectivity explains change of contrast**



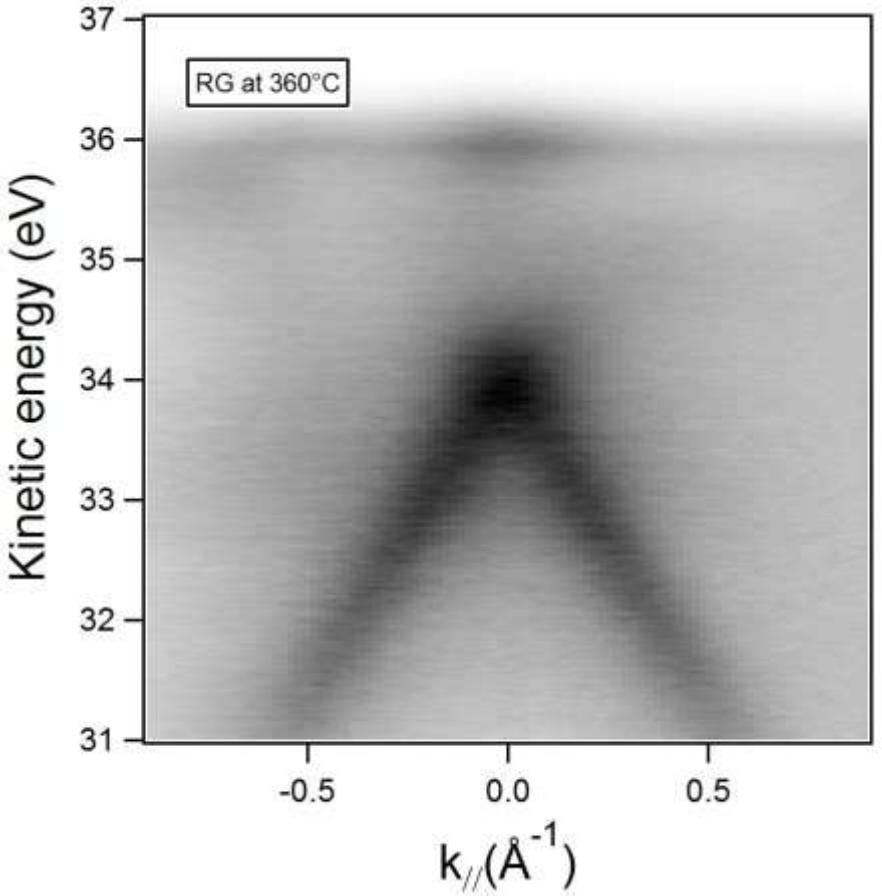

All movies: LEEM FoV 6 um, electron energy: 11 eV

# Coupling-decoupling is revealed by μ-ARPES

Elettra Sincrotrone Trieste

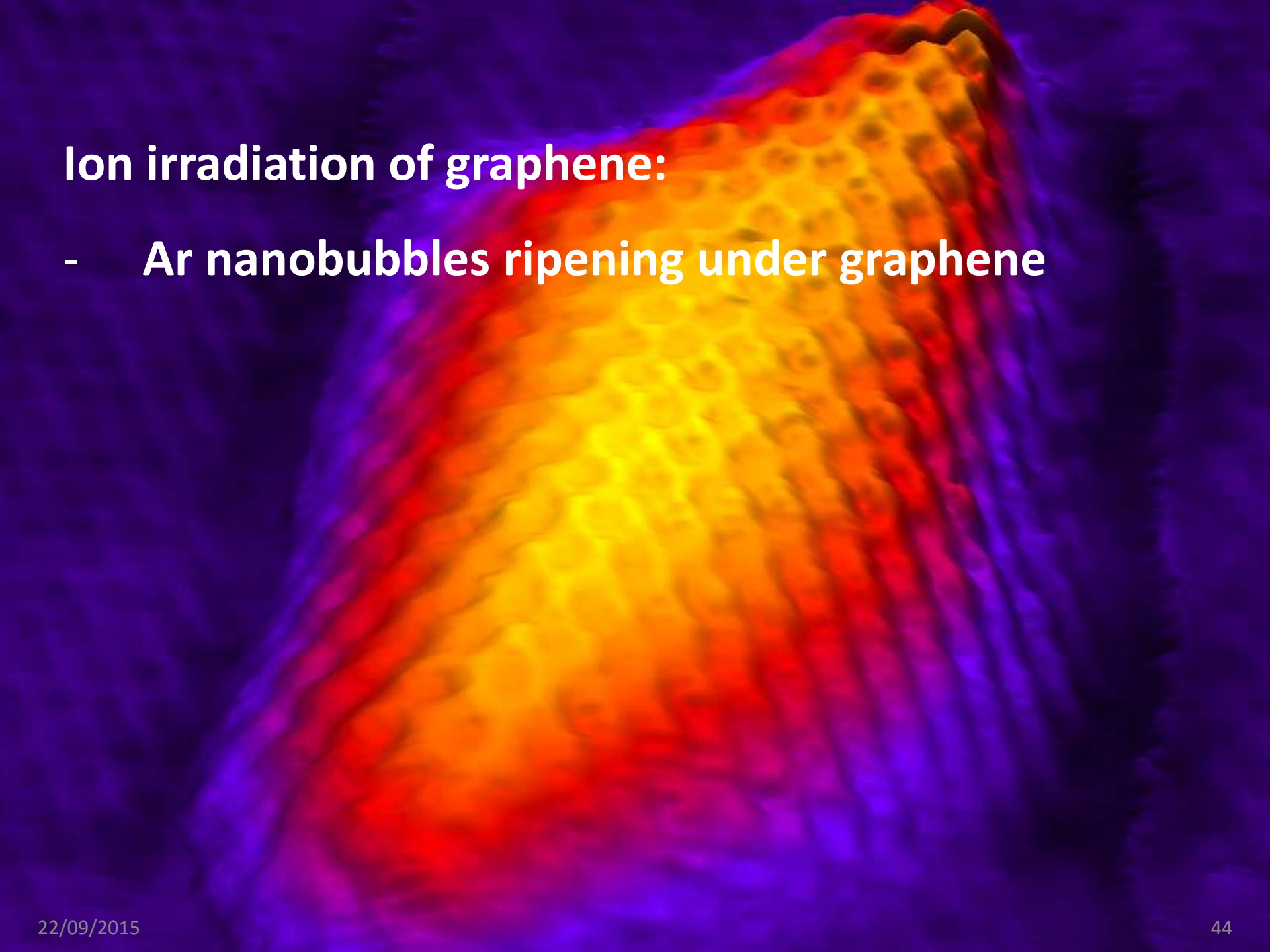



Rotated graphene with Ni-carbide underneath at room temperature; There's no double layer




Rotated graphene without Ni-carbide underneath at 365°C

**See poster P113 Patera *et al.***



## Ion irradiation of graphene:

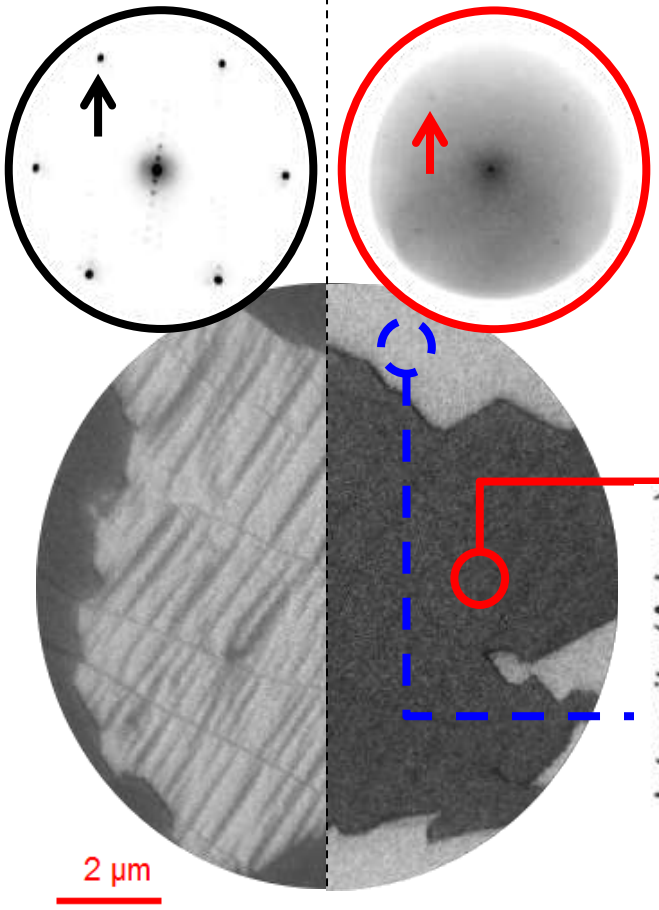
- Ar nanobubbles ripening under graphene

# Morphology of Ar⁺ irradiated graphene/Ir(100)

Elettra Sincrotrone Trieste

(a) LEED

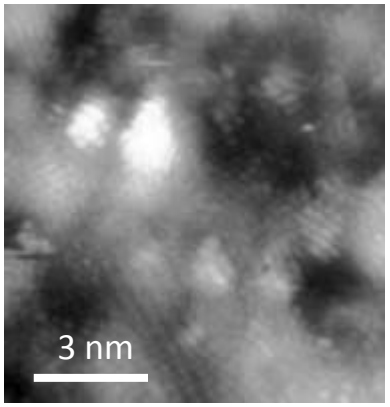
before irradiation | after irradiation



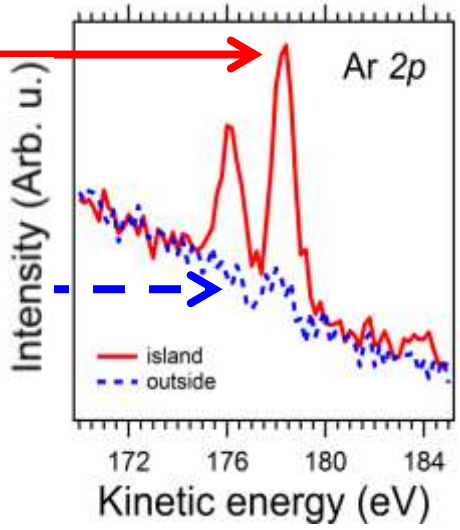

LEEM 12 eV

Irradiation with 0.5keV Ar⁺ 7 s

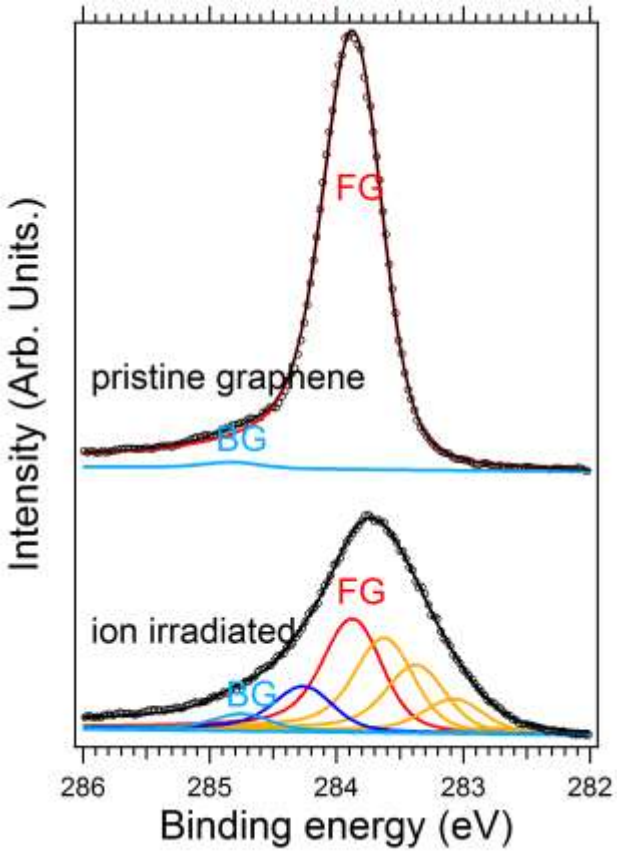
(b) STM




(c) XPEEM




Rough morphology, but …
graphene is <u>continuous</u>
**average height 0.15 nm!**

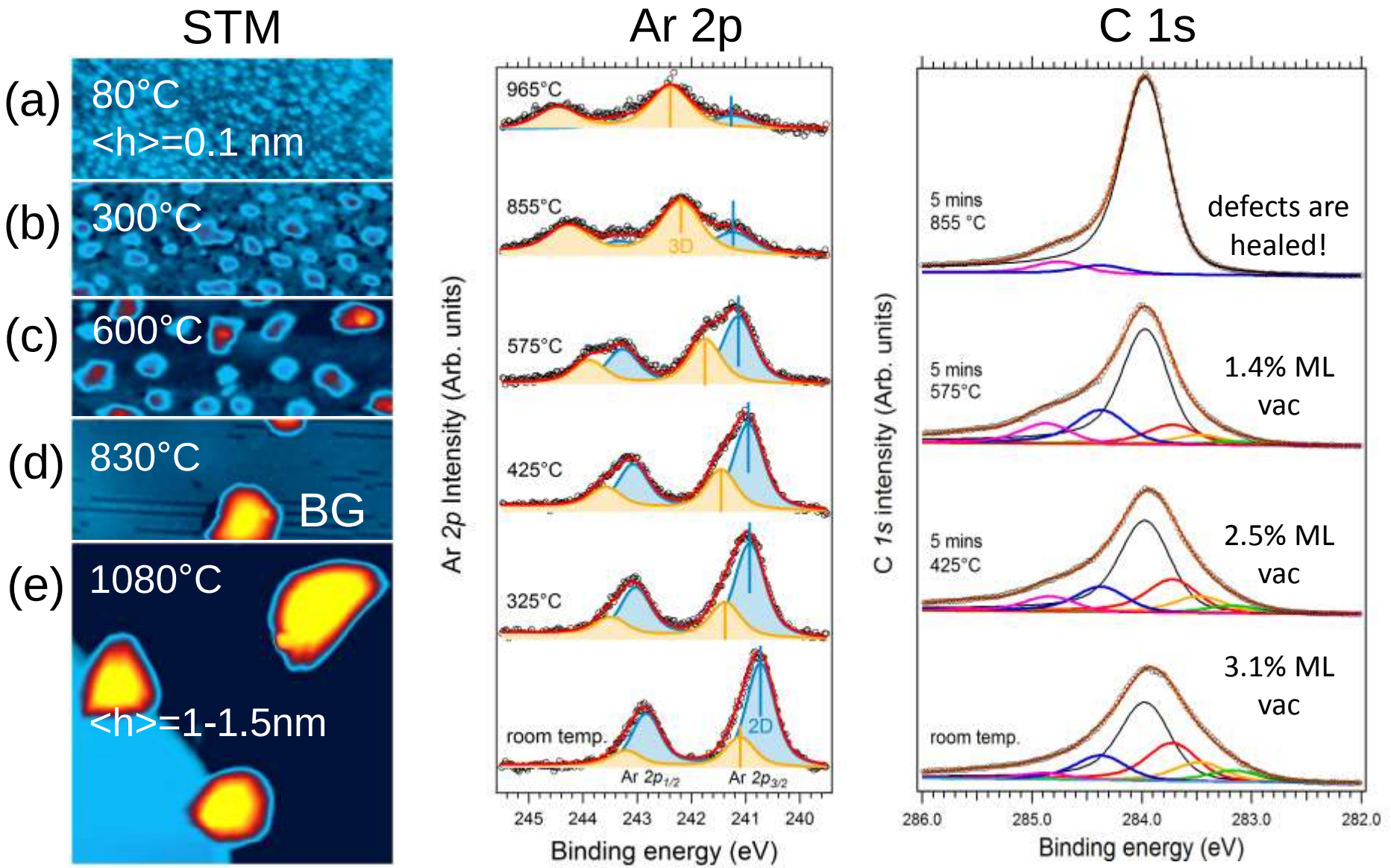





G. Zamborlini et al., *Nano Lett.*, 2015, 15 (9), pp 6162–616

# Evolution upon annealing: STM and μ-XPS

Elettra Sincrotrone Trieste

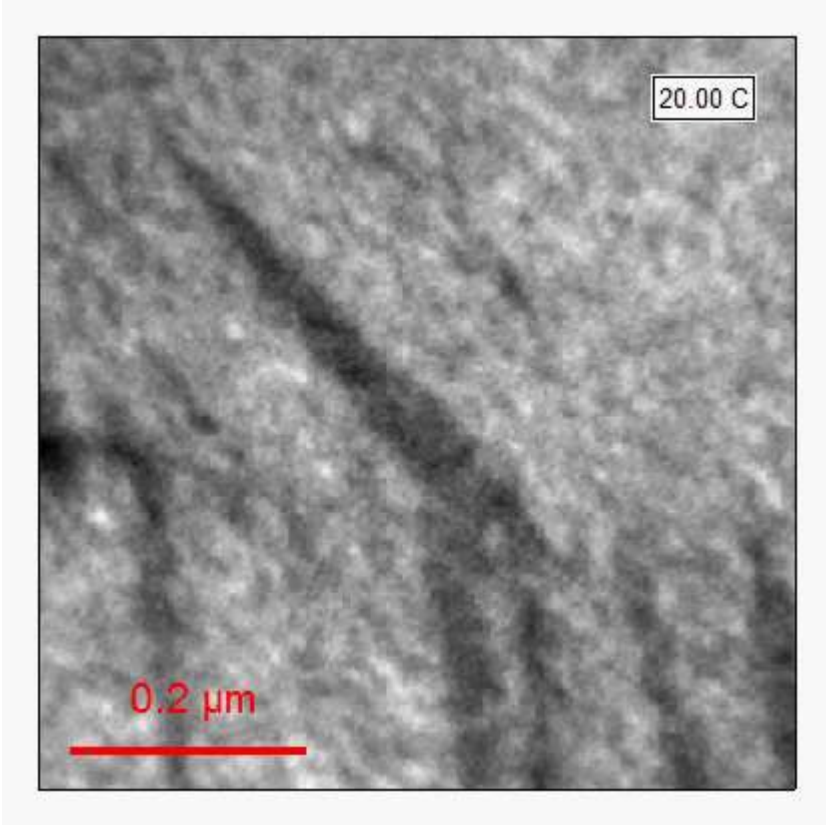


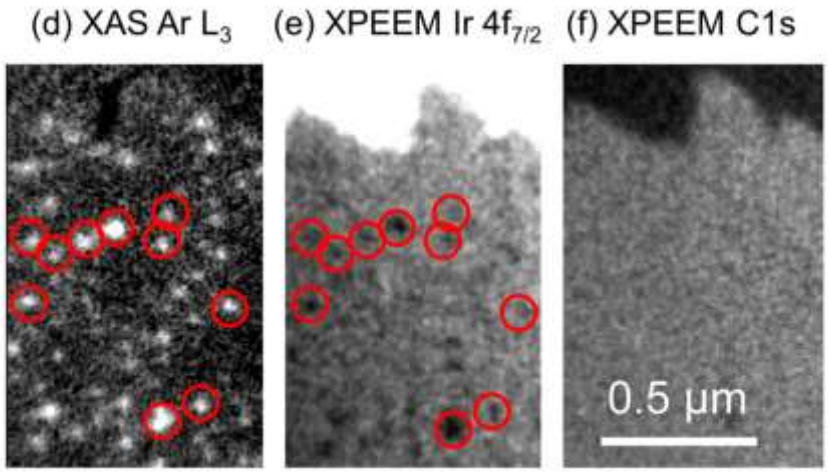

Irradiation with 0.1keV $Ar^+$ 150 s and 5 min annealing; The XPS data were acquired at RT

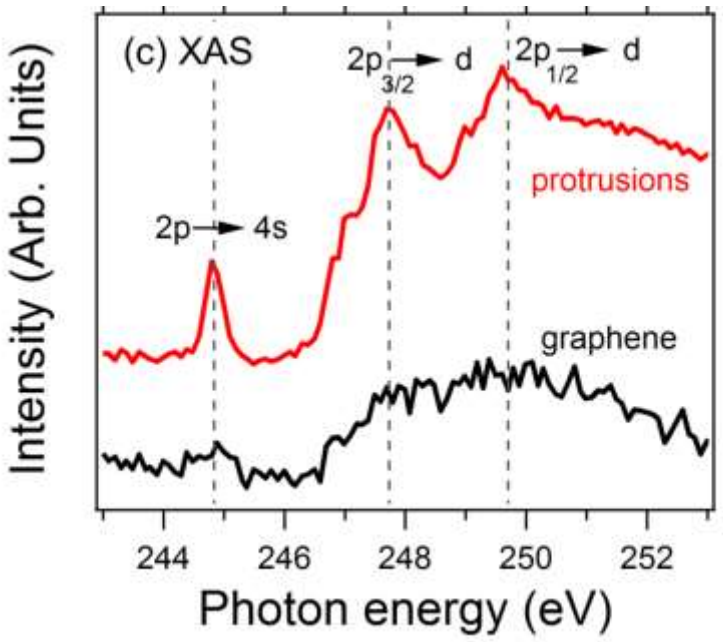
# LEEM & XPEEM formation of Ar nanobubbles

Elettra Sincrotrone Trieste

LEEM movie 12 eV





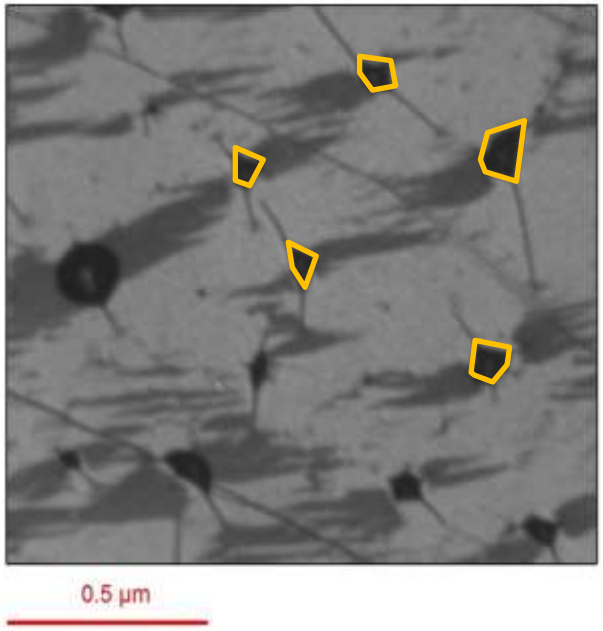

G. Zamborlini et al., *Nano Lett.*, 2015, 15 (9), pp 6162–616

# NB formation for g/Ne/Ir(100)

Elettra Sincrotrone Trieste

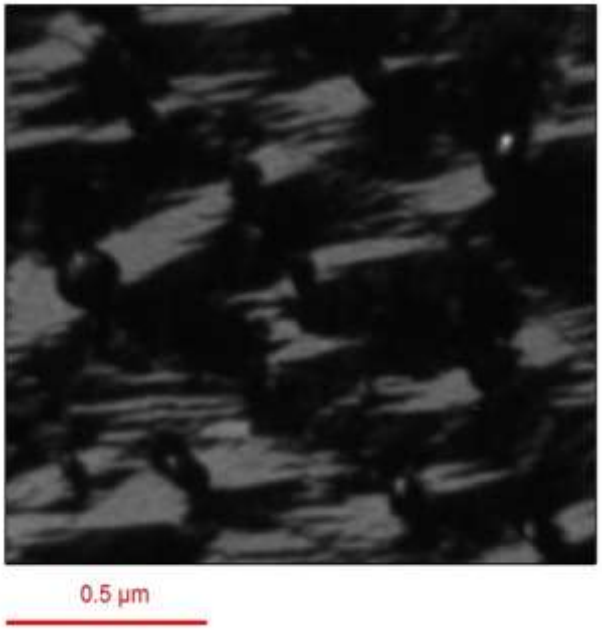
100 eV Ne+ ion irradiation was followed by 5 min annealing to 650 °C and subsequent cooling to RT

bright-field LEEM 12 eV

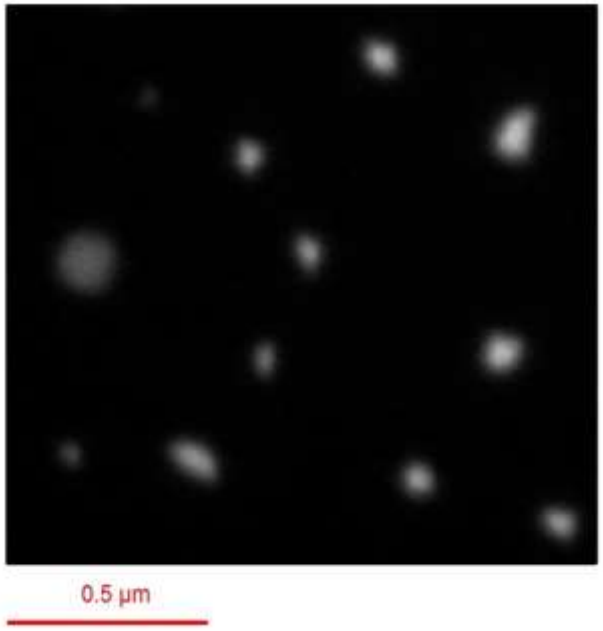



- Wrinkles surround the larger particles
- At RT, bubbles have a polygonal shape → solid?

dark-field LEEM BG phase




XPEEM imaging Ne 2p



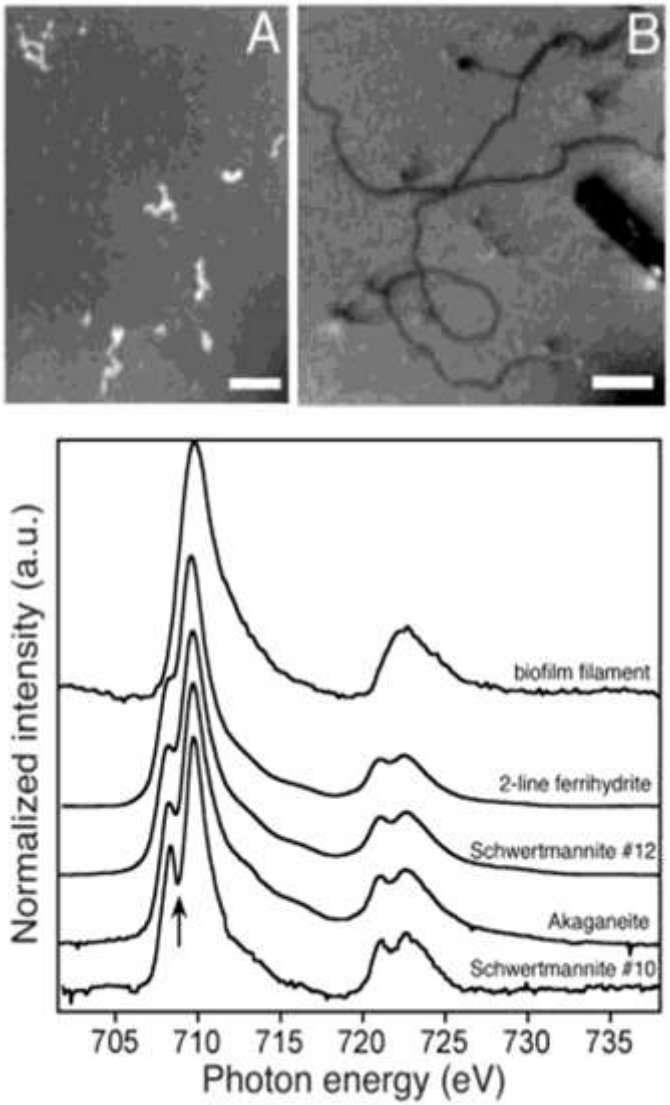

- elemental composition below graphene!
- XPS from individual particles
- Shift to high BE for large clusters

# XAS-PEEM applications to biosciences

biomineralization

# Applications of XAS in biology: biomineralization





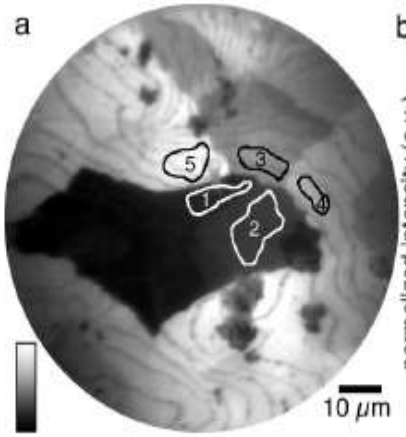

- Bio-mineralization resulting from microbal activity
- X-PEEM images of (A) non mineralized fibrils from the cloudy water above the biofilm (scale bar, 5 um)
- (B) mineralized filaments and a sheath from the biofilm (scale bar, 1 um); (bottom)
- X-PEEM Fe L-edge XANES spectra of the FeOOH mineralized looped filament shown in (B), compared with iron oxyhydroxide standards, arranged (bottom to top) in order of decreasing crystallinity.

P.U.P.A Gilbert *et al. (ALS group)*, *Science* **303** 1656-1658, 2004.

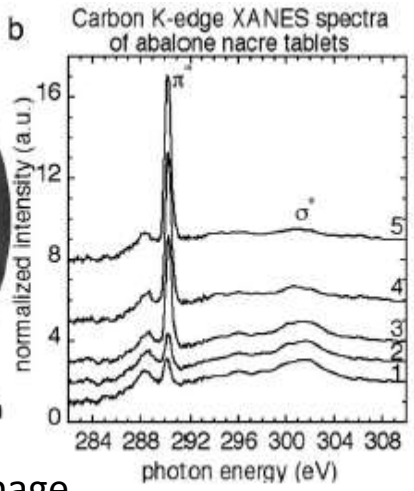
# Nano-scale architecture of Nacre

Elettra Sincrotrone Trieste

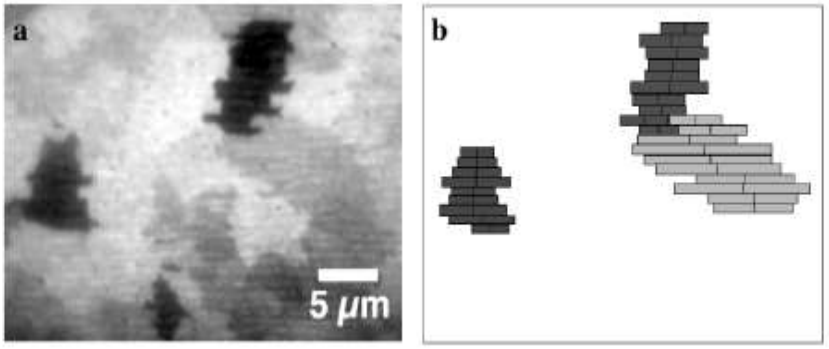
Carbon K-edge image




Carbon K-edge XANES




Oxygen K-edge XAS image




$$I(\vartheta,\theta,T) = a + b(3\cos^2\vartheta - 1)\langle Q_{zz}\rangle$$

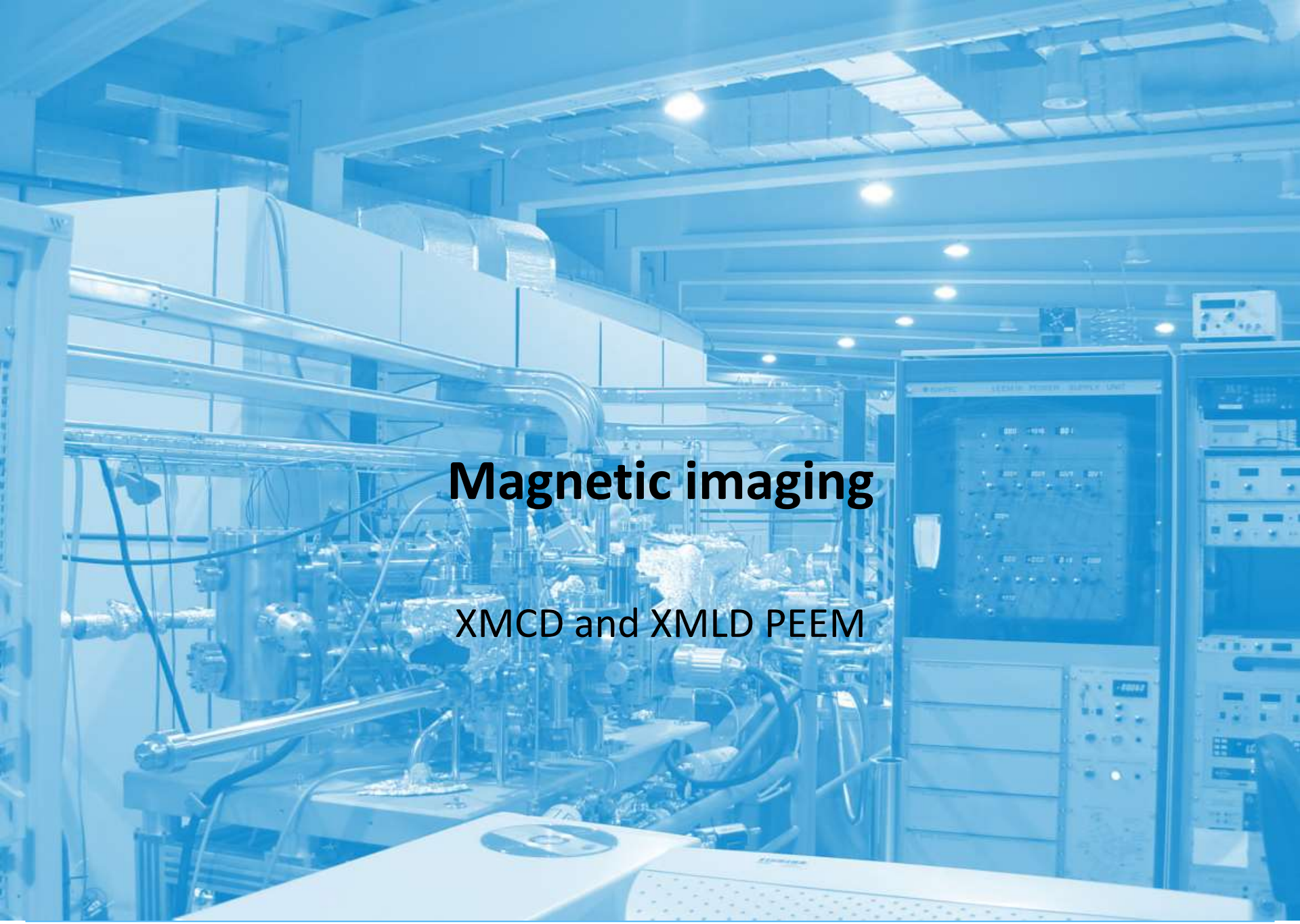
$$+ c(3\cos^2\theta - 1)\langle M^2\rangle_T + d\sum_{i,j}\langle \hat{s}_i \cdot \hat{s}_j\rangle_T$$

Contrast is observed between adjacent individual nacre tablets, arising because different tablets have different crystal orientations with respect to the radiation's polarization vector.

The 290.3 eV peak corresponds to the C 1*s* → *Pi** transition of the CO bond. Synchrotron radiation is linearly polarized in the orbit plane. Under such illumination, the

intensity of the peak depends on the crystallographic orientation of each nacre tablet with respect to the polarization. This was the first observation of x-ray linear dichroism in a bio-mineral.

R.A. Metzler *et al.*, *Phys.Rev.Lett.* **98**, 268102 (2007)

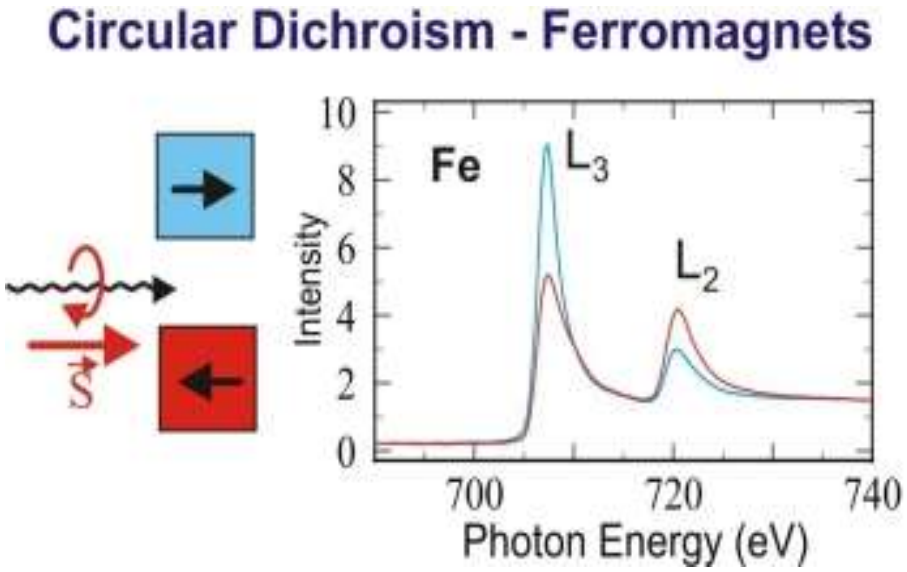


# Magnetic imaging

XMCD and XMLD PEEM

# Magnetic imaging: XMCD

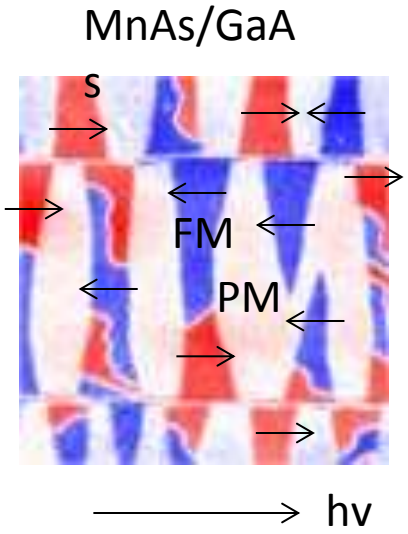
Elettra Sincrotrone Trieste




X-ray magnetic circular dichroism (XMCD) is the dependence of *x-ray absorption* on the relative orientation of the local magnetization and the polarization vector of the circularly polarized light

✓Element sensitive technique

✓ Secondary imaging with PEEM determine large probing depth (10 nm), buried interfaces.

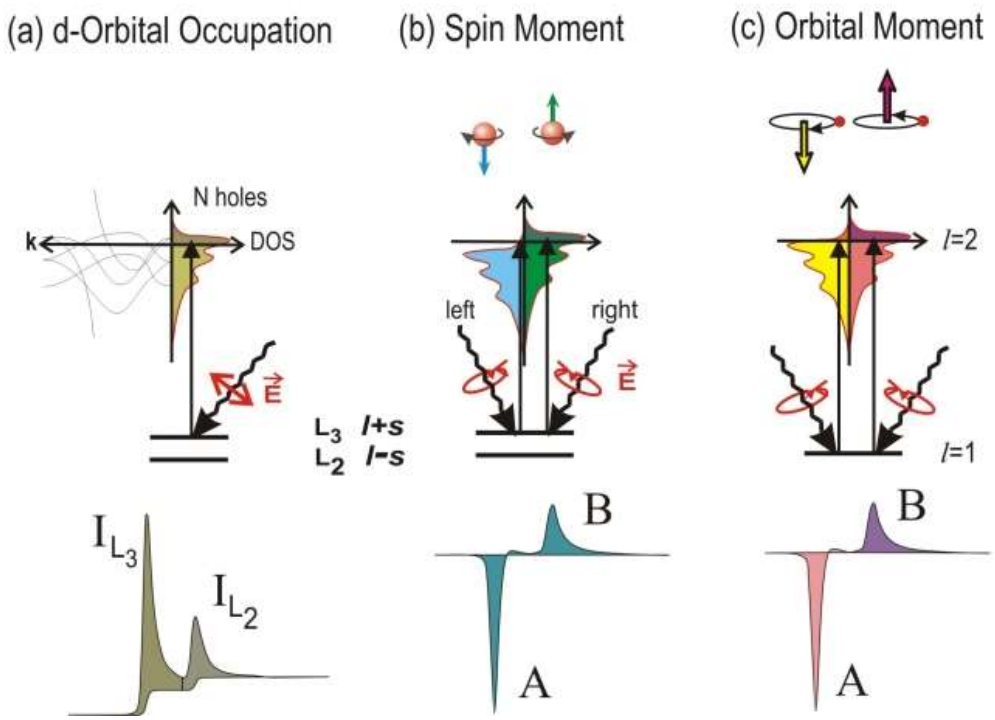



## Magnetic domain imaging

At resonance, the secondary electron yield is proportional to the dot product between the magnetization direction and the photon helicity vector, which is parallel or anti-parallel to the beam propagation direction

# XMCD principles





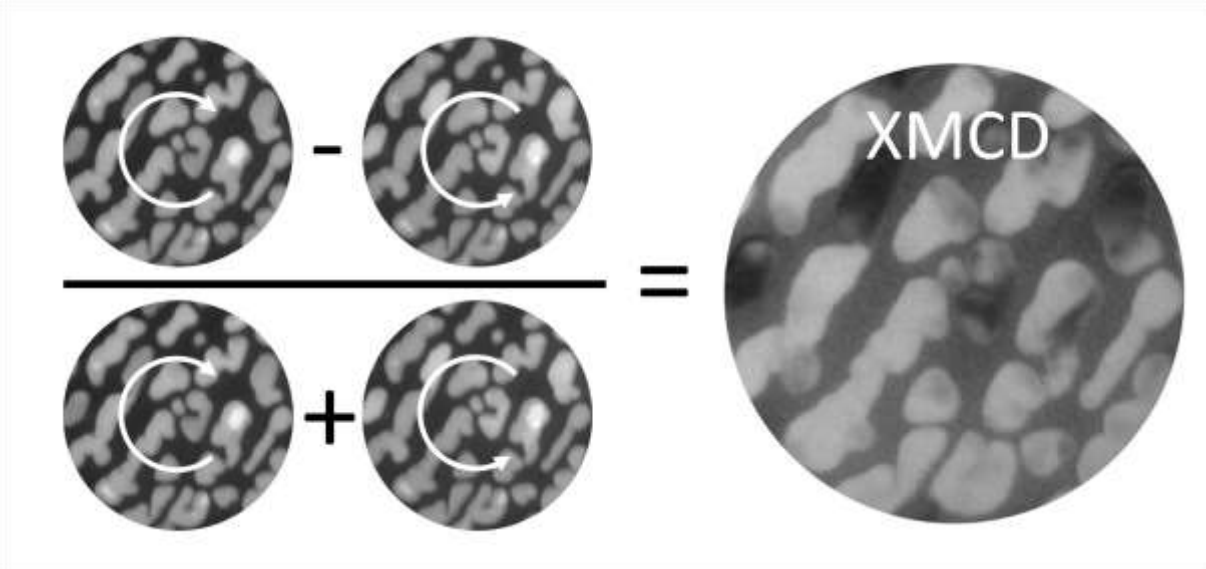

- We **PROBE** 3d elements by exciting 2p into unfilled 3d states
- Dominant channel: 2p → 3d
- White line intensity of the L3 and L2 resonances with the number N of empty d states (holes).

- By using circularly polarized radiation, the angular momentum of the photon can be transferred in part to the spin through the spin-orbit coupling. Photoelectrons with opposite spins are created in the cases of left and right handed polarization. Spin polarization is opposite also for $p_{3/2}$ ($L_3$) and $p_{1/2}$ (L2) levels.
- The spin-split valence shell is thus a detector for the spin of the excited photoelectron. The size of the dichroism effect scales like cosθ, where θ is the angle between the photon spin and the magnetization direction.
- **Refs: IBM. J . Res. Develop. 42, 73 (1998) and J. Magn. Magn. Mater. 200, 470 (1999).**

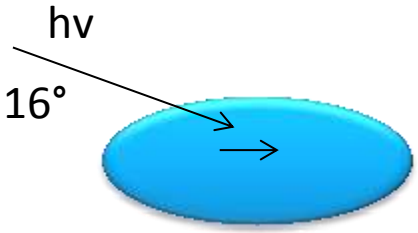
# Image algebra

Elettra Sincrotrone Trieste

The size of the dichroism effect scales like cosθ, where θ is the angle between the photon spin and the magnetization direction. Hence the maximum dichroism effect (typically 20%) is observed if the photon spin and the magnetization directions are parallel and anti-parallel. Sum rules allows measuring orbital and spin moments




## Geometry



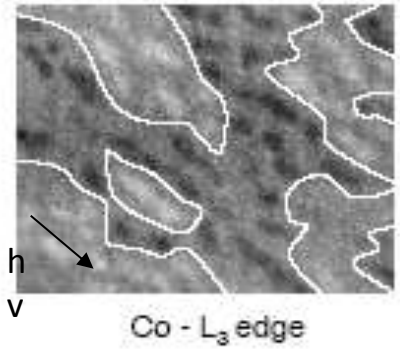

the illumination geometry,
→ *in plane* component of M

# Examples of XMCD-PEEM applications

Elettra Sincrotrone Trieste

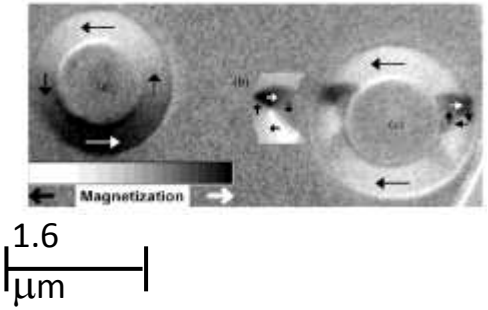
## MAGNETIC STATE using XMCD & XMLD

### Co nanodots on Si-Ge

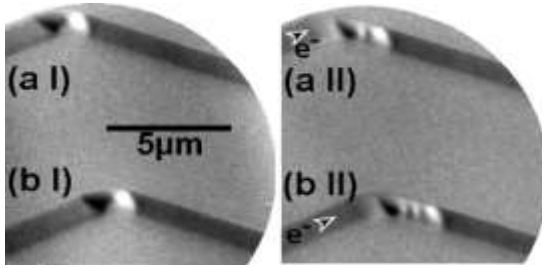



A. Mulders et al, Phys. Rev. B 71, 214422 (2005).

### patterned structures

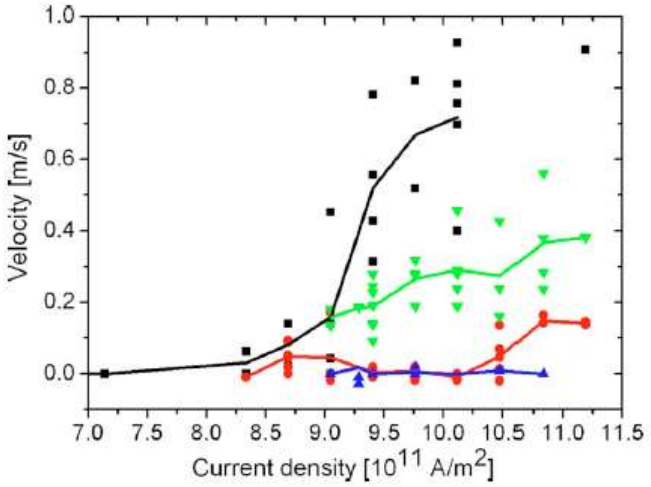



### pulse injection




M. Klaeui et al, PRL , PRB 2003 - 2010

### domain wall motion induced by spin currents



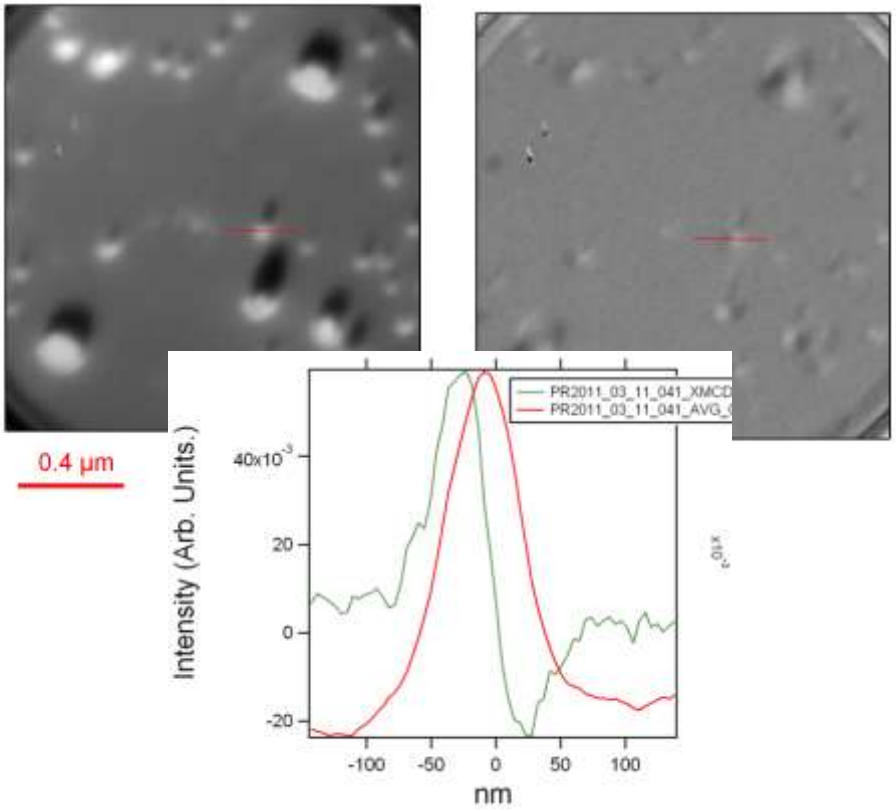

Laufemberg et al, APL 88, 232507(2006).

# Examples of XMCD-PEEM applications

Elettra Sincrotrone Trieste

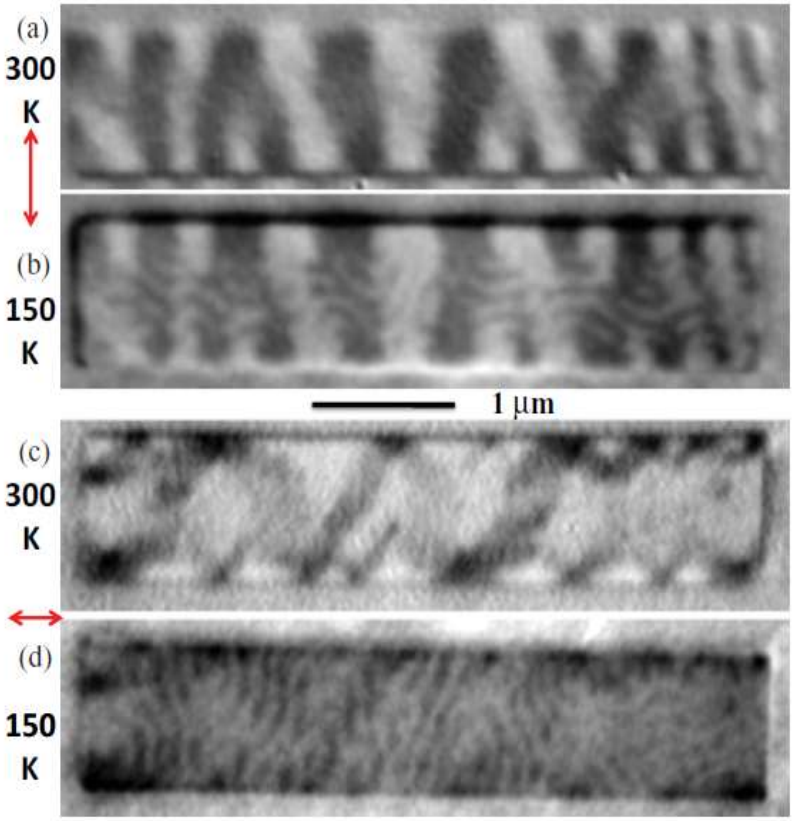
## nano-magnetism of (Ga,Fe)N films

Fe L3 edge (chemical) Fe L3 edge (XMCD)




I Kowalik, D. Arvanitis, M.A. Niño et al., in preparation

## Magnetization in NiPd nanostructures

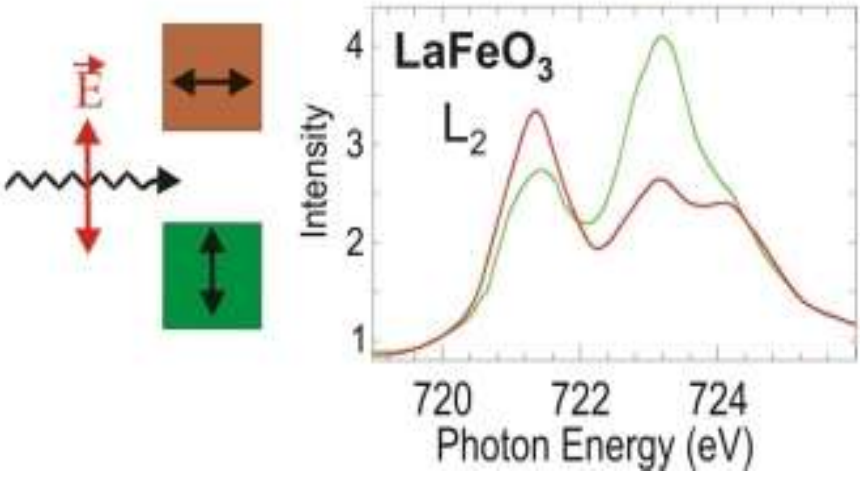



J.-Y. Chauleau, Phys. Rev. B 84, 094416 (2011)

# Magnetic imaging basics: XMLD

Elettra Sincrotrone Trieste

## Linear Dichroism - Antiferromagnets




In the presence of spin order the spin-orbit coupling leads to preferential charge order relative to the spin direction, which is exploited to determine the spin axis in antiferromagnetic systems.

✓Element sensitive technique

✓ Secondary imaging with PEEM determine large probing depth (10 nm), buried interfaces.

✓Applied in AFM systems (oxides such as NiO)

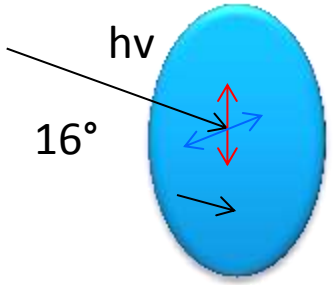
## Absorption intensity at resonance

$$I(\vartheta,\theta,T) = a + b(3\cos^2\vartheta - 1)\langle Q_{zz}\rangle$$

$$+ c(3\cos^2\theta - 1)\langle M^2\rangle_T + d\sum_{i,j}\langle \hat{s}_i \cdot \hat{s}_j\rangle_T$$

1st term: quadrupole moment, i.e.electronic charge (not magnetic!)

2nd term determines XMLD effect; $\Theta$ is the angle between E and magnetic axis A; XMLD max for E || A;




Linear vertical and linear horizontal polarization of the photon beam

# Applications of XMCD and XMLD

Elettra Sincrotrone Trieste

**Direct observation of the alignment of ferromagnetic spins by antiferromagnetic spins**

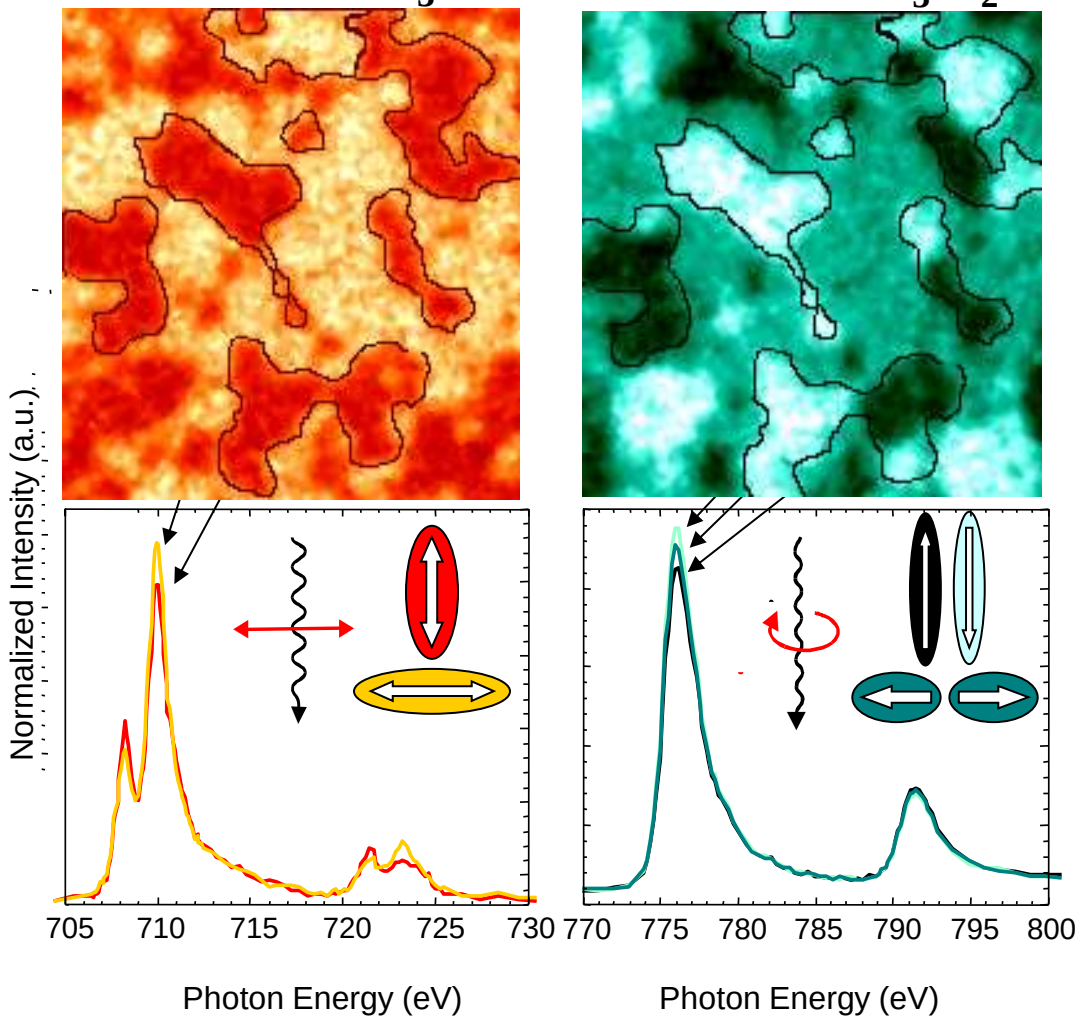
F. Nolting*, A. Scholl*, J. Stöhr†, J. W. Seo‡§, J. Fompeyrine§, H. Siegwart§, J.-P. Locquet§, S. Anders*, J. Lüning†, E. E. Fullerton†, M. F. Toney†, M. R. Scheinfein‖ & H. A. Padmore*

Nature, 405 (2000), 767.

ferromagnet/antiferromagnet
Co/LaFeO3 bilayer
interface exchange coupling
between the two materials

$LaFeO_3$ layer
**XMLD Fe $L_3$**

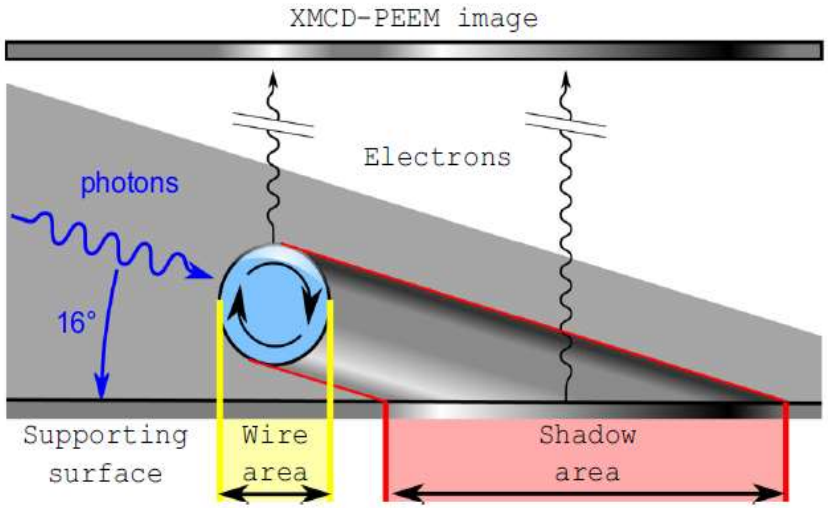
Co layer
**XMCD Co $L_3/L_2$**

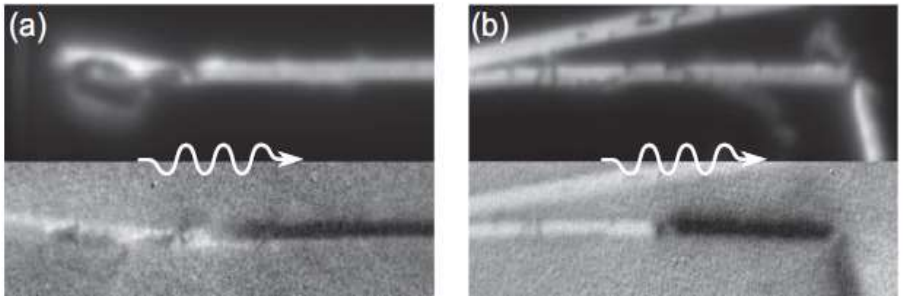


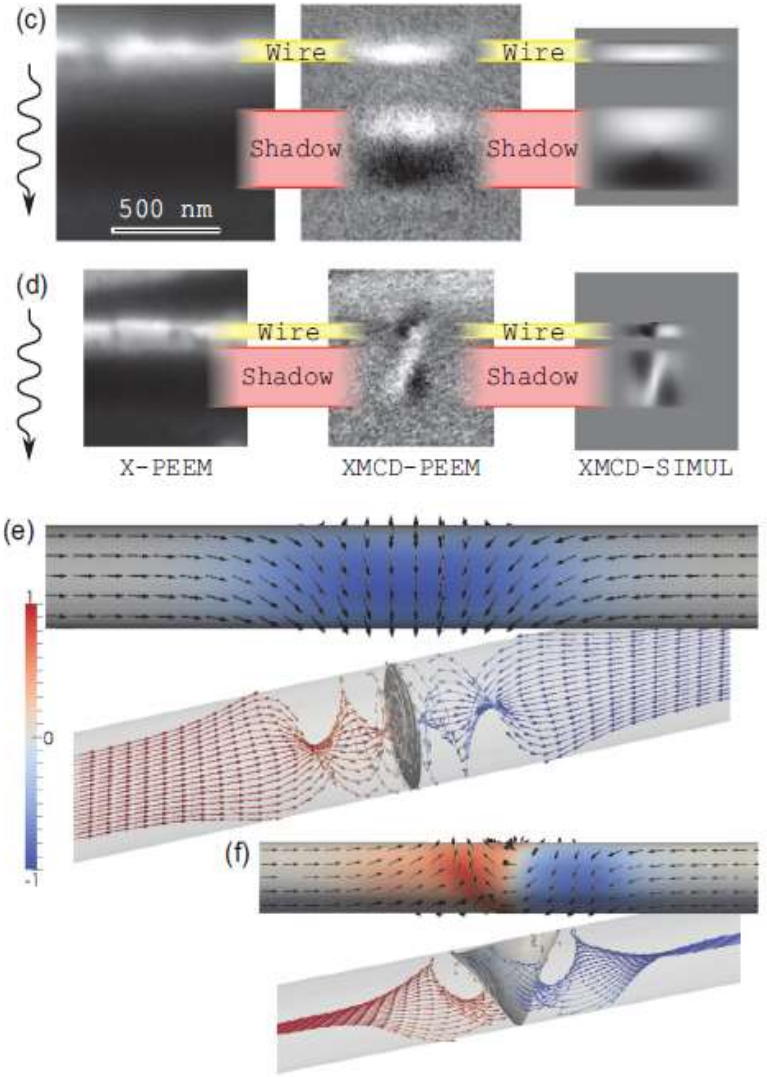
# DW imaging in magnetic wires

Elettra Sincrotrone Trieste

Observation of Bloch-point domain walls in cylindrical magnetic wir



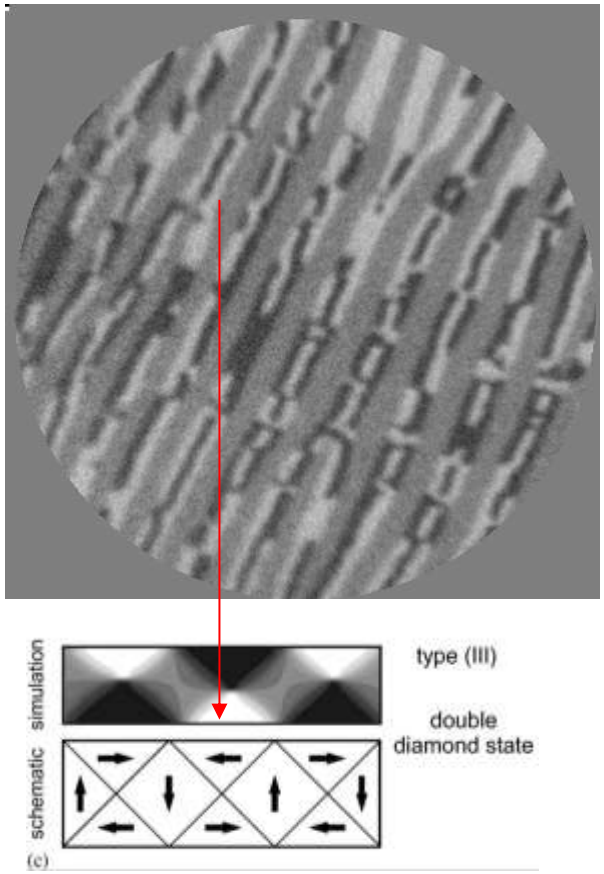



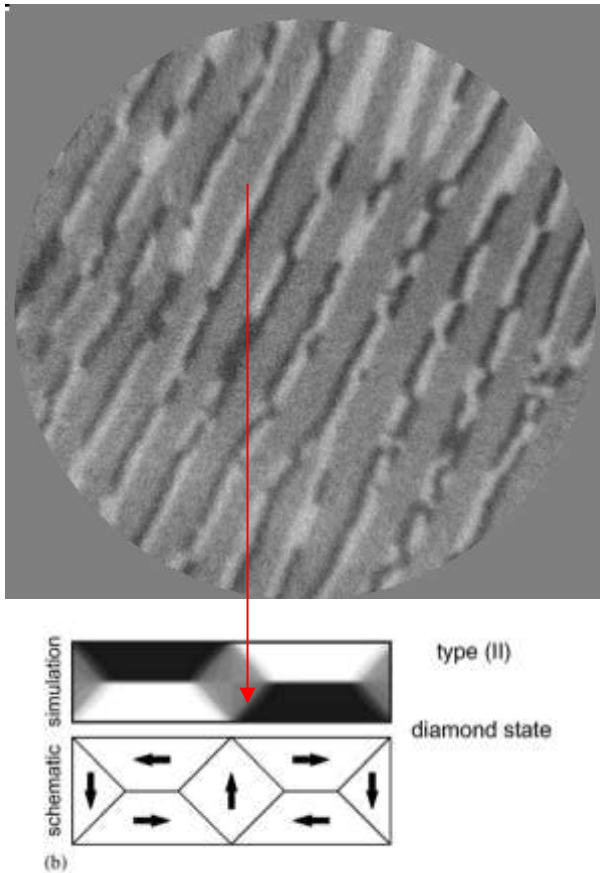

S. Da Col *et al.*, Phys. Rev. B**89**, 180405(R) (2014)

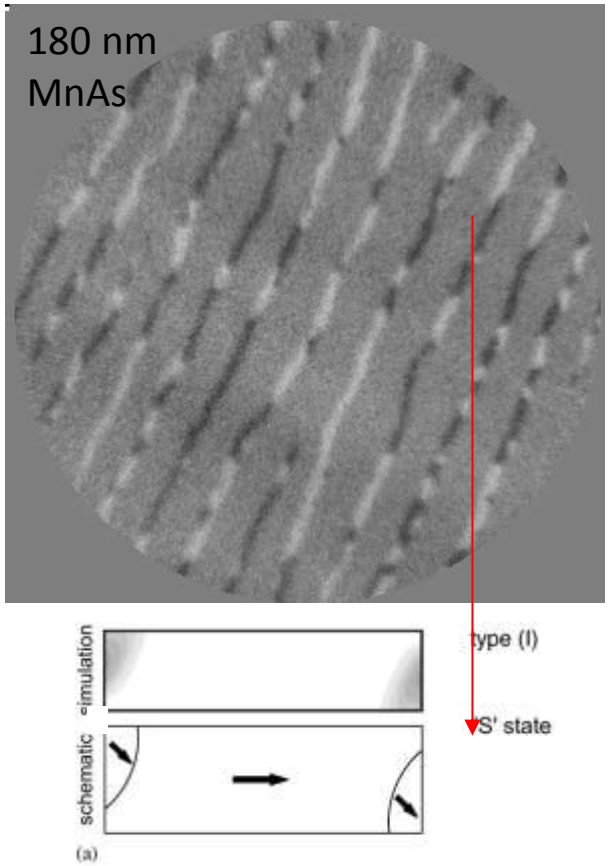
# Limited probing depth of XMCD: MnAs/GaAs

Elettra Sincrotrone Trieste

Experiment: Straight walls; Head to head domains

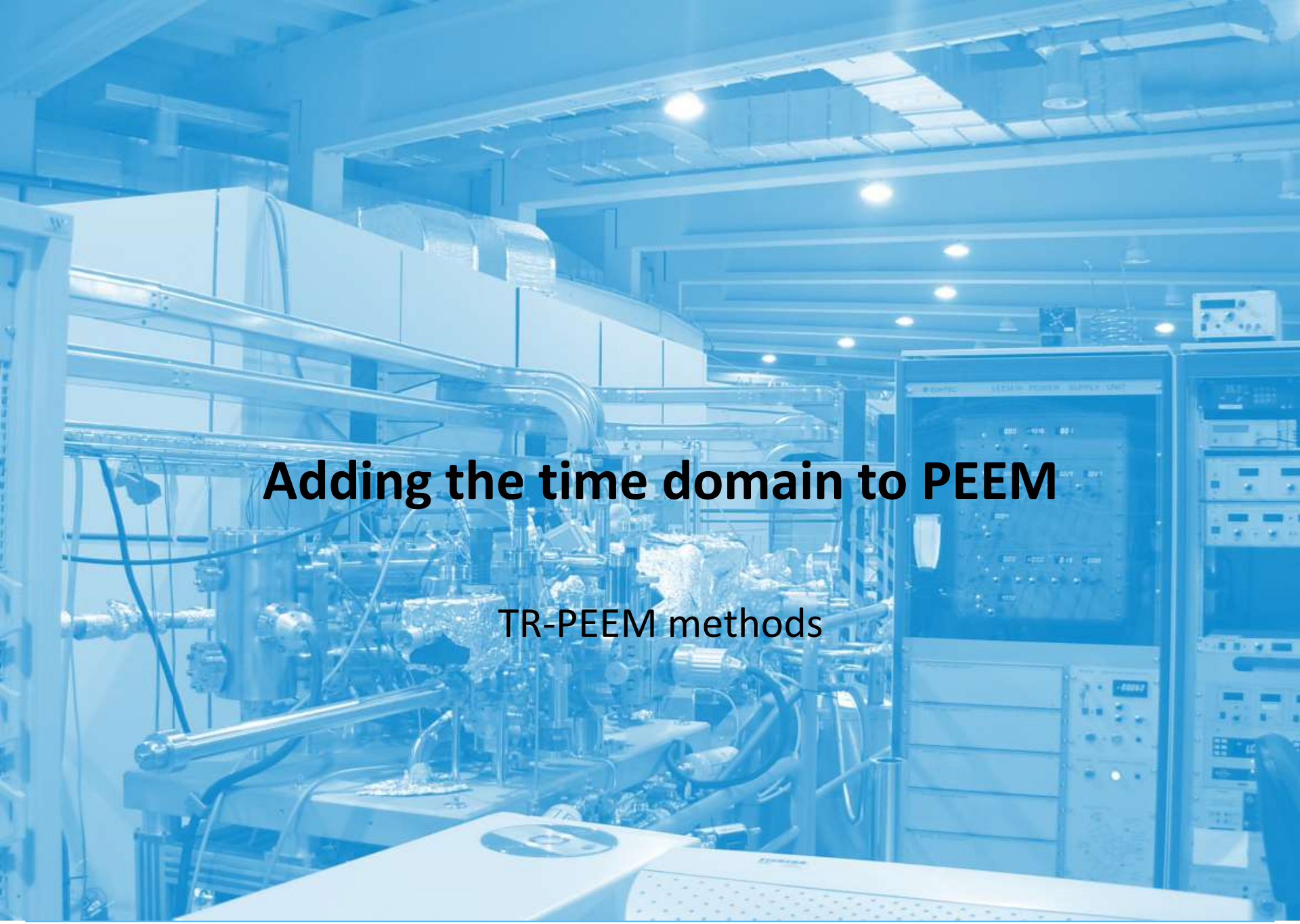



Simulation: Cross sectional cut: diamond state

R. Engel-Herbert et al, J. Magn. Magn. Mater. 305, (2006) 457



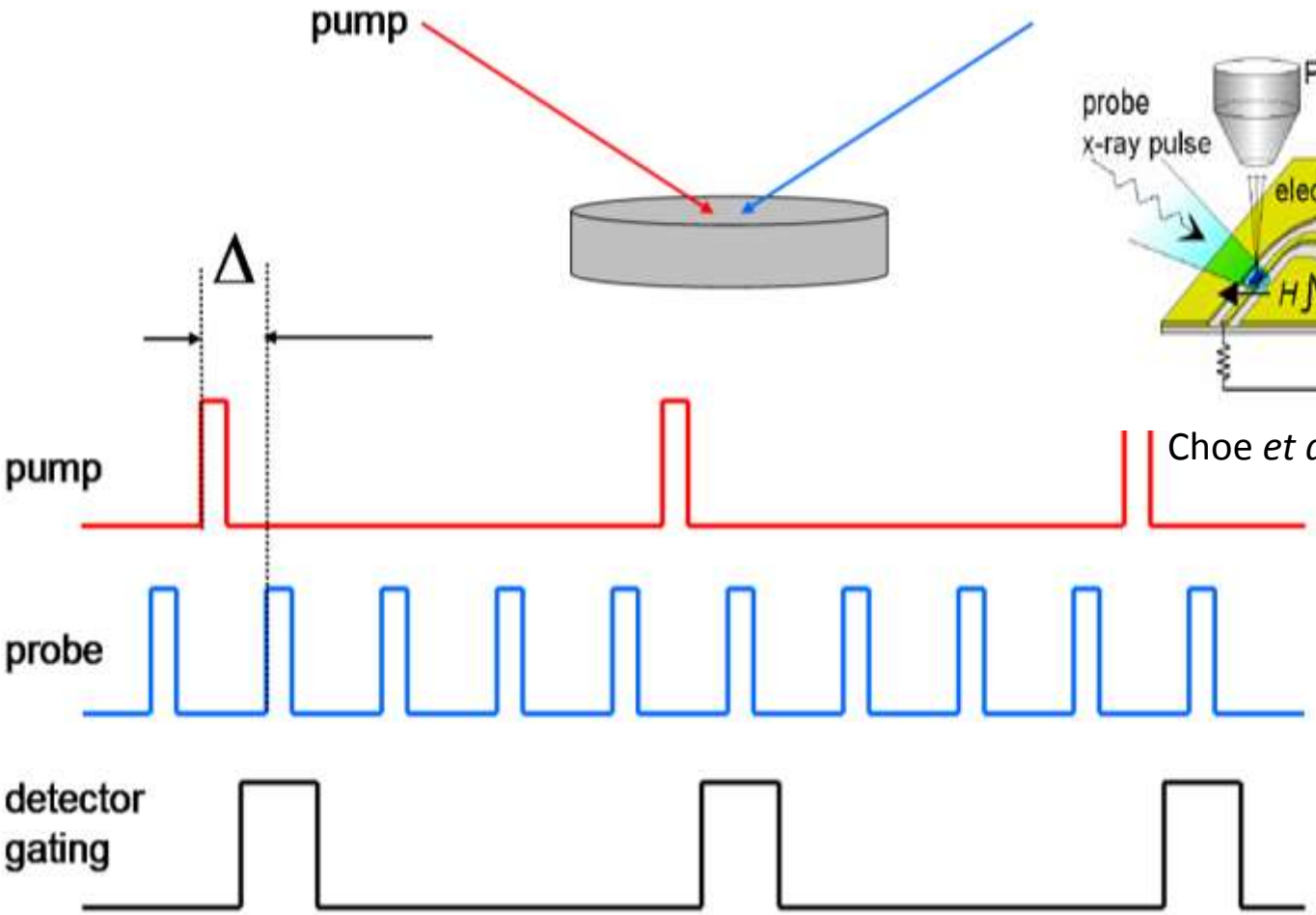
# Adding the time domain to PEEM

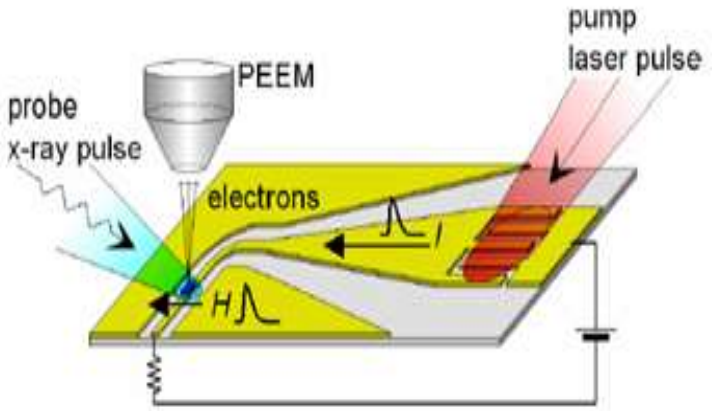
TR-PEEM methods

# Time-resolved PEEM: the stroboscopic approach

Elettra Sincrotrone Trieste

Stroboscopic experiments combine high lateral resolution of PEEM with high time resolution, taking advantage of pulsed nature of synchrotron radiation

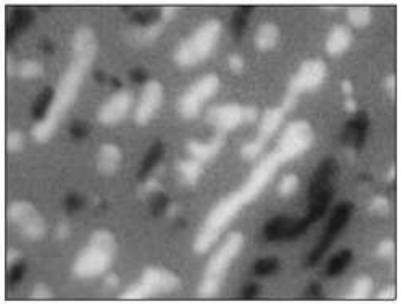


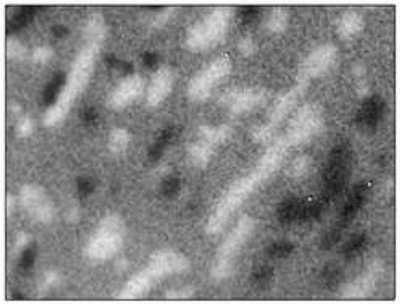

Choe *et al.,* Science 304, 420 (2004)

# Detector gating for time-resolved XMCD PEEM

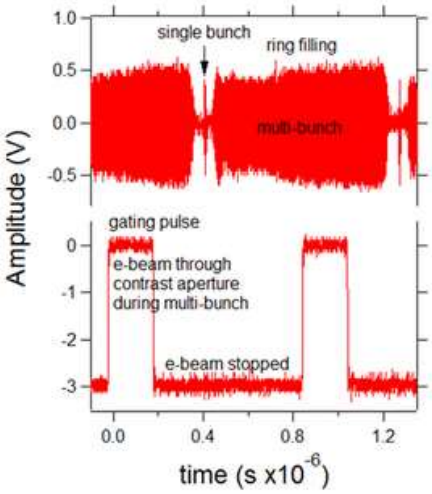
Elettra Sincrotrone Trieste



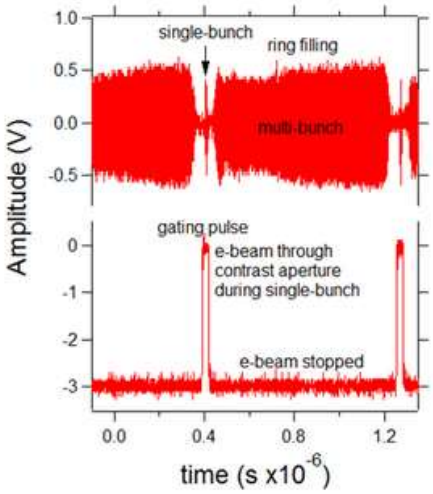
**Multi-bunch image**
32 images per helicity
Image exposure 4 s
Acquisition time: 5':18"



**Single bunch image**
24 images per helicity
Image exposure 20 s
Acquisition time: 17':40"




pulse width 200 ns

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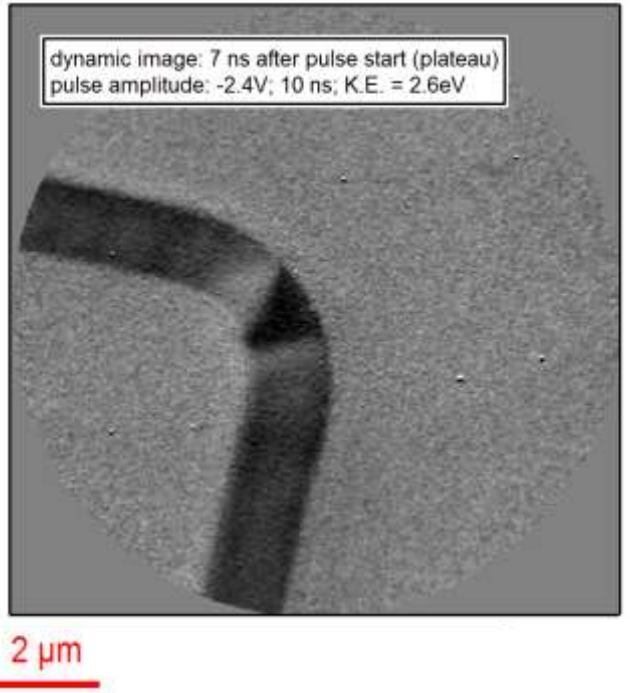


Current-induced motion of magnetic domain walls in Permalloy (Fe20Ni80) nanostripes, through the spin-transfer torque (STT) effect. Our measurements reveal clear eformations of the domain wall shape

J. Vogel, A. Locatelli *et al.,* in preparation

# Time resolved XMCD-PEEM: applications

Elettra Sincrotrone Trieste

- **Switching processes** (magnetisation reversal) in magnetic elements ( in spin valves, tunnel junction)
  - Nucleation, DW propagation or both?
  - Effect of surface topography, morphology crystalline structure etc.
  - Domain dynamics in Landau flux closure structures.
- response of vortices, domains, domain walls in Landau closure domains in the **precessional regime**
- **Stroboscopic technique**:
  - only reversible processes can be studied by pump – probe experiments
  - Measurements are quantitative

# Magnetic excitations in LFC structures

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**Quantitative Analysis of Magnetic Excitations in Landau Flux-Closure Structures Using Synchrotron-Radiation Microscopy**

J. Raabe,[1,*] C. Quitmann,[1] C. H. Back,[2] F. Nolting,[1] S. Johnson,[1] and C. Buehler[1]

The time dependent magnetization is described by the phenomenological Landau-Lifshitz-Gilbert equation

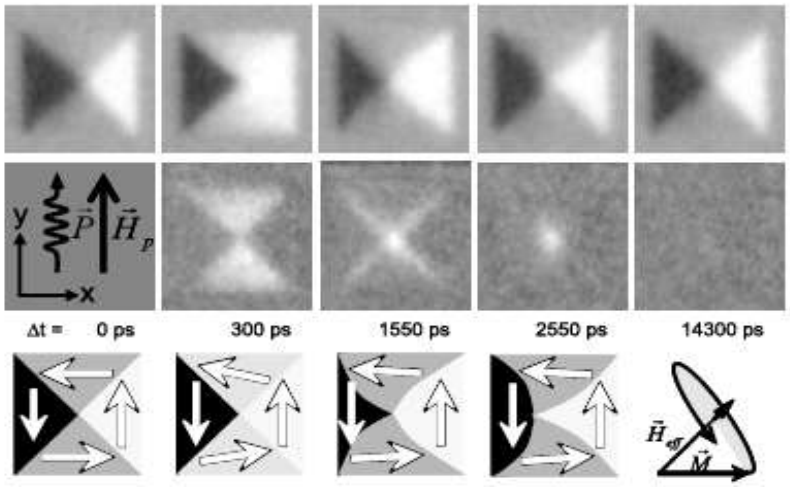
$$\frac{d}{dt}\vec{M} = -\gamma_0 \vec{M} \times \vec{H}_{\text{eff}} + \frac{\alpha}{M}\left(\vec{M} \times \frac{d}{dt}\vec{M}\right).$$

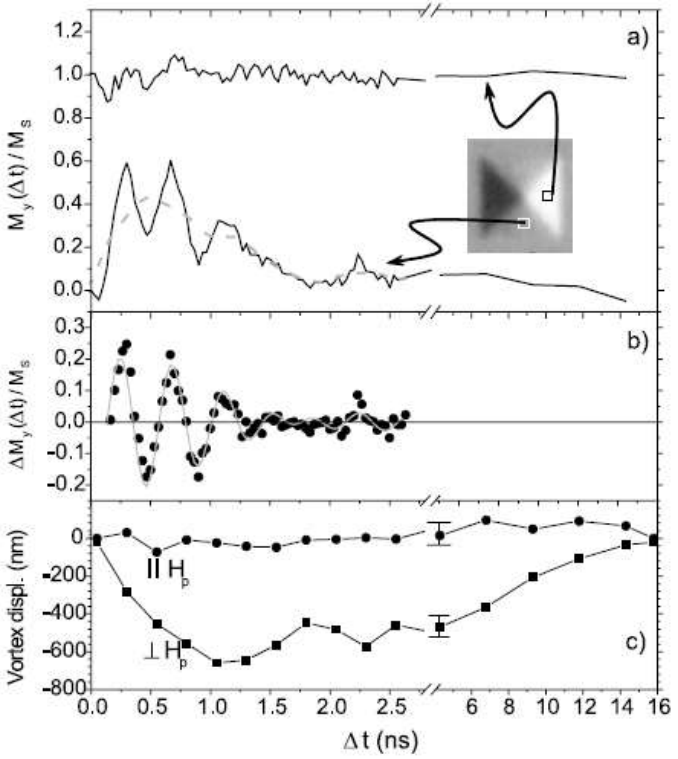
The first term describes the precession of the magnetization $\vec{M}$ about the total effective field $\vec{H}_{\text{eff}}$. The second term describes the relaxation back into the equilibrium state using the dimensionless damping parameter $\alpha$.

torque $\vec{T} = -\gamma_0 \vec{M} \times \vec{H}_{\text{eff}}$

xmcd

$t_i$-$t_0$



# Summary

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- XPEEM is a versatile full-field imaging technique. Combined with SR it allows us to implement laterally resolved versions of the most popular x-ray spectroscopies taking advantage of high flux of 3$^{rd}$ generation SR light sources.

- In particular, XAS-PEEM combines element sensitivity with chemical sensitivity (e.g. valence), and, more importantly, magnetic sensitivity. Magnetic imaging has been the most successful application of PEEM (next tutorial lecture!).

- XPEEM or energy-filtered PEEM adds true chemical sensitivity to PEEM. Modern instruments allow to combine chemistry with electronic structure using ARUPS.

- XPEEM can be complemented by LEEM, which adds structure sensitivity and capability to monitor dynamic processes.

- Lateral resolution will approach the nm range as AC instruments become available. Limitations due to space charge are not yet clear

- Novel application field are being approached, such as biology, geology and earth sciences. HAXPES will increase our capabilities to probe buried structures (bulk).

# Review work

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## Reviews and topical papers on x-ray spectromicroscopy and XPEEM


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# Credits & Acknowledgments

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## Thank you for attention!

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