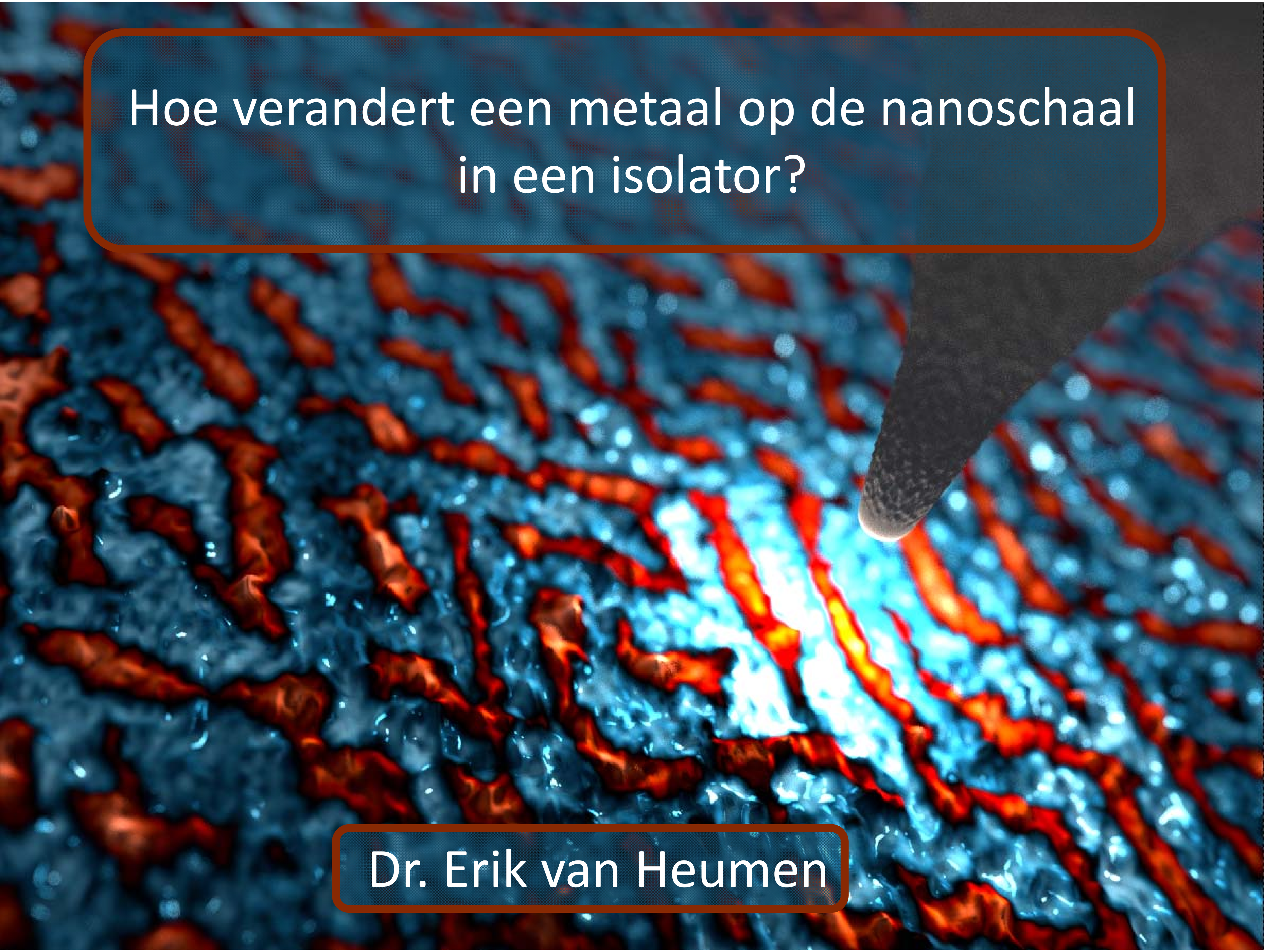
Hoe verandert een metaal op de nanoschaal in een isolator?

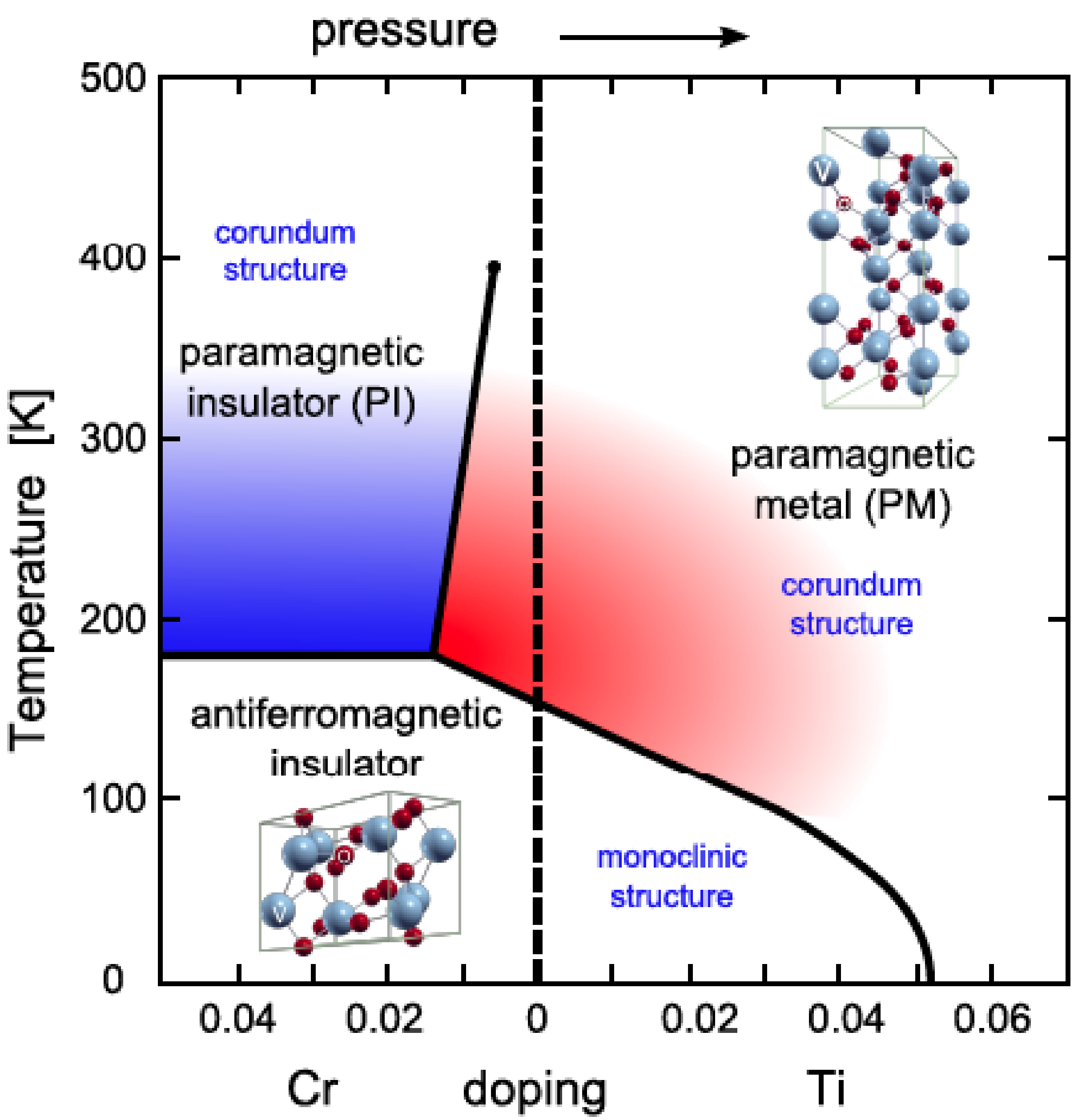


Dr. Erik van Heumen

Outline

- Hoe/waarom verandert een metaal in een isolator?
- Hoe maak je dit zichtbaar op de nanoschaal?

Metaal-Isolator overgang in V_2O_3



Sterk wisselwerkend metaal

Structurele en magnetische overgangen

Wat drijft de overgang van metaal naar isolator?

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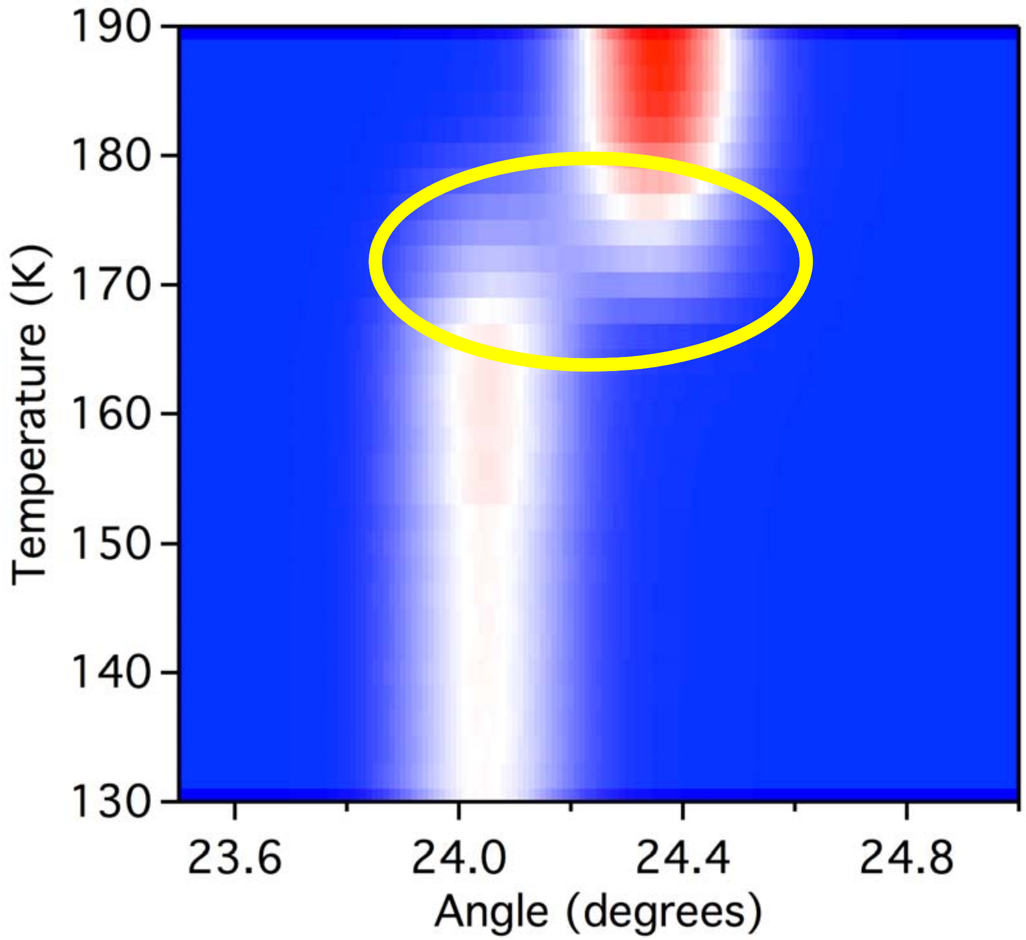
V_2O_3 kristal structuur

300 nm film V_2O_3 op saffier

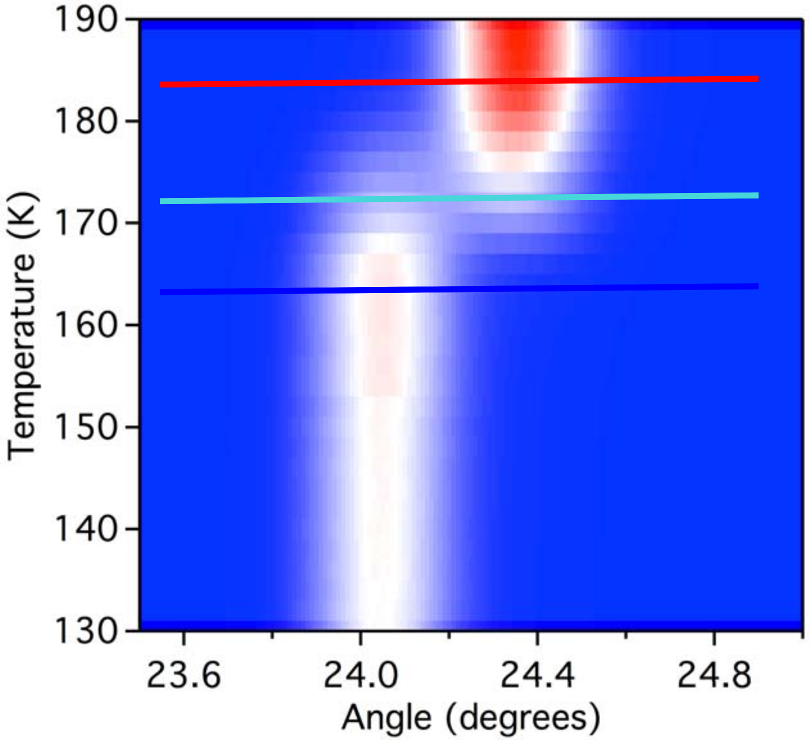
rontgen diffractie: ([110] and [012] peaks)

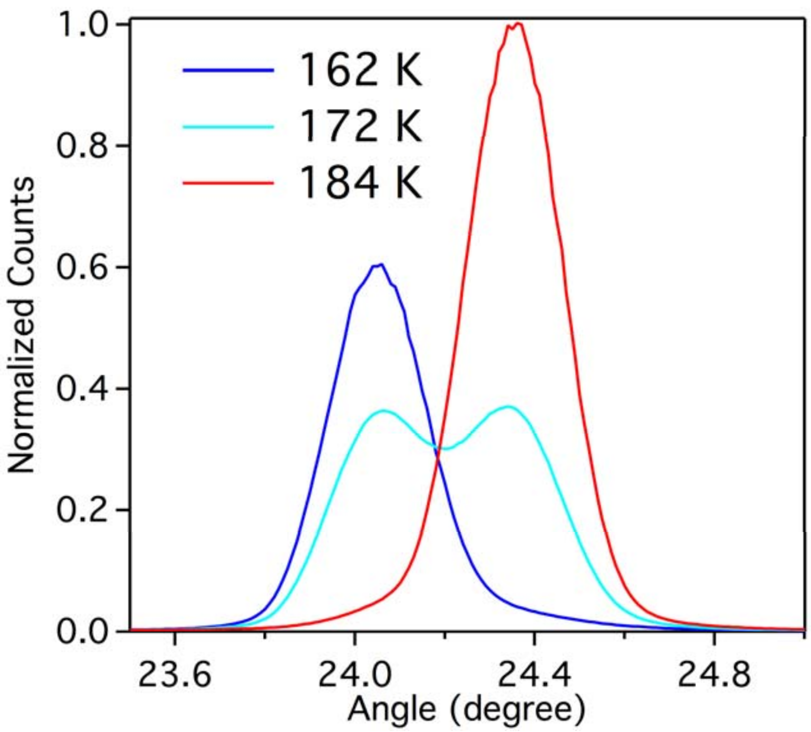


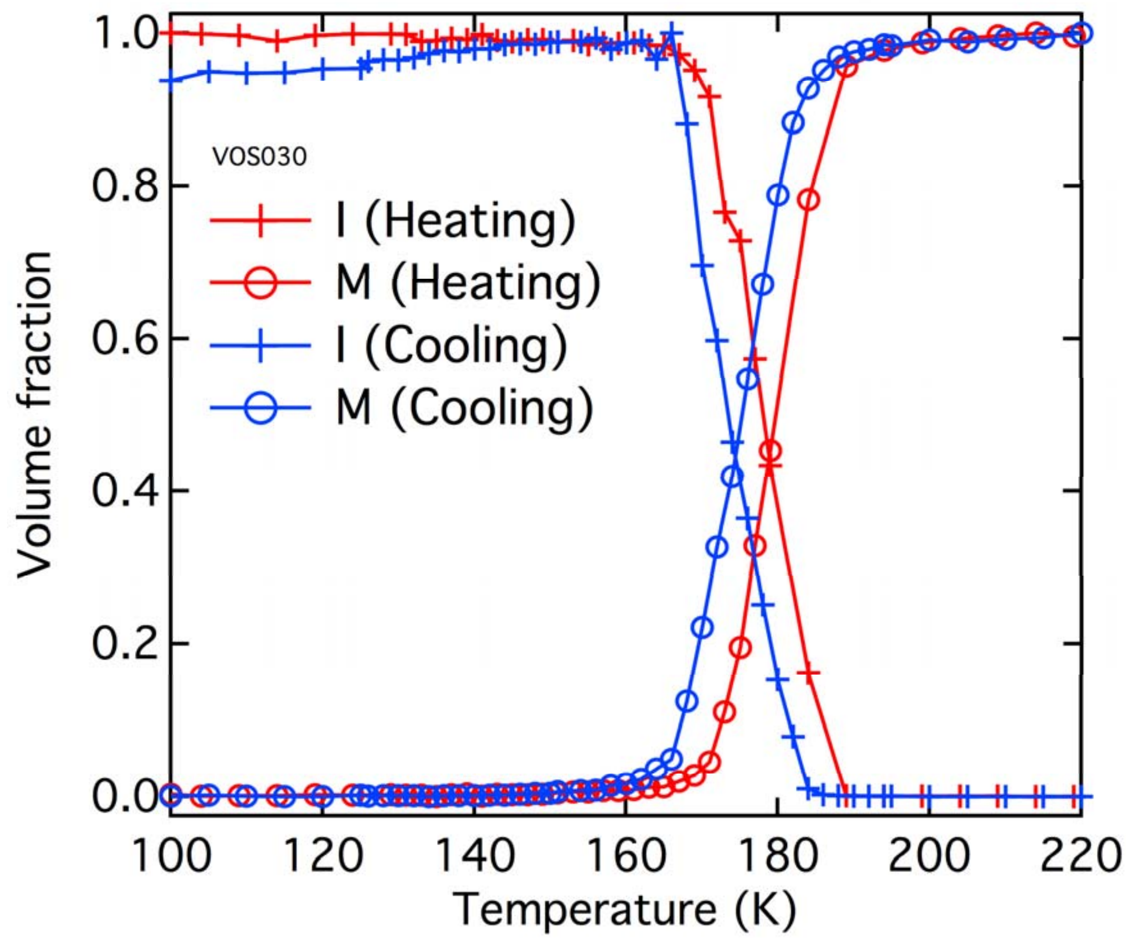
2 structuren bij dezelfde T

C Meneghini et al., J. Phys.: Condens. Matter **21** (2009) 355401

V_2O_3 kristal structuur







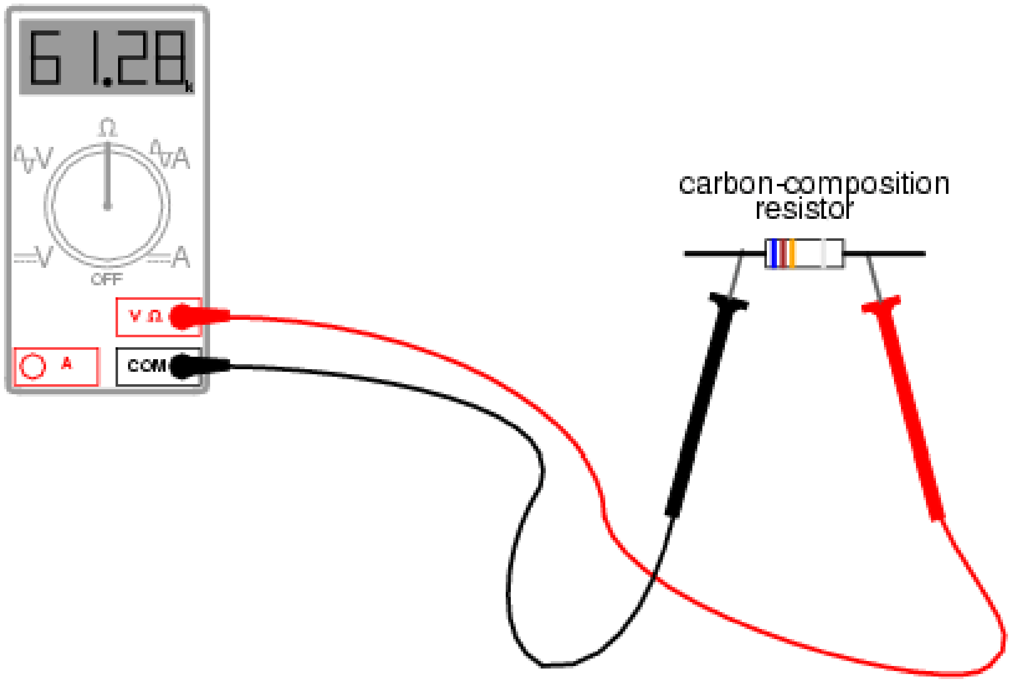
Volgen de elektronen de kristal structuur?

Outline

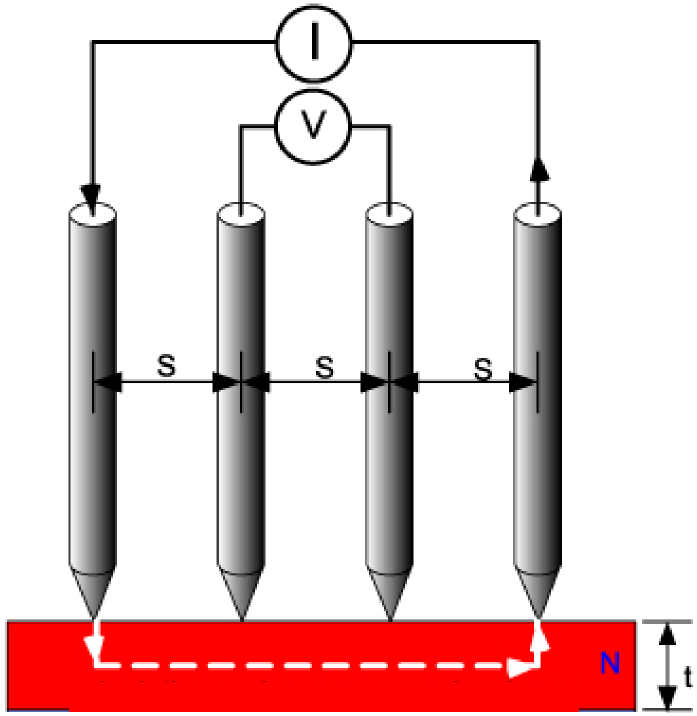
- Hoe/waarom verandert een metaal in een isolator?
- Hoe maak je dit zichtbaar op de nanoschaal?

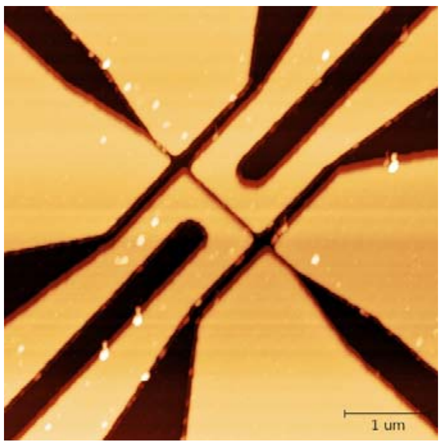
Weerstand?

Methode nr. 1



Methode nr. 2

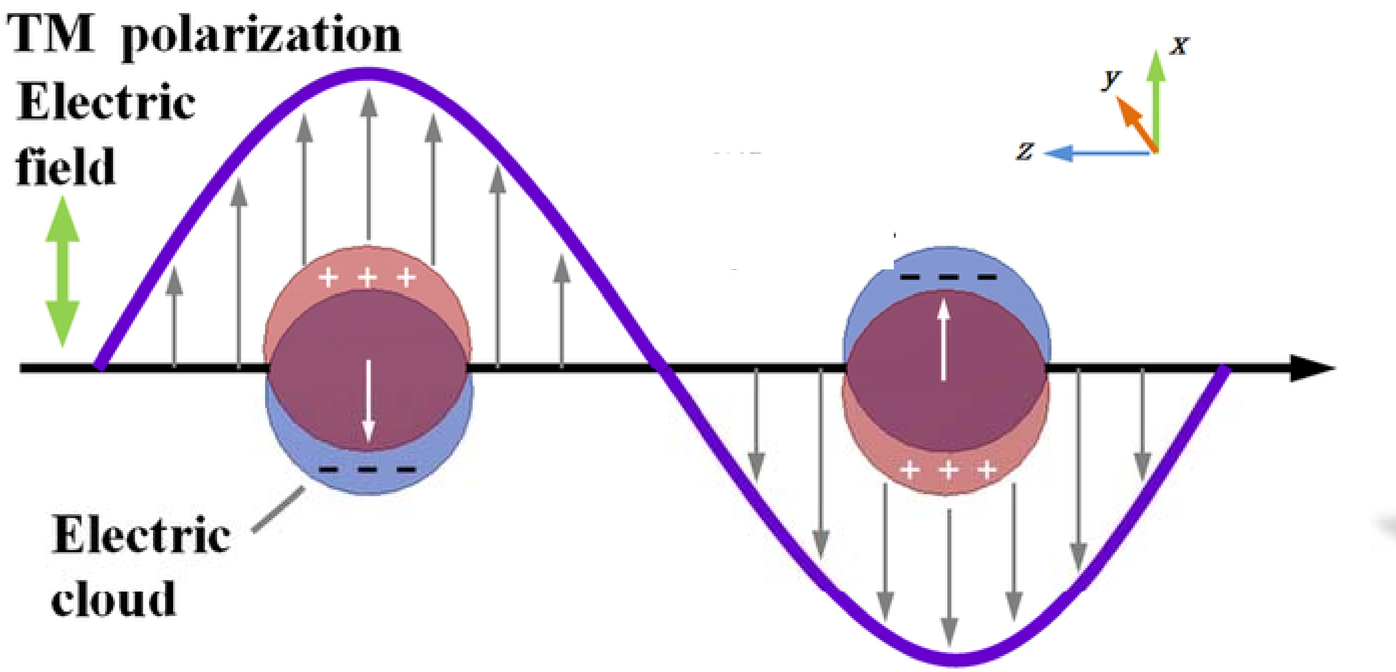




50 nm contact afstand !

A. Caviglia, TUDelft

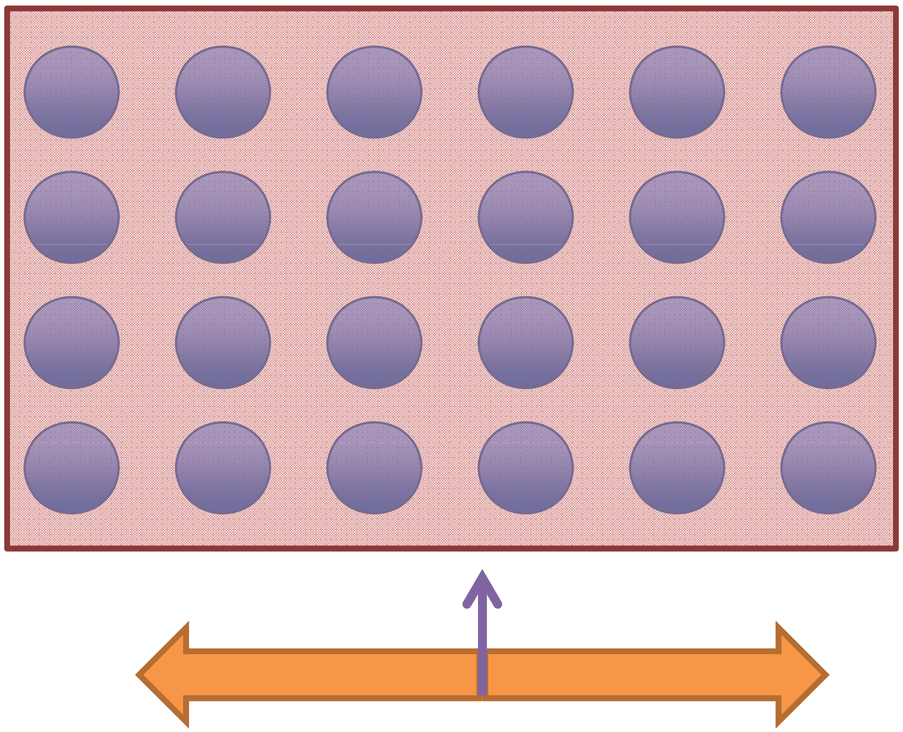
- Licht (foton) is een wisselend elektromagnetisch veld!



Het Drude model

Vrije lading

Ionen



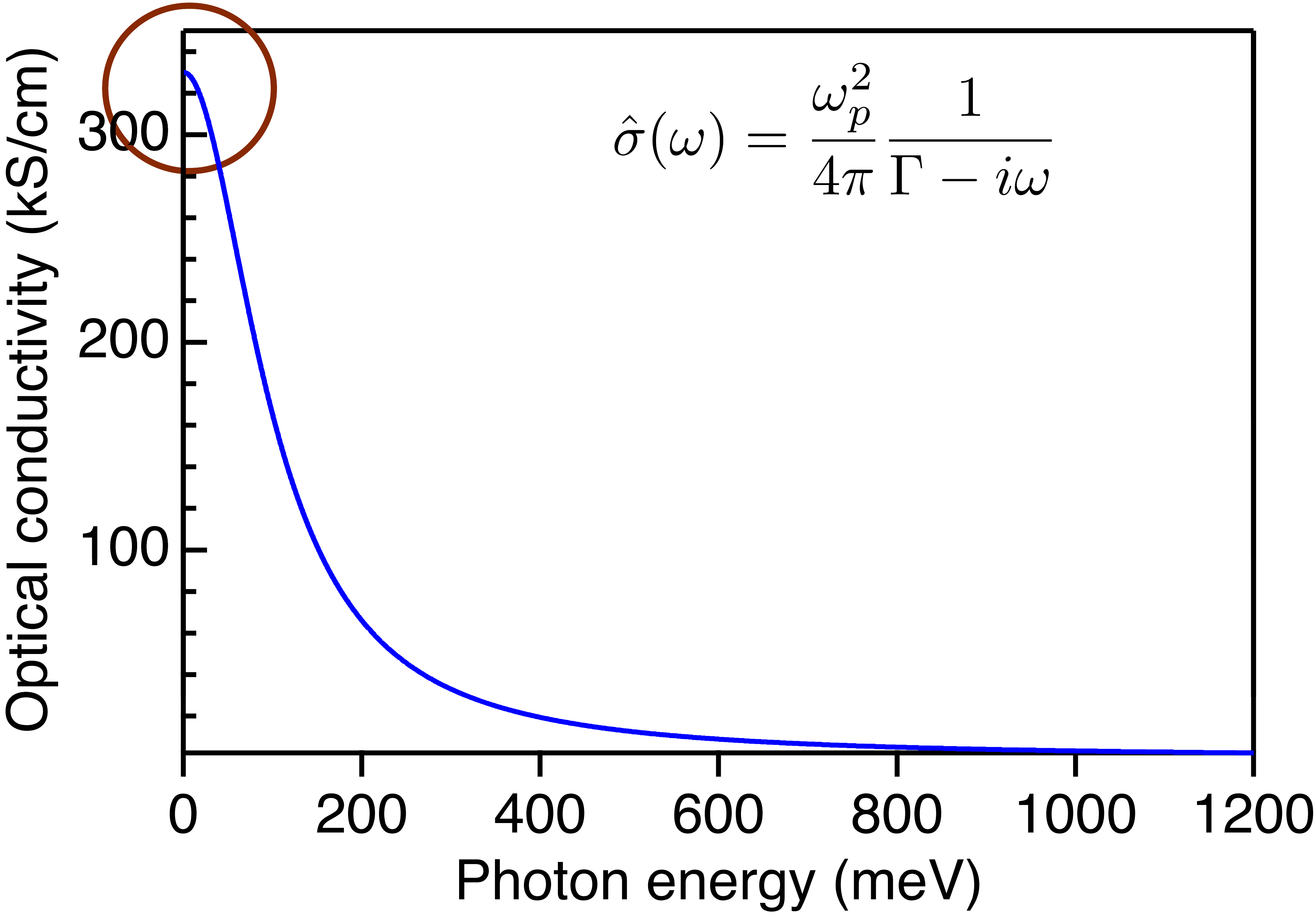
foton

- Het Drude model beschrijft metalen.
- Elektronen botsen met ionen.

Paul Drude

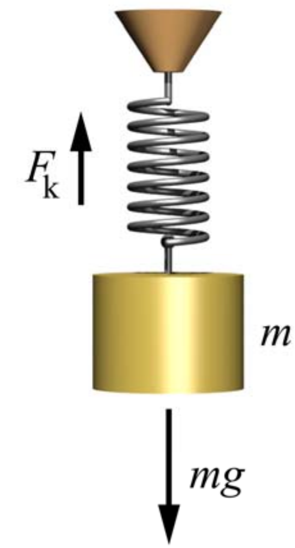
De optische geleiding

1/weerstand!



De optische geleiding

- Lorentz bedacht wat er gebeurde als de elektronen ’vast’ zaten.
- Hij nam aan dat er een ‘nieuwe’ kracht was die de elektronen aan de kernen gebonden hield (wet van Hooke).
- Dit is een model voor een isolator!



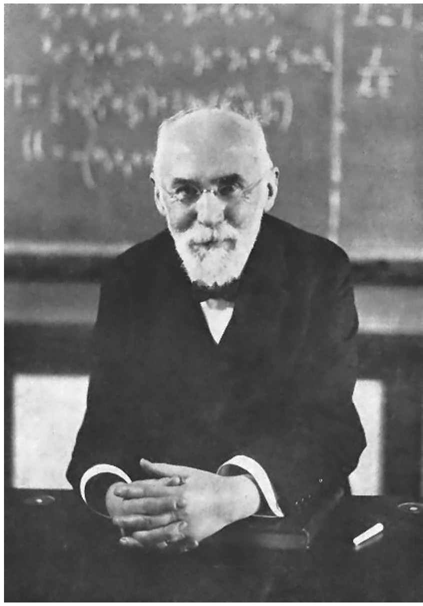
Drude

$$\hat{\sigma}(\omega) = \frac{\omega_p^2}{4\pi} \frac{1}{\Gamma - i\omega}$$

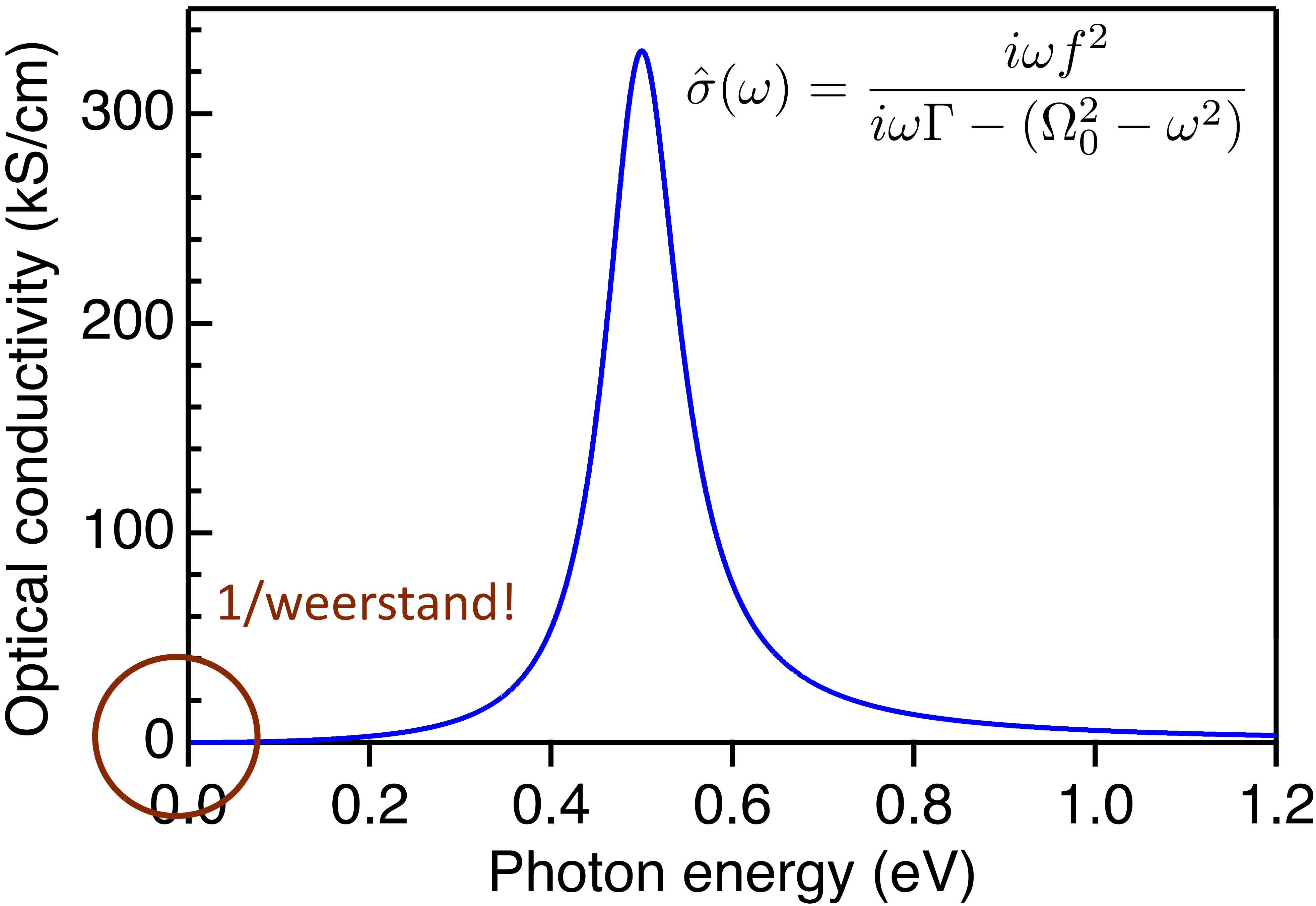
Lorentz

$$\hat{\sigma}(\omega) = \frac{i\omega f^2}{i\omega\Gamma - (\Omega_0^2 - \omega^2)}$$

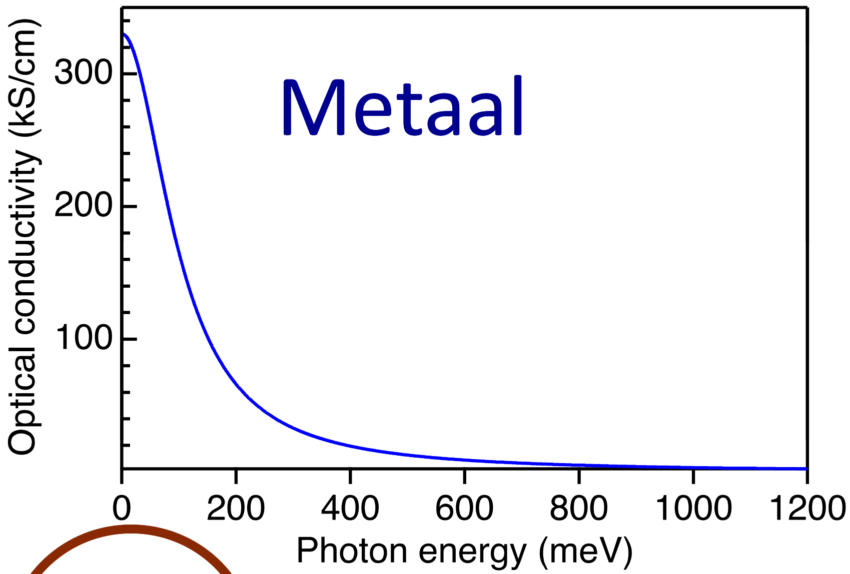
$$\Omega_0 = \sqrt{\frac{k}{m_e}}$$



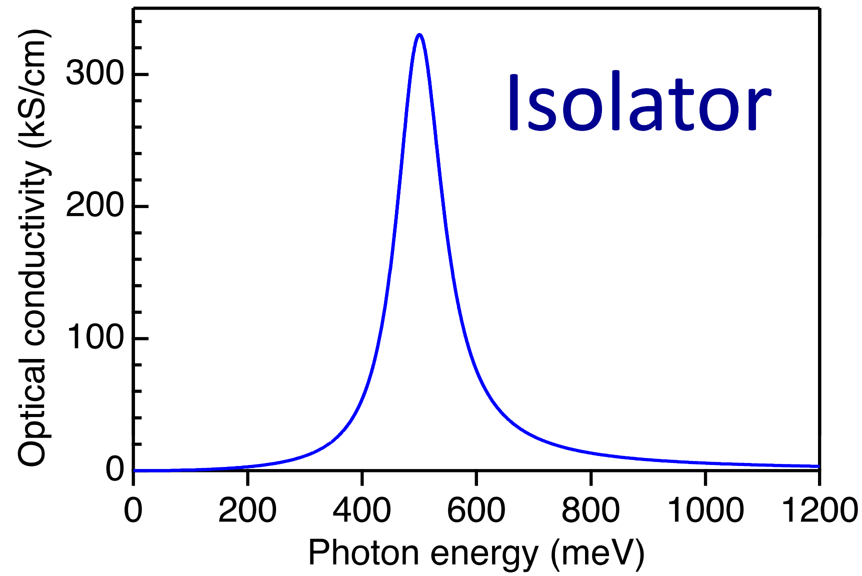
De optische geleiding



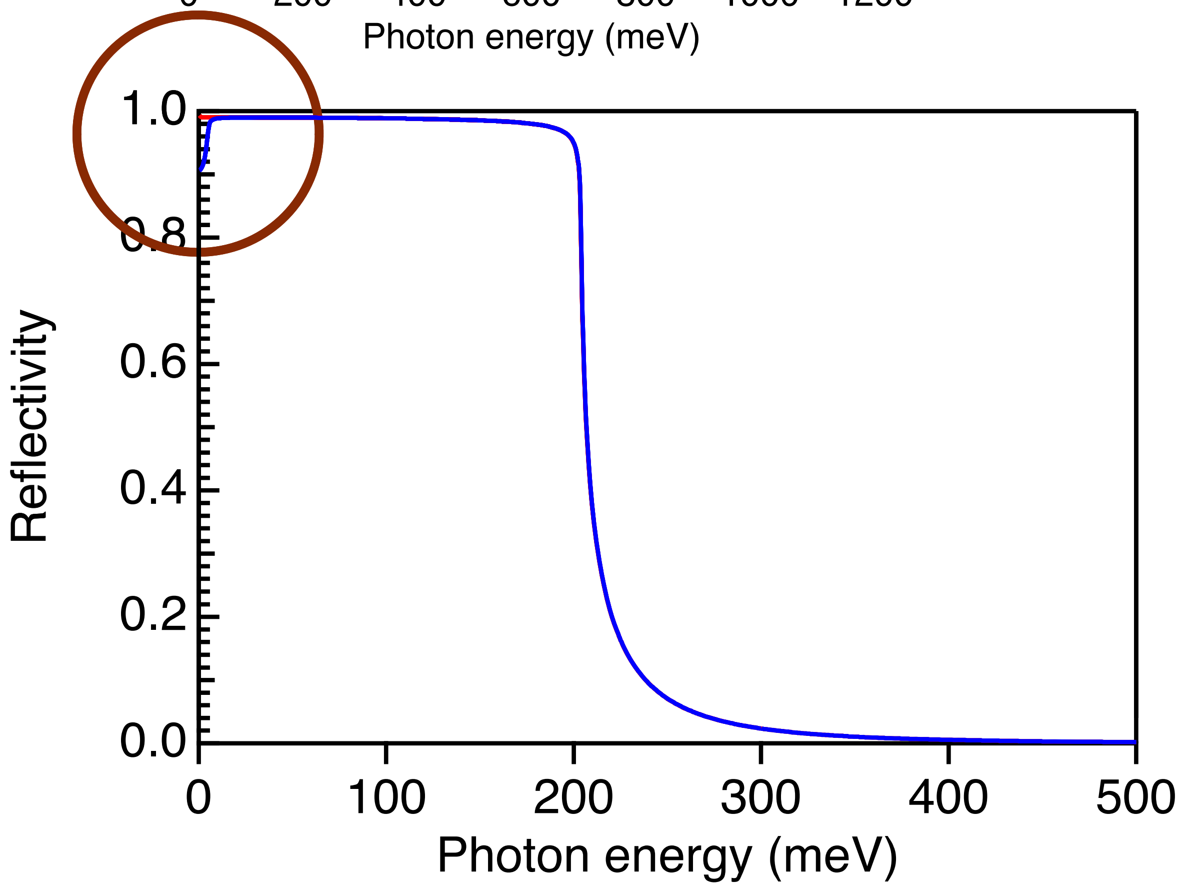
Probleem



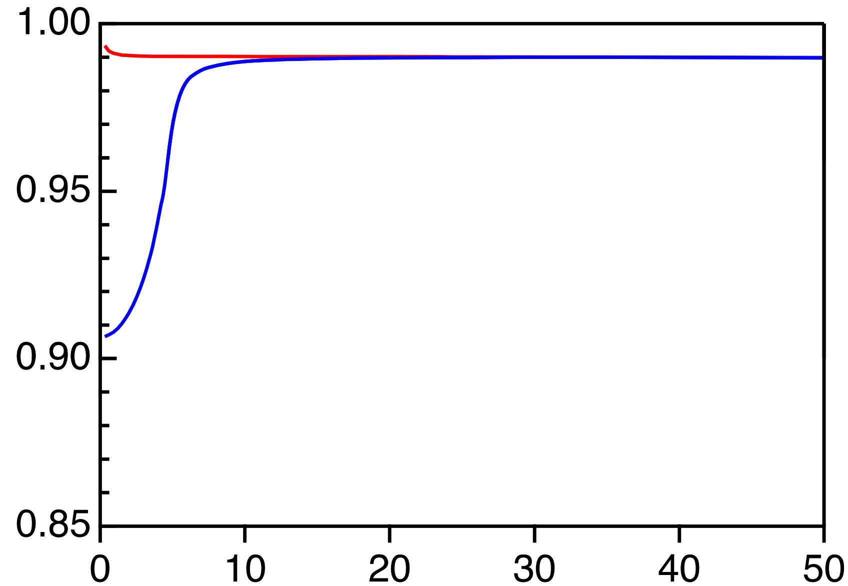
Metaal
Optical conductivity (kS/cm)
300
200
100
0
200
400
600
800
1000
1200
Photon energy (meV)



Isolator
Optical conductivity (kS/cm)
300
200
100
0
200
400
600
800
1000
1200
Photon energy (meV)

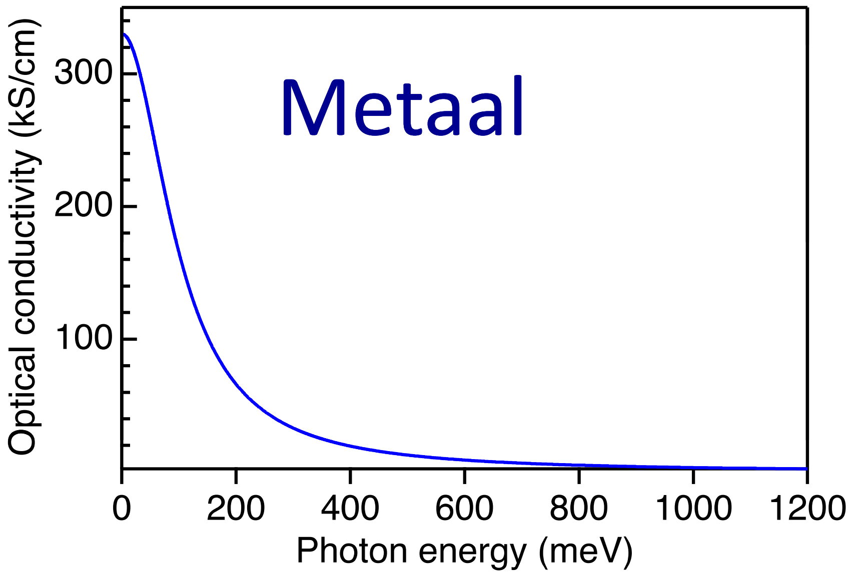


Reflectivity
1.0
0.8
0.6
0.4
0.2
0.0
0
100
200
300
400
500
Photon energy (meV)

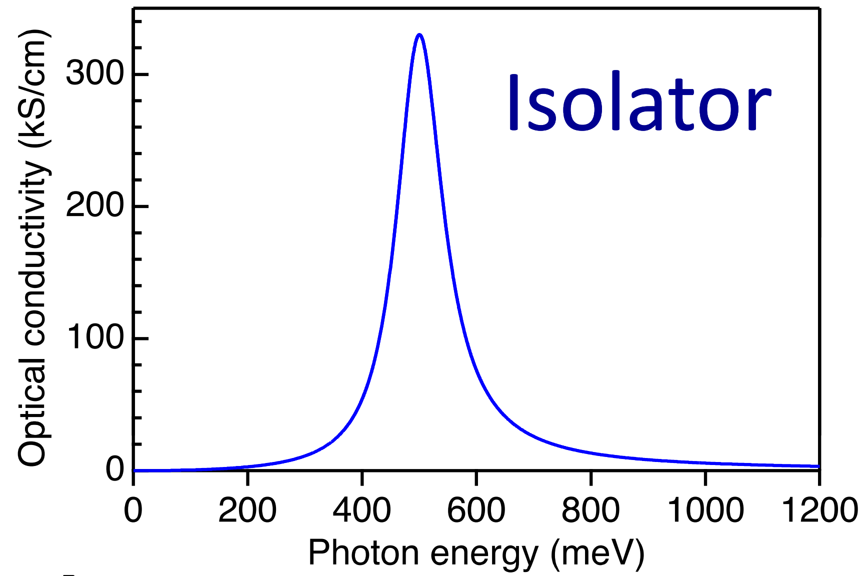


1.00
0.95
0.90
0.85
0
10
20
30
40
50

Probleem



Metaal
Optical conductivity (kS/cm)
300
200
100
0
200
400
600
800
1000
1200
Photon energy (meV)



Isolator
Optical conductivity (kS/cm)
300
200
100
0
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400
600
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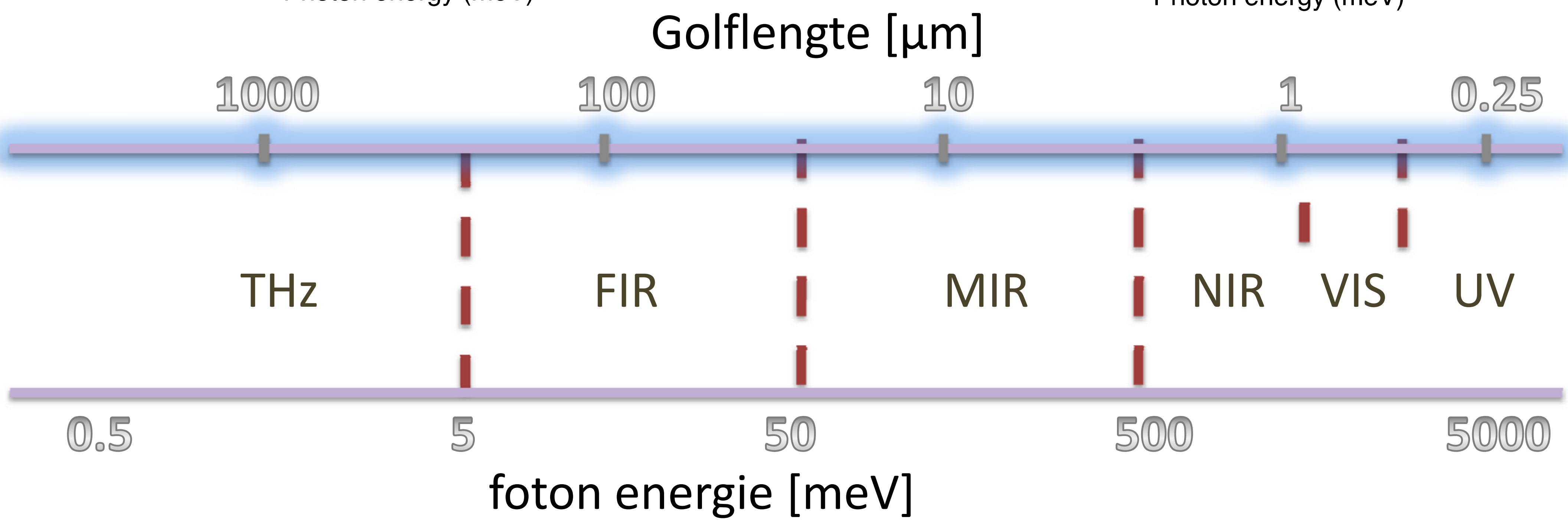
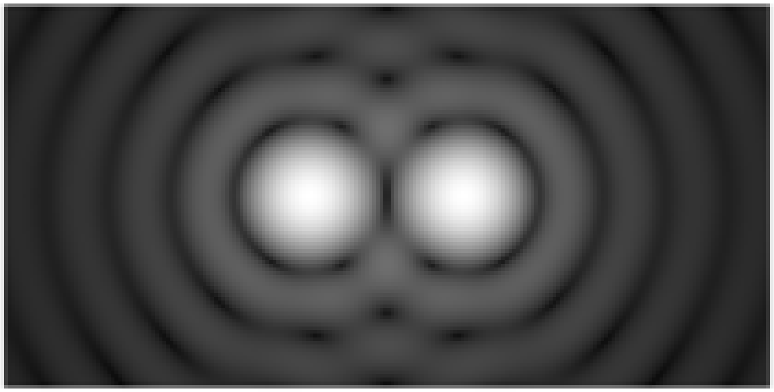
Photon energy (meV)



Golflengte [µm]
1000
100
10
1
0.25
THz
FIR
MIR
NIR
VIS
UV
0.5
5
50
500
5000
foton energie [meV]

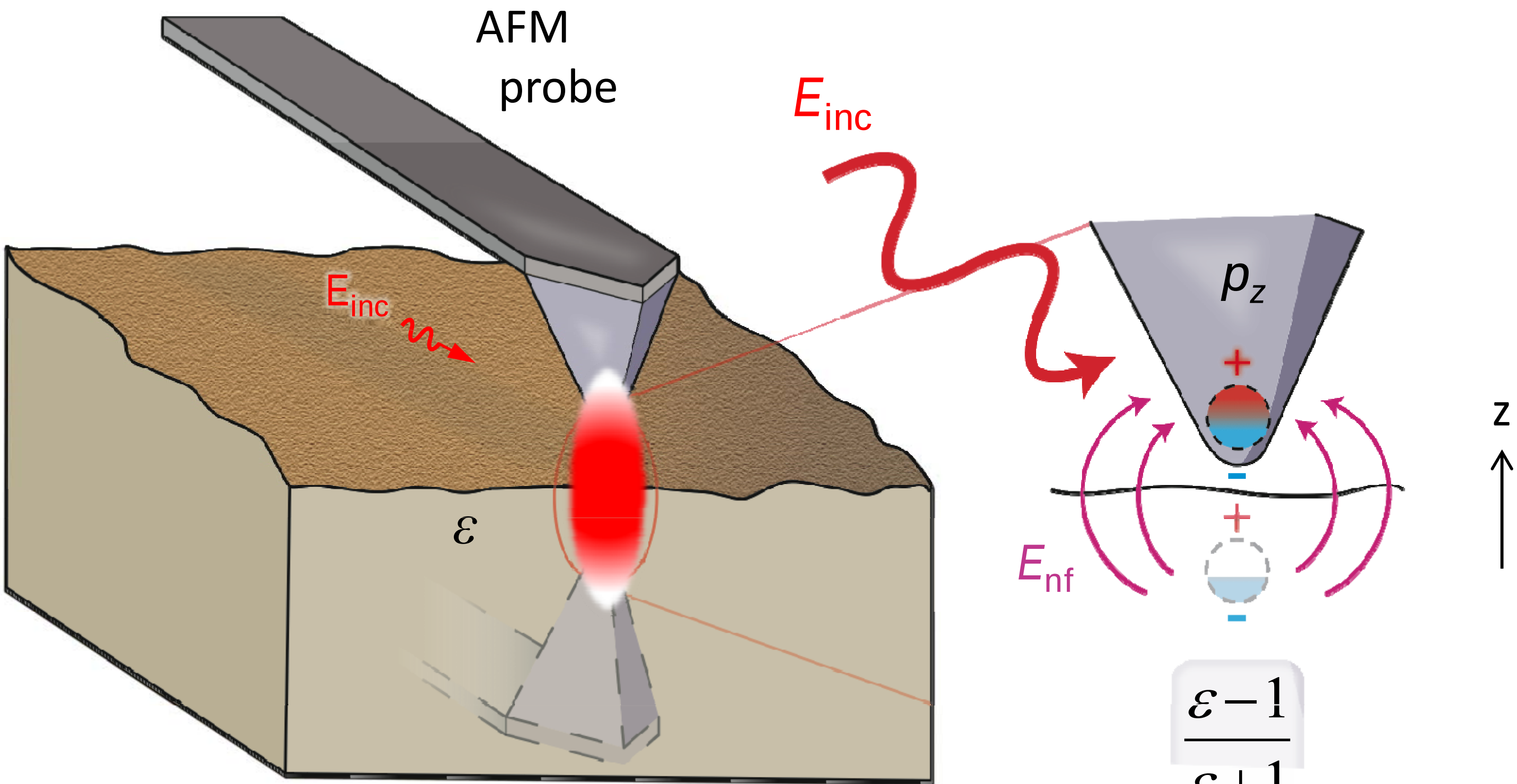
De diffractie limiet



Objecten kleiner dan de golflengte kun je niet onderscheiden!

Het optische verschil tussen metaal en isolator zie je bij 10-100 µm.

Nabije veld spectroscopie

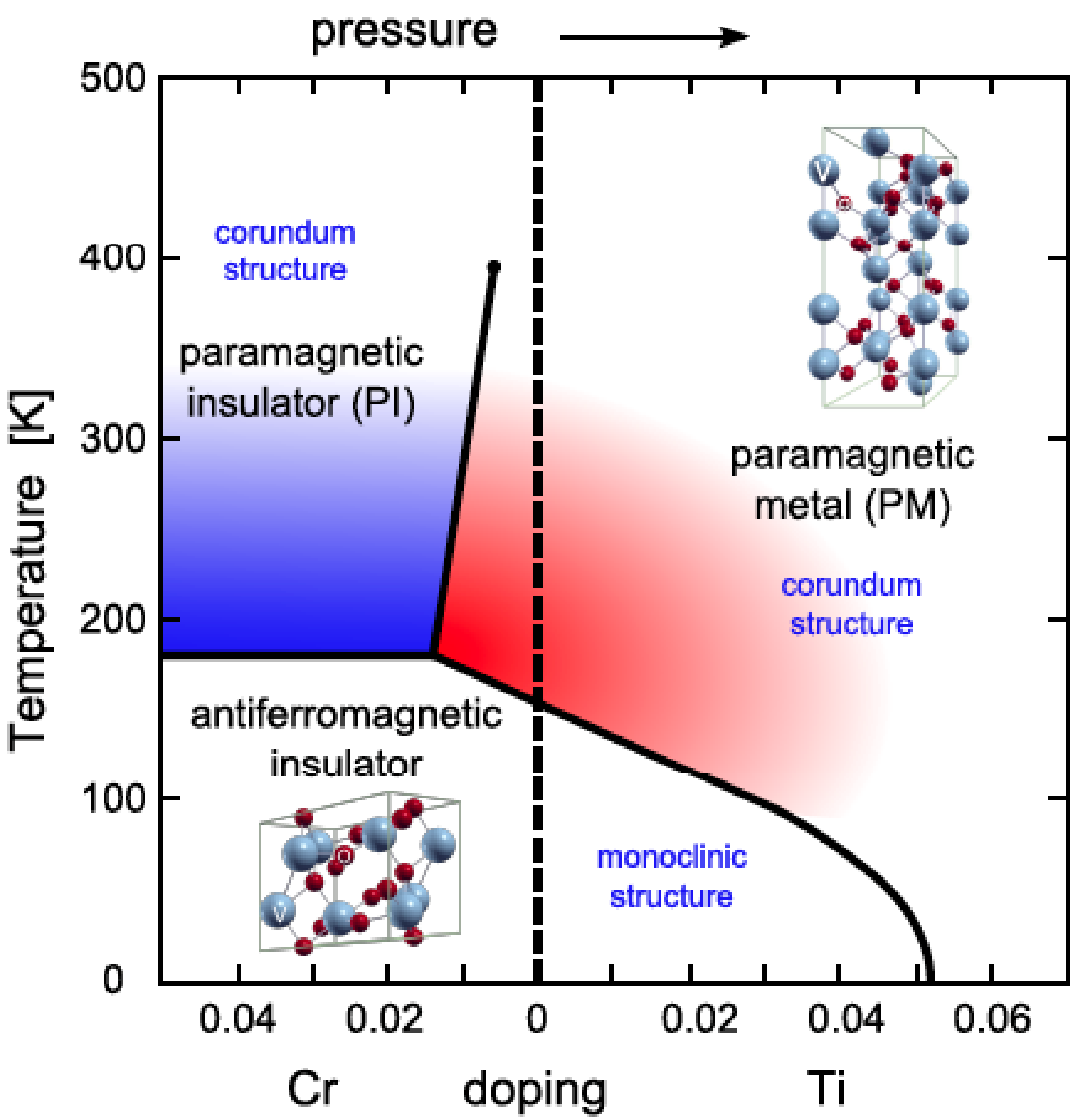


$$\frac{\varepsilon-1}{\varepsilon+1}$$

- Als je een metalen naald met laser licht bestraalt onstaat een dipool
- Door E_{scat} te meten terwijl de naald het oppervlak aftast, zie je optisch contrast

- E_{scat} bevat lokale informatie over optische geleiding met 20 nm resolution (≈ straal van AFM punt)

Metaal-Isolator overgang in V_2O_3



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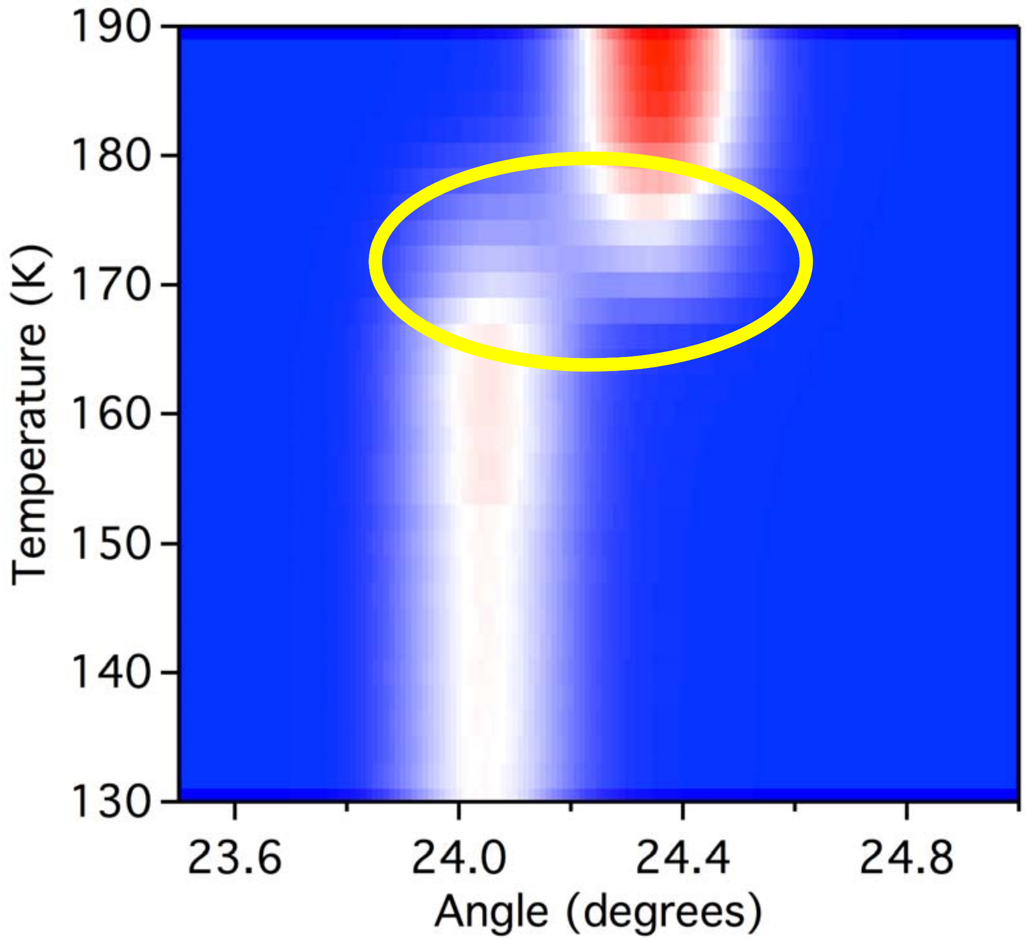
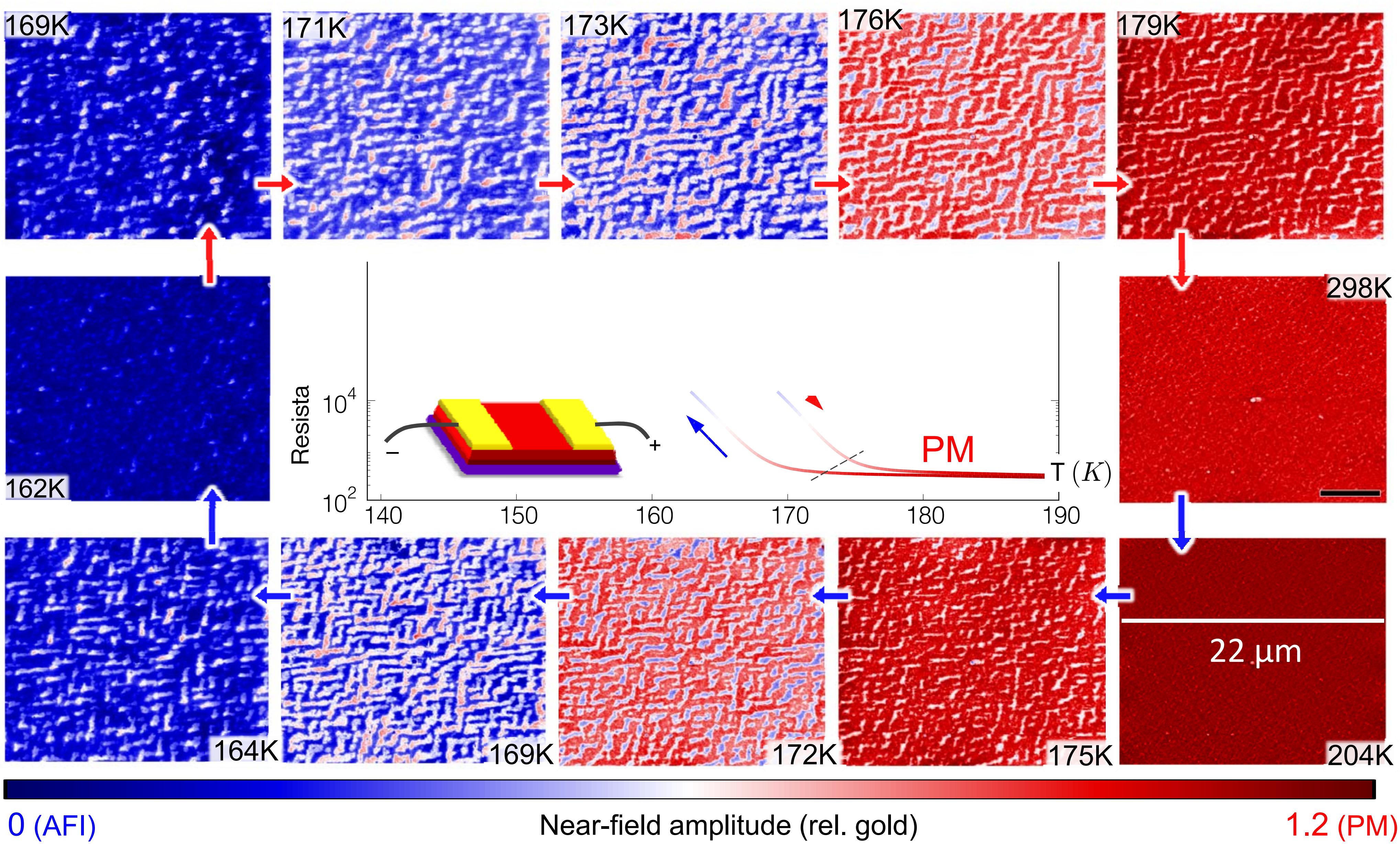


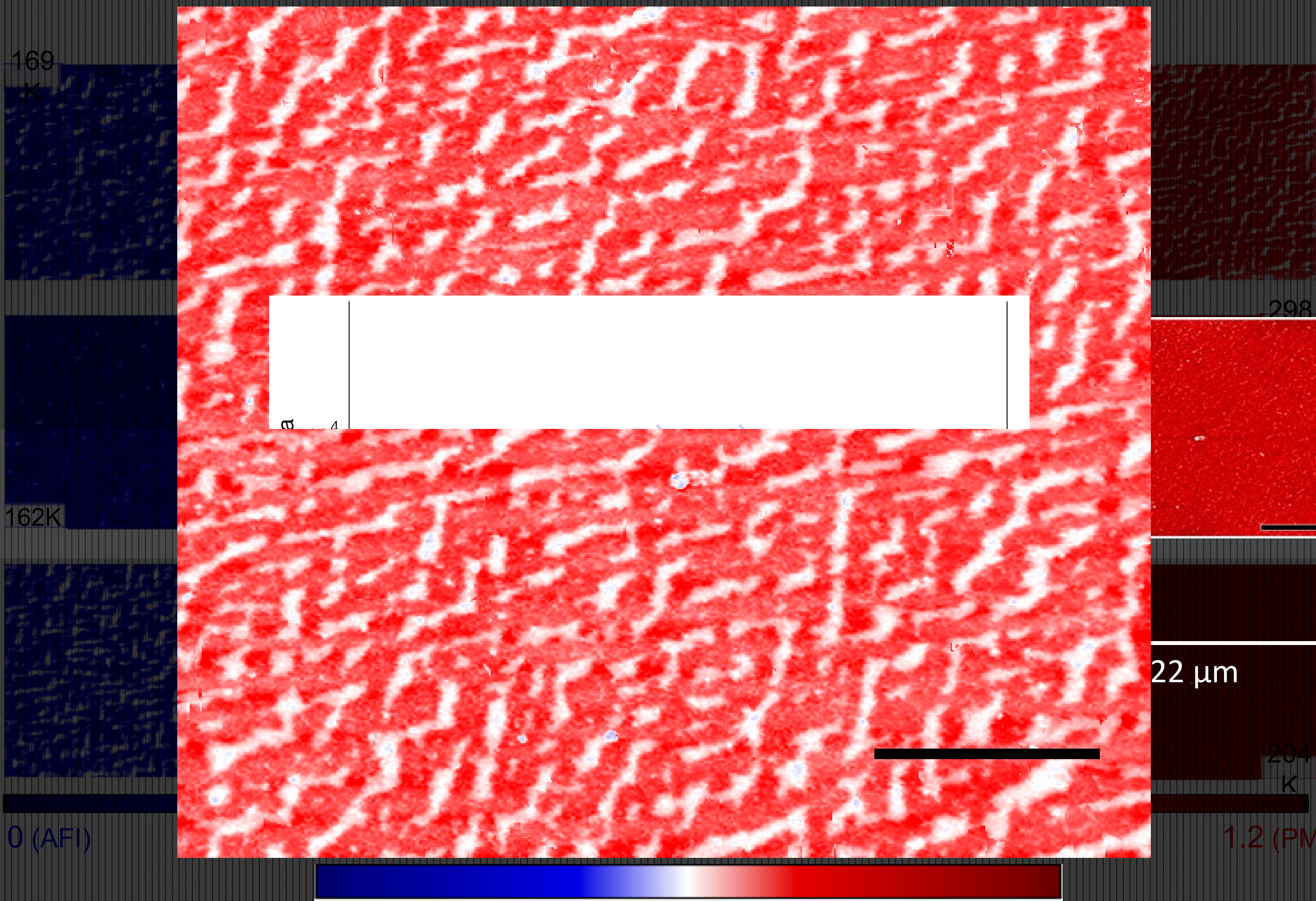
2 structuren bij dezelfde T

C Meneghini et al., J. Phys.: Condens. Matter **21** (2009) 355401

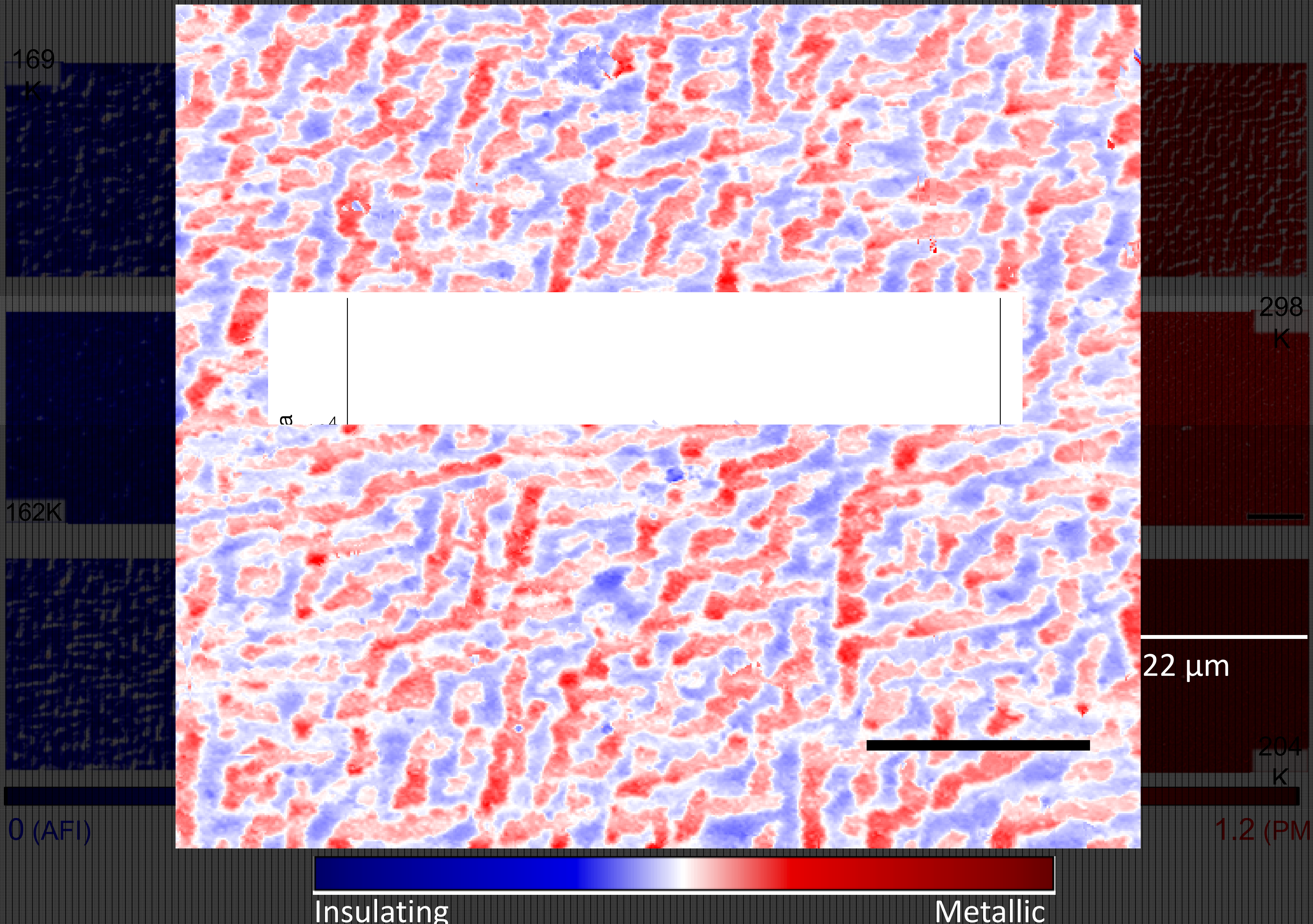
Near-field maps



Near-field maps



Near-field maps



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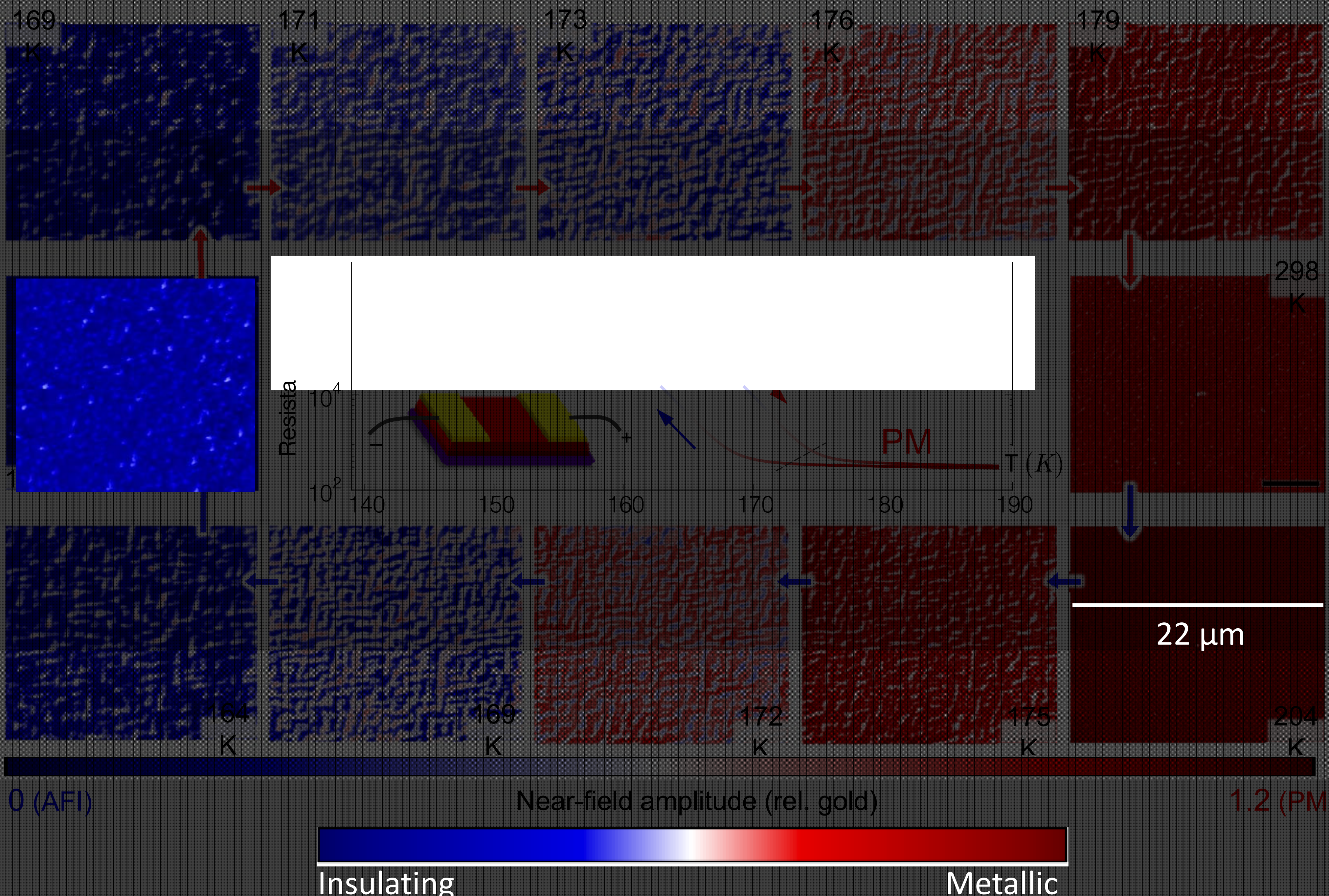

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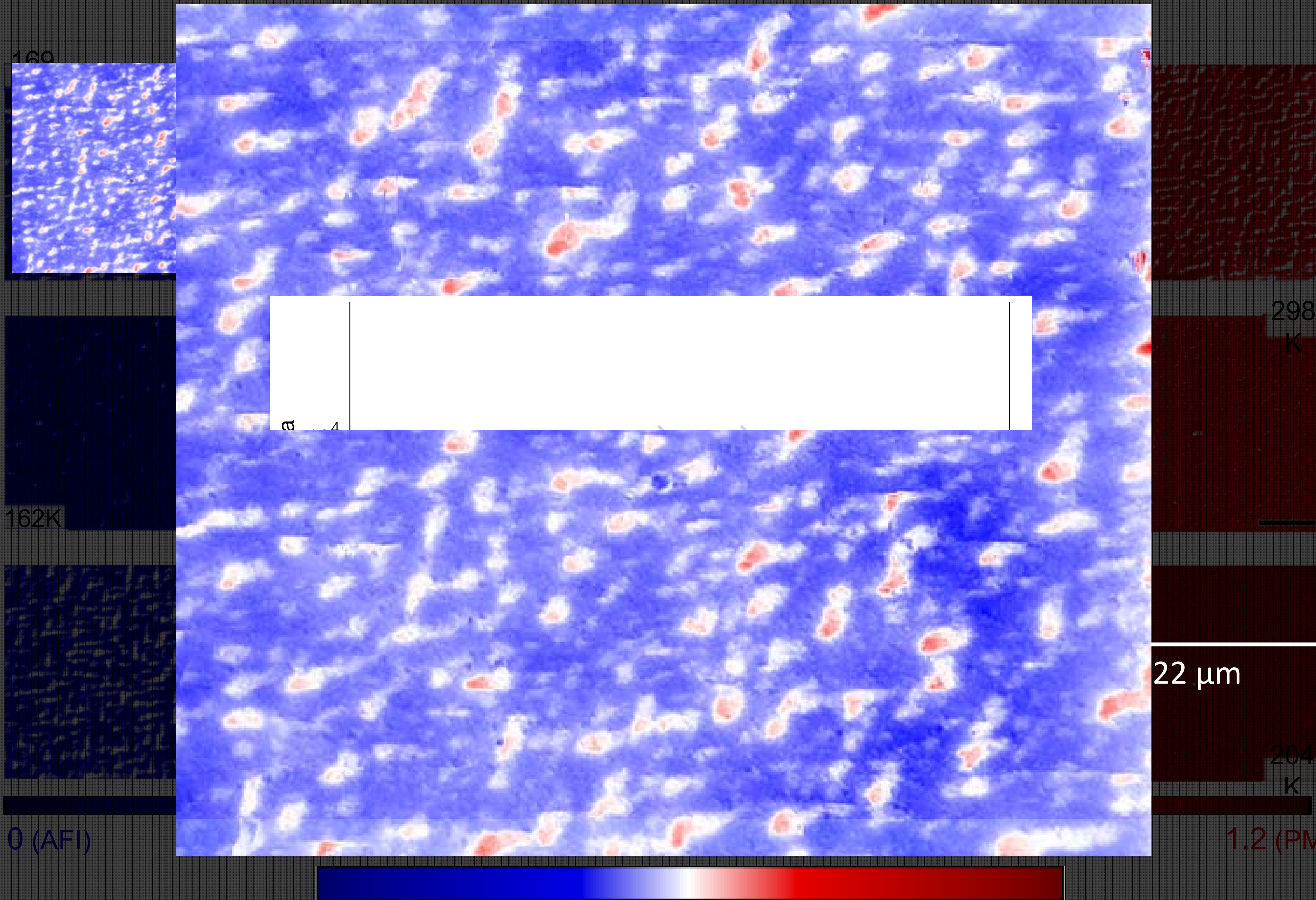
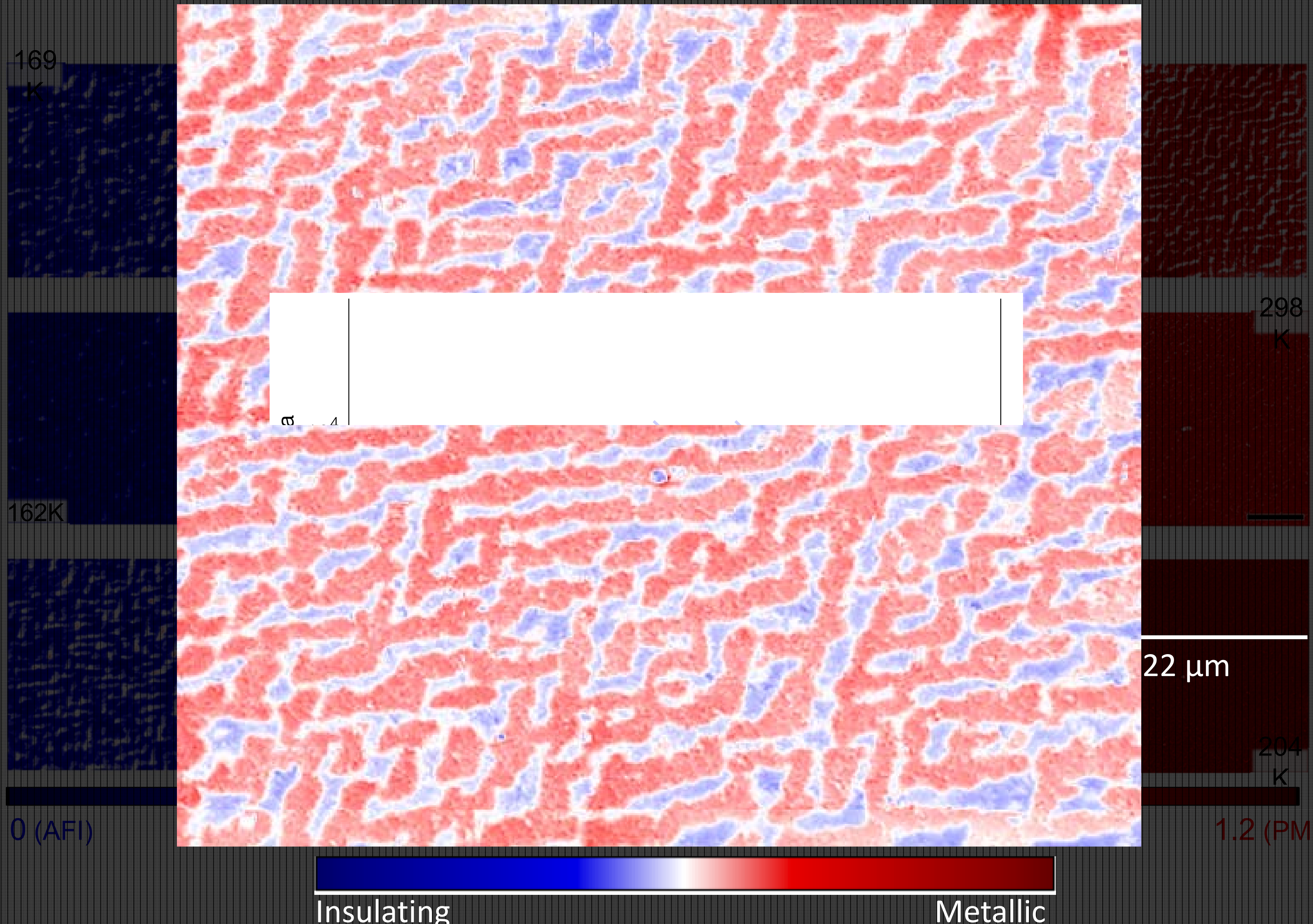
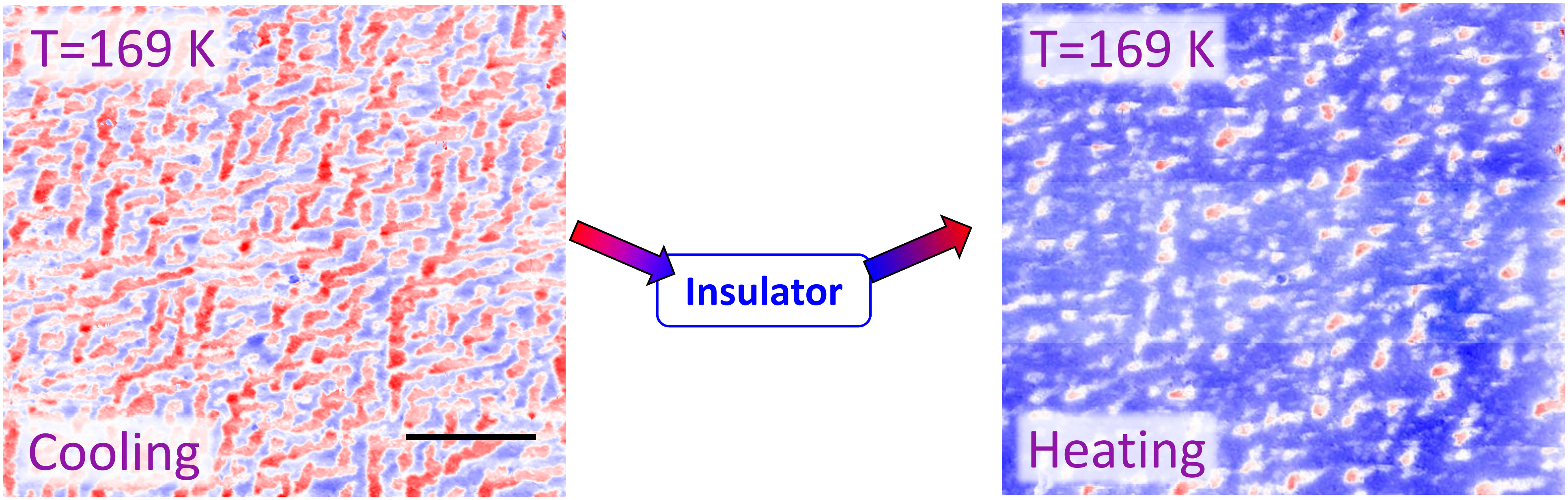


Near-field maps

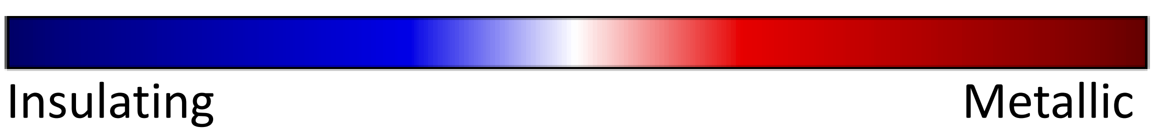


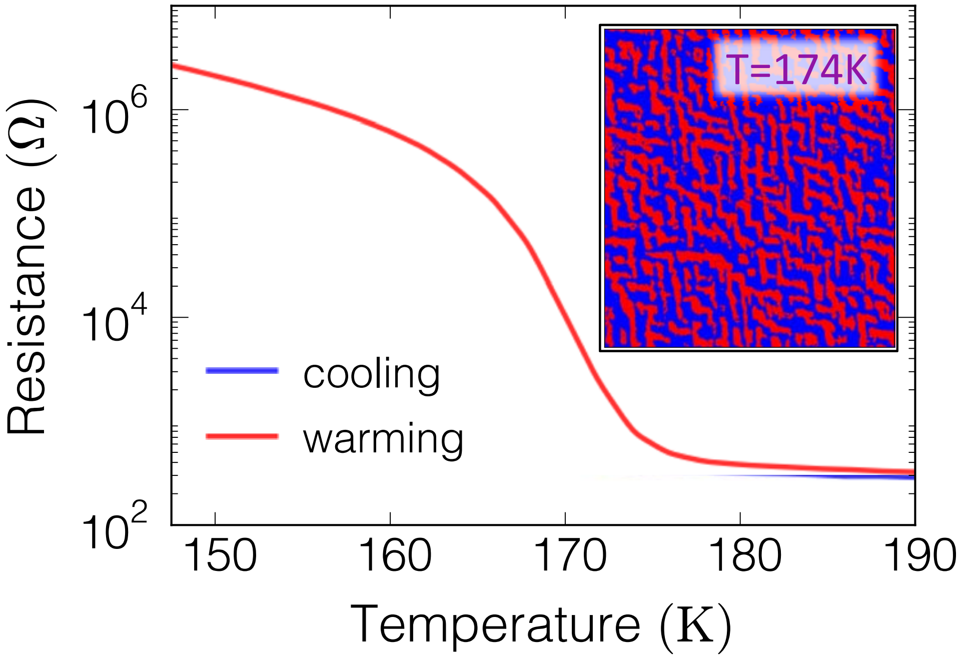
Two facets of the metal-insulator transition

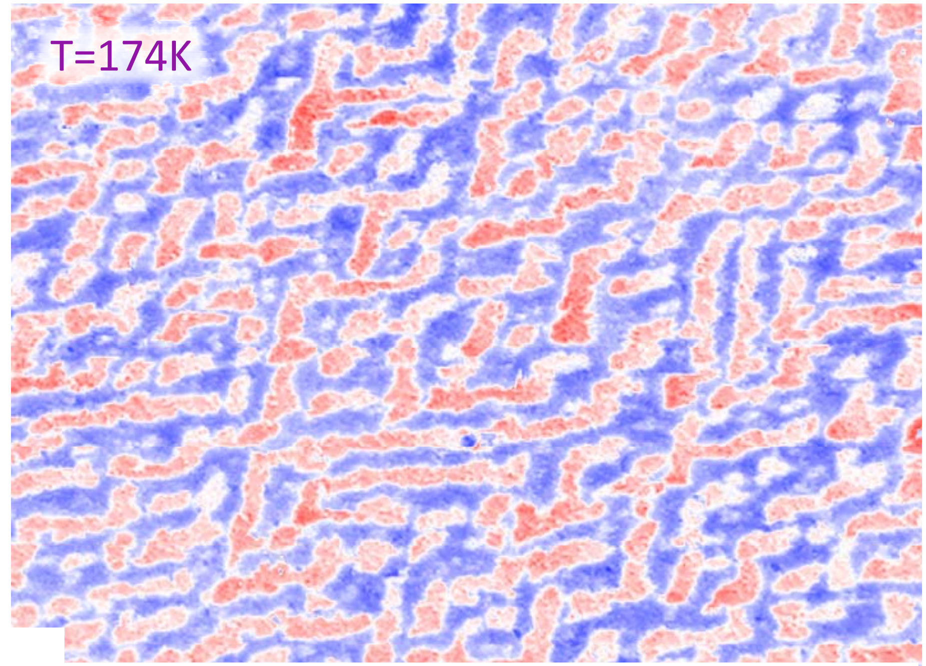


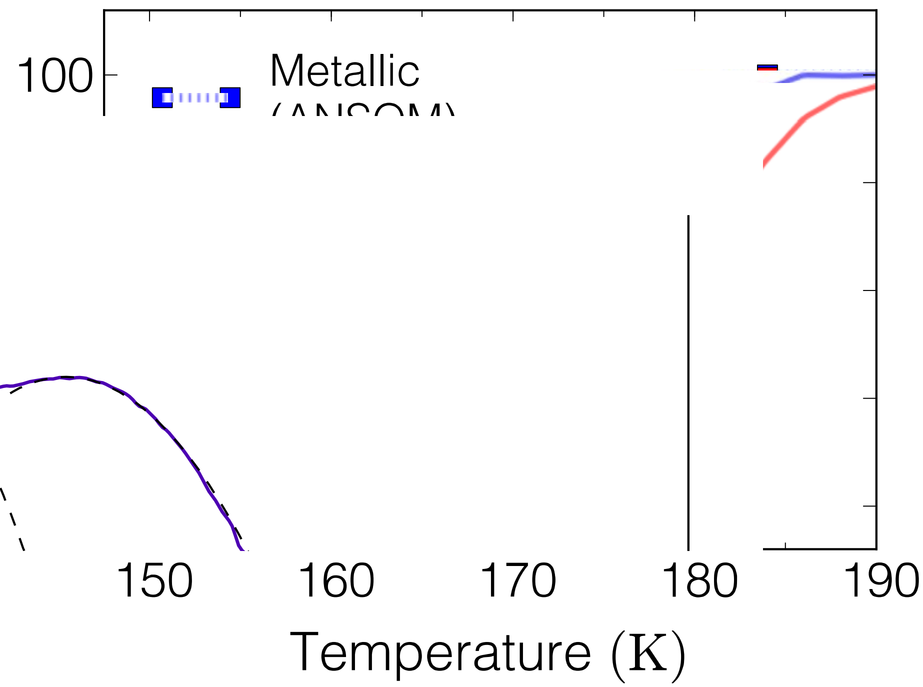
- Conducting stripes
- XRD: transition 75 % completed

- Nucleating conducting puddles
- XRD: transition <5 % completed









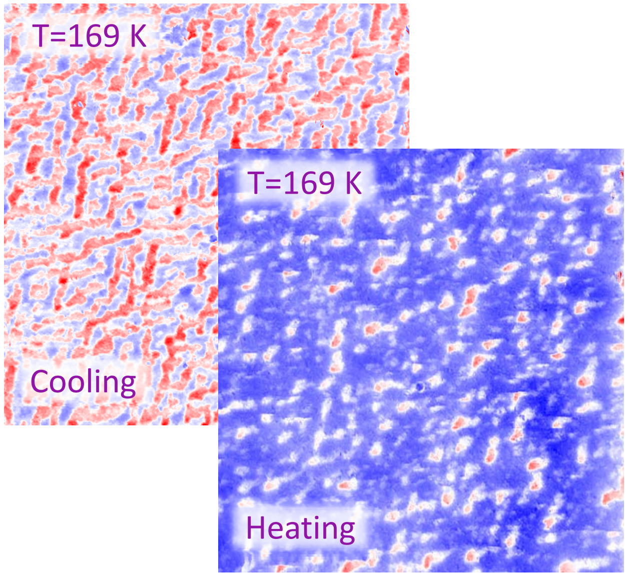
- *V*
  v
  o
- E
  fı

M... overgang kan ook binnen
monoclinische structuur

Sig

(

Samenvatting



- De verandering van de weerstand wordt gedreven door percolatie.
- De metaal-isolator overgang is niet direct gekoppeld aan de kristal structuur.
- Waarom een gestreept patroon?

Mogelijk antwoord

- Koppeling van elektronen aan ‘stress velden’

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

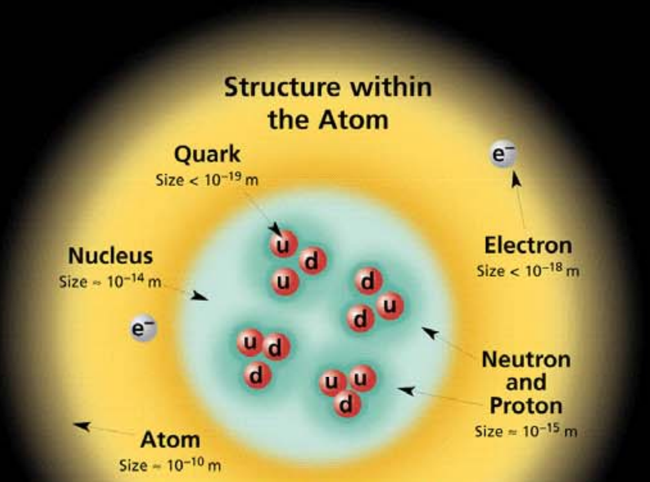
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 140 types of mesons.

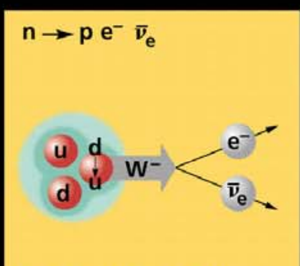
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Matter and Antimatter

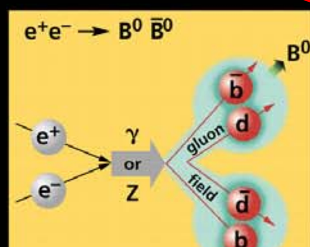
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

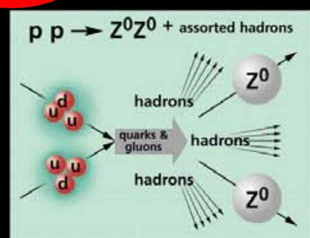
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

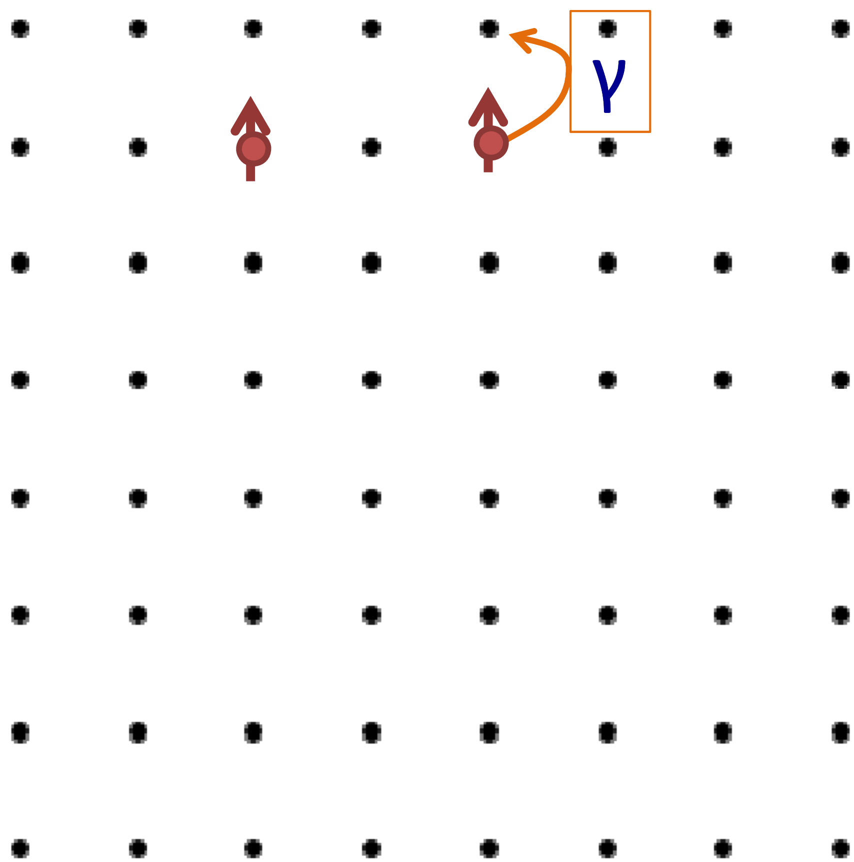
Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

This chart has been made possible by the generous support of:

U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

The Hubbard model

- Neem een rooster van atomen.



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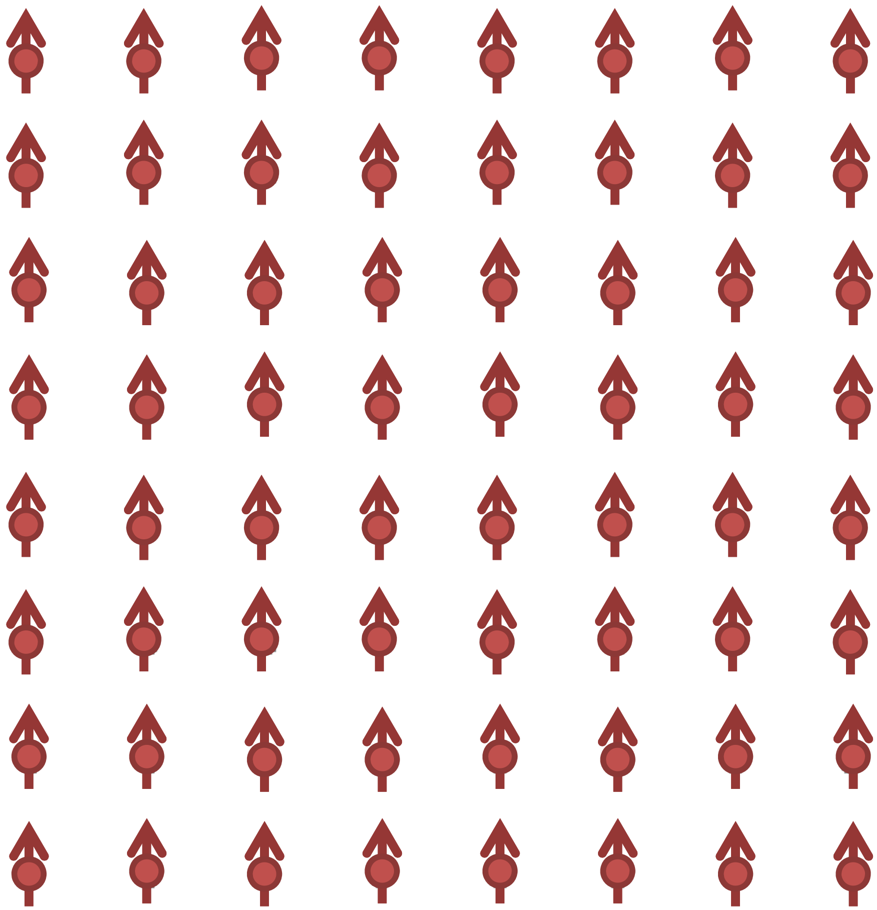
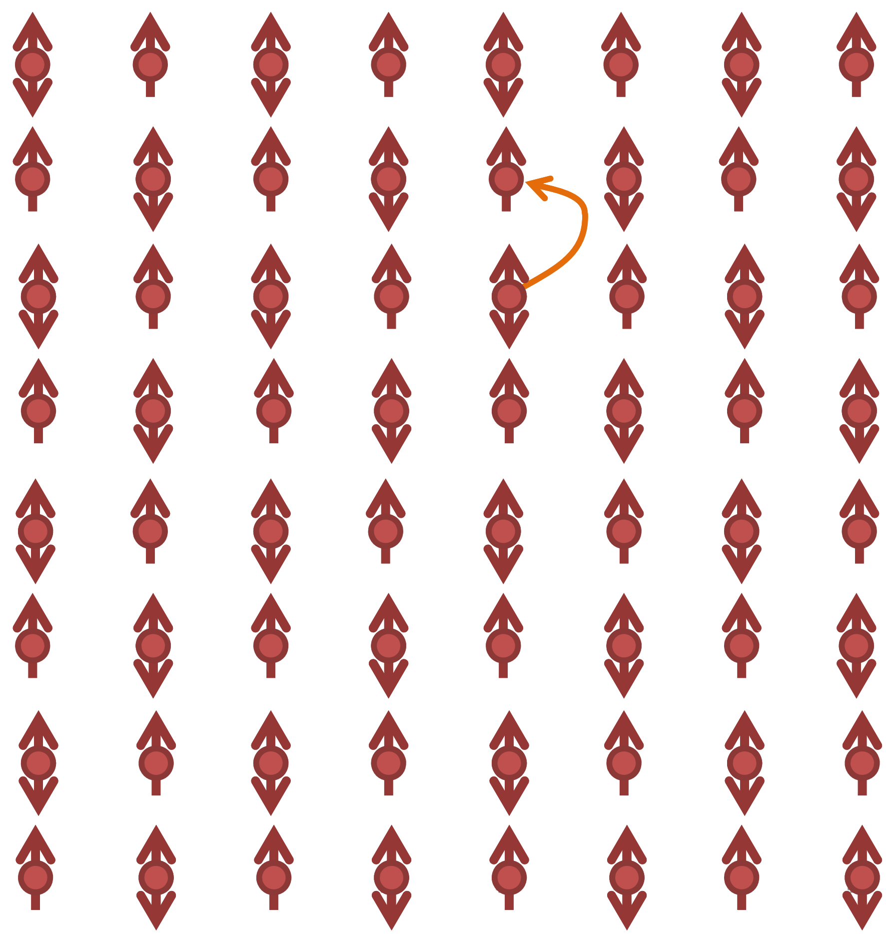
- Neem een rooster van atomen.



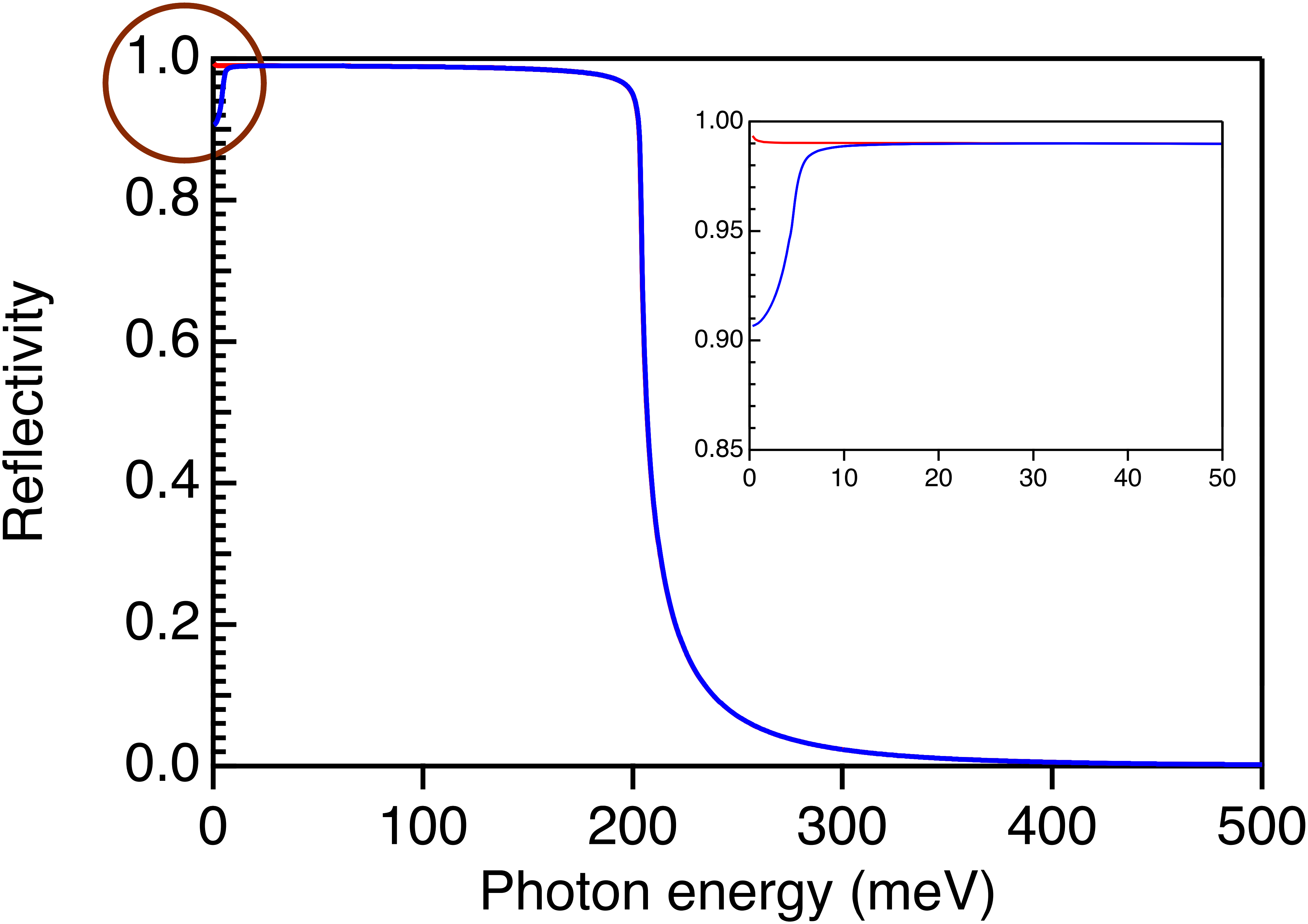
The Hubbard model

- Neem een rooster van atomen.

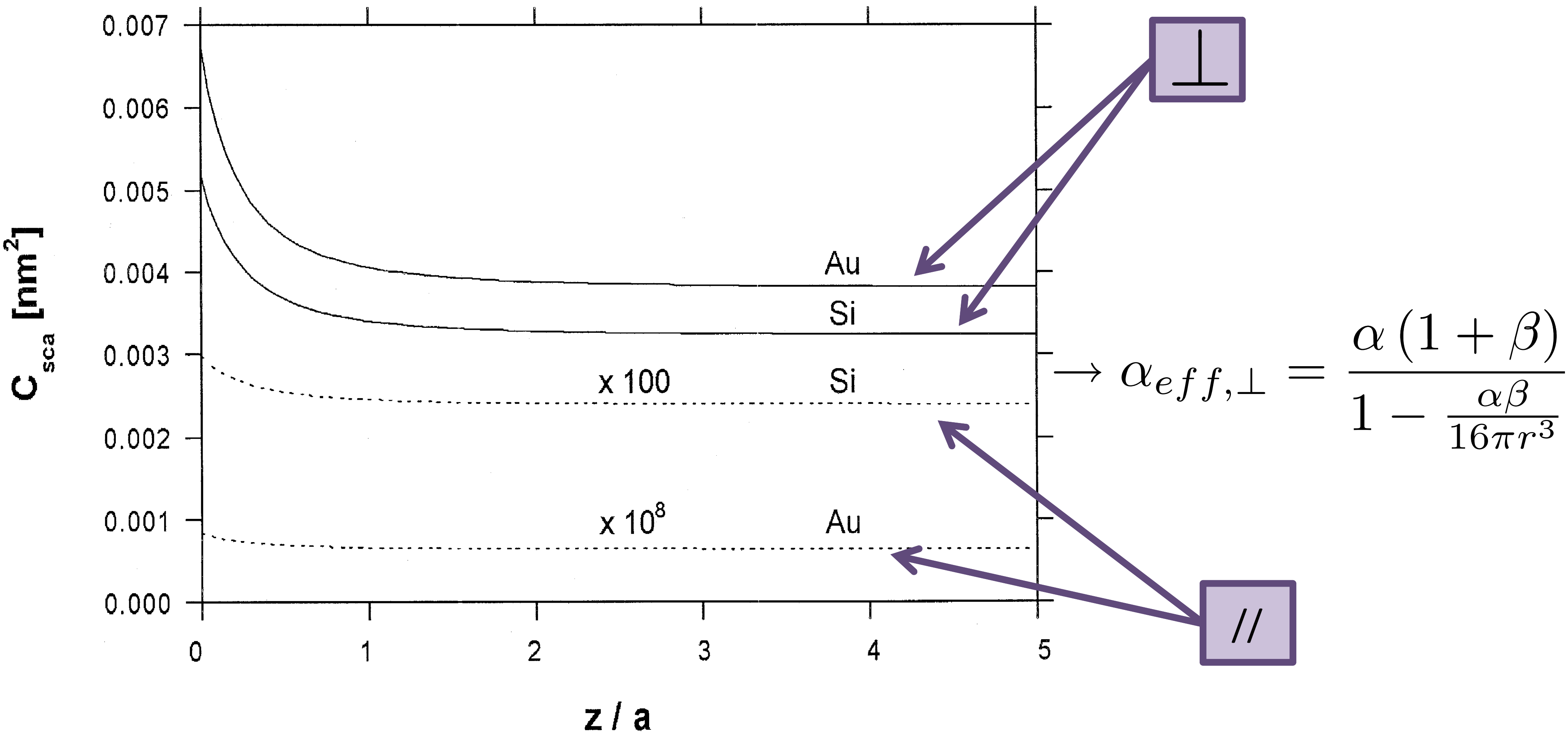


Mott-Hubbard isolator

- Met anti-parallelle spins winnen ze E_{kin}


1.0
0.8
0.6
0.4
0.2
0.0
Reflectivity
0
100
200
300
400
500
Photon energy (meV)
1.00
0.95
0.90
0.85
0
10
20
30
40
50

Near field enhancement



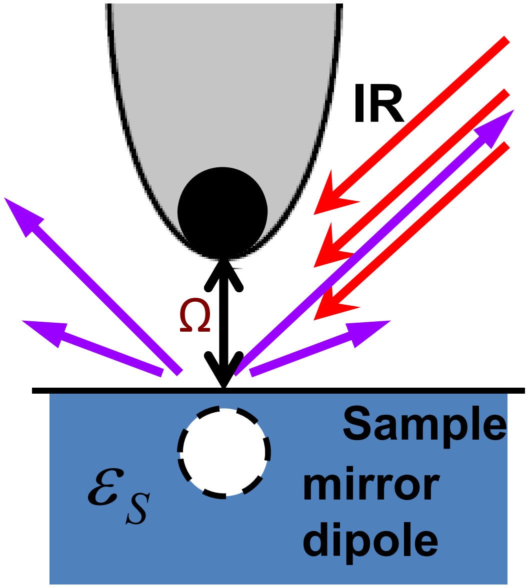
C_{sca} = scattering cross-section

- Strong enhancement when tip aproaches sample
- Enhancement for *perpendicular* polarization

Knoll, B. & Keilmann, F. Optics comm. **182**, 321–328 (2000).

Detection scheme

$$E_s = E_{BG} + E_{NF}$$



$$I \propto |E_s|^2 = E_s E_s^*$$

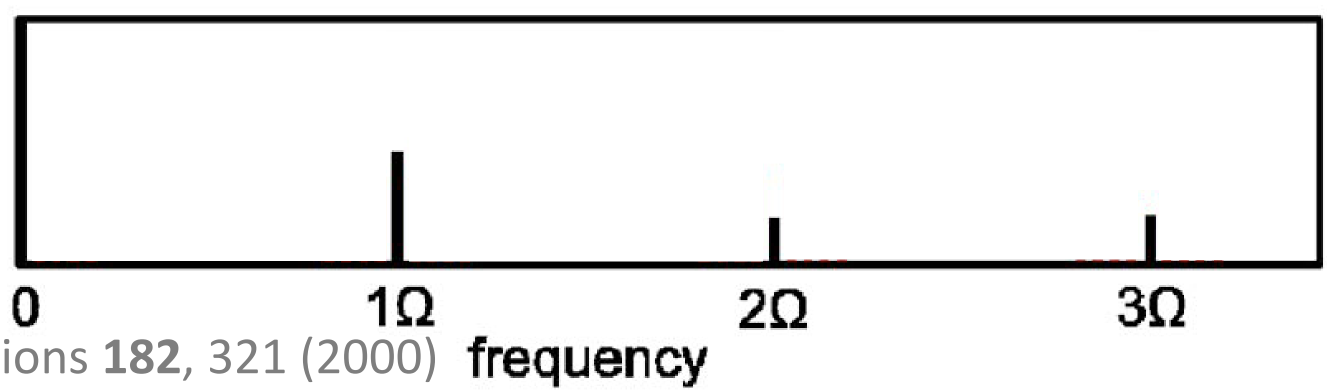
$$\propto |E_{BG}|^2 + |E_{NF}|^2 + E_{BG}E_{NF}^* + E_{BG}^* E_{NF}$$

Modulate AFM tip at Ω

$$E_s = \sum_n \tau_n exp(in\Omega t) \quad \Big| \quad \tau_n = s_n e^{i\phi_n} + s_{b,n} e^{i\phi_{b,n}}$$

$$I \propto \sum_{n,n'} \tau_n \tau_{n'}^* exp(i(n-n')\Omega t)$$

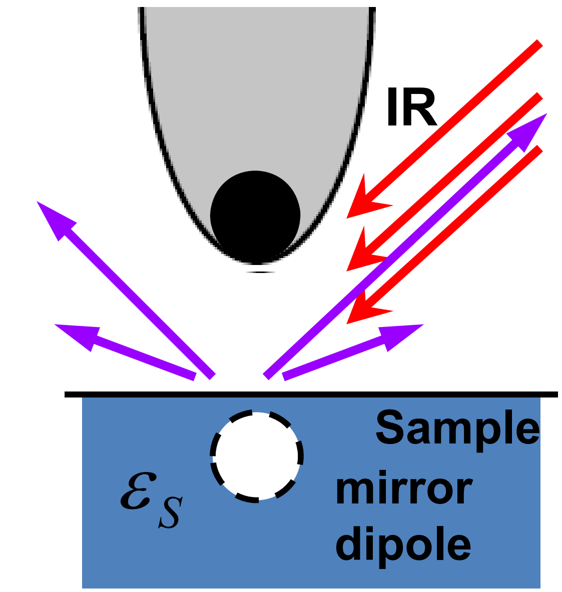
$$n^{th} \quad harmonic \rightarrow 2\kappa s_{b,0} s_n \cos(\phi_{b,0} - \phi_n)$$



Knoll et al., Optics Communications **182**, 321 (2000)
Ocelic et al., APL **89**, 101124 (2006)

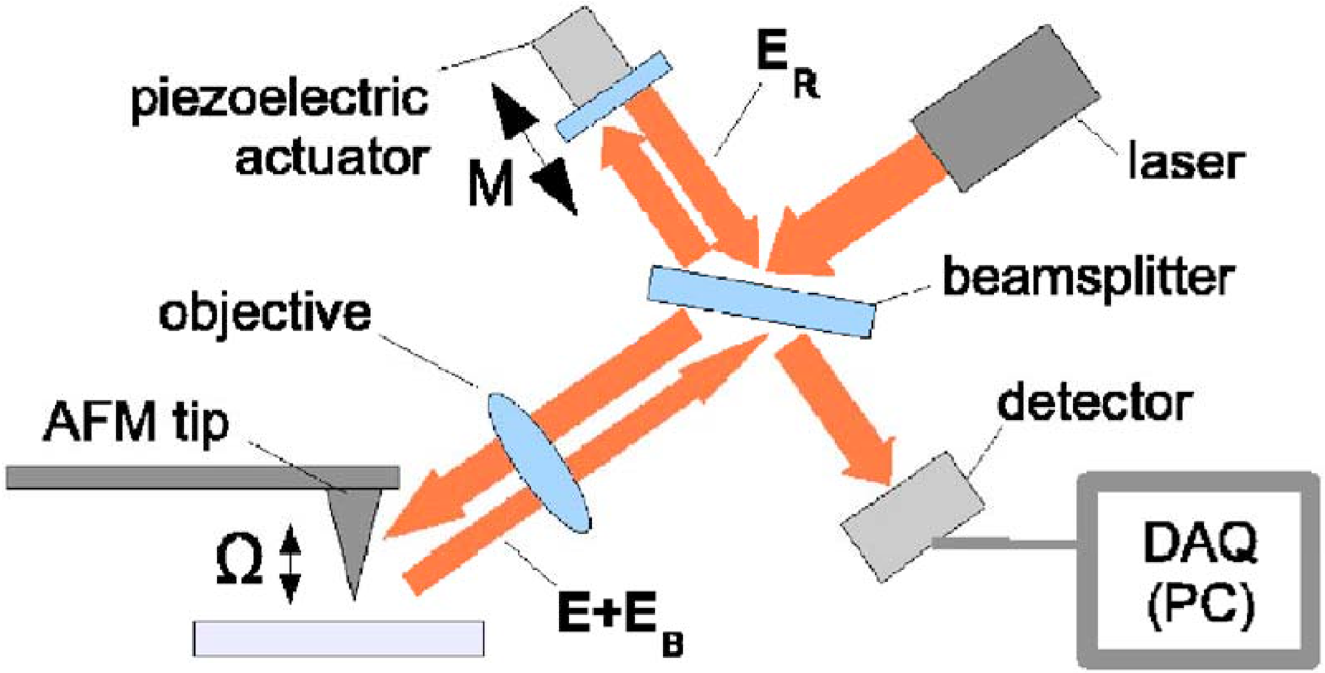
Interferometric detection

$$E_s = E_{BG} + E_{NF}$$



How to remove background?

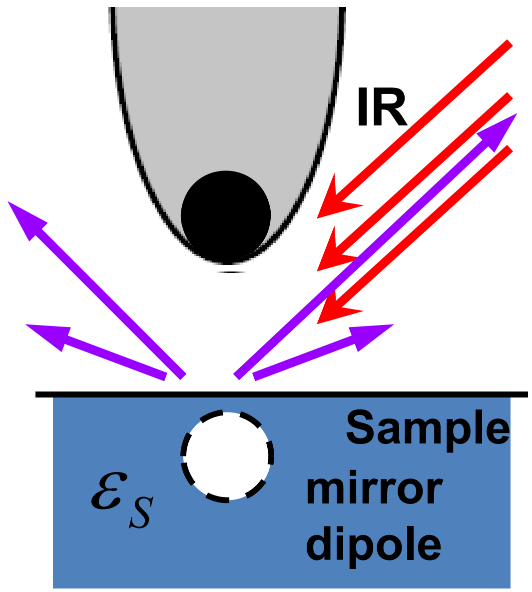
Pseudo-heterodyne detection



Ocelic et al., APL **89**, 101124 (2006)

Interferometric detection

$$E_s = E_{BG} + E_{NF}$$



How to remove background?

Pseudo-heterodyne detection

$$E_R = \rho exp(i\gamma \sin(Mt) + i\phi_R)$$
$$= \sum_m \rho_m exp(imMt)$$
$$\rho_m = \rho J_m(\gamma) exp(i\phi_R + im\pi/2)$$

$$I_{n,m} \propto 2\rho\kappa J_m(\gamma) s_{s,n} \cos(\phi_{s,n} - \psi_R - m\pi/2)$$

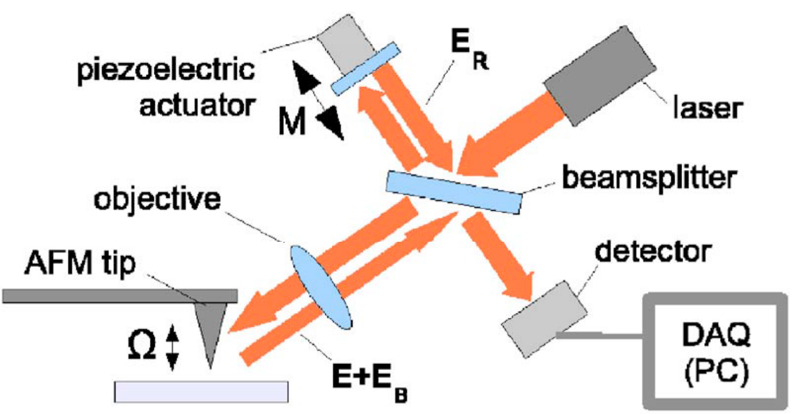
Ref. amplitude

Bessel function

NF amplitude

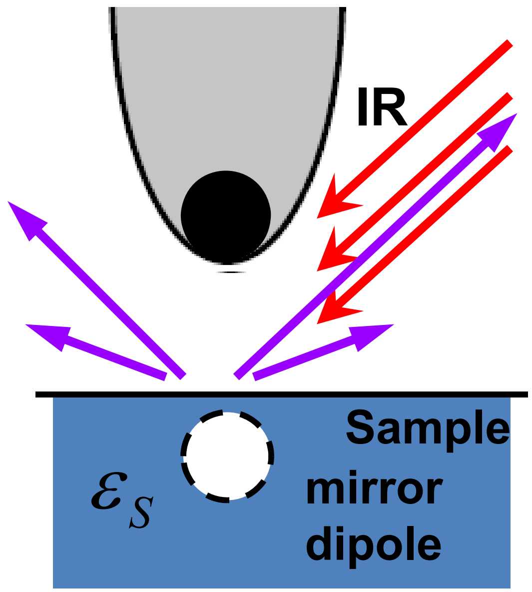
NF phase

Ref. phase



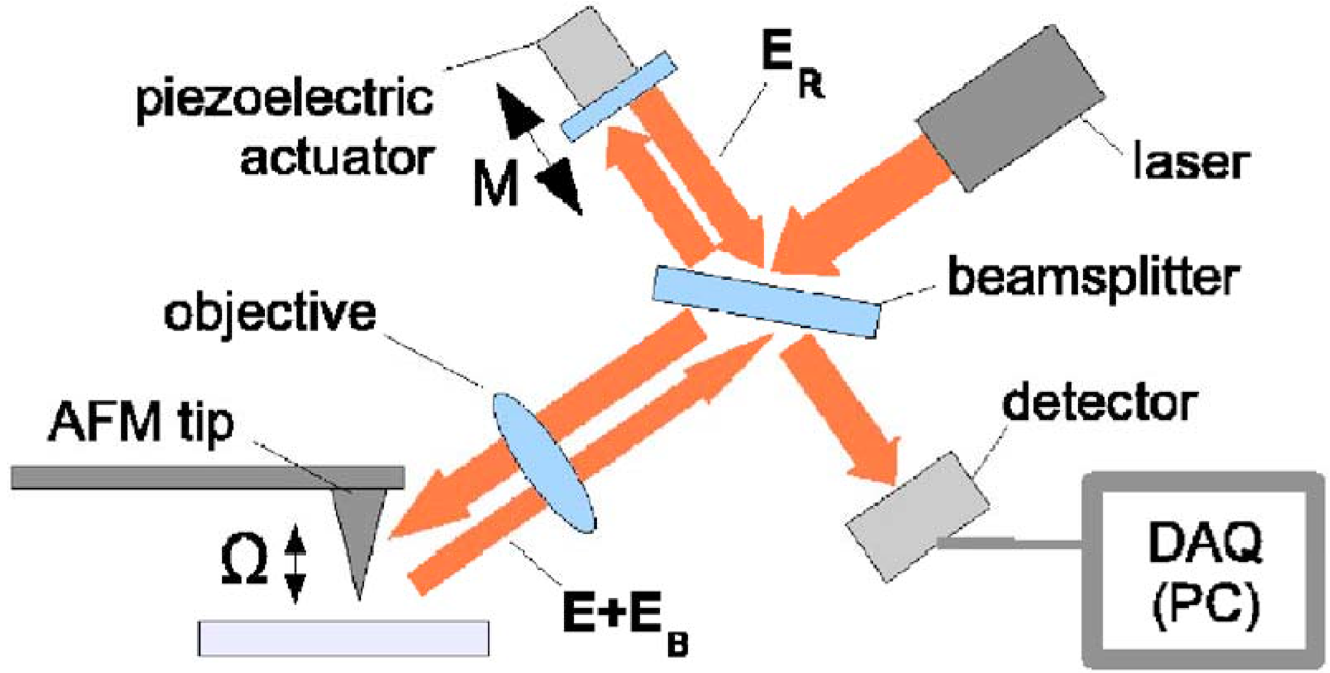
Interferometric detection

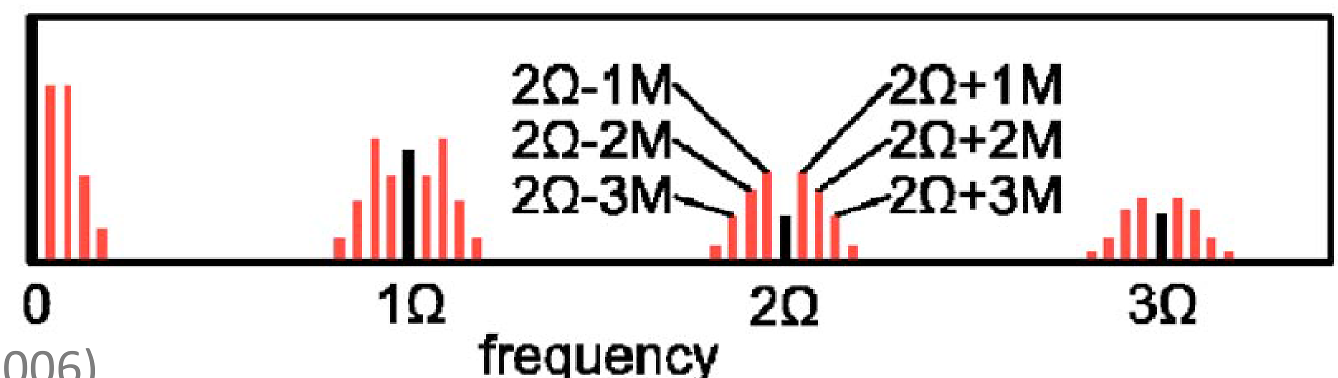
$$E_s = E_{BG} + E_{NF}$$



How to remove background?

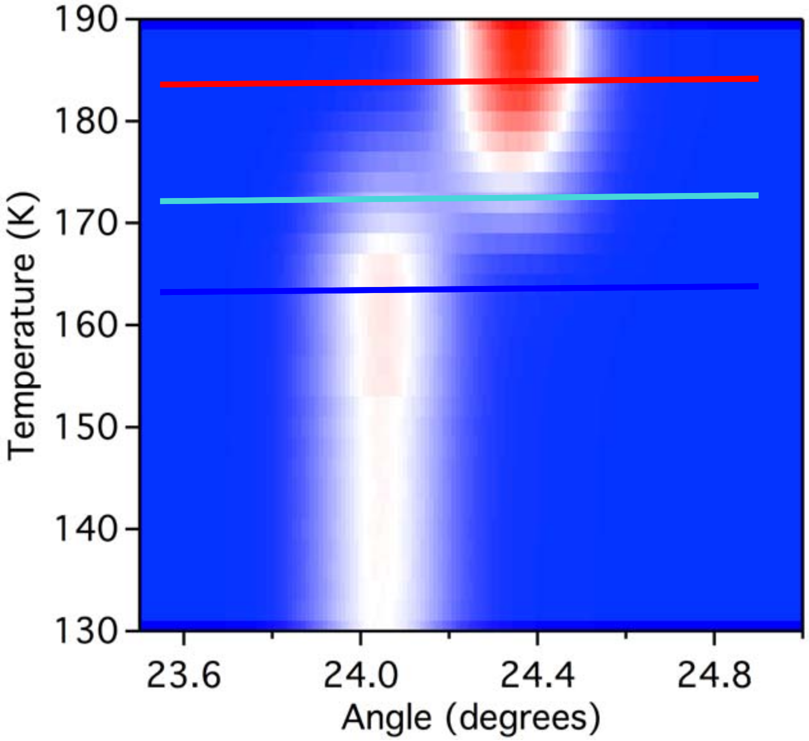
Pseudo-heterodyne detection

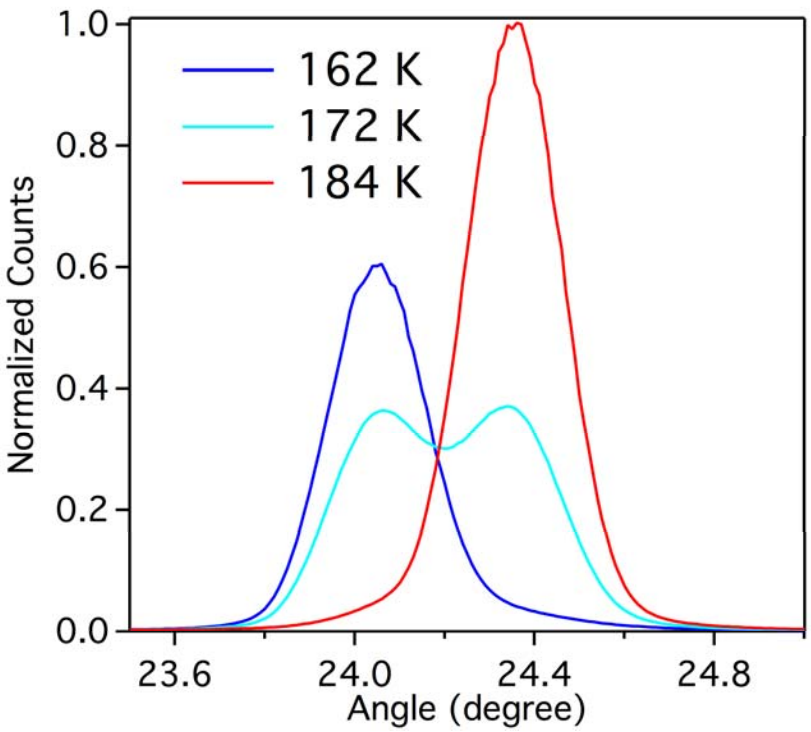


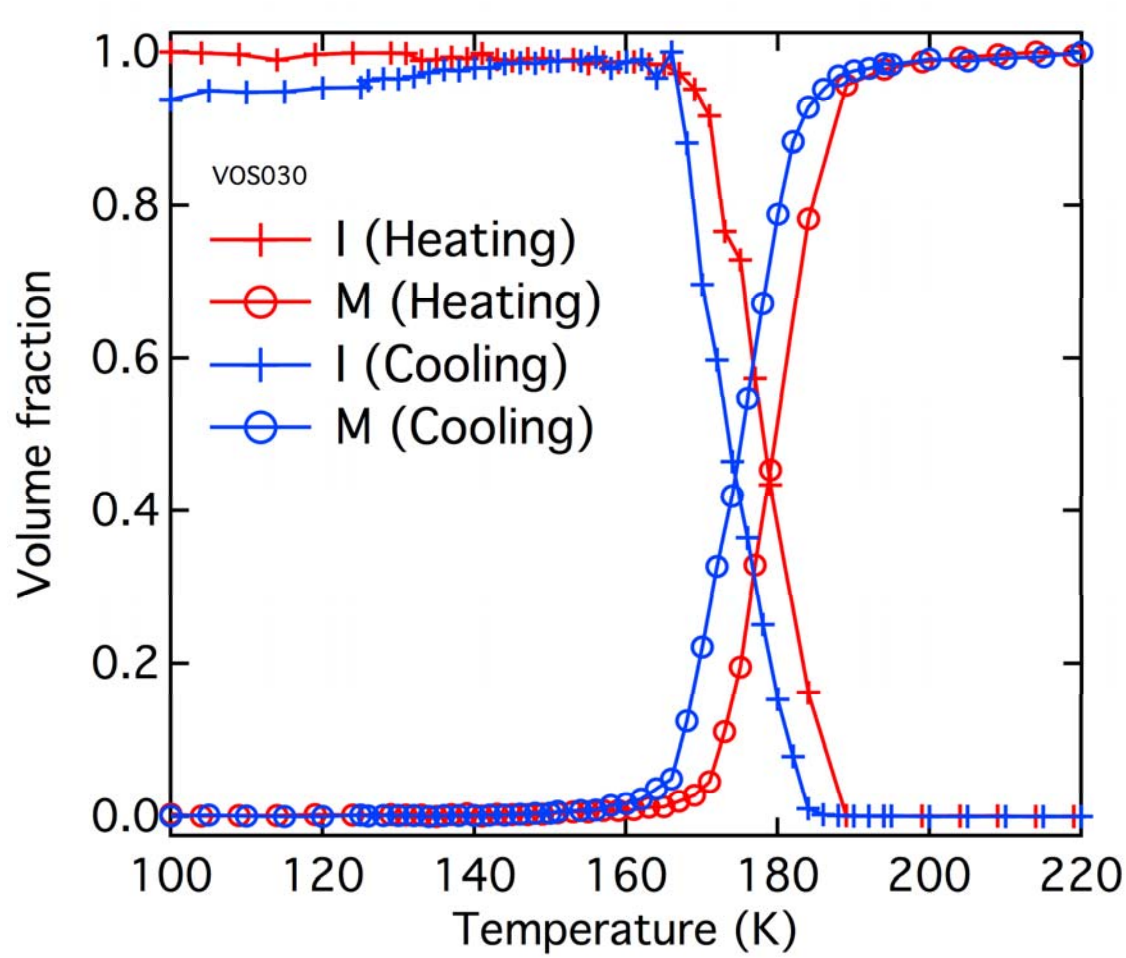


Ocelic et al., APL **89**, 101124 (2006)

V_2O_3 kristal structuur







Volgen de elektronen de kristal structuur?

Introductie

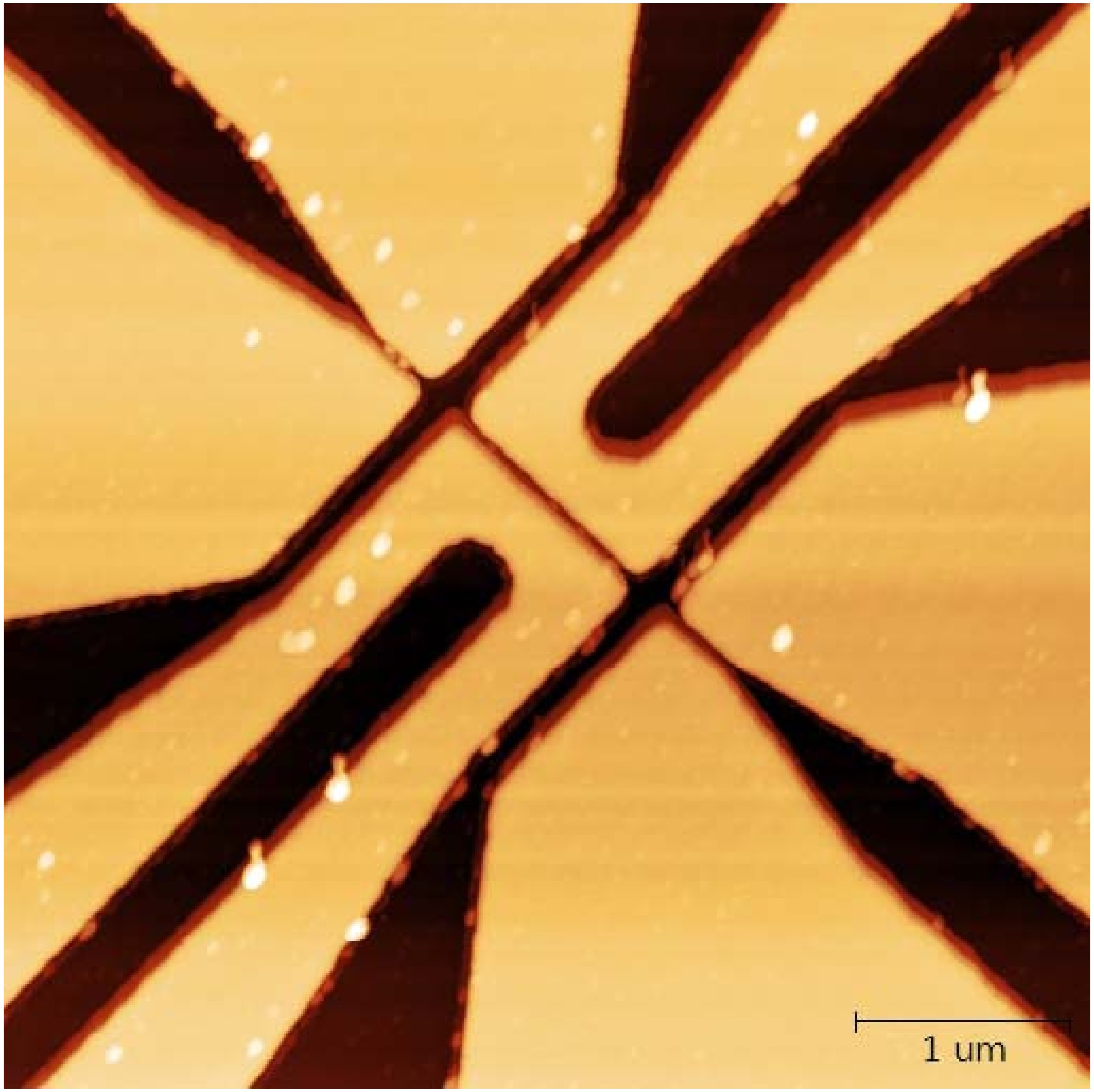
- Wat is het verschil tussen een metaal en een isolator?

- Hoe verandert een metaal in een isolator?

  Kan een metaal in een isolator veranderen?

e-beam lithography

50 nm contact afstand !



A. Caviglia, TUDelft

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

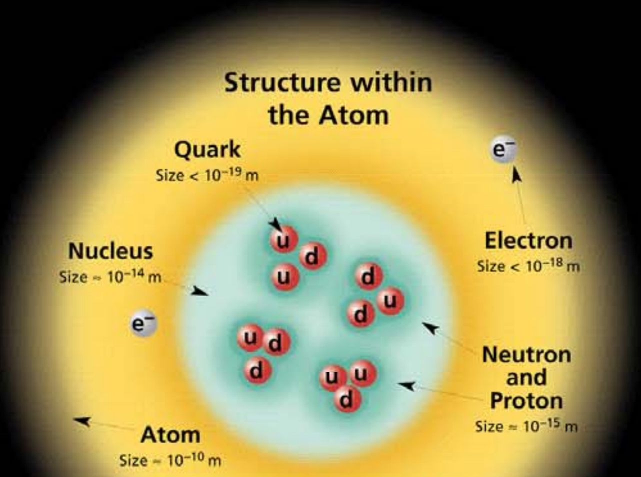
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

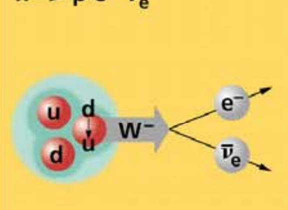
Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

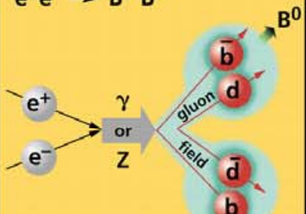
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

$n \rightarrow p\, e^-\, \bar{\nu}_e$



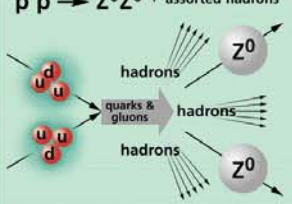
A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

$e^+e^- \rightarrow B^0\, \bar{B}^0$



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.

p p → Z^0Z^0 + assorted hadrons



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

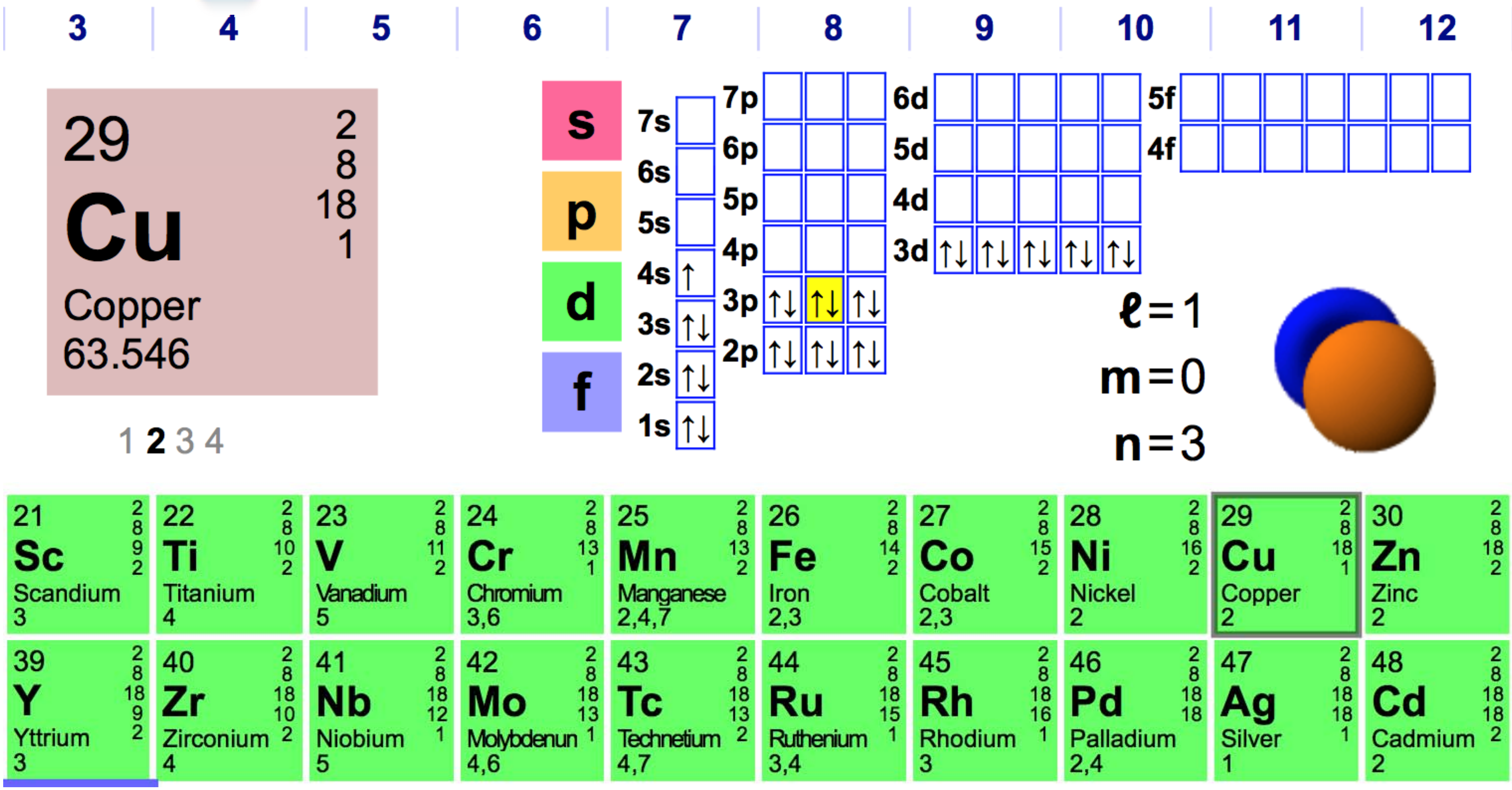
The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

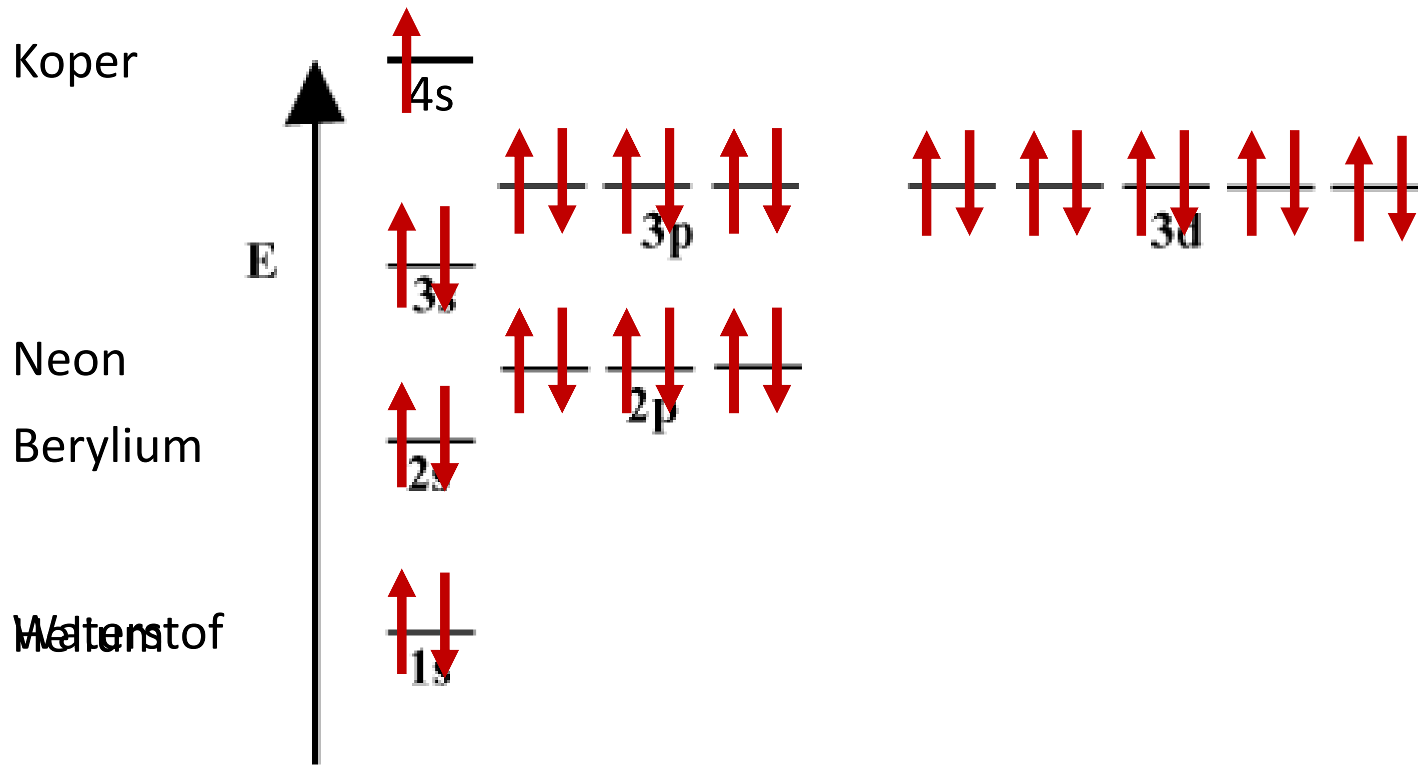
This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org

- Hoe verandert een metaal in een isolator?
  - Elektronen zijn fermionen.
  - Ze wisselwerken via de Coulomb interactie.

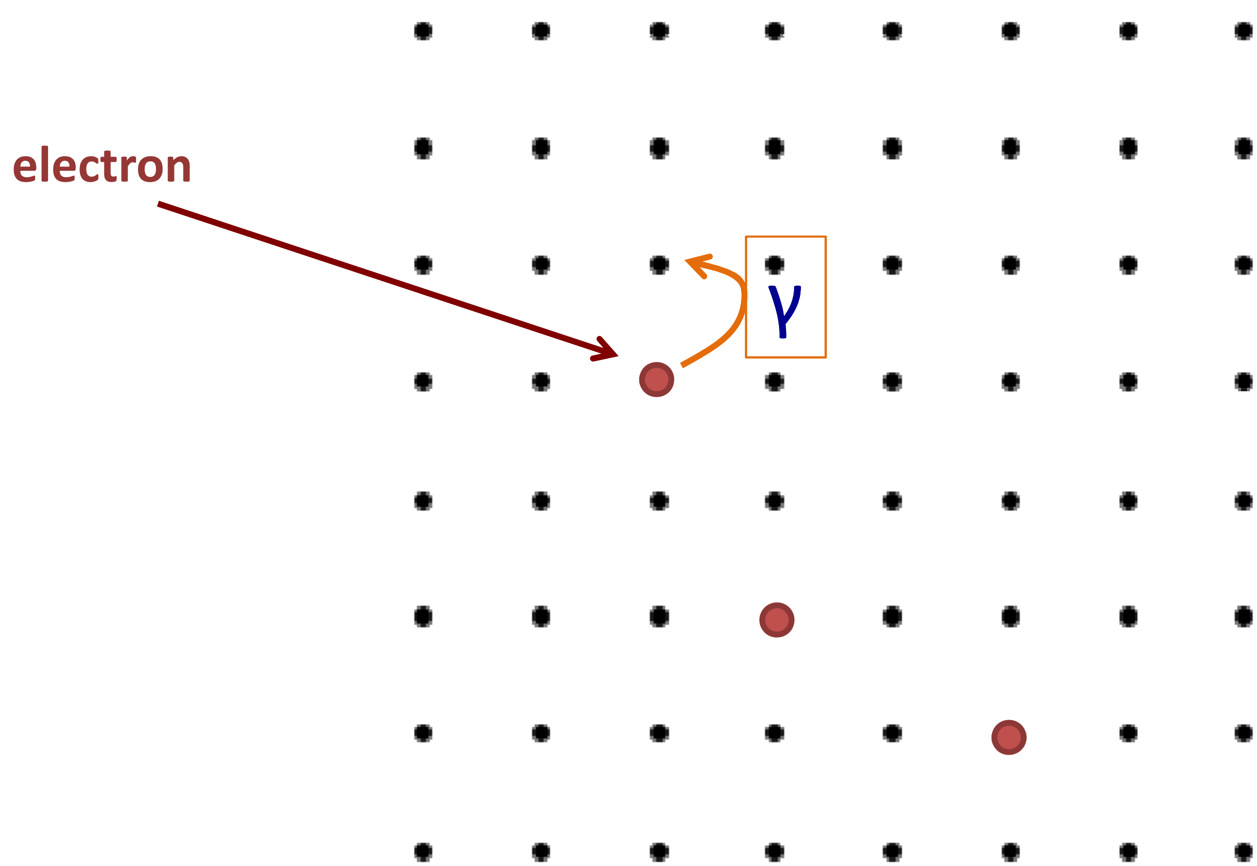


Hoe verandert een metaal in een isolator?



Model voor een metaal

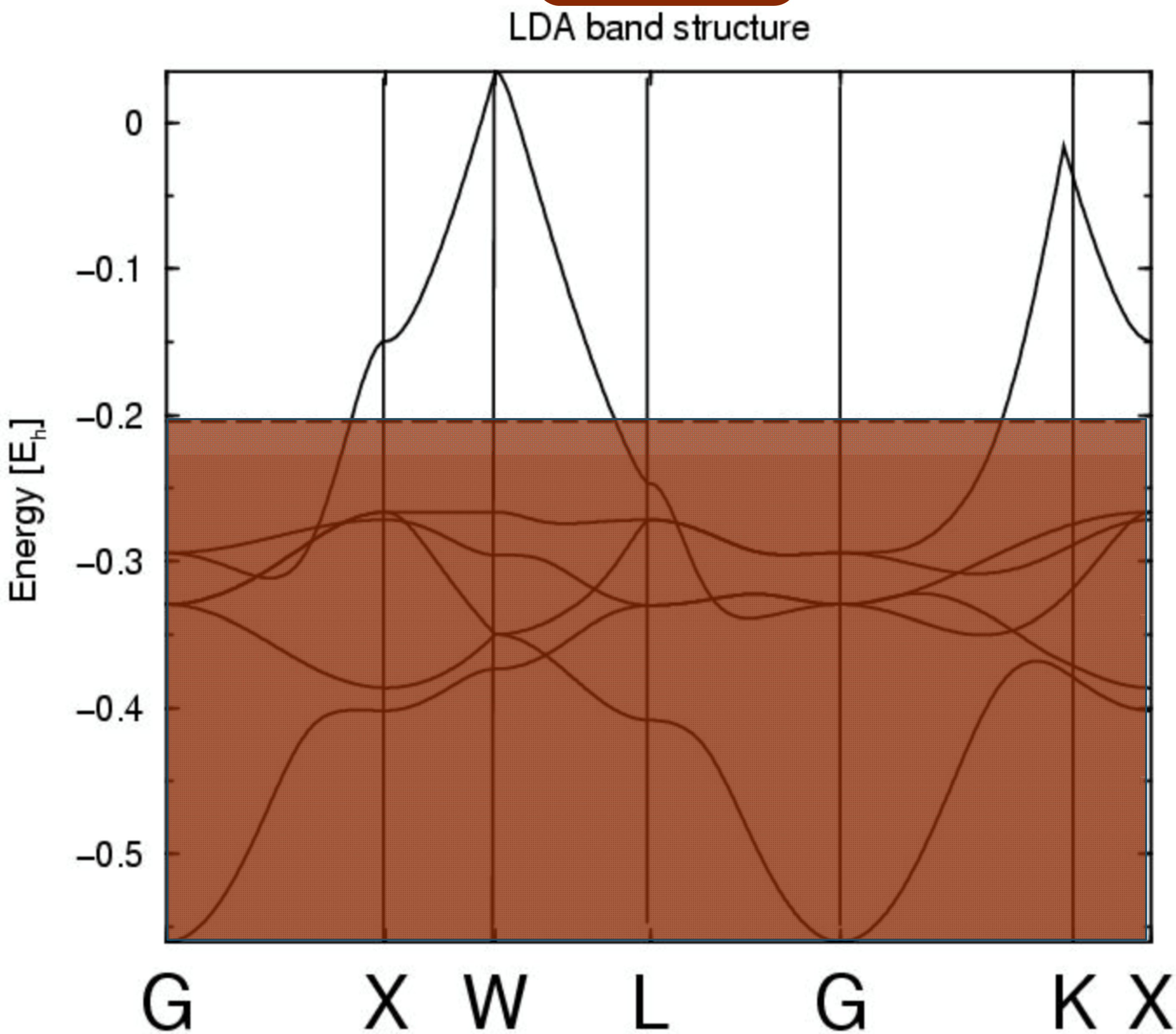
- Neem een rooster van atomen.

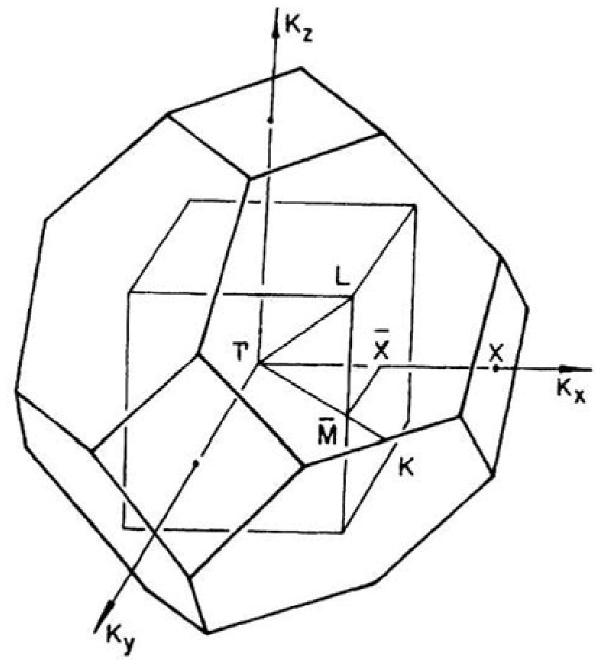


γ geeft de kans dat een elektron zich verplaatst

Model voor een metaal

Koper





Het Hubbard model

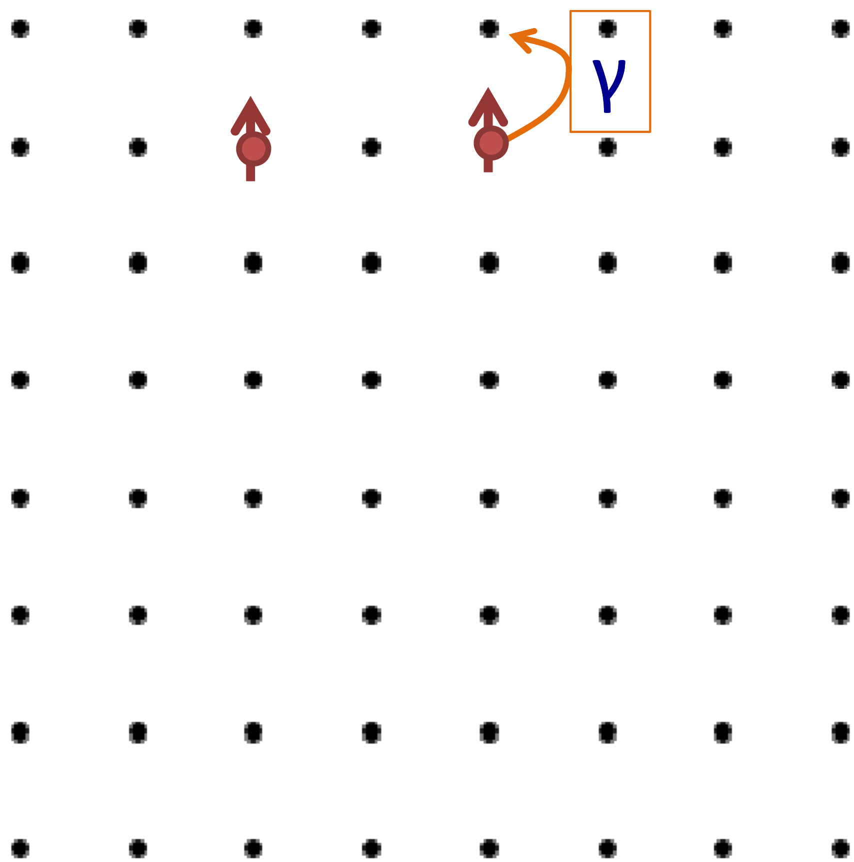
- Het simpelste model voor wisselwerkende electronen.

$$H_{int} = \begin{cases} U & e_1 \text{ en } e_2 \text{ op hetzelfde roosterpunt} \\ 0 & e_1 \text{ en } e_2 \text{ niet op hetzelfde punt} \end{cases}$$

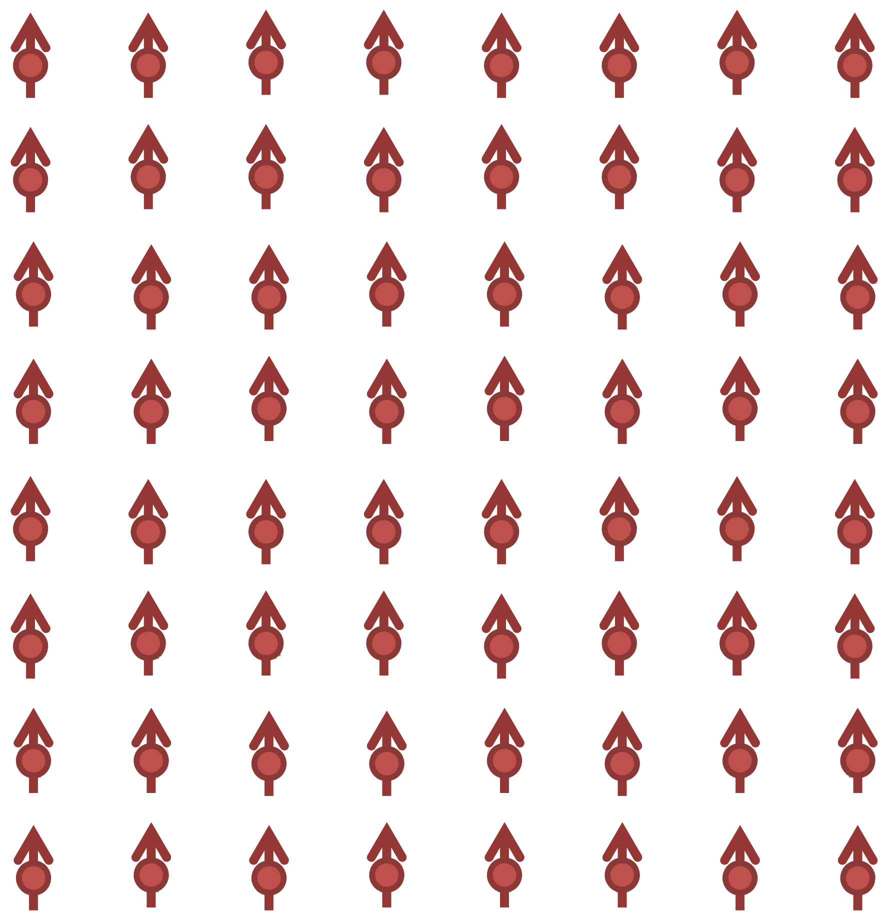
- Twee fermionen kunnen alleen op hetzelfde roosterpunt zijn als hun spin anti-parallel is.

The Hubbard model

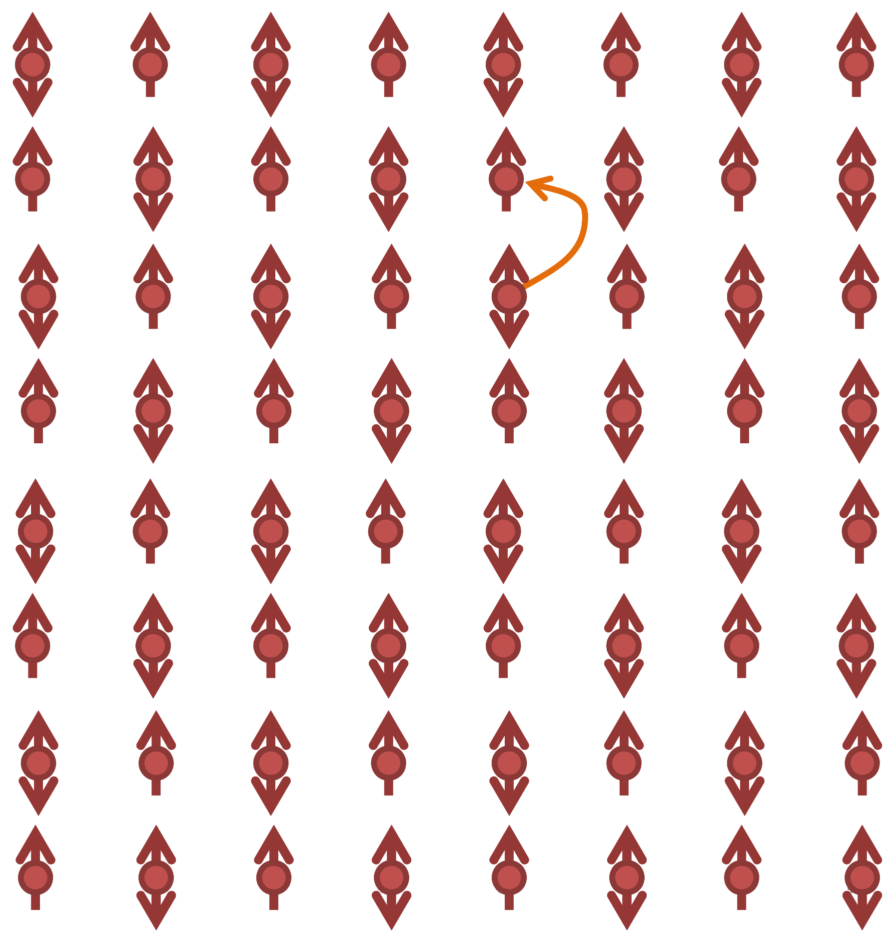
- Neem een rooster van atomen.



- Neem een rooster van atomen.



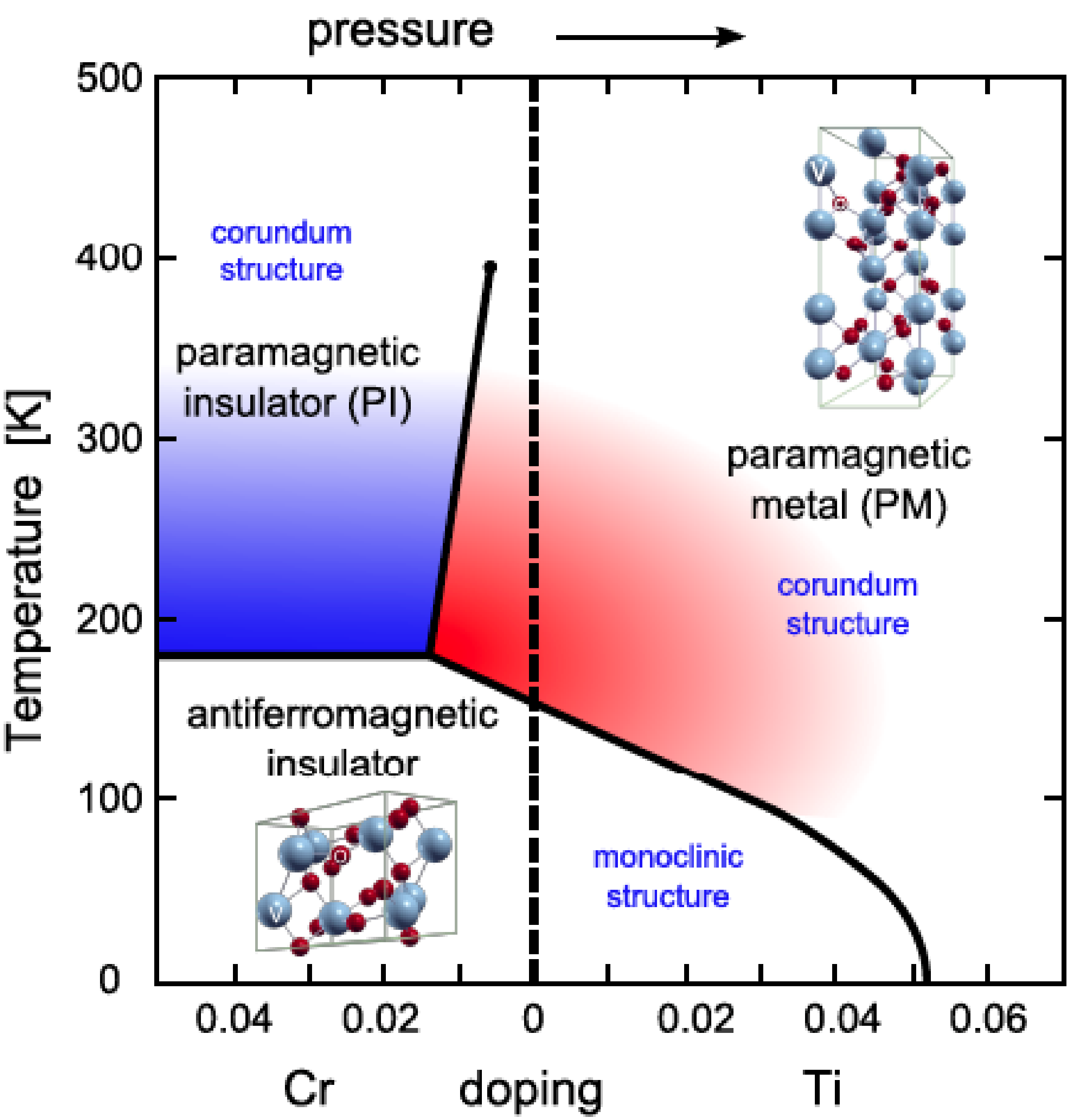
- Als alle spins dezelfde kant opstaan, zitten de elektronen vast!



Mott-Hubbard isolator

- Met anti-parallelle spins winnen ze E_{kin}

Metaal-Isolator overgang in V_2O_3



Sterk wisselwerkend metaal

Structurele en magnetische overgangen

Wat drijft de overgang van metaal naar isolator?

McWhan et al., PRL 23, 1384 (1969)
Hansmann et al. Phys. Status Solidi B 250, 1251 (2013)