

Direkte måling af elektronstrukturen i graphen og ultrahurtig dynamik af masseløse Dirac Fermioner



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Fysiklærerdag
Fredag d. 24. januar 2014



Eksperimentel overfladefysik og
fastes stoffers elektronstruktur

Philip Hofmann
Marco Bianchi
Lucas Baretto
Maciek Dendzik
Matteo Michiardi

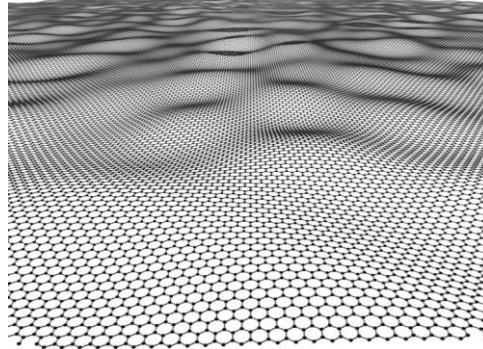
Indhold

- ➔ Graphen
Kulstof i to dimensioner
- ➔ Vinkelopløst fotoemissions spektroskopi
Direkte billeder af Dirac kegler i graphen
- ➔ Elektronstruktur film med ultrahurtige lyskilder
Varme elektroner i graphen kan føre til effektive solceller

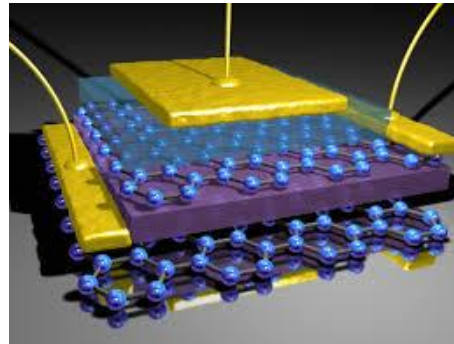
Graphen

Drømme og perspektiver

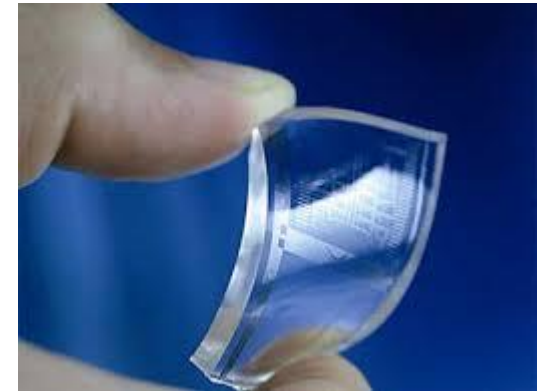
Fleksibilitet og styrke i 2D



Hurtige elektroniske komponenter



Effektive coatings



Kilder:

Graphenea

Samsung

Novoselov *et al.*, Nature 490, 192 (2012).

Graphen

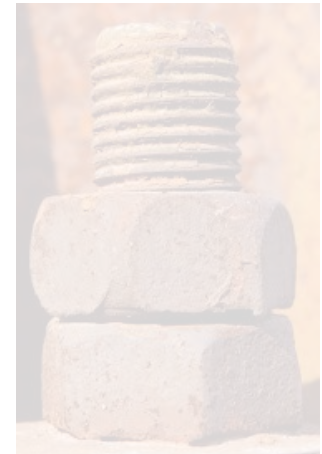
Drømme og perspektiver

Fleksibilitet og
styrke i 2D

Hurtige elektroniske
komponenter

Effektive coatings

**Simpelt og stabilt
materiale med
spændende fysiske
egenskaber!**



Kilder:

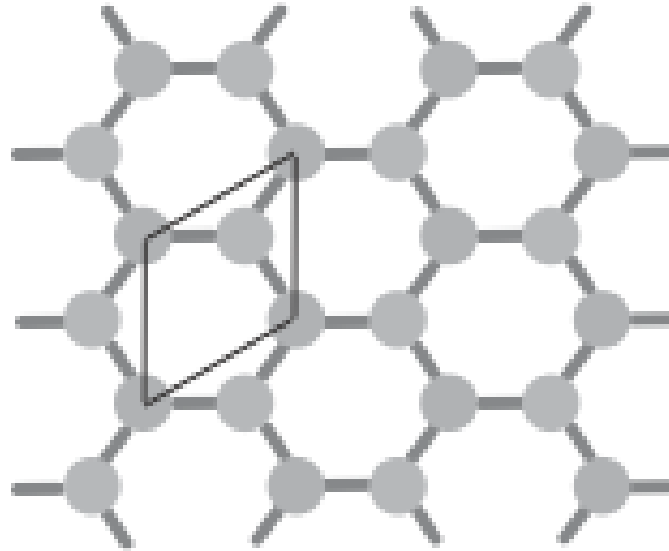
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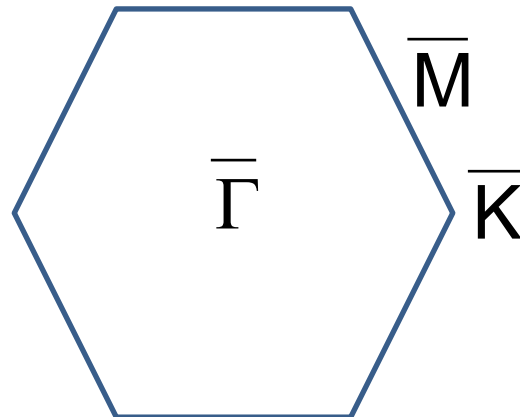
Graphen

Krystalstruktur



Gitter og
enhedscelle

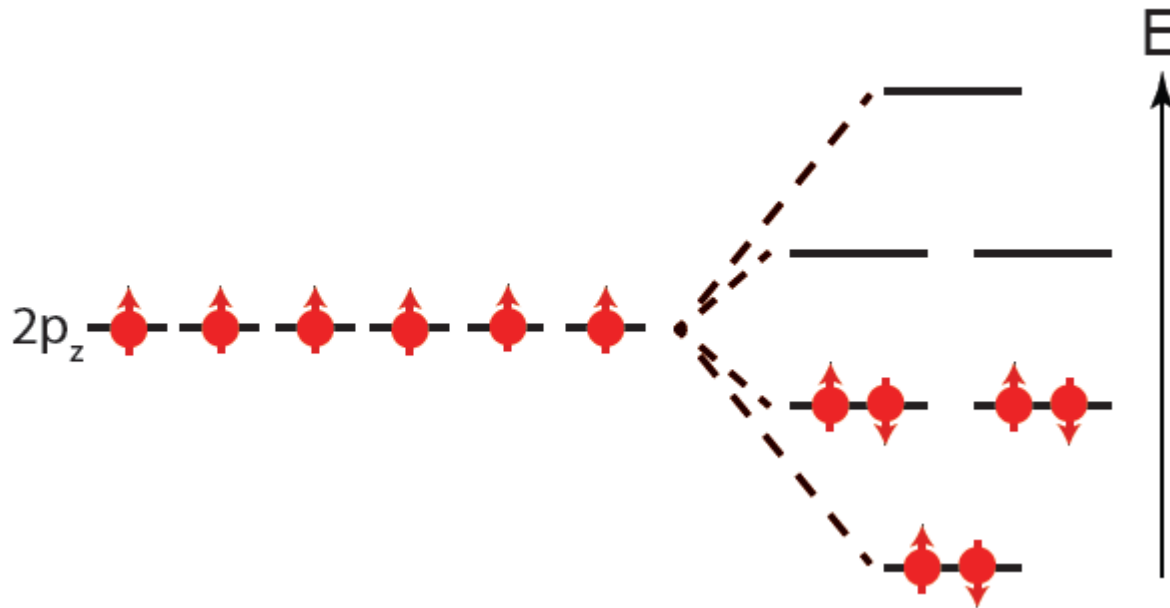
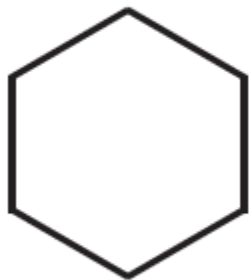
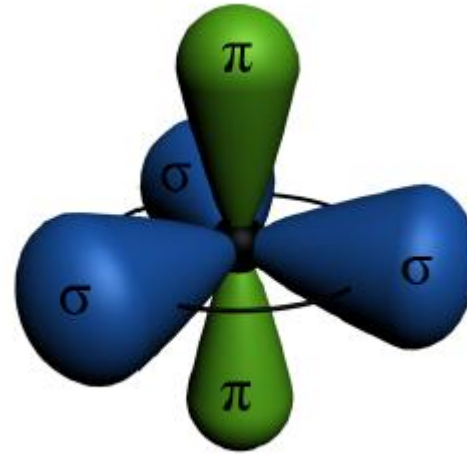
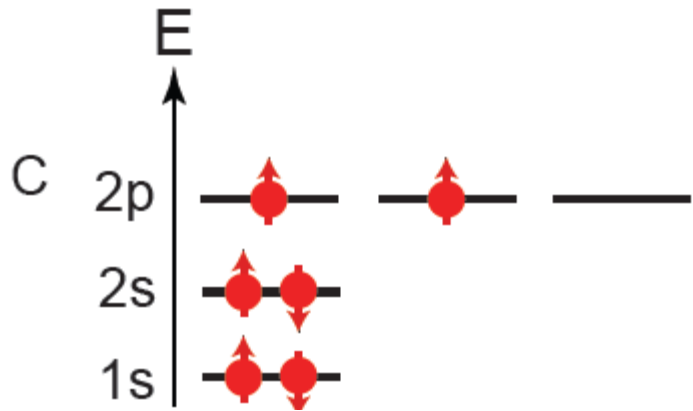
Det reciprokke gitter
Impulsrum/k-rum



Brillouin zone

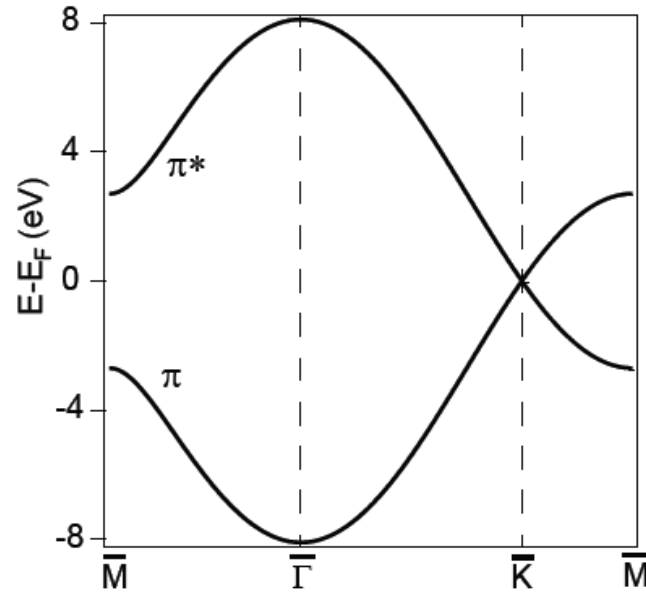
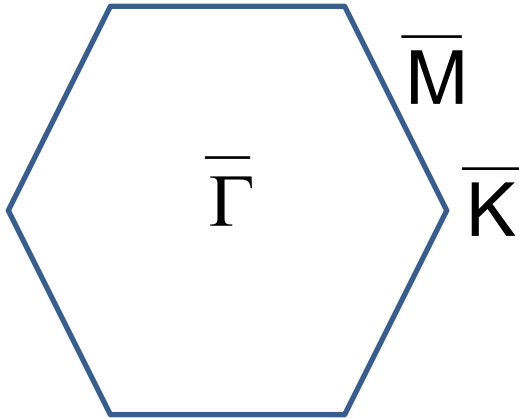
Graphen

Elektronstruktur



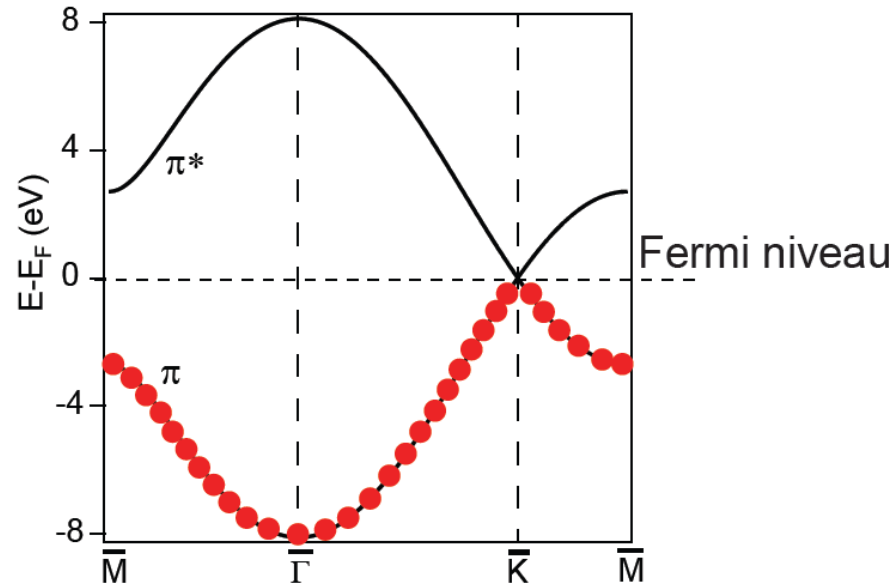
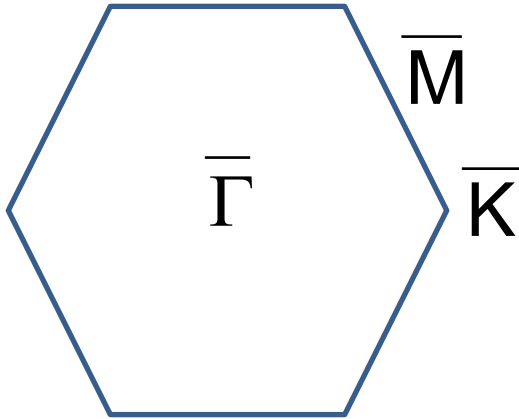
Graphen

Elektronstruktur



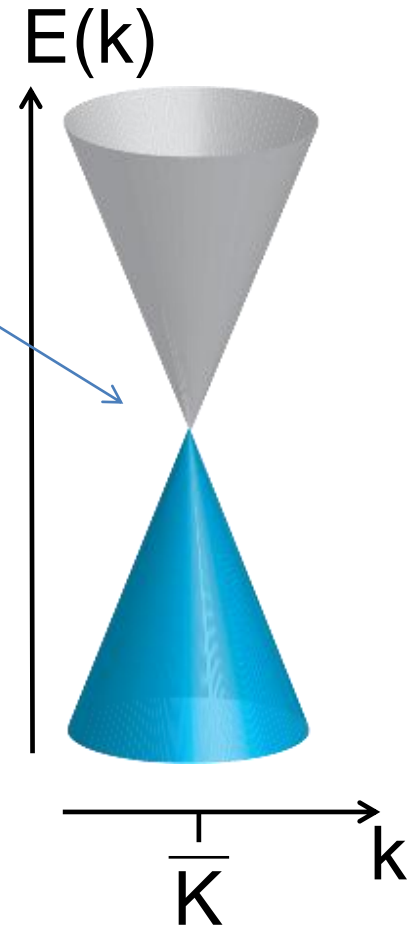
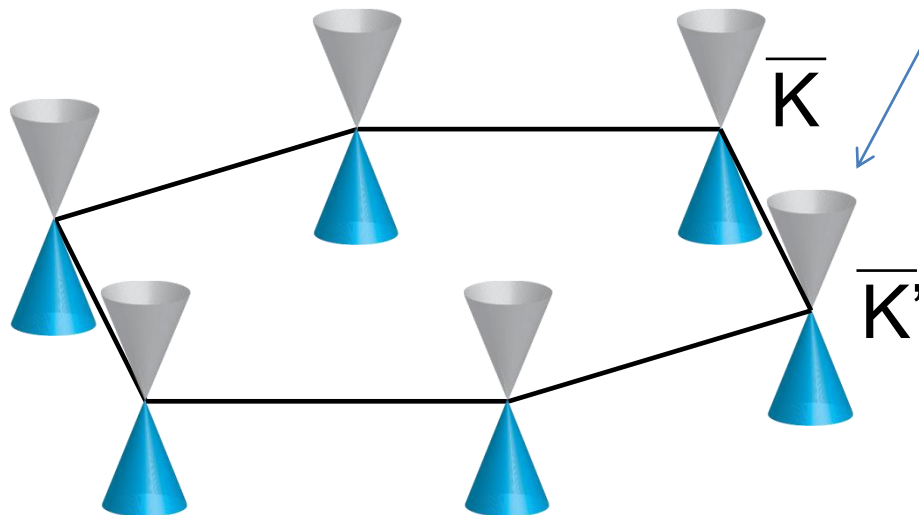
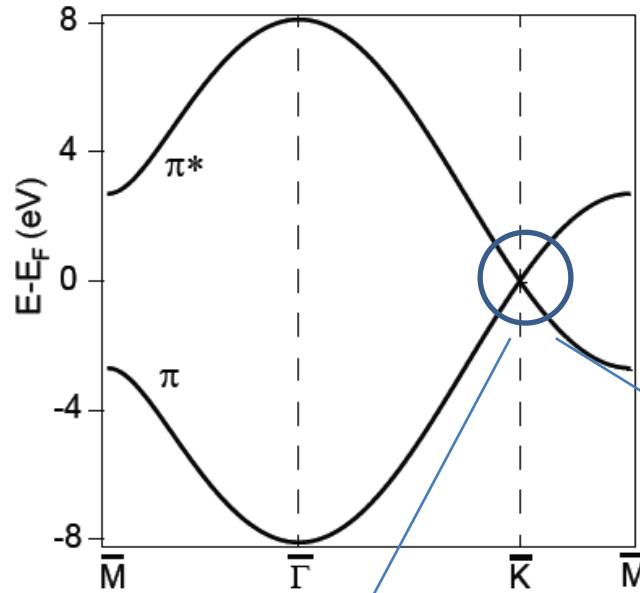
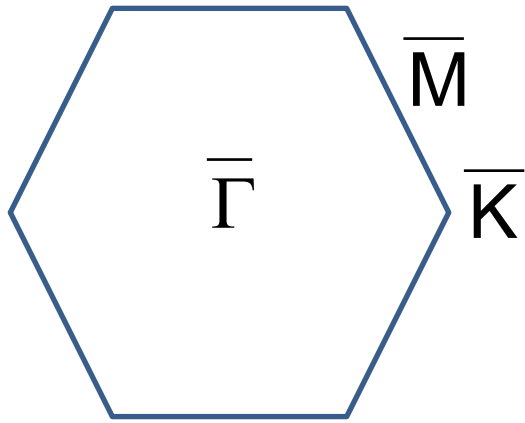
Graphen

Elektronstruktur



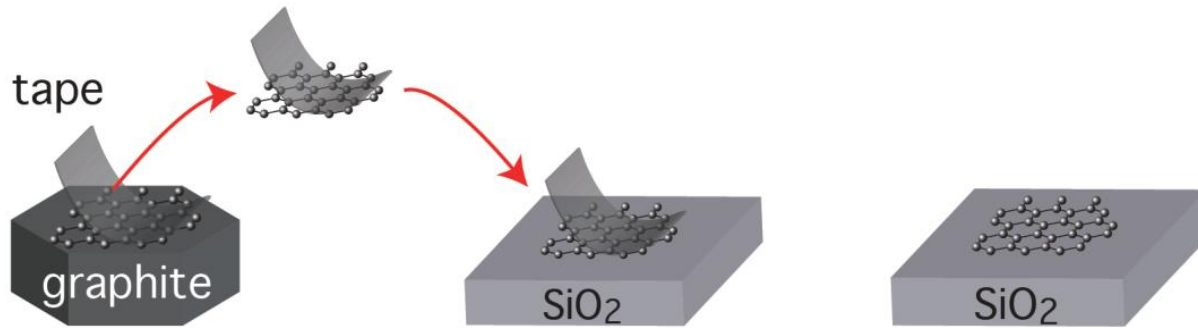
Graphen

Elektronstruktur



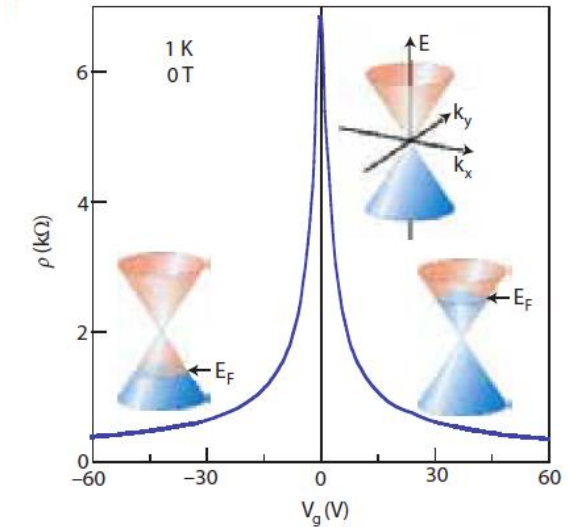
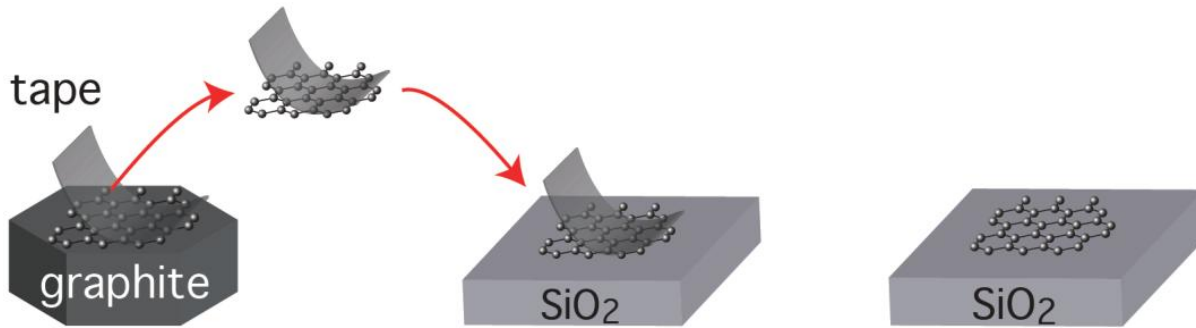
Graphen

2D elektroniske komponenter



Graphen

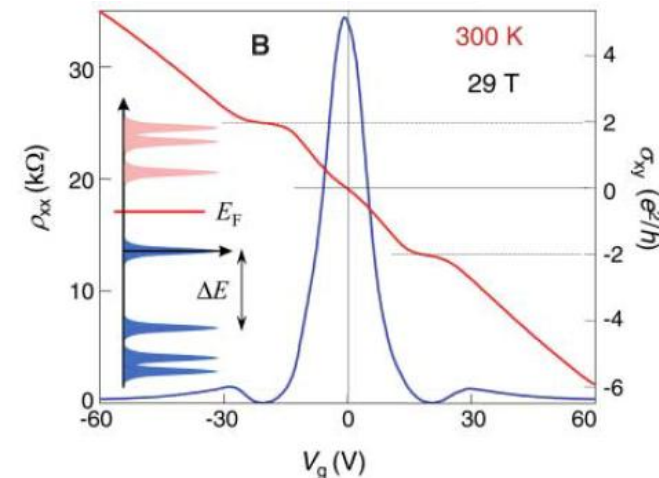
2D elektroniske komponenter



- Ambipolær felt-effekt

- Kæmpe mobilitet $> 200.000 \text{ cm}^2/\text{Vs}$

- Kvante Hall effekt ved stuetemperatur

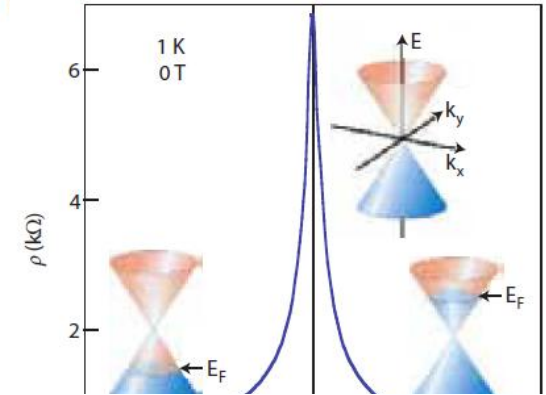
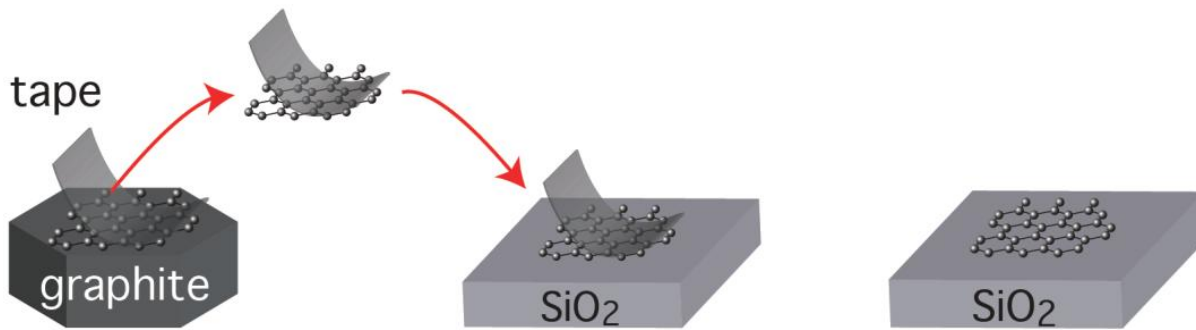


A. K. Geim & K. S. Novoselov, Nat. Mater. **6** 183 (2007)

K. S. Novoselov *et al.*, Science **315** 1379 (2007)

Graphen

2D elektroniske komponenter



Vol 438|10 November 2005|doi:10.1038/nature04233

nature

”relativistic”

LETTERS

Two-dimensional gas of massless Dirac fermions in graphene

K. S. Novoselov¹, A. K. Geim¹, S. V. Morozov², D. Jiang¹, M. I. Katsnelson³, I. V. Grigorieva¹, S. V. Dubonos² & A. A. Firsov²

Graphen

Massless "relativistic" Dirac Fermions

Dirac-lignende Hamilton operator

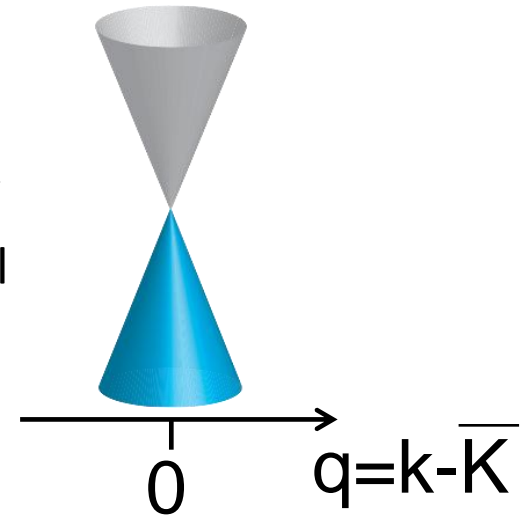
$$\hat{H} = \hbar v_F \begin{pmatrix} 0 & q_x + iq_y \\ q_x - iq_y & 0 \end{pmatrix}$$

$$E(q) = \pm \hbar v_F |q|$$

Hvorfor masseløs?

$$m^* = \hbar^2 \left(\frac{d^2 E(k)}{dk^2} \right)^{-1}$$

masseløs/
semimetal



Graphen

Massless "relativistic" Dirac Fermions

masseløs

$$\hat{H} = \hbar v_F \begin{pmatrix} 0 & q_x + iq_y \\ q_x - iq_y & 0 \end{pmatrix}$$

$$E(q) = \pm \hbar v_F |q|$$

relativistisk energi

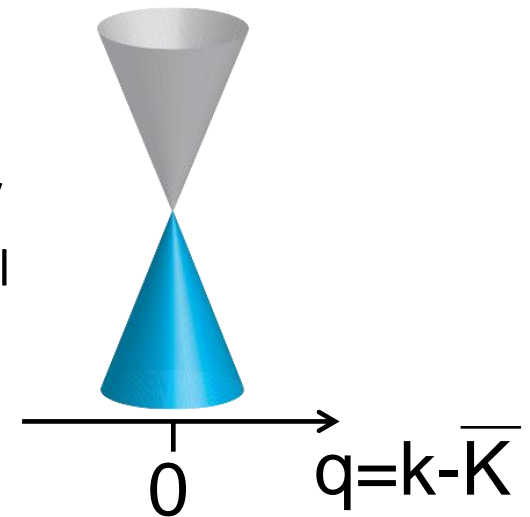
$$E = \pm pc = \pm \hbar kc$$

$$E = \pm \sqrt{(mc^2)^2 + (pc)^2}$$

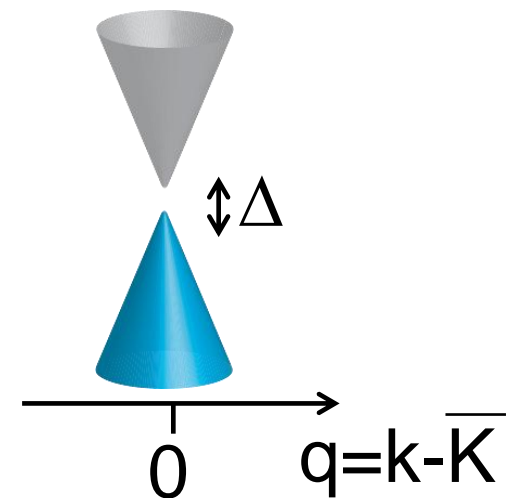
massiv

$$E(q) = \pm \sqrt{\Delta^2 + \hbar^2 v_F^2 |q|^2}$$

masseløs/
semimetal



massiv/
halvleder



Graphen

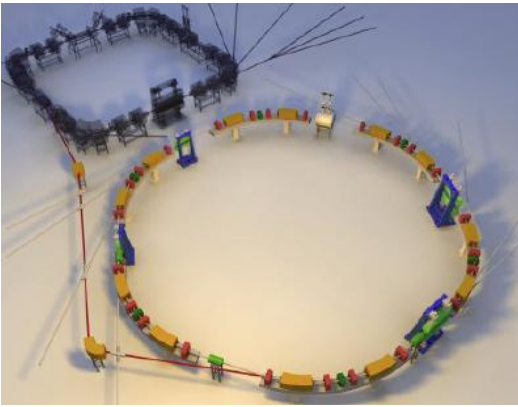
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ARPES Forsøg

Eksperimentet

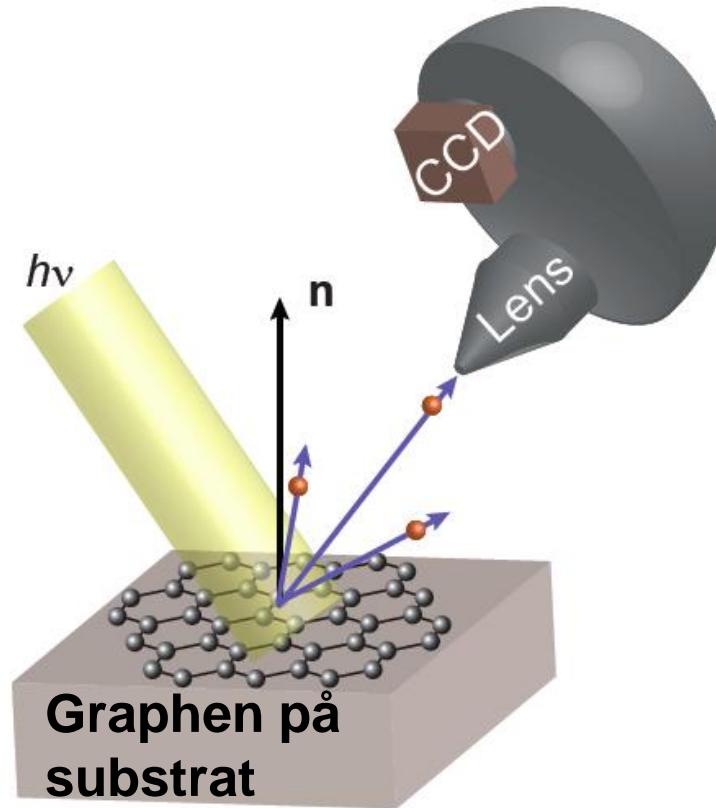
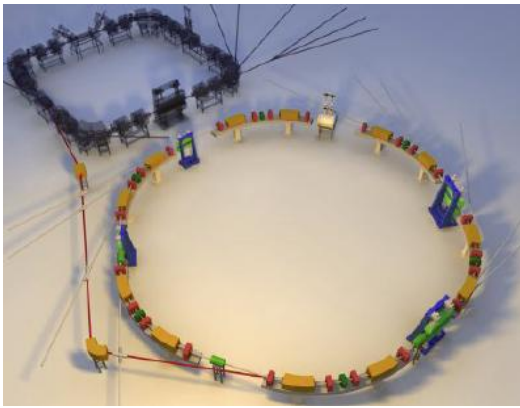
- Synkrotronstråling fra ASTRID/ASTRID2



ARPES Forsøg

Eksperimentet

- Synkrotronstråling fra ASTRID/ASTRID2
- Fotoelektrisk effekt



Impulsbevarelse:

$$|\mathbf{k}_{\parallel,f}| = |\mathbf{k}_{\parallel,i}| = \sqrt{\frac{2mE_{kin}}{\hbar^2}} \sin(\Theta)$$

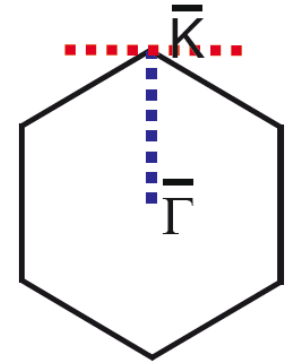
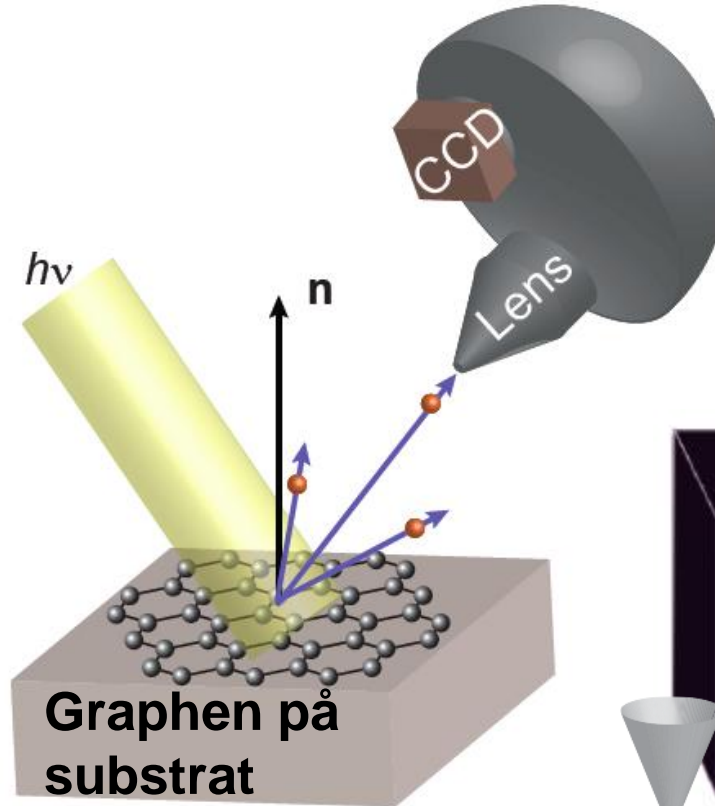
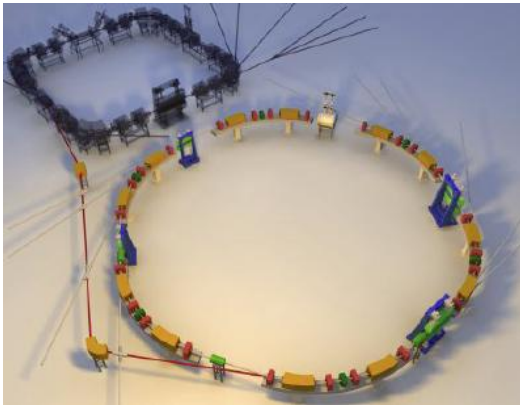
Energibevarelse:

$$E_{kin} = h\nu - E_{bin} - W$$

ARPES Forsøg

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- Fotoelektrisk effekt



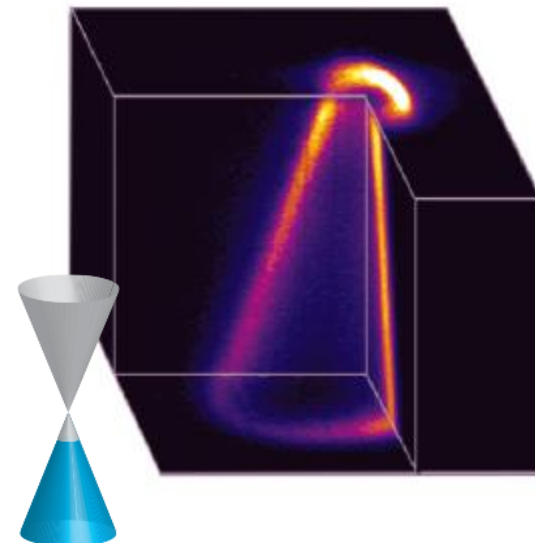
**Graphen
Dirac kegle**

Impulsbevarelse:

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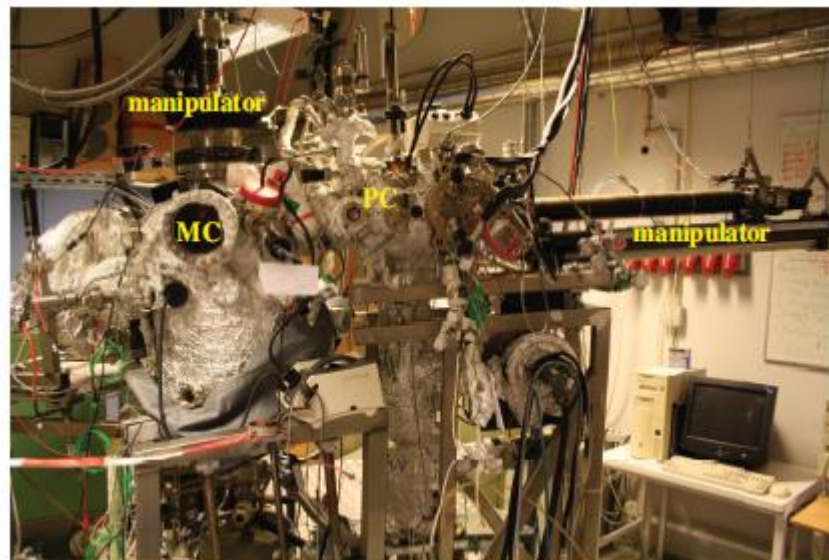
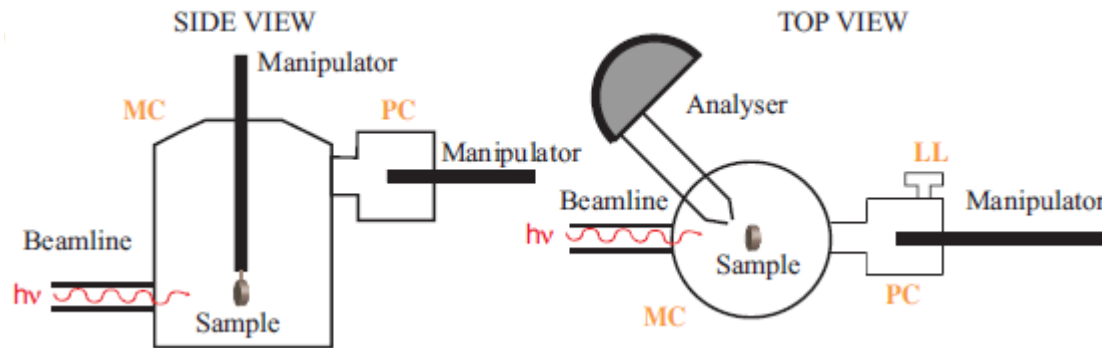
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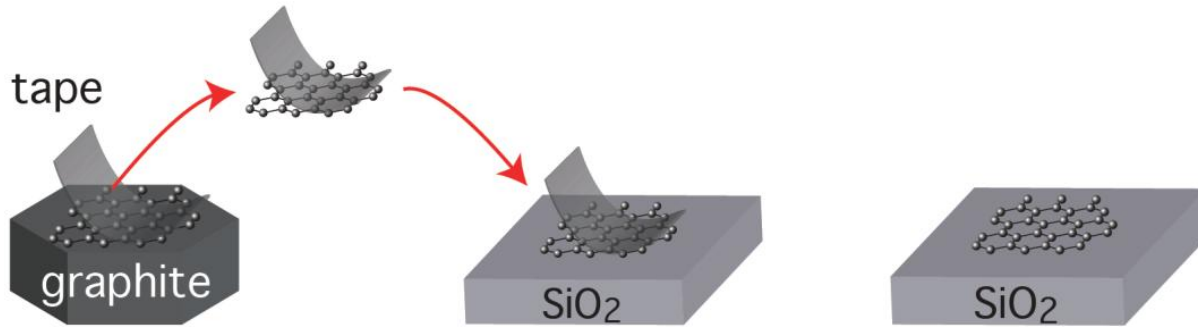
ARPES Forsøg

Den gamle SGM3 beamline:



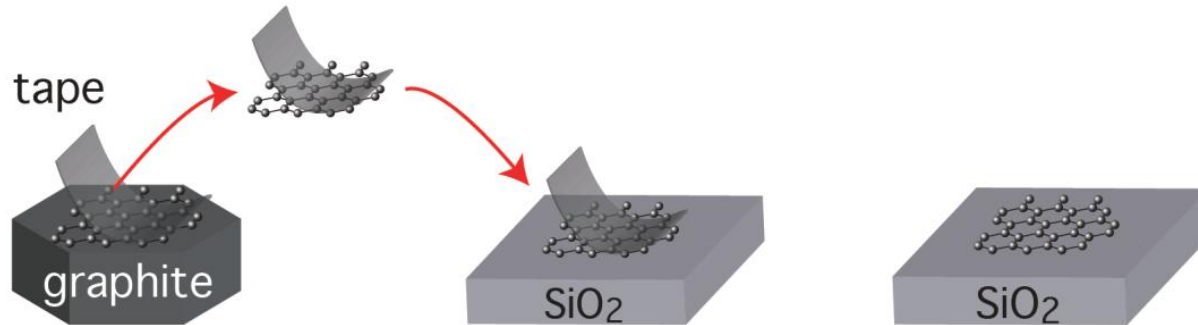
Epitaksial Graphen i UHV

Exfoliering

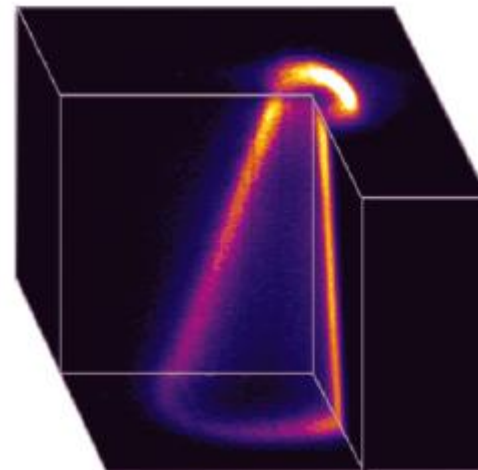
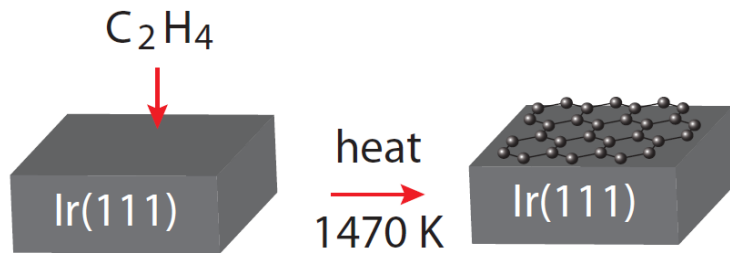


Epitaksial Graphen i UHV

Exfoliering



Epitaksial vækst

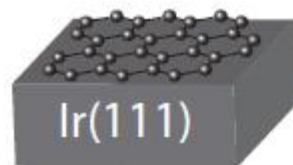
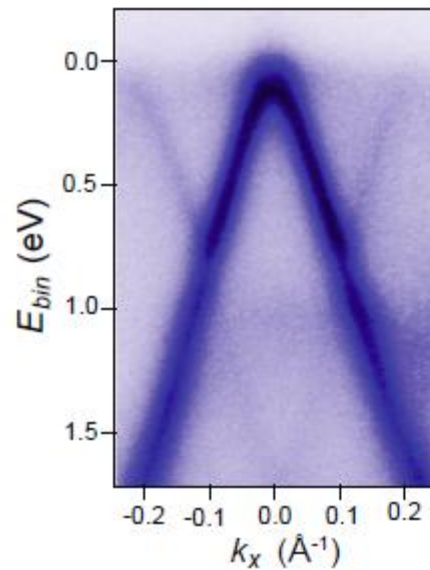
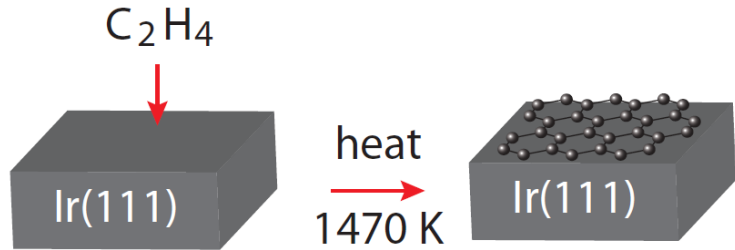


Iridium
krystal



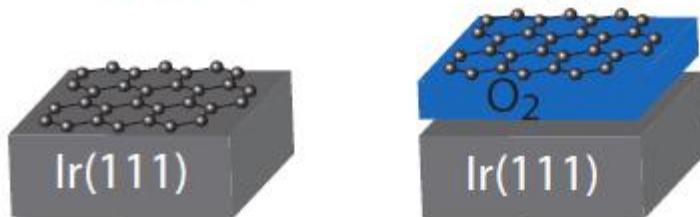
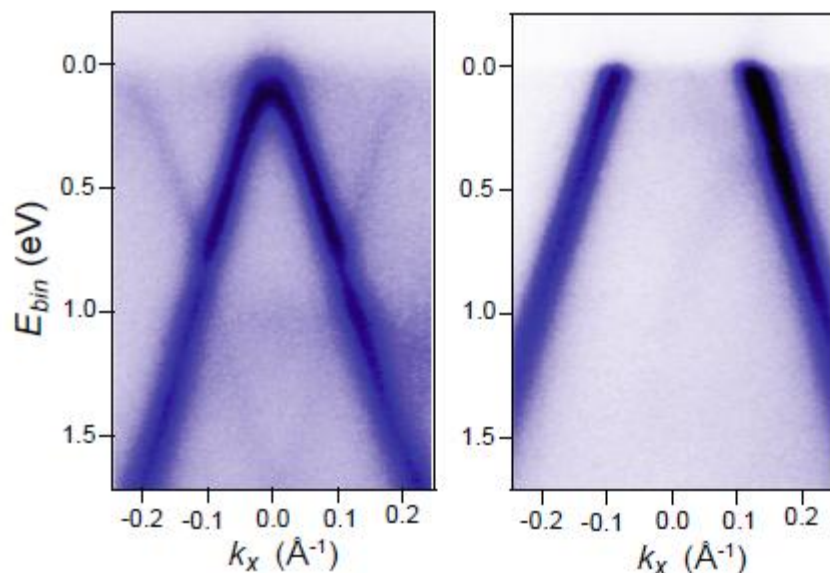
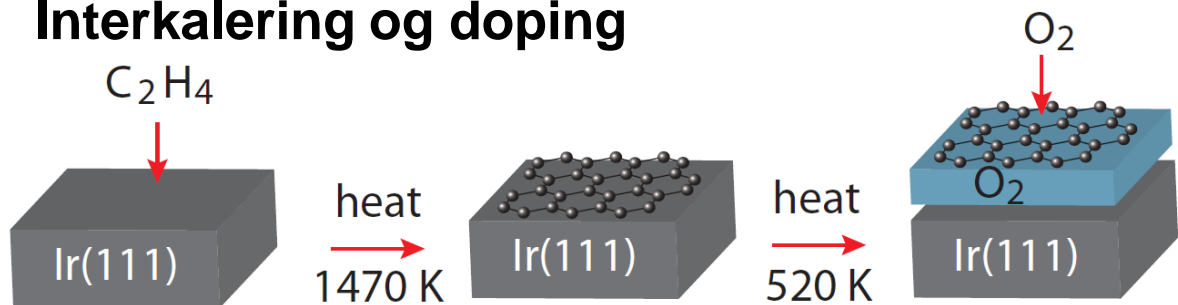
Epitaksial Graphen i UHV

Interkalering og doping



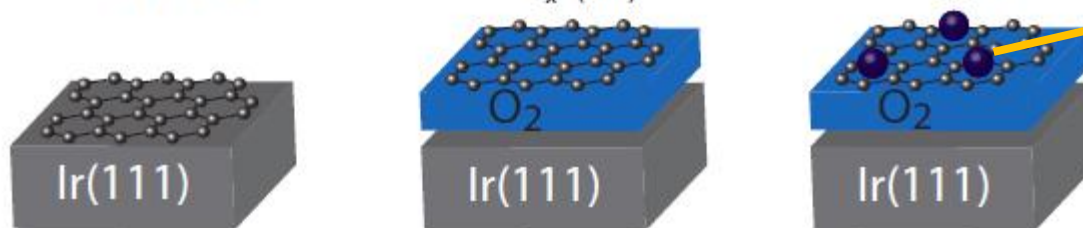
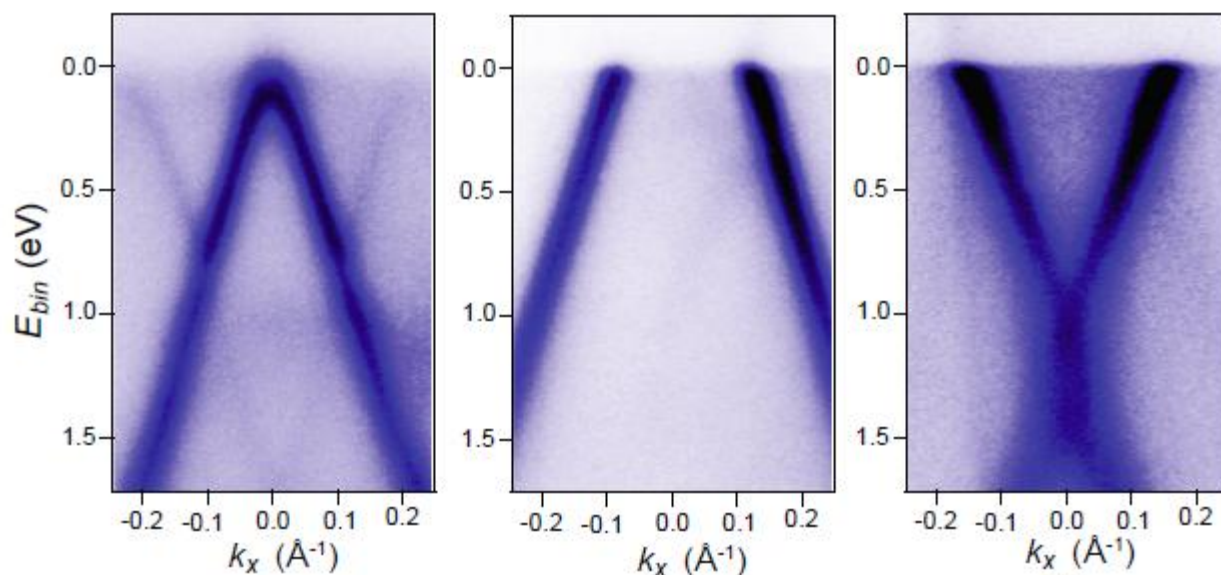
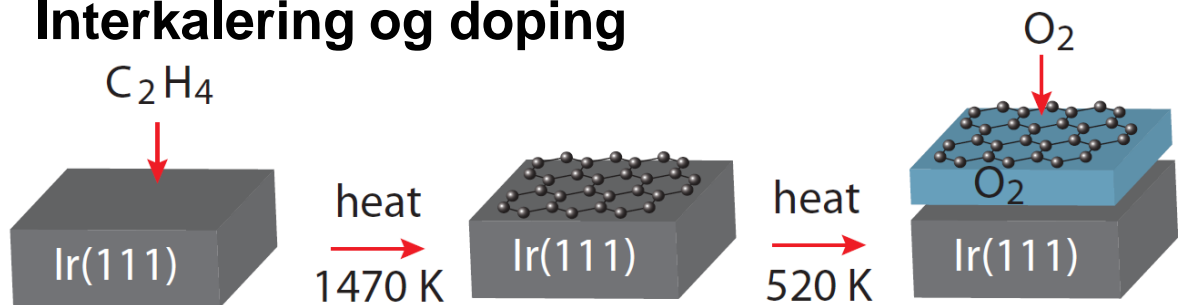
Epitaksial Graphen i UHV

Interkalering og doping



Epitaksial Graphen i UHV

Interkalering og doping



Rb,
K,
Cs

Graphen

Kulstof i to dimensioner

Vinkelopløst fotoemissions spektroskopi

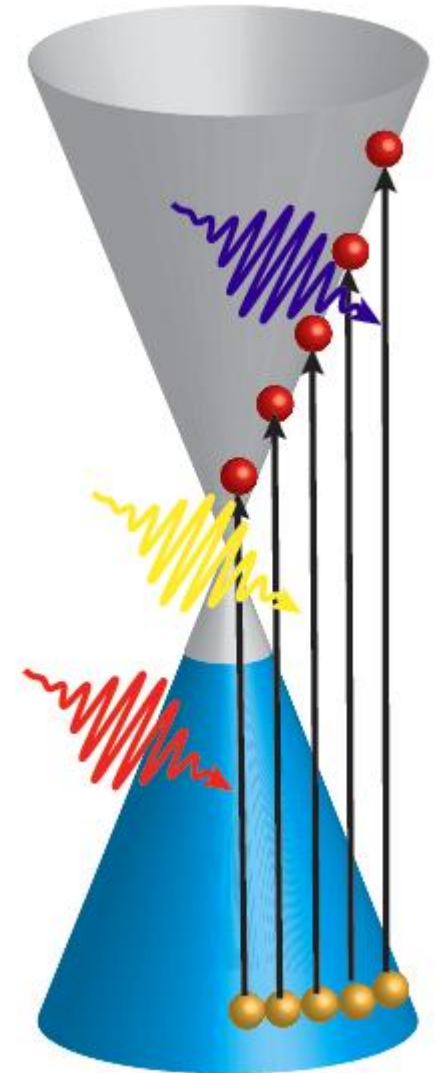
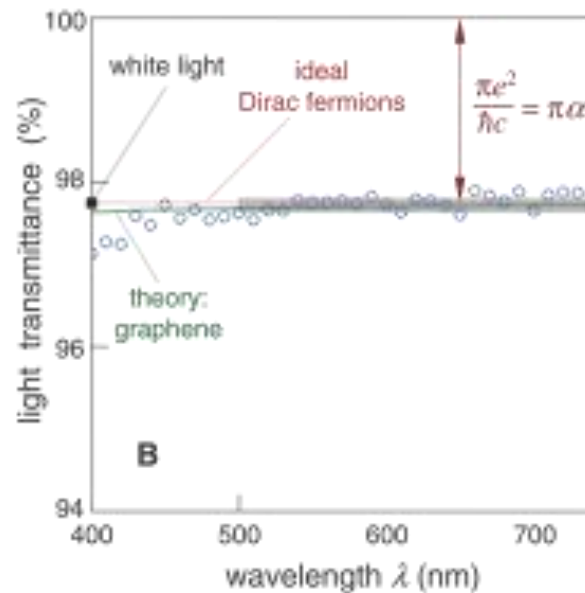
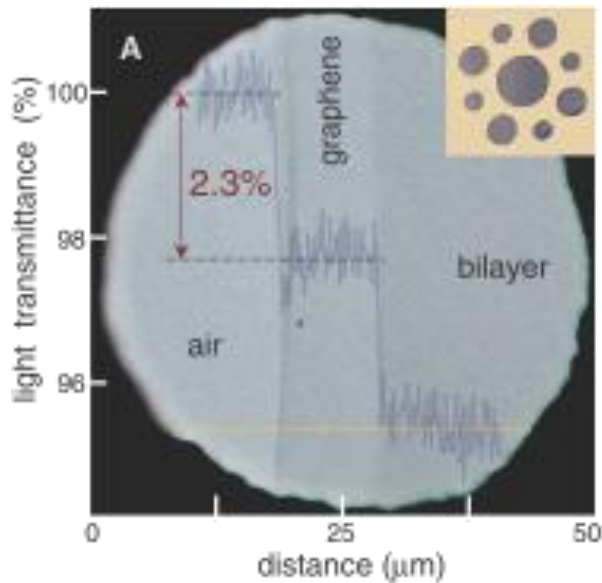
Direkte billeder af Dirac kegler i graphen



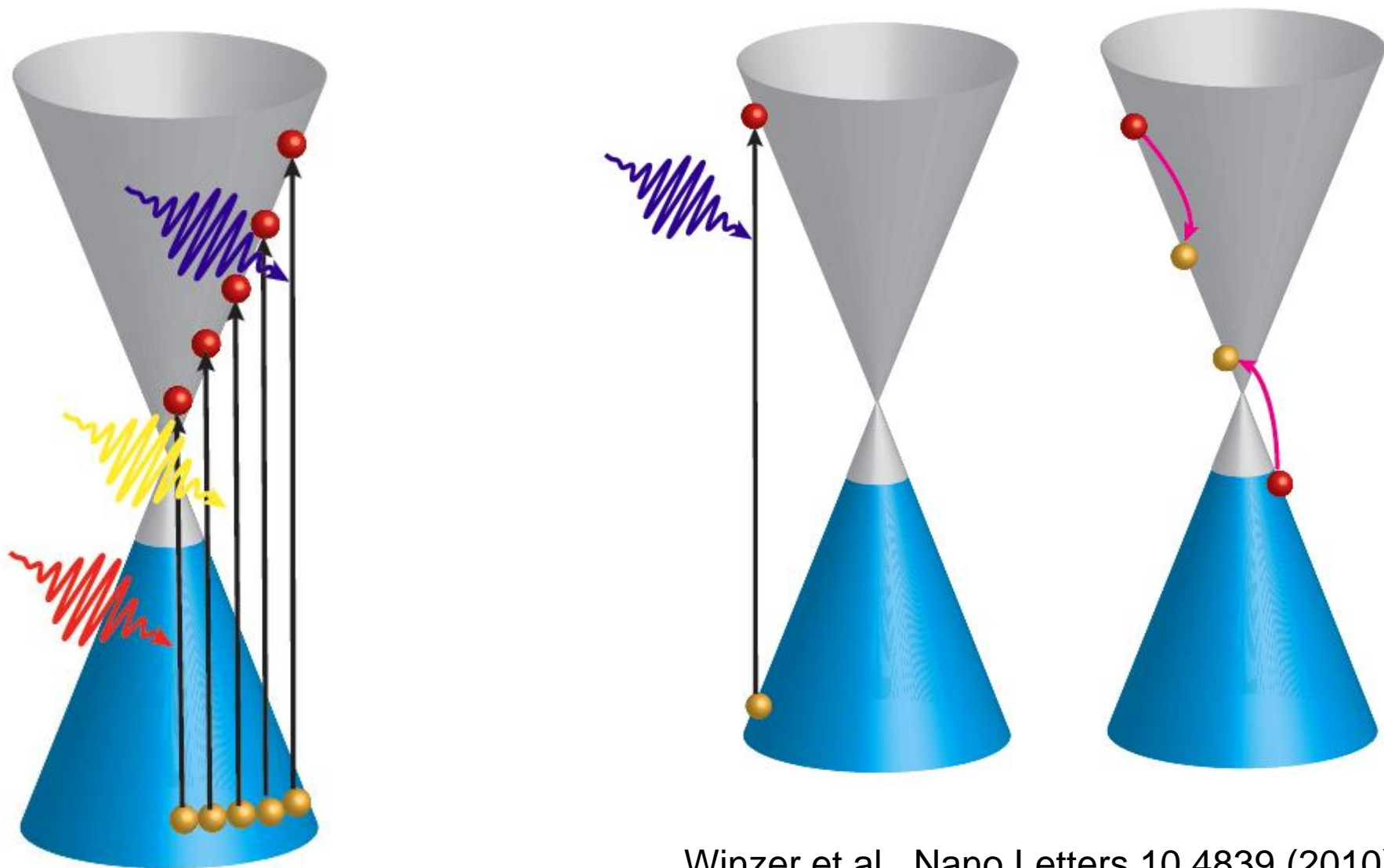
Elektronstruktur film med ultrahurtige lyskilder

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Graphen er meget transparent...



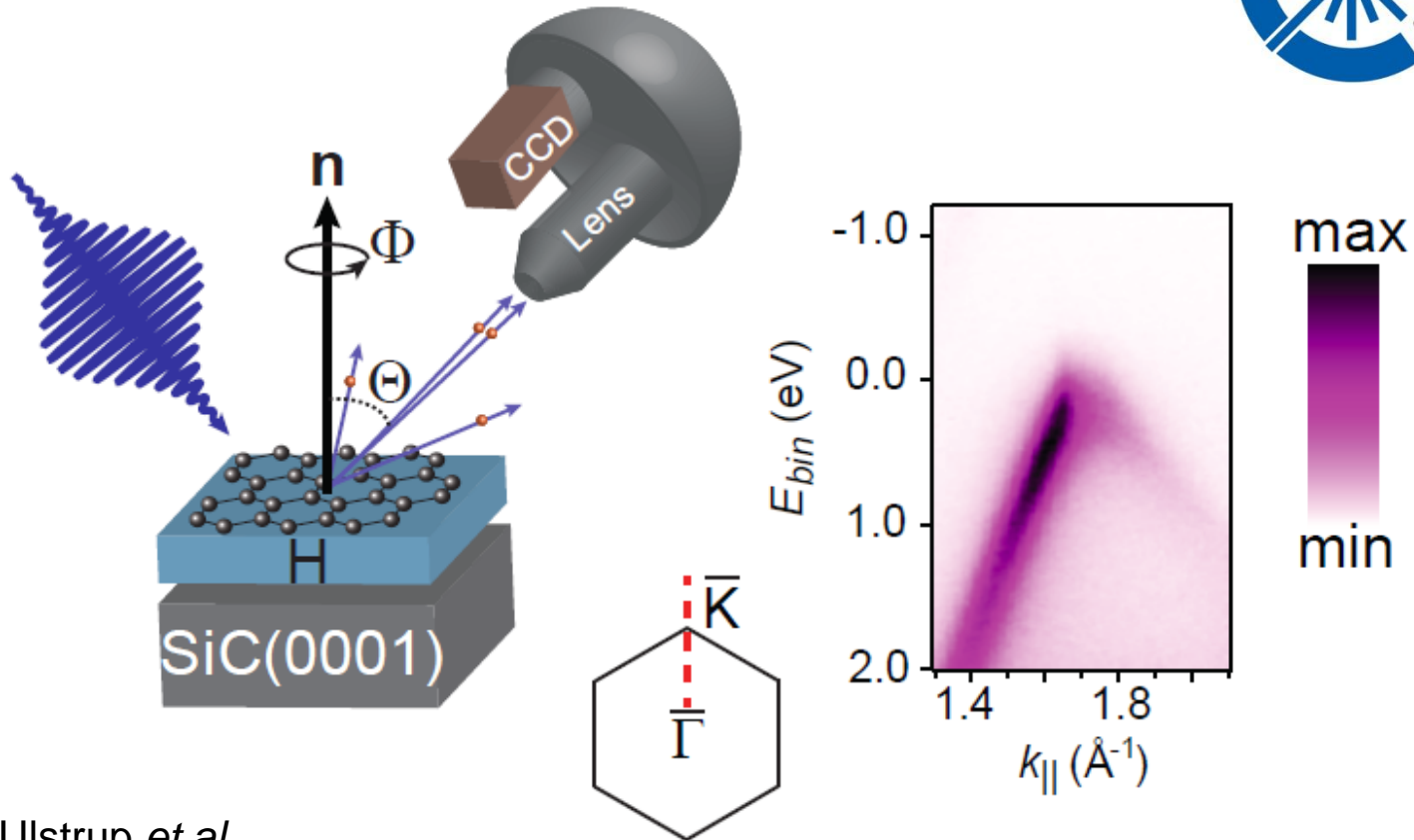
...men måske interessant for solceller



Winzer et al., Nano Letters 10 4839 (2010)
Song et al., Nano Letters 11 4688 (2011)

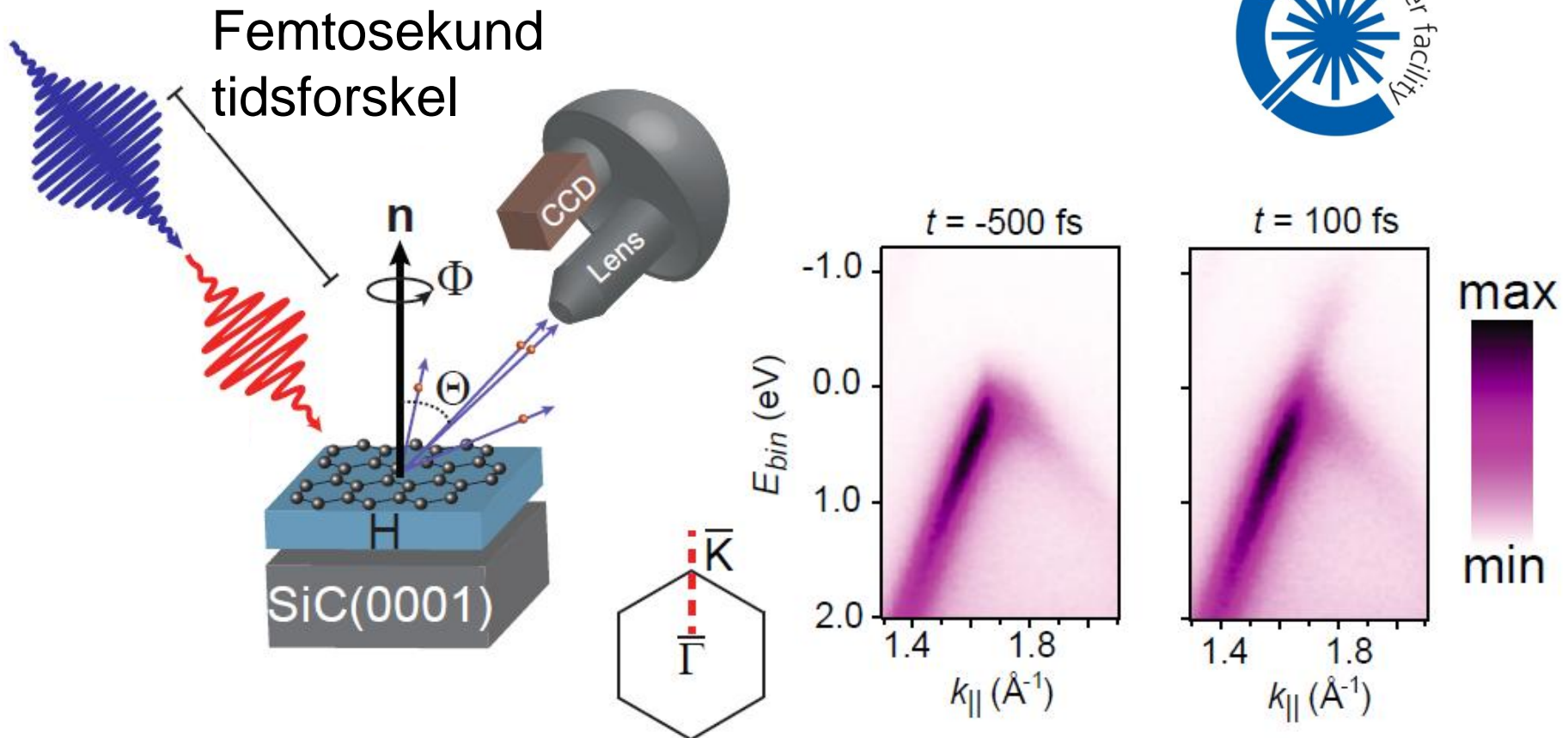
Tidsopløst ARPES

ARPES med ultrahurtig, høj-energi laserkilde

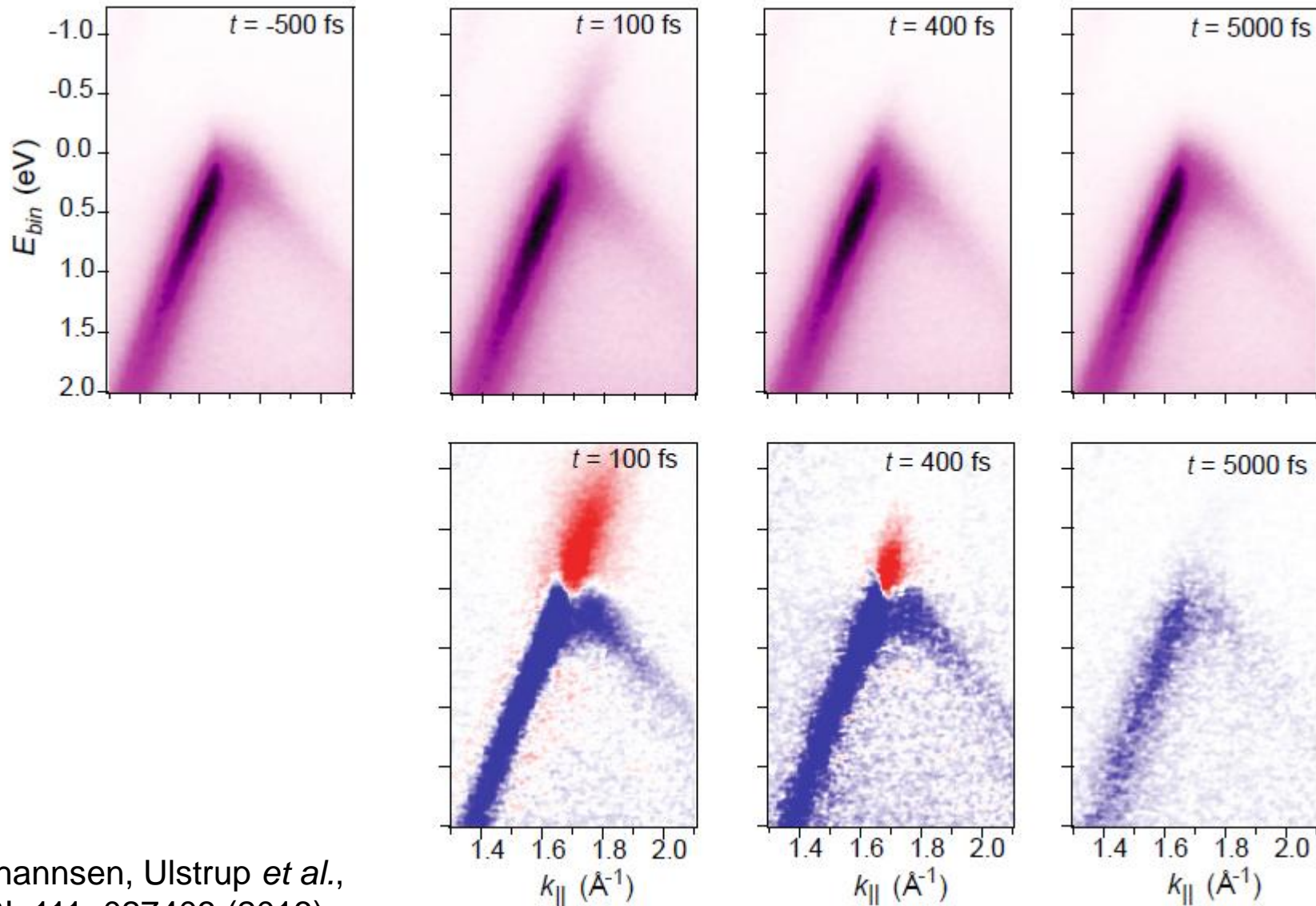


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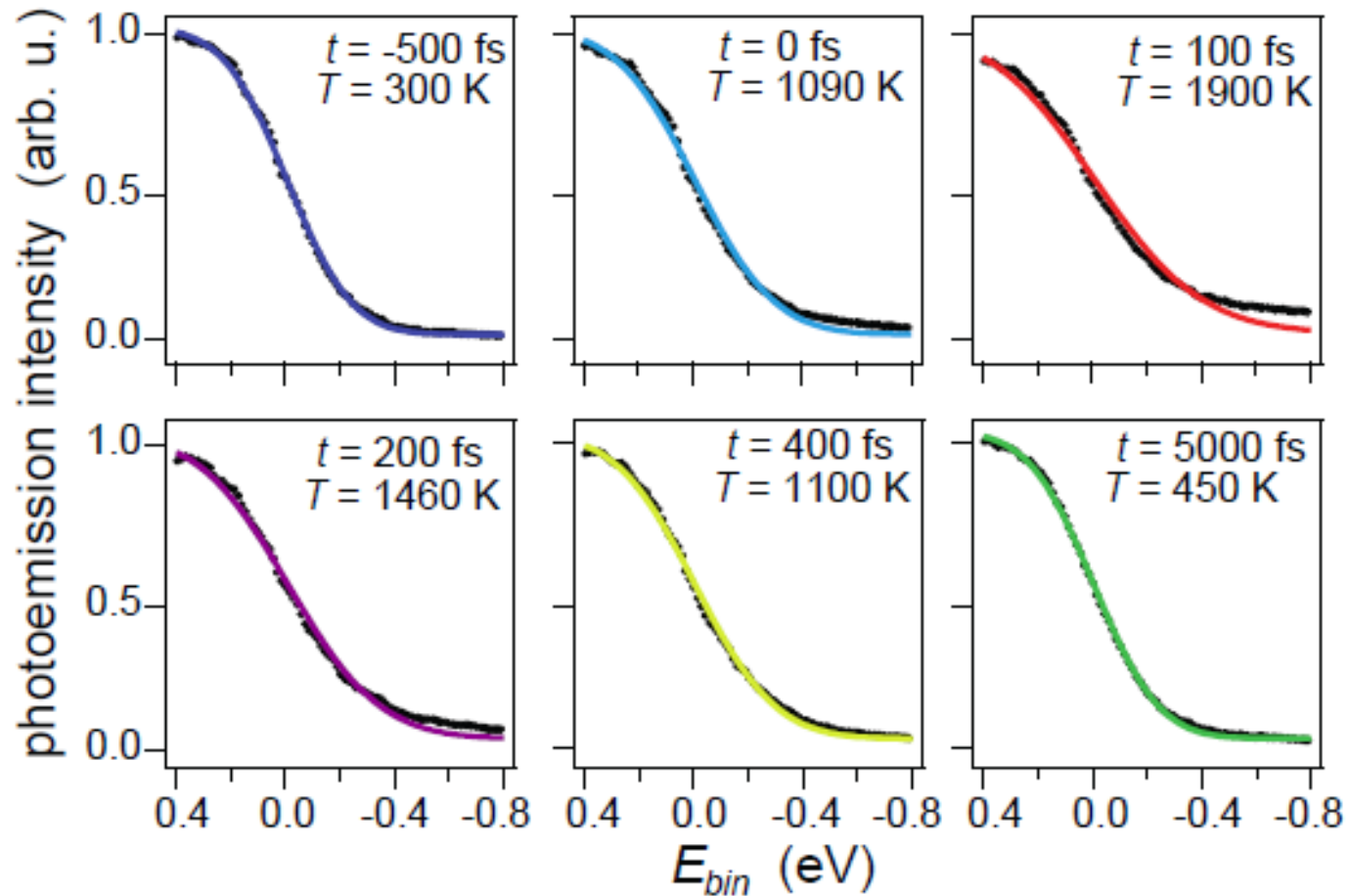
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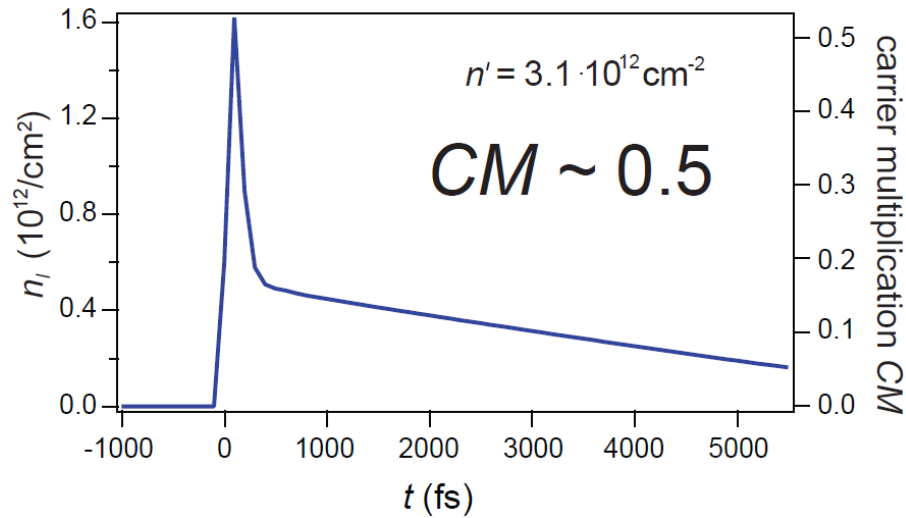
Snapshots af varme elektroner



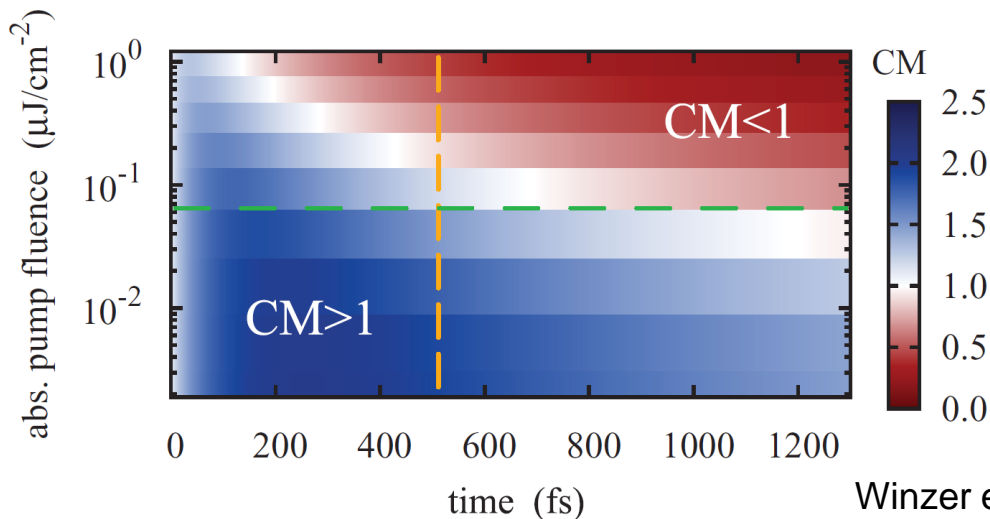
Snapshots of warm electrons



Carrier Multiplication



Vores abs.
energitæthed



Konklusioner



**Graphen er meget transparent og ledende
(transparente elektroder)**



**Graphen kan absorbere lys med alle frekvenser
(solceller)**



**Vi kan fremstille og tune egenskaberne af graphen i UHV
via epitaksial vækst, interkalering og doping**



**Fotoemissions spektroskopi giver direkte billeder af et
materiales elektronstruktur**

Konklusioner



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Tak!!!