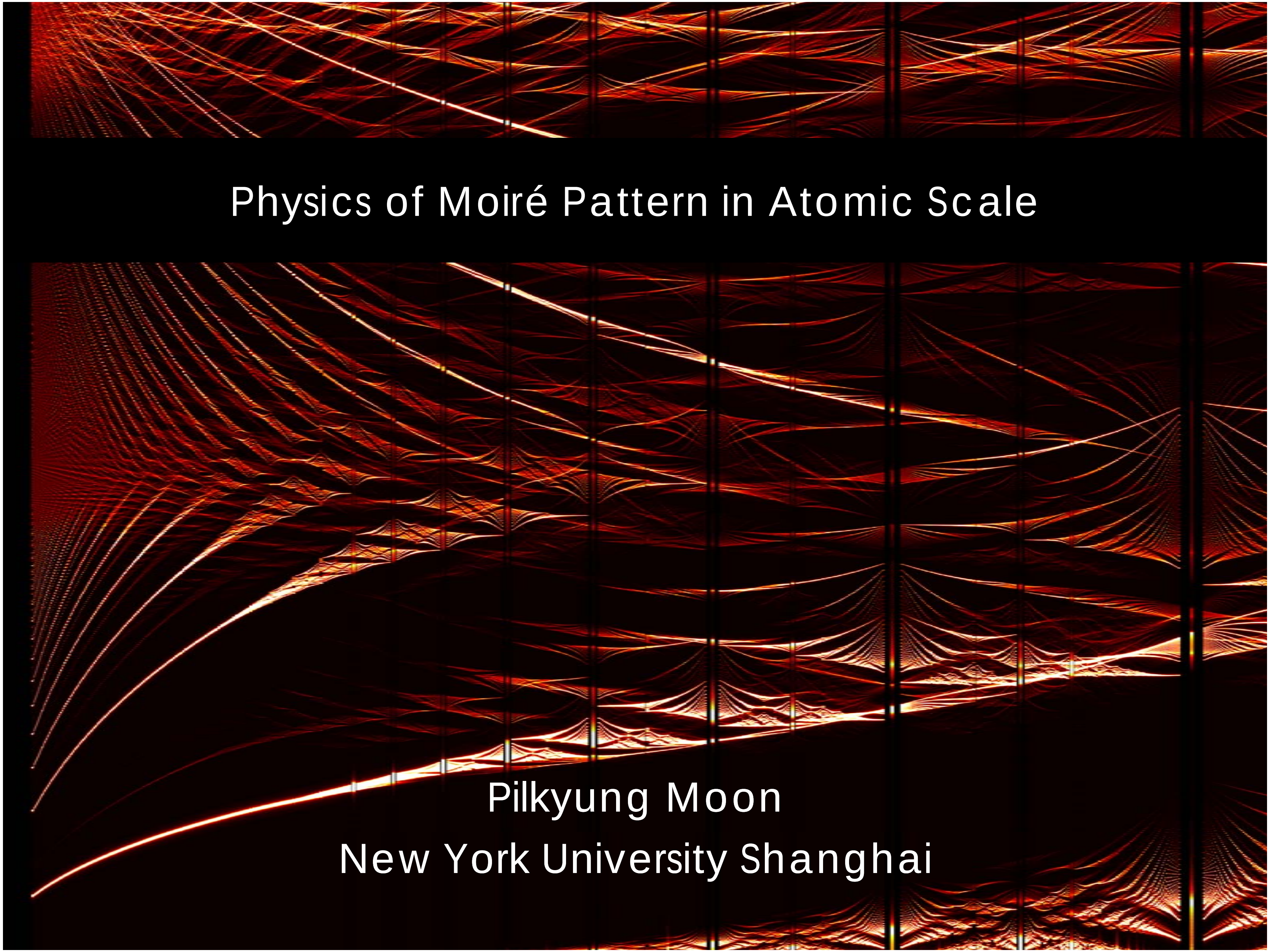
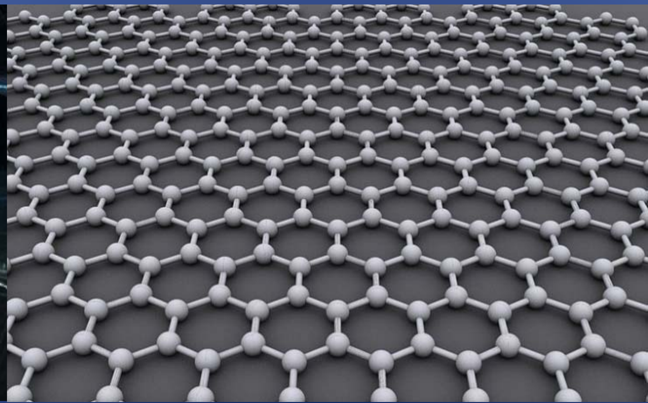
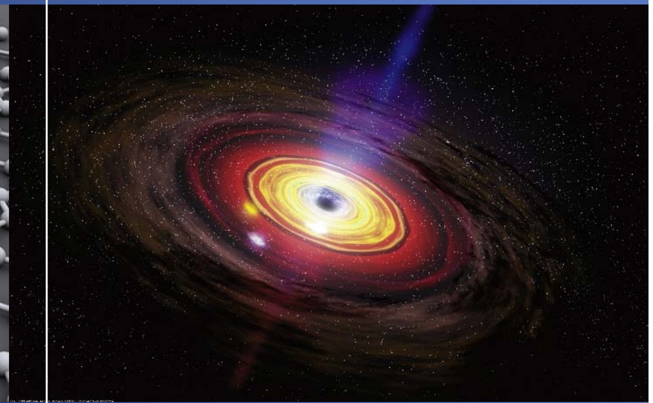


Physics of Moiré Pattern in Atomic Scale

Pilkyung Moon
New York University Shanghai

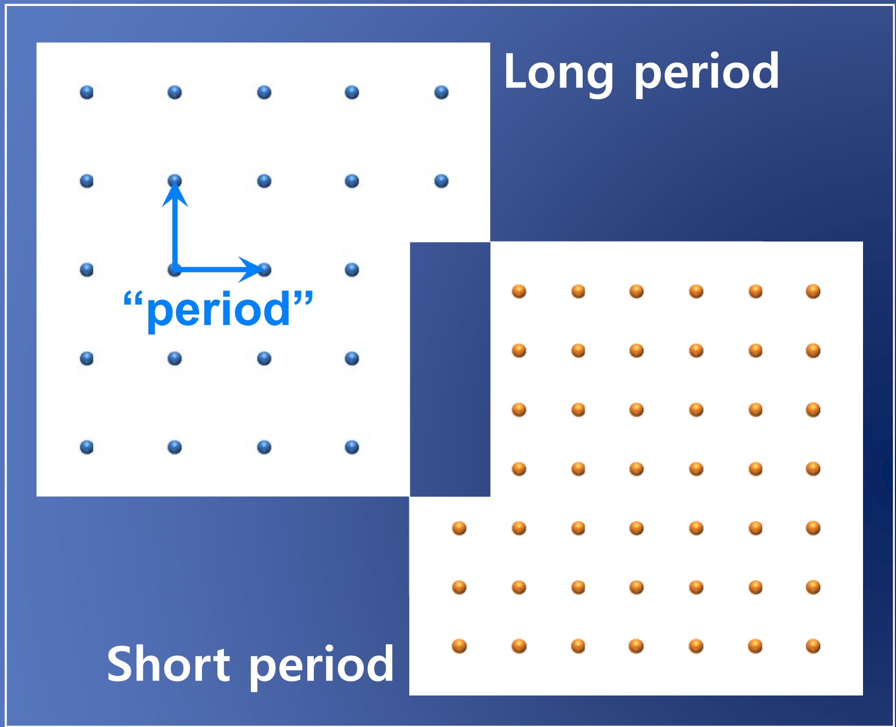
Physics

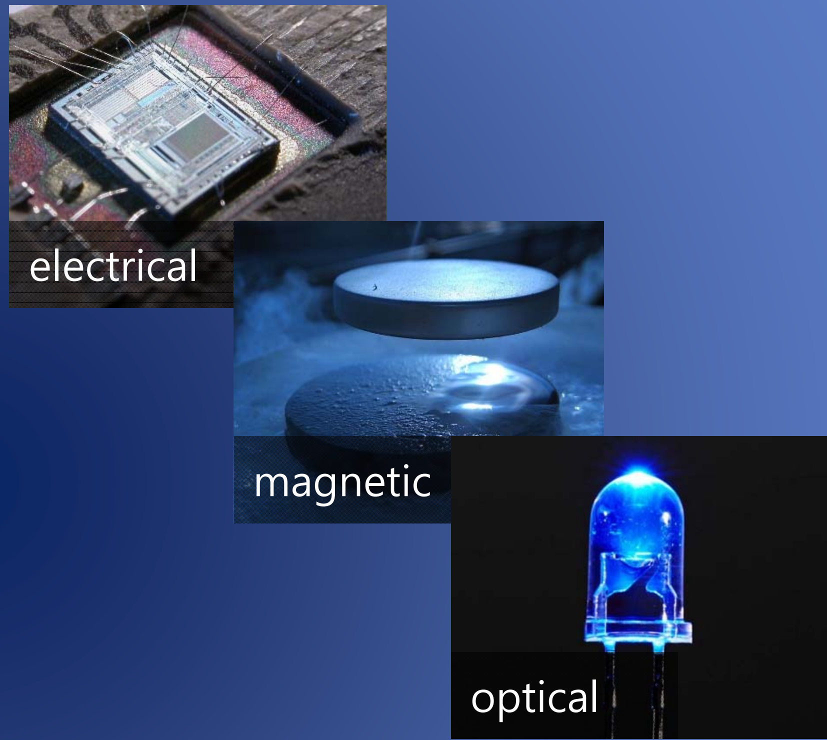




Solid State Physics

- **Atomic species**
- **Periodicity of atoms** → **determine material properties**

Period of atoms → Material properties



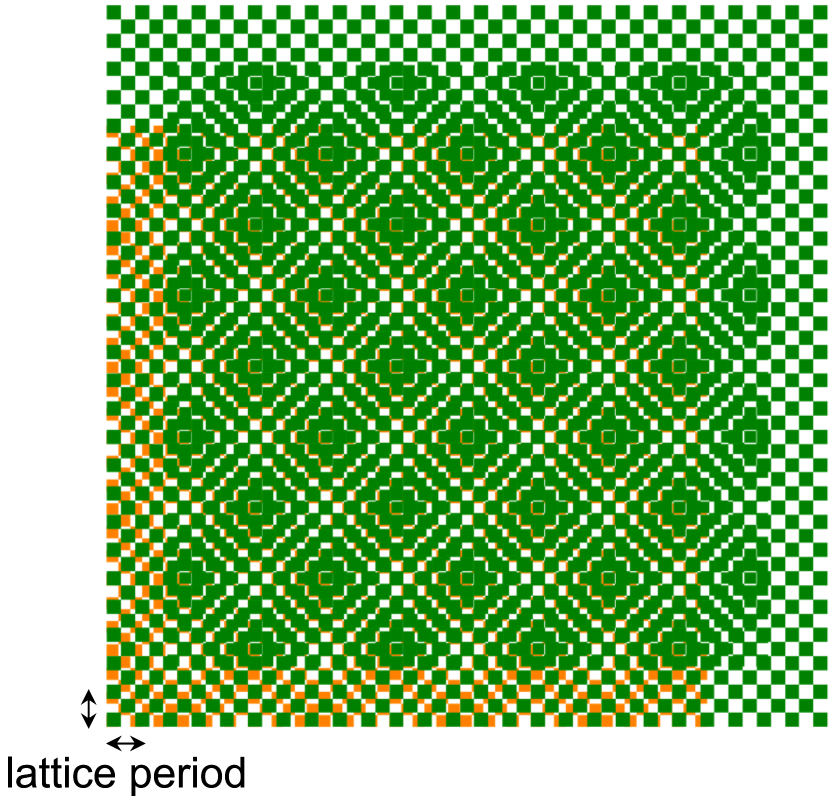


- **Period : <u>0.1-1 nm</u> (1 nm = 10^{-9} m)**
- **Compression / elongation : < 1%**

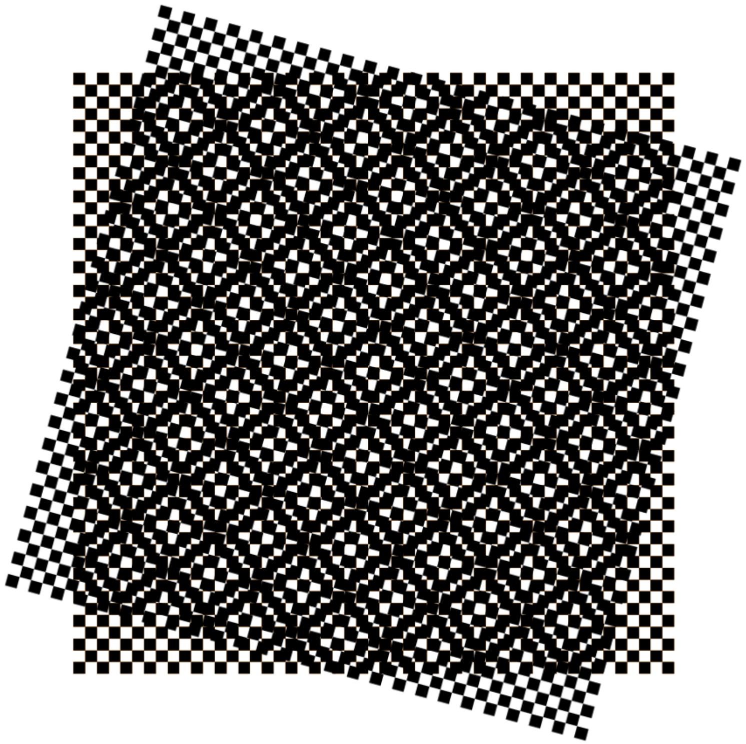
→ **limit variability !!**

Moiré Crystal

Interference of periodic patterns

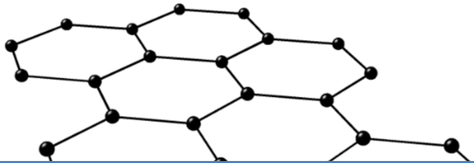


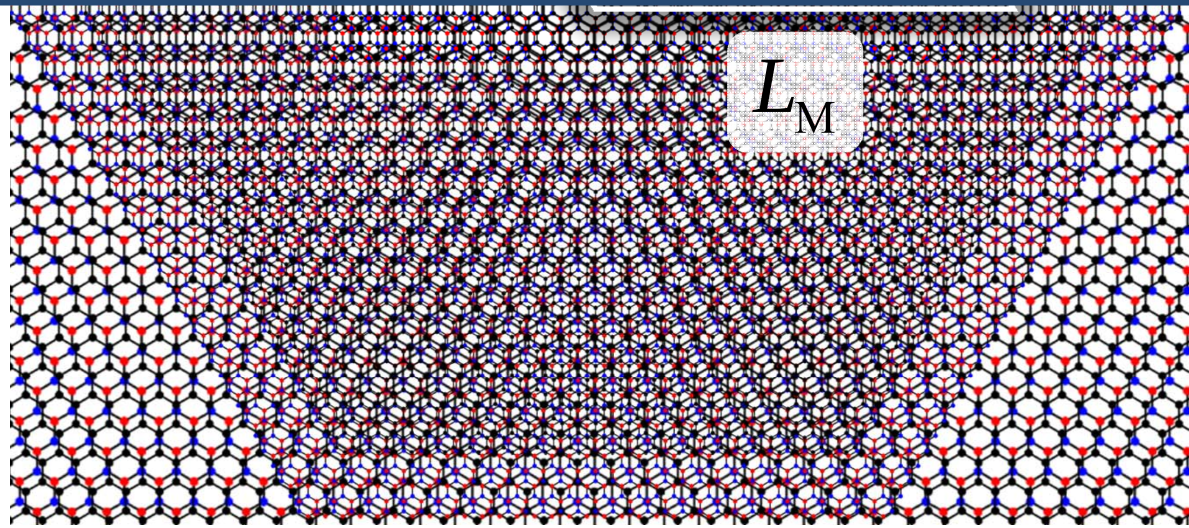
difference in lattice period



difference in lattice orientation

Moiré Crystal

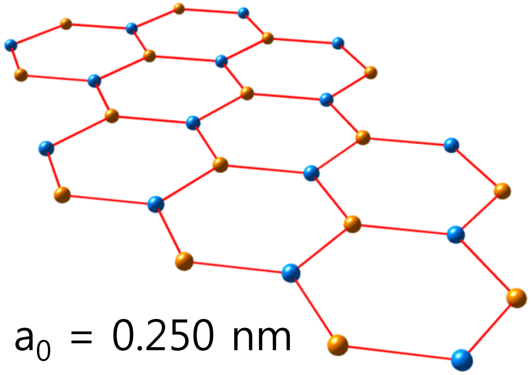




conventional materials: a_0 ~ **0.1-1 nm**

moiré crystal: L_M ~ **1-100 nm (*)**

* tunable with interlayer registry



a_0 = 0.250 nm

hexagonal BN

$$L_M = \frac{(1+\varepsilon)}{\sqrt{\varepsilon^2 + 2(1+\varepsilon)(1-\cos\theta)}}\, a_0$$

(ε: lattice mismatch,

θ: lattice misorientation)

Angle Dependence (Absorption Spectrum)

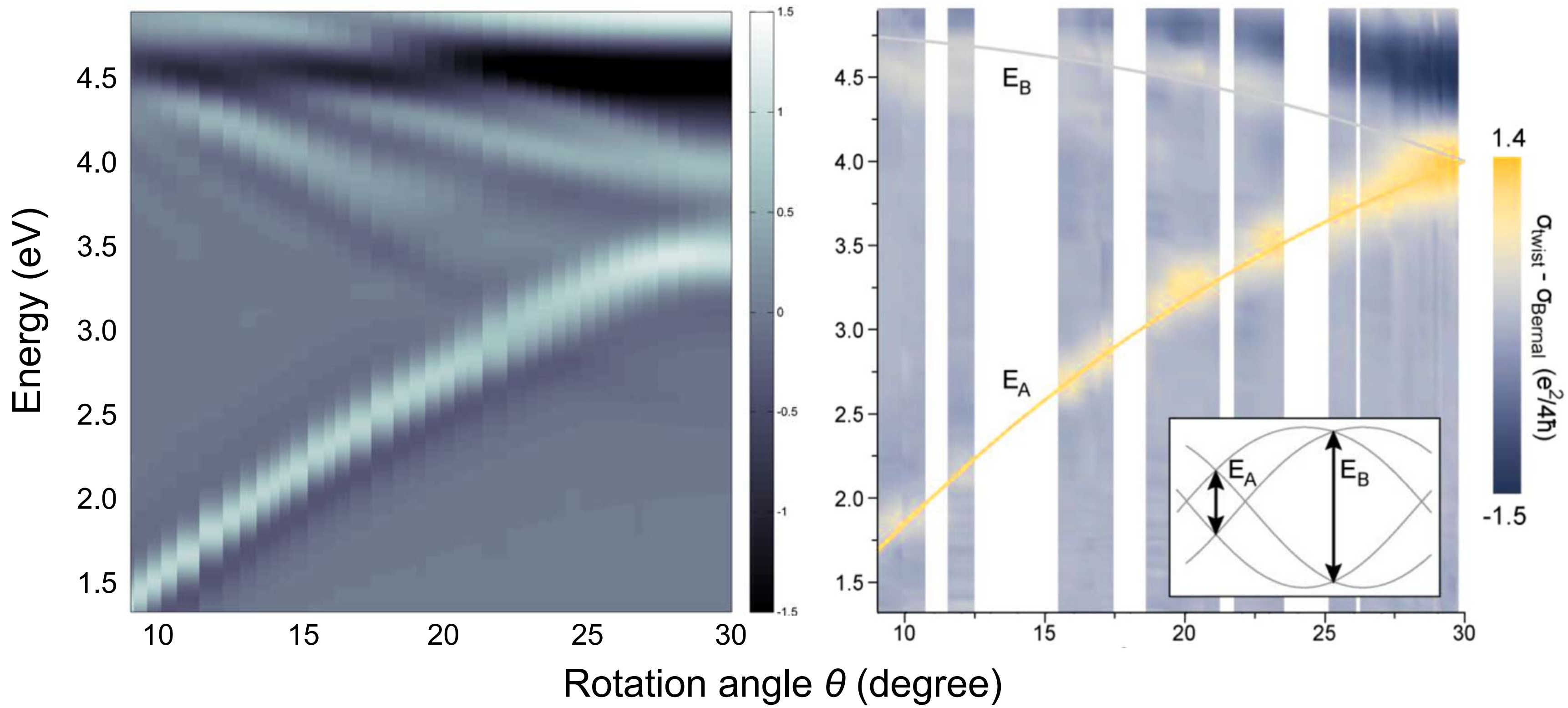
$(\sigma_{\text{twisted bilayer graphene}} - \sigma_{\text{Bernal}})$

Theory

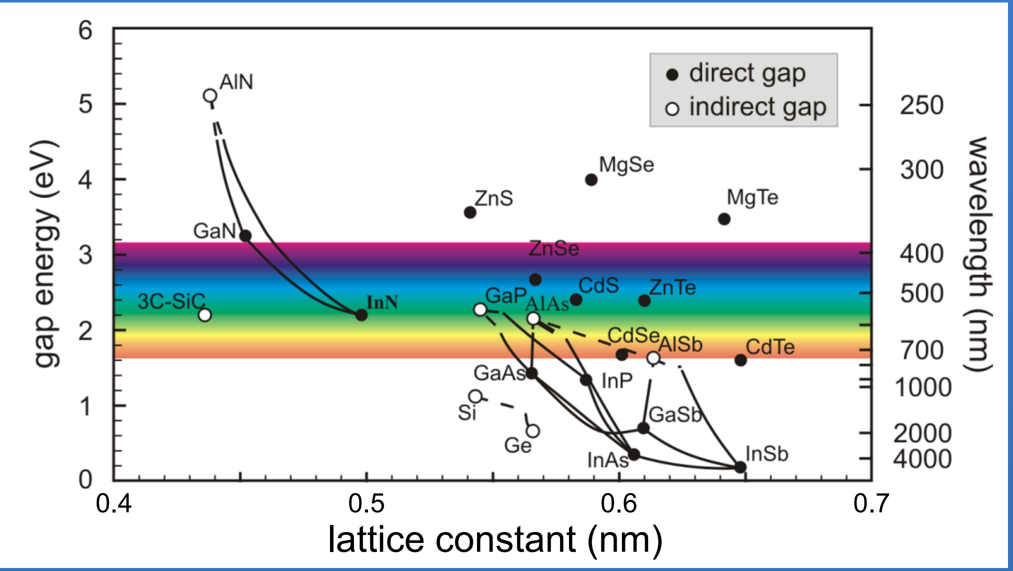
Moon and Koshino,
Phys. Rev. B 87, 205404 (2013).

Experiment

R. W. Havener, Y. Liang, L. Brown,
L. Yang, and J. Park, Nano Lett. 14, 3353 (2014).



Wide Spectral Range

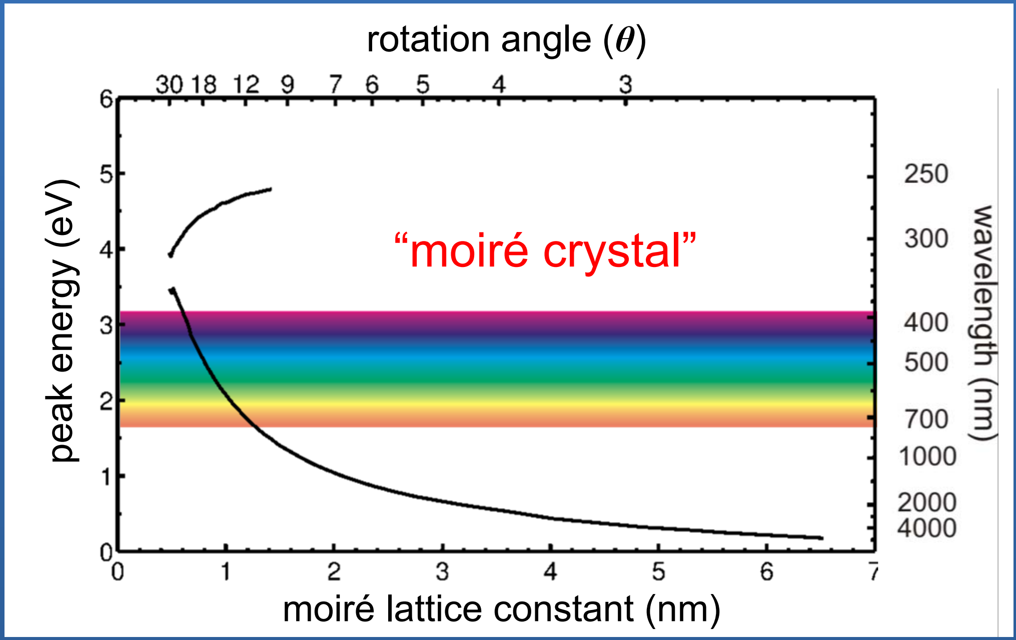


III-V materials, composite

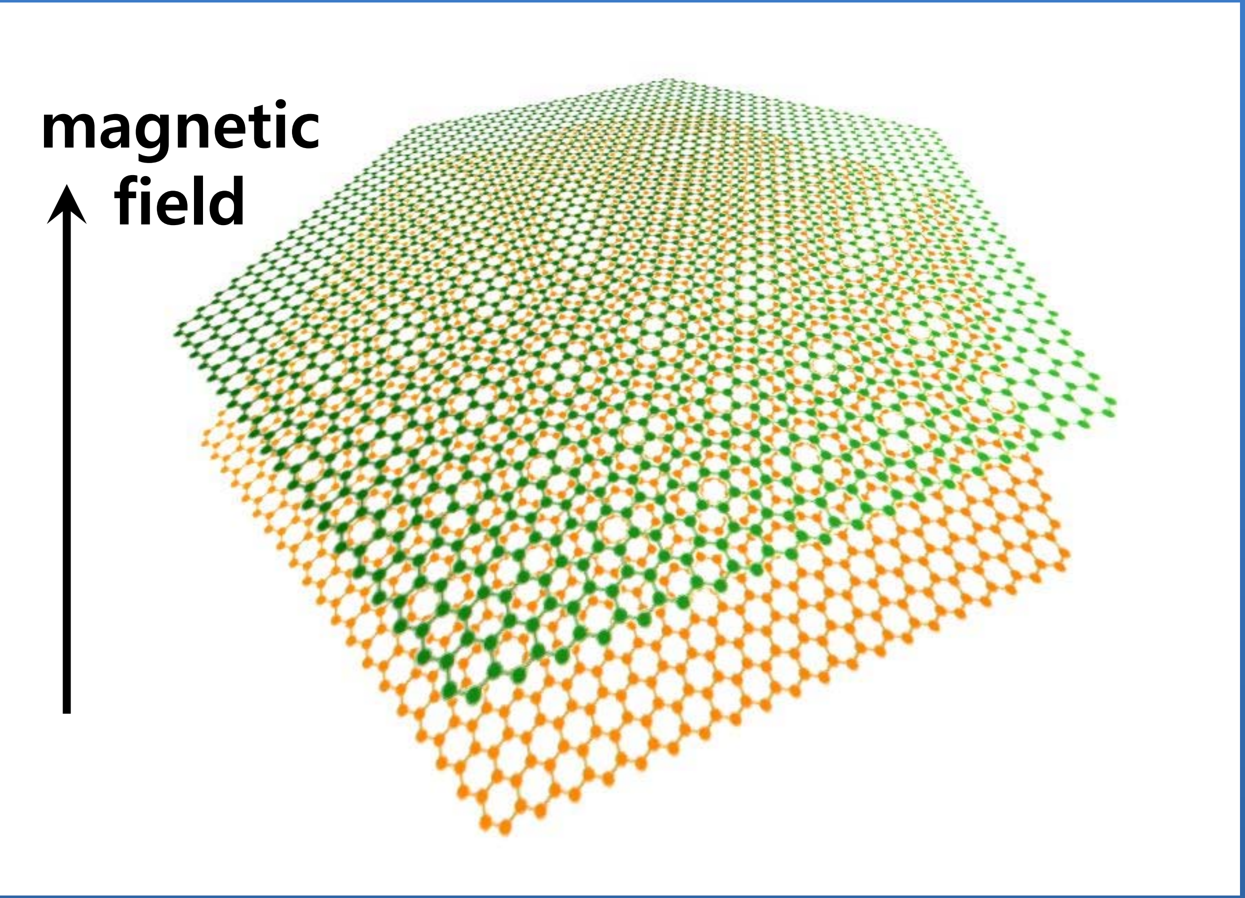
Moiré crystal

- from terahertz to UV -

(Moon and Koshino)



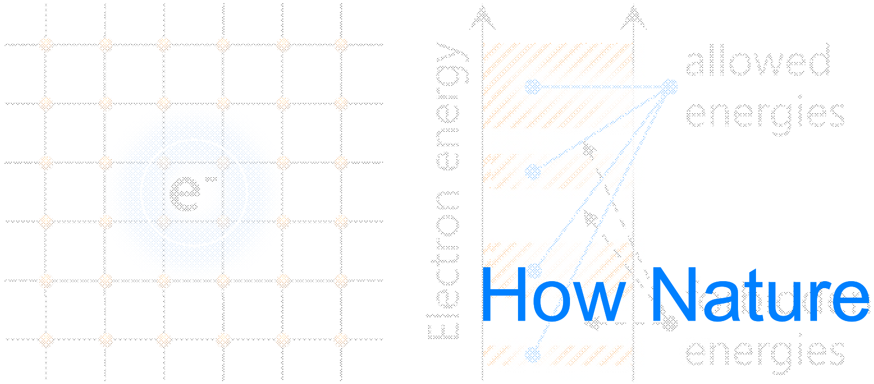
Moiré Crystal in Magnetic field



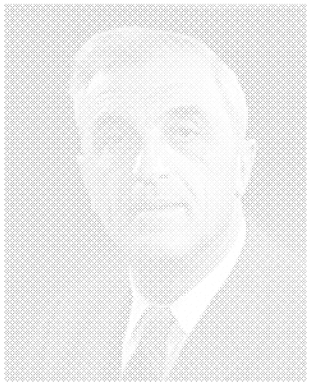
How the spectrum looks like?

How Nature harmonizes the two?

Electron in Periodic Lattice



“energy bands” (finite widths)

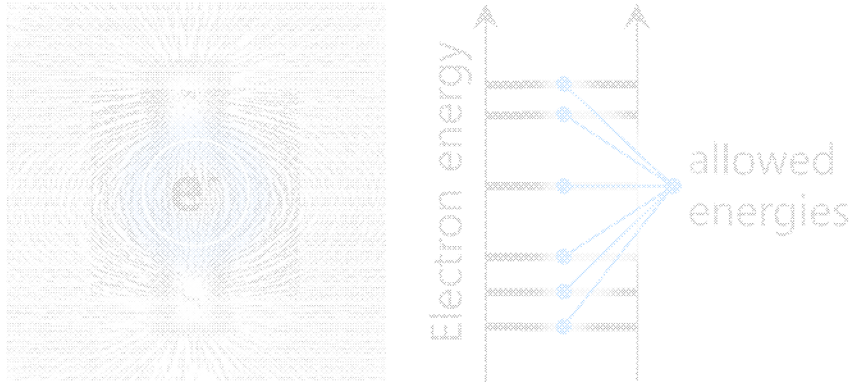


Felix Bloch

Zeitschrift für Physik

52, 555 (1929)

Electron in Magnetic Field



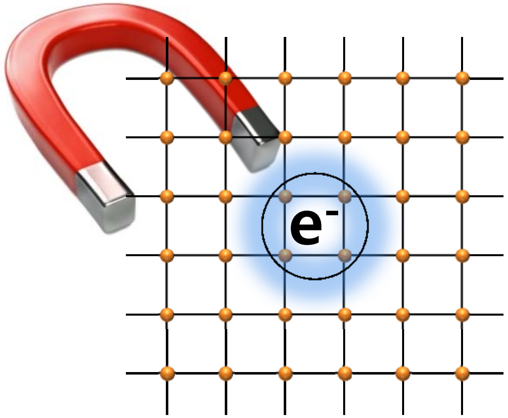
Lev Landau

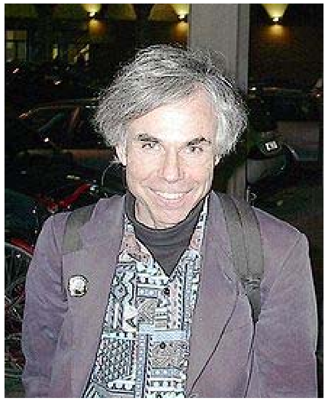
Zeitschrift für Physik

64, 629 (1930)*

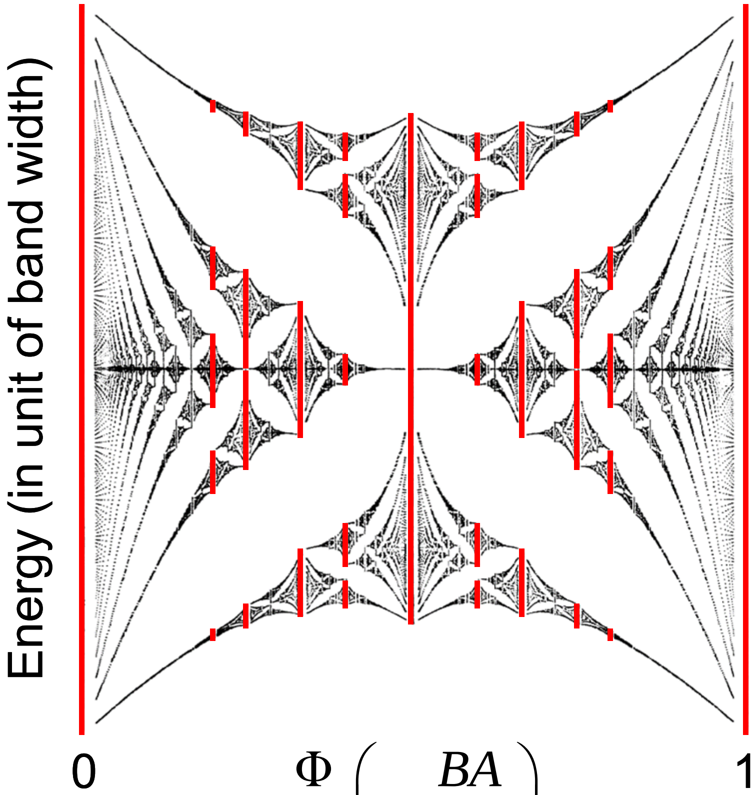
...(*age 22)

Hofstadter Butterfly





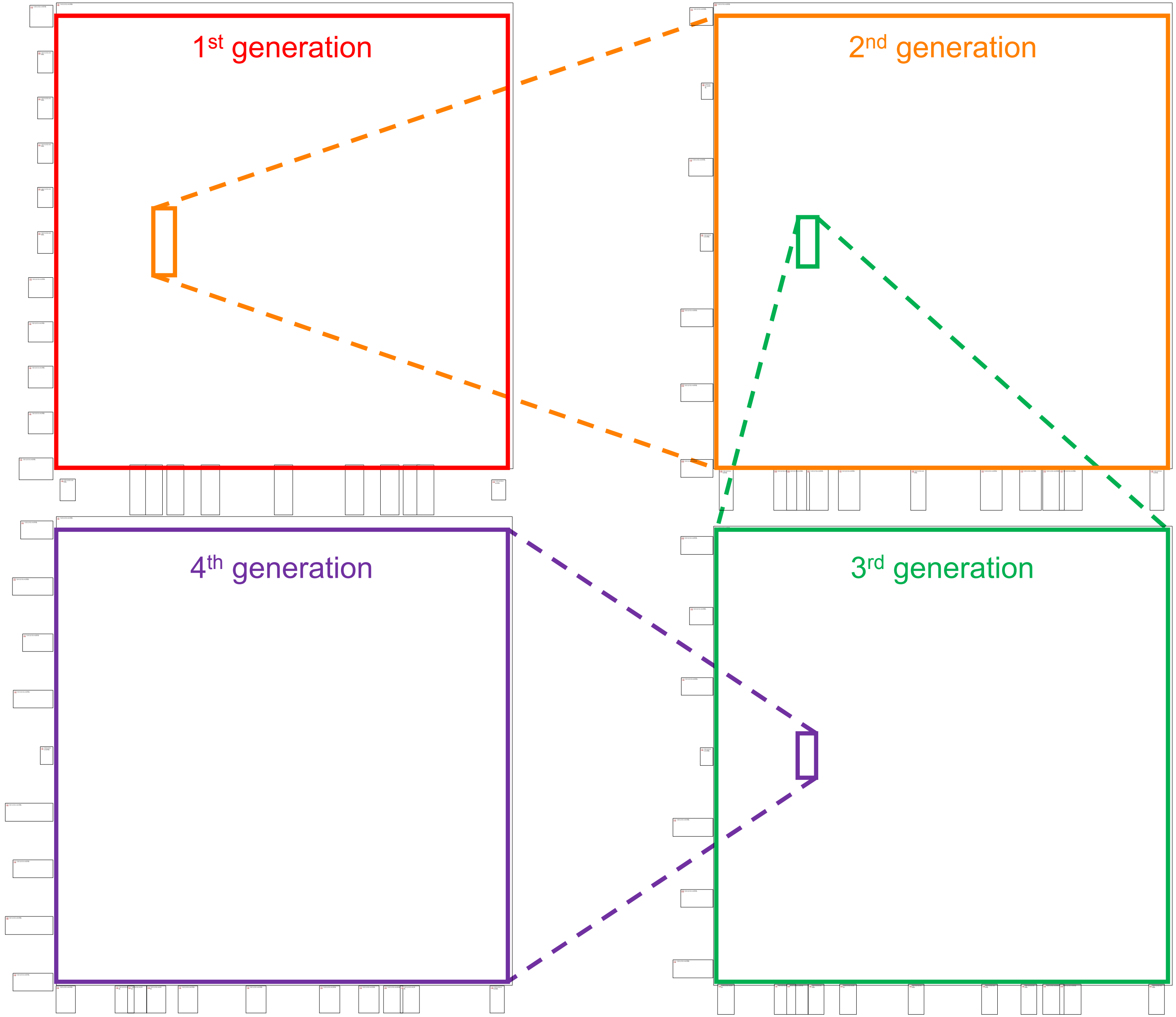
D. R. Hofstadter,
Phys. Rev. B 14, 2239 (1976)



$$\frac{\Phi}{\Phi_0}\left(=\frac{BA}{h/e}\right)$$

Φ	magnetic flux
Φ_0	magnetic flux quantum
B	magnetic field

Fractal (Self-Similar) Energy Spectrum



Condition to Observe Hofstadter Butterfly

The two scale are quite different !!

lattice period (~ 0.1 nm)

magnetic length

B (T)	l_B (nm)
1	25.7
10	8.11
⋮	⋮
10,000	0.257

Hofstadter Butterfly by High Magnetic Field

$B \sim O(10^4\ \mathrm{T})$ for usual crystalline solids [$L \sim O(0.1\ \mathrm{nm})$]

Energy (in unit of band width)

0

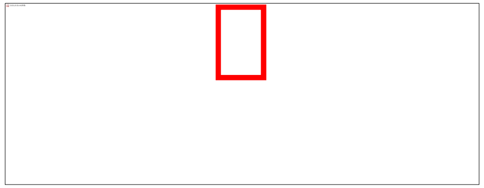
~80,000 T

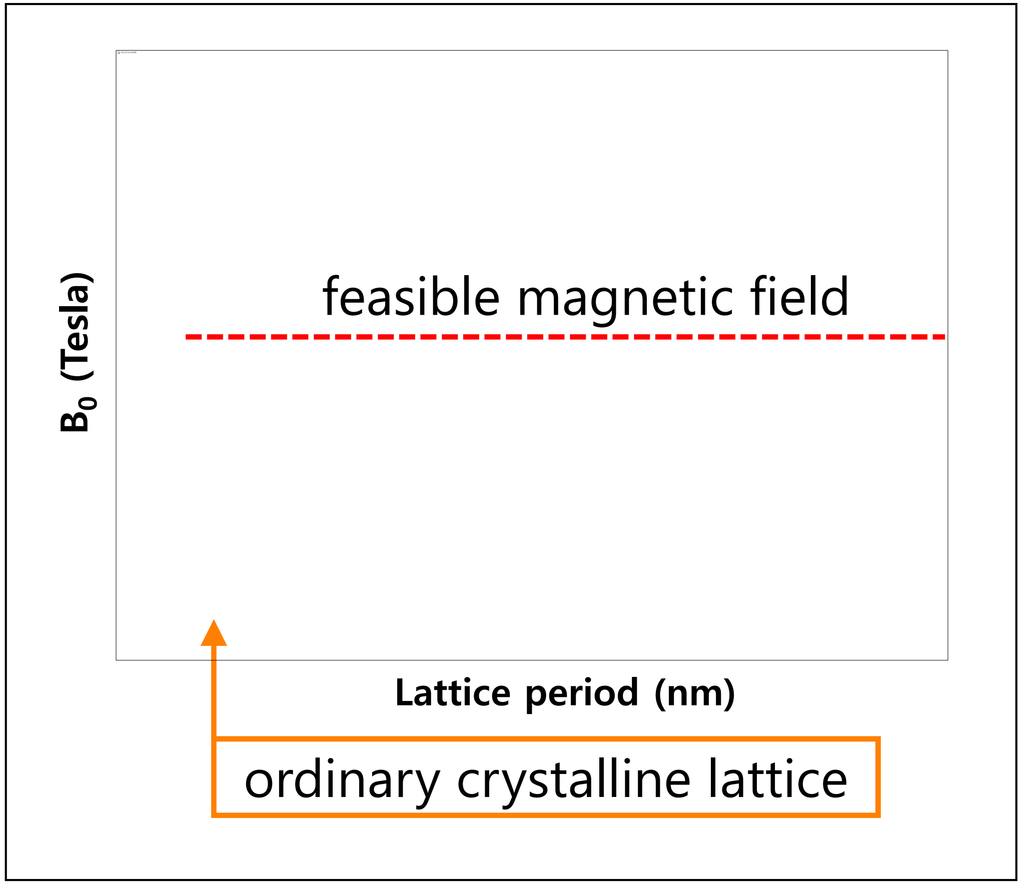
spectrum obtained by blowing off the facility

当前无法显示此图像。

2,800 T

Hofstadter Butterfly by Large Lattice

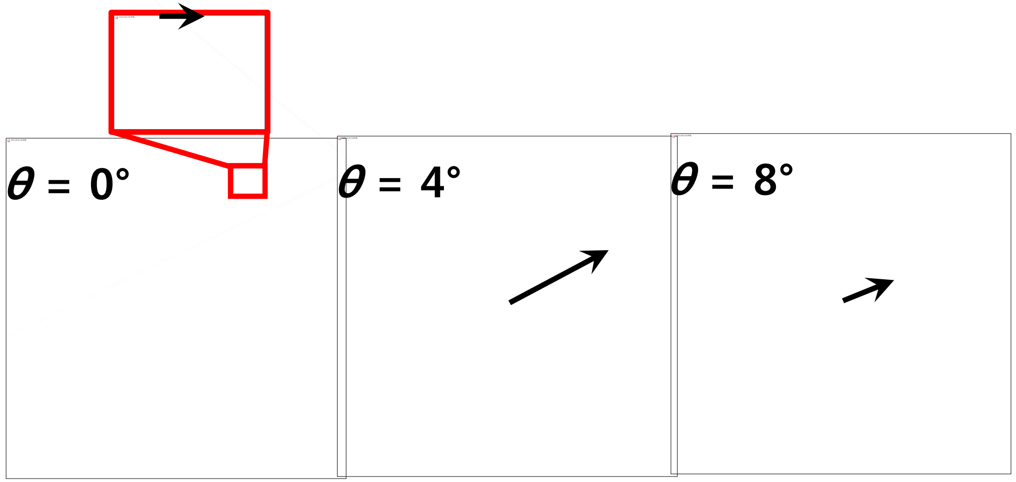




Hofstadter Butterfly by Large Lattice

Moiré Superlattice

superlattice by incoherent stacking of atomic lattices



$\Phi / \Phi_0 \geq 1$ (strong field regime)	R. Bistritzer and A. H. MacDonald, Phys. Rev. B 84, 035440 (2011).	
$\Phi / \Phi_0 \geq 0$ (entire regime)	**Moon and Koshino, Phys. Rev. B 85, 195458 (2012).**	**Hofstadter butterfly at moderate B !**

Hofstadter Butterfly by Moiré Superlattice

$\theta = 9.43°$ **nearly monolayer's Landau levels**

Moon and Koshino, Phys. Rev. B 85, 195458

+2

+1

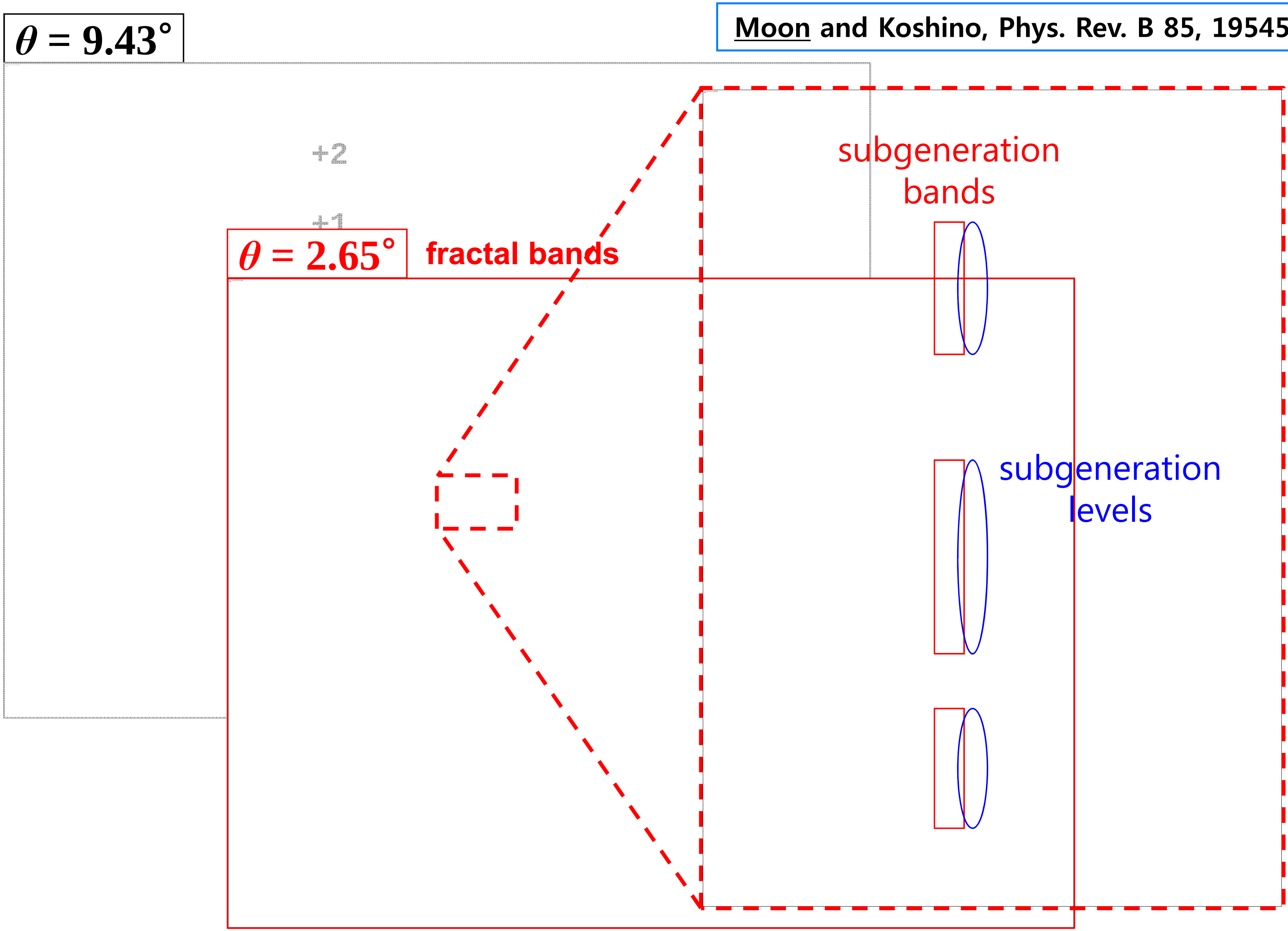
n = 0

-1

-2

Hofstadter Butterfly by Moiré Superlattice

Moon and Koshino, Phys. Rev. B 85, 195458



Bilayer graphene / hBN

C. R. Dean, L. Wang, P. Maher, C. Forsythe,
F. Ghahari, Y. Gao, J. Katoch, M. Ishigami,
P. Moon, M. Koshino, T. Taniguchi, K. Watanabe,
K. L. Shepard, J. Hone, and P. Kim,
Nature 497, 598 (2013).

(——: theory)

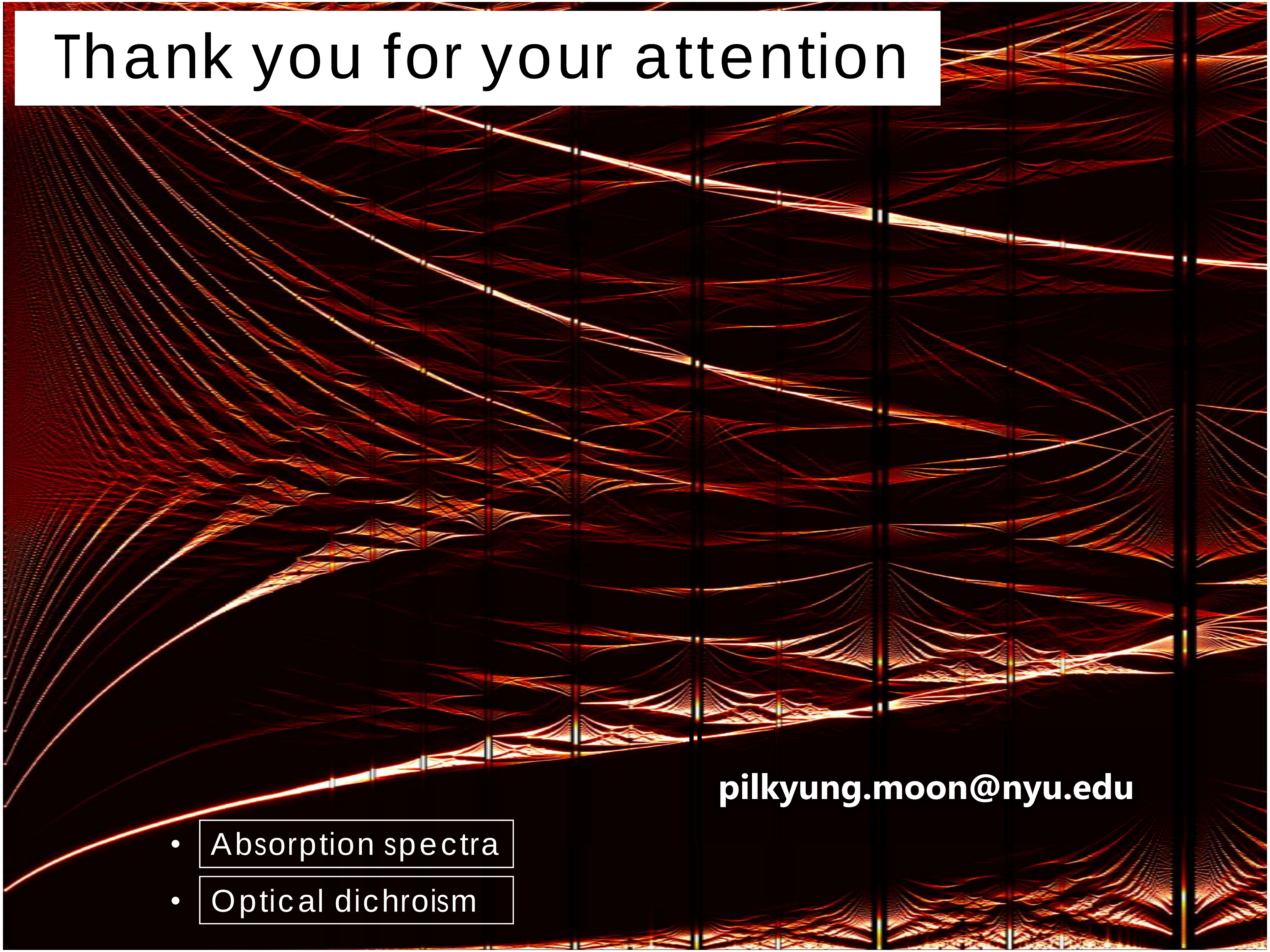
Monolayer graphene / hBN

B. Hunt, J. D. Sanchez-Yamagishi, A. F. Young,
M. Yankowitz, B. J. LeRoy, K. Watanabe,
T. Taniguchi, P. Moon, M. Koshino,
P. Jarillo-Herrero, and R. C. Ashoori,
Science 340, 1427 (2013).

Conclusion

Der Schmetterlingsjäger (The butterfly hunter) by Carl Spitzweg (1840), Butterfly and Chinese wisteriaflowers by Xü Xi (970)

Thank you for your attention



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- Absorption spectra
- Optical dichroism