

Dirac electrons in a dodecagonal graphene quasicrystal

(It was published online at Science, 28 June, 2018)

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Mikito Koshino,

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(It was published online tomorrow at Science, 28 June, 2018)



Sung Joon Ahn
(Sungkyunkwan
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Experiments

Prof. Joung Real Ahn (Sungkyunkwan University, Korea)

Prof. Se-Jong Kahng (Korea University, Japan)

Prof. Philip Kim (Harvard University, USA)

Prof. Cheol-Woong Yang (Sungkyunkwan University, Korea)

Theoretical calculations


Prof. Pilkyung Moon (New York University Shanghai, China)

Prof. Mikito Koshino (Osaka University, Japan)

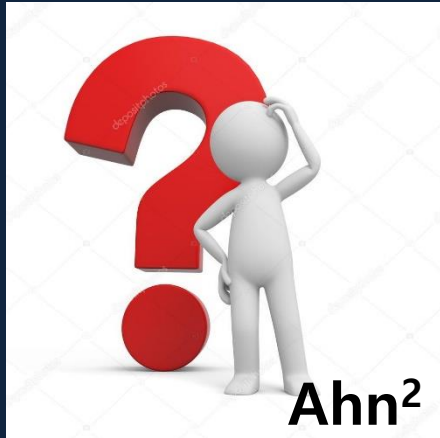
Prof. Young-Woo Son (Korea Institute for Advanced Study, Korea)

Motivation-1

Quantum mechanics

<p>Non-relativistic electrons</p>	<p>Crystal (Periodic)</p>	<p>Quasicrystal (Quasiperiodic)</p>	<p>Amourphous (Disorder)</p>
<p>Relativistic electrons (Dirac electrons)</p>	<p>Crystal (Periodic) Graphene</p>	<p> Ahn² (Sung Jun Ahn, Joung Real Ahn)</p>	

Motivation-2



Graphene
Andre Konstantin Geim
(2010, Nobel Prize)



Quasicrystal
Dan Shechtman
(2011, Nobel Prize)

Motivation-3

Graphene
Geim



Philosophy of graphene
"Just do it?"

Just tape it !

Quasicrystal
Shechtman



Just rotate it !?

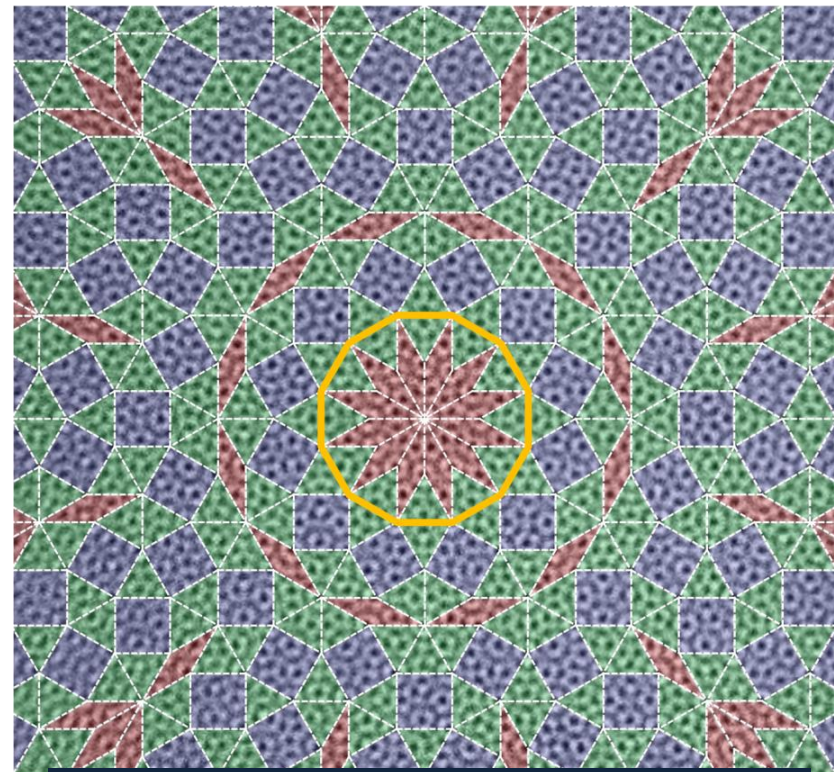
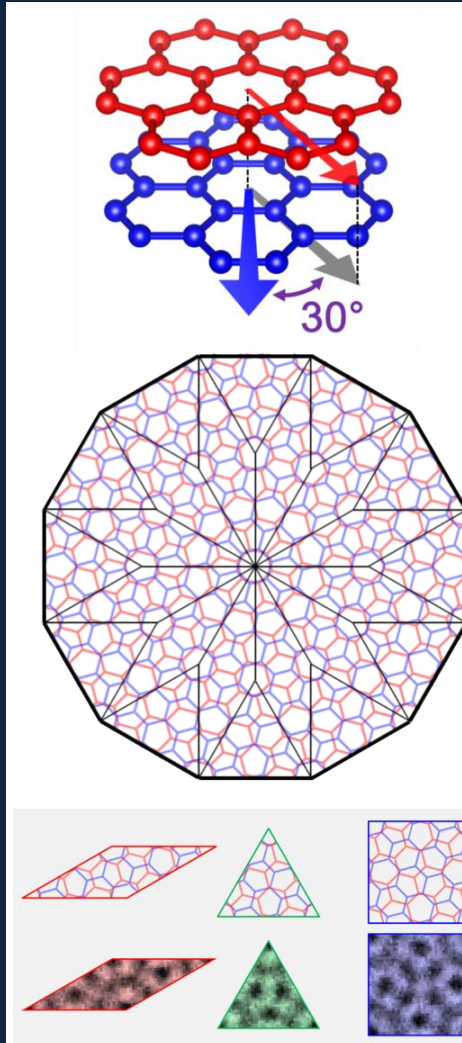
Everything is simple when it is understood

Smoking gun-1 : Quasicrystal (atomic structure)



Just rotate it !?

Twisted bilayer graphene with exact R30°



**Dodecagonal graphene quasicrystal
(TEM image)**

3 nm

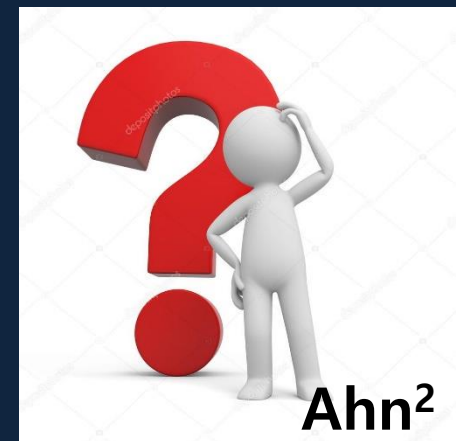
Remaining question ?



It is nice !
but
Is it real a CVID process for nuclear weapons ?
(Complete, Verifiable, Irreversible
Dismantlement)



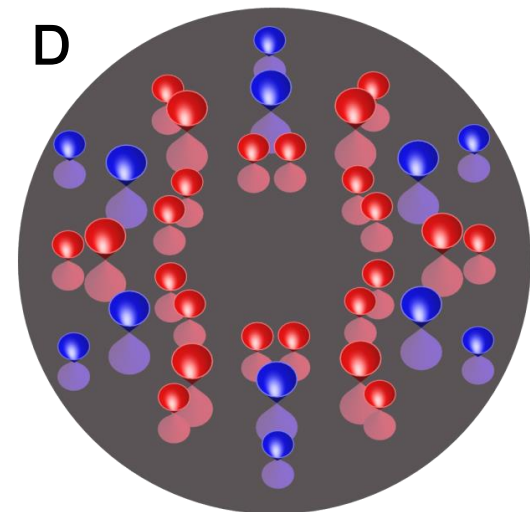
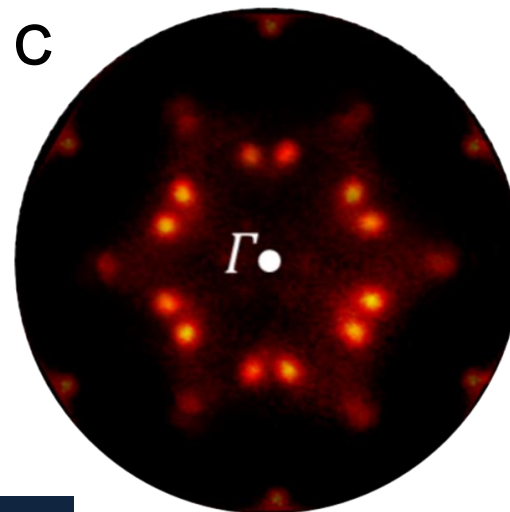
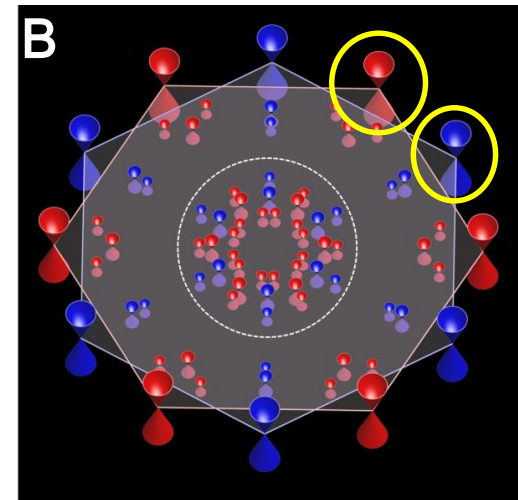
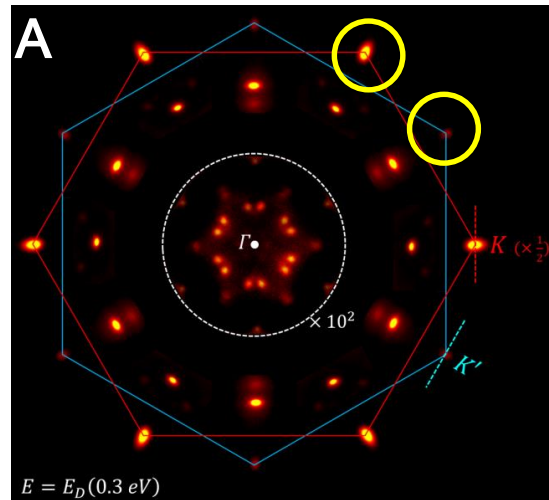
It's beautiful !
but
Is it a quasicrystal just
in an atomic structure ?



Smoking gun-2 : Quasicrystal (electronic structure)



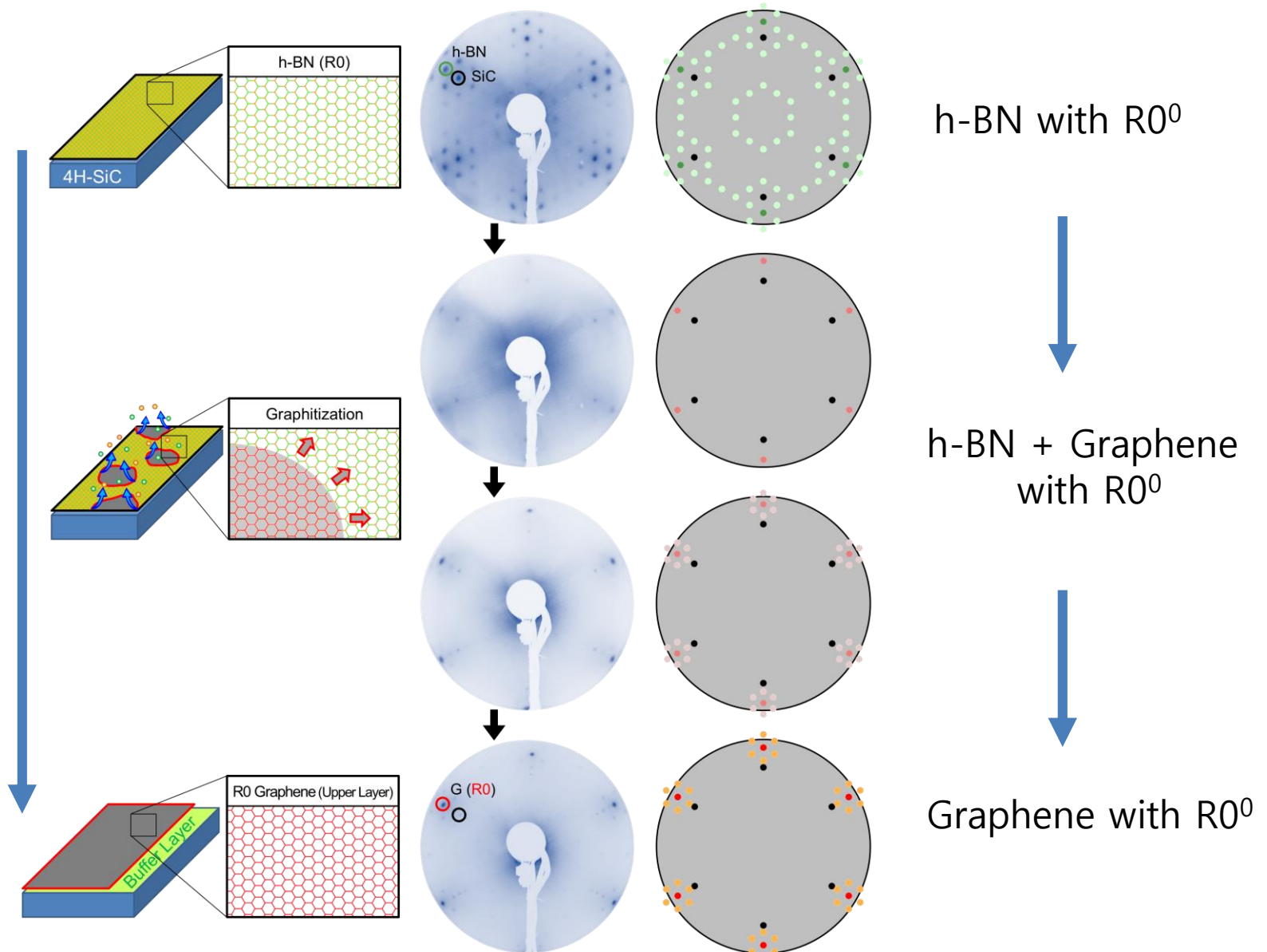
Real
Dirac electrons
in a quasicrystal



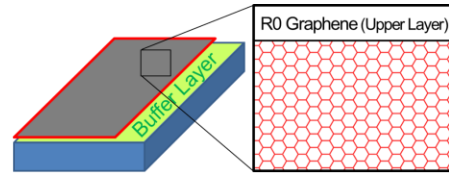
ARPES intensity map

How to grow a graphene quasicrystal ?

How to grow a graphene quasicrystal-1



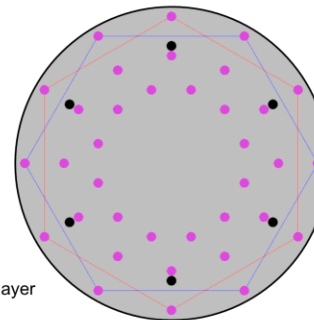
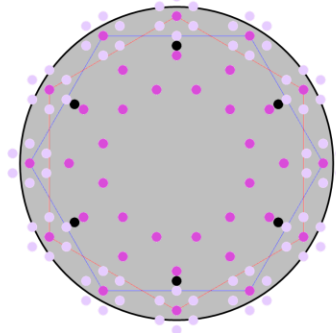
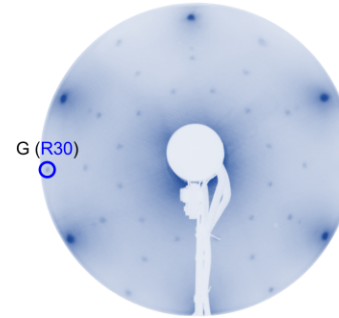
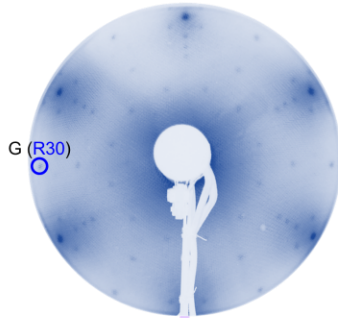
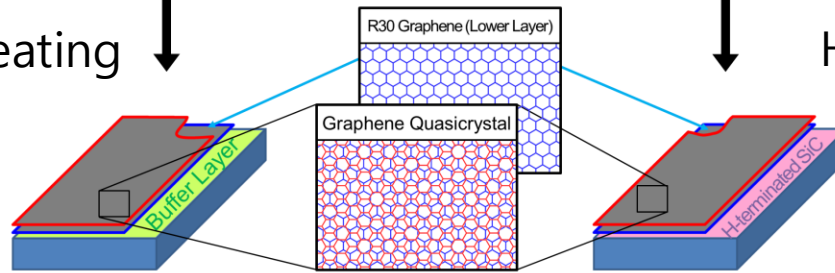
How to grow a graphene quasicrystal-2



Graphene with $R0^0$

Method 1
Further thermal heating

Method 2
H intercalation



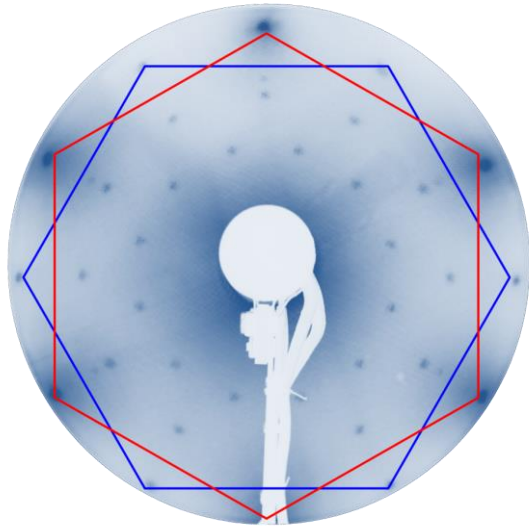
- SiC Bulk
- 12-fold Quasicrystal
- Moiré pattern from buffer layer ($6\sqrt{3} \times 6\sqrt{3} R30$)

Graphene with $R0^0$
+
Graphene with $R30^0$
on
buffer layer/SiC

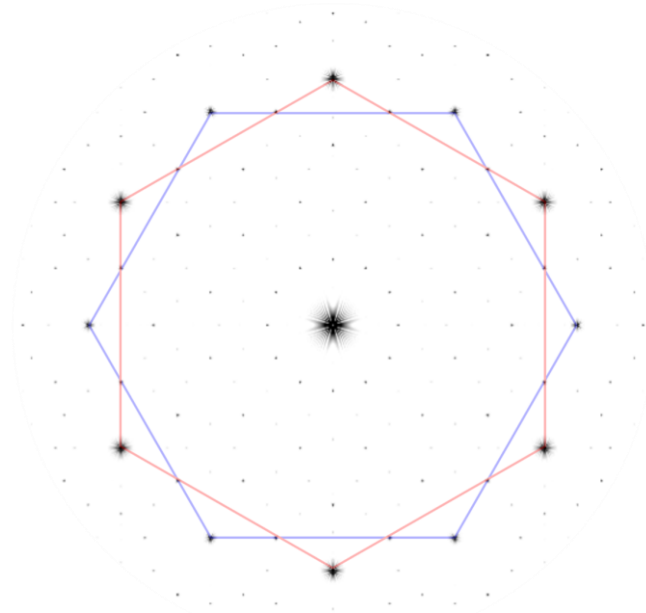
Graphene with $R0^0$
+
Graphene with $R30^0$
on
H-terminated SiC

Low energy electron diffraction (LEED)

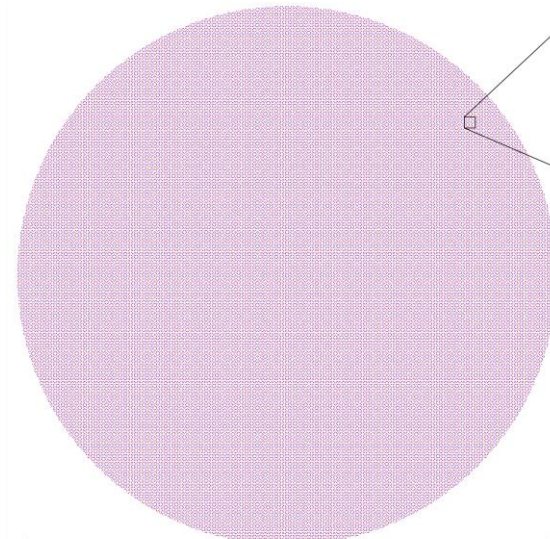
Low energy electron diffraction (LEED) pattern



LEED - Experiment

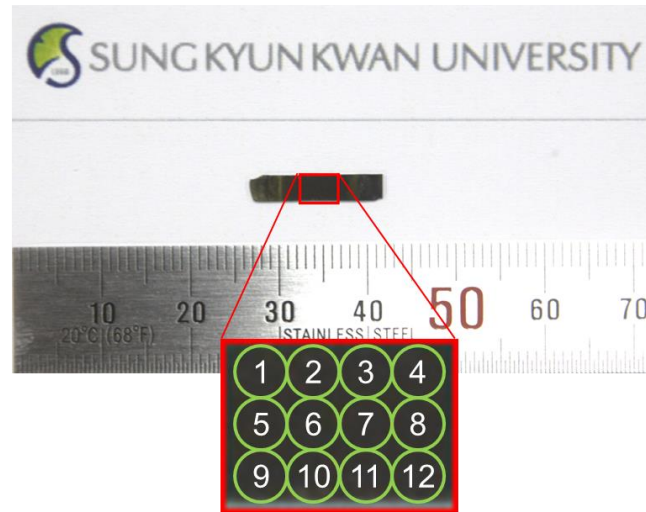


FFT of the atomic structure
of the graphene quasicrystal

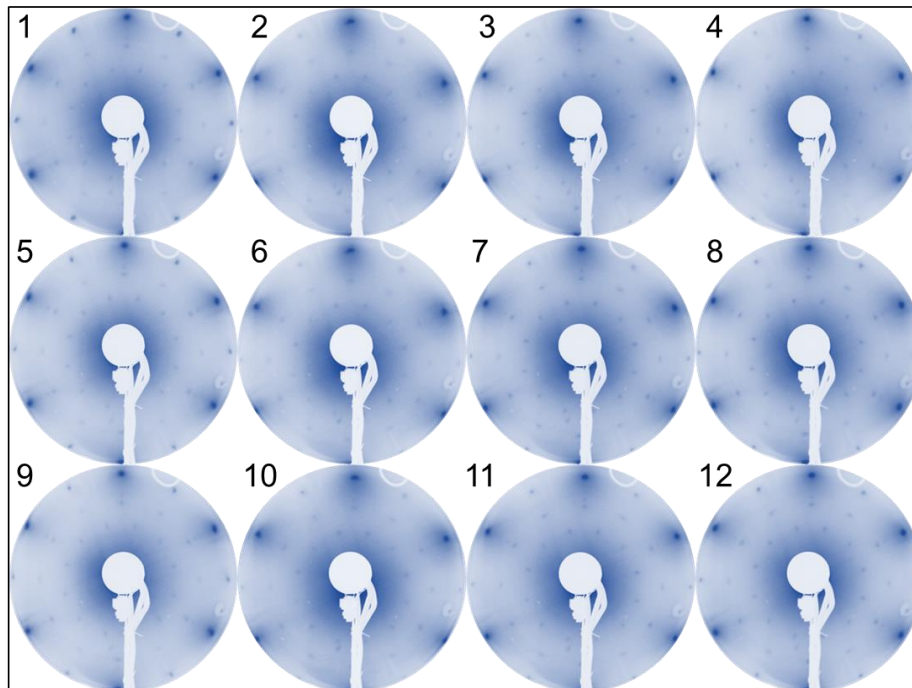


$$D = 172|\vec{a}_{gr}| \approx 42.3nm$$

Low energy electron diffraction (LEED) pattern

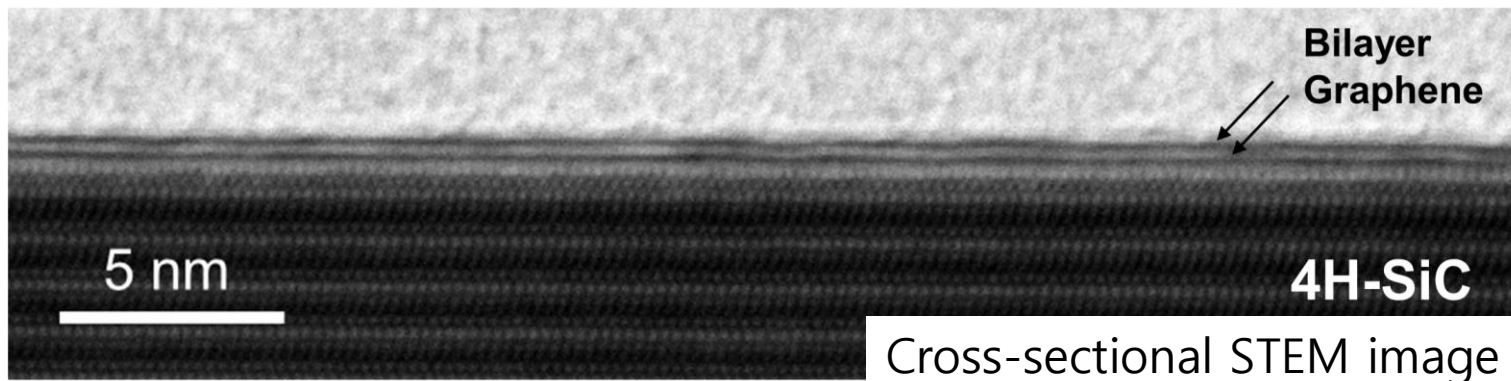
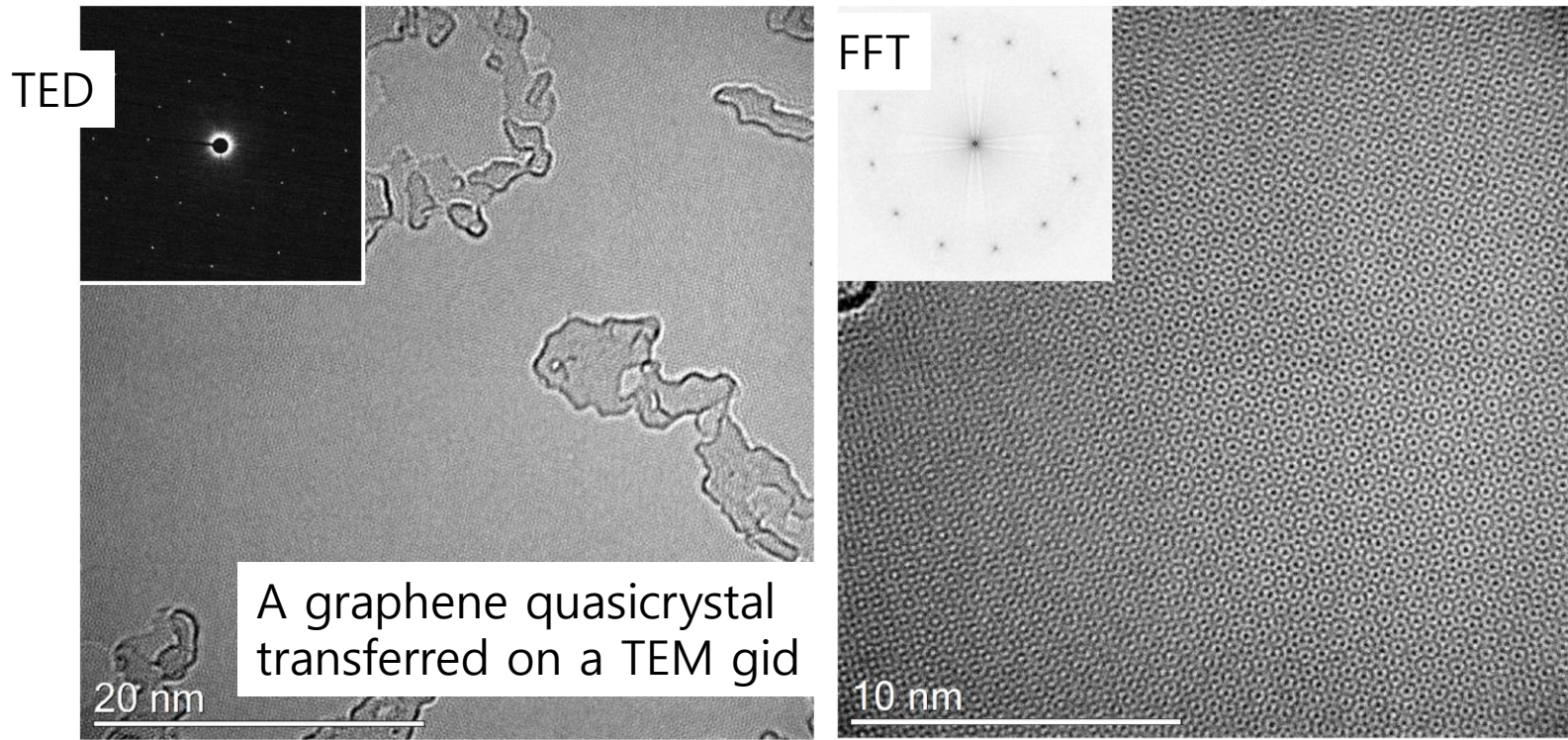


Up to 3x4 mm²

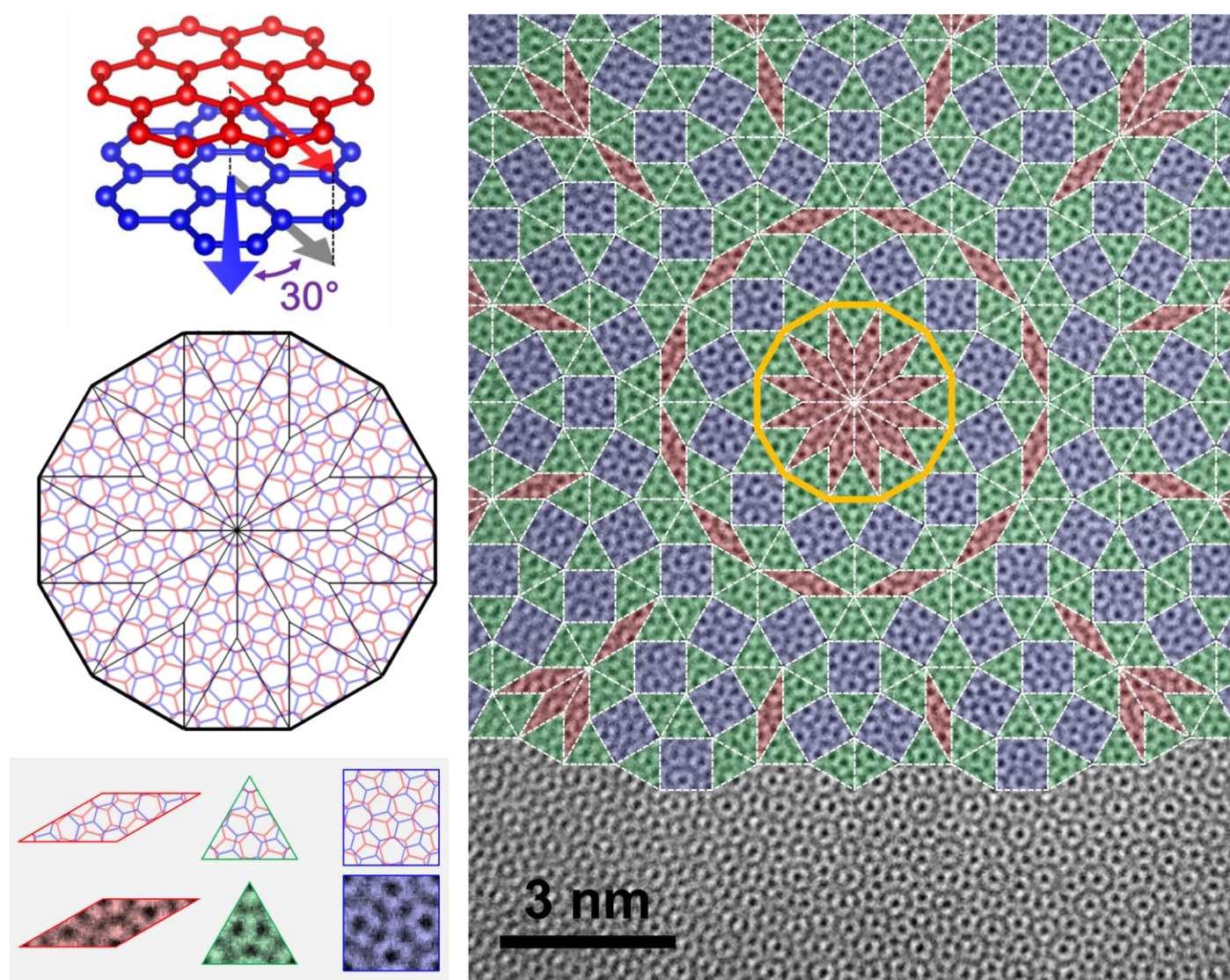


Transmission electron microscopy (TEM)

Transmission electron microscopy (TEM) image

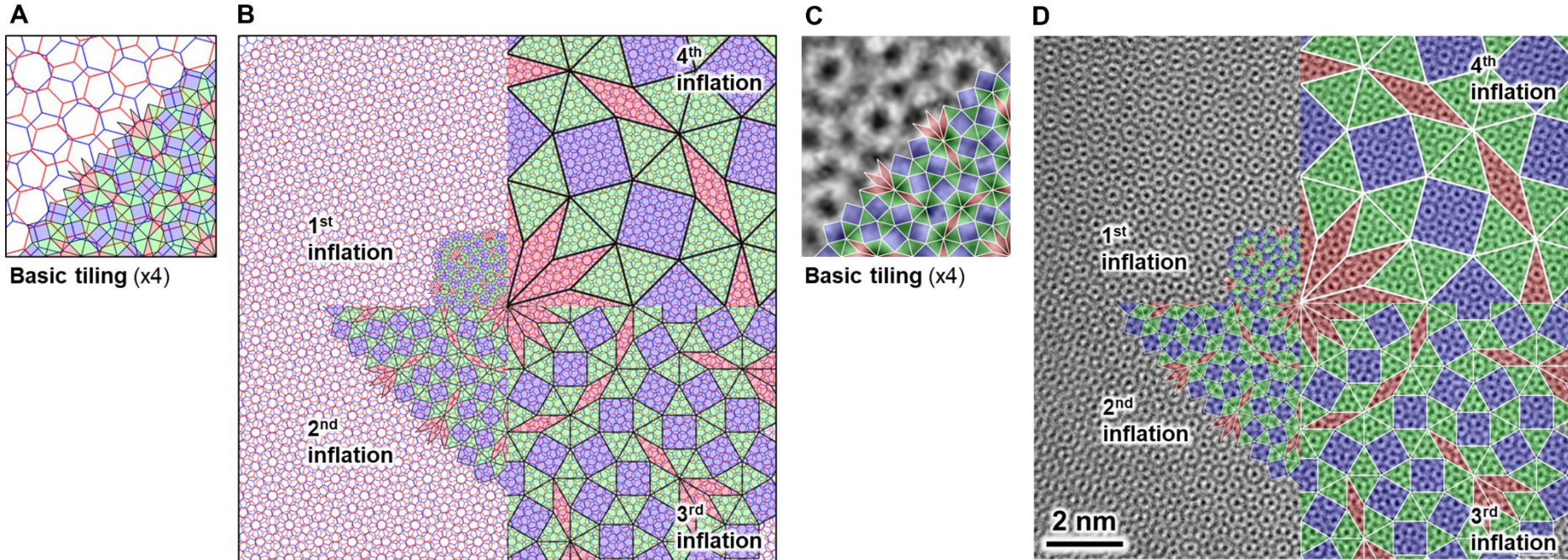


Transmission electron microscopy (TEM) image



Stampfli tiles (rhombuses (red), equilateral triangles (green), squares (blue))

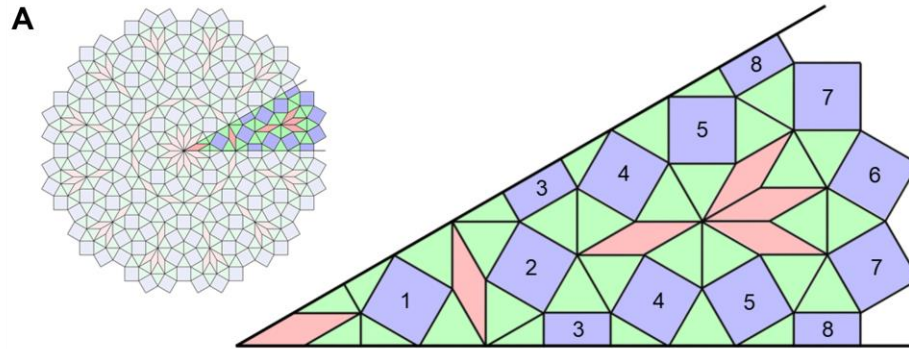
Transmission electron microscopy (TEM) image



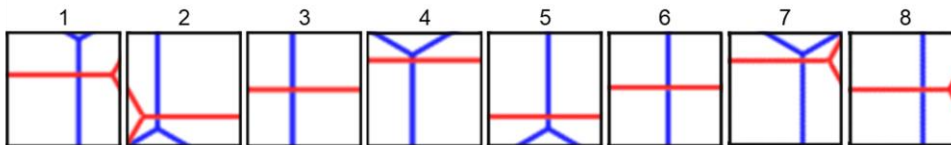
Scaling factor $\sqrt{2 + \sqrt{3}}$

Stampfli tiles (rhombuses (red), equilateral triangles (green), squares (blue))

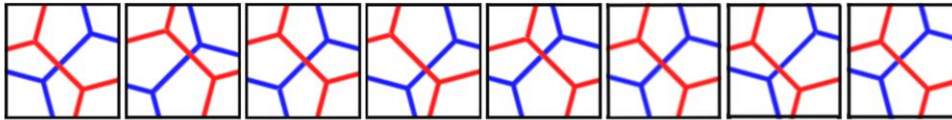
Transmission electron microscopy (TEM) image



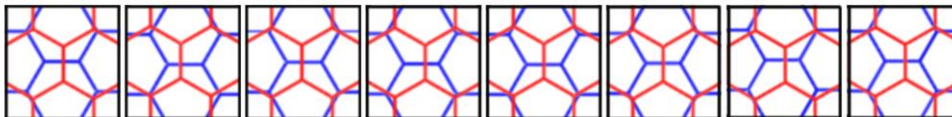
B Basic tiling



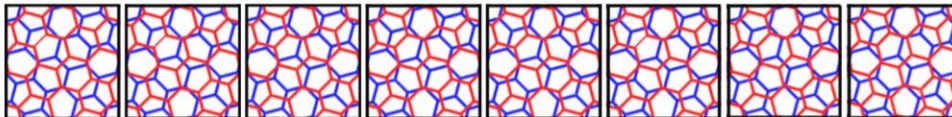
C 1st Inflation



D 2nd Inflation



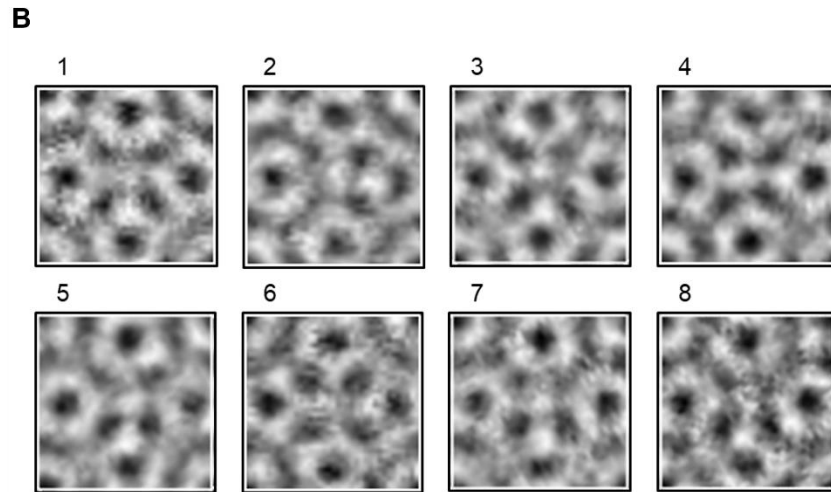
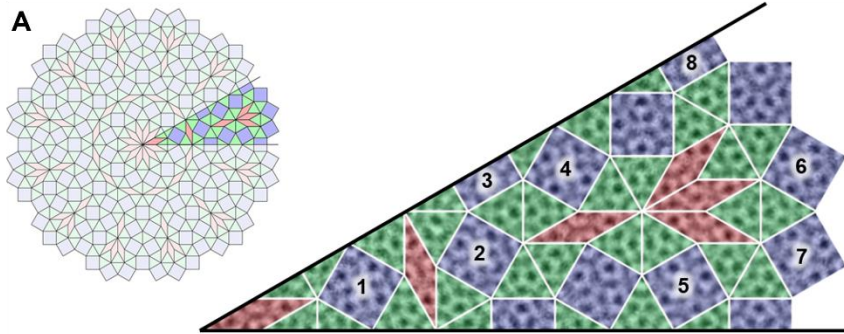
E 3rd Inflation



**Internal structures
of the same Stampfli tile**

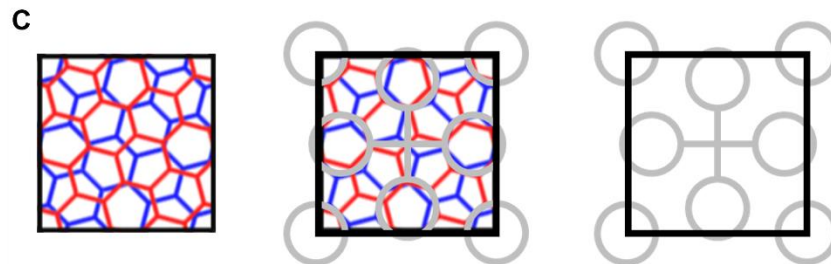
(Atomic structure model)

Transmission electron microscopy (TEM) image

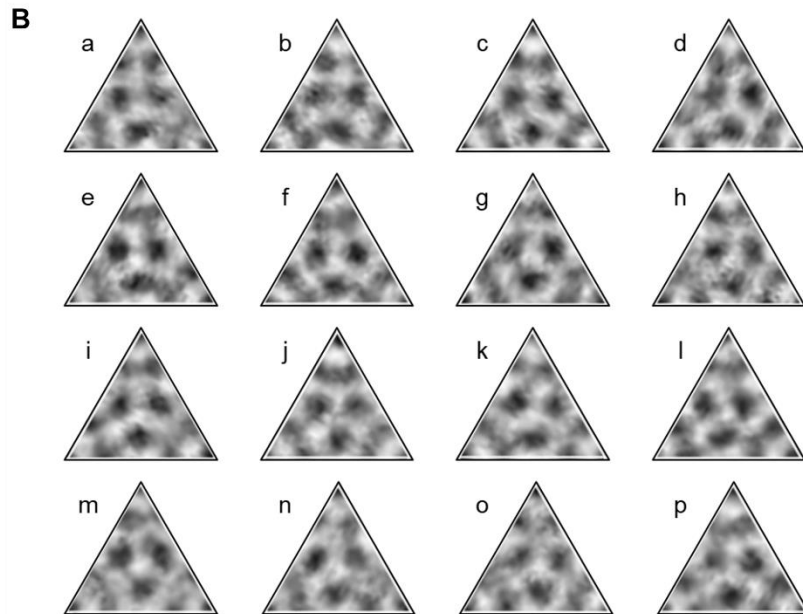
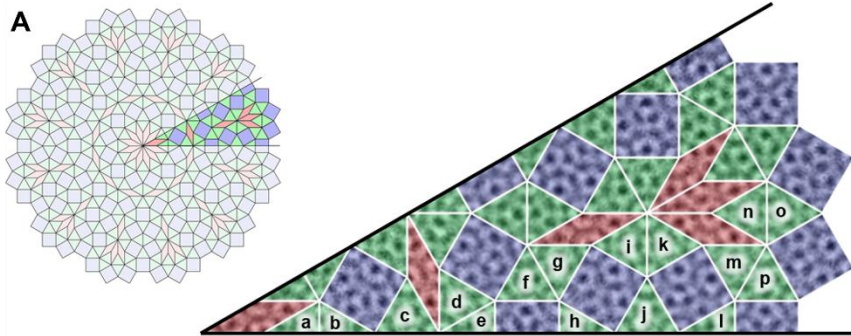


**Internal structures
of the same Stampfli tile**

(TEM images)

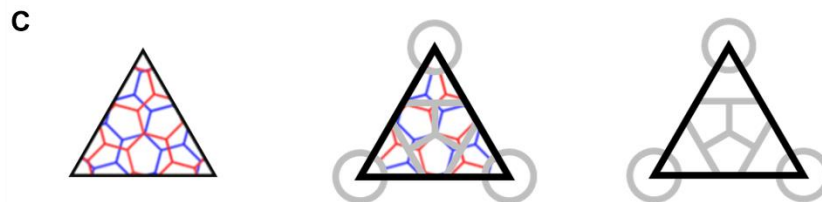


Transmission electron microscopy (TEM) image



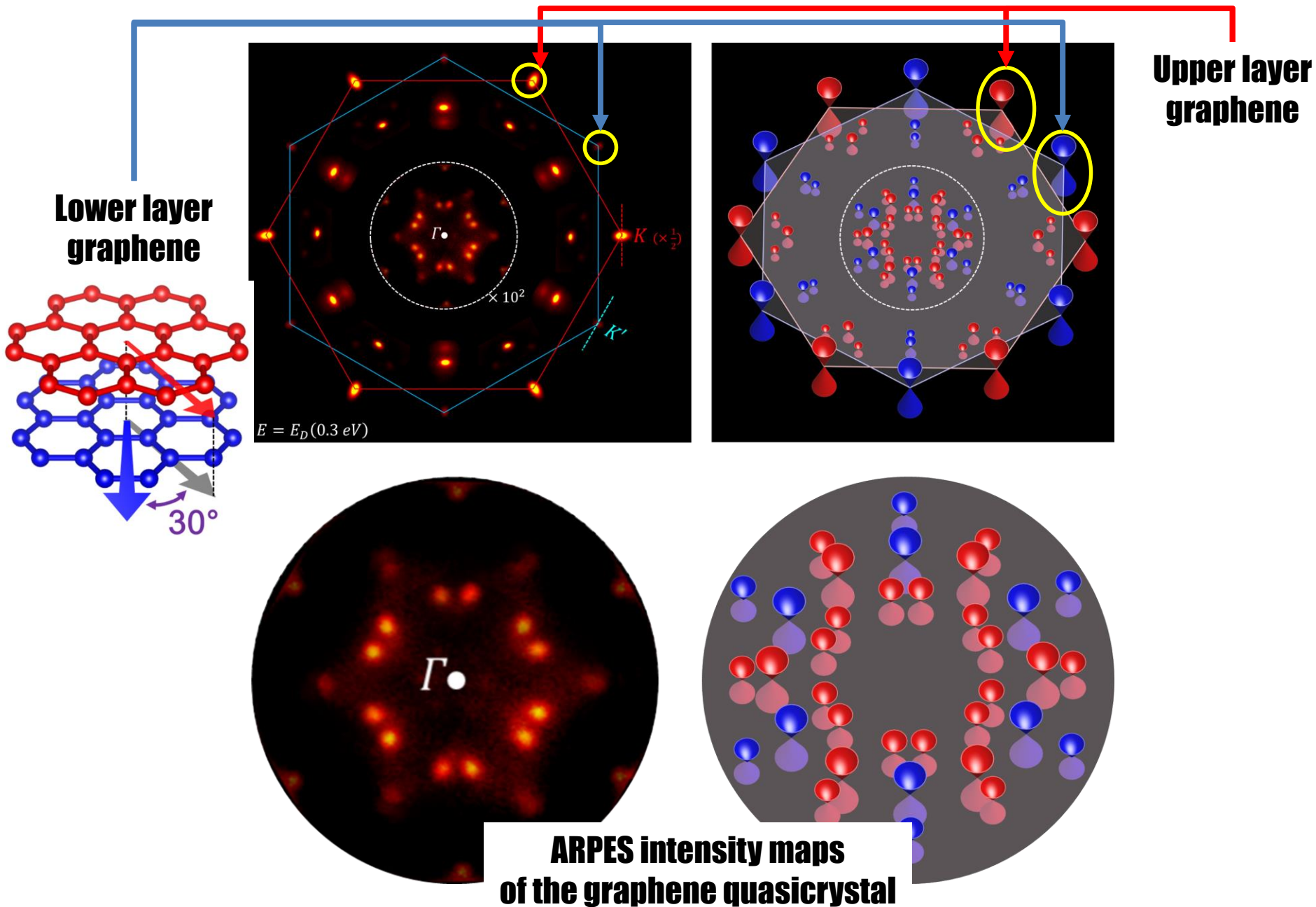
**Internal structures
of the same Stampfli tile**

(TEM images)



**Angle-resolved photoemission spectroscopy
(ARPES)**

Angle-resolved photoemission spectroscopy

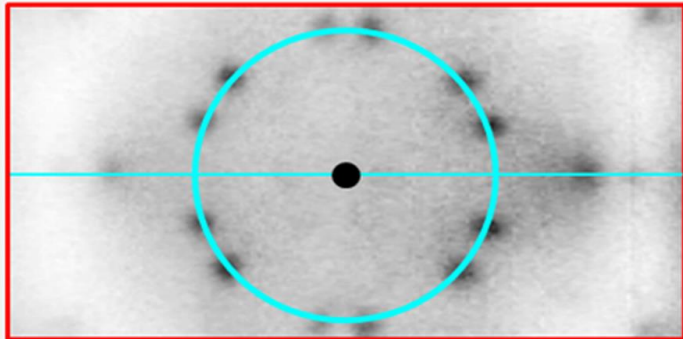
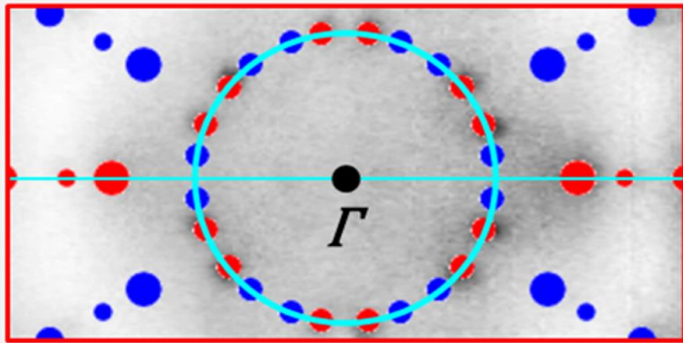


Angle-resolved photoemission spectroscopy

Exact rotational angle = 30 degree

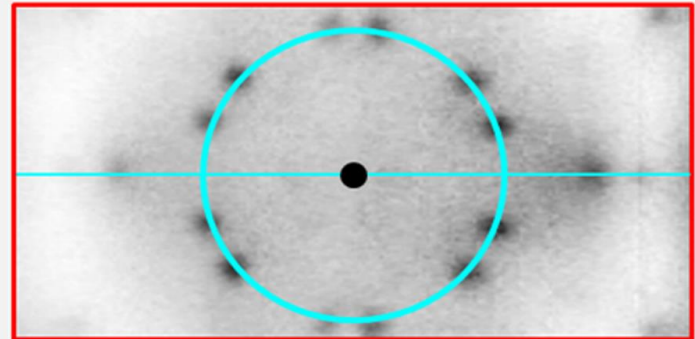
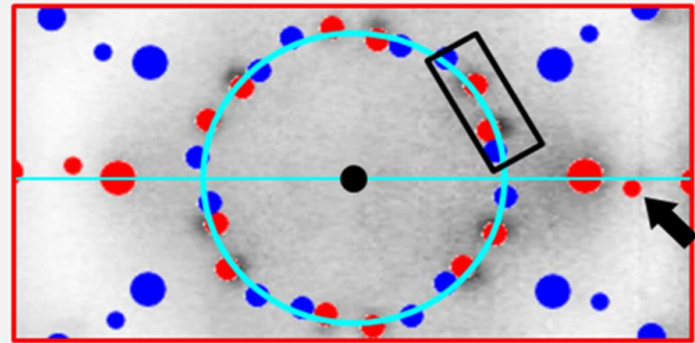
Quasicrystal

Incommensurate phase ($\theta=30^\circ$)



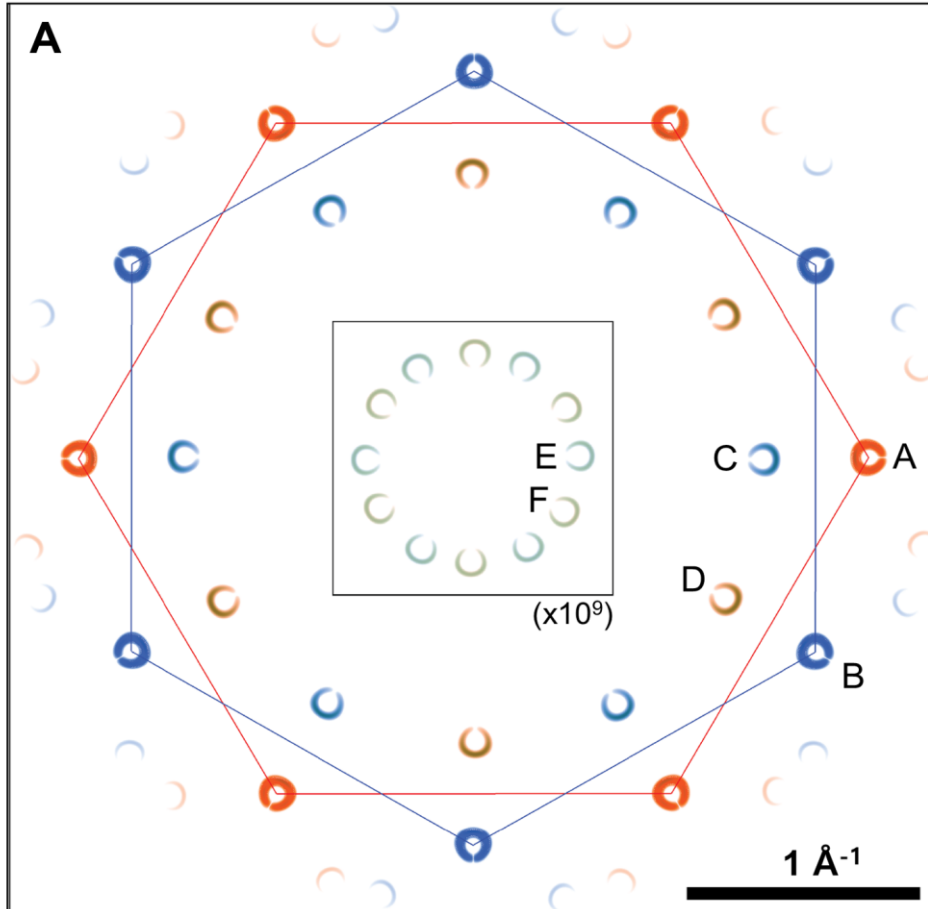
Quasicrystal approximant

Commensurate phase ($\theta=29.958^\circ$)

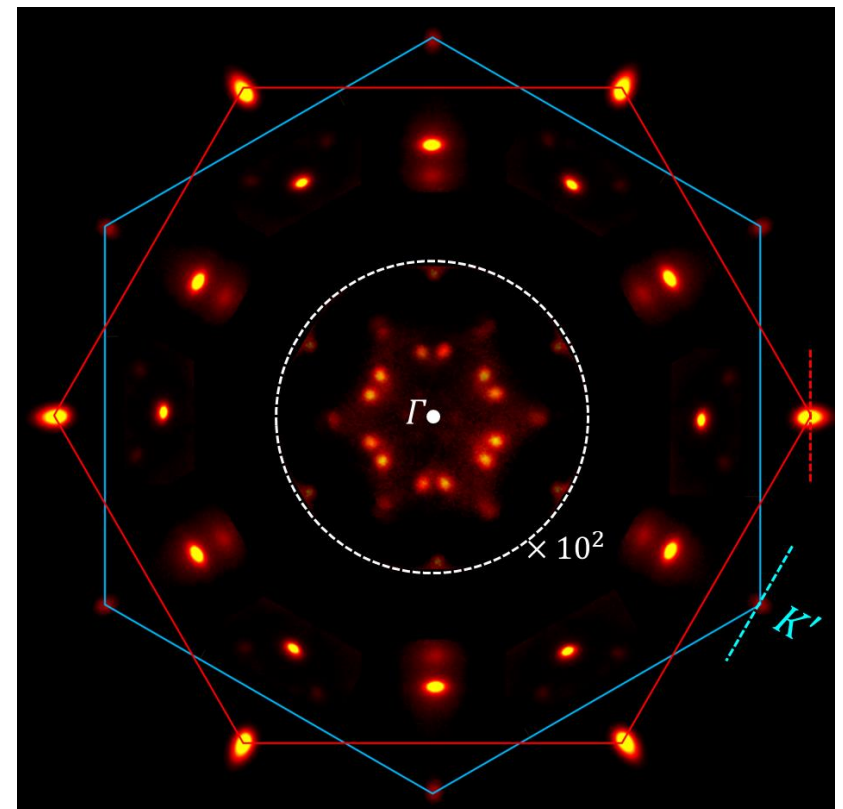


Angle-resolved photoemission spectroscopy

Theoretical calculations – Tight-binding approach

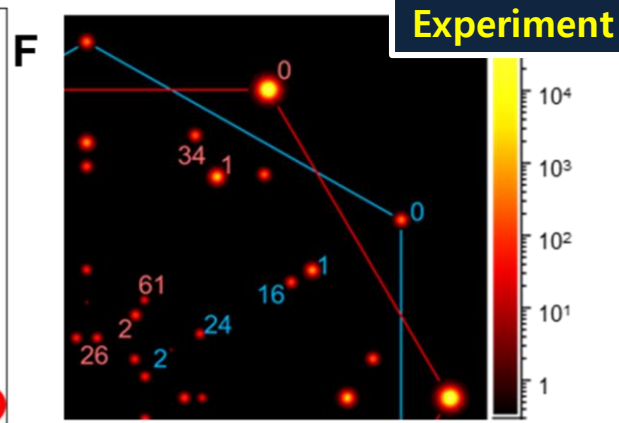
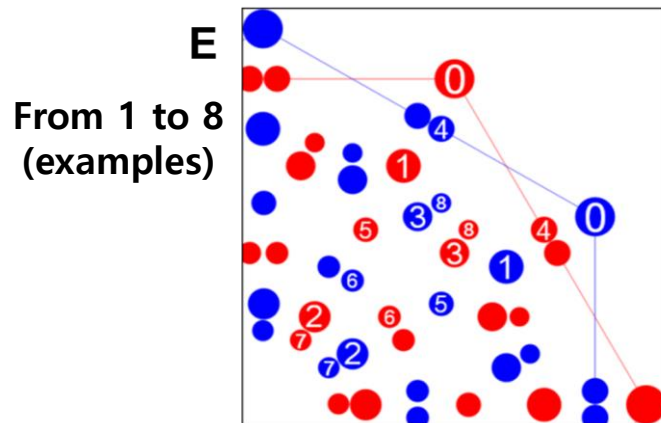
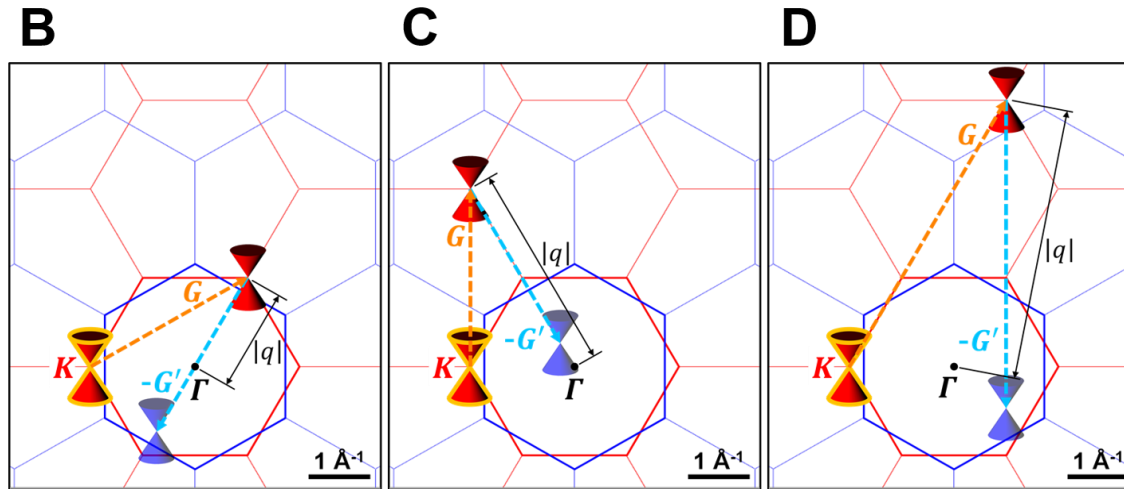


Experiments



Angle-resolved photoemission spectroscopy

Theoretical calculations – Tight-binding approach

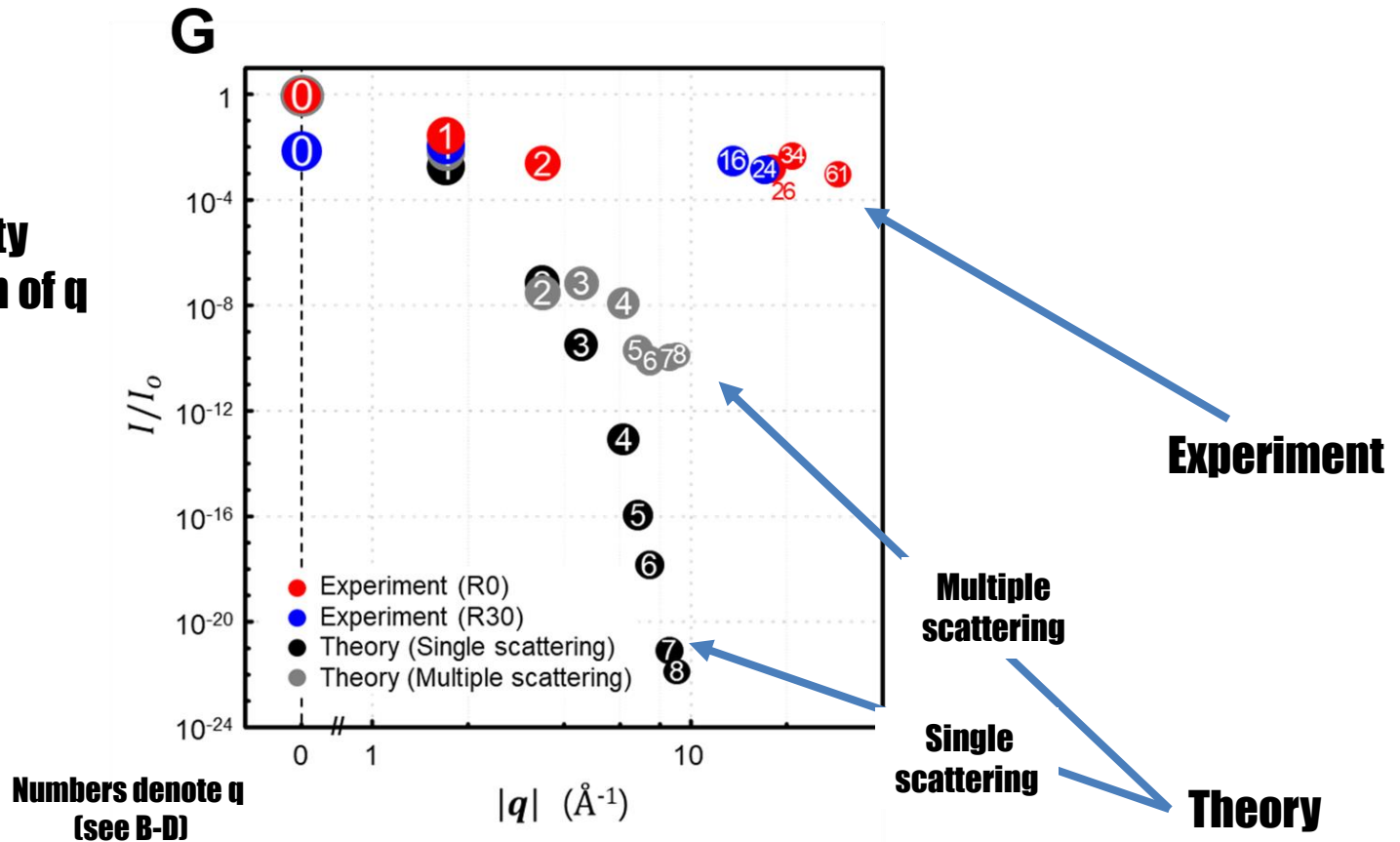


The Dirac cones were numbered from the smallest q
(see B-D)

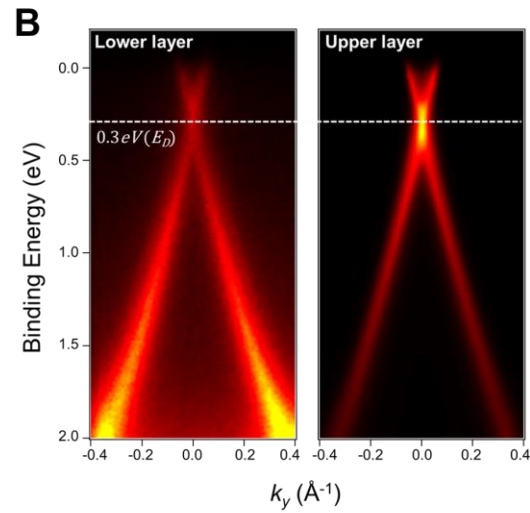
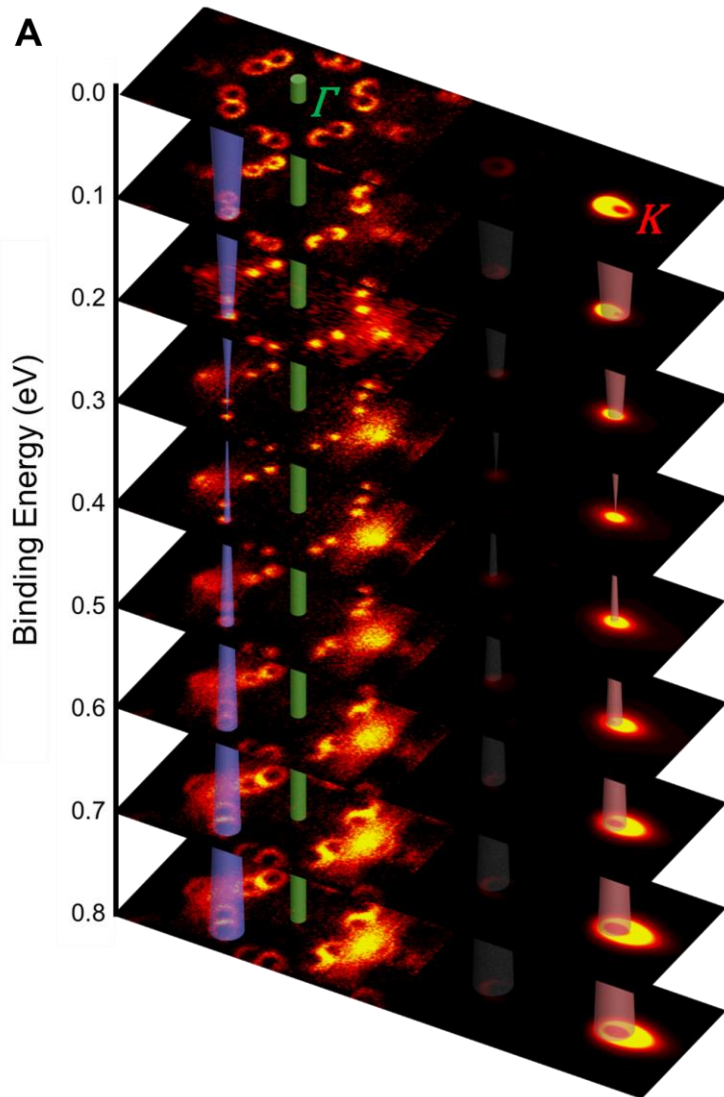
Angle-resolved photoemission spectroscopy

Theoretical calculations – Tight-binding approach

**G. Intensity
as a function of q**

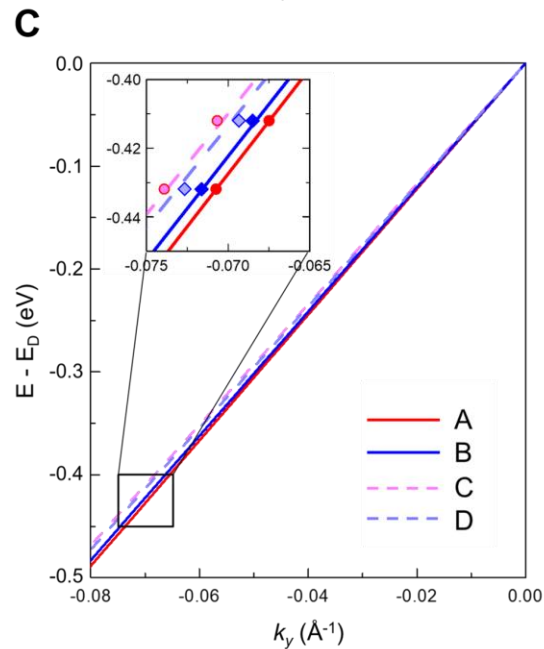


Angle-resolved photoemission spectroscopy



**Dirac point of
the upper layer
graphene $\sim 0.29\text{ eV}$**

**Dirac point of
the upper layer
graphene $\sim 0.30\text{ eV}$**



**Fermi velocities of
Dirac cones are
nearly identical**

Conclusion

Quantum mechanics

Non-relativistic
electrons

Crystal
(Periodic)

Quasicrystal
(Quasiperiodic)

Amourphous
(Disorder)

Relativistic
electrons
(Dirac electrons)

Crystal
(Periodic)

Graphene

Ahn²



(Sung Jun Ahn,
Joung Real Ahn)

**New experimental research field just began
: Dirac electrons in a quasicrystal**

Conclusion



- 1. New experimental research field just began
: Dirac electrons in a quasicrystal
(which can be extended to other physical systems)**
- 2. This and following exciting experimental results
in this field will require new theoretical approaches**
- 3. This will contribute to theoretical calculations
for a solid without a translational symmetry**



You can contact

Prof. Pilkyung Moon (New York University Shanghai, China)

(Workshop 3, Wed 27, 18:15-18:30)

Prof. Young-Woo Son (Korea Institute for Advanced Study, Korea)



for detailed theoretical calculations and backgrounds

They are in this Graphene-2018 conference **somewhere (?)**

Thank You

&

**See you at the new experimental research field
(Dirac electrons in a quasicrystal)**