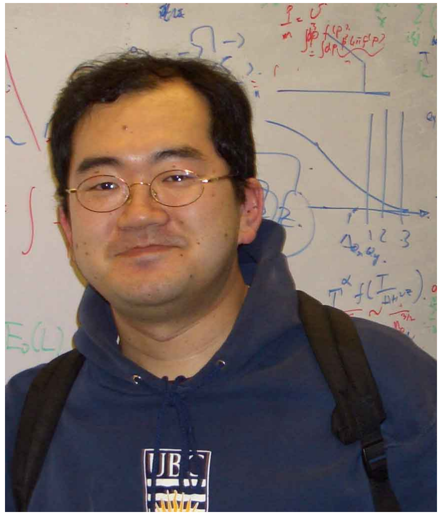
Superconductivity & **Non-Fermi Liquids** in **domain wall networks** of **2D CDW systems**

Gil Young Cho

[1] POSTECH [2] IBS CALDES

Collaborators



Masaki Oshikawa
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Han Woong Yeom
(POSTECH/IBS CALDES)

Funding

ibs
Center for Artificial Low D Electronic Systems

•ASIAN OFFICE OF AEROSPACE R&D•
BRIDGING SCIENCE & TECHNOLOGY

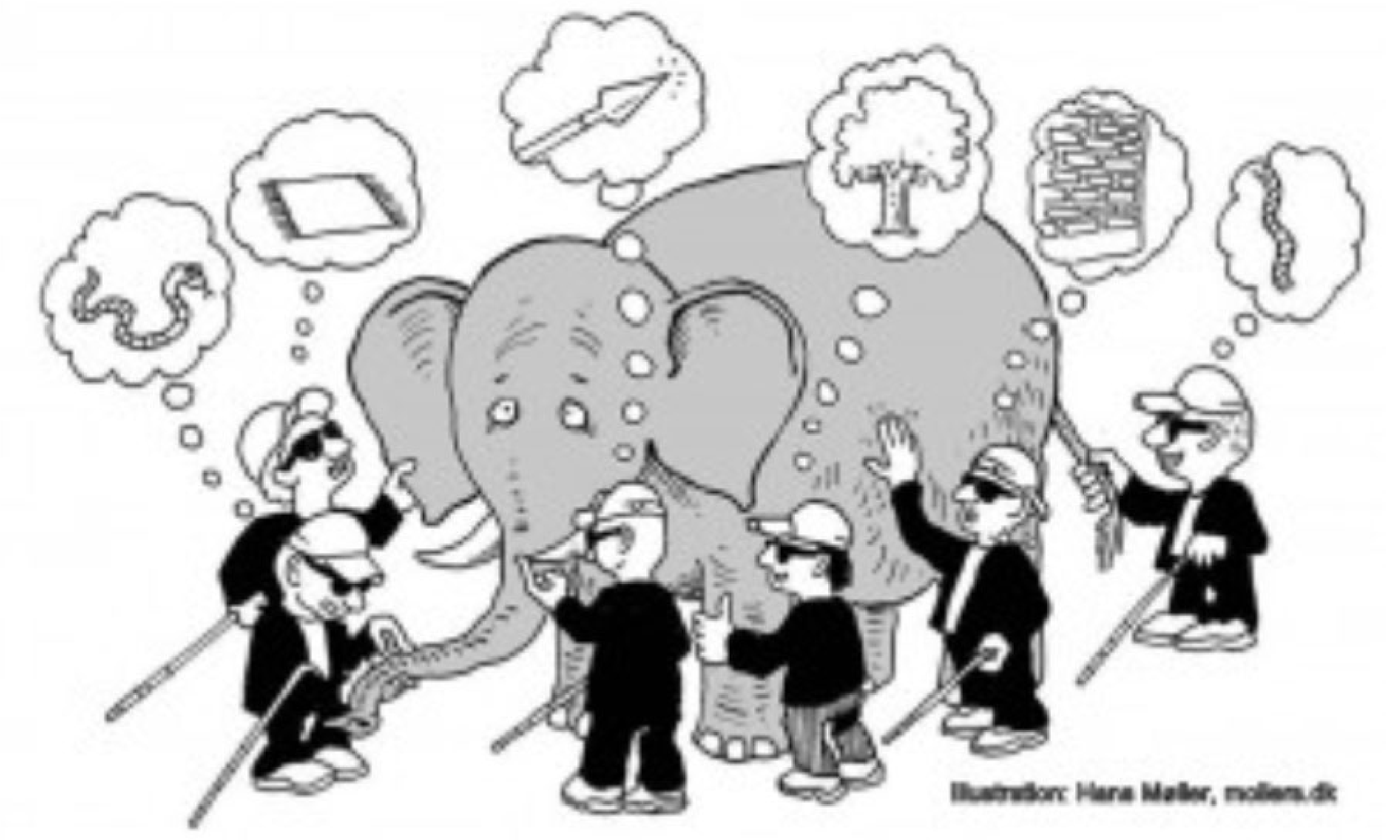
NRF

SAMSUNG

[1] Park, **GYC**, Lee, Yeom, Nature Communications (2019)
[2] Lee, Geng, Park, Oshikawa, Lee, Yeom, **GYC**, Physical Review Letters (2020)
[3] Lee, Oshikawa, **GYC**, Physical Review Letters (2021)

[4] Kang, Lee, **GYC**, Physical Review Letters (2021)
[5] Park, Kim, **GYC**, Lee, Physical Review Letters (2019)
[6] Park, Lee, (…), **GYC,** Lee, Nature (2022) **- if time allows…**

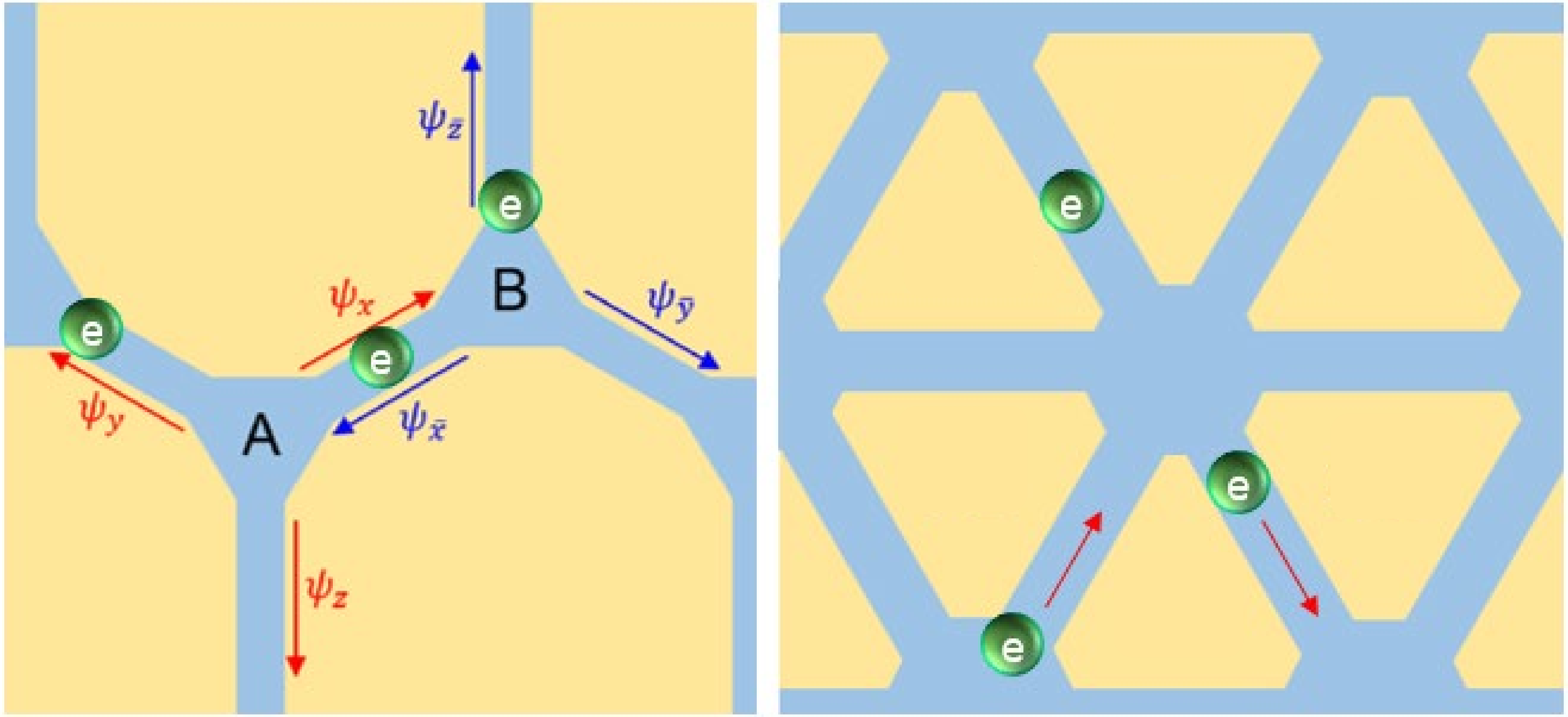
Warning: I am ***not really a specialist of a particular material***…



Based on my (***possibly wrong***) understandings on materials/experiments.

(although I consulted with many experimentalists)

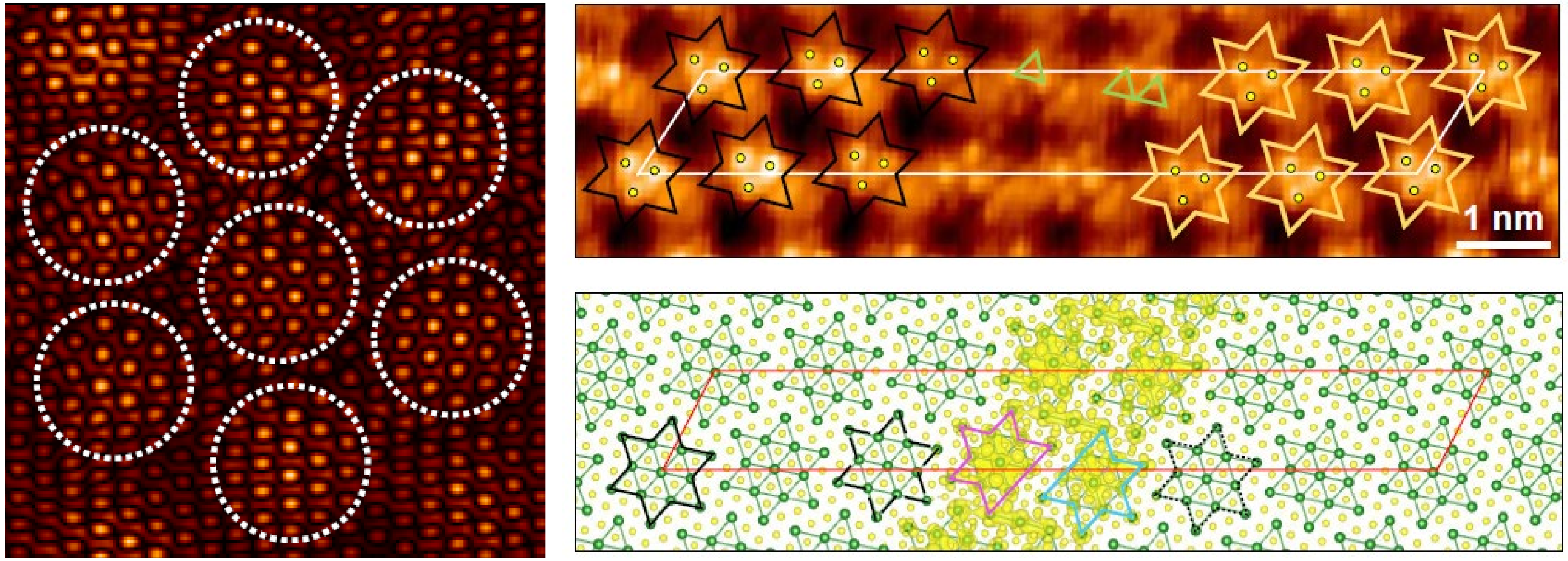
Goal: Exploring Electronic Properties of Quasi-1d Systems



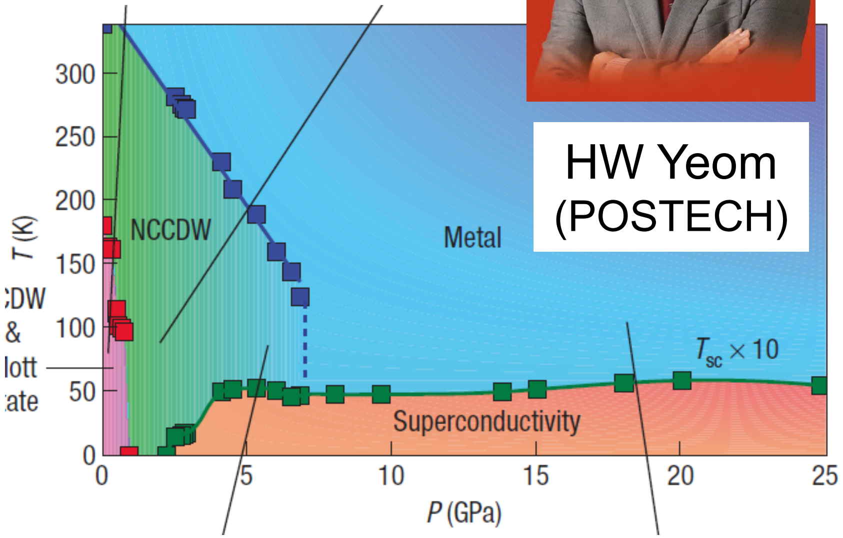
Flat bands, superconductivity, topological states & Non-Fermi liquids

The pattern that captured my eyes:

Experiments: STM on nearly-commensurate charge-density wave in 1T-TaS_2



[Park, **GYC**, Lee, Yeom, Nat. Comm. (2019)]



Phase diagram
[Sipos et. al. Nat. Mat. (2008)]

HW Yeom
(POSTECH)

1. Lateral size of domain wall network ~ O(80) A.

2. *Only* domain walls are metallic.

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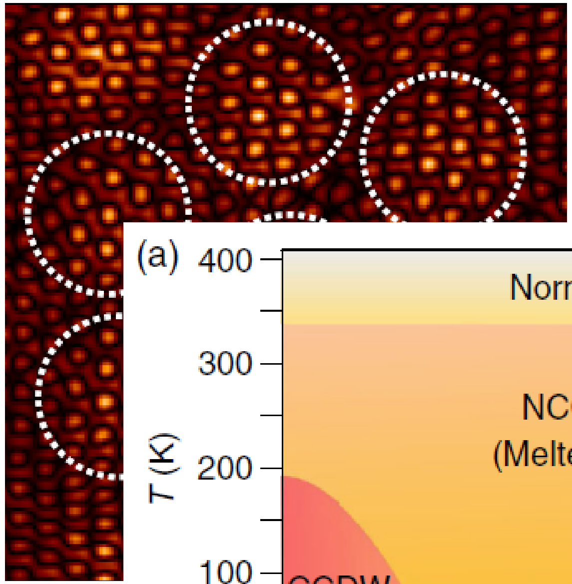
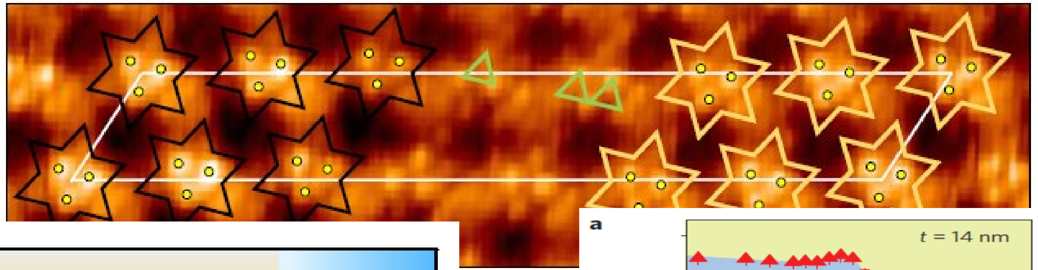
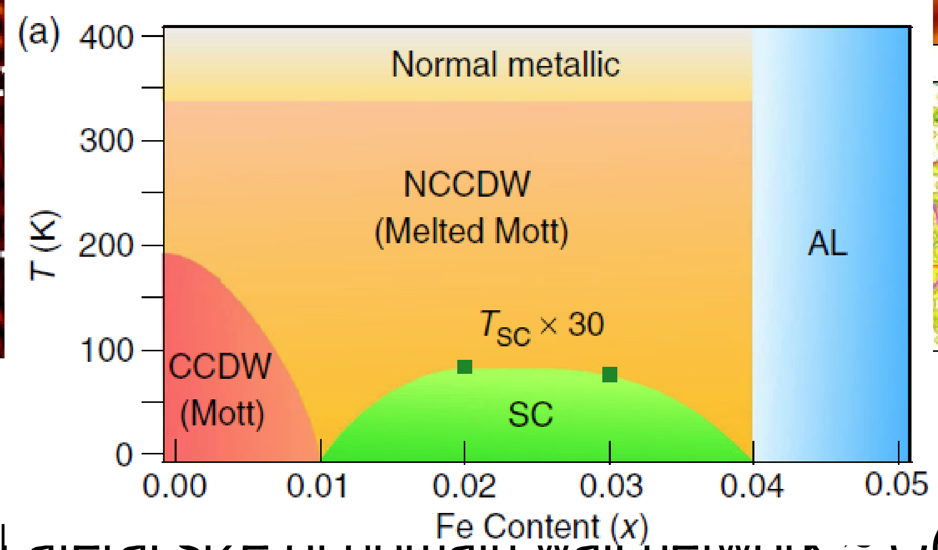
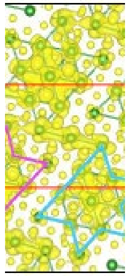
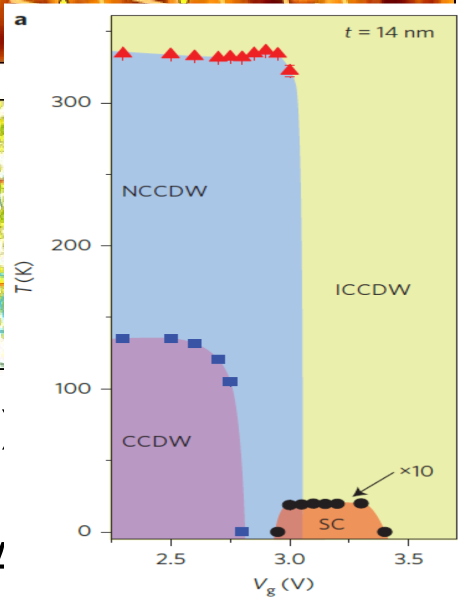








(2019)



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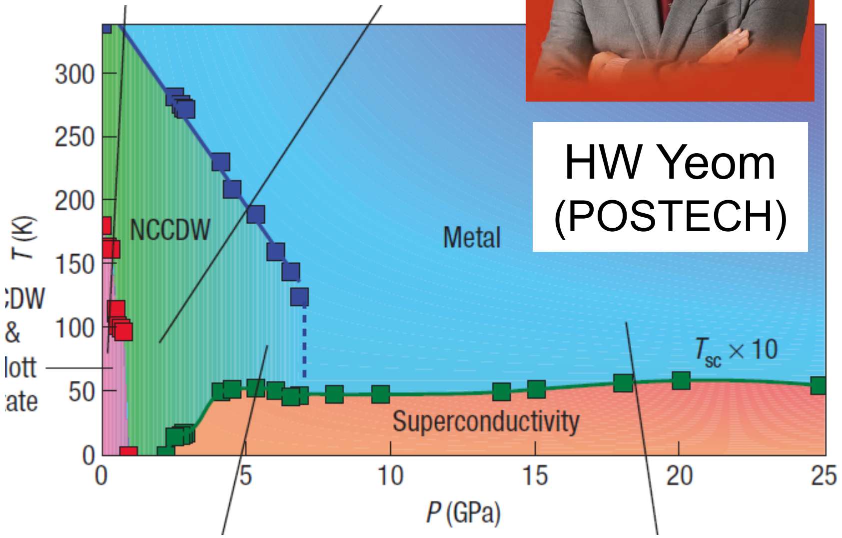

Phase diagram
[Sipos et. al. Nat. Mat. (2008)]

1. Lateral size of domain wall network ~ O(80)

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What's the electronic structure? Why superconducting?

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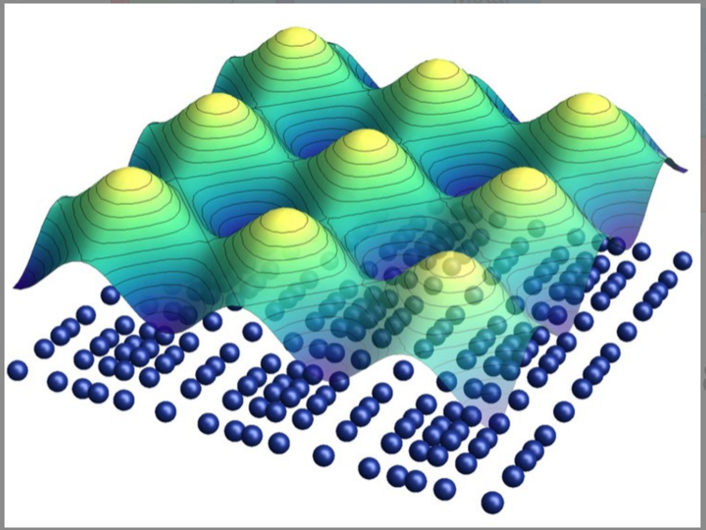
HW Yeom (POSTECH)

Cf: certain density waves can be topological, too.



GYC, Soto-Garrido, Fradkin, Phys. Rev. Lett. (2015)

Can it be topological?

Any correlation-driven phenomena?

[Ref. JW Park, **GYC**, J Lee, HW Yeom, Nat. Comm. (2019)]

1. Lateral size of domain wall network ~ O(80) A.

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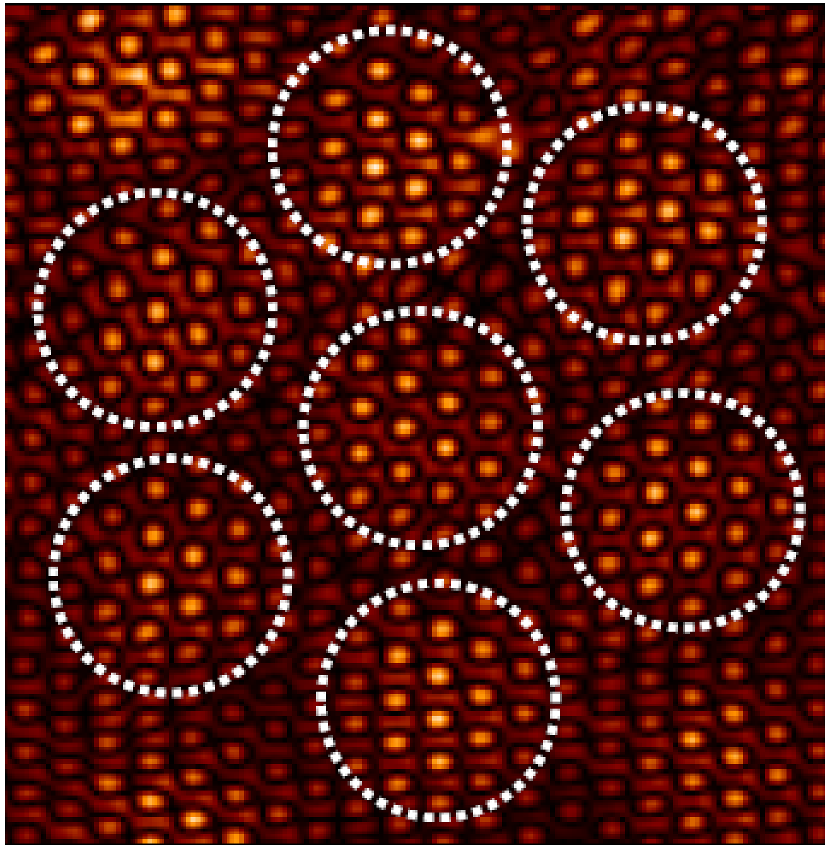
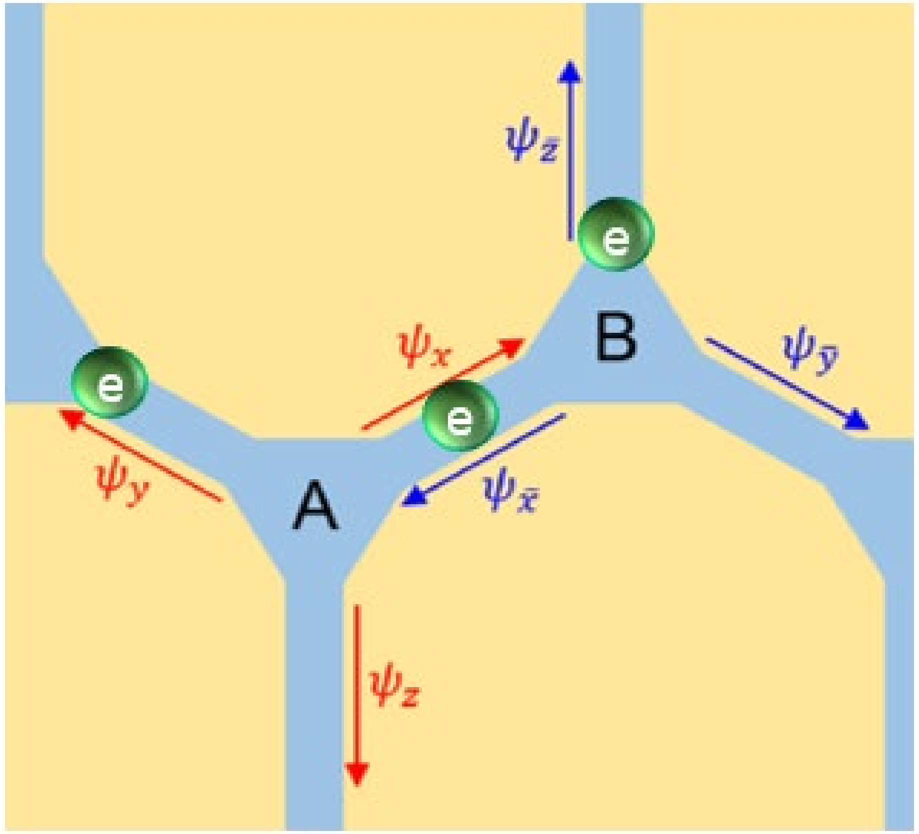
What's the electronic structure? Why superconducting?

To the *1st* order approximation:

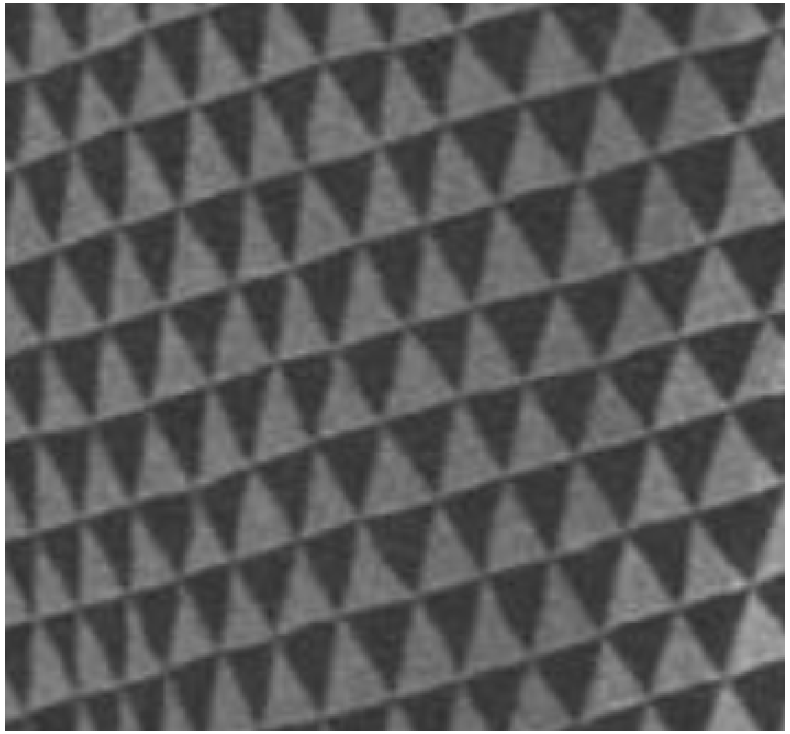




Problem: ***1D*** mobility of electrons, combined with ***2D*** superstructures.

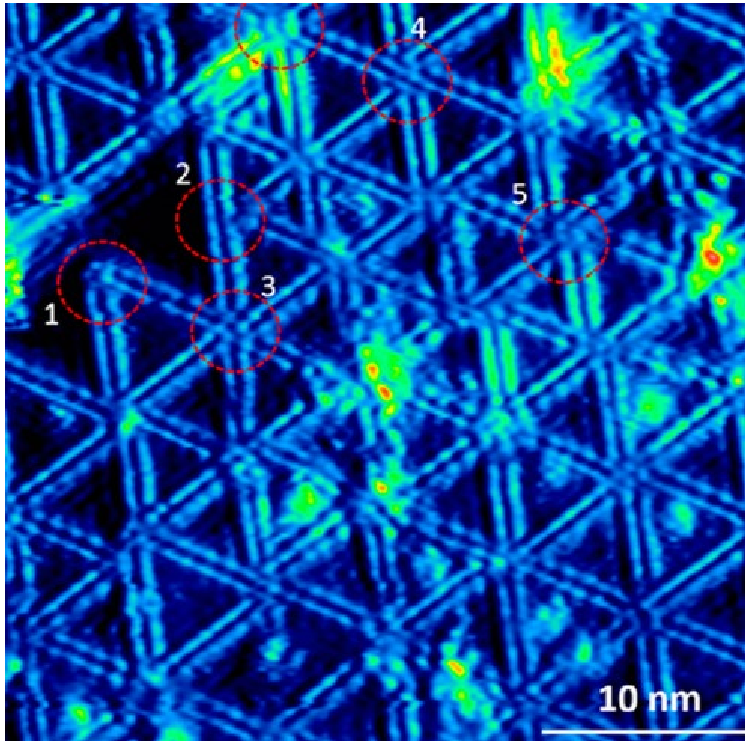
[Lee, Geng, Park, Oshikawa, Lee, Yeom, **GYC***, Physical Review Letters (2020)]

This structure is *more common* than one naively thinks:



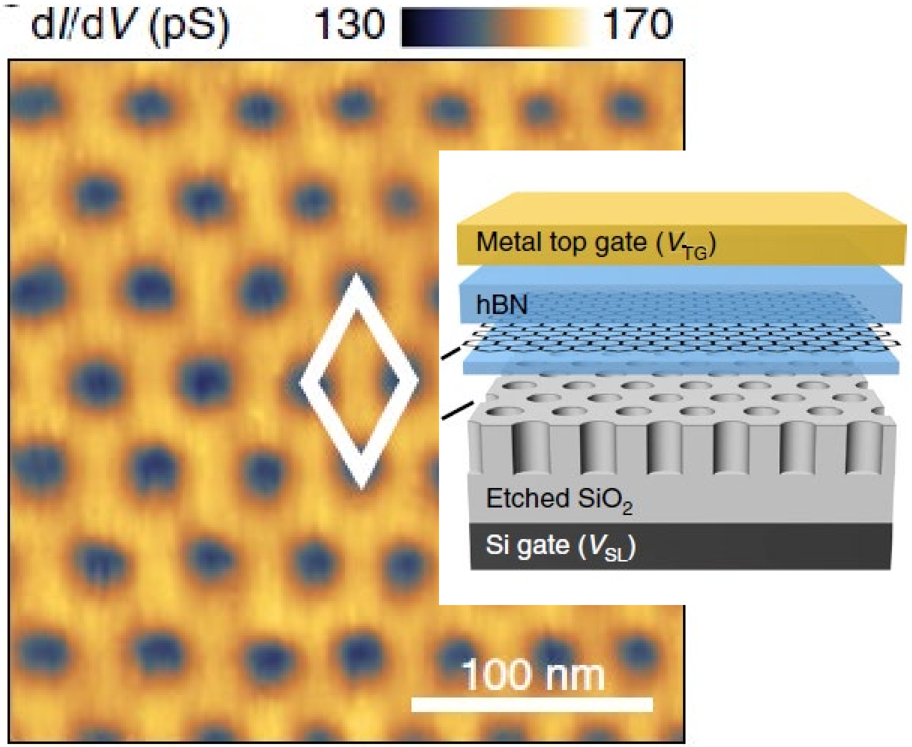
Twisted Bilayer Graphene

[Yoo et.al. Nat. Matt. (2019)]



Moiré $MoSe_2$

[Ma et.al. ACS Nano (2019)]

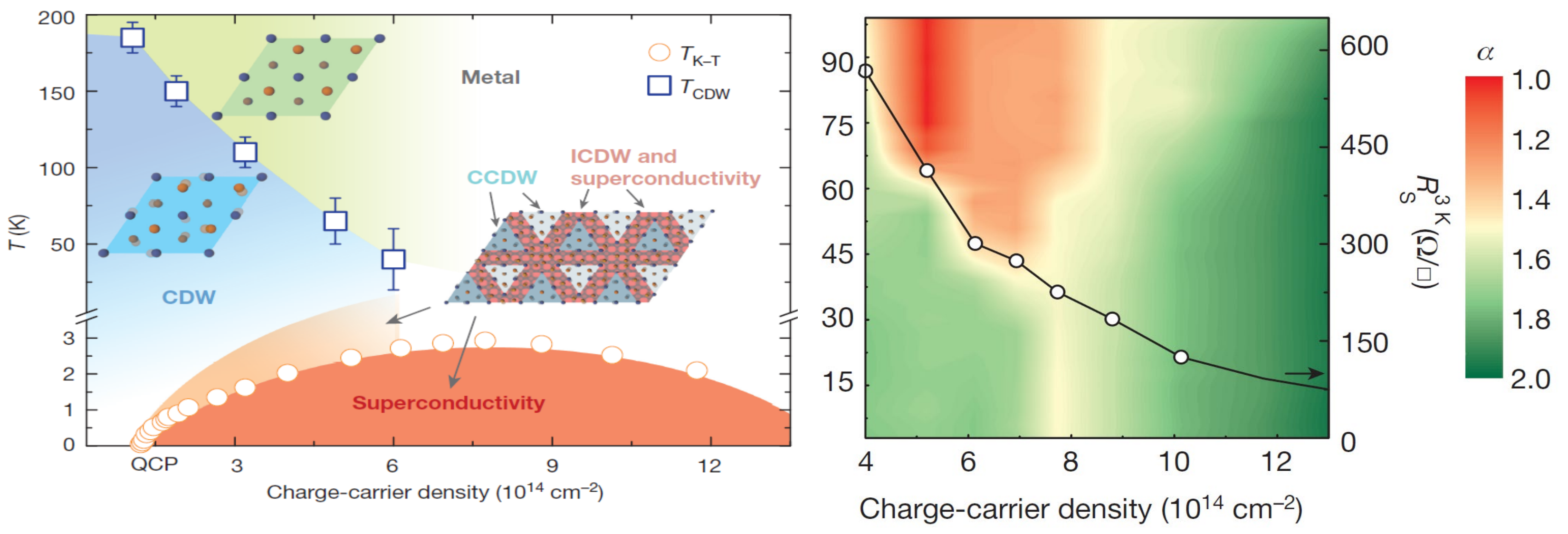


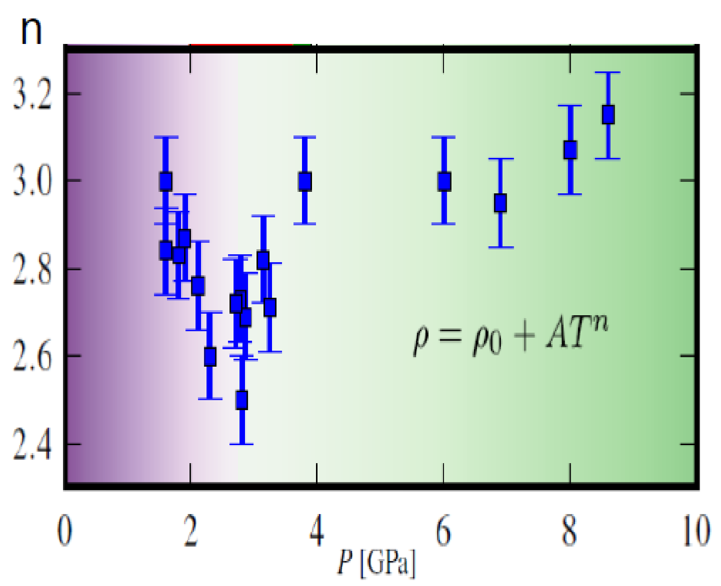
Patterned Network on Graphene

[Forsythe et.al. Nano Lett (2018)]

More interesting examples?

Experiments: 1T-$TiSe_2$





[Ref. Li et.al., Nat. (2016)]

[Ref. Kusmartseva et. al. PRL (2009)]

1. Non-Fermi Transport $\boldsymbol{R \sim R_0 + A\,T^n}$, varying exponent $\boldsymbol{n \approx 1 \sim 3}$
2. Emerging superconductivity, and domain wall networks (Little-Park effect)

Correlation effect seems important in these materials!

Cam we *explain* these?

[1] Park, **GYC**, Lee, Yeom*, Nature Communications (2019)
[2] Lee, Geng, Park, Oshikawa, Lee, Yeom, **GYC***, Physical Review Letters (2020)
[3] Lee, Oshikawa, **GYC***, Physical Review Letters (2021)

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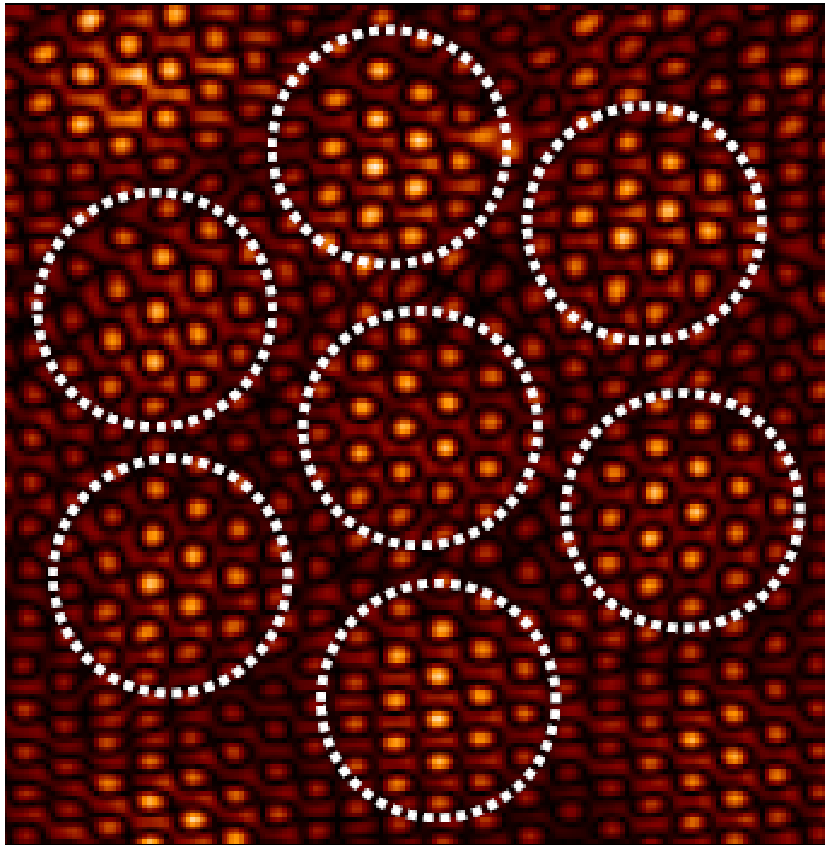
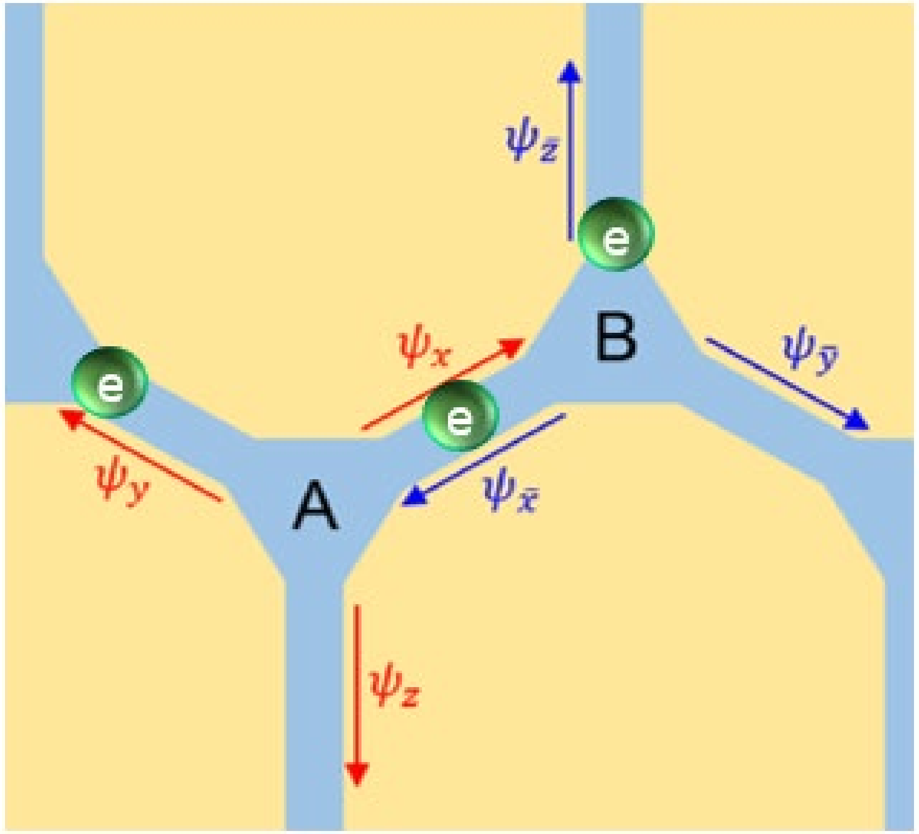
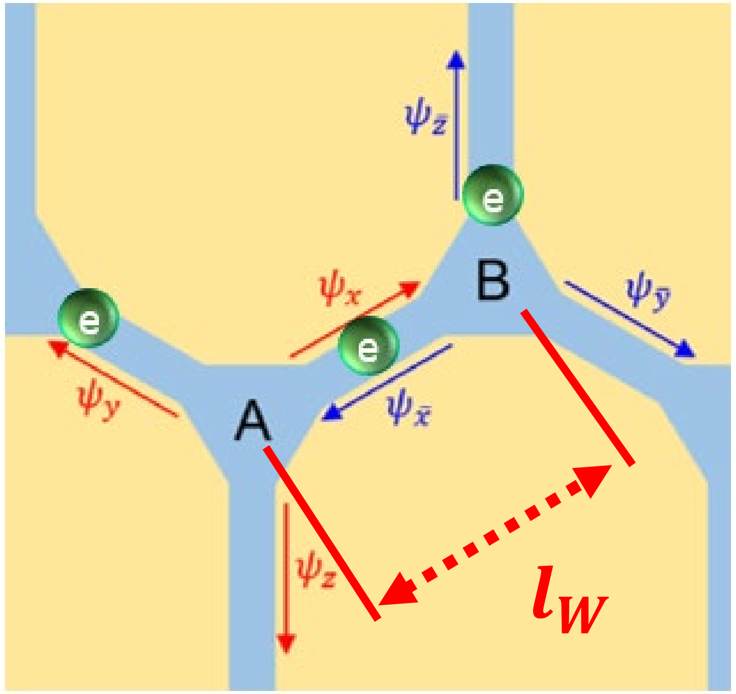


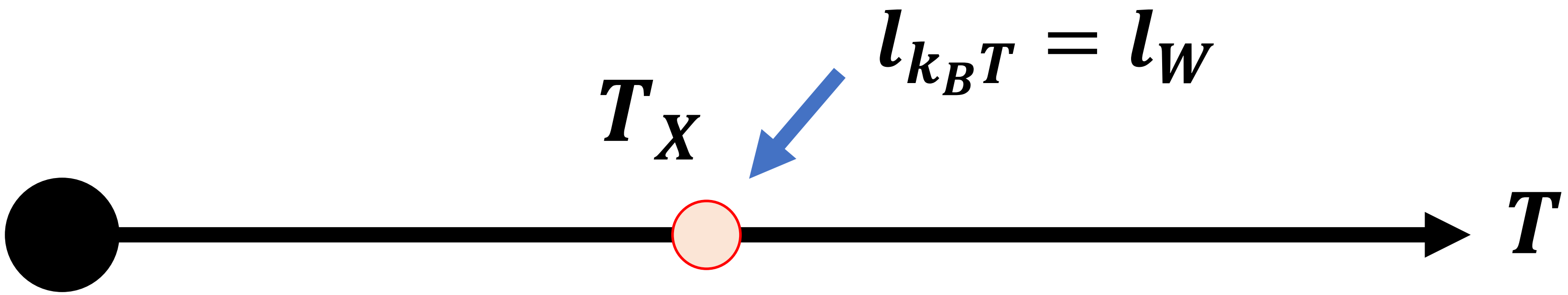


Problem: *1D* mobility combined with *2D* superstructures.

[Lee, Geng, Park, Oshikawa, Lee, Yeom, **GYC***, Physical Review Letters (2020)]

Key observation: Dimensional Crossover T_X





2d Physics $(l_{k_BT} > l_W)$

[Lee, Geng, … **GYC**, PRL (2020)]

1d Physics $(l_{k_BT} < l_W)$

[Lee, Oshikawa, **GYC,** PRL (2021)]

Wire length l_W *vs.* **Thermal coherence $l_{k_BT} = \frac{\hbar v_F}{k_BT}$**

[Lee, Oshikawa, **GYC***, Phys. Rev. Lett. 126, 186601 (2021)]

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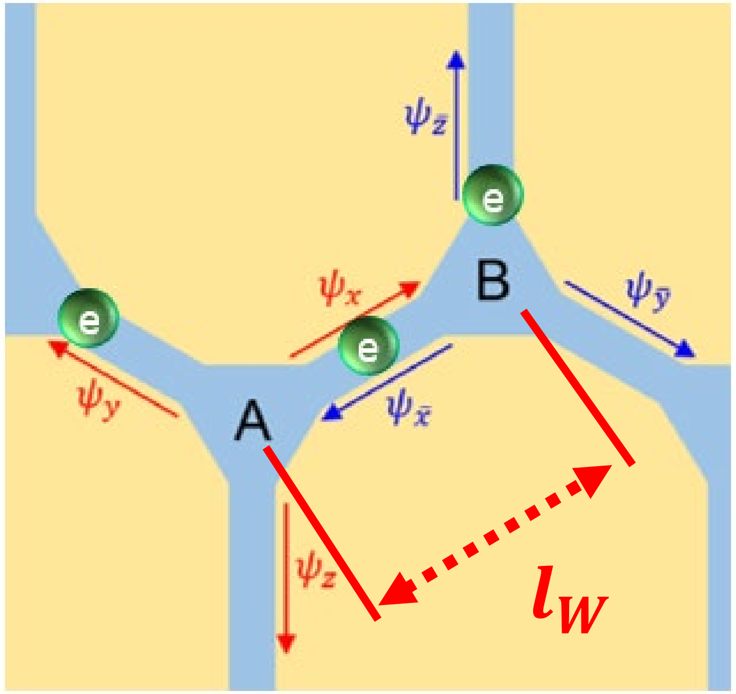

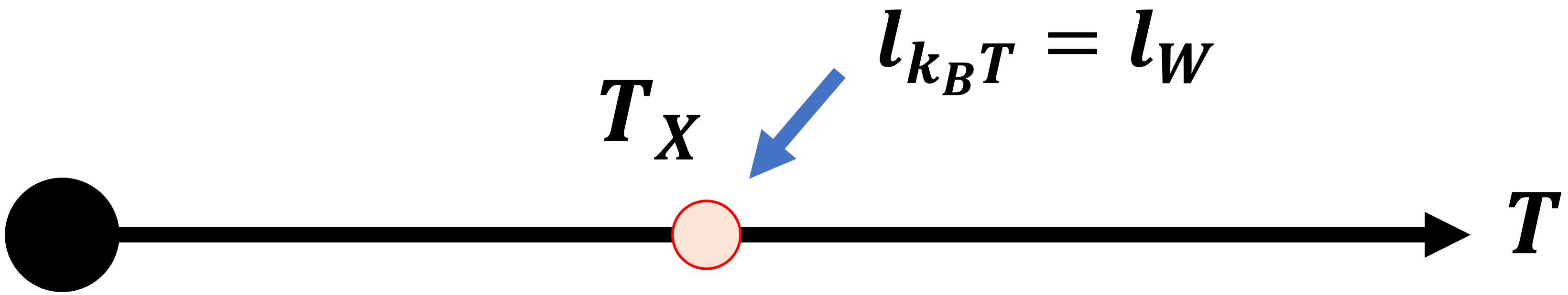

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1d Physics $(l_{k_BT} < l_W)$

[Lee, Oshikawa, **GYC,** PRL (2021)]

- **$TiSe_2$: O(10)K** (assuming e.g. that the electrons are flowing along 1D domain walls)
- **Twisted bilayer graphene: O(50)K** (for 140 nm)
- **TaS_2: O(100)K**

[Lee, Oshikawa, **GYC***, Phys. Rev. Lett. 126, 186601 (2021)]

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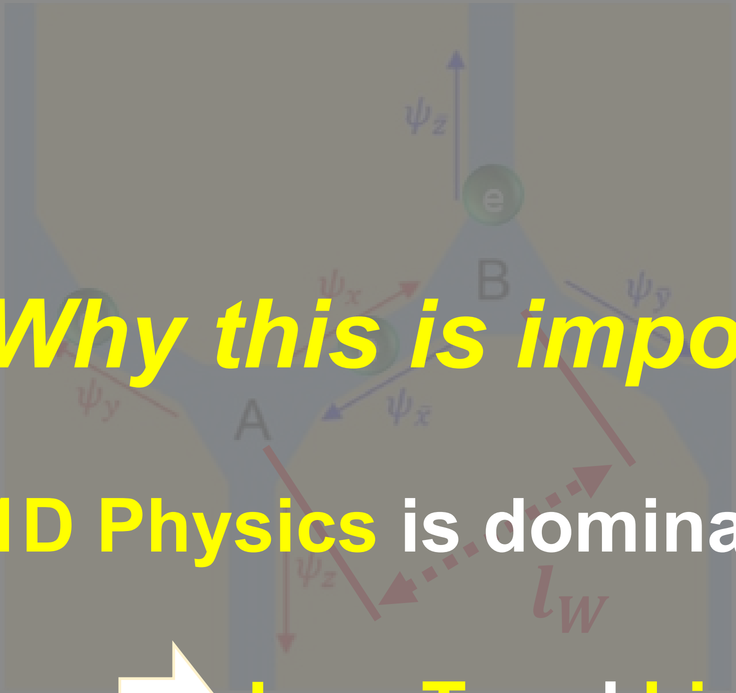

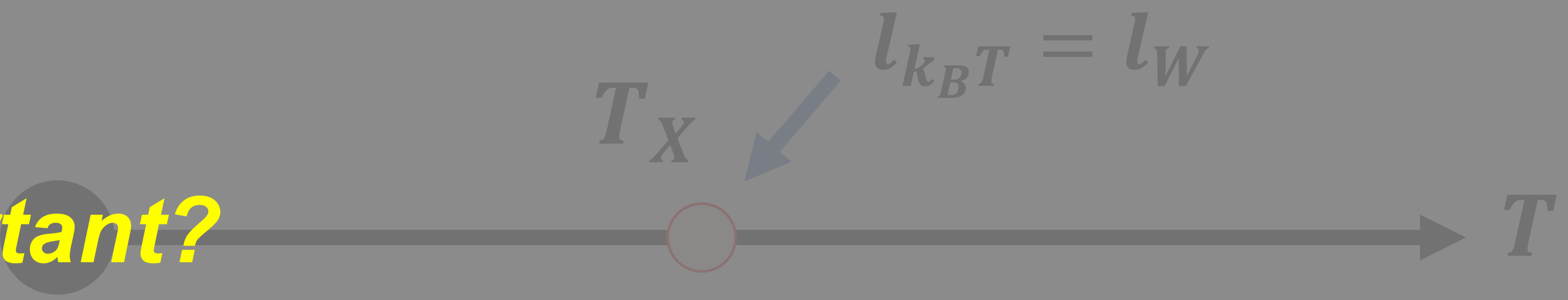

Why this is important?

1D Physics is dominated by non-Fermi liquids, *a.k.a.* Luttinger liquid.

Low-T and high-T should be differently accessed in theory.

2d Physics $(l_{k_BT} > l_W)$ **1d Physics** $(l_{k_BT} < l_W)$

[Lee, Geng, … **GYC**, PRL (2020)] [Lee, Oshikawa, **GYC**, PRL (2021)]

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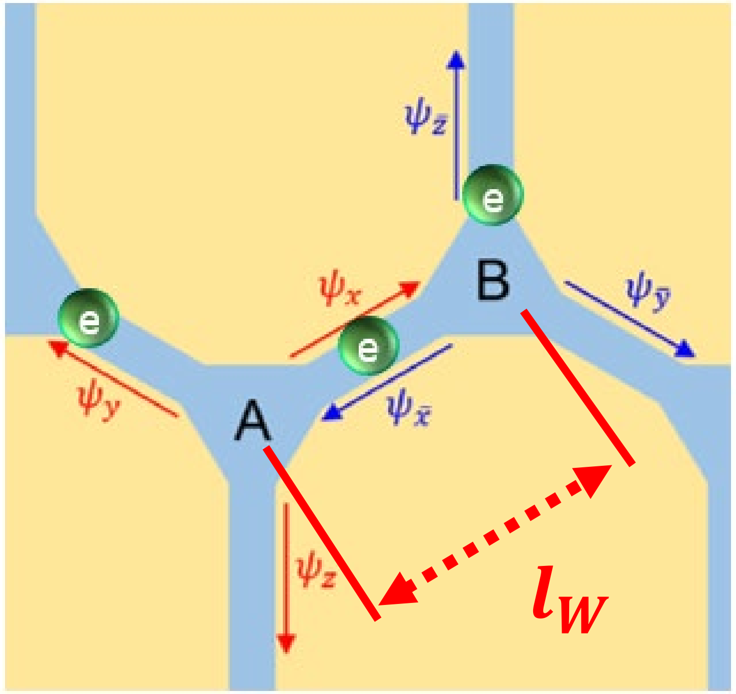
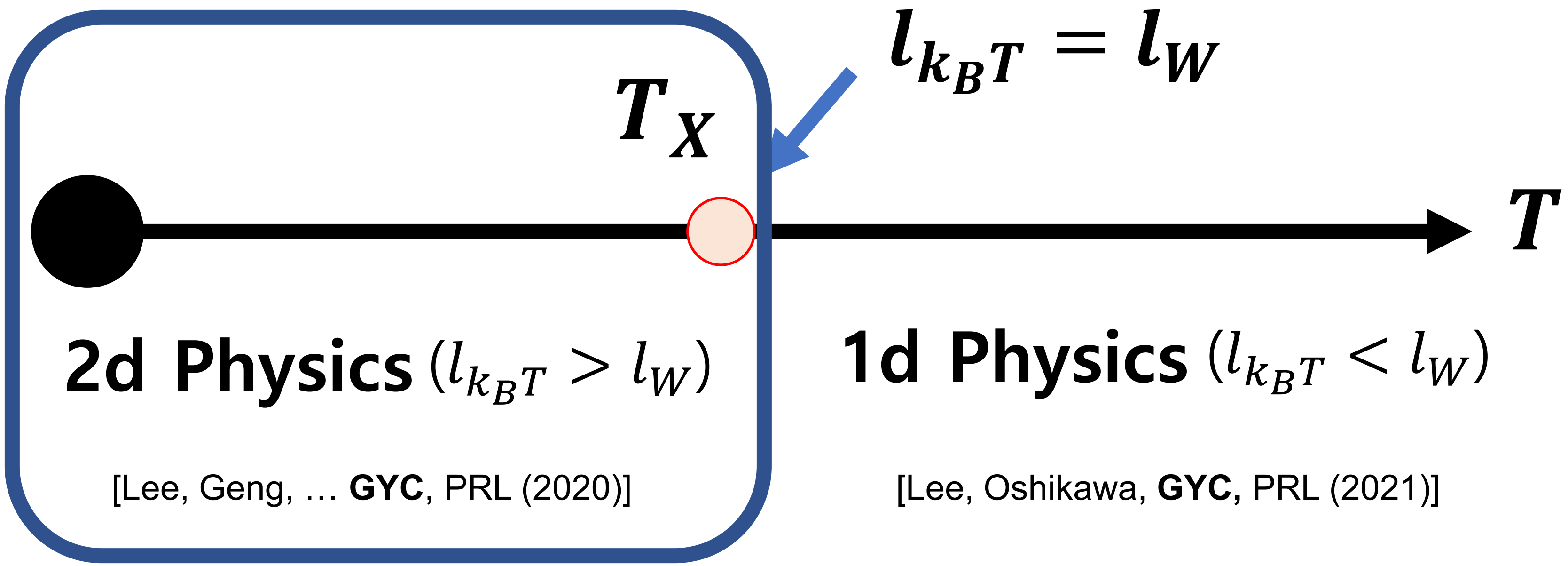
Key observation: Dimensional Crossover T_X



Relatively *easier* problem.



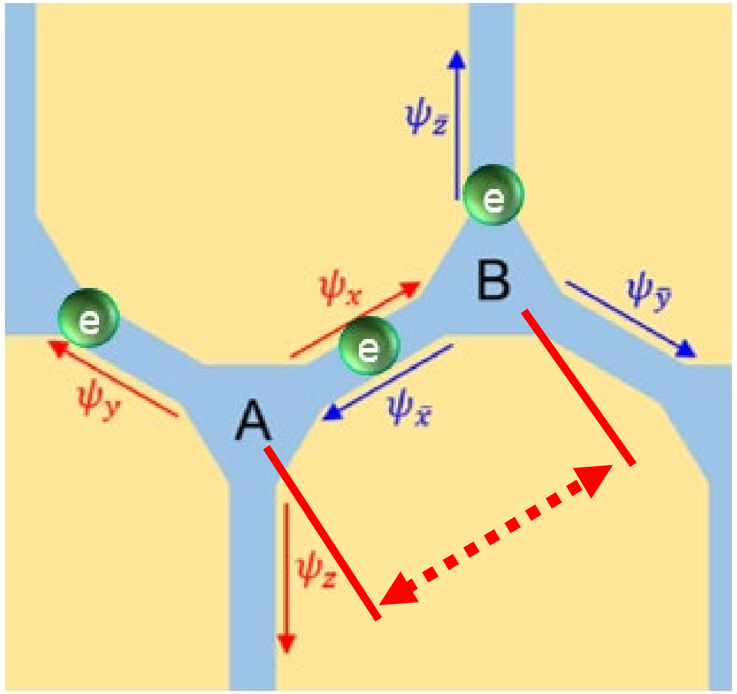
- **$TiSe_2$: O(10)K** (assuming e.g. that the electrons are flowing along 1D domain walls)
- **Twisted bilayer graphene: O(25)K** (for 300 nm)
- **TaS_2: O(100)K**

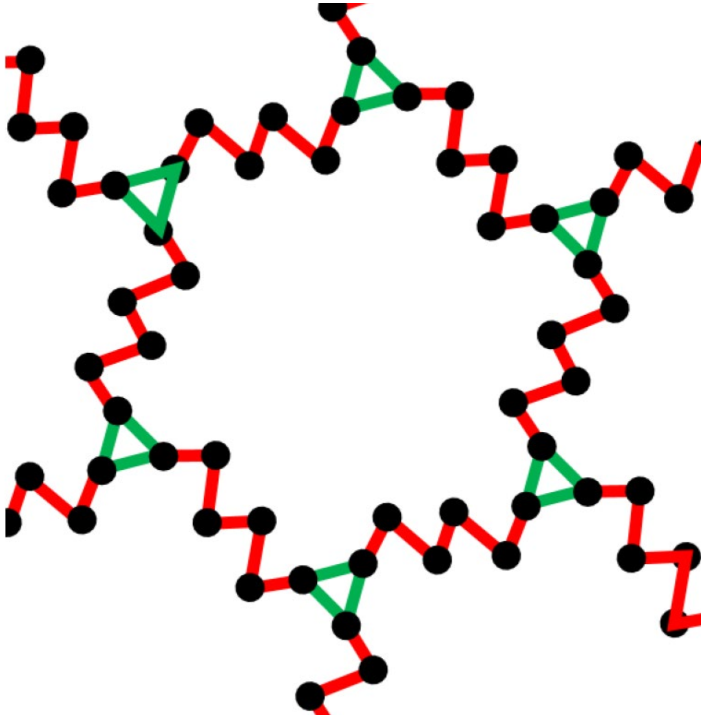
[Lee, Oshikawa, **GYC***, Phys. Rev. Lett. 126, 186601 (2021)]

2D limit: $T < T_X$

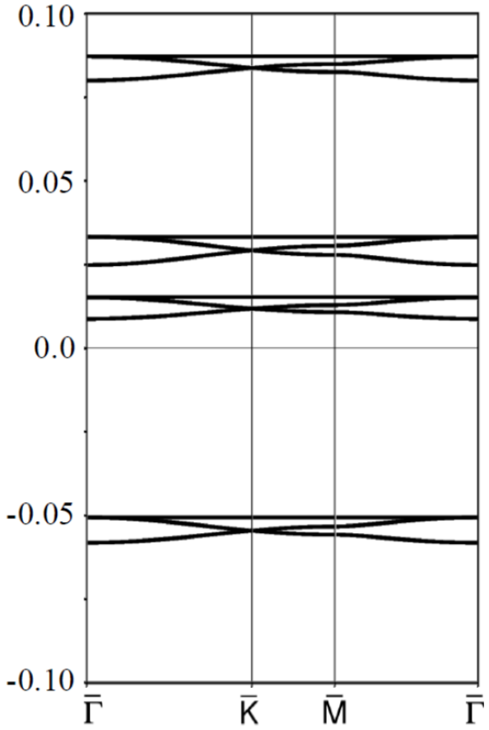
2D limit: Cascade of ***stable*** flat bands & Superconductivity

[Lee, Geng, Park, Oshikawa, Lee, Yeom, **GYC***, Phys. Rev. Lett. 124, 137002 (2020)]





eV



(with realistic parameters, geometry)

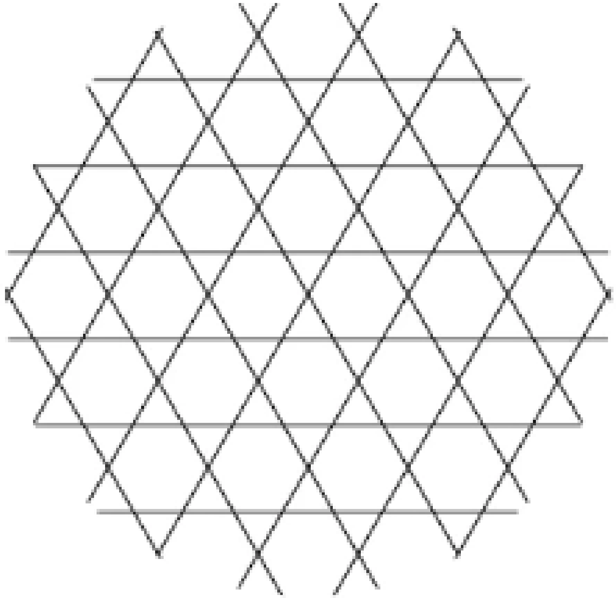
1. Not only one, but ***many, many flat bands***.

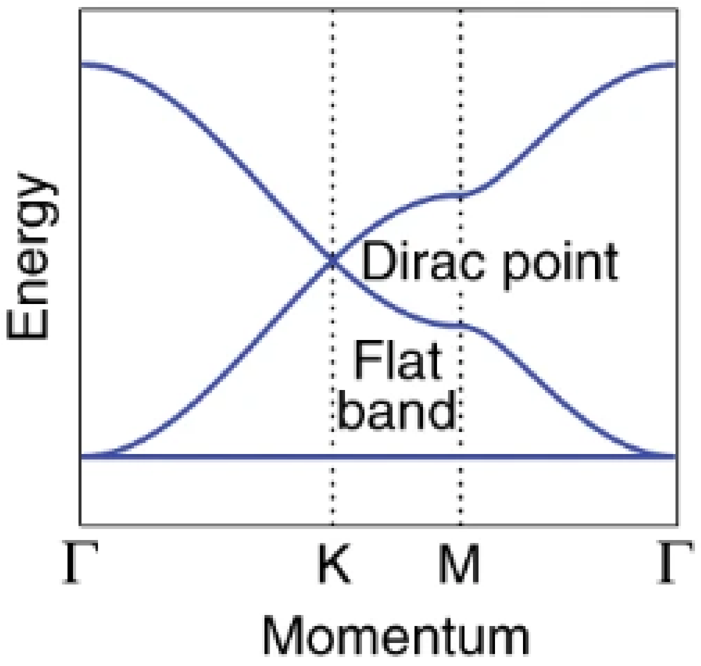
2. Flatness is ***stable***, i.e. protected by locality, time-reversal & crystal symmetry.

Stability = relevance to the real, experimental systems!

Of course, flat band is *not* new.

1. Kagome Lattice





- **Single flat band**
- **NN-Hopping *Only***

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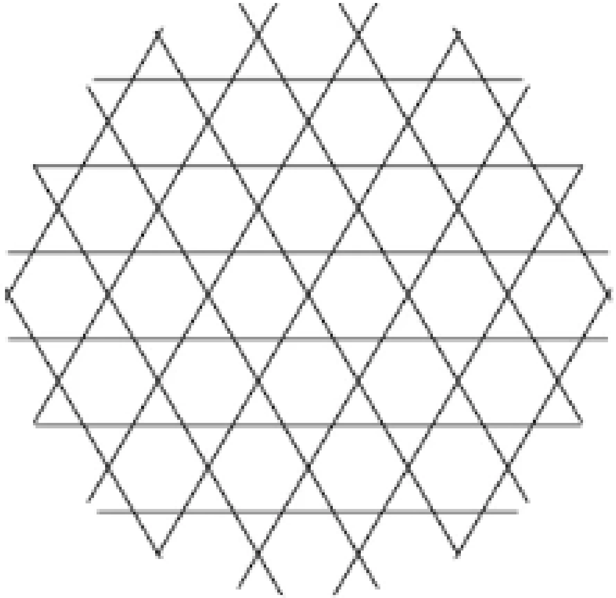

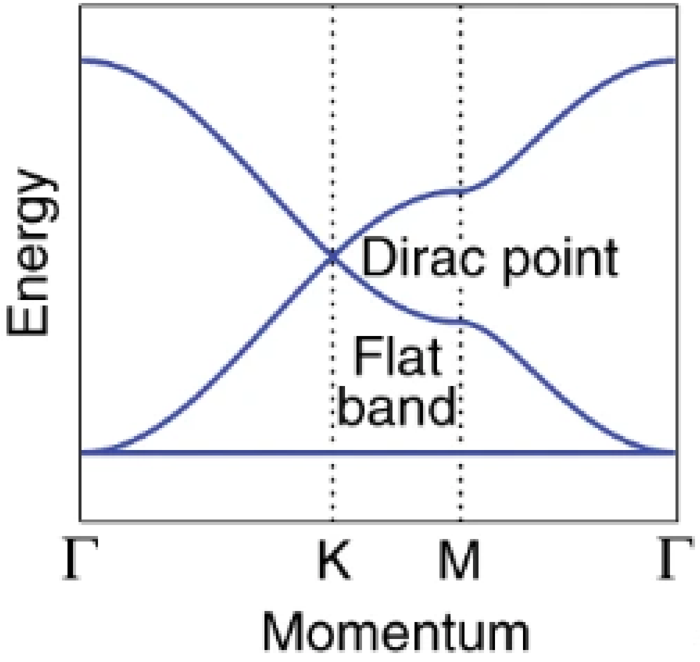

- **Single flat band**
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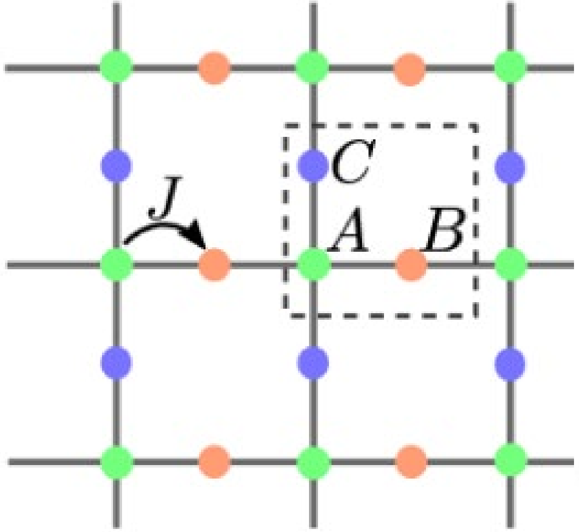
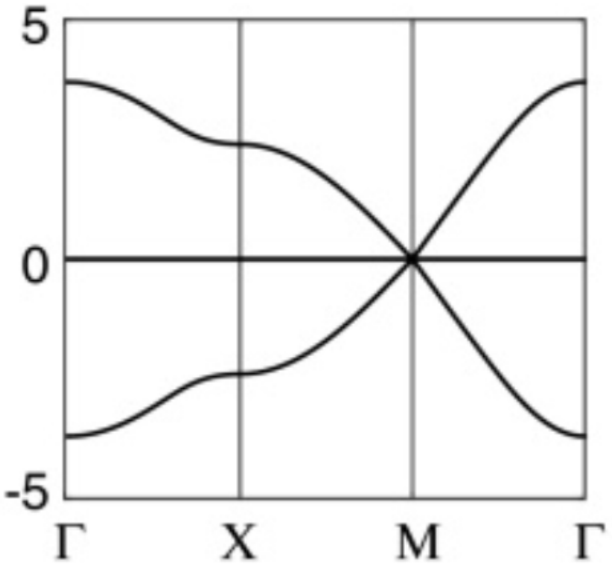
2. Lieb Lattice

- **Single flat band**
- **NN-Hopping**

(sublattice symmetric hopping)





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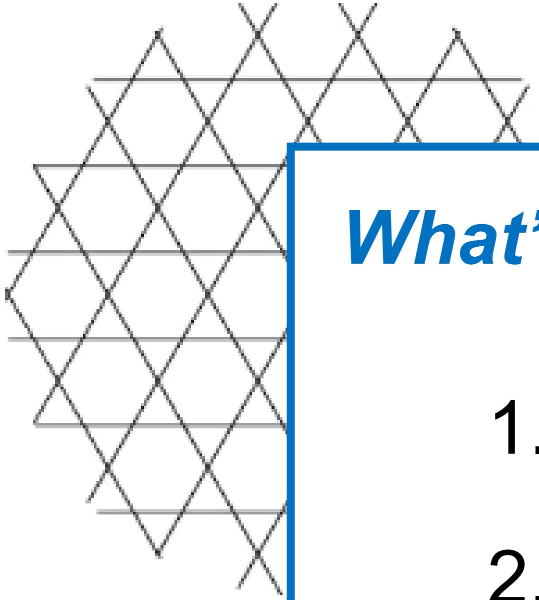


What's new in our model is:

1. Multiple, ***not just one***, Flat bands

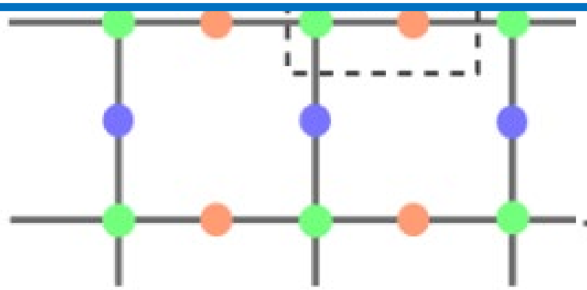
2. Unusual Stability & Protecting symmetries

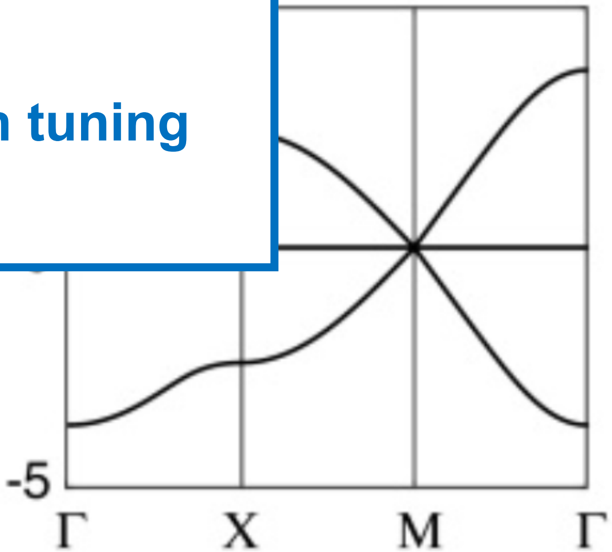
Easier **to observe the physics of flat bands without much tuning**

- NN-Hopping

(sublattice symmetric hopping)

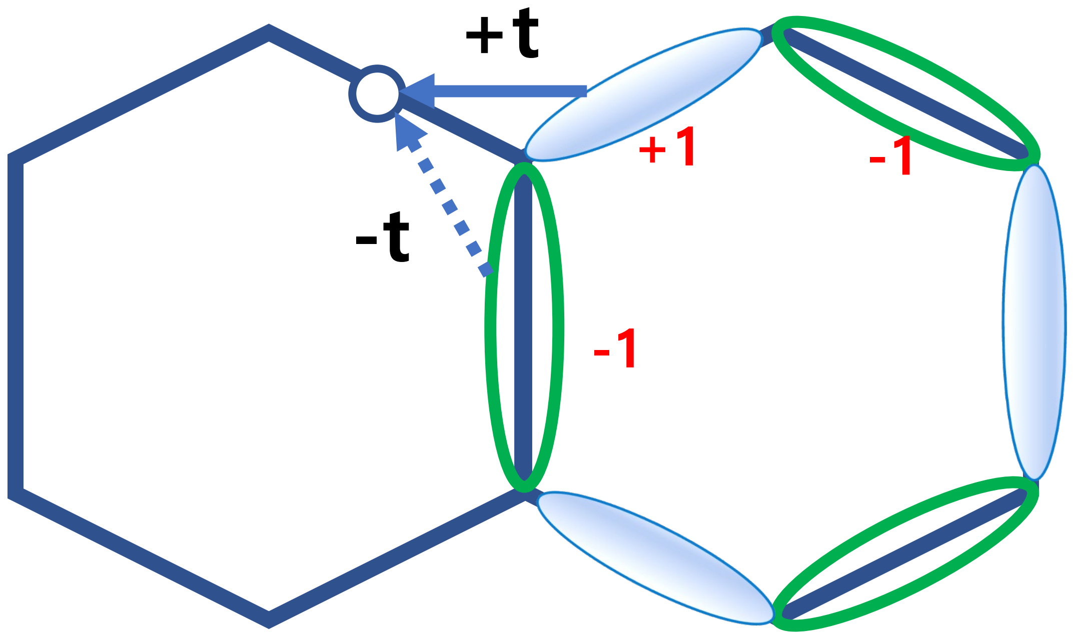
eb Lattice





Emergence of flat bands & their stability

Numerics: flat band states have $\Psi(\mathrm{x}) = 0$ at the nodes. [**Cf.** Bergman, Wu, Balents 2008]



Standing waves inside each wire.

Hence, flat bands are protected by:

(1) [Locality] Hopping is shorter than wire length [~ 80A in 1T-TaS_2]

(2) [Symmetry] $D_6 \times T$ symmetry

(3) Multiple standing waves = Repeated, Multiple flat bands

[Lee, Geng, Park, Oshikawa, Lee, Yeom, **GYC***, Phys. Rev. Lett. 124, 137002 (2020)]

Emergence of flat bands & their stability

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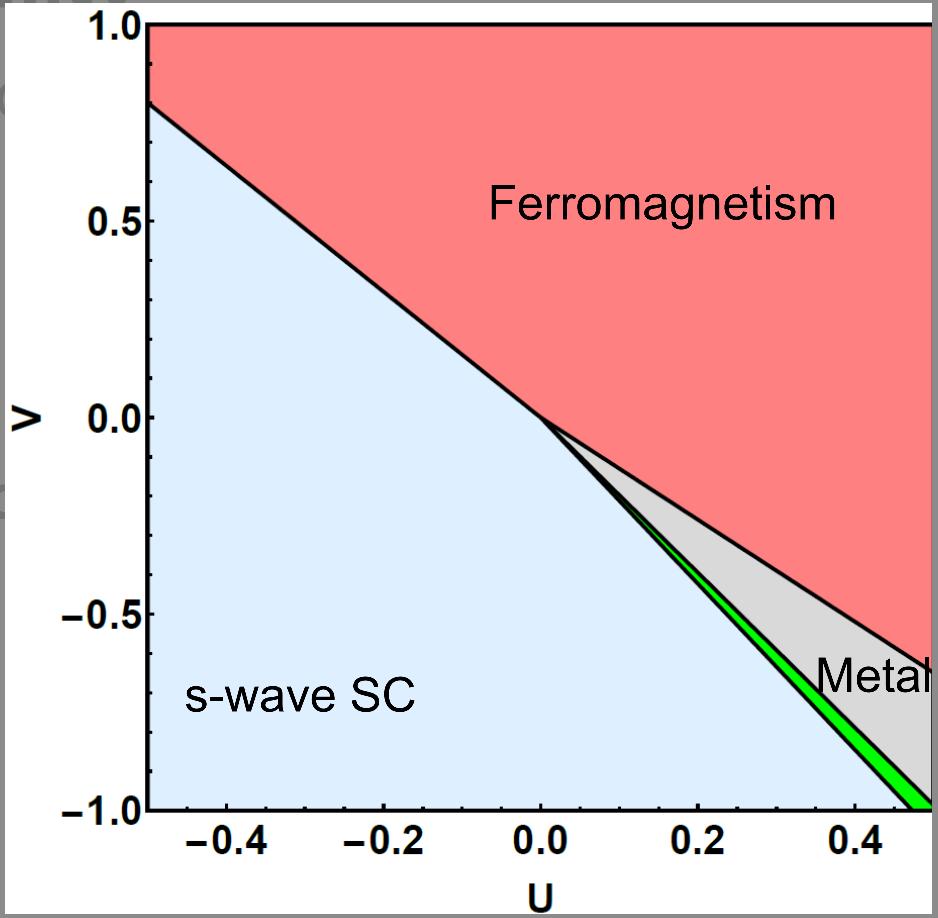
Including interactions

$$H_{int} = U \sum_{\boldsymbol{r}} n_{\boldsymbol{r}}^2 + V \sum_{\langle \boldsymbol{r}, \boldsymbol{r}' \rangle} n_{\boldsymbol{r}} n_{\boldsymbol{r}'}$$

(**cf.** phonon-electron interaction.)



Broad range of *s-wave SC* & *Ferromagnetism*

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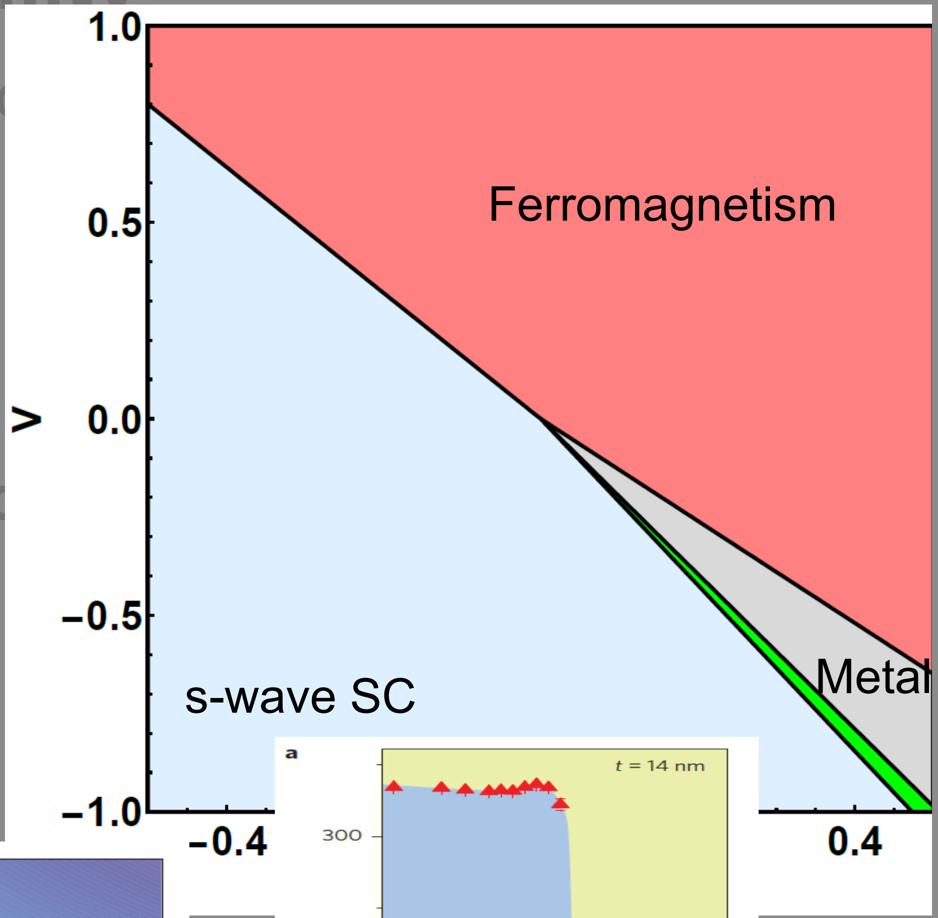
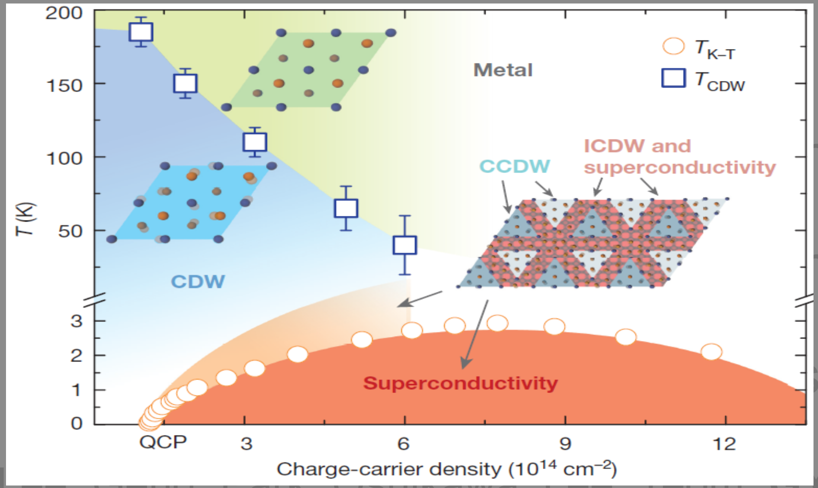
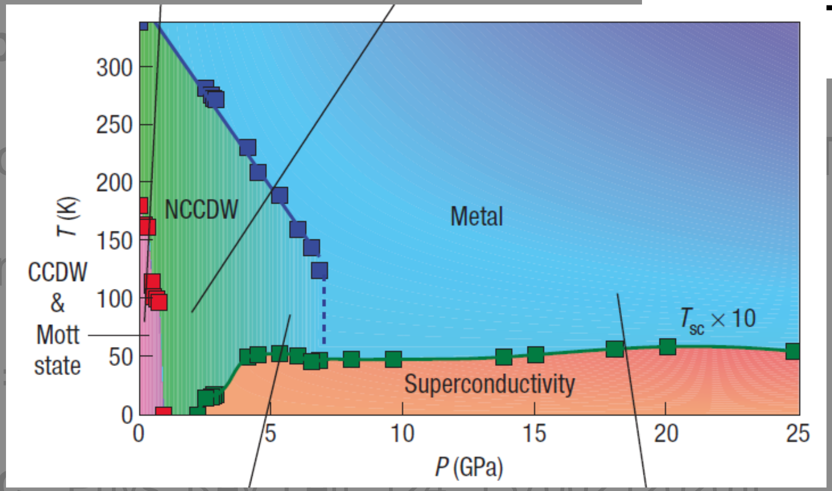
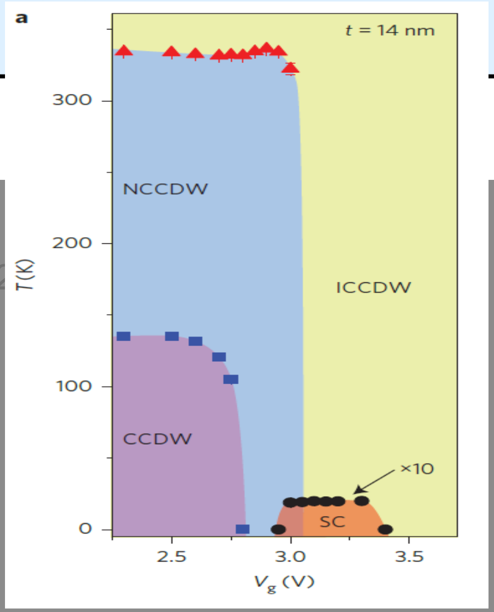


Broad range of *s-wave SC* & *Ferromagnetism*



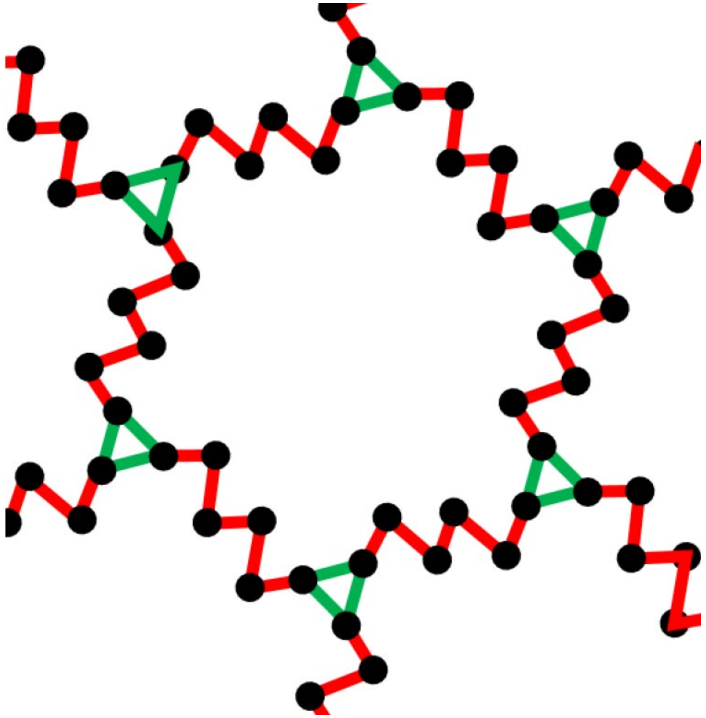


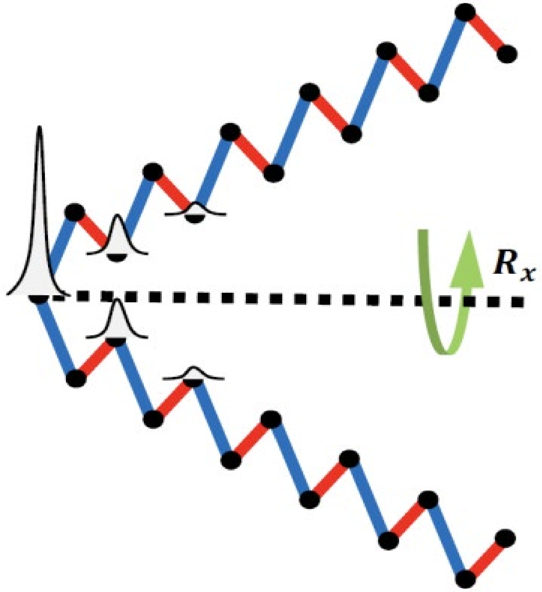


[Lee, Geng, Park, Oshikawa, Lee, Yeom, GYC , Phys. Rev. Lett. 124, 137002 (2020)]

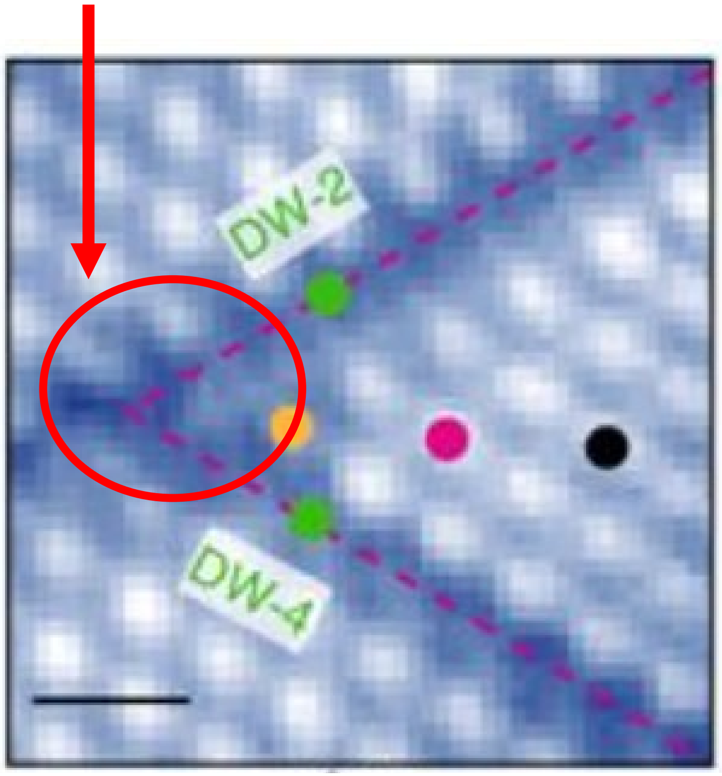
2D limit: “Higher-order” topology

[Lee, Geng, Park, Oshikawa, Lee, Yeom, **GYC***, Phys. Rev. Lett. 124, 137002 (2020)]





LDOS peak ?



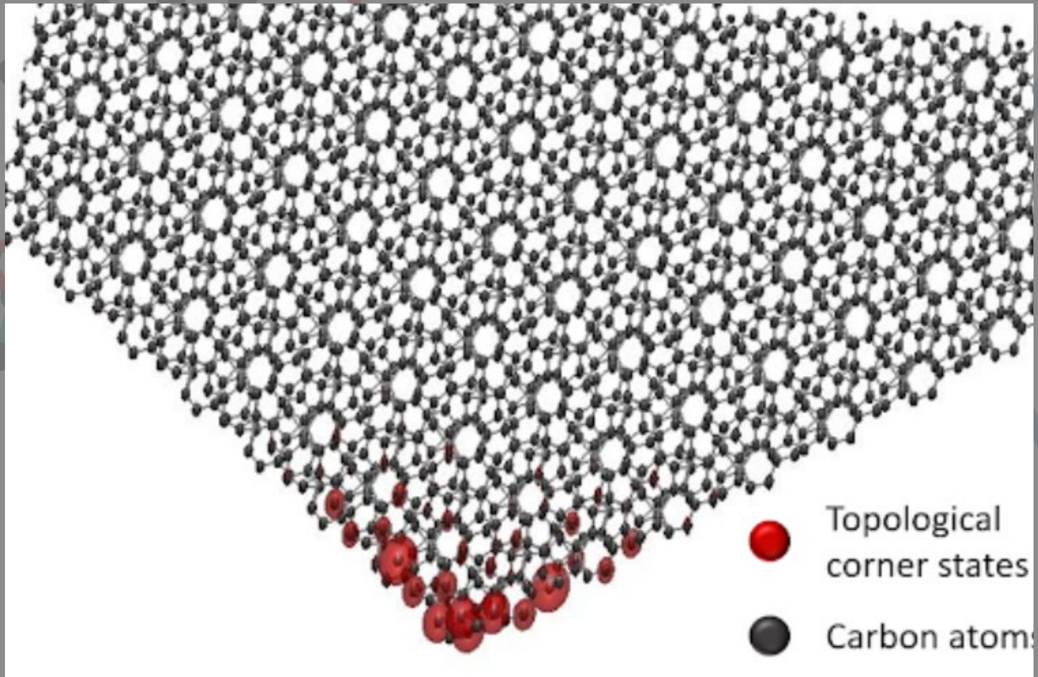
[Ref: Cho et al, Nat. Comm.(2017)]

2D limit: “Higher-order” topology

[Lee, Geng, Park, Oshikawa, Lee, Yeom, **GYC***, Phys. Rev. Lett. 124, 137002 (2020)]

LDOS peak ?

This looks very similar to the corner state of the higher-order TI



PHYSICAL REVIEW LETTERS **123,** 216803 (2019)

Editors' Suggestion

Higher-Order Topological Insulator in Twisted Bilayer Graphene

Moon Jip Park,[1,*] Youngkuk Kim,[2,†] Gil Young Cho,[3,‡] and SungBin Lee[1,§]

Hidden Higher-order Topology

[Ref: Yeom’s group, Nat. Comm.(2017)]

…which one can actually make a more precise connection.

Domain wall networks provide a natural platform for “higher-order” topology.

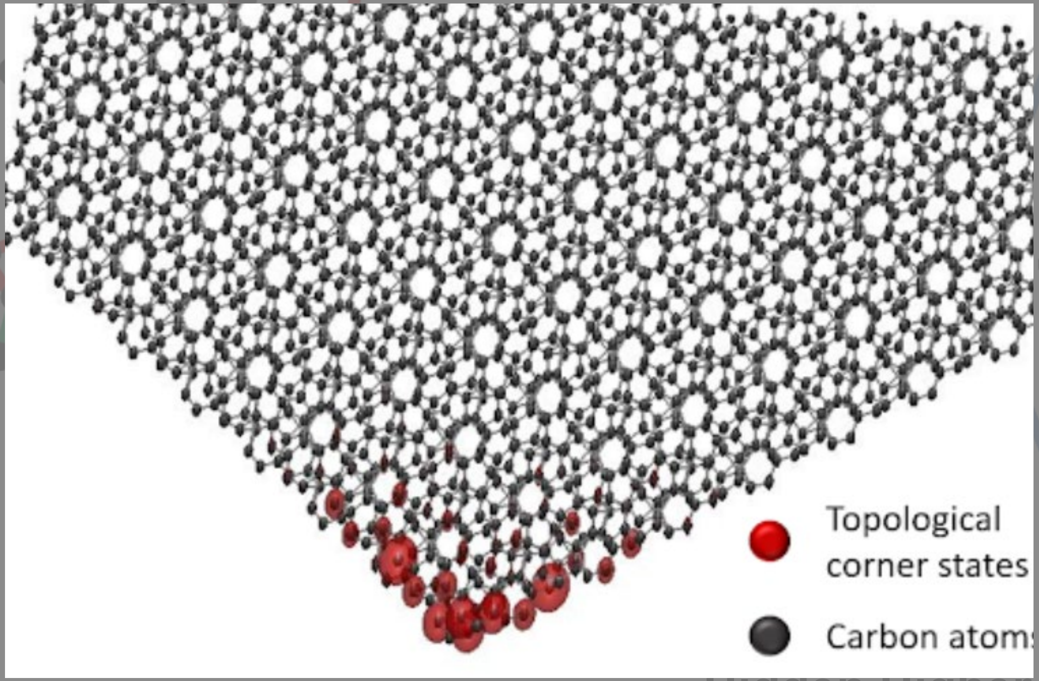
(when gapped)

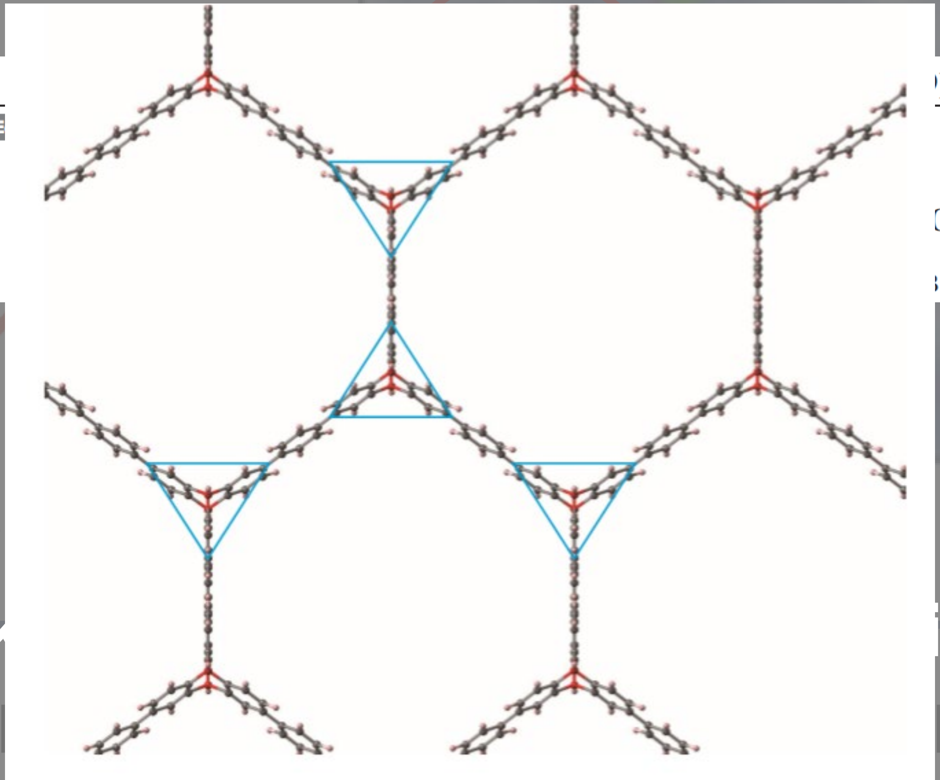
2D limit: "Higher-order" topology

[Lee, Geng, Park, Oshikawa, Lee, Yeom, **GYC***, Phys. Rev. Lett. 124, 137002 (2020)]

LDOS peak ?

This looks very similar to the corner state of the higher-order TI





…which one can actually mak… …ion.

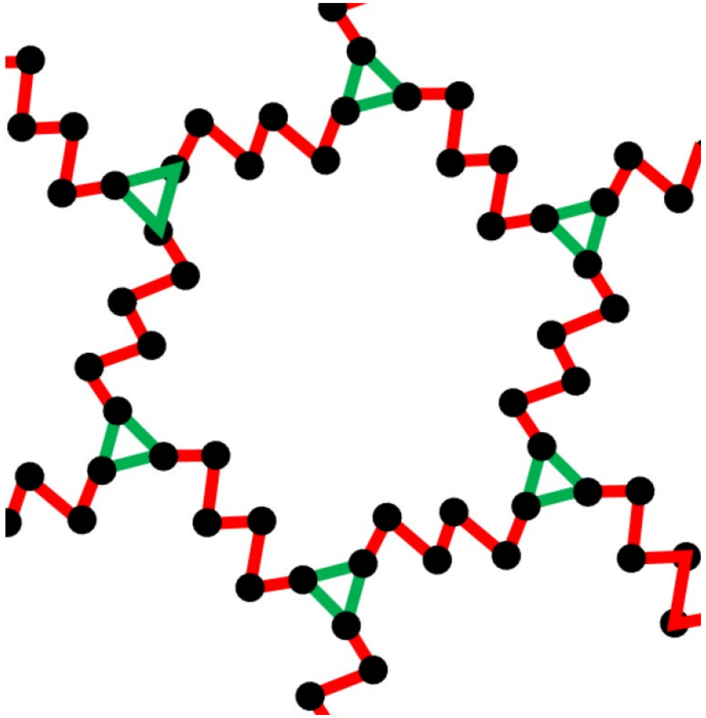
Domain wall networks provide a natural … …pology.

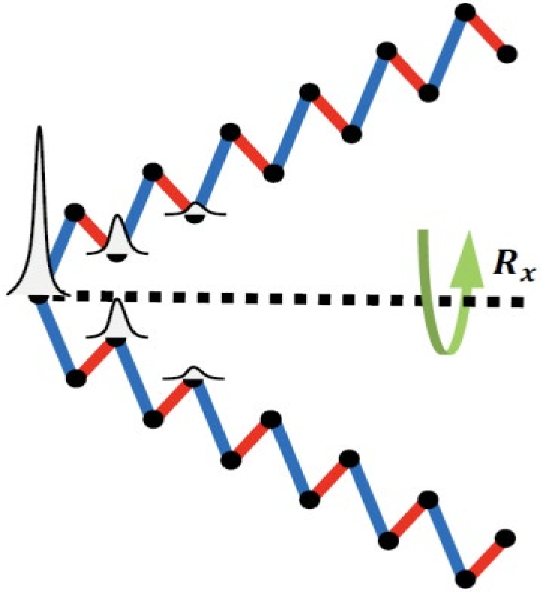
(when gapped)

Triptycene (Hatsugai's group, Phys. Rev. Mat. 2019)

2D limit: "Higher-order" topology

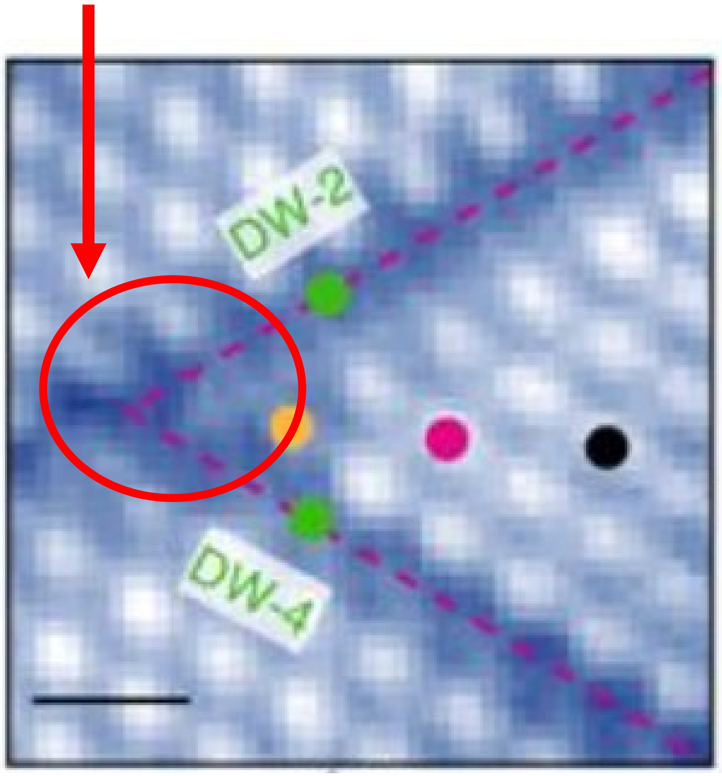
[Lee, Geng, Park, Oshikawa, Lee, Yeom, **GYC***, Phys. Rev. Lett. 124, 137002 (2020)]





Hidden Higher-order Topology

LDOS peak ?



[Ref: Yeom's group, Nat. Comm.(2017)]

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2D limit: Higher-order topology

[Lee, Geng, Park, Oshikawa, Lee, Yeom, **GYC***, Phys. Rev. Lett. 124, 137002 (2020)]

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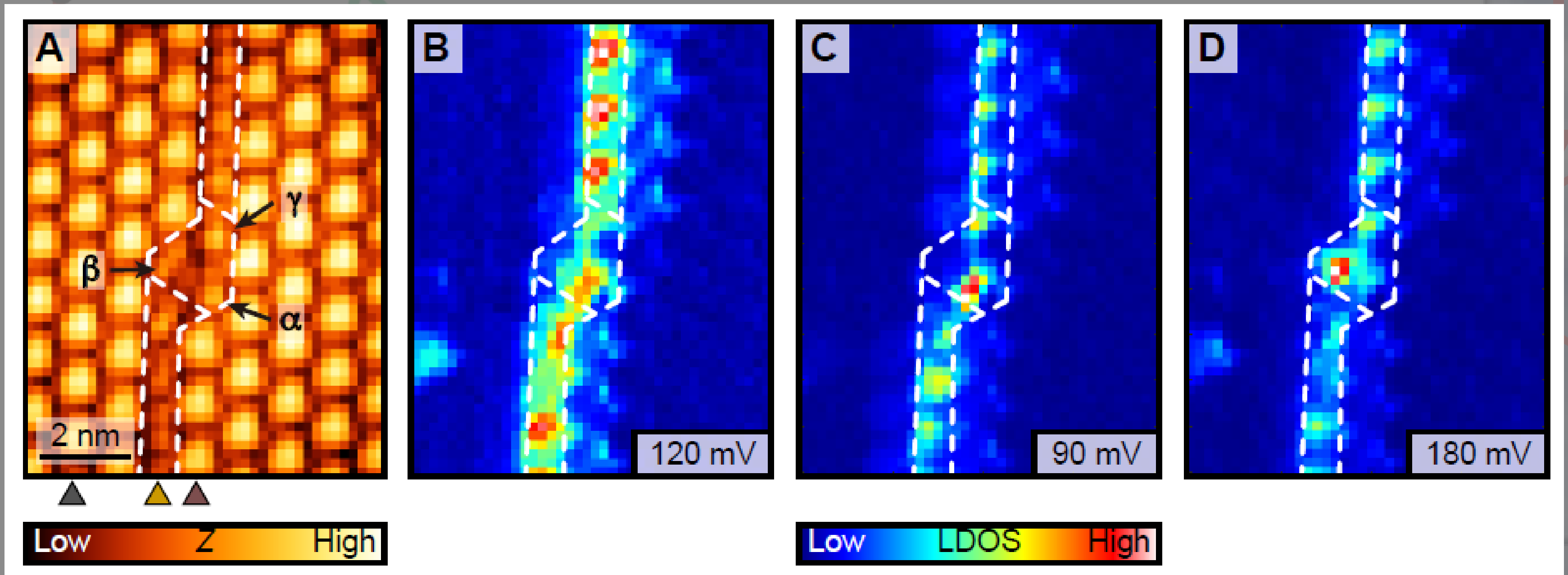
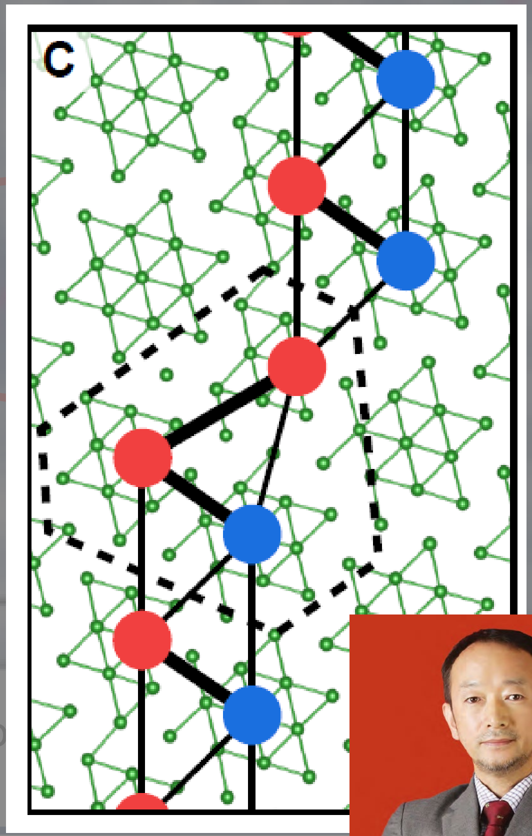




Lee, Park, **GYC**, Yeom, submitted to *PRL*

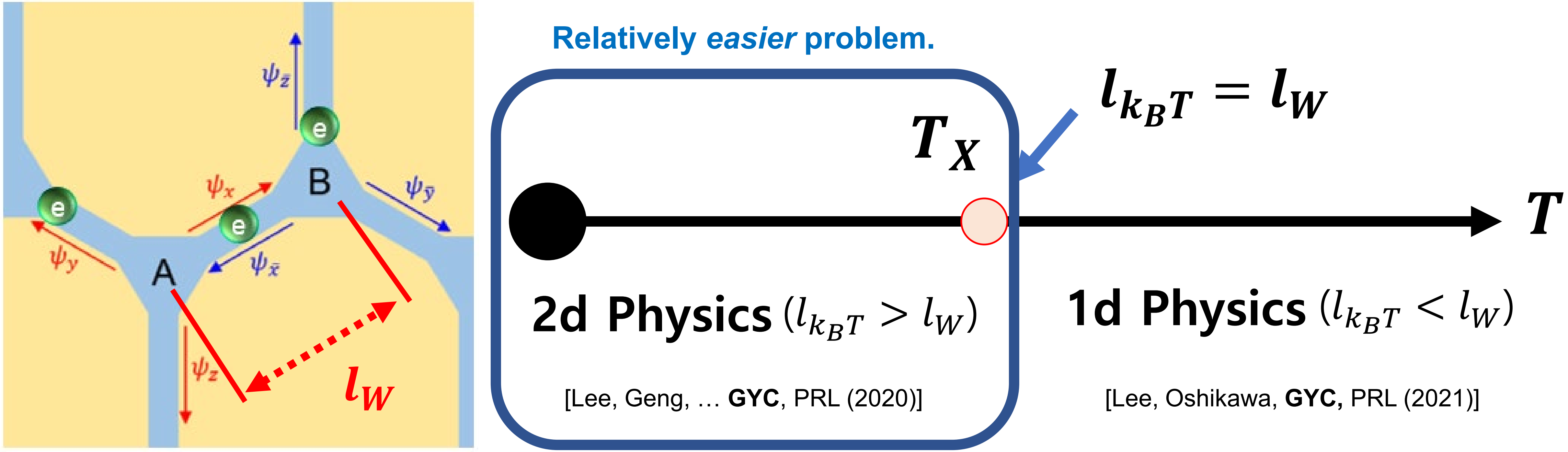
ef: Yeo

HW Yeom
(POSTECH)

Domain wall networks provide a natural platform for higher-order t

(when gapped)

Key observation: Dimensional Crossover T_X

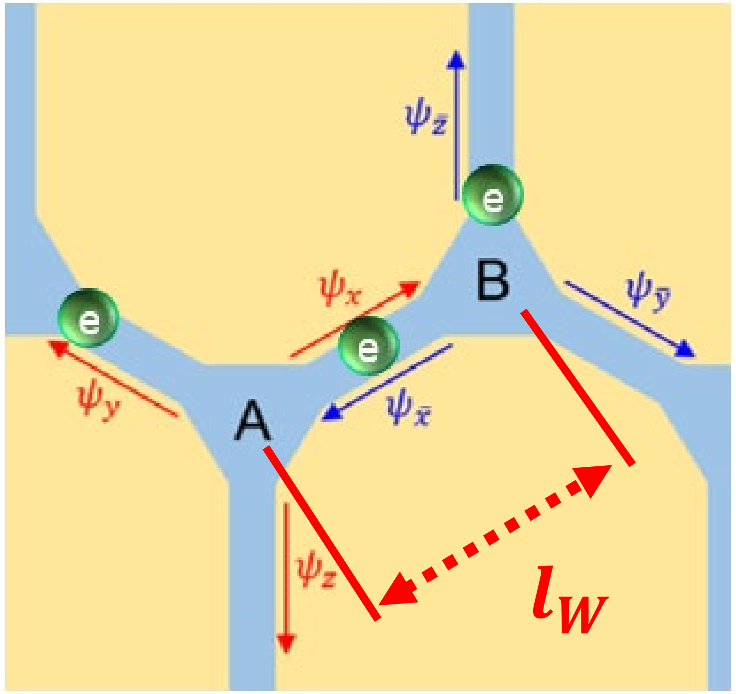


- **Cascades of stable flat bands**
- **Superconducting instabilities & experimental implications**
- **Higher-order topology & STM experiments**

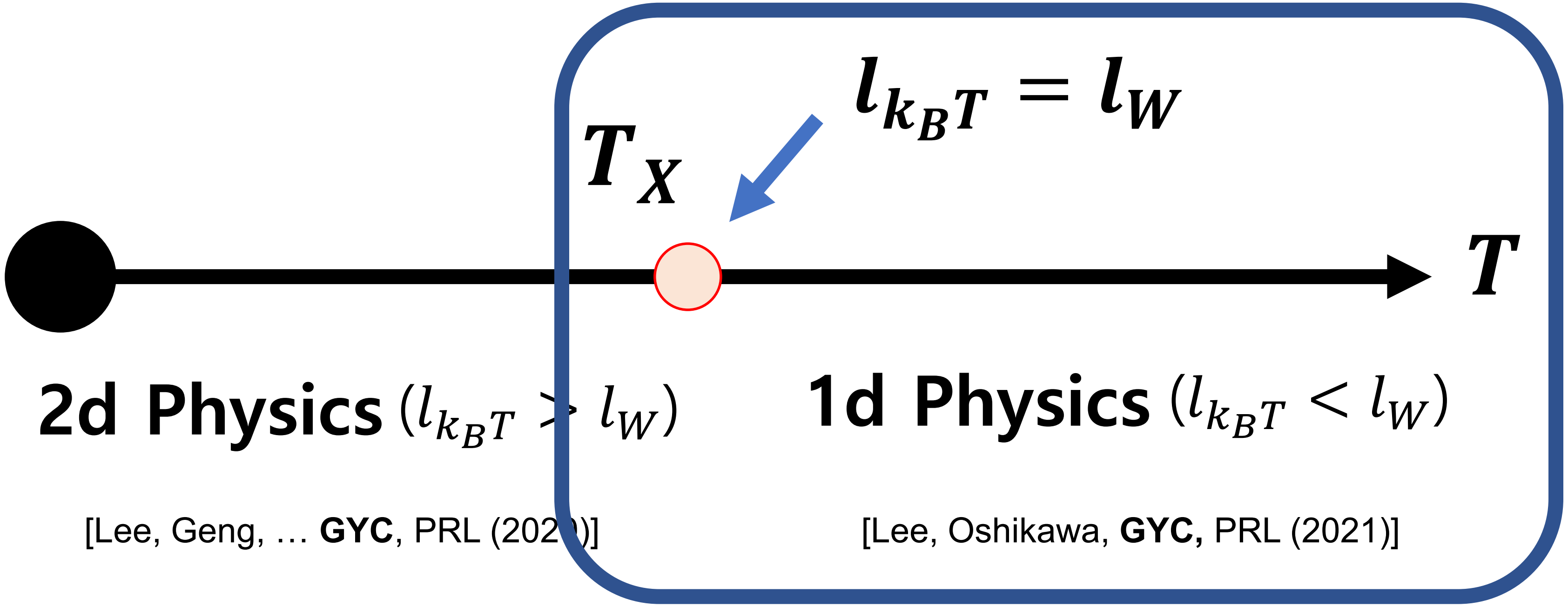
[Lee, Geng, Park, Oshikawa, Lee, Yeom, **GYC***, Phys. Rev. Lett. (2020); Lee, Park, **GYC**, Yeom, submitted to Phys. Rev. Lett.]

1D limit: $T > T_X$

Key observation: Dimensional Crossover T_X



What do we expect?



- **$TiSe_2$: O(10)K** (assuming e.g. that the electrons are flowing along 1D domain walls)
- **Twisted bilayer graphene: O(25)K** (for 300 nm)
- **TaS_2: O(100)K**

[Lee, Oshikawa, **GYC***, Phys. Rev. Lett. 126, 186601 (2021)]

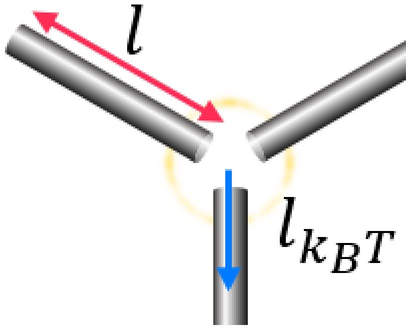
Quasi-1D: Plethora of Non-Fermi Liquids above T_X

[Lee, Oshikawa, **GYC***, Phys. Rev. Lett. 126, 186601 (2021)]

Dimensionally

1D & 0D systems

For $T > T_X$:



Luttinger Liquids

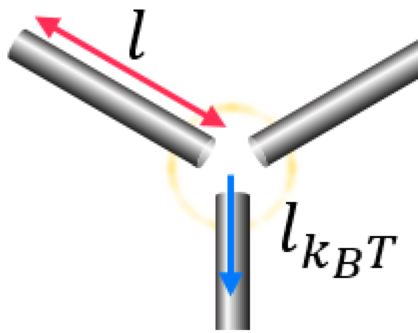
& Junctions

Quasi-1D: Plethora of Non-Fermi Liquids above T_X

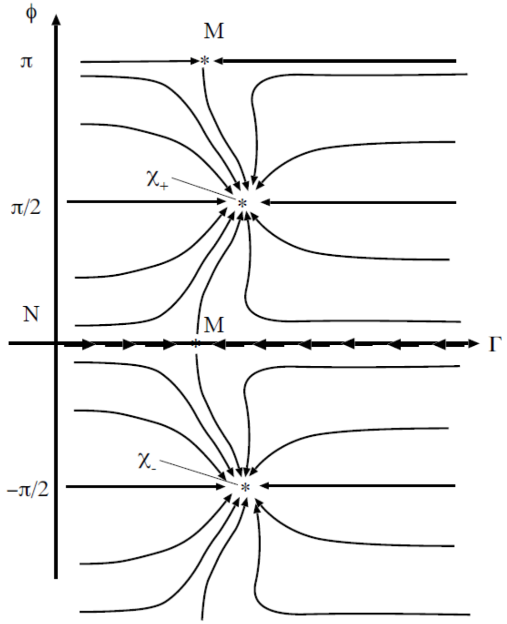
[Lee, Oshikawa, **GYC***, Phys. Rev. Lett. 126, 186601 (2021)]

Dimensionally 1D & 0D systems → **"Fixed Points" of an Y-junction** → **2D NFLs**

For $T > T_X$:



Luttinger Liquids & Junctions



[Oshikawa, Chamon, Affleck (2005)]

(1) Electric conductivity

$$g(T) \sim g_0 + c\, T^{\alpha(K)}$$

...where $\{g_0, \alpha(K)\}$ are *universal.*

- Classification is possible.

  (e.g. triangular ~ 220 types)

(2) Exotic states

- Emergent nematic phase
- Spin-charge separation

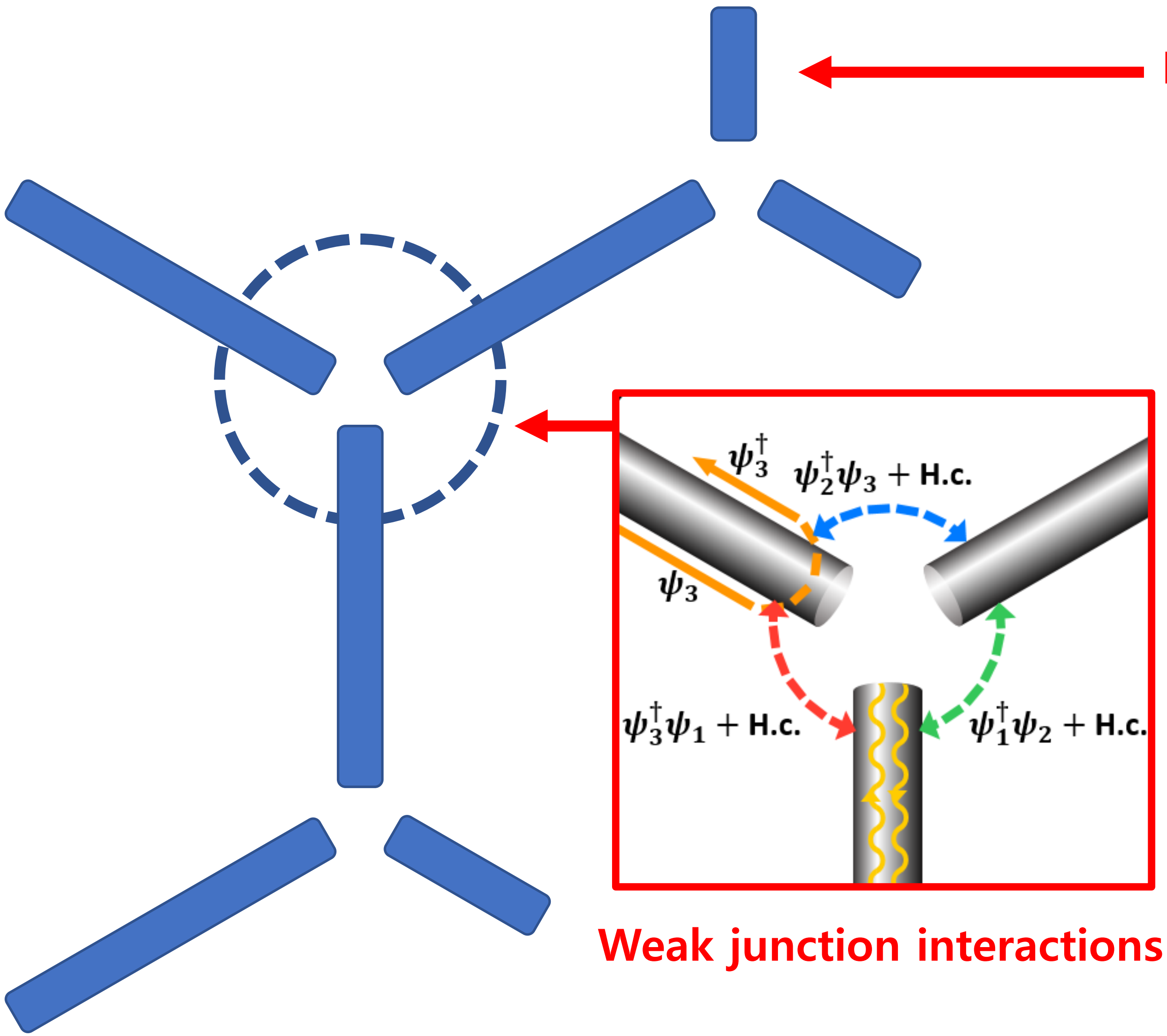
Toy Model: strange insulator phase

$$g(T) \approx g_0 + c\, T^{\alpha(K)}$$

$g_0 \to 0$, $\alpha(K) \to 2K - 2$

[Lee, Oshikawa, **GYC***, Phys. Rev. Lett. 126, 186601 (2021)]

Toy model: repulsive, spinless electrons



Luttinger liquid: $H = \frac{v}{2}\int dx \left[\frac{1}{K}(\partial_x\theta)^2 + K(\partial_x\phi)^2\right]$

(Luttinger parameter $K > 1$, repulsive)

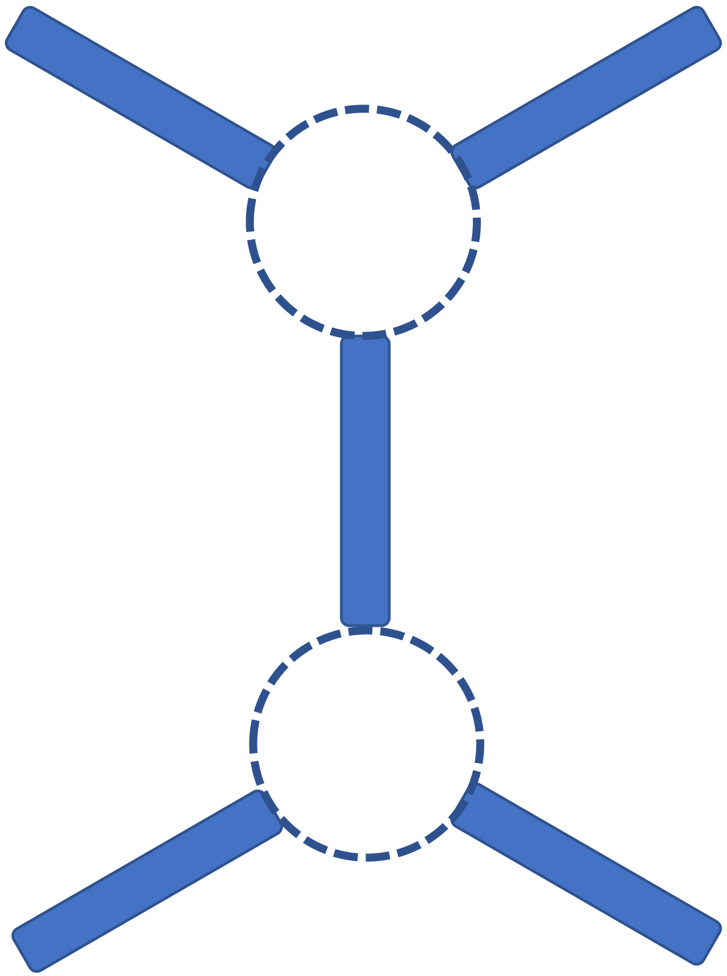
Weak junction interactions

Q. What would happen

if the temperature gets lowered?

A. System evolves along the RG flow.

Toy model: repulsive, spinless electrons



Decoupled fixed point emerges.

(**Cf.** it is also known as Neumann BC)

What do we expect out of this fixed point?

(1) Electrically insulating for $T > T_X$.

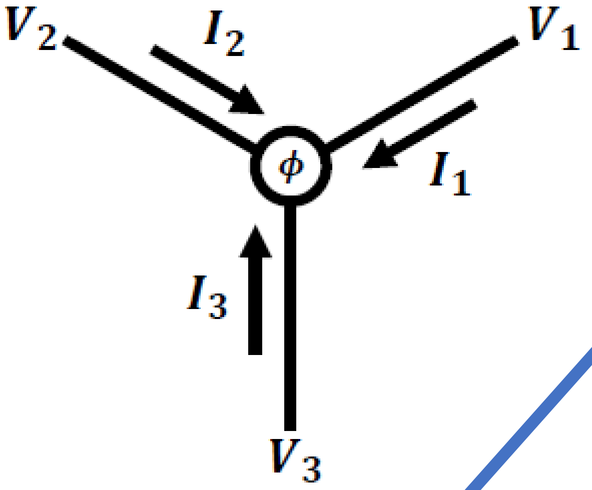
- Even the electron hopping is irrelevant (!)

(2) Thermodynamically metal

- Luttinger liquid excitations are *intact*.

Electric conductivity in temperature T?

Relating "microscopic" junction to "macroscopic" network



$$I_a = \sum_b G_{ab} V_b$$

Conductance of the junction

$$\begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix} = \begin{pmatrix} G_S & (G_A - G_S)/2 & -(G_A + G_S)/2 \\ -(G_A + G_S)/2 & G_S & (G_A - G_S)/2 \\ (G_A - G_S)/2 & -(G_A + G_S)/2 & G_S \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \\ V_3 \end{pmatrix}$$

Key observations:

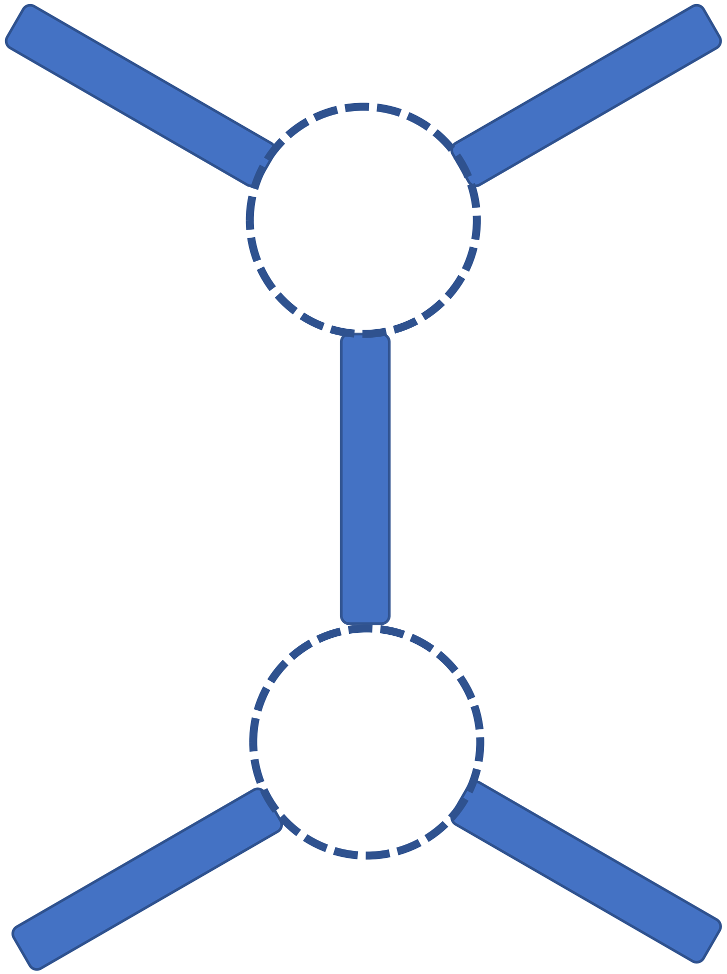
(1) G_s and G_A are **determined by the fixed point of the 0D junction**

(2) G_s and G_A determine **the 2D conductivity**:

$$g_{xx}(T) = \sqrt{3}\frac{G_s(T)}{4} \quad \& \quad g_{xy}(T) = \frac{G_A(T)}{4}$$

(g_{ab} = "macroscopic" data, $G_{S/A}$ = "microscopic" data)

Toy model: repulsive, spinless electrons



Decoupled fixed point emerges.

(**Cf.** it is also known as Neumann BC)

Perturbative expansions to the leading order are…

$$\mathbf{g}_{\mathbf{xx}}(\mathbf{T}) \approx \mathbf{0} + \frac{\sqrt{3}\pi e^2 t^2}{2h} \tau_c^{2K} \frac{\pi^{2K-1}\,\Gamma\left(\frac{1}{2}\right)\Gamma(K)}{\Gamma\left(\frac{1}{2}-K\right)} \boldsymbol{T^{2K-2}}$$

(for $K > 1$)

$$\mathbf{g}_{\mathbf{xy}}(\mathbf{T}) \approx \mathbf{0} + \boldsymbol{O}\left(\boldsymbol{T^{2K-2}}\right)$$

Determined by the *leading irrelevant operator* at the fixed point

(universal data of the fixed point)

For this "decoupled" fixed point, $\boldsymbol{\Delta} = \boldsymbol{K}$ ⇒ $\boldsymbol{\delta g} \sim \boldsymbol{T^{2\Delta-2}}$

Toy model: repulsive, spinless electrons

Locally critical umklapp scattering and holography

(AdS/CFT duality)

Sean A. Hartnoll[♭] and Diego M. Hofman[♯]

Abstract

Efficient momentum relaxation through umklapp scattering, leading to a power law in temperature d.c. resistivity, requires a significant low energy spectral weight at finite momentum. One way to achieve this is via a Fermi surface structure, leading to the well-known relaxation rate $\Gamma \sim T^2$. We observe that local criticality, in which energies scale but momenta do not, provides a distinct route to efficient umklapp scattering. We show that umklapp scattering by an ionic lattice in a locally critical theory leads to $\Gamma \sim T^{2\Delta_{k_L}}$. Here $\Delta_{k_L} \geq 0$ is the dimension of the (irrelevant or marginal) charge density operator $J^t(\omega, k_L)$ in the locally critical theory, at the lattice momentum k_L. We illustrate this result with an explicit computation in locally critical theories described holographically via Einstein-Maxwell theory in Anti-de Sitter spacetime. We furthermore show that scattering by random impurities in these locally critical theories gives a universal $\Gamma \sim (\log \frac{1}{T})^{-1}$.

$$R(T) \sim \frac{1}{T^{2\Delta}}$$

We have achieved a microscopic model of strange insulator behaviors!

Experiment in graphene ?

ARTICLE

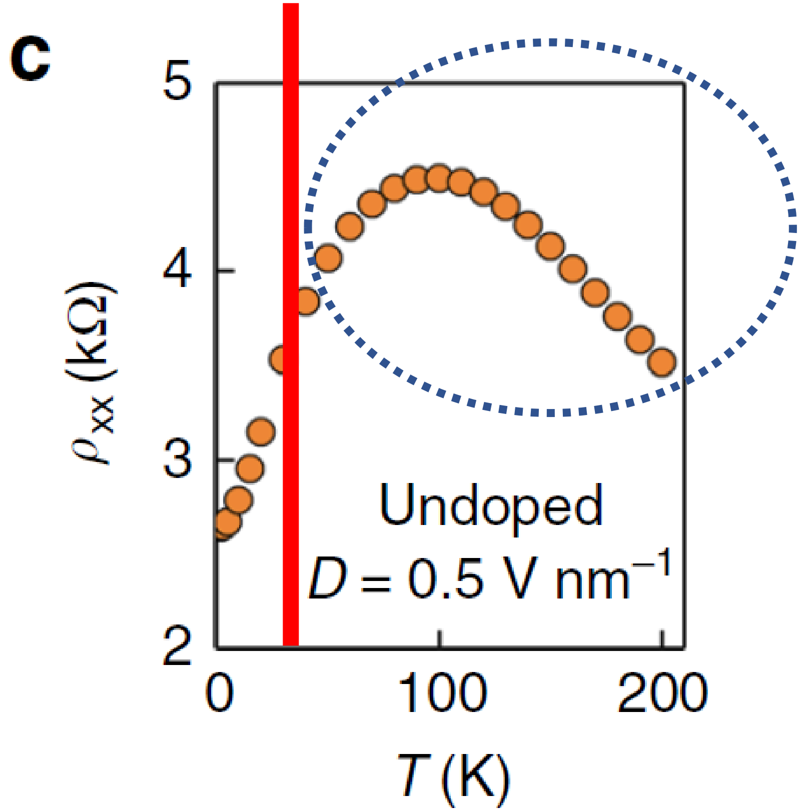
https://doi.org/10.1038/s41467-019-11971-7 OPEN

Giant oscillations in a triangular network of one-dimensional states in marginally twisted graphene

S.G. Xu[1,2,5], A.I. Berdyugin[1,5], P. Kumaravadivel[1,2], F. Guinea[1], R. Krishna Kumar[1,2], D.A. Bandurin[1], S.V. Morozov[3], W. Kuang[1], B. Tsim[1,2], S. Liu[4], J.H. Edgar[4], I.V. Grigorieva[1], V.I. Fal'ko[1,2], M. Kim[1] & A.K. Geim[1,2]

(**cf.** Phonon effects)

$T_X \sim 50K$ (for 140 nm)



Hopefully to see this in the future experiments

Remark:

In all cases, we find:

Power-law correction in temperature T

(fixed by the leading irrelevant operator)

$$g(T) \approx \mathbf{g_0} + c\, T^{\boldsymbol{\alpha(K)}}$$

Universal conductance of the junction

(determined by the junction BCs)

"K" **is the *exactly marginal parameter*.**

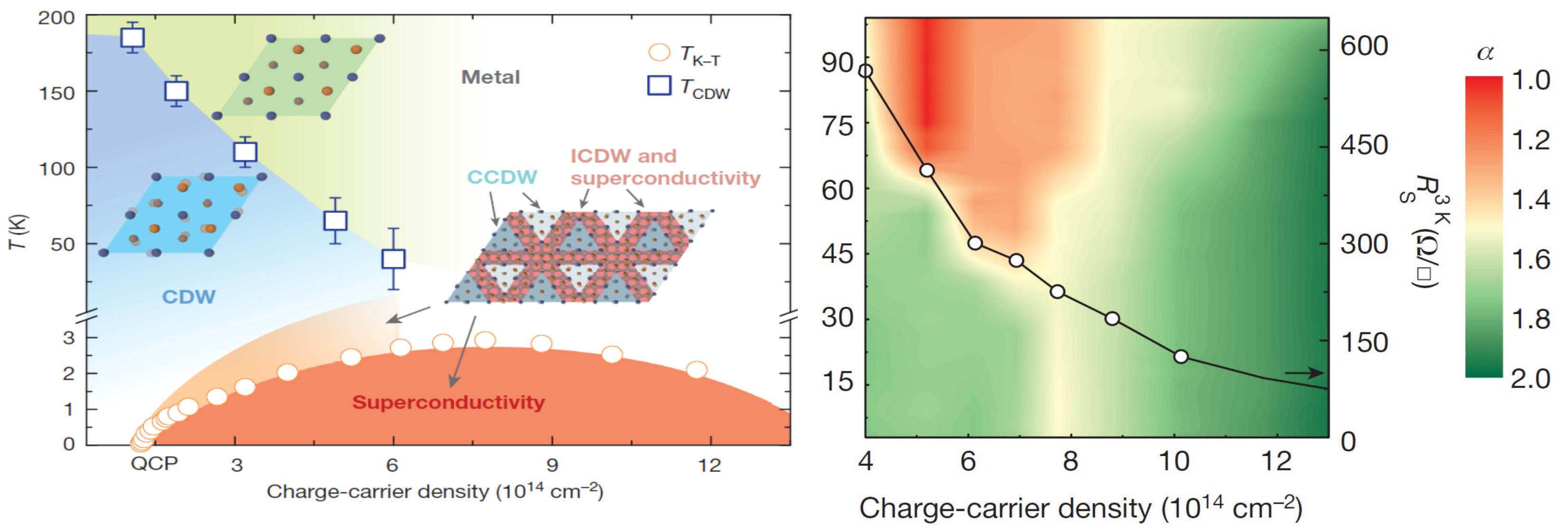
This will *continuously evolve* when experimental parameters,

e.g., gating or pressure, are changed.

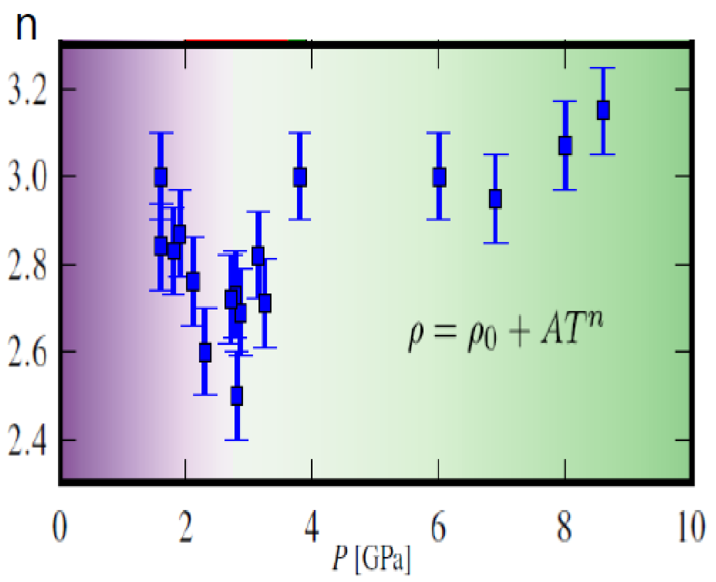
This is markedly different from a regular 2D Fermi liquid!

[Lee, Oshikawa, **GYC***, Phys. Rev. Lett. 126, 186601 (2021)]

Strongly Reminiscent of Experiments...



[Ref. Li et.al., Nat. (2016)]



[Ref. Kusmartseva et. al. PRL (2009)]

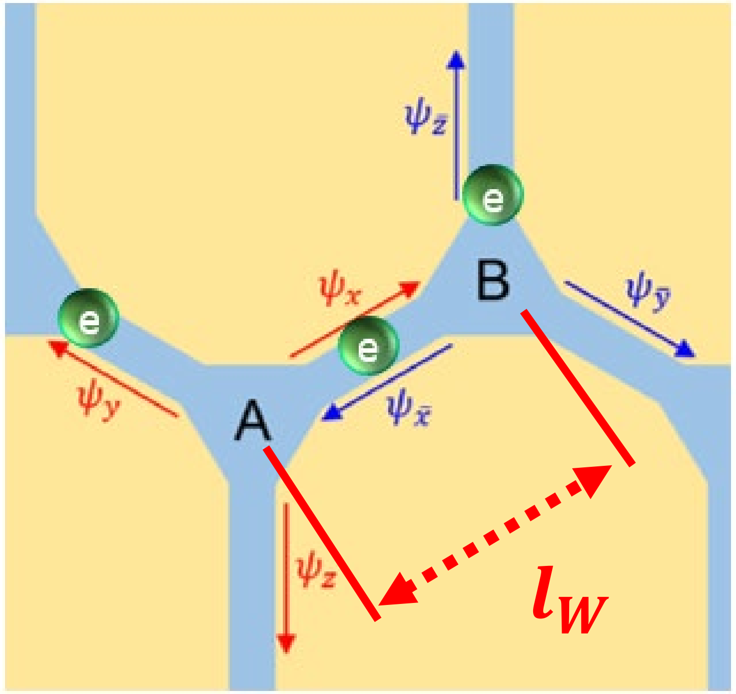
1. Non-Fermi Transport $R \sim R_0 + A\,T^n$, varying exponent $n \approx 1{\sim}3$

2. Emerging superconductivity, and domain wall networks (Little-Park effect)

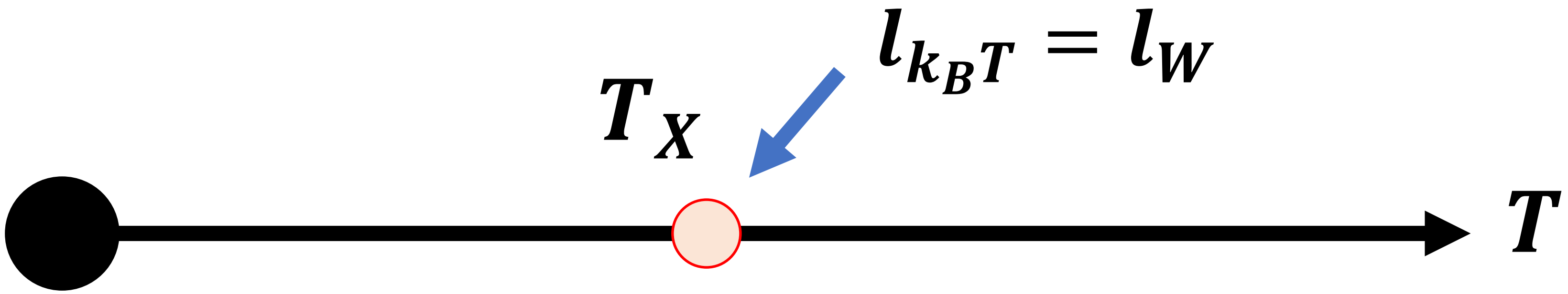
Correlation effect seems important in these materials!

Conclusions

Key observation: Dimensional Crossover T_X



Relatively *easier* problem.



2d Physics $(l_{k_B T} > l_W)$

[Lee, Geng, … **GYC**, PRL (2020)]

1d Physics $(l_{k_B T} < l_W)$

[Lee, Oshikawa, **GYC,** PRL (2021)]

- **Cascades of stable flat bands**
- **Superconducting instabilities & experimental implications**
- **Higher-order topology & STM experiments**
- **Non-Fermi liquids (high-*T* regime)**

If there's *1 min*…

Steady non-equilibrium quantum states:

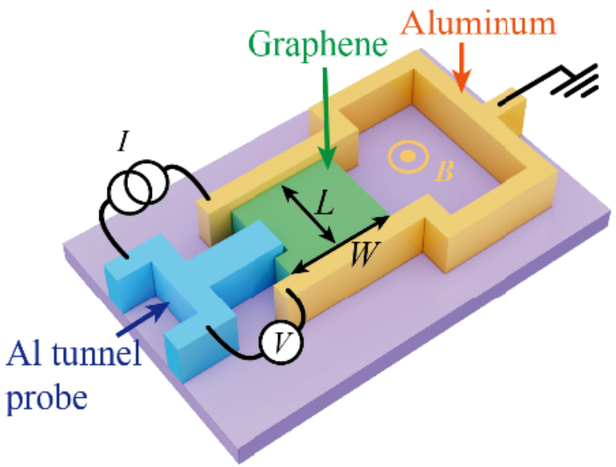
Article

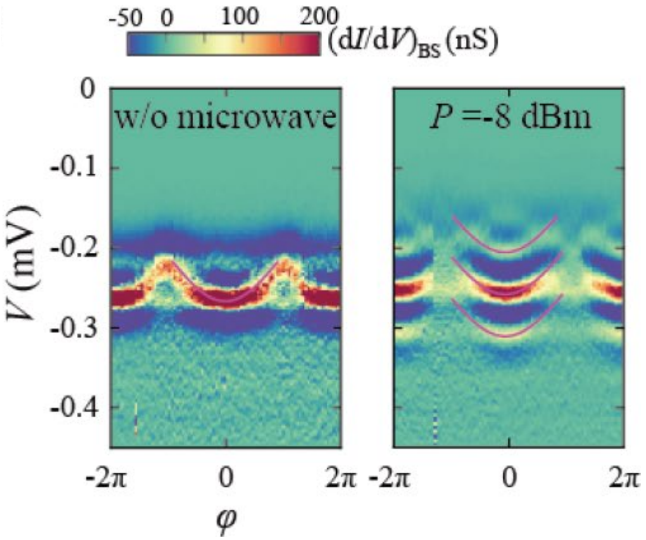
Steady Floquet–Andreev states in graphene Josephson junctions

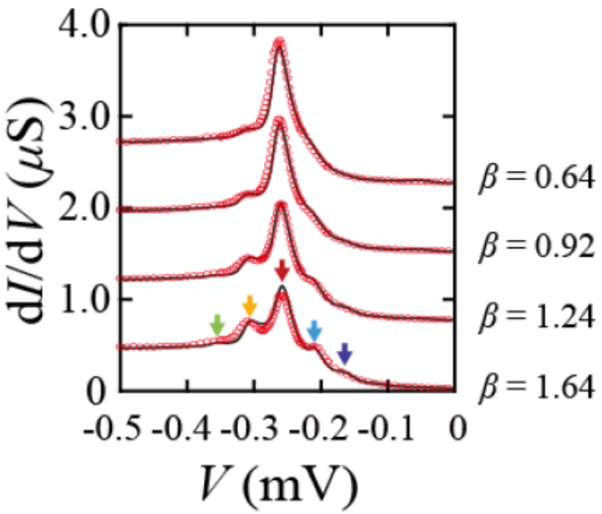
$\sim O(10^{17})$ **longer life time than previous pulse-generated Floquet states**

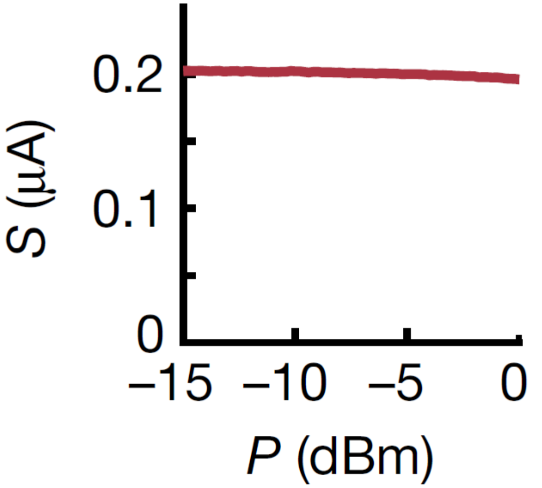
> 25 hr

~250 ps









Upshot: graphene + continuous irradiation of microwaves = steady Floquet states

$$\beta = e v_F\,|\vec{E}|/\hbar\omega$$

Diagnostics of *steady* states: spectral sum rules

[Park, Lee, (…), **GYC,** Lee, Nature (2022)]

THANK YOU!