Superconductivity from skyrmion condensation in magic angle graphene

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Random Interactions Seminar

Tata Institute of Fundamental Research

November 16, 2020

In collaboration with:

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Harvard

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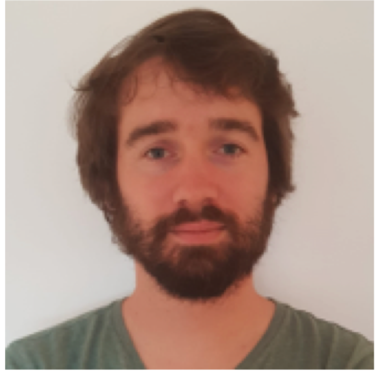
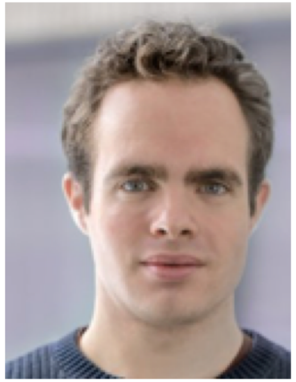
Stanford



Nick Bultinck
UC Berkeley



Mike Zaletel
UC Berkeley

SC, N. Bultinck, M. P. Zaletel, PRB **101**, 165141 (2020)

N. Bultinck[*], E. Khalaf[*], S. Liu, SC, A. Vishwanath, M. P. Zaletel, PRX **10**, 031034 (2020)

E. Khalaf[*], SC[*], N. Bultinck, M. P. Zaletel, A. Vishwanath, arXiv:2004.00638

SC, M. Ippoliti, M. P. Zaletel, arXiv:2010:01144

Magic angle graphene

- Bilayer graphene with a relative twist angle ***θ***
- Nearly flat bands close to the *magic angle* ***θ*** ~ 1.09°

Bistritzer, MacDonald, PNAS 2011

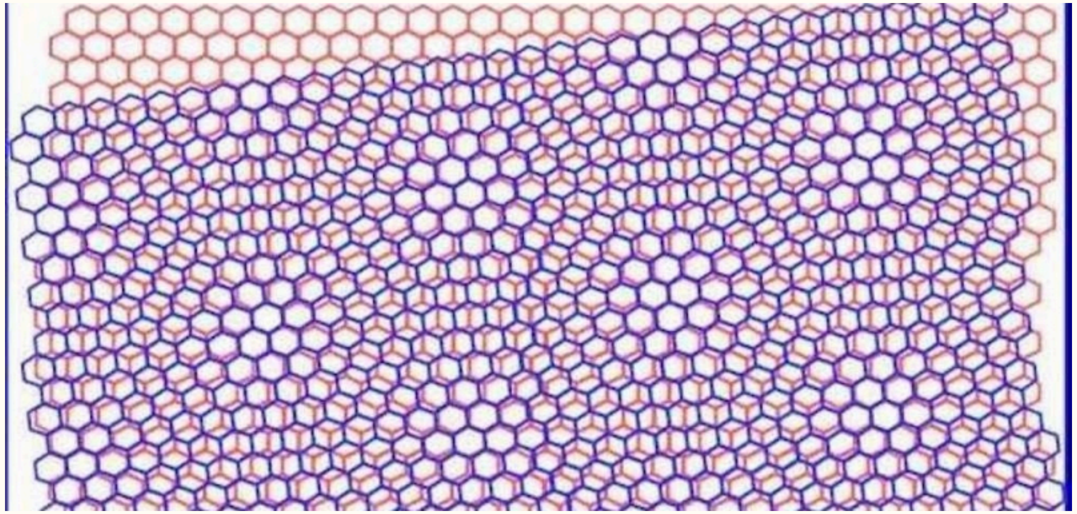
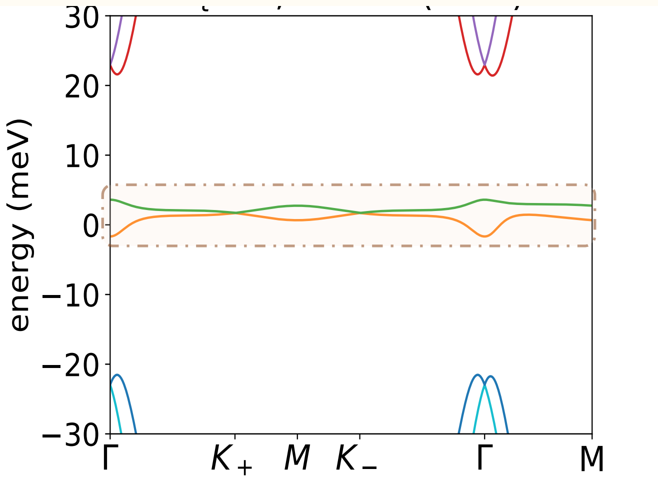


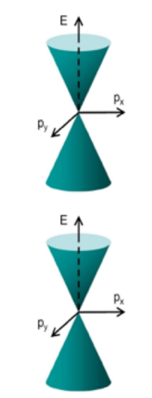
Figure: UPI.com

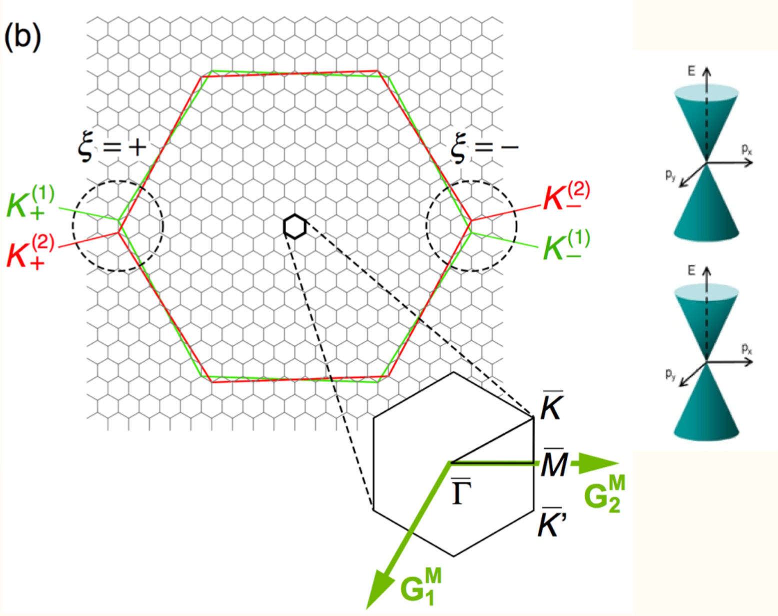
Magic angle graphene

- 8 *active* low-energy bands (2 layer, 2 valley, 2 spin)
- Inversion C_{2z} and time-reversal T protects Dirac cones

Po *et al*, PRX 2018





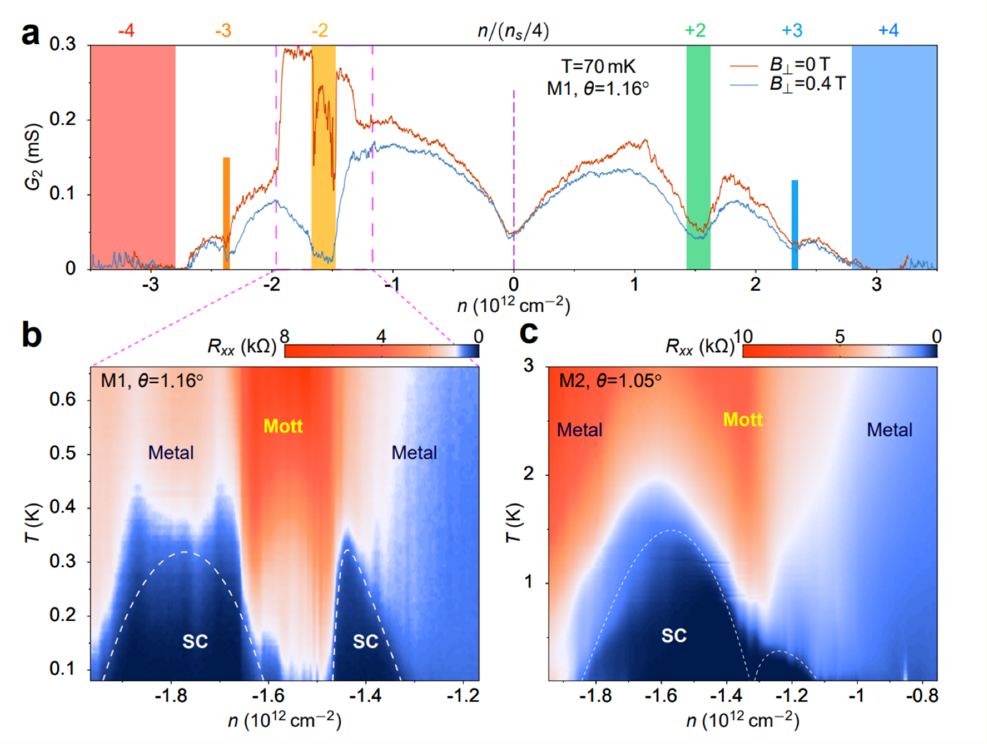


Related work: Yuan *et al*, Koshino *et al,* Isobe *et al*, Zou *et al*, Kang *et al*, lots of others…

Figure: Koshino *et al*, PRX 2018

Magic angle graphene

- Correlated insulators at integer fillings of Moire unit cells
- Superconductivity on doping away from these insulators



Cao *et al*, Nature² (2018), Lu *et al*, Nature (2019), Yankowitz *et al*, Science (2019), Choi *et al* , N. Physics (2019), Jiang *et al*, Nature (2019), Several others…

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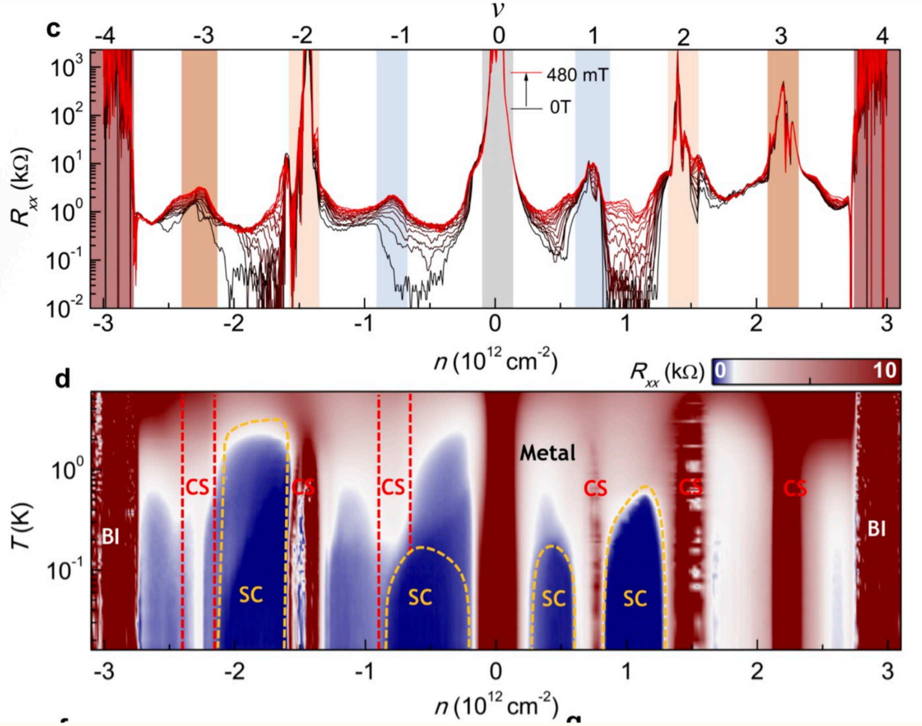
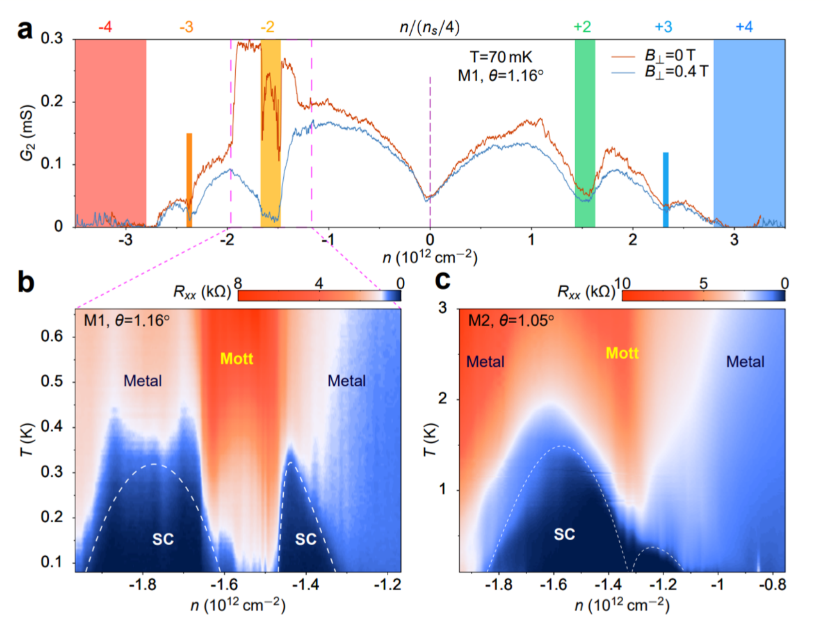


Cao *et al,* Nature[2] (2018), Lu *et al,* Nature (2019), Yankowitz *et al*, Science (2019), Choi *et al* , N. Physics (2019), Jiang *et al*, Nature (2019), Several others…

Magic angle graphene

- What is the nature of the correlated insulators?
  What is the nature and mechanism of superconductivity?

- This talk: Offer a possible intuitive answer to these questions at even integer fillings + back up with DMRG numerics on related model



Cao *et al*, Nature[2] (2018), Lu *et al*, Nature (2019), Yankowitz *et al*, Science (2019), Choi *et al* , N. Physics (2019), Jiang *et al*, Nature (2019), Several others…

Outline

- Landau Level picture of MAG
- Charged excitations and pairing
- DMRG evidence of superconductivity
- Conclusions and outlook

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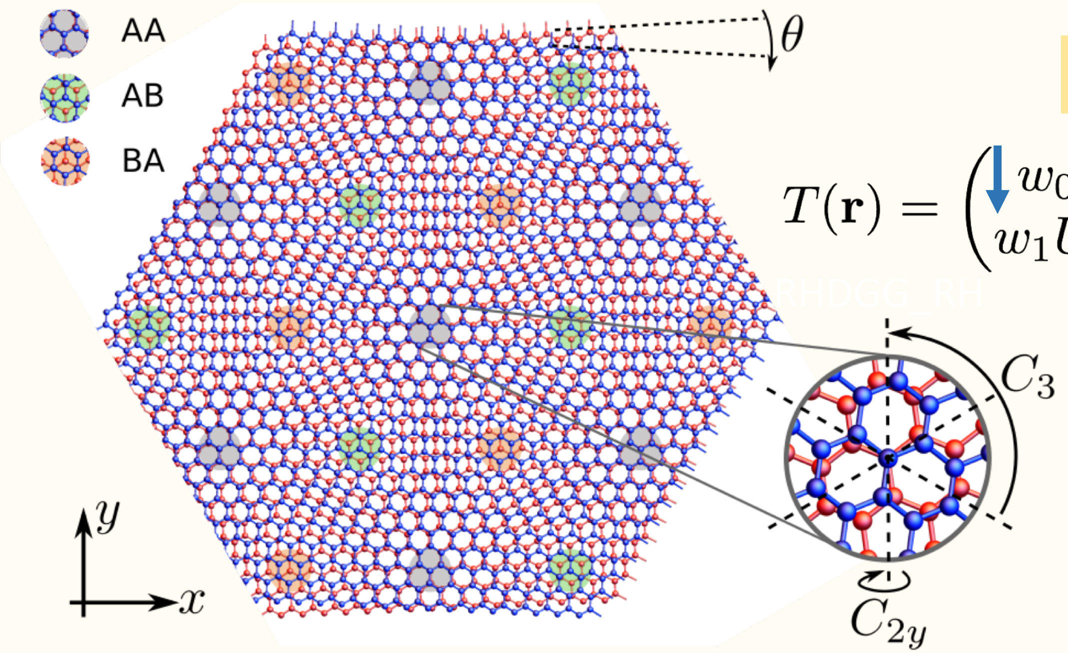
Landau level picture of MAG

- Approach from a quantum Hall perspective: the chiral limit



$$T(\mathbf{r}) = \begin{pmatrix} w_0 U_0(\mathbf{r}) & w_1 U_1(\mathbf{r}) \\ w_1 U^*(-\mathbf{r}) & w_0 U_0(\mathbf{r}) \end{pmatrix}$$

A_1 B_1 A_2 B_2

w_0/w_1 goes down due to lattice relaxation

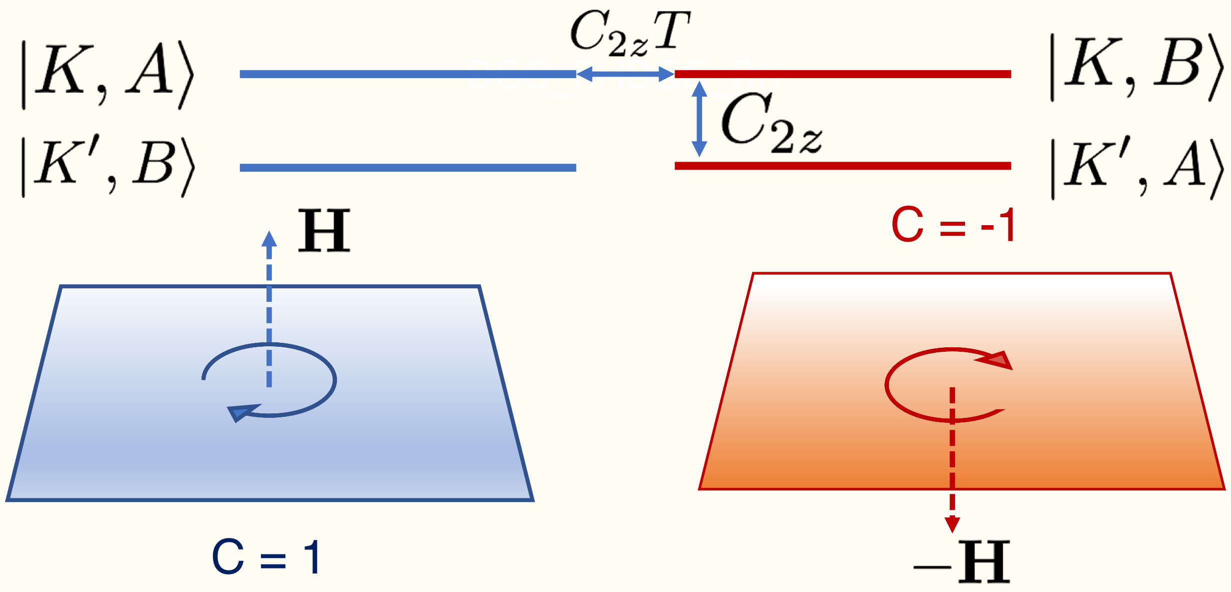
Bistritzer, MacDonald PNAS (2011),

Landau level picture of MAG

- Chiral limit (turn off w_0 = AA hopping between layers): Additional chiral symmetry allows for sublattice and valley polarized basis

  Jose et al, PRL (2012), Tarnopolsky *et al*, PRL (2019), J. Liu *et al,* PRB (2019)

- Exactly flat Chern bands: each band behaves like a lowest Landau level, but different bands see opposite effective magnetic fields



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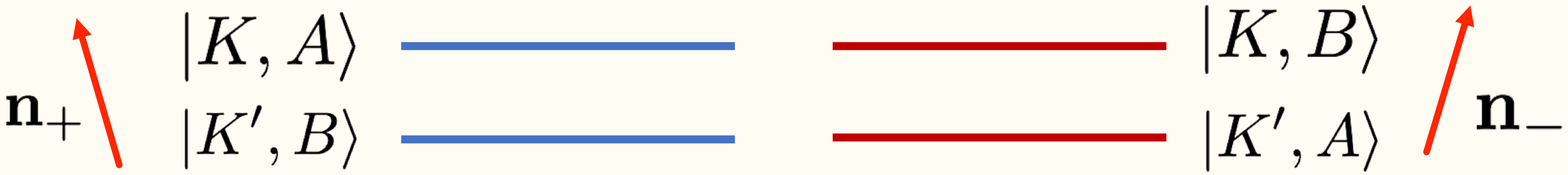
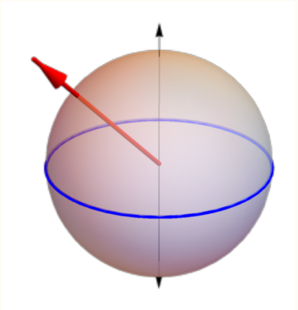


Interaction-driven ferromagnet in each Chern-sector or *layer,* as expected from Stoner criteria



Landau level picture of MAG

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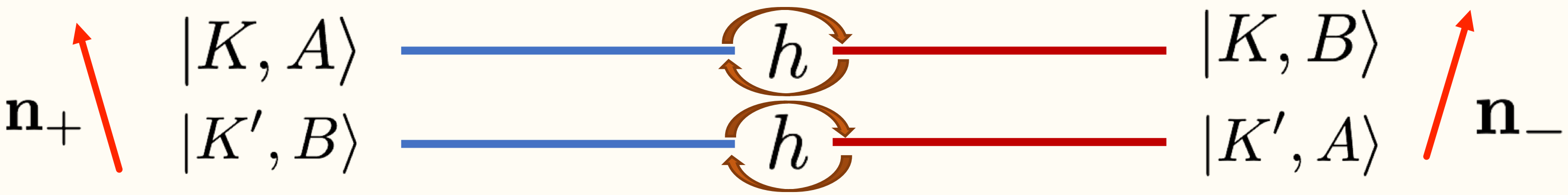
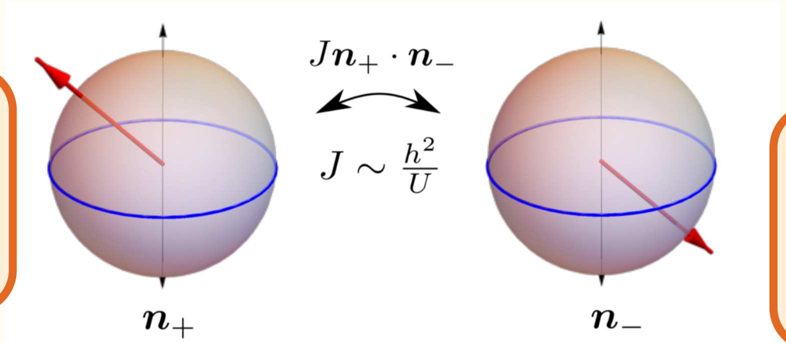


Bultinck, Khalaf, SC *et al*, PRX (2020)

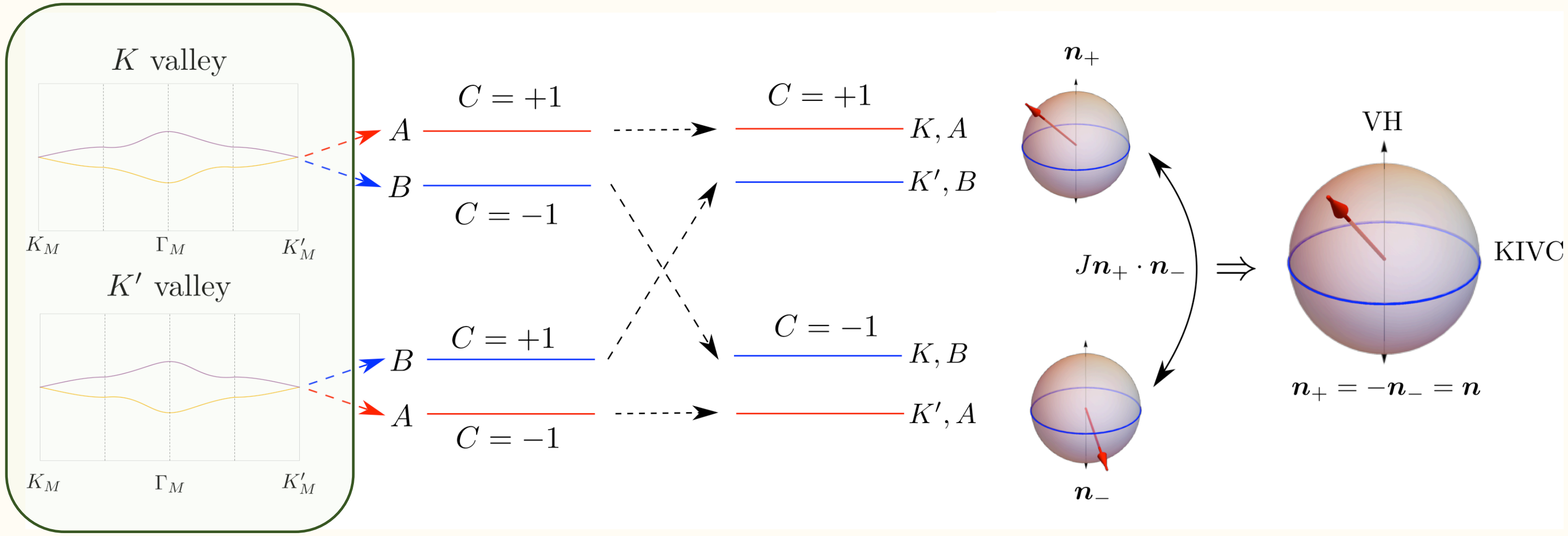
Ferromagnet in each Chern-sector or *layer*



Ground state: easy-plane AF or KIVC

Landau level picture of MAG

Schematic overview



MAG flat bands → Chiral limit

Chern bands

FM in each Chern sector

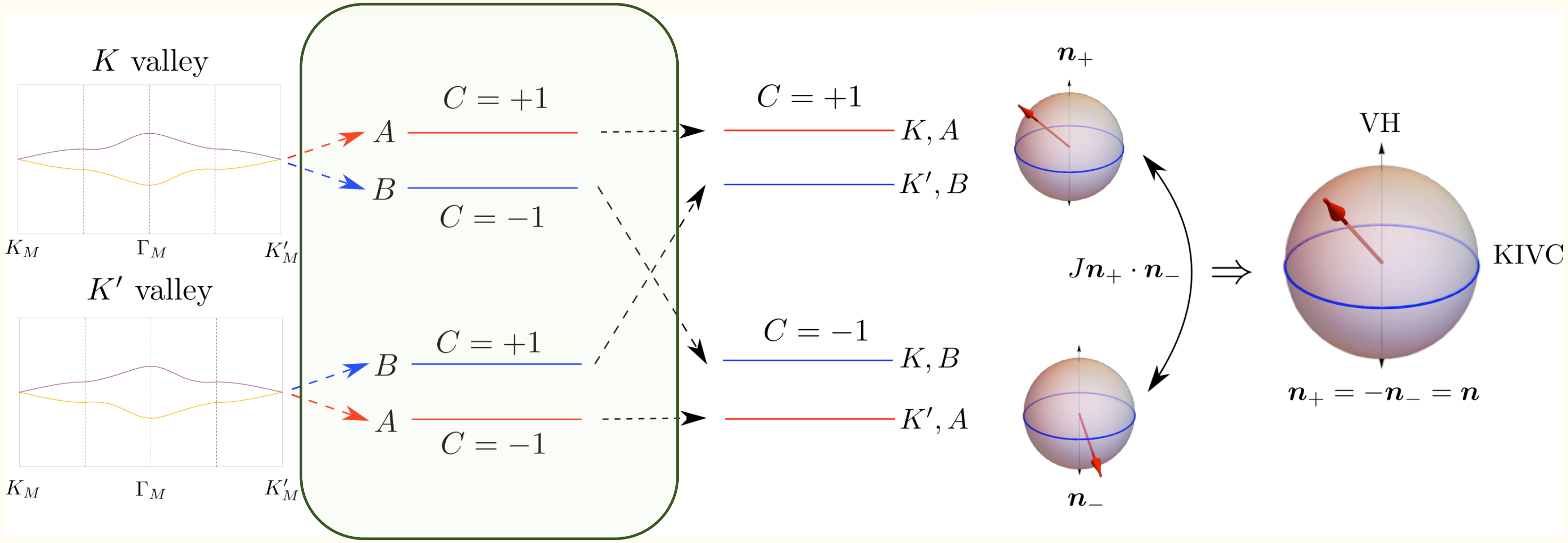
Dispersion → AF superexchange

Bultinck, Khalaf, SC *et al*, PRX (2020)

Ground state: easy-plane AF or KIVC

Landau level picture of MAG

Schematic overview



MAG flat bands

Chiral limit → Chern bands

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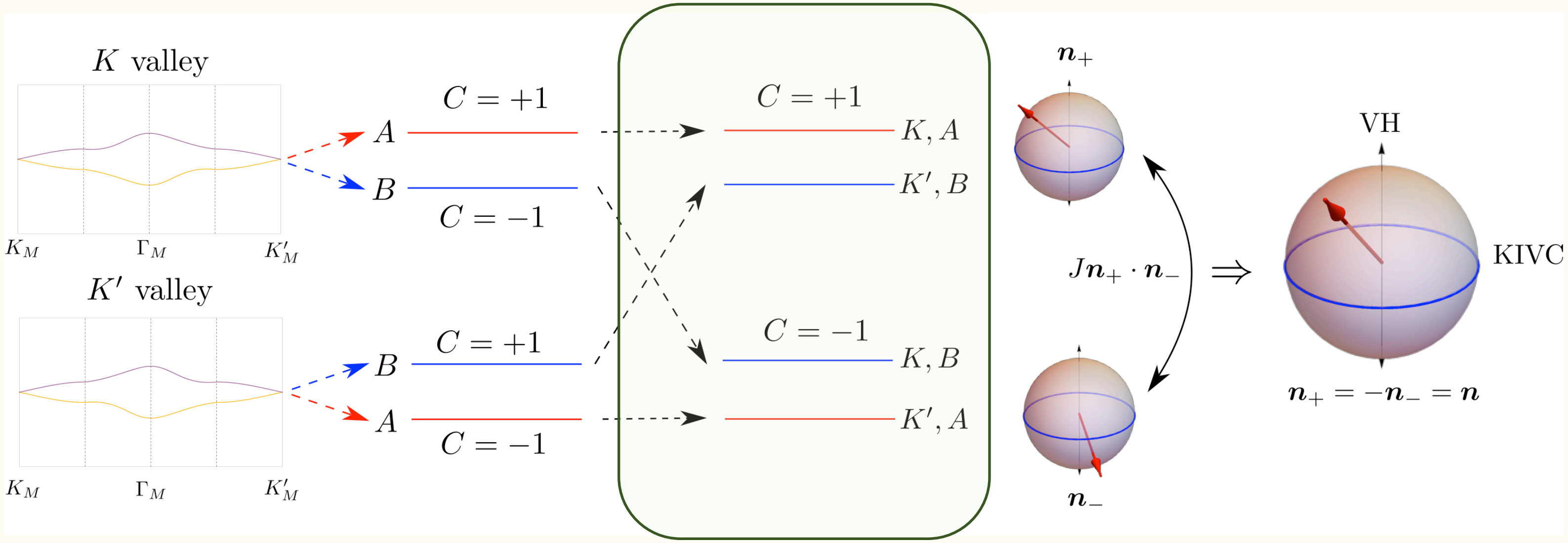

MAG flat bands

Chiral limit

Chern bands → FM in each Chern sector

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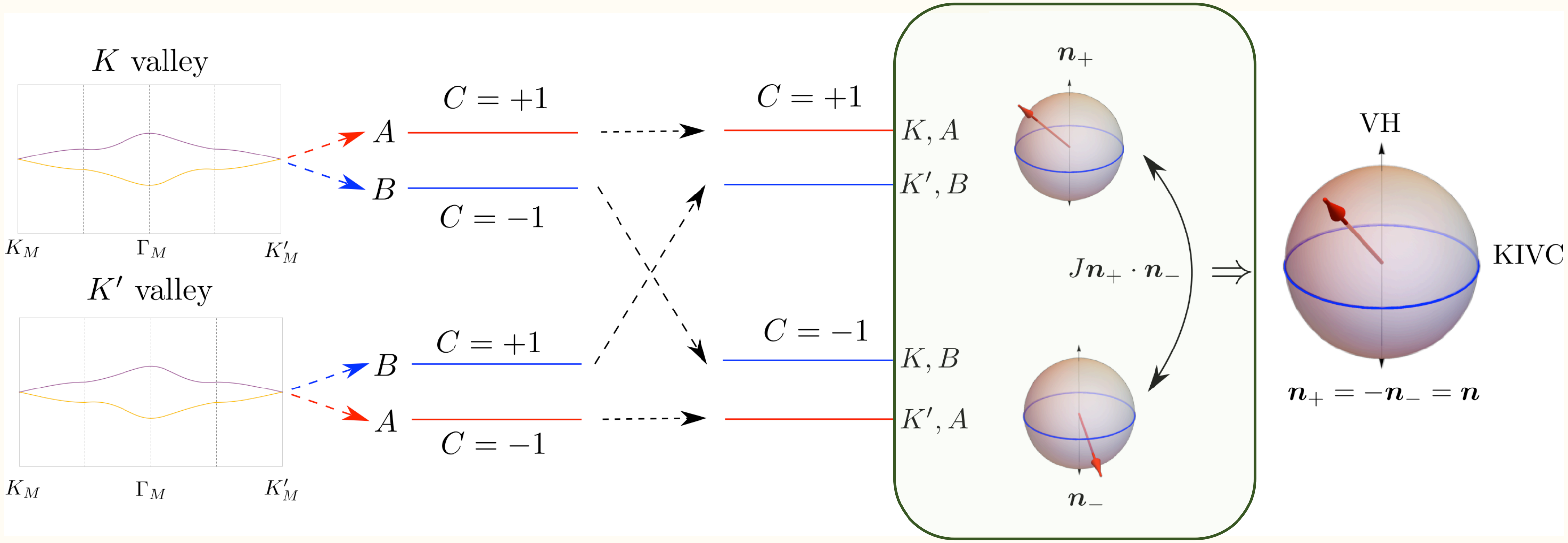

MAG flat bands

Chiral limit

Chern bands

FM in each Chern sector → Dispersion → AF superexchange

Bultinck, Khalaf, SC *et al*, PRX (2020)

Ground state: easy-plane AF or KIVC

Landau level picture of MAG

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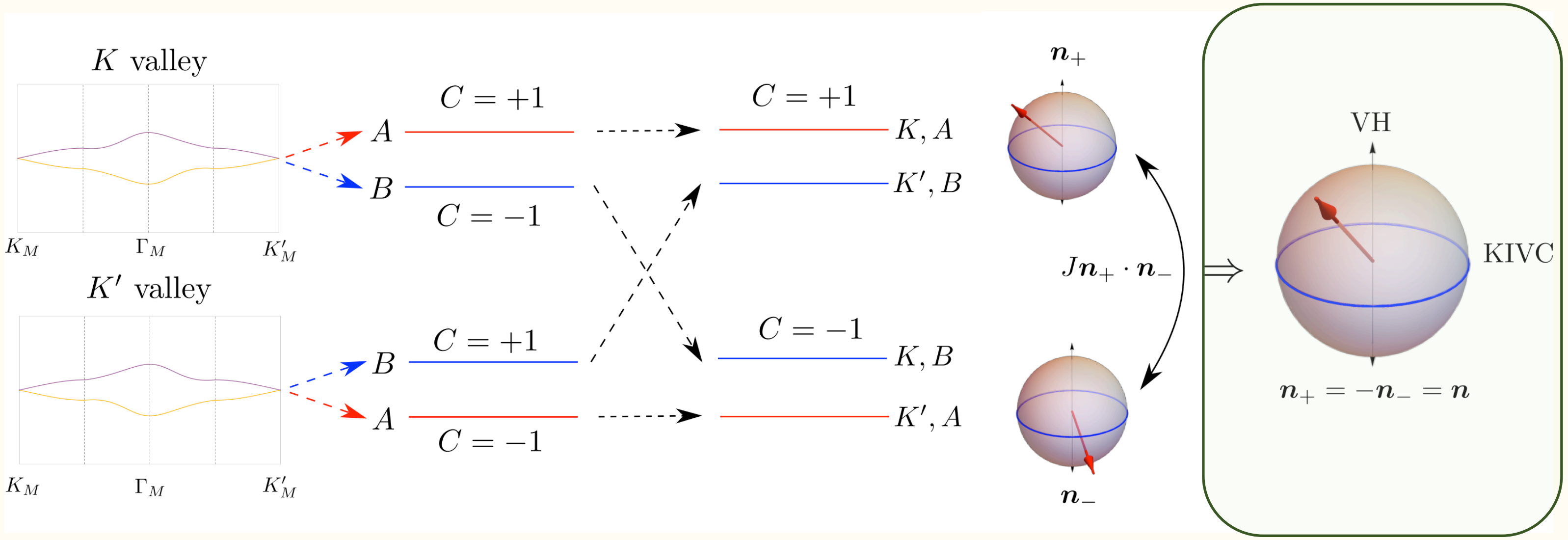

MAG flat bands

Chiral limit

Chern bands

FM in each Chern sector

Dispersion → AF superexchange

↓

Ground state: easy-plane AF or KIVC

Bultinck, Khalaf, SC *et al*, PRX (2020)

Outline

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- Conclusions and outlook

Charged excitations and pairing

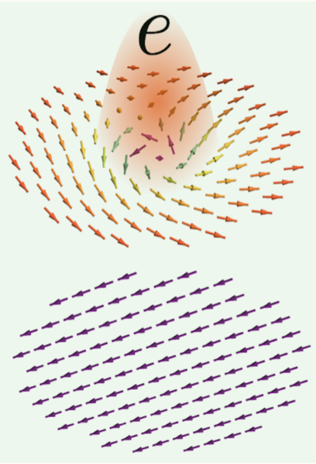
- In addition to particle-hole excitations, have topological textures: skyrmions in each *layer* carry charge

Sondhi *et al*, PRL (1993)
Moon *et al*, PRB (1994)

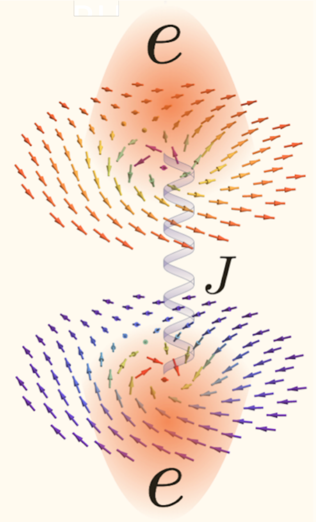
$$Q_{physical} = CQ_{topological}$$

- Consider two positive charges in opposite QH *layers*: Repelled by Coulomb but attracted by local antiferromagnetism J
- *All electronic pairing mechanism* without phonons/ retardation

Related work: Grover, Senthil, PRL 2008
Wang *et al*, arXiv: 2006.13239



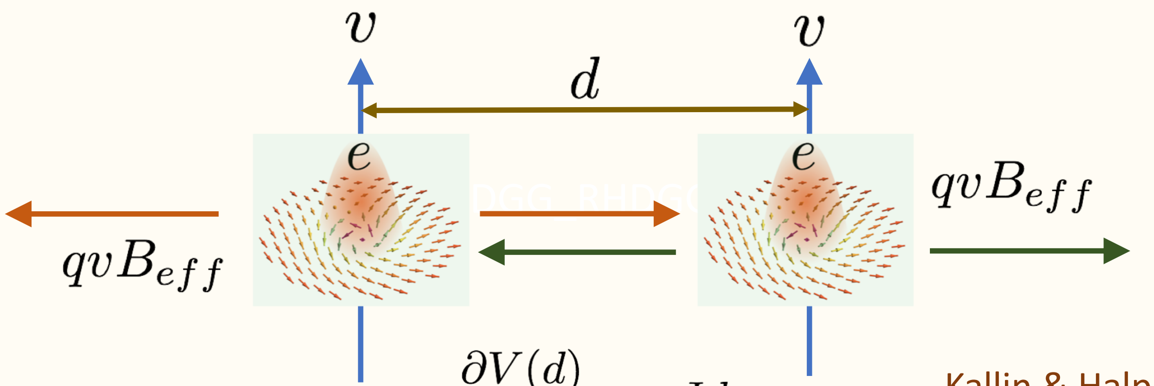
Single skyrmion pays a large exchange penalty



Sk-Ask pair can spread out to minimize Coulomb without losing exchange

Charged excitations and pairing

- For charge e textures, kinetic energy quenched by magnetic field
- Charge 2e skyrmion with charge e in each layer sees *no net magnetic field* , can therefore be mobile



$$\frac{\partial V(d)}{\partial d} = aJd$$

Kallin & Halperin, PRB (1984)
K. Yang, PRL (2001)

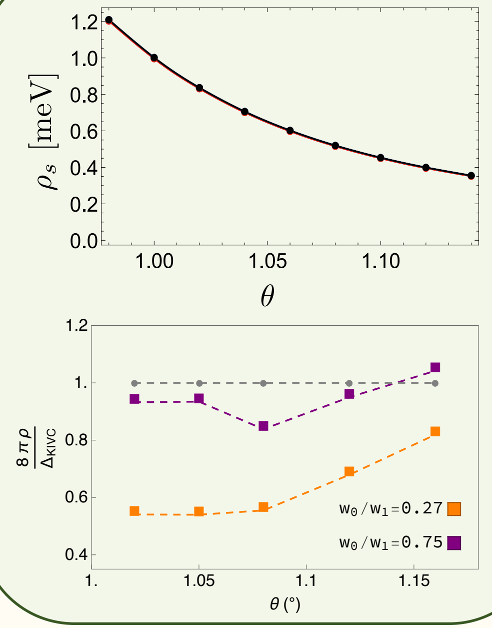
$$E = V_0 + aJd^2/2 = V_0 + \frac{(qB_{eff})^2}{2aJ} v^2$$

$T_c \sim 1/M_{pair} \sim J \sim 1$ K in MAG

Khalaf, SC *et al*, arXiv:2004.00638

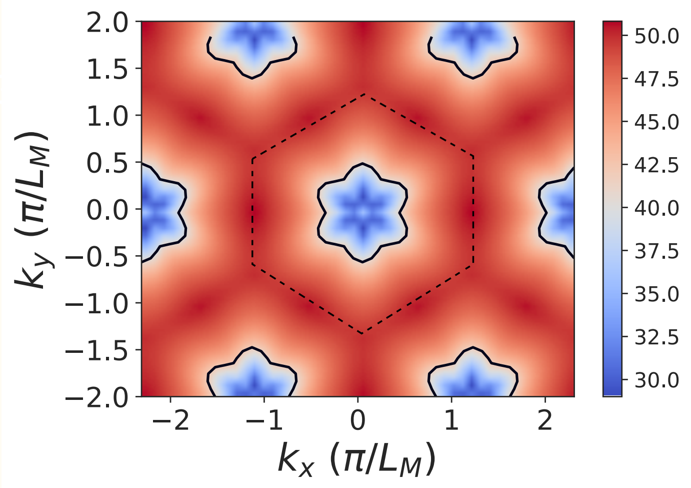
Charged excitations and pairing

- Are skyrmions energetically relevant to MAG?
- Need stiffness to be small



Δ_{KIVC} = gap from HF numerics

Small critical doping beyond which charges enter as 2e skyrmions

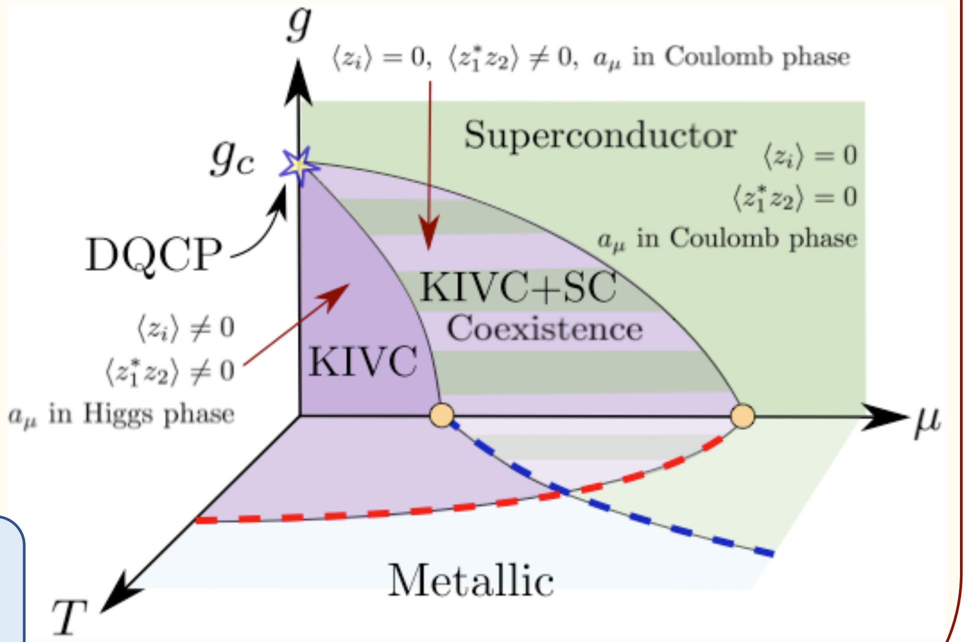


Khalaf, SC *et al*, arXiv:2004.00638

Charged excitations and pairing

- CP^1 formulation: $\mathbf{n} = z^\dagger \boldsymbol{\eta} z$, introduces gauge field a_μ (phase of spinor z)
- Charge density ∝ curl(**a**)
- KIVC phase: z_i condensed, vortices in a_μ (charges) disallowed: Insulating phase
- Chemical potential acts act magnetic field, nucleates vortices in **n** (2e skyrmions): coexistence phase

Doped phase diagram

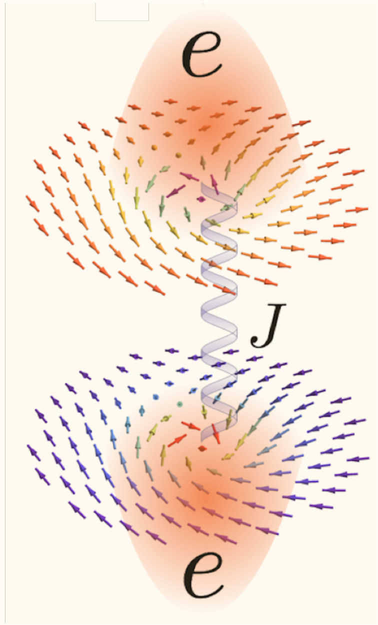


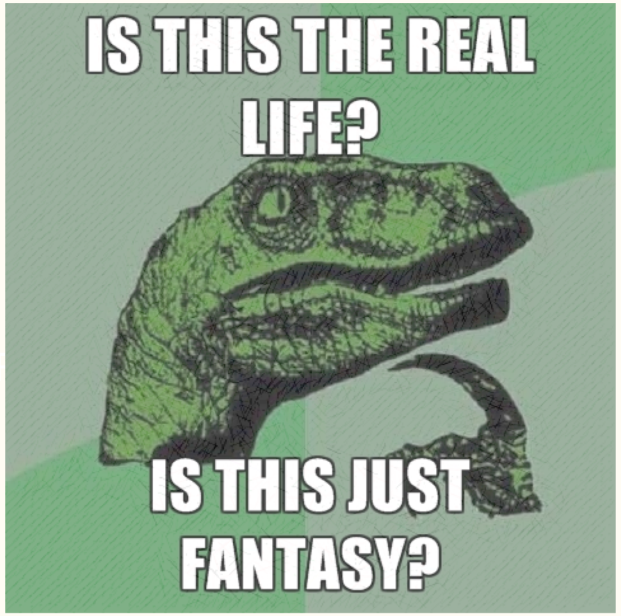
PH transformation in one Chern sector shows KIVC and SC are dual (like AFM and SC in high T_c cuprates)

Khalaf, SC *et al*, arXiv:2004.00638

Charged excitations and pairing

Skyrmion pairing superconductivity





Quote: Queen, Figure credits: http://creatememe.chucklesnetwork.com/memes/16712

Outline

- Landau level picture of MAG
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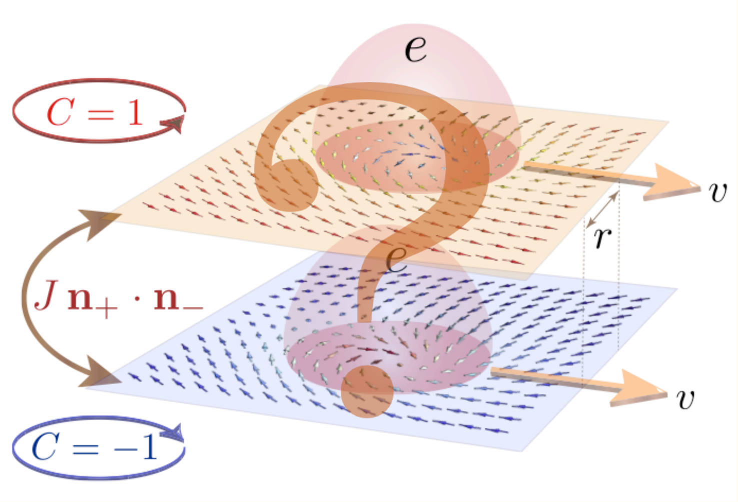
- DMRG evidence of superconductivity
- Conclusions and outlook

DMRG evidence for superconductivity

- Essential ingredients:

1. Spinful (nearly) flat bands with opposite Chern number ± 1
2. AF interaction between the Chern sectors, in addition to Coulomb repulsion



- Test: AF couple spinful lowest Landau levels, amenable to DMRG

Zaletel *et al*, PRL (2013)

DMRG evidence for superconductivity

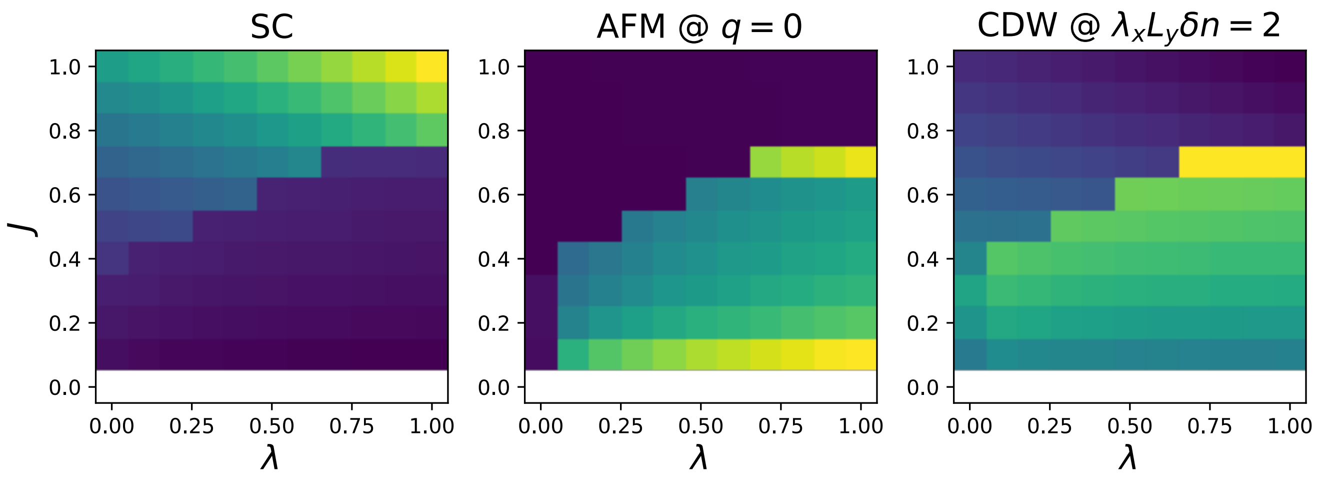
- iDMRG for coupled Landau level model on a cylinder (L_y = 8-12 ℓ_B)

Ippoliti *et al*, PRB (2018)

$$H = \psi^\dagger \frac{(\mathbf{p} + e\gamma^z \mathbf{A})^2}{2m} \psi + \frac{1}{2} \int : n(r) V_C(r - r') n(r') : - E_C \ell_B^2 \sum_{i=x,y,z} J_i : \left(\psi^\dagger \gamma^z \eta^i \psi(r)\right)^2 :$$

$$J_x = J_y = J + \lambda, J_z = J - \lambda$$

Phase diagram at doping 2 + 1/4

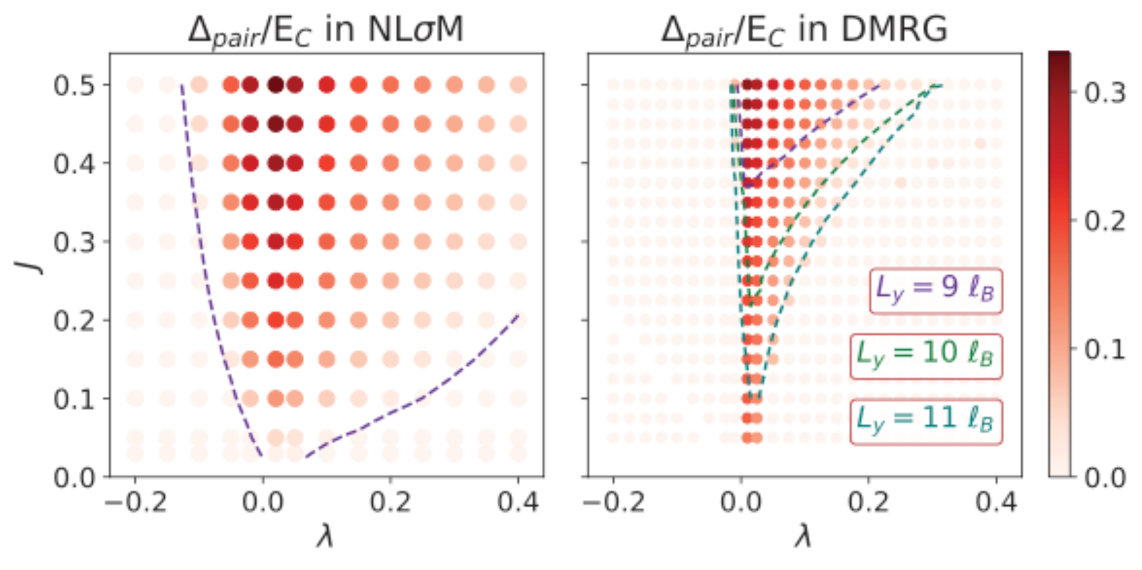


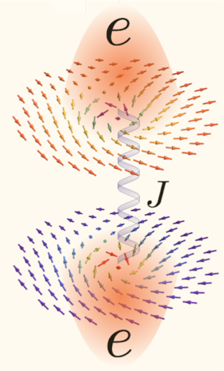
Related work: Kang and Vafek, Soejima, Parker *et al* (2020)

DMRG evidence for superconductivity

- Segment DMRG to determine energy of charged excitations

$$\Delta_{pair} = 2\ E_{1e} - E_{2e}$$

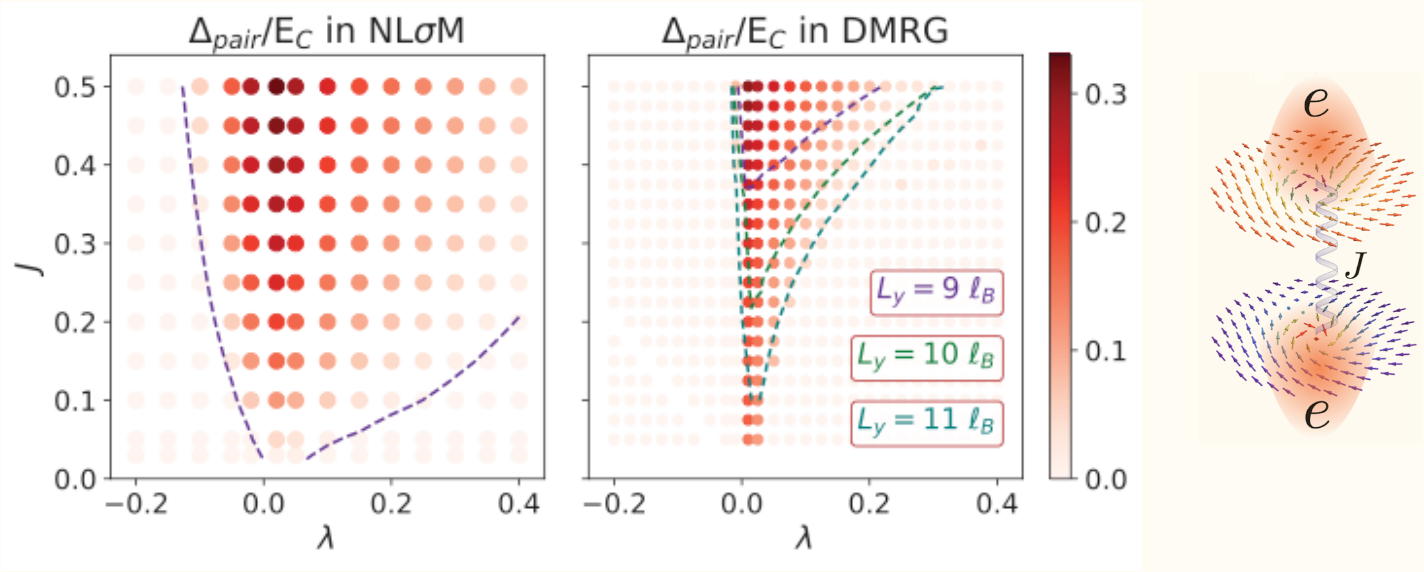




- Numerics for quantum system confirm classical expectations!

DMRG evidence for superconductivity

- Critical $J_*(\lambda) \to 0$ as $\lambda \to 0$, indicative of collective pairing mechanism
- Pairing is much more favorable in the easy plane case (good for MAG!)



- Good qualitative agreement between quantum and classical numerics

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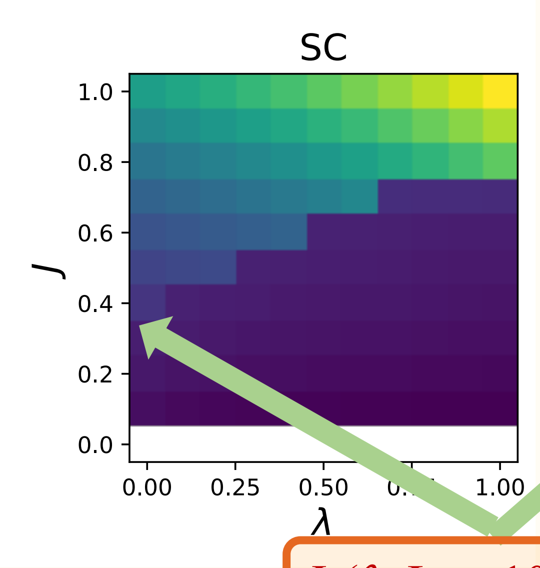

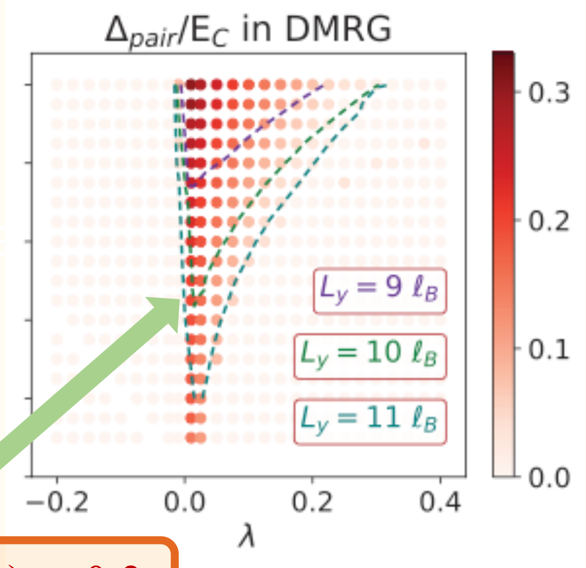

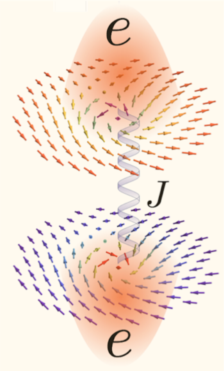

$J_*(\lambda, L_y = 10\ell_B) \cong 0.3$

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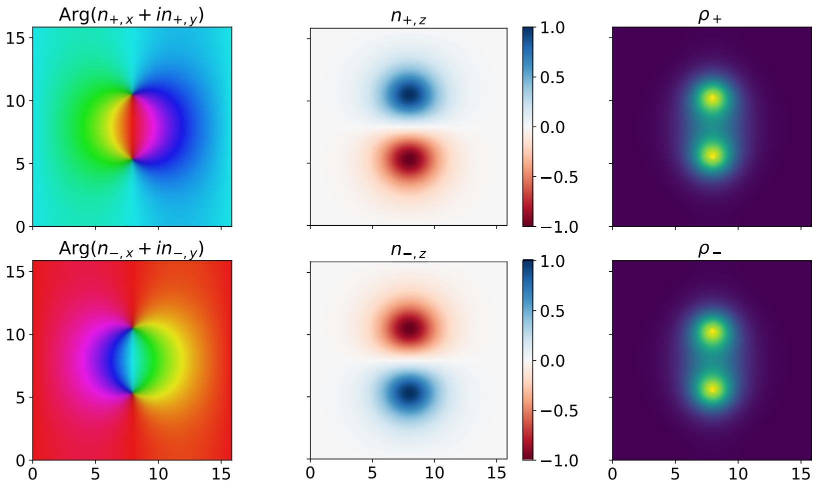

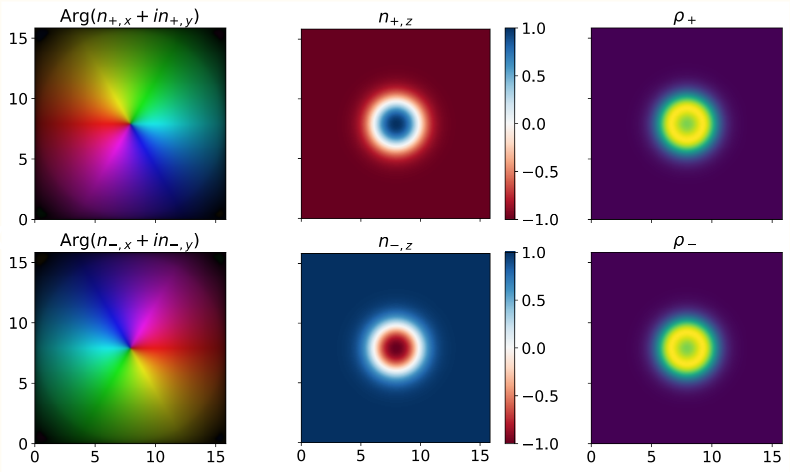

Easy plane: Charges deform into topologically equivalent meron pairs

Easy axis: Charge density remains radially symmetric, incurs larger Coulomb penalty

DMRG evidence for superconductivity

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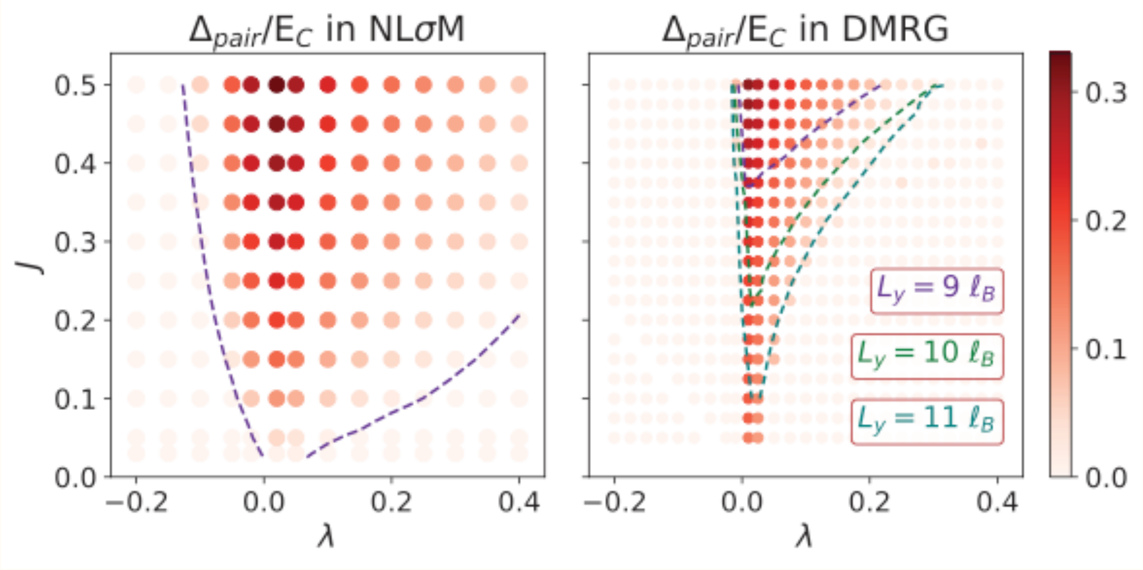
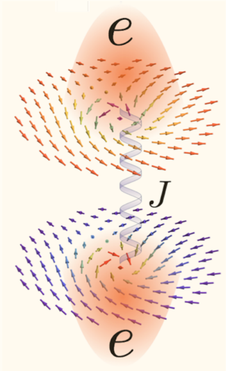
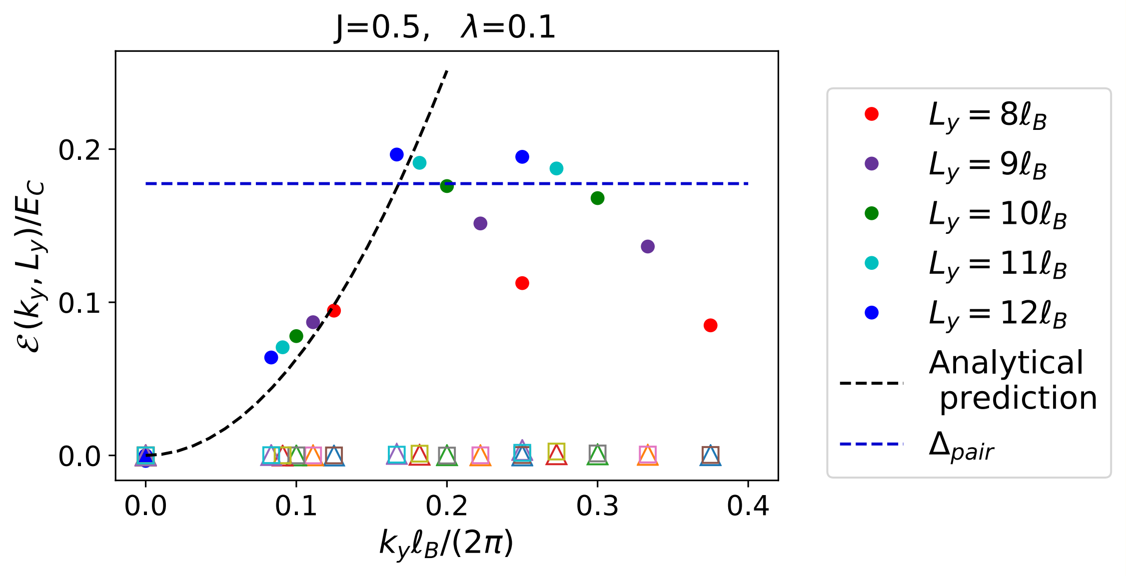




- Quantum zero-point fluctuations ∝ J raise the energy of 2e skyrmions

DMRG evidence for superconductivity

- As $\lambda \to 0$, effective mass $M_{2e} \propto J^{-1}$ as expected from semiclassical study
- At larger momenta k_y, charges from opposite layers get separated, with Chern resolved dipole moment $\propto k_y$: paying AF exchange penalty



Zaletel *et al*, PRB (2018)

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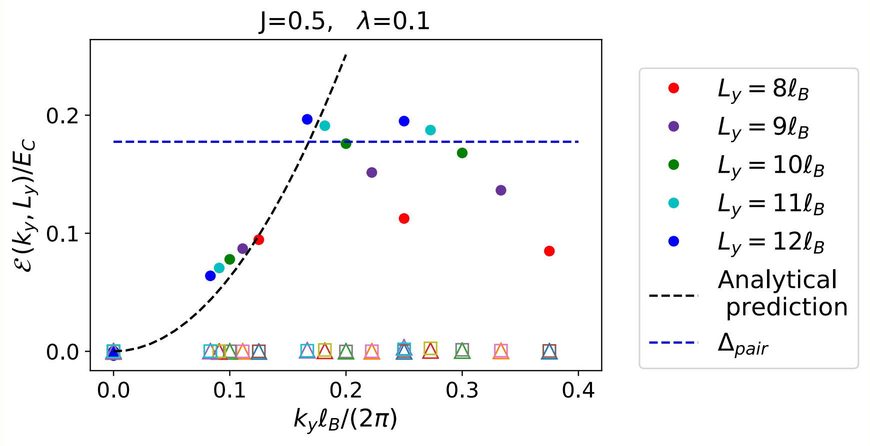

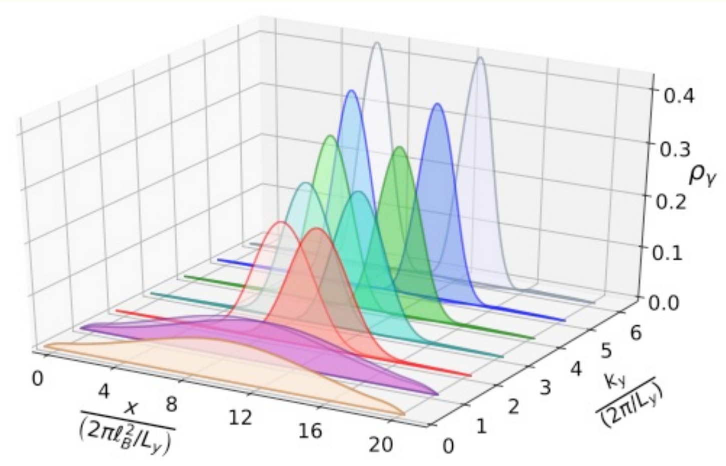

- Again, numerics for quantum system confirm classical expectations!

Conclusions and Outlook

- Skyrmion-antiskyrmion pair condensation provides an attractive mechanism for superconductivity in systems exhibiting tunnel-coupled Chern bands with opposite Chern numbers

- MATBG has the right physical ingredients to realize this mechanism: required band topology and low iso-spin stiffness ~ 1 meV

Saito *et al*, arXiv:2008:10830

- Open questions --- Effects of:

1. Non-uniform Berry curvature
2. Disorder
3. Spin-orbit coupling

Saito *et al*, Nature (2020)

- Influence of fluctuating order parameter modes on transport?

Thank you for your attention!