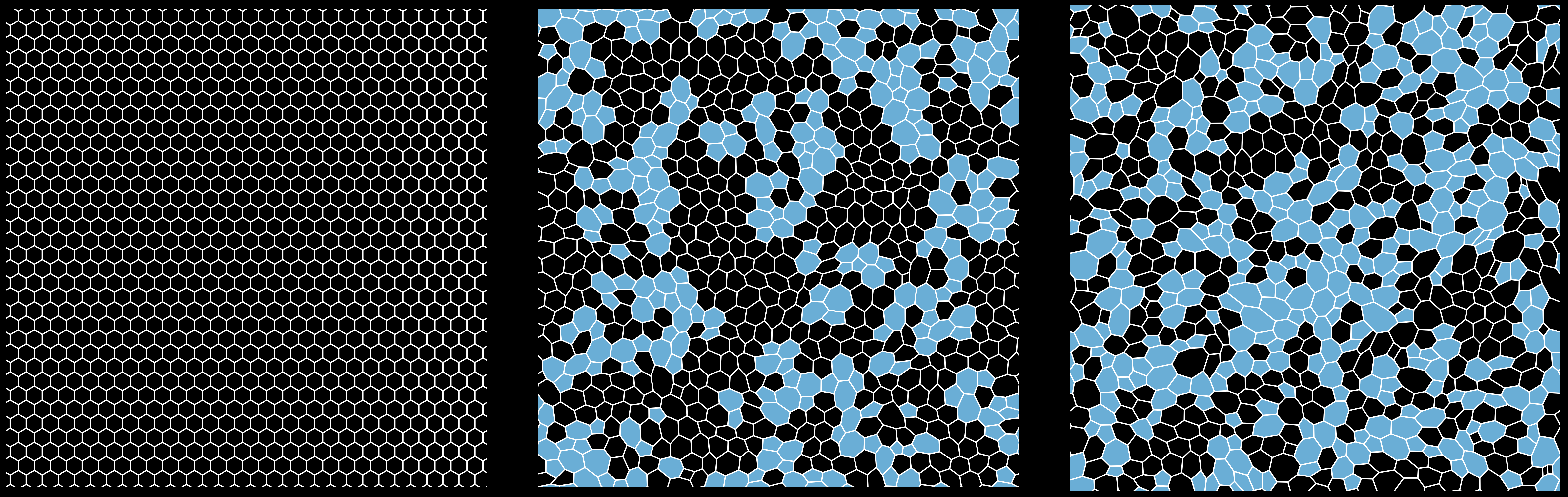
Amorphous and polycrystalline routes towards a chiral spin-liquid



Adolfo G. Grushin, Néel Institute, CNRS

QuanDi — June 8th, 2023

Cécile Repellin

LPMMC / Grenoble

AGG, C. Repellin Phys. Rev. Lett. **130**, 186702 (2023)

TOPOMORPH

European Research Council

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SCHINES FET-OPEN

AGENCE NATIONALE DE LA RECHERCHE ANR

Q. Marsal, D. Varjas, AGG PNAS, (2020)

D. Muñoz-Segovia,et al 2301.02686

Q. Marsal, D. Varjas, AGG Phys. Rev. B (2023)

Corbae et al, AGG, Lanzara, Hellmann Nat. Materials (2023)

Cyocis, Marsal et al, Hellmann, AGG, Lanzara 2302.05945

Review: P. Corbae, et al arXiv: 2301.04176, EPL (2023)

Topological solids 101

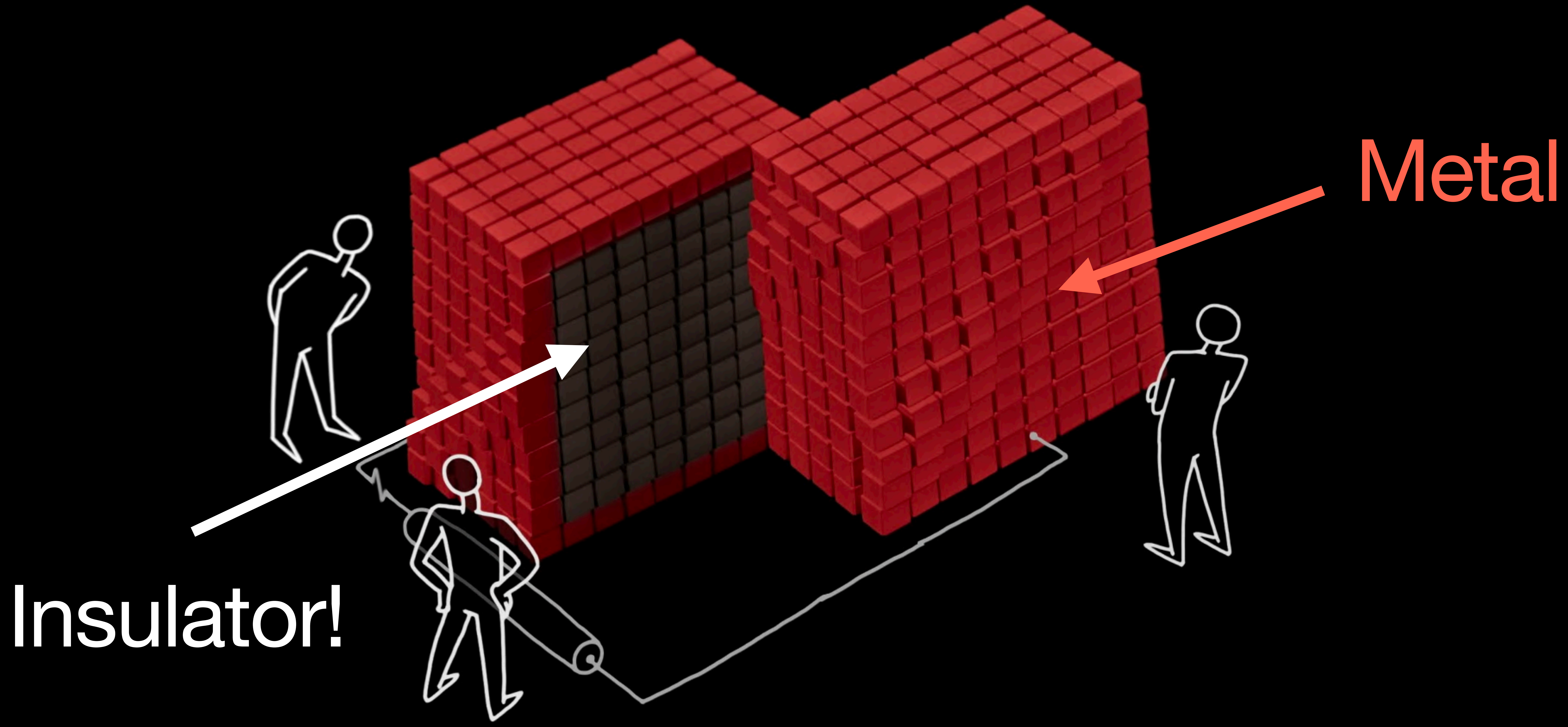
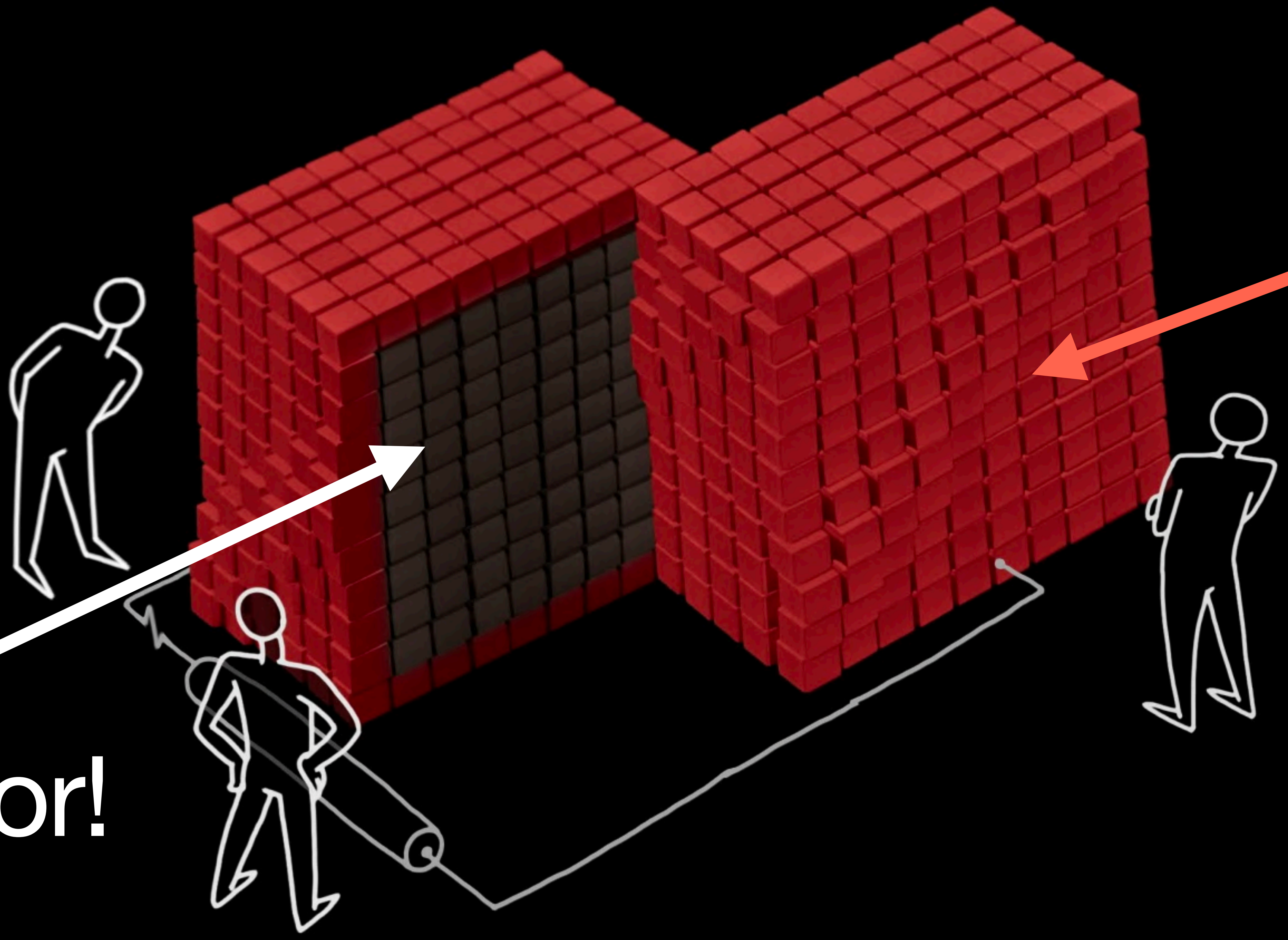


Image: Le Nobel Chevelu

Topological solids 101



Metal

Insulator!

Image: Le Nobel Chevelu

Topological solids

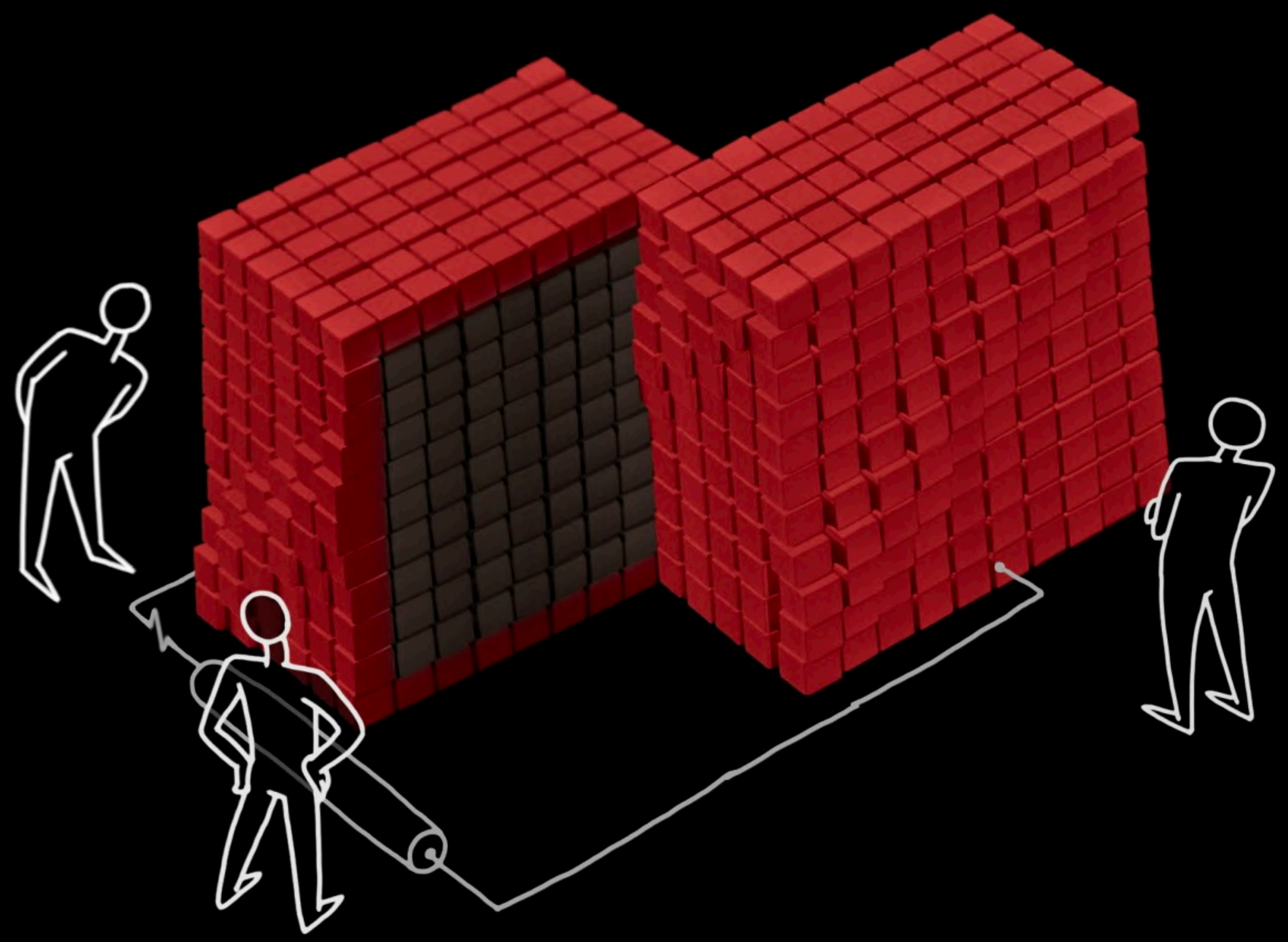
Topological
>50%

Crystals

Vergniory et al. Nature (2019)

Zhang et al. Nature (2019)

Tang et al. Nature (2019)



Topological solids

Topological >50%

Crystals

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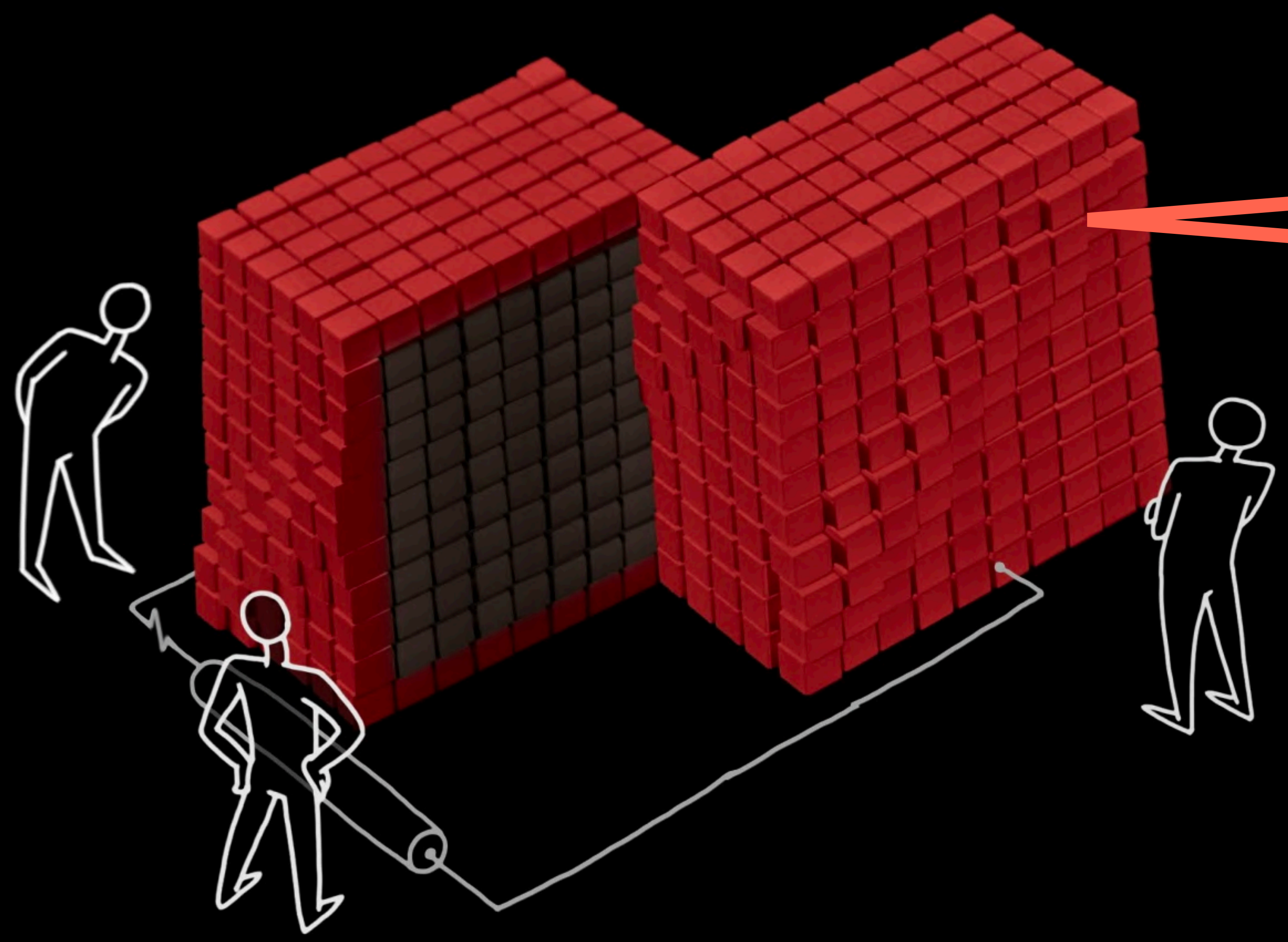
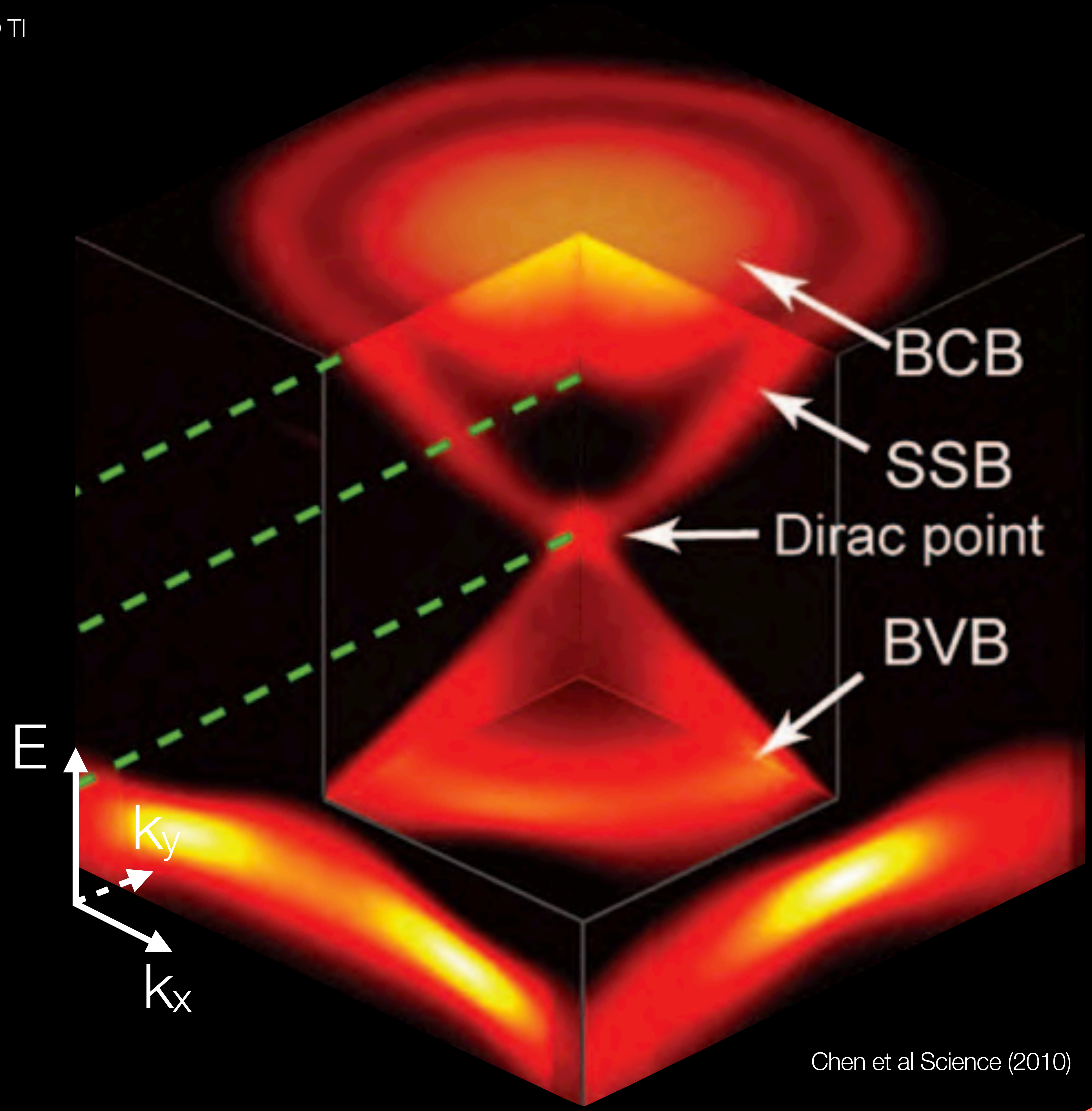


Bi_2Se_3

3D TI



Chen et al Science (2010)

How do we find topological insulators?

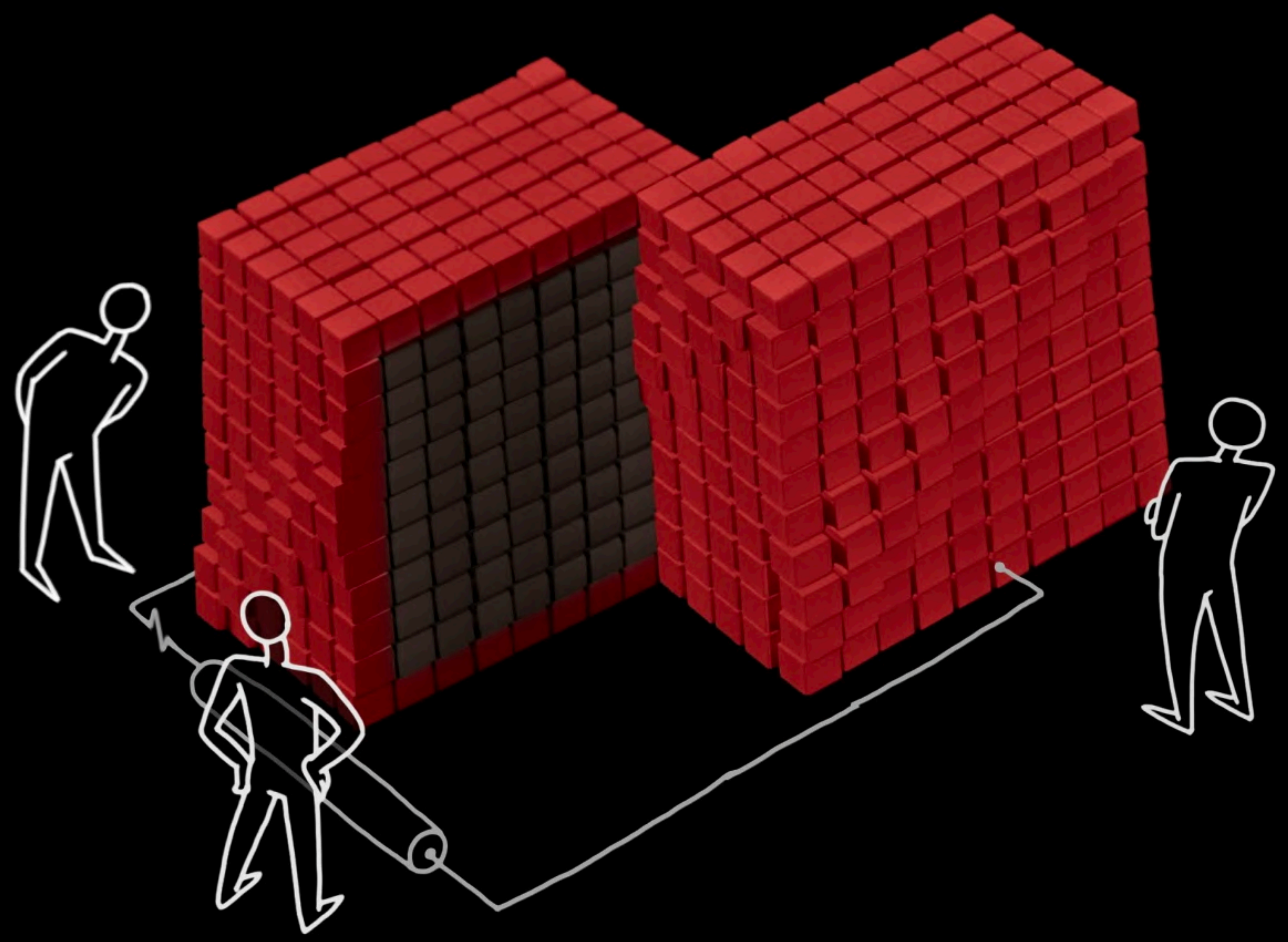
Topological
>50%

Crystals

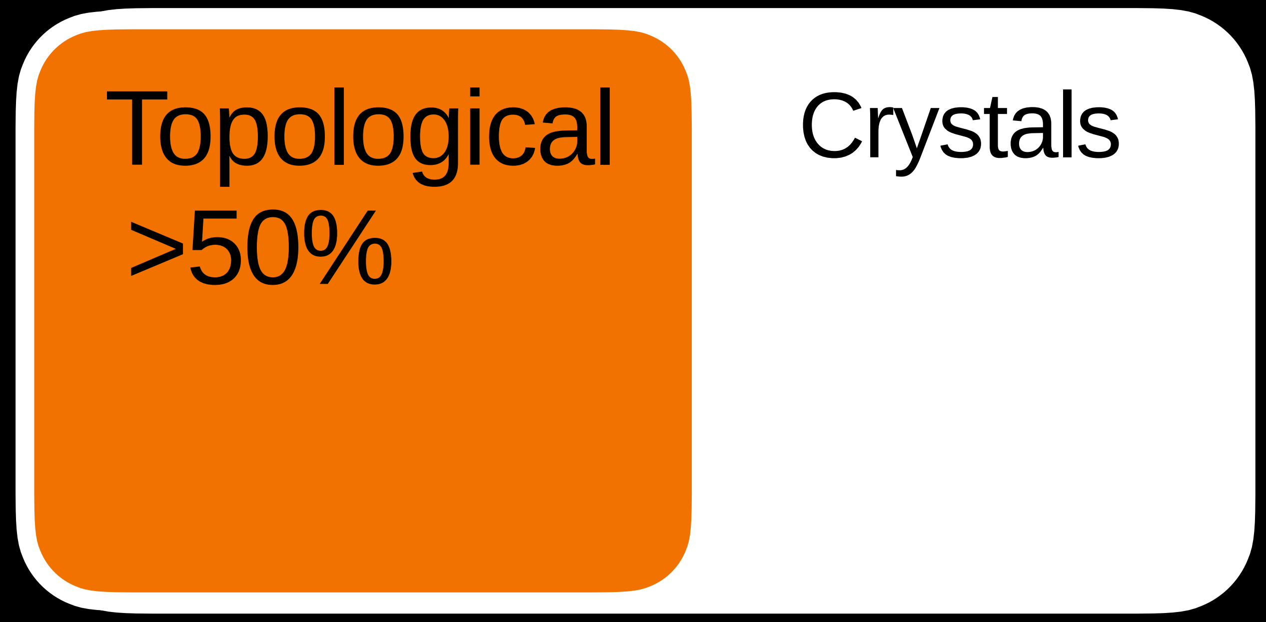
Vergniory et al. Nature (2019)

Zhang et al. Nature (2019)

Tang et al. Nature (2019)



How do we find topological insulators?



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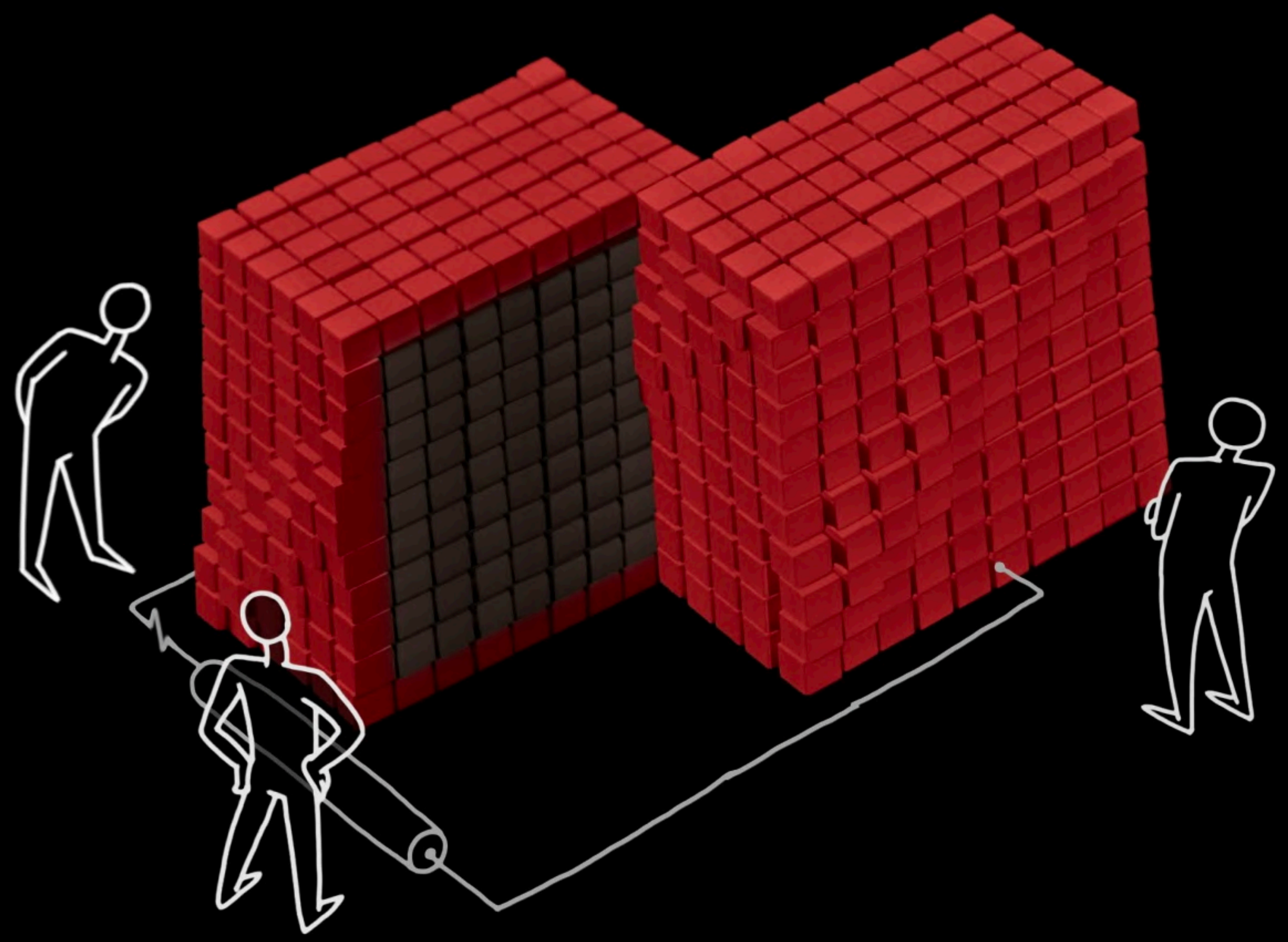
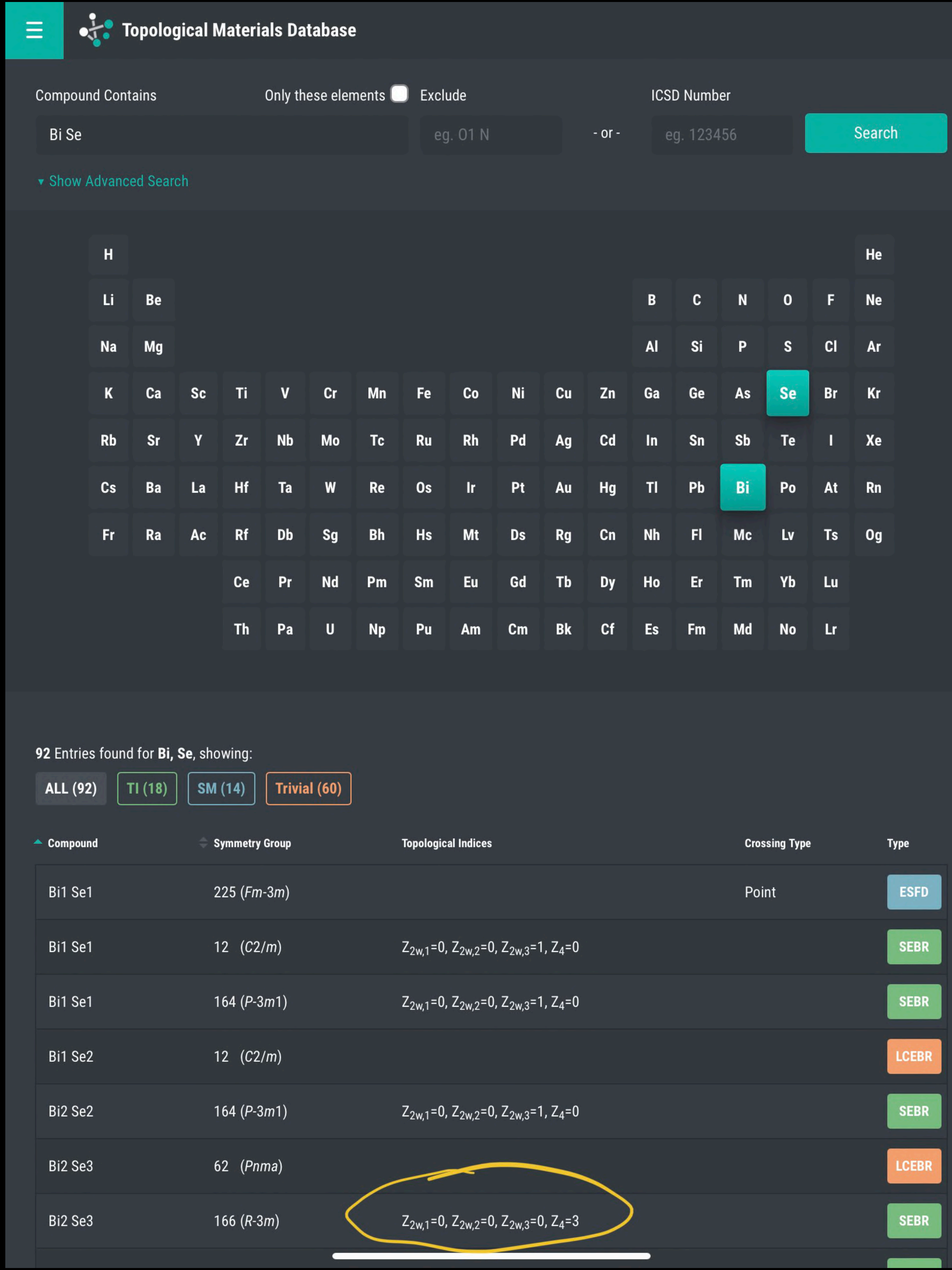
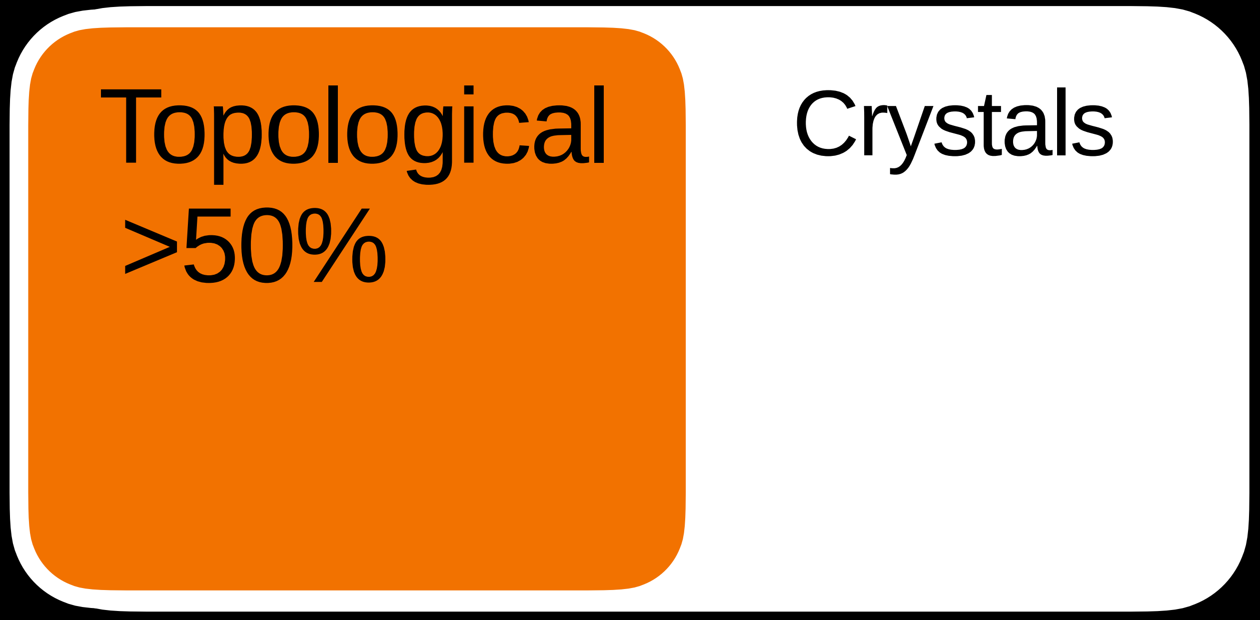




How do we find topological insulators?



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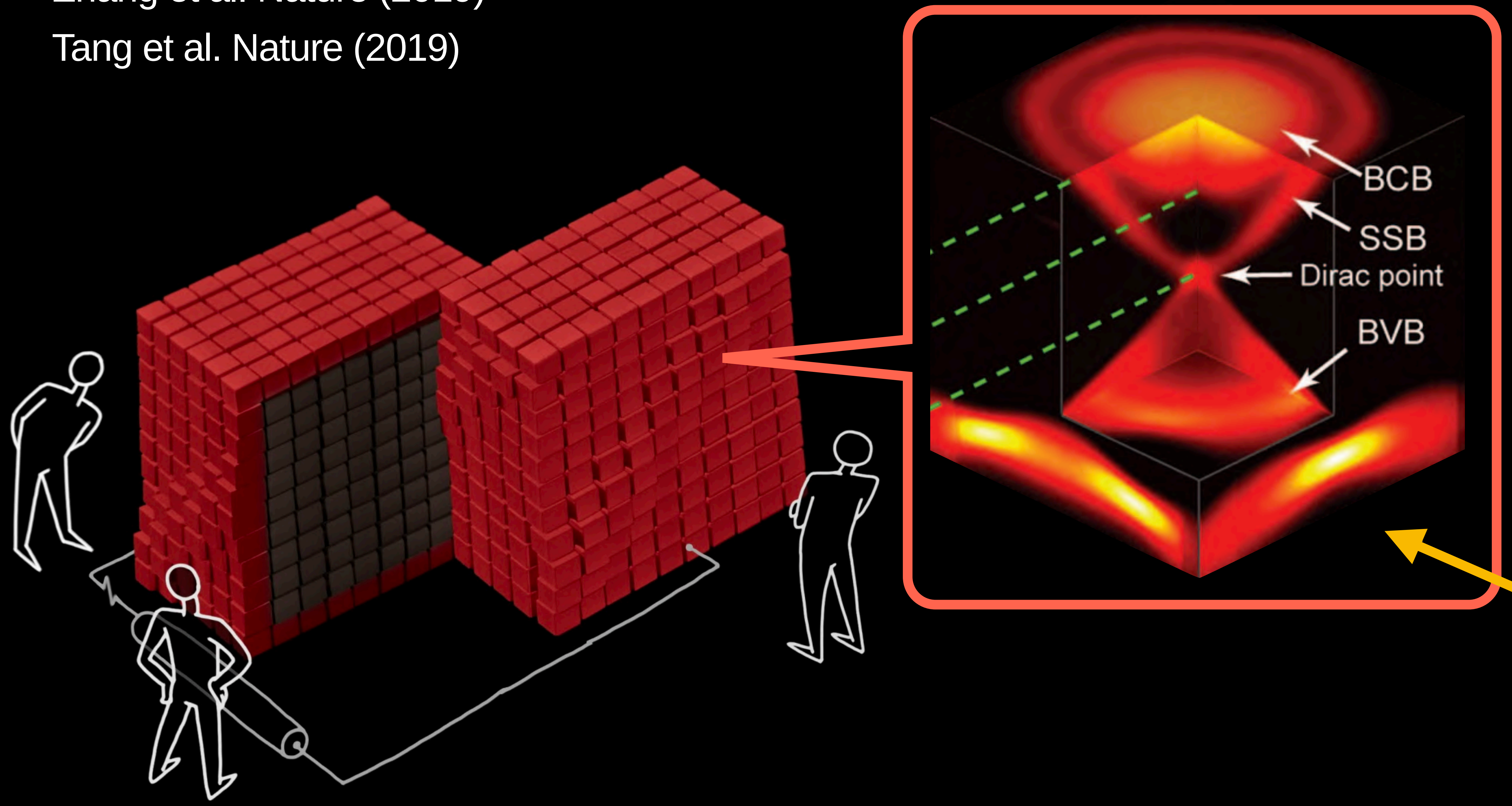
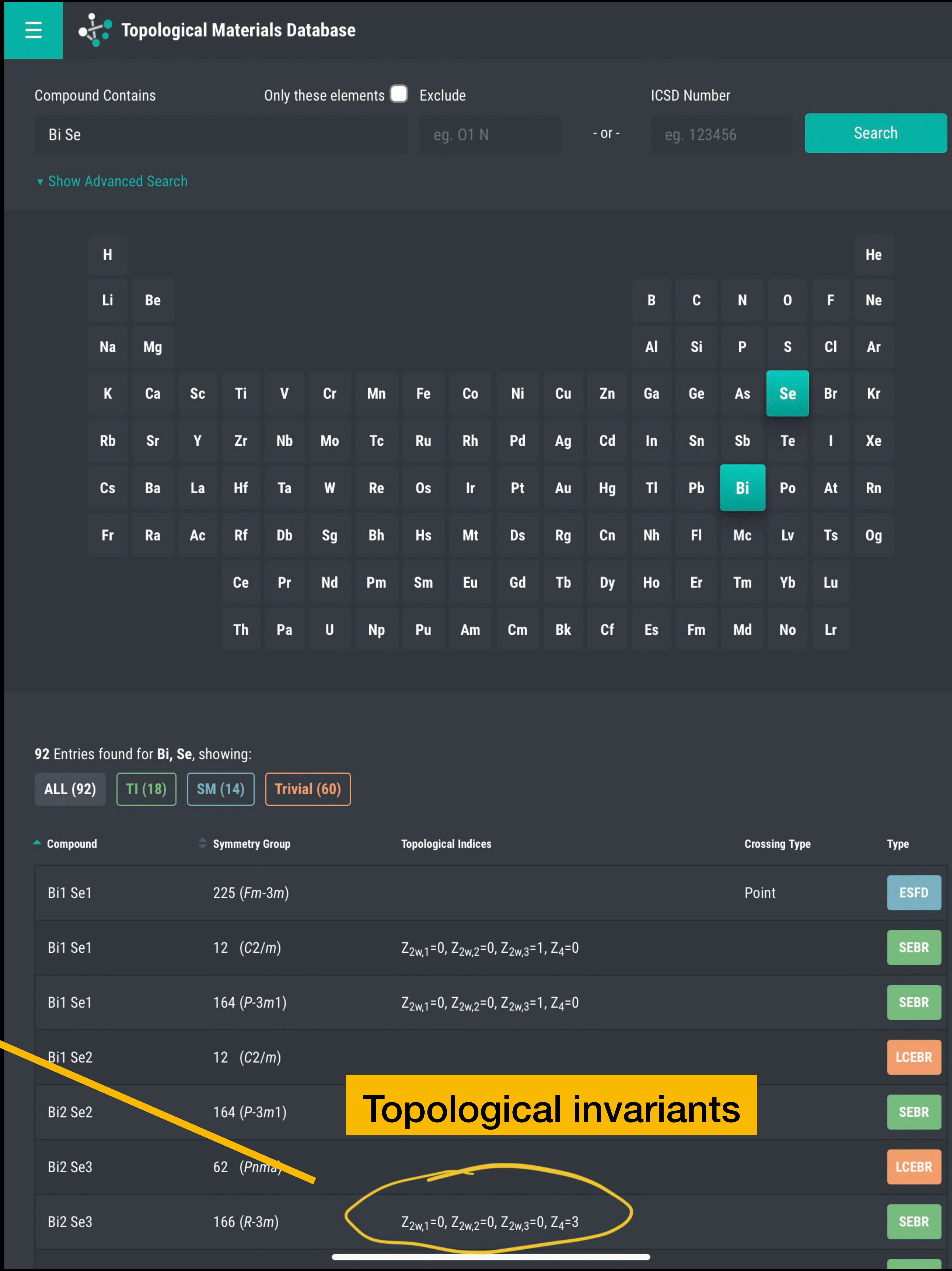
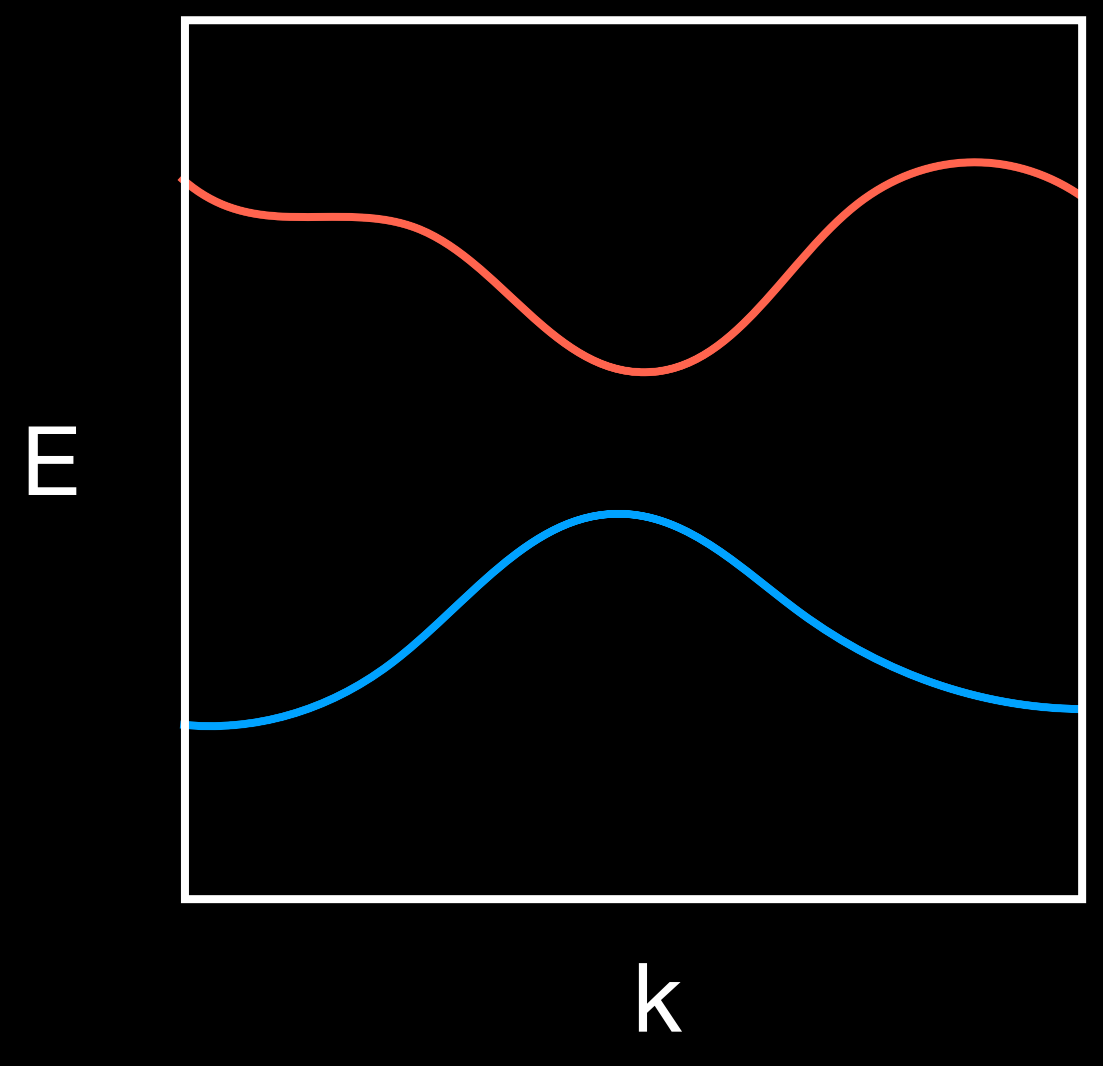




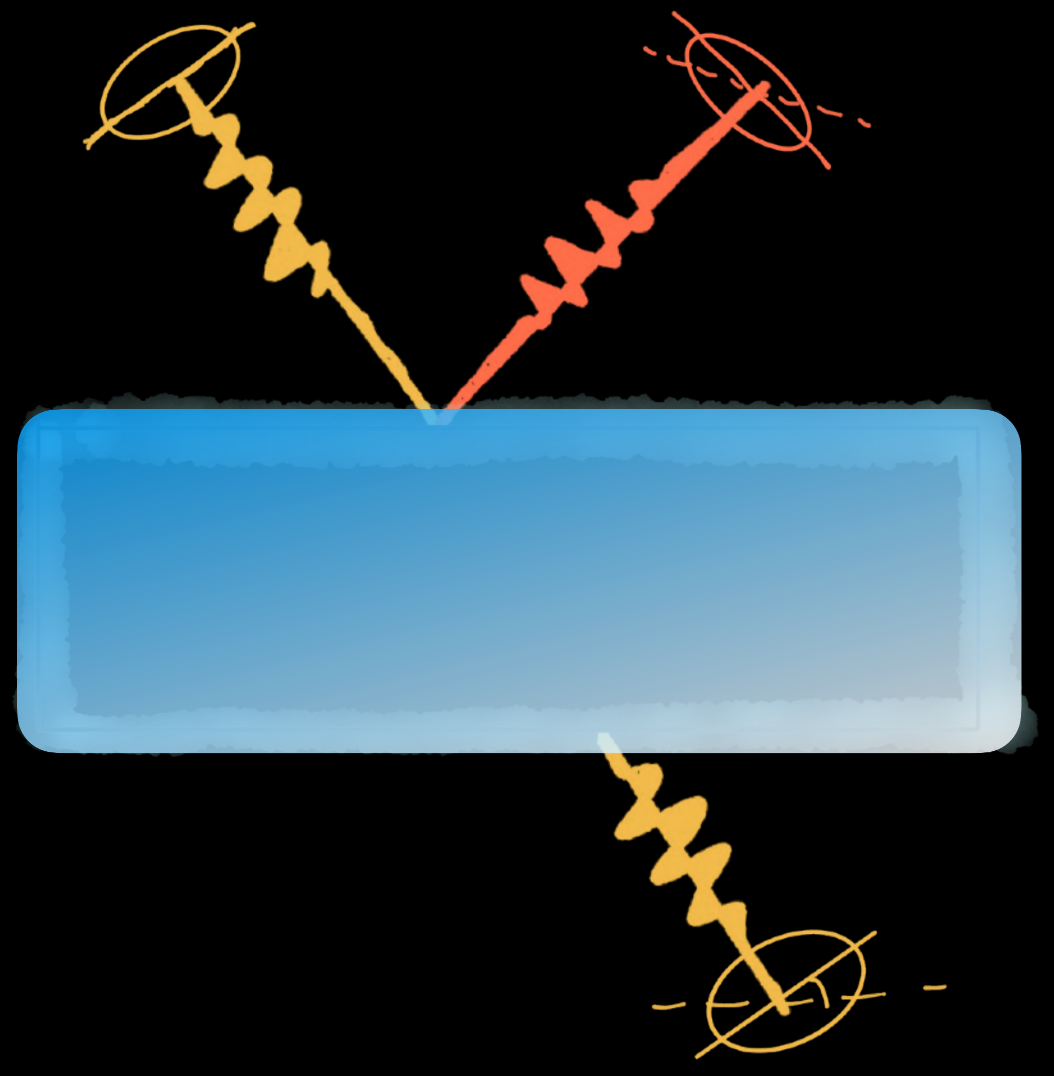
Compound	Symmetry Group	Topological Indices	Crossing Type	Type
Bi1 Se1	225 (*Fm-3m*)		Point	ESFD
Bi1 Se1	12 (*C2/m*)	$Z_{2w,1}=0, Z_{2w,2}=0, Z_{2w,3}=1, Z_4=0$		SEBR
Bi1 Se1	164 (*P-3m1*)	$Z_{2w,1}=0, Z_{2w,2}=0, Z_{2w,3}=1, Z_4=0$		SEBR
Bi1 Se2	12 (*C2/m*)			LCEBR
Bi2 Se2	164 (*P-3m1*)			SEBR
Bi2 Se3	62 (*Pnma*)			LCEBR
Bi2 Se3	166 (*R-3m*)	$Z_{2w,1}=0, Z_{2w,2}=0, Z_{2w,3}=0, Z_4=3$		SEBR

How do we find topological insulators?

wave function in momentum space → Topological invariants → Quantized responses



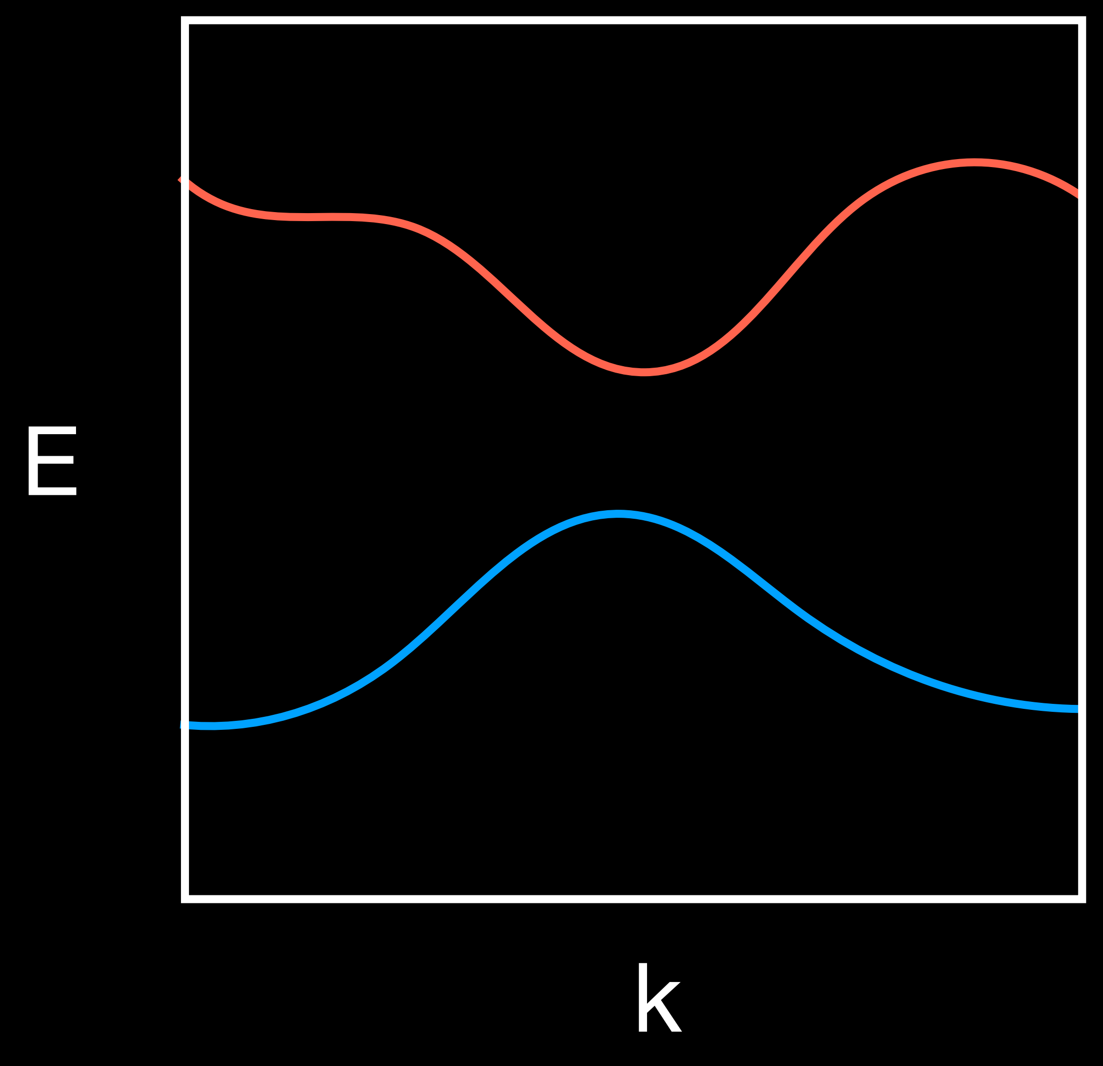
$\mathbb{Z}$



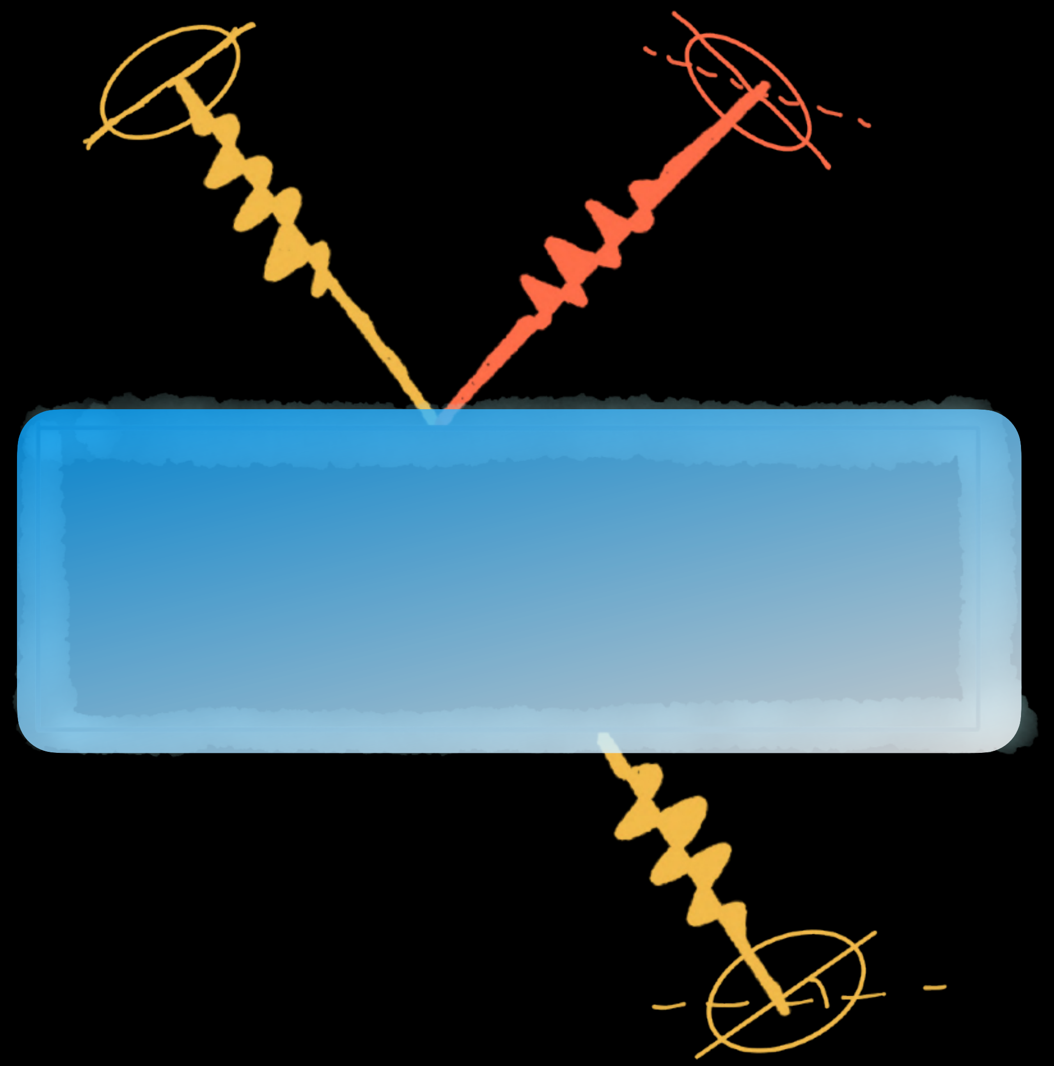
e.g. quantised quantum Hall
quantised Kerr rotation

How do we find topological insulators?

wave function in momentum space → Topological invariants → Quantized responses



$\mathbb{Z}$



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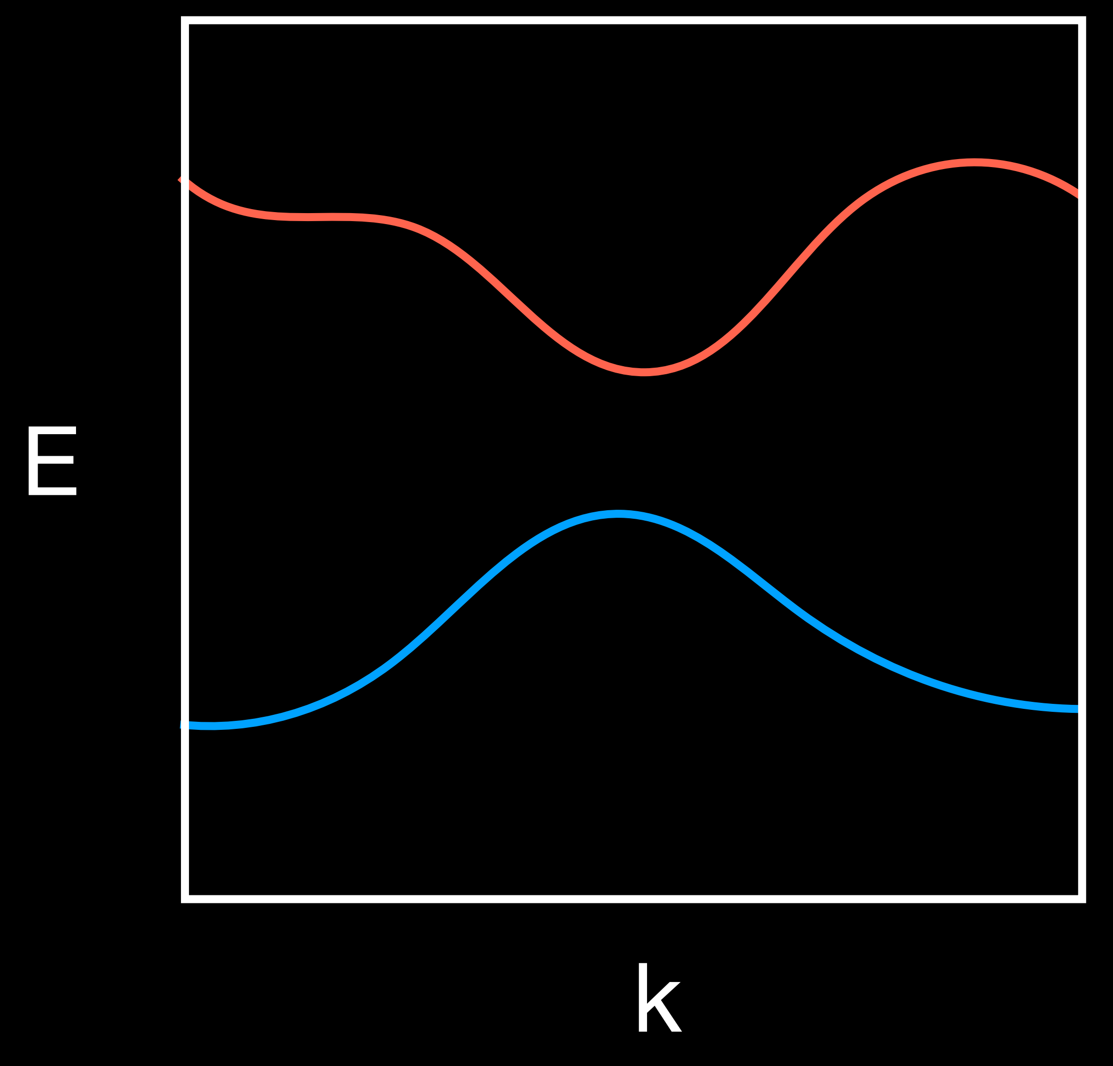
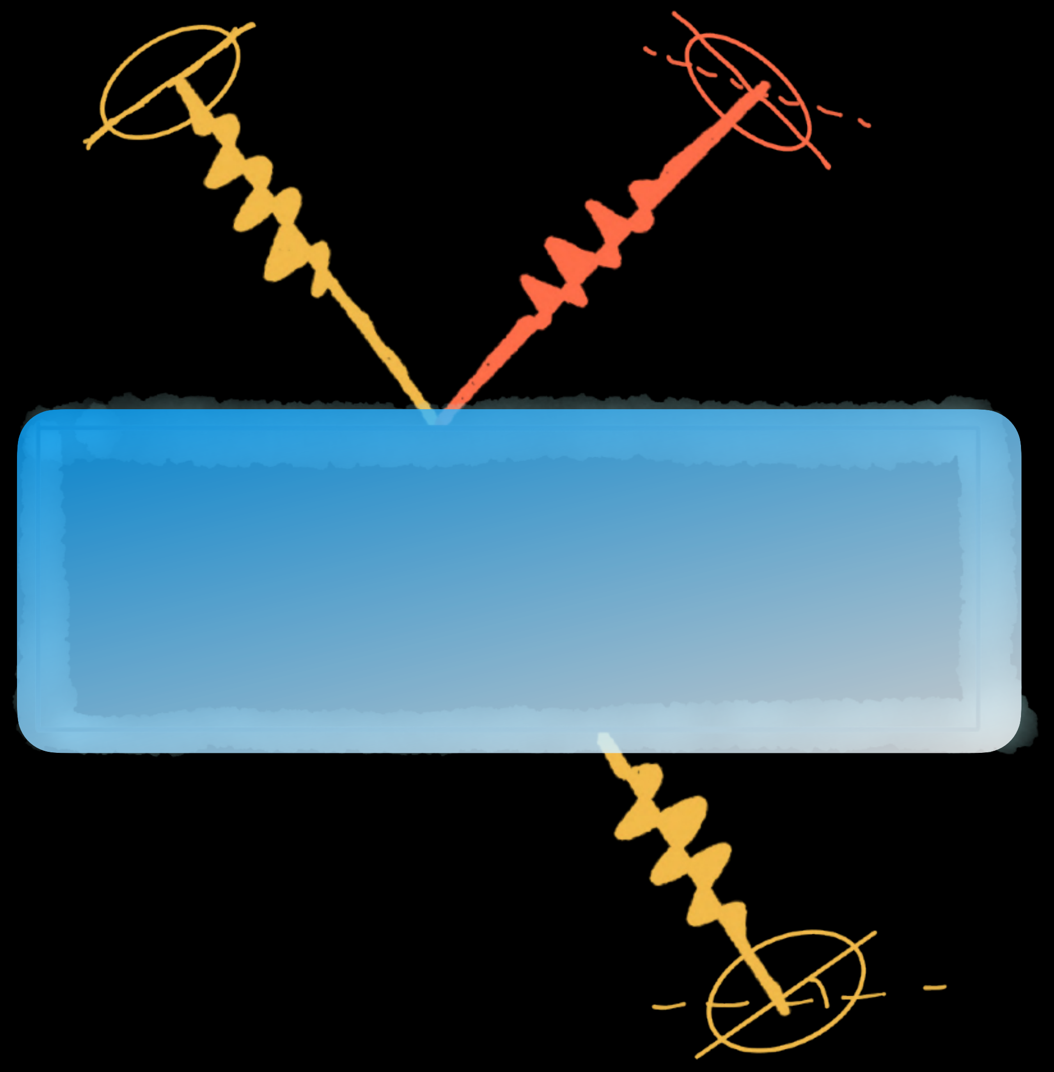
wave function in momentum space → Topological invariants → Quantized responses



$\mathbb{Z}$

impractical / numerically costly



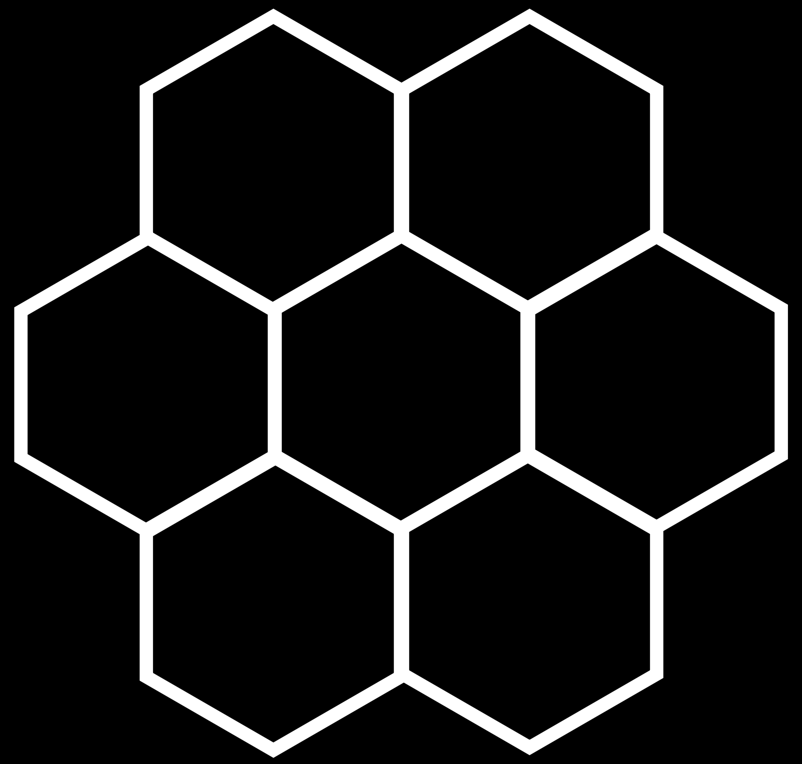
e.g. quantised quantum Hall
quantised Kerr rotation

How do we find topological insulators?

Bradlyn et al Nature (2017) Kruthoff et al. Phys. Rev. X (2017) Po et al. Nat. Comm (2017) Song et al. Nat. Comm (2018)

How do we find topological insulators?

Space Group



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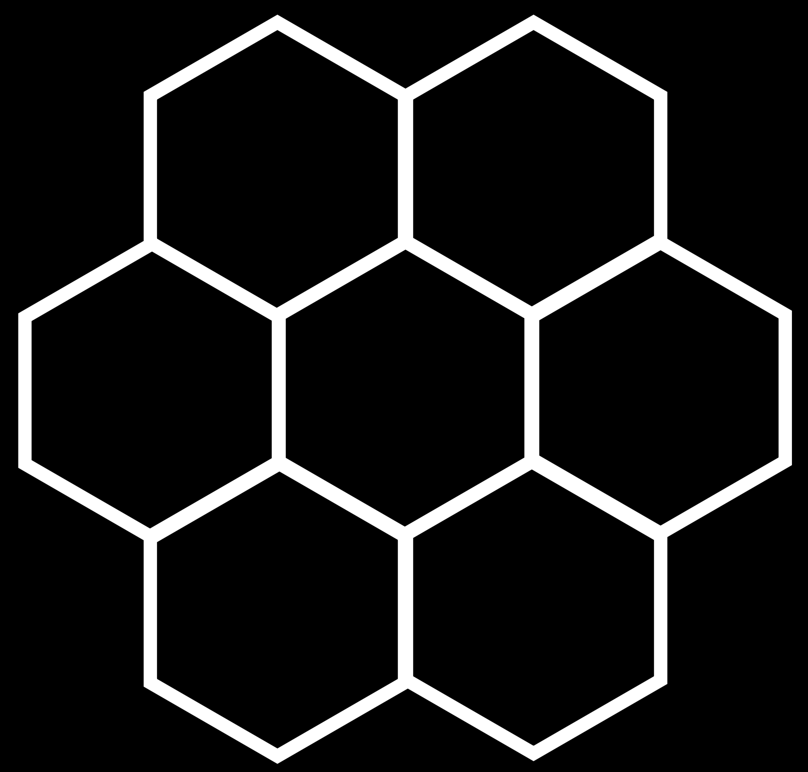
How do we find topological insulators?

Space Group



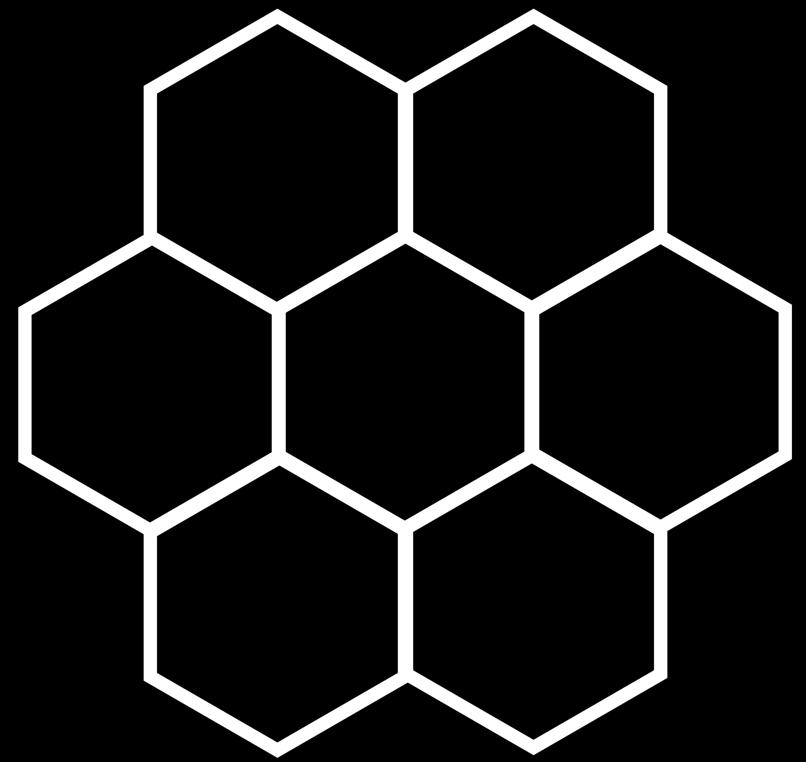
— lattice symmetries

translations, rotations, inversions, mirrors

Bradlyn et al Nature (2017) Kruthoff et al. Phys. Rev. X (2017) Po et al. Nat. Comm (2017) Song et al. Nat. Comm (2018)

How do we find topological insulators?

Space Group



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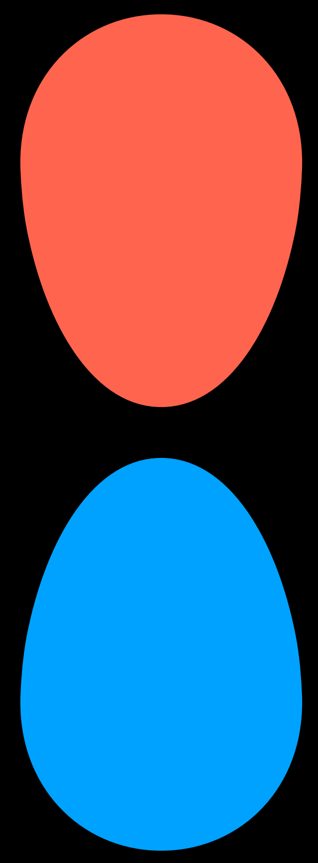
translations, rotations, inversions, mirrors

Orbitals



— wavefunctions

s, p, d…

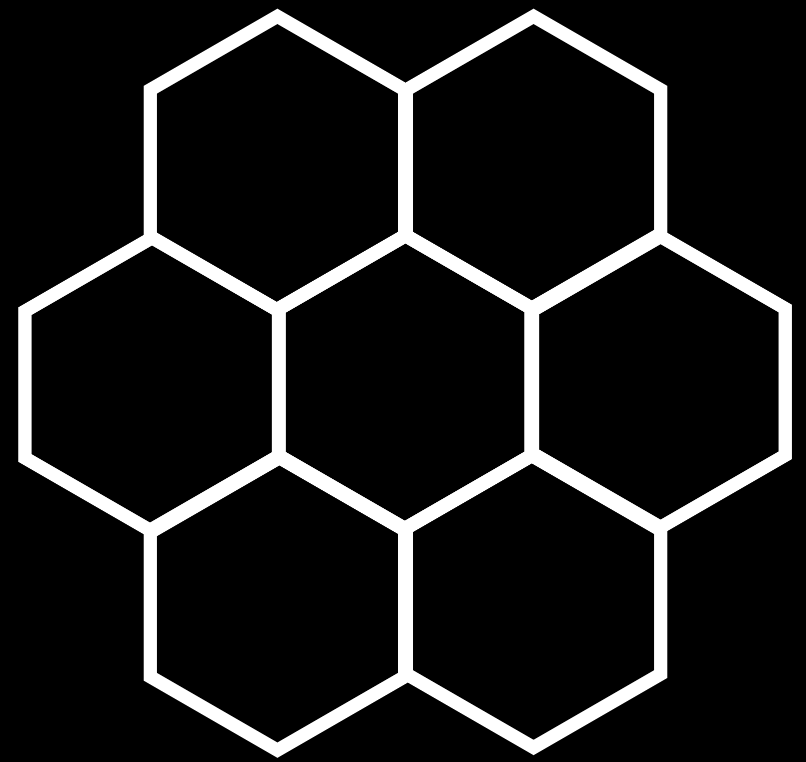
Bradlyn et al Nature (2017) Kruthoff et al. Phys. Rev. X (2017) Po et al. Nat. Comm (2017) Song et al. Nat. Comm (2018)

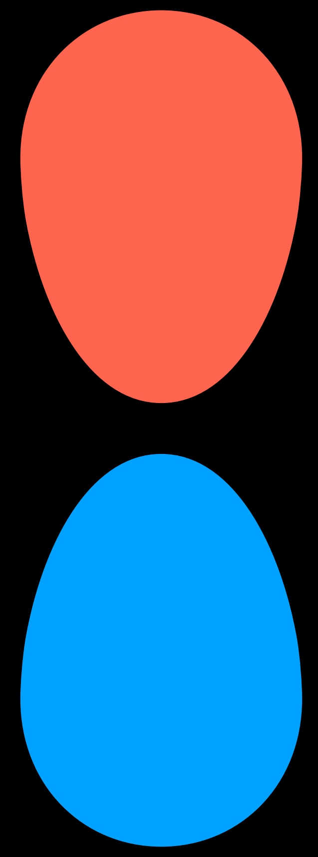
How do we find topological insulators?

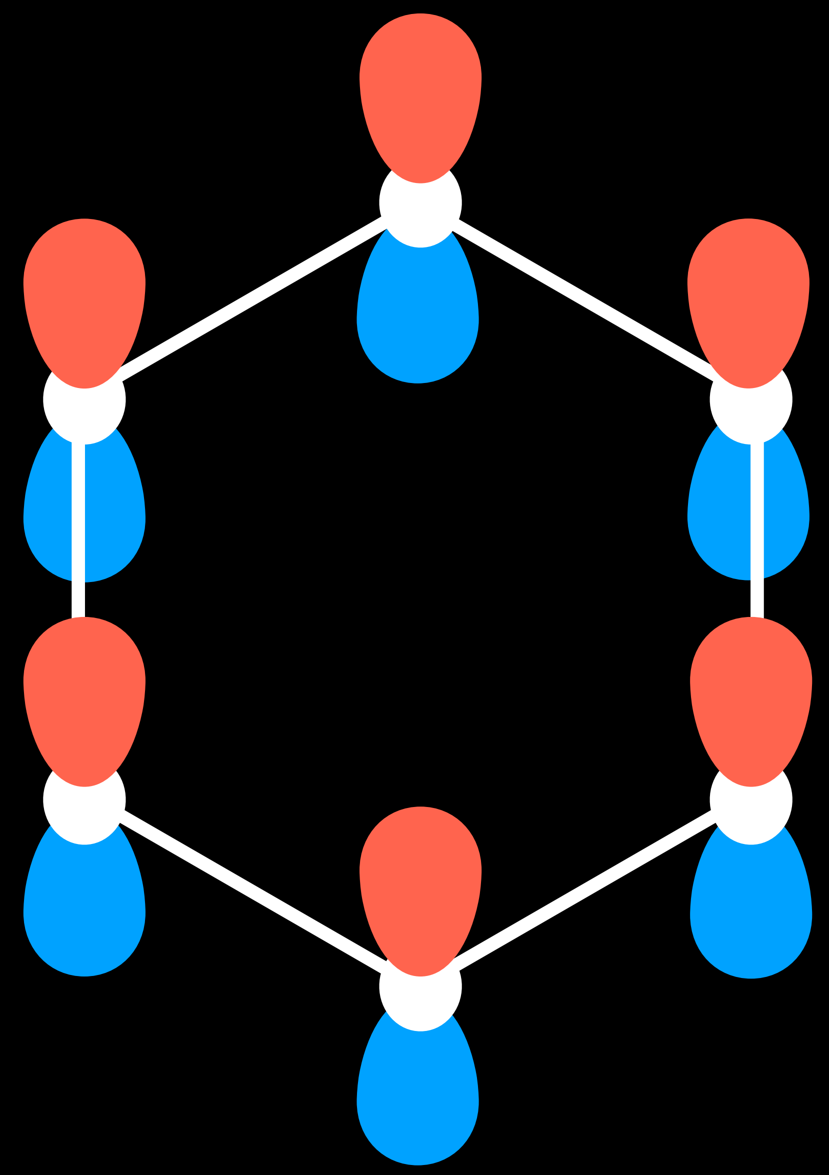
Space Group

Orbitals

Atomic positions







— lattice symmetries

— wavefunctions

— band connectivity + symmetries labels

translations, rotations, inversions, mirrors

s, p, d…

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How do we find topological insulators?

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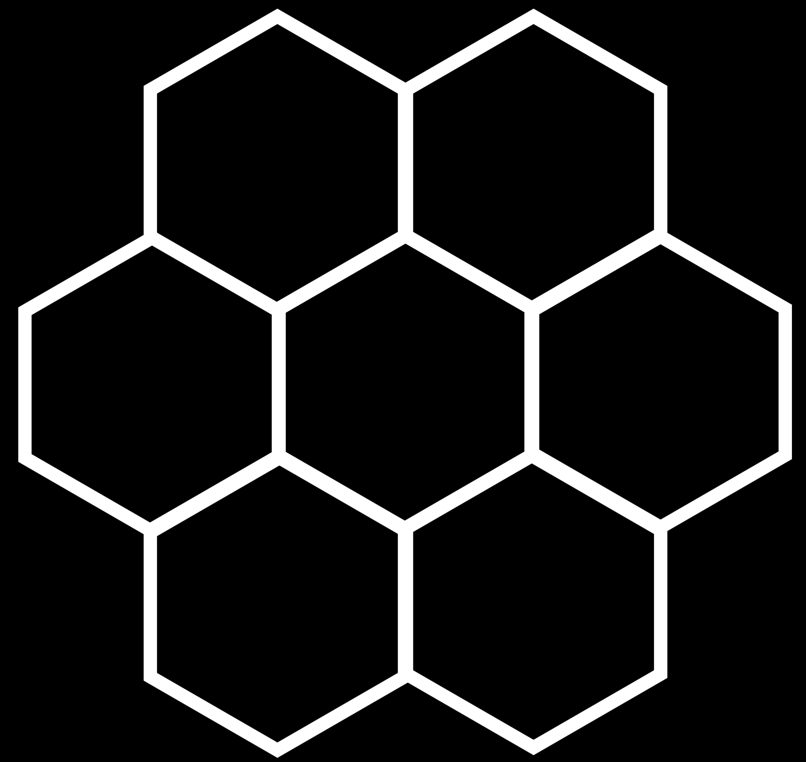

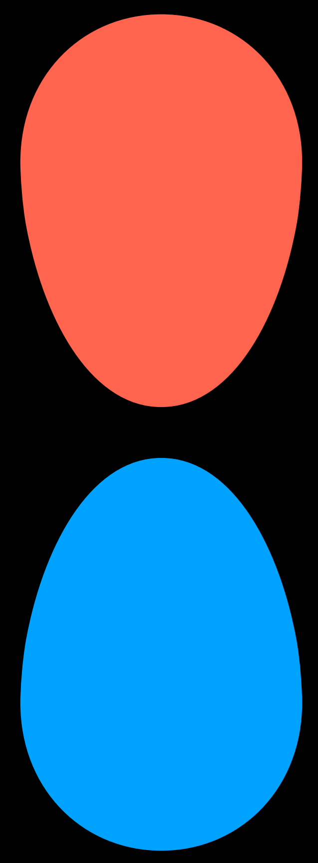

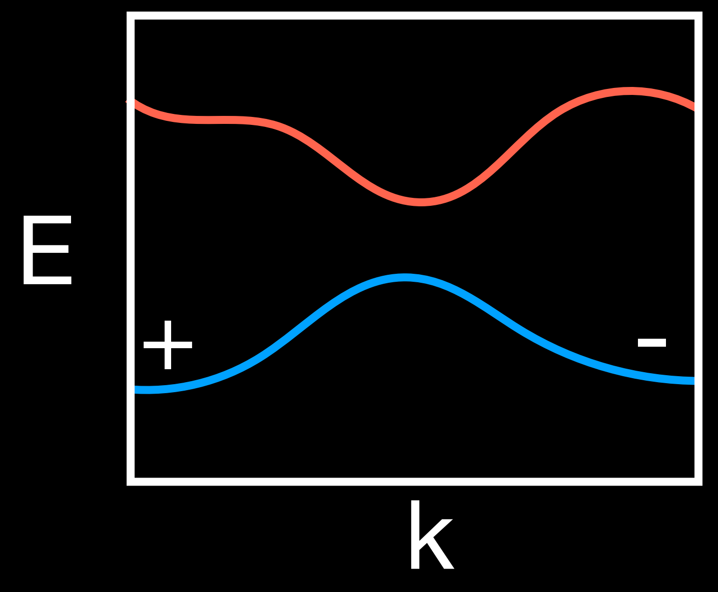

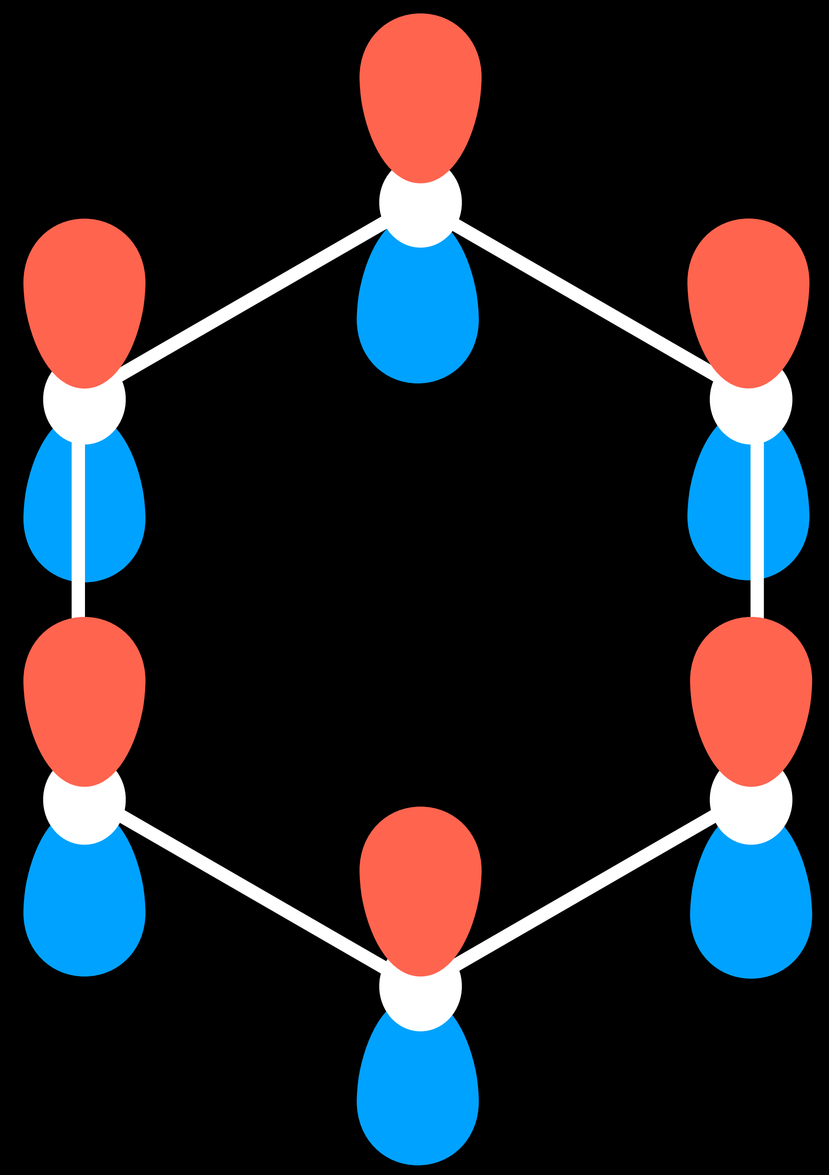

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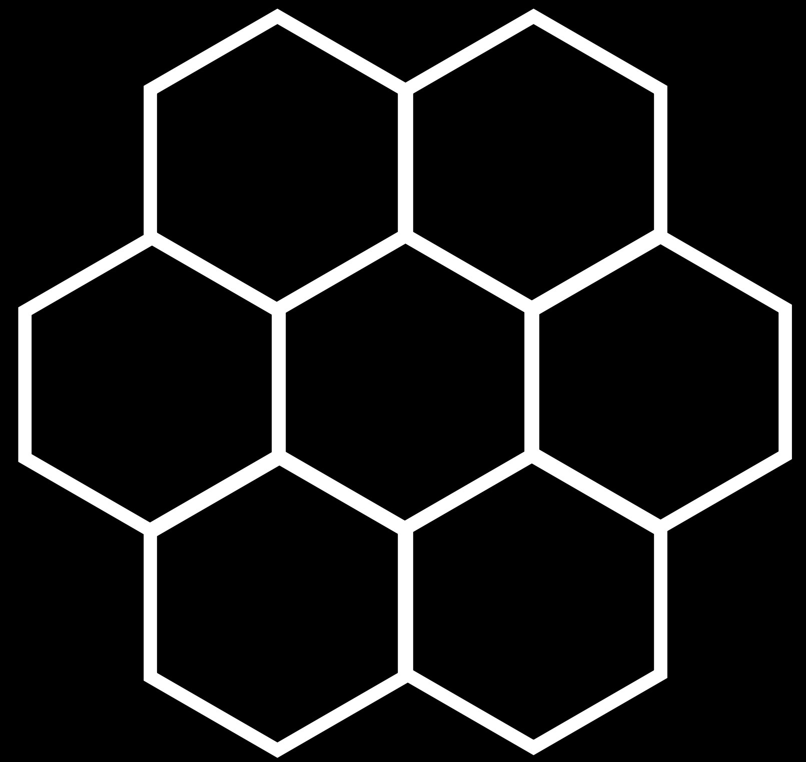
Space Group



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translations, rotations, inversions, mirrors

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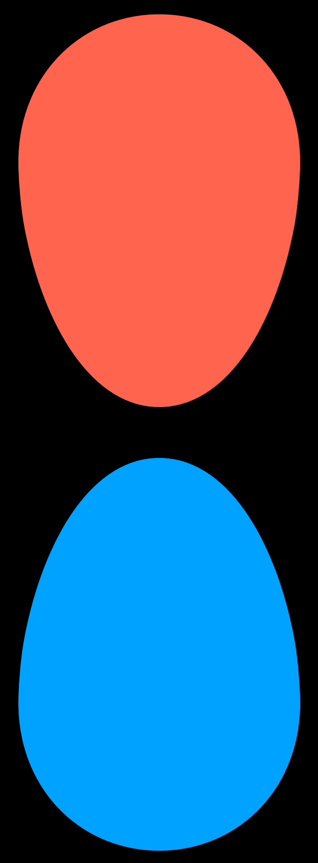
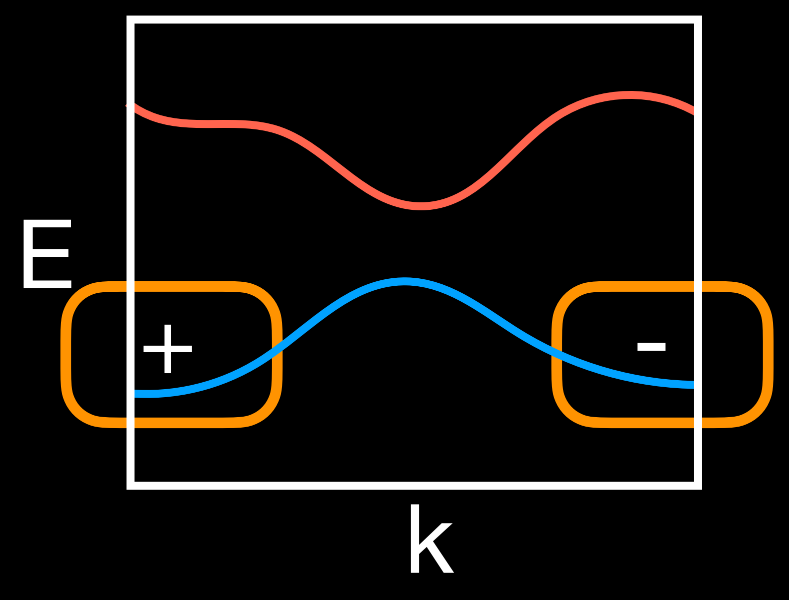
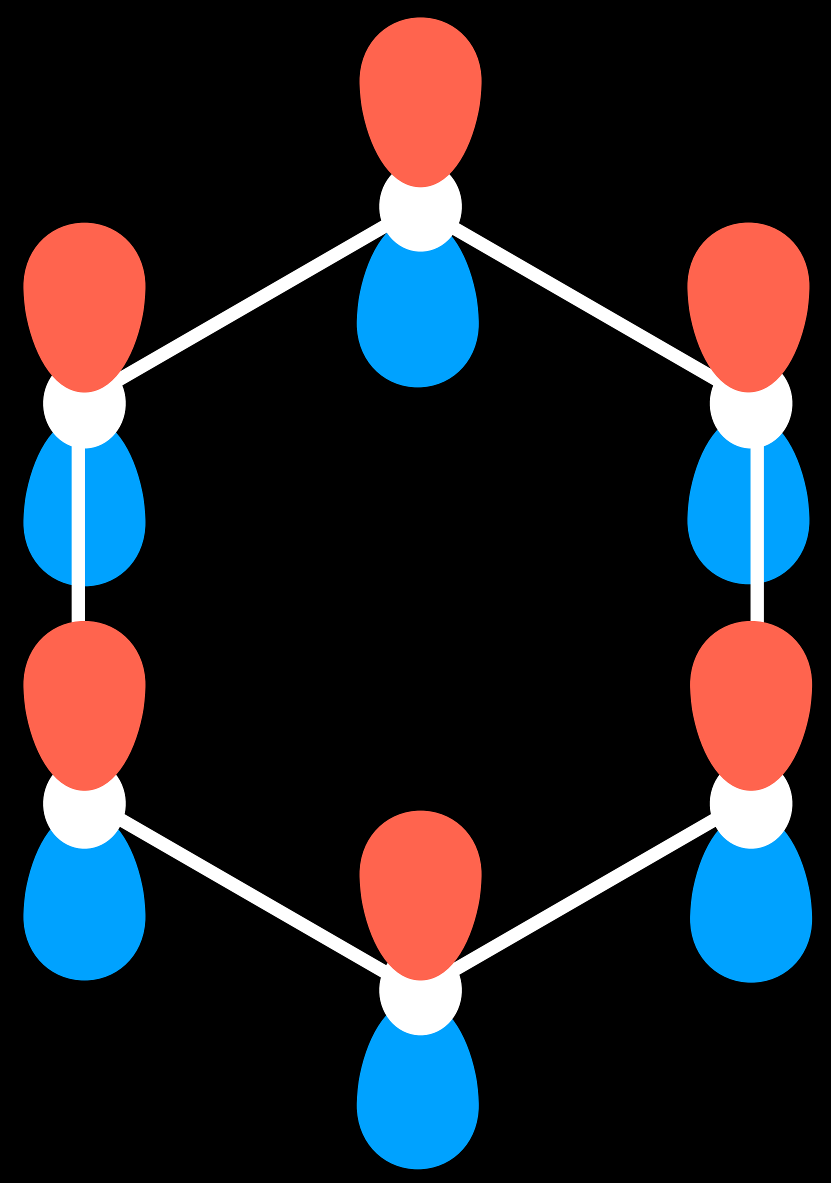


— wavefunctions

s, p, d…

Atomic positions



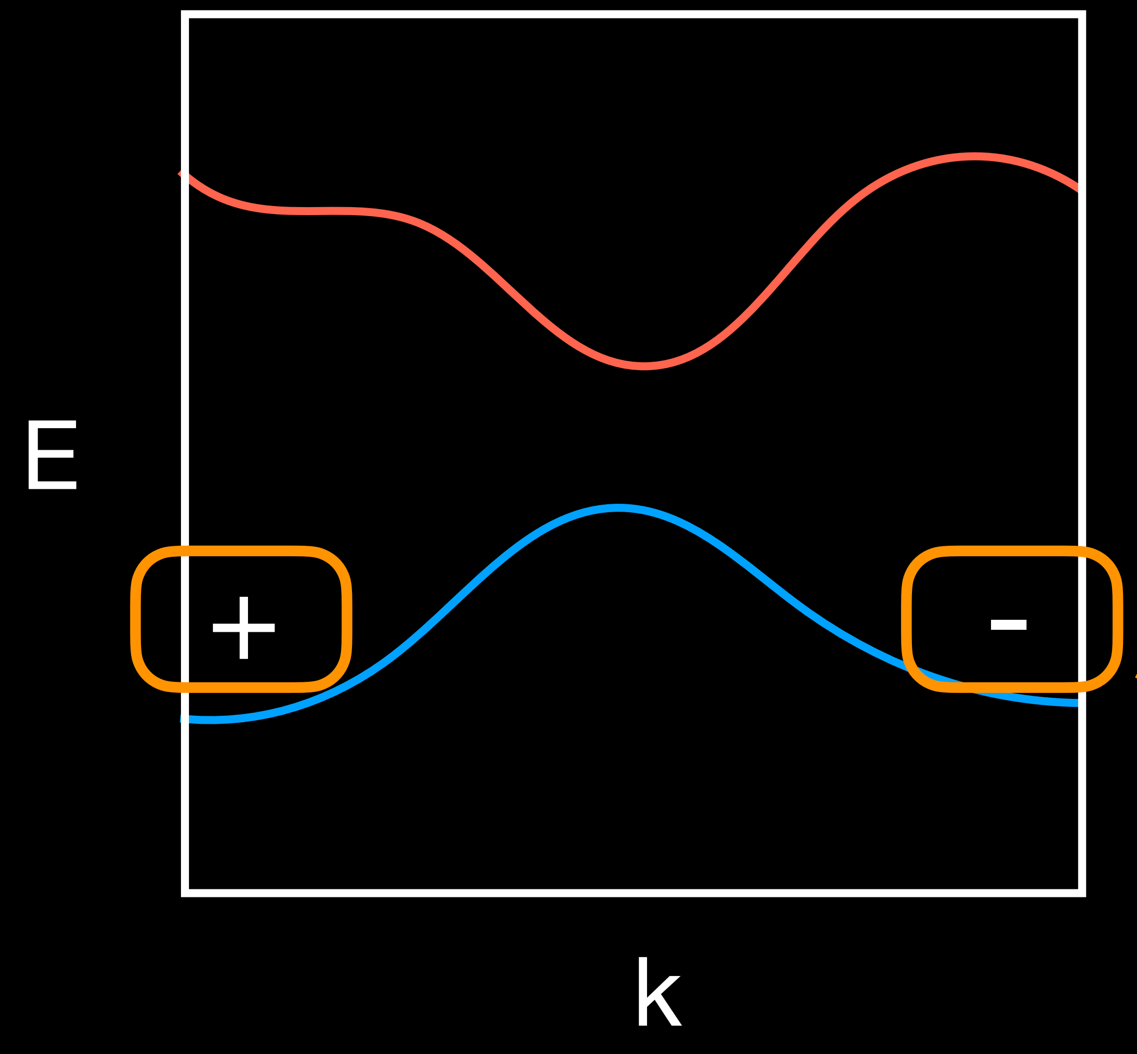


— band connectivity + symmetries labels

Bradlyn et al Nature (2017) Kruthoff et al. Phys. Rev. X (2017) Po et al. Nat. Comm (2017) Song et al. Nat. Comm (2018)

How do we find topological insulators?

band connectivity + symmetries labels

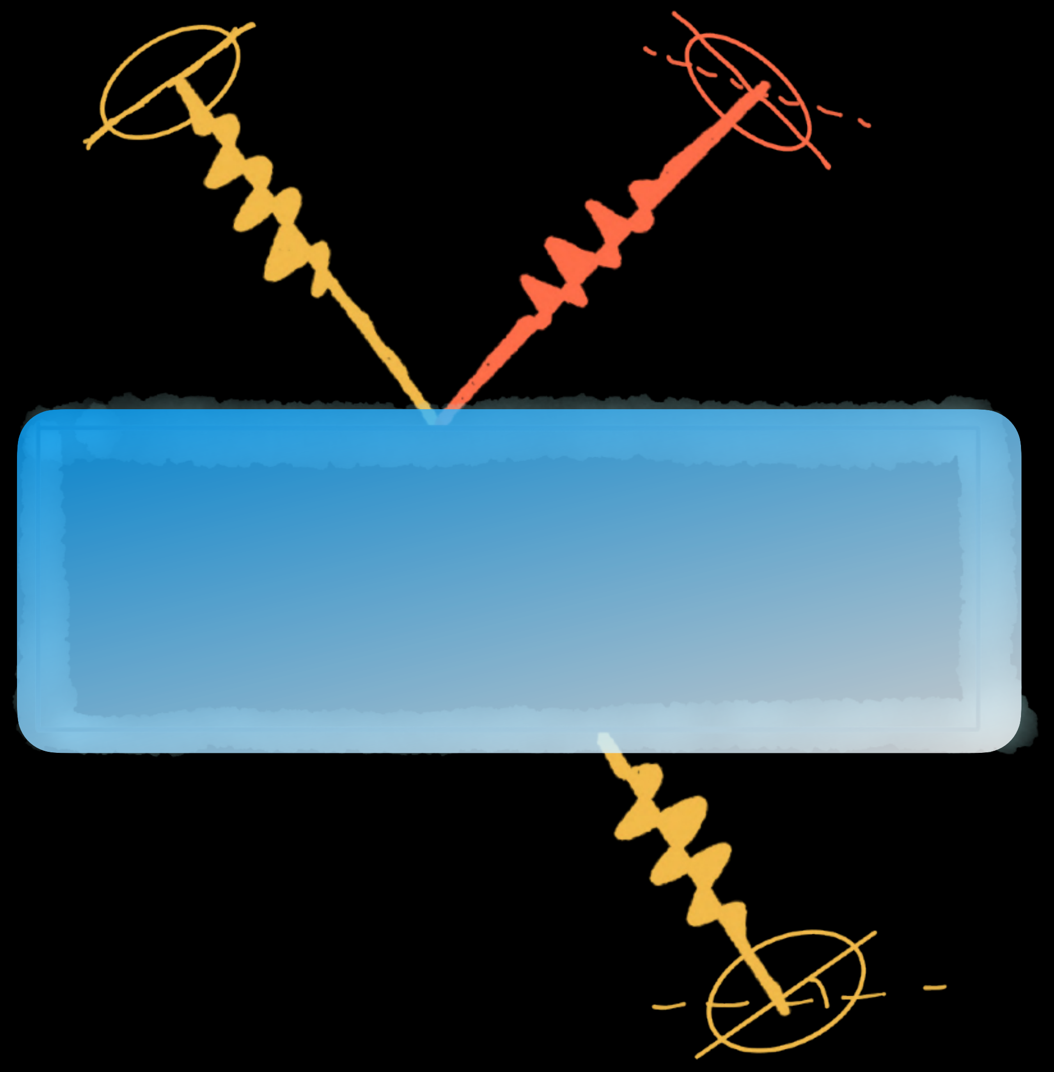


Topological invariants

$$(-1)^{\nu} = \prod_{\text{TRIM}} \zeta_i$$

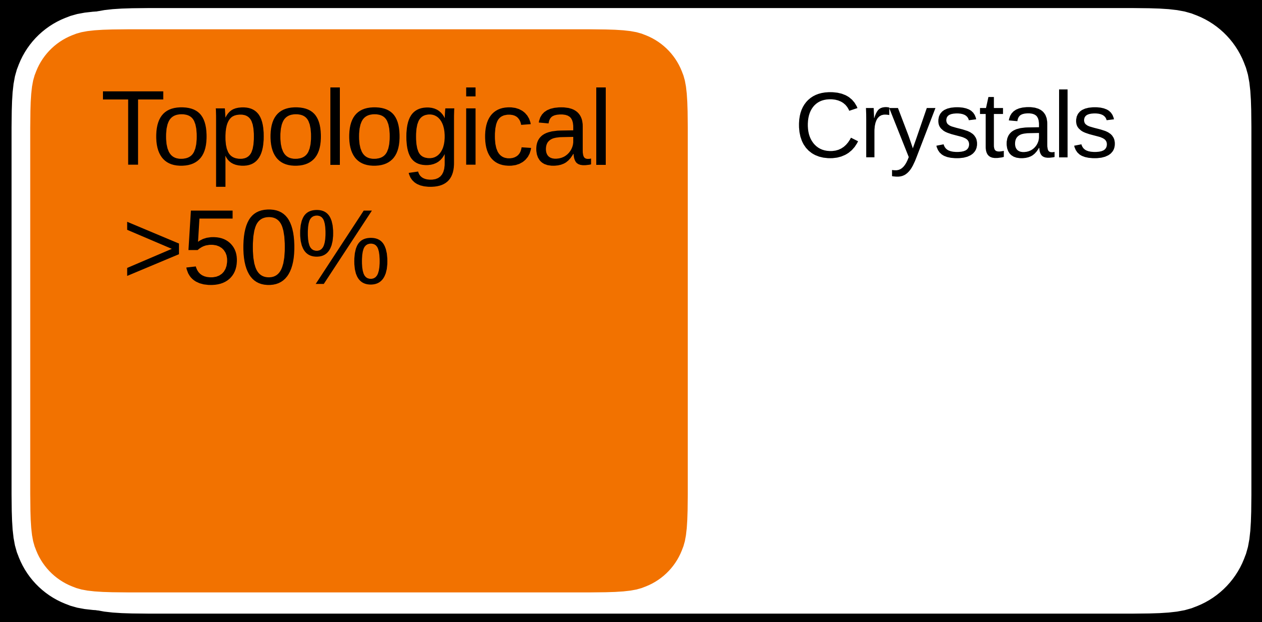
symmetry eigenvalues

Quantized responses



e.g. quantised quantum Hall
quantised Kerr rotation

Topological solids



Vergniory et al. Nature (2019)

Zhang et al. Nature (2019)

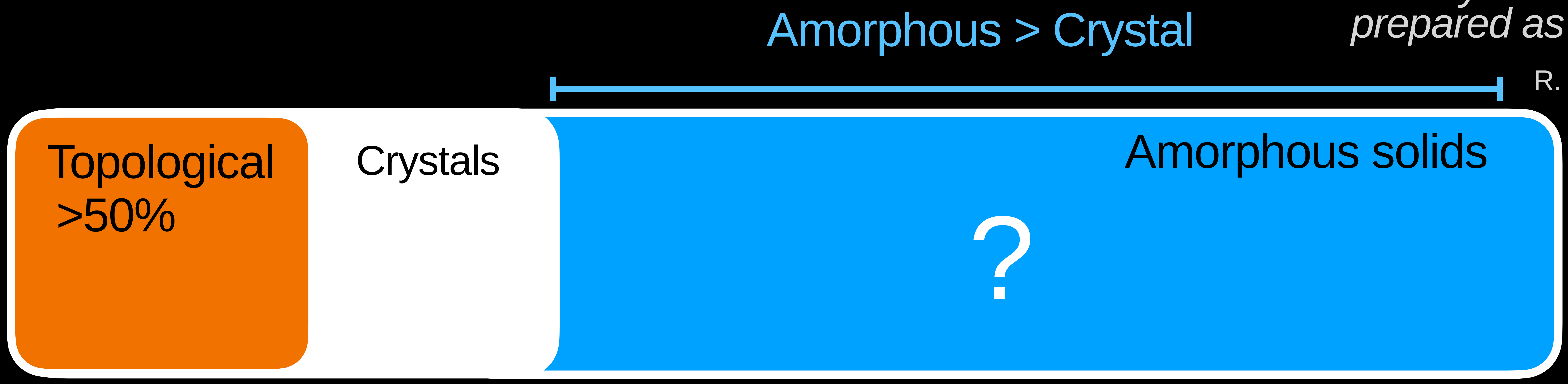
Tang et al. Nature (2019)

Topological solids

Topological solids

"Nearly all materials can […] be prepared as amorphous solids"

R. Zallen, *Amorphous Solids*



Topological solids

"Nearly all materials can […] be prepared as amorphous solids"

R. Zallen, *Amorphous Solids*

Amorphous > Crystal

Topological >50%

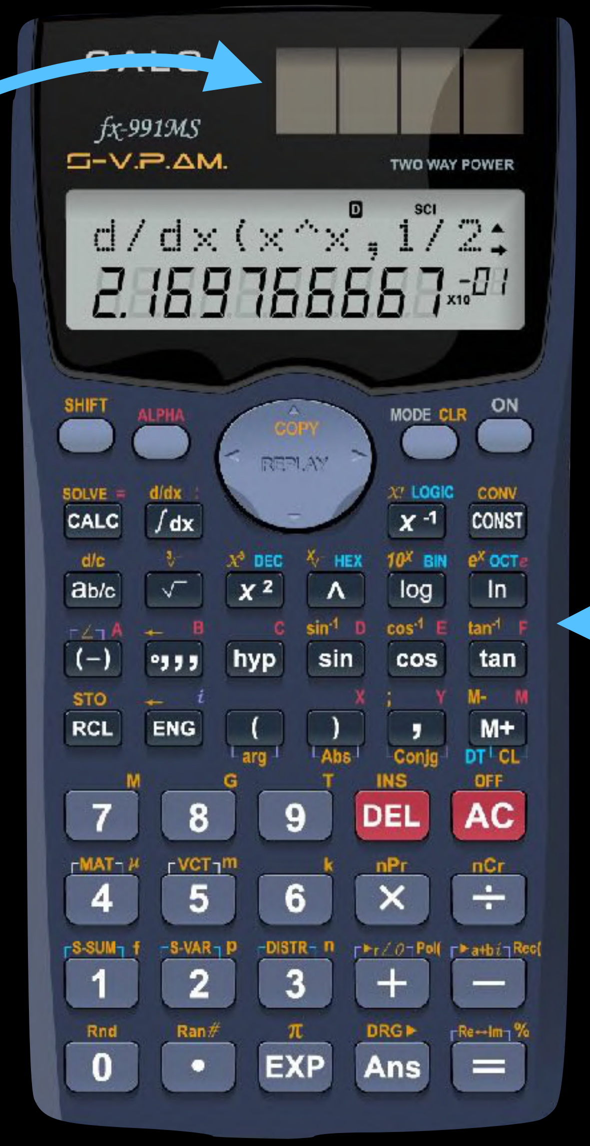
Crystals

Amorphous solids

?

Cheap and scalable

Solar cells



Memories

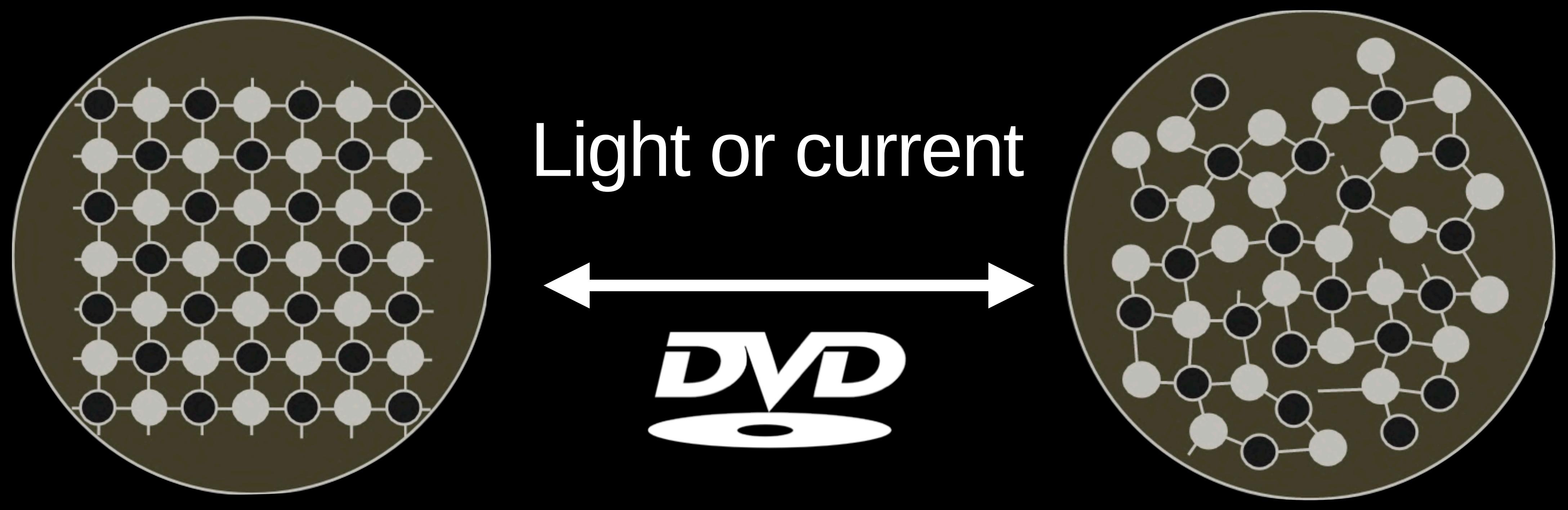
Topological solids

"Nearly all materials can […] be prepared as amorphous solids"

R. Zallen, *Amorphous Solids*

Amorphous > Crystal

Different capabilities



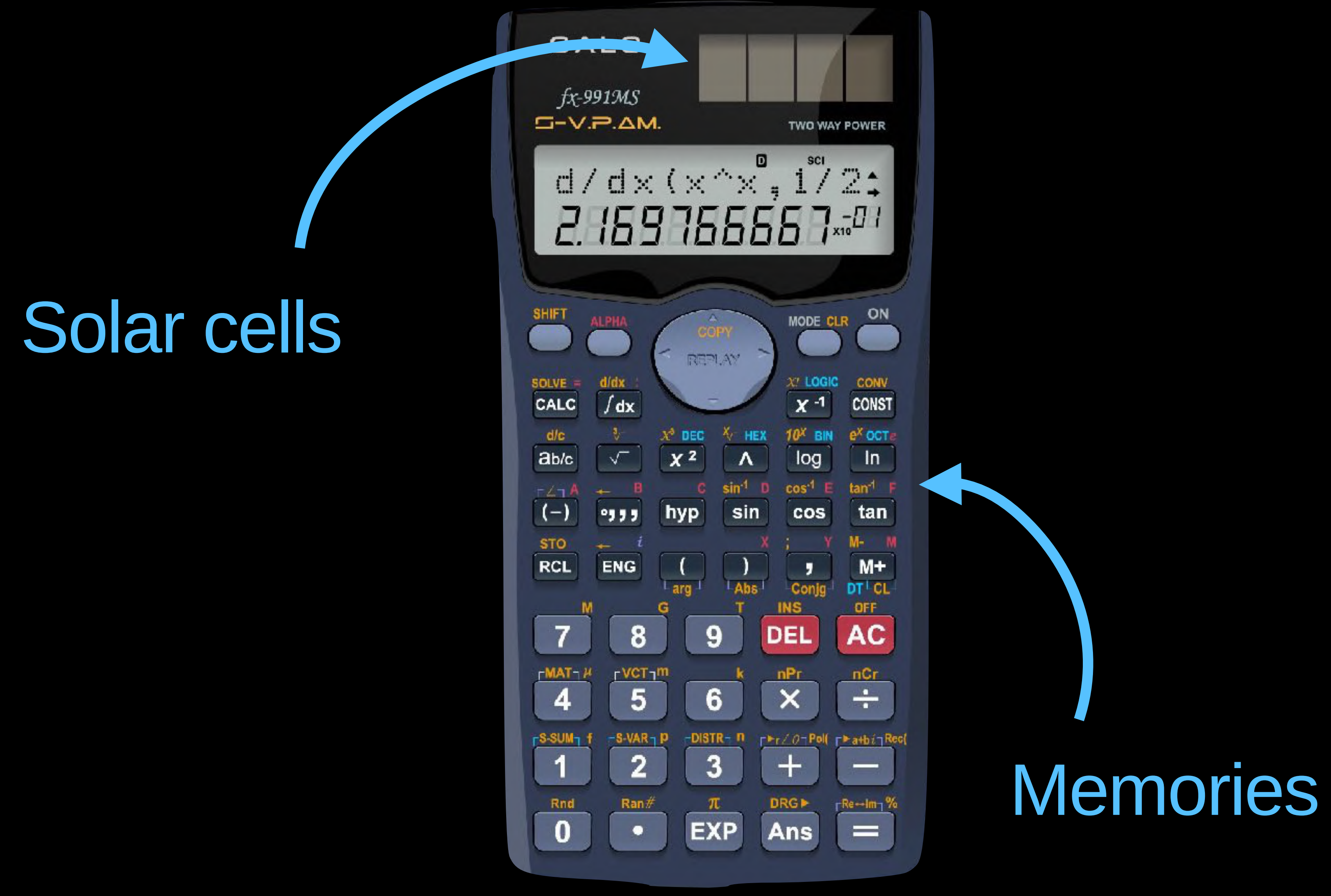
Crystal

Amorphous

Mathias, Naboro Nat Mat (2007)

Q. Marsal, D. Varjas, AGG Phys Rev B, (2023)

Cheap and scalable

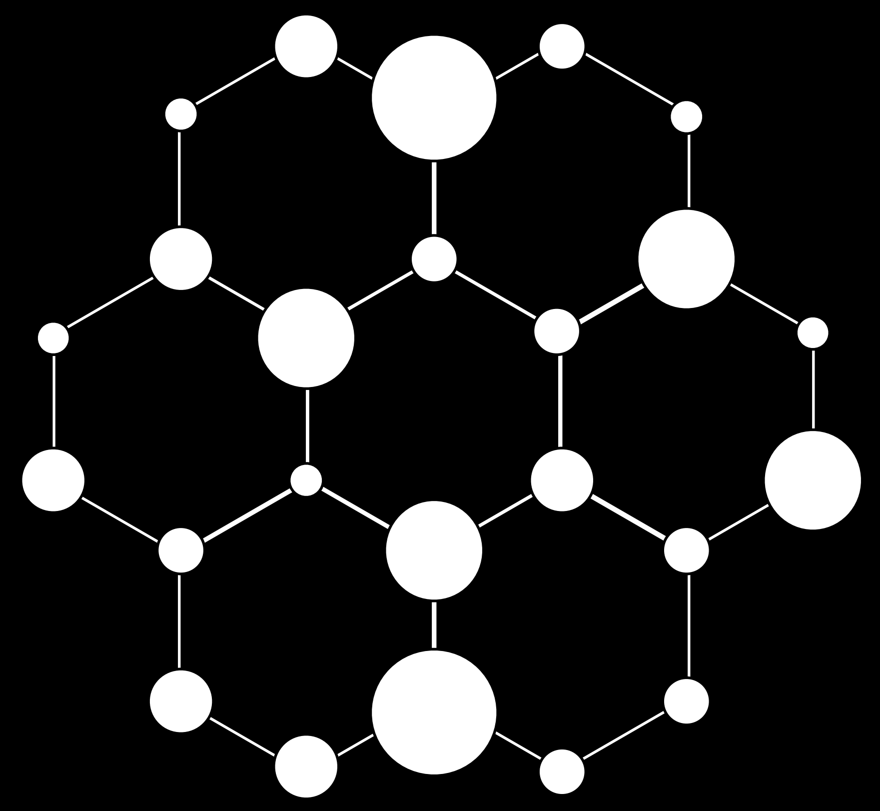


Topology survives disorder

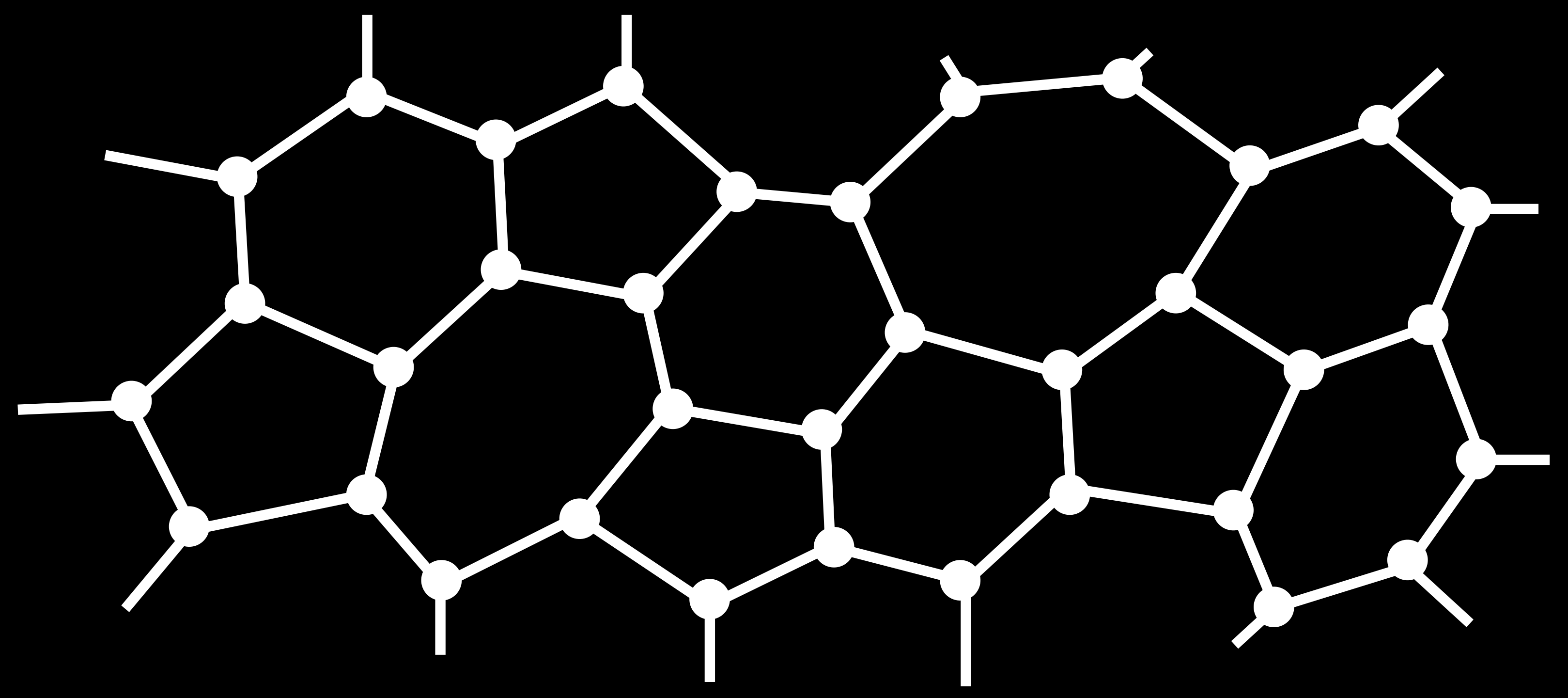
Some choices

Bond disorder

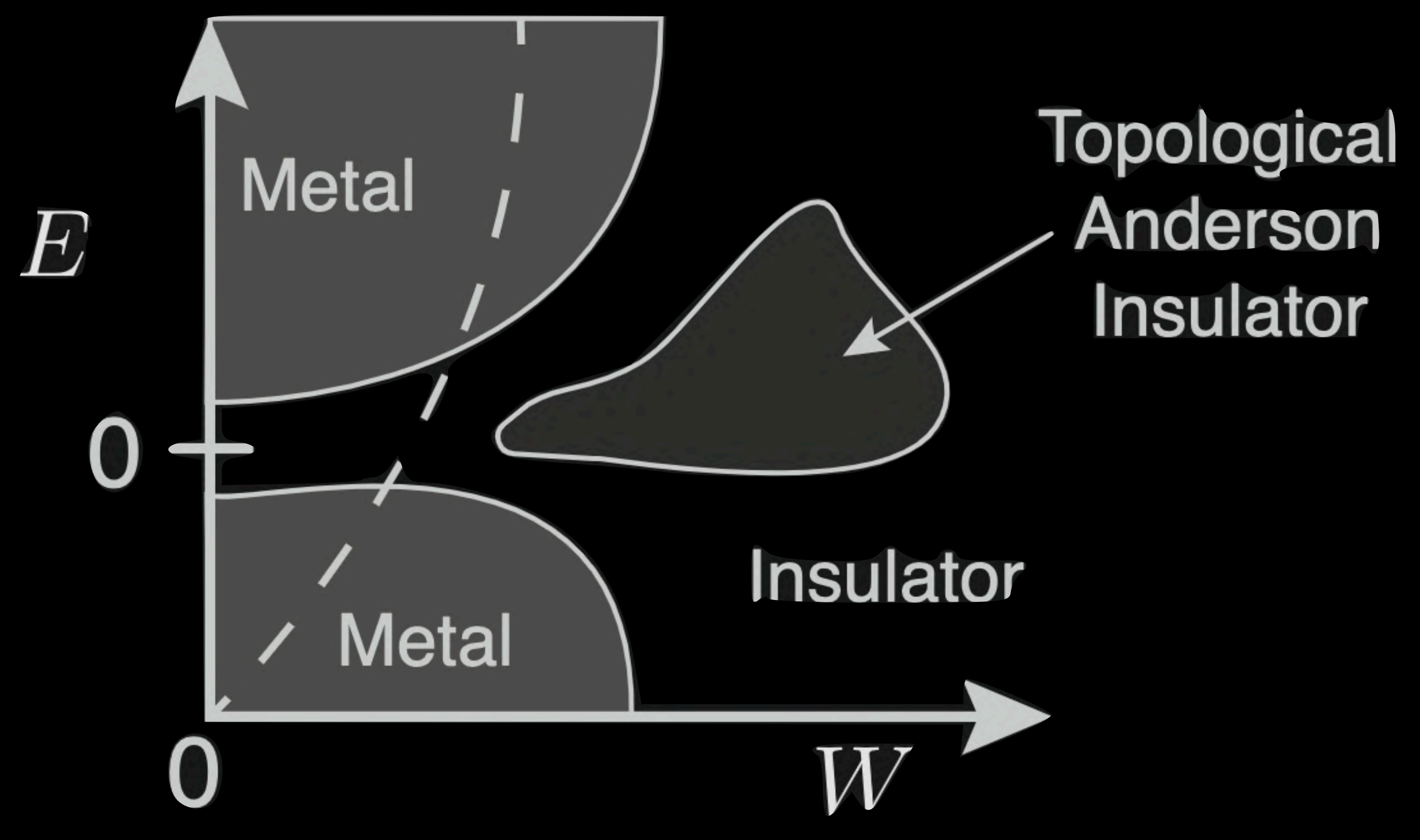
Onsite disorder



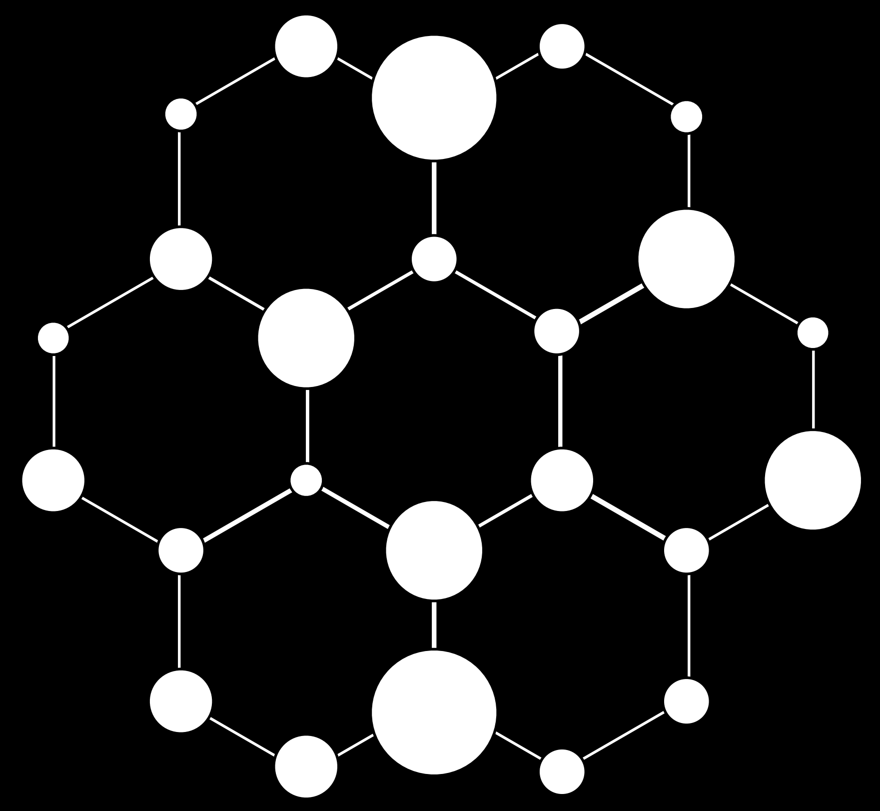
Structural disorder



Topology from disorder



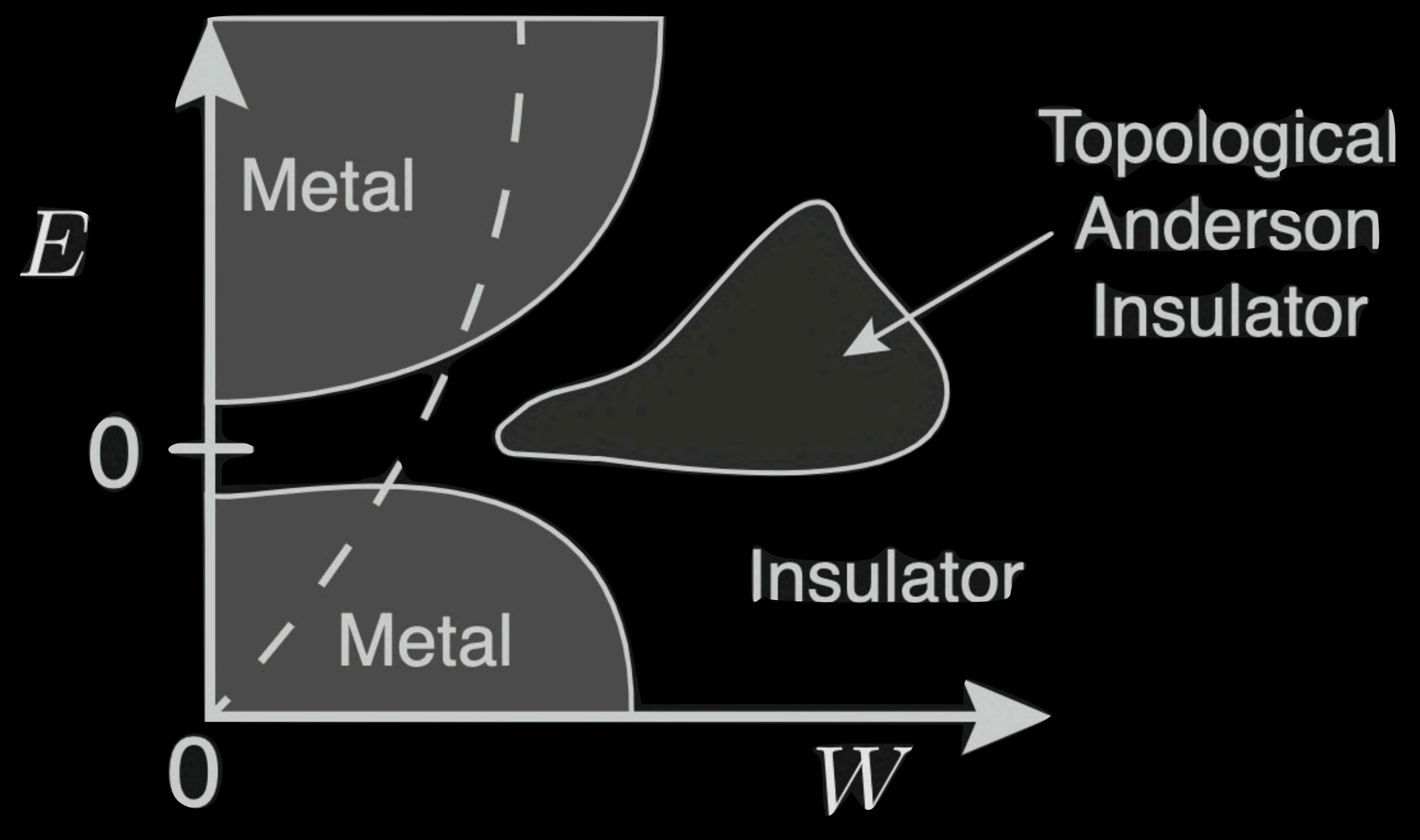
Onsite disorder



Li et al PRL (2009)
Groth et al. PRL (2009)

Topology without translations

Disordered systems



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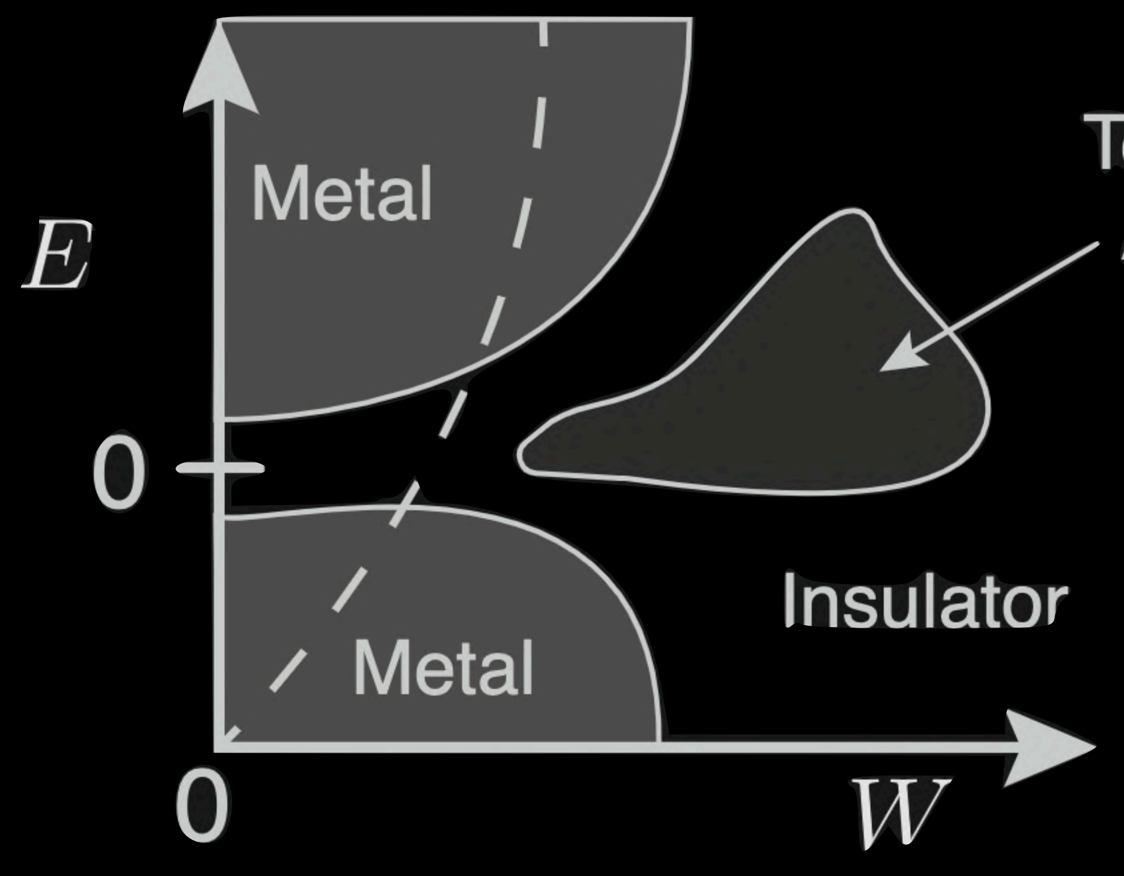
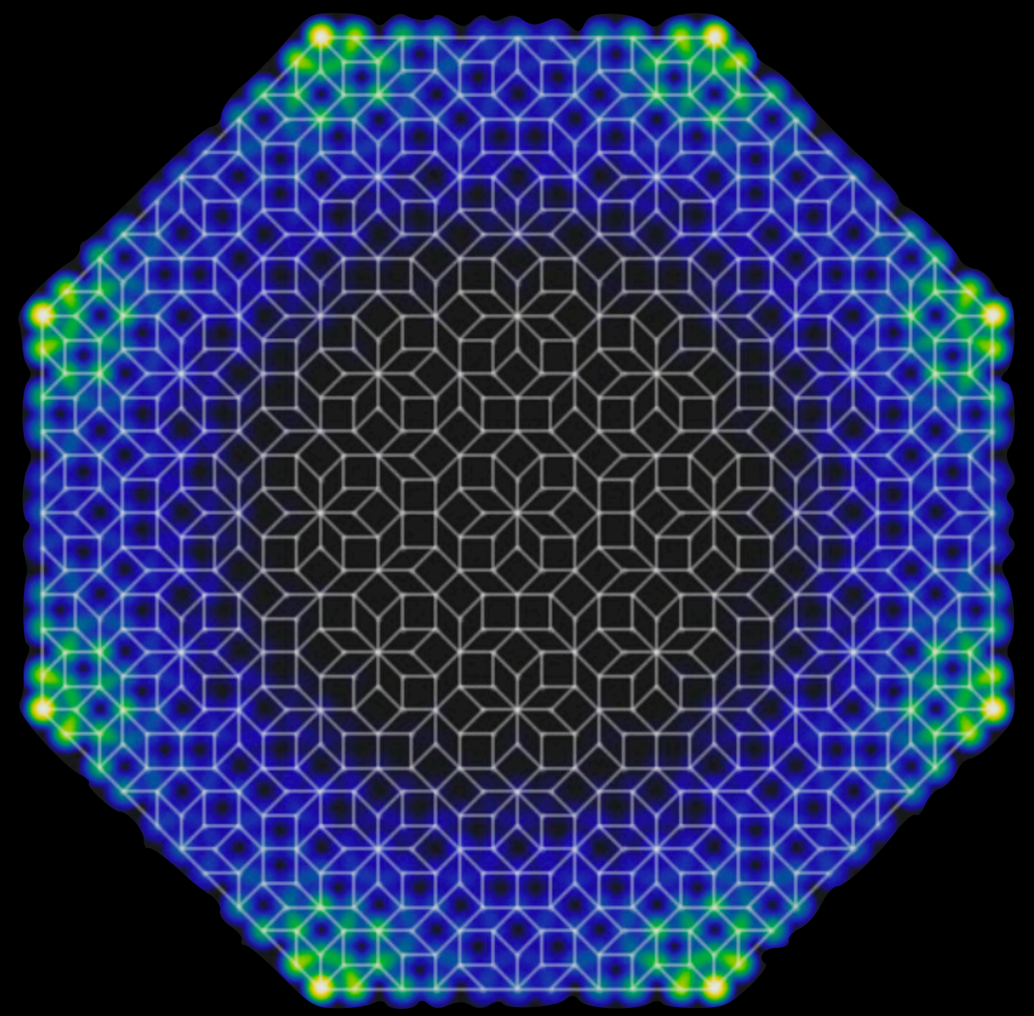
Topology without translations

Disordered systems



Li et al PRL (2009)
Groth et al. PRL (2009)

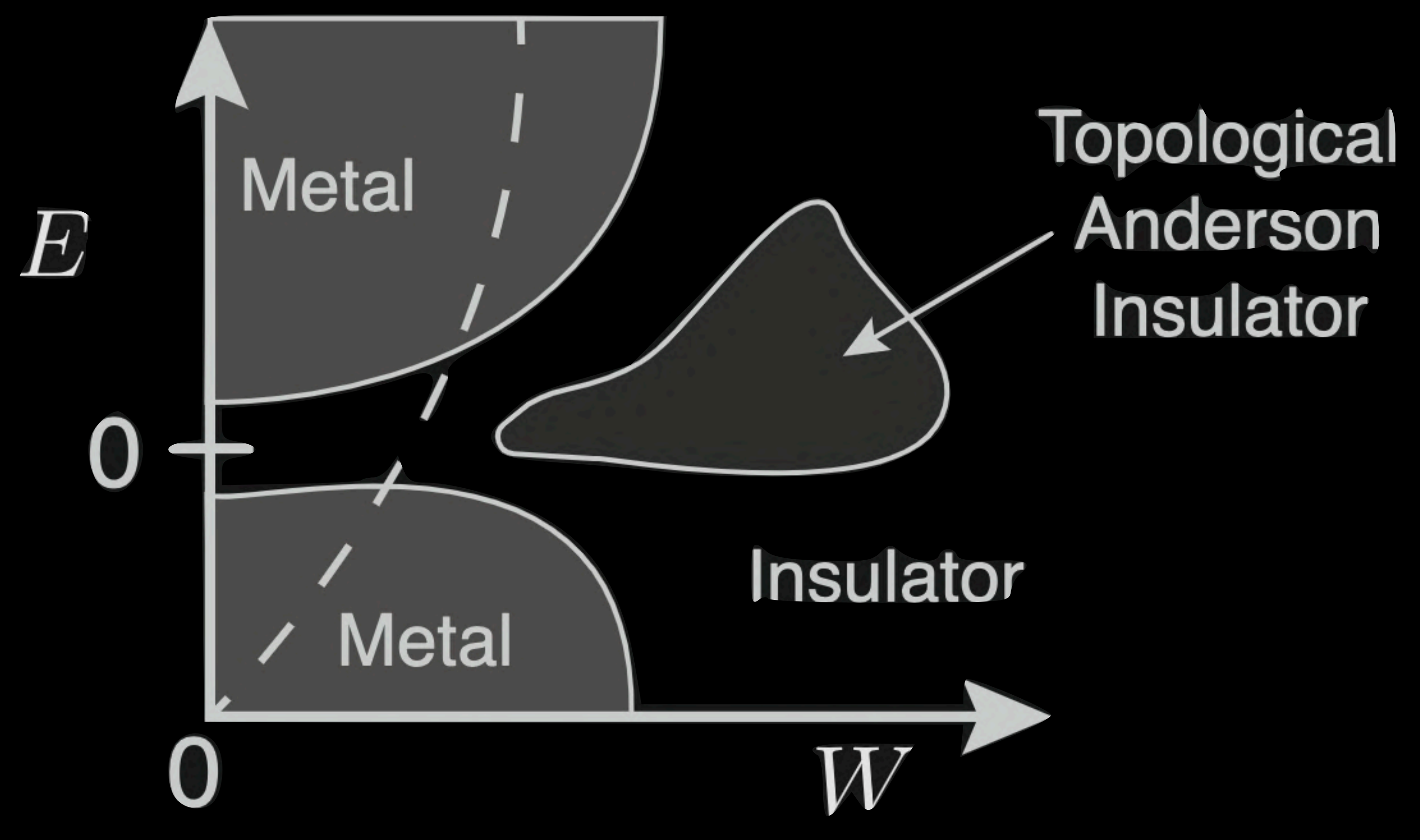
Quasicrystals



Fuchs and Vidal PRB (2016)
Varjas et al. PRL (2019)
Else et al. PRL (2021)

Topology without translations

Disordered systems



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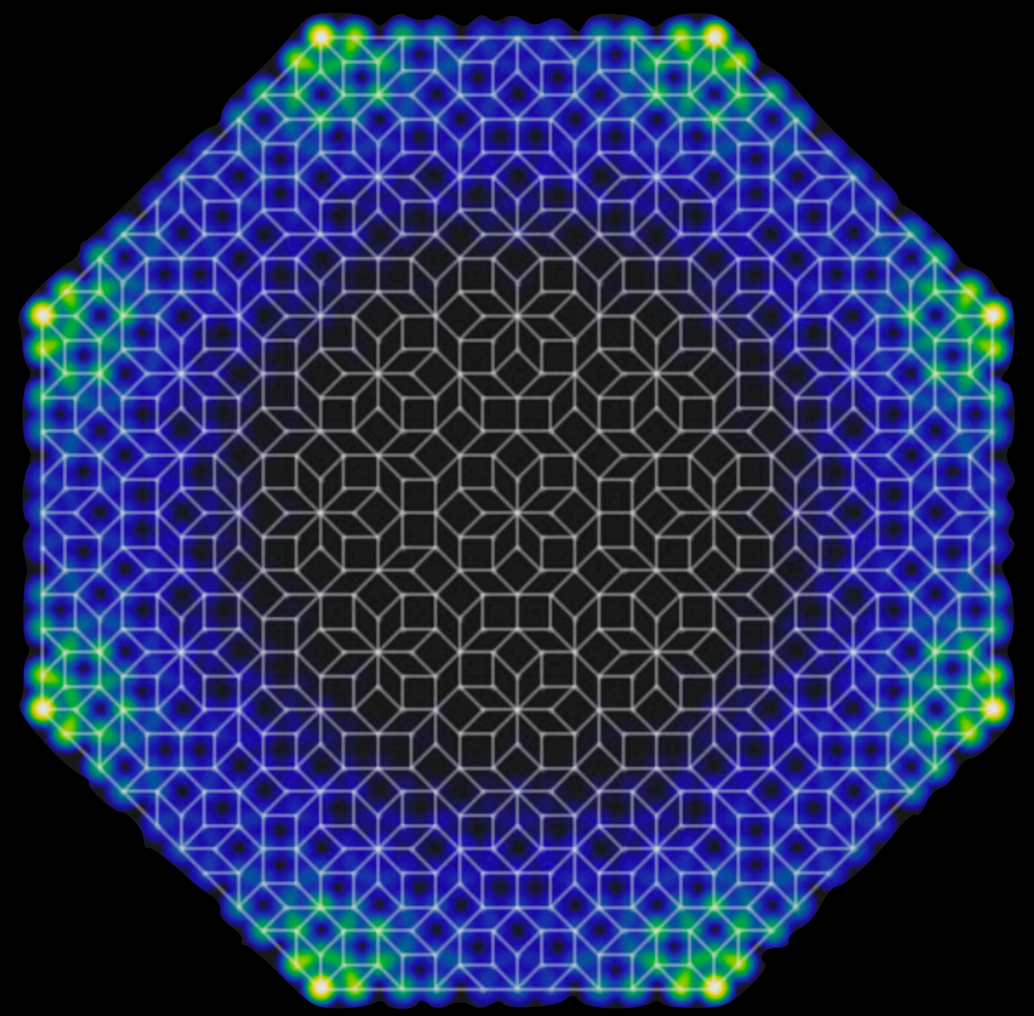

Fuchs and Vidal PRB (2016)
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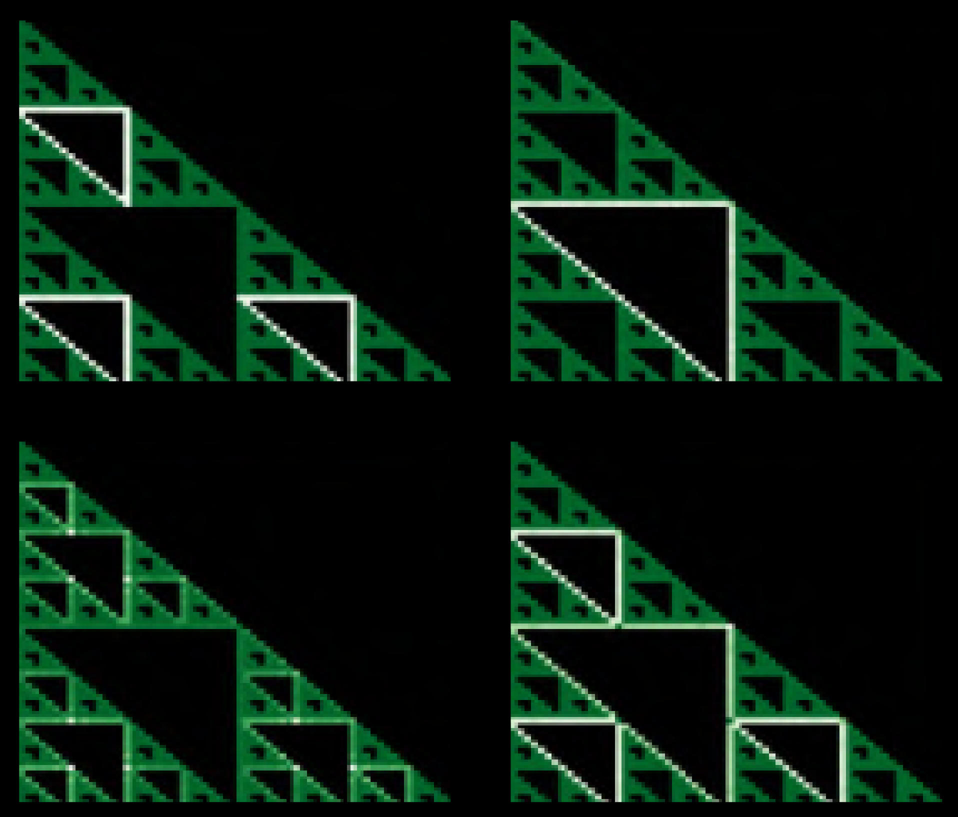
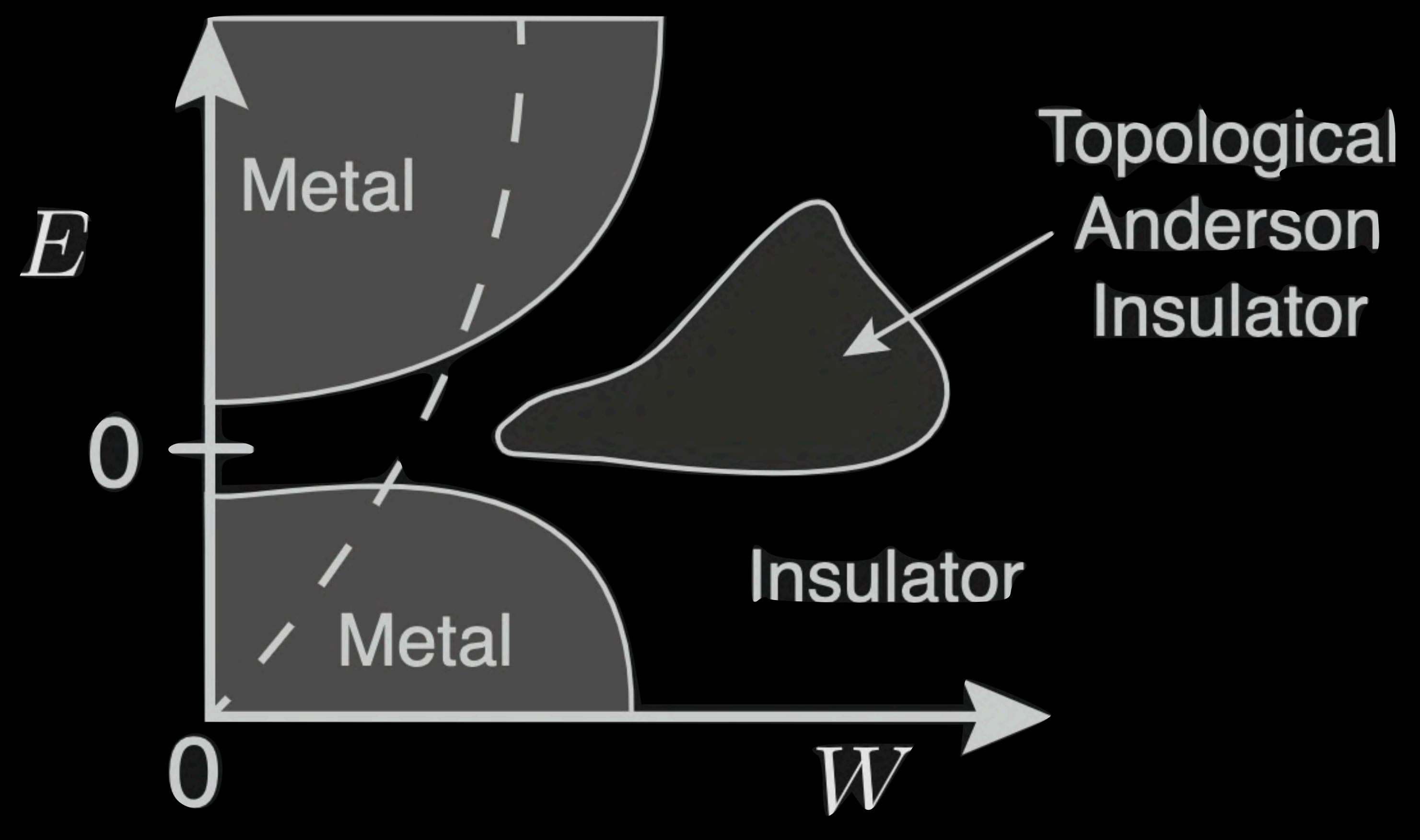
Fractals



Brzezinska et al. PRB (2018)

Topology without translations

Disordered systems



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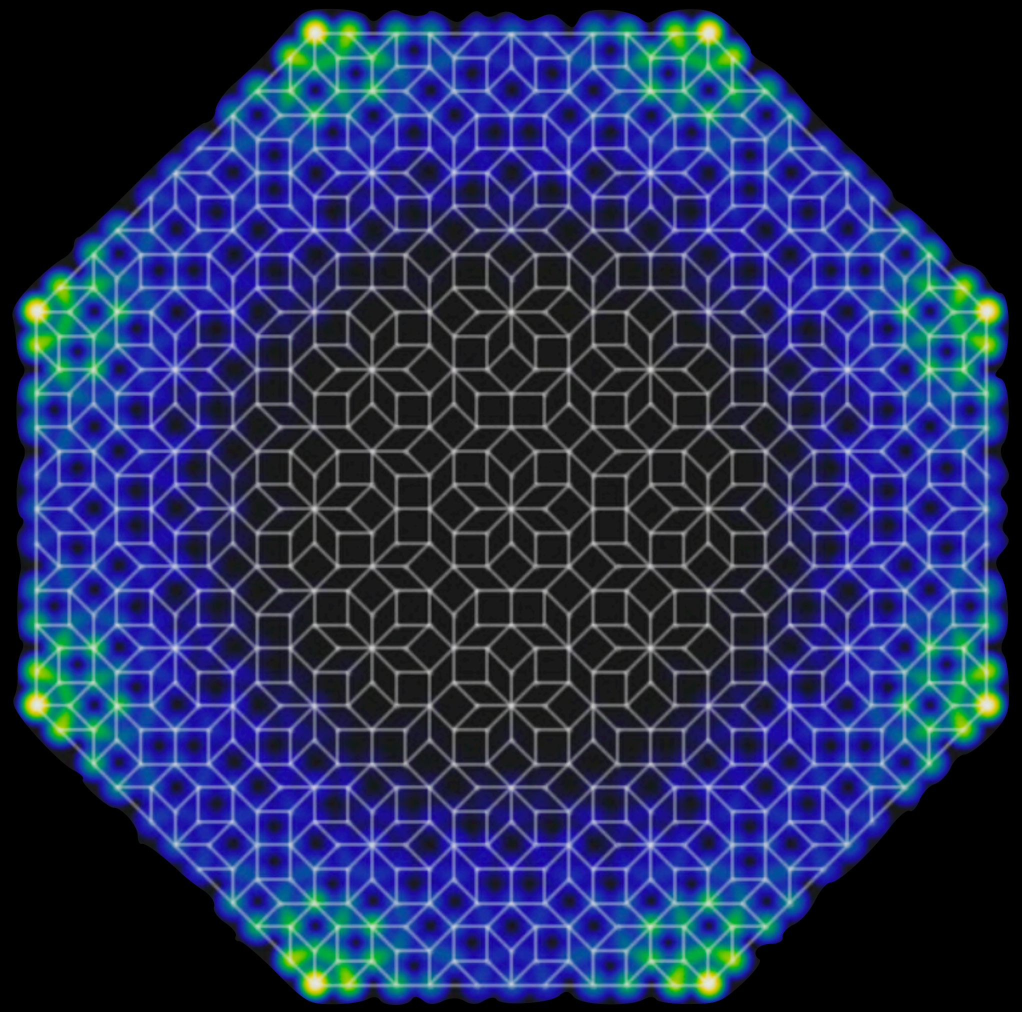
Quasicrystals



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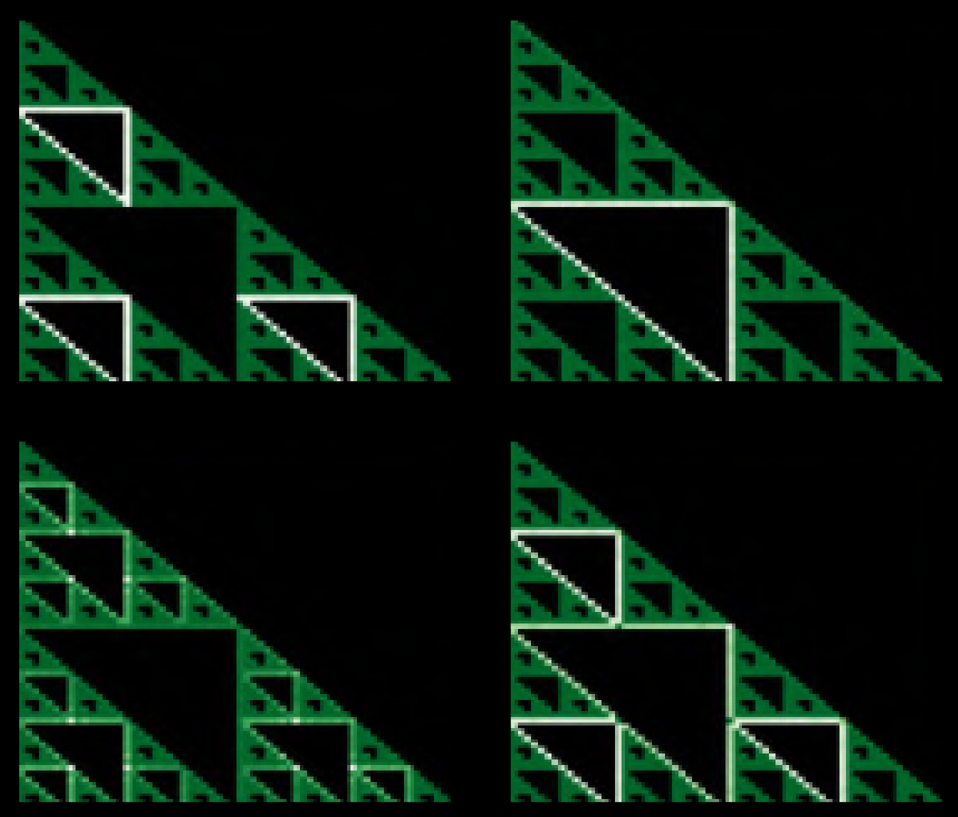
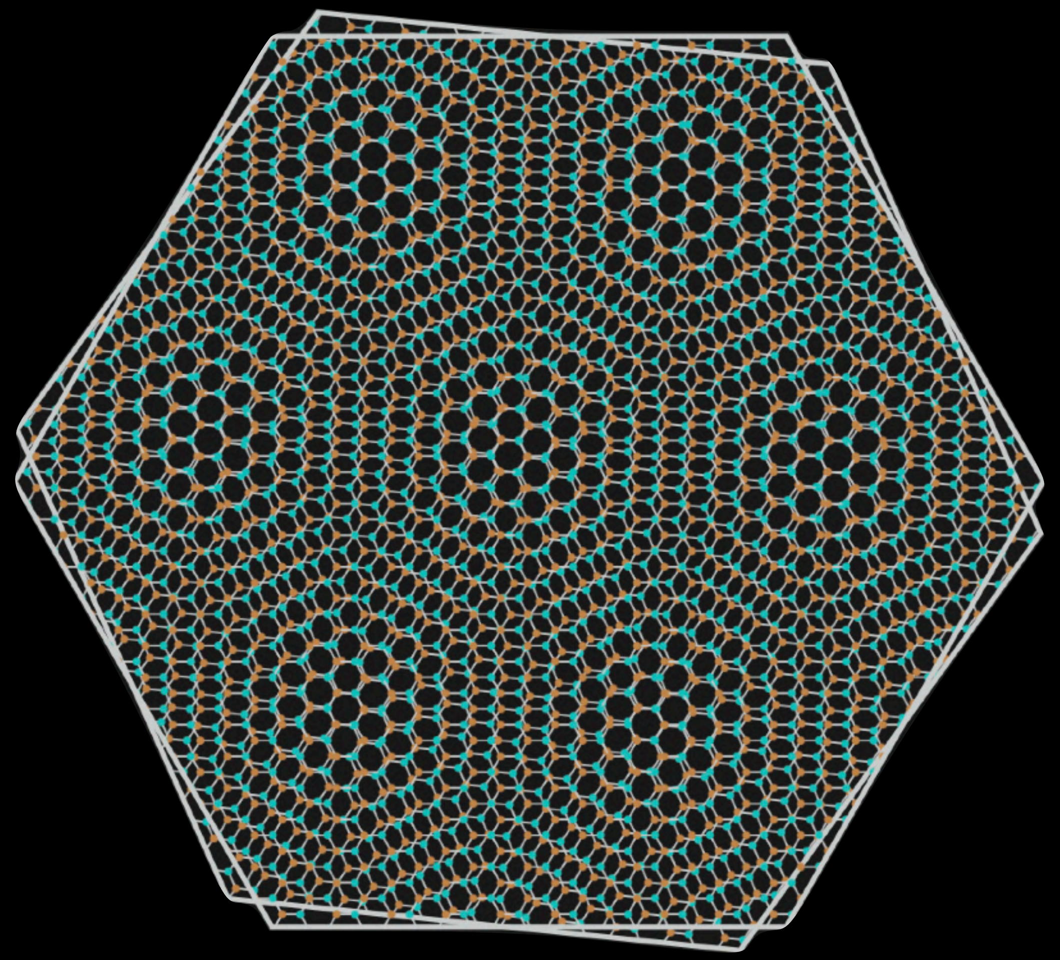
Fractals



Brzezinska et al. PRB (2018)

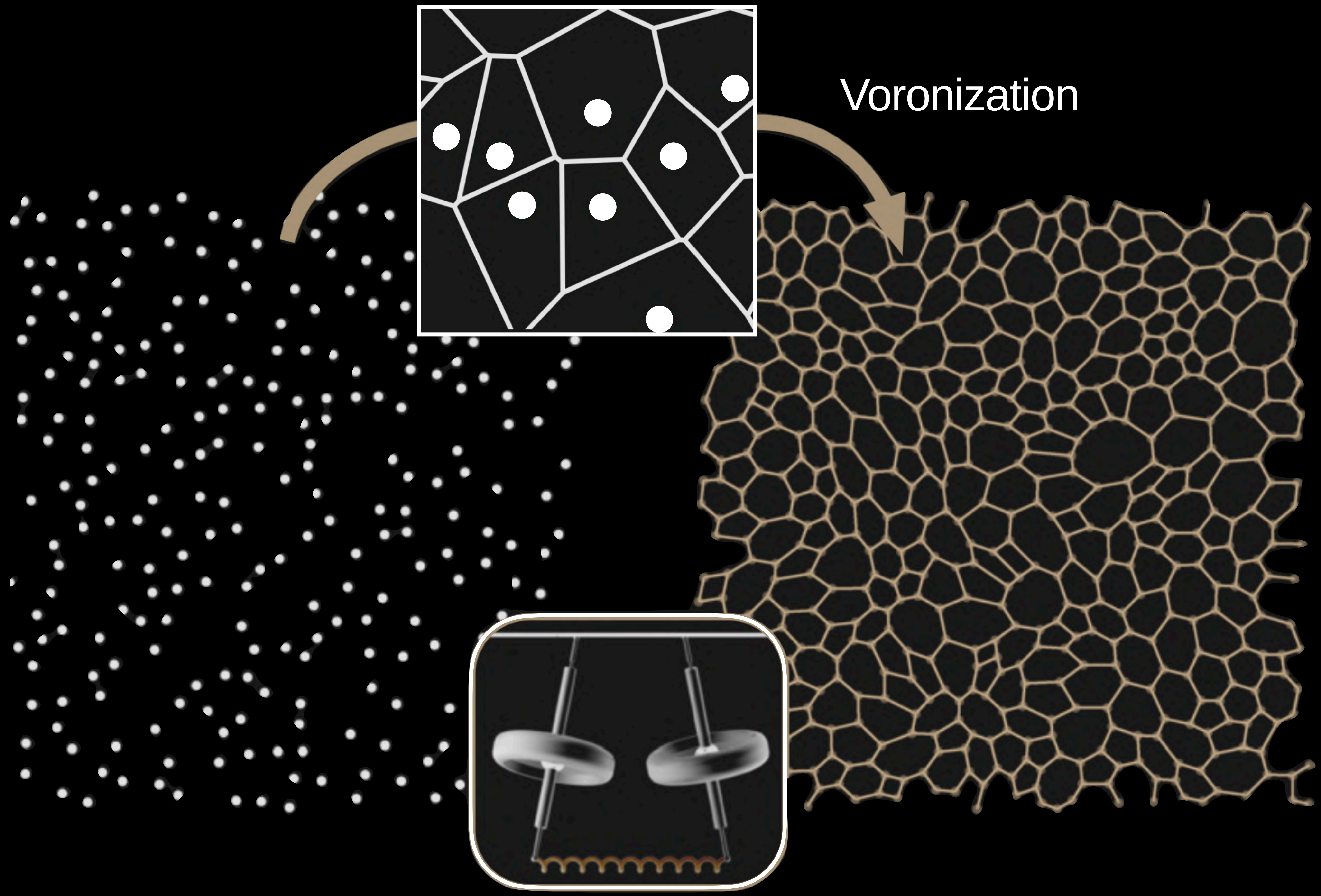
Moiré superlattices



Cao et al. Nature (2018)

A recent addition: amorphous topological phases

Synthetic systems:



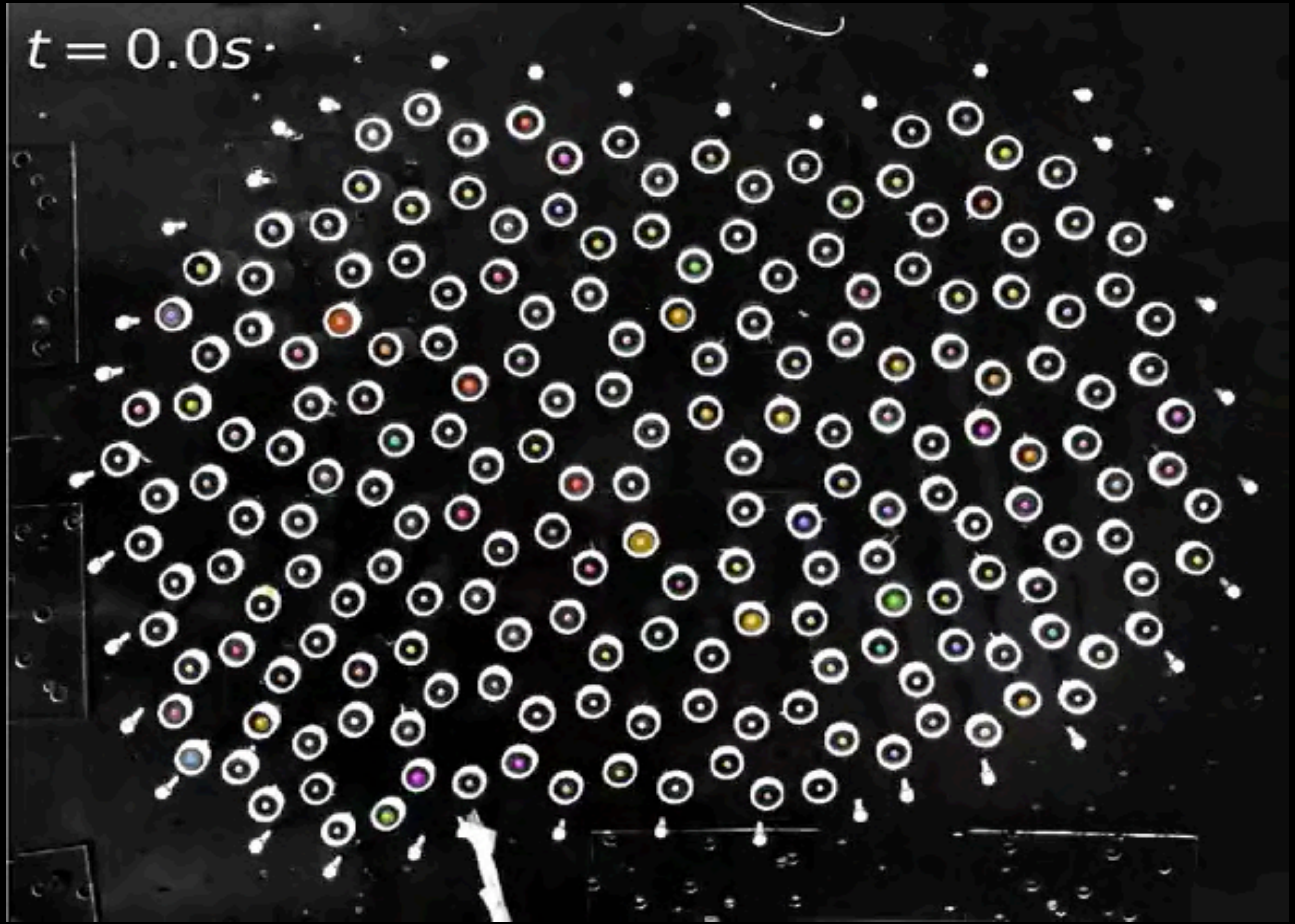
Theory:

Mitchell, et al. Nat Phys (2018)
Agarwala, Shenoy PRL (2017)
Xia and Fan PRB (2017)
Mansha and Shong PRB (2018)

Exp: Mitchell, et al. Nat Phys (2018)

A recent addition: amorphous topological phases

Synthetic systems:



Theory:

Mitchell, et al. Nat Phys (2018)
Agarwala, Shenoy PRL (2017)
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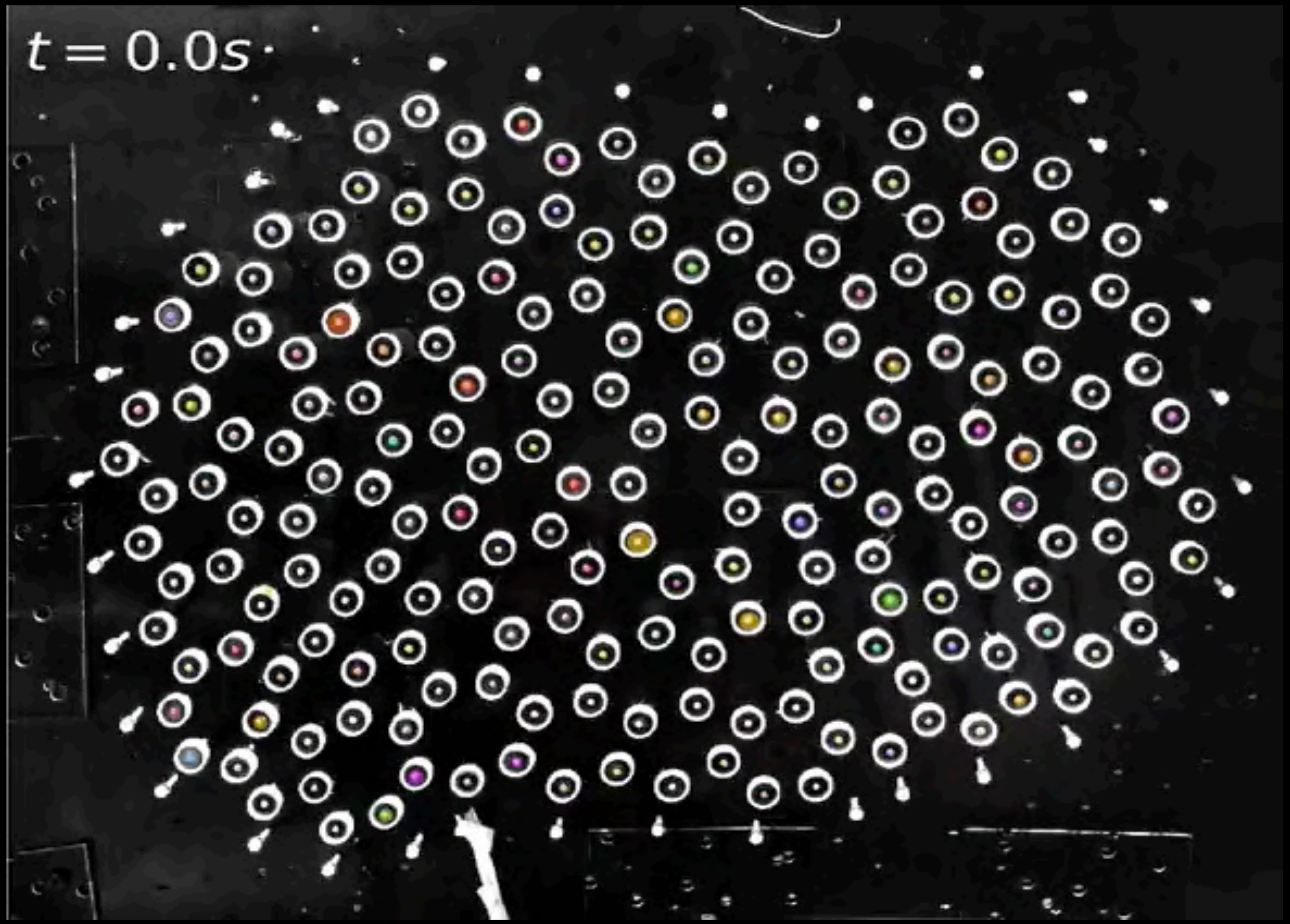

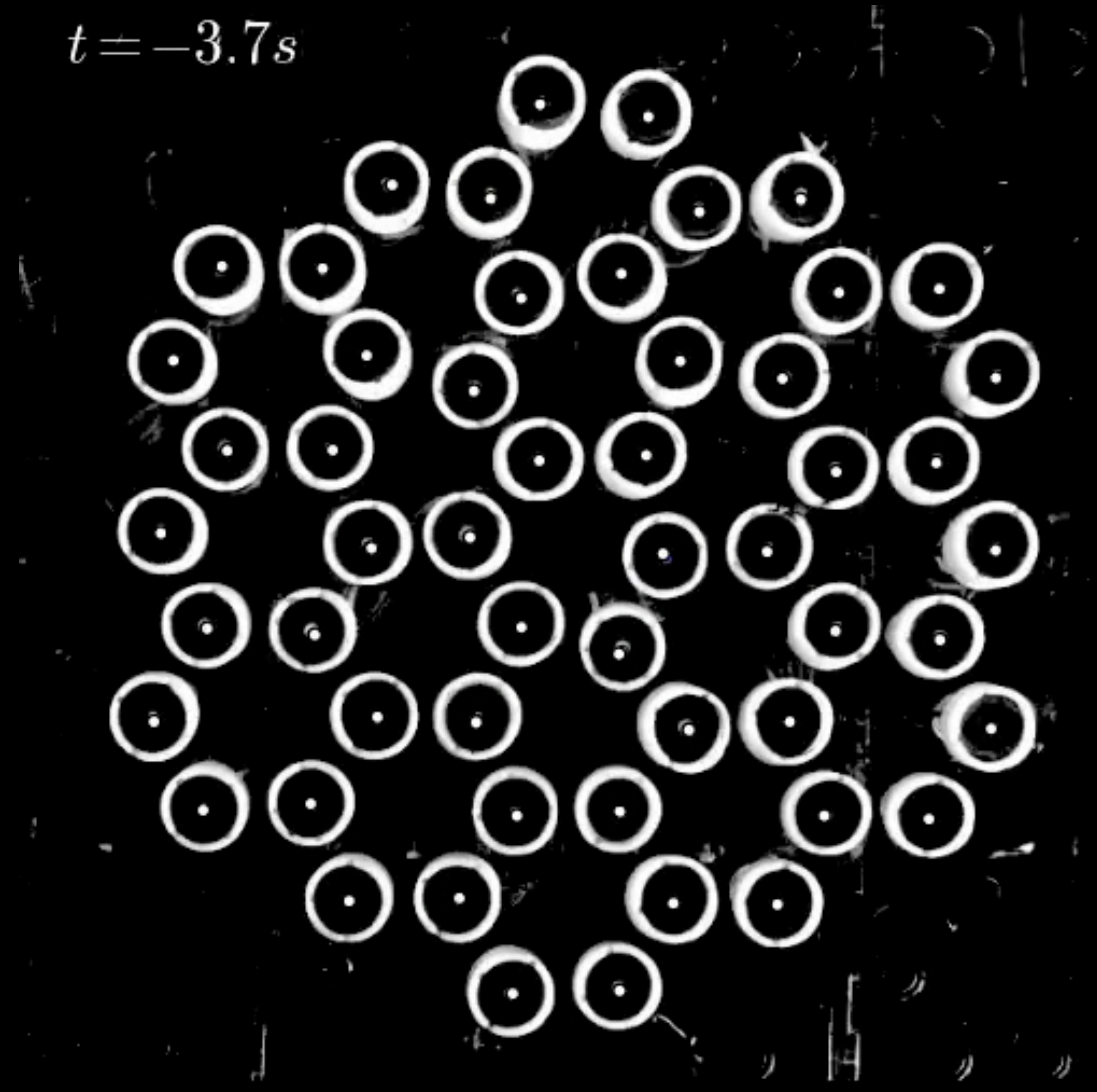

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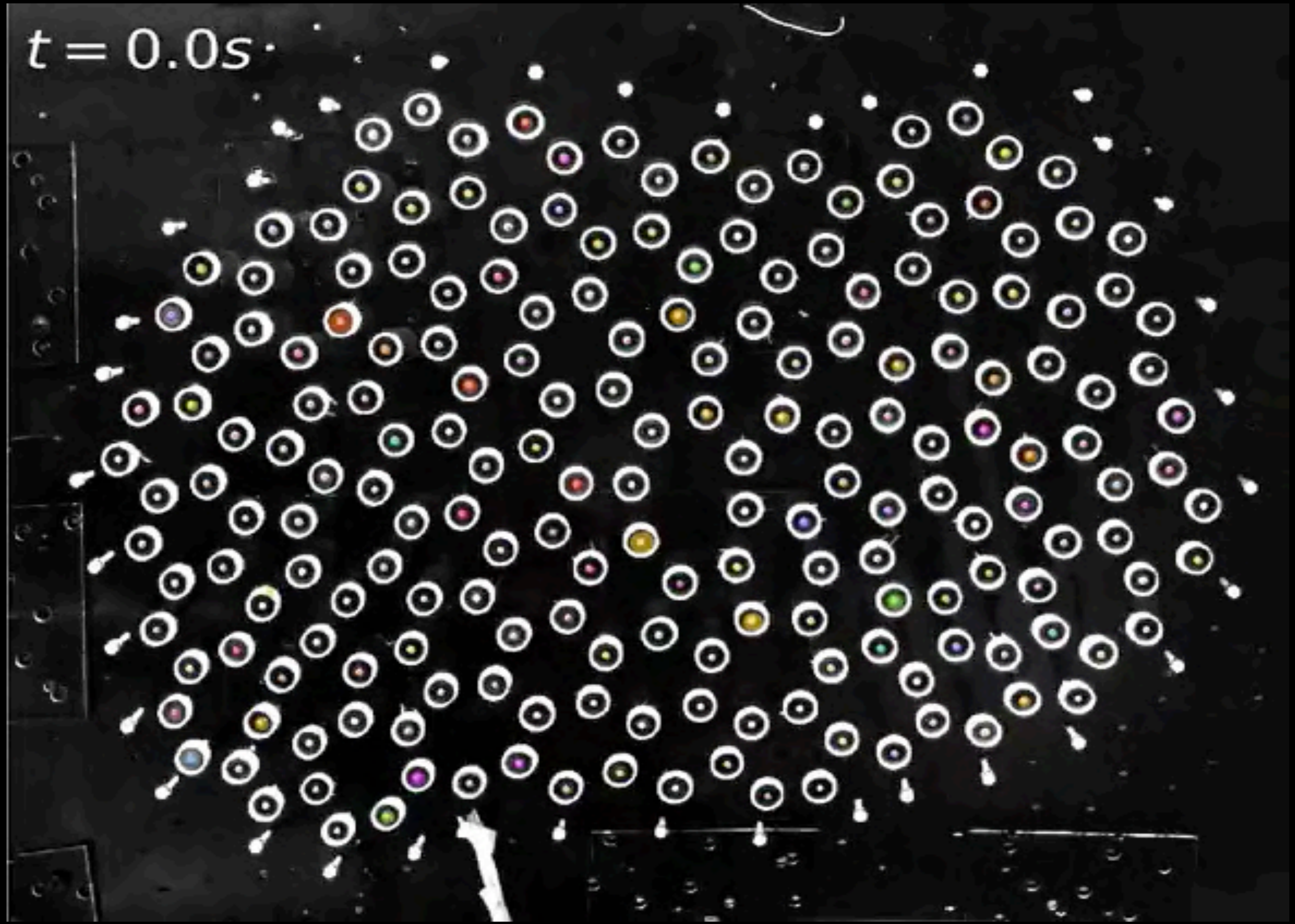

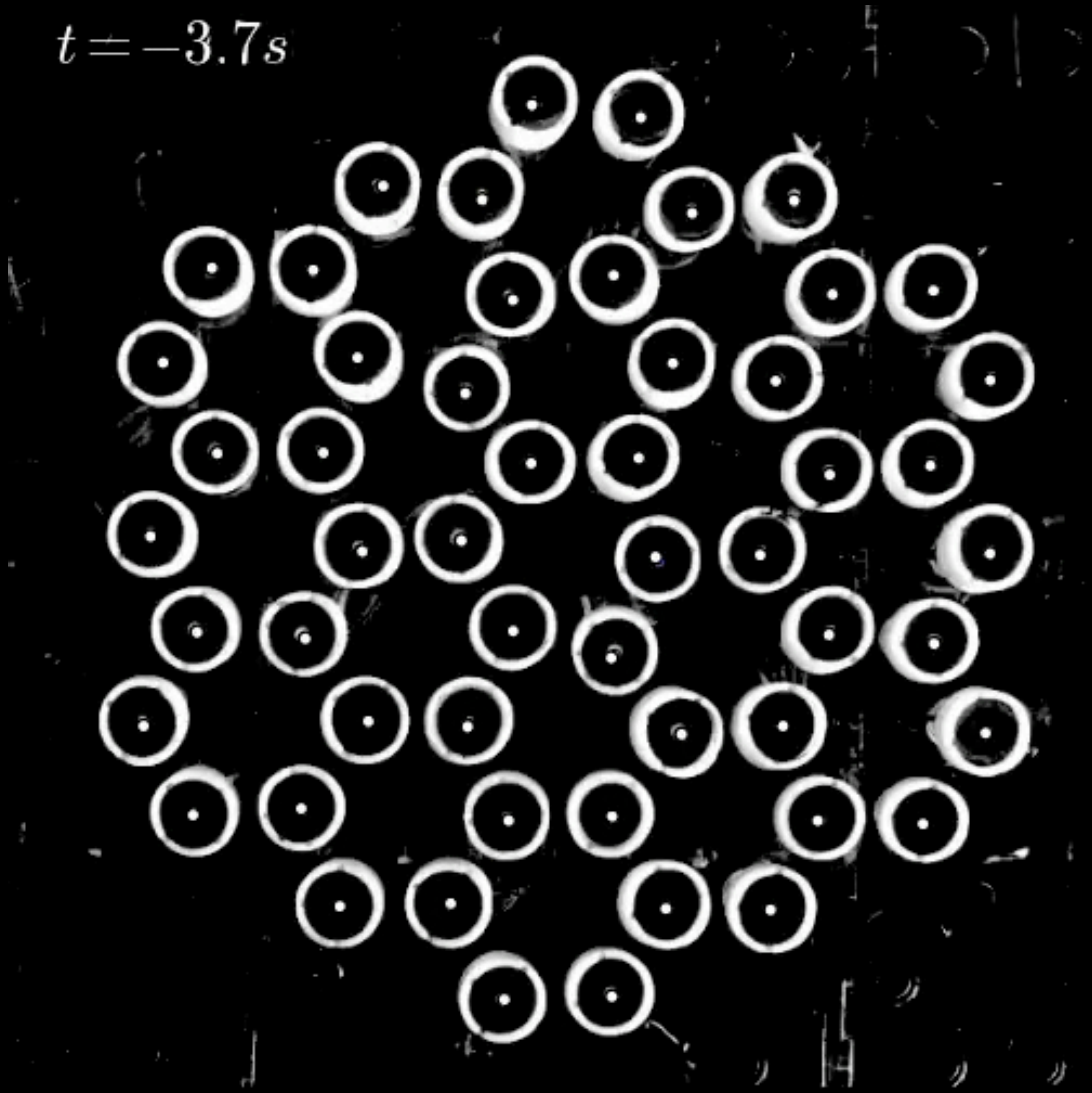

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Exp:

Mitchell, et al. Nat Phys (2018)
Liu et al PRL (2020)
Zhou et al Light: Science and App. (2020)
Jia, et al Sci. Adv. (2023)
Zhang, et al Sci. Advances (2023)

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How do we find topological amorphous solids?

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Any different physics compared to crystals?

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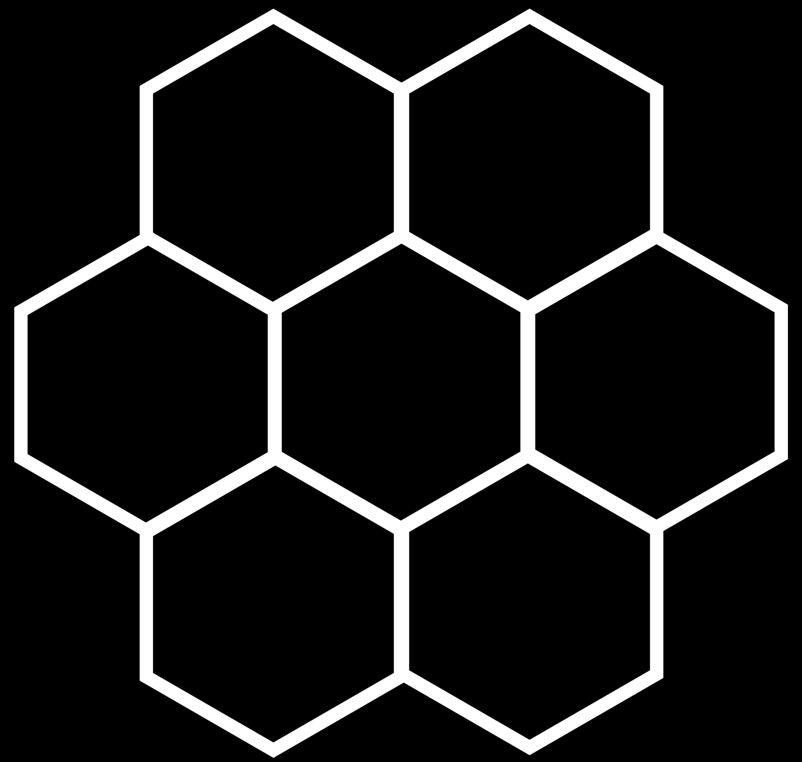
Any different physics compared to crystals?

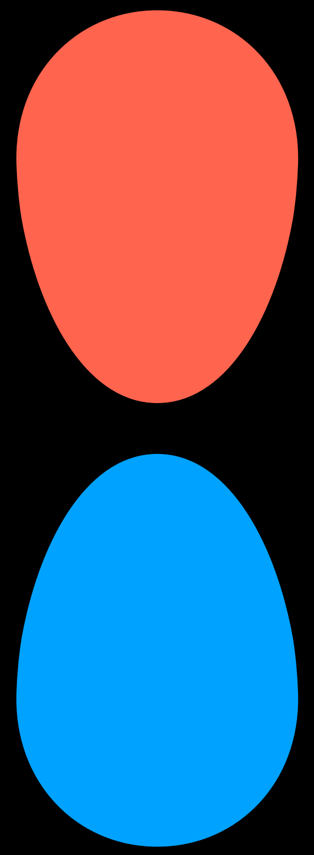
How do we find amorphous topological insulators?

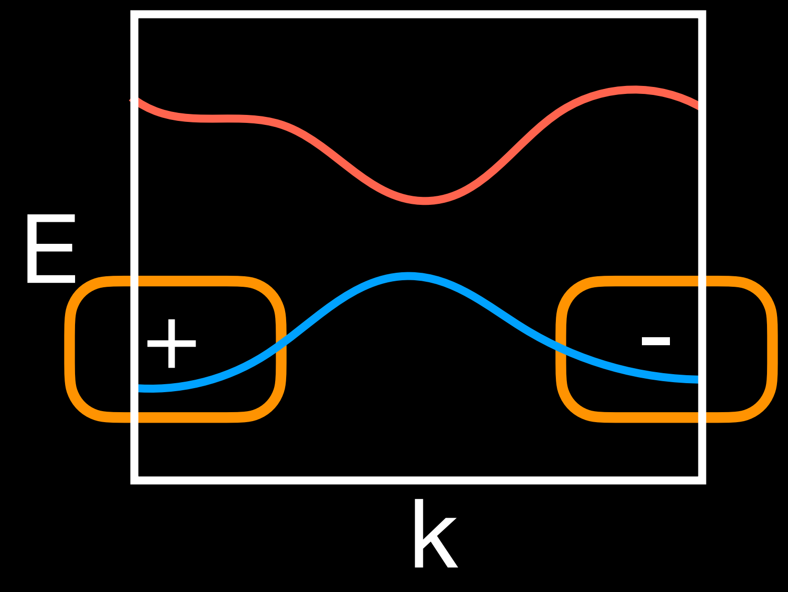
Space Group

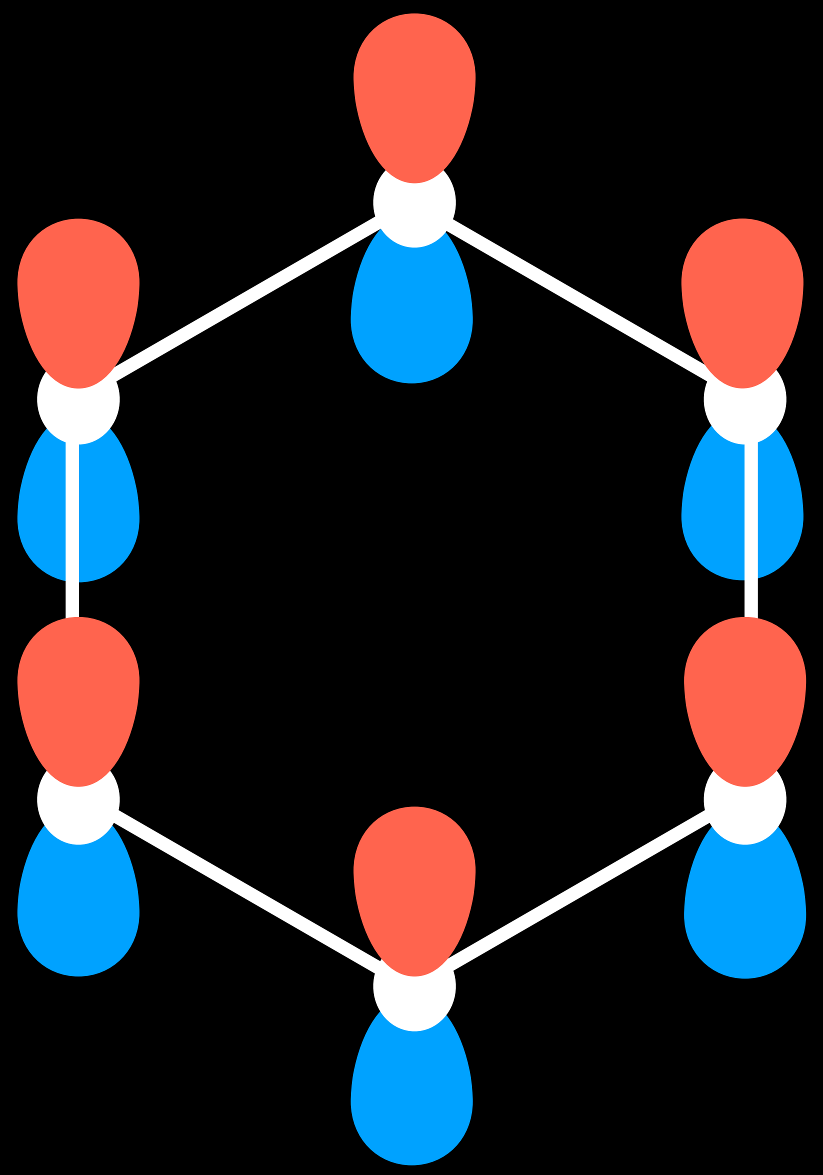
Orbitals

Atomic positions









— lattice symmetries

— wavefunctions

— band connectivity + symmetries labels

translations, rotations, inversions, mirrors

s, p, d…

Bradlyn et al Nature (2017) Kruthoff et al. Phys. Rev. X (2017) Po et al. Nat. Comm (2017) Song et al. Nat. Comm (2018)

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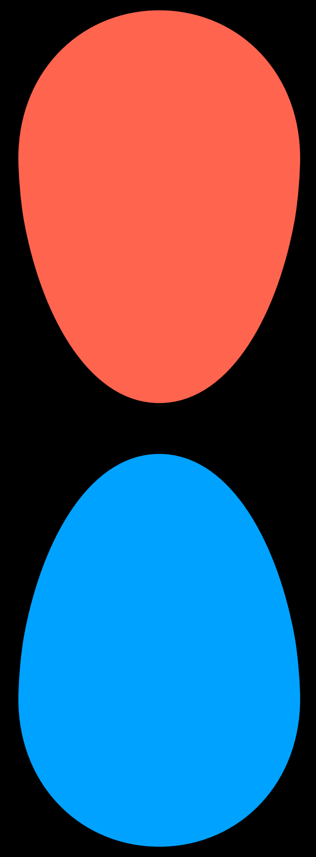

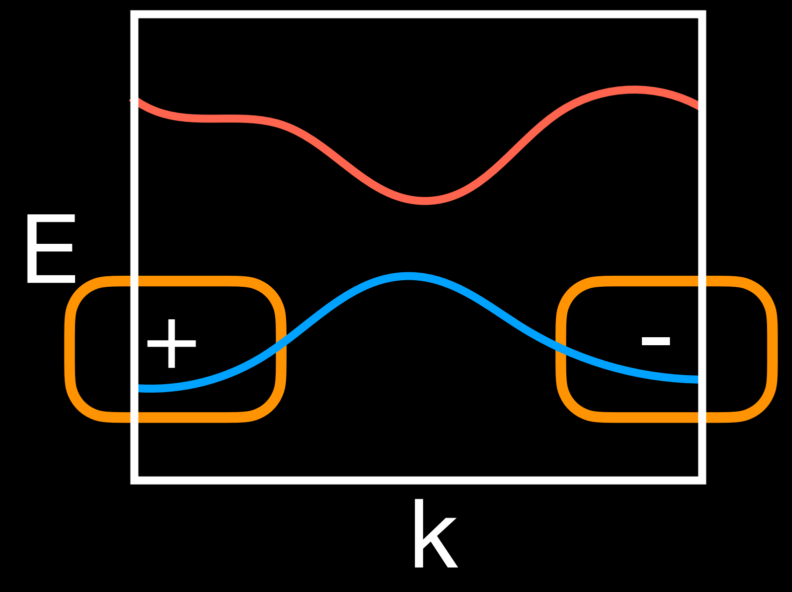

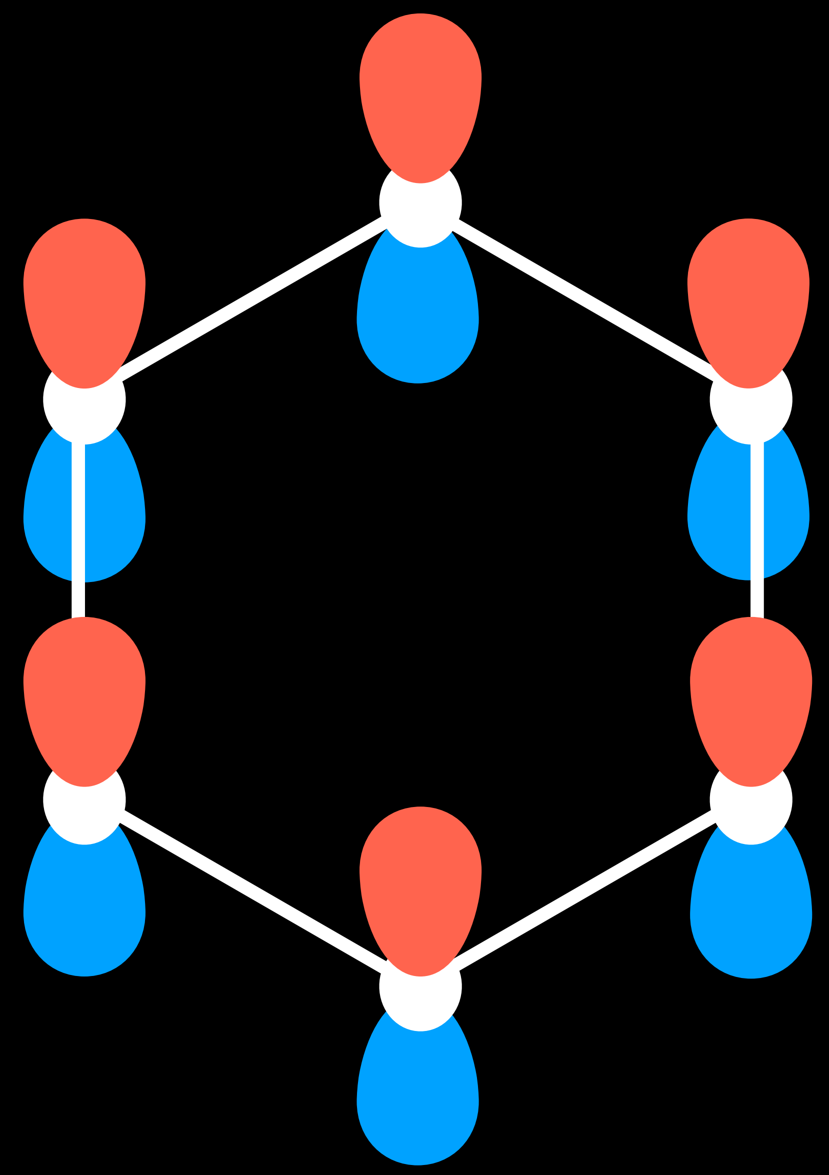

No long-range order

— lattice symmetries

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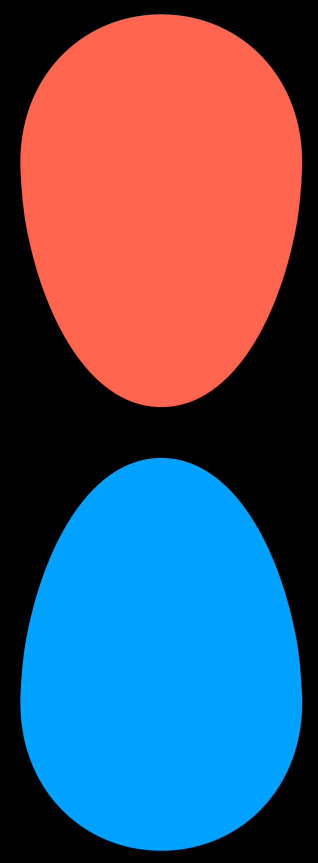

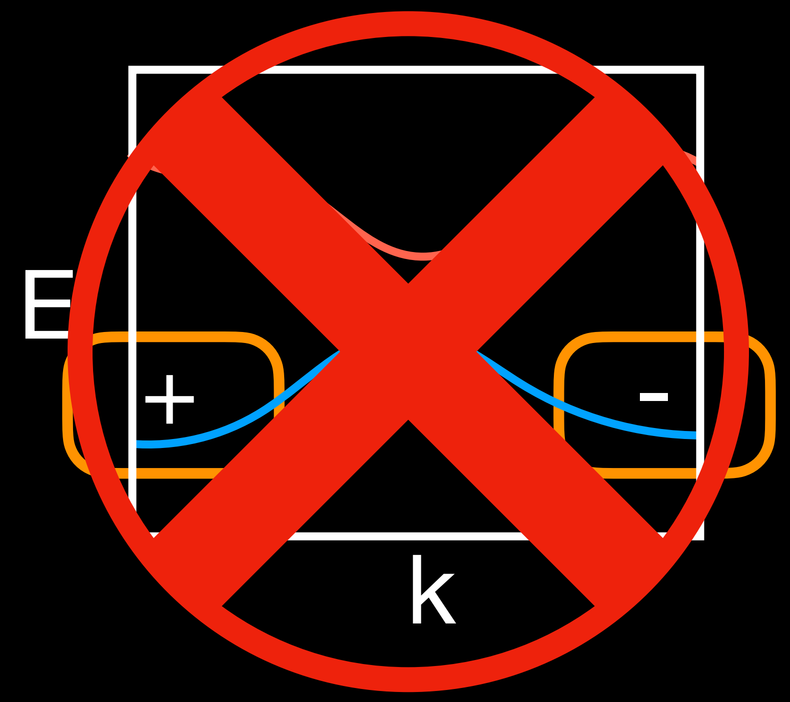

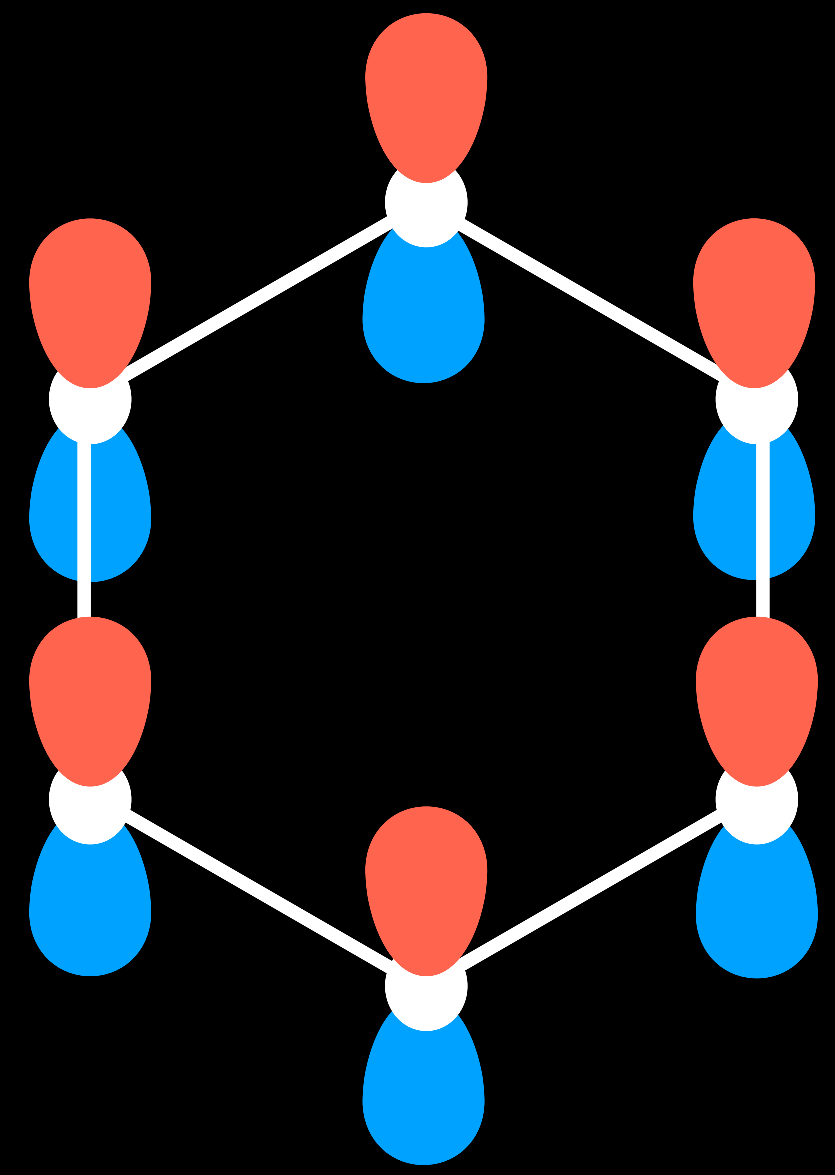

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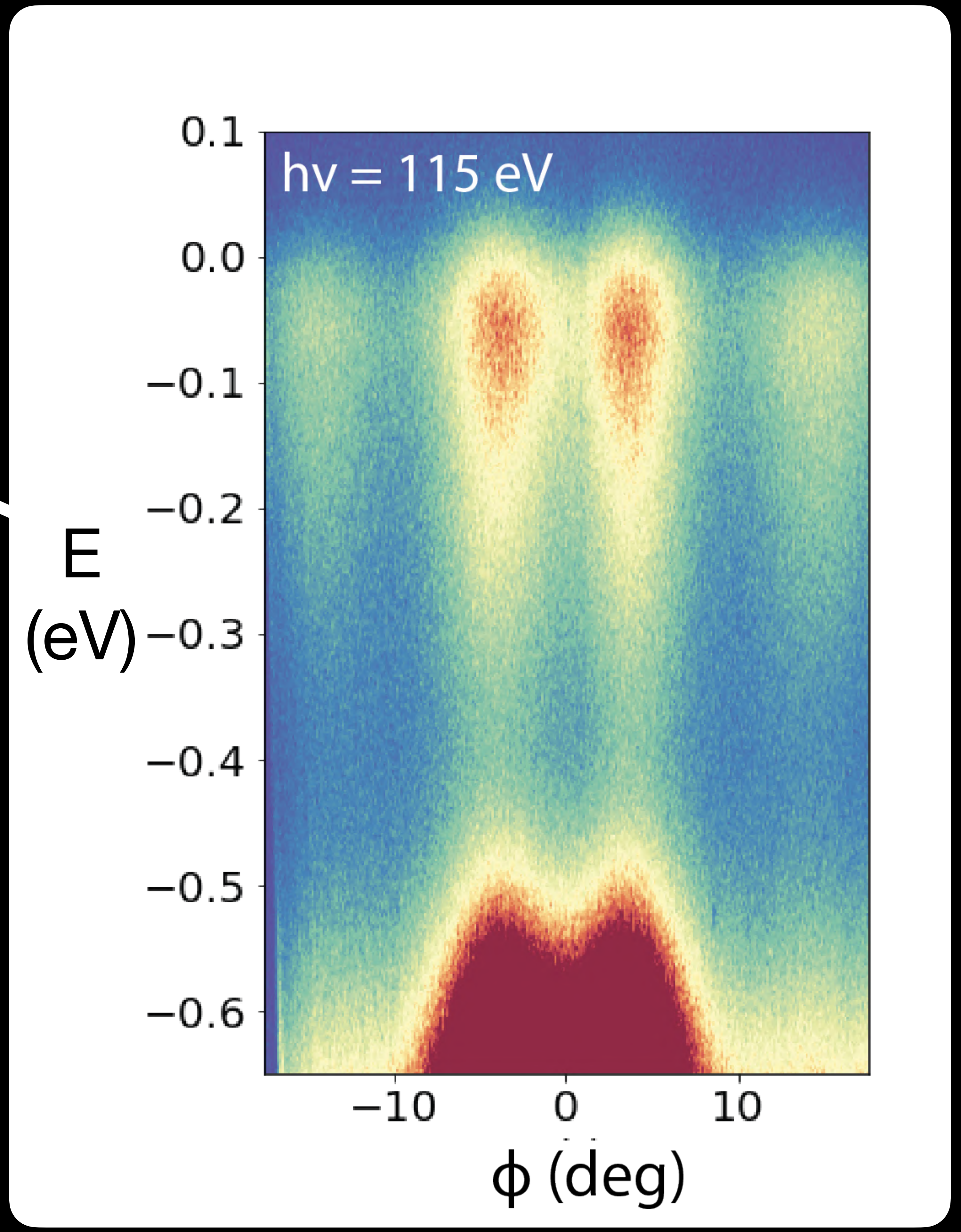
Overlooked topological solids?

We just know one! = hard to predict

solid state: a-Bi_2Se_3



Corbae et al, AGG, Lanzara, Hellmann Nat Materials (2023)

Cyocis, Marsal et al, Hellmann, AGG, Lanzara 2302.05945

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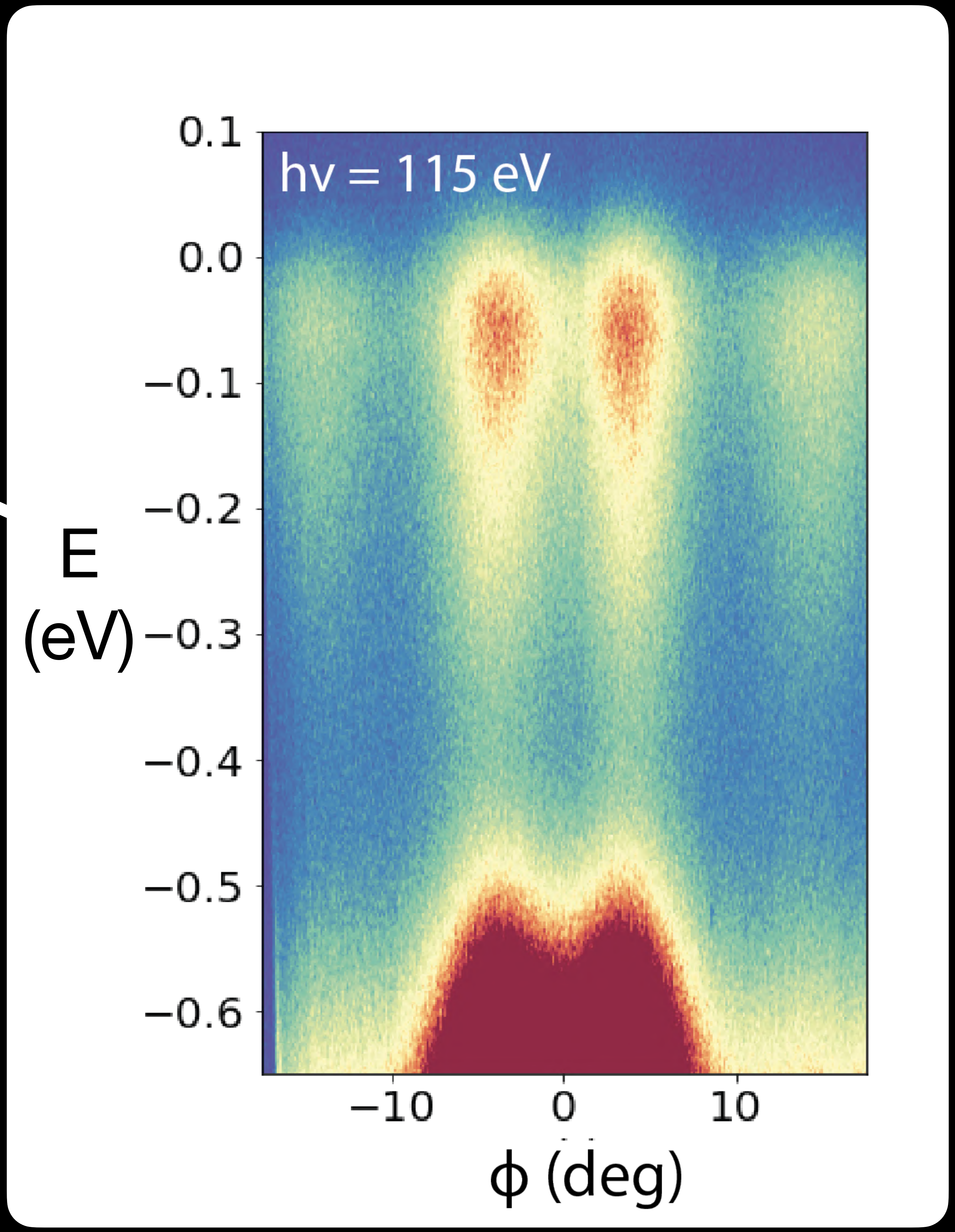

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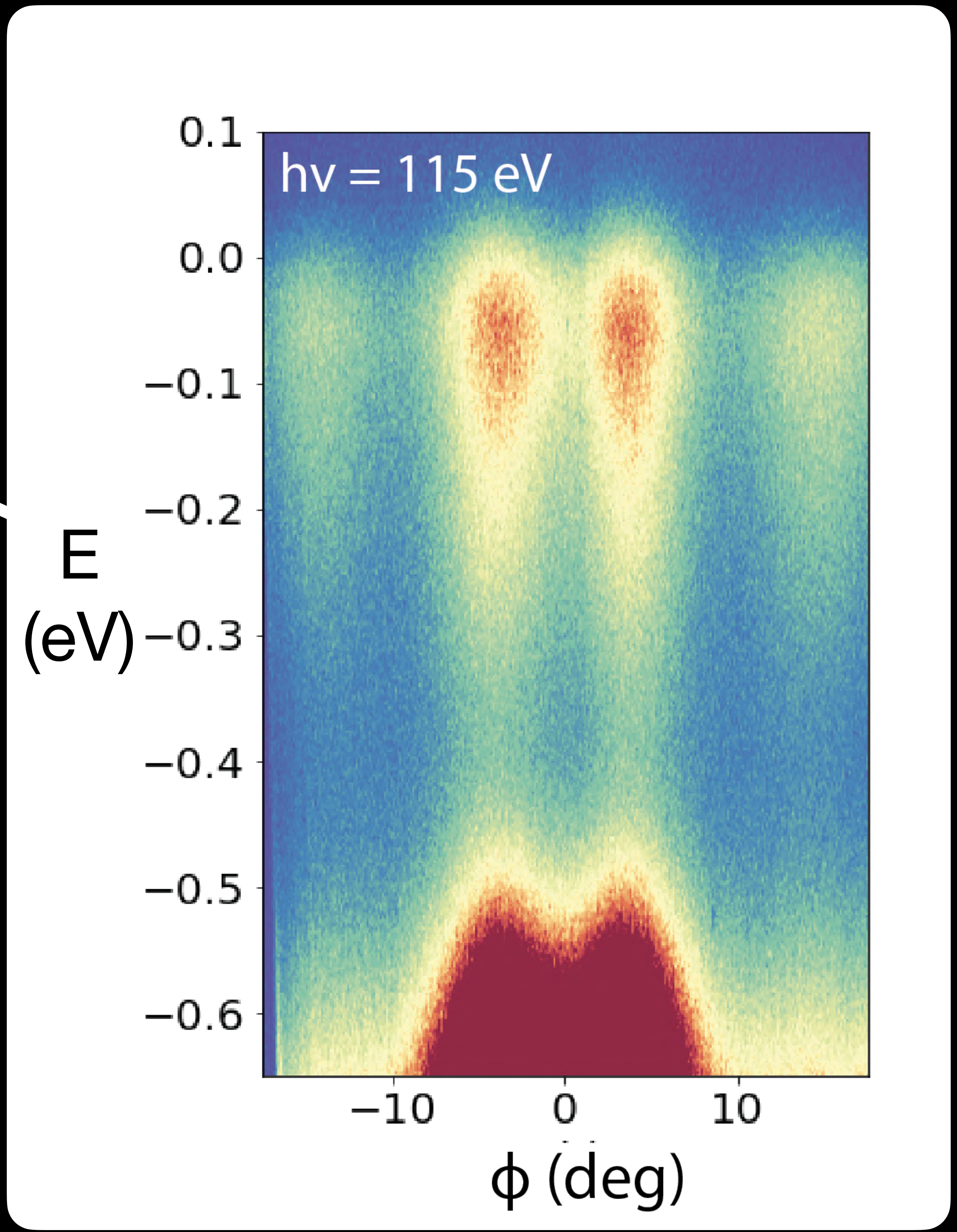

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MPI PKS

Structural spillage

D. Muñoz-Segovia, et al arXiv: 2301.02686

Daniel Muñoz-Segovia
DIPC

Paul Corbae
Berkeley

Frances Hellmann
Berkeley

Sinead Griffin
Berkeley

Daniel Varjas
MPI-PKS

Amorphous graphene

Amorphous graphene

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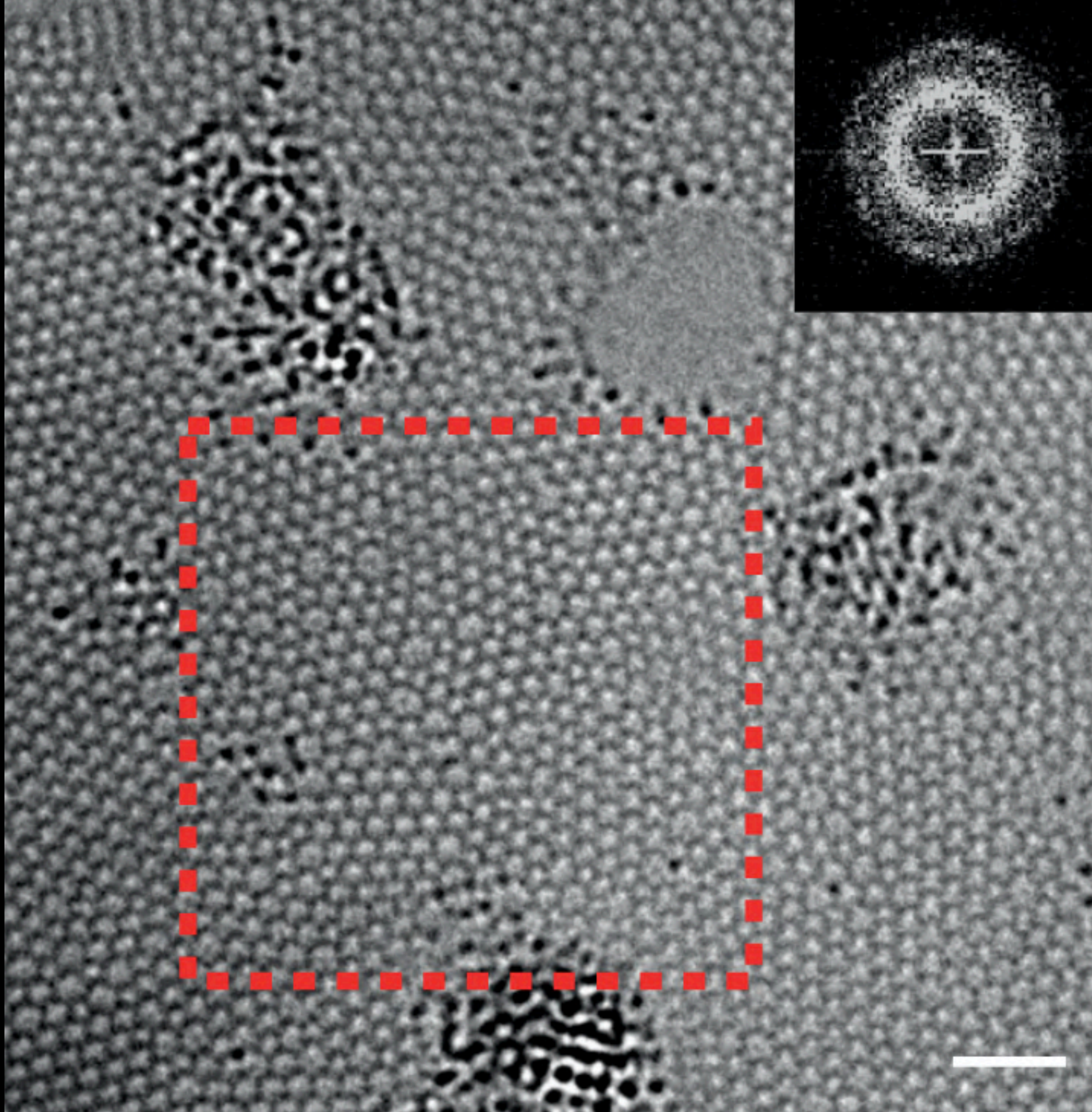
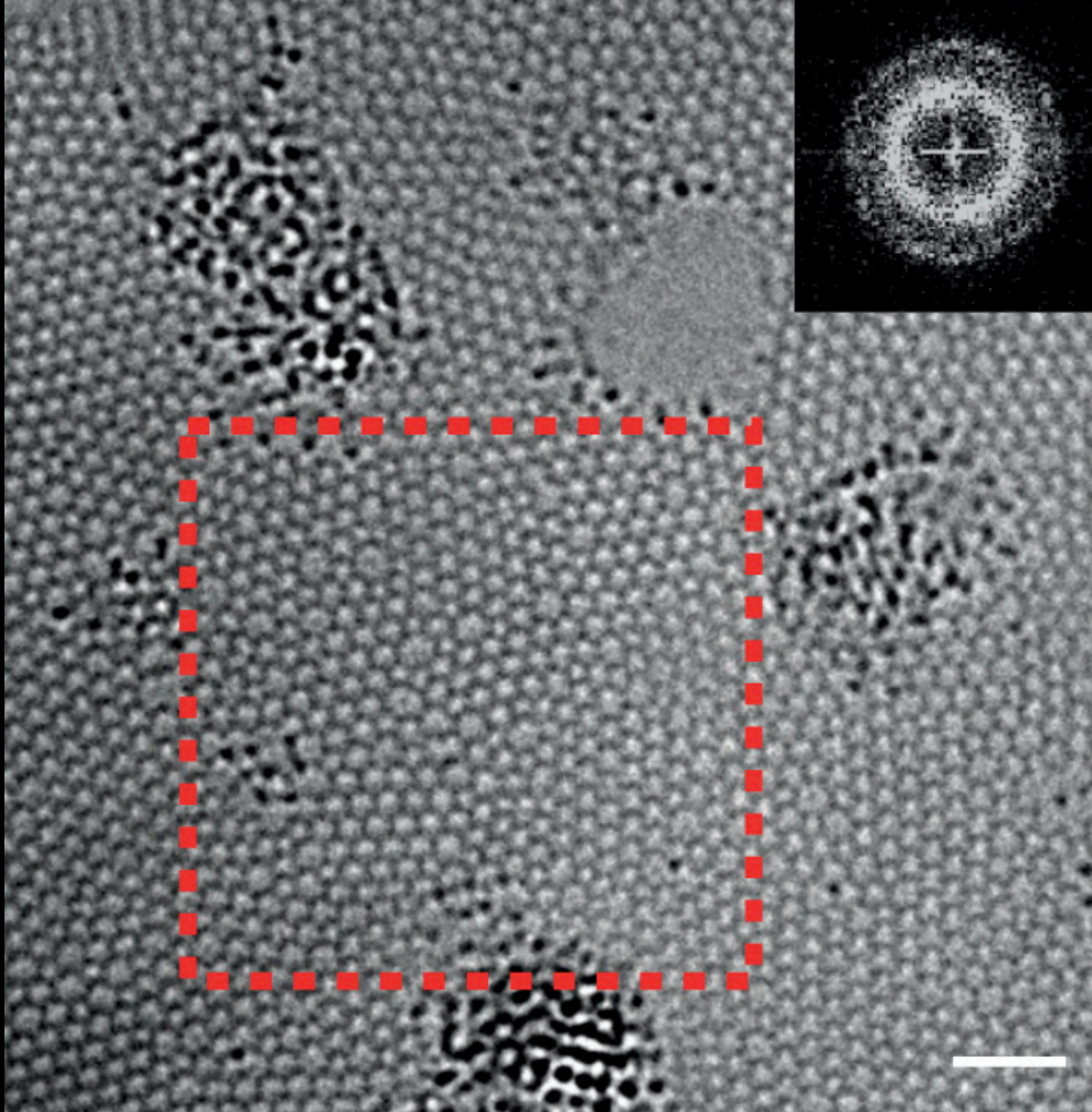


Toh et al. Nature (2020)

Amorphous graphene

Local order = locally similar to crystal



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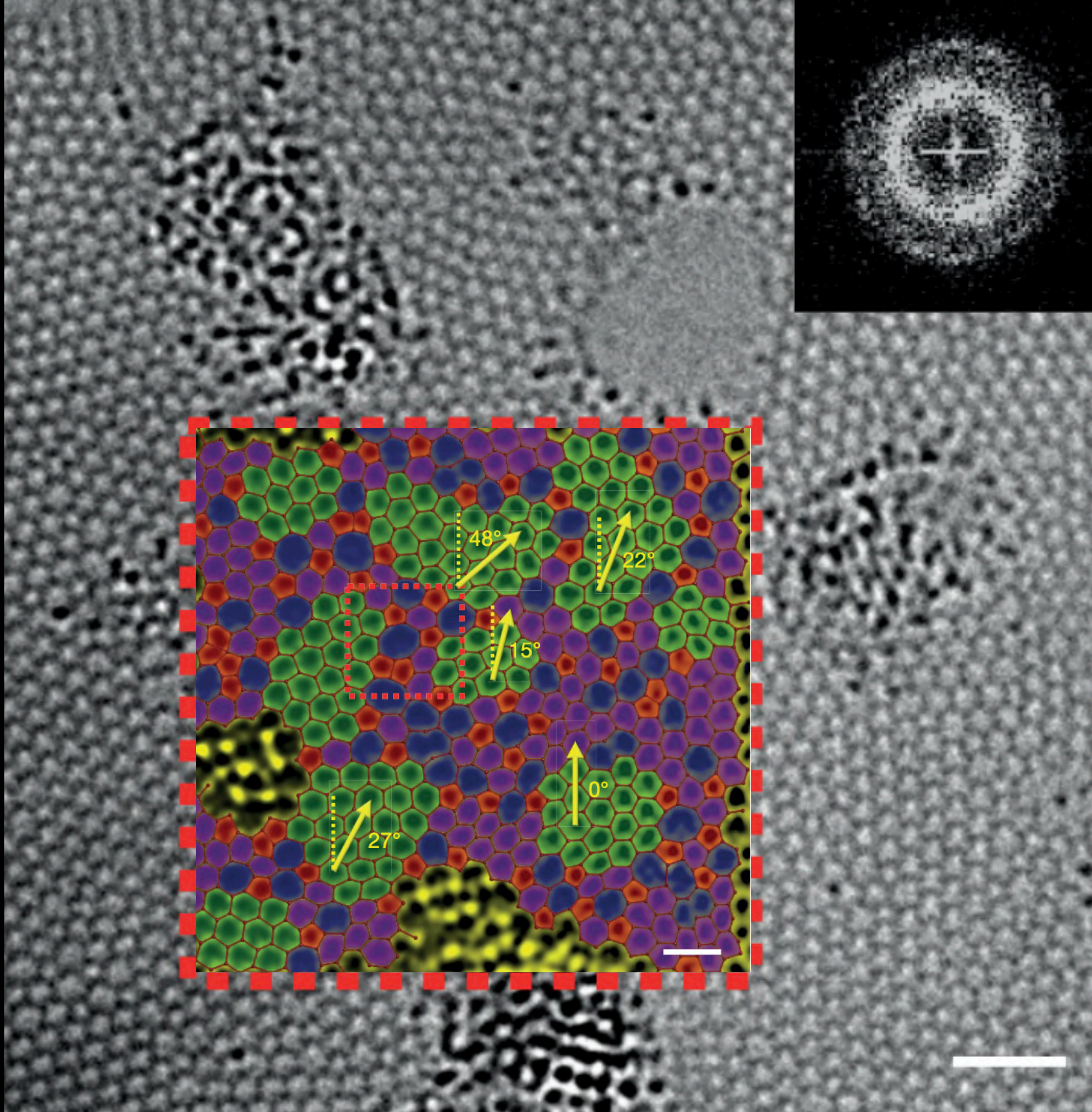

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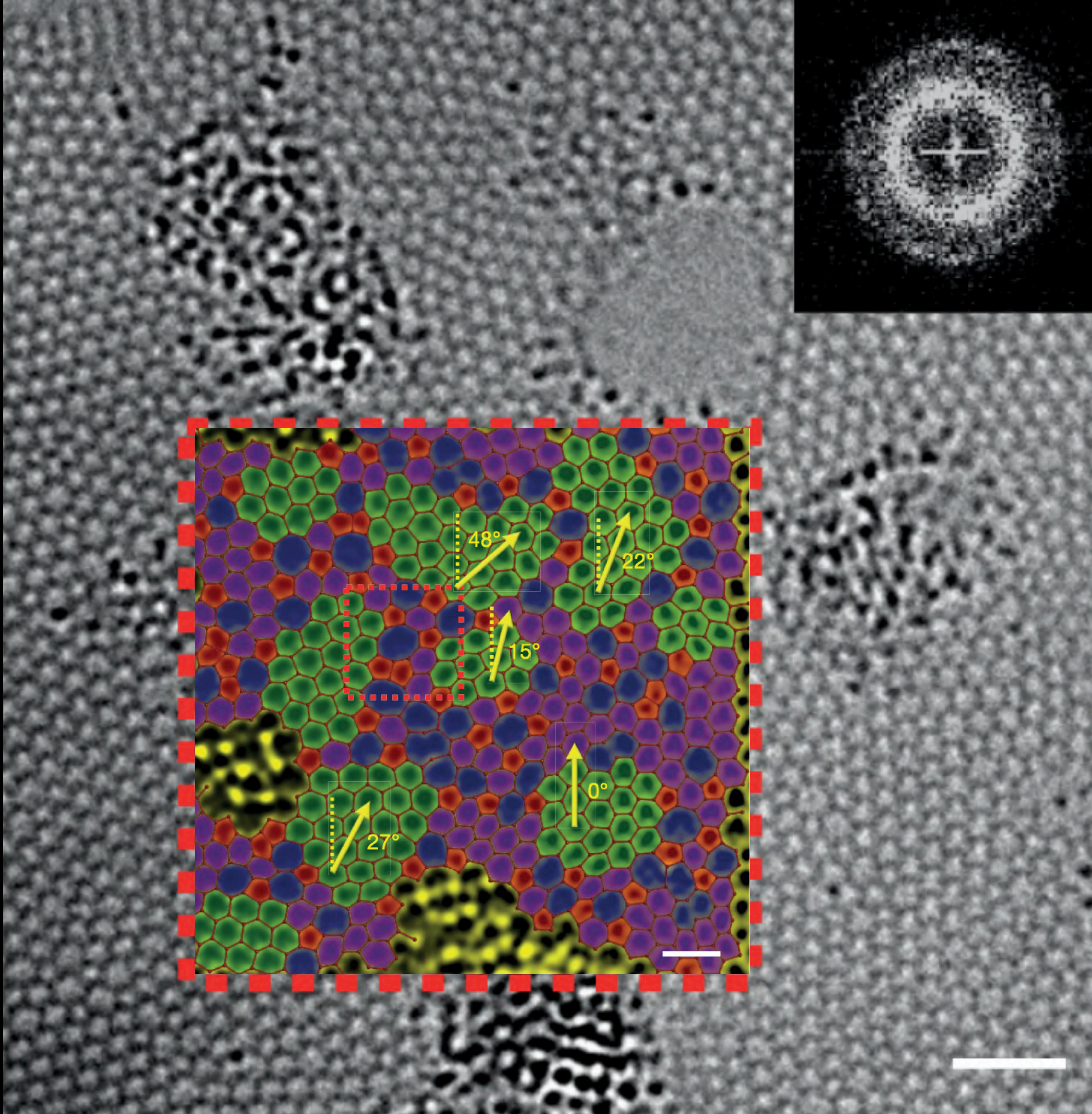

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Local order = locally similar to crystal

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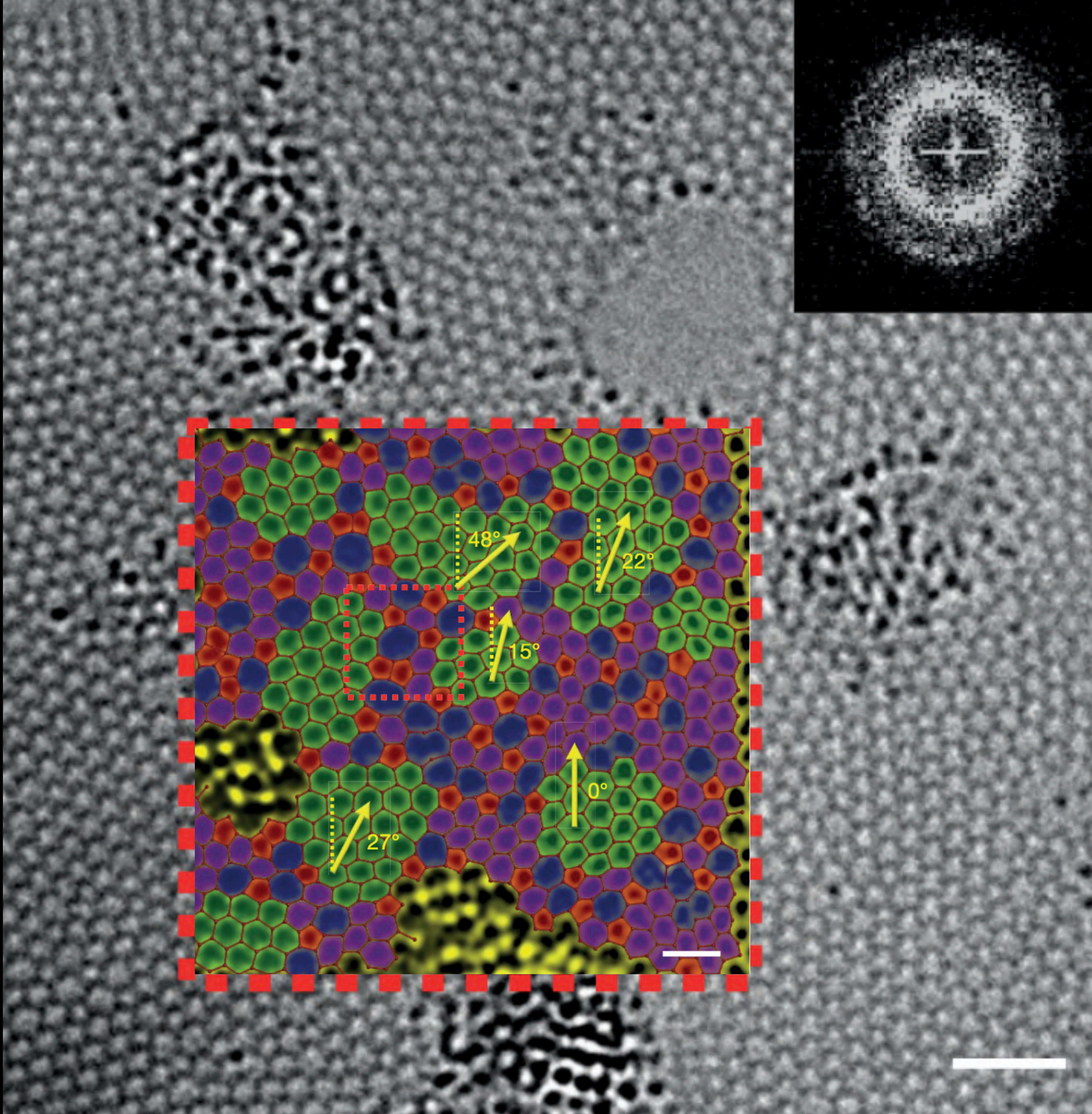
2. Similar lattice scales



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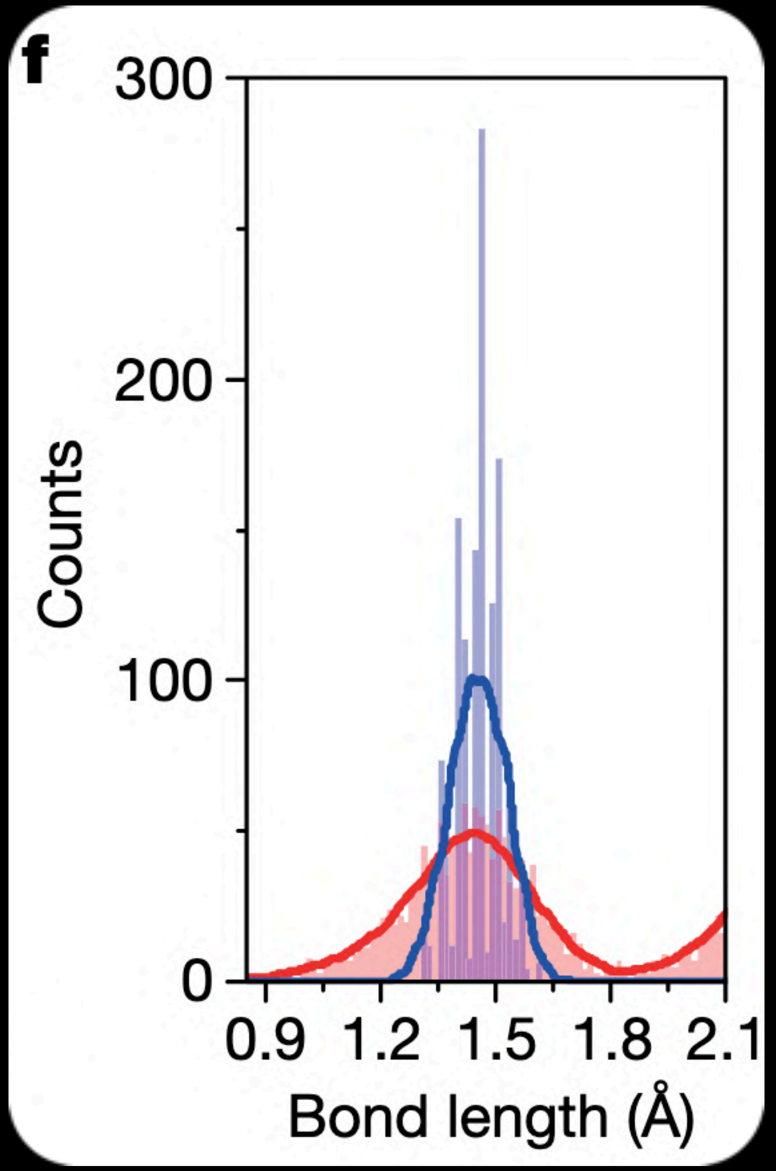

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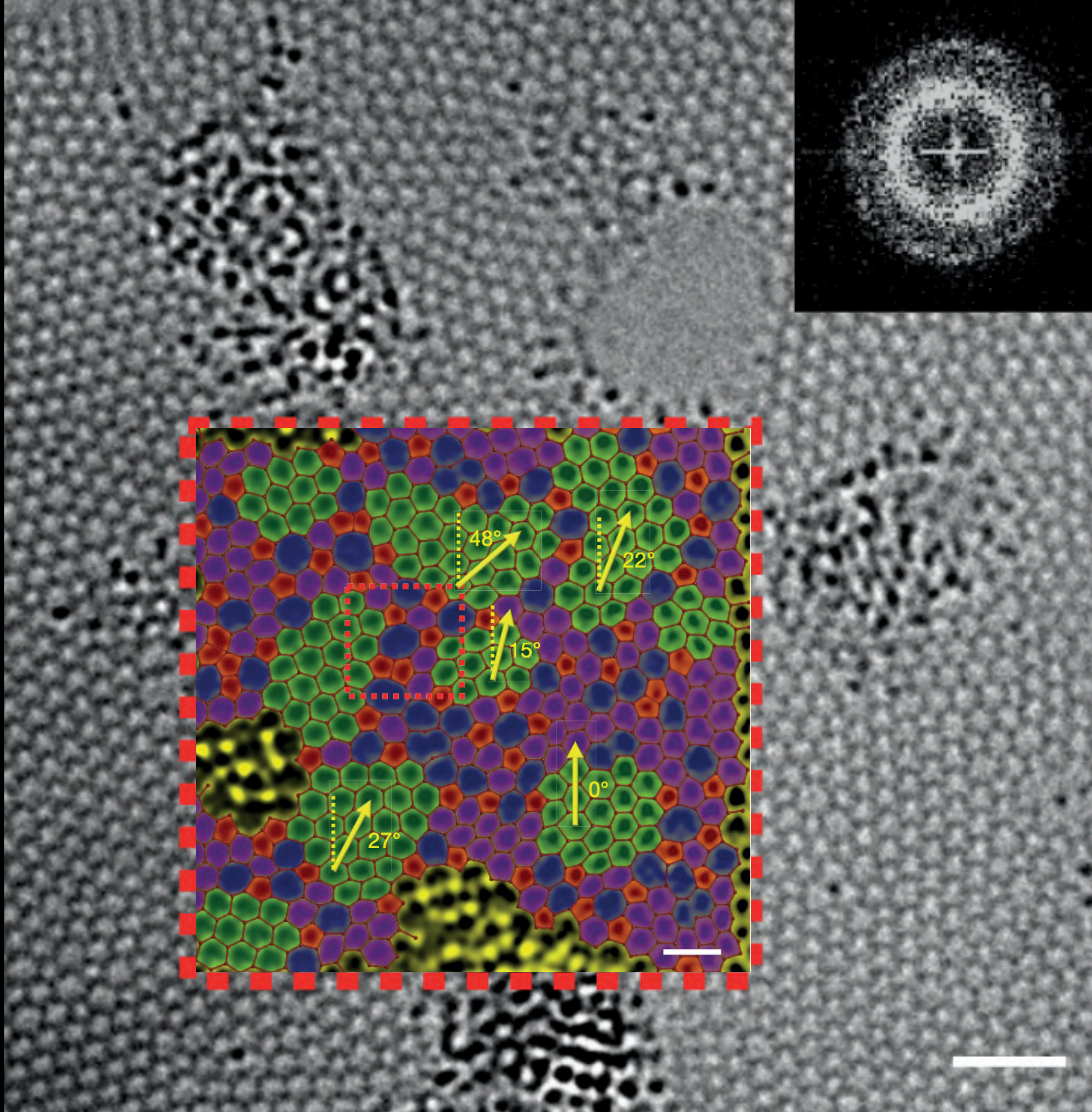

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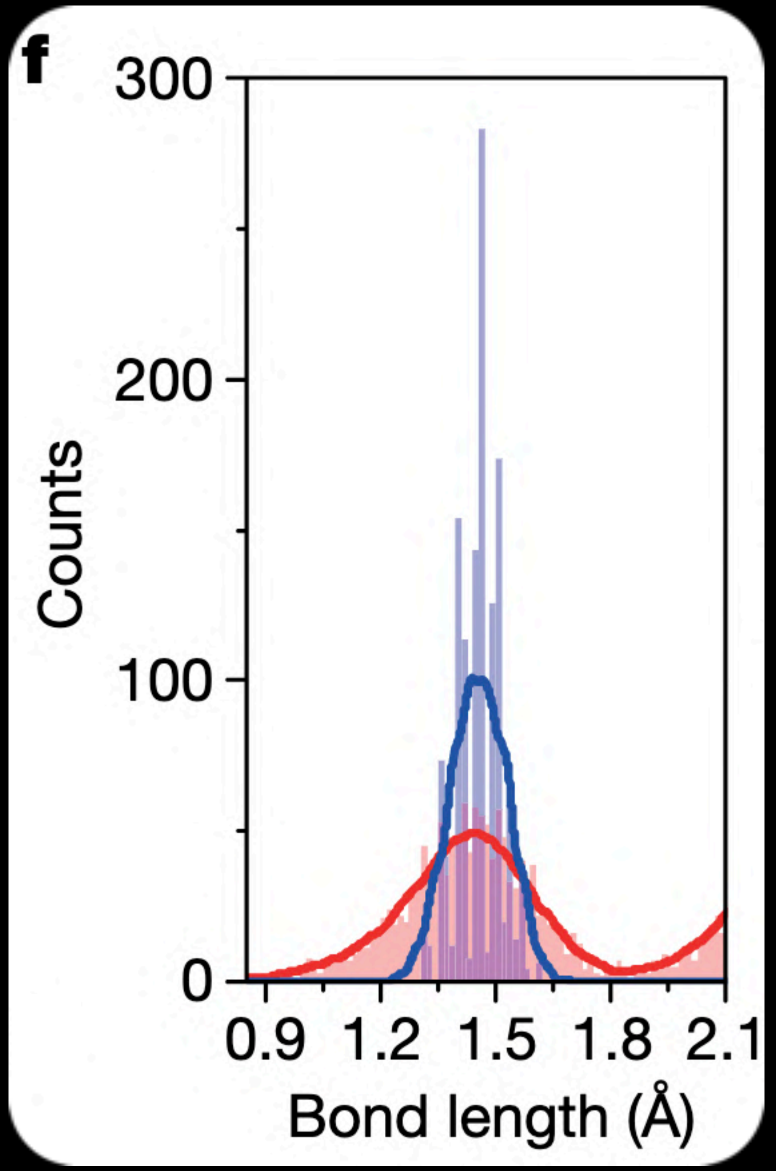
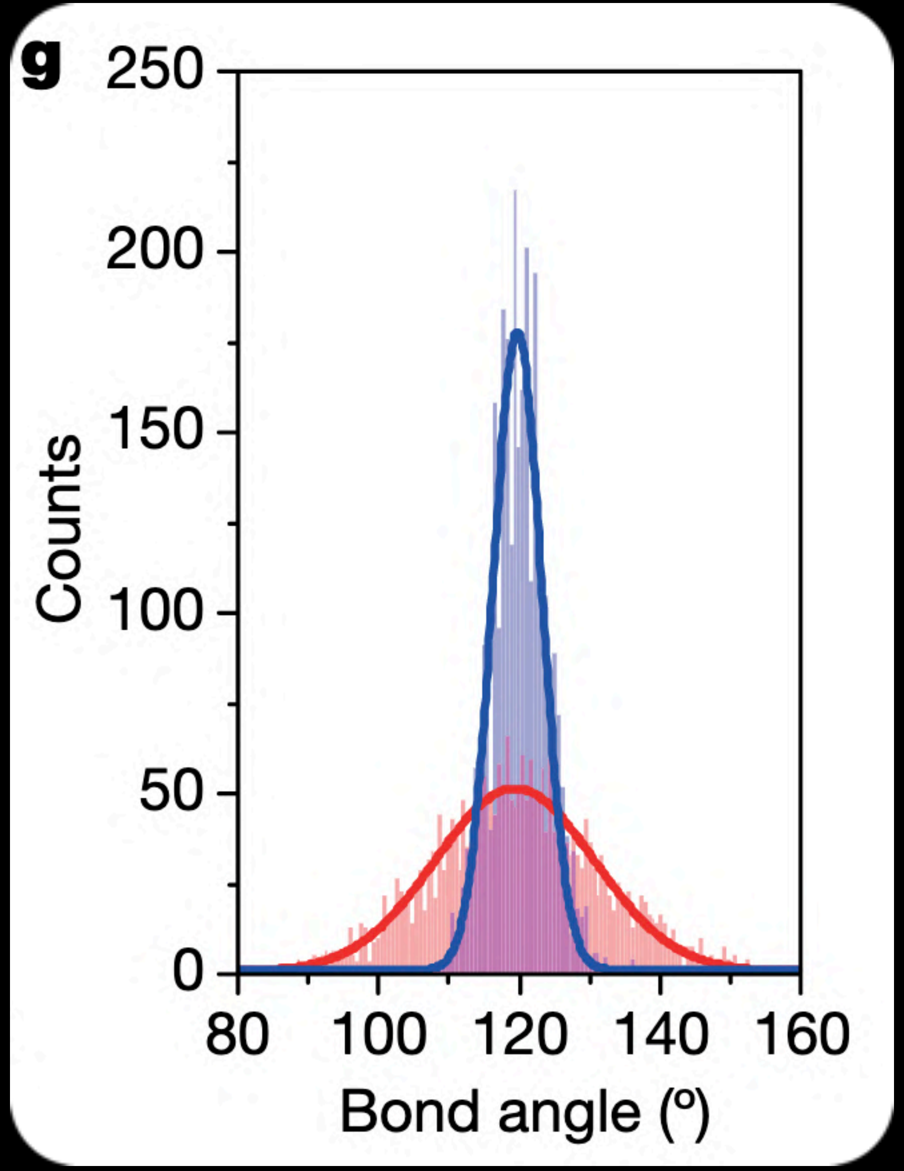
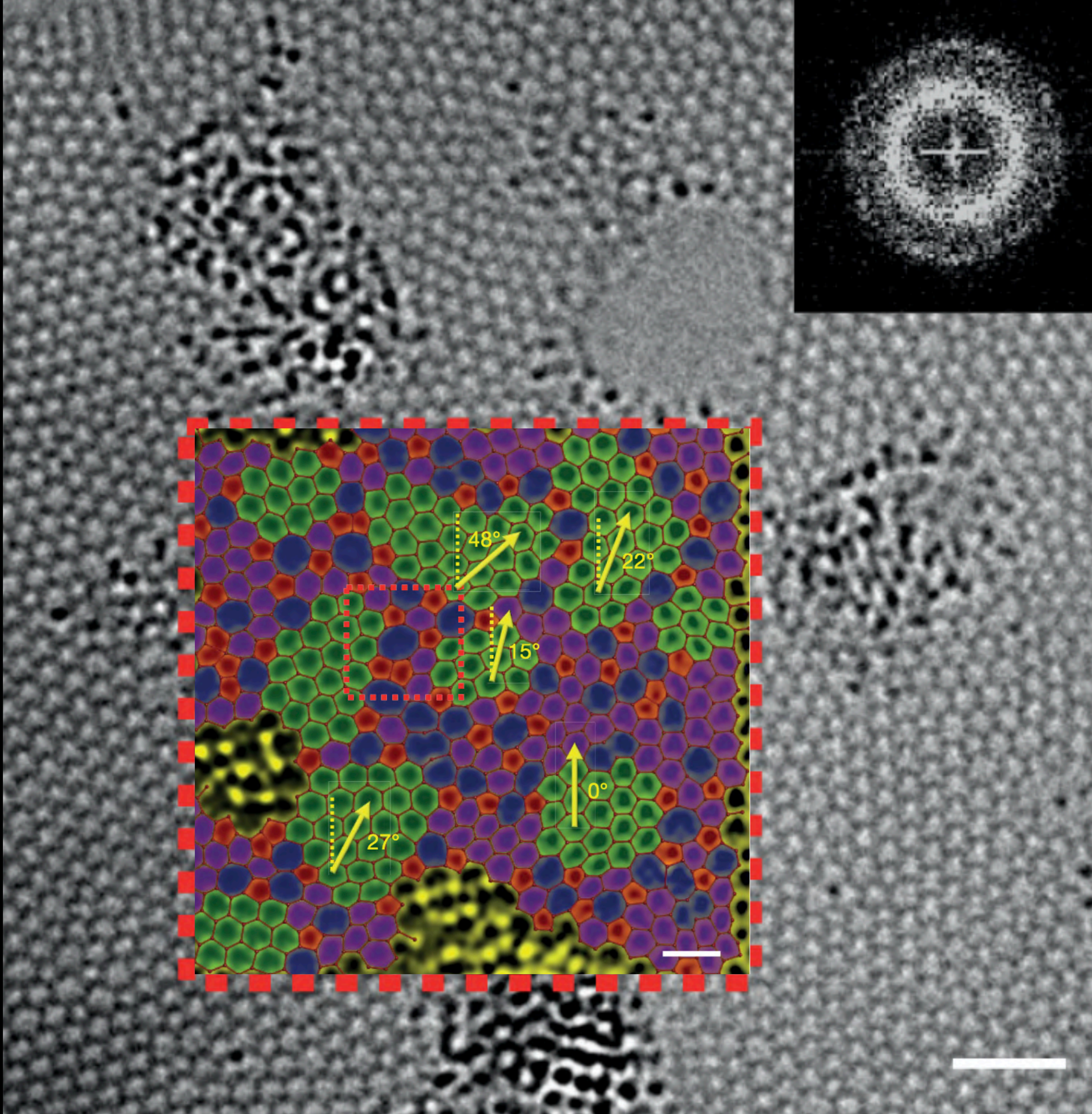


Bond-angles





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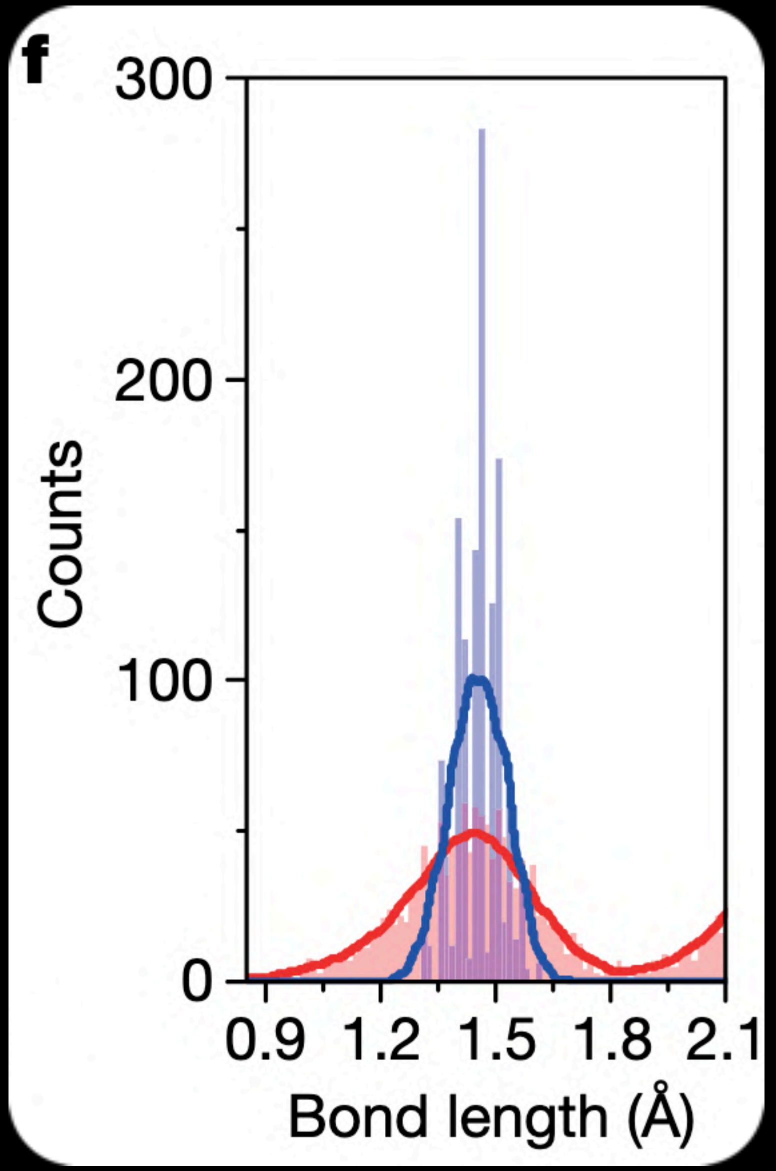

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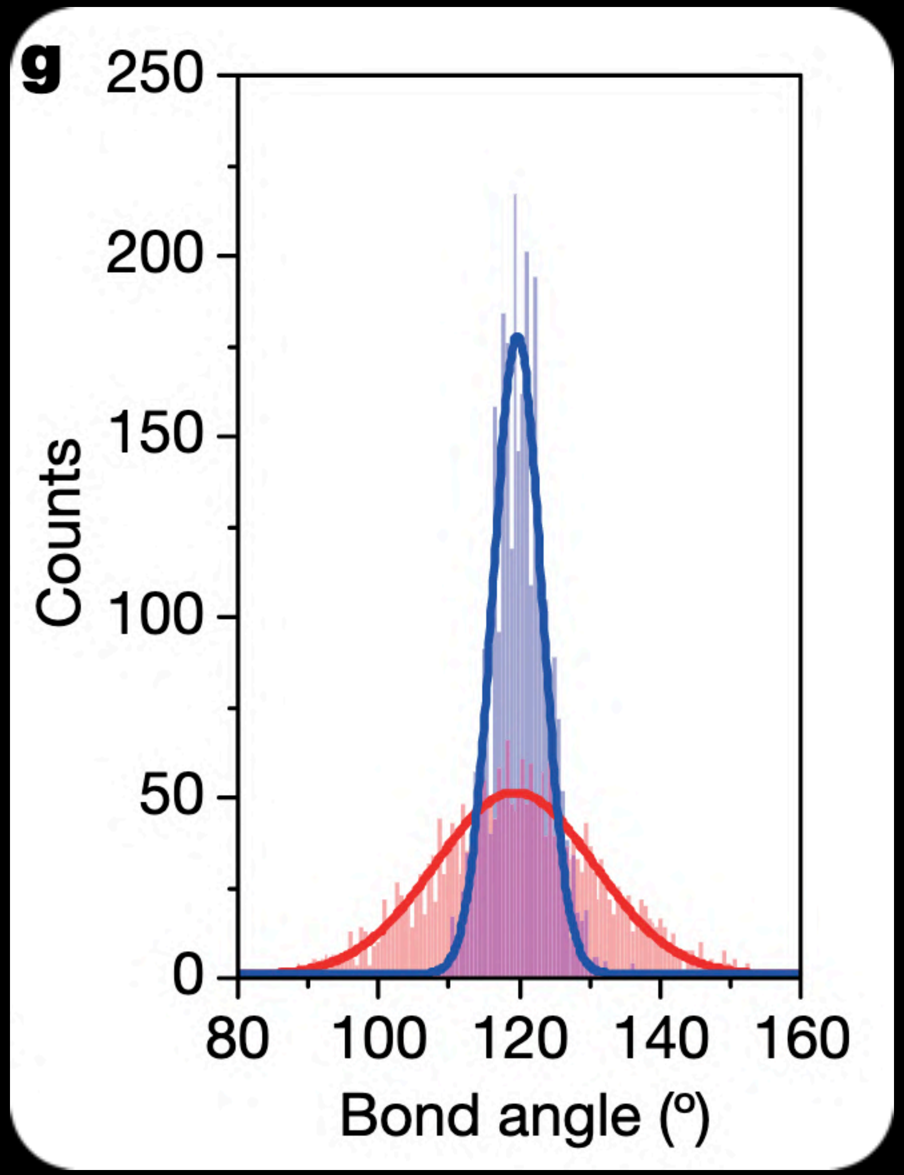

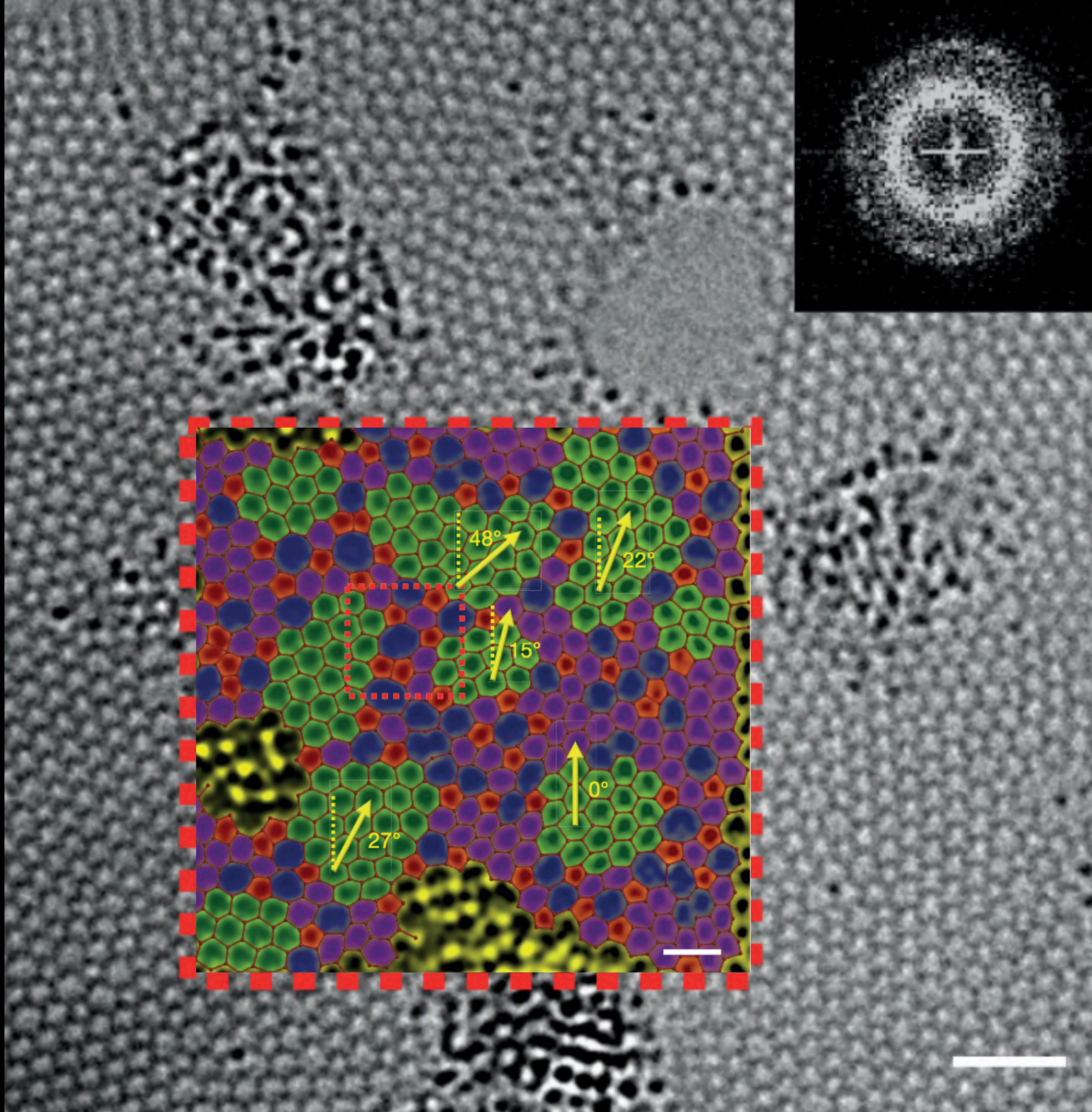

3. Crystalline and amorphous regions coexist

Toh et al. Nature (2020)

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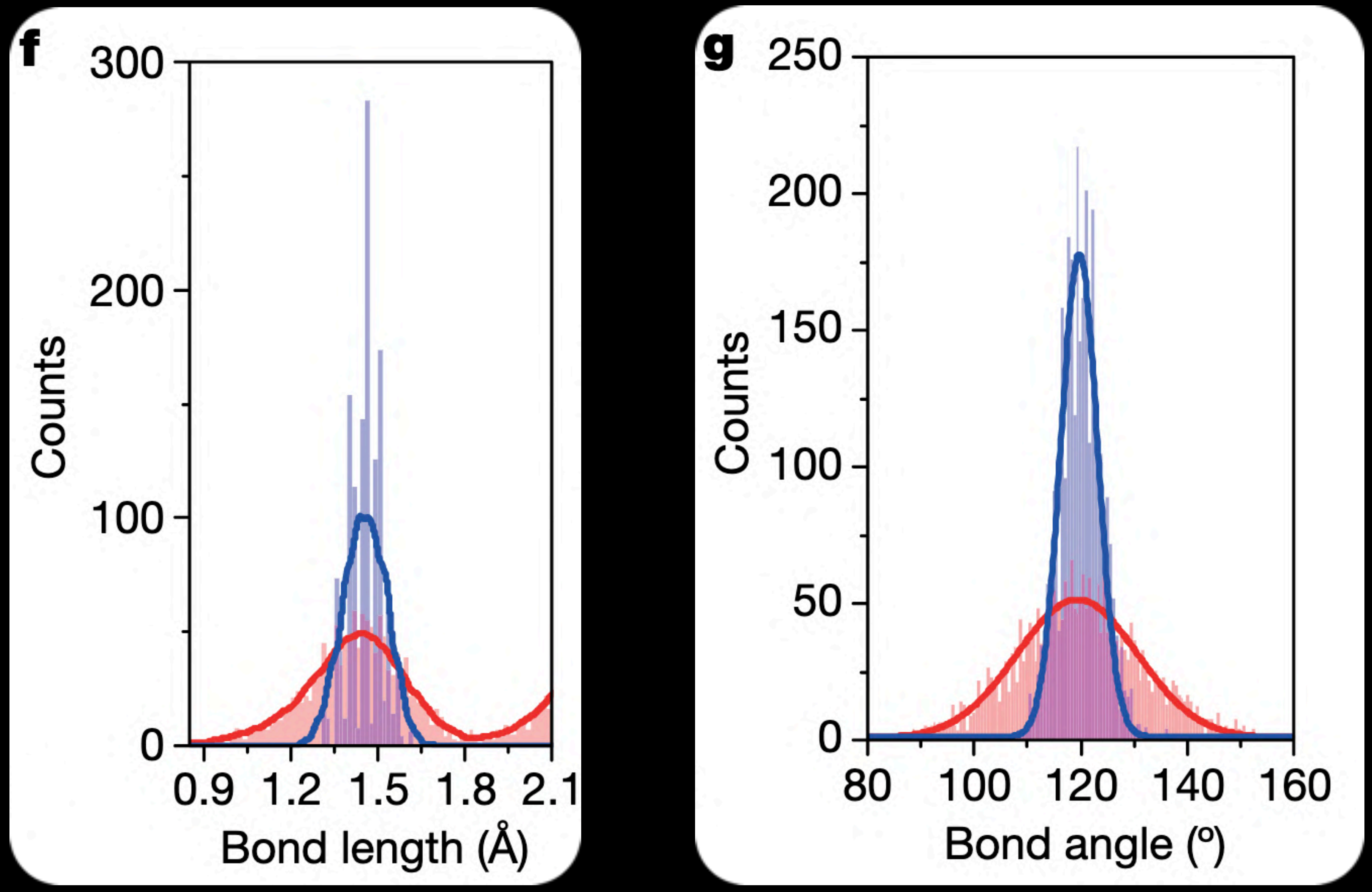
Bond lengths   Bond-angles



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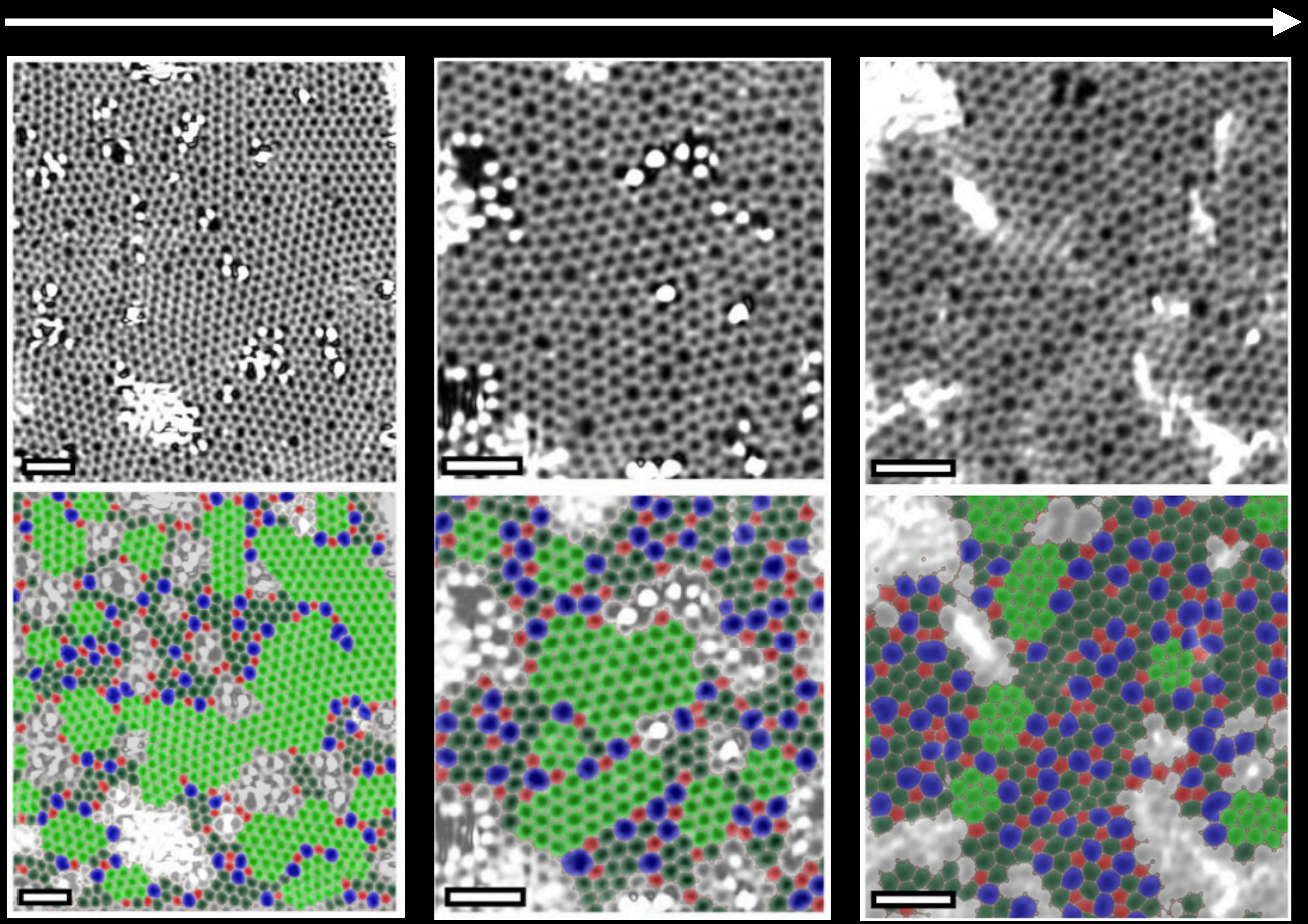
Toh et al. Nature (2020)

structural disorder



Tian et al. Nature (2023)

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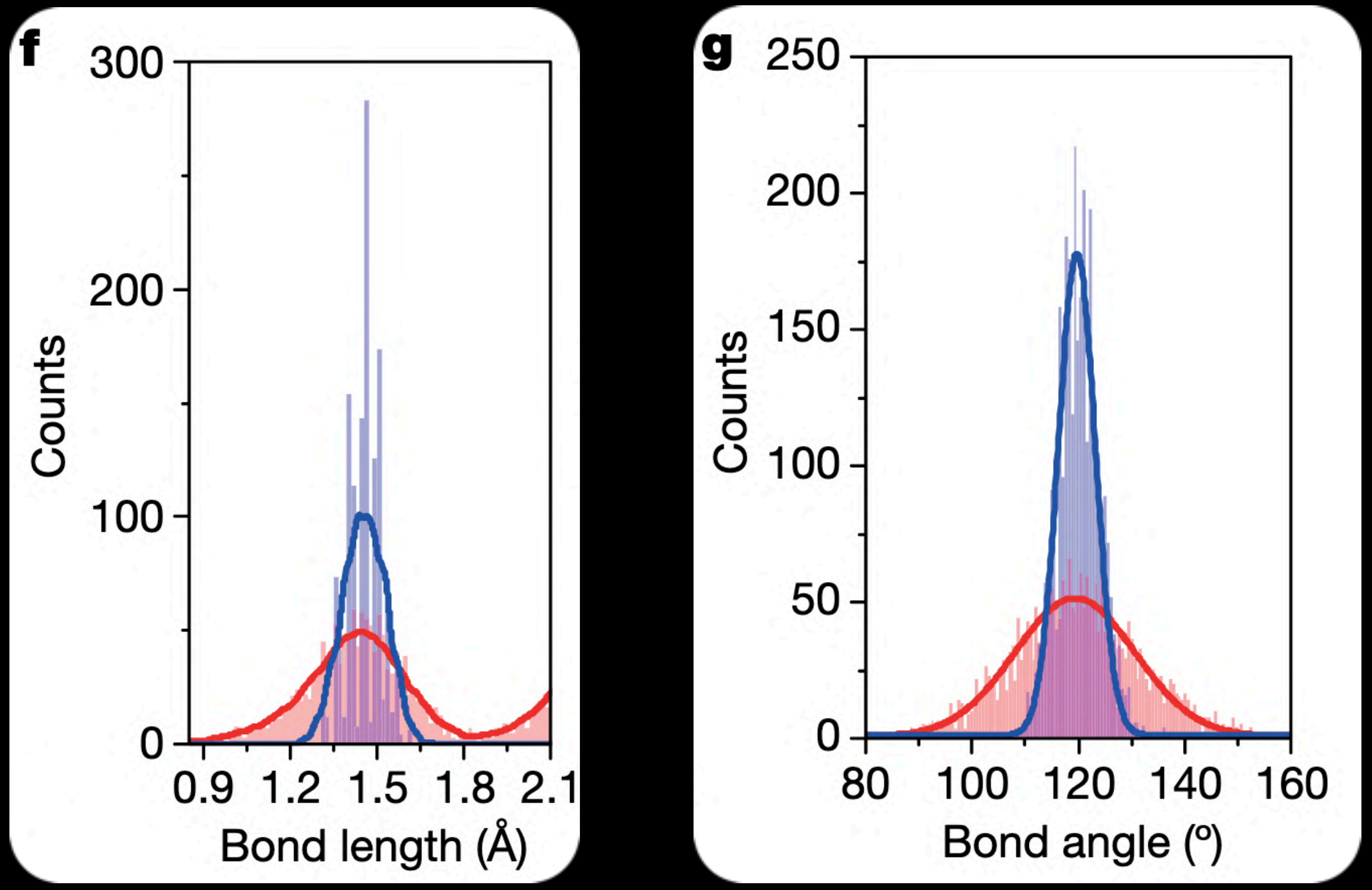

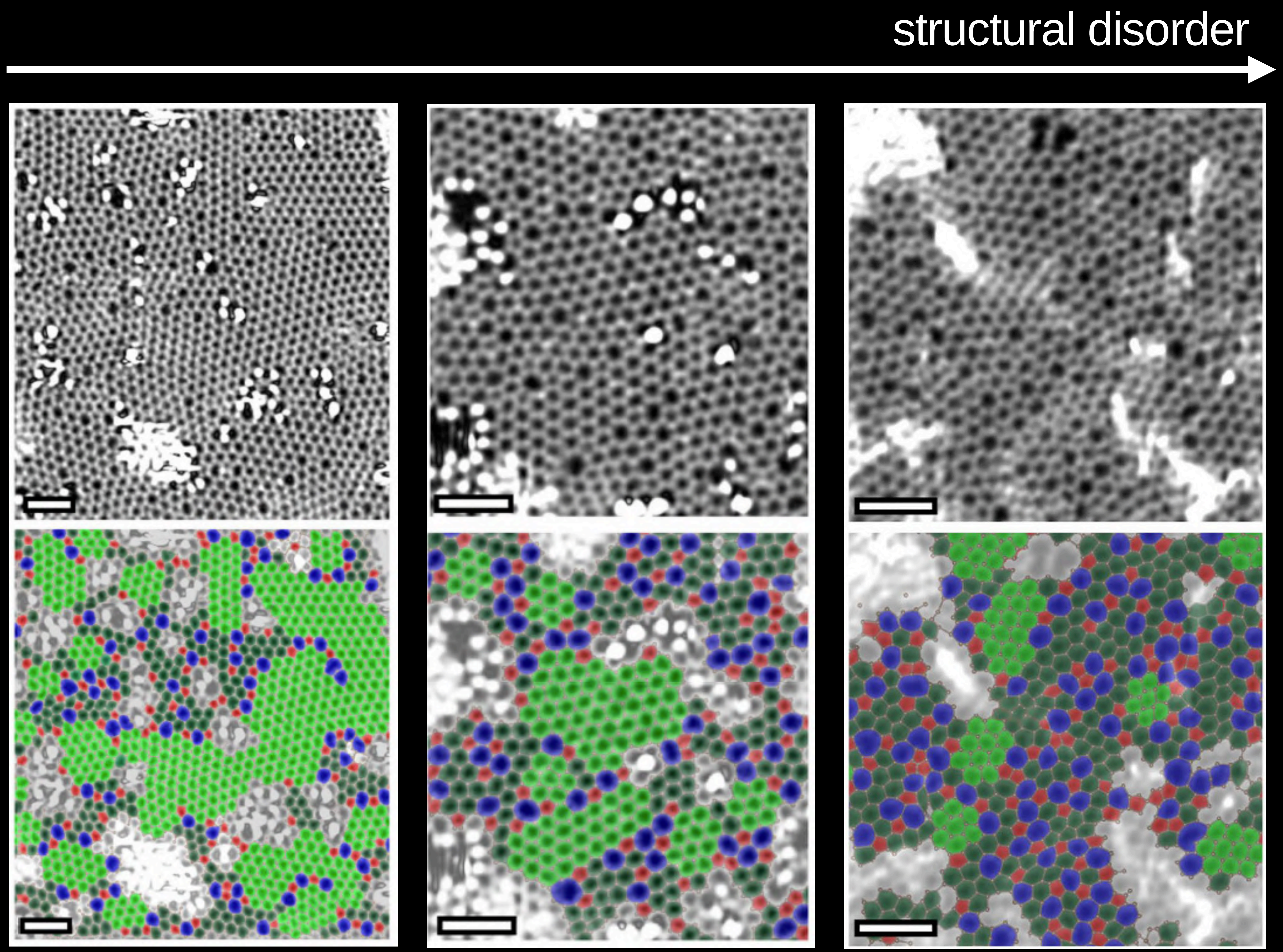

3. Crystalline and amorphous regions coexist

Toh et al. Nature (2020)

4. Lattice disorder can be controlled

Tian et al. Nature (2023)

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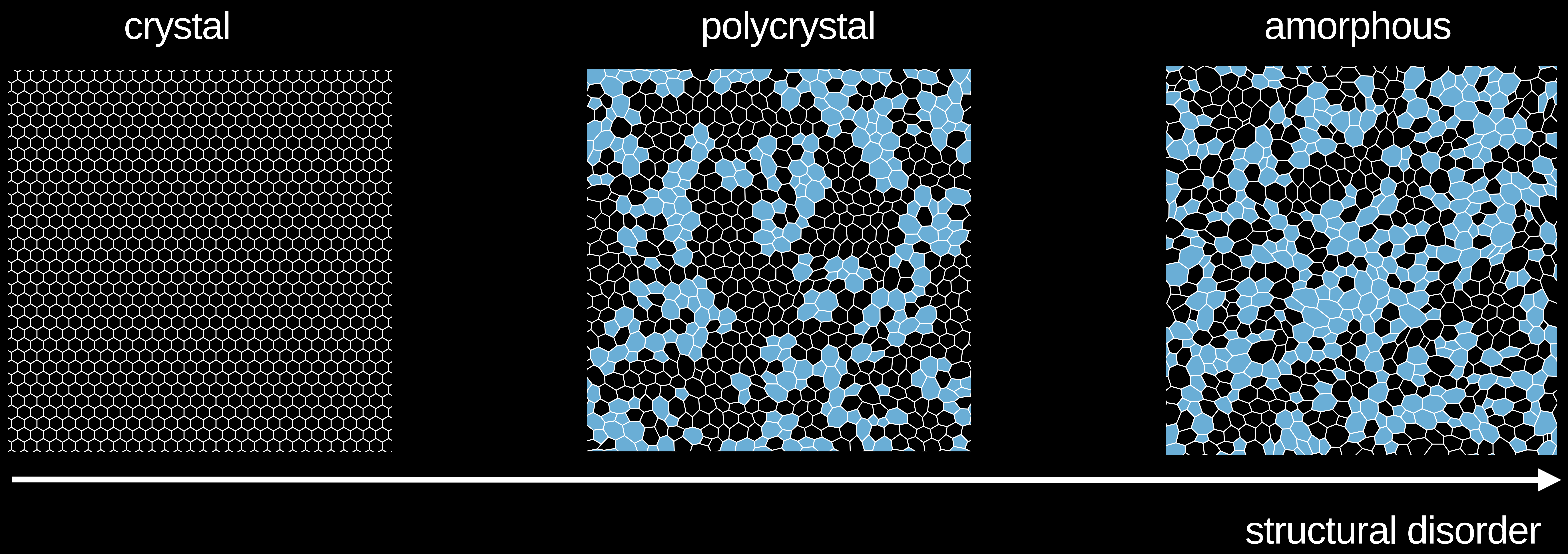
Any different physics compared to crystals?

Can this knob drive a topological transition?

AGG, C. Repellin PRL (2023)

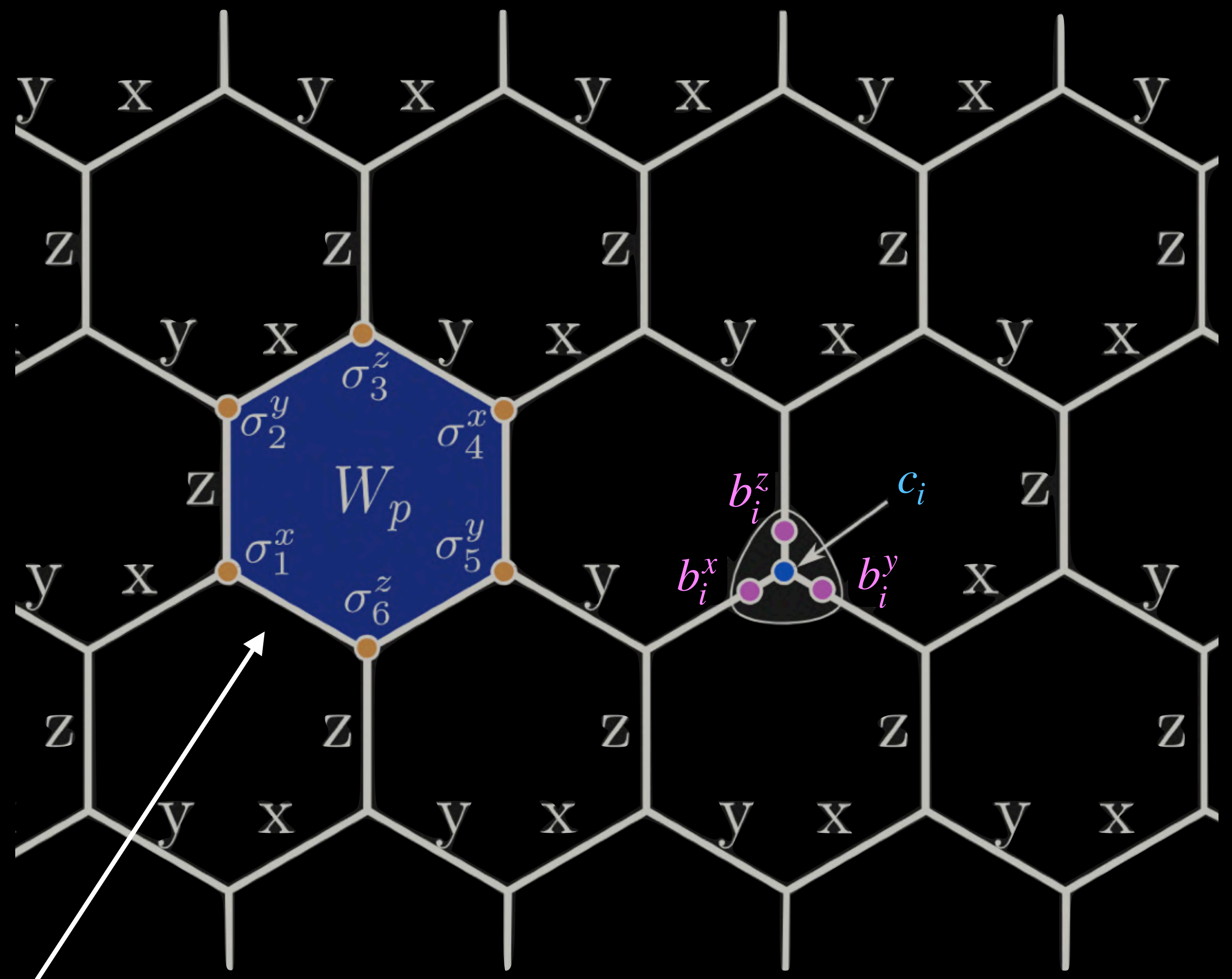


Kitaev model

Honeycomb

Kitaev Ann. Phys. (2006)

$$H = -\sum_{\langle ij \rangle} J_\alpha^K \sigma_i^\alpha \sigma_j^\alpha$$



$$W_p = \sigma_1^x \sigma_2^y \sigma_3^z \sigma_4^x \sigma_5^y \sigma_6^z$$

$$\phi_p = \pm 1$$

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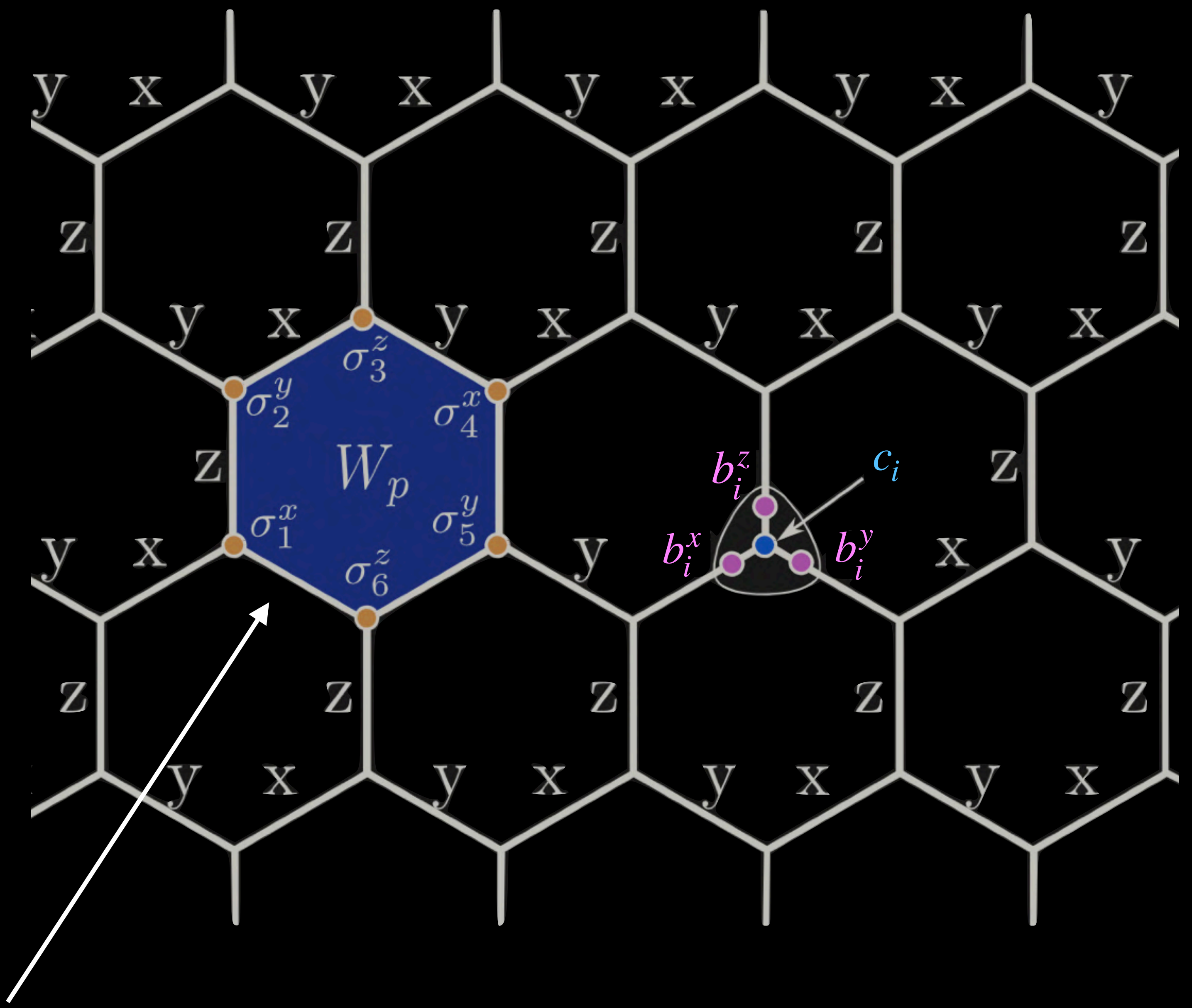

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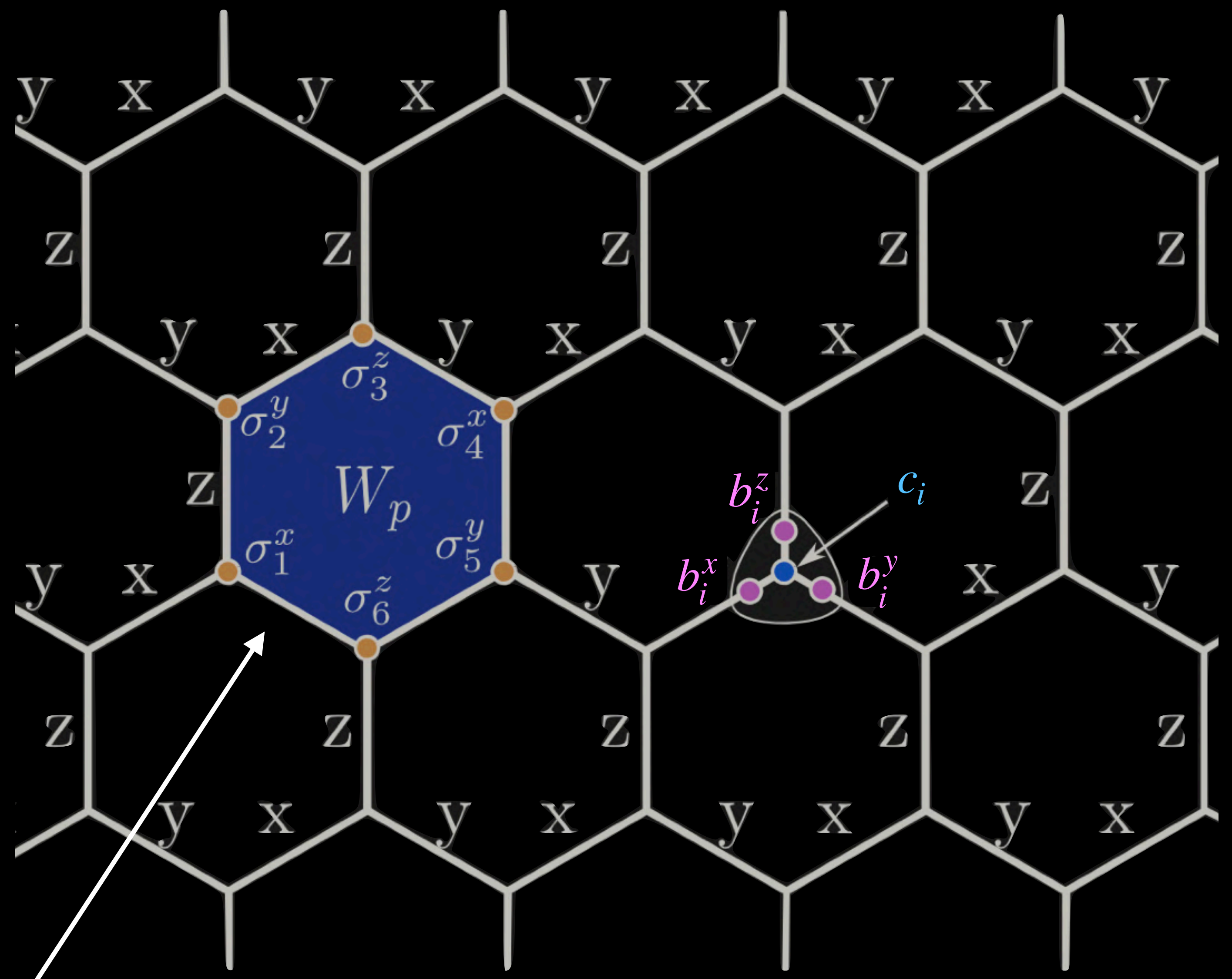

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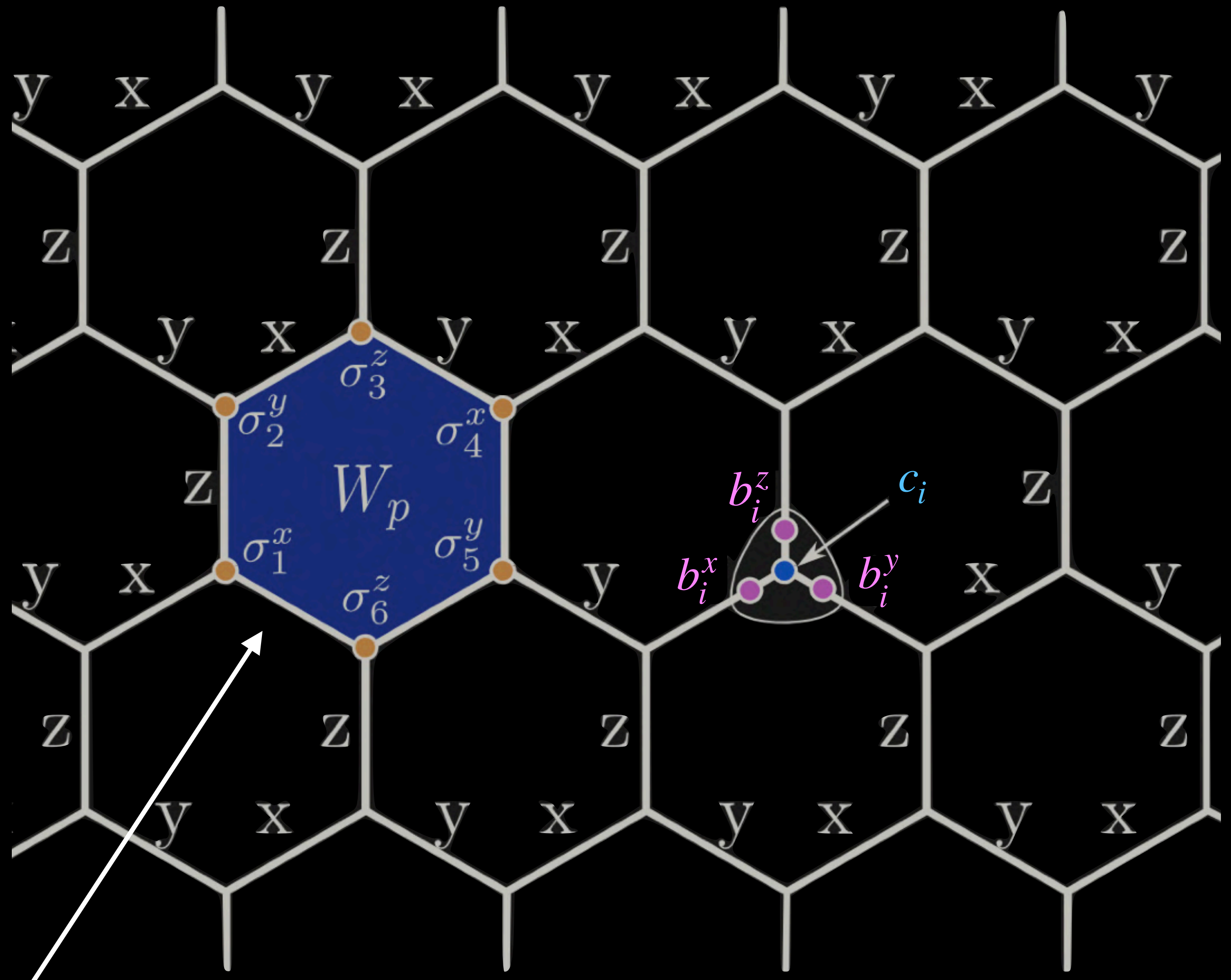
$$u^\alpha_{ij} \equiv i b^\alpha_i b^\alpha_j$$



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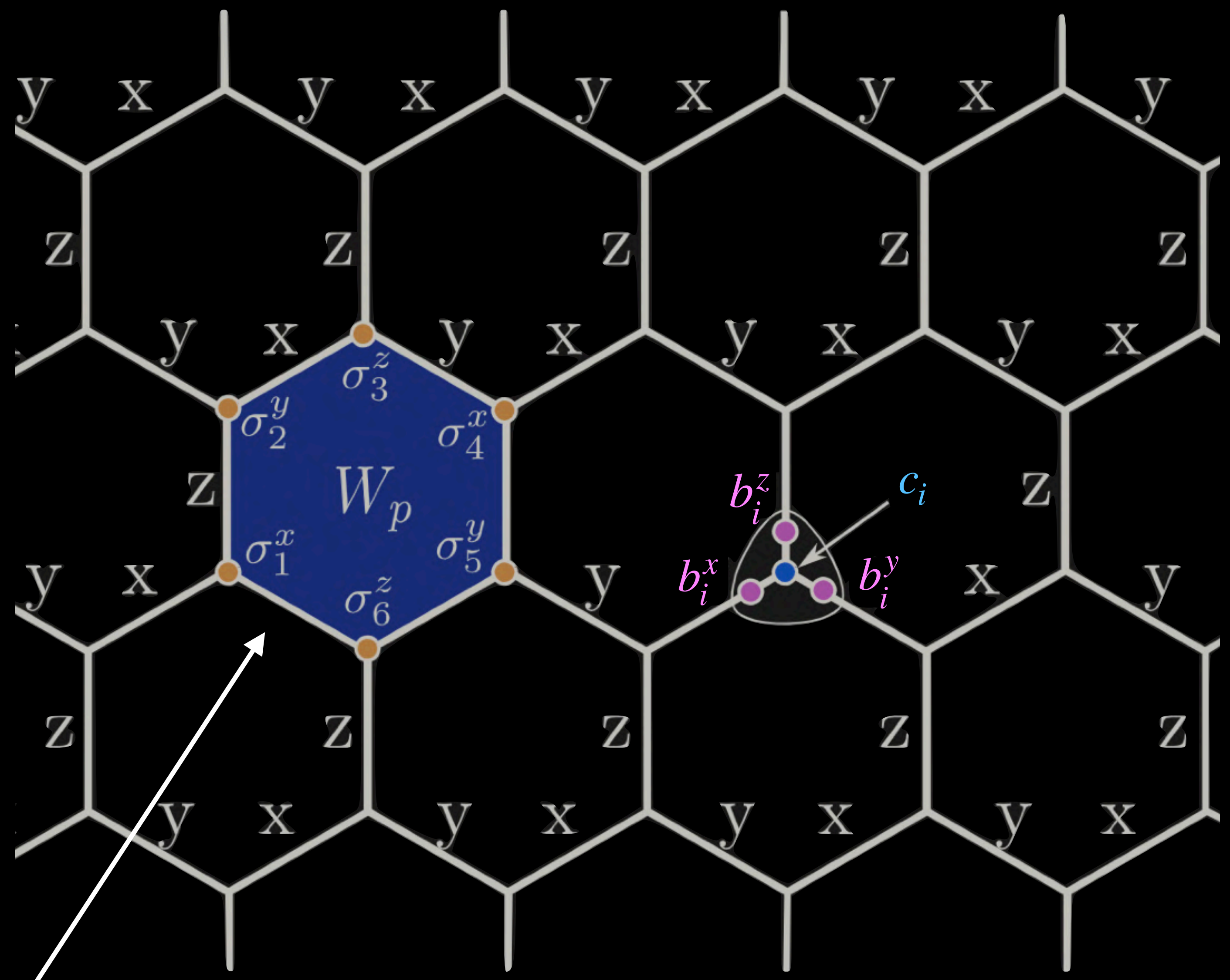

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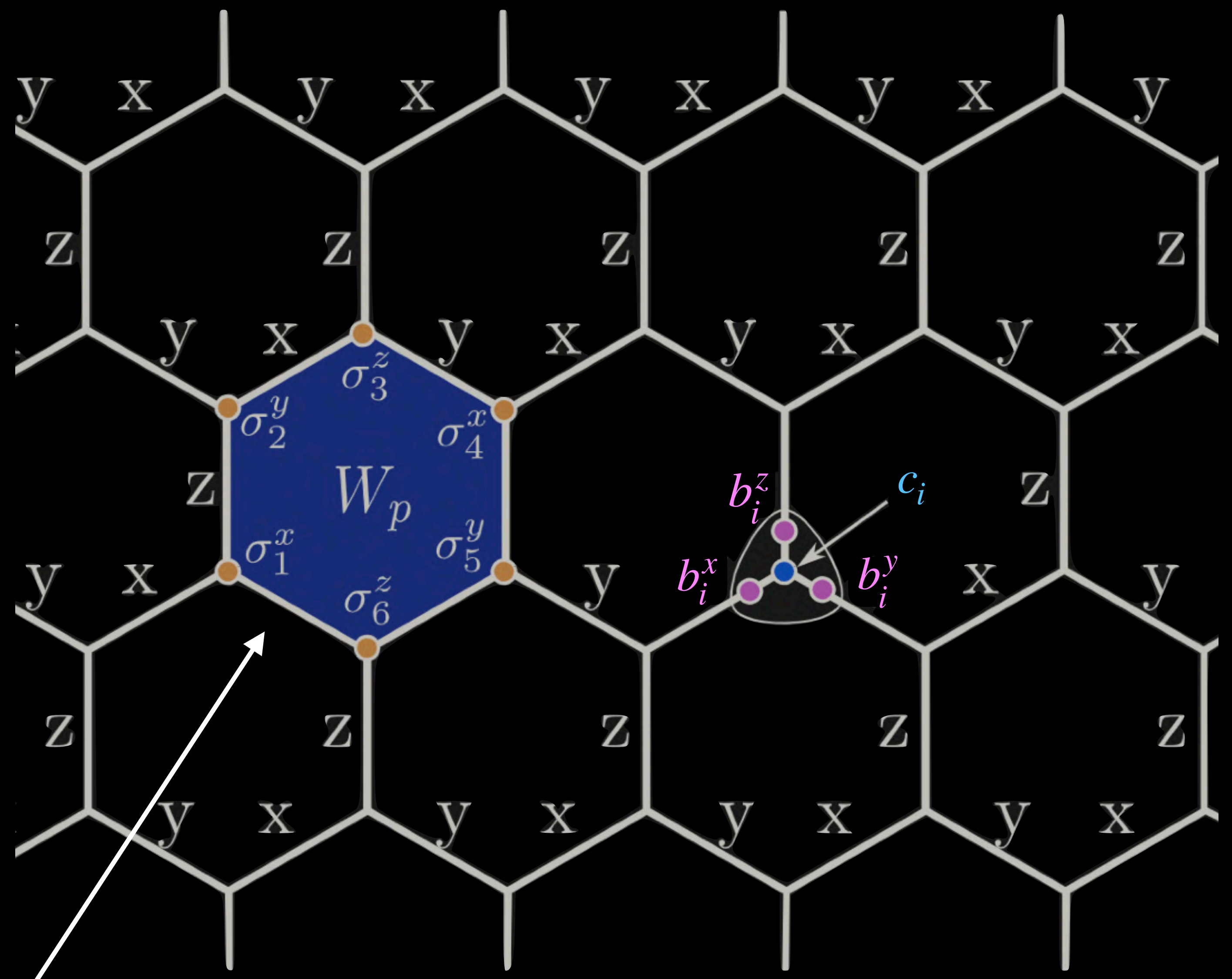

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flux / plaquette = 0 minimizes the energy

Lieb PRL 1994

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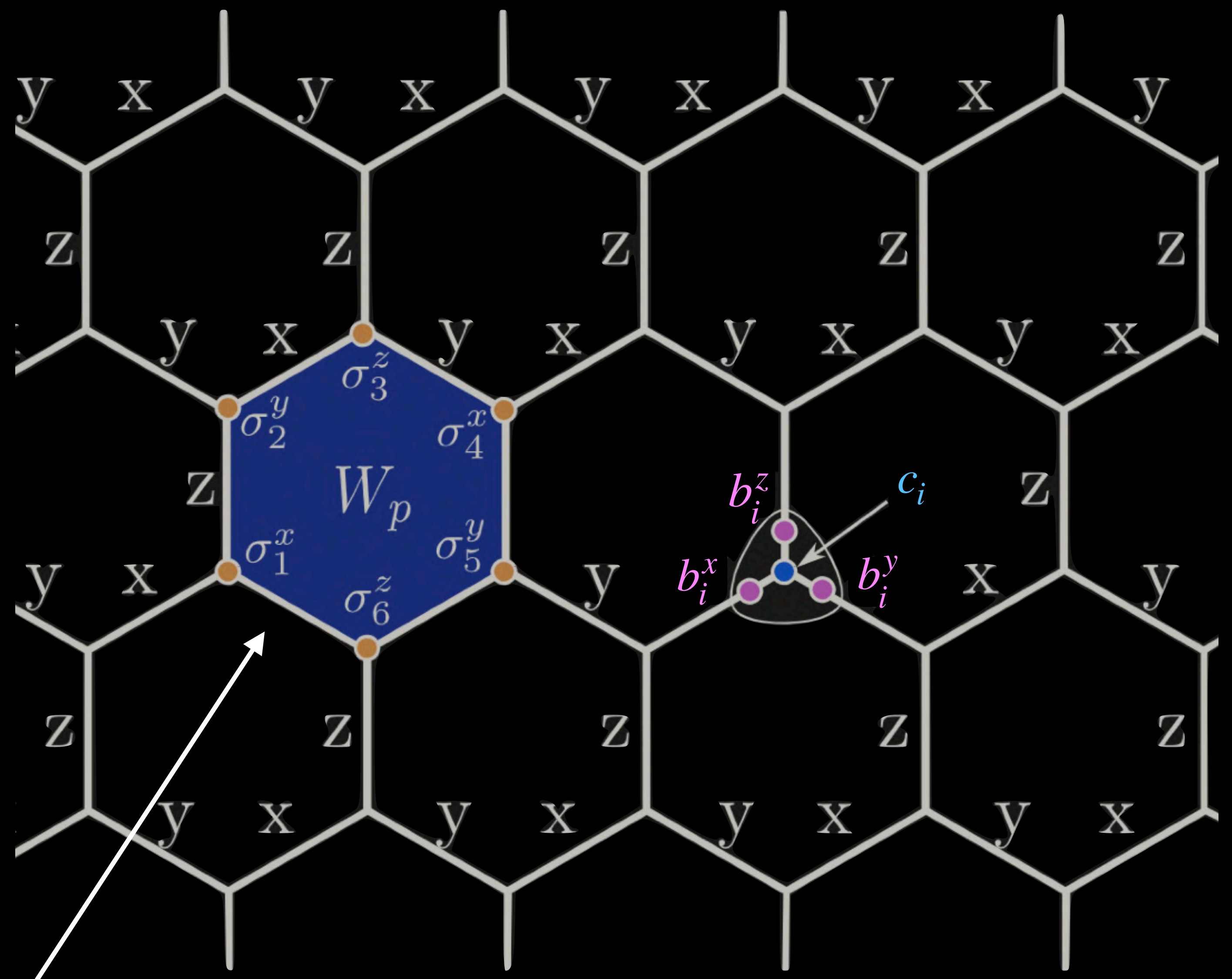

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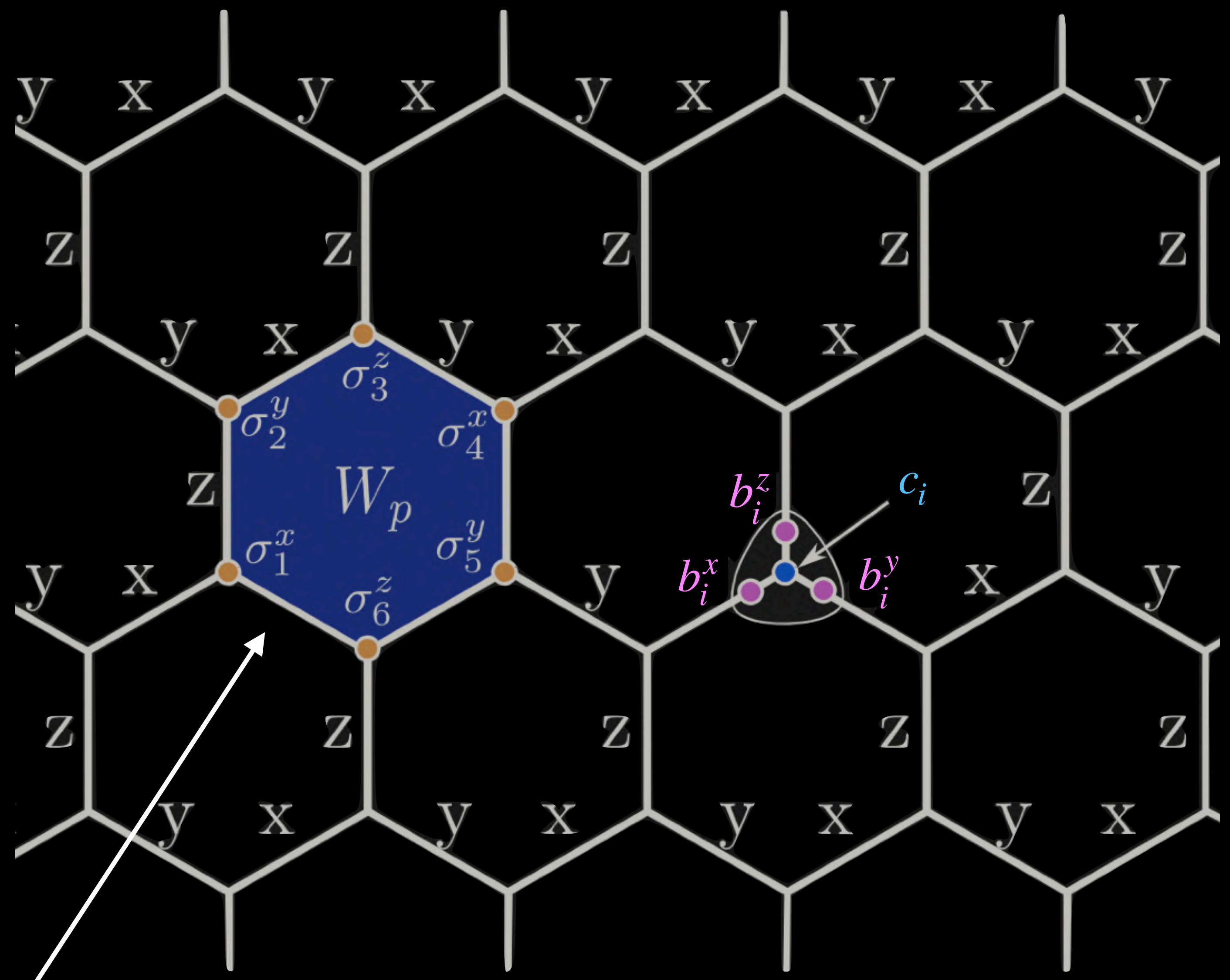

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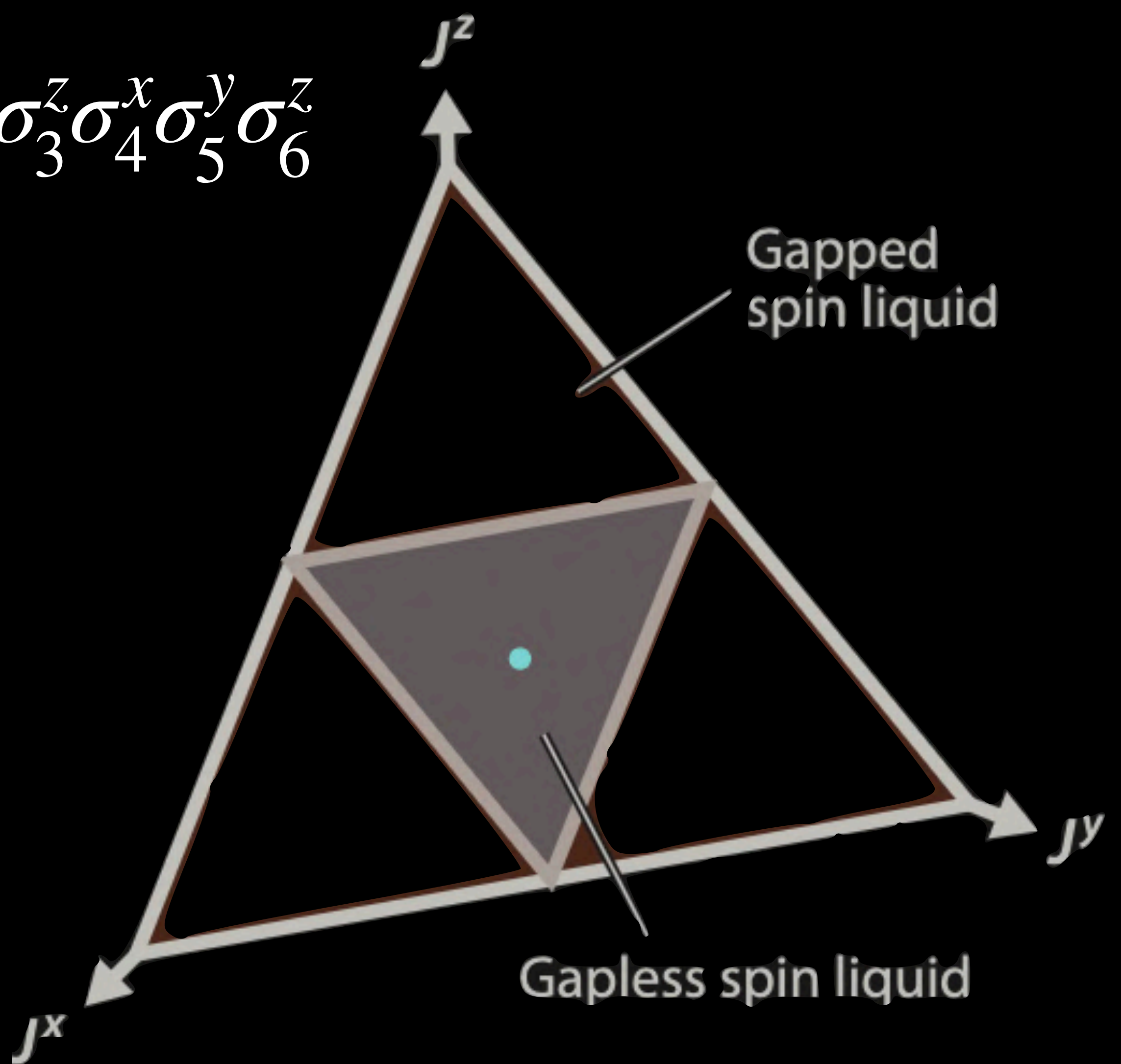

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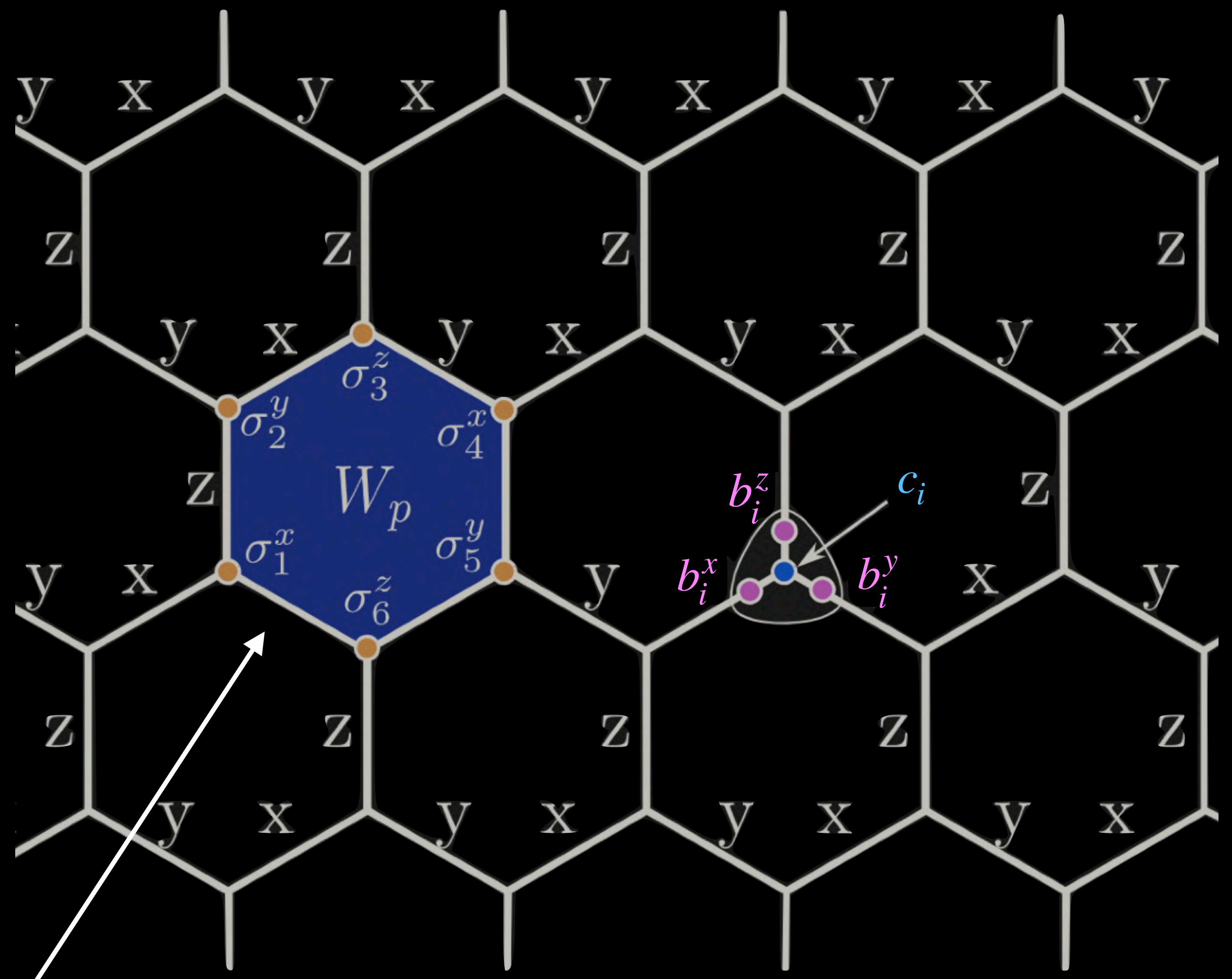

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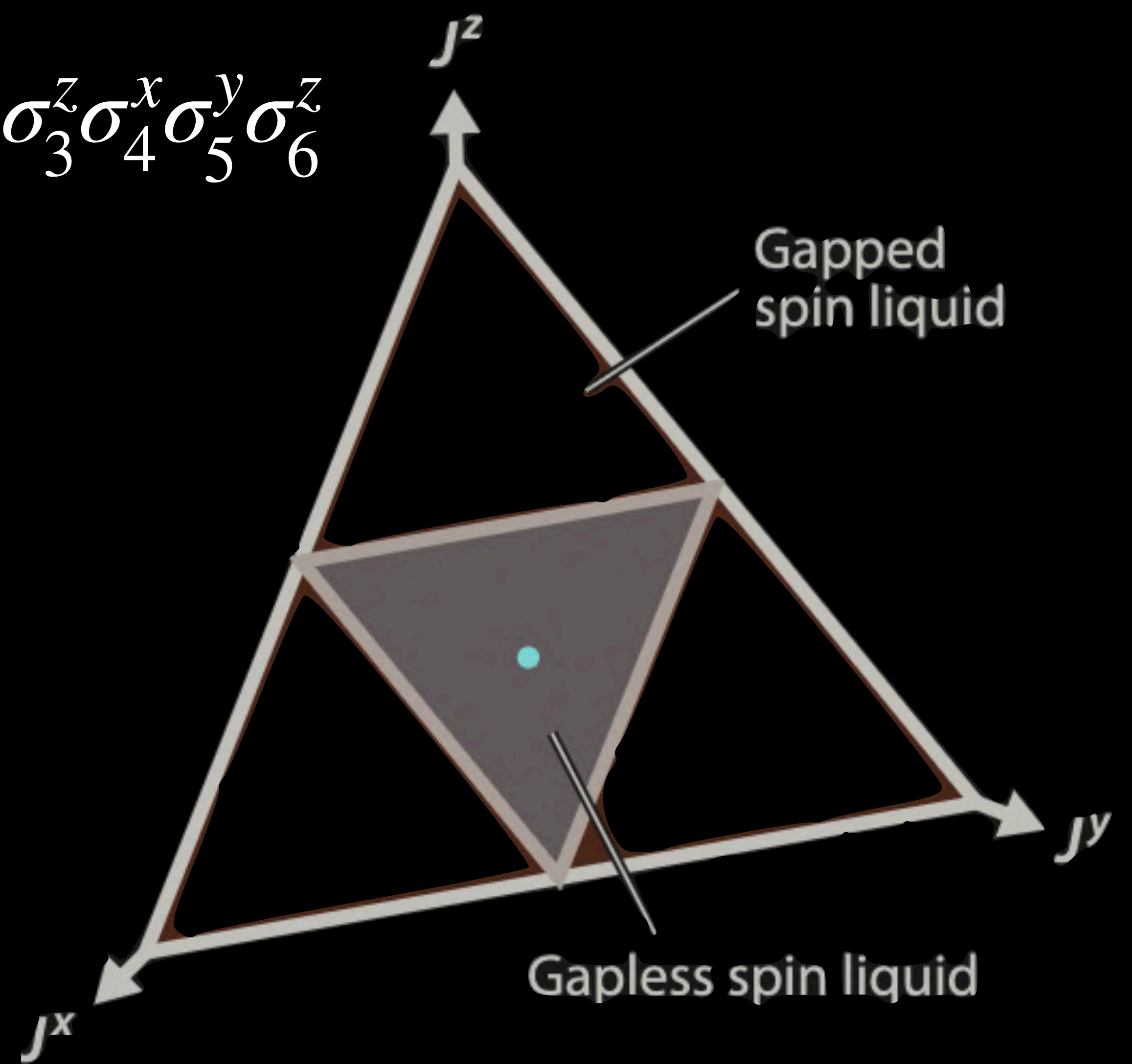

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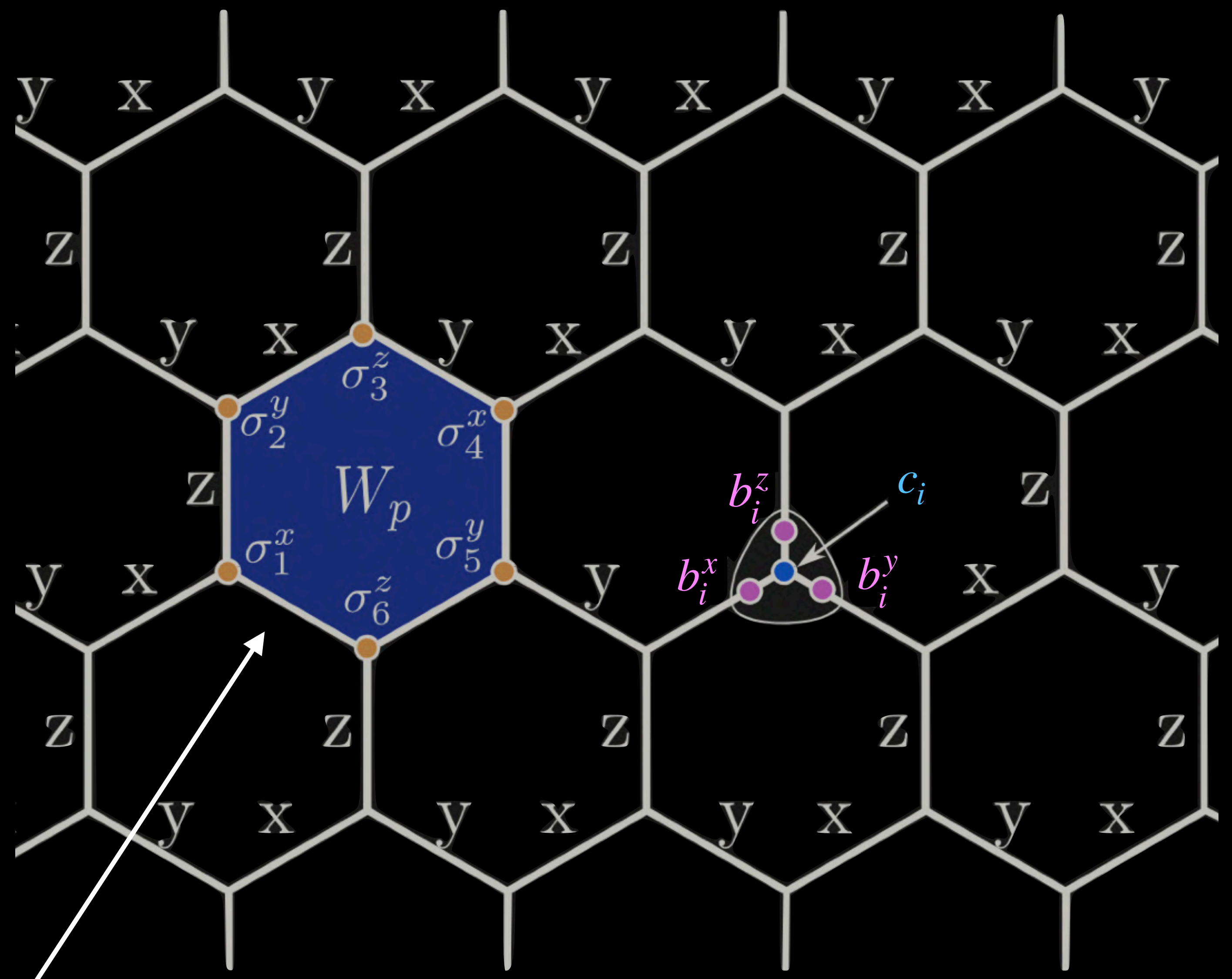
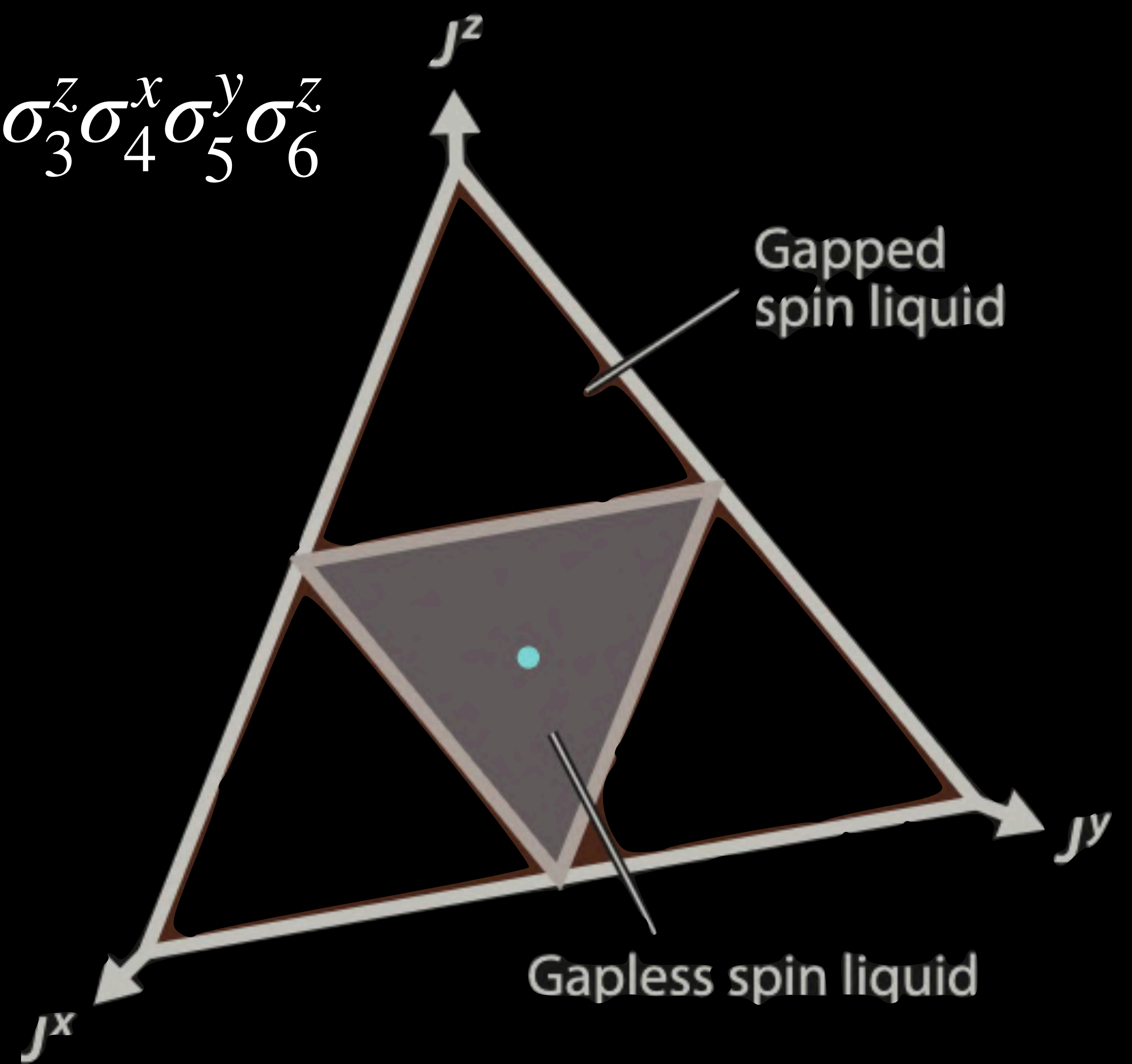
Kitaev Ann. Phys. (2006)



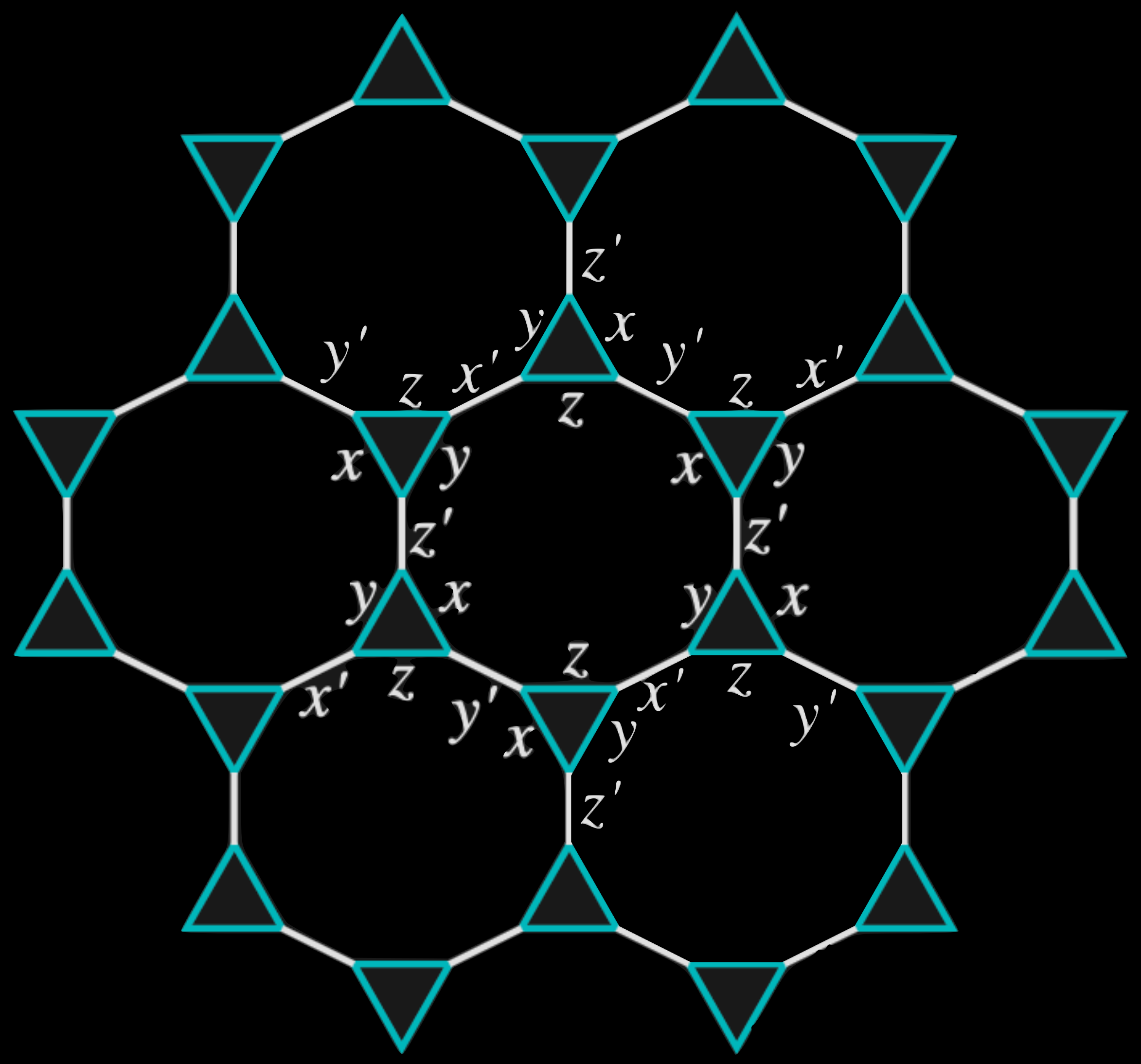
$$W_p = \sigma_1^x \sigma_2^y \sigma_3^z \sigma_4^x \sigma_5^y \sigma_6^z$$

$$\phi_p = \pm 1$$



Decorated Honeycomb

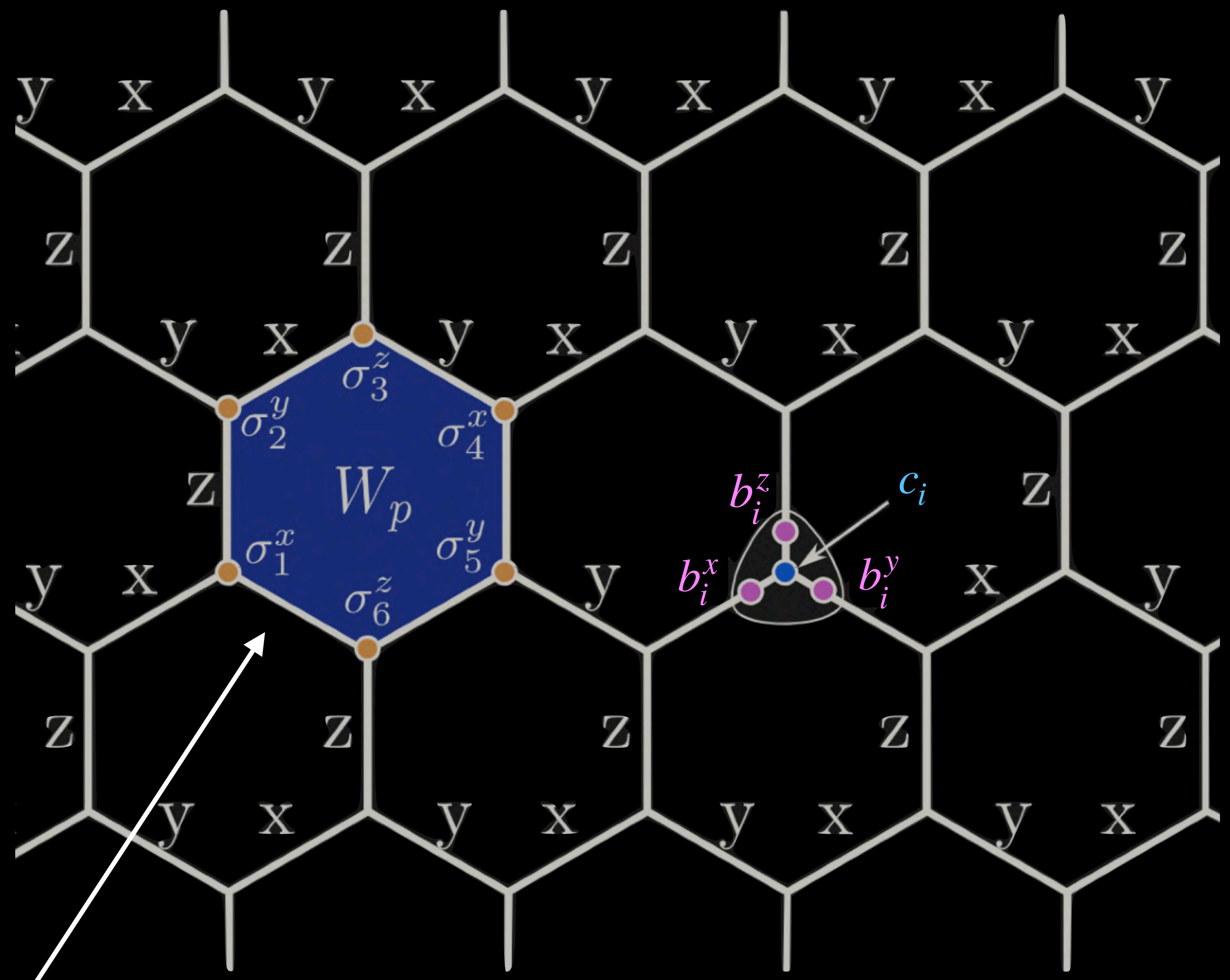
Yao and Kivelson PRL (2007)



Kitaev models

Honeycomb

Kitaev Ann. Phys. (2006)



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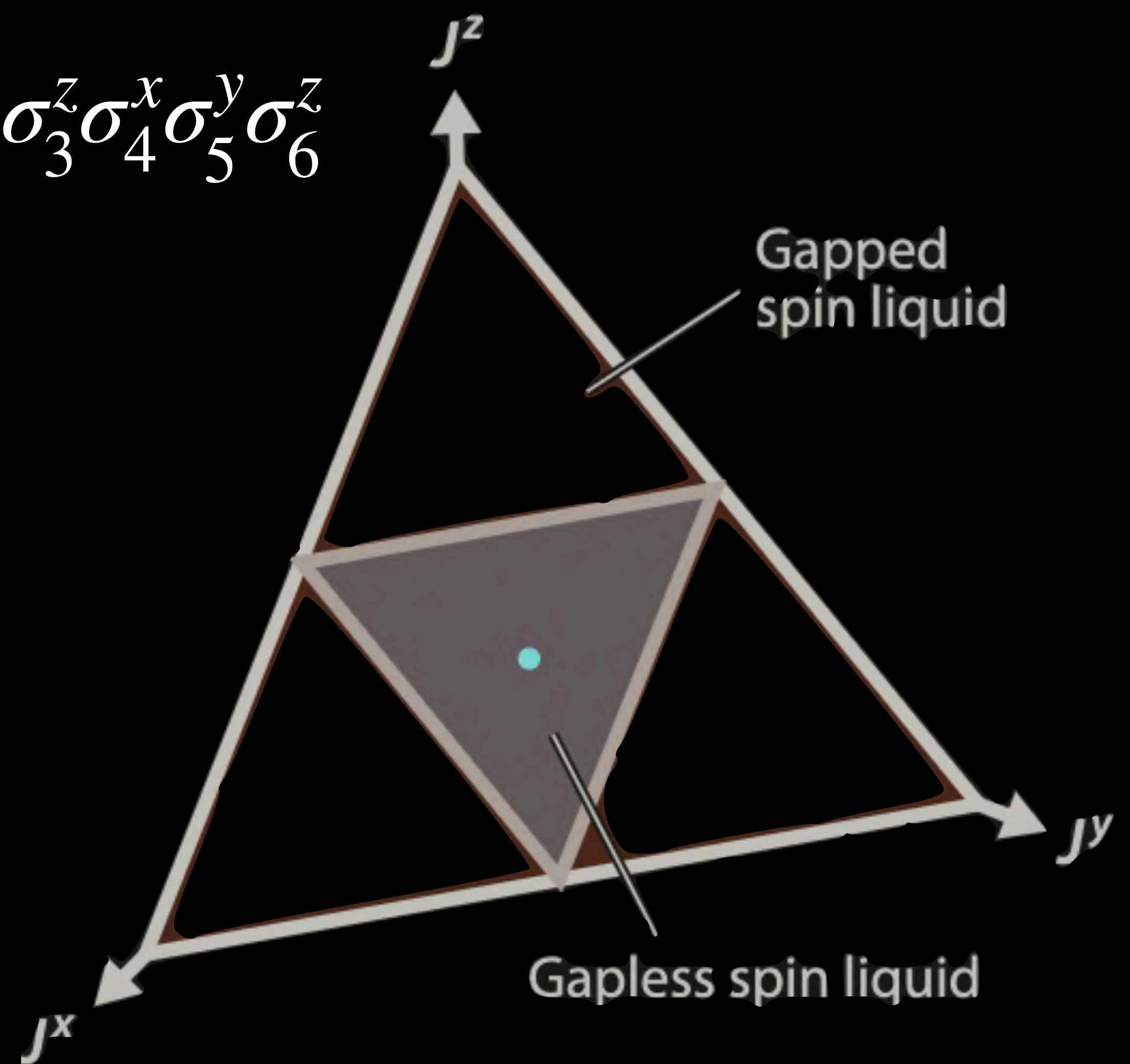

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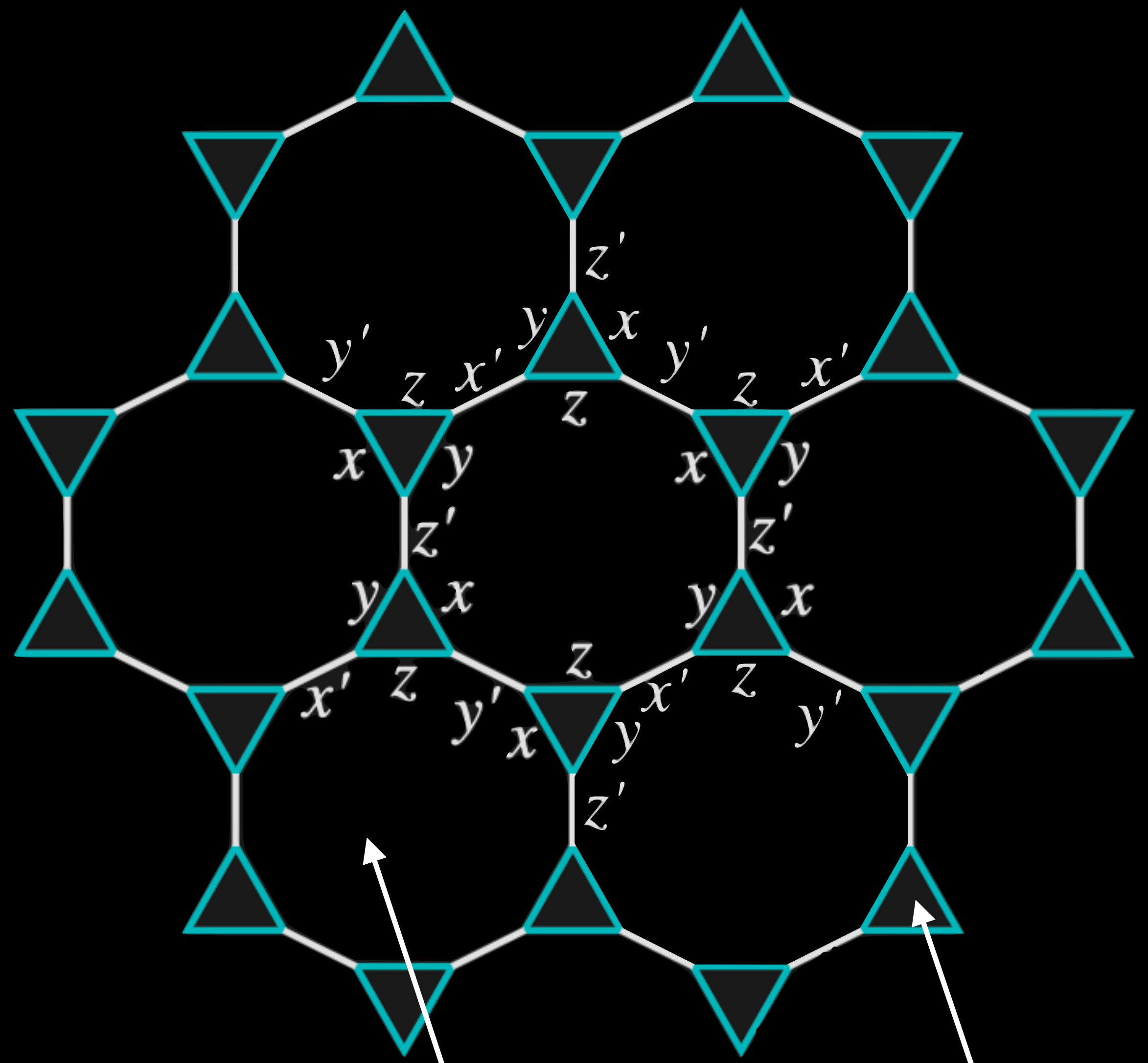
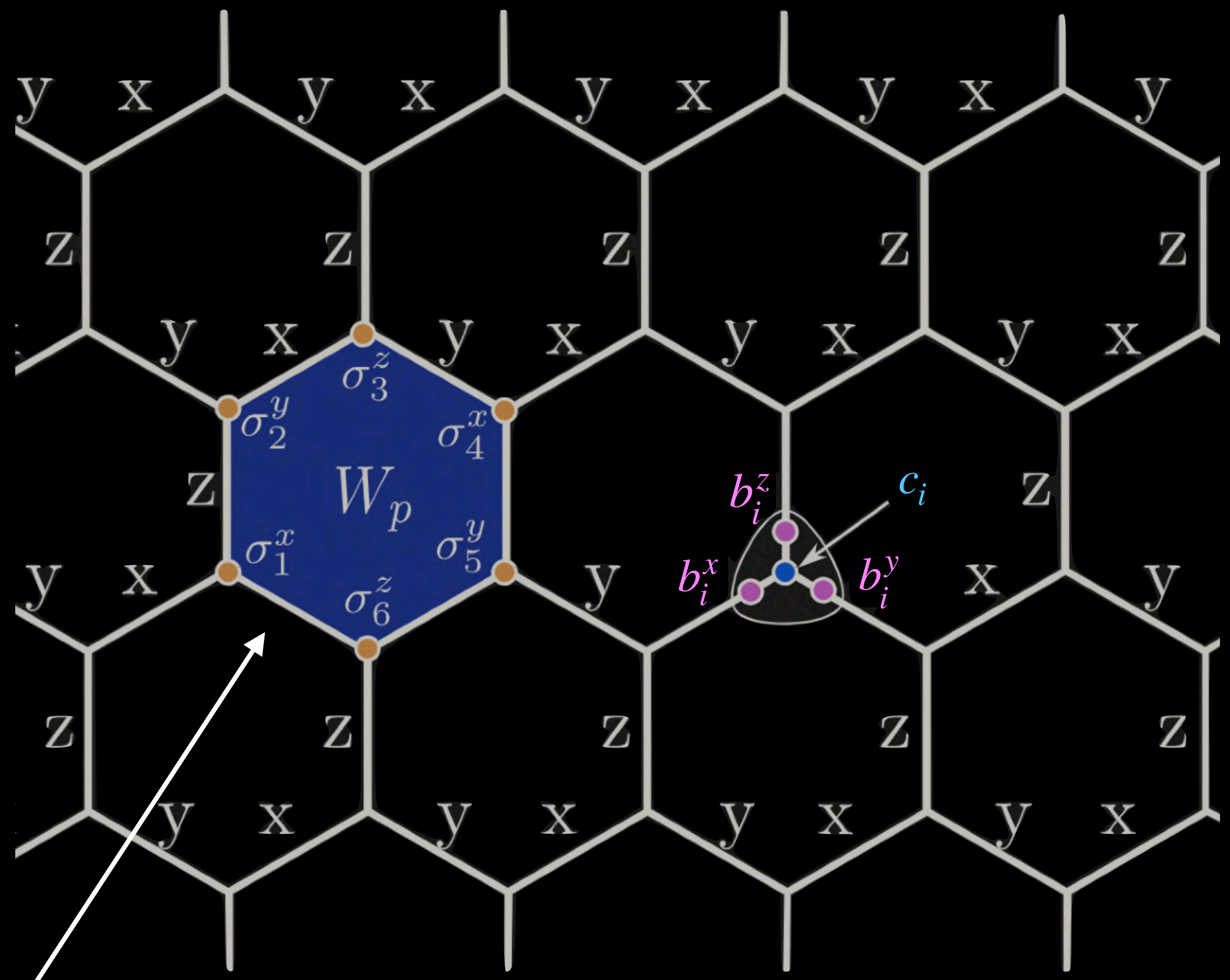


$\phi_p = \pm 1$ $\phi_p = \pm i$

Kitaev models

Honeycomb

Kitaev Ann. Phys. (2006)



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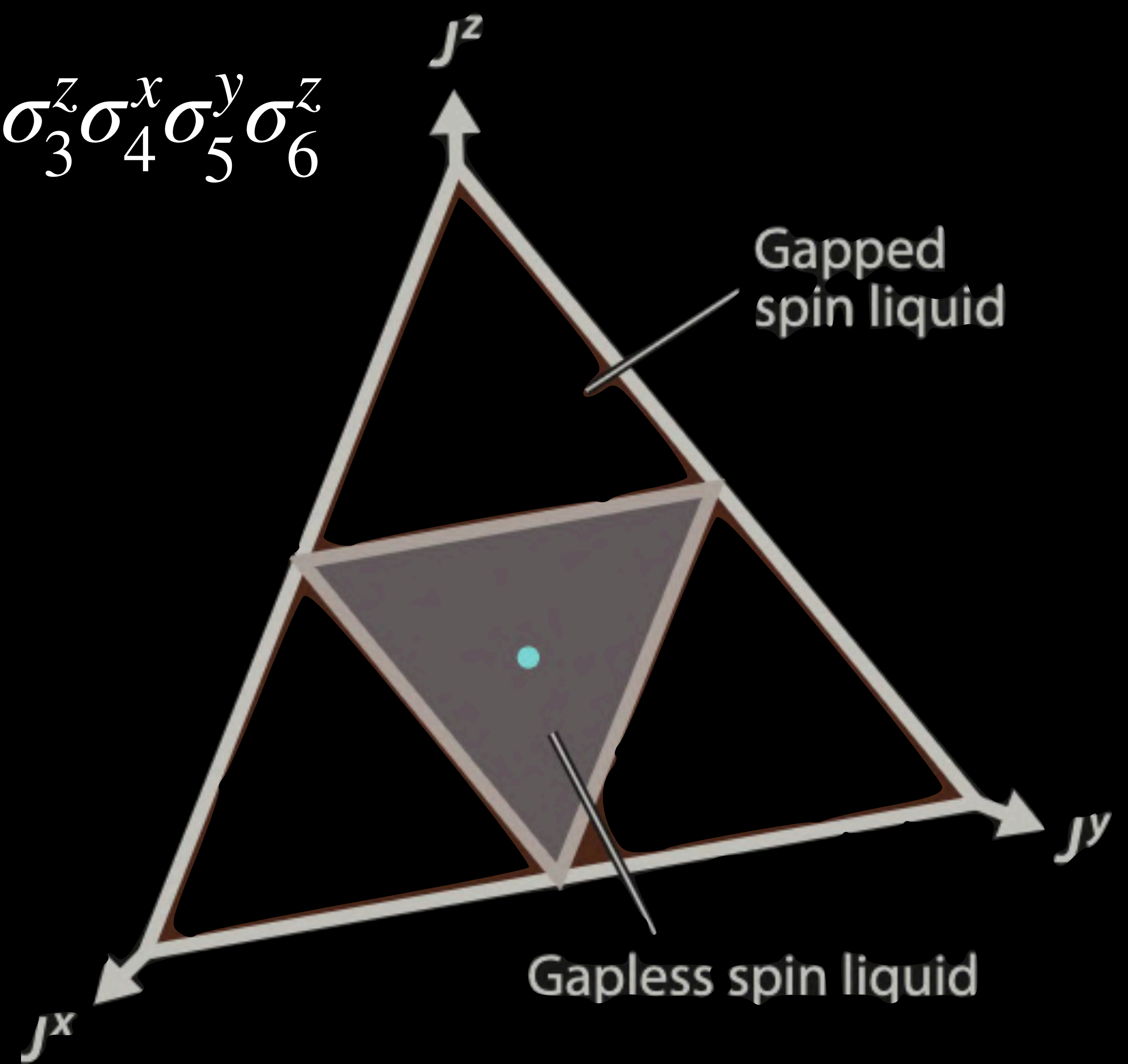

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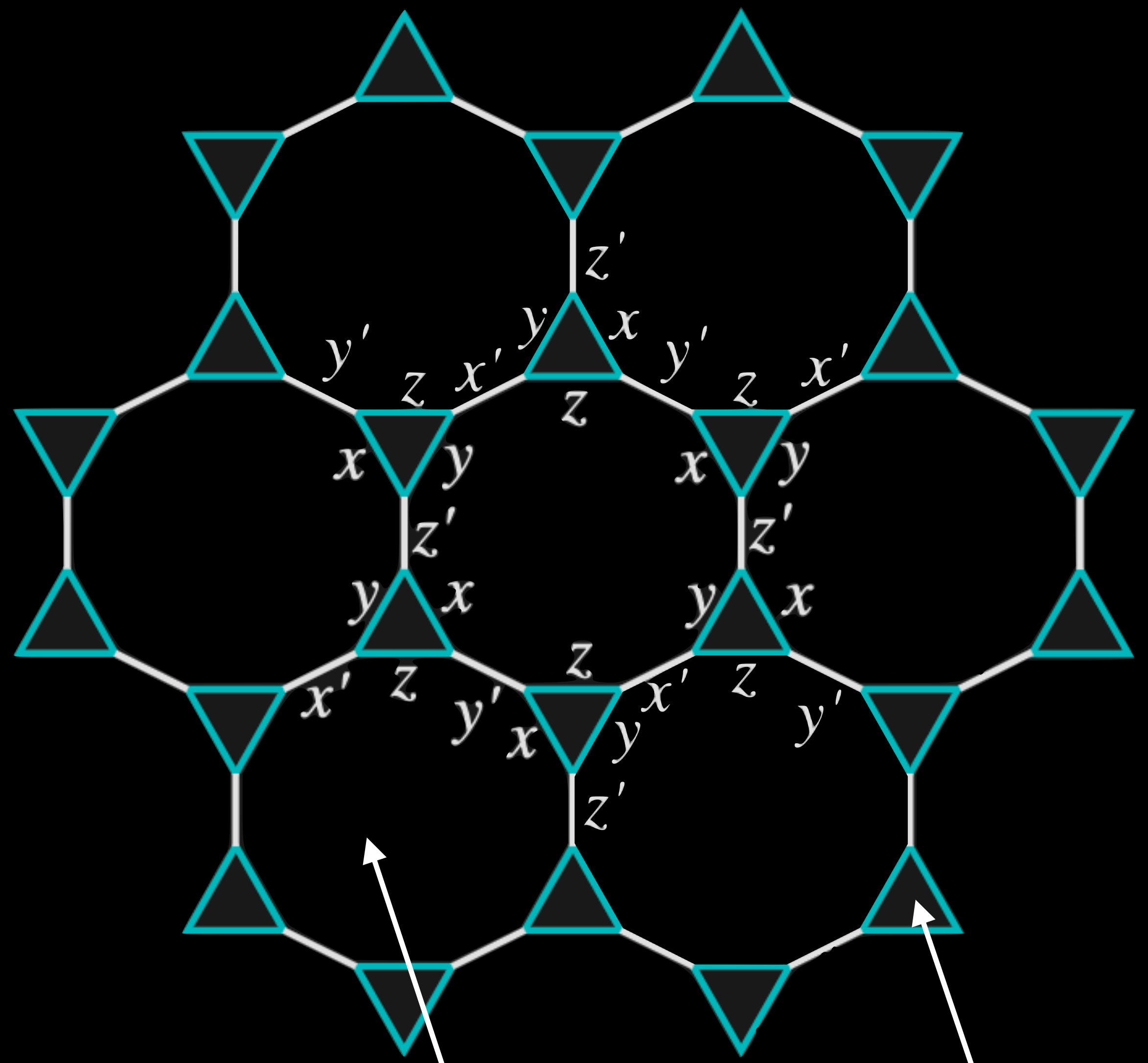

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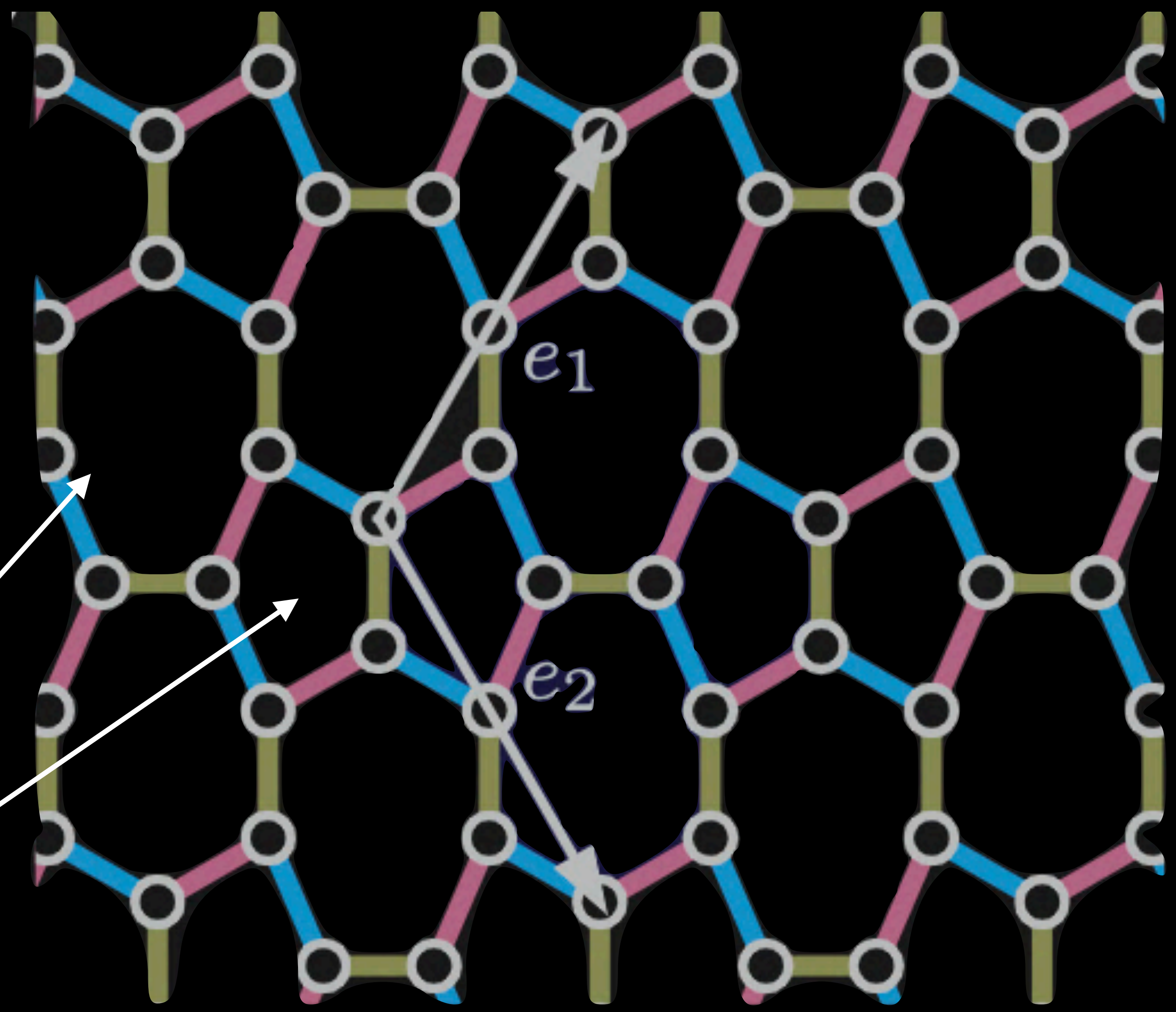
Pentaheptite lattice

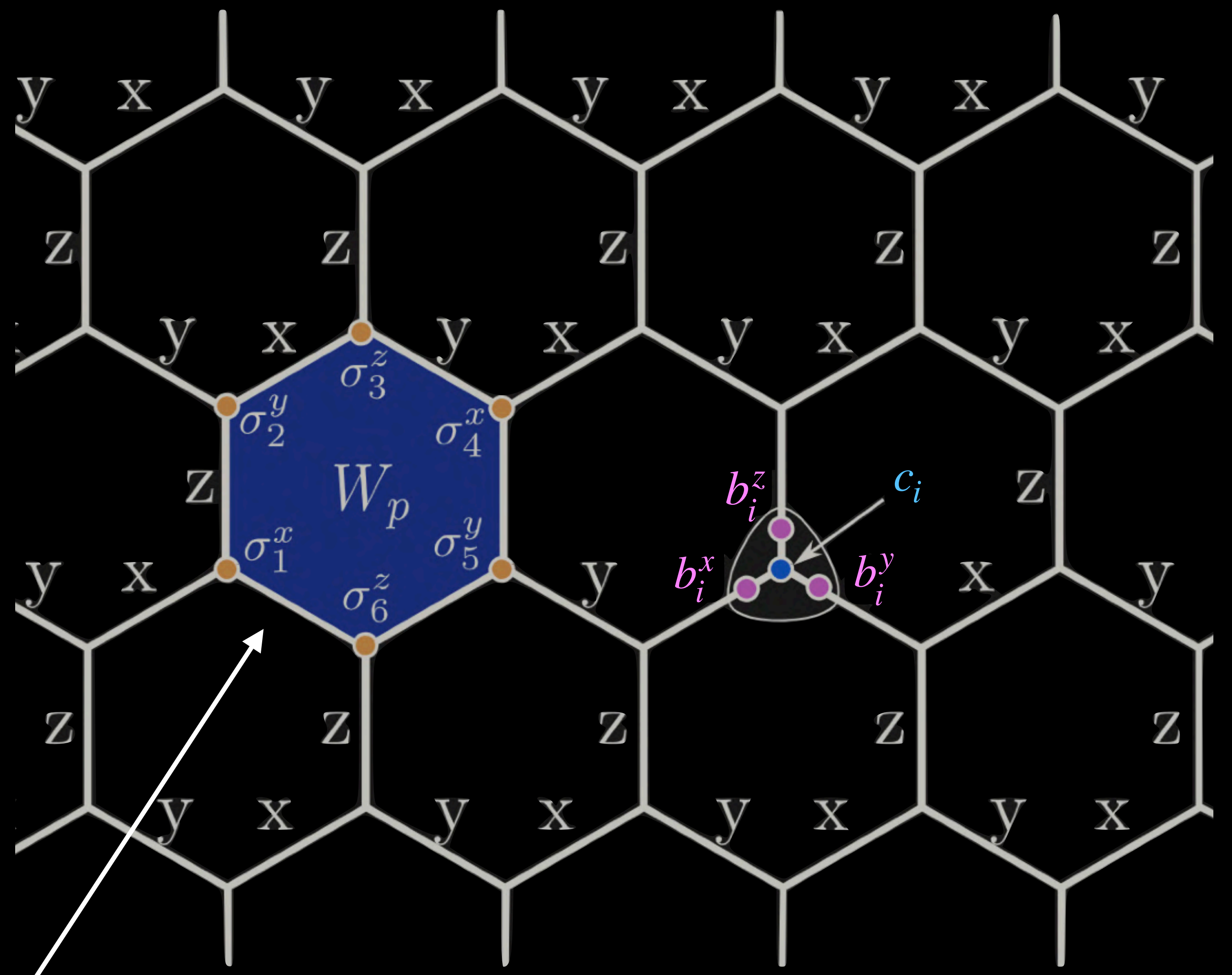
Peri et al PRB (2020)



Kitaev models

Honeycomb

Kitaev Ann. Phys. (2006)



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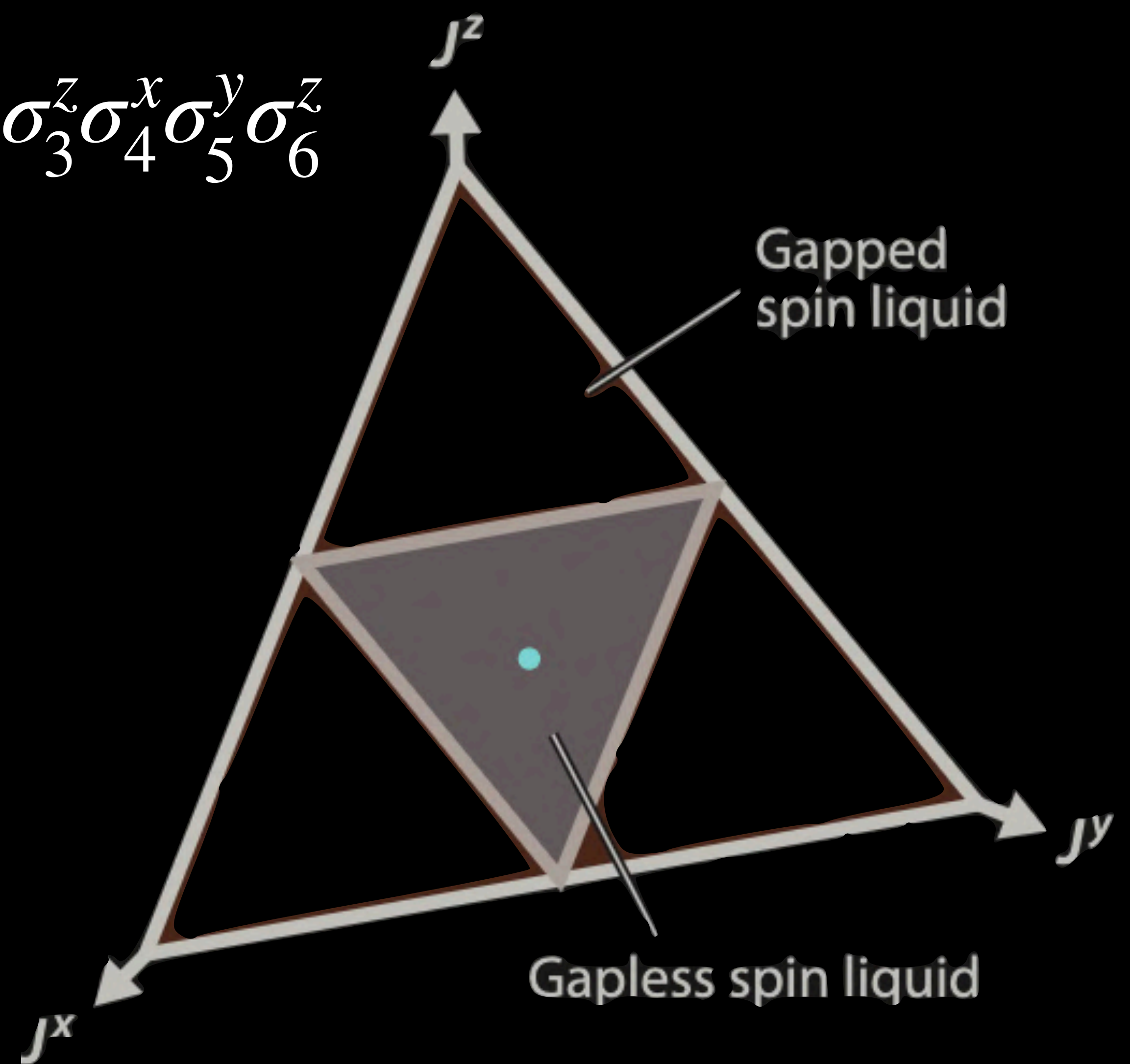

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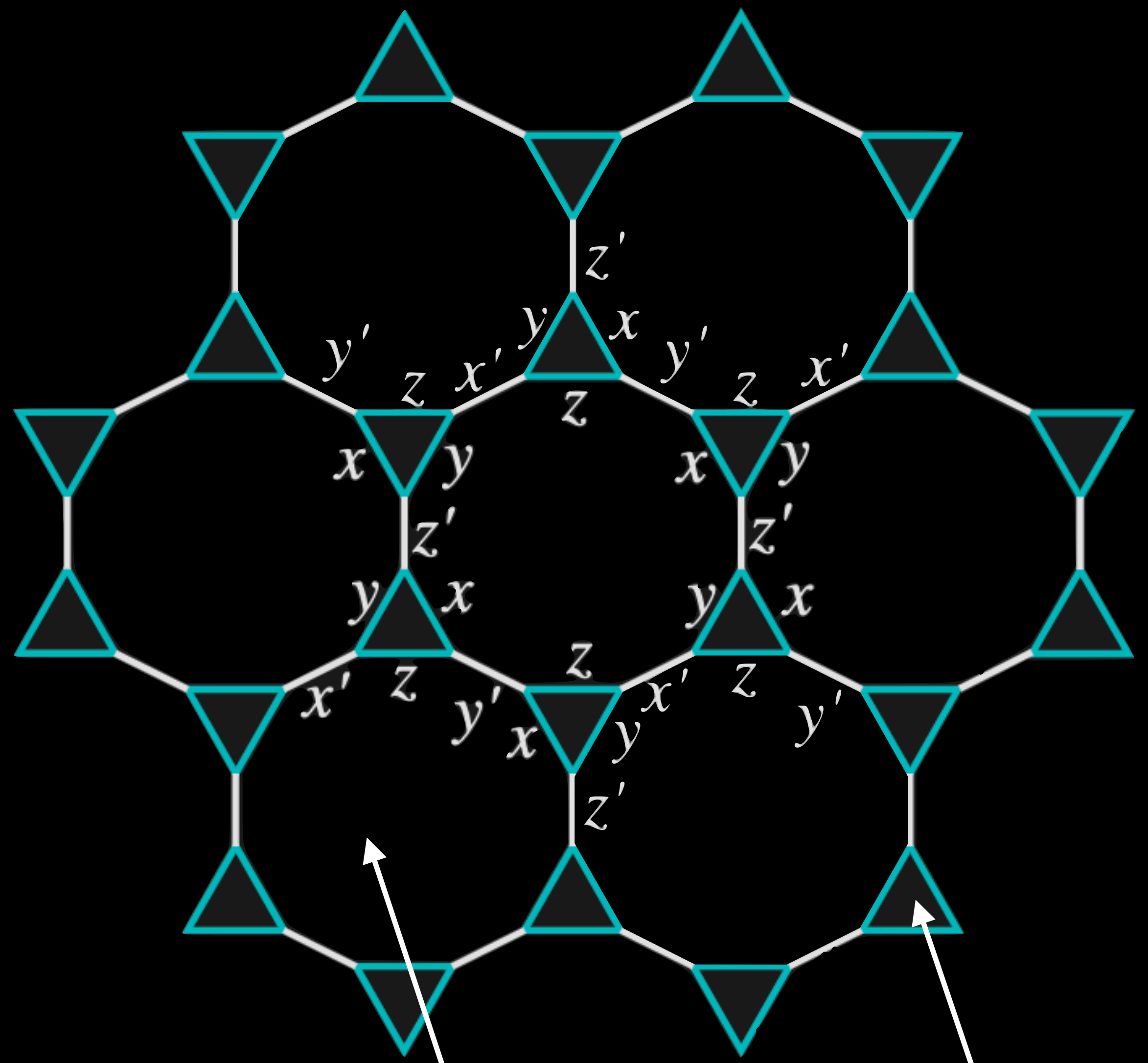

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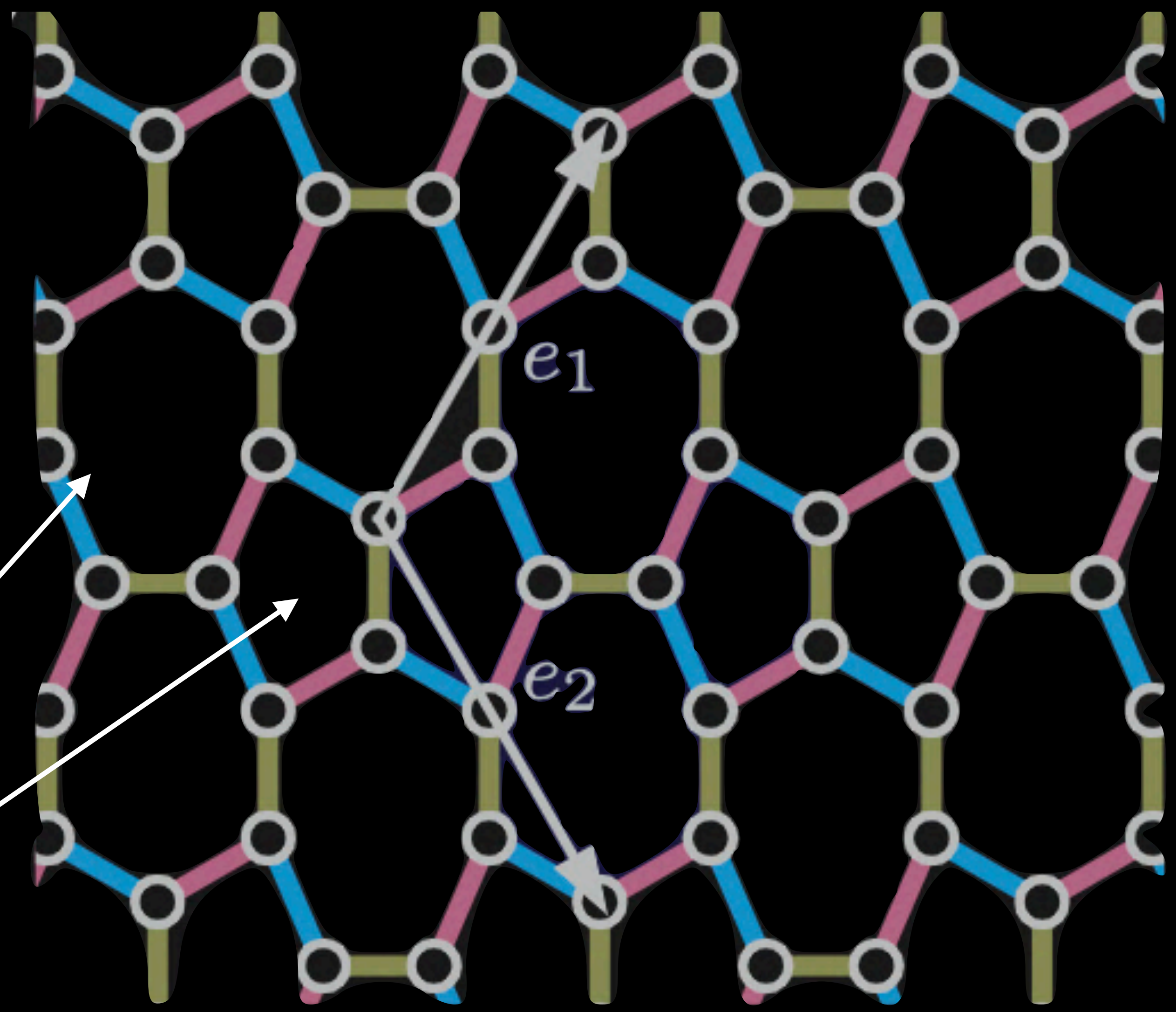

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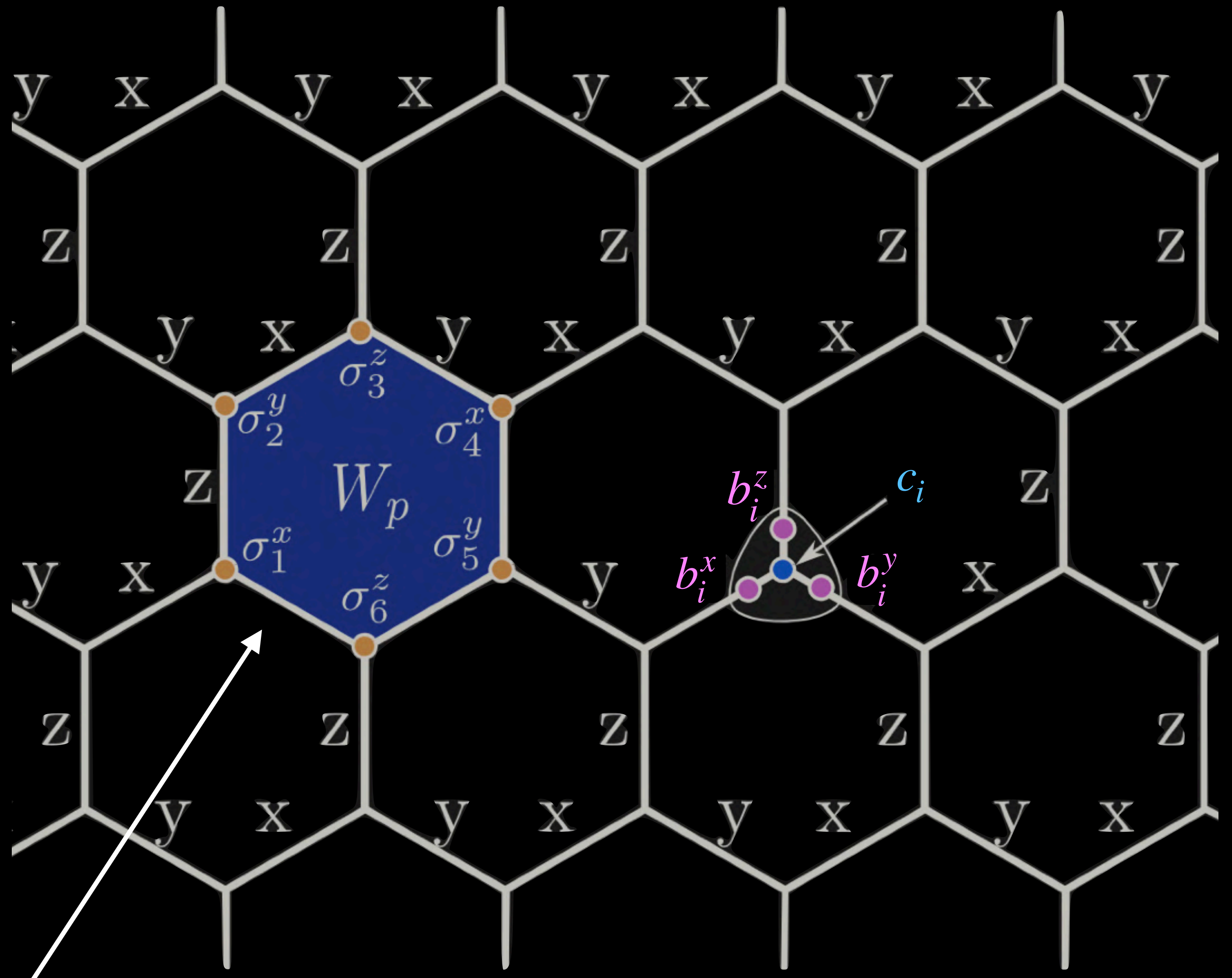
Odd plaquettes break TRS

Kitaev models

Honeycomb

Kitaev Ann. Phys. (2006)



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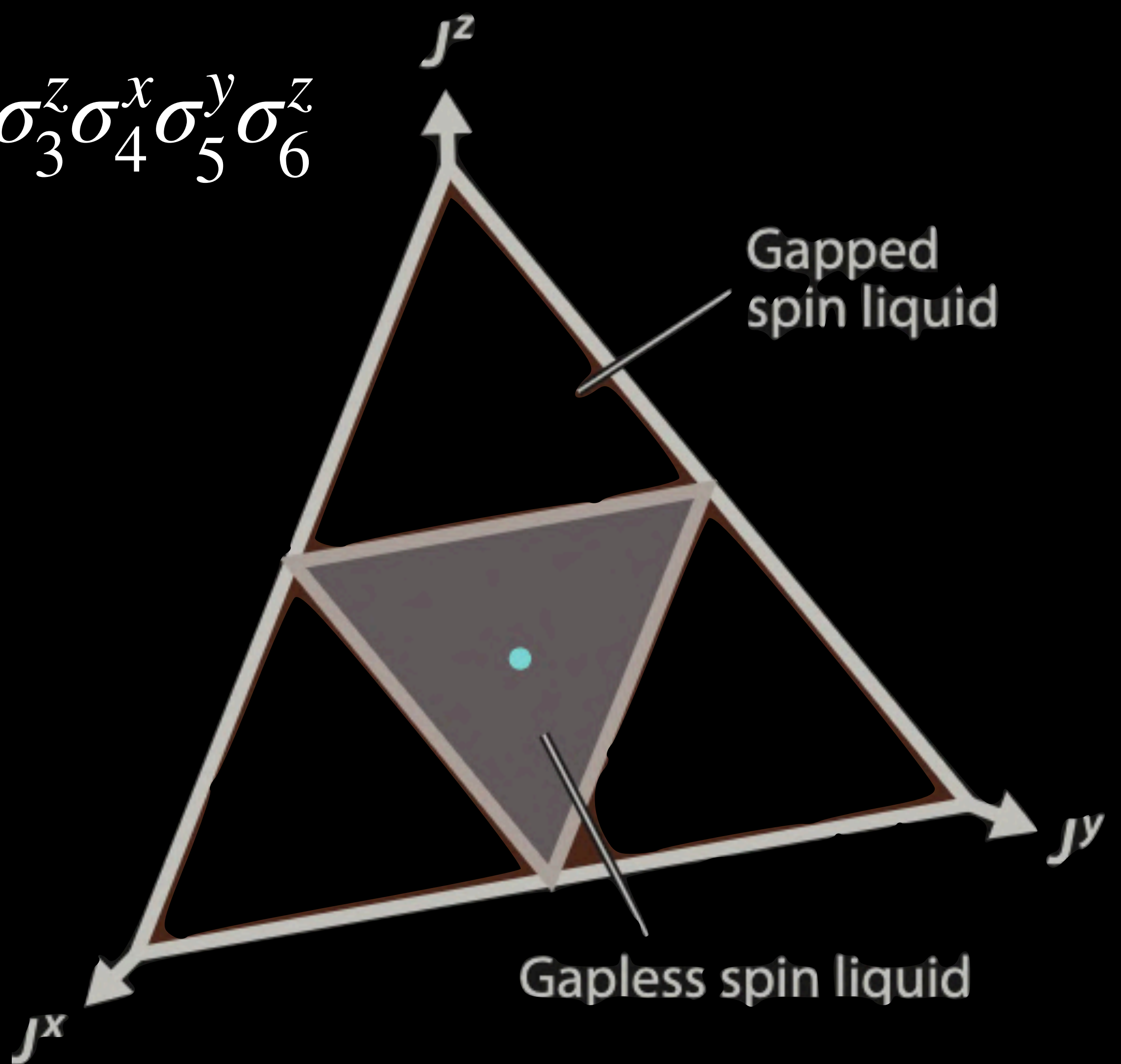

Decorated Honeycomb

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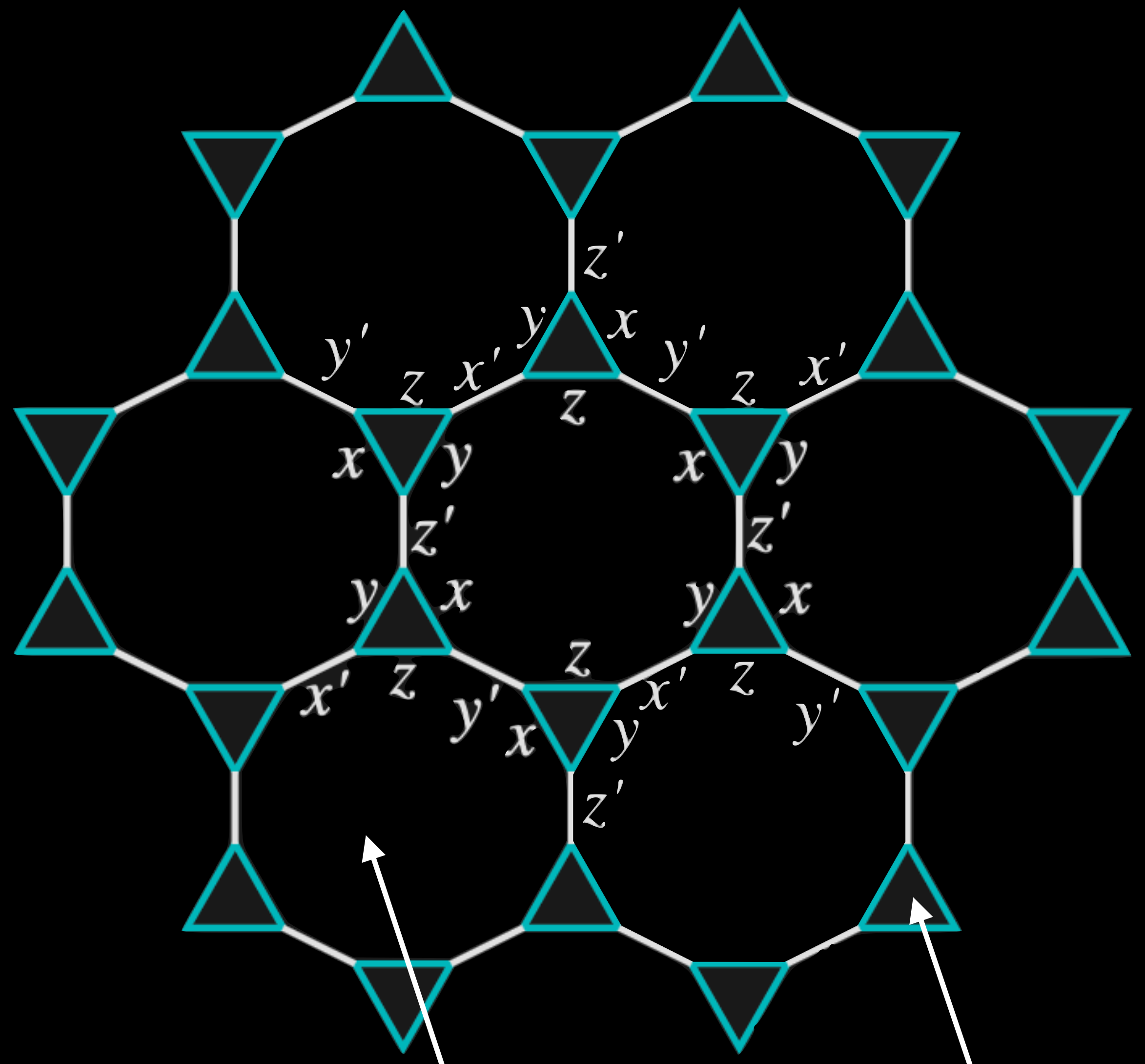

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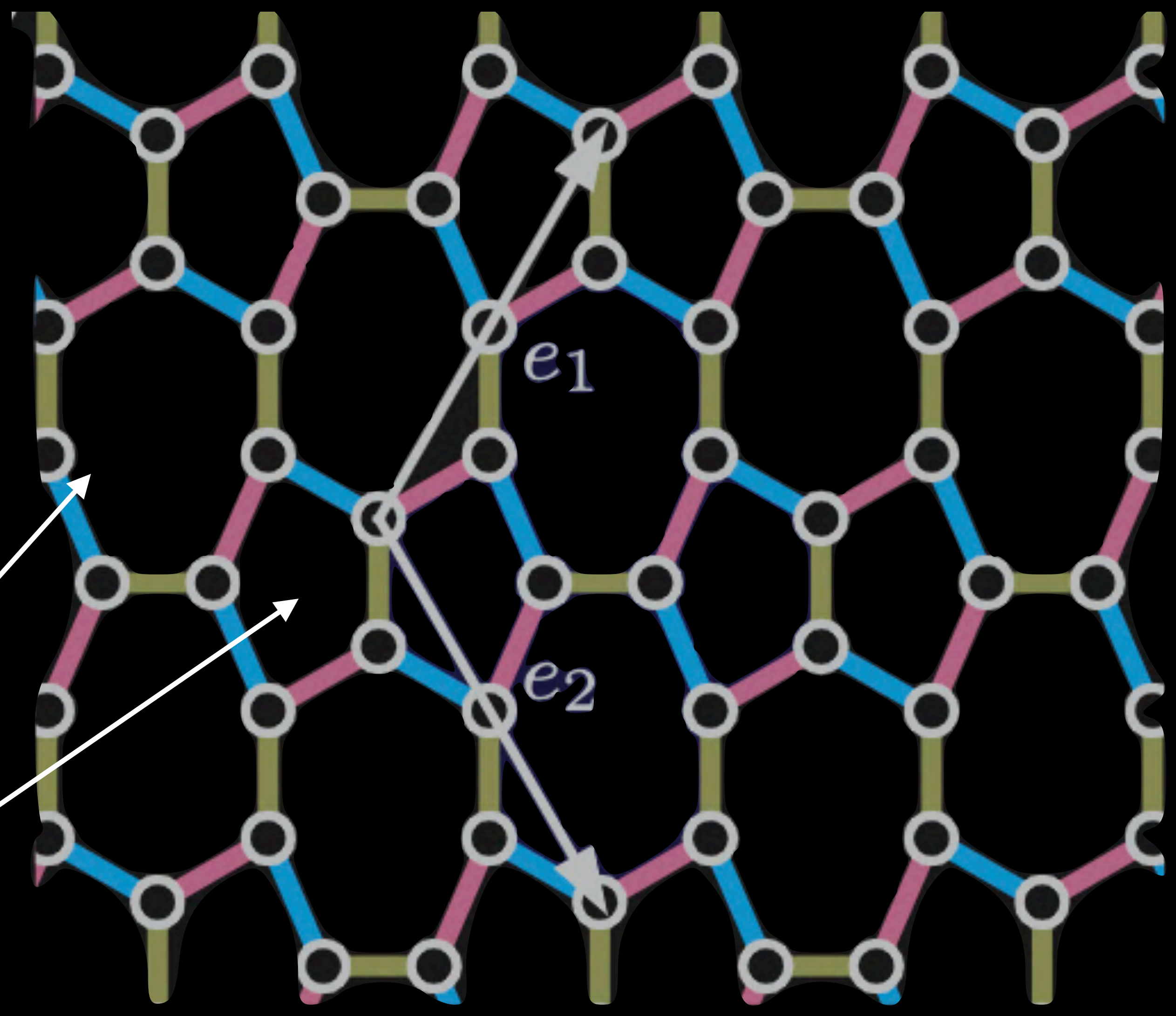


Odd plaquettes break TRS → **Gapped chiral spin-liquid!**

= chiral majorana edge states

non-abelian excitations

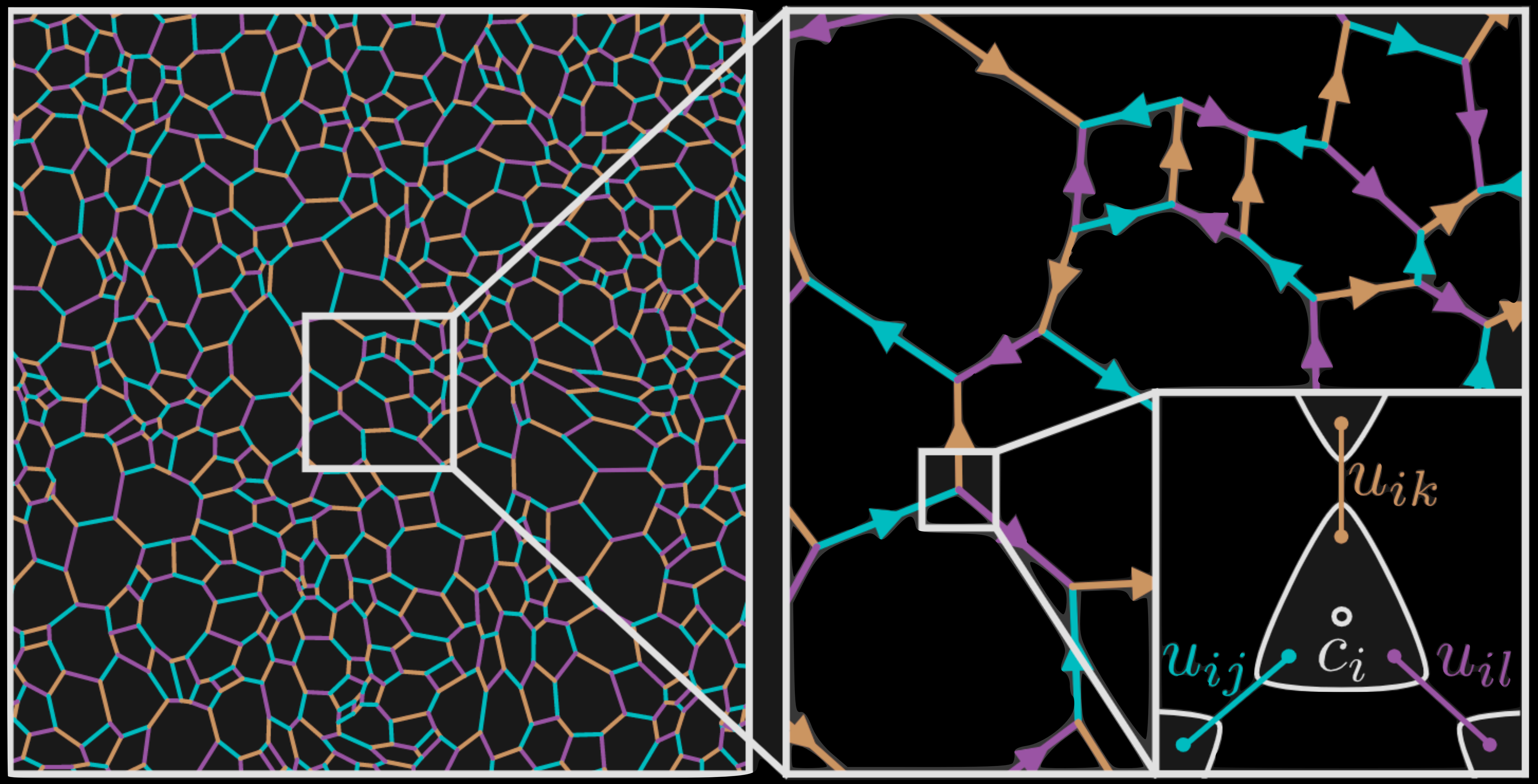
Amorphous Kitaev model

G. Casella et al 2208.08246

Lattice

Groundstate

$$\phi_p = -(\pm i)^{n_{sides}}$$



Amorphous Kitaev model

G. Casella et al 2208.08246

Lattice

Groundstate

LDOS

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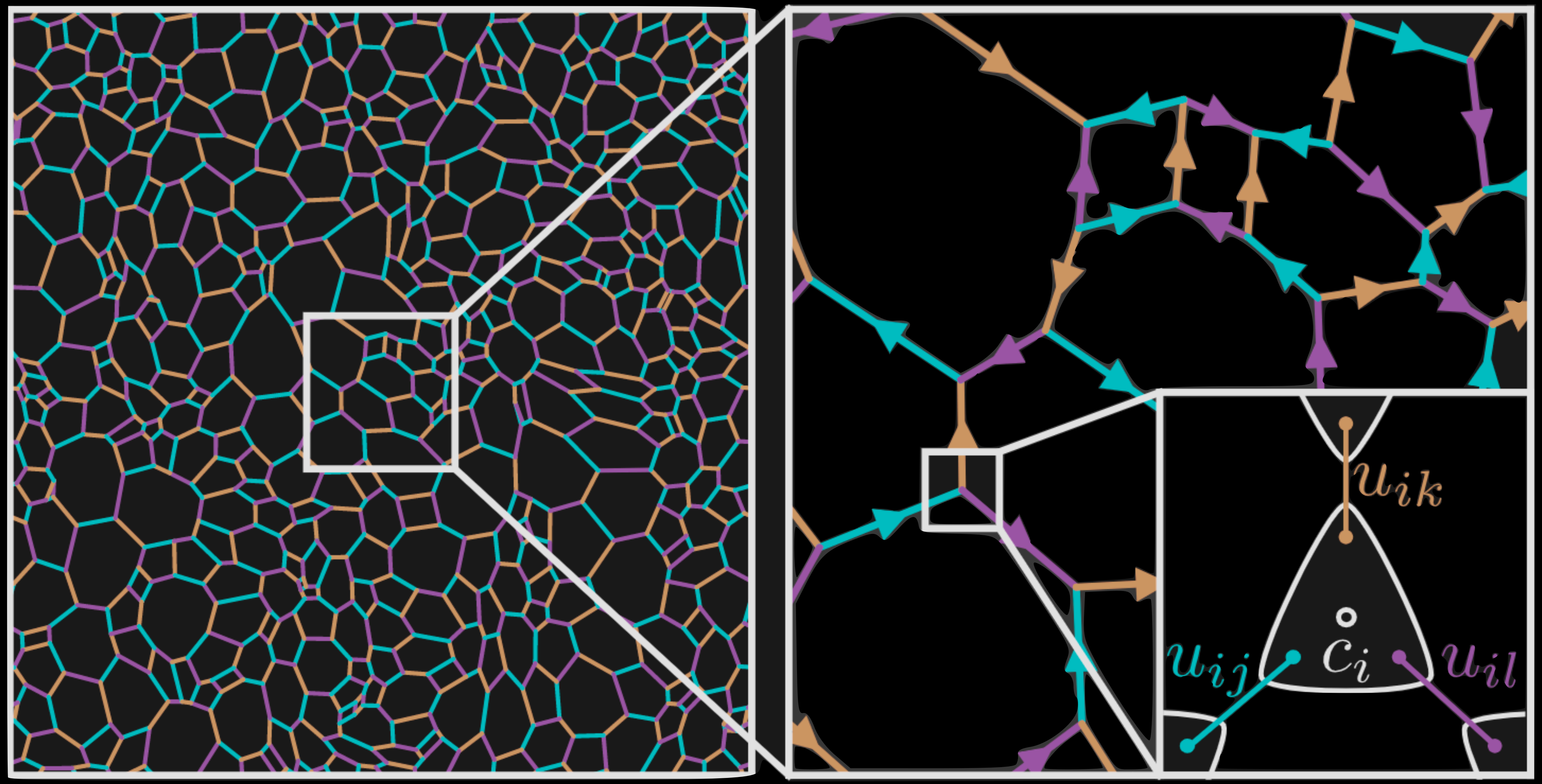

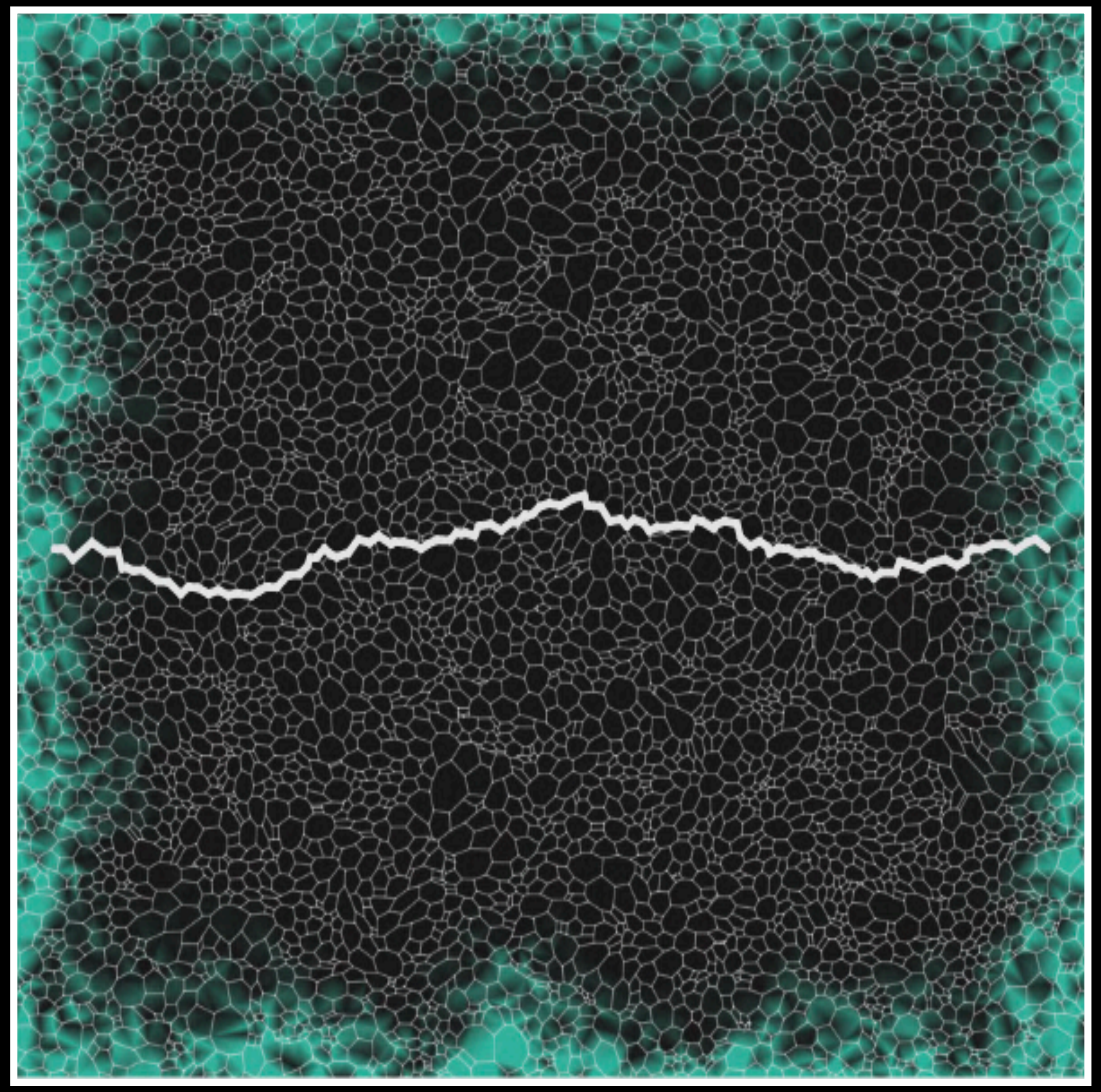

Amorphous Kitaev model

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Lattice

Groundstate

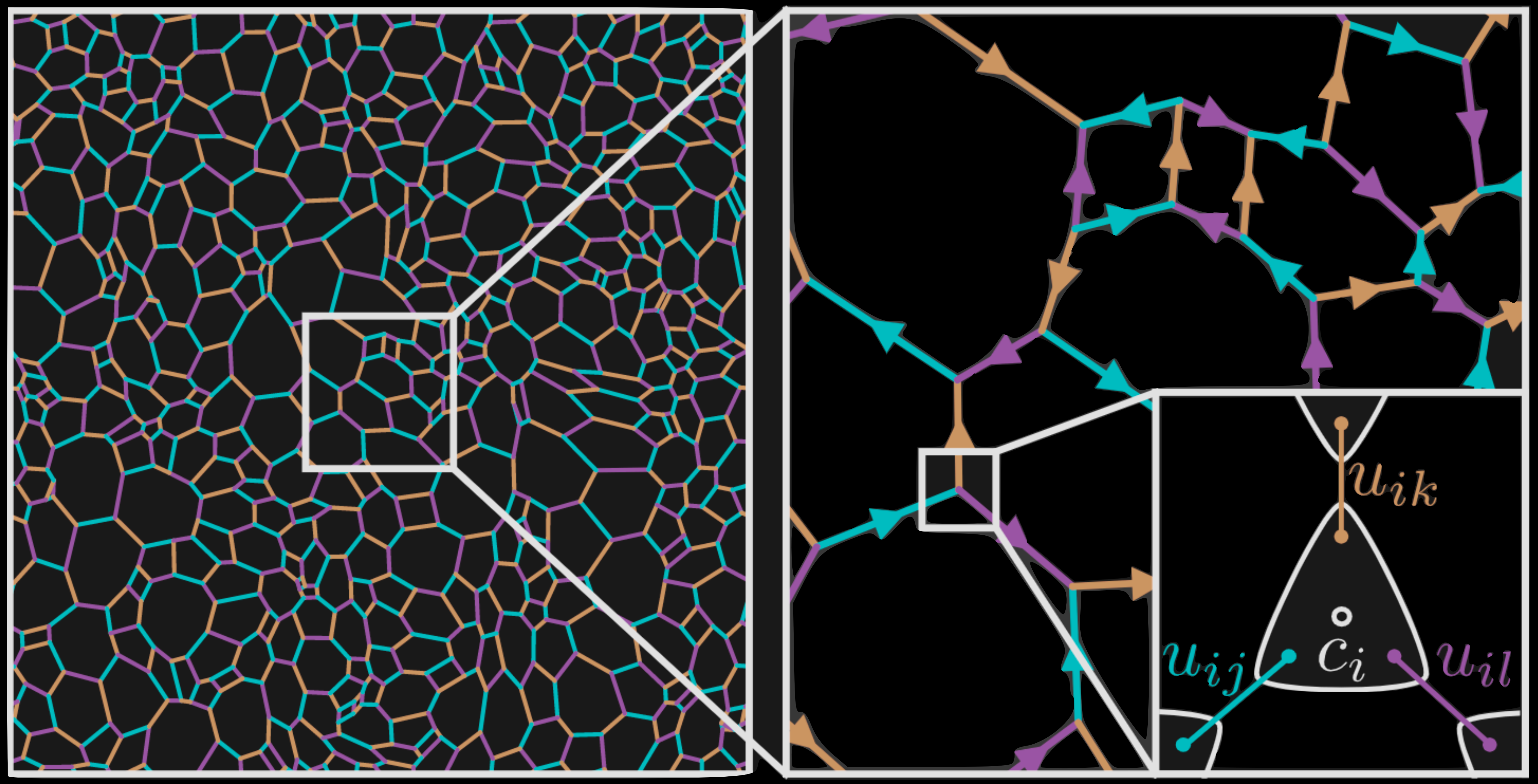
$$\phi_p = -(\pm i)^{n_{sides}}$$

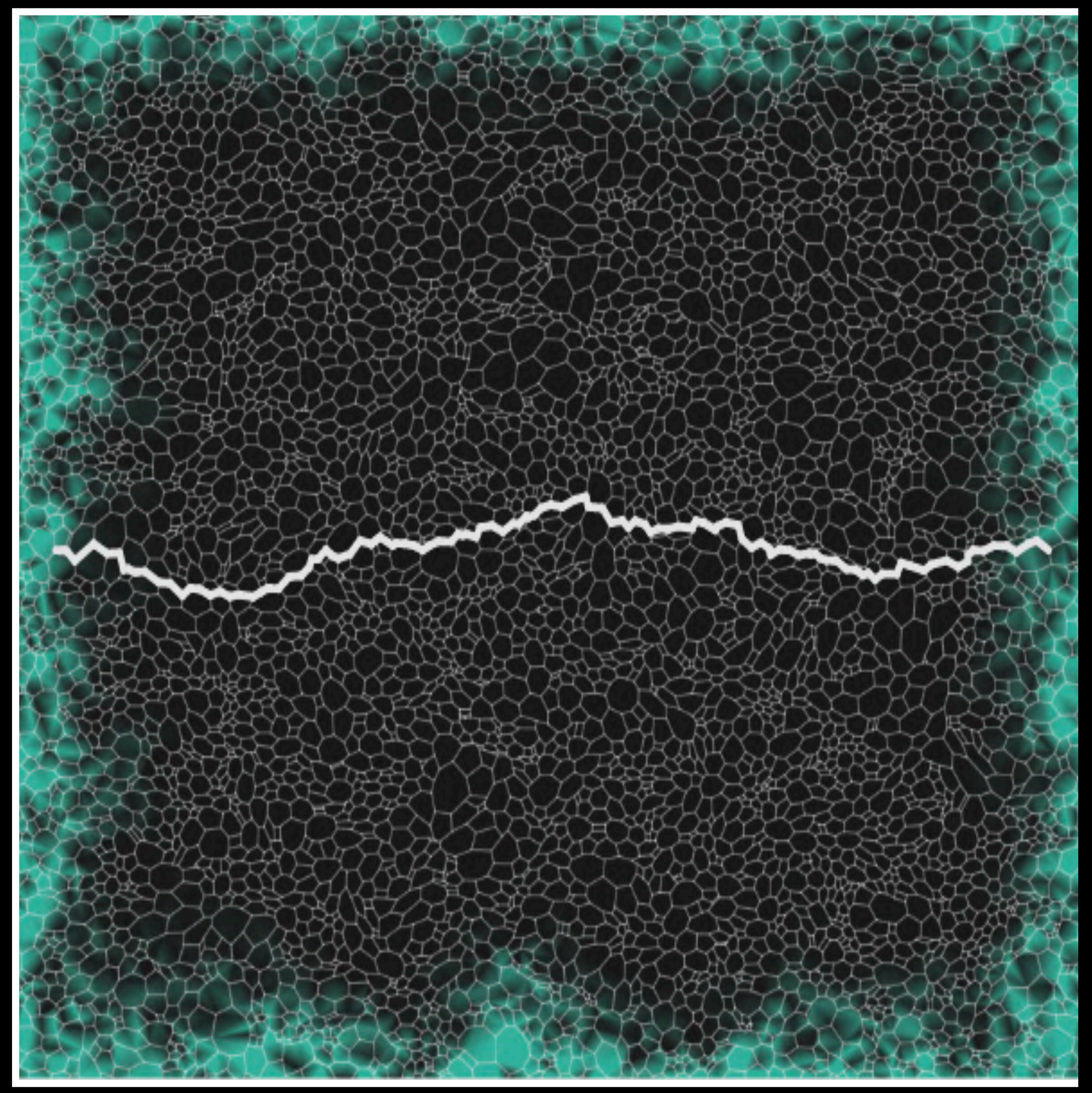
LDOS

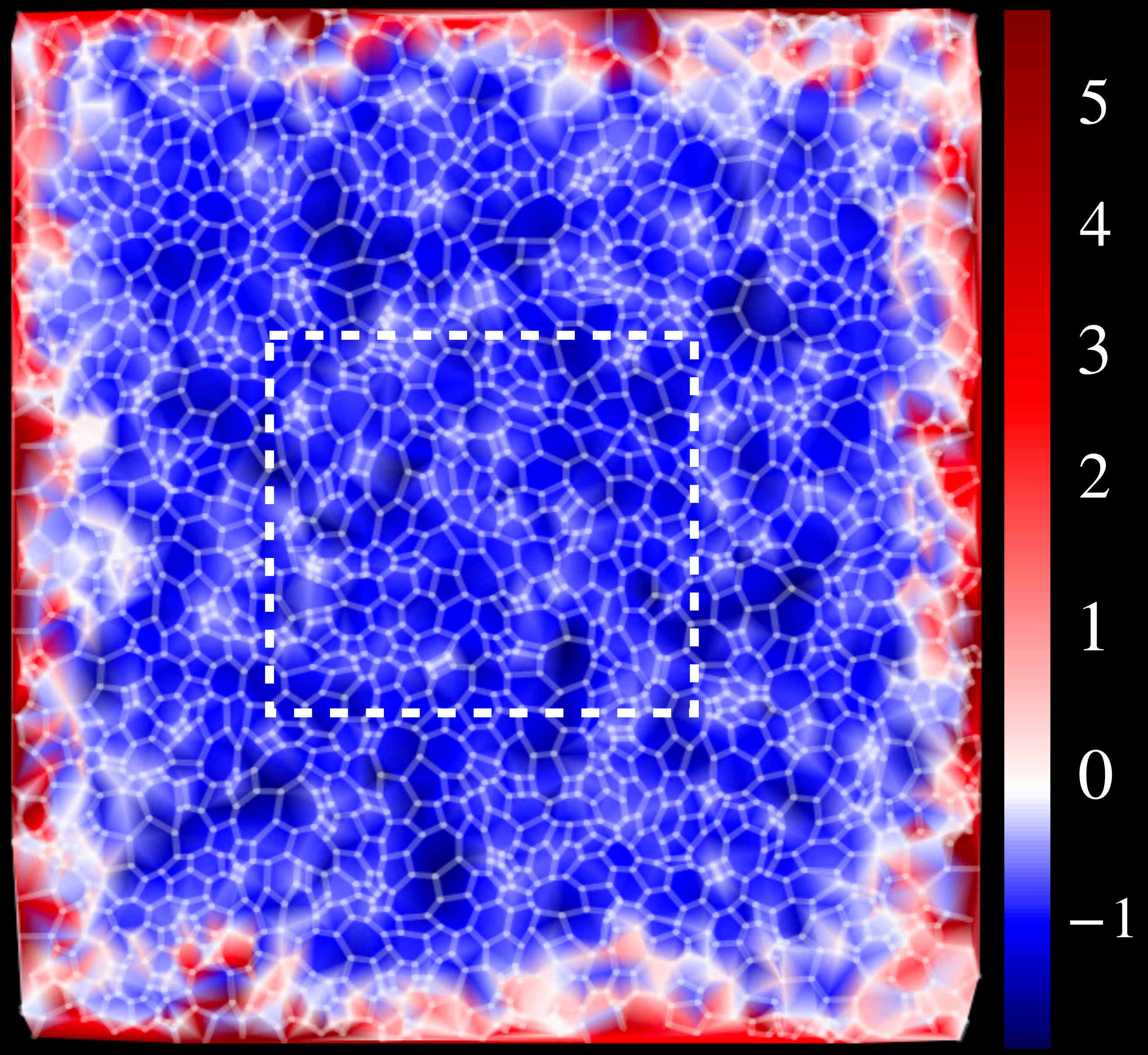
Local Chern marker

Bianco and Resta, PRB (2011)

$$C(\mathbf{r}) = 2\pi \,\mathrm{Im}\langle \mathbf{r} | [Q\hat{x}, P\hat{y}] | \mathbf{r} \rangle$$







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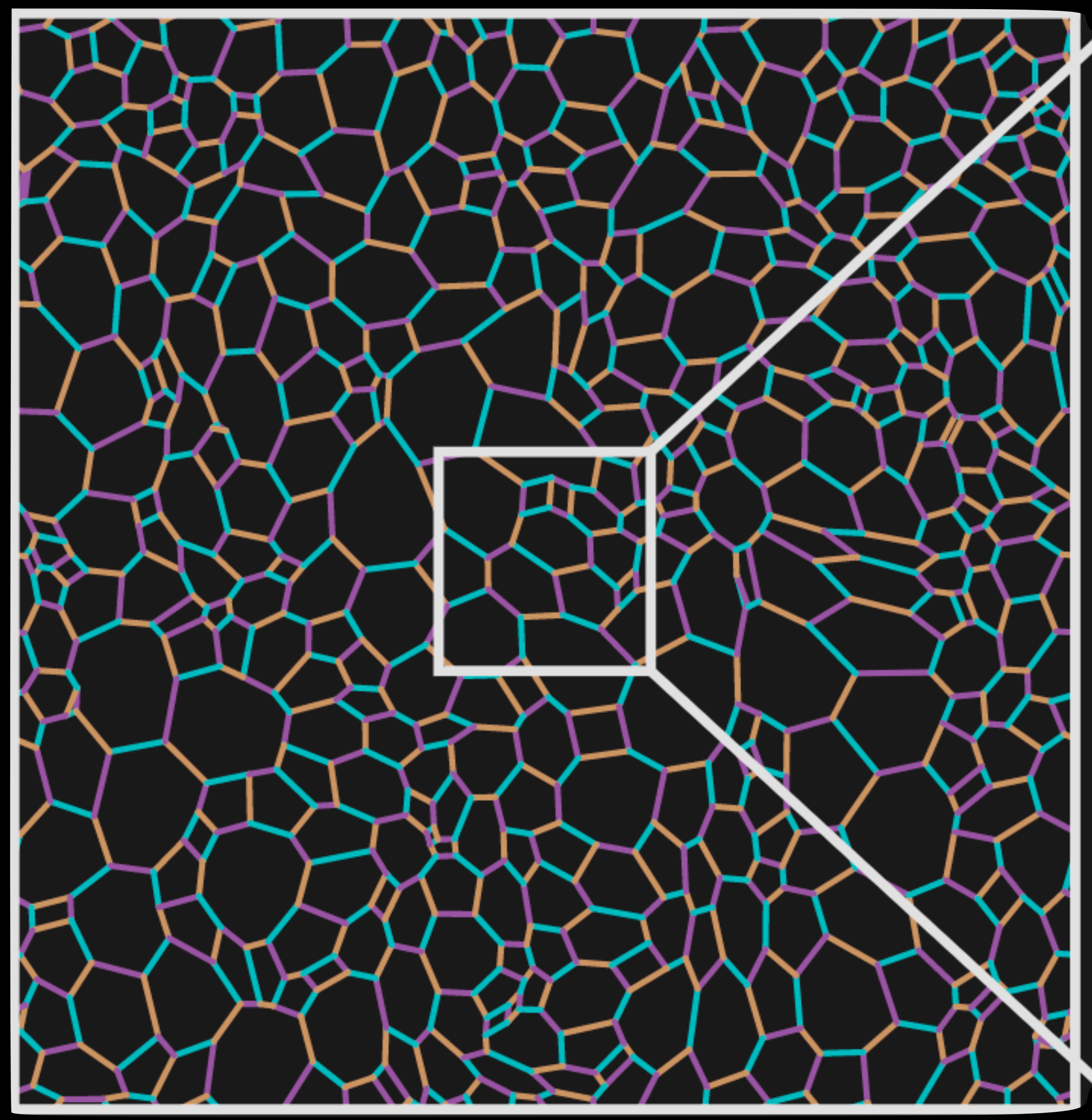
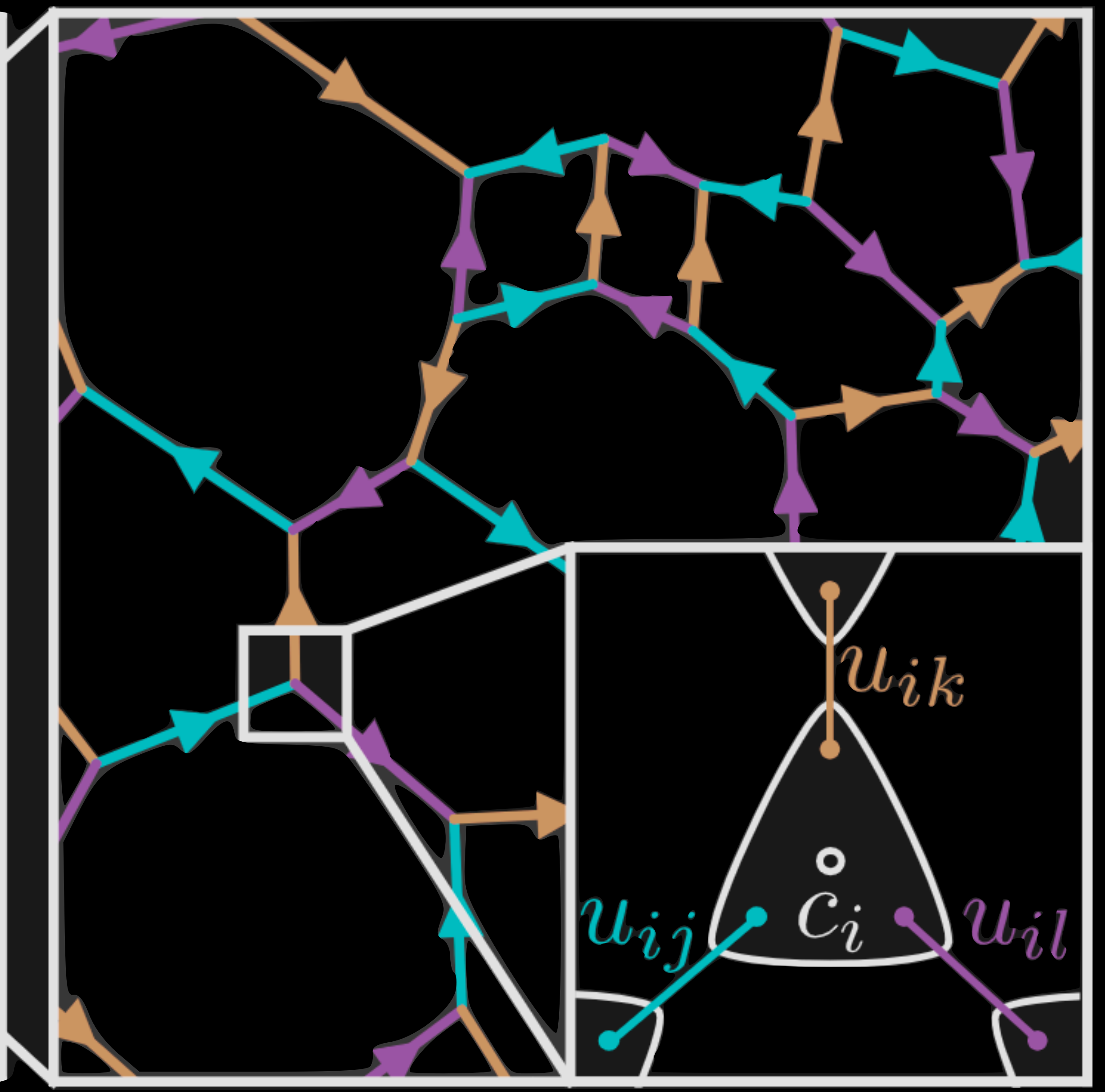
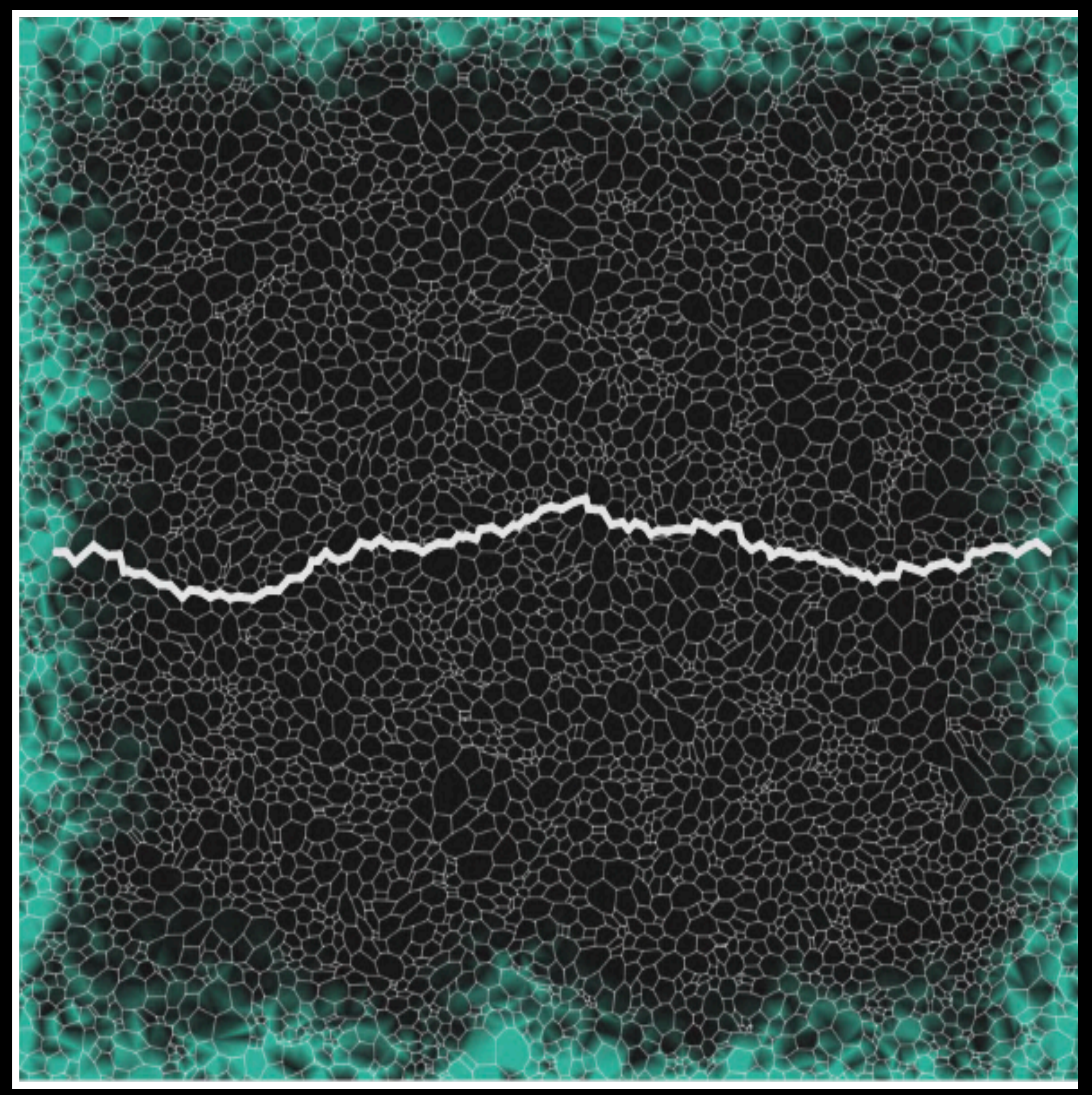
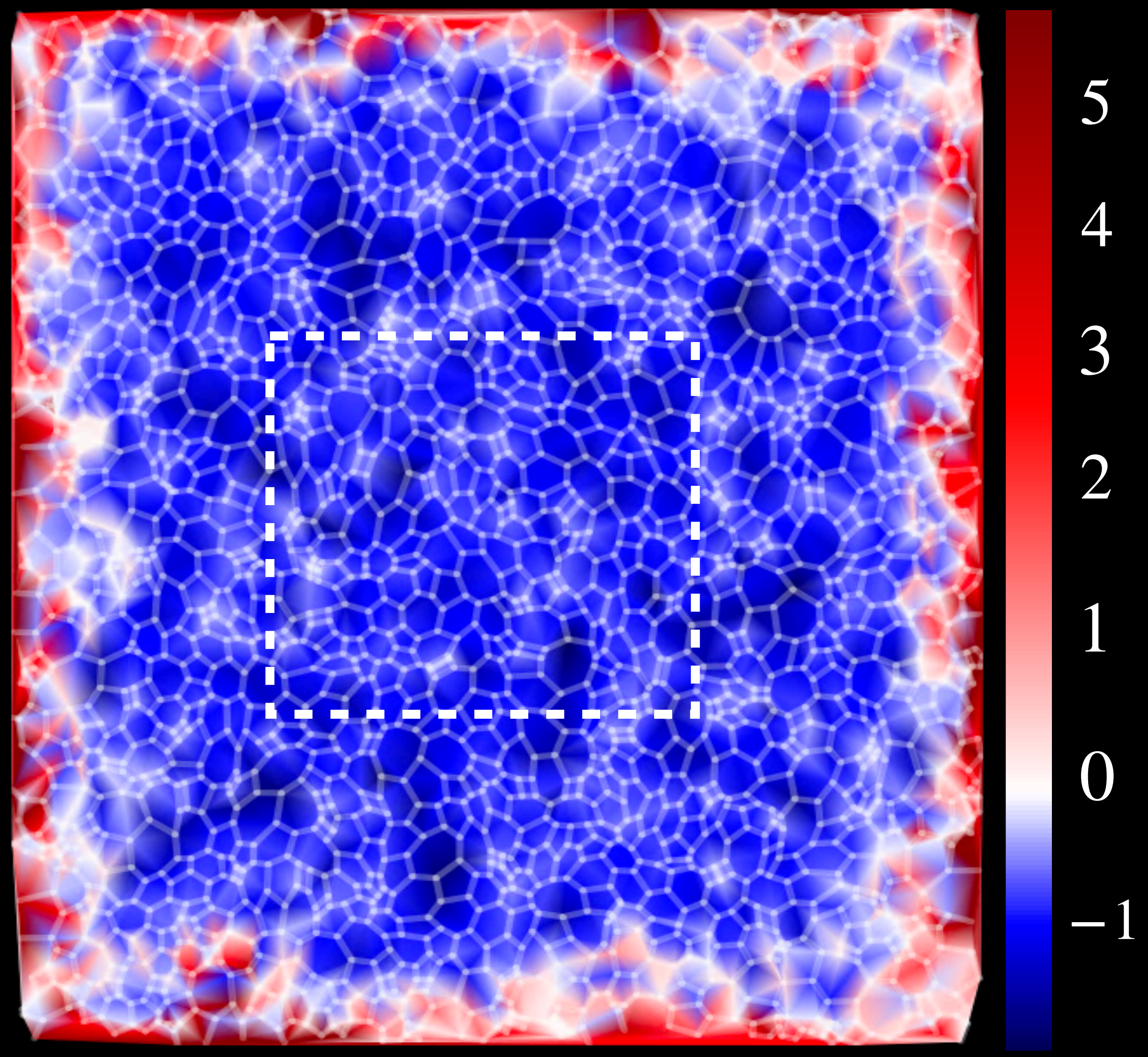








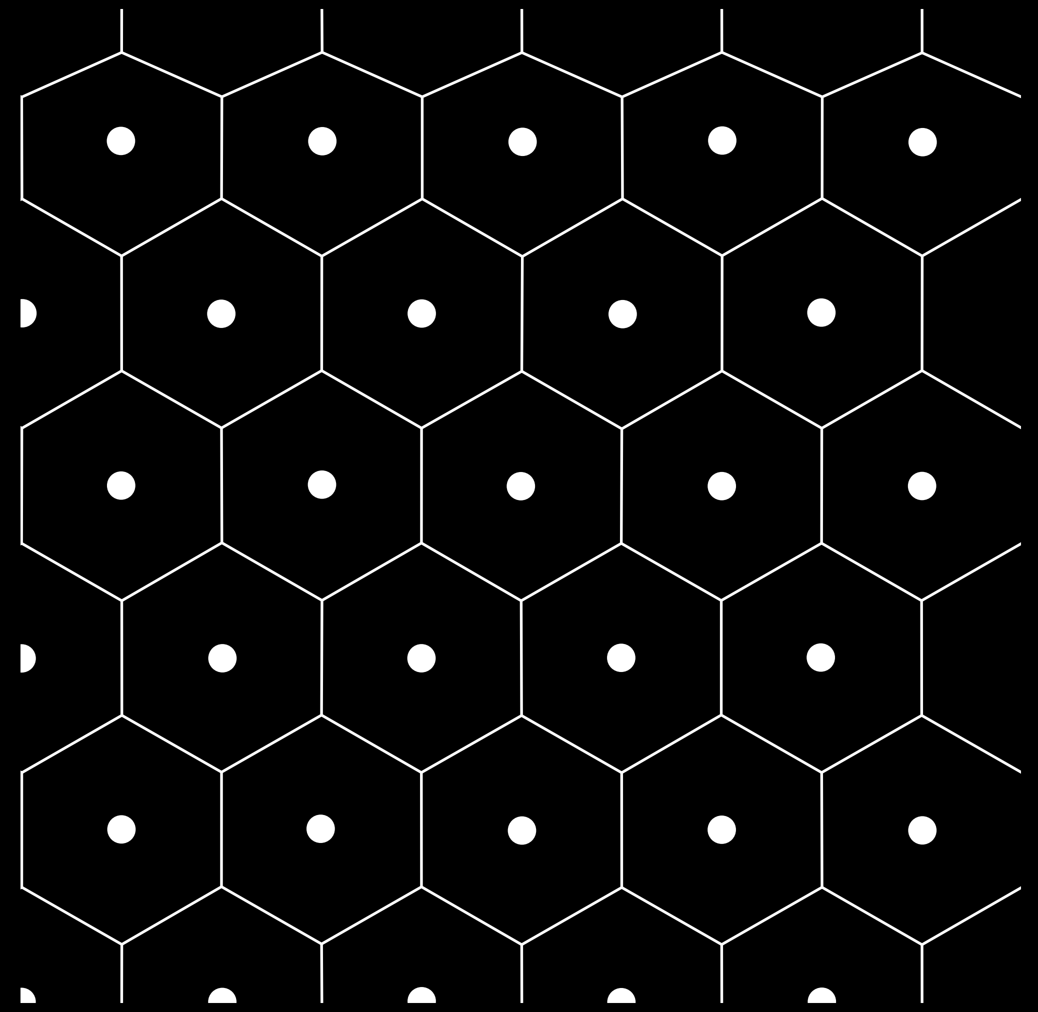
Chiral spin-liquid!

= chiral majorana edge states

non-abelian excitations

Controlling lattice disorder

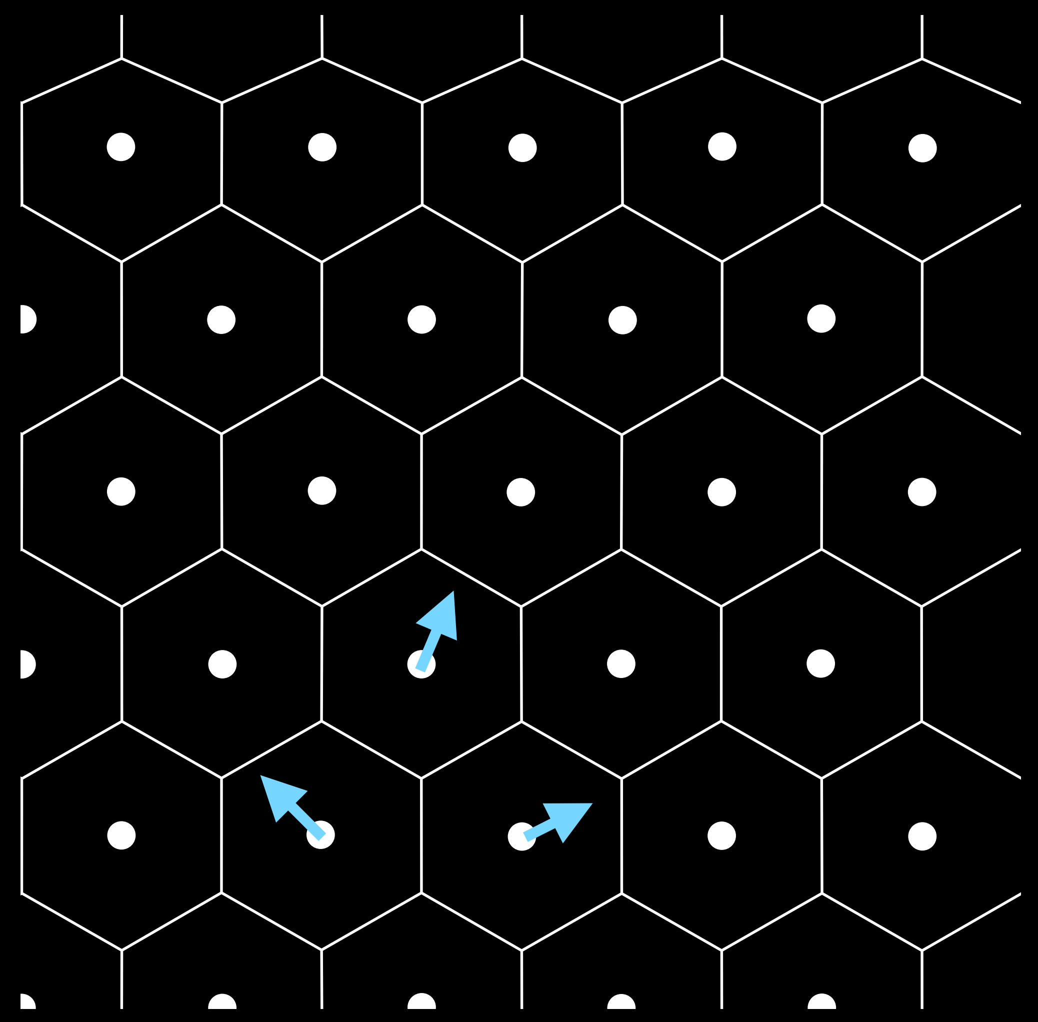
Voronization



AGG, C. Repellin PRL (2023)

Controlling lattice disorder

Voronization



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Controlling lattice disorder

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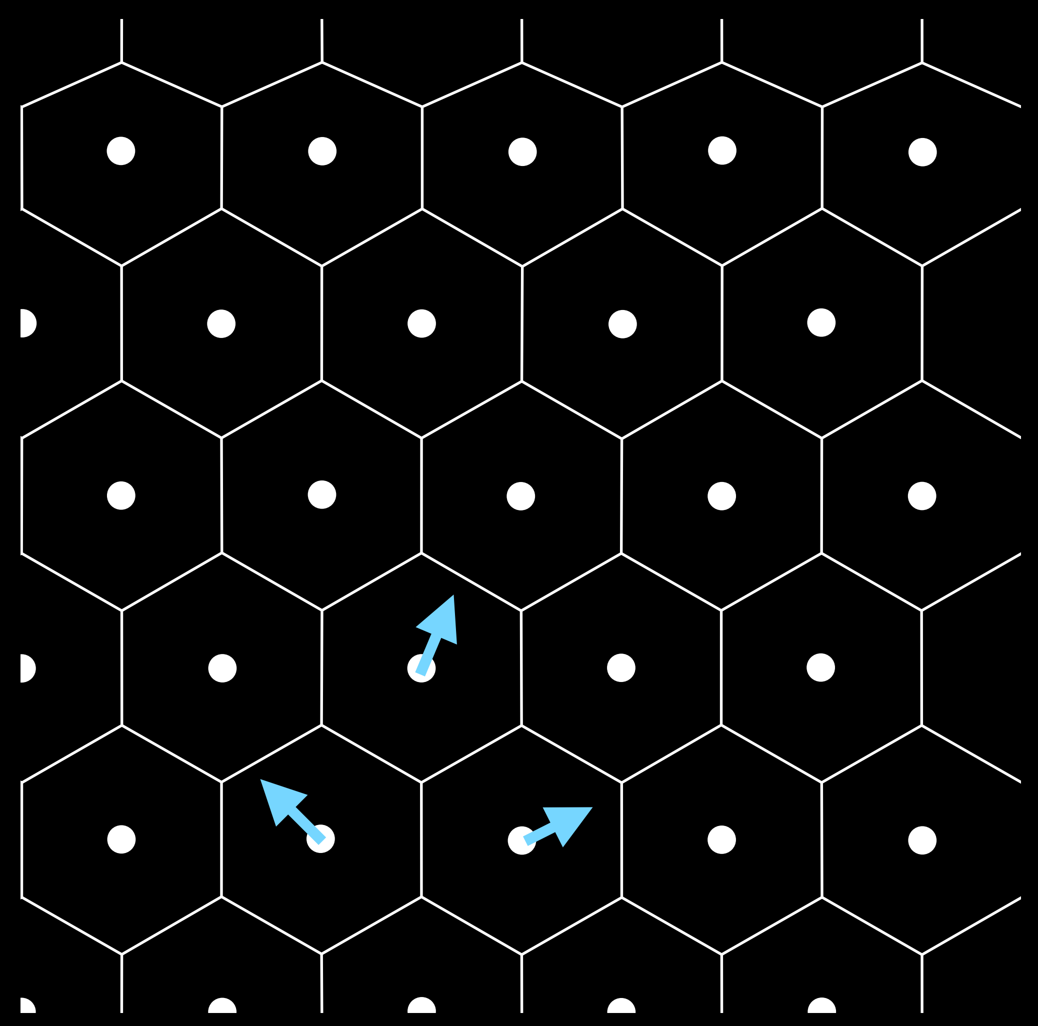

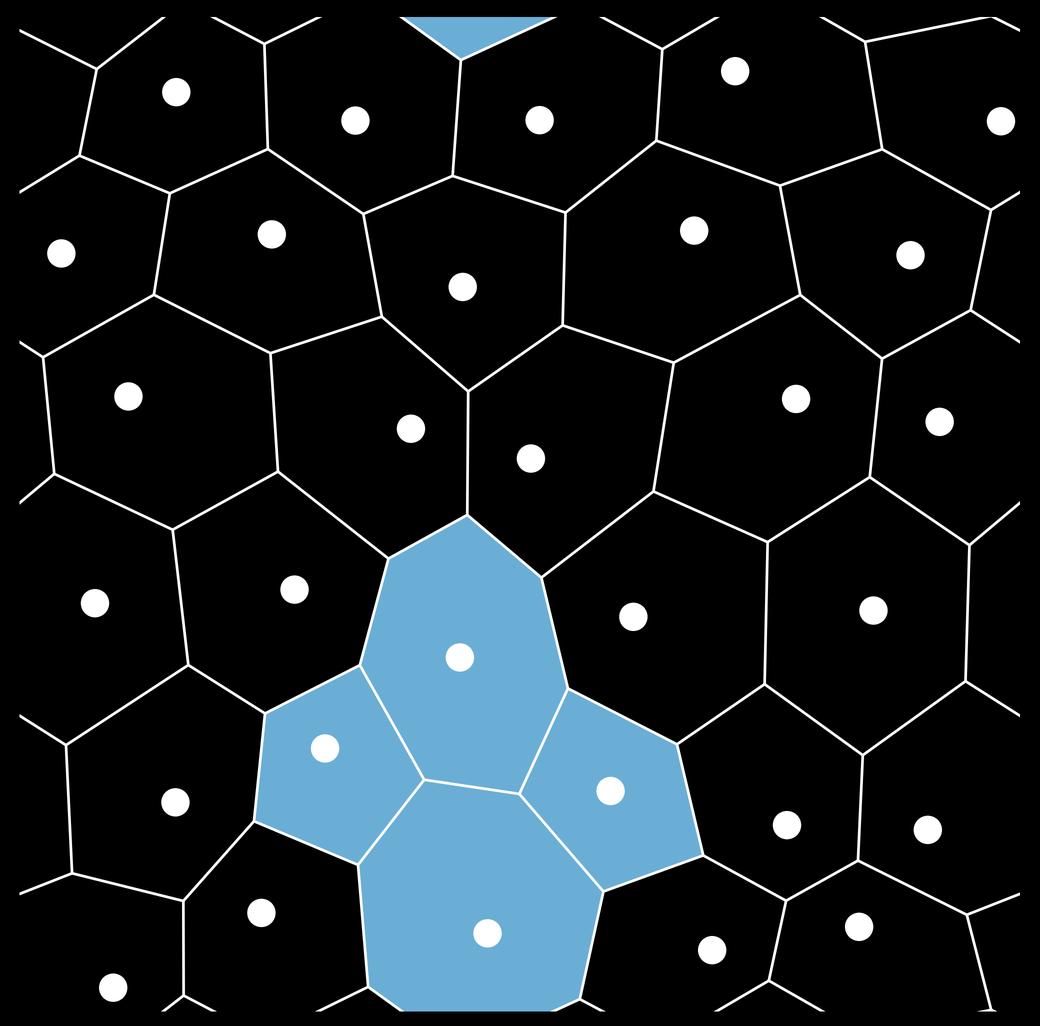

structural disorder

AGG, C. Repellin PRL (2023)

Controlling lattice disorder

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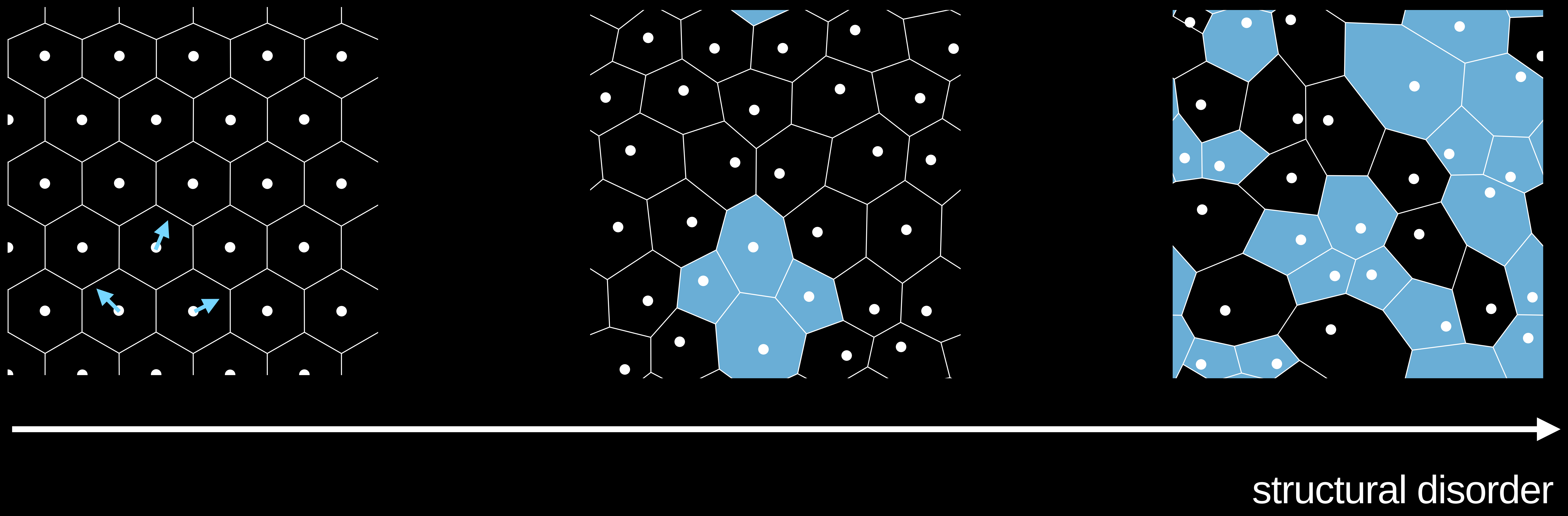
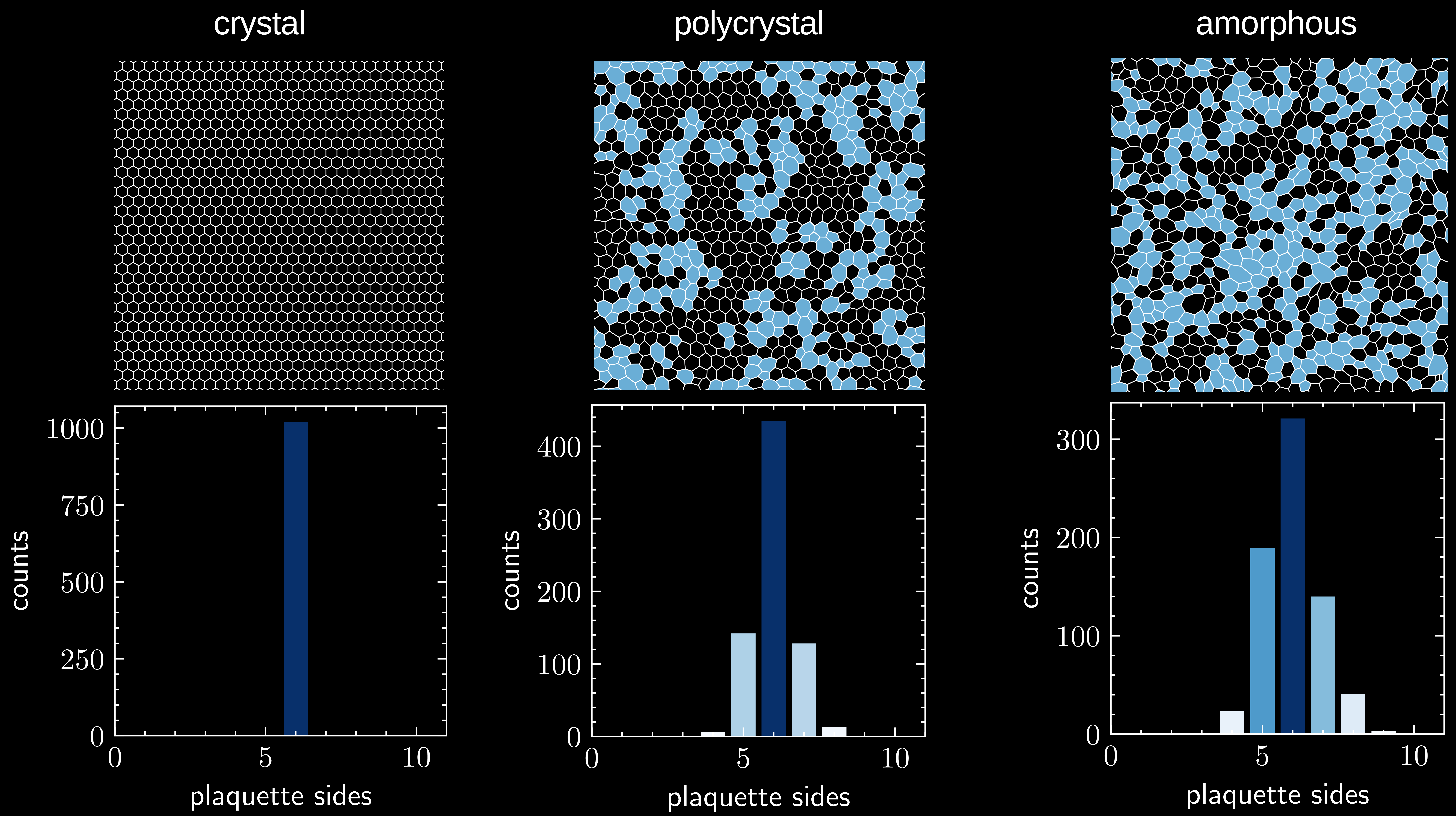
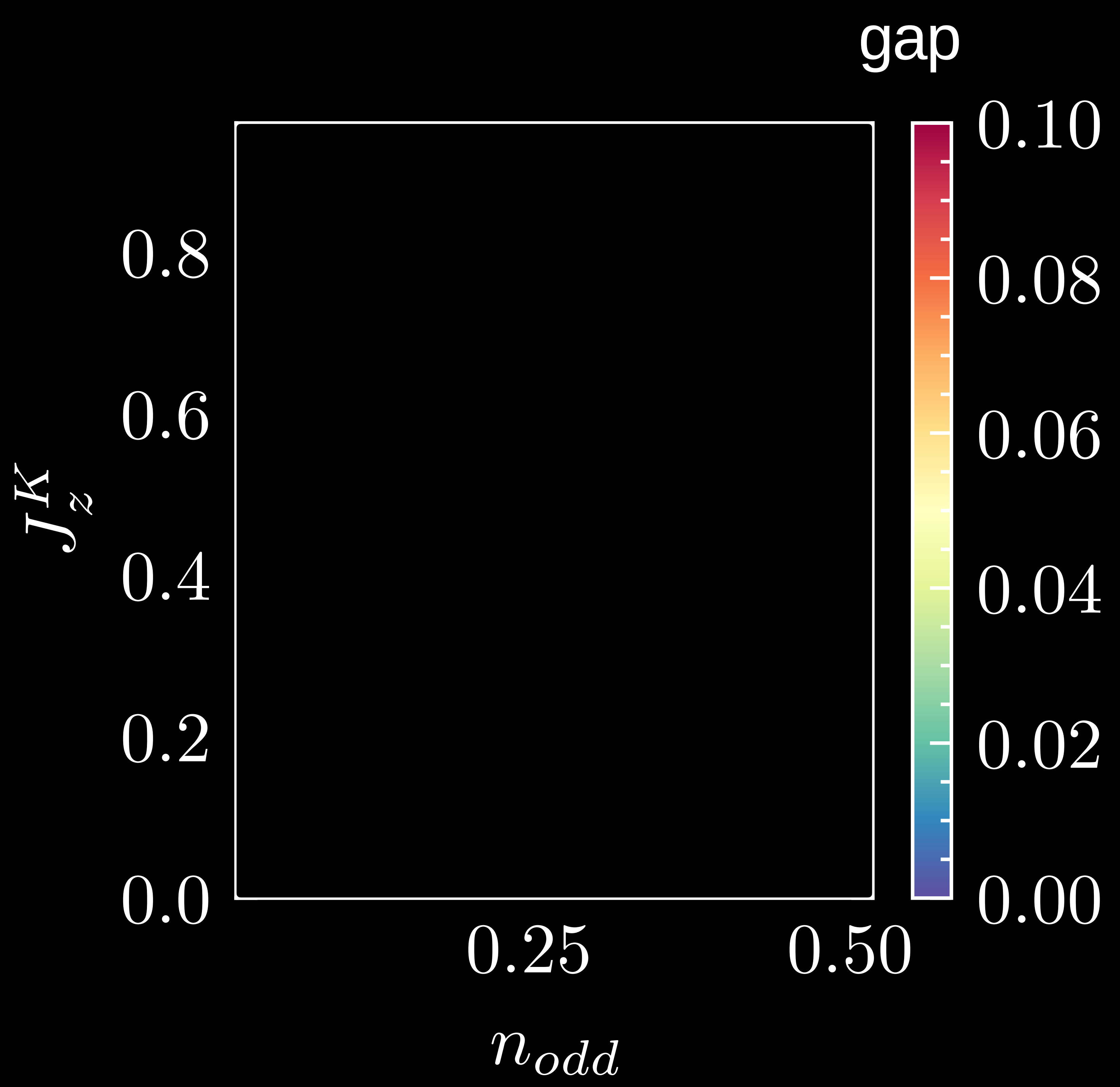


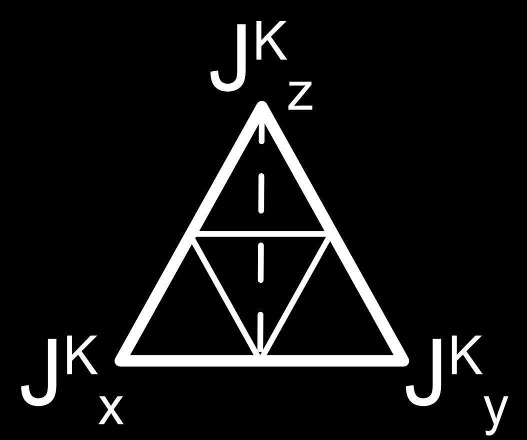
AGG, C. Repellin PRL (2023)

Controlled Voronization



A topological gap as disorder is increased





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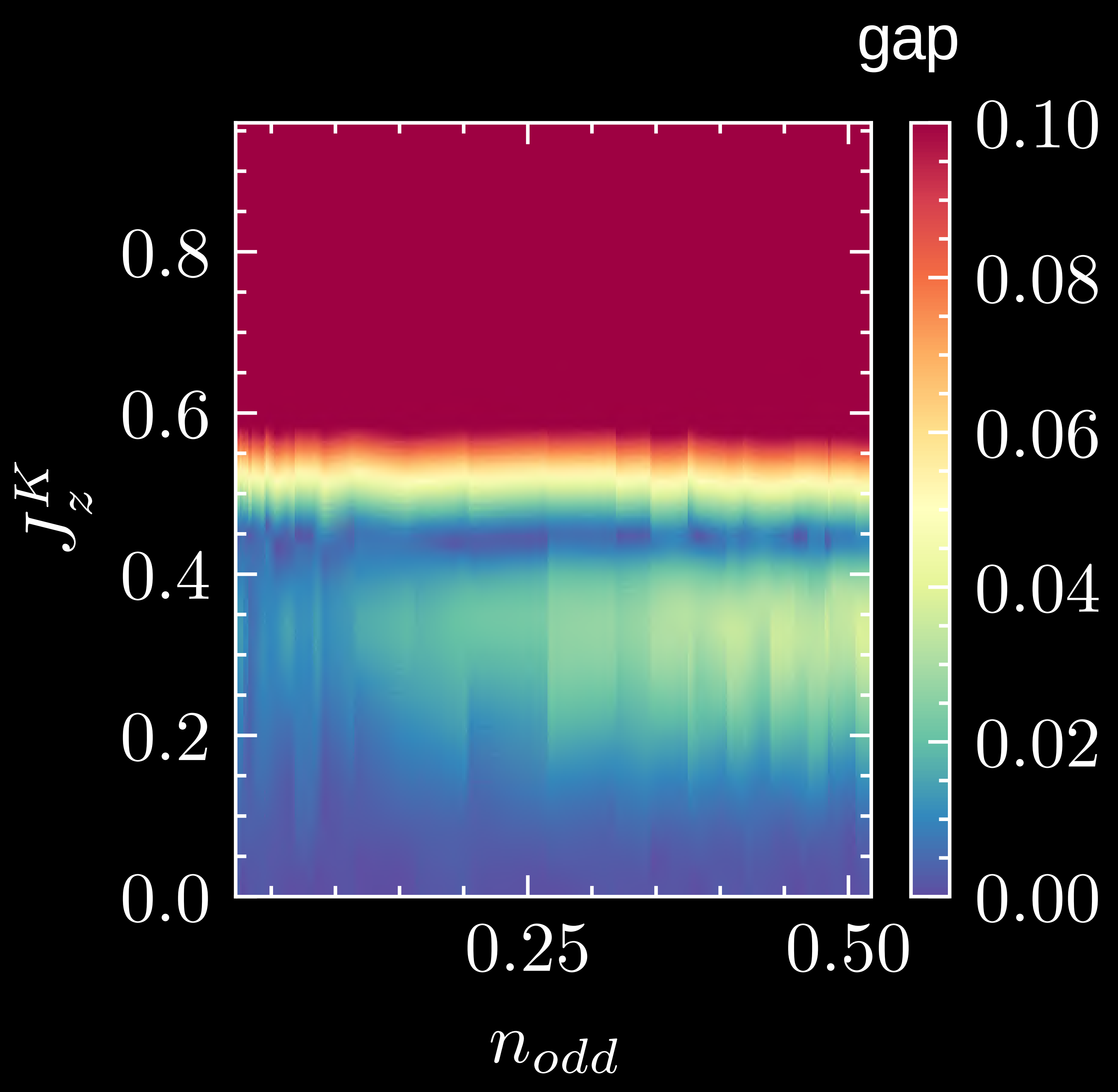

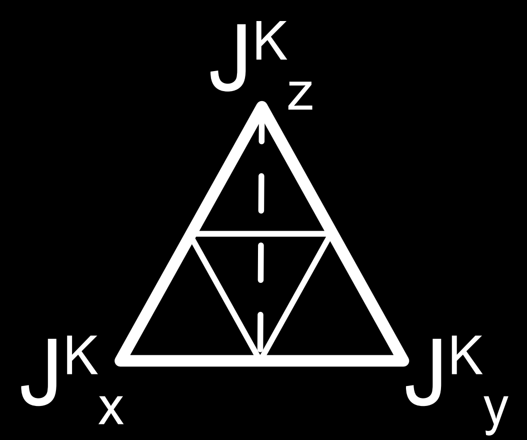

AGG, C. Repellin PRL (2023)

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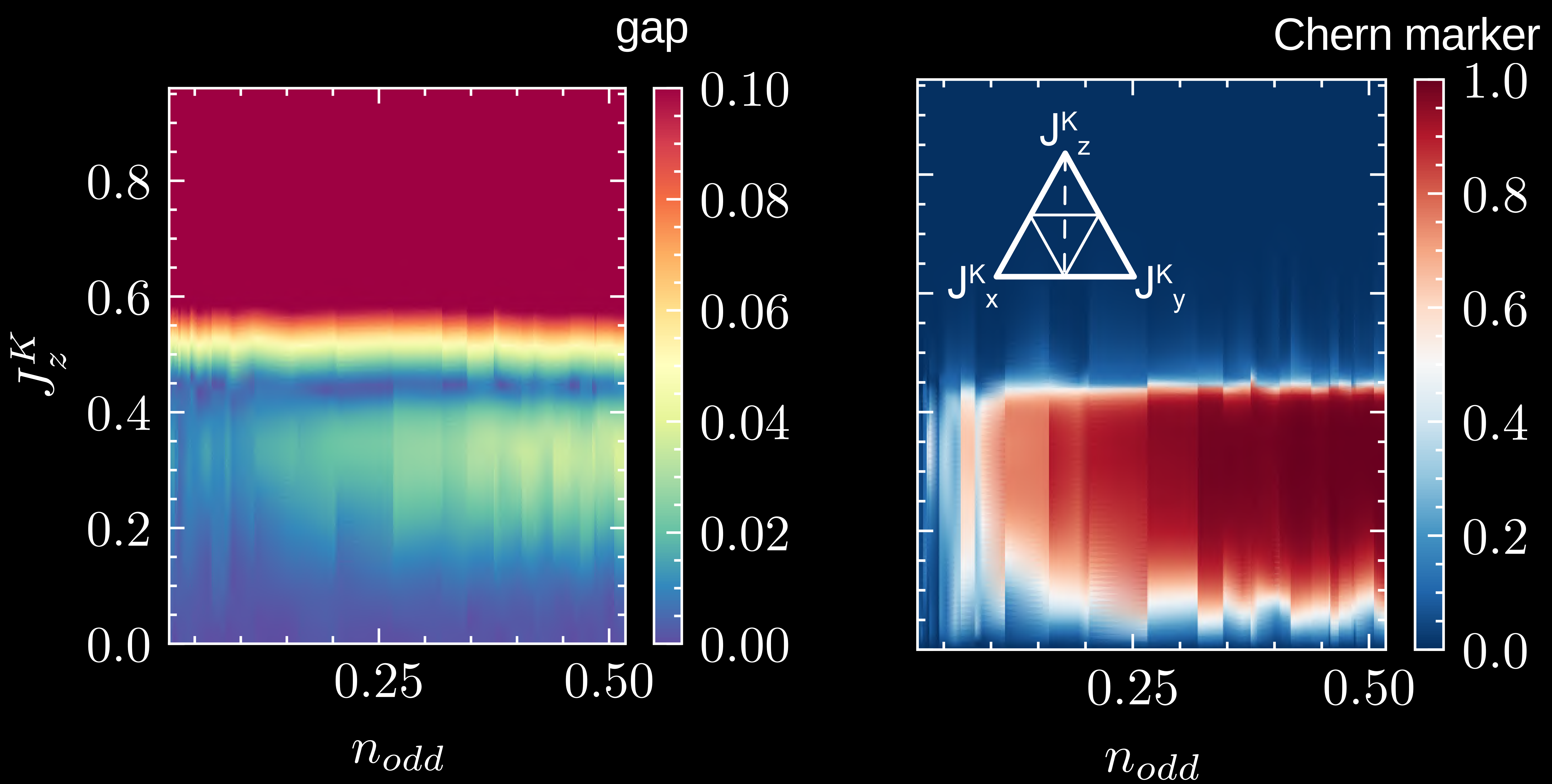

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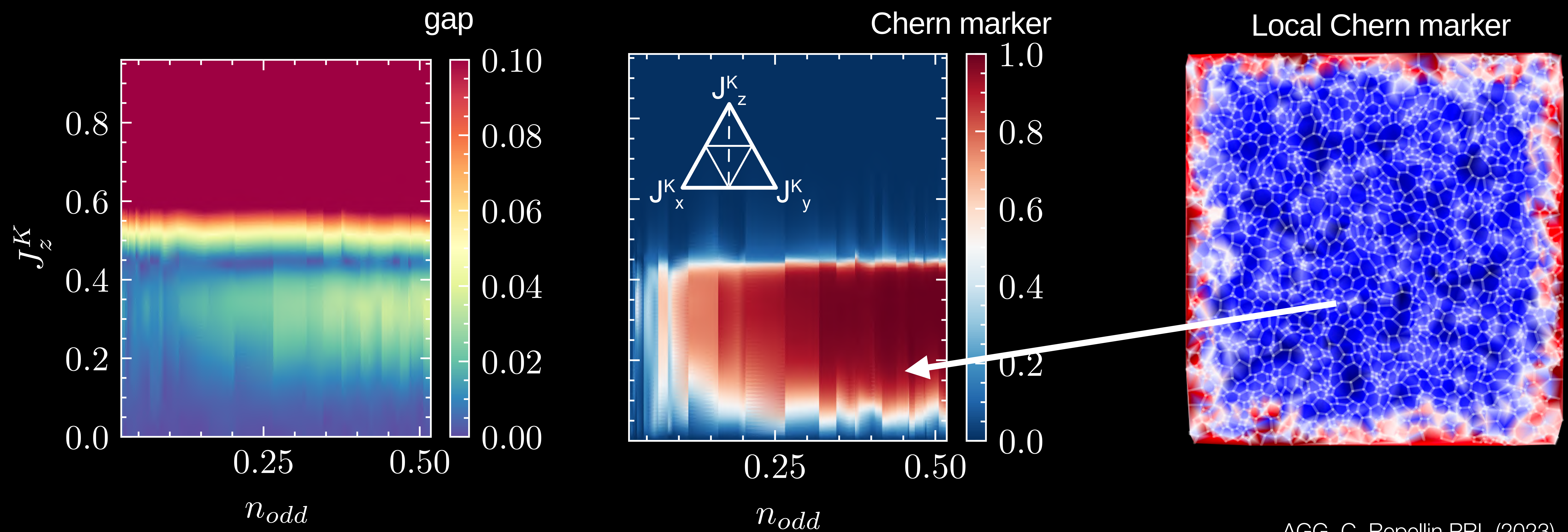

AGG, C. Repellin PRL (2023)

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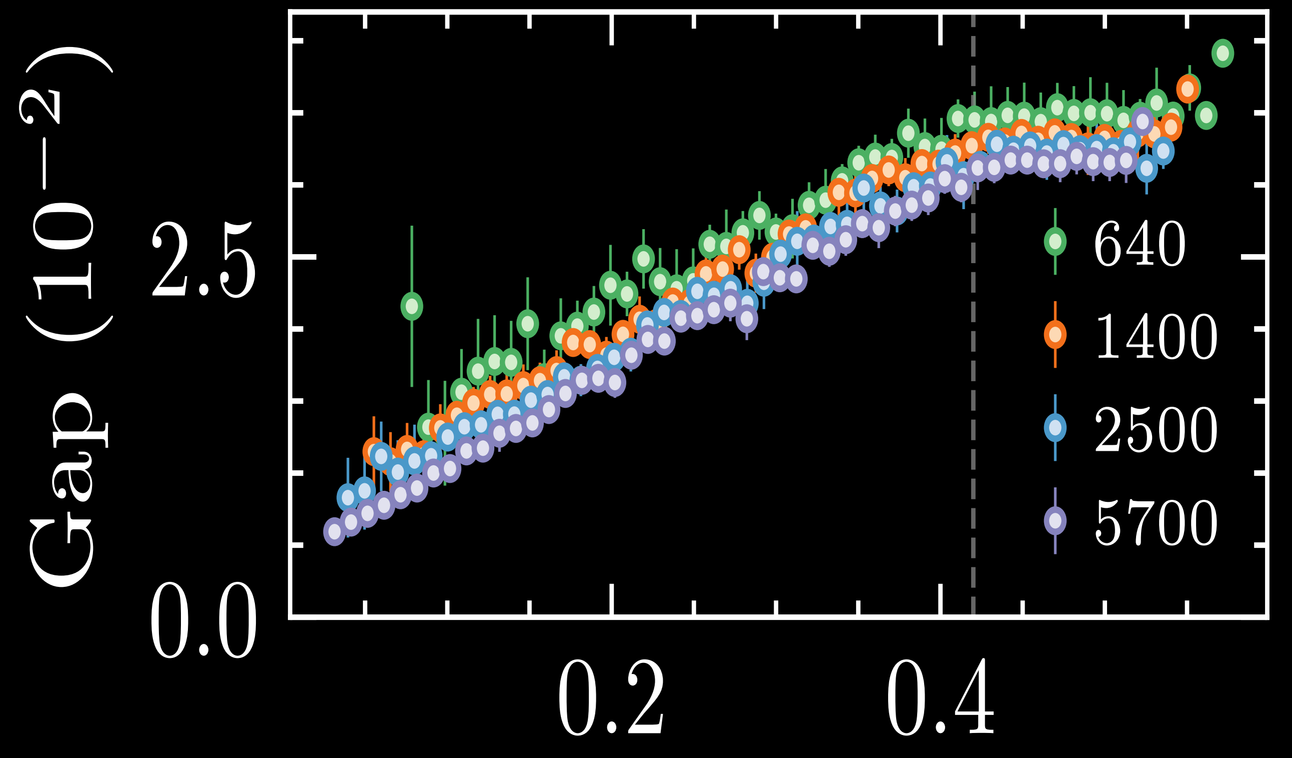

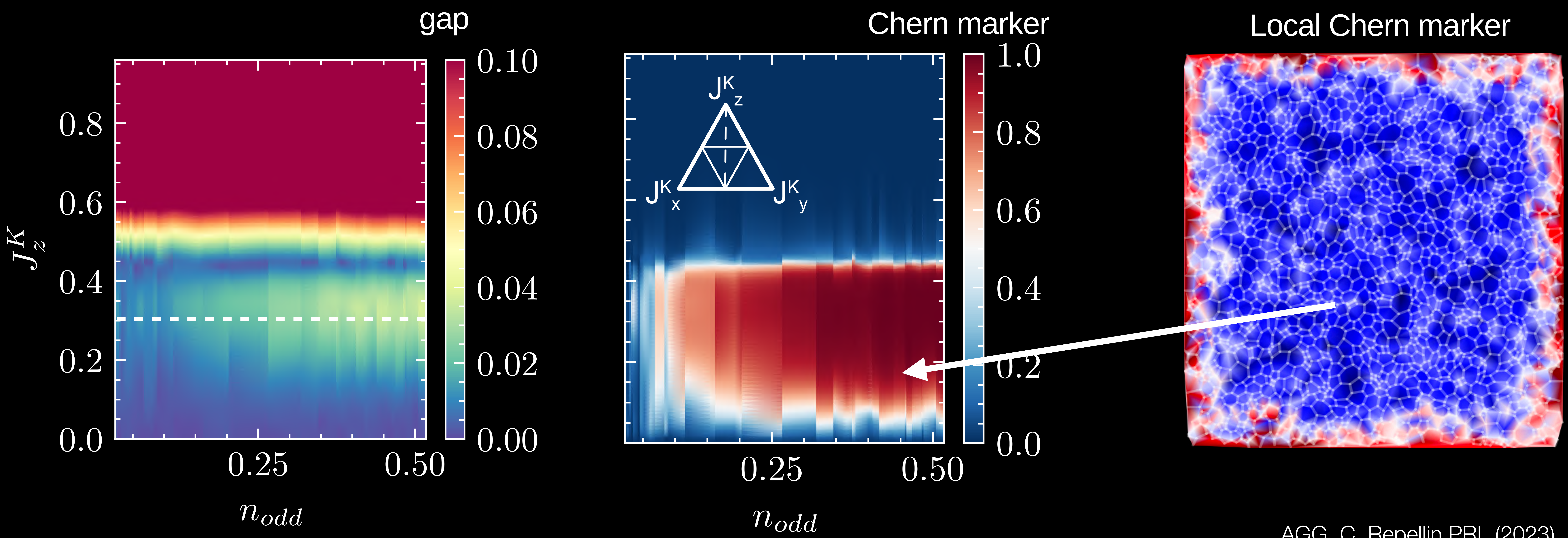

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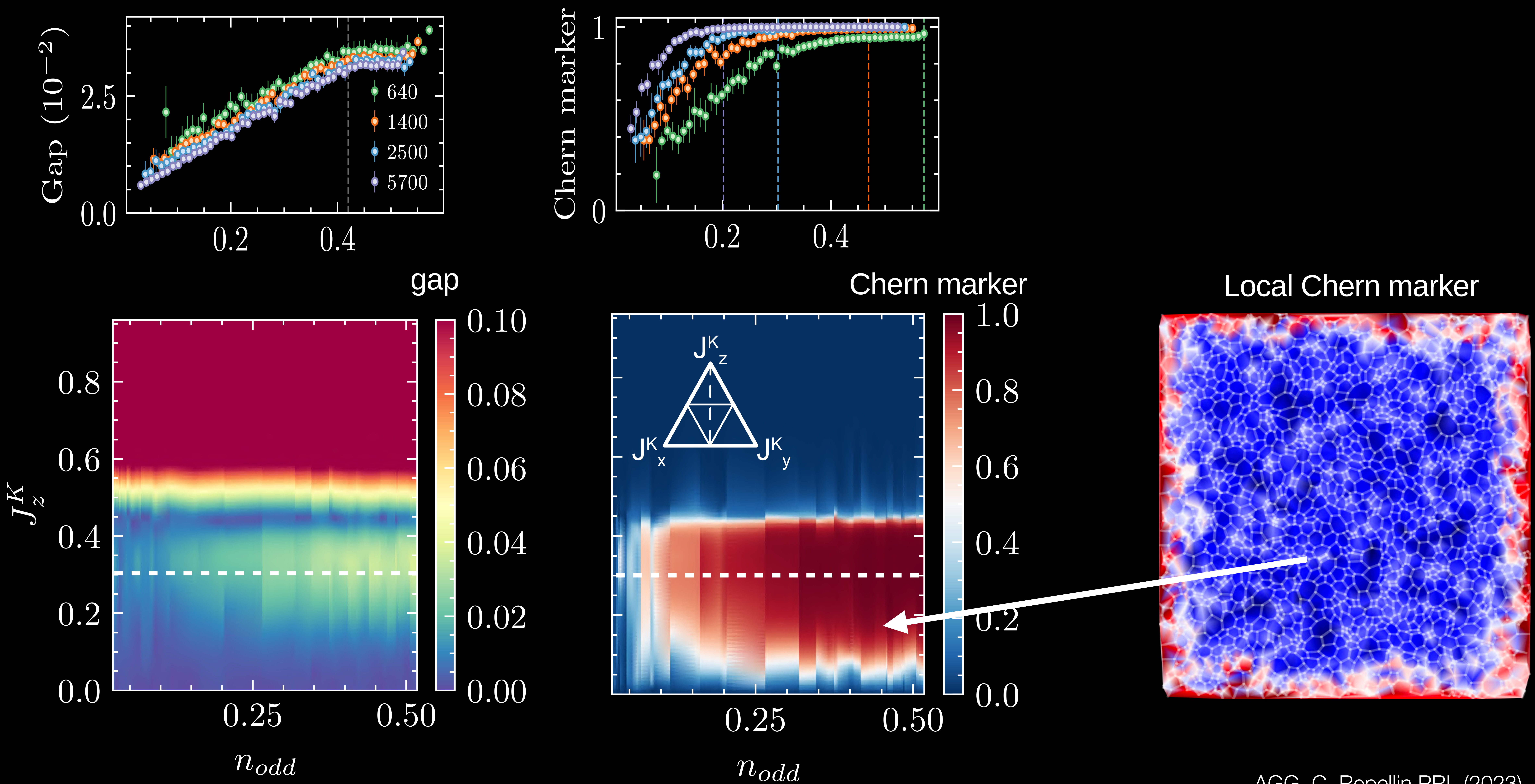

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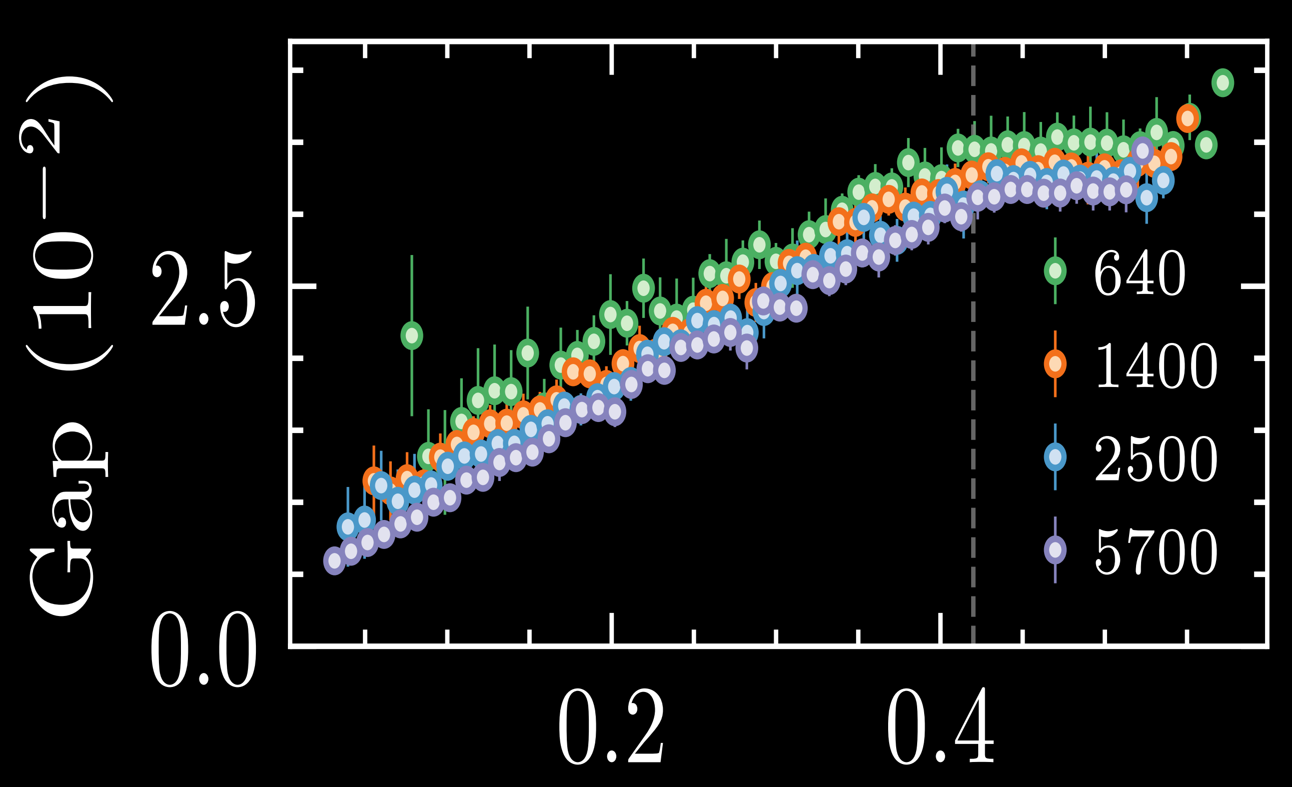
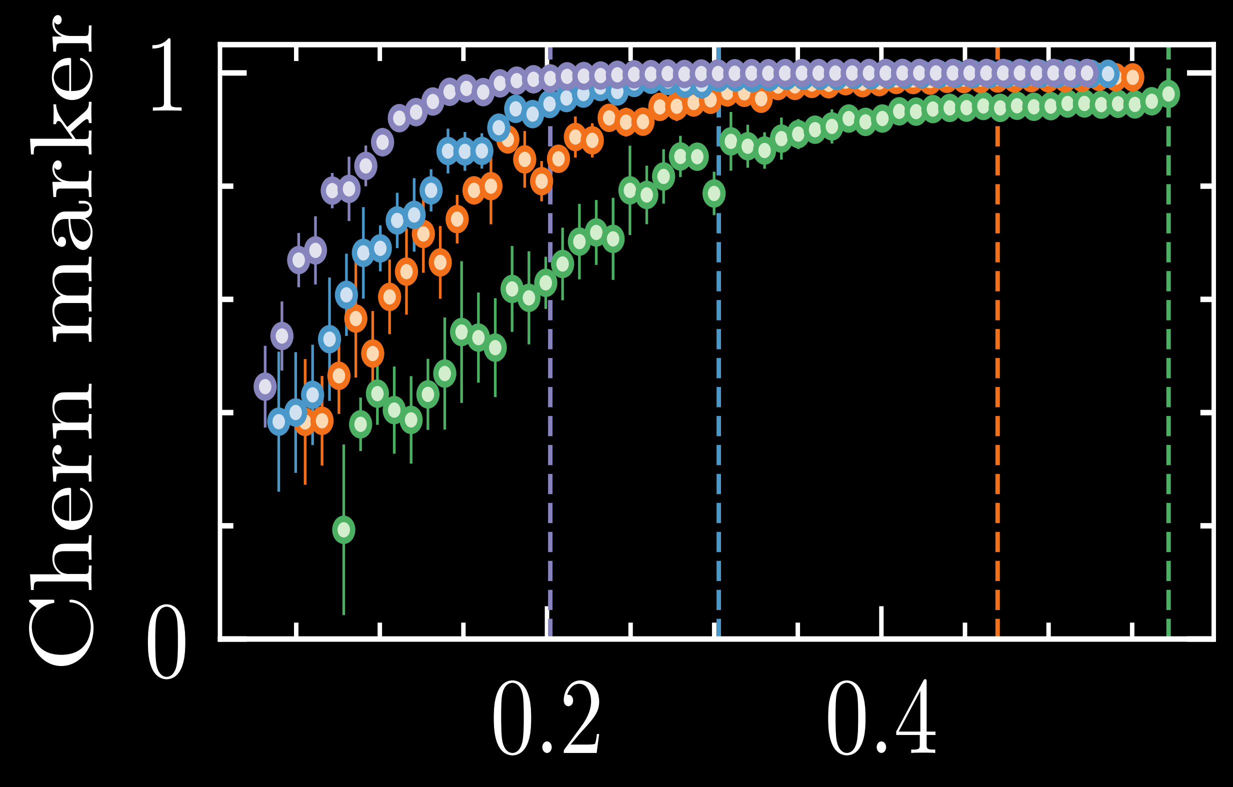
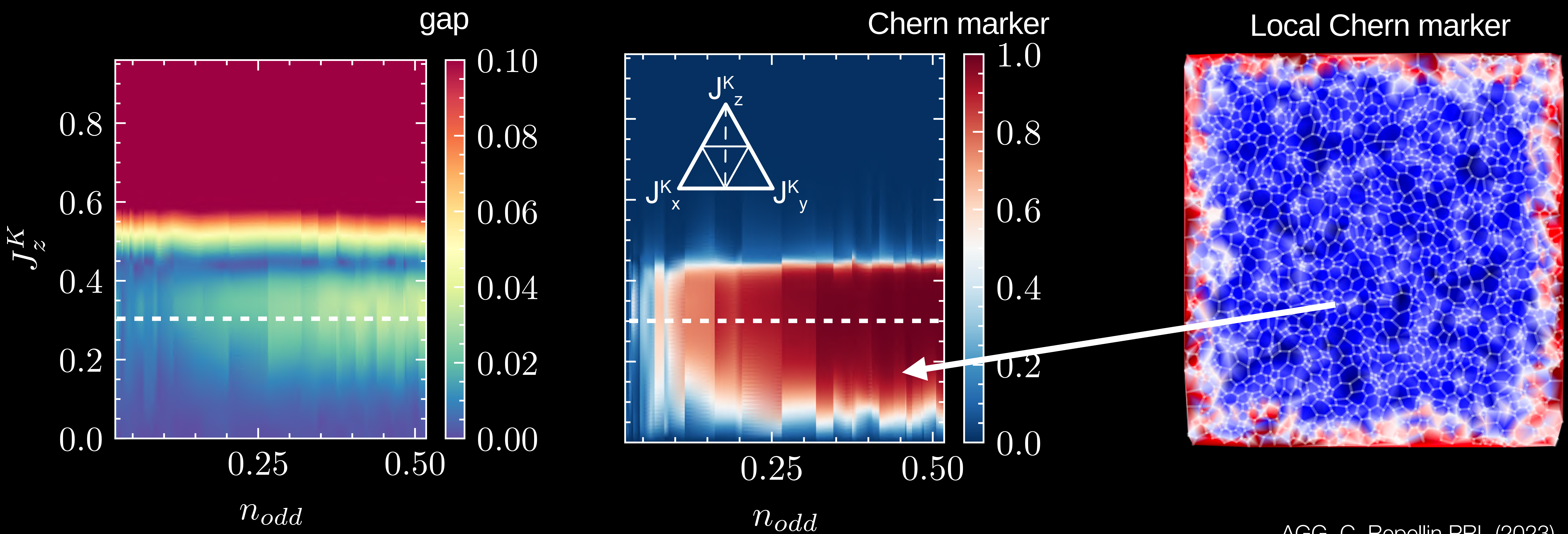




small density of odd plaquettes is enough!



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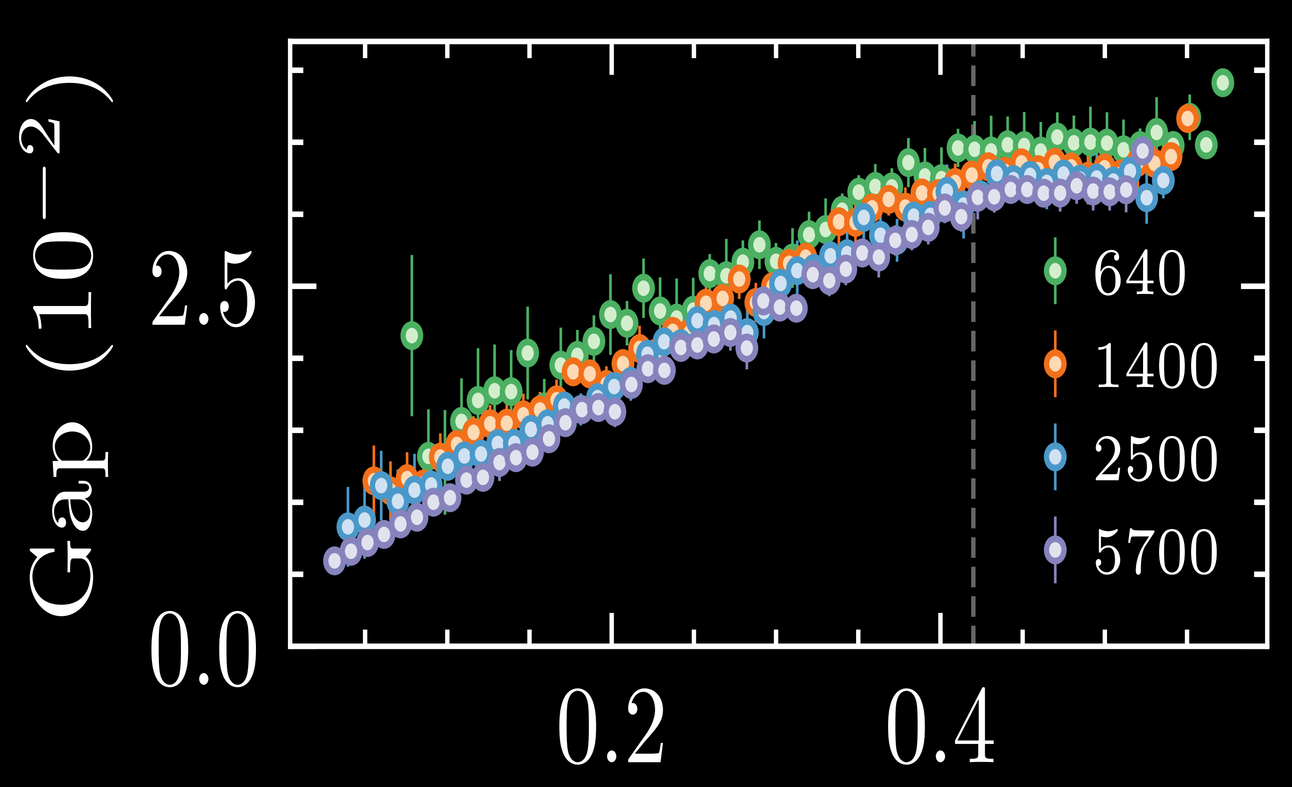
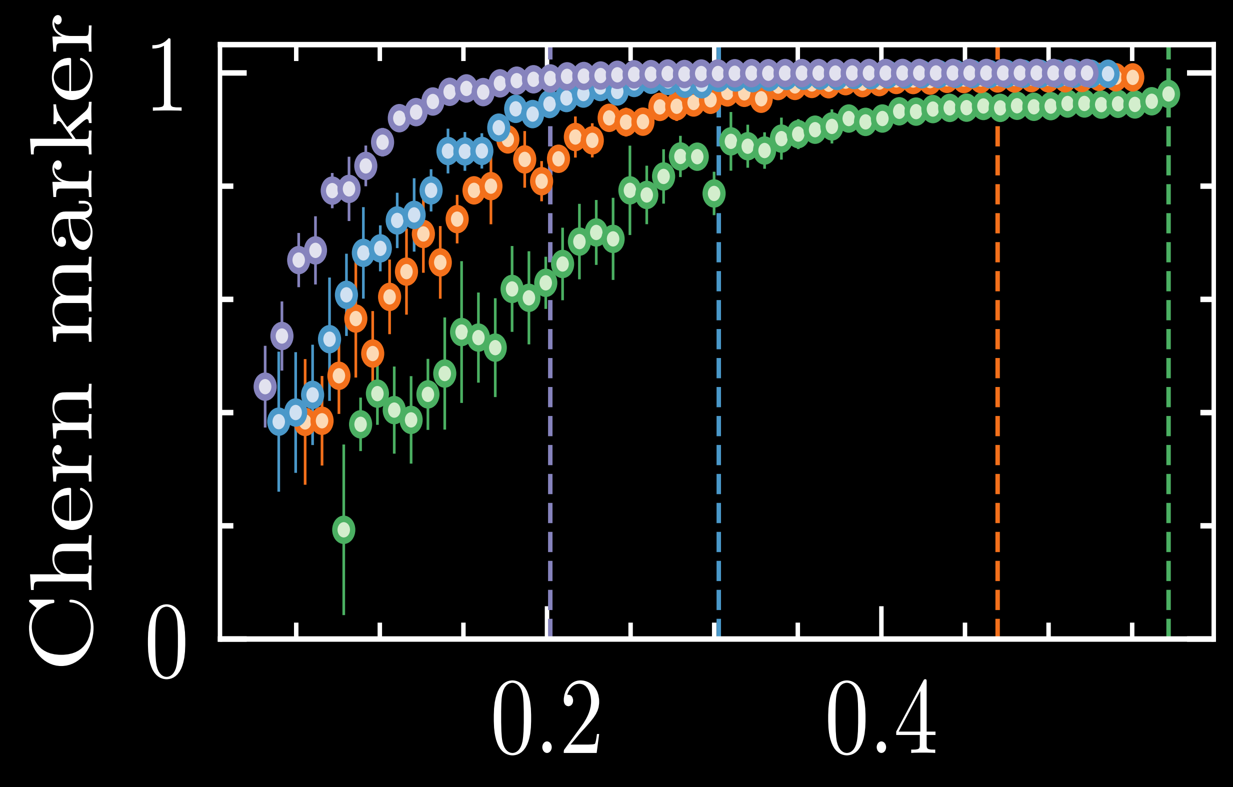
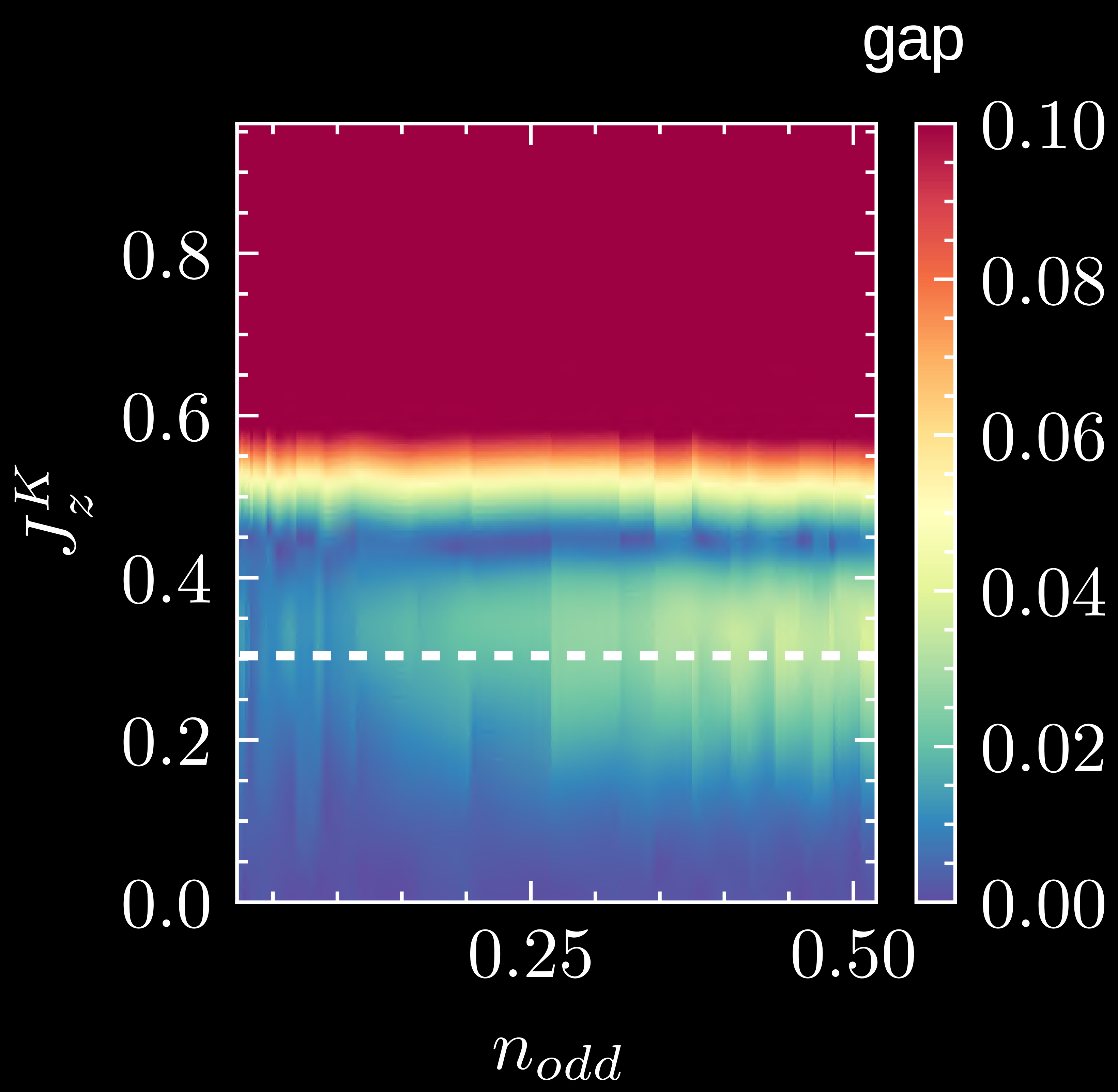
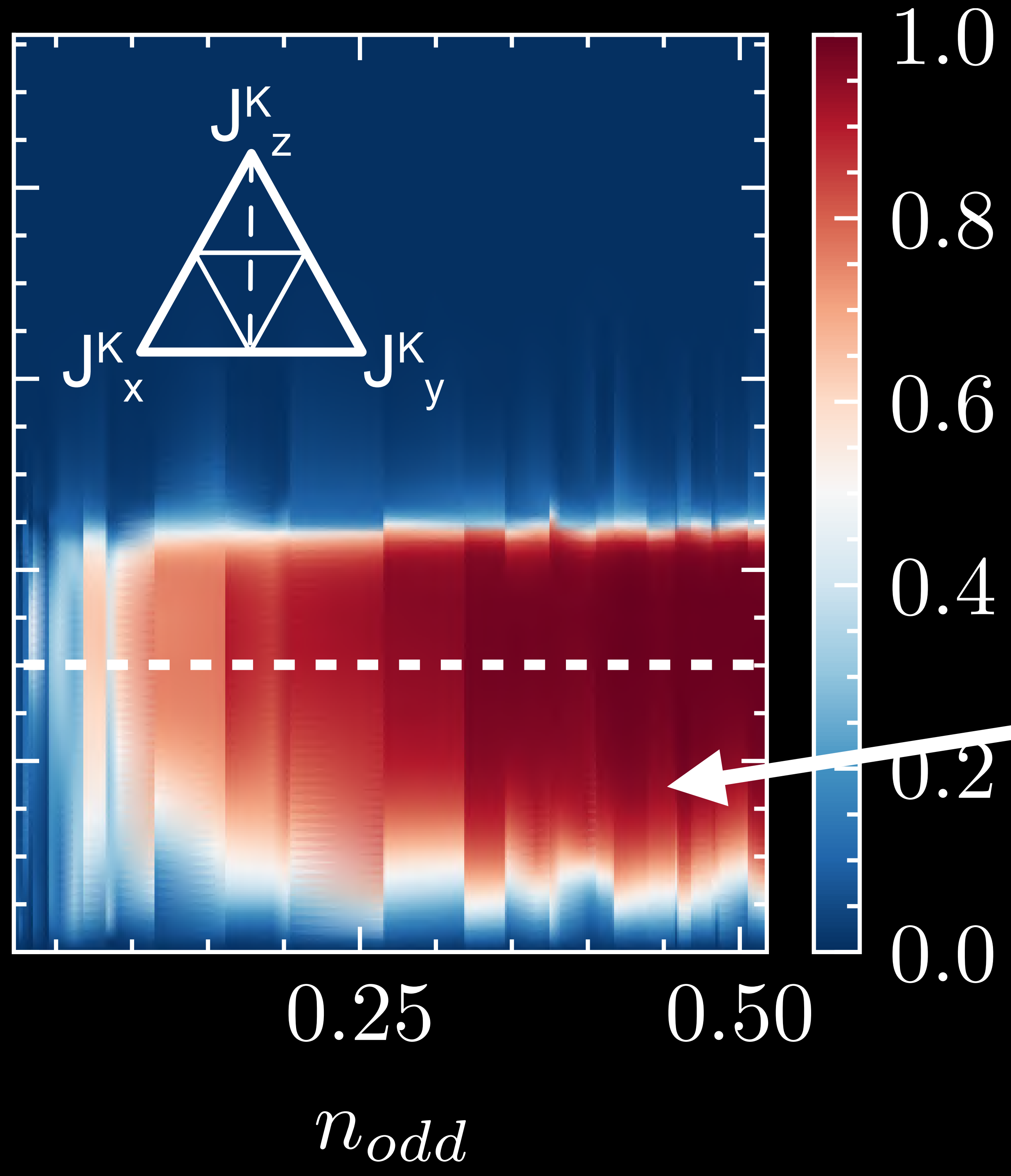




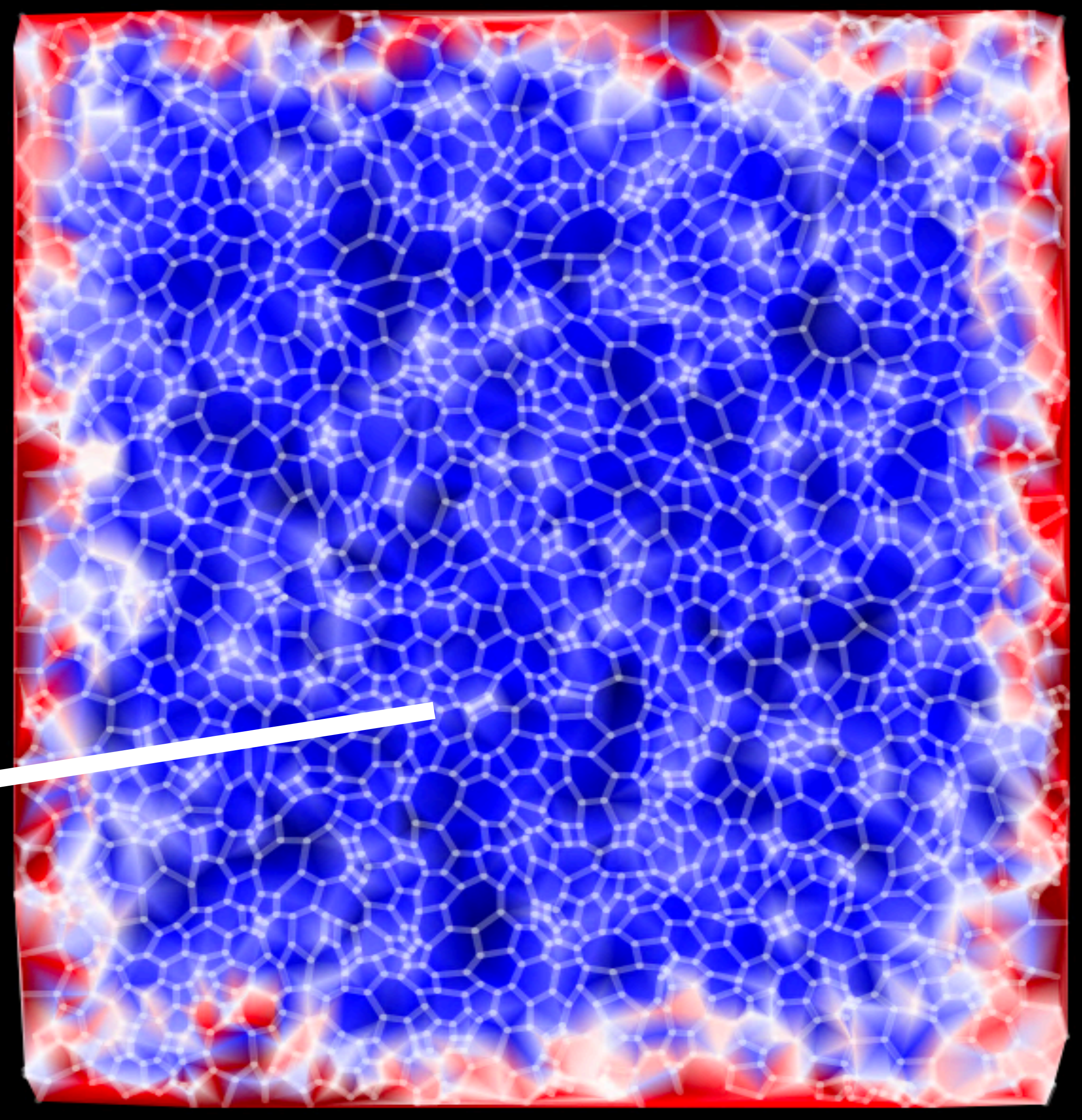
small density of odd plaquettes is enough!

75% max gap at 30% of odd-plaquettes (~ a-graphene)





Local Chern marker



AGG, C. Repellin PRL (2023)

Spin-chirality

$$\hat{\chi}_{ijk} = \mathbf{S}_i \cdot \left(\mathbf{S}_j \times \mathbf{S}_k\right)$$

AGG, C. Repellin PRL (2023)

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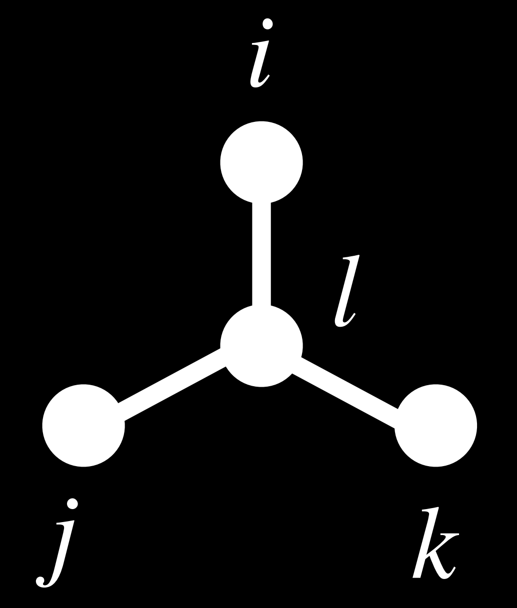

local spin-chirality $\langle \hat{\chi}_l \rangle = \langle \hat{\chi}_{ilj} \rangle + \langle \hat{\chi}_{jlk} \rangle + \langle \hat{\chi}_{kli} \rangle$

AGG, C. Repellin PRL (2023)

Spin-chirality

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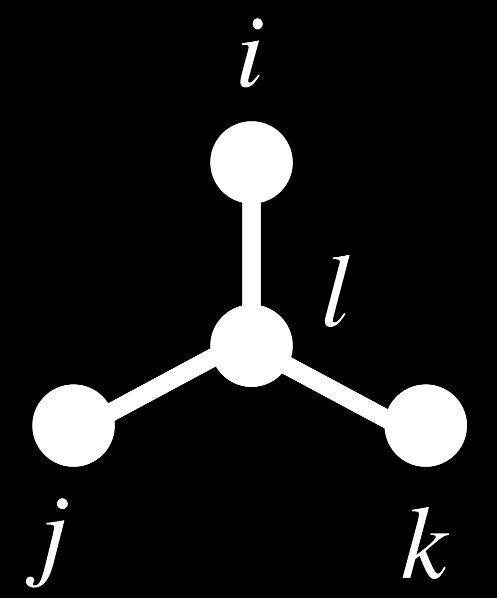

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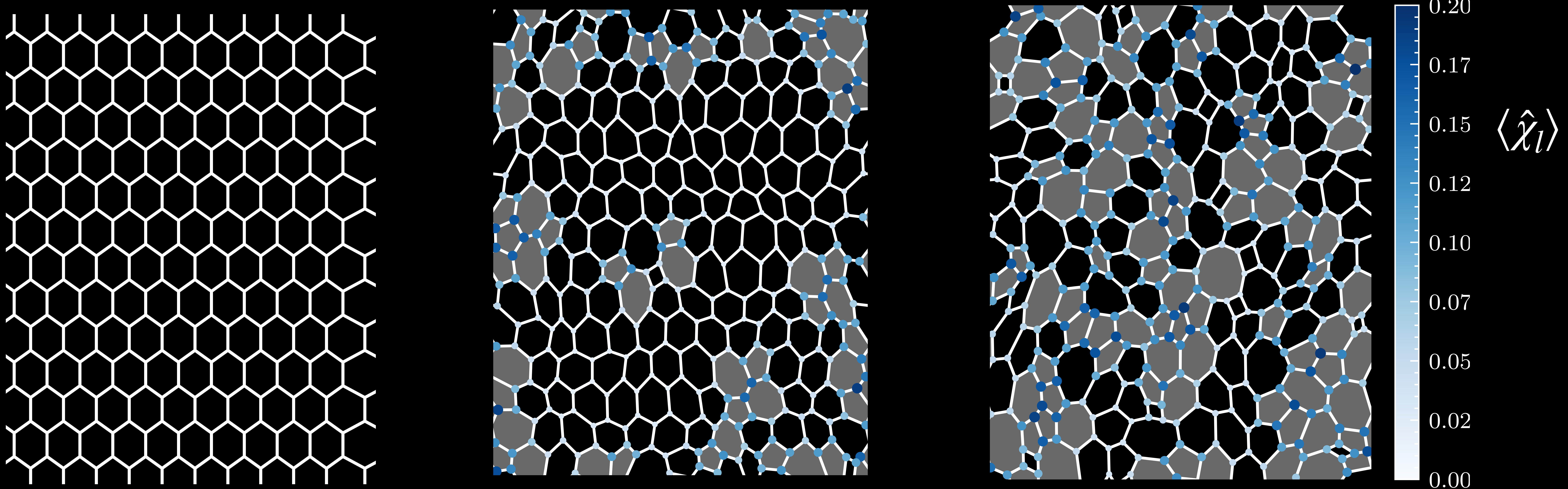
crystal polycrystal amorphous



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How stable is it?

Stability

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Stability

Kitaev + Heisenberg

$$H = J^K \sum_{\langle ij \rangle} \sigma_i^\alpha \sigma_j^\alpha + J^H \sum_{\langle ij \rangle} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j$$

AGG, C. Repellin PRL (2023)

Stability

Kitaev + Heisenberg

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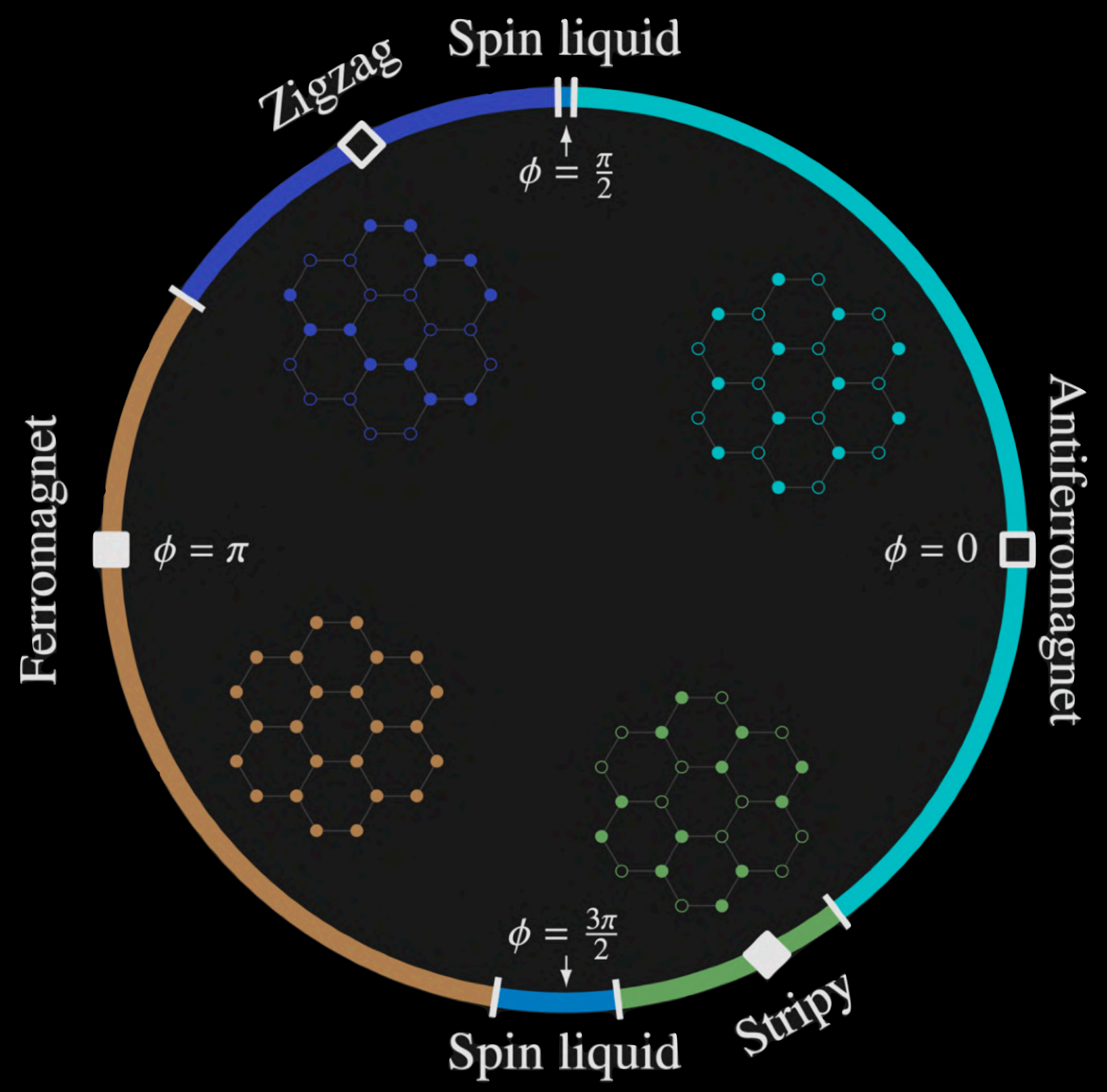

$$J^H = \cos\phi, J^K = \sin\phi$$

Rau et al Ann. Rev. Cond. Mat. Phys. (2015)

AGG, C. Repellin PRL (2023)

Stability

Kitaev + Heisenberg

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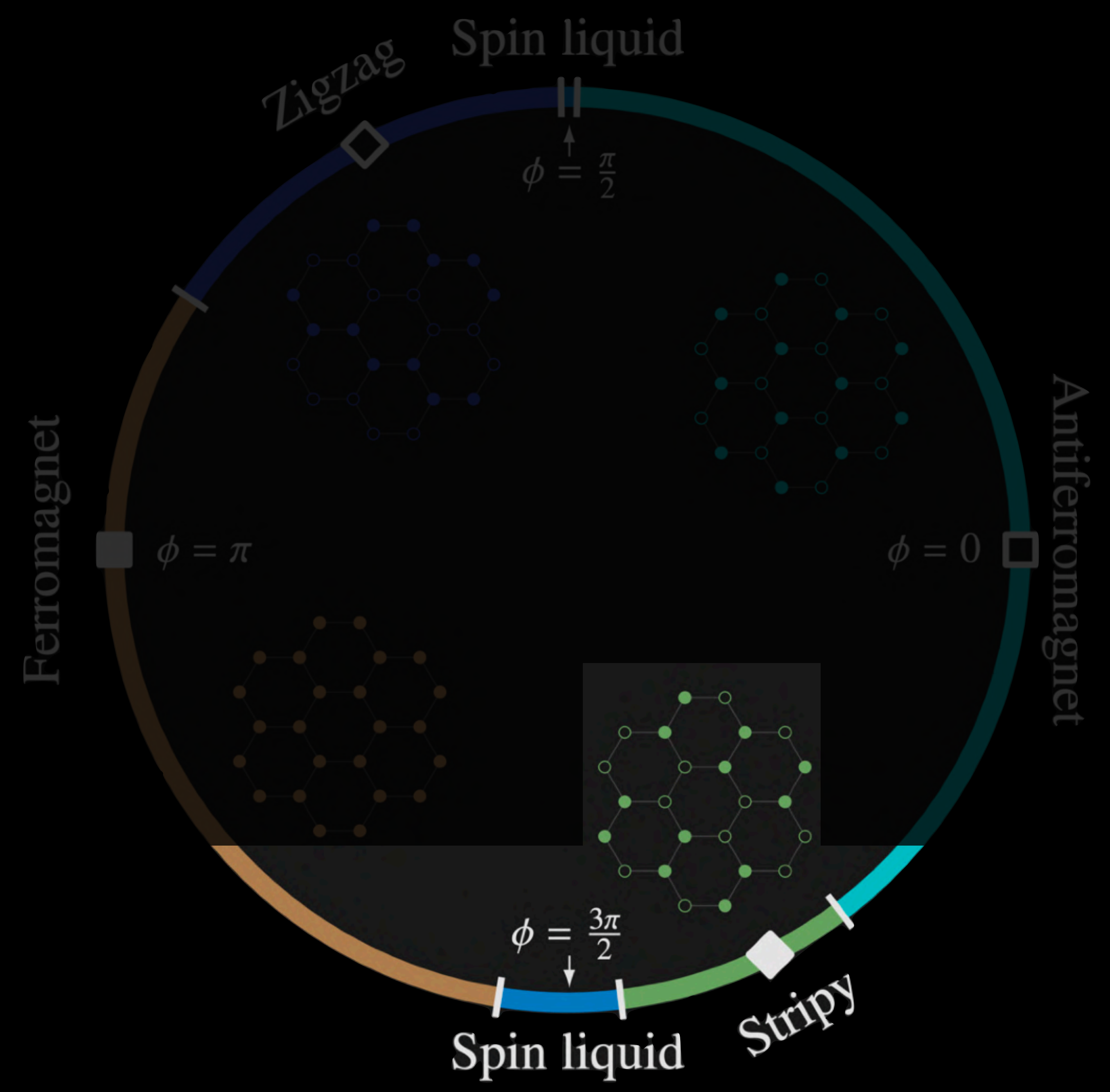

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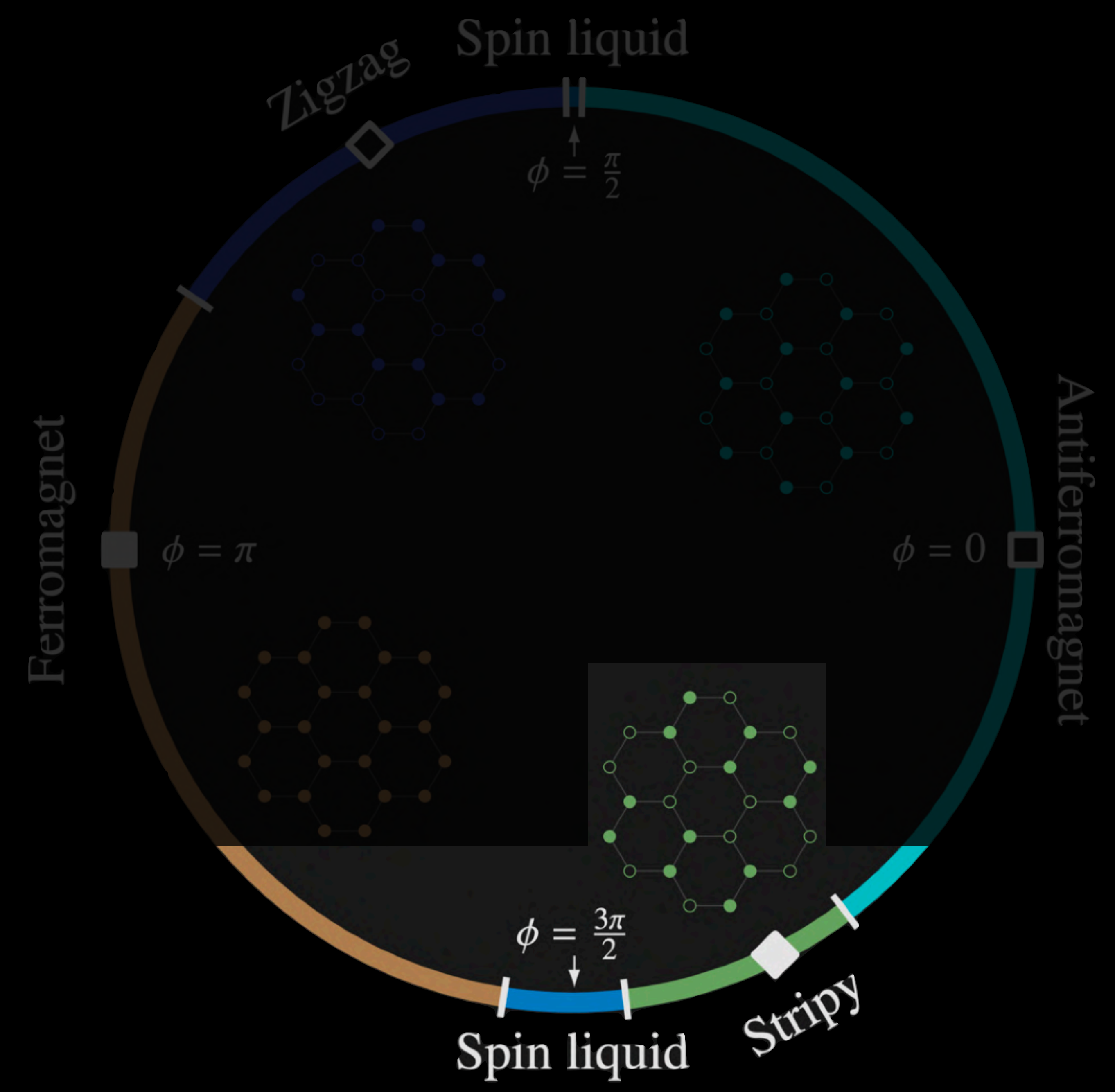

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Rau et al Ann. Rev. Cond. Mat. Phys. (2015)

Exact diagonalization

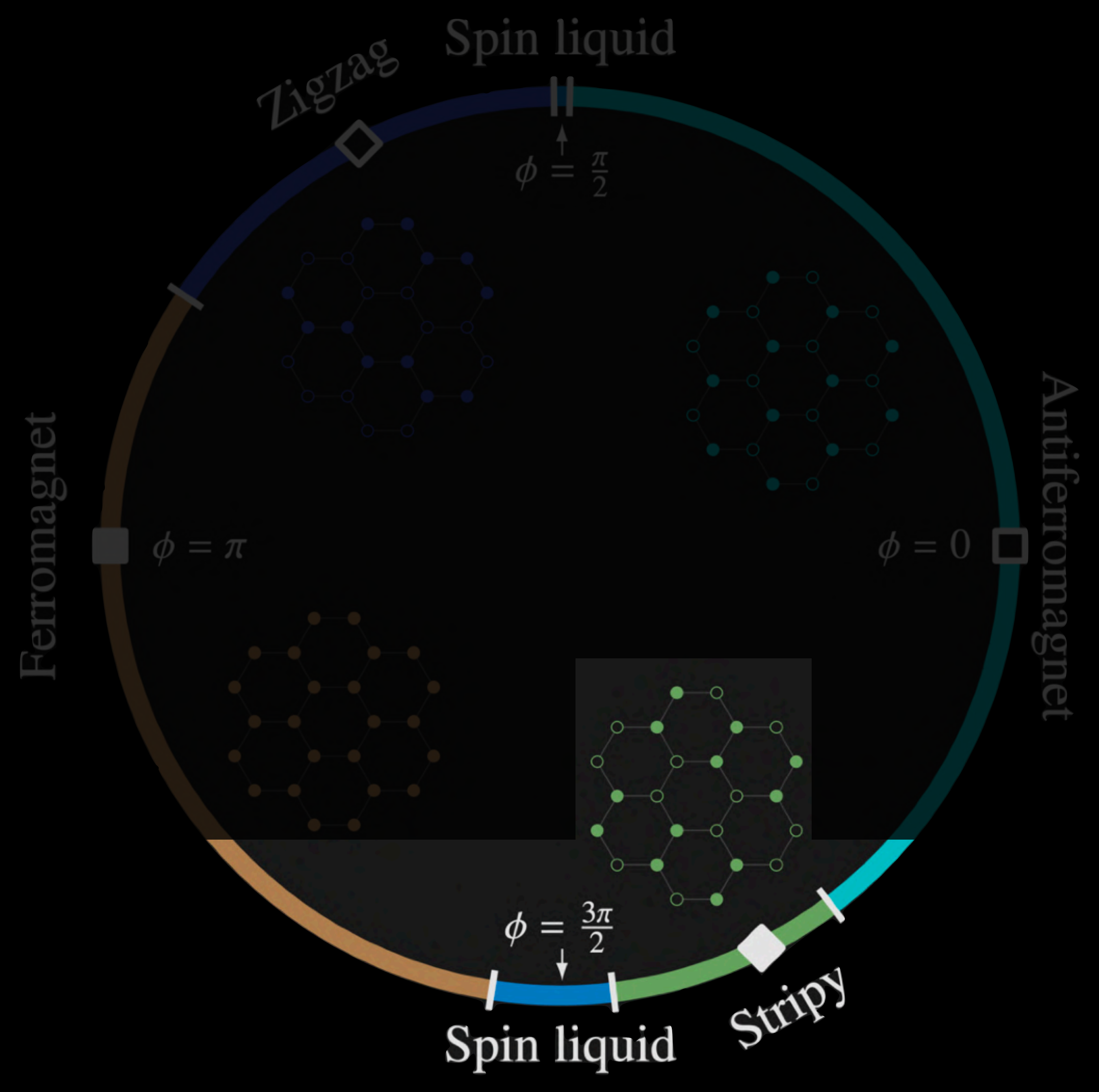
26 spins, 6 plaquettes

AGG, C. Repellin PRL (2023)

Stability

Kitaev + Heisenberg

$$H = J^K \sum_{\langle ij \rangle} \sigma_i^\alpha \sigma_j^\alpha + J^H \sum_{\langle ij \rangle} \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j$$

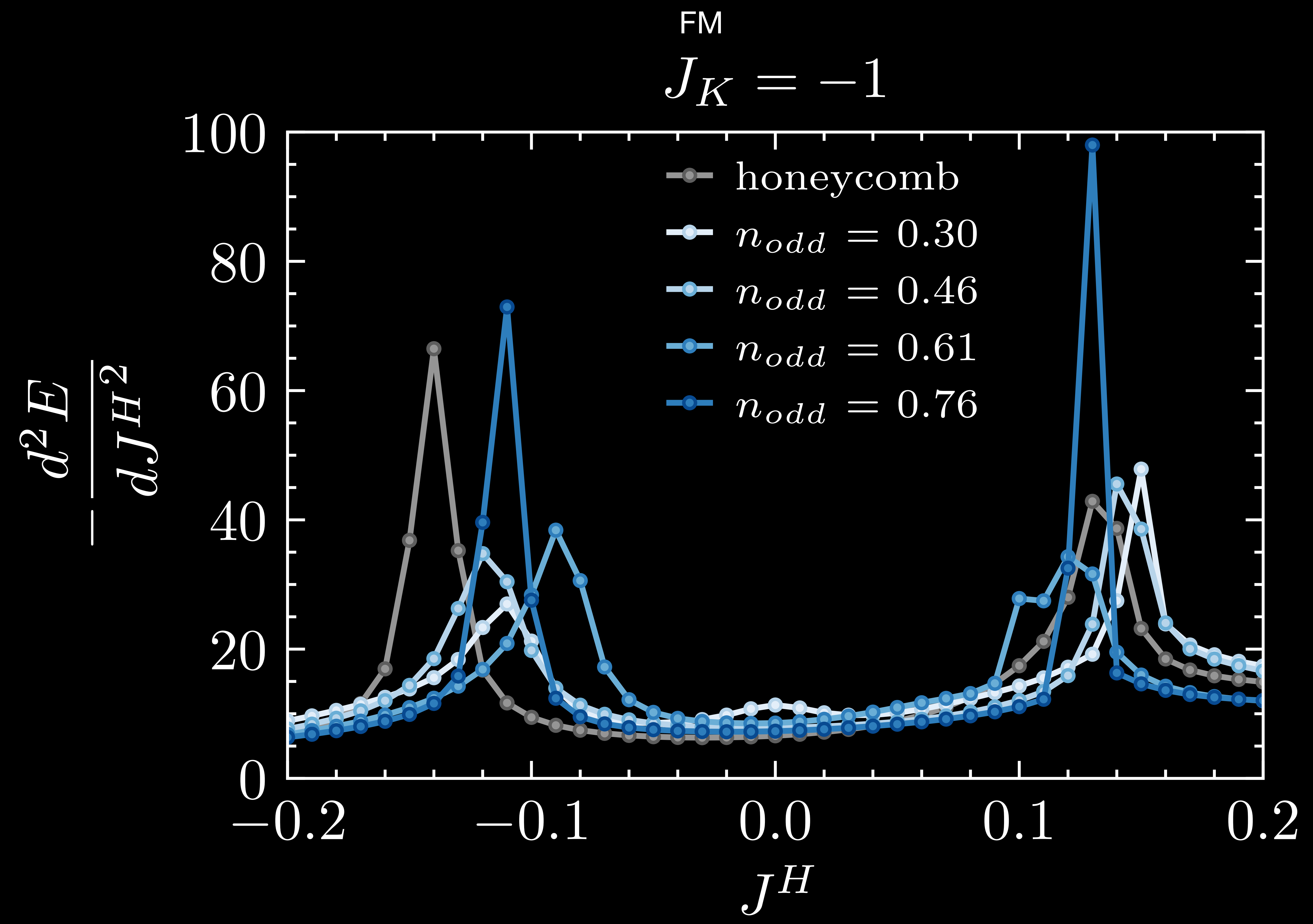


$$J^H = \cos\phi, J^K = \sin\phi$$

Rau et al Ann. Rev. Cond. Mat. Phys. (2015)

Exact diagonalization

26 spins, 6 plaquettes



AGG, C. Repellin PRL (2023)

Stability

Kitaev + Heisenberg

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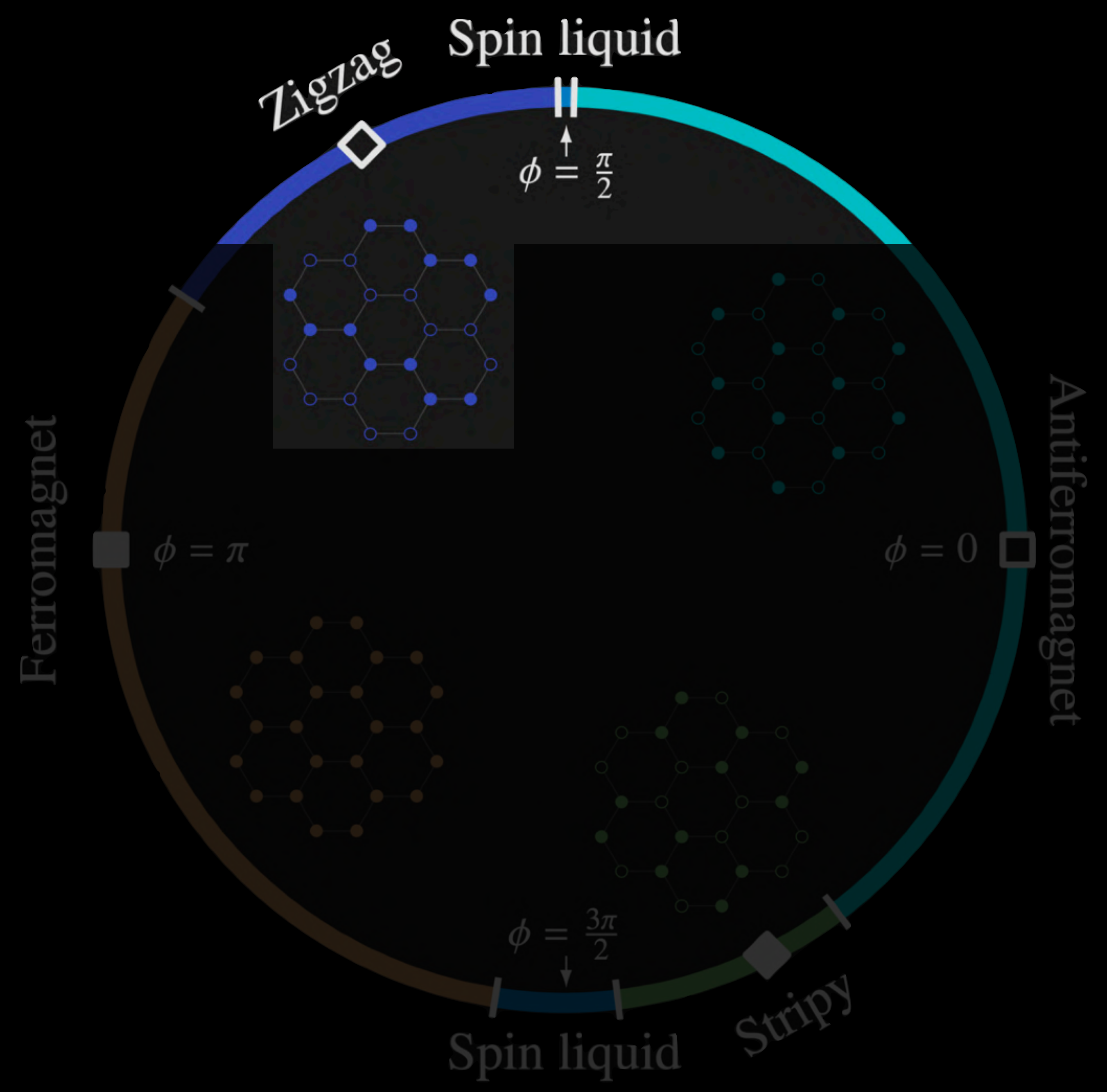

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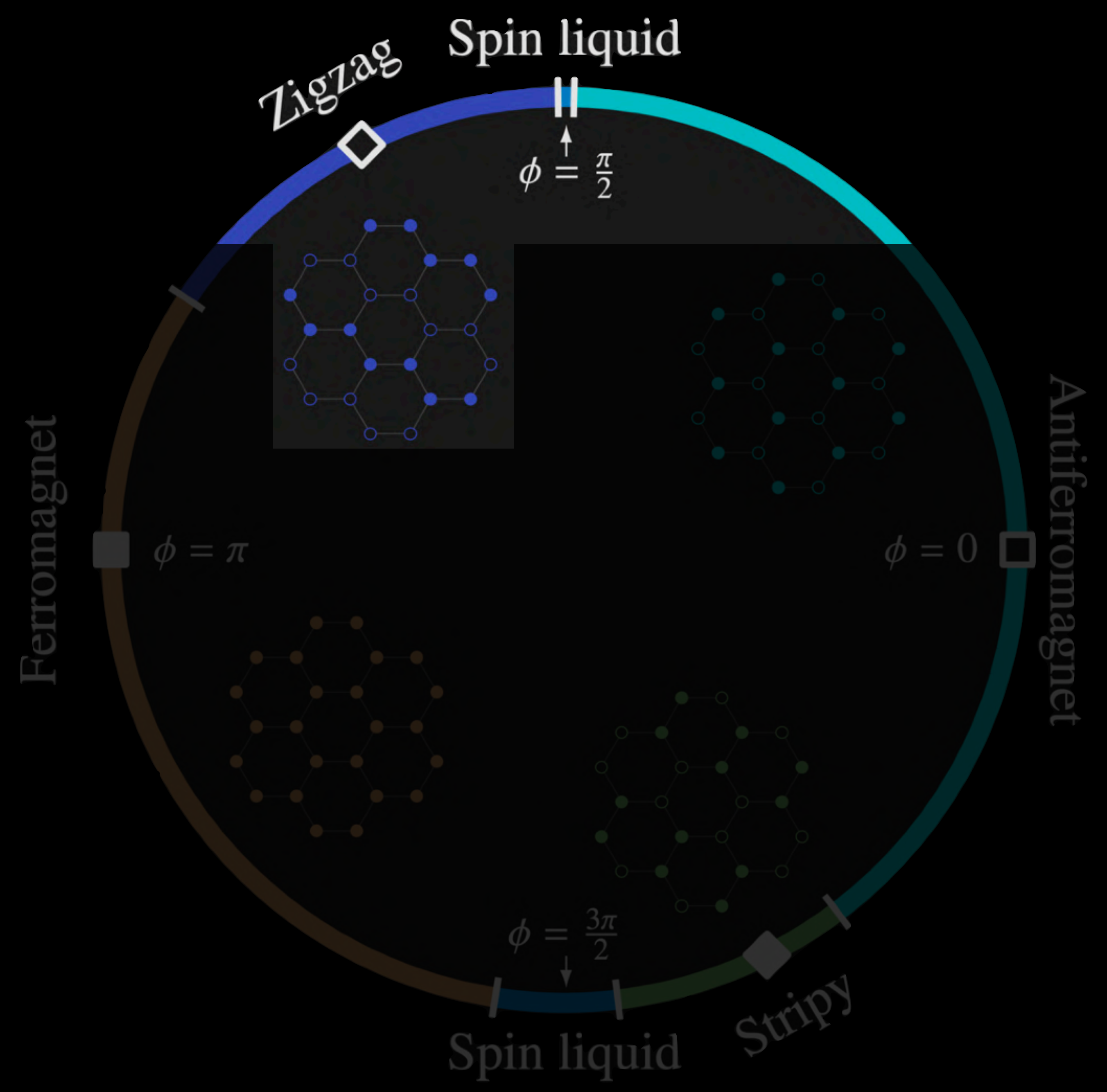

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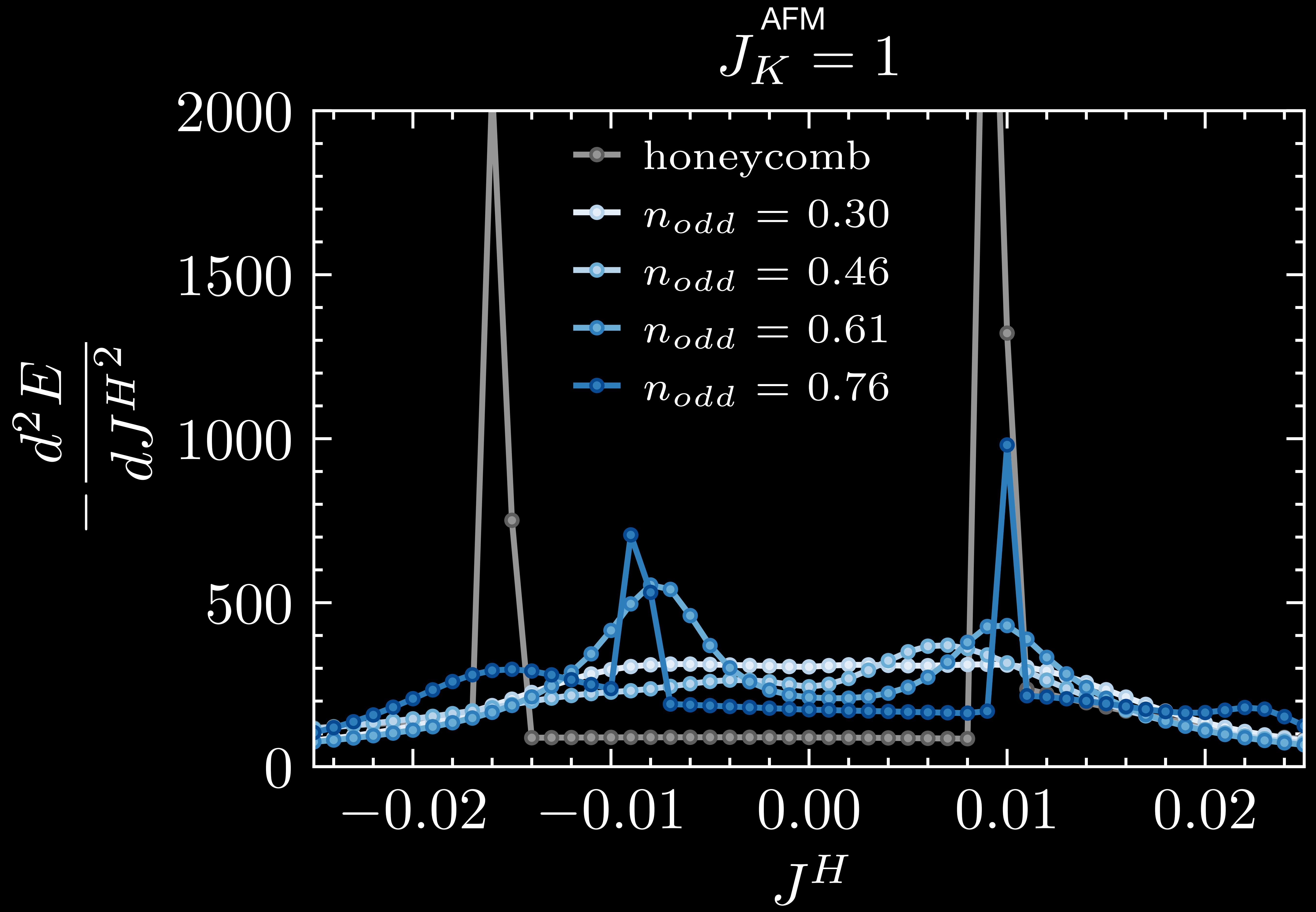

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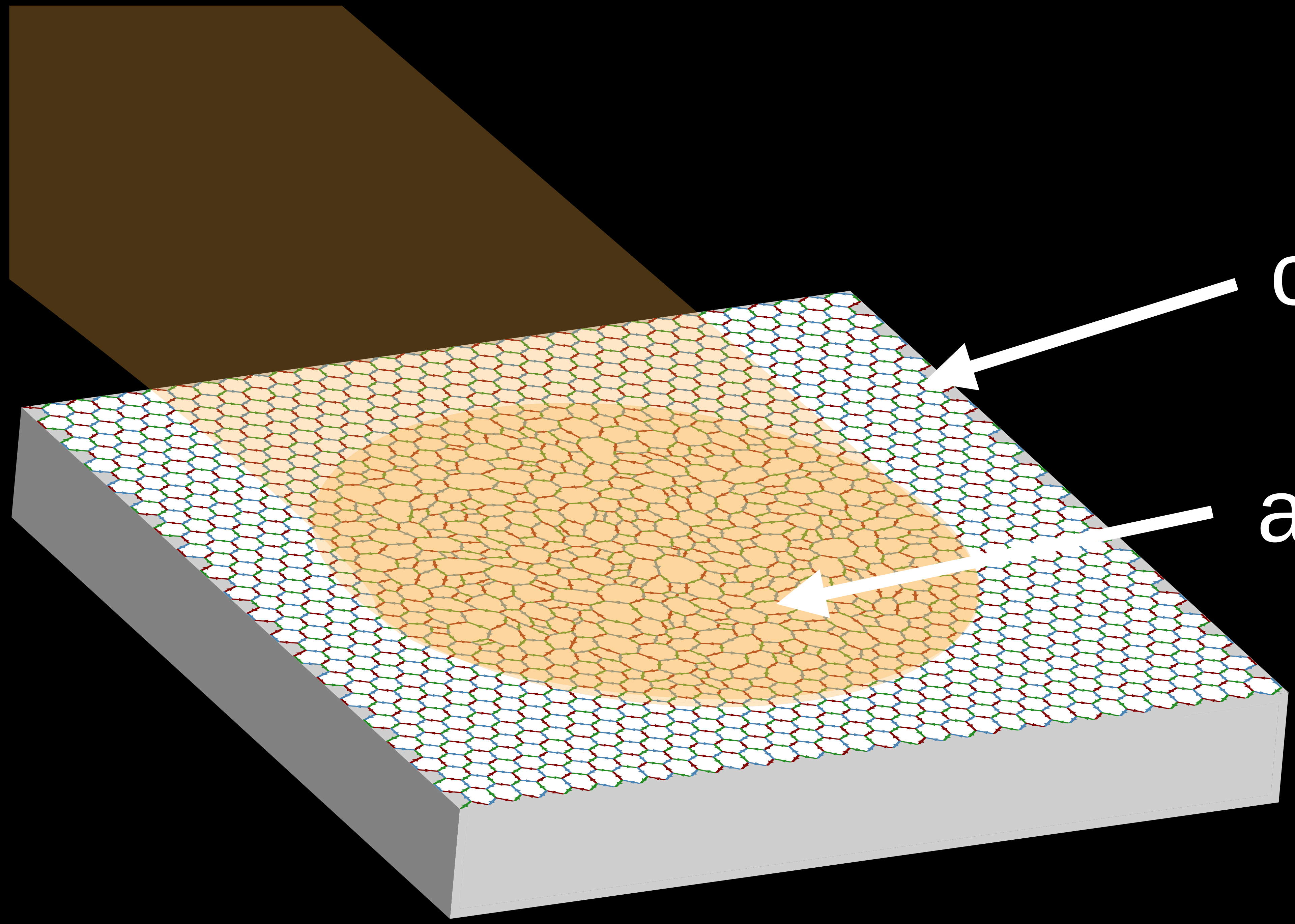
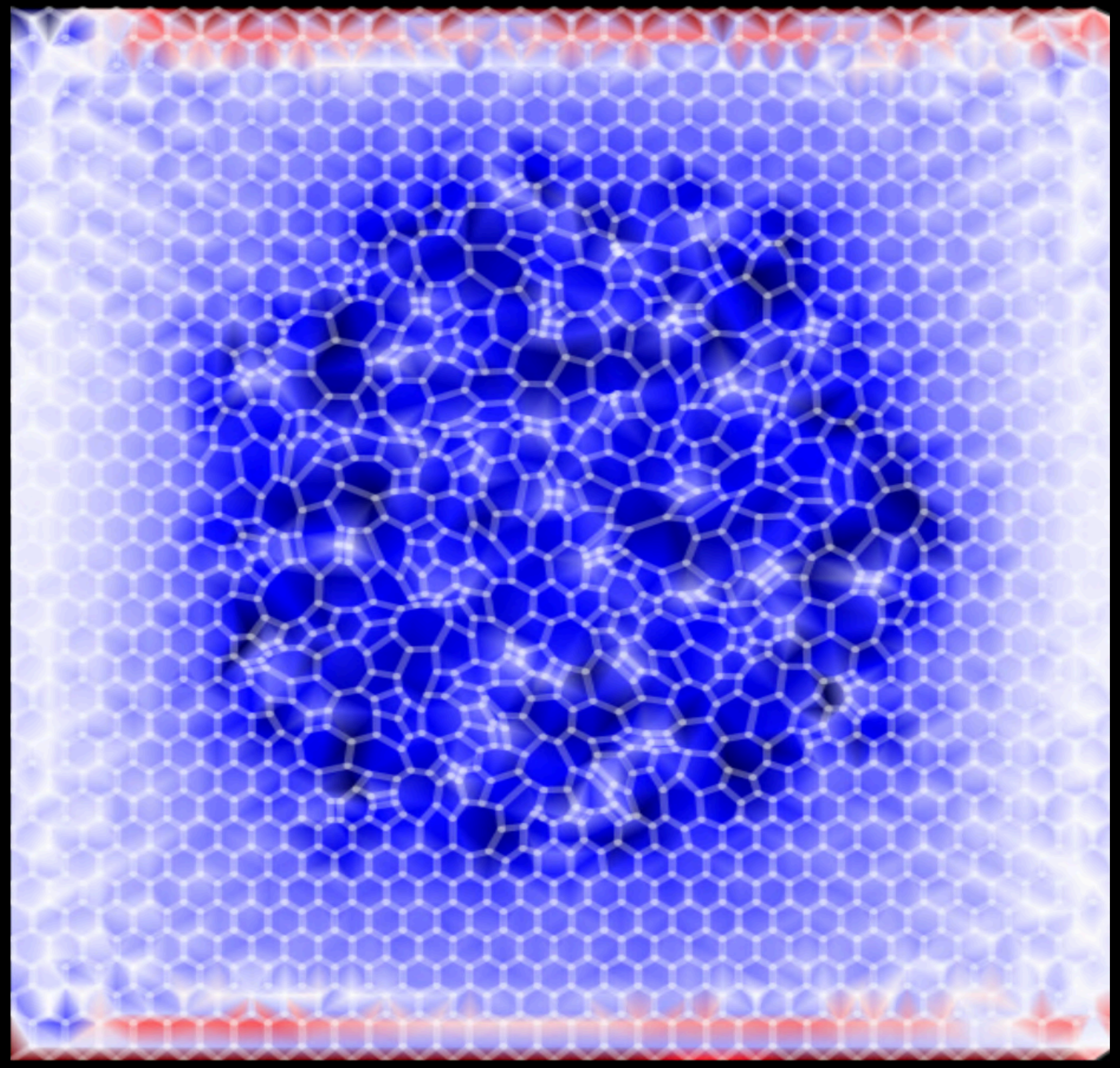
Engineering structural disorder?

focused ion beam



see A. Bake et al **14**, Nat. Comm 1693 (2023)

Local Chern marker



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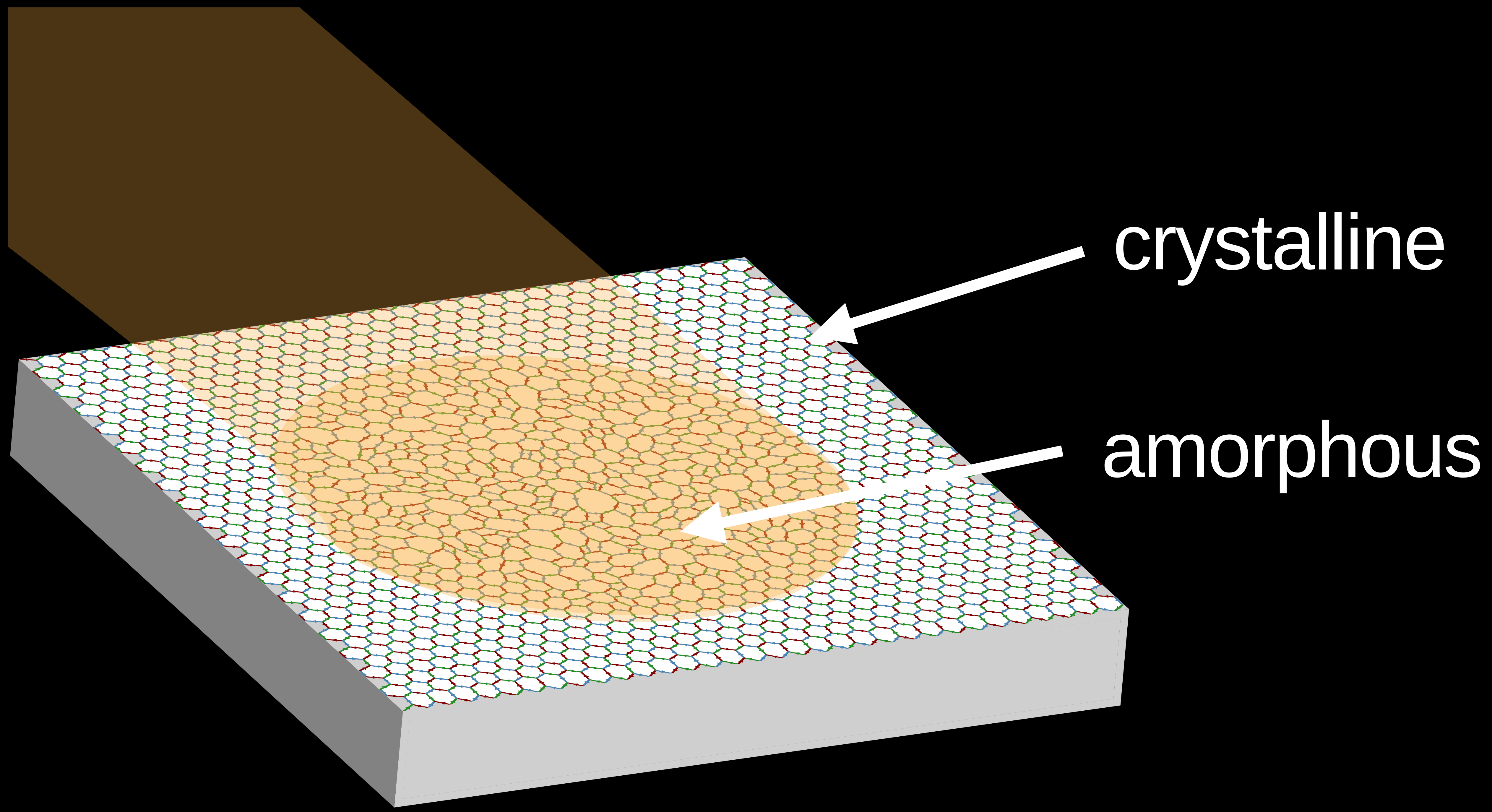

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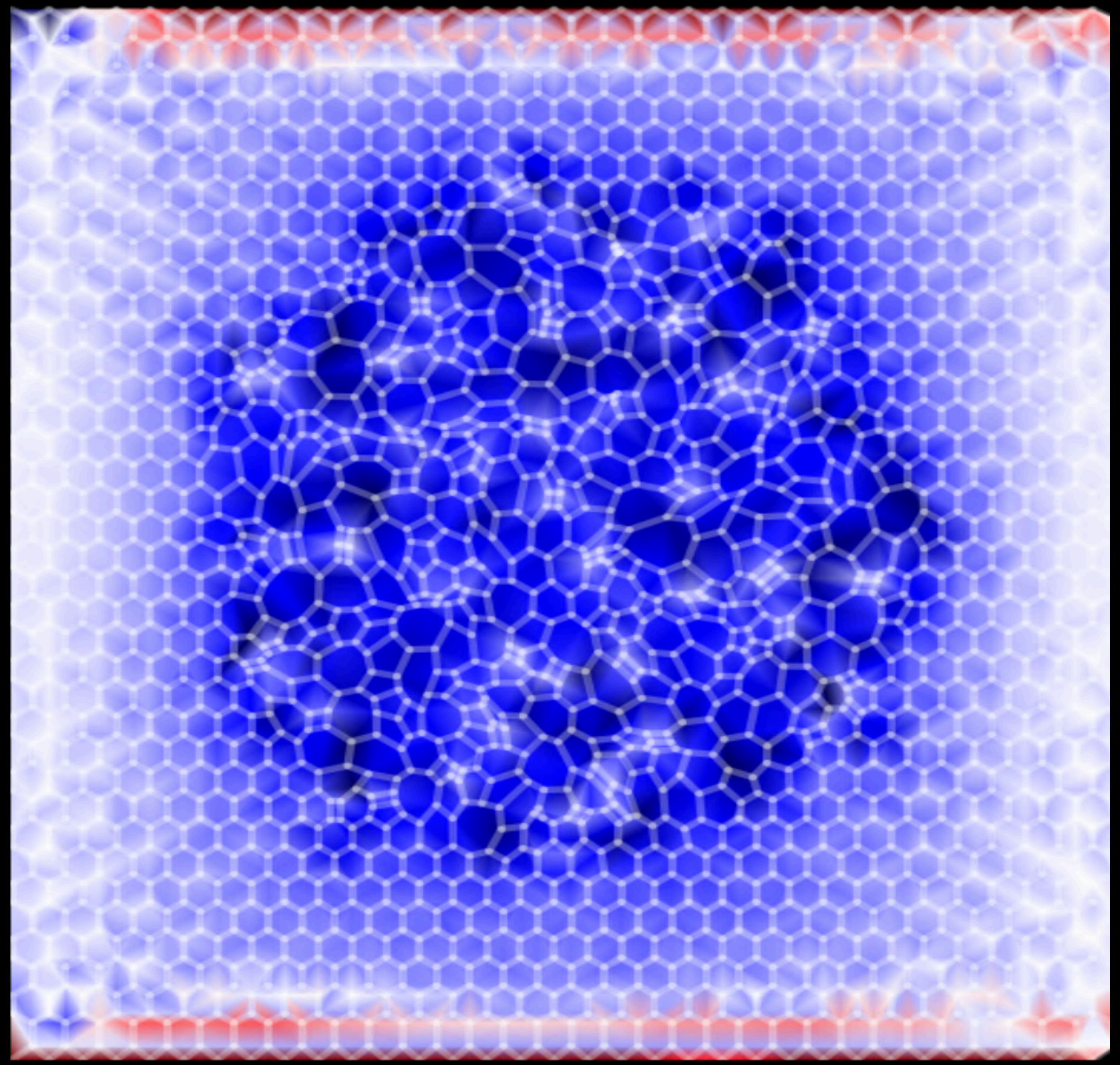

quantised thermal Hall:
Reed and Green *PRB* (2000)

$$\frac{\kappa_{xy}}{T} = \nu \left(\frac{\pi^2 k_B^2}{6h} \right) \qquad \nu = 1$$

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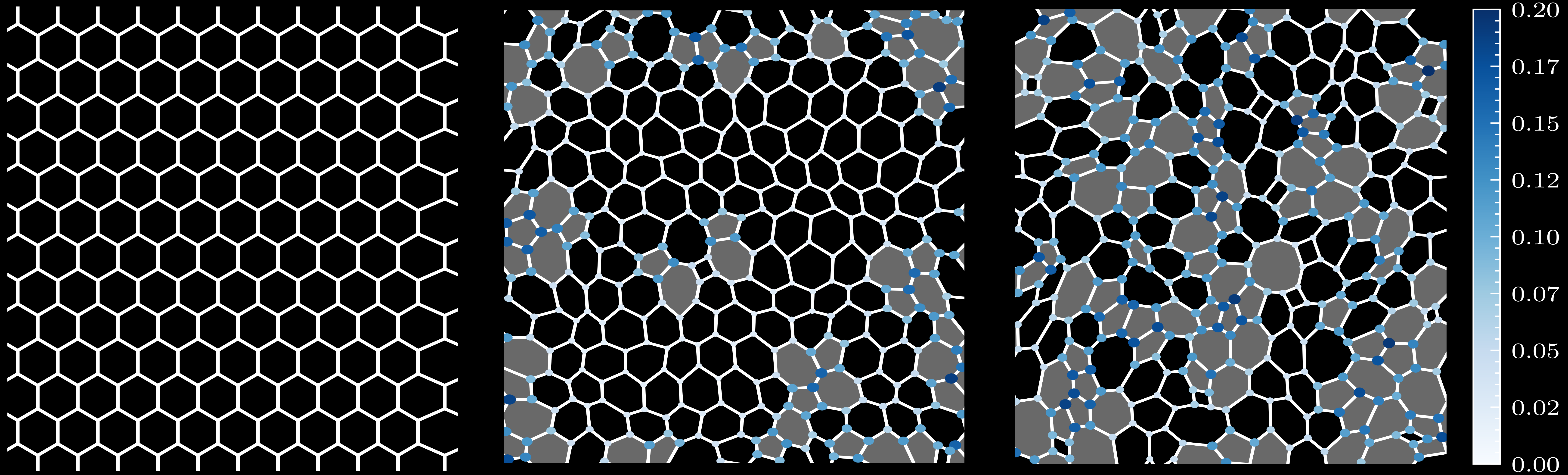
Amorphous and polycrystalline routes towards a chiral spin-liquid

Cécile Repellin
LPMMC / Grenoble

gapless QSL → gapped chiral QSL



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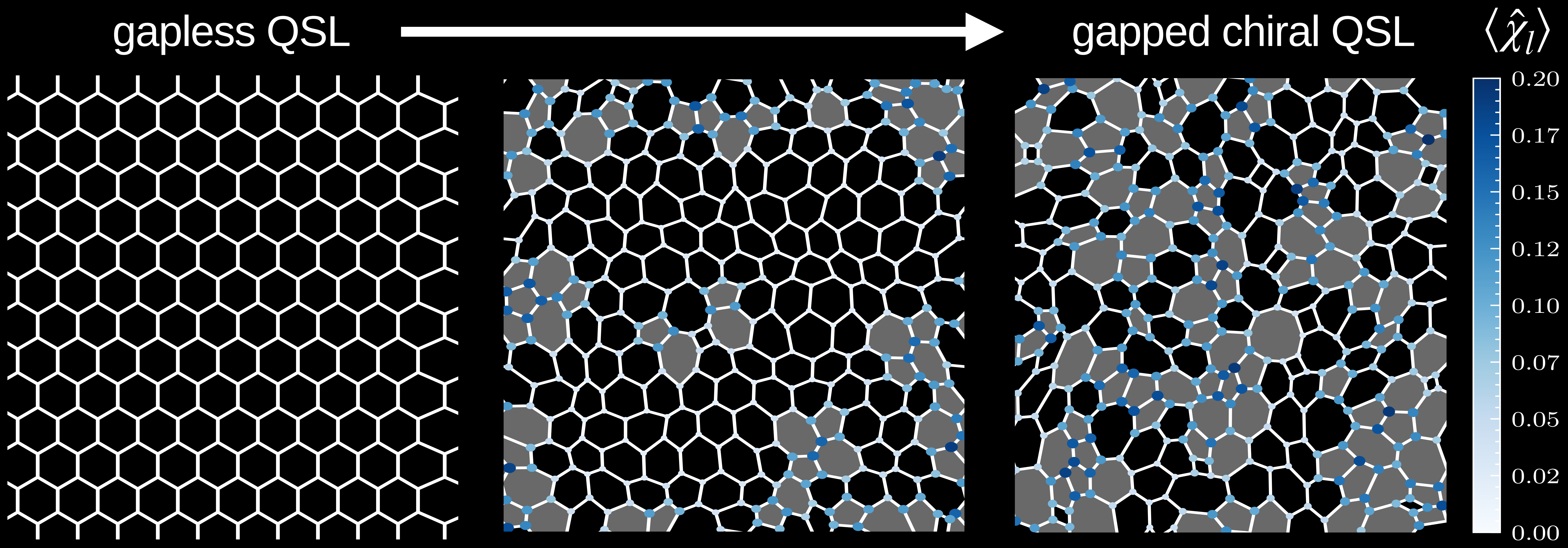

amorphous Kitaev lattice =
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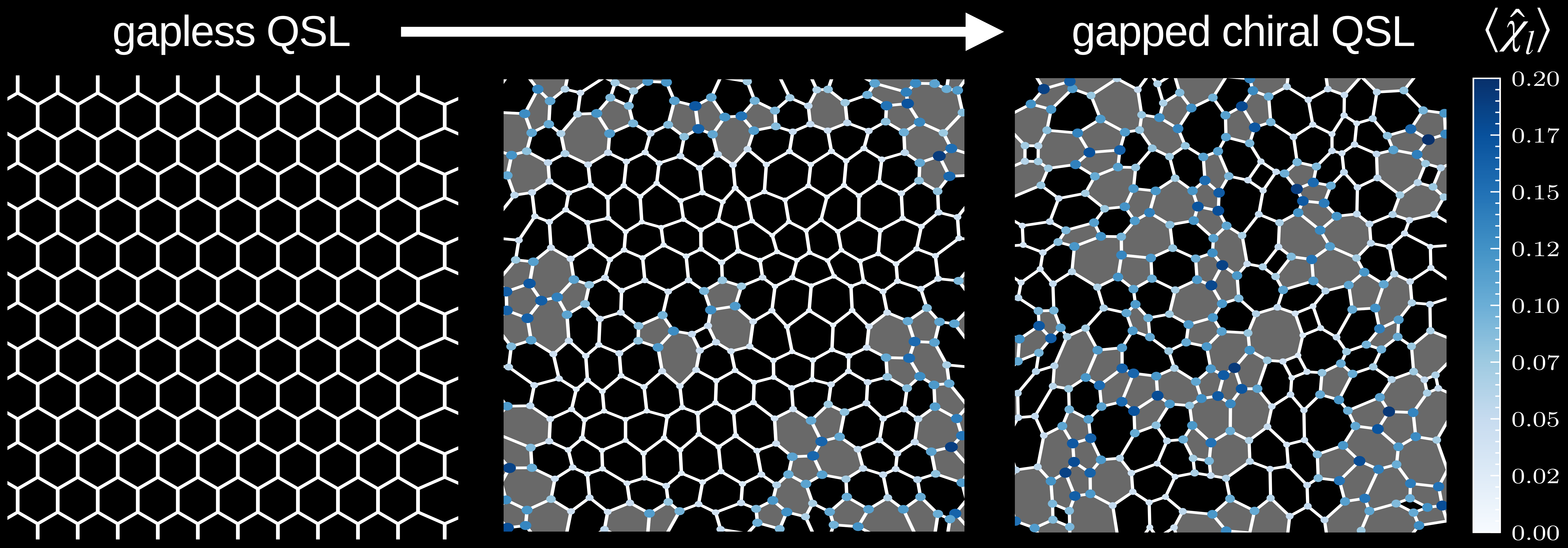

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75% max gap size at 30% of odd-plaquettes (~a-graphene)

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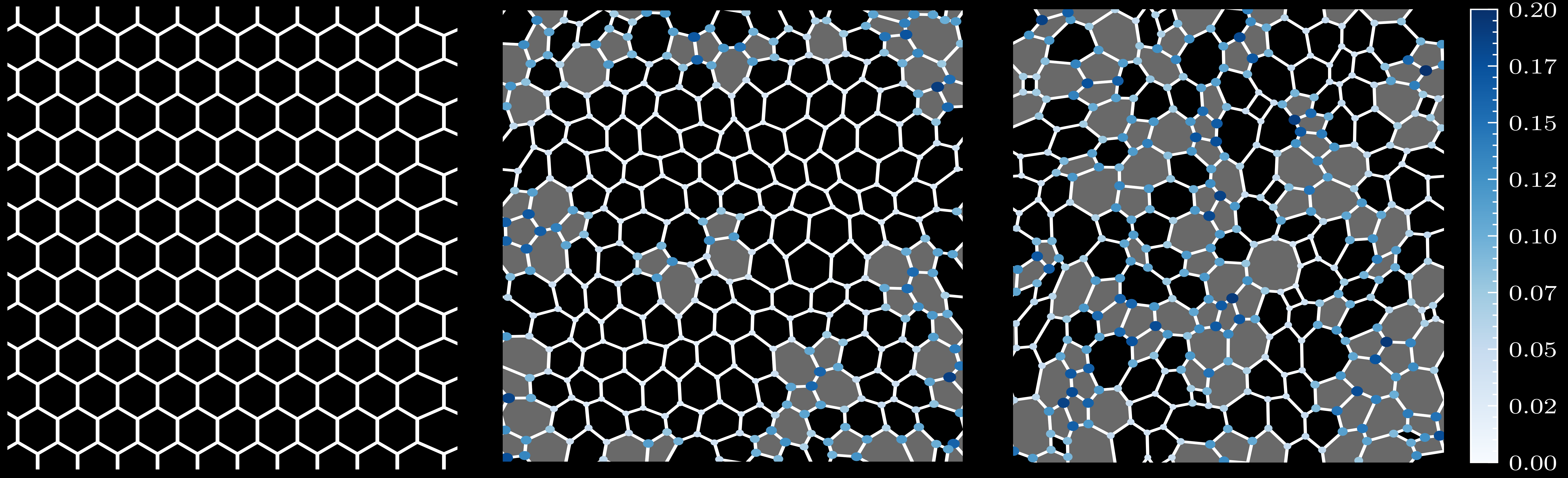

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