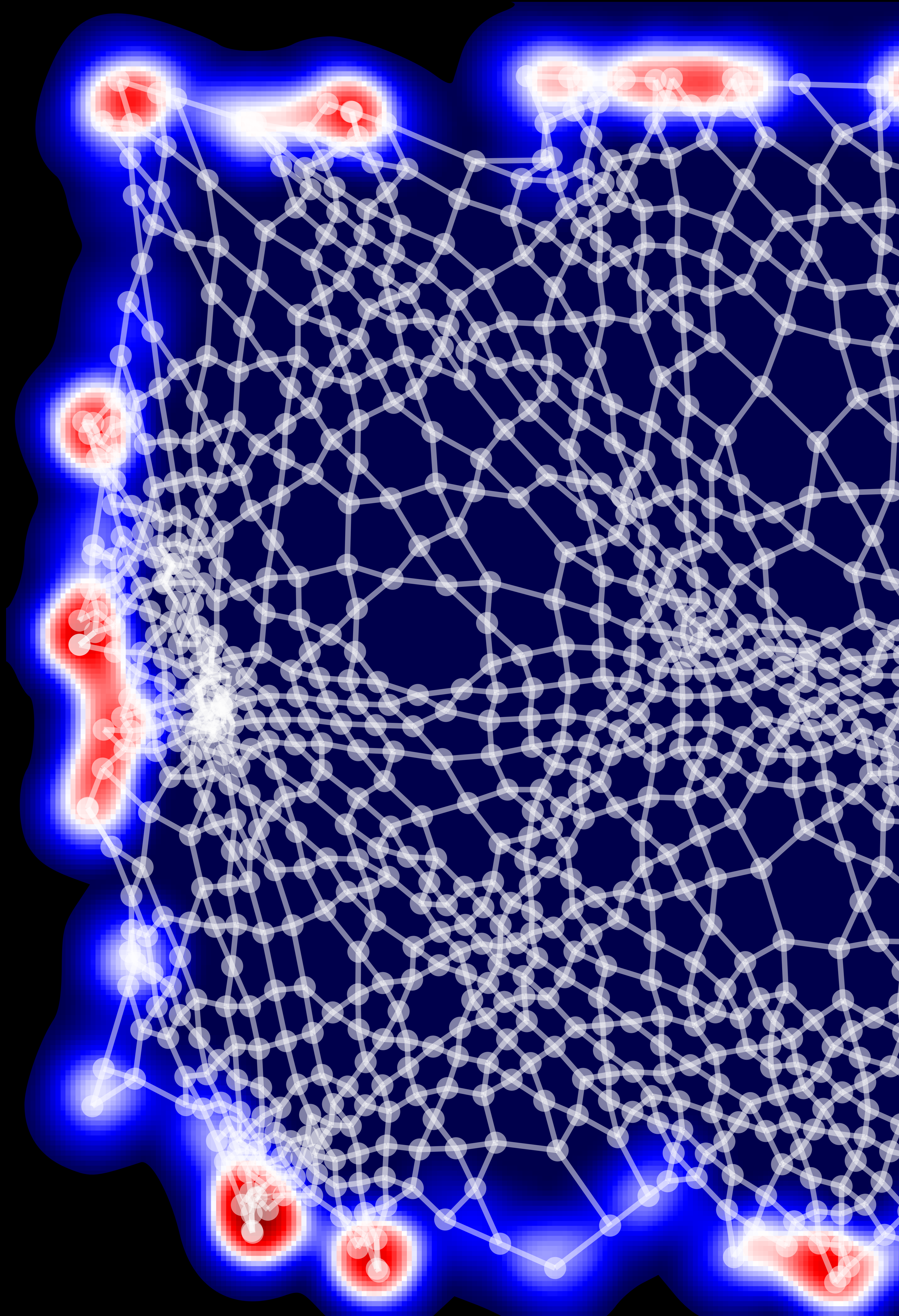
Amorphous topological solids

from flat bands to chiral spin liquids

Adolfo G. Grushin, Néel Institute, CNRS

150 years of the SFP — Paris, July 7th, 2023



TOPOMORPH

European Research Council

FET-OPEN SCHINES

AGENCE NATIONALE DE LA RECHERCHE ANR

Topological solids 101

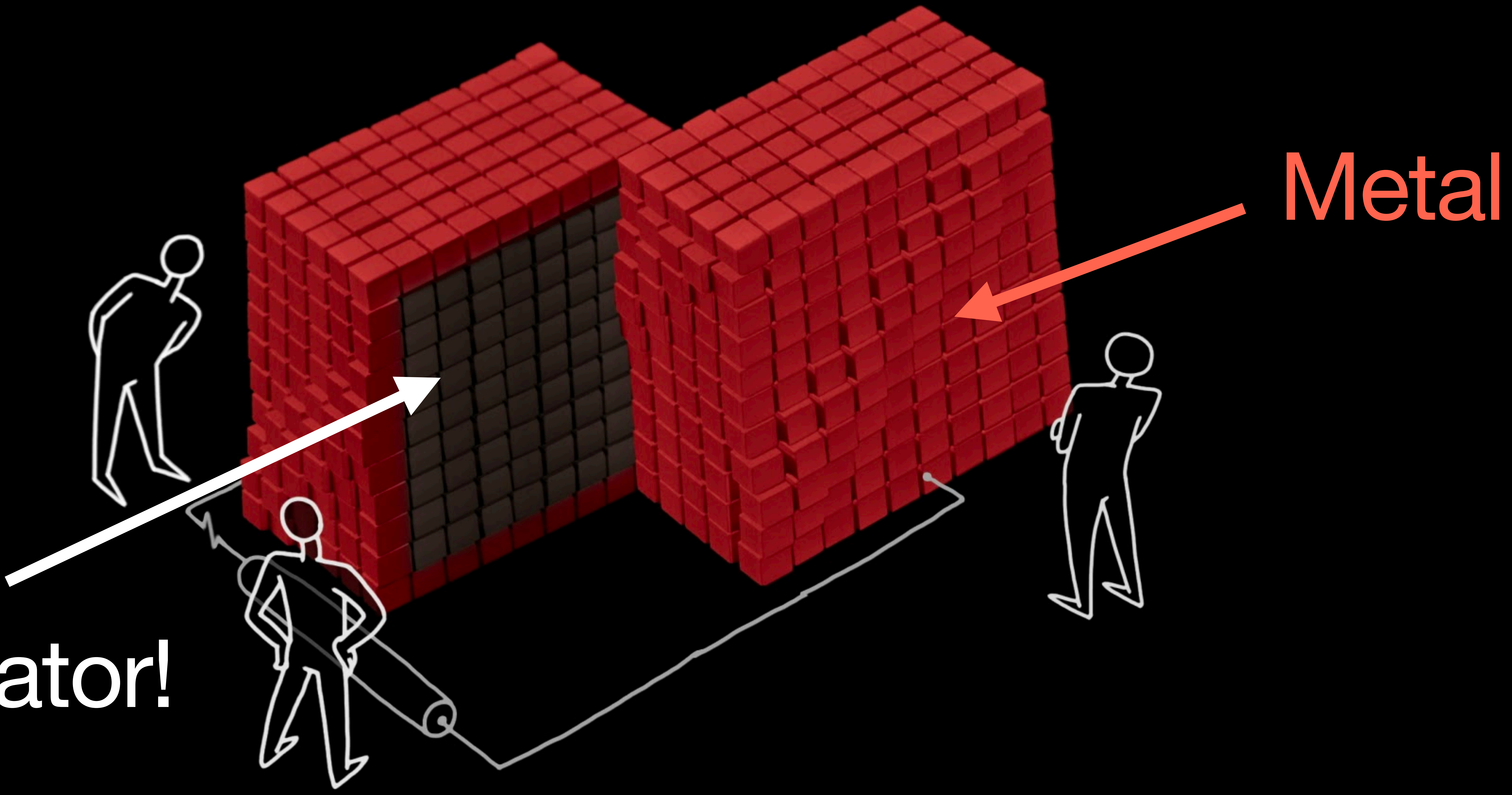
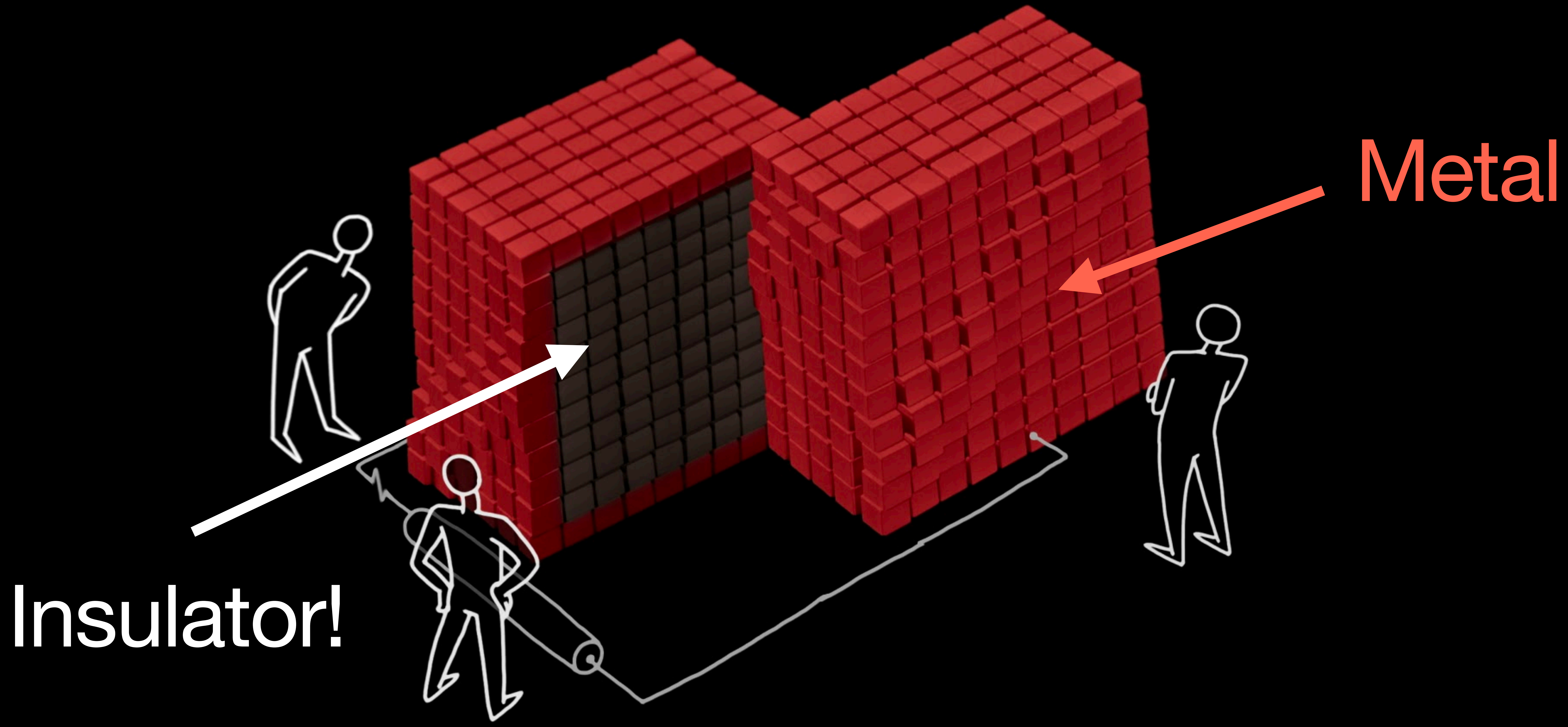


Image: Le Nobel Chevelu

Topological solids 101



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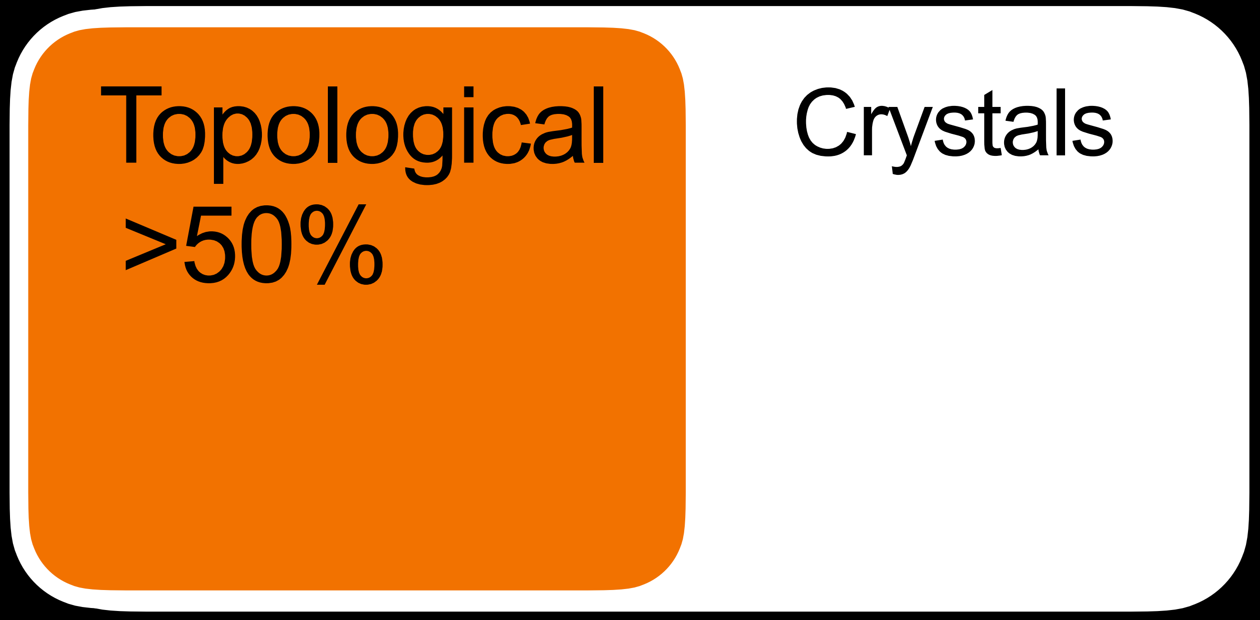

Vergniory et al. Nature (2019)
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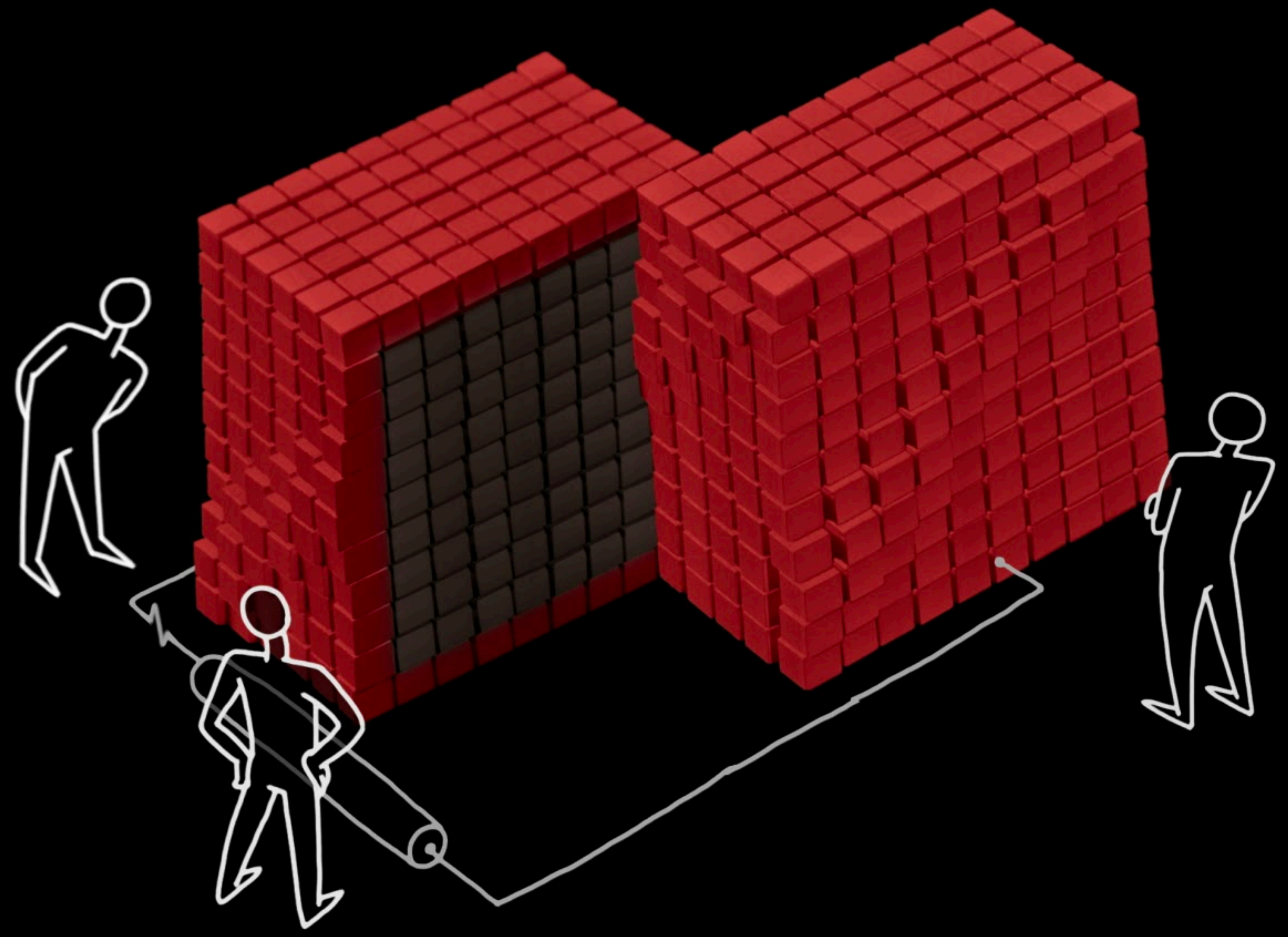

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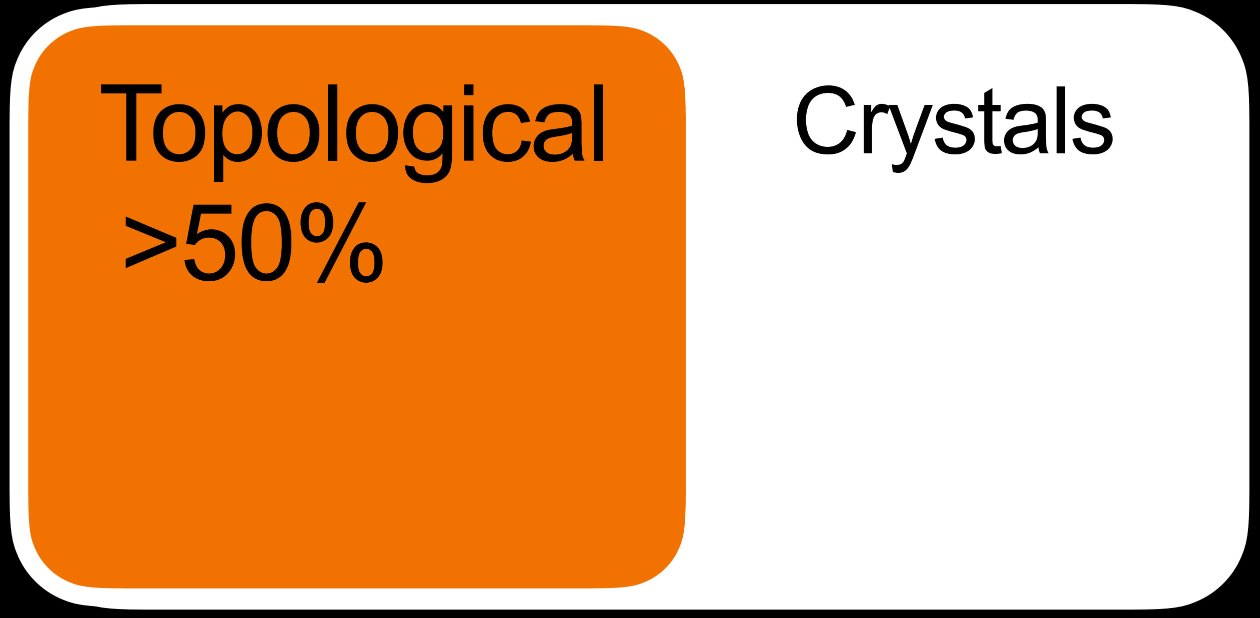

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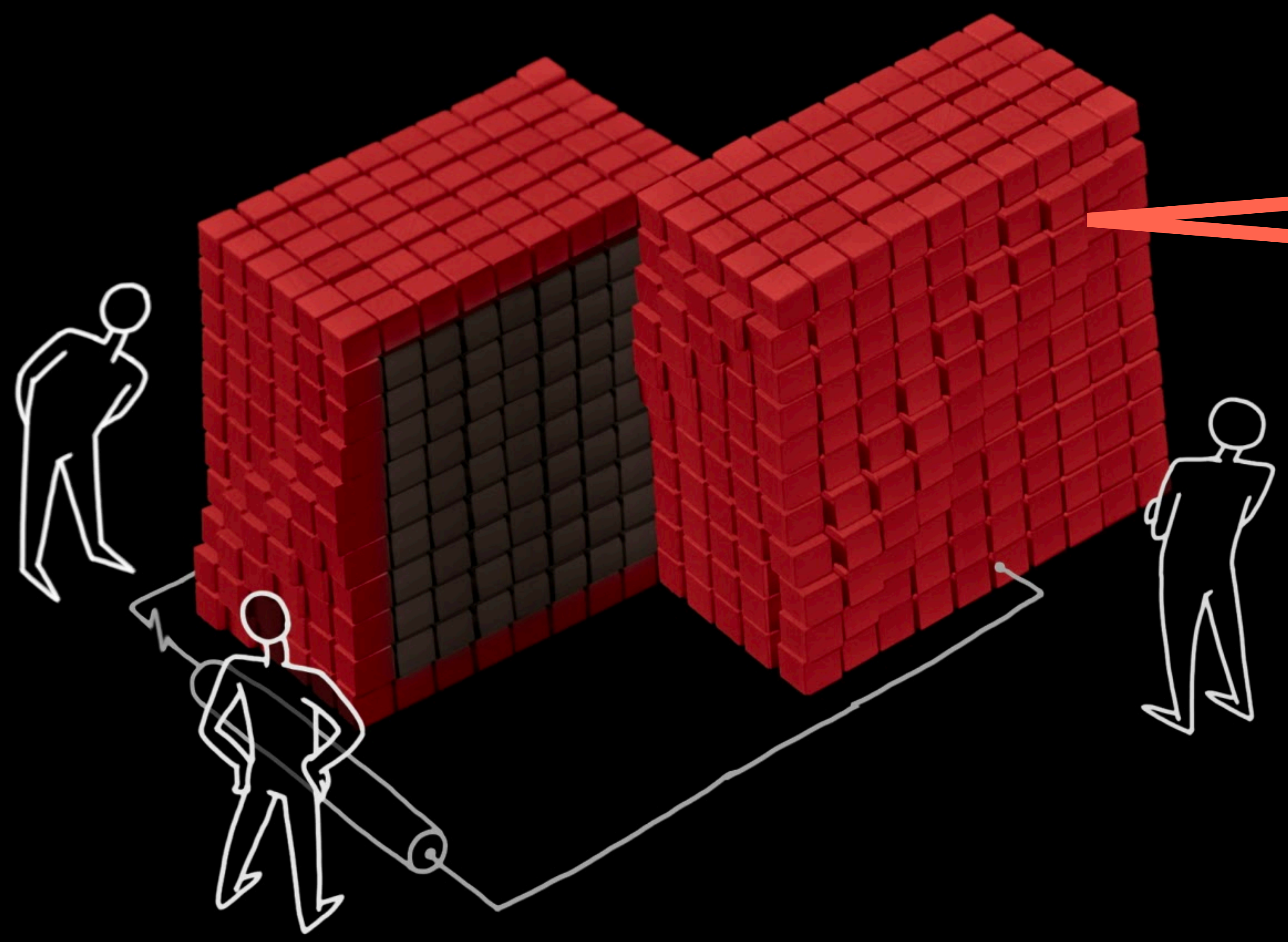
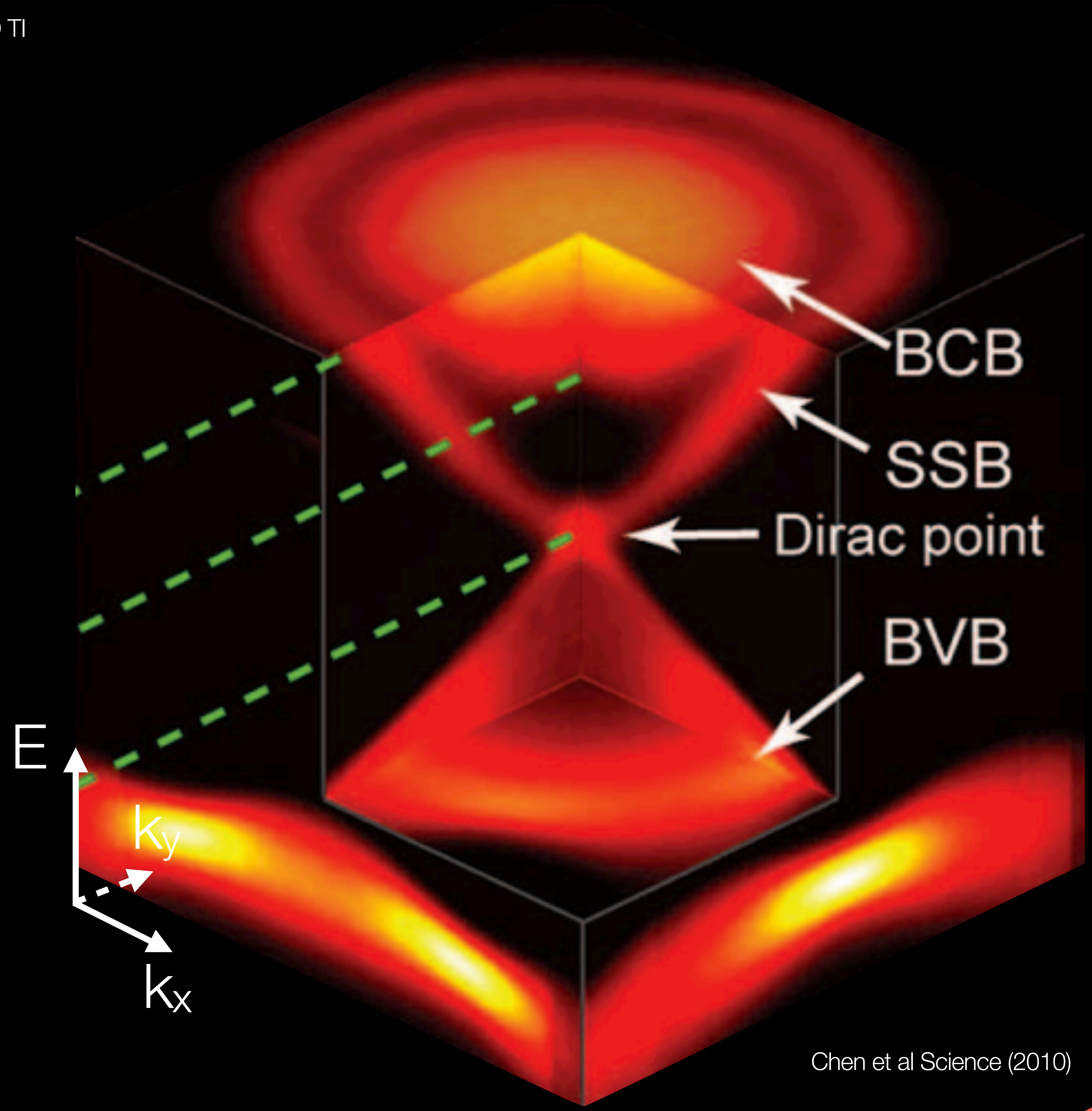


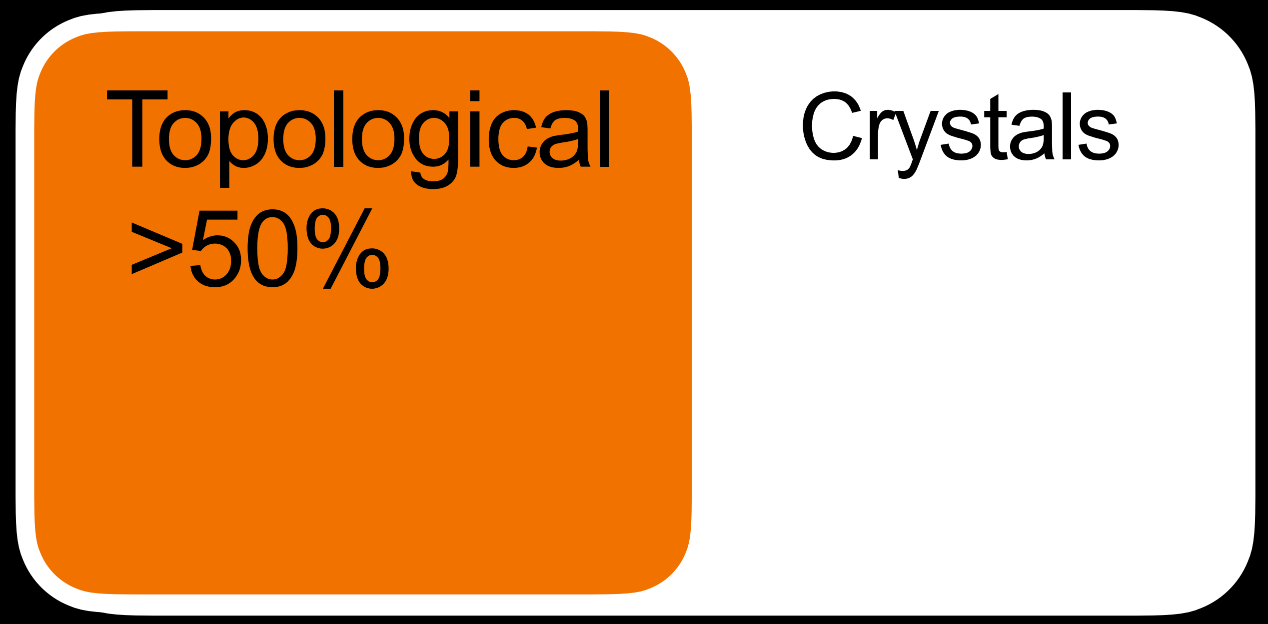
Bi_2Se_3

3D TI



Chen et al Science (2010)

How do we find topological insulators?



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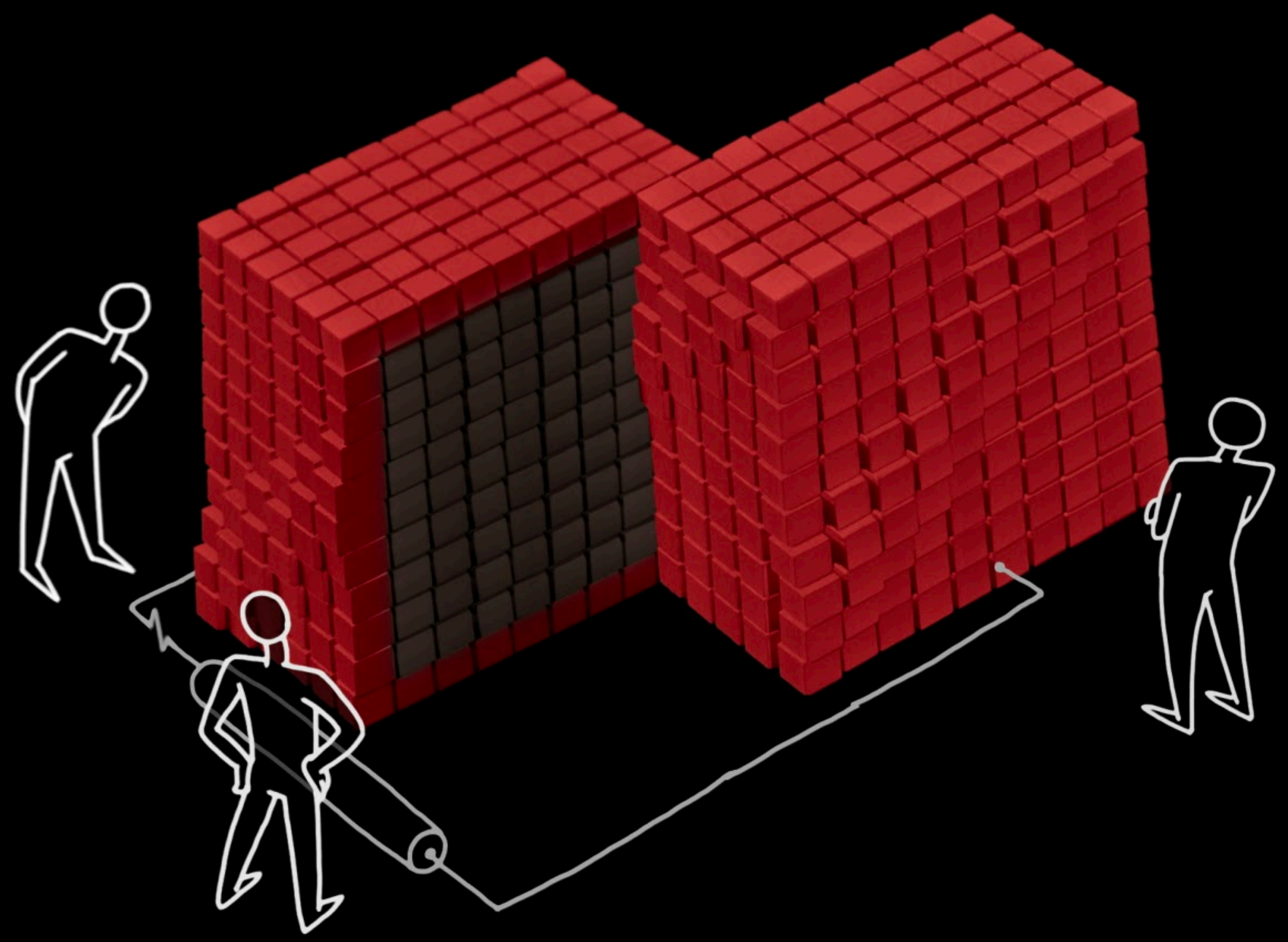

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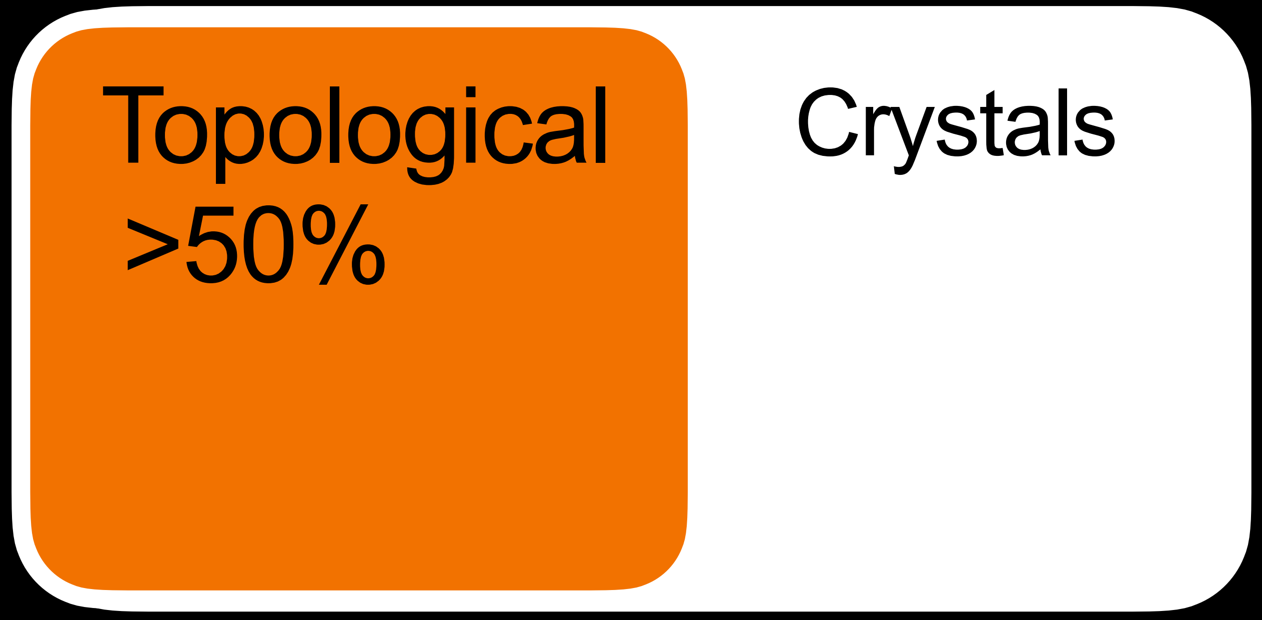

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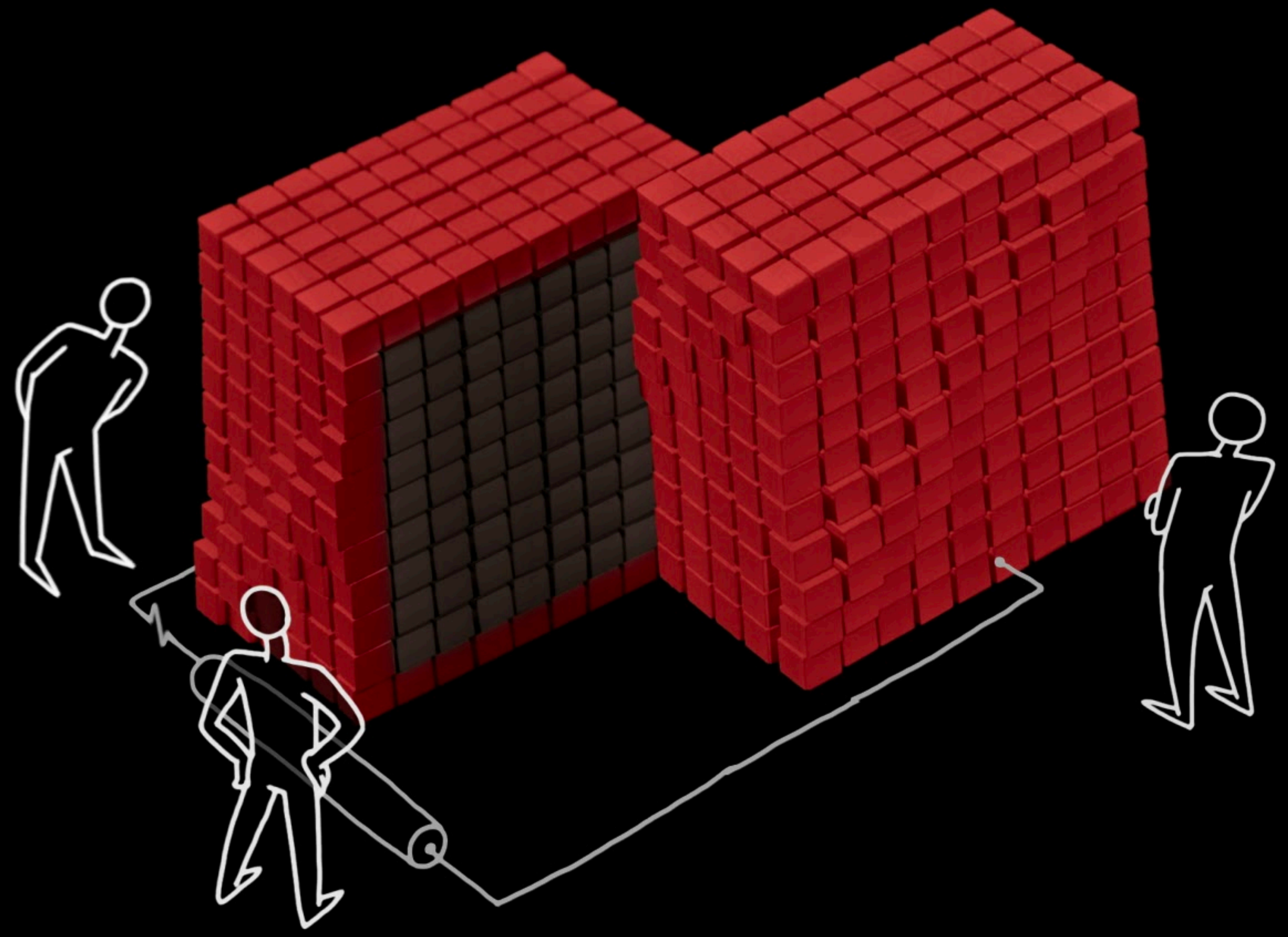

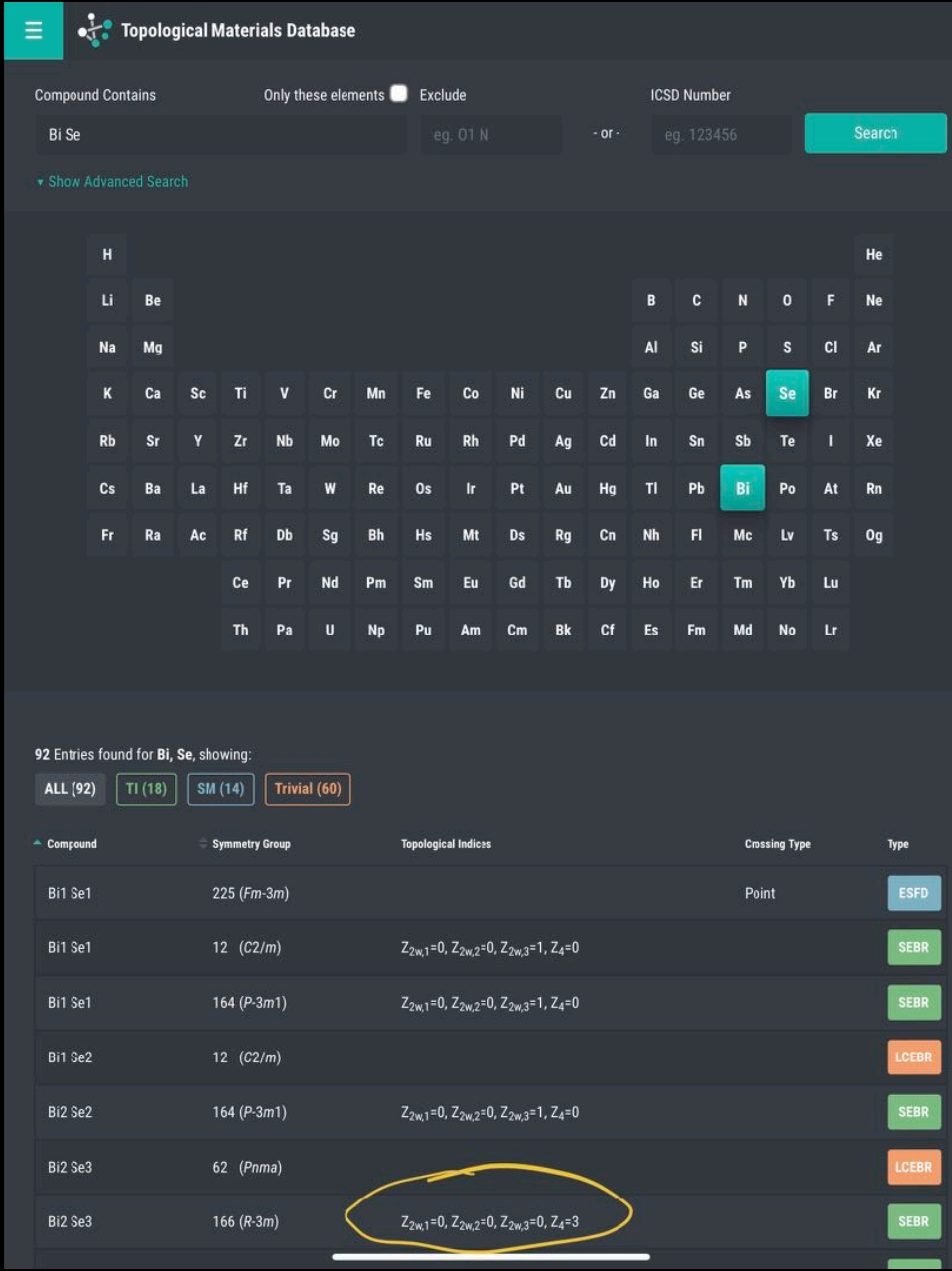

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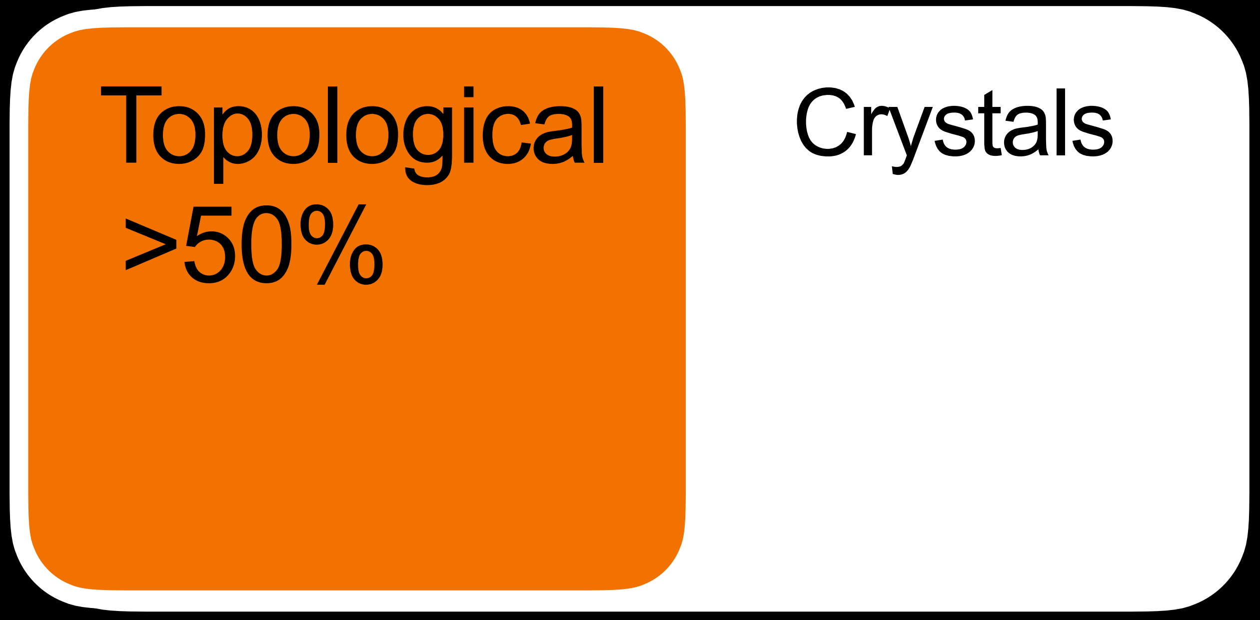

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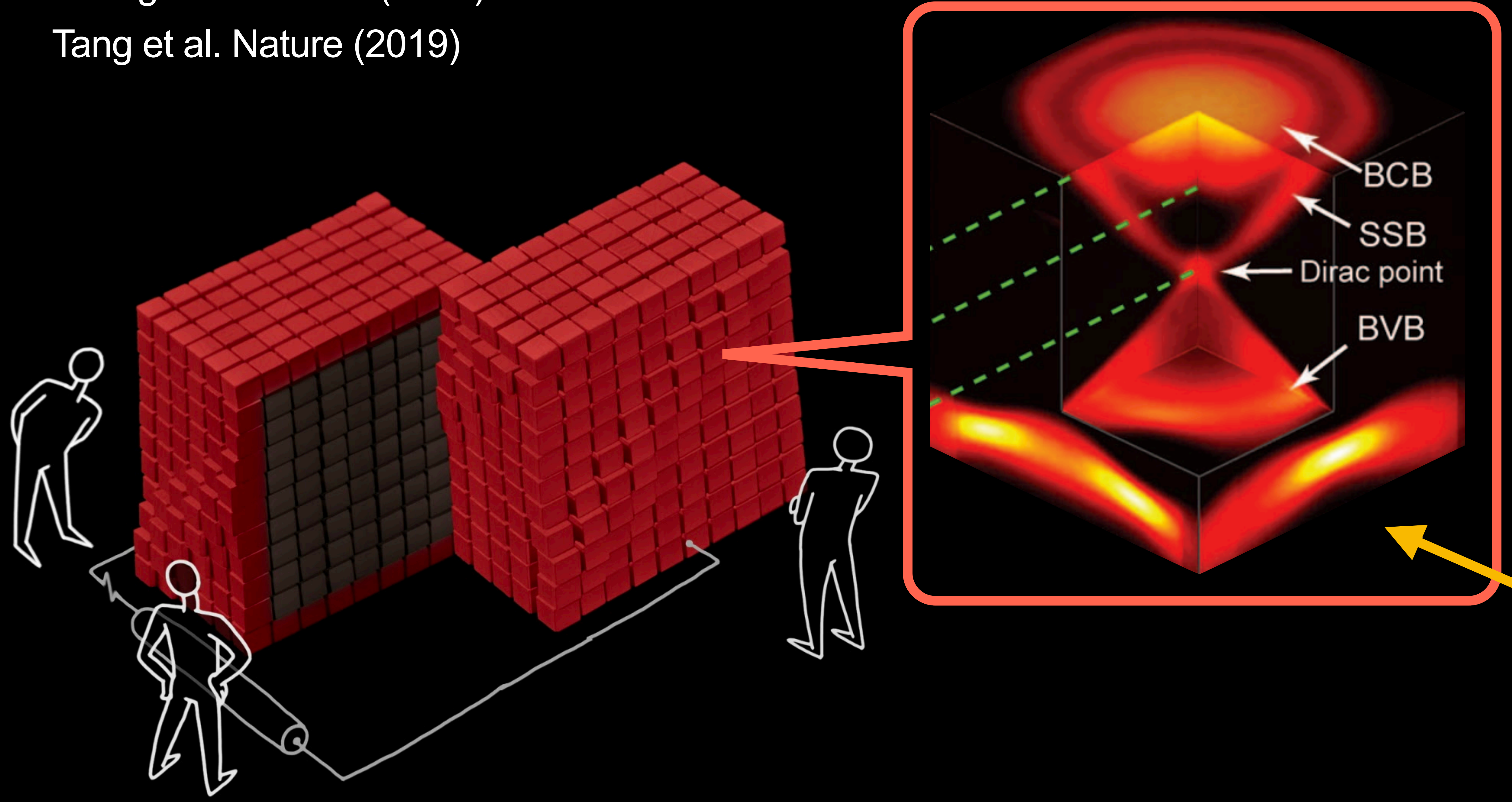
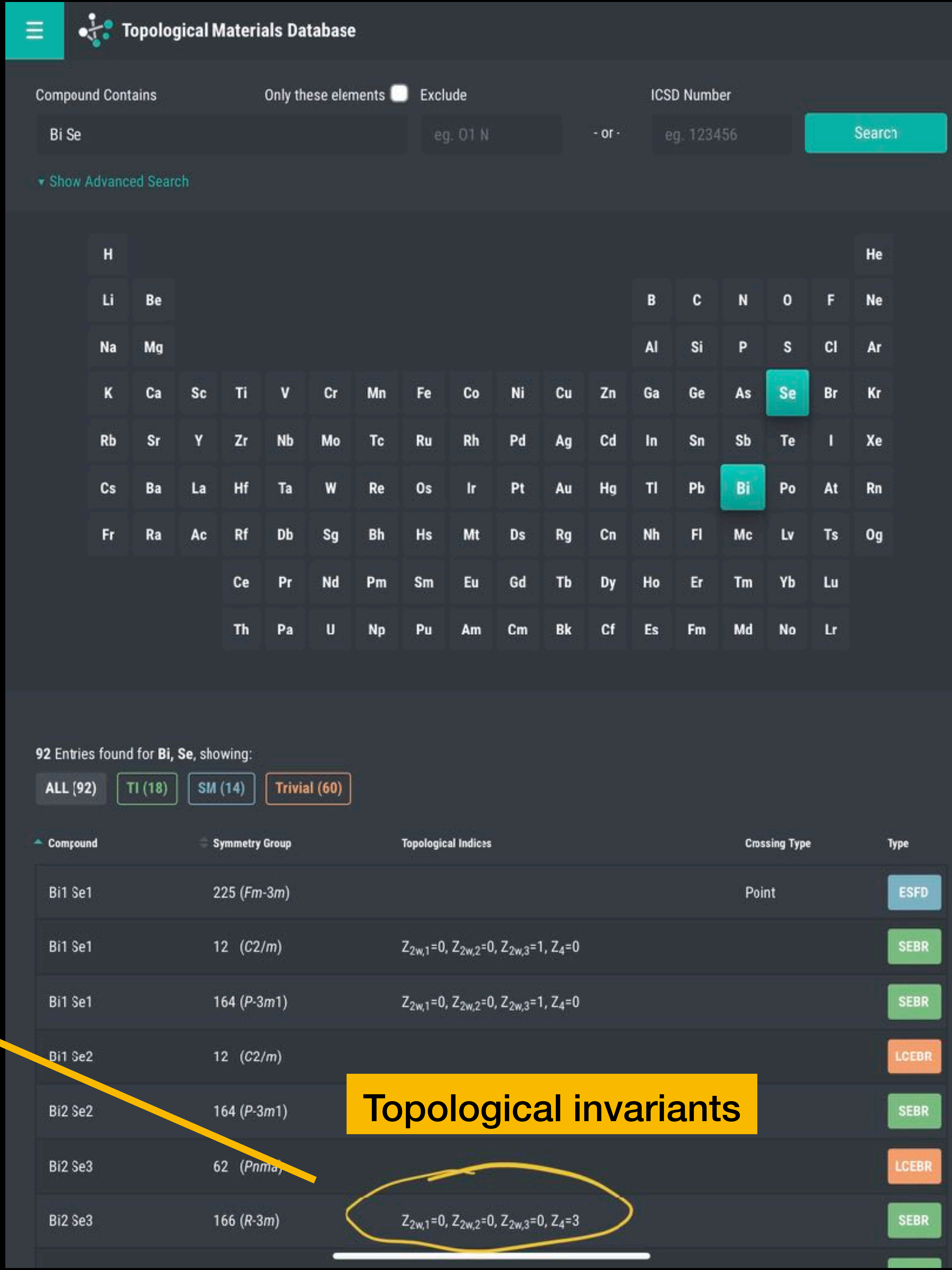
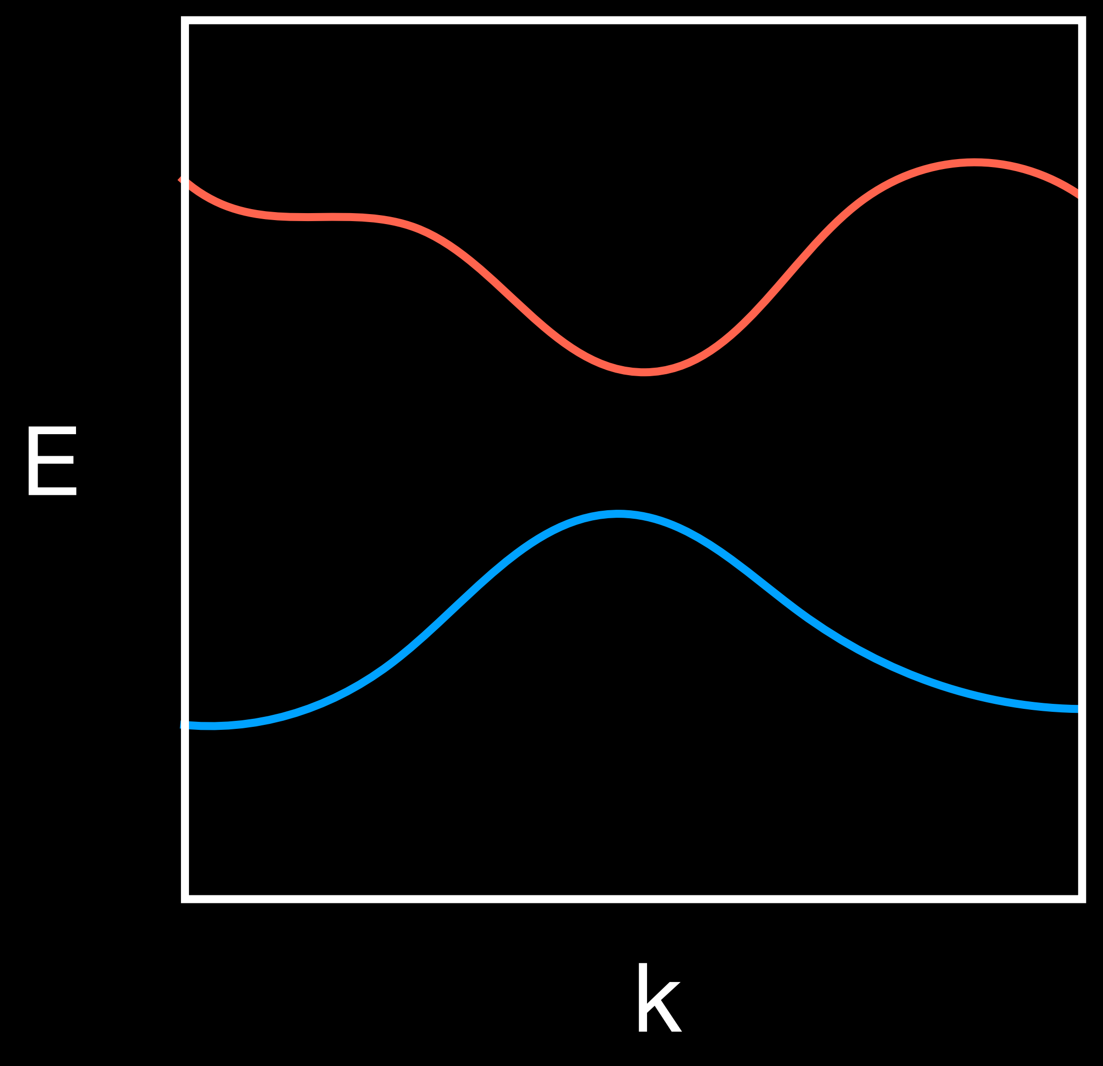


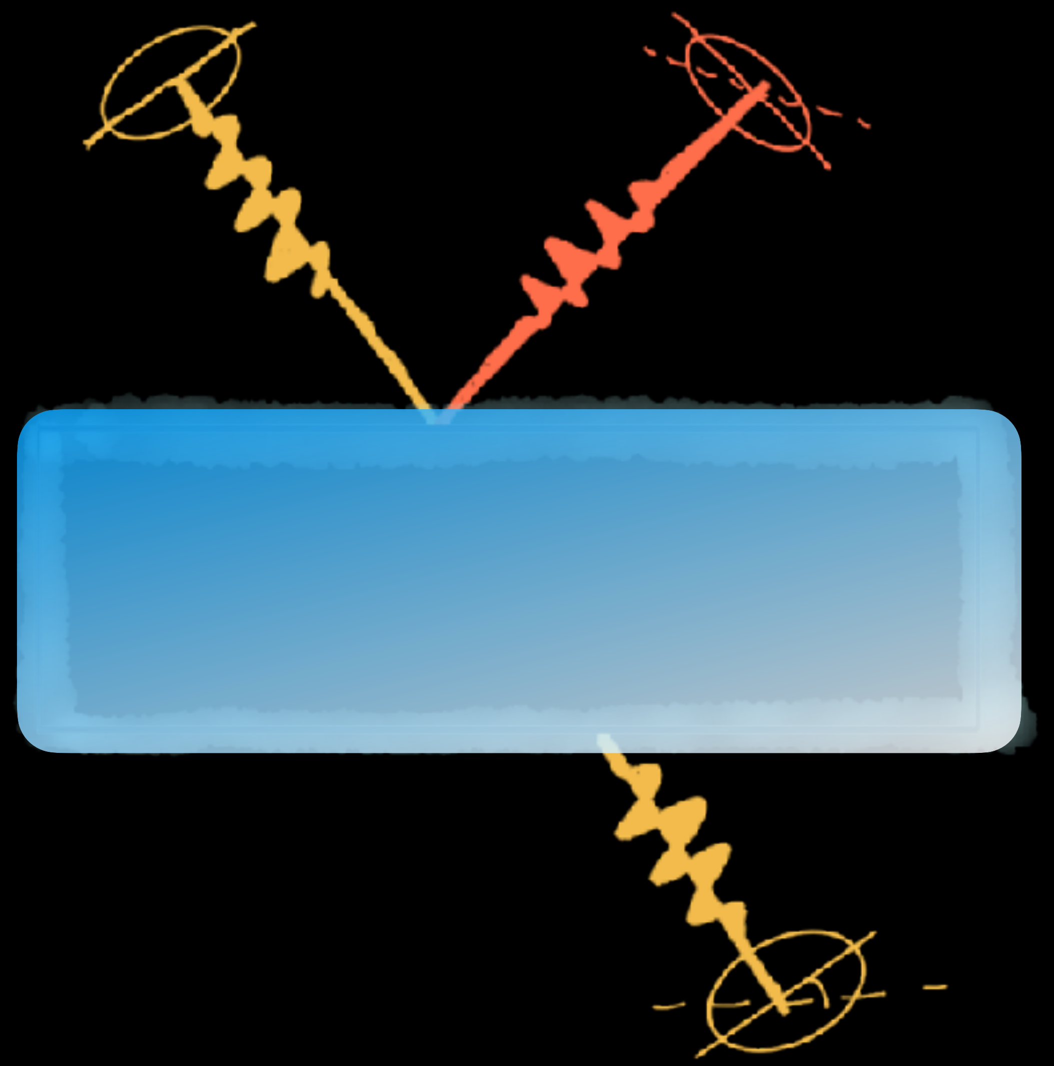


How do we find topological insulators?

wave function in momentum space → Topological invariants → Quantized responses



$\mathbb{Z}$



e.g. quantised quantum Hall
quantised Kerr rotation

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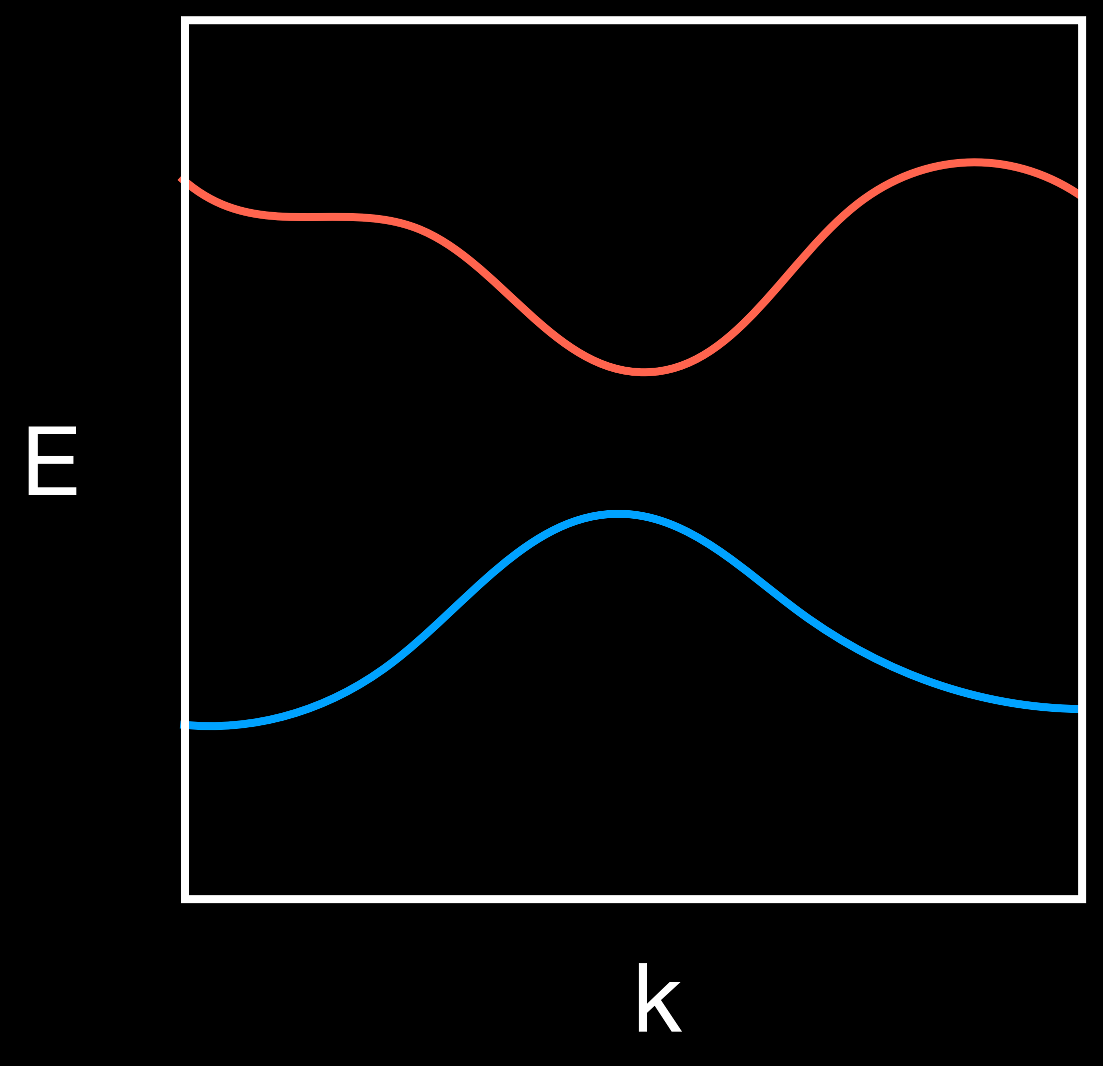

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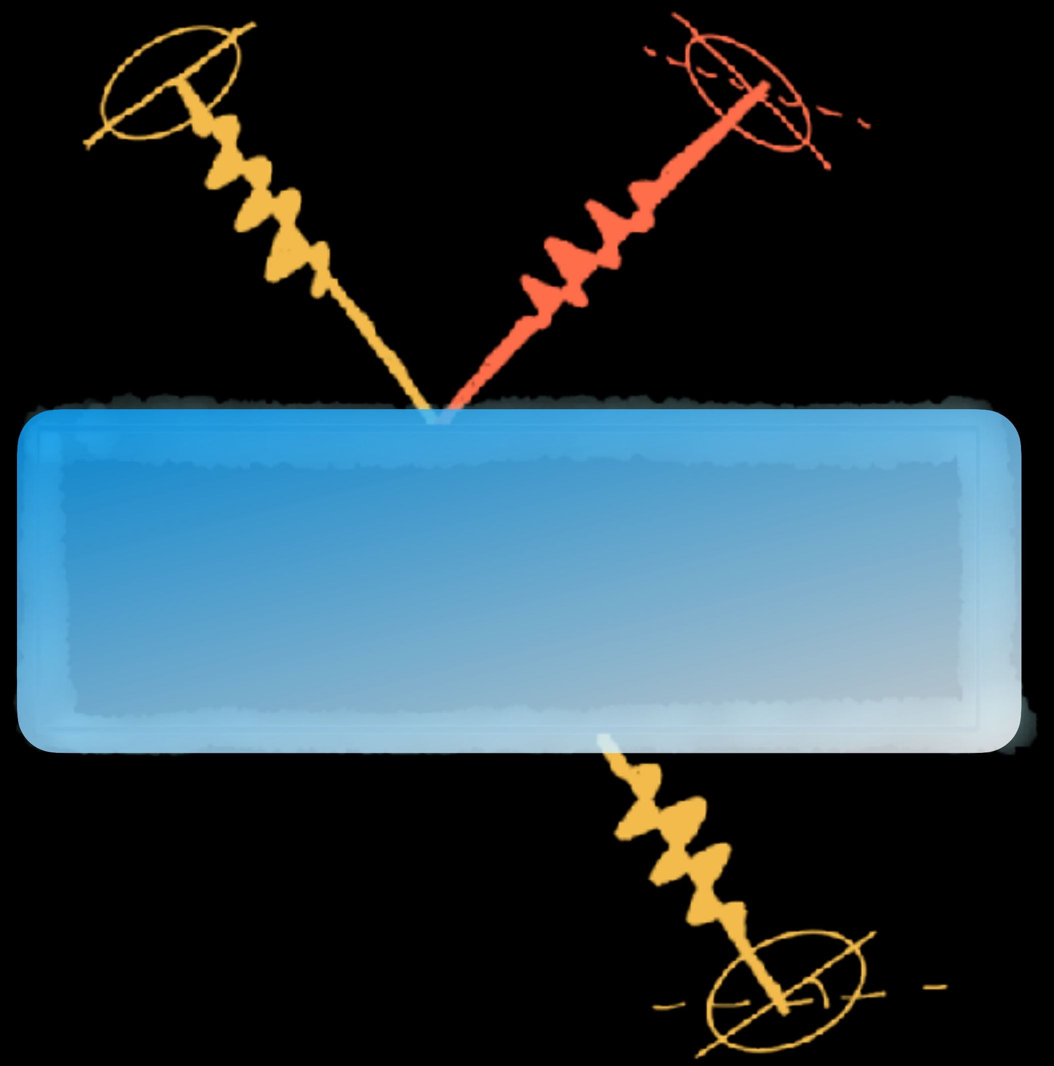

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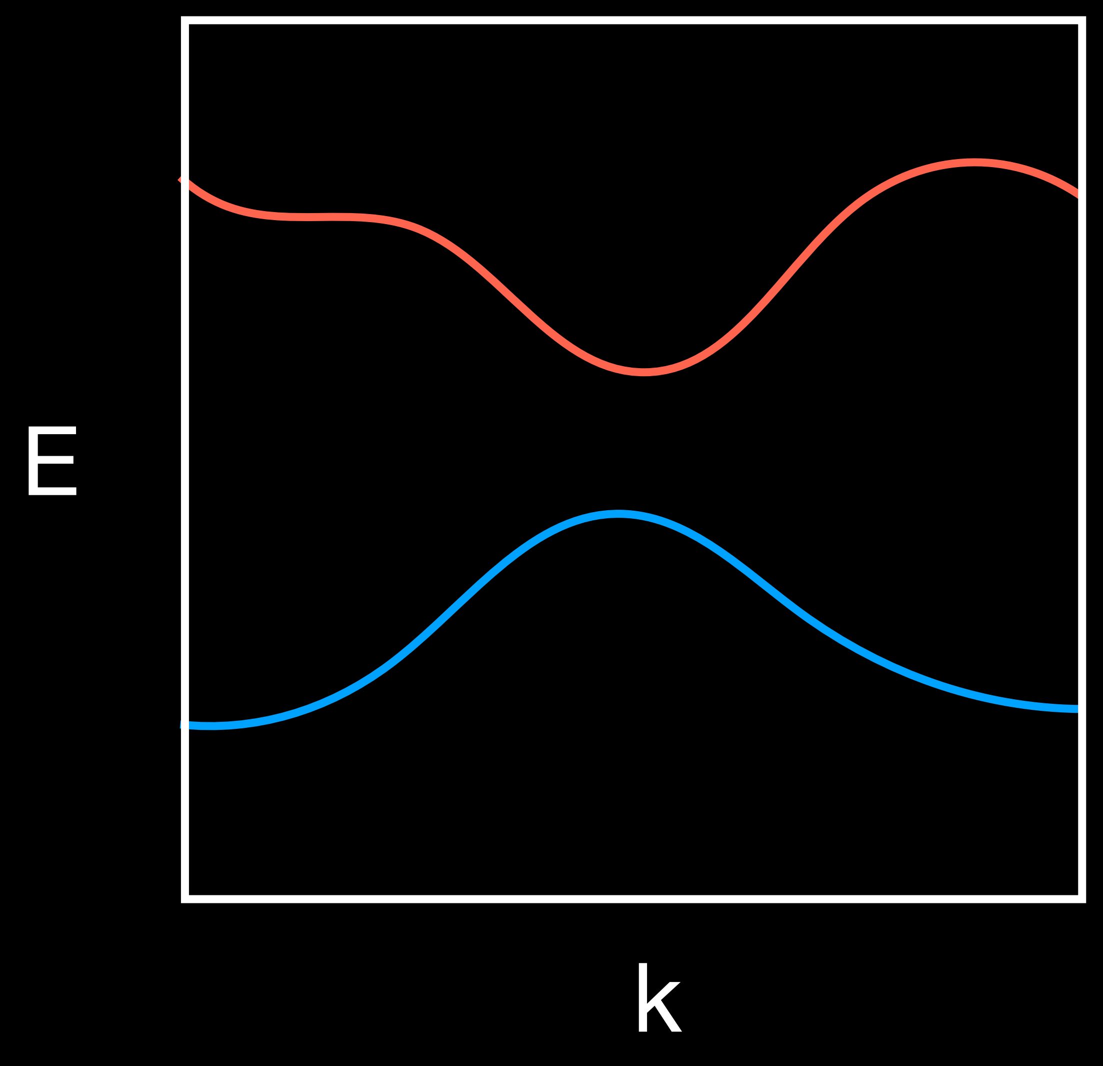
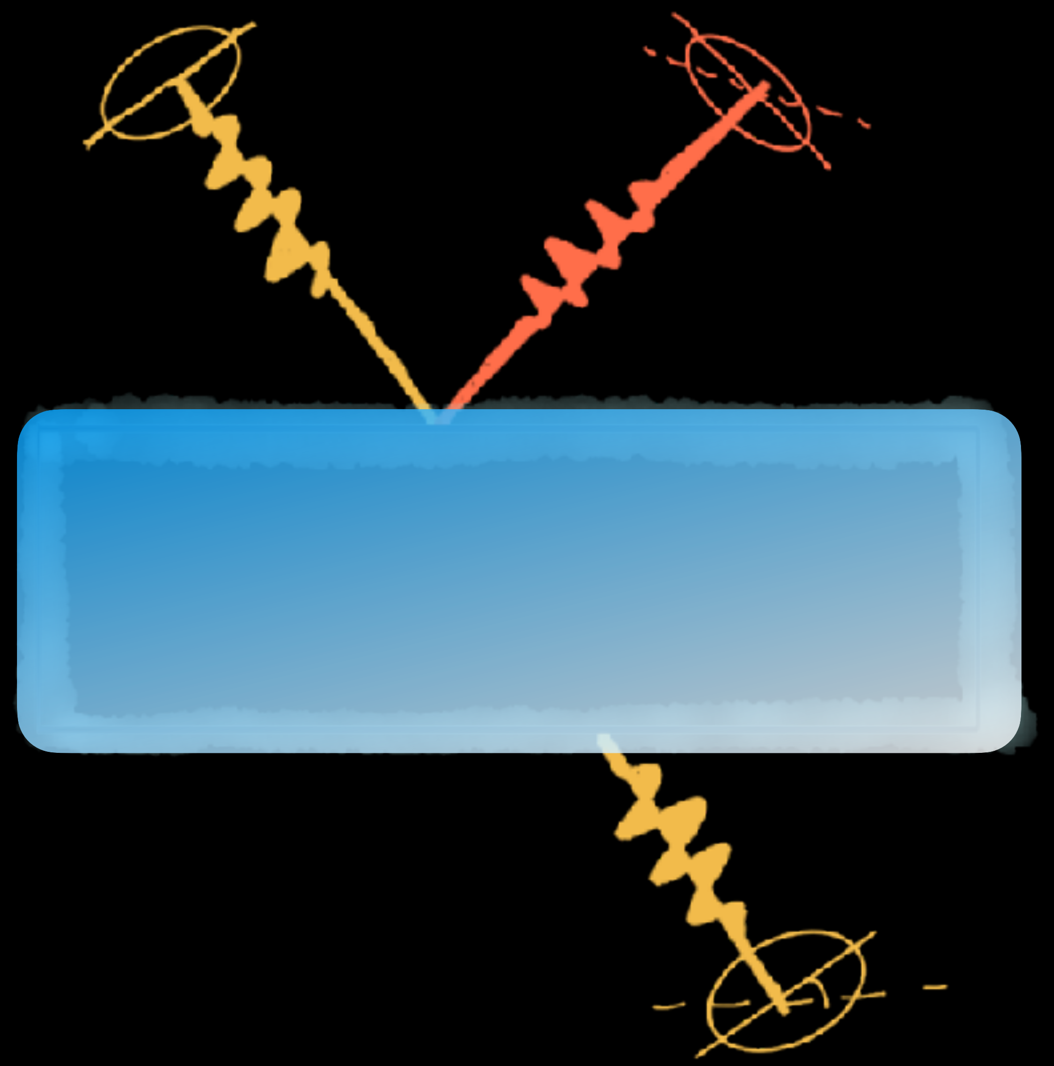


$$\mathbb{Z}$$

impractical / numerically costly



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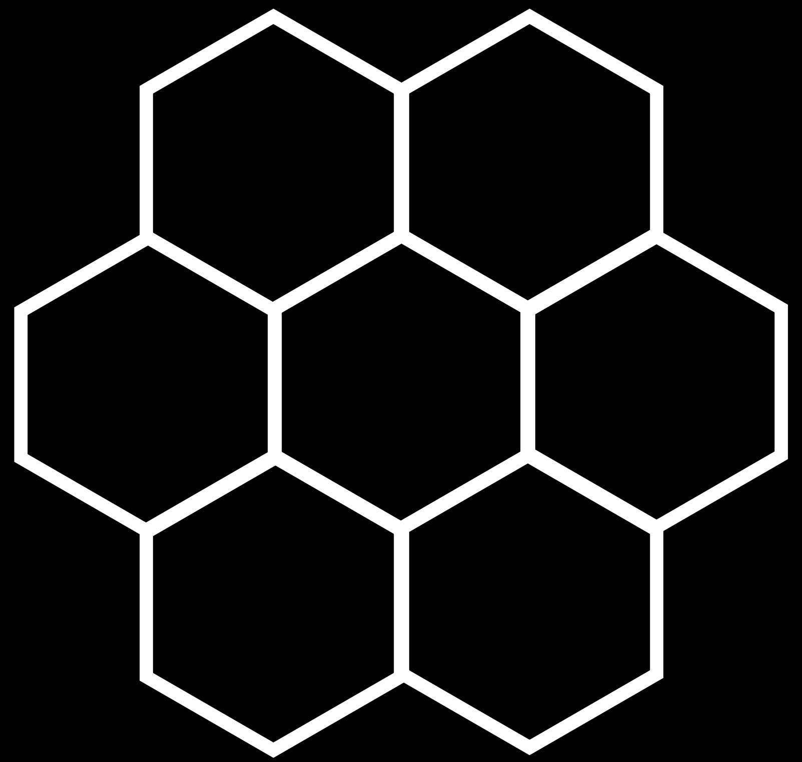
Bradlyn et al Nature (2017) Kruthoff et al. Phys. Rev. X (2017) Po et al. Nat. Comm (2017) Song et al. Nat. Comm (2018)

How do we find topological insulators?

Space Group



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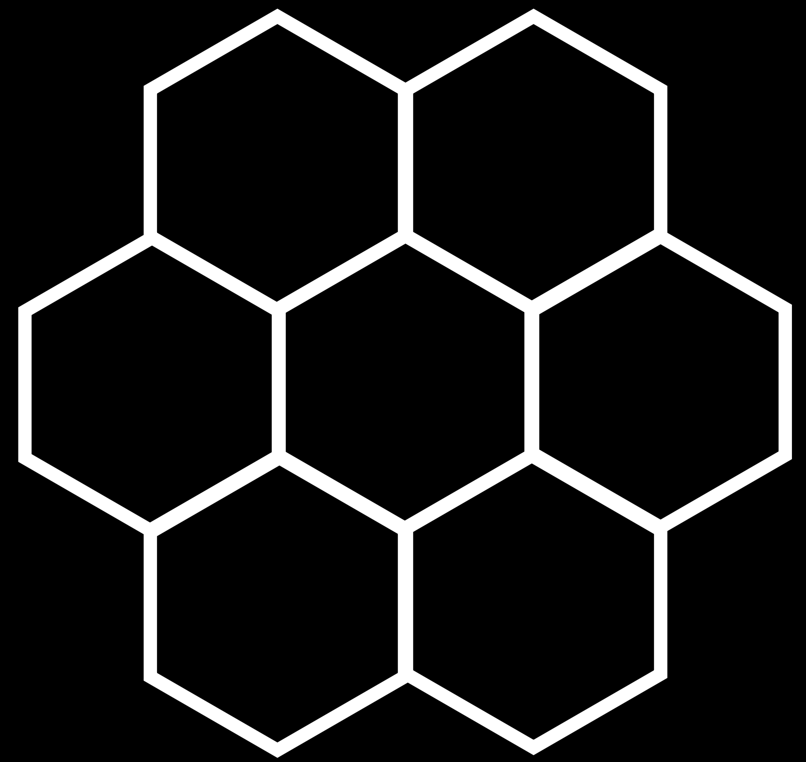

— lattice symmetries

translations, rotations, inversions, mirrors

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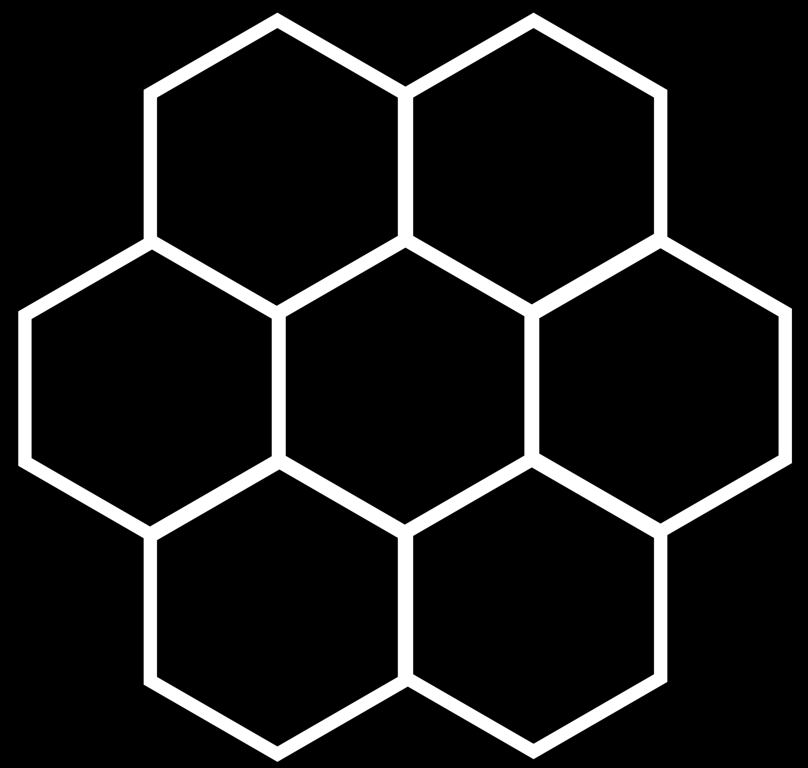

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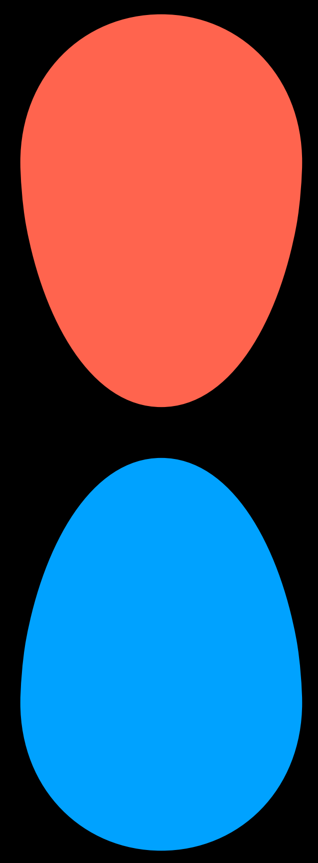

— wavefunctions

s, p, d…

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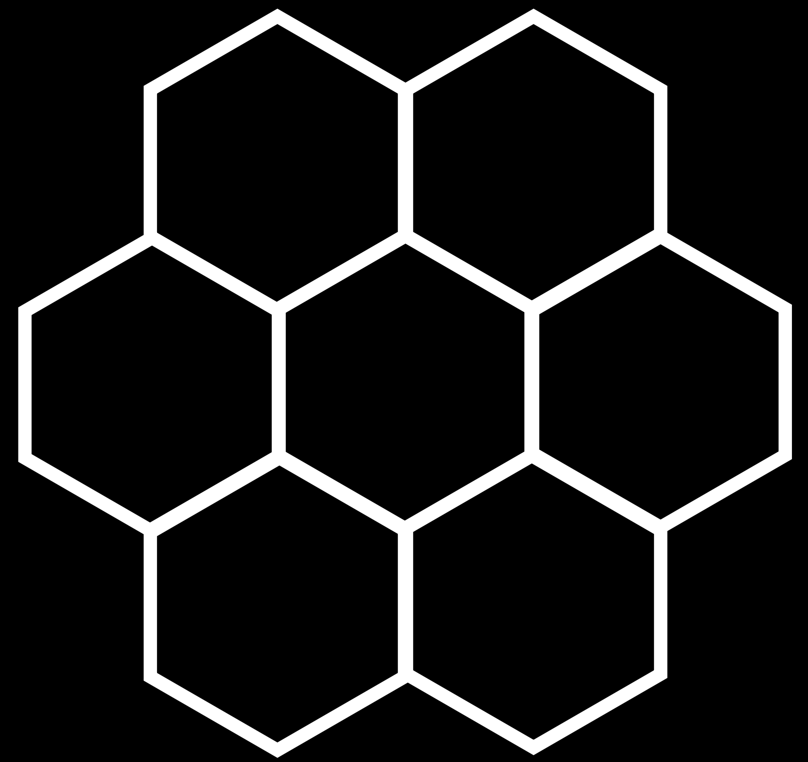

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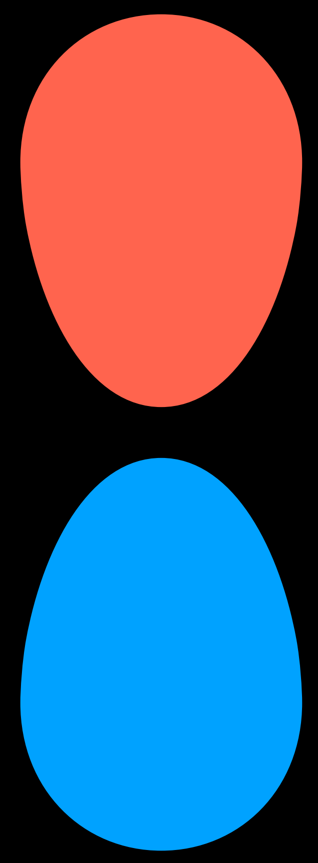

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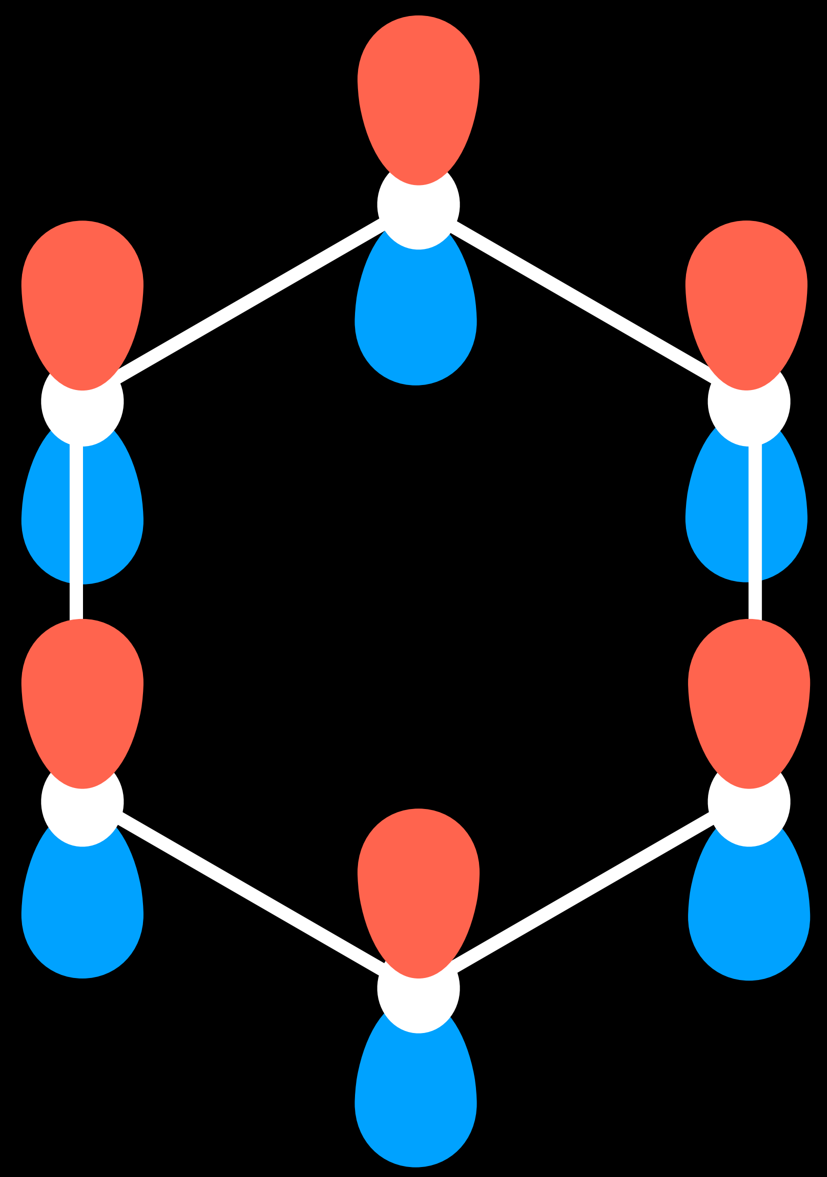
s, p, d…

Atomic positions



— band connectivity + symmetries labels

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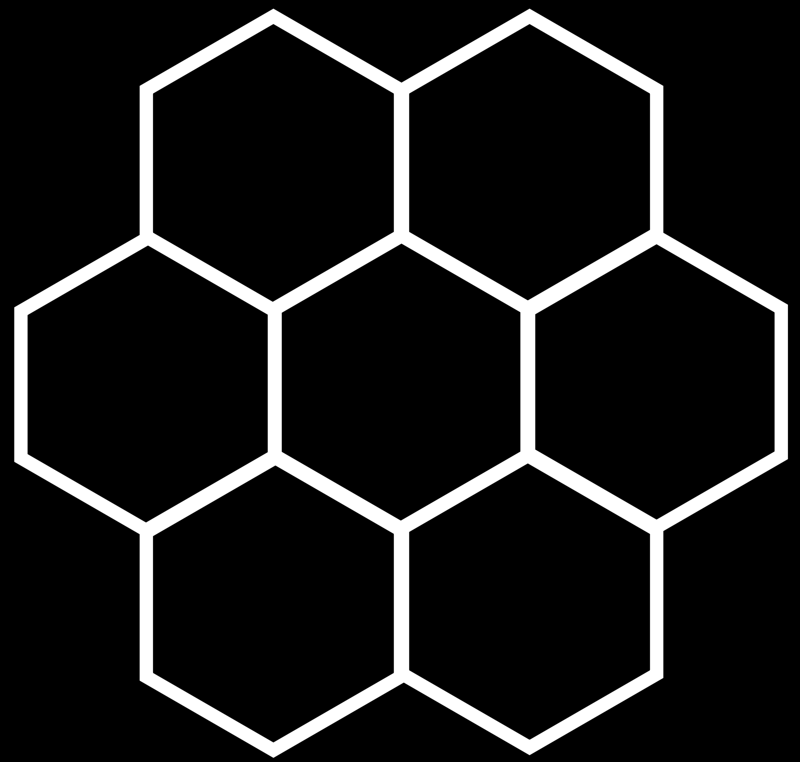

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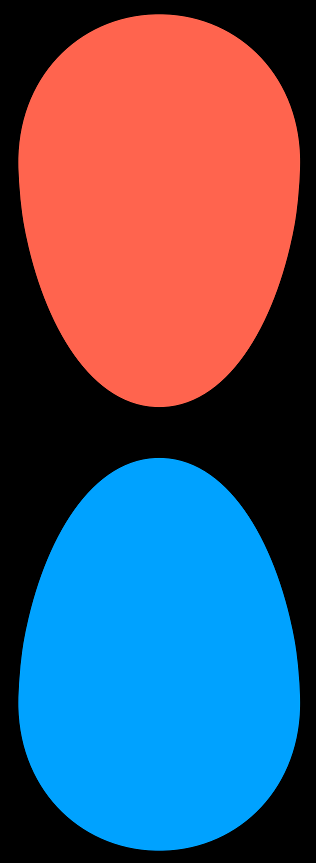

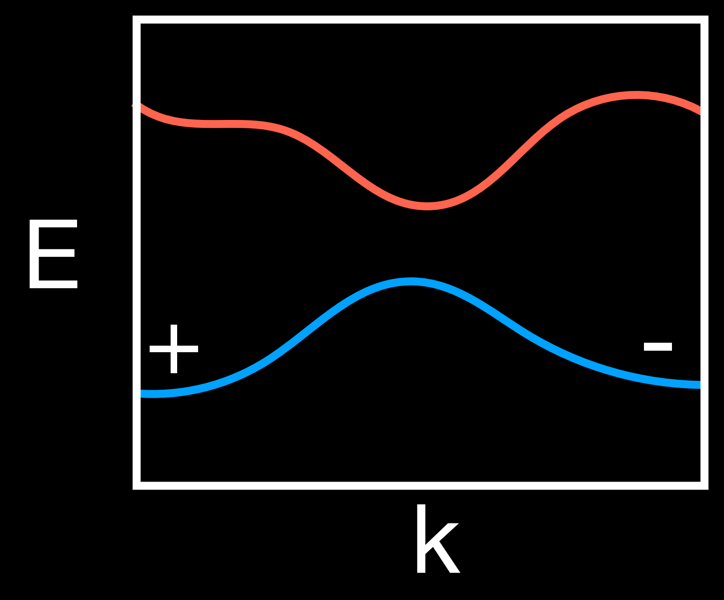

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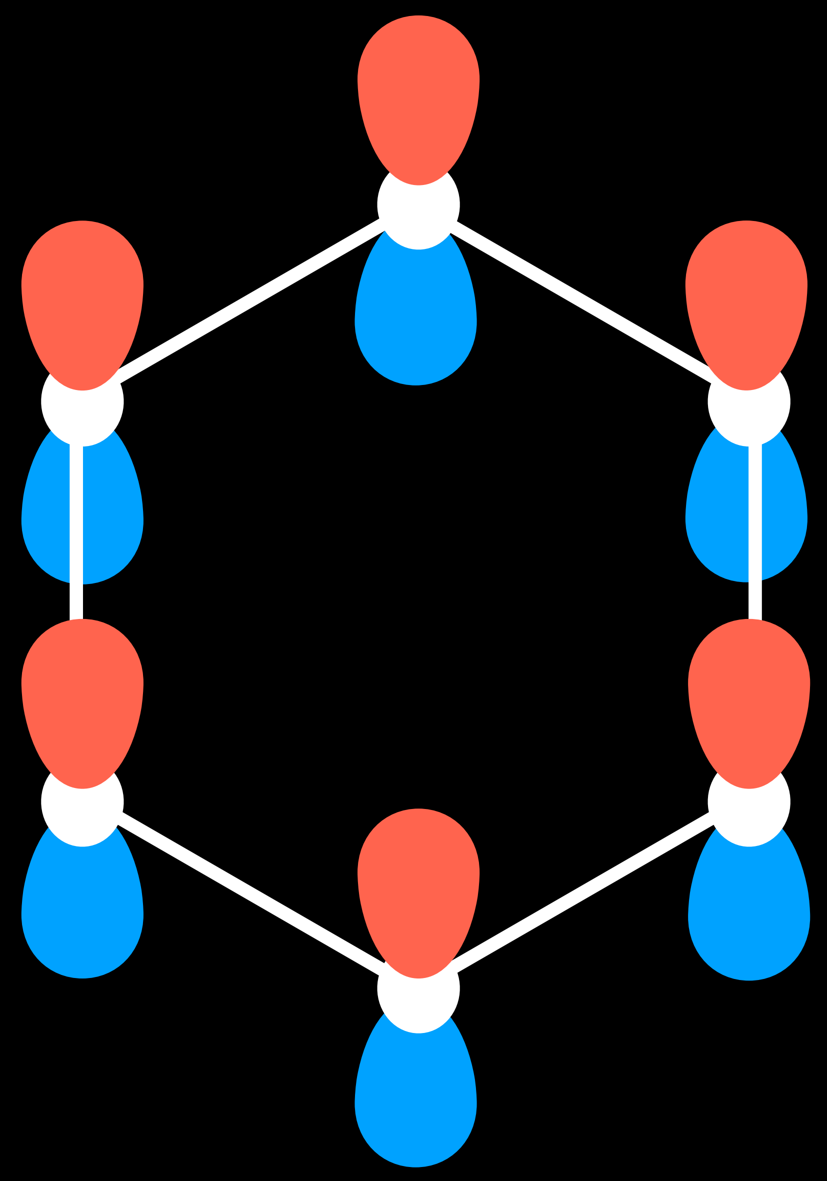

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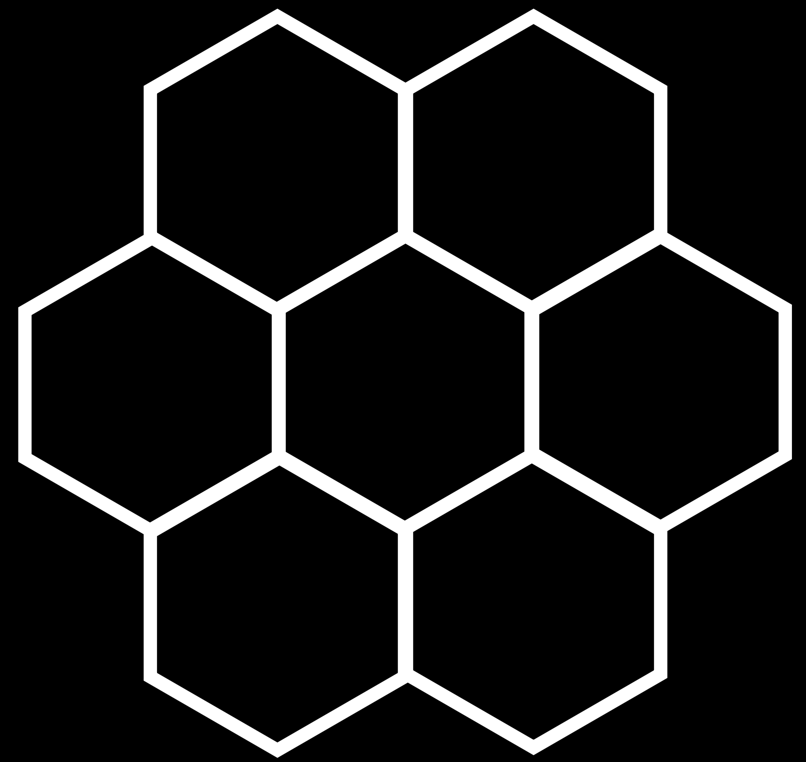

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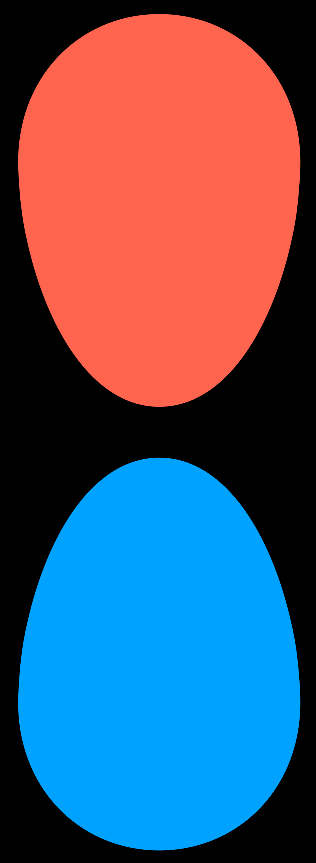

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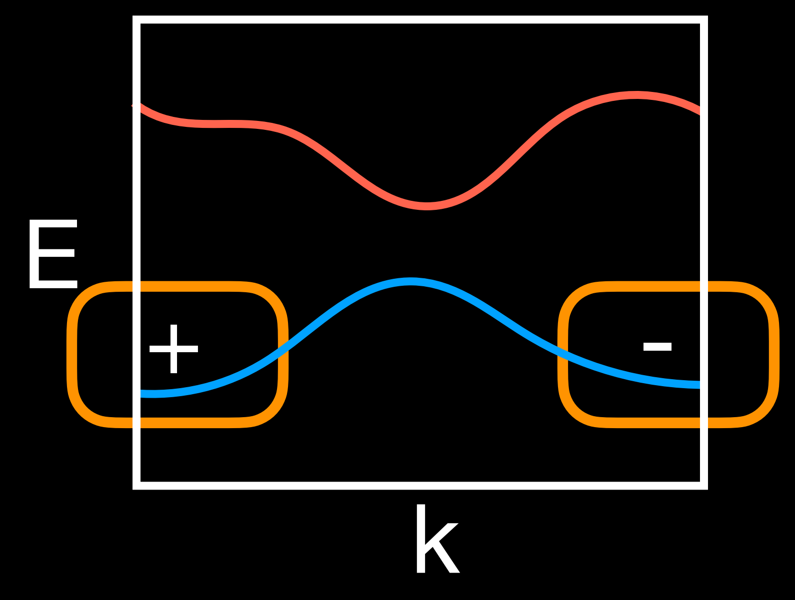

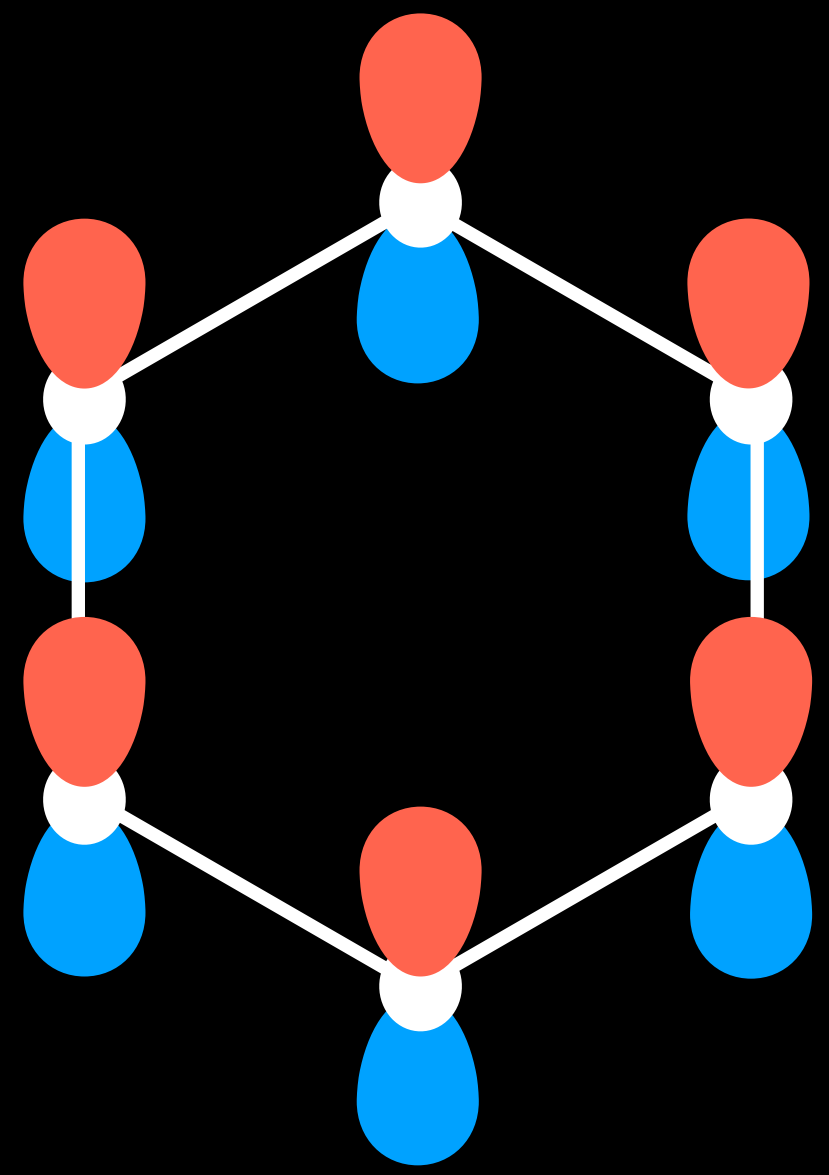

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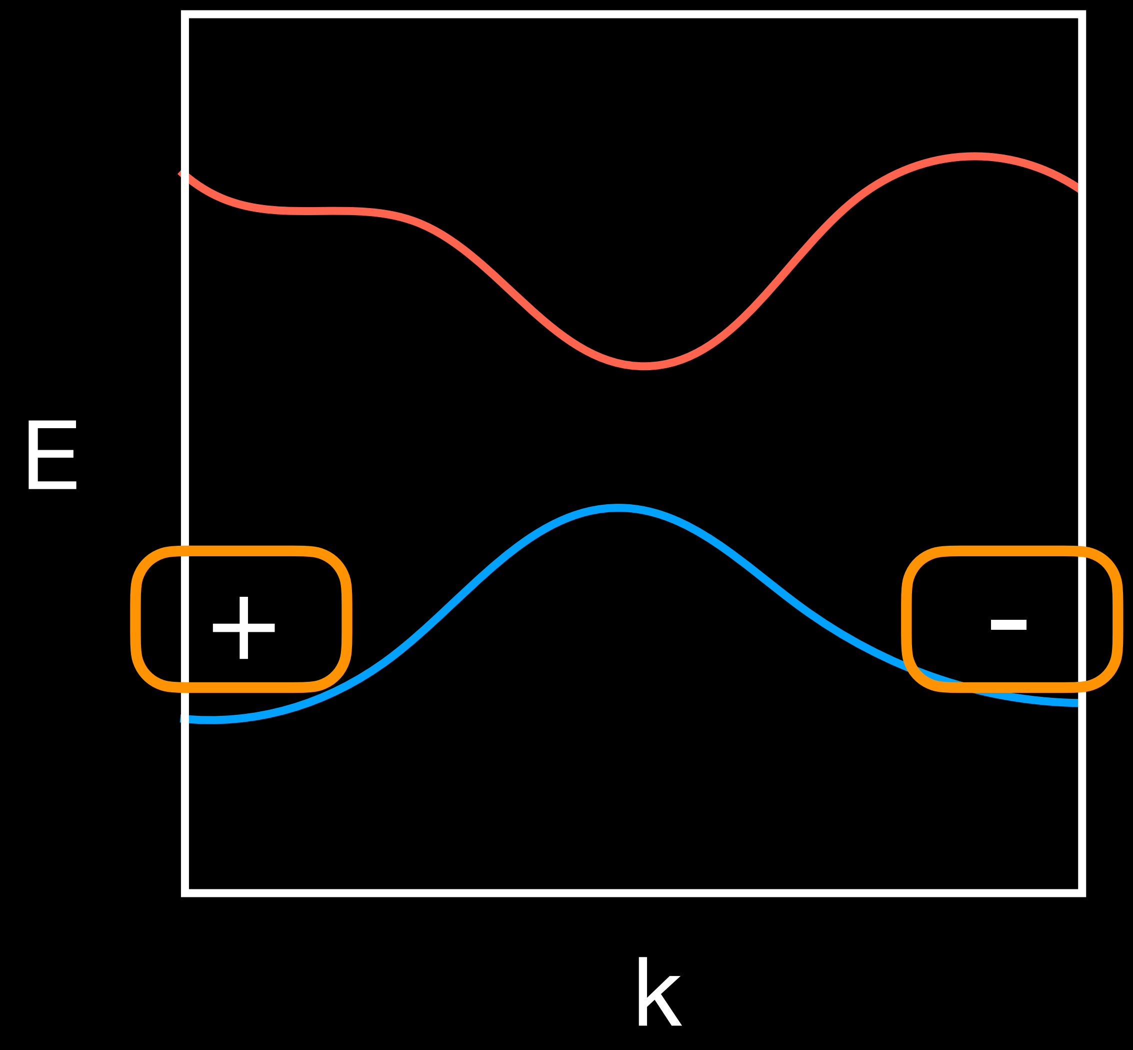
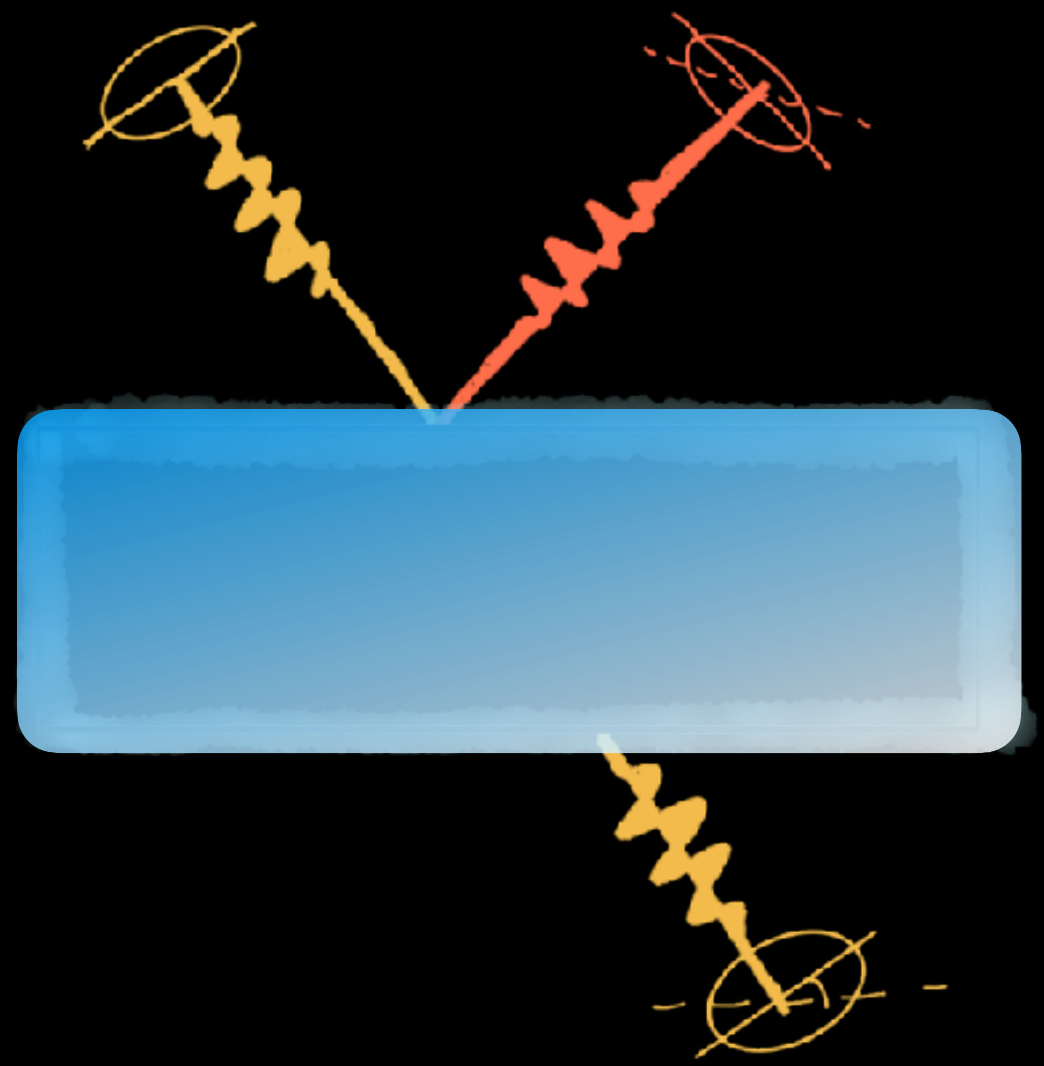


Topological invariants

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

symmetry eigenvalues

Quantized responses



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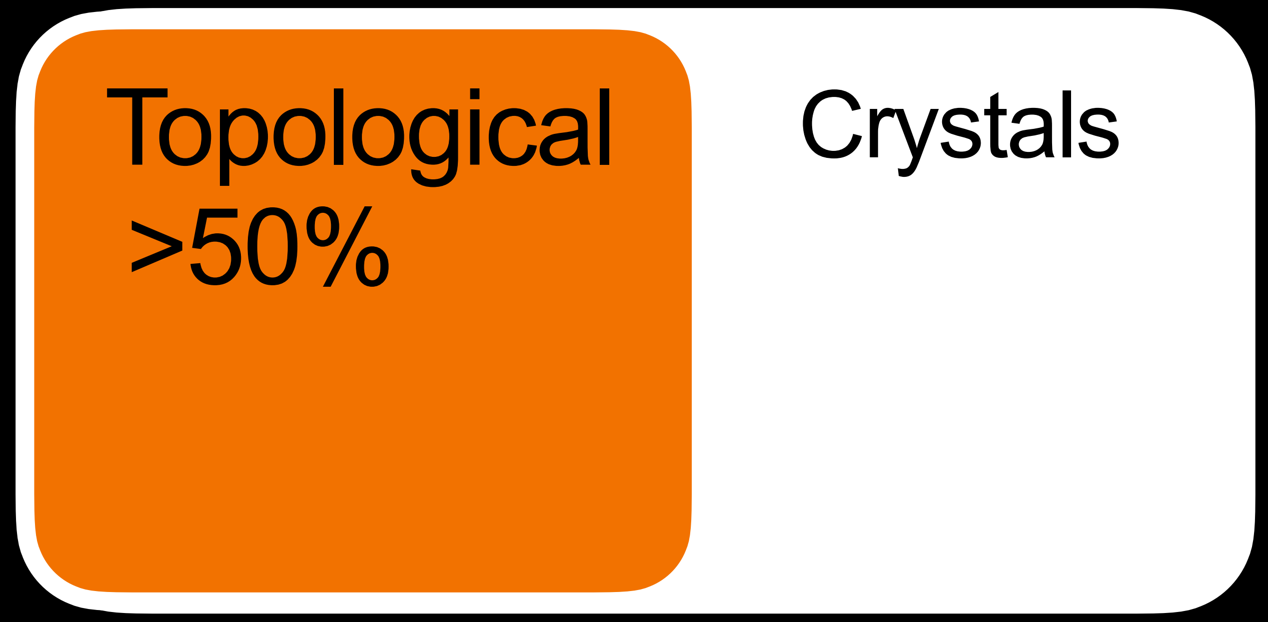
Topological solids



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Amorphous topological solids?

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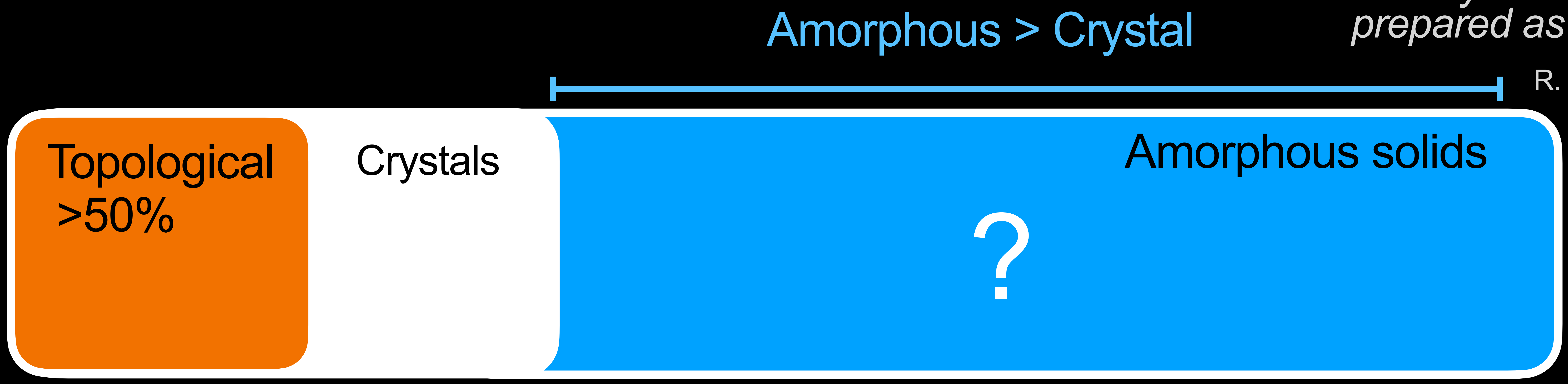
"Nearly all materials can […] be prepared as amorphous solids"

R. Zallen, *Amorphous Solids*



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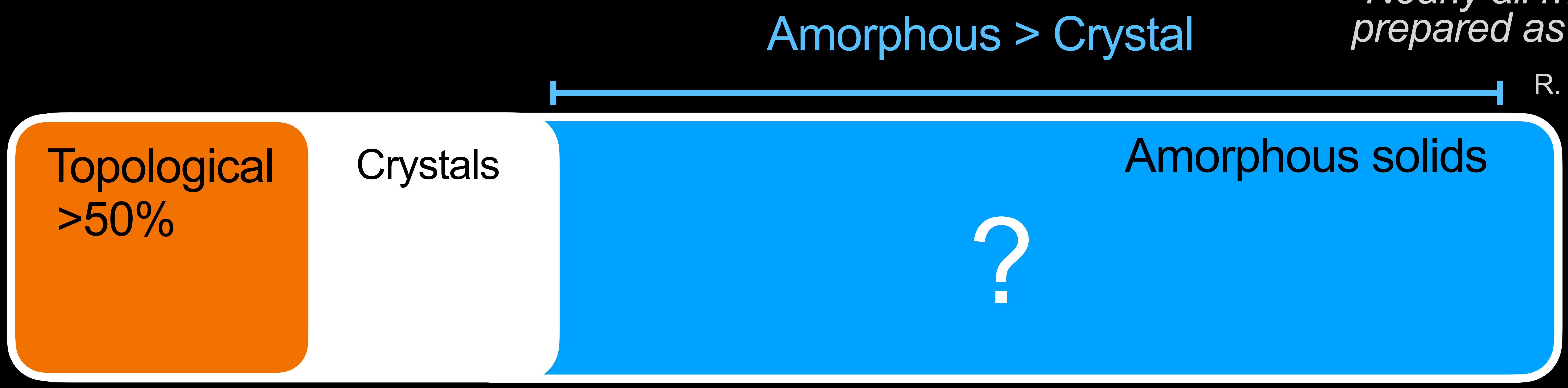
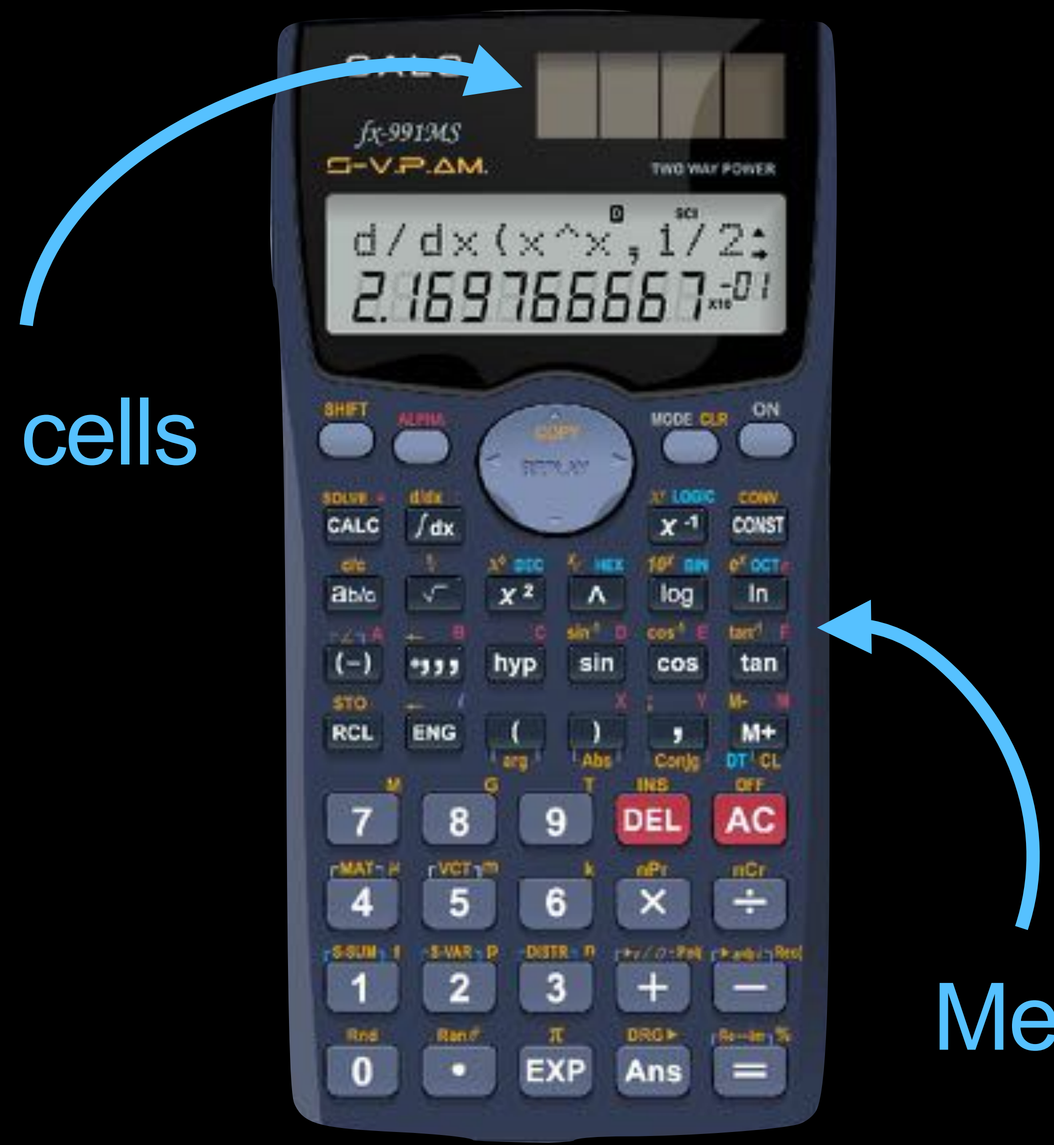


Cheap and scalable



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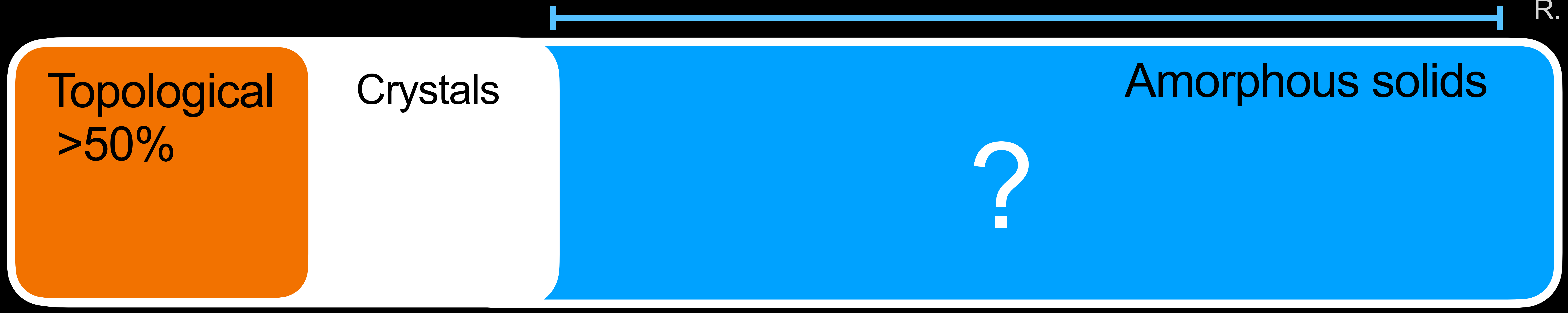
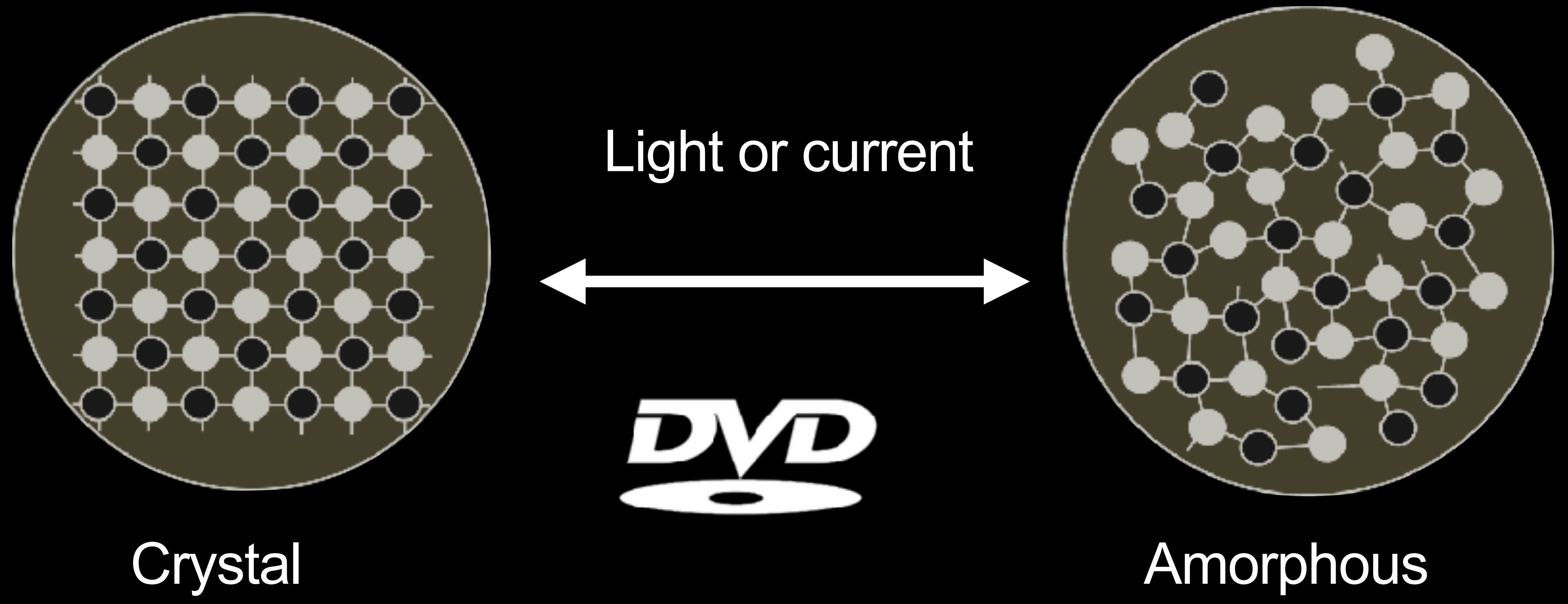


Switchable



Mathias, Naboro Nat Mat (2007)

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

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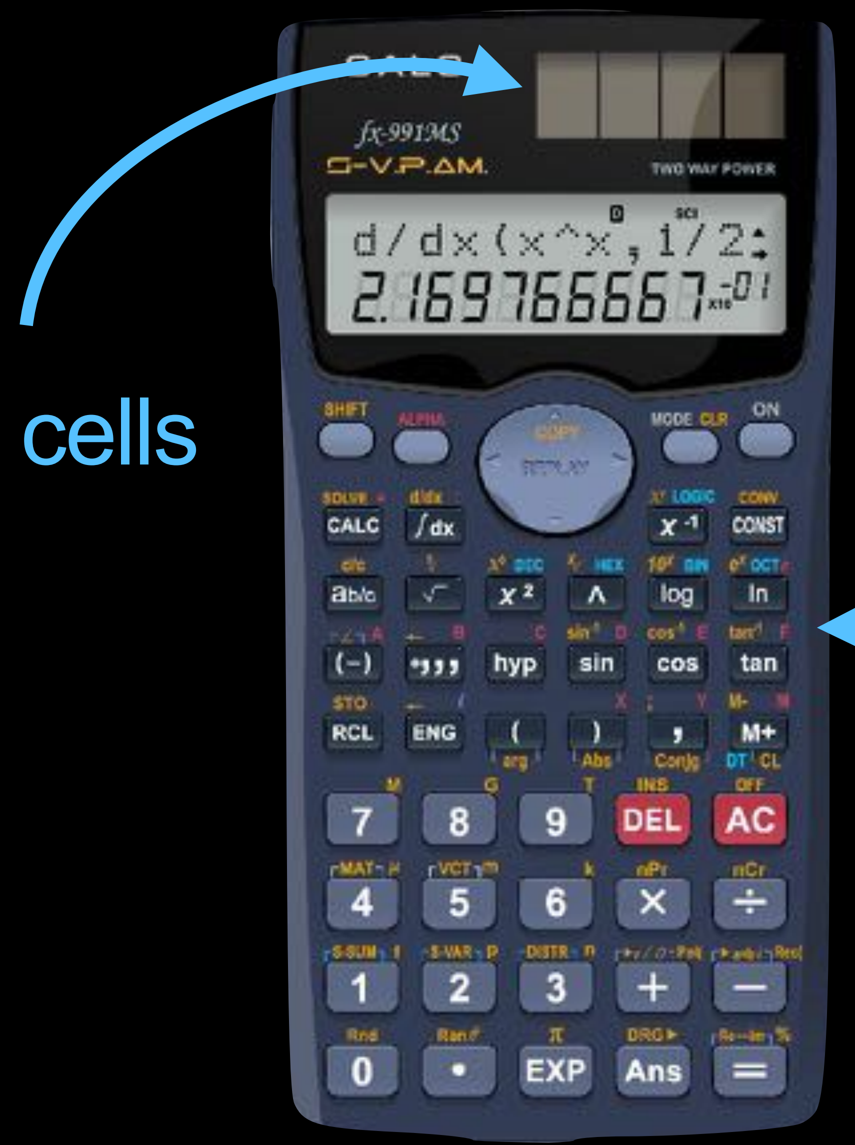

Topological amorphous phases

Do they exist?

How do we find them in real solids?

Any different physics compared to crystals?

Topological amorphous phases

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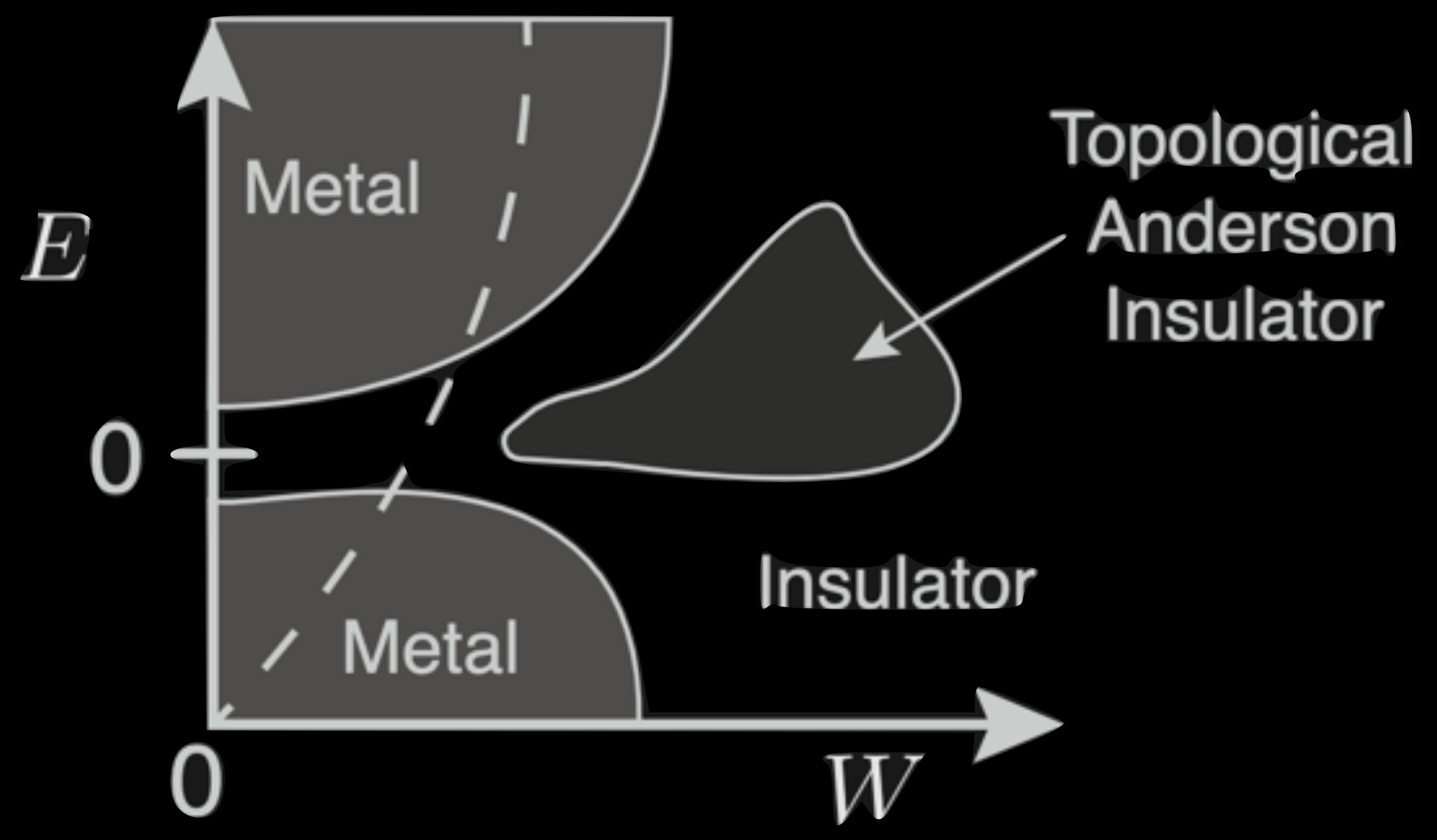
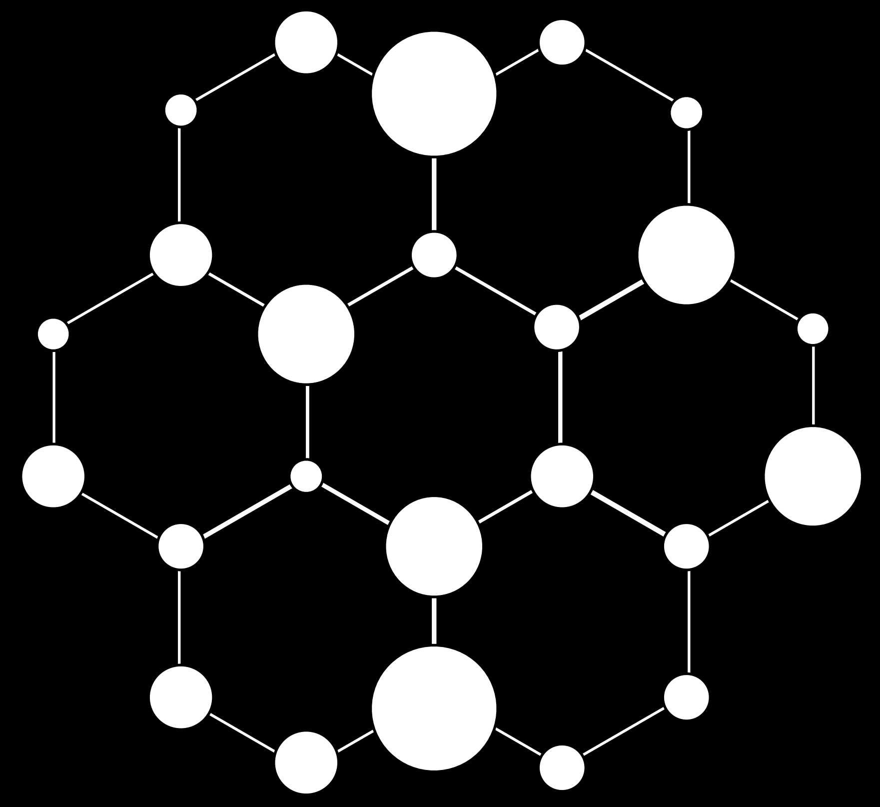
Topological induced by disorder



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

Onsite disorder

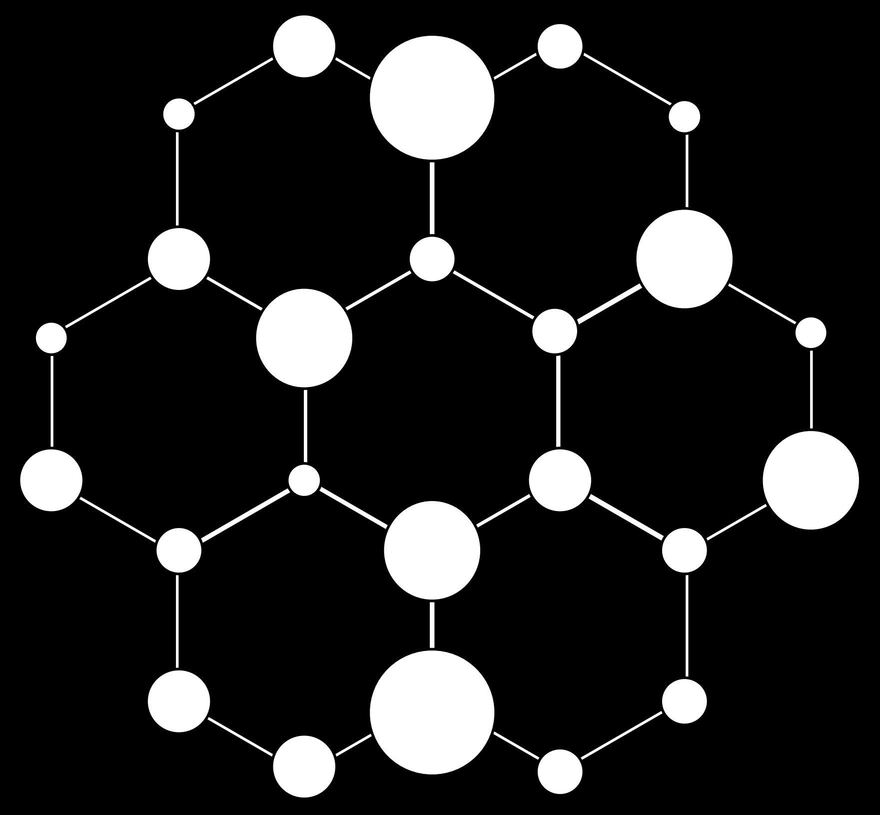


Topology survives disorder

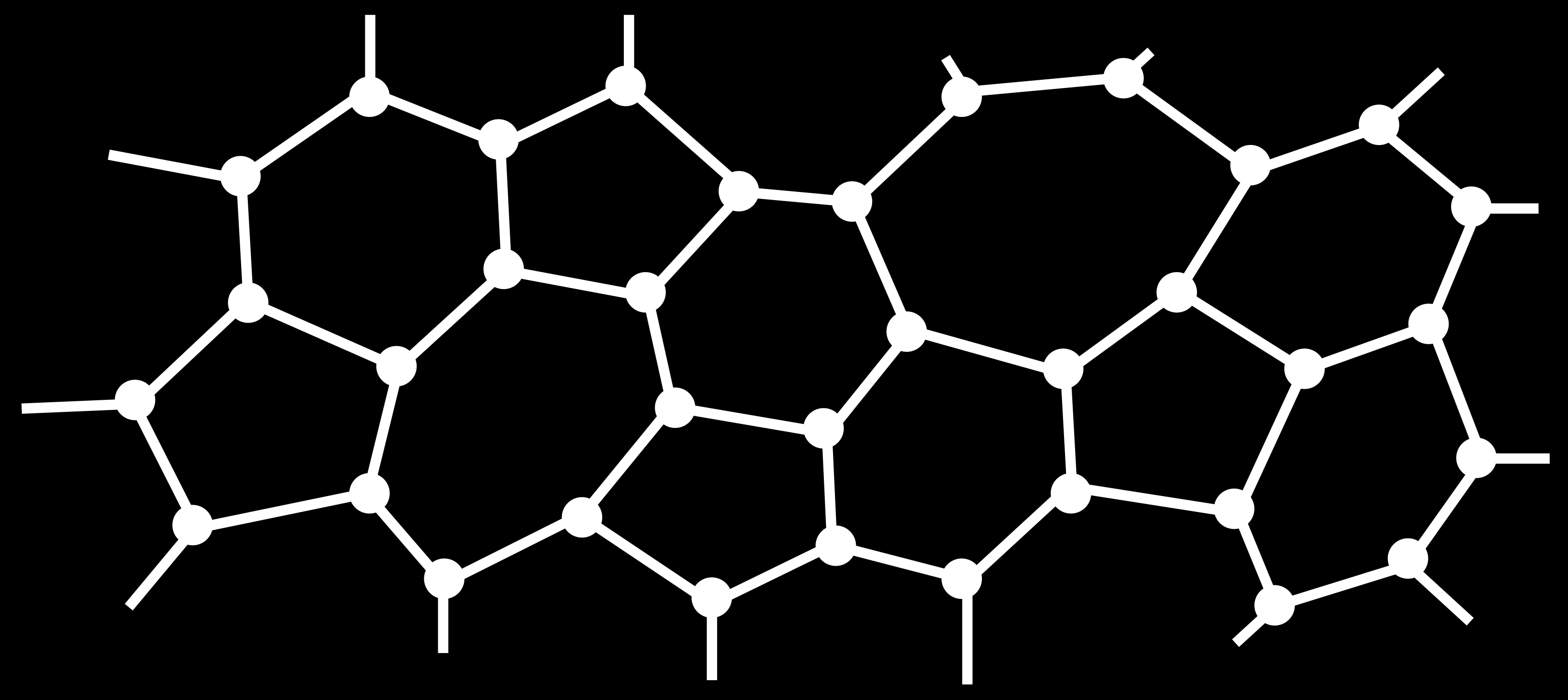
Some choices

Bond disorder

Onsite disorder



Structural disorder



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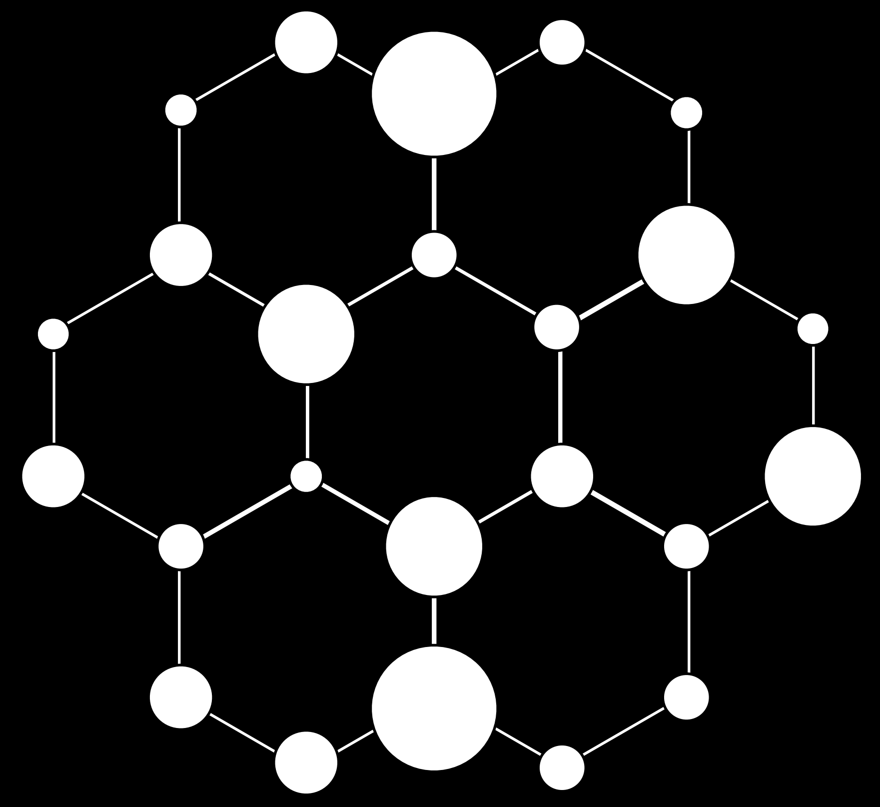

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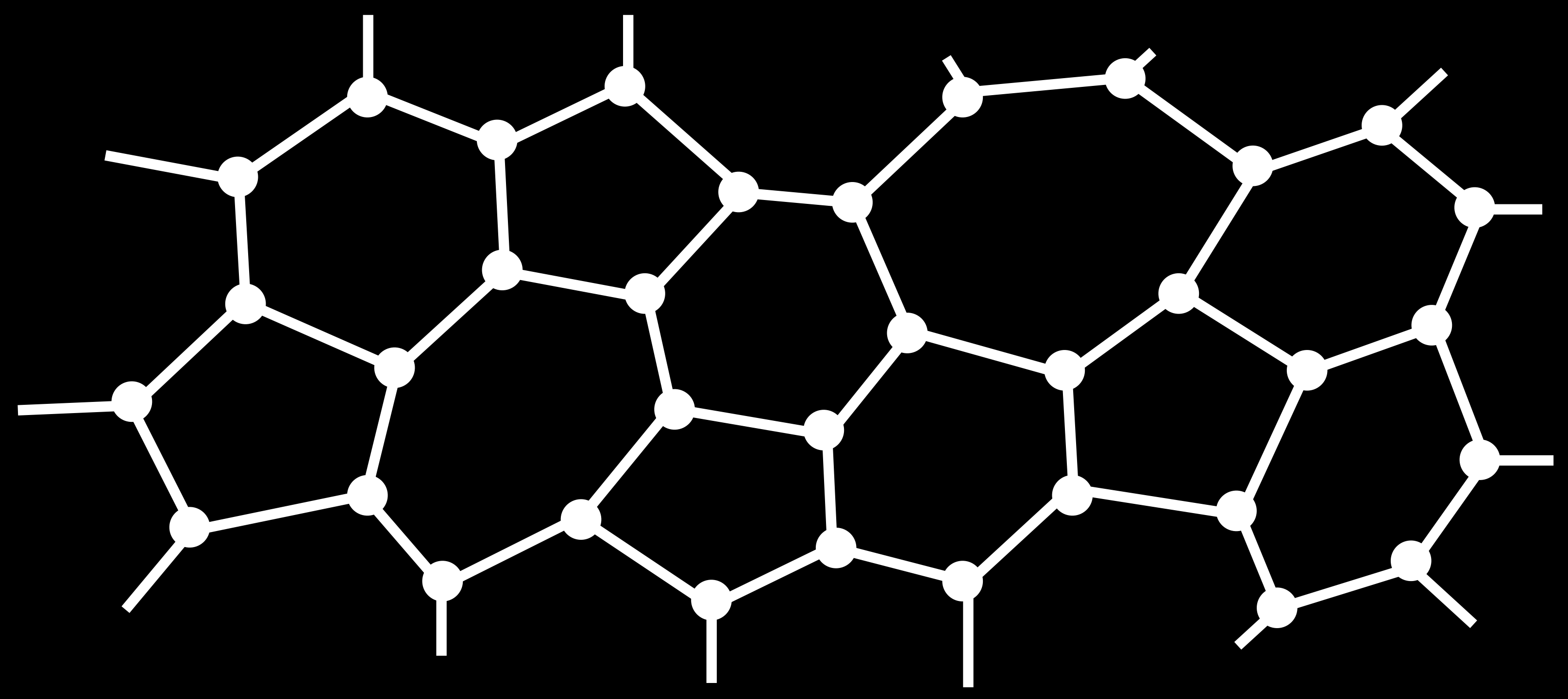

Typical Anderson problem: crystal + disorder

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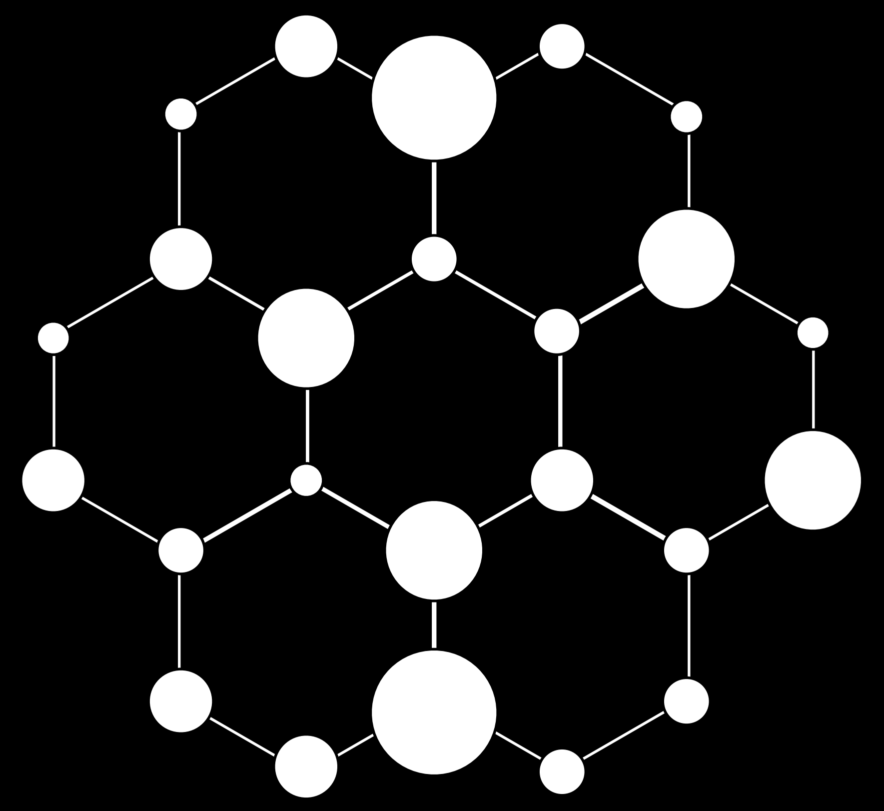

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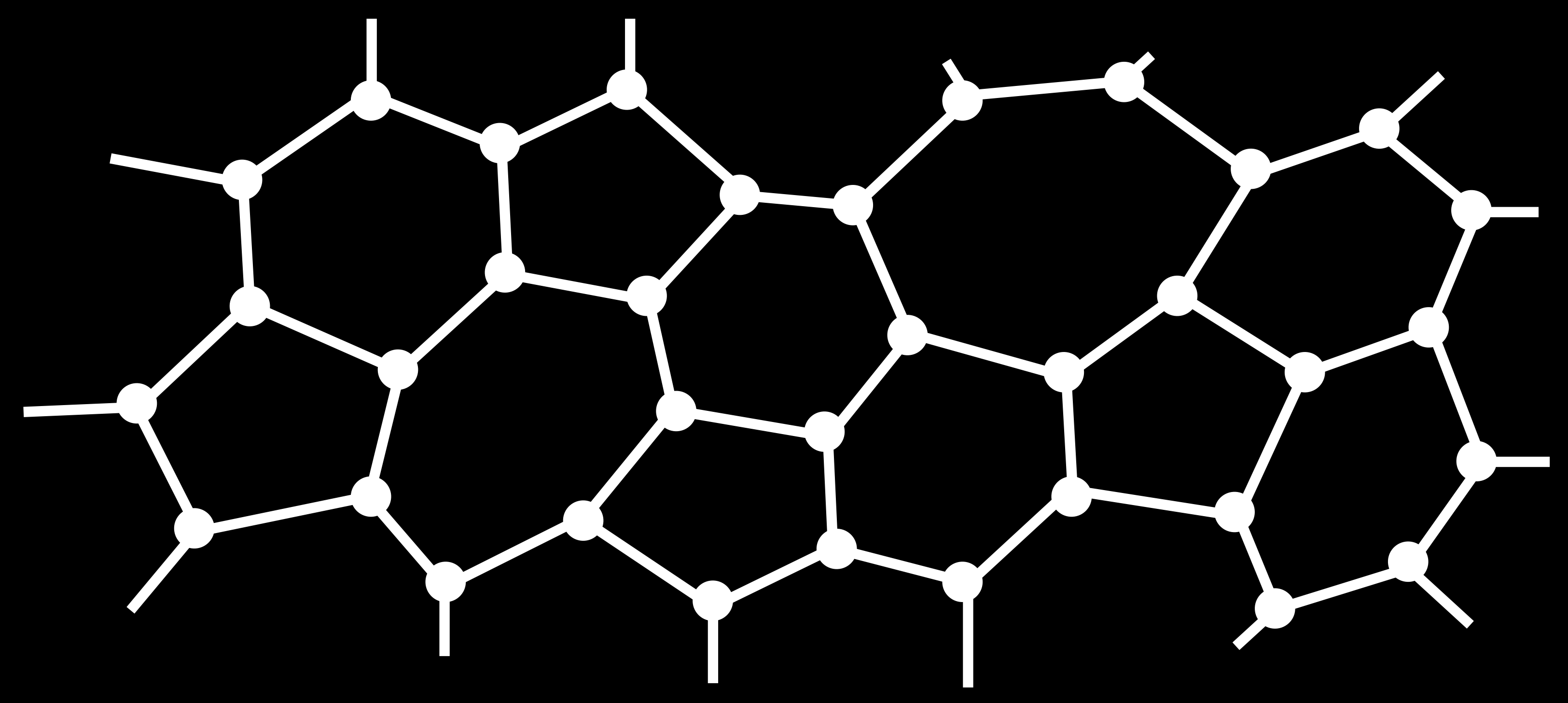
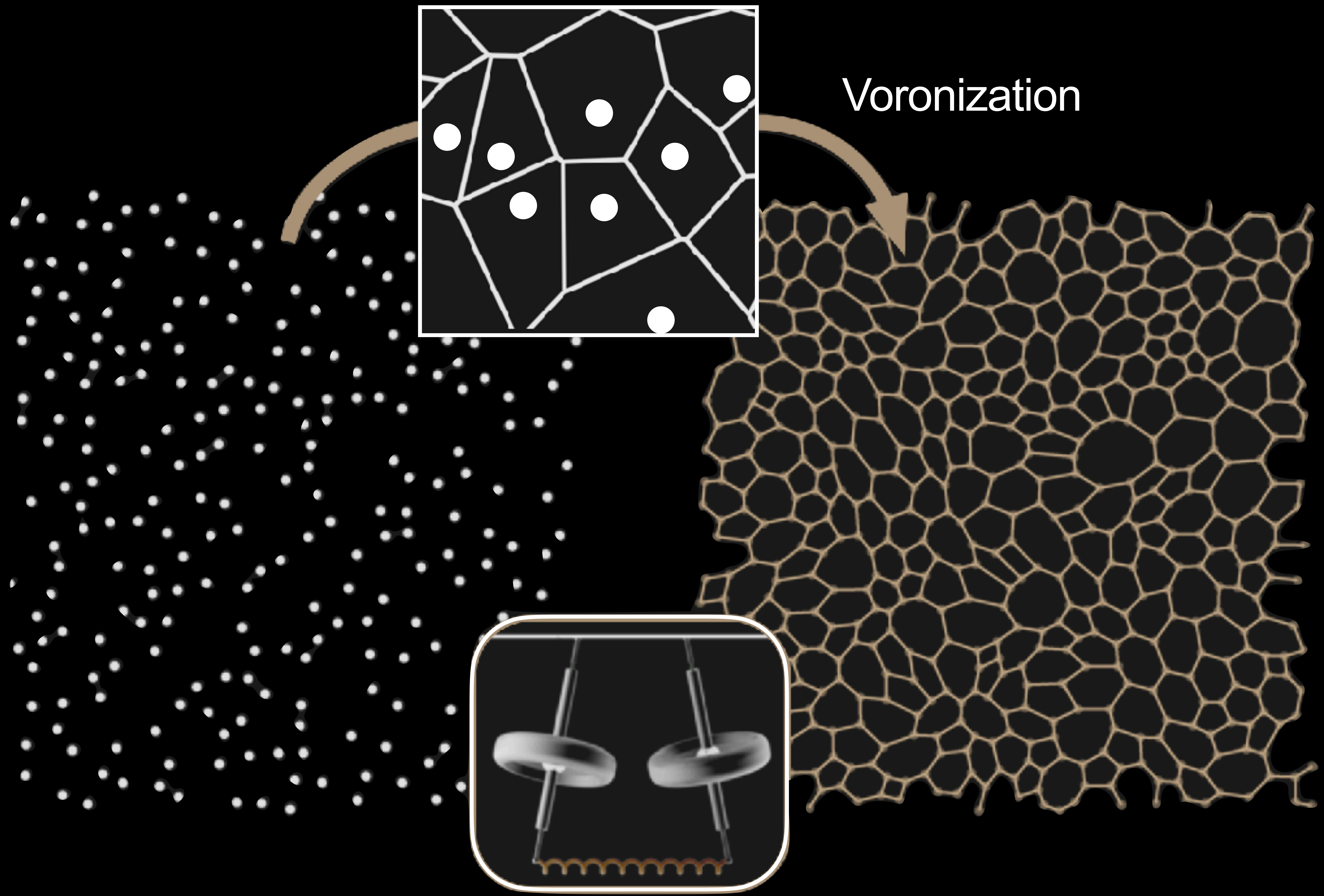


Is this any different?

Amorphous topological phases exist

Synthetic systems:



Theory:

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

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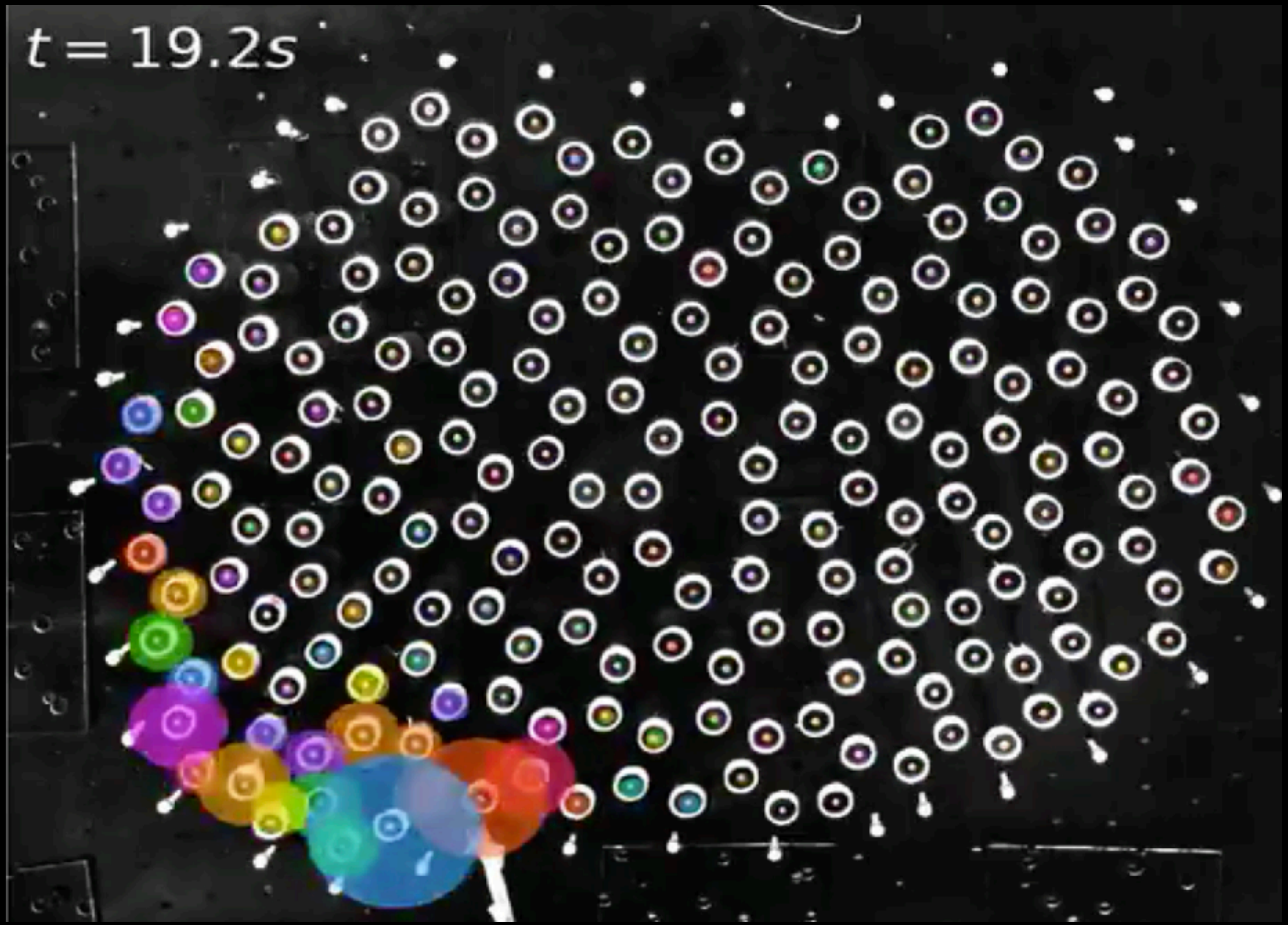

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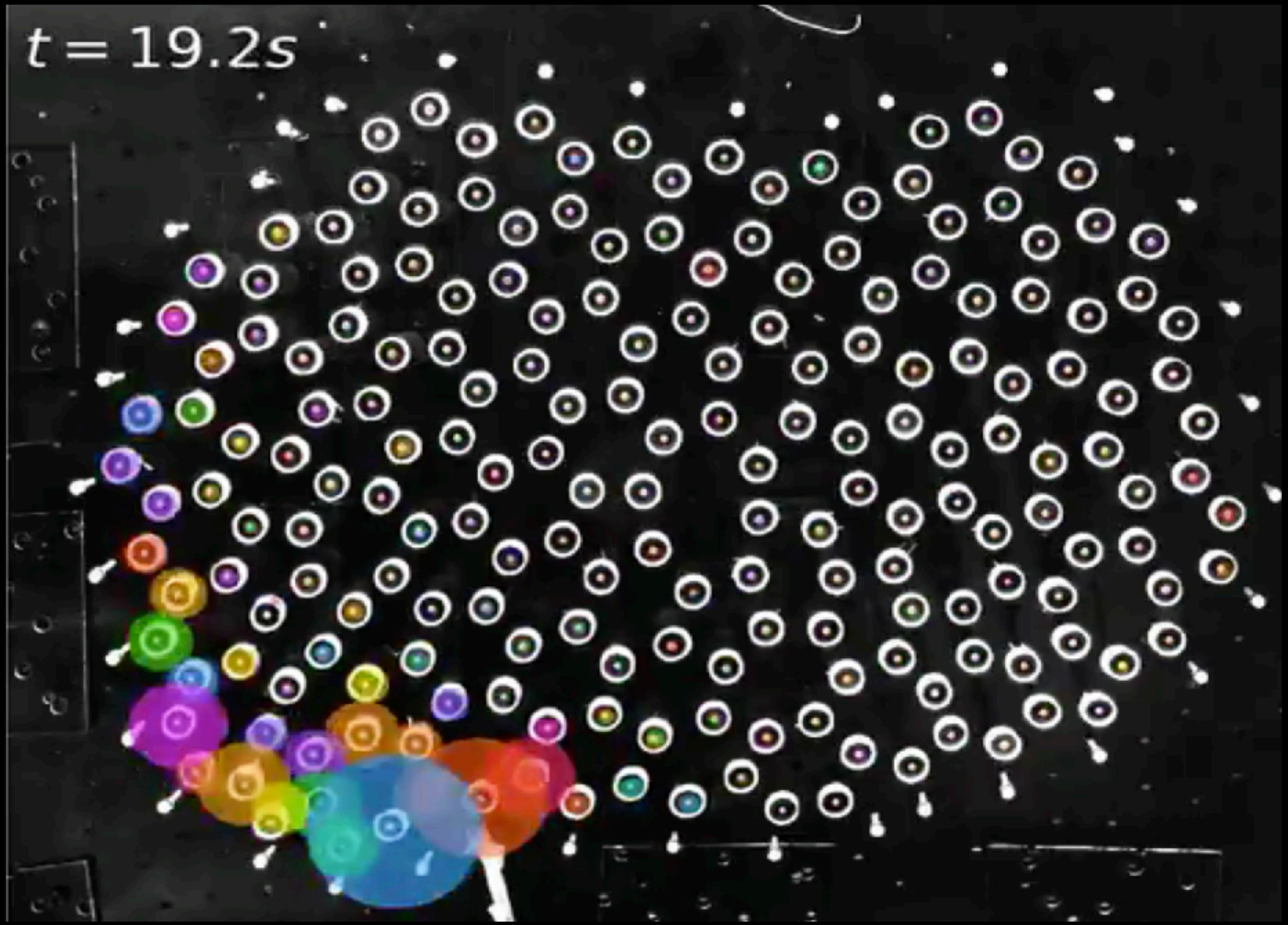

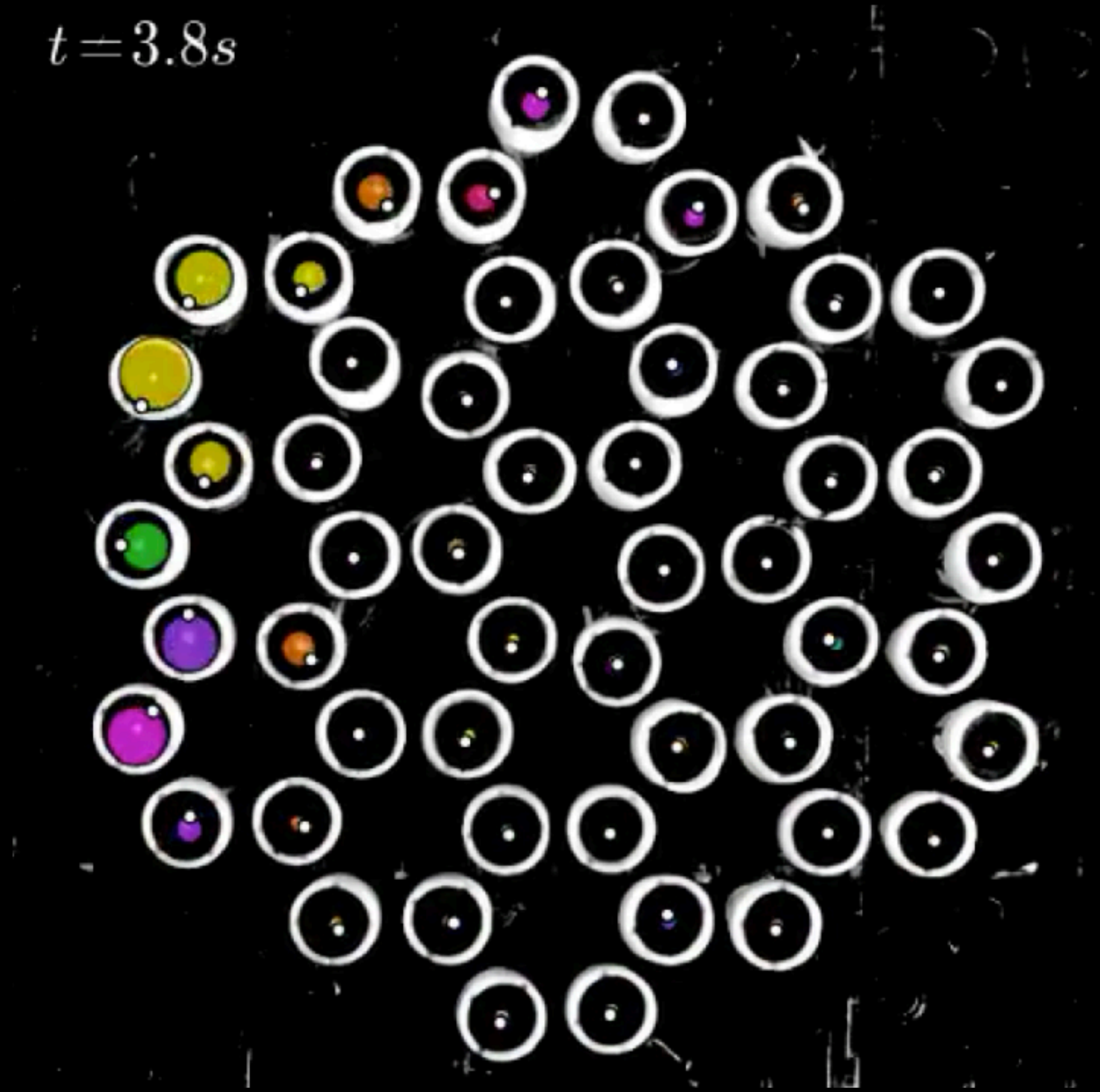

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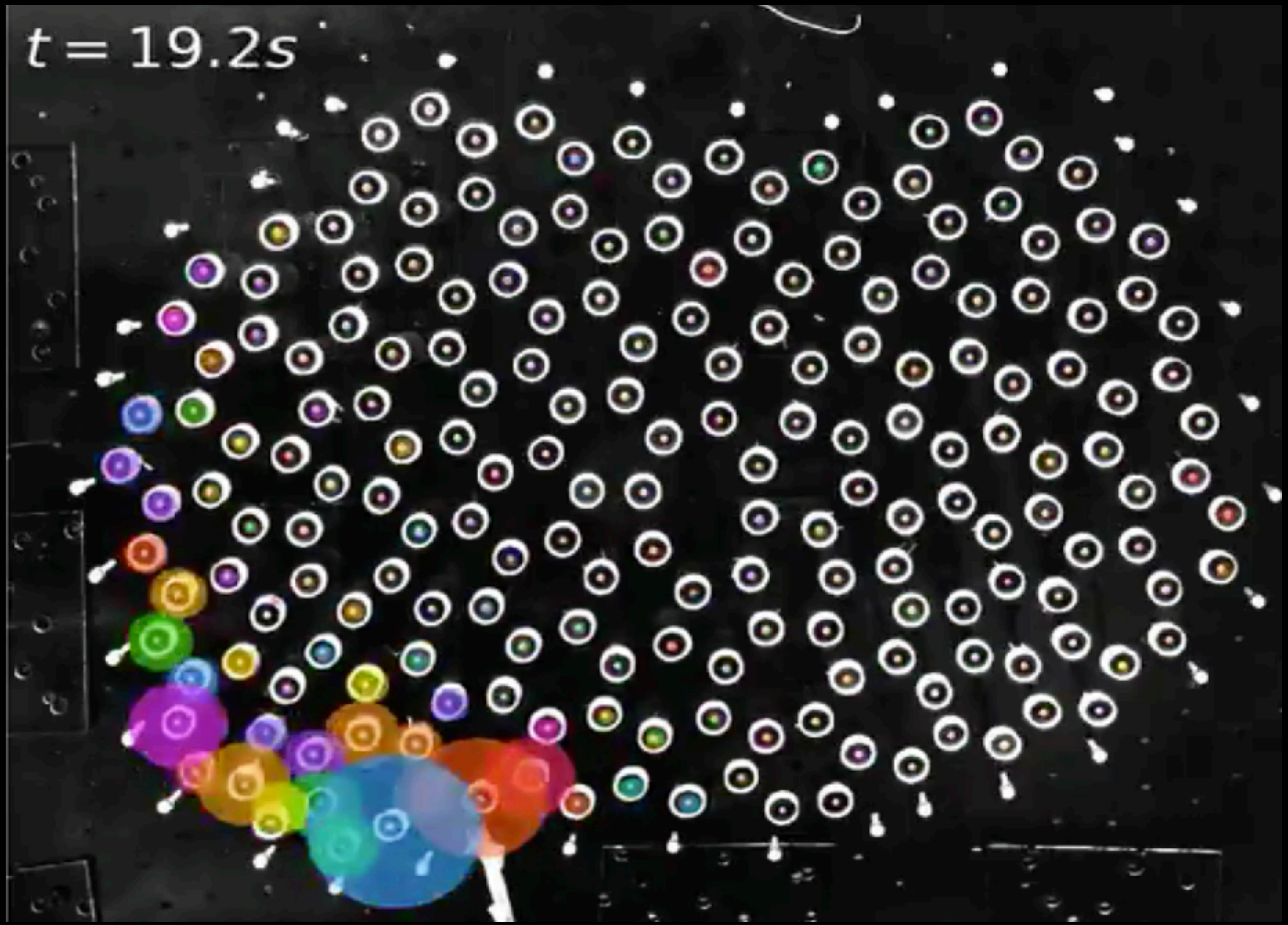

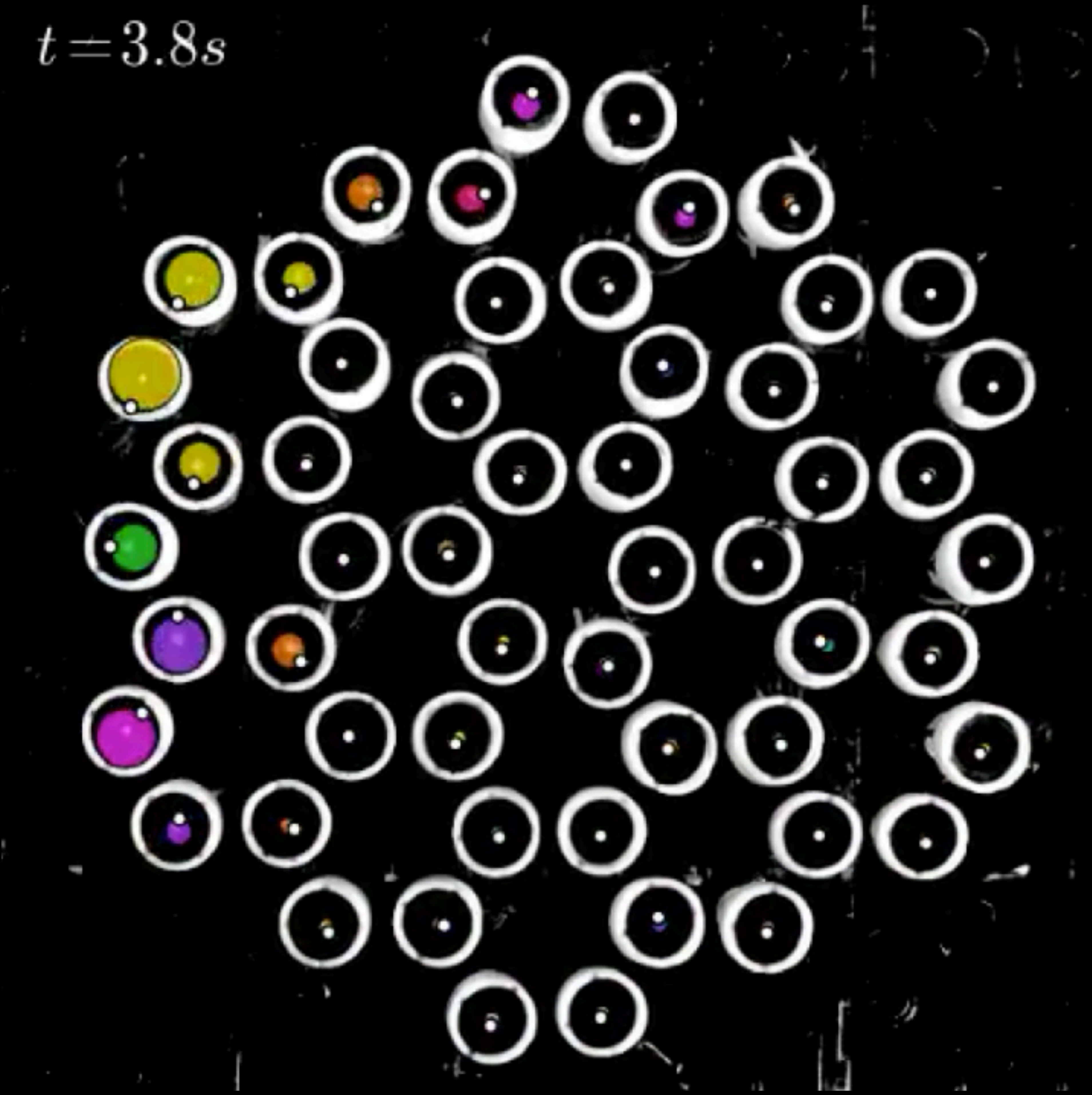

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Liu et al PRL (2020)
Zhou et al Light: Science and App. (2020)
Jia, et al Sci. Adv. (2023)
Zhang, et al Sci. Advances (2023)

Nash, et al. PNAS (2015)

Topological amorphous phases

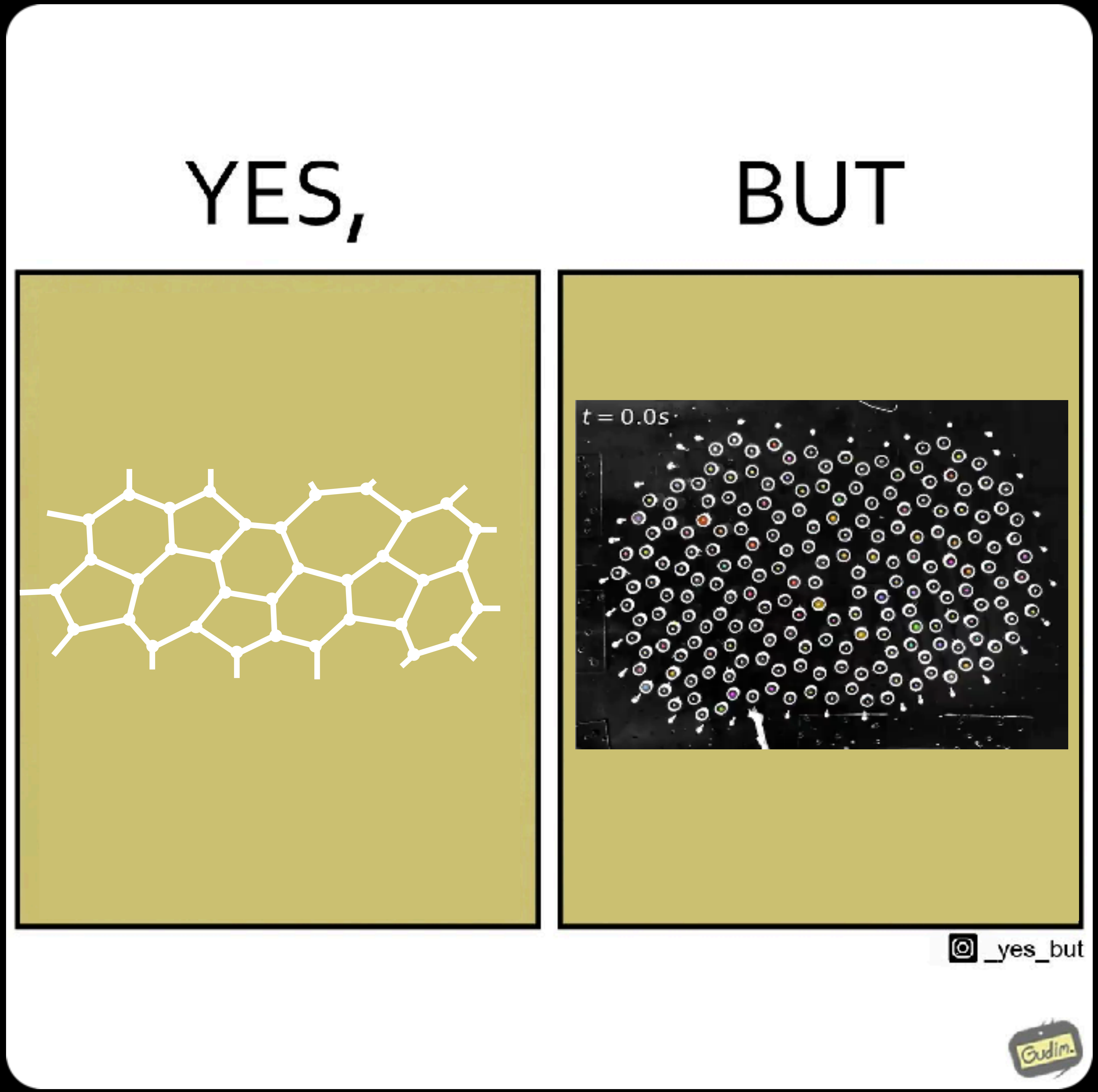
Do they exist?

Topological amorphous phases

Do they exist?

Topological amorphous phases

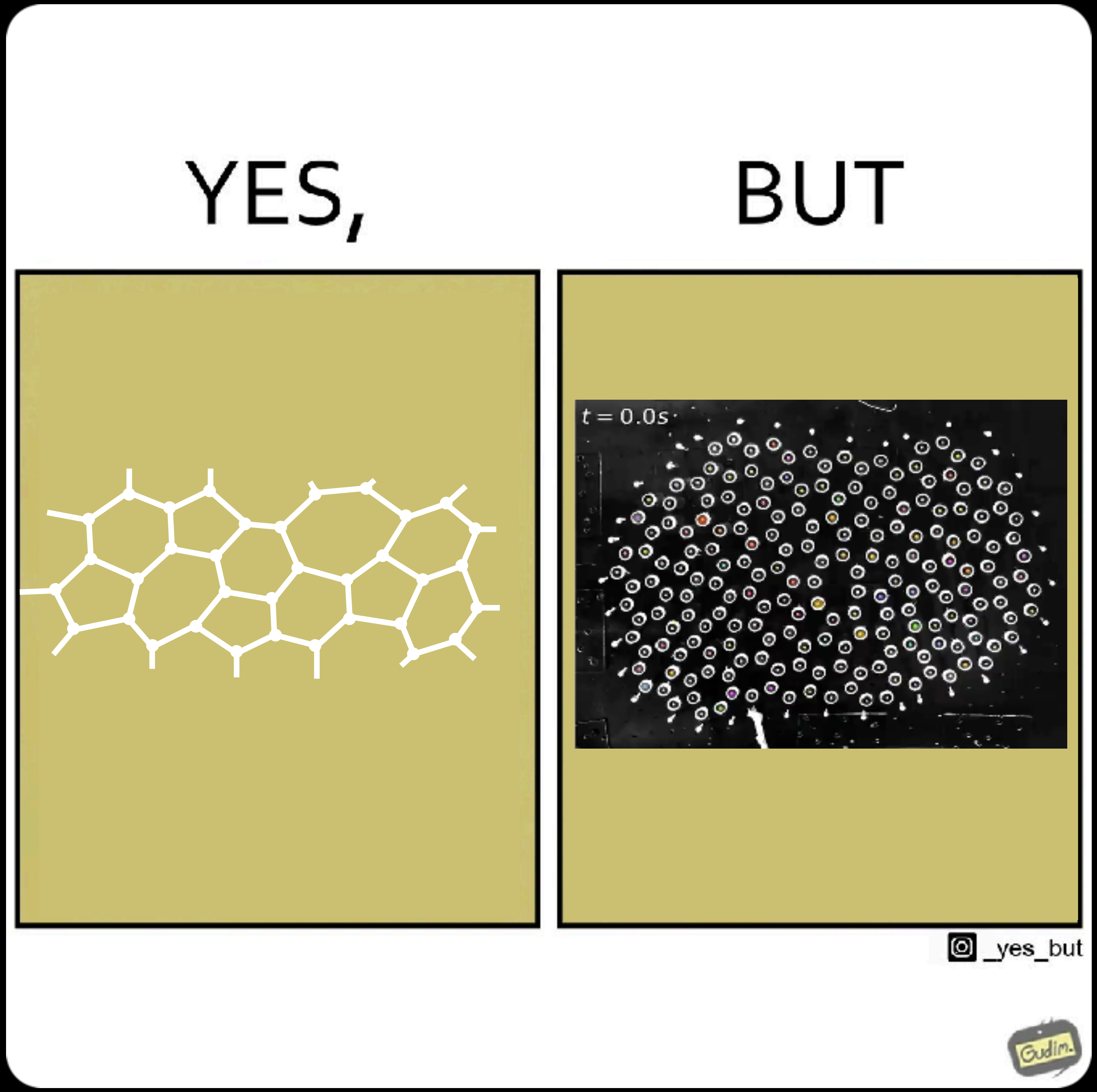
Do they exist?



Topological amorphous phases

Do they exist?

How do we find them in real solids?



Topological amorphous phases

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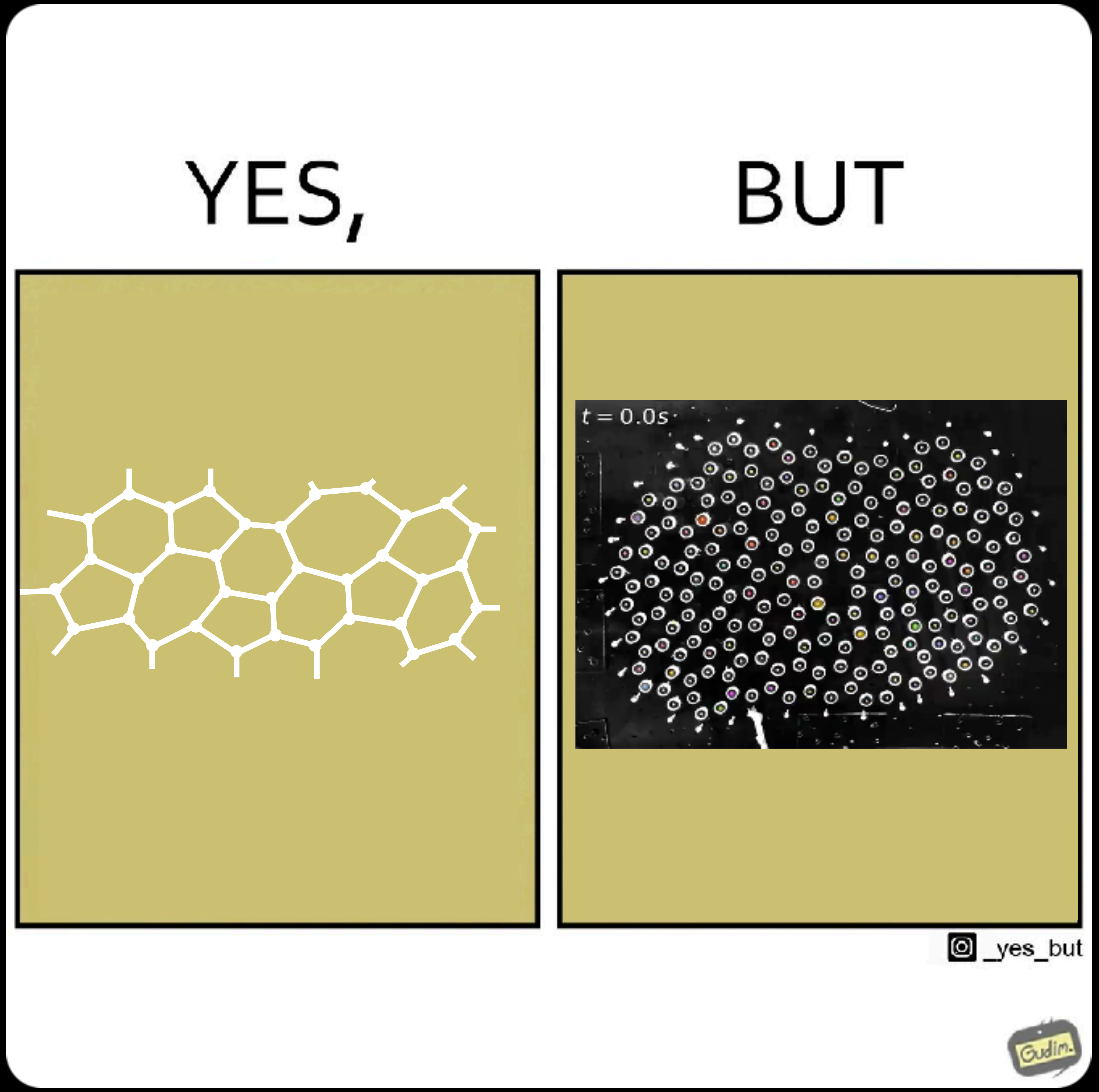
Any different physics compared to crystals?



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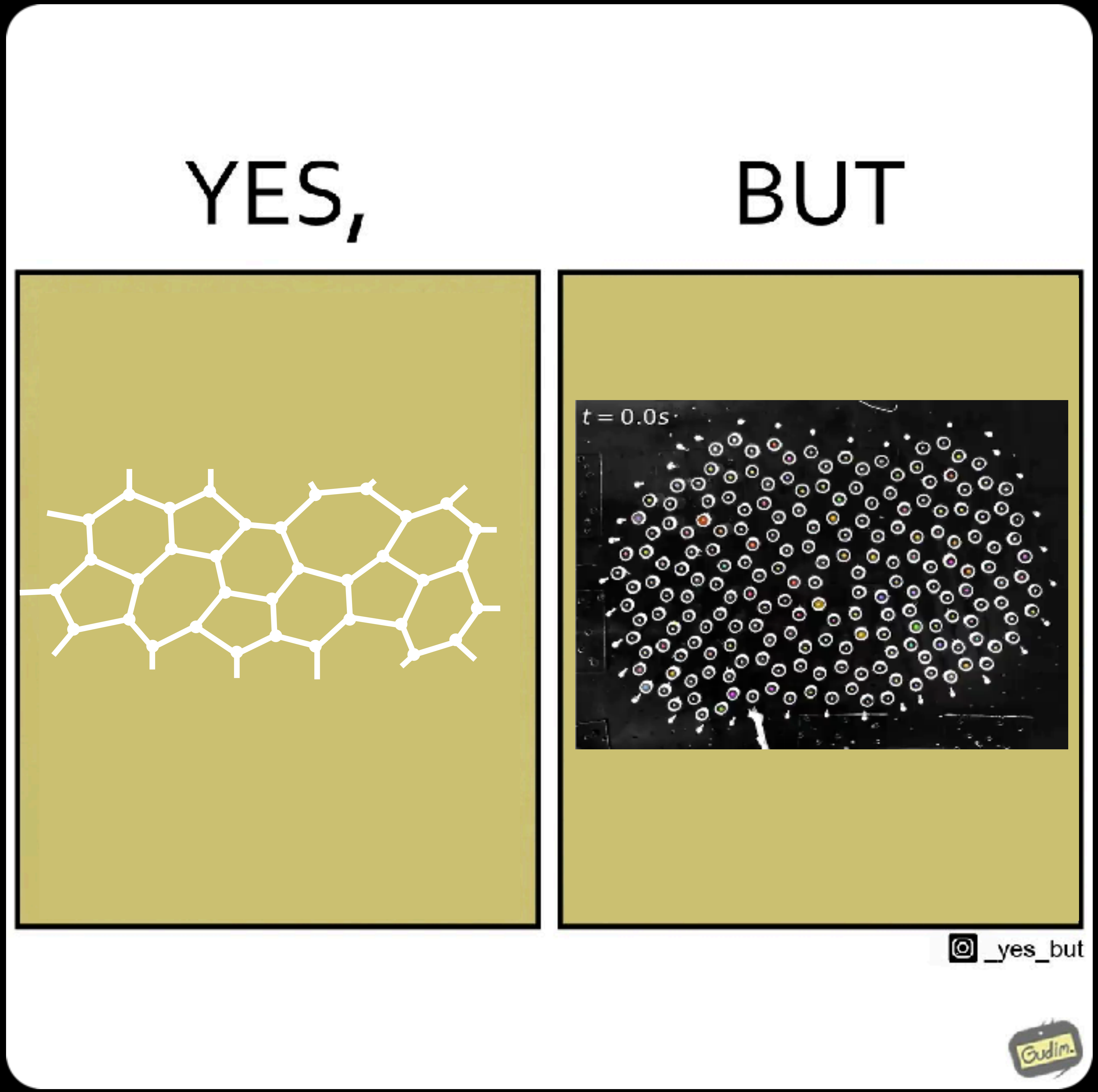
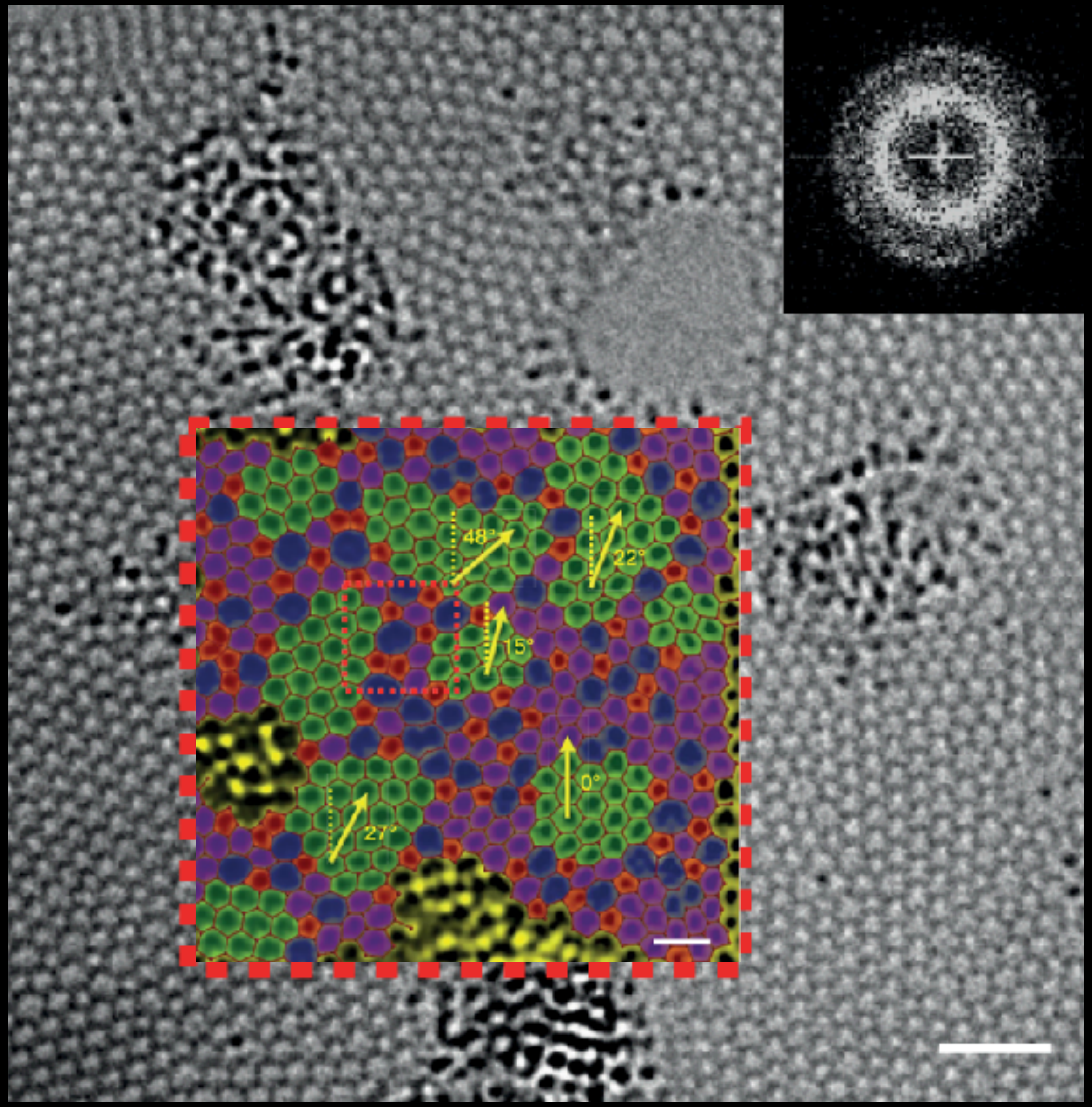


Topology in real amorphous solids

Amorphous graphene

Toh et al. Nature (2020)



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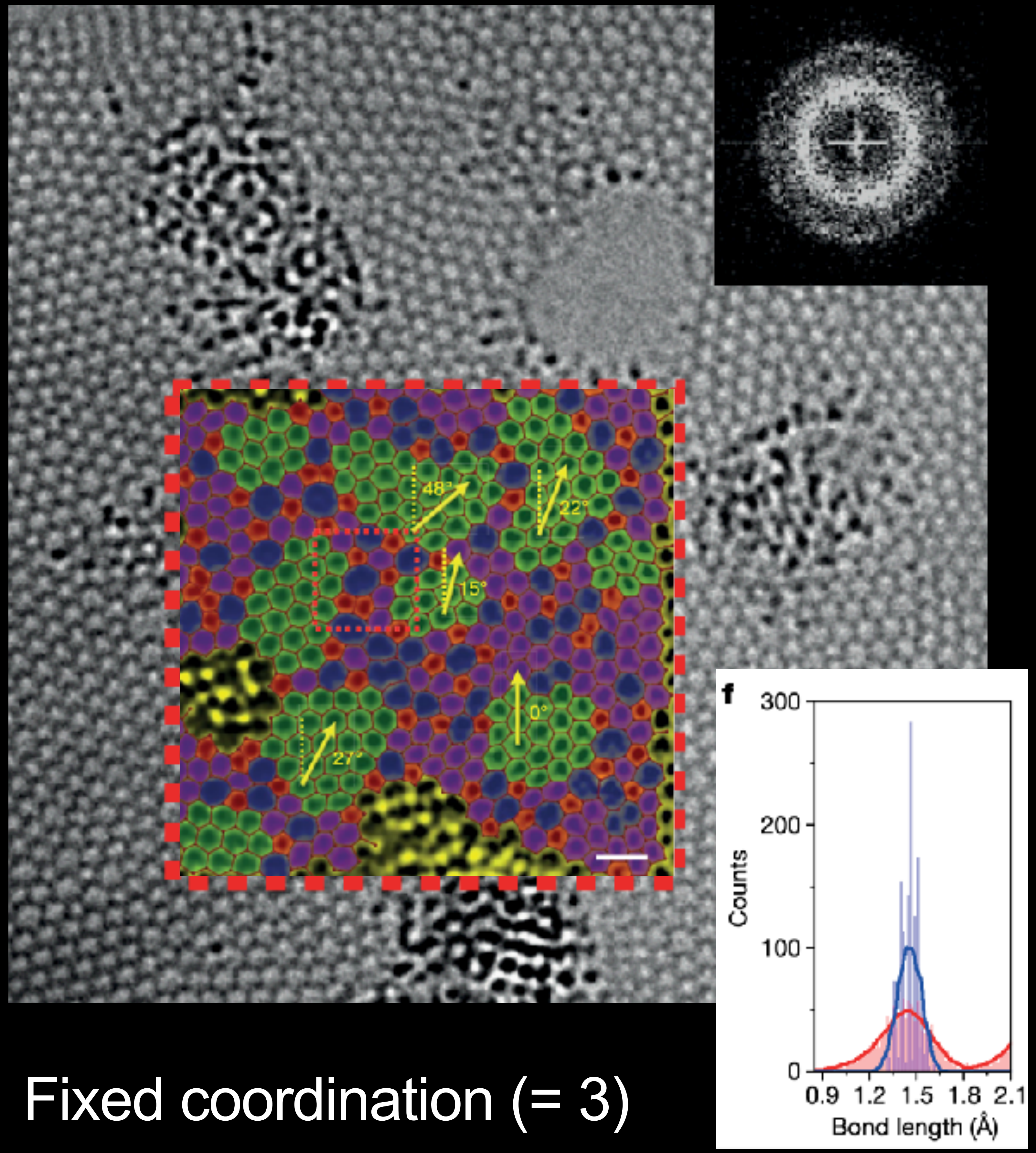


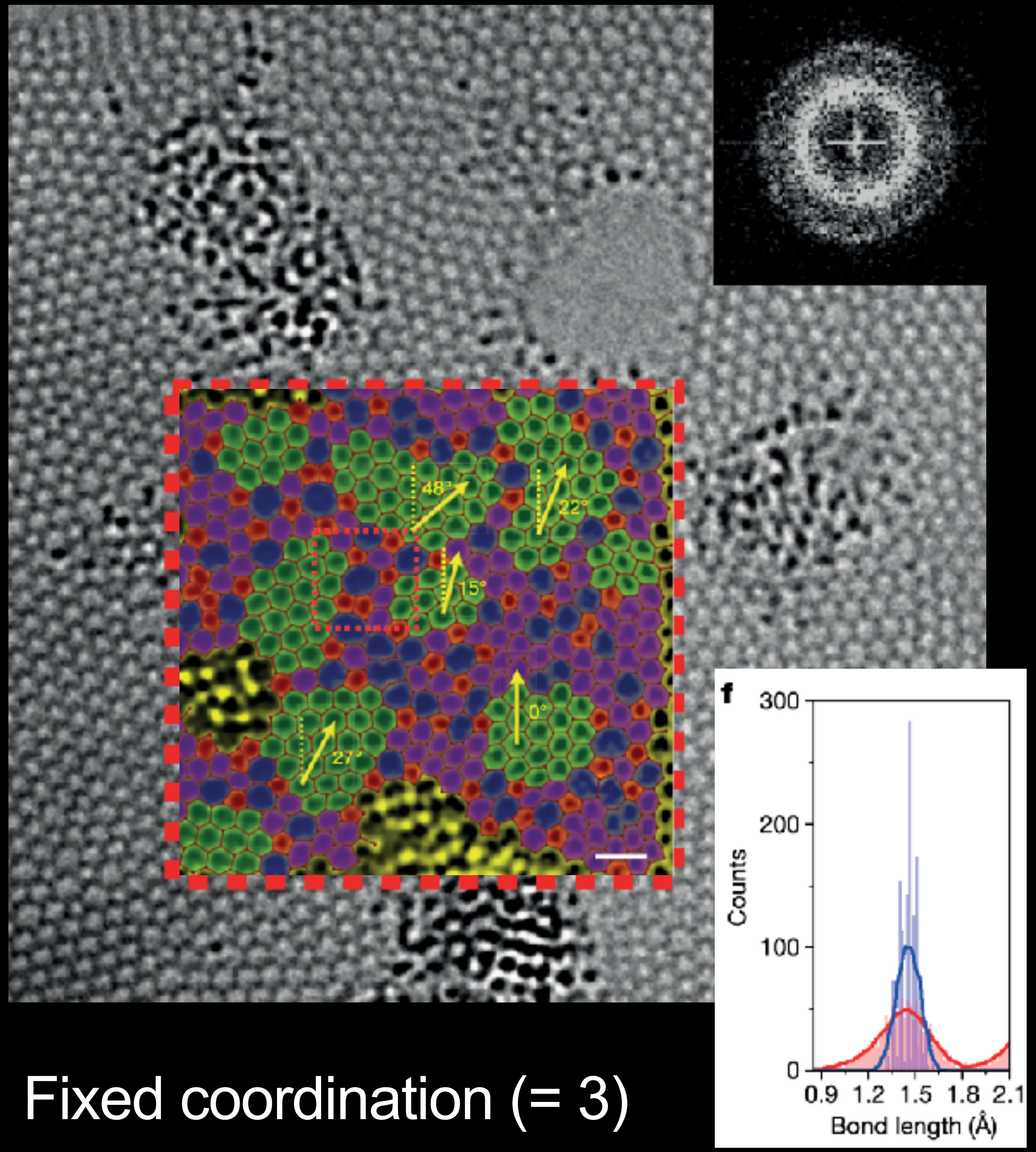
Fixed coordination (= 3)

Bond-angles and distances ~ to crystal

Topology in real amorphous solids

Amorphous graphene

Toh et al. Nature (2020)



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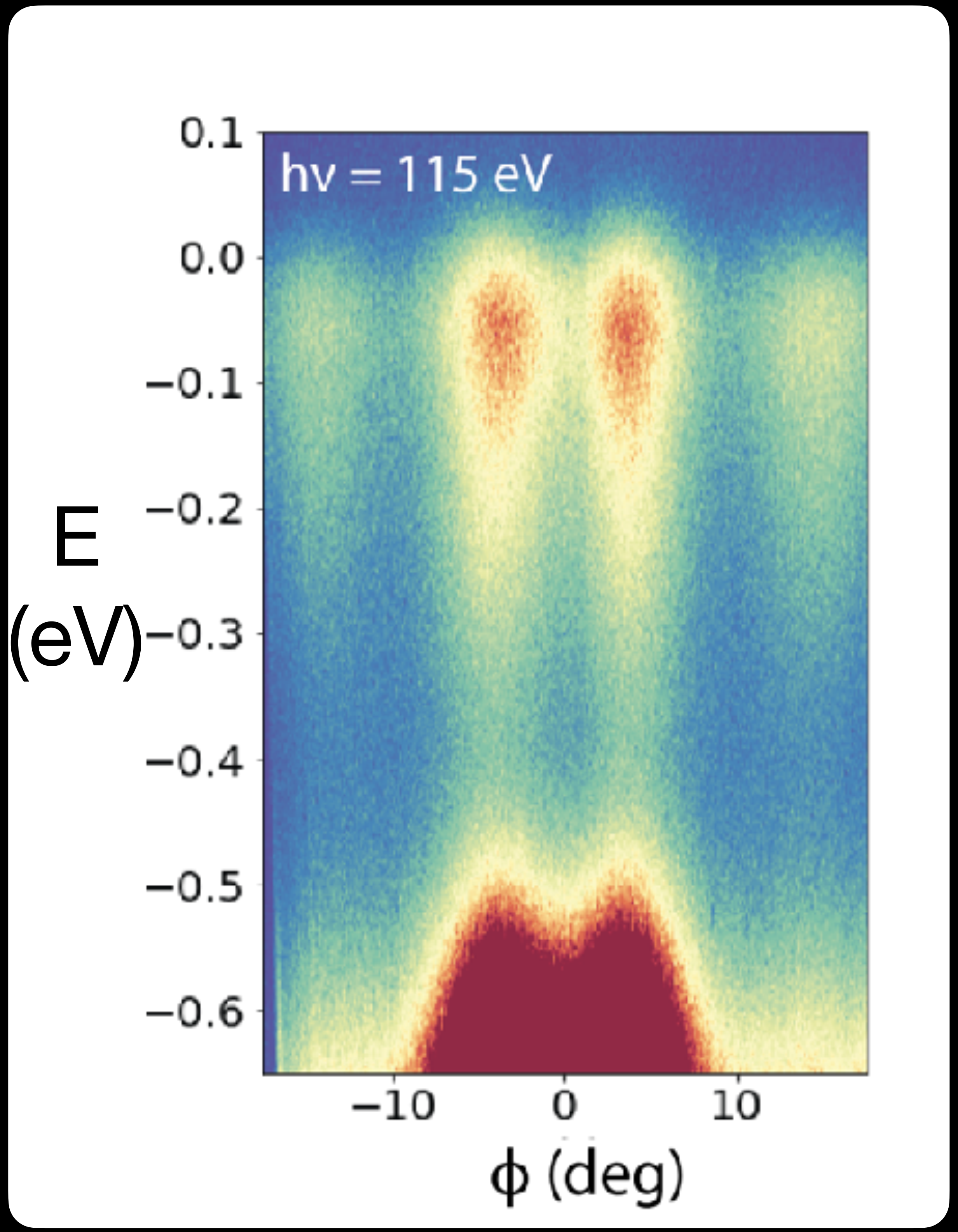
a-Bi_2Se_3



Spin-polarized surface states

Corbae et al Nat Materials (2023)

Brillouin-zone-like repetitions

Cyocis, Marsal et al, 2302.05945

Topology in real amorphous solids

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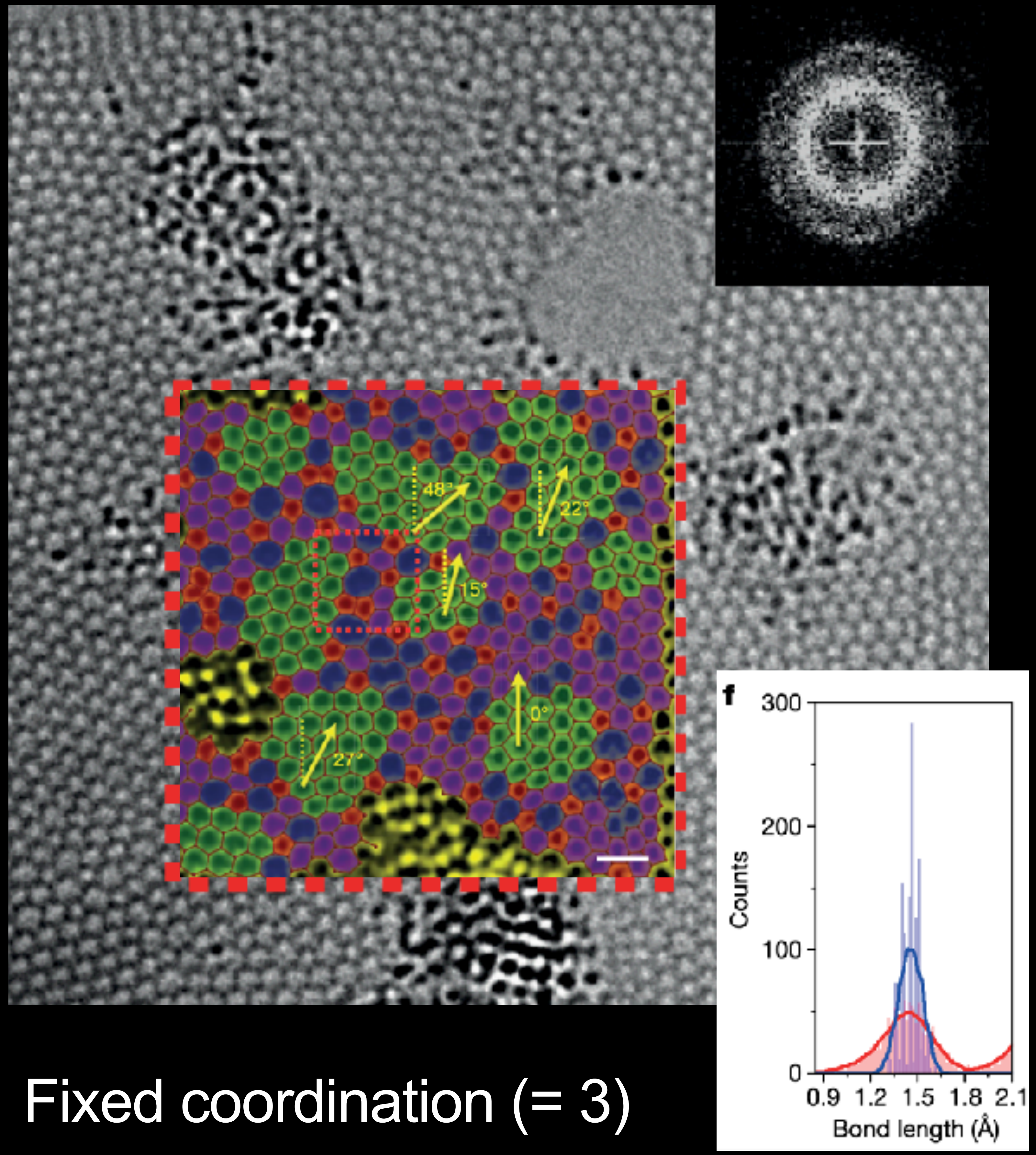

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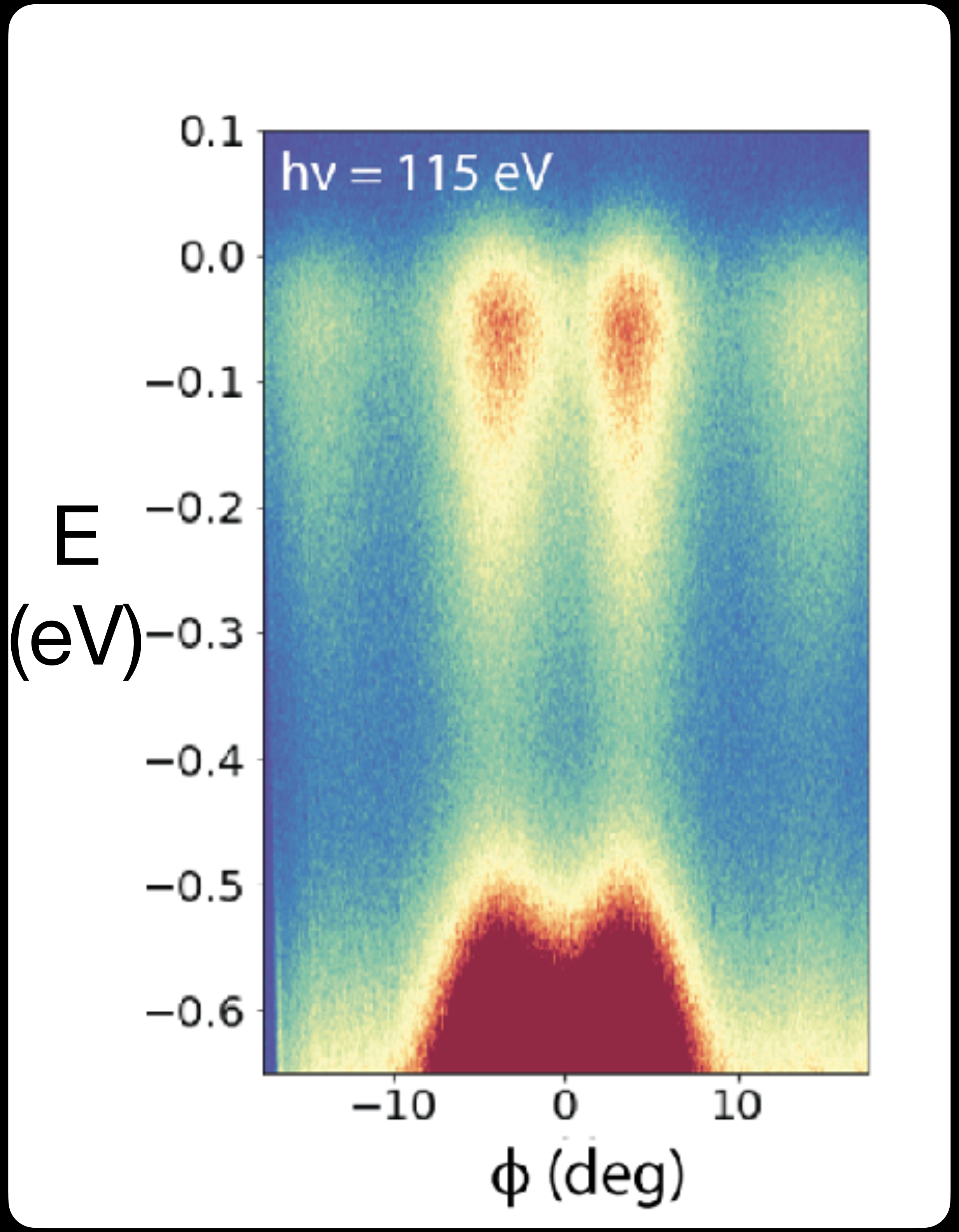

Spin-polarized surface states

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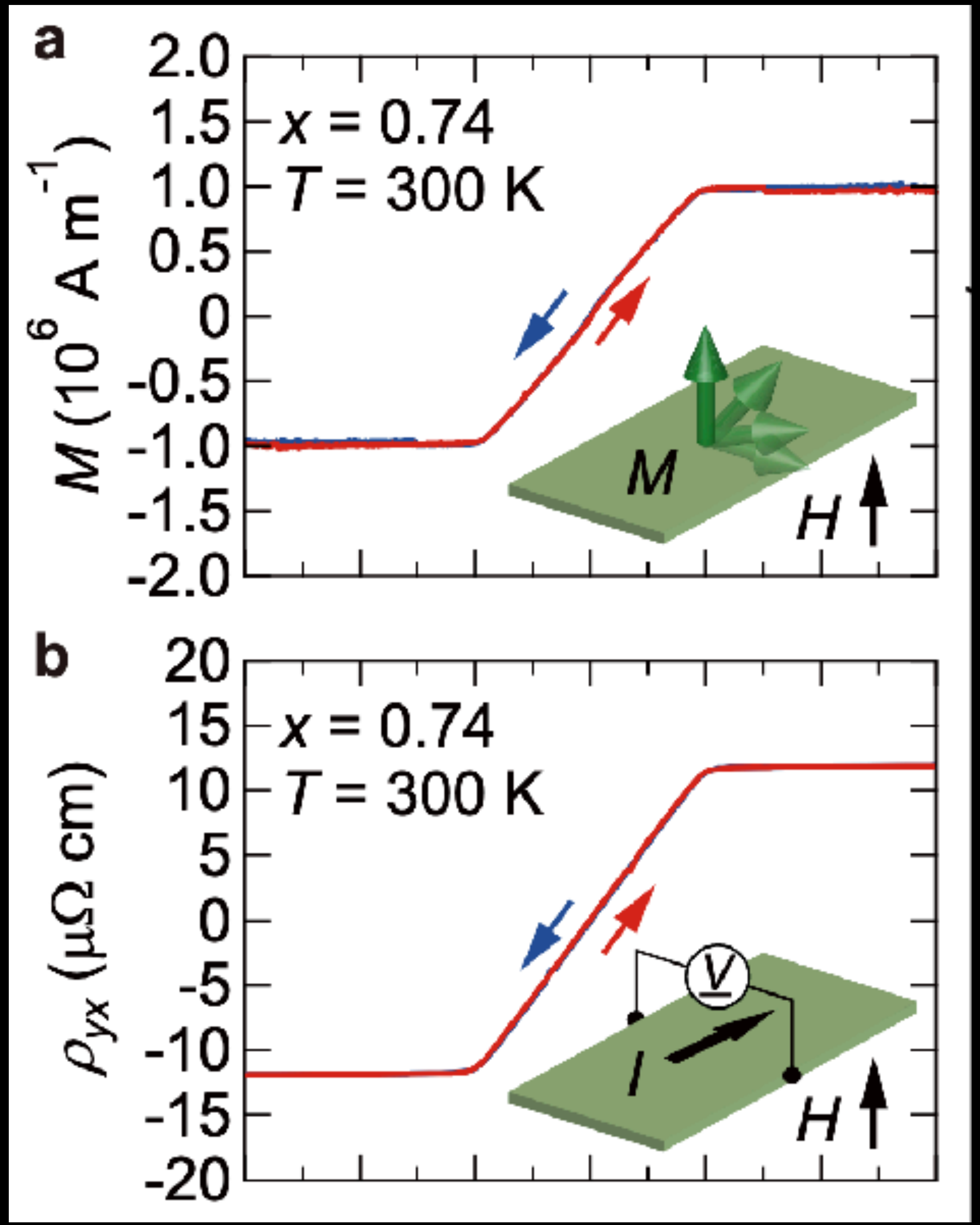
Brillouin-zone-like repetitions

Cyocis, Marsal et al, 2302.05945

a-ferromagnetic thin films

Fe_xGe_{1-x}, Fe_xSn_{1-x}, Co_xSi_{1-x} …



Larger AHE than crystal

Souma et al PRB (2020)

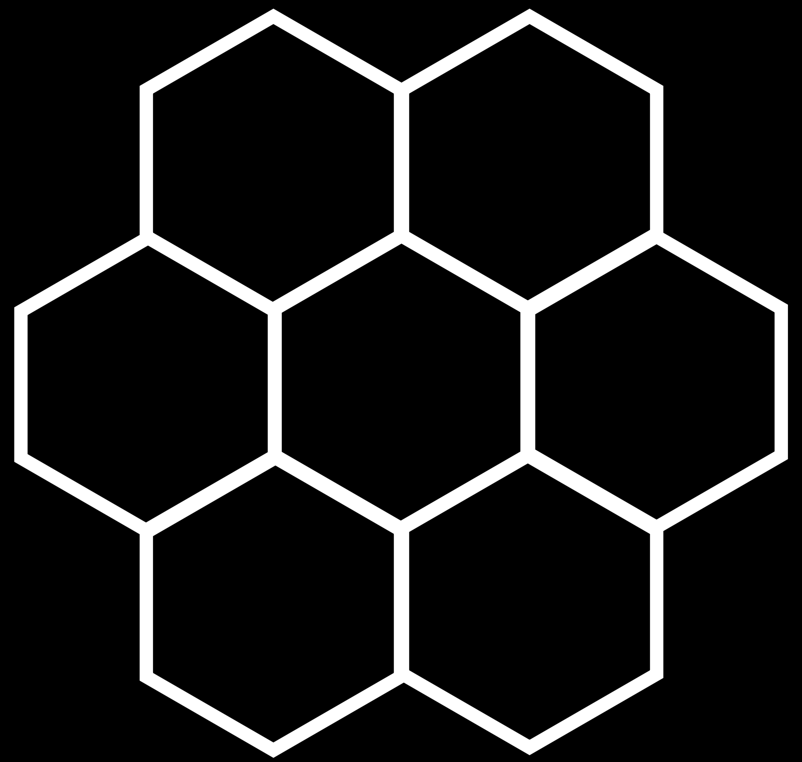
Fujiwara, K. et al. Nat. Commun. 14, 3399 (2023).

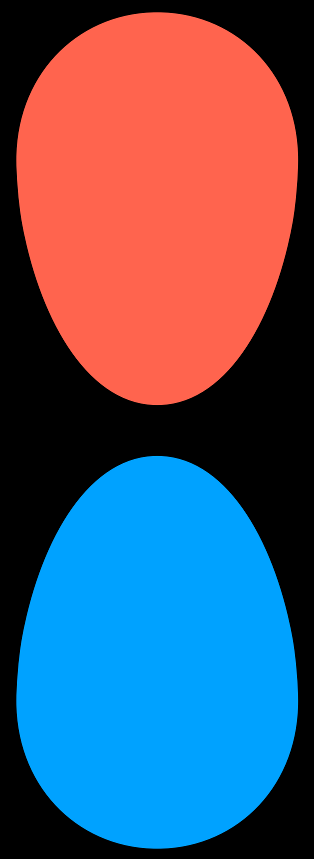
Peculiar magneto-resistance (a-CoSi)

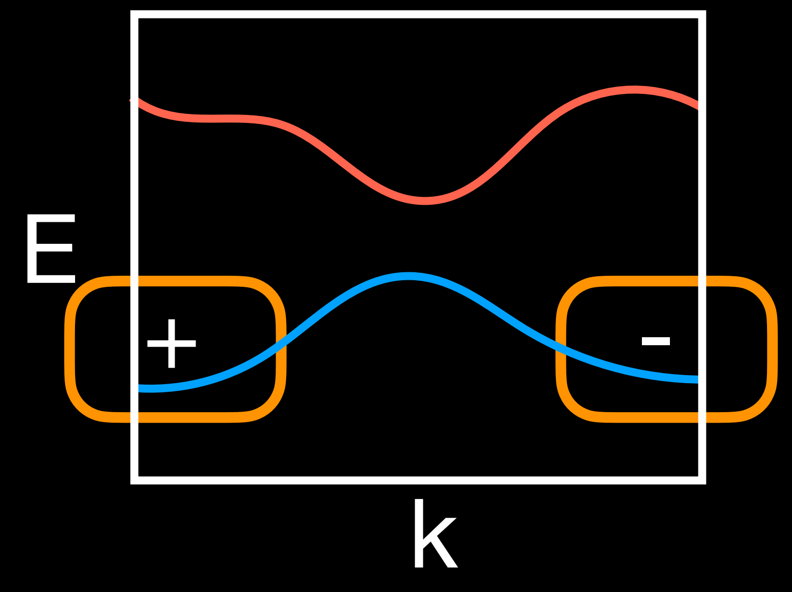
Molinari, K. et al. ACS App. Elec. Mat. (2023)

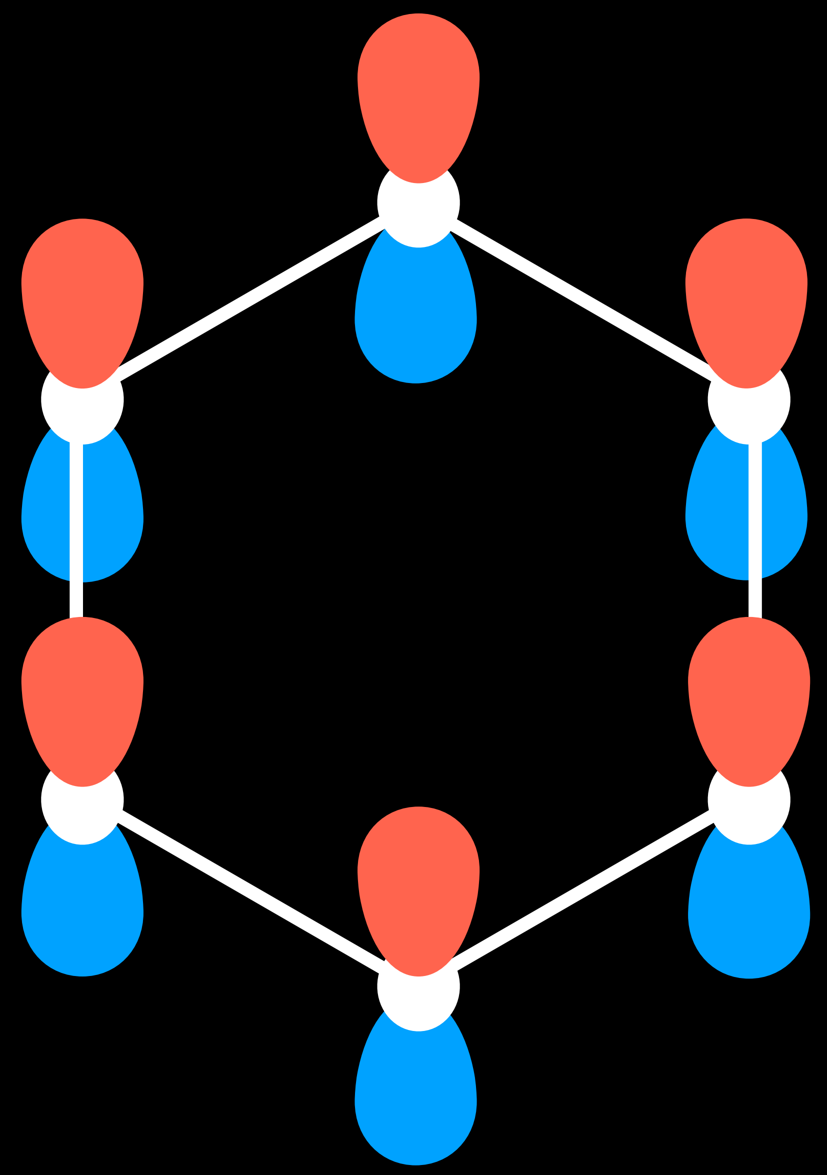
How do we find amorphous topological insulators?

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)

How do we find amorphous topological insulators?

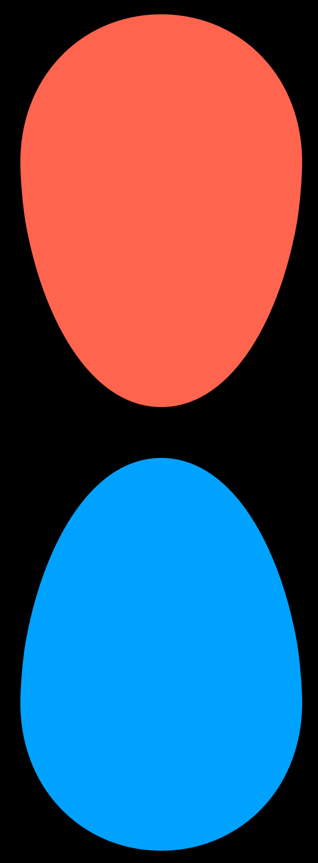
Space Group

No long-range order

— lattice sy… tries

translations, r… ions, inversions, mirrors

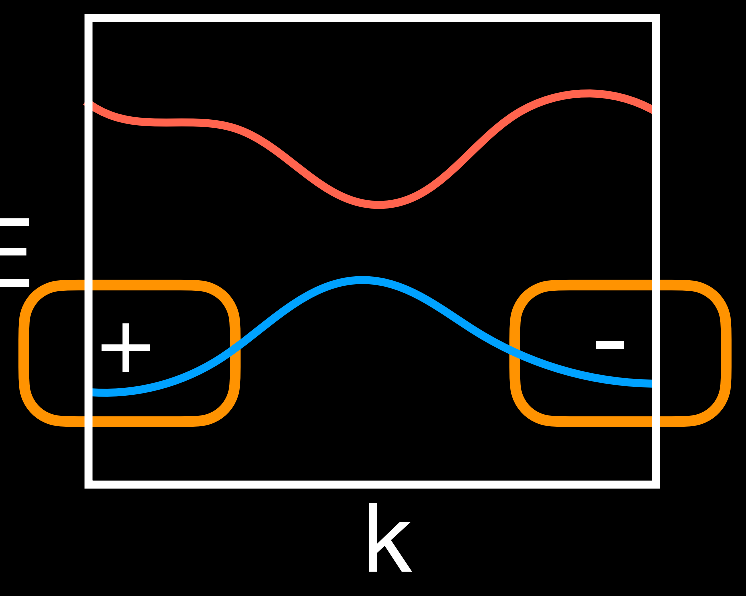
Orbitals

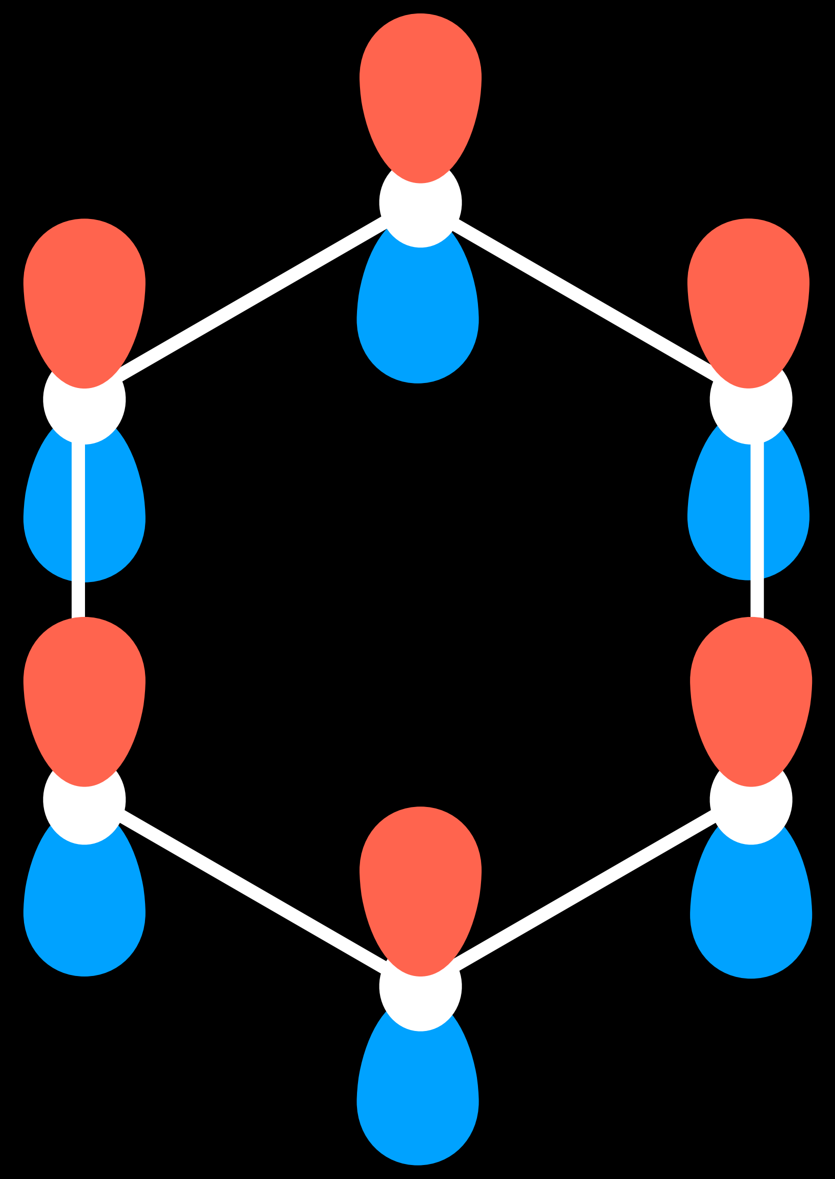


— wavefunctions

s, p, d…

Atomic positions





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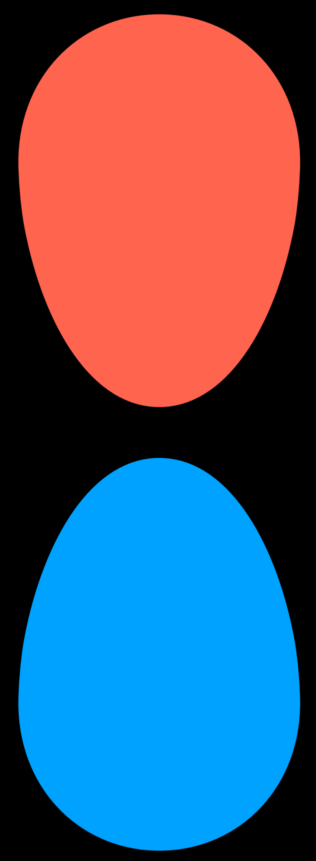

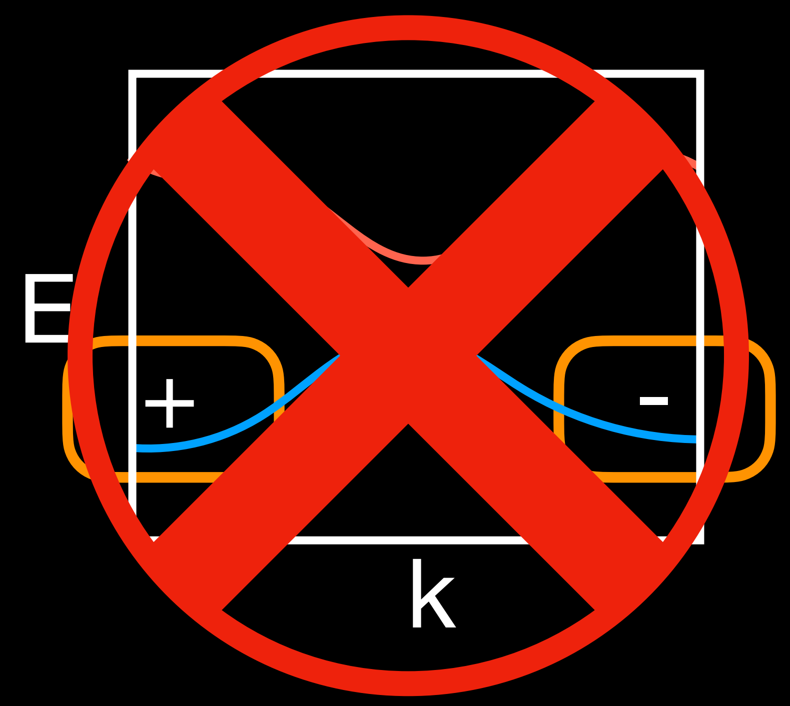

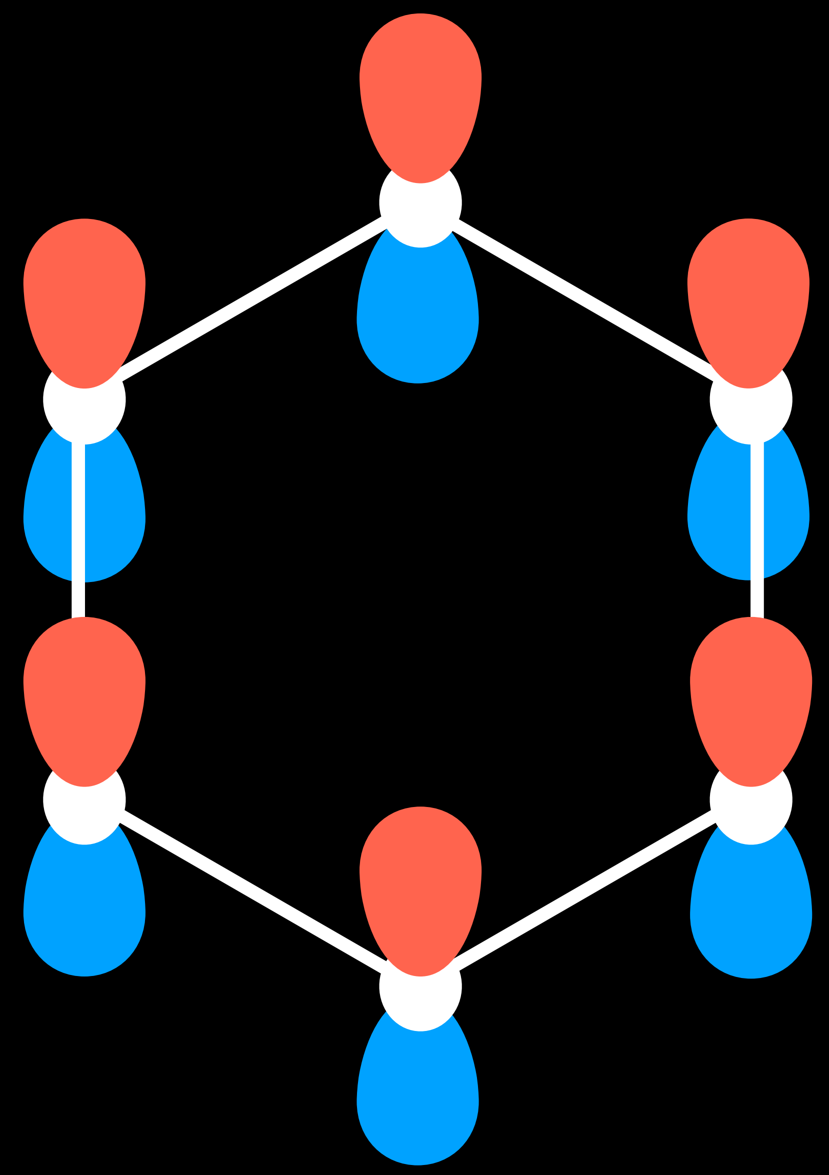

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How do we find amorphous topological insulators?

Model Hamiltonians

ab-initio simulations

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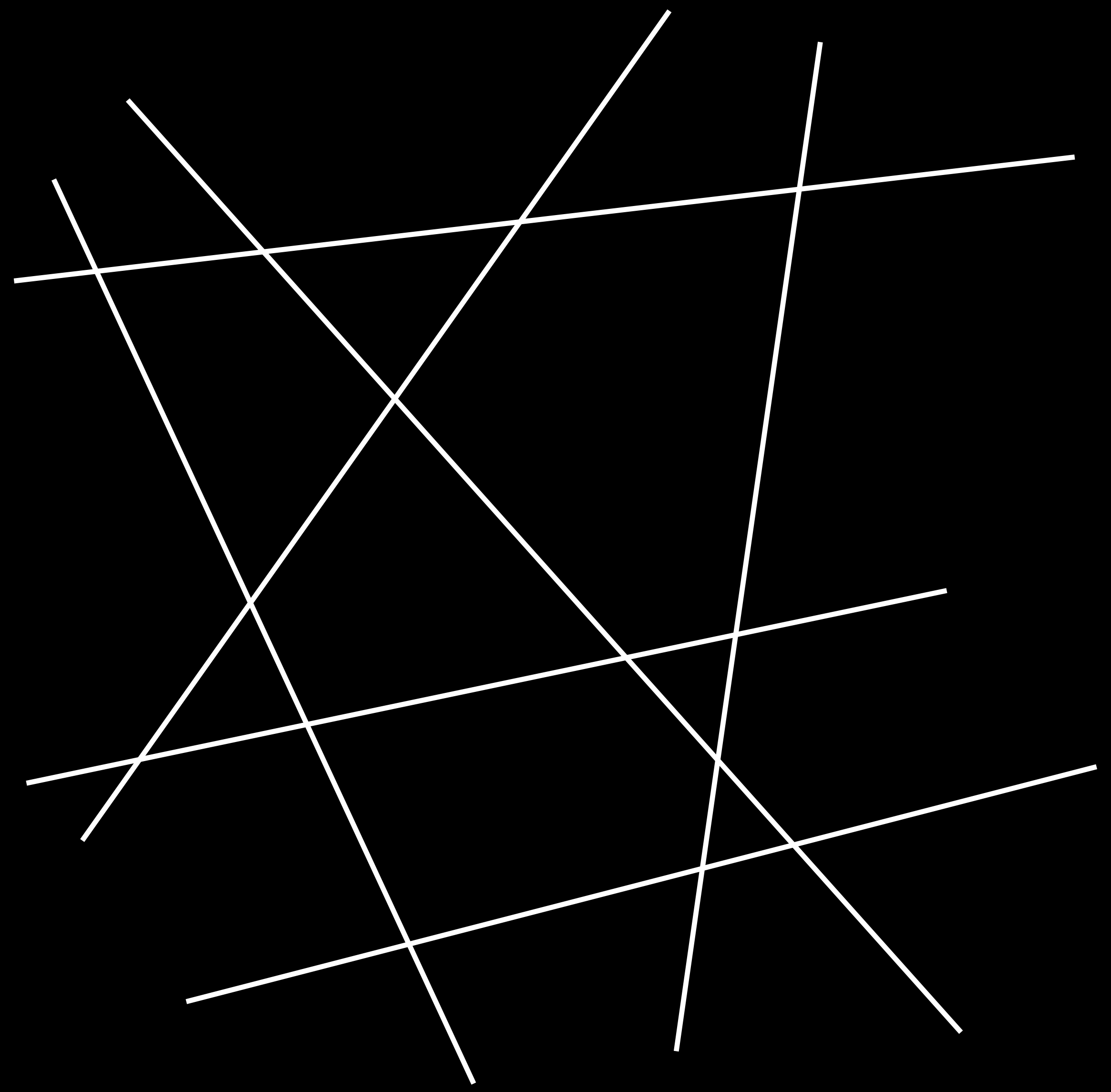
Model Hamiltonians



ab-initio simulations

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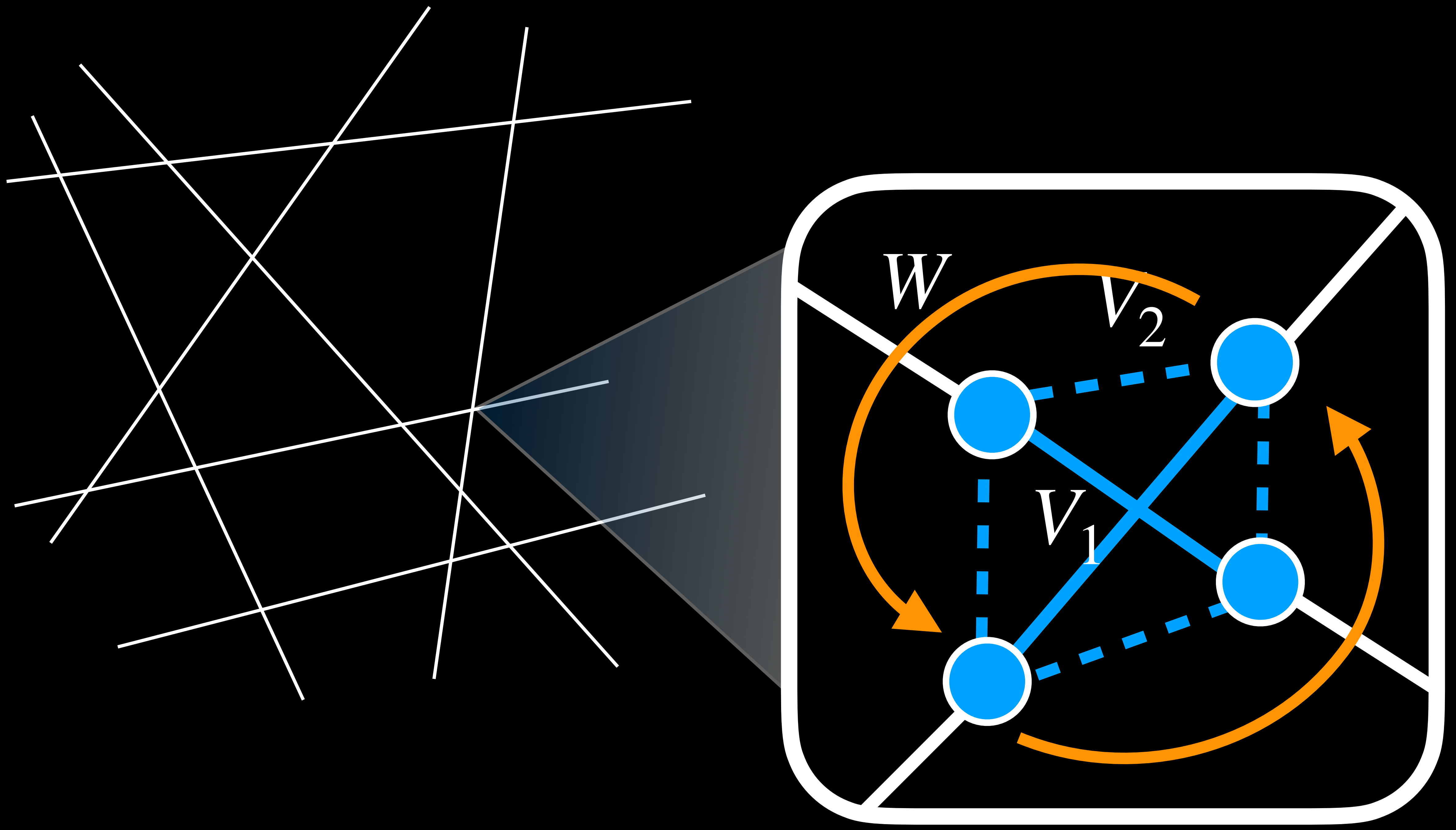

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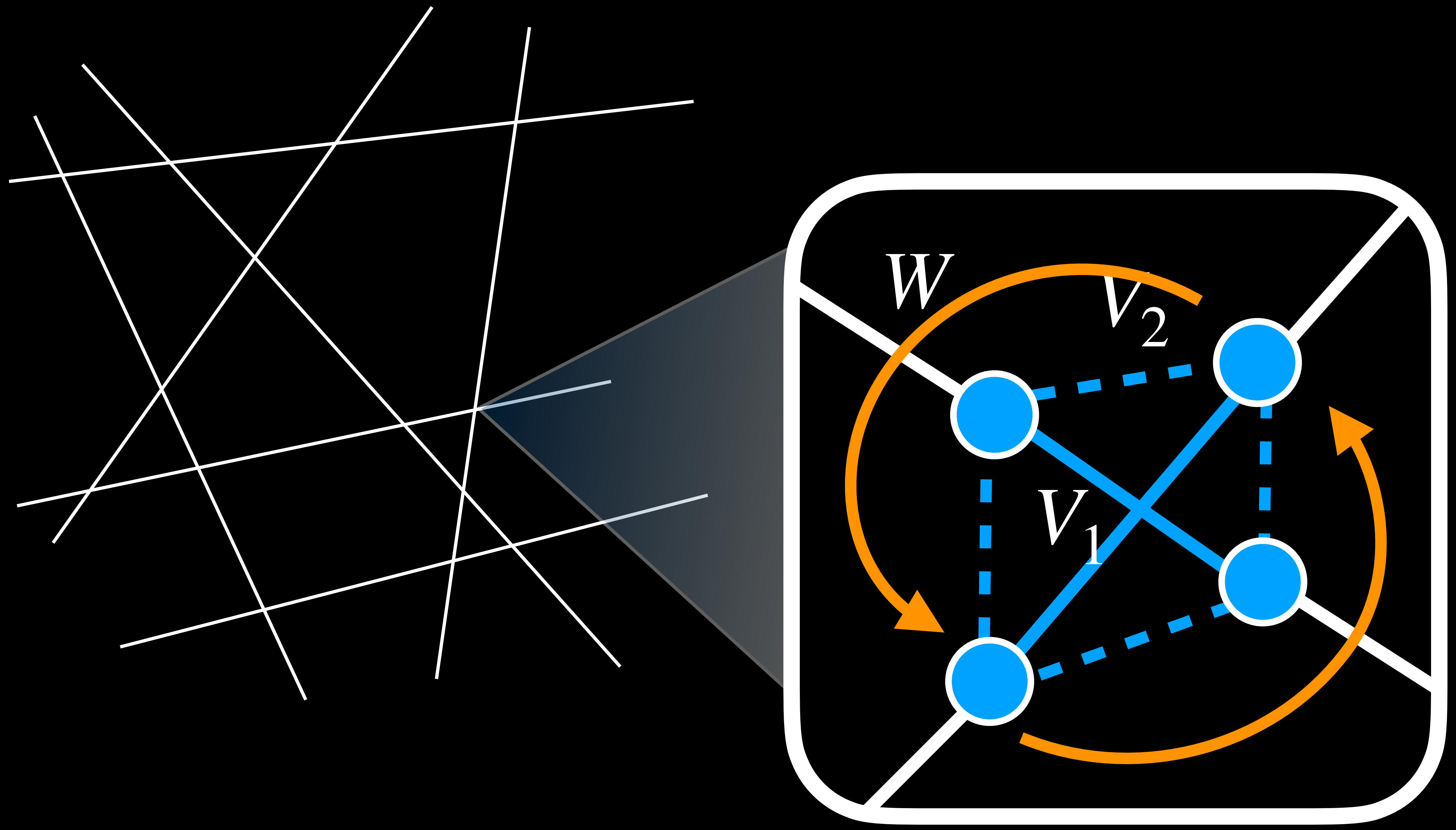


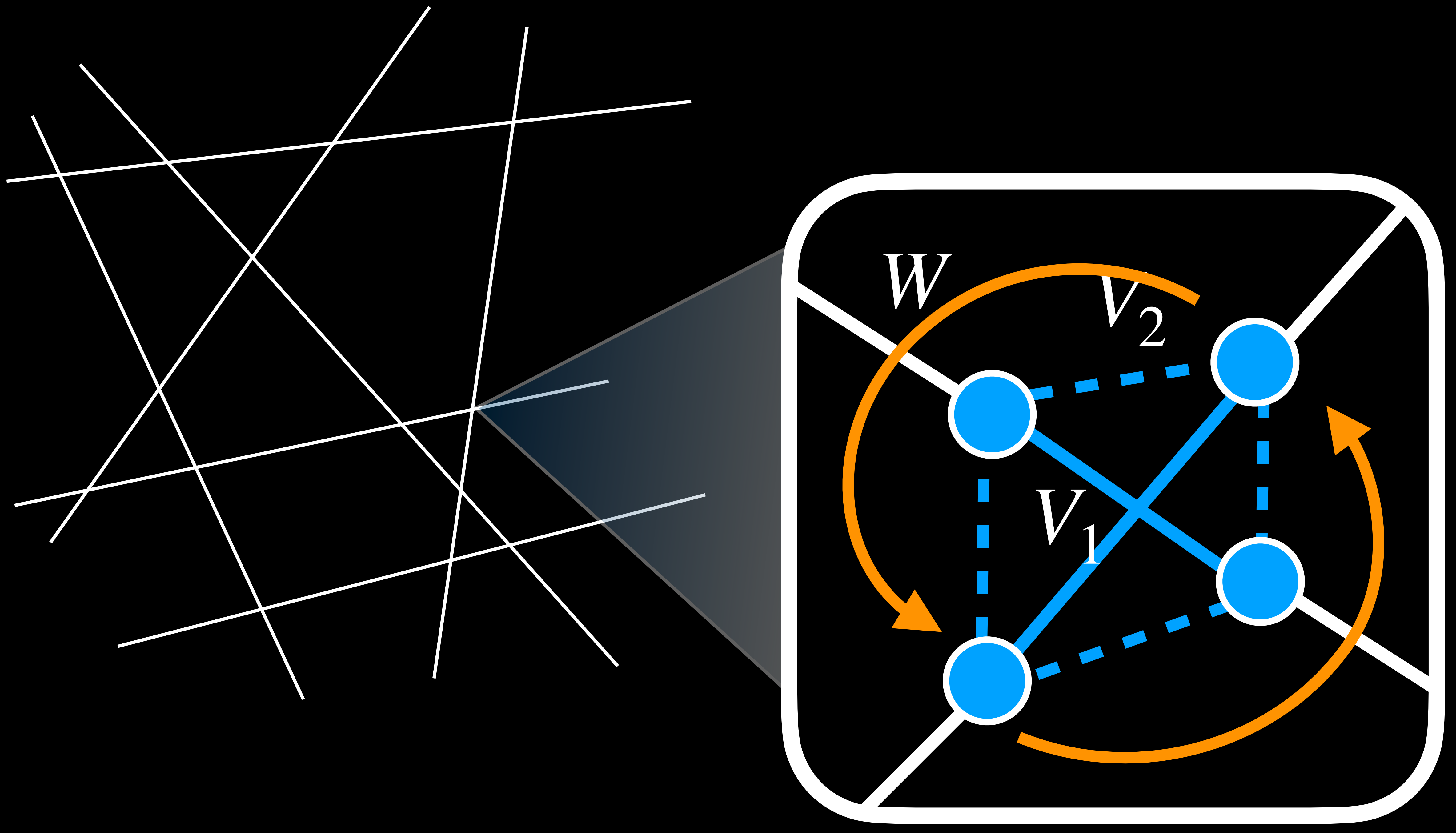
Symmetry indicators Q. Marsal, D. Varjas, AGG PNAS, (2020)

Quentin Marsal
Néel Institute

Daniel Varjas
MPI PKS

How do we find amorphous topological insulators?

Model Hamiltonians



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Corbae et al, Nat Materials (2023)

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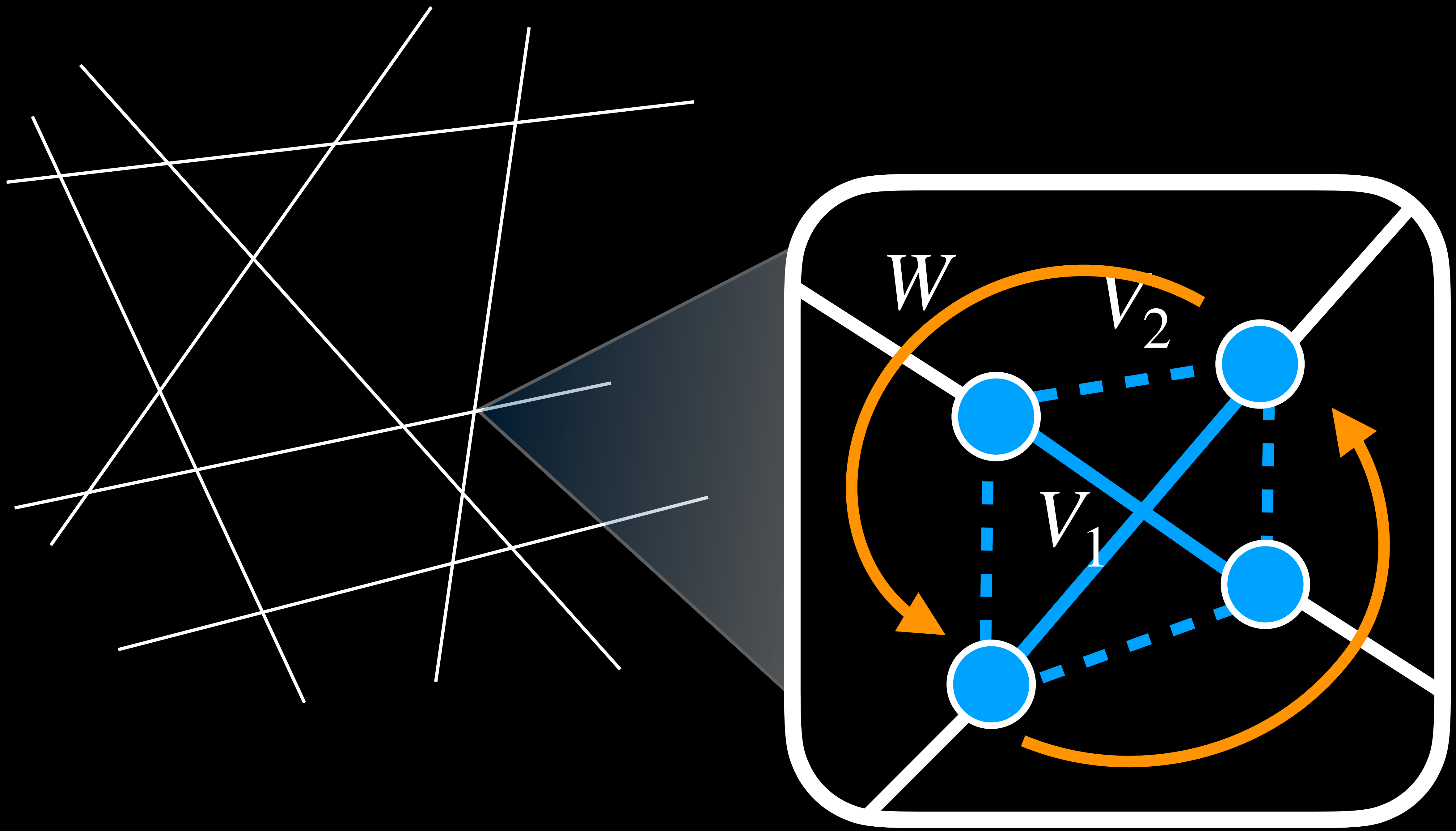

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$$\gamma = \mathrm{Tr}[(P - \tilde{P})^2]/2$$

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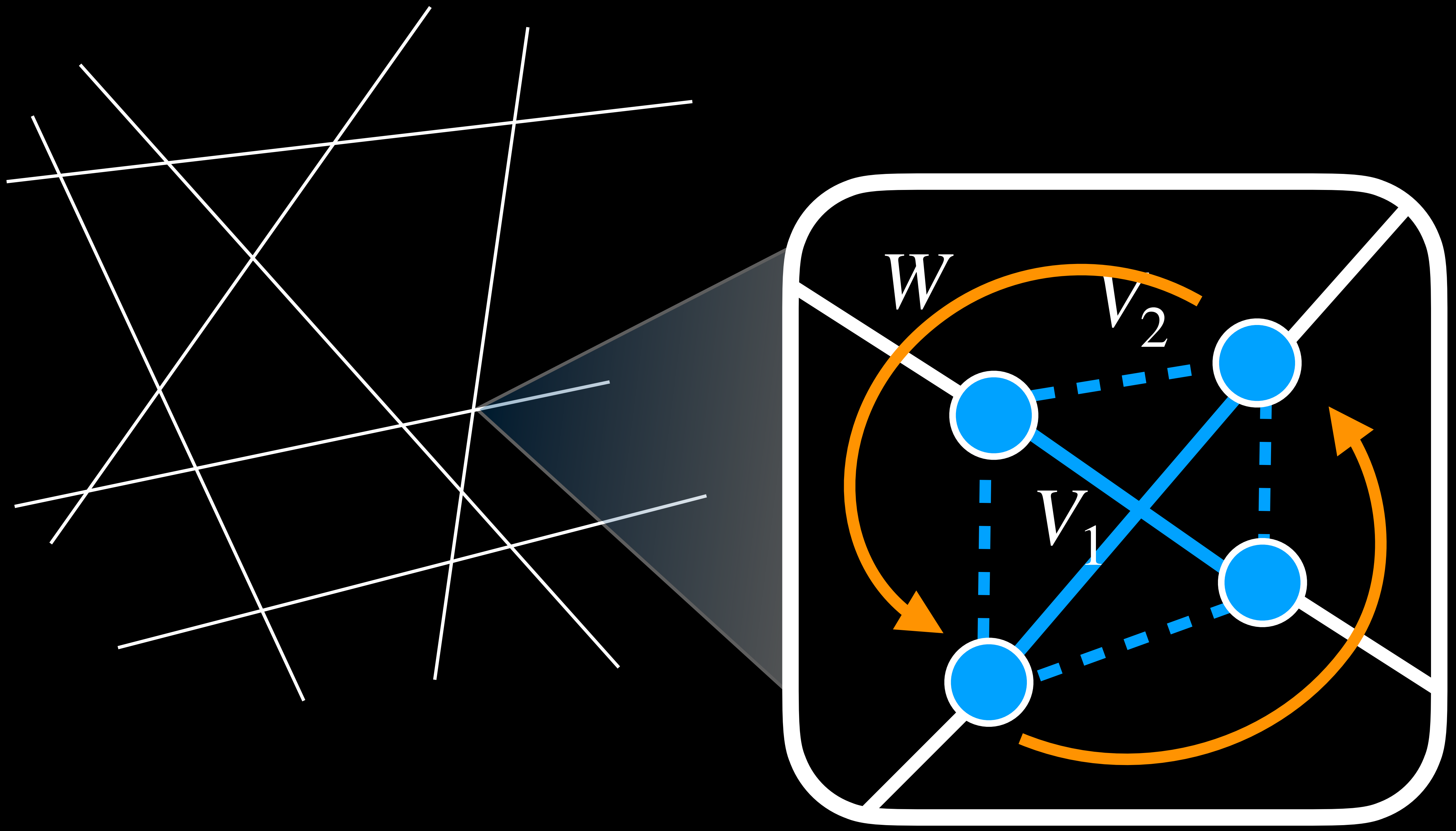

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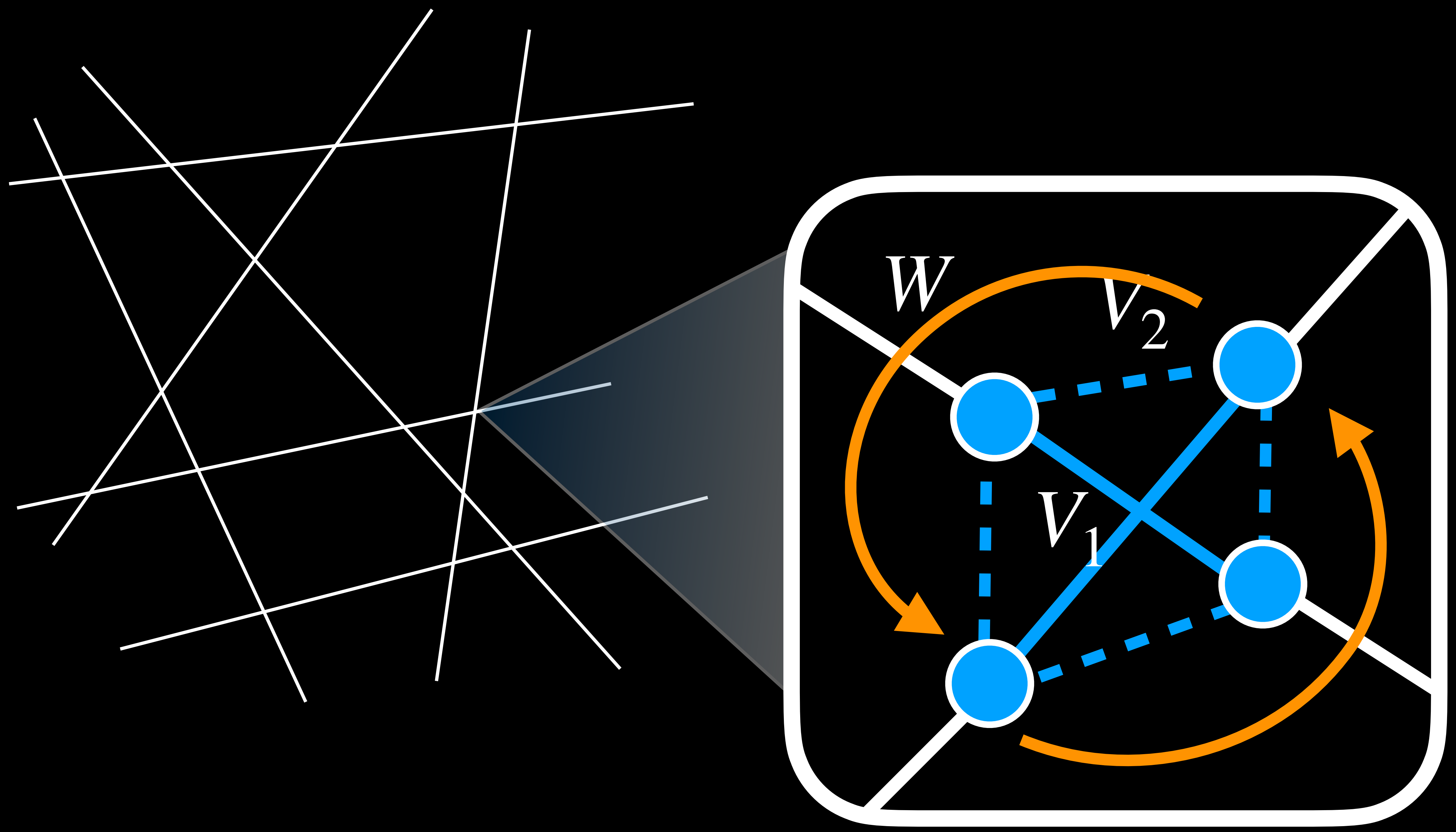

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Reference system (known)

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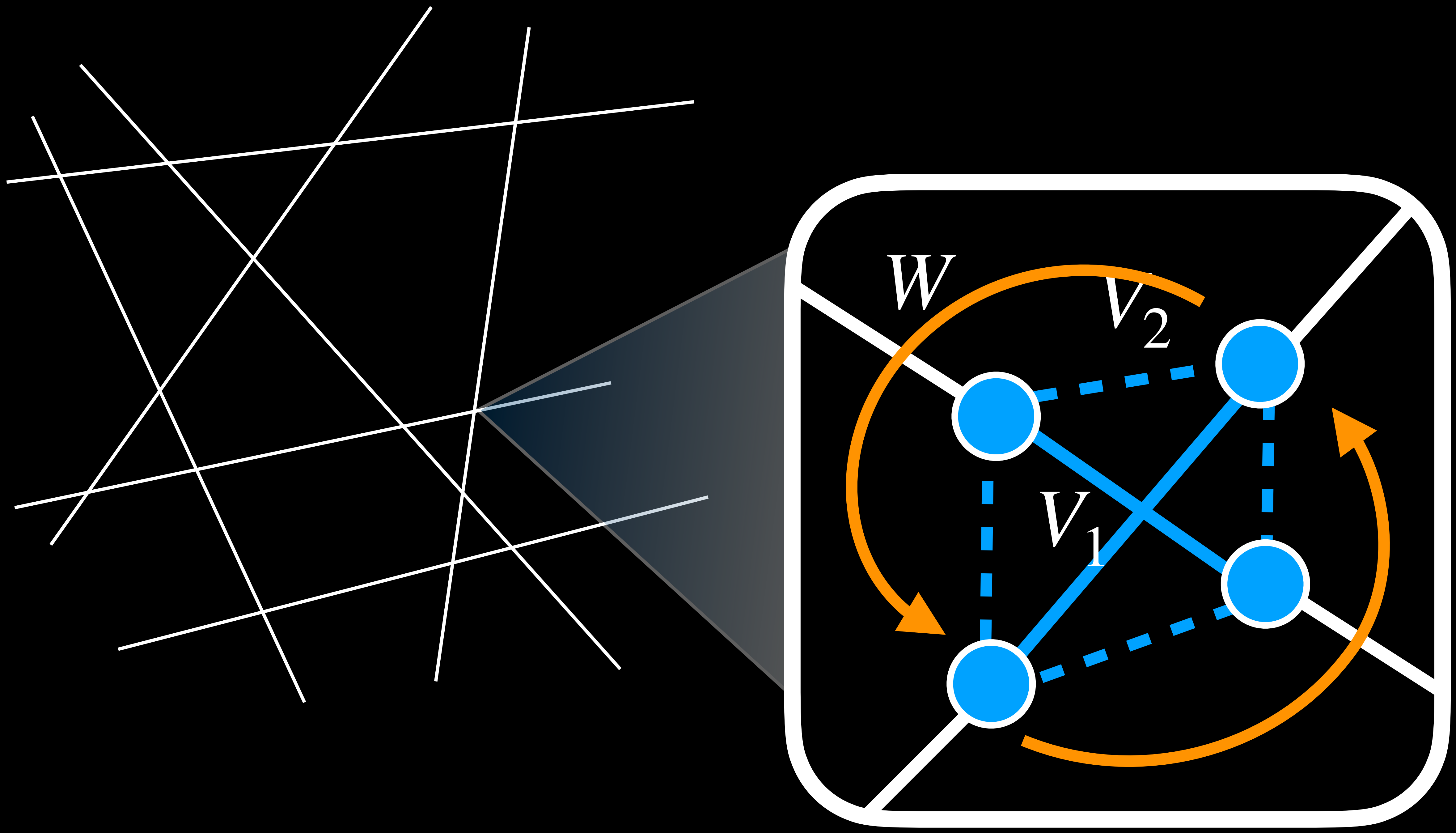

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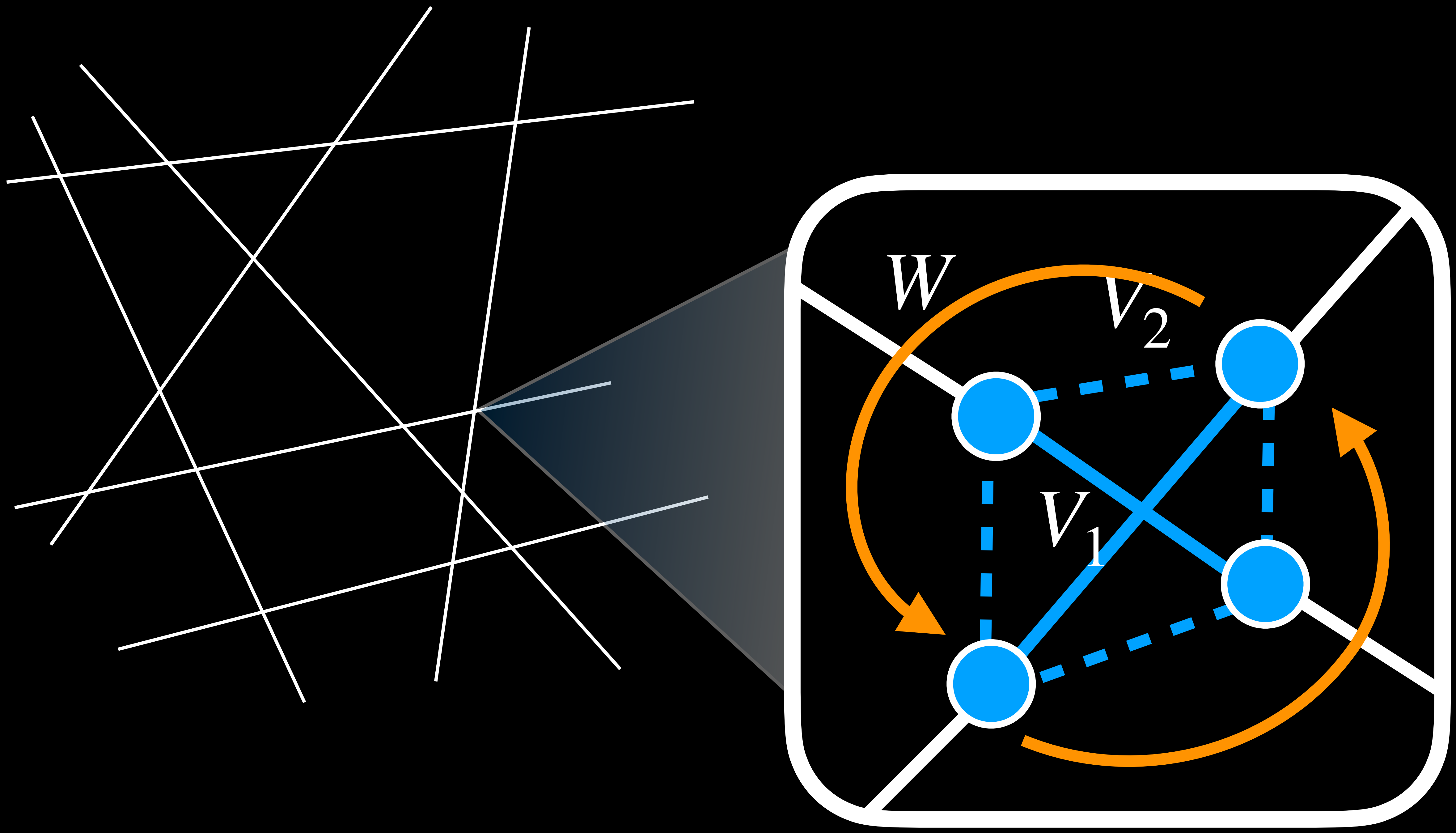

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Corbae et al, Nat Materials (2023)

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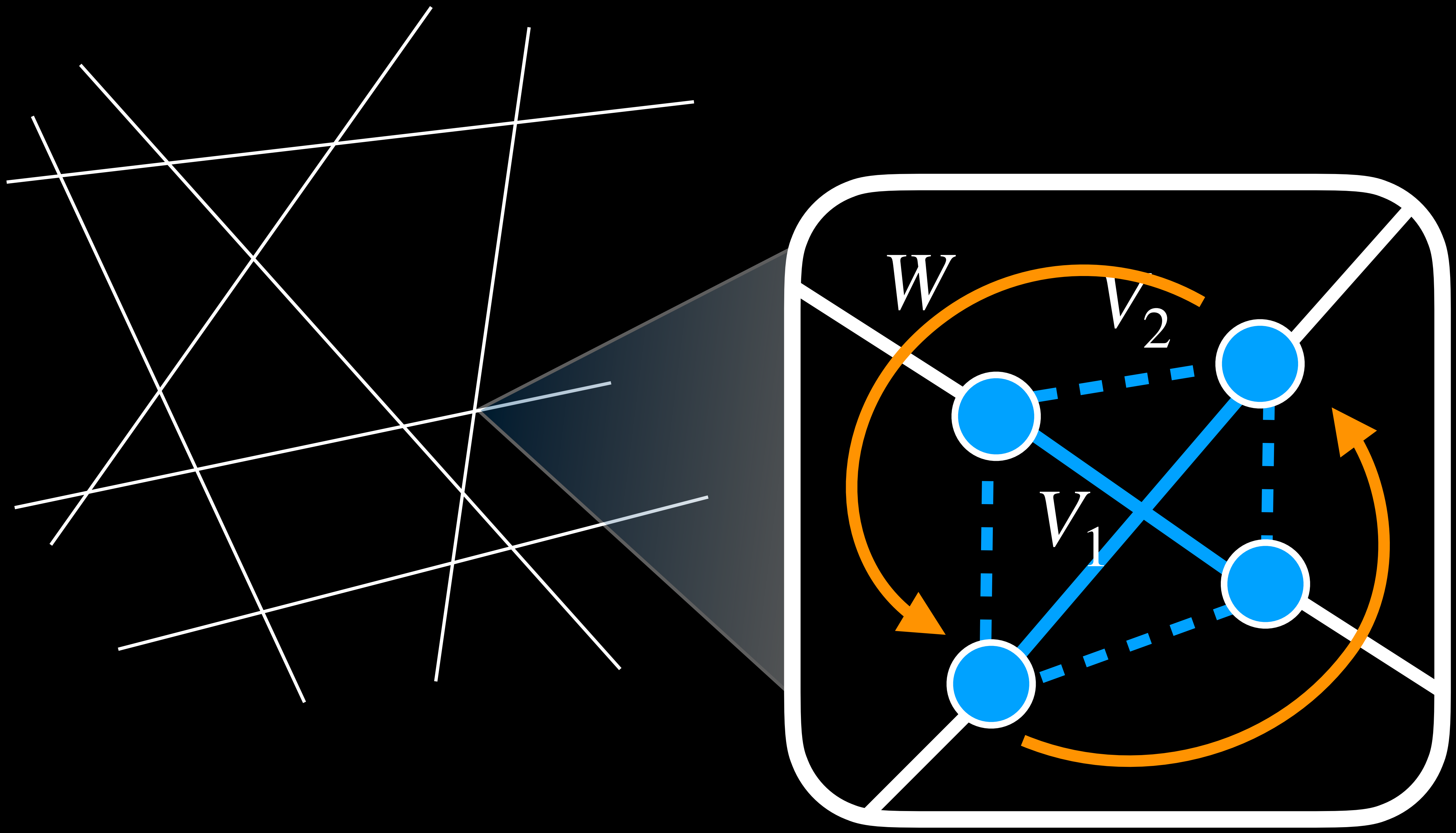
Liu and Vanderbilt PRB (2014)

Test system (unknown) — Reference system (known)

amorphous vs crystalline

How do we find amorphous topological insulators?

Model Hamiltonians



ab-initio simulations

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Liu and Vanderbilt PRB (2014)

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amorphous vs crystalline

Symmetry indicators

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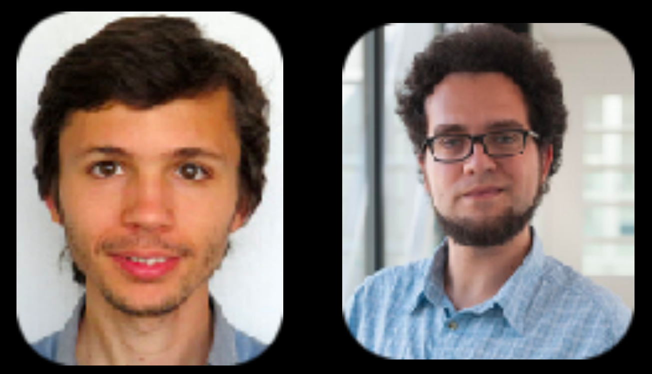


Quentin Marsal, Néel Institute

Daniel Varjas, MPI PKS

captures topological transition in a-Bi_2Se_3

Corbae et al, Nat Materials (2023)

Structural spillage

arXiv: 2301.02686

Daniel Muñoz-Segovia, DIPC

Paul Corbae, Berkeley

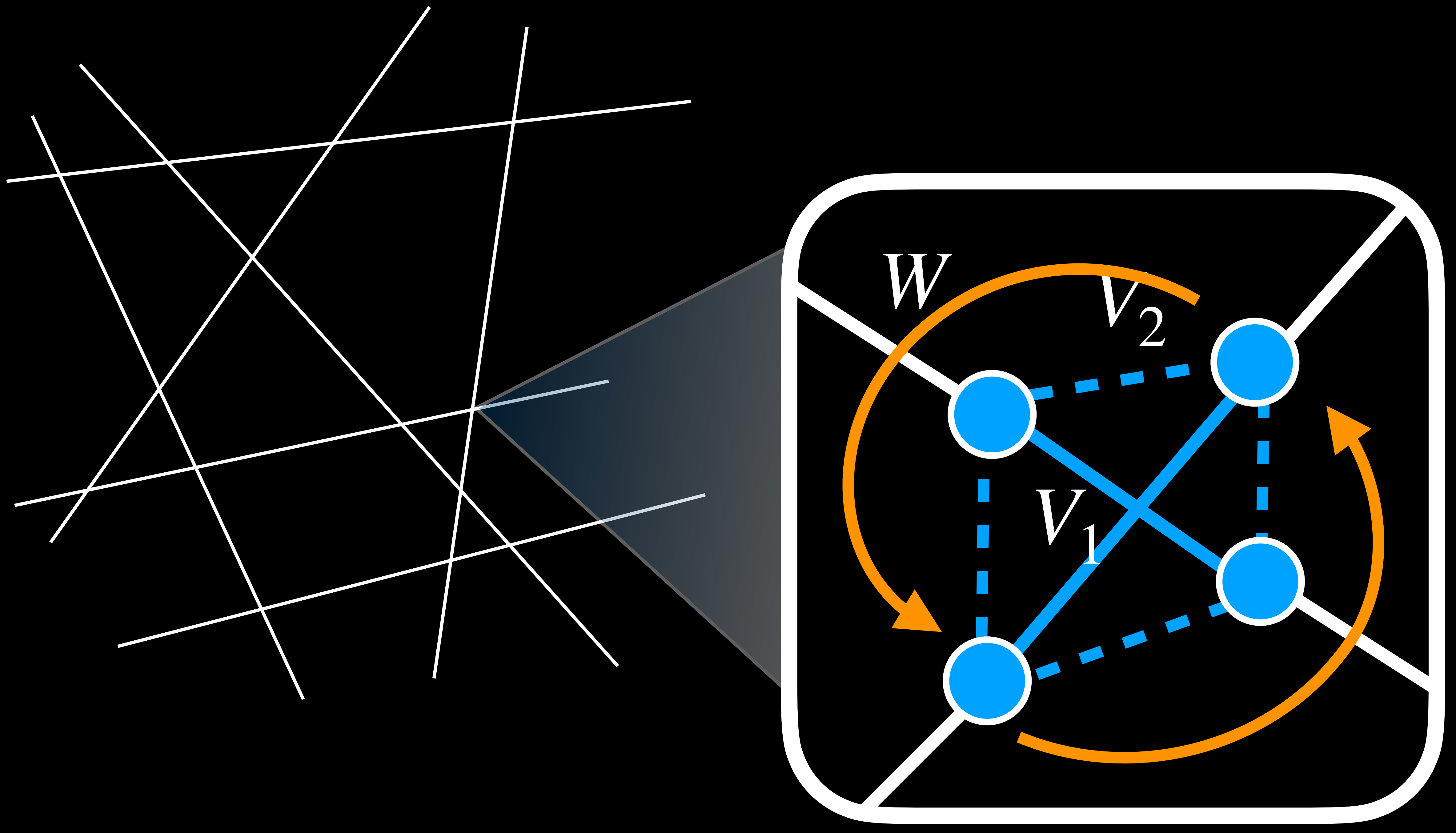
Frances Hellmann, Berkeley

Sinead Griffin, Berkeley

Daniel Varjas, MPI-PKS

How do we find amorphous topological insulators?

Model Hamiltonians



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Liu and Vanderbilt PRB (2014)

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amorphous vs crystalline

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Néel Institute

Daniel Varjas
MPI PKS

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Corbae et al, Nat Materials (2023)

Structural spillage

arXiv: 2301.02686

predicts a-Bismuthene and its bilayer as QSH

Daniel Muñoz-Segovia
DIPC

Paul Corbae
Berkeley

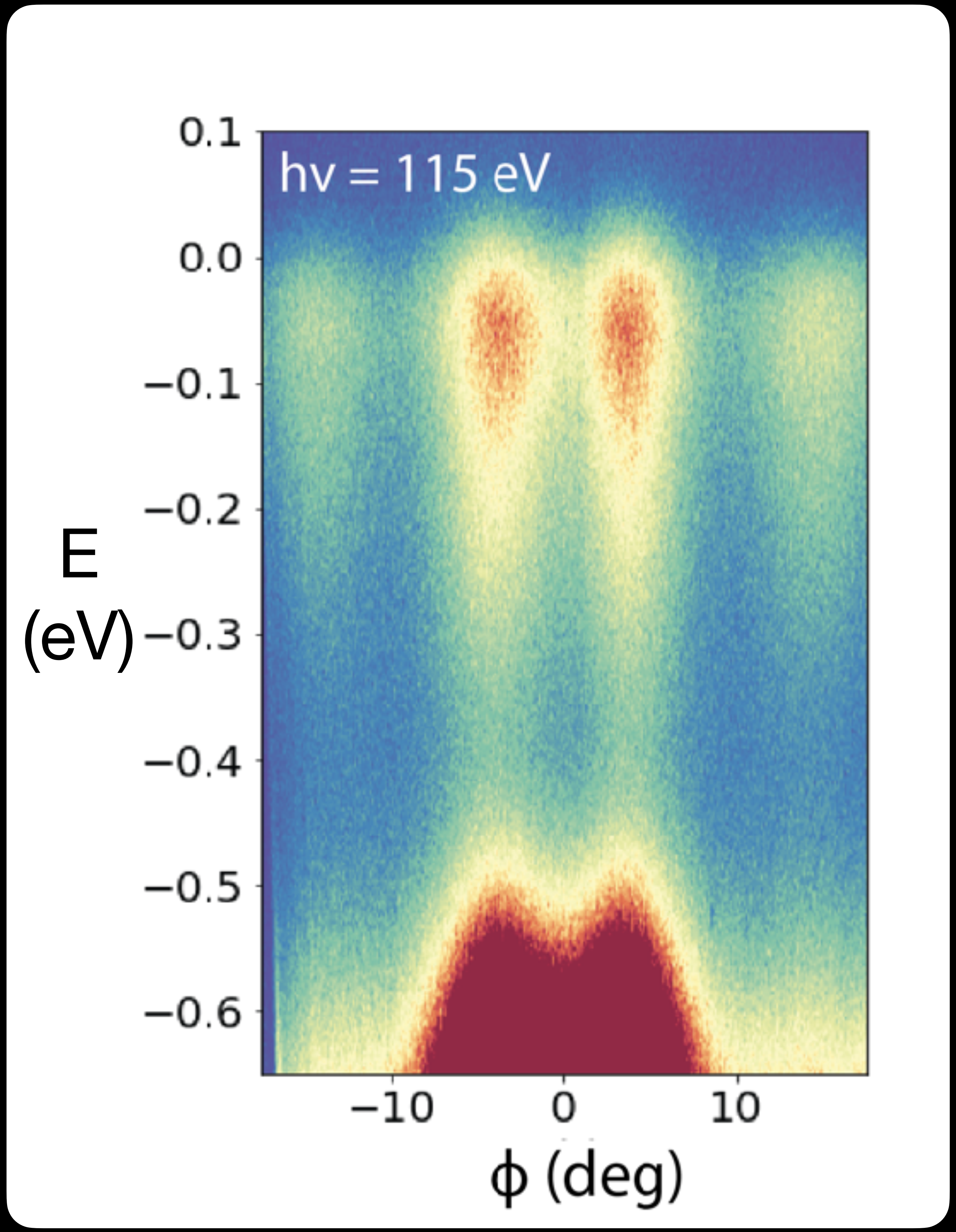
Frances Hellmann
Berkeley

Sinead Griffin
Berkeley

Daniel Varjas
MPI-PKS

Topological amorphous phases

solid state: a-Bi_2Se_3



Do they exist?

Yes, also in solids

How do we find them in real solids?

Use spillage or symmetry indicators (topological markers)

Any different physics compared to crystals?

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

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

How to drive a topological transition with structural disorder?

Reversible switch — fast

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

Controllable growth — slow

AGG, C. Repellin Phys. Rev. Lett (2023)

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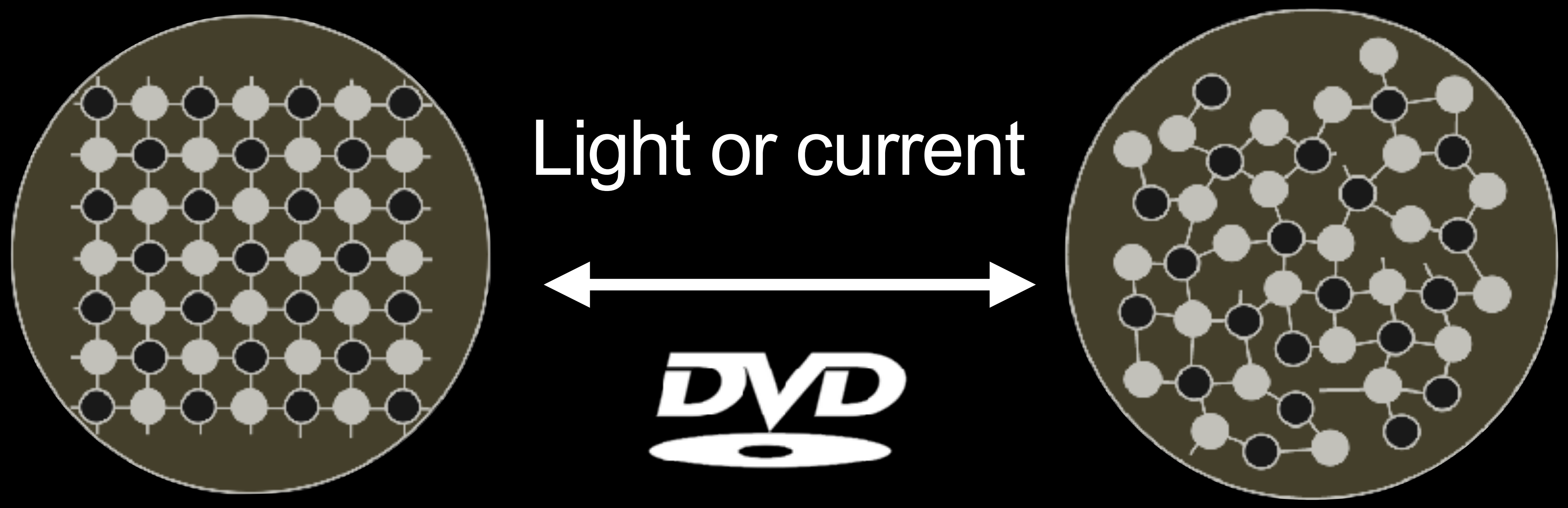
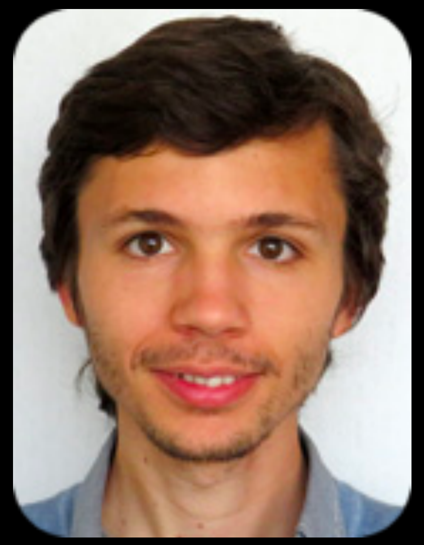


Crystal

Amorphous



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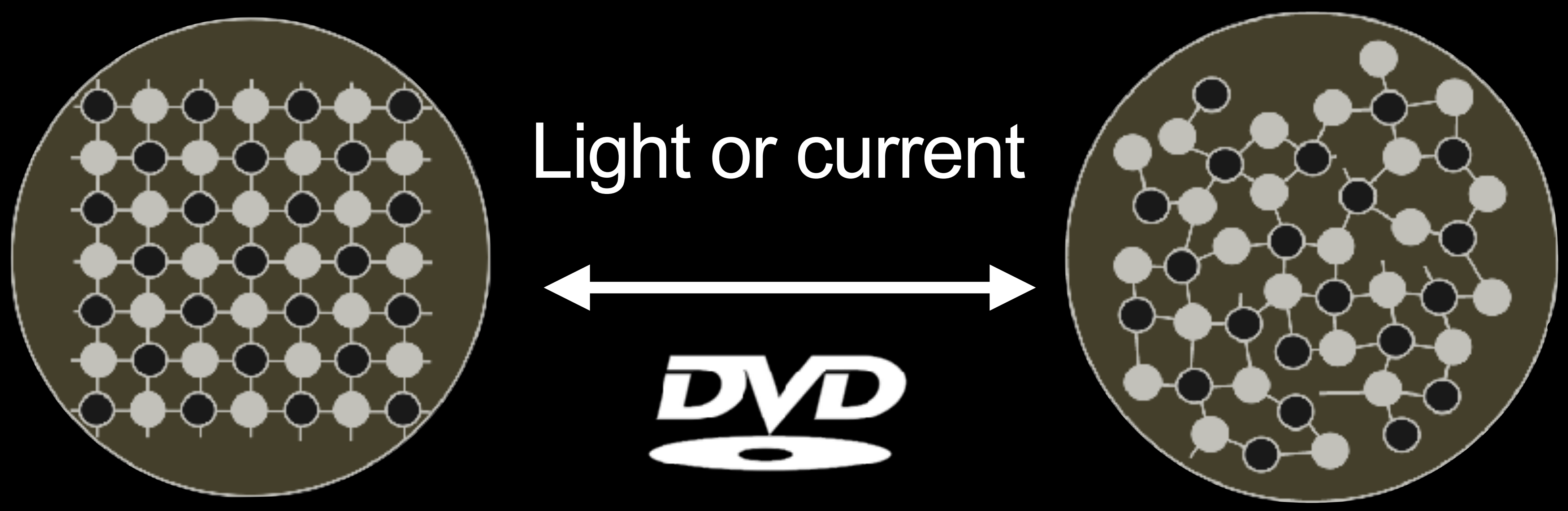

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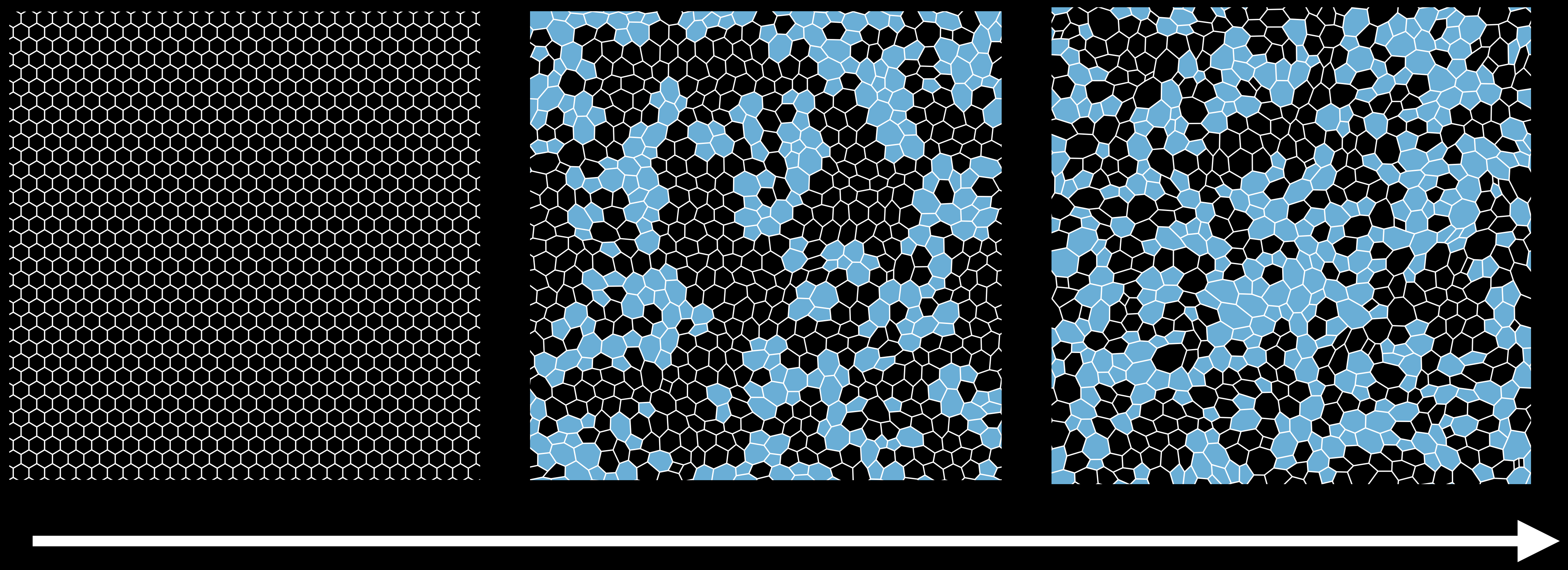
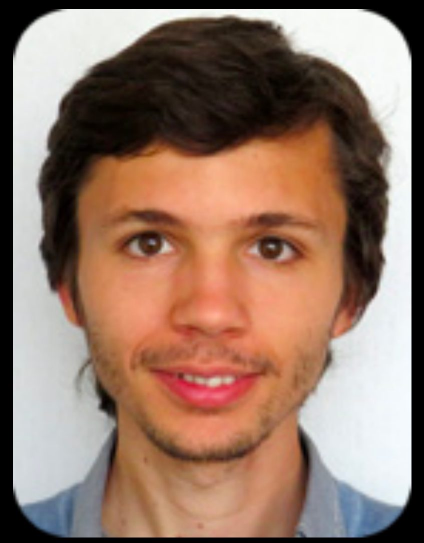


structural disorder



Q. Marsal,
Néel Institute

D. Varjas,
MPI PKS

Cécile Repellin
LPMMC / Grenoble

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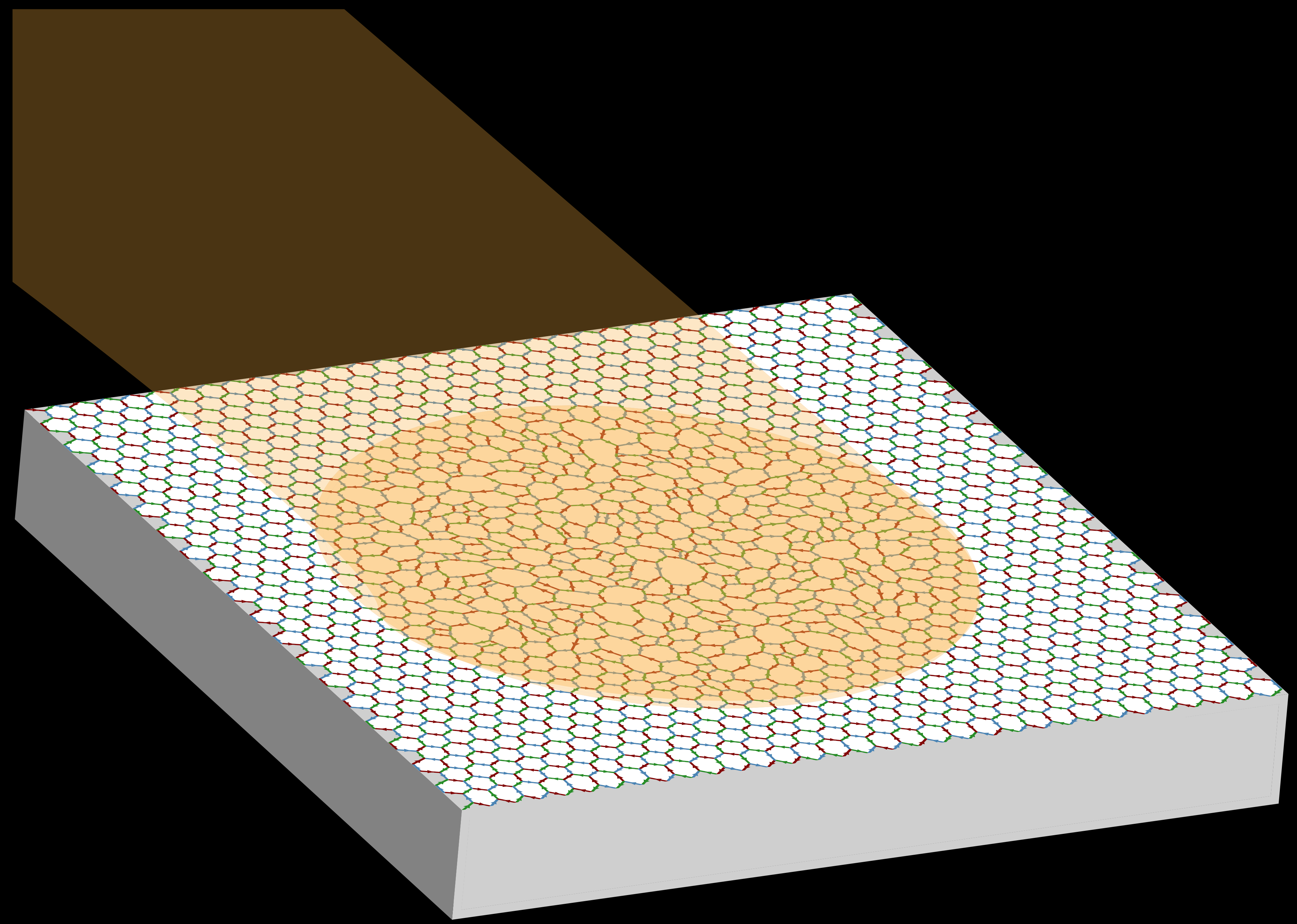
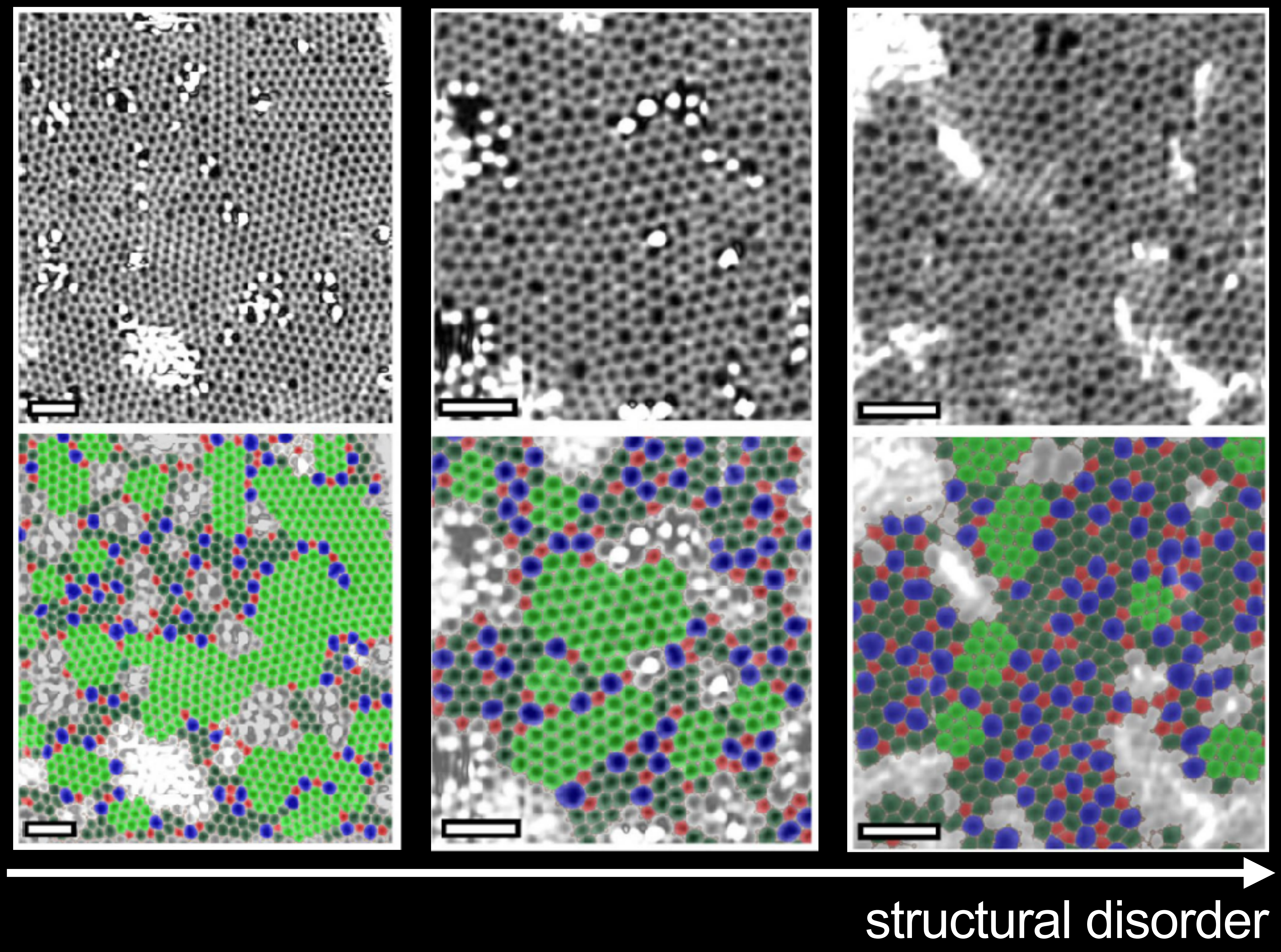


A. Bake et al **14**, Nat. Comm 1693 (2023)

Controllable growth — slow

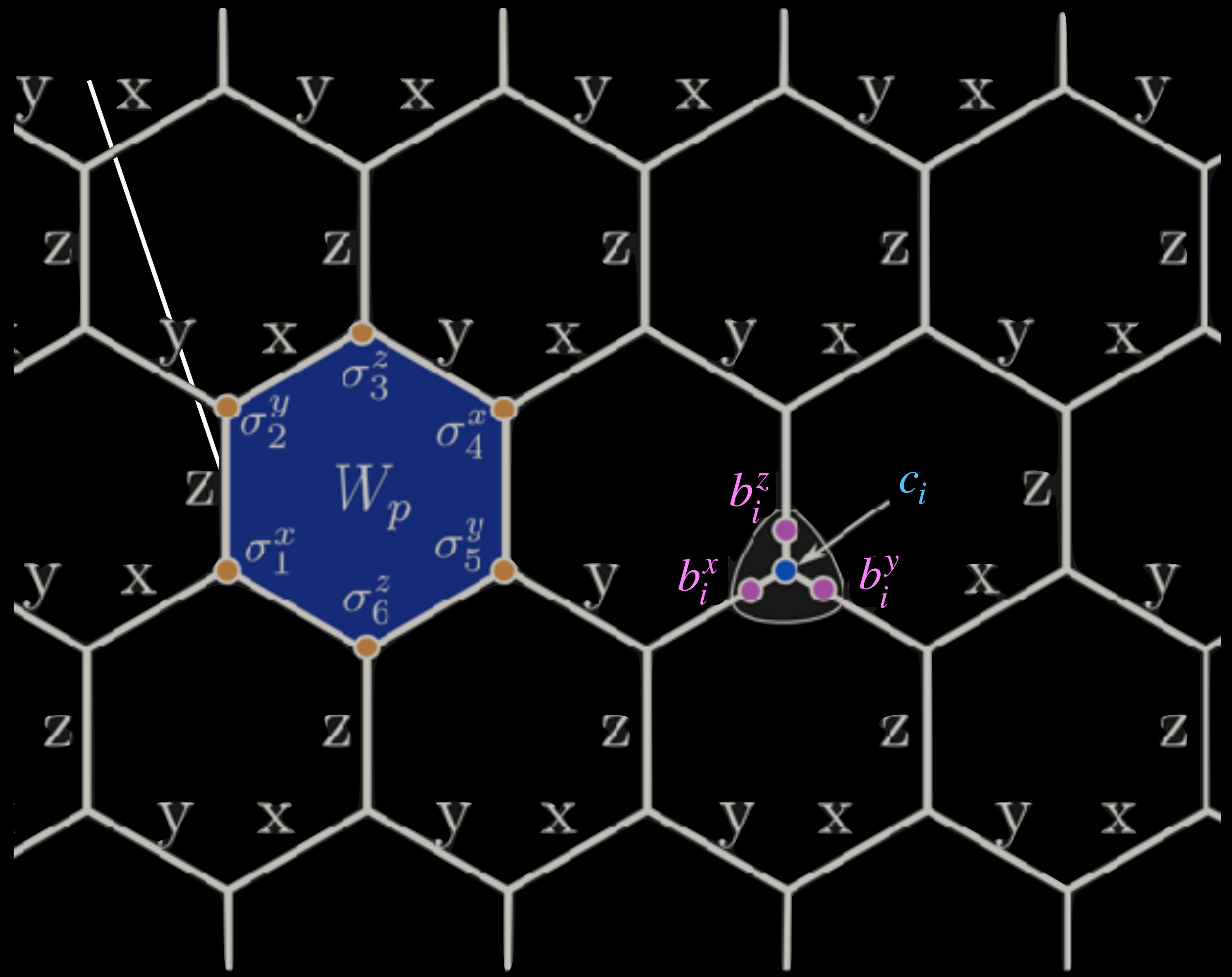
Amorphous graphene
Tian et al. Nature (2023)



amorphous Kitaev honeycomb model

Kitaev Ann. Phys. (2006)

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



gapless spin-liquid

amorphous Kitaev honeycomb model

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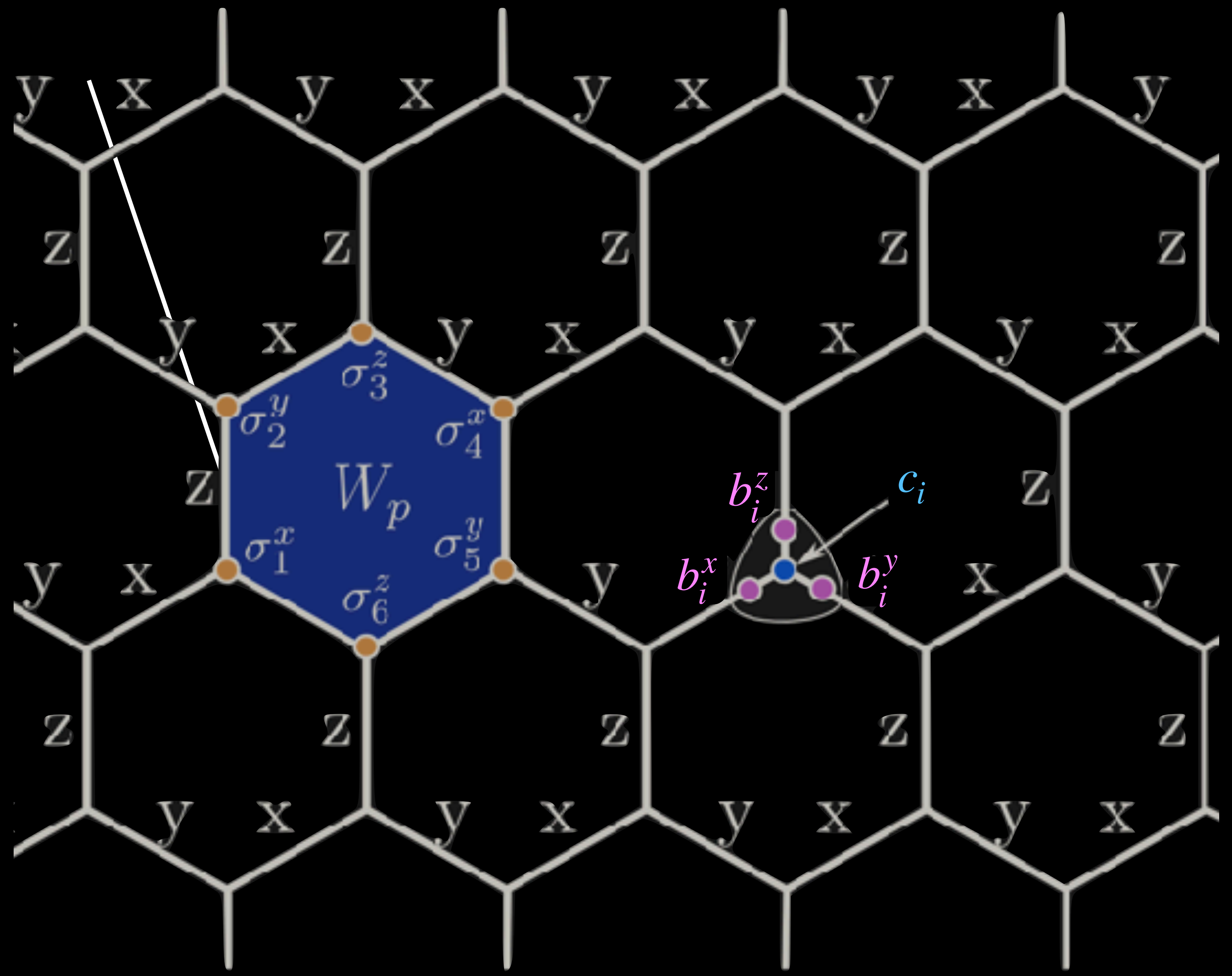

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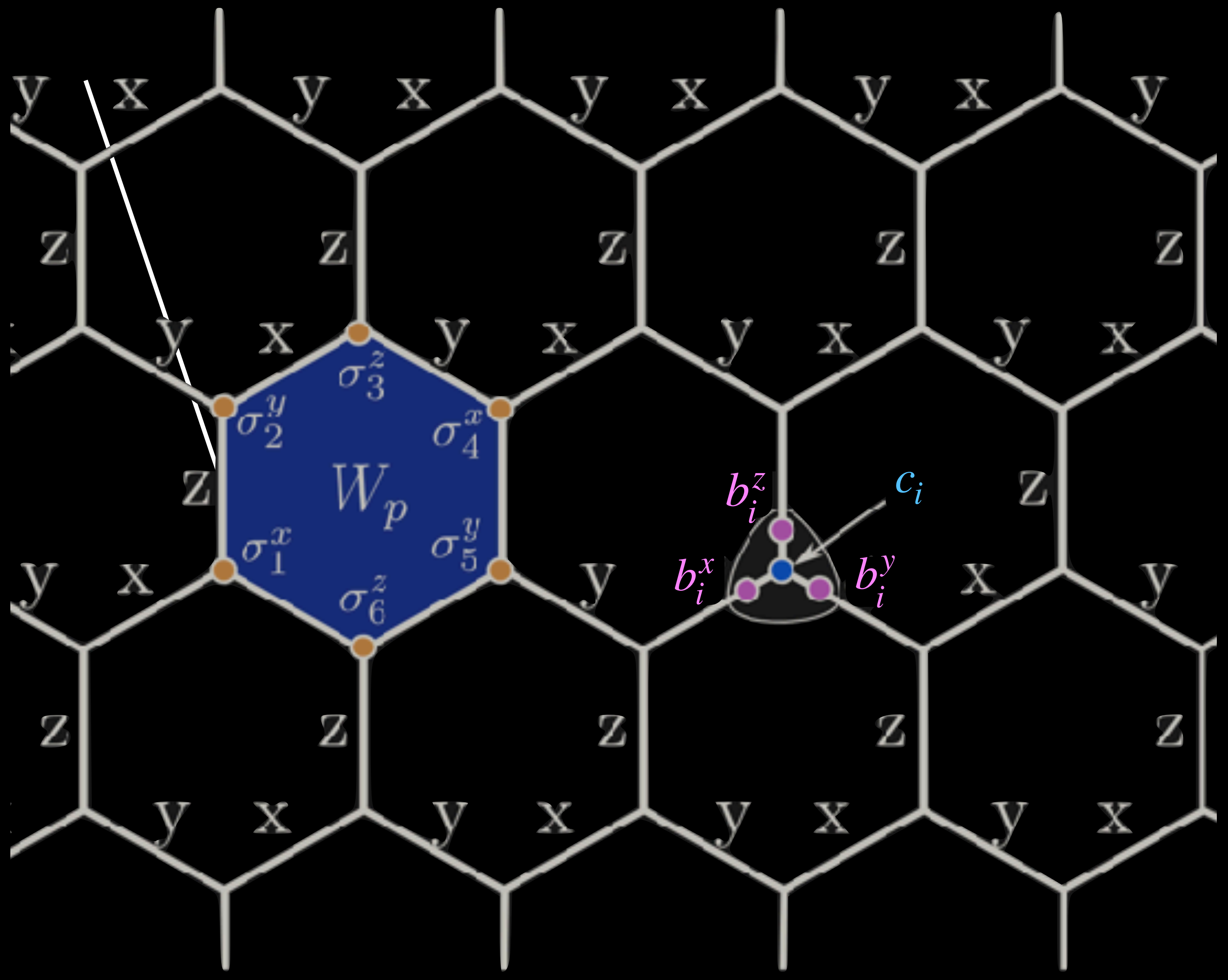
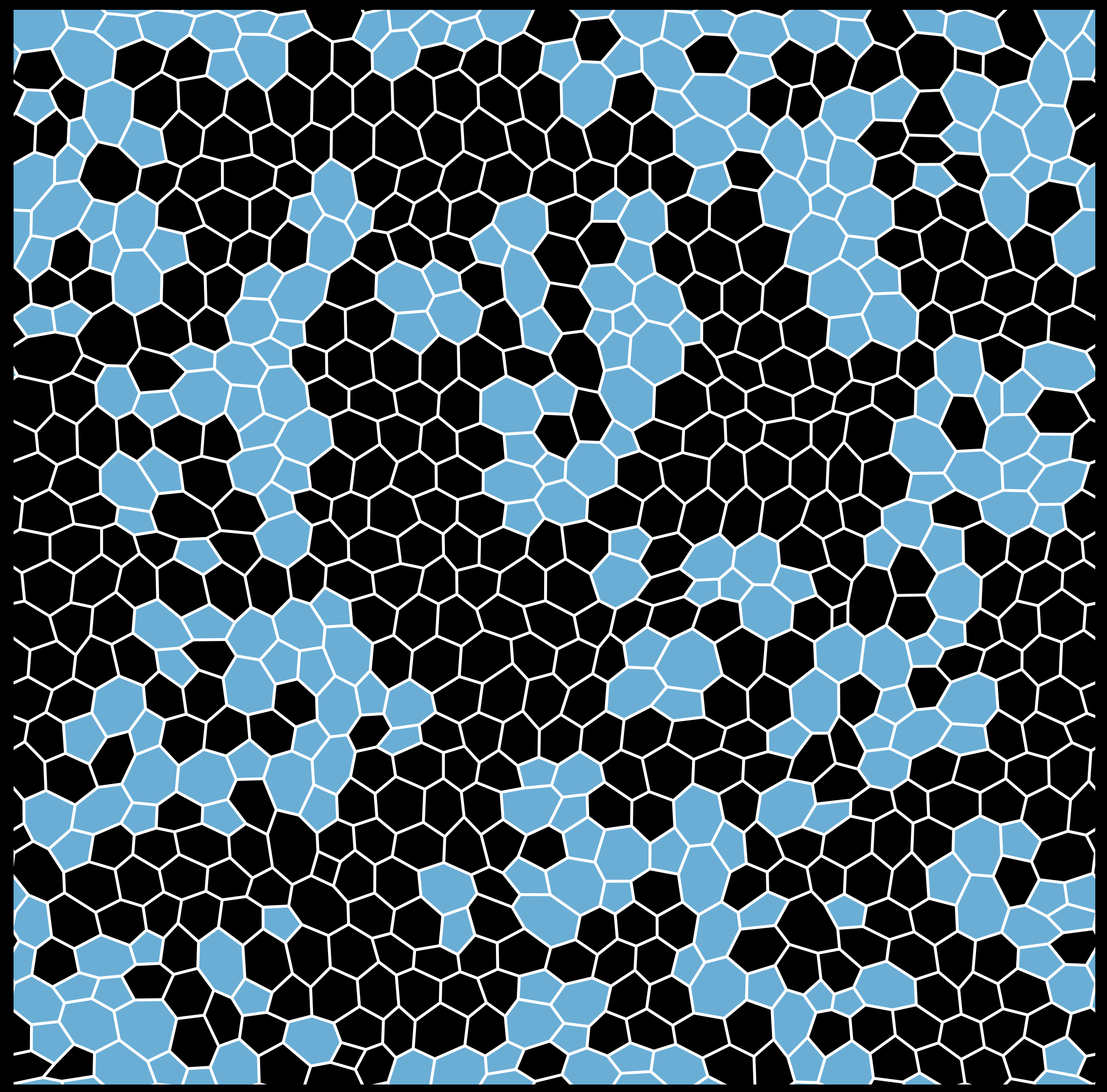
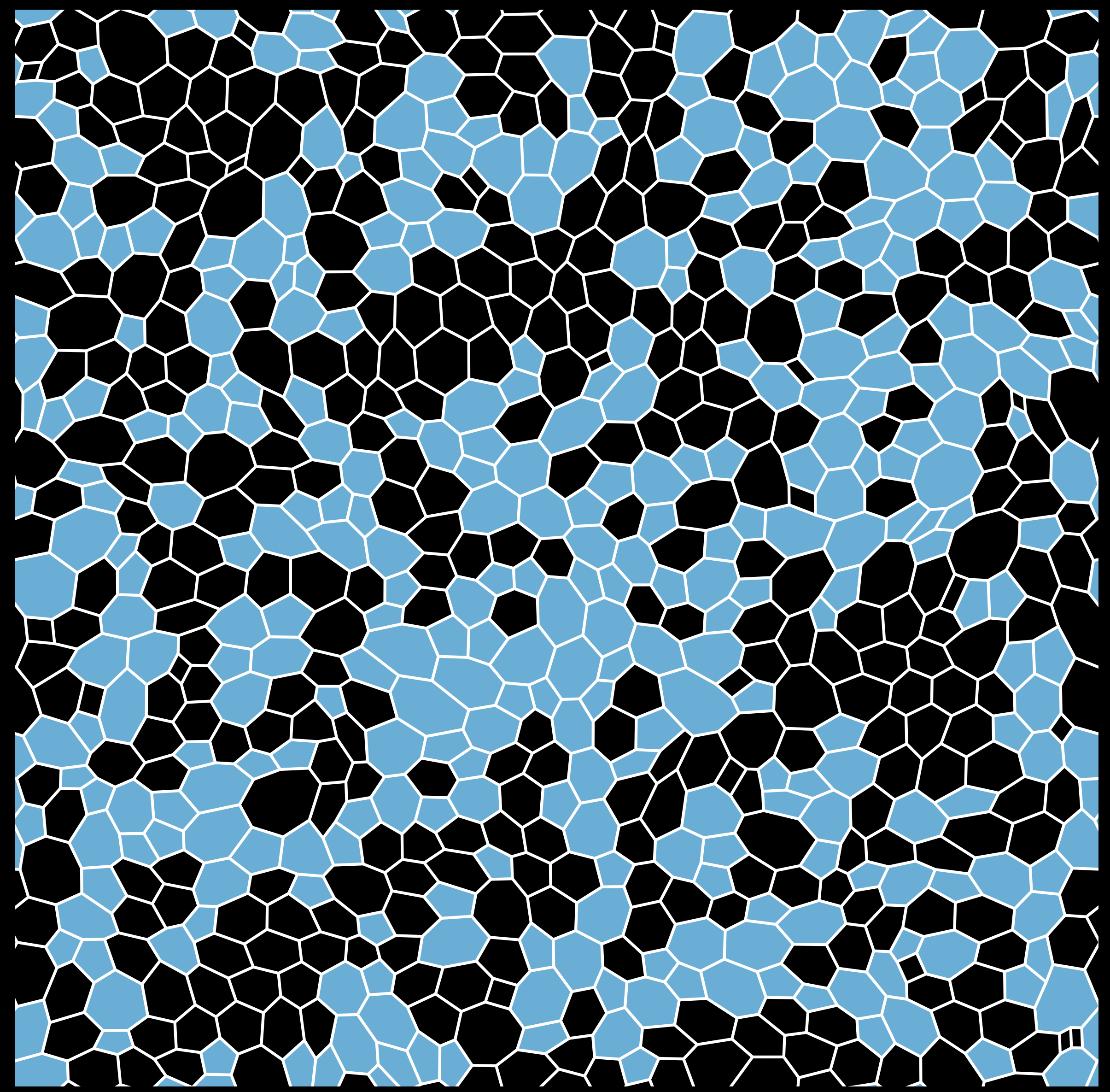




$\phi_p = -(\pm i)^{n_{sides}}$ G. Casella et al 2208.08246



structural disorder

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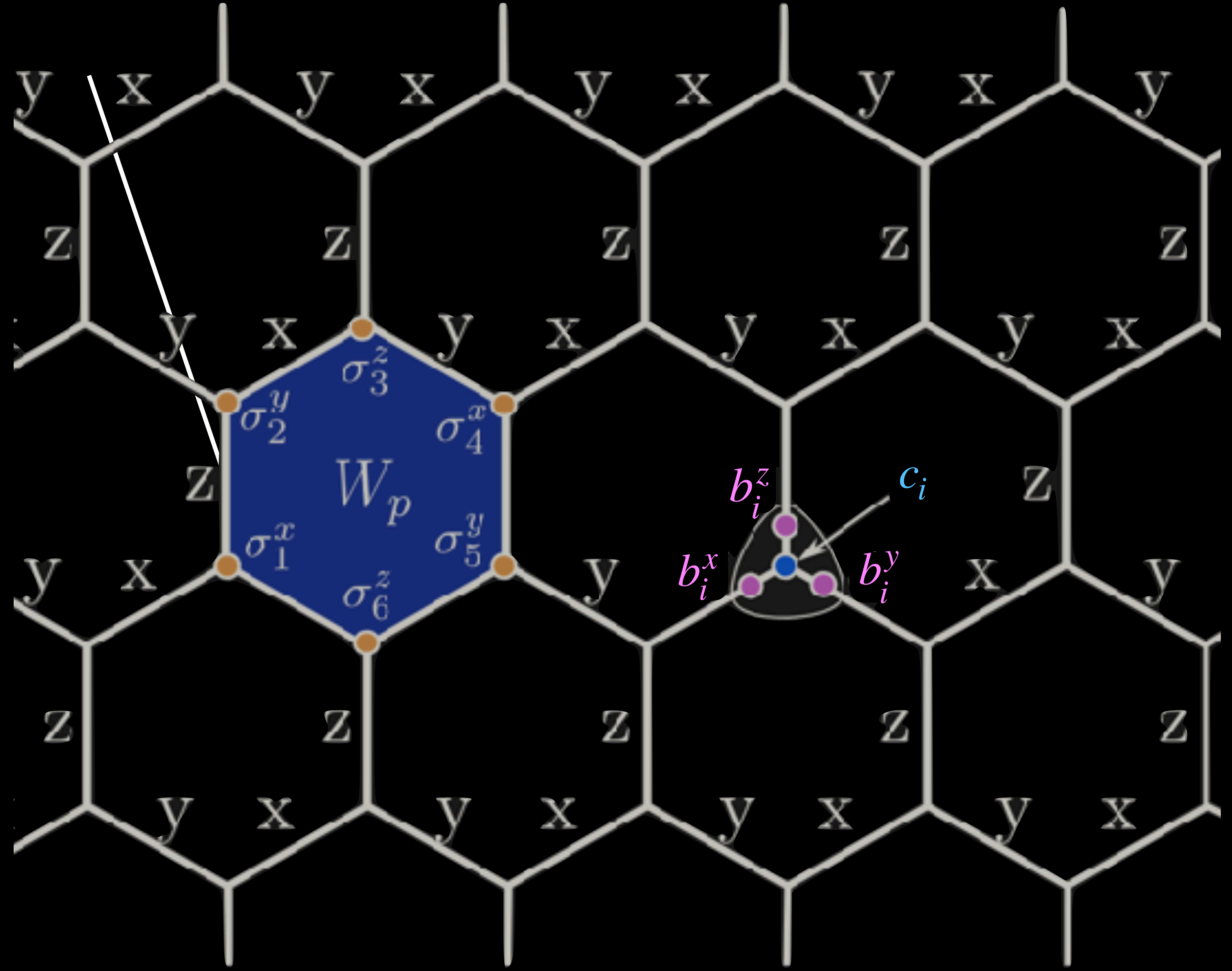

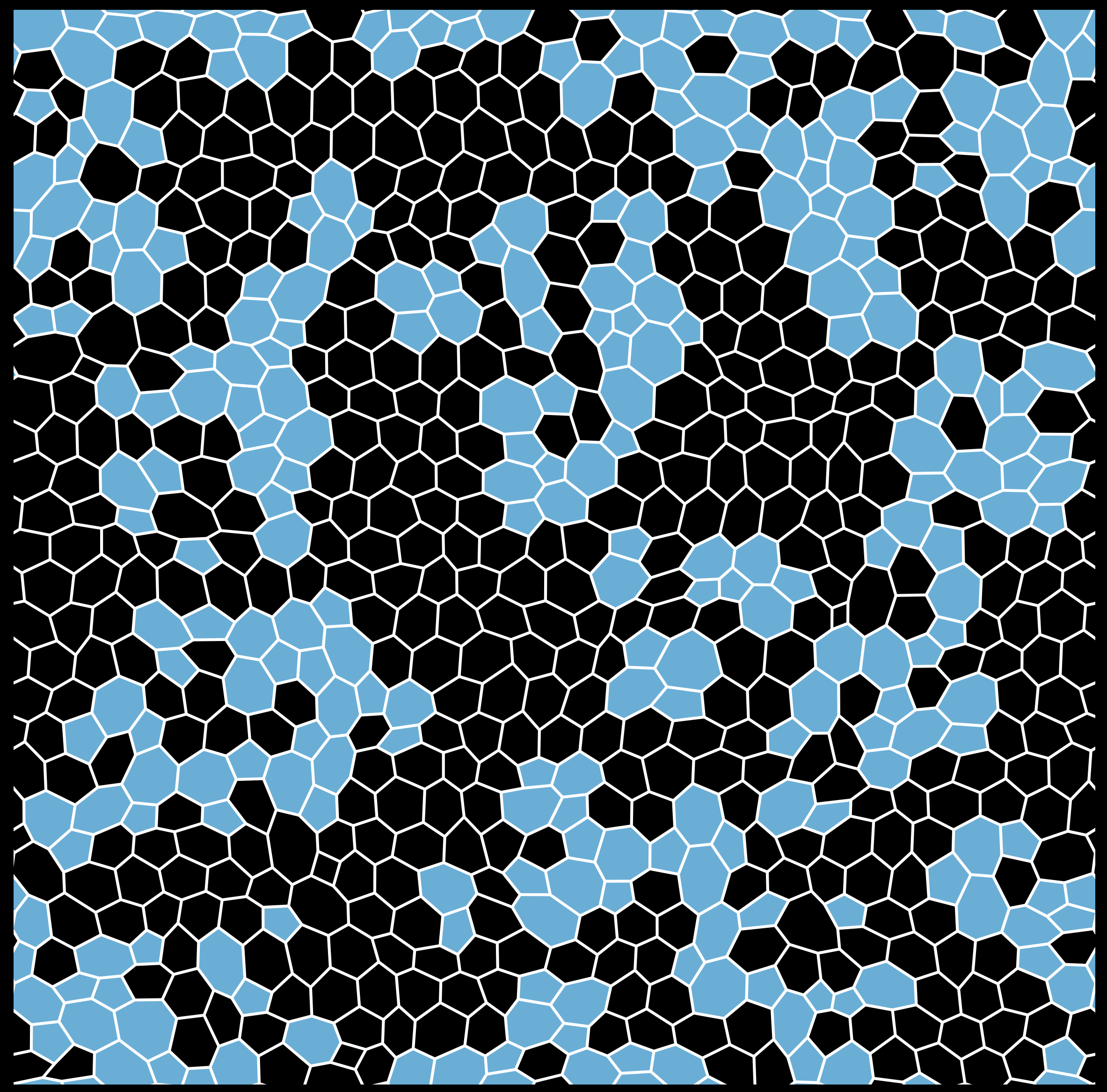

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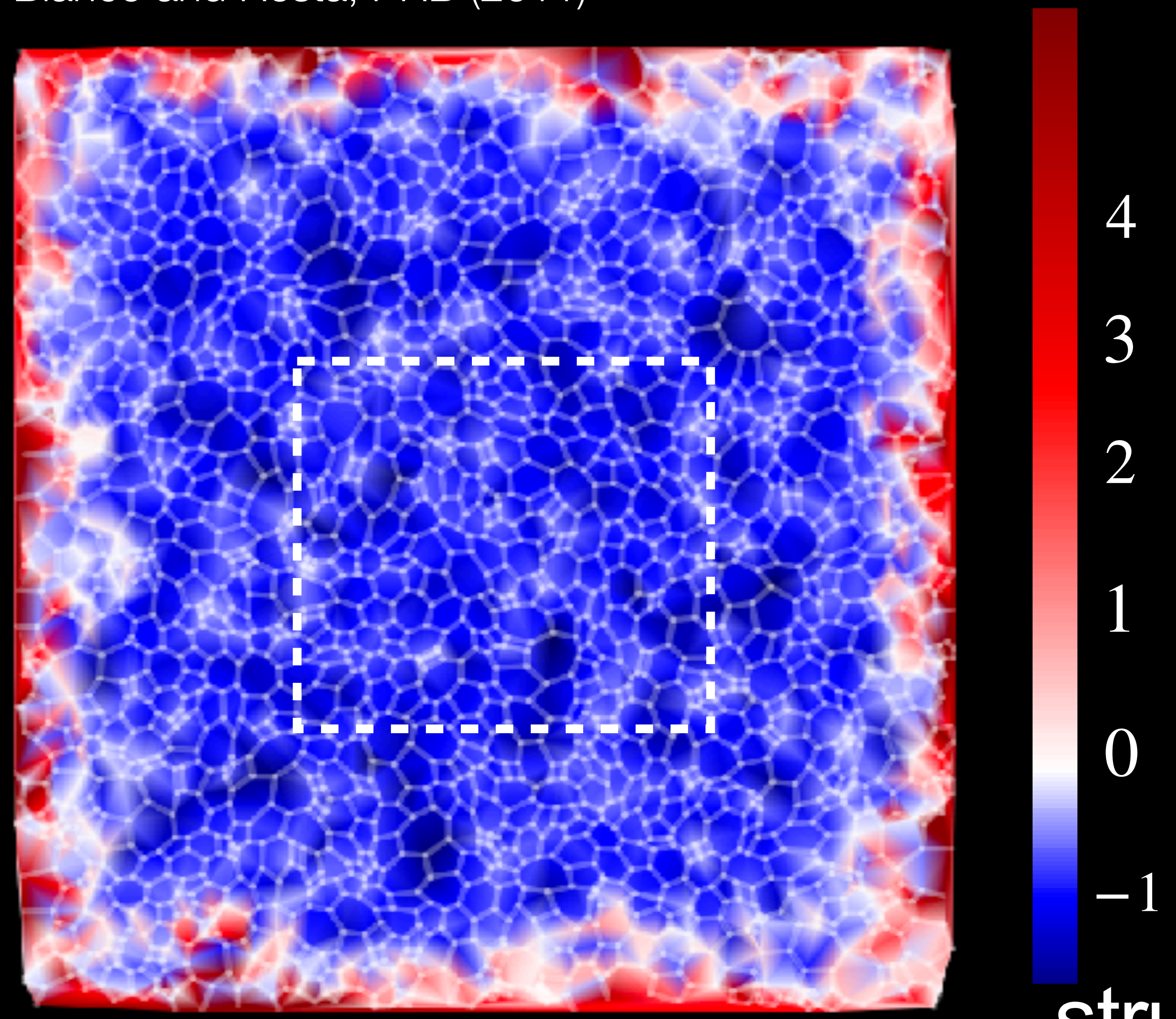
Bianco and Resta, PRB (2011)



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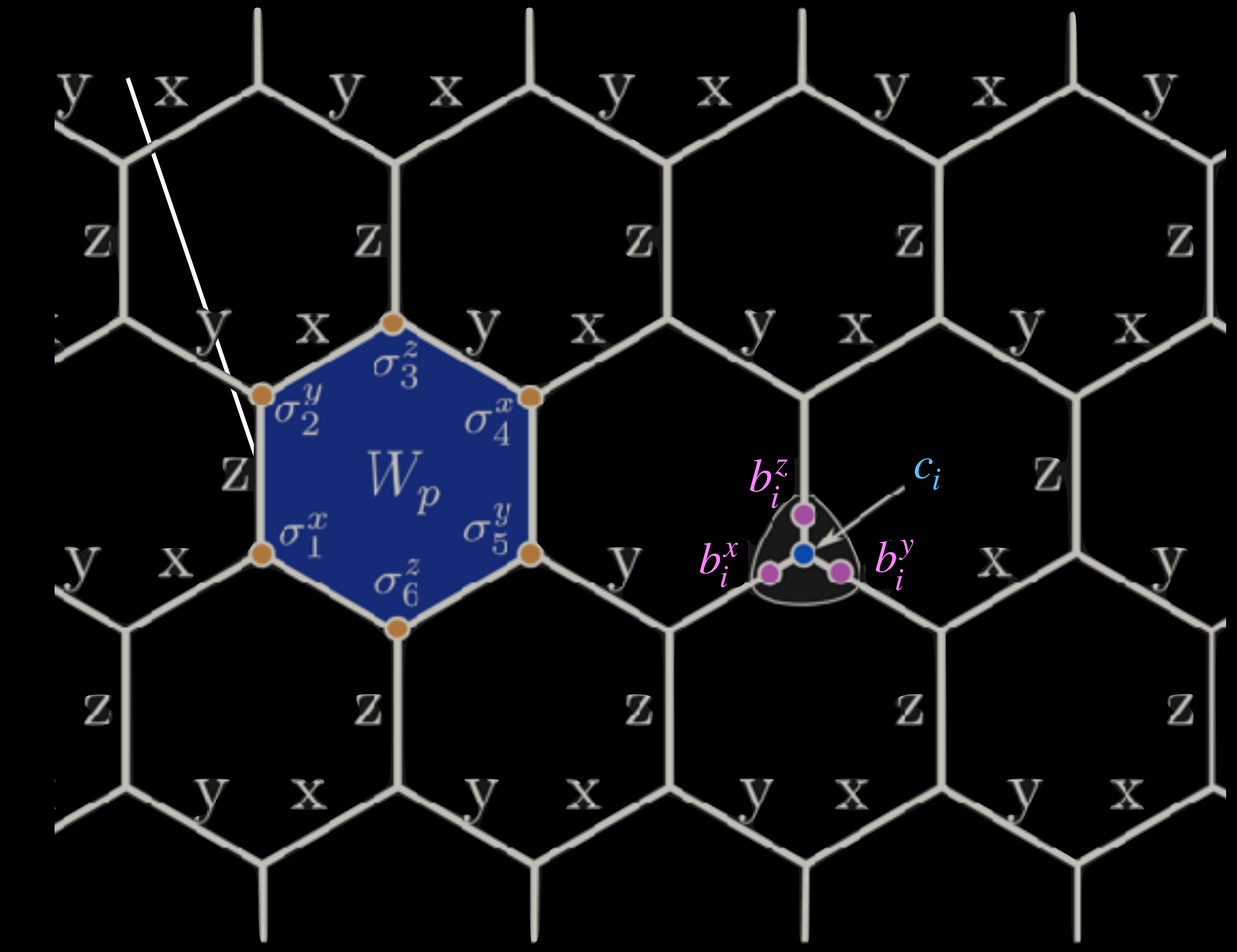

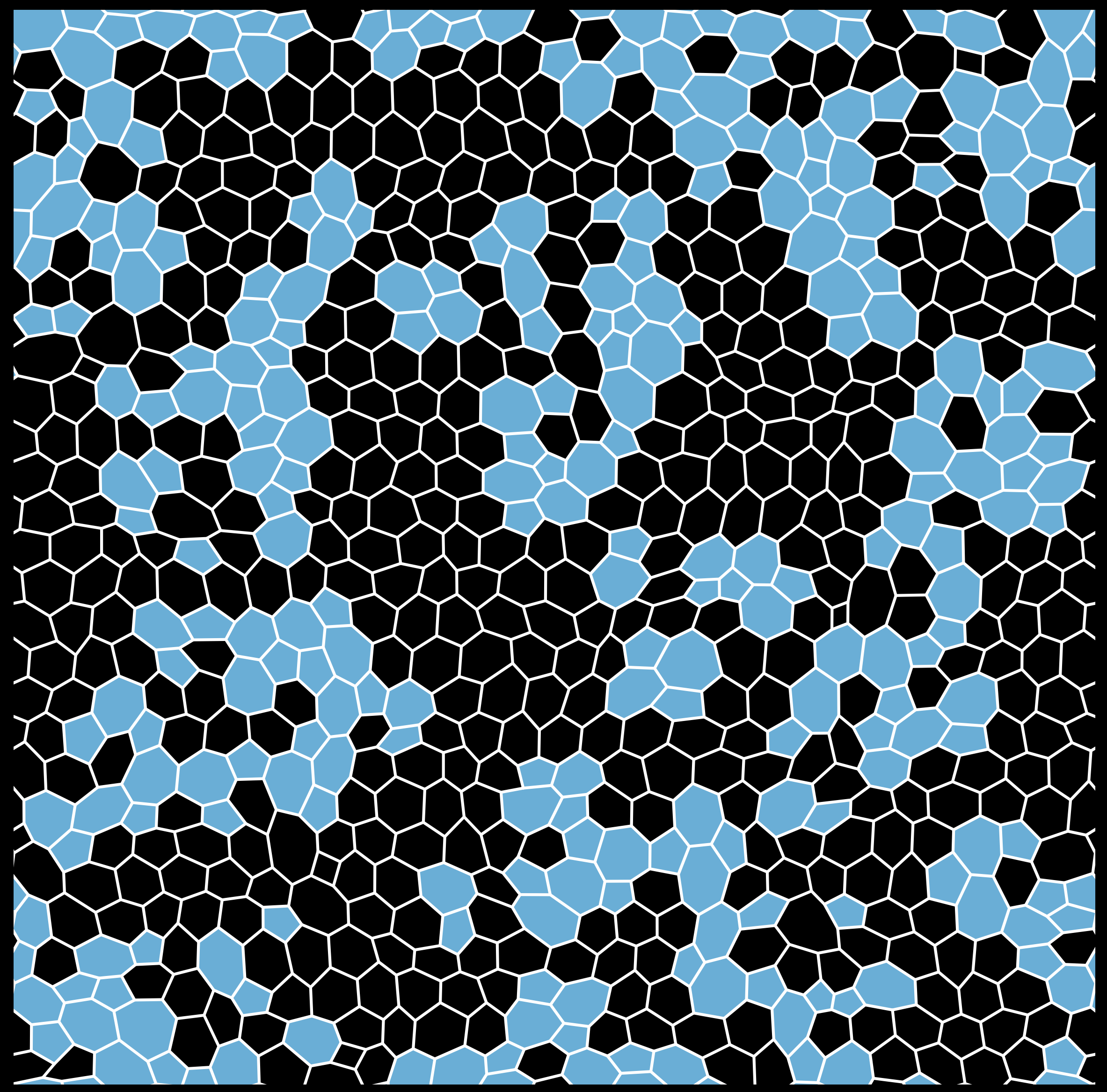

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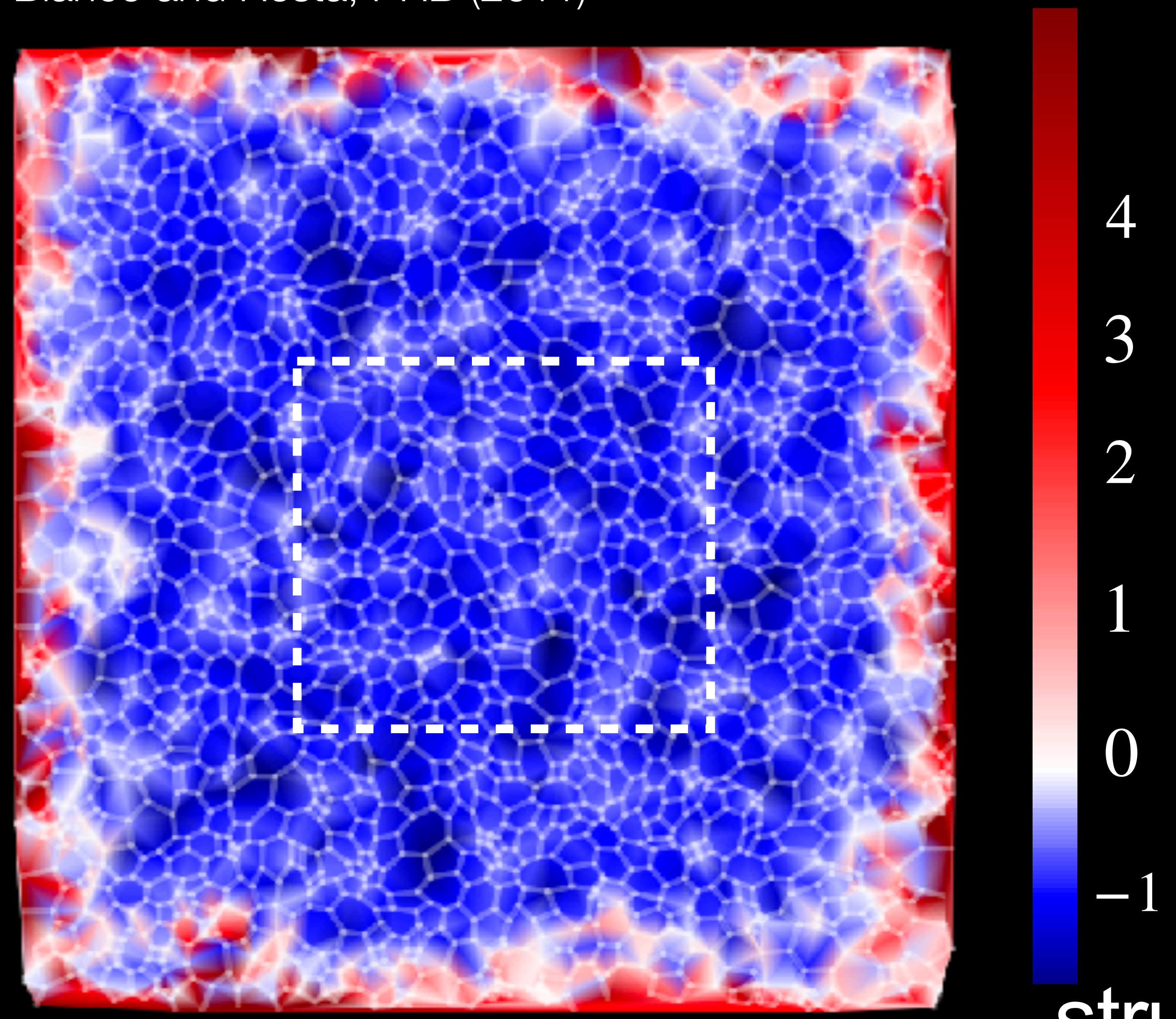

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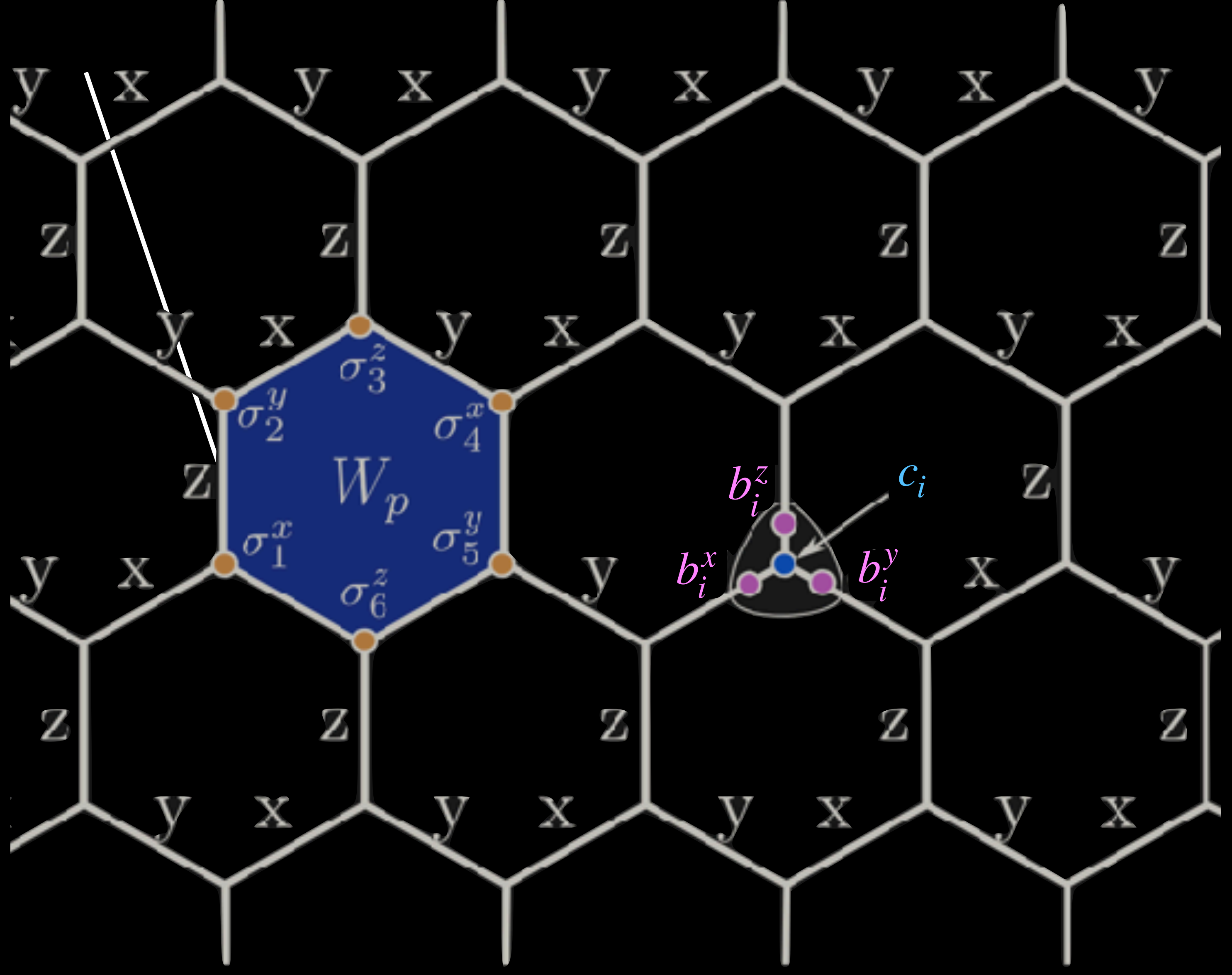

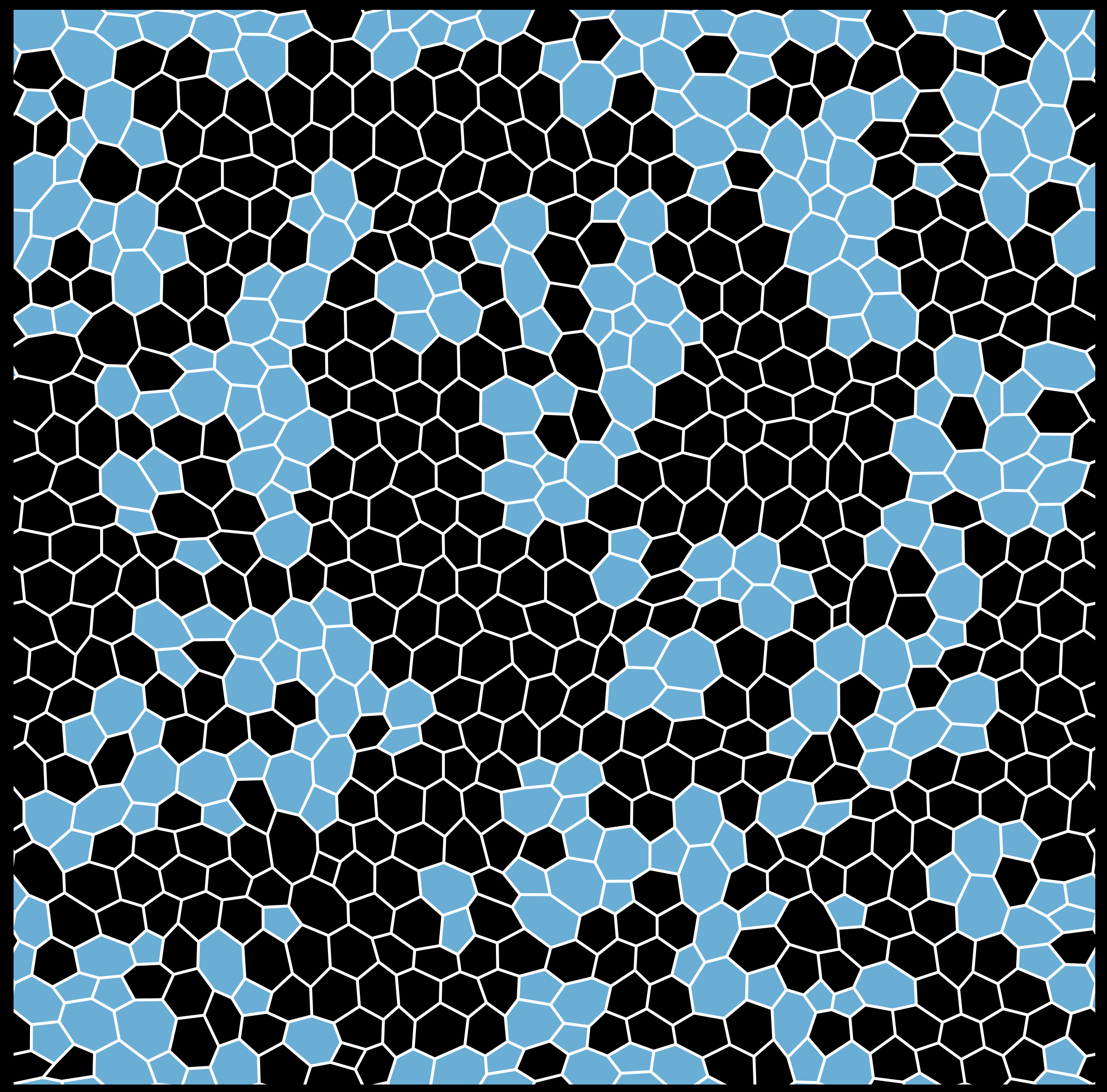

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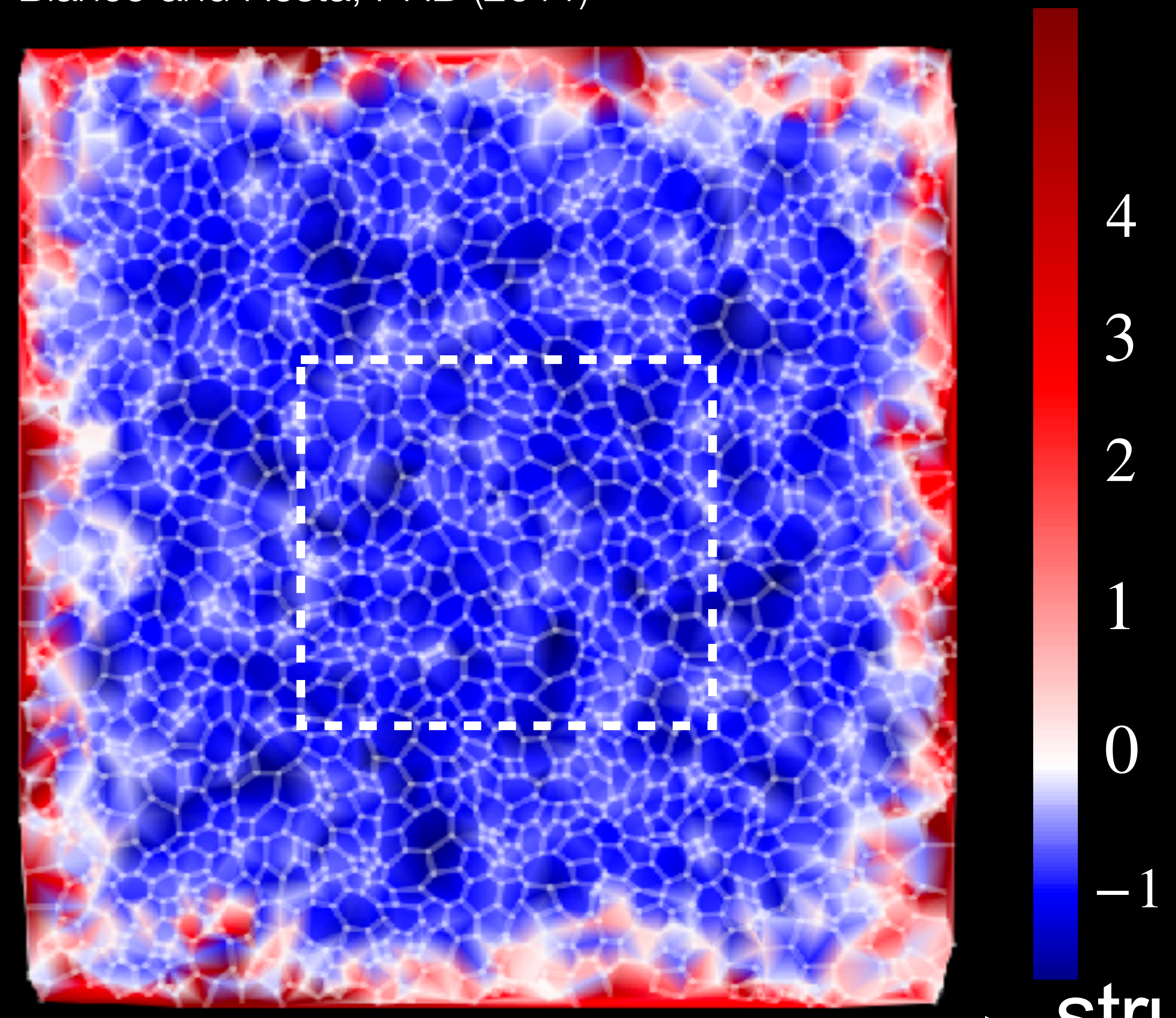

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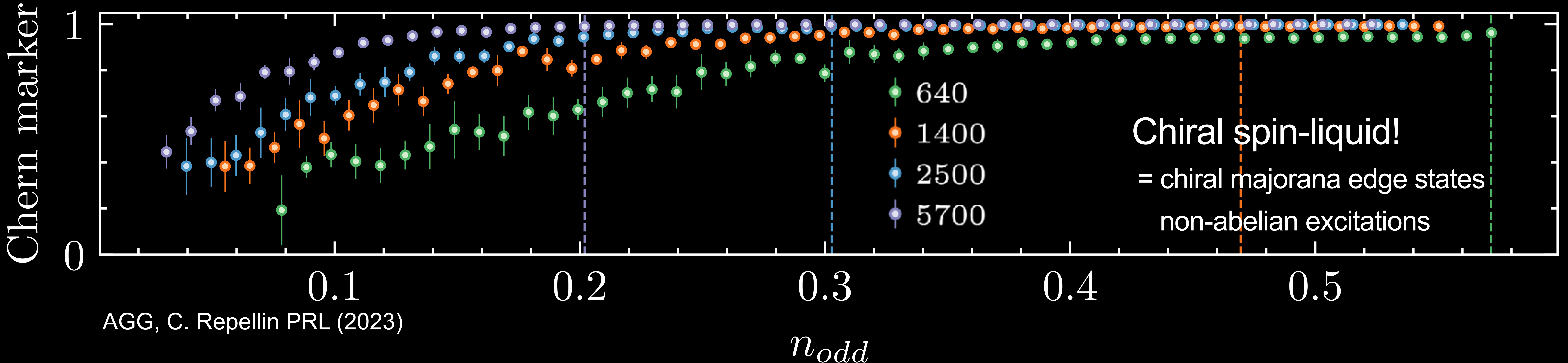

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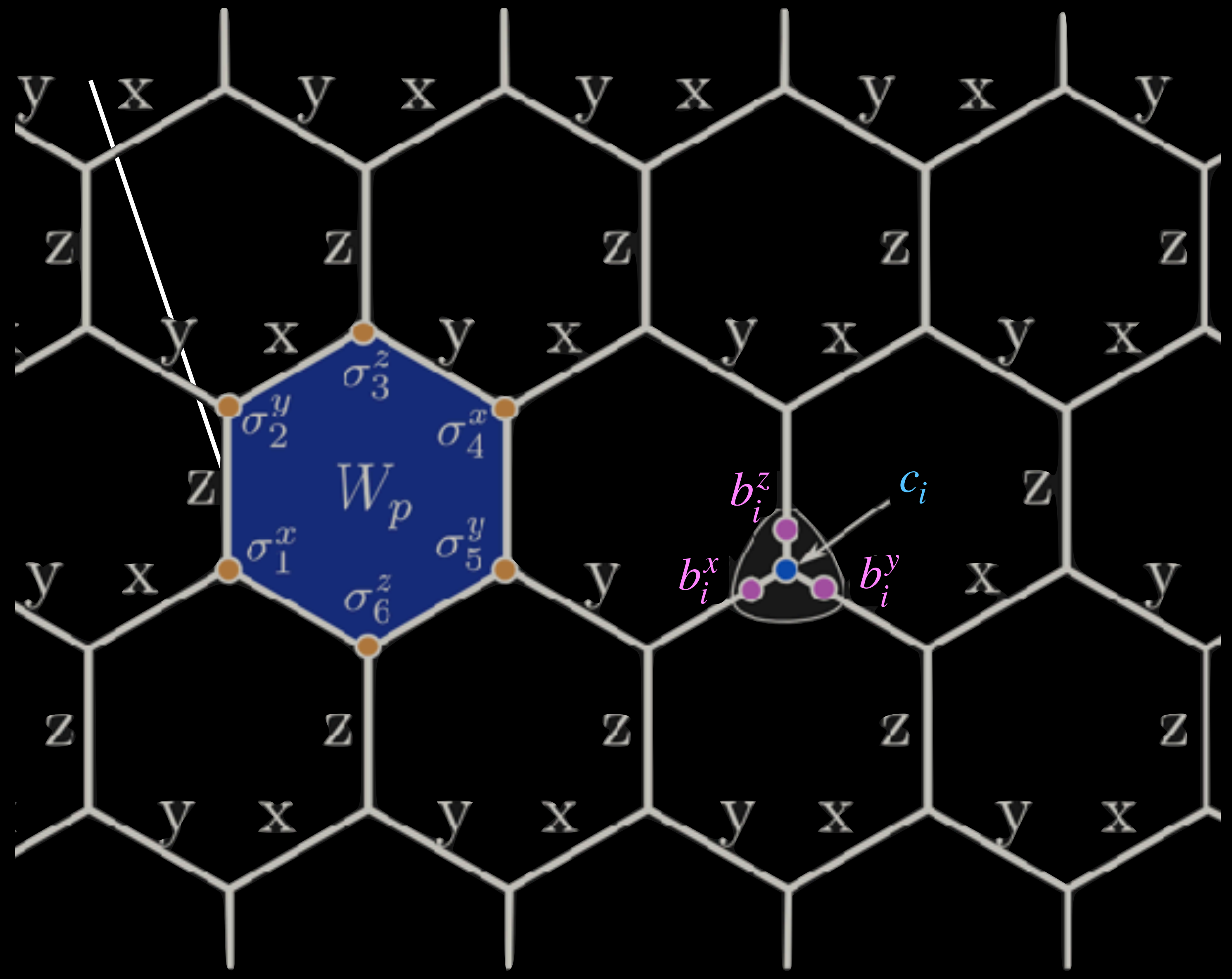

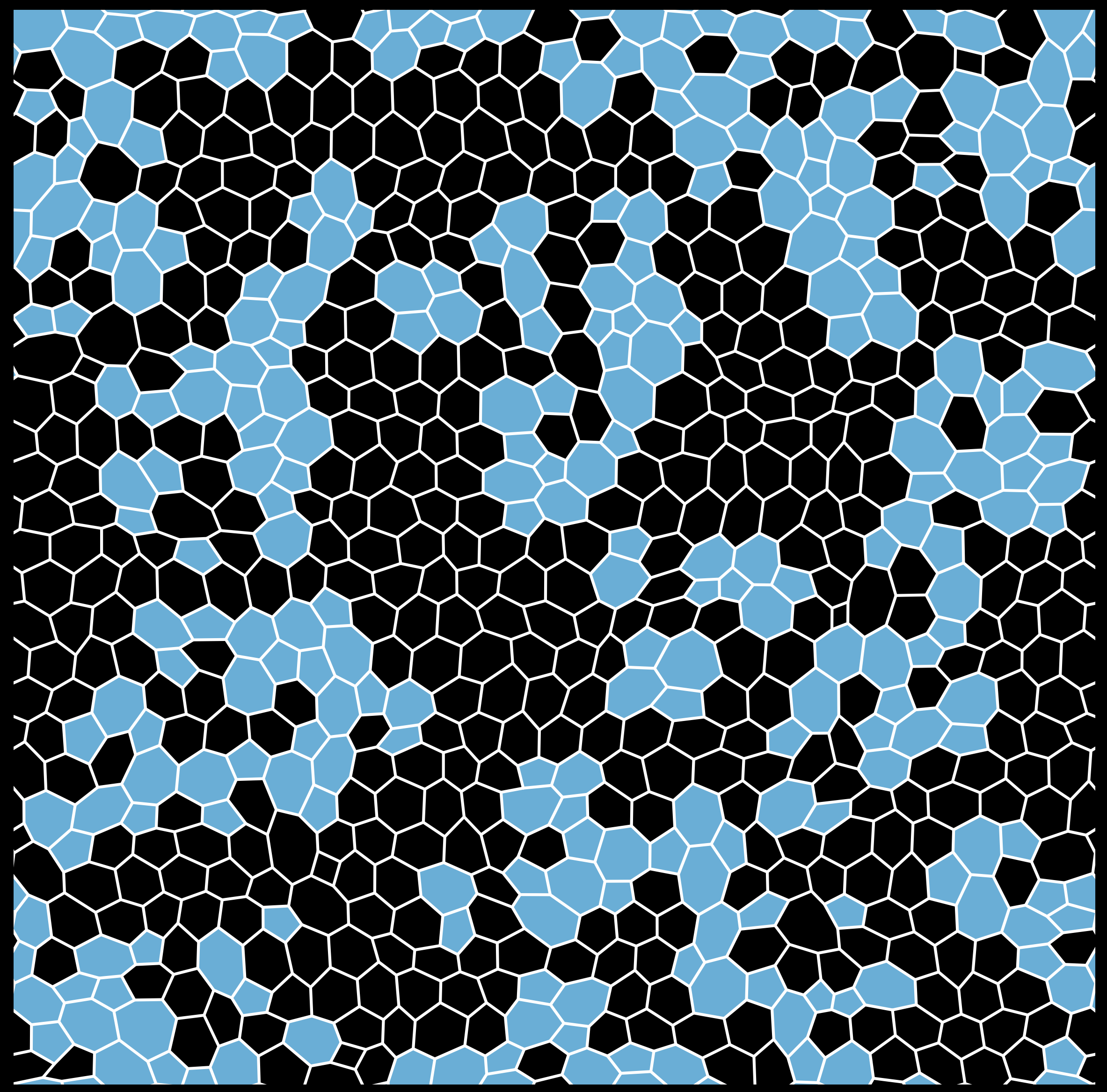

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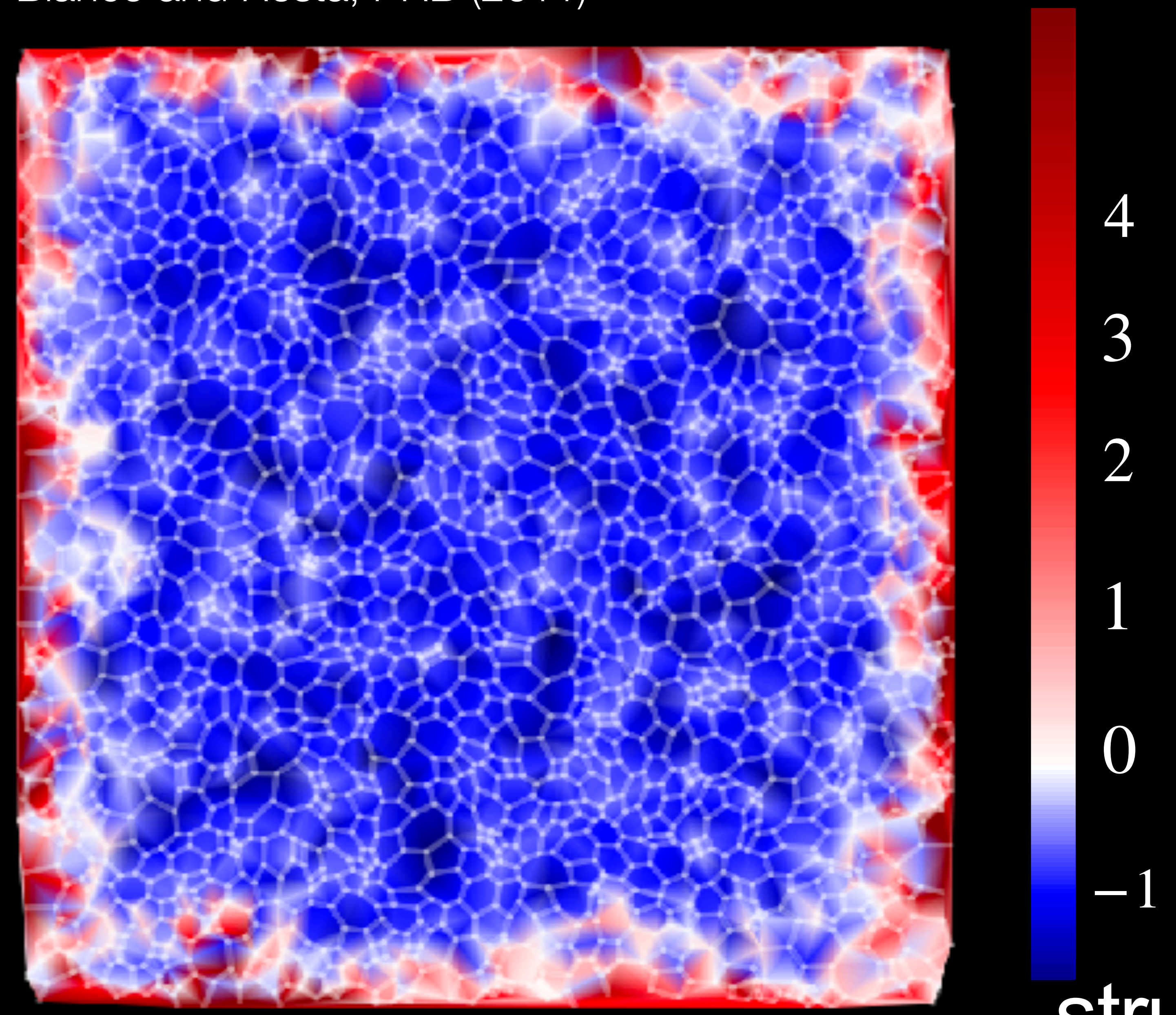

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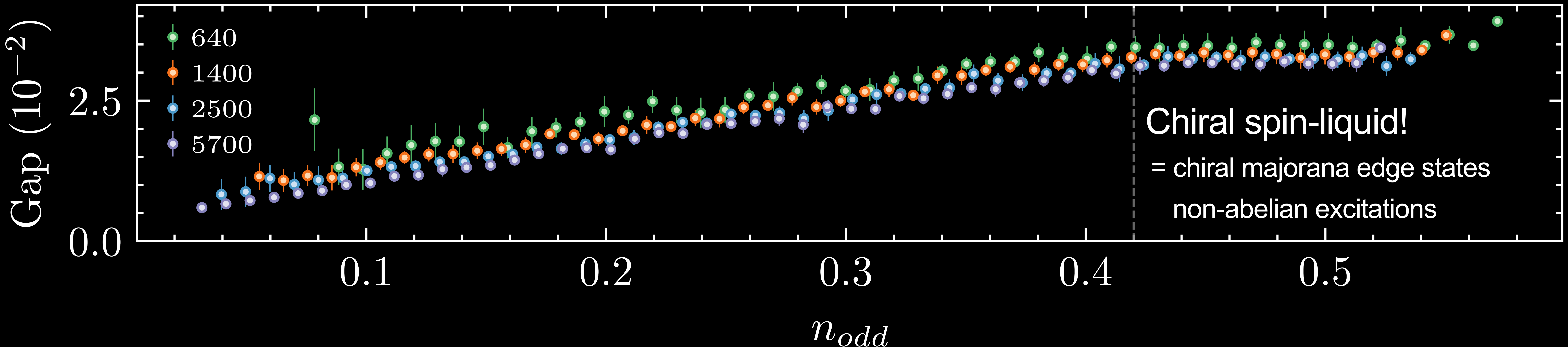

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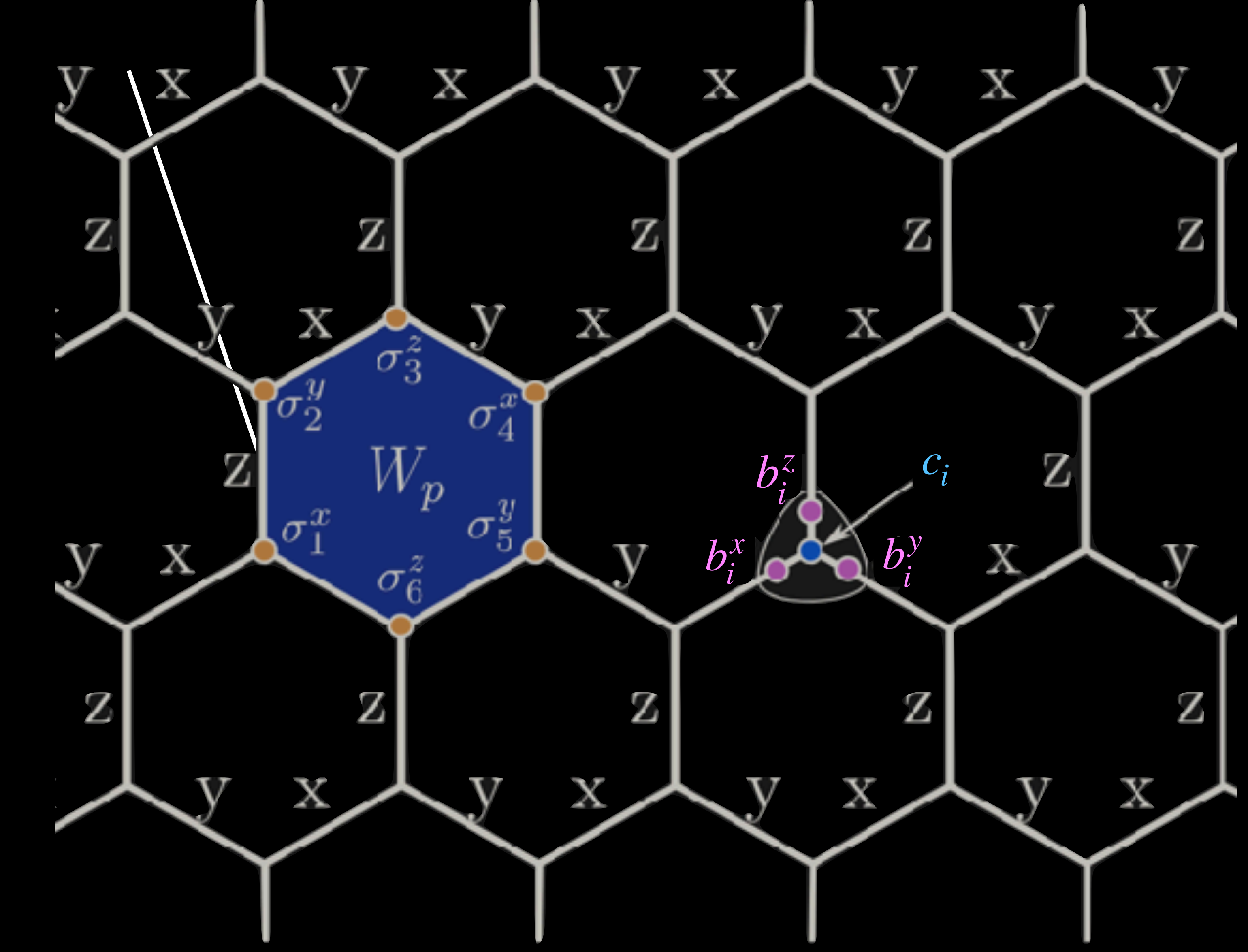

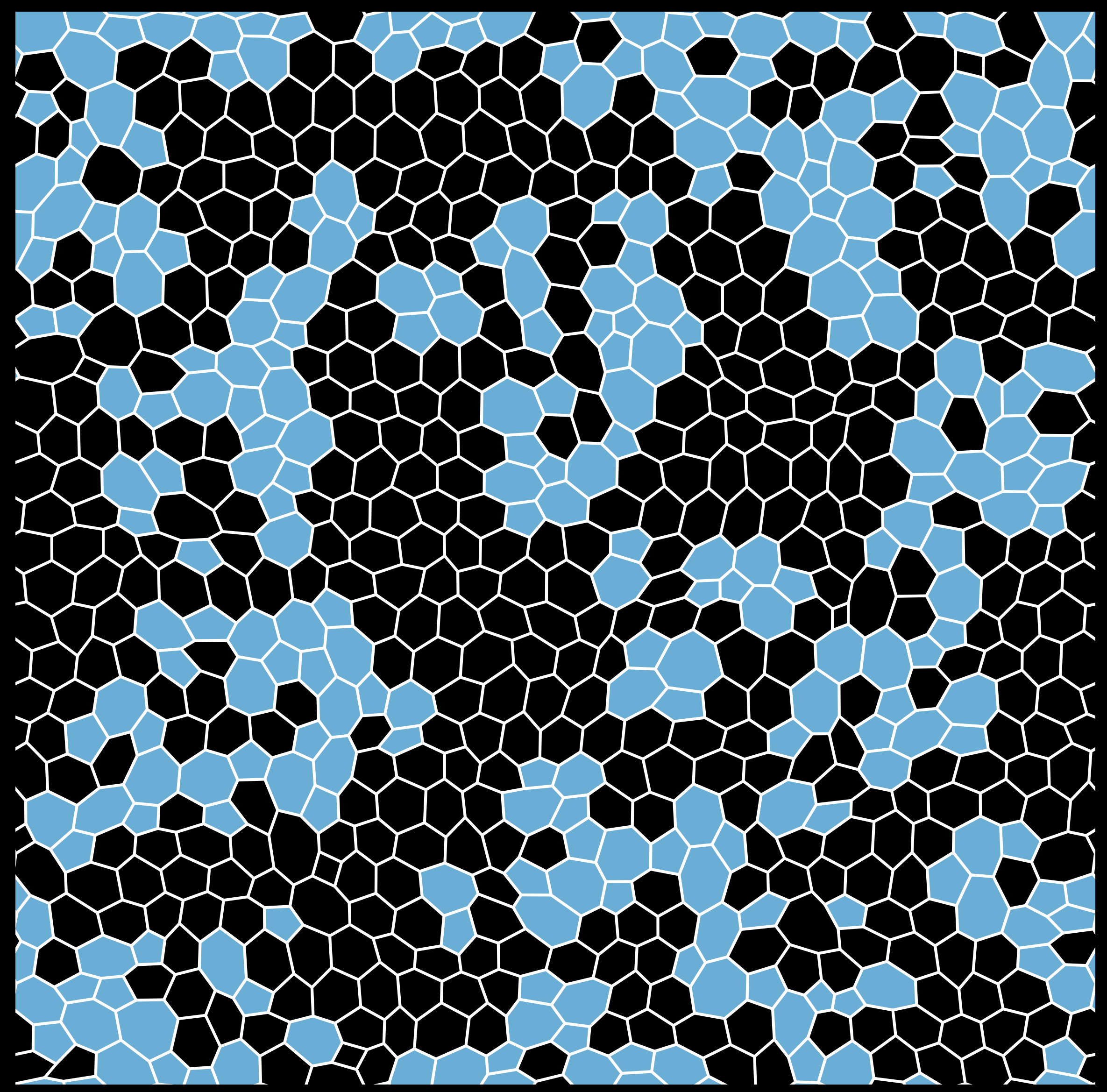

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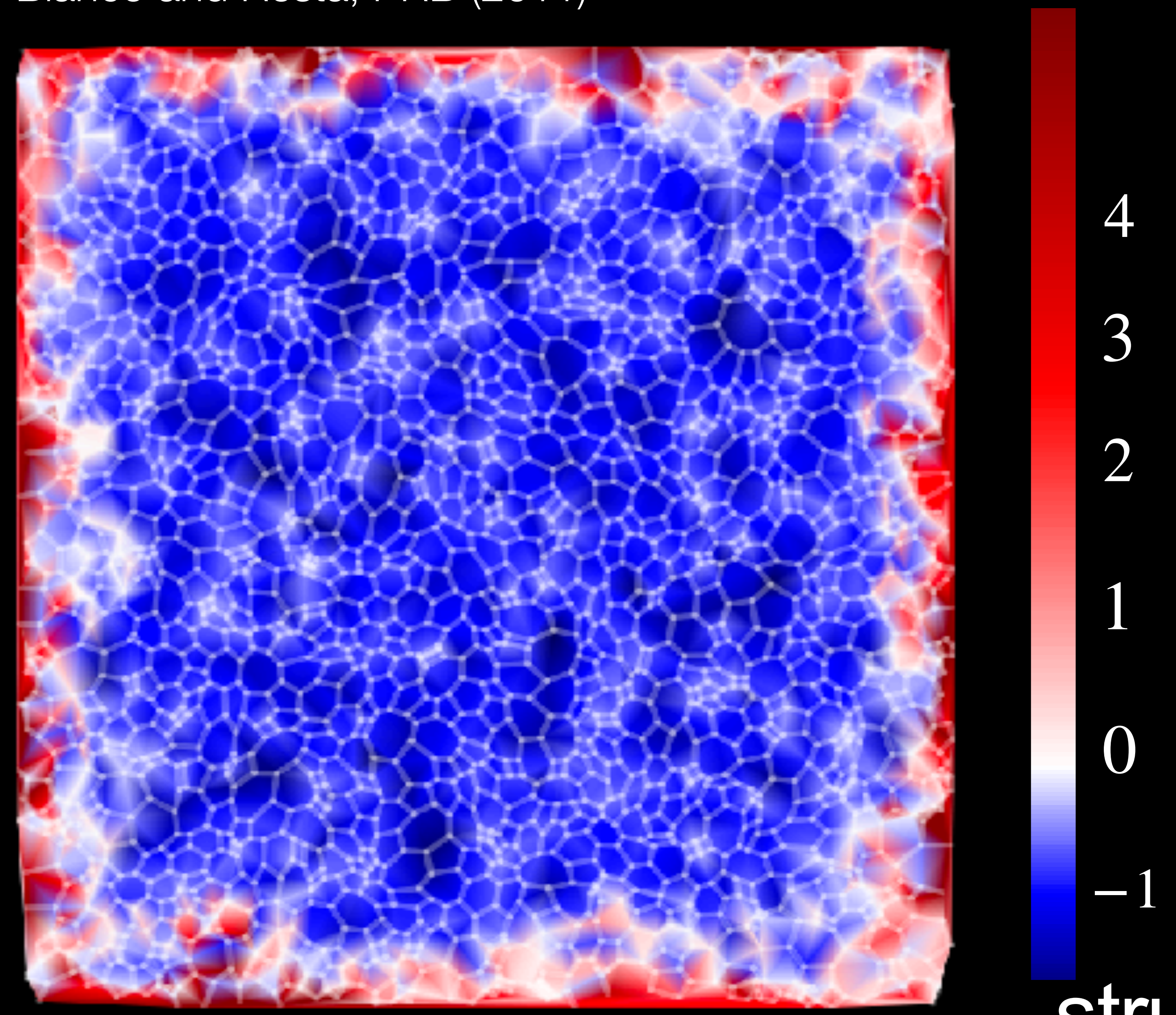

Open questions

Topological amorphous solids database?

$$\gamma = \mathrm{Tr}[(P - \tilde{P})^2]/2$$

Muñoz-Segovia et al arXiv: 2301.02686

2306.17117

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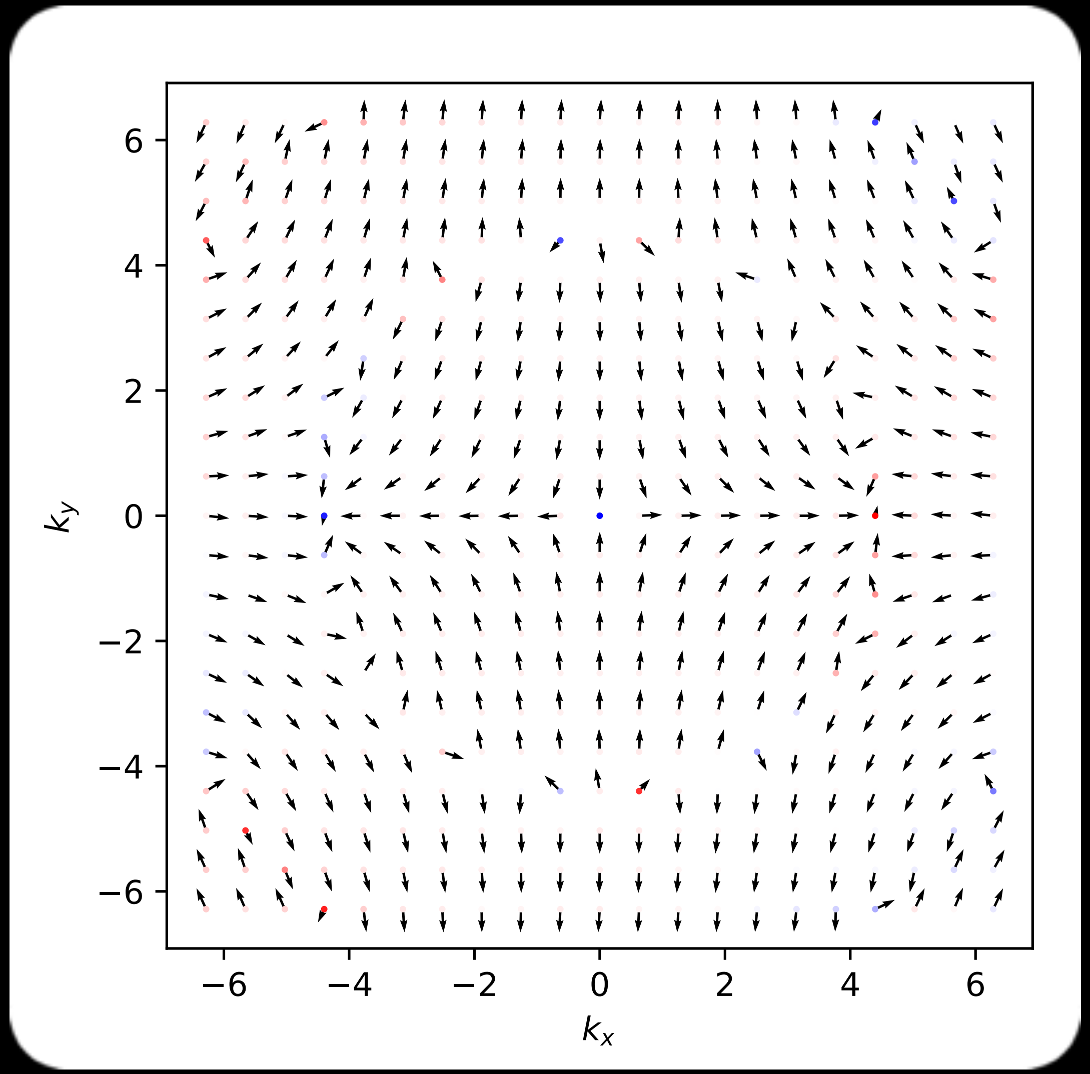

Nielsen-Ninomiya survives amorphicity

Poster!

Justin Schirmann

Selma Franca
2306.17117

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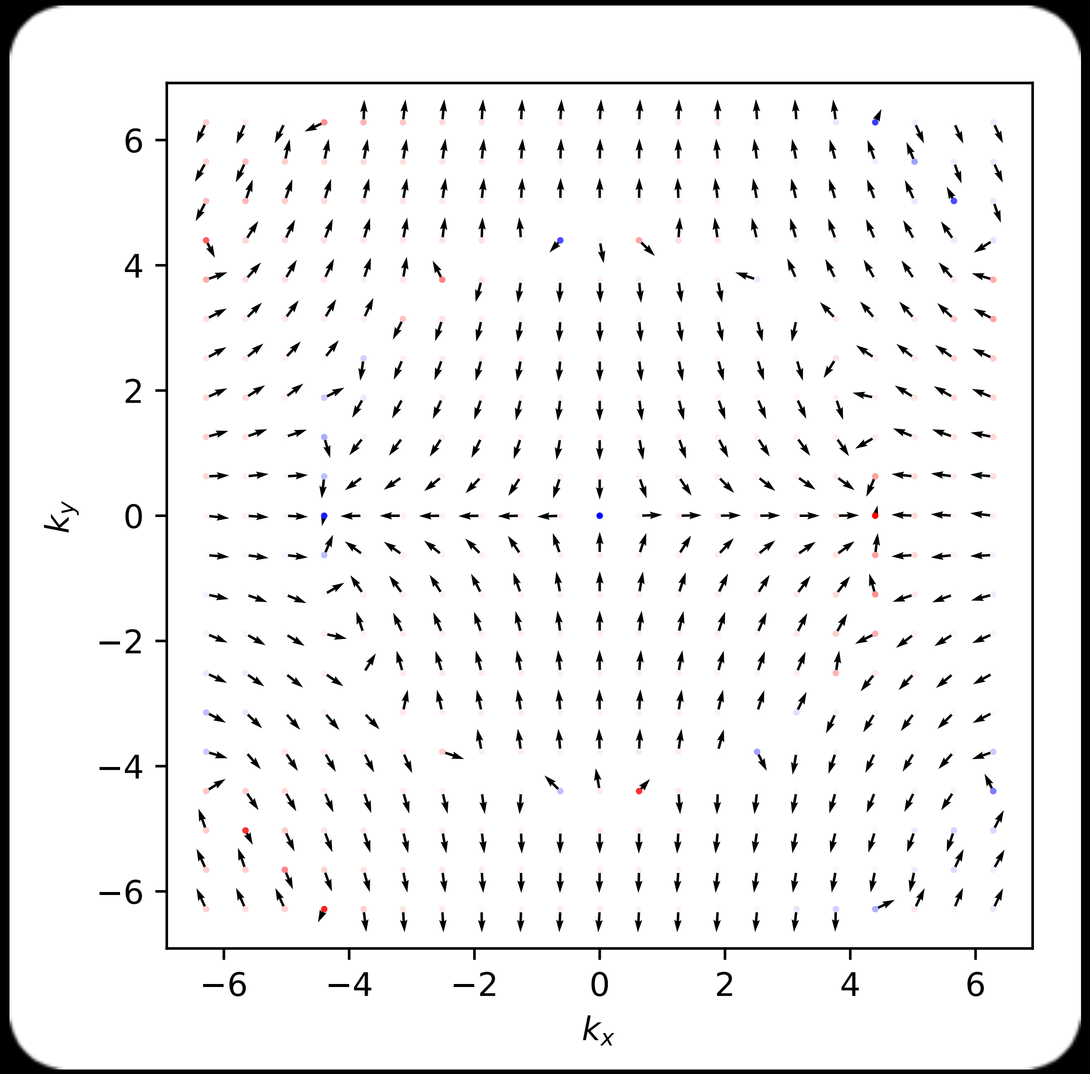

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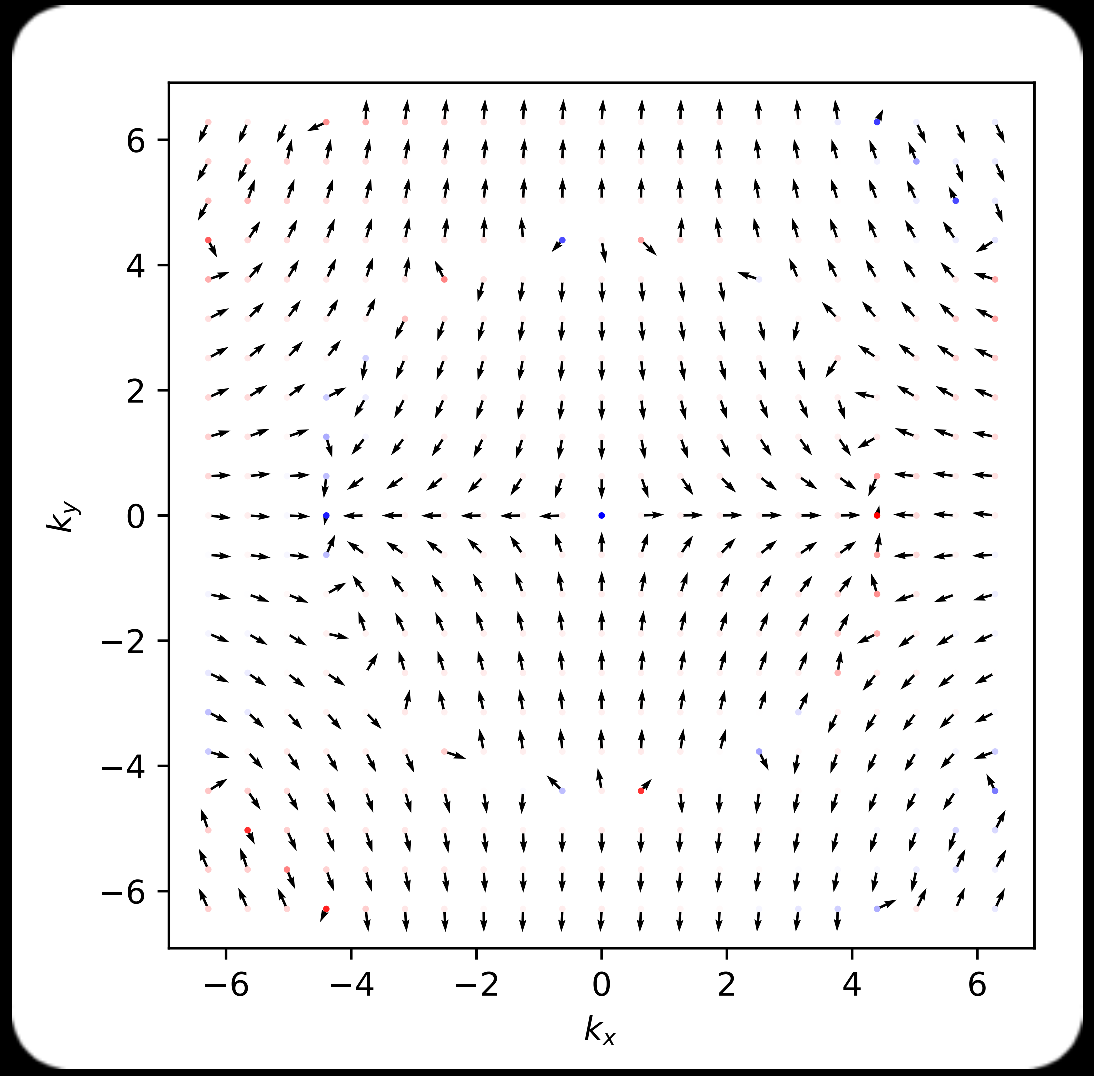

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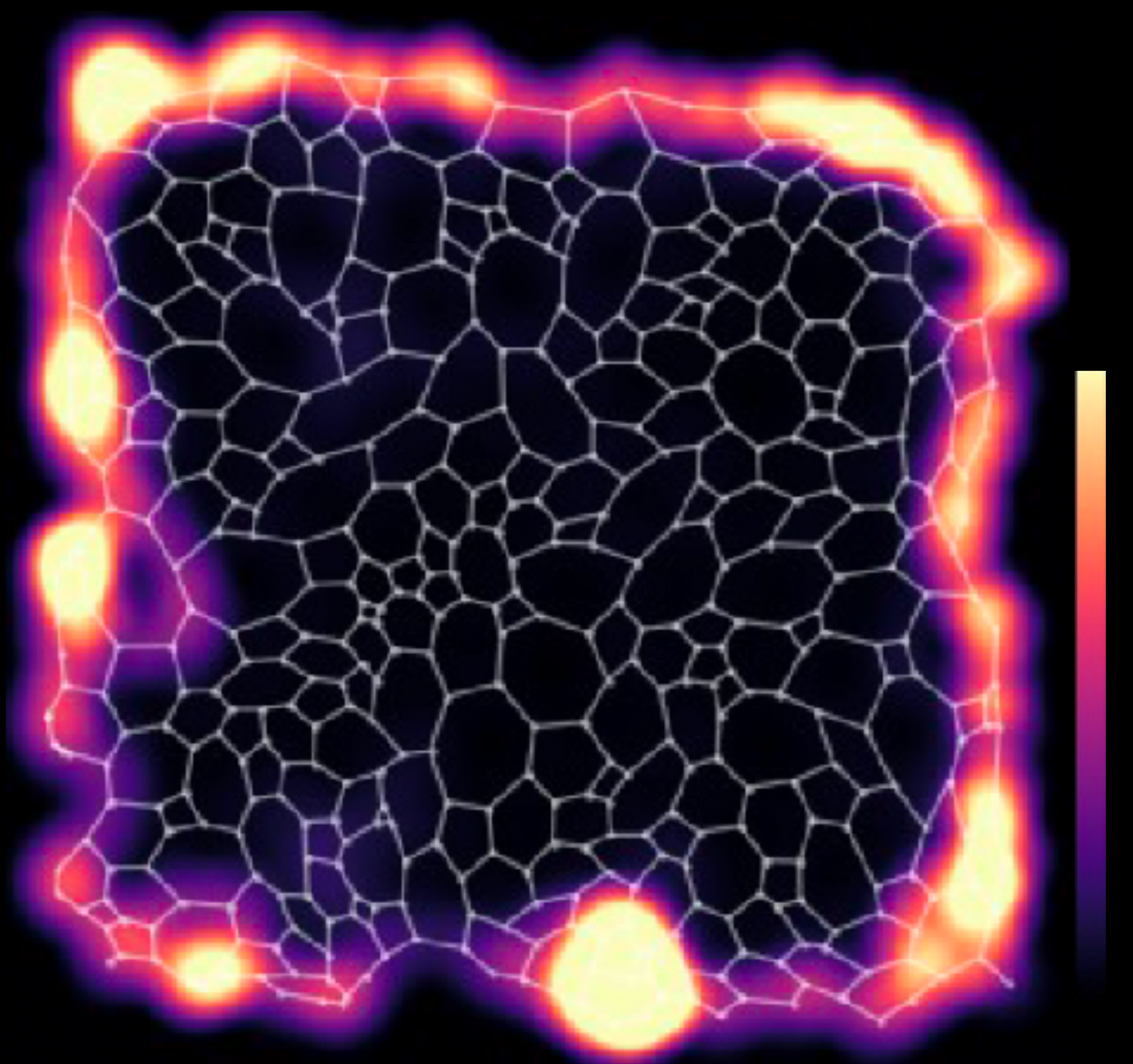

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Low vortexability = FQHE ground state

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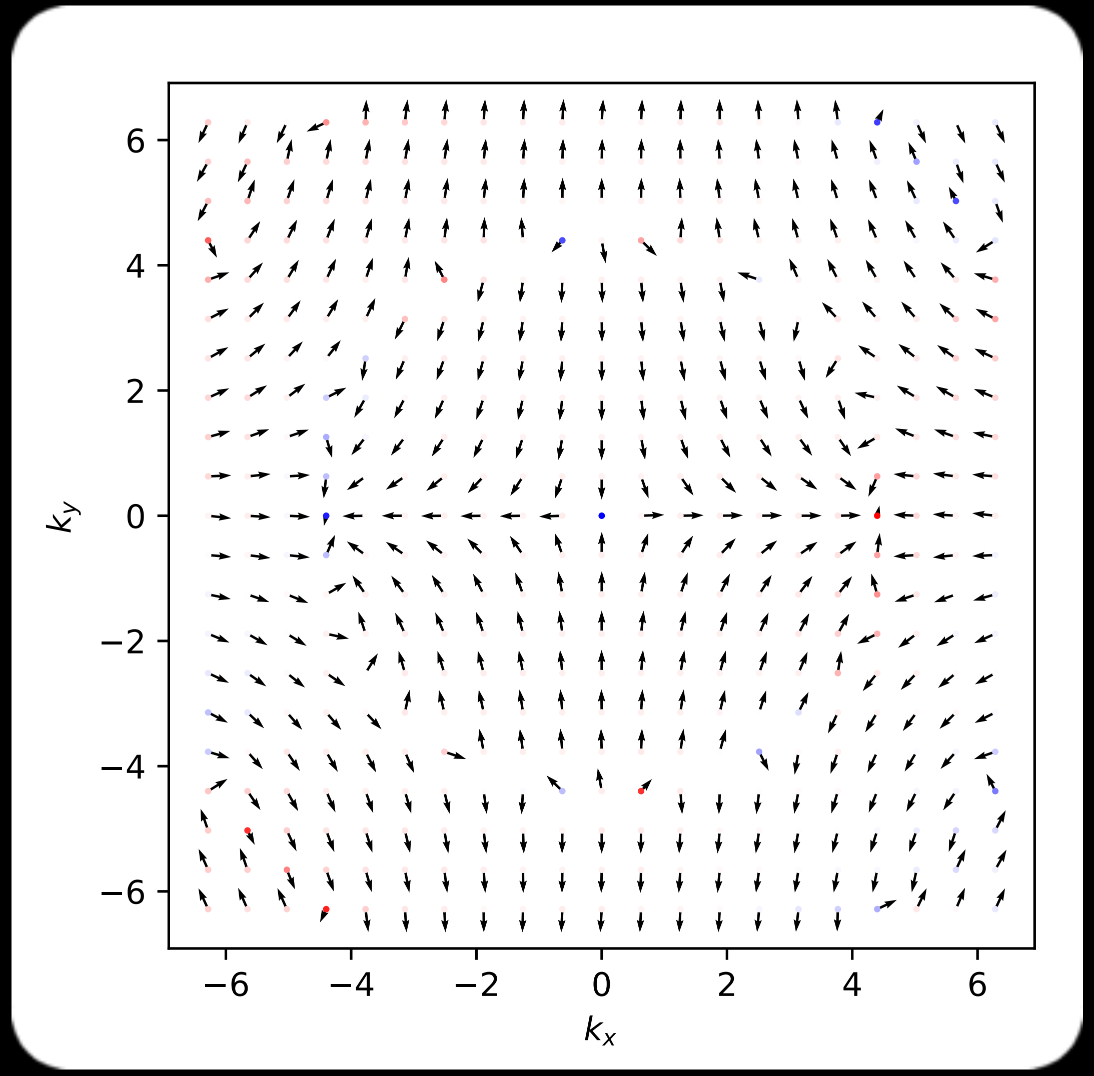

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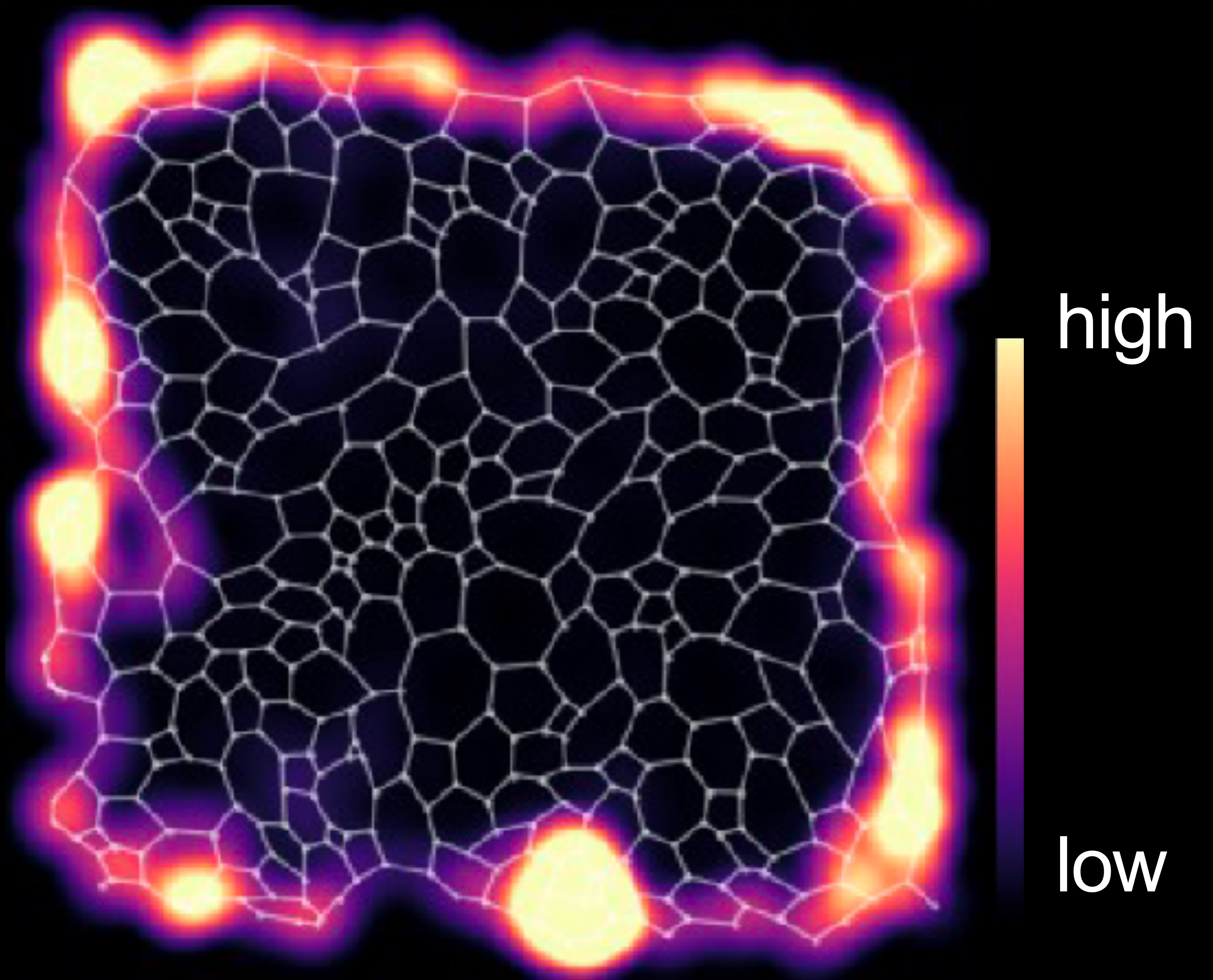

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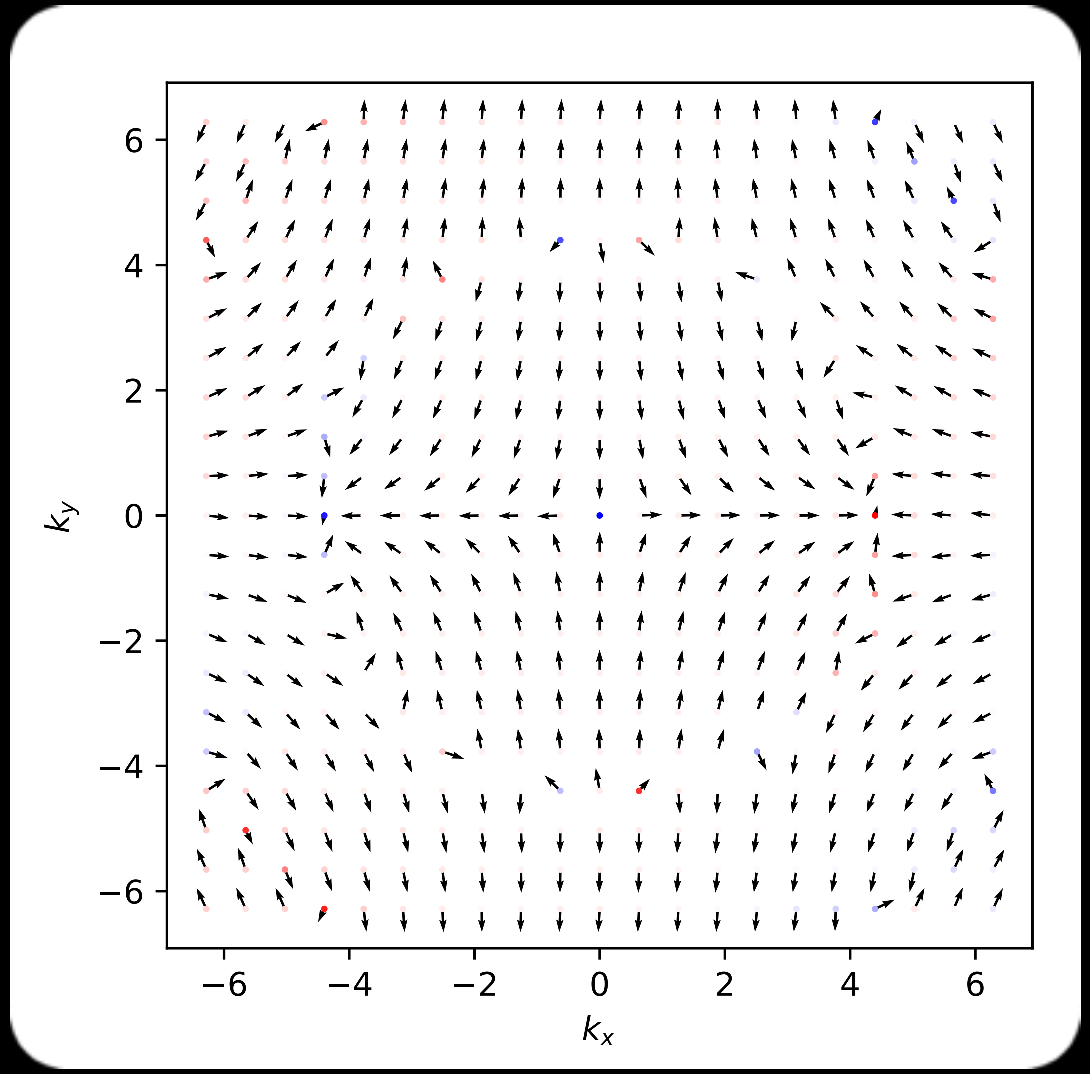

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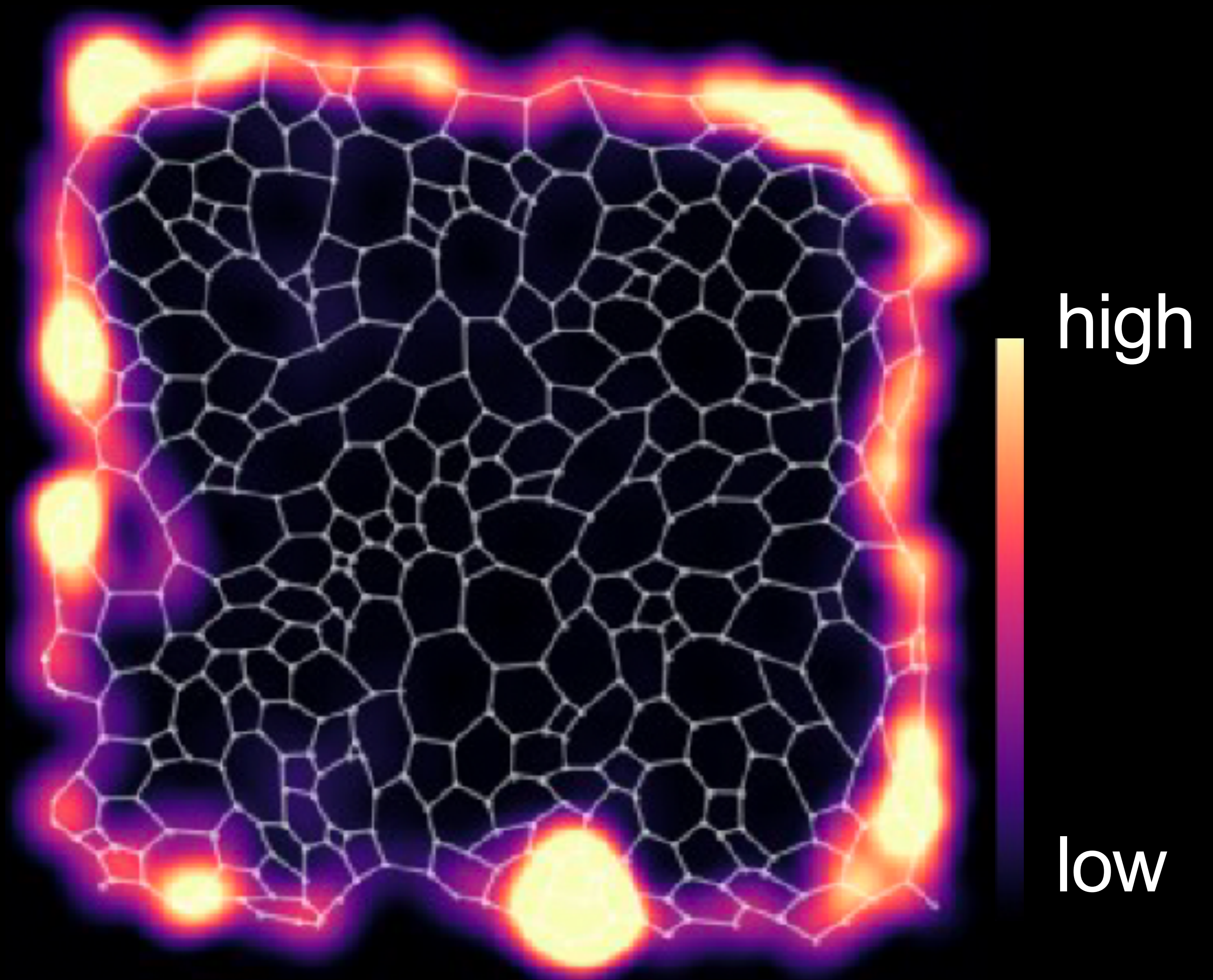

Low vortexability = FQHE ground state

amorphous topological superconductors?

Material	Crystal T_c	Amorphous T_c
Bi	10^{-4} K	6 K
Be	0.03 K	10 K
Ga	1 K	8 K

Poster!

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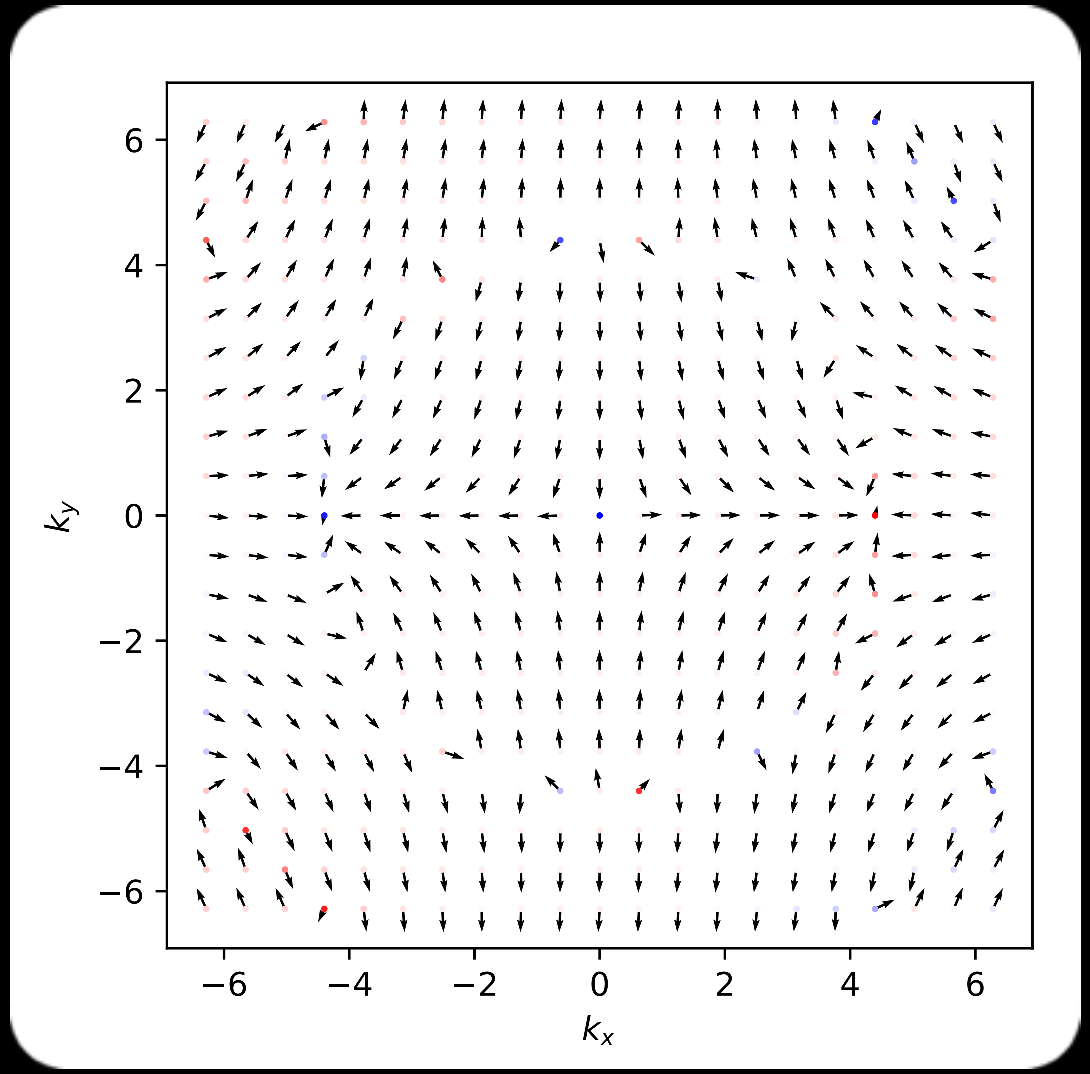

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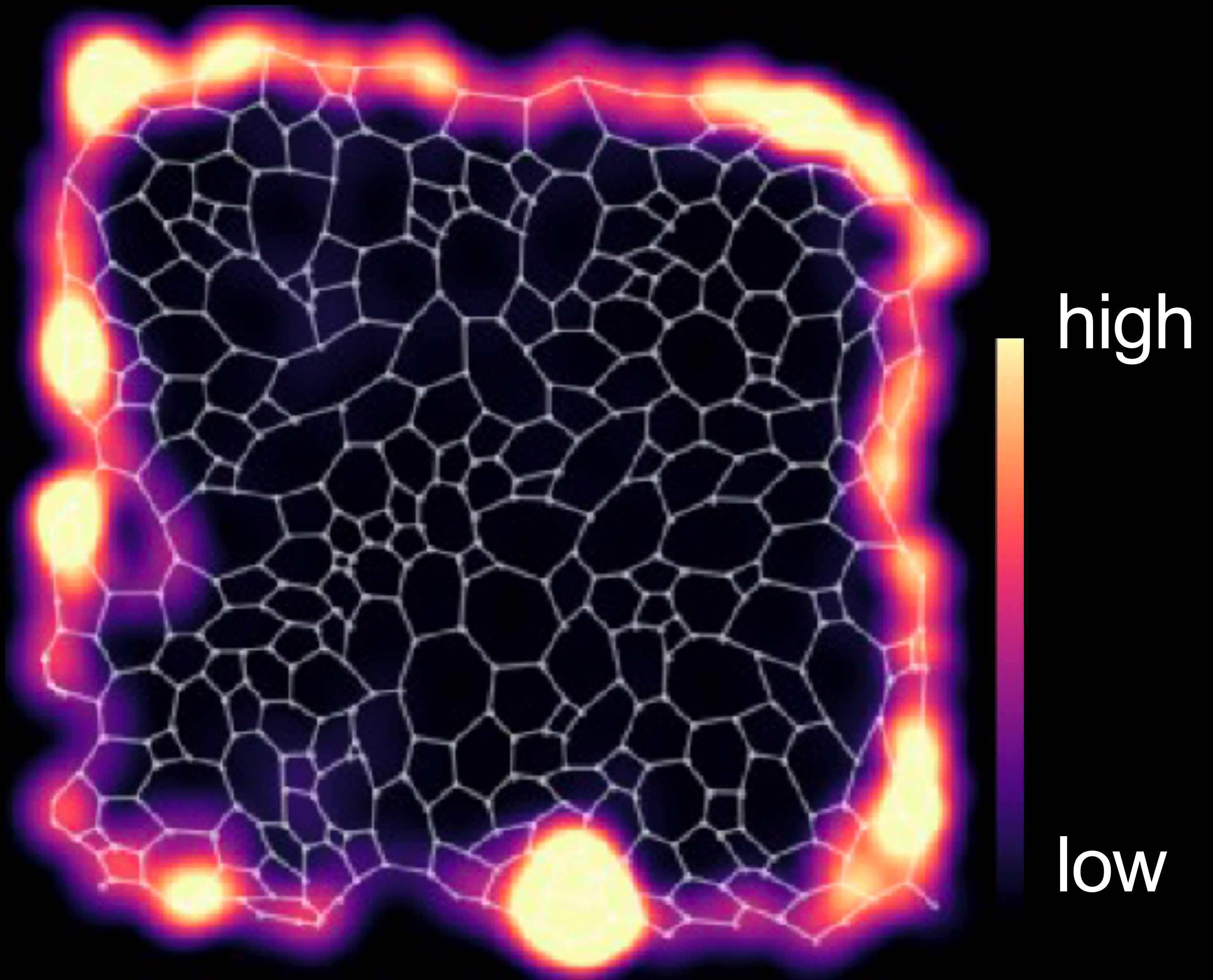

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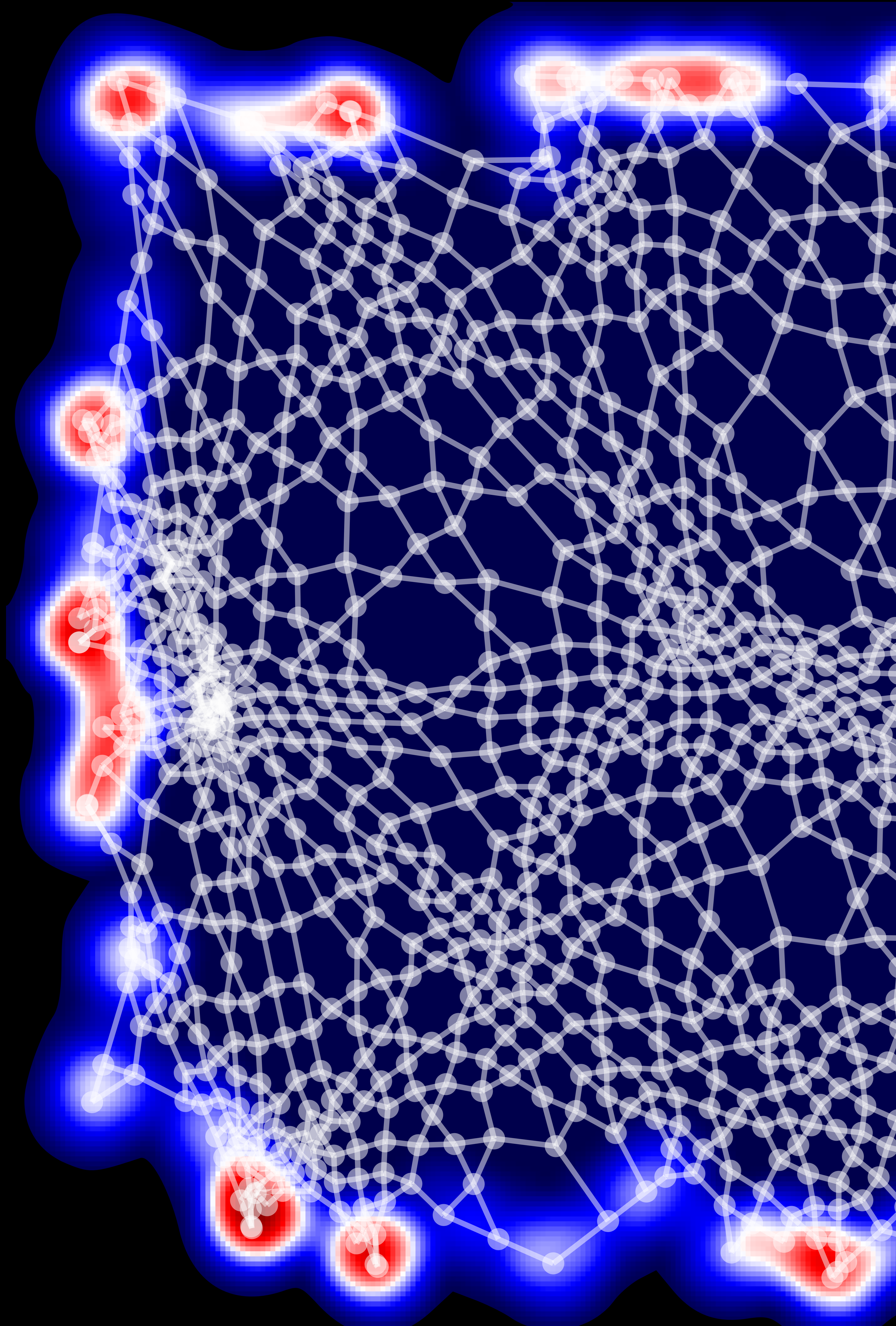
Amorphous topological solids

from flat bands to chiral spin liquids

Adolfo G. Grushin, Néel Institute, CNRS

150 years of the SFP — Paris, July 7th, 2023



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How do we find topological amorphous solids?

Any different physics compared to crystals?

Amorphous graphene

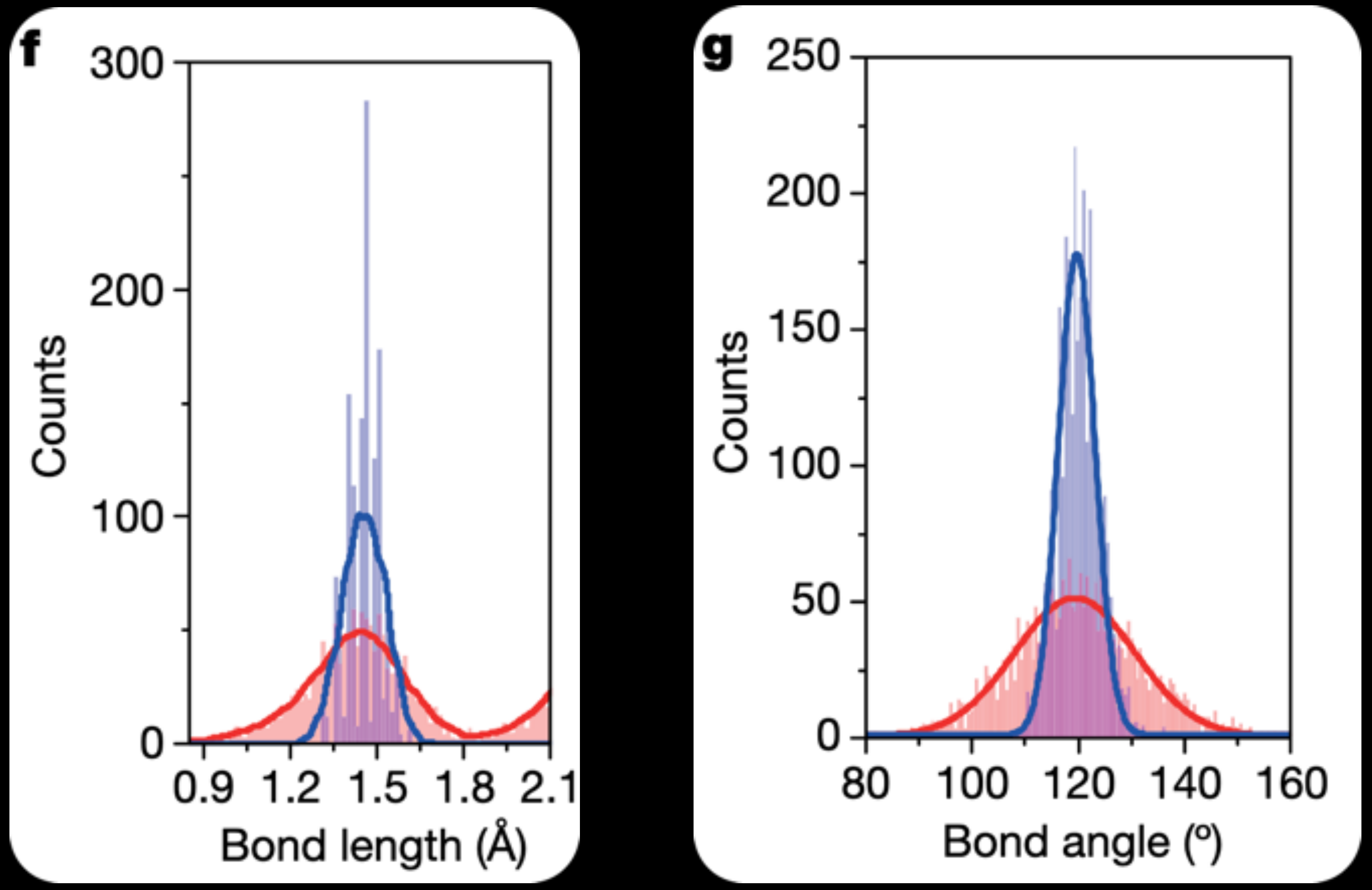
Local order = locally similar to crystal

1. Fixed coordination (= 3)

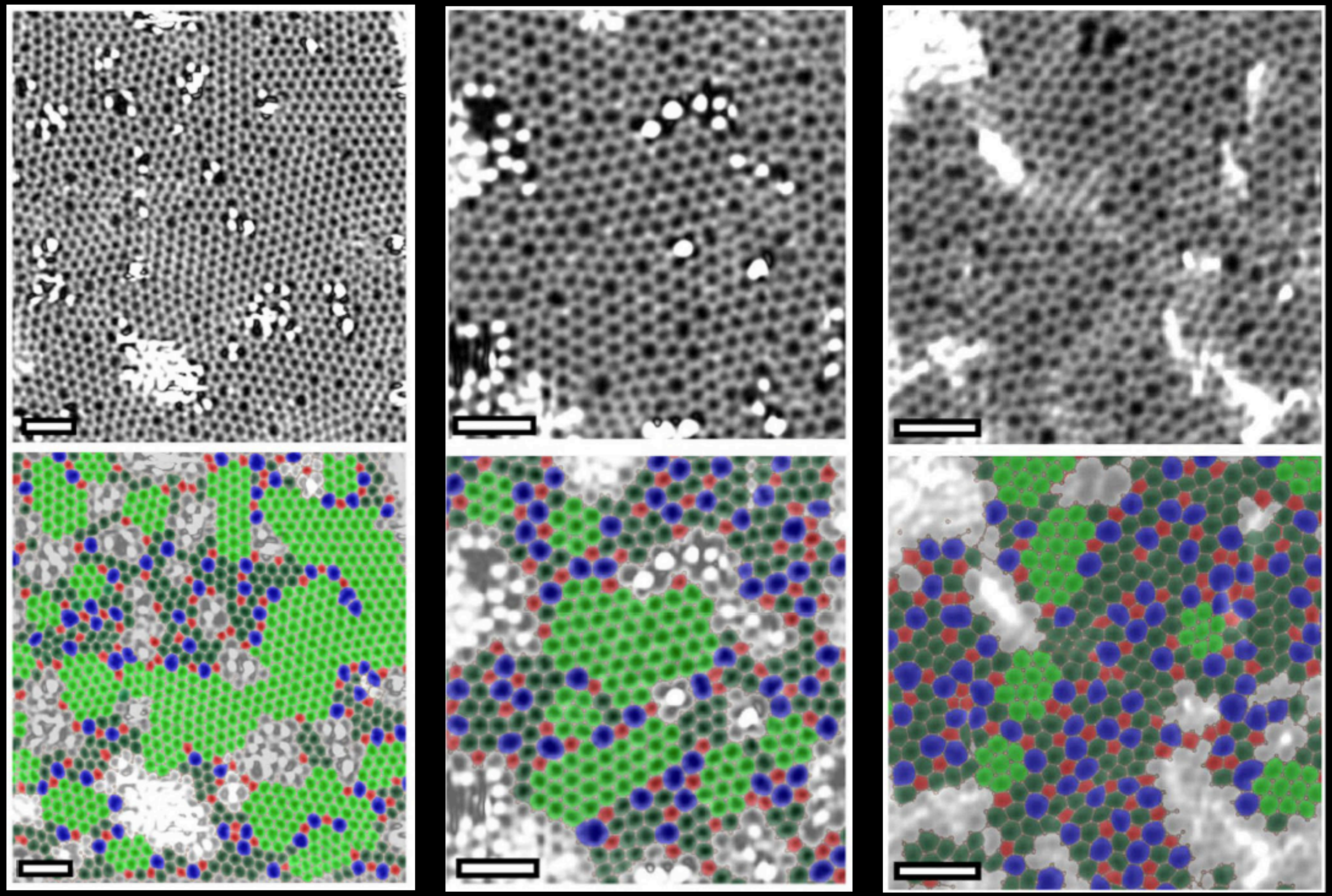
2. Similar lattice scales

Bond lengths

Bond-angles



structural disorder



3. Crystalline and amorphous regions coexist

Toh et al. Nature (2020)

Tian et al. Nature (2023)

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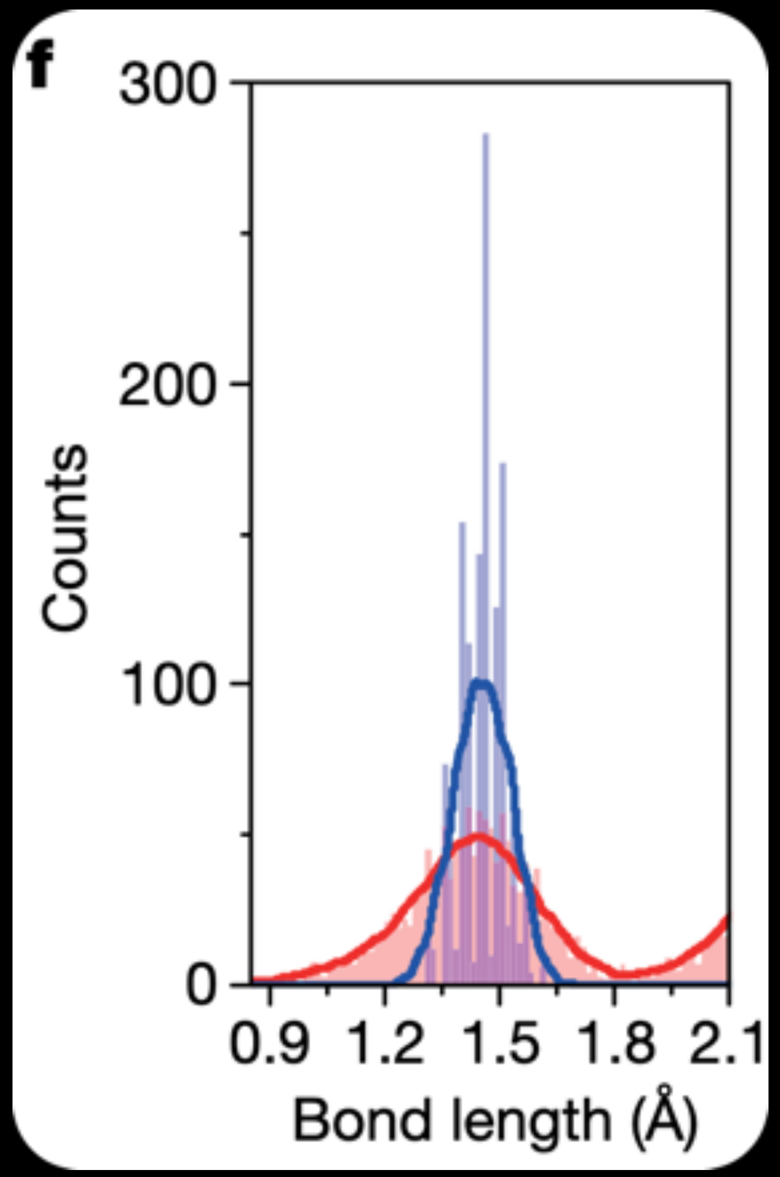

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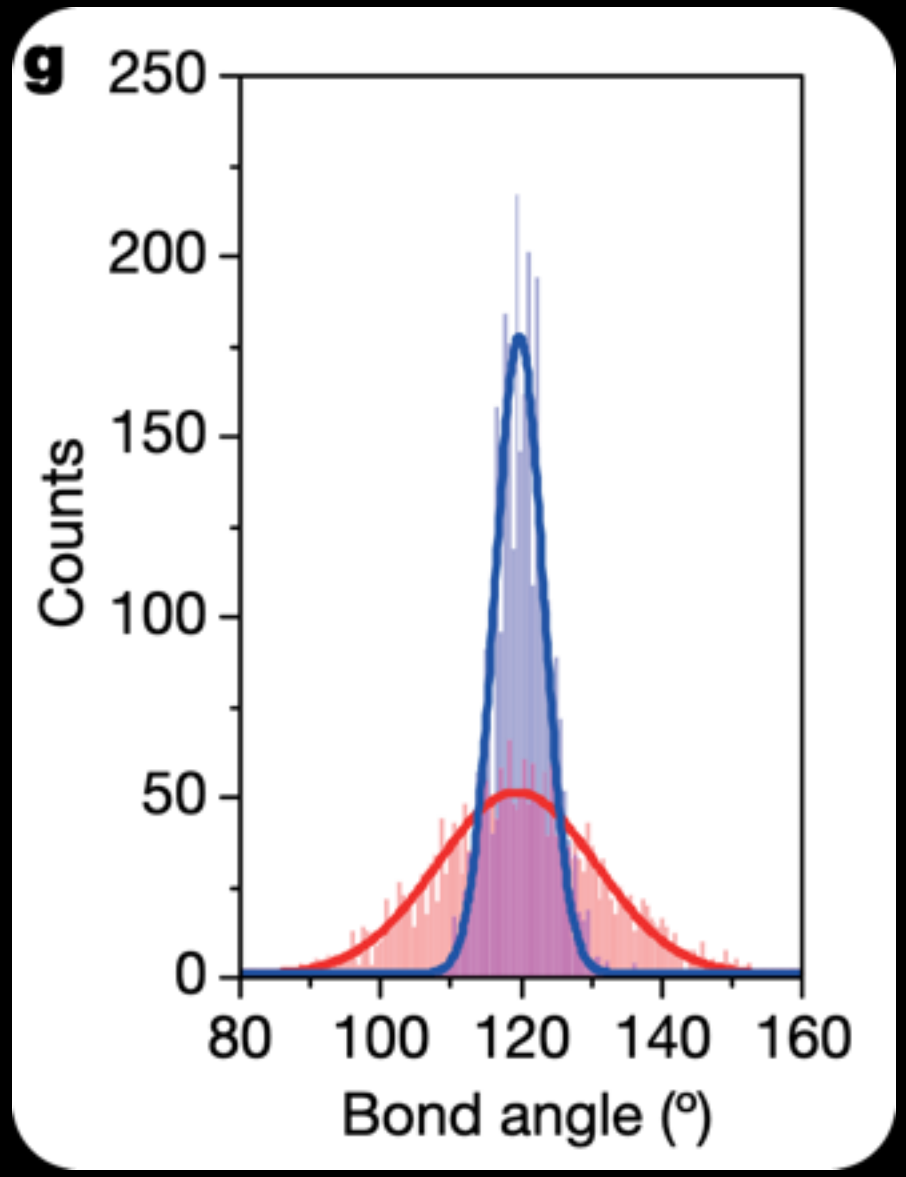

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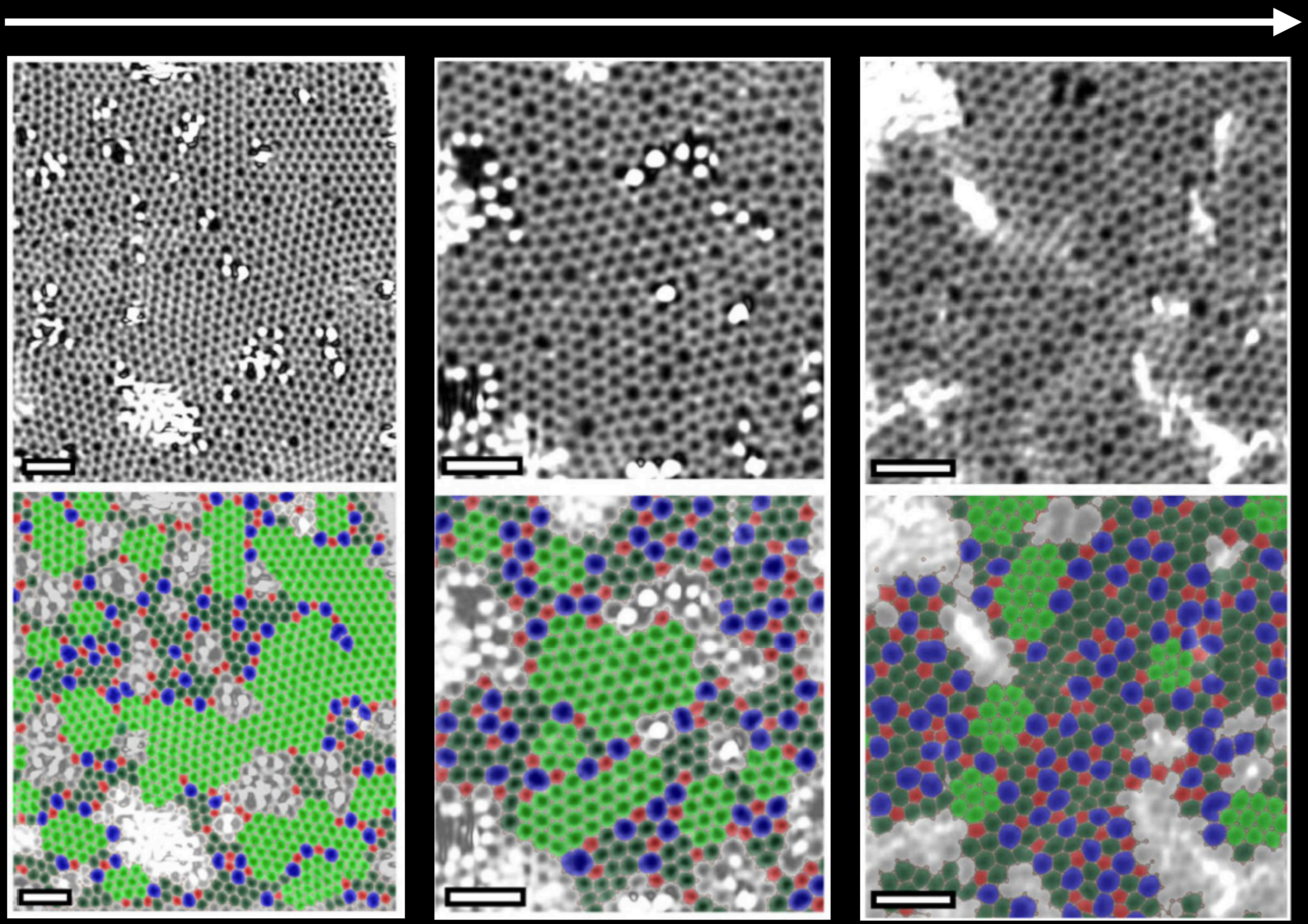

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Toh et al. Nature (2020)

4. Lattice disorder can be controlled

Tian et al. Nature (2023)

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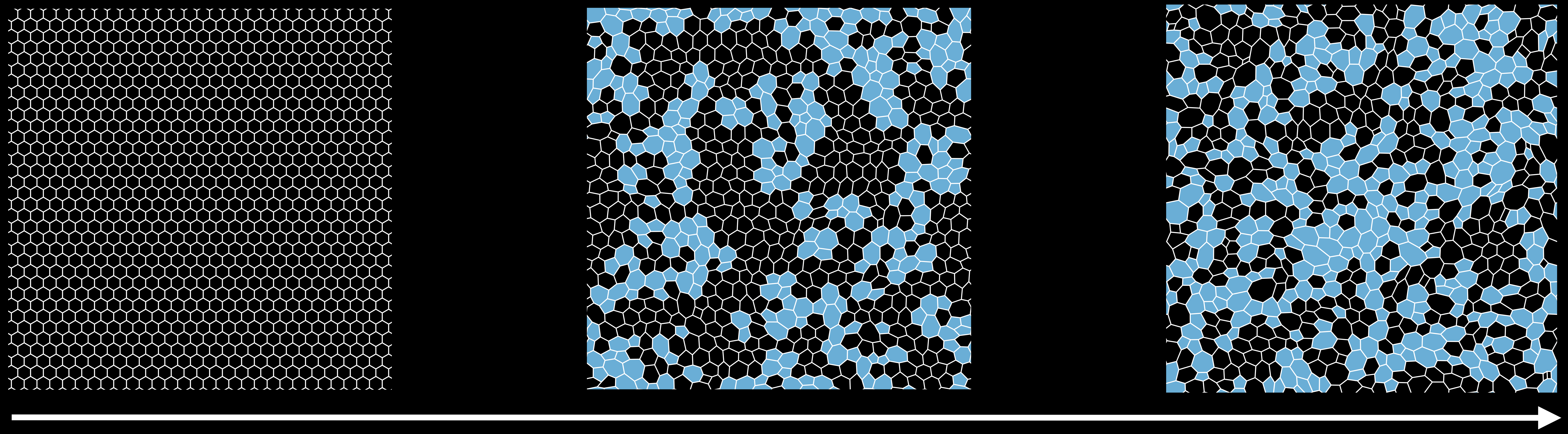
Can this knob drive a topological transition?

AGG, C. Repellin PRL (2023)

crystal polycrystal amorphous

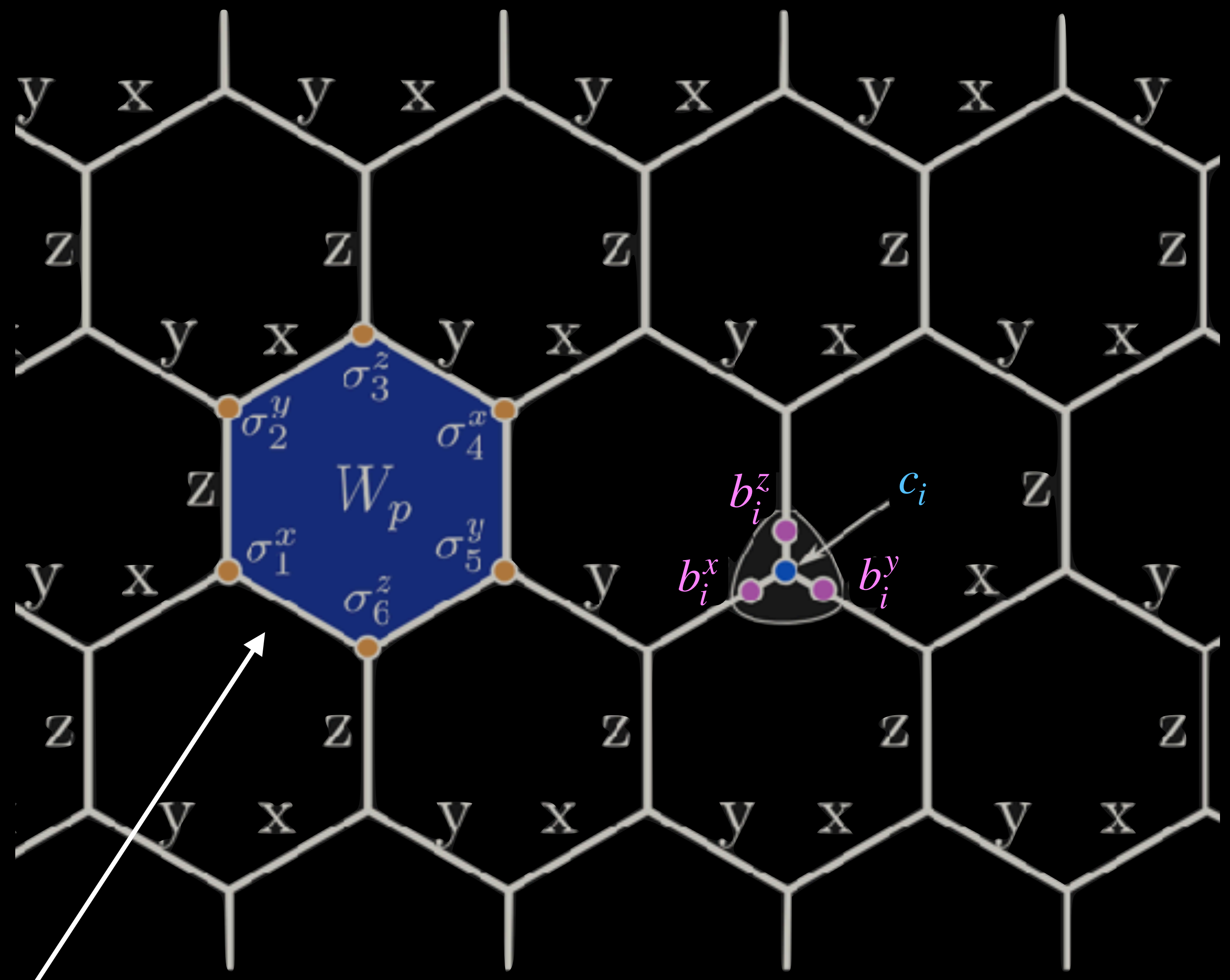


structural disorder

Kitaev models

Honeycomb

Kitaev Ann. Phys. (2006)



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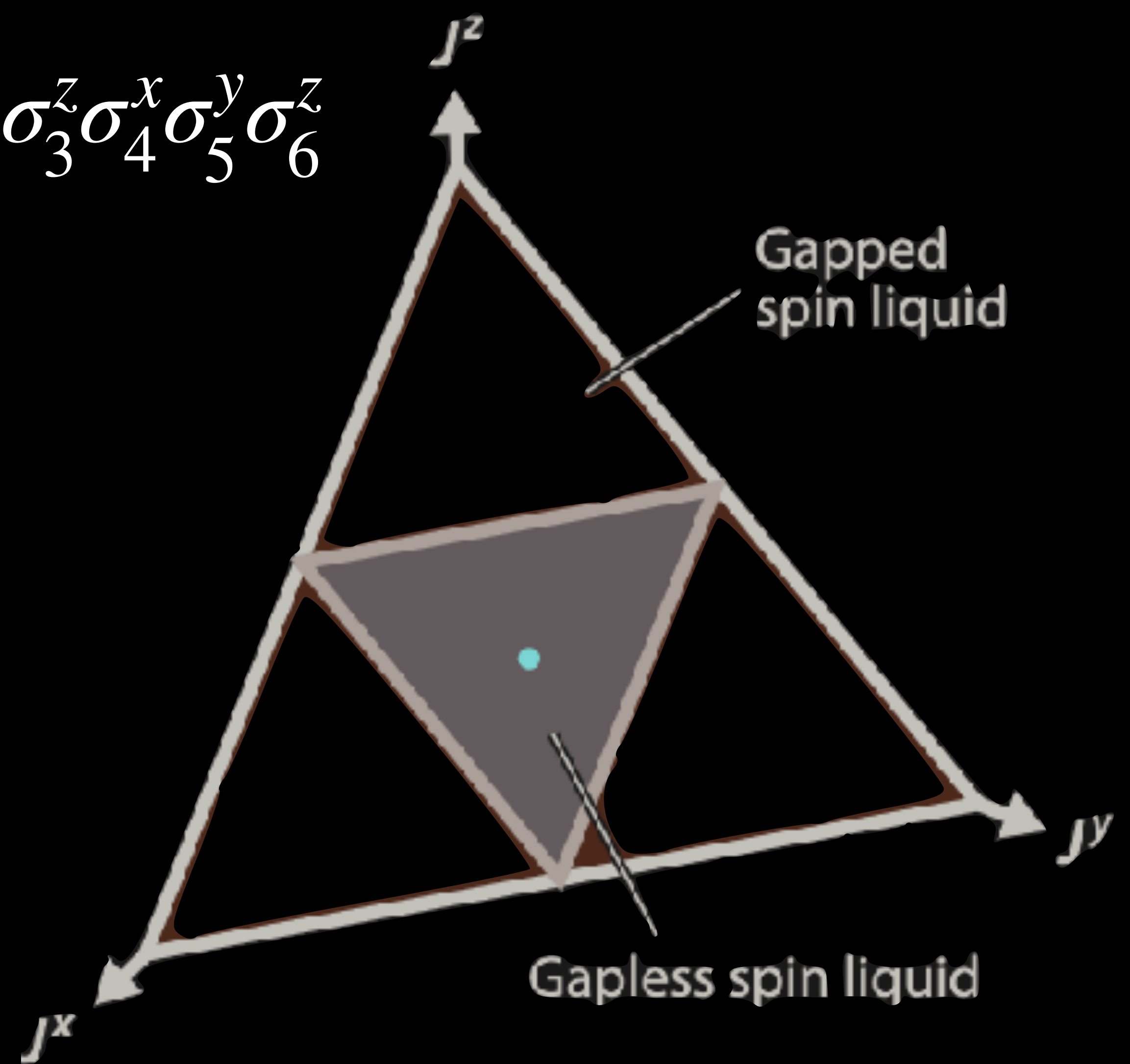

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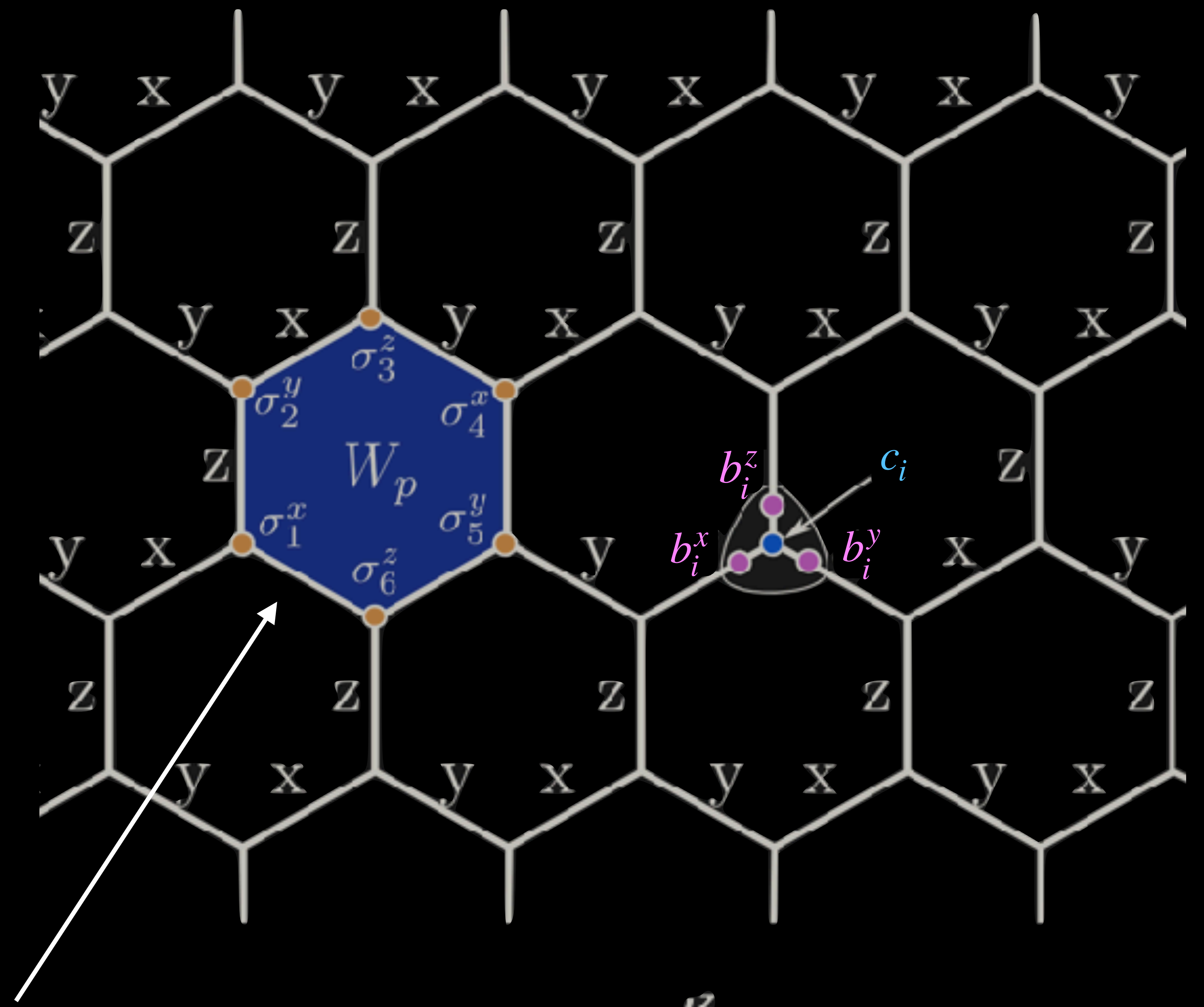

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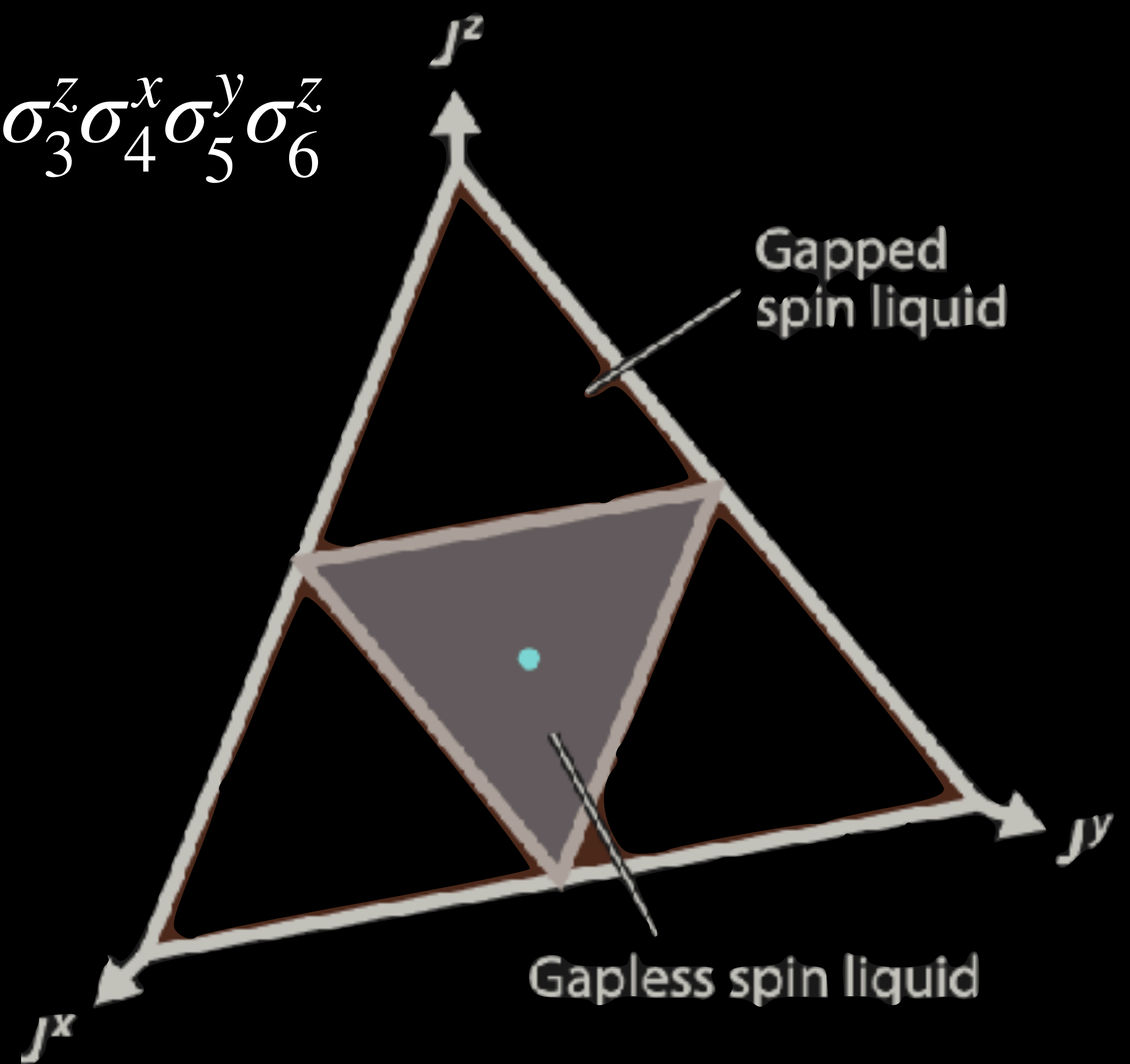
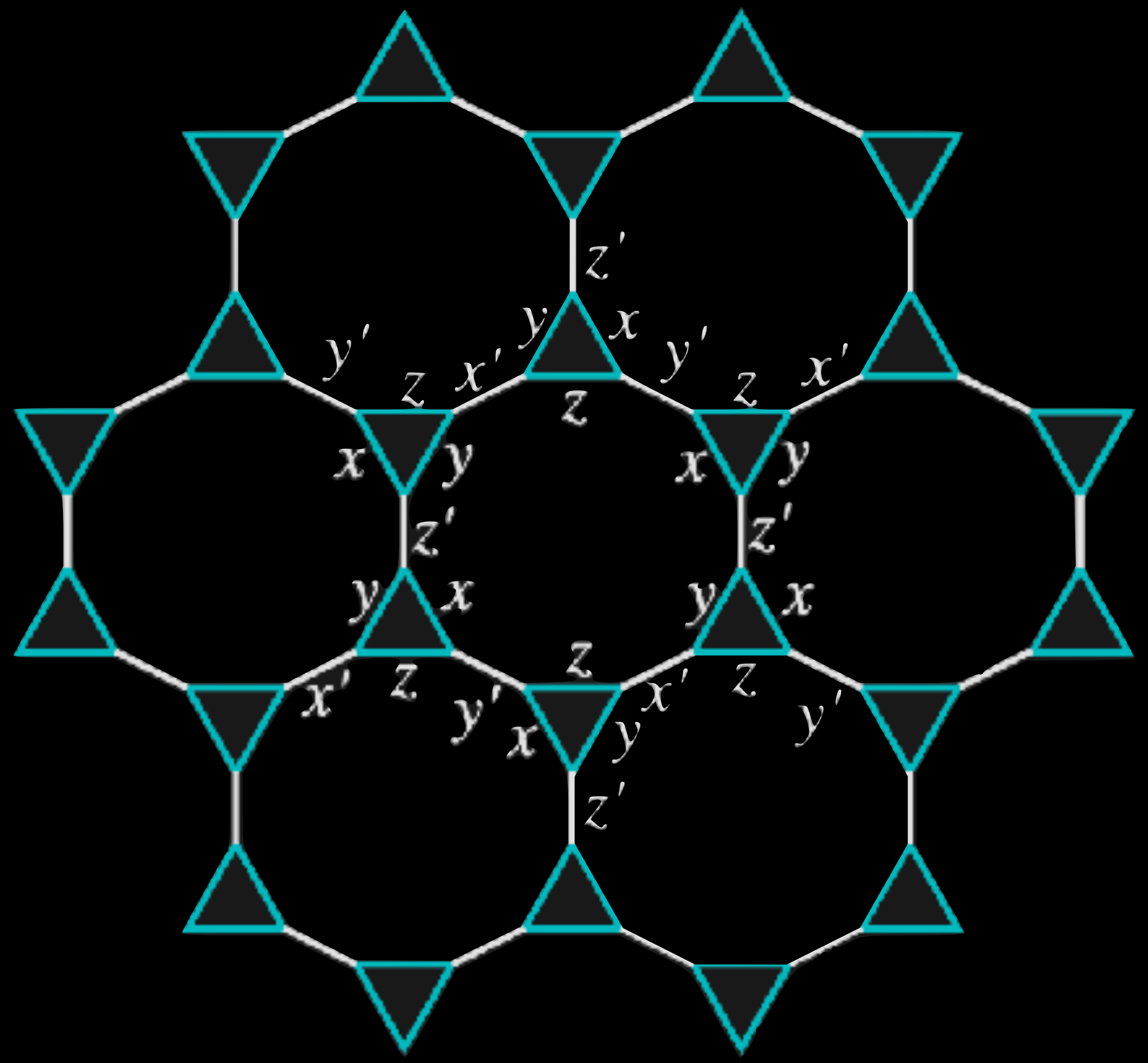


Decorated Honeycomb

Yao and Kivelson PRL (2007)



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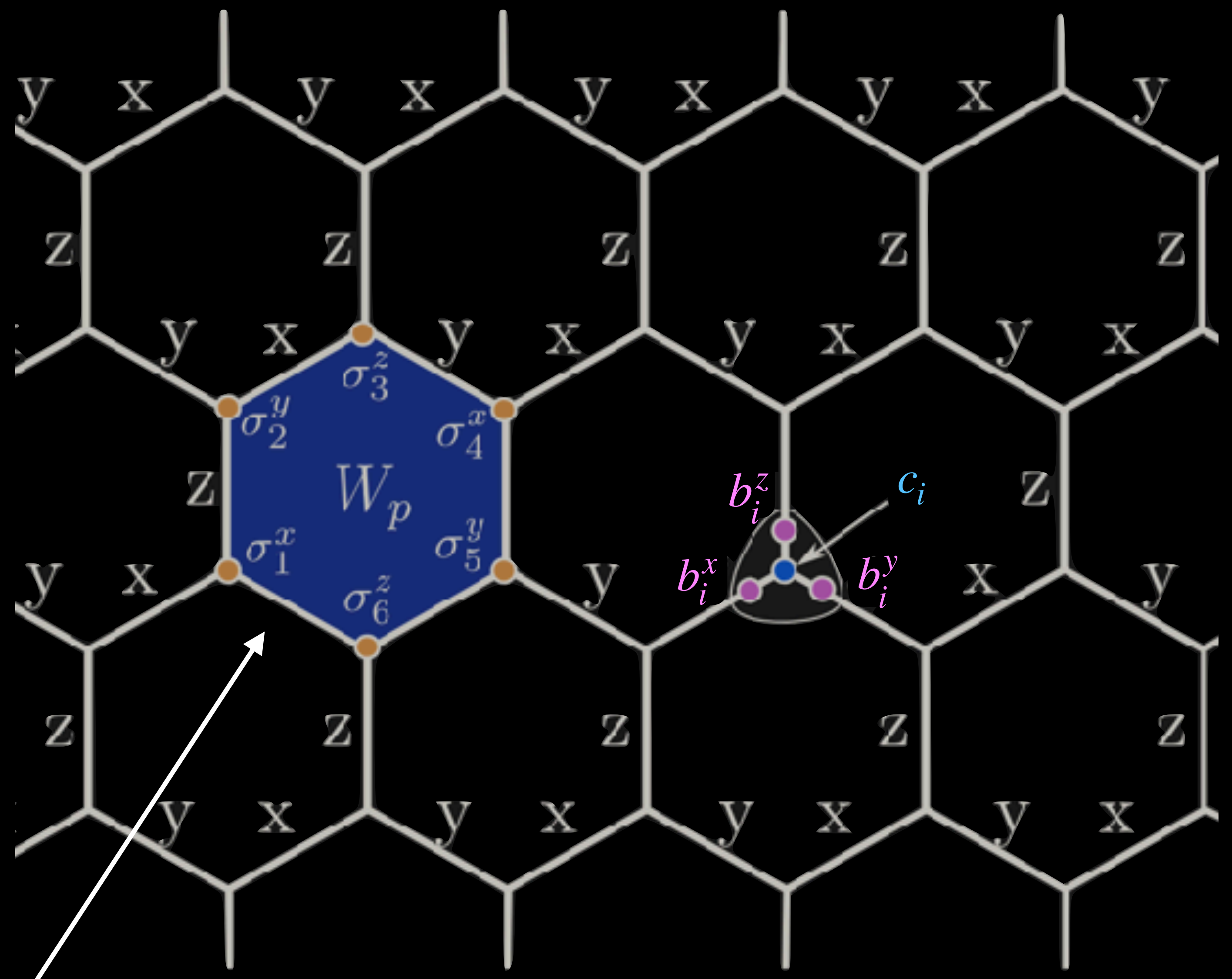

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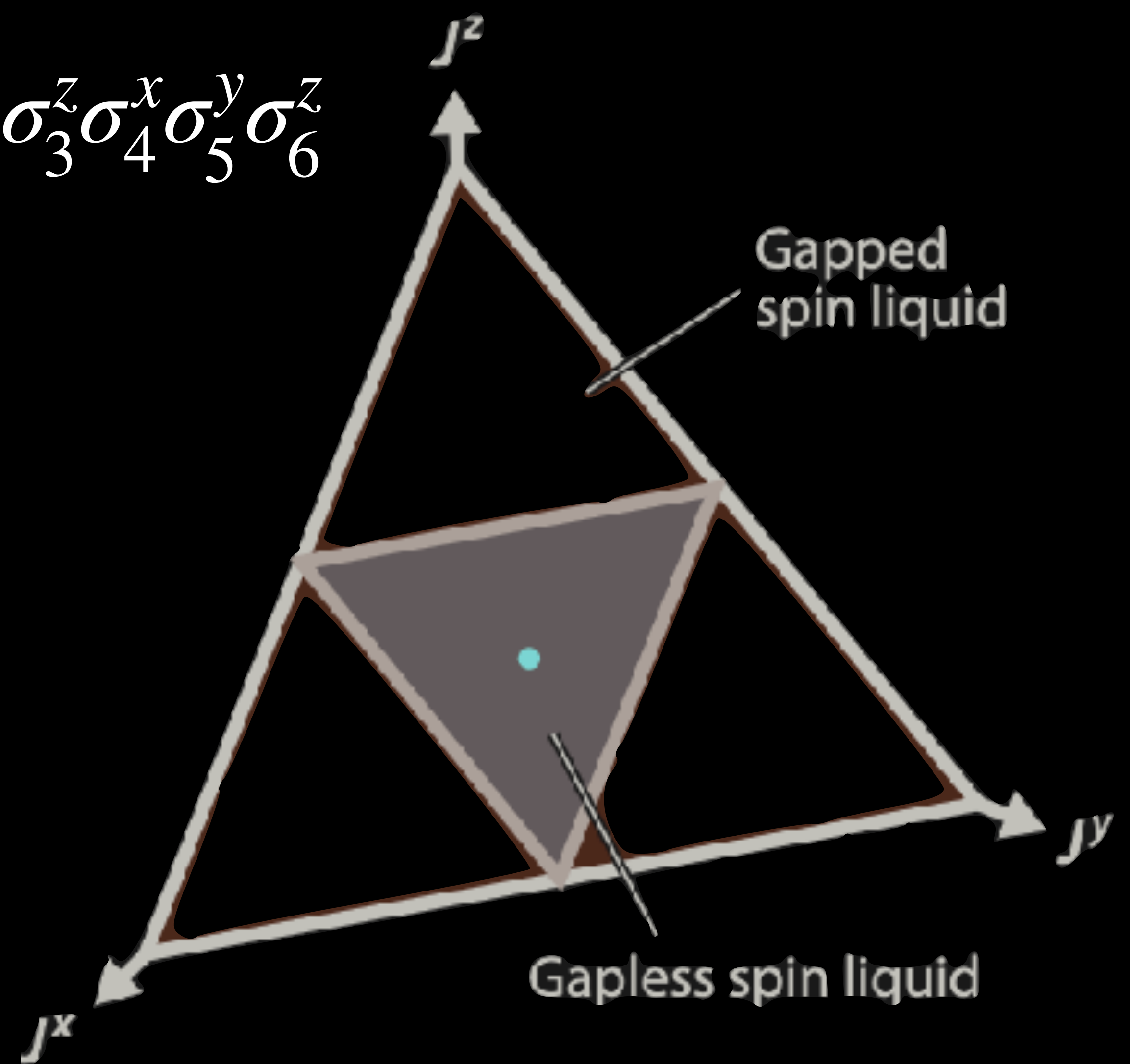

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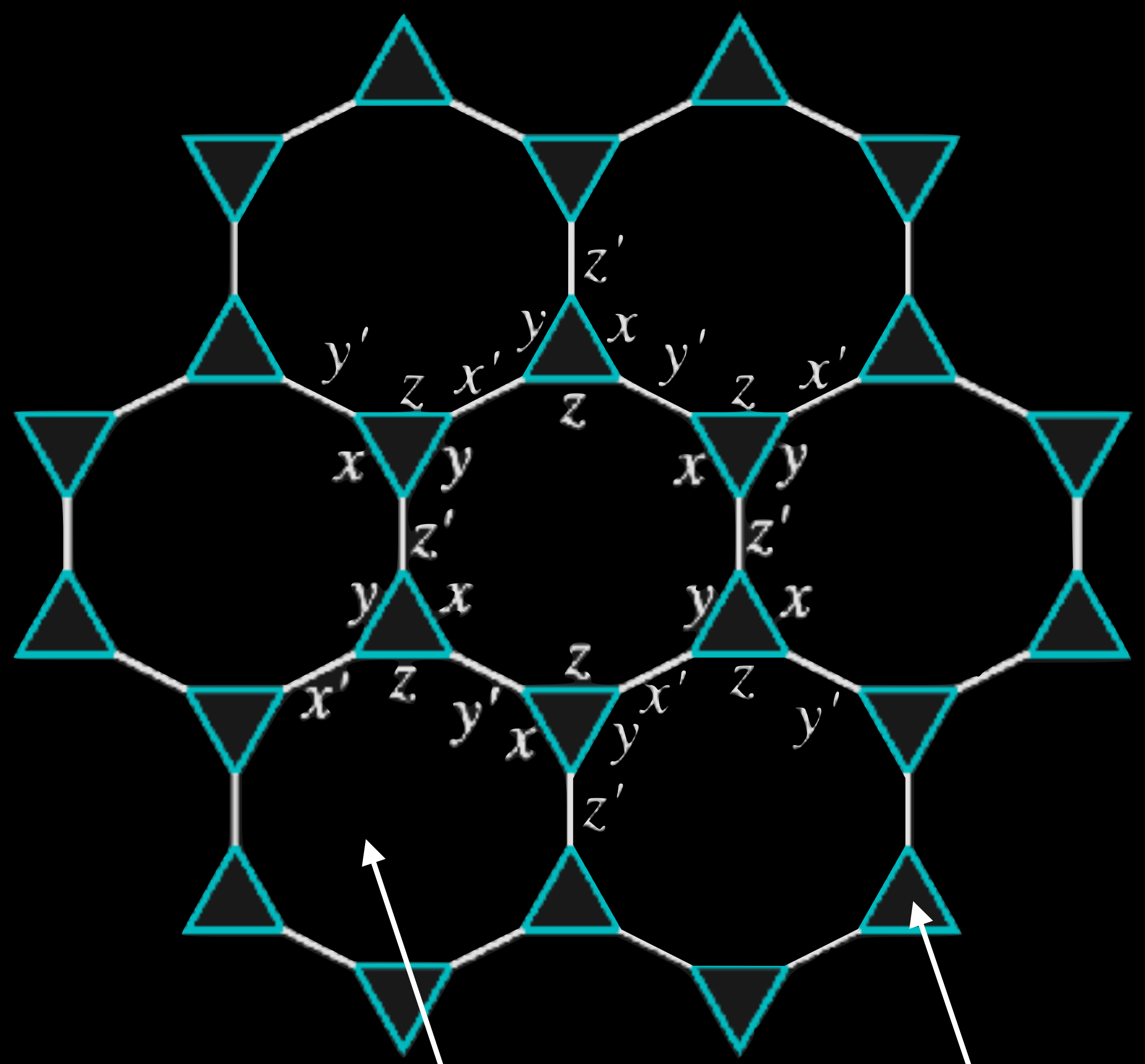

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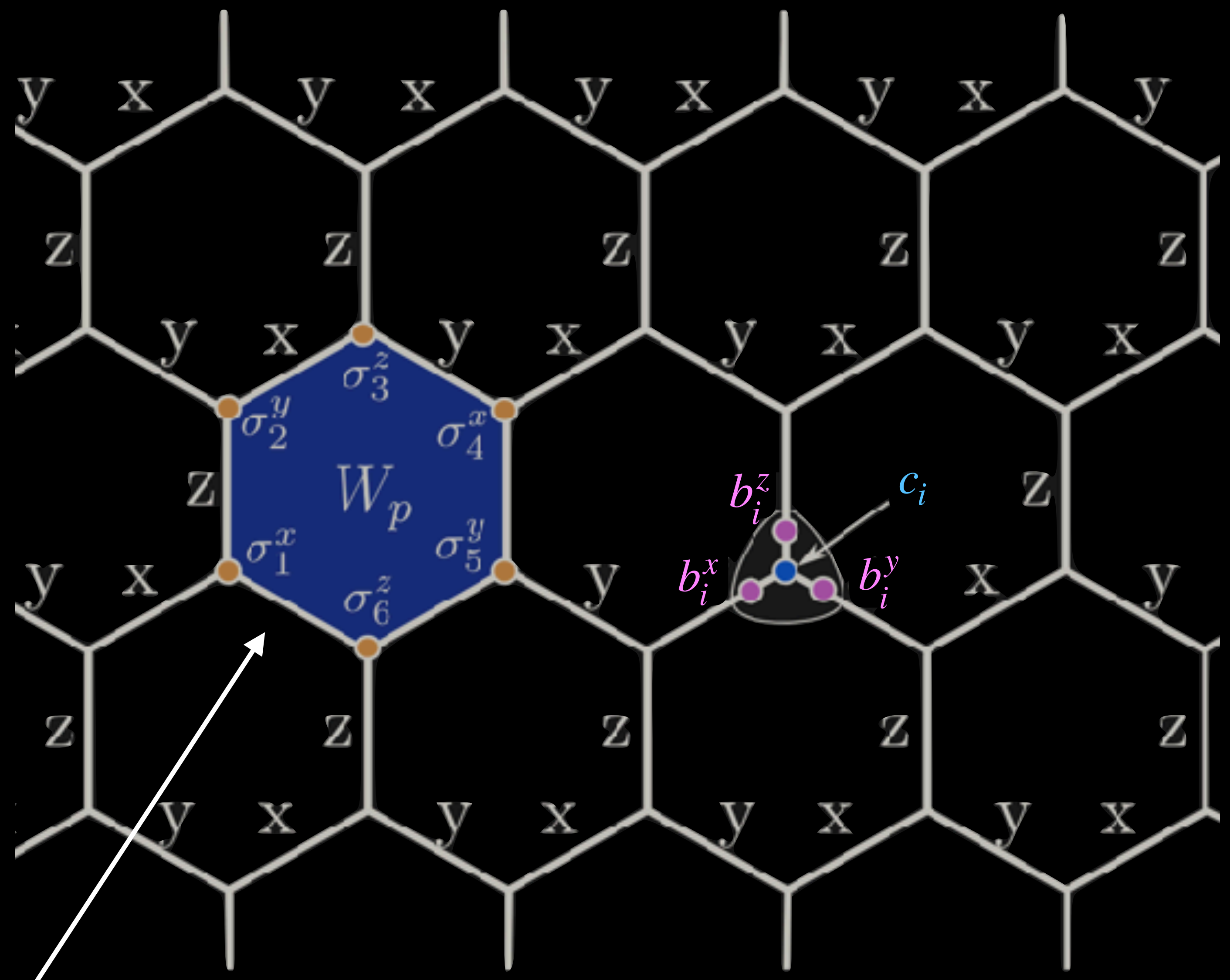

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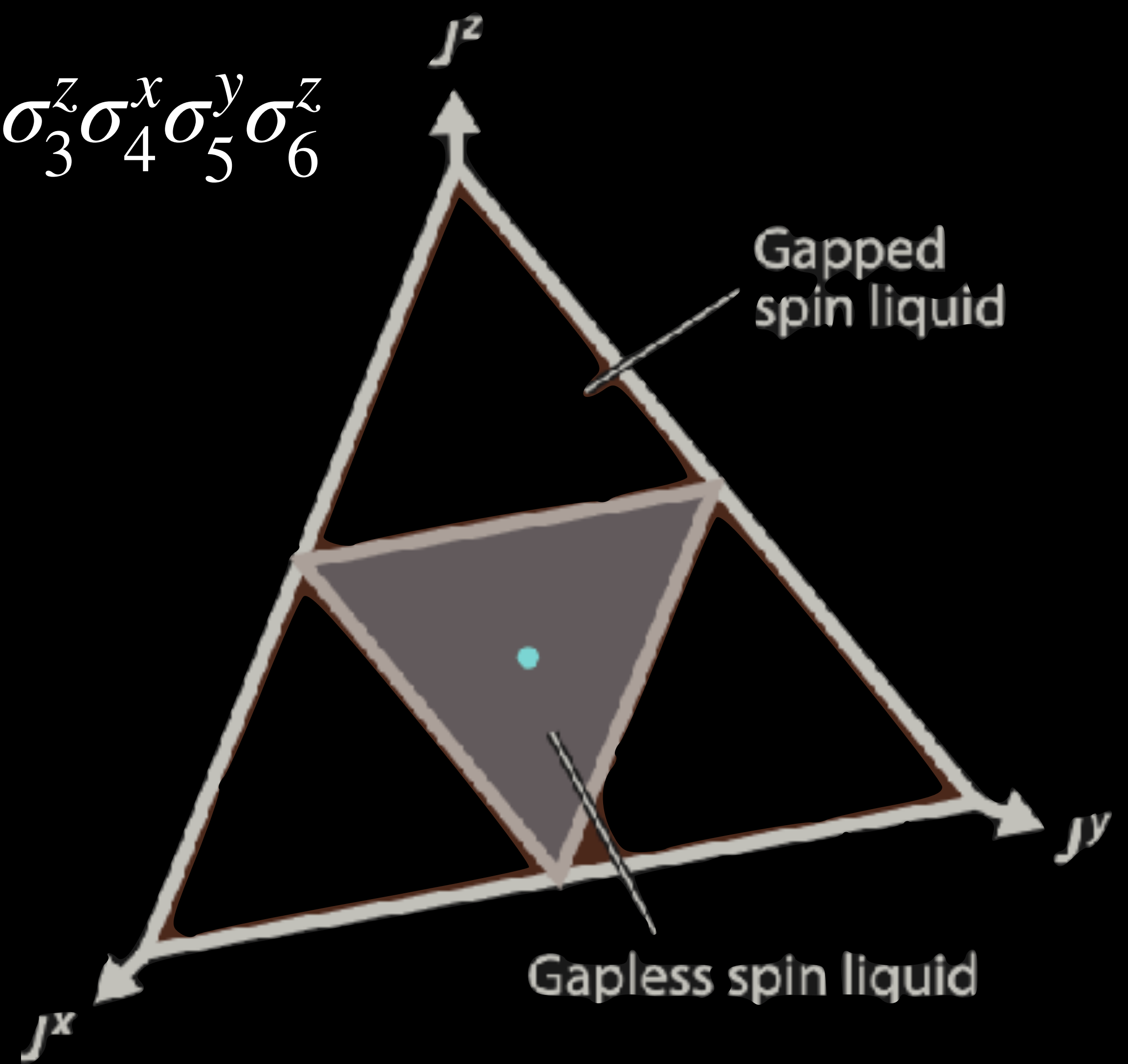

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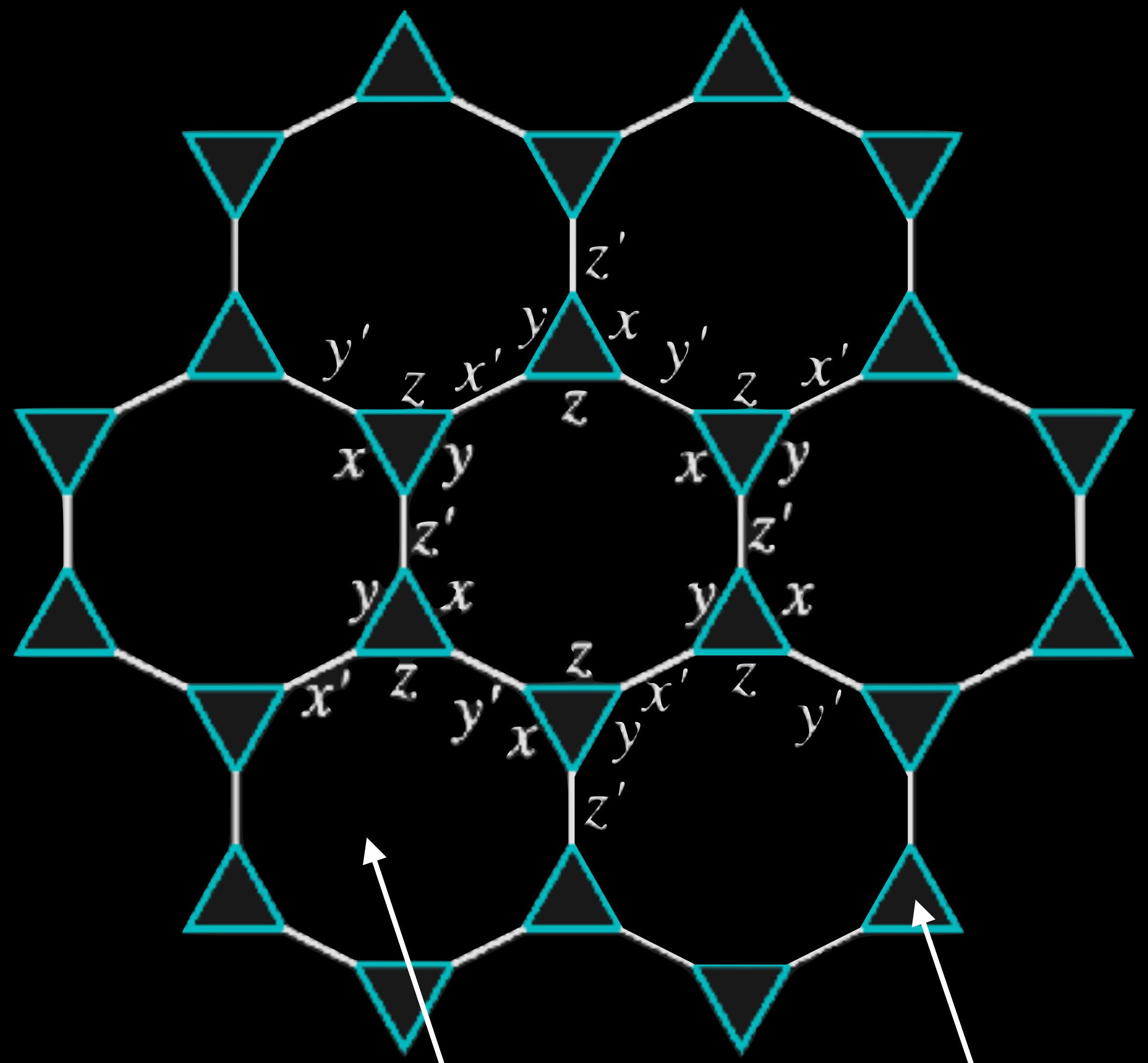

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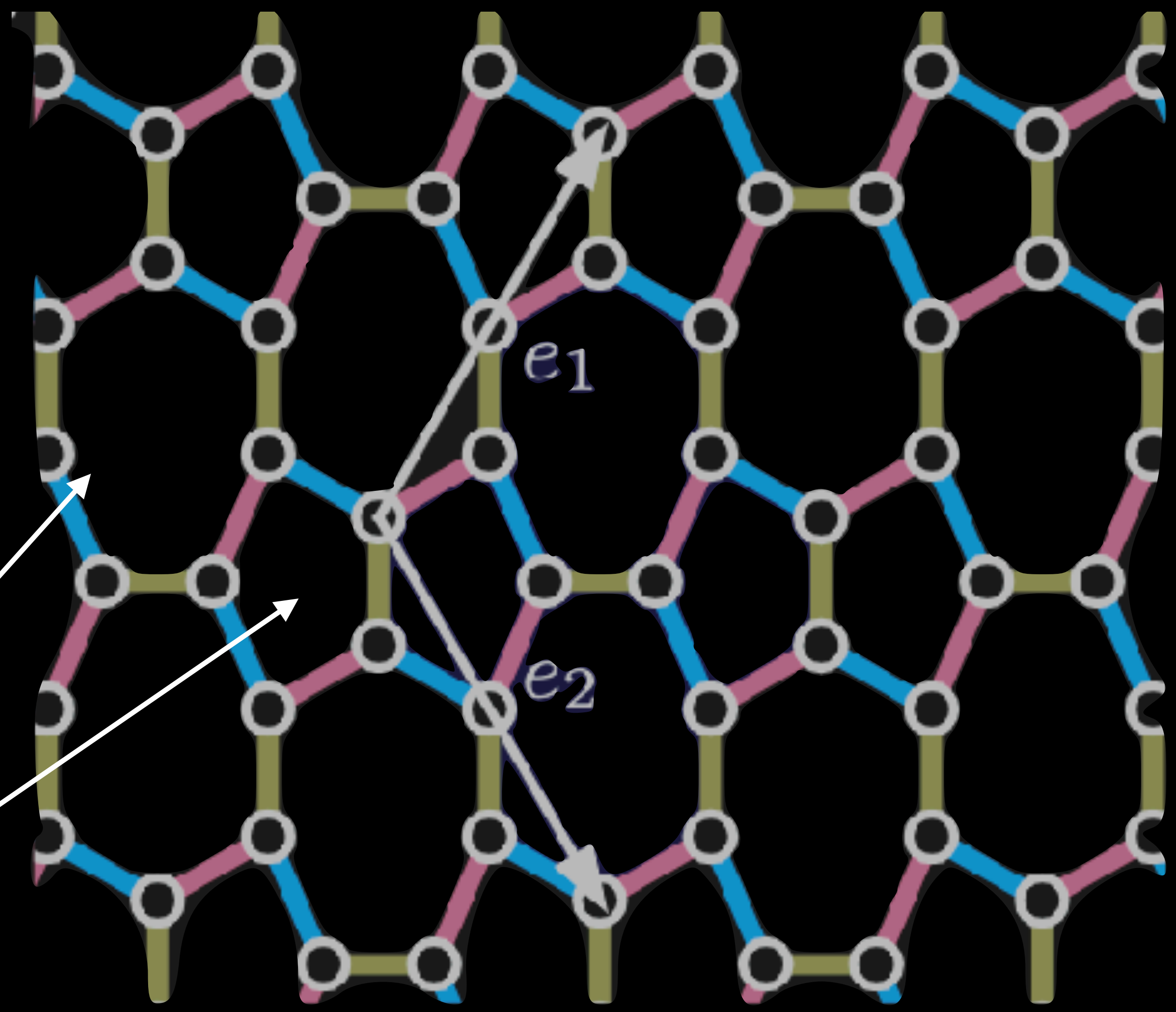
Pentaheptite lattice

Peri et al PRB (2020)



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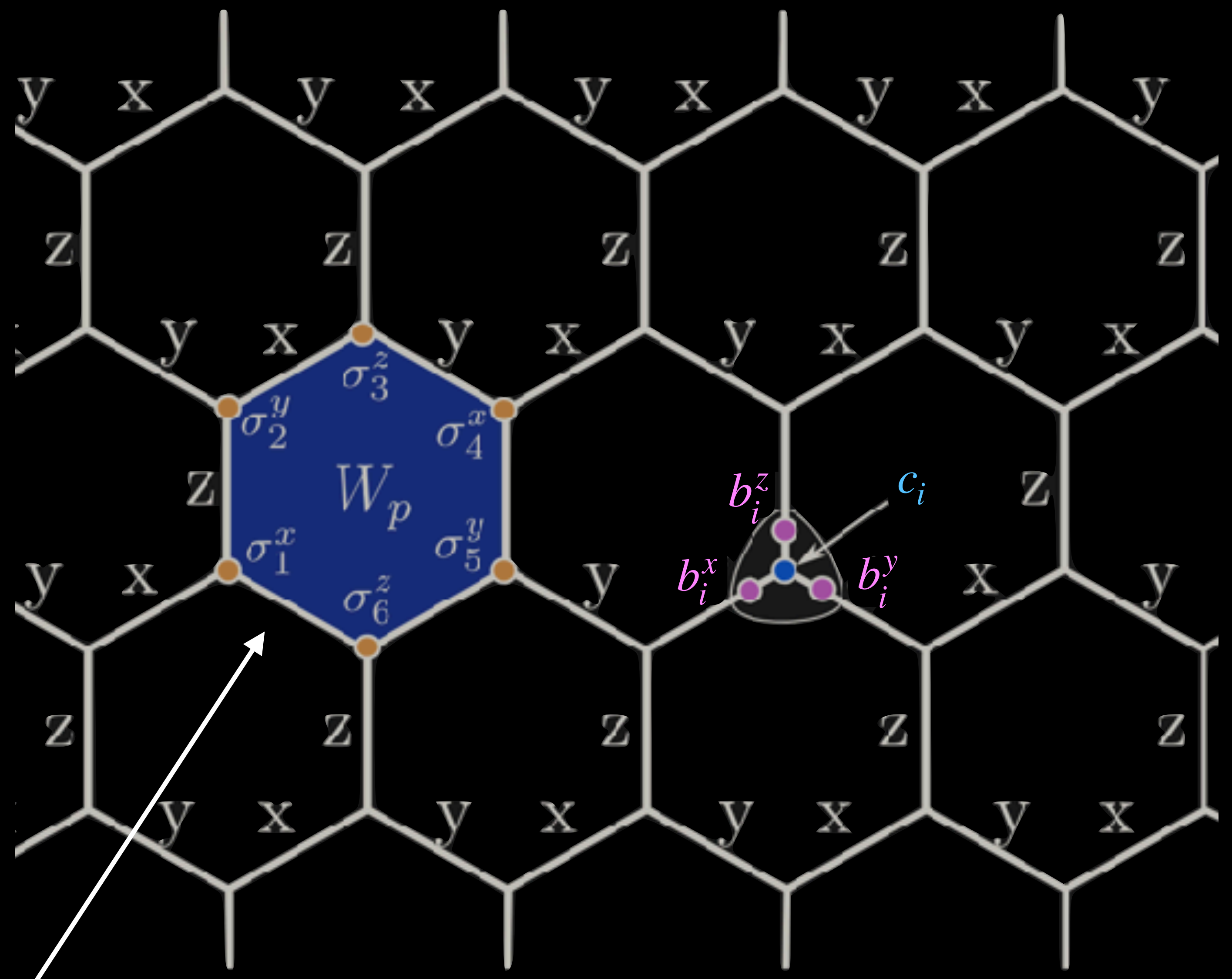

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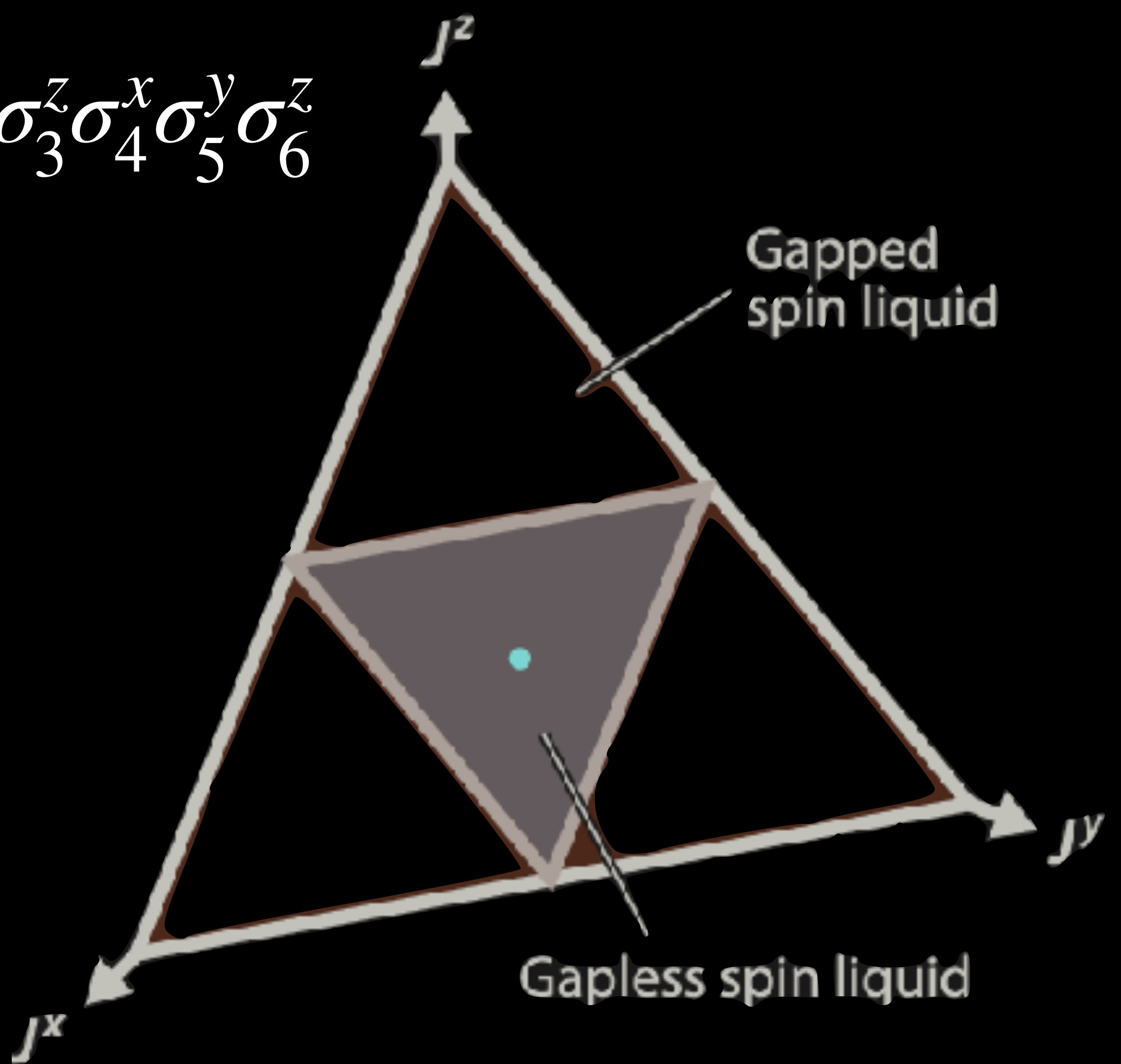

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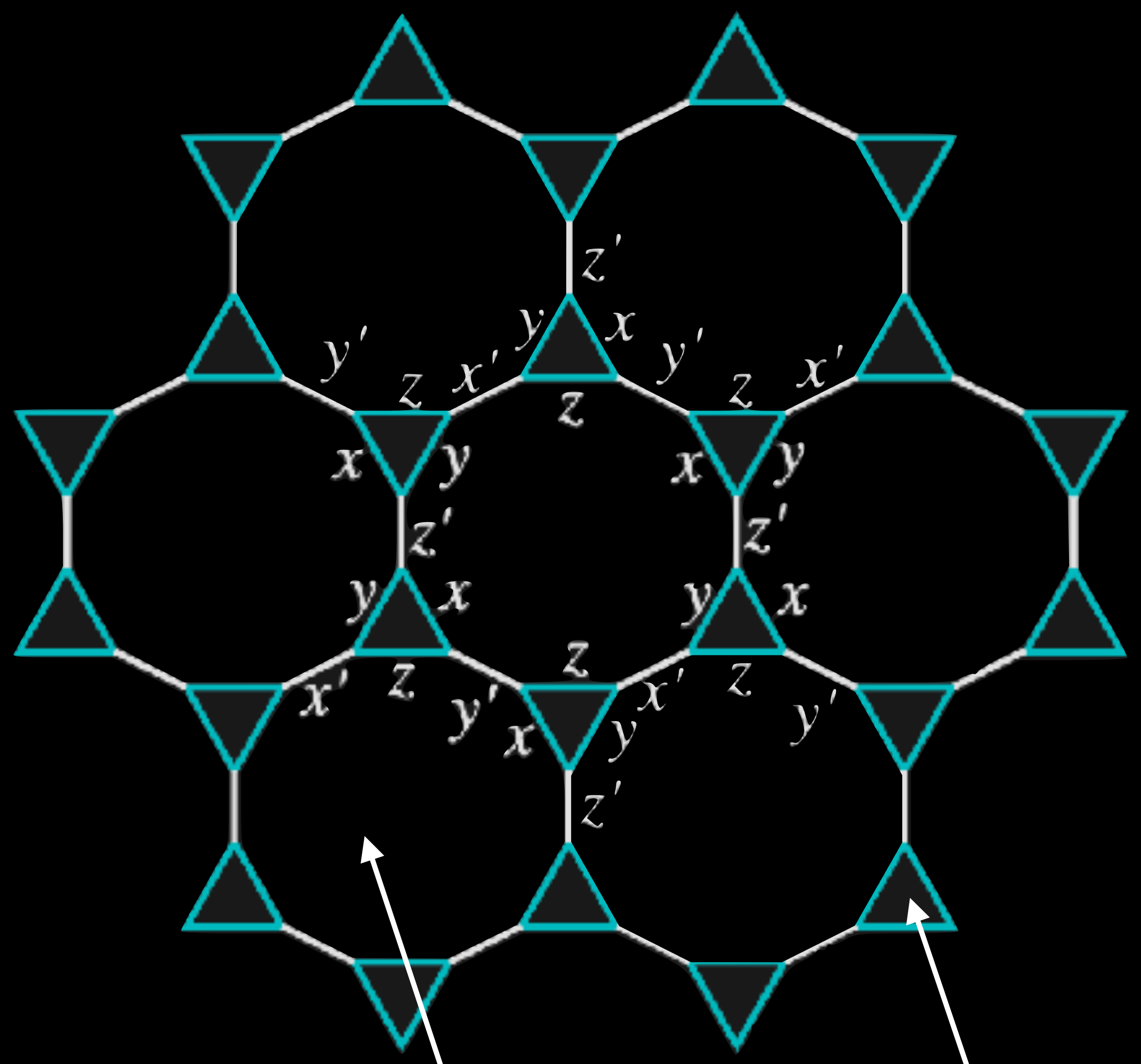

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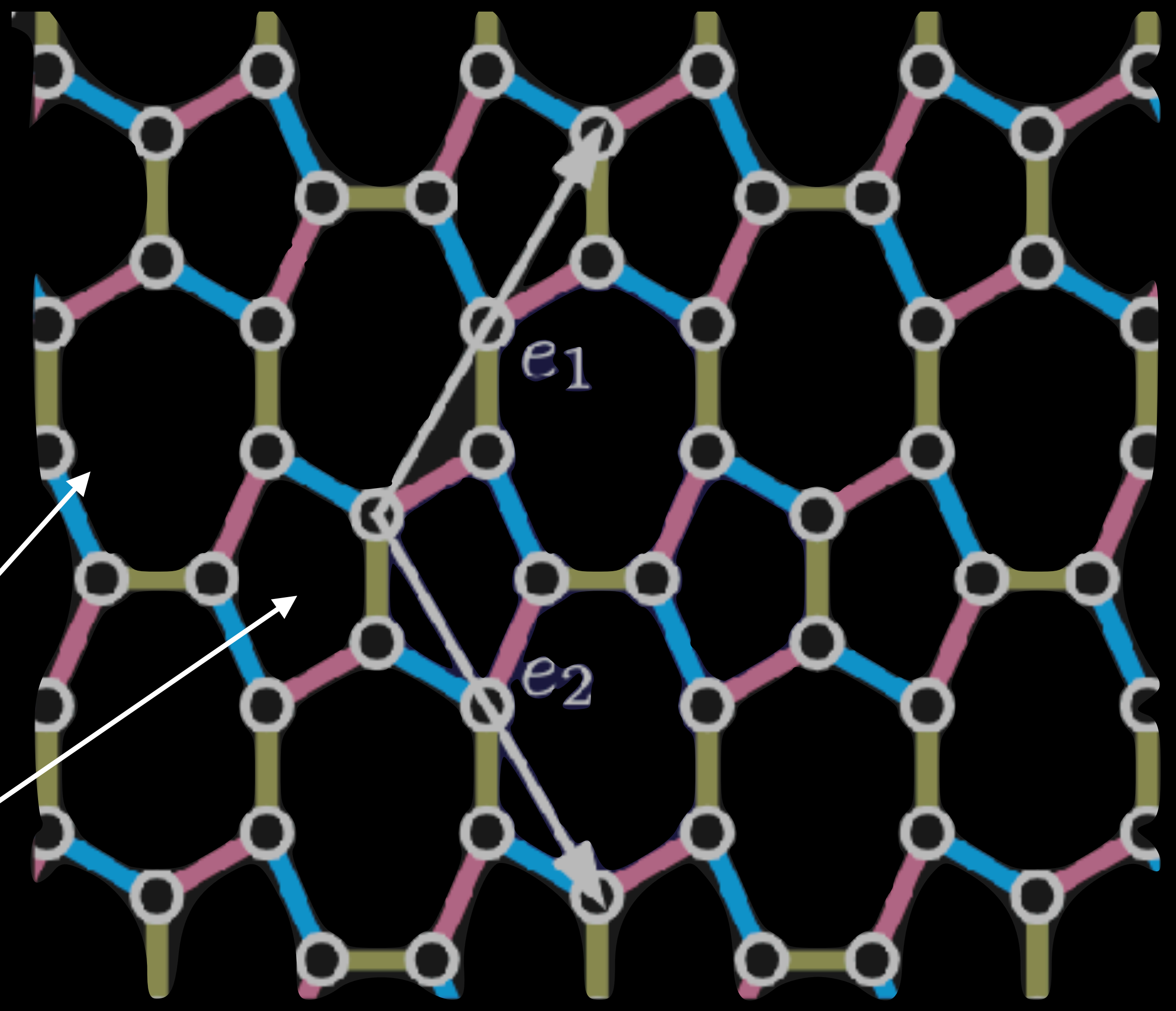

Odd plaquettes break TRS

Kitaev models

Honeycomb

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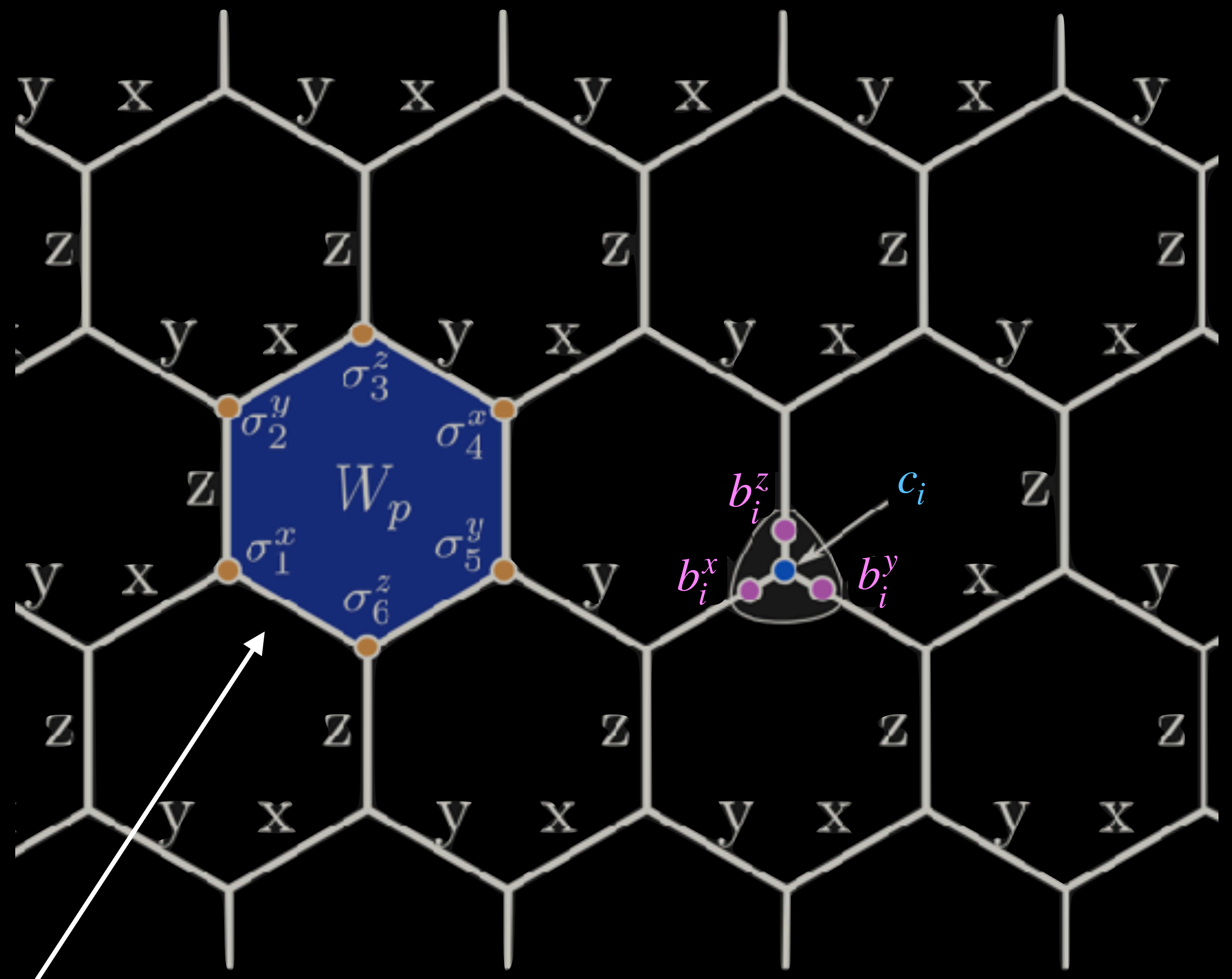

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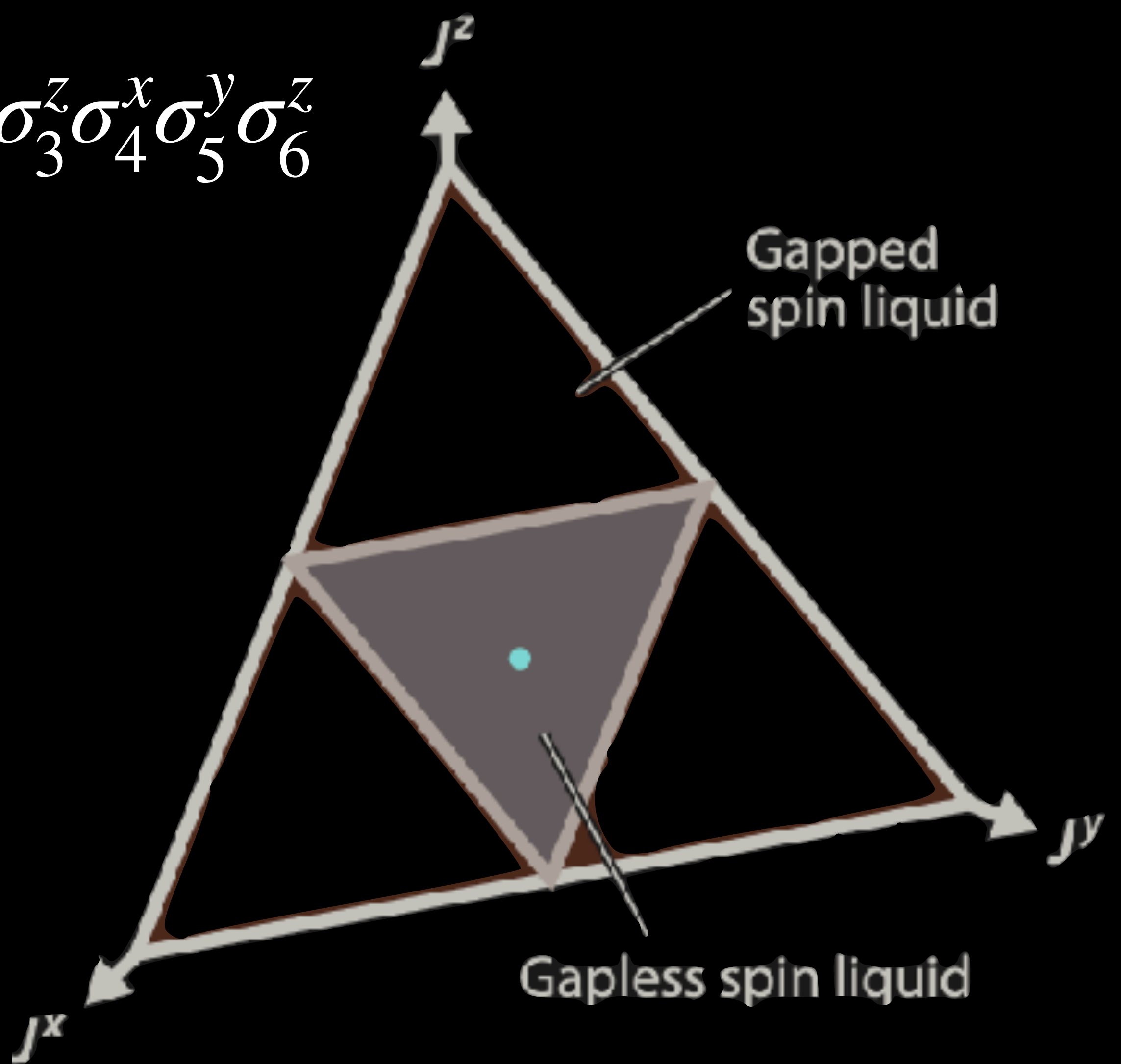

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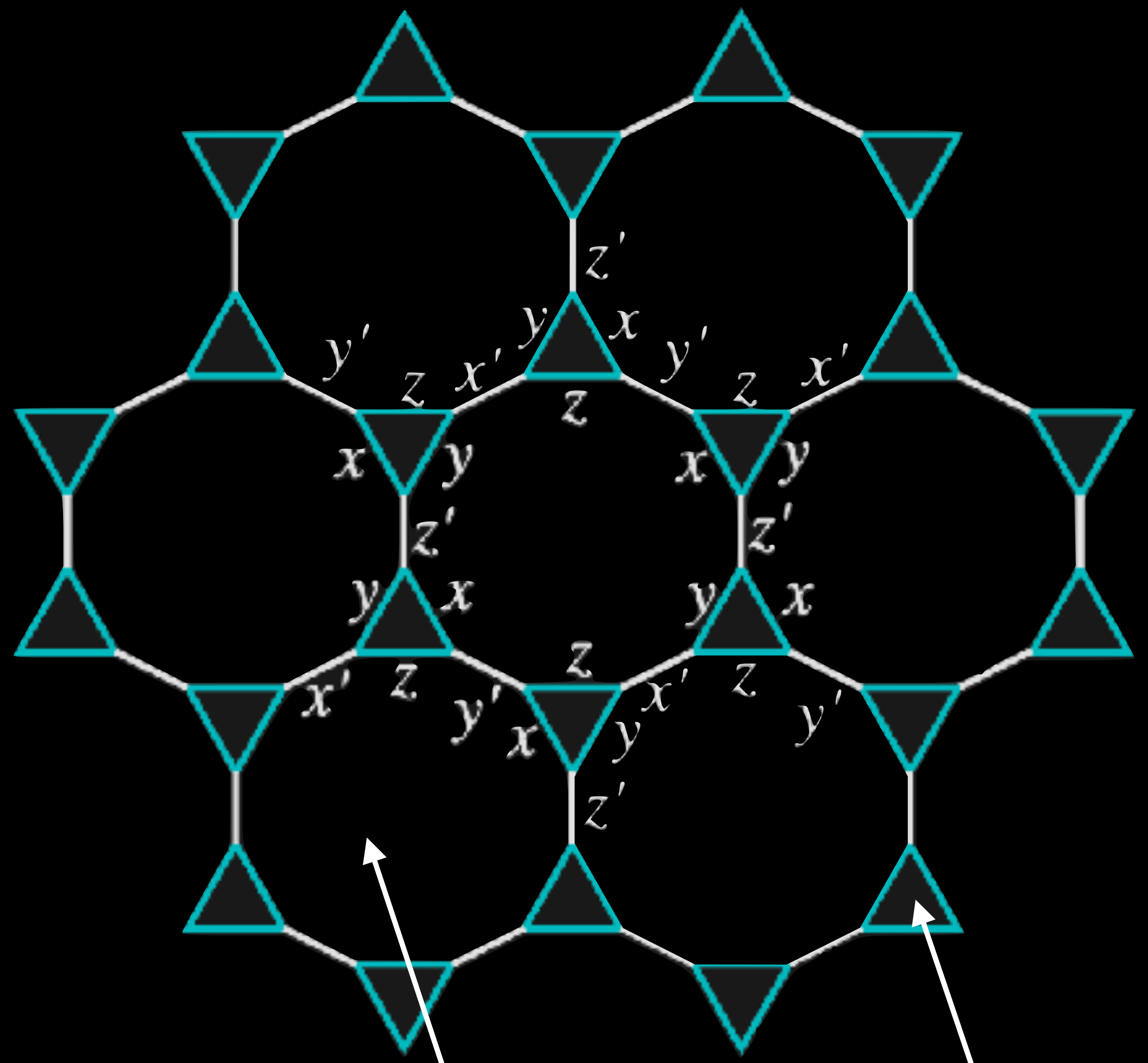
Yao and Kivelson PRL (2007)

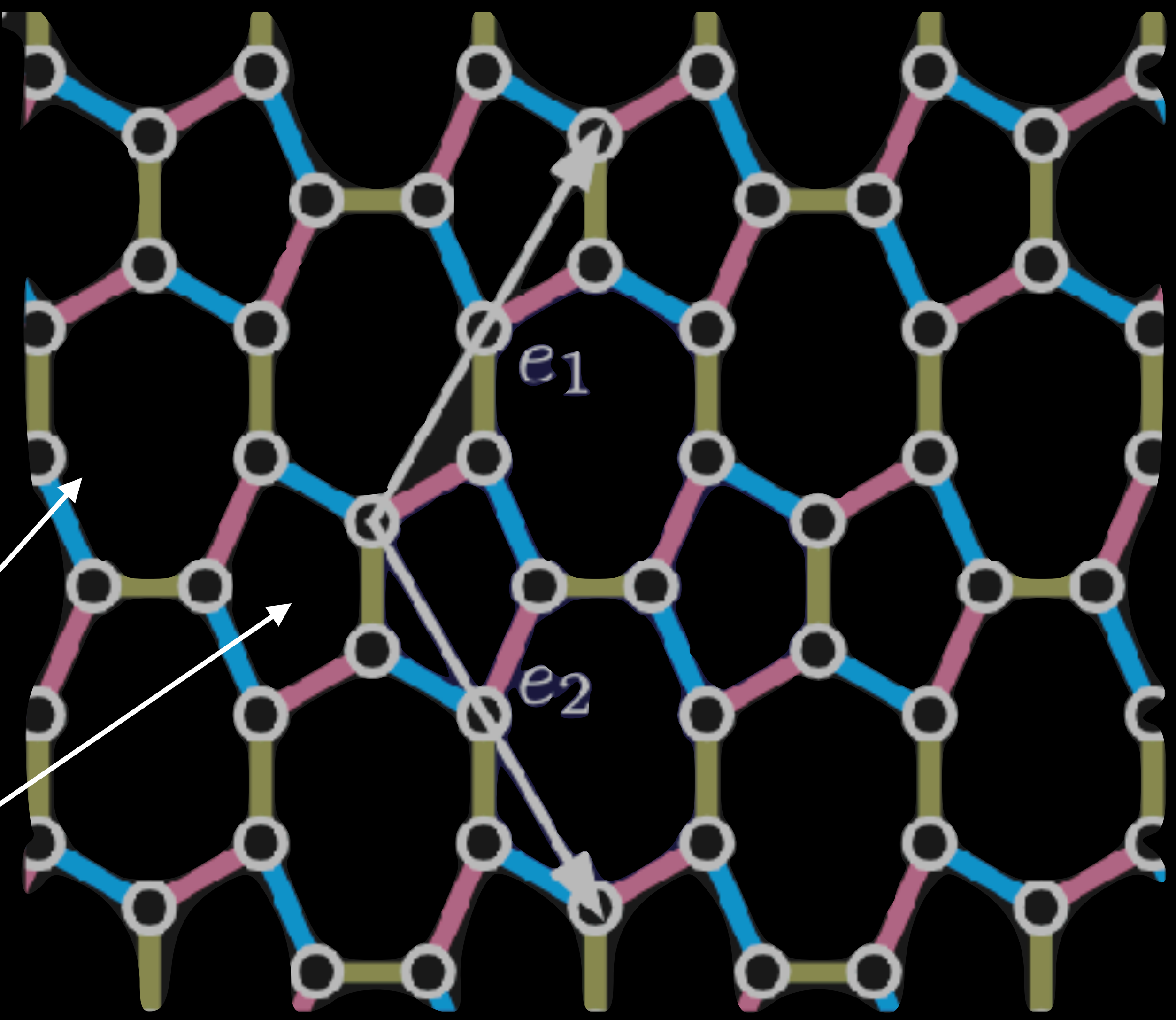


$$\phi_p = \pm 1 \qquad \phi_p = \pm i$$

Odd plaquettes break TRS →

Pentaheptite lattice

Peri et al PRB (2020)



Gapped chiral spin-liquid!

= chiral majorana edge states

non-abelian excitations

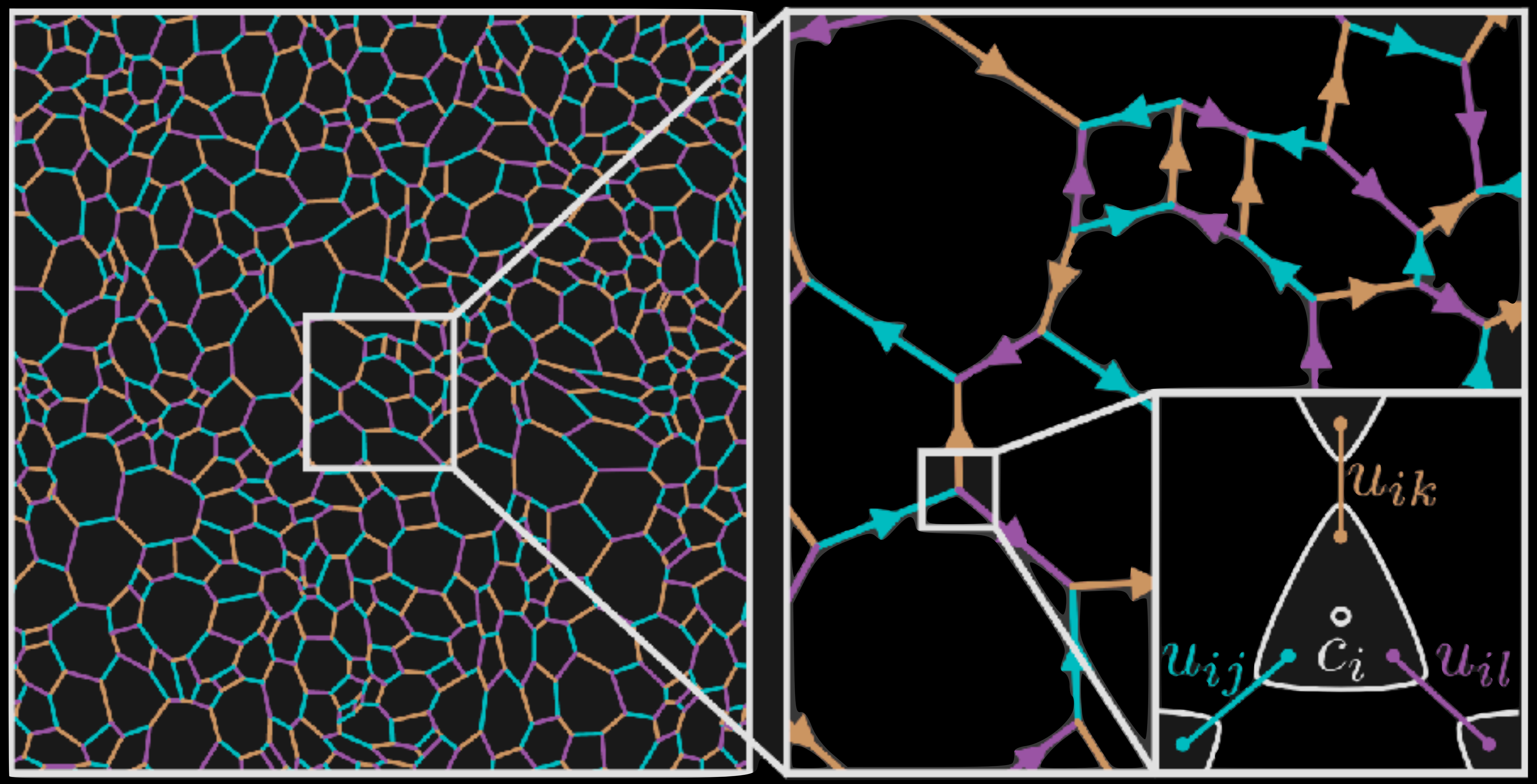
Amorphous Kitaev model

G. Casella et al 2208.08246

Lattice

Groundstate

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



Amorphous Kitaev model

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Lattice

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LDOS

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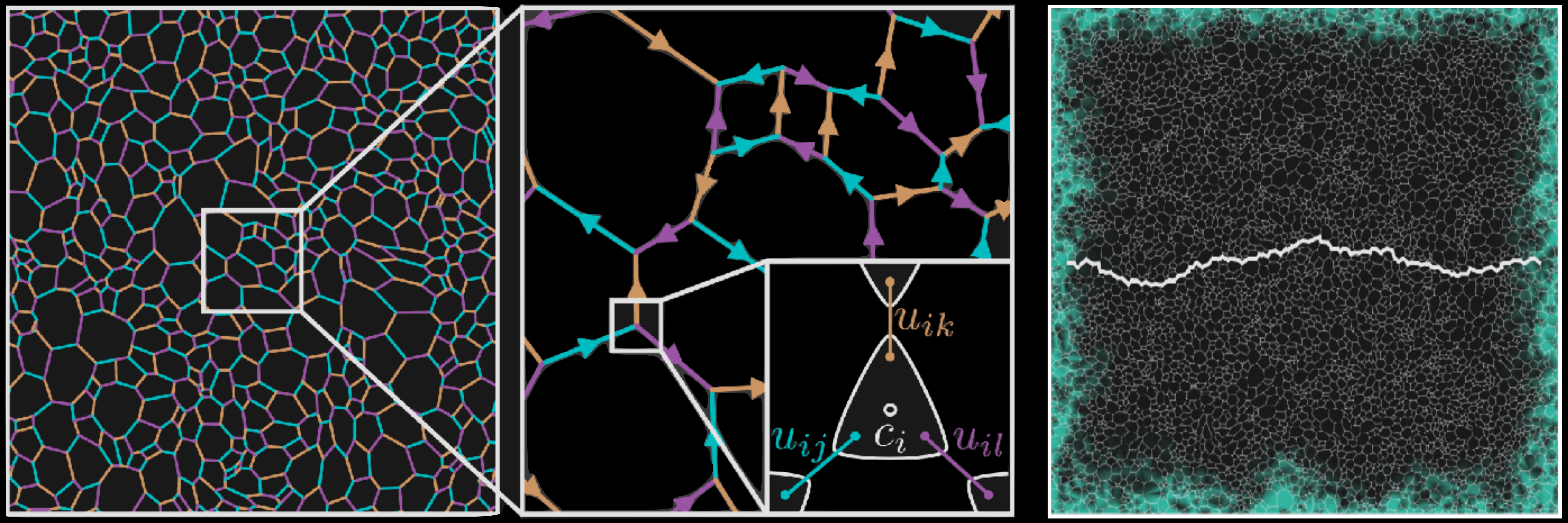

Amorphous Kitaev model

G. Casella et al 2208.08246

Lattice

Groundstate

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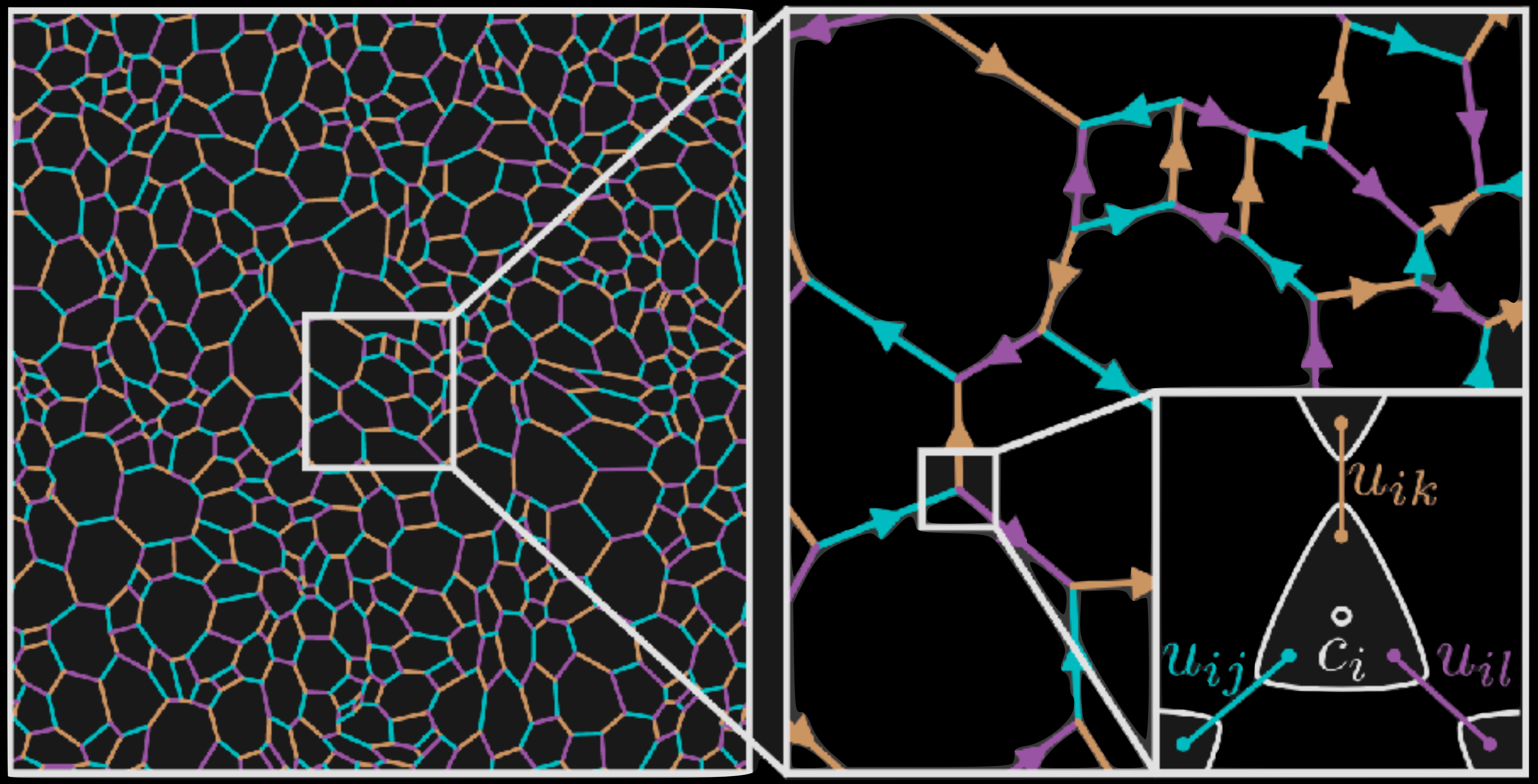
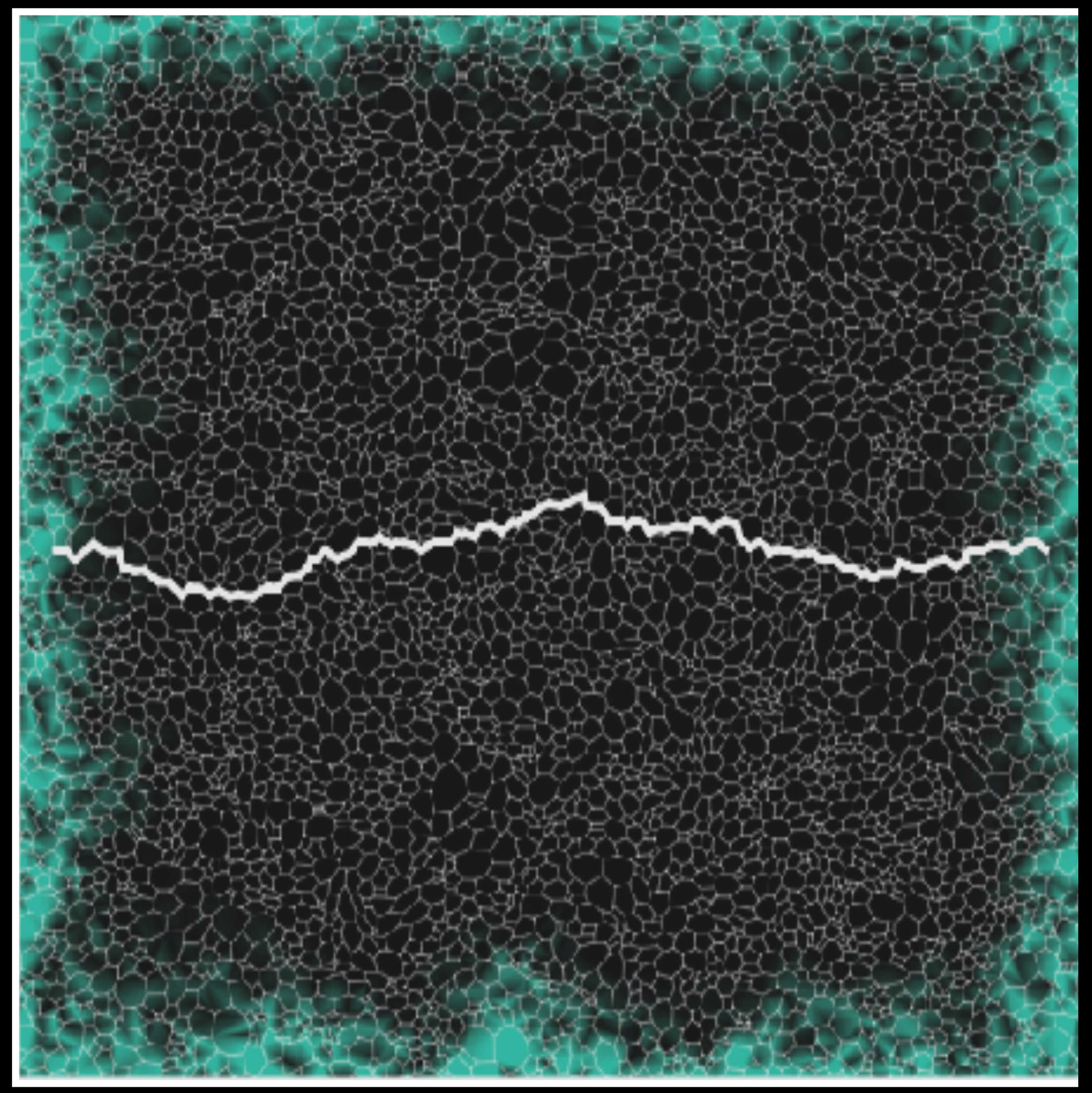
LDOS

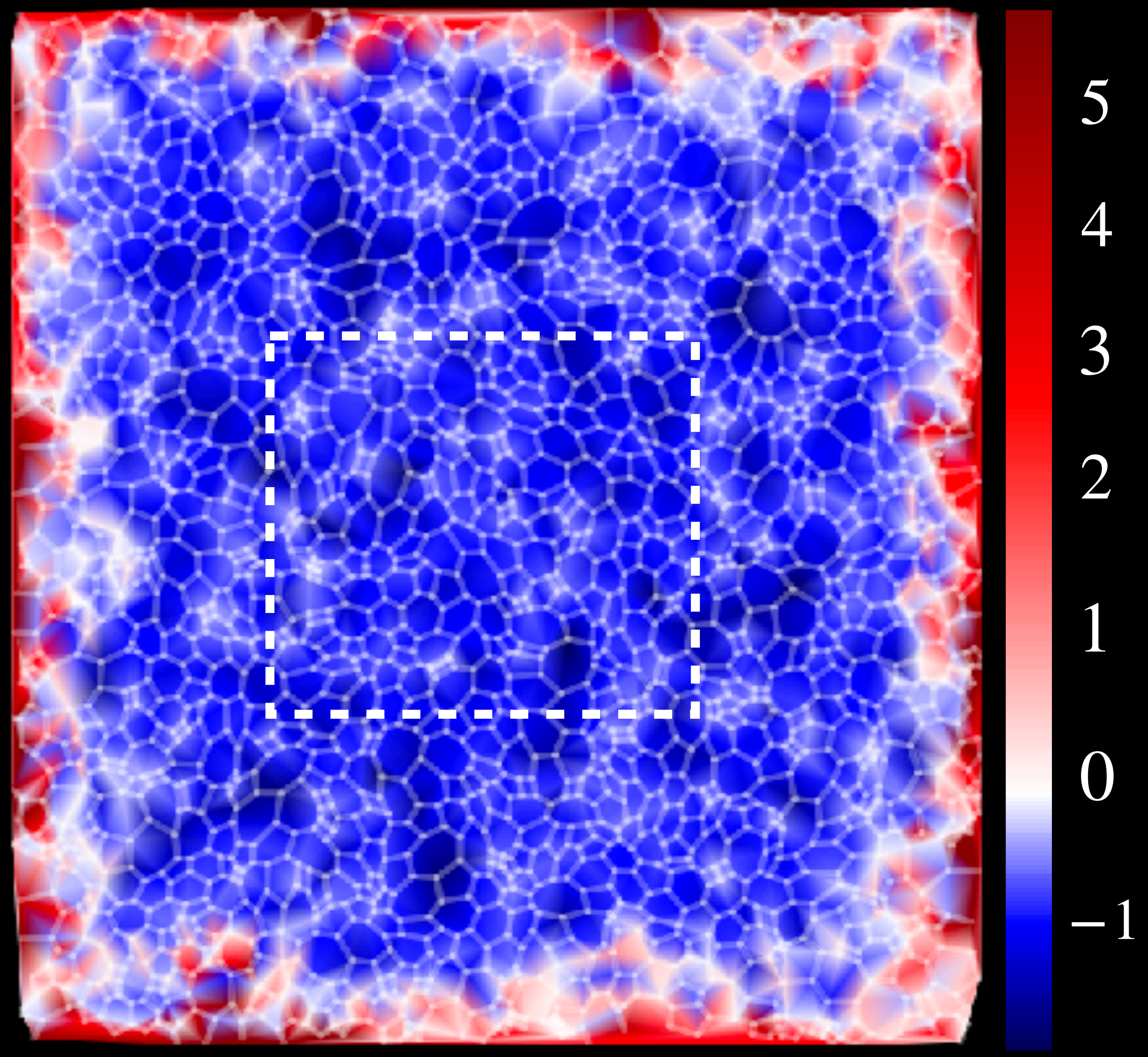
Local Chern marker

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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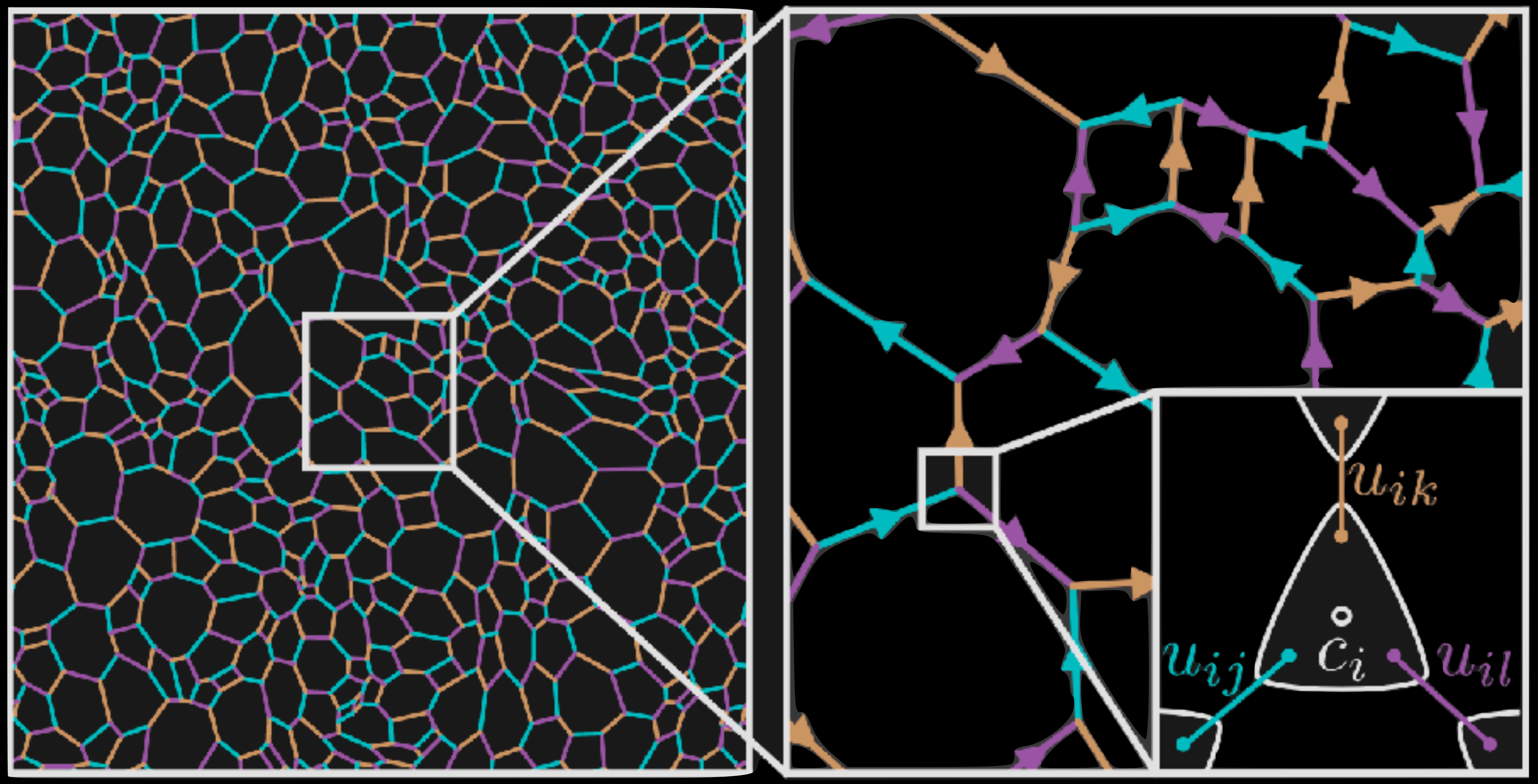
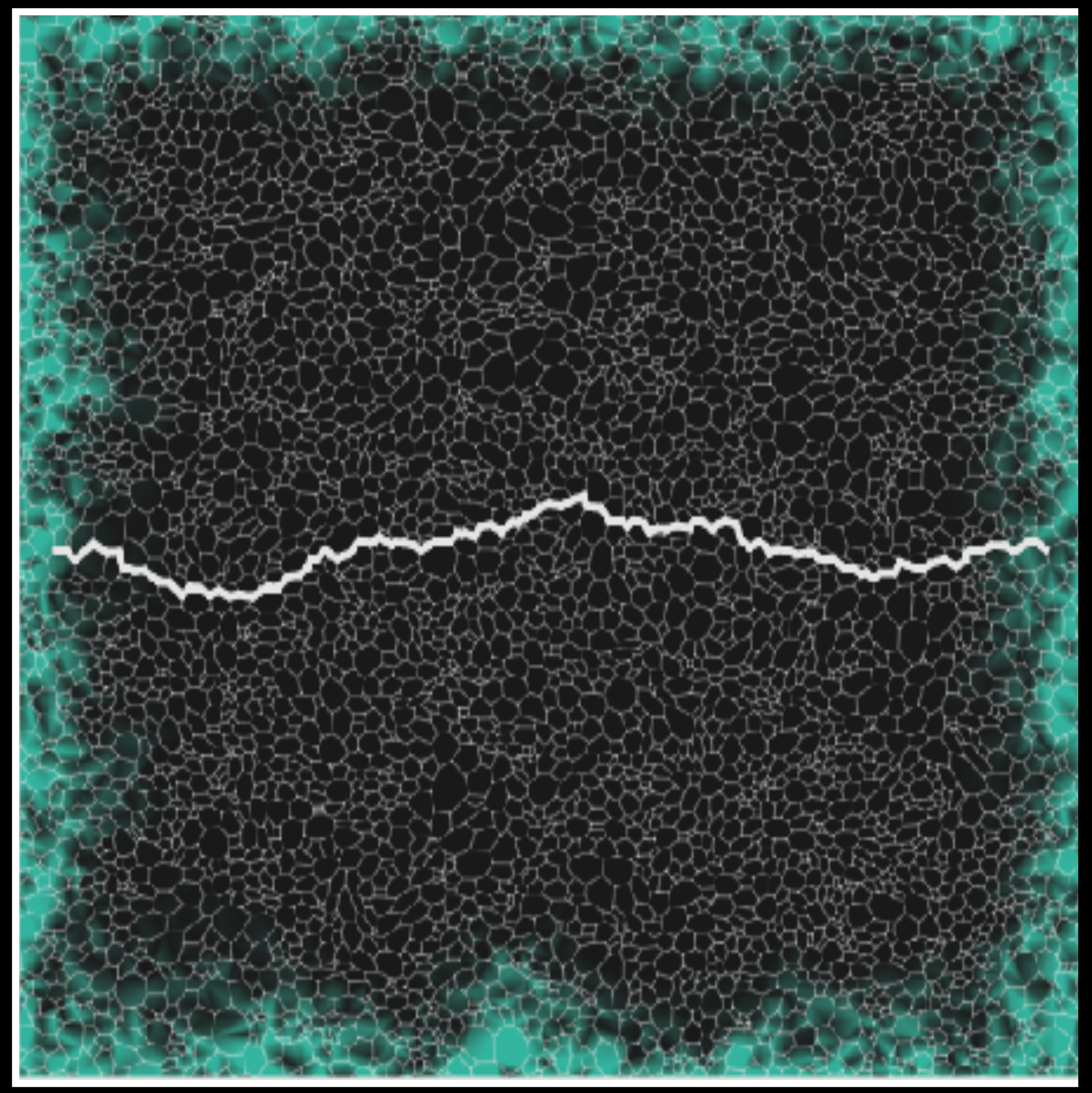
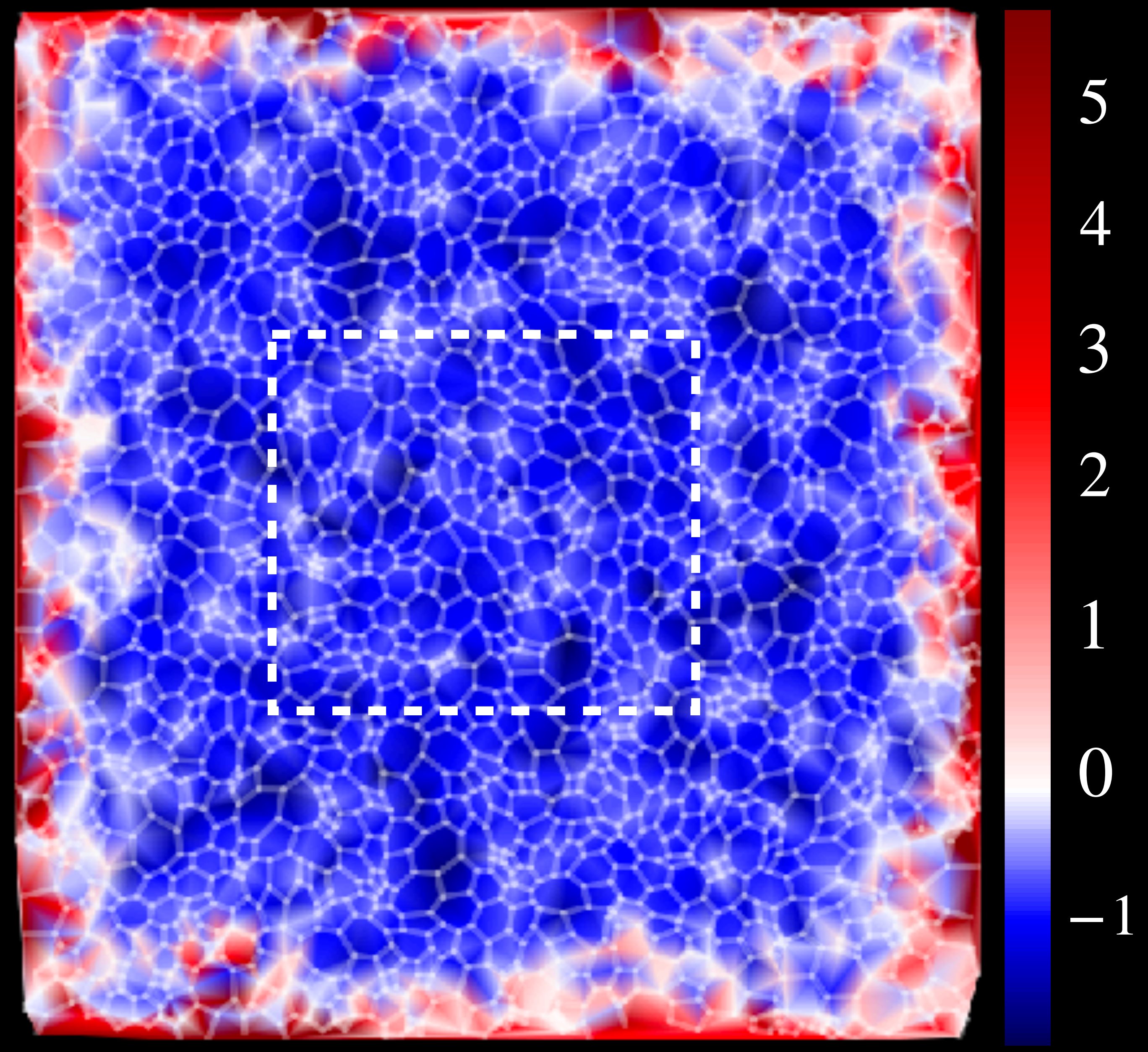






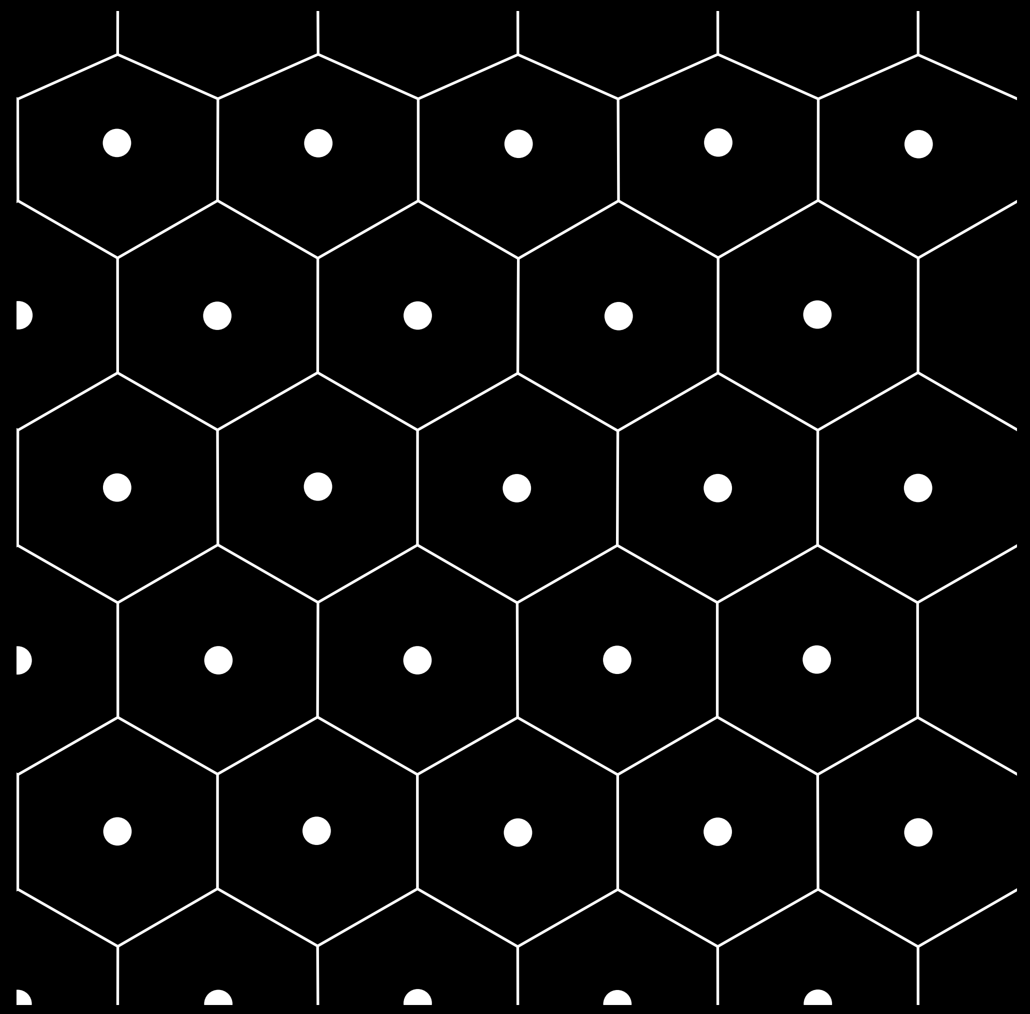
Chiral spin-liquid!

= chiral majorana edge states

non-abelian excitations

Controlling lattice disorder

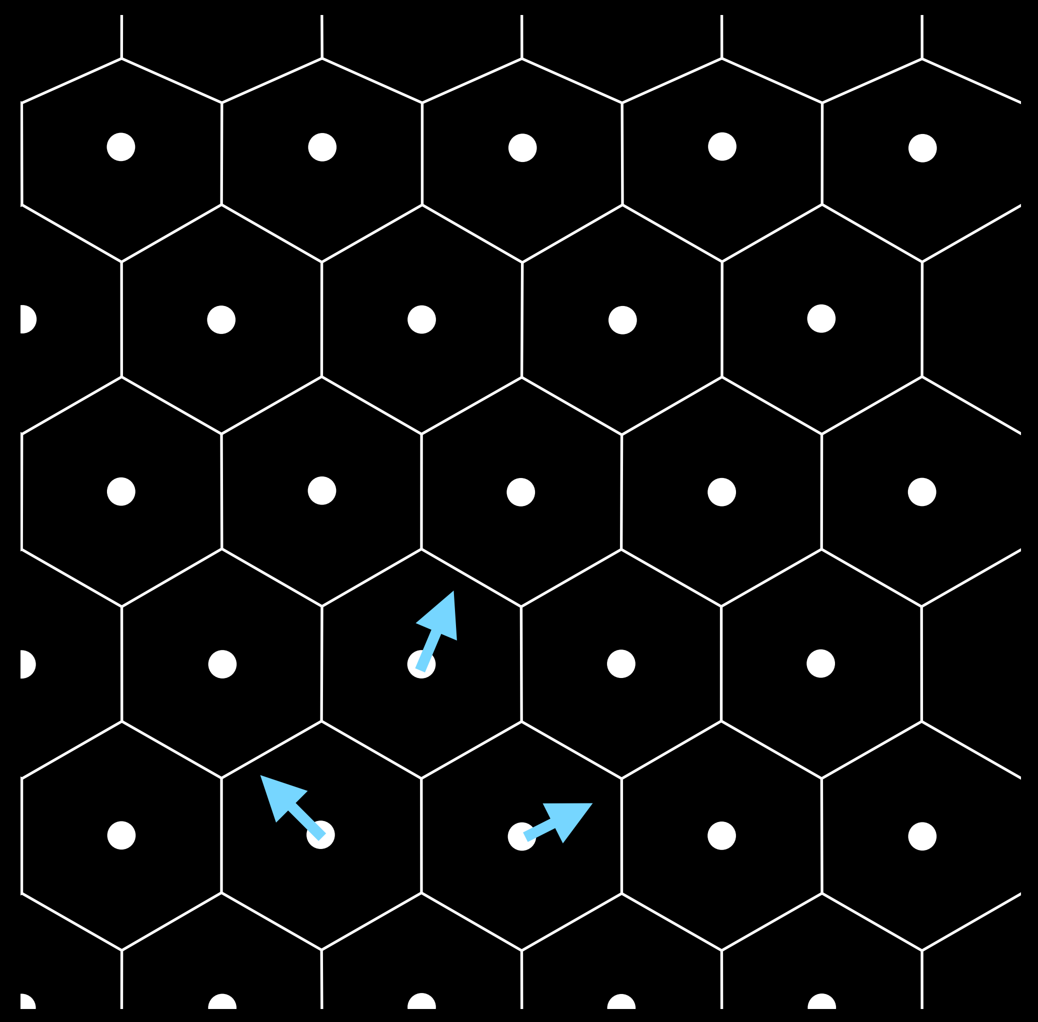
Voronization



AGG, C. Repellin PRL (2023)

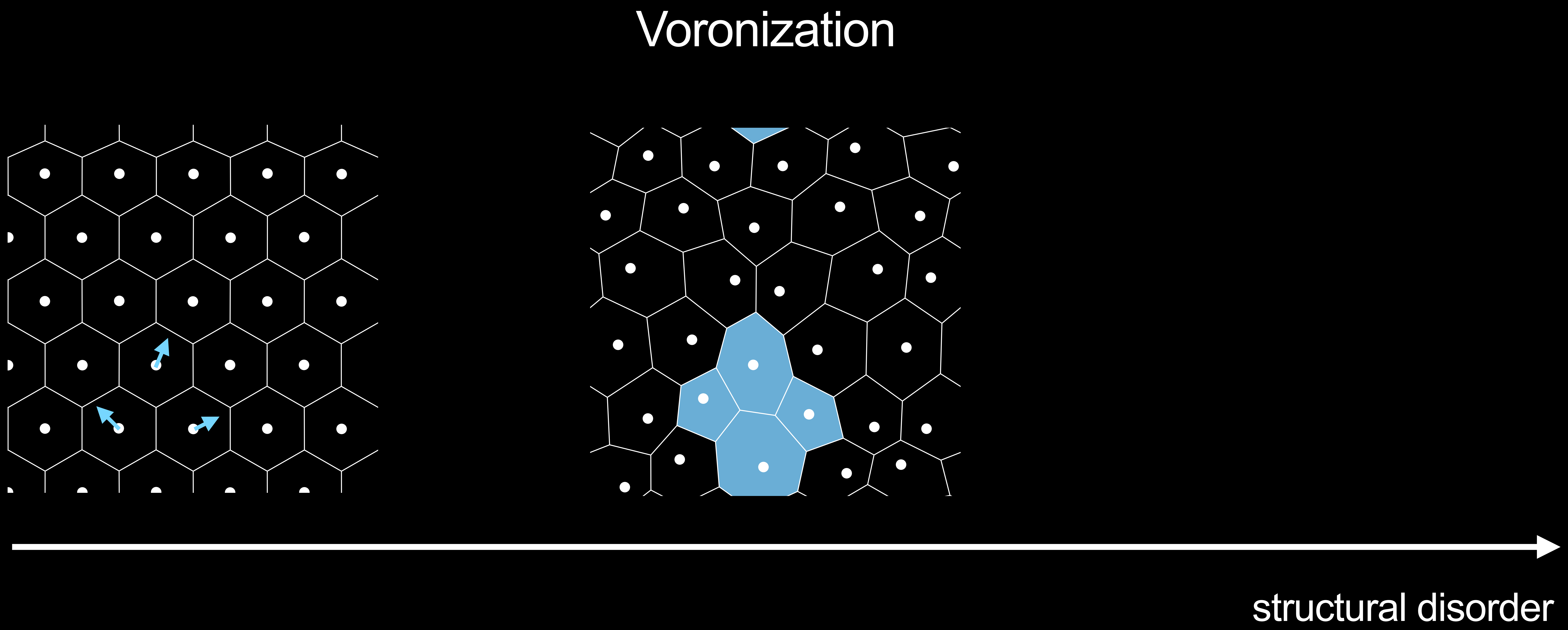
Controlling lattice disorder

Voronization



AGG, C. Repellin PRL (2023)

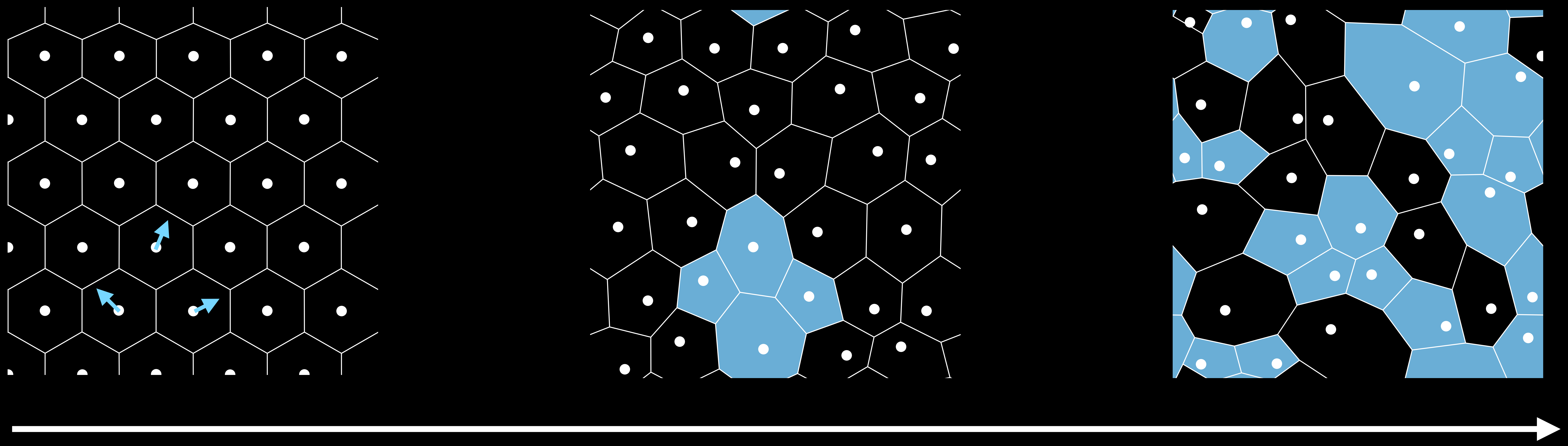
Controlling lattice disorder



AGG, C. Repellin PRL (2023)

Controlling lattice disorder

Voronization



structural disorder

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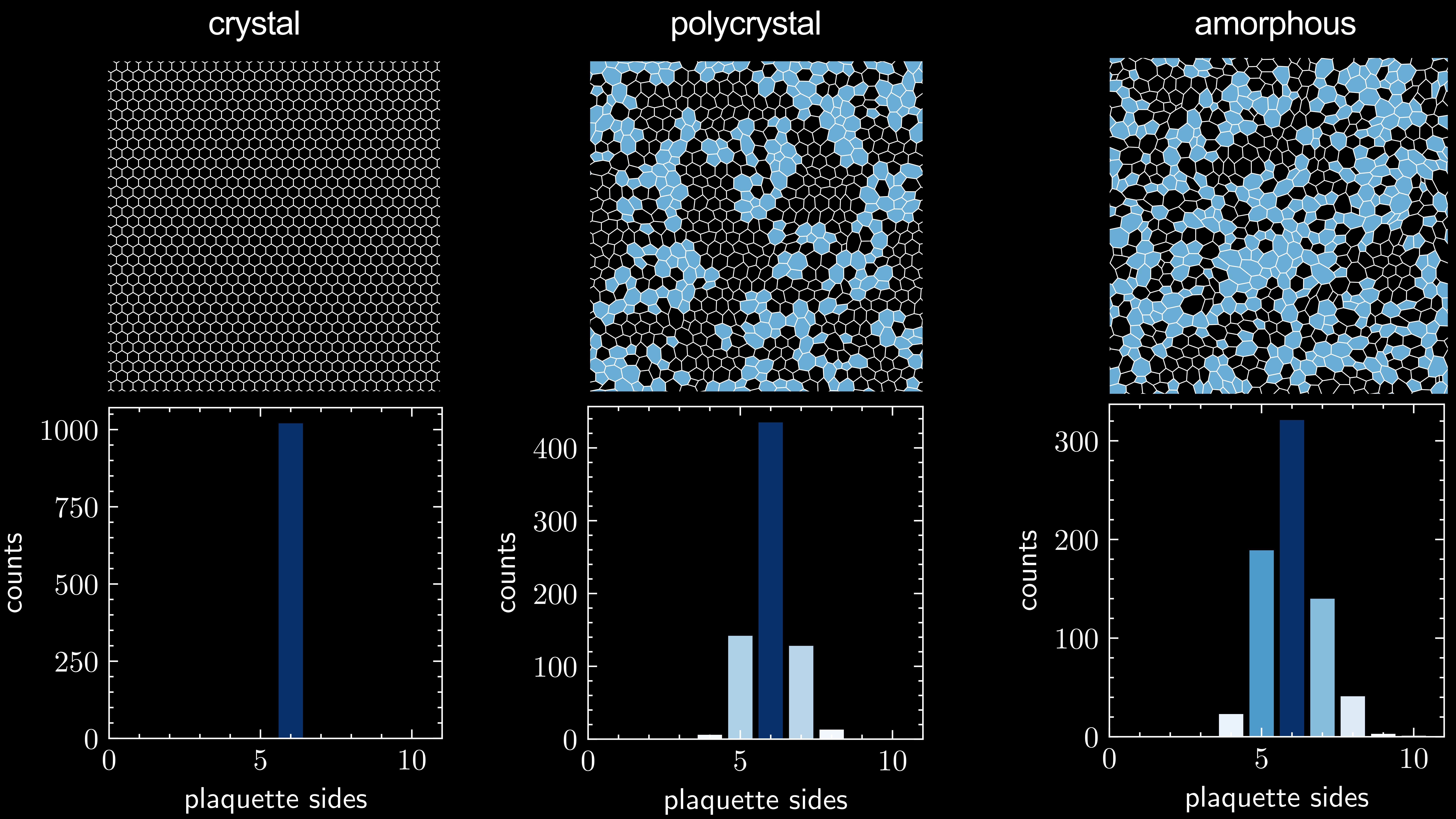
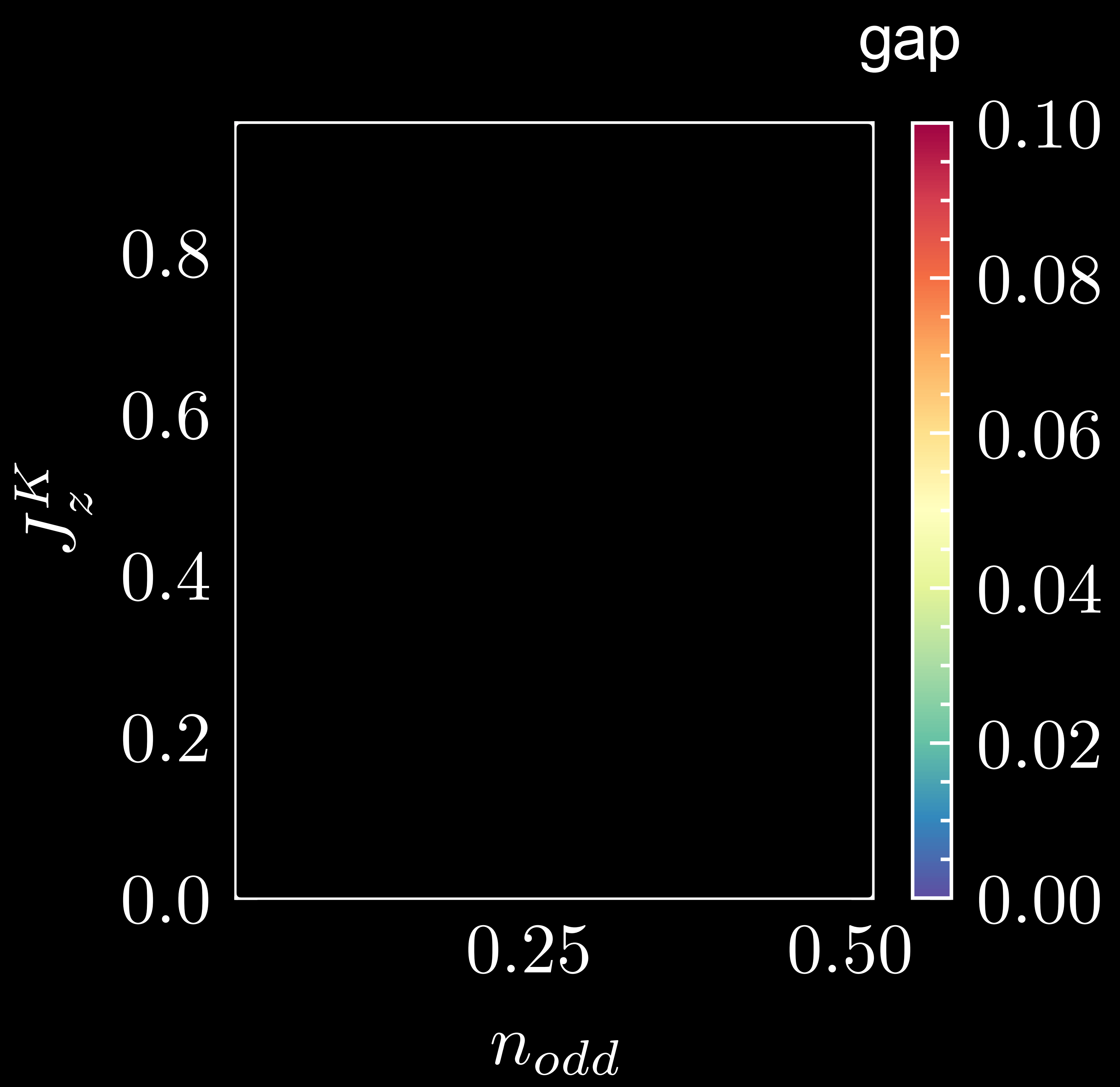
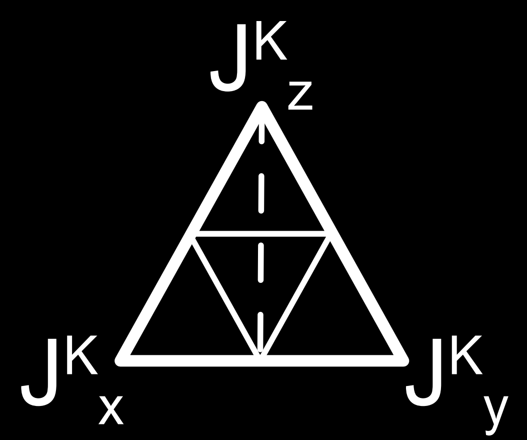
Controlled Voronization



A topological gap as disorder is increased





AGG, C. Repellin PRL (2023)

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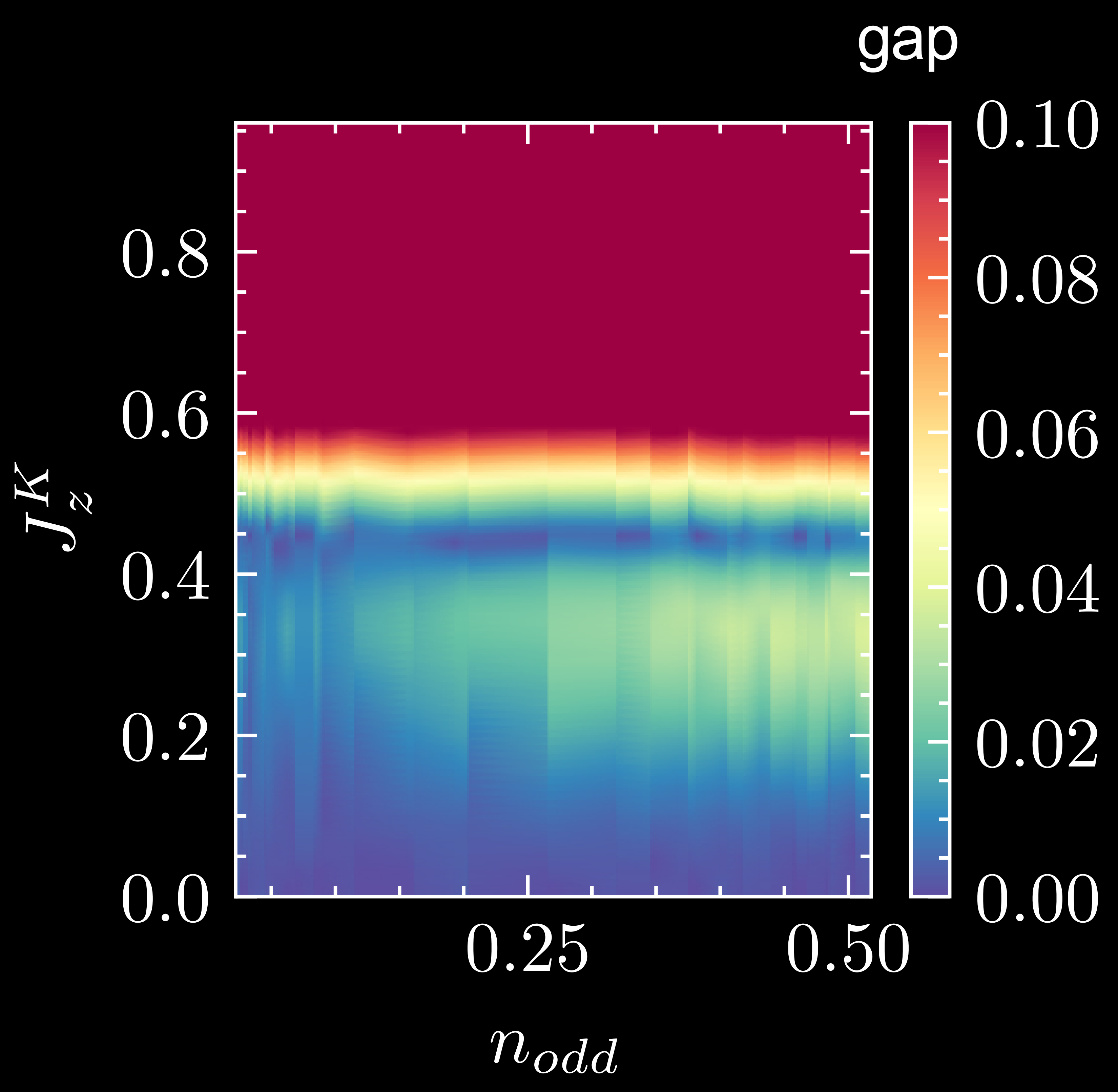

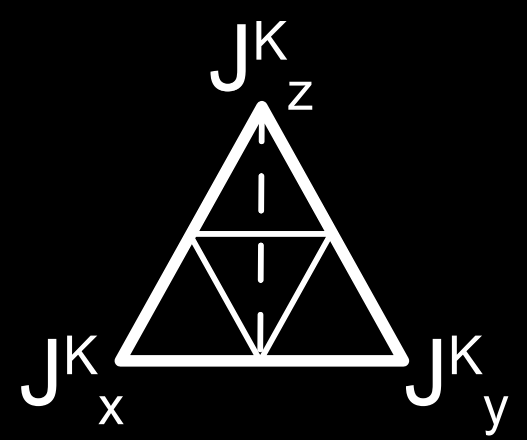

AGG, C. Repellin PRL (2023)

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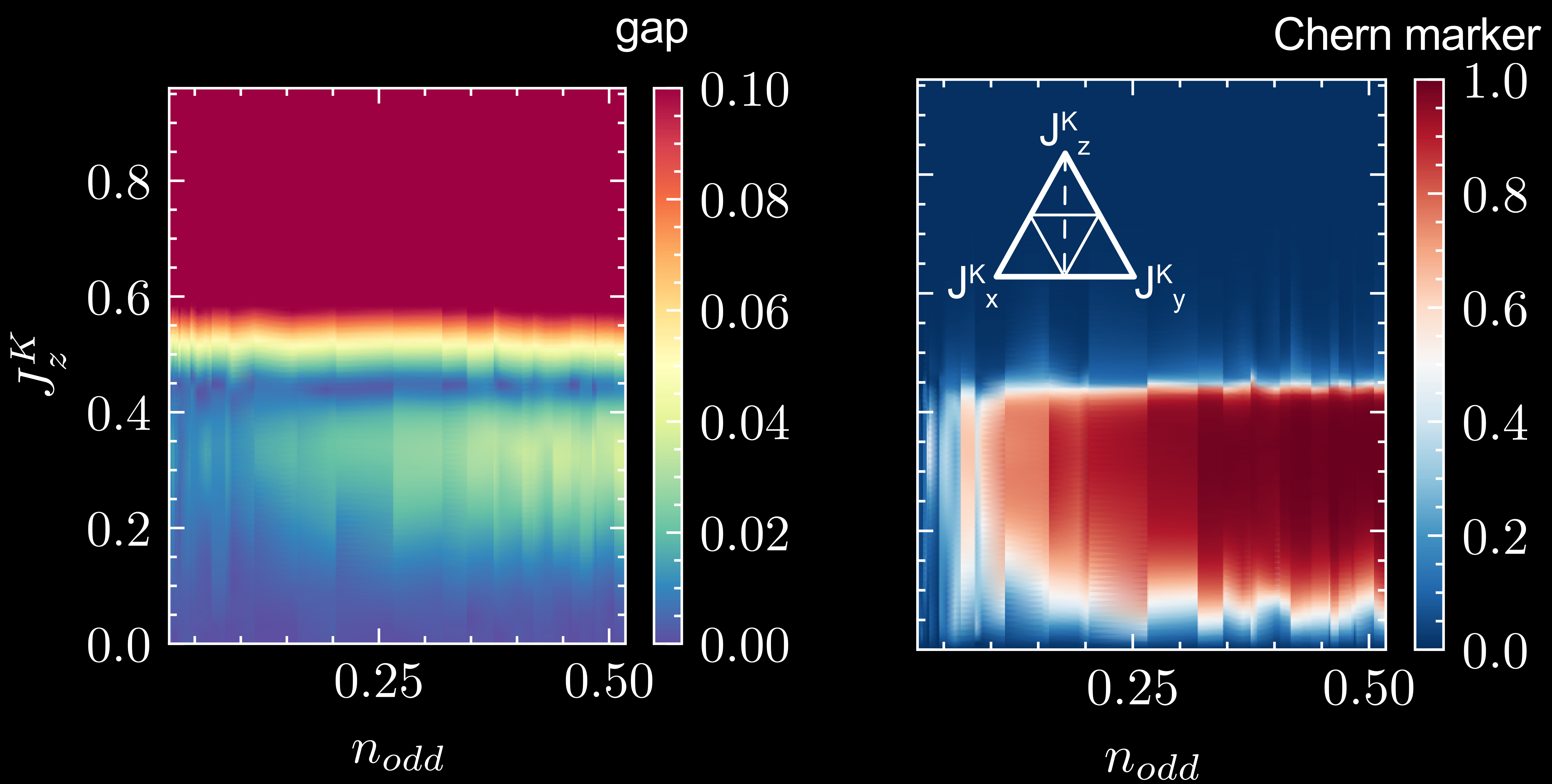

AGG, C. Repellin PRL (2023)

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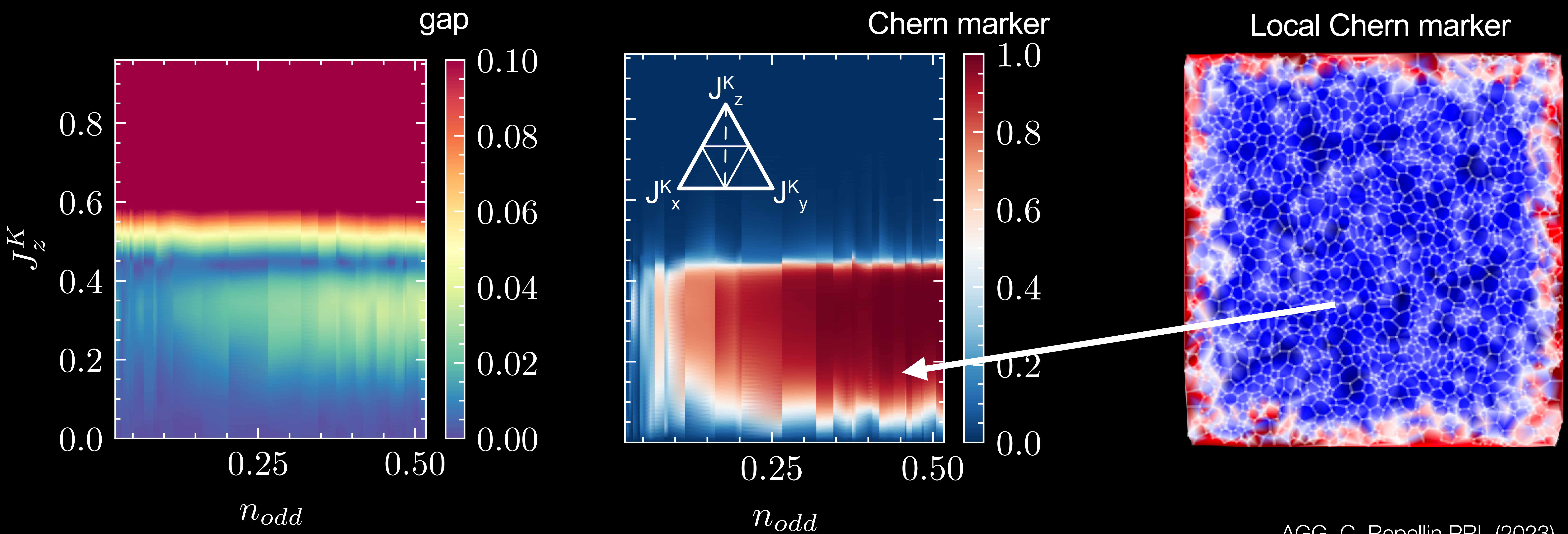

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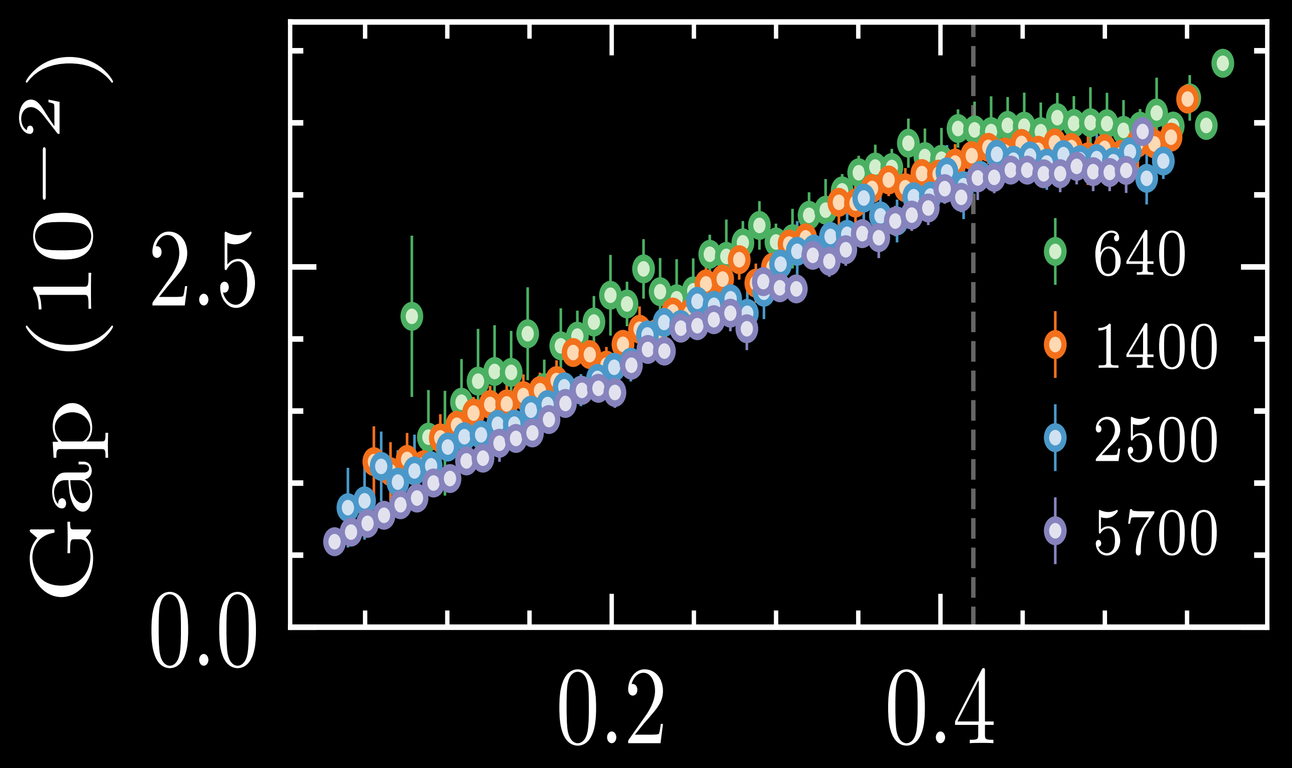

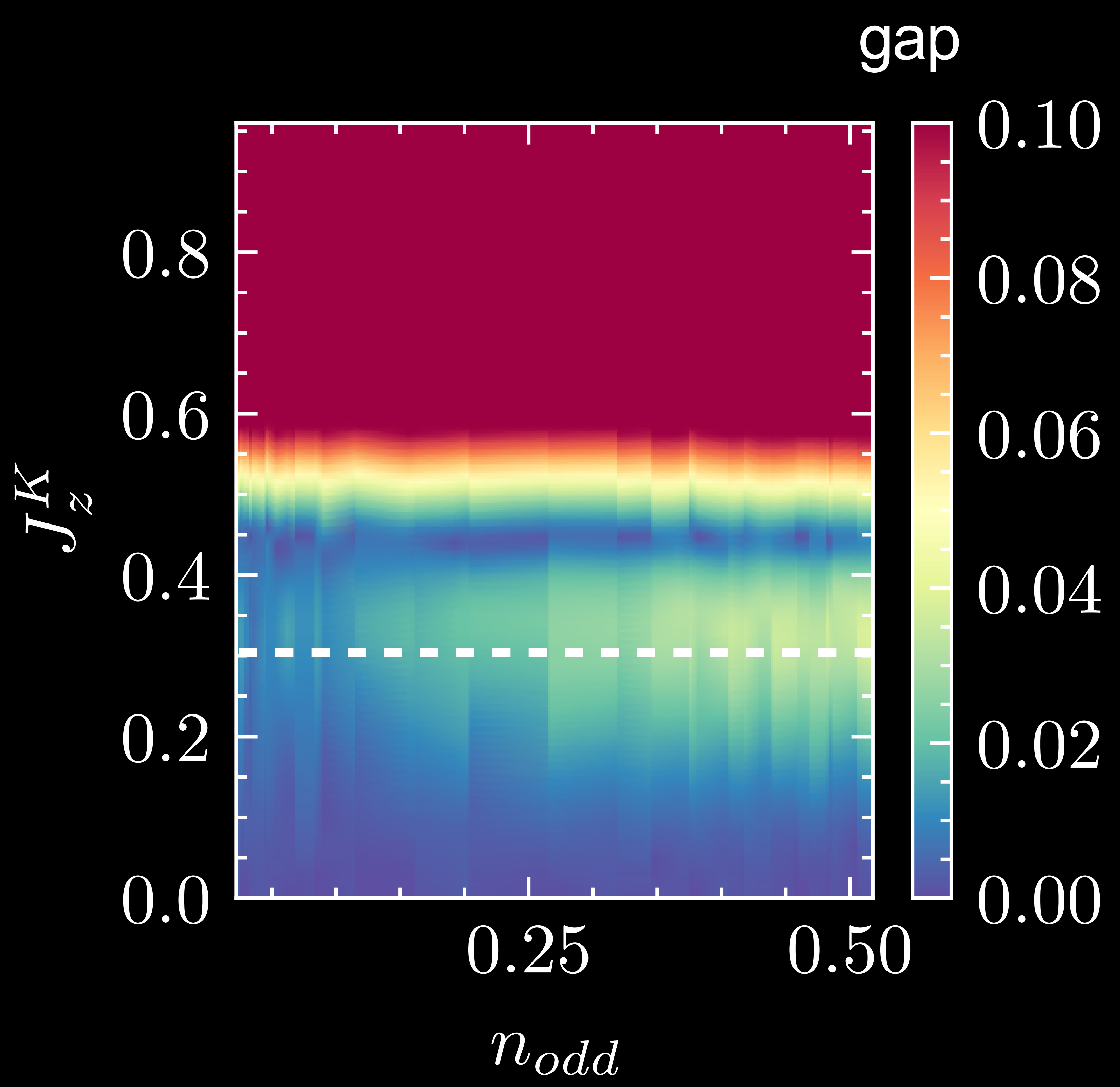

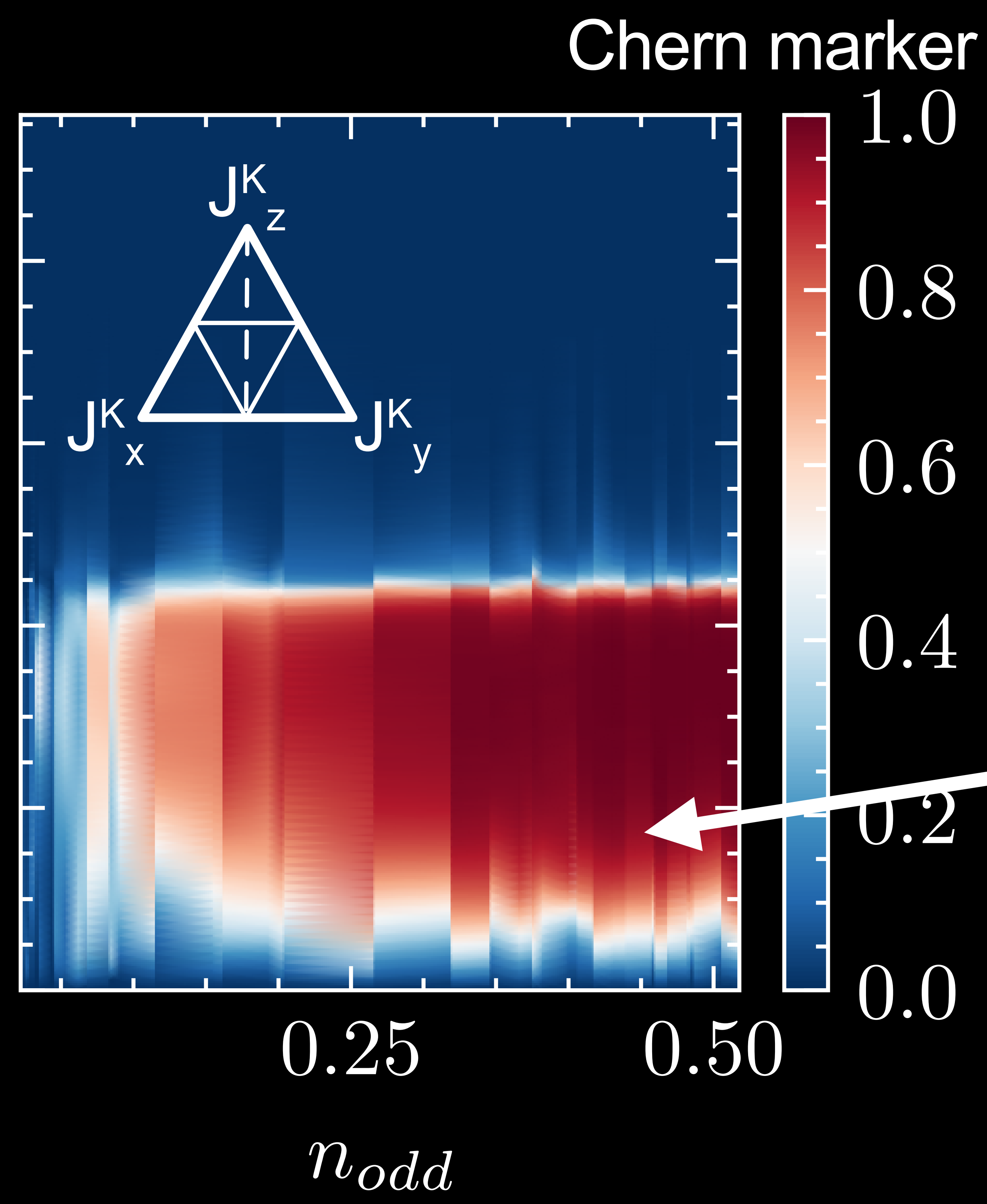

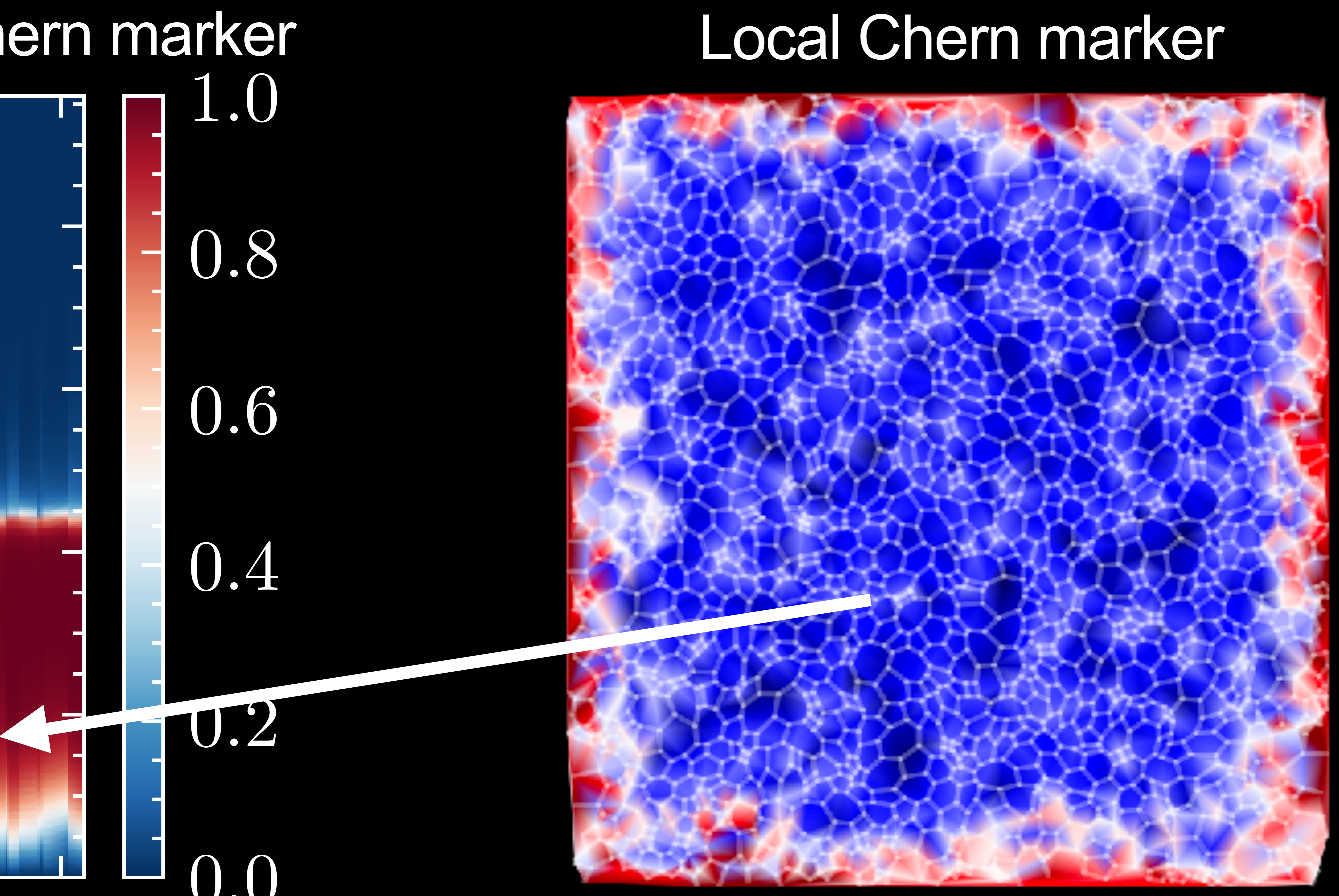

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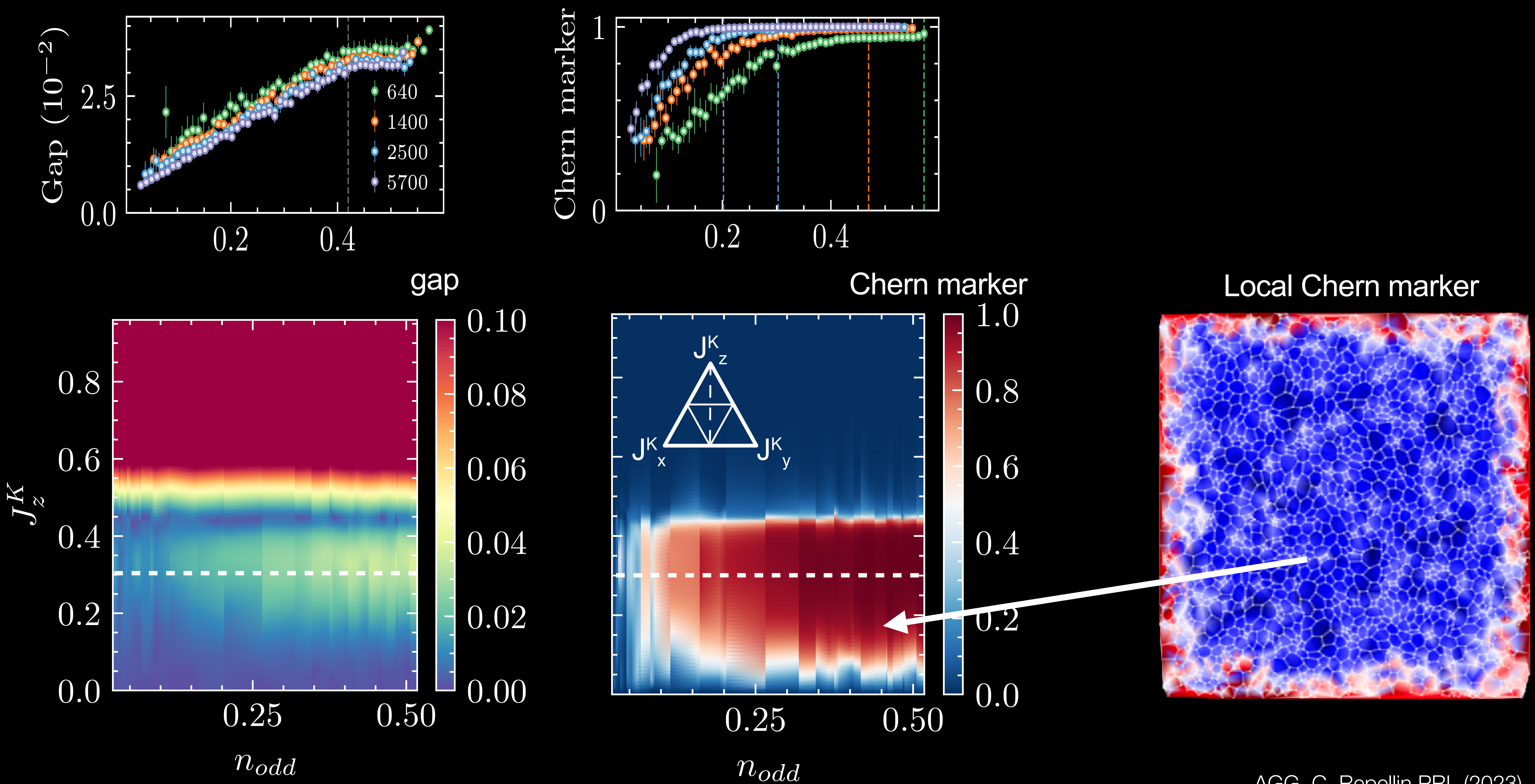
A topological gap as disorder is increased



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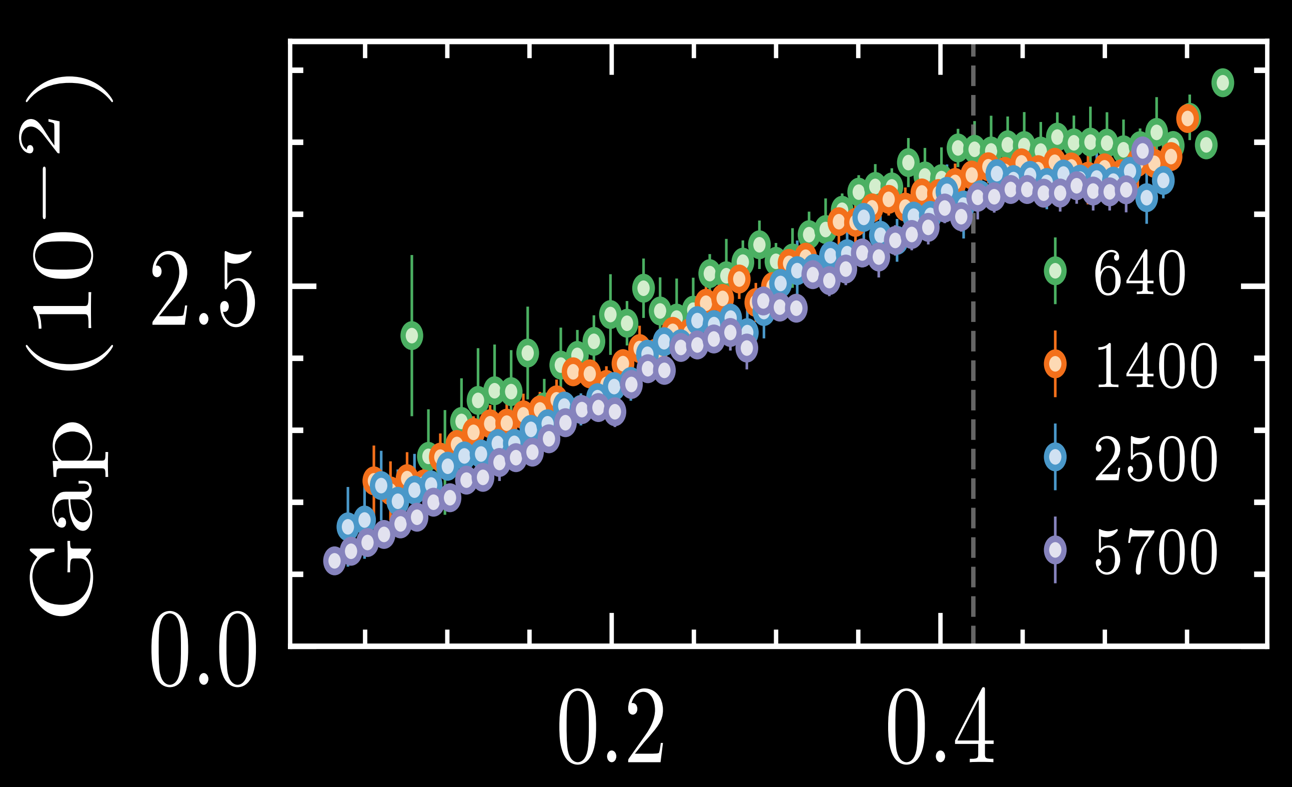
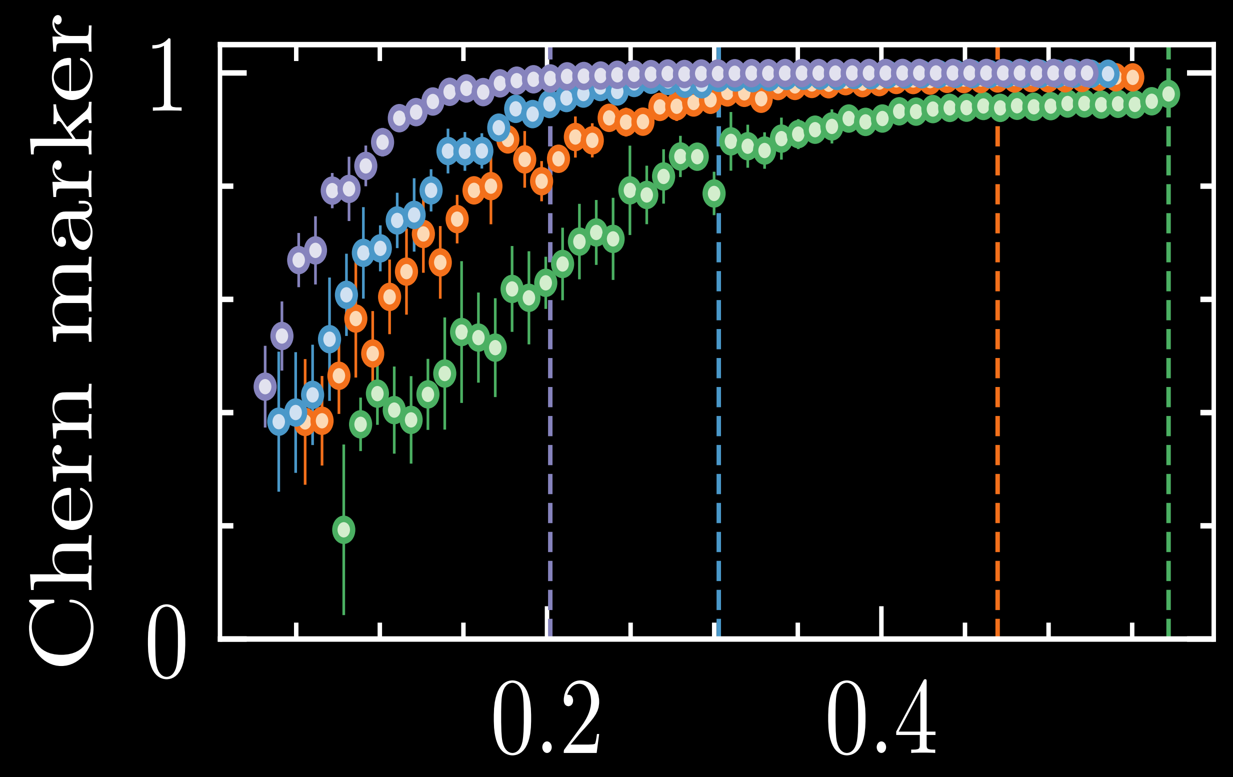
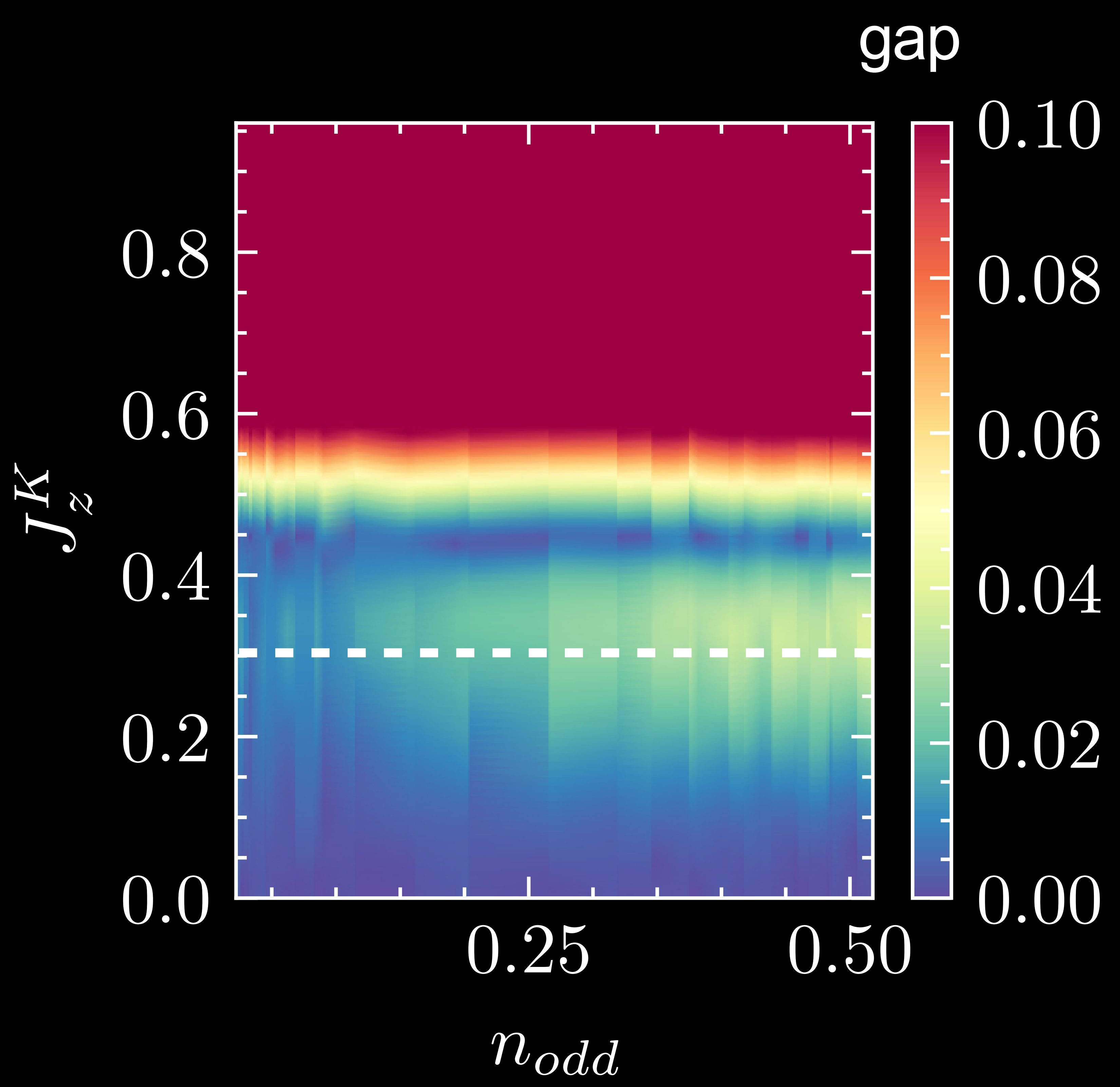
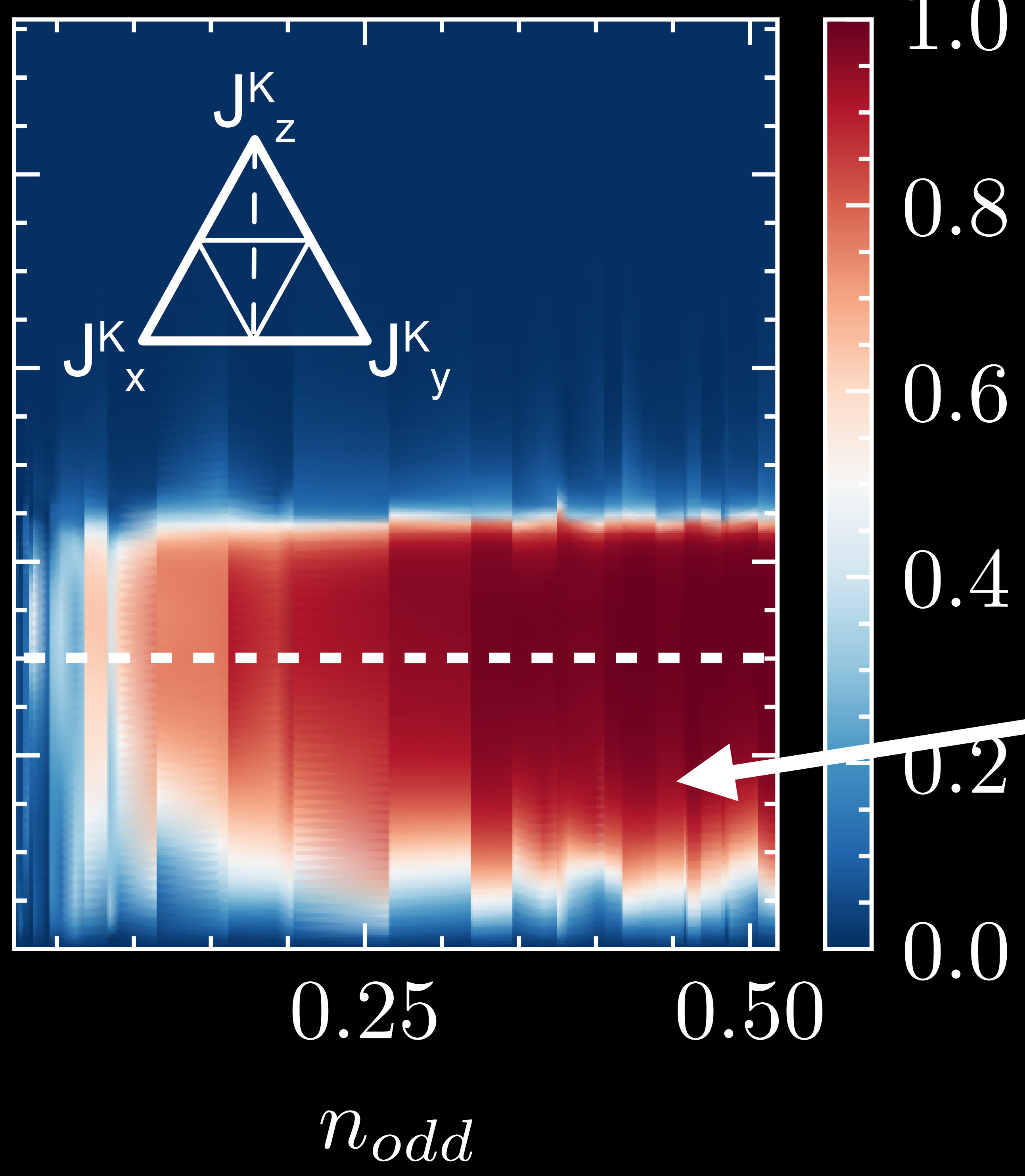


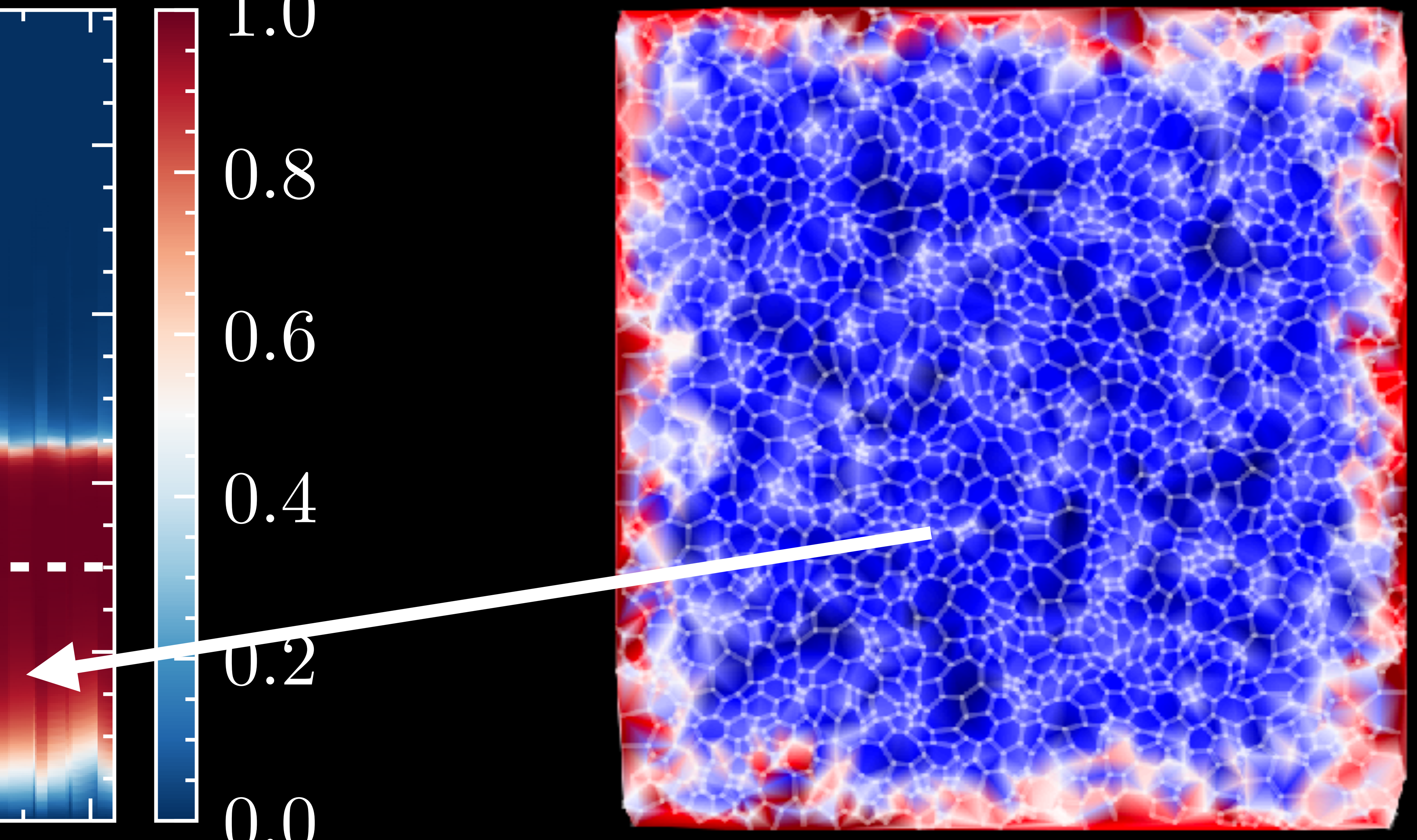


small density of odd plaquettes is enough!





Local Chern marker



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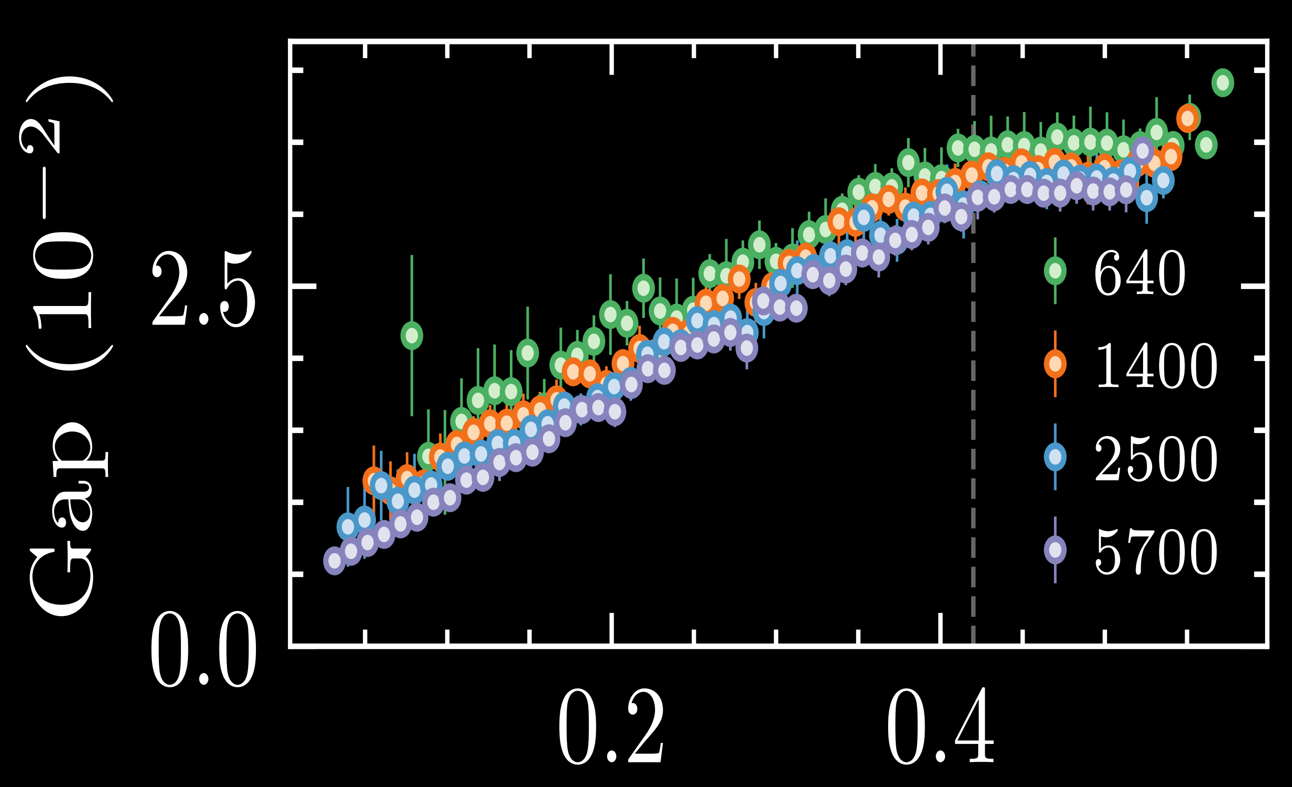
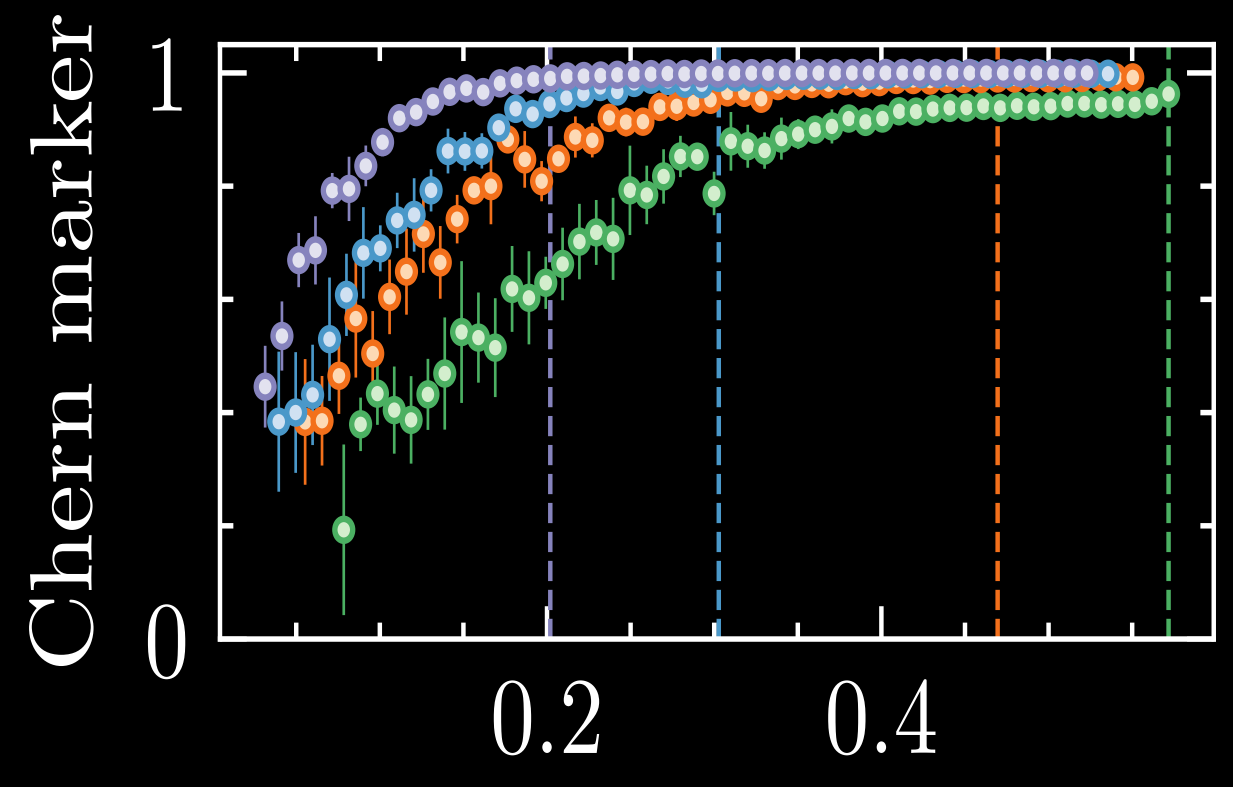
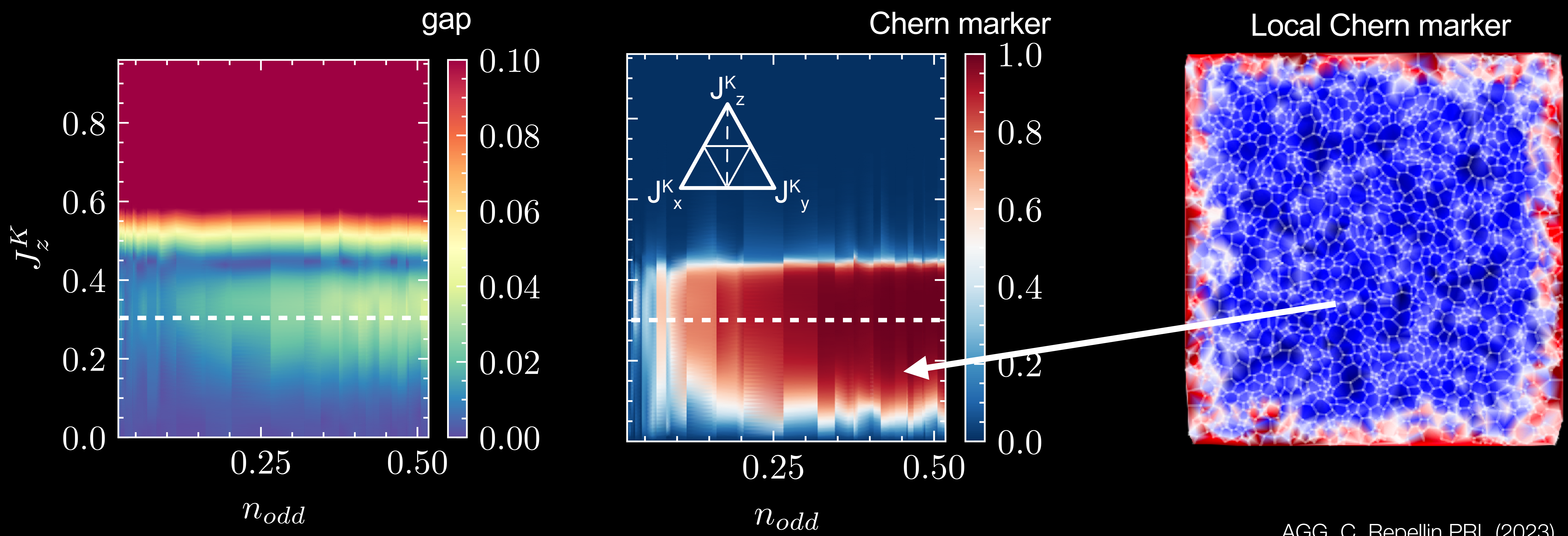




small density of odd plaquettes is enough!

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



AGG, C. Repellin PRL (2023)

Spin-chirality

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

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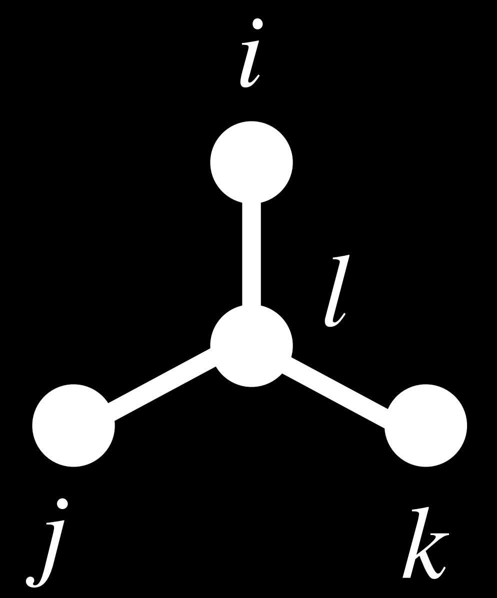

local spin-chirality $\langle \hat{\chi}_l \rangle = \langle \hat{\chi}_{ilj} \rangle + \langle \hat{\chi}_{jlk} \rangle + \langle \hat{\chi}_{kli} \rangle$

AGG, C. Repellin PRL (2023)

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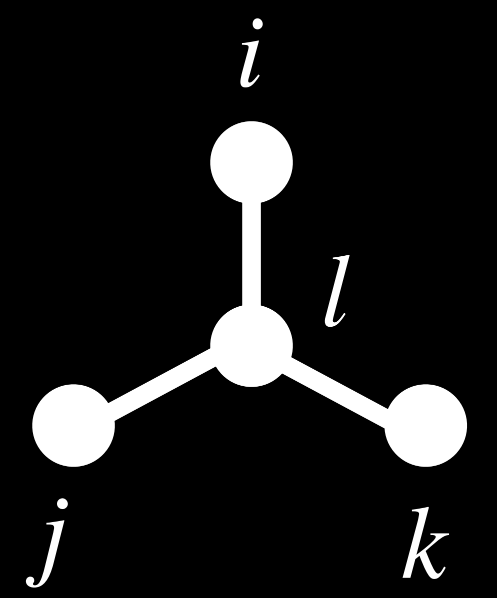

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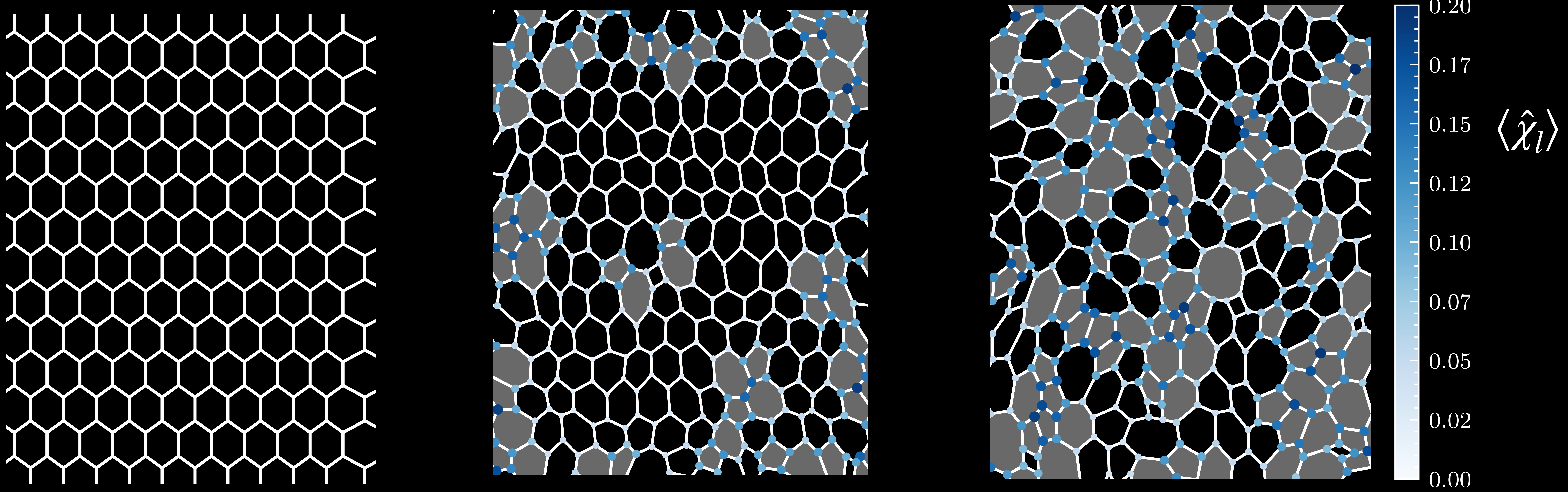
crystal | polycrystal | amorphous



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How stable is it?

Stability

AGG, C. Repellin PRL (2023)

Stability

Kitaev + Heisenberg

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

AGG, C. Repellin PRL (2023)

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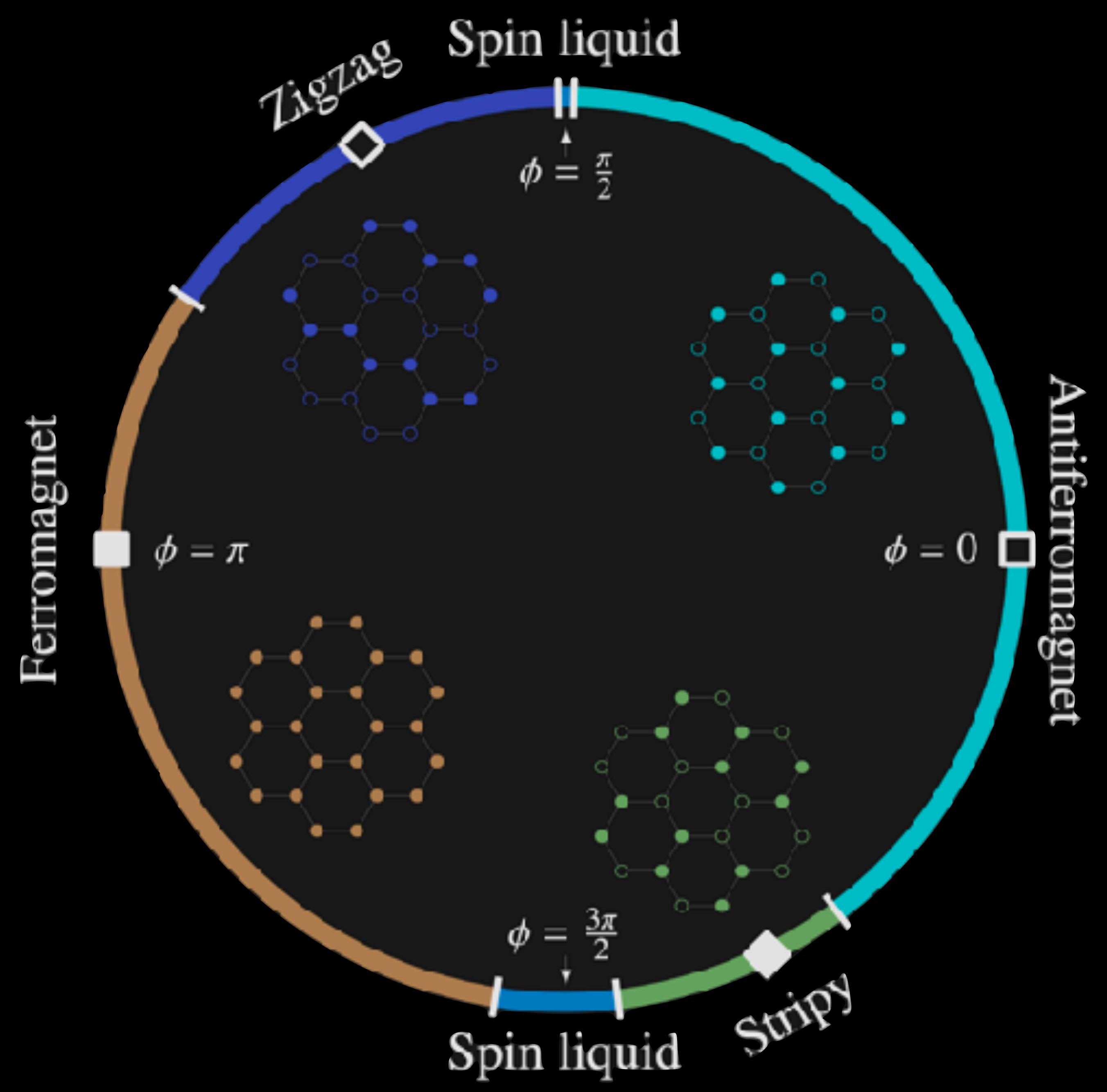

$$J^H = \cos\phi, J^K = \sin\phi$$

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

AGG, C. Repellin PRL (2023)

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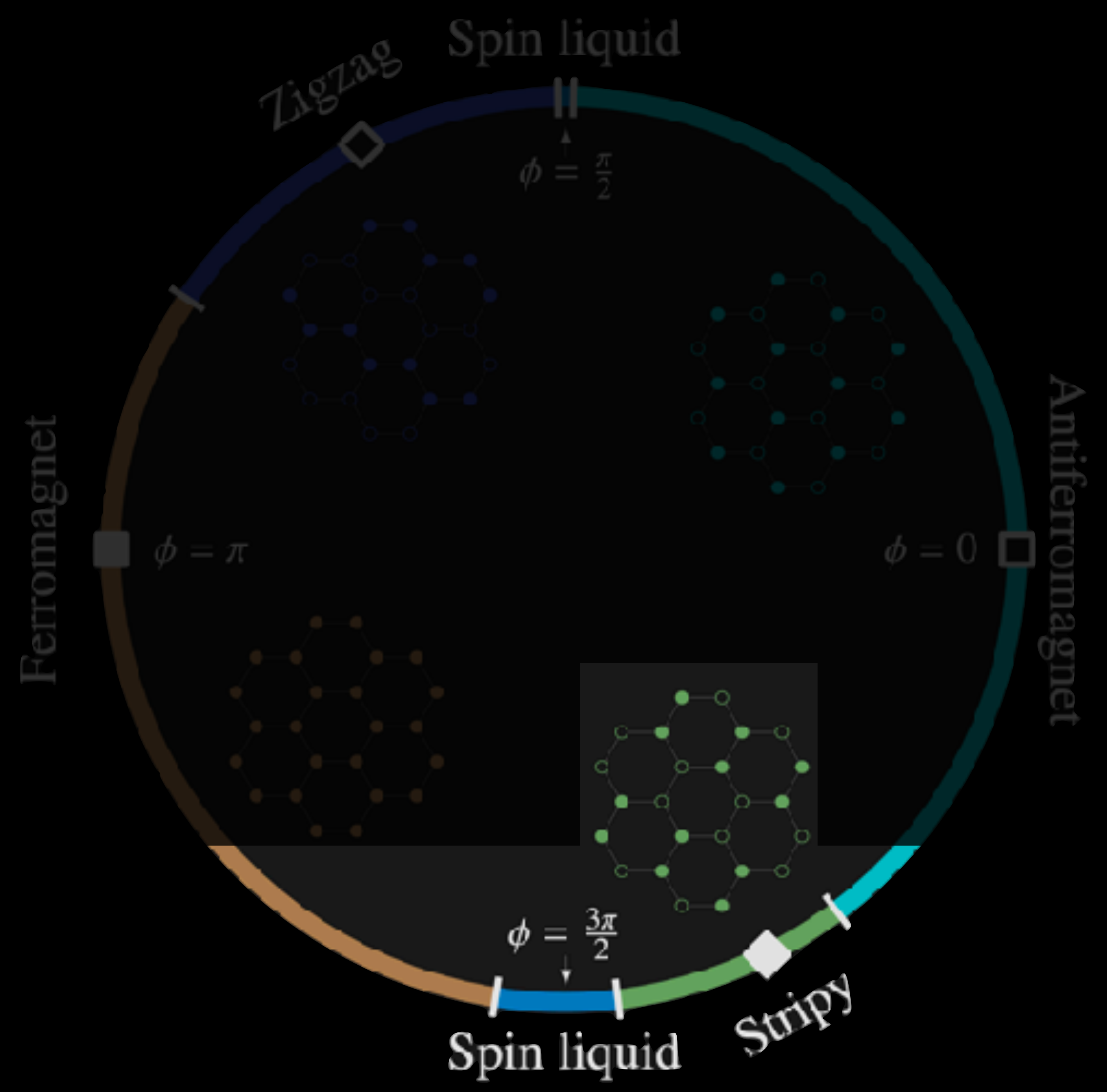

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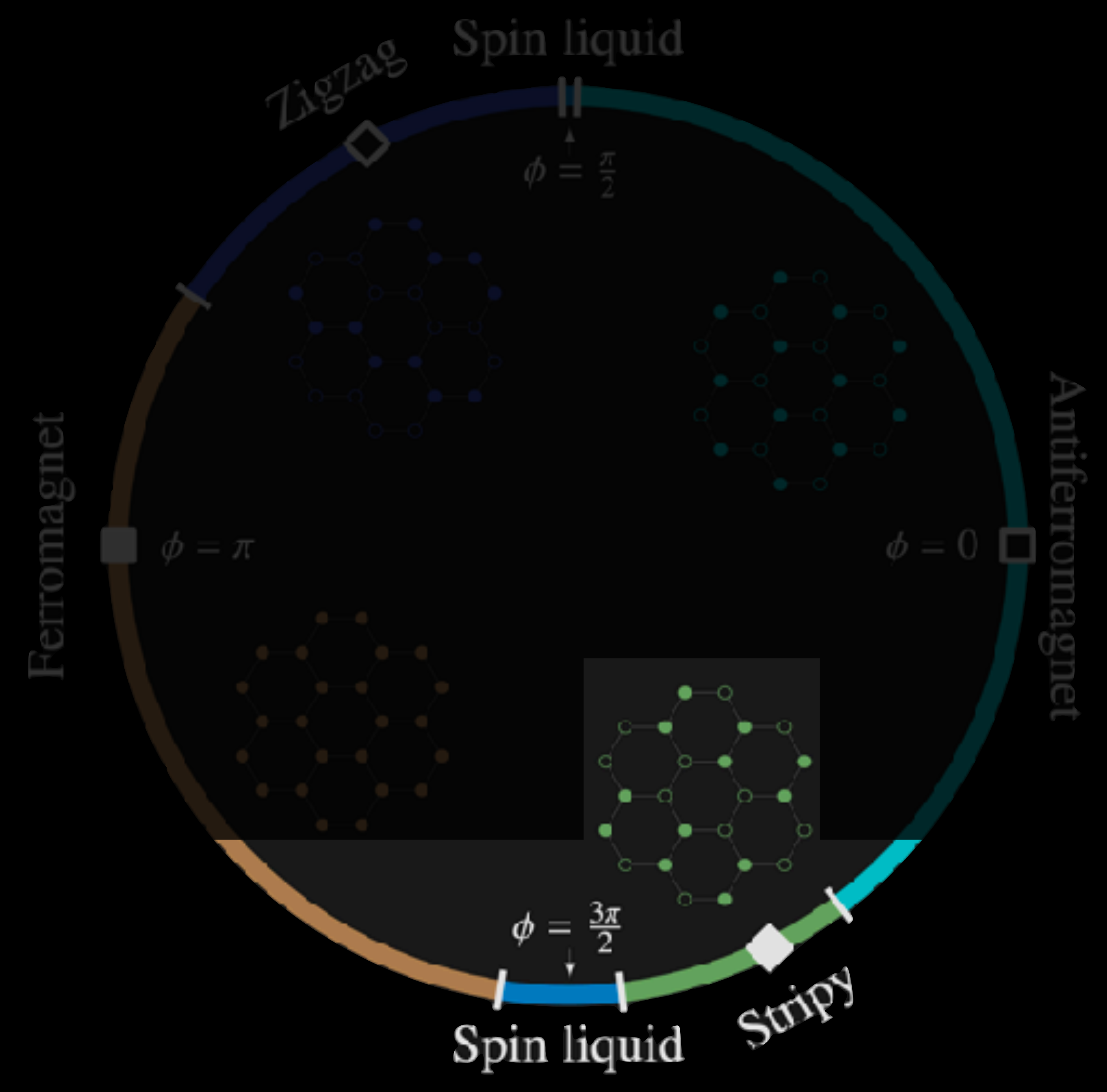

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Rau et al Ann. Rev. Cond. Mat. Phys. (2015)

Exact diagonalization

26 spins, 6 plaquettes

AGG, C. Repellin PRL (2023)

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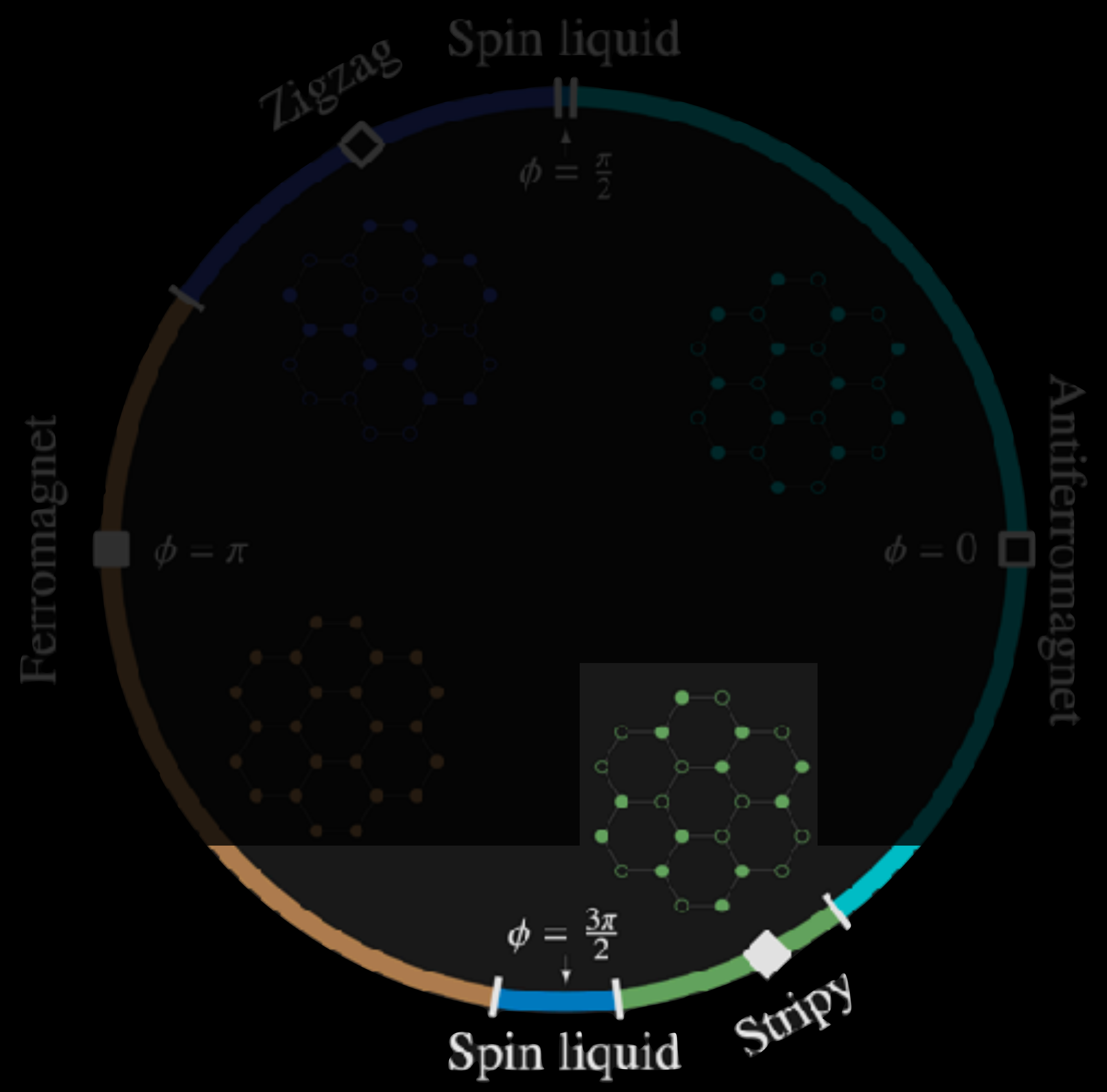

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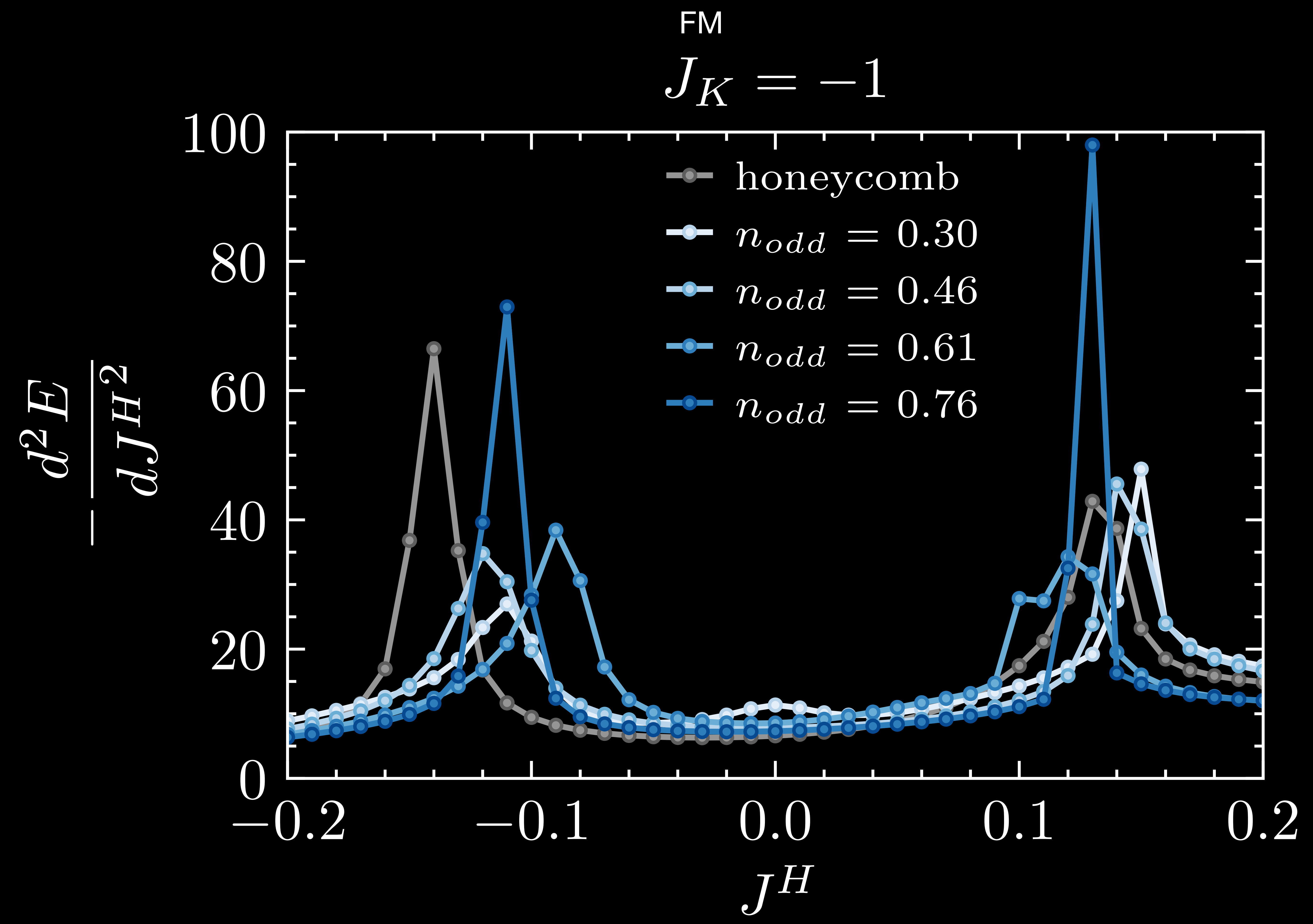

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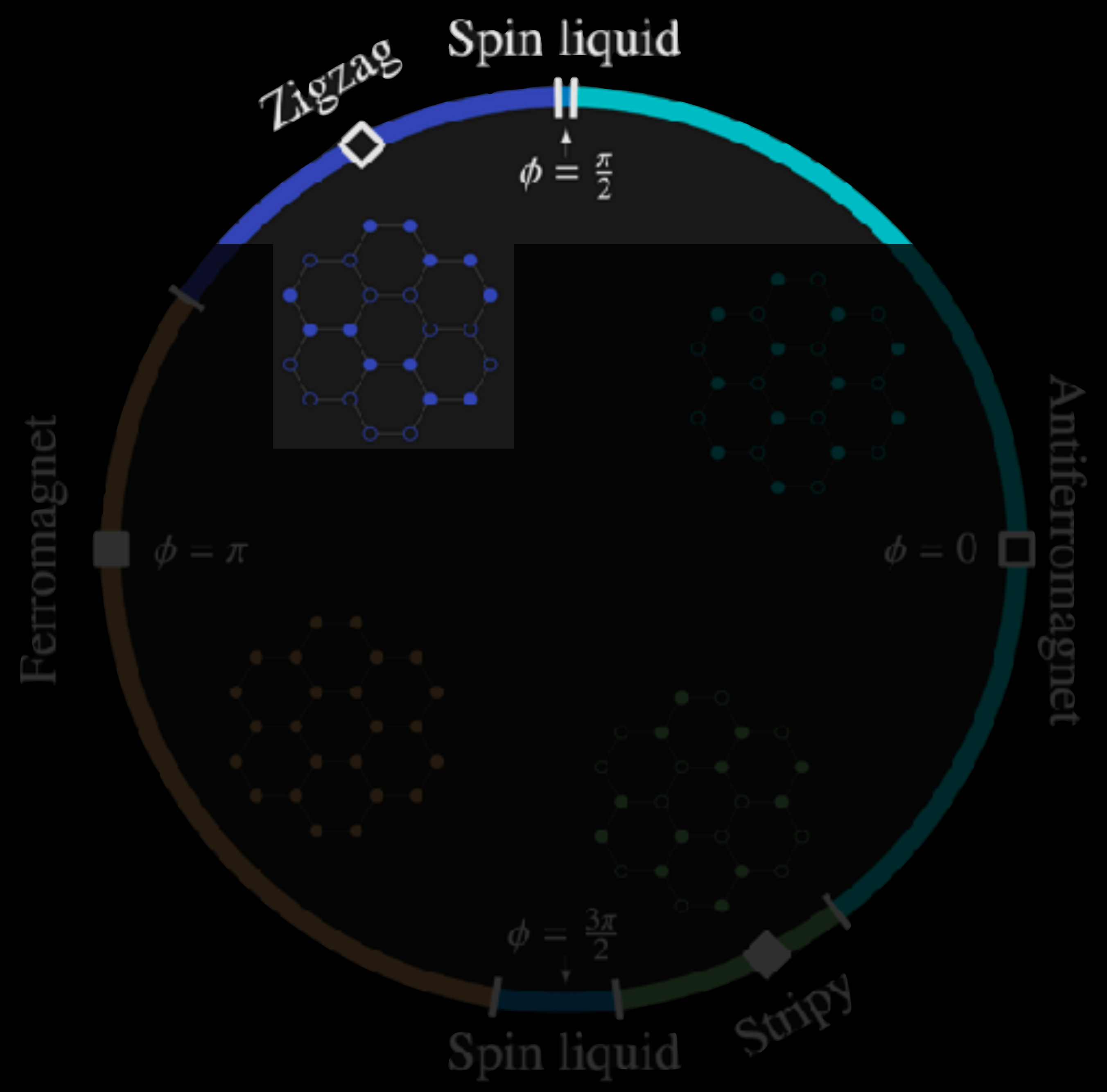

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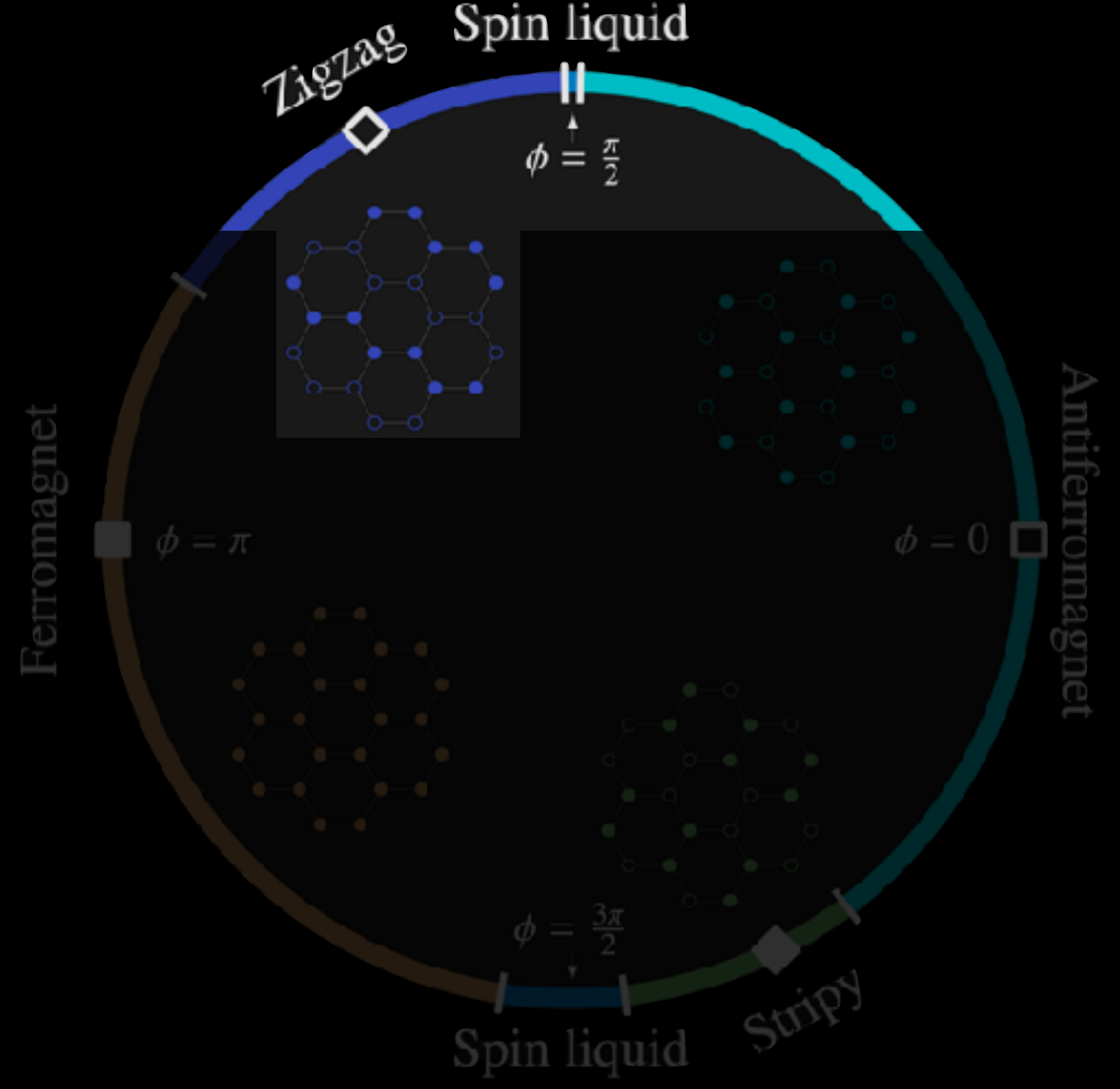

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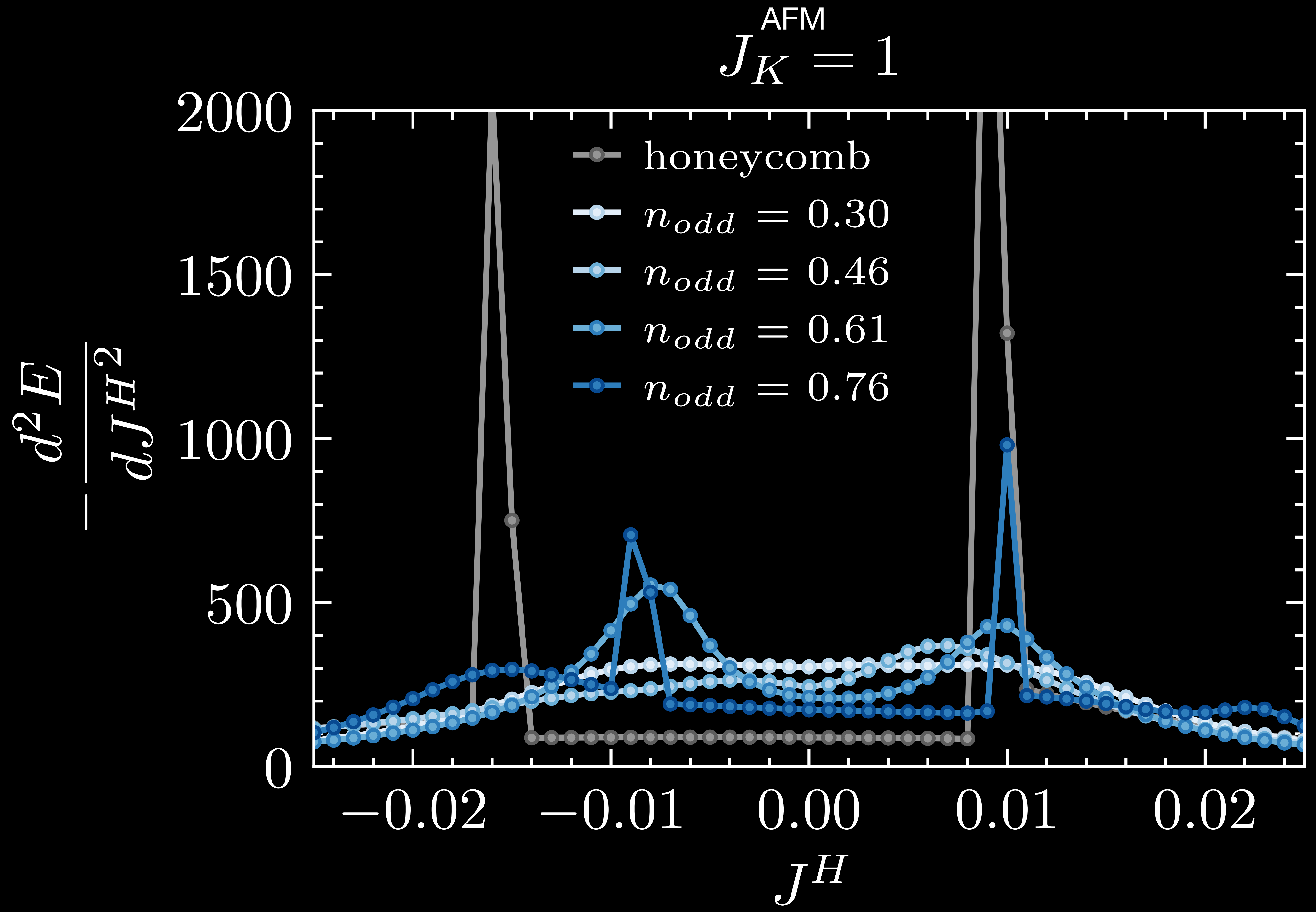

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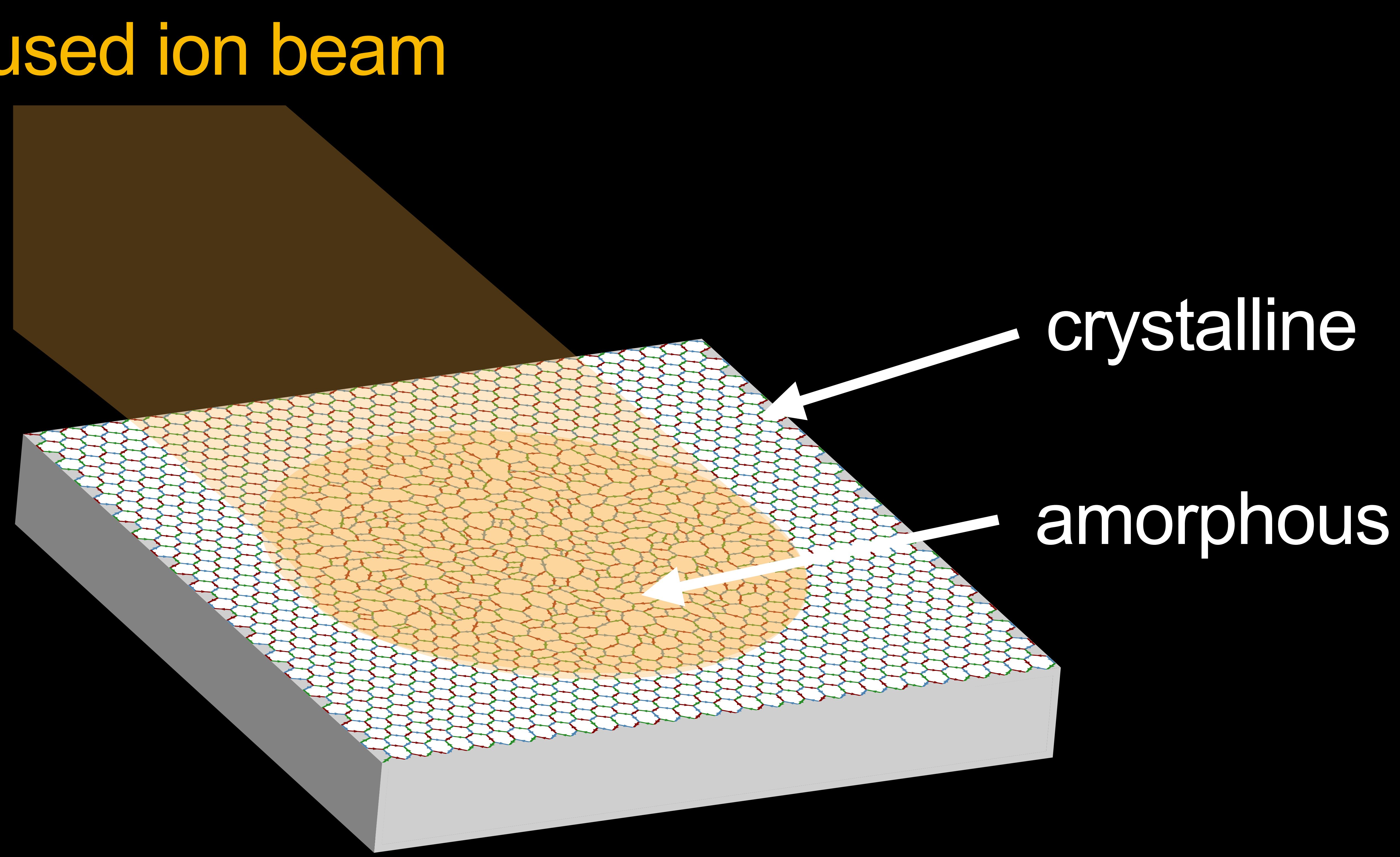
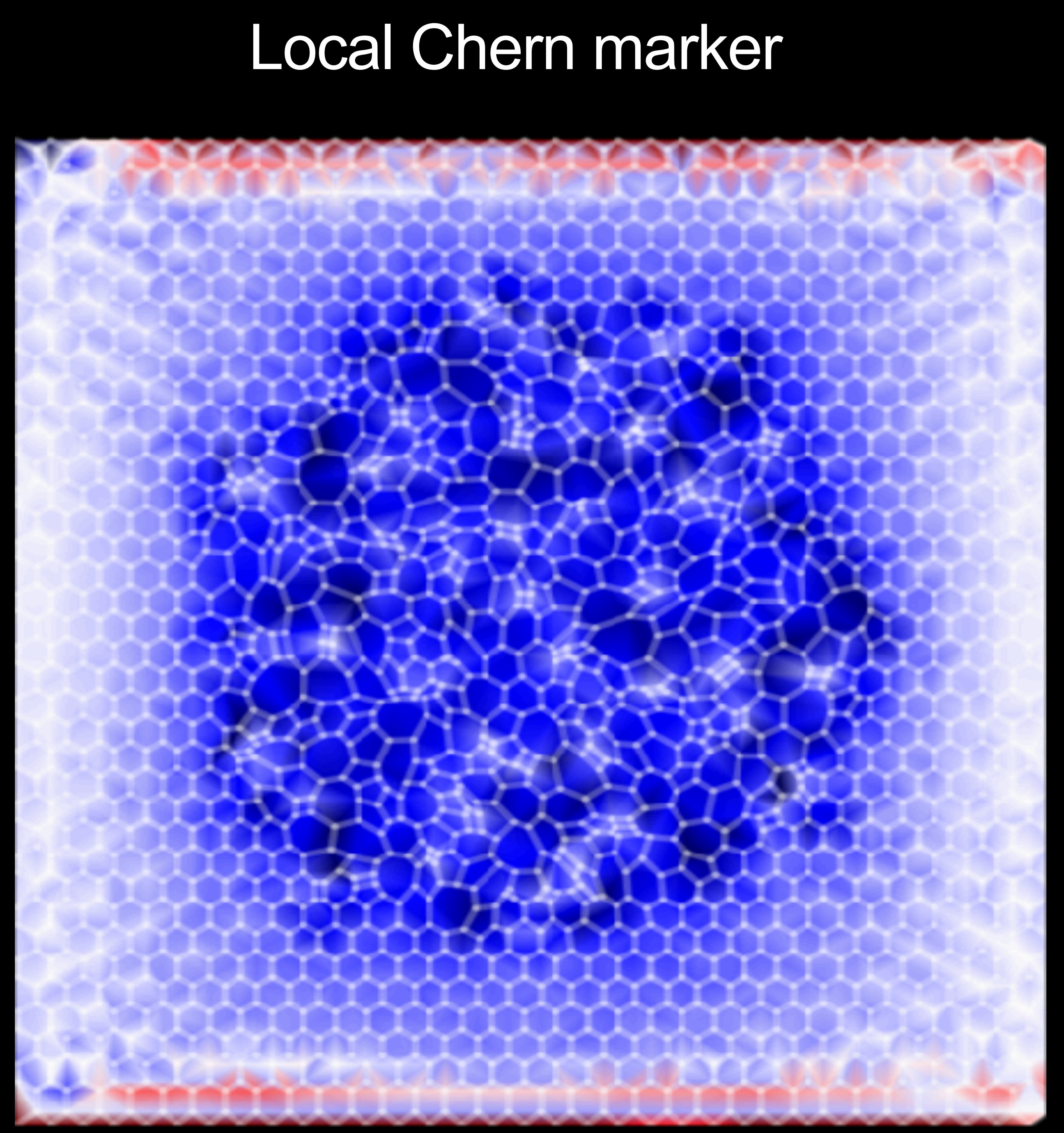
Engineering structural disorder?



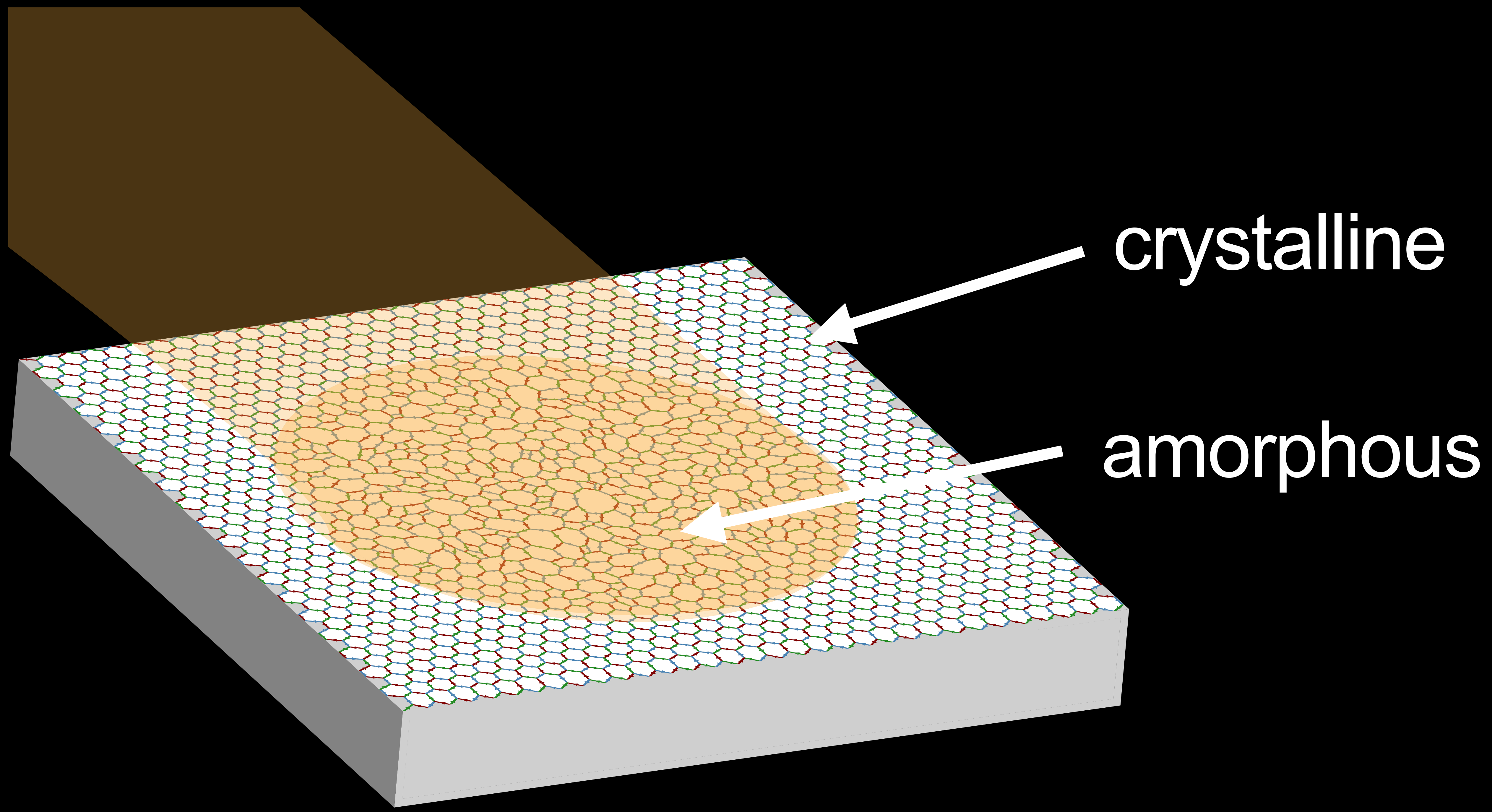
A. Bake et al **14**, Nat. Comm 1693 (2023)



AGG, C. Repellin PRL (2023)

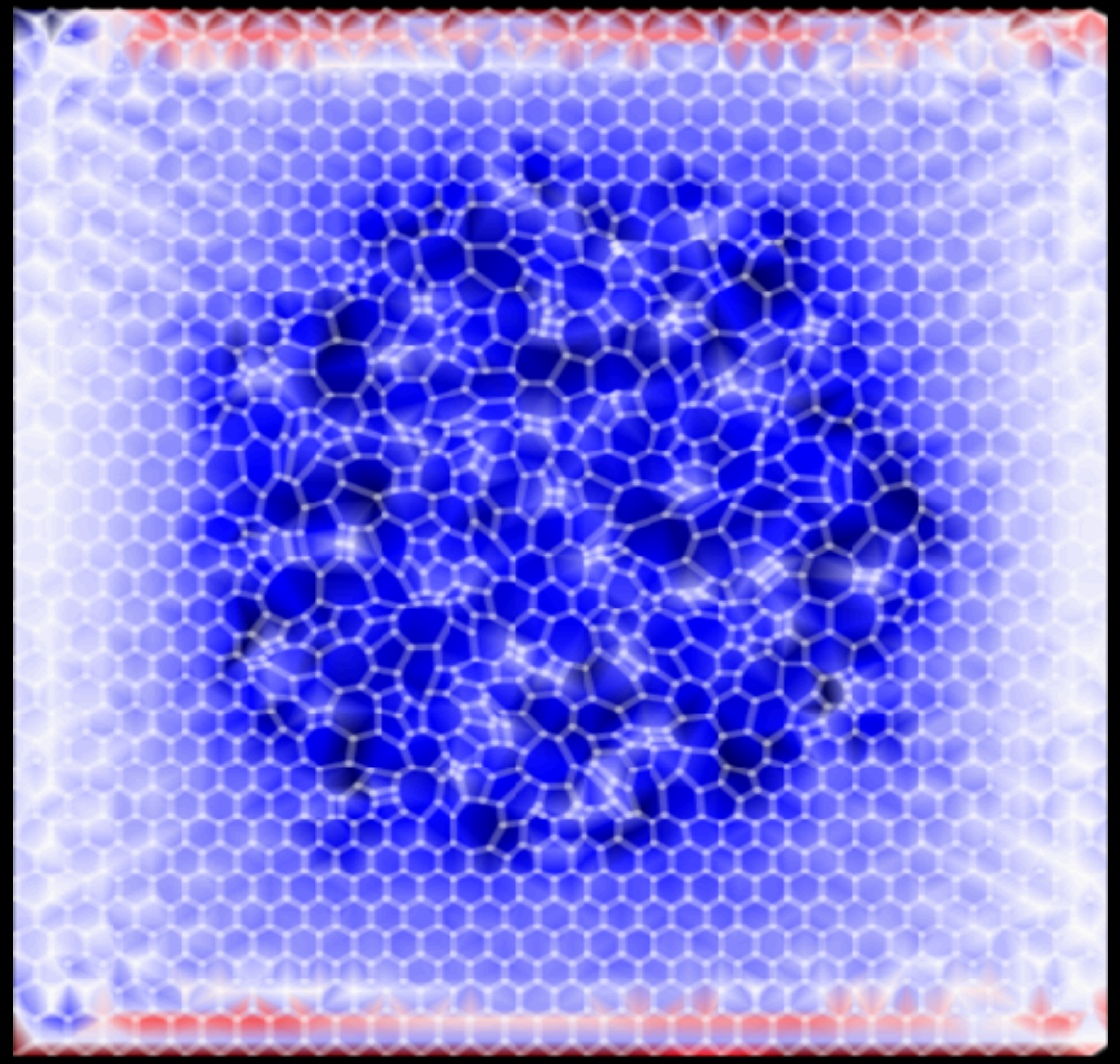
Engineering structural disorder?

focused ion beam



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

Local Chern marker



quantised thermal Hall:

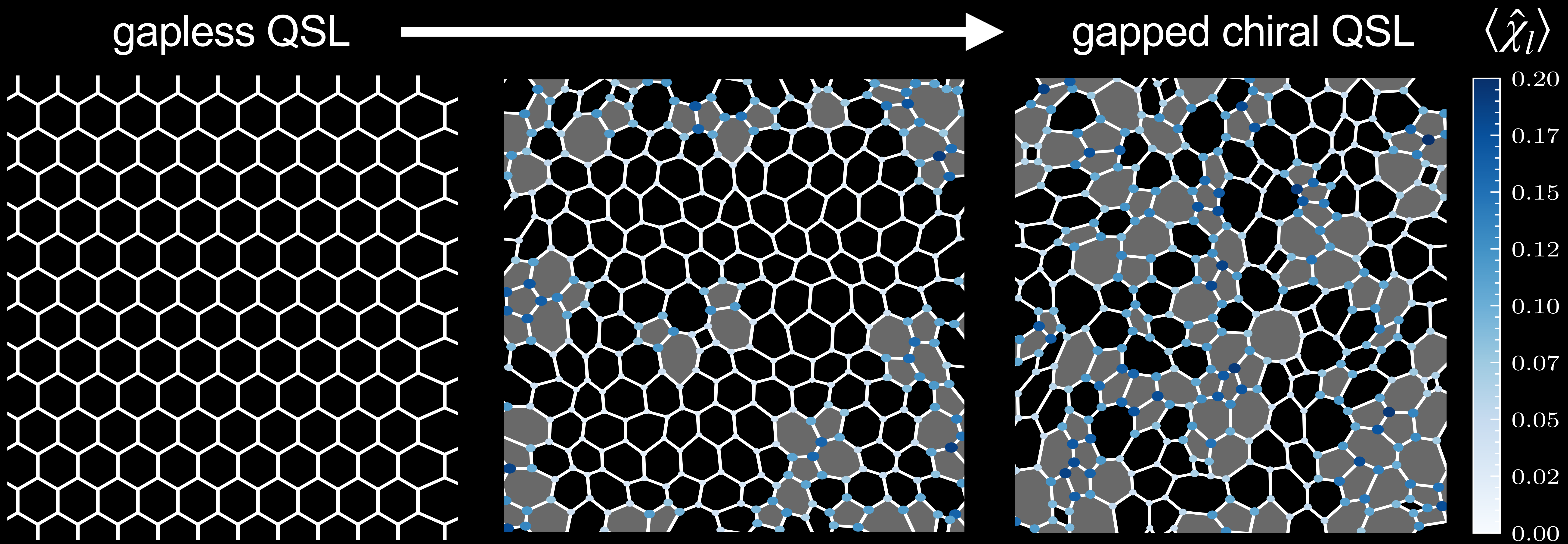
Reed and Green *PRB* (2000)

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

AGG, C. Repellin PRL (2023)

Amorphous and polycrystalline routes towards a chiral spin-liquid

Cécile Repellin
LPMMC / Grenoble



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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)

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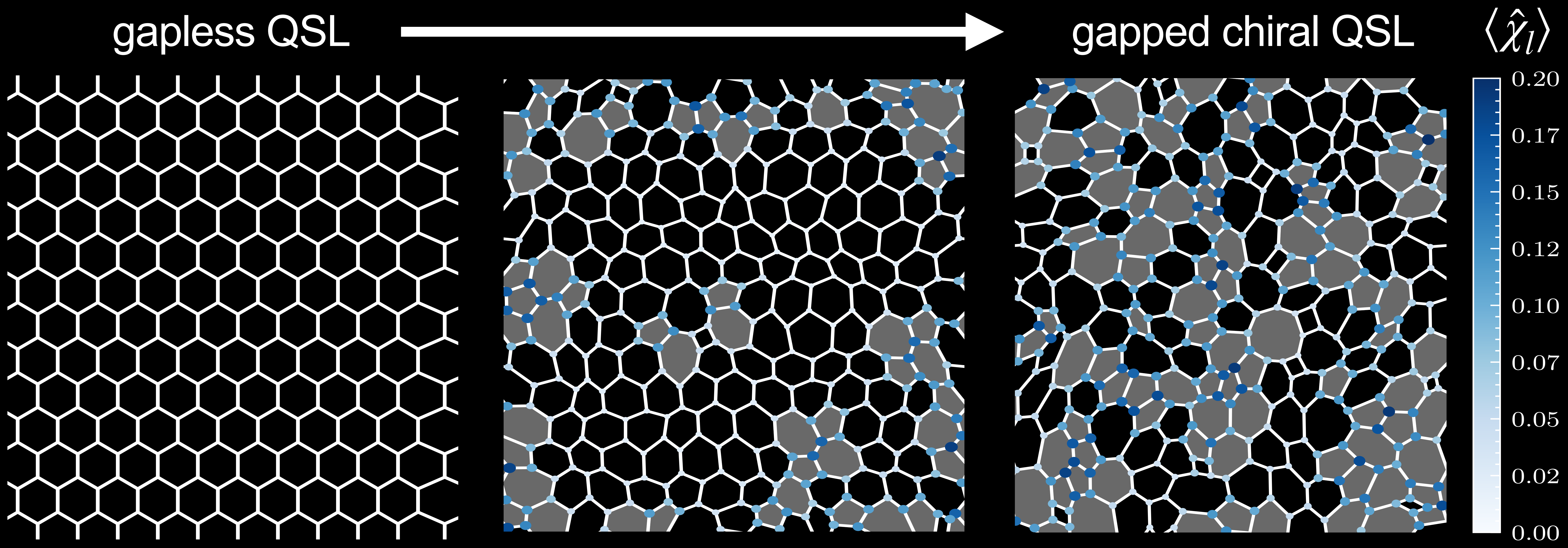

amorphous Kitaev lattice =
gapped chiral spin-liquid

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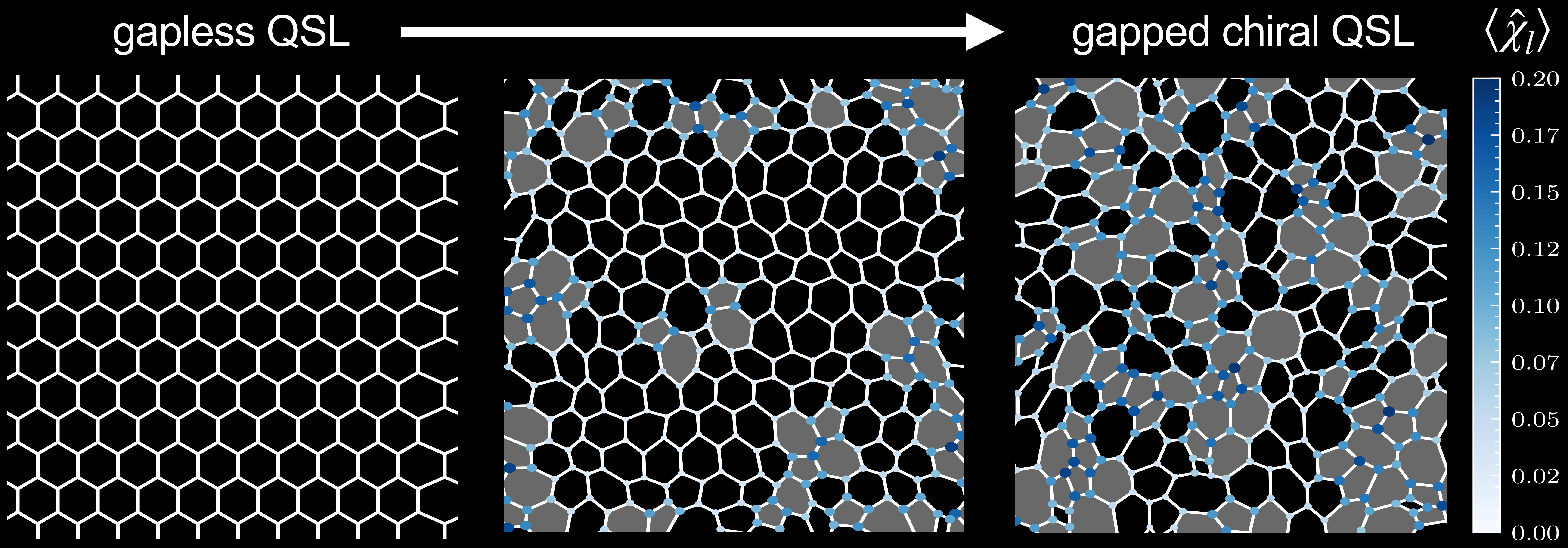

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75% max gap size at 30% of odd-plaquettes (~a-graphene)

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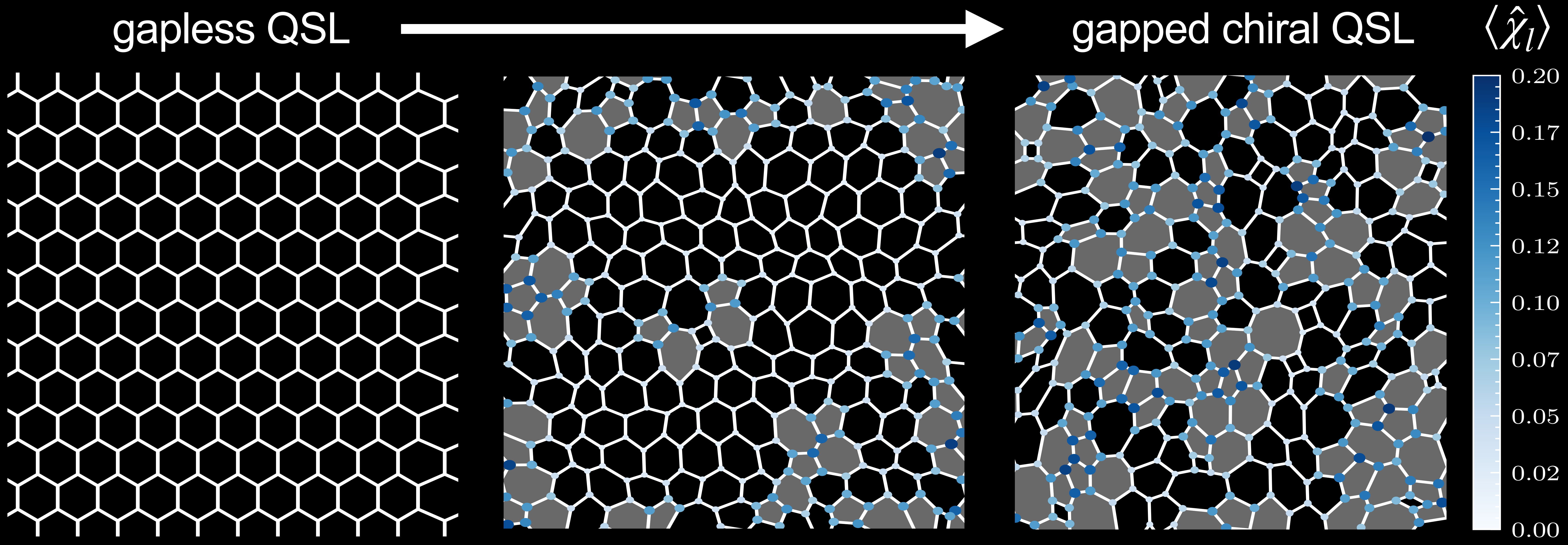
Q. Marsal, D. Varjas, AGG PNAS, (2020)
D. Muñoz-Segovia,et al 2301.02686
Q. Marsal, D. Varjas, AGG Phys. Rev. B (2023)
Corbae et al, AGG, Lanzara, Hellmann Nat. Materials (2023)
Cyocis, Marsal et al, Hellmann, AGG, Lanzara 2302.05945
Review: P. Corbae, et al arXiv: 2301.04176, EPL (2023)

Amorphous and polycrystalline routes towards a chiral spin-liquid

Cécile Repellin
LPMMC / Grenoble



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

amorphous Kitaev lattice =
gapped chiral spin-liquid

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

chiral QSL as robust as gapless QSL

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