Hard Condensed Matter

NORDITA

The Nordic Institute for Theoretical Physics

Theoretical Quantum Matter

Dirac Materials
Dark Matter
Detection

Alexander
Balatsky

Partick Wong

Gabriel Cardoso

Quantum Printing
Amorphous oxides for Qubits
Inverse design through AI

H. Yerzhakov

Tien-Tien Yeh

Light –
Superconductors
interaction

A. Tyner

Avinash Pathapati

Material Informatics
Machine Learning Two-Level
Organic Materials
Database (OMDB)

Dynamical Order
Odd-frequency
superconductivity

[Homepage](#): for more info

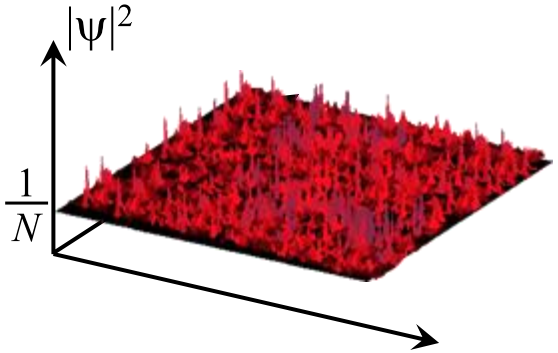
NORDITA Ass. Prof.
in TQM group

Ivan
Khaymovich

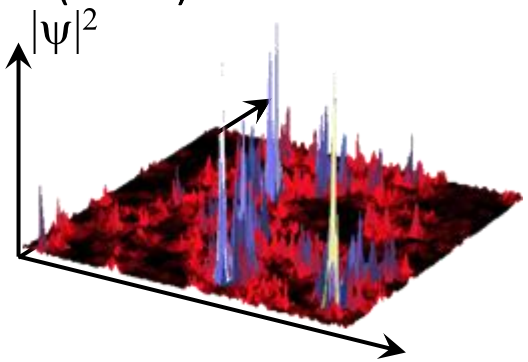
Ergodicity breaking phases States

ergodic metal — non-ergodic phase — insulator — disorder

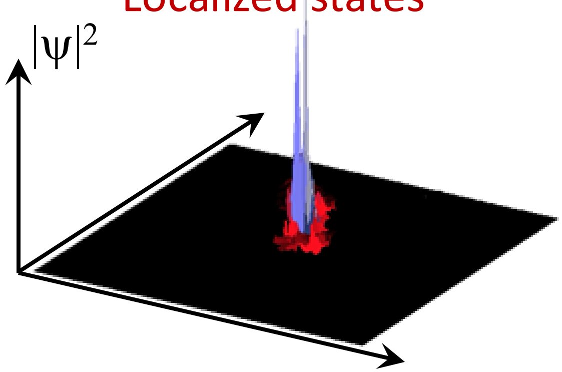
Ergodic states



(Multi)fractal states



Localized states



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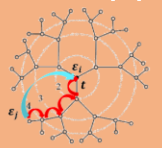
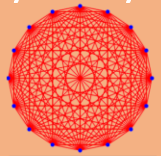
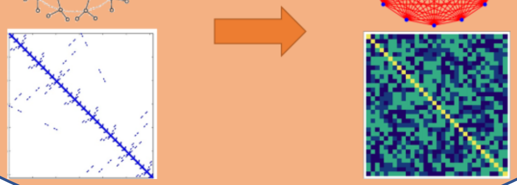
Ergodicity breaking phases

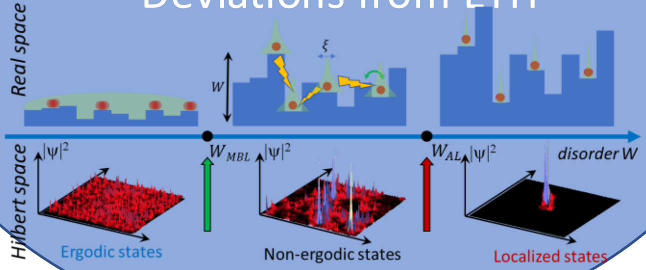
Random-matrix theory:
- Multifractal phases
-Mapping to many-body models



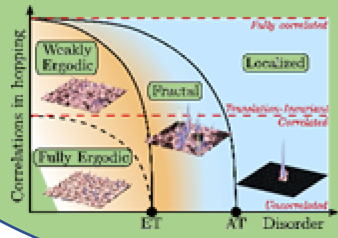


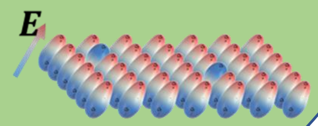


Many-body systems:
- Many-body localization vs Hilbert-space multifractality,
- Multifractality/entanglement
- Deviations from ETH



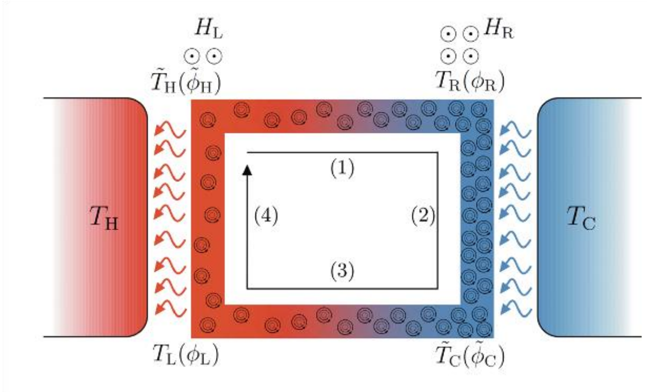
Long-range systems:
- Integrability, correlations,
- non-Hermitian/open models
- Localization and multifractality





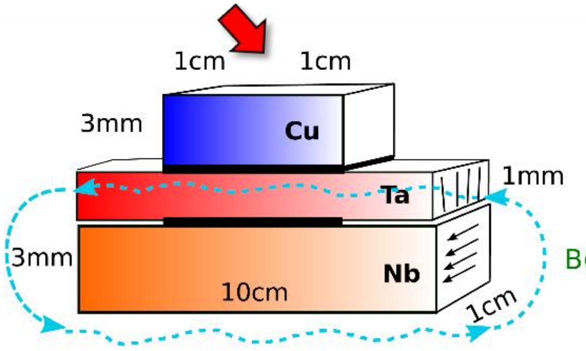
SCAN ME

Principles of solid-state quantum refrigeration and thermodynamic control in the nanoscale

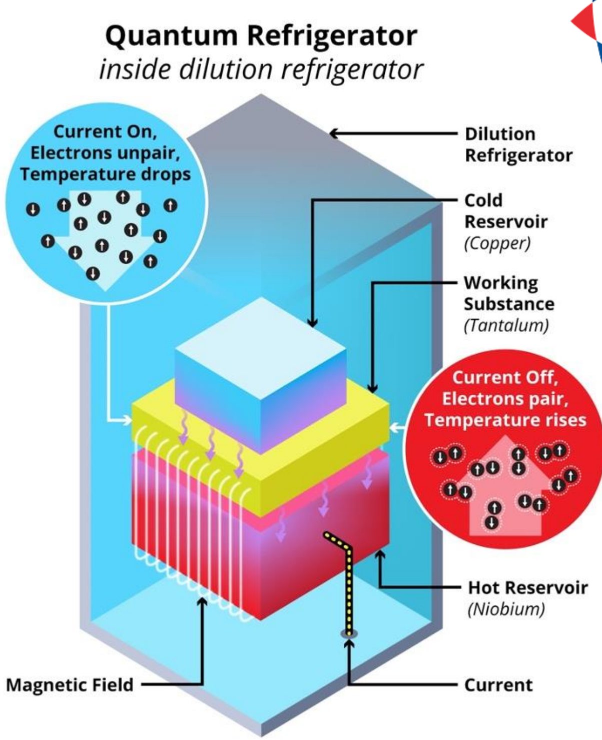


Fluxons in type II superconductors can act as puddles carrying heat in circulation.

"The qubit goes here"



Adiabatic magnetization of type I superconductor for cooling below 10mK



(University of Rochester illustrations / Michael Osadciw)

Sreenath Manikandan

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Quantum Structure of Gravitational Radiation

Quasi-normal modes from nonlinear Gravitational Effects

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SCAN ME

Ergodicity breaking phases

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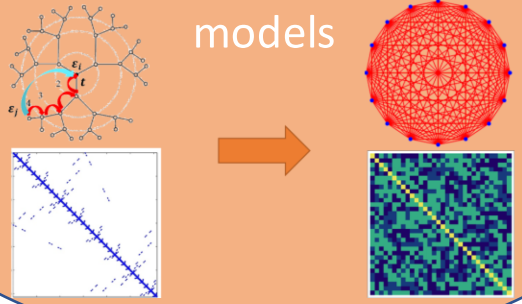
-Mapping to many-body models



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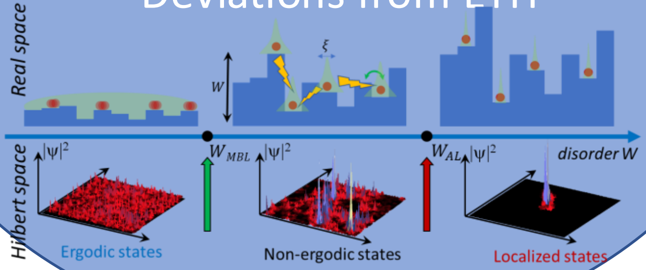

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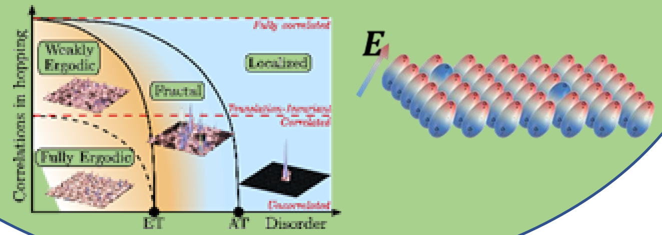

Mikael Fogelström

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MSc projects:

Superconducting hybrid structures

Nanowires, Josephson junctions, microwave resonators

— key building blocks of next generation quantum devices —

1.What may You do

1. **Model proximity-induced superconductivity** in low-dimensional devices
2. Analyse **microwave/THz response** and kinetic inductance
3. Study **Andreev bound states** and Josephson physics
4. Work with **high-performance numerical codes** (Fortran, Python, etc.)

2.What You Will Learn

1. Quasiclassical Green-function methods
2. Superconducting transport and device physics
3. Numerical simulation & data analysis
4. Research-level scientific workflows

Topological Insulators Revolution

Adrien Bouhon
Assistant Professor
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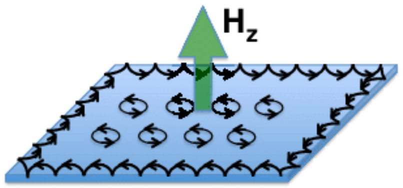
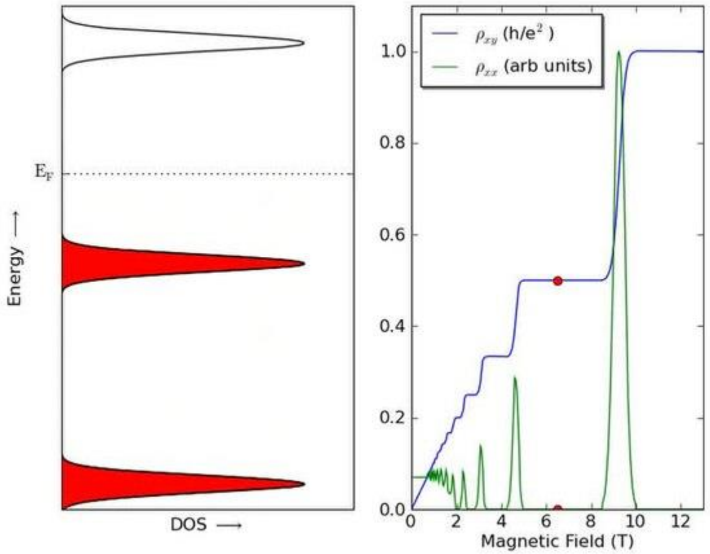
Quantum Hall Effect
(Klaus von Klitzing., 1980)

External Magnetic Field



(b) Quantum Hall effect



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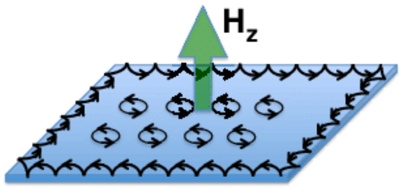
Anomalous QHE
Haldane (1988)

Intrinsic Magnetization



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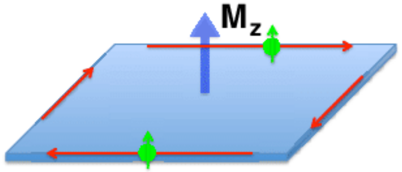
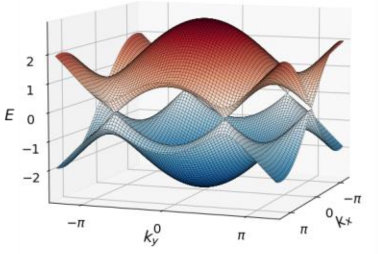
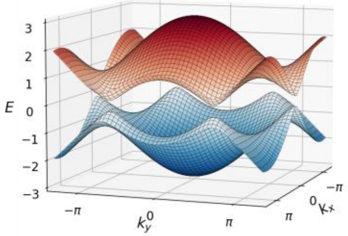
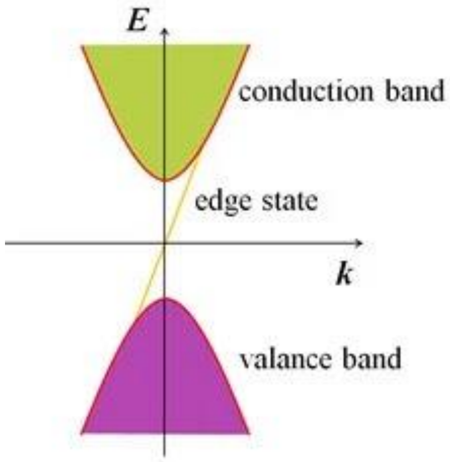


(d) Quantum Anomalous Hall effect





Graphene



(b)

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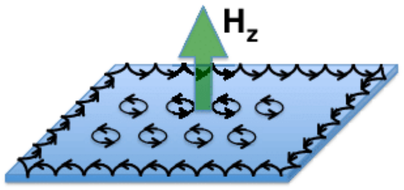
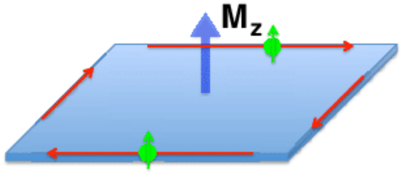
Quantum Spin Hall Effect
Kane & Mele (2005)

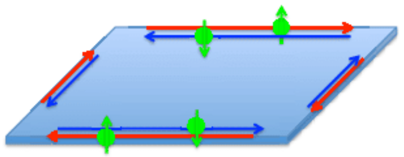
protected by
Fermionic
Time Reversal Symmetry



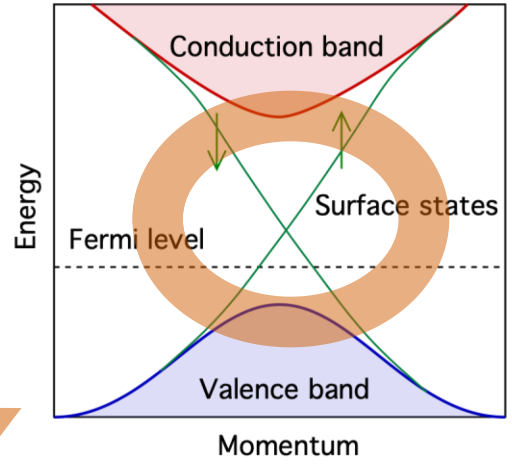
(b) Quantum Hall effect



(d) Quantum Anomalous Hall effect



(f) Quantum Spin Hall effect



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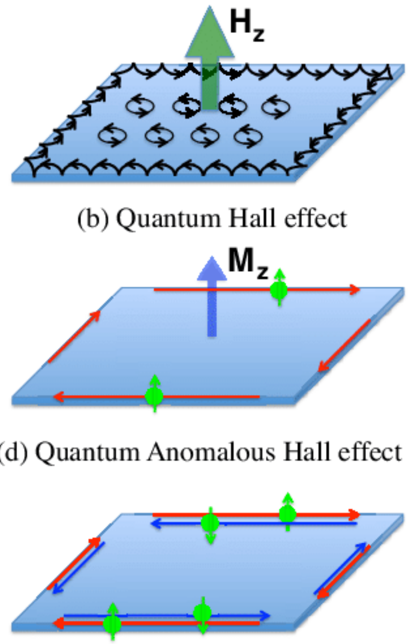


(b) Quantum Hall effect

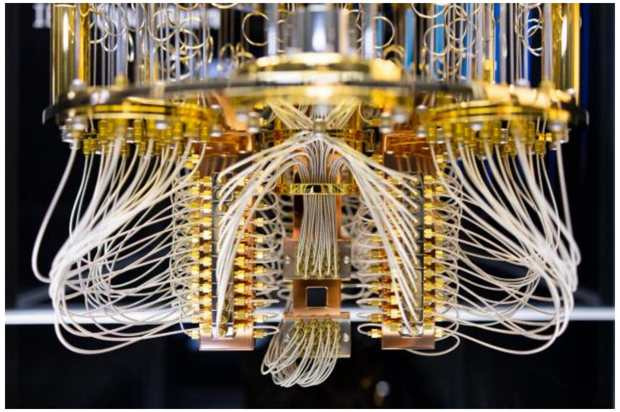
(d) Quantum Anomalous Hall effect

(f) Quantum Spin Hall effect

Robust quantum surface states

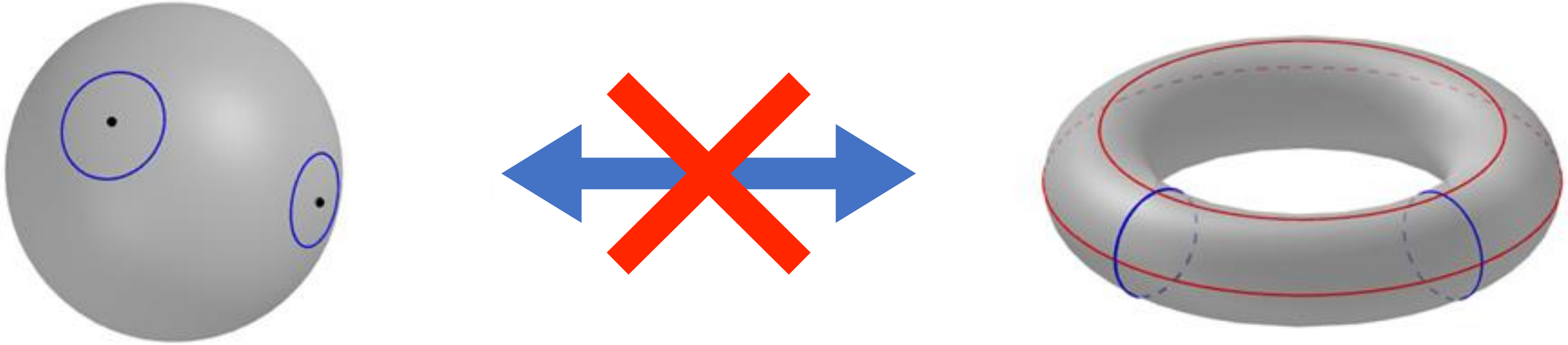
Substrate for QBits of Quantum Computers

Important Investments
Race for the Quantum Supremacy
States (USA, Chine, Emirates, etc.) and
companies (Google, etc.)



Topological?

<u>Topology</u>: classification of manifolds with respect to their global features

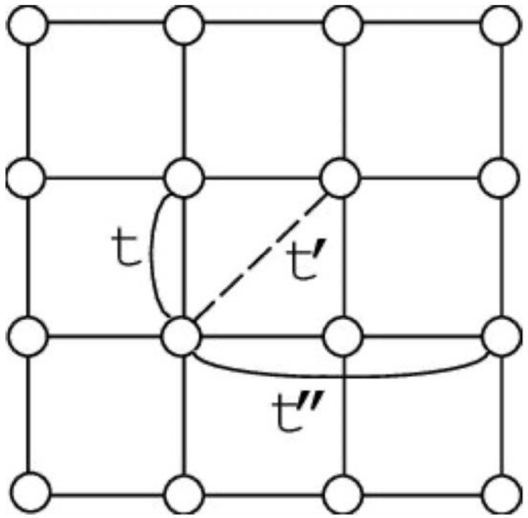


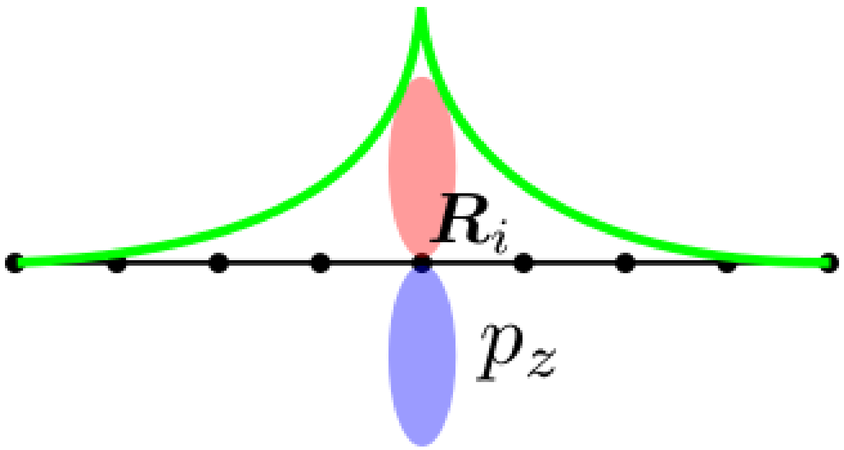
$g = 0$

Exemple of topological invariant:
the genus g

$g = 1$

Quantum Materials Modeling

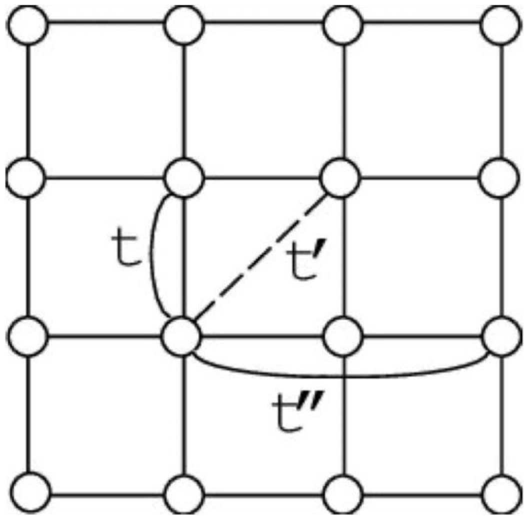




Kohn-Sham Hamiltonian

$$t_{\alpha\sigma,\beta\sigma'}(\boldsymbol{R}_i - \boldsymbol{R}_j) = \int d\boldsymbol{x}\; w_{\alpha\sigma}(\boldsymbol{x} - \boldsymbol{R}_i - \boldsymbol{r}_\alpha)^*\; \mathfrak{h}(\boldsymbol{x})\; w_{\beta\sigma'}(\boldsymbol{x} - \boldsymbol{R}_j - \boldsymbol{r}_\beta)$$

Quantum Materials Modeling



$$H(\boldsymbol{k}) \in \mathbb{C}^N \times \mathbb{C}^N$$

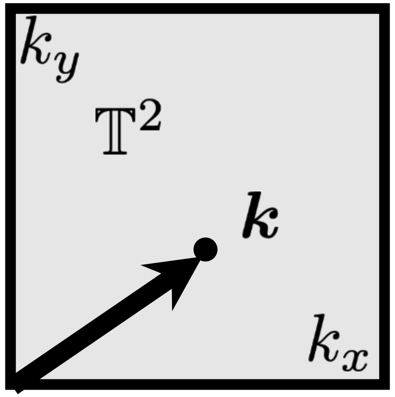
N degrees of freedom per unit cell:
Wyckoff positions, sub-lattice sites,
electronic orbitals, spins

Bloch picture:

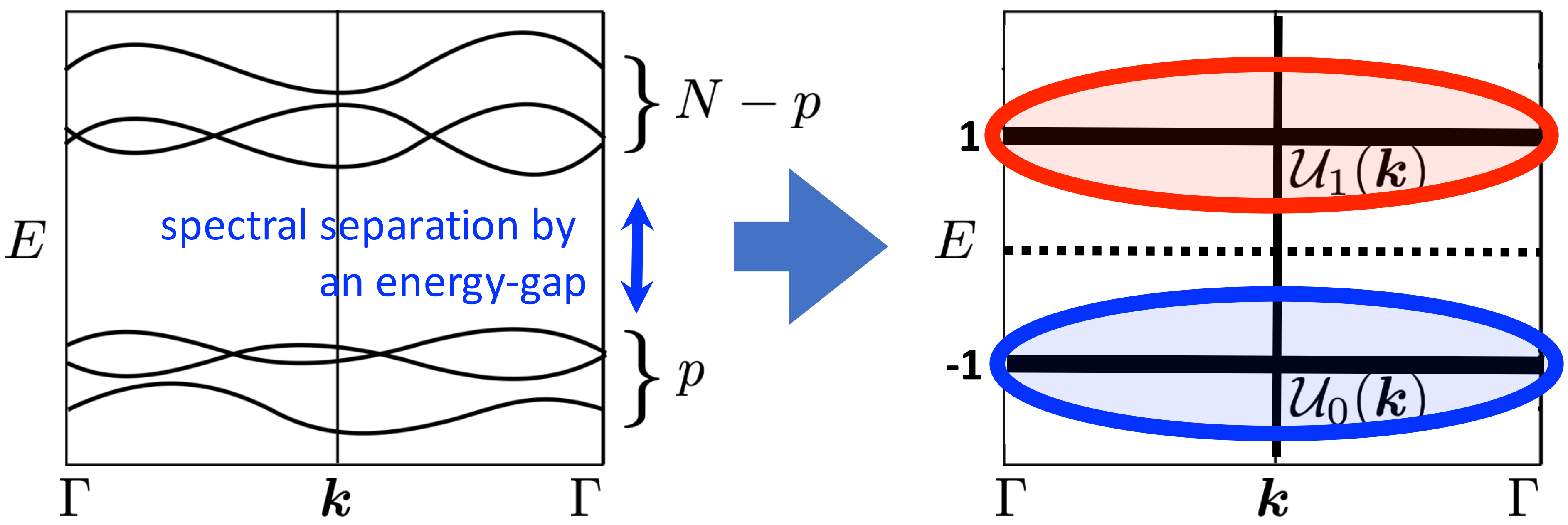
$$H_{\alpha\sigma,\beta\sigma'}(\boldsymbol{k}) = \sum_j \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{R}_j+\boldsymbol{r}_\beta-\boldsymbol{0}-\boldsymbol{r}_\alpha)}\, t_{\alpha\sigma,\beta\sigma'}(\boldsymbol{0}-\boldsymbol{R}_j)$$

Localized Wannier ➔ Finite Fourier series (analytical)

Brillouin zone



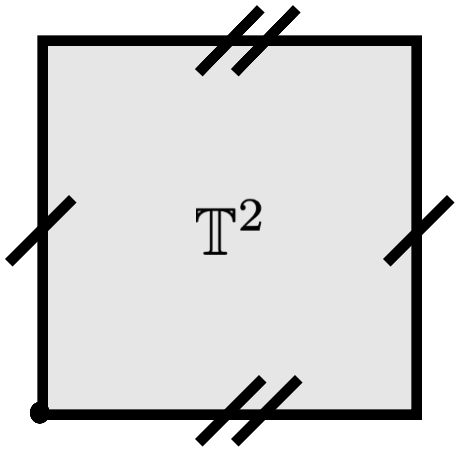
Space of gapped Hamiltonian



Grassmannian
(gauge structure)

$$\mathsf{Gr}^{\mathbb{C}}_{p,N} \cong \mathsf{U}(N)/[\mathsf{U}(p) \times \mathsf{U}(N-p)]$$

Homotopy classification of gapped Hamiltonian



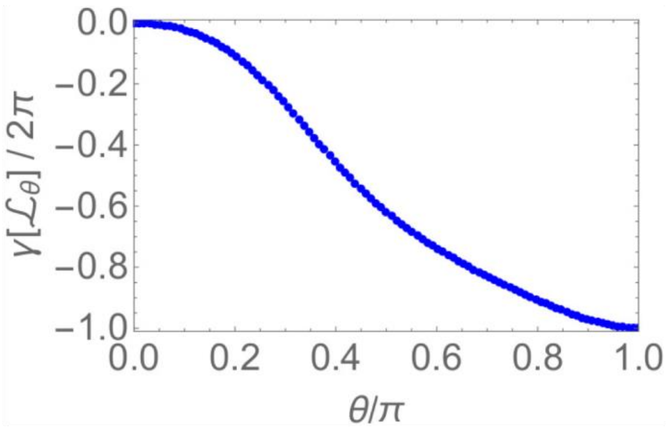
$$\xrightarrow{H(\boldsymbol{k})} \quad \mathsf{Gr}^{\mathbb{C}}_{p,N} \cong \mathsf{U}(N)/\left[\mathsf{U}(p)\times\mathsf{U}(N-p)\right]$$

(Bott periodicity)

$$\begin{aligned}
\left[\mathbb{T}^2, \mathsf{Gr}^{\mathbb{C}}_{p,N}\right] \cong \pi_2\left(\mathsf{Gr}^{\mathbb{C}}_{p,N}\right) &\cong \pi_1\left(\mathsf{U}(p)\right) \\
&= \pi_1\left(\mathsf{SU}(p)\times\mathsf{U}(1)\right) \\
&= \pi_1\left(\mathsf{SU}(p)\right)\times\pi_1\left(\mathsf{U}(1)\right) \\
&= \pi_1\left(\mathsf{U}(1)\right) = \mathbb{Z}
\end{aligned}$$

(Chern number)

Chern number as the chirality of a Weyl node



Flow of Berry phase = Chern number

$$\Delta\gamma_B = \gamma_B[\mathrm{NP}] - \gamma_B[\mathrm{SP}] = 2\pi\ c_1[\mathcal{S}]$$

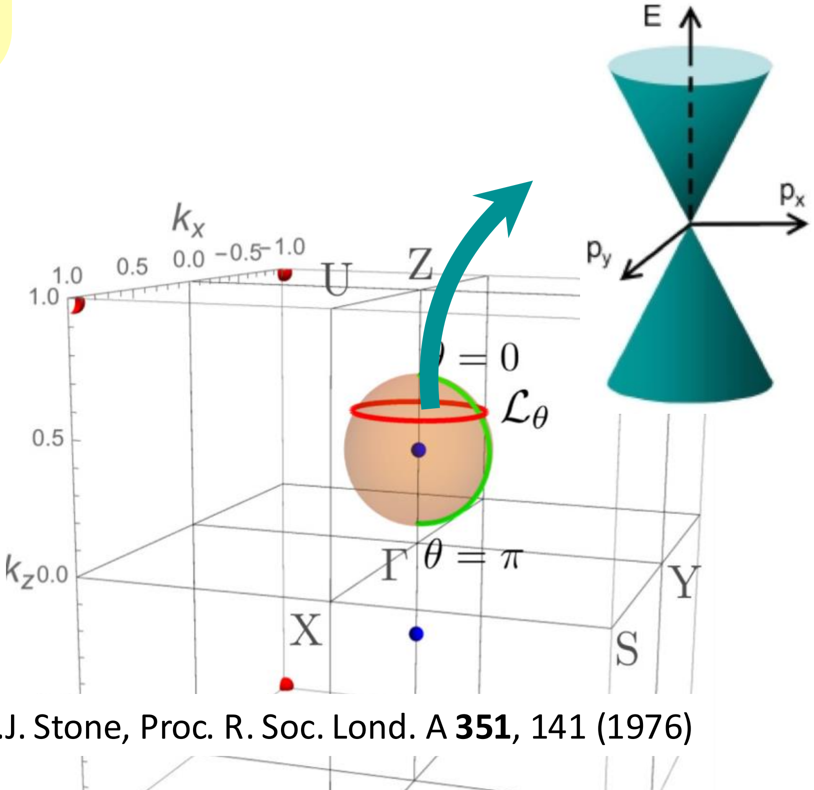
Loop integral over the occupied band subspace:

➔ Wilson loop

$$\mathcal{W}[l_\theta] = \exp\left\{\oint_{l_\theta} \mathcal{A}(\boldsymbol{k}) \cdot d\boldsymbol{l}\right\} \in U(p)$$

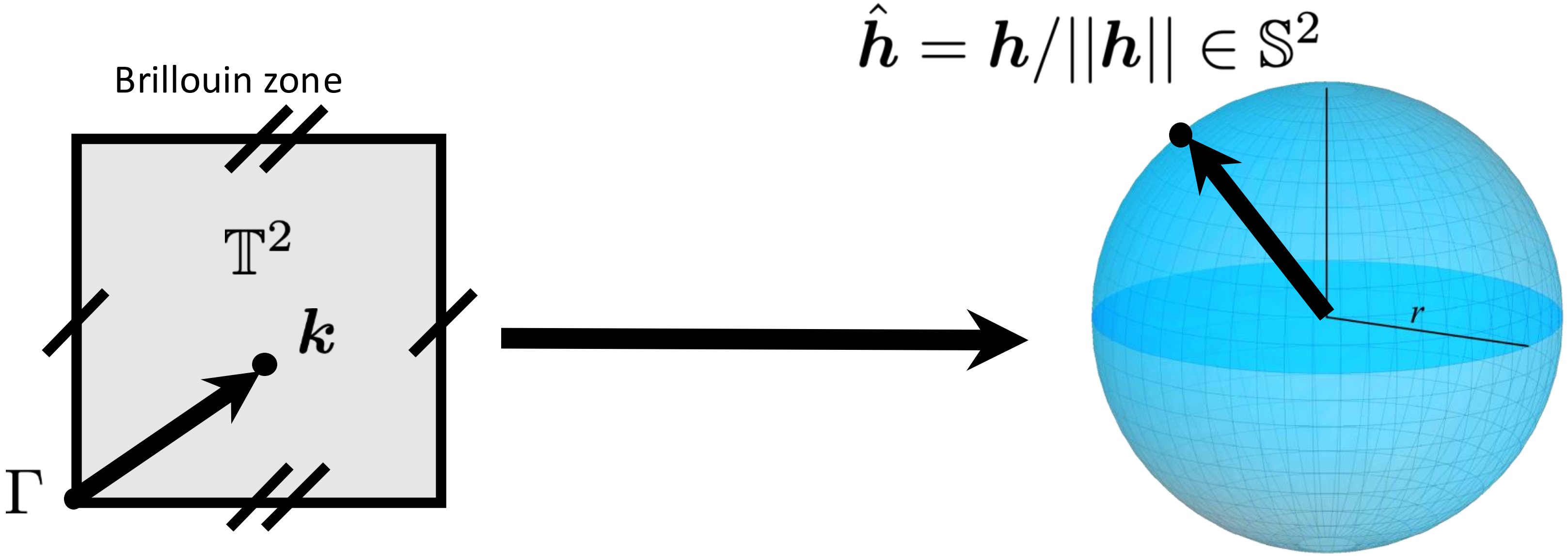
➔ Berry phase

$$e^{i\gamma_B[l_\theta]} = \det \mathcal{W}[l_\theta] \in U(1)$$



A.J. Stone, Proc. R. Soc. Lond. A **351**, 141 (1976)

Gapped graphene: Chern insulator



Chern number: (Skyrmion number)

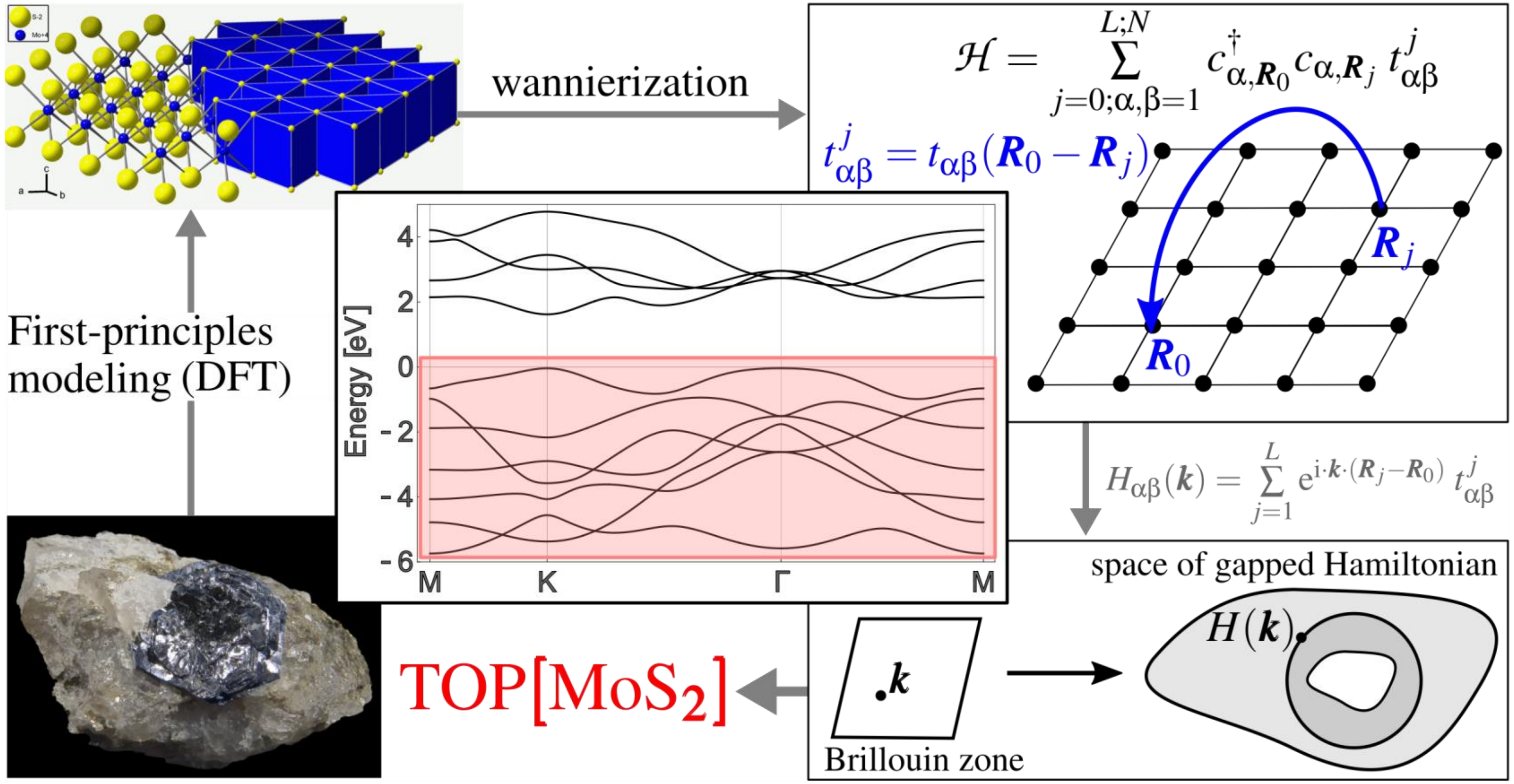
$$c_1 = \frac{1}{4\pi}\int_{\mathbb{T}^2} \hat{\boldsymbol{h}} \cdot \partial_{k_x}\hat{\boldsymbol{h}} \times \partial_{k_y}\hat{\boldsymbol{h}}\, dk_x dk_y \in \mathbb{Z}$$

Zoo of Topological Insulators

AZ	s\d	0	1	2	3	4	5	6	7
A	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0
AIII	1	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
AI	0	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$
BDI	1	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$
D	2	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0
DIII	3	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$
AII	4	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0
CII	5	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
C	6	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0
CI	7	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$

2D Chern insulator

Topological Inverse Problem



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Optimized Topological Quantum Systems
Exotic topology and geometry of crystalline systems

Adrien Bouhon

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December 2025

Marie Curie Fellowship

Swedish Research Council