Hard Condensed Matter

NORDITA

The Nordic Institute for Theoretical Physics

Theoretical Quantum Matter

Alexander Balatsky

D. Kuzmanovski

A. Tyner

A. Pathapati

Material Informatics

Organic Materials Database (OMDB)

Dynamical Order

Odd-frequency superconductivity

H. Yerzhakov

Tien-Tien Yeh

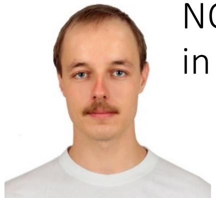
Light – Superconductors interaction

J. Schaltegger

Dirac Materials

Dark Matter Detection

[Homepage](#): for more info



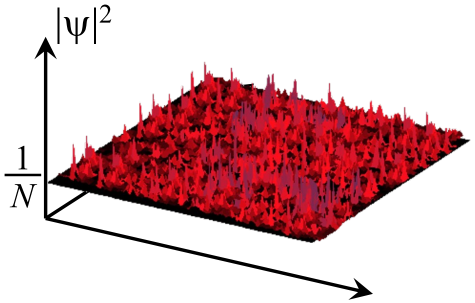
Ivan Khaymovich

NORDITA Ass. Prof. in TQM group

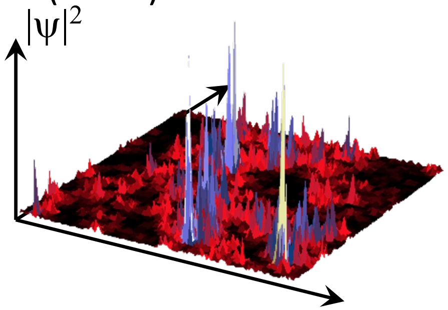
Ergodicity breaking phases States

ergodic metal — non-ergodic phase — insulator → disorder

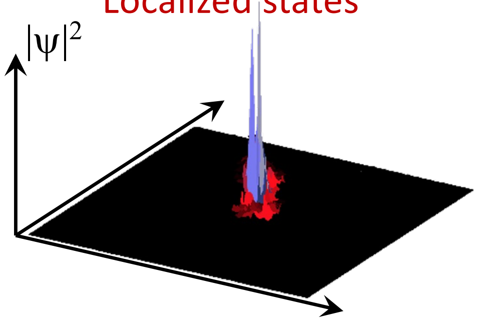
Ergodic states



(Multi)fractal states



Localized states



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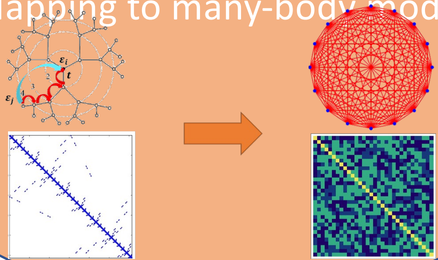
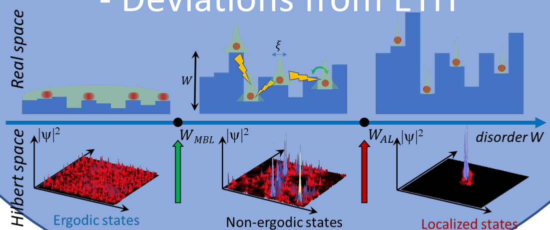
Ergodicity breaking phases

SCAN ME

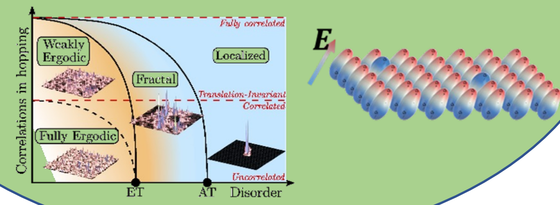
Random-matrix theory:
- Multifractal phases
-Mapping to many-body models



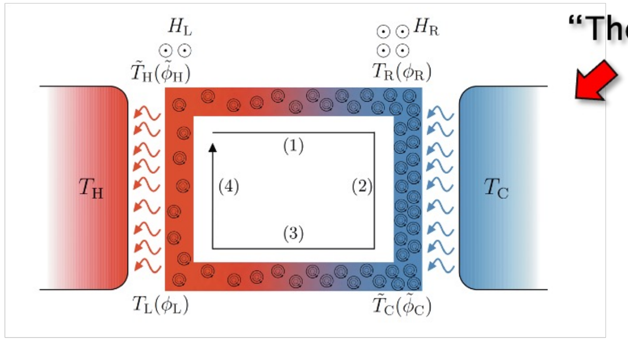
Many-body systems:
- Many-body localization vs Hilbert-space multifractality,
- Multifractality/entanglement
- Deviations from ETH



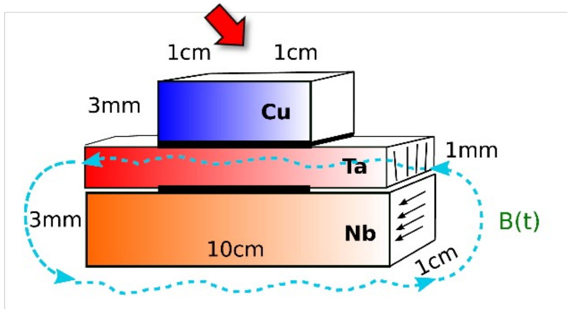
Long-range systems:
- Integrability, correlations,
- non-Hermitian/open models
- Localization and multifractality



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

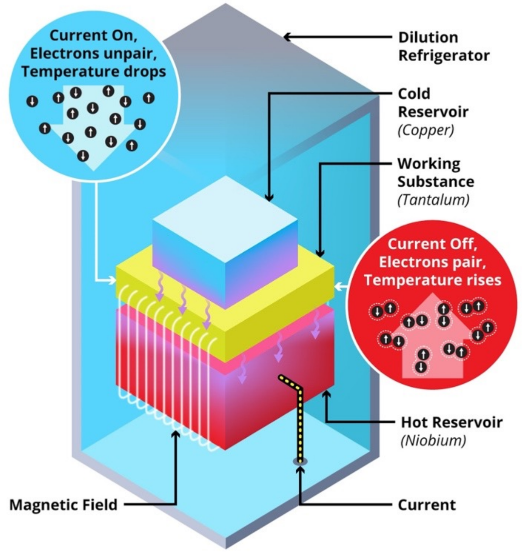


"The qubit goes here"



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

Adiabatic magnetization of type I superconductor for cooling below 10mK



(University of Rochester illustrations / Michael Osadciw)

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Topological Insulators Revolution

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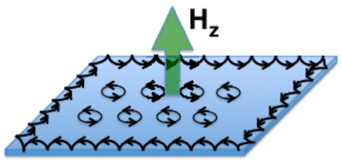
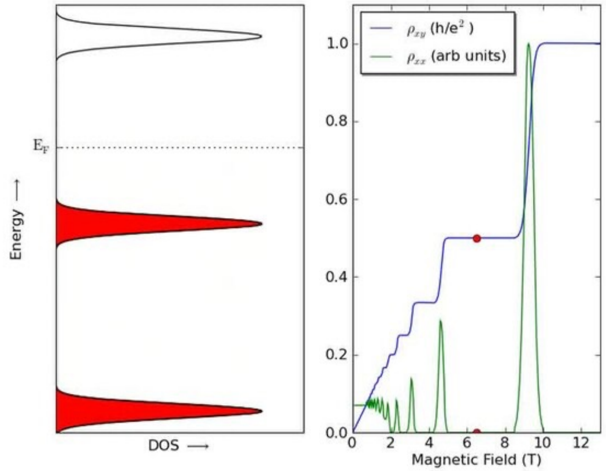
Quantum Hall Effect
(Klaus von Klitzing., 1980)

External Magnetic Field



(b) Quantum Hall effect



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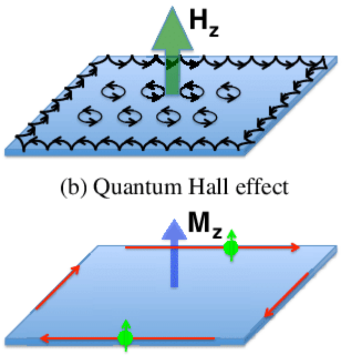
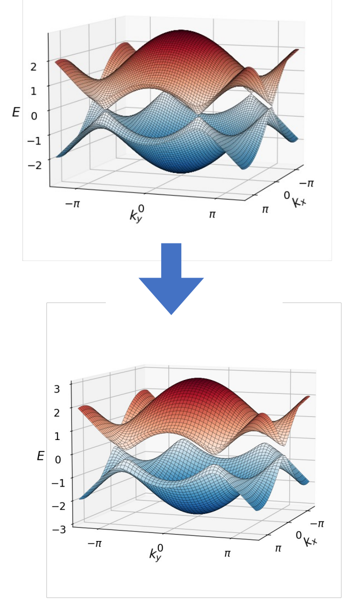
Quantum Hall Effect
(Klaus von Klitzing., 1980)
External Magnetic Field

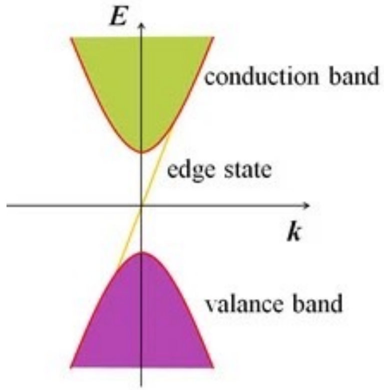
Anomalous QHE
Haldane (1988)
Intrinsic Magnetization



(b) Quantum Hall effect
(d) Quantum Anomalous Hall effect



Graphene



(b)

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Quantum Hall Effect
(Klaus von Klitzing., 1980)

External Magnetic Field

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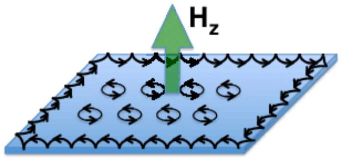
Haldane (1988)

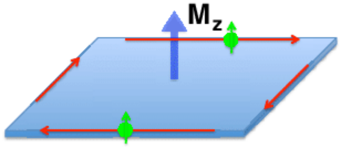
Intrinsic Magnetization

Quantum Spin Hall Effect
Kane & Mele (2005)

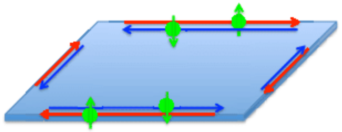
protected by
Fermionic
Time Reversal Symmetry



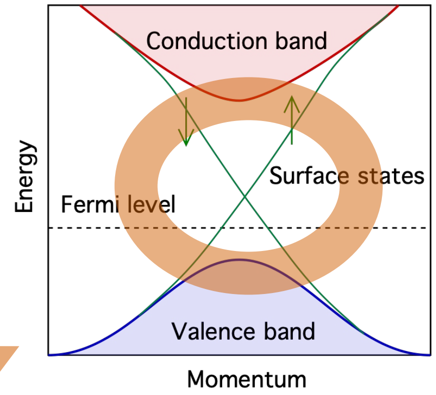
(b) Quantum Hall effect



(d) Quantum Anomalous Hall effect



(f) Quantum Spin Hall effect



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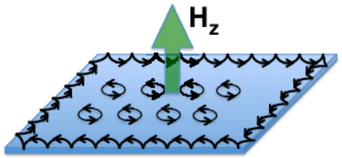
Quantum Hall Effect
(Klaus von Klitzing., 1980)

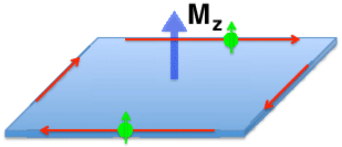
External Magnetic Field



(b) Quantum Hall effect

Anomalous QHE
Haldane (1988)

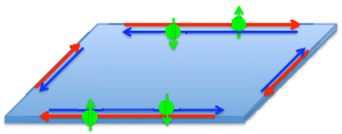
Intrinsic Magnetization



(d) Quantum Anomalous Hall effect

Quantum Spin Hall Effect
Kane & Mele (2005)

protected by
Fermionic
Time Reversal Symmetry

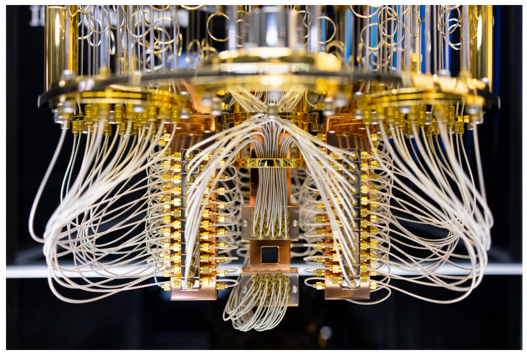


(f) Quantum Spin Hall effect

Robust quantum surface states

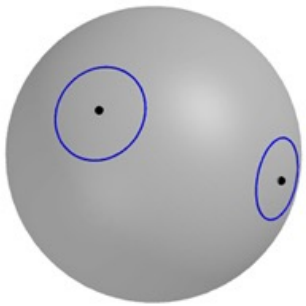
Substrate for QBits of Quantum Computers

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

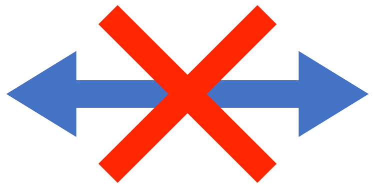


Topological?

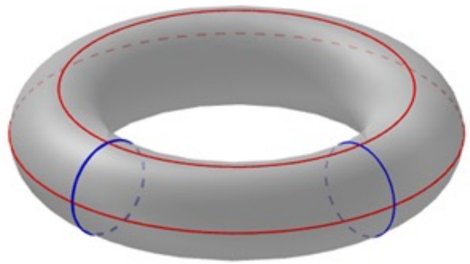
Topology: classification of manifolds with respect to their global features



$g = 0$

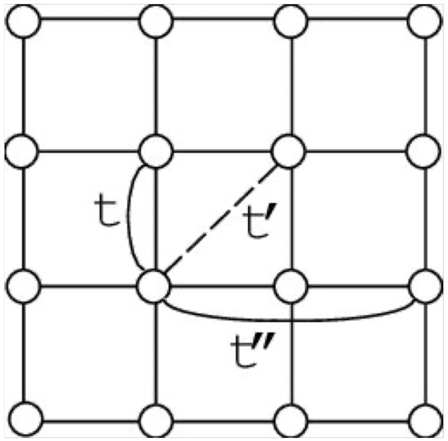


Exemple of topological invariant:
the genus g

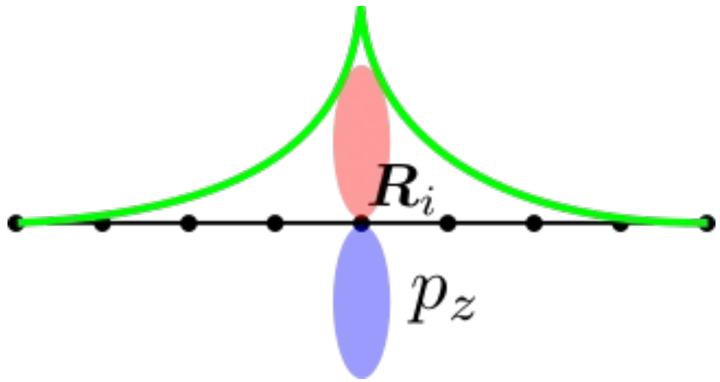


$g = 1$

Quantum Materials Modeling



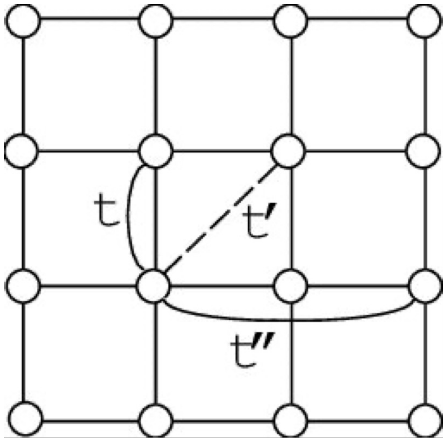
Localized Wannier functions



Kohn-Sham Hamiltonian

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

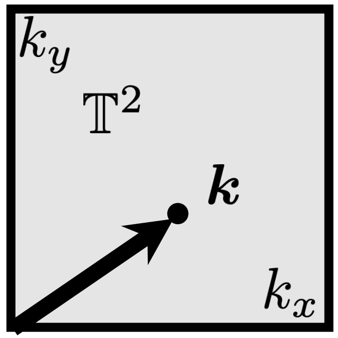
Quantum Materials Modeling



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

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

Brillouin zone

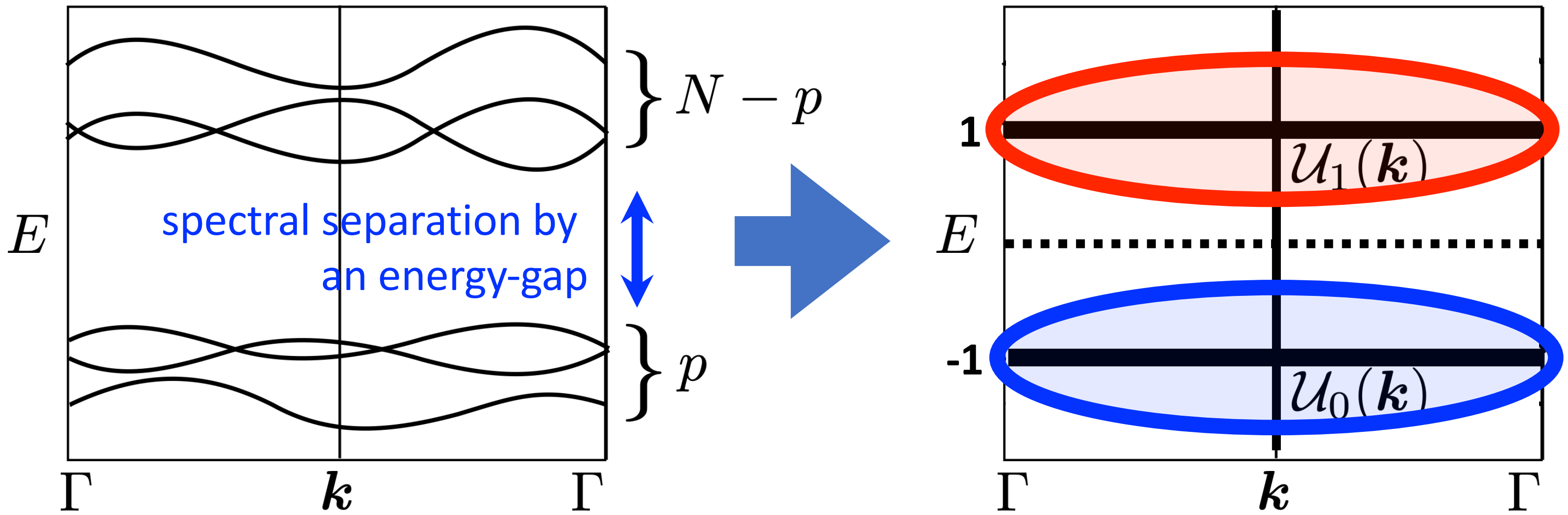


Bloch picture:

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

Localized Wannier ➔ Finite Fourier series (analytical)

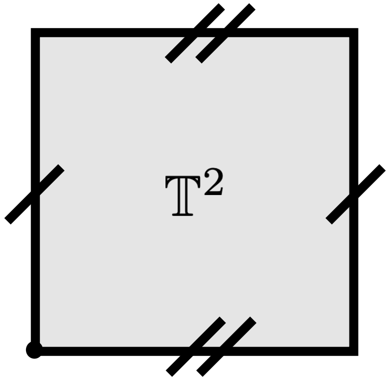
Space of gapped Hamiltonian



Grassmannian (gauge structure)

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

Homotopy classification of gapped Hamiltonian



$H(\boldsymbol{k})$

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

(Bott periodicity)

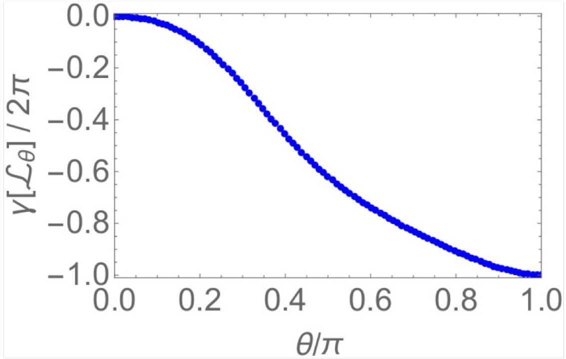
$$\left[\mathbb{T}^2, \mathsf{Gr}^{\mathbb{C}}_{p,N}\right] \cong \pi_2\left(\mathsf{Gr}^{\mathbb{C}}_{p,N}\right) \cong \pi_1\left(\mathsf{U}(p)\right)$$
$$= \pi_1\left(\mathsf{SU}(p)\times\mathsf{U}(1)\right)$$
$$= \pi_1\left(\mathsf{SU}(p)\right)\times\pi_1\left(\mathsf{U}(1)\right)$$
$$= \pi_1\left(\mathsf{U}(1)\right)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

(Chern number)

Chern number as the chirality of a Weyl node

Flow of Berry phase = Chern number

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



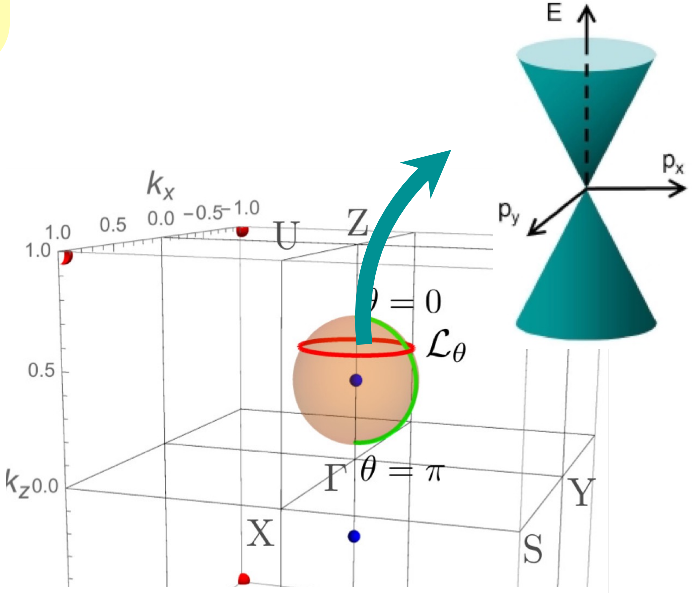
Loop integral over the occupied band subspace:

➔ 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

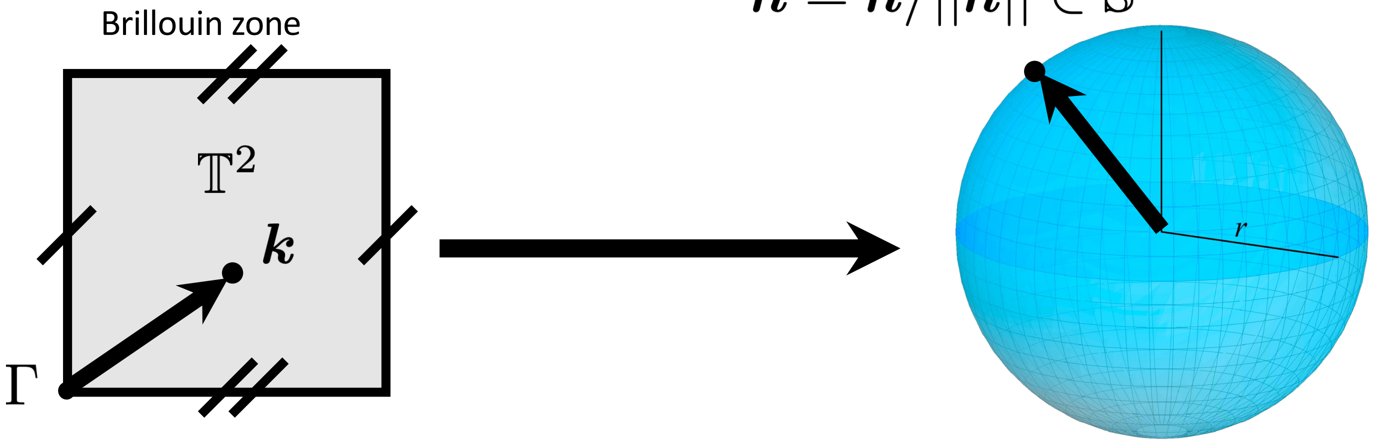
$$e^{i\gamma_B[l_\theta]} = \det \mathcal{W}[l_\theta] \in U(1)$$



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

Gapped graphene: Chern insulator

$$\hat{\boldsymbol{h}} = \boldsymbol{h}/||\boldsymbol{h}|| \in \mathbb{S}^2$$



Chern number: (Skyrmion number)

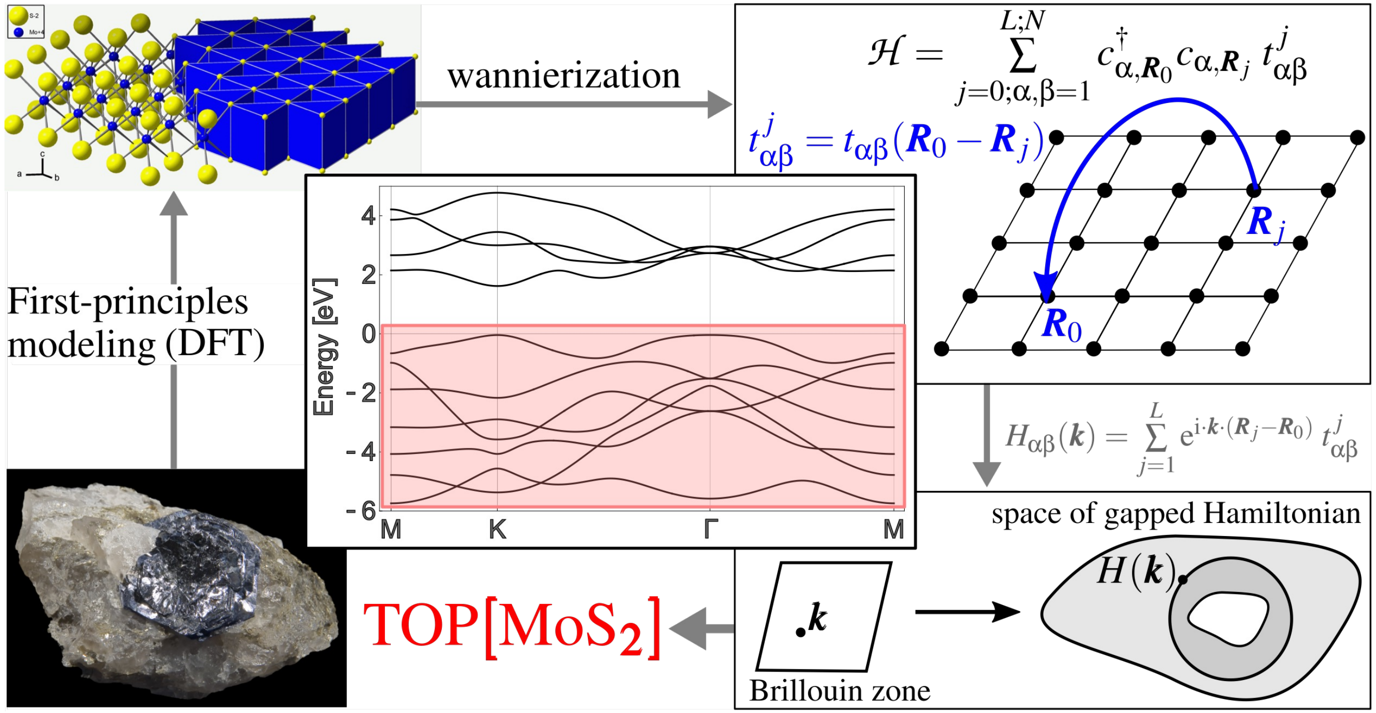
$$c_1 = \frac{1}{4\pi} \int_{\mathbb{T}^2} \hat{\boldsymbol{h}} \cdot \partial_{k_x} \hat{\boldsymbol{h}} \times \partial_{k_y} \hat{\boldsymbol{h}} \, dk_x dk_y \in \mathbb{Z}$$

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

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Marie Curie Fellowship

Swedish Research Council