Quantum Hall Effects in Heterostructures of Transition-Metal Oxides

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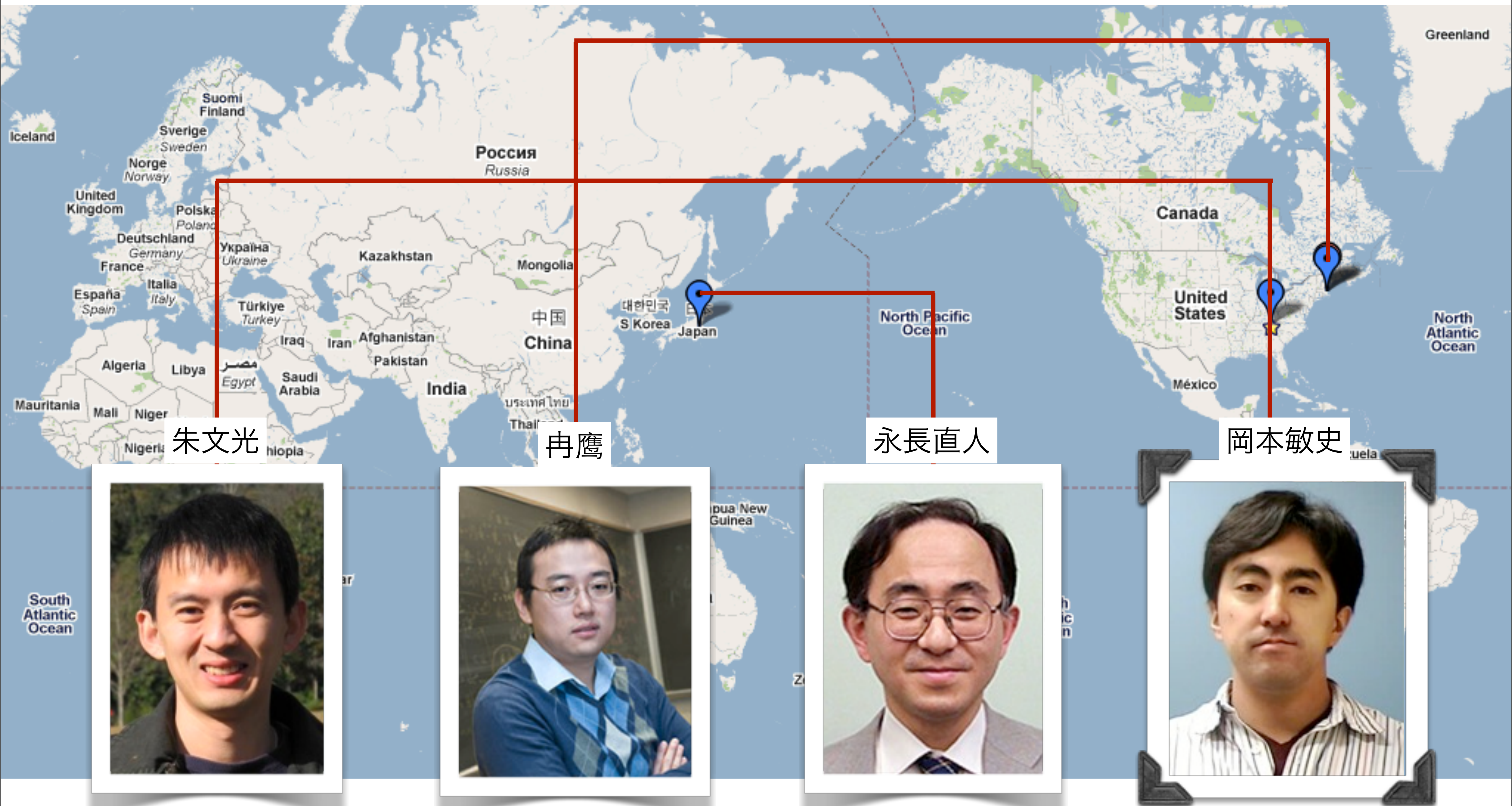
Collaborators



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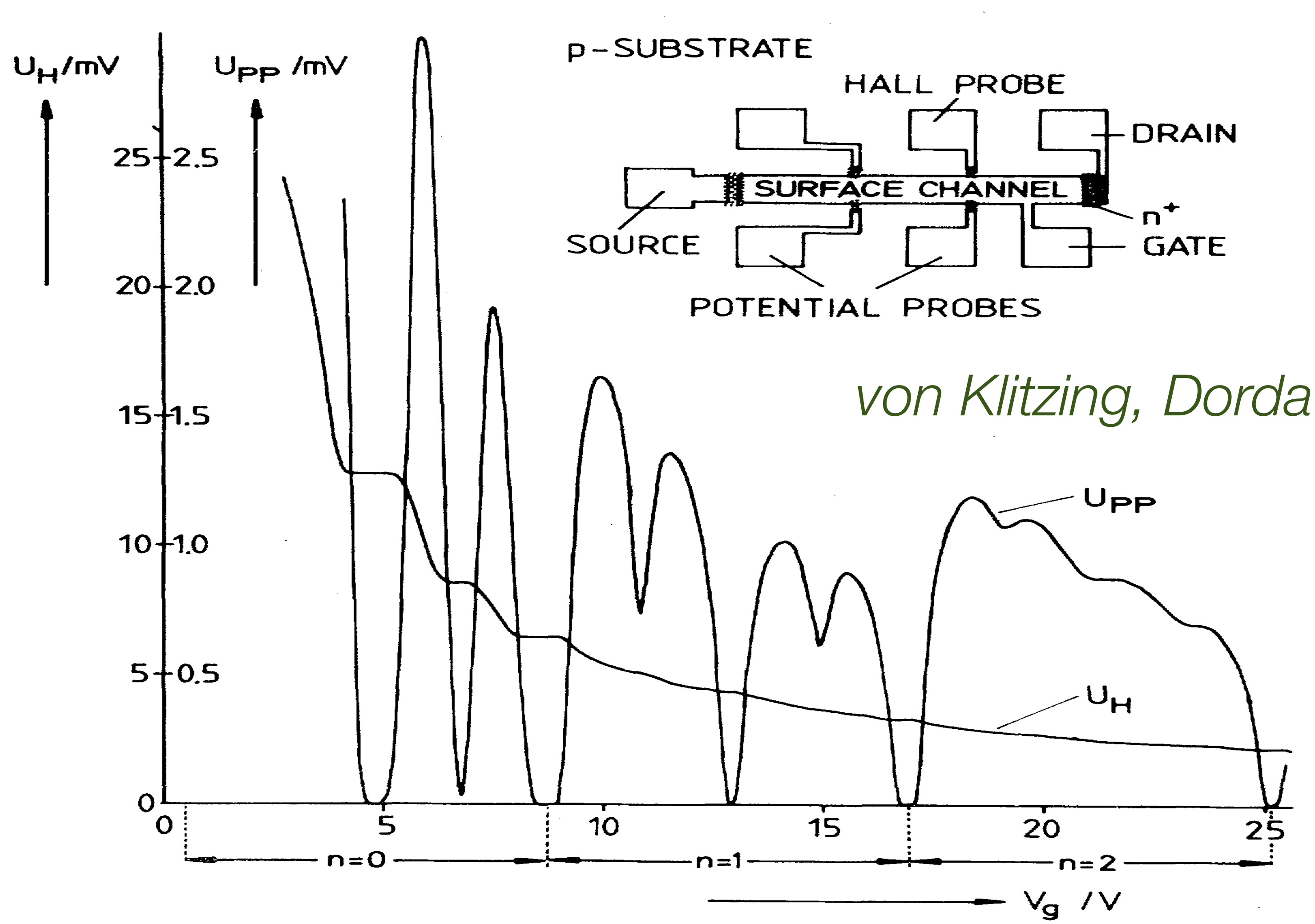
Outline

- The quest for topological states of matter
  - Quantum Hall Effect
  - Topological Insulators
- Heterostructures of transition-metal oxides
  - Quantum spin Hall effect
  - Integer quantum Hall effect
  - Fractional quantum Hall effect
- Summary

The Quest for Topological States of Matter

The QHE: A Tribute to Materials Advance



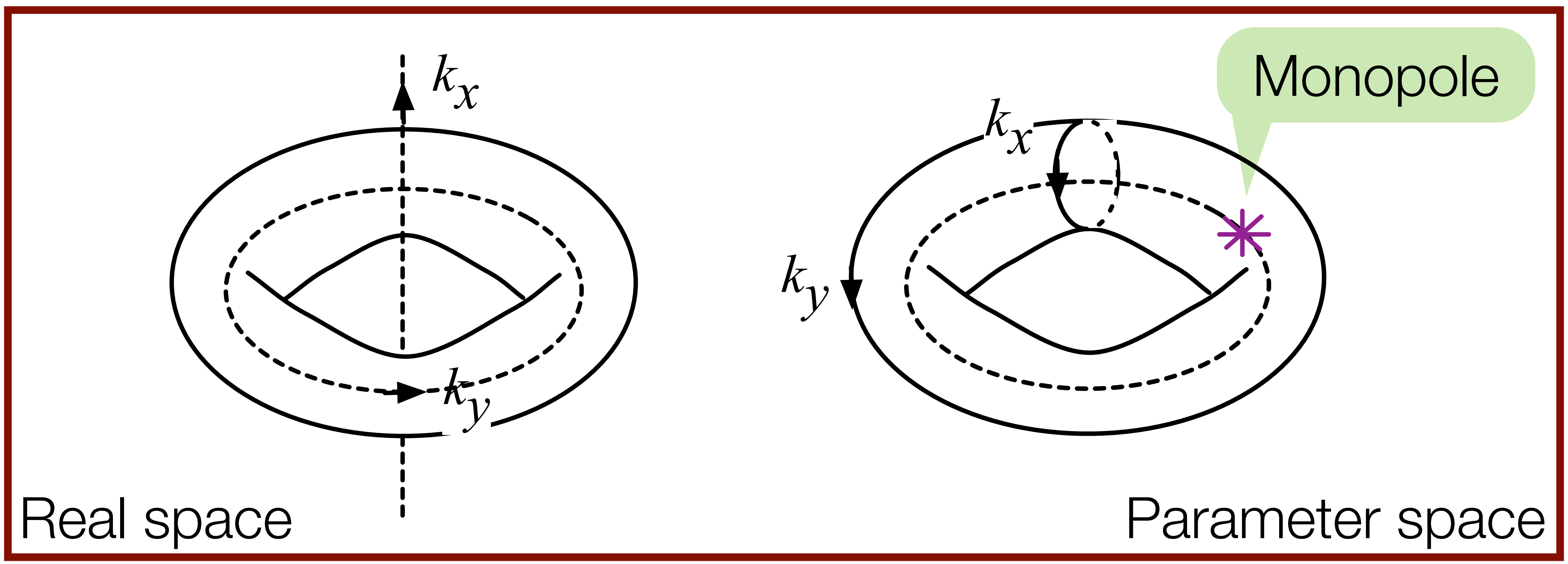
von Klitzing, Dorda & Pepper, 1980

"It should also be mentioned that advances in technology and production methods within semiconductor electronics have played a crucial role in the study of two-dimensional electron systems, and were a precondition for the discovery of the quantised Hall effect."—*Press Release: The 1985 Nobel Prize in Physics*

Precise Quantization: Topological Origin

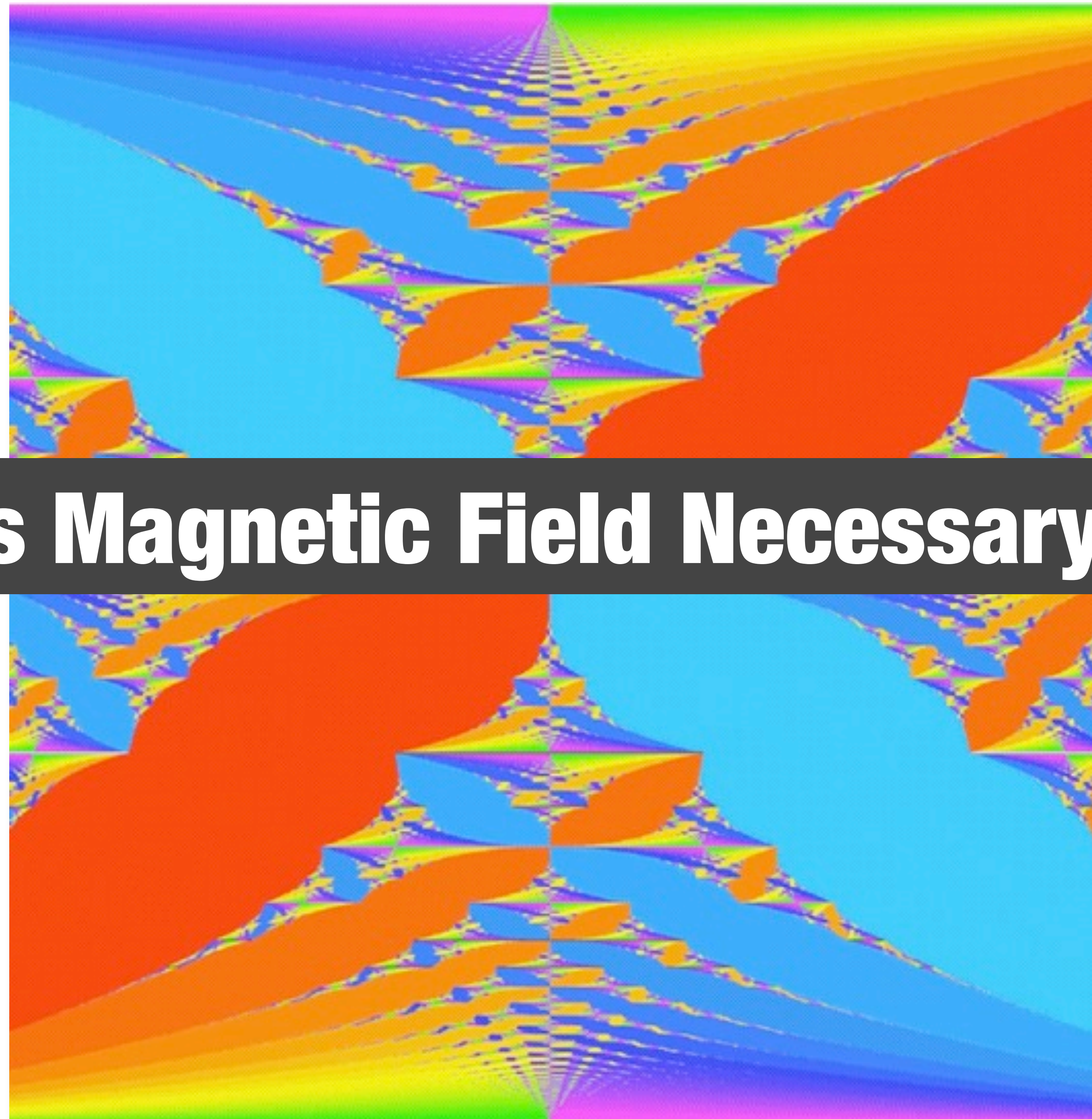
- Hall plateau: Localization physics
- Precise quantization: Nontrivial topology

$$\sigma_{xy} = \frac{ie^2}{2\pi h} \int d^2k \left(\left\langle \frac{\partial \Phi_0}{\partial k_x} \middle| \frac{\partial \Phi_0}{\partial k_y} \right\rangle - \left\langle \frac{\partial \Phi_0}{\partial k_y} \middle| \frac{\partial \Phi_0}{\partial k_x} \right\rangle \right)$$



Thouless et al, 1982; Niu, Wu & Thouless, 1985

The Magnetic Butterfly

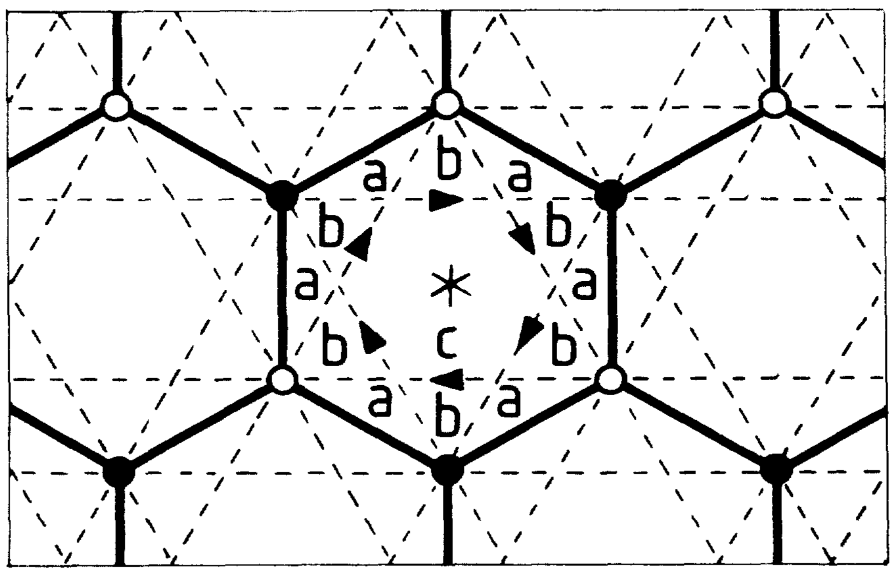


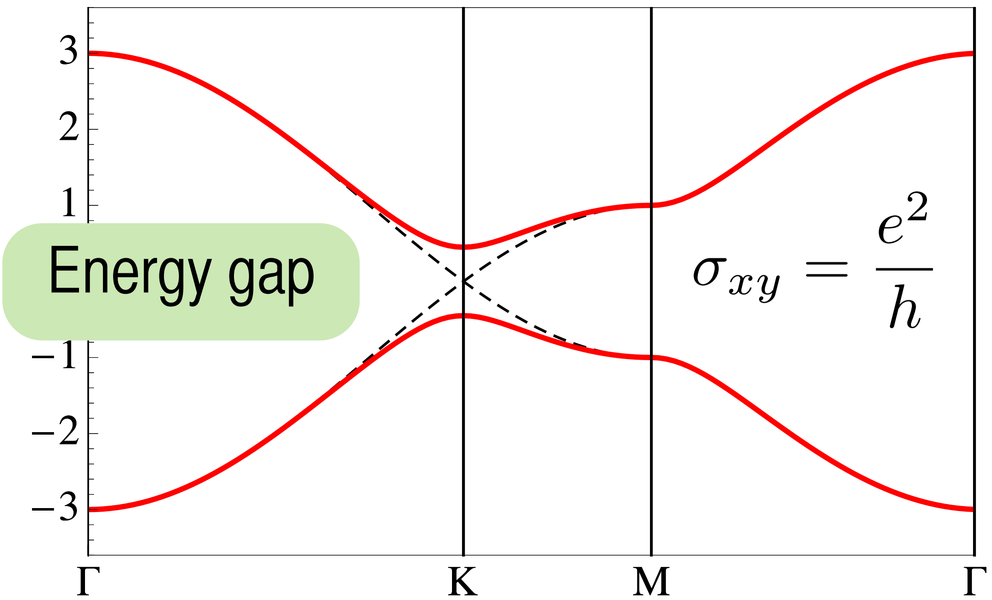
Is Magnetic Field Necessary?

Hofstadter's Butterfly. *Credit: J.E. Avron*

QHE without Landau Levels

Haldane, 1988





- Periodic magnetic field with *zero* total flux through the unit cell
- Next nearest neighbor hopping becomes complex, opens a band gap

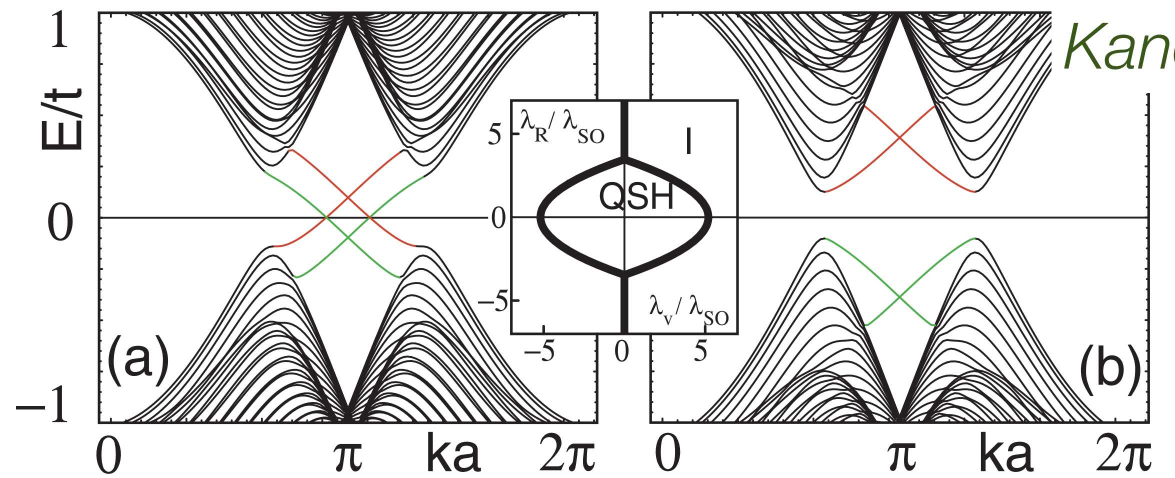
Nontrivial topology in simple band insulators

QSHE driven by Spin-Orbit Interaction

T-symmetry breaking	$\Delta_{\mathrm{Haldane}}\sigma_z\tau_z$
Spin-orbit interaction	$\Delta_{\mathrm{SO}}\sigma_z\tau_z s_z$

$(\sigma_z, \tau_z, s_z) =$
(sublattice, valley, spin)

- s_z conserved: Two copies of Haldane model
- s_z not conserved: Edge states **still** protected by T-symmetry

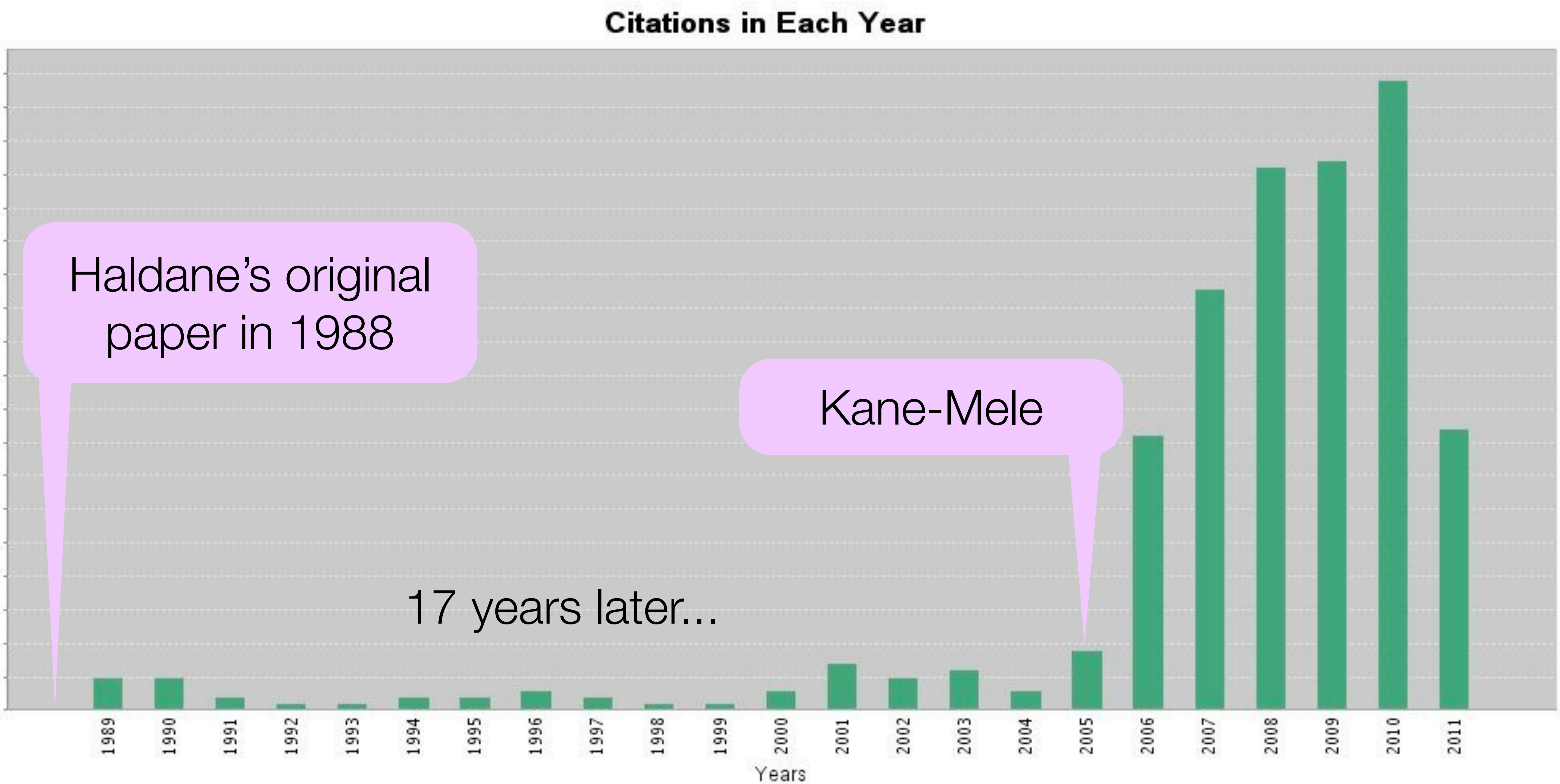


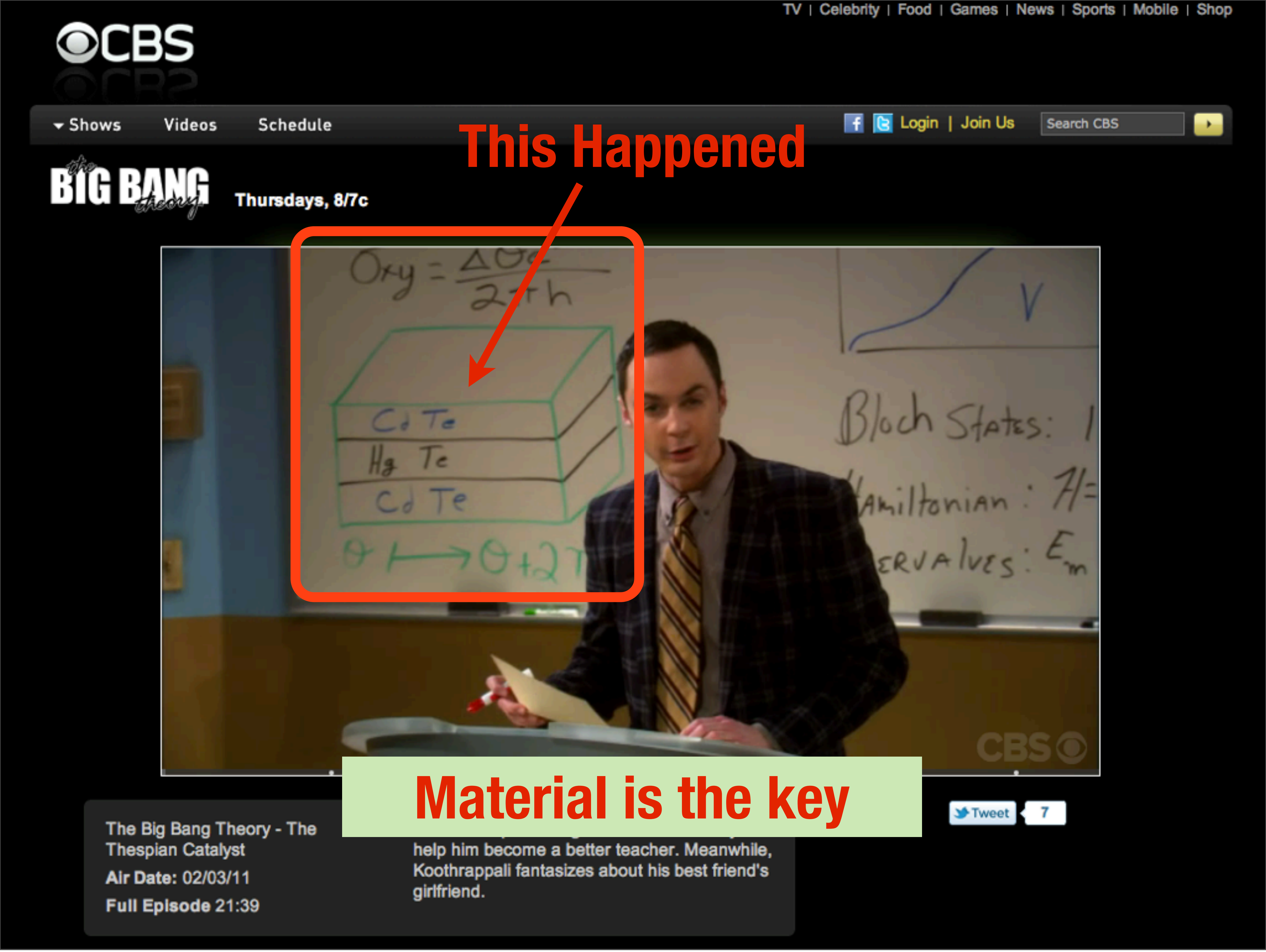
Kane & Mele, 2005

Topological insulators are characterized by nontrivial band topology (Z_2) driven by spin-orbit interaction and support robust "helical" edge/surface states

2D: Kane & Mele, PRL 2005; Bernevig, Hughes, & Zhang (2006)
3D: Fu, Kane & Mele, 2007; Moore & Balents (2007)

Haldane: What has Just Happened?

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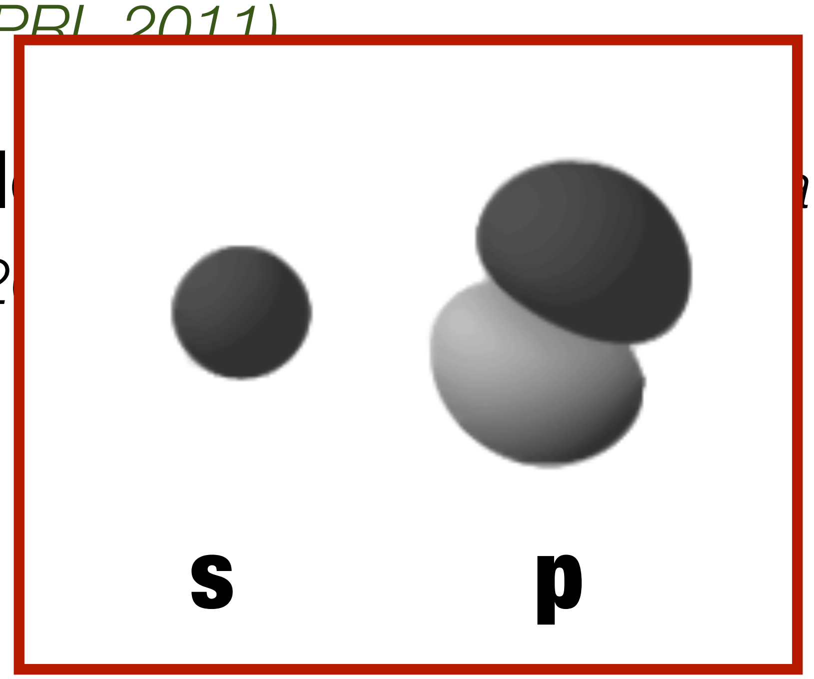
Air Date: 02/03/11
Full Episode 21:39
help him become a better teacher. Meanwhile, Koothrappali fantasizes about his best friend's girlfriend.

Topological Insulators: A Growing Family

- **CdHgTe/HgTe/CdHgTe** *(Bernevig et al, Science 2006, Konig et al, Science 2007)*
- **$Bi_{1-x}Sb_x$** *(Fu and Kane, PRB 2007, Hsieh et al, Nature 2008)*
- **Bi_2Se_3, Bi_2Te_3, Sb_2Te_3** *(Zhang et al, Nat Phys 2009, Xia et al, Nat Phys 2009, Chen et al, Science 2009)*
- **$TlBiTe_2$ and $TlBiSe_2$** *(Lin et al, PRL 2010, Yan et al, EPL 2010, Sato et al, PRL 2010, Chen et al, PRL 2011)*
- Half-heuslers, Chal *at. 2010, Chadov et al, Nat Mat 2010, Xiao et al, PRL, 2*
- Many more...



What About d-Orbitals?

Specialize in **superconductivity**, **magnetism**, **ferroelectricity**, **Mott insulating**, etc.

+

Topological order

- Proximity effects between TIs and symmetry-breaking states, (magnetoelectric effects, Majorana fermions)
- Competing phases: Mott vs. TI

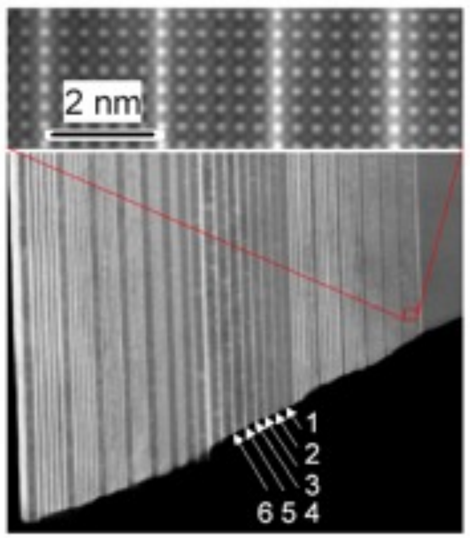
Shitade et al, 2009; Pesin & Balents, 2010

Heterostructures of Transition-Metal Oxides

Heterostructures of Transition-Metal Oxides

Artificial charge-modulation in atomic-scale perovskite titanate superlattices

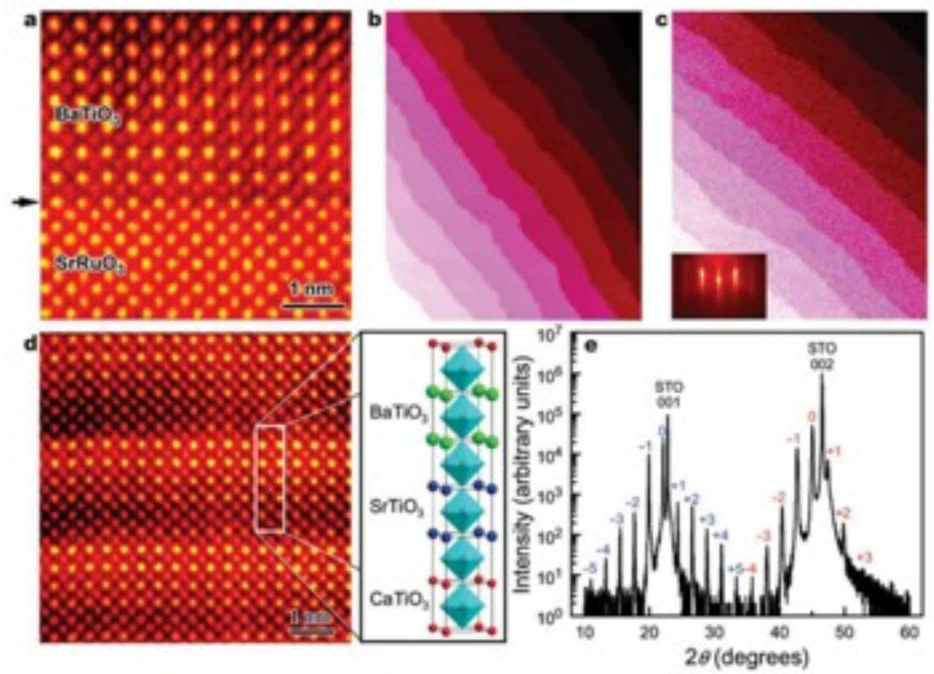
A. Ohtomo, D. A. Muller, J. L. Grazul & H. Y. Hwang



Strong polarization enhancement in asymmetric three-component ferroelectric superlattices

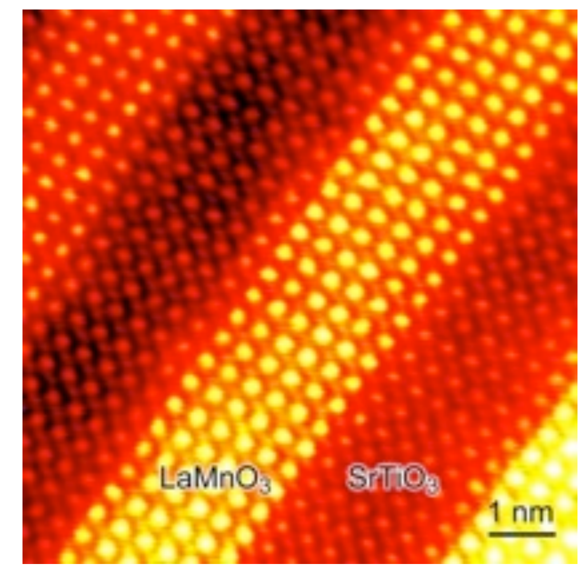
Ho Nyung Lee, Hans M. Christen, Matthew F. Chisholm, Christopher M. Rouleau & Douglas H. Lowndes

Condensed Matter Sciences Division, Oak Ridge National Laboratory, Oak Ridge,



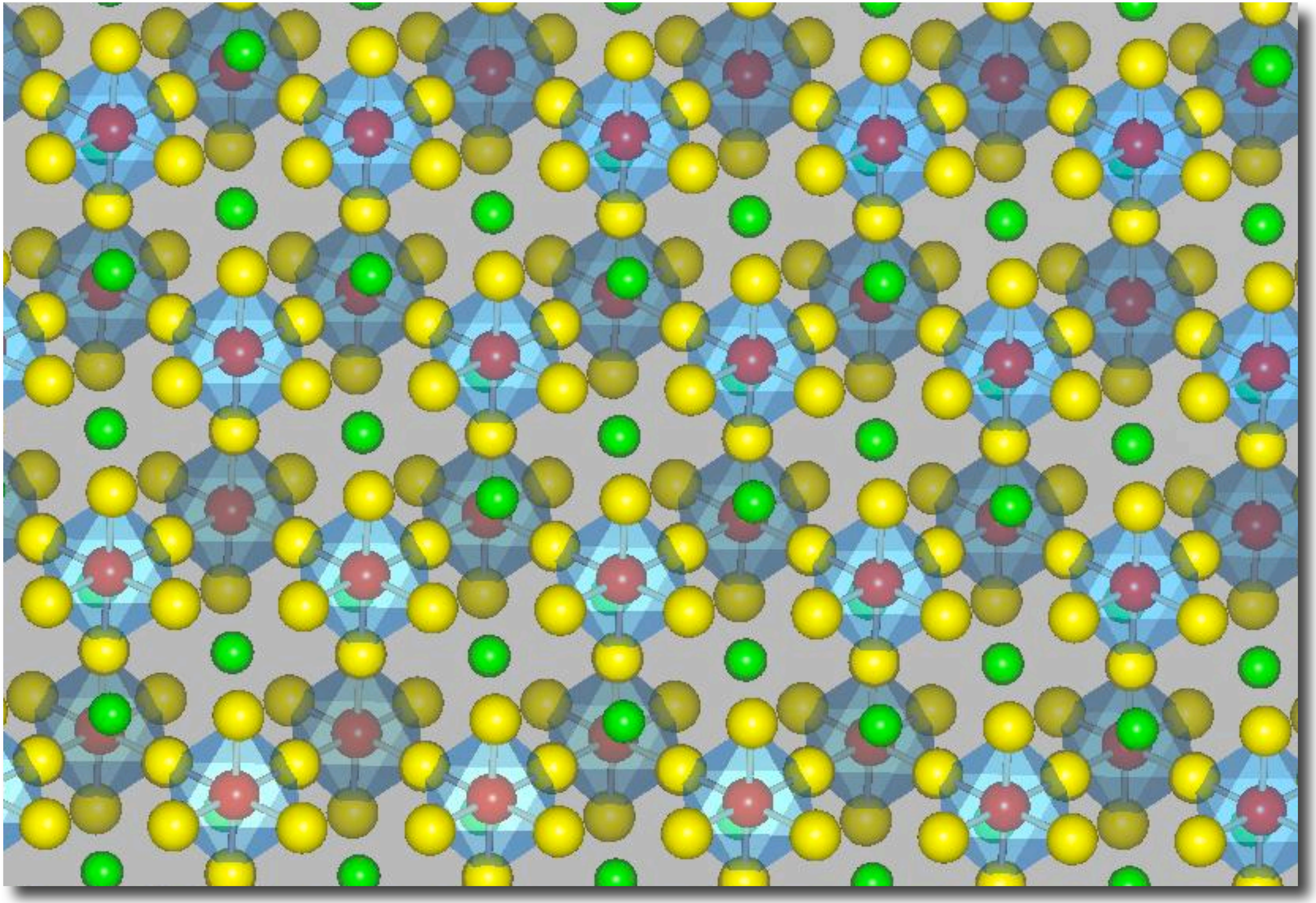
$[LaMnO_3]_n[SrTiO_3]_m$ superlattice

by courtesy of H. N. Lee, ORNL



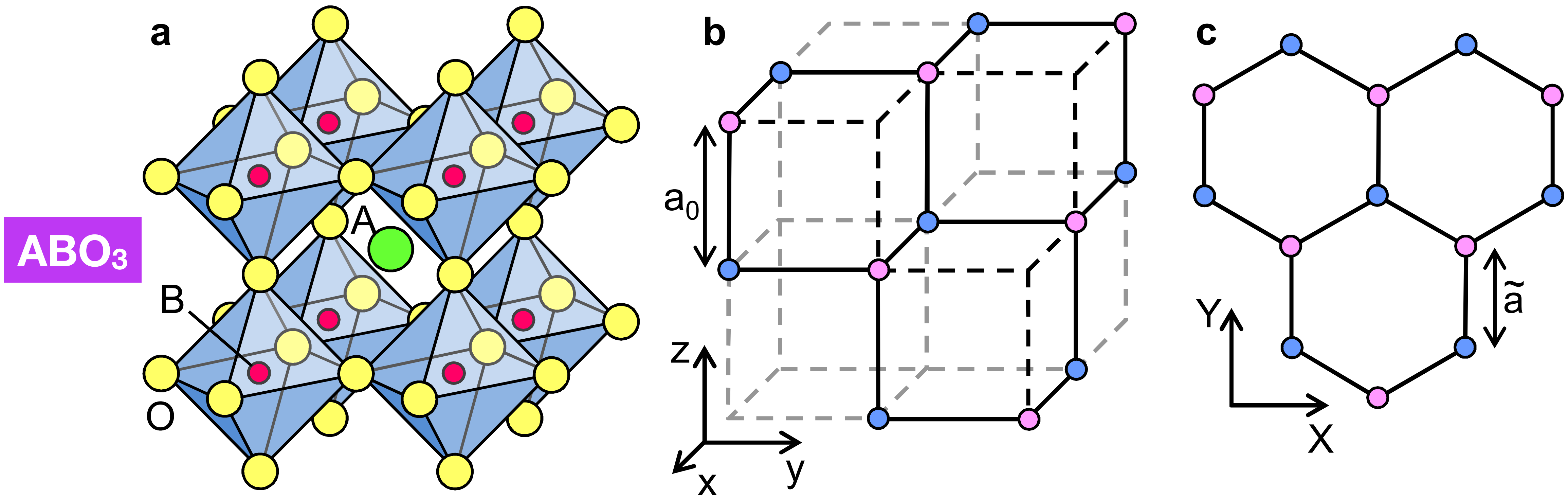
- Layered structure can be prepared with atomic precision
- Great flexibility: tunable lattice constant, carrier concentration, spin-orbit interaction, correlation strength

Perovskite (111)-bilayer



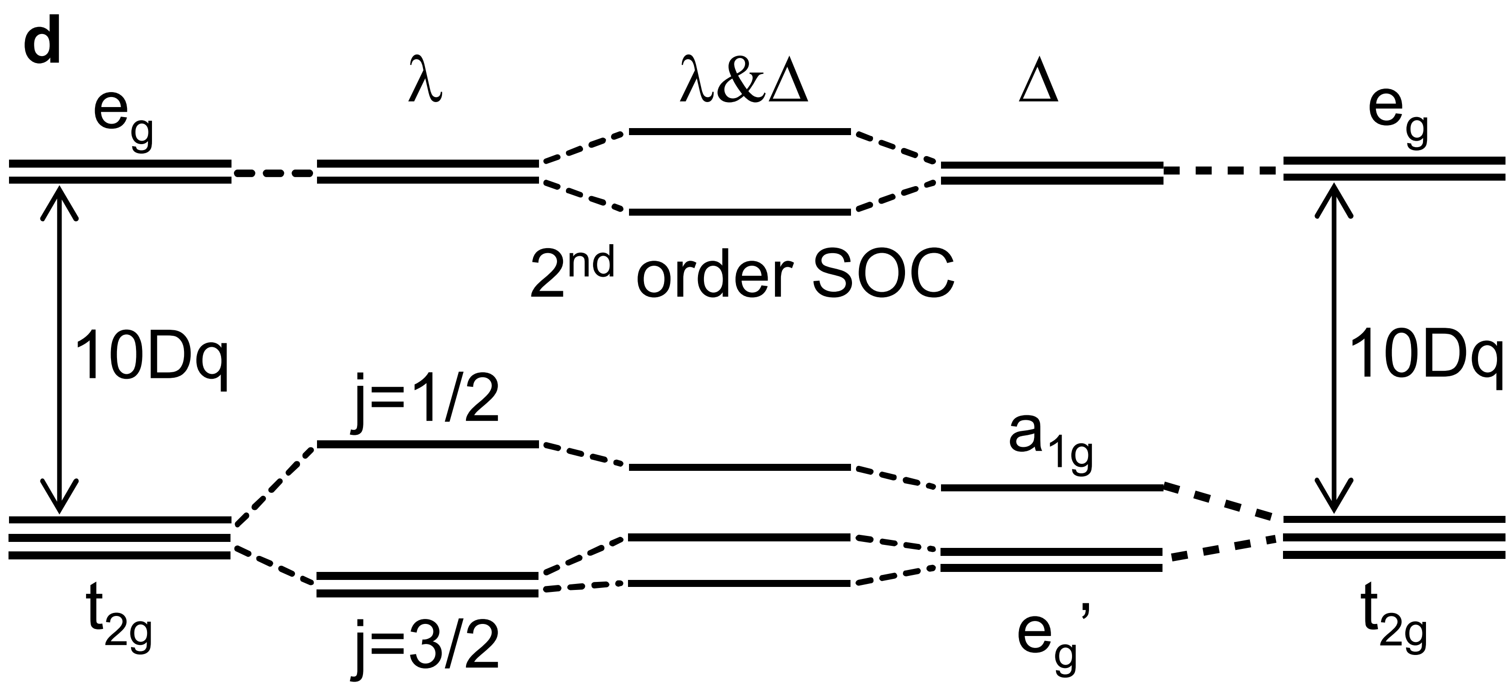
Credit: Satoshi Okamoto

Perovskite (111)-bilayer



- Honeycomb lattice: Similar physics to graphene is expected
- Sublattices on different layer: Inversion symmetry breaking can be externally controlled (i.e., gating or asymmetric substrates)
- Reduced crystal field symmetry: Octahedral to **trigonal**

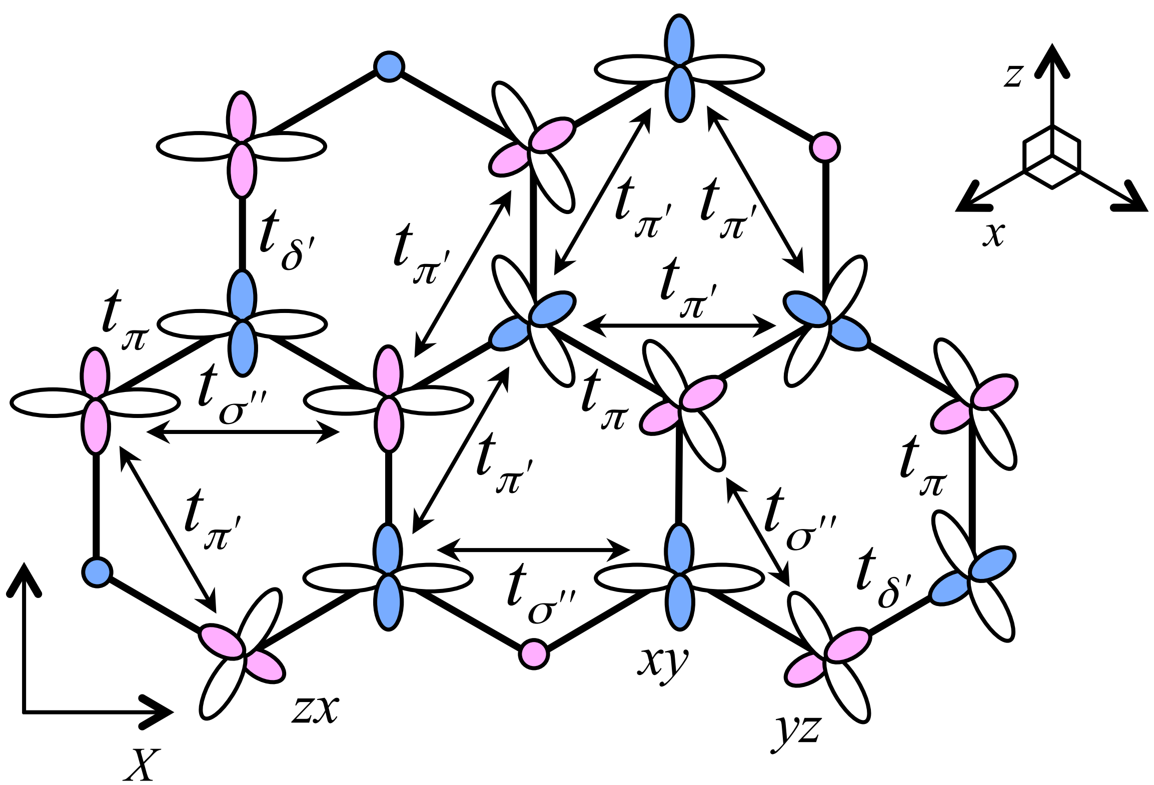
Atomic Orbitals in Crystal Field + SO



Spin-orbit interaction + **Trigonal symmetry**

t_{2g} orbitals

$$H = H_{\text{hop}} + \lambda \sum_i \vec{L}_i \cdot \vec{s}_i + H_{\text{crystal}} + \frac{V}{2} \sum_i \xi_i c_i^\dagger c_i$$

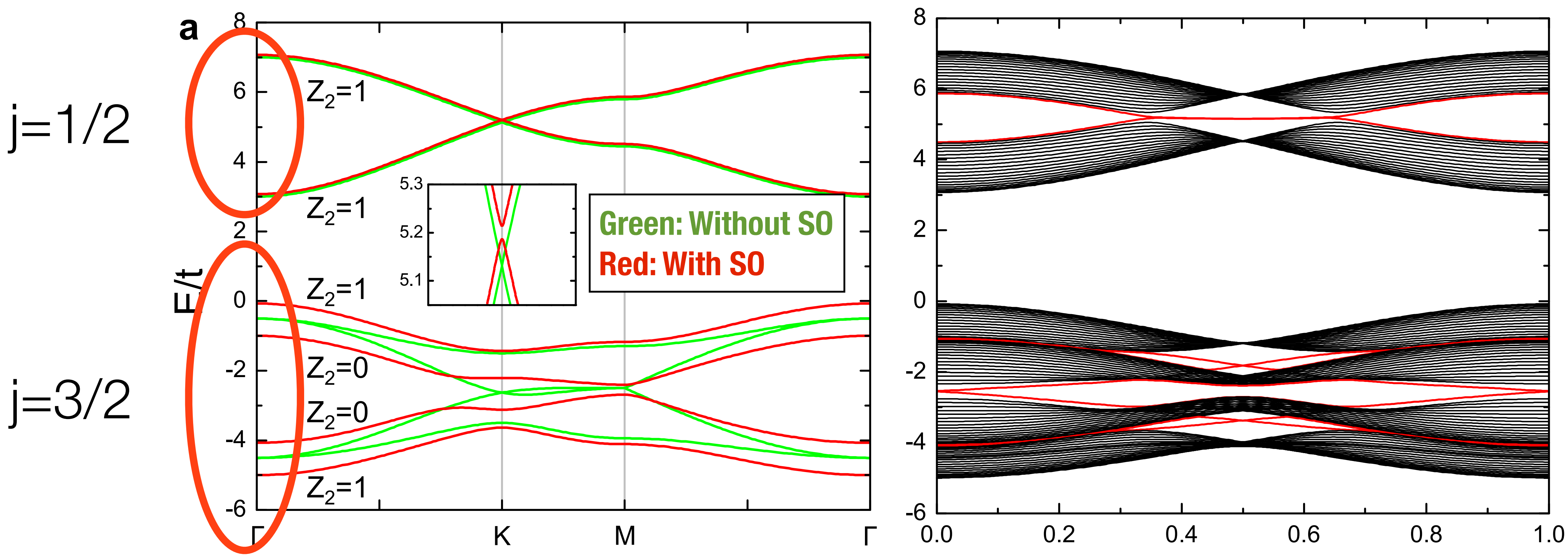


t_{2g} Orbitals - Strong SOC

$$\frac{\lambda}{t} > \frac{8}{3}$$

j=1/2 and j=3/2 manifolds are completely separated

t_{2g}^2, t_{2g}^5 are possible candidates

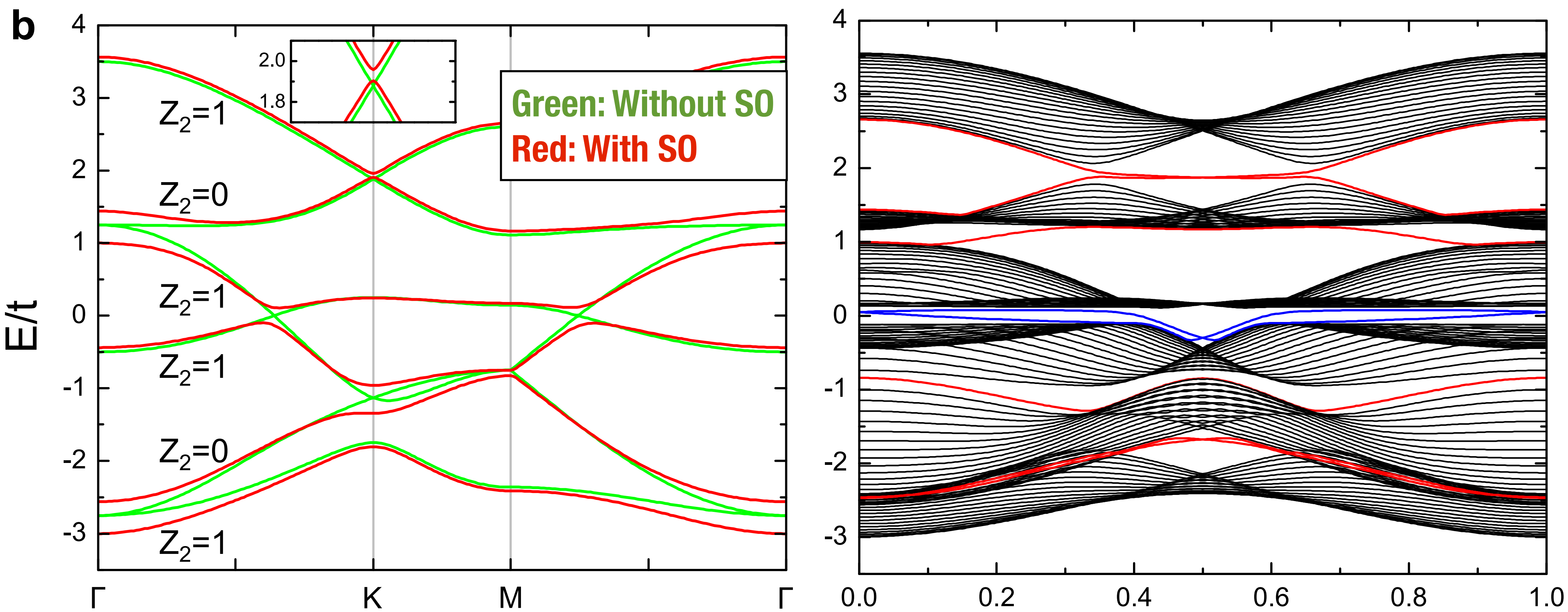


t_{2g} Orbitals - Weak SOC

$$\frac{\lambda}{t} < \frac{8}{3}$$

j=1/2 and j=3/2 manifolds are mixed away from Gamma

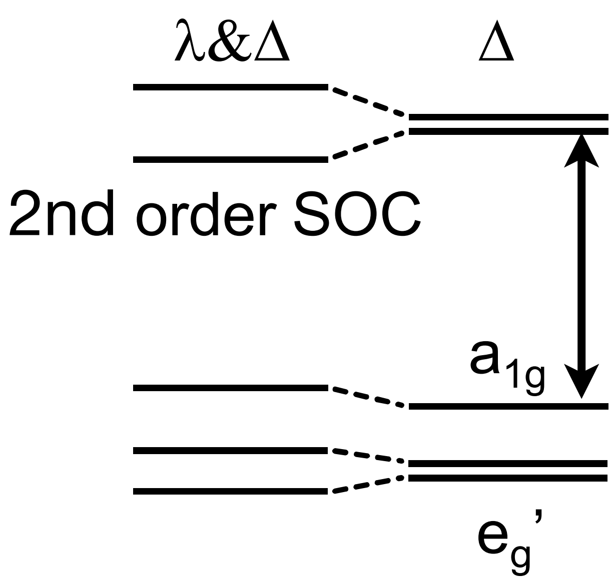
$t_{2g}^2, t_{2g}^4, t_{2g}^5$ are possible candidates



e_g Orbitals

$$H = H_{\rm hop} + H_{\rm SO} + \frac{V}{2}\sum_i \xi_i c_i^\dagger c_i$$

Allowed by trigonal symmetry



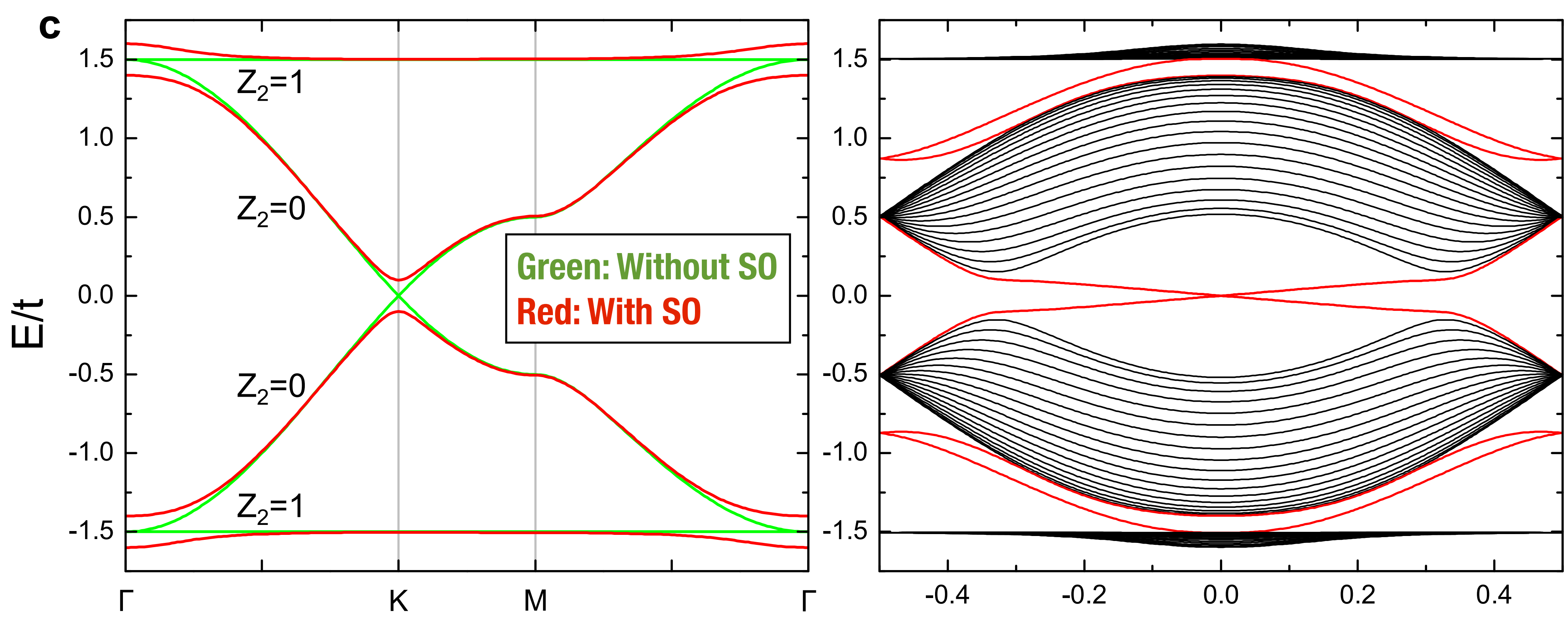
$$H_{\rm SO}^{lm} = \lambda^2 \sum_{\tau \notin e_g} \frac{\langle l|\vec{L}\cdot\vec{s}|\tau\rangle\langle\tau|\vec{L}\cdot\vec{s}|m\rangle}{E_{eg} - E_\tau}$$

Vanishes in the limit of **Δ→**0

Similar to graphene, see *Min et al, PRB 2006*

e_g Orbitals

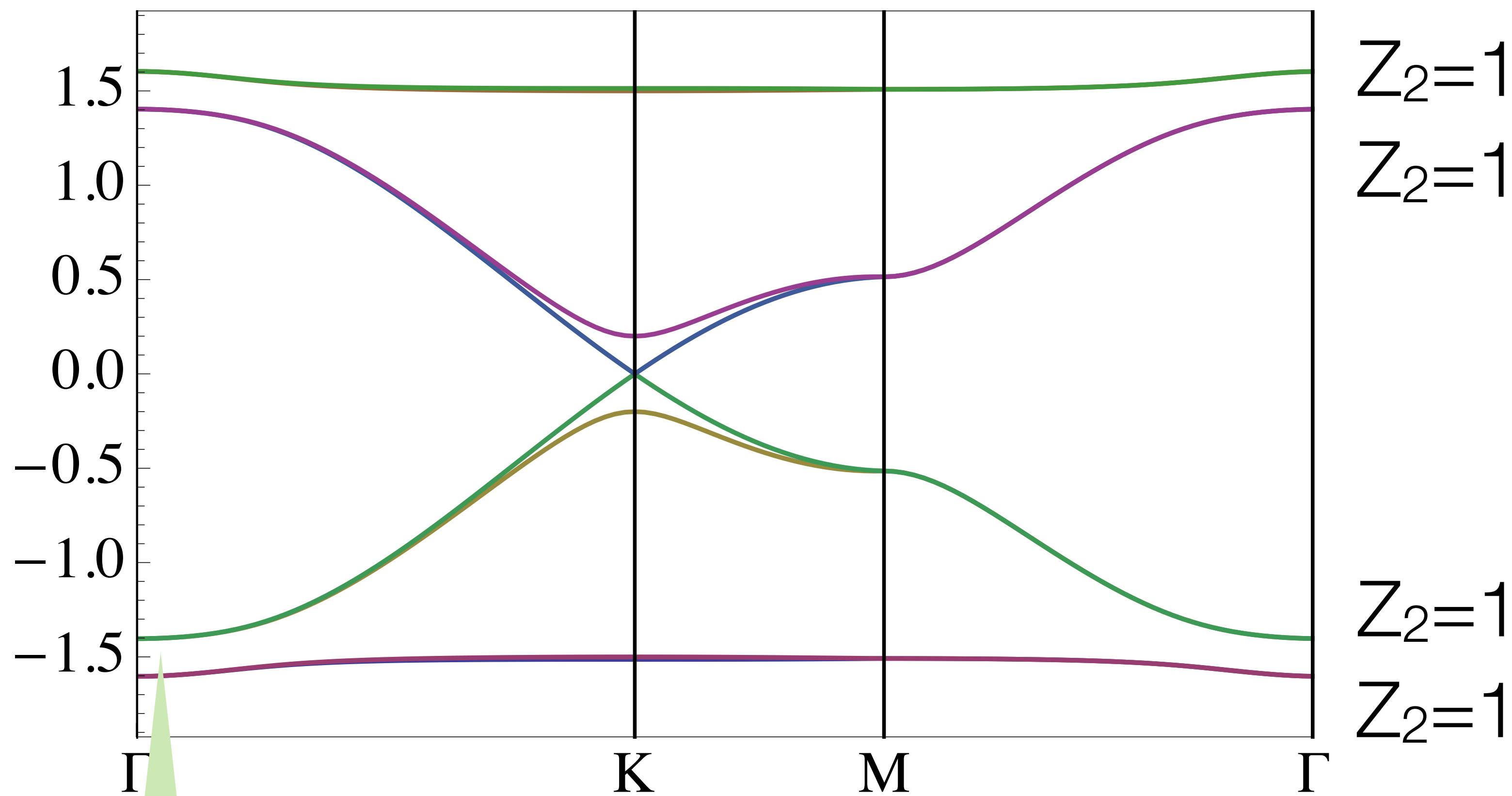
e_g^1, e_g^2, e_g^3 are possible candidates



Nearly flat Z_2 band obtained if $V_{dd\delta}/V_{dd\sigma}\sim 0$

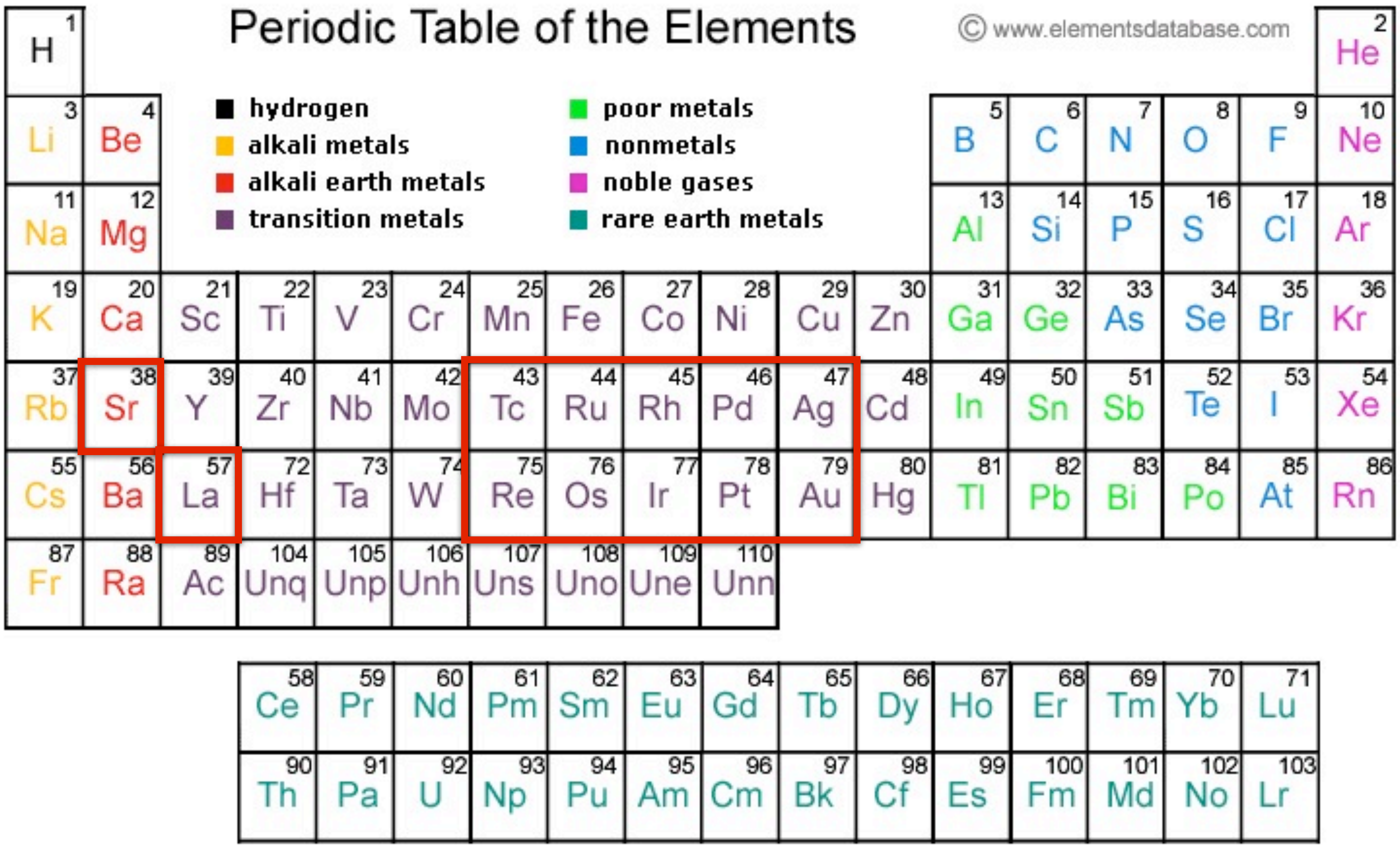
Control of Topological Order

- Topological order can be destroyed by inversion symmetry breaking



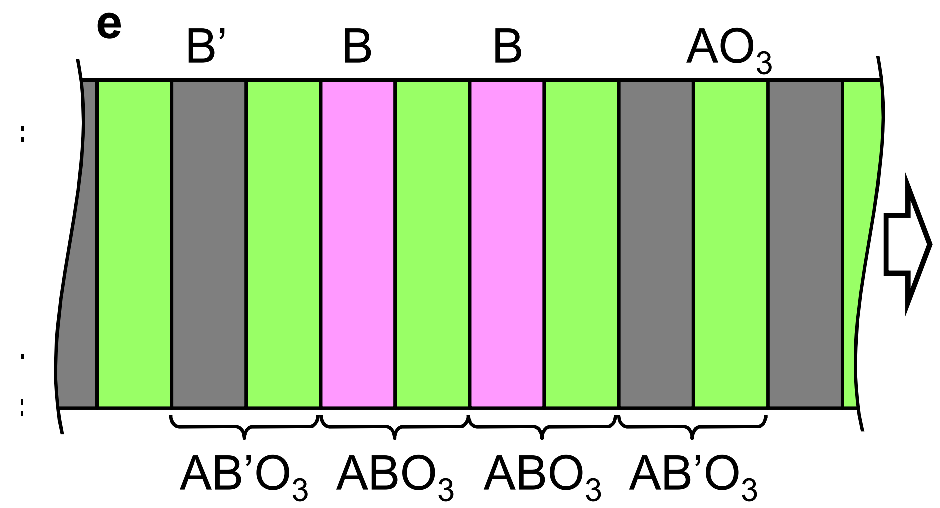
This gap is robust against inversion symmetry breaking, closes if the Jahn-Teller effect is strong

Materials Consideration



Materials Consideration

A=La^{3+}, Sr^{2+}
$LaBO_3$ → B^{3+}
$SrBO_3$ → B^{4+}



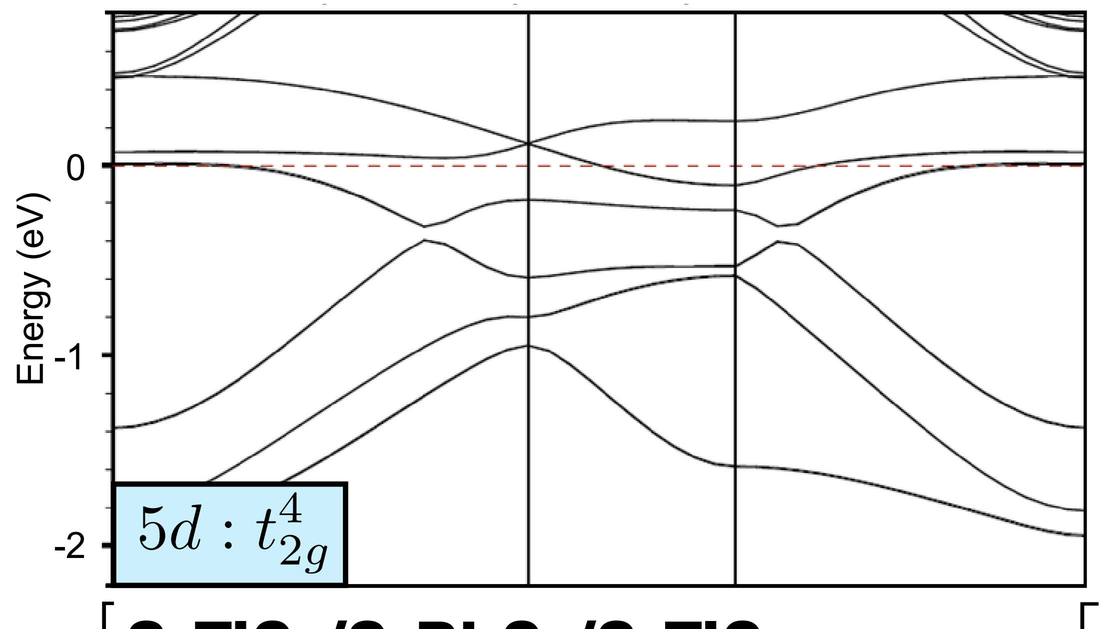
$AB'O_3$: $LaAlO_3$ and $SrTiO_3$

TABLE SI: List of candidate materials

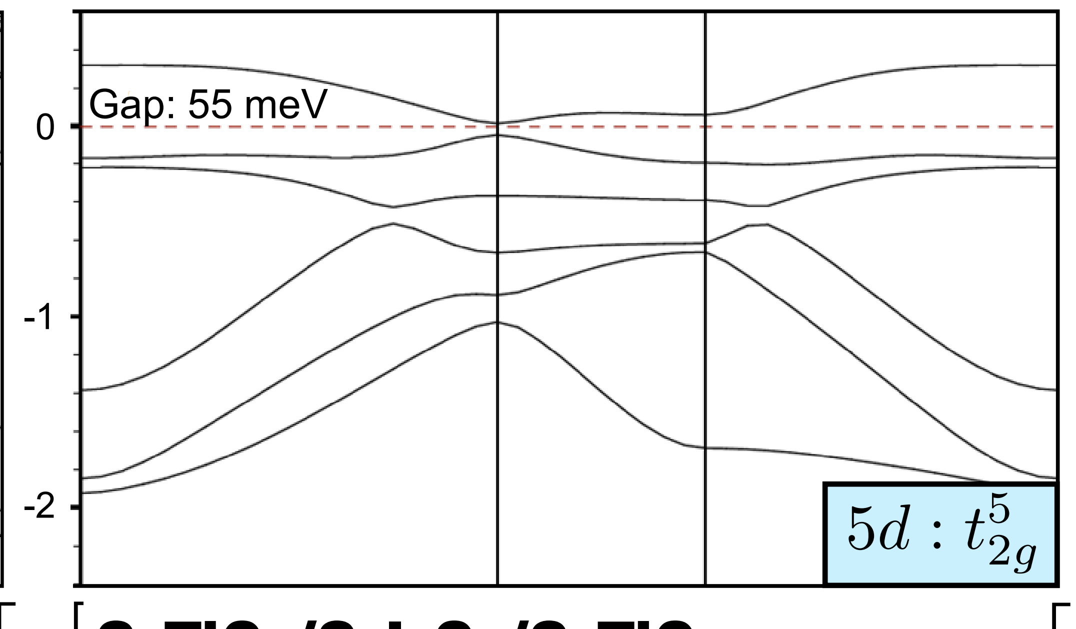
	Configuration	Bulk	Superlattice
$LaReO_3$	t_{2g}^4	—	—
$LaRuO_3$	t_{2g}^5	metallic Ref. [2]	—
$SrRhO_3$	t_{2g}^5	metallic Ref. [3]	Ref. [4]
$SrIrO_3$	t_{2g}^5	metallic Refs. [5, 6]	metallic Ref. [7]
$LaOsO_3$	t_{2g}^5	—	—
$LaAgO_3$	e_g^2	metallic (band calc.) Ref. [8]	—
$LaAuO_3$	e_g^2	Refs. [9, 10]	—

t_{2g} Systems

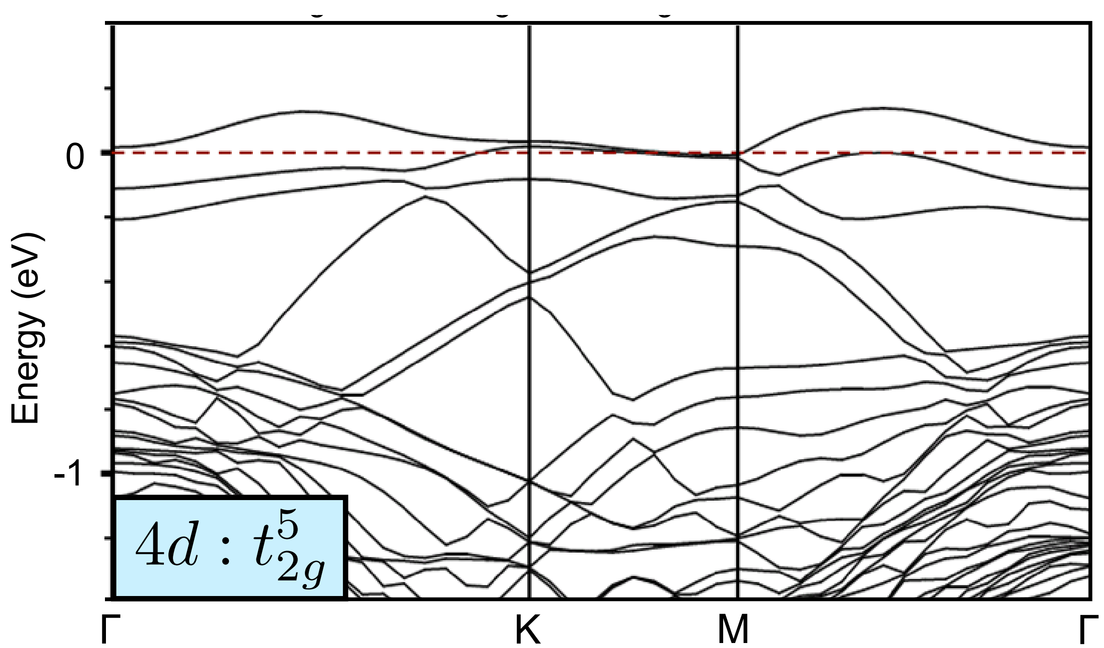
$LaAlO_3/LaReO_3/LaAlO_3$



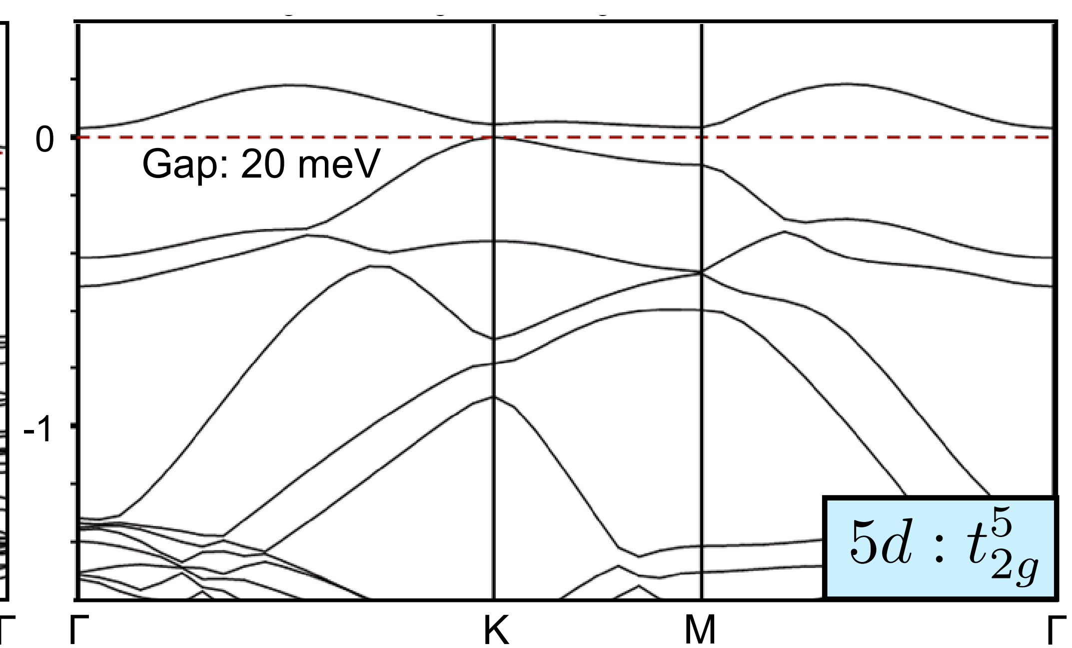
$LaAlO_3/LaOsO_3/LaAlO_3$



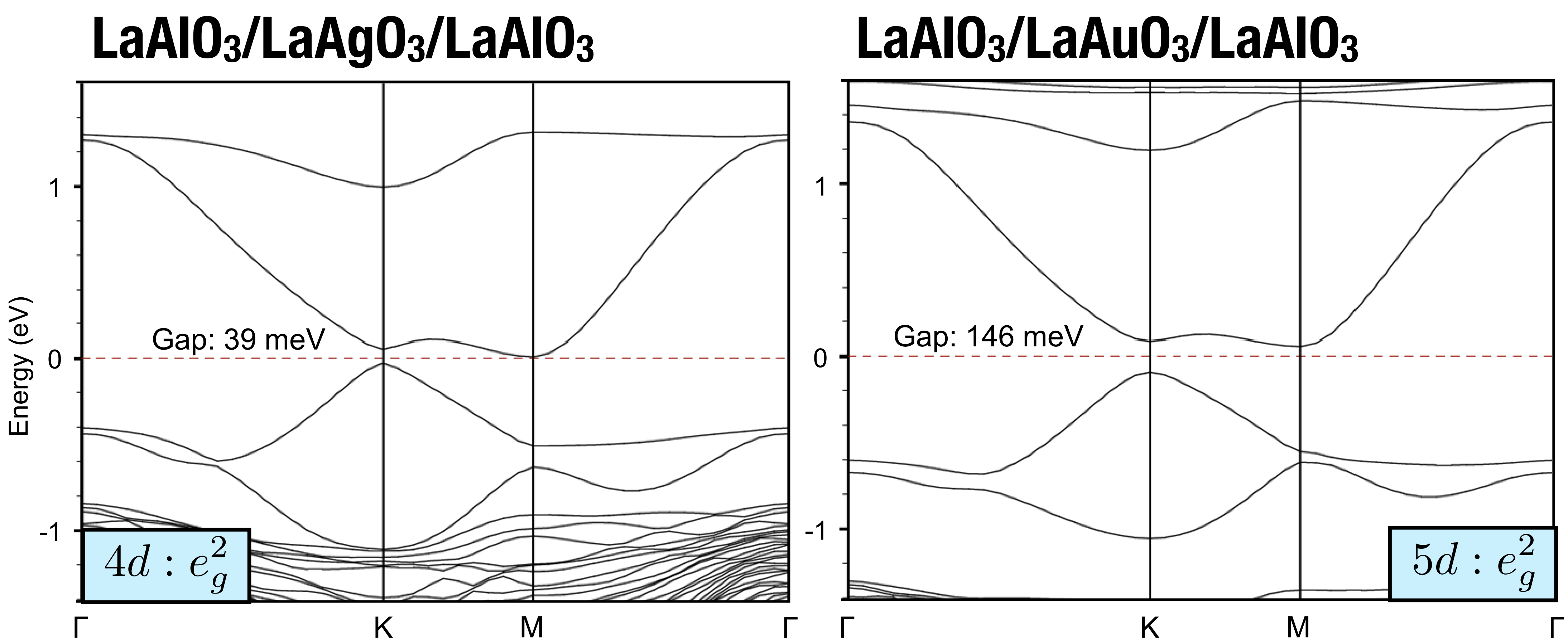
$SrTiO_3/SrRhO_3/SrTiO_3$



$SrTiO_3/SrIrO_3/SrTiO_3$



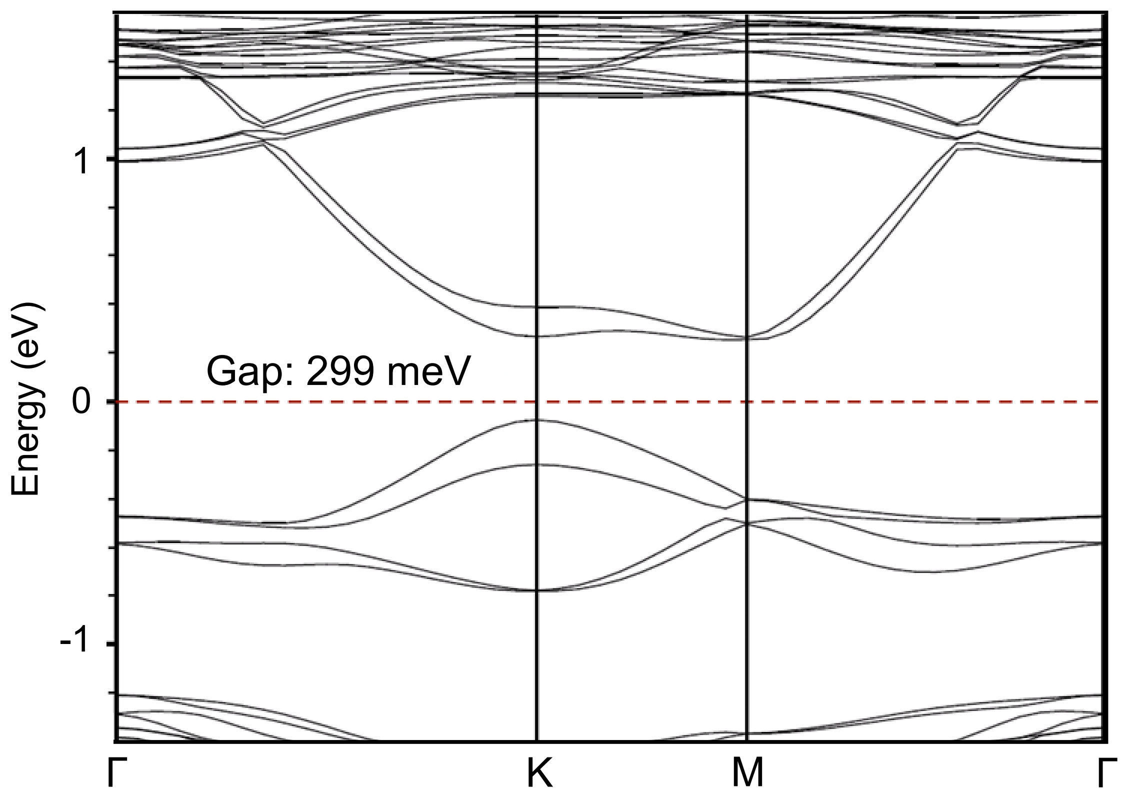
e_g Systems



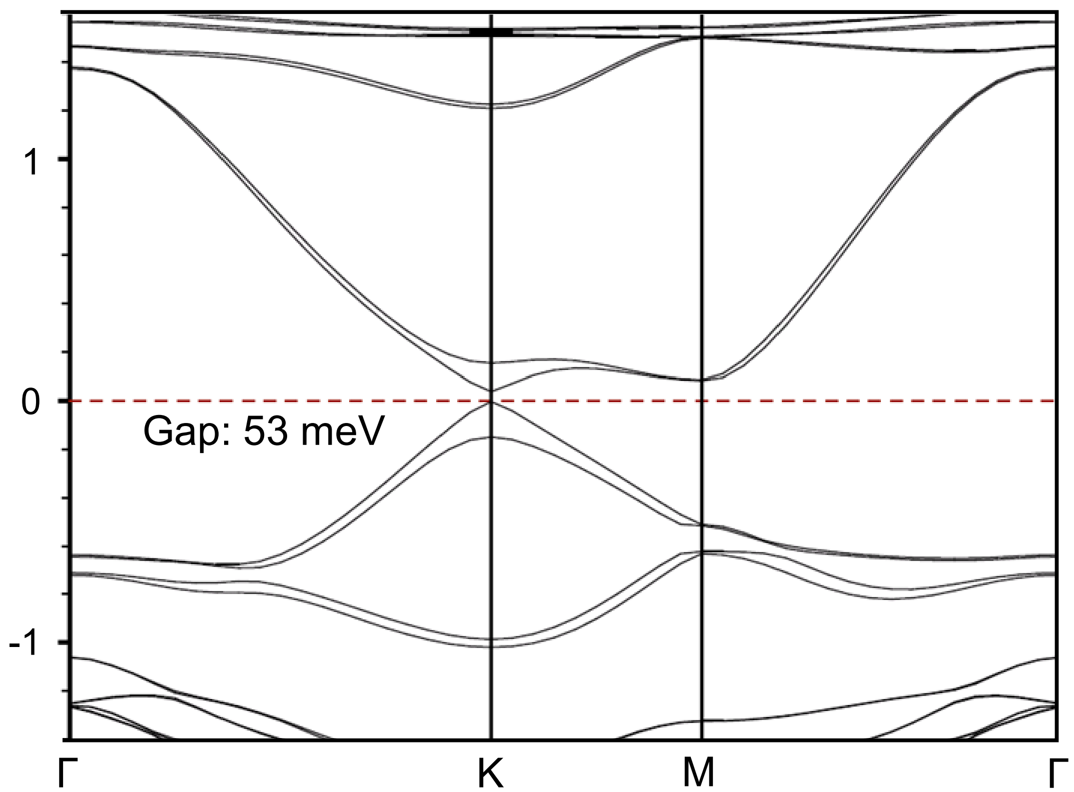
$LaAuO_3$ bilayer has an energy gap ~ 2000 K

Asymmetric Substrates

$LaAlO_3/LaAuO_3/LaScO_3$



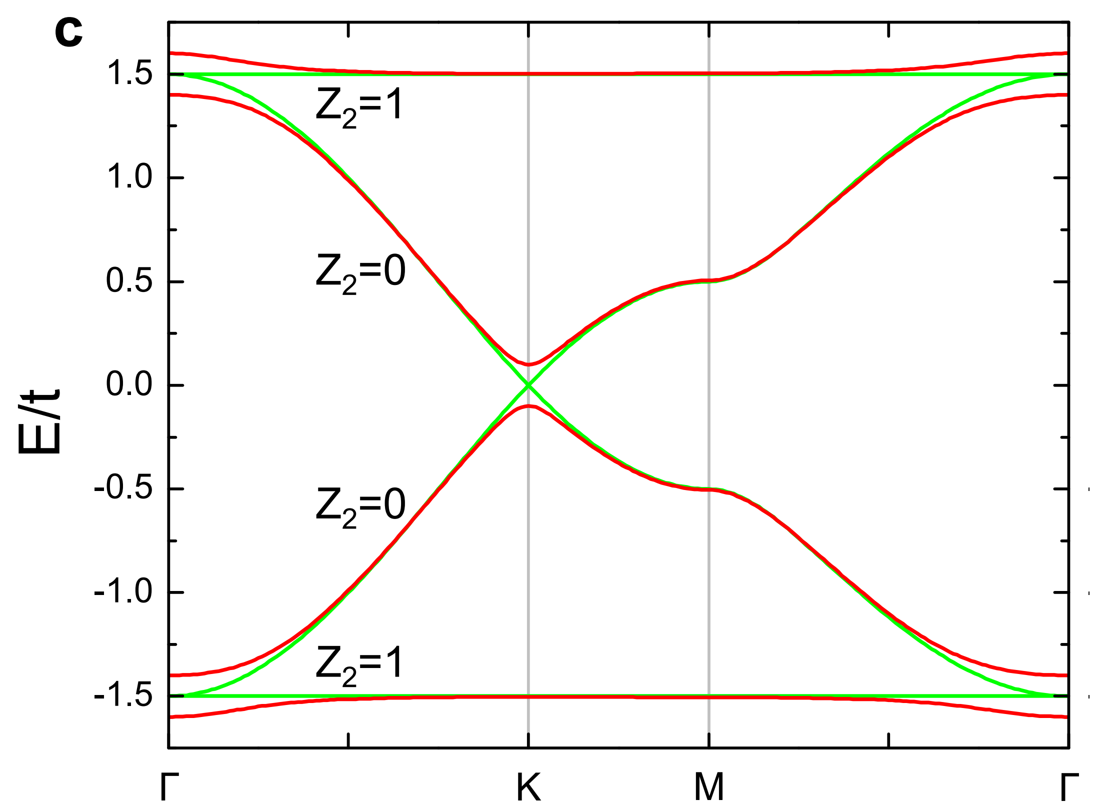
$LaAlO_3/LaAuO_3/YAlO_3$



Trivial insulator

Topological insulator

Physics inside Flat Z_2 Bands



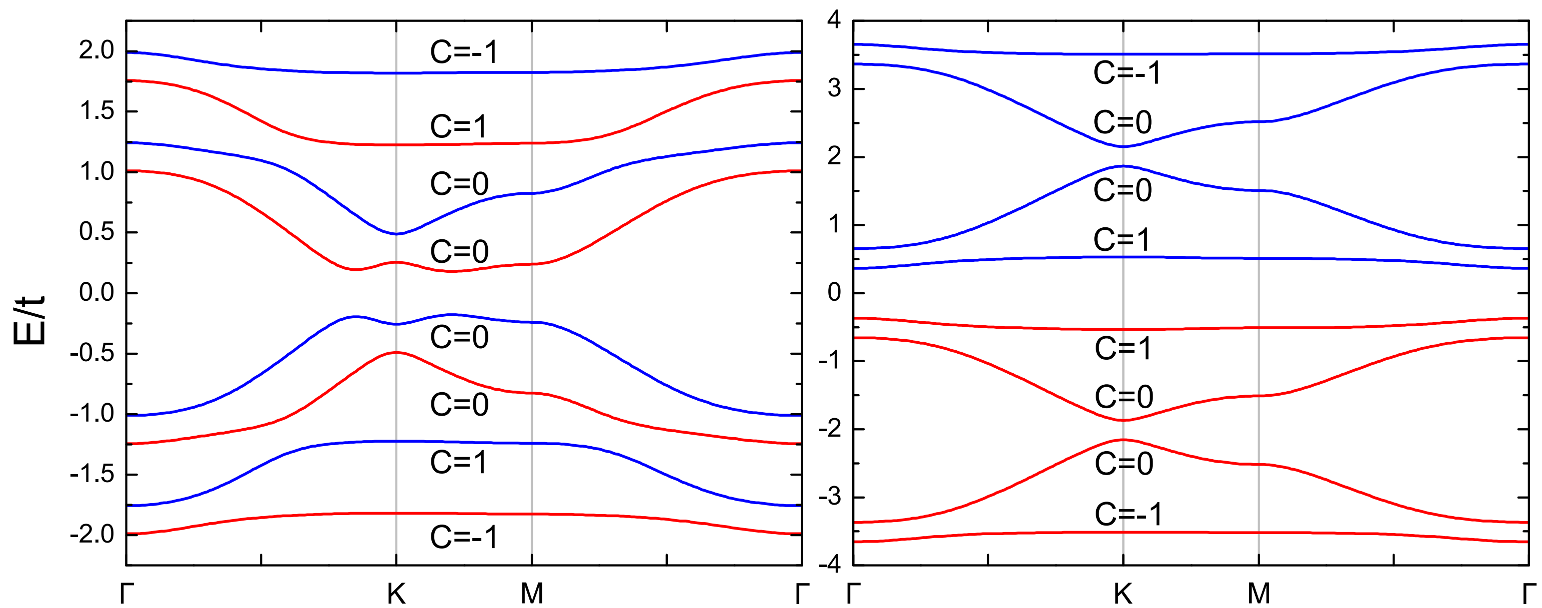
Integer Quantum Hall Effect

How to break time-reversal symmetry?

- External: Ferromagnetic or G-type antiferromagnetic substrate
- Internal: Stoner instability (U/Bandwidth>>1)

Mean field Hamiltonian $H = H_{eg} + \vec{h} \cdot \vec{\sigma}$

$e_g^{0.5}, e_g^{3.5}$



e_g^1

Small h   Large h

Fractional Quantum Hall Effect

$$H = H_{eg} + h\sigma_z + H_I$$

$$H_I = U \sum_{i,\alpha} n_{i\alpha\uparrow} n_{i\alpha\downarrow} + U' \sum_{i,\alpha>\beta} n_{i\alpha} n_{i\beta} + V_{\langle ij \rangle} n_i n_j$$

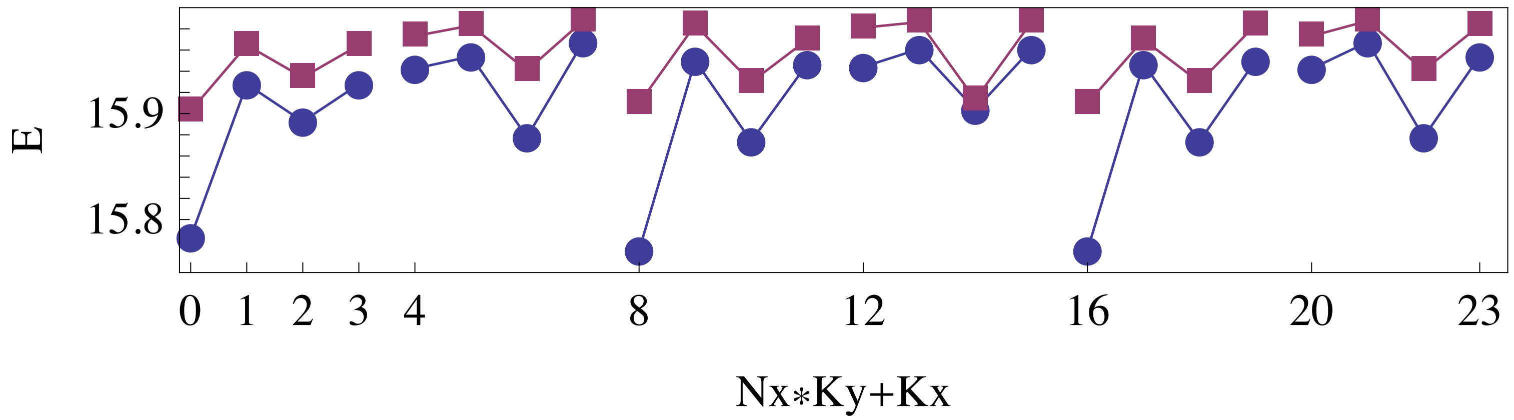
U: Onsite intra-orbital repulsion
U': On-site inter-orbital repulsion
V: Nearest-neighbor repulsion

$$U = U' = t, V = 0.5t$$

What is the Hall conductance for a 1/3 filled nearly flat band

Fractional Quantum Hall Effect

- 3-fold degenerate GS



- Chern number

$$\sigma_{xy} = \frac{e^2}{hg} \sum_{K=1}^{g} \int_0^{2\pi} \int_0^{2\pi} d\phi_1 d\phi_2$$

$$\left(\left\langle \frac{\partial \Phi_0}{\partial \phi_1} \middle| \frac{\partial \Phi_0}{\partial \phi_2} \right\rangle - \left\langle \frac{\partial \Phi_0}{\partial \phi_2} \middle| \frac{\partial \Phi_0}{\partial \phi_1} \right\rangle \right)$$

g=3, C_1=0.3344, C_2=0.3311,C_3=0.3344

Other proposals, see Tang et al PRL; Neupert et al PRL; Sun et al PRL, 2011

What is Next?

- Competition between Jahn-Teller effect and TI phase
- Detailed adjustment of the band dispersion
- Complete phase diagram (multi-orbital Kane-Mele-Hubbard model)
- Identification of materials suitable for IQHE and FQHE
- The nature of the FQHE state in the absence of LL

Actually grow the sample

$LaAuO_3$

Summary

- Heterostructures of transition metal oxides provide an exciting platform for topological electronics
- Lots of perovskite (111)-bilayers are possible candidates for topological insulators. In particular, $LaAuO_3$ has a band gap ~ 200meV
- Lots of possibilities for realizing novel quantum phases, such as IQHE and FQHE
- Lots to be done...

Manuscript can be found on arXiv