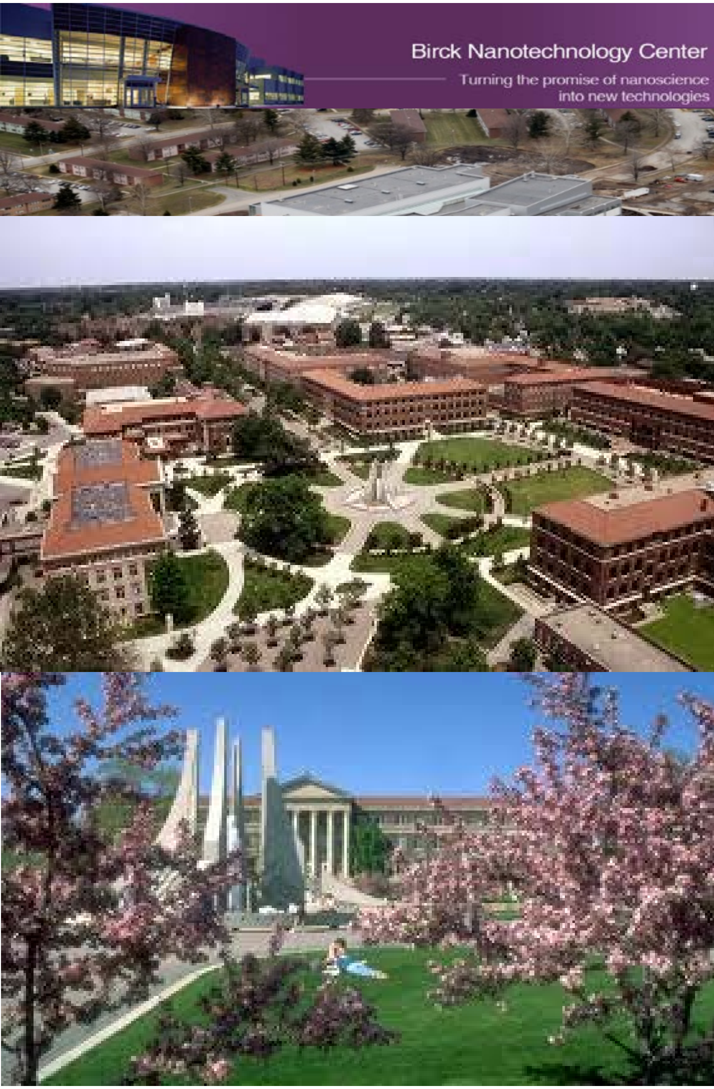


PURDUE QUANTUM CENTER

PQC WORKSHOP 2017

COHERENT EFFECTS IN PHYSICS AND CHEMISTRY

April 28th (Fri), 12-5pm in MRGN 121/MANN

Quantum Coherent Transport in Atoms & Electrons

Yong P. Chen, Quantum Matter and Devices Laboratory

Dept. of Physics and School of Electrical & Computer Engineering,

Birck Nanotechnology Center & Purdue Quantum Center,

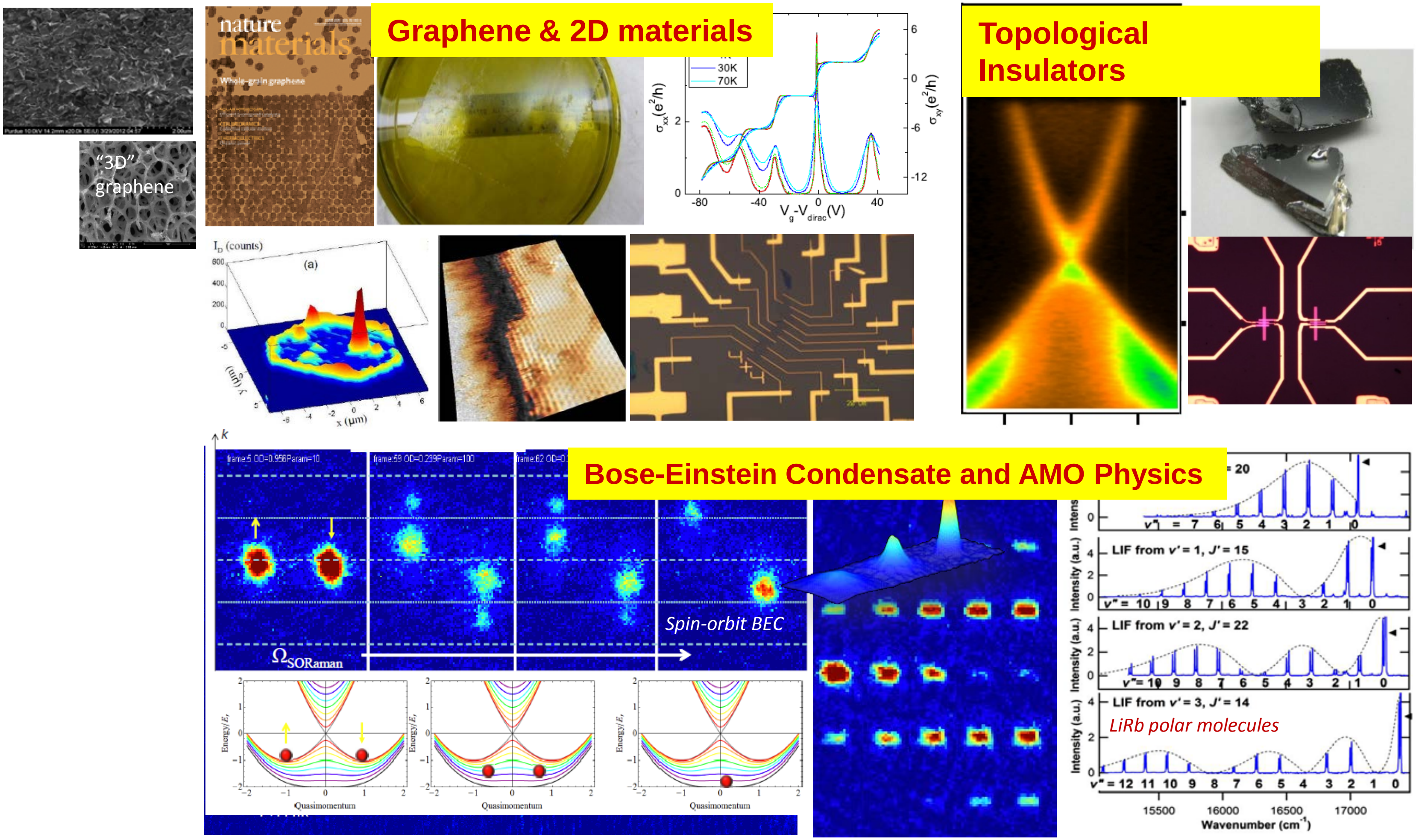
Purdue University, West Lafayette INDIANA 47907 USA

http://www.physics.purdue.edu/quantum

http://engineering.purdue.edu/PQC/

Research in Quantum Matter and Device (QMD) Laboratory

http://www.physics.purdue.edu/quantum *|QMD>=|physics>+|engineering>*



Electrons

Photons

Atoms

molecules

General remark

Two-path interference

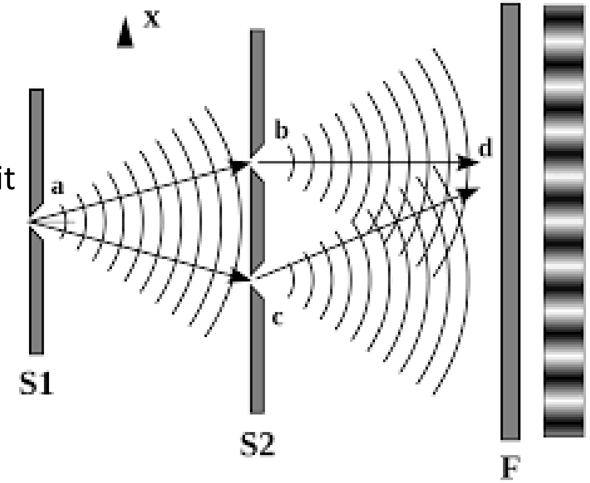
"Path" can be in

- Real (r) –space
- Momentum (k) – space
- More abstract/complicated "configuration"/Hilbert space….
  [sometimes related to "topology"]

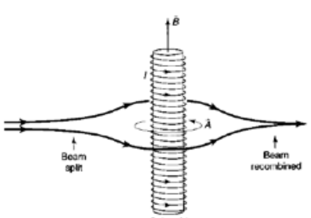
"Wave" can be

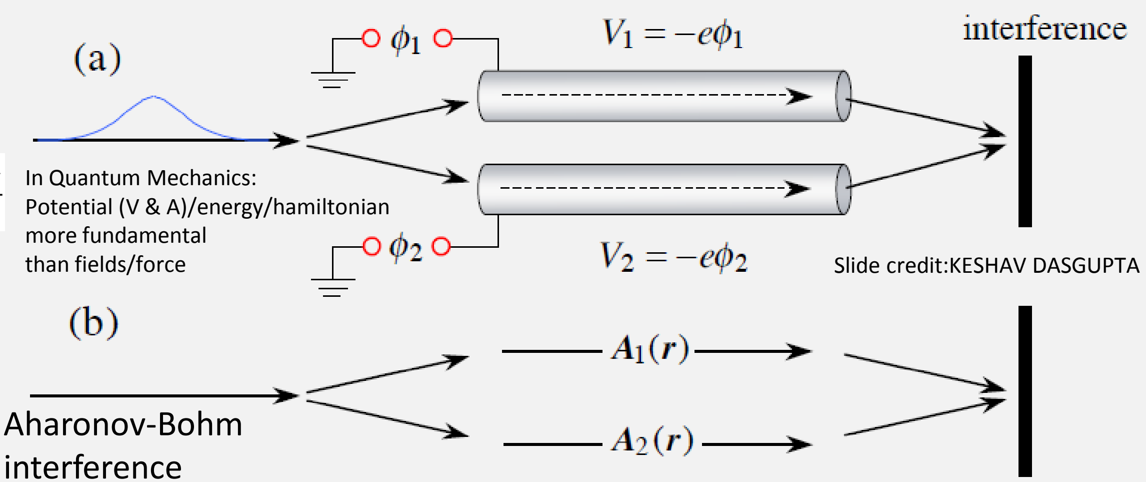
- Light (classical E&M or quantum)
- electrons
- atoms
- other "matter wave" or more complex quantum systems

Young' double-slit interference (optics/light ***wave***)



$$\left[\frac{1}{2m}\left(\frac{\hbar}{i}\nabla - q\mathbf{A}\right)^2 + V\right]\Psi = i\hbar\frac{\partial\Psi}{\partial t}$$

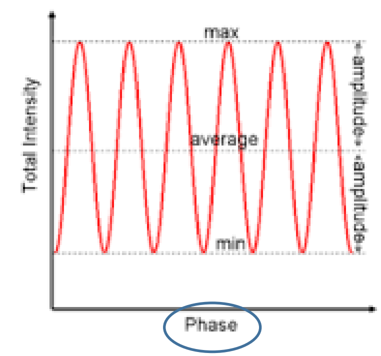




In Quantum Mechanics:
Potential (V & A)/energy/hamiltonian
more fundamental
than fields/force

Aharonov-Bohm interference

Slide credit:KESHAV DASGUPTA



Outline

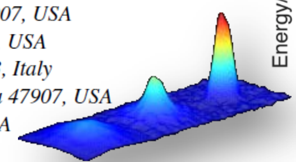
- **Quantum Coherent Transport of Atoms (cold atom BEC): A Spin-resolved Atom Interferometer (Stuckelberg Interference)**

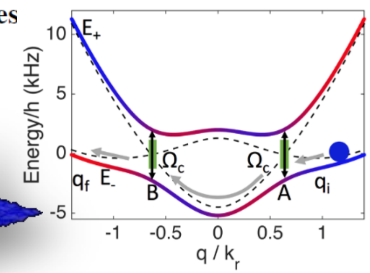
PHYSICAL REVIEW A **95**, 043623 (2017)

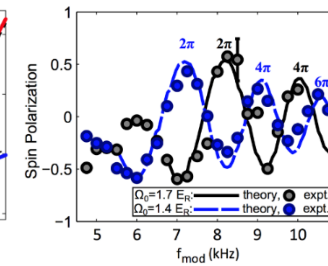
Stueckelberg interferometry using periodically driven spin-orbit-coupled Bose-Einstein condensates

Abraham J. Olson,[1] David B. Blasing,[1] Chunlei Qu,[2,3] Chuan-Hsun Li,[4] Robert J. Niffenegger,[1] Chuanwei Zhang,[2] and Yong P. Chen[1,4,5,*]

[1] *Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA*
[2] *Department of Physics, The University of Texas at Dallas, Richardson, Texas 75080, USA*
[3] *INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, Povo 38123, Italy*
[4] *School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907, USA*
[5] *Purdue Quantum Center, Purdue University, West Lafayette, Indiana 47907, USA*







$ ARO-DURIP, NSF-GRF, Purdue OVPR

- **Quantum Coherent Transport of Electrons (spin-helical Dirac fermions on topological insulators): a "half-integer" Aharonov-Bohm Effect (electronic interferometer)**

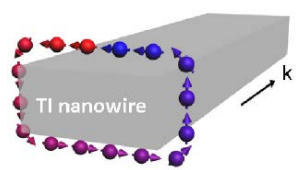
nature nanotechnology

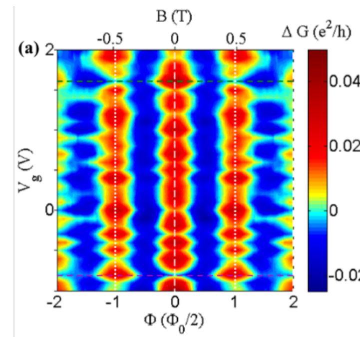
ARTICLES

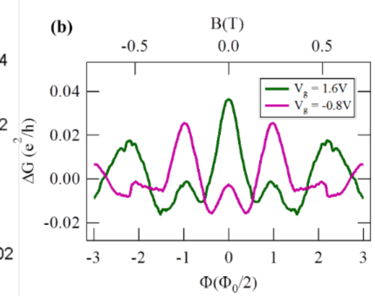
PUBLISHED ONLINE: 18 JANUARY 2016 | DOI: 10.1038/NNANO.2015.293

Magnetic field-induced helical mode and topological transitions in a topological insulator nanoribbon

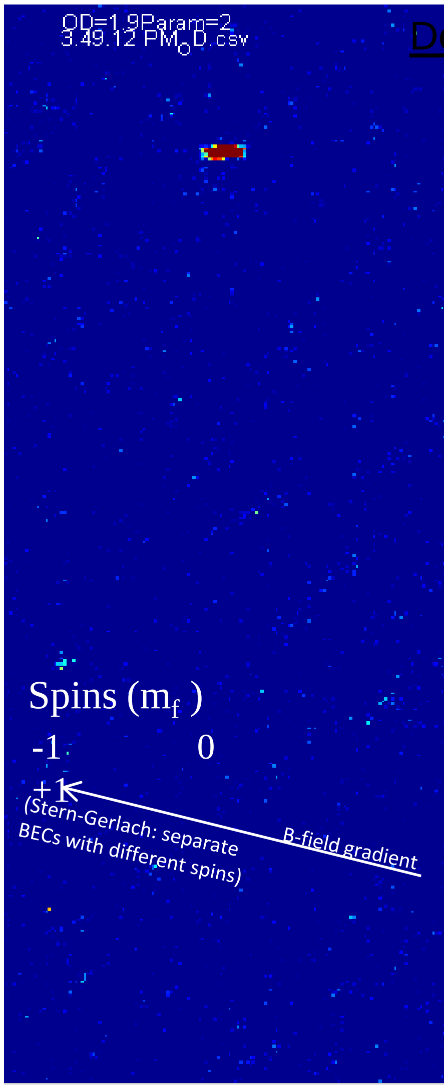
Luis A. Jauregui[1,2], Michael T. Pettes[3†], Leonid P. Rokhinson[1,2,4], Li Shi[3,5] and Yong P. Chen[1,2,4*]



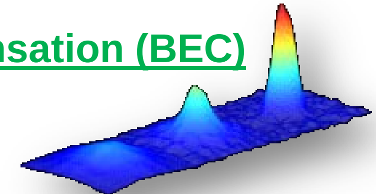




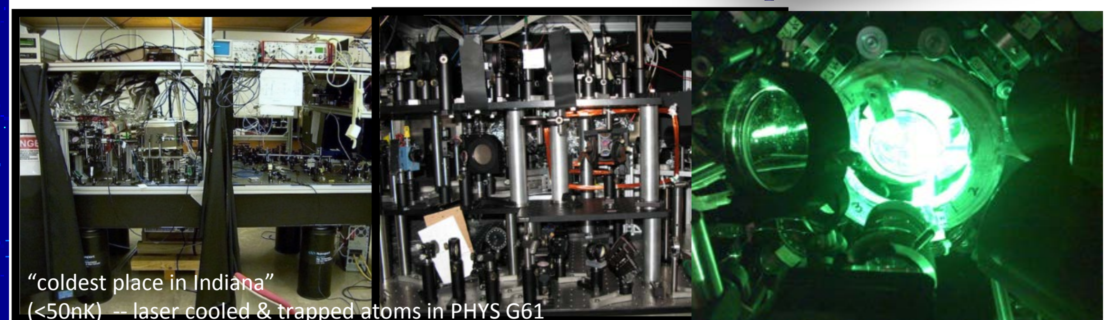
cold atoms/BEC --- "seeing" quantum mechanics & dynamics!
("slowed down" and "blown up" so much that you can shoot photos & videos!)

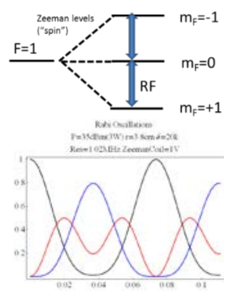


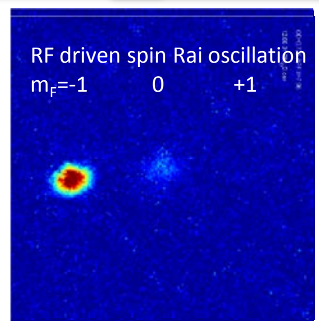
Demo with our Bose-Einstein Condensation (BEC)



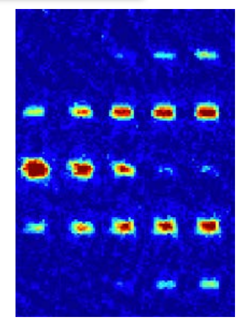
Purdue QMD's "all-optical" Rb87 BEC apparatus
With synthetic gauge fields and spin-orbit coupling







coherent oscillation of BEC between 3 spin states



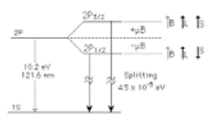
BEC (matter wave) diffraction from laser standing wave (optical grating)

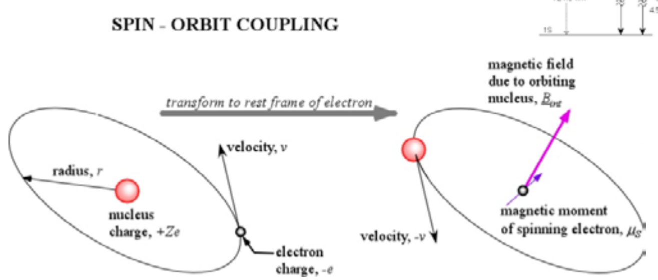
How to create an atomic beam splitter -- a trick: “Spin Orbit Coupling” (SOC)

Review of electronic SOC:

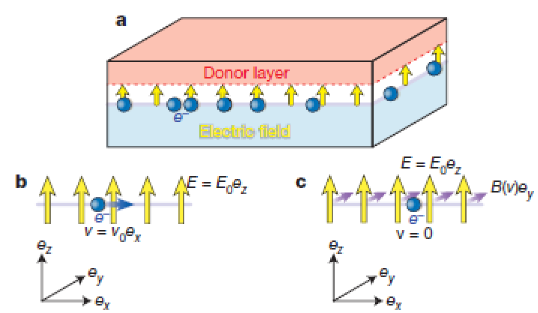
a relativistic effect --- moving E-field acts as B-field: $\vec{B}_{SO} \sim \left(\frac{h}{mc^2}\right) \vec{v} \times \vec{E}$

Atomic Fine Structure

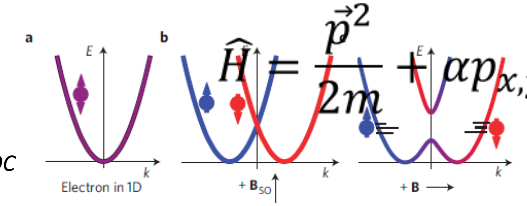




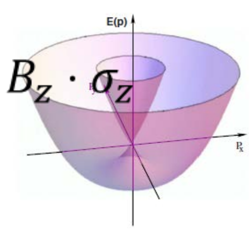
Inversion Symmetry Breaking



Can simulate these (solid state & beyond) SOC with neutral atoms



$$\hat{H} = \frac{\vec{p}^2}{2m} + \alpha p_{x,y} \cdot \sigma_{x,y} + B_z \cdot \sigma_z$$



(2D Rashba SO)

REVIEW

doi:10.1038/nature11841

Spin–orbit coupling in quantum gases

Victor Galitski[1,2] & Ian B. Spielman[1]

Spin–orbit coupling links a particle's velocity to its quantum-mechanical spin, and is essential in numerous condensed matter phenomena, including topological insulators and Majorana fermions. In solid-state materials, spin–orbit coupling originates from the movement of electrons in a crystal's intrinsic electric field, which is uniquely prescribed in any given material. In contrast, for ultracold atomic systems, the engineered 'material parameters' are tunable: a variety of synthetic spin–orbit couplings can be engineered on demand using laser fields. Here we outline the current experimental and theoretical status of spin–orbit coupling in ultracold atomic systems, discussing unique features that enable physics impossible in any other known setting.

REVIEWS OF MODERN PHYSICS, VOLUME 83, OCTOBER–DECEMBER 2011

Colloquium: Artificial gauge potentials for neutral atoms

Jean Dalibard* and Fabrice Gerbier†

Laboratoire Kastler Brossel, CNRS, UPMC, Ecole normale supérieure, 24 rue Lhomond, 75005, Paris, France

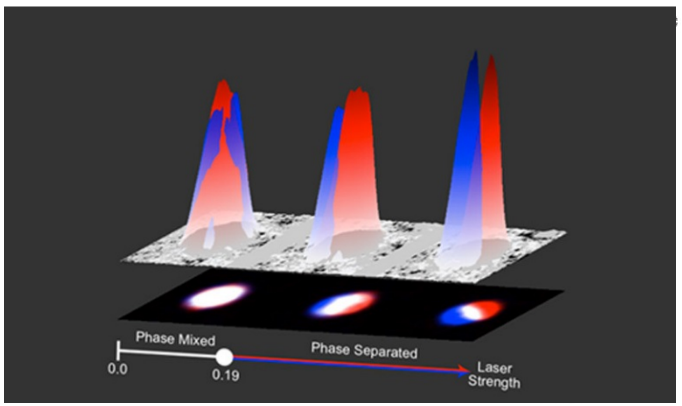
Gediminas Juzeliūnas‡

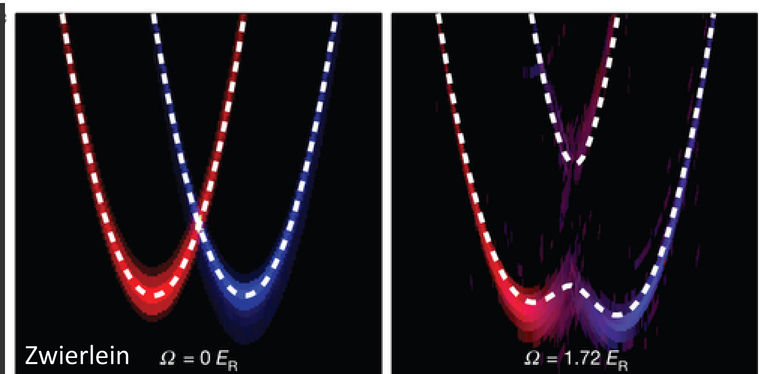
Institute of Theoretical Physics and Astronomy, Vilnius University, A. Goštauto 12, Vilnius 01108, Lithuania

Patrik Öhberg§

SUPA, Department of Physics, Heriot-Watt University, Edinburgh, EH14 4AS, United Kingdom

(published 30 November 2011)





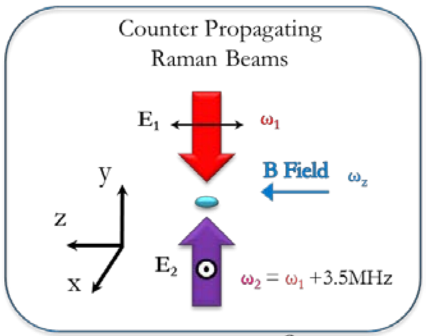
(**spin-orbit BEC – I.Spielman/NIST**)
[also USTC, SXU, WSU, Purdue, ..]

(**spin-orbit fermi gas**)
[MIT, SXU, NIST, ..]

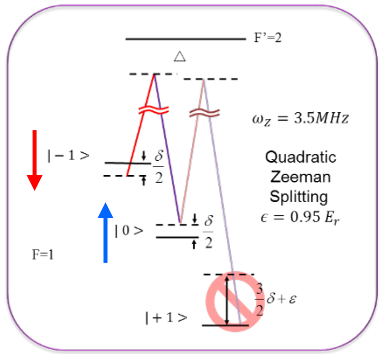
See also reviews by: H. Zhai'11; Y. Li-G.Martone-S.Stringari'14, J.Zhang'14 etc.

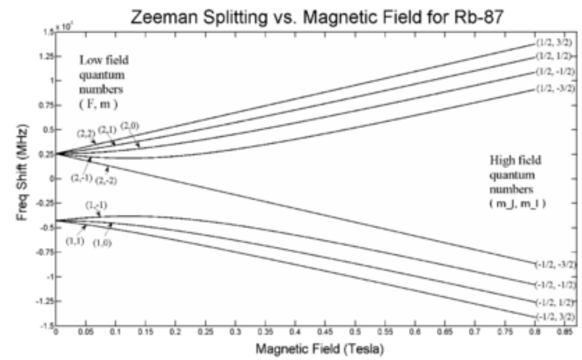
Note: there are several other ways to generate SOC and gauge fields (e.g., modulation..)

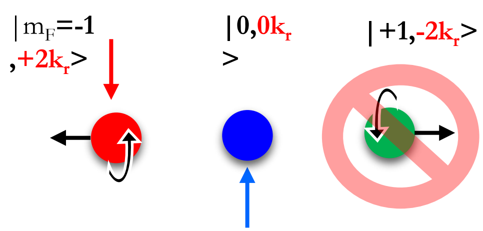
Synthetic Spin Orbit Coupling (SOC) by Raman



$k_r = \frac{2\pi}{\lambda}$

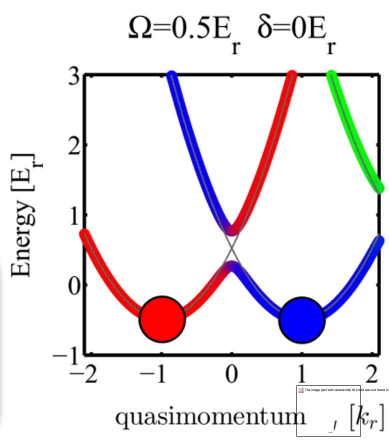






$$H = \frac{\hbar}{2m}(\vec{p} - q\vec{A})^2 \Rightarrow \tilde{k}_{y,\min} = \frac{qA_y}{\hbar}$$

$$\frac{\partial \vec{A}_y(t)}{\partial t} = \vec{E}_y \qquad \frac{\partial \vec{A}_y(x)}{\partial x} = \vec{B}_z$$



Dressed bandstructure

$$\tilde{H} = \begin{pmatrix} \frac{\hbar^2}{2m}(p_y + k_r)^2 + \frac{\delta}{2} \\ \frac{\Omega}{2} \end{pmatrix}$$

control knobs

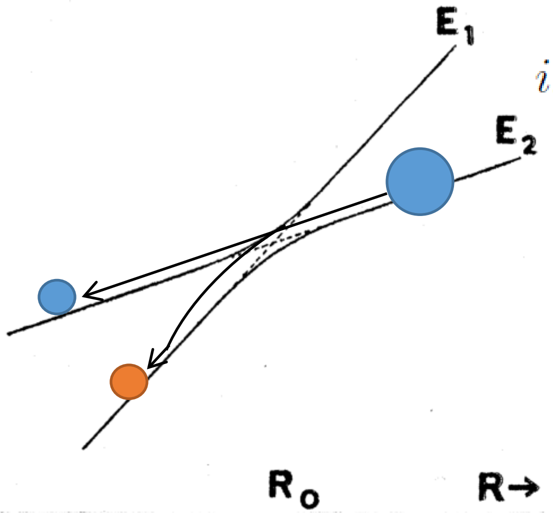
SOC "fictitious" B field

$$= \frac{\hbar^2 k_r^2}{2m} I + \frac{\hbar^2}{2m} p_y^2 I + \frac{\hbar^2}{}$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},$$

Landau-Zener Transitions: a quantum crossroad "beam splitter"

$$i\hbar\frac{\partial}{\partial t}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} = \begin{pmatrix}E_1(R,t) & \Omega/2\\ \Omega/2 & E_2(R,t)\end{pmatrix}$$



—Crossing of energy levels in idealised problem.
Full lines are adiabatic eigenwerte.

$$P_{LZ} = \frac{N_{dia}}{N_{dia} + N_{ad}}$$

$$P_{LZ} = \exp\left[-2\pi\frac{(\Omega/2)^2}{\hbar v\beta}\right]$$

$$v = \frac{dR}{dt}$$

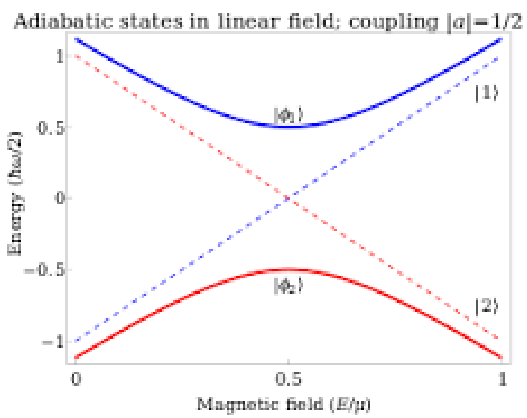
$$\beta = [\partial E_1(x)/\partial x - \partial E_2(x)/\partial x]_{x=x_c}$$

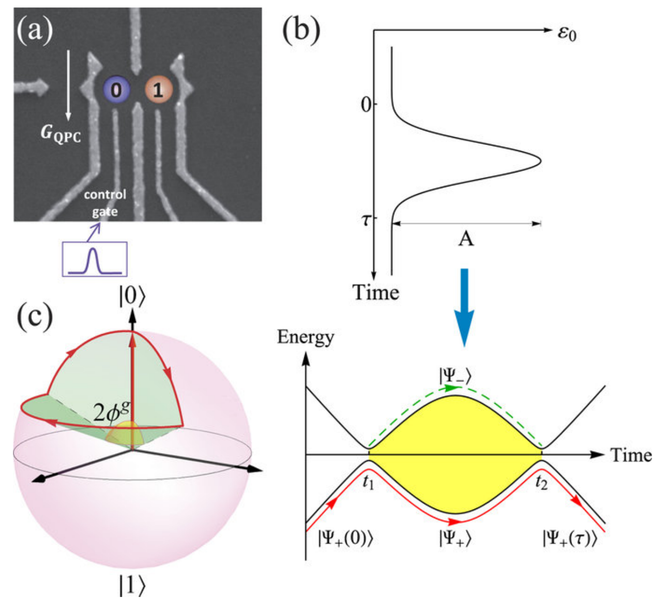
$\Omega/2$ = coupling between diabatic states

$$\beta = [\partial E_1(R)/\partial R - \partial E_2(R)/\partial R]_{R_c}$$

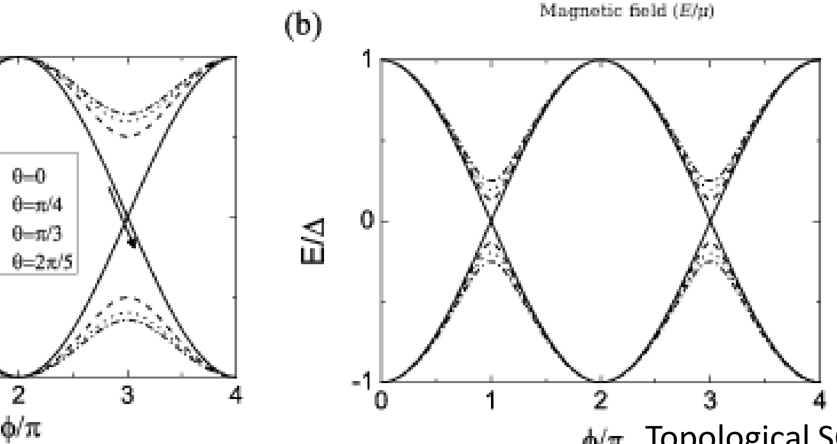
Importance of Landau-Zener

Quantum dynamics,
Quantum state control/transfer/measurement…



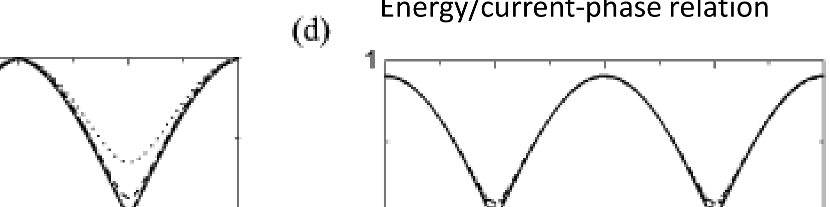


Guo et al'15



Topological SC

Energy/current-phase relation



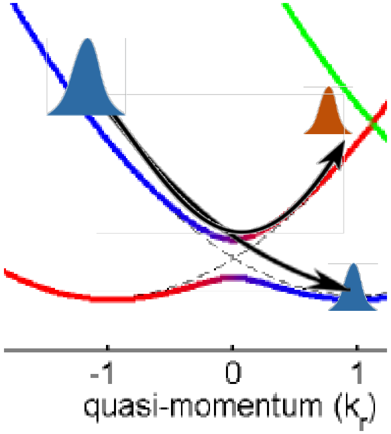
LZ transition for a SO coupled BEC

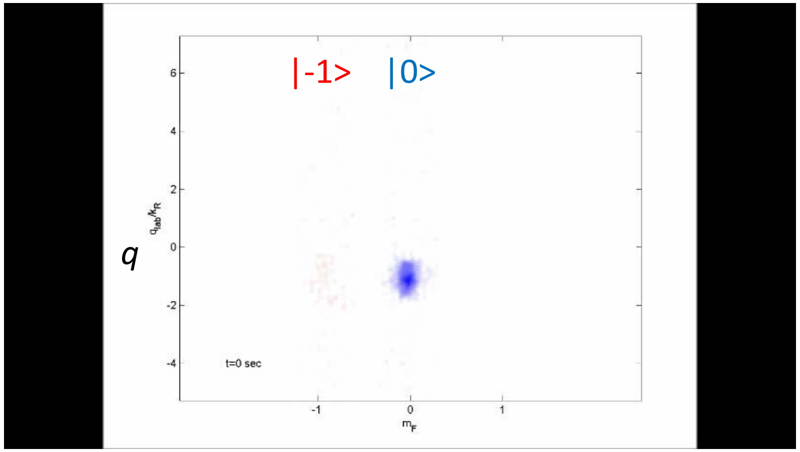
$$P_{LZ} = \frac{N_{dia}}{N_{dia} + N_{ad}} = \exp\left[-2\pi \frac{(\Omega/2)^2}{\hbar v \beta}\right]$$

$v \equiv \frac{dq}{dt}$

$\beta \equiv$ difference in slopes of $E_{dia}(q)$

$\Omega/2 \equiv$ Raman coupling

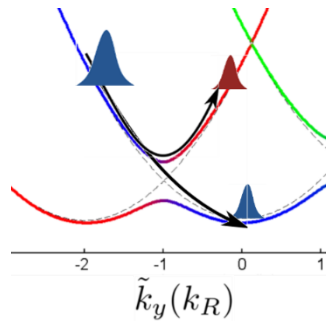


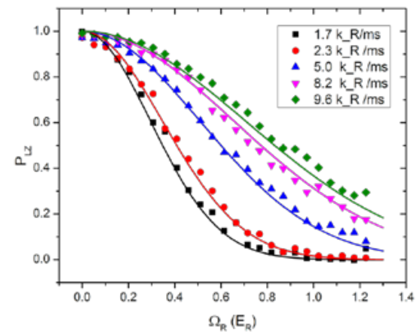


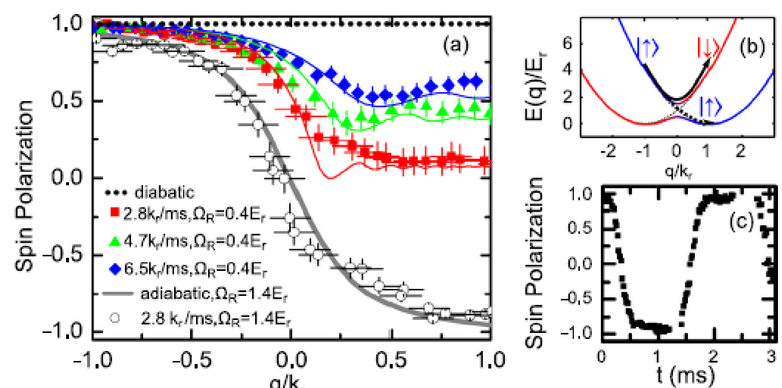
Tunable Landau-Zener Transition (between SOC dressed bands)

- Landau-Zener model
  Varied **<u>all three parameters</u>**
- acceleration in SO gauge fields by gravity or trapping potential
- Spin dependent "atomtronic" transistor
- Non-adiabatic breakdown of spin-momentum locking in SOC BEC
- (spin-dependent) atomi ***beam splitter*** *(in momentum space)*

$$P_{LZ} = \exp\left[-2\pi\frac{(\Omega/2)^2}{\hbar v \beta}\right]$$

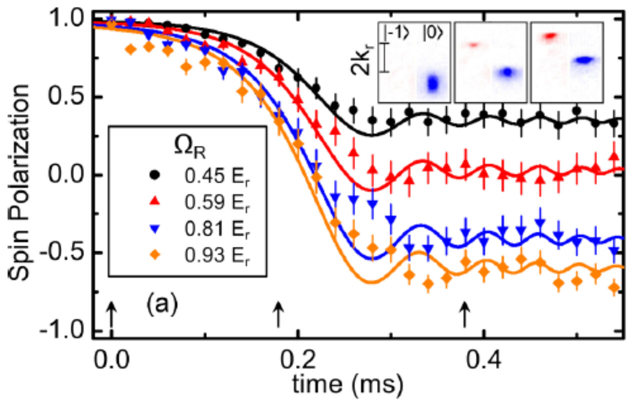


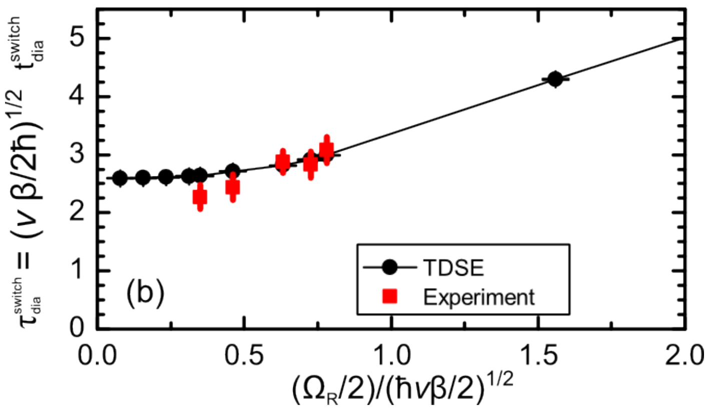




Abraham J. Olson, et al, Phys.Rev. A 90, 013616 (2014) [theory: C. Greene]

Time-dependent LZ measurements

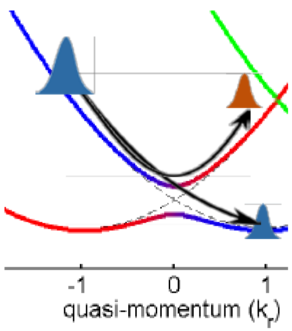




$$dq/dt = 5.0k_r/\mathrm{ms}$$

$$\beta = 4E_R/k_r$$

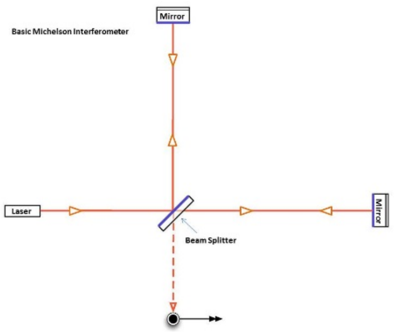
Adiabatic limit ~2.5 agrees with
N.V. Vitanov, Phys. Rev. A (1999)



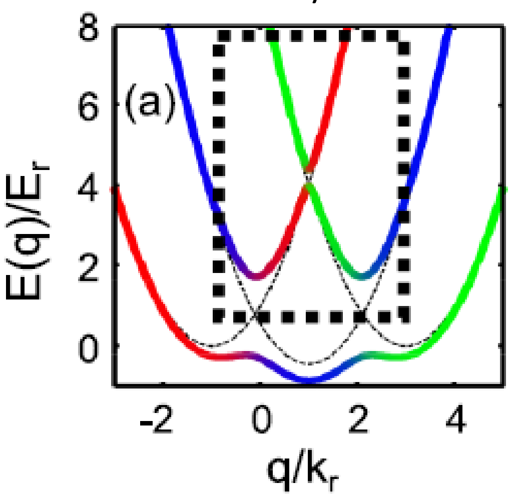
t-dependent Schrodinger equation in k space (S.Wang & C. Greene)

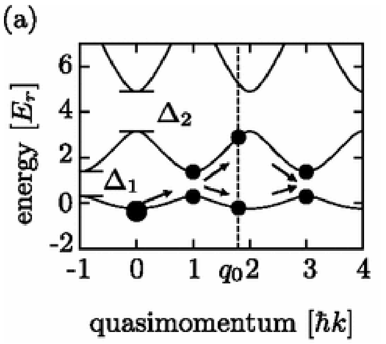
$$i\hbar\partial_t\Psi(q,t) = \hat{H}\Psi(q,t) = \left[-\frac{1}{2}m\omega^2\frac{\partial^2}{\partial q^2} + \begin{pmatrix} \frac{\hbar^2}{2m}(q+k_R)^2 - \delta/2 & \Omega_R/2 \\ \Omega_R/2 & \frac{\hbar^2}{2m}(q-k_R)^2 + \delta/2 \end{pmatrix} \right]\Psi(q,t),$$

Landau-Zener beamsplitter twice: Stuckelberg Interference



"leaky" interferometer!

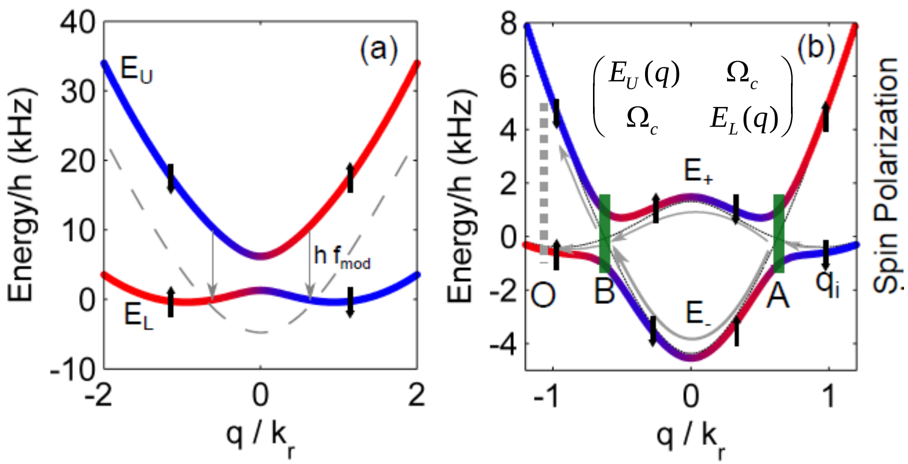




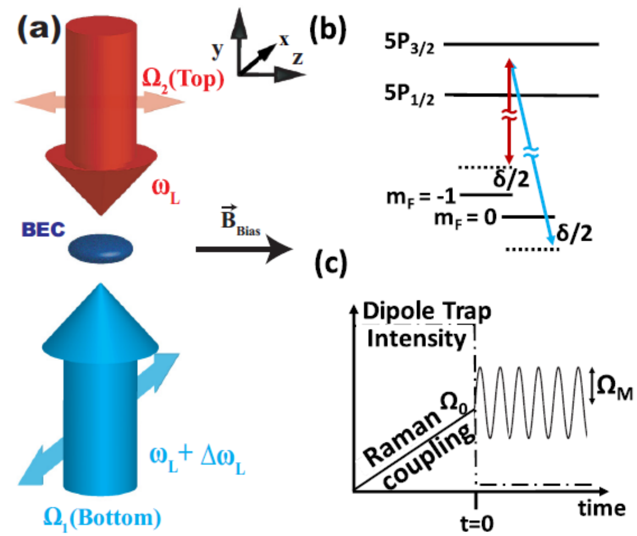
Optical lattice (Weitz'10)

Stueckelberg interference and engineering an atom-interferometer with light-induced synthetic gauge fields

Abraham J. Olson* and , *et al.*

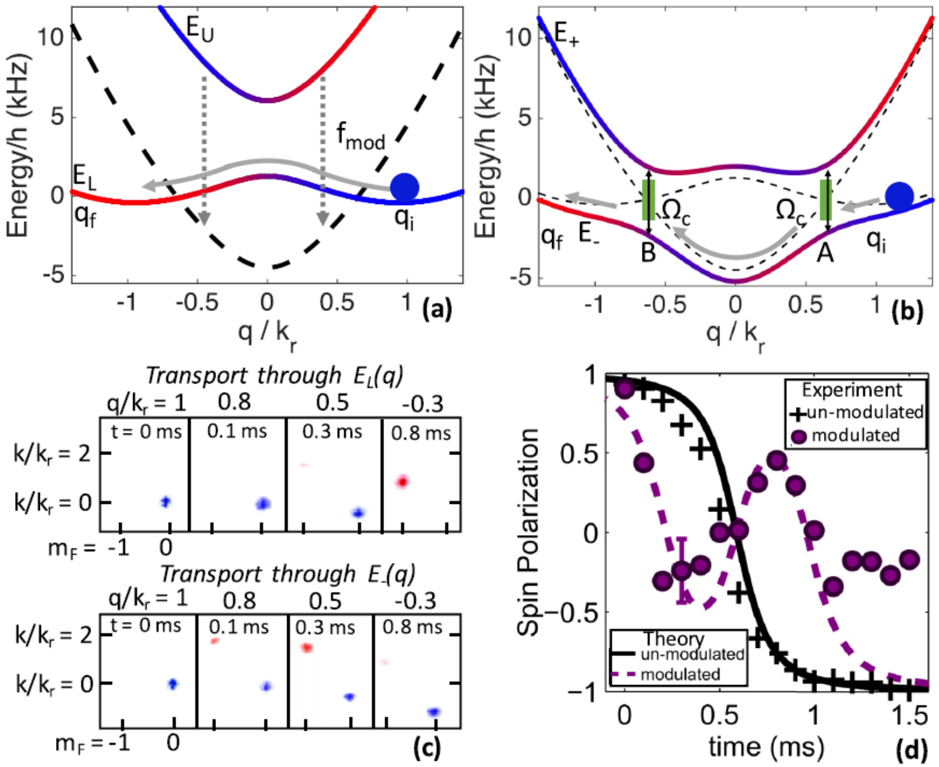


$$\Omega_R(t) = \Omega_0 + \Omega_M cos(2\pi f_{mod} t)$$

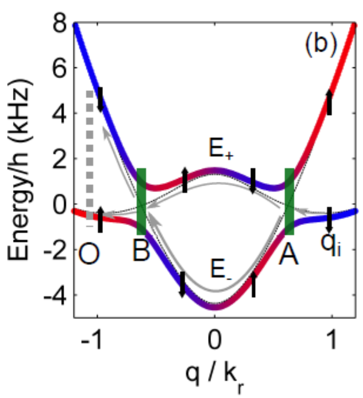


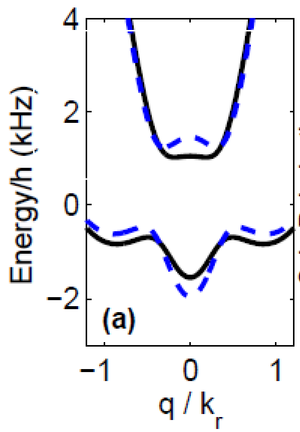
- Modulate Raman beam intensity → induce inter-dressed band coupling
  → "dressing" dressed band → create "2nd generation" synthetic SOC/dressed bands
- Creates 2 atomic beam splitters in k space
- Stuckelberg Atom interferometer
  (oscillation of spin output)

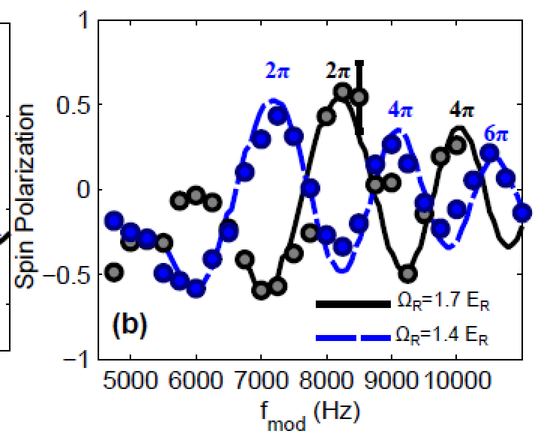
A new-spin-momentum texture!



Observation of Stueckelberg interference in dressed bands: oscillating spin polarization





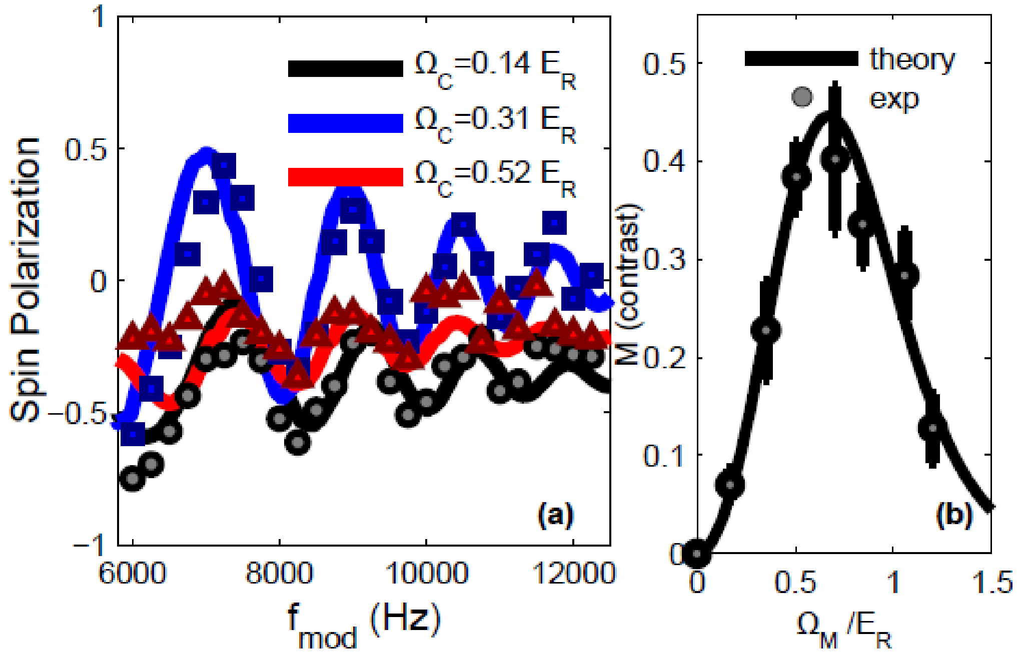


$$\Phi(\alpha) = \int_{q_A}^{q_B} [E_+(q) - E_-(q)] dq/(\hbar\alpha).$$

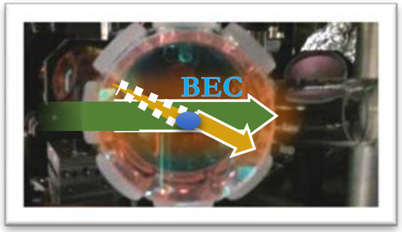
$$\mathcal{S}(\alpha) = 4[P_{LZ}(\alpha) - P_{LZ}(\alpha)^2] \cos[\Phi(\alpha)] - [1 - 2P_{LZ}(\alpha)]^2.$$

Compare to previous LZS interference in optical lattice (no spin): Arimondo'09; Weitz'10

‘Fringe’ contrast vs modulation

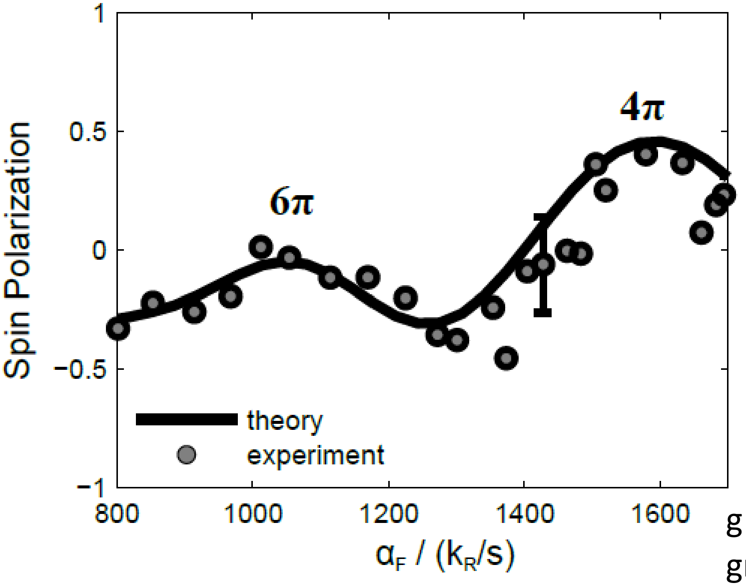


Measuring acceleration (proof of principle)



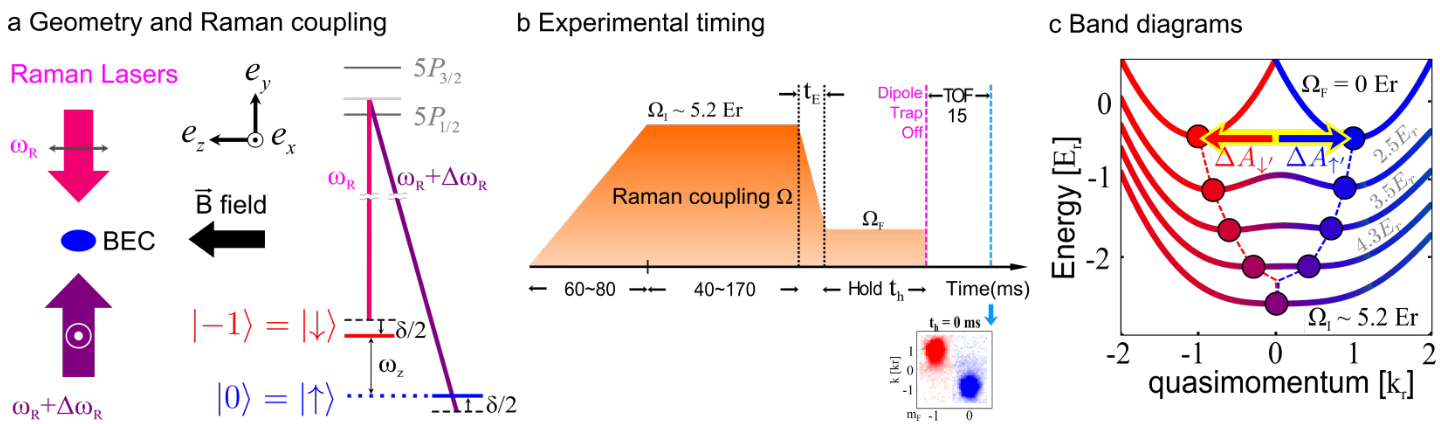
1550nm cross-beam optical trap
(optical tweezer)

A.J. Olson *et al.*, Phys. Rev. A 87, 053613 (2013)



g
gravity

New experiment: quantum quench and coherent atomic spin current

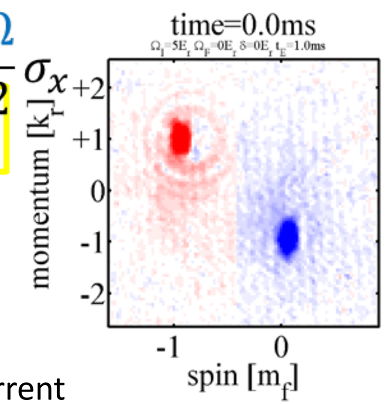


"quantum quench"

$$H = \frac{\hbar^2}{2m} p_y^2 I + \frac{\hbar^2 k_r}{m} p_y \sigma_z + \frac{\Omega}{2}\sigma_x$$

$$E_\sigma = \frac{\delta A_\sigma}{\delta t} \approx \frac{\Delta A_\sigma}{t_E}$$

"Collide 2 spinor BECs in trap"



SDM previous studied in non SOC quantum gases,
eg. fermi gas: Sommer [Zwierlein] et al'11 by magnetic gradient
bosons: Koller et al'12; Maddaloni et al'00
theory (fermi gas): Stringari'99, etc.

Spin Dipole Mode (SDM) --- AC spin current

What is the effect of SOC?

<u>Outline</u>

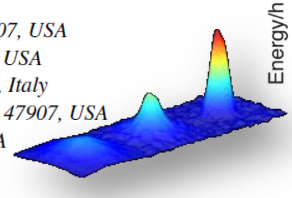
- **Quantum Coherent Transport of Atoms (cold atom BEC): A Spin-resolved Atom Interferometer (Stuckelberg Interference)**

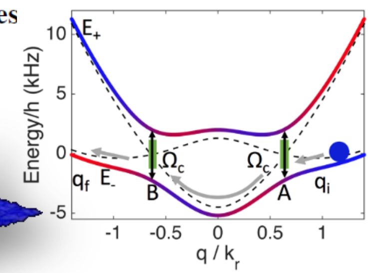
PHYSICAL REVIEW A **95**, 043623 (2017)

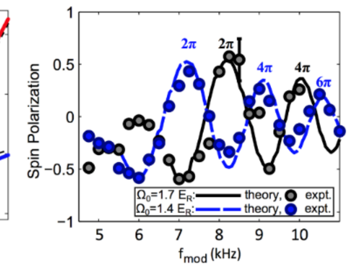
Stueckelberg interferometry using periodically driven spin-orbit-coupled Bose-Einstein condensates

Abraham J. Olson,[1] David B. Blasing,[1] Chunlei Qu,[2,3] Chuan-Hsun Li,[4] Robert J. Niffenegger,[1] Chuanwei Zhang,[2] and Yong P. Chen[1,4,5,*]

[1]*Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA*
[2]*Department of Physics, The University of Texas at Dallas, Richardson, Texas 75080, USA*
[3]*INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, Povo 38123, Italy*
[4]*School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907, USA*
[5]*Purdue Quantum Center, Purdue University, West Lafayette, Indiana 47907, USA*







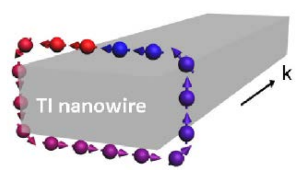
- **Quantum Coherent Transport of Electrons (spin-helical Dirac fermions on topological insulators): a "half-integer" Aharonov-Bohm Effect (electronic interferometer)**

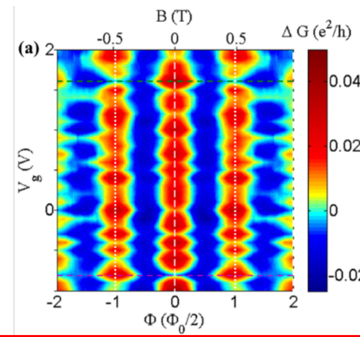
$ DARPA, Intel, Purdue-PCTM

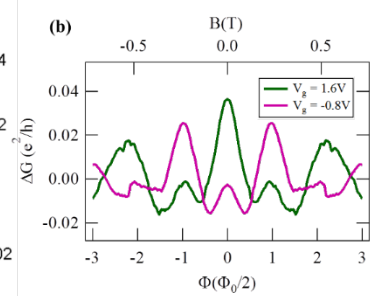
nature nanotechnology | ARTICLES
PUBLISHED ONLINE: 18 JANUARY 2016 | DOI: 10.1038/NNANO.2015.293

Magnetic field-induced helical mode and topological transitions in a topological insulator nanoribbon

Luis A. Jauregui[1,2], Michael T. Pettes[3†], Leonid P. Rokhinson[1,2,4], Li Shi[3,5] and Yong P. Chen[1,2,4*]

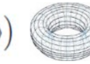






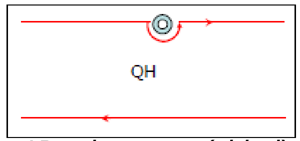
From Quantum Hall Effect (QHE) to Topological Insulator (TI)

$$K = \frac{i}{2\pi} \times \int_{BZ} d^2k \left(\left\langle \frac{\partial \Phi_0}{\partial k_x} \middle| \frac{\partial \Phi_0}{\partial k_y} \right\rangle - \left\langle \frac{\partial \Phi_0}{\partial k_y} \middle| \frac{\partial \Phi_0}{\partial k_x} \right\rangle \right)$$

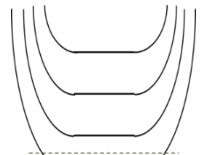


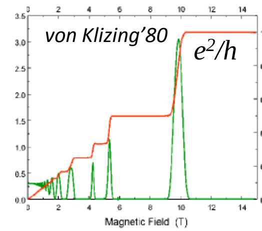
Thouless

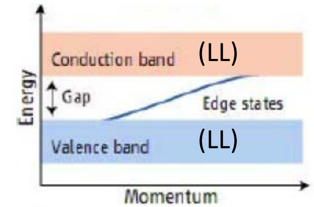
2D Quantum Hall
[*time-reversal breaking*: external B≠0]



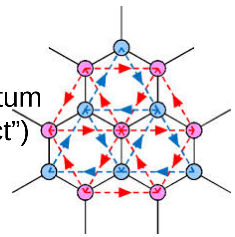
1D edge state (chiral)

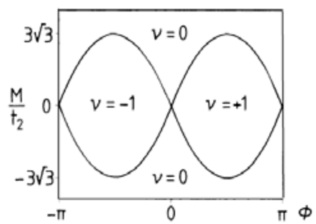


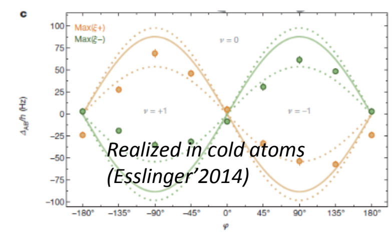




Haldane Model '88
(2D "Chern insulator"/"quantum anomalous Hall (QAH) effect")
[time-reversal breaking; B=0 (no LL)]

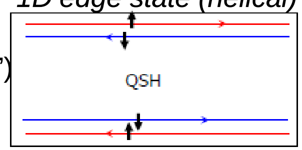




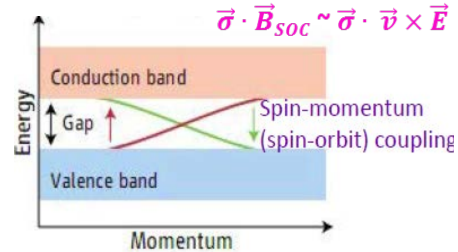


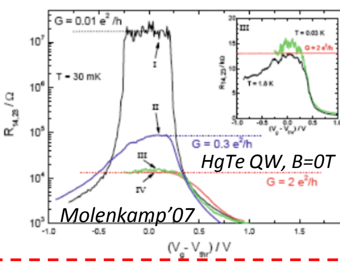
2D Quantum Spin Hall
("2D topological insulator")
[*time-reversal invariant*: B=0] (2D TI)

1D edge state (helical)



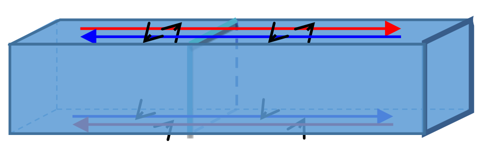
Kane-Mele'05; S.C.Zhang et al'06



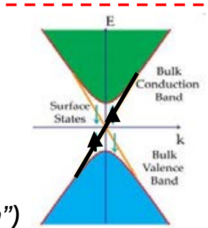


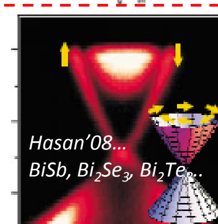
3D (strong)
Topological Insulator
[*time-reversal invariant*: B=0]

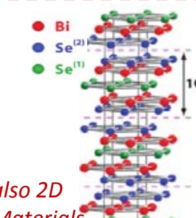
Fu-Kane'07;Moore-Balents'07;Roy'09;Qi-Zhang'08...



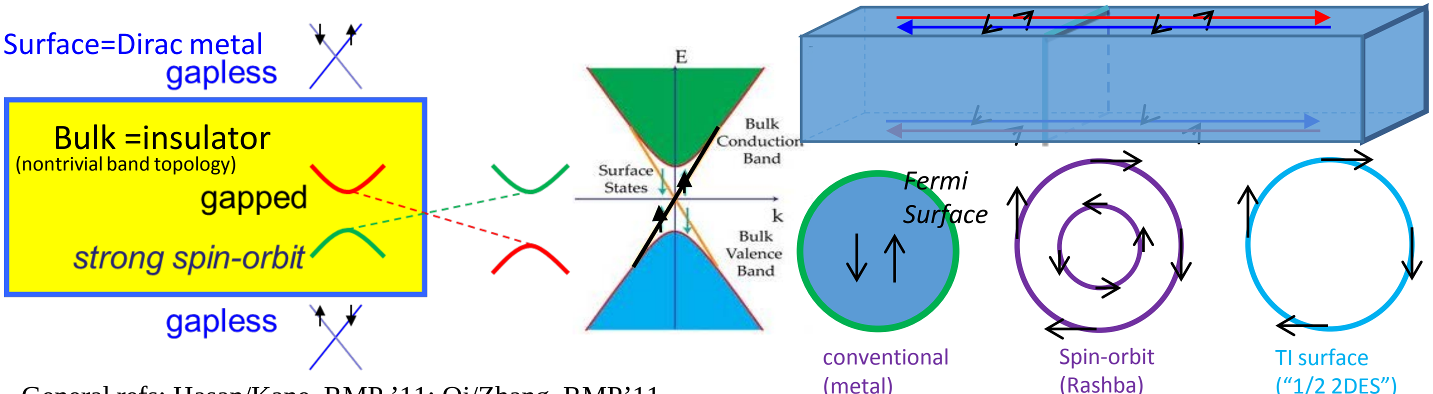
2D surface state ("spin-helical Dirac fermion")







(3D) Topological Insulator & Topological Surface State



General refs: Hasan/Kane, RMP '11; Qi/Zhang, RMP'11

Key Properties *(inter-related)*	***Benefits/Potential Device Applications***
Topological Protection (reduce backscattering) [assuming time-reversal symmetry]	High mobility/conductivity (*FET*) [in absence of magnetic impurities]
Dirac fermions (linear E-k dispersion) $H(\mathbf{q}) = \hbar v_F \mathbf{q} \bullet \vec{\sigma} \times \hat{n}$ *real spin* [odd # Dirac cones]	"graphene-like" physics & devices (eg. *Klein tunneling; electron "optics" etc.*)
Spin-momentum locking (in-plane polarized) $\vec{S} \sim \vec{k} \times \hat{n} \sim \hat{n} \times \vec{j}$ [Berry phase real & k space]	Spin-polarized surface current (*spintronics: all-electric spin injection etc.*)
"Axion" electrodynamics $\Delta \mathcal{L} = \theta (e^2/2\pi h) \mathbf{E} \cdot \mathbf{B}$ (topological magneto-electric effect)	E-field controlled magnetism (*magnetoelectric & spintronic devices etc.)*

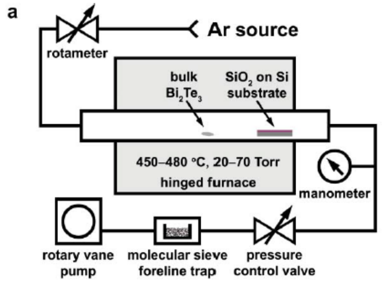
Chen, Proc. SPIE **8373**, 83730B (2012)

Material challenge: reduce bulk conduction

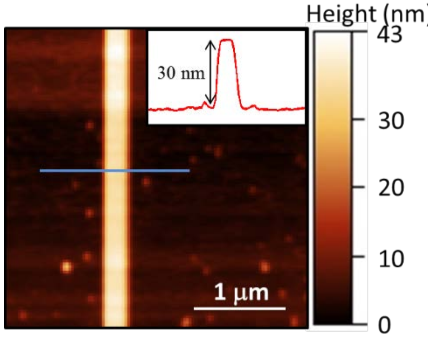
Physics challenge: what are hallmarks of "topological transport"? ["1/2"]

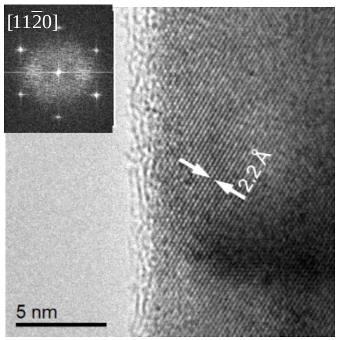
Experiment#2 --- Access/reveal surface state Dirac fermions in TI Nanoribbons

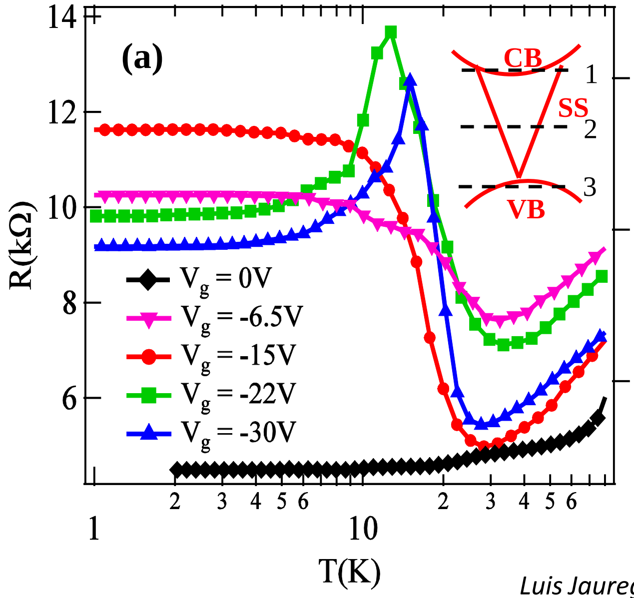
Bi_2Te_3 nanoribbon: Gate-tuned bulk metal-insulator transition & ambipolar field effect

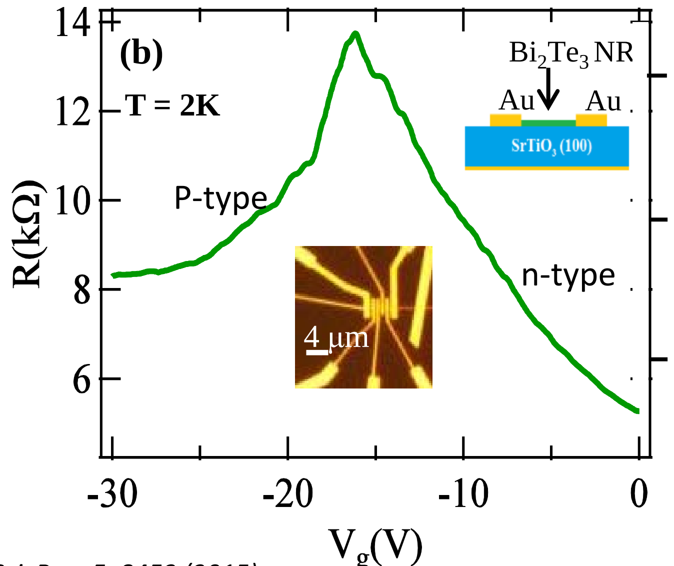


VLS growth by M.Pettes & L.Shi (UT-Austin)
(similar to Y.Cui et al.'10)







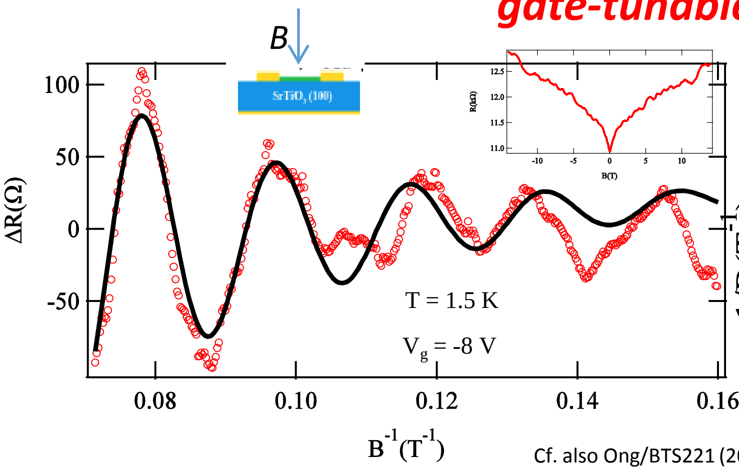


Luis Jauregui et al. Sci. Rep. 5, 8452 (2015)

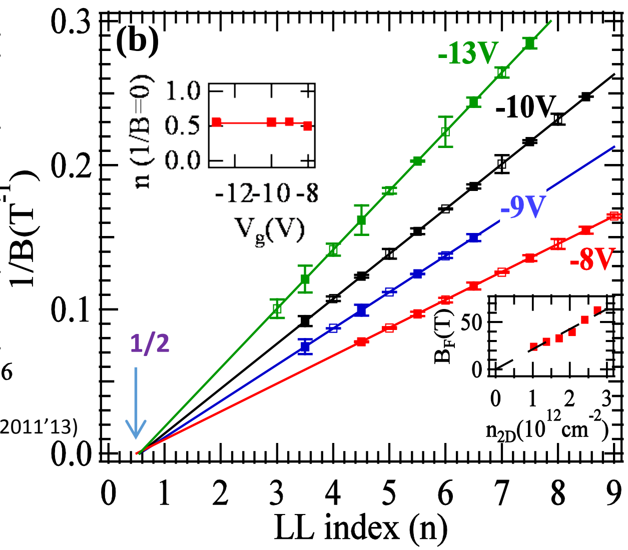
Shubnikov-de Haas (SdH) oscillations :

Luis Jauregui et al. Sci. Rep. 5, 8452 (2015)

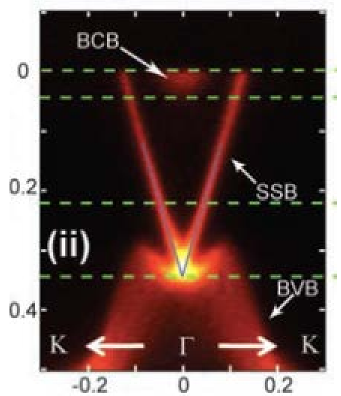
gate-tunable surface state (SS) Dirac fermions



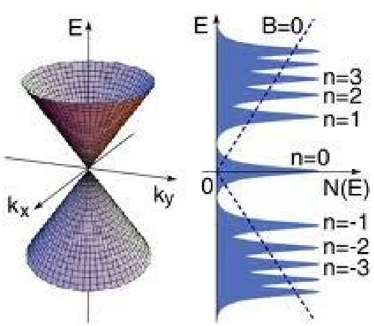
Cf. also Ong/BTS221 (2011'13)



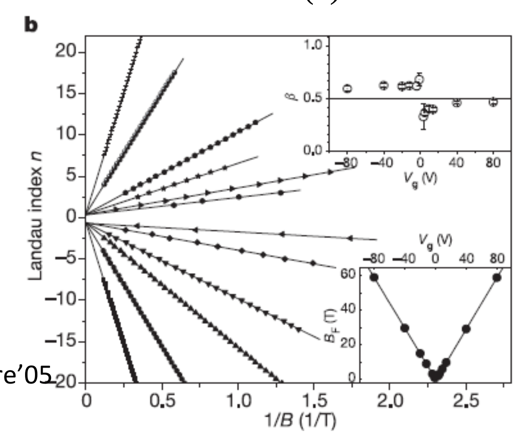
Note: only n-type SS
Dirac fermion accessible in Bi_2Te_3



(YL.Chen/ZX Shen et al. Science'09)

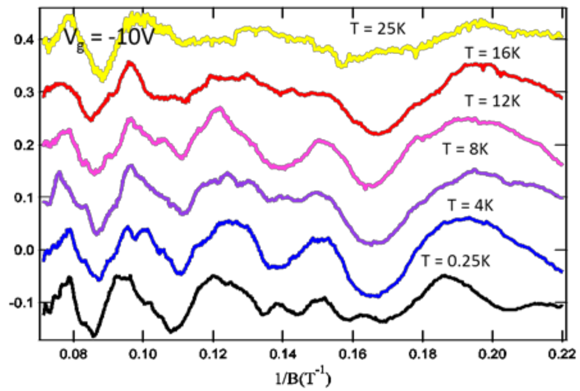


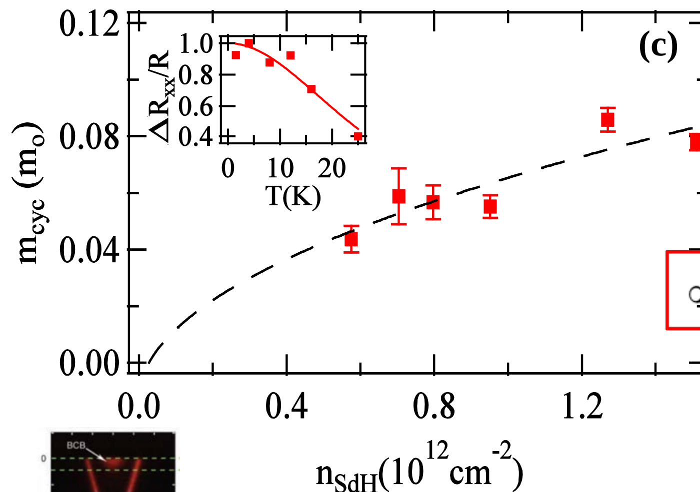
Y.Zhang & P.Kim et al.Nature'05
(graphene)



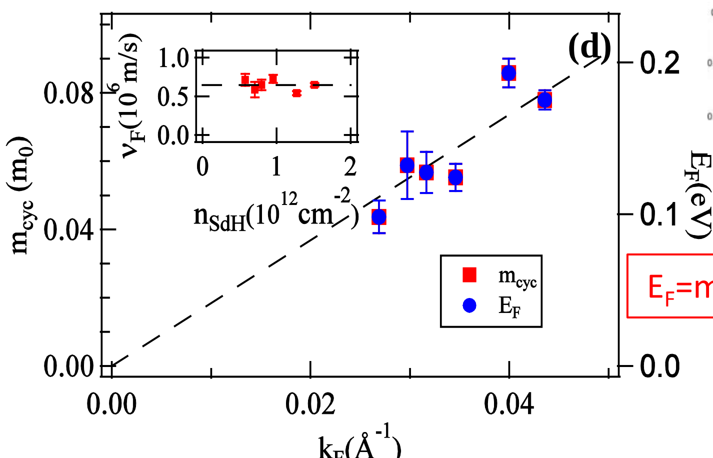
Gate tunable effective (cyclotron) mass ($\propto\sqrt{n}\propto k_F$)
→ transport signature for **linear E-k dispersion** of *SS Dirac fe*

L. Jauregui et al. Sci. Rep. ‘15

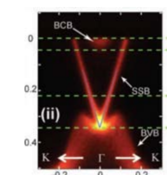


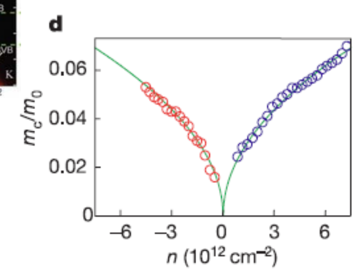


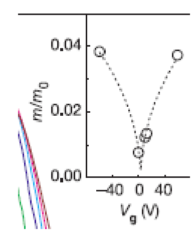
$\propto\sqrt{n}$



$E_F=m^*v_F^2$



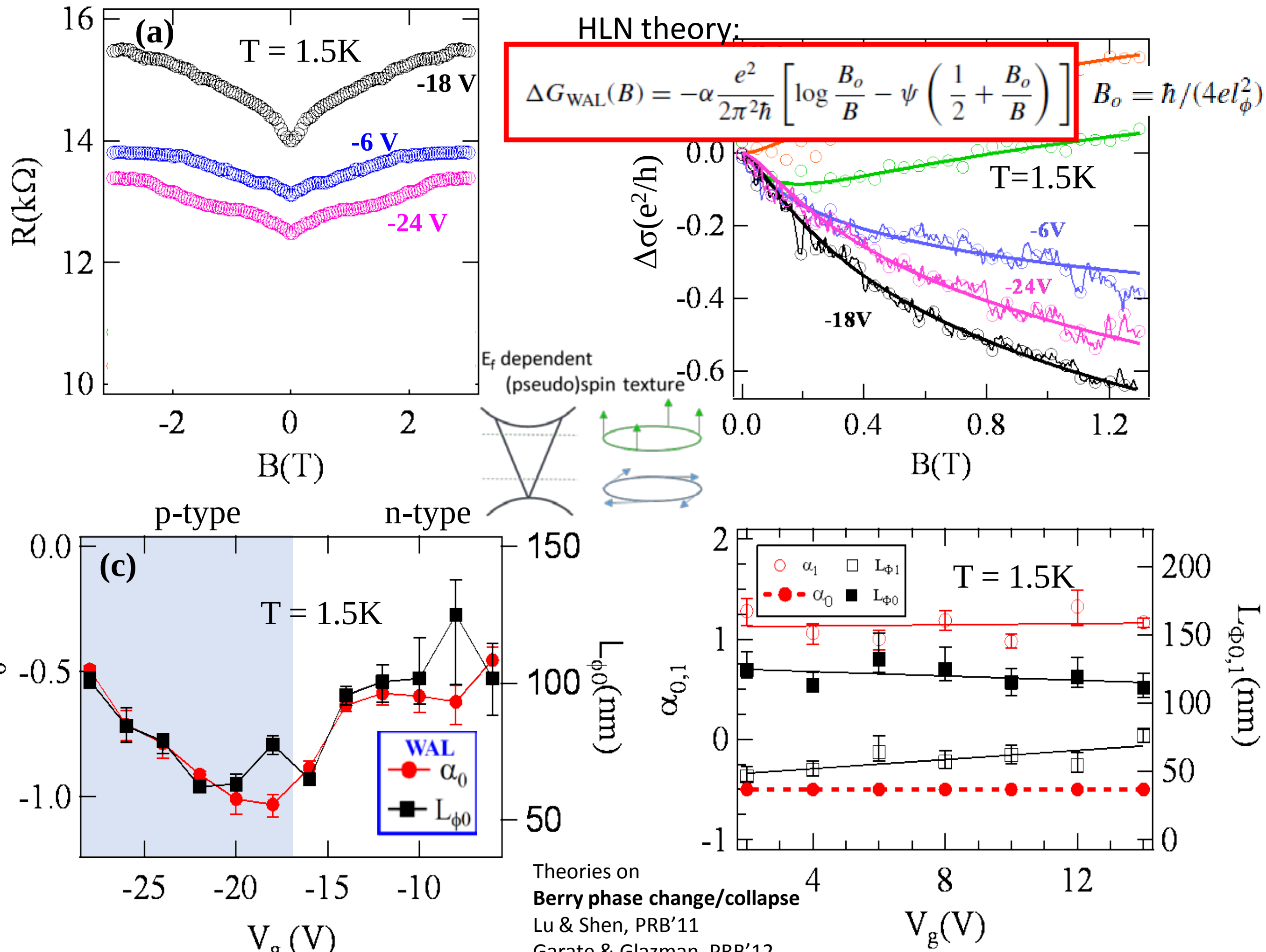




Graphene data from K.Novoselov et al’ Nature’05
Y.Zhang et al’Nature’05

Luis Jauregui et al. Sci. Rep. 5, 8452 (2015)

Gate-tuned weak antilocalization (WAL) and transition to weak localization (WL)



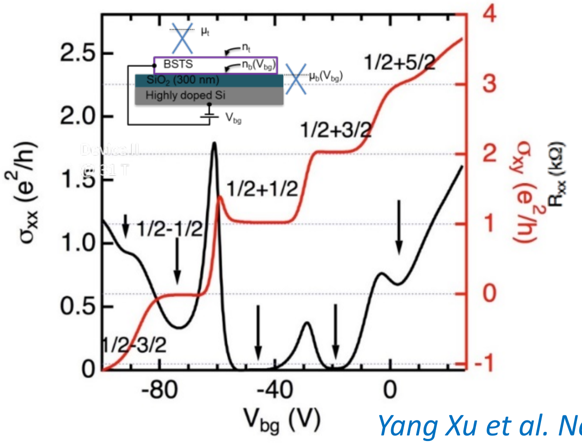
HLN theory:

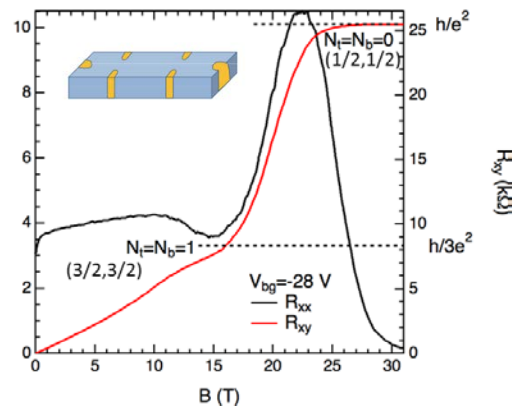
$$\Delta G_{\mathrm{WAL}}(B) = -\alpha \frac{e^2}{2\pi^2\hbar}\left[\log\frac{B_o}{B} - \psi\left(\frac{1}{2}+\frac{B_o}{B}\right)\right] \qquad B_o = \hbar/(4el_\phi^2)$$

Theories on
Berry phase change/collapse
Lu & Shen, PRB'11
Garate & Glazman, PRB'12

A Fingerprint:

"Half-integer" QHE --- of two-component (surface) Dirac fermions

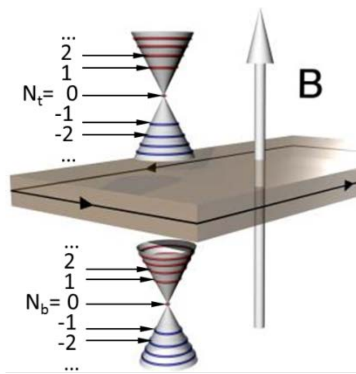




Yang Xu et al. Nature Physics **10**, 956 (2014);

Each surface: $\sigma_{xy}=(1/2)e^2/h$

---*"1/4-graphene"*



$\nu_t=N_t+1/2$

$\nu_b=N_b+1/2$

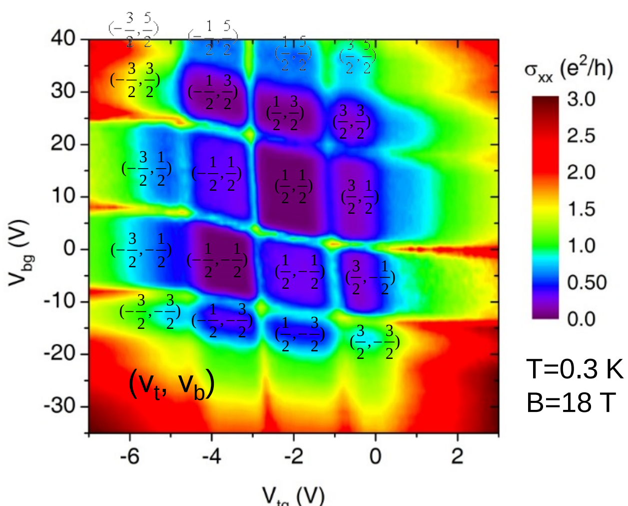
Hall conductivity:

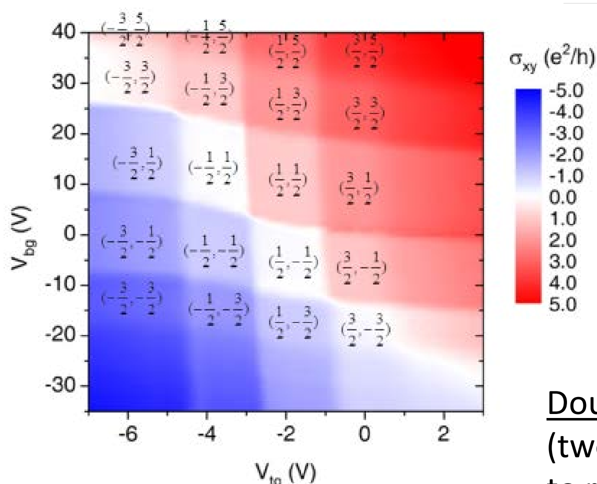
$\sigma_{xy}=\nu e^2/h$

$=(\nu_t+\nu_b)e^2/h$

$=(N_t+1/2+N_b+1/2)\ e^2/h$

$=(N_t+N_b+1)\ e^2/h$





Yang Xu et al. Nature Comm. 7, 11434 (2016)

Dirac fermions: $\sigma_{xy}=g(N+1/2)e^2/h$

g=4 for graphene

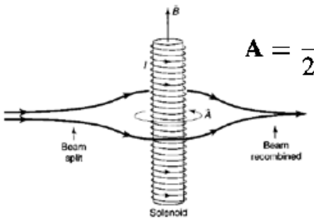
g=1 for a TI surface

Also MBE:
Y. Tokura'15 ($Bi_xSb_{2-x}Te_3$);
S. Oh'15 (Bi_2Se_3)
(also HgTe:
Molenkamp'11'15)

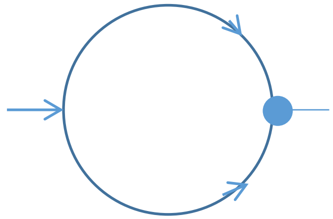
Double Gated TI QHE
(two surfaces independently gated
to resolve its contribution)

Aharonov-Bohm quantum interference → oscillations (ABO)

$$\left[\frac{1}{2m}\left(\frac{\hbar}{i}\nabla - q\mathbf{A}\right)^2 + V\right]\Psi = i\hbar\frac{\partial \Psi}{\partial t}$$

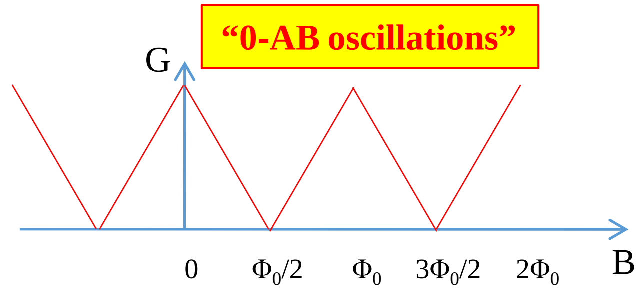


$$\mathbf{A} = \frac{\Phi}{2\pi r}\hat{\phi},$$



phase difference $= \frac{q\Phi}{\hbar}$

$$\gamma_n(T) = \frac{q}{\hbar}\oint \mathbf{A}(\mathbf{R})\cdot d\mathbf{R} = \frac{q}{\hbar}\int(\nabla\times\mathbf{A})\cdot d\mathbf{a} = \frac{q\Phi}{\hbar}$$



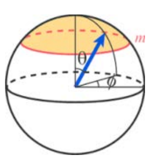
Period = Φ_0 = h/e

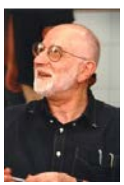
$$\Psi = e^{ig}\Psi',$$

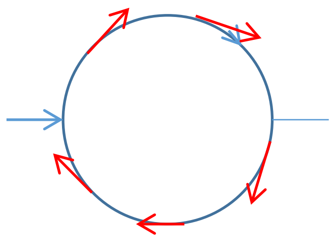
$$g(\mathbf{r}) \equiv \frac{q}{\hbar}\int_{\mathcal{O}}^{\mathbf{r}} \mathbf{A}(\mathbf{r}')\cdot d\mathbf{r}',$$

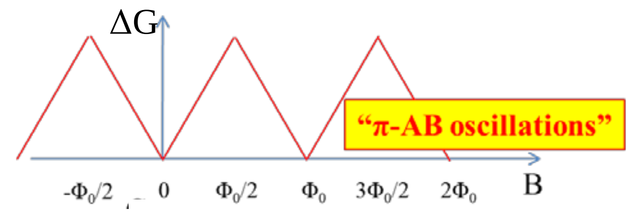
Spin helical electron→ additional/**Berry phase** π

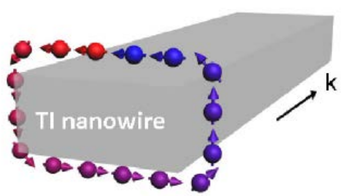
"half-integer" ABO





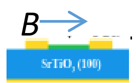


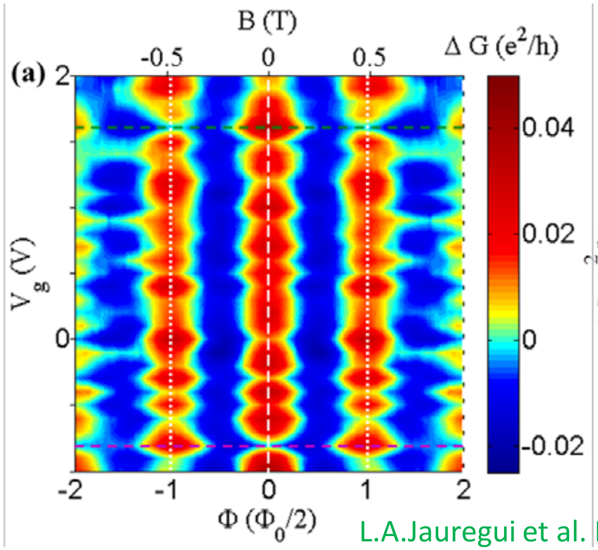


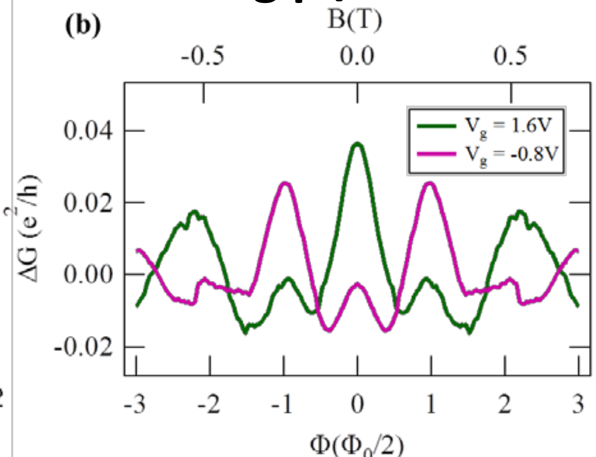


J. H. Bardarson, et al. PRL 105, 156803 (2010)
Y. Zhang, et al. PRL 105, 206601 (2010)
A. Cook, et al 2012 & 2011

Alternating pi/0 ABO!





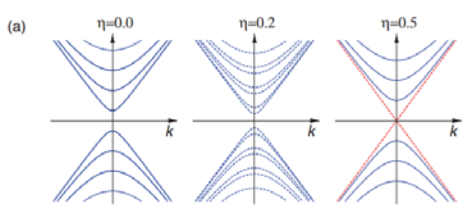


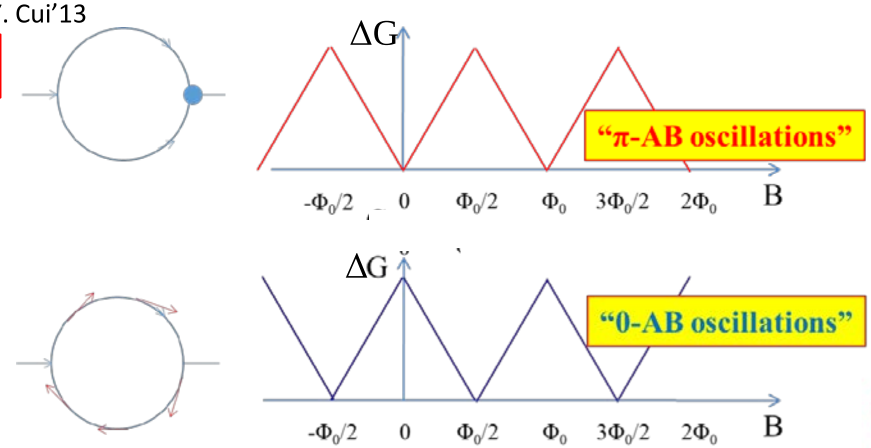
in collab:
M. Pettes/L.Shi (UT Austin)
L. Rokhinson (Purdue)

L.A.Jauregui et al. Nature Nano 11, 345 (2016)

See also: N. Mason'15; Y. Cui'13

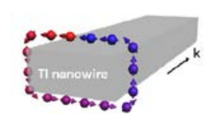
B-driven topological transition in TSS sub-bands!





$\vec{S} \sim \vec{k} \times \hat{n}$

Berry-phase (real space rotation)--not in CNT!

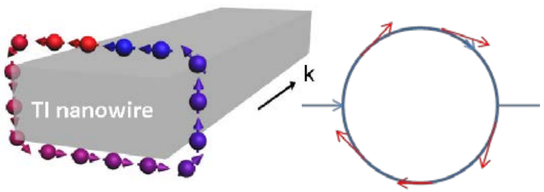


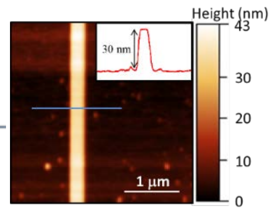
J. H. Bardarson, et al. PRL 105, 156803 (2010); Y. Zhang et al'2010; Cook/Franz '2011

Another unique transport signature of TI spin-helical surface Dirac fermions:

"half-integer"(pi) AB oscillations & <u>alternating 0-ABO/pi-ABO periodic in k_F</u> *--- due to quantized TSS sub-bands and B field driven topological transitions in TI nanowire/nanoribbon*

Luis Jauregui, et al. Nature Nanotechnology (2016)



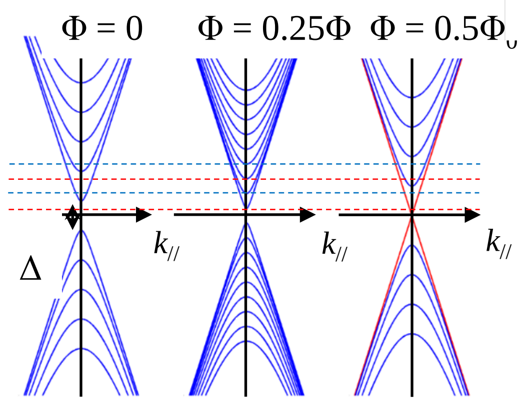


VLS-grown TI (Bi_2Te_3) Nanoribbon (NR)

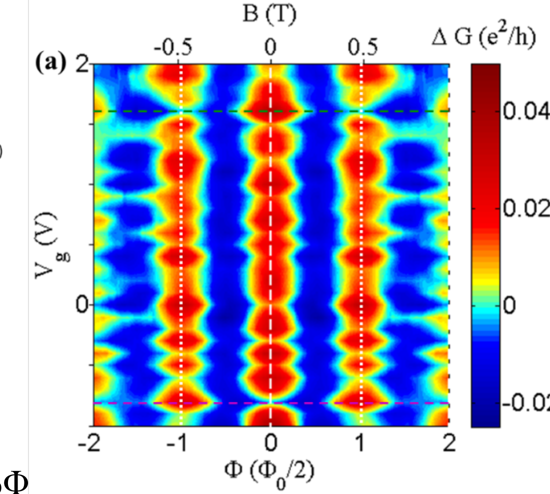
$$E_{kl} = \pm \upsilon_F \hbar \sqrt{k^2 + \frac{(l + 1/2 - \Phi/\Phi_0)^2}{R^2}}$$

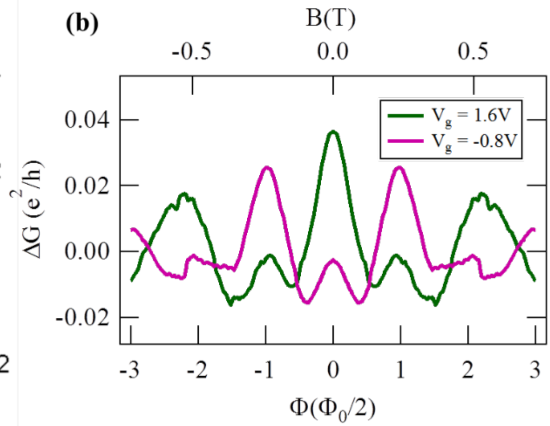
$$\vec{S} \sim \vec{k} \times \hat{n}$$

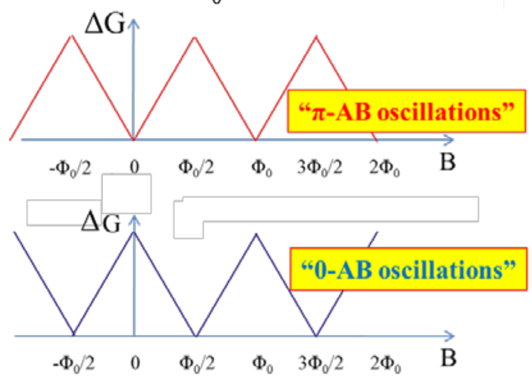
Berry-phase *(real space rotation)-- not in CNT!*



See also Bi_2Se_3: N. Mason'15 (exfoliated); Y. Cui'13 (VLS)

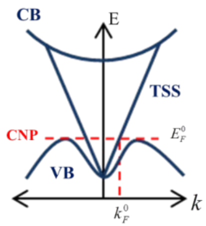


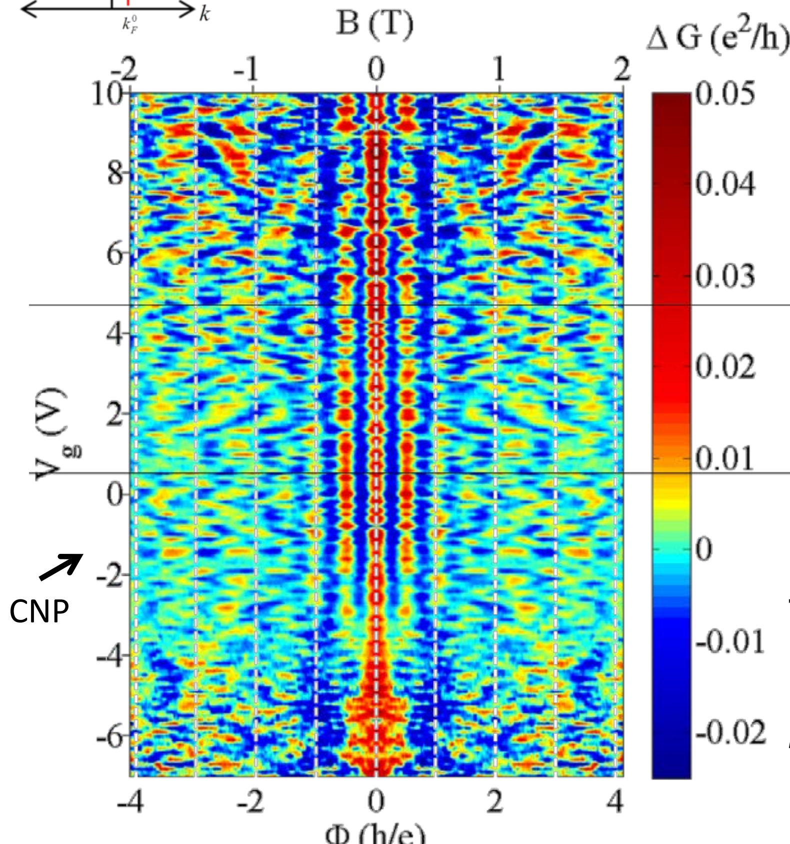




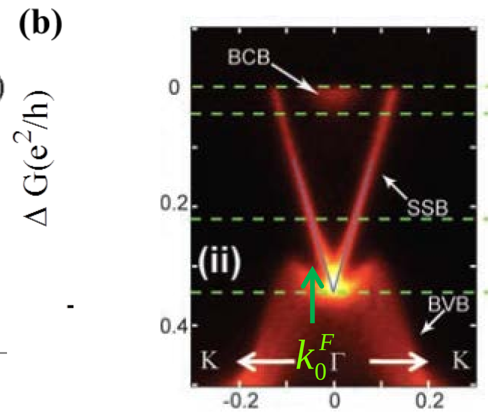
in collab:
M. Pettes/L.Shi (UT Austin); L. Rokhinson (Purdue)

Probe TSS & band structures

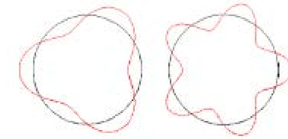




L.A.Jauregui et al. Nature Nano 11, 345 (2016)

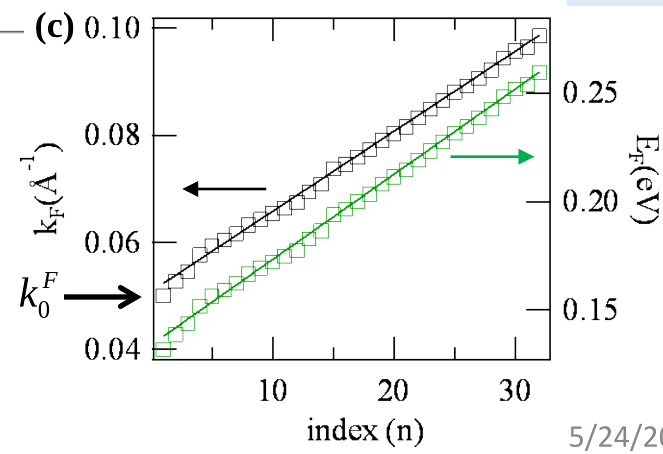


(Y.L.Chen/Z.X Shen et al. Science'09)



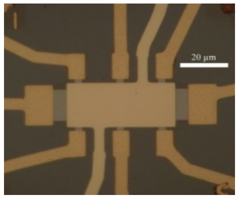
circumferentially quantized Surface state electrons

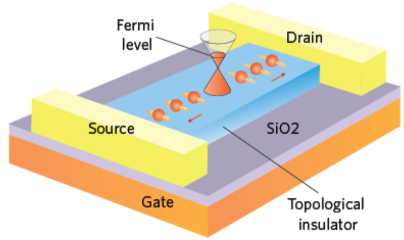
Gate-dependent,
k_F-periodic oscillation!

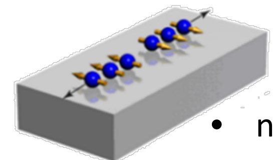


TI electronic transport: Rich physics and Potential Device Applications

Want: Topological Surface State (TSS) Transport (spin –helical Dirac fermion)



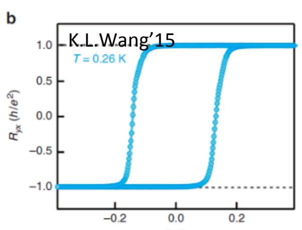


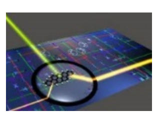


- nanoelectronics
- spintronics
- Thermoelectrics …

TI surface state (Dirac fermion, spin polarized)

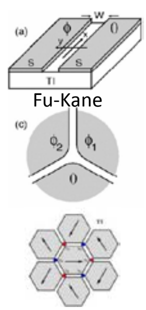
TI + magnetism
Quantum Anomalous Hall
[QK.Xue et al'13]
Topological magnetoelectric
"*axion*" eletrodynamics
Topological Phase Transition

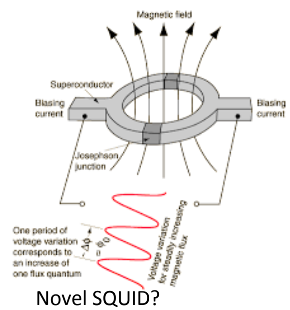




Ultralow power dissipation (dissipationless) interconnect/FFIT

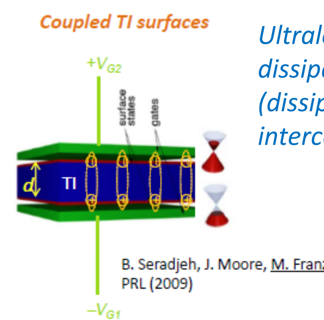
TI + superconductor
(*Majorana* fermions)
Non-Abelian statistics (1D/2D)



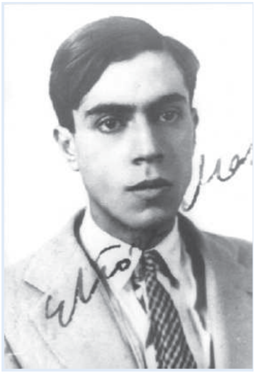


Topological quantum computing

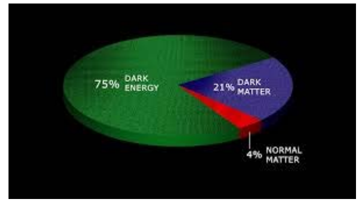
TI + TI
(Excitonic condensate)
[electronic superfluid]



Ultralow power dissipation (dissipationless) interconnect/BiSFET



Majorana (fermion)



- **Neutrino?**
- **Supersymmetric partner**

e.g. of *photon: photino*

…

WIMPs (dark matter) ?…

Axion (boson)

Peccei and Quinn QCD

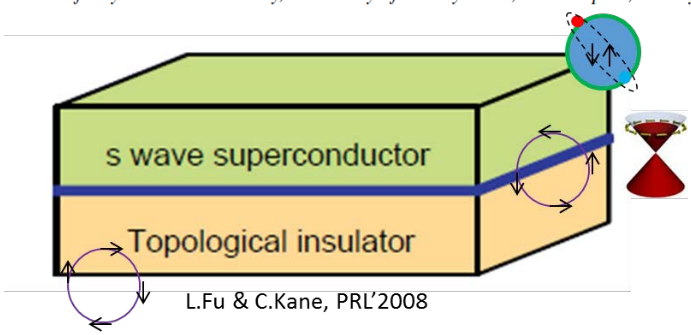
A light mass dark matter candidate

PRL **100,** 096407 (2008)

Superconducting Proximity Effect and Majorana Fermions at the Surface of a Topological Insulator

Liang Fu and C. L. Kane

Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA



L.Fu & C.Kane, PRL'2008

How Axions May Explain Time's Arrow | Quanta Magazine

QUANTA MAGAZINE Illuminating science

QUANTIZED: PHYSICS

Time's (Almost) Reversible Arrow

By Frank Wilczek

January 7, 2016

Dynamical axion field in topological magnetic insulators

NATURE PHYSICS | VOL 6 | APRIL 2010

Rundong Li[1], Jing Wang[1,2], Xiao-Liang Qi[1] and Shou-Cheng Zhang[1]*

Axions are weakly interacting particles of low mass, and were postulated more than 30 years ago in the framework of the Standard Model of particle physics. Their existence could explain the missing dark matter of the Universe. However, despite

Topological magnetoelectric effect
- Modified Maxwell equations by axion field

Modified Maxwell equations

$$\vec{\nabla}\cdot\vec{E} = \rho - \kappa\vec{\nabla}\theta\cdot\vec{B}$$

$$\vec{\nabla}\times\vec{E} = -\partial\vec{B}/\partial t$$

$$\vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{B} = \partial\vec{E}/\partial t + \vec{j} + \kappa(\partial\theta/\partial t\vec{B} + \vec{\nabla}\theta\times\vec{E})$$

constitutive relations

$$\vec{D} = \epsilon\vec{E} + \kappa\theta\vec{B}$$

$$\vec{H} = \frac{1}{\mu}\vec{B} - \kappa\theta\vec{E}$$

Slide credit:
J. Ihm

F. Wilczek *PRL* **58**, 1799 (1987)

X.-L.Qi *et al.*, *PRB* **78**, 195424 (2008):
S.-C.Zhang group

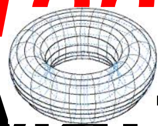
$\theta = 0$ for NI and π for TI

$-\kappa\vec{\nabla}\theta\cdot\vec{B}$: topological charge (ρ_t)

$\kappa(\partial\theta/\partial t\vec{B} + \vec{\nabla}\theta\times\vec{E})$: topological current ($\vec{j}_t$)

Topological magnetoelectric effect can be described phenomenologically in terms of axion electrodynamics.

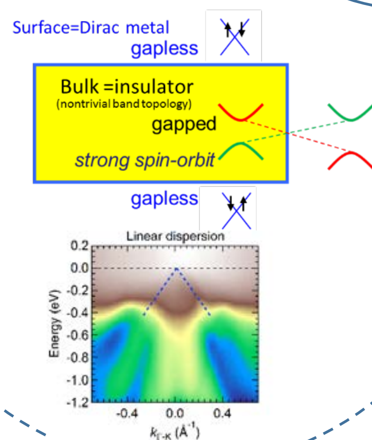
Topological Quantum Matter



today: electrons & atoms & photons…

“clean”

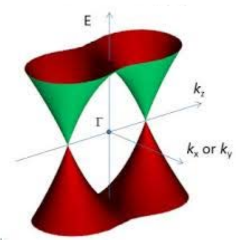
***Topological* Insulator**

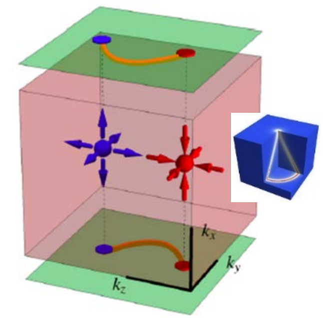


Dirac/Weyl fermions

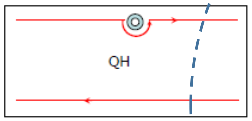
***Topological* semimetal/metal**

2011’*2015-*



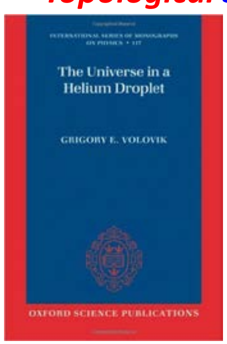


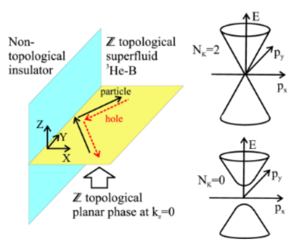
QHE

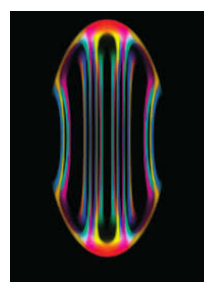


Majorana “fermions”

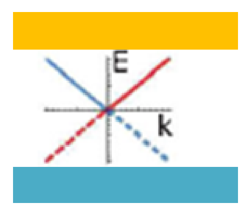
***Topological* Superfluid/Bose-Einstein condensate (BEC)**

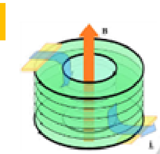


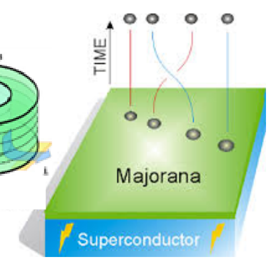




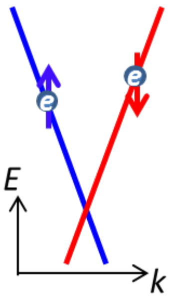
***Topological* Superconductor (SC)**



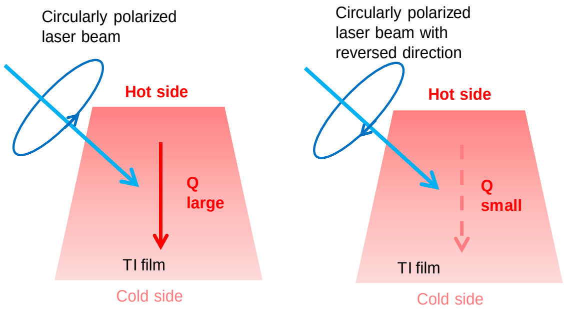




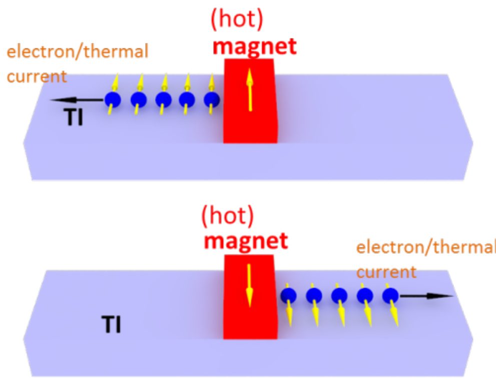
Can we have **Topological Thermal Transport**?: ***spin-momentum-locked*** *heat carriers*



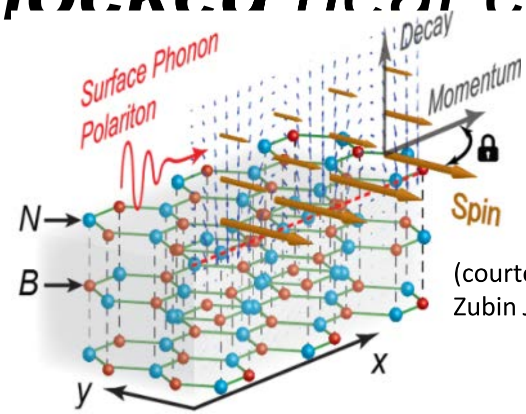
topological insulator (TI) surface **electrons**



TI

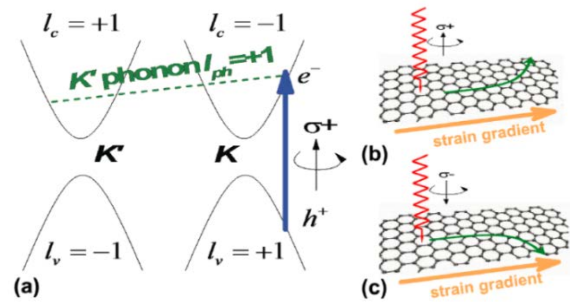


phonon-photon **polaritons**



(courtesy Zubin Jacob)

chiral **phonons**



Valley phonon Hall effect (courtesy Qian Niu)

NSF EFRI "NewLaw" (2016): Yong P. Chen, Xianfan Xu, Zubin Jacob (Purdue) & Qian Niu (UT Austin)

Outline

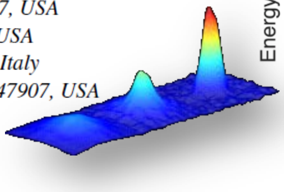
- **Quantum Coherent Transport of Atoms (cold atom BEC): A Spin-resolved Atom Interferometer (Stuckelberg Interference)**

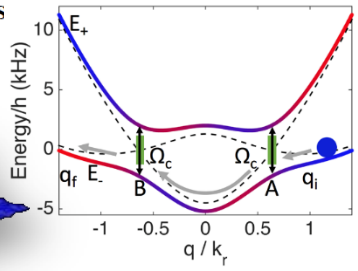
PHYSICAL REVIEW A **95**, 043623 (2017)

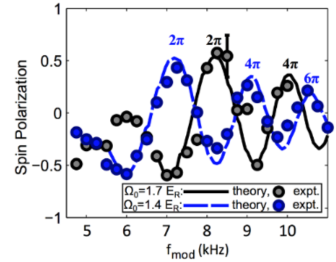
Stueckelberg interferometry using periodically driven spin-orbit-coupled Bose-Einstein condensates

Abraham J. Olson,[1] David B. Blasing,[1] Chunlei Qu,[2,3] Chuan-Hsun Li,[4] Robert J. Niffenegger,[1] Chuanwei Zhang,[2] and Yong P. Chen[1,4,5,*]

[1]*Department of Physics and Astronomy, Purdue University, West Lafayette, Indiana 47907, USA*
[2]*Department of Physics, The University of Texas at Dallas, Richardson, Texas 75080, USA*
[3]*INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, Povo 38123, Italy*
[4]*School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907, USA*
[5]*Purdue Quantum Center, Purdue University, West Lafayette, Indiana 47907, USA*







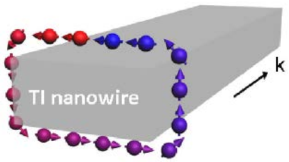
$ ARO-DURIP, NSF-GRF, Purdue OVPR

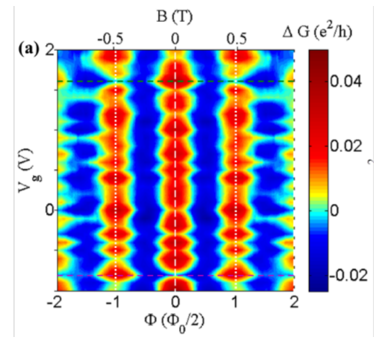
- **Quantum Coherent Transport of Electrons (spin-helical Dirac fermions on topological insulators): a "half-integer" Aharonov-Bohm Effect (electronic interferometer)**

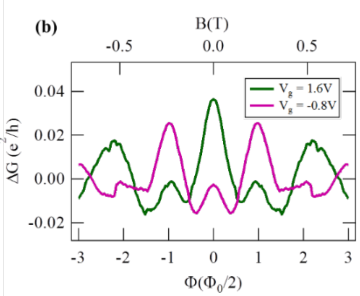
nature nanotechnology
ARTICLES
PUBLISHED ONLINE: 18 JANUARY 2016 | DOI: 10.1038/NNANO.2015.293

Magnetic field-induced helical mode and topological transitions in a topological insulator nanoribbon

Luis A. Jauregui[1,2], Michael T. Pettes[3†], Leonid P. Rokhinson[1,2,4], Li Shi[3,5] and Yong P. Chen[1,2,4★]





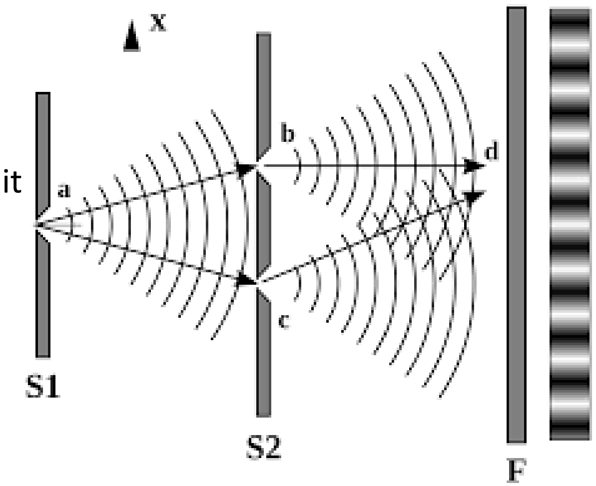


General remark

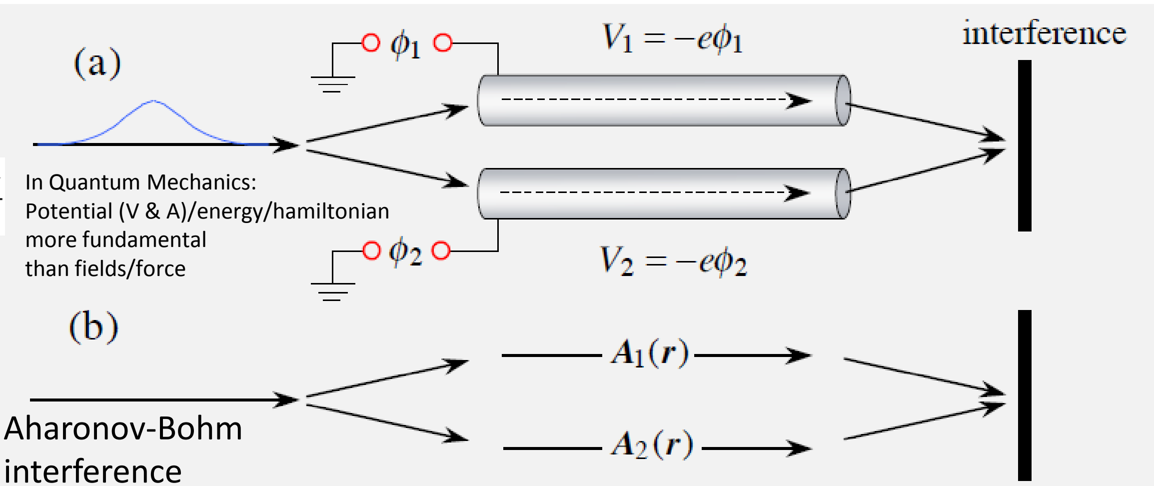
Two-path interference

"Path" can be in
- Real (r) –space
- Momentum (k) – space
- More abstract/complicated "configuration"/Hilbert space….
  [sometimes related to "topology"]

Young' double-slit interference (optics/light ***wave***)

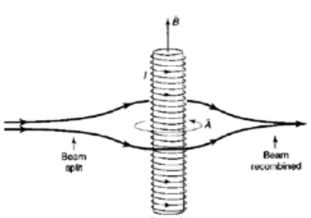


"Wave" can be
- Light (classical E&M or quantum)
- electrons
- atoms
- other "matter wave" or more complex quantum systems



$$\left[\frac{1}{2m}\left(\frac{\hbar}{i}\nabla - q\mathbf{A}\right)^2 + V\right]\Psi = i\hbar\frac{\partial\Psi}{\partial t}$$

In Quantum Mechanics:
Potential (V & A)/energy/hamiltonian more fundamental than fields/force



Aharonov-Bohm interference