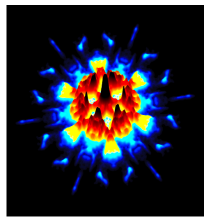
Theory Panel 2: (2nd Principles, mixed bag)

- (Sinova) Topological thermoelectrics and a mixed bag of questions

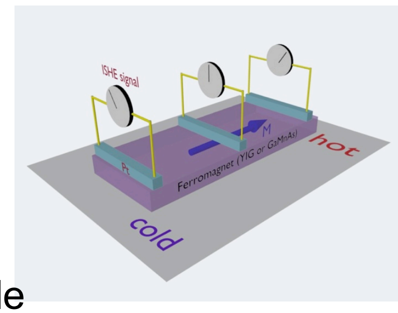
(2 hours)

Topological Insulators



Kane and Mele

Spin Caloritronics



- (Onoda) Thermoelectric and transport properties of gapped TI coupled to magnetic systems

(-20 minutes)

- (Xie) Spin superconductor in ferromagnetic graphene

(-20 minutes)

- (Lee) Magnetization dynamics coupled with spin and spin waves

(-20 minutes)

Lorentz center

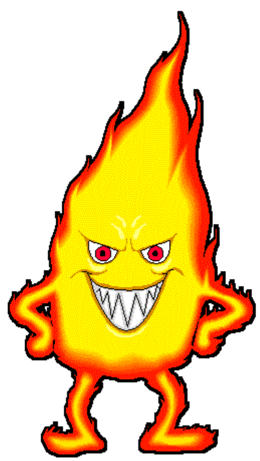
Spin Caloritronics?

Workshop February 9 - 13 2009, Leiden, The Netherlands

Key discussion during the workshop: what to call the field

Heattronics? Thermomagnotronics? Nanospinheat ? Calefactronics?
Fierytronics? Coolspintronics? Thermospintronics?

What I learned in kinder garden: Fire is cool

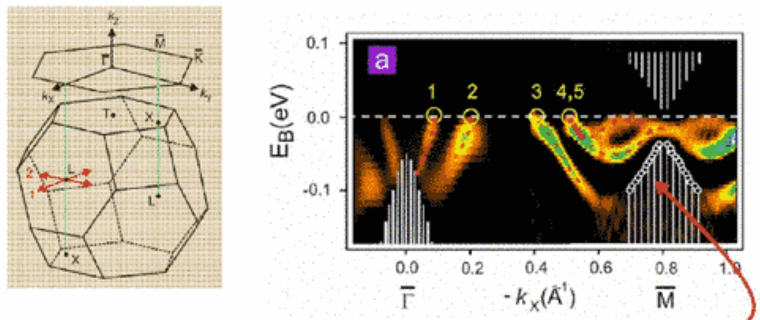


What I learned in Leiden: Spin+Fire is cooler

3D Topological Band Insulators

- Experimental Candidate $Bi_{0.9}Sb_{0.1}$

D. Hsieh, D. Qian, L. Wray, Y. Xia, Y. S. Hor, R. J. Cava and M. Z. Hasan, Nature (08) in press

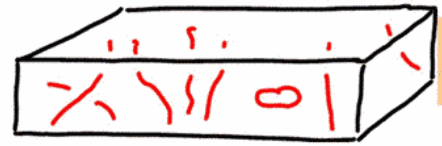


- Bulk Dirac points at L project to M in surface Brillouin Zone

$$\nu_0 = 1; \mathbf{M}_\nu = (1,1,1)$$

Experimental Signatures

- Resistivity: dislocation contribution could dominate over surface conduction.

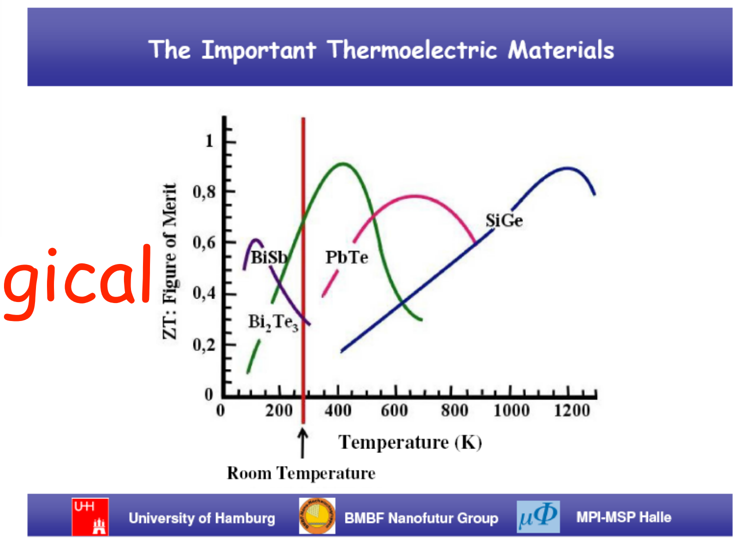


$$\rho = \frac{h}{2e^2}\frac{1}{l\,n_d} \approx 10^{-2}\Omega\mathbf{m}$$

$n_d \approx 10^{12} m^{-2}$

$l \approx 1\mu m$

- Scanning Tunneling Microscopy: Can determine atomic defect structure and Local Density of States (LDOS). 1D modes – finite DOS. Dirac point – vanishing density of states.



High ZT is related to topological protected states

Prediction: ZT will be MUCH larger in HgTe wells in the inverted regime and in thin ribbon 3D TI through 1D channels

Topological thermoelectrics

JAIRO SINOVA
Texas A&M University
Institute of Physics ASCR

Open postdoc position (free stakes; summers in Prague; winters in Texas; cowboy hat; free rodeo classes)

Oleg Tretiakov, Artem Abanov, Suichi Murakami

Research fueled by:

From topological insulators to thermoelectrics

Seebeck coefficient

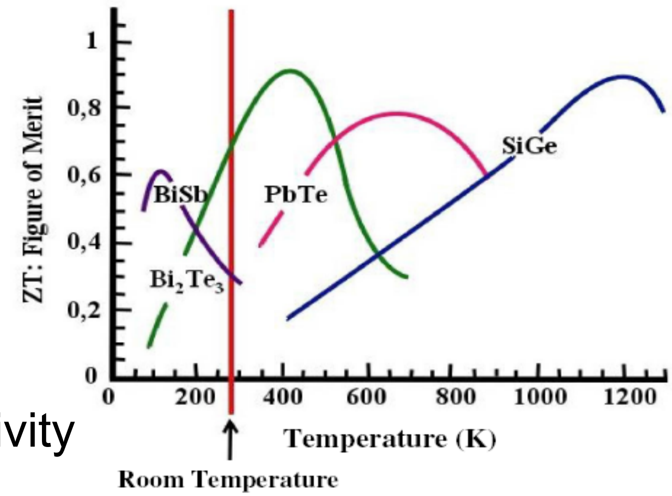
$$S = \frac{\pi k_\beta^2 T}{3e}\left[\frac{\partial \ln \sigma(E)}{\partial E}\right]_{E_F}$$

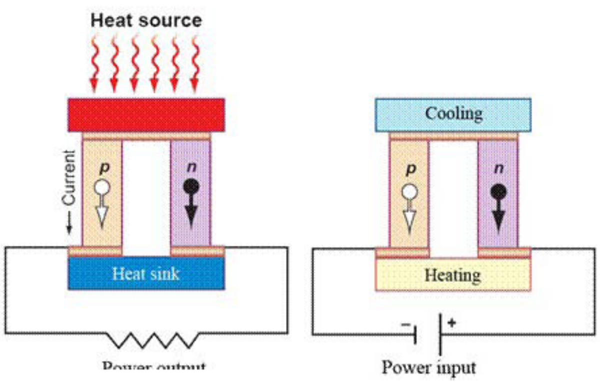
electrical conductivity

$$ZT = \frac{\sigma S^2}{\kappa_e + \kappa_l} T$$

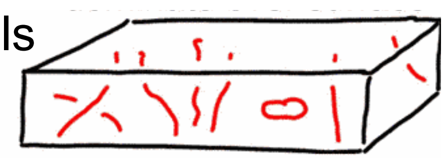
electric thermal conductivity

phonon thermal conductivity





Dislocations have 1D channels which also protected



Vishwanath et al 09

$\kappa_l \downarrow \quad \sigma \uparrow \quad S \updownarrow$?

?

Can we obtain high ZT through the topological protected states; are they related to the high ZT of these materials?

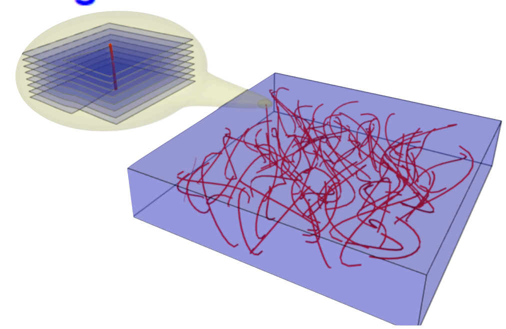
Possible large ZT through dislocation engineering

APPLIED PHYSICS LETTERS 97, 073108 (2010)

Large thermoelectric figure of merit for three-dimensional topological Anderson insulators via line dislocation engineering

O. A. Tretiakov, Ar. Abanov,[1] Shuichi Murakami, and Jairo Sinova[1]

(Received 23 July 2010; accepted 30 July 2010; published online 18 August 2010)



$$\frac{1}{ZT} = \frac{(L_0^b + snL_0^{1D})(L_2^b + snL_2^{1D} + \kappa_{ph}T)}{(L_1^b + snL_1^{1D})^2} - 1$$

$Bi_{1-x}Sb_x$ (0.07 < x < 0.22)

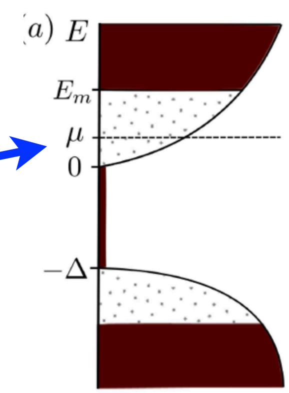
where the L's are the linear Onsager dynamic coefficients

$$L_\alpha^{1D} = -\frac{l}{sh}\int \mathcal{T}(E) f'(E)(E-\mu)^\alpha dE$$

$$L_\alpha^b = -\tau \int_{E_m}^{\infty} D(E) f'(E) v^2 (E-\mu)^\alpha dE$$

$$L_\alpha^b = \frac{2\sqrt{2m^*}}{\pi^2\hbar^3}\tau c T^{\alpha+3/2}\int_{\frac{E_m-\mu}{T}}^{\infty} dx \frac{x^\alpha (x+\mu/T)^{3/2} e^x}{(e^x+1)^2}$$

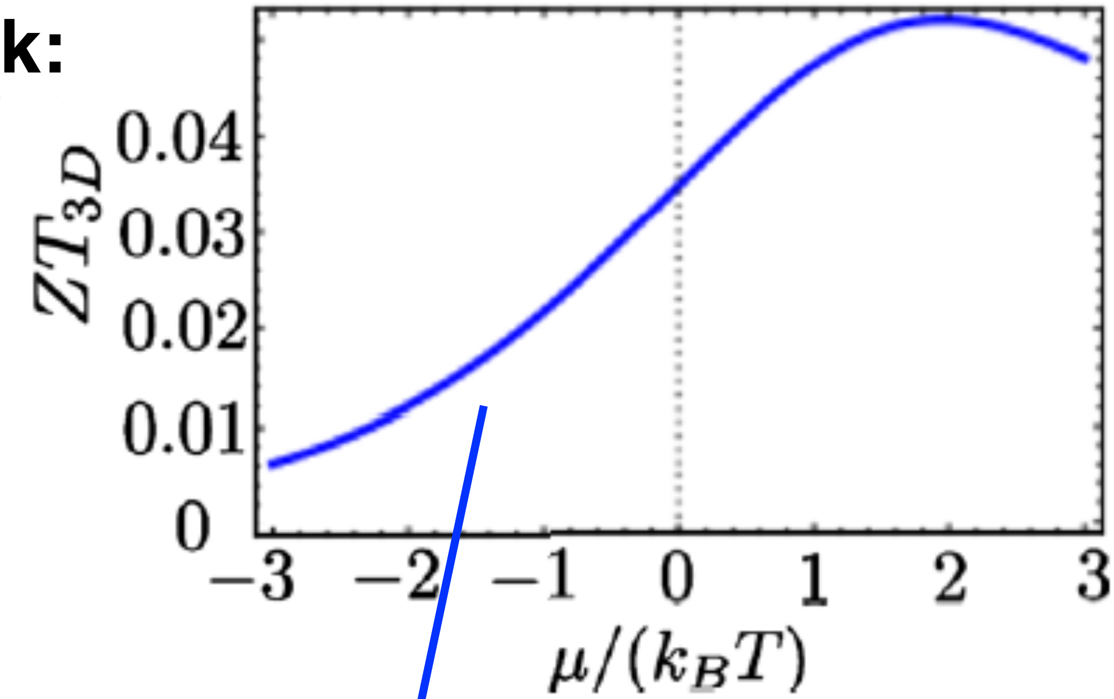
Localized bulk states

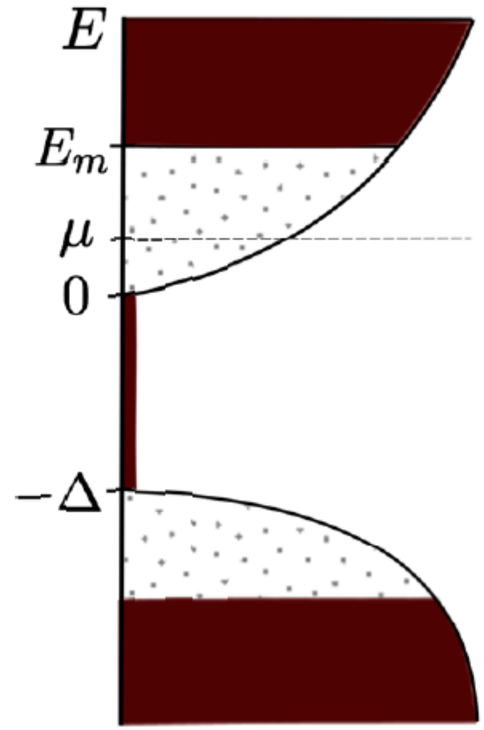


Tretiakov, Abanov, Murakami, Sinova APL 2010

Bulk contribution

Bulk:

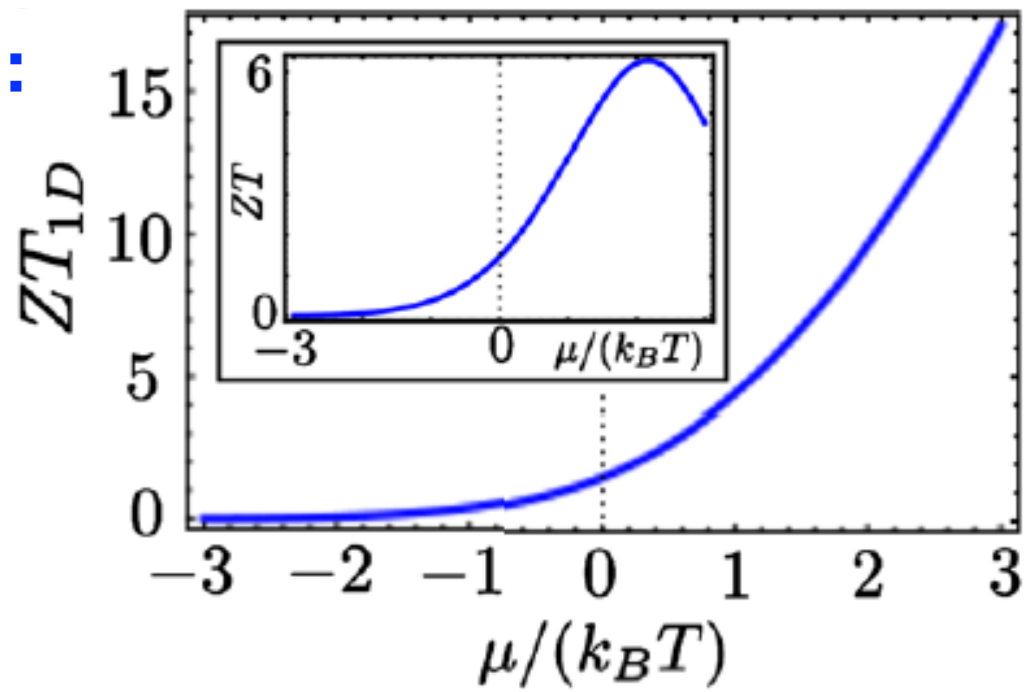




Contribution to ZT from the bulk is very small

ZT of one perfectly conducting 1D wire

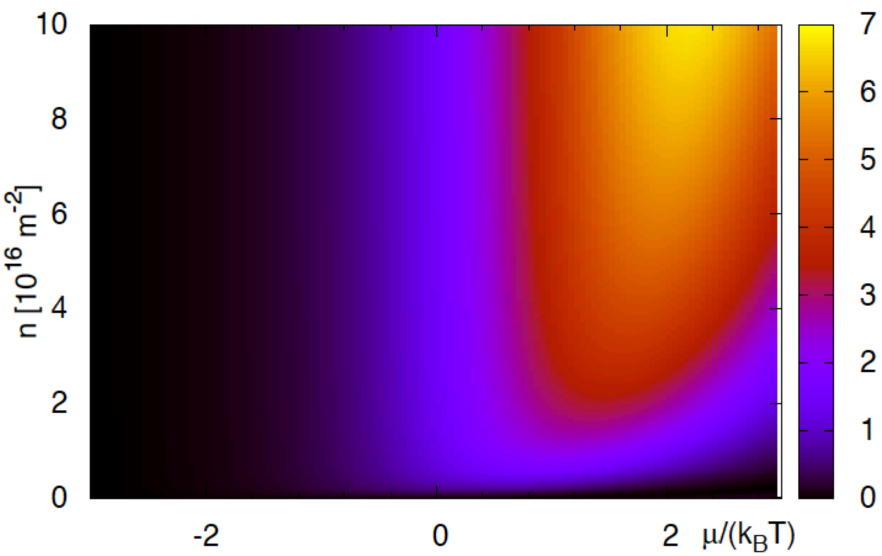
Limiting case:

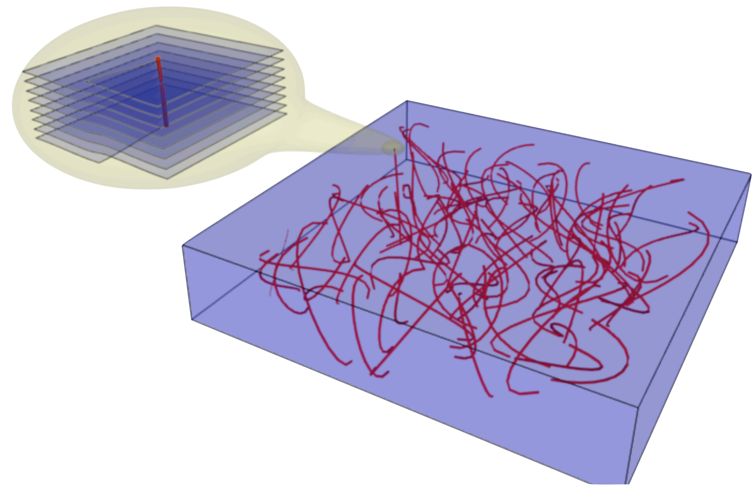


infinite density of dislocations

$$ZT_{1D} = \lim_{n\to\infty} ZT = \frac{(L_1^{1D})^2}{L_0^{1D} L_2^{1D} - (L_1^{1D})^2}$$

Possible large ZT through dislocation engineering





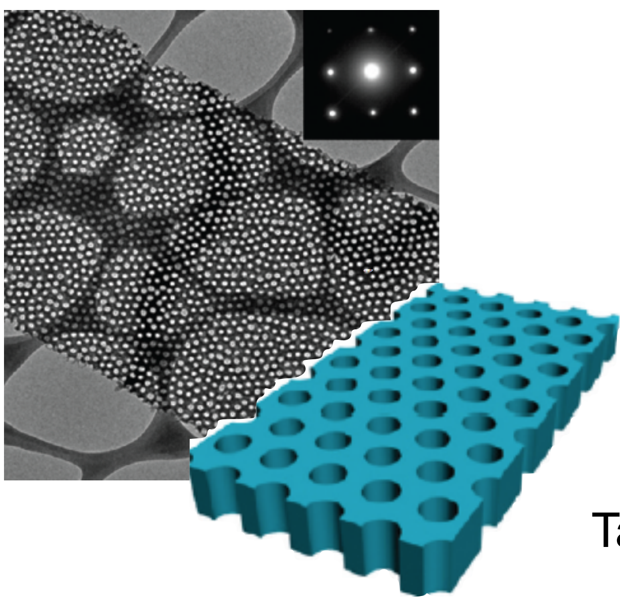
Remains **very** speculative but simple theory
gives large ZT for reasonable parameters

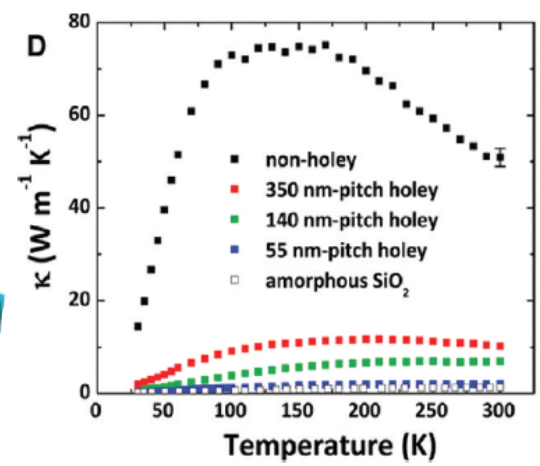
Tretiakov, Abanov, Murakami, Sinova APL 2010

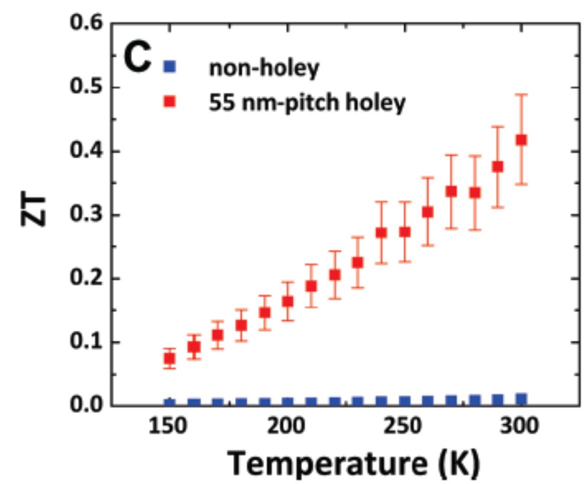
Beyond $Bi_{1-x}Sb_x$ ($0.07 < x < 0.22$)

So far only one material is believed to have protected 1D states on dislocations: how to further exploit TI properties to increase ZT?

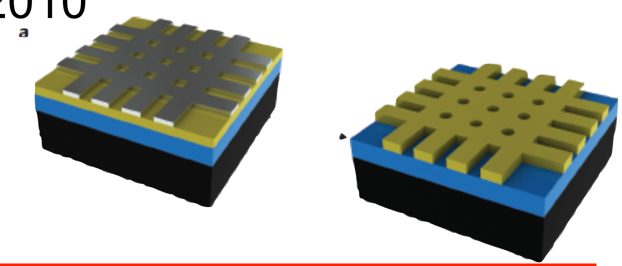
Analogy to HolEy Silicon







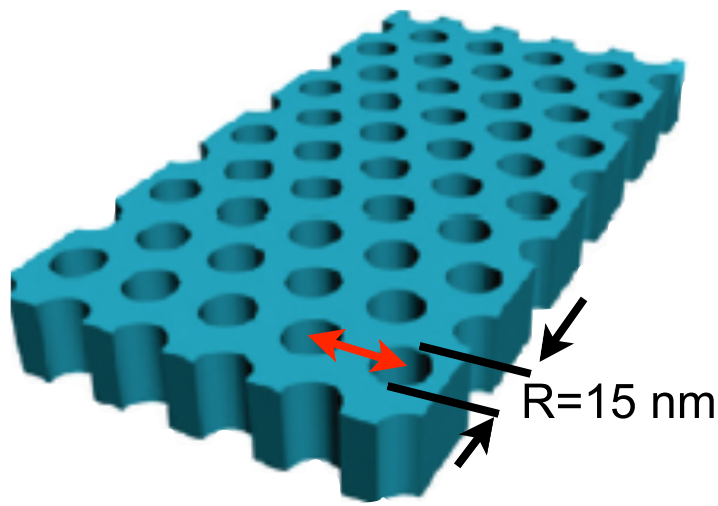
Tang *et al* Nano Letters 2010



Also phononic nanomesh structures (Yu, Mitrovic, et al Nature Nanotechnology 2010)

Extending the idea to the entire class of TI insulators

- The surface of the holes provide the needed anisotropic transport
- Similar theory analysis as in 1D protected states but not as robust
- Curvature of the holes can be critical for TI to remain protected (Ostrovsky et al PRL 10, Zhang and Vishwanath PRL 10)



$$\frac{1}{ZT} = \frac{(L_0^b + NL_0^s)(L_2^b + NL_2^s + (\kappa_{ph} + N\kappa_{ph}^s)T)}{(L_1^b + NL_1^s)^2} - 1$$

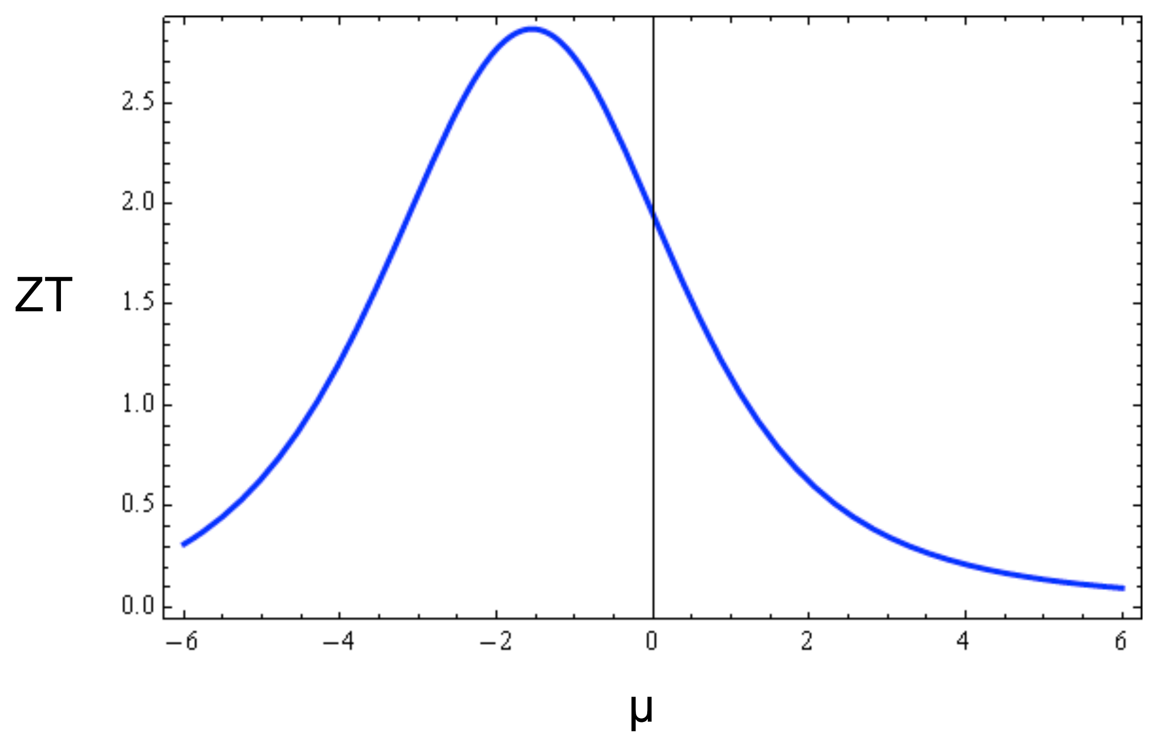
$$L_\alpha = L_\alpha^b + NL_\alpha^s$$

$$\kappa_{ph} \approx 0.01 \mathrm{Wm}^{-1}\mathrm{K}^{-1}$$

$$ZT_{2D} = \lim_{n\to\infty} ZT = \frac{(L_1^s)^2}{L_0^s(L_2^s + \kappa_{ph}^s T) - (L_1^s)^2}$$

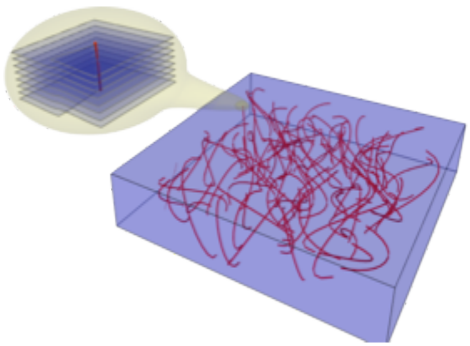
Tretiakov, Abanov, Sinova (in preparation) 2011

Preliminary results (week ago)



Summary of topological thermoelectrics

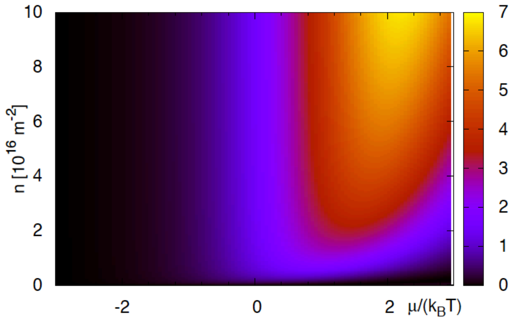
•Qualitative theory was developed on how to increase *ZT* in topological insulators via line dislocations.



•The interplay of topologically protected transport through the dislocations and Anderson insulator in the bulk.

•Estimated *ZT* ~ 10 at room temperature.

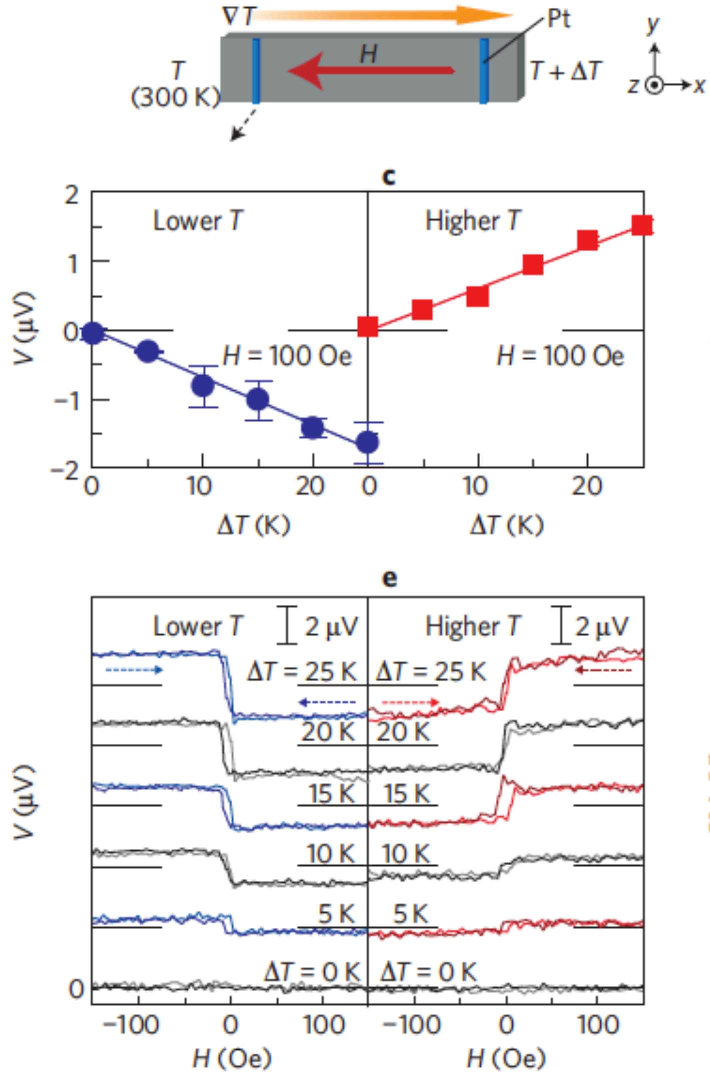
•Idea can be extended to the entire range of TI

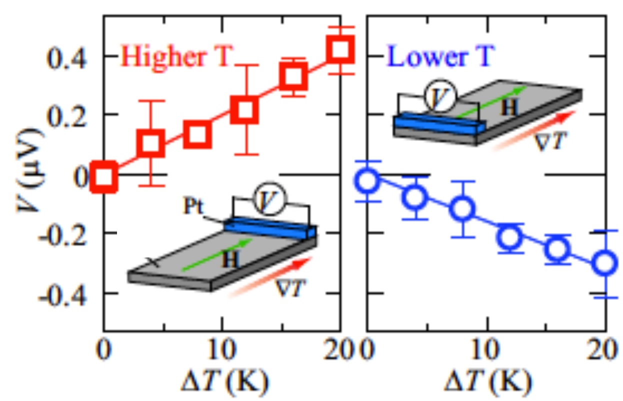


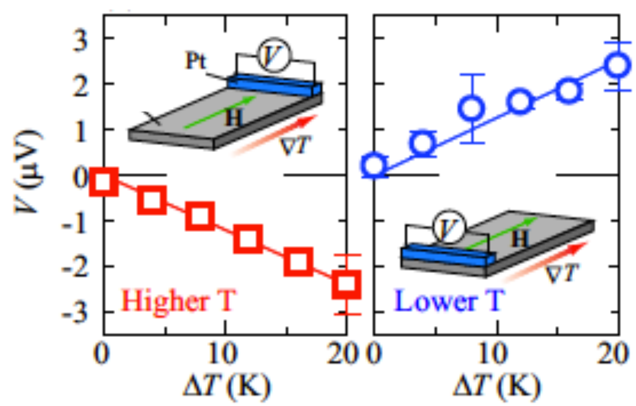
NOW SOME RANDOM THOUGHTS FROM THIS WEEK: DISCUSSION TIME

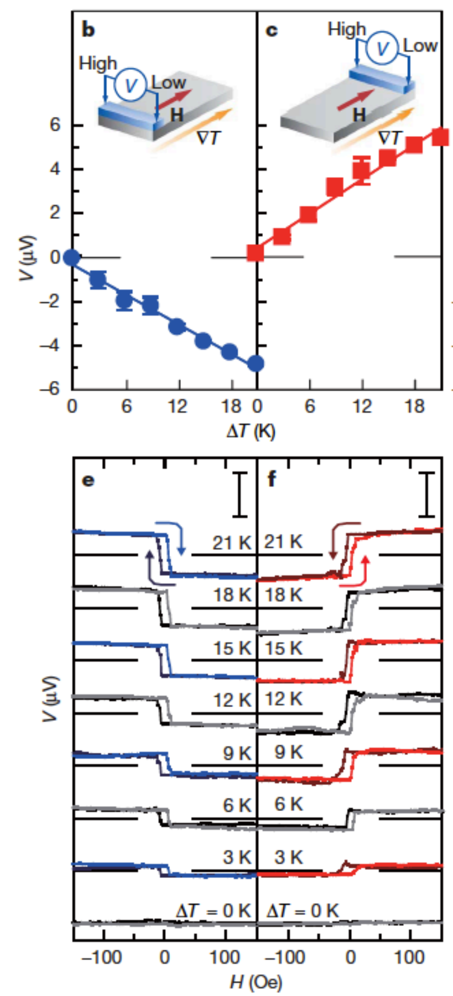
Which one is which?

Spin Seebeck? or Spin ....something? (Ron Jansen)

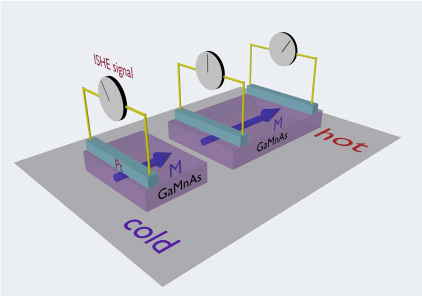








THINGS HAVE GOTTEN MORE SOPHISTICATED SINCE THE NAME DEBATE



- More experiments in more materials (Spin Seebeck)
  - Several teams see the same effect.
  - Phonon’s on the substrate playing a key role
  - Sign changes with different materials
  - Experiments are a bit too complicated (too many competing thing; sometime more does not lead to better understanding)

- Theory of Spin Seebeck (an evolution): some progress and some difficulties
  - There seems to be agreement on the mechanism that injects the spin-current (spin-pumping); is it the only one possibility?
  - Different scenarios that create the non-equilibrium condition for finite spin pumping (magnon-phono drag, Sanders-Walton)
  - SIGN PROBLEM: if correct the theory has problems

- Magnetic heat engines: a clear definition of ZT in magnetic systems
  - AGAIN: is there a ZT (e.g. can one create a heat engine) from spin Seebeck?

Checks (Japan Group)

Spin Seebeck measured in different materials: Ni (opposite sign) and Fe

BUT ISHE FMR measurement gives same sign!!!

Did not try non-ferromagnetic metals

No V(ISHE) signal seen when:

- Permalloy without Pt bar contacts
- When whole sample is made of Pt
- Permalloy with Cu leads
- If $\Delta T = 0$
- In YIG, SiO_2 between the Pt (this check is not done in FeNi)

Checks (OSU Group)

- **Bilayer system: WHY additive; why GaMnAs overwhelms MnAs? Obviously exchange bias plays a role but how? Shouldn't the focus be to simplify (YT)**
- GaMnAs (Magnetic Semiconductor) measured as a function of T
- Measured paramagnetic sample with Pt contacts = 0 signal
- Did measurements to try to exclude the Planar Nernst contributions
- Measured transverse V w/ Pt point contacts, one observes Nernst contribution and ISHE (Nernst overpowers?)

Wish lists of Checks (To do)

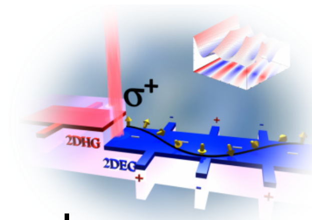
- Kerr Microscopy??
- Measure regular Seebeck in cut samples (as a thermometer)
- Different widths of Pt and sample
- Instead of cut, remove the sapphire and leave a slip (done)
- Metal with Pt strip (check missing from Japanese group) (done?)
- Heat pulse experiments (heat solitons) - form DC to AC
- Separate contacts on edges of sample and Pt strip (measure a vertical voltage?)
- How does signal depend on geometry of Pt (ex. bigger depth leading to shorting)

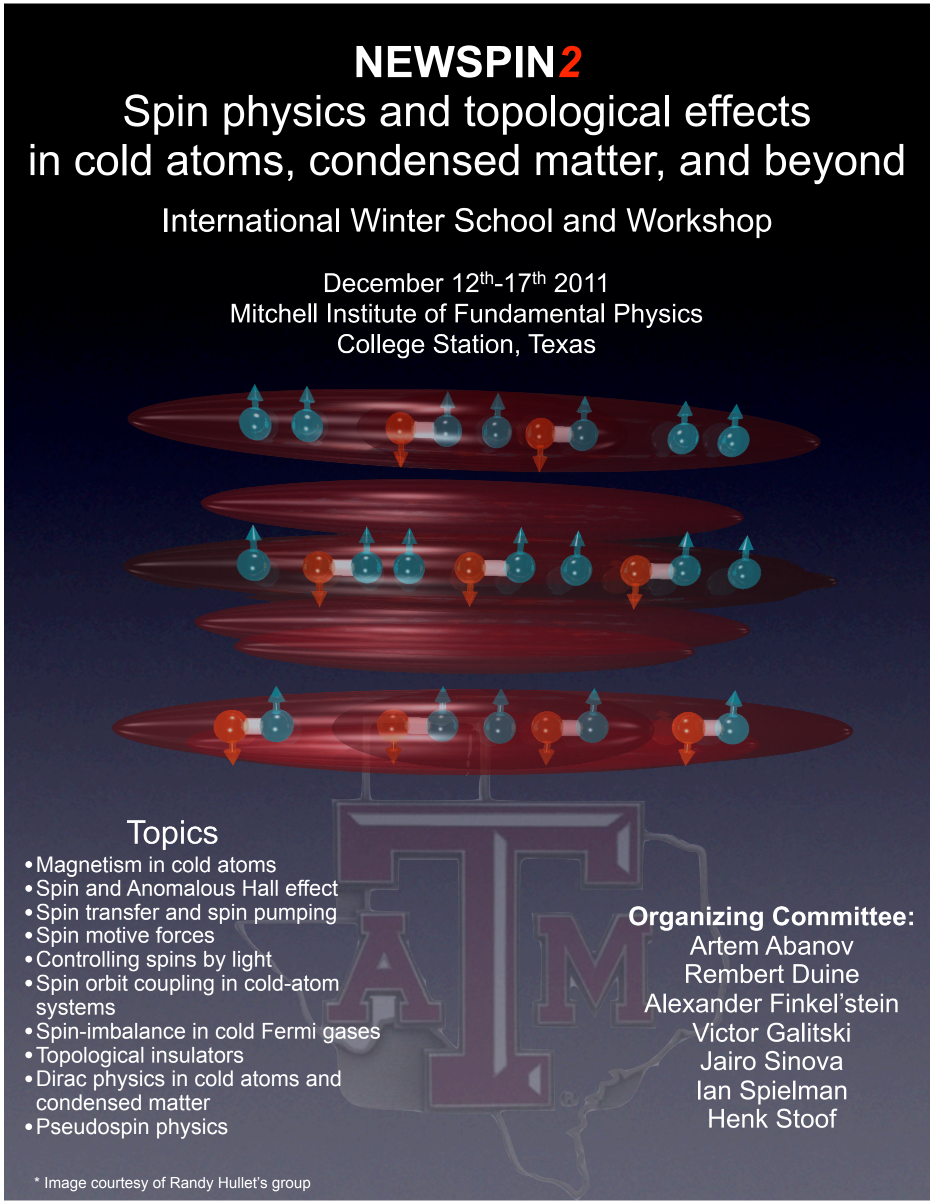
We need to do the spin caloritronics tango

It IS true that it takes two to tango

BUT it takes MANY to do the spin caloritronics tango!!

Spin in Cold Atoms and CM systems





3 day Winter School
and 3 day Workshop

http://newspin2.physics.tamu.edu/