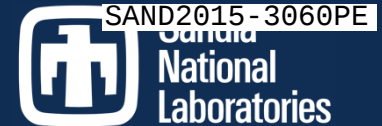


*Exceptional service in the national interest*



# Hybridizing superconductors and topological matters

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**Sandia National Laboratories**

**4/28/2015 @ UT Dallas**



Office of  
Science



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**User facilities:**

- **National High Magnetic Field Laboratories (FSU)**
- **Center for Integrated Nanotechnologies (LANL and SNL)**



## **1. Superconductors**

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## **2. Topological matters**

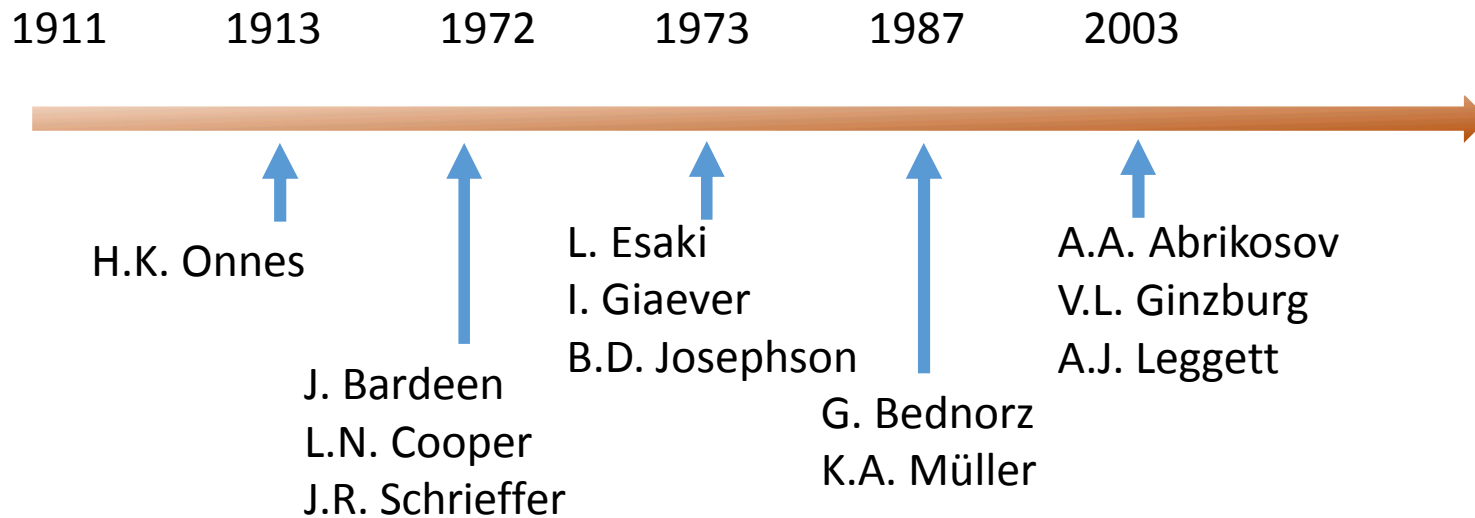
## **3. Hybridizing superconductors and topological matters**

## **4. Outlook**

# 1. Superconductors



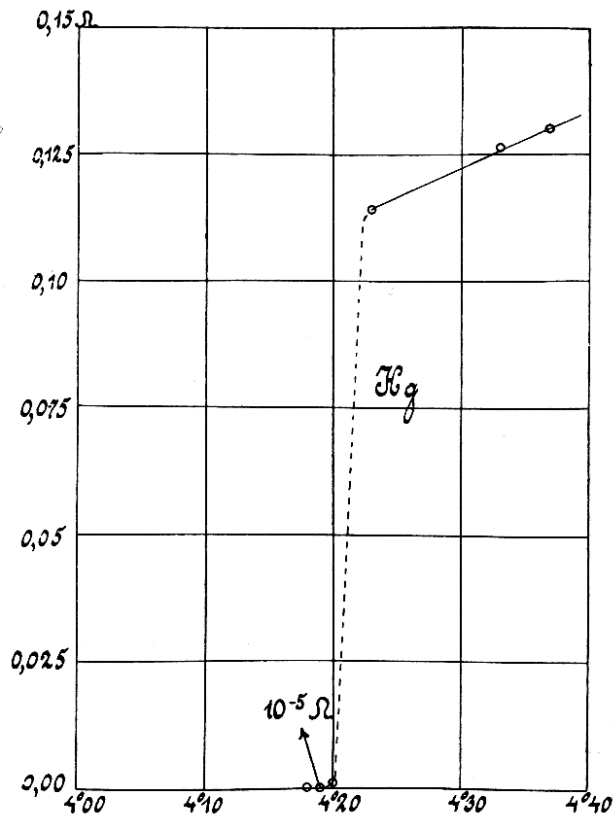
## Nobel Prize for Superconductivity



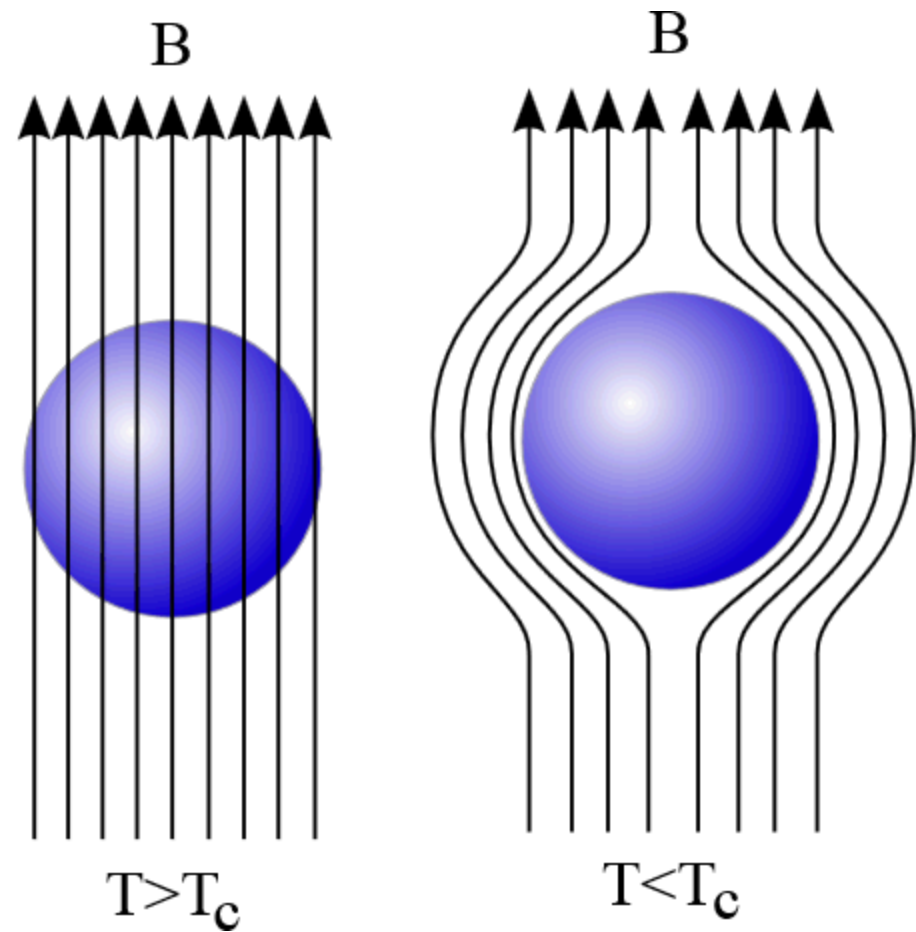
# What is superconductivity?

## Two characteristic properties

### 1. Zero electrical resistance



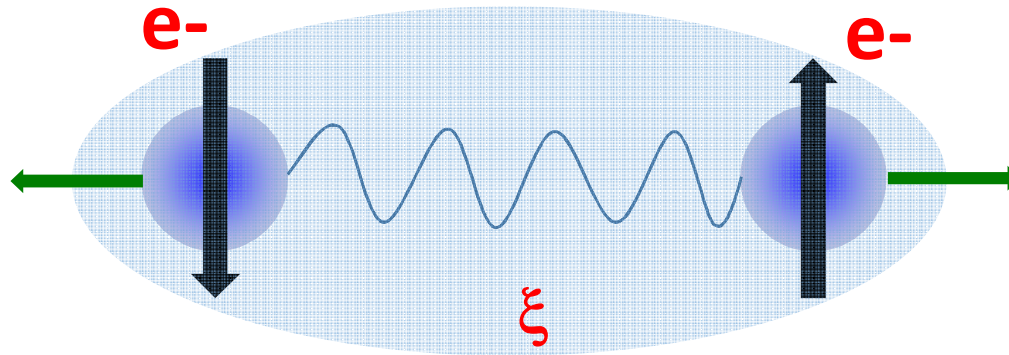
### 2. Meissner effect (expulsion of magnetic fields)



# What is superconductivity?

BCS picture:

- Superconductivity is a macroscopic quantum condensate of Cooper pairs



- Superconducting wavefunction

$$\psi \propto \psi_0 e^{-i\phi}$$

# Element Superconductors

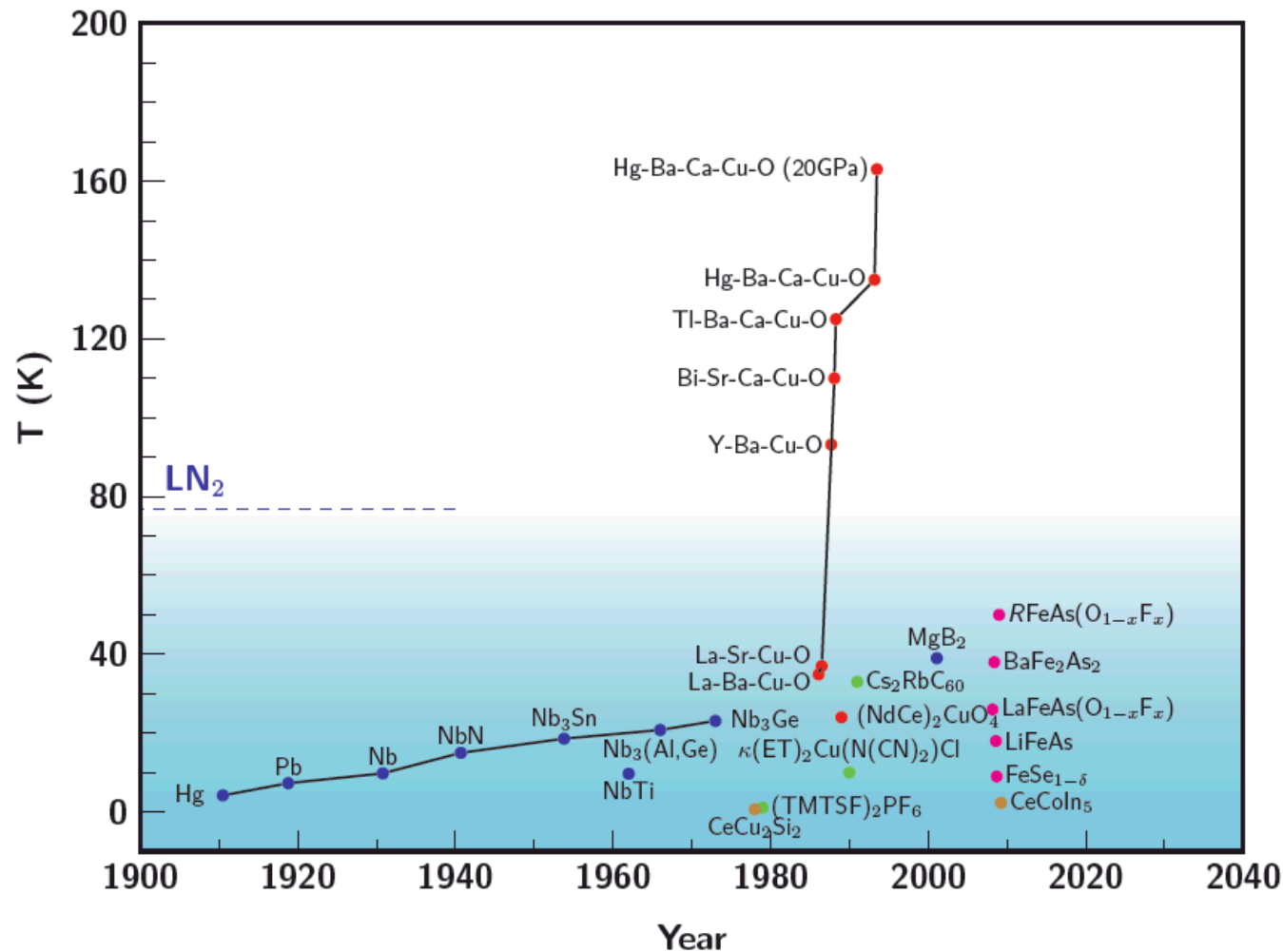
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| KNOWN SUPERCONDUCTIVE ELEMENTS |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| </                             |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |

\* Lanthanide Series

+ Actinide Series

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|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|
| 58<br>Ce | 59<br>Pr | 60<br>Nd | 61<br>Pm | 62<br>Sm | 63<br>Eu | 64<br>Gd | 65<br>Tb | 66<br>Dy | 67<br>Ho | 68<br>Er  | 69<br>Tm  | 70<br>Yb  | 71<br>Lu  |
| 90<br>Th | 91<br>Pa | 92<br>U  | 93<br>Np | 94<br>Pu | 95<br>Am | 96<br>Cm | 97<br>Bk | 98<br>Cf | 99<br>Es | 100<br>Fm | 101<br>Md | 102<br>No | 103<br>Lr |

# Evolution of superconductors



- Elements and conventional SCs
- High T<sub>c</sub> cuprates
- Iron-based SCs
- Heavy fermions
- Organic SCs

# My research on cuprates

In  $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$

1. Change Sr doping. Charge glass **coexists** and **competes** with SCFs at low T.

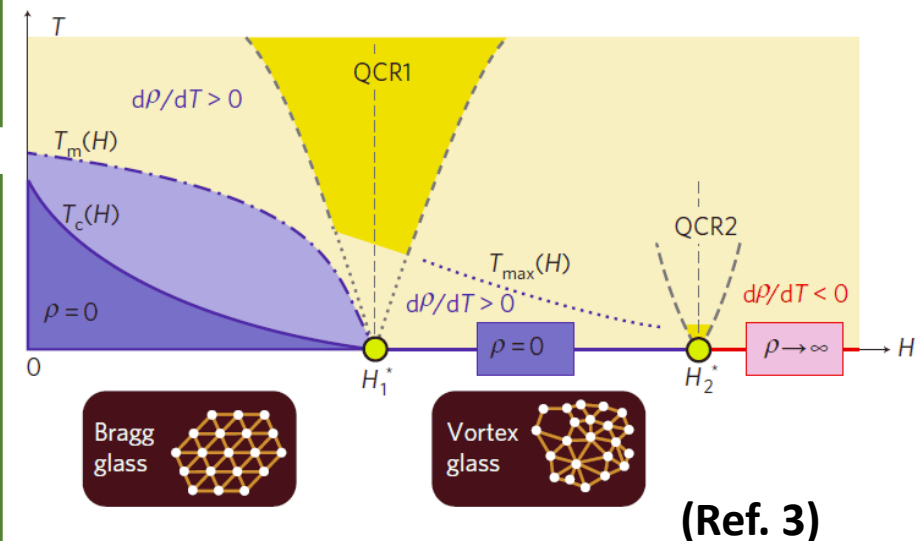
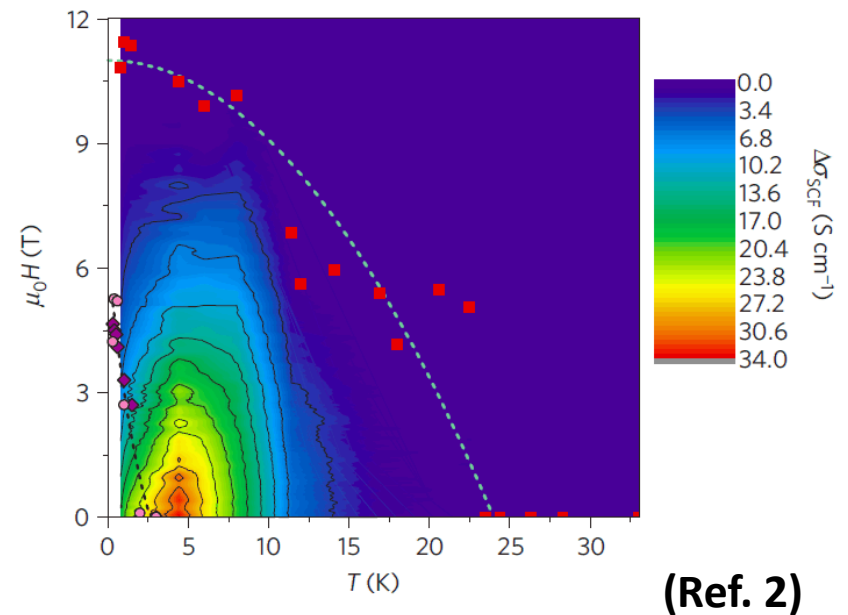
Emergence of SC. (Ref. 1,2)

2. Tuning H field. Two quantum phase **transitions** in H-tuned superconductor-insulator transition (SIT). Two steps. (Ref. 3)

3. Tuning T in zero field. **Berezinskii-Kosterlitz-Thouless** transition. (Ref. 4)

## Publications:

1. X. Shi, et al., **Physica B**, 407, 1915 (2012)
2. X. Shi, et al., **Nature Materials**, 12, 47 (2013)
3. X. Shi, et al., **Nature Physics**, 10, 437 (2014)
4. X. Shi, et al., in preparation (2015)



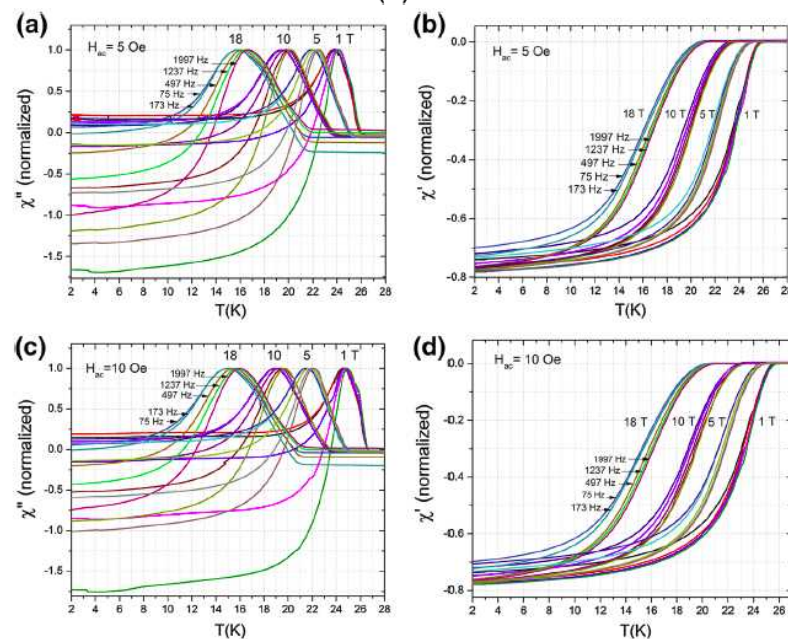
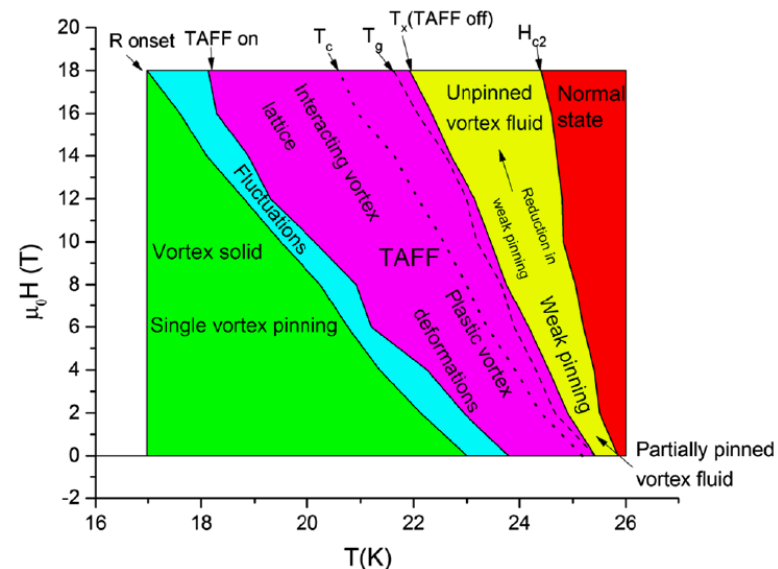
# My research on pnictides

## In $\text{Ba}(\text{FeAs})_2$ samples

1. Doping effect. Transport studies on  $\text{Ba}(\text{FeCo})_2\text{As}_2$ ,  $\text{Ba}(\text{FeNi})_2\text{As}_2$ ,  $(\text{BaK})\text{Fe}_2\text{As}_2$ .
2. New and detailed phase diagram for vortex dynamics.
3. Magnetization studies. Ac loss.

## Publications:

1. M. Nikolo, et al., *J. Supercond. Nov. Mag.* 27, 1983 (2014)
2. M. Nikolo, et al., *J. Supercond. Nov. Mag.* 27, 2231 (2014)
3. M. Nikolo, et al., *J. Low Temp. Phys.* 178, 188 (2015)
4. M. Nikolo, et al., *J. Low Temp. Phys.* 178, 345 (2015)



**1. Superconductors**

**2. Topological matters**

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**3. Hybridizing superconductors and topological matters**

**4. Outlook**

## 2. Topological matters



### Nobel Prize for Topological Matters

1879

1985

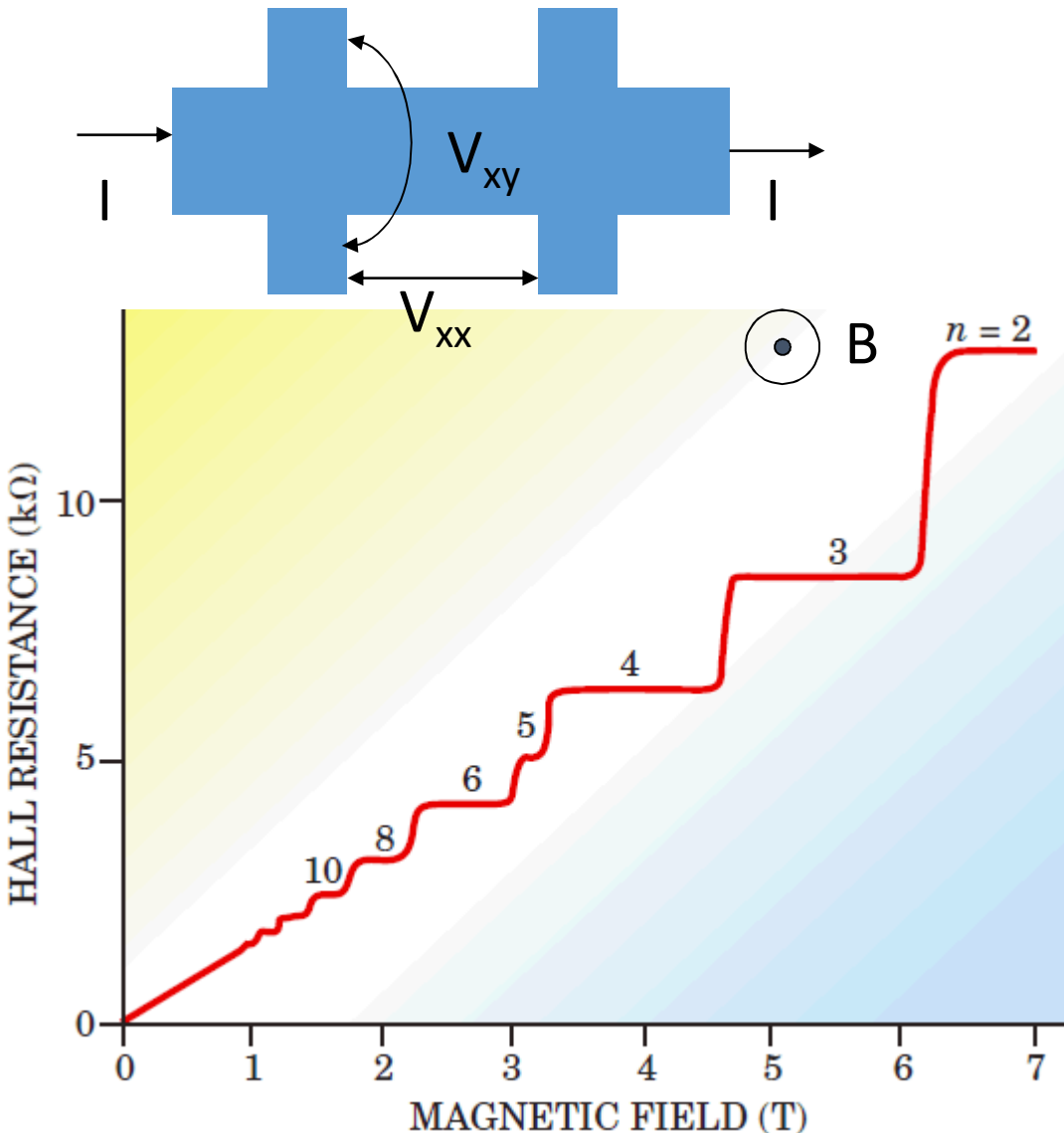
1998

K. v. Klitzing  
**Integer quantum Hall effect**

R.B. Laughlin  
H.L. Störmer  
D.C. Tsui

**fractional quantum Hall effect**

# Integer quantum Hall effect



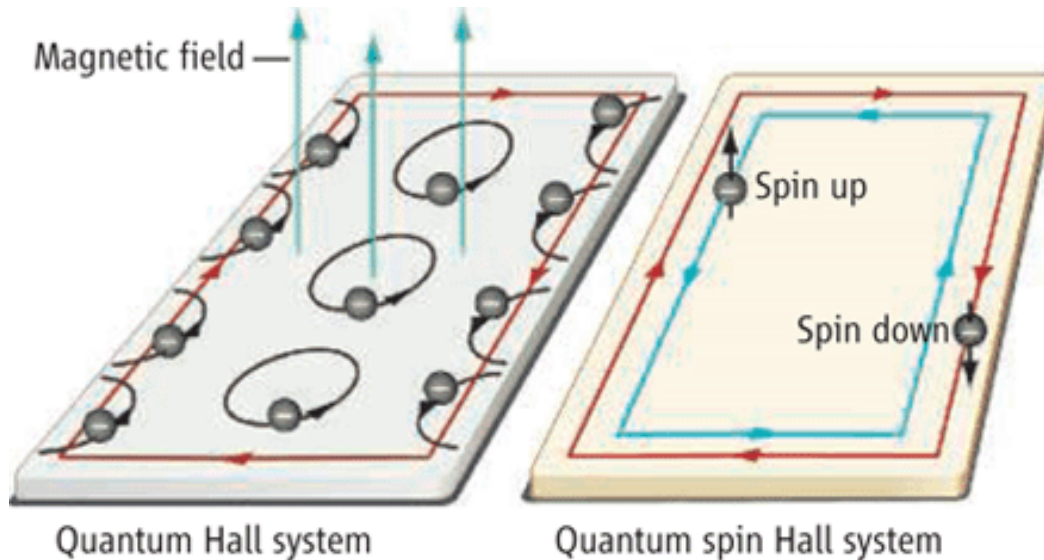
Low temperature observations in 2DEG:

$$\sigma_{xx} = 0$$

$$\sigma_{xy} = n \frac{e^2}{h}$$

- IQHE is robust
- Insulating bulk and conductive edge

# From IQHE to QSHE

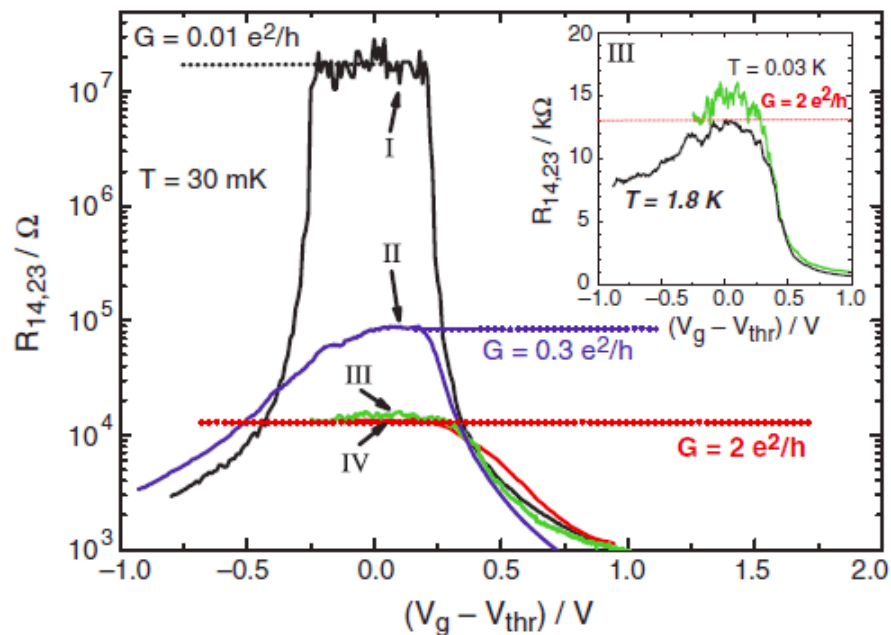


N. Nagaosa, Science, 318, 758 (2007)

- Strong **spin-orbital interaction** → **lock of momentum and spin**
- **QSHE=two copies of IQHE**
- **No need for external field**
- **QSHI is a 2D TI: insulating bulk and conductive edge**

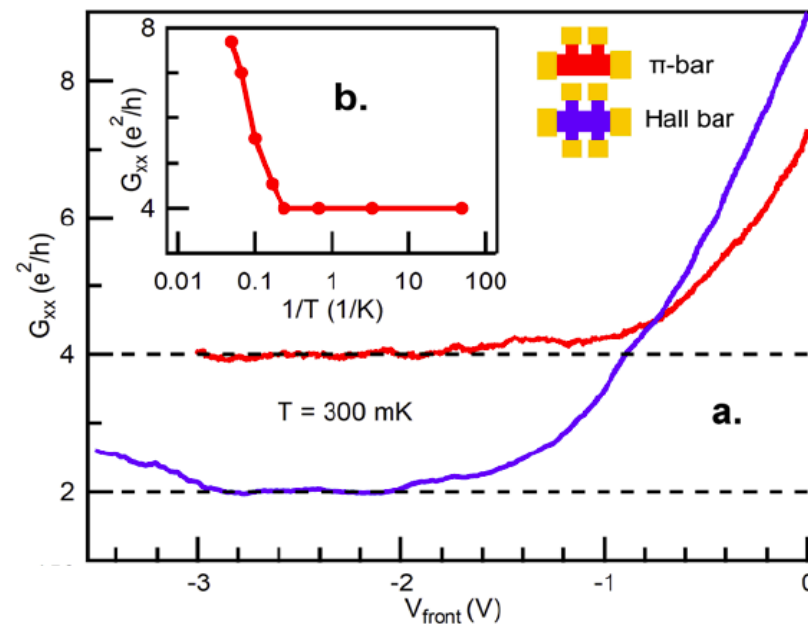
# Topological insulator in 2D

## HgTe/HgCdTe quantum well



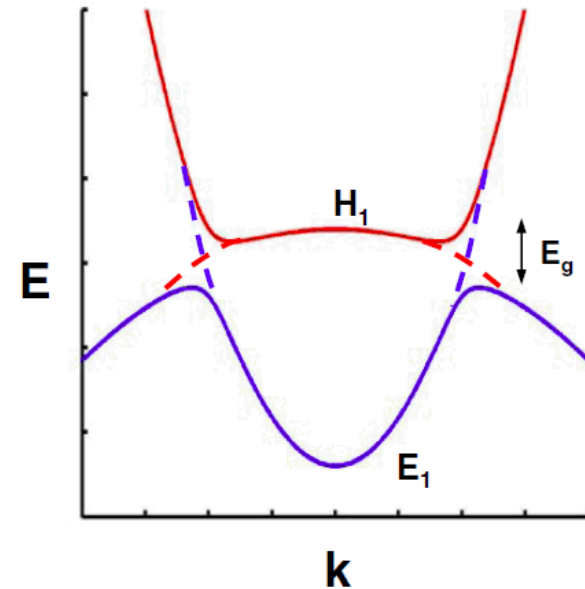
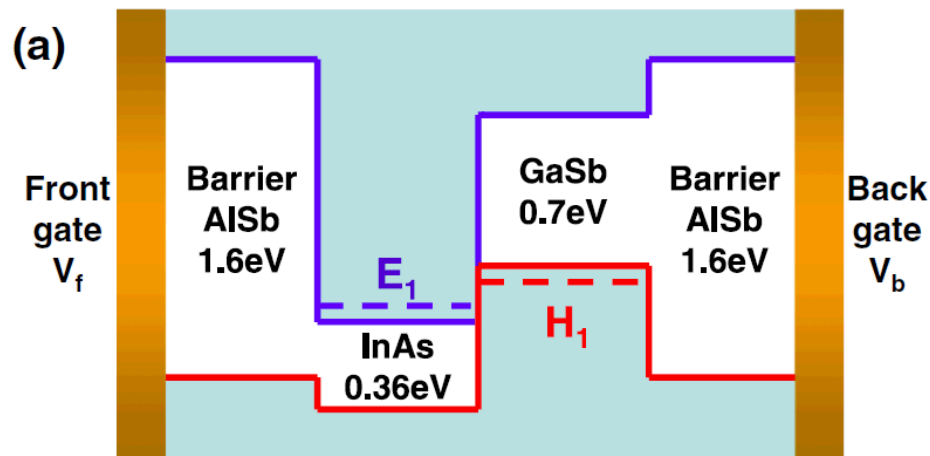
M. König, et al., Science, 318, 766 (2007)

## InAs/GaSb quantum well bilayer



L. Du, et al., Phys. Rev. Lett., 114, 096802 (2015)

# Band structure of InAs/GaSb

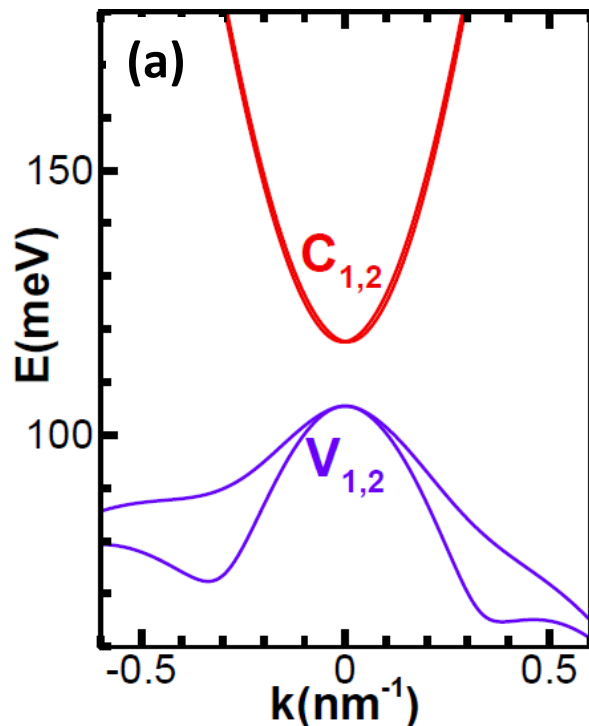


**Theoretic calculation:  
inverted InAs/GaSb is a 2D topological insulator**

C. Liu et al., Phys. Rev. Lett. 100, 236601 (2008)

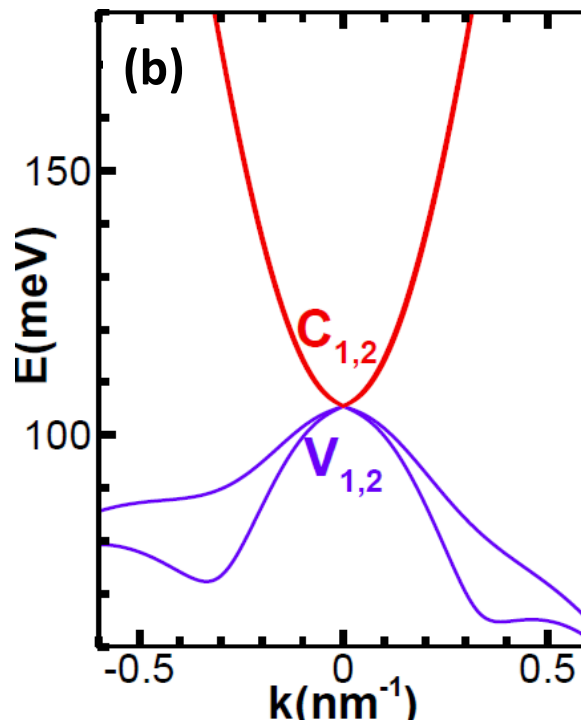
## 8-band k.p calculation (fix GaSb quantum well width=5nm)

Type I

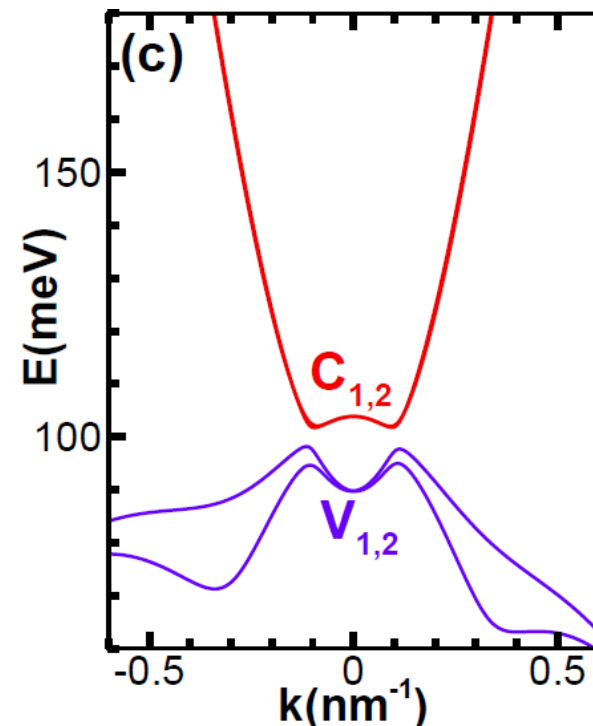


Topological trivial  
 $d > 10$  nm (InAs)

Type II



critical QW width  
 $d = 10$  nm (InAs)



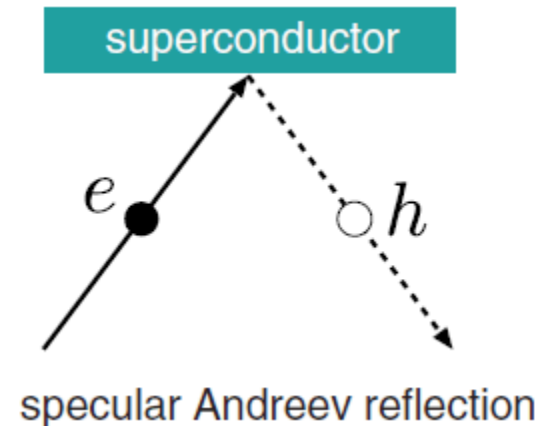
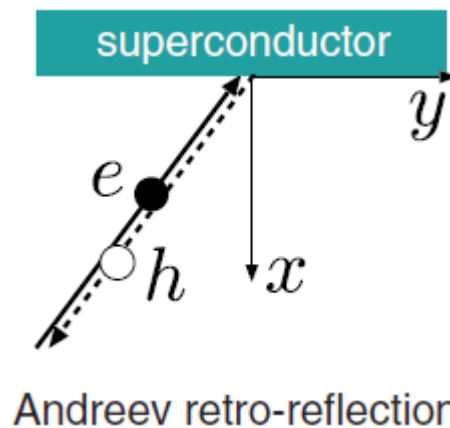
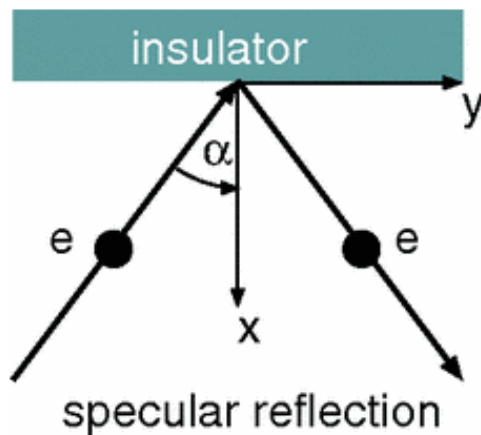
Topological insulator  
 $d < 10$  nm (InAs)

1. Superconductors
  2. Topological matters
  3. Hybridizing superconductors and topological matters
- 
4. Outlook

# 3. Hybridizing SC and TI

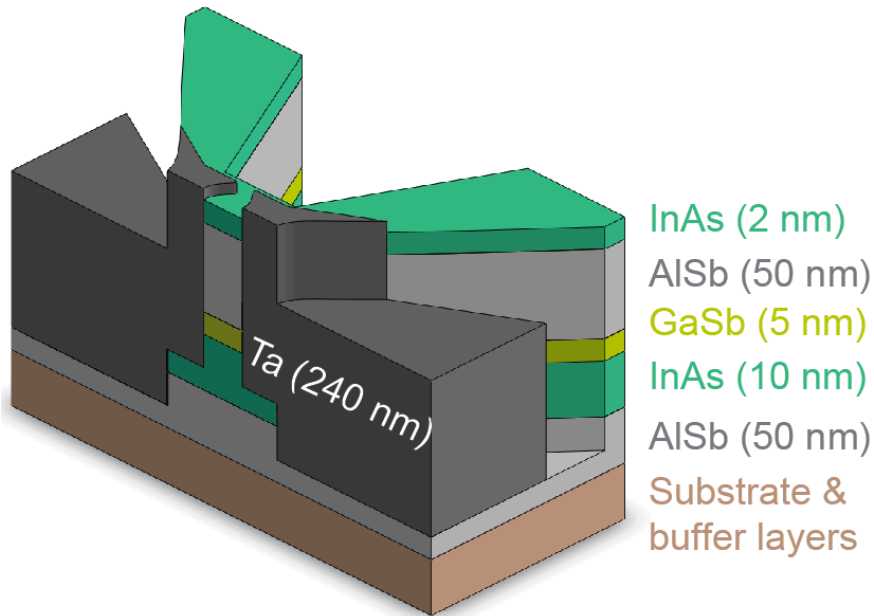
## Importance of a S-N interface

1. **Proximity effect.** Leak of superconductivity into normal metal
2. **Andreev reflection.** Electron-hole conversion



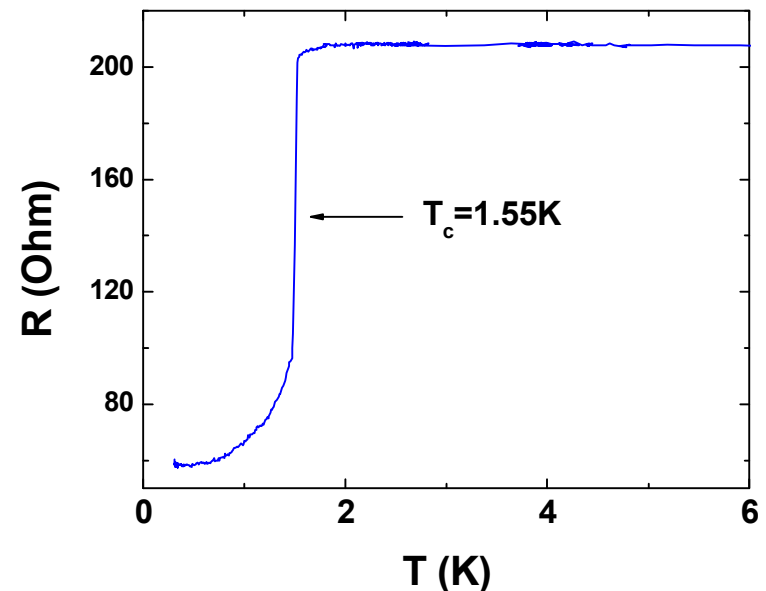
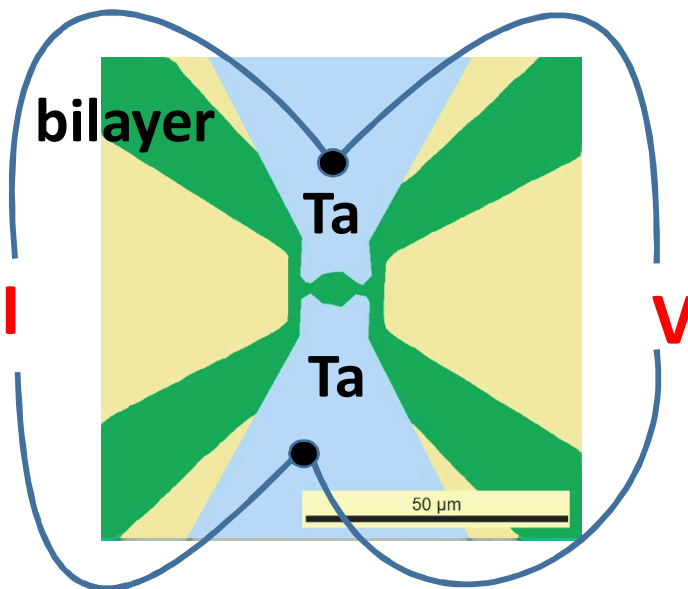
C. W. J. Beenakker, Phys. Rev. Lett. 97, 067007 (2006)  
C. W. J. Beenakker, Rev. Mod. Phys. 80, 1337 (2008)

# Experiment: S-N-S junction

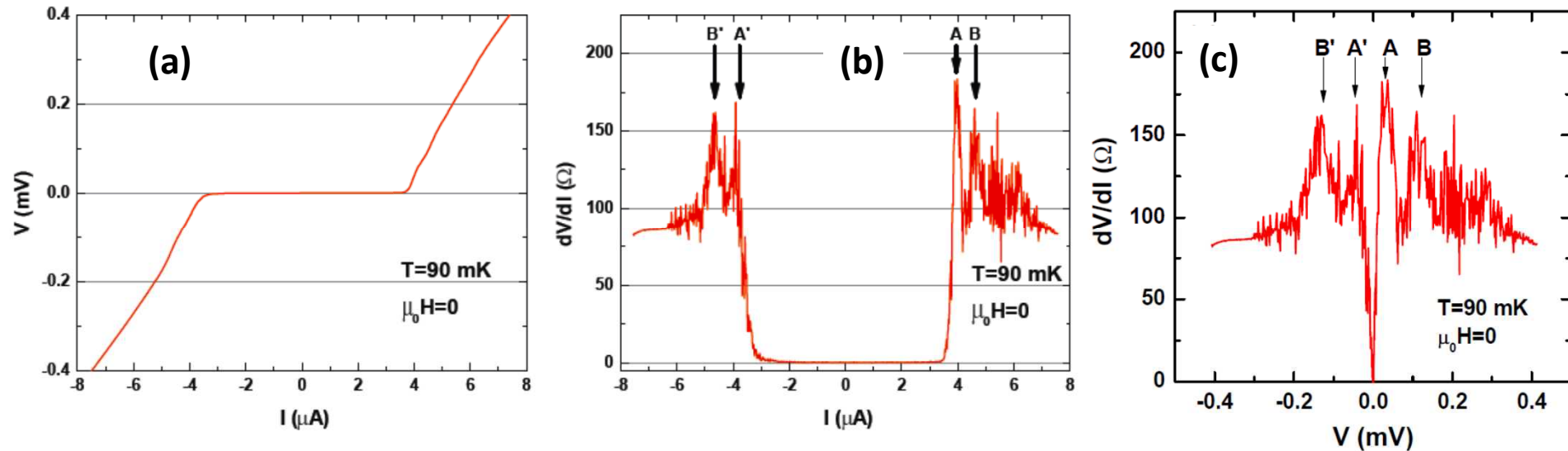


## Ta-InAs/GaSb-Ta junction

- Ta is a s-wave SC
- Clean interface
- S-N-S junction
- **Critical InAs QW width:  $d=10$  nm**
- **LARGE Junction:  $W=12\text{ }\mu\text{m}$   $L=2\text{ }\mu\text{m}$**

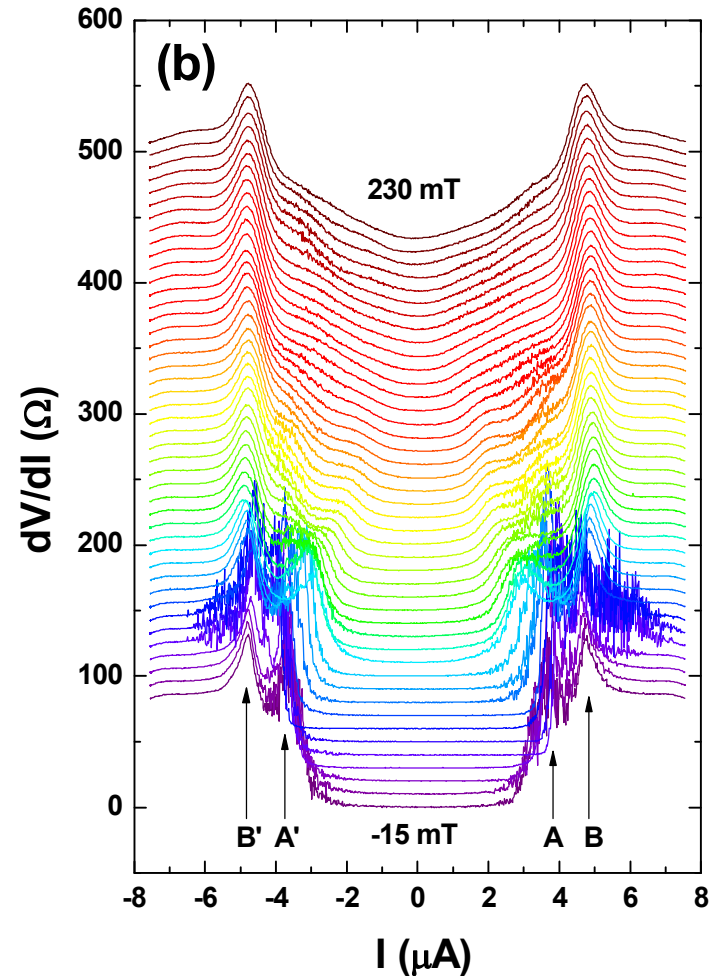
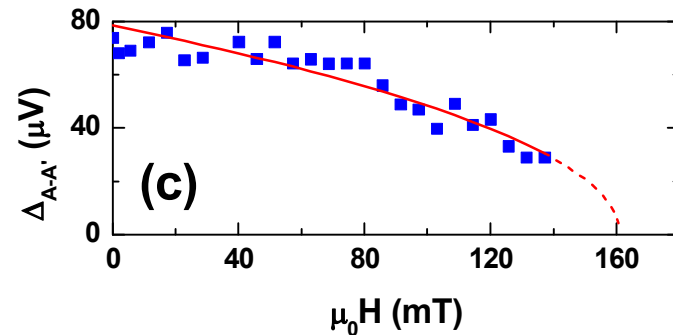
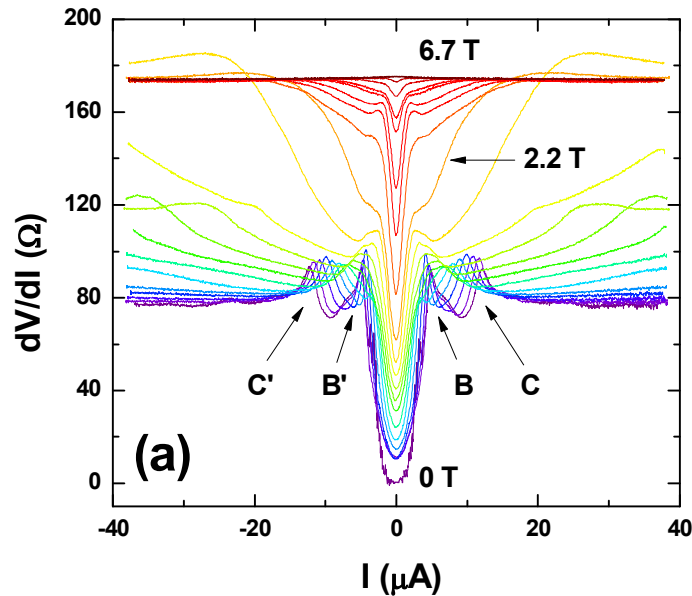


# Observation of supercurrent



- $I_c \sim 3.5$   $\mu$ A
- Random oscillations (vanish quickly as H field applied)
- Multiple peaks

# Magnetic Field dependence

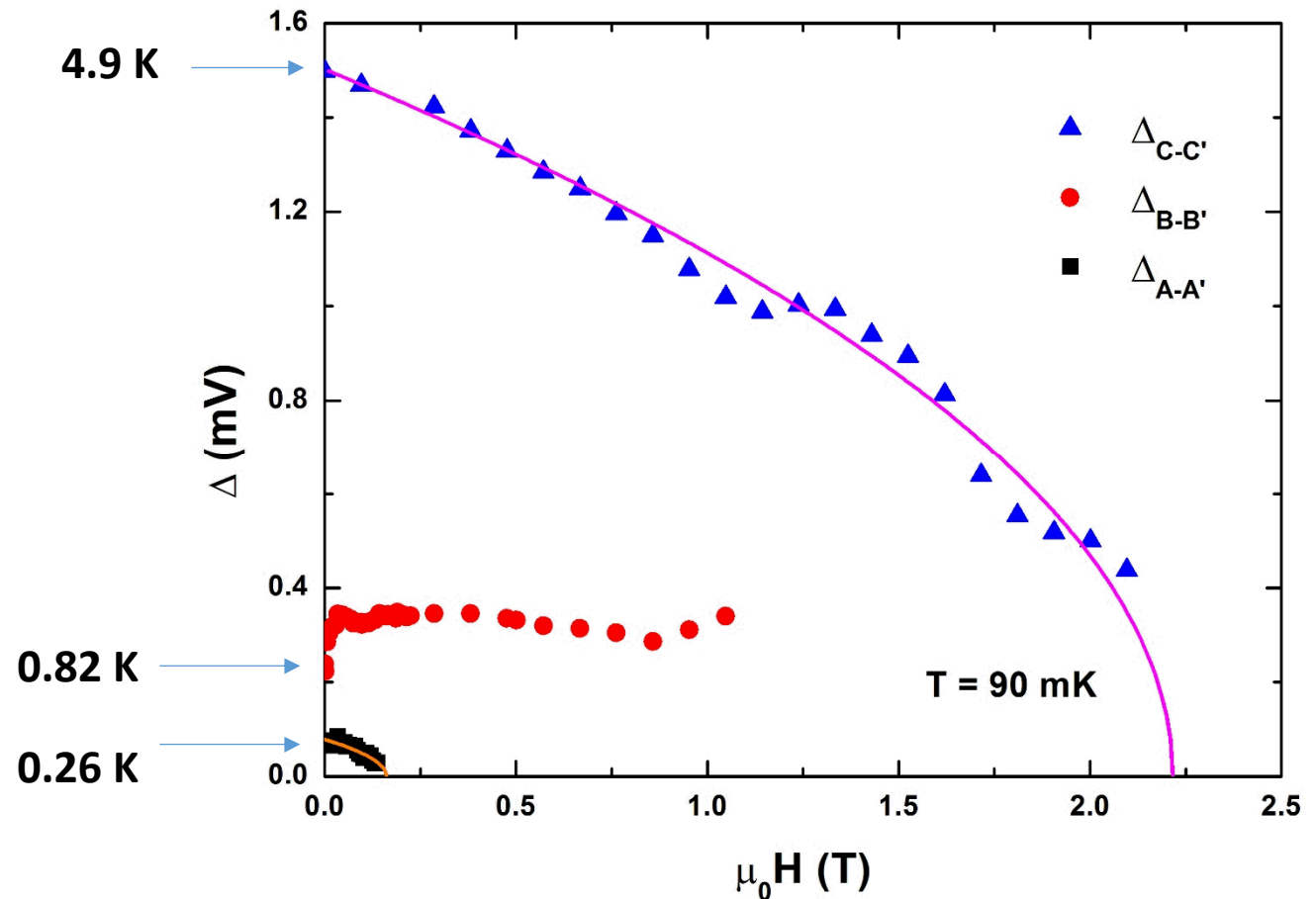


- 3 pairs of peaks  $\Rightarrow$  3 energy scales
- Need  $\mu_0 H > 5.7$  T to fully recovery the normal state
- BCS fit for AA' pair  $\Delta$  ( $\mu V$ ) =  $78.3 (1 - H/161 \text{ mT})^{1/2}$

# Gap evolution

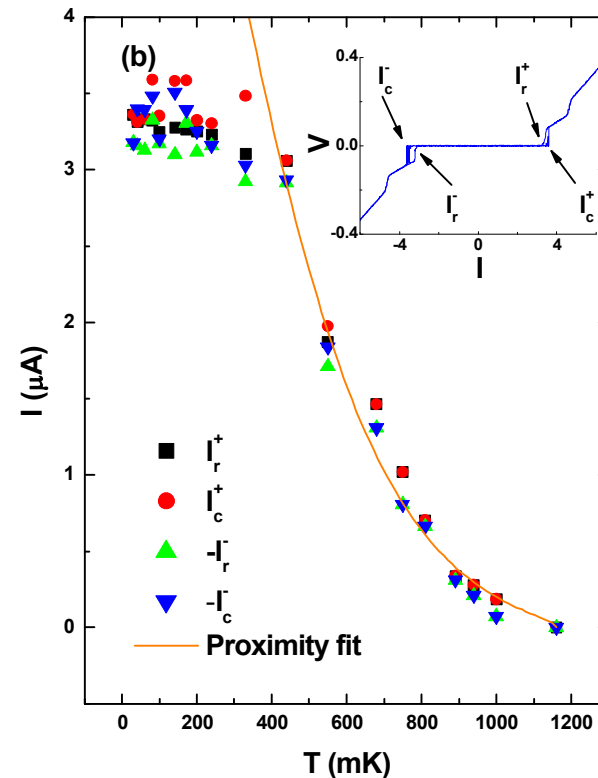
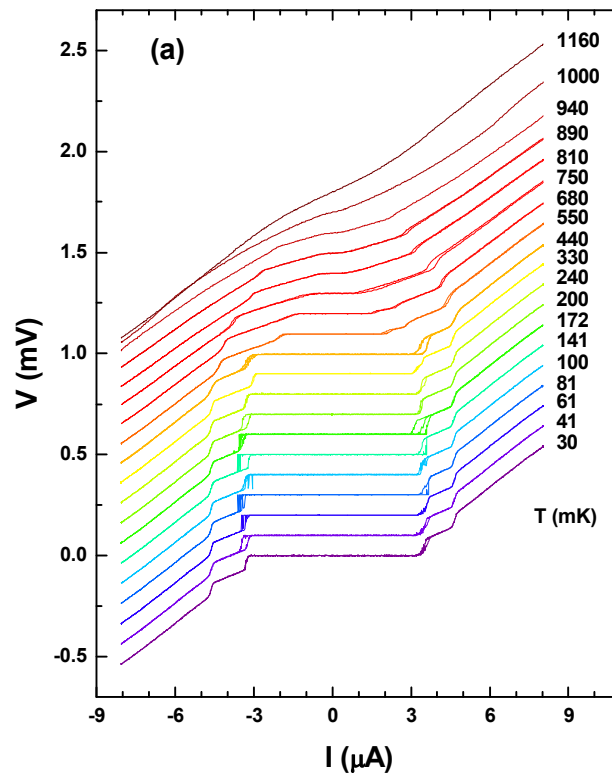
Note:

BCS gap:  $\Delta = 1.76 k_B T_c$



- Different field dependence indicates three different superconductors
- Field enhanced superconductivity

# T dependence



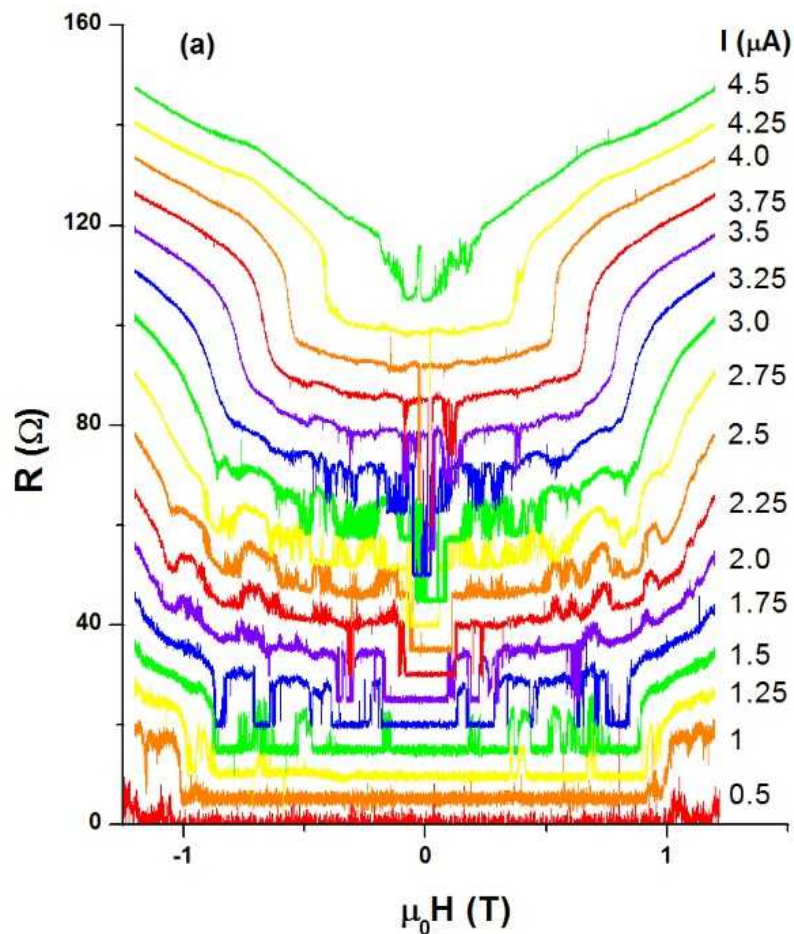
- $T_c$ : 1.16 K
- Small hysteresis

- Proximity-induced SC

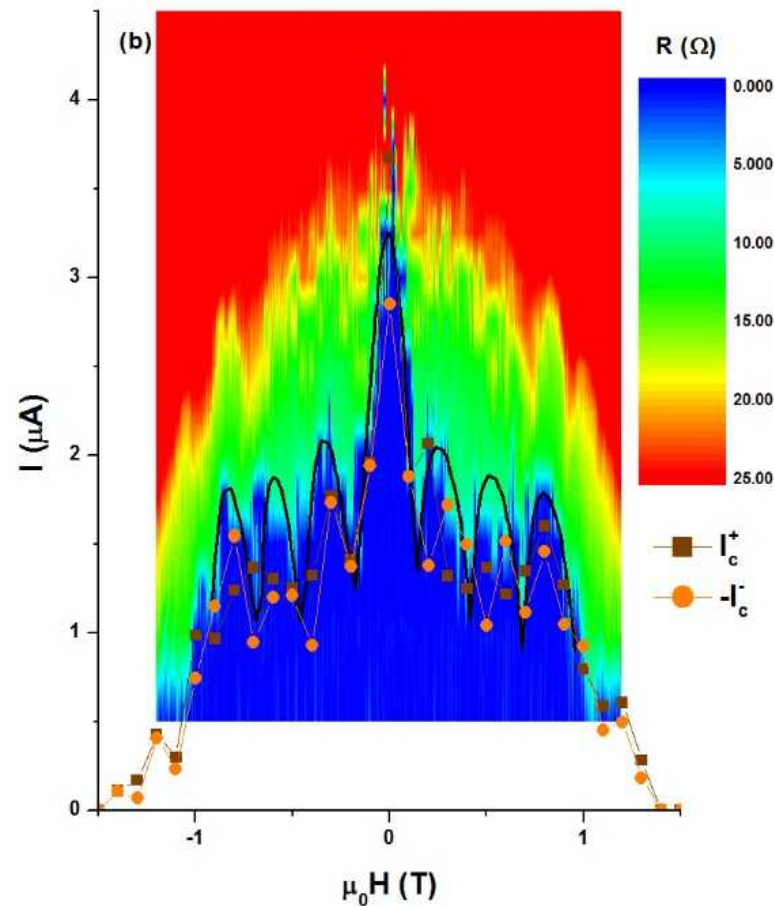
$$I_c \propto \left( \frac{\Delta_N(T)}{\cosh[L/2\xi_N(T)]} \right)^2 \frac{1}{\xi_N(T)}$$

- coherence length of the bilayer 480 nm

# Quantum interference

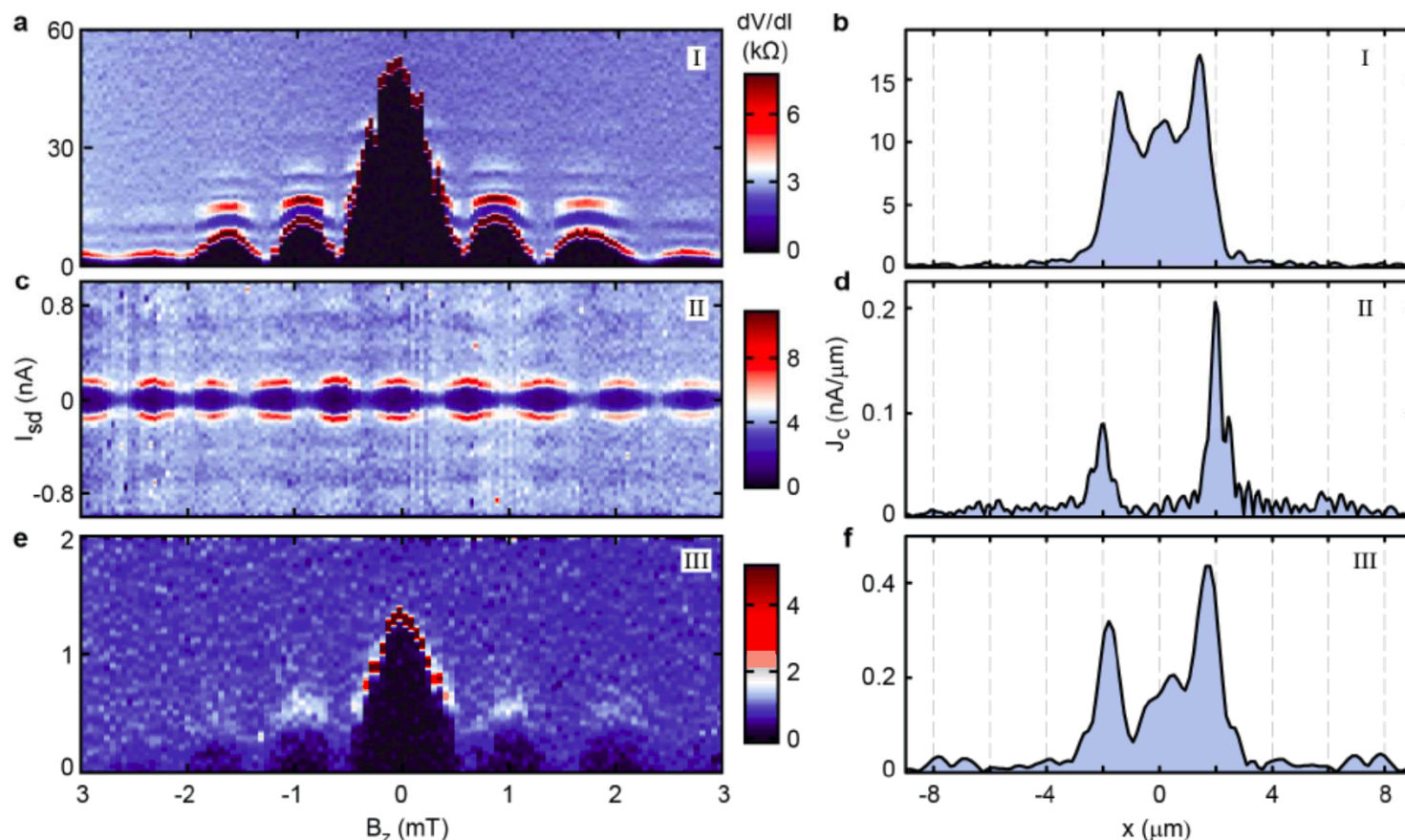


- $H_c = 1 \text{ T} \gg 0.082 \text{ T}$   
(bulk  $H_c$ )



- Fraunhofer-like pattern  
 $300 \Phi_0/\text{lobe}$  !

# Comparing to a short junction



Experiments: (short junction, inverted region)  
Detecting the edge state superconductivity

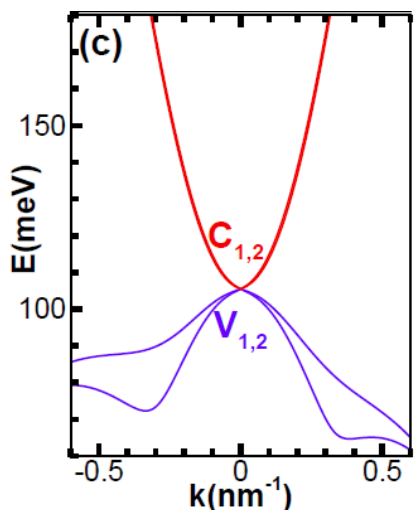
Pribrig et al., ArXiv:1408.1701

400 nm vs. 2000 to 4000 nm

# Giant induced SC

|                 | This research<br>Arxiv: 1410.7342   | Pribiag et al.,<br>ArXiv:1408.1701        |
|-----------------|-------------------------------------|-------------------------------------------|
| Sample          | $d=d_c$<br>(critical, Dirac cone)   | $d>d_c$<br>(inverted)                     |
| Superconductor  | Ta                                  | Al                                        |
| Junction        | Long<br>( $2 \gg 0.08 \text{ um}$ ) | Short<br>( $0.4-0.6 \ll 2-4 \text{ um}$ ) |
| Induced sc      | Edge+bulk                           | Edge+bulk                                 |
| $T_c$           | 1.16 K                              | 0.13 K (?)                                |
| $J_c$ (nA/um)   | 350                                 | 15                                        |
| $\mu_0 H_c$ (T) | 1                                   | 0.011                                     |

# Summary of this experiment



Ta (S)

**Critical width**  
**InAs/GaSb (QSH)**

Ta (S)

$$n = 1.8 \times 10^{11} \text{ cm}^{-2}$$
$$\mu = 1.17 \times 10^5 \text{ cm}^2/\text{Vs}$$
$$E_F = 0.5 \text{ meV or } 5.6 \text{ K}$$

More details:

Shi et al., Arxiv: 1410.7342

## Sample:

- **Critical QW width: Dirac-cone**
- **Long junction**  
 $L (2\text{mm}) \gg \xi (78 \text{ nm})$
- **Clean sample**  
 $l (822 \text{ nm}) \gg \xi (78 \text{ nm})$

## Observations:

- **Giant proximity-induced SC**  
 $T_c = 1.16 \text{ K}$ ,  $H_c = 1 \text{ T}$ ,  $I_c = 3.5 \text{ } \mu\text{A}$
- **Both edge and bulk SCs**
- **H-enhanced superconductivity**

1. Superconductors
  2. Topological matters
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-

# A big family of ...

## Topological Matters

| Dimension | System | Type       | Symmetry            | Materials                                                                |
|-----------|--------|------------|---------------------|--------------------------------------------------------------------------|
| 2D        | TI     | 1D edge    | Time reversal       | InAs/GaSb,<br>HgTe/HgCdTe                                                |
| 3D        | TI     | 2D surface | Time reversal       | Bi <sub>2</sub> Se <sub>3</sub> , Sb <sub>2</sub> Te <sub>3</sub> , ...  |
|           | TCI    | 2D surface | Crystal symmetry    | SnTe, (PbSn)Te, ...                                                      |
|           | TKI    | 2D surface | Wavefunction parity | SmB <sub>6</sub> , Ce <sub>3</sub> Bi <sub>4</sub> Pt <sub>3</sub> , ... |

New topological systems ....

QSHI = Quantum Spin Hall Insulator

TI = Topological Insulator

TCI = Topological Crystalline Insulator

TKI = Topological Kondo Insulator

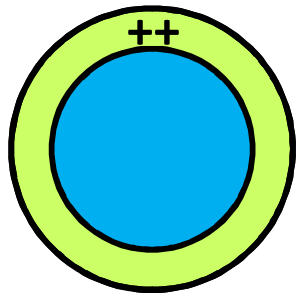
**New state of matters**

**Novel phenomena emerge as superconductors are in proximity of topological matters**

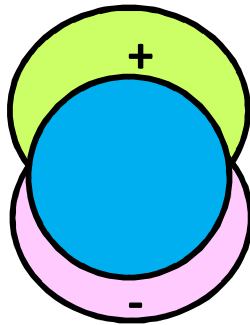
# A big family of ...

## Superconductors

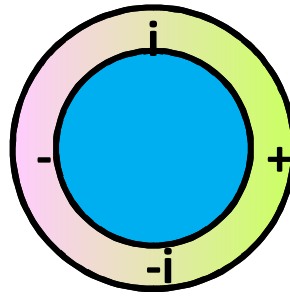
### Varieties of SC gap symmetry



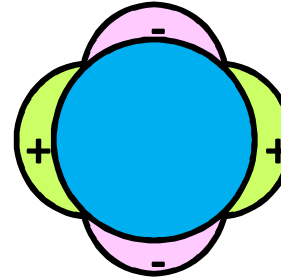
s-wave  
BCS



p-wave  
( $p_y$ )



p-wave  
( $p_x + i p_y$ )



d-wave  
cuprates

s+-  
pnictides

others...

## Studies on hybridized topological matters and superconductors:

- Properties about topological matters
- Novel superconductivity in topological state
- Almost unlimited combination of structures
- New interactions can be introduced. eg. magnetism
- Practical devices and applications
- More...