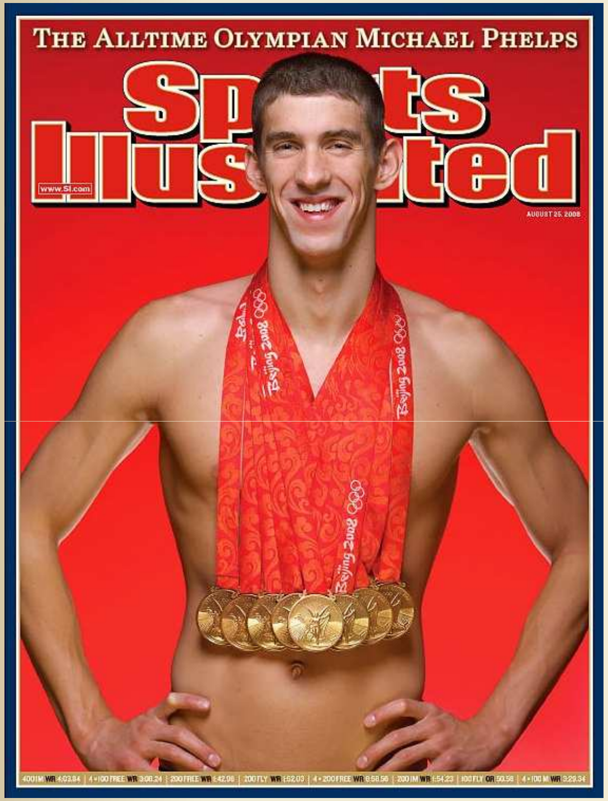
Feb. 04, University of Virginia

2008


THE ALLTIME OLYMPIAN MICHAEL PHELPS
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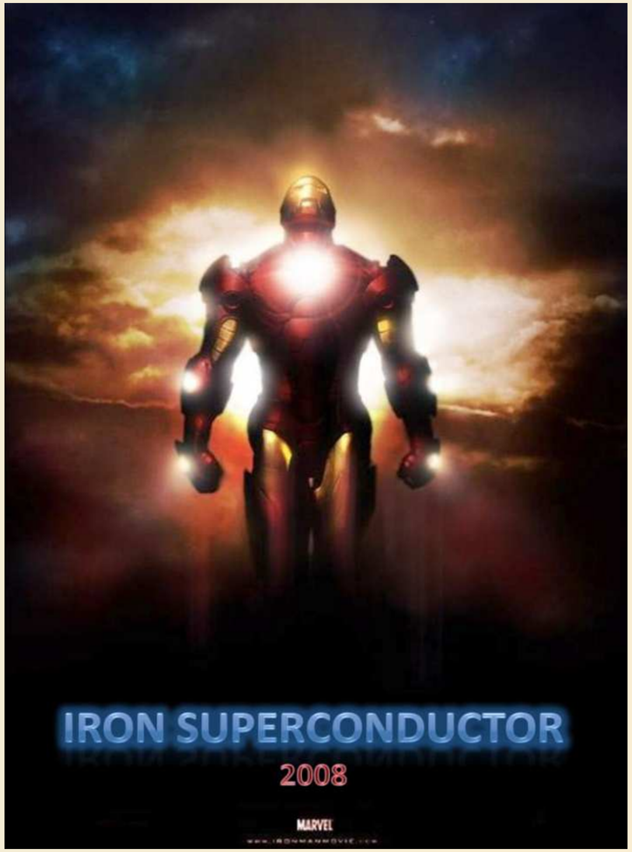

IRON SUPERCONDUCTOR
2008
MARVEL

MIND THE GAP

of

IRON Superconductors

Outline

- **Introduction**
- **Point Contact (PC) spectroscopy**
  - Spin Transfer Torque (STT) Effects
- **Point Contact Andreev Reflection (PCAR) spectroscopy**
  - Spin polarization
  - Superconducting gap
  - Pseudogaps ?
- **Summary**

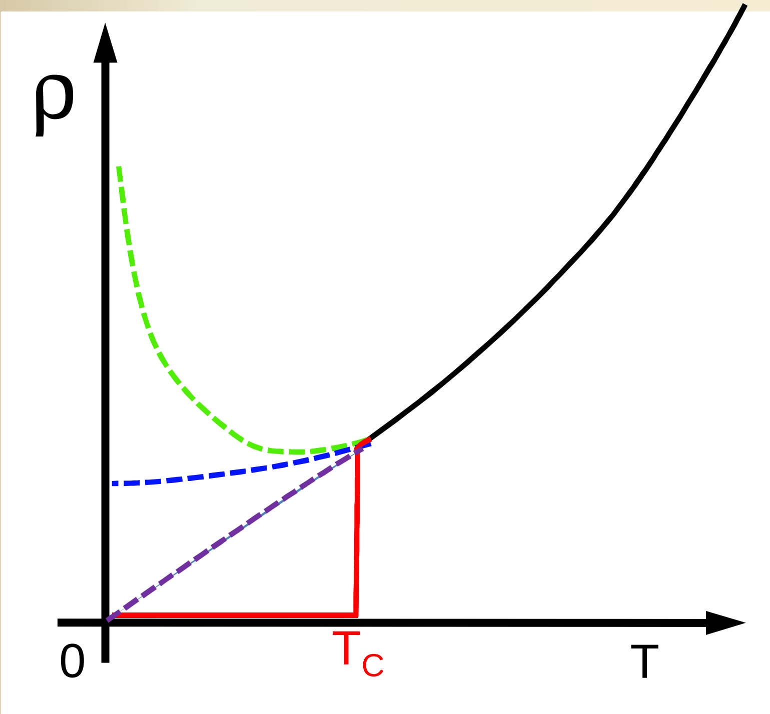
Discovery of Superconductivity

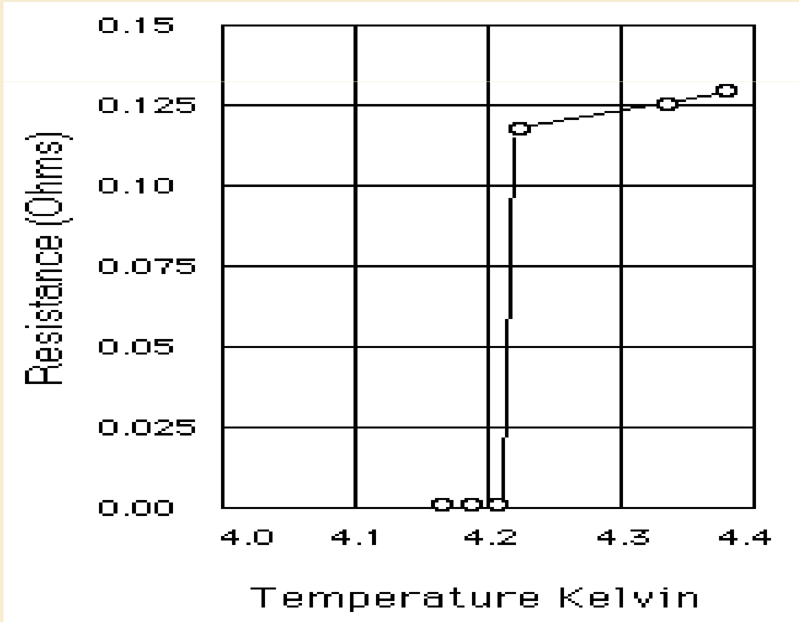
Heike Kamerlingh Onnes

Liquefied Helium (1908), b.p. = 4.17 K

Discovered superconductivity (1911) in Hg T_C = 4.21 K

Nobel prize (1913)





The saga of superconductivity began.

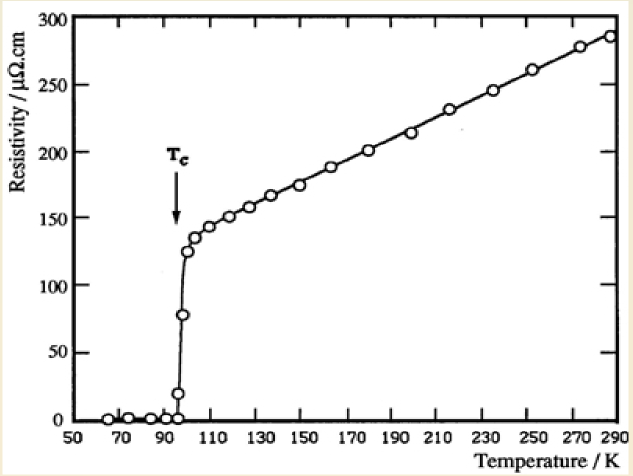
Perfect Conductivity and Perfect Diamagnetism

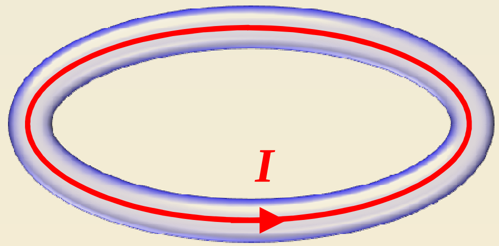
Zero resistance

Perfect conductivity

Persistent current ***I***

over 10^5 years

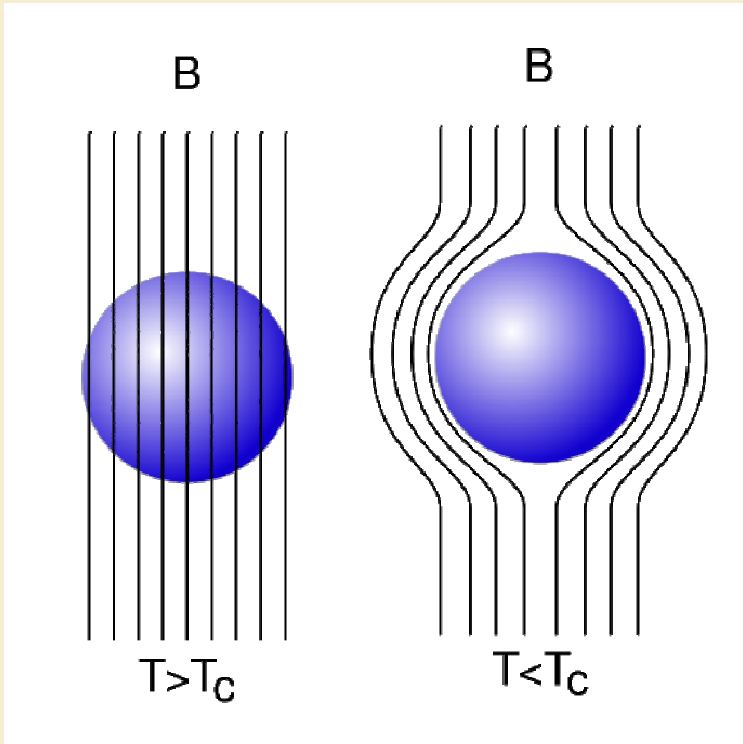




Meissner effect

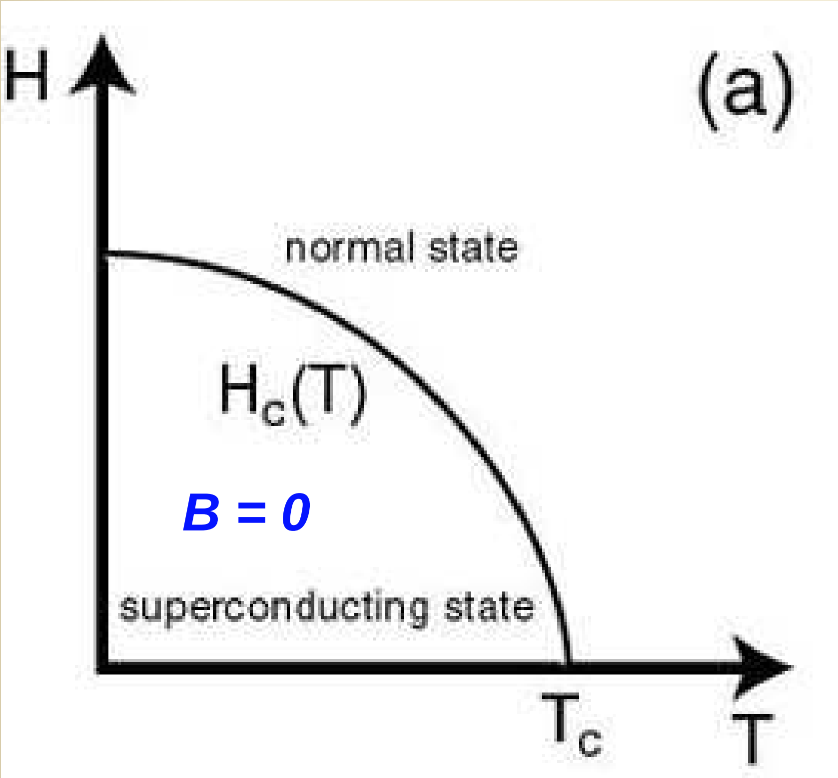
Perfect diamagnetism

No field inside SC



Type I and Type II Superconductors

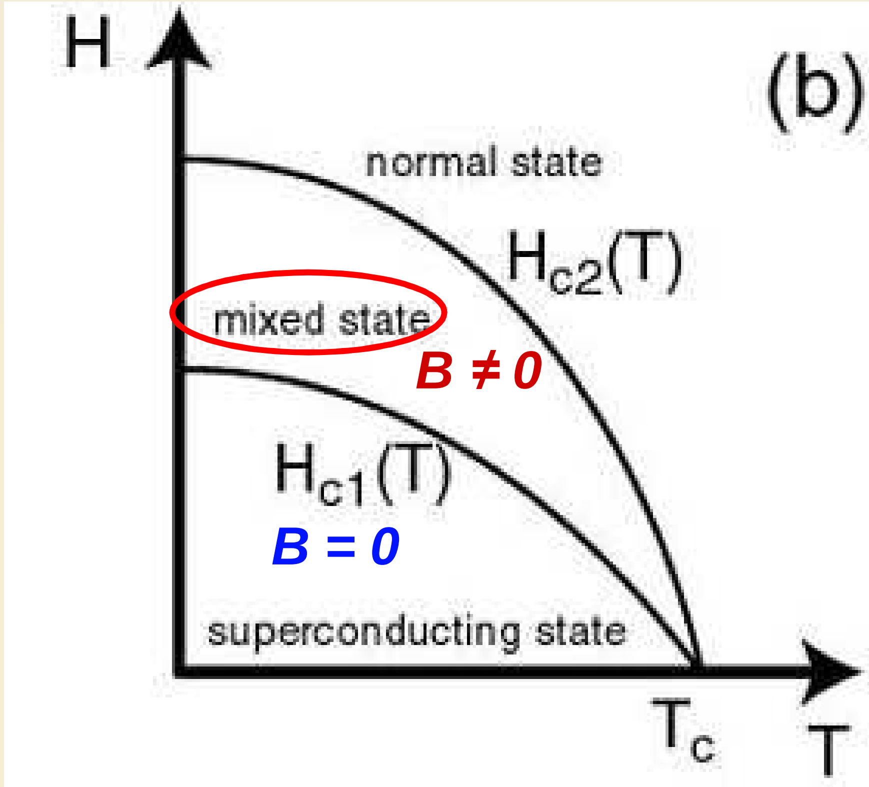
Type I (Pb, Al, etc)



Meissner ($H < H_C$)

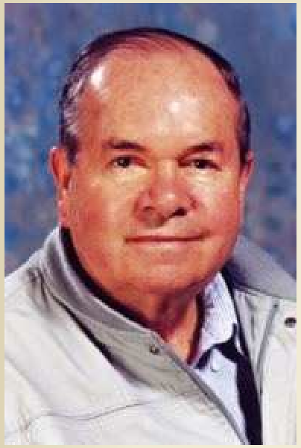
$H_C(0) \approx 0.1$ Tesla

Type II (NbTi, Nb_3Sn, etc)



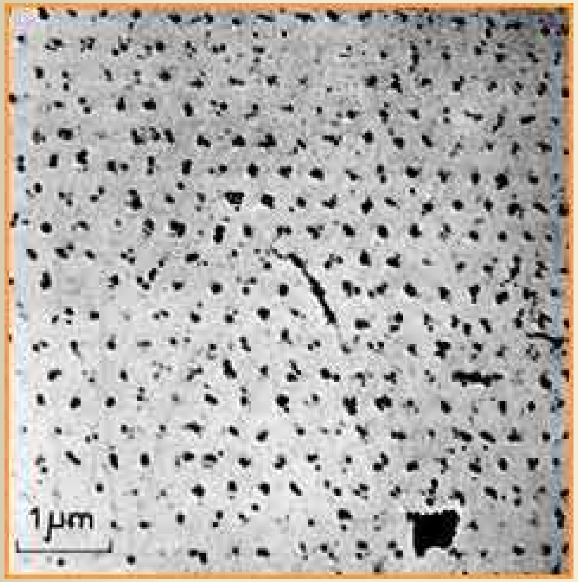
Meissner ($H < H_{C1}$)
Mixed state ($H_{C1} < H < H_{C2}$)
$H_{C2}(0)$ very large

Vortices in Mixed State

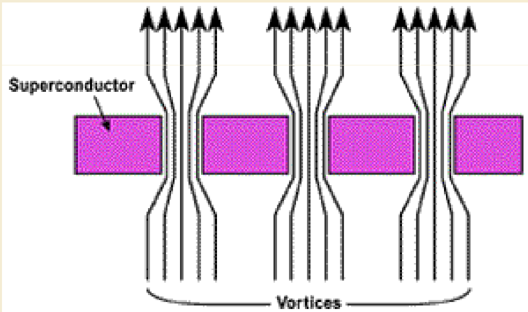


Abrikosov Vortex Lattices in Superconductors (1957)

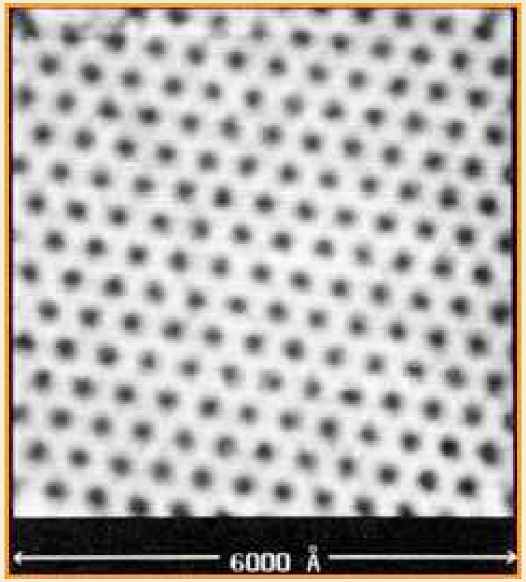
Nobel Prize (2003)



Essmann (1967) (Bitter, Pb)



$\Phi_o = hc/2e \approx 20$ G-μm^2

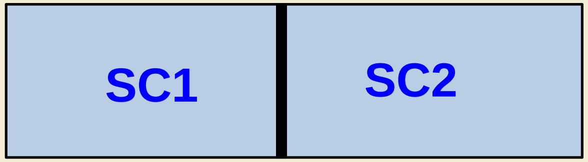


Hess (1989) (STM, $NbSe_2$)

Josephson Effect

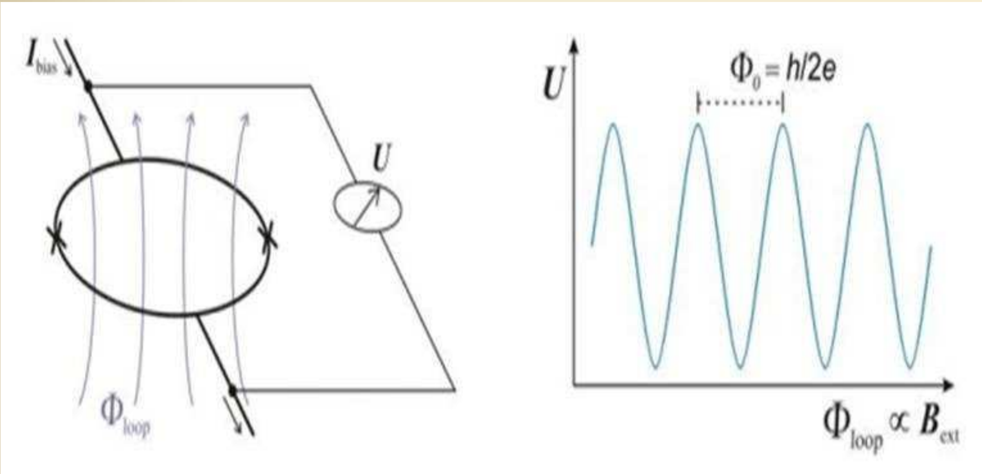
Brian D. Josephson

1962 Theoretical prediction of Josephson effect
1973 Nobel prize



$$I(t) = I_C \sin(\phi(t))$$

ϕ: phase difference

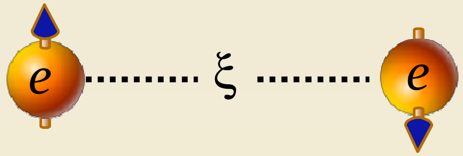


$$\Phi_0 = \frac{h}{2e} = 2.067833636 \times 10^{-15} Wb$$

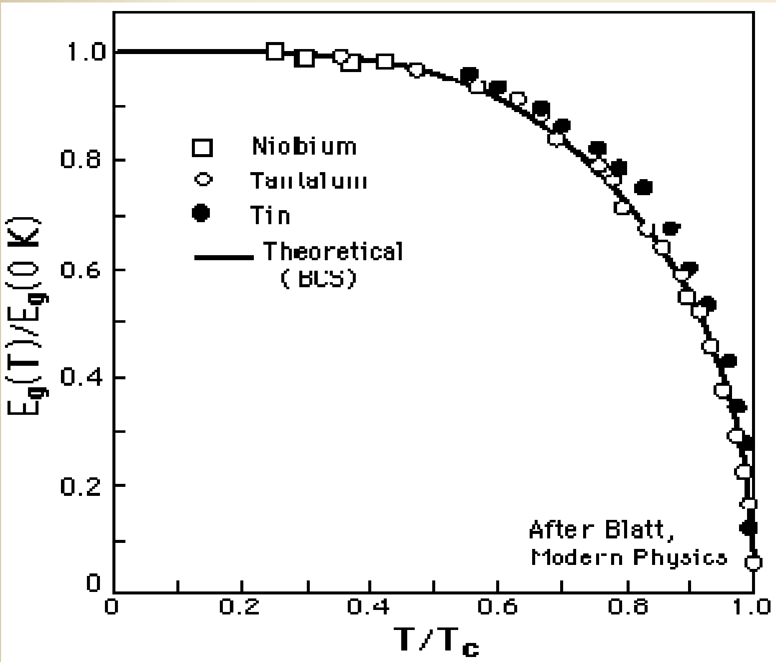
Superconducting Quantum Interference Device (**SQUID**)
Most sensitive detector

Bardeen-Cooper-Schrieffer (BCS) Theory (1957)

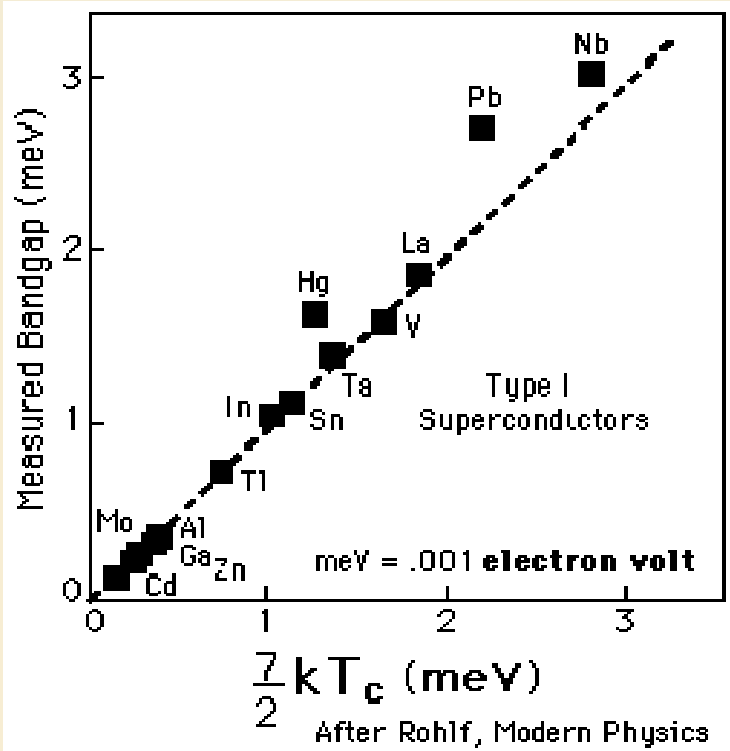
Bardeen-Cooper-Schrieffer
Nobel Prize, 1972



Cooper pairs

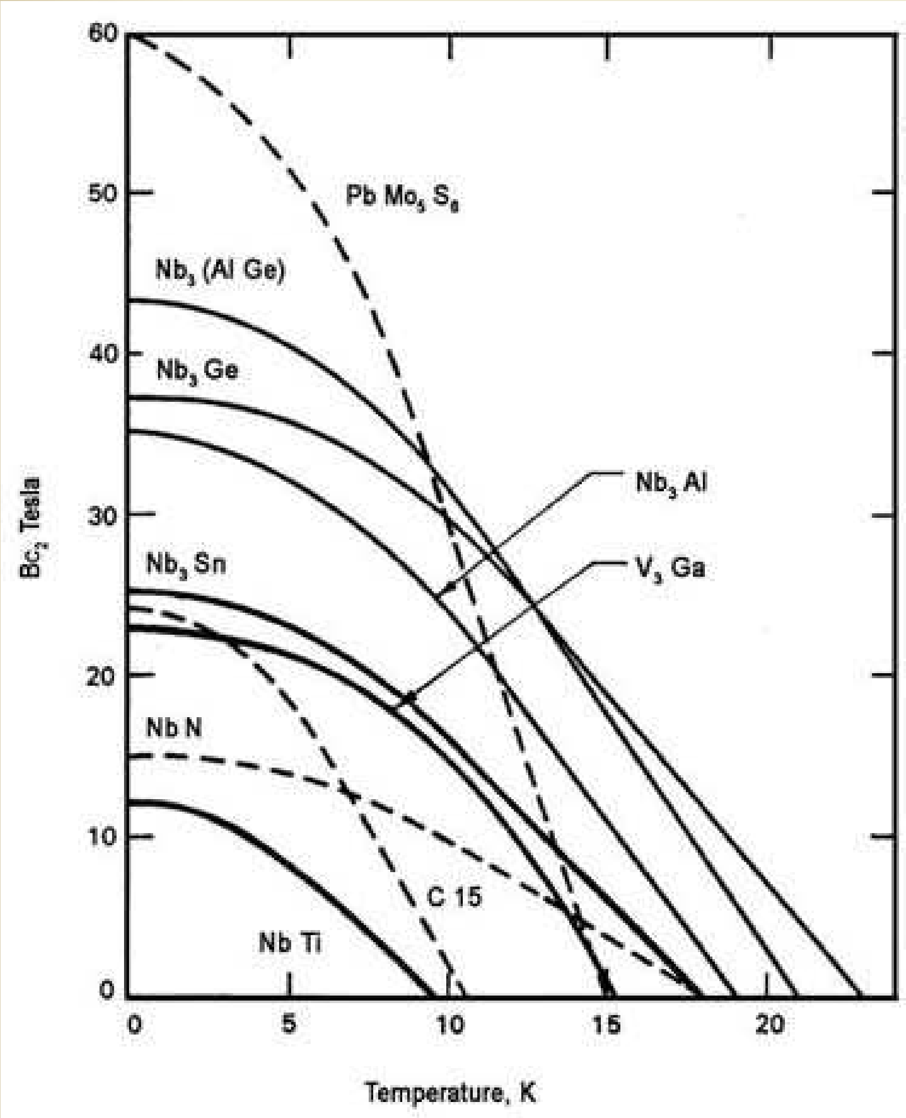


Superconducting Gap
$E_g = 2\ \Delta$



$2\Delta(0)/k_B T_C = 3.53$

Very large H_{c2} for Type II Superconductors



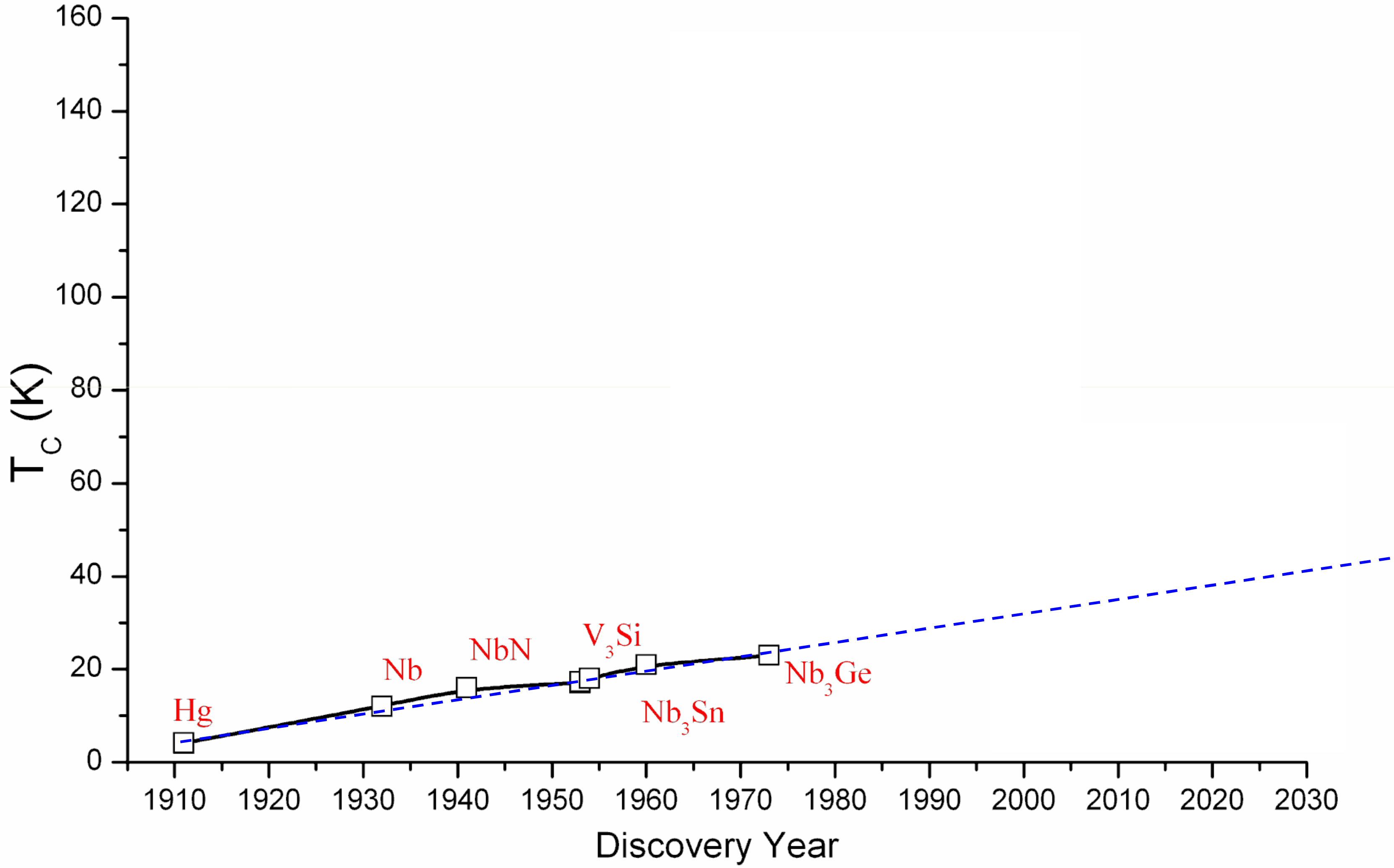
High H_{C2} is necessary

Superconducting magnets

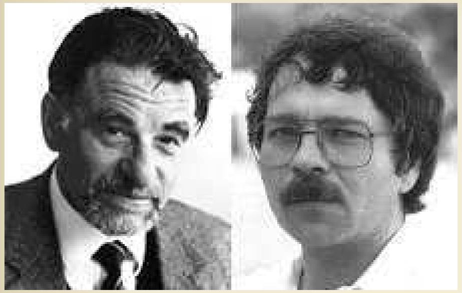
Magnetic levitation

High T_C is always beneficial

T_C vs. Discovery Year



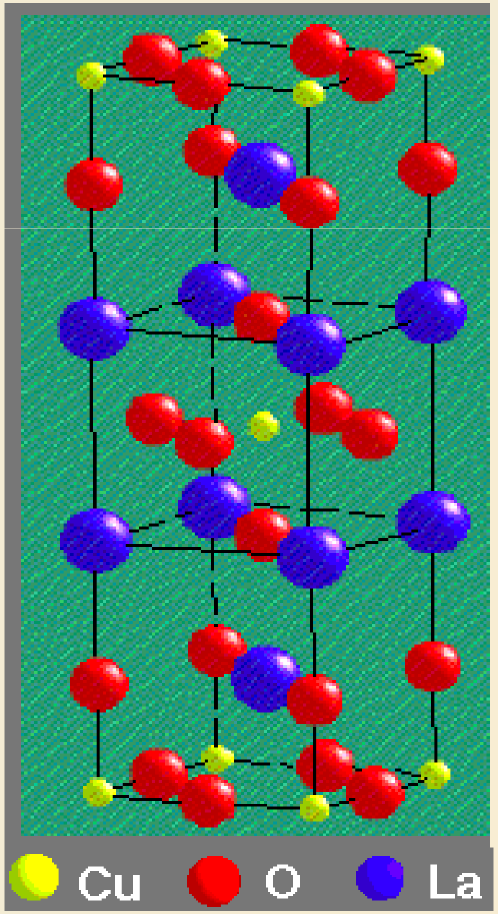
Discovery of Cuprates (1986)



Alex Müller and Georg Bednorz

Discovered $(La\text{-}Ba)_2CuO_4$ in 1986, T_C = 30 K

Nobel prize, 1987



CuO_2 Plane

La_2CuO_4

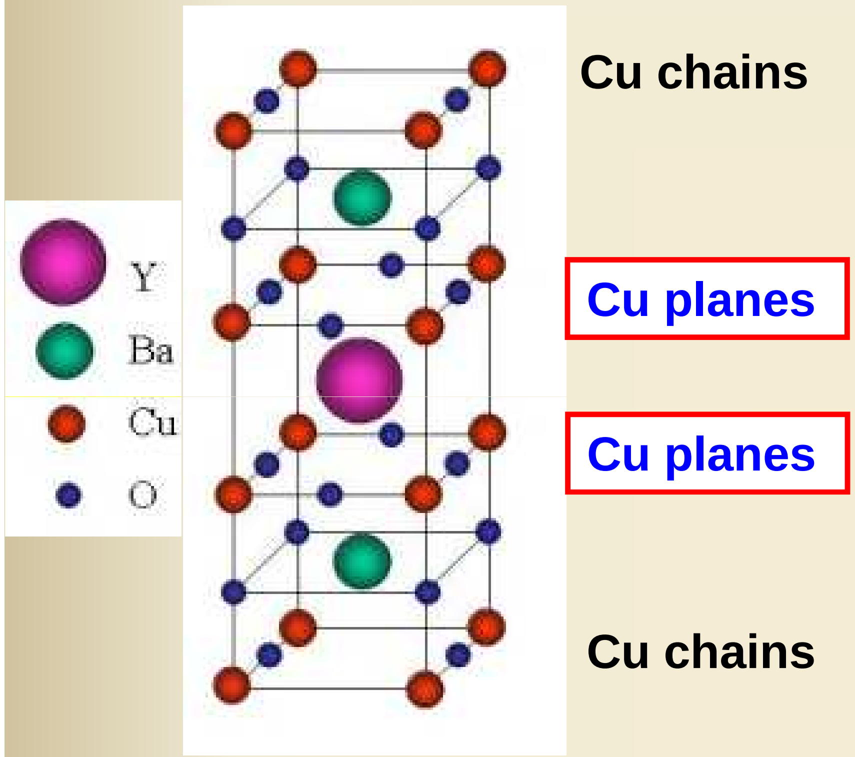
$(La\text{-}Sr)_2CuO_4$

$(La\text{-}Ba)_2CuO_4$

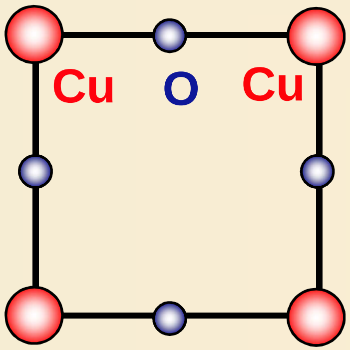
$T_C \sim 30 – 40$ K

Cuprates

$YBa_2Cu_3O_7$ **T_C = 90 K**



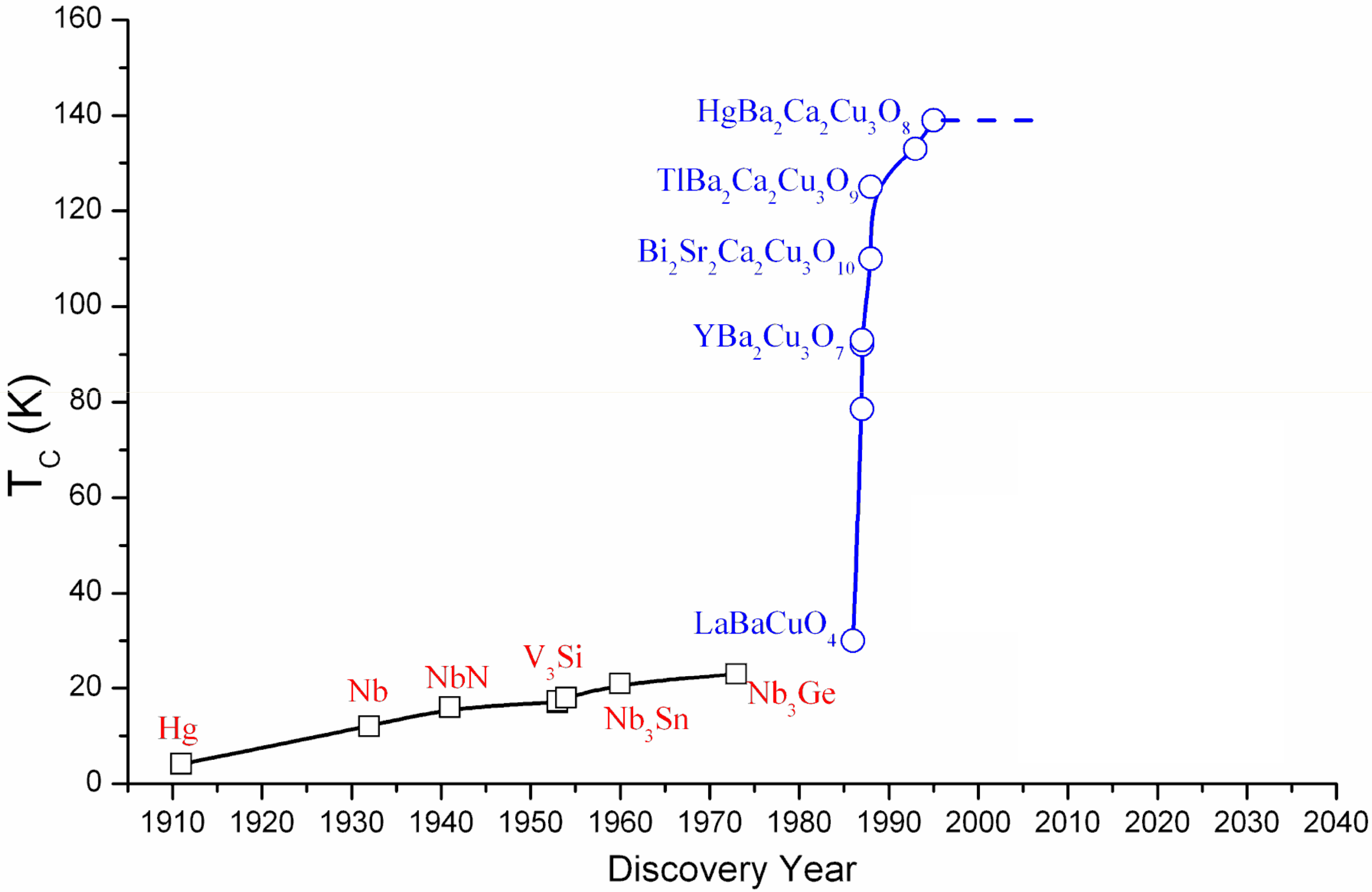
Cuprates	**T_C**
$(La\text{-}Sr)_2CuO_4$	35 K
$YBa_2Cu_3O_7$	90 K
$Bi_2Sr_2Ca_2Cu_3O_{10}$	105 K
$TlBa_2Ca_2Cu_3O_9$	125 K
$HgBa_2Ca_2Cu_3O_8$	140 K



CuO_2 plane

Responsible for high T_C and a host of unusual properties

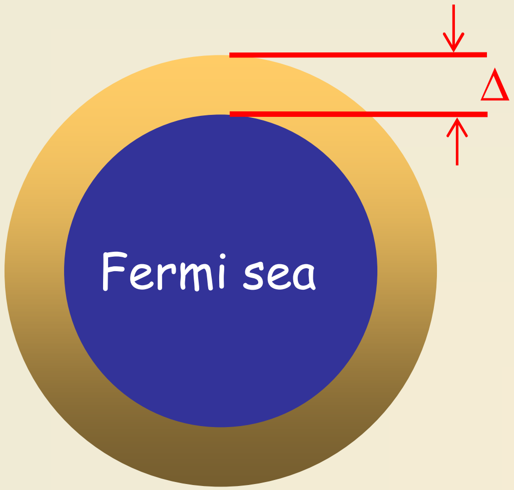
T_C vs. Discovery Year



Mind the Gap


"This is a beautiful film -- do not miss Mind The Gap!"
MIND THE GAP
MIND THE GAP
MIND THE GAP

s-wave and *p*-wave Superconductor

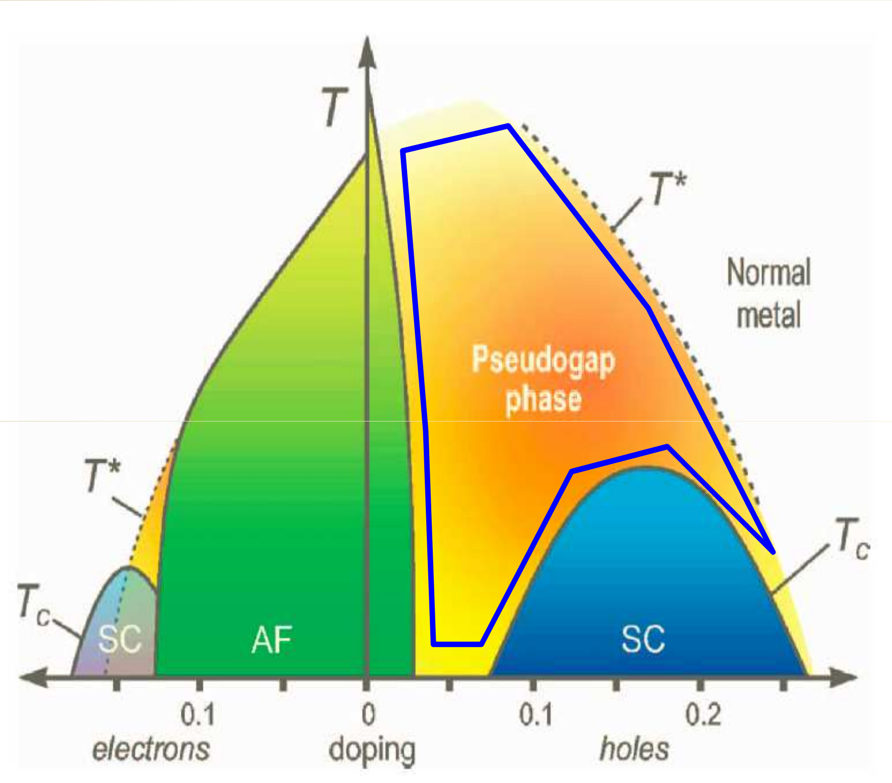


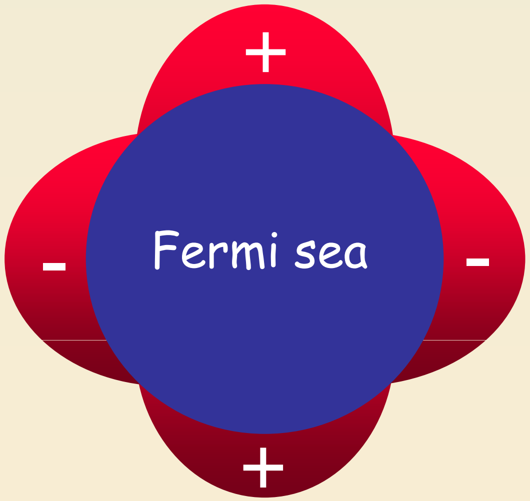
s-wave (isotropic)
Conventional SC (Nb, Pb, Al,…)
$T_C < 25$ K

p-wave
Superfluid ^3He, Sr_2RuO_4(?)
$T_C \sim 1$ mK - 1 K

d-wave Superconductor

Fisher *et al.*, RMP **79**, 353 (2007)





$d_{x^2-y^2}$

d-wave symmetry

Parent compound: Mott insulator

Cuprates: CuO_2 plane

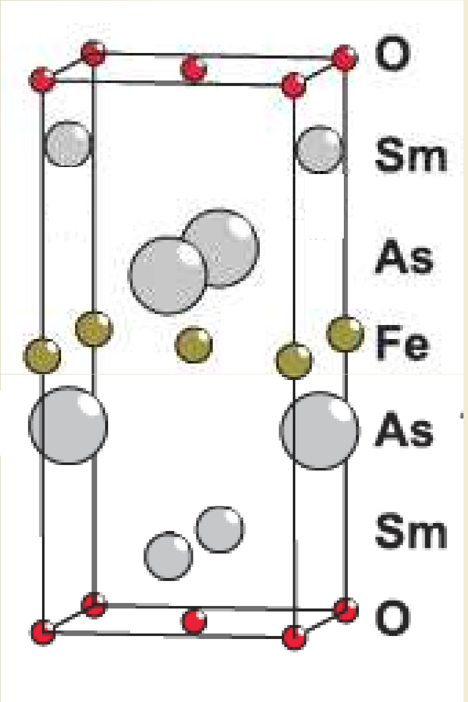
$T_C < 160$ K

New Oxypnictides Fe Superconductors (2008)

"Single layer"

SmFeAsO

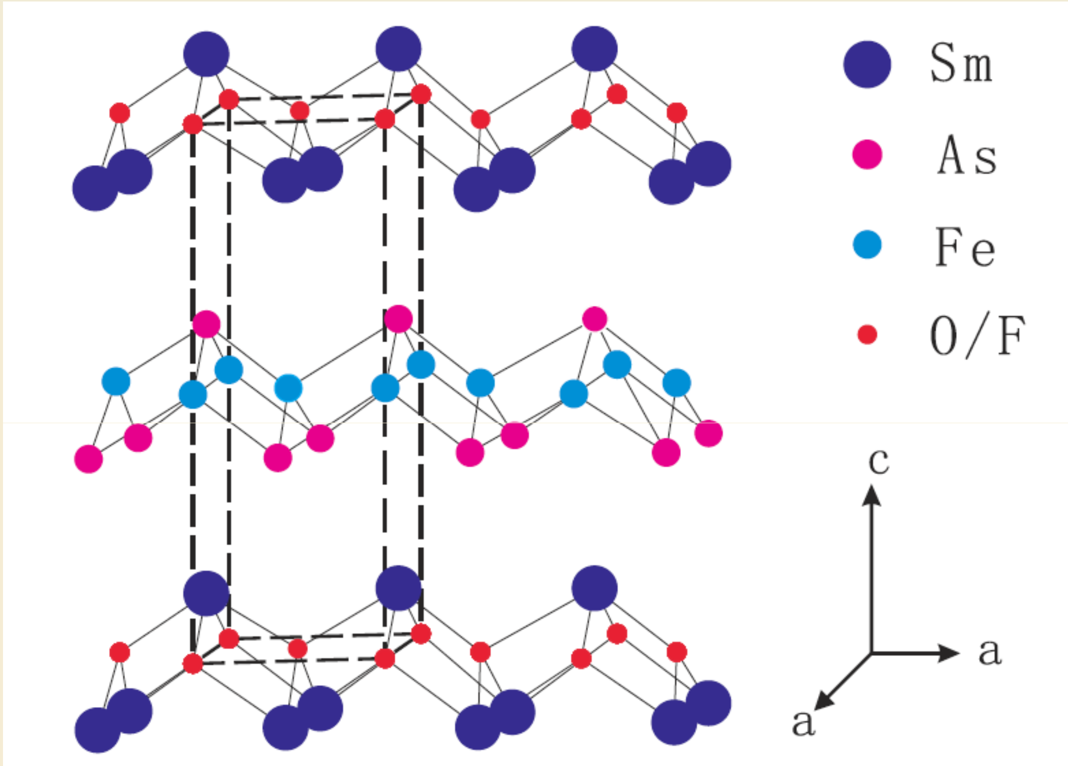
Pnictogen (P, As, Sb)



$(SmO)^+$

$(FeAs)^-$

$(SmO)^+$

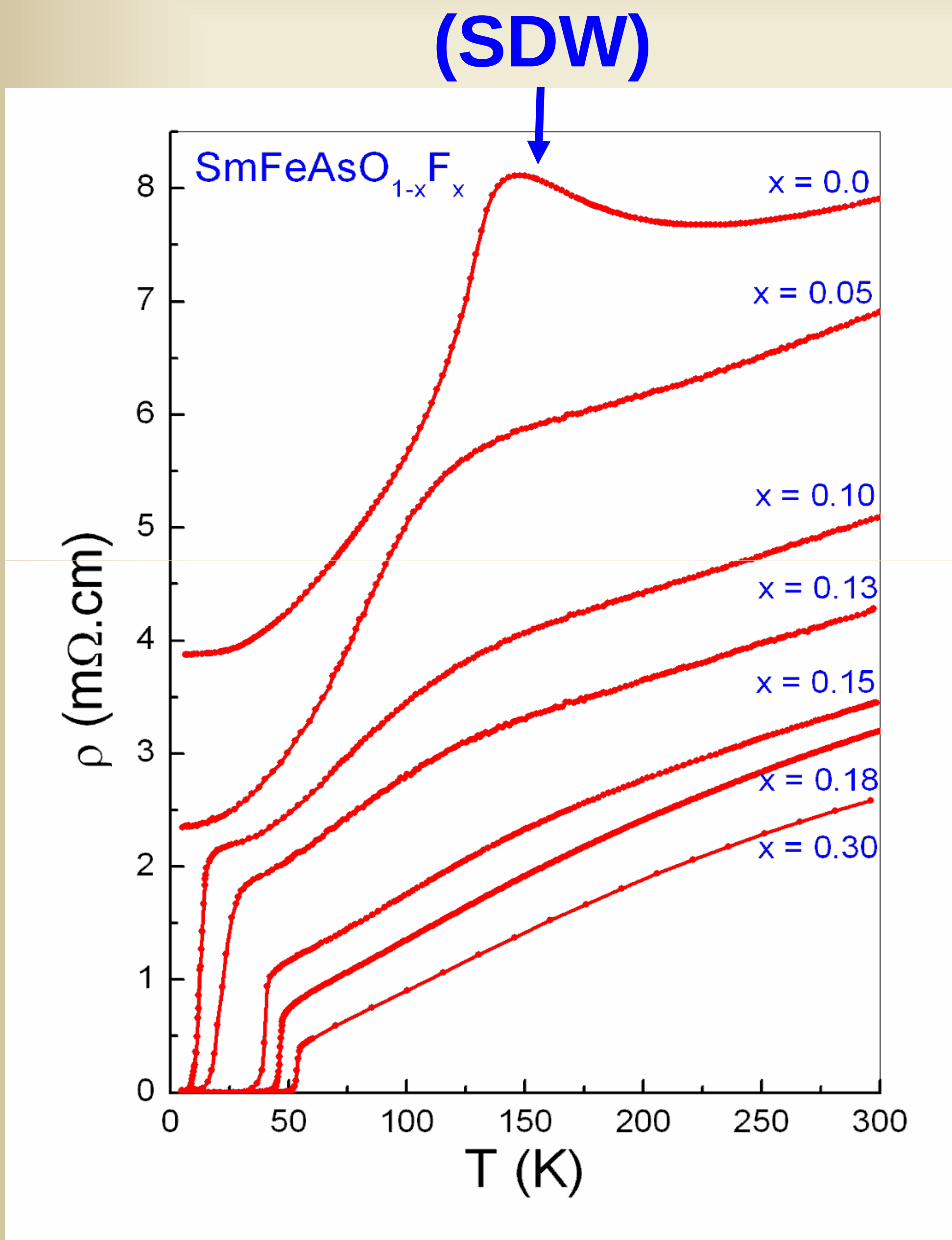


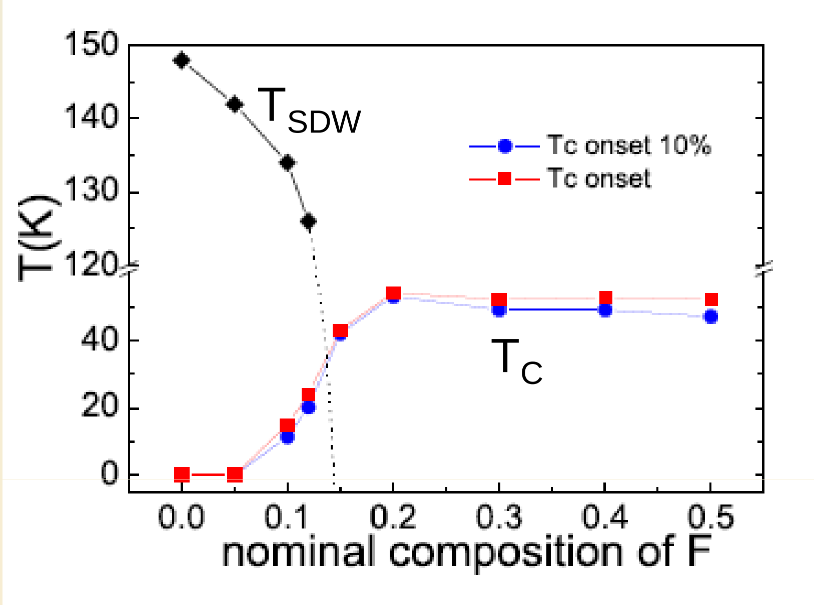
No CuO_2 plane

Contains Fe

Contains As

Discovery of Fe-Superconductors (2008)





New Fe-SC:

$SmFeAsO_{1-x}F_x$ (1111) T_C ~ 55K

Parent compound:

SmFeAsO metallic

Spin density wave (**SDW**) ~ 160K

Fe-Superconductors

New Fe-SC:

$SmFeAsO_{1-x}F_x$ (1111), T_C ~ 55K

Parent compound:

SmFeAsO metallic

Spin density wave (**SDW**) at 160K

$$\Delta = ?$$

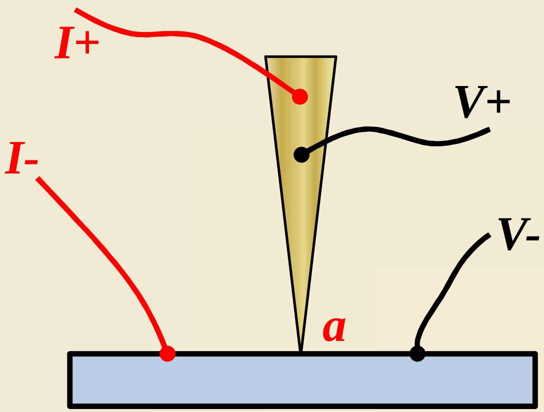
What value?

What structure?

What temperature dependence?

Are there pseudogaps?

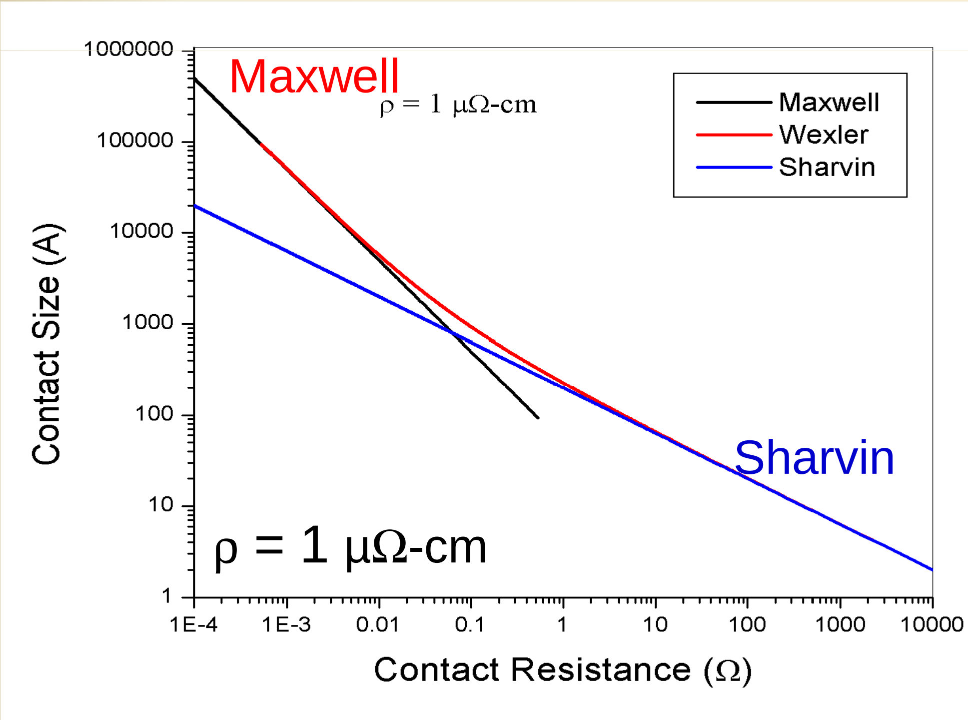
Point Contact



$$R_{Maxwell} = \frac{\rho}{2a}$$ ***a >> l, diffusive***

$$R_{Wexler} = \frac{4\rho l}{3\pi a^2}\left(1 + \frac{3\pi}{8}\frac{a}{l}\right)$$

$$R_{Sharvin} = \frac{4\rho l}{3\pi a^2}$$ ***a << l, ballistic***



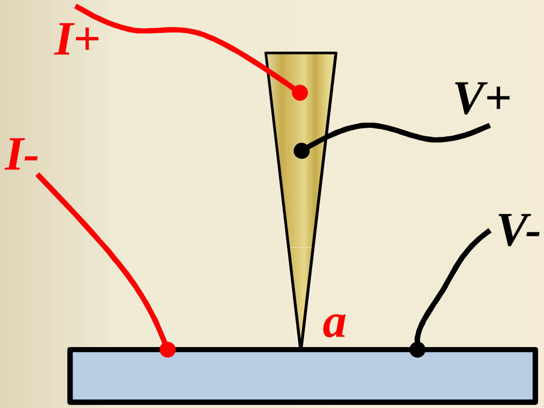
ρ : resistivity

a : contact size

l : mean free path

Different regime with different physics

Point Contact Spectroscopy



- **Phonon spectra**
  - Phonon
- **Spin transfer torque effect**
  - Contact size: a ~ nm
  - Current: I = 1 mA
  - Current density: $j = 10^{10}$ A/cm^2
- **Point Contact Andreev Reflection**
  - Spin polarization
  - Superconducting gap
- **Thermal transport**
  - ballistic, diffusive
- **…**

Spin Transfer Torque Effect

Contact size: *a* ~ nm
Current: *I* = 1 mA
Current density: *j* = 10^{10} A/cm^2

T. Y. Chen, Y. Ji and C. L. Chien, ***Appl. Phys. Lett.* 84**, 380 (2004).

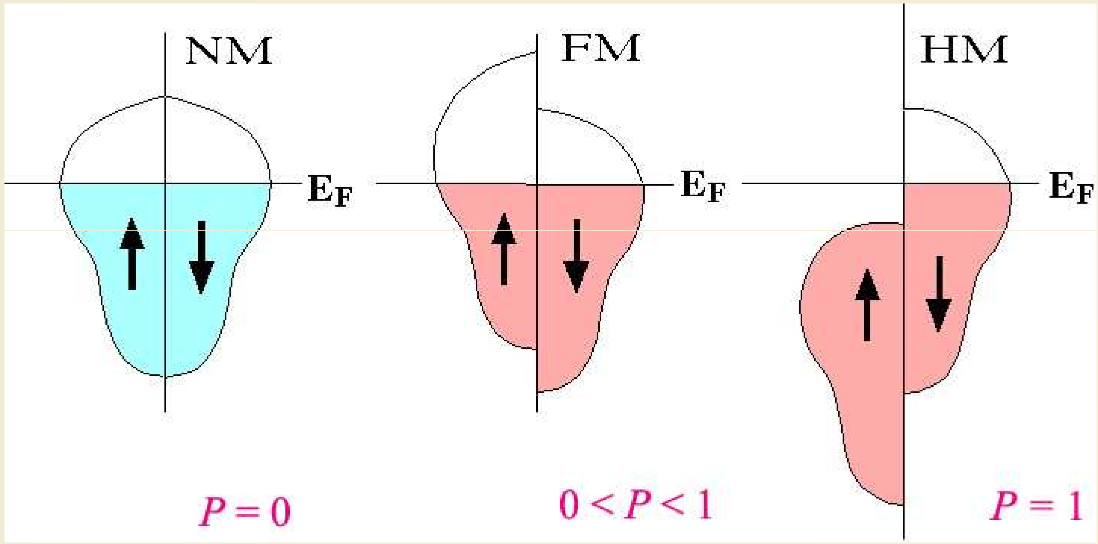
T. Y. Chen, Y. Ji, C. L. Chien and M. D. Stiles, ***Phys. Rev. Lett.* 93**, 026601 (2004).

T. Y. Chen, S. X. Huang, C. L. Chien and M. D. Stiles, ***Phys. Rev. Lett.* 96**, 207203 (2006).

Spin Polarization (*P*)

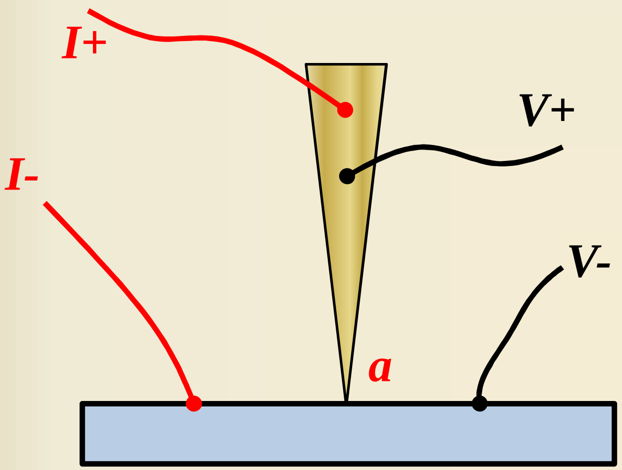
$$P_0 = \frac{N_\uparrow(E_F) - N_\downarrow(E_F)}{N_\uparrow(E_F) + N_\downarrow(E_F)}$$

$N(E_F)$: density of states at Fermi energy



P: crucial for spintronics

Point Contact Andreev Reflection (PCAR)



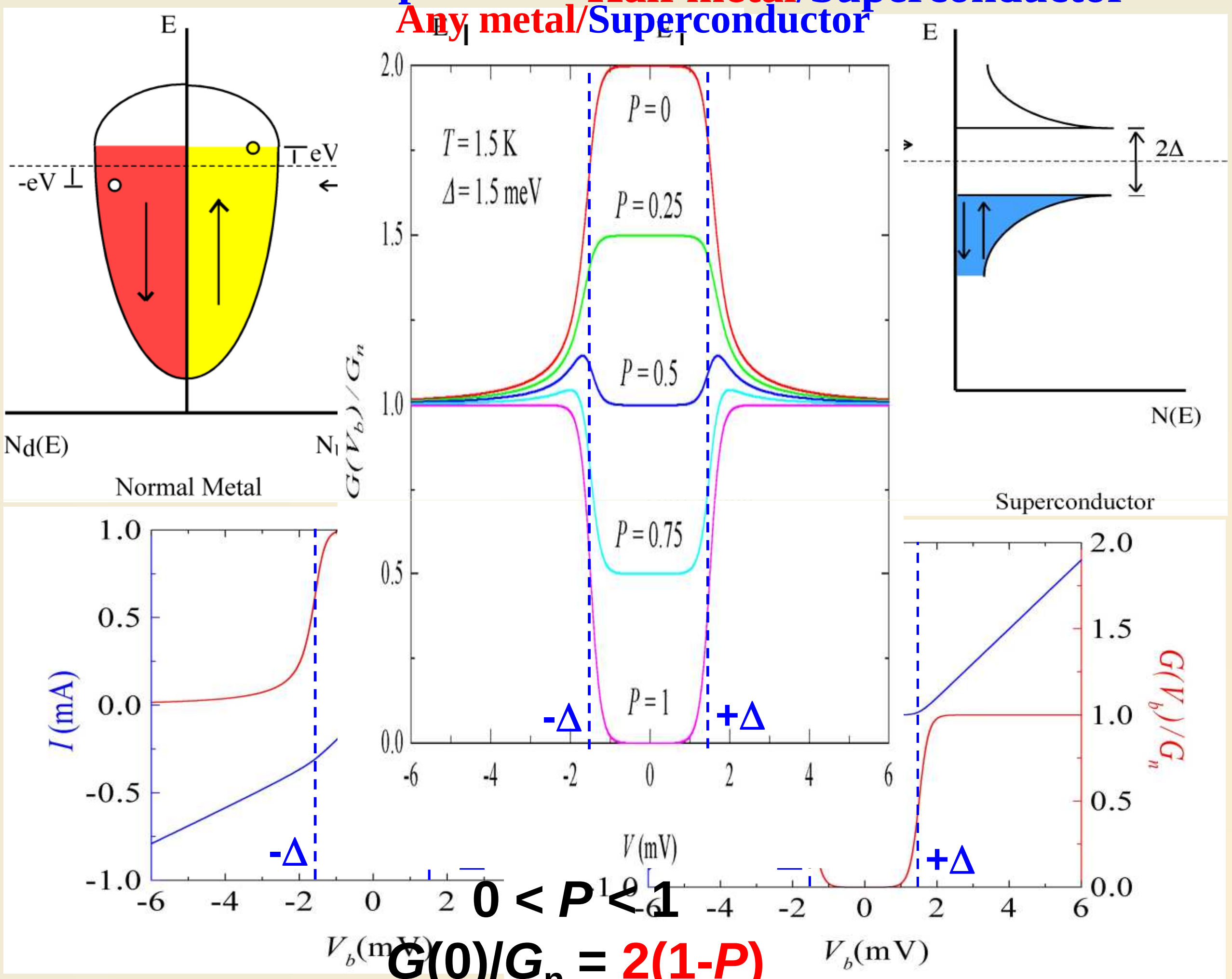
Tip:
Conducting, semiconducting, superconducting

Sample:
Conducting, semiconducting, superconducting

Normal metal/superconductor interface: Andreev Reflection

Measures spin polarization (***P***) and superconducting gap (*Δ*)

Determination of Spin Polarization by PCAR



$0 < P < 1$

$G(0)/G_n = 2(1-P)$

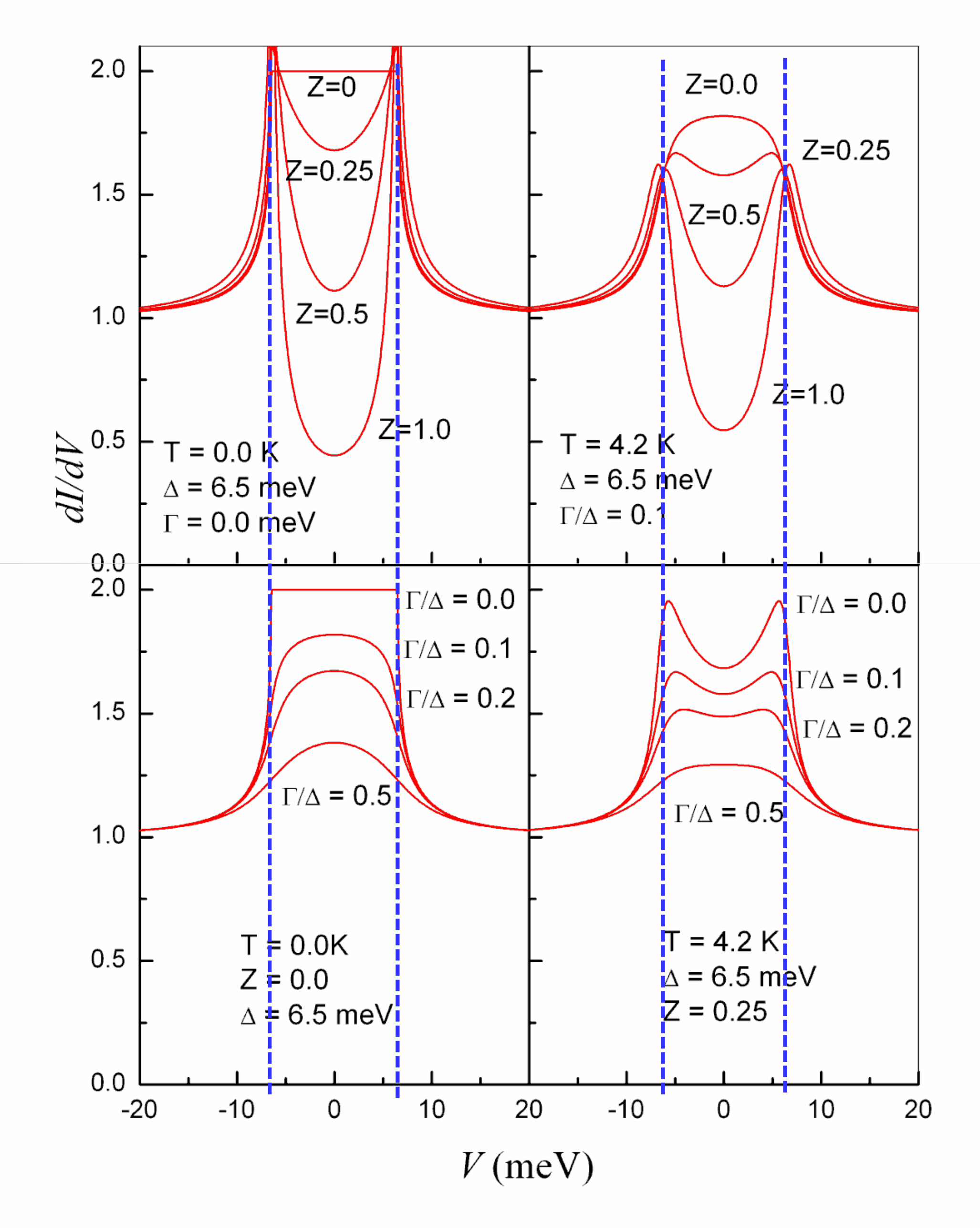
$G(0)/G_n = 2 \quad P = 0$

$G(0)/G_n = 0 \quad P = 1$

P **of metal, and** ***Δ*** **of SC can be determined.**

Ideal contact, clean limit

Interfacial Scattering (Z) and inelastic scattering (Γ)



- Interfacial: ***Z***
  suppresses in-gap conductance
- Inelastic: Γ
  affects conductance at gap
- Thermal: ***T***
  smears out conductance

Analyzing entire conductance

Blonder-Tinkham-Klapwijk (BTK) theory

Point Contact Andreev Reflection Spectroscopy

Using known SC (Nb, Pb) to determine *P* of metal

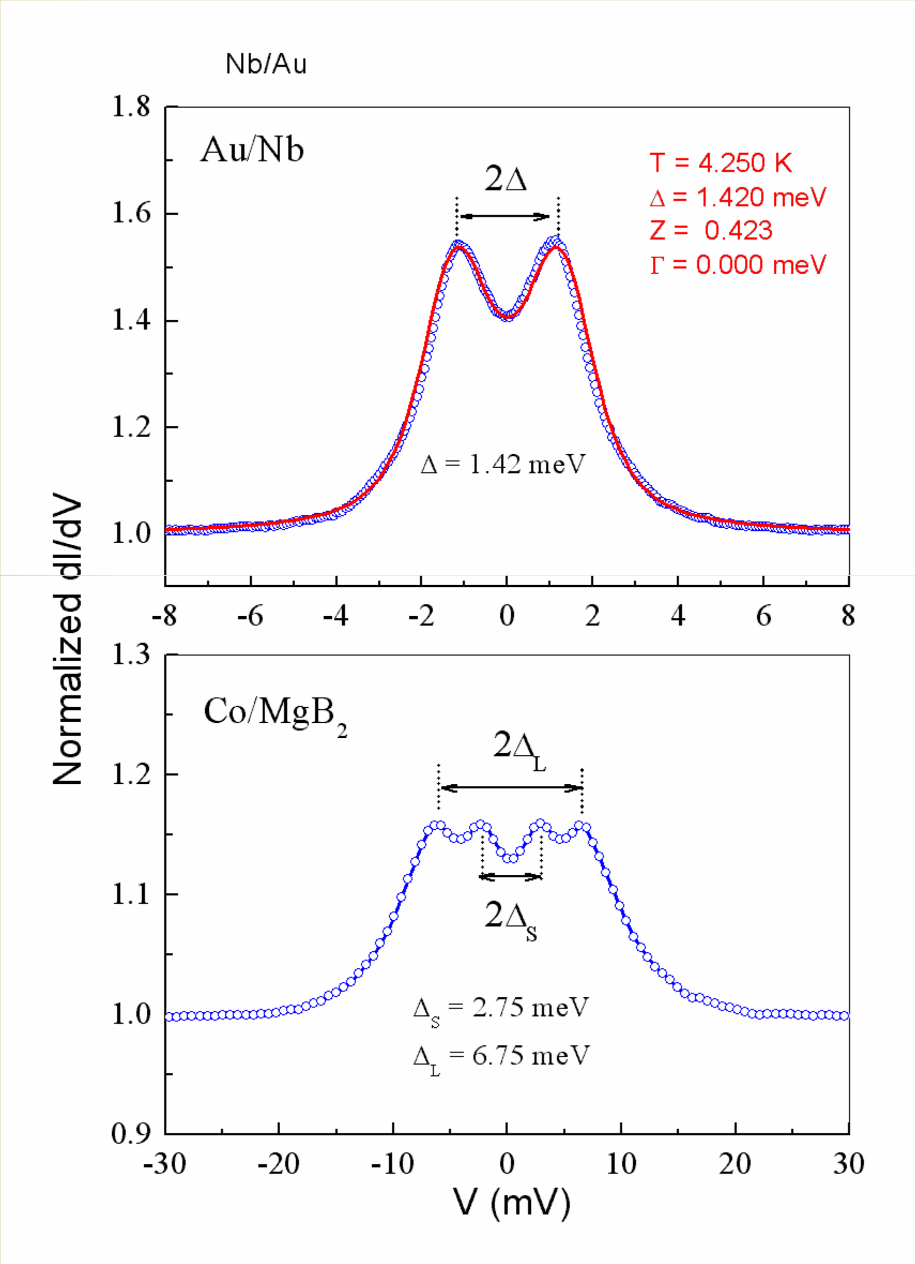
- S. X. Huang, T. Y. Chen, and C. L. Chien, **Appl. Phys. Lett. 92**, 242509 (2008).
- T. Y. Chen, C. L. Chien and C. Petrovic, **Appl. Phys. Lett. 91**, 142505 (2007).
- C. Leighton, M. Manno, A. Cady, J. W. Freeland, L. Wang, K. Umemoto, R. M. Wentzcovitch, T. Y. Chen, C. L. Chien, P. L. Kuhns, M. J. R. Hoch, A. P. Reyes, W. G. Moulton, E. D. Dahlberg, J. Checkelsky and J. Eckert, **J. Phys.: Condens. Matter 19**, 315219(2007) (invited review).
- L. Wang, T. Y. Chen, C. L. Chien, and C. Leighton, **Appl. Phys. Lett. 88**, 232509 (2006).
- L. Wang, T. Y. Chen, C. L. Chien, J. G. Checkelsky, J. C. Eckert, E. D. Dahlberg, K. Umemoto, R. M. Wentzcovitch, and C. Leighton, **Phys. Rev. B 73**, 144402 (2006).
- L. Wang, K. Umemoto, R.M. Wentzcovitch, T. Y. Chen, C.L. Chien, J.G. Checkelsky, J.C. Eckert, E.D. Dahlberg and C. Leighton, **Phys. Rev. Lett. 94**, 056602 (2005).
- L. Wang, T. Y. Chen and C. Leighton, **Phys. Rev. B 69**, 094412 (2004).
- Lance Ritchie and Gang Xiao, Y. Ji, T. Y. Chen, C. L. Chien, Ming Zhang, Jinglan Chen, Zhuhong Liu, Guangheng Wu, and X. X. Zhang, **Phys. Rev. B 68**, 104430 (2003).

Using known metal (Au, Co) to determine *Gap* of SC

Nb, MgB_2, $SmFeAsO_{0.85}F_{0.15}$

T. Y. Chen, Z. Tesanovic, R. H. Liu, X. H. Chen, and C. L. Chien, ***Nature* 453**, 1224 (2008)

AR Spectroscopy Measurements of Gaps



One gap of Nb (T_C = 9.27 K)

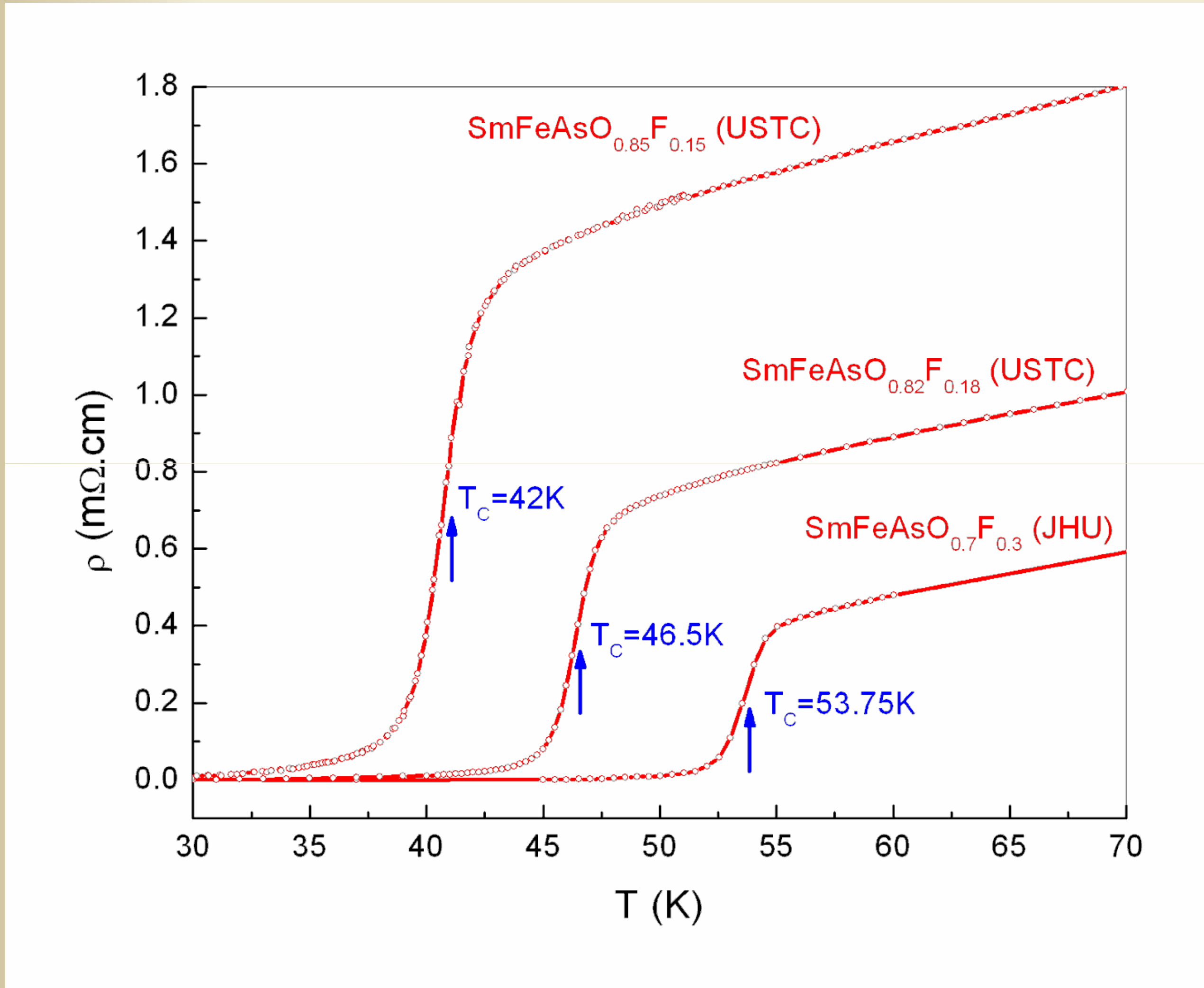
Δ_{Nb} = 1.42 meV

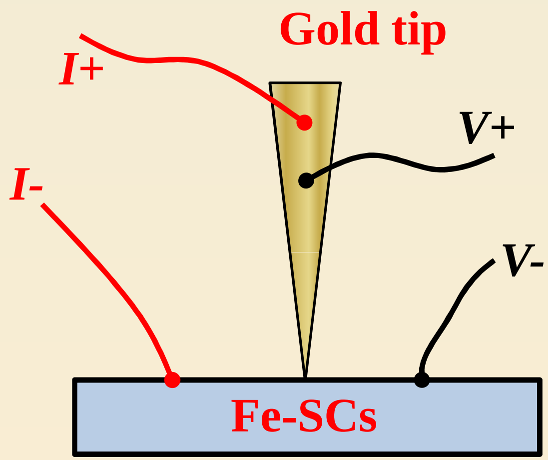
Two gaps of MgB_2 (T_C = 36.5 K)

Δ_L = 6.75 meV

Δ_S = 2.75 meV

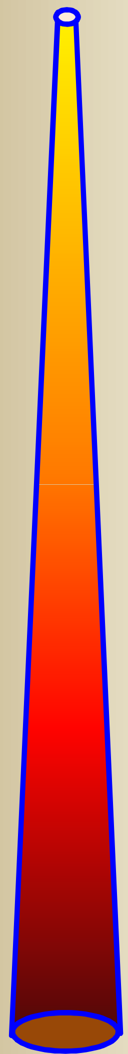
Superconducting $SmFeAsO_{1-x}F_x$ (x=0.15, 0.18, 0.30)



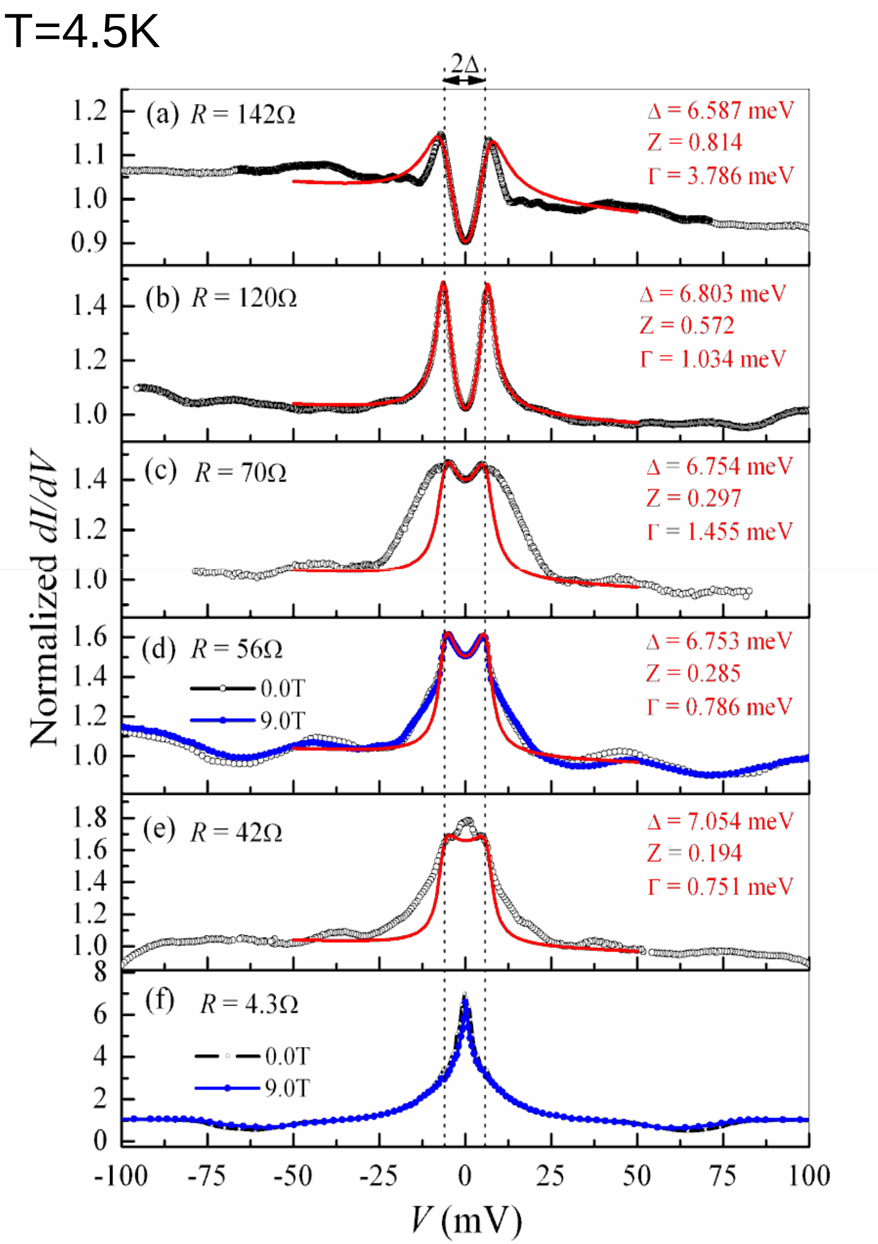


$SmFeAsO_{0.85}F_{0.15}$ (T_C = 42 K)

Small contact



Large contact



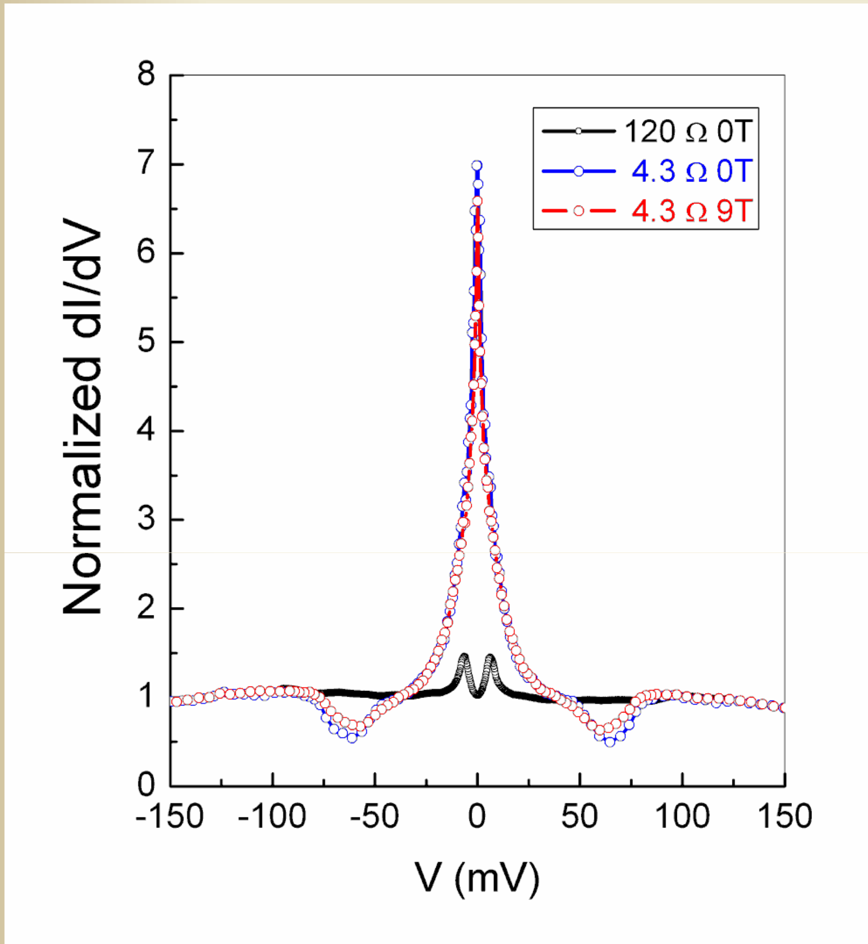
Same 2Δ for all G(V)

- **Structure:**
  - ~ isotropic
- **Value:**
  - 2Δ = **13.34 ± 0.71** meV
  - $2\Delta/k_BT_C$ = **3.68**
  - close to **3.53**
  - (BCS s-wave)

Complications:

- **Extra features to ± 100 mV**
  - due to SC
- **Slanted background**
  - nothing to do with SC
  - mismatch of Fermi energy
- **Emergence of ZBA**
  - due to SC
- **Small effect in 9 T field at 4.5K**

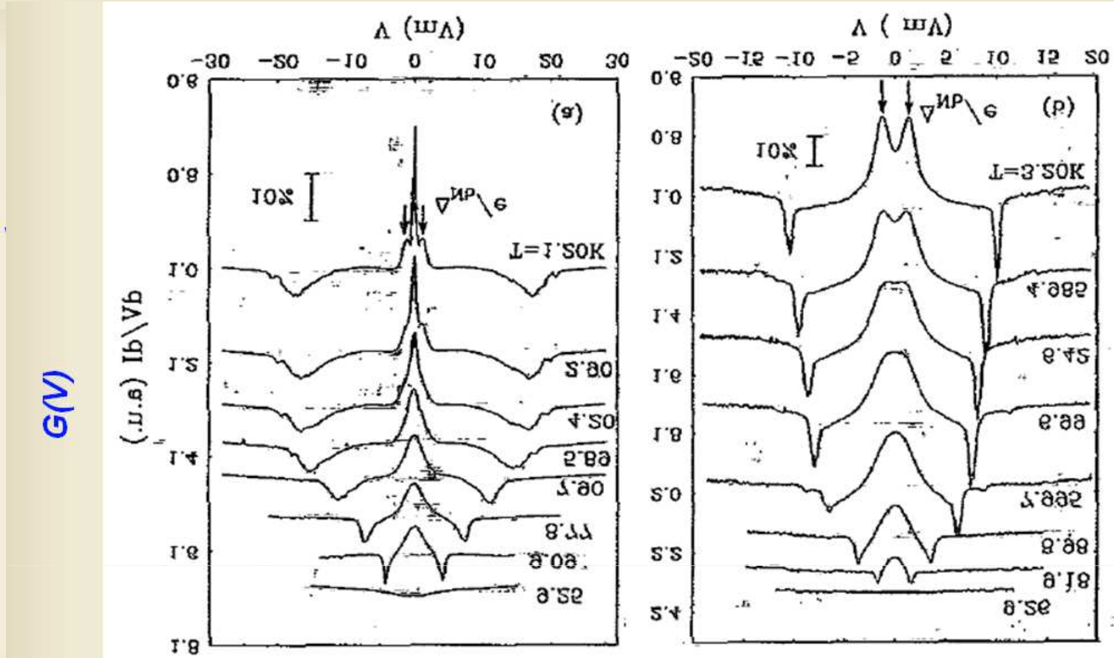
Emergence of Zero Bias Anomaly (ZBA)



- **Emerges systematically**
- **ZBA obscures gap**
- **ZBA due to SC**
- **H field has negligible effect**

- ❑ **ZBA is a signature of *d*-wave pairing (???).**
- ❑ **ZBA depends strongly on *B* field, whereas gap does not (???).**
  (A scheme to obtain gap structure by subtraction)

ZBAs in s-wave Superconductors



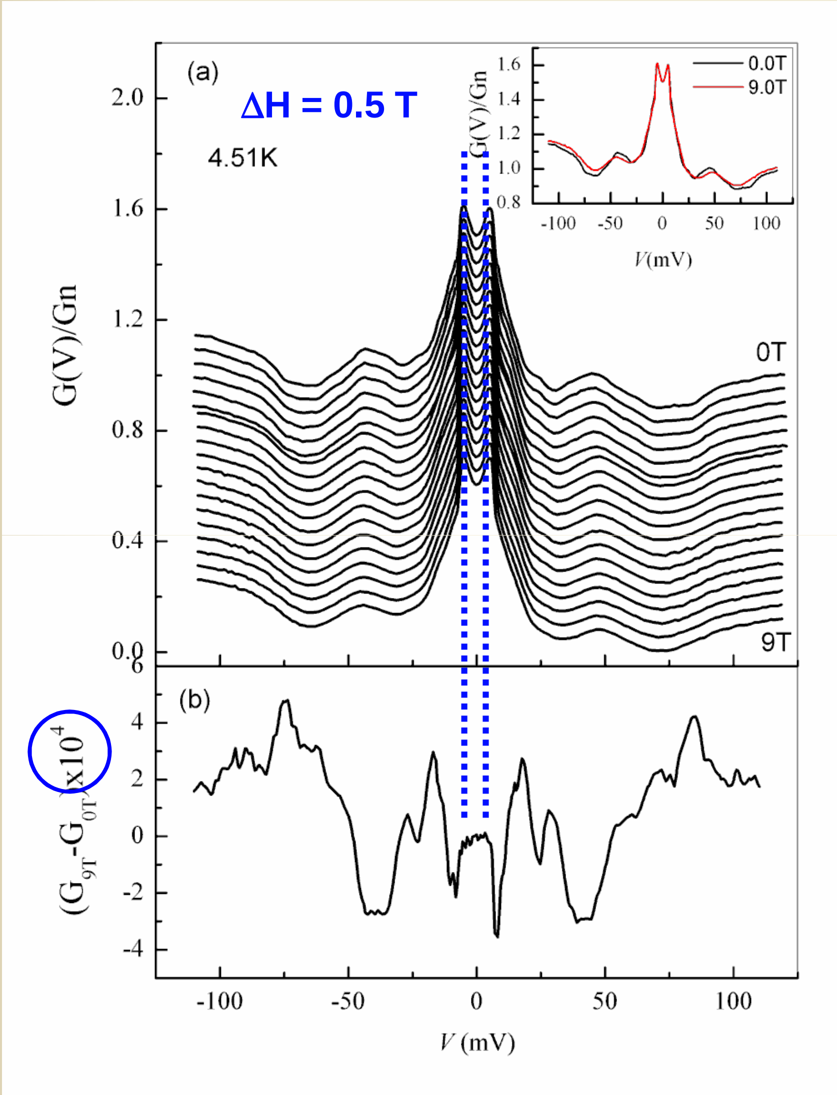
ZBA is a signature of *d*-wave pairing (???).

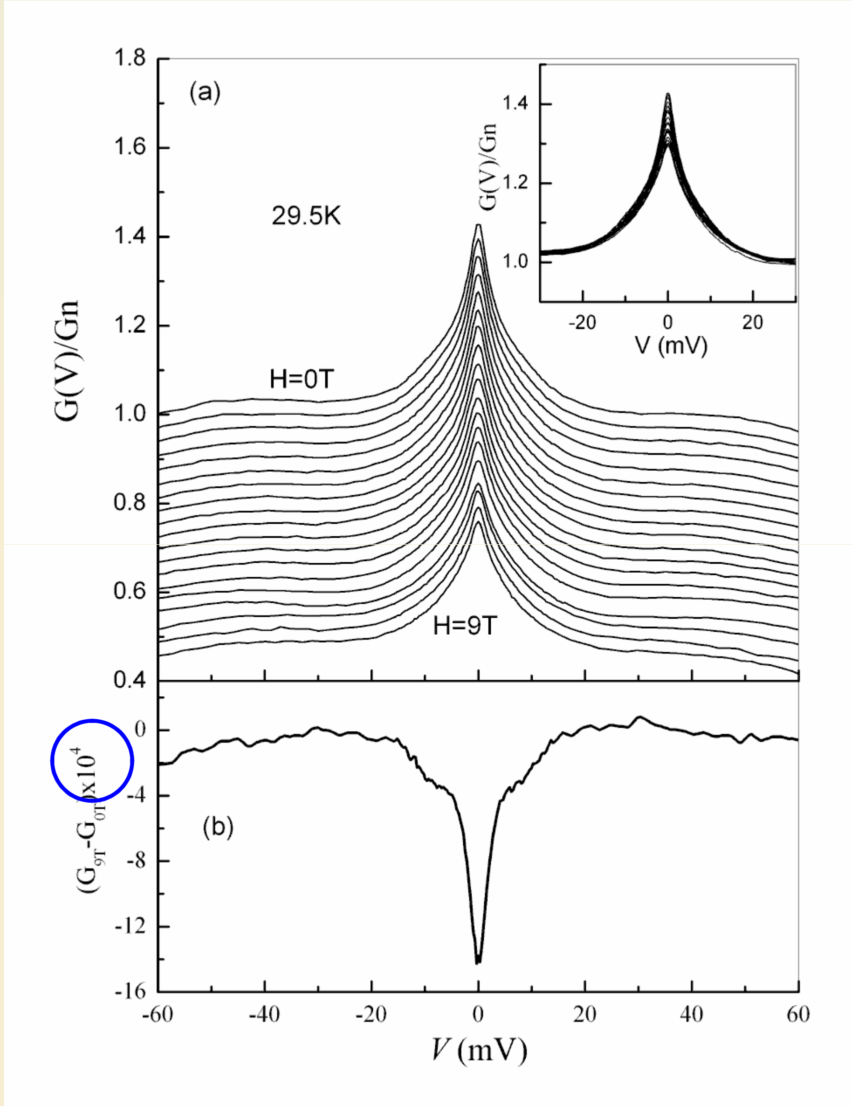
d-wave may give ZBA.

But, ZBA does not imply *d*-wave
since *s*-wave also gives ZBA.

P. Xiong, G. Xiao, R. B. Laibowitz, Phys. Rev. Lett. **71**, 1907 (1993)

Neither Gap nor ZBA depends strongly on H





Subtraction does not reveal the superconducting gap

Zero Bias Anomaly (ZBA)

- **ZBA is a signature of *d*-wave pairing (???).**

  d-wave may give ZBA.

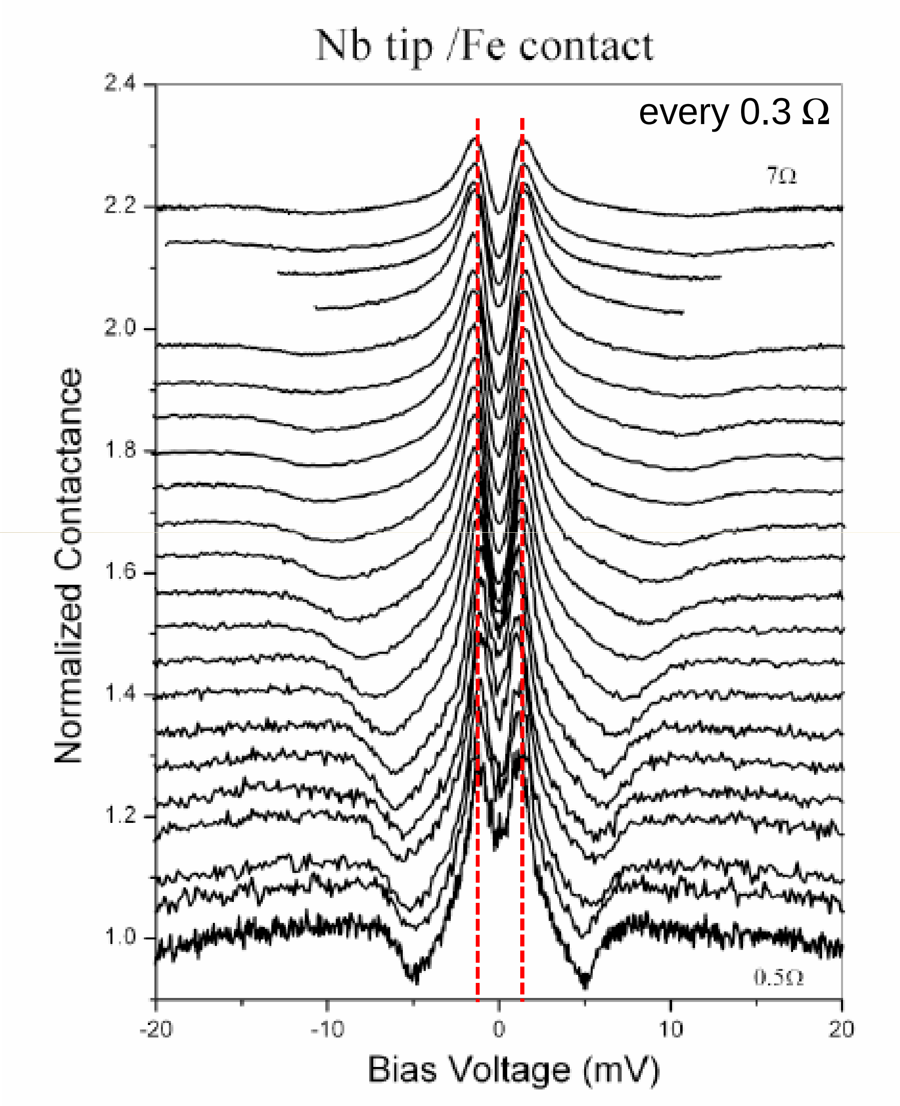
  But, ZBA does not imply *d*-wave
  since *s*-wave also gives ZBA.

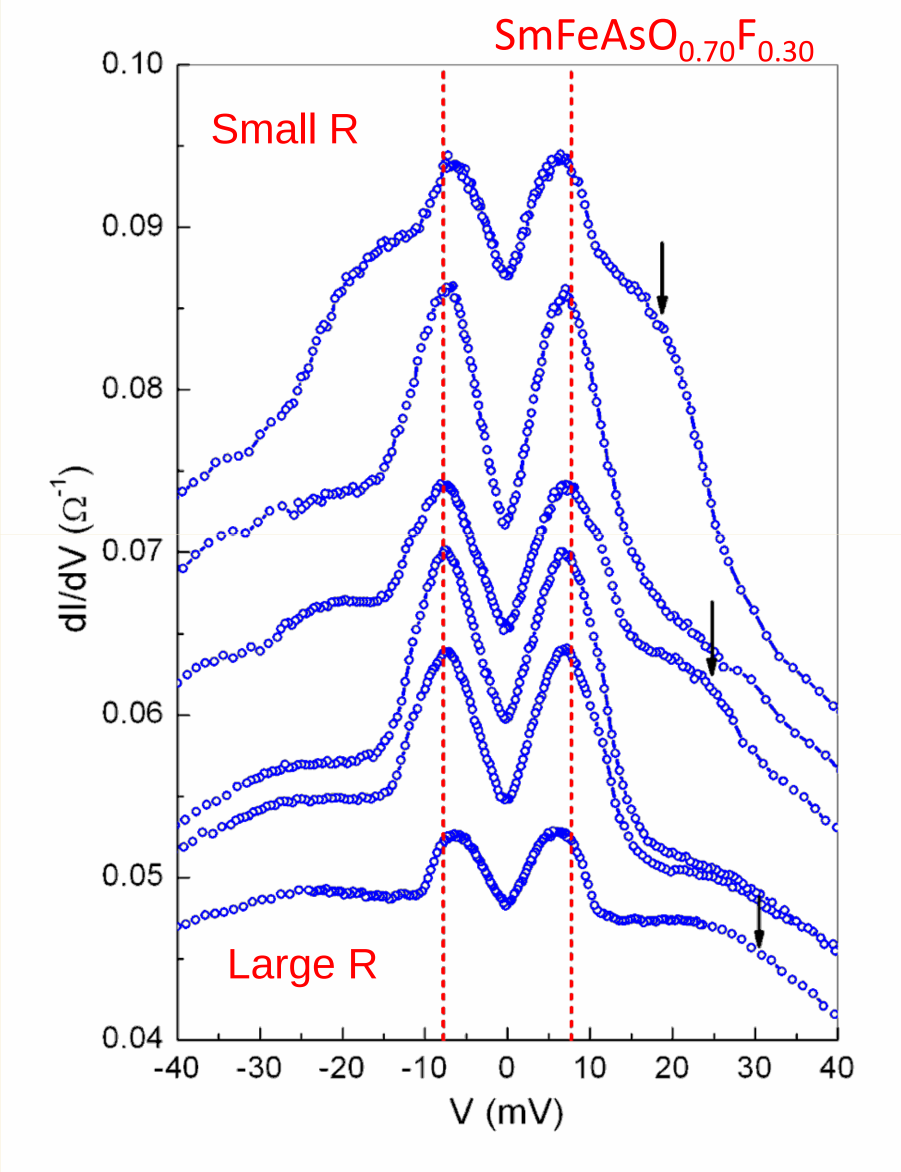
- **ZBA depends strongly on *B* field, whereas gap does not (???).**
  (A scheme to obtain gap structure by subtraction)

  Neither ZBA nor gap depends strongly on *B* field.

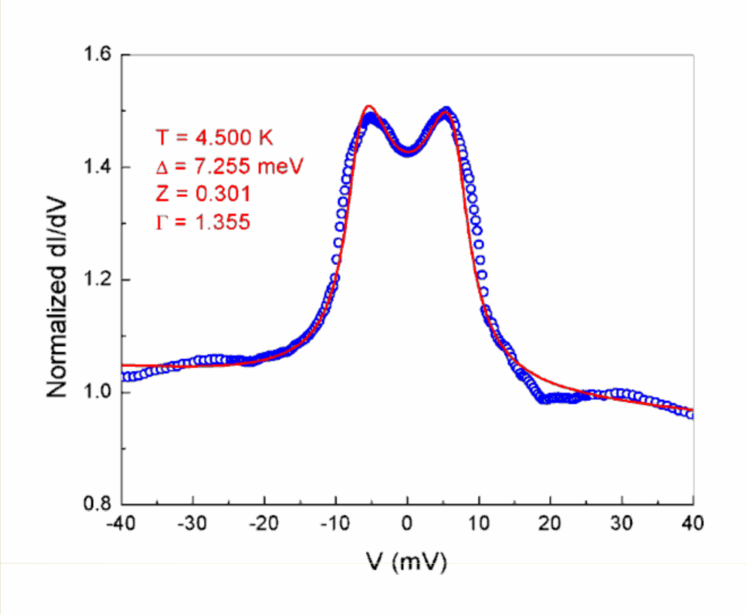
  Subtraction method does not work.

A real gap is independent of contacts

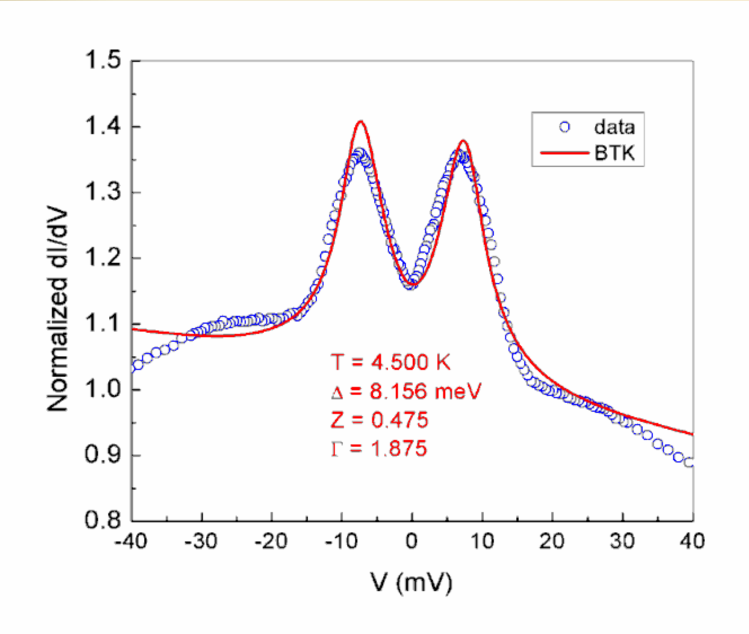




$SmFeAsO_{0.82}F_{0.18}$ (T_C = 46.5 K), $SmFeAsO_{0.70}F_{0.30}$ (T_C = 53.75 K)



$SmFeAsO_{0.82}F_{0.18}$:
T_C = 46.5 K
Δ = 7.26 meV
$2\Delta/k_BT_C$ = **3.62**



$SmFeAsO_{0.70}F_{0.30}$:
T_C = 53.75 K
Δ = 8.16 meV
$2\Delta/k_BT_C$ = **3.52**

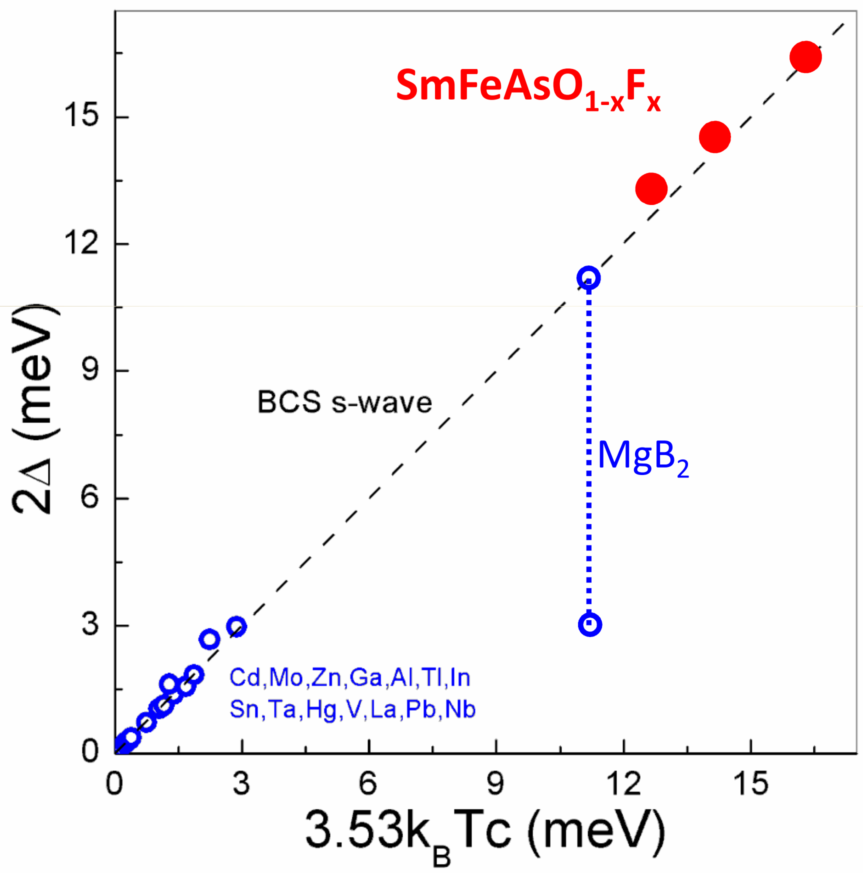
Superconducting Gap

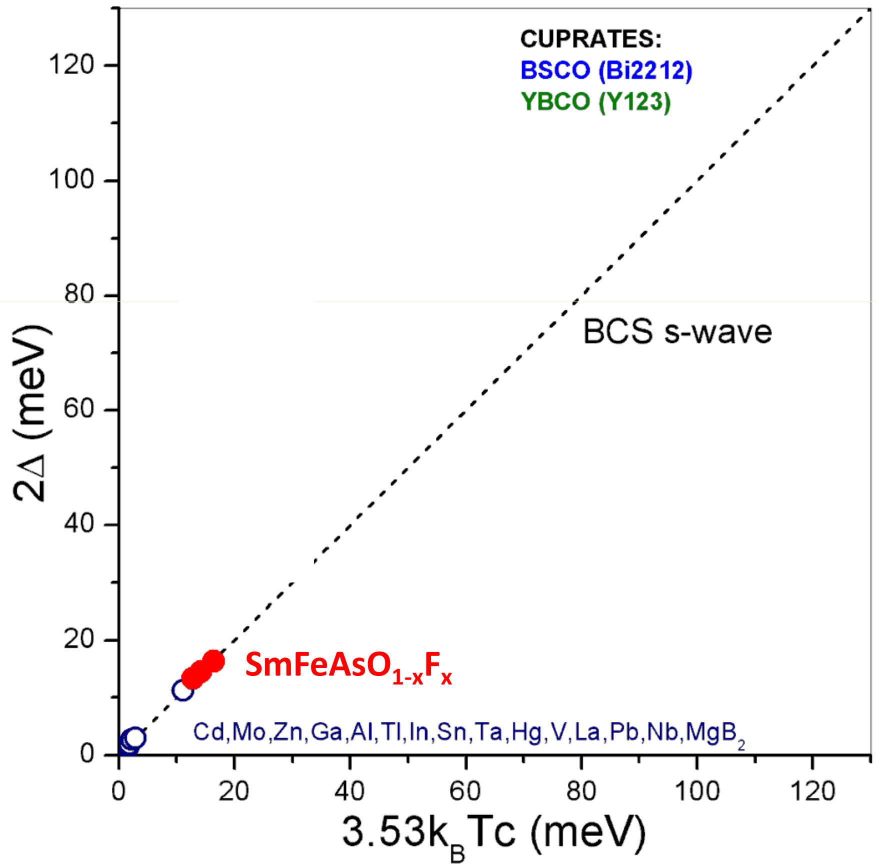
Theory:

$$\frac{2\Delta(0)}{k_B Tc} = \begin{cases} 3.53 & s\text{-wave} \\ 4.06 & p\text{-wave} \\ 4.28 & d\text{-wave} \end{cases}$$

This work:

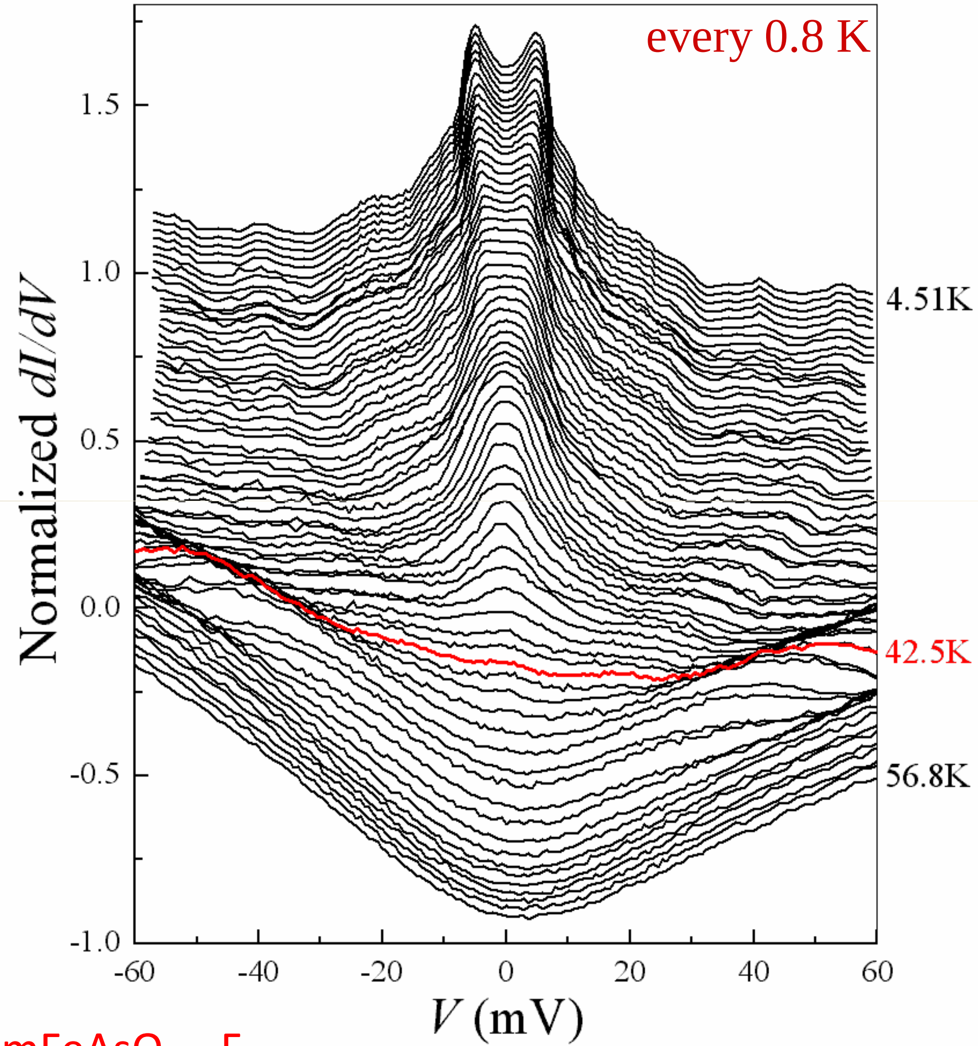
$$\frac{2\Delta}{k_B T_C} = \begin{cases} 3.68 & SmFeAsO_{0.85}F_{0.15} \\ 3.62 & SmFeAsO_{0.82}F_{0.18} \\ 3.52 & SmFeAsO_{0.70}F_{0.30} \end{cases}$$





Rohlf, Modern Physics
Fisher *et al.,* Rev. Mod. Phys. 79, 000353 (2007)

Temperature-Dependence of Gap



$SmFeAsO_{0.85}F_{0.15}$

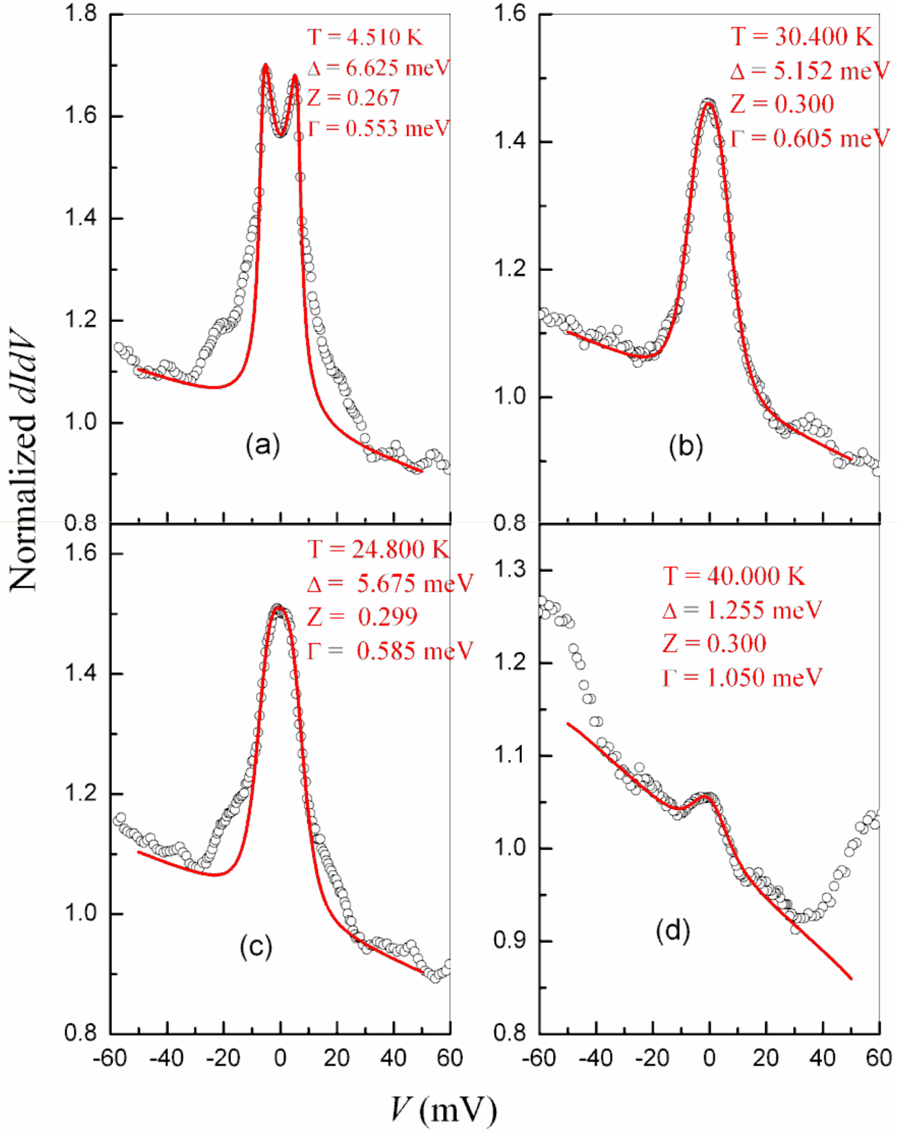
Double-peak (gap):
decreasing splitting
decreasing intensity
vanishes at T_C = 42 K

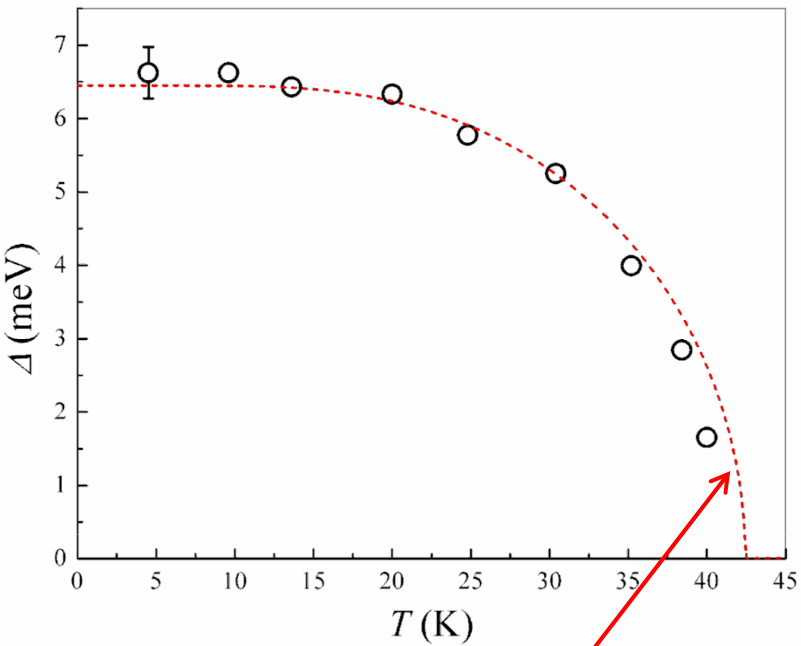
Extra features
(due to superconductivity)
vanishes at T_C = 42 K

Asymmetrical background
(due to normal state)
remains at $T > T_C$

T. Y. Chen, Z. Tesanovic, R. H. Liu, X. H. Chen, and C. L. Chien, *Nature* **453**, 1224 (2008)

BCS-Like Temperature Dependence



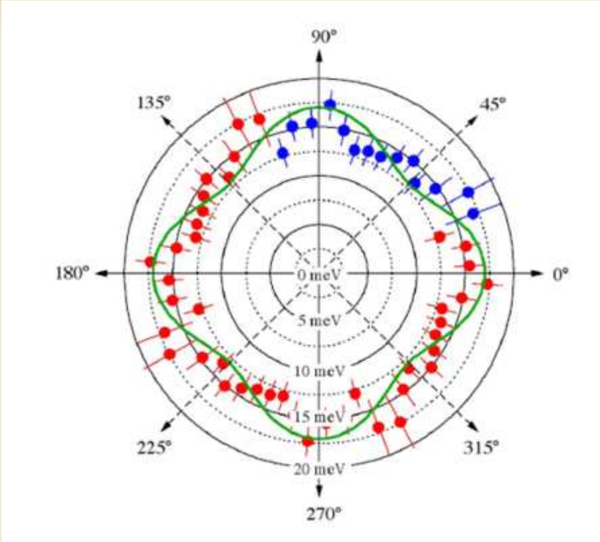


BCS s-wave

At each T:
Gap value from analyzing data using modified BTK theory

Gaps from Other Measurements

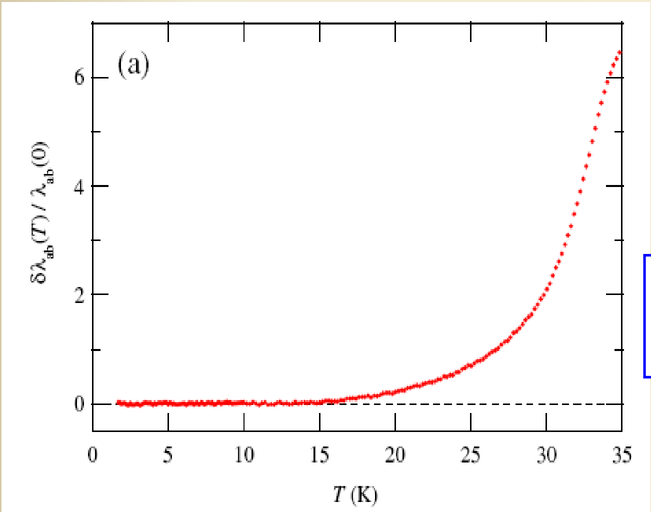
ARPES



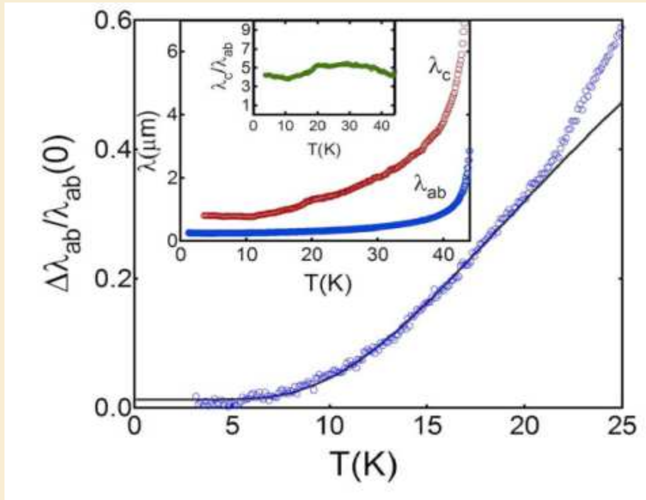
$NdFeAsO_{0.9}F_{0.1}$ (0807.0815.Kondo)
Fully gapped, nearly isotropic **s-wave** symmetry

Nearly isotropic, fully gapped

Penetration Depth



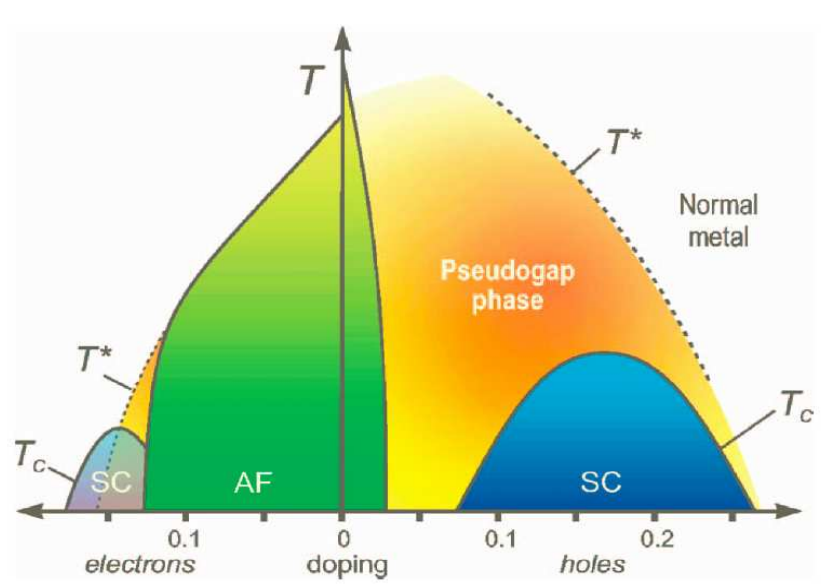
$$\frac{\Delta\lambda(T)}{\lambda(0)} = \sqrt{\frac{\pi\Delta_0}{2T}} \exp\left(-\frac{\Delta_0}{T}\right)$$

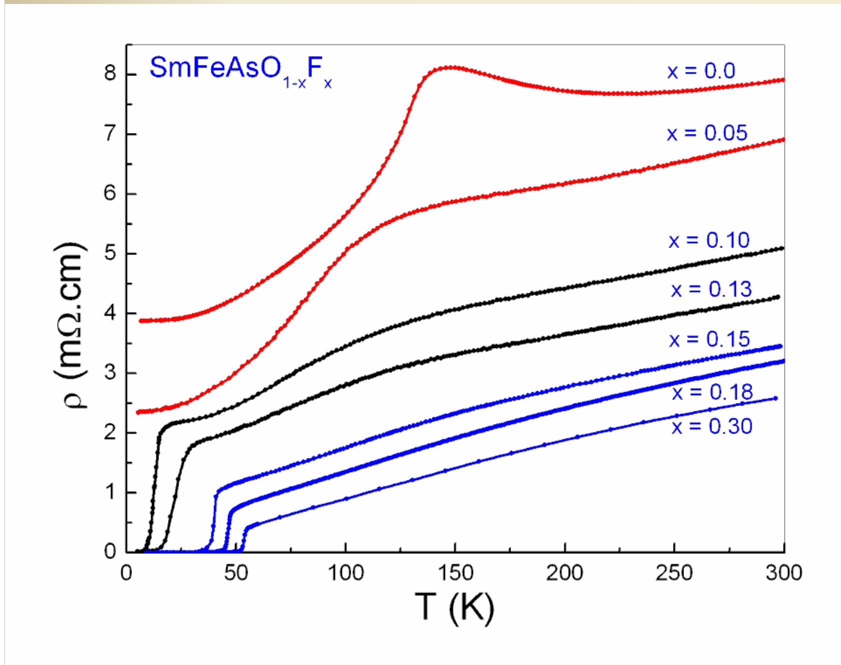


$PrFeAsO_{1-y}$ (0806.3149. Hashimoto)
A single, fully gapped nearly isotropic gap

$NdFeAsO_{0.9}F_{0.1}$ (0807.0876.Martin)
A single, fully gapped nearly isotropic gap

Pseudogaps ?





Pseudogap
in both non-SC and SC cuprates

No pseudogaps found in SC samples

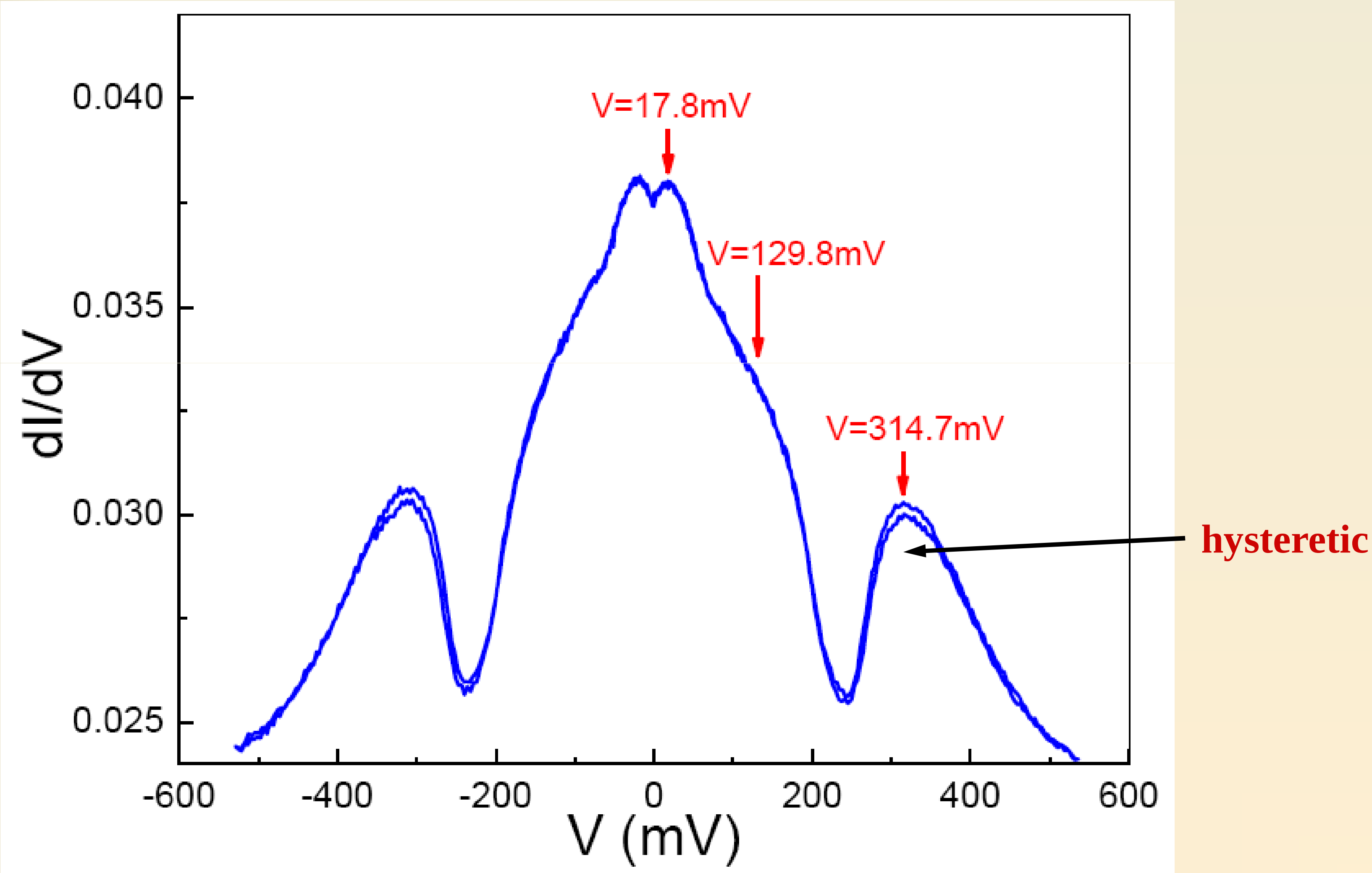
Non-SC samples ?

Characteristics of Pseudogaps

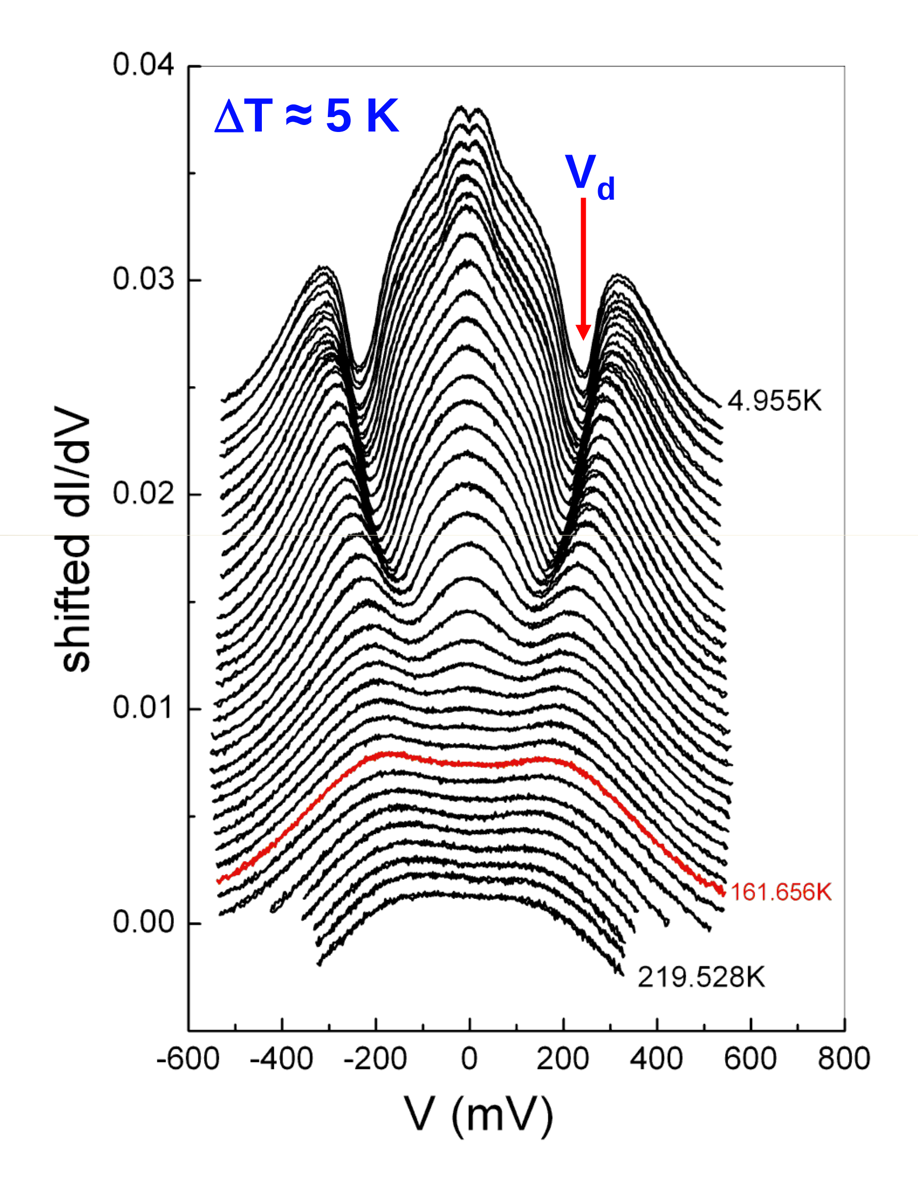
- **Pseudogap may induce conductance peaks.**
- **Pseudogap should be non-hysteretic.**
- **Pseudogap must be contact-independent.**

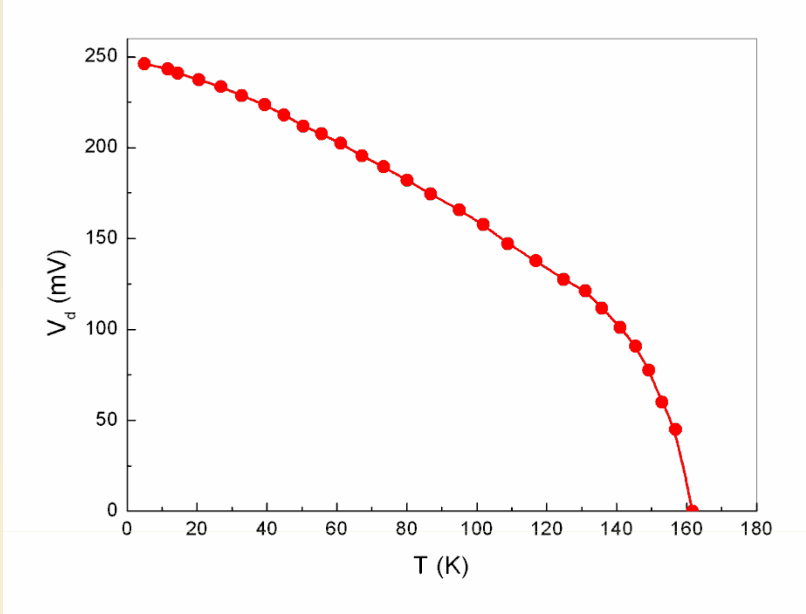
Conductance Peaks in parent SmFeAsO

Conductance peaks “suggesting” pseudogaps



Temperature Dependence of Conductance Peaks



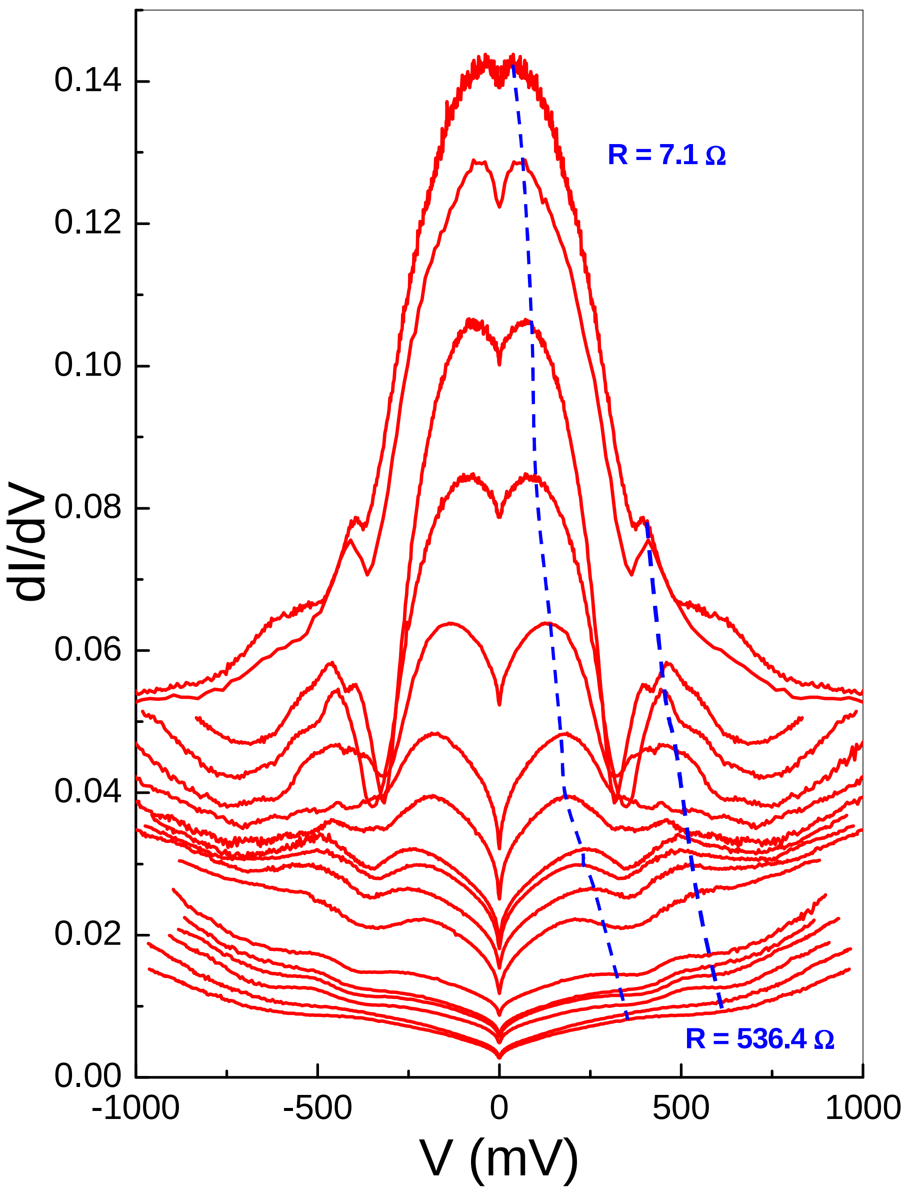


Structure disappears above 160 K

SmFeAsO with SDW at 160 K

Pseudogap for SDW ???

Systematic Contact-Dependent Conductance



Various contact resistance: from 7 Ω to 536 Ω

Various conductance peaks: from 3 mV to 300 mV

Strongly depend on contact resistance

NOT pseudogaps!

Pseudogaps?

- **Pseudogap may induce conductance peaks**

  But, conductance peaks do *not* imply pseudogaps
  since resistance anomaly *also* gives conductance peaks.

- **Pseudogap should be non-hysteretic.**

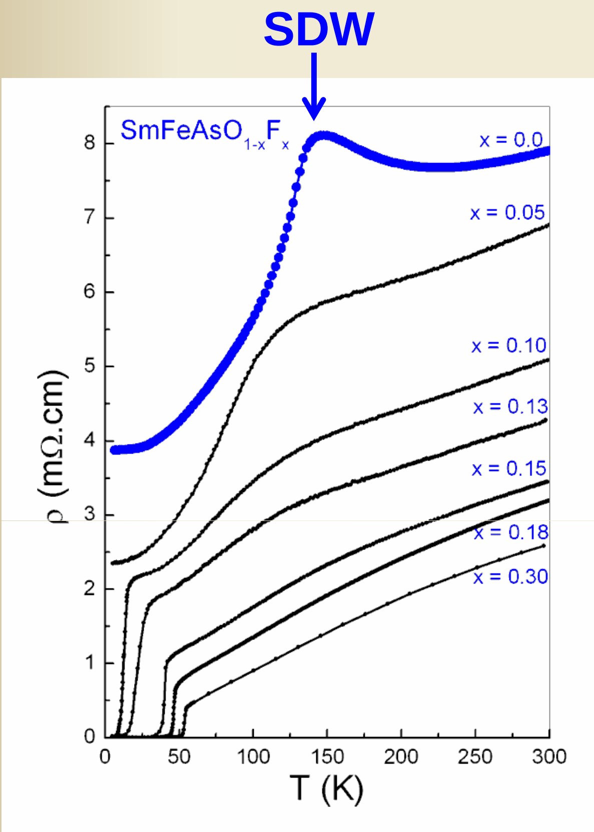
  Spin density wave (SDW) results in *hysteretic behavior* in magnetic structure, crystalline structure, and resistance.

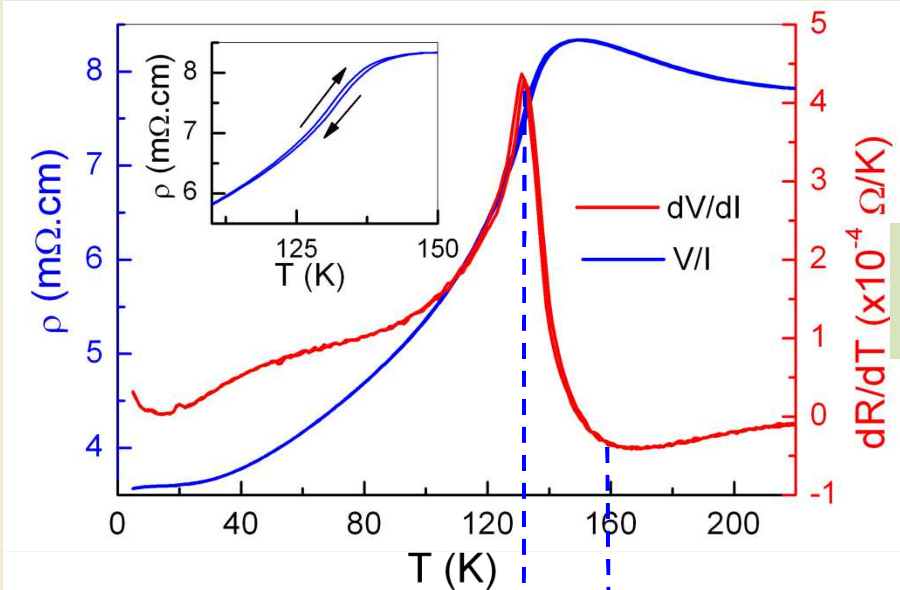
- **Pseudogap must be contact-independent**

  Contact-dependent peaks are not pseudogaps

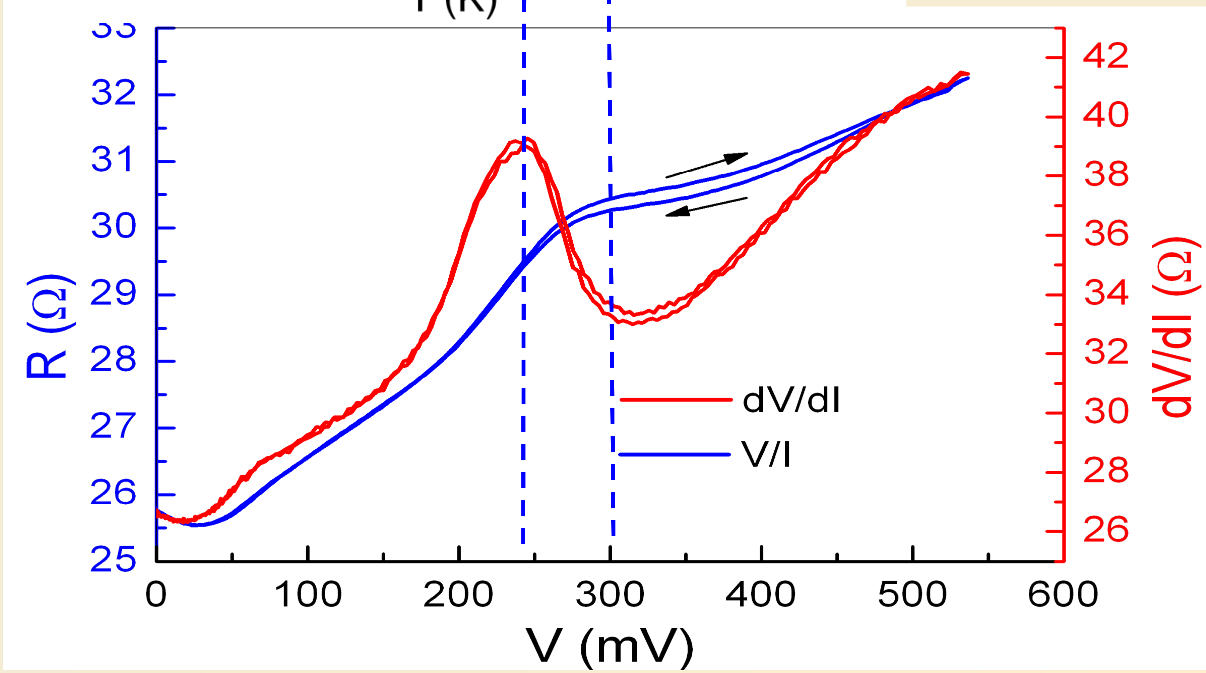
Not pseudogaps, what are they ?

Conductance Peaks due to Ballistic Heating !



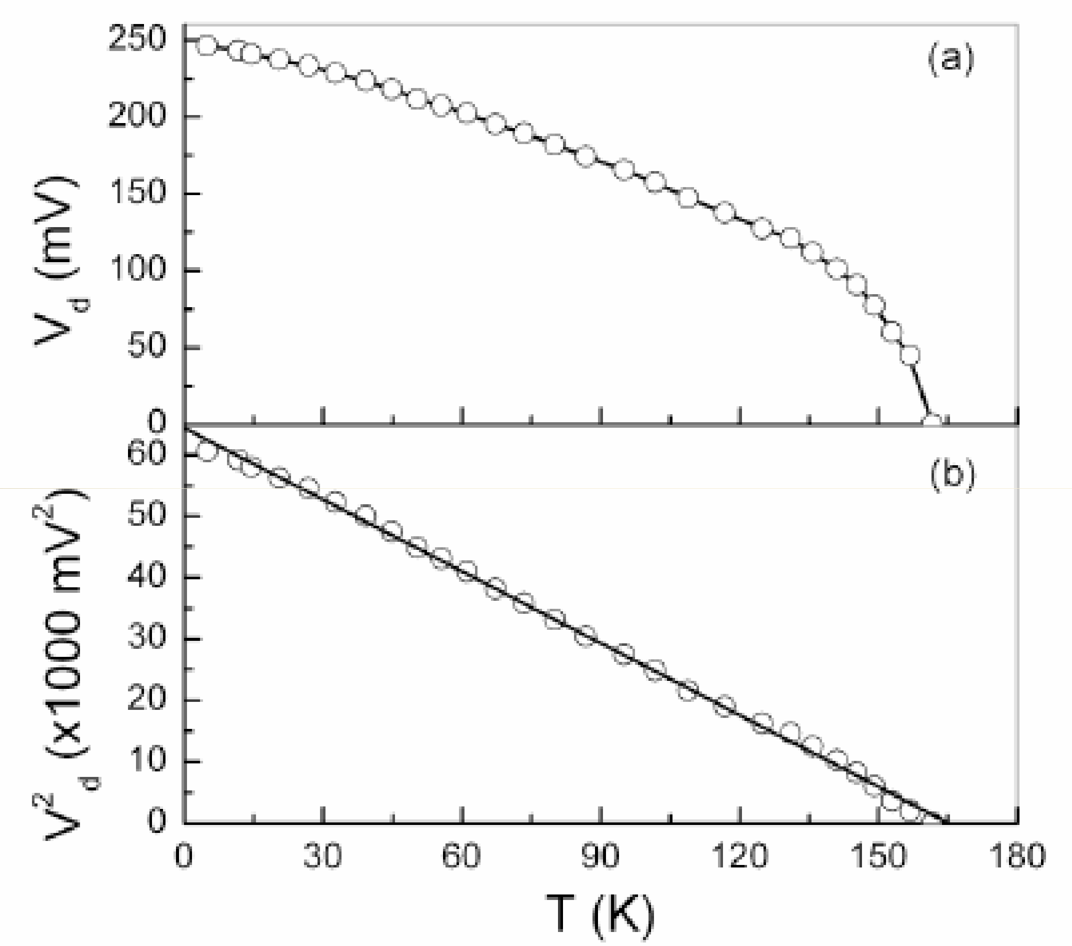


SmFeAsO with SDW at 160 K



Point contact on SmFeAsO

Temperature dependence of "Pseudogap"



SmFeAsO with SDW transition at 160 K

$V^2 \sim (T_{SDW} - T)$

Ballistic heating effect

NOT pseudogaps, but SDW transition!

Summary

Superconducting gap (Δ) of $SmFeAsO_{1-x}F_x$ (x = 0.15, 0.18, 0.30):

- Gap value

  $2\Delta/k_BT_C$ = **3.68, 3.62, 3.52**

  close to **3.53** (BCS s-wave)

- Gap structure

  ≈ Isotropic single gap

- Gap temperature dependence

  BCS-like

- No pseudogaps

Perhaps due to interband $S_{\pm}$ mechanism

T. Y. Chen, Z. Tesanovic, R. H. Liu, X. H. Chen, and C. L. Chien, *Nature* **453**, 1224 (2008)

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Sunxiang Huang, JHU

Dr. **Mark Stiles**, NIST

Prof. **Zlatko Tesanovic**, Johns Hopkins University

Prof. **Xianhui Chen**, University of Science and Technology of China

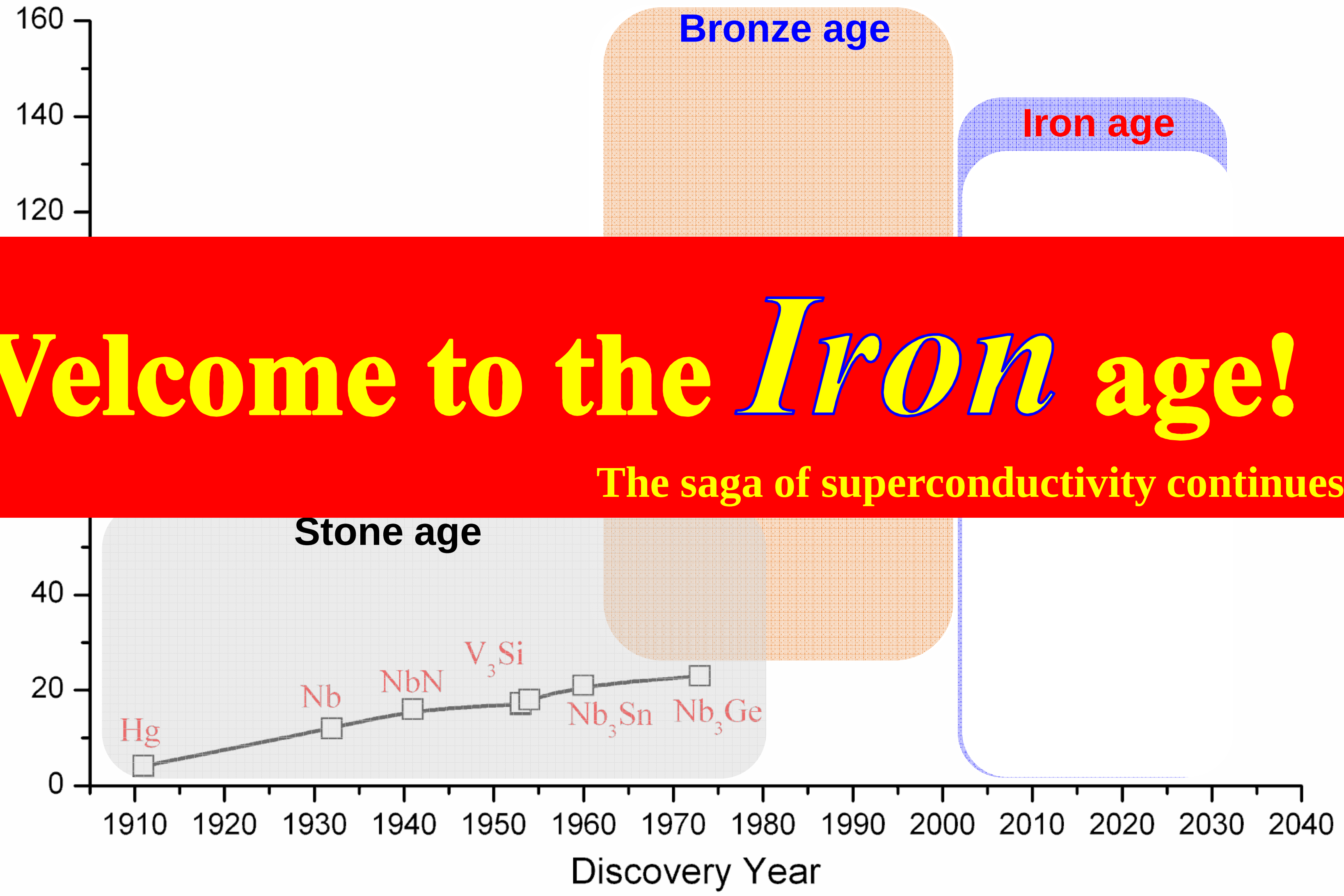
Prof. **Yi Ji**, University of Delaware

Fe Superconductors

- Large varieties of materials
  - 1111: LaFeAsO, CeFeAsO, SmFeAsO, …
  - 122: $BaFe_2As_2$, $CaFe_2As_2$, …
  - 111: LiFeAs, …
  - 11: FeSe, FeTe, …
  - More to come…
- Highest T_c~55K achieved in **$SmFeAsO_{1-x}F_x$ ("single layer")**
- Metallic parent compound with common SDW feature
- Fully gapped, nearly s-wave symmetry
- FeAs plane can be doped with Co

Very different from Cuprates!

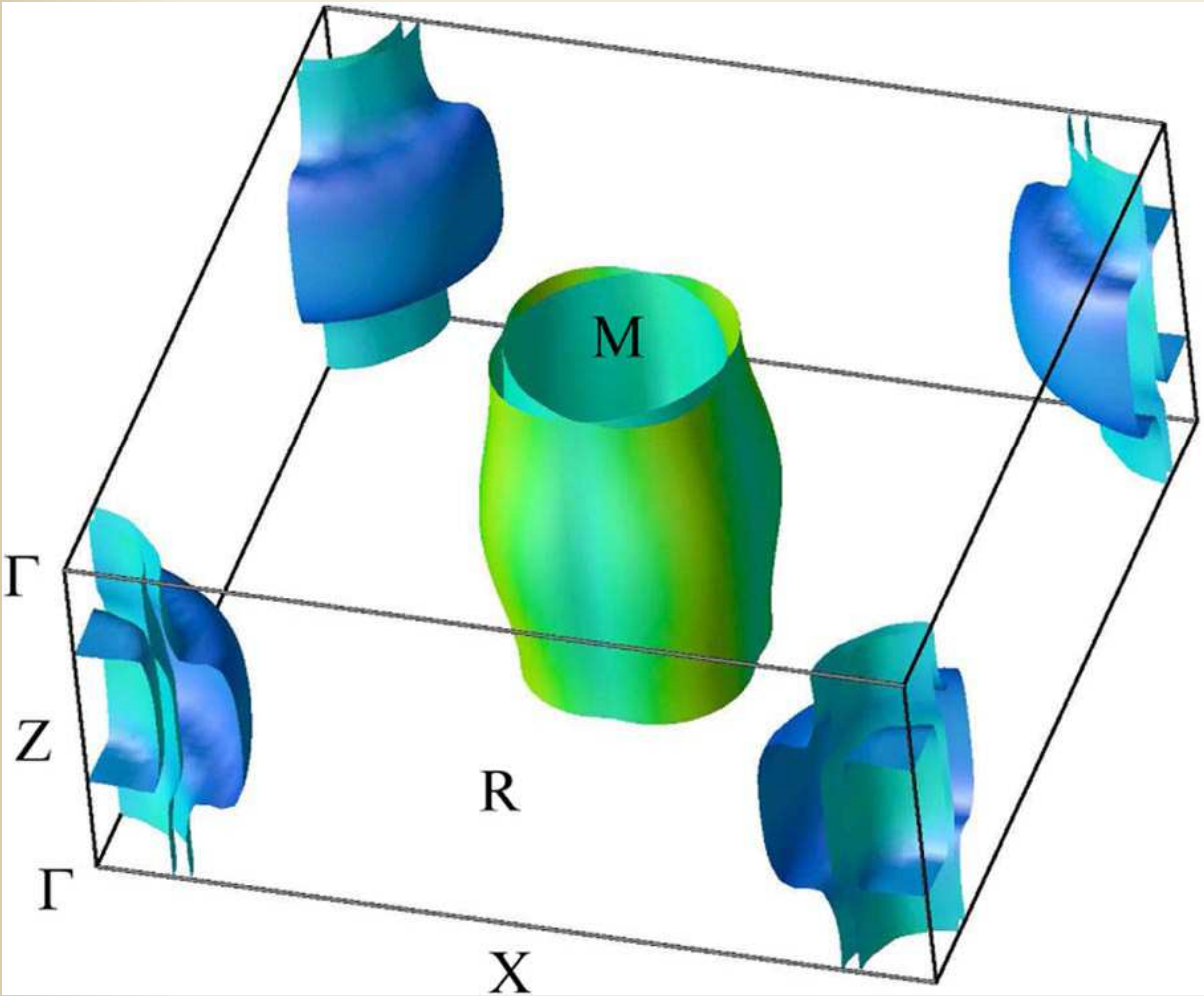
Saga of Superconductivity



Welcome to the *Iron* age!

The saga of superconductivity continues…

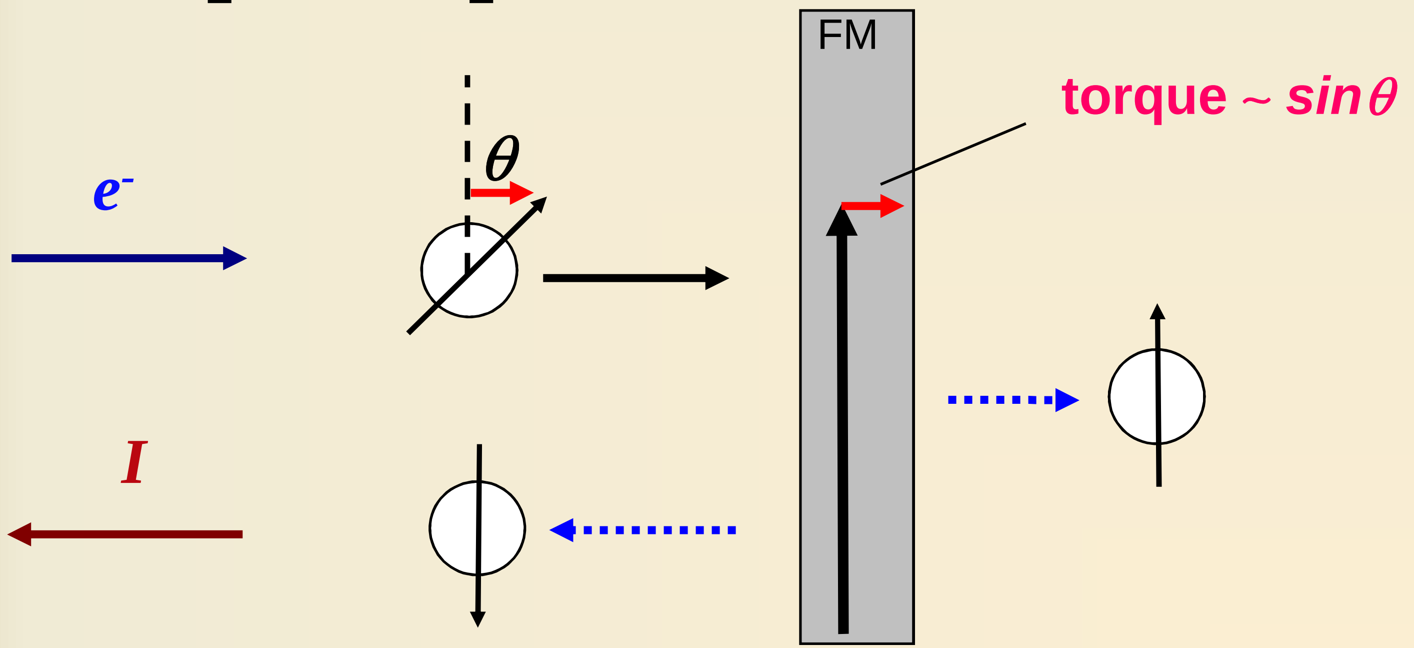
Fermi Surface of Fe-SC



5 sheets:
2 electron sheets at MA
2 hole sheets at Γ
1 hole pocket at Z

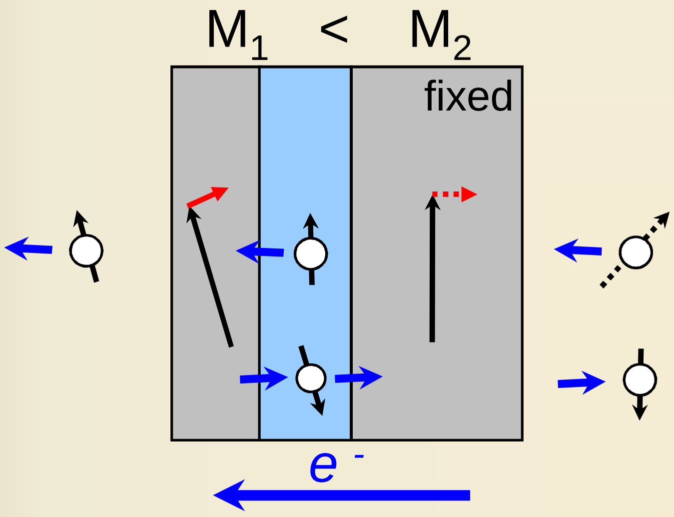
Spin-Transfer Torque: Single Electron Scenario

$$\psi = \cos\frac{\theta}{2}|\uparrow> + \sin\frac{\theta}{2}|\downarrow>$$



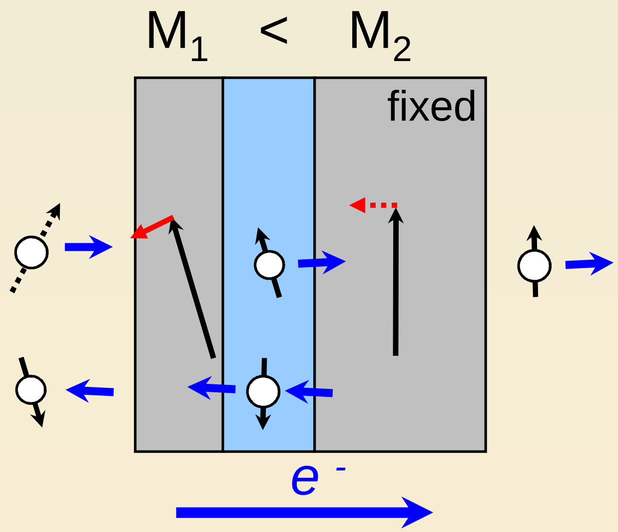
Slonczewski, JMMM **159**, L1 (1996)
Waintal *et al.*, PRB **62**, 12317 (2000)

Switching via Spin-Transfer Torque



favor ***parallel***

low R
I



favor ***anti-parallel***

high R
I

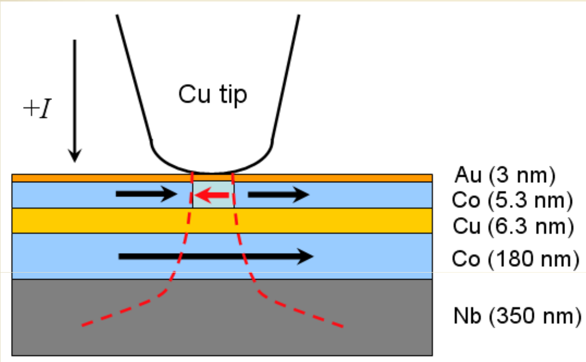
detect switching through GMR effect

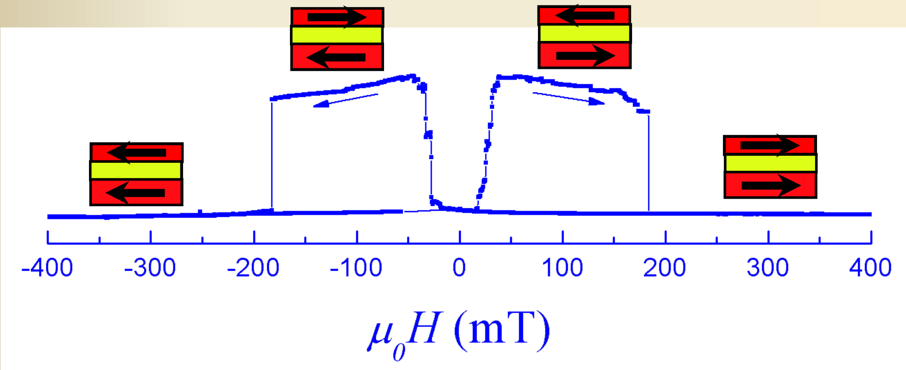
Slonczewski, JMMM 159, L1 (1996); Waintal et al., PRB 62, 12317 (2000)

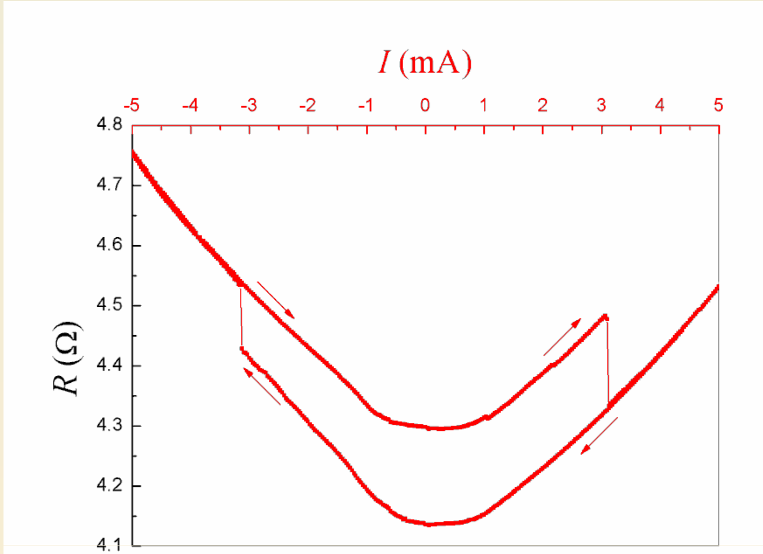
Switching via Spin Transfer Torque (STT) Effect

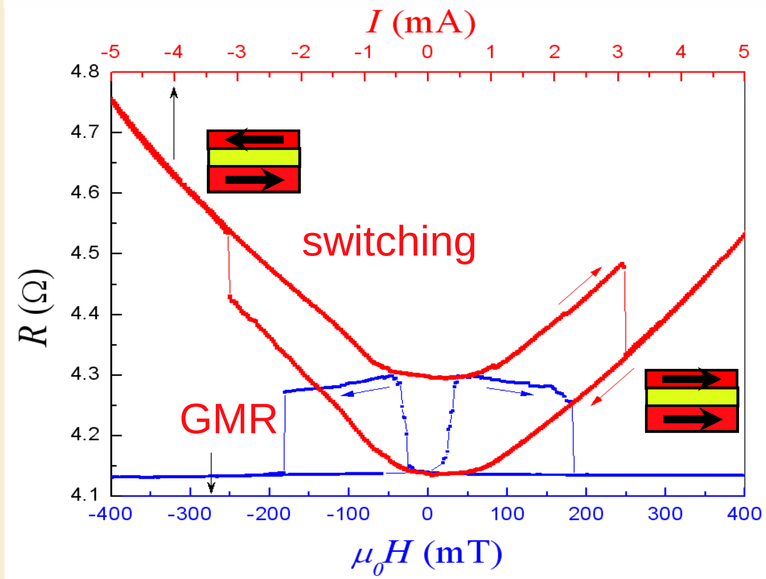
$j_C \sim 10^7$ A/cm^2

Nano-pillar, point contact



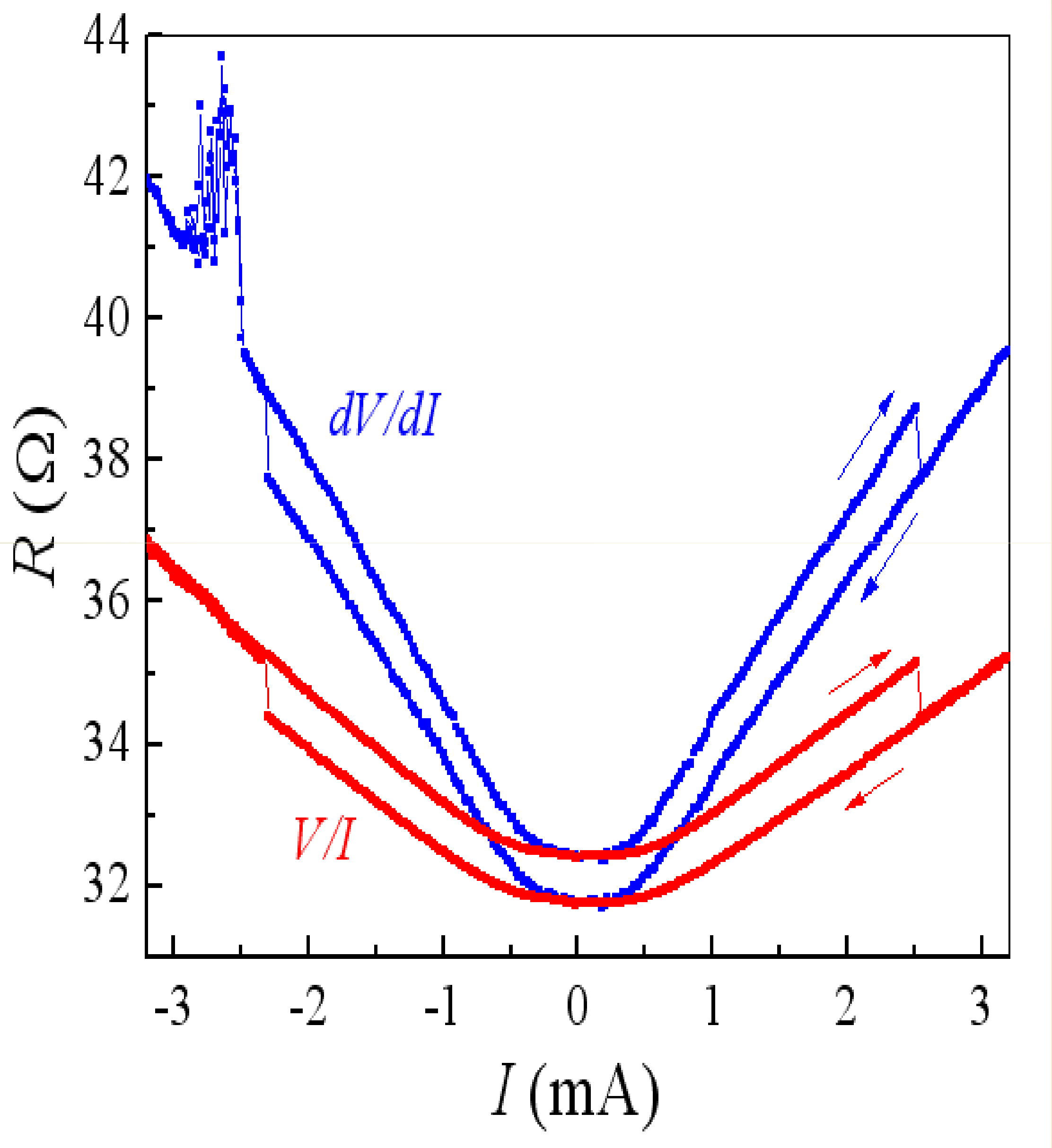


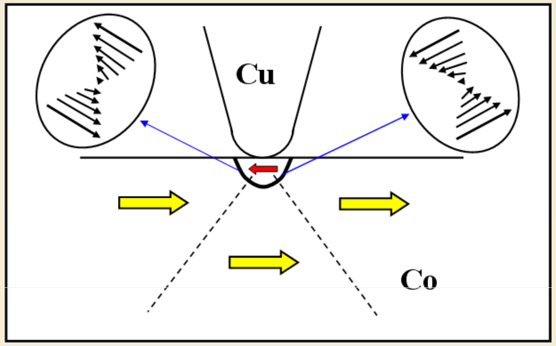




T. Y. Chen, Y. Ji and C. L. Chien, *Appl. Phys. Lett.* **84**, 380 (2004).

STT in Magnetic Nanostructures



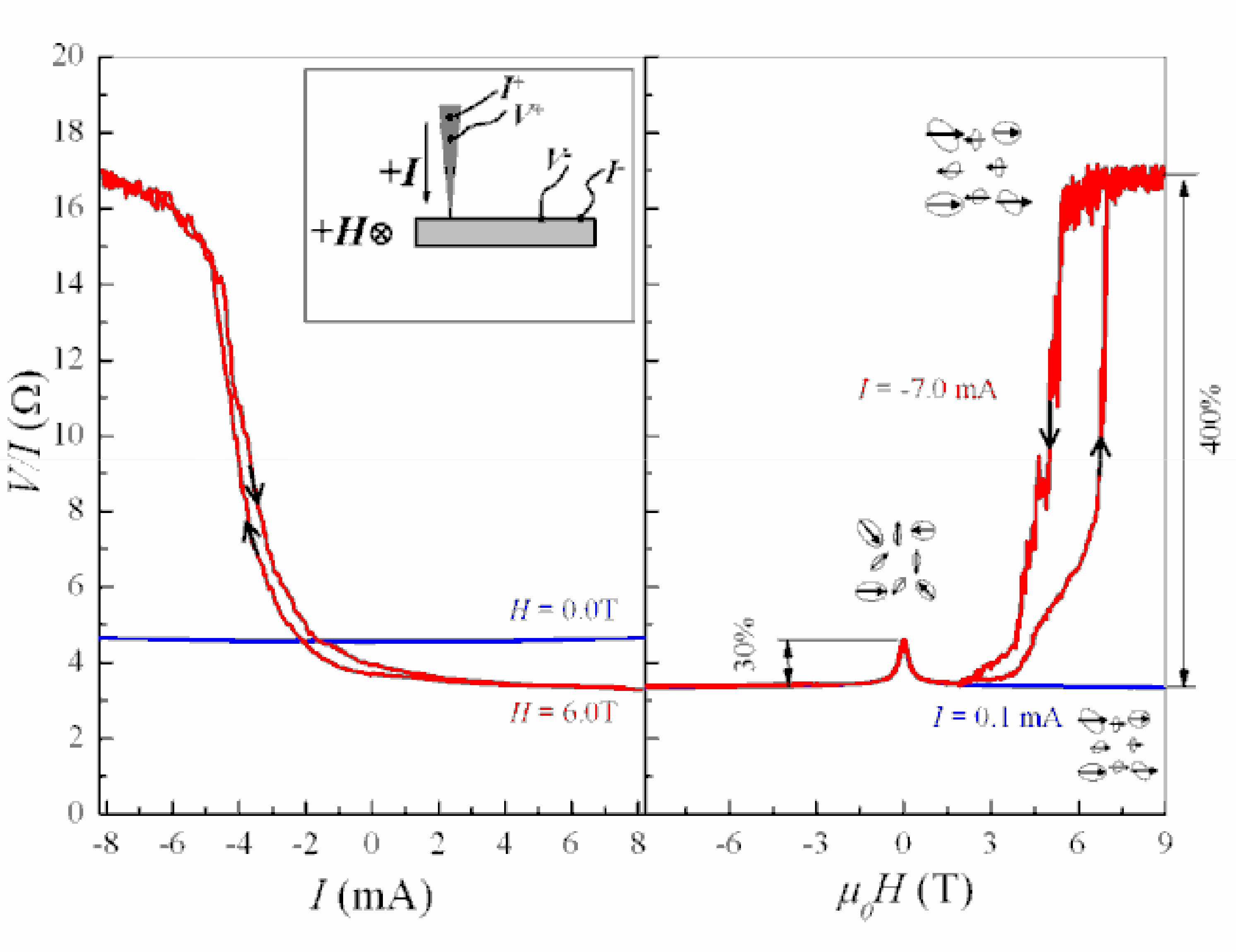


New form of STT effect

Inverse of the domain wall MR

T. Y. Chen, Y. Ji, C. L. Chien and M. D. Stiles, ***Phys. Rev. Lett.*** **93**, 026601 (2004).

New Spin Structure Realized by STT



New spin structure, largest MR of over 400%

T. Y. Chen, S. X. Huang, C. L. Chien and M. D. Stiles, ***Phys. Rev. Lett.*** **96**, 207203 (2006).

Cryogenic Dewar

- Temperature control: 1.5 K to 400 K
- Magnetic field: 0 - 9 T
- Rotating magnetic field without mechanical motion
- Nitrogen jacket

- Sensitive transport system
  Two lock-in from Stanford research
  10-channel switching box
  Current source, nano-voltmeter

Budget: 150K

Purposes

- Point contact spectroscopy
- Transport study of nanostructure
- Spin injection and detection studies

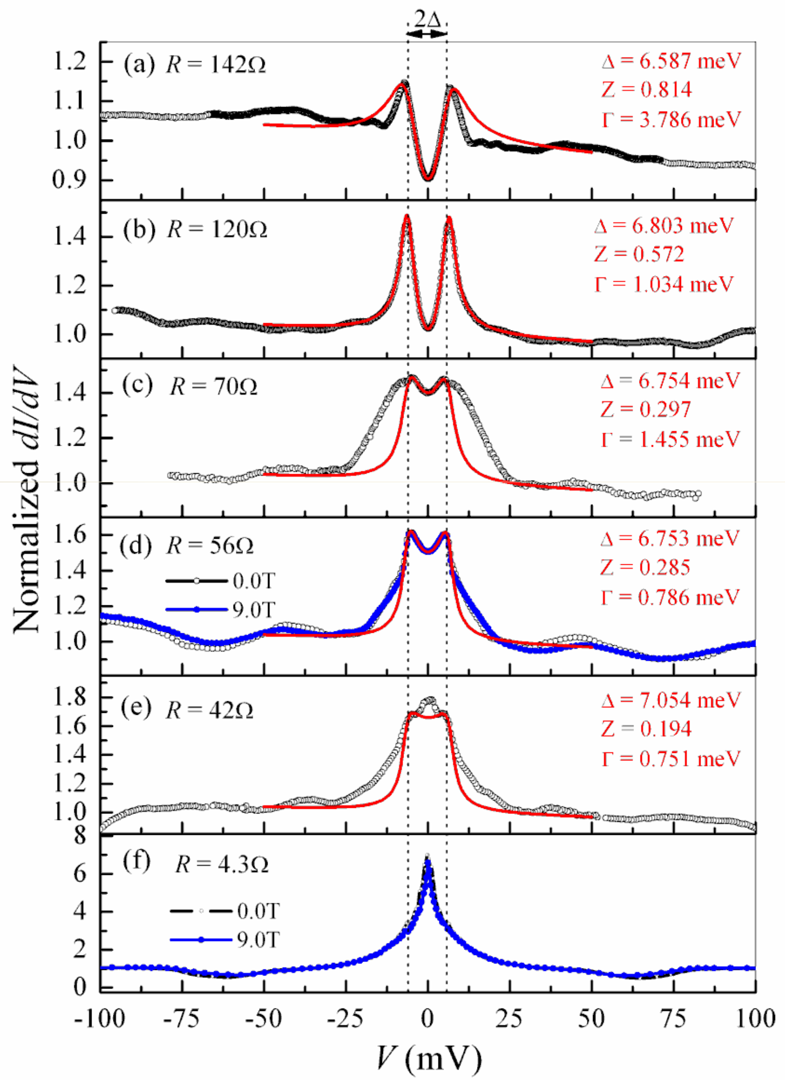
Sputtering System

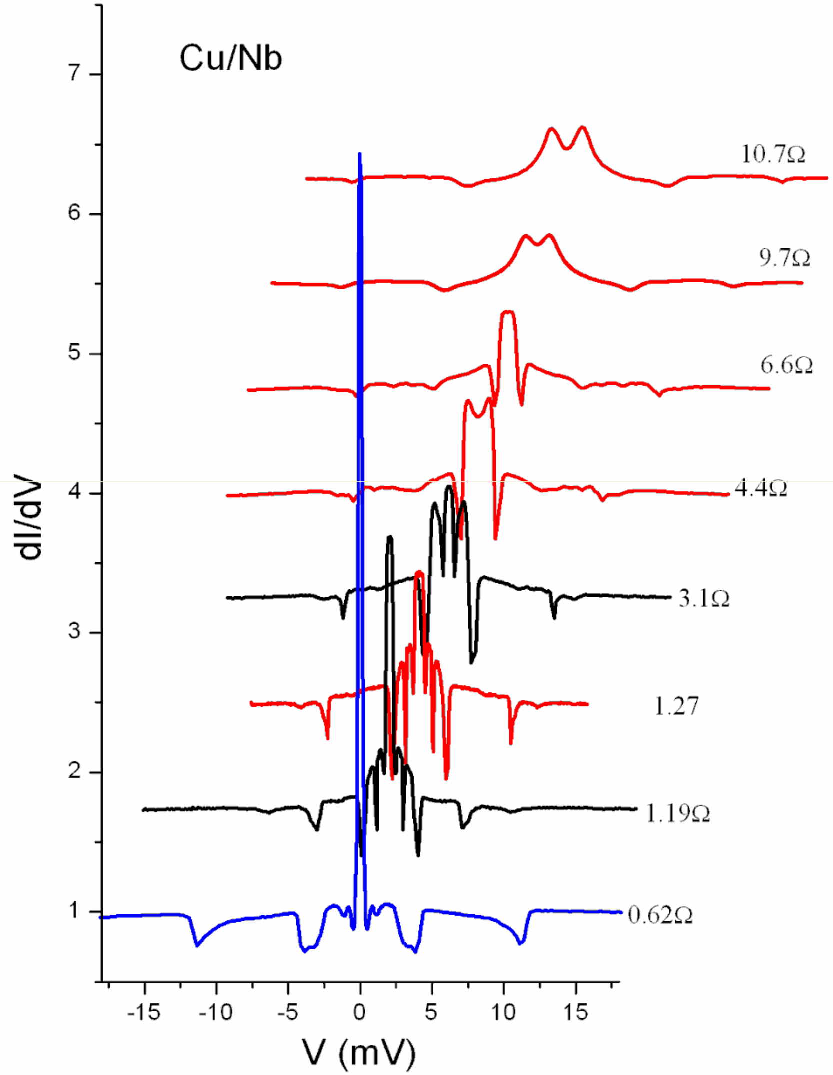
Specific features:
Tilt gun, co-sputtering
Evaporator

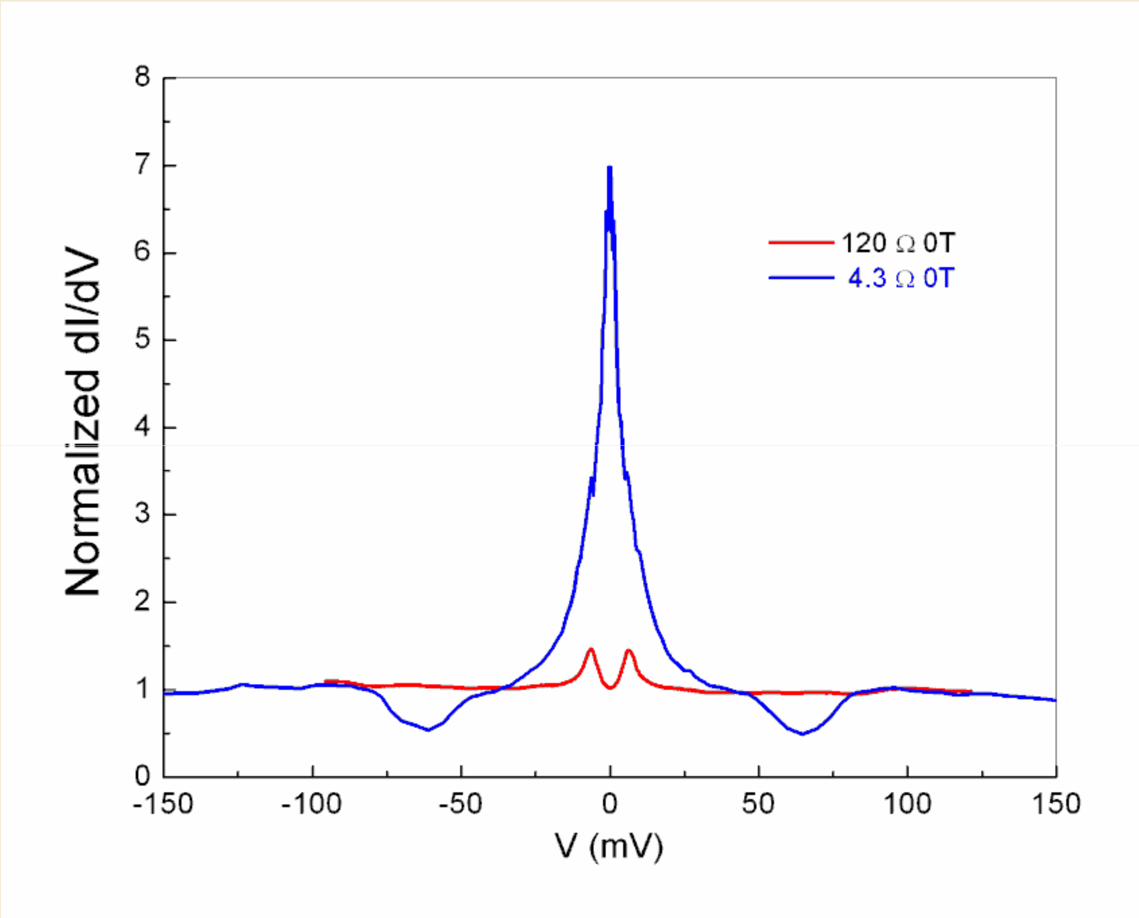
Vibrating Sample Magnetometer

Thin film
Study oxides for energy

Dependence of Contact Resistance

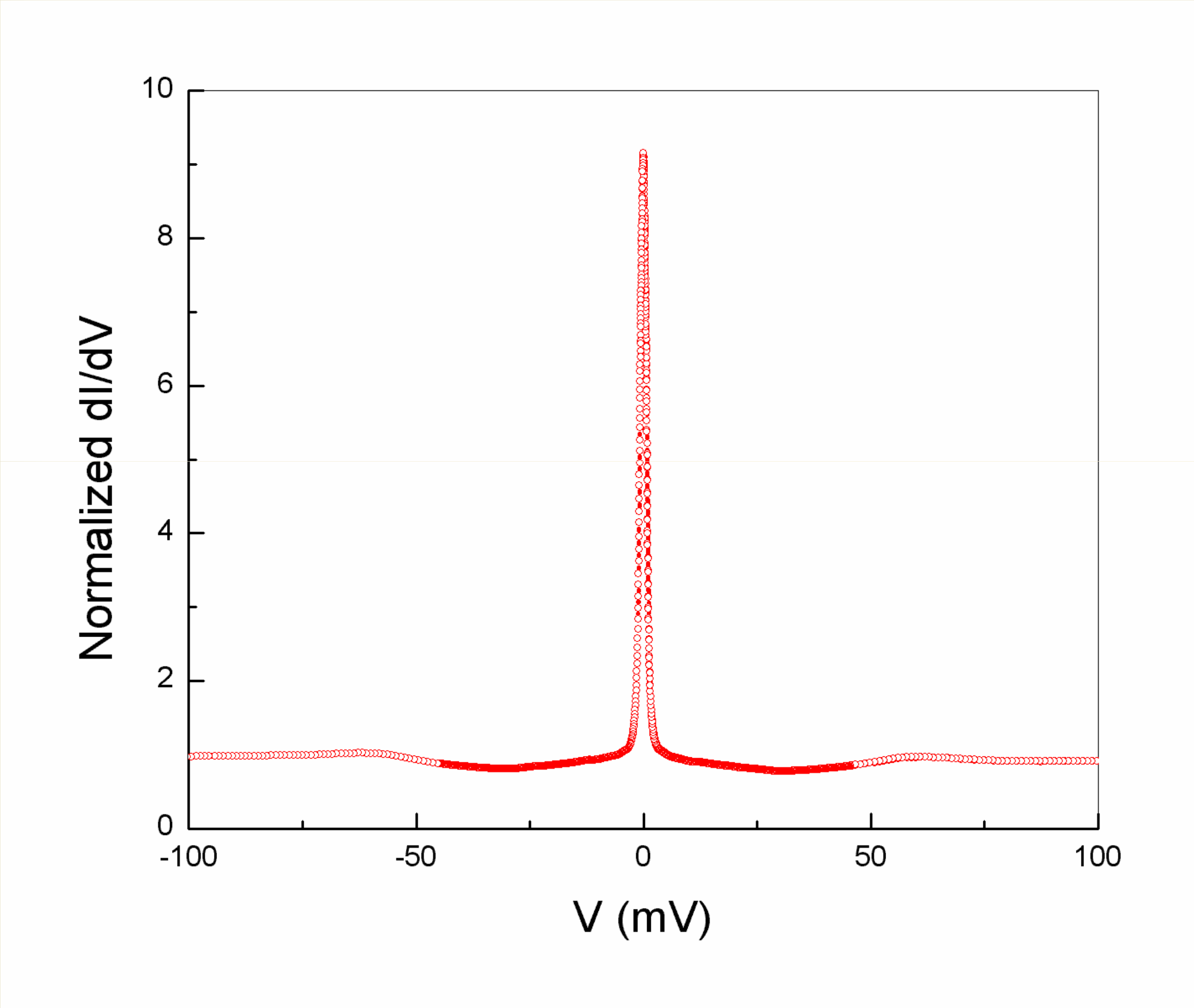


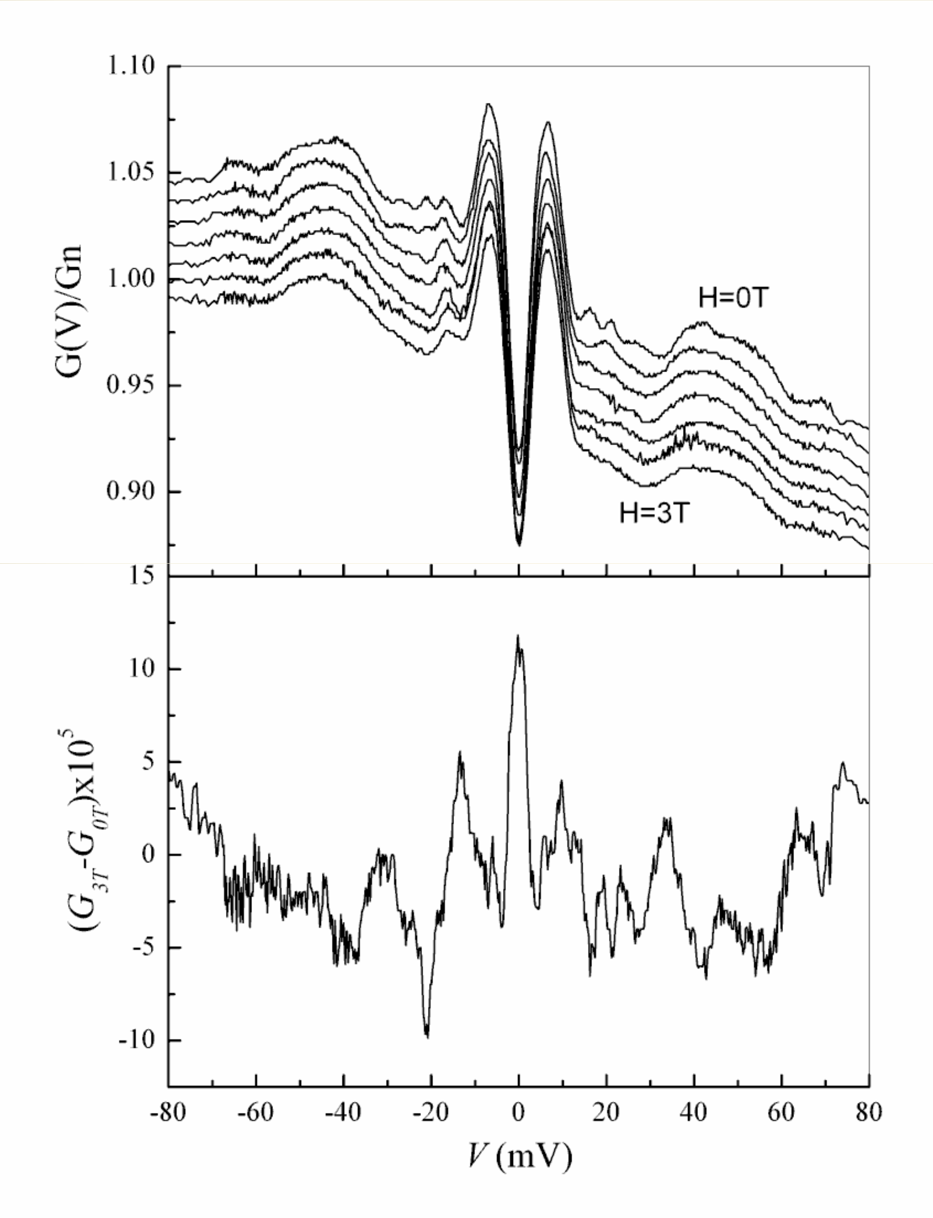




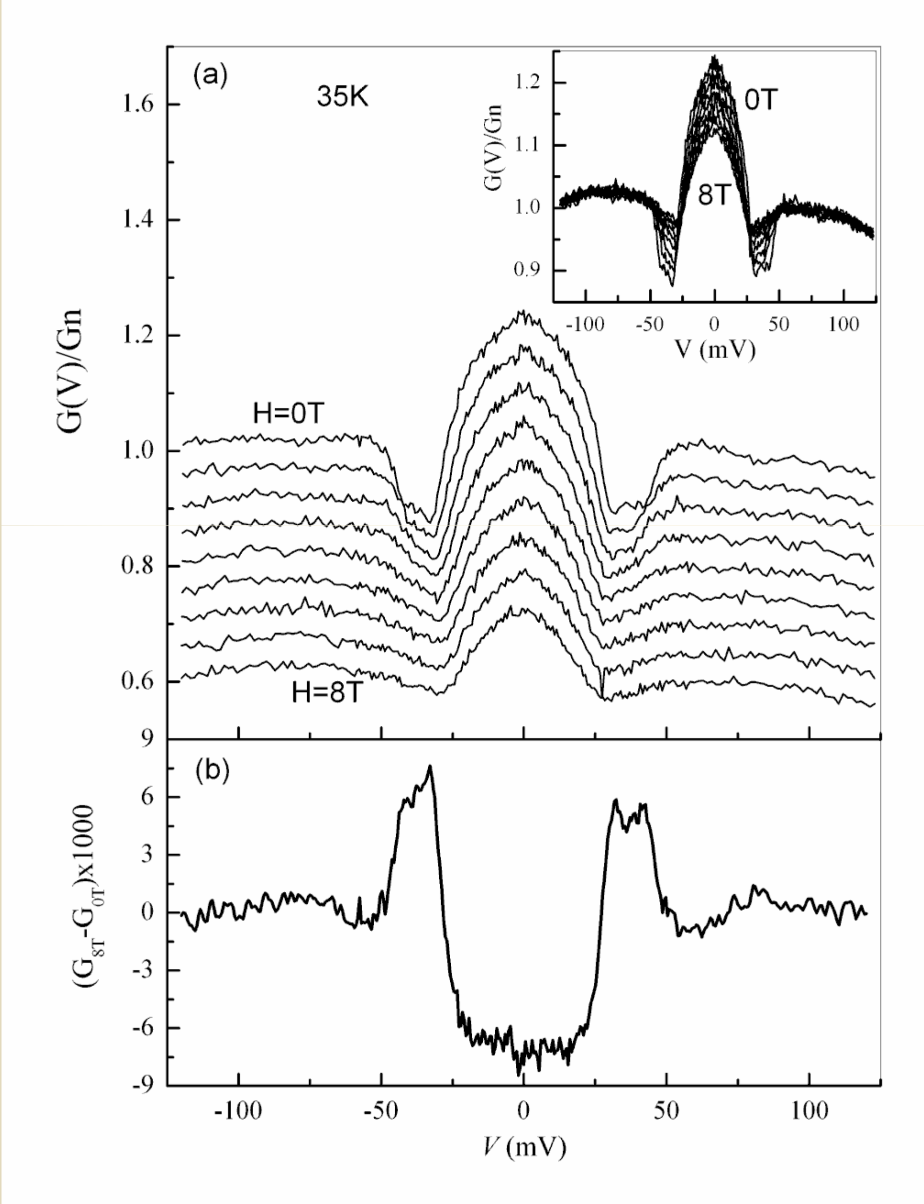
Normalized dI/dV
V (mV)
120 Ω 0T
4.3 Ω 0T
0
1
2
3
4
5
6
7
8
-150
-100
-50
0
50
100
150

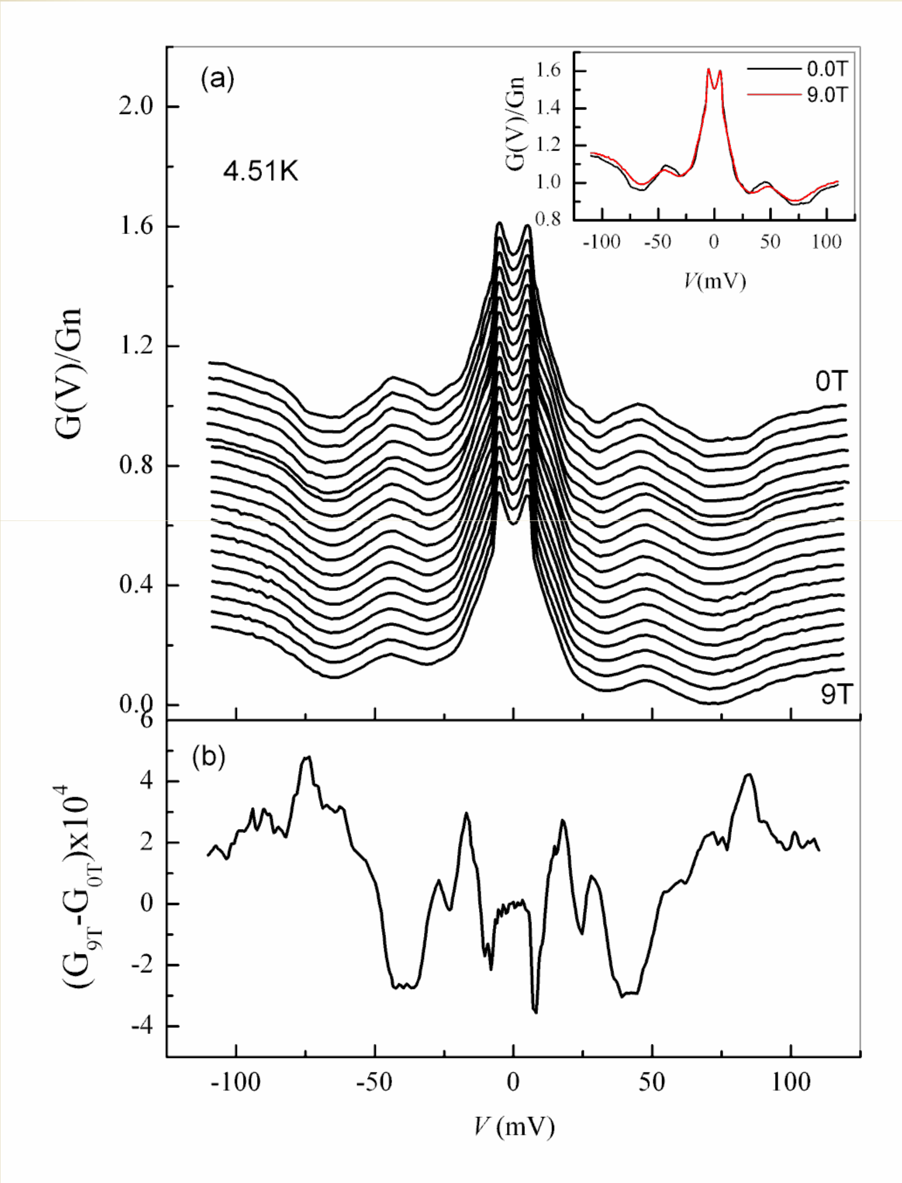
ZBA shape is different for different contacts

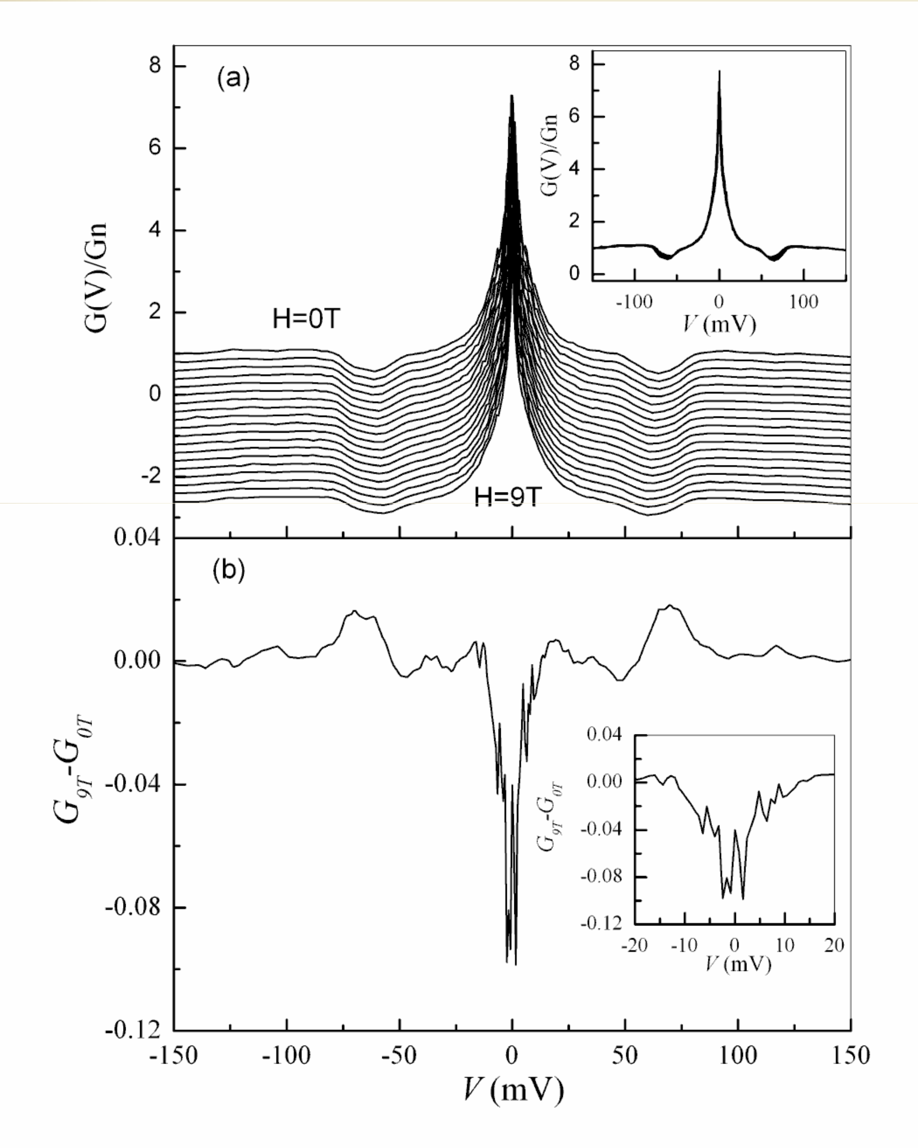




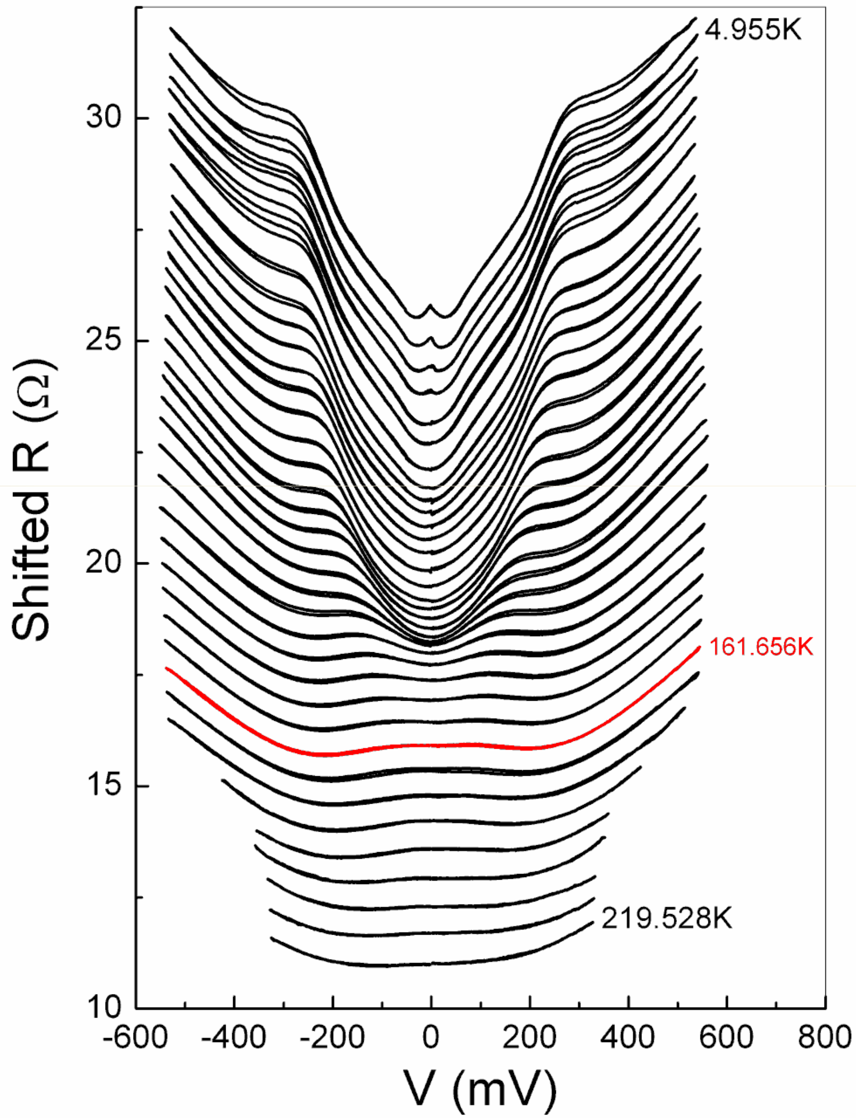
1.10
1.05
1.00
0.95
0.90
G(V)/Gn
H=0T
H=3T
15
10
5
0
-5
-10
$(G_{3T}-G_{0T})$x10[5]
-80
-60
-40
-20
0
20
40
60
80
V (mV)


(a)
35K
G(V)/Gn
H=0T
H=8T
0T
8T
V (mV)
(b)
$(G_{8T}-G_{0T})$x1000
V (mV)


(a)
4.51K
0T
9T
G(V)/Gn
0.0
0.4
0.8
1.2
1.6
2.0
0.0T
9.0T
G(V)/Gn
V(mV)
(b)
$(G_{9T}-G_{0T})x10^4$
-100
-50
0
50
100
V (mV)

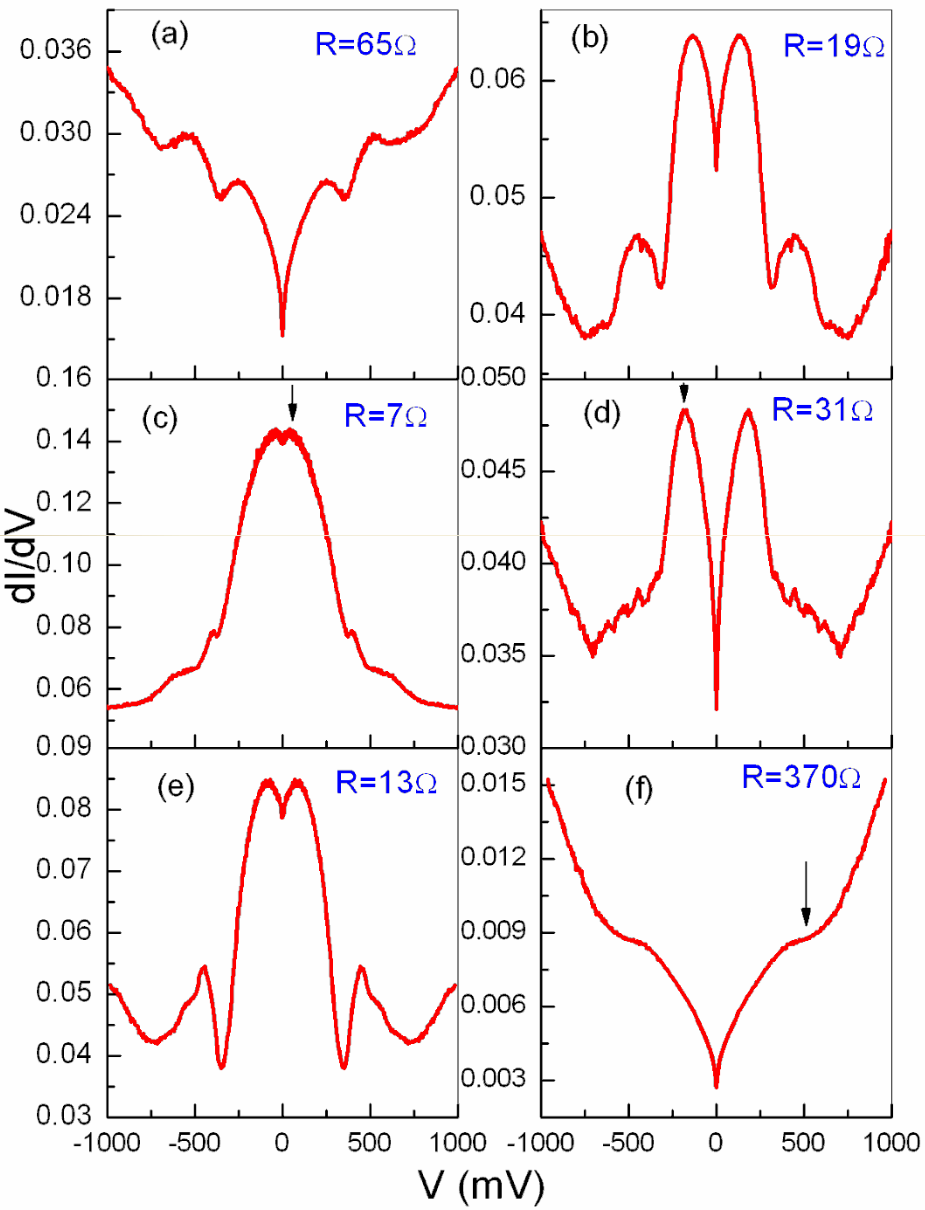


(a)
H=0T
H=9T
G(V)/Gn
(b)
G_{9T}-G_{0T}
V (mV)



4.955K
161.656K
219.528K
Shifted R (Ω)
V (mV)
10
15
20
25
30
-600
-400
-200
0
200
400
600
800

Various Contacts



Various contact, various peak values from 5 mV to 500 mV

A real pseudogap must be intrinsic independent of contact