ICMT Workshop on Topological Phases
University of Illinois at Urbana-Champaign --- October 25, 2008

Experimental evidence for Complex Chiral Superconductivity in Sr_2RuO_4 and UPt_3

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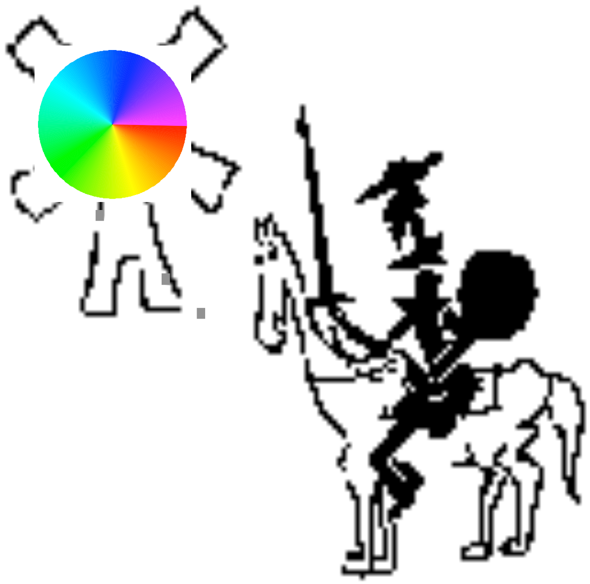
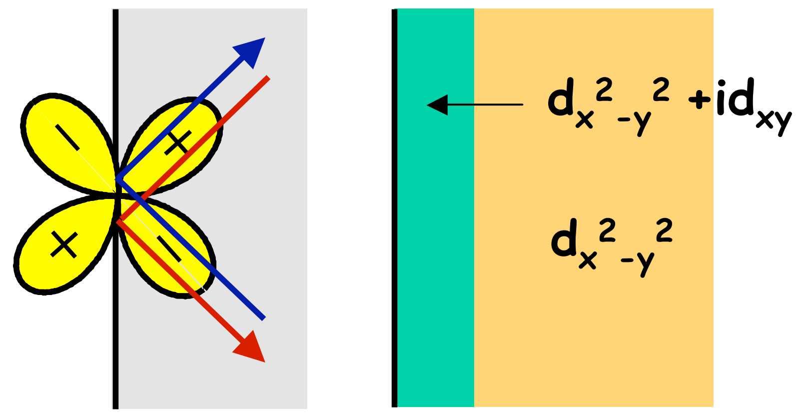
The Quest for Complex Superconductors

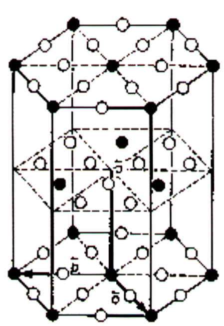


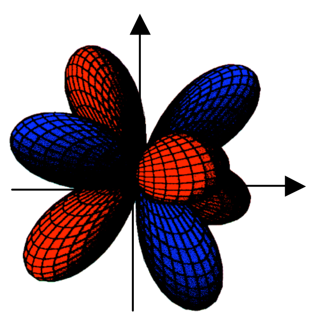
Surface states in anisotropic superconductors?

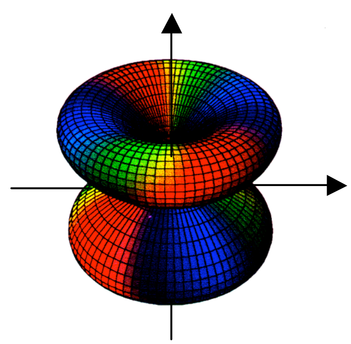


Heavy Fermion superconductors?

UPt_3 $T_{cA} = 0.50$ $T_{cB} = 0.45K$



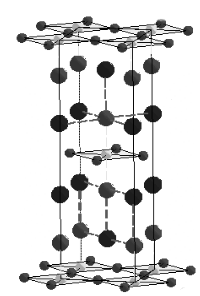


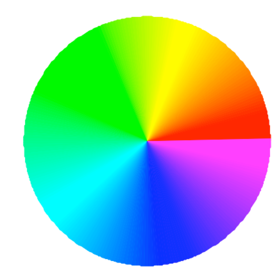


$(k_x^2 - k_y^2)\, k_z$ $(k_x + ik_y)^2\, k_z$

Ruthenate superconductors

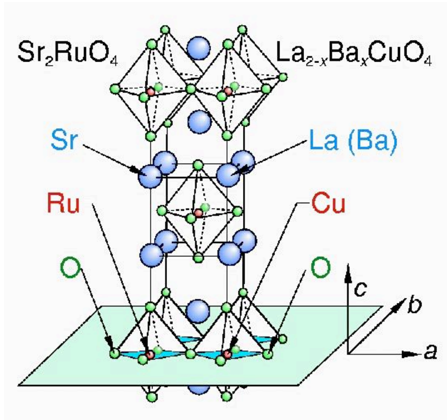
Sr_2RuO_4 $T_c = 1.5K$





$p_x + ip_y$

Ruthenate superconductor: Sr_2RuO_4 (Y. Maeno, 1994)

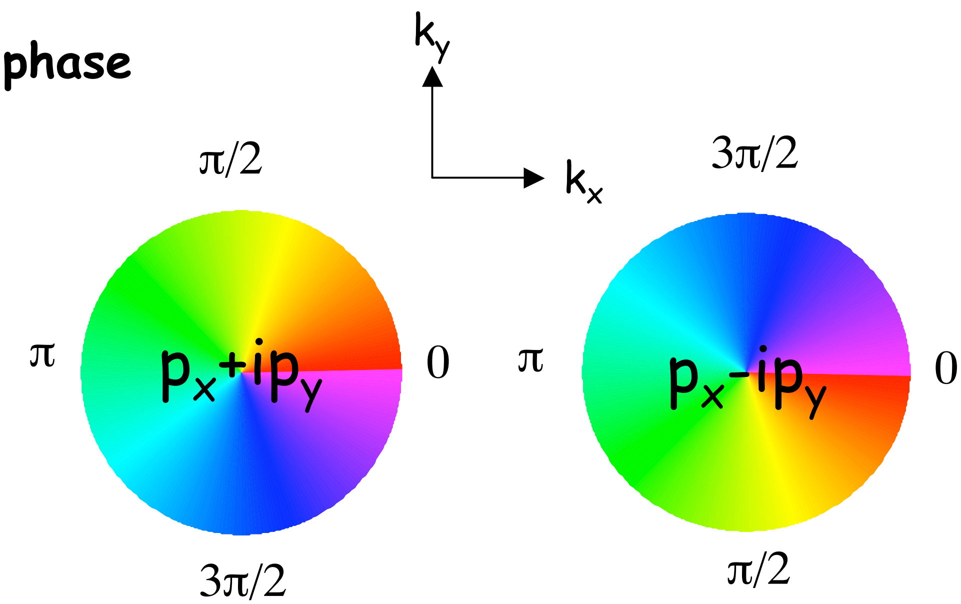


- perovskite structure but Cu-free (T_c = 1.5 K)
- close to a ferromagnetic transition
- electrodynamics strongly non-local ($\xi \sim \lambda$)
- unusual interface phases (3K phase at Ru-inclusions)
- suspected multiple superconducting bands
- suspected to be unconventional
- suspected to be p-wave
- suspected to break time-reversal symmetry
-

Proposed order parameter: **complex p_x+ip_y state** (M. Rice and M. Sigrist)

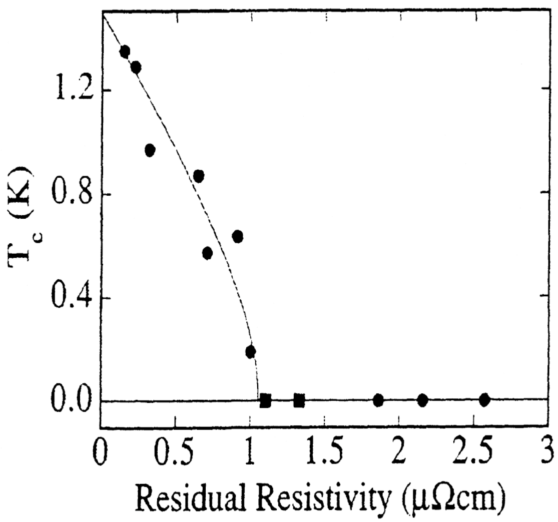
2D analogue of ^{3}He A-phase

- Isotropic energy gap (magnitude)
- Continuous linear phase variation
- Broken time-reversal symmetry
- Possibility of chiral domains

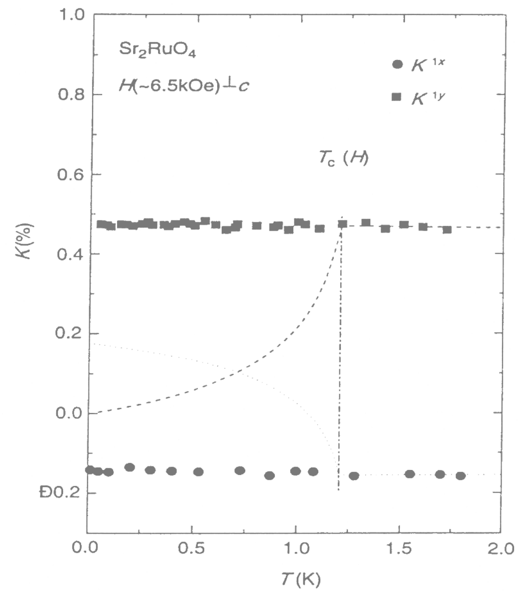


Experimental case for complex p-wave

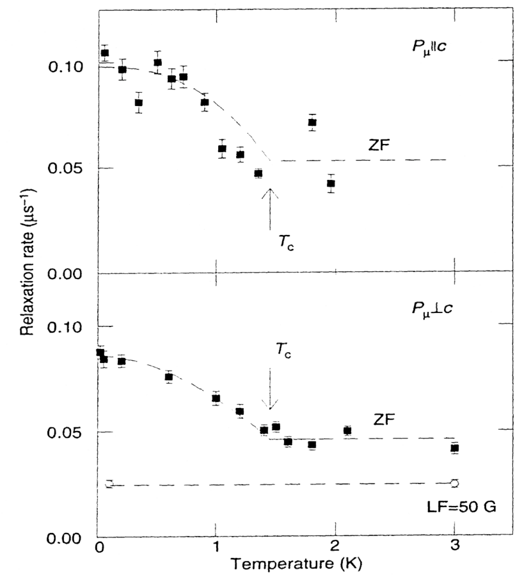
Sensitivity to impurities
(Mackenzie …)



NQR Knight shift
(Ichida…)

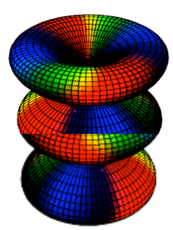


μSR relaxation
(Luke …)



Evidence for line nodes
(many groups)

specific heat
penetration depth
NMR spin relaxation
thermal conductivity



nodes in c-axis (finite k)?

Anomolous flux pinning
(Mota …)

Vortex pinning on chiral domain walls

SSM imaging
(Moler …)

No spontaneous currents from chiral domains

Kerr effect
(Kapitulnik …)

Broken time-reversal symmetry

SQUID interferometry
(Y. Liu …)

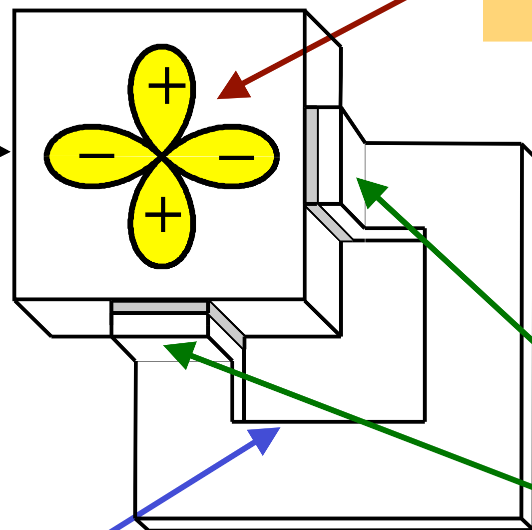
Sign change between opposite faces

Measuring phase anisotropy --- the corner SQUID

Order parameter alignment

domains align N-S, not a-b

Unconventional SC single crystal



Conventional SC thin film loop

Josephson tunnel junctions

tunneling selects direction in k-space

dc SQUID

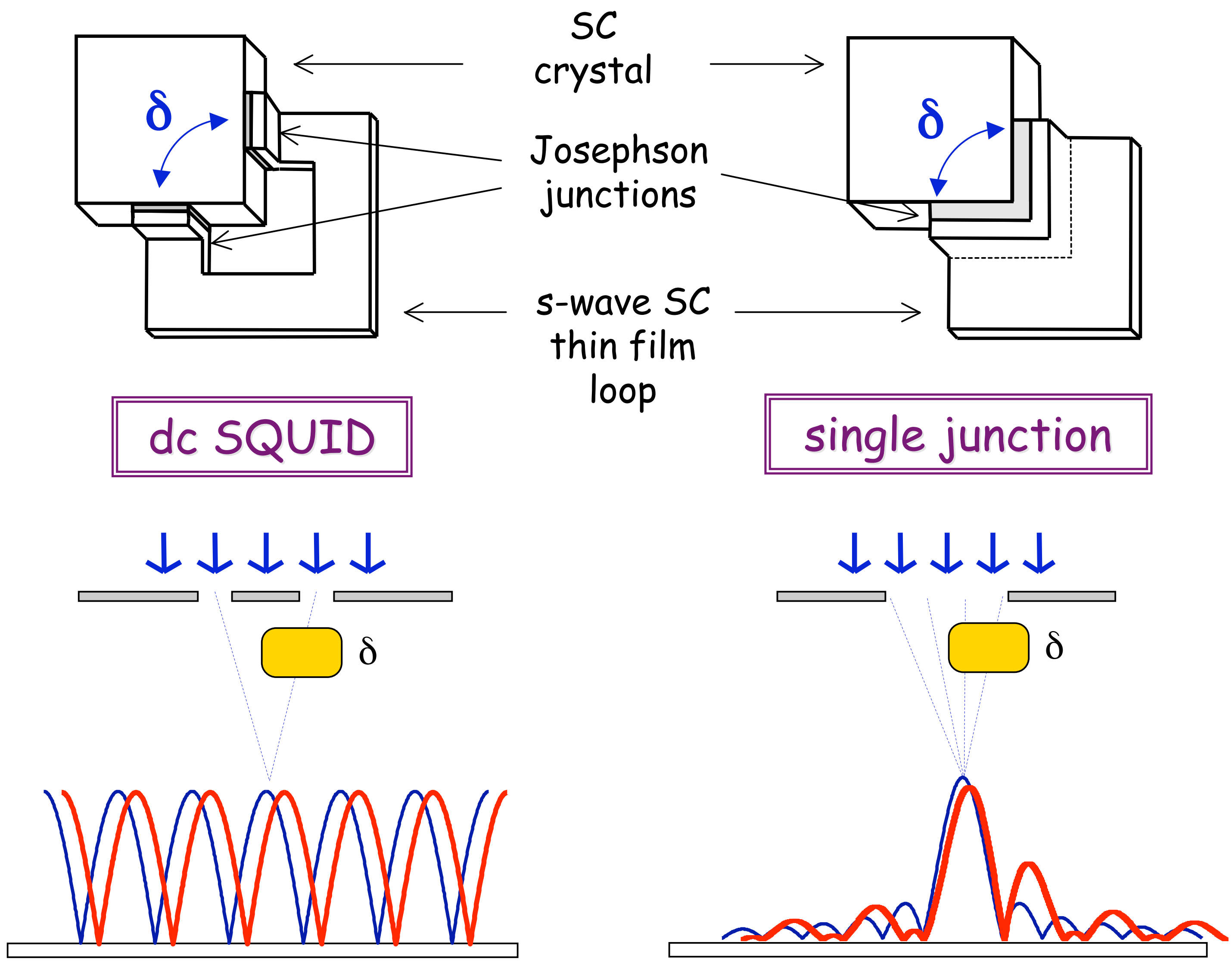
(Superconducting QUantum Interference Device)

measures the phase shift inside the crystal between orthogonal directions

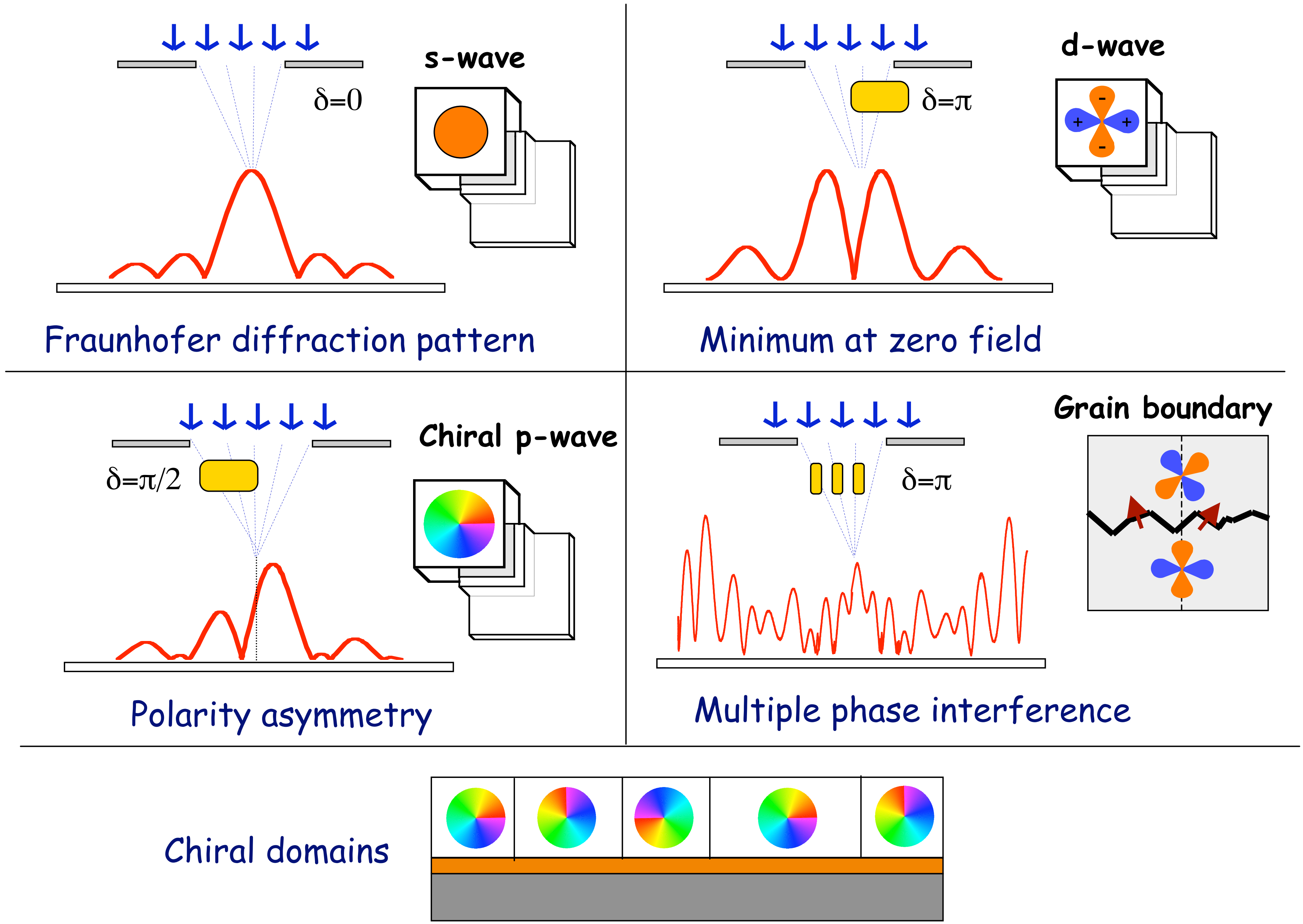
Wollman, Ginsberg, Leggett, Van Harlingen (1993)

Josephson interferometry

measuring the phase shift between different directions

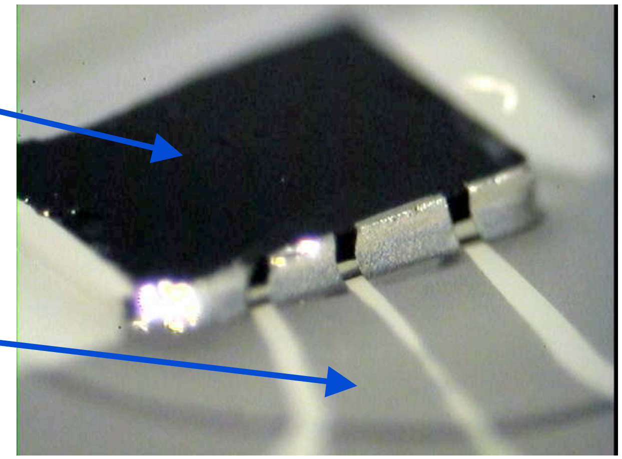


Josephson phase interferometry

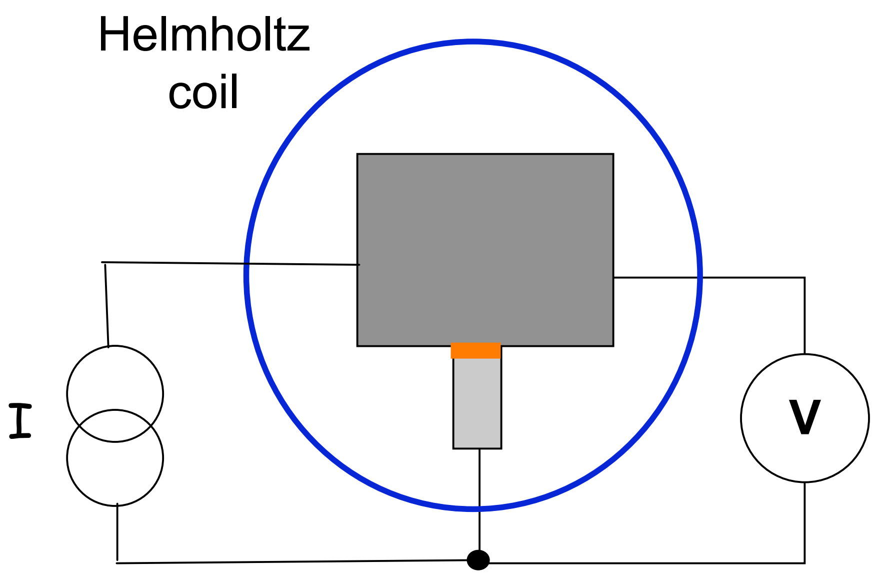


Sample fabrication

- Cleave or polish single crystal
- Glue on substrate, mask leads
- Ion mill surface to clean
- Thermal evaporation of Cu and Pb
- Can make edge or corner junctions



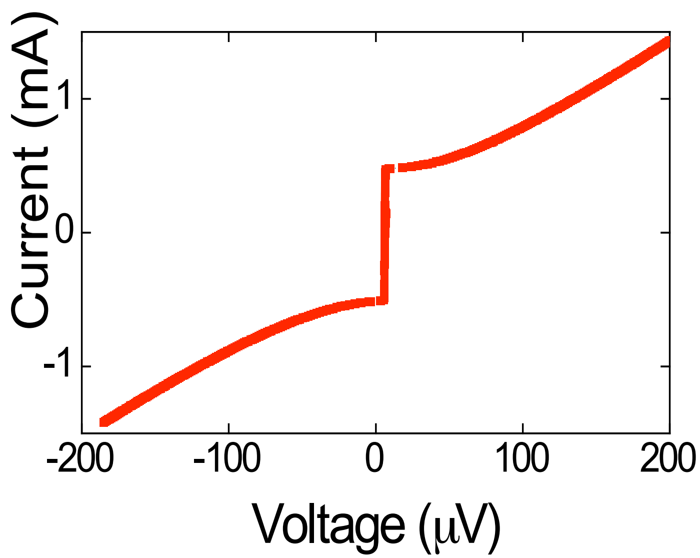
Measurement setup

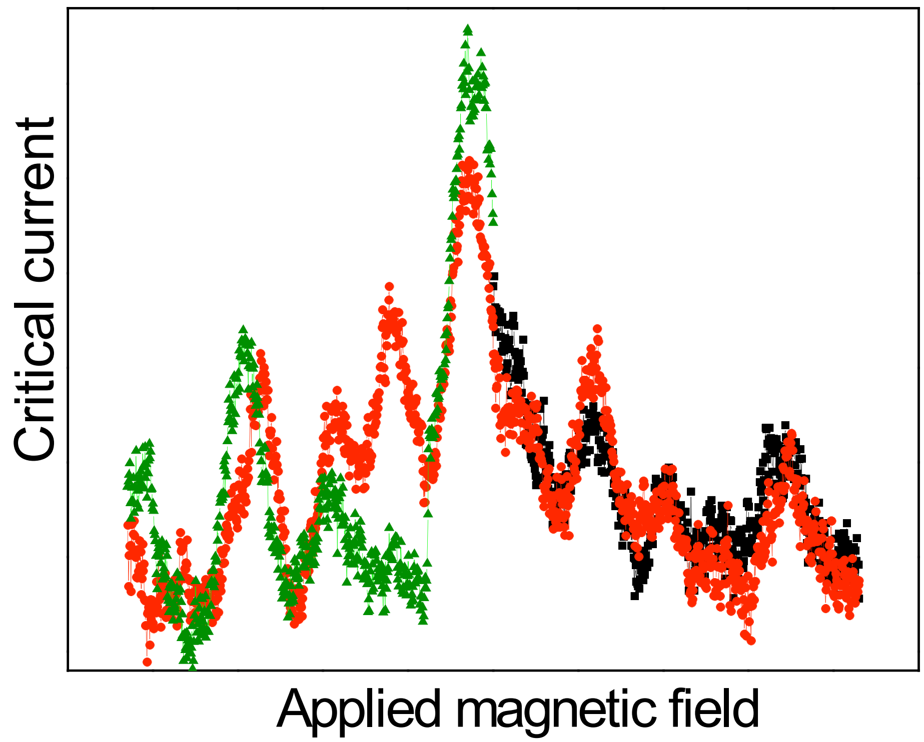


- Measurements in ^{3}He refrigerator
- dc SQUID potentiometer for voltage measurements
- Helmholtz coil to apply vertical field

Critical current modulation in Sr_2RuO_4/Au/Pb edge junctions

Resistively-shunted junction
IV characteristics

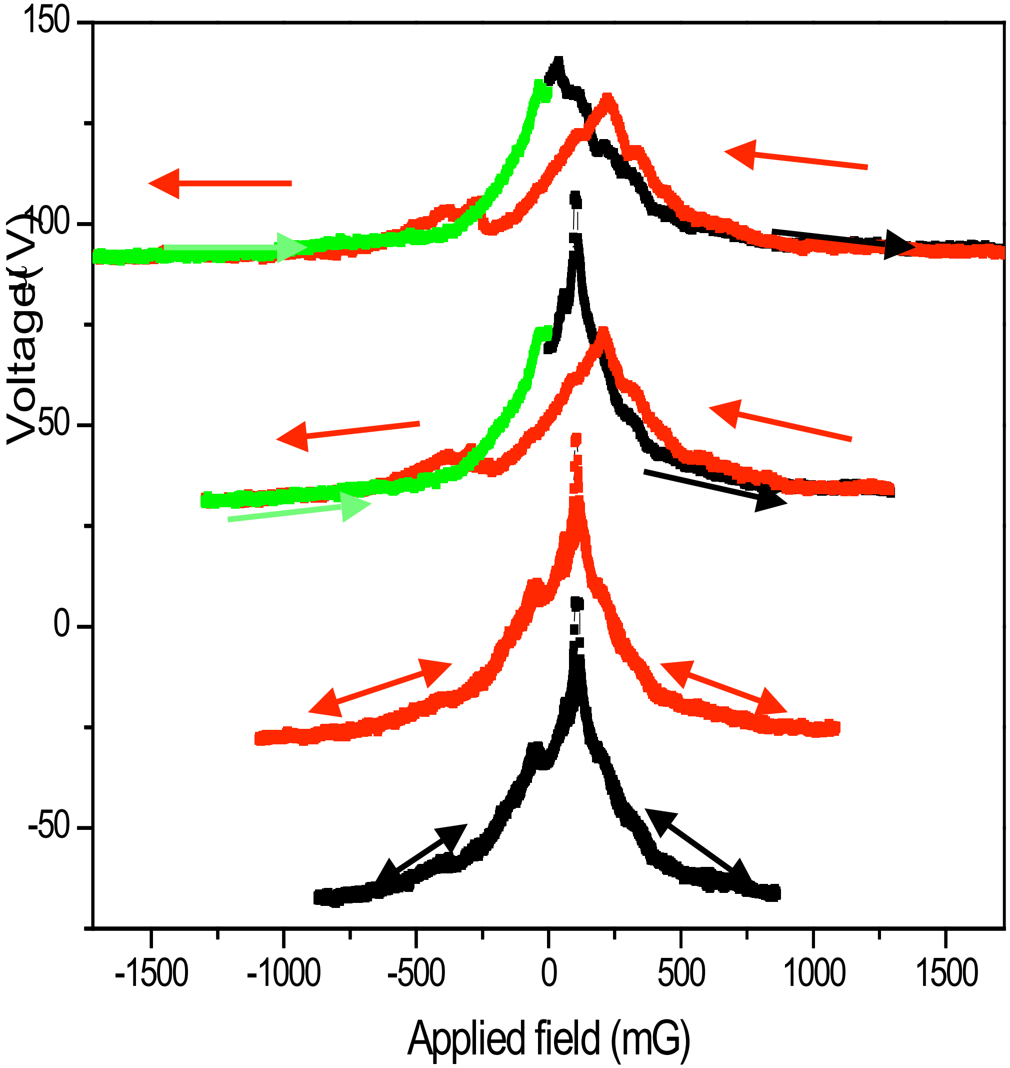




Many features <u>never</u> seen in cuprates or conventional superconductors:

- Polarity asymmetry
- Hysteresis
- Abrupt jumps in critical current
- Two-level “telegraph” switching noise
- Different patterns on different crystals/faces/thermal cycles

Critical current/voltage hysteresis in magnetic field sweeps

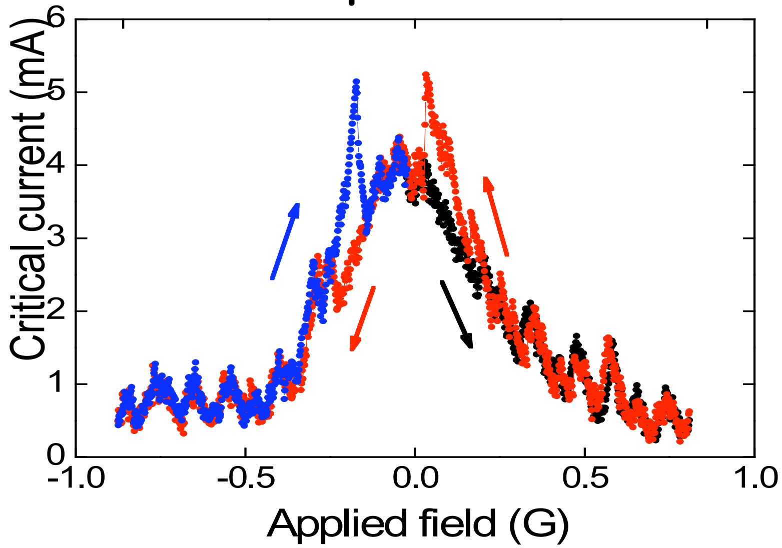


- Retraces below threshold field (~1.2G for this sample)
- Constant hysteresis above threshold field
- Hysteresis "heals" if sweep reduced (de-Gaussing?)

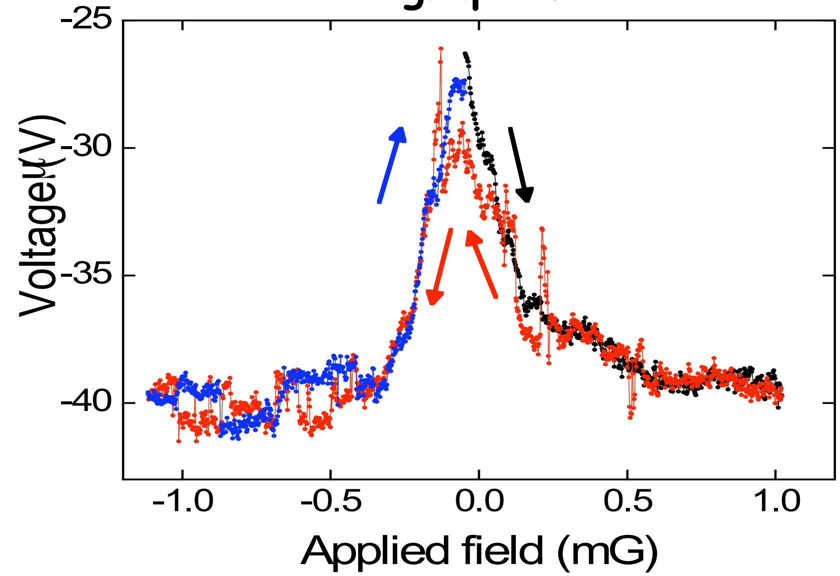
Pinned domains interacting with magnetic field?

Critical current switches noise in SRO junctions

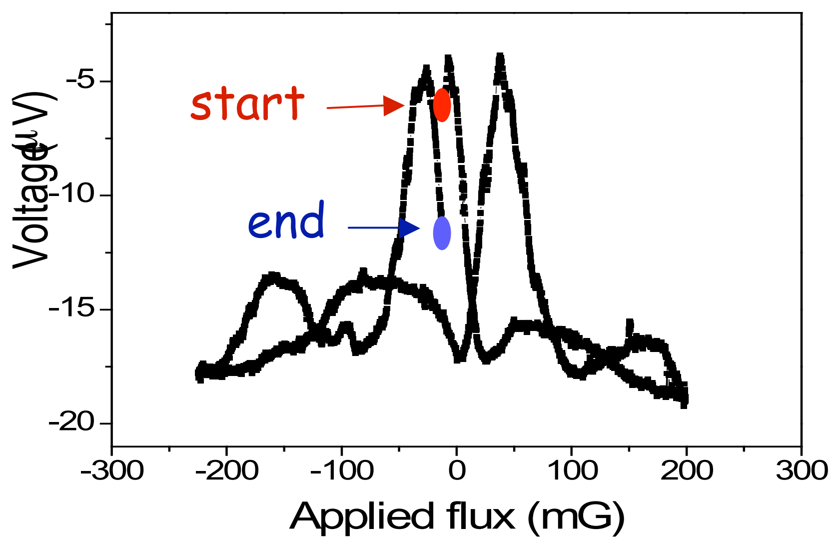
Abrupt switches

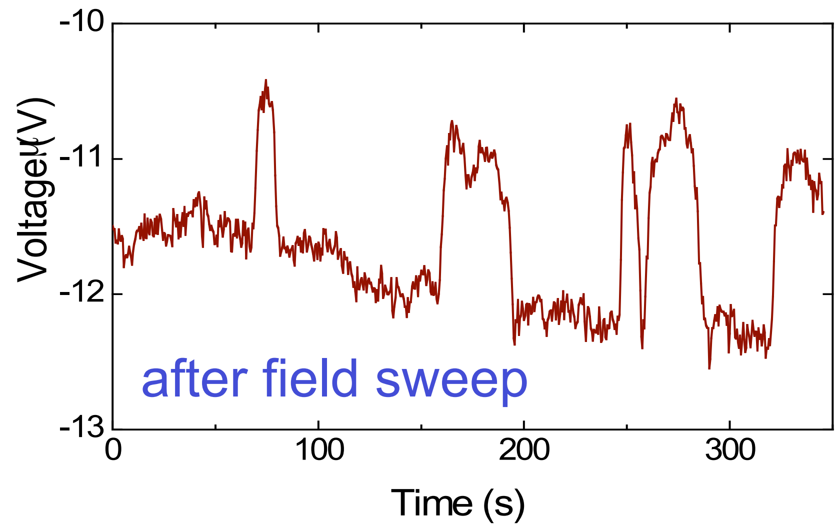


Telegraph noise

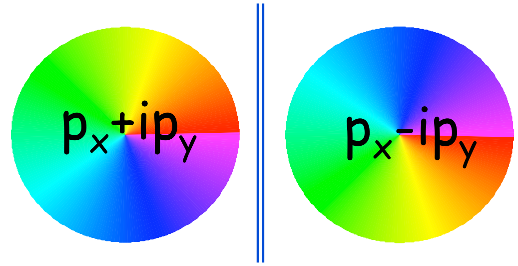


Switches in timetraces

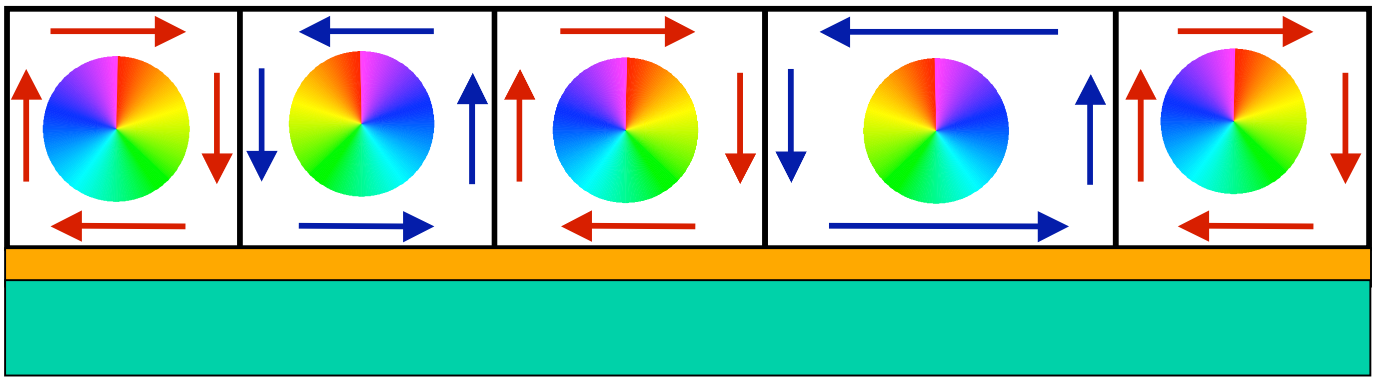




Chiral order parameter domains



Francoise Kidwingira, J. D. Strand, D. J. Van Harlingen, Yoshiteru Maeno, Science <u>314</u>, 1267 (2006)



Chiral currents flow around domain edges --- estimated domain size ~ 0.1-1μm

Evidence for domains

- Phase interference explains variety of diffraction patterns
- Switching between different domains configurations
- Hysteresis caused by domain wall motion and pinning

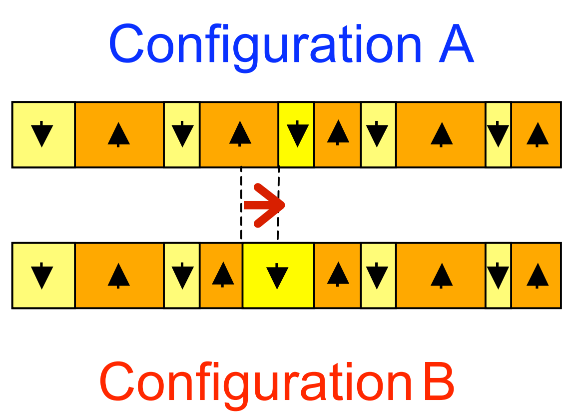
Energy competition for domains formation?

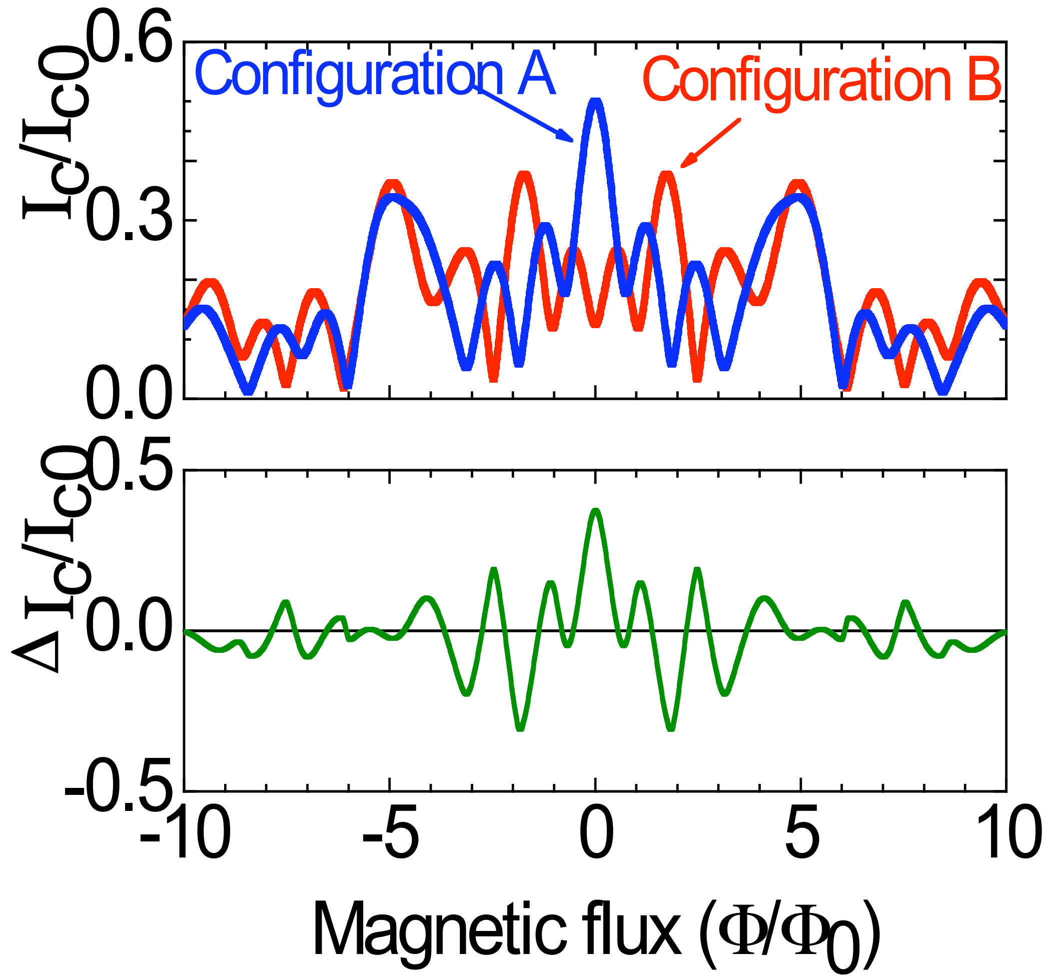
COST = Josephson domain wall energy ~ cos(ϕ)

GAIN = lower chiral field energy

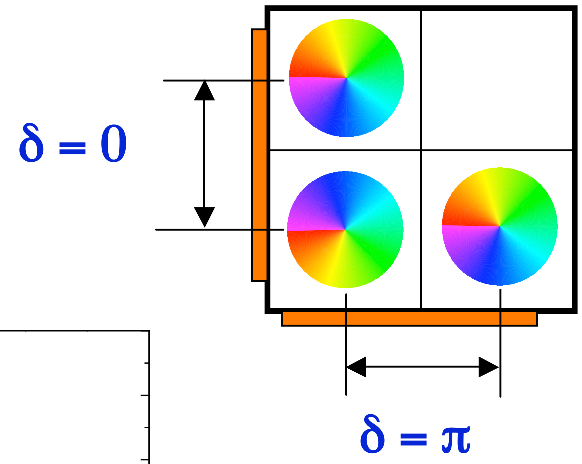
Sensitivity to single domain switching

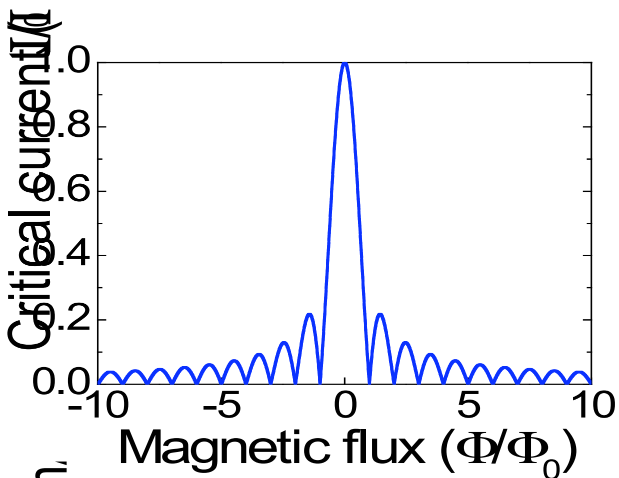
Motion of a single domain wall dramatically changes the critical current diffraction pattern → accounts for switching noise observed





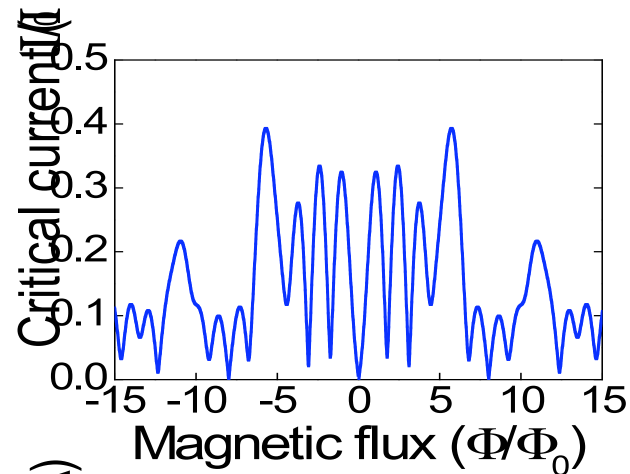
Diffraction patterns: chiral domains

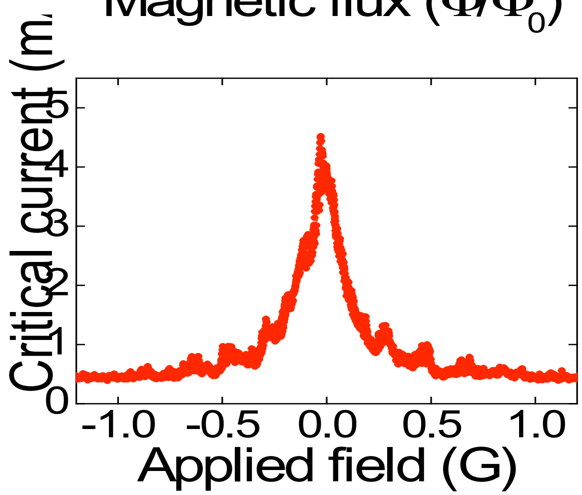




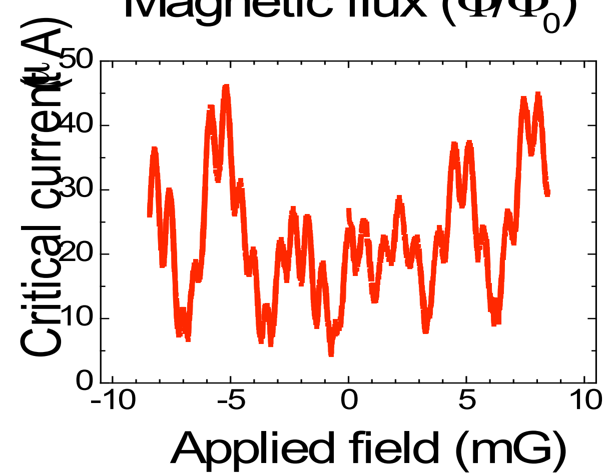
Simulation

(10 domains)



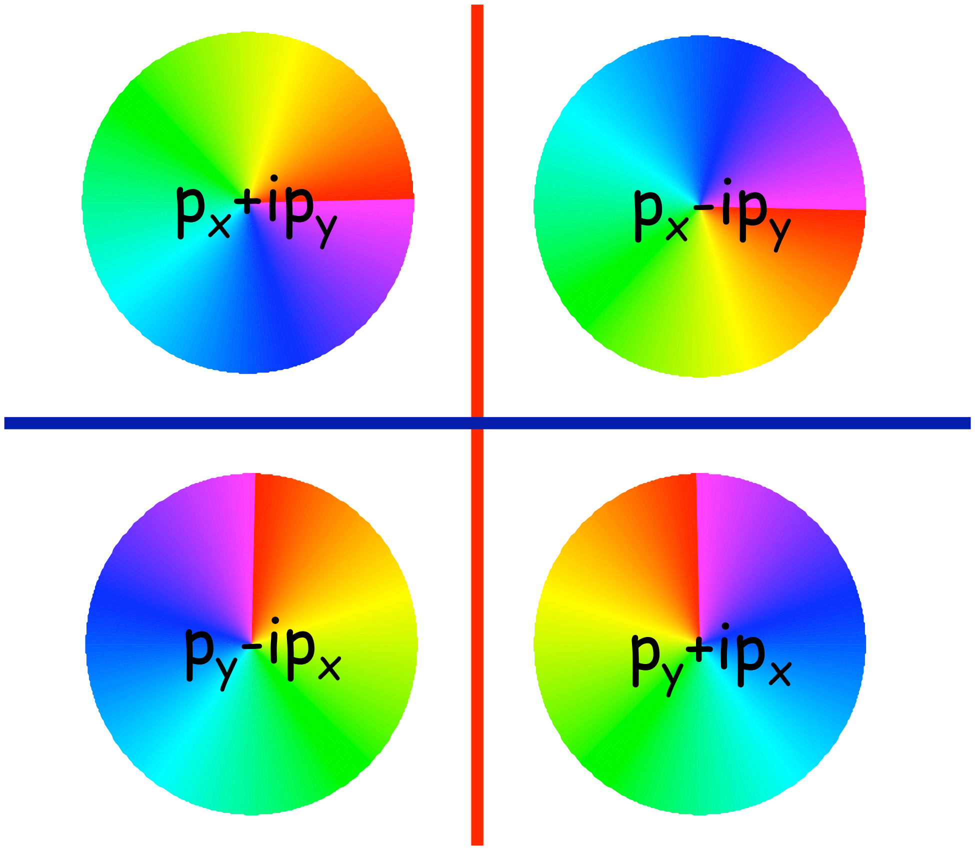


Measurement



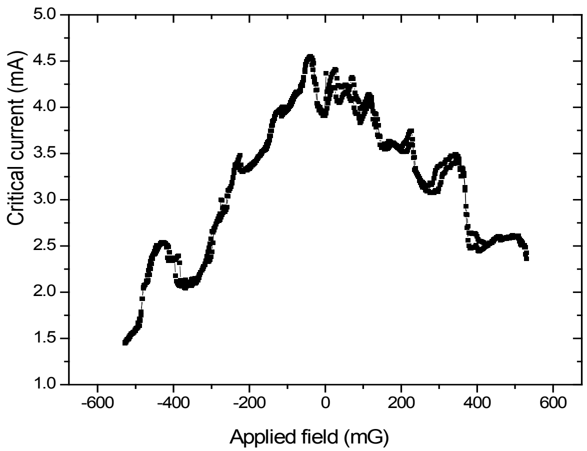
Two types of chiral domain walls

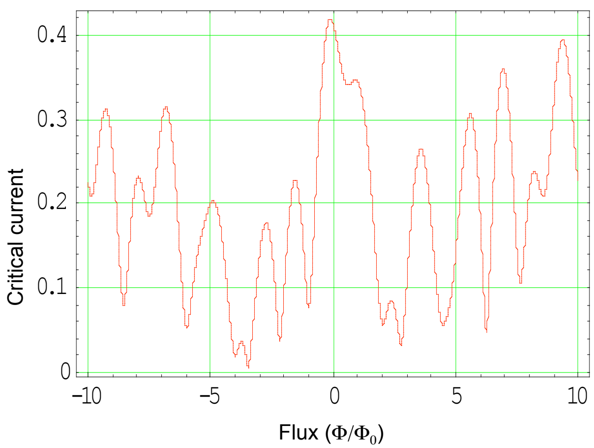
PARALLEL
chiral domains
(change in rotation of phase)

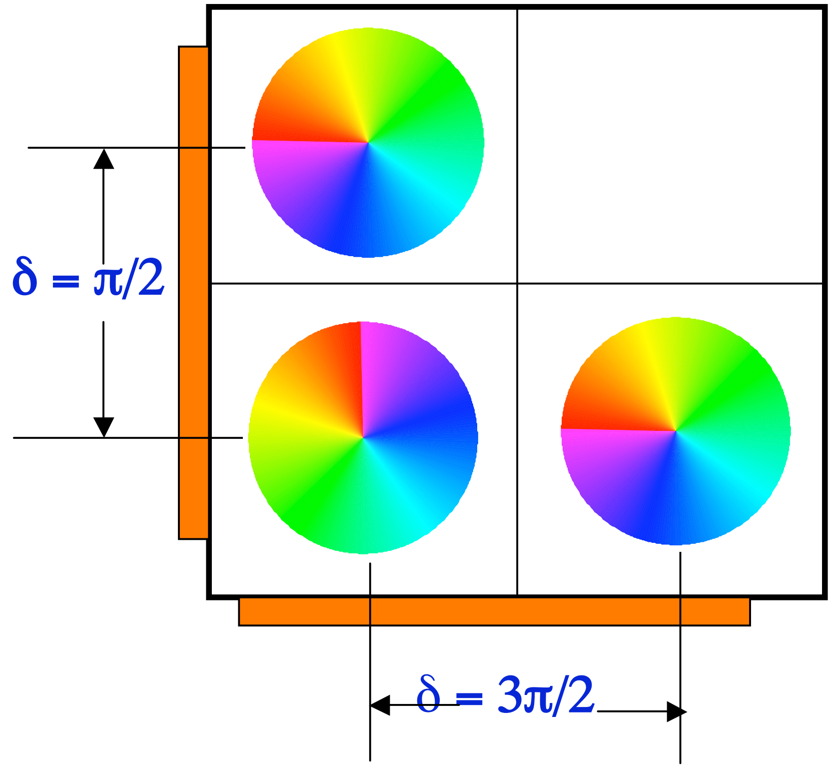


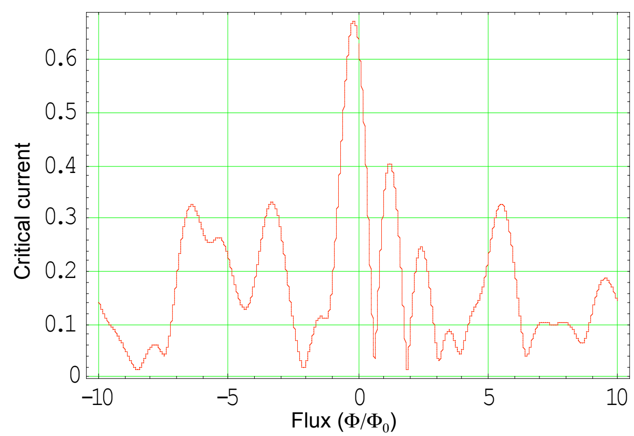
PERPENDICULAR
chiral domains
(change in alignment of the
real component)

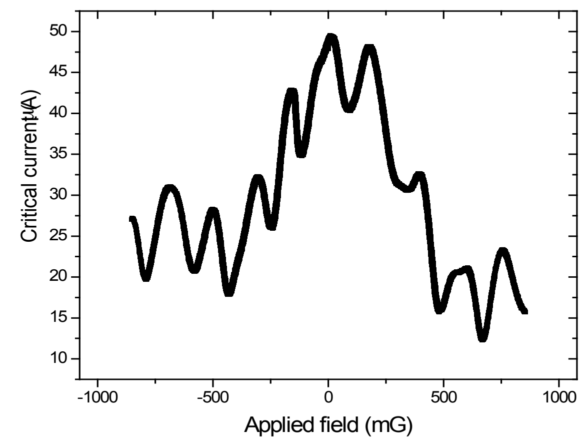
Perpendicular chiral domains









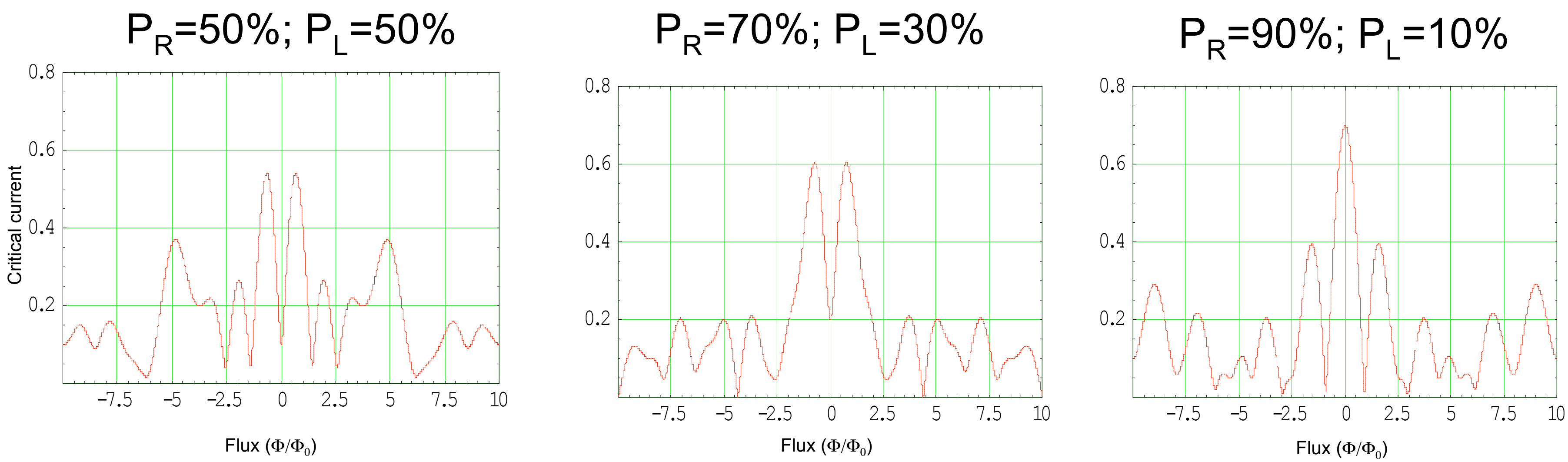


Field cooling: simulations

Chiral domain currents couple to applied magnetic fields

Applied field breaks chiral degeneracy, favoring on chirality

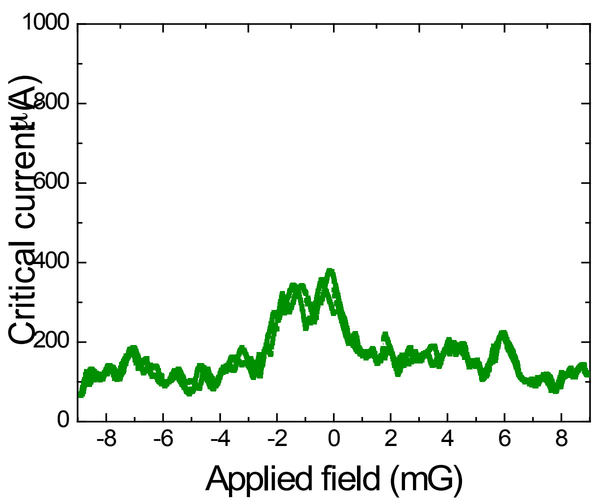
P_R: probability of right-hand chiral domains
P_L : probability of left-hand chiral domains



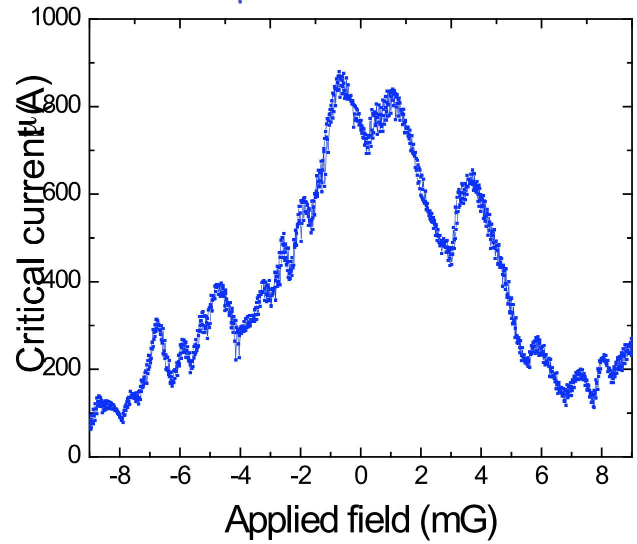
- Enhancement of I_c from alignment of domains
- Changes structure from “grating-like” to “Fraunhofer-like”

Field cooling: critical current enhancement

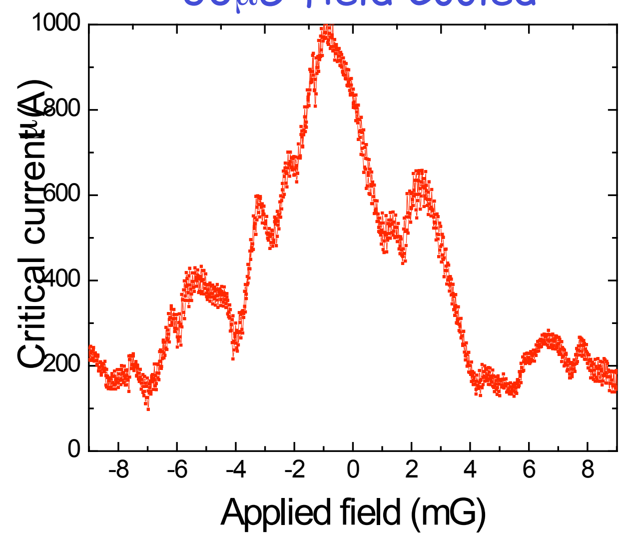
Zero field Cooled



30μG field Cooled



-30μG field Cooled



Enhancement only for limited field range because of vortex trapping

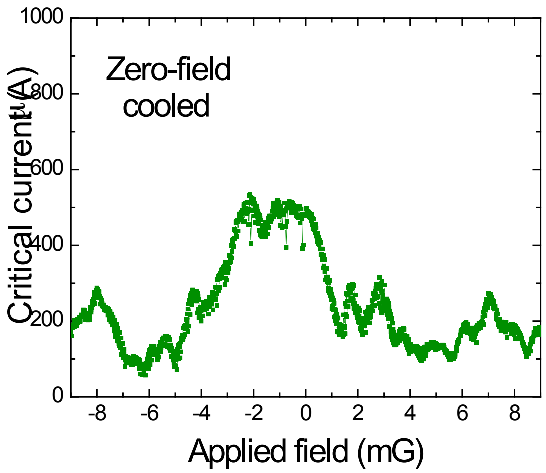
Dramatic increase in I_c for both polarities

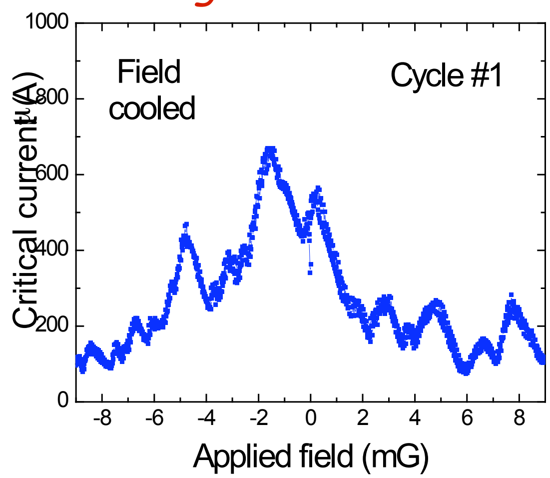
Field range scales with junction size but is surprisingly small (< 1mG)

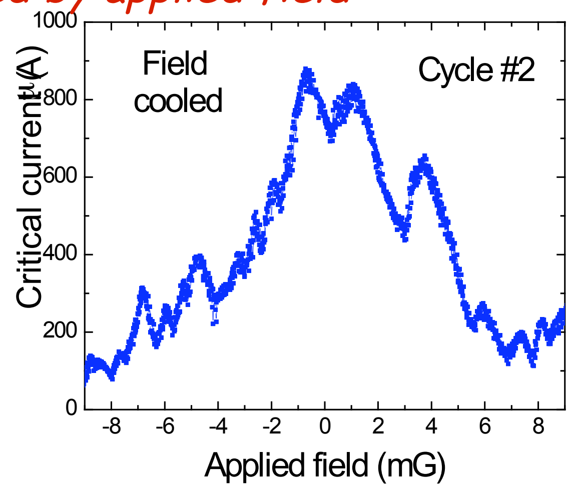
Field cooling: domain training and memory effects

Critical current increases gradually with successive field-cooling cycles

Possible mechanism: domain alignment can be trained by applied field

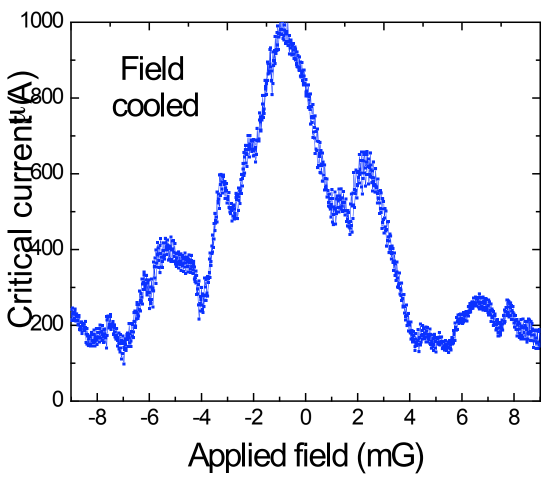


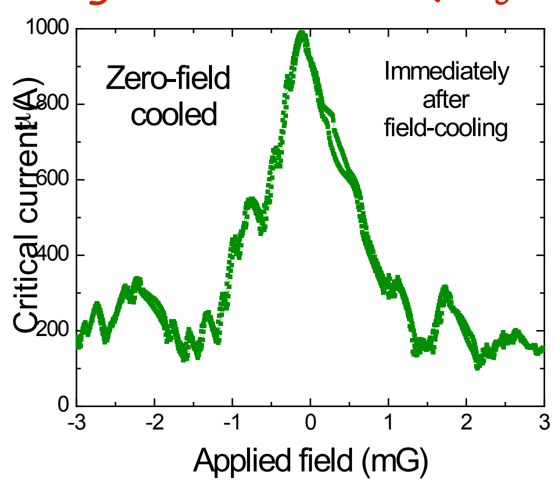


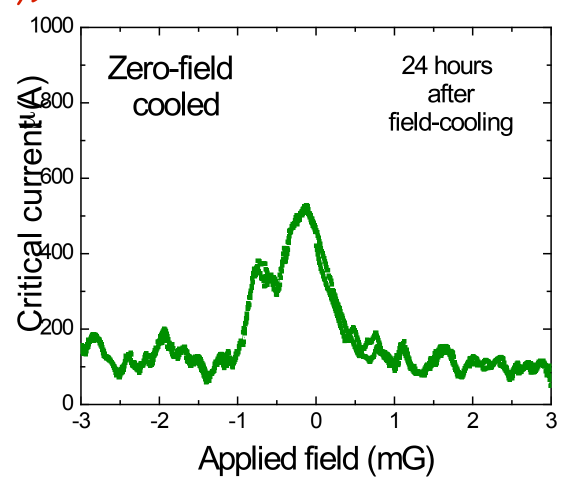


Critical current retains enhancement after zero-field cooling, decays over time

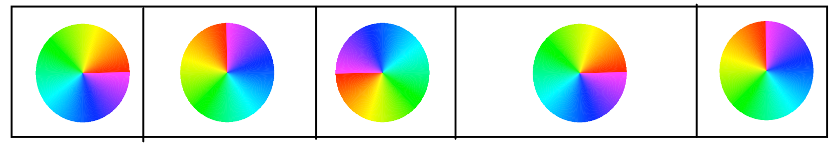
Possible mechanism: ferromagnetic inclusions ($Sr_3Ru_2O_7$) or surface states







Summary of Sr_2RuO_4



- Evidence for p_x+ip_y order parameter symmetry
- Observe dynamical chiral domains
- Observe coupling of domains to magnetic fields ⇨ enhanced critical currents
- Observe anomalous domain training and memory effects

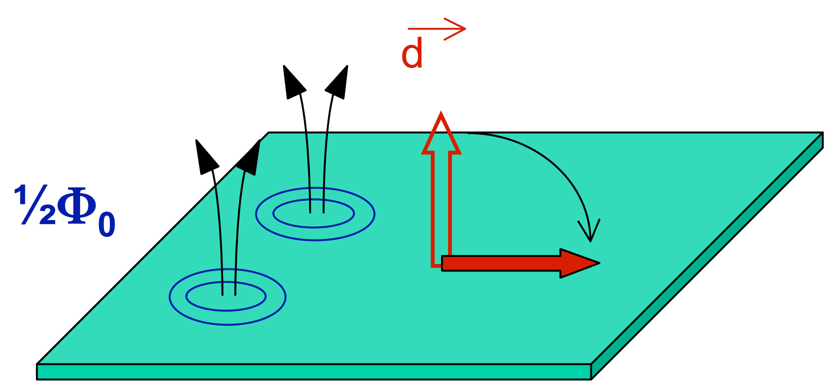
Issues:

- Spontaneous moment from chiral currents not yet observed?
- Domain size?

Illinois	0.1-1 μm + dynamics	interferometry (at surface)
Penn State	large static domains	interferometry
Stanford	< 1 μm	scanning SQUID microscopy
Stanford	10-100μm	Kerr effect

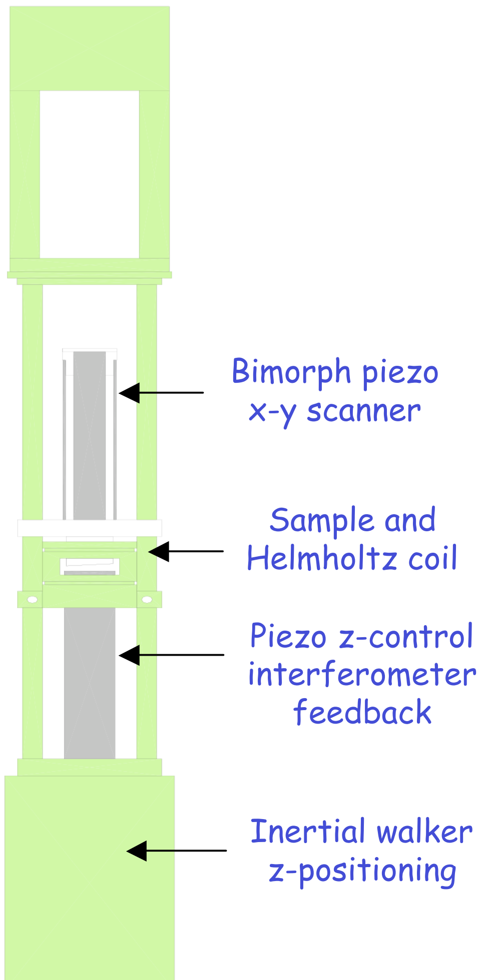
- Non-Abelian quasiparticles states?

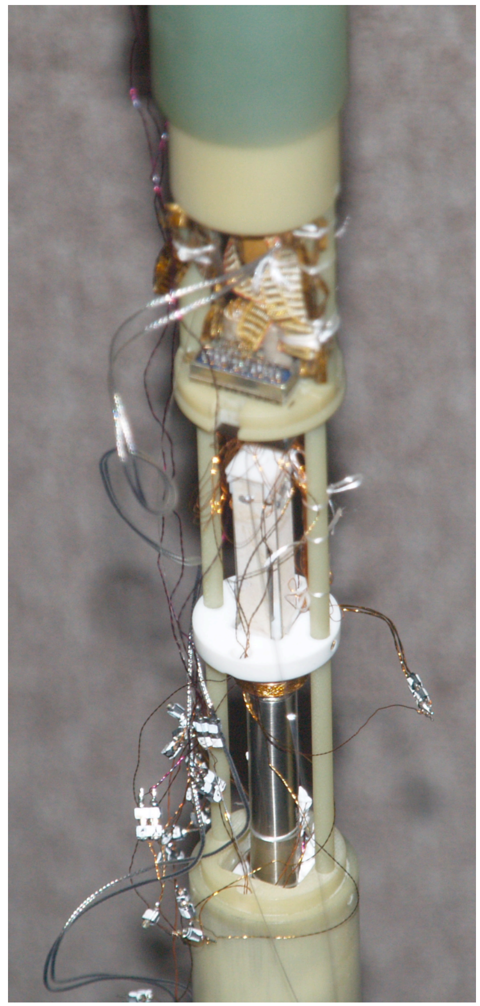
Rotating d-vector into plane is expected to nucleate half-integer vortices



Imaging chiral domains: Scanning SQUID Microscopy

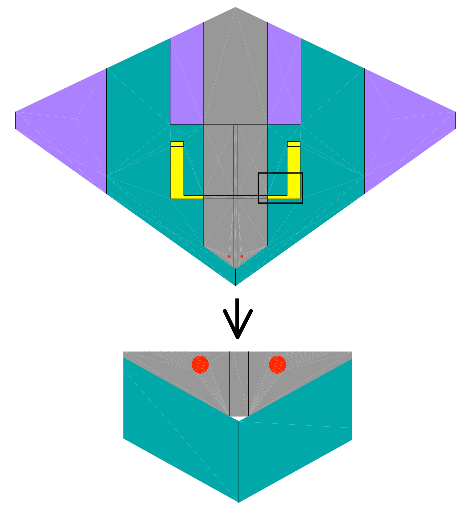
Developing instruments to map domain structure via chiral current distribution
Designed for Oxford top-loading dilution refrigerator temperatures (2K-10mK)



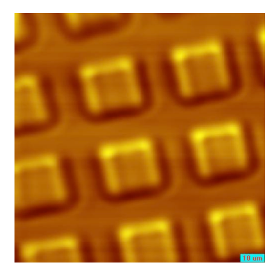


Sensors: dc SQUIDs

Spatial resolution: <1μm



Simultaneous imaging of topography and magnetic field distribution

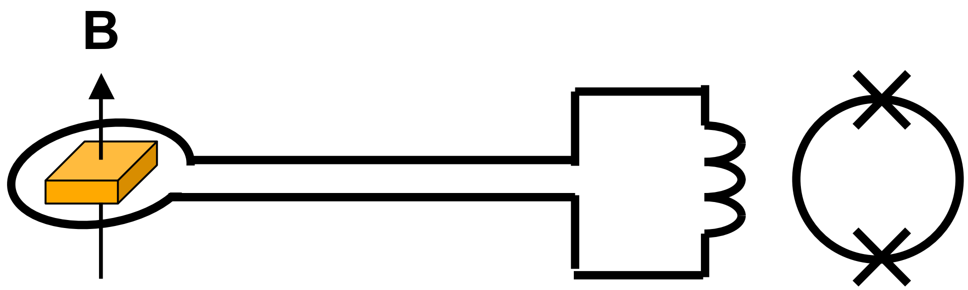


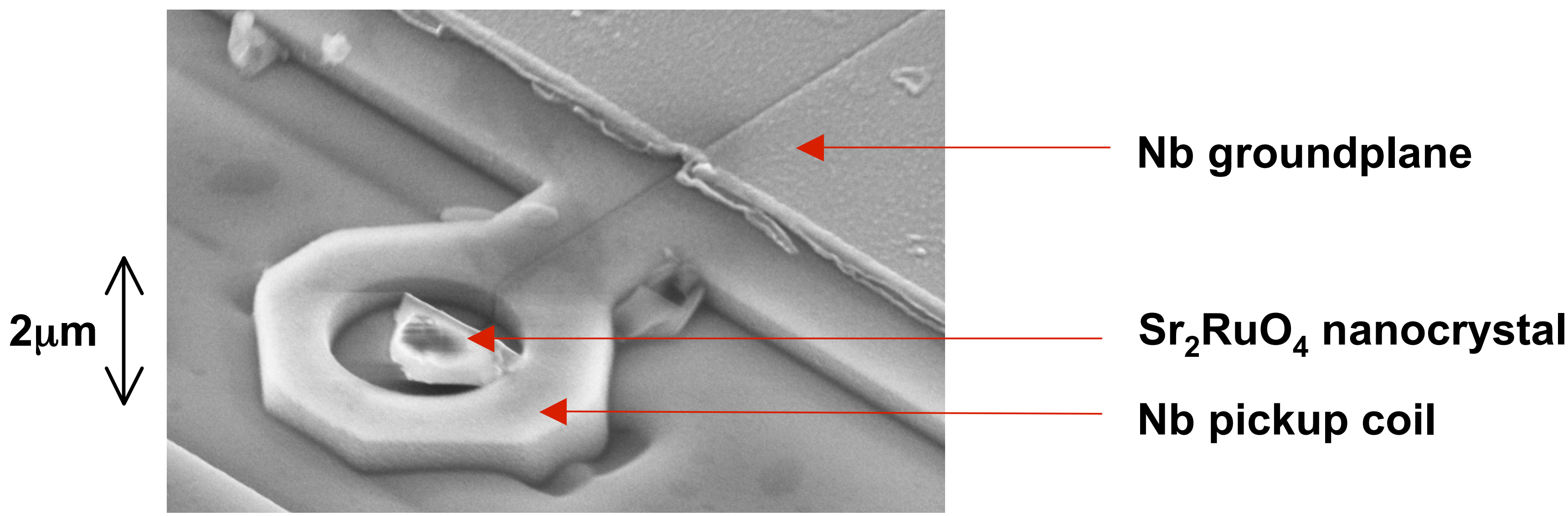
Magnetic measurements on Sr_2RuO_4 nanocrystals

Dale Van Harlingen, Raffi Budakian, Dan Bahr, Micah Stoutimore

Objective: search for spontaneous supercurrents/magnetic moments and exotic vortex nucleation and dynamics in nanocrystals of Sr_2RuO_4

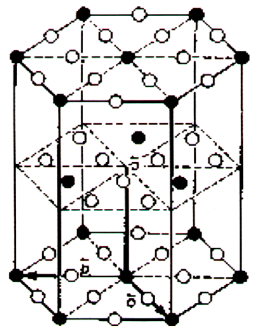
Technique: dc SQUID nanosuceptometry





Chiral triplet superconductor? heavy fermion UPt_3

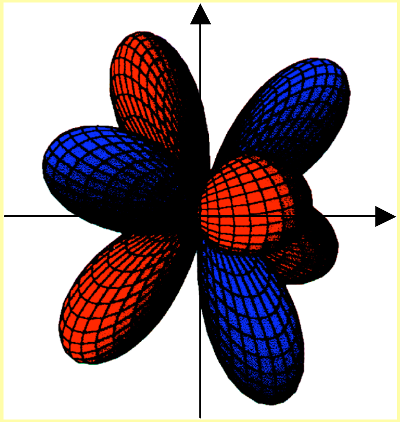
Two superconducting phases:



hexagonal structure

upper-phase <u>real</u>

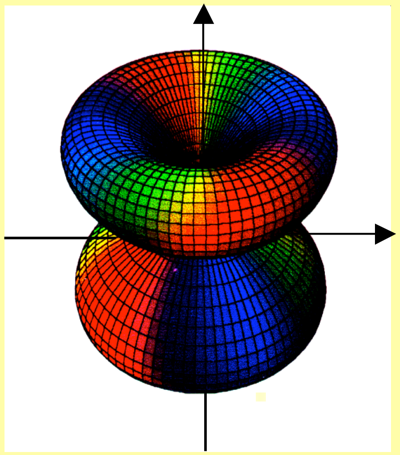
$(k_x^2 - k_y^2)\, k_z$



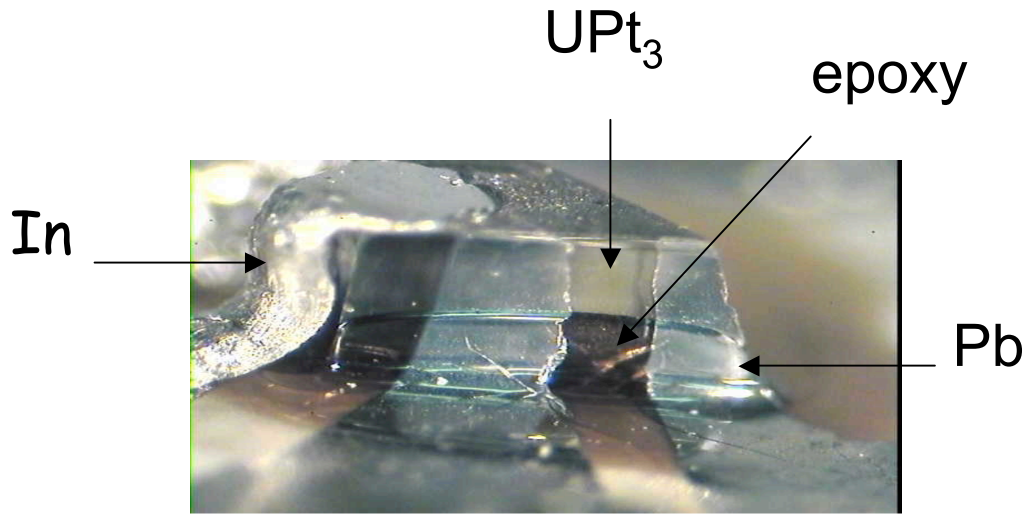
$T_{cU} \sim 0.50K$

lower-phase <u>complex</u>

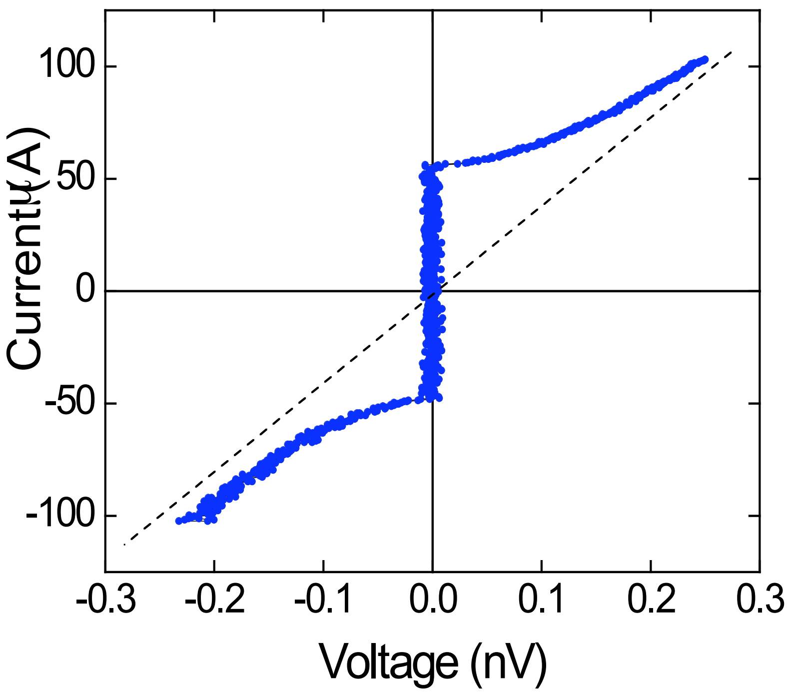
$(k_x + i k_y)^2\, k_z$

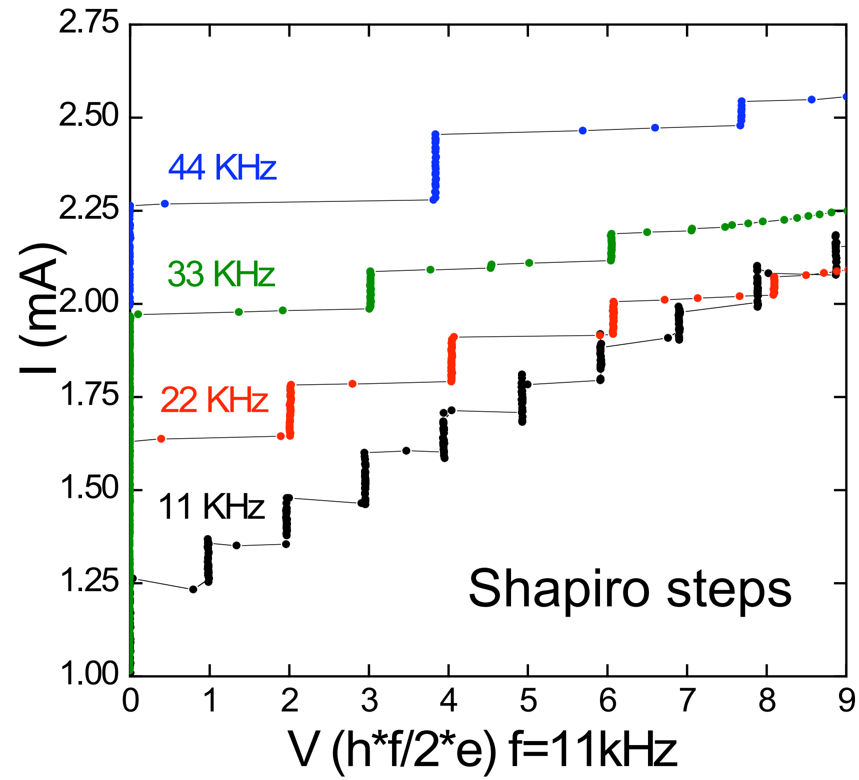


$T_{cL} = T_{cU} - 50mK$

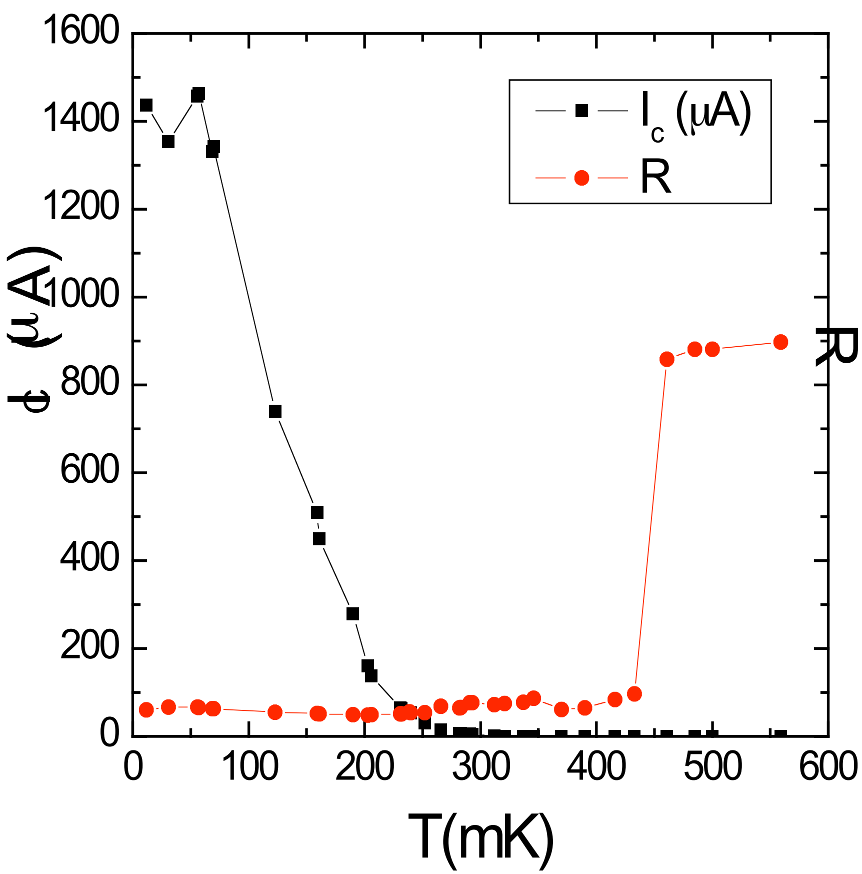


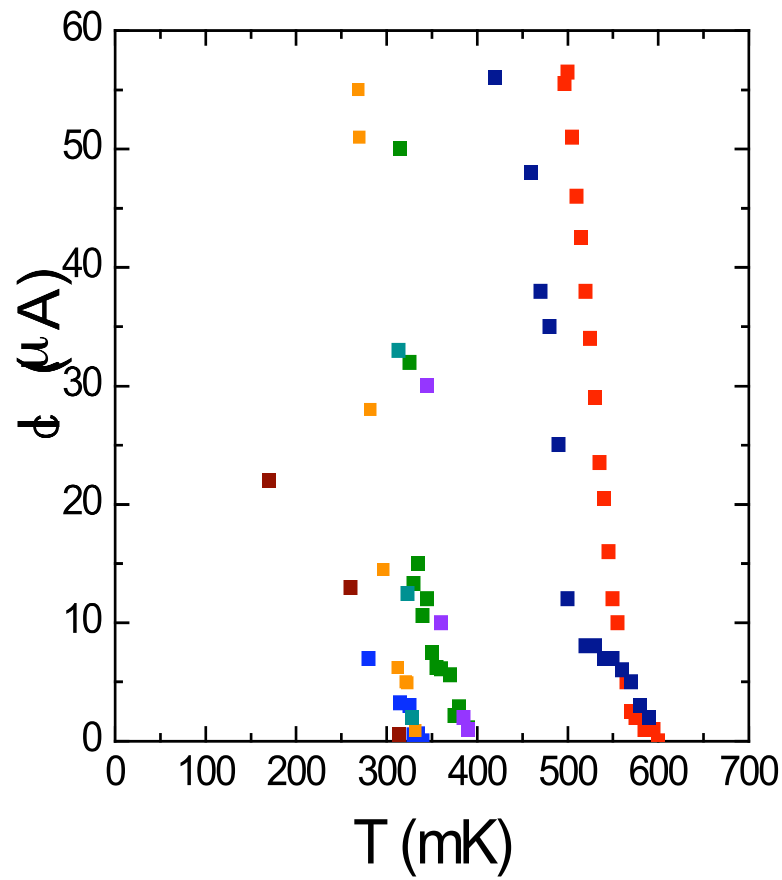
Crystals grown by
Bill Halperin *et al.*
(Northwestern)





Critical current vs. temperature



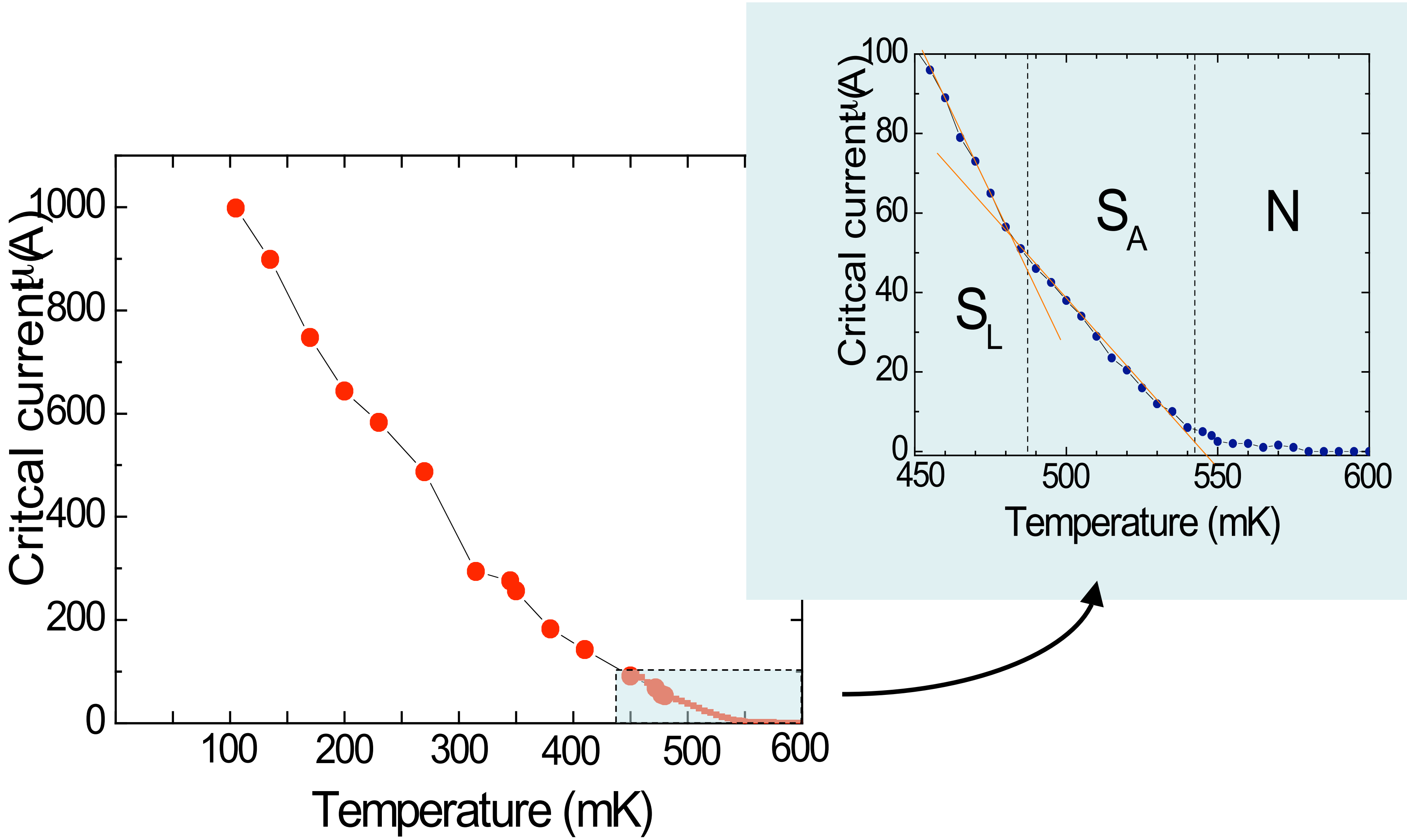


Similar to Sumiyama et al.

Two regimes of critical current onsets observed:
~300-400mK <<T_c *or* ~500-600mK = T_c

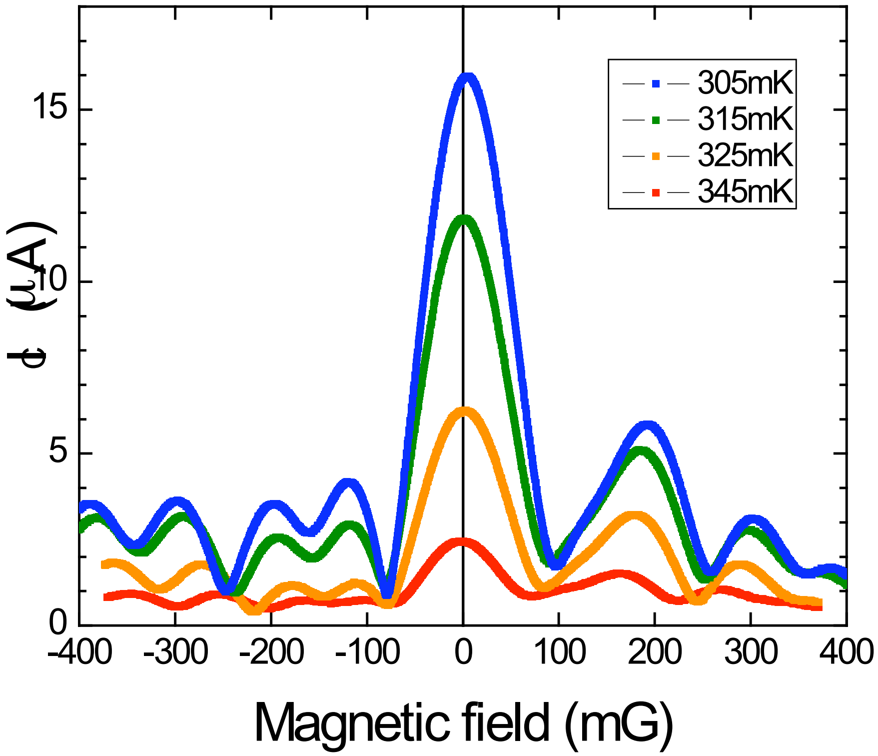
Likely cause is the condition of the surface --- exploring different annealing and polishing schemes and various tunneling orientations

High temperature regime junctions

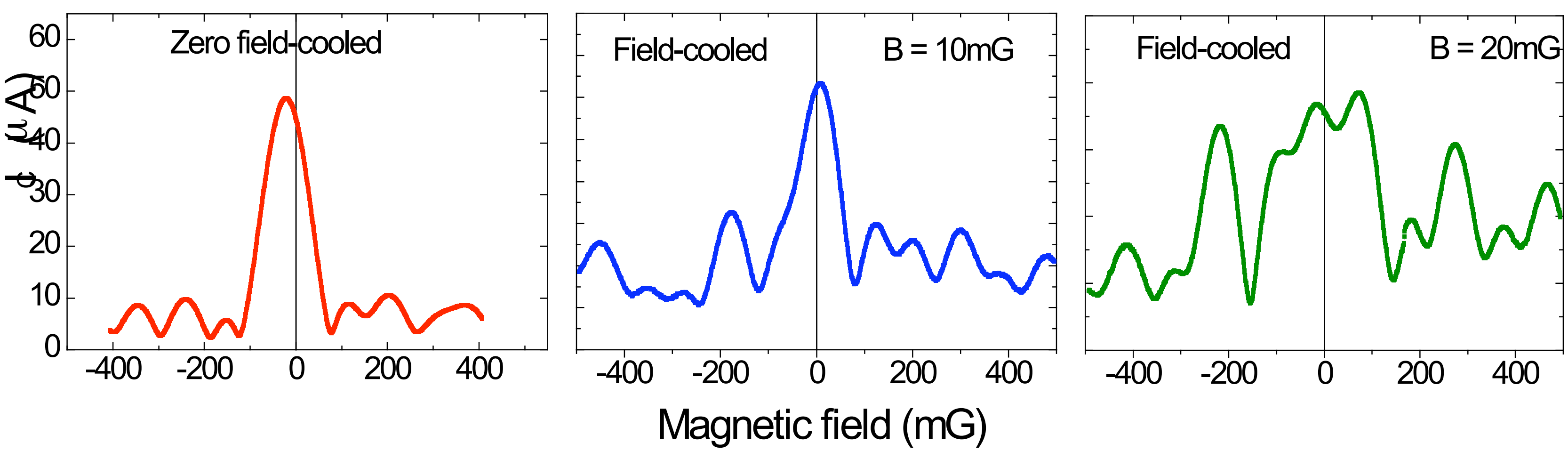


Observe both upper and lower temperature phases --- opportunity to study symmetry transition

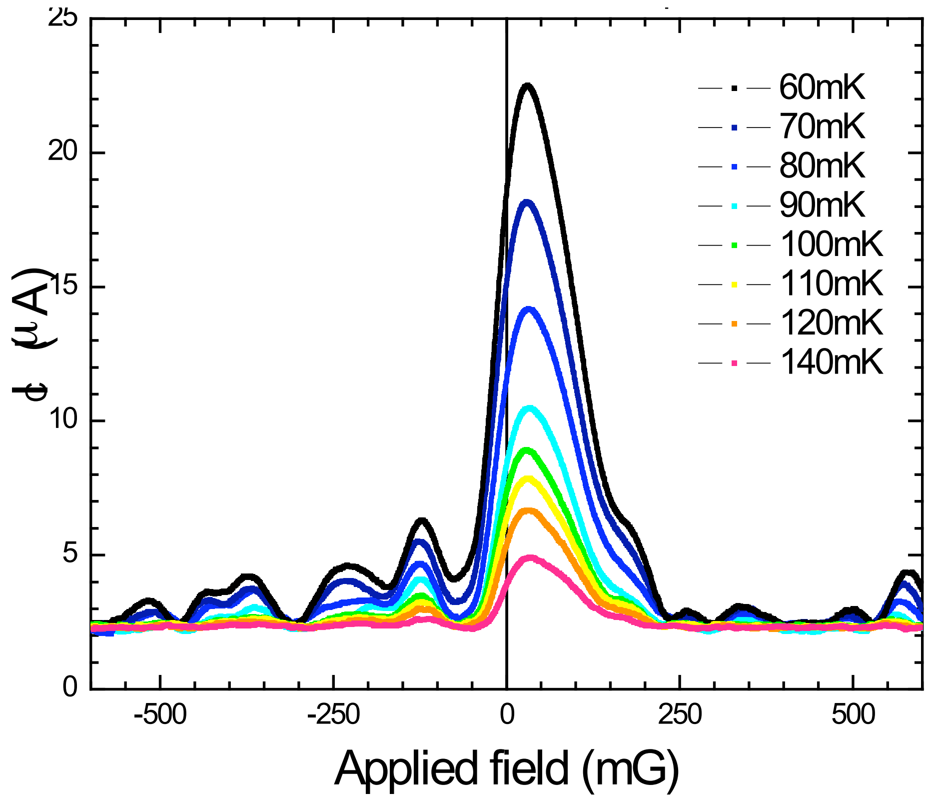
Single-face junction measurements



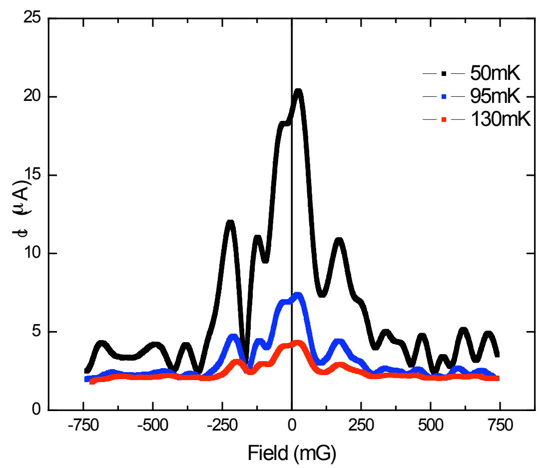
- Fraunhofer-like patterns
- Patterns retrace → no hysteresis, no switching noise
- Can induce anisotropy by field-cooling → entry of vortices

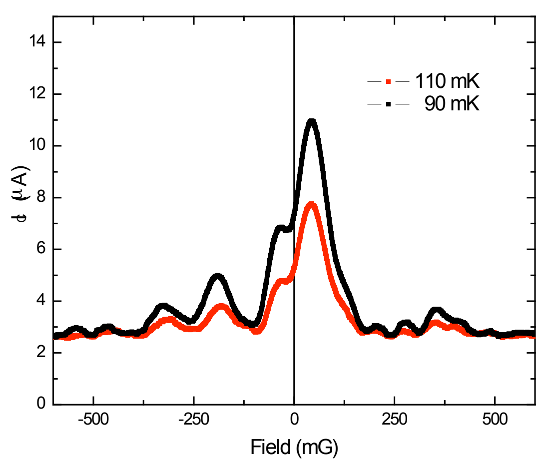


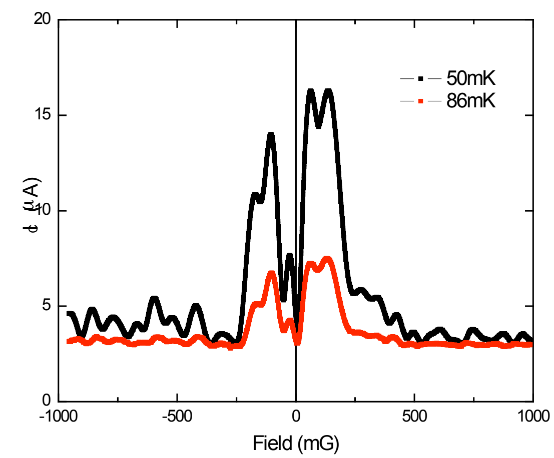
Corner junction measurements



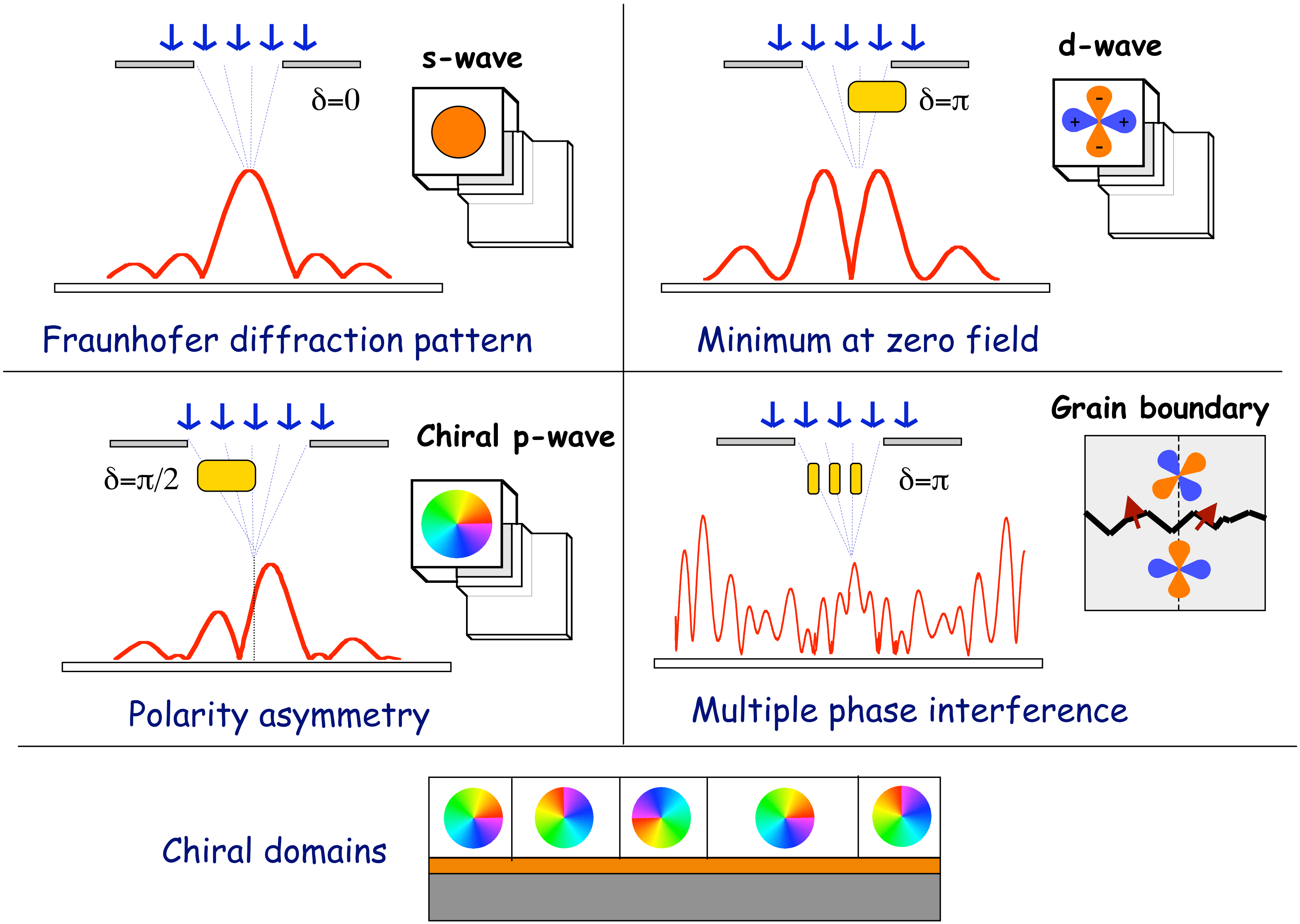
- Asymmetric patterns --- consistent with phase shifts other than 0 or π
- Patterns change on successive cooling --- consistent with spontaneously broken chiral symmetry or chiral domains or trapped vortices







Josephson phase interferometry



Summary of UPt_3

- Observe two superconducting phases
- Evidence for complex order parameter symmetry in corner junctions at low temperature (well into low T phase)
- No chiral domain structure and dynamics observed in single-face junctions
- Mystery why critical current is suppressed near T_c in some junctions
- Not as good a candidate for topological QC as Sr_2RuO_4 because of strong spin orbit coupling and 3D structure --- perhaps in thin films