Characterization of Surface Magnetic States in Superconducting Circuits

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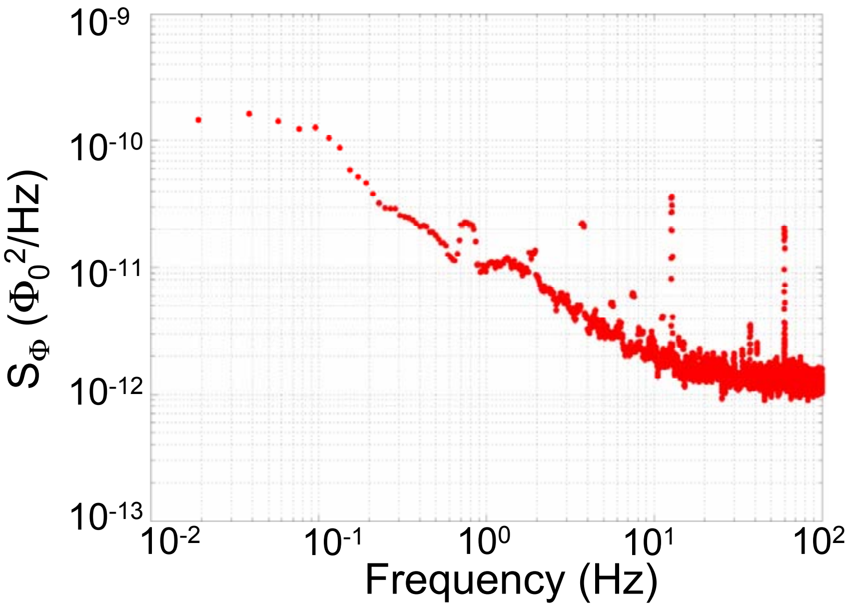
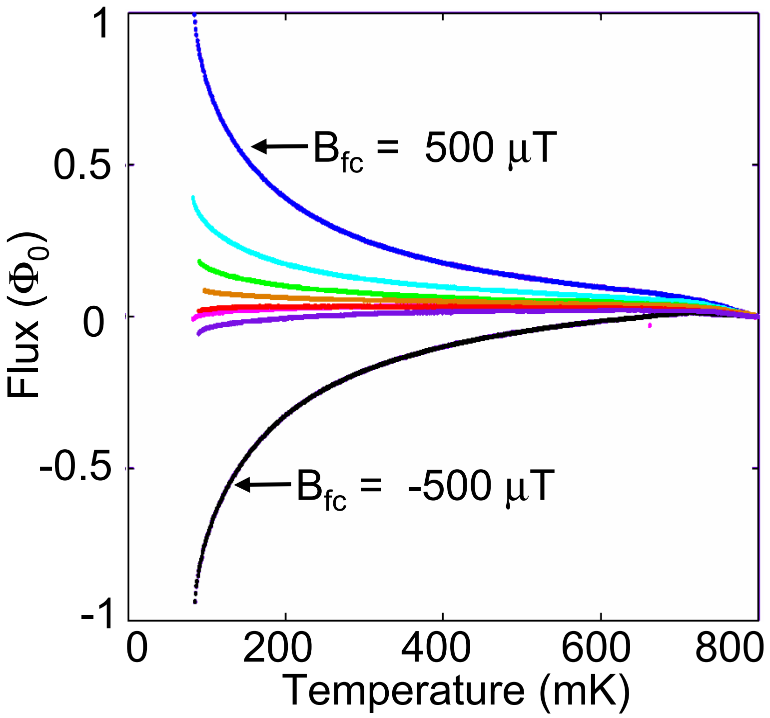
Acknowledgement: D.P. Pappas, J. Kline, M. Gershenson, J.M. Martinis





Outline

Motivation: Dephasing in superconducting qubits

1/f **Flux Noise in the dc SQUID**

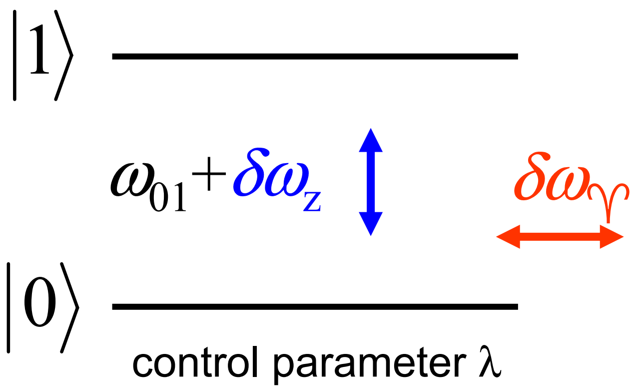
Magnetism in superconducting circuits
at millikelvin temperatures

1/f inductance noise in the dc SQUID

Novel surface treatments – new results

Outlook and future work

Dissipation and Dephasing in Qubits



$|1\rangle$

$\omega_{01}+\delta\omega_z$

$\delta\omega_\perp$

$|0\rangle$

control parameter λ

$$H = -\frac{1}{2}\hbar\left[\left(\omega_{01}+\delta\omega_z\right)\sigma_z + \delta\omega_\perp\sigma_\perp\right]$$

transverse relaxation

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

$$\boxed{T_1^{-1} = \pi\left(\frac{\partial\omega_\perp}{\partial\lambda}\right)^2 S_\lambda(\omega_{01})}$$

High-frequency
transverse noise in λ:

energy relaxation

$$\boxed{T_\phi^{-1} = \pi\left(\frac{\partial\omega_z}{\partial\lambda}\right)^2 S_\lambda(\omega=0)}$$

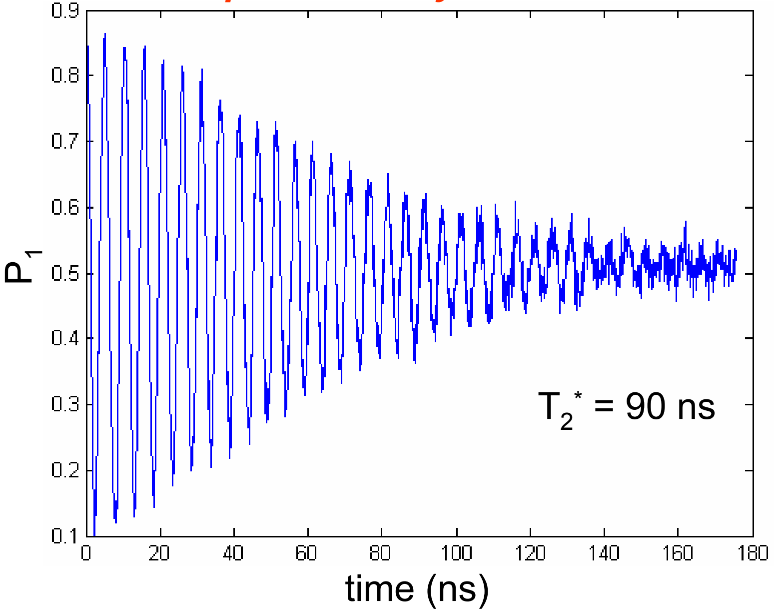
Low-frequency
longitudinal (white) noise
in λ:

pure dephasing

Ithier et al., PRB 72, 134519 (2005)

Dephasing from *1/f* Noise

Phase qubit Ramsey



$$\boxed{S_\lambda = \frac{A}{\omega}} \rightarrow$$

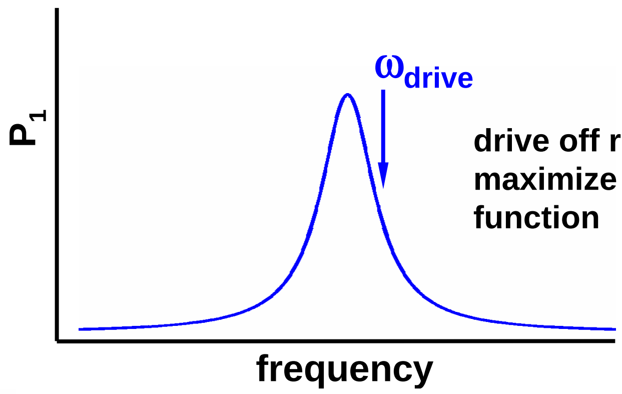
$$\langle \Delta\phi^2 \rangle = 2\left(\frac{\partial \omega_z}{\partial \lambda}\right)^2 A \ln\left(\frac{1}{\omega_m t}\right) t^2$$

$$f_{Ramsey}(t) = \exp\left[-\left(\frac{\partial \omega_z}{\partial \lambda}\right)^2 A \ln\left(\frac{1}{\omega_m t}\right) t^2\right]$$

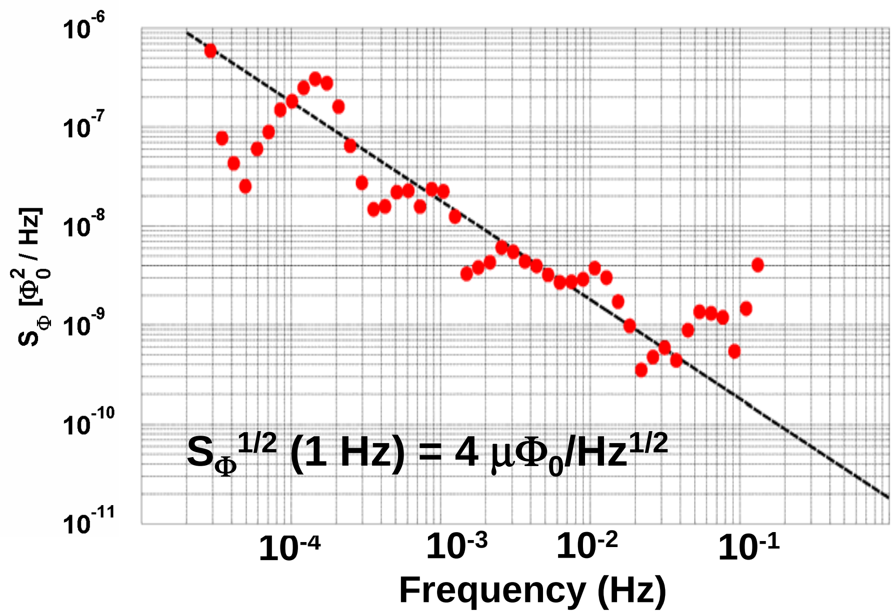
Gaussian decay envelope as a probe of 1/f noise magnitude

cf. *Yoshihara et al., PRL 97, 167001 (2006)*

Direct measurement of bias noise



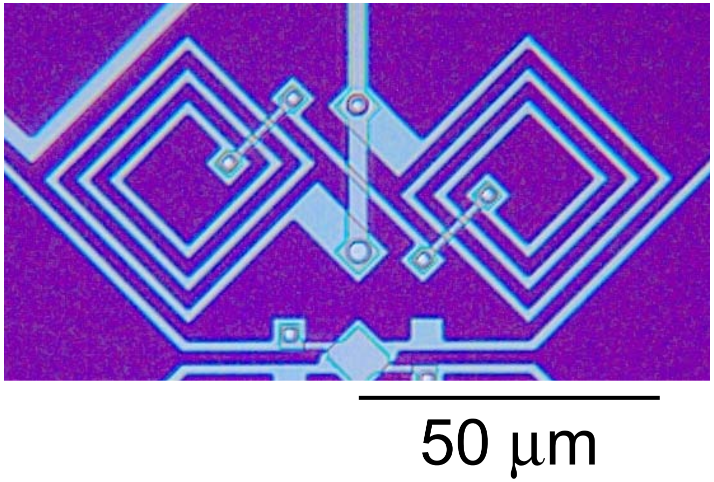
drive off resonance, maximize transfer function

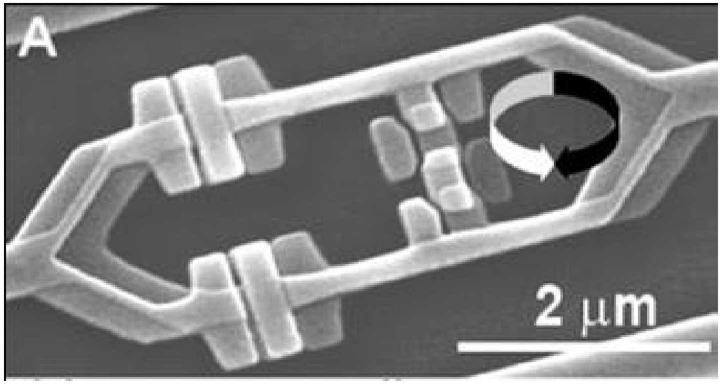


$S_\Phi^{1/2}$ (1 Hz) = 4 $\mu\Phi_0/\mathrm{Hz}^{1/2}$

Bialczak et al., PRL 99, 187006 (2007)

1/f Flux Noise in Superconducting Qubits





Delft flux qubit

Phase qubit

$L = 720$ pH
$S_\Phi^{1/2}$ (1 Hz) = 2-4 $\mu\Phi_0/\mathrm{Hz}^{1/2}$

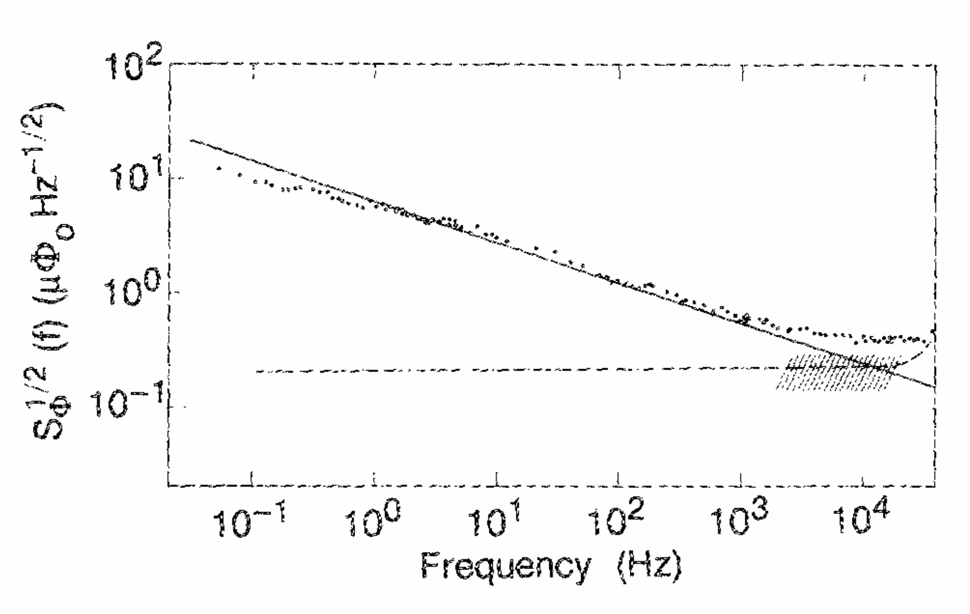
Flux qubit

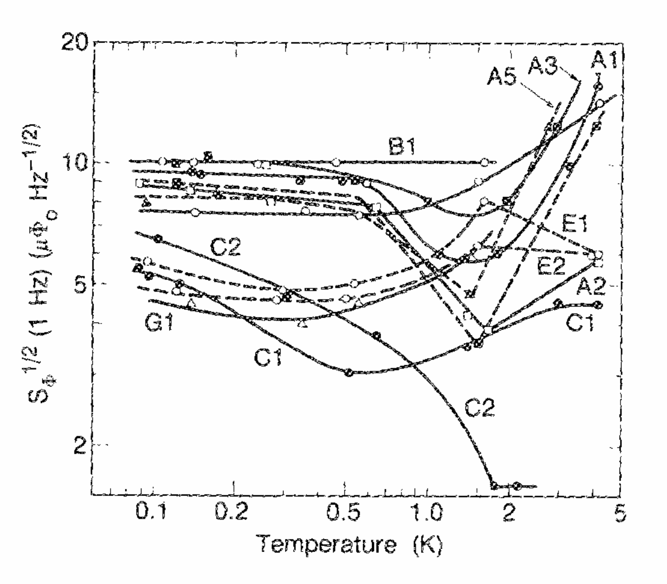
$L = 3 - 5$ pH
$S_\Phi^{1/2}$ (1 Hz) = 1 $\mu\Phi_0/\mathrm{Hz}^{1/2}$
(NEC, NTT)

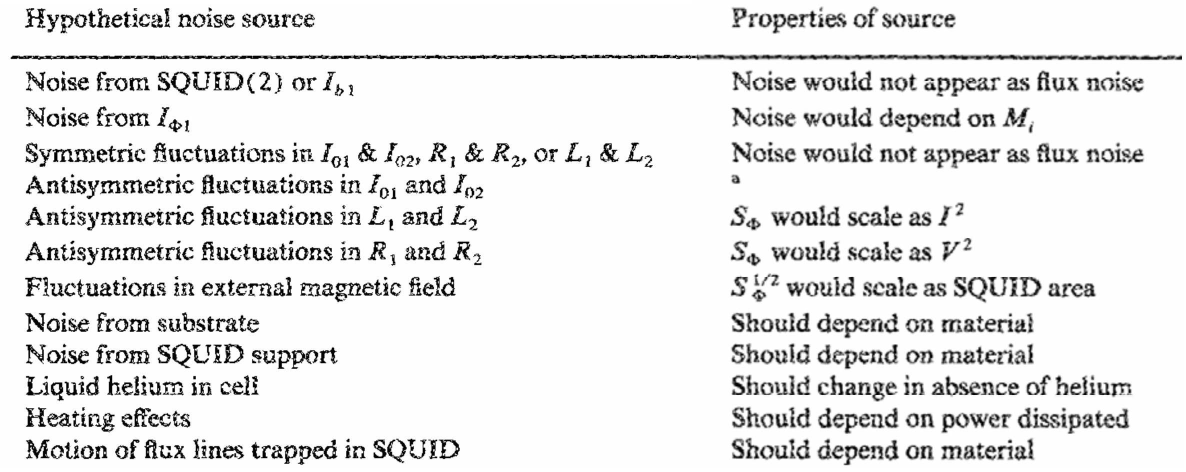
Universal flux noise? Compatible with earlier SQUID measurements

1/f Flux in SQUIDs

[Wellstood *et al.*, APL **50** 772 (‘87)]







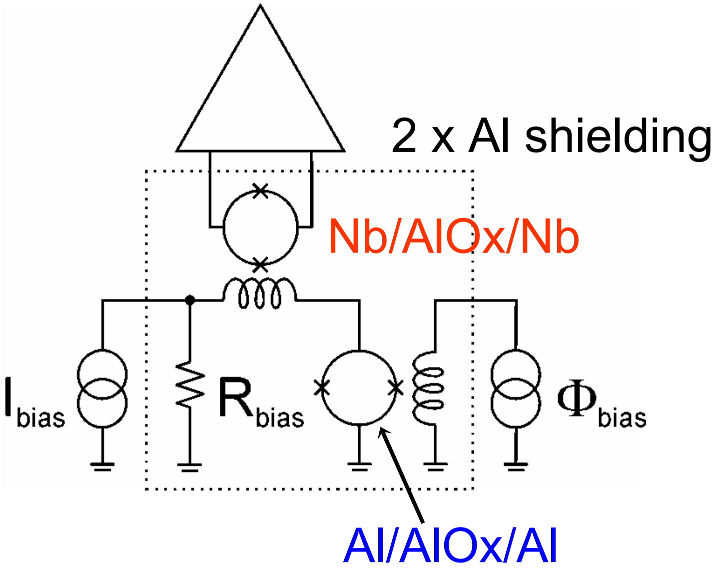
Hypothetical noise source	Properties of source
Noise from SQUID(2) or I_{b1}	Noise would not appear as flux noise
Noise from $I_{\Phi 1}$	Noise would depend on M_i
Symmetric fluctuations in I_{01} & I_{02}, R_1 & R_2, or L_1 & L_2	Noise would not appear as flux noise
Antisymmetric fluctuations in I_{01} and I_{02}	[a]
Antisymmetric fluctuations in L_1 and L_2	S_Φ would scale as I^2
Antisymmetric fluctuations in R_1 and R_2	S_Φ would scale as V^2
Fluctuations in external magnetic field	$S_\Phi^{1/2}$ would scale as SQUID area
Noise from substrate	Should depend on material
Noise from SQUID support	Should depend on material
Liquid helium in cell	Should change in absence of helium
Heating effects	Should depend on power dissipated
Motion of flux lines trapped in SQUID	Should depend on material

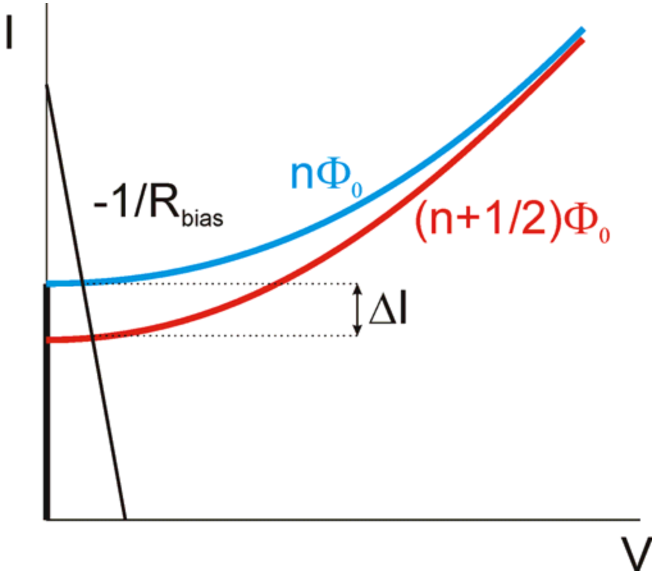
“universal” *1/f* flux noise

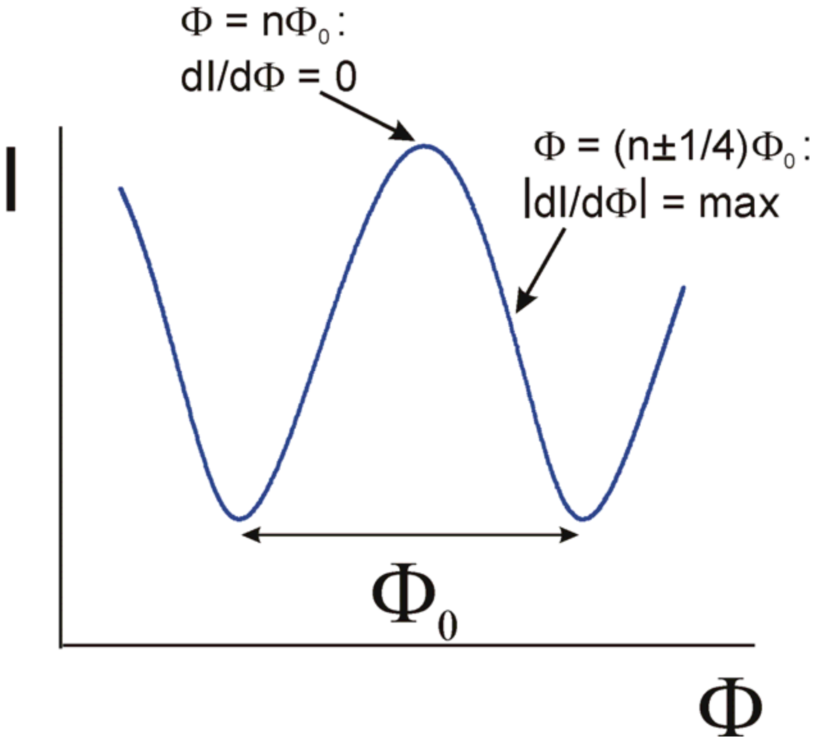
independent of : **inductance**
materials
geometry

mechanism unknown

Madison SQUID Measurements

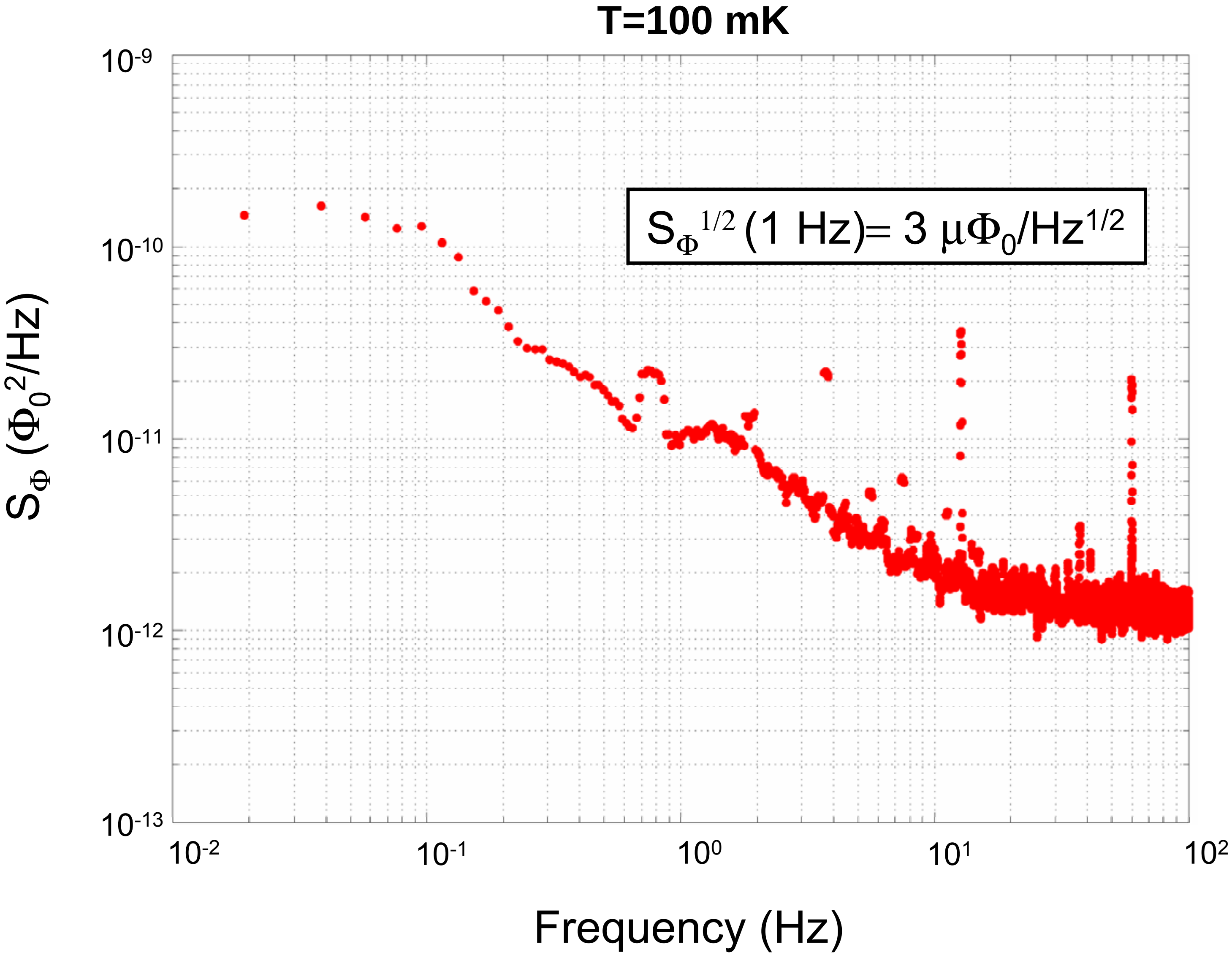






power gain: 27 dB

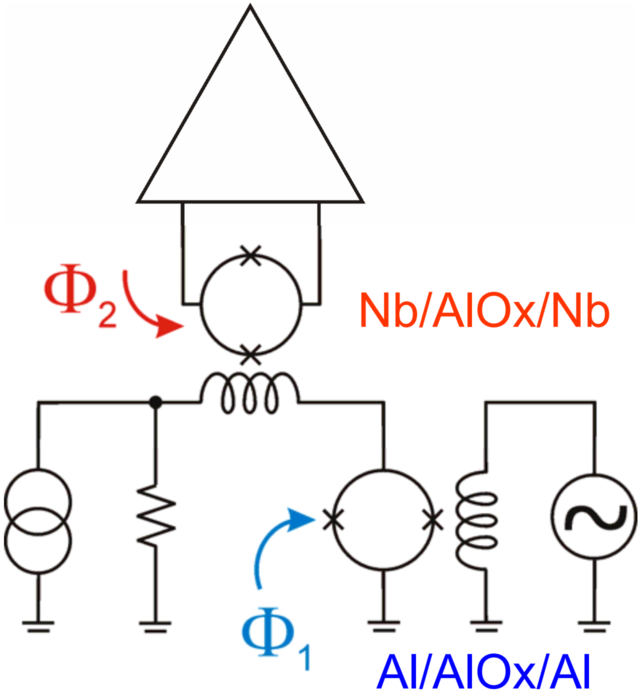
Flux Noise Spectrum

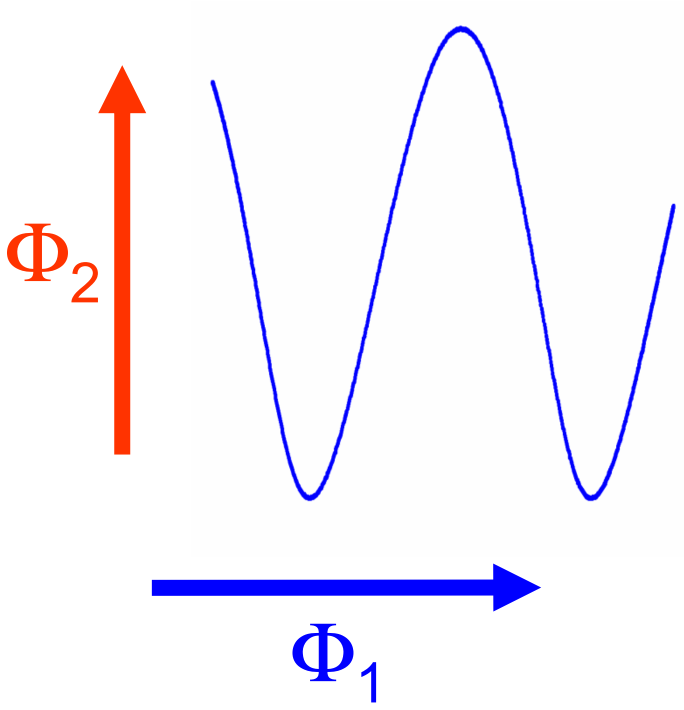


T=100 mK

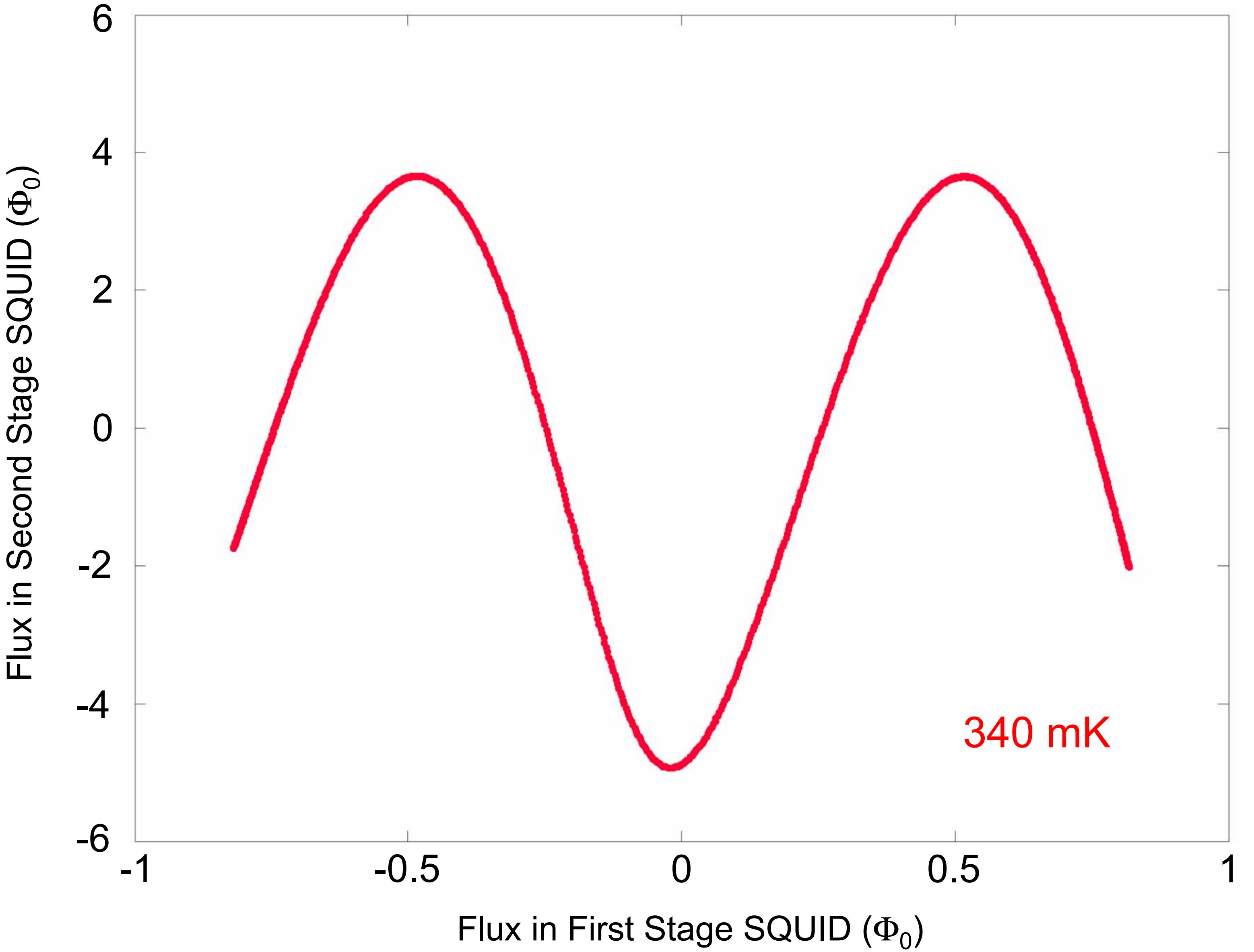
$S_\Phi^{1/2}$ (1 Hz)= 3 $\mu\Phi_0/\mathrm{Hz}^{1/2}$

Measurement of $\frac{\partial \Phi}{\partial T}$

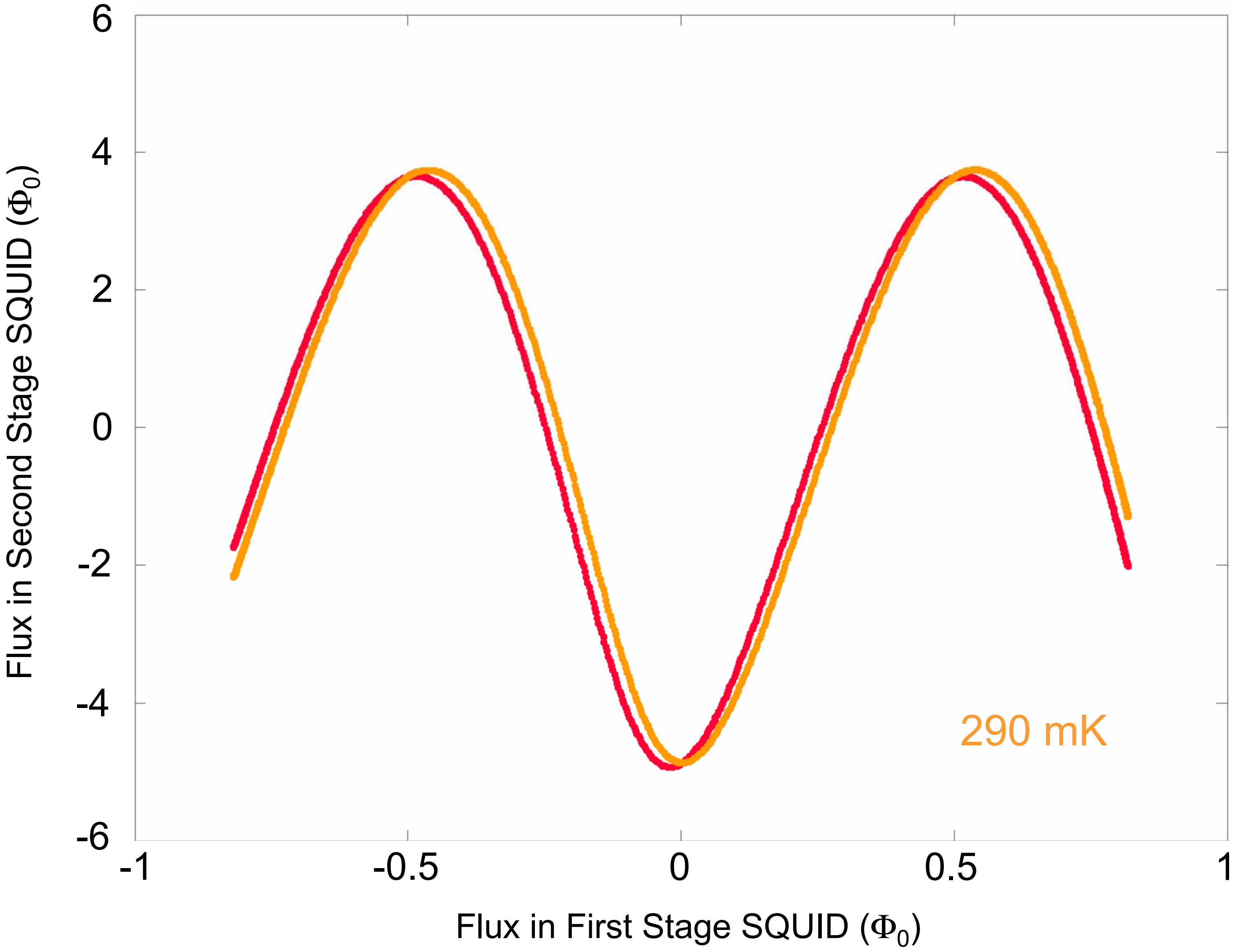




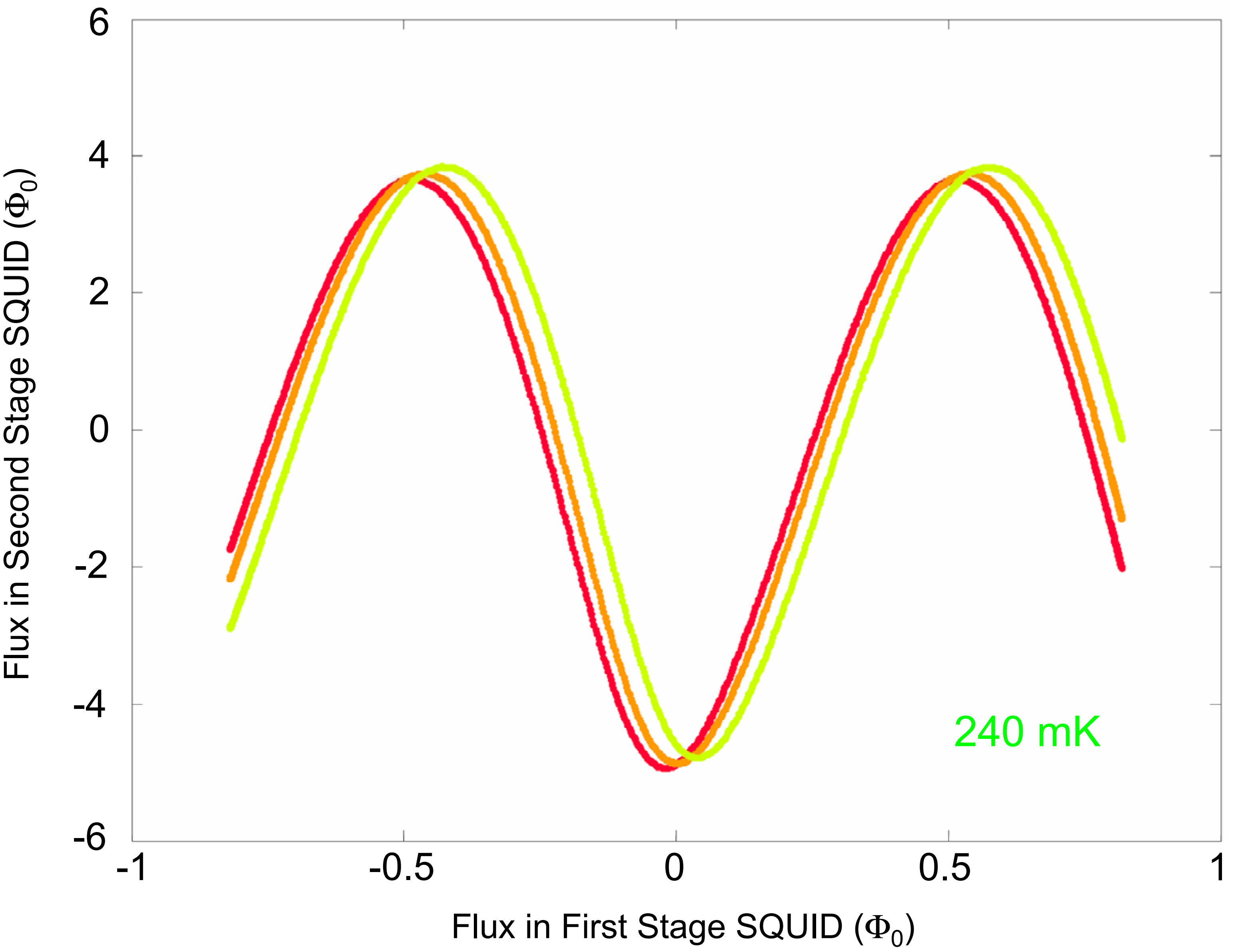
I-Φ vs. T


6
4
2
0
-2
-4
-6
-1
-0.5
0
0.5
1
Flux in Second Stage SQUID (Φ_0)
Flux in First Stage SQUID (Φ_0)
340 mK

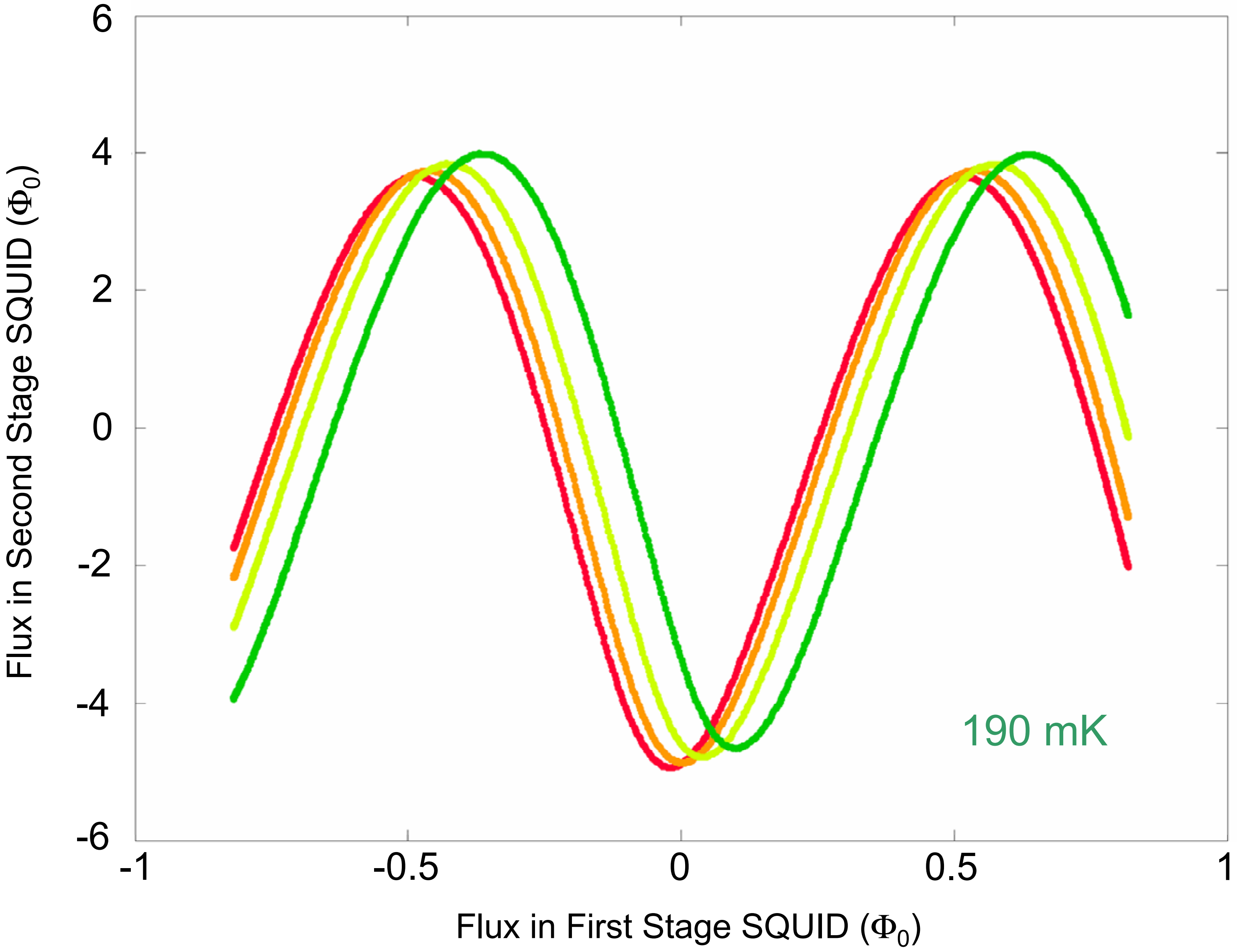
I-Φ vs. T


Flux in Second Stage SQUID (Φ_0)
6
4
2
0
-2
-4
-6
-1
-0.5
0
0.5
1
Flux in First Stage SQUID (Φ_0)
290 mK

I-Φ vs. T

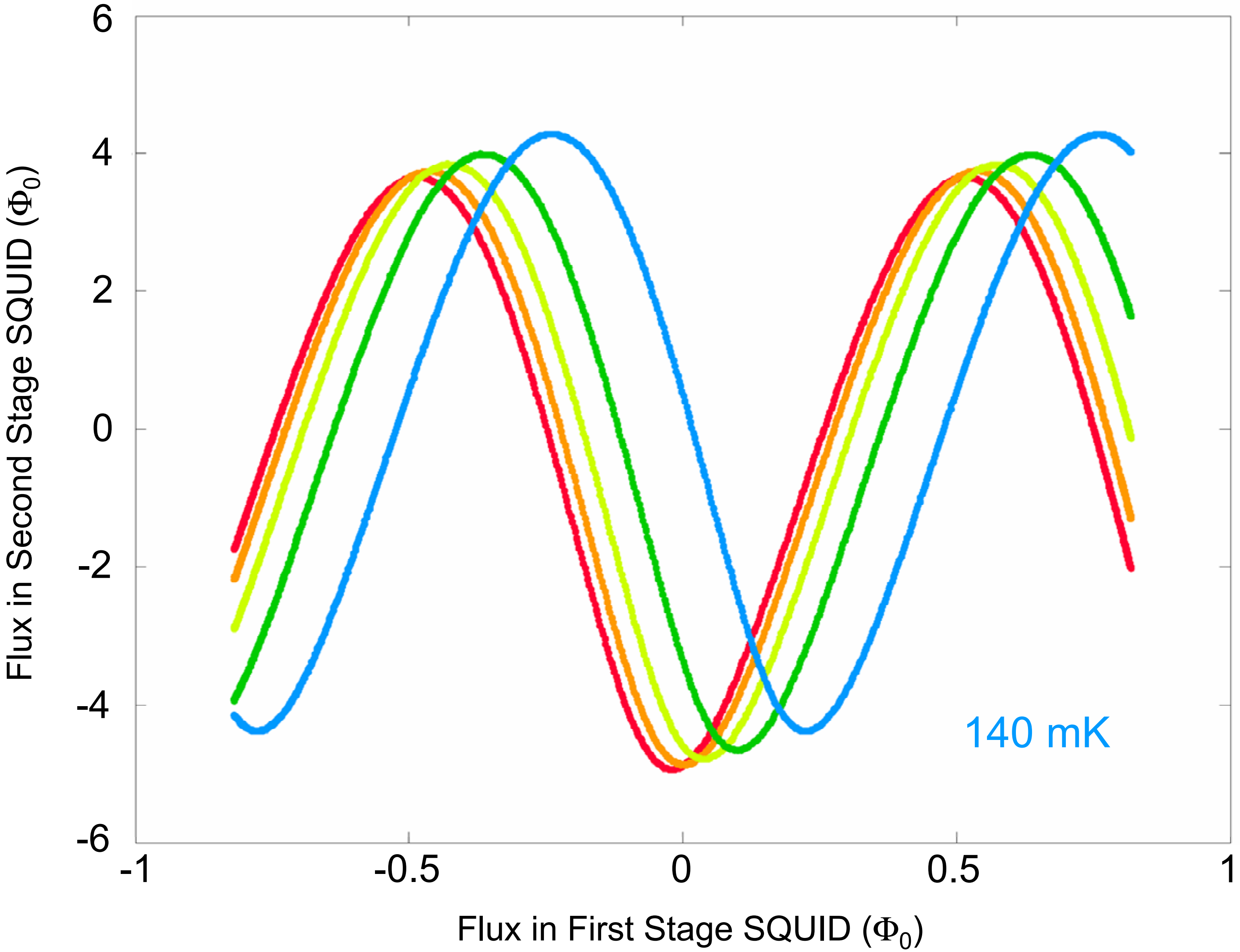

6
4
2
0
-2
-4
-6
-1
-0.5
0
0.5
1
Flux in Second Stage SQUID (Φ_0)
Flux in First Stage SQUID (Φ_0)
240 mK

I-Φ vs. T

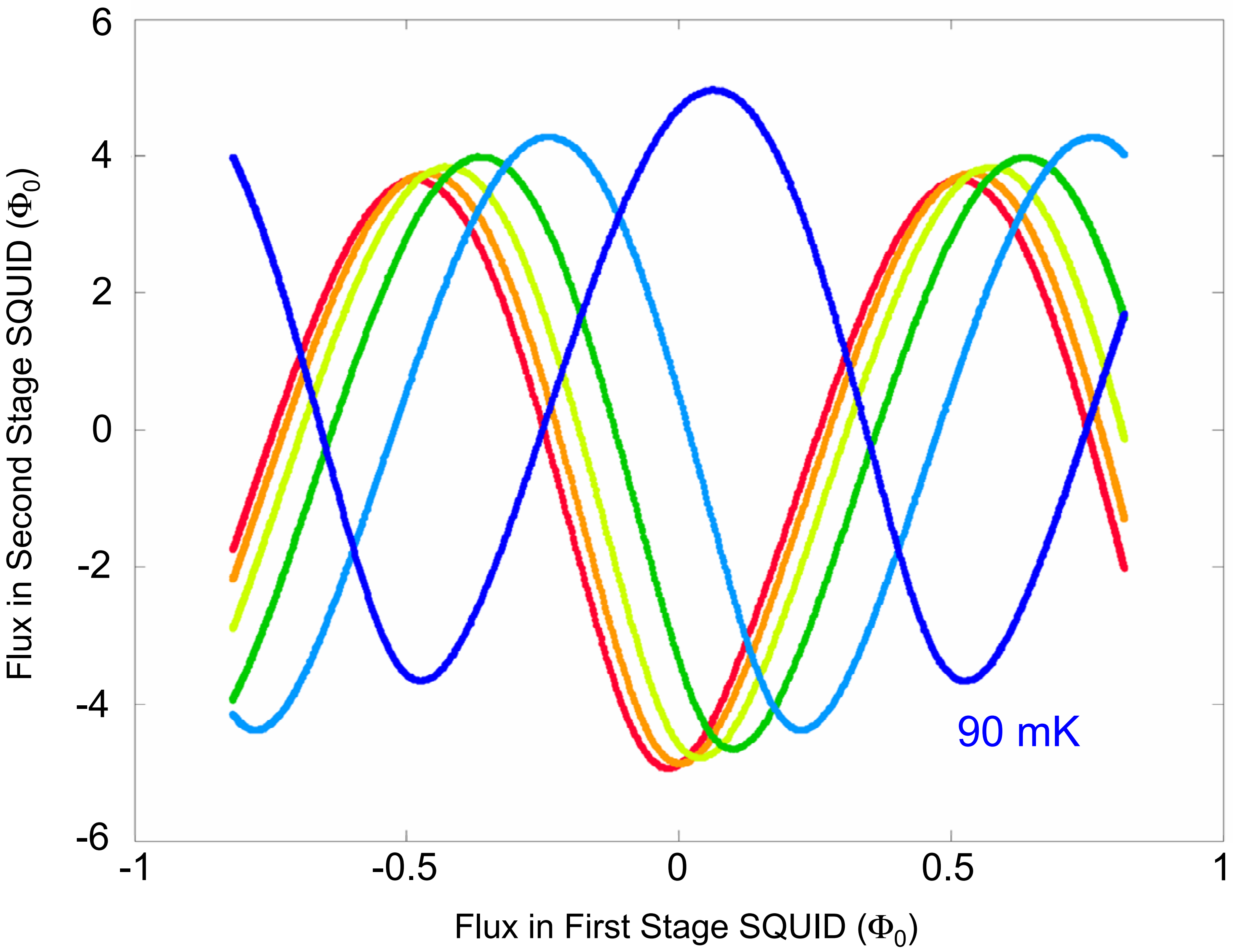


6
4
2
0
-2
-4
-6
-1
-0.5
0
0.5
1
Flux in Second Stage SQUID (Φ_0)
Flux in First Stage SQUID (Φ_0)
190 mK

I-Φ vs. T

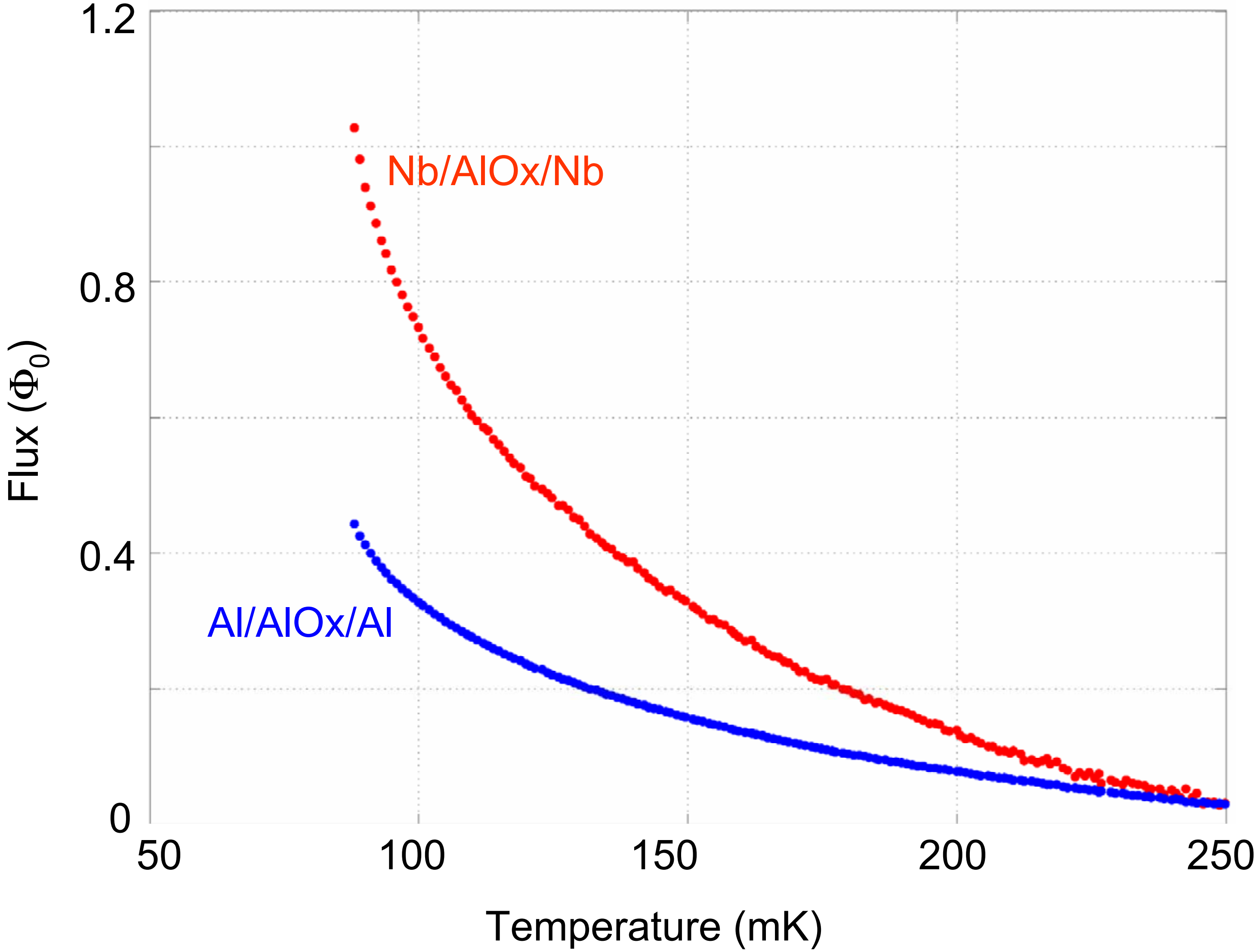

6
4
2
0
-2
-4
-6
-1
-0.5
0
0.5
1
Flux in Second Stage SQUID (Φ_0)
Flux in First Stage SQUID (Φ_0)
140 mK

I-Φ vs. T

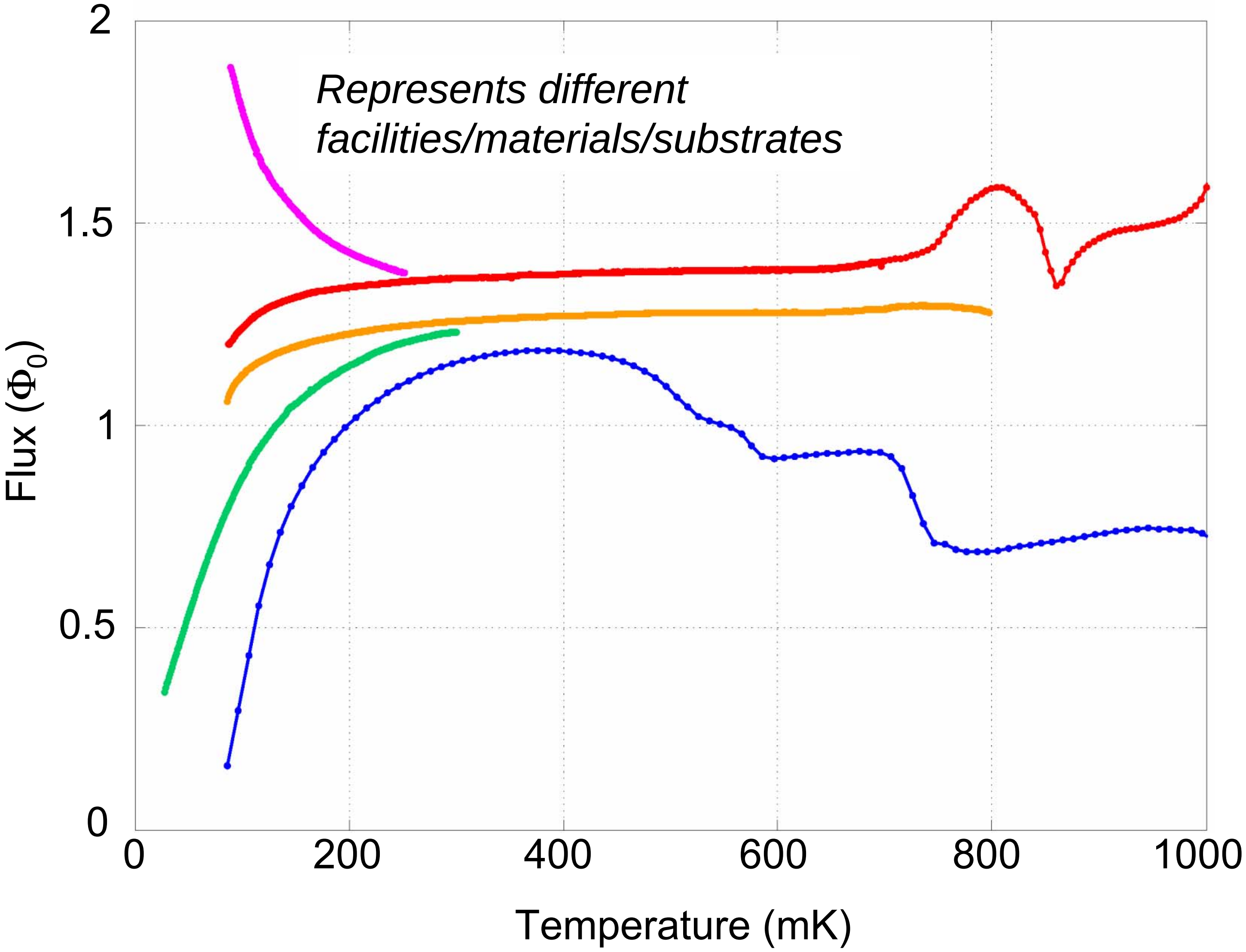


6
4
2
0
-2
-4
-6
-1
-0.5
0
0.5
1
Flux in Second Stage SQUID (Φ_0)
Flux in First Stage SQUID (Φ_0)
90 mK

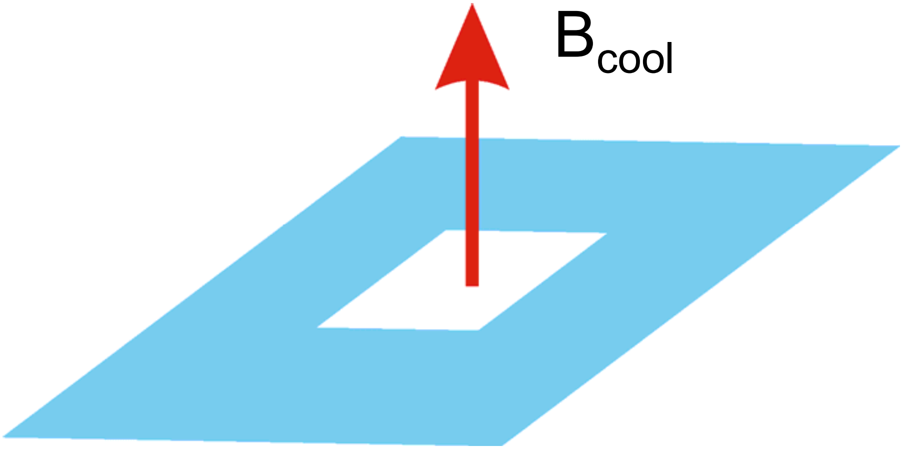
Flux vs. Temperature



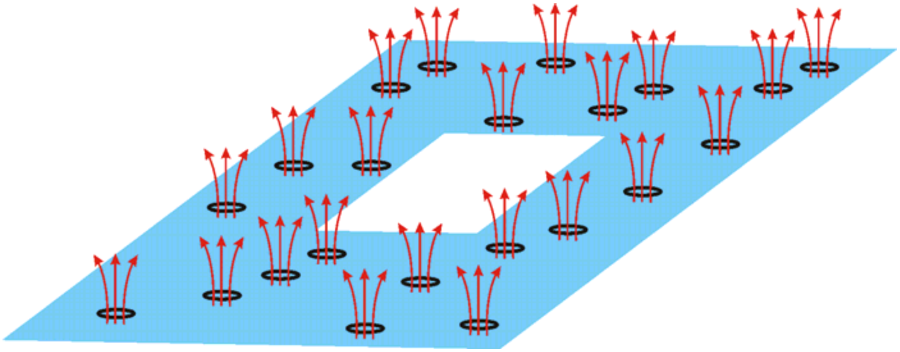
Many Samples, Similar Results



Field Cool Experiments



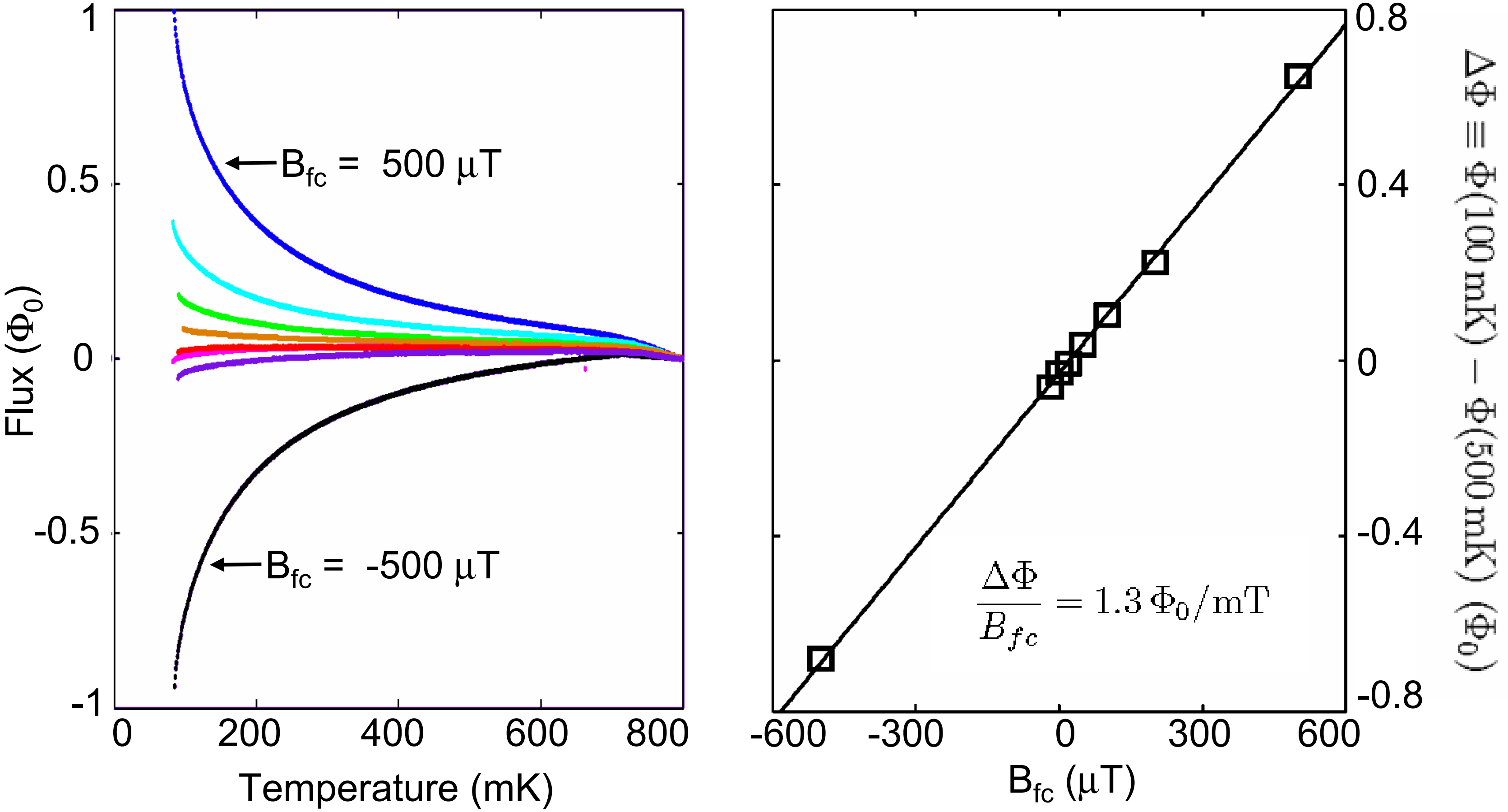
$$\sigma_{vortex} \approx \frac{B_{cool}}{\Phi_0}$$



$T > T_c$

$T < T_c$

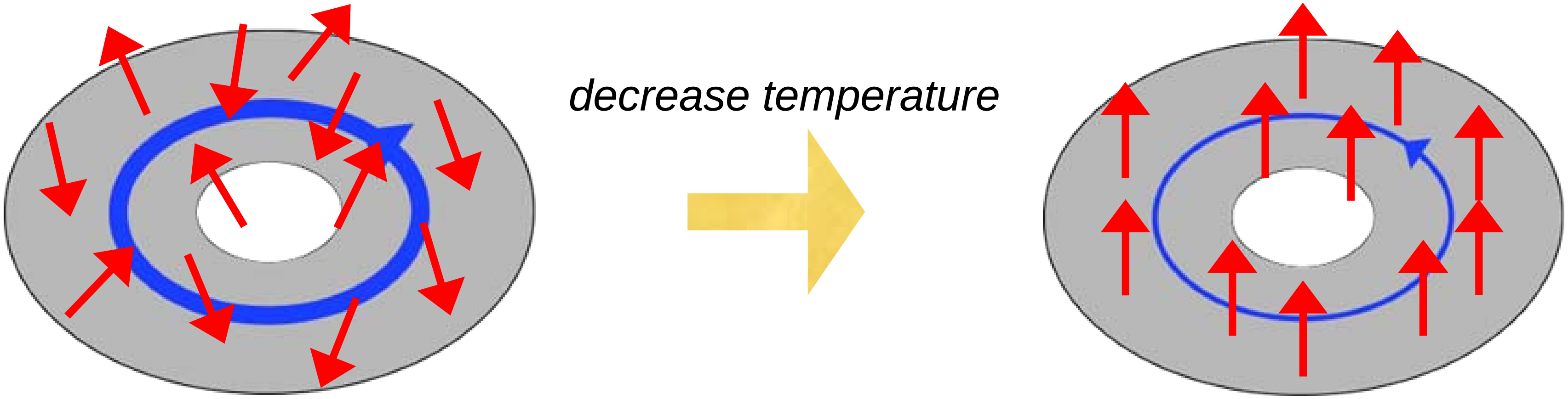
Field Cool Experiments



Temperature-dependent flux scales linearly with density of vortices

Interpretation: Polarization of Unpaired Spins in Vortex

$$B_{vortex} \approx 40\,\mathrm{mT} \qquad T \sim \frac{\mu_B B_{vortex}}{k_B} \sim 30\,\mathrm{mK}$$



- Circulating current decreases due to flux quantization
- Flux coupled to vortex by polarization of spins ~ 10 $\mu\Phi_0$
- Substantial fraction of the vortex current couples to the SQUID

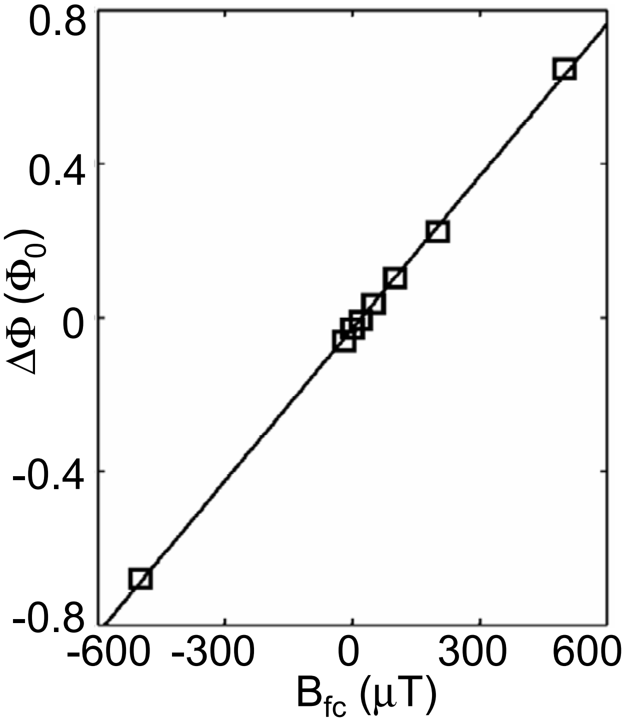
1: Calculate flux coupled to SQUID from vortex

2: Calculate flux coupled to vortex from uniform density of spins

[Sendelbach *et al.* arXiv:0802.1511 (08)]

Interpretation of Field Cool Data

Polarization of unpaired spins in vortex



$$B_{vortex} \approx 40\,\mathrm{mT}$$

$$T \sim \frac{\mu_B B_{vortex}}{k_B} \sim 30\,\mathrm{mK}$$

A_{SQ} = SQUID Area

L_V = Vortex Self Inductance

ΔP_{eff} = Change in effective spin polarization

σ_S = Spin Density

$$\frac{\Delta\Phi}{B_{fc}} = 0.14\frac{A_{SQ}}{\Phi_0}\mu_B \boxed{\sigma_s} L_v \Delta P_{eff}$$

Implies: $\boxed{\sigma_s = 5 \times 10^{17}\,\mathrm{m}^{-2}}$

Quantitative agreement with

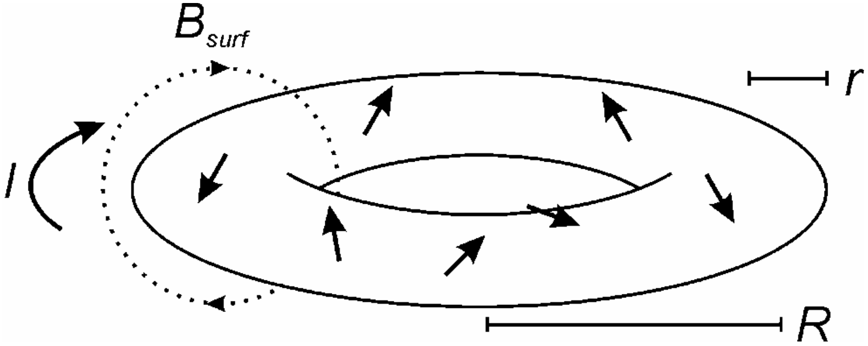
Bluhm *et al*., PRL 103, 026805 (09)

Noise from Surface Spins

Simplified toroidal model of SQUID

$$\Phi_{dipole \to SQUID} = \frac{\mu_0 m}{2\pi r}$$

(reciprocity)



$$S_\Phi \propto \sigma_s \, (rR) \left(\frac{1}{r^2}\right) \sim \left(\frac{R}{r}\right)$$

Noise independent of overall device scale
(more realistic SQUID geometry gives only log corrections)

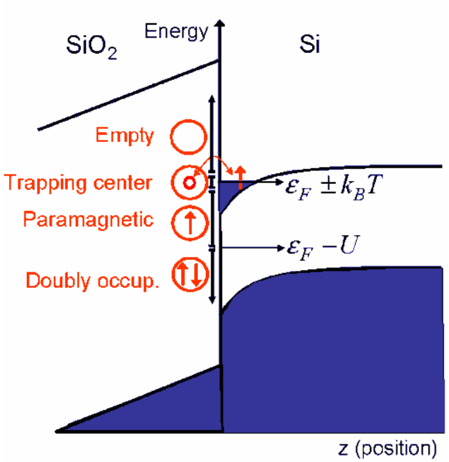
Theoretical Models

Koch *et al.* [PRL **98**, 267003 (07)]

- magnetic two-level state (TLS) defects
- TLS density σ ~ 5x10^{17} m^{-2} compatible with measured noise

de Sousa [PRB **76**, 245306 (07)]

- Unpaired spin density a factor 10^4 – 10^5 greater than TLS density
- Spins coupled to TLS defects

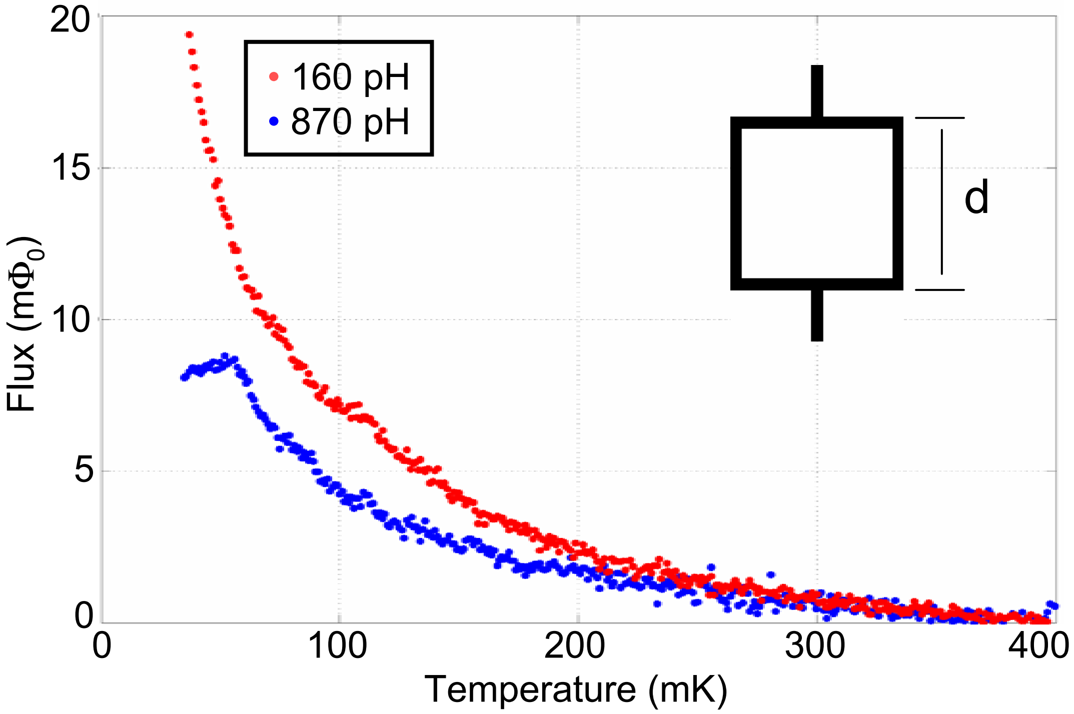


L. Faoro and L.B. Ioffe [PRL **100**, 227005 (08)]

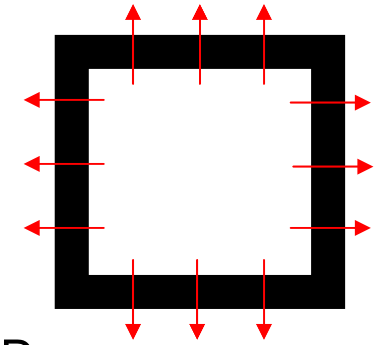
- spins at S-I interface (surface density of spins σ ~ 10^{16}-10^{17} m^{-2})
- RKKY interaction, spin diffusion in nonuniform current distribution of SQUID

$$S_\Phi = \frac{8}{\pi}\mu_0^2\mu_B^2\sigma\left(\frac{R}{w}\right)\frac{1}{\omega}$$

Interaction of Surface Spins



For Optimally Oriented Spins:



$\Phi_{max}=2\mu_0\mu_B\sigma_s d$

For 160pH SQUID:

d = 50μm
σ_s = 5 ×10^{17} m^{-2}

Yields: $\Phi_{max} = 280$ mΦ_0

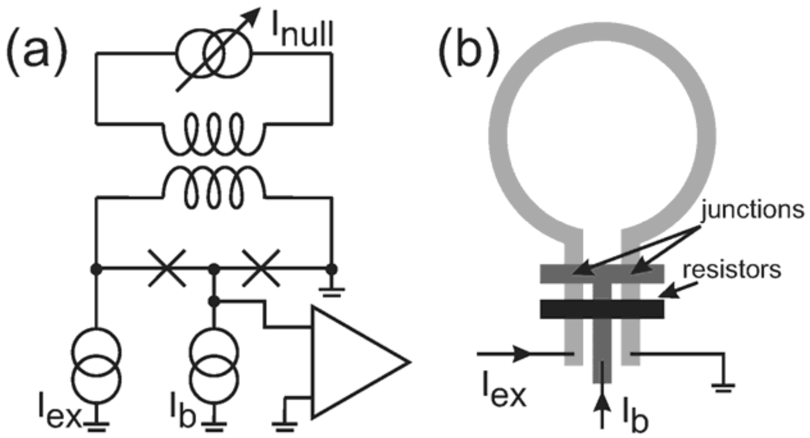
Measured change of 19 mΦ_0 suggests a high degree of spin polarization

Note: Cusp

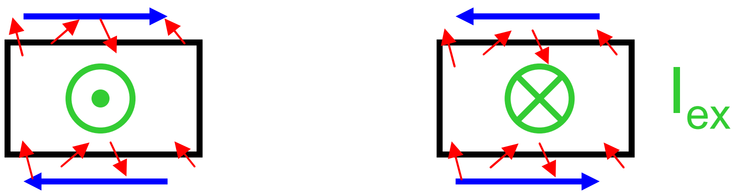
-Reminiscent of spin glass at freezing temperature??

Faoro/Ioffe model gives interaction energy of 20 mK

Investigations of Surface Spin Susceptibility



Cross sectional view



Surface magnetic field
creates optimal spin alignment

SQUID “susceptometer”
optimized for surface spins

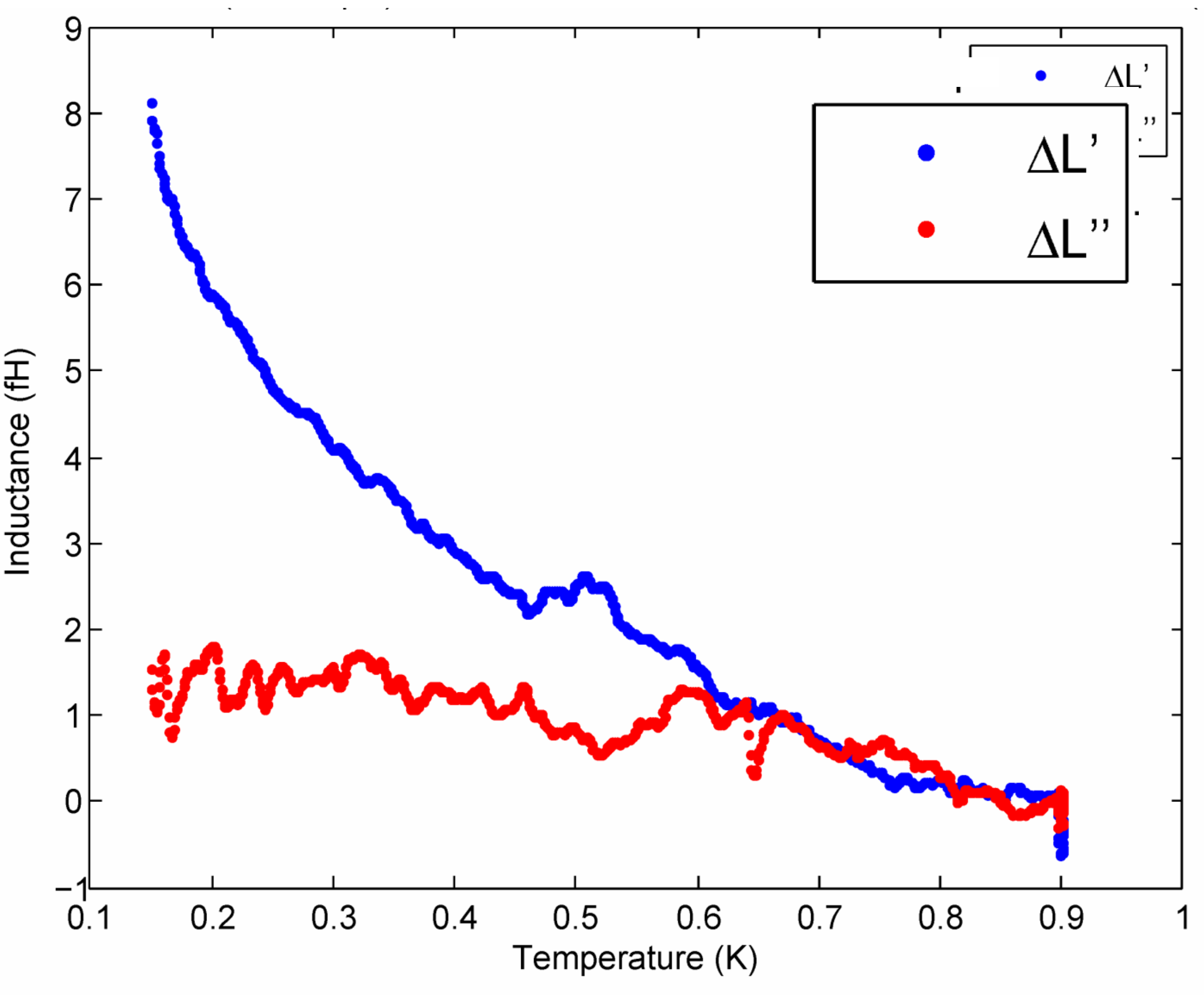
$$L = L_{geo} + L_{kin} + \boxed{L_{spin}}$$

Inject I_{ex} (f_0)
Measure Φ

→ Determine $L(T ; f_0)$

$L(T ; f_0)$ ✪ $\chi(T ; f_0)$

Investigations of Surface Spin Susceptibility

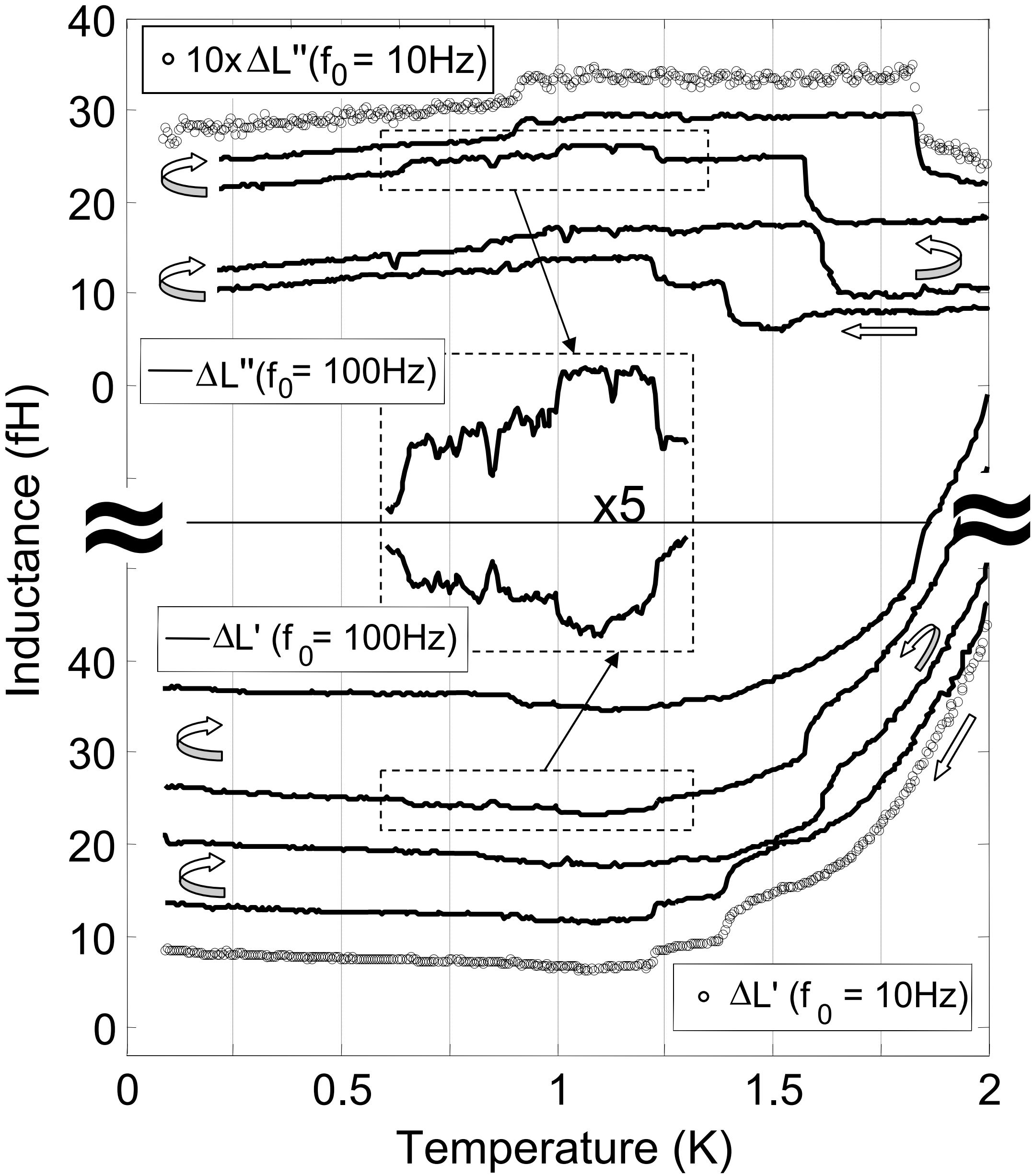


more or less Curie-like behavior

seen in < 10% of cooldowns!

Investigations of Surface Spin Susceptibility

Rich, history-dependent structure in ΔL(T)



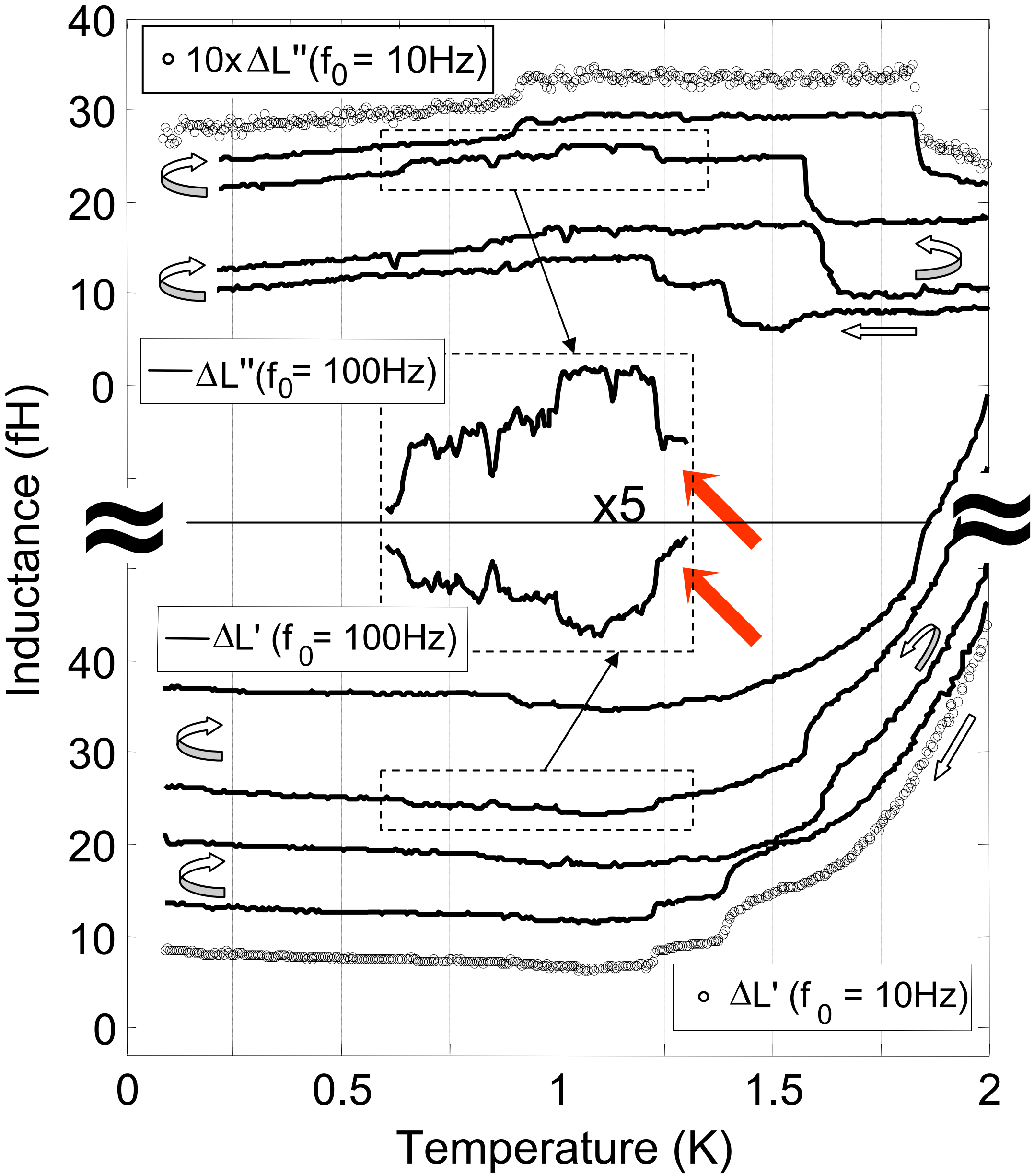
Investigations of Surface Spin Susceptibility

Rich, history-dependent structure in ΔL(T)

Correlated jumps in L', L''

Jumps in L' independent of f_0

Jumps in L'' scale linearly with f_0



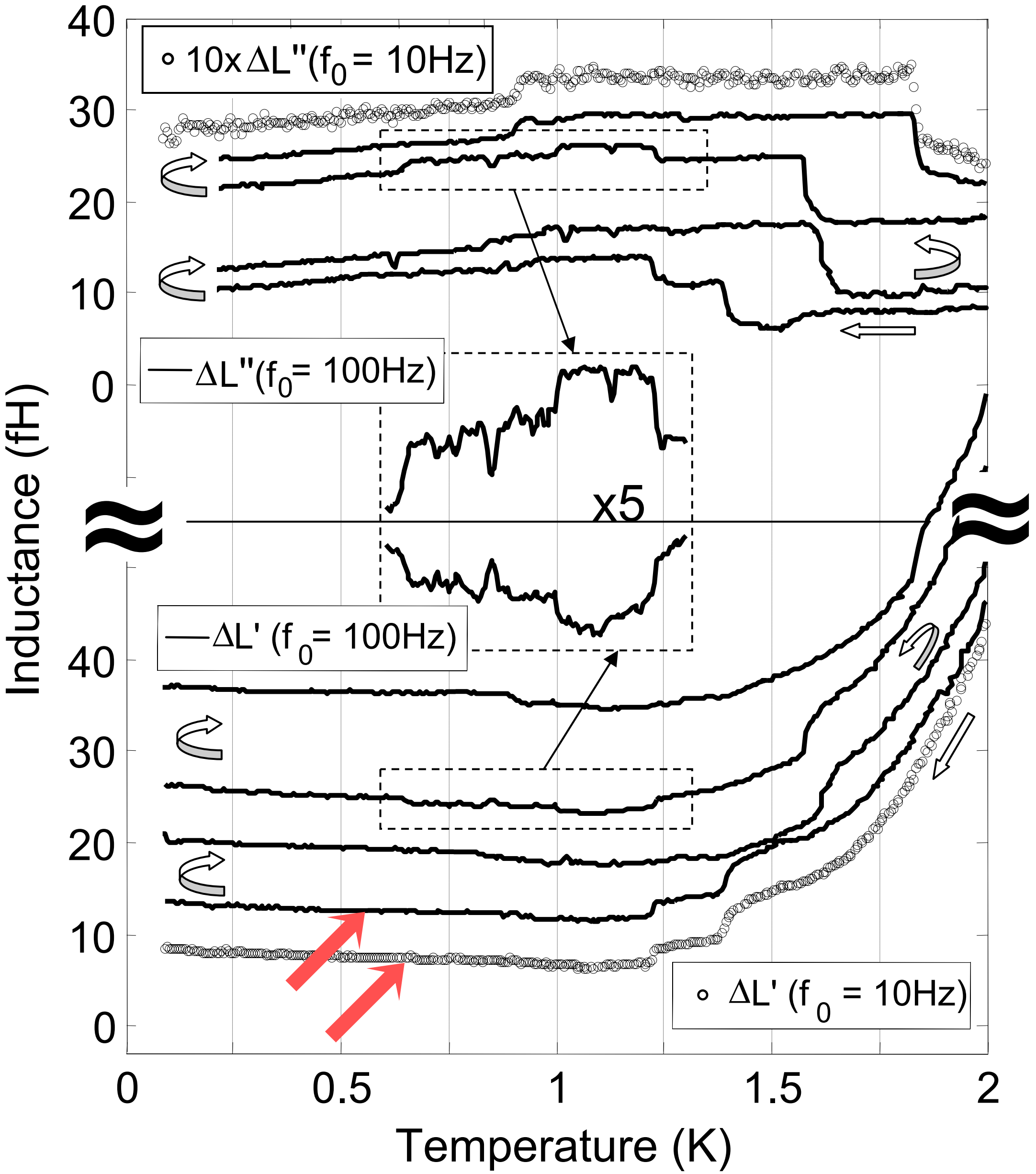
Investigations of Surface Spin Susceptibility

Rich, history-dependent structure in $\Delta L(T)$

Correlated jumps in L', L''

Jumps in L' independent of f_0

Jumps in L'' scale linearly with f_0



Investigations of Surface Spin Susceptibility

Rich, history-dependent structure in ΔL(T)

Correlated jumps in L', L''

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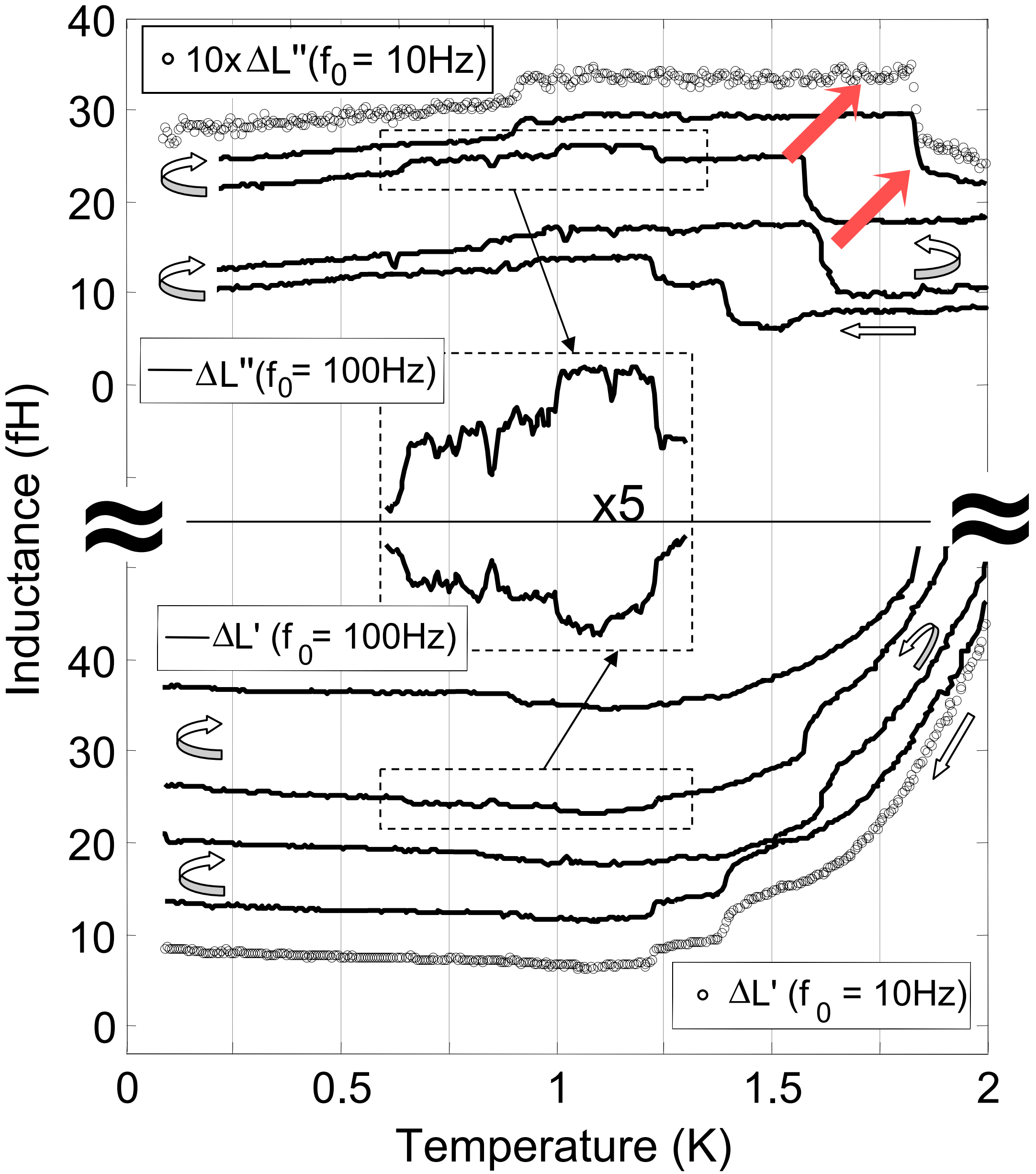


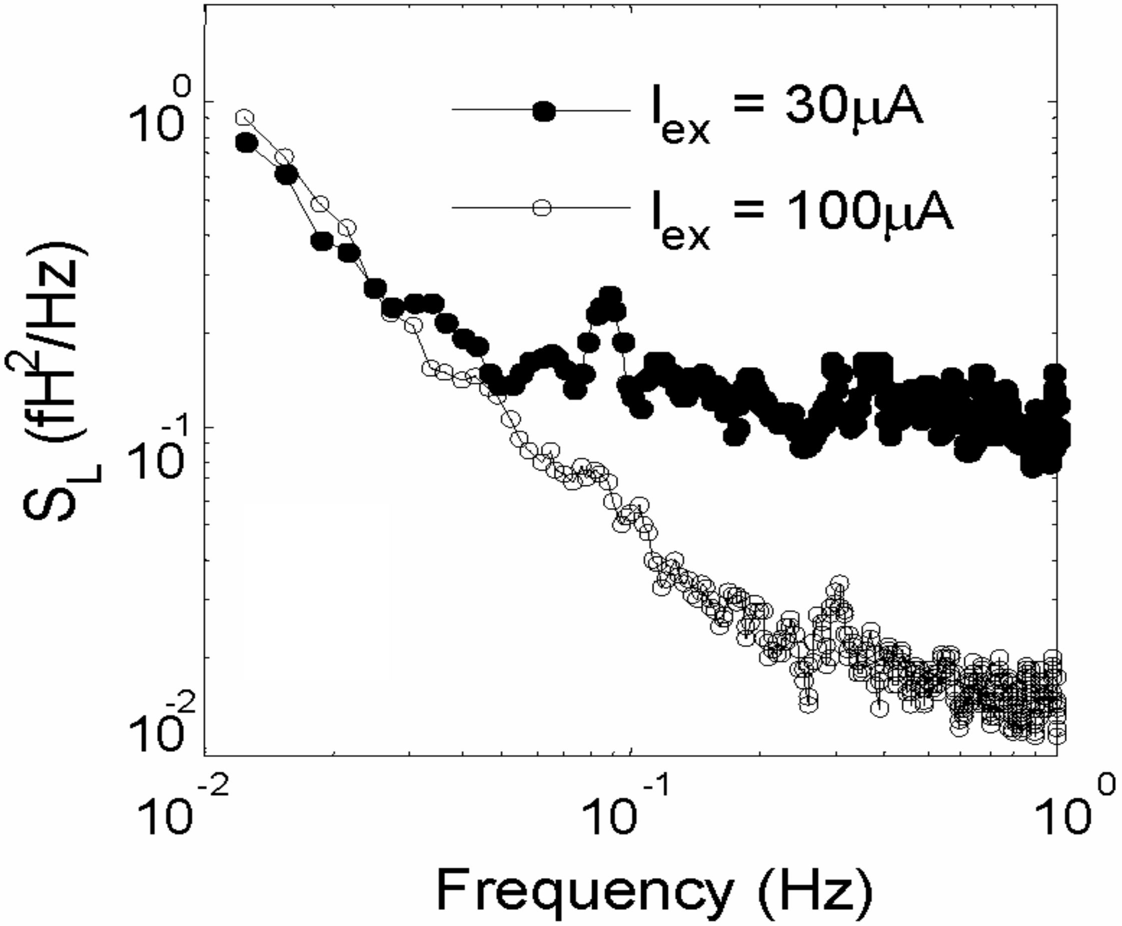
Inductance Noise in the dc SQUID

Stabilize temperature, monitor SQUID inductance over time, compute power spectrum

Noise power scales as I_{ex}^2

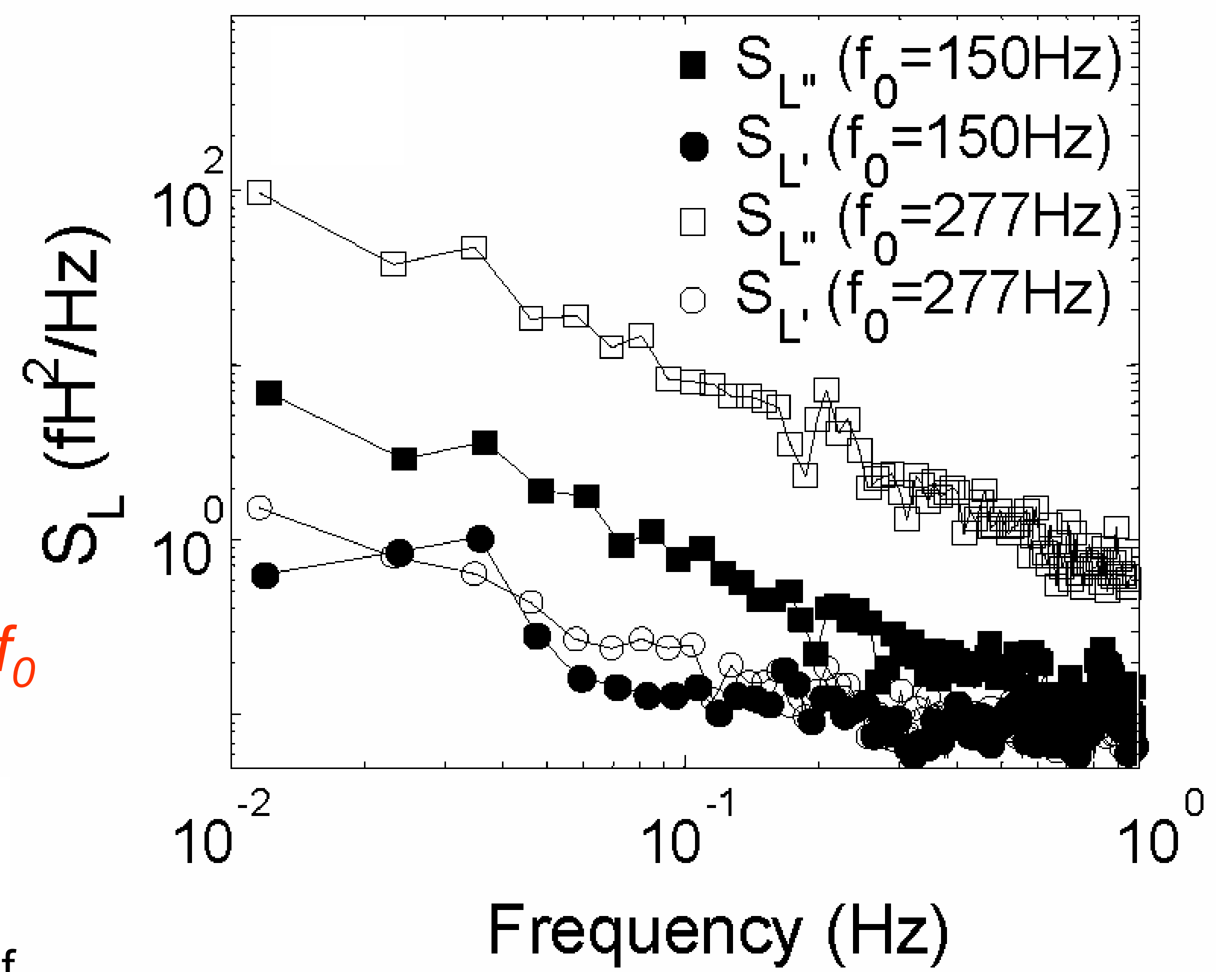
→ *Inductance noise*

Inductance noise scales with frequency as *1/f*



Inductance Noise in the dc SQUID

Scaling with probe frequency



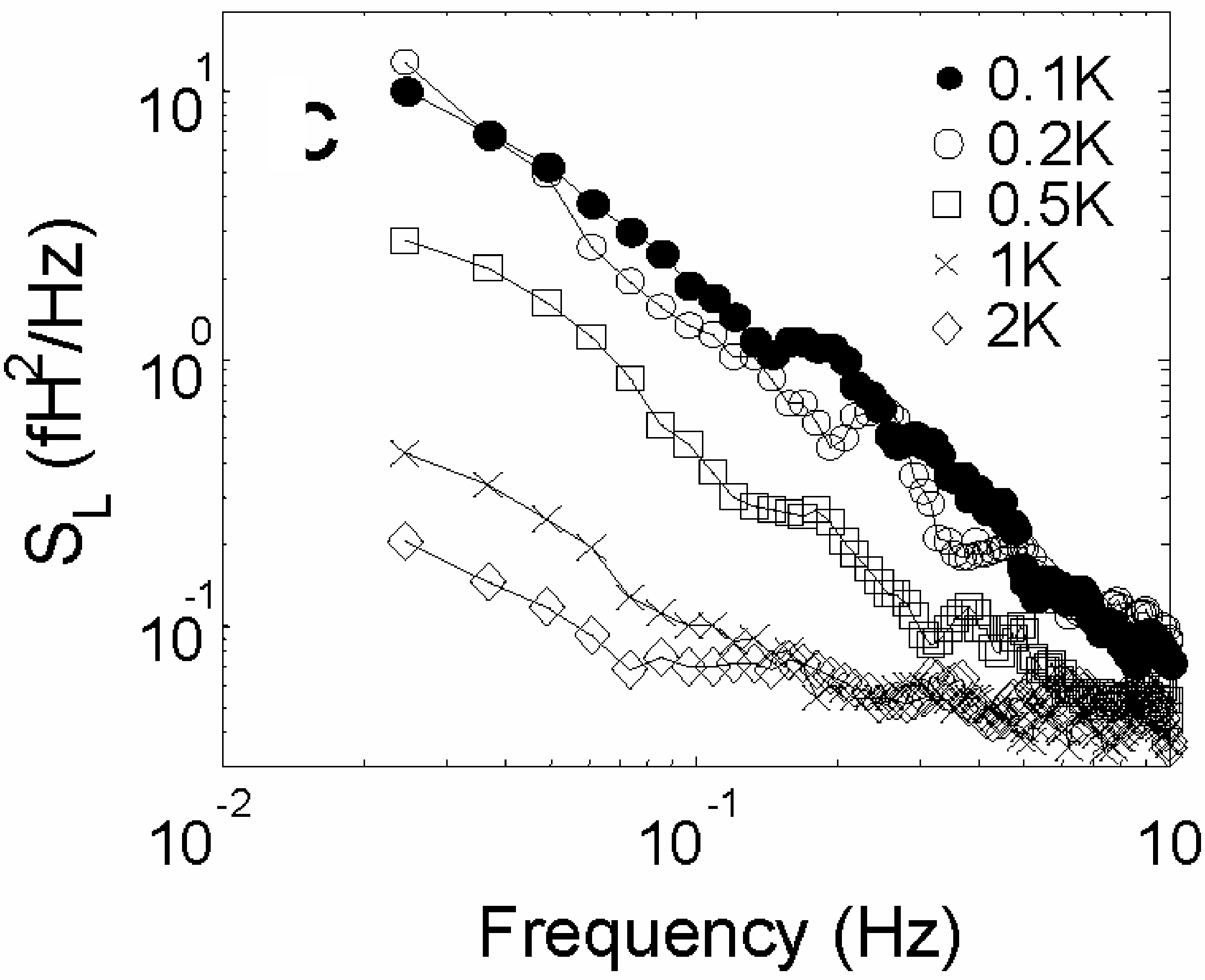
$S_{L'}$ independent of f_0

$S_{L''}$ scales as f_0^2

(compatible with scaling of Individual inductance jumps)

Inductance Noise in the dc SQUID

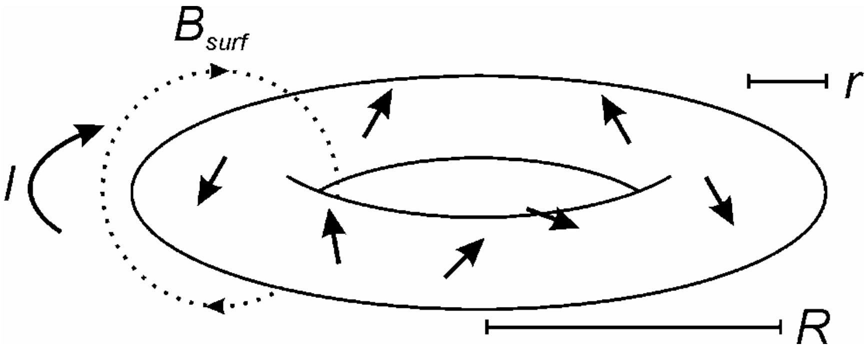
Temperature dependence



Spin Cluster Interpretation

$$L'_{spin} = \frac{\mu_0^2 \mu^2}{2k_B T} \sigma \frac{R}{r}$$

For σ = 5e17 m^{-2}, $\mu = \mu_B$ expect spin contribution to inductance of order 100 aH at 100 mK (noninteracting spins)



toroidal model of SQUID

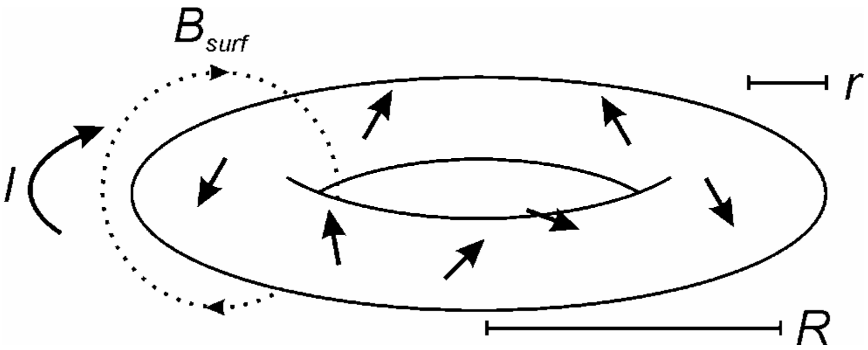
Spin Cluster Interpretation

$$L'_{spin} = \frac{\mu_0^2 \mu^2}{2 k_B T} \sigma \frac{R}{r}$$

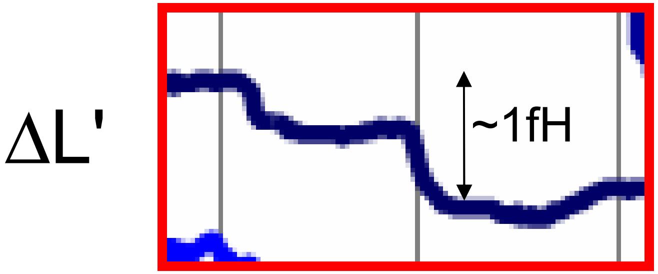
For σ = 5e17 m^{-2}, $\mu = \mu_B$ expect spin contribution to inductance of order 100 aH at 100 mK (noninteracting spins)

Fluctuating moment gives fluctuating inductance

effective moment $\mu = \alpha\, \mu_B$;
α is dimensionless cluster size



toroidal model of SQUID

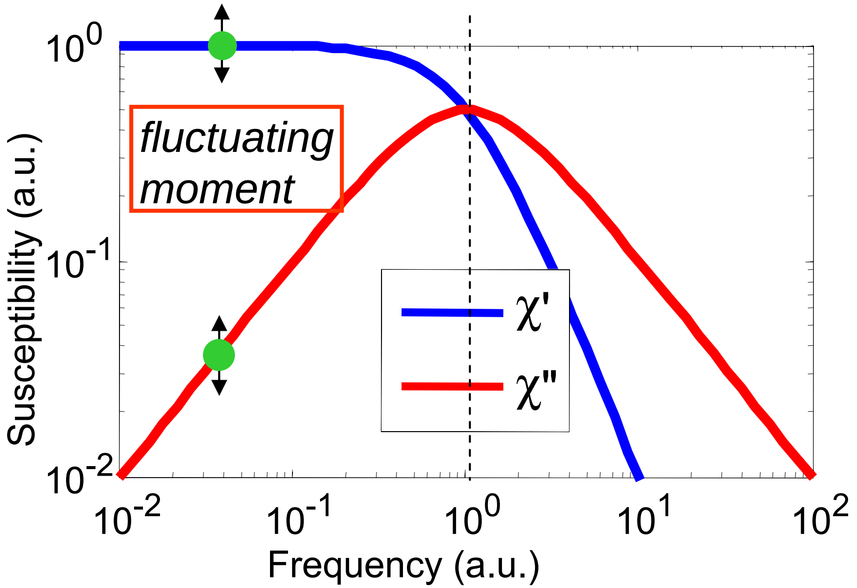


Magnitude of observed jumps suggests presence of superparamagnetic spin clusters with α 🕓 10-100

Spin Cluster Interpretation

Expectation:

$$\chi(f_0) = \int \; g(\tau) \, \frac{\chi_T(\tau)}{1 + i2\pi f_0 \tau} \, d\tau$$



Observation that

$\Delta L'$ is independent of f_0,

$\Delta L'' \propto f_0$

indicates that $2\pi f_0 \tau \ll 1$

$$L' = L_0$$

$$L'' = 2\pi f_0 \tau L_0$$

$$\Delta L' = \boxed{\Delta L_0}$$

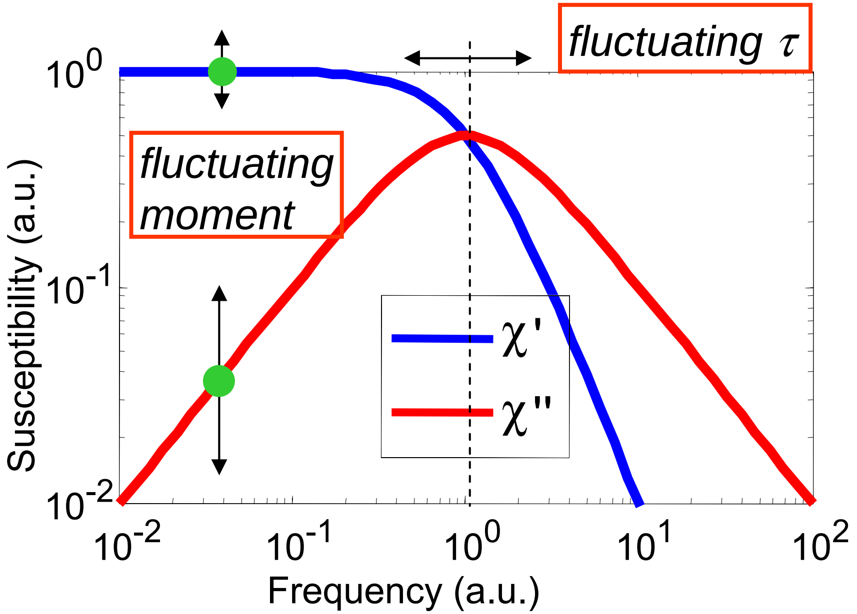
$$\Delta L'' = 2\pi f_0 \tau \boxed{\Delta L_0}$$

noise driven by fluctuating cluster sizes

Spin Cluster Interpretation

Expectation:

$$\chi(f_0) = \int \; g(\tau) \, \frac{\chi_T(\tau)}{1 + i2\pi f_0 \tau} d\tau$$


fluctuating τ

fluctuating moment

Relative magnitude of $\Delta L'$, $\Delta L''$

can be explained in terms of fluctuating spin relaxation times τ

$$L' = L_0$$

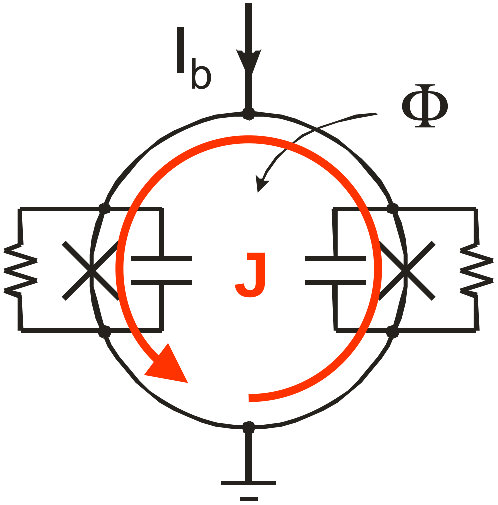
$$L'' = 2\pi f_0 \tau L_0$$

$$\Delta L' = \boxed{\Delta L_0}$$

$$\Delta L'' = 2\pi f_0 L_0 \boxed{\Delta\tau}$$

coupled fluctuation of cluster size and τ

$$S_L \rightarrow S_\Phi??$$



During normal SQUID operation, device supports circulating currents J of order I_0

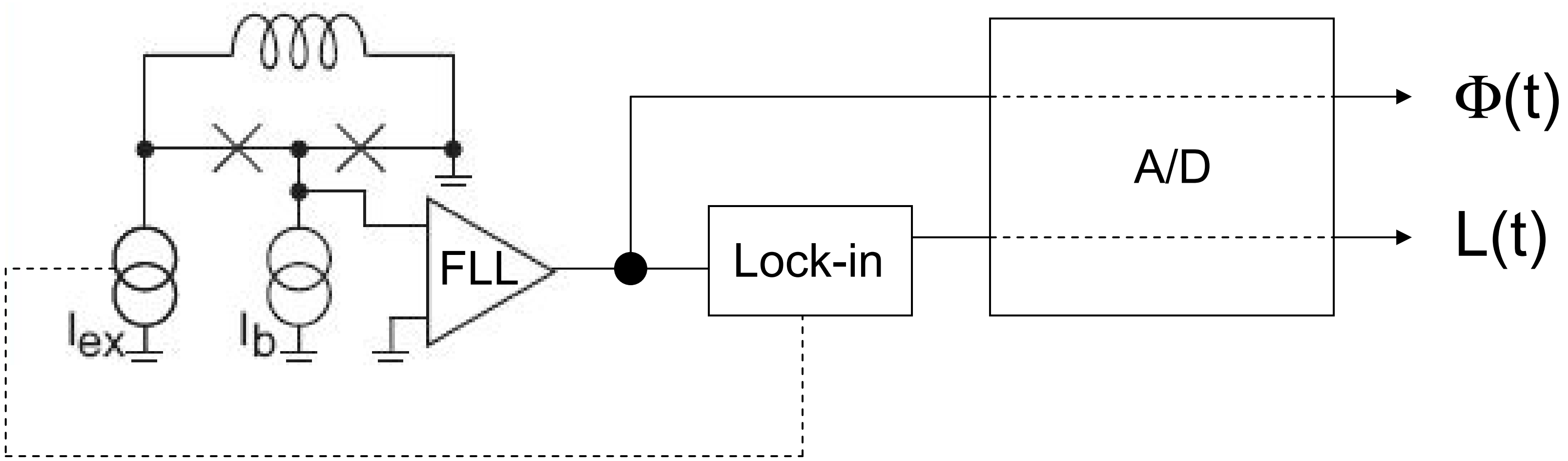
→ Fluctuating inductance could lead to flux noise

Expectation:

$S_\Phi/\Phi_0^2 = (\beta_L^2/16)(S_L/L^2)$, where $\beta_L = 2LI_0/\Phi_0$

For S_L/L^2 = -120 dB/Hz, $\beta_L = 1$,
above relation predicts flux noise that is 1-2 orders of magnitude too small

Correlation Measurements

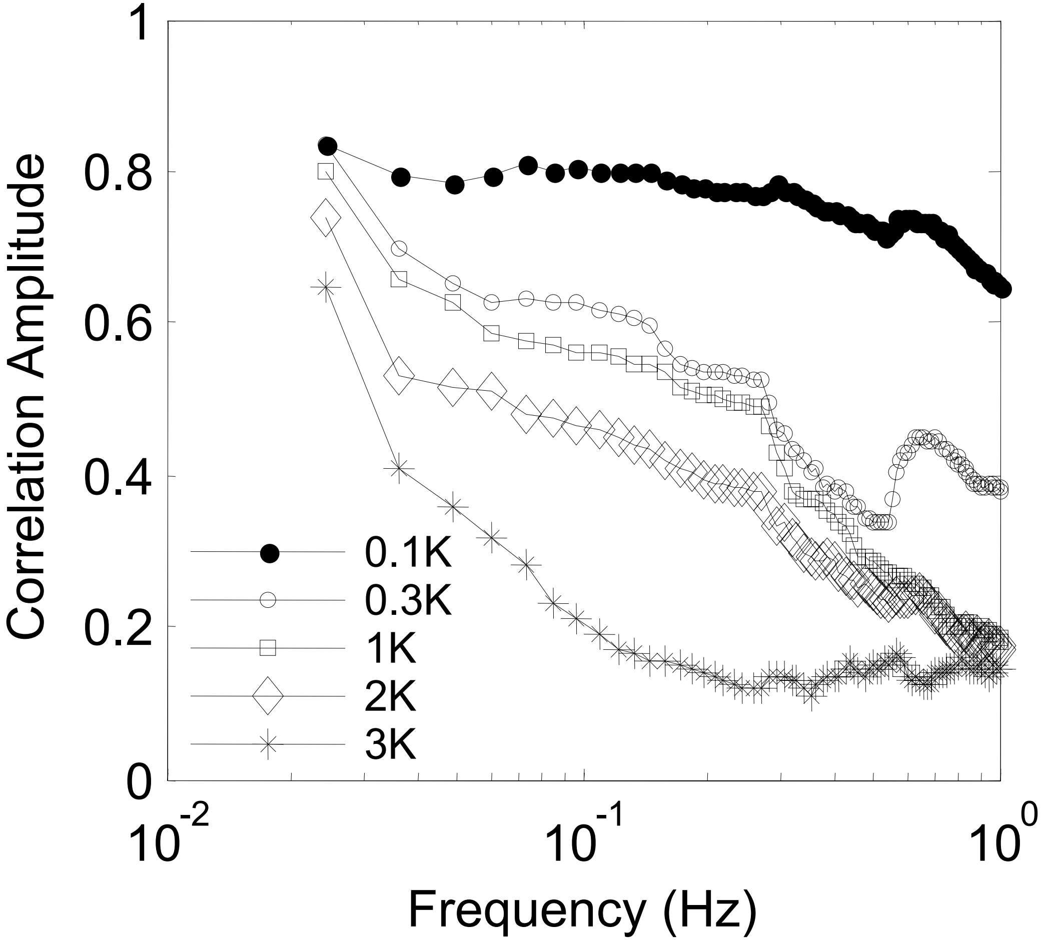


Simultaneously probe SQUID inductance and quasistatic flux threading the device

→ *Look at cross spectrum* $\boldsymbol{S_{L\Phi}}$

Cross Spectrum of Inductance and Flux Noise

abs($S_{L''\Phi}/(S_{L''}S_{\Phi})^{1/2}$)



Strong correlation indicates similar microscopic noise source

Phase of Φ-L Cross Spectrum

$$\Phi \xrightarrow{T} -\Phi$$ (odd under time reversal)

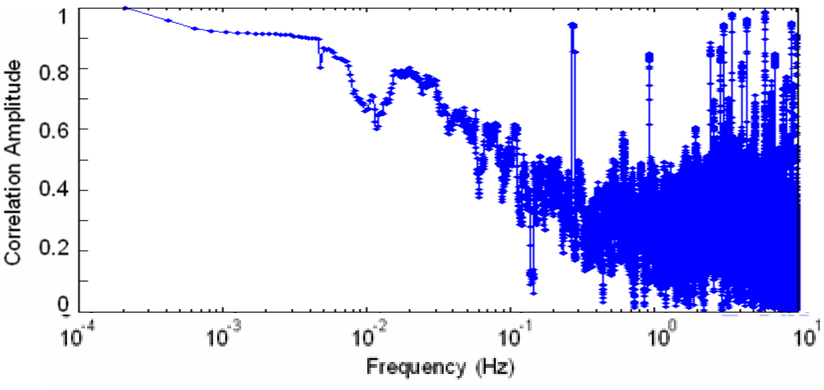
$$L \xrightarrow{T} L$$ (even under time reversal)

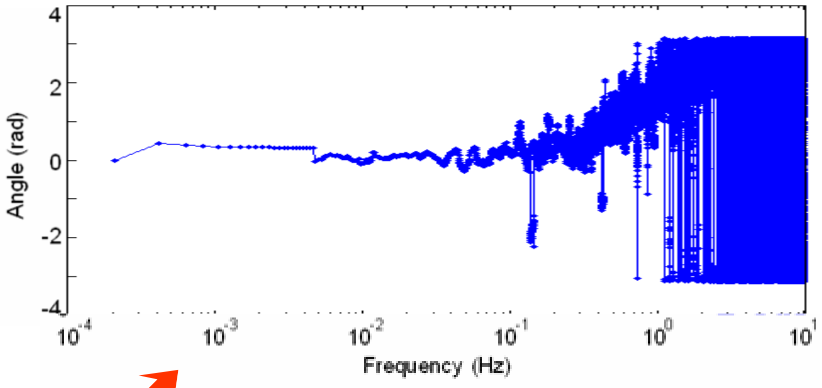
expect even-odd correlation to vanish, on average

Both Correlated and Anticorrelated Fluctuators

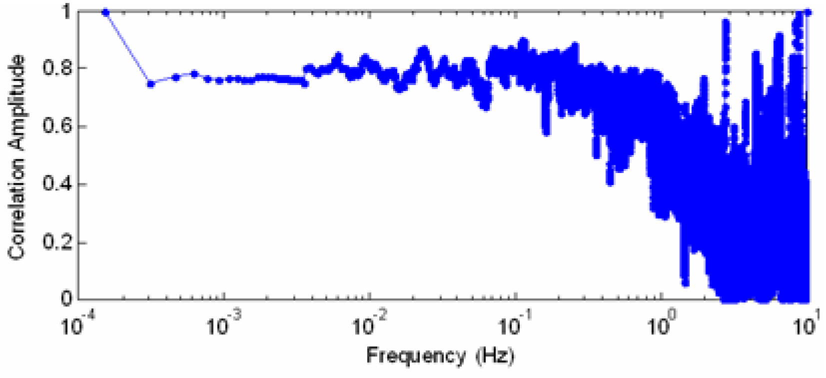
$S_{L''\Phi}$ Correlation Amplitude

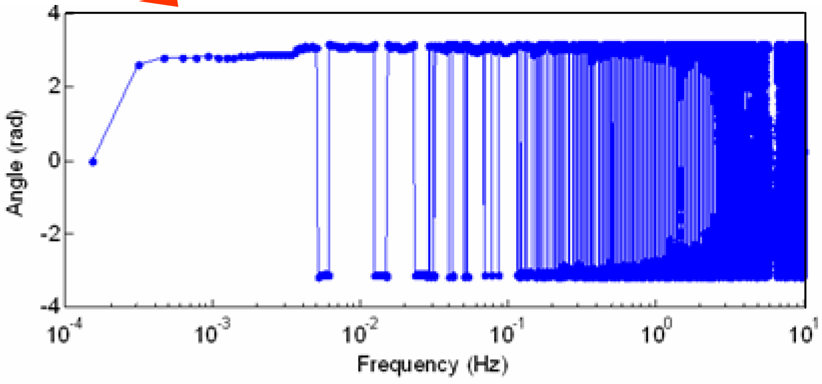
$S_{L''\Phi}$ Correlation Angle





same sample, different cooldowns



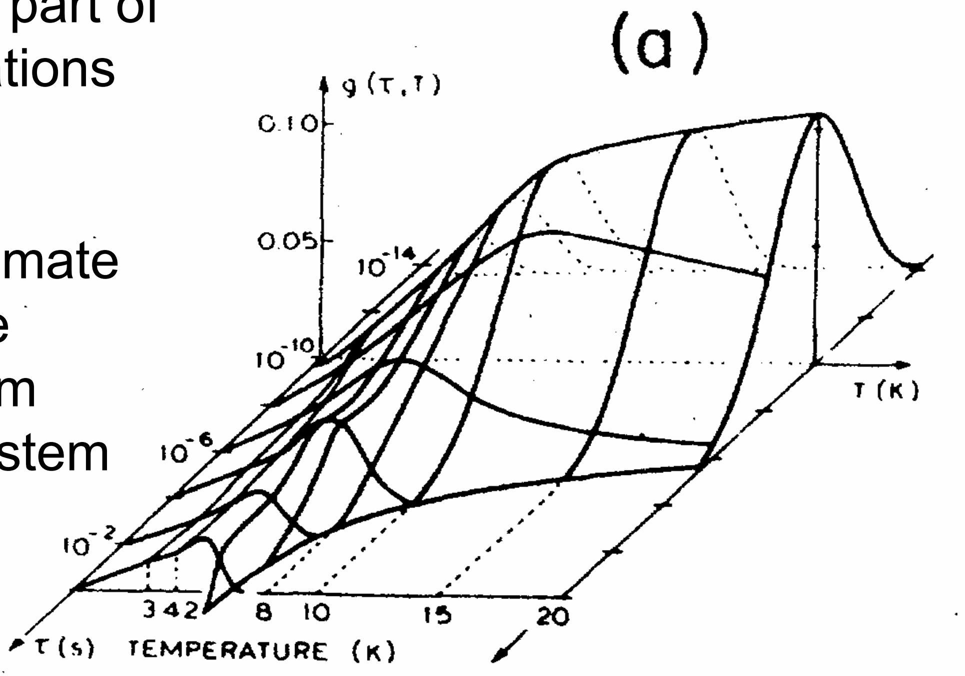


Interpretation – Evolution of Relaxation Time Distribution

-Fluctuations in the real part of the inductance indicate cooperative dynamics of spin clusters

-Fluctuations of the imaginary part of the inductance point to fluctuations in spin relaxation times

-Correlation data indicates intimate connection between flux noise and cooperative nonequilibrium dynamics of a surface spin system

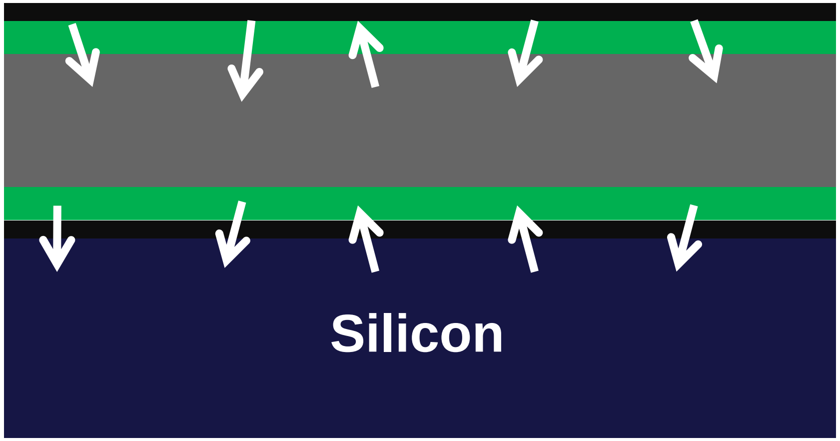


[L.E. Wenger, 1983]

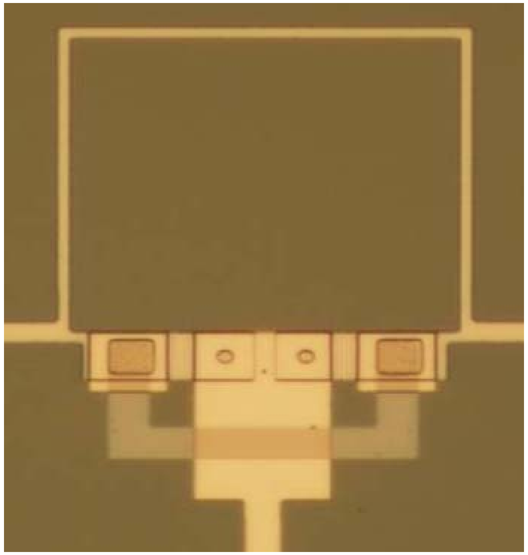
Fe Doping of SC Films

Collaboration with J. Kline, D.P. Pappas, NIST

Layer Stackup



Fe (x.xx nm)
AlOx(2nm)
Al(80nm)
AlOx(2nm)
Fe (x.xx nm)



Devices characterized to date:

1. **control sample (NIST-grown Al)**
2. **0.01 nm Fe (~ 0.05 ML, $\sigma \sim$ 5e17 m^{-2})**
3. **0.1 nm Fe (~ 0.5 ML, $\sigma \sim$ 5e18 m^{-2})**
4. **0.3 nm Fe (~ 1.5 ML, $\sigma \sim$ 1.5e19 m^{-2})**

Fe Doping of SC Films

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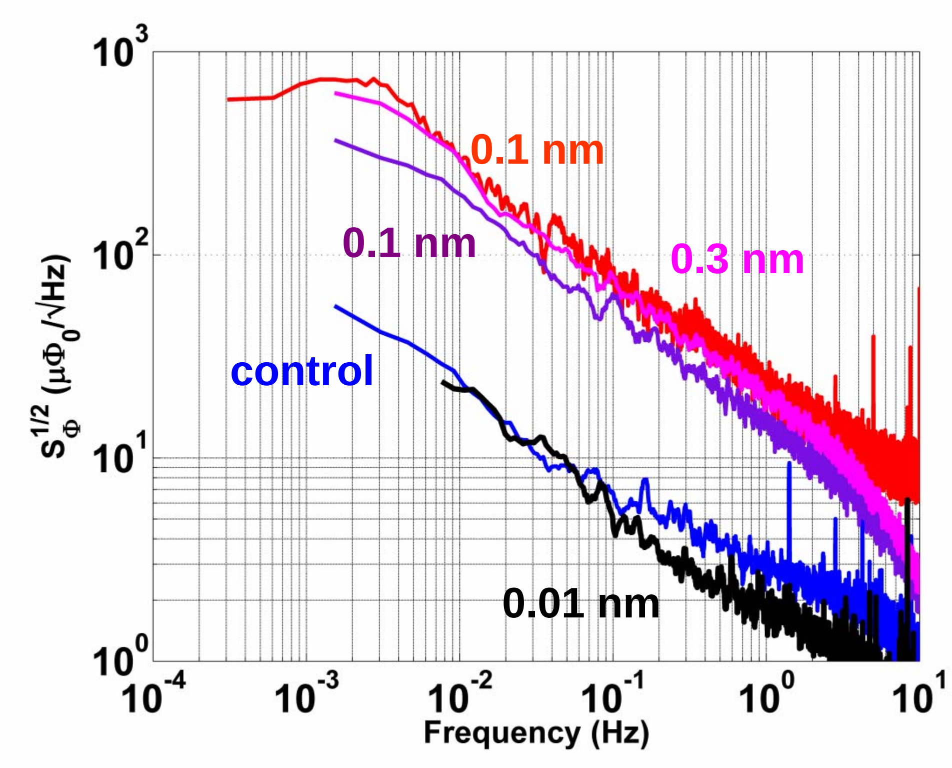

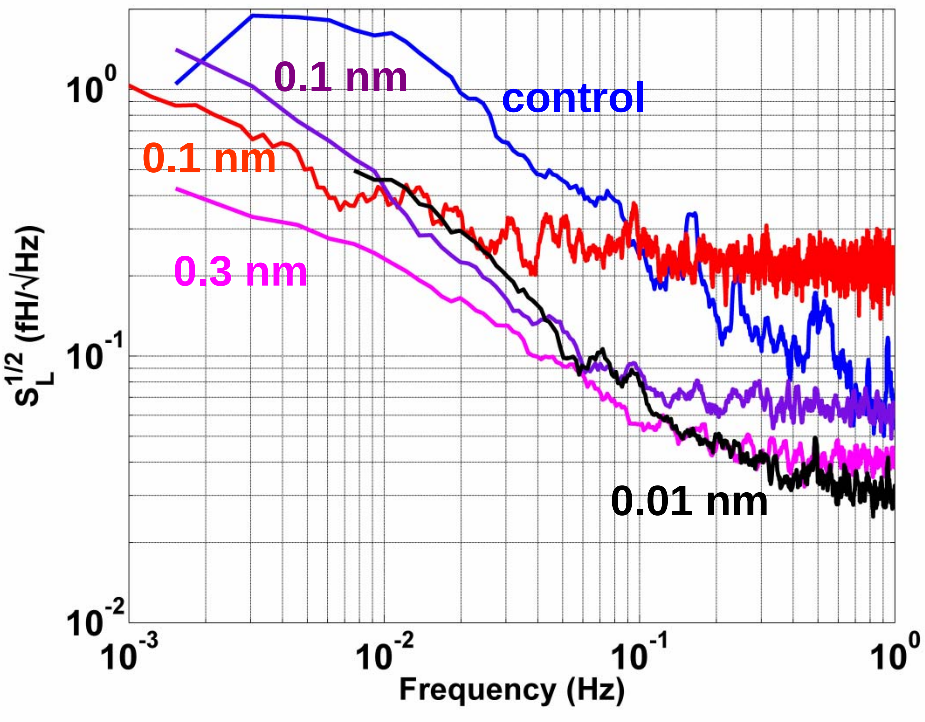

Improvement at 0.01 nm Fe doping?

Need to verify reproducibility,
perform finer scan of parameter space

Outlook and Future Work

Continued investigations of spin ordering at low temperature
Careful study of surface spin susceptibility

Refinement of theoretical models

Possible surface treatments to minimize noise and dephasing

Surprising influence of Fe, FTS doping also sheds light on underlying mechanism

Deeper understanding of *1/f* flux noise will facilitate optimization of refocusing schemes

Sendelbach *et al.* arXiv:0802.1511 (08)

Sendelbach *et al. PRL* 100, 227006 (08)

Sendelbach *et al. PRL* 103, 117001 (09)