The Unusual Behavior of

Excess Low-Frequency Flux Noise

at

Temperatures Below 1K

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Outline

I. Introduction to 1/f flux noise

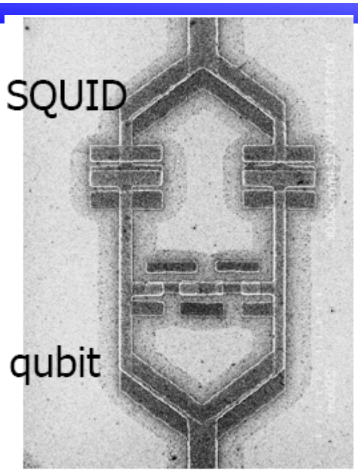
II. Experimental arrangements

III. Some basic facts about excess flux noise

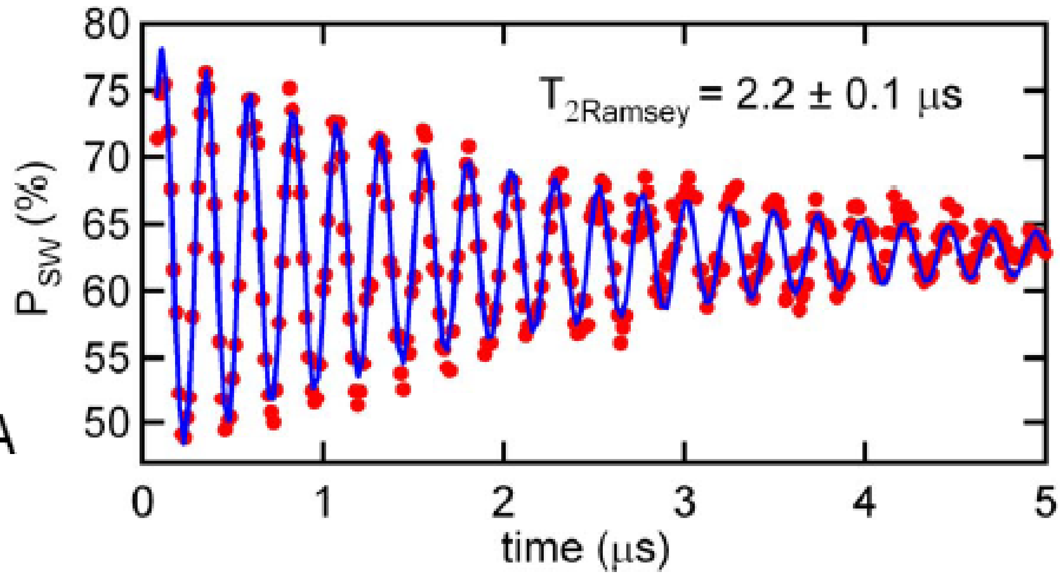
IV. Some details:
- how we know its flux noise,
- how we know the electron temperature,
- distribution of amplitudes,
- device parameters and other devices

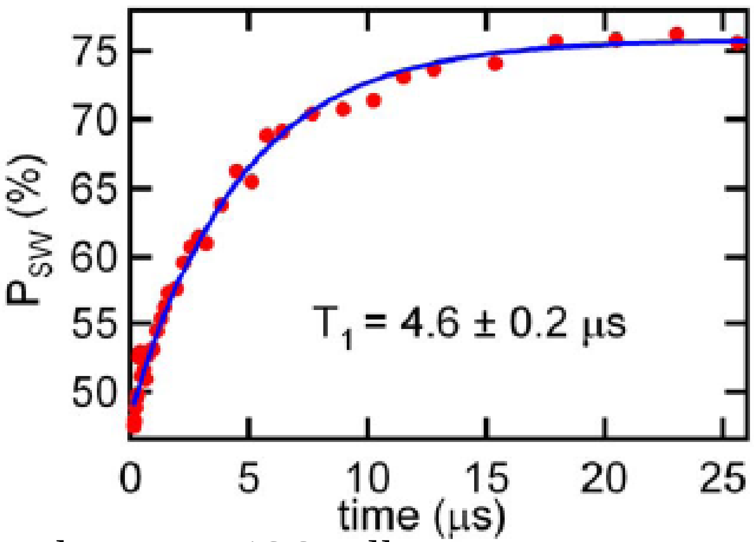
V. Conclusions

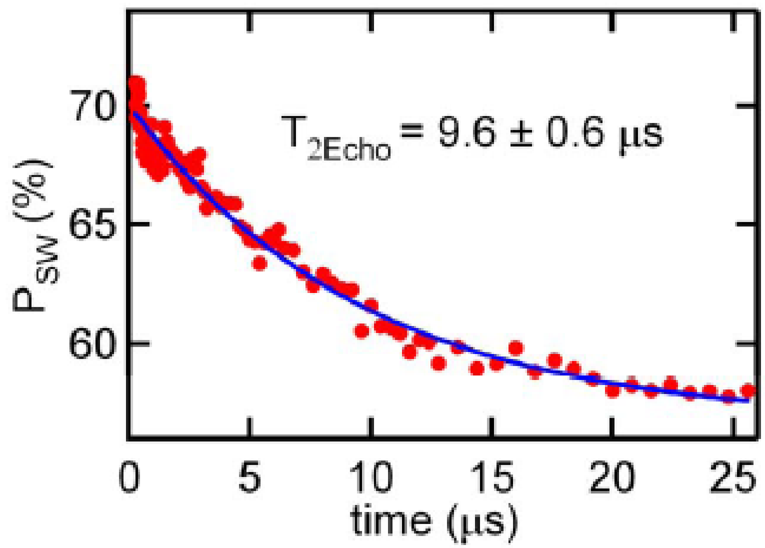
Nakamura et al. results on Flux Qubit with best coherence



Δ/h=2.557 GHz, I_P=157 nA
2.3 $\mu\Phi_0/\mathrm{Hz}^{1/2}$ @ 1Hz



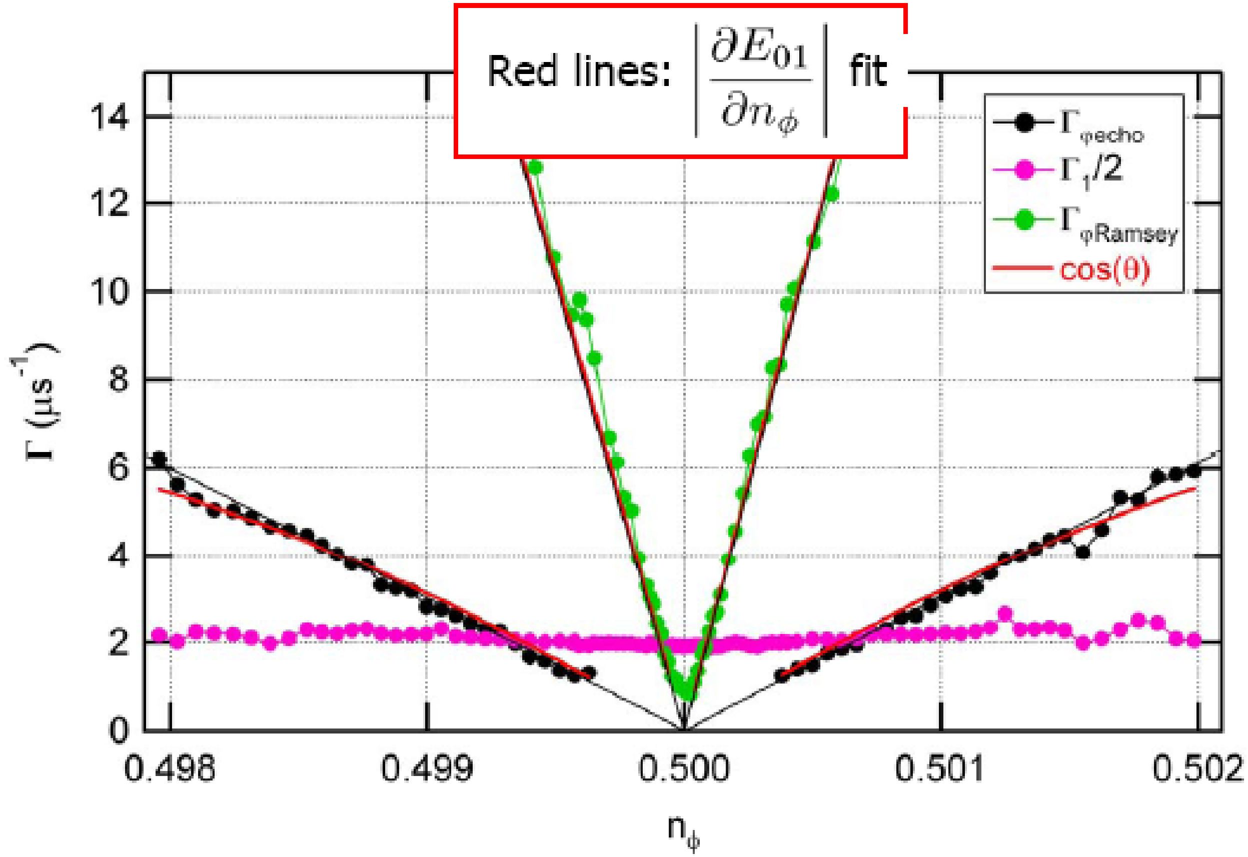




from Nakamura DiSQ talk

$\Gamma_{\varphi Ramsey}$, $\Gamma_{\varphi echo}$ vs n_ϕ : flux bias dependence

Nakamura et al



$$\frac{\Gamma_{\varphi Ramsey}}{\Gamma_{\varphi echo}} \sim 7$$

For $S_{n_\phi}(\omega) = \frac{A}{|\omega|}$ $\quad P_{echo}(t) = \exp\left(-\frac{\Gamma_1}{2}t\right)\exp\left(-\Gamma^2_{\varphi echo}t^2\right)$ $\quad \Gamma_{\varphi echo} = \frac{\sqrt{A \ln 2}}{\hbar}\left|\frac{\partial E_{01}}{\partial n_\phi}\right|$

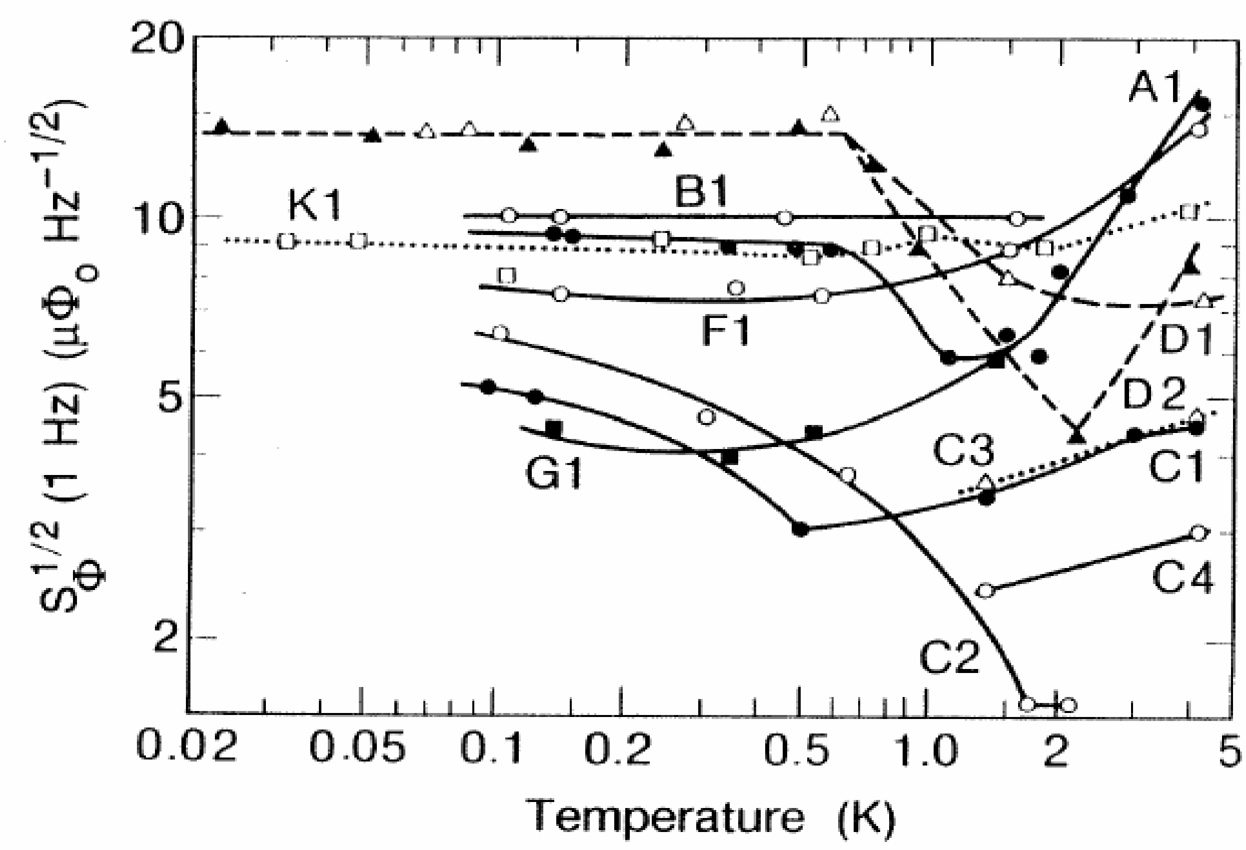
$\Rightarrow$ $A \sim (10^{-6}\Phi_0)^2$

Flux noise, not charge noise nor critical current noise

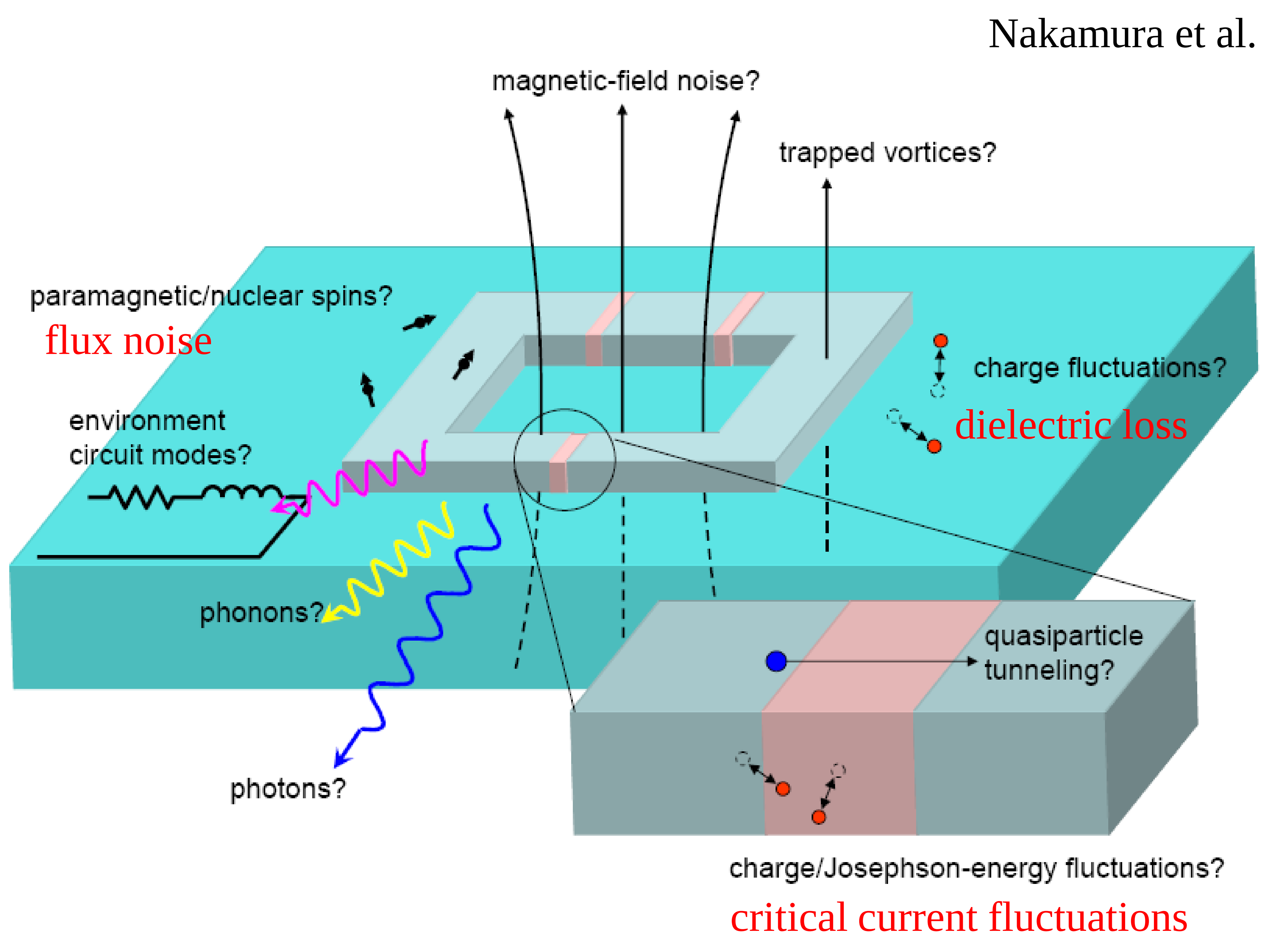
F. Yoshihara et al. PRL 97, 167001 (2006

Measured flux noise at 1Hz for several SQUIDs

"Low Frequency Noise in dc Superconducting Quantum Interference Devices Below 1K",
F. C. Wellstood, C. Urbina, and J. Clarke, Appl. Phys. Lett., 50, 772 (1987).

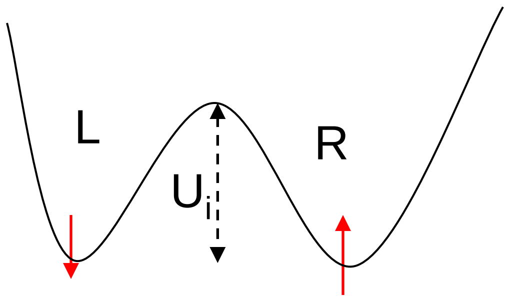


- noise **increases** as T **decreases** below 1 K and then levels off
- noise roughly independent of SQUID size
- different devices with same shape produce similar noise


Nakamura et al.
magnetic-field noise?
trapped vortices?
paramagnetic/nuclear spins?
flux noise
charge fluctuations?
dielectric loss
environment
circuit modes?
phonons?
quasiparticle
tunneling?
photons?
charge/Josephson-energy fluctuations?
critical current fluctuations

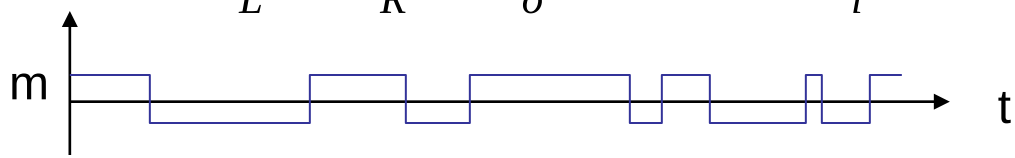
The accepted explanation for 1/f noise (Dutta and Horn)

(1) Assume many two-level (magnetic dipole) fluctuators with equal well depths



(2) suppose that each system fluctuates randomly between L and R with mean lifetime:

$$\tau_L = \tau_R = \tau_o e^{U_i/kT} = 2\tau_i$$



(3) The magnetic moment of each fluctuator gives telegraph noise that produces a (1-sided) power spectrum (Machlup, J.A.P. 1954)):

$$S_{mi}(f) = \frac{4\sigma_m^2 \tau_i}{1+\omega^2\tau_i^2}$$ Lorentzian spectrum

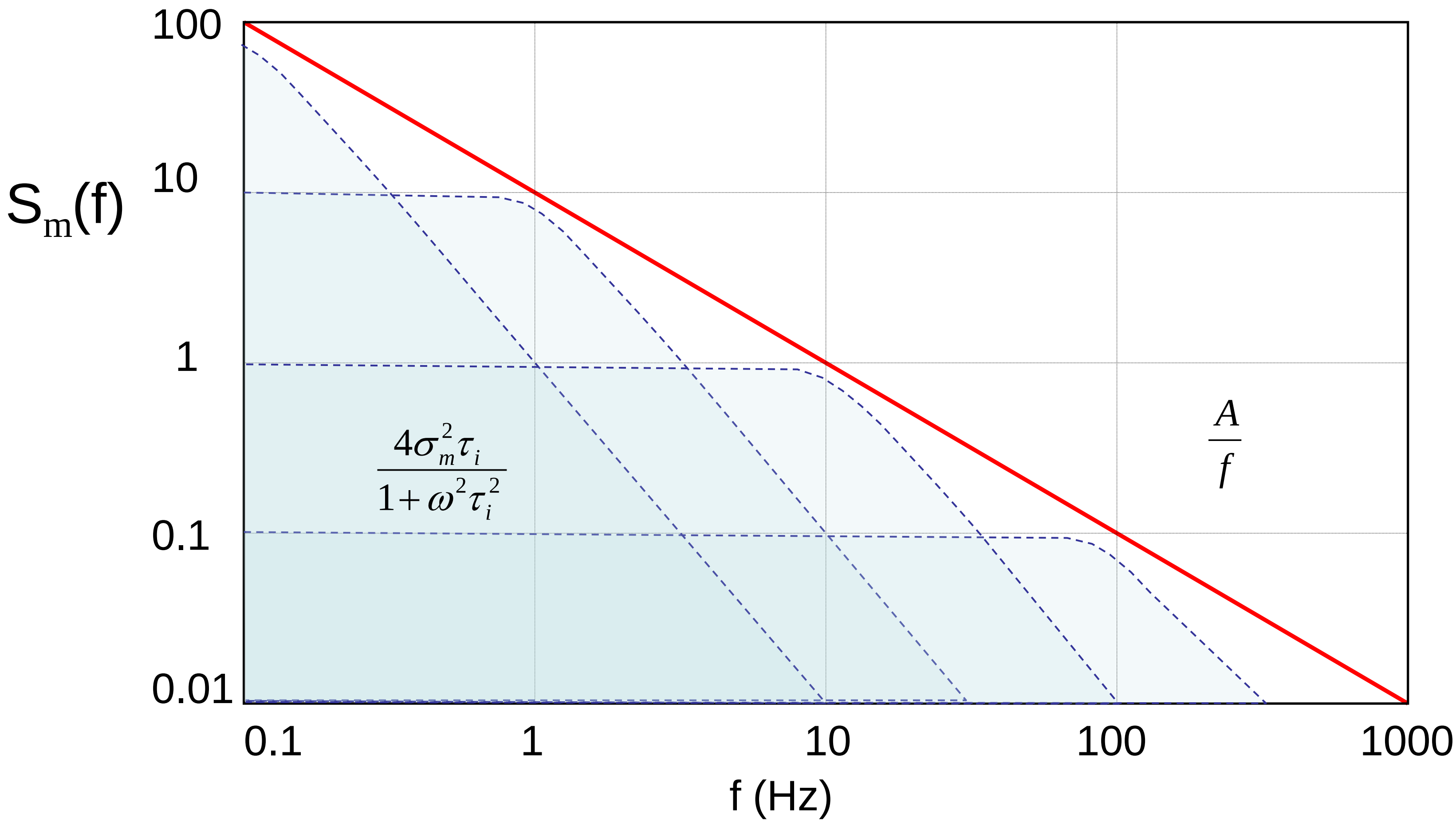
Note that: the mean square standard deviation in the magnetic moment from the i-th fluctuator is:

$$\sigma_m^2 = \int_0^\infty S_{mi}(f)df = \int_0^\infty \frac{4\sigma_m^2\tau_i}{1+\omega^2\tau_i^2}df = \frac{4\sigma_m^2}{2\pi}\int_0^\infty \frac{2\pi\tau_i\, df}{1+\omega^2\tau_i^2}$$

$$= \frac{2\sigma_m^2}{\pi}\int_0^\infty \frac{dy}{1+y^2} = \frac{2\sigma_m^2}{\pi}\left(a\tan(\infty) - a\tan(0)\right) = \sigma_m^2$$

independent of τ_i

The accepted explanation for 1/f noise (Dutta and Horn)



need equal number of Lorentzians in each decade of frequency or to get 1/f

…… $D(\tau)d\tau \sim \frac{d\tau}{\tau}$

(4) Assume that there is a uniform distribution of barriers U, *i.e.* D(U) dU = C” dU

notice that $U = kT\ln\left(2\tau/\tau_o\right)$ $D(\tau) = D(U)\dfrac{dU}{d\tau} = \dfrac{C''kT}{\tau}$

(5) The total noise spectrum is

$$S_m^{tot}(f) = \int_0^{\infty} S_{mi}(f)D(U)dU = 4\sigma_m^2 C''\int_0^{\infty}\frac{\tau_i}{1+\omega^2\tau_i^2}dU$$

Now substitute: $\tau = \dfrac{\tau_o}{2}e^{U/kT}$

and find: $$S_m^{tot}(f) = 4\sigma_m^2 C''\int_0^{\infty}\frac{\dfrac{\tau_o}{2}e^{U/kT}}{1+\omega^2\dfrac{\tau_o^2}{4}e^{2U/kT}}dU$$

change variables to $y = \dfrac{\omega\tau_o}{2}e^{U/kT}$

1/f noise goes away as T decreases

$$S_m^{tot}(f) = \frac{4\sigma_m^2 C''kT}{\omega}\int_0^{\infty}\frac{\dfrac{\omega\tau_o}{2}e^{U/kT}}{1+\omega^2\dfrac{\tau_o^2}{4}e^{2U/kT}}\frac{dU}{kT} = \frac{4\sigma_m^2 C''kT}{\omega}\int_0^{\infty}\frac{dy}{1+y^2} = \boxed{\frac{\sigma_m^2 C''kT}{f}}$$

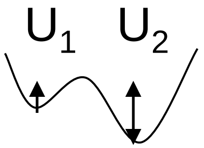
(4) Assume that there is a uniform distribution of barriers U, *i.e.* D(U) dU = C" dU

notice that $U = kT\ln(2\tau/\tau_o)$ $\qquad D(\tau) = D(U)\dfrac{dU}{d\tau} = \dfrac{C''kT}{\tau}$

(5) The total noise spectrum is

expected noise to scales as T/f, which is not seen!

Kenyon et al. found T^2/f for uniform distribution of well barrier heights and well asymmetry…



T^2/f or T/f works well for critical current noise, charge noise and might explain flux noise above 1 K but not below 1 K

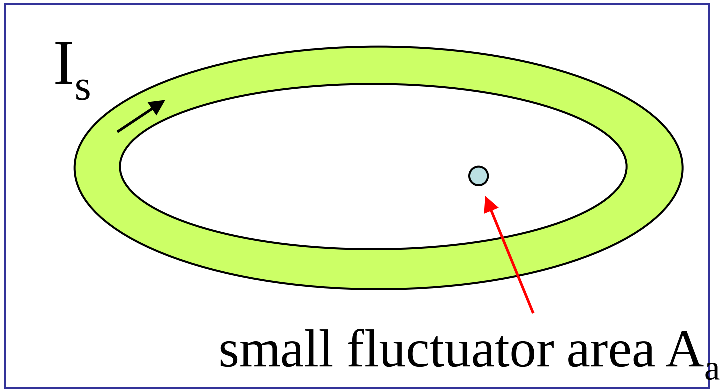
playing around with D(U) can yield different slopes, but the temperature dependence doesn't look like data

$$S_m^{tot}(f) = \frac{4\sigma_m^2 C''kT}{\omega}\int_0^\infty \frac{\frac{\omega\tau_o}{2}e^{U/kT}}{1+\omega^2\frac{\tau_o^2}{4}e^{2U/kT}}\frac{dU}{kT} = \frac{4\sigma_m^2 C''kT}{\omega}\int_0^\infty \frac{dy}{1+y^2} = \boxed{\frac{\sigma_m^2 C''kT}{f}}$$

Flux noise power from fluctuators uniformly spread in 3D

consider flux coupled into i-th small loop when current I_s flows in SQUID

$$\Phi_{sa} = I_s M_i = \overline{B}_s(r,r') \cdot \overline{A}_a$$



mutual inductance between SQUID and i-th small loop $\Rightarrow$ $M_i = \dfrac{\overline{B}_s(r,r') \cdot \overline{A}_a}{I_s}$

Flux coupled into SQUID by i-th small loop is:

$$\Phi_i = M_i I_a = \frac{\overline{B}_s(r,r') \cdot \overline{A}_a}{I_s} I_a$$

Let $I_a=|I_a|\sigma$, where $\sigma=+/-1$.
Flux noise power spectral density from current fluctuating in i-th small loop

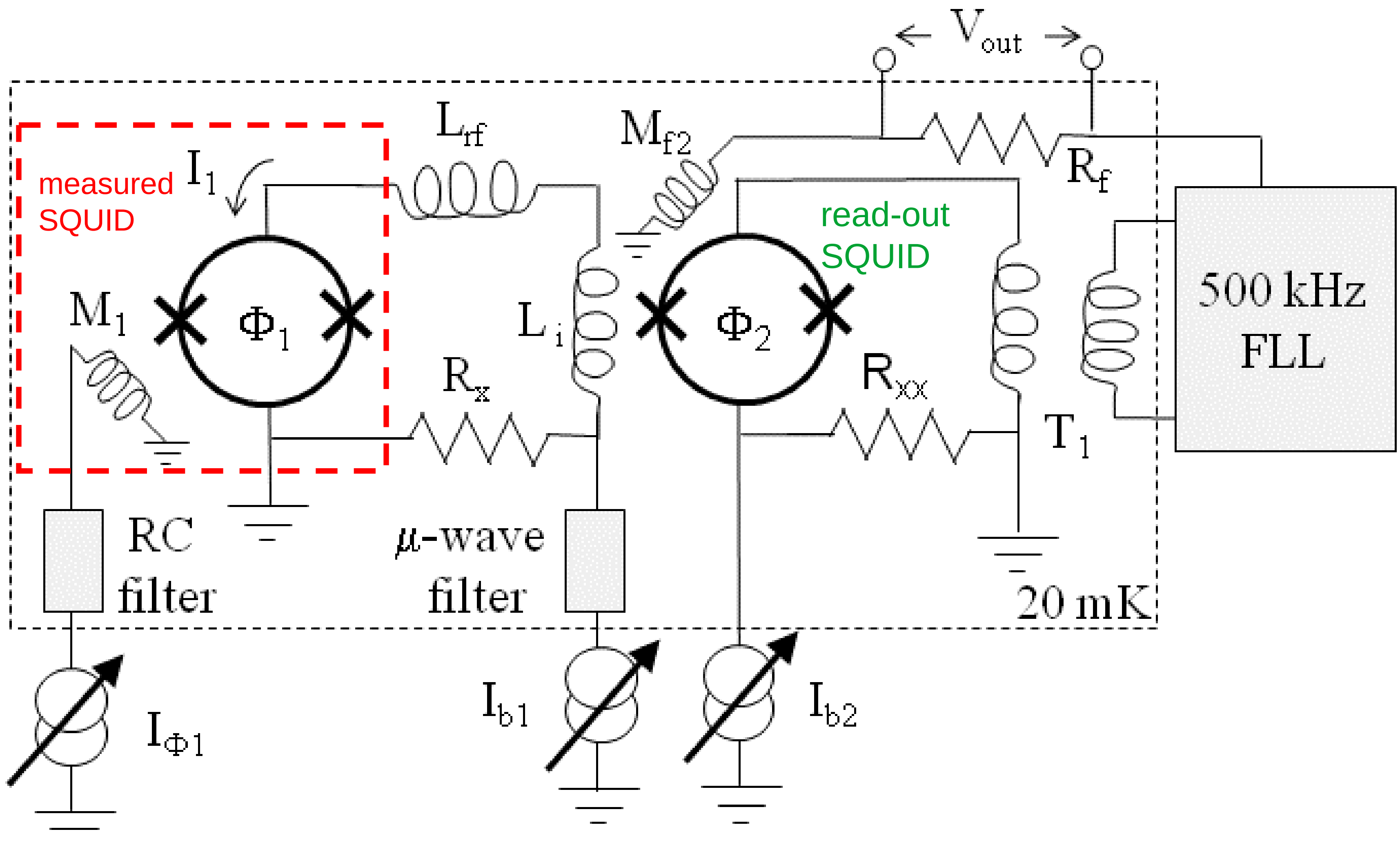
$$S_{\Phi i}(f) = \left[\frac{\overline{B}_s(\bar{r},\bar{r}') \cdot \overline{A}_{aj}}{I_s}\right]^2 I_a^2 S_{\sigma i}(f)$$

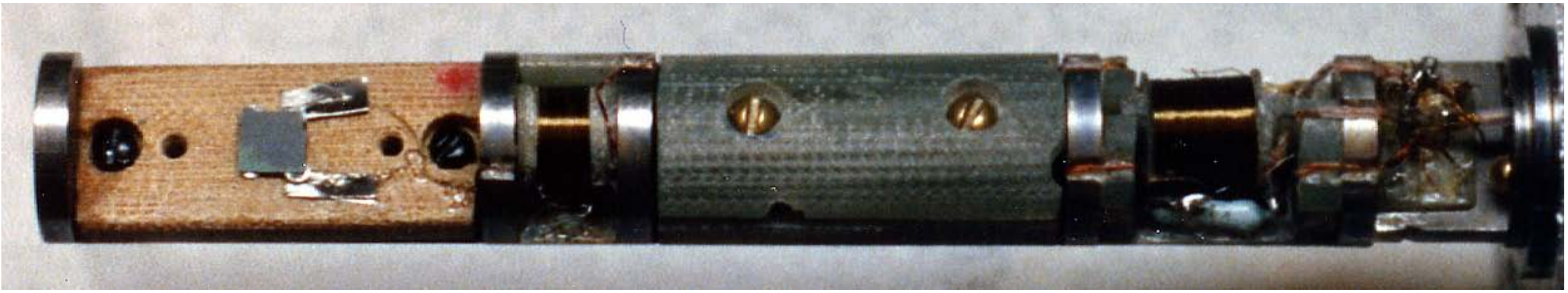
Total flux noise power spectral density from all small loops in half-space below the SQUID

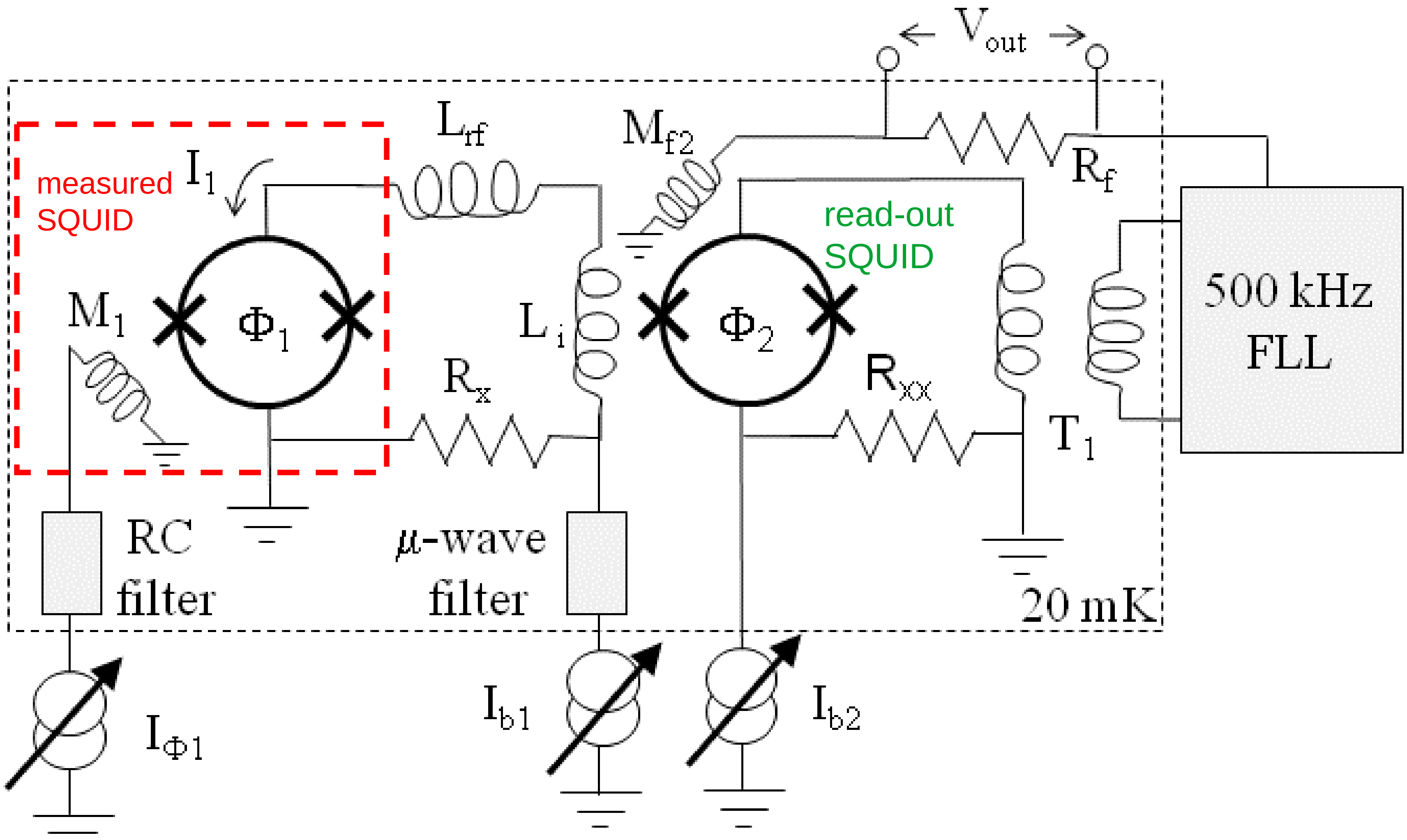
$$S_\Phi = \sum_{i=1}^{N} S_{\Phi i} = \frac{1}{2}\int\left[\frac{\overline{B}_s(\bar{r},\bar{r}') \cdot \overline{A}_{aj}(\bar{r}')}{I_s}\right]^2 I_a^2 S_{\sigma i} n dV'$$

$$= \frac{n}{2}\left(\frac{I_a A_a}{I_s}\right)^2 \left(\int \left|\overline{B}_s(\bar{r},\bar{r}')\right|^2 \left\langle \cos^2(\theta(\bar{r}'))\right\rangle dV'\right) S_{\sigma i} = \boxed{\frac{1}{6} n \mu_o \mu_B^2 L \left\langle S_\sigma \right\rangle}$$

Flux noise measurement technique

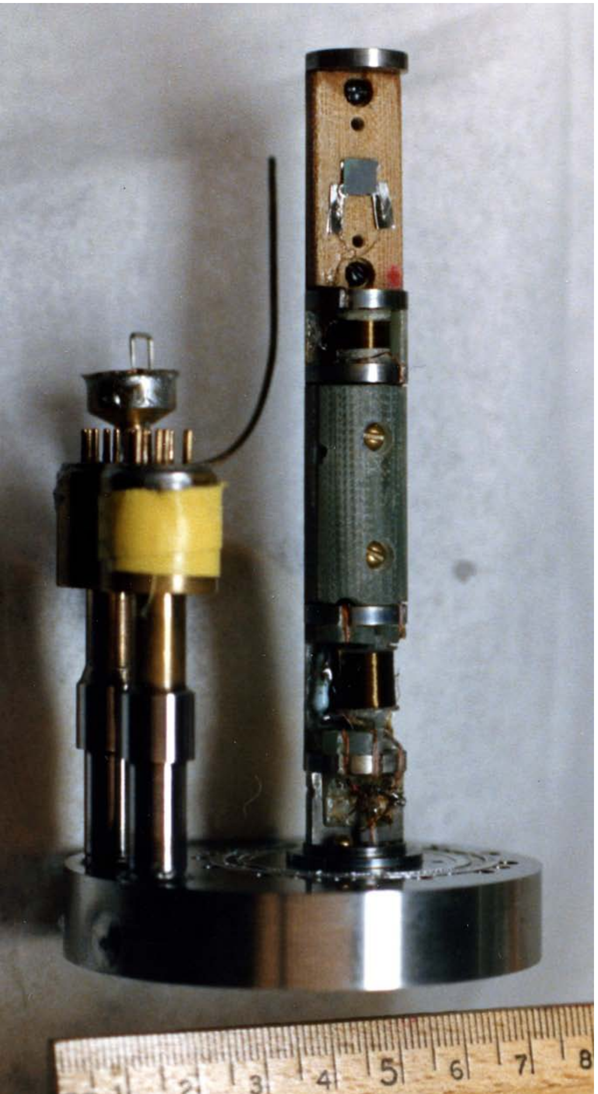


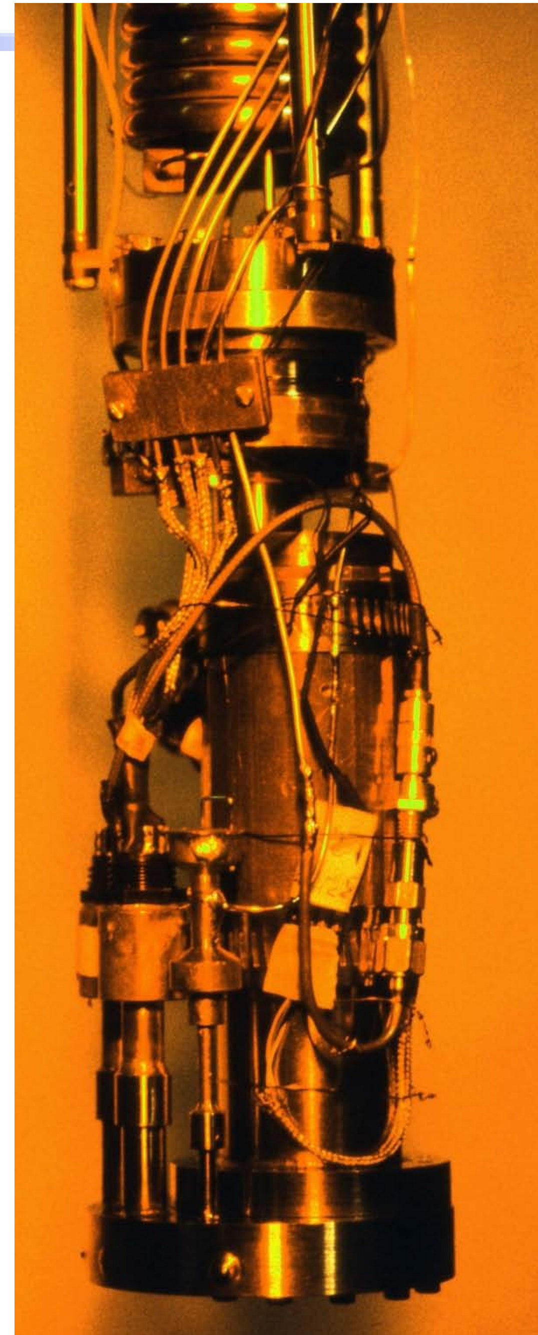




V out
measured SQUID
I1
L rf
M f2
R f
read-out SQUID
M1
Φ1
L i
Φ2
R x
R xx
T1
500 kHz FLL
RC filter
μ-wave filter
20 mK
I b1
I b2
I Φ1

Flux noise measurement technique





Surround cell with:

Vaccum can

aluminum dewar

2 mu-metal cylinders

cu-mesh shielded room

in second basement lab

Cell filled with liquid helium
Measurements made from 4.2 K to 0.02 K,

on shunted SQUIDs in the continuously running state (Power ~ few pW),

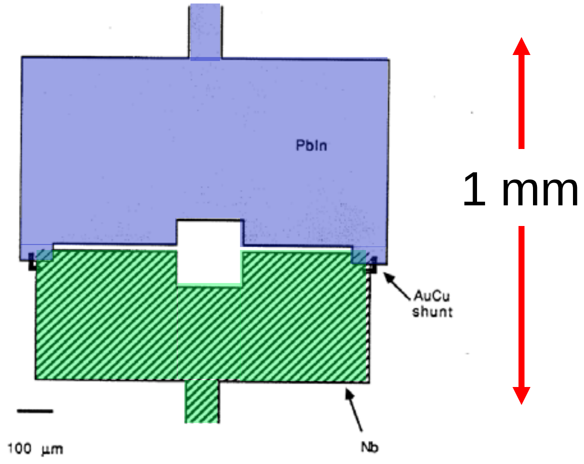
in low-field,

in '84-87

Clarke’s dilution refrigerator lab - Second Basement of Birge Hall ~1985

Nb/NbOx/PbIn SQUID

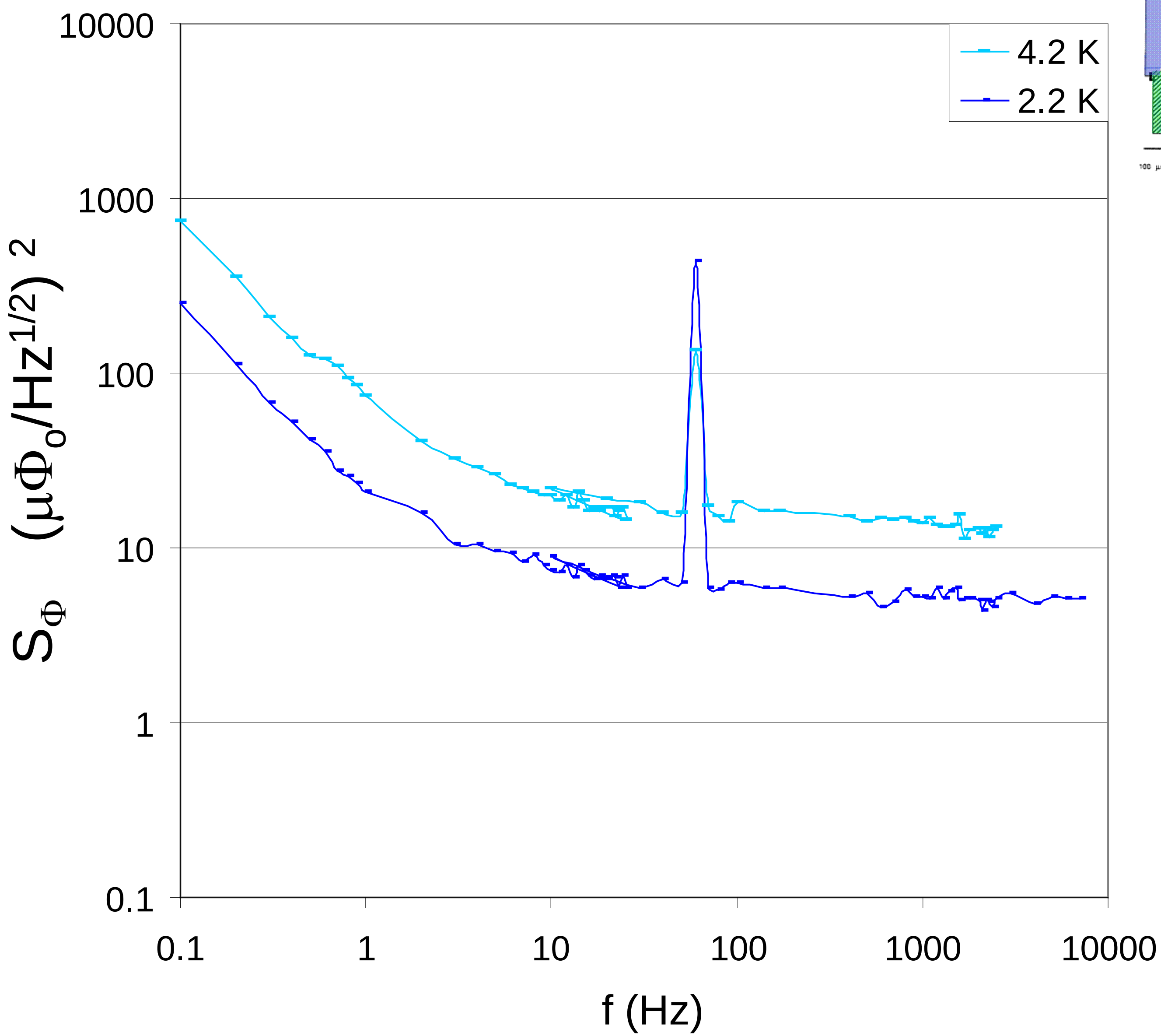
Type D

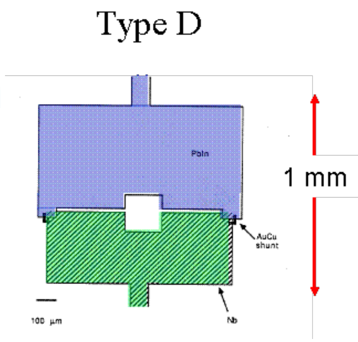


Typical Fabrication Procedure:

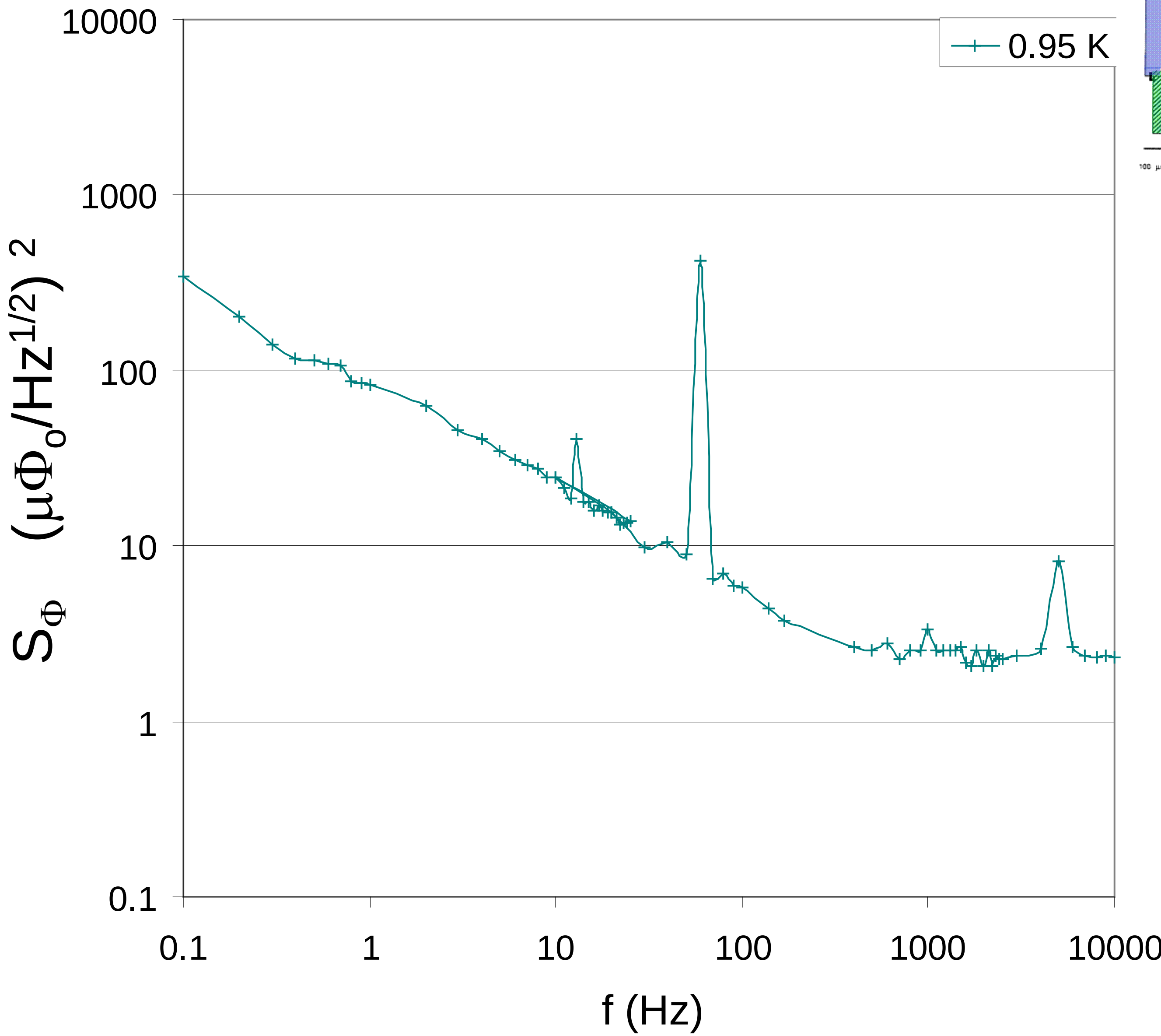
1) Clean 2” wafer (Si, Oxidized Si, or sapphire), pattern photoresist, deposit Cr or Ti and then AuCu, liftoff in acetone
2) clean, sputter Nb
   pattern photoresist
   plasma etch in SF6O2
3) clean, pattern photoresist
   deposit Cr or Ti and then SiO,
   liftoff in acetone
4) clean, pattern photoresist
   deposit Cr or Ti and then SiO
   liftoff in acetone
5) clean, pattern photoresist
6) Dice wafer into 5 mm chips
7) Use Ar-Ion mill to clean Nb surface,
   transfer chip in air to oxidation chamber,
   oxidize in Ar+O2 plasma
   evaporate Pb+ 5%In
   liftoff in acetone

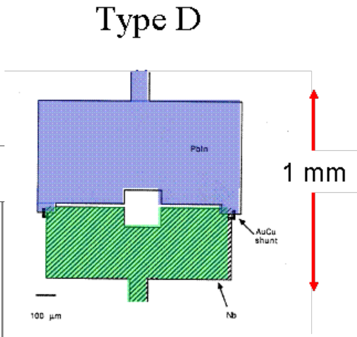
Flux noise spectrum: SQUID D2



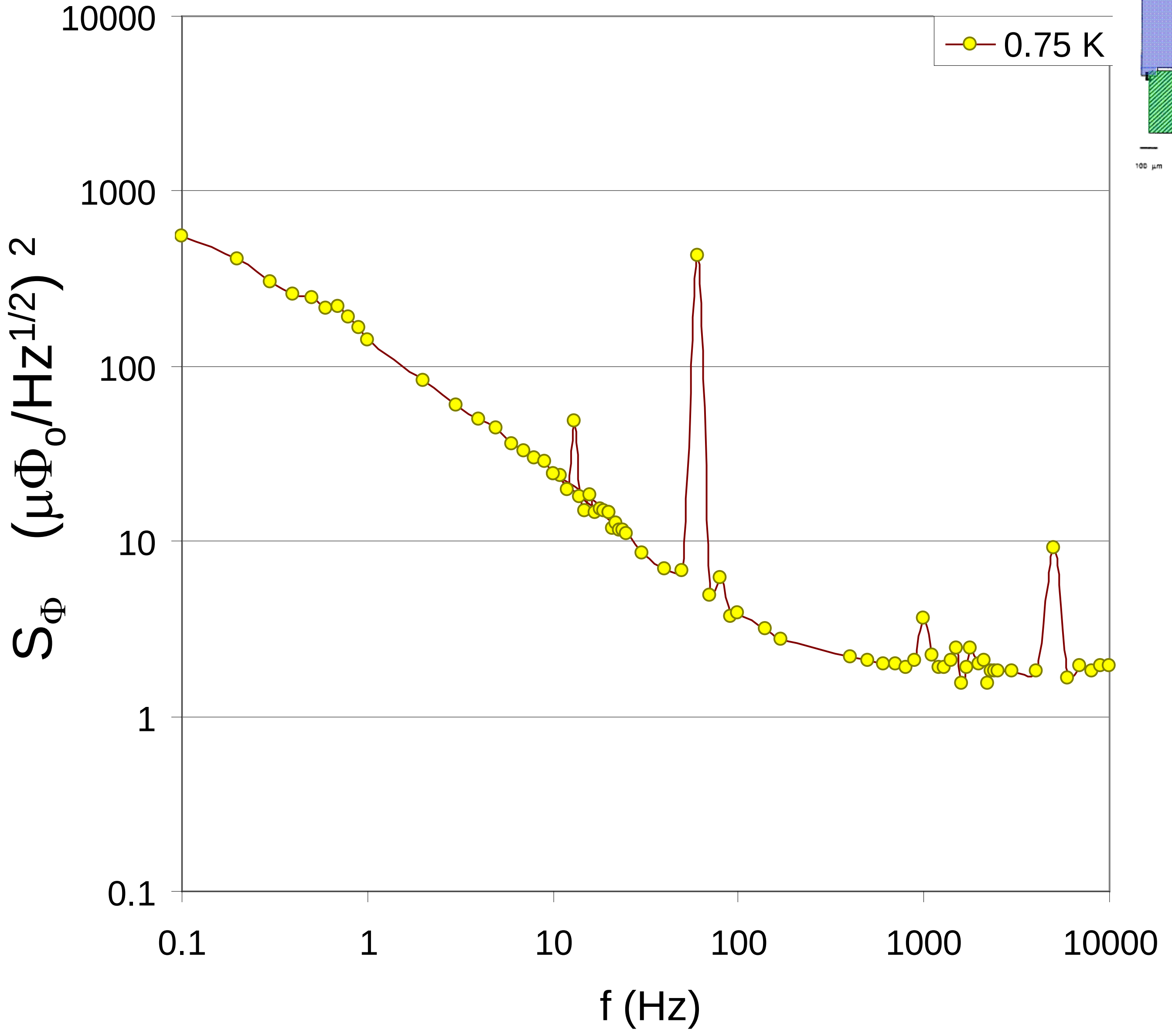


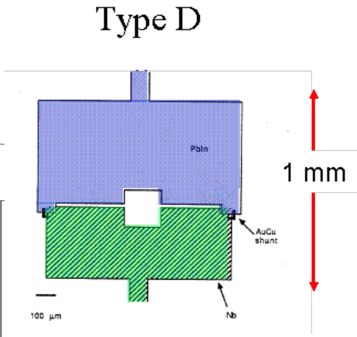
Flux noise spectrum: SQUID D2



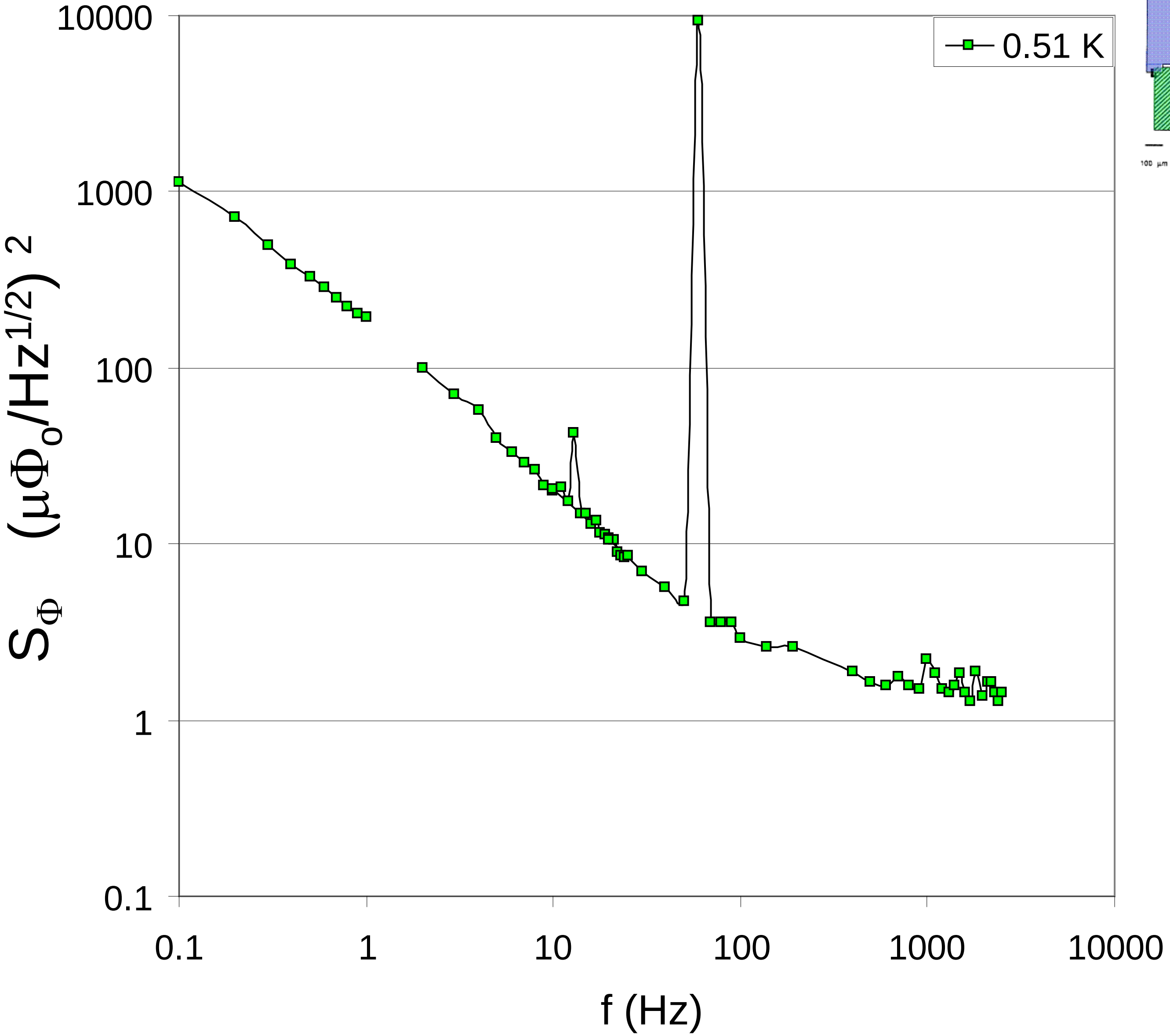


Flux noise spectrum: SQUID D2

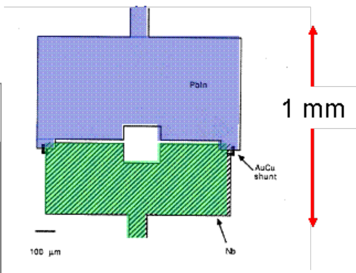




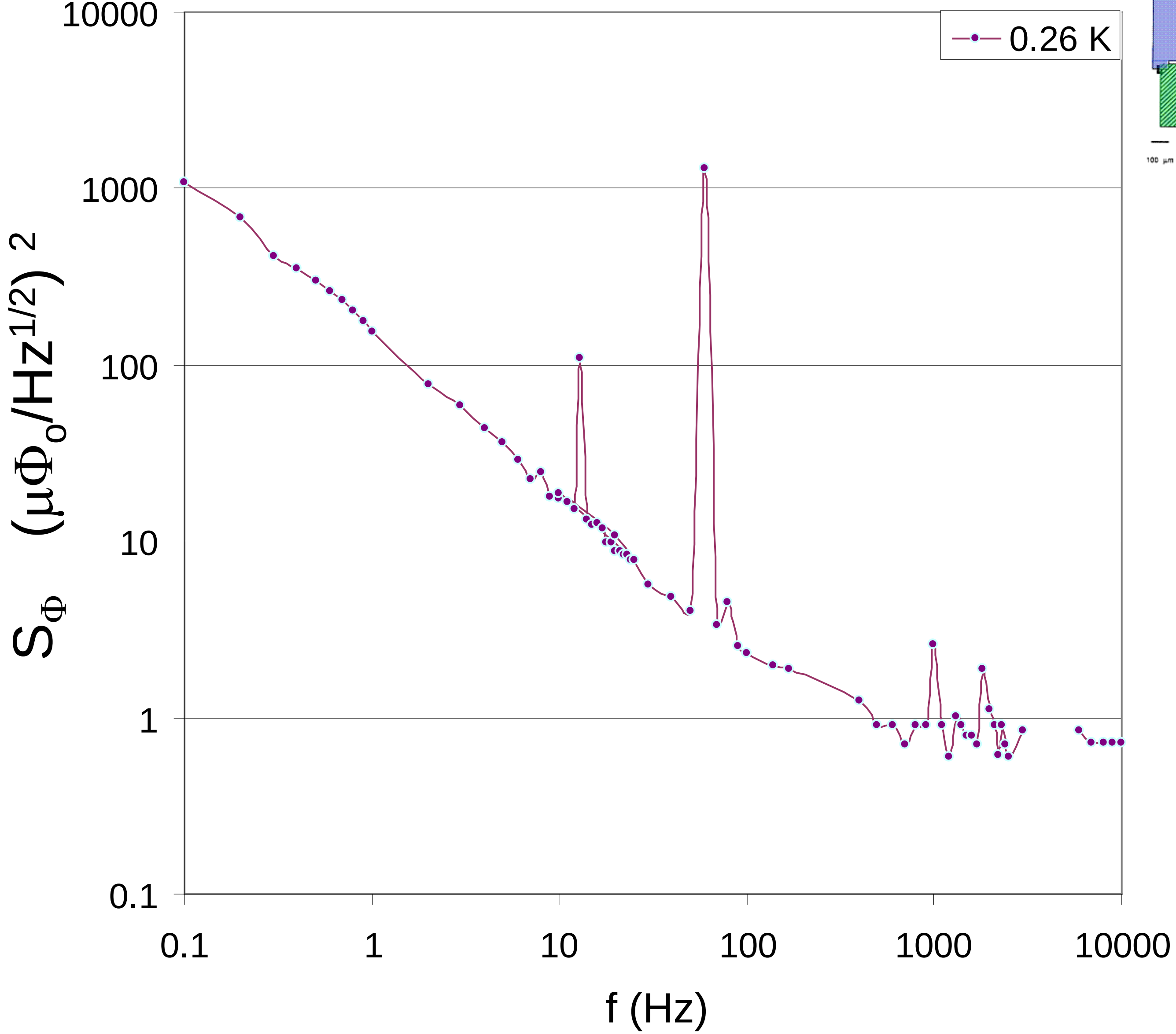
Flux noise spectrum: SQUID D2

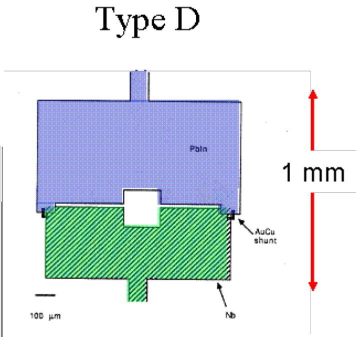


Type D

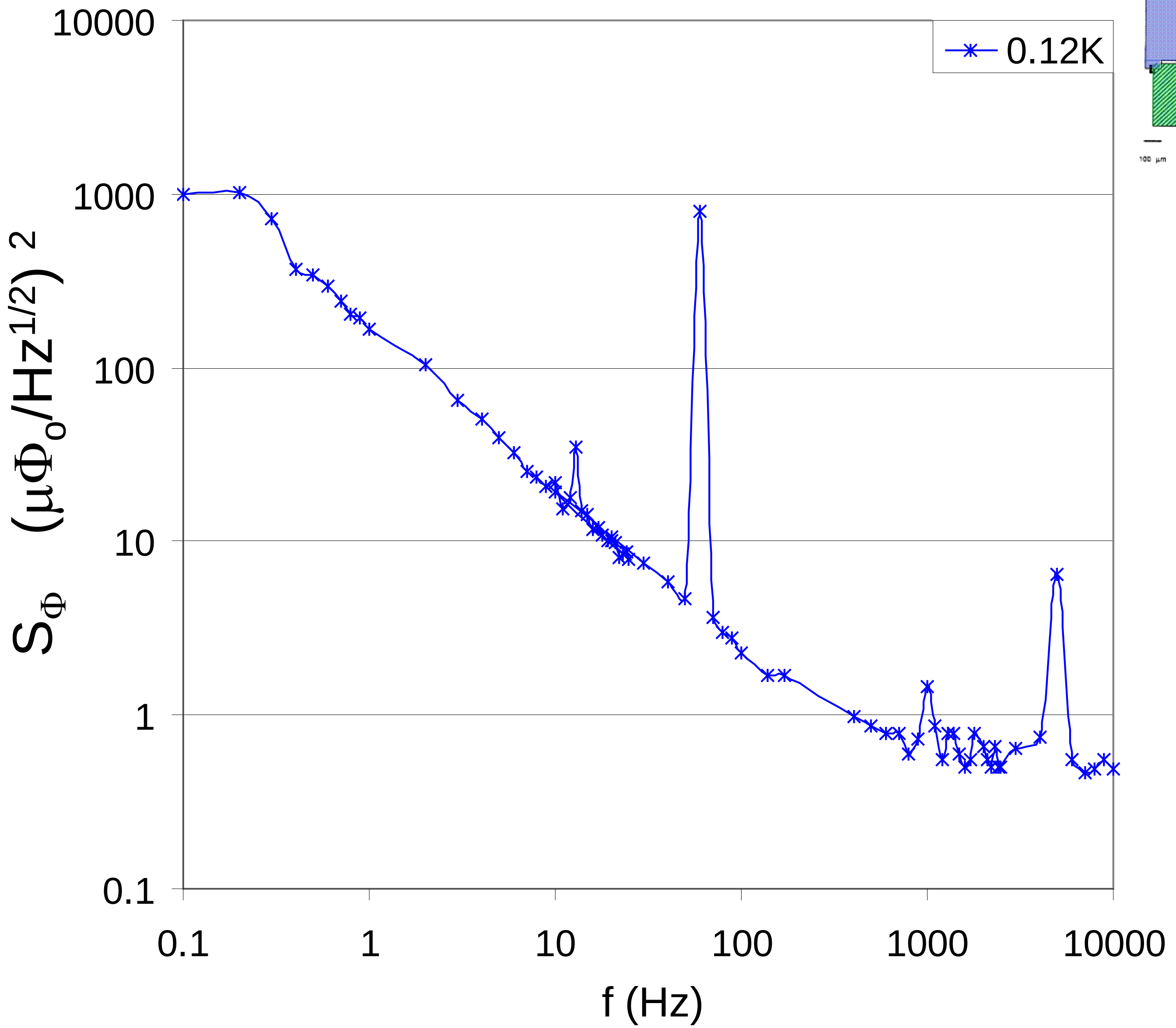


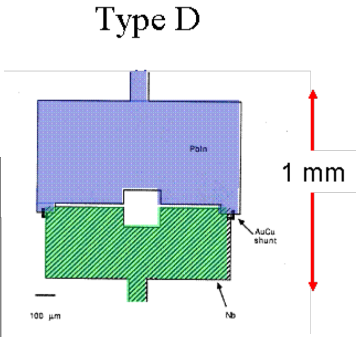
Flux noise spectrum: SQUID D2



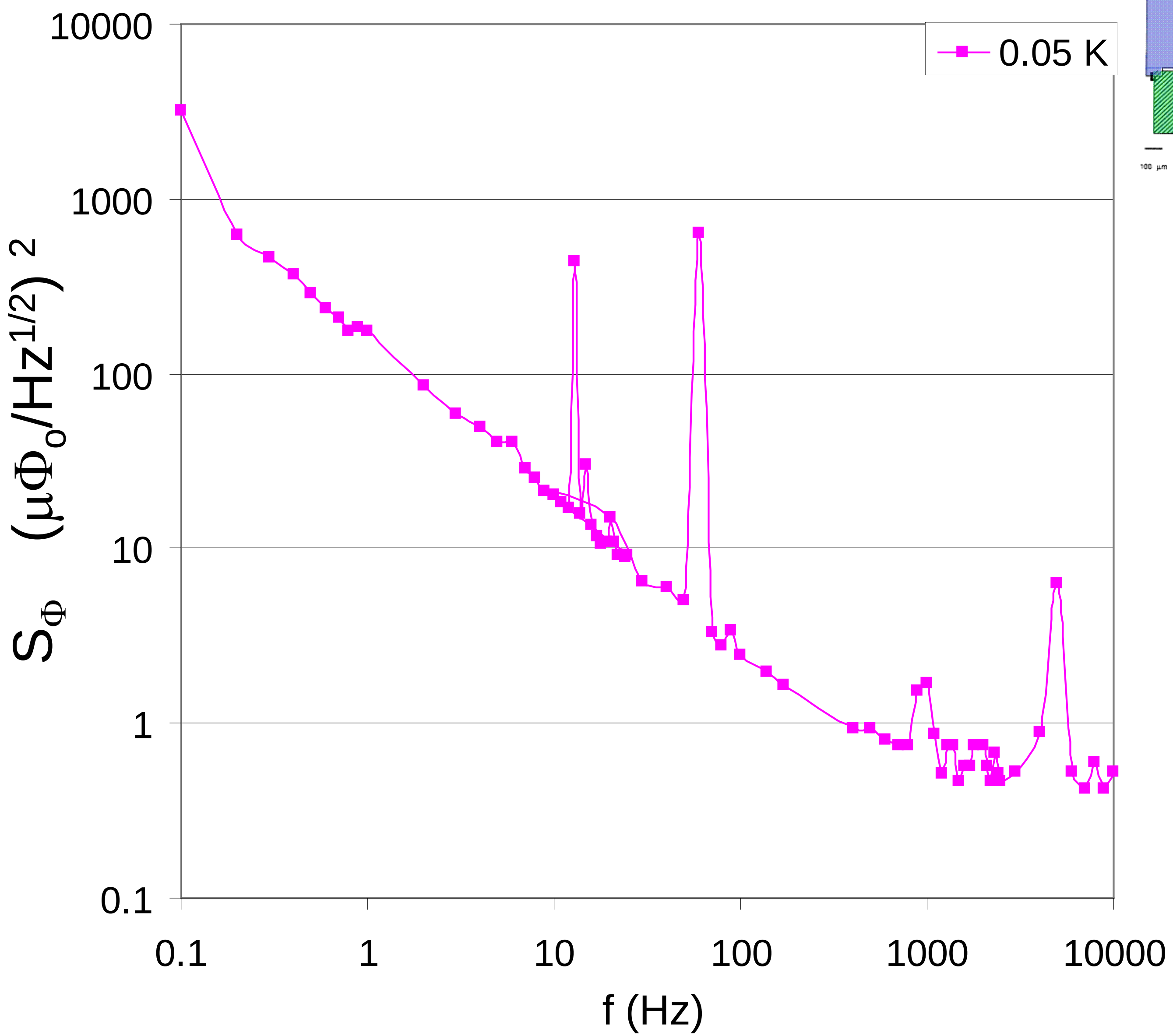


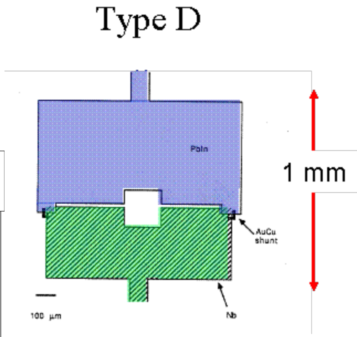
Flux noise spectrum: SQUID D2



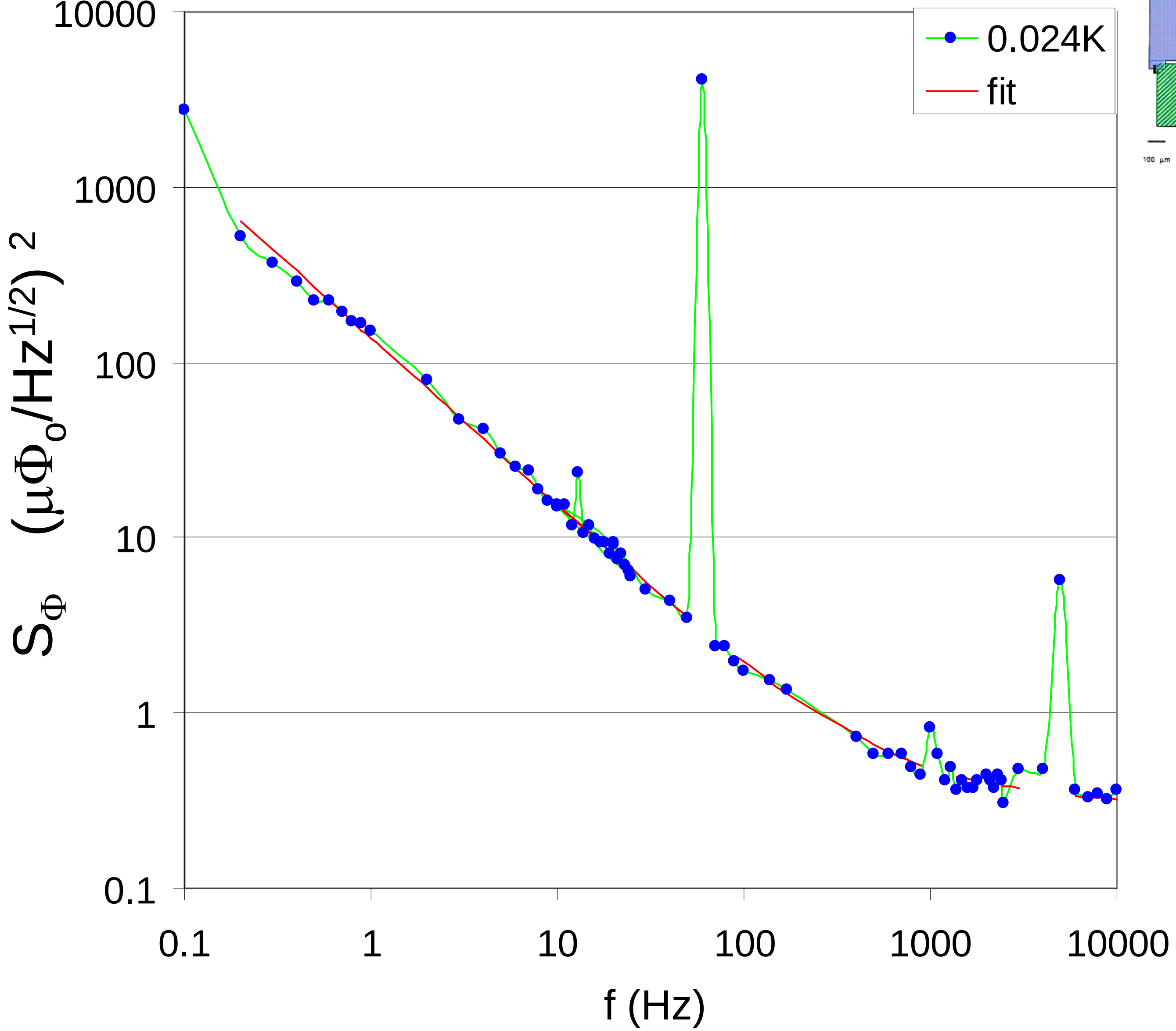


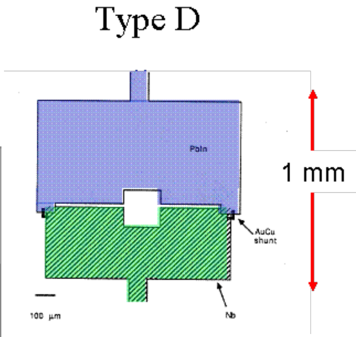
Flux noise spectrum: SQUID D2



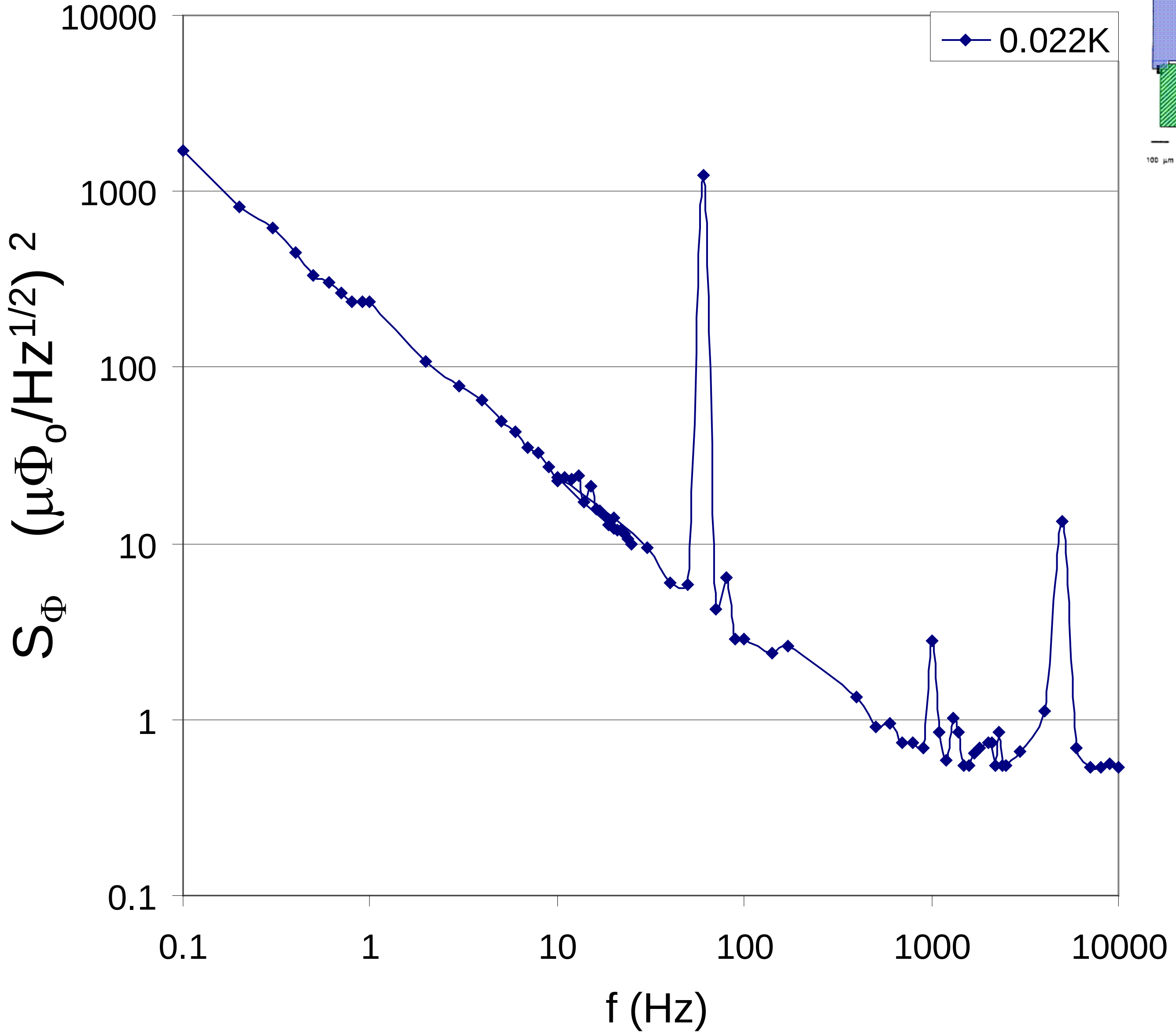


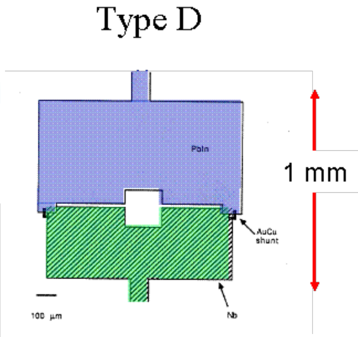
Flux noise spectrum: SQUID D2



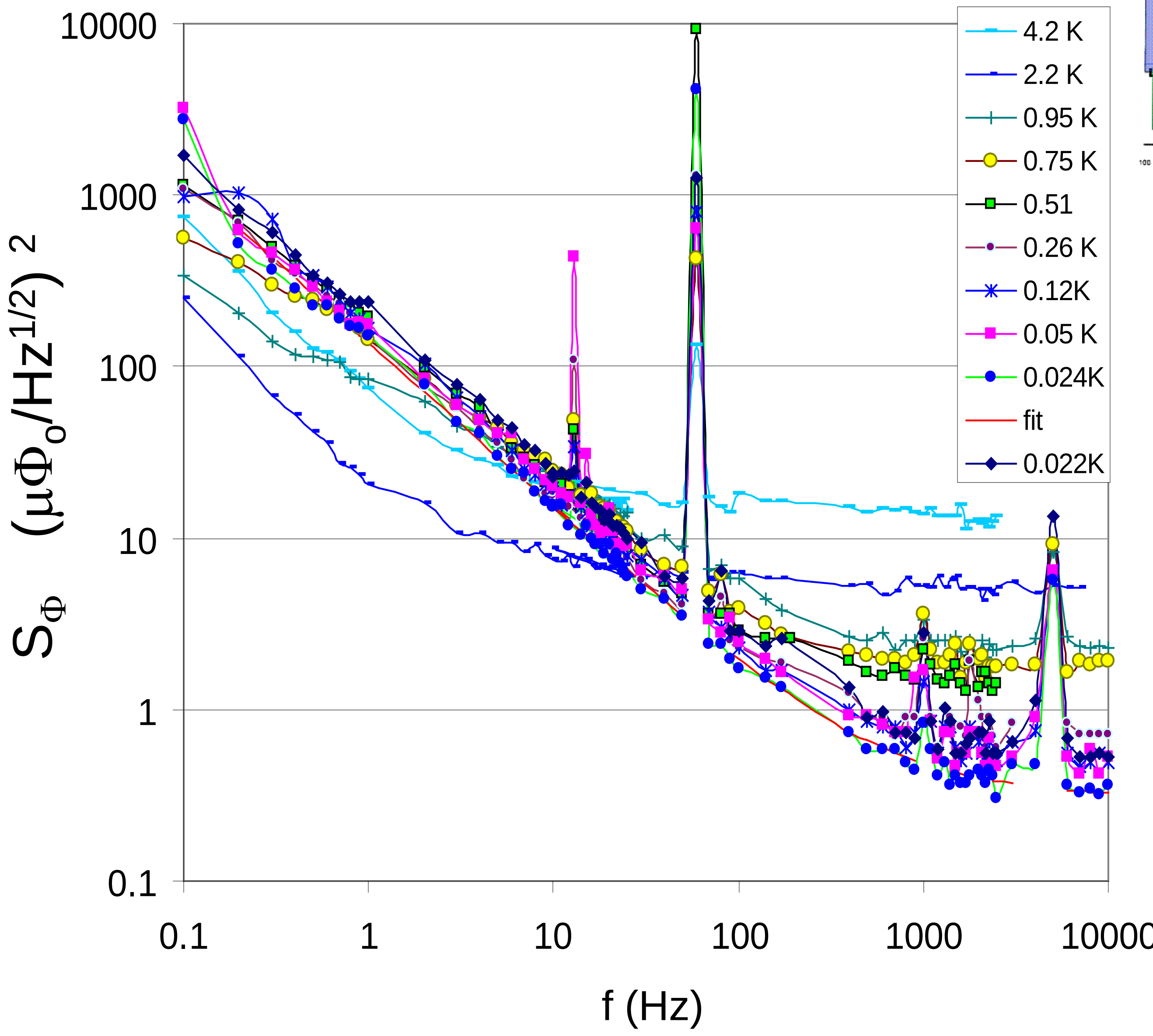


Flux noise spectrum: SQUID D2

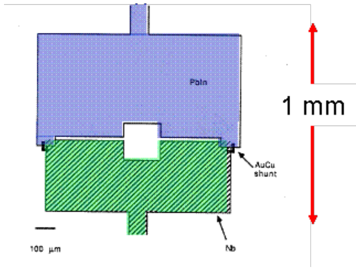




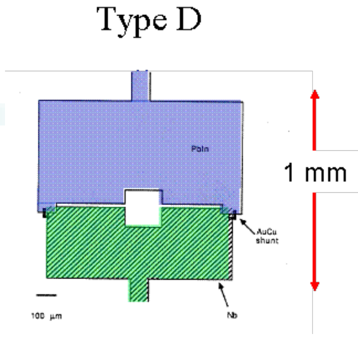
Flux noise spectrum: SQUID D2

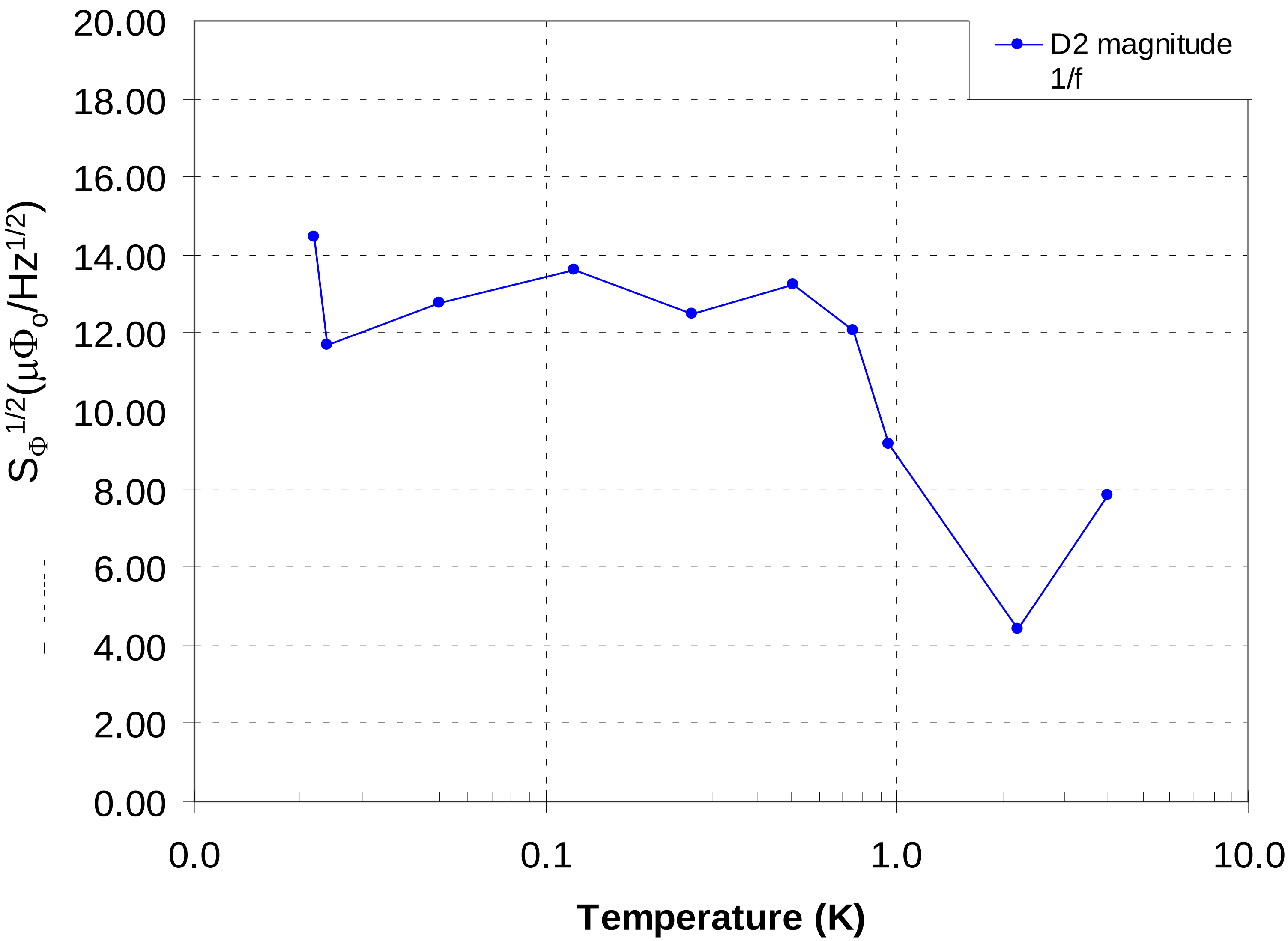


Type D



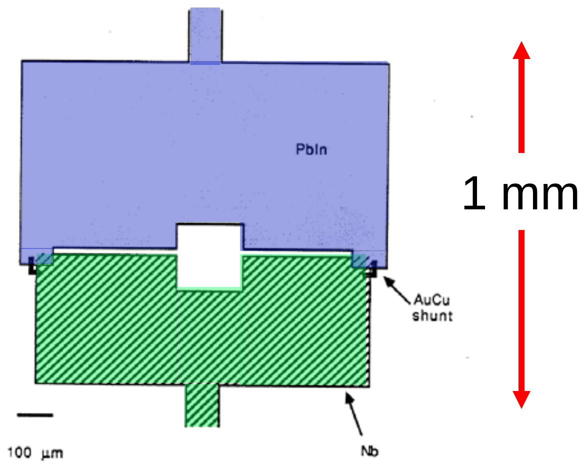
RMS flux noise power spectral density at 1Hz vs T in device D2





"Big" SQUIDs

Type D



Type M

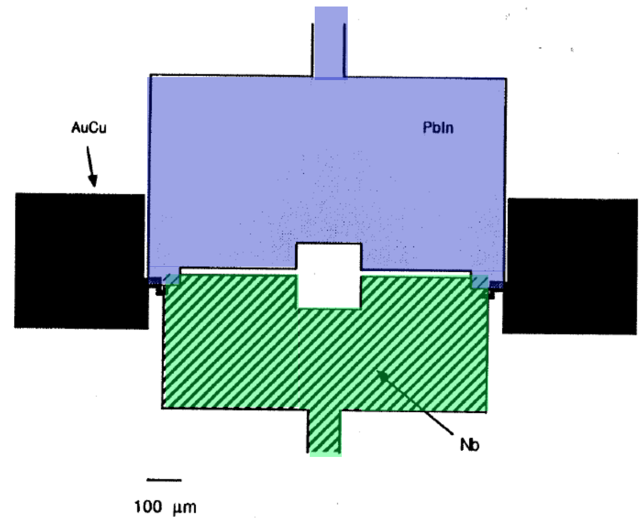
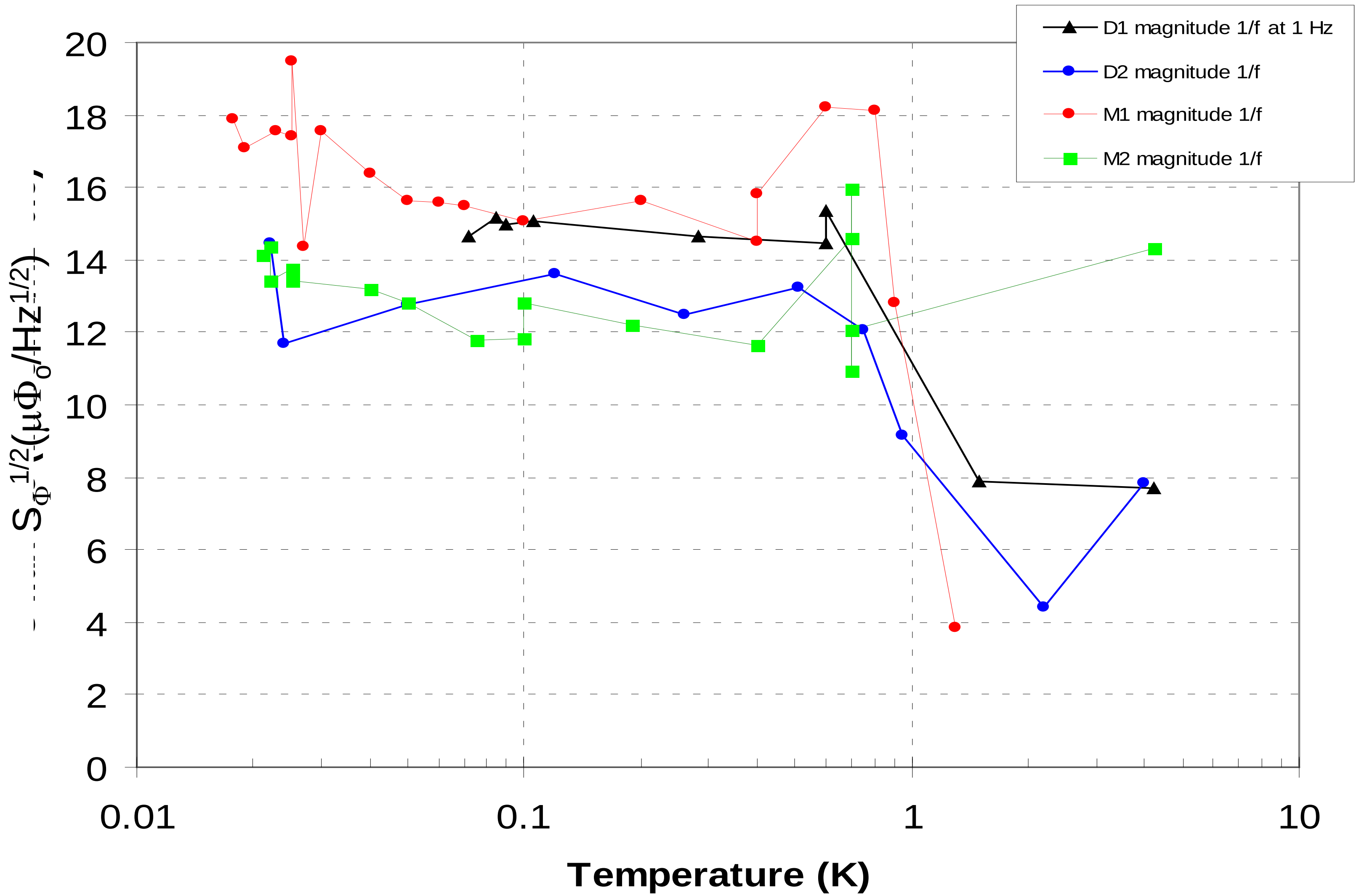


Fig. 1.16 Schematic of a Type M dc SQUID.

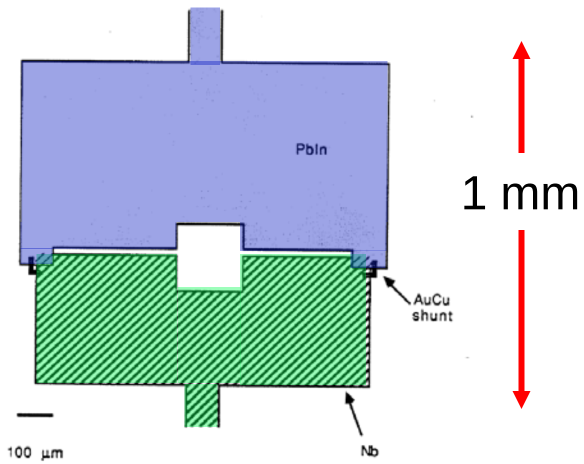
RMS flux noise power spectral density at 1Hz vs T



- noise magnitude **increases** as T **decreases** below 1 K
- different devices with same shape produce similar noise

"Big" SQUIDs

Type D



Type M

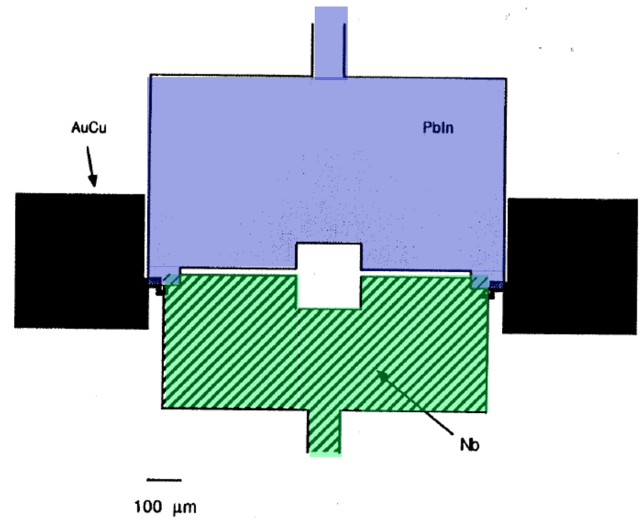
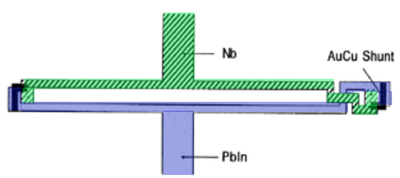


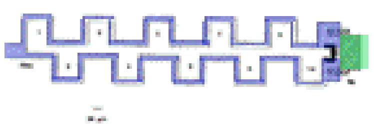
Fig. 1.16 Schematic of a Type M dc SQUID.

Type K

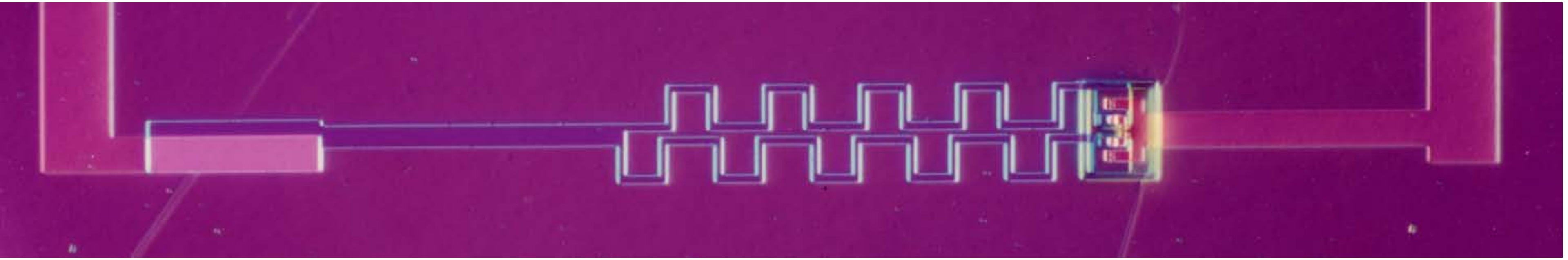


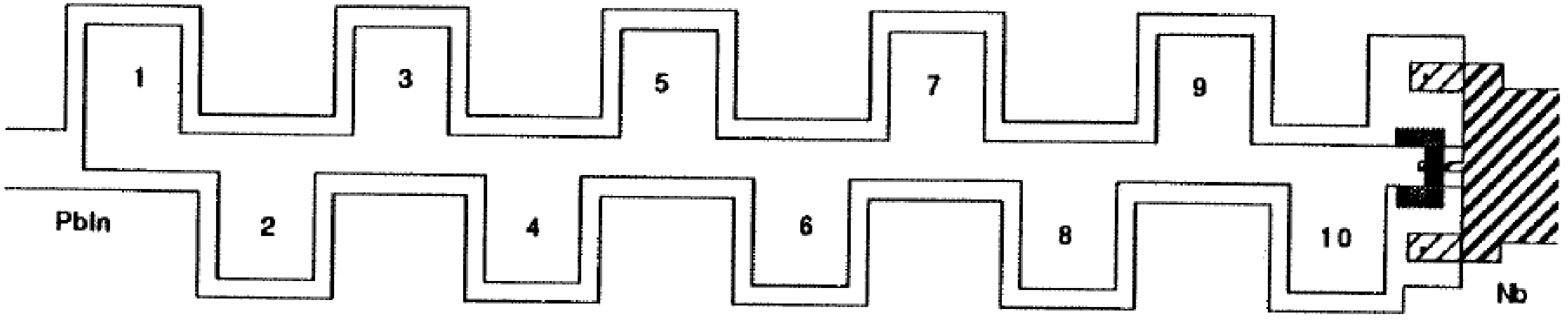
built on sapphire

Type P



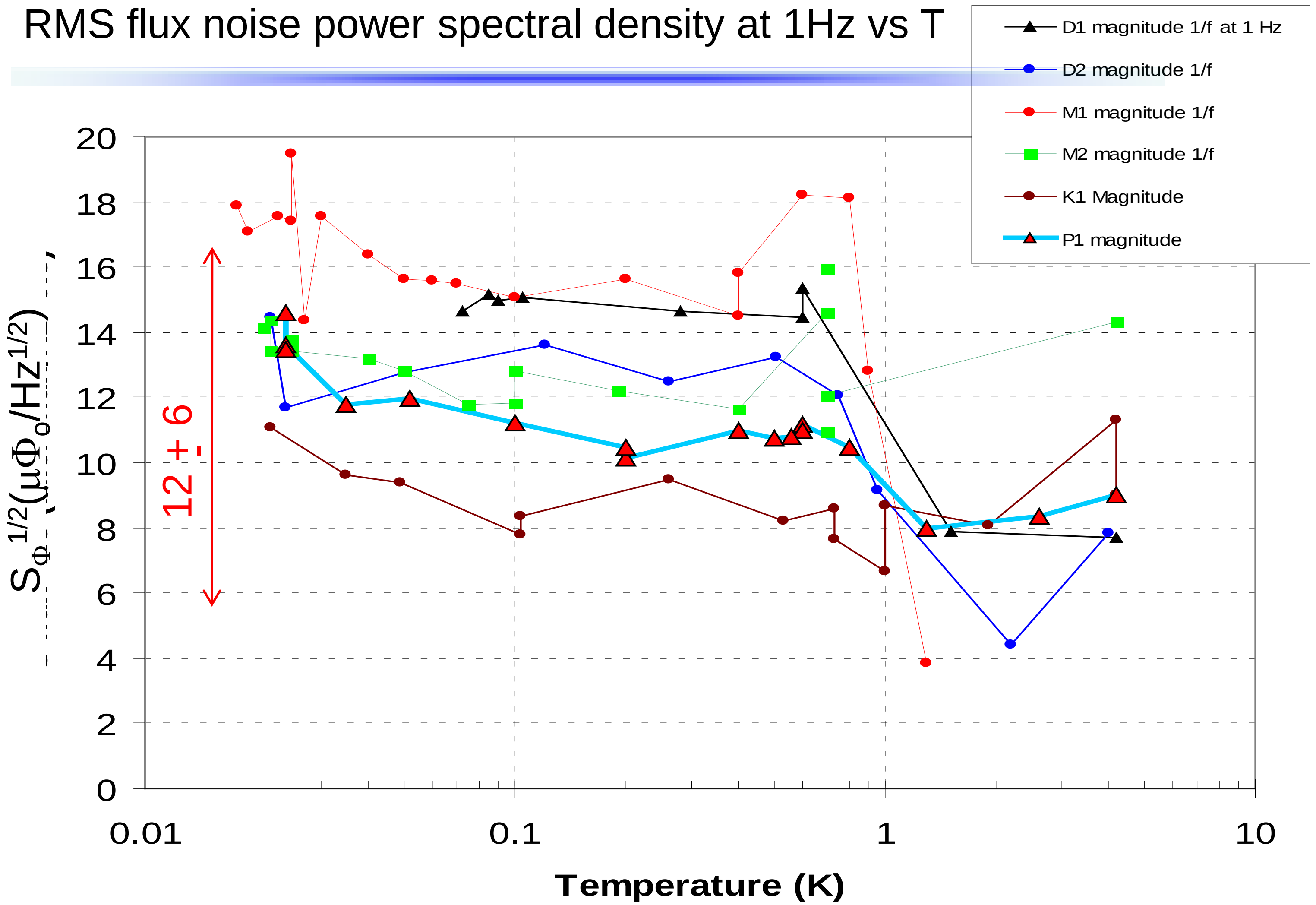
Type P





100 μm

RMS flux noise power spectral density at 1Hz vs T



- noise magnitude **increases** as T **decreases** below 1 K
- different devices with same shape produce similar noise
- noise depends weakly on SQUID "size" (linewidth ? overall length?)
- noise present with sapphire or Si substrates

"Small" SQUIDs

Type C

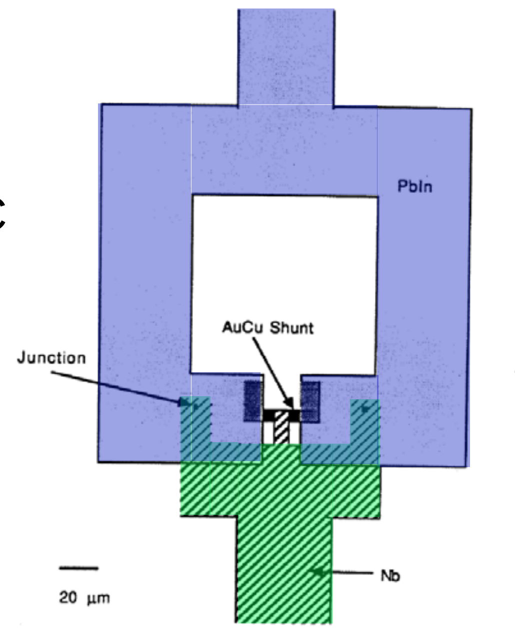


Fig. 1.7 Schematic of a Type C dc SQUID.

Type J

built on sapphire

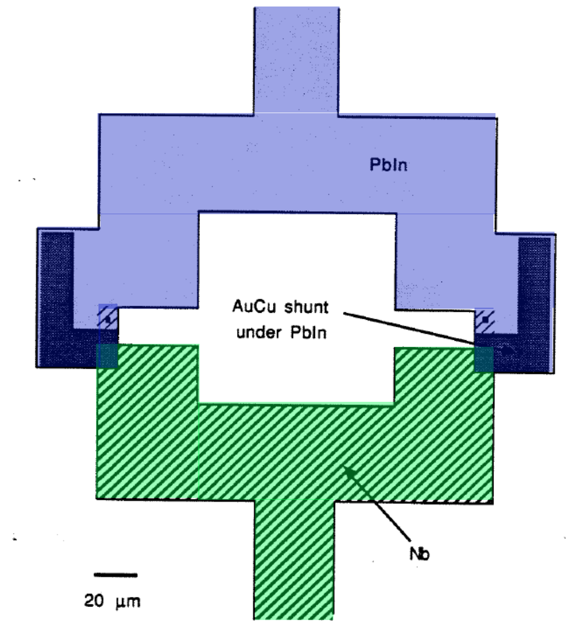


Fig. 1.13 Schematic of a Type J dc SQUID.

Type O

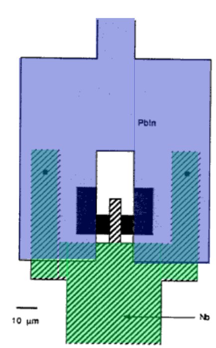


Fig. 1.18 Schematic of a Type O dc SQUID.

100 µm

Type F

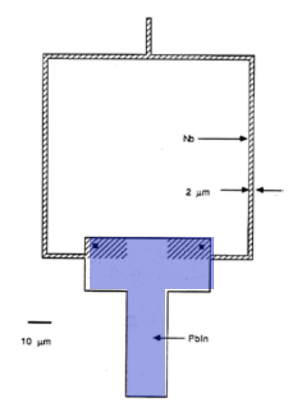
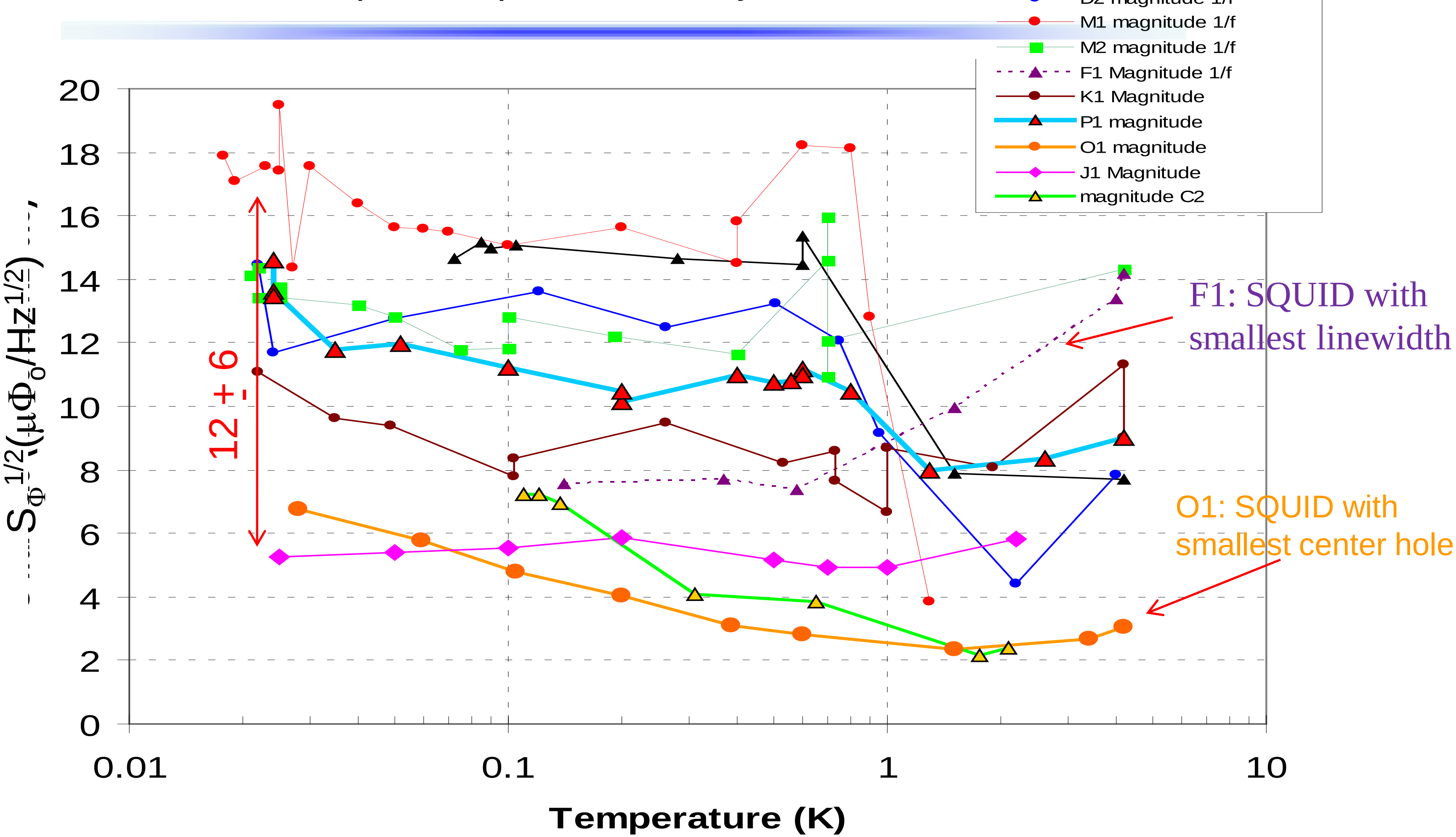


Fig. 1.10 Schematic of a Type F dc SQUID.

RMS flux noise power spectral density at 1Hz vs T



- noise magnitude **increases** as T **decreases** below 1 K
- different devices with same shape produce similar noise
- noise depends weakly on size of SQUID center hole
- noise independent of materials & substrate (Si, sapphire, oxidized Si)

Flux noise power and magnetic loss tangent

- Fluctuation-dissipation theorem:

  when there is noise there is an associated dissipation

- For magnetic dissipation in a loop, we can define a complex permeability $\mu = \mu_1 - i\mu_2$ and a complex inductance

$$L_c = (\mu_1 - i\mu_2)\mu_o F(a,b,...)$$

- The impedance of the loop is:

$$Z(\omega) = i\omega L_c = i\omega(\mu_1 - i\mu_2)\mu_o F(a,b,...) = i\omega\mu_1\mu_o F(a,b,...)\left(1 - i\frac{\mu_2}{\mu_1}\right)$$

$$= i\omega L\left(1 - i\frac{\mu_2}{\mu_1}\right) = i\omega L + \omega L\tan(\delta_m) = i\omega L + R_m(\omega)$$

- The flux noise produced in the loop is then:

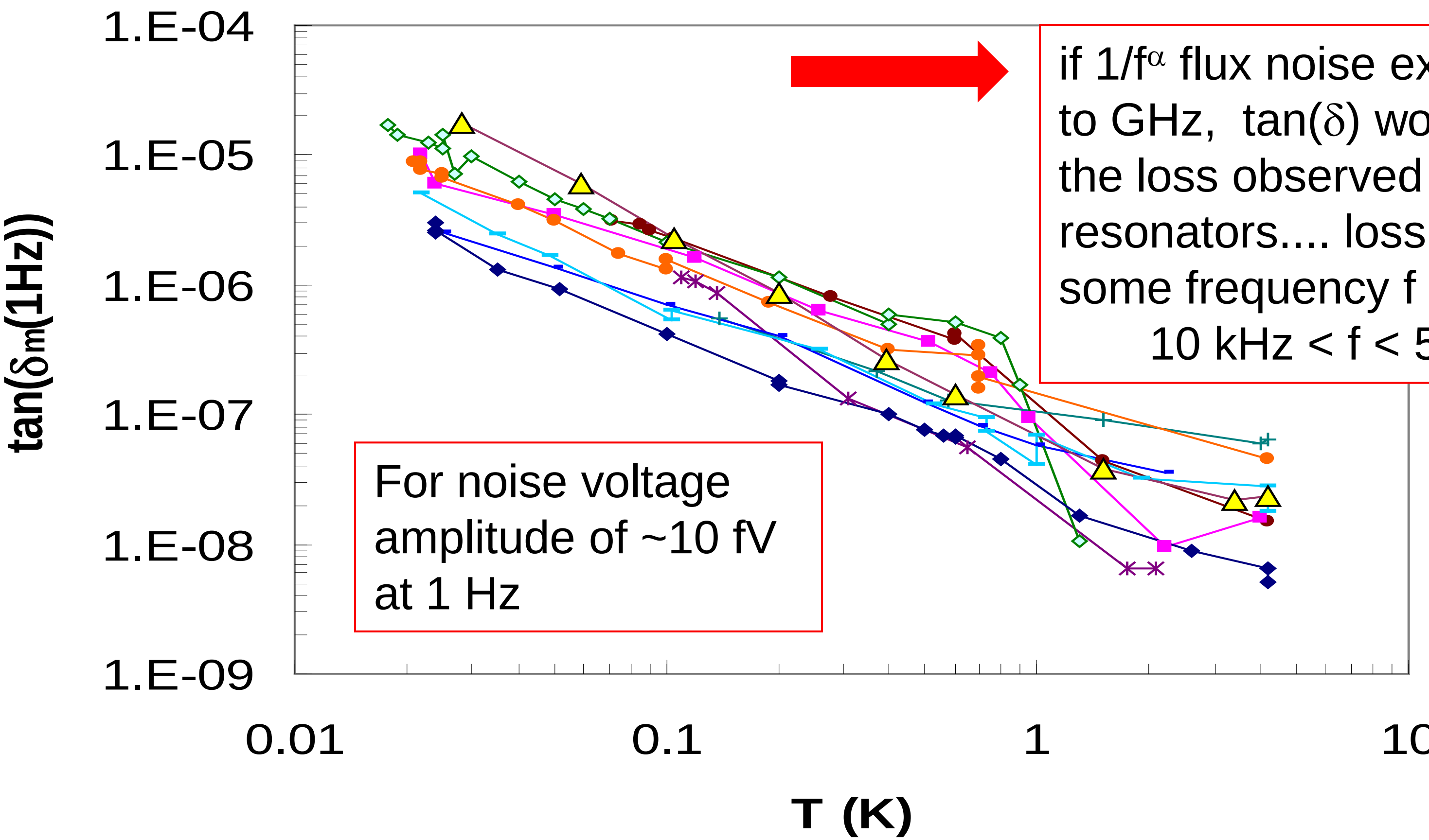
$$\mathrm{S}_\Phi(\mathrm{f}) = \mathrm{S}_\mathrm{I}(\mathrm{f})L^2 = \frac{\mathrm{S}_\mathrm{v}(\mathrm{f})L^2}{\omega^2 L^2 + \mathrm{R}_\mathrm{m}^2} = \frac{4\mathrm{k}_\mathrm{B}\mathrm{T}L^2 \cdot \mathrm{Im}(\mathrm{Z}(\omega))}{\omega^2 L^2 + \omega^2 L^2\tan^2(\delta_m)} = \frac{4\mathrm{k}_\mathrm{B}\mathrm{T}L^2 \cdot \omega L\tan(\delta_m)}{\omega^2 L^2 + \omega^2 L^2\tan^2(\delta_m)}$$

Flux noise power and magnetic loss tangent

- For $\tan(\delta_m) \ll 1$, we find

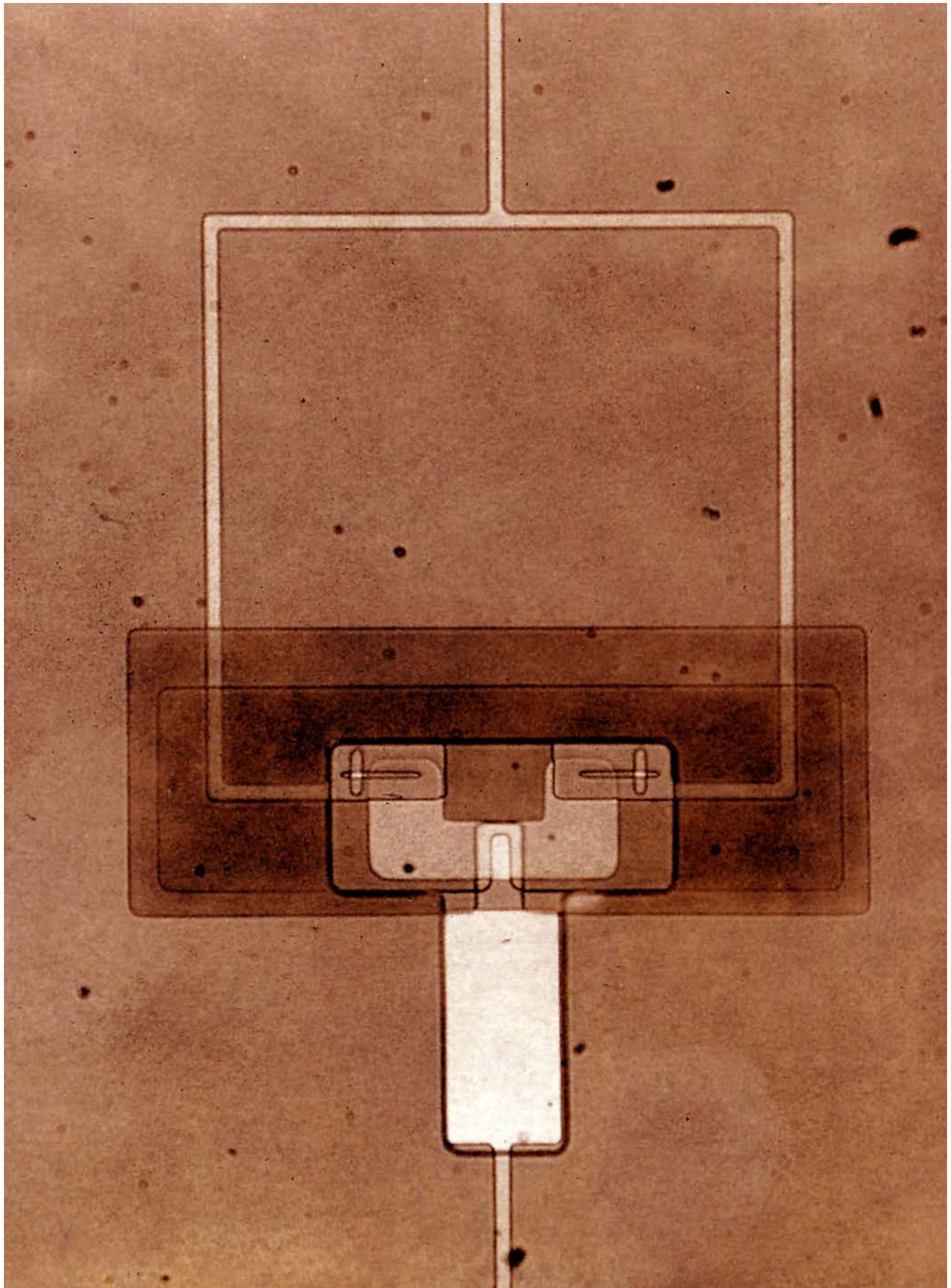
$$S_\Phi(f) \cong \frac{4k_B T L}{2\pi f}\tan(\delta_m) \quad \Longrightarrow \quad \boxed{\tan(\delta_m) \cong \frac{\pi f\, S_\Phi(f)}{2k_B T L}}$$

- If $\tan(\delta_m)$ is independent of frequency, then we get $1/f^{1}$ noise, If flux noise independent of T, then $\tan(\delta)$ scales as 1/T.



if $1/f^{\alpha}$ flux noise extrapolates out to GHz, $\tan(\delta)$ would dominate the loss observed in thin-film sc resonators.... loss must roll-off at some frequency f such that
10 kHz < f < 5 GHz

For noise voltage amplitude of ~10 fV at 1 Hz



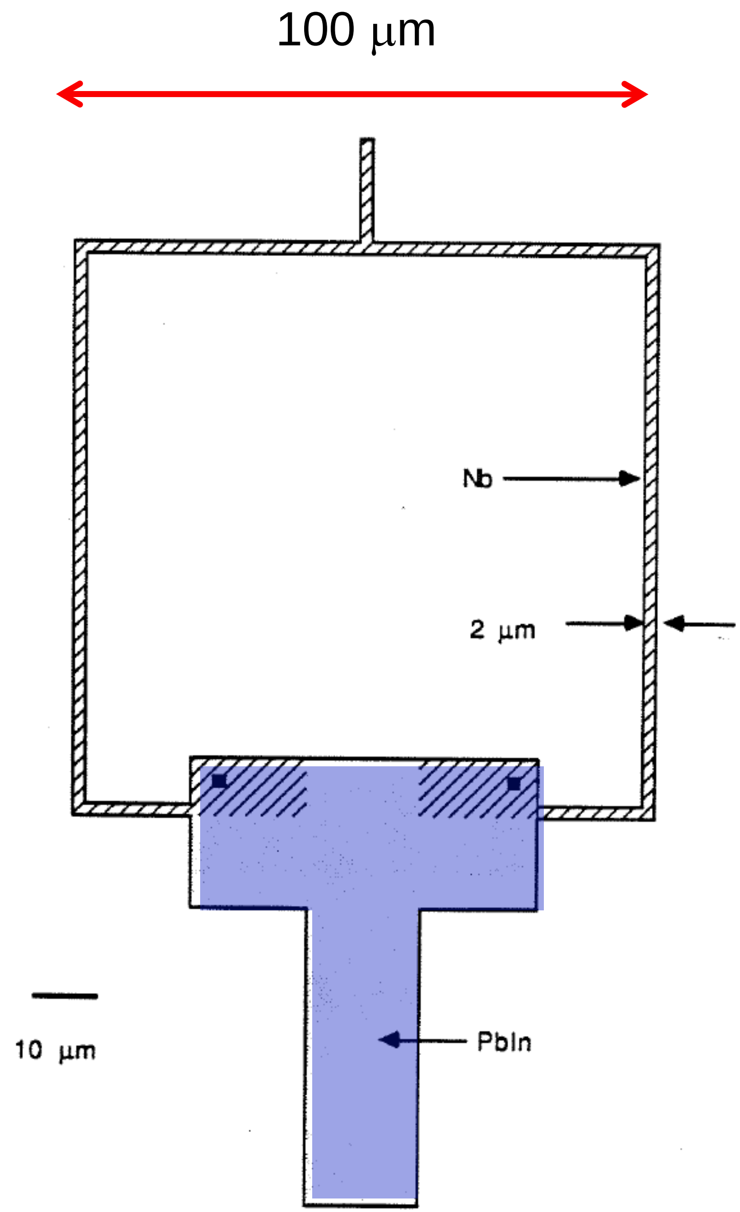
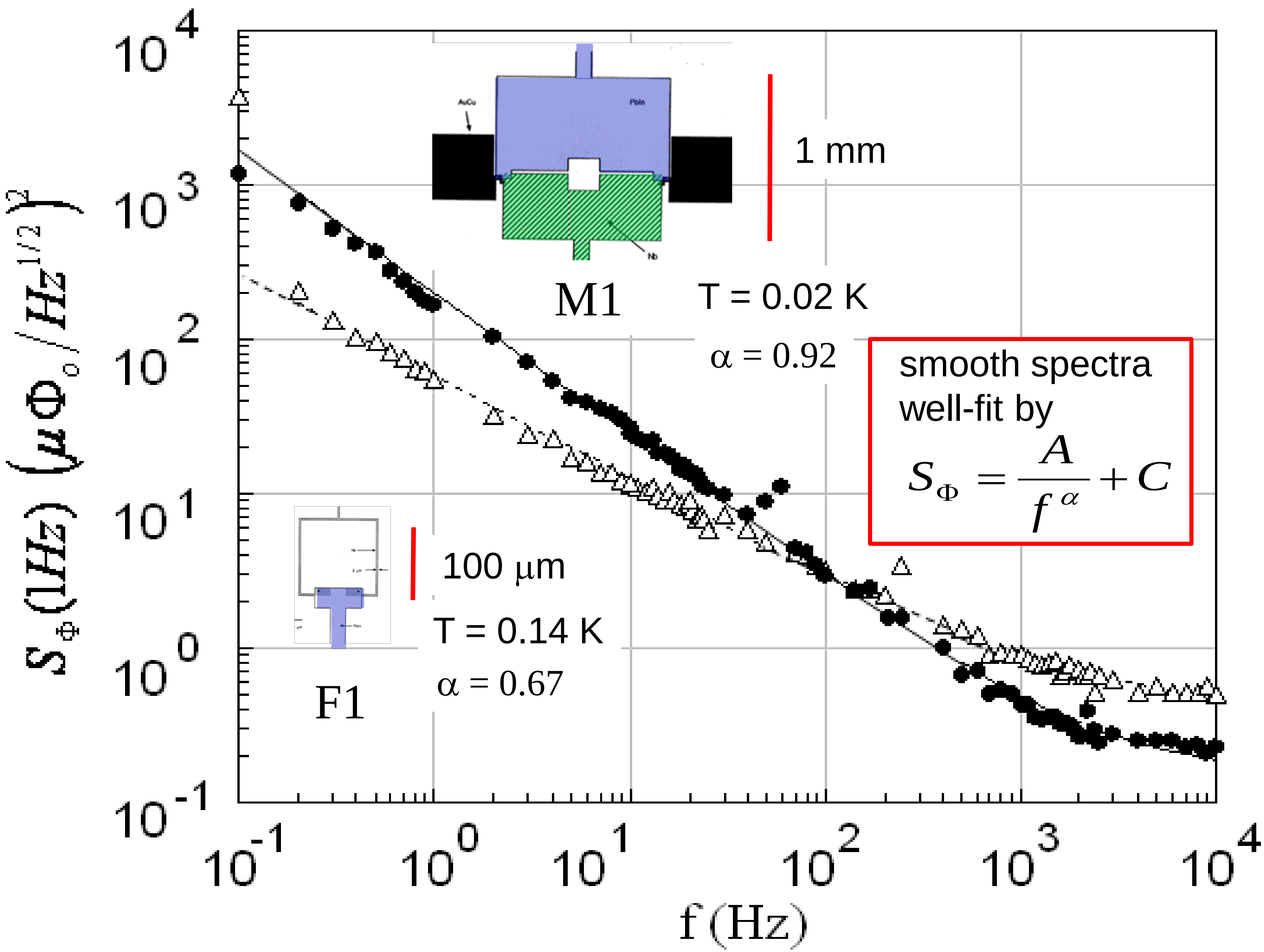
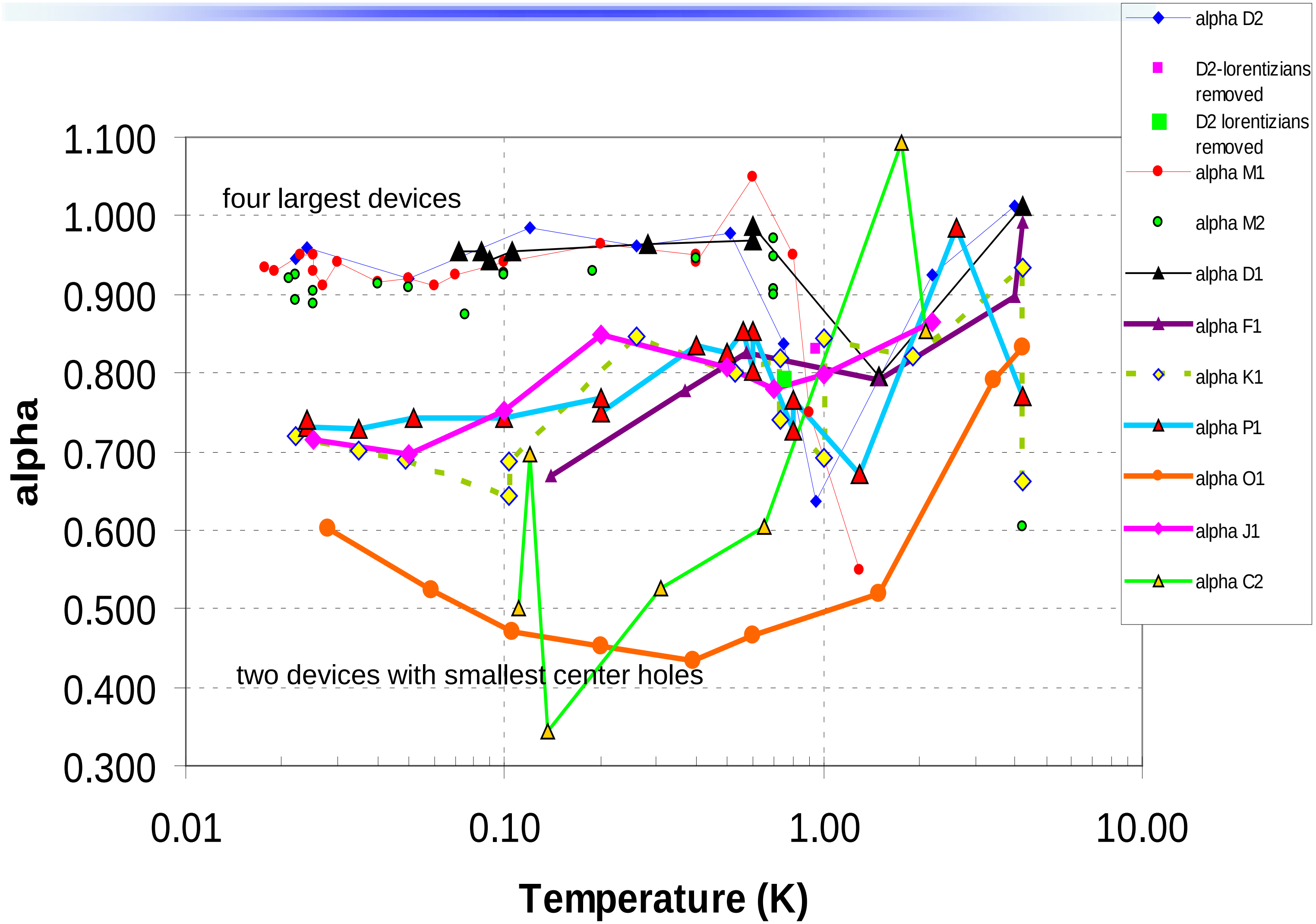


Fig. 1.10 Schematic of a Type F dc SQUID.

Flux noise power spectrum in two SQUIDs



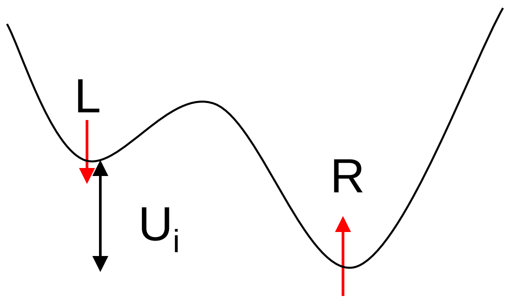
Temperature dependence of the slope α of the $1/f^{\alpha}$ flux noise



- devices with similar shapes had similar slope α
- small devices tend to have lower alphas with stronger T dependence
- only biggest devices (D1, D2, M1, M2) had α close to1

An "explanation" for $1/f^{2/3}$ noise

(1) Assume two-level magnetic dipole fluctuators with energy difference $U_i << kT$



(2) Assume that transitions from the upper to lower state takes time:

$$T_1 = \tau_{LR} = \frac{\tau_o}{F_i^3} = \tau_{RL} = 2\tau_i$$

(3) Assume F_i is an (unknown) physical parameter that has a uniform distribution; D(F) dF = C" dF and note that:

$$F = \left(\frac{\tau_o}{2}\right)^{-1/3} \tau^{-1/3} \Rightarrow D(\tau) = D(F)\left|\frac{dF}{d\tau}\right| = \frac{C''}{3}\left(\frac{\tau_o}{2}\right)^{-1/3}\frac{1}{\tau^{4/3}}$$

Then the total noise spectrum is

$$S_m^{tot}(f) = \int_0^\infty S_{mi}(f) D(F) dF = C''4\sigma_m^2 \int_0^\infty \frac{dF}{1+\omega^2\left(\tau_o / F^3\right)^2}\frac{\tau_o}{F^3}$$

$$S_m^{tot}(f) = C''4\sigma_m^2 \int_0^\infty \frac{dF}{1+\left(\omega\tau_o / F^3\right)^2} \frac{\tau_o}{F^3}$$

now change variables to $y = \dfrac{\omega\tau_o}{F^3}$

and notice $F = \left(\omega\tau_o\right)^{1/3} y^{-1/3}$ $\qquad dF = -\dfrac{1}{3}\left(\omega\tau_o\right)^{1/3} y^{-4/3} dy$

$$S_m^{tot}(f) = \frac{C''4\sigma_m^2}{\omega} \int_0^\infty \frac{\frac{1}{3}\left(\omega\tau_o\right)^{1/3} y^{-4/3} dy}{1+y^2}\, y = \frac{C''4\sigma_m^2 \tau_o^{1/3}}{3\omega^{2/3}} \int_0^\infty \left(\frac{1}{y^{1/3}}\right) \frac{dy}{1+y^2}$$

$$\Rightarrow \boxed{S_m^{tot}(f) = \frac{C''4\sigma_m^2 \tau_o^{1/3}}{3(2\pi)^{2/3}} \frac{\pi}{2\sin(\pi/3)} \frac{1}{f^{2/3}}}$$

Temperature independent $1/f^{2/3}$ noise…assuming kT>>U.

Putting in all the thermal factors one finds the noise falls off rapidly for kT<<U and is flat for kT>>U….

Key Question: We assumed $T_1 = \dfrac{\tau_o}{F^3}$, but what is the factor F?

Answer: Don’t know if this is the correct explanation (and its not likely it is!). If F does exist, its not known what it is physically.

How do we know its really a flux noise: I-V and I-Φ: SQUID D2 at 0.95 K

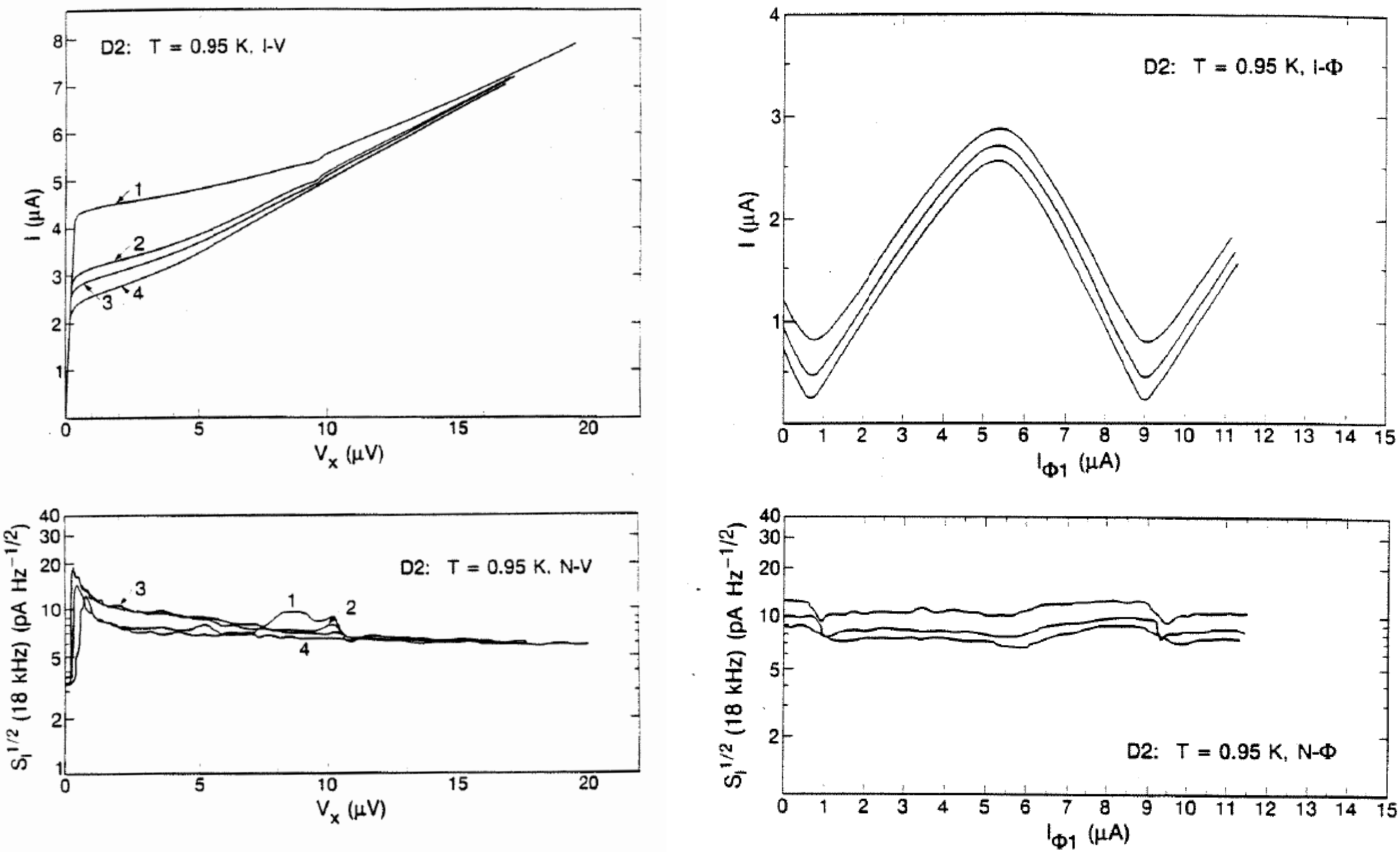


Fig. 4.5 (e) I-V of SQUID D2 at 0.95K, the curves 1 to 4 curves are for fixed flux bias current: 5.33, 7.98, 0, and 0.7 μA, respectively. (f) Noise vs V for the same flux bias currents as in (e).(9-1-86).

Flux noise: Total noise at the output scales with flux gain

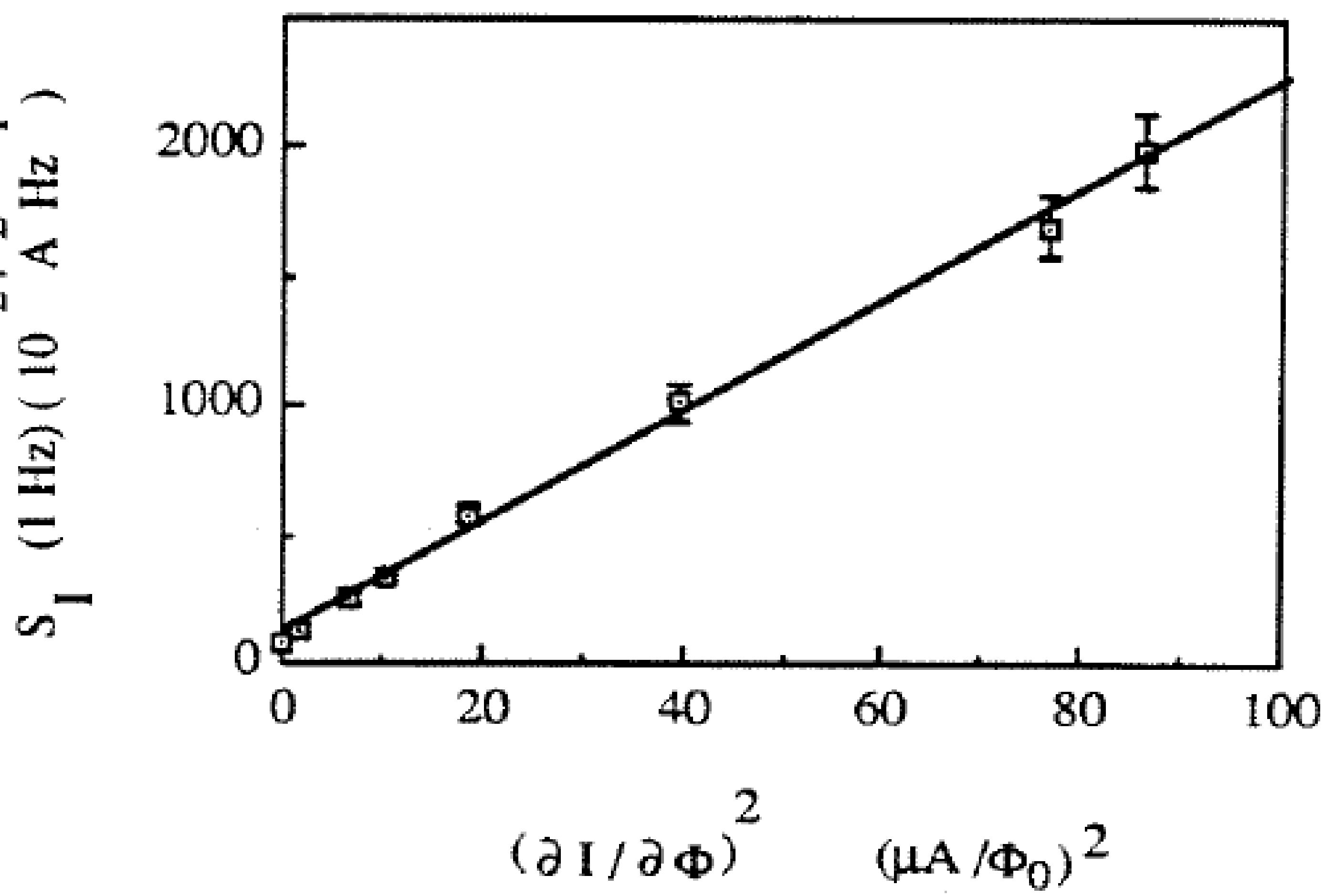
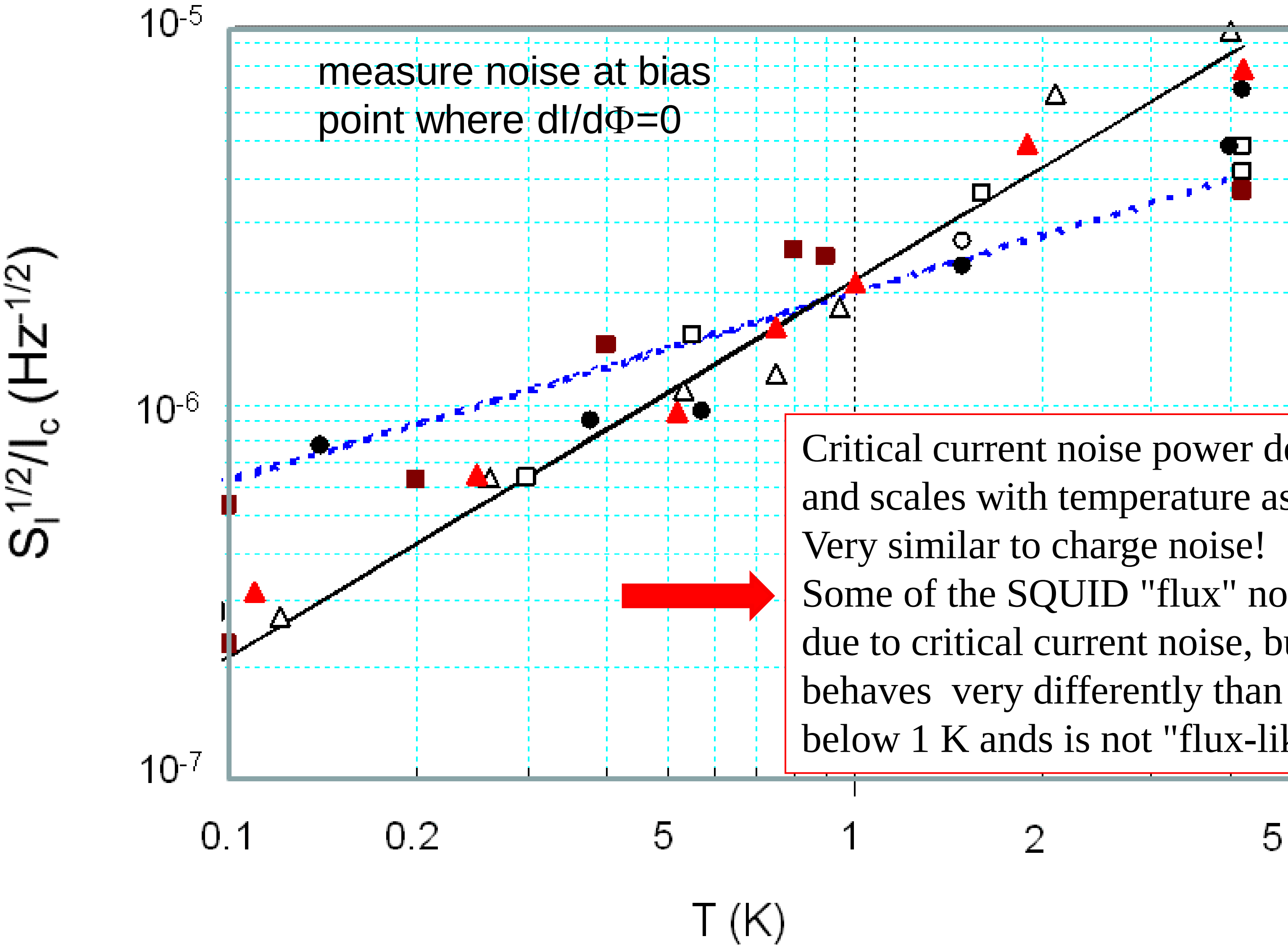


Fig .8.6 (a) Output rms excess current noise at 1 Hz vs. flux gain for SQUID E2 at 110 mK. (b) Output excess noise power at 1 Hz vs. square of flux gain. Solid line is linear plus constant fit.

Critical Current Noise

"Flicker (1/f) noise in the critical current of Josephson junctions at 0.09--4.2 K",
F. C. Wellstood, C. Urbina, and John Clarke, Appl. Phys. Lett. **85**, 5296 (2004).



Critical current noise power depends on I_o and scales with temperature as T or T^2.
Very similar to charge noise!
Some of the SQUID "flux" noise above 1 K is due to critical current noise, but I_o noise behaves very differently than flux noise below 1 K ands is not "flux-like"

Hot electrons in cold SQUIDs (the electron temperature in the shunts)

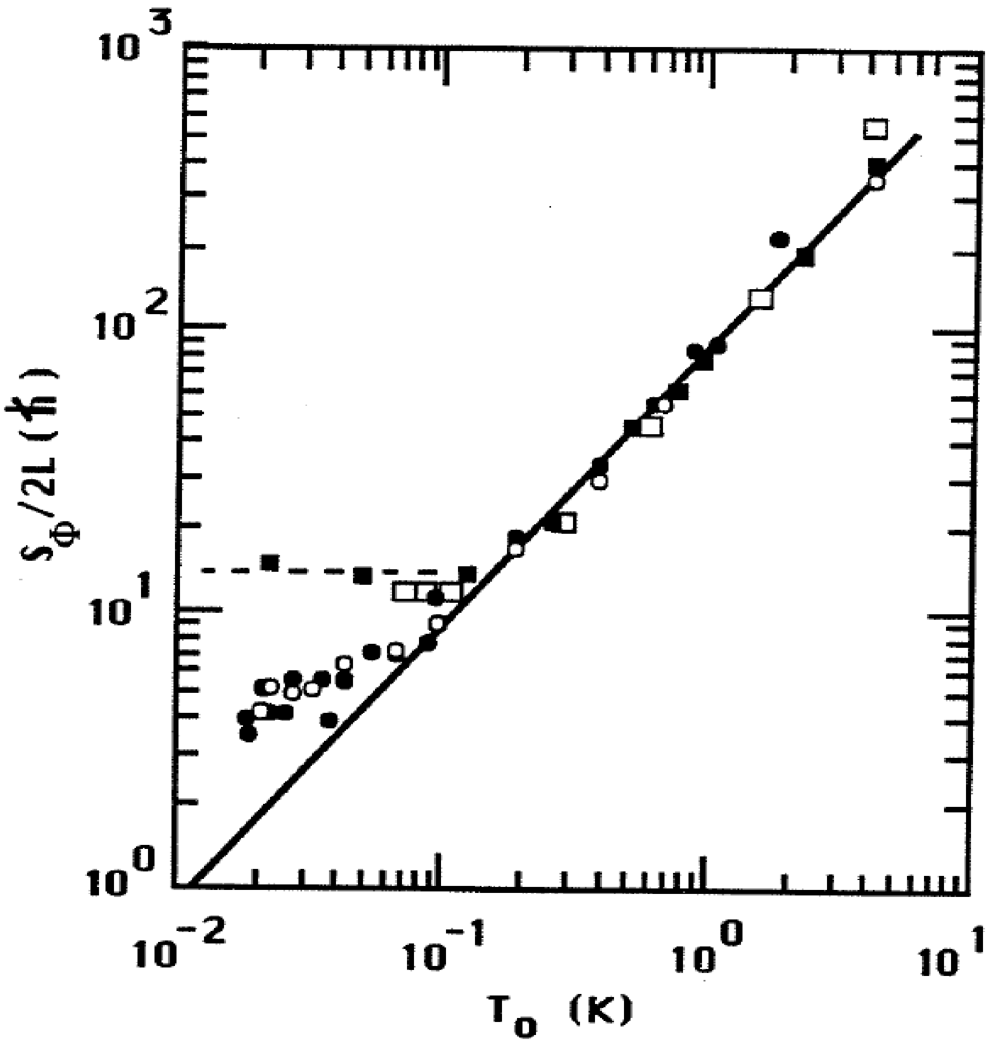


Fig. 11.6 Flux noise energy vs. T_0 for SQUIDs □ D1, ■ D2, ● M1, ○ M2. SQUIDs were biased near $\Phi_0/4$, with the operating points given in Table II. Solid line is prediction of Tesche and Clarke.[2]

Hot electrons in cold SQUIDs (the electron temperature in the shunts)

Table 11.1 Operating points for the SQUIDs D1, D2, M1, and M2. V is the voltage at which the SQUID is biased, I is the current flowing through the SQUID, P is the power dissipated in the SQUID, Ω is the shunt volume, A is the shunt area in contact with the substrate.

Device	V (μV)	I (μA)	P (pW)	P/Ω (Wm^{-3})	P/A (Wm^{-2})	$T_{min}=(P/\Sigma\Omega)^{1/5}$ (K)
D1	1.1	5	5.4	1.9×10^5	5.6×10^{-3}	0.151
D2	1.1	3.5	3.8	1.3×10^5	$4. \times 10^{-3}$	0.140
M1	1.2	4.5	5.4	1.2×10^3	3.5×10^{-5}	0.055
M2	4.0	5	20.	1.4×10^2	1.3×10^{-4}	0.036

"Hot-electron effects in metals", F. C. Wellstood, C. Urbina, and J. Clarke, Phys. Rev. B **49**, 5942 (1994).

"Hot-electron limitation to the sensitivity of the dc superconducting quantum interference device", F. C. Wellstood, C. Urbina, and J. Clarke, Appl. Phys. Lett. **54,** 2599 (1989).

Gaussian distribution of amplitudes

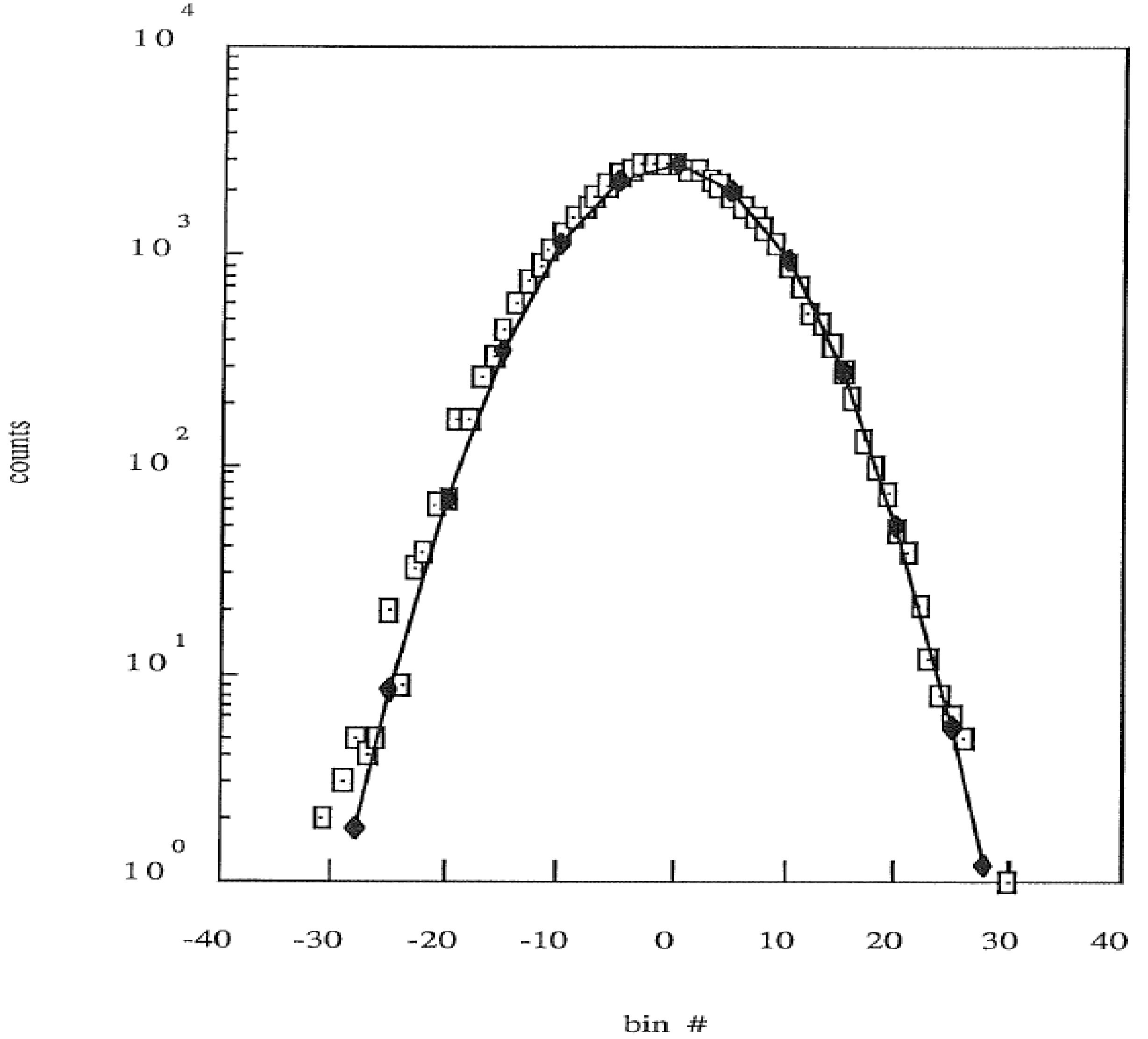


Fig. 8.10 Noise amplitude distribution from SQUID M1.: number of times the output acheived a certain amplitude vs. the amplitude. Solid line is gaussian fit to data.

Parameters of measured devices

Device	Date	T (mK)	$2I_0$ (μA)	A	r	α	β	L (nH)
A1	7- 2-85	150	3.66	0.484	0.632	0.45	0.7	0.396
A2 (*)	7-21-85	130	10.8	0.328	0.61	0.6	1.35	0.26
A3 (**)	5-25-85	160	5.78	0.635	0.779	0.22	0.495	0.18
A4	8-10-85	120	0.71	0.89	0.99	0.0	0.16	0.47
A'5	9-16-85	170	6.23	0.392	0.754	0.39	1.2	0.399
A6 (***)	2-19-87	1390	2.04	0.6	0.83	0.18	0.58	0.59
A7 (***)	2-16-87	4200	17.2	0.176	0.953	0.25	4.0	0.48
A8 (***)	2-12-87	4200	3.84	0.53	0.905	0.11	0.79	0.43
B1	10-27-87	160	3.00	0.304	0.709	0.55	1.7	1.17
C1	9-21-85	120	6.15	0.32	0.60	0.68	0.52	0.18
C2	11-15-85	150	5.32	0.618	0.826	0.18	0.55	0.214
C3	1-31-86	1400	21.2	0.292	1.0	0.0	2.1	0.205
C4	2- 6-86	1400	7.1	0.55	0.954	0.06	0.75	0.219
C5	2- 8-86	1400	3.07	0.379	0.766	0.62	0.24	0.16
D1	5-30-86	110	6.34	0.313	0.597	0.64	1.35	0.44
D2	8-29-86	50	4.55	0.414	0.772	0.35	1.1	0.50
E1	2-19-86	95	5.51	0.563	0.96	0.05	0.725	0.27
E2	5-21-86	510	15.1	0.291	0.96	0.13	2.1	0.29
F1	2-27-86	140	5.73	0.32	0.945	0.15	1.93	0.70
G1	3-12-86	110	4.15	0.39	0.76	0.61	0.24	0.12
I1	6-27-87	105	4.13	0.668	0.905	0.09	0.45	0.225
J1	8- 5-86	50	21.6	0.283	0.919	0.25	2.1	0.20
K1	8-14-86	35	11.42	0.23	0.939	0.23	2.9	0.53
M1	10-31-87	25	5.64	0.39	0.99	0.02	1.4	0.514
M2	5- 6-88	20	6.2	0.35	0.71	0.55	1.4	0.47
N2	12-11-87	20	17.7	0.196	0.886	0.5	3.4	0.398
O1	5-19-87	30	1.36	0.97	0.964	0.05	0.03	0.046
P1	6- 5-87	23	1.77	0.352	0.665	0.55	1.25	1.46
NBS1	7-21-87	20		(see Chapter 8)				0.08
FIN1	4-10-88	43		(see Chapter 8)				0.04

(*) 20 turn input coil, left open for measurement of β.
(**) Magnetometer configuration. (geometry described in Chapter 3)
(***) These were variants of the type A, discussed in Chapter 7.

REVIEW OF SCIENTIFIC INSTRUMENTS 79, 053704 (2008)

Gradiometric micro-SQUID susceptometer for scanning measurements of mesoscopic samples

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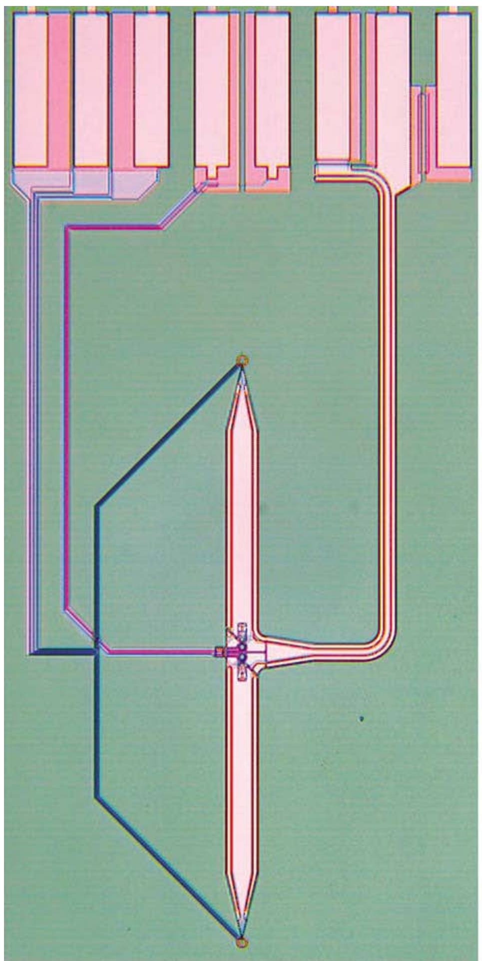
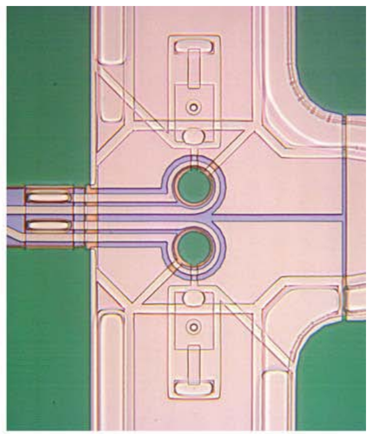
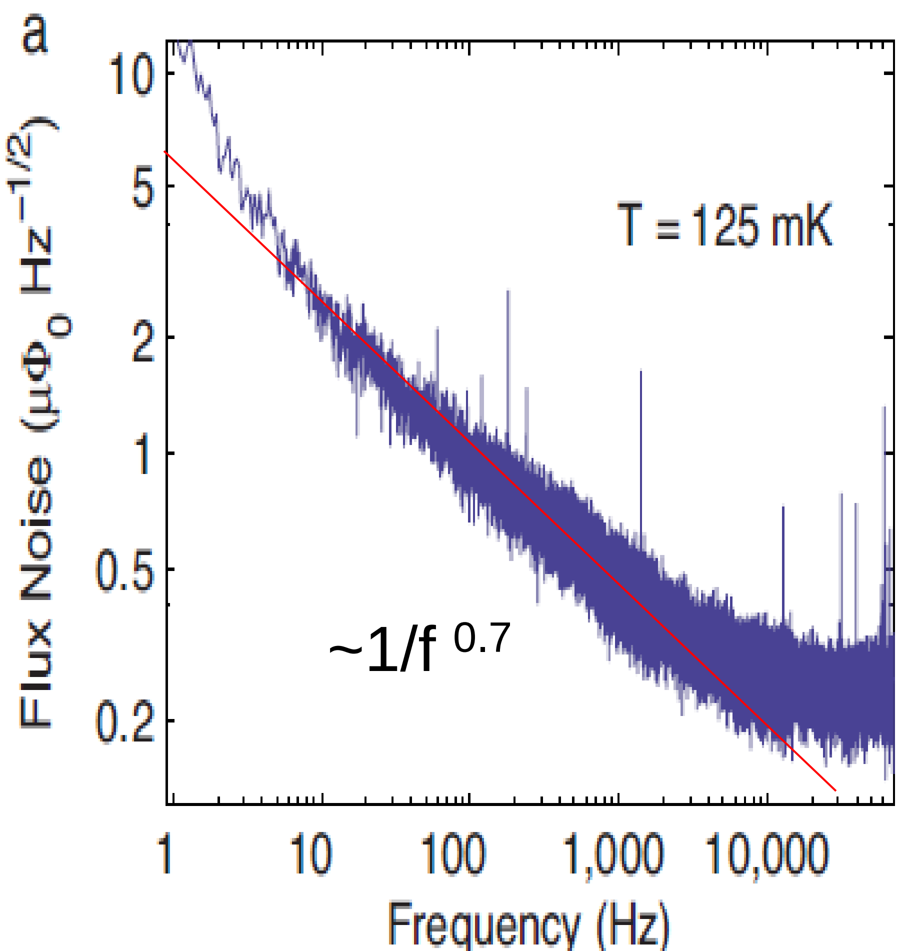
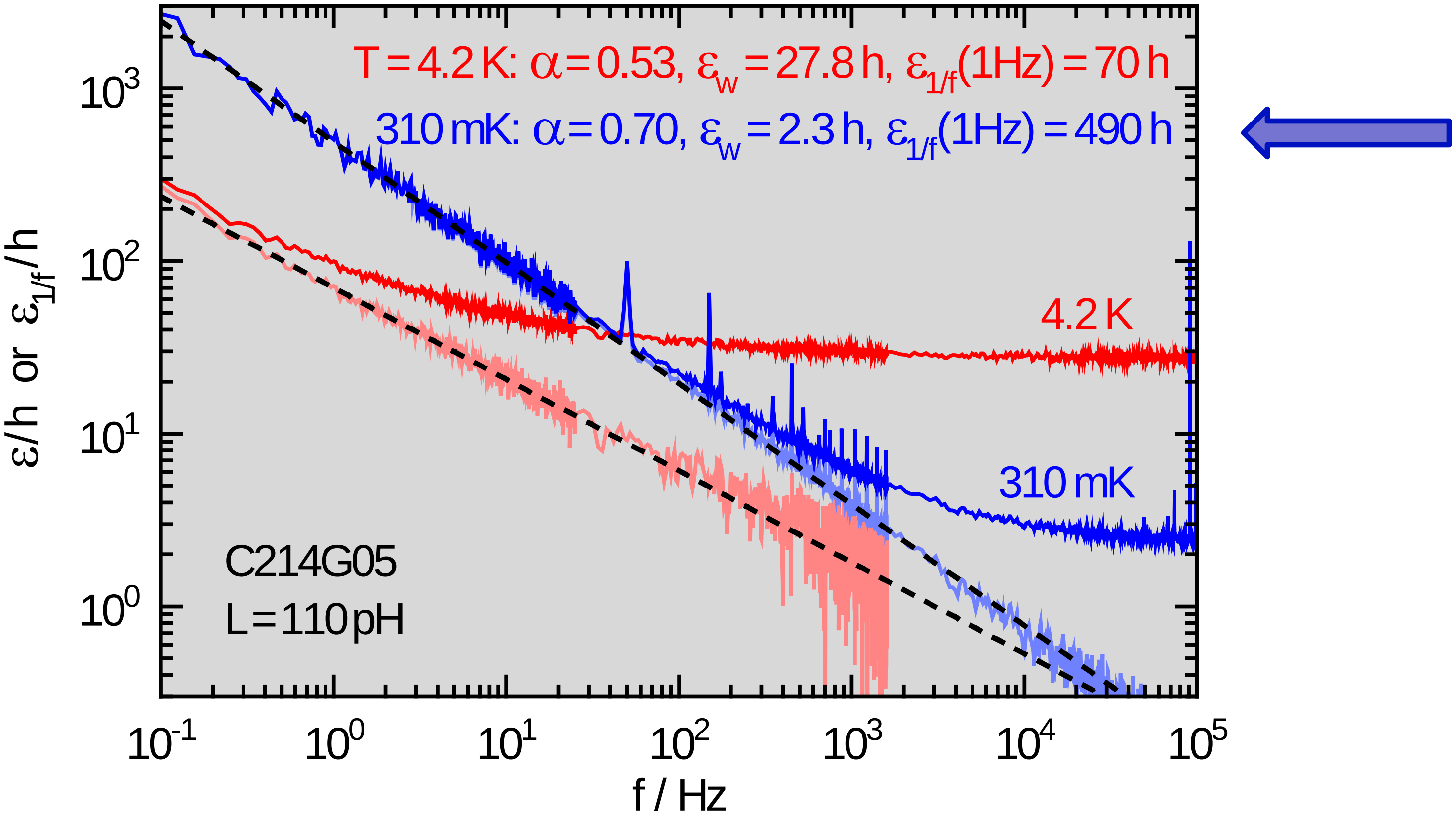






Investigation of Low-frequency Excess Flux Noise in dc SQUIDs at mK Temperatures

D. Drung, J. Beyer, J.-H. Storm, M. Peters, and T. Schurig
Physikalisch-Technische Bundesanstalt (PTB), Berlin, Germany



4.2 K → <320 mK: white noise **falls**, but 1/*f* noise **rises**

For this example: mK noise **higher** than 4.2 K noise above **≈40 Hz**

Conclusions

- Low-frequency excess flux noise has some unusual properties below 1 K:
  - smooth, featureless spectra (except maybe near 0.7K)
  - does not depend on materials... but comes from them
  - does not behave like excess charge or critical current noise
  - increases in magnitude as T decreases below 1 K.... Why?
  - may level out to 5-15 $\mu\Phi_o/Hz^{1/2}$ below about 0.5 K
  - depends weakly on the SQUID area (can't be B noise)
  - implies significant $\tan(\delta)$ if 1/f noise extends to GHz

- The slope" α of the $1/f^{\alpha}$ noise depends on the loop geometry
  - α can be significantly less than 1
  - α depends on temperature
  - α depends on geometry of the SQUID... How is this possible?
  - α tended to be smaller for smaller SQUIDs.... Why?
  - recent data on small Al flux qubits suggests α=1, but is it?