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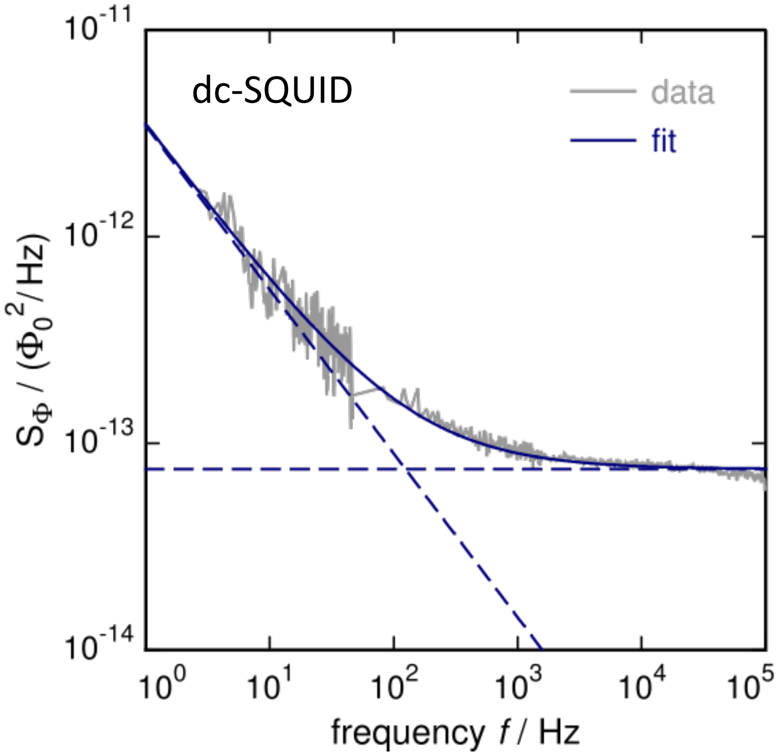
Kirchhoff-Institute for Physics
Heidelberg University

New insights in low-frequency excess flux noise of superconducting quantum devices

S. Kempf, A. Ferring, D. Uhrig, A. Fleischmann, C. Enss

Flux noise of a superconducting quantum device



$$S_\Phi = S_{\Phi,\mathrm{w}} + \frac{S_{\Phi,1/f}(1\,\mathrm{Hz})}{f^\alpha}$$

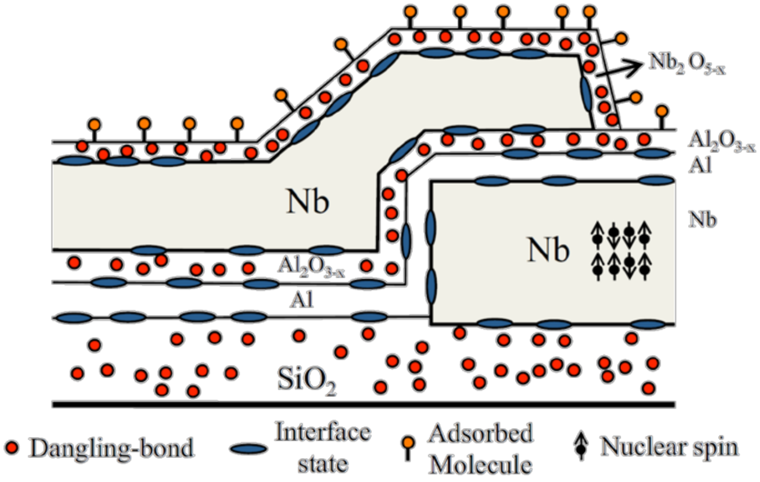
white noise

low-frequency noise

low-frequency noise makes life hard:

- averaging / measurement times
- quantum coherence
- dephasing
- …

Sources of low-frequency noise



S. LaForest *et al.*, PRB **92** (2015) 054502

‚external‘ sources

- insufficient shielding
- vortex motion
- RT electronics
- magnetic impurities on device

JJ related sources

- critical current fluctuations
- TLSs within barrier

‚wiring‘ related sources

- low-frequency excess flux noise

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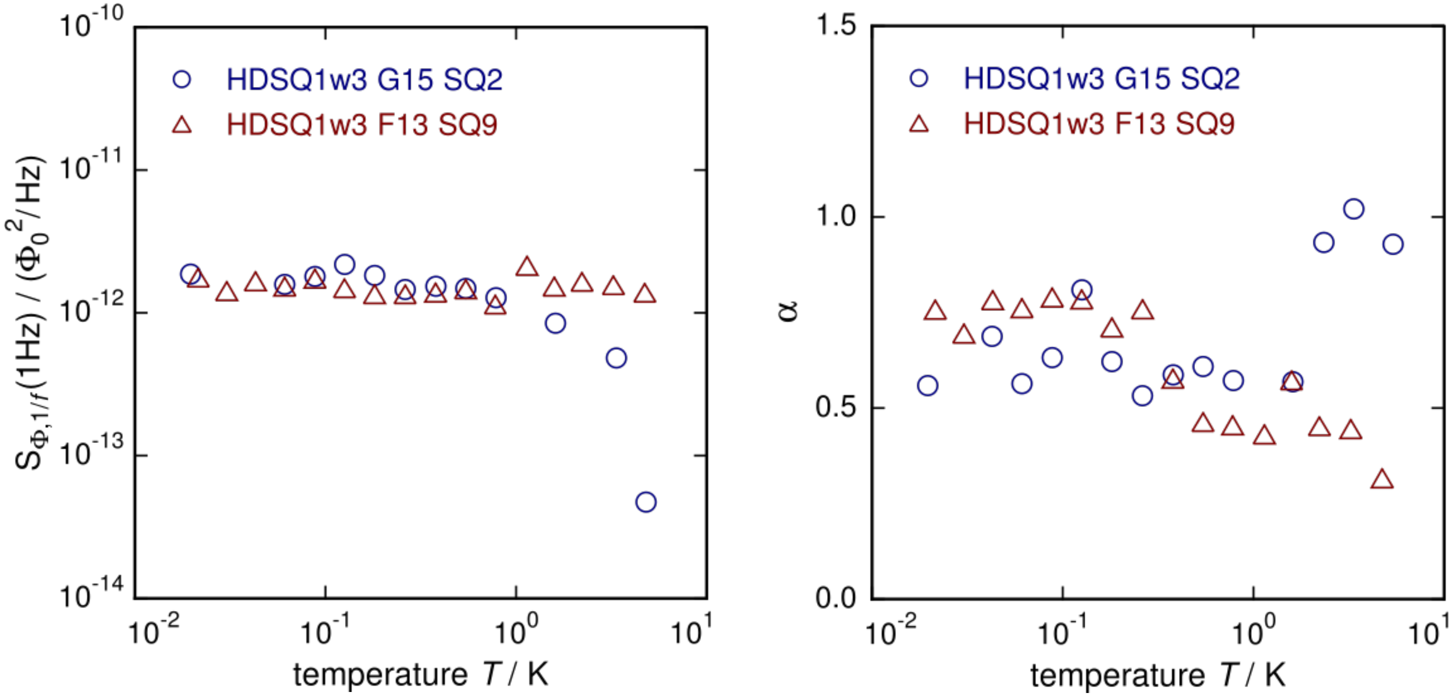
Temperature dependence of low-frequency noise

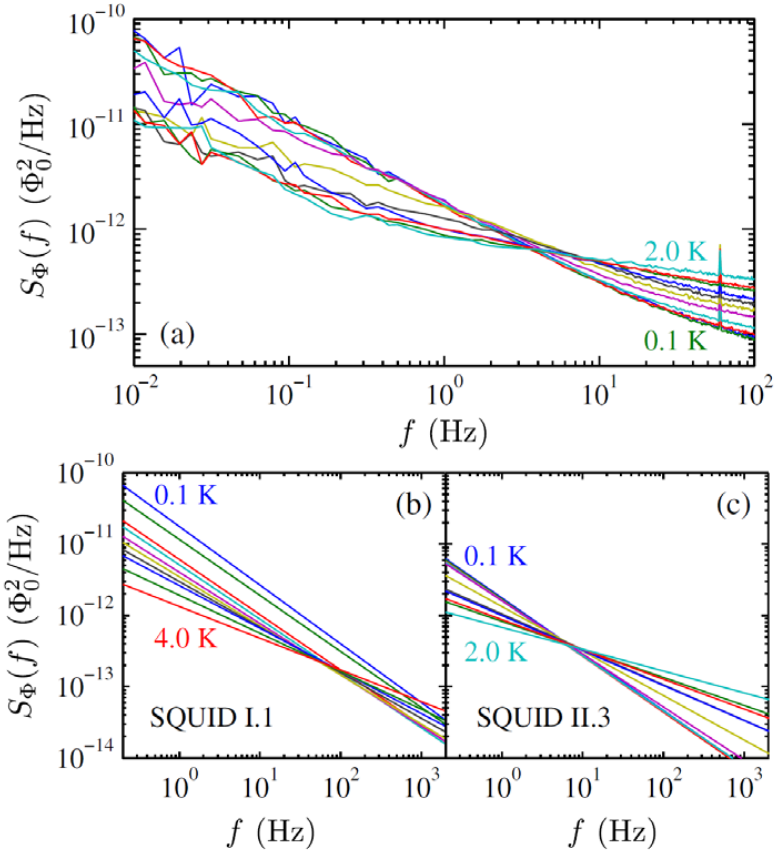
In general: amplitude of flux noise increases with decreasing temperature

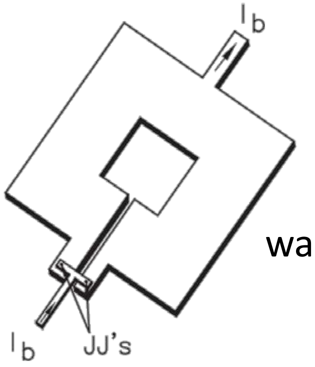


but: different behavior for different SQUIDs

Pivoting of noise spectra

S.M. Anton *et al.*, PRL **110** (2013) 147002





washer SQUID

noise spectra pivot about a frequency f_c

correlation between $S_{\Phi,1/f}(1\,\mathrm{Hz})$ and α

$$S_{\Phi,1/f}(1\,\mathrm{Hz}) = S_{\Phi,1/f}(f_c) \times \left(\frac{f_c}{f}\right)^{\alpha}$$

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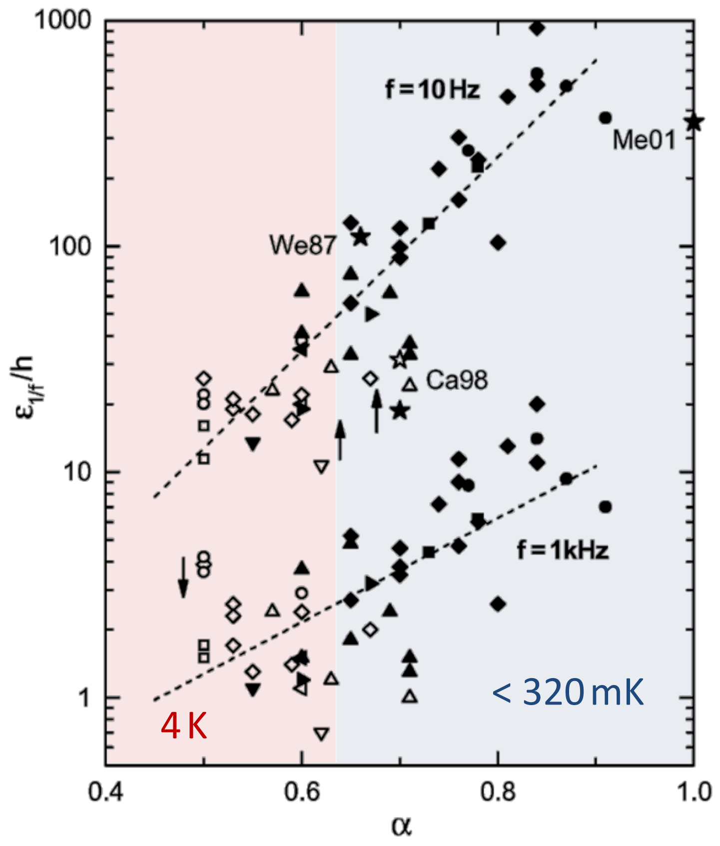
Universality



D. Drung *et al.*, IEEE Trans. Appl. Supercond. **21** (2011) 340

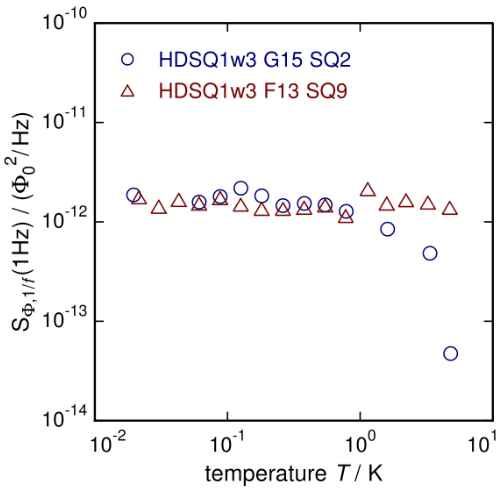
investigation of gradiometers, SSAs, …
('more complex SQUIDs')

- universal temperature behavior (independent of SQUID type)
- universal behavior among different SQUIDs
- correlation between $\varepsilon_{1/f}$(1 Hz) and α

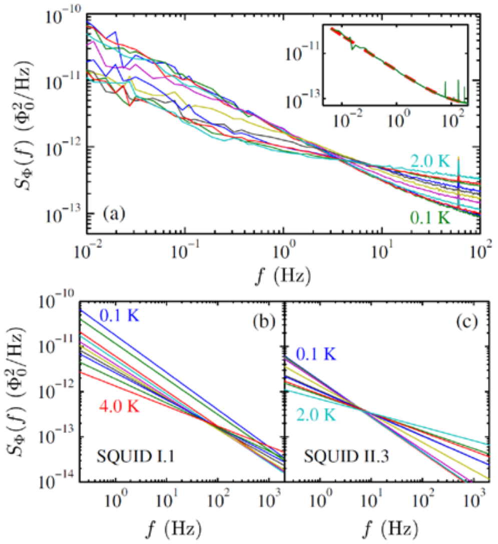
$$\varepsilon_{1/f} = 0.09\,h \times \left(\frac{200\,\mathrm{kHz}}{f}\right)^{\alpha}$$

What we have learned so far…

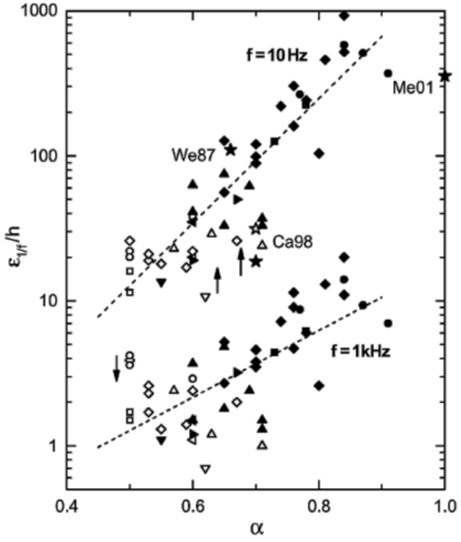
flux noise increases towards lower temperatures



pivoting for simple SQUIDs



universal behaviour



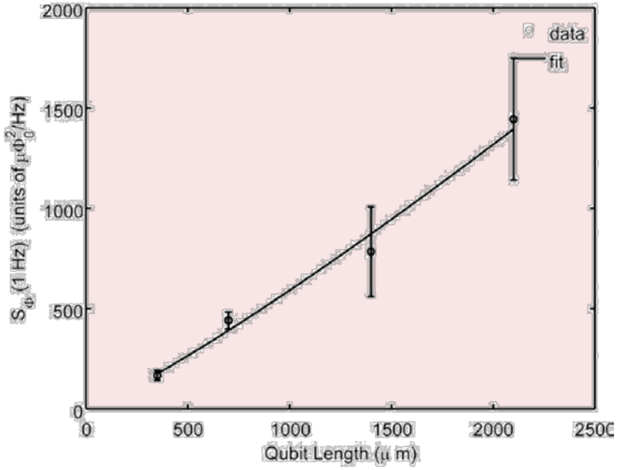
Open questions:

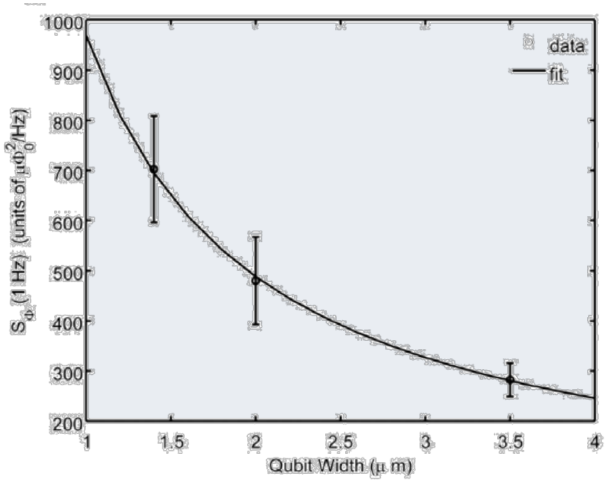
Pivoting for more complex SQUIDs?

More correlations?
Dependences?
Non-universalities?

Flux noise versus energy sensitivity

- Flux noise versus washer SQUID/qubit dimensions -





T. Lanting *et al.*, PRB **79** (2009) 060509R

Prediction for flux noise

$$\langle \Phi^2 \rangle \simeq \frac{2\mu_0^2}{3}\mu_B^2 \sigma \frac{R}{W}\left[\frac{\ln(2bW/\lambda^2)}{2\pi} + 0.27\right]$$

R.C. Bialczak *et al.*, PRL **99** (2007) 187006

analytical expression experimentally verified

$$S_{\Phi,1/f}(1\,\mathrm{Hz}) = A_0 L^\beta$$

$$A_0 = (1.7 \pm 0.3) \times 10^{-10}\ \Phi_0^2/\mathrm{Hz}$$

$$\beta = 1.14 \pm 0.15$$

$$S_{\Phi,1/f}(1\,\mathrm{Hz}) = B_0 W^\gamma$$

$$B_0 = (9.6 \pm 0.5) \times 10^{-10}\ \Phi_0^2/\mathrm{Hz}$$

$$\gamma = -0.98 \pm 0.1$$

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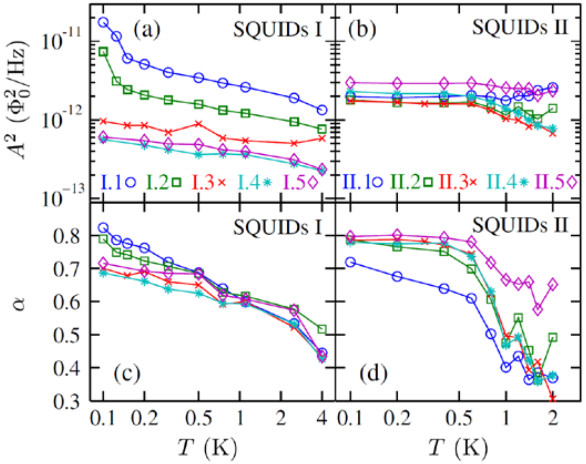
Flux noise versus energy sensitivity

flux noise



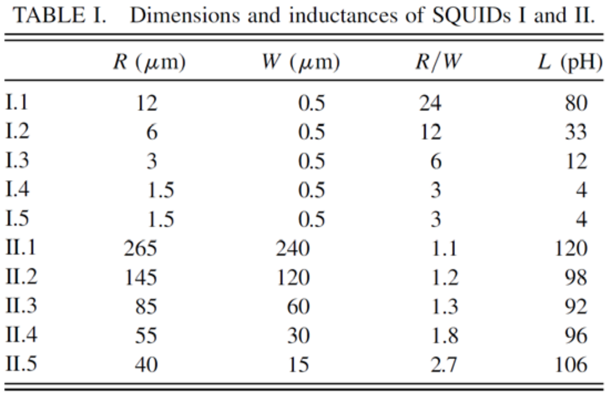
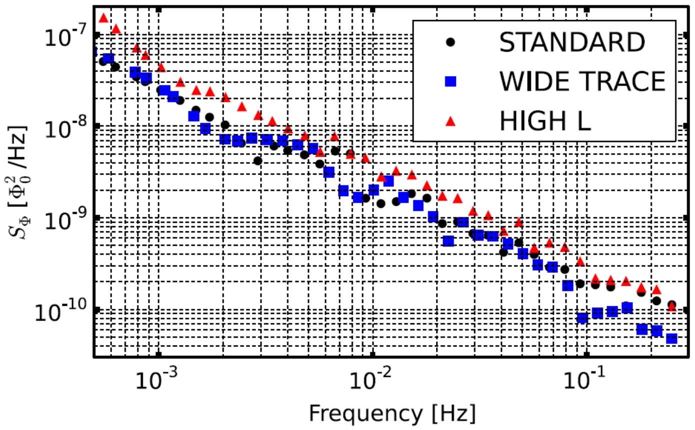


TABLE I. Dimensions and inductances of SQUIDs I and II.

	R (μm)	W (μm)	R/W	L (pH)
I.1	12	0.5	24	80
I.2	6	0.5	12	33
I.3	3	0.5	6	12
I.4	1.5	0.5	3	4
I.5	1.5	0.5	3	4
II.1	265	240	1.1	120
II.2	145	120	1.2	98
II.3	85	60	1.3	92
II.4	55	30	1.8	96
II.5	40	15	2.7	106

S.M. Anton *et al.*, PRL **110** (2013) 147002

energy sensitivity



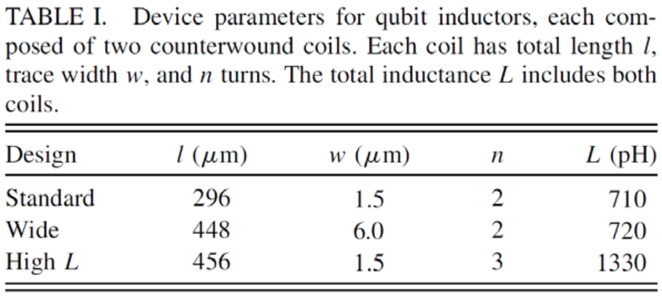


TABLE I. Device parameters for qubit inductors, each composed of two counterwound coils. Each coil has total length l, trace width w, and n turns. The total inductance L includes both coils.

Design	l (μm)	w (μm)	n	L (pH)
Standard	296	1.5	2	710
Wide	448	6.0	2	720
High L	456	1.5	3	1330

D. Sank *et al.*, PRL **109** (2012) 067001

Analyzed data set

Comprehensive analysis ($T < 1$ K):

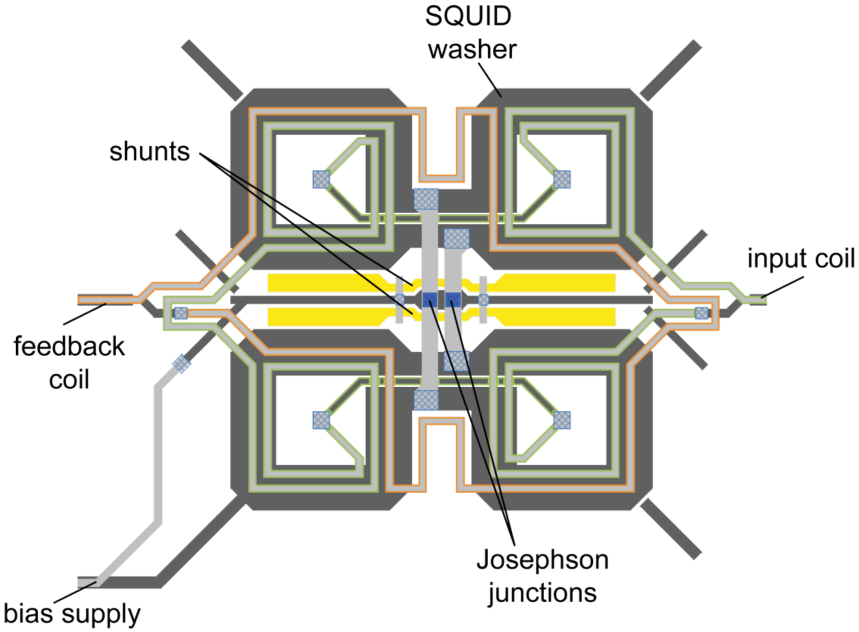
- 84 superconducting quantum devices
- 373 individual noise spectra

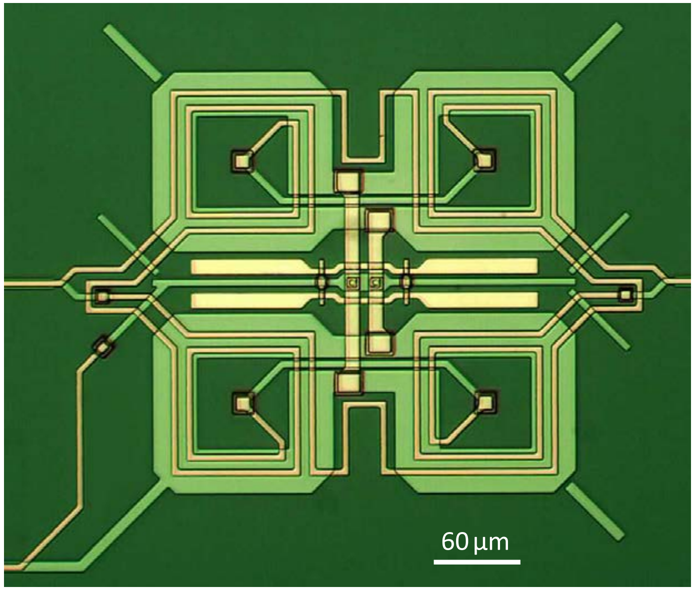
- 21 SQUIDs (109 spectra) measured by us
- 15 SQUIDs home-made, 6 SQUIDs provided by PTB Berlin

- literature
  - F.C. Wellstood *et al.*, Appl. Phys. Lett. **50** (1987) 772
  - R.C. Bialczak *et al.*, PRL **99** (2007) 187006
  - S.M. Anton *et al.*, PRL **110** (2013) 147002
  - D. Drung *et al.*, IEEE Trans. Appl. Supercond. **21** (2011) 340
  - S.M. Anton *et al.*, PRB **85** (2012) 224505
  - F.C. Wellstood *et al.*, IEEE Trans. Appl. Supercond. **21** (2011) 856
  - T. Lanting *et al.*, PRB **89** (2014) 014503
  - D. Sank *et al.*, PRL **109** (2012) 067001
  - R. Harris *et al.*, PRB **81** (2010) 134510

Single SQUIDs

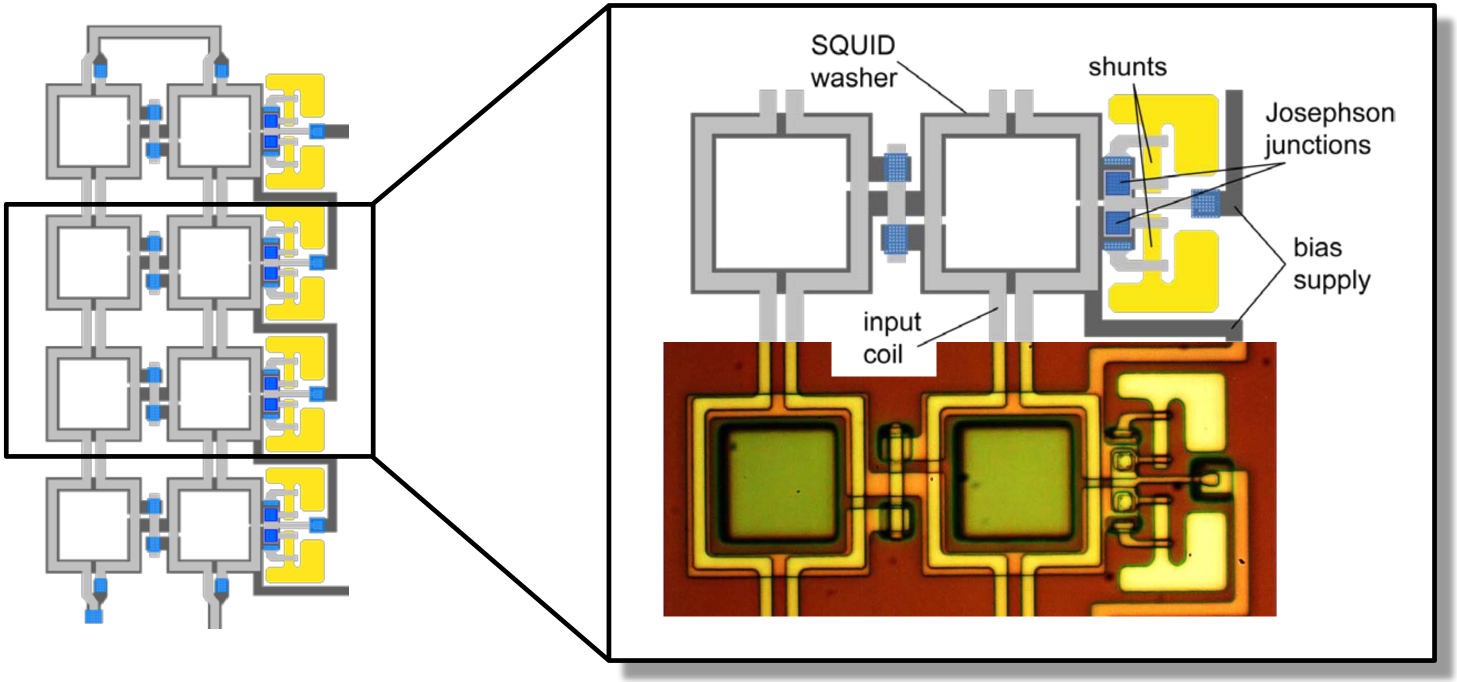
Second-order parallel gradiometer with separate input and feedback coils





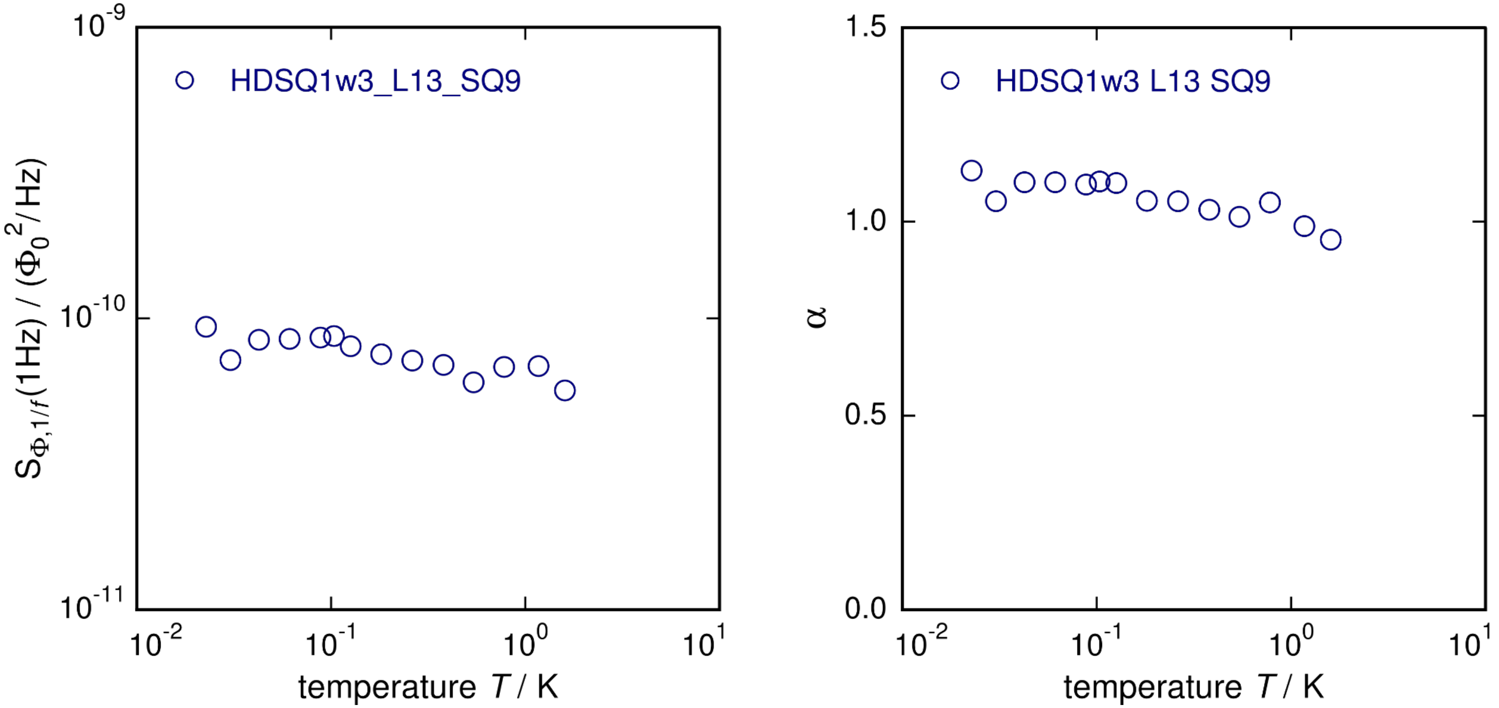
N-SQUID series arrays

N-SQUID series array of *N* first-order dc-SQUID series gradiometers

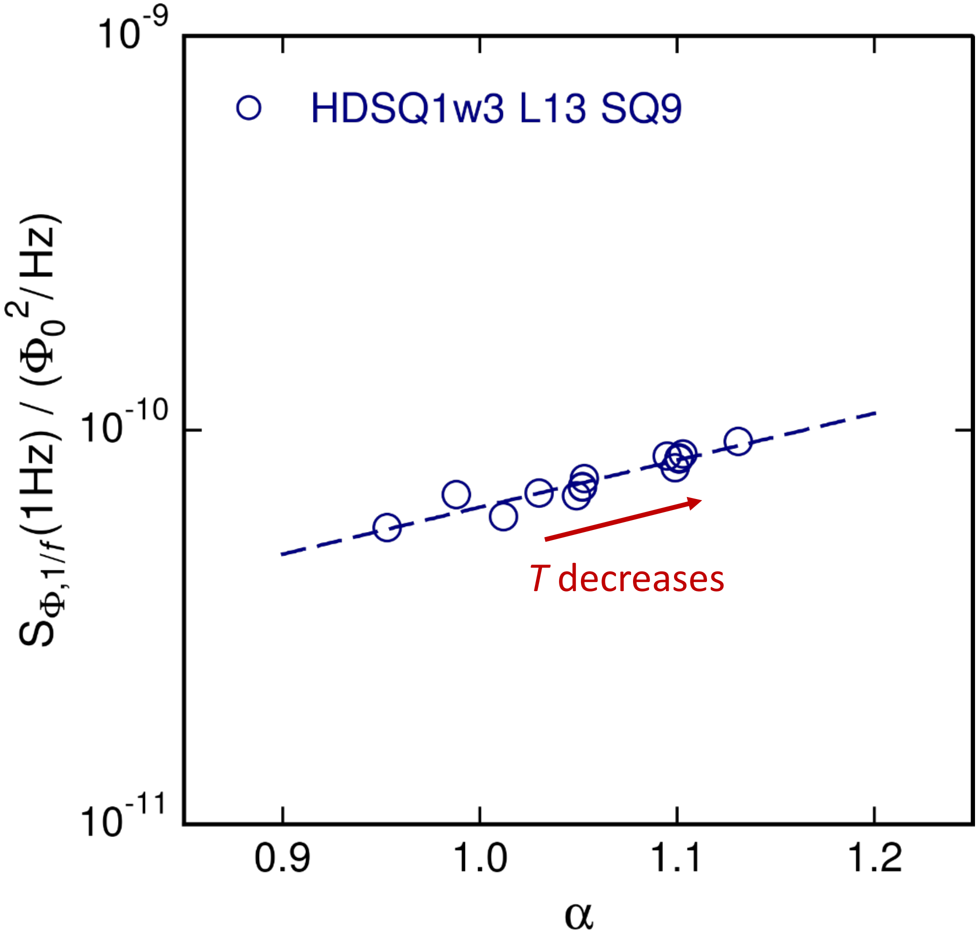


Temperature dependence of low-frequency noise

16-SQUID series array



Temperature dependence (continued)



advanced SQUIDs show pivoting, too

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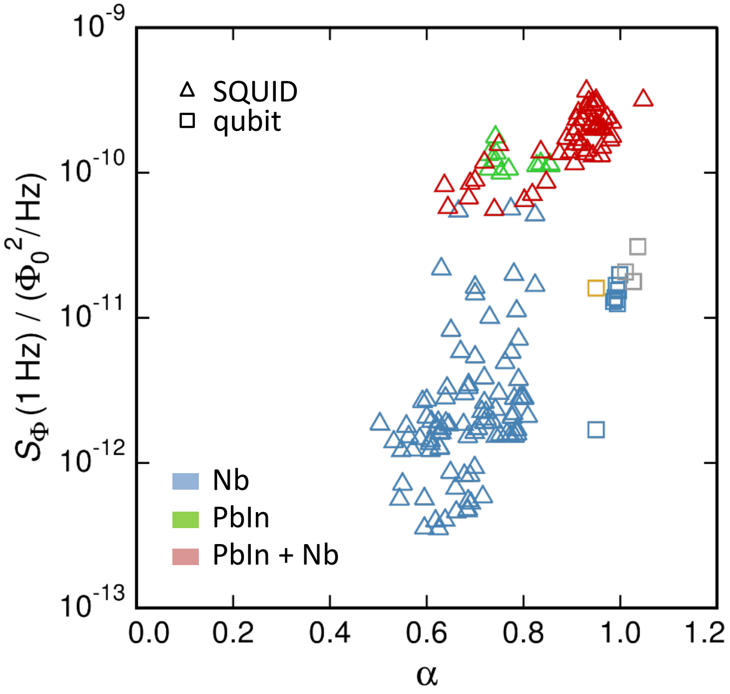
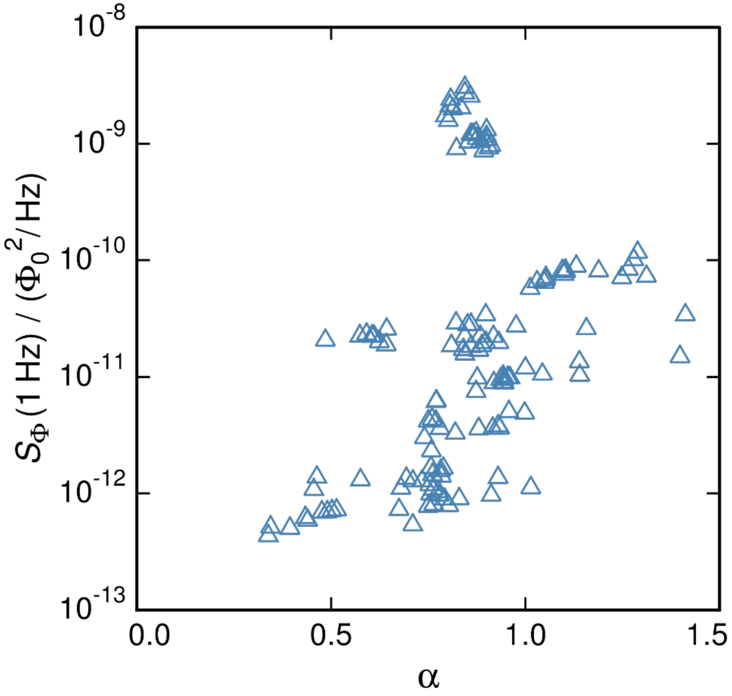
Look at the large data set

single SQUIDs / qubits



SQUID arrays



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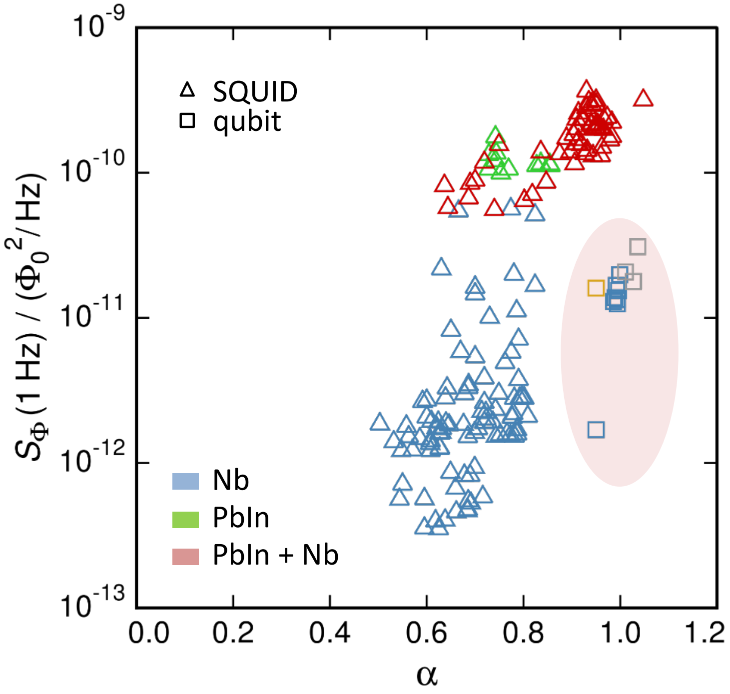
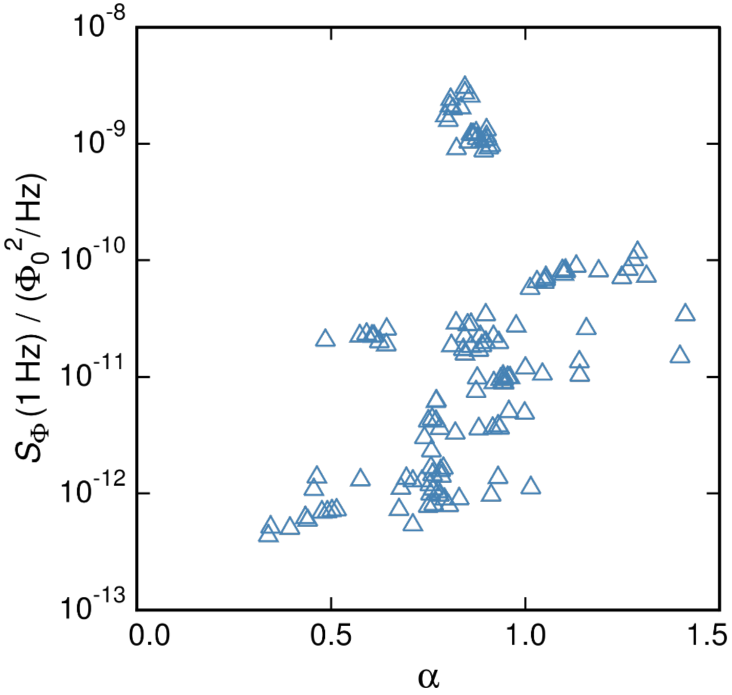
Look at the large data set (continued, I)

single SQUIDs / qubits

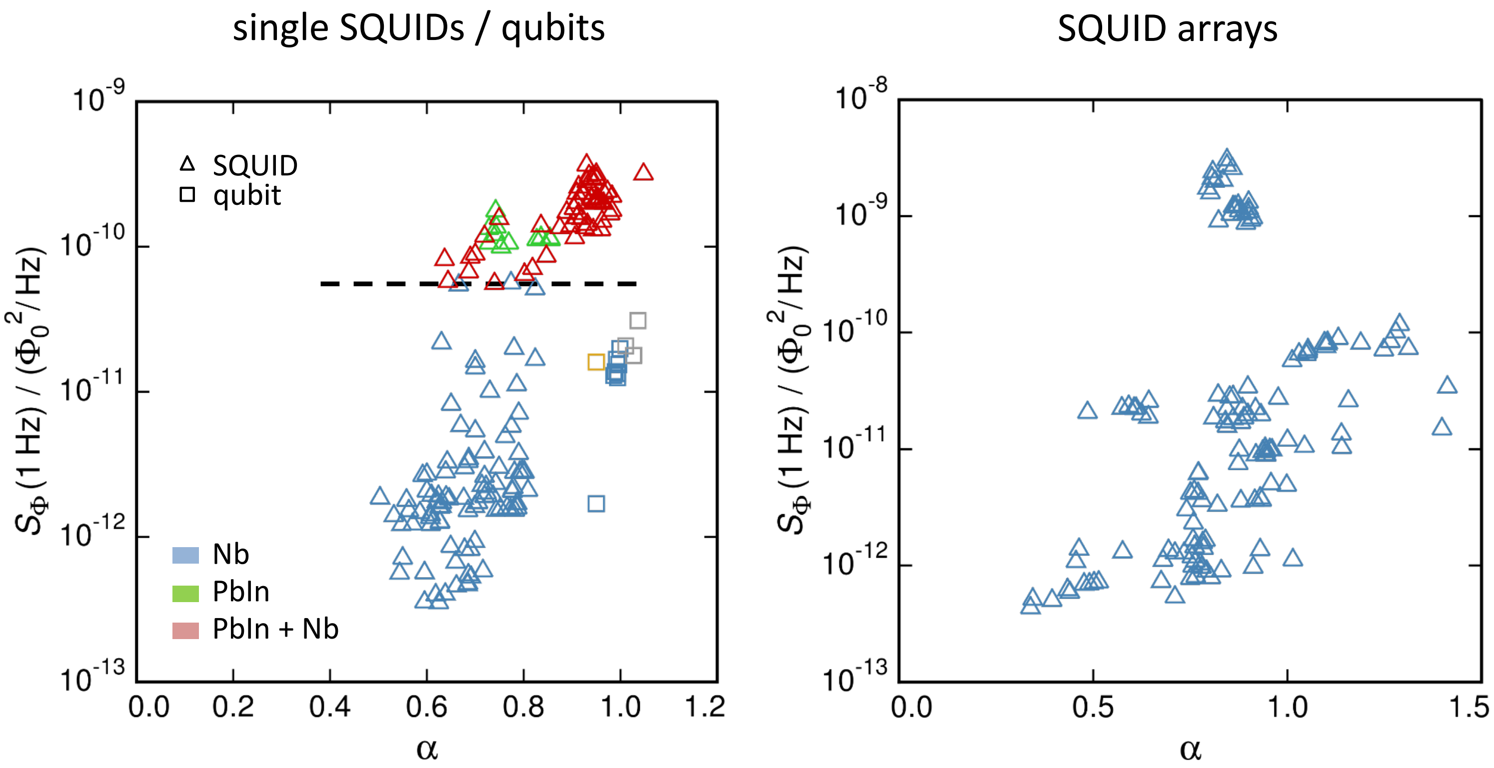


SQUID arrays



- qubits show α ≈ 1

Look at the large data set (continued, II)



- qubits show α ≈ 1
- PbIn / PbIn + Nb show higher noise than Nb

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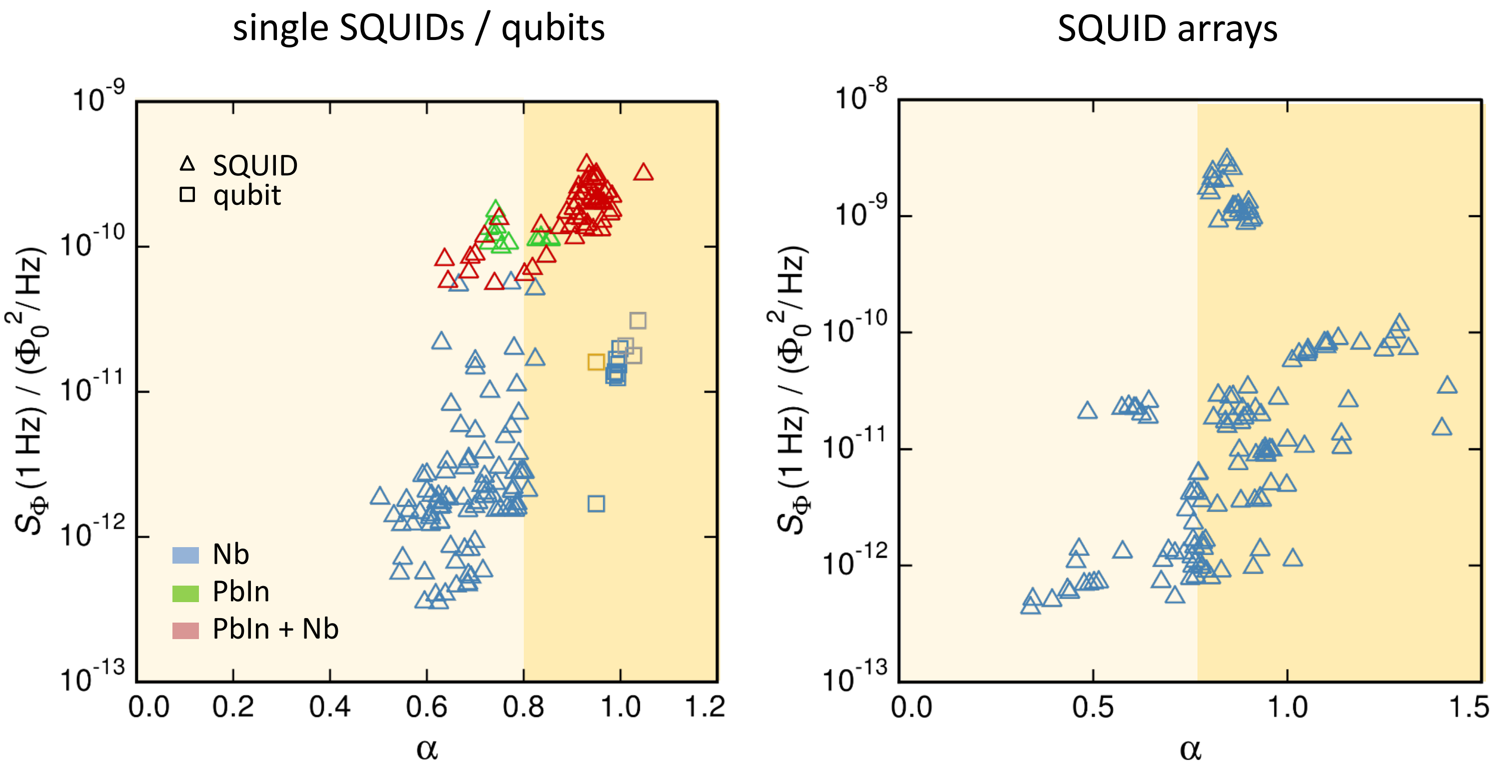
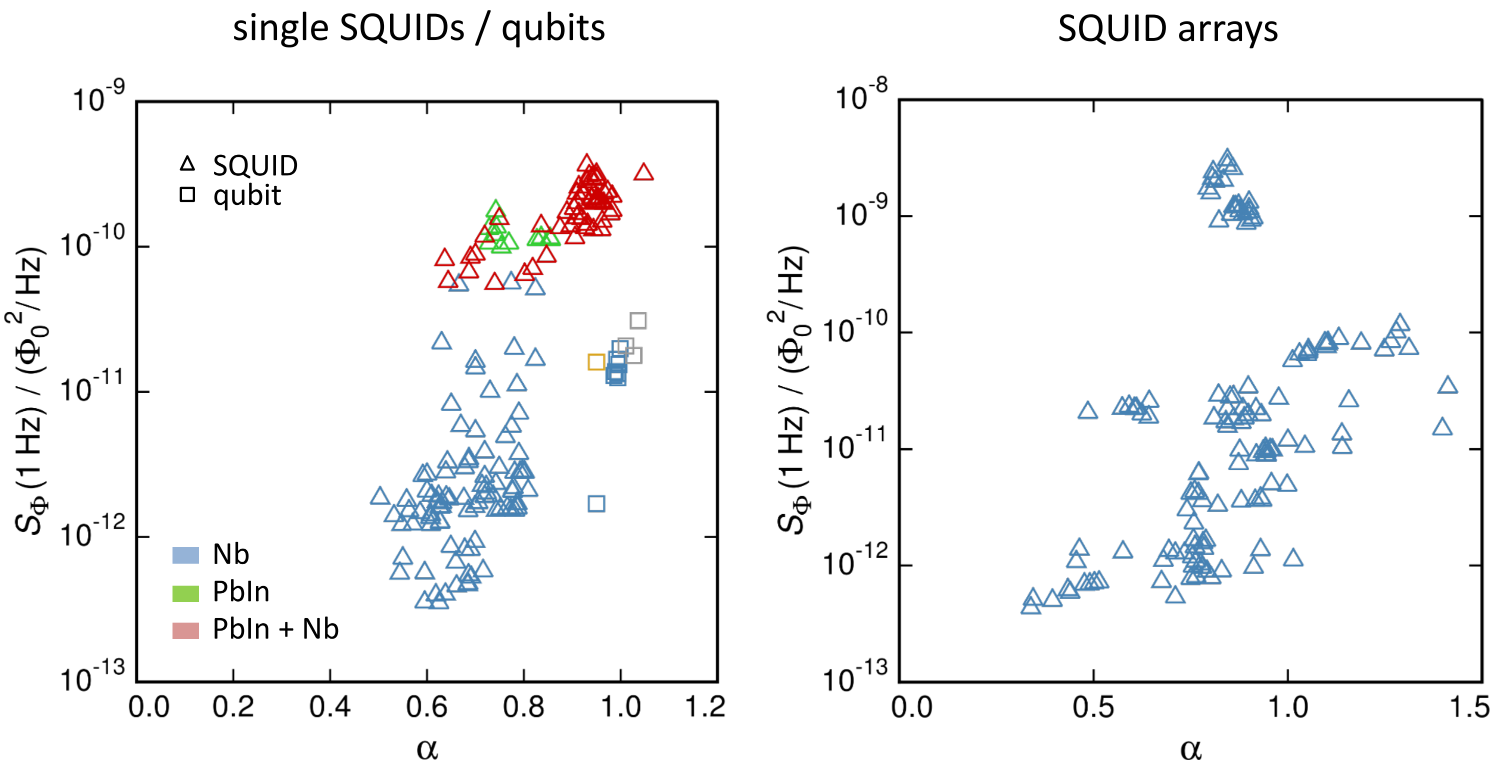
Look at the large data set (continued, III)



- qubits show α ≈ 1
- PbIn / PbIn + Nb show higher noise than Nb
- Nb SQUID arrays show higher a than single Nb SQUIDs

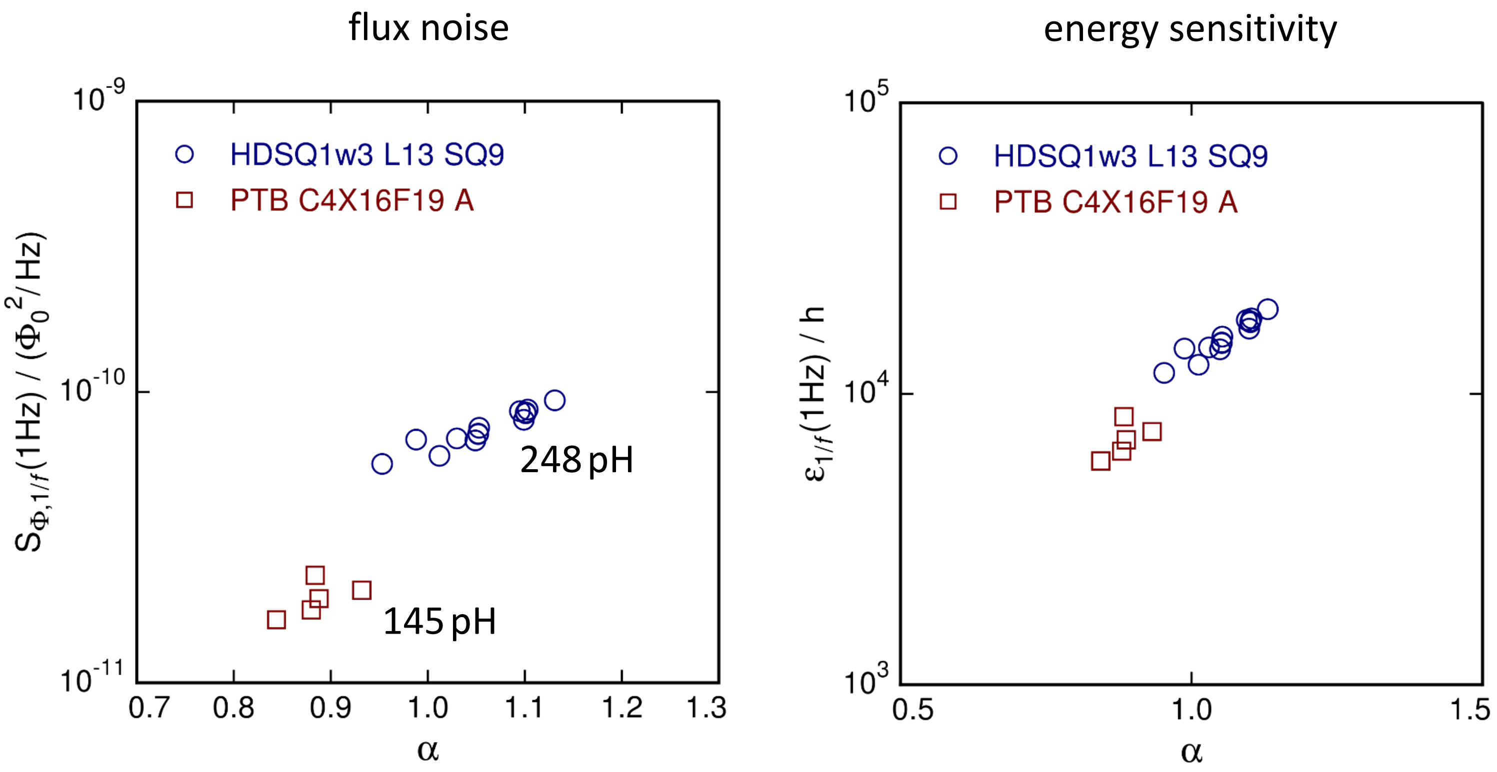
Look at the large data set (continued, IV)



material and device-type dependence of low-frequency excess flux noise

➡ possibility to engineer flux noise spectra

Flux noise and energy sensitivity versus α for two SQUIDs: comparison



correlation among different SQUIDs?

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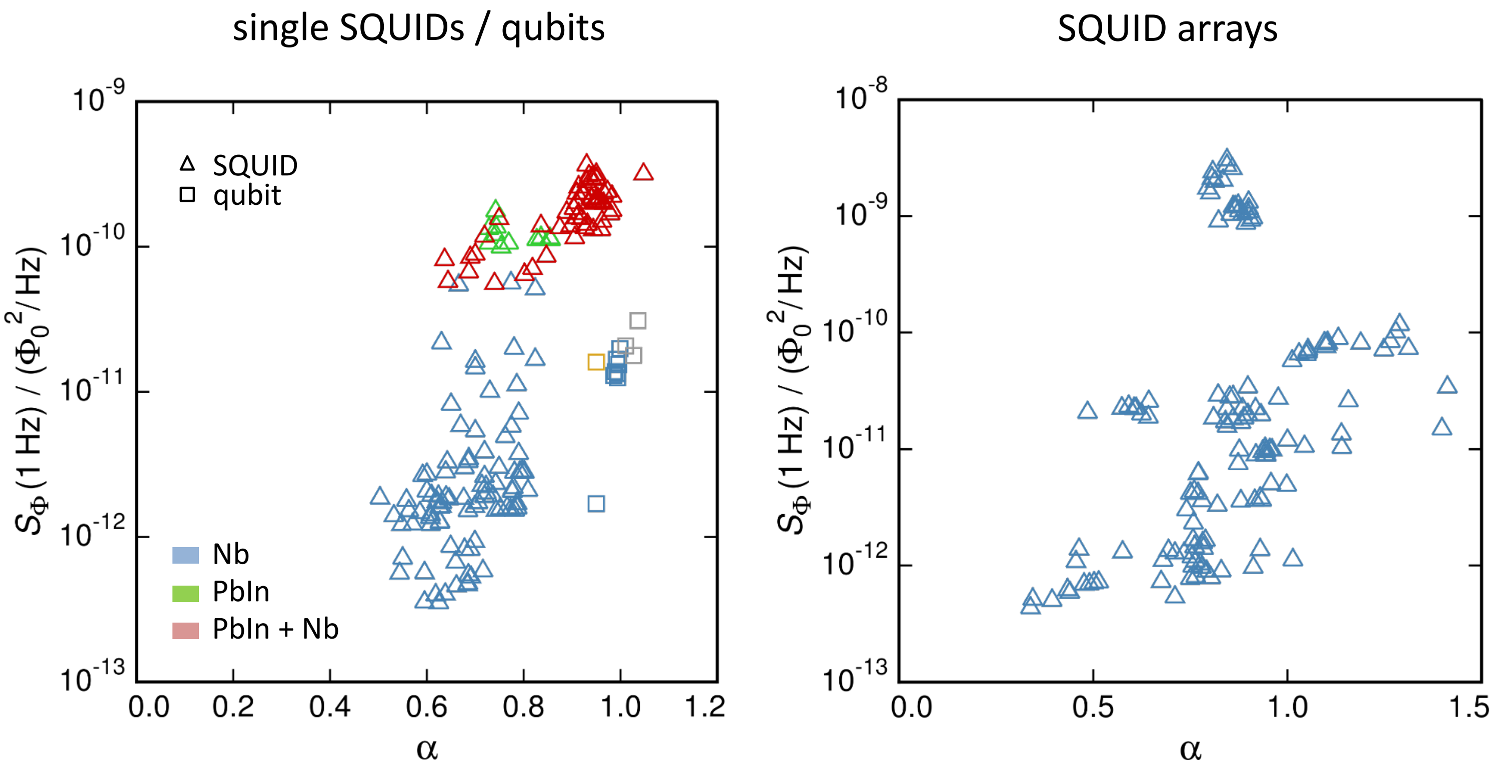
Large data set revisited (I)



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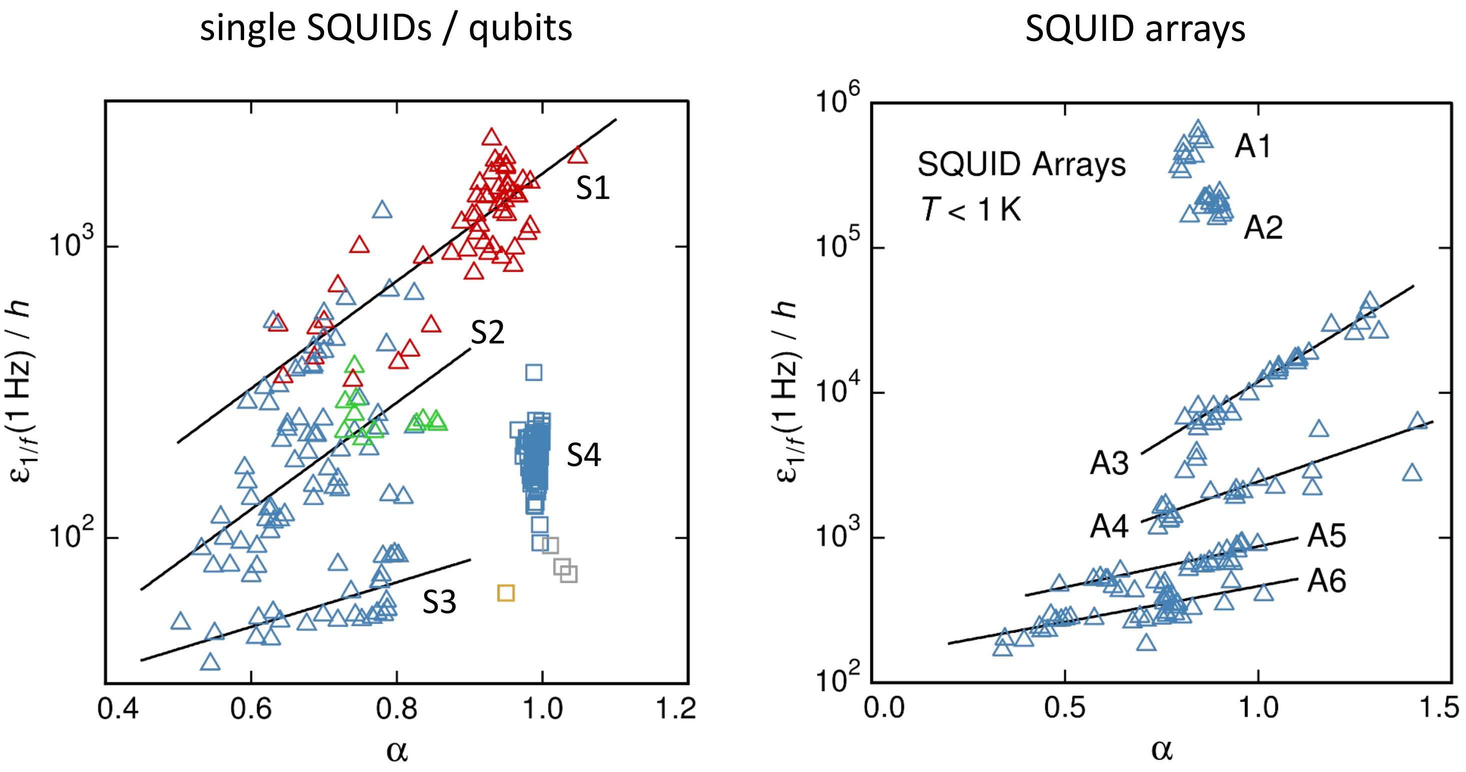
Large data set revisited (II)



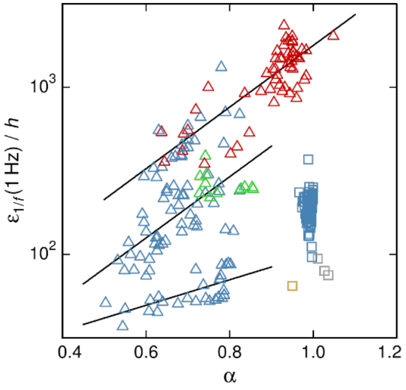
correlation between noise magnitude and exponent among different SQUIDs
and for different temperatures

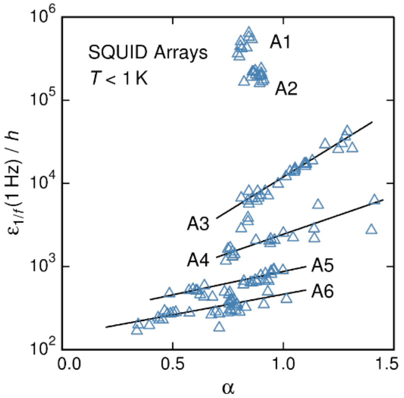
Large data set revisited (III)

group	N_{SQ}	N_{spec}	$f_{\mathrm{c}}/\mathrm{Hz}$	$\epsilon_{1/f}(f_{\mathrm{c}})/h$
S1	14	70	68.8 ± 18.4	25.5 ± 5.7
S2	15	58	67.9 ± 36.7	10.0 ± 3.8
S3	7	28	5.8 ± 2.1	17.2 ± 4.5
A3	6	30	44.2 ± 7.1	269.0 ± 45.2
A4	6	17	8.3 ± 2.7	294.8 ± 89.5
A5	3	26	3.7 ± 0.5	237.8 ± 26.4
A6	5	37	3.1 ± 0.6	148.1 ± 19.4

- pivot frequency depends on SQUID type
- SSAs show higher noise at pivot frequency

Summary and outlook





recent insights in low-frequency excess flux noise

- spectra pivot for advanced SQUIDs, too
- device type and material dependence
- universal correlation between noise magnitude and exponent
- possibility to engineer low-frequency noise

what‘s next?

- energy sensitivity vs. flux noise
- material dependence (nuclear spins, RKKY interaction, …)

Thank you for your attention!