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Noise spectroscopy of superinductors using fluxonium qubits

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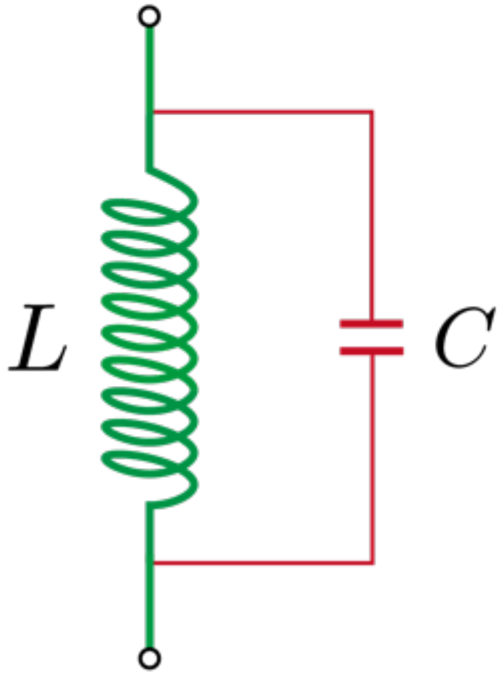
Superinductors



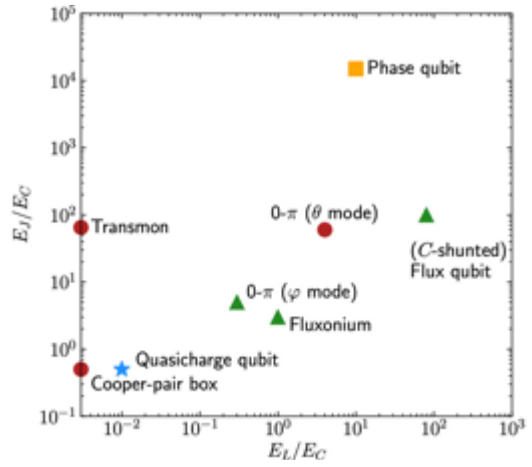
$$Z = \sqrt{L/C} \gtrsim R_Q$$

$$R_Q = \frac{h}{(2e)^2} \approx 6.5\ k\Omega$$

$$L \gtrsim 300\ \text{nH}$$

Applications of superinductors

High impedance qubits

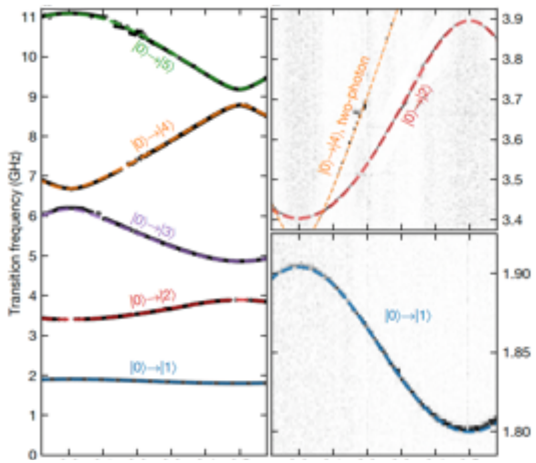


- $E_L/E_C \lesssim 1$ for qubits like fluxonium, blochnium, and $0-\pi$.

- Impedance exceeding the resistance quantum R_Q.

PRX Quantum **2**, 040204 (2021)

Flux noise suppression



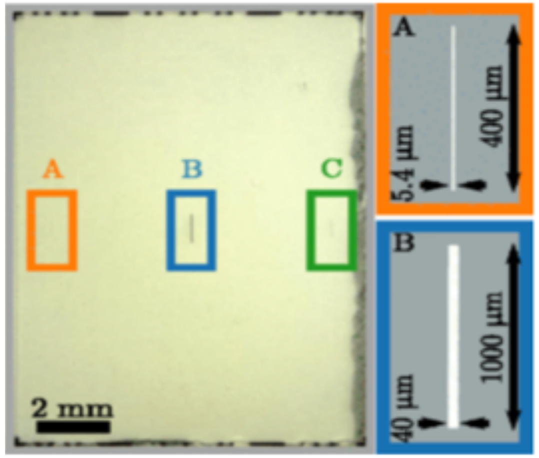
- Dephasing ~ $\frac{\partial\omega}{\partial\Phi}A\sqrt{\ln 2}$

- Relaxation

~ $\Re[Y(\omega)] = \frac{\tan\delta_L}{\omega L}$.

Nature **585**, 368 (2020)

Miniaturized circuits



- Large L, small C

- Small footprint for future large scale implementation.

Phys. Rev. Lett. **121**, 117001 (2018)

Superinductance from kinetic inductance

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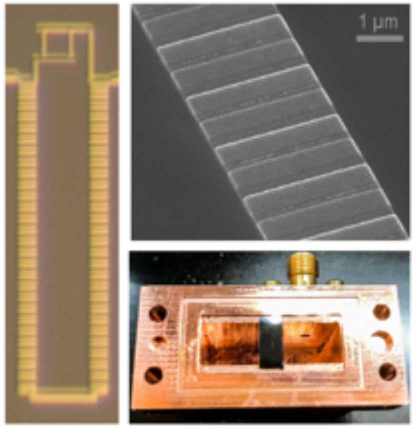
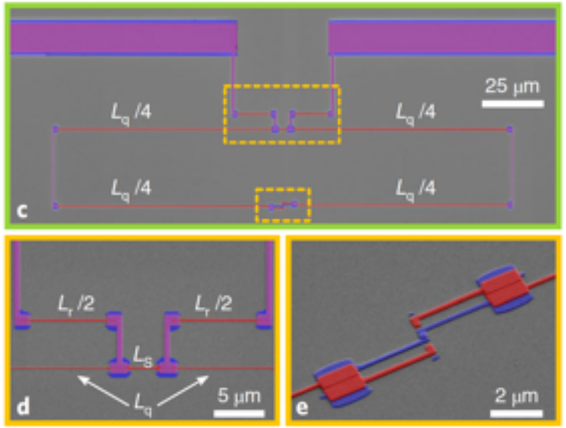
"Ordered" Josephson-junction array

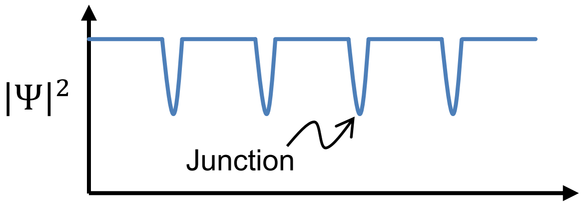


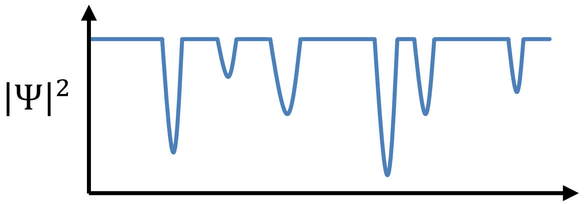
Phys. Rev. Lett., **120** 150503 (2018)

Disordered superconductor



Nat. Mater., **18** 816 (2019)





Conductivity ↓ → L_k ↑

Charge density ↓ → L_k ↑

What are the decoherence mechanisms?

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- Dielectric loss

  Somoroff, A. *et al*. arXiv:2103.08578 (2021)
  Nguyen, L. et al. Phys. Rev. X 9, 041041 (2019)
  Zhang, H. et al. Phys. Rev. X 11, 011010 (2021)

- Quasiparticles tunneling

  Pop, I. M. *et al.* Nature 508, 369 (2014)
  Vool, U. *et al.* Phys. Rev. Lett. 113, 247001 (2014)
  Grünhaupt L. et al. Phys. Rev. Lett. 121, 117001 (2018)

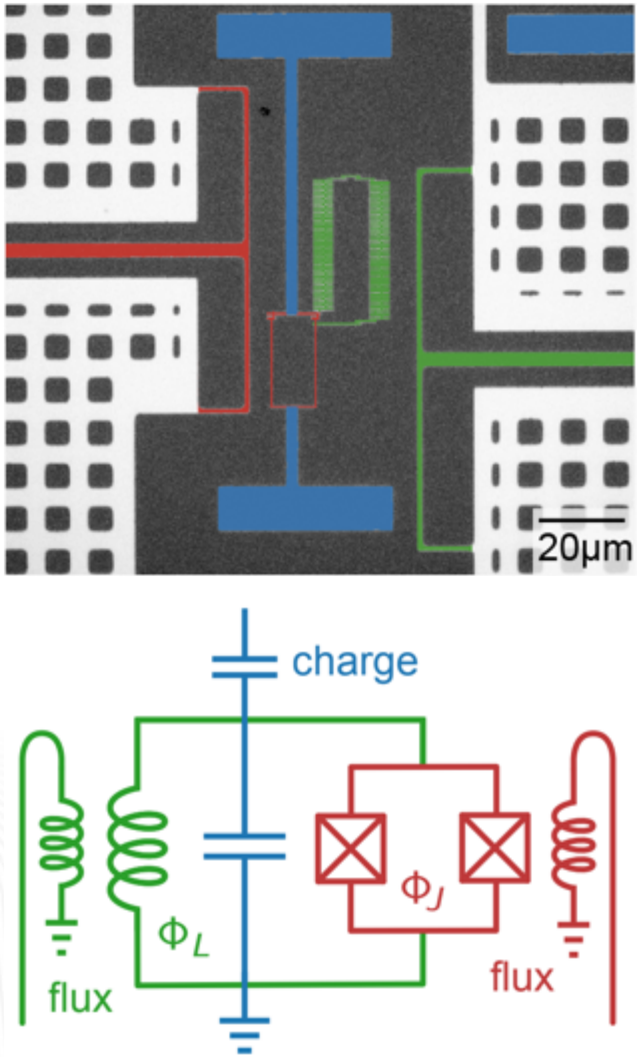
- Coherent phase slip in the junction array

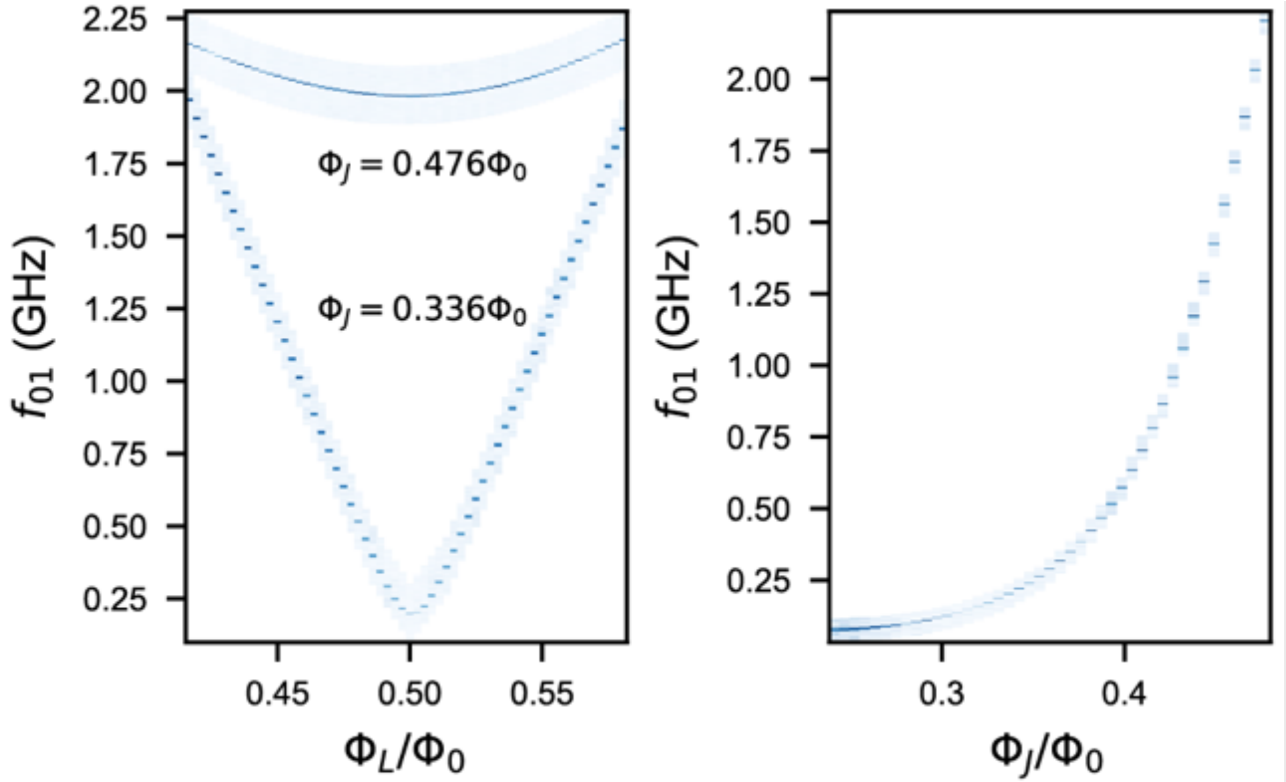
  Manucharyan, V. et al. Phys. Rev. B 85, 024521 (2012)

- Other mechanisms such as long live TLS

  Spiecker, M. et al. arXiv:2204.00499 (2022)

Tunable fluxonium with individual flux control





Two major challenges in decoherence studies:

- **Device-to-device variation**
- **Cooldown-to-cooldown variation**

Mitigated by *in-situ* tunability of circuit parameters like E_J

Relaxation and dephasing

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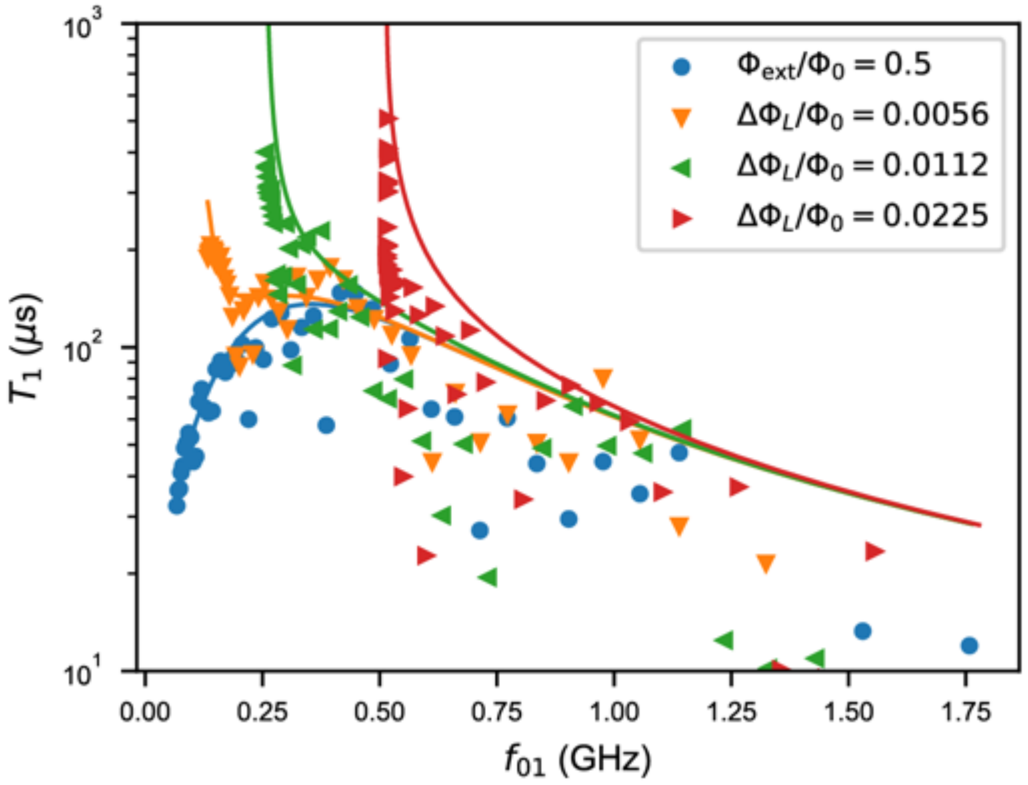
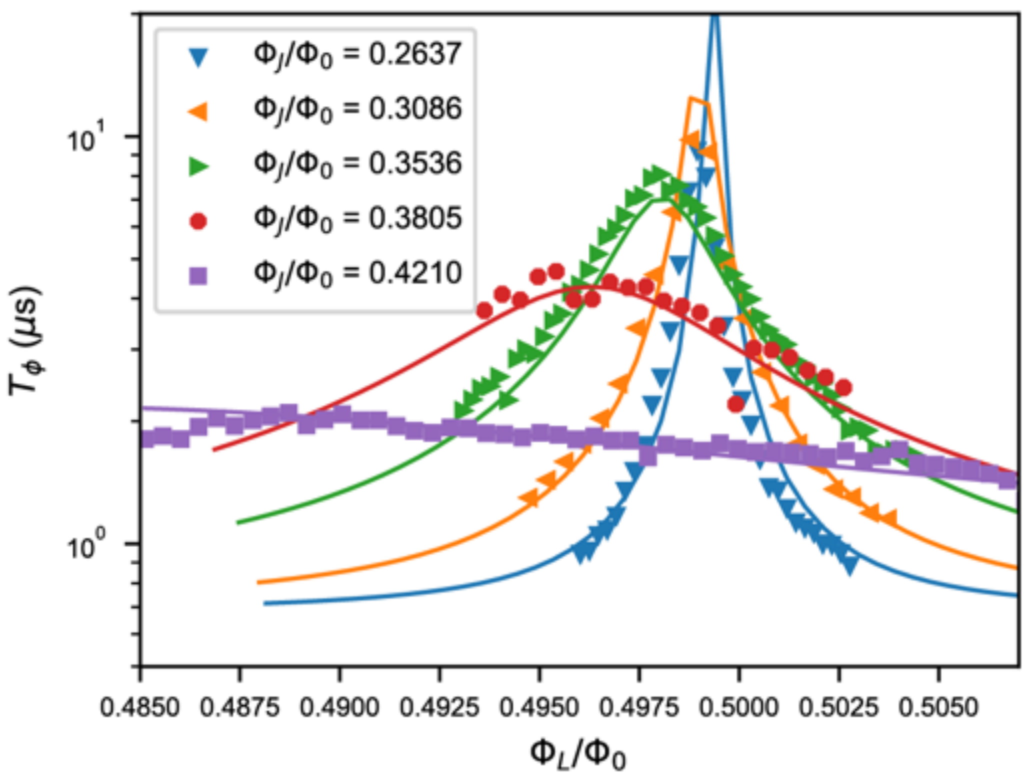




$$\Gamma_1^{diel} = \frac{\hbar\omega_{01}^2}{4E_C}|\langle 0|\varphi|1\rangle|^2 \tan\delta_C(\omega_{01}) \coth\frac{\hbar\omega_{01}}{2k_B T_{eff}}$$

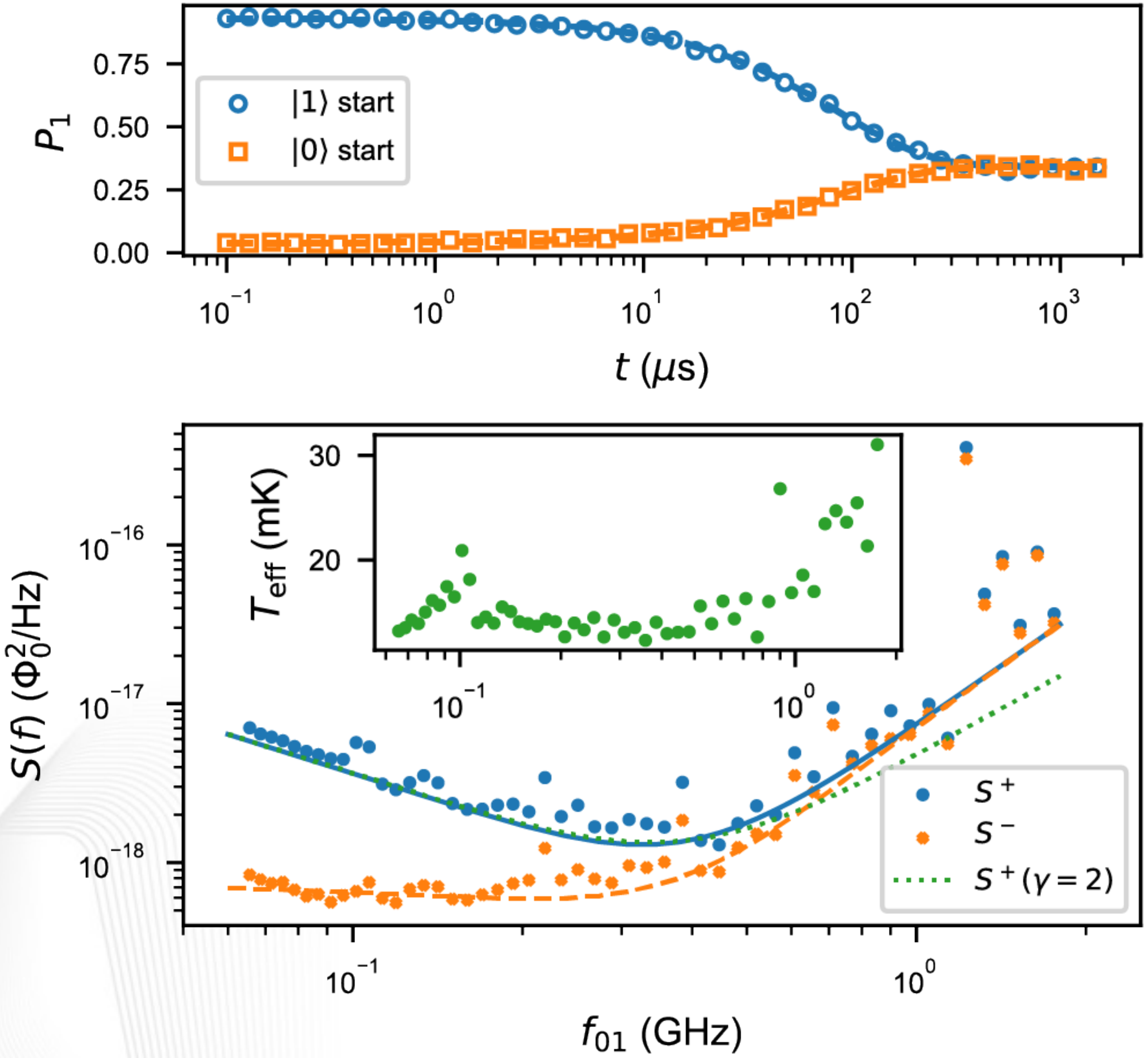
$$\Gamma_1^{1/f} = \frac{E_L^2}{\hbar^2\varphi_0^2}|\langle 0|\varphi|1\rangle|^2 \frac{2\pi A_L}{\omega_{01}}\left(1 + \exp\frac{-\hbar\omega_{01}}{k_B T_{eff}}\right)$$

$\tan\delta_C = 2\times10^{-6}$ and

$A_L = 14\ \mu\Phi_0/\sqrt{Hz}$

Fits all the data

Noise spectroscopy



Noise spectra in flux noise:

$$S^+(\omega) = \frac{(2e)^2L^2}{T_1|\langle 0|\hat{\varphi}|1\rangle|^2}$$

$$S^-(\omega) = S^+(\omega)\tanh\frac{\hbar\omega}{2k_BT}$$

Classical-to-quantum transition

Fitting function:

$$S^+(\omega) = \frac{2\pi A_L}{\omega}\left(1+\exp\frac{-\hbar\omega}{k_BT}\right) + \frac{\hbar^3\varphi_0^2}{4E_CE_L^2}\tan\delta_C \times\omega^{\gamma}$$

Flux-to-dielectric-loss transition

Sun, H., Feng W. *et al*. arXiv:2302.08110 (2023)

Decoupling to TLS at low frequencies

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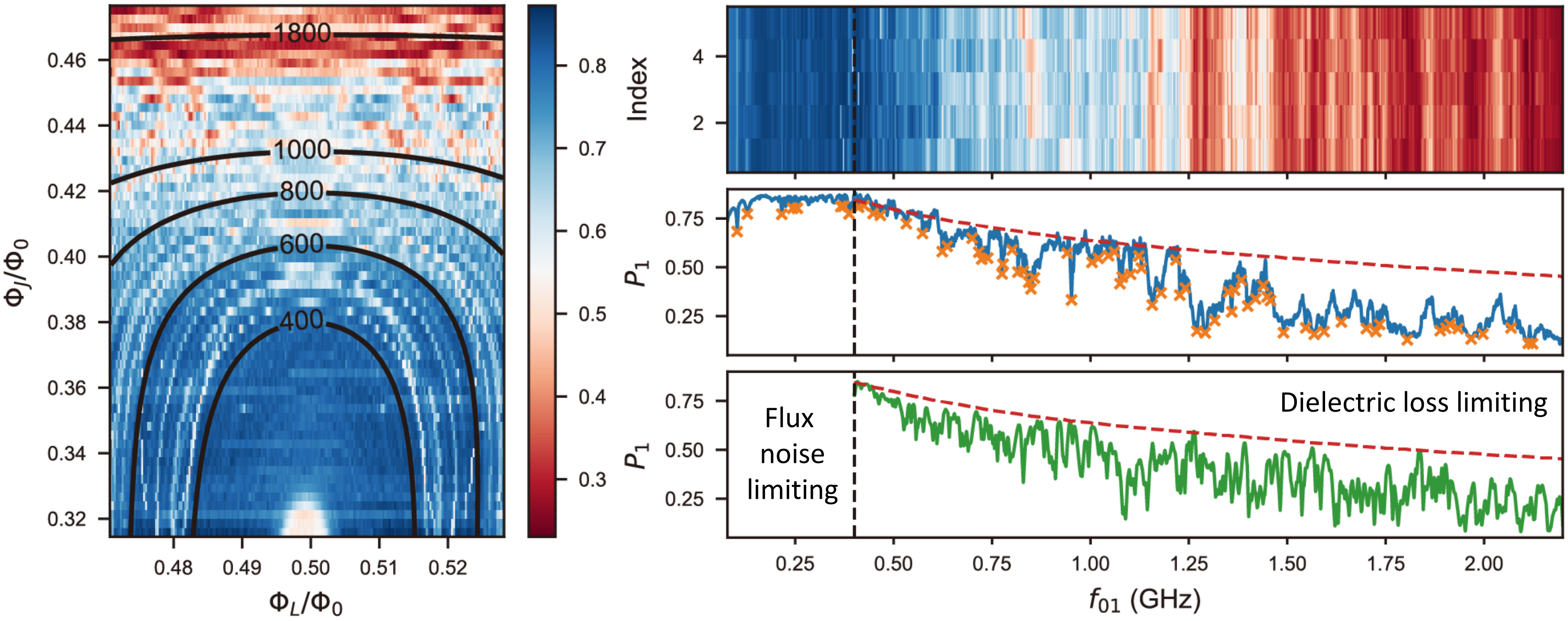
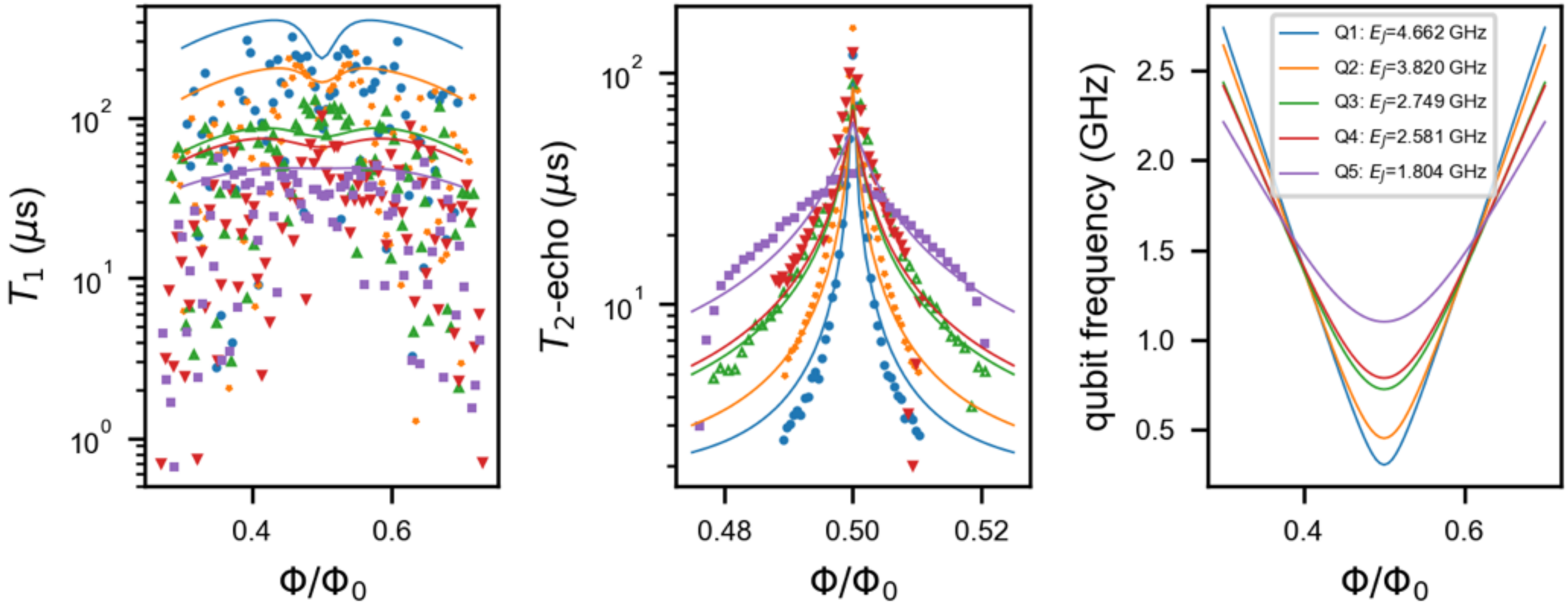


$$\Gamma_1 = \frac{\hbar\omega_{01}^2}{4E_C}\tan\delta_C\,|\langle 0|\hat{\varphi}|1\rangle|^2$$

Sun, H., Feng W. *et al*. arXiv:2302.08110 (2023)

Additional data on multiple devices

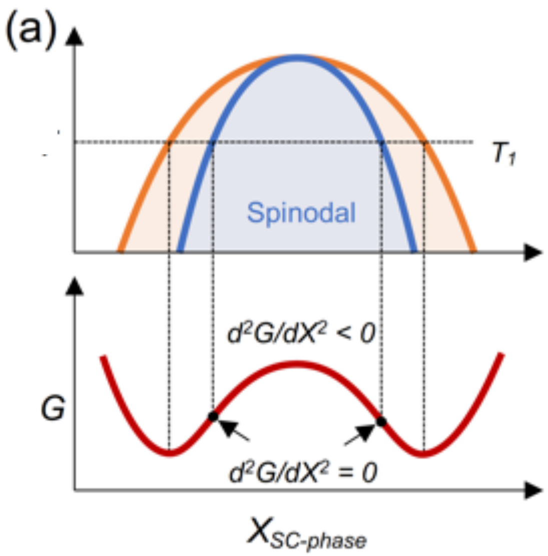


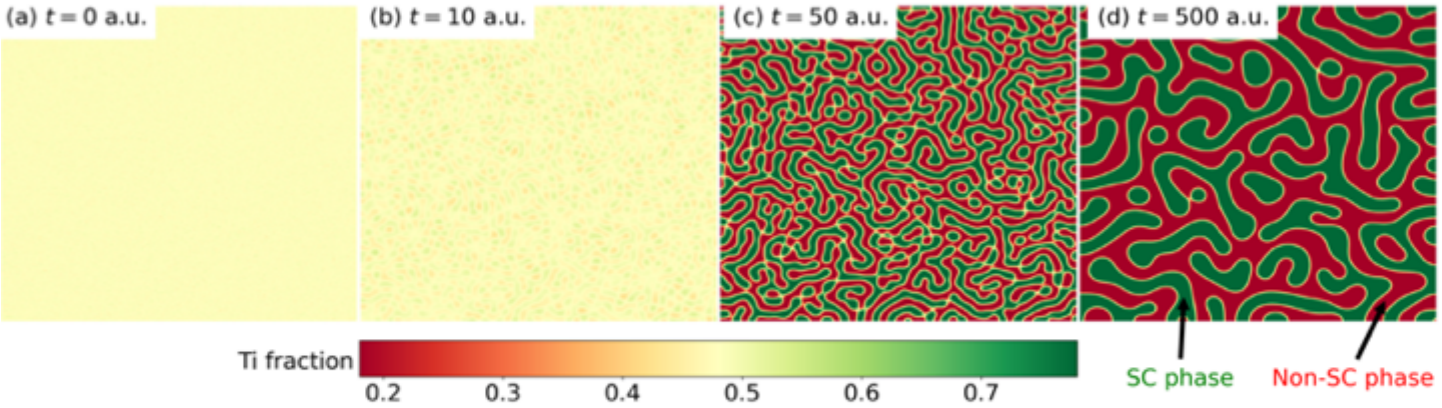
$tan\,\delta_C \sim 3\times10^{-6}$ and

$A\sim7\ \mu\Phi_0/\sqrt{Hz}$ fits all the data

How about the noise in disordered superinductors?

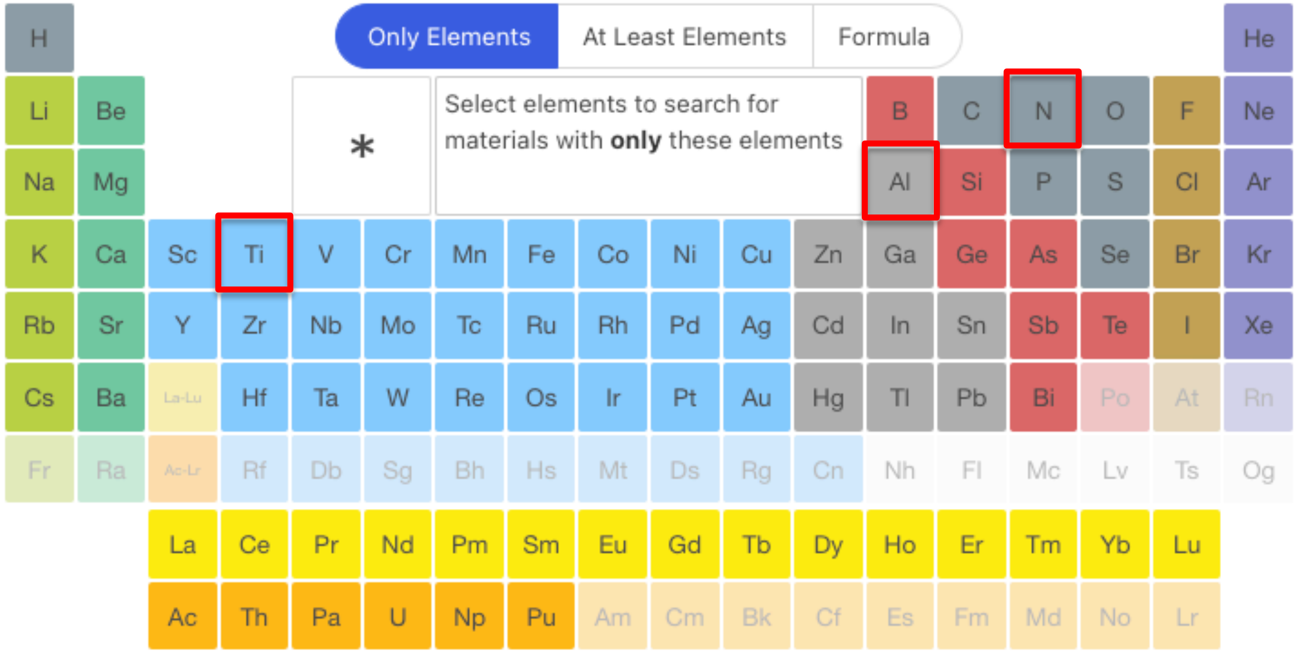
An alternative method: spinodal materials

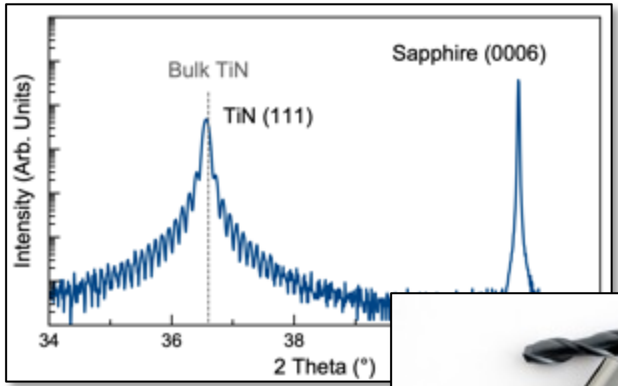




- Spinodal decomposition is a spontaneous phase segregation process ($\partial^2 G/\partial^2 X < 0$) in the compound.
- As given in our numerical simulation, clear phase segregation evolves as a result of the atomic diffusion.

Ti-Al-N



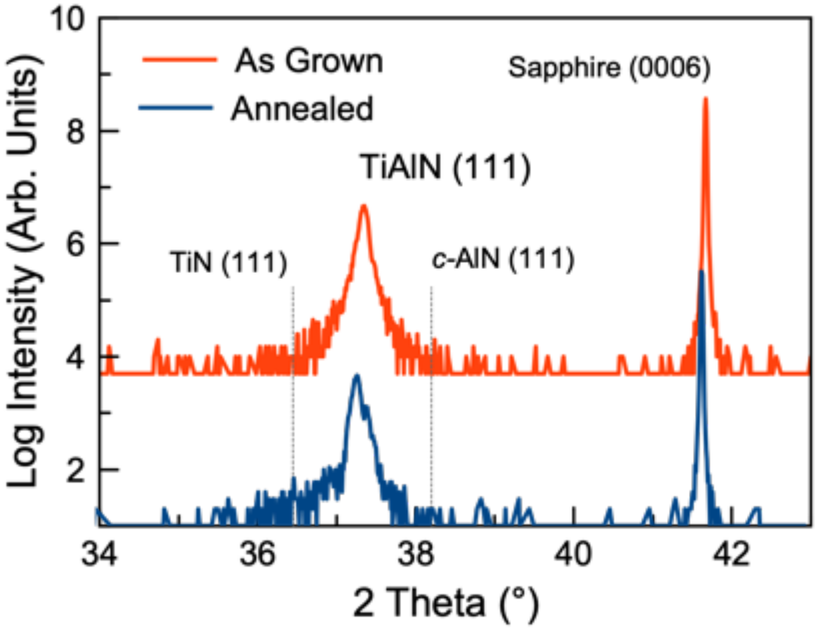


- TiN: a well-known low-loss superconducting material, can be grown with excellent quality.
- AlN: a wide bandgap insulator without complex AlN_x compounds.
- A well studied system in hard-coating.

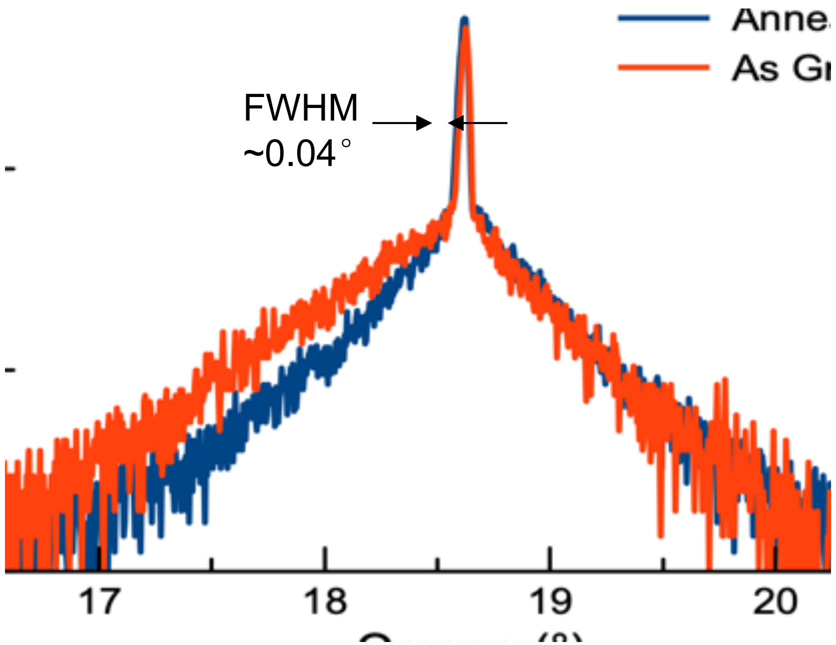
R. Gao *et al.*, *Phys. Rev. Mater.*, **6** 036202 (2022)

❑ Structure evolution after annealing (30min@1000° C)

XRD line scans



Rocking curves



Gao, R. *et al*. Adv. Mater. 34, 2201268 (2022)

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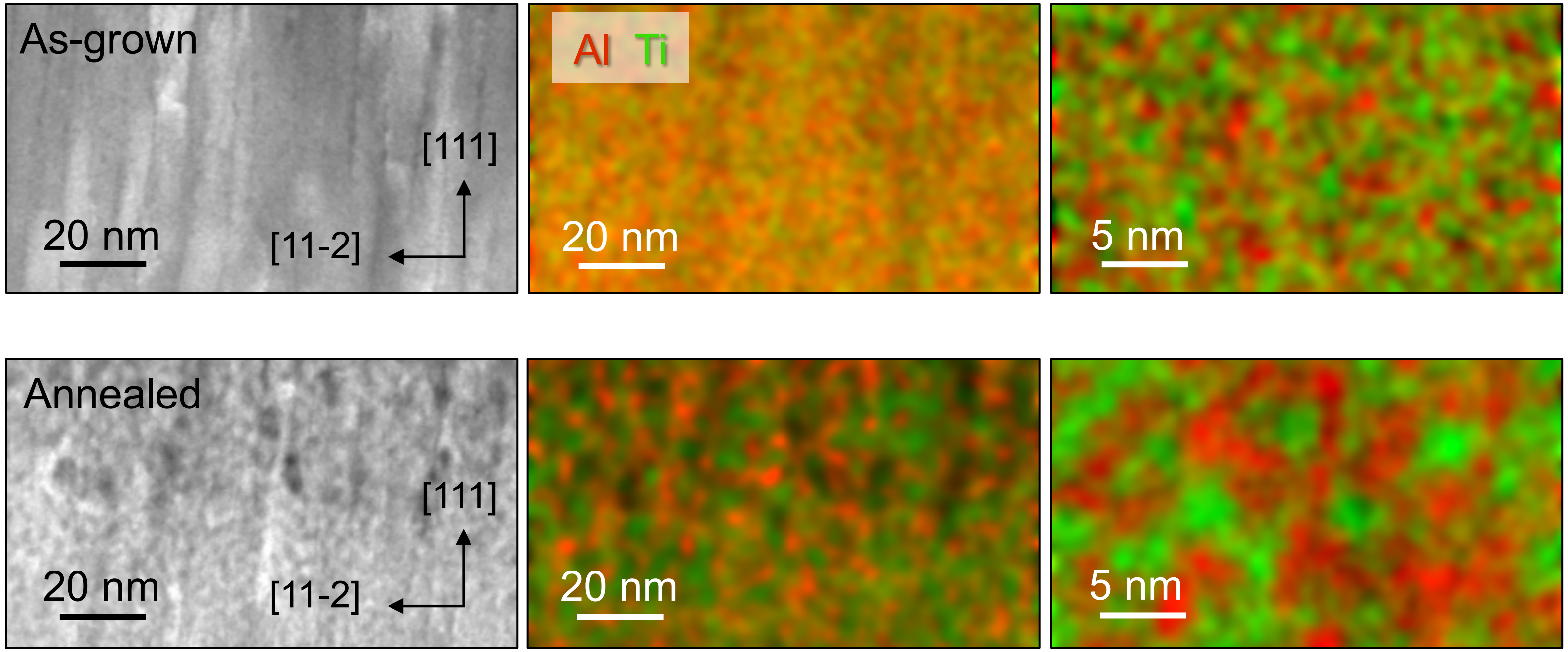
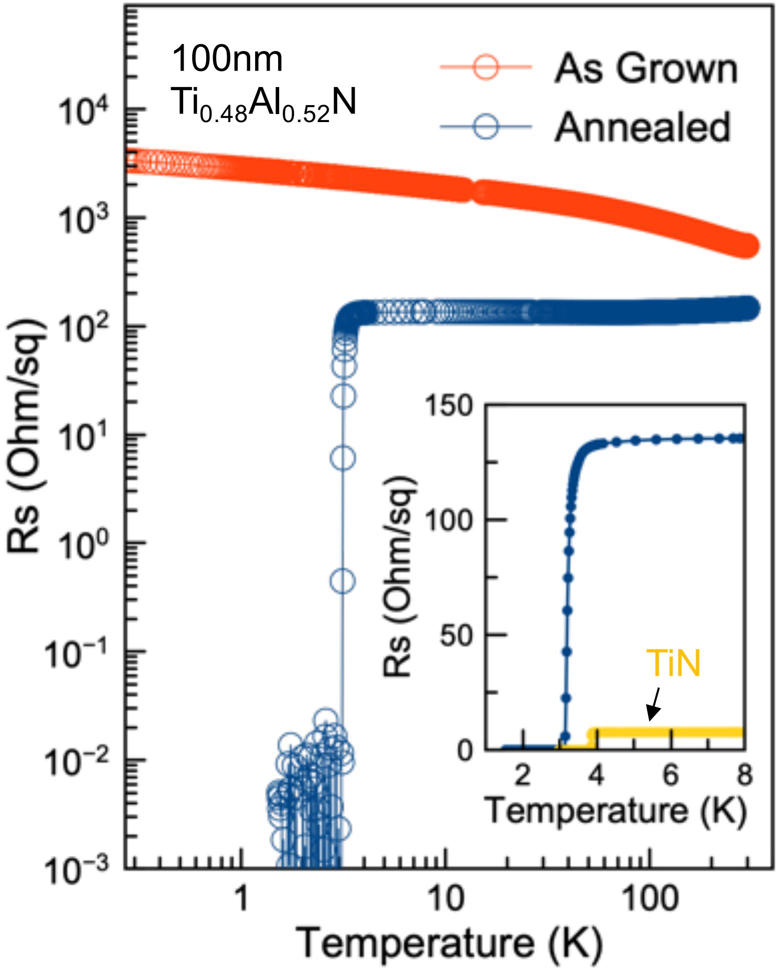
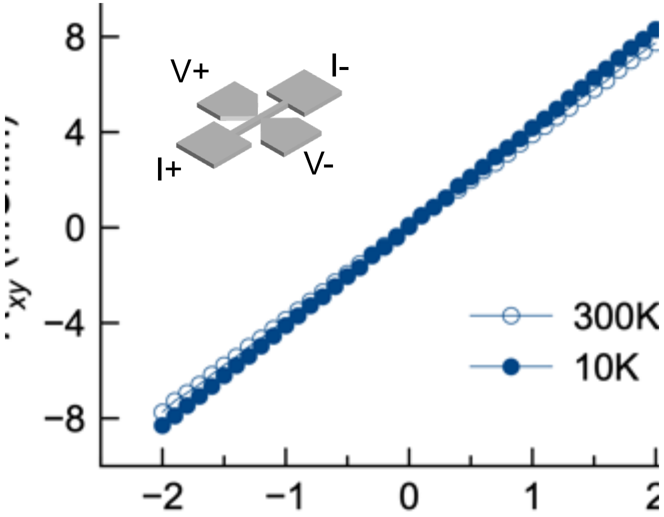
❑ TEM-EDX studies:



Gao, R. *et al*. Adv. Mater. 34, 2201268 (2022)

Electrical properties



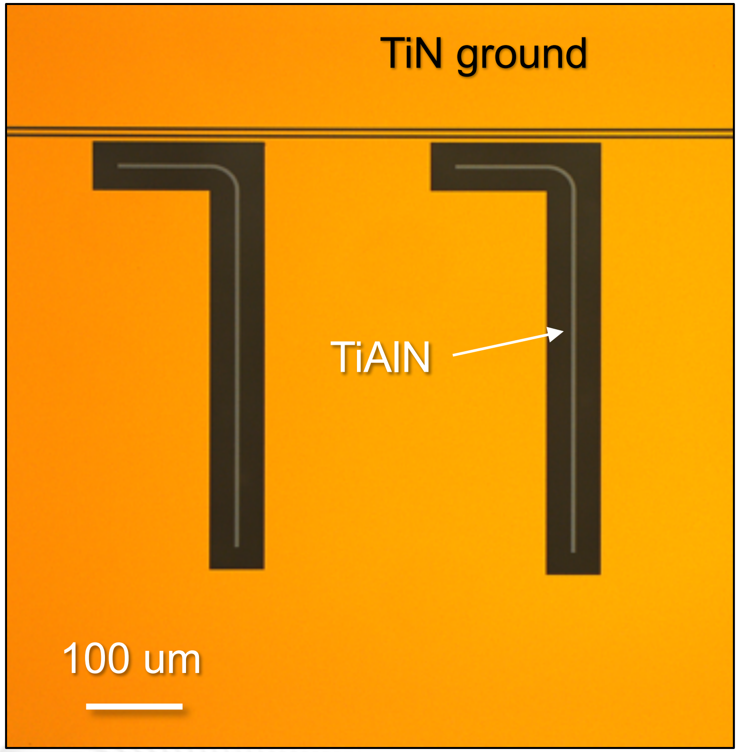


Materials	$d\ (nm)$	$l\ (nm)$	n_e^{10K} (cm^{-3})	$k_F l$
TiN	98	1.33	4.46×10^{22}	14.6
TiAlN	100	0.18	1.60×10^{22}	1.38

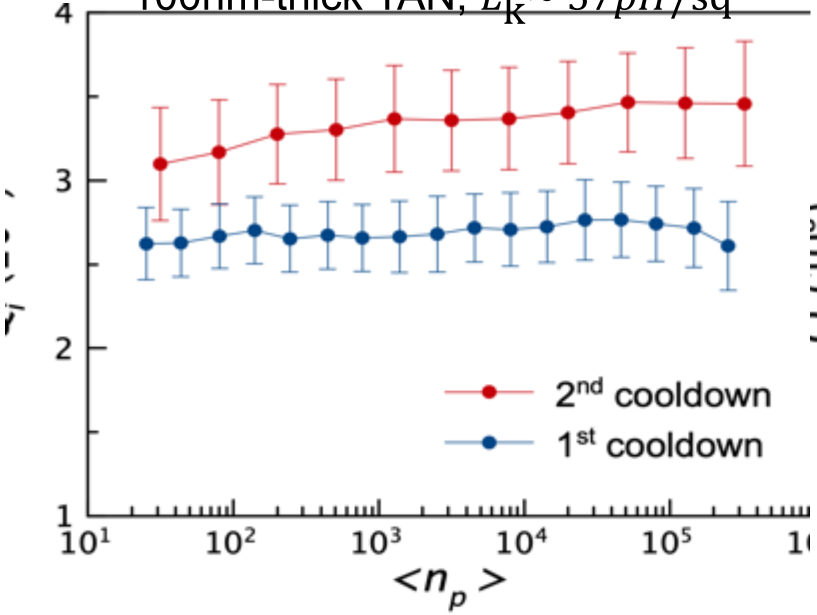
- A sharp increase in sheet resistance → $L_k = 57\ pH/sq$ for a 100nm-thick film, ~ 2 orders of magnitude larger than TiN.
- The annealed TiAlN behave as a strongly disordered material ($k_F l \to 1$).

Gao, R. *et al*. Adv. Mater. 34, 2201268 (2022)

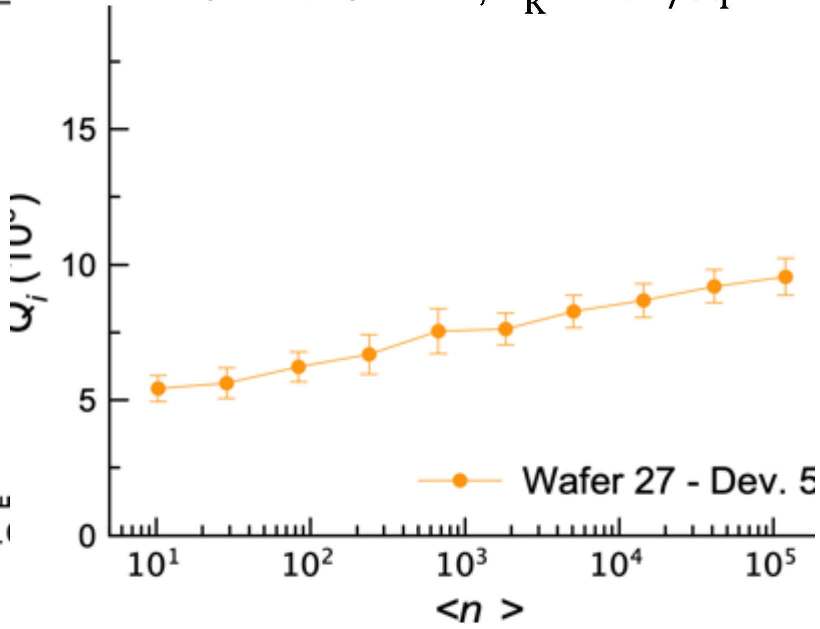
Ultra-high inductance with decent quality



100nm-thick TAN, $L_k \sim 57pH/sq$

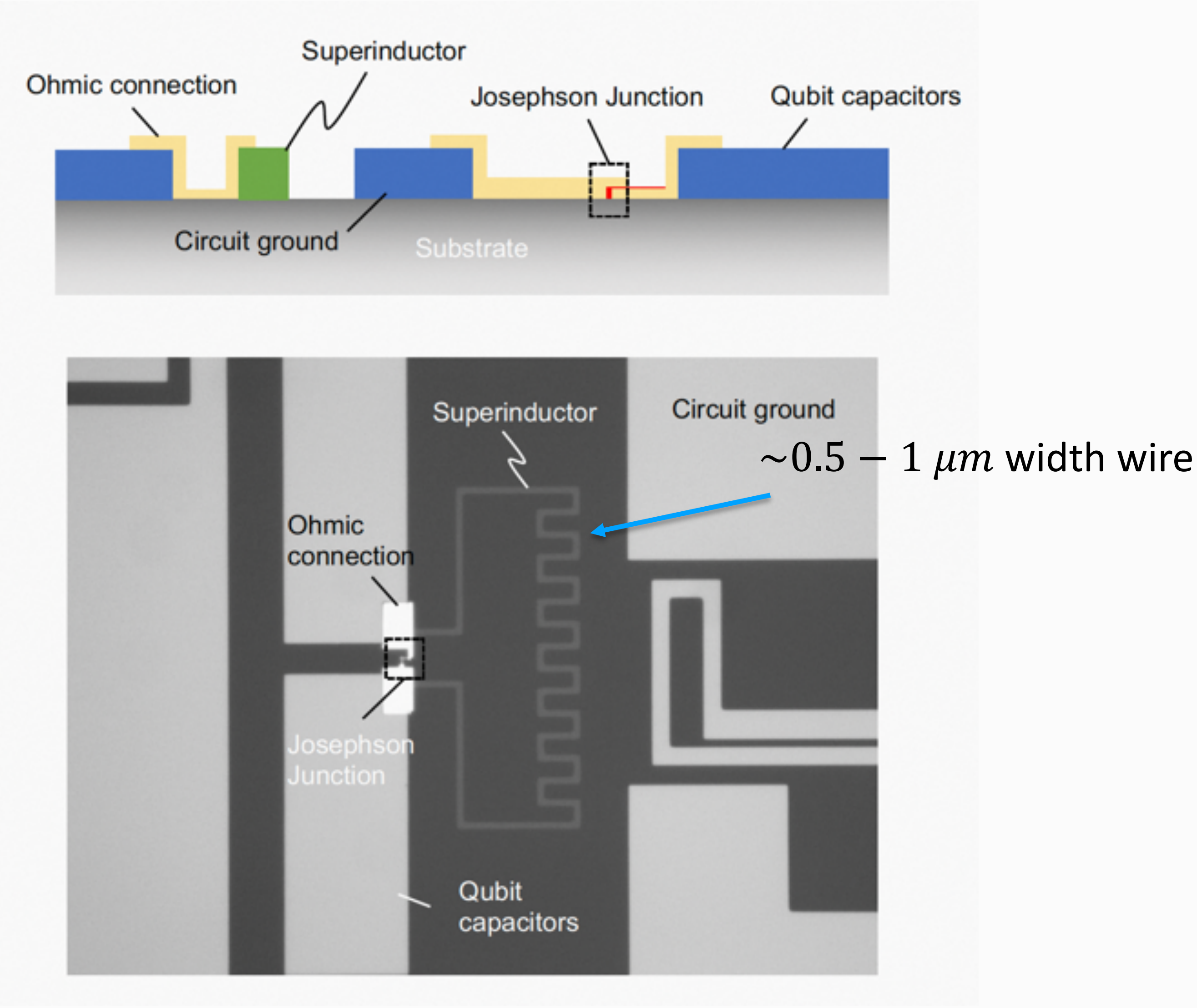


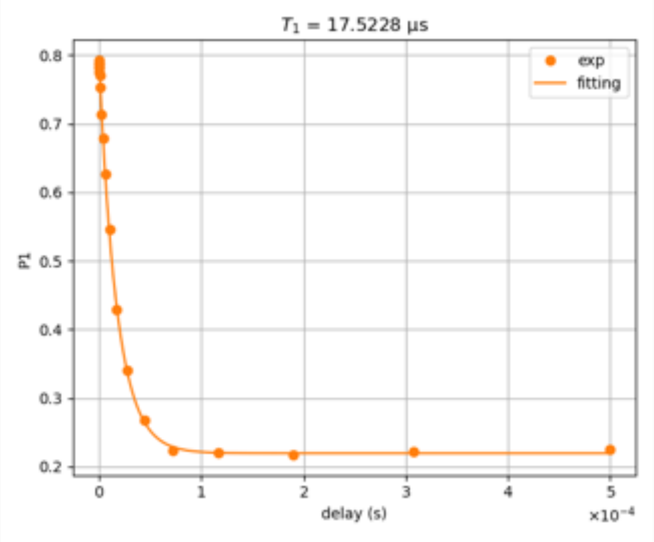
20nm-thick TAN, $L_k \sim 1nH/sq$

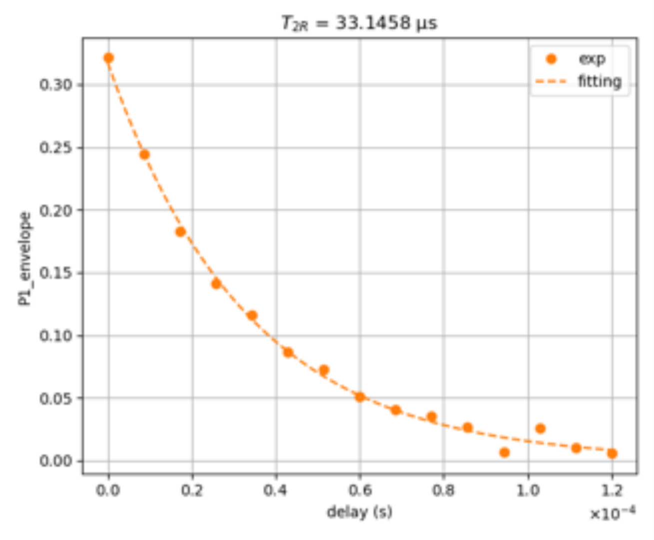


Gao, R. *et al*. Adv. Mater. 34, 2201268 (2022)

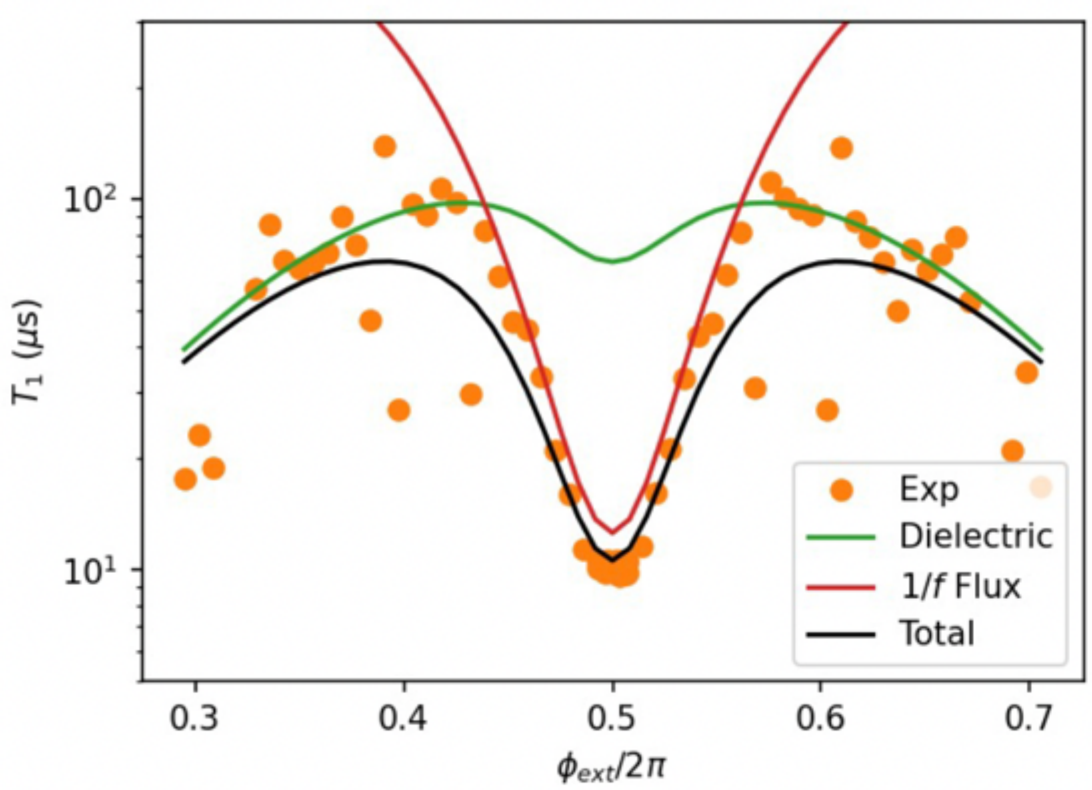
Superinductor from disordered materials

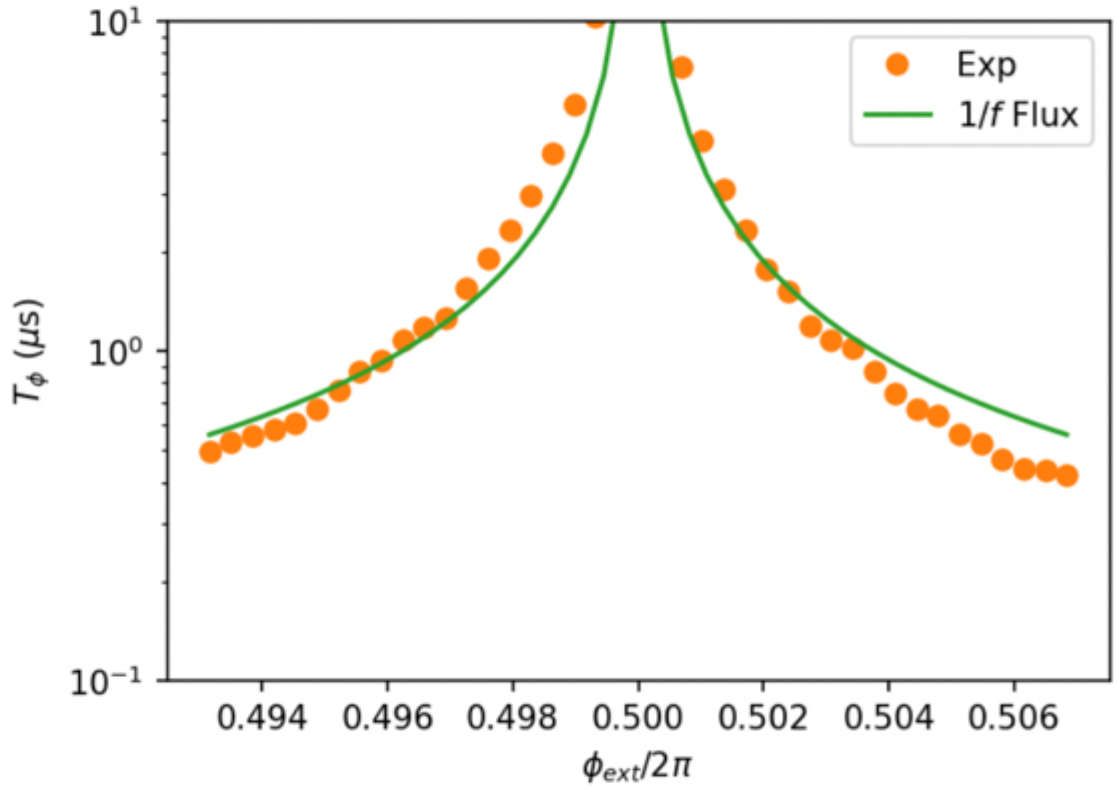






Noise properties of Ti-Al-N qubit





From relaxation:
$\tan \delta_C < 2.5\times10^{-6}$ and
$A \sim 110\ \mu\Phi_0/\sqrt{Hz}$

From dephasing:
$A \sim 90\ \mu\Phi_0/\sqrt{Hz}$ from echo and
$A \sim 40\ \mu\Phi_0/\sqrt{Hz}$ from Ramsey

Work in progress: what is the tunning knob?

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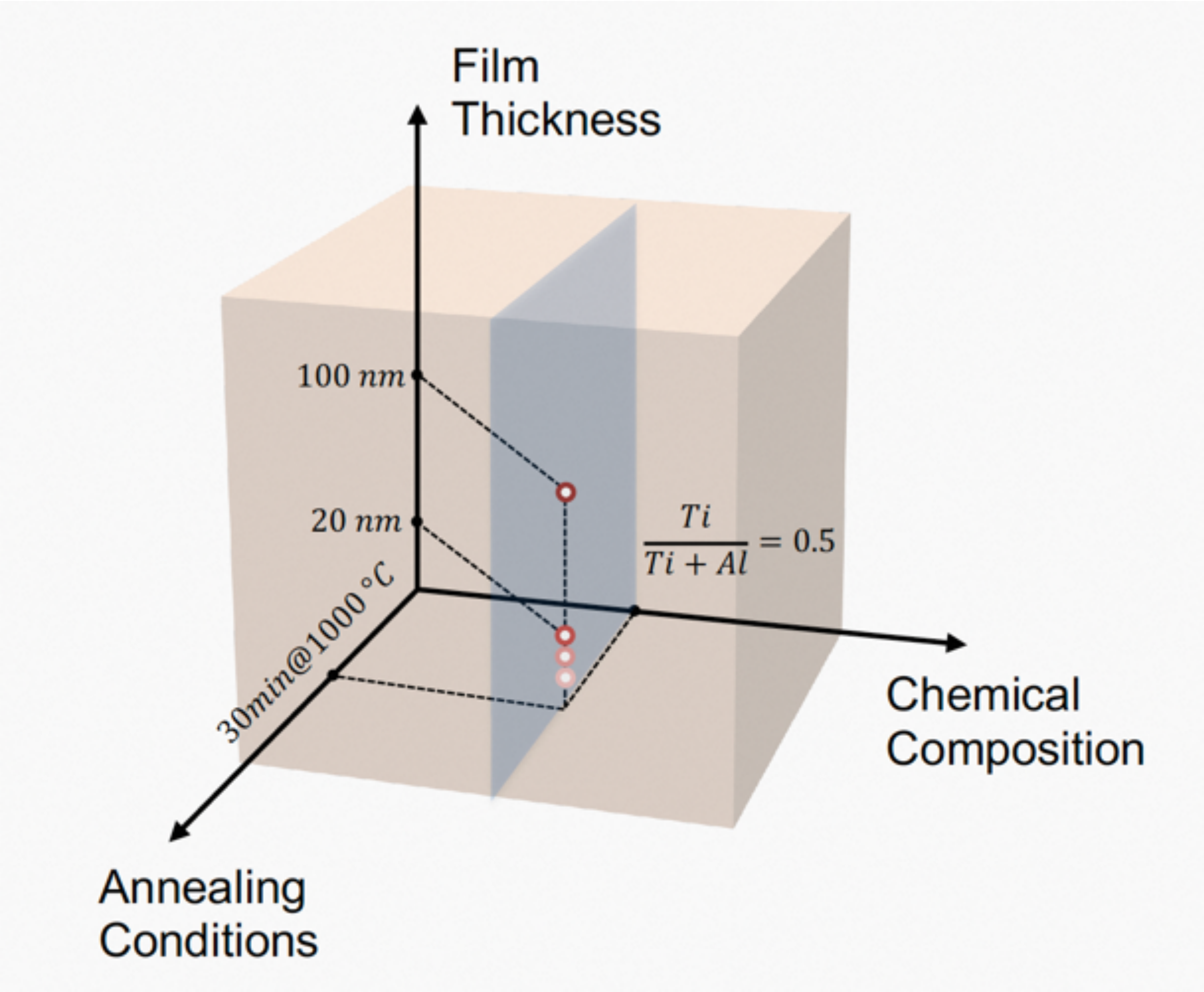
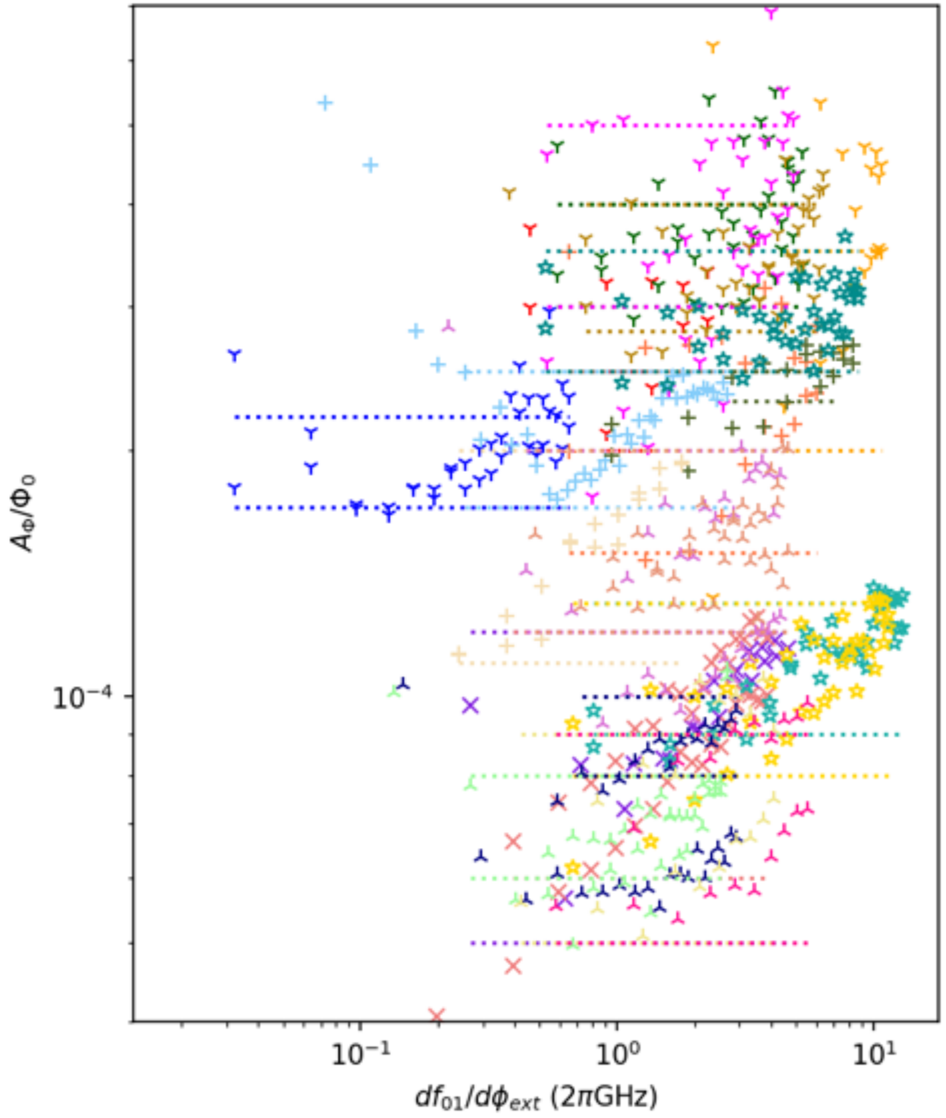
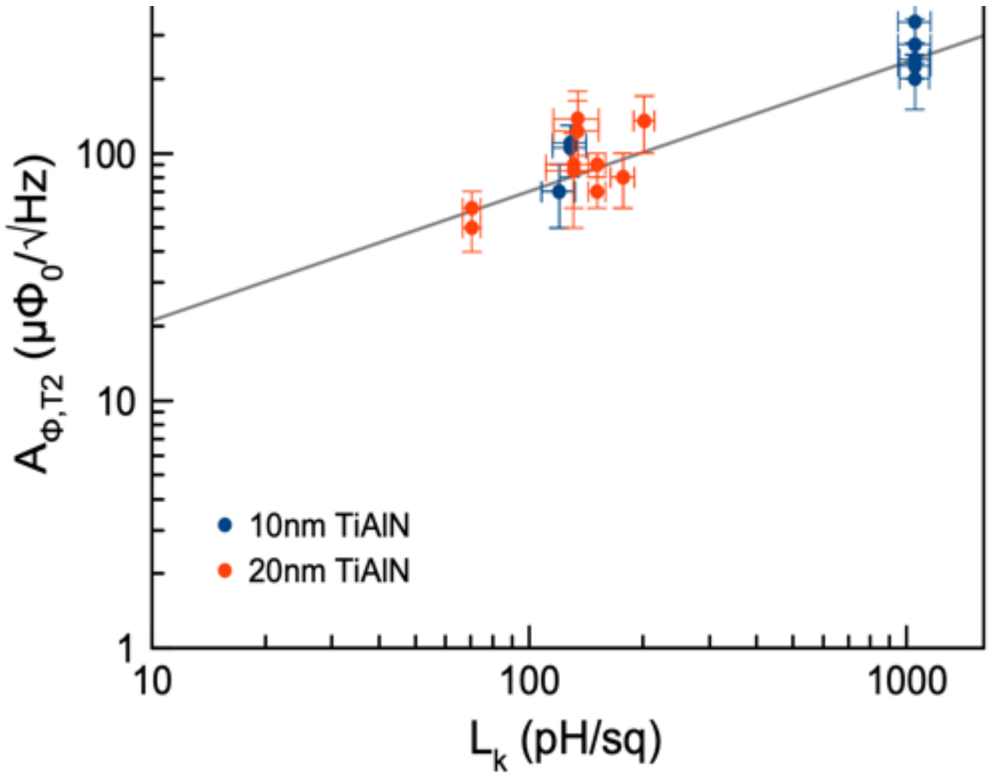




Correlation between flux noise and L_k?



Conclusion

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- Noise spectroscopy with fluxonium qubits
  - Dielectric loss or charge TLS + 1/f flux noise as a general noise model for noise in superinductors.
  - Low-frequency fluxonium is decoupled from these TLS.
  - Flux noise is suppressed by large L but still important.
  - No signiture of quasiparticle observed.

- Disordered superinductors with Ti-Al-N (credit to Ran Gao)
  - Consistent with the above noise model.
  - Decent dielectric loss but high level of flux noise or inductive loss.
  - Noise level correlates with L_k or the disorderness?

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