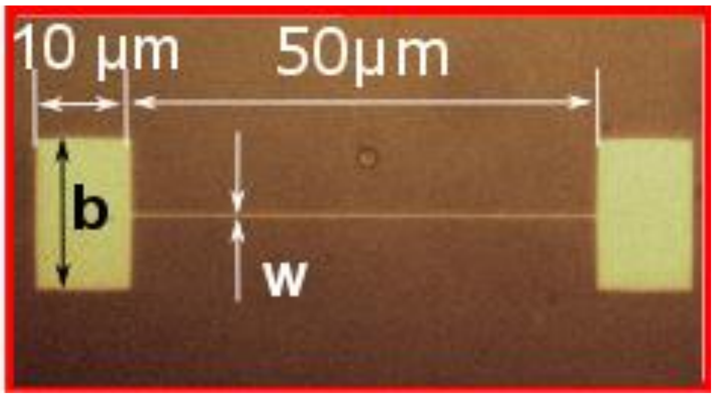
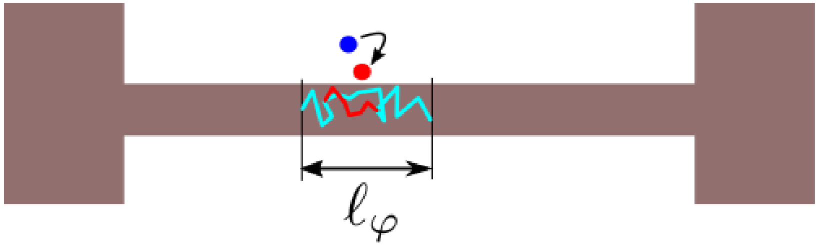
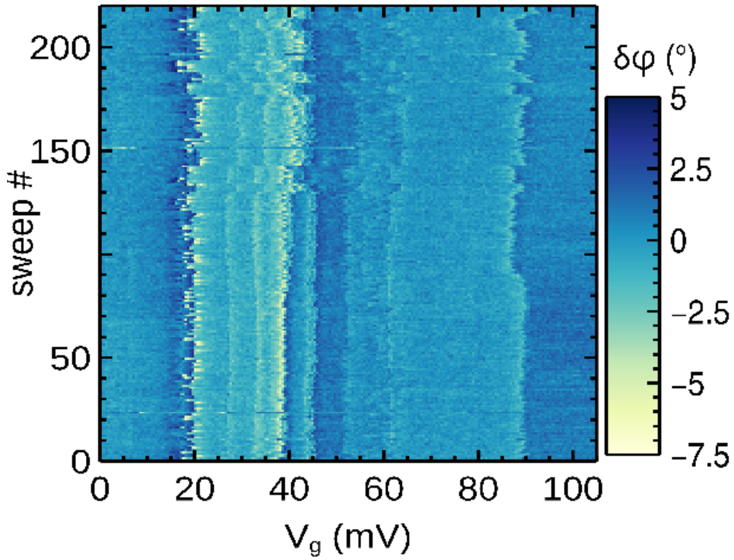
Charged fluctuators as a limit to the coherence of superconductors

Hélène le Sueur [1,2]







[1] Quantronics Group, Service de Physique de l'Etat Condensé, **CEA Saclay**
[2] Centre de Sciences Nucléaires et de Sciences de la Matière, **CNRS Orsay**

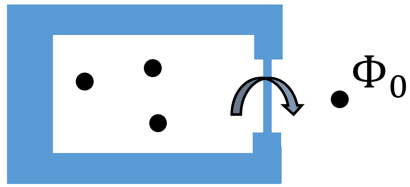
Many promises for disordered superconductors:

Lossless high impedances

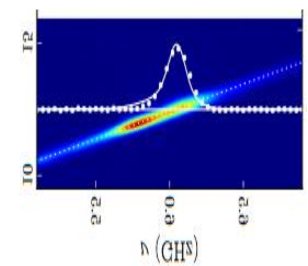
$$Z_C = \sqrt{\frac{L}{C}} \leqslant Z_{\rm vac} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 377\,\Omega \quad \Longrightarrow \quad \delta\varphi < \delta q \, \frac{Z_{\rm vac}}{R_Q} \approx 0.06\, \delta q$$

Adding inductance (Josephson or Kinetic) opens new perspectives

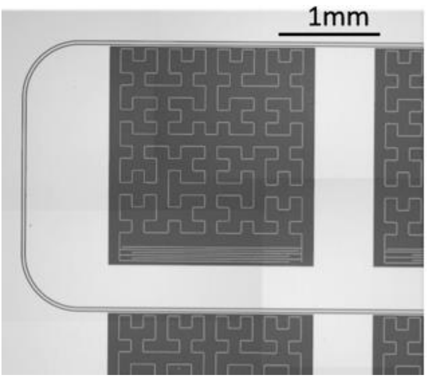
- **New types of circuits** dual to Josephson circuits
  (charge localization versus phase localization)

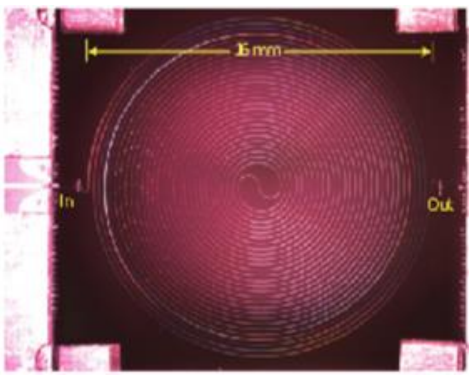


- **Strong coupling between electrons and photons**
  (Josephson photonics)



- **High Lk and high non linearities** (at the single photon level?)
  (KIDs, parametric amplifiers, tunable superinductors,
  SSPDs, Qbits, …)





BUTs ! (there are -at least- 2)

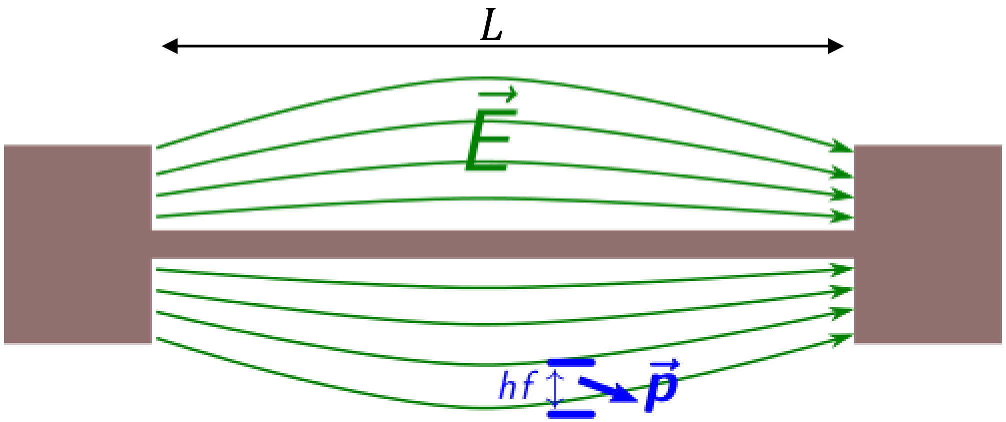
BUT #1

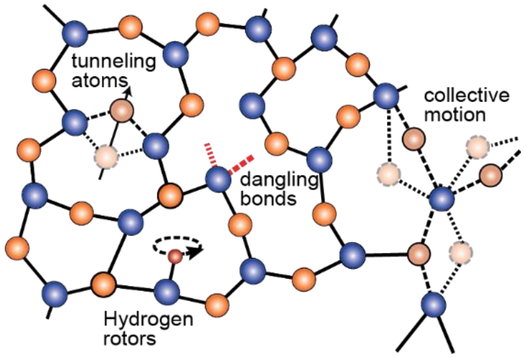
High Z means coupling to charge noise

Sensitive to offset charge

charge getting localized => less screening

Coupling of a high Z electromagnetic mode to a charged dipole





Coupling $g = \vec{p}.\overrightarrow{E_{ZPF}} \sim \frac{a_0}{L}\sqrt{\frac{\pi Z_C}{2 R_Q}}\, h\, f$ $\qquad Z_C = \sqrt{\frac{L}{C}}$

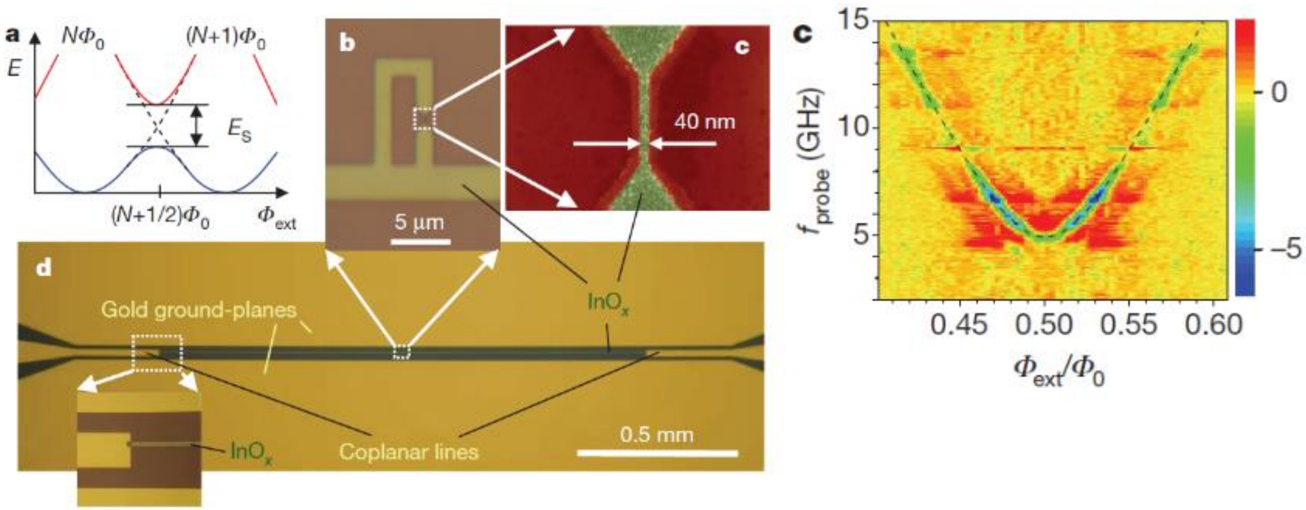
high Z modes more sensitive to TLS loss

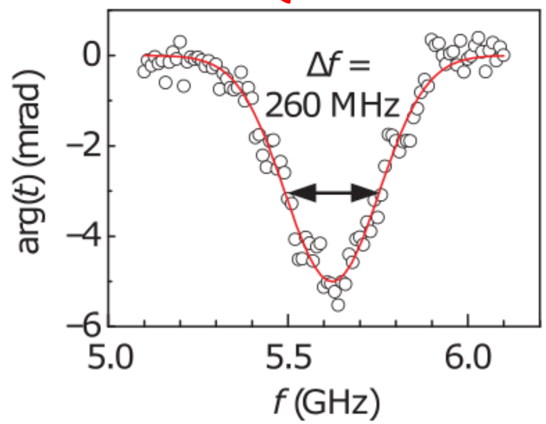
BUT #2

Disordered superconductors are messy

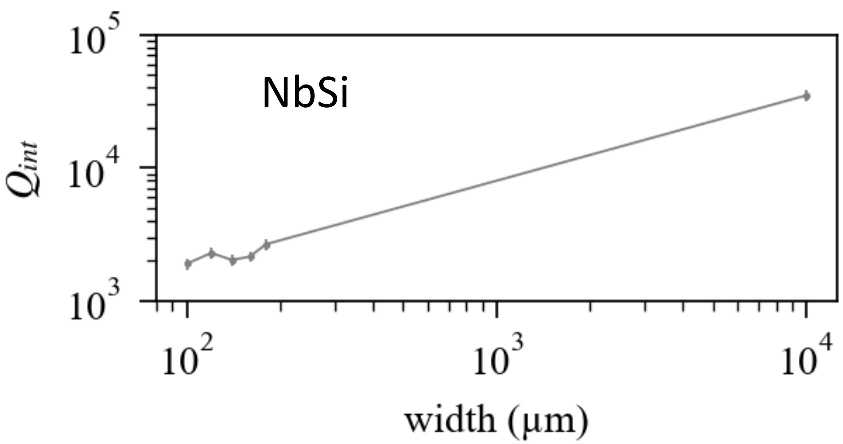
- Losses and decoherence for mesoscopic circuits (obs. InOx, NbN, TiN)
  see e.g. O. Astafiev's group

Q ~ 10 !





- **Width dependence** of resonator properties



1/f noise PSD $\propto 1/w^2$

TiN

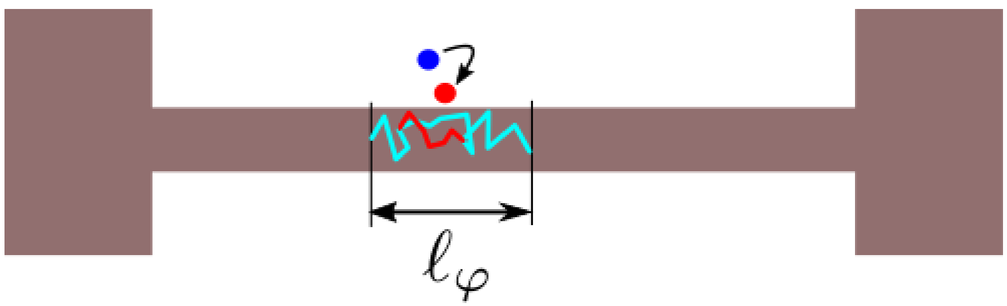
see e.g. J. Gao's talk

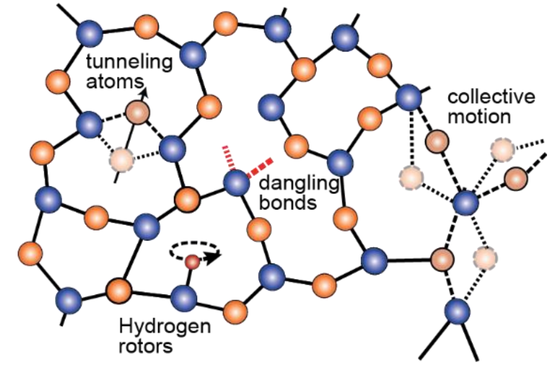
Is there a universality to it?

Kinetic Inductance fluctuations: charged TLS modify electronic interferences

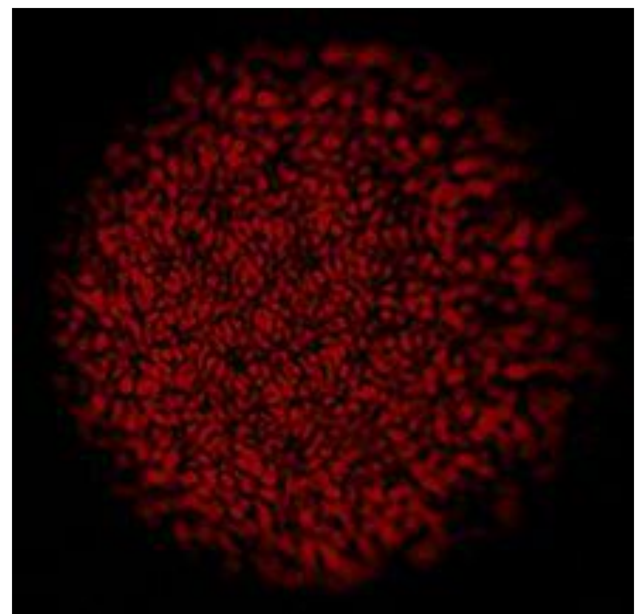
A new mechanism in superconductors!

arXiv:1810.12801





optical analog: speckle pattern



Change of scattering $\rightarrow \ \delta G_N$

Kinetic Inductance fluctuations: charged TLS modify electronic interferences

A new mechanism in superconductors!

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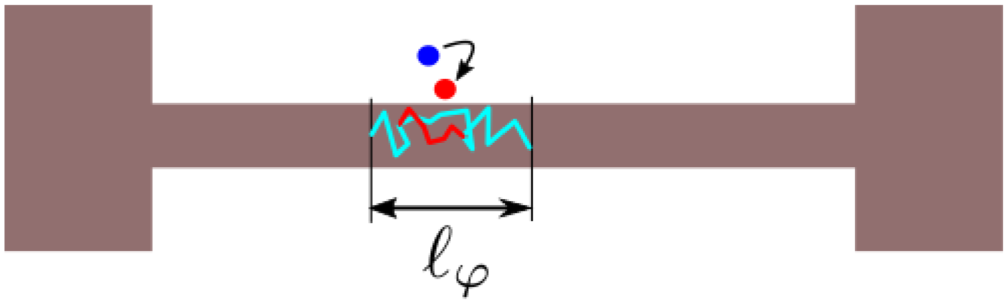

Change of scattering $\rightarrow \delta G_N \rightarrow \delta L_K \rightarrow \delta f_0$ **frequency noise**

Kinetic Inductance fluctuations: charged TLS modify electronic interferences

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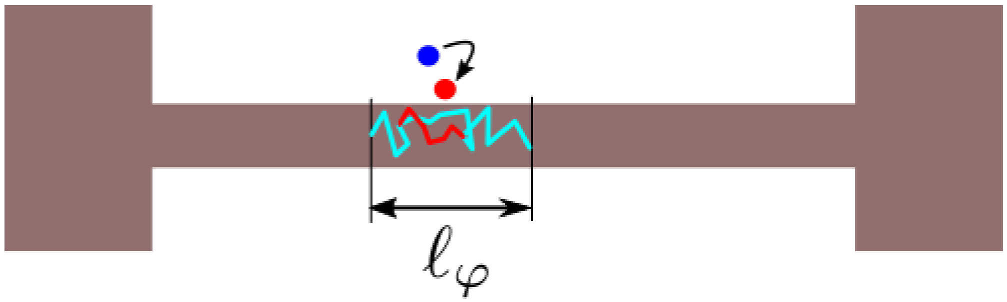


Change of scattering $\rightarrow \ \delta G_N \rightarrow \ \delta L_K \rightarrow \ \delta f_0$ **frequency noise**

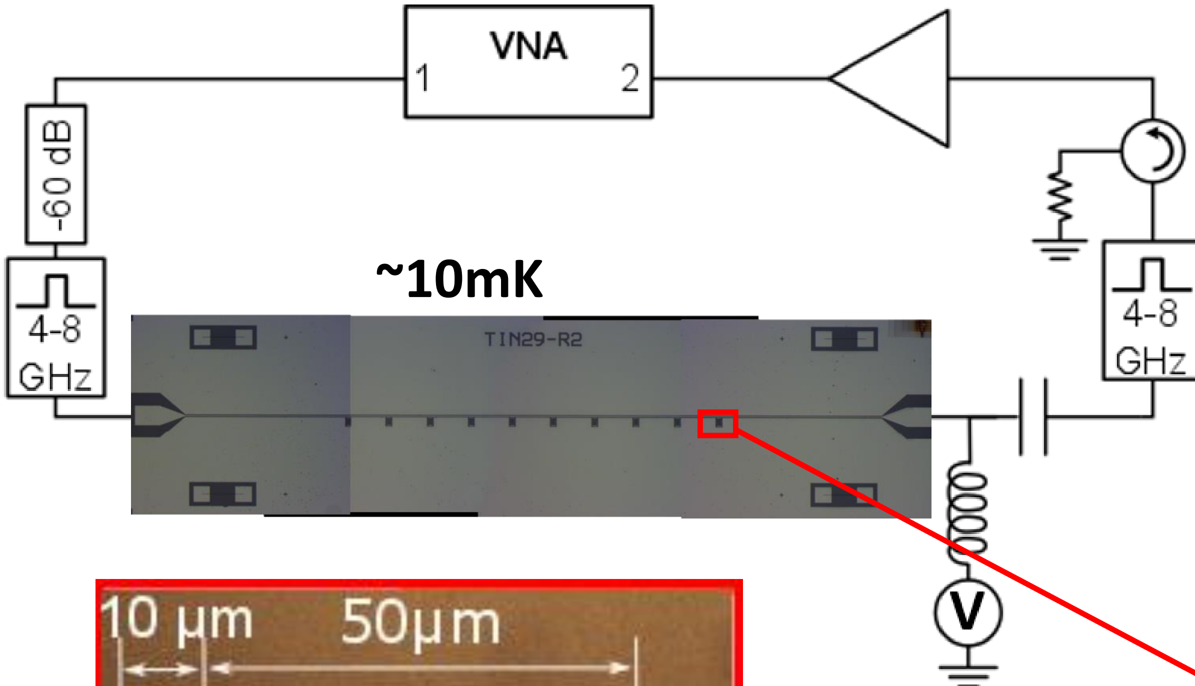
mesoscopic fluctuations:
$0 \leq \ \delta G_N \leq \ G_0$

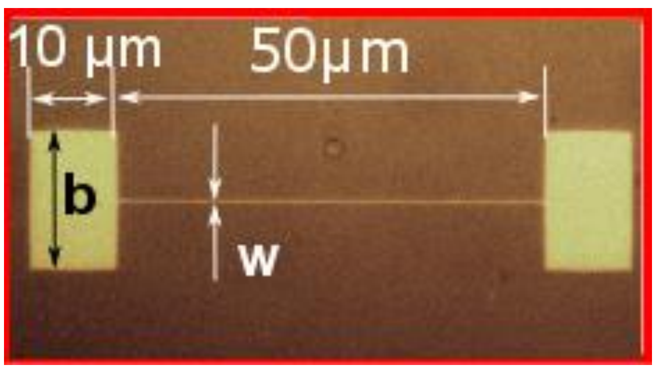
relative fluctuations enhanced in the weak localization regime

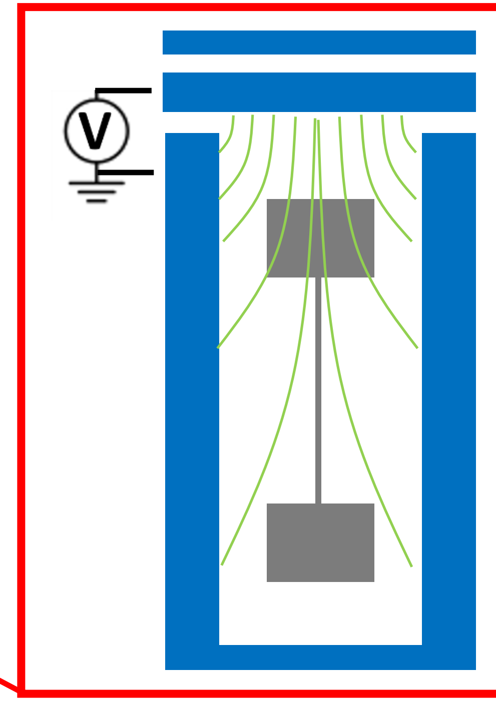
+ apparent internal Q

$$\frac{\delta f_0}{f_0} \sim \alpha \frac{\delta G_N}{G_N} \quad \Rightarrow \quad {Q_{TLS}}^{-1} = \alpha \frac{\langle \delta G_N \rangle_{rms}}{G_N}$$

Nanowire (100 - 600nm) resonators 4-8GHz





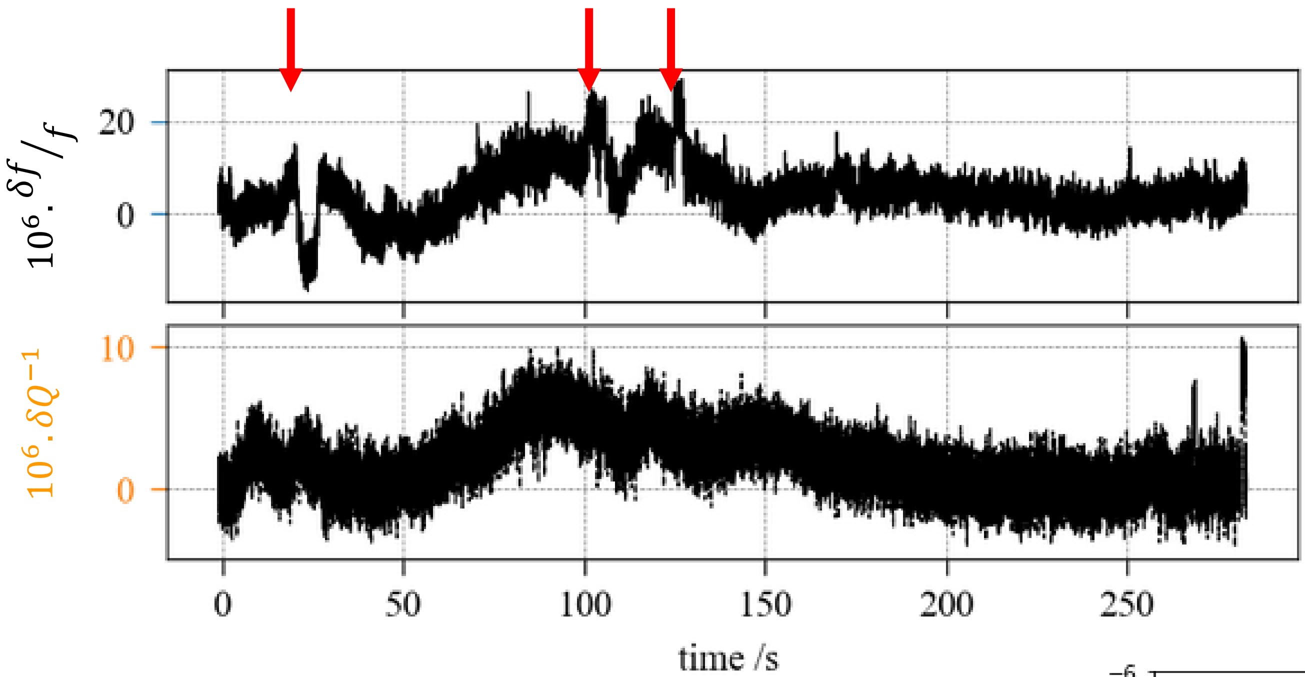


NbSi 15nm, $T_C \sim 1K$, **1nH/□**

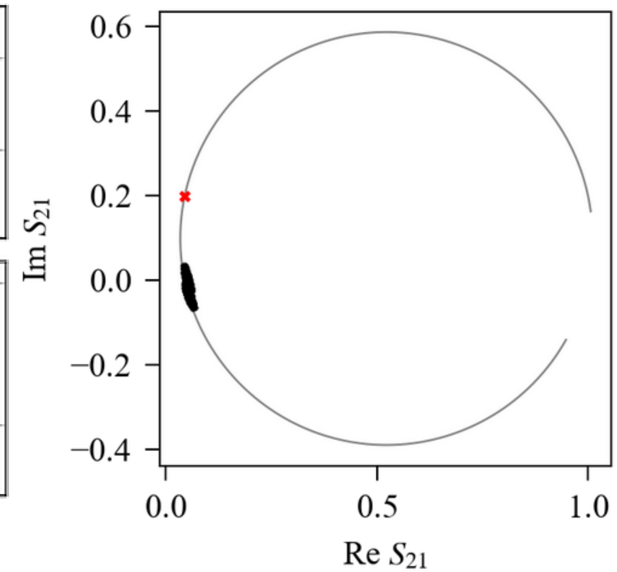
TiN 5nm,$T_C \sim 2.5K$, **400pH/□**

Minimize TLS participation ratio (capacitive pads separated)
DC Electric field to tune TLS energy
ground plane and feedlines in Al

Time variation of resonance frequency

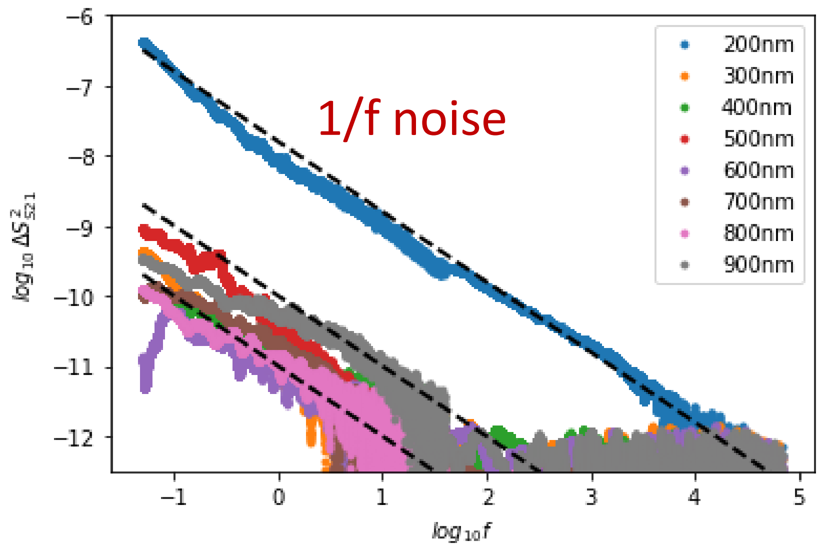


200nm TiN, 11mK

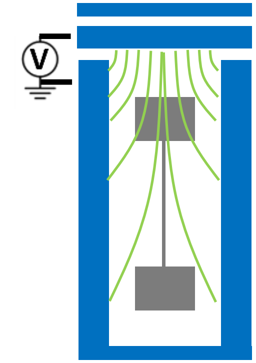


Individual jumps + fluctuating background

frequency drift => apparent Q_{int}

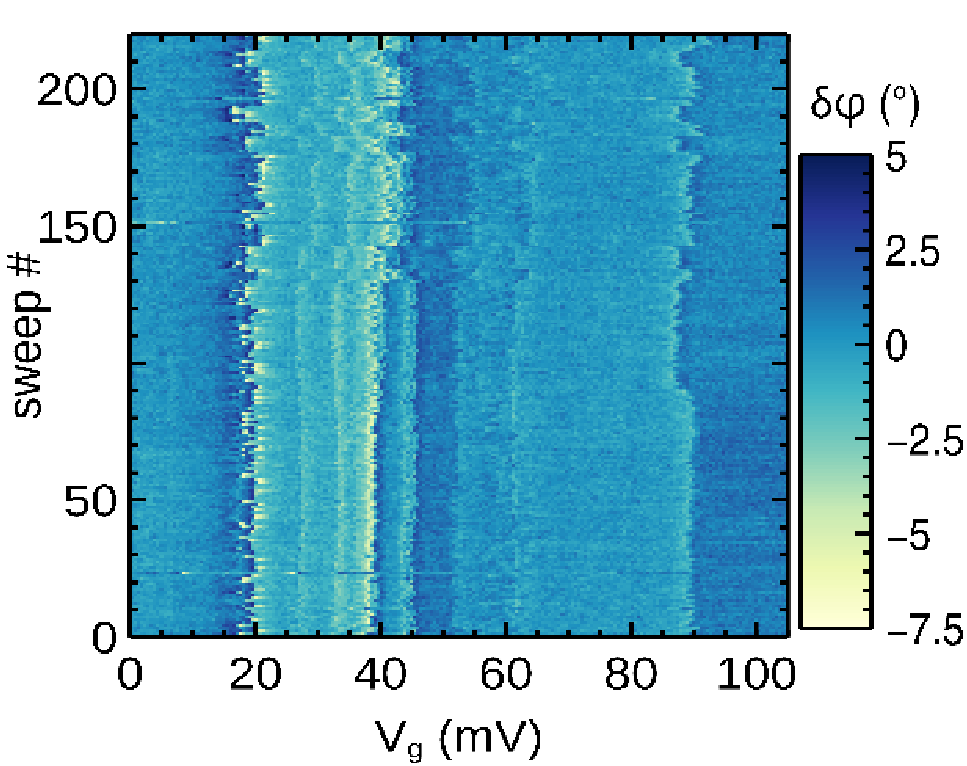


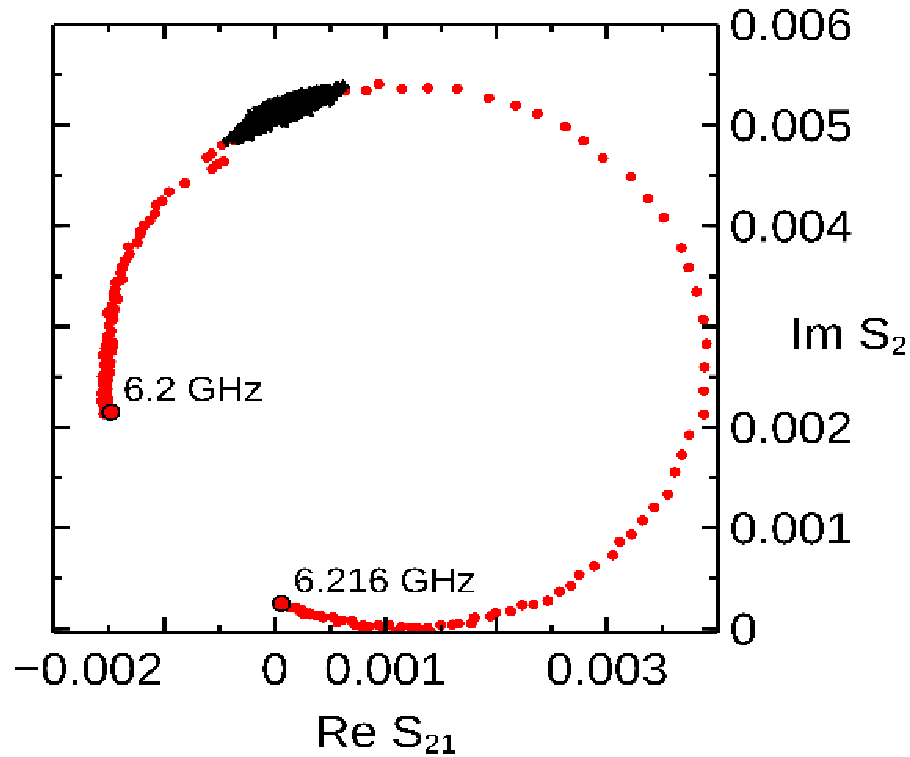
Sensitivity of resonator to DC electric field



fix signal frequency, sweep V

100nm NbSi, 32mK

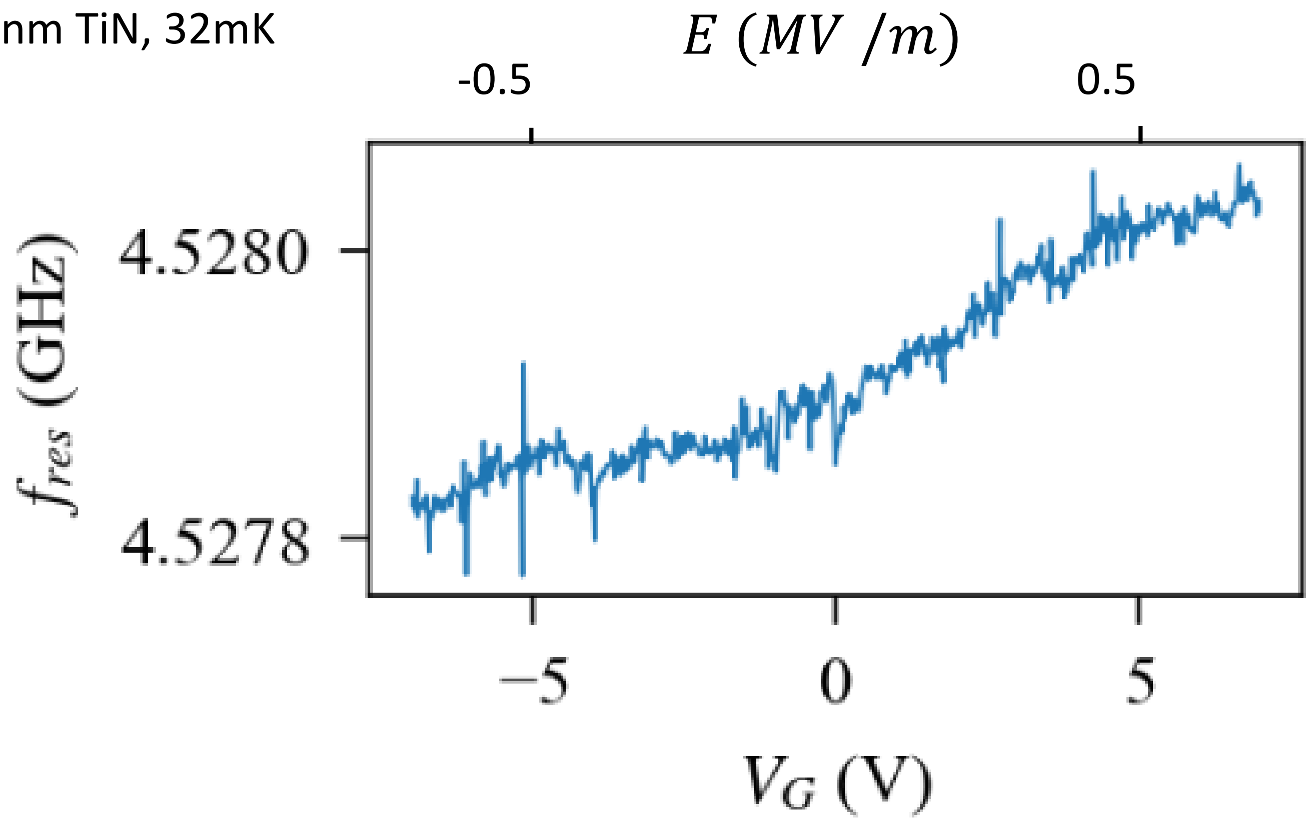


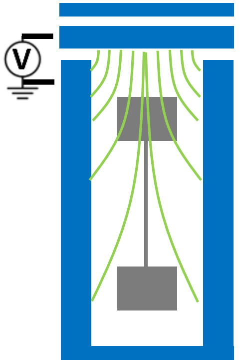


same observations for all nano-resonators

Gate voltage dependence

80nm TiN, 32mK



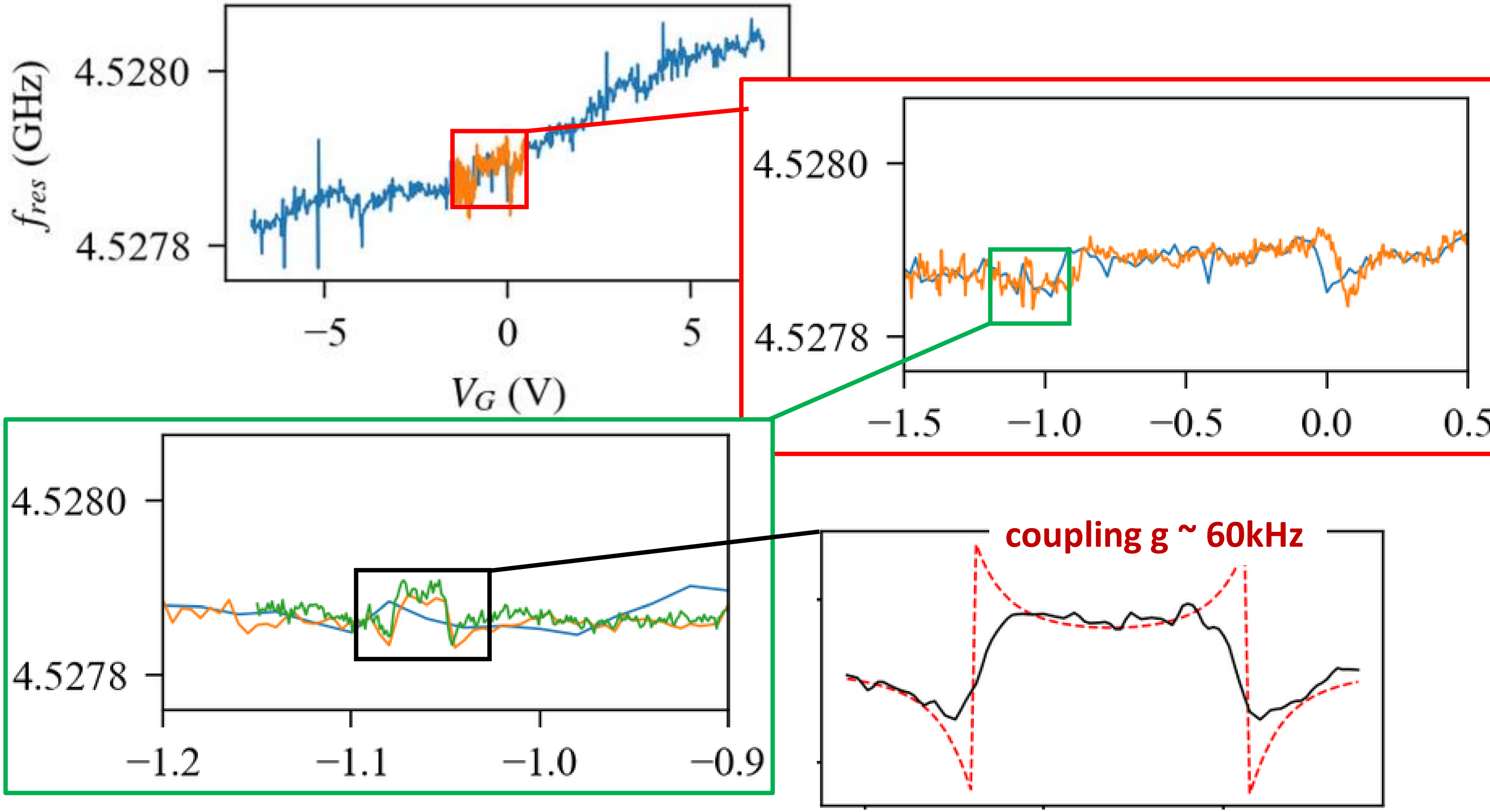


average slope: $\delta f/f \sim 5.10^{-5} - 2.10^{-4}$ @ $1MV\ /m$

Kerr of Si ?
Change in density of TLS ?
(ionized traps)

Gate voltage dependence

80nm TiN, 32mK



measured up to ~1MHz in NbSi

$$f = \frac{1}{2\pi\sqrt{(L_K + \cancel{L_{geom}})C}}$$

δC versus δL_K

δC (« GTM »)	δL_K (« UCF »)
• **resonant coupling + blurring bath**	• **non resonant** and **resonant coupling**

$\sim 5.10^{-11} m$ (→ a_0)

$Z_C \sim 6k\Omega$

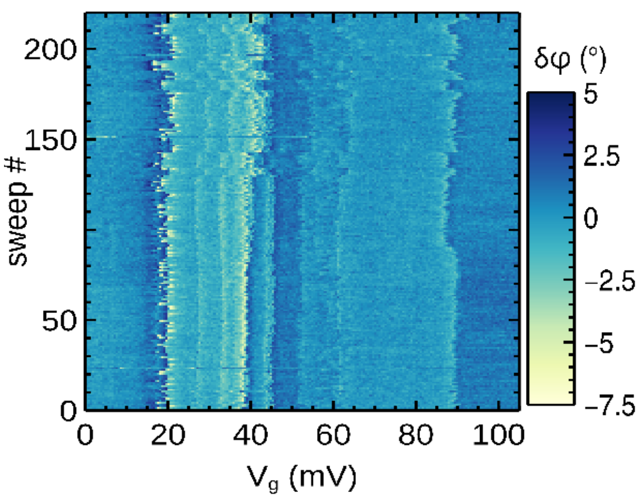
$$g = \vec{p}.\overrightarrow{E_{ZPF}} \sim \frac{a_0}{L}\sqrt{\frac{\pi Z_C}{2 R_Q}}\, h f \sim 10^{-6} hf$$

$f \sim 5$GHz → ~~g~5kHz~~ (too low)

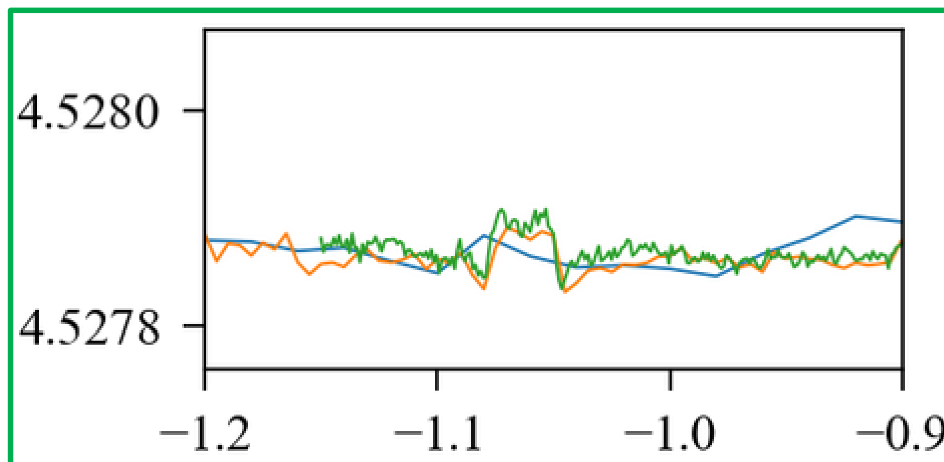
g ? theory needed

NbSi 100nm

measured g up to 1MHz



TiN 80nm

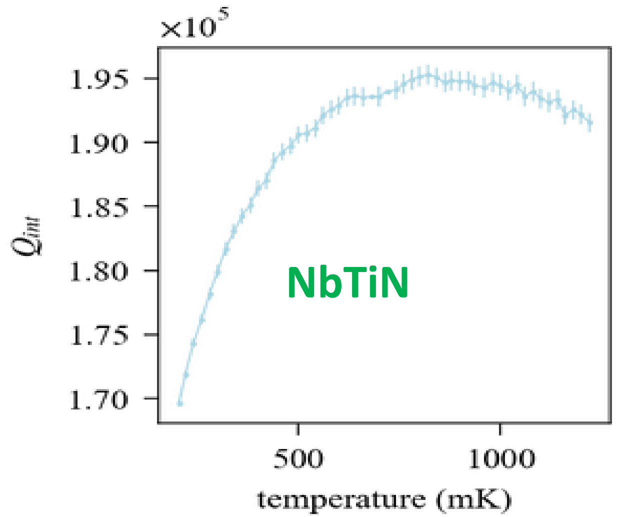


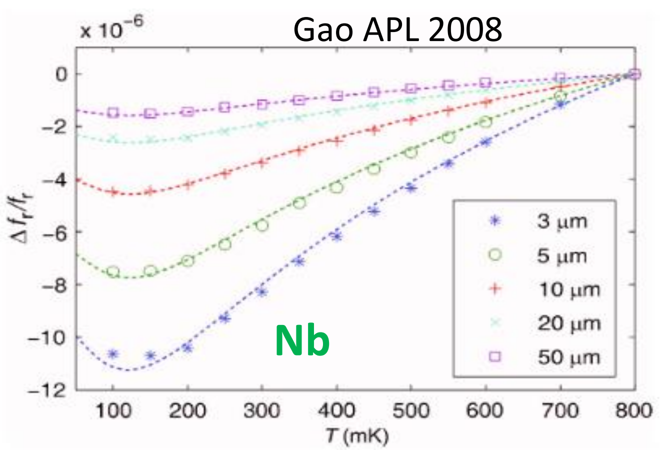
$$f = \frac{1}{2\pi\sqrt{(L_K + \cancel{L_{geom}})C}}$$

δC versus δL_K

δC (« GTM »)	δL_K (« UCF »)

- $Q_{int}(T)$ ↗ (saturation of TLS)
  $f_0(T)$ non monotonous



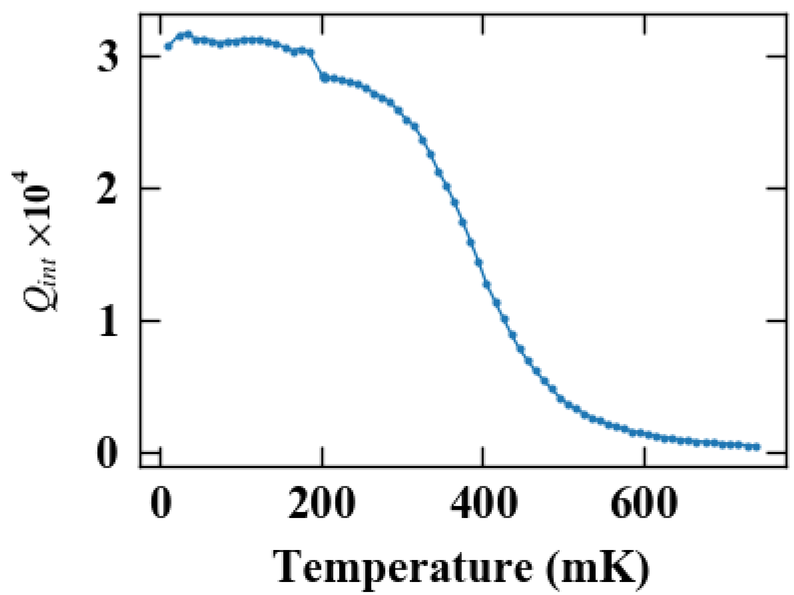


$$f = \frac{1}{2\pi\sqrt{(L_K + L_{geom})C}}$$

δC versus δL_K

δC (« GTM »)	δL_K (« UCF »)
• $Q_{int}(T)$ ↗ (saturation of TLS) $f_0(T)$ non monotonous	• $Q_{int}(T)$ ↘ (thermal activation of TLS) see eg Gustafsson Phys. Rev. B 88, 245410

TiN nanowire 200nm



similar structures on others NW

also: $L_{phi}(T)$ ↘ ⇒ vanishing T dependence

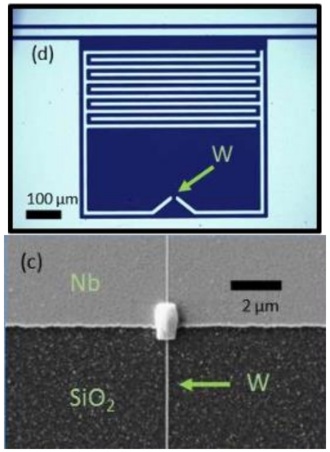
$$f = \frac{1}{2\pi\sqrt{(L_K + L_{geom})C}}$$

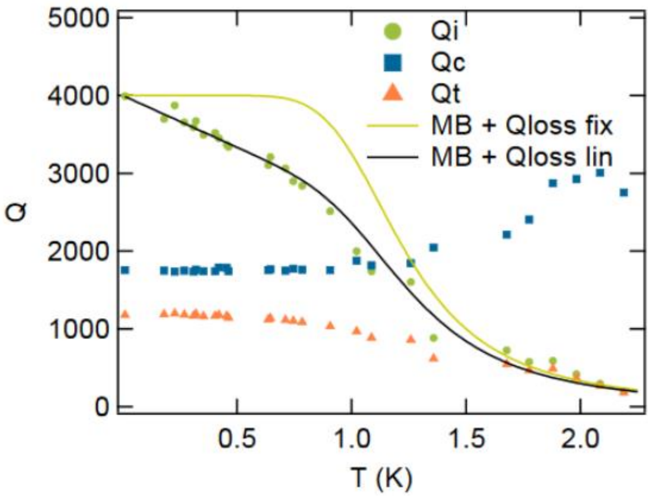
δC versus δL_K

δC (« GTM »)	δL_K (« UCF »)
• $Q_{int}(T)$ ↗ (saturation of TLS) $f_0(T)$ non monotonous	• $Q_{int}(T)$ ↘ (thermal activation of TLS) see eg Gustafsson Phys. Rev. B 88, 245410

W nanowire 35nm

see eg J. Basset arXiv:1811.06496

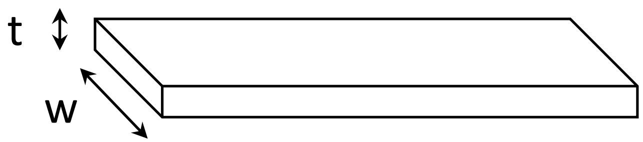




δC versus δL_K : On going work

δC	δL_K

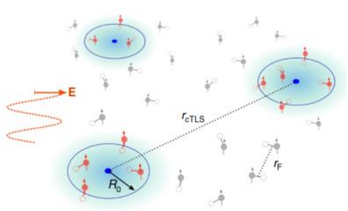
- scaling of fluctuations with $\sqrt{Z_{res}}$
- true losses Q_{int}
- No effect of wire width if $w \gg t$

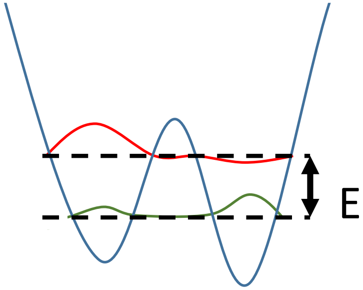


influence of interfaces:

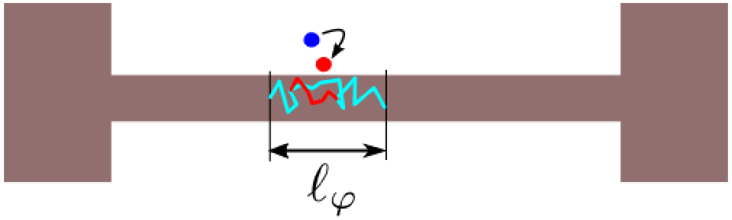
$$\frac{S}{V} \propto \frac{2}{w} + \frac{2}{t} \sim \frac{2}{t}$$

- δC related to $\delta \varepsilon_r$





- scaling with Z_{res}
- apparent Q_{int} (should improve at high BW)
- Larger fluctuations in narrower wires

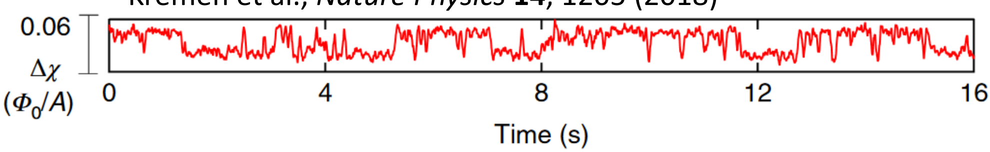


$$\delta G_N \propto G_0 \qquad \Rightarrow \frac{\delta G_N}{G_N} \propto \frac{1}{w}$$

$$G_N \propto w\, G_0$$

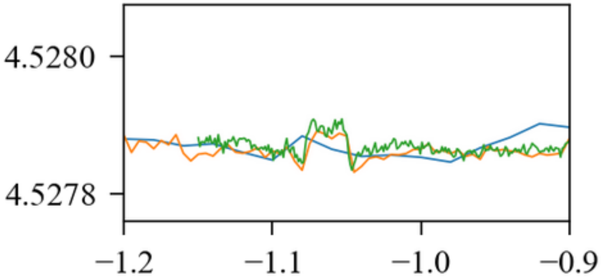
- δL_K comes from δR_N and / or $\delta\Delta$

Kremen et al., *Nature Physics* **14**, 1205 (2018)



On going work

We **propose a new *dephasing* mechanism in superconductors** , linking microscopic (electronic) to macroscopic (electromagnetic) coherence

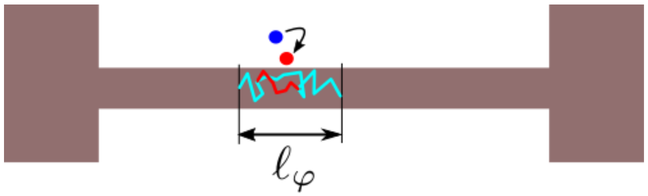


- Origin of fluctuations from **charged defects** is evidenced
- **resolve individual TLS** coupled to nanowires transport

Important consequences

- Increased *apparent* RF losses on small size disordered superconductors
- may explain some puzzles of Disordered Superconductors
  (e.g. Larger fluctuations in narrow wires / thermal activation of internal losses)
- Sets a **limit to the coherence of superconducting devices**

Next

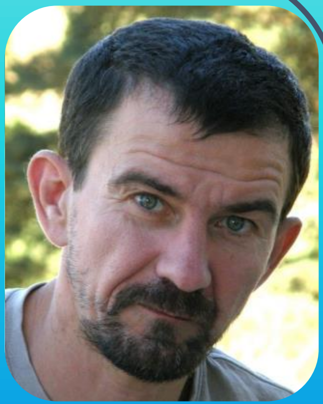


- **Detailed theory needed**
- Method to determine L_φ in the superconducting state ?

Thank you!

Master | PhD | post-doc | co-PI | NbSi synthesis



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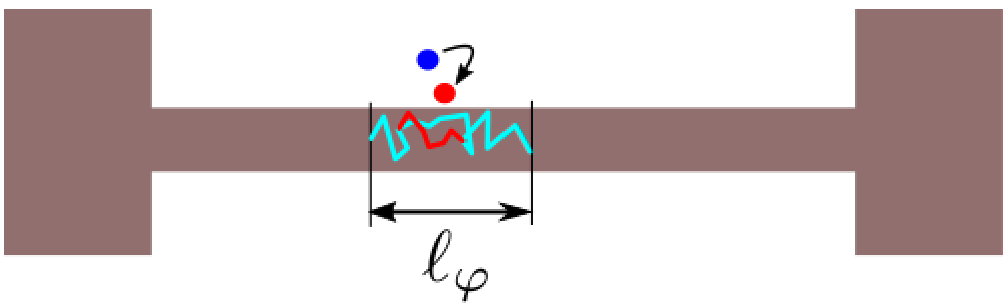
Kinetic Inductance fluctuations: charged TLS modify electronic interferences

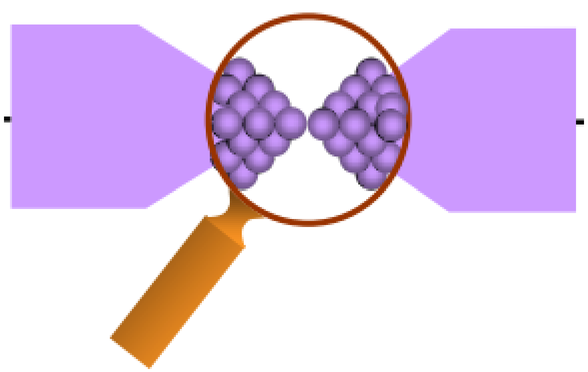
A new mechanism in superconductors!

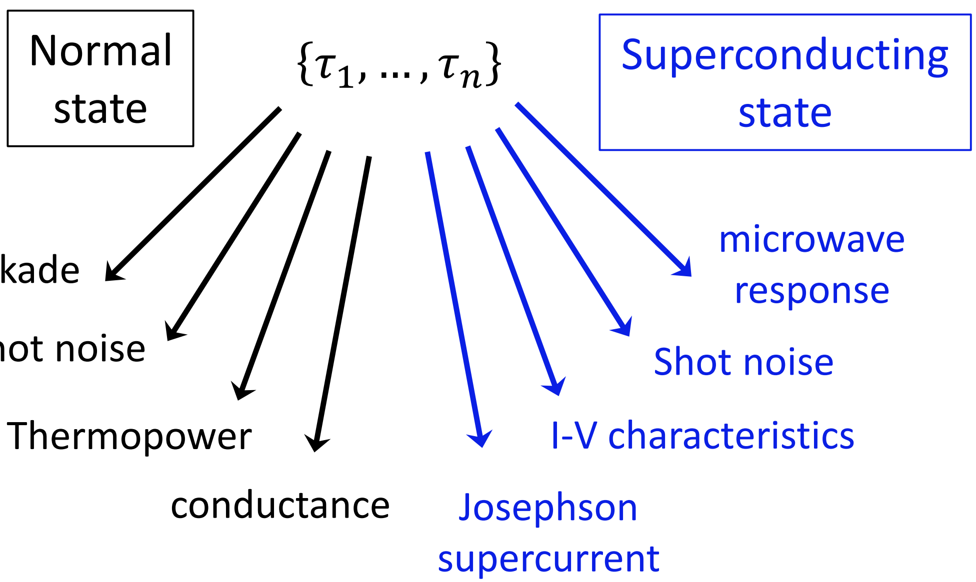
arXiv:1810.12801



Change of scattering $\rightarrow$ $\boldsymbol{\delta G_N \rightarrow \delta L_K}$

« mesoscopic PIN code »





Cuevas, Levy-Yeyati, Averin, Urbina *et al.* Quantronics …

Kinetic Inductance fluctuations: charged TLS modify electronic interferences

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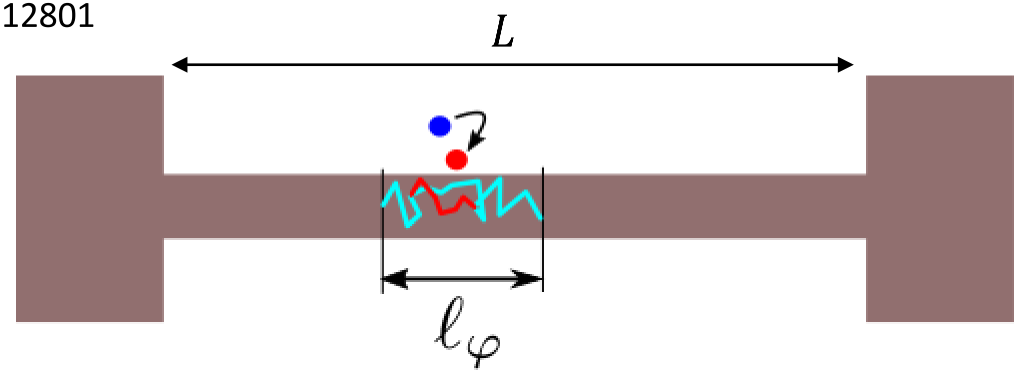


mesoscopic fluctuations:
$0 \leq \delta G_N \leq G_0$

Change of scattering $\rightarrow \boldsymbol{\delta G_N} \rightarrow \boldsymbol{\delta L_K} \rightarrow \boldsymbol{\delta f_0}$

$$\frac{\delta f_0}{f_0} \sim \alpha \frac{\delta G_N}{G_N} \Rightarrow Q_{TLS}{}^{-1} = \alpha \frac{\langle \delta G_N \rangle_{rms}}{G_N}$$

TLS dephase electrons: $L_{\varphi,TLS} = \sqrt{D\,\tau_{TLS}}$

($\tau_{TLS} > \hbar/_{\Delta}$: superconductivity not affected - Anderson theorem)

wire longer than L_φ:

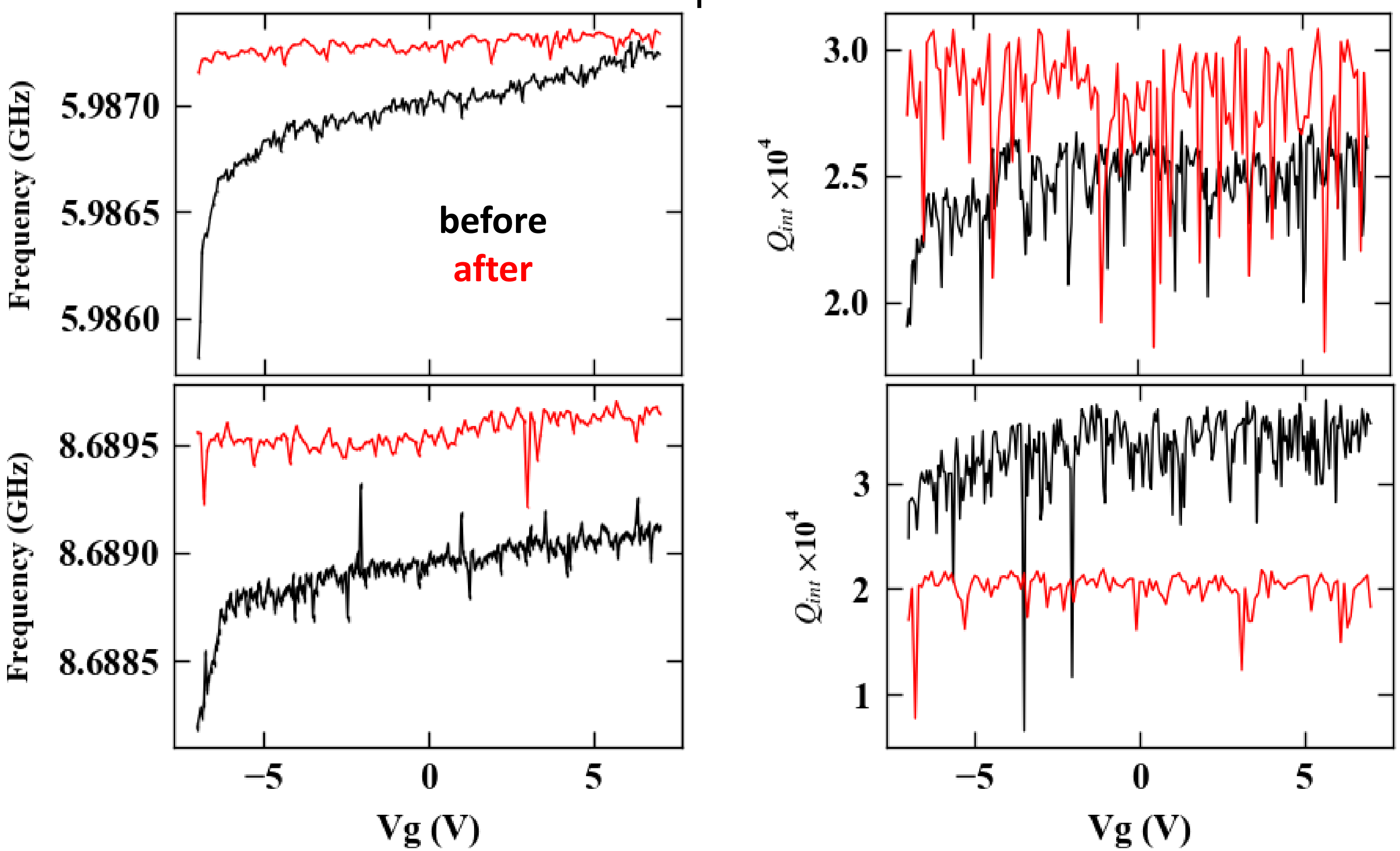
$$0 \leq \delta G_N \leq \left(\frac{L_\varphi}{L}\right)^2 G_0 \Rightarrow Q_{TLS}{}^{-1} = \alpha \left(\frac{L_\varphi}{L}\right)^{3/2} G_0 \frac{L}{w} R_\blacksquare$$

δC and δL_K phenomenologies

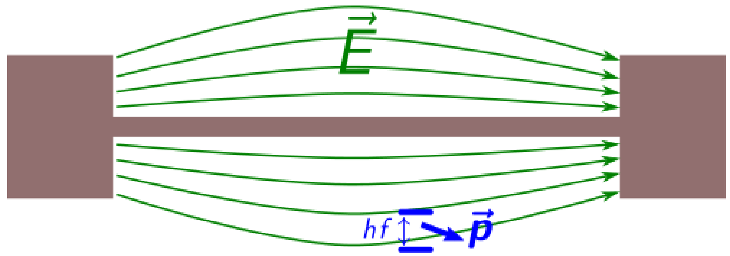
δC	δL_K
• Quenching of disorder : nothing special	• Quenching of disorder : **should change f0 and Q**

200nm

400nm

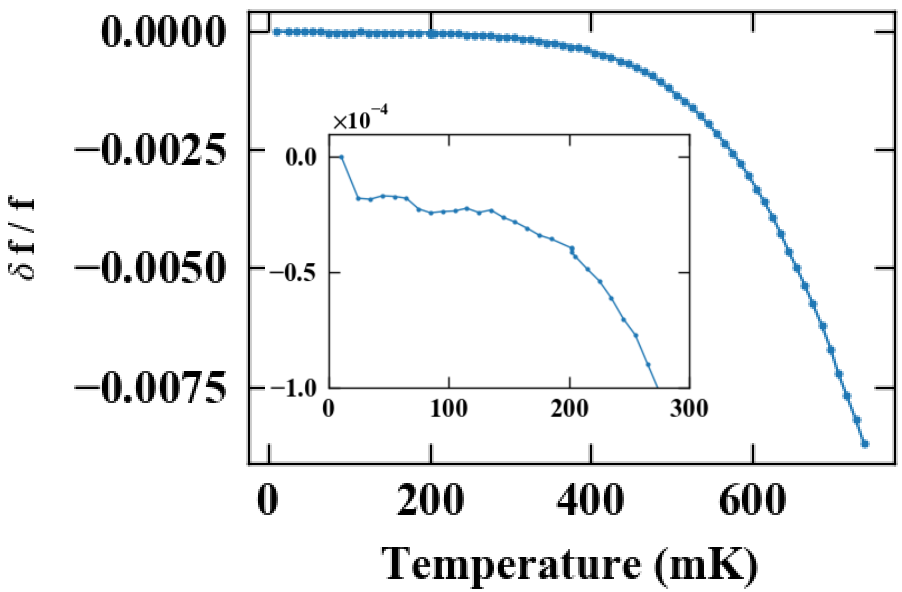


Is it Capacitance fluctuations?

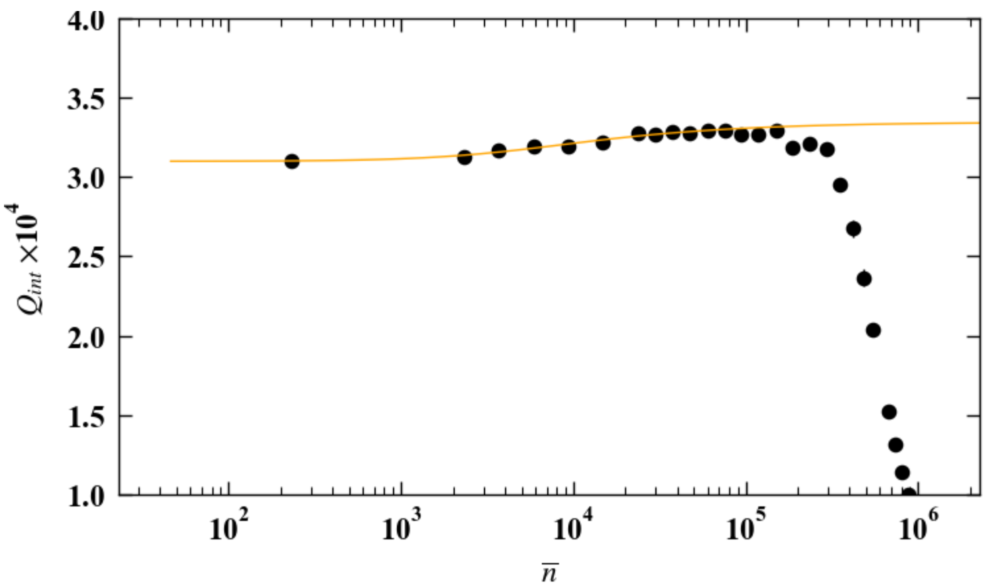


TiN 5nm nanoresonators

frequency shift (T)



quality factor (P)



no « GTM like » variation

Very weak « GTM like » variation