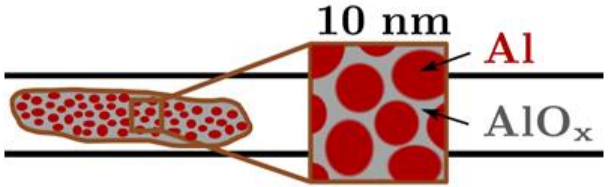
Limit testing granular Aluminum for cQED

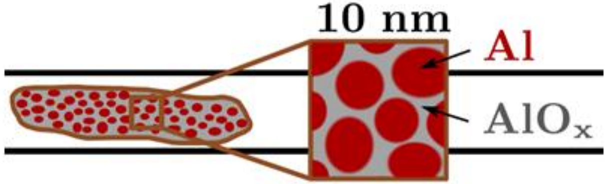


Ioan M. Pop

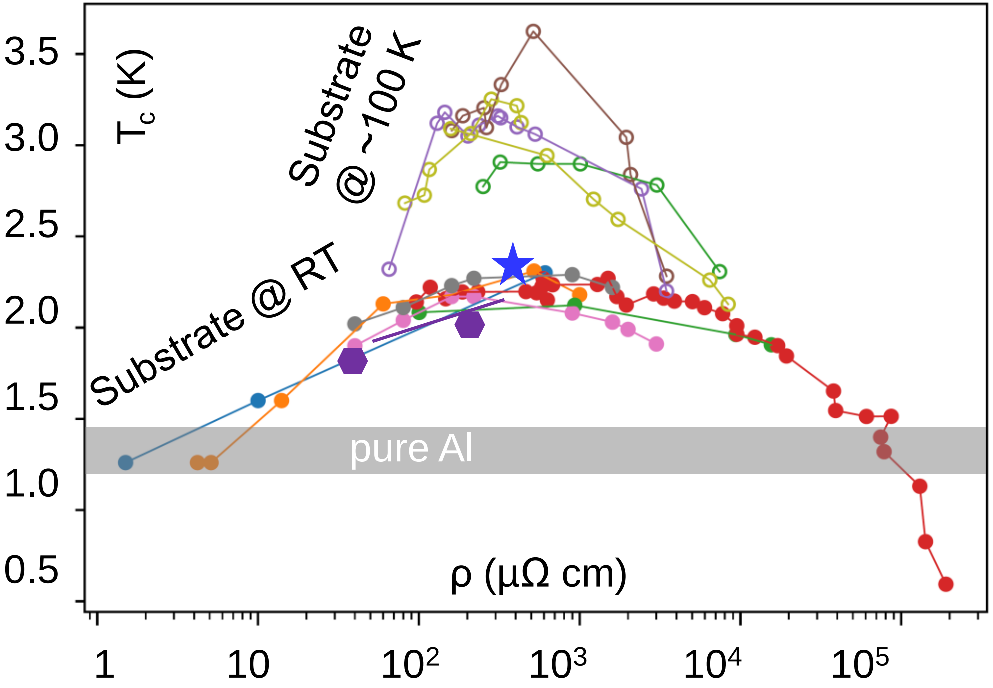
Karlsruhe Institute of Technology

Bundesministerium für Bildung und Forschung
QUANTERA
DFG
Baden-Württemberg Stiftung
European Commission
Alexander von Humboldt

grAl: a long time fascinating material

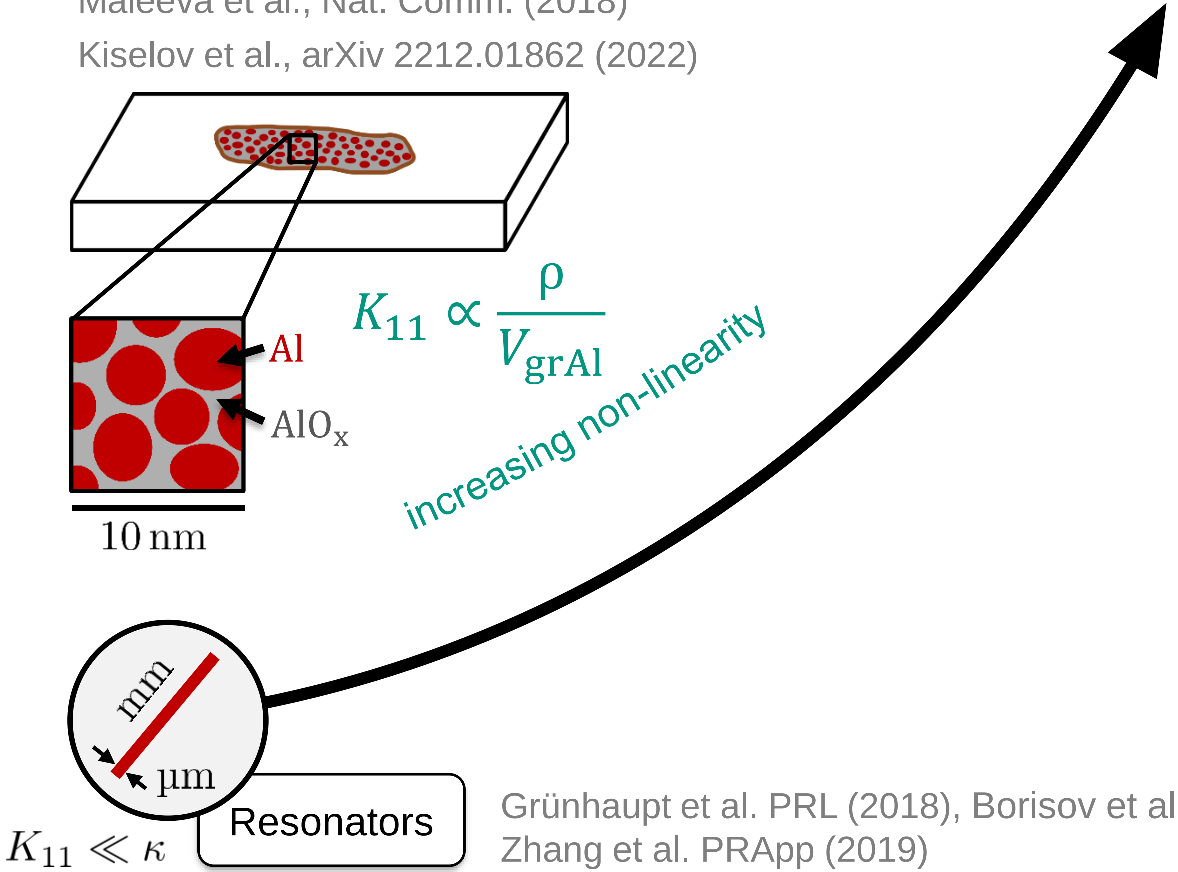


Abeles (1968)
Cohen (1968)
Deutscher (1973)
Dynes (1984)
Buisson (1994)
Sun (2012)
Bachar (2013)
Pracht (2016)
Levy-Berthrand (2019)
Valenti (2019)
Moshe (2019)



Limit-Testing the Versatility of Granular Aluminum

Maleeva et al., Nat. Comm. (2018)
Kiselov et al., arXiv 2212.01862 (2022)

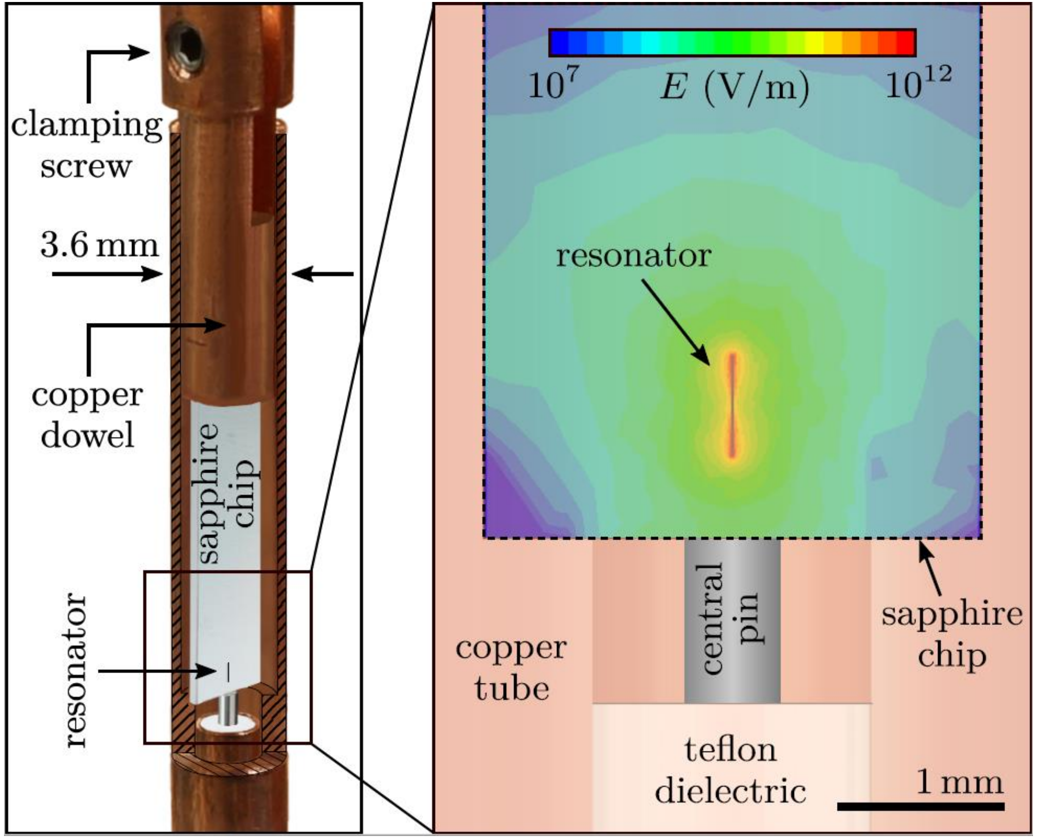


Grünhaupt et al. PRL (2018), Borisov et al. APL (2020)
Zhang et al. PRApp (2019)

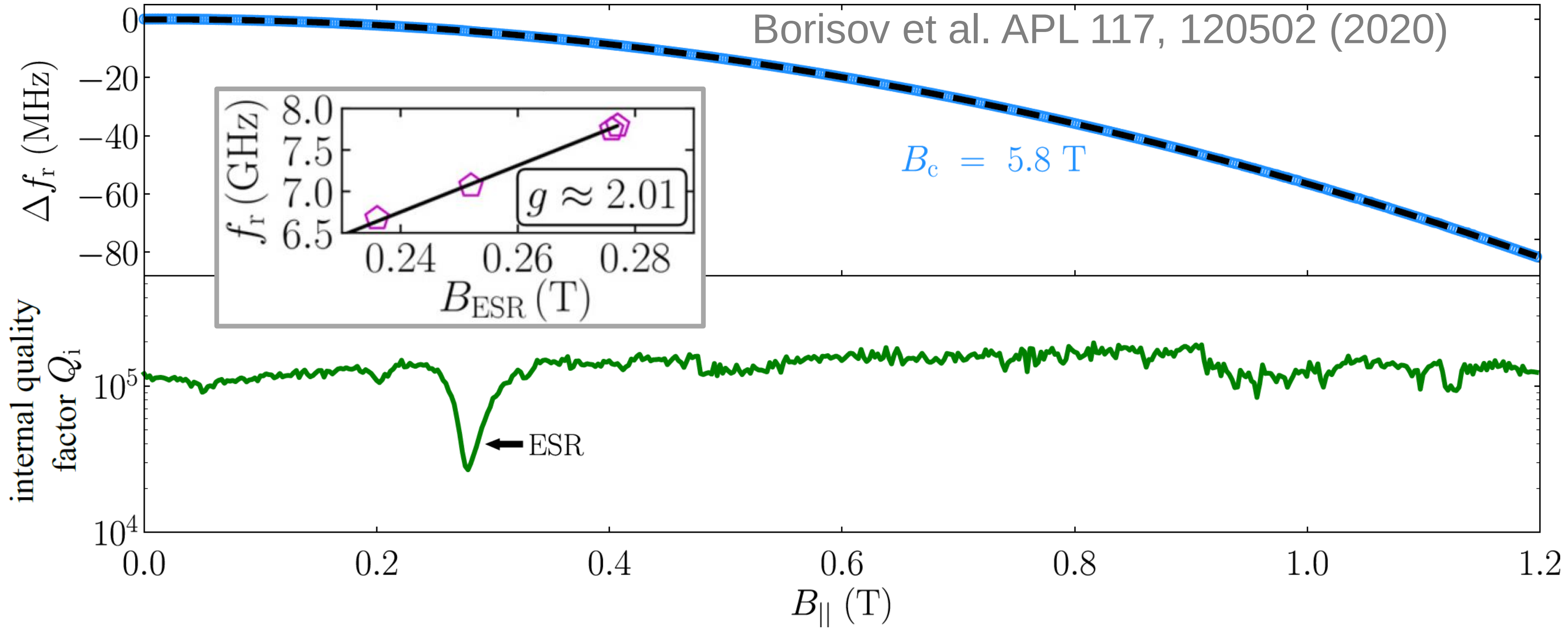
Magnetic Field Resilience of Superconducting Resonators

grAl: Borisov et al. APL (2020)
NbN: Niepce et al. PR Appl. (2019)
TiN: Shearrow et al. APL (2018)
NbTiN: Samkharadze et al. PR Appl. (2016)
…

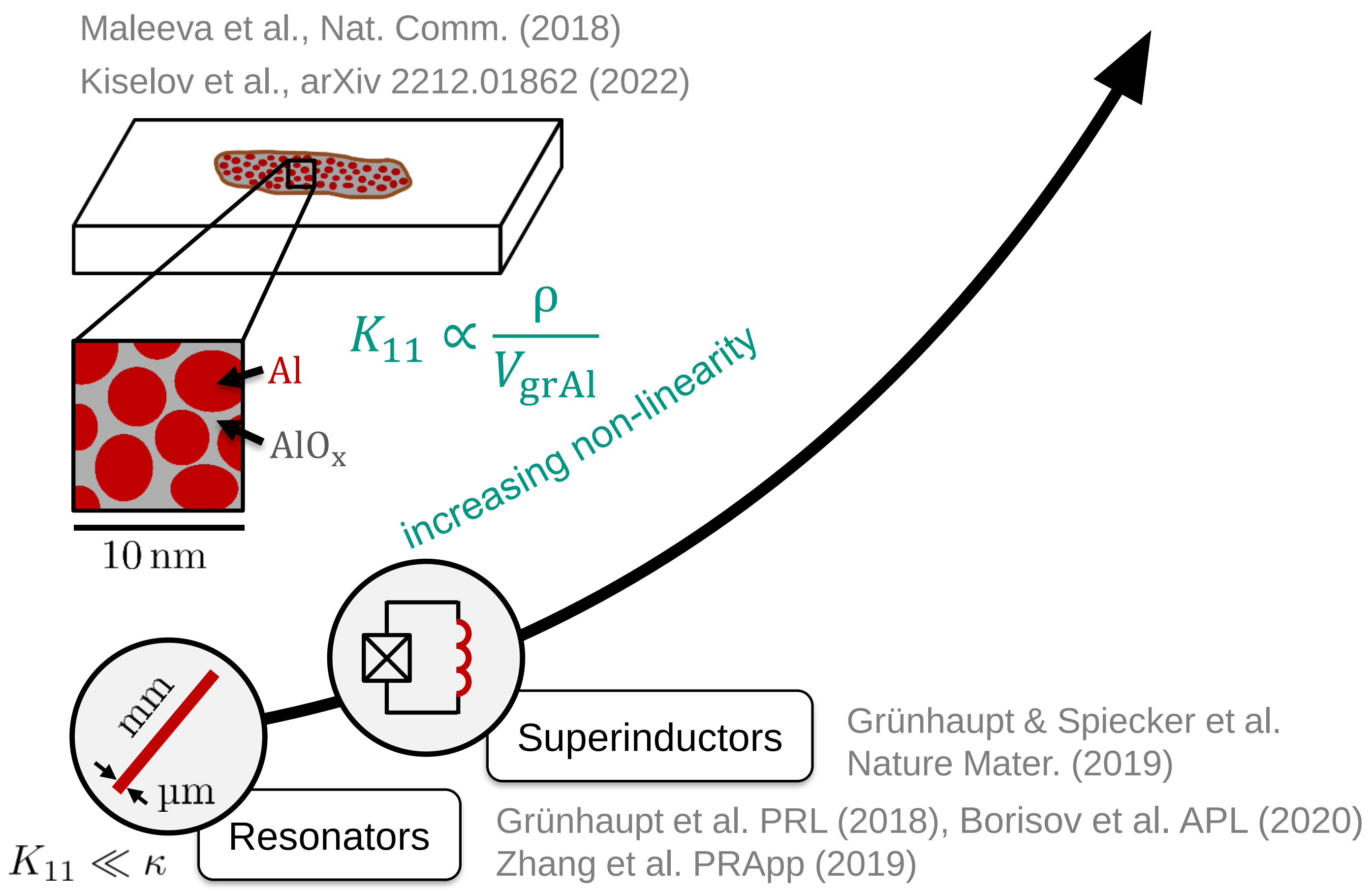
Sample Holder



grAl resilience in magnetic fields

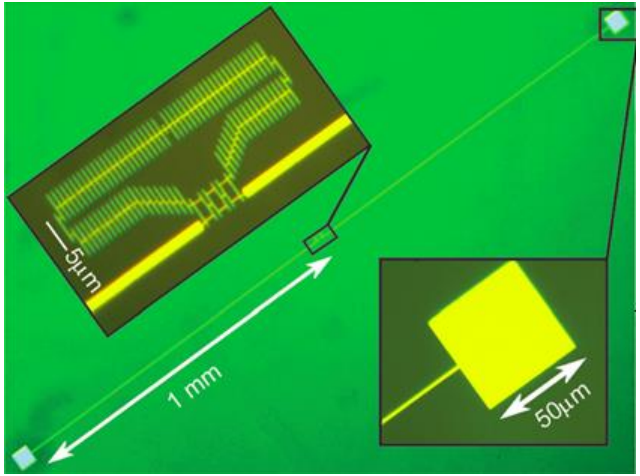


Limit-Testing the Versatility of Granular Aluminum



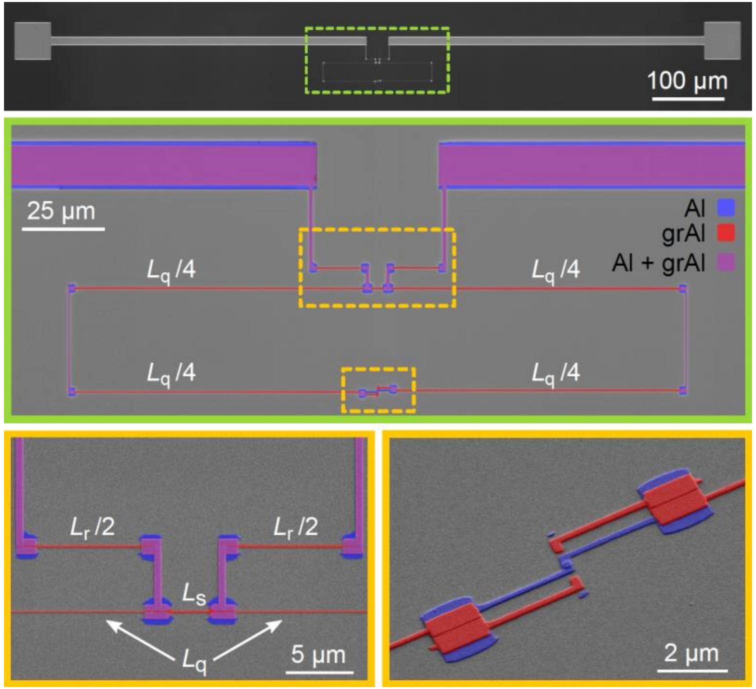
The grAl fluxonium

About 100 JJ typically required for a fluxonium qubit



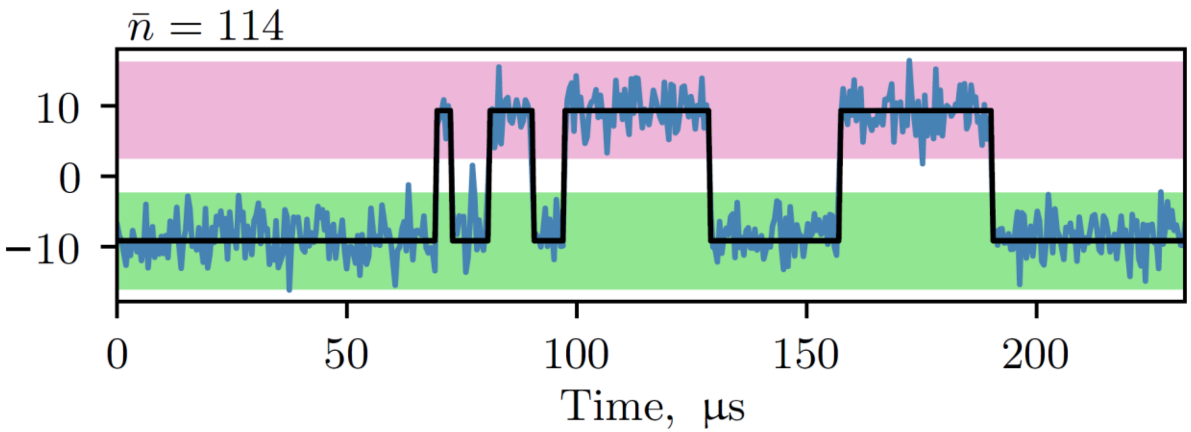
Vool, Pop et al.
Phys Rev. Lett. 113 (2014)

Now how about a 99% discount?



Grünhaupt, Spiecker et al., *Nature Materials* **18**, 816 (2019)

GrAl fluxonium: resilience to readout photons

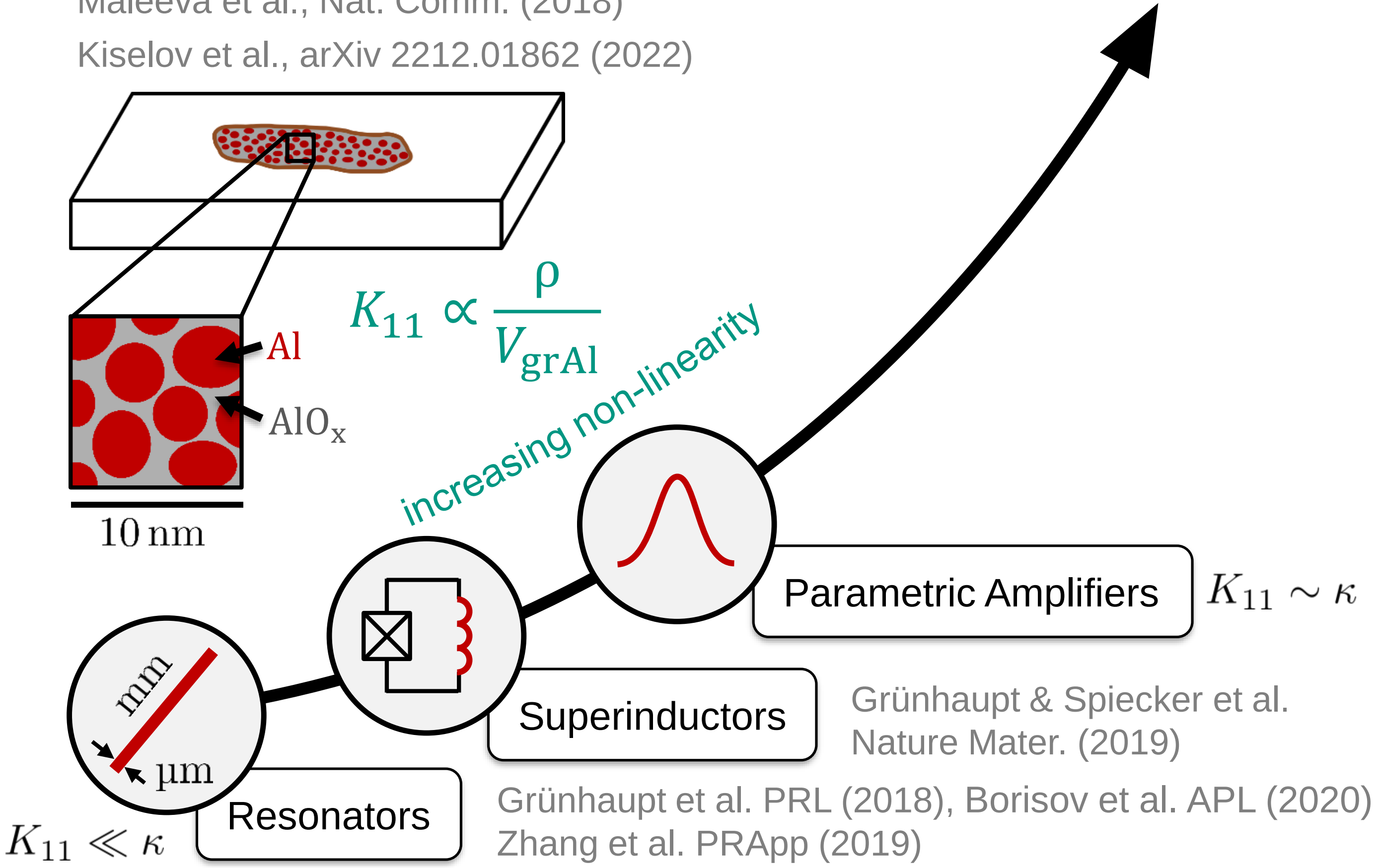


Gusenkova, Spiecker et al., *Phys. Rev. Applied* **15**, 064030 (2021)
Takmakov, Winkel, et al., *Phys. Rev. Applied* **15**, 064029 (2021)

Limit-Testing the Versatility of Granular Aluminum

Maleeva et al., Nat. Comm. (2018)

Kiselov et al., arXiv 2212.01862 (2022)

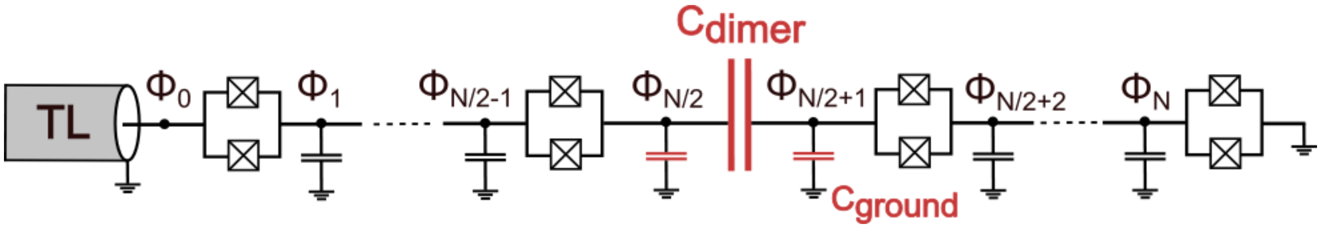


Grünhaupt & Spiecker et al.
Nature Mater. (2019)

Grünhaupt et al. PRL (2018), Borisov et al. APL (2020)
Zhang et al. PRApp (2019)

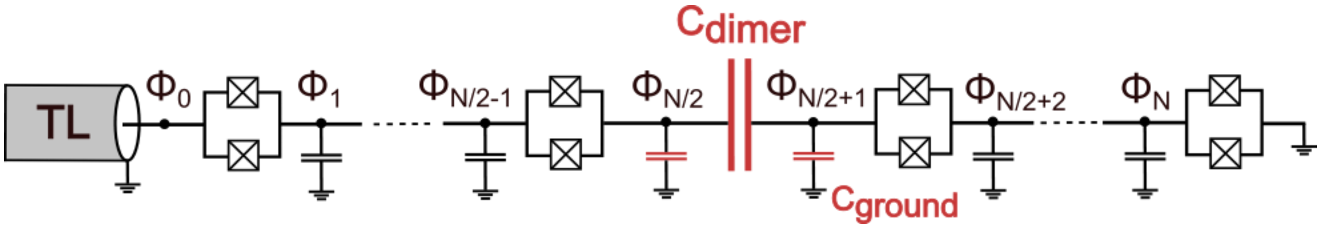
Magnetic Field Resilient Parametric Amplifiers

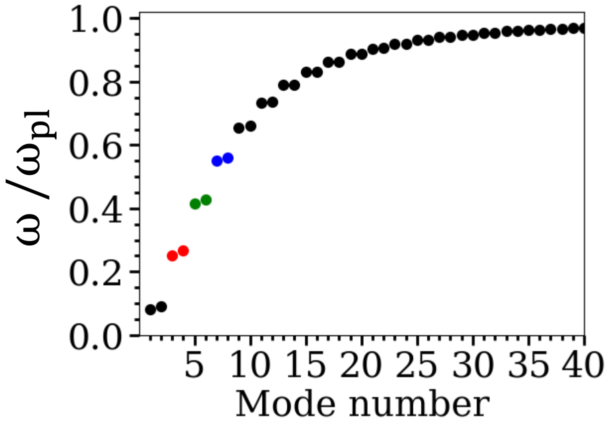
Dimer Josephson Junction Array Amplifier (DJJAA)



Winkel & Takmakov et. al. PRApp (2020)

Dimer Josephson Junction Array Amplifier (DJJAA)





Winkel & Takmakov et. al. PRApp (2020)

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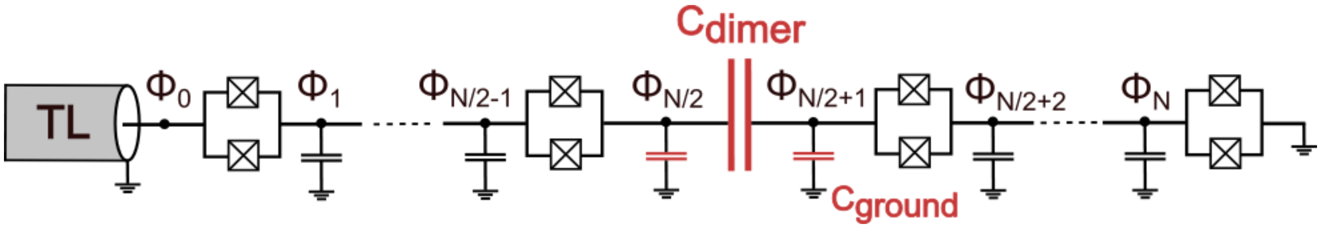
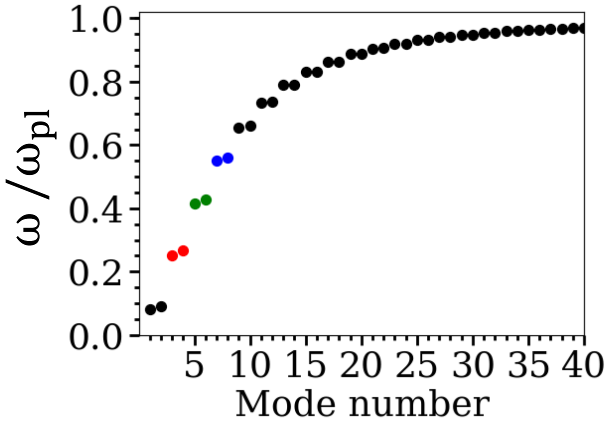
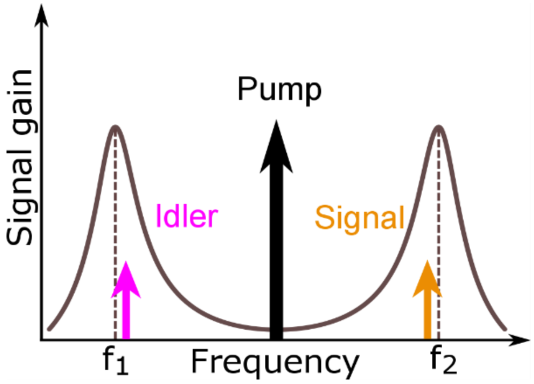
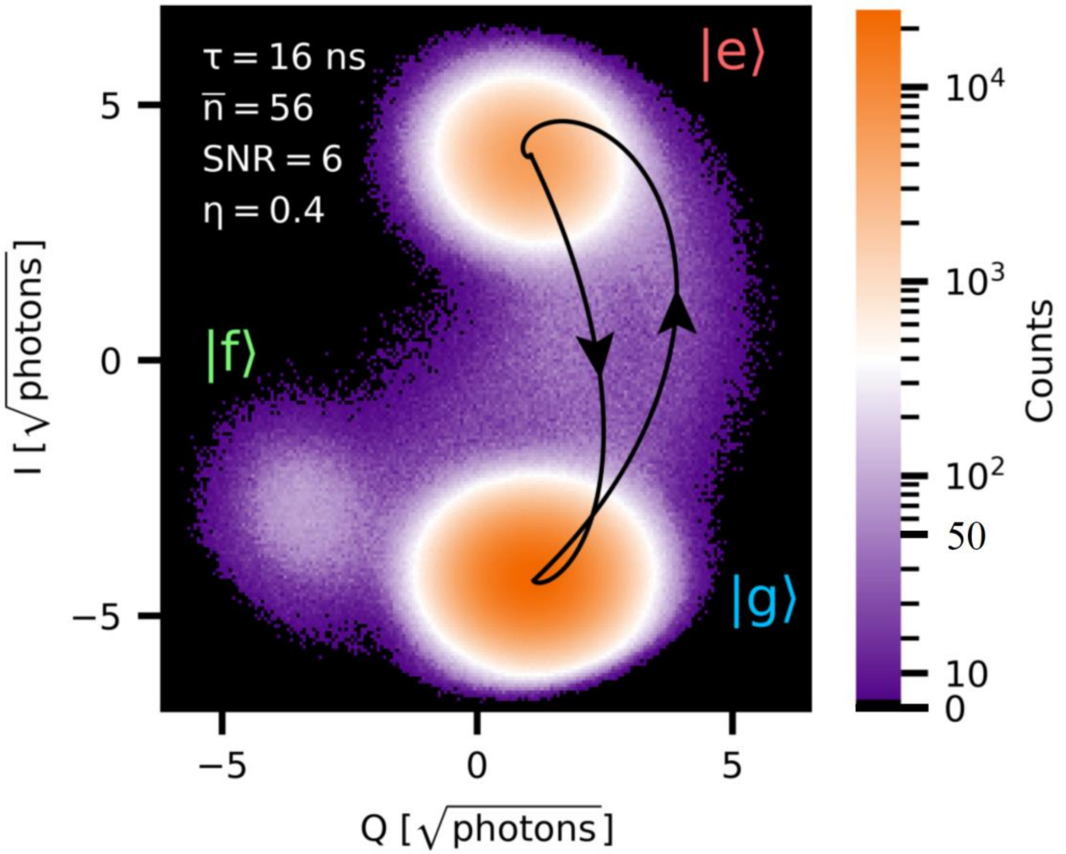






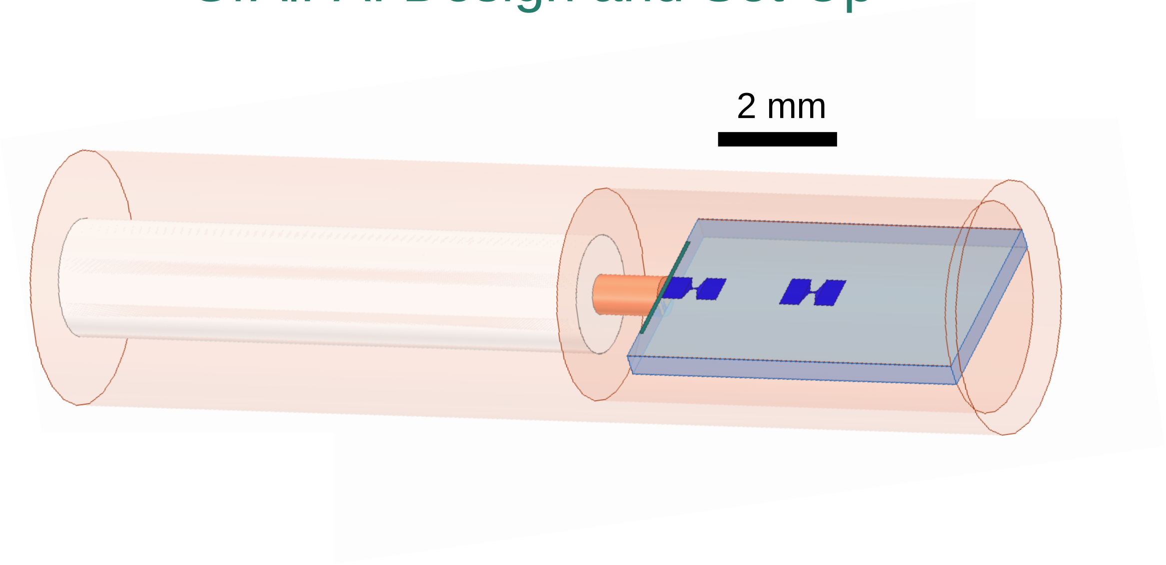
Winkel & Takmakov et. al. PRApp (2020)

GrAl fluxonium + high dynamic range DJJAA

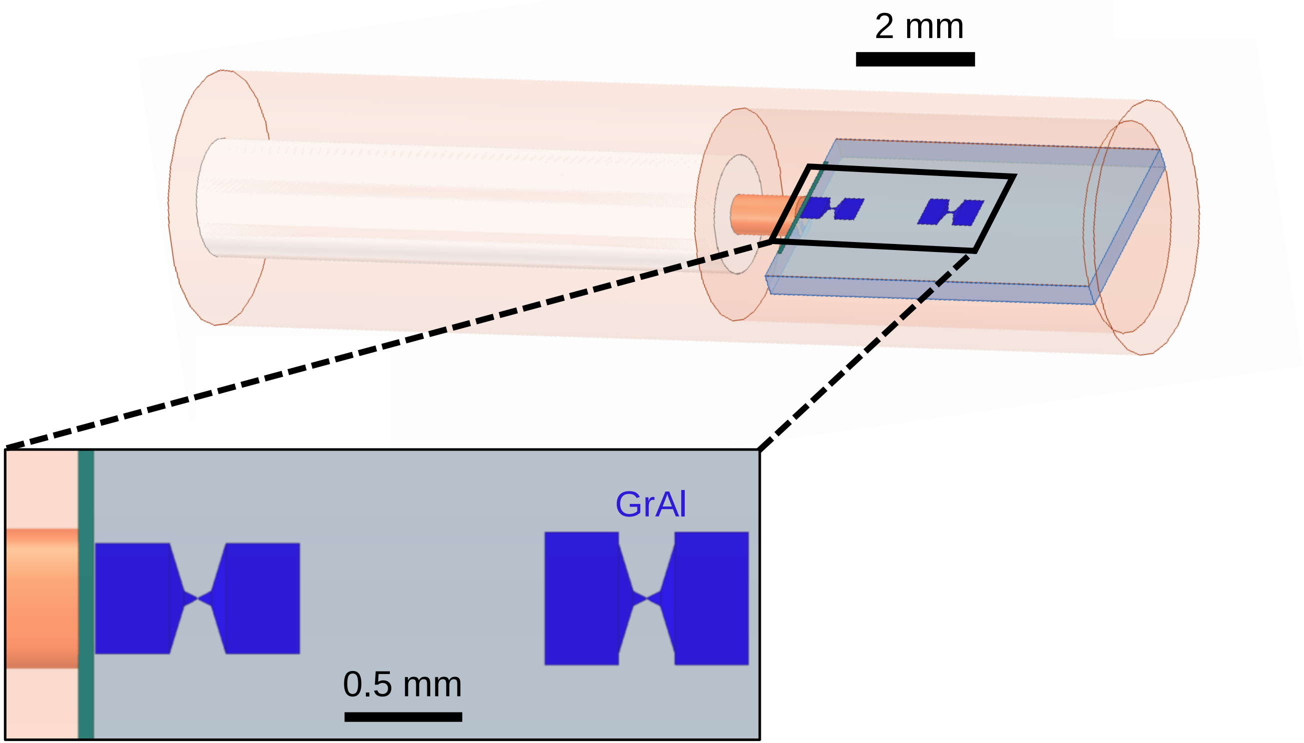


Takmakov & Winkel et al., PRApp (2021)

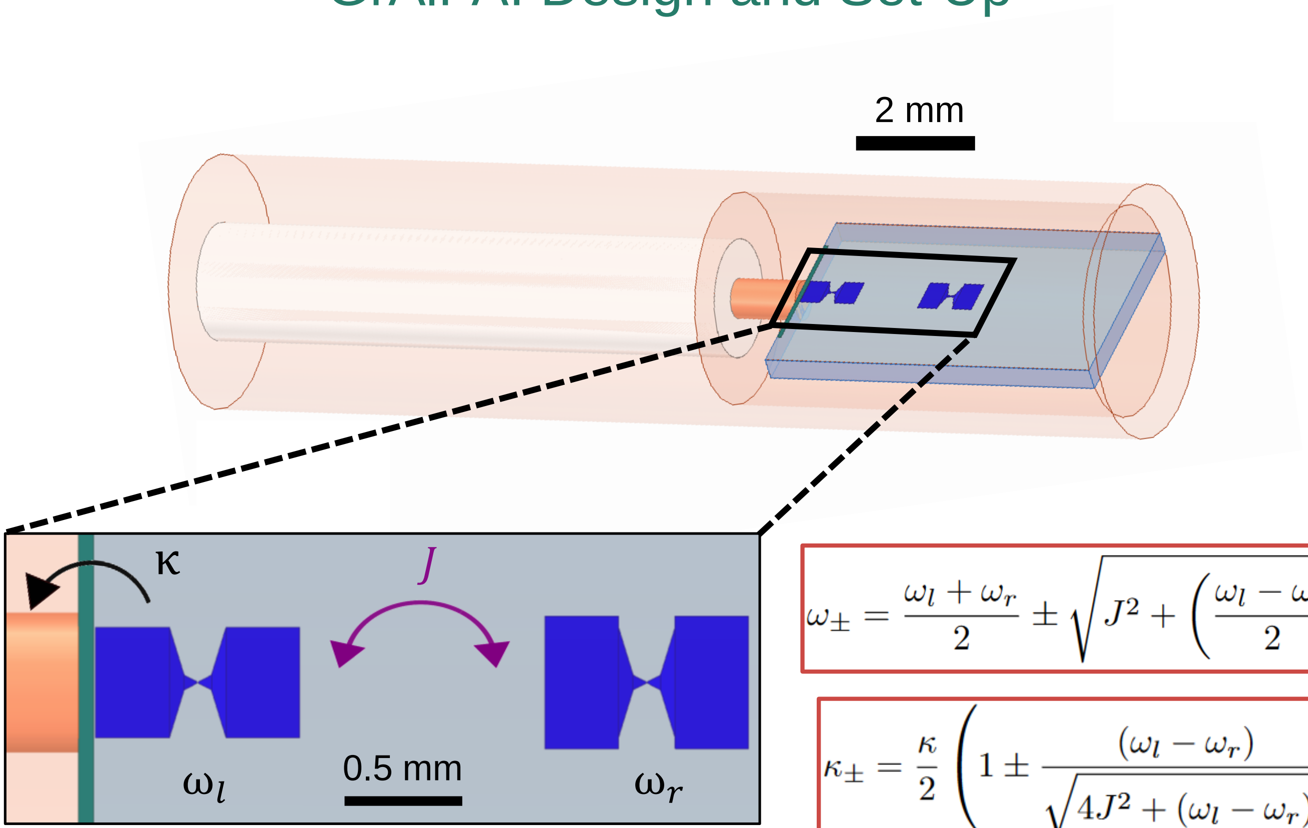
GrAlPA: Design and Set-Up



GrAlPA: Design and Set-Up



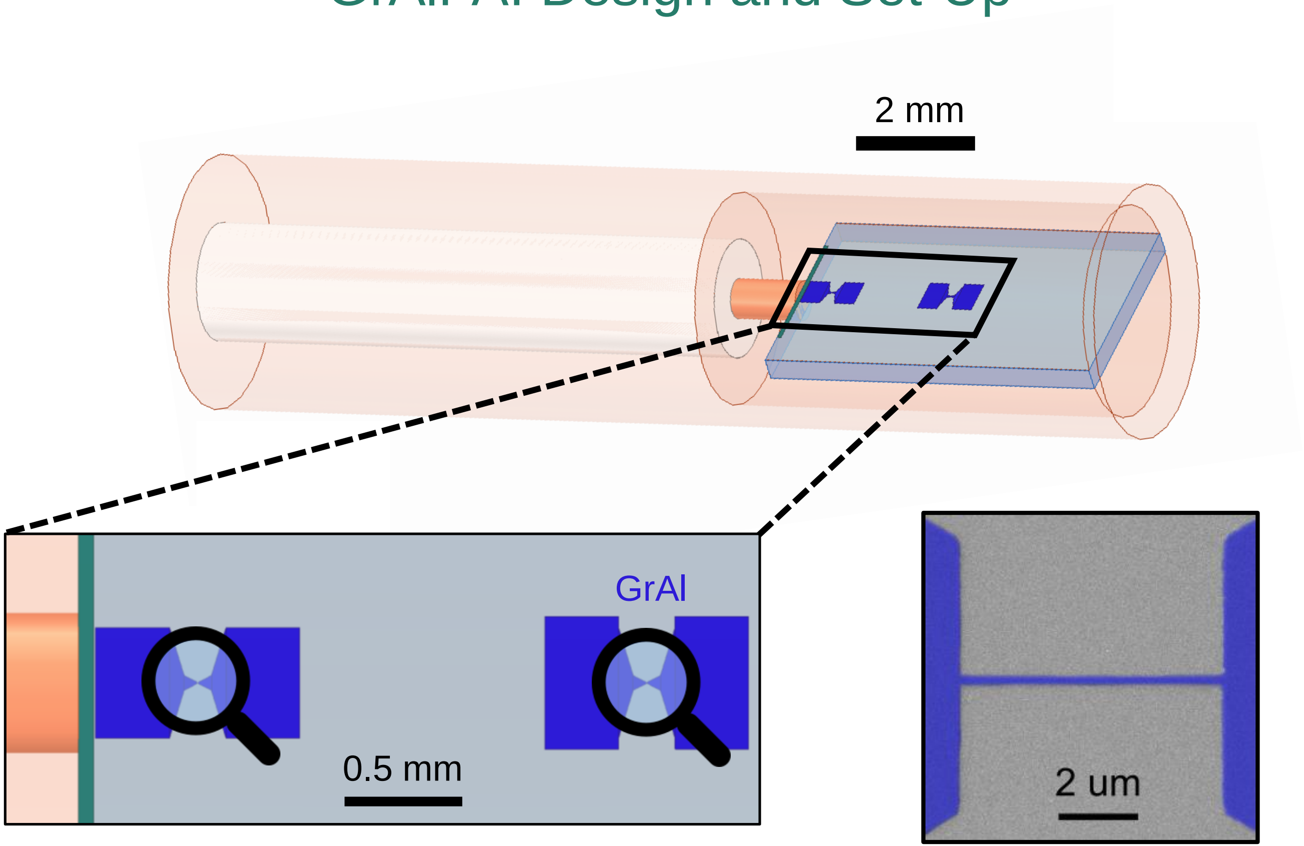
GrAlPA: Design and Set-Up



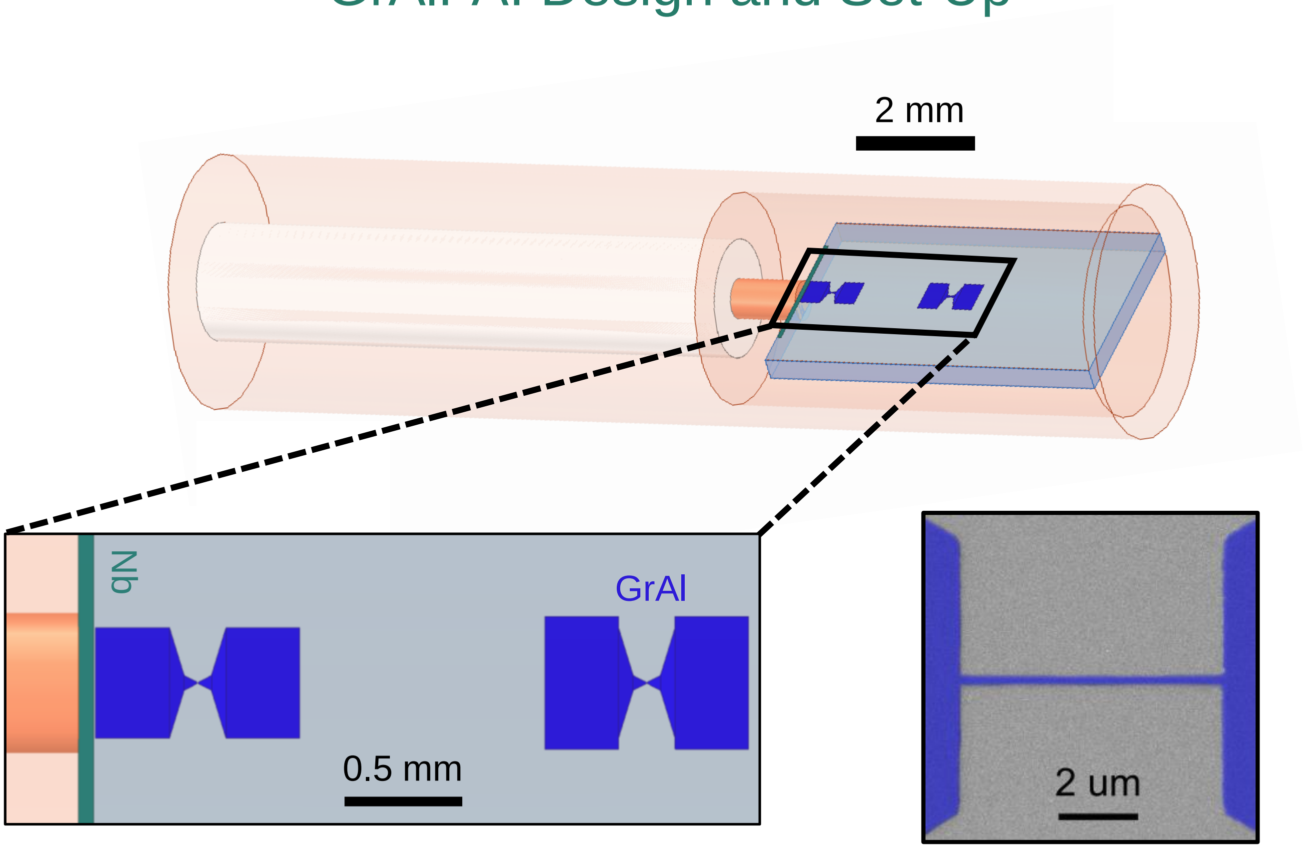
$$\omega_\pm = \frac{\omega_l + \omega_r}{2} \pm \sqrt{J^2 + \left(\frac{\omega_l - \omega_r}{2}\right)^2}$$

$$\kappa_\pm = \frac{\kappa}{2}\left(1 \pm \frac{(\omega_l - \omega_r)}{\sqrt{4J^2 + (\omega_l - \omega_r)^2}}\right)$$

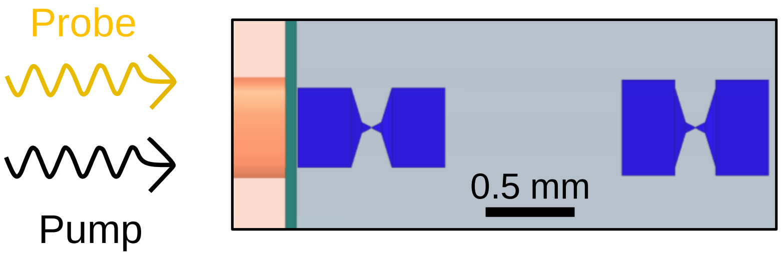
GrAlPA: Design and Set-Up



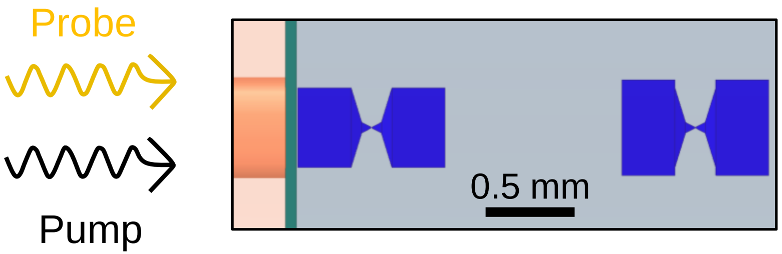
GrAlPA: Design and Set-Up

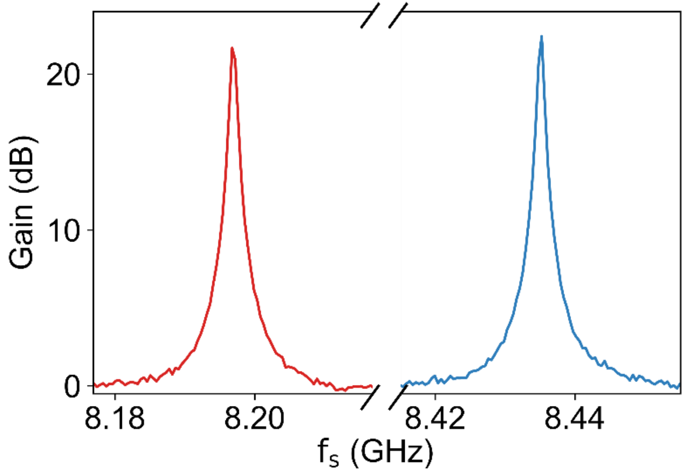


Gain Performance



Gain Performance

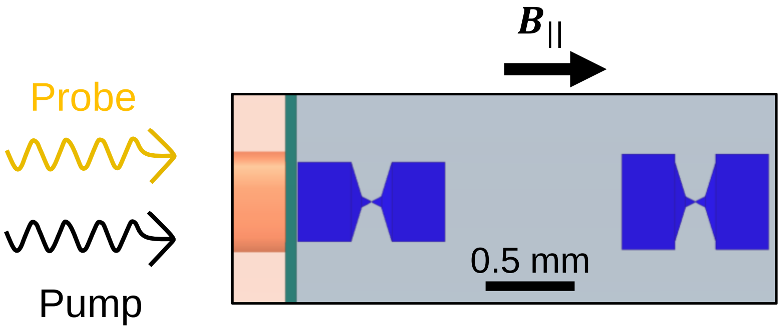


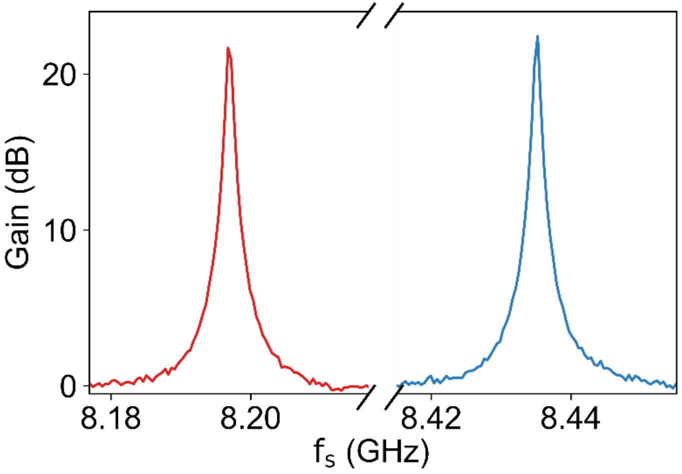


$$\mathrm{BW} \sim \mathrm{MHz}$$

$$P_{\mathrm{sat}} \sim -100\,\mathrm{dBm}$$

Gain Performance

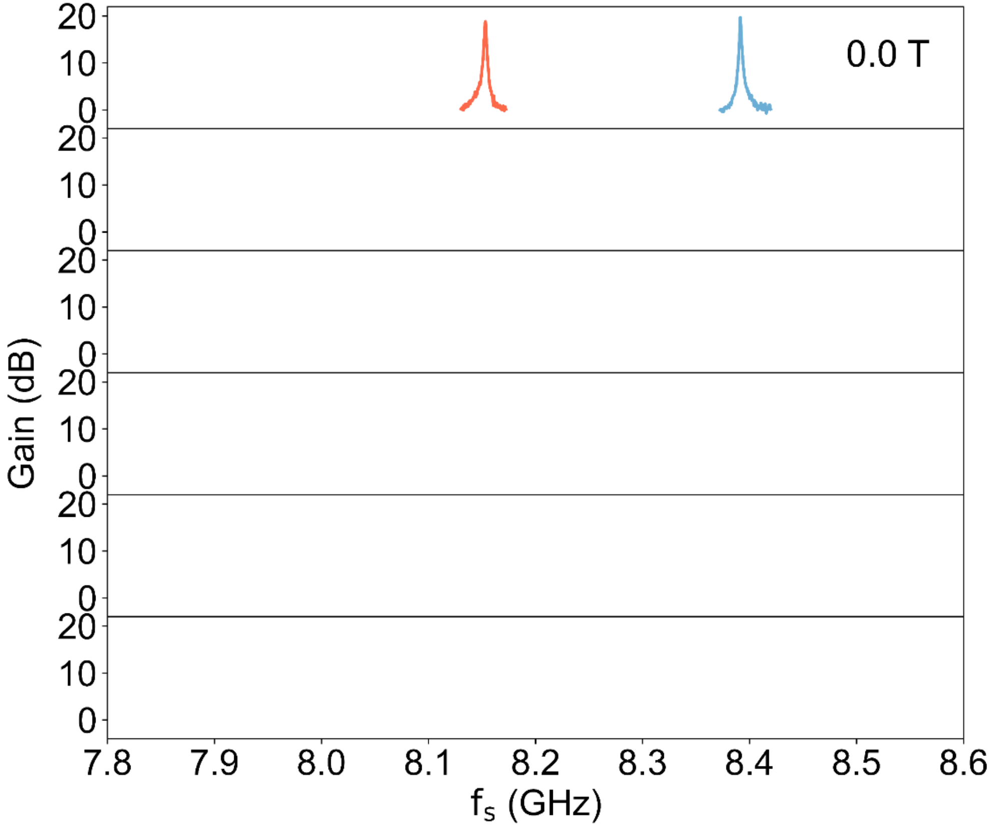




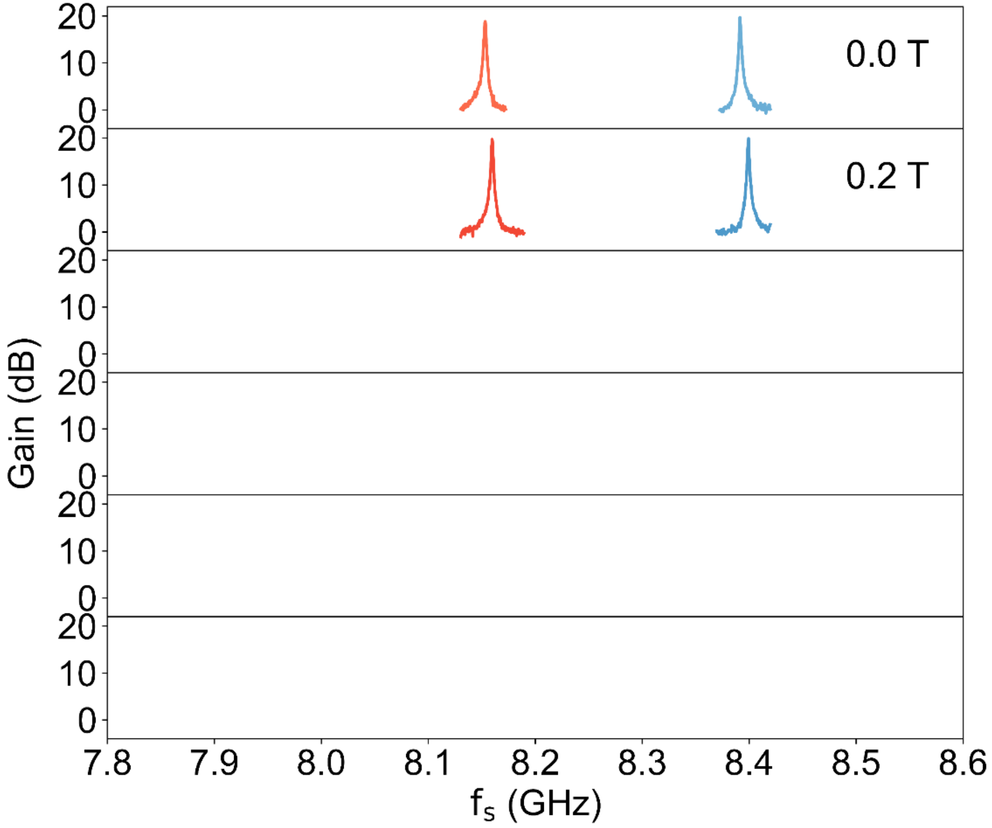
$$\mathrm{BW} \sim \mathrm{MHz}$$

$$\mathrm{P_{sat}} \sim -100\,\mathrm{dBm}$$

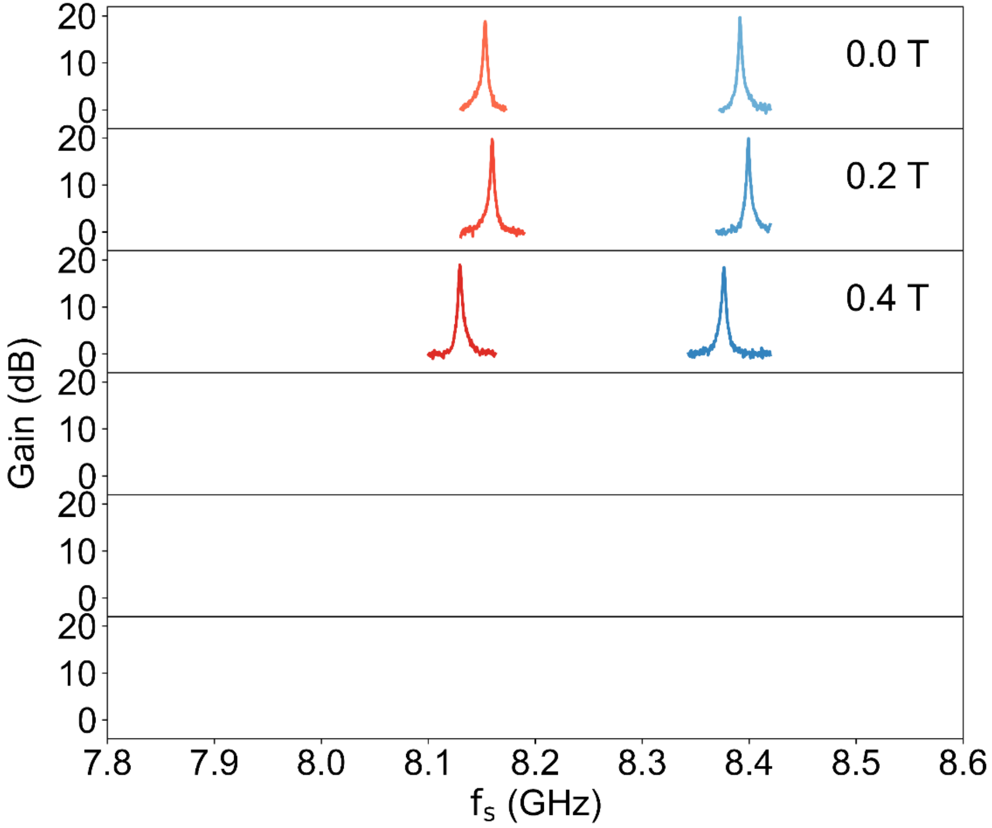
Amplification at High Magnetic Fields



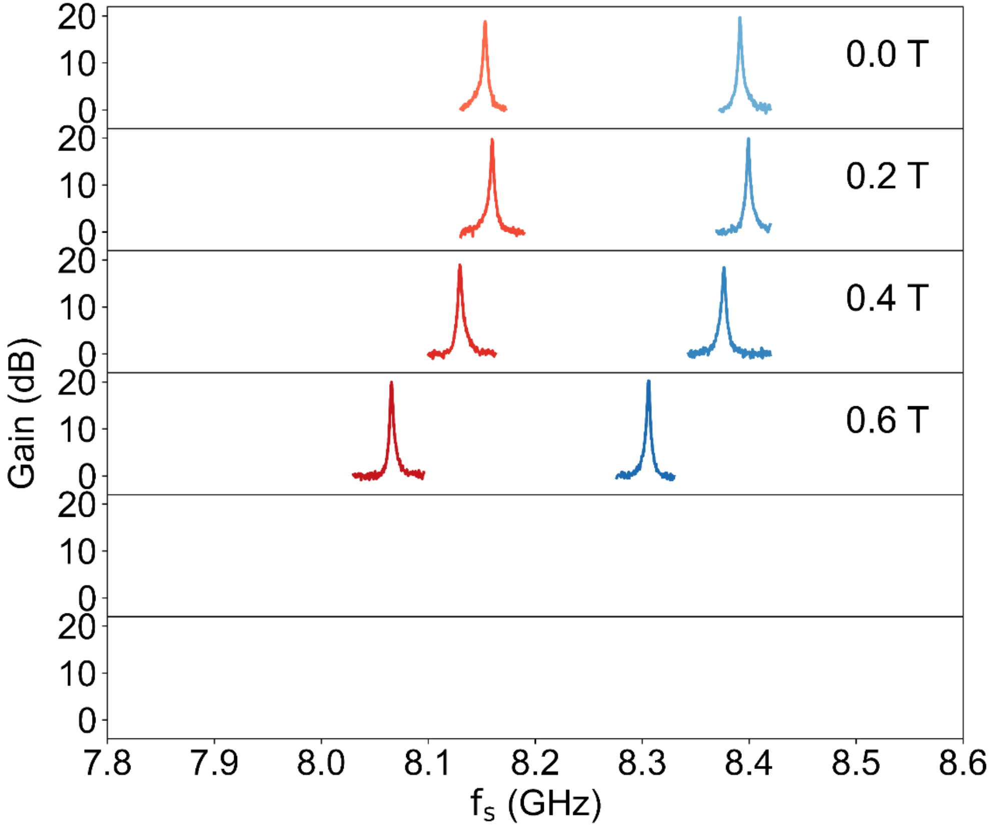
Amplification at High Magnetic Fields



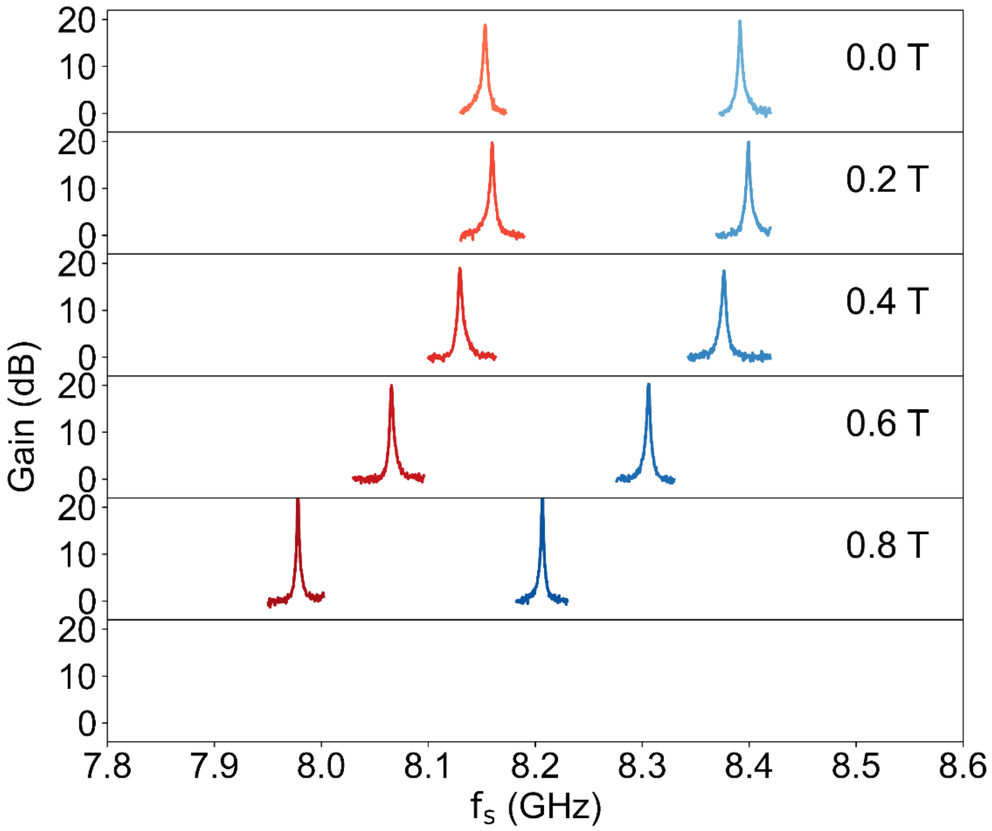
Amplification at High Magnetic Fields



Amplification at High Magnetic Fields

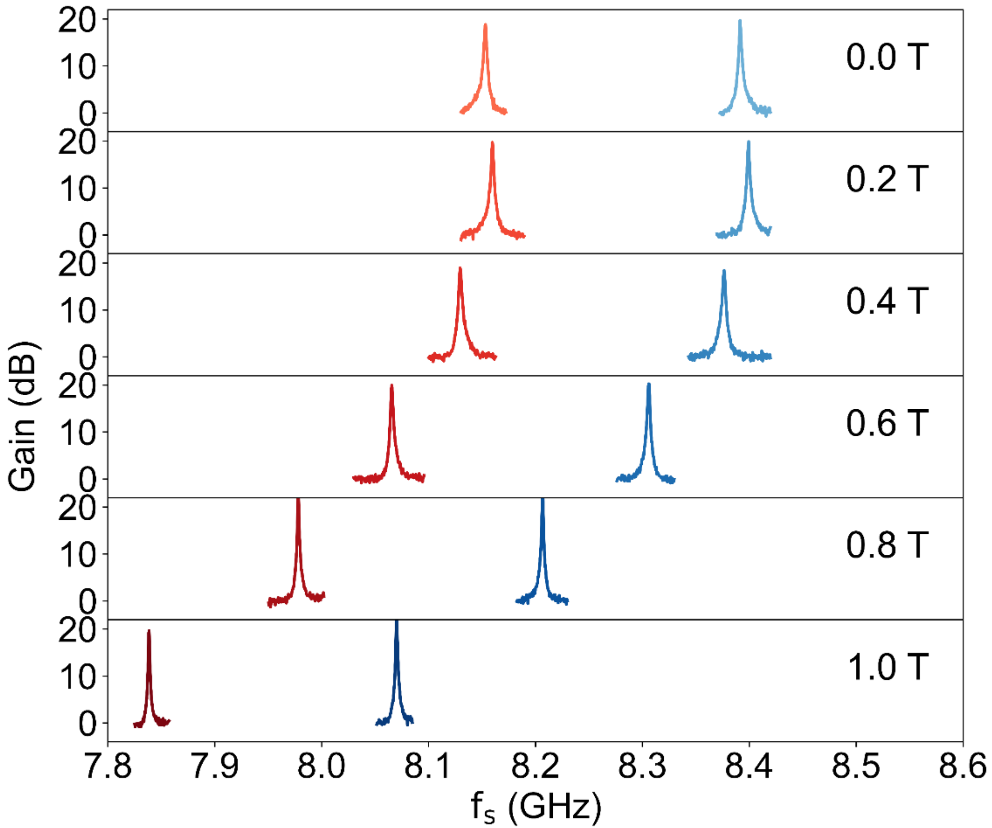


Amplification at High Magnetic Fields

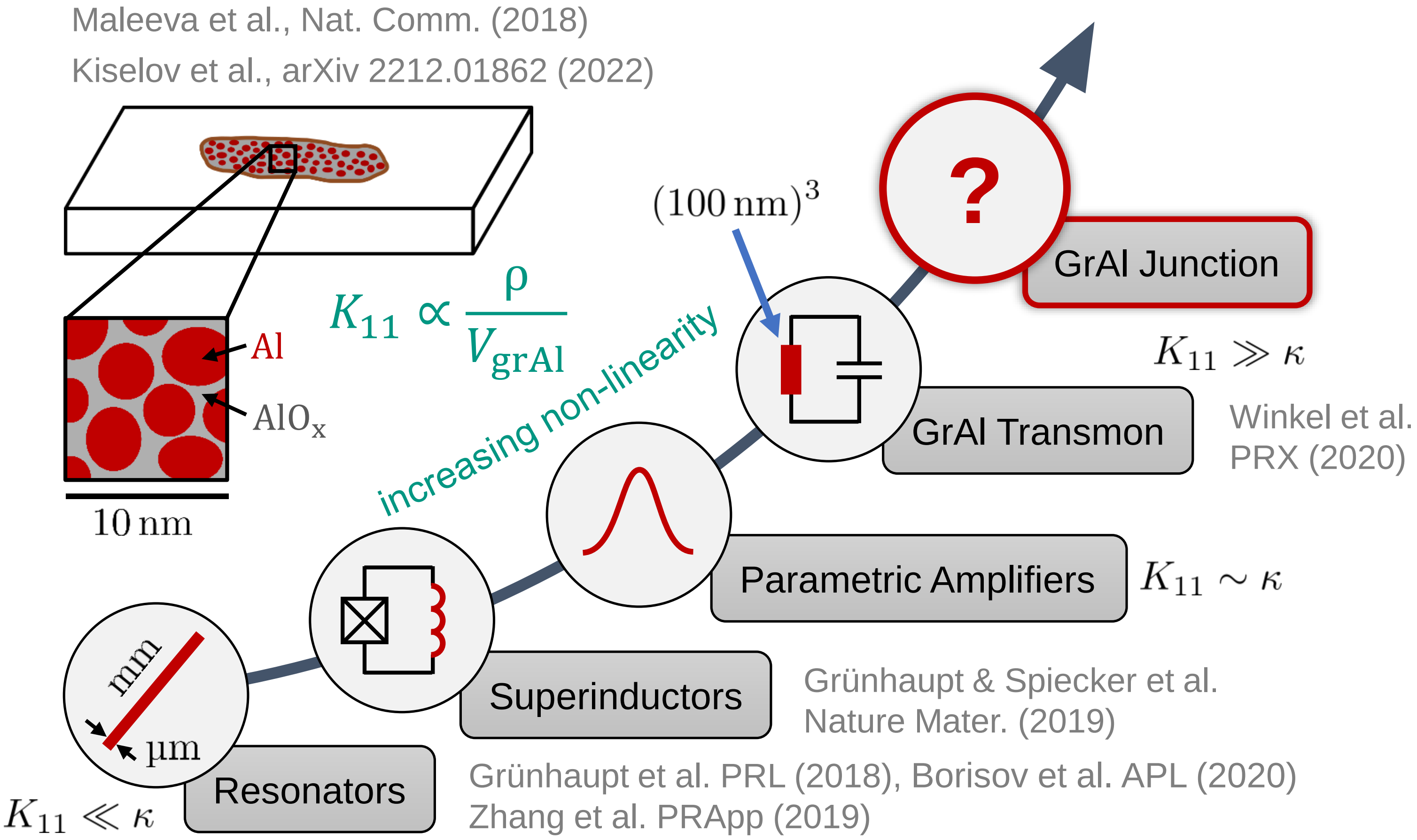


Amplification at High Magnetic Fields

Non-Degenerate 20 dB gain up to $B_{||}$ = 1 T



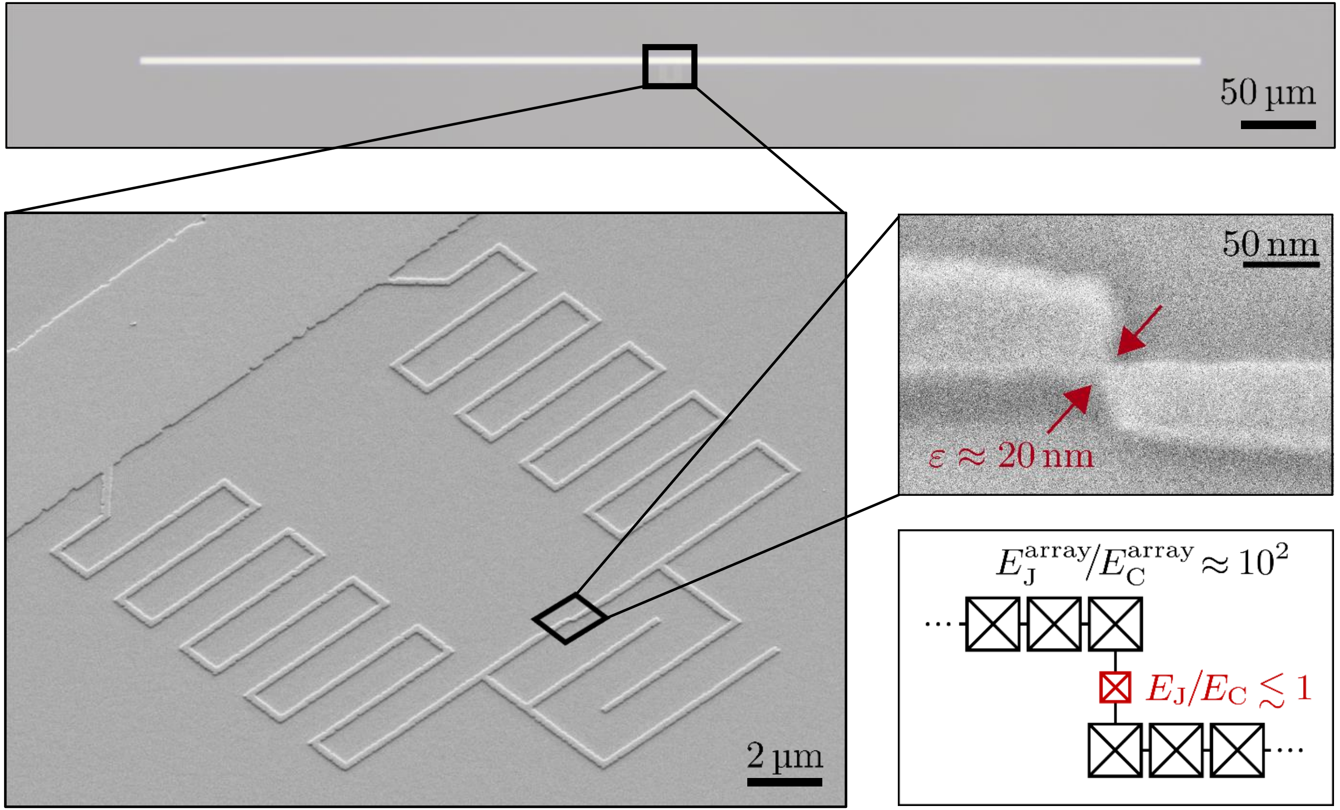
Limit-Testing the Versatility of Granular Aluminum



Gralmonium: a nano-junction Fluxonium

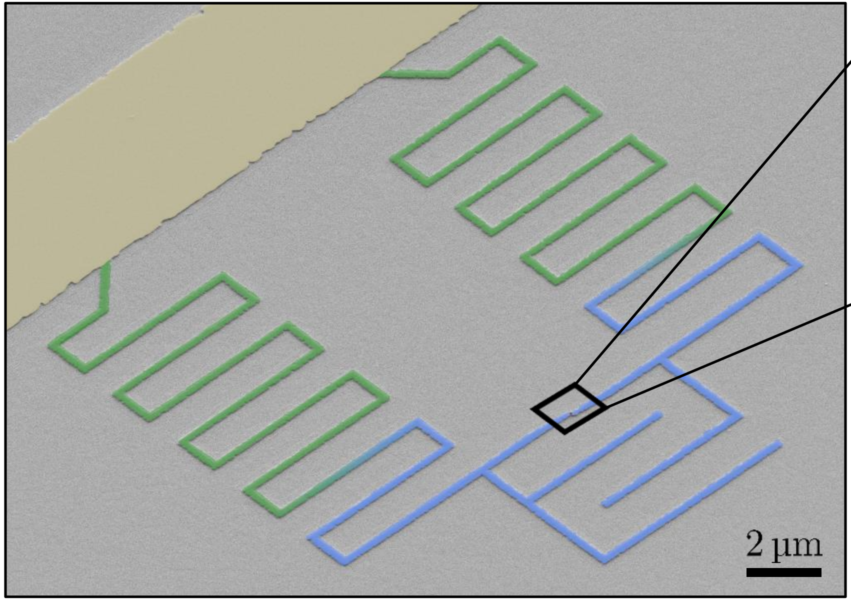
Rieger & Günzler et al.
Nature Mater. **22** (2023)

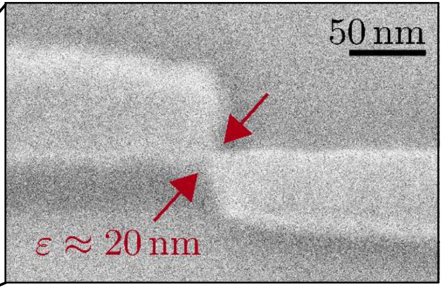
The Gralmonium Circuit & the GrAl Nano-Junction

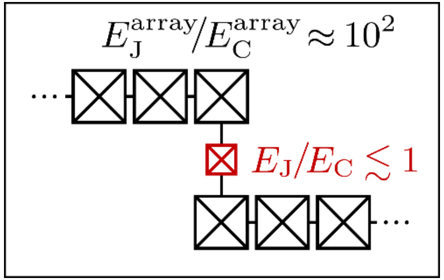


Fluxonium as a Testbed for Energy-Phase-Relation

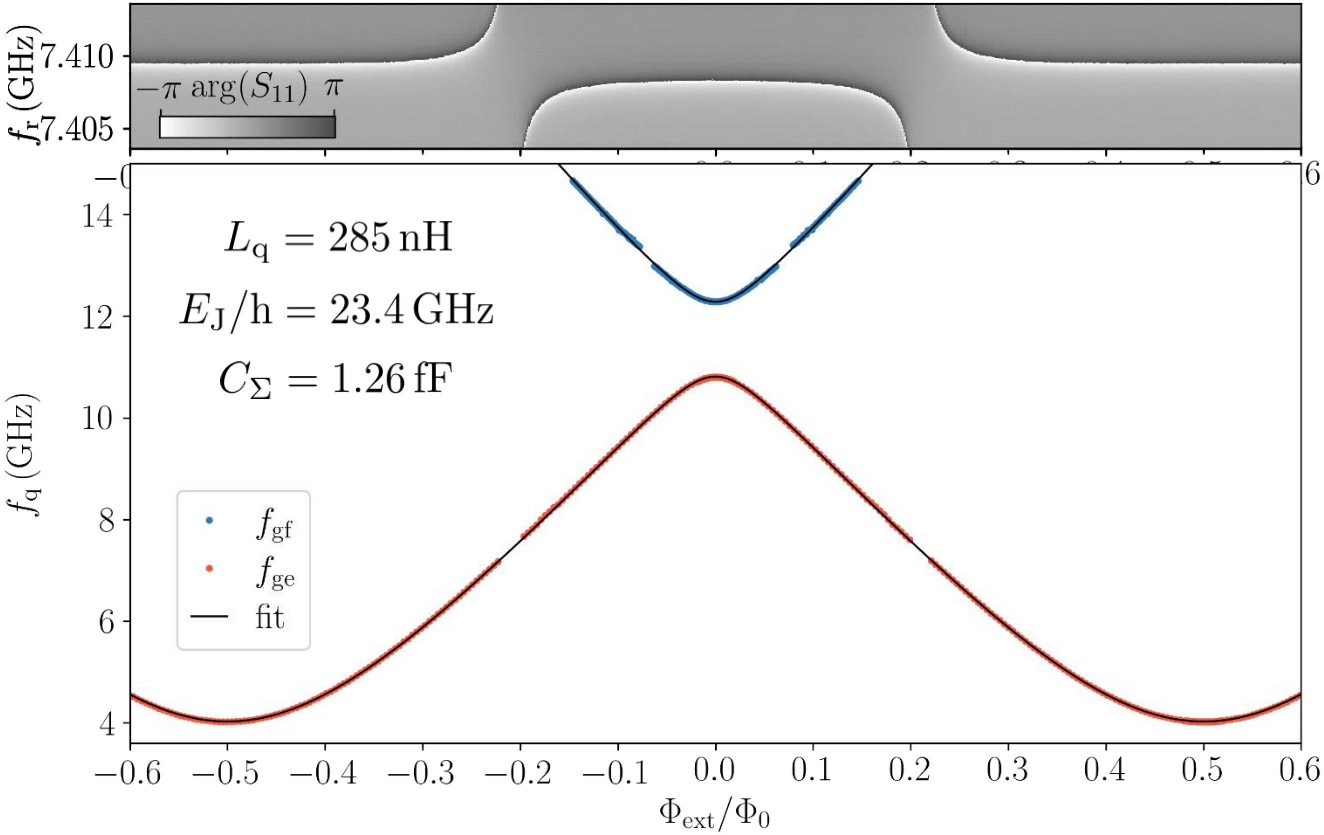
$$H = \frac{1}{2}E_\mathrm{L}\left(\varphi - 2\pi\frac{\Phi_\mathrm{ext}}{\Phi_0}\right)^2 + 4E_\mathrm{C}^{\Sigma}n^2 - E_\mathrm{J}\cos\varphi$$



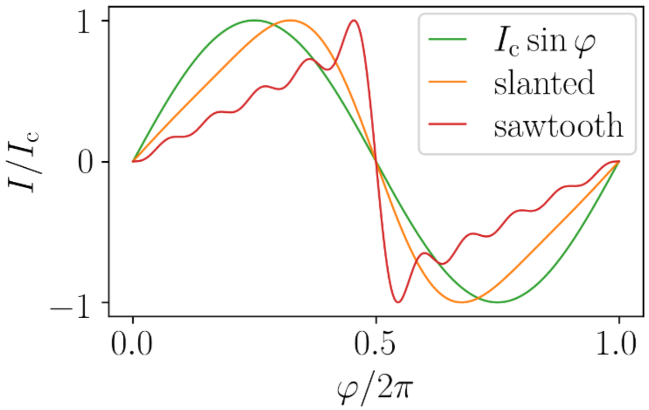




Spectroscopy Confirming a Standard Fluxonium

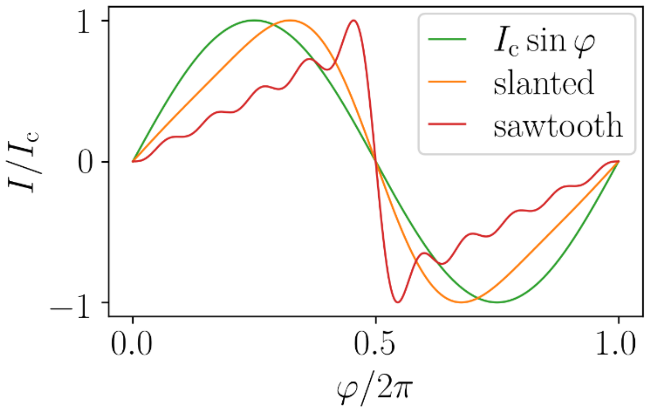


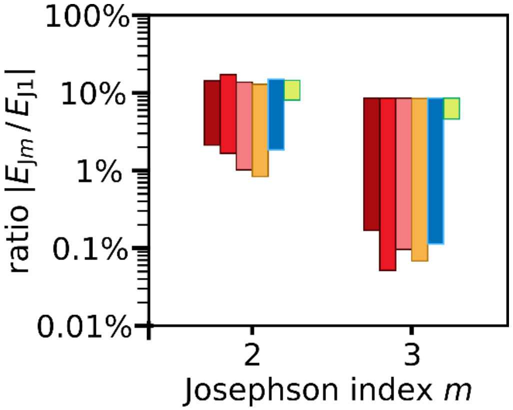
How Sinusoidal is the GrAl Nano-Junction CφR?



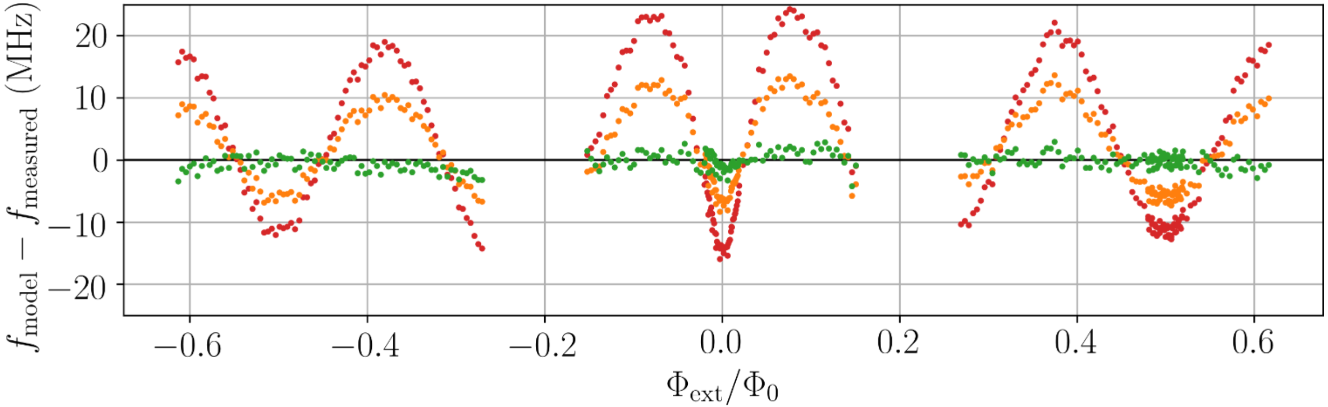
< 5% of $\cos(2\varphi)$

How Sinusoidal is the GrAl Nano-Junction CφR?



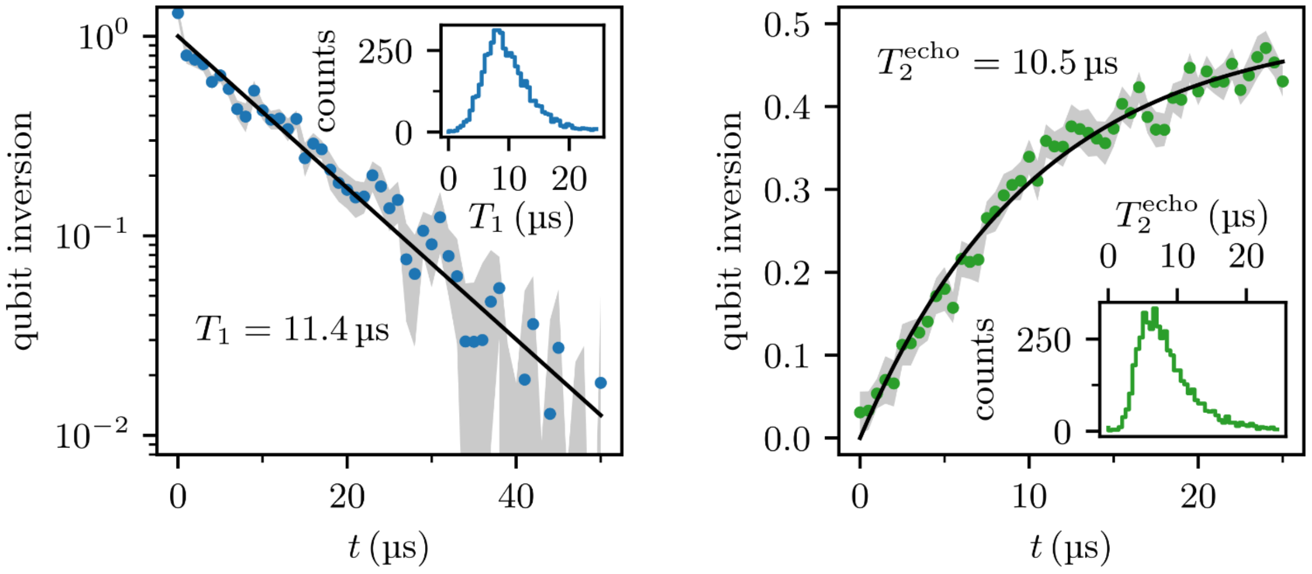


Willsch & Rieger et al.
arXiv:2302.09192 (2023)



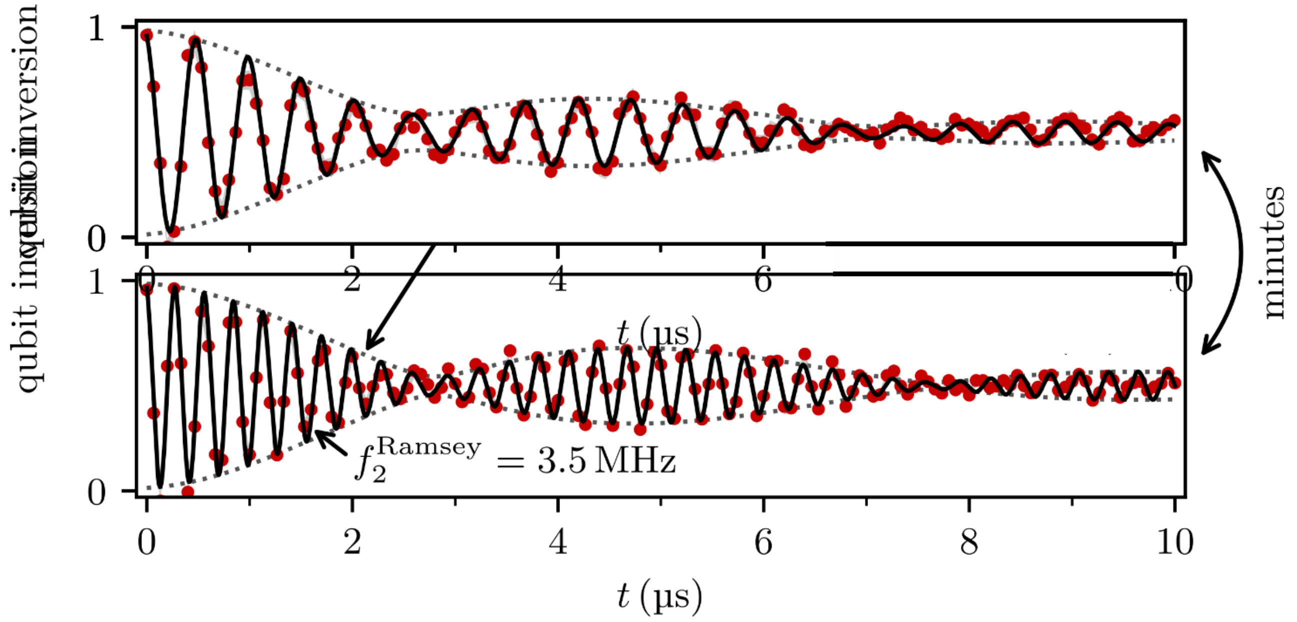
$< 5\%$ of $\cos(2\varphi)$

Time Domain Characterization

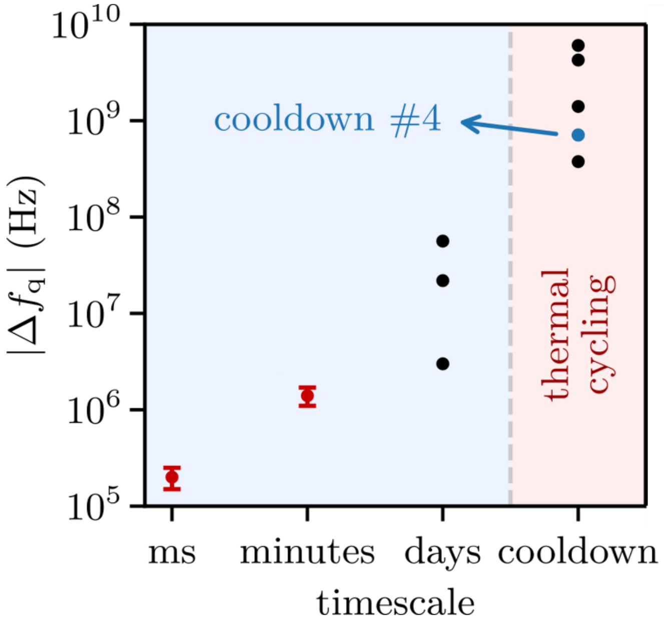


$\Phi_{\mathrm{ext}}/\Phi_0 = 0.5$

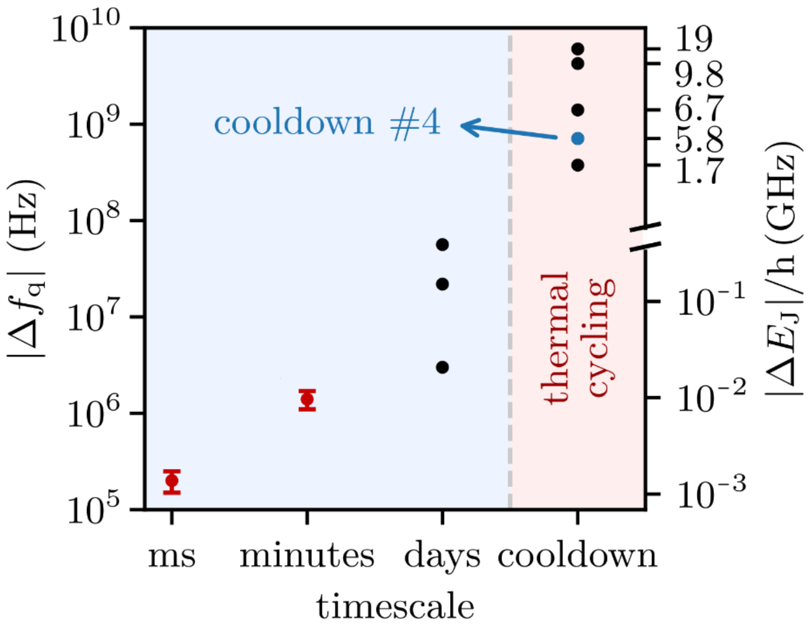
Departing from Expectations…



Unconventional Fluctuations

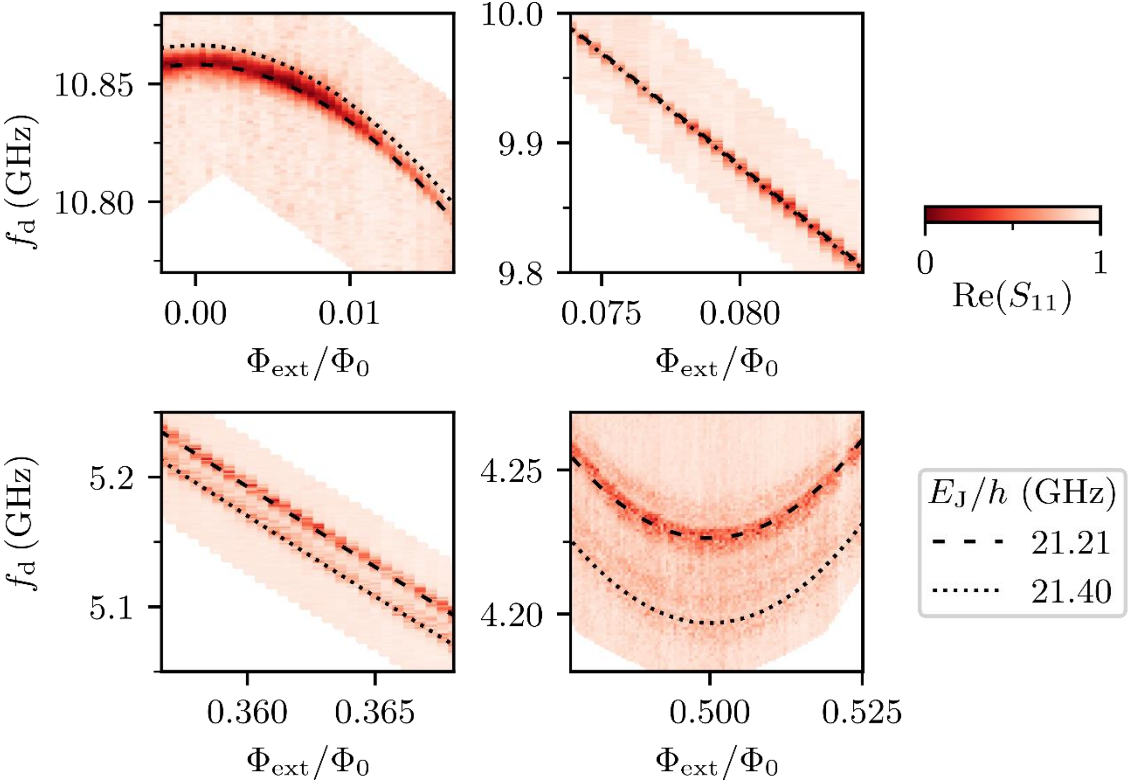


Unconventional Fluctuations

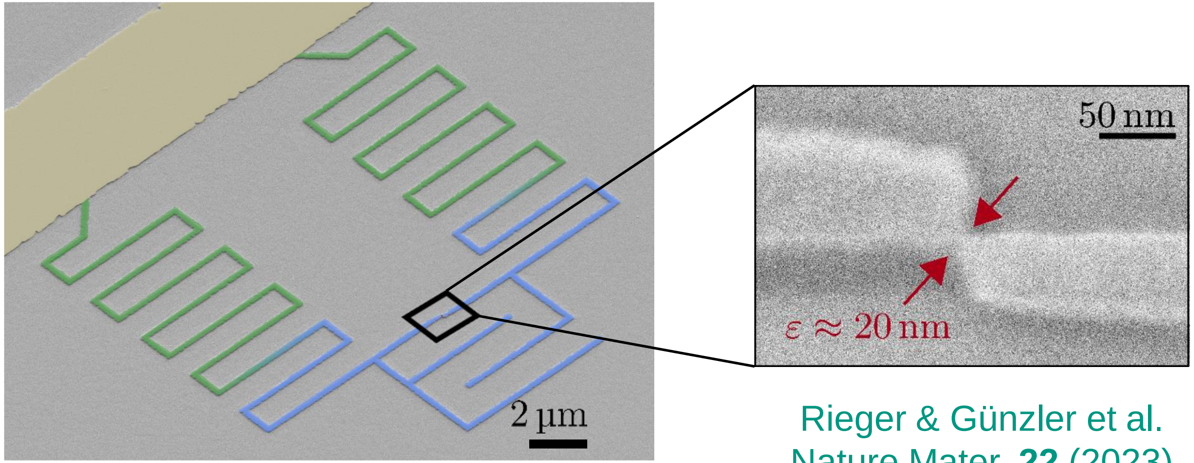


$$\nu = \frac{4}{\sqrt{\pi}} \left(8E_J^3 E_C^\Sigma\right)^{1/4} \exp\left(-\sqrt{8E_J/E_C^\Sigma}\right)$$

E_J Toggling in the Gralmonium Spectrum vs Flux



The Future of the Gralmonium and Tesla fields cQED



Rieger & Günzler et al.
Nature Mater. **22** (2023)

Coherent, single-layer nano-junction fluxonium qubit

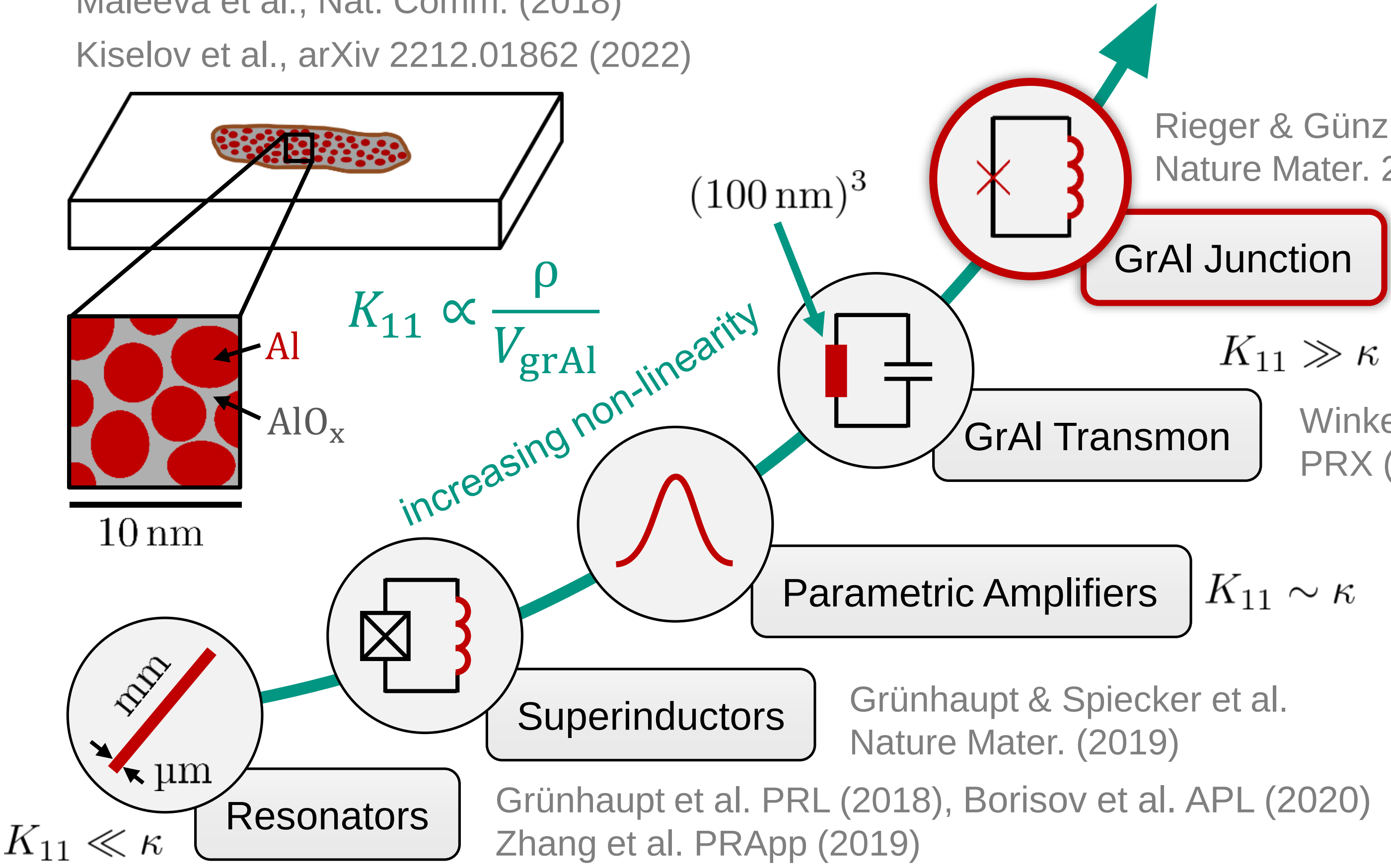
Stabilize qubit frequency

Measure in magnetic field

Limit-Testing the Versatility of Granular Aluminum

Maleeva et al., Nat. Comm. (2018)

Kiselov et al., arXiv 2212.01862 (2022)



Rieger & Günzler et al. Nature Mater. 22 (2023)

Winkel et al. PRX (2020)

Grünhaupt & Spiecker et al. Nature Mater. (2019)

Grünhaupt et al. PRL (2018), Borisov et al. APL (2020)

Zhang et al. PRApp (2019)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Simon II.
Patrick
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Mahya
Ioan
autumn 2022