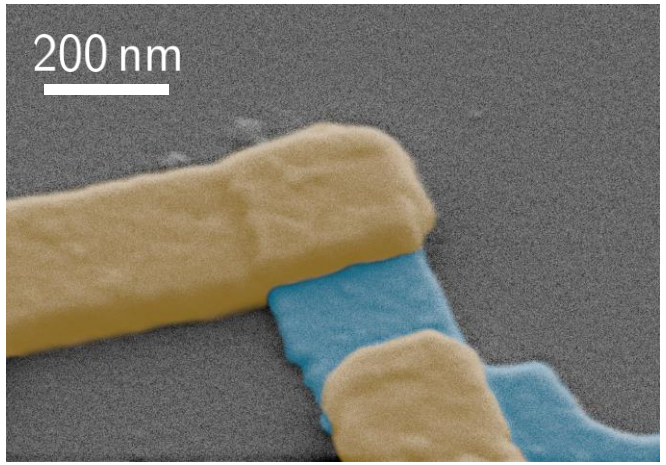
Observation of Josephson Harmonics in Tunnel Junctions

Dennis Willsch
Dennis Rieger
et al.

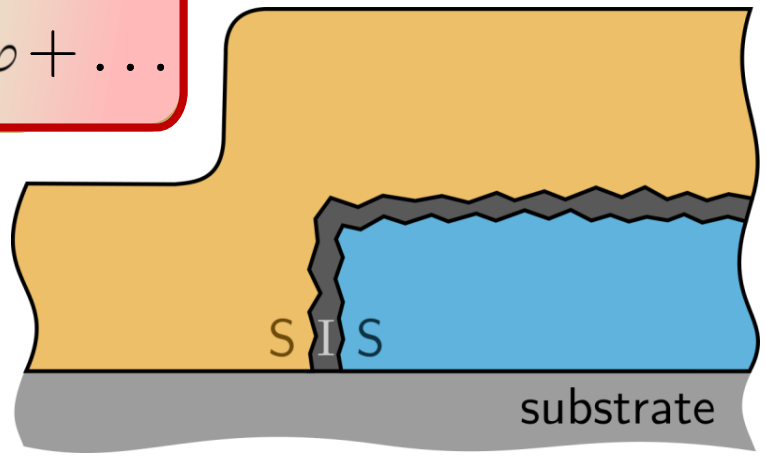
arXiv:2302.09192

Josephson (1962)



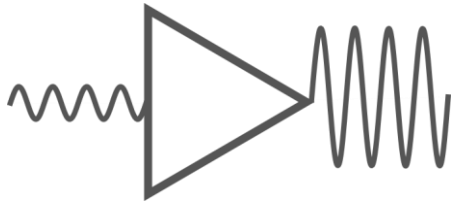
$$I_s = I_c \sin\varphi + \dots$$
$$H_J = -E_J \cos\varphi + \dots$$

$\Leftrightarrow$

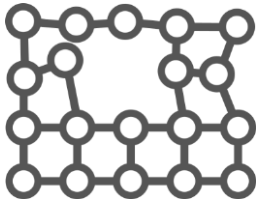


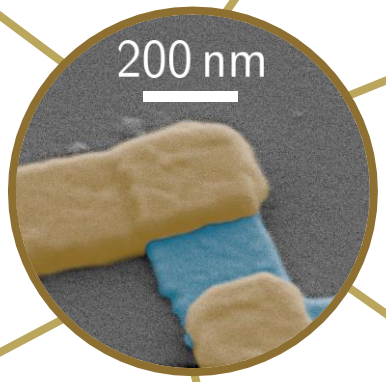
The Stakeholders in the Josephson Effect

Quantum Amplification

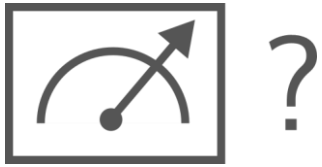


Material Science





Quantum Detection



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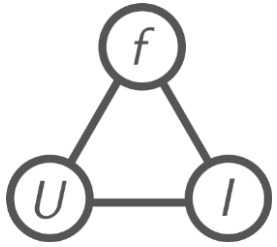
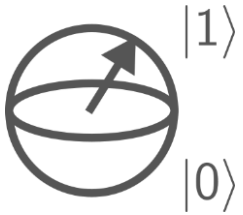
Metrology



…

Quantum Information



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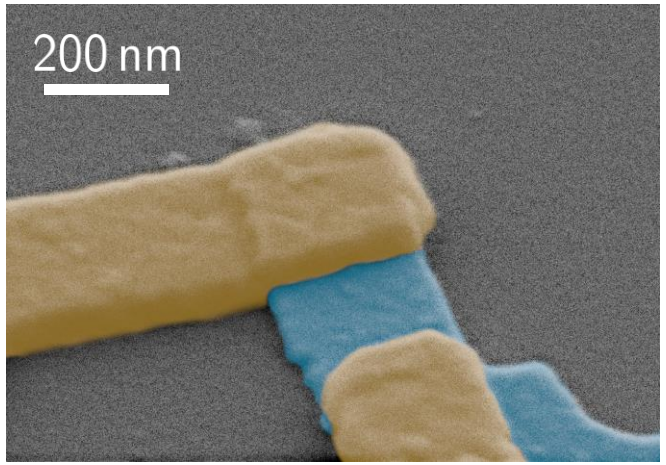

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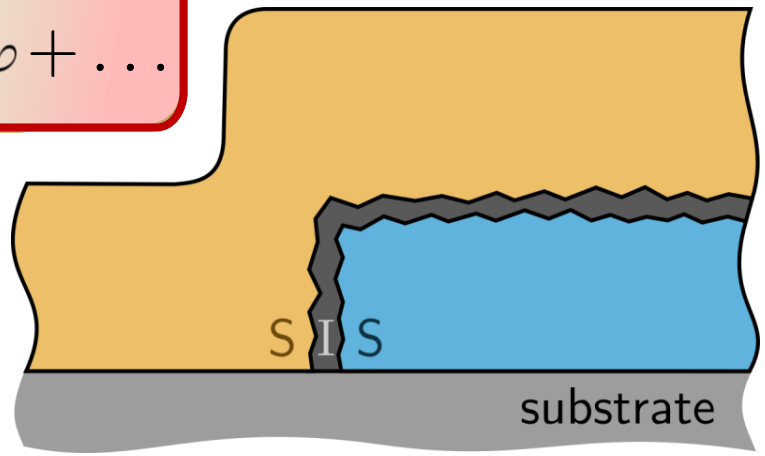
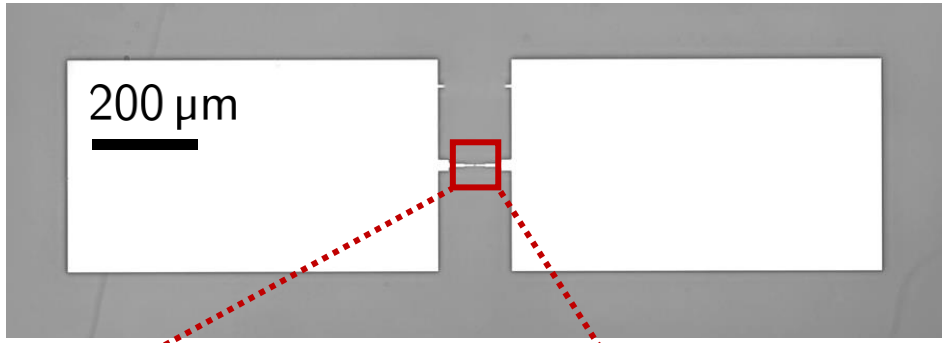
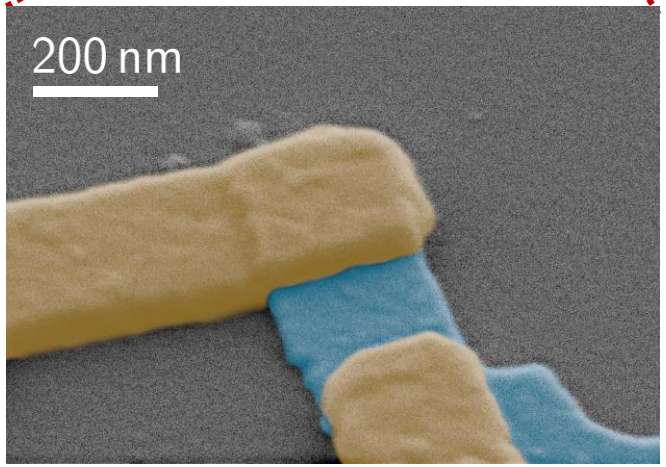
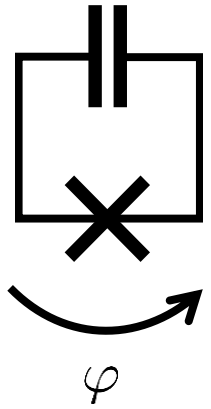
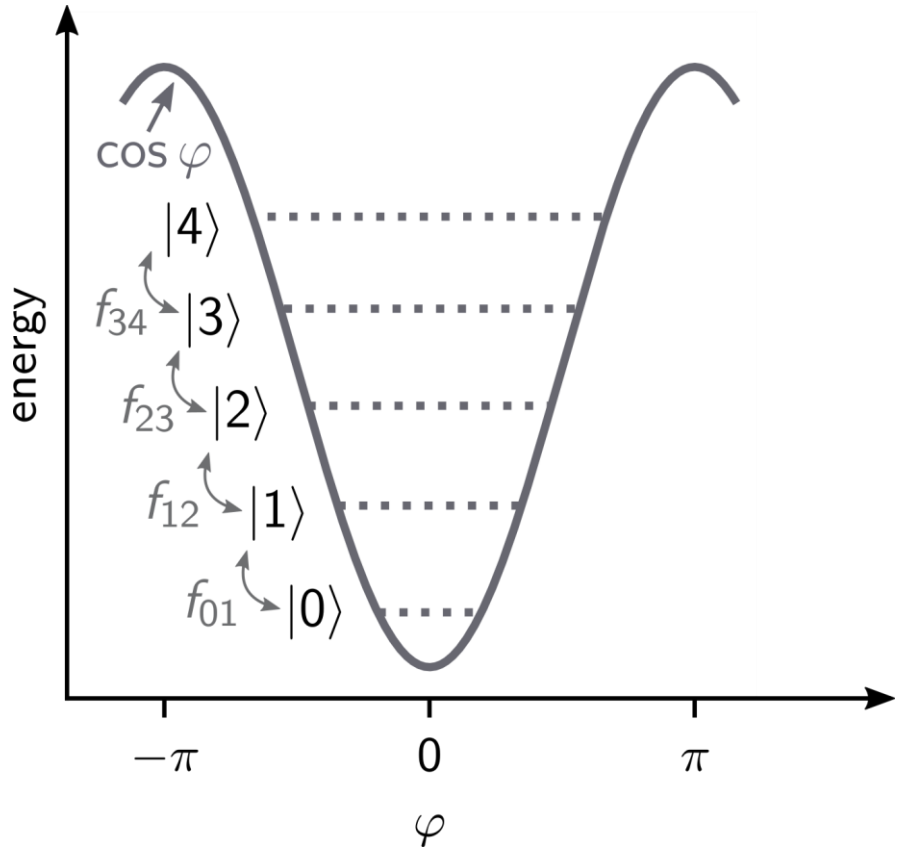


The Transmon Qubit as a Testbed for the Current-Phase-Relation



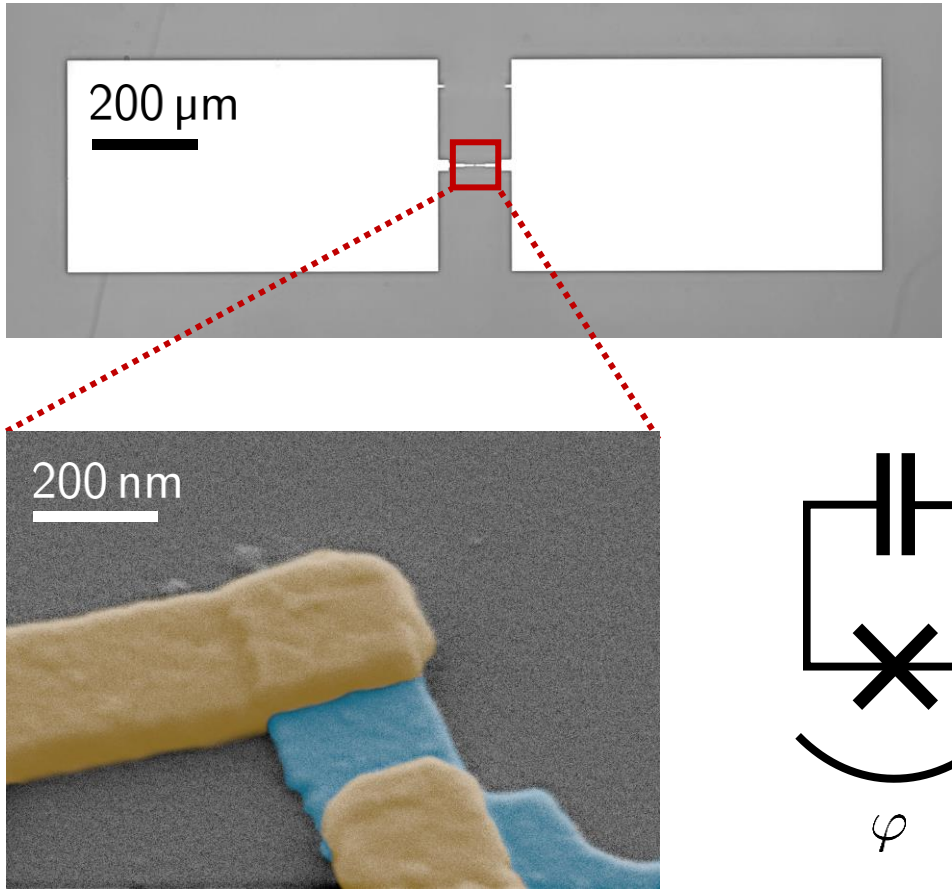


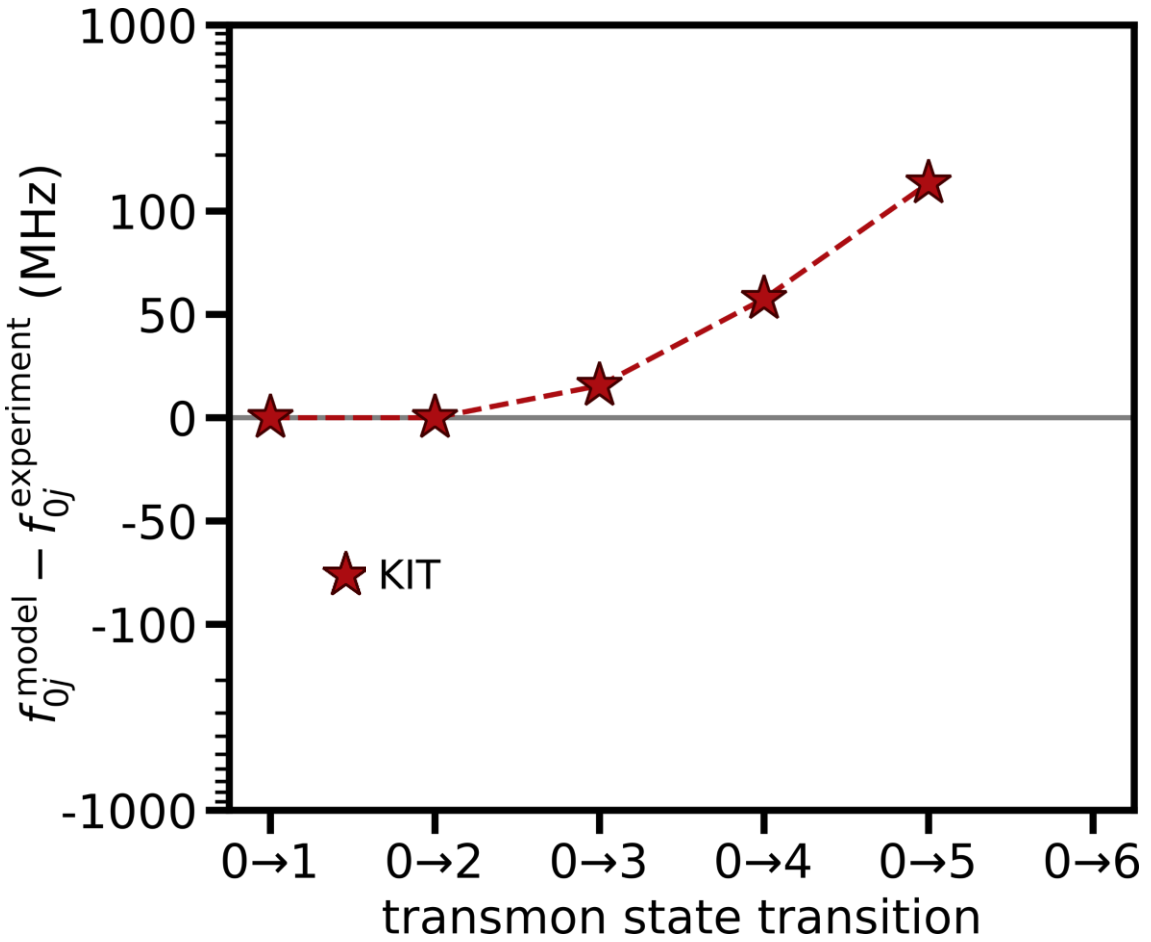




$$H = 4E_c n^2 - E_J \cos\varphi$$

The Transmon Qubit as a Testbed for the Current-Phase-Relation





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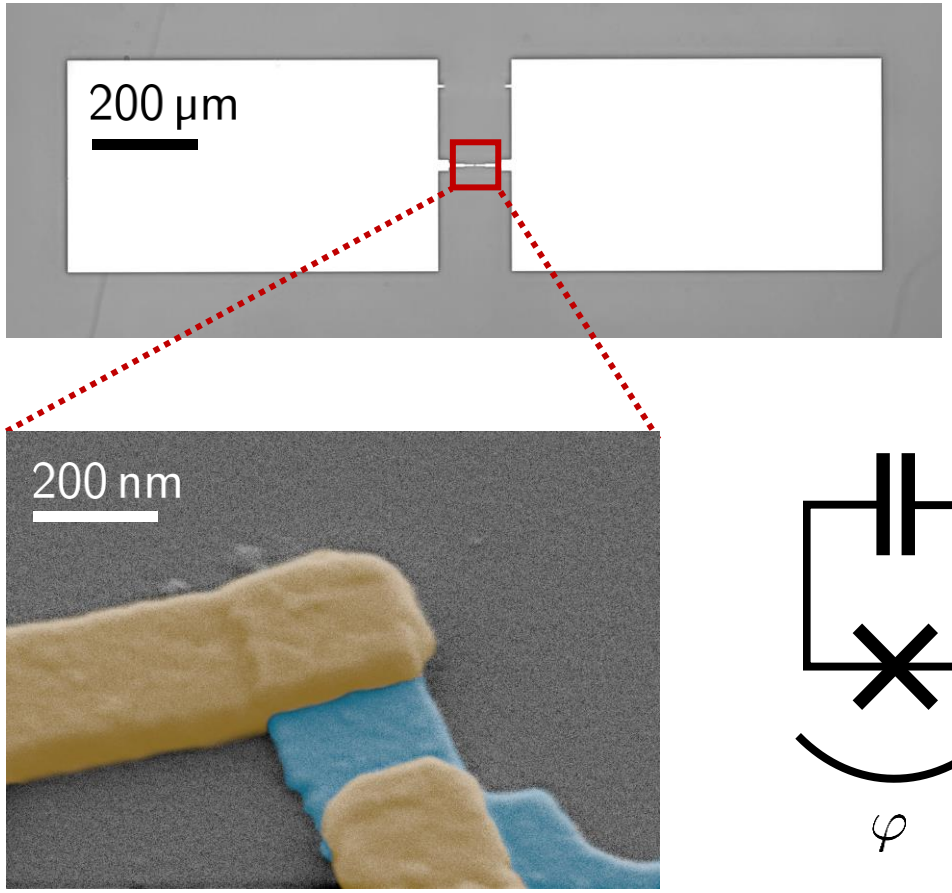

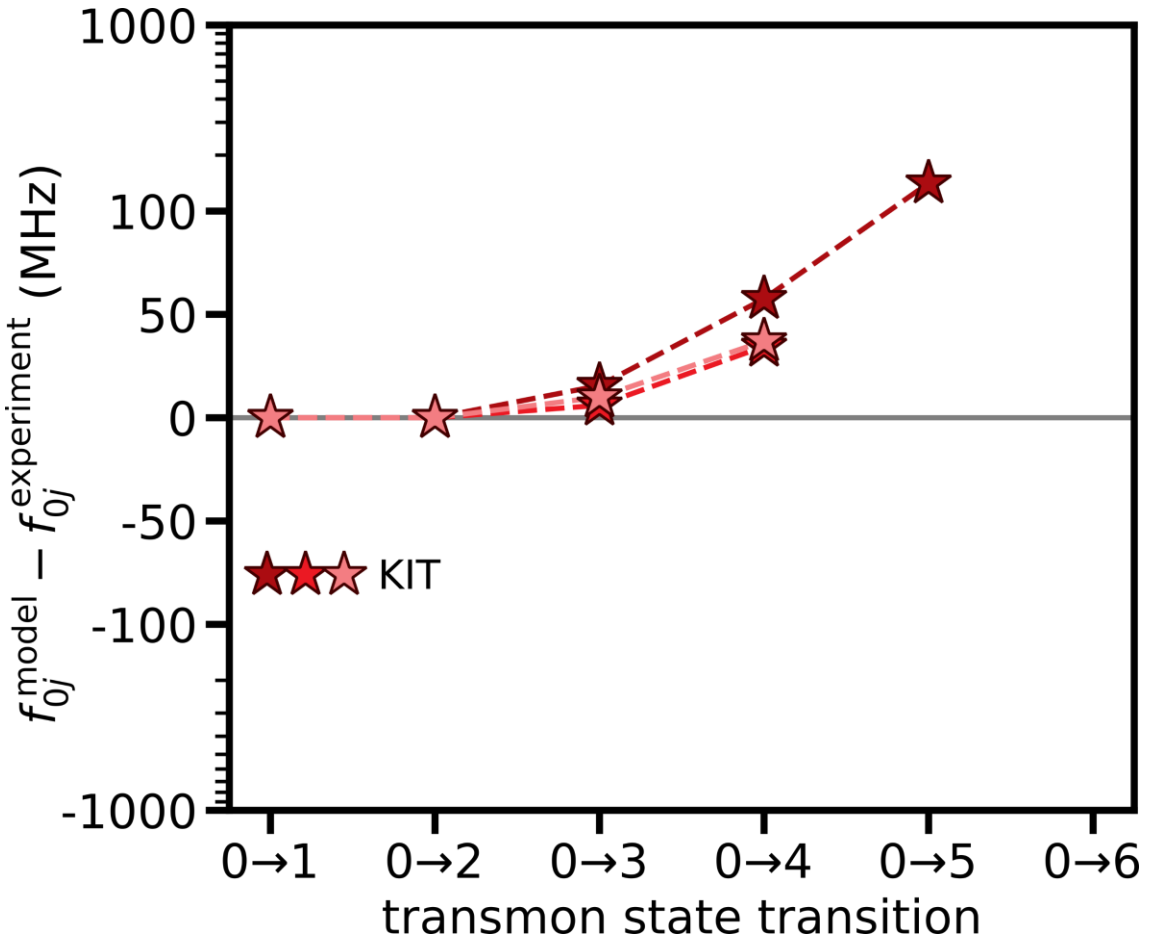

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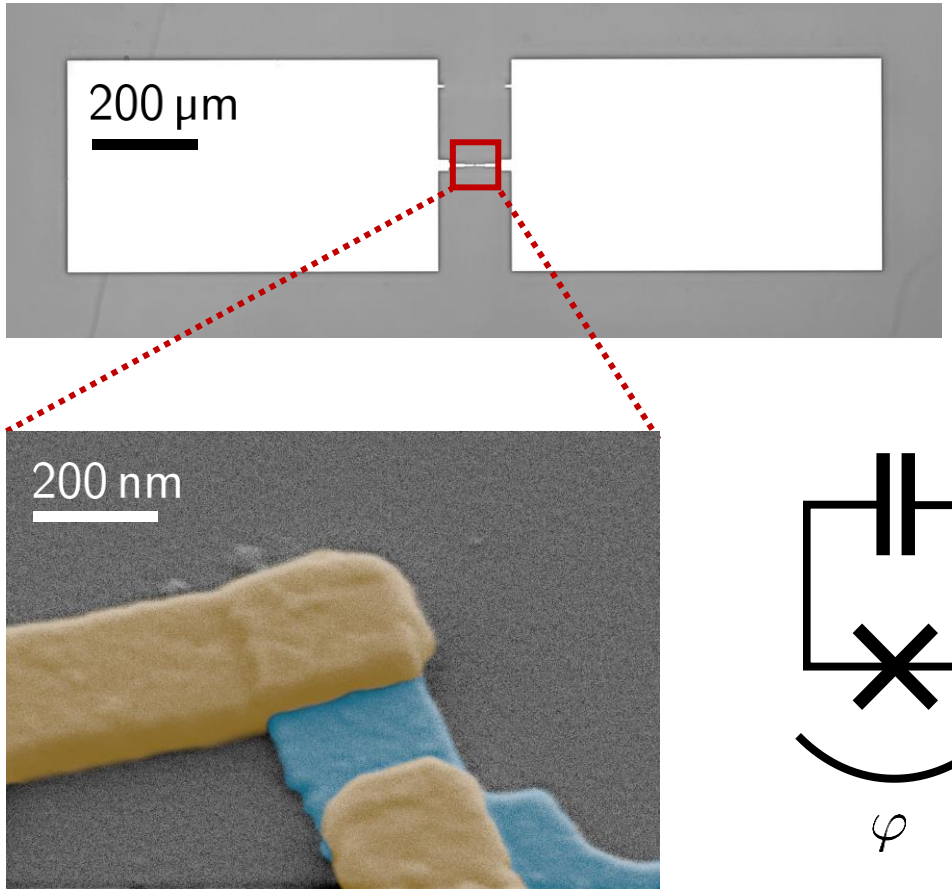

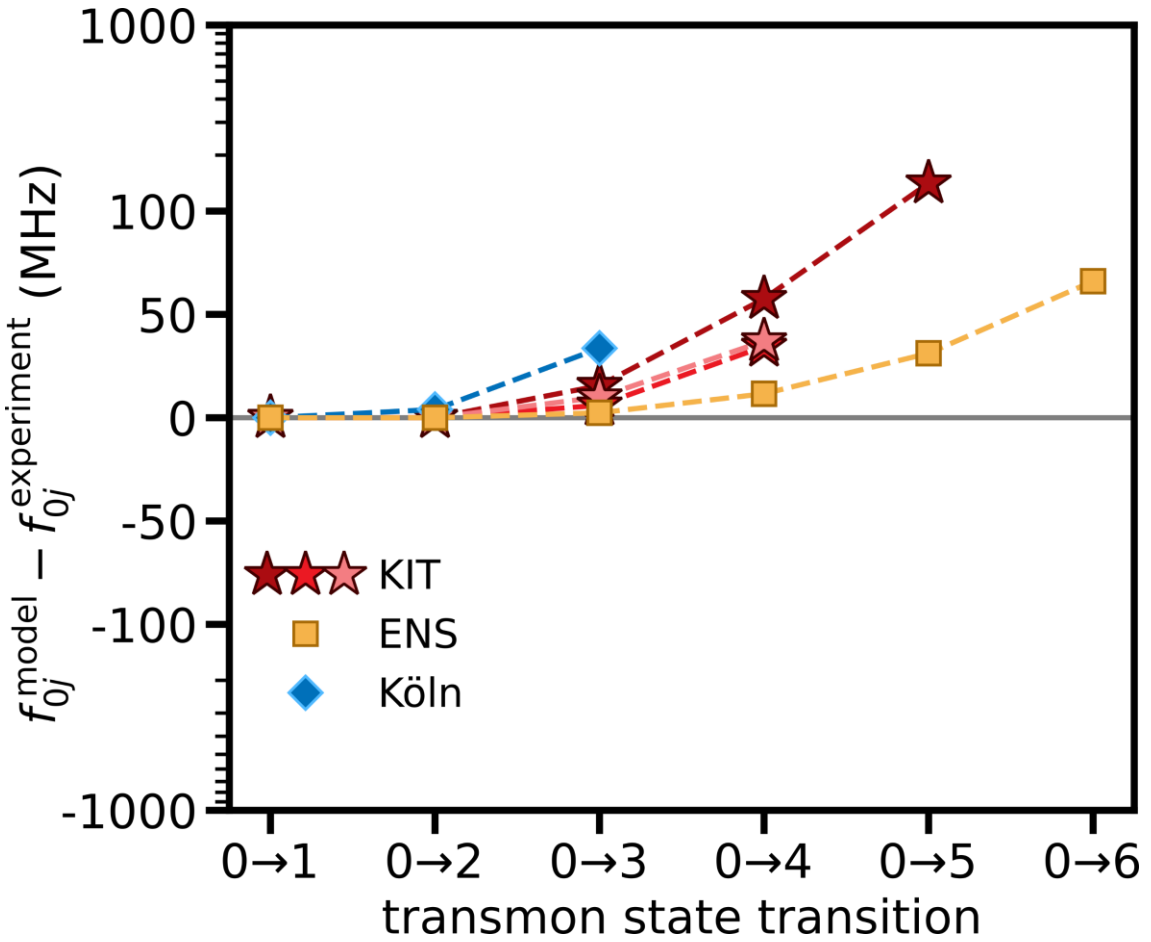

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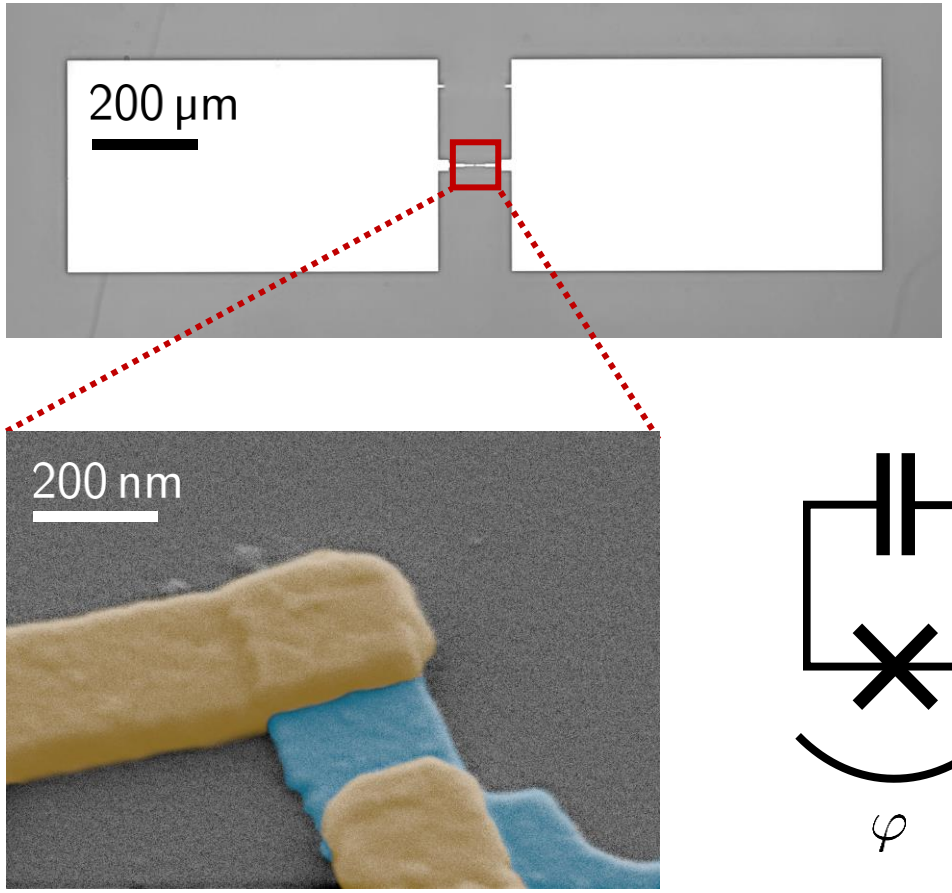
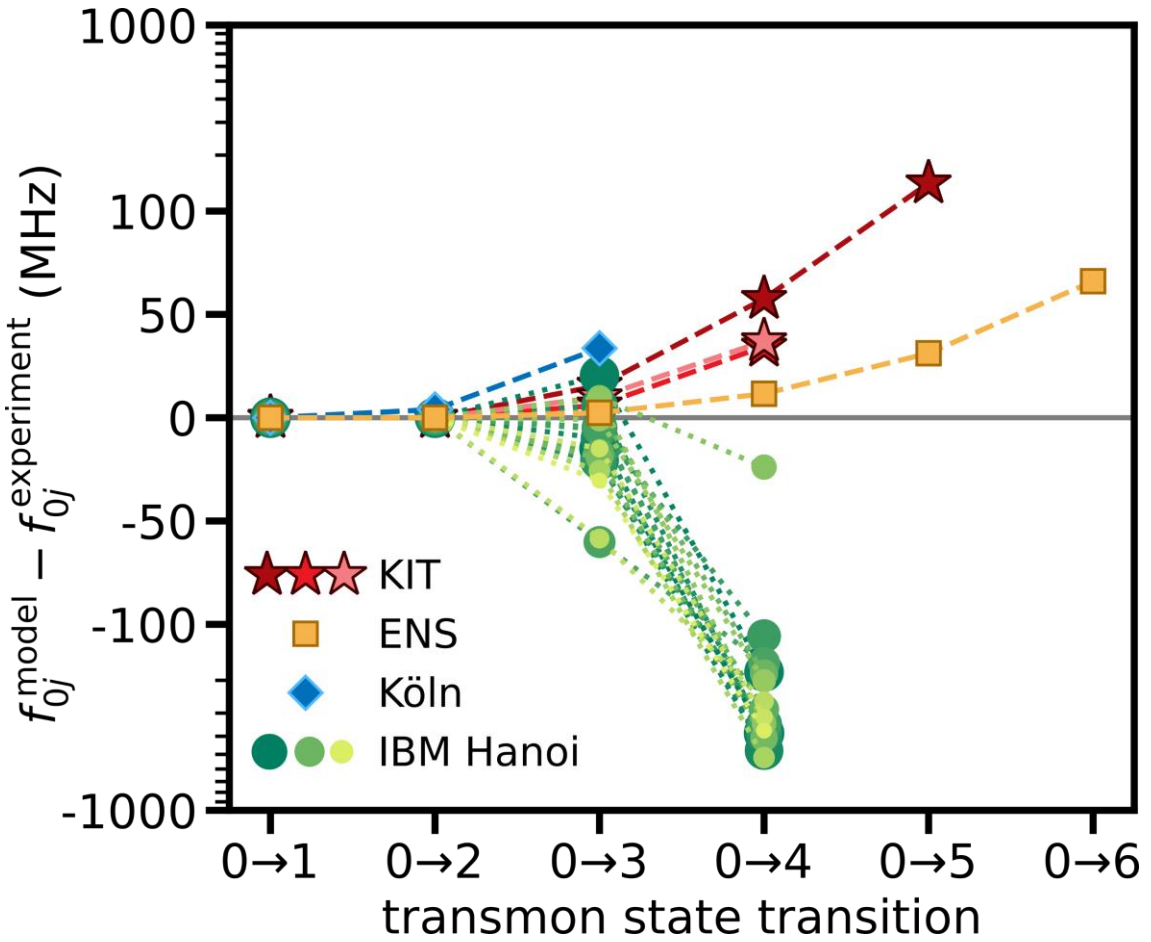




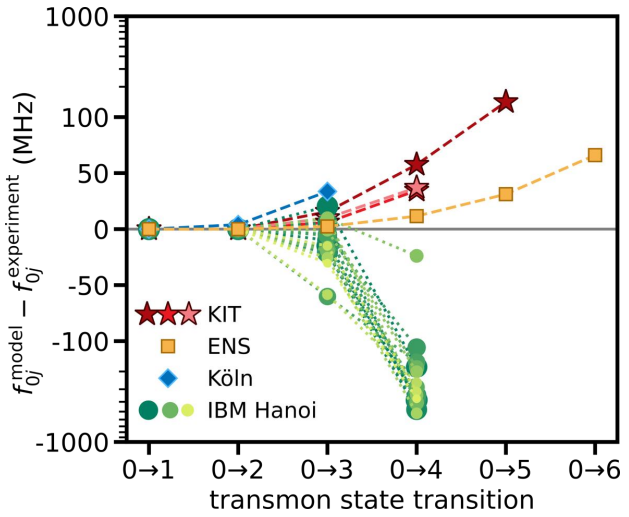
$$H = 4E_c n^2 - E_J \cos\varphi$$

Trying to Fix the Standard Transmon Model

Standard transmon model:

$$H = 4E_C(n - n_g)^2 - E_J \cos\varphi + \Omega a^\dagger a + Gn(a + a^\dagger)$$

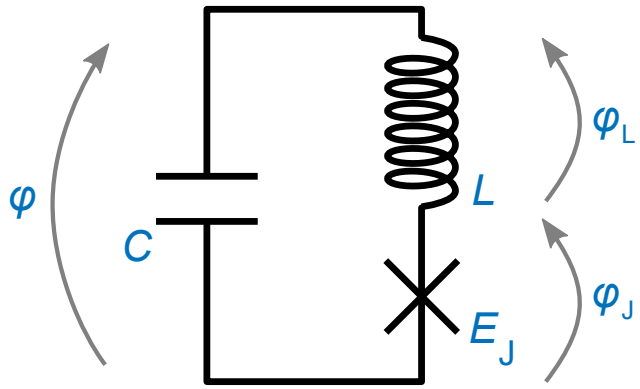
J. Koch et al. – PRA (2007)



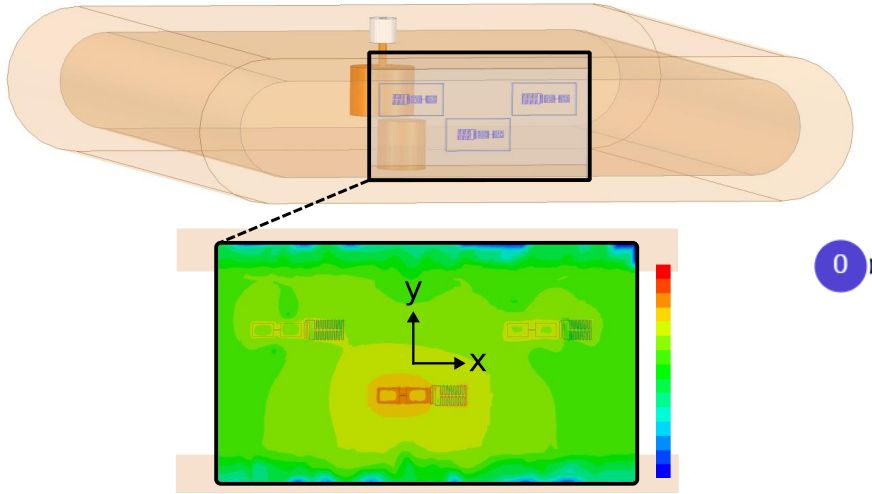
Attempts to fix this:

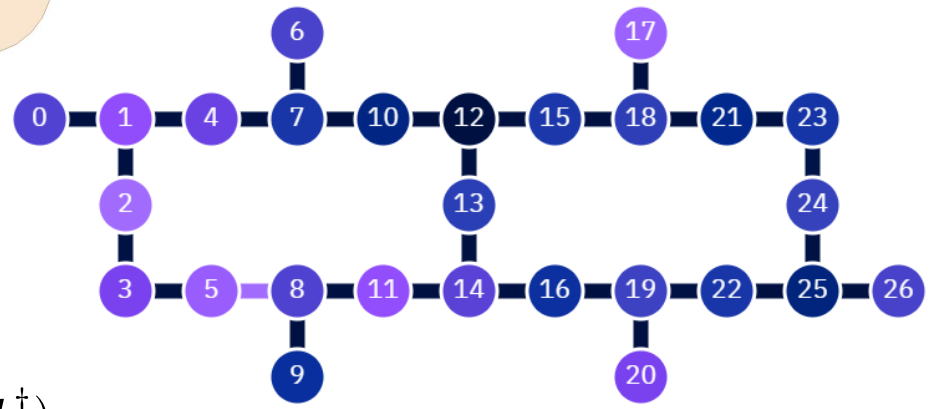
- Series inductance
- Hidden electromagnetic modes
- Coupling to other transmons
- …

… didn't work! What to do?



$\varphi_\Delta = \varphi_J - \varphi_L$

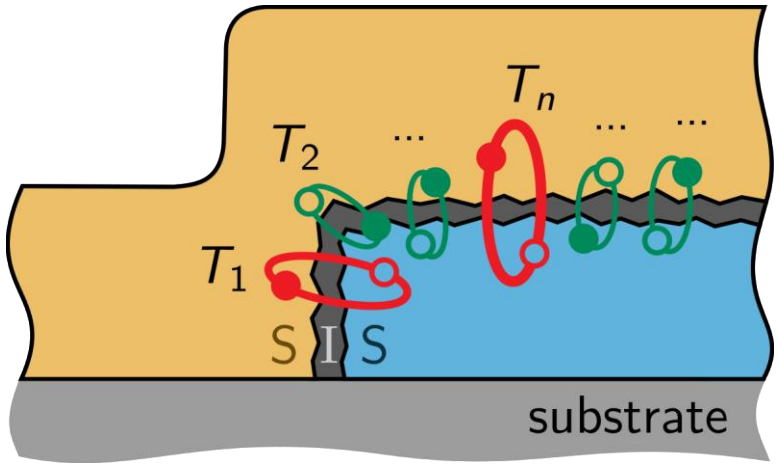


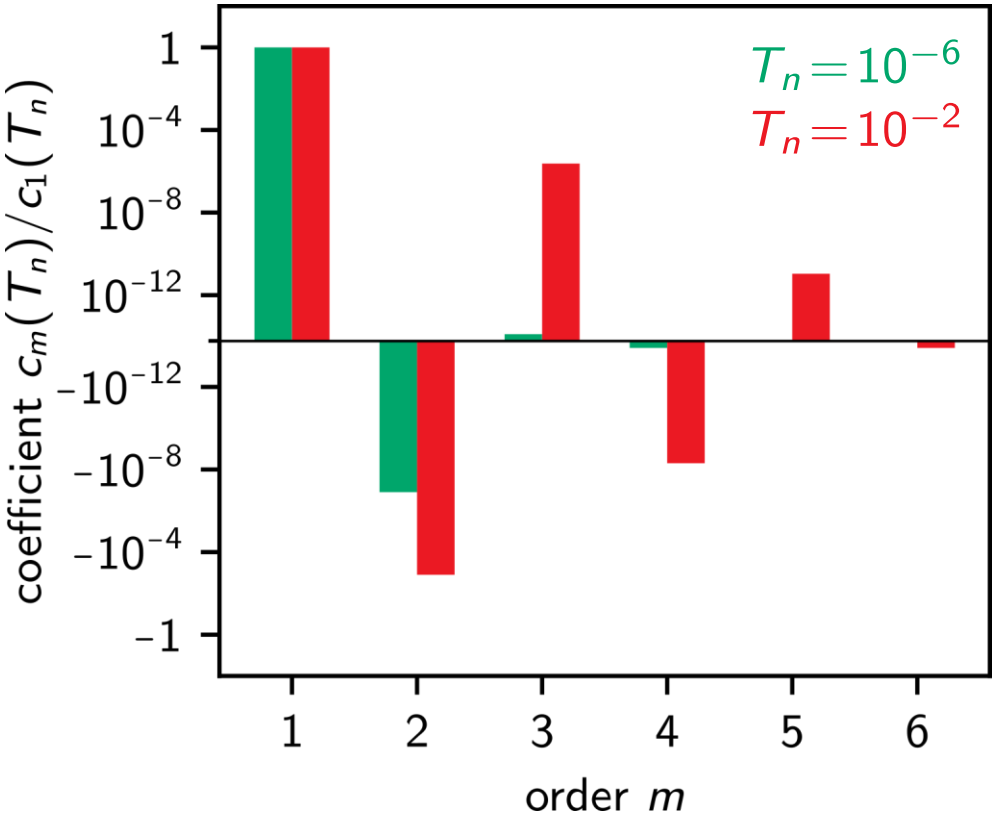


$$H = 4E_C n^2 - \sum_{m\geq 1} E_{Jm} \cos(m\varphi)$$

$$H' = H + \Omega_{dark} b^\dagger b + G_{dark} n(b + b^\dagger)$$

Reality Check for a Standard Tunnel Junction

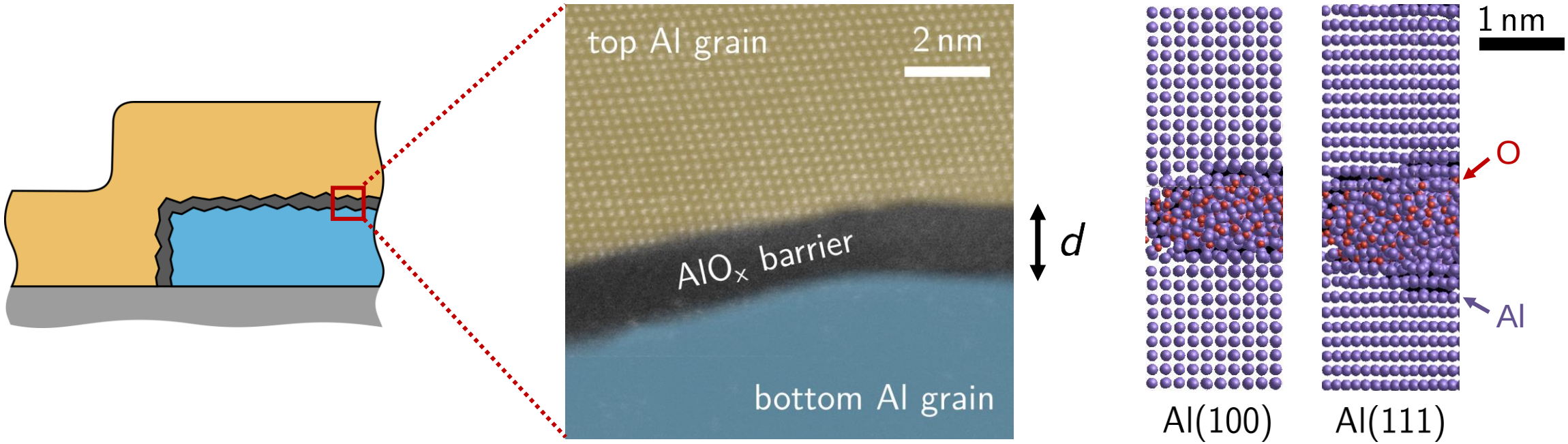




$$I_n(\varphi) = \frac{e\Delta}{2\hbar} \frac{T_n \sin\varphi}{\sqrt{1 - T_n \sin^2(\varphi/2)}} = \sum_m c_m(T_n) \sin m\varphi$$

Beenakker, Transport phenomena in mesoscopic systems (1992)

Setting the Expectation for Harmonics in Tunnel Junctions



Schüffelgen Group, FZ Jülich

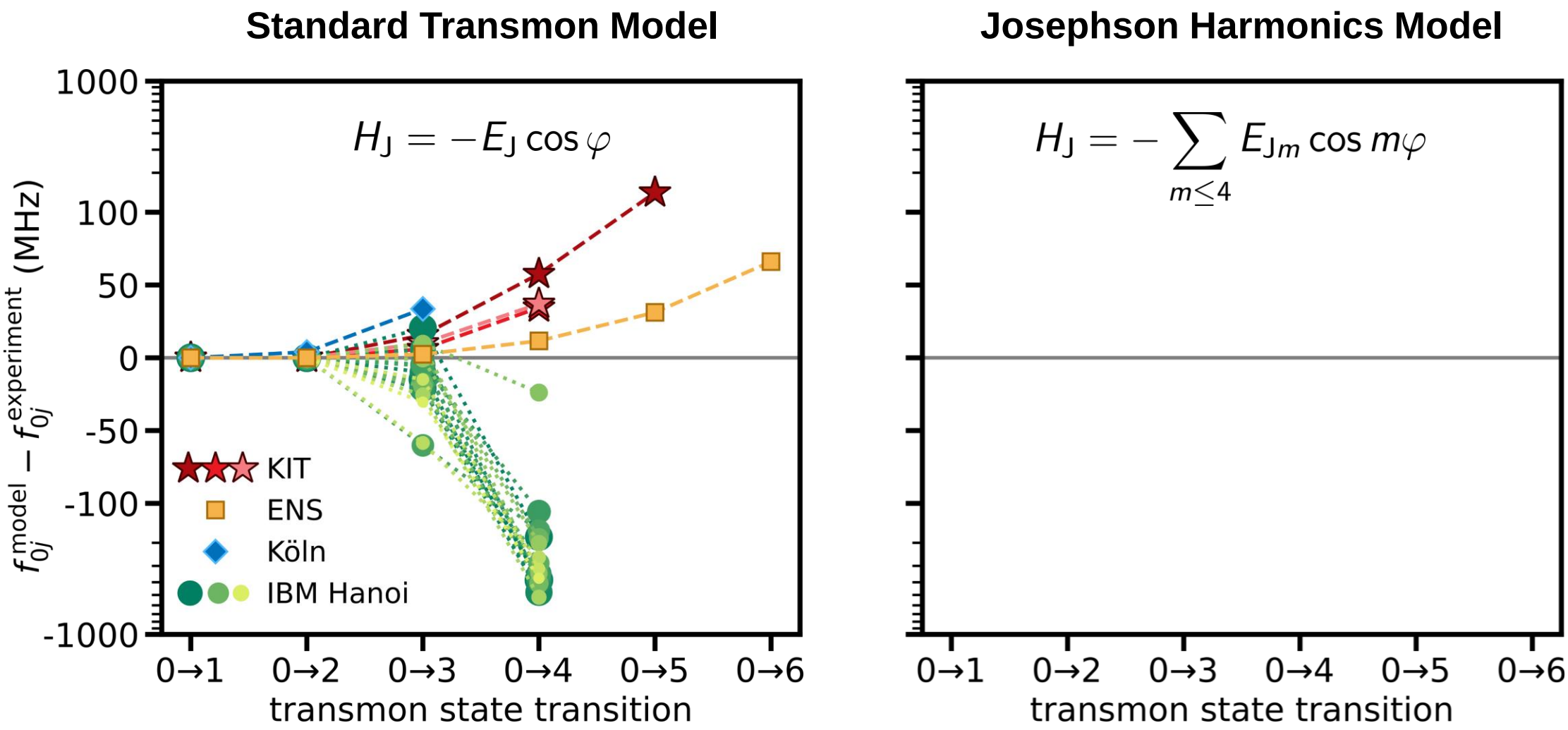
Morari Group, Cluj, Romania

Mesoscopic model:
Tunneling through barrier with
Gaussian thickness distribution

→ several % of $\sin m\varphi$

Gianluigi Catelani, FZ Jülich

Sinusoidal CφR Fails to Describe Measured Transmon Spectra



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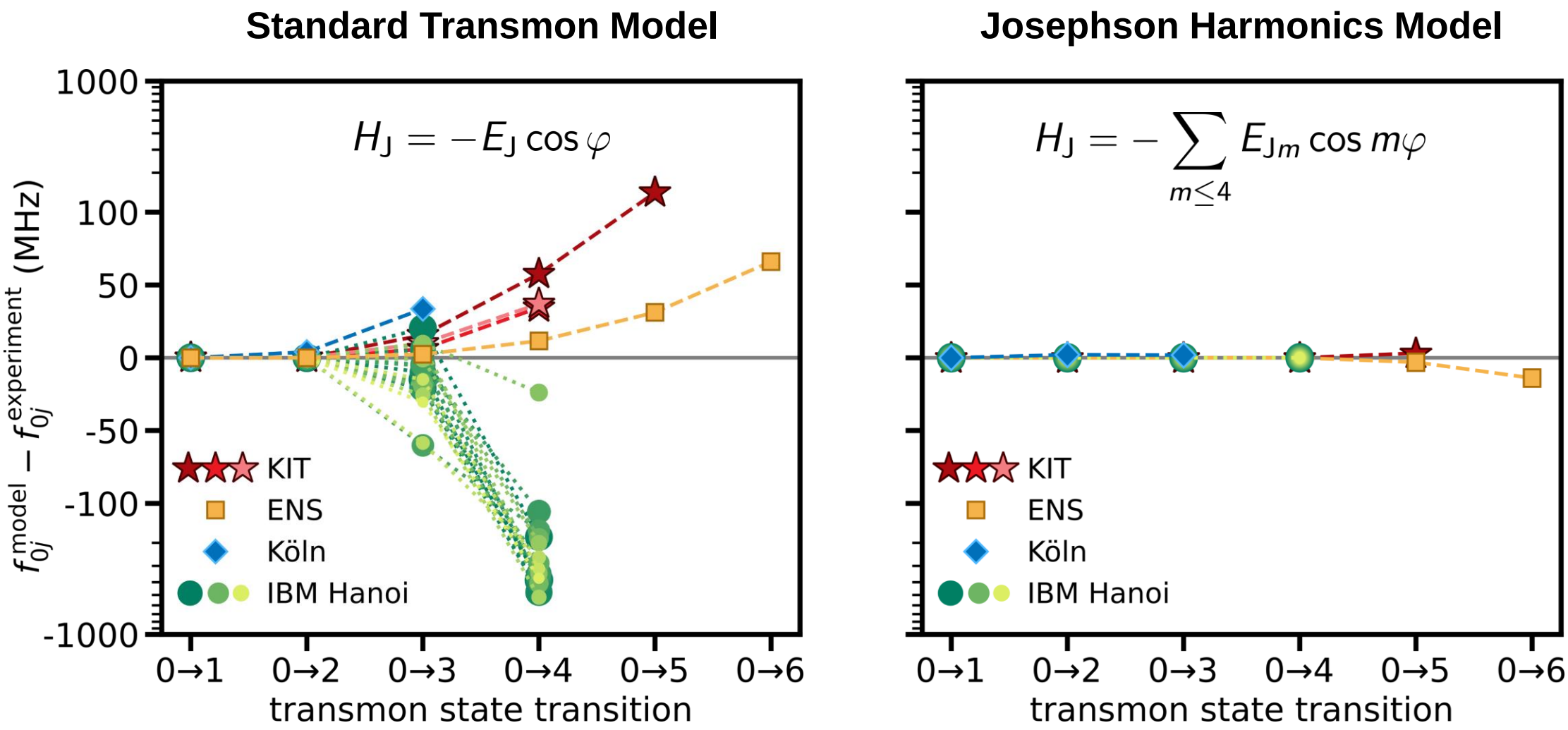
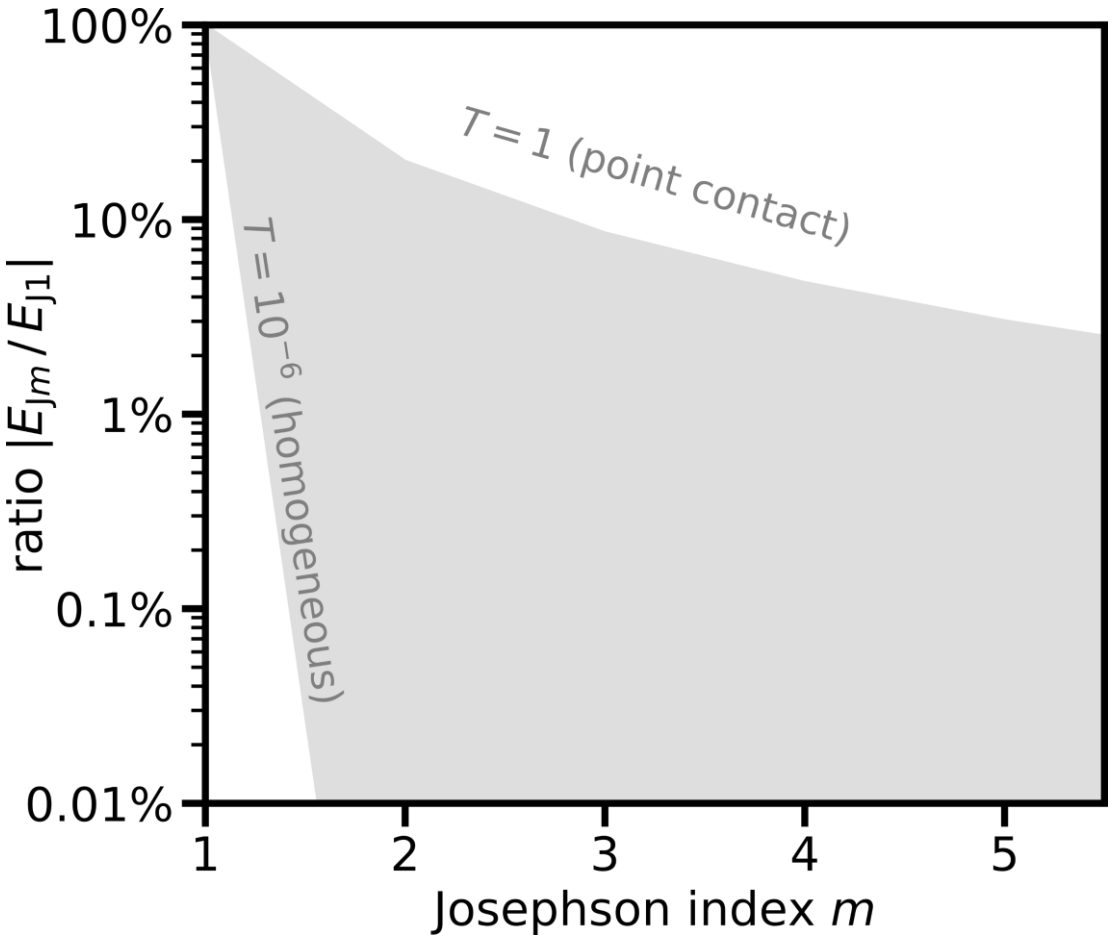


Magnitude of Josephson Harmonics in Tunnel Junctions

$$H = 4E_c n^2 - \cancel{E_J \cos\varphi} - \sum_m E_{Jm} \cos m\varphi$$



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$$H = 4E_c n^2 - \cancel{E_J \cos\varphi} - \sum_m E_{Jm} \cos m\varphi$$

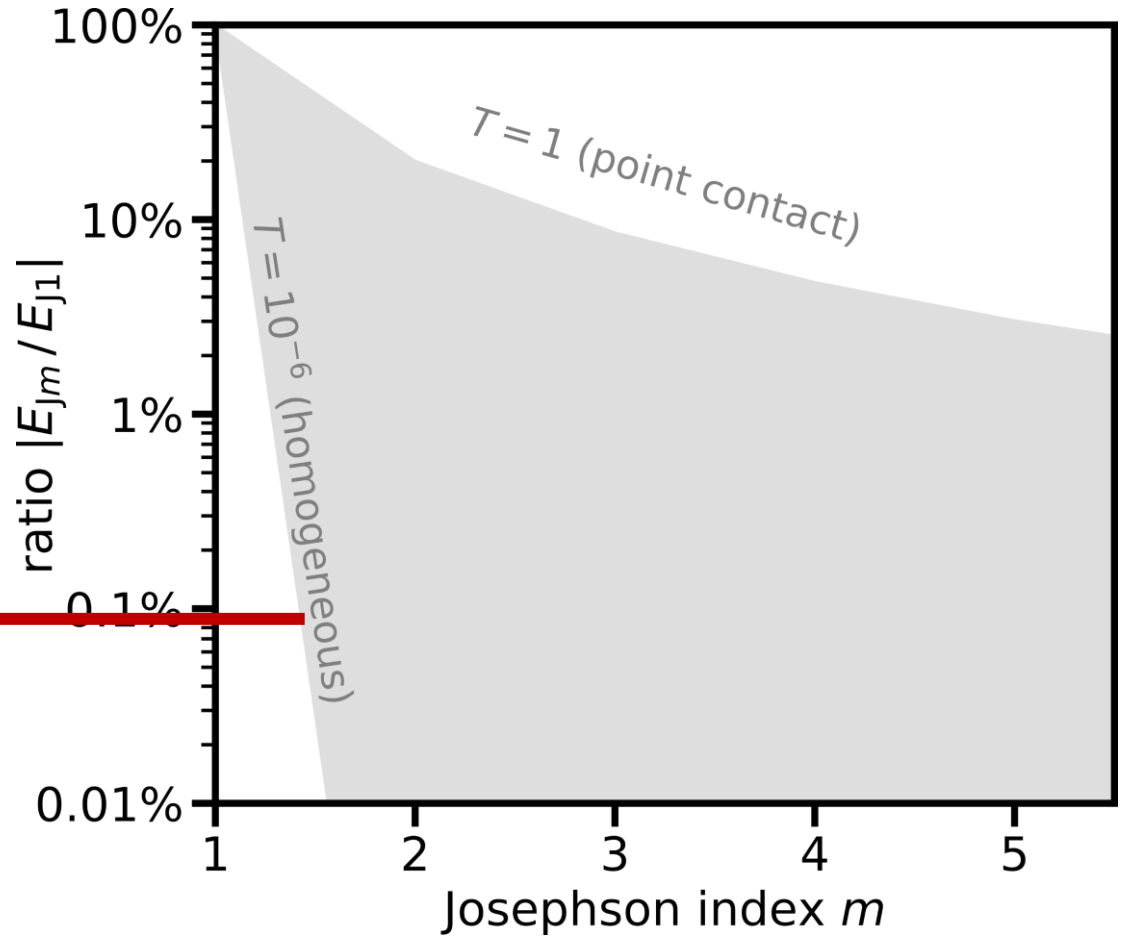
$N \sim 10^6$ conduction channels

↓

each with $T \sim 10^{-6}$ transparency

↓

$I_c \sin\varphi$



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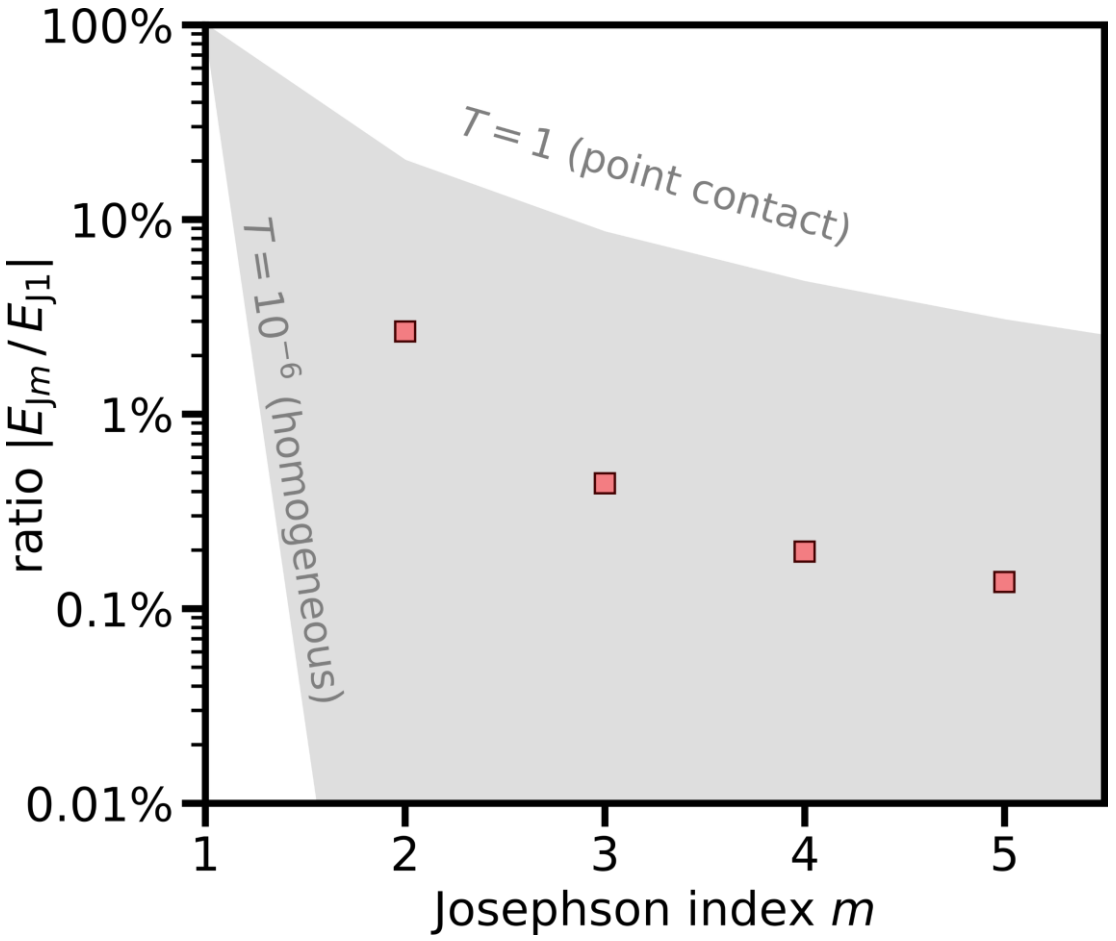

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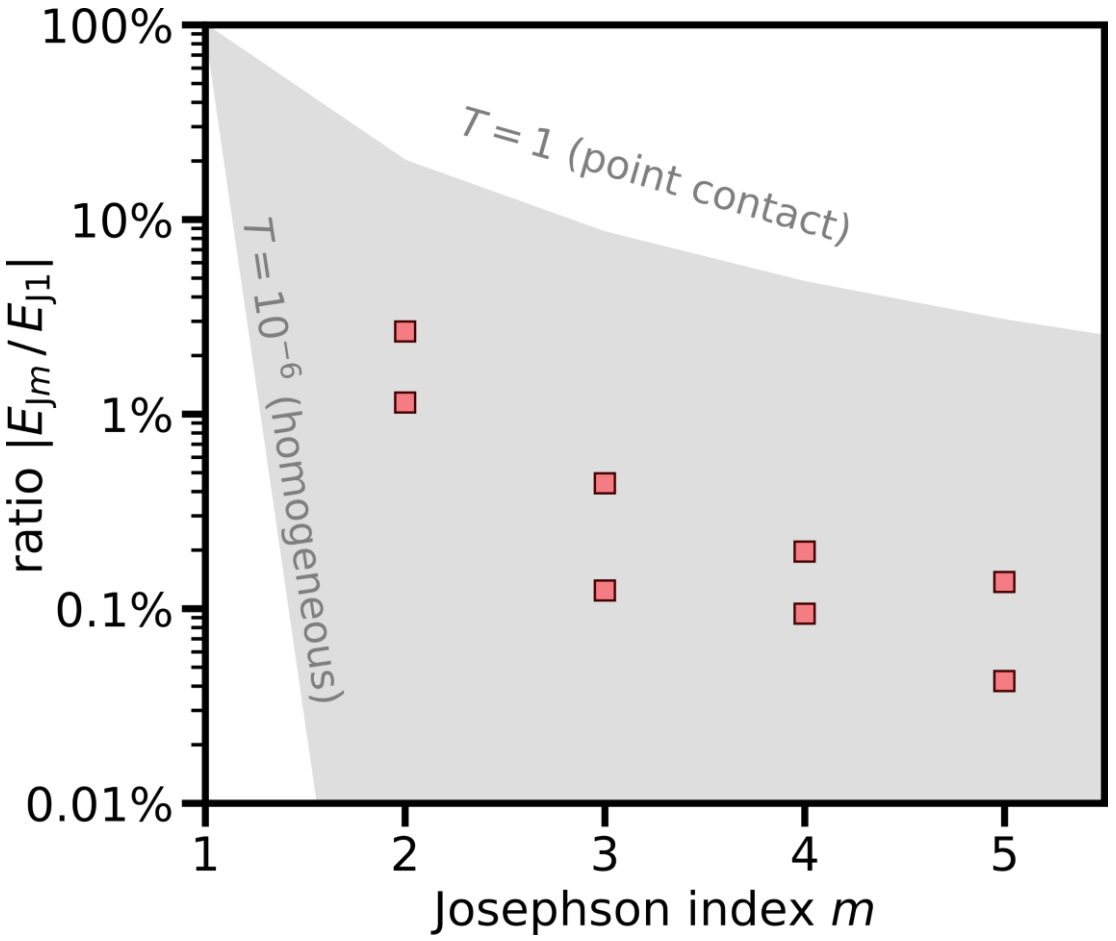

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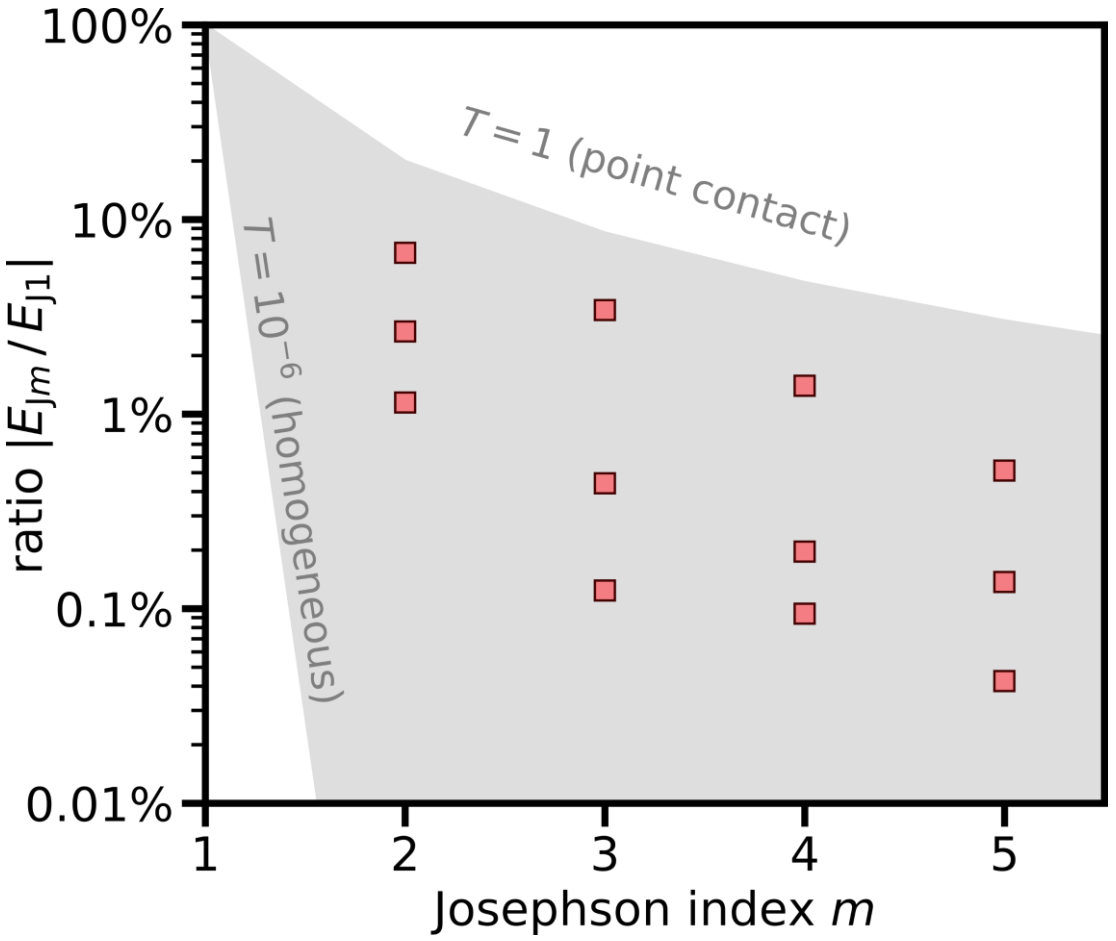

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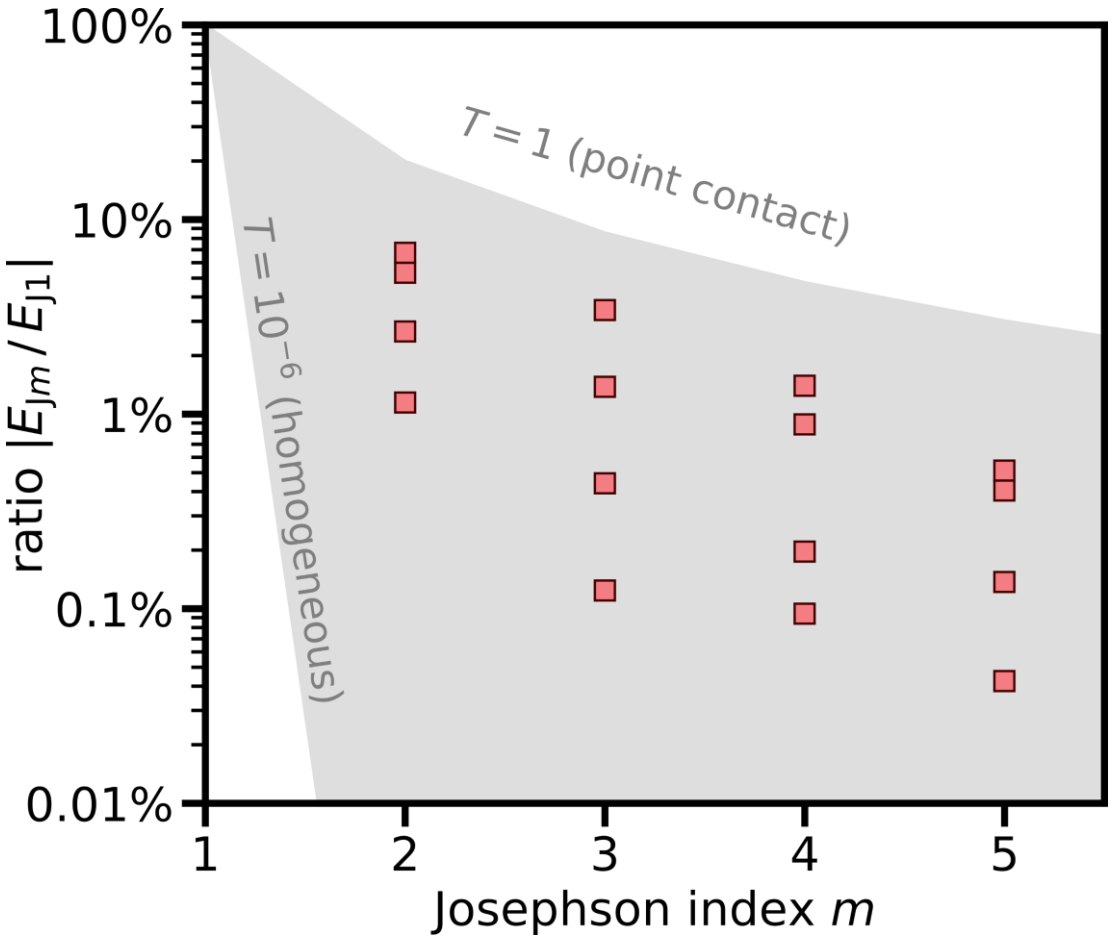

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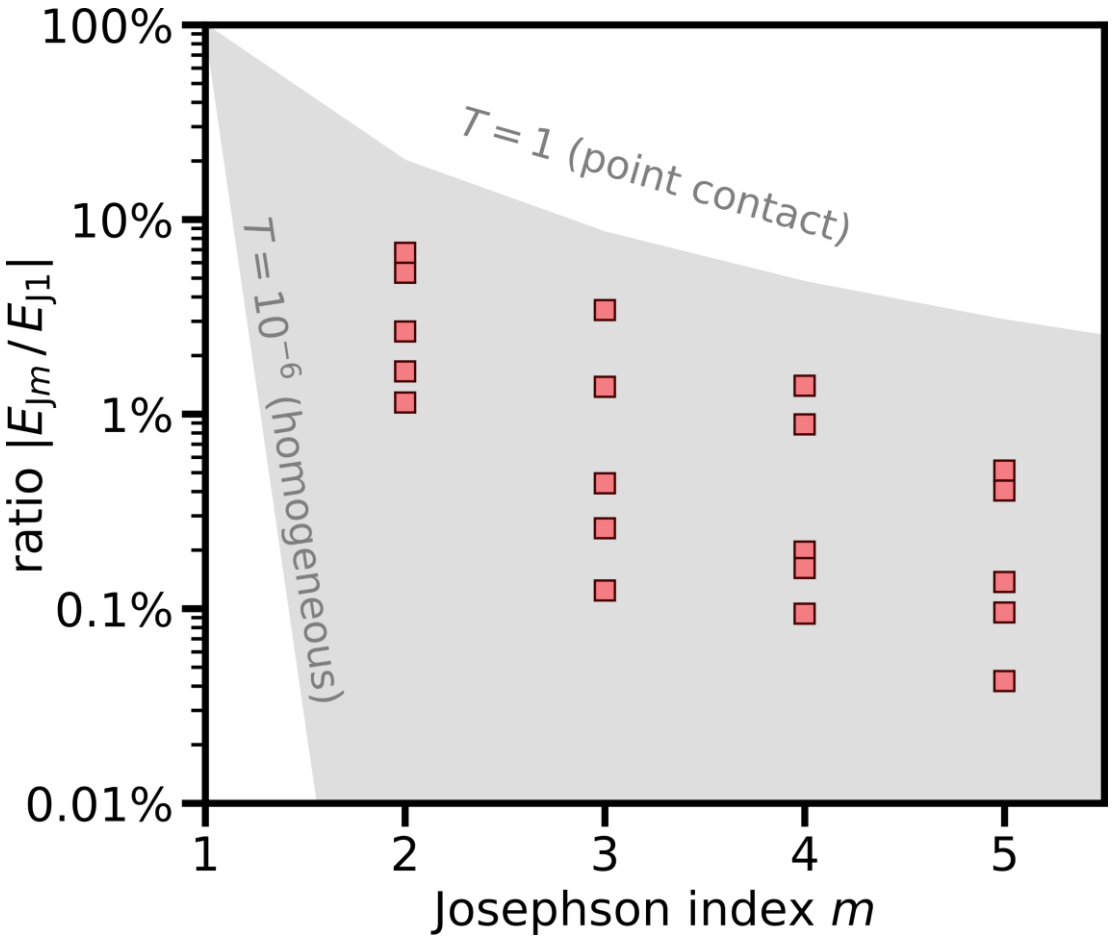

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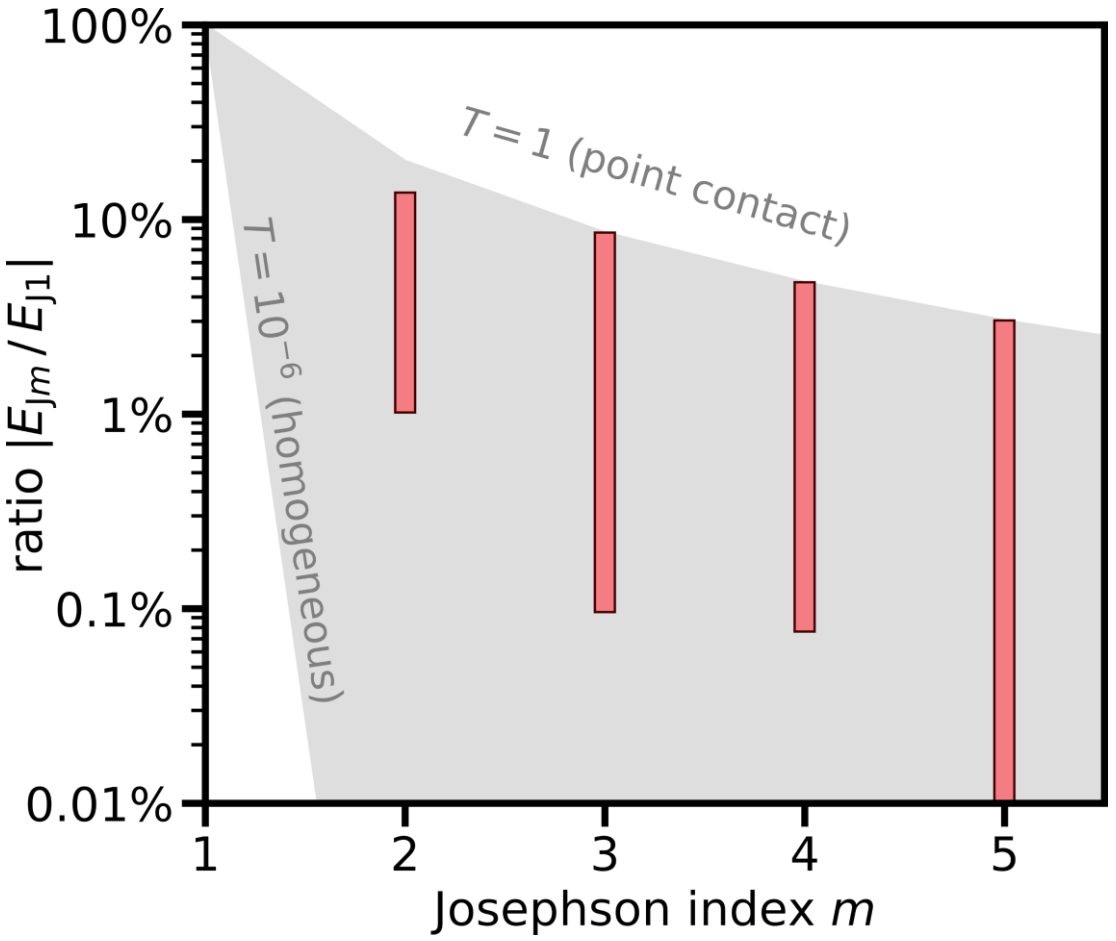

Magnitude of Josephson Harmonics in Tunnel Junctions

Schüffelgen Group, FZ Jülich

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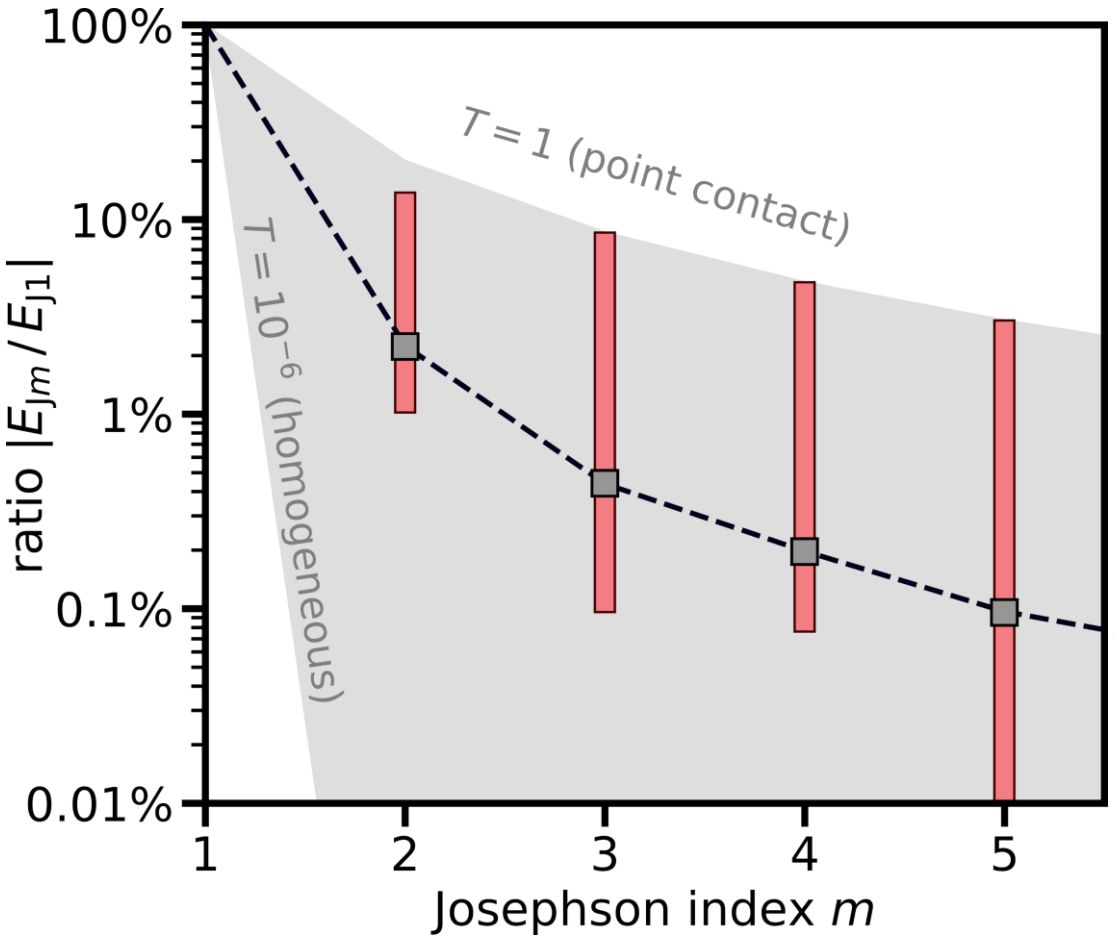

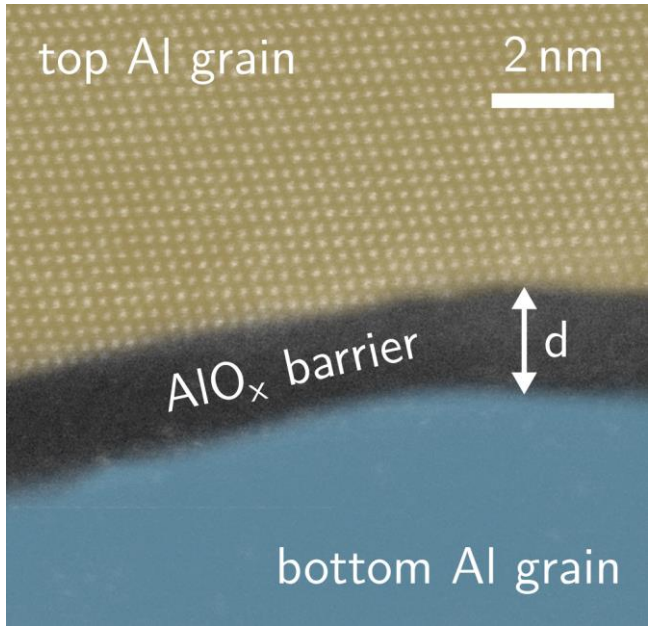

Mesoscopic model with Gaussian thickness

$E_{Jm}(\bar{d}, \sigma_d)$

$\bar{d} = 1.6$ nm

$\sigma_d = 0.4$ nm

Gianluigi Catelani, FZ Jülich

Magnitude of Josephson Harmonics in Tunnel Junctions

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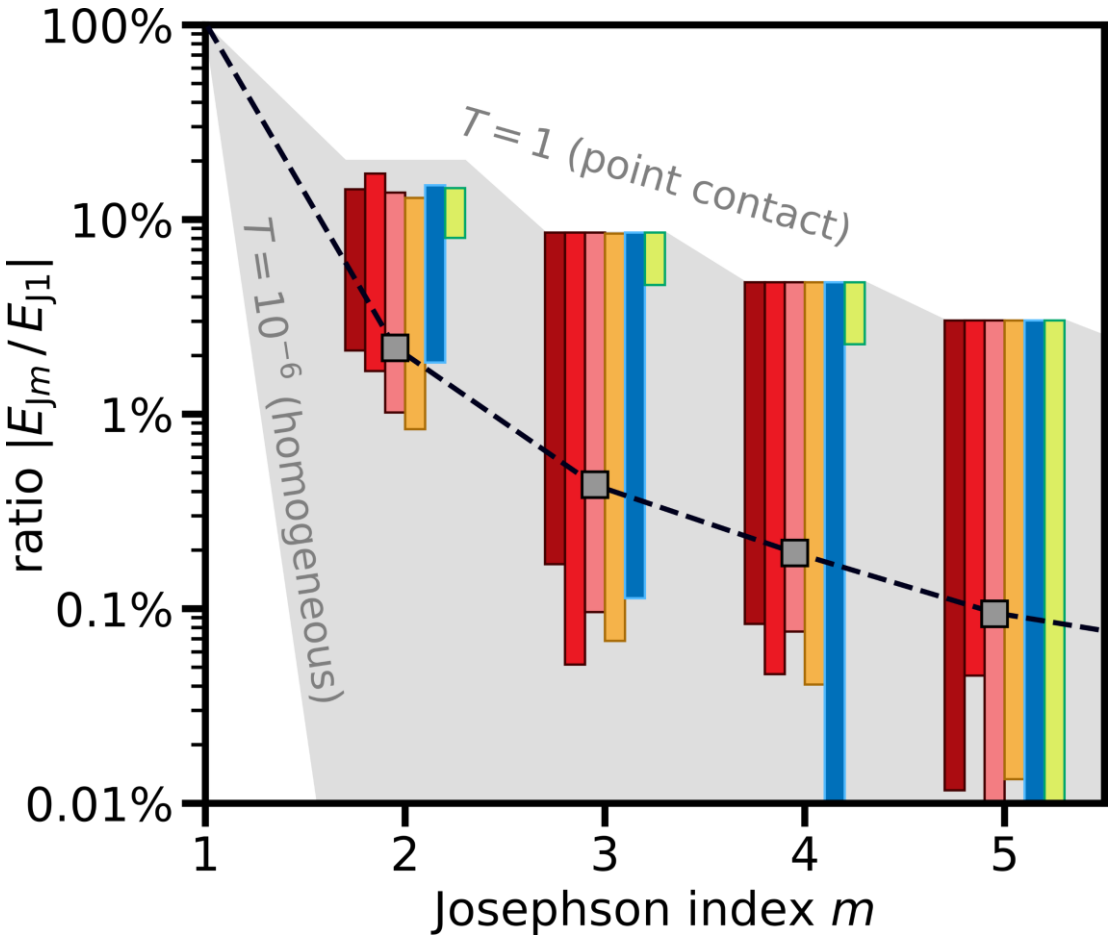
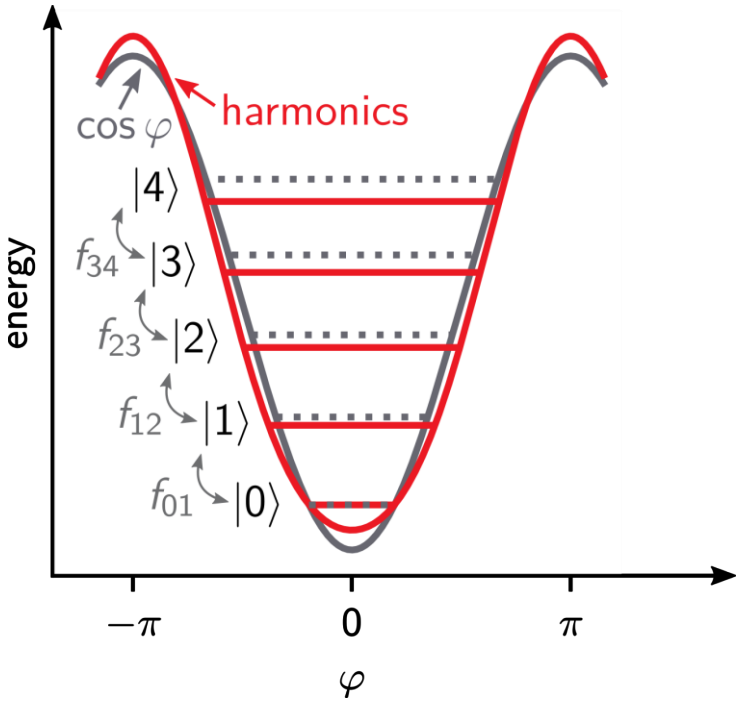
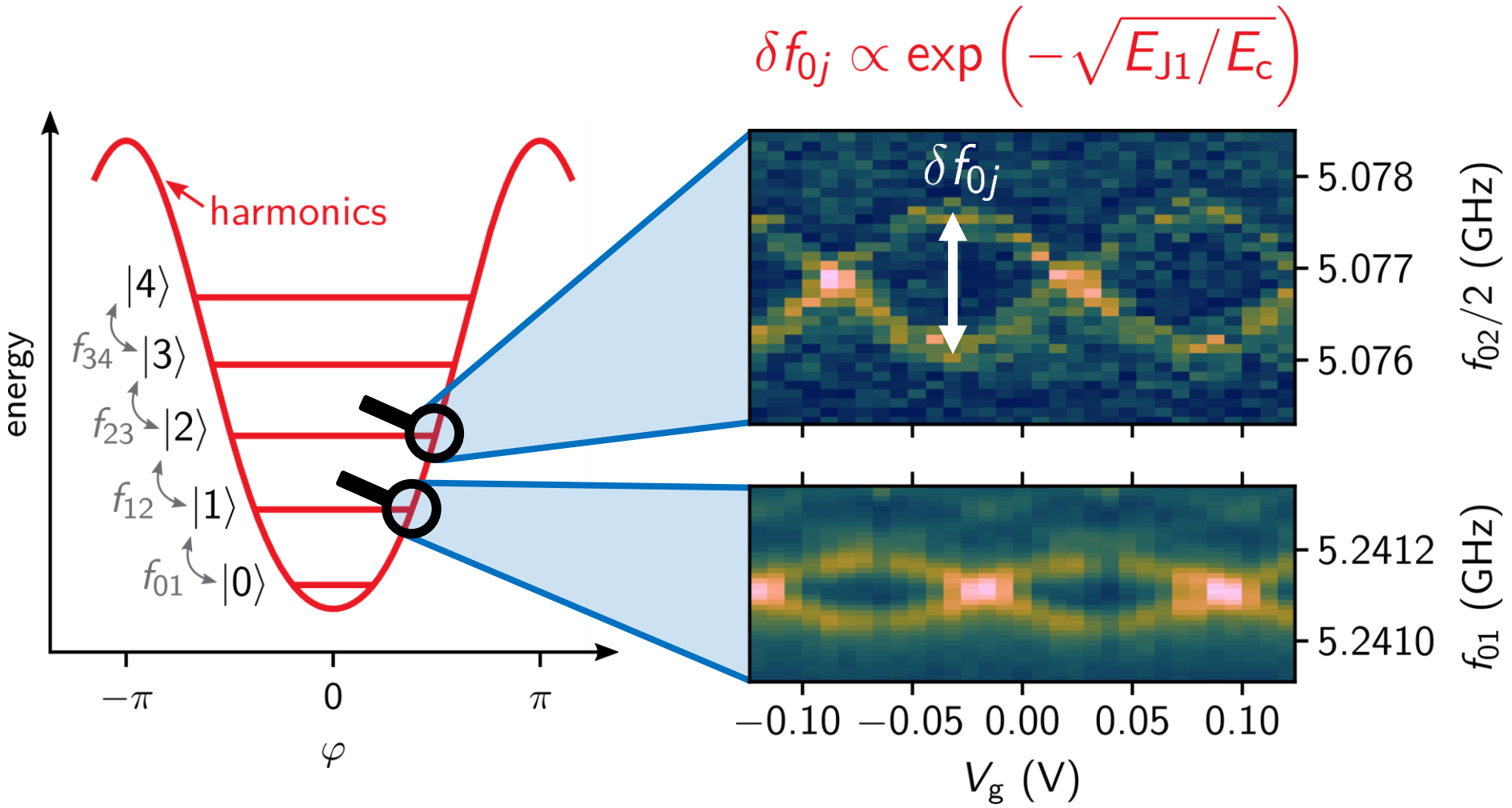


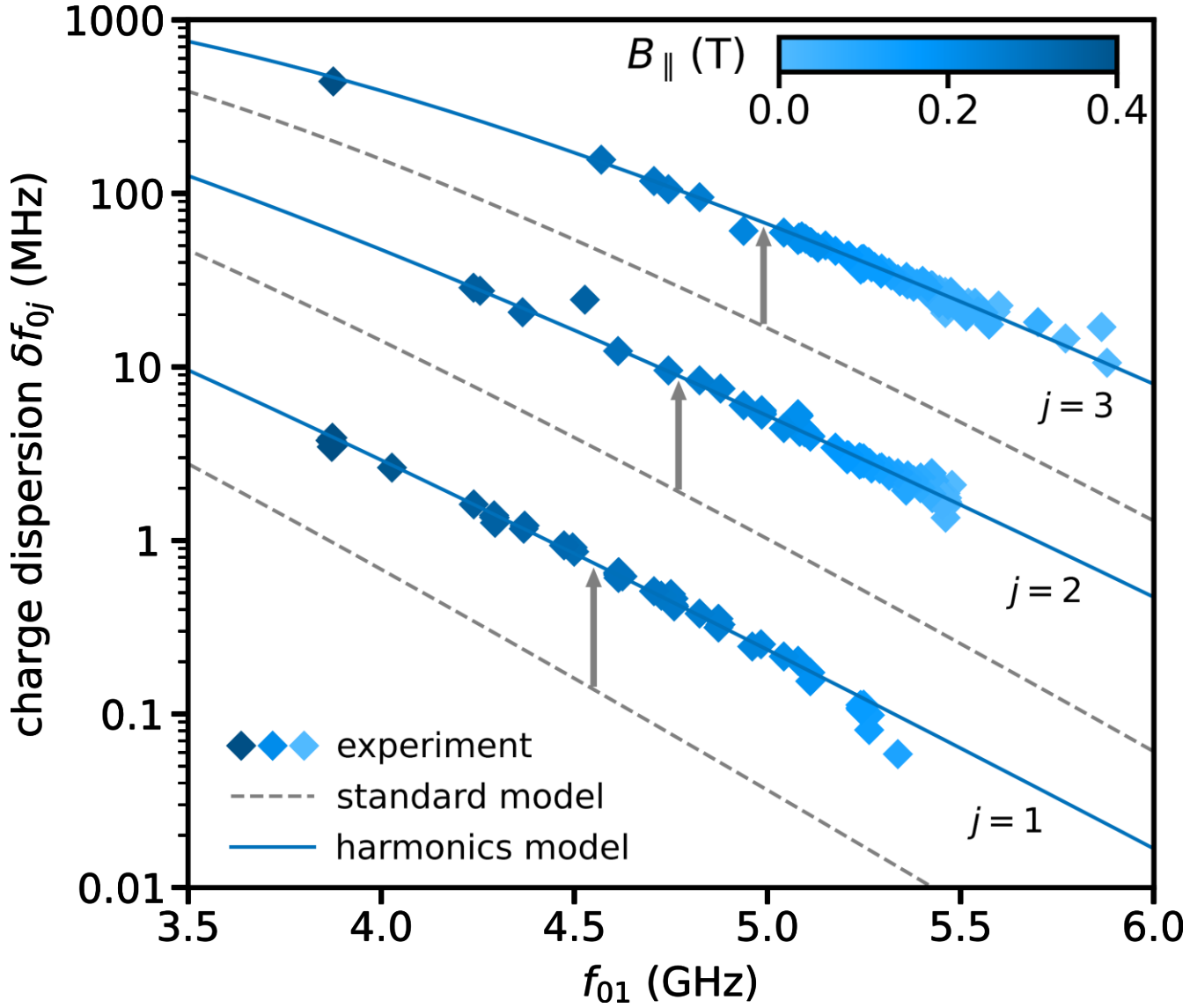


KIT
ENS
Köln
IBM Hanoi

Charge Dispersion: Another Relevant Aspect

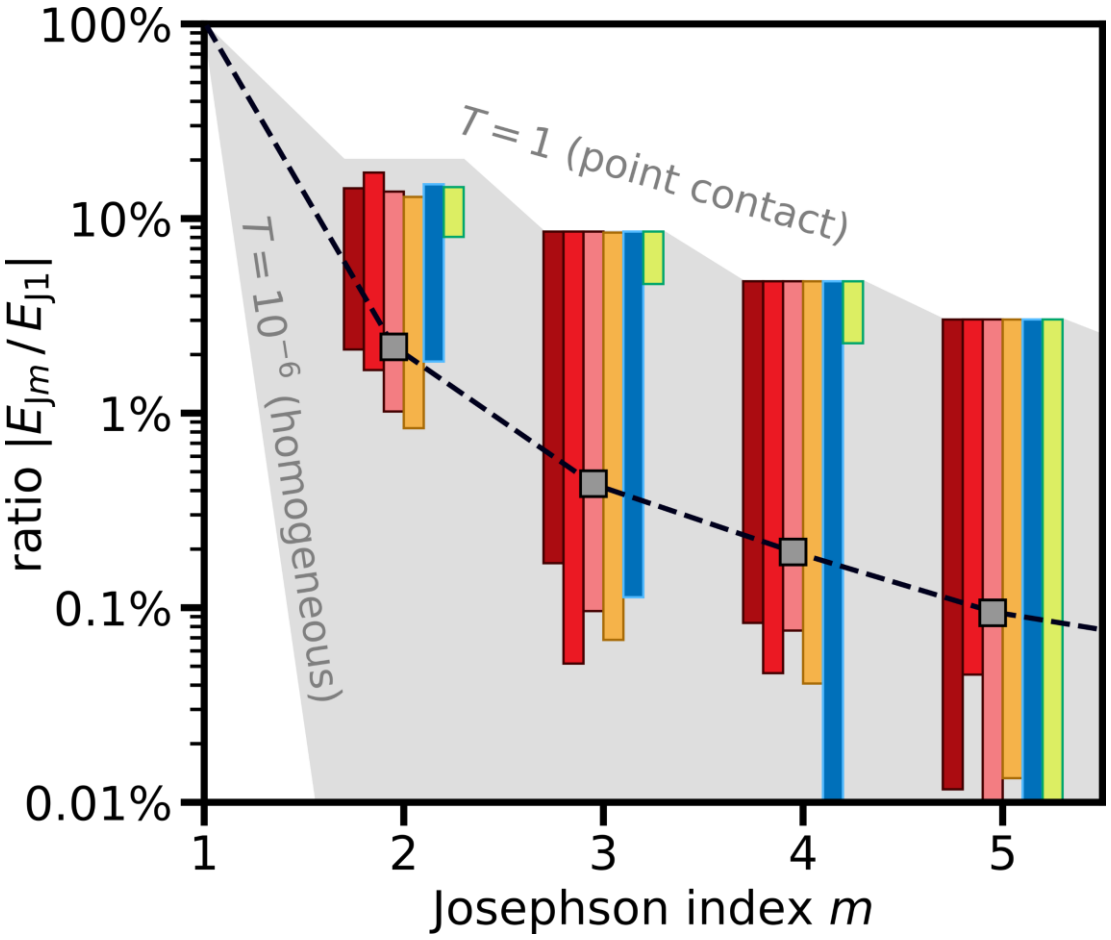


Charge Dispersion: An Exponentially Sensitive Test of the Model



Dickel Group,
University of Cologne

Observation of Josephson Harmonics in Tunnel Junctions



Theory:

Inclusion of harmonics in established models!

Experiment:

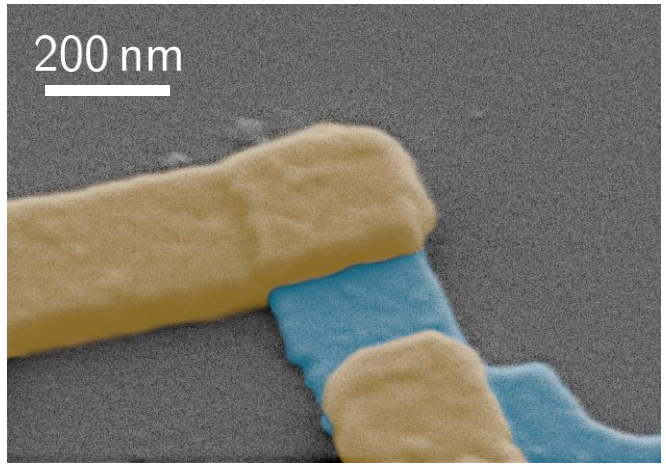
Can we engineer these harmonics?

What is an optimal range?

Should we strive to grow highly homogeneous barriers?

Observation of Josephson Harmonics in Tunnel Junctions

arXiv:2302.09192 (2023)



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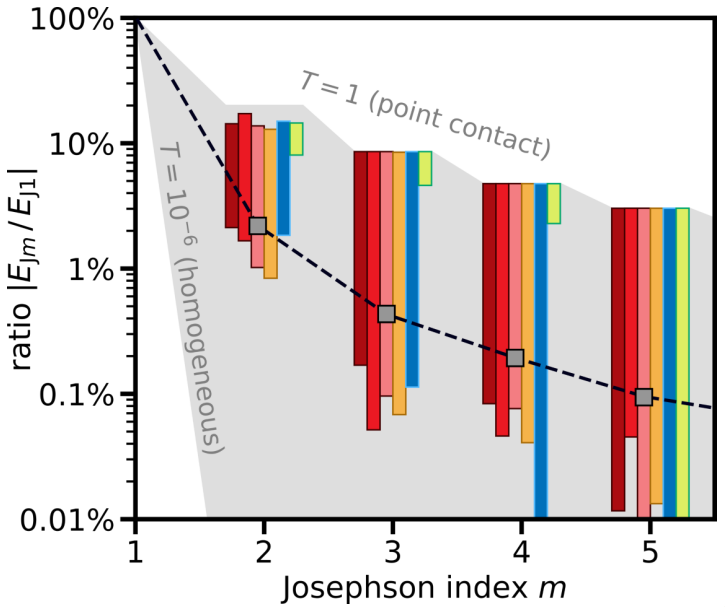

Thank You Very Much

Dennis Willsch,[1,*] Dennis Rieger,[2,3,*] Patrick Winkel,[2,3,4,5] Madita Willsch,[1,6] Christian Dickel,[7] Jonas Krause,[7] Yoichi Ando,[7] Raphaël Lescanne,[8,9] Zaki Leghtas,[8] Nicholas T. Bronn,[10] Pratiti Deb,[10] Olivia Lanes,[10] Zlatko K. Minev,[10] Benedikt Dennig,[2,3] Simon Geisert,[2] Simon Günzler,[2] Sören Ihssen,[2] Patrick Paluch,[2,3] Thomas Reisinger,[2] Roudy Hanna,[11,12] Jin Hee Bae,[11] Peter Schüffelgen,[11] Detlev Grützmacher,[11,12] Luiza Buimaga-Iarinca,[13] Cristian Morari,[13] Wolfgang Wernsdorfer,[2,3] David P. DiVincenzo,[14,12] Kristel Michielsen,[1,6,12] Gianluigi Catelani,[15,16] and Ioan M. Pop[2,3,†]