

Observation of Josephson Harmonics in Tunnel Junctions

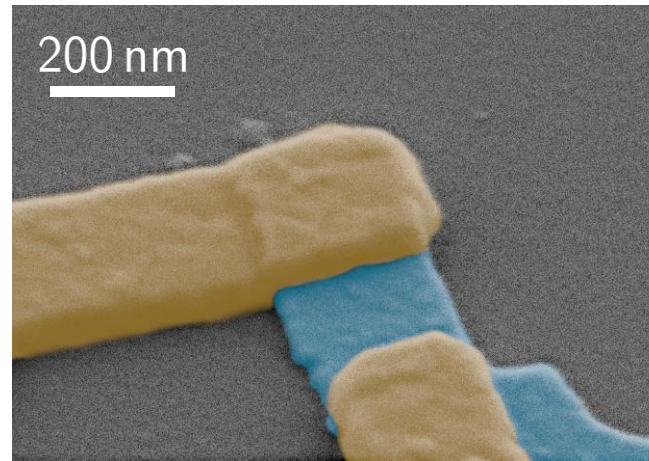


Madita Willsch
Peter Schüffegen
David DiVincenzo
Kristel Michielsen
Gianluigi Catelani

Dennis Willsch & Dennis Rieger et al.
arXiv:2302.09192



Patrick Winkel
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Zaki Leghtas
Raphaël Lescanne



Nicholas T. Bronn
Pratiti Deb
Olivia Lanes
Zlatko K. Minev



Köln University:
Christian Dickel
Jonas Krause
Yoichi Ando

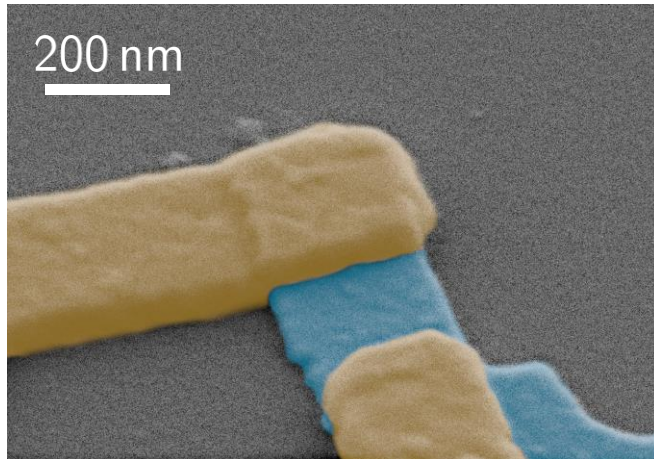


Cluj, Romania:
Luiza Buimaga-Iarinca
Cristian Morari

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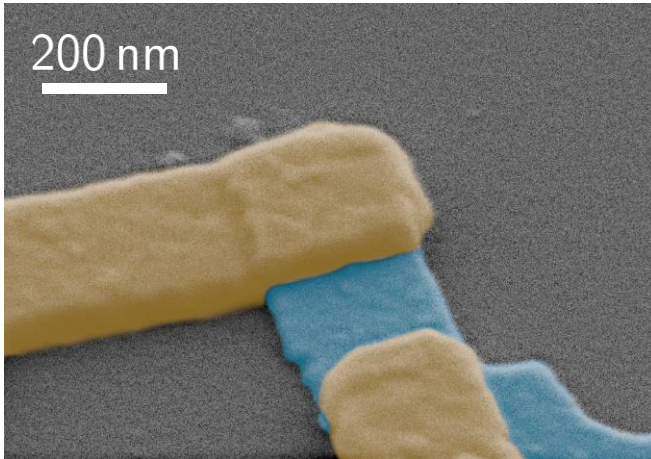
***Part 1: Exposing
Josephson Harmonics***

Observation of Josephson Harmonics in Tunnel Junctions

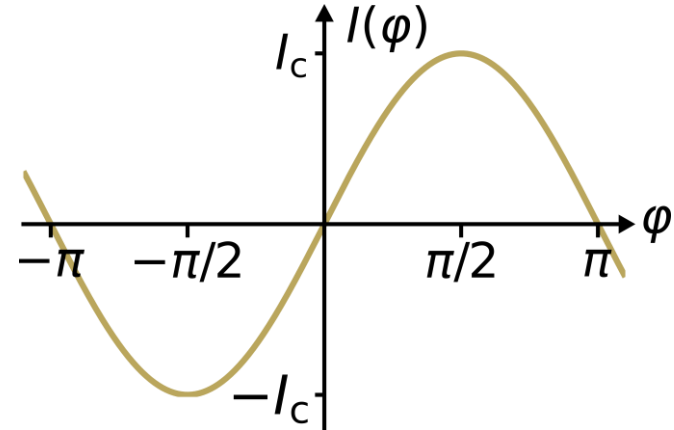
Dennis Willsch & Dennis Rieger et al.

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Josephson (1962)



$$I_s = I_c \sin \varphi$$

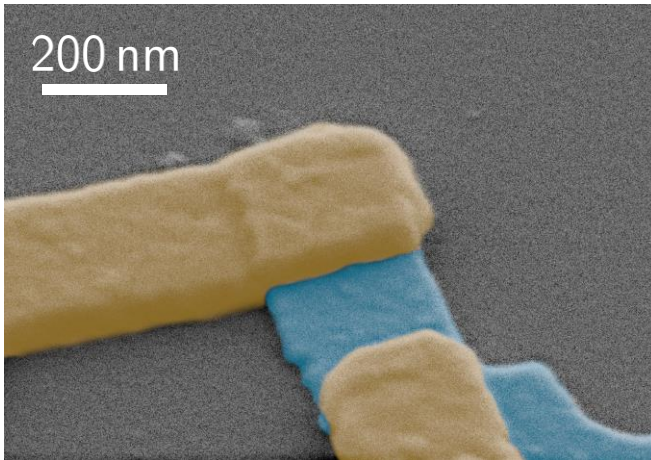


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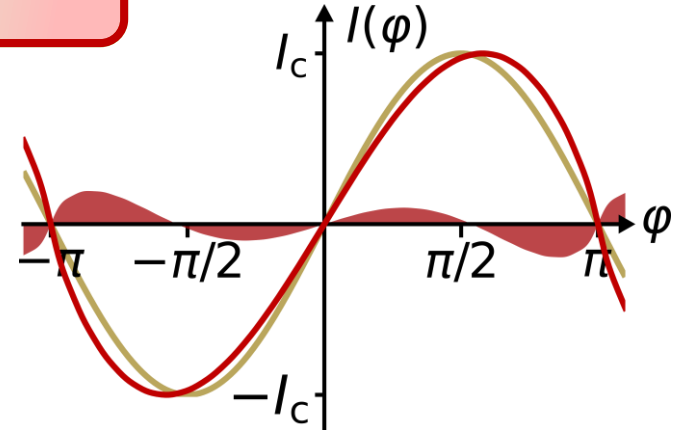
Dennis Willsch & Dennis Rieger et al.

arXiv:2302.09192

Josephson (1962)

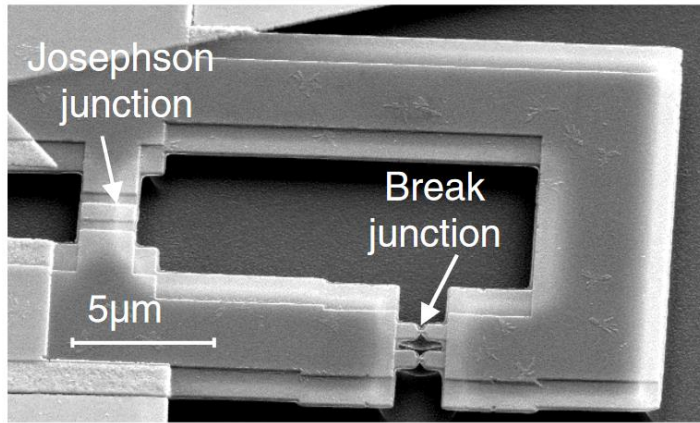


$$I_s = I_c \sin \varphi + \dots$$

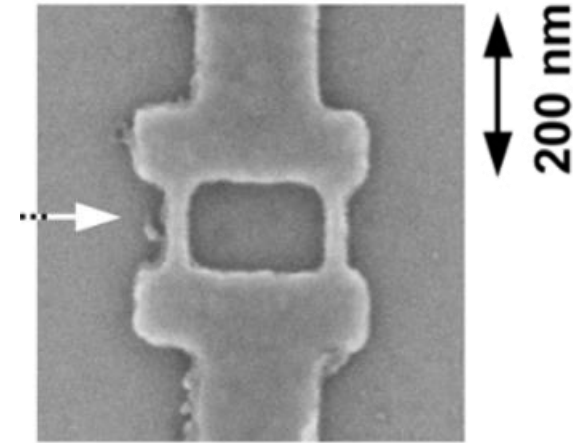


Harmonics Are Not a Surprise...for Many Types of Junctions

**Point
Contact**



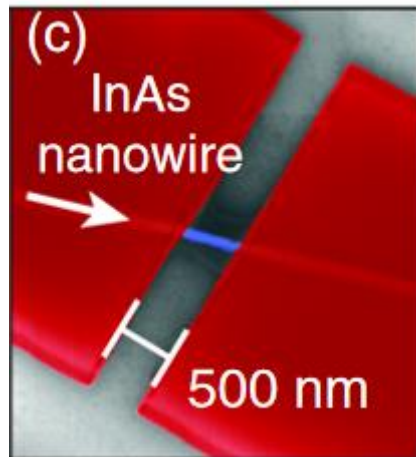
Della Rocca et al., PRL **99** (2007)



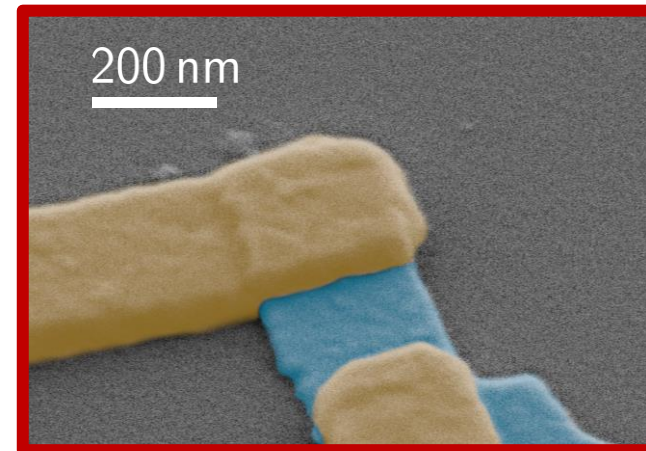
Constriction

Wernsdorfer, Supercond.
Sci. Technol. 22 (2009)

**Semiconductor
Junction**



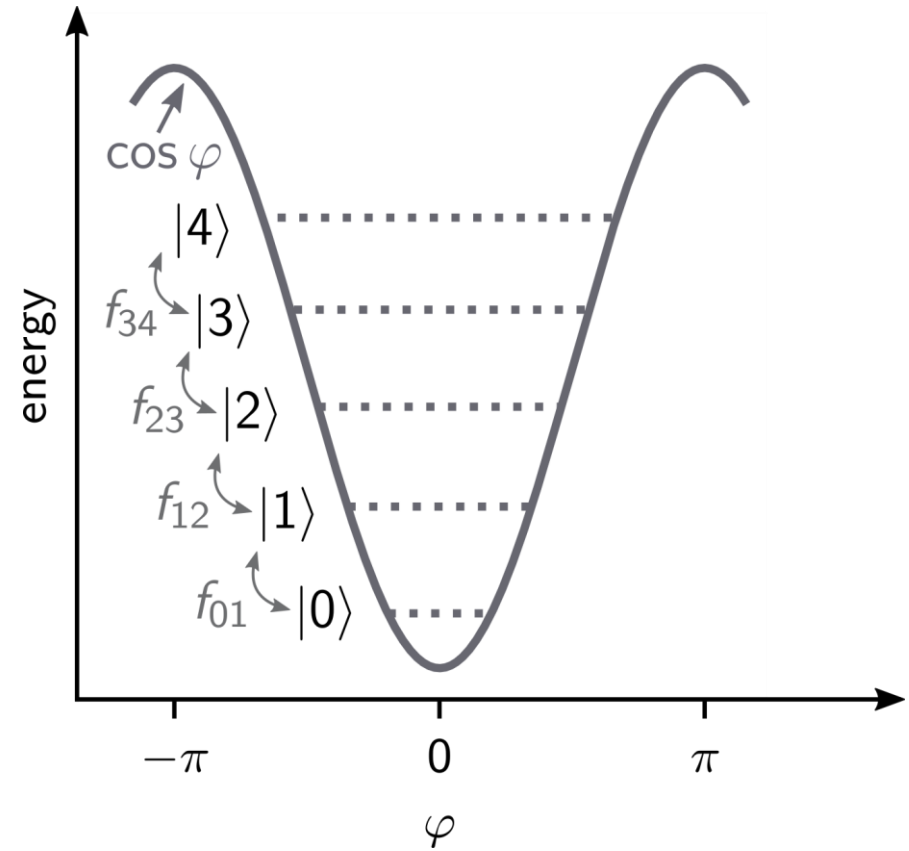
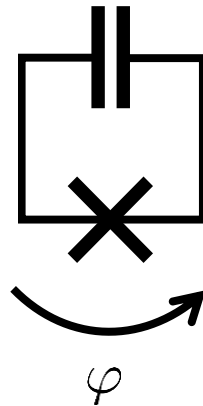
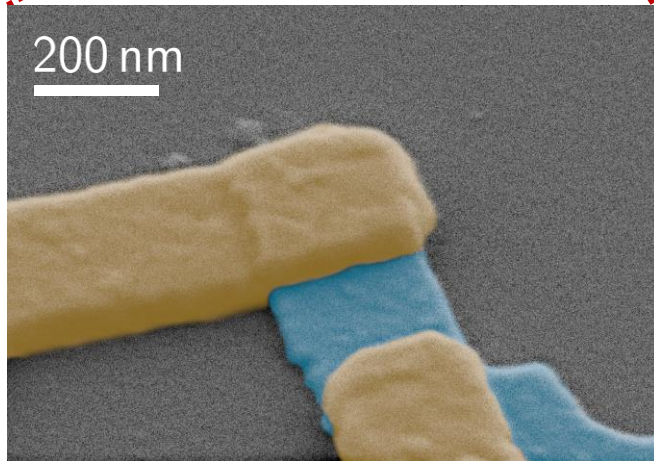
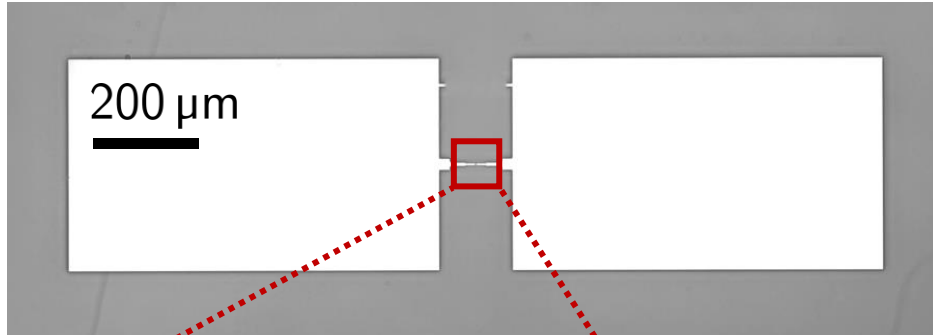
Lange et al., PRL **115** (2015)



**Tunnel
Junction**

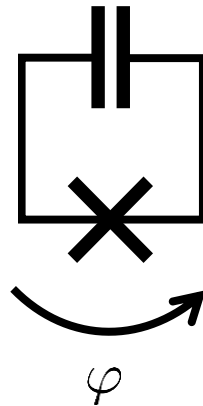
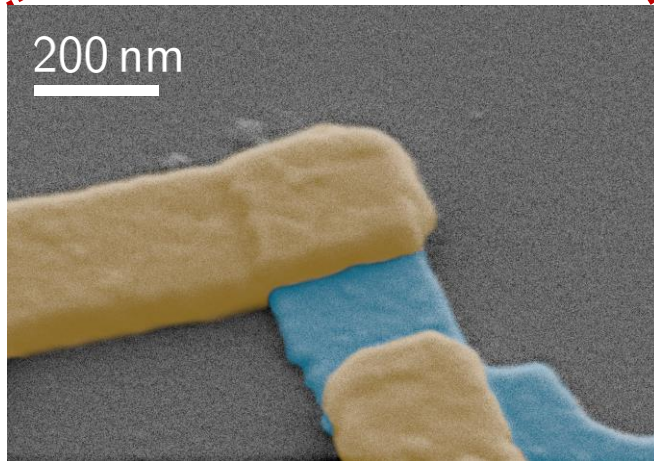
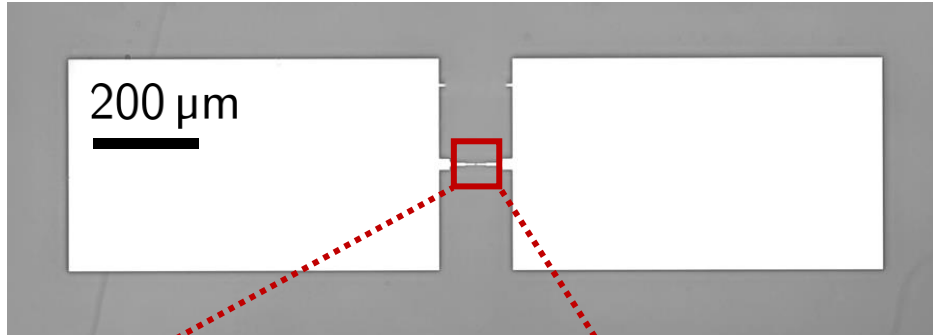
Harmonics?

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

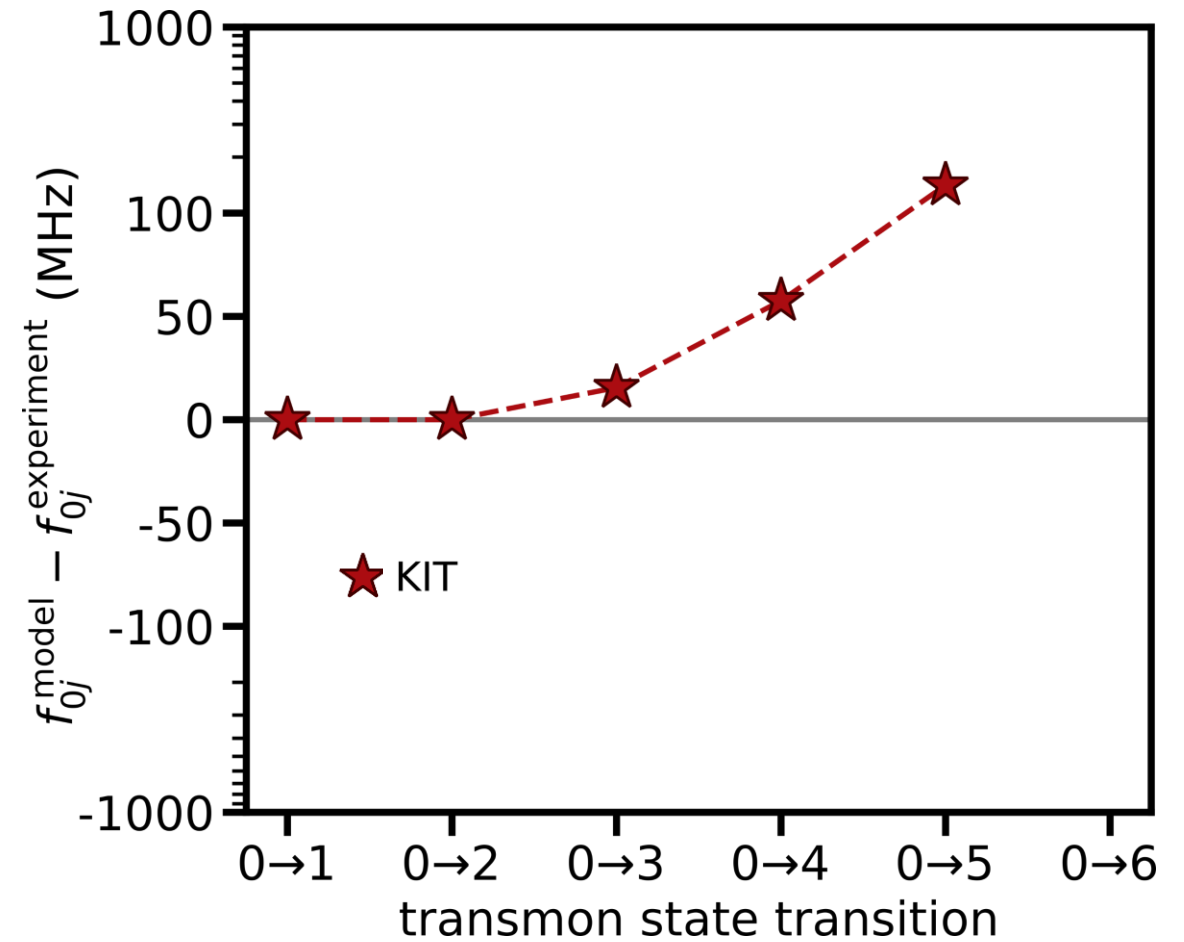


$$H = 4E_c n^2 - E_J \cos \varphi$$

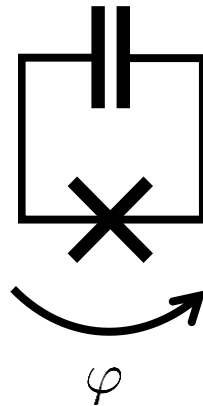
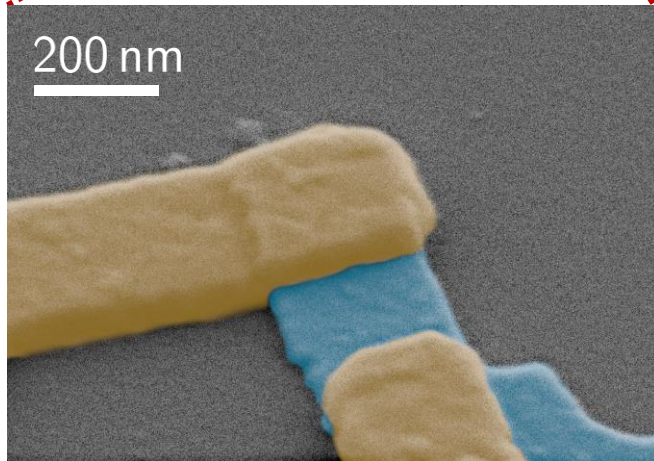
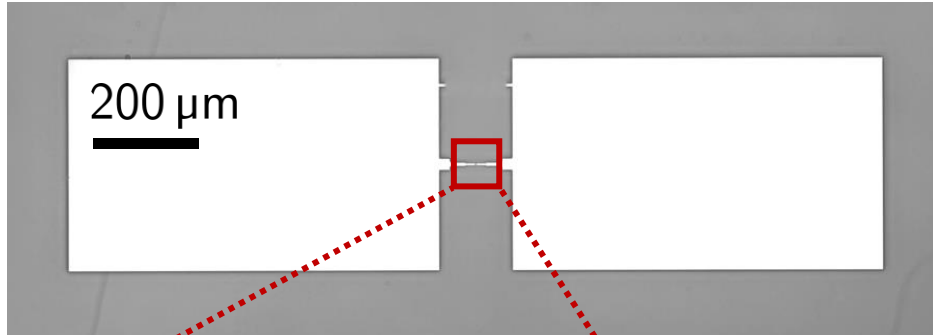
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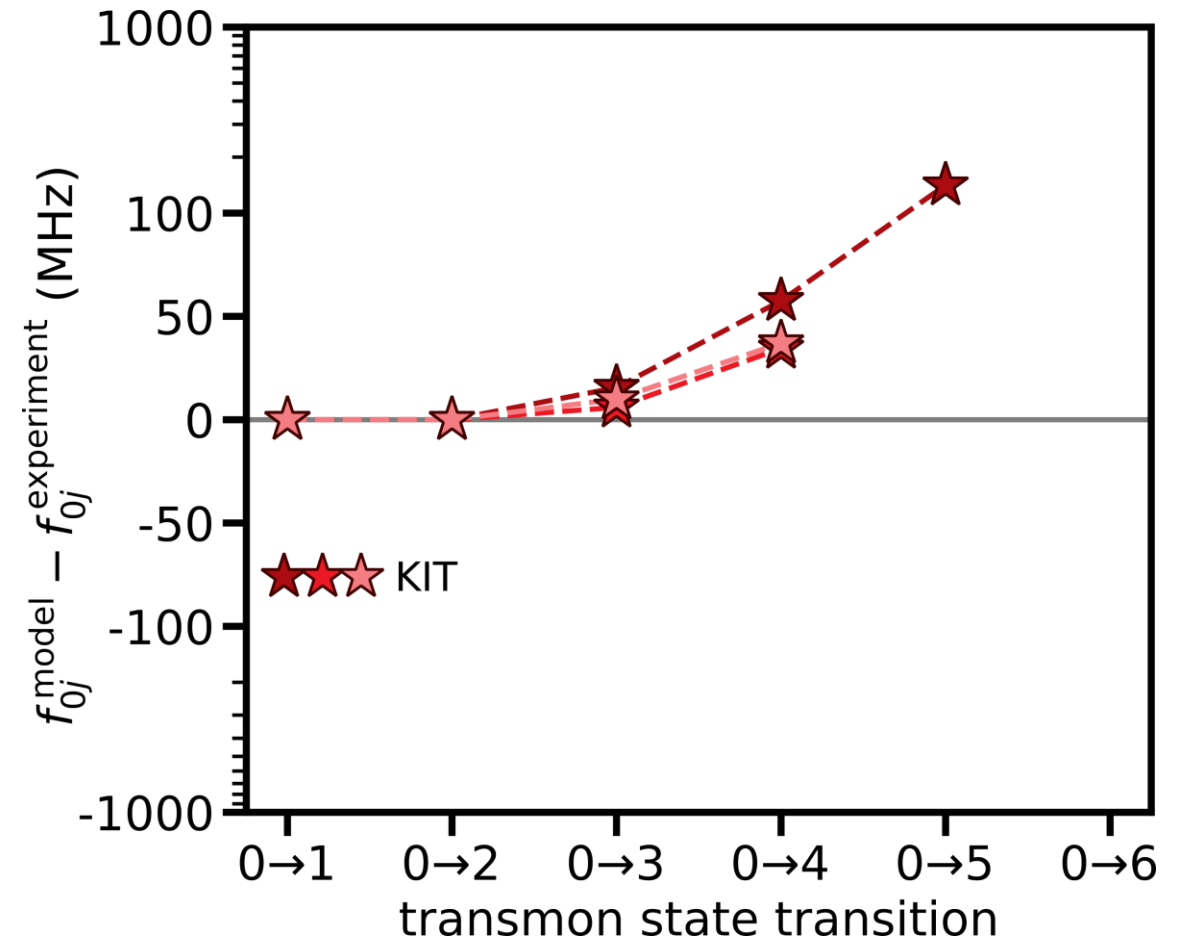
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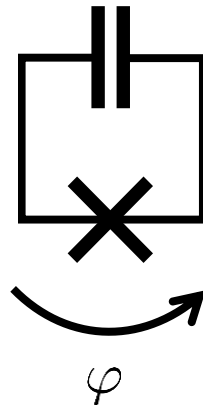
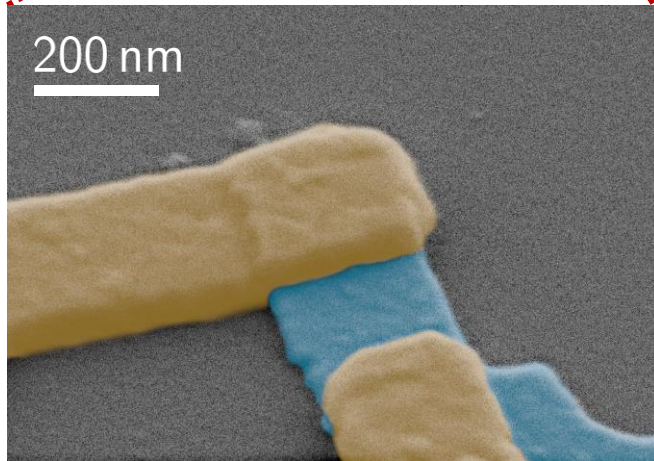
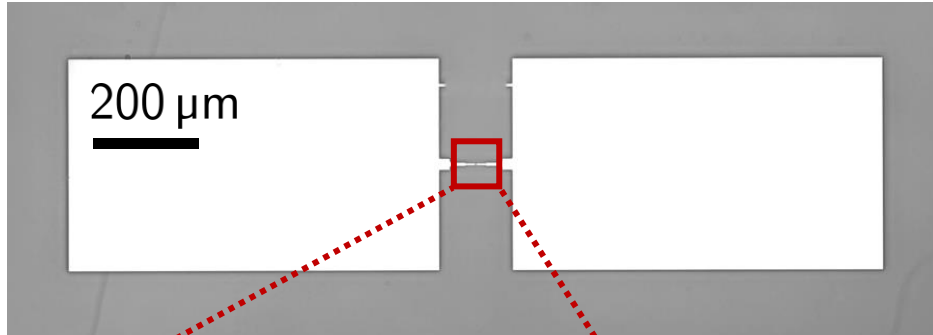
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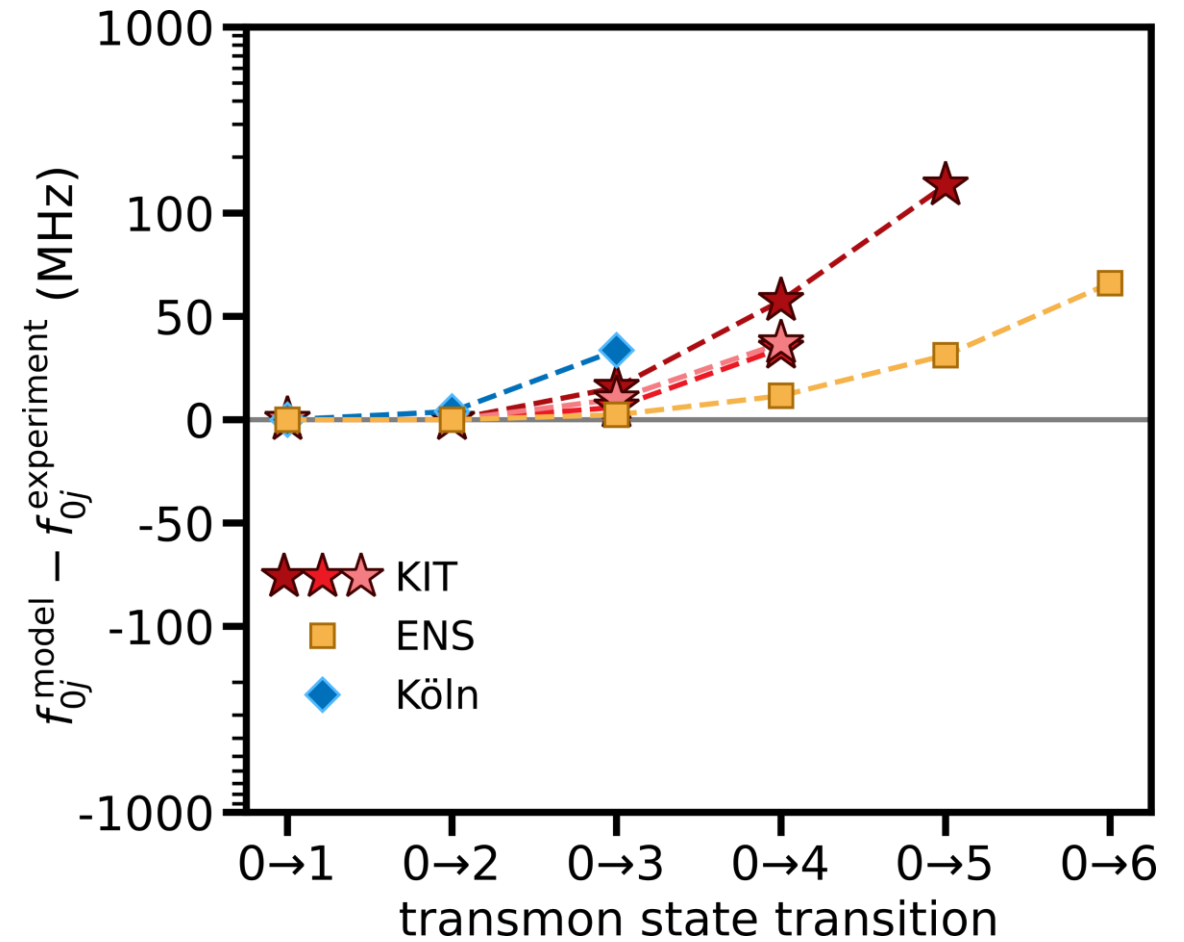
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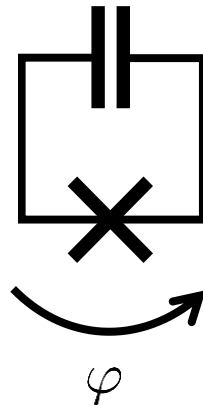
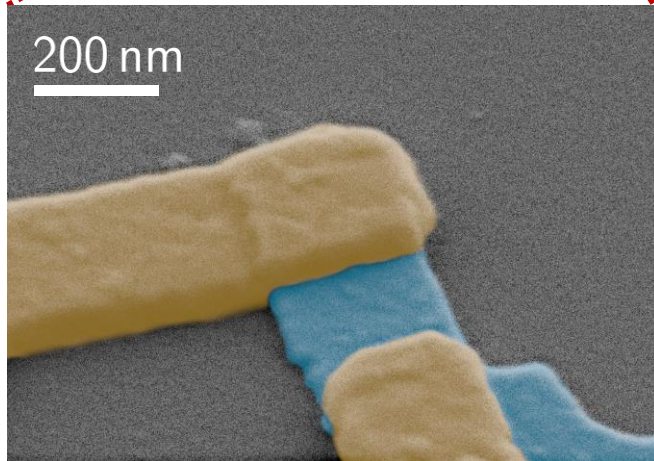
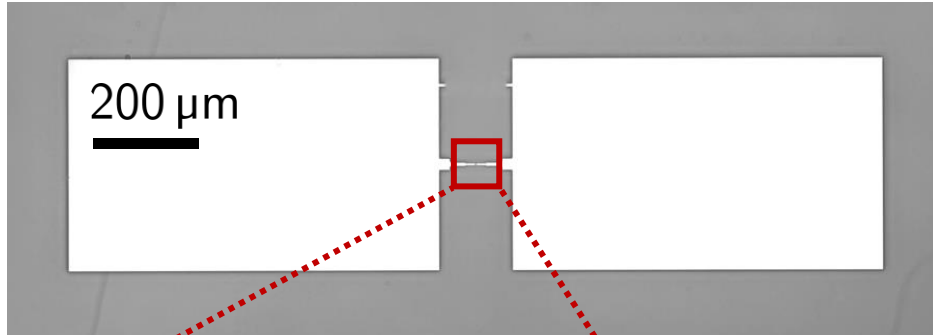
The Transmon Qubit as a Testbed for the Current-Phase-Relation



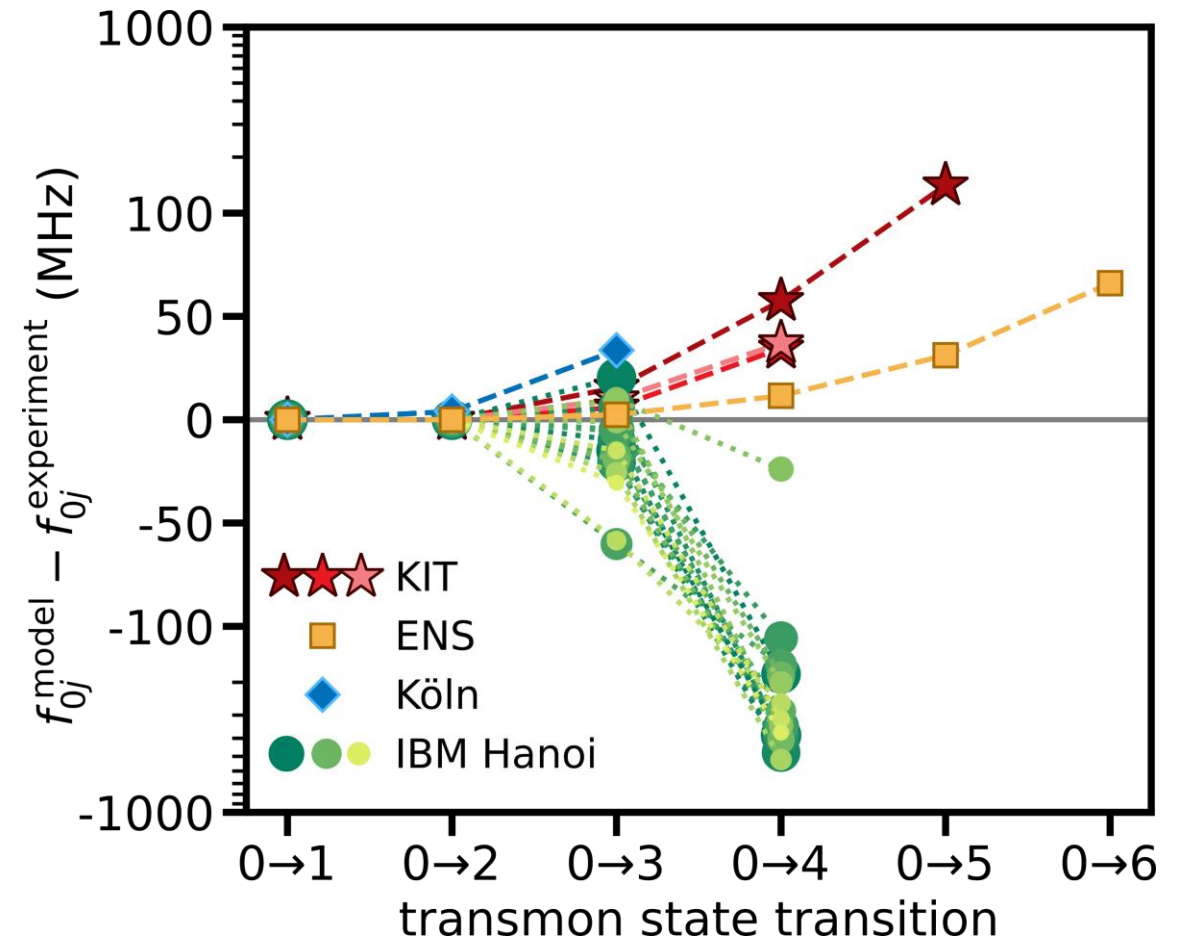
$$H = 4E_c n^2 - E_J \cos \varphi$$



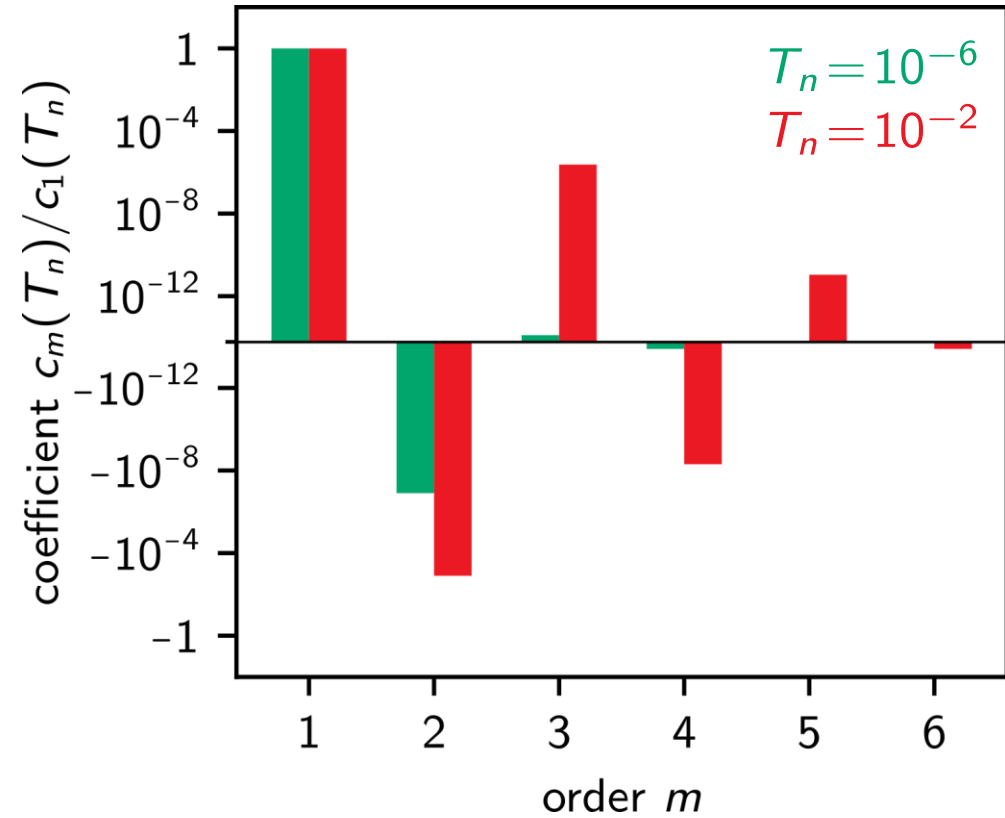
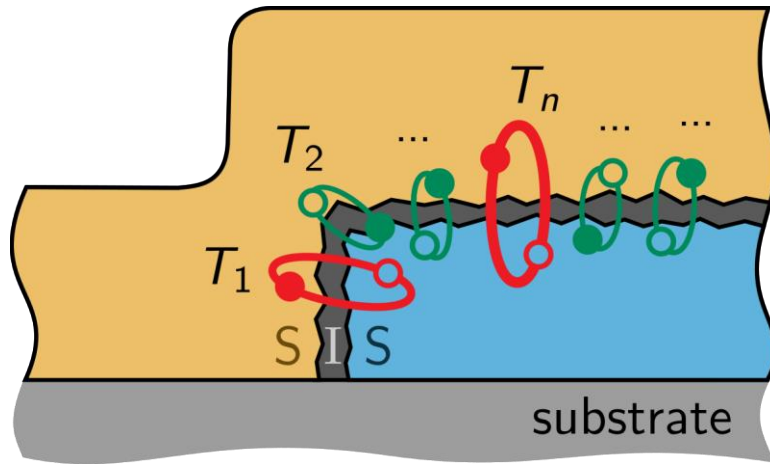
The Transmon Qubit as a Testbed for the Current-Phase-Relation



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

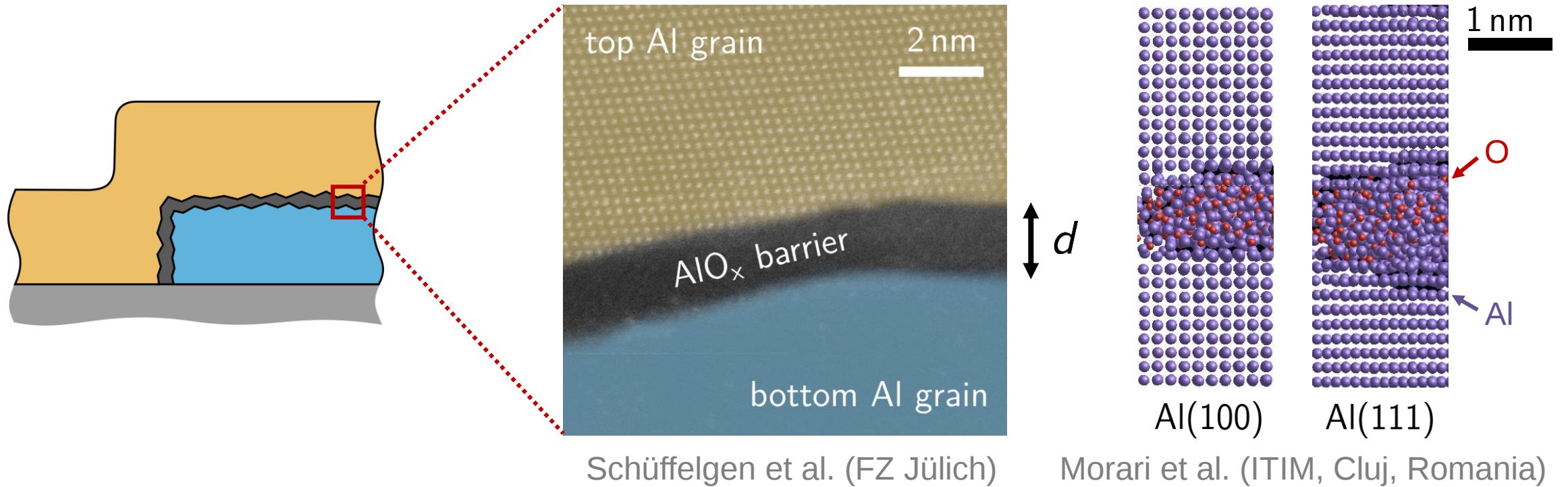


Reality Check for a Standard Tunnel Junction



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

Setting the Expectation for Harmonics in Tunnel JJ

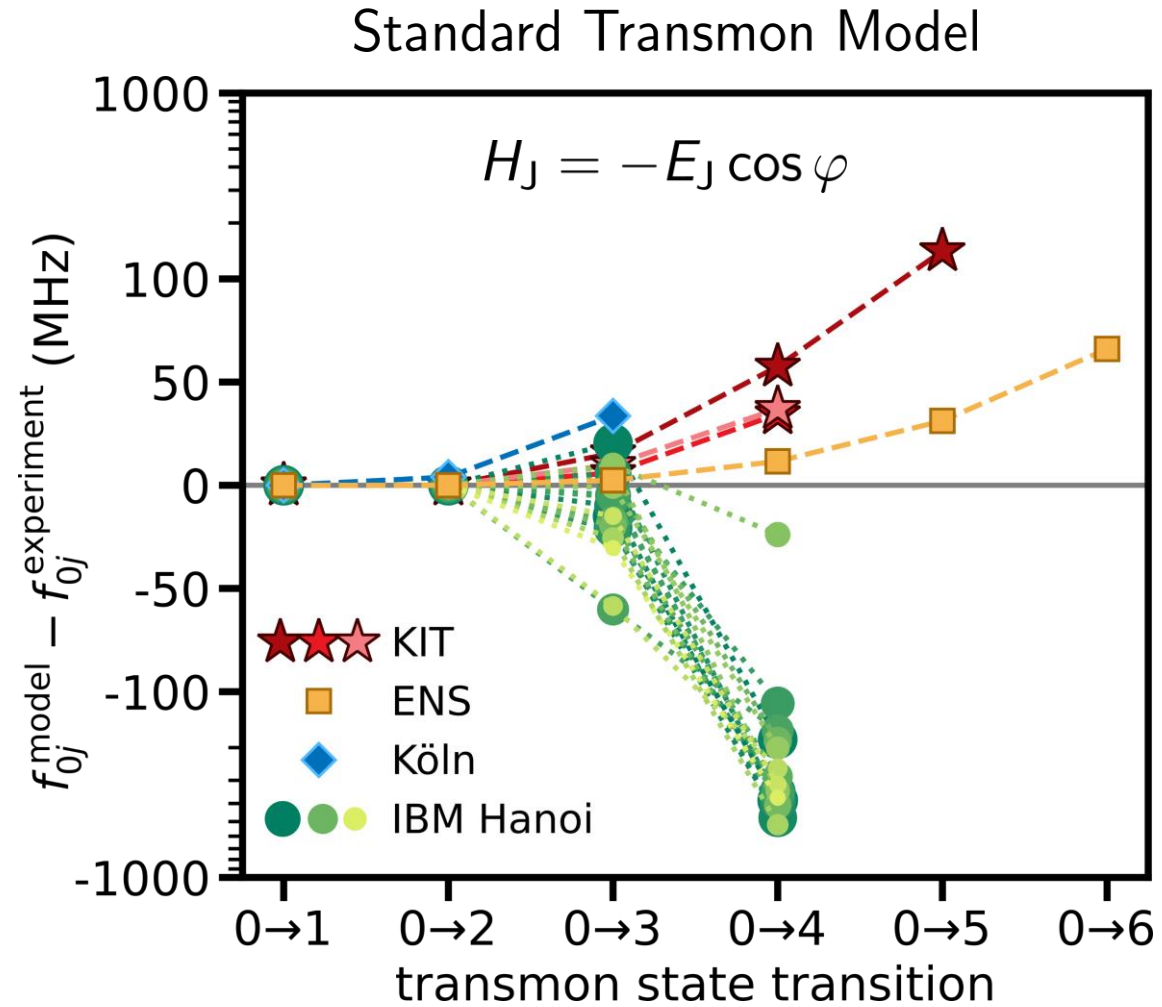


Mesososcopic Model

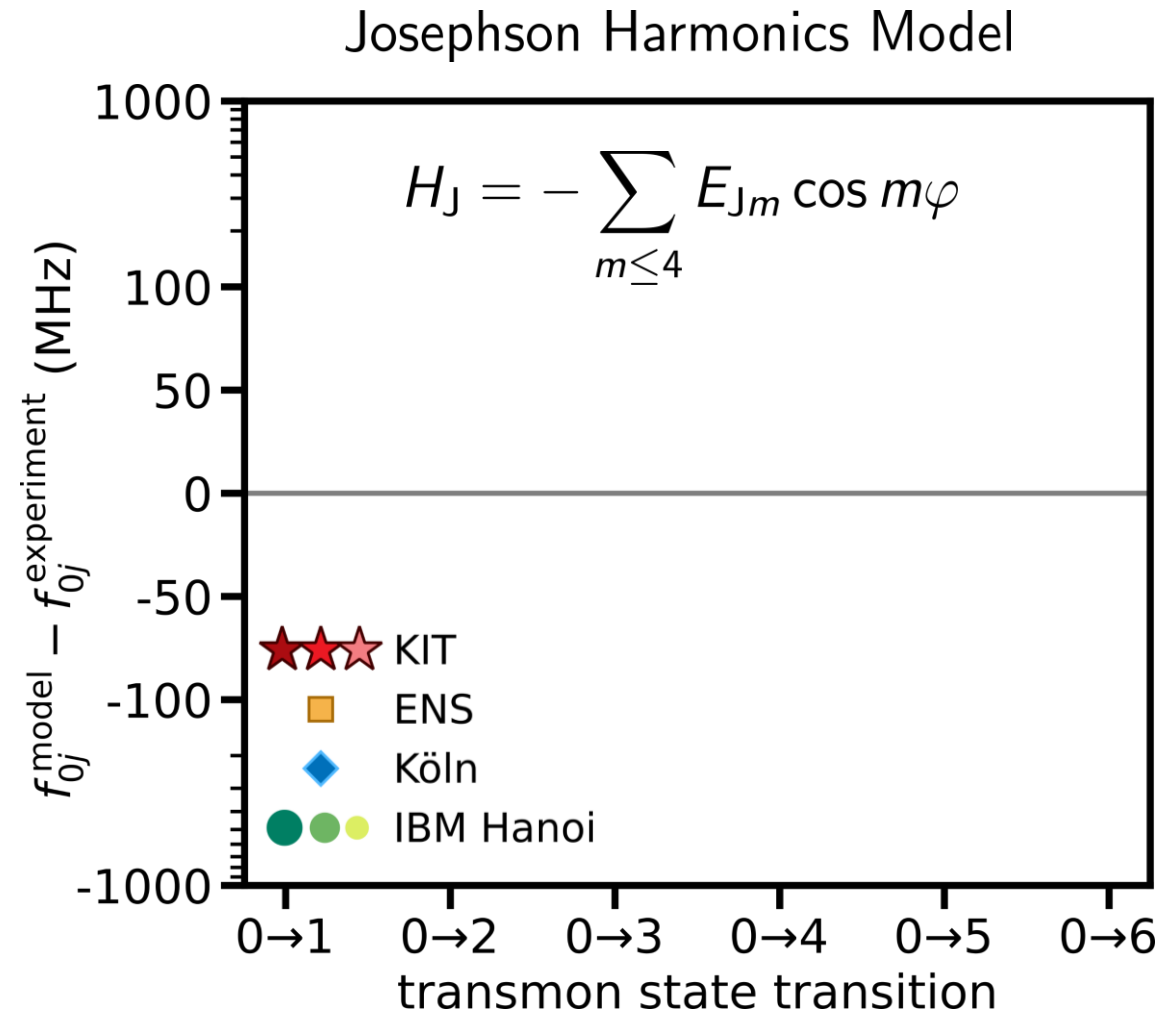
Gaussian thickness distribution $\longrightarrow$ few % of $\sin 2\varphi$

Gianluigi Catelani (FZ Jülich)

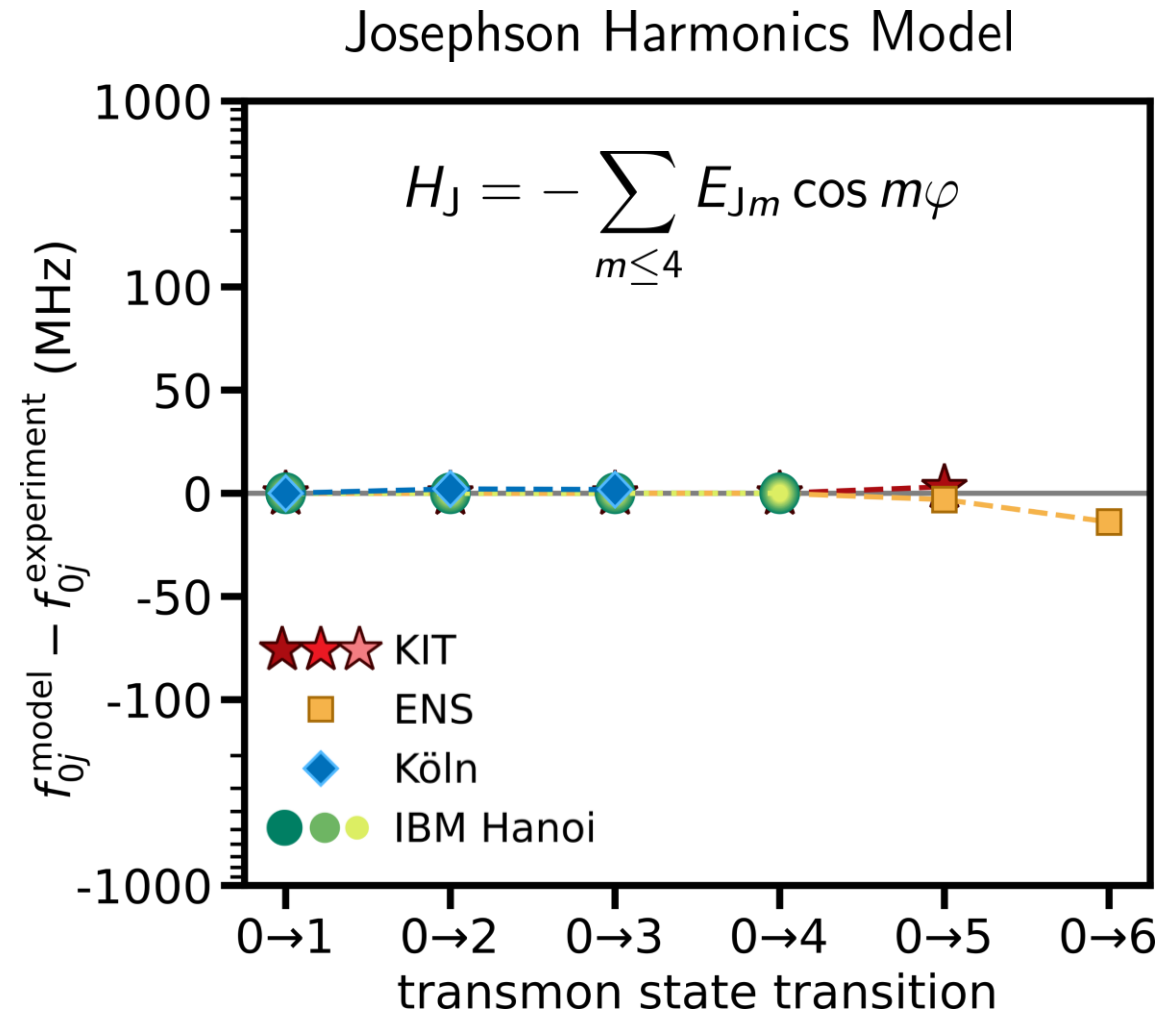
Sinusoidal $C\phi$ R Fails to Describe Measured Transmon Spectra



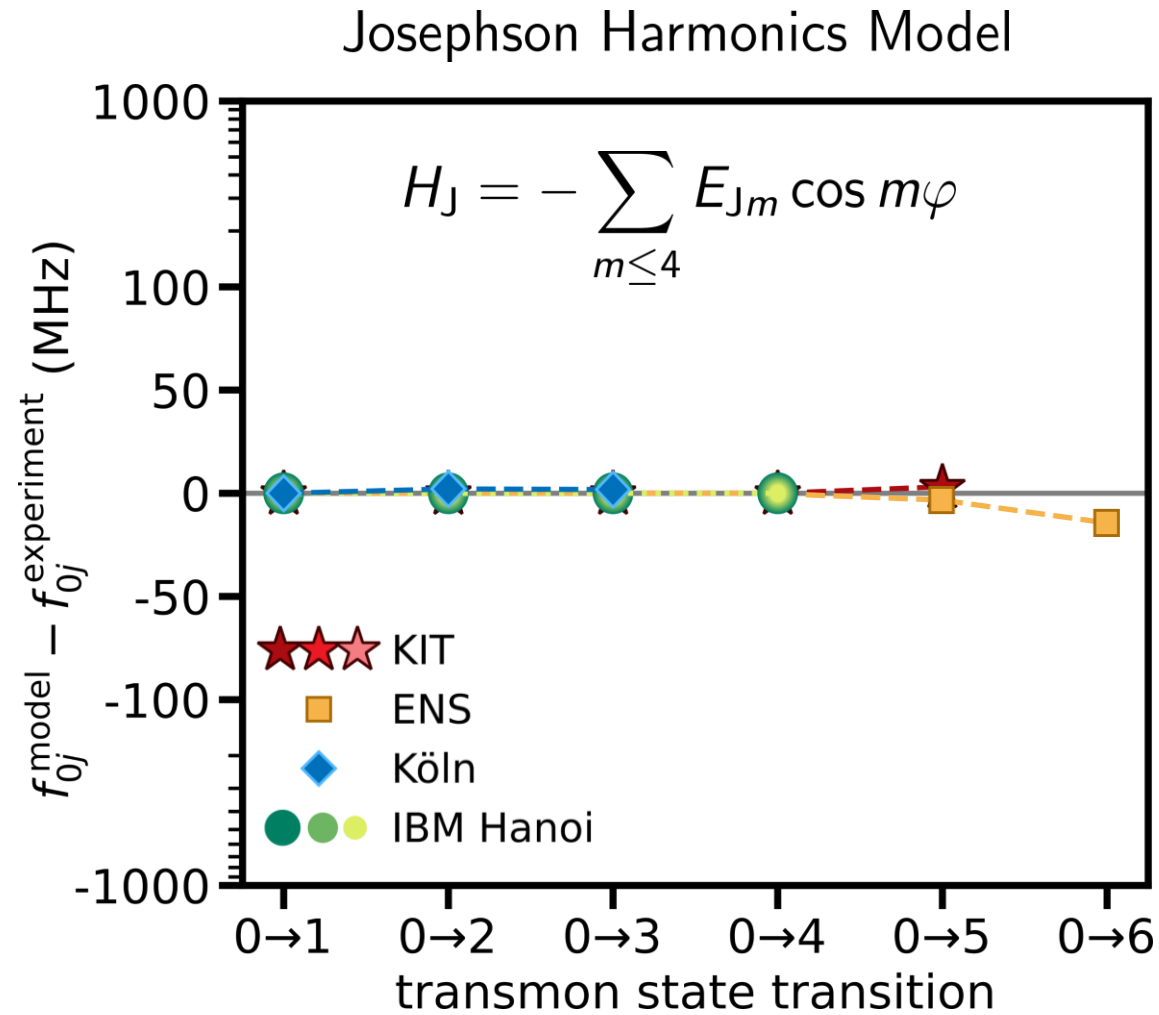
Josephson Harmonics to the Rescue



Josephson Harmonics to the Rescue



Josephson Harmonics to the Rescue

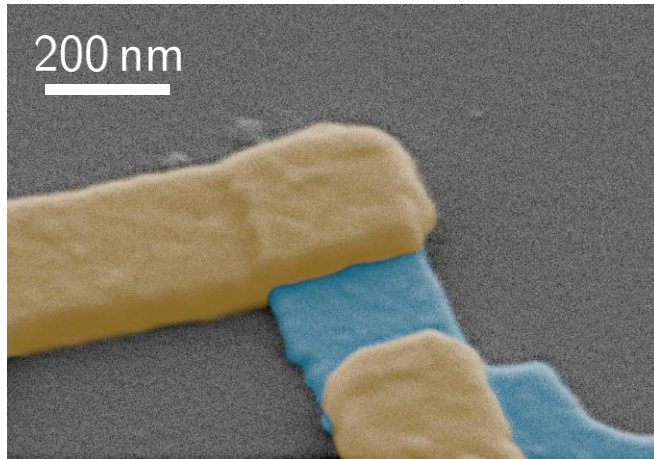


Dyson, Nature **427**,
297 (2004)

Observation of Josephson Harmonics in Tunnel Junctions

Dennis Willsch & Dennis Rieger et al.

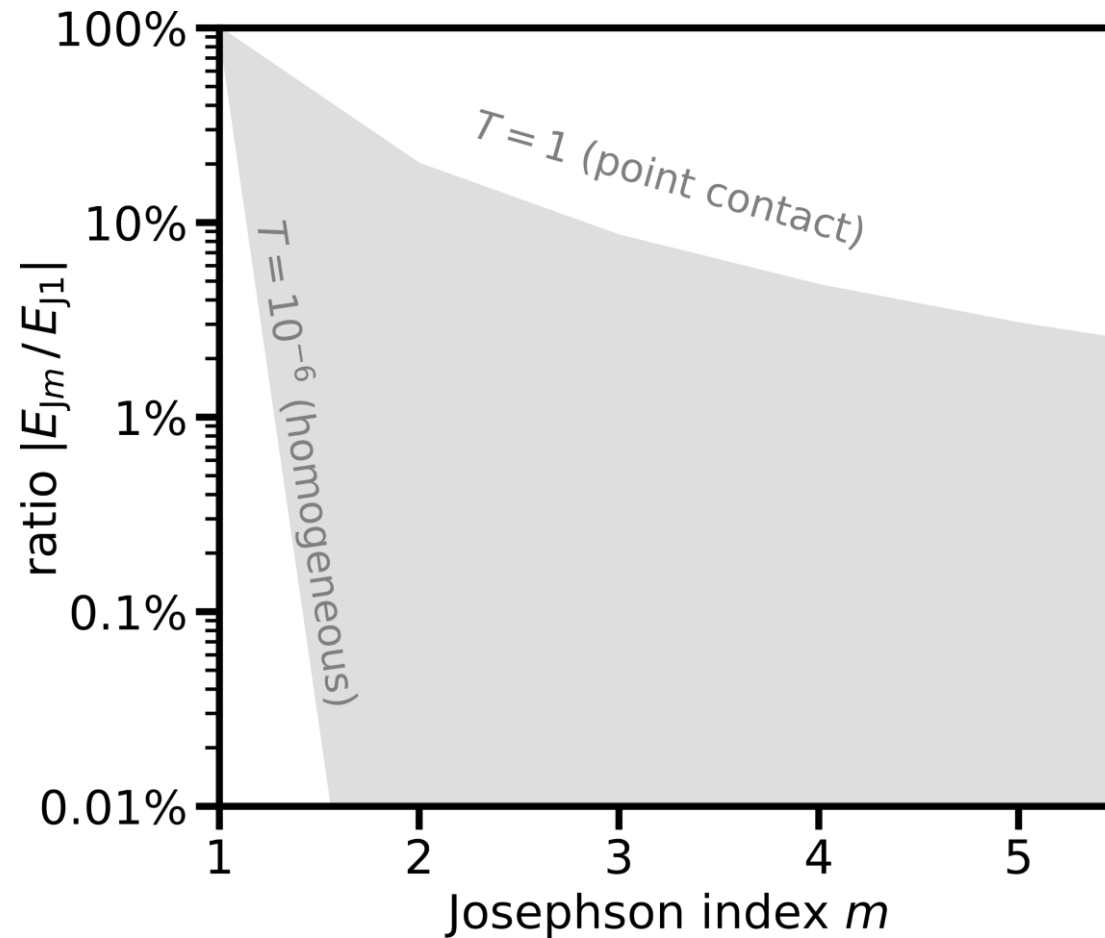
arXiv:2302.09192



***Part 2: Embracing
Josephson Harmonics***

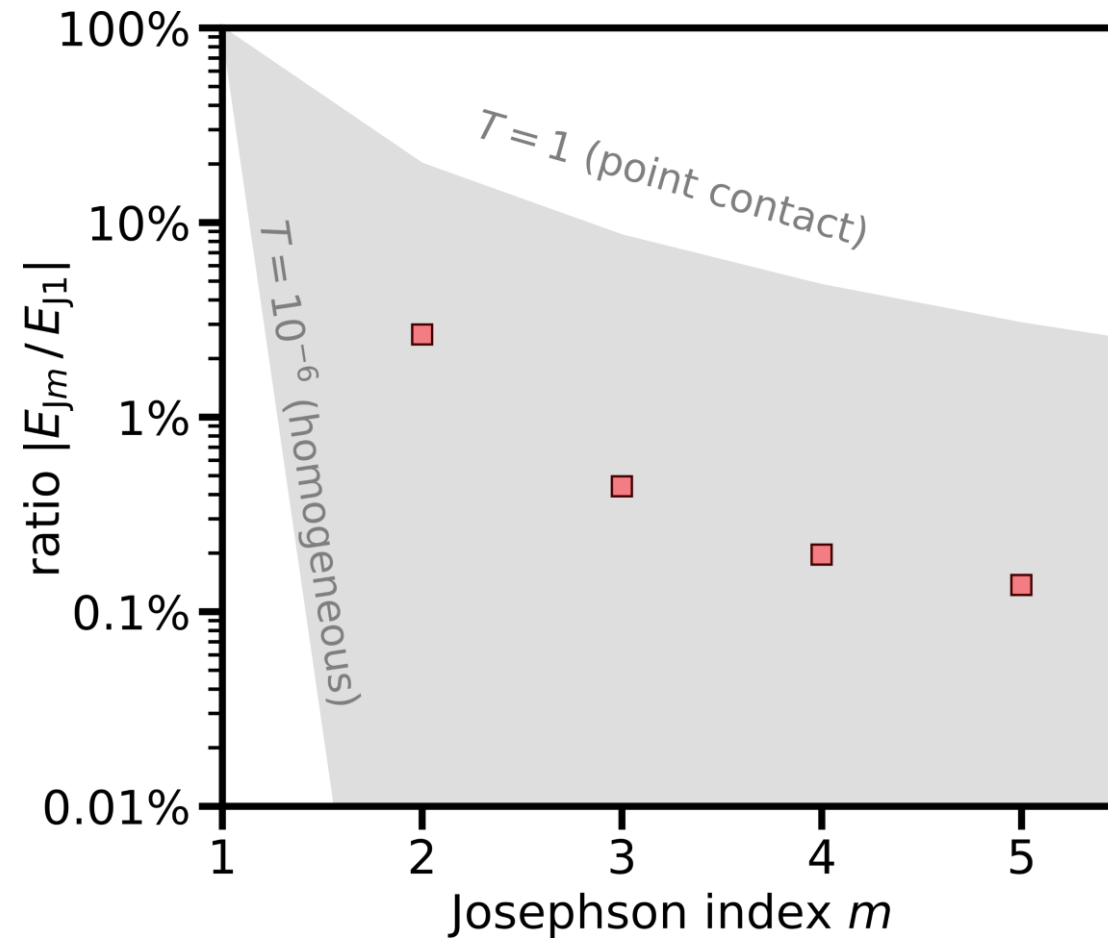
Magnitude of Josephson Harmonics in Tunnel Junctions

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



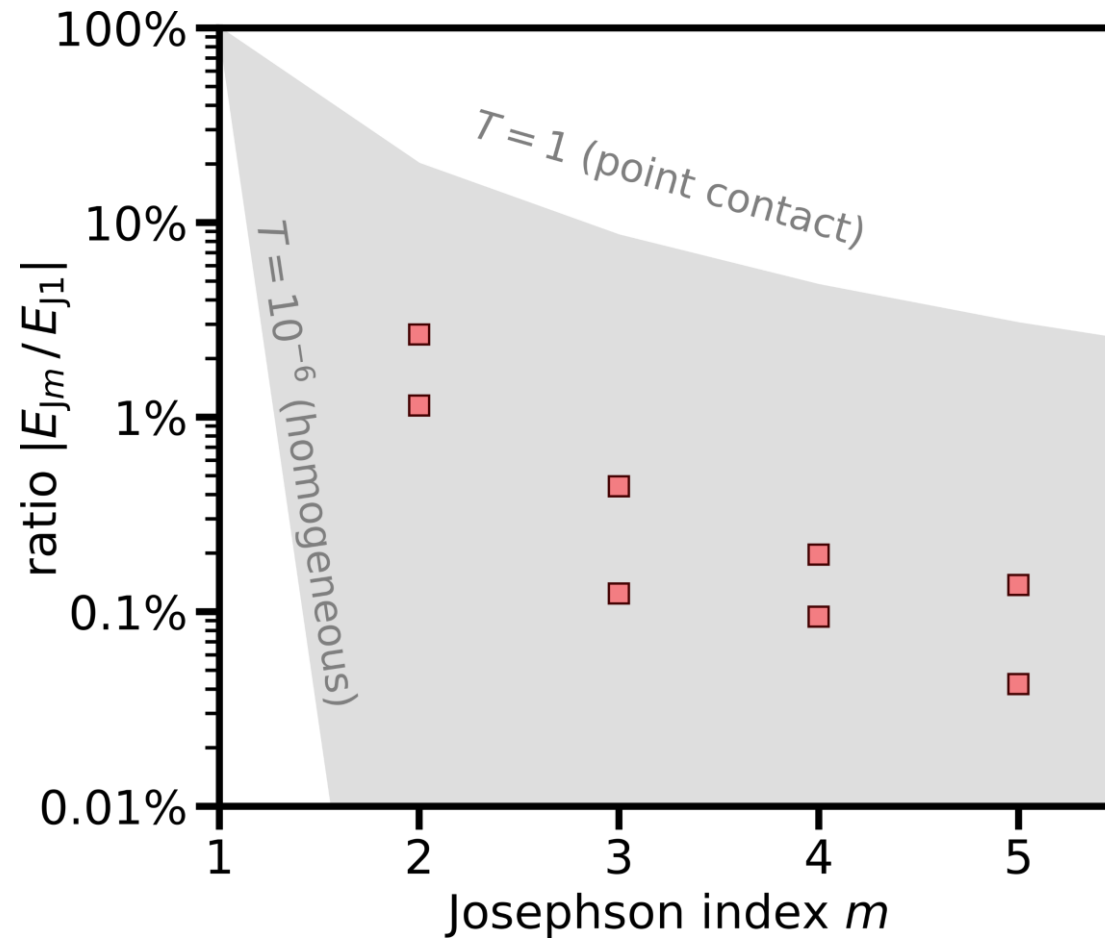
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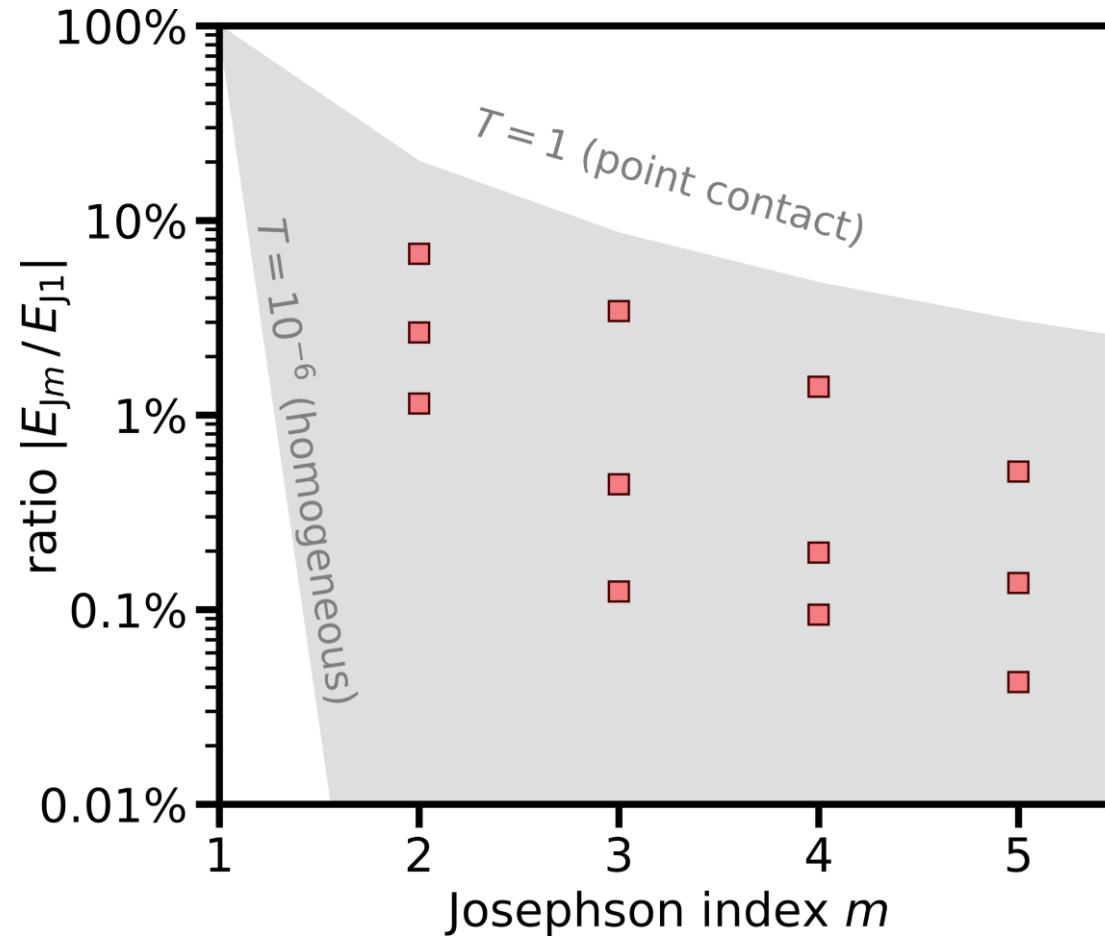
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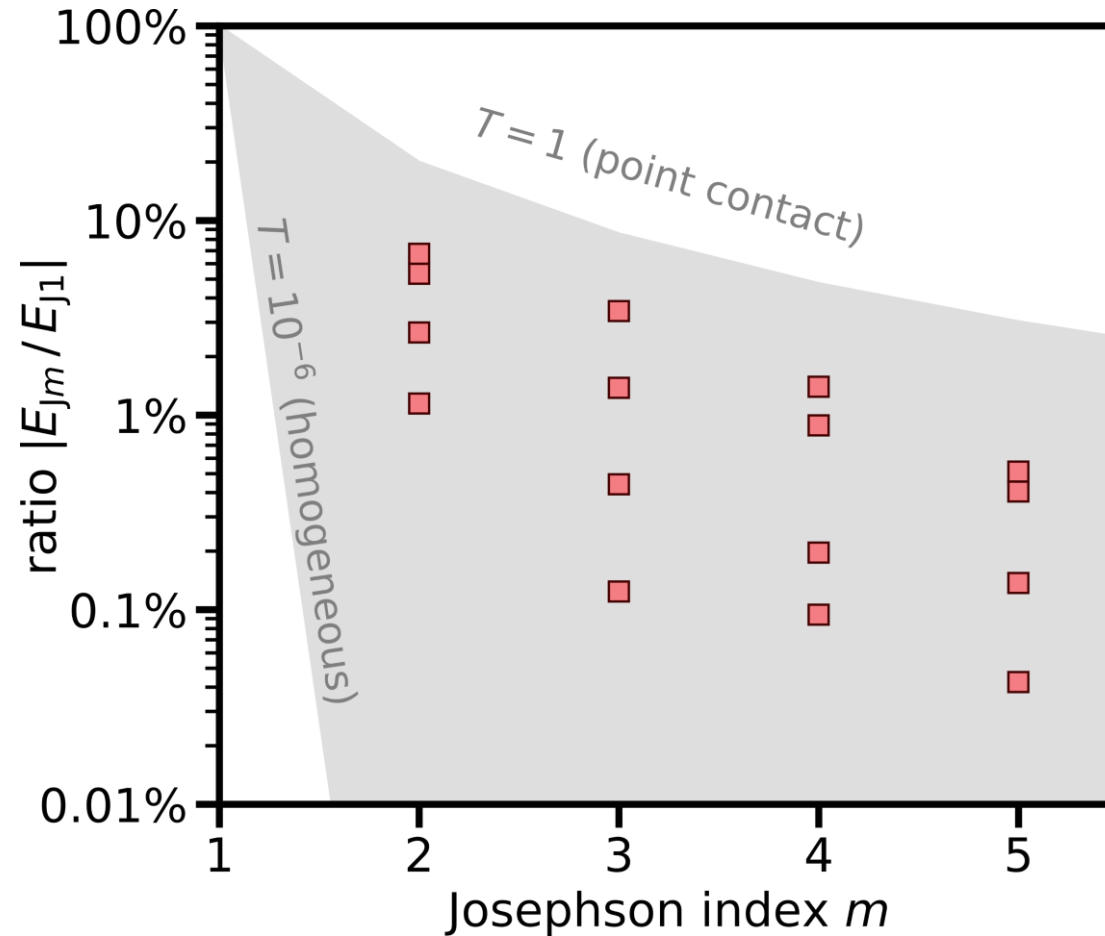
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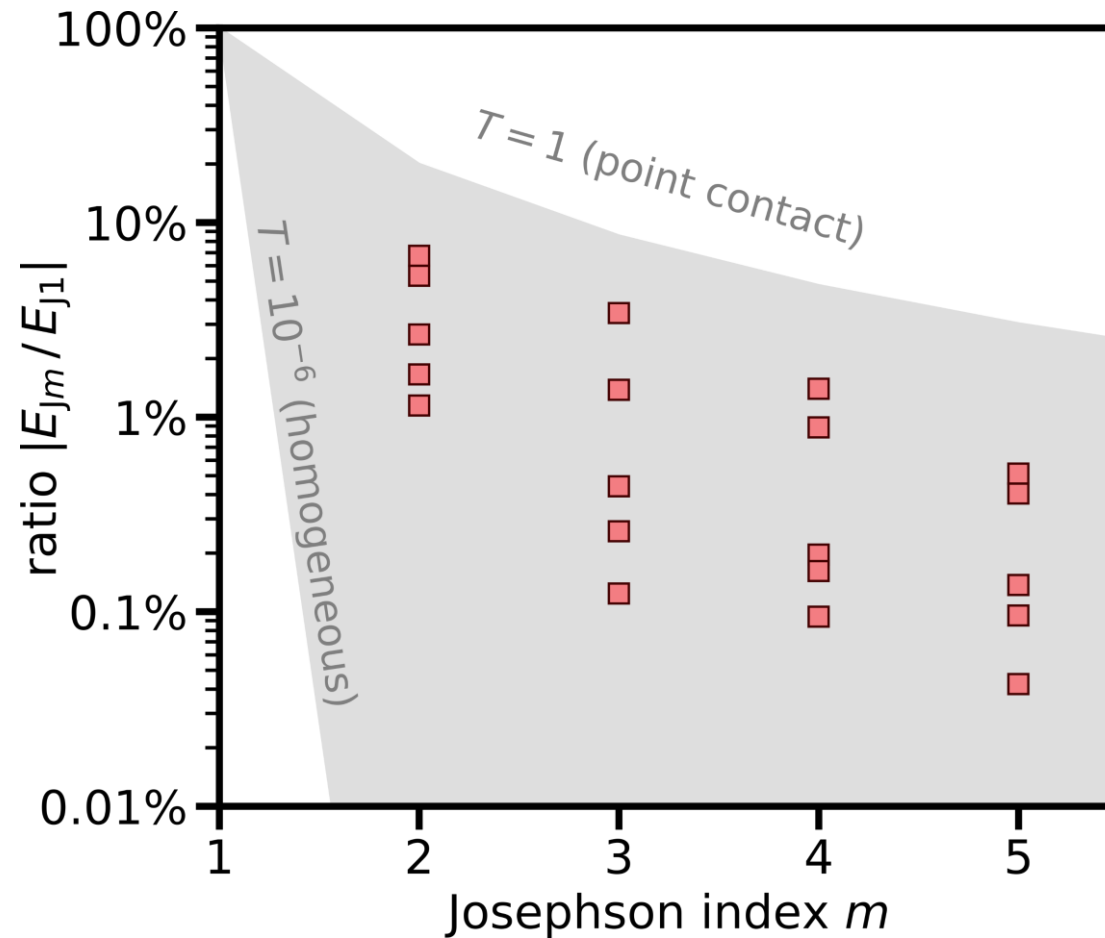
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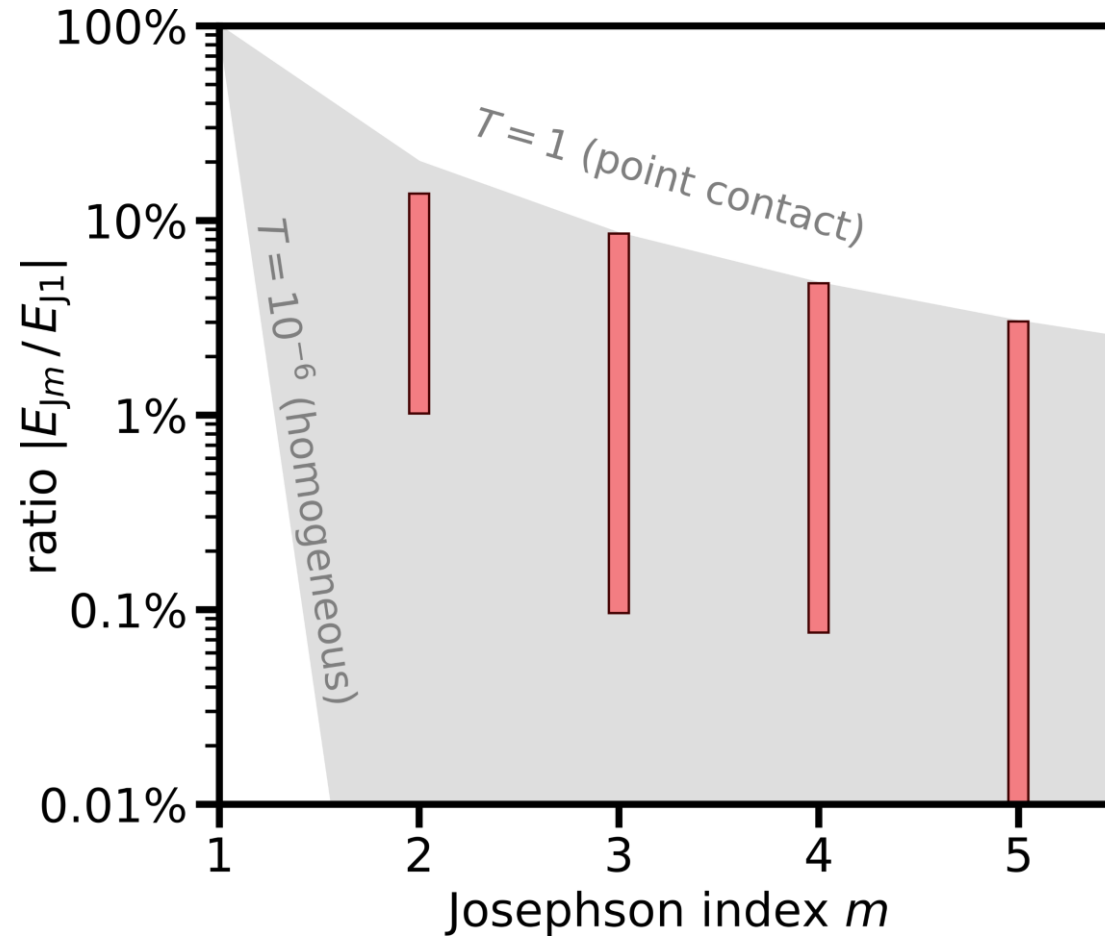
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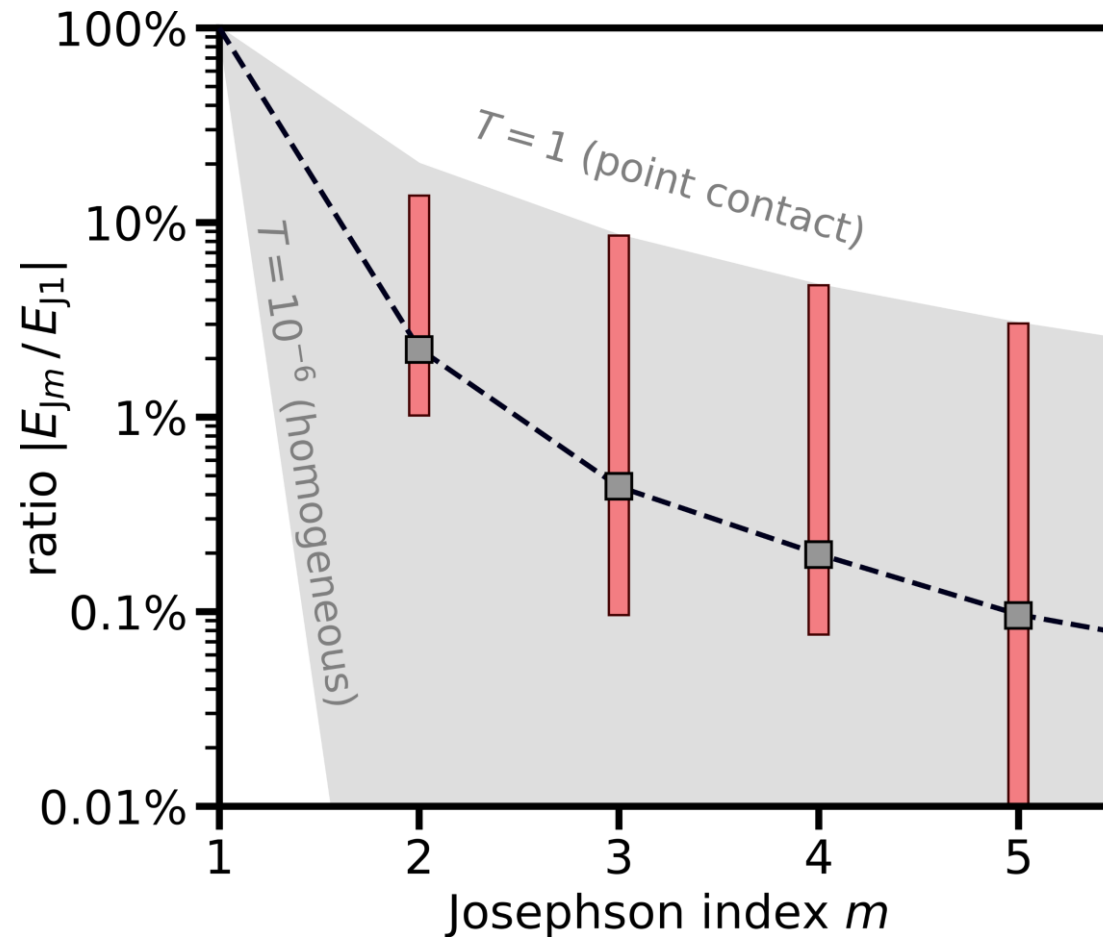
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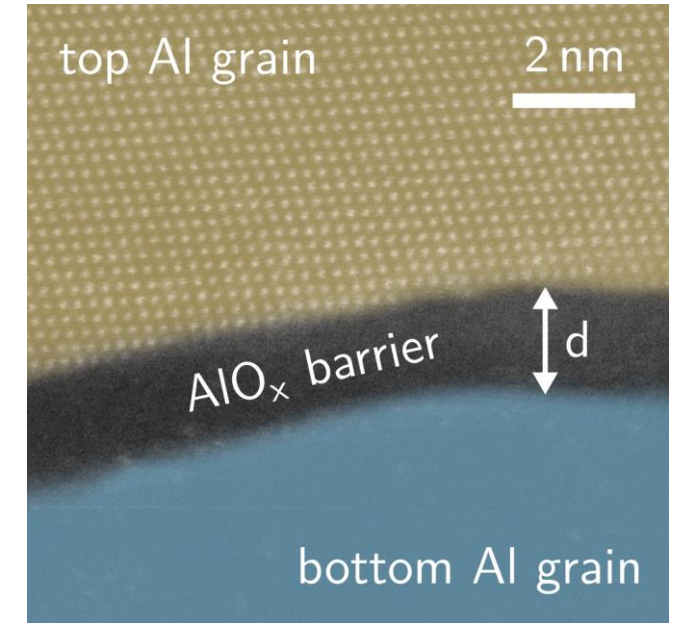


Magnitude of Josephson Harmonics in Tunnel Junctions

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



Schüffelgen et al. (FZ Jülich)



Mesoscopic model with
Gaussian thickness

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

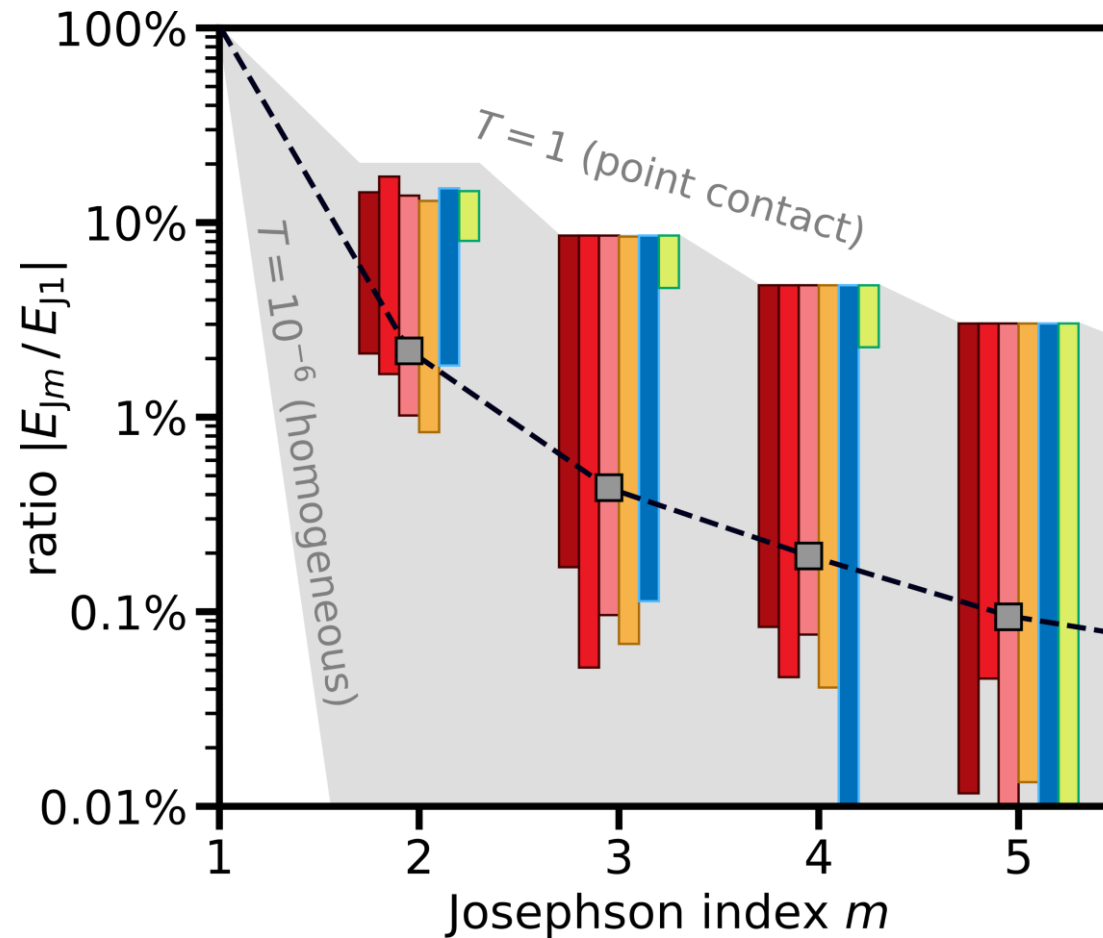
$$\bar{d} = 1.6 \text{ nm}$$

$$\sigma_d = 0.4 \text{ nm}$$

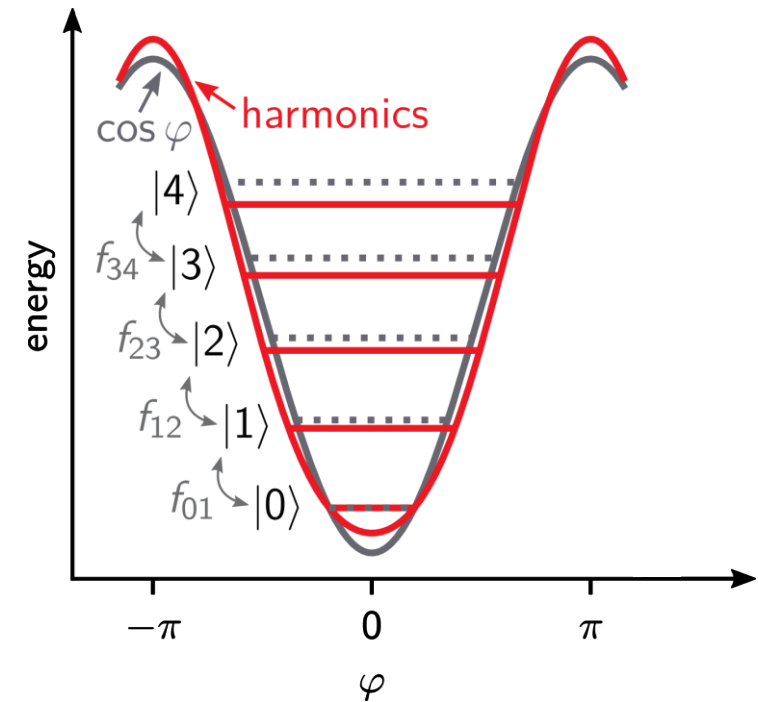
Gianluigi Catelani (FZ Jülich)

Magnitude of Josephson Harmonics in Tunnel Junctions

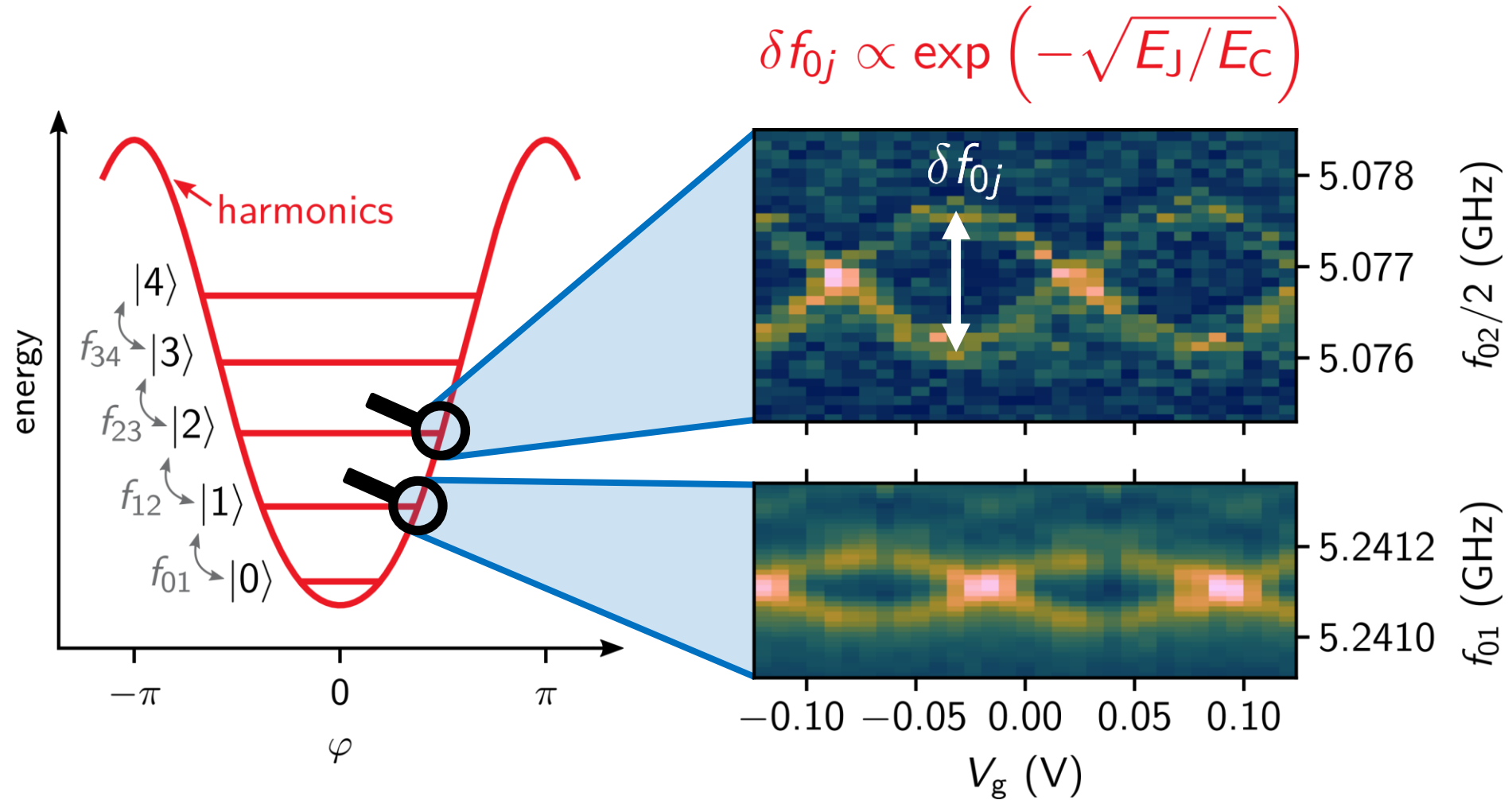
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- ★ ★ ★ KIT
- ENS
- ◆ Köln
- ● ● IBM Hanoi

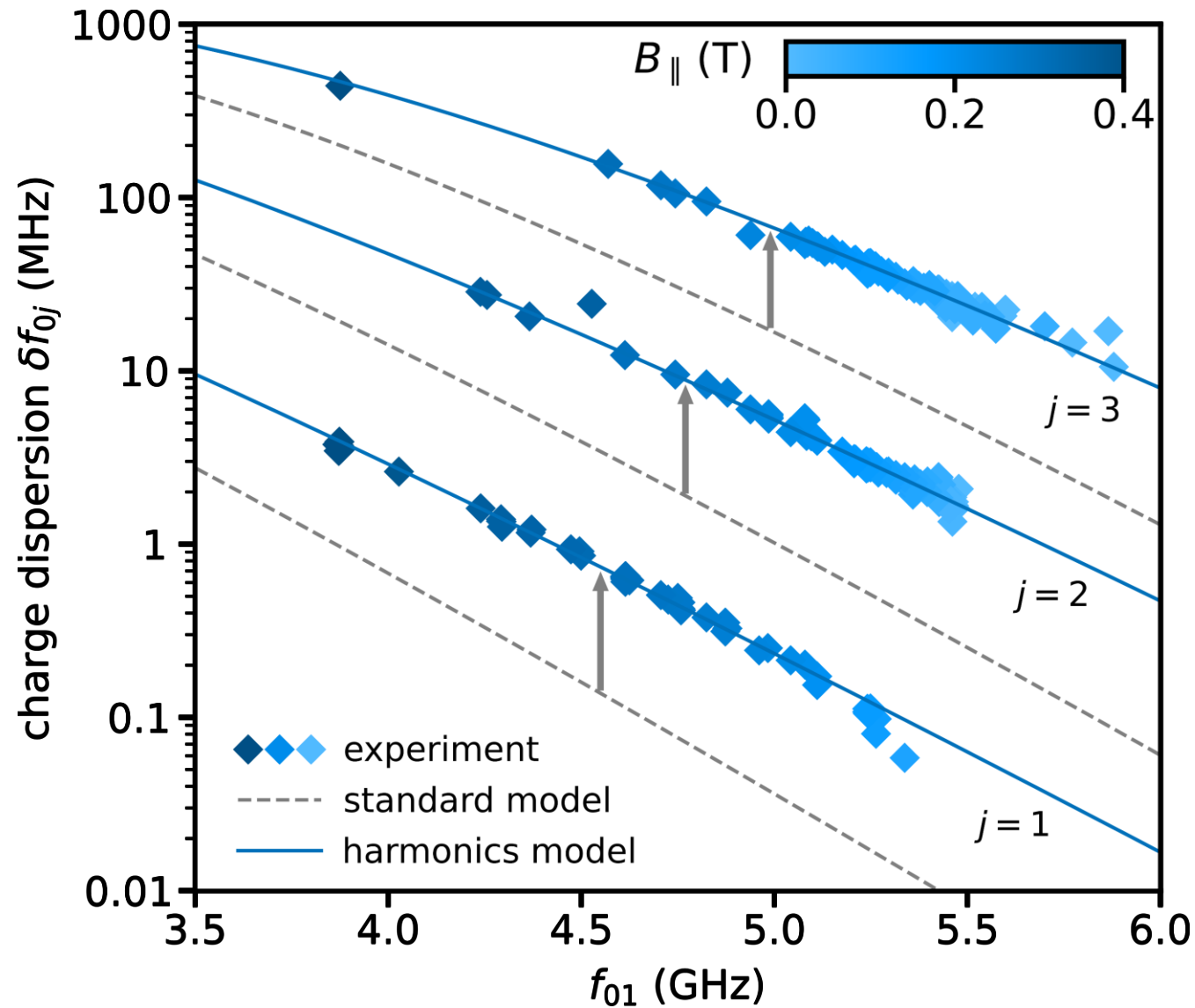


Josephson Harmonics Impact the Charge Dispersion



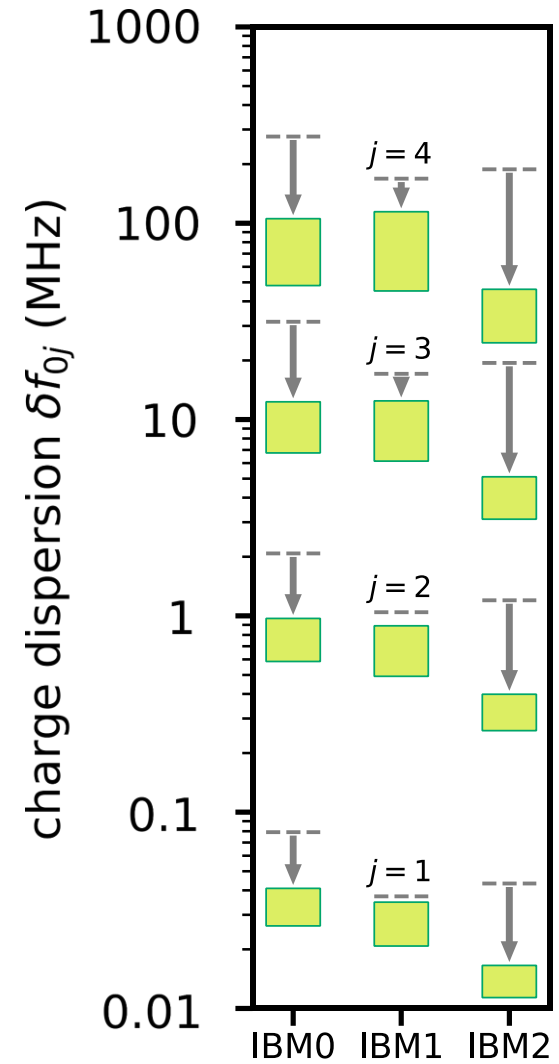
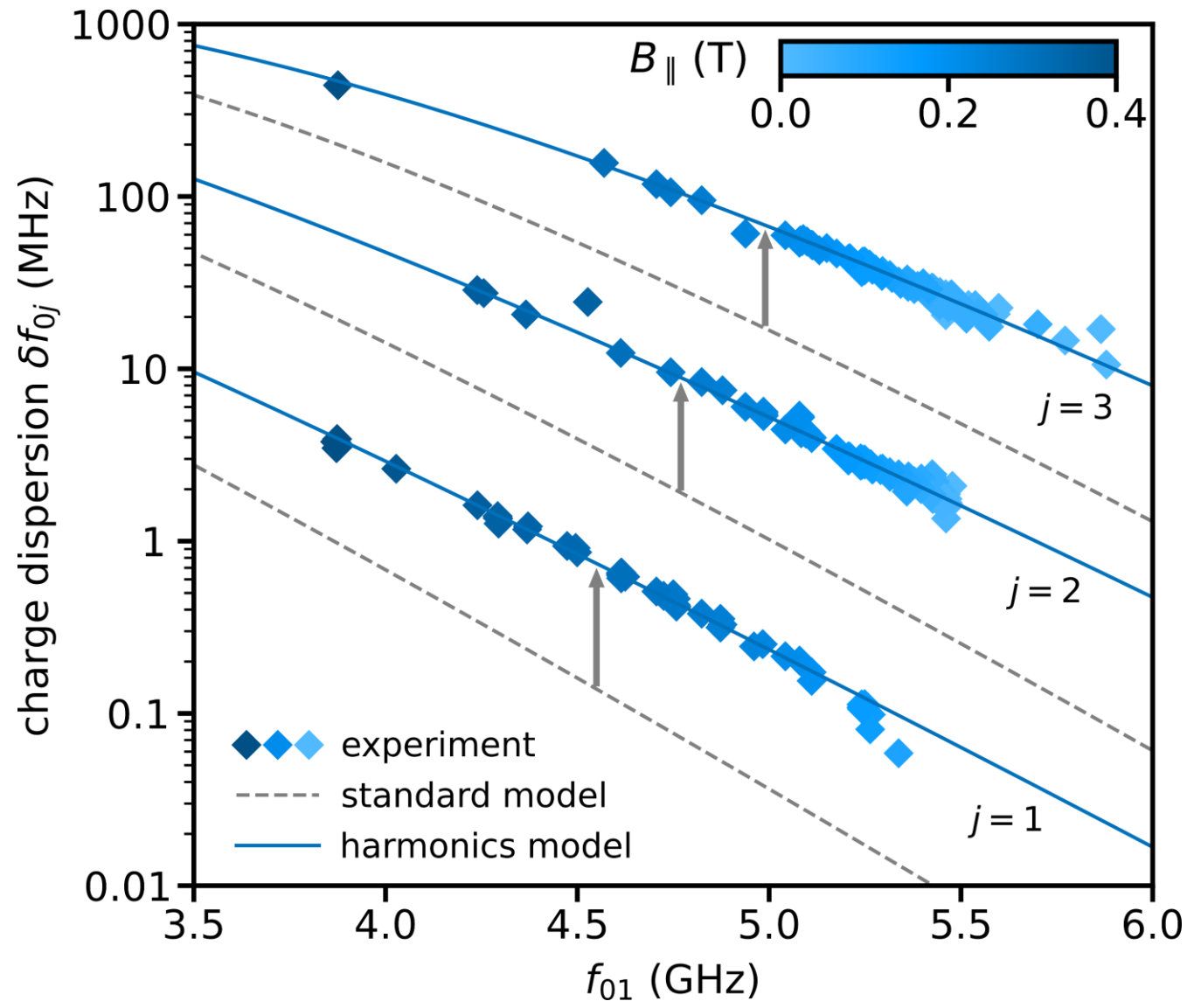
Dickel et al. (University of Cologne)

Charge Dispersion: An Exponentially Sensitive Test of the Model

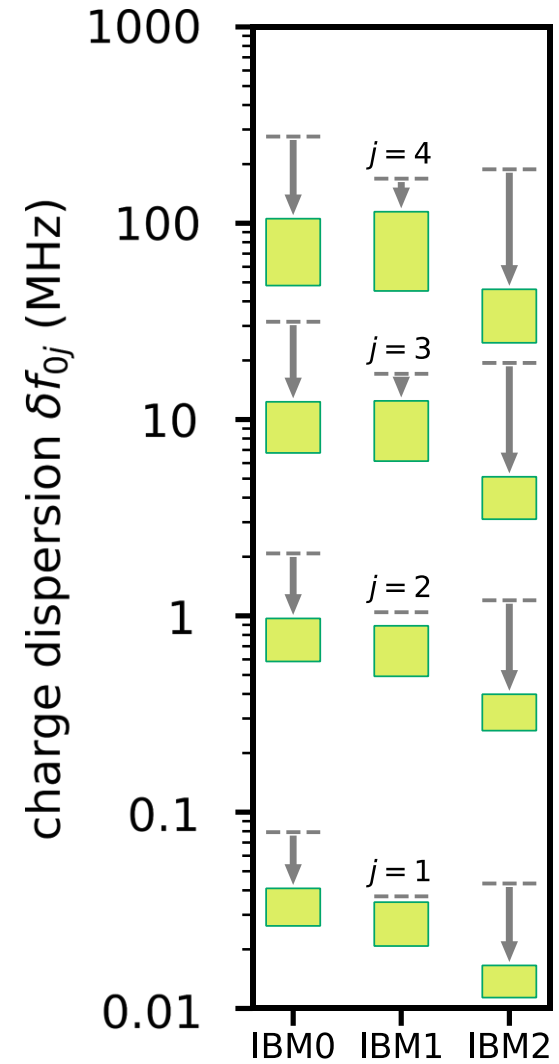
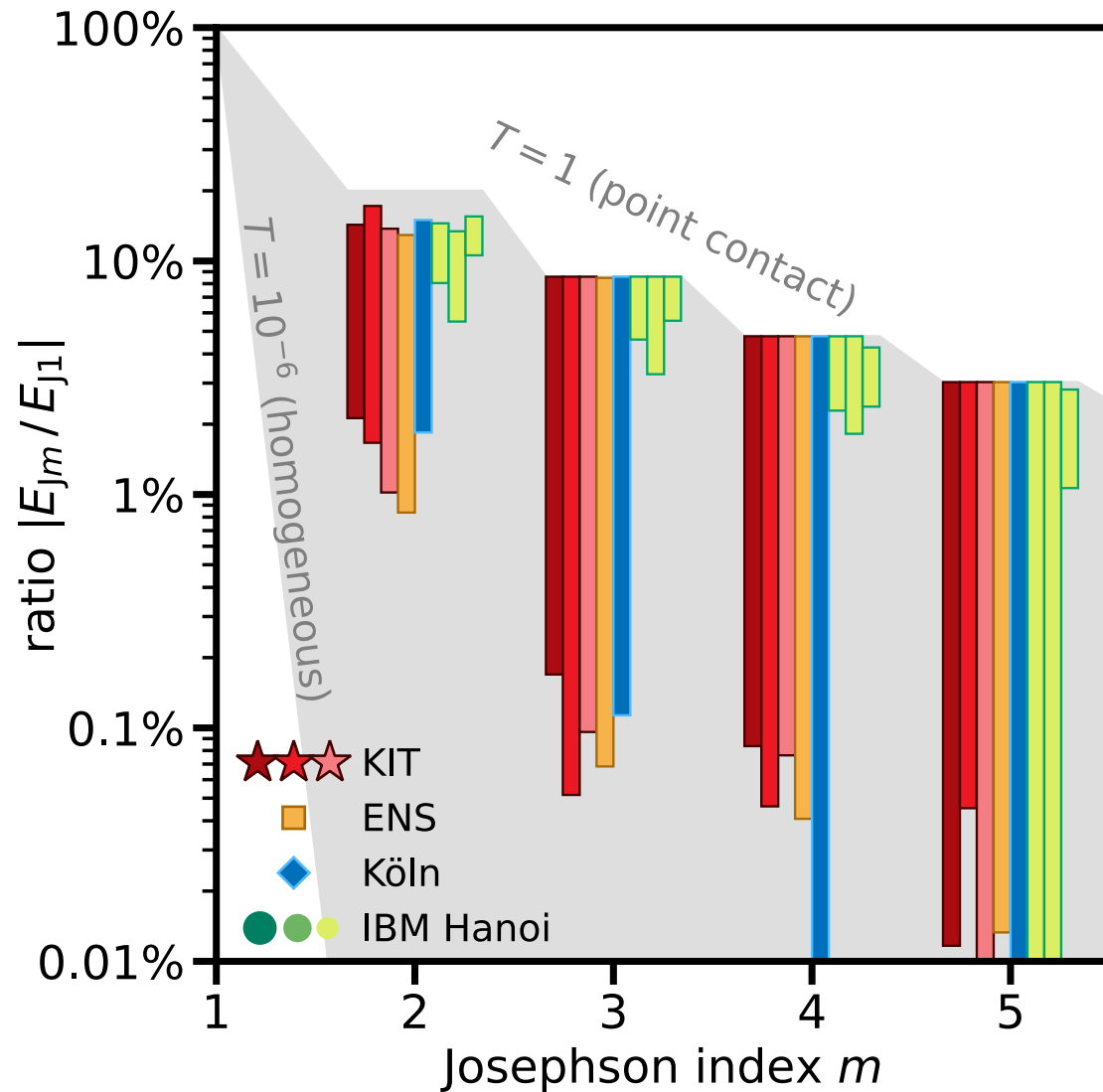


Dickel et al.,
University of Cologne

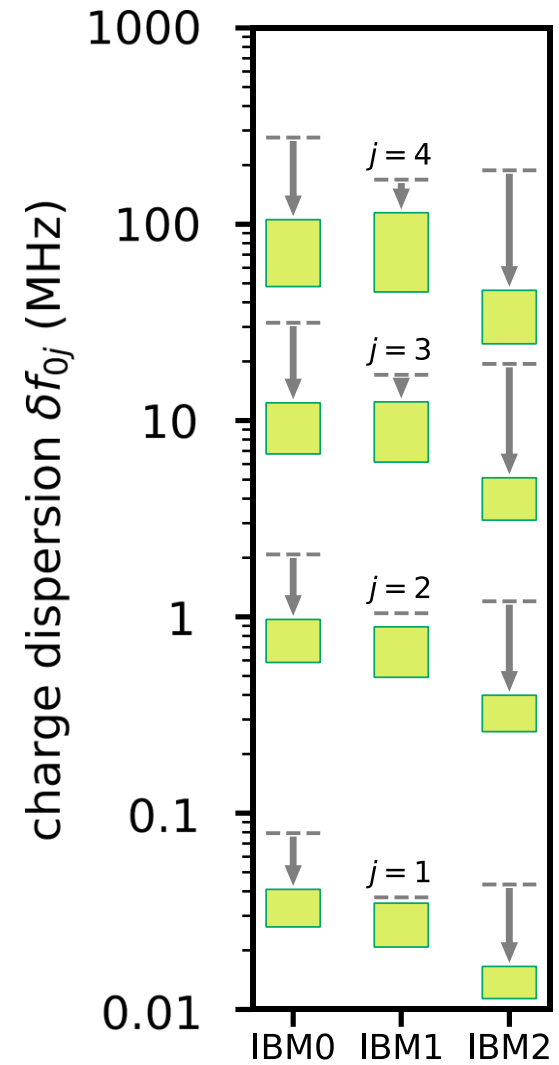
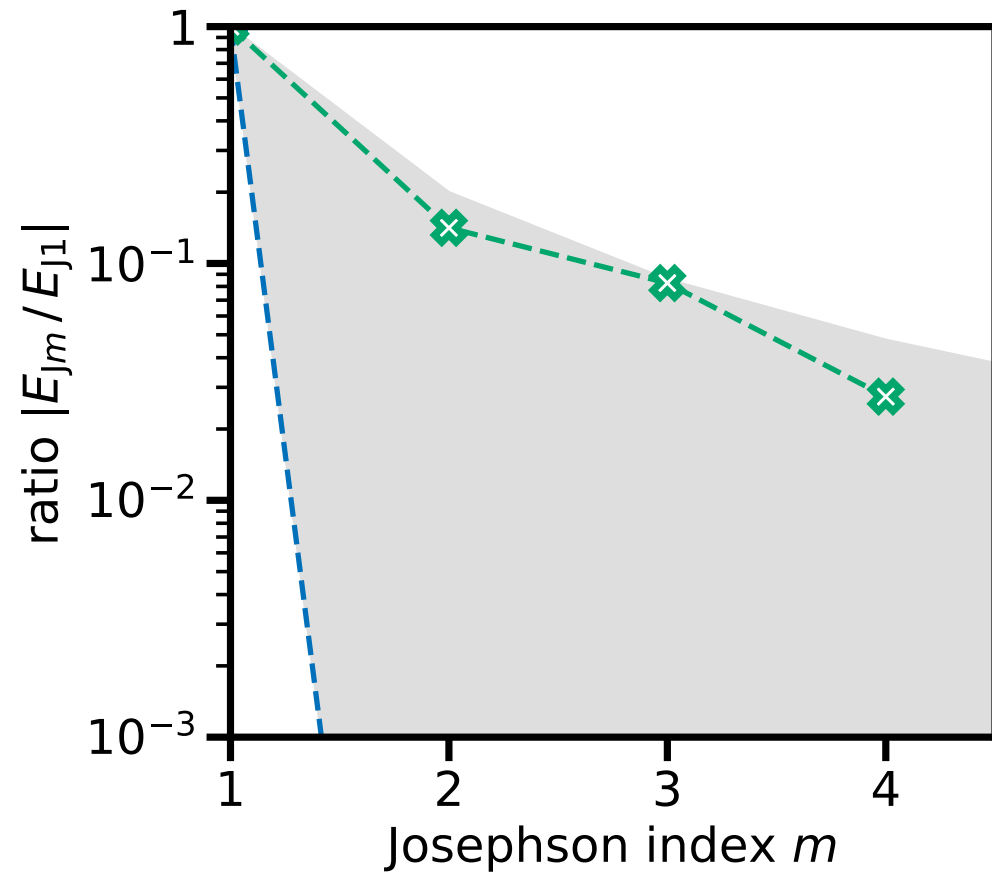
Charge Dispersion: Can also be Reduced with Harmonics!



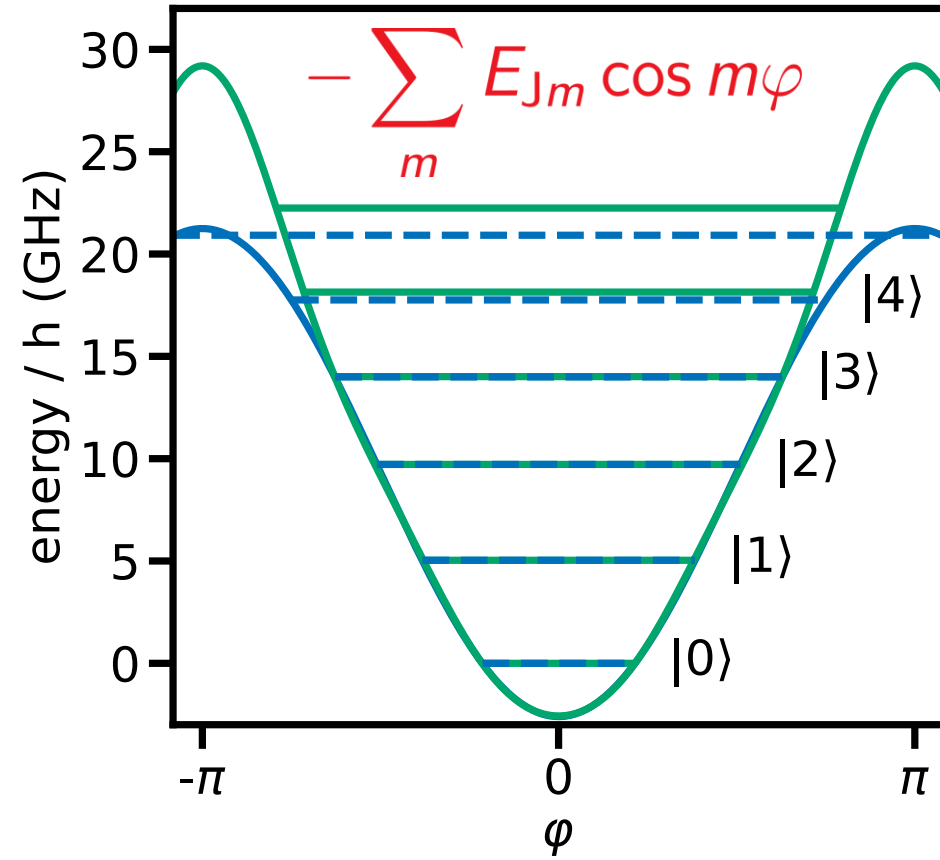
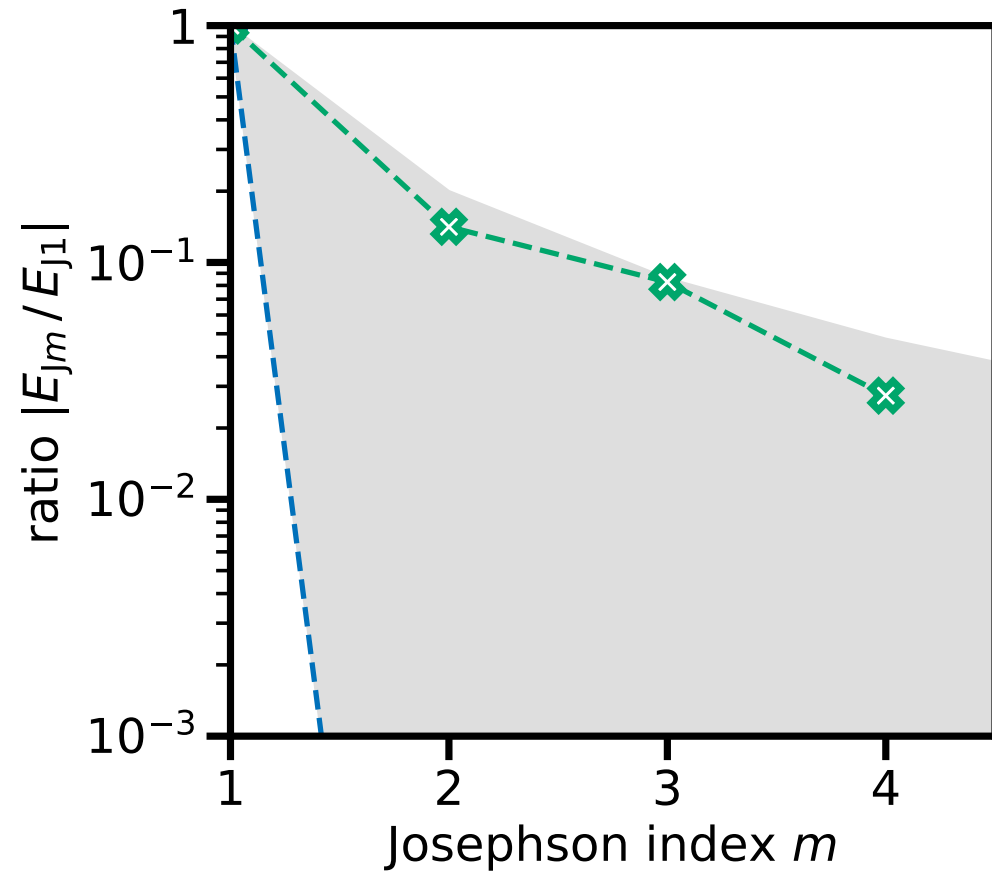
Charge Dispersion: Can also be Reduced with Harmonics!



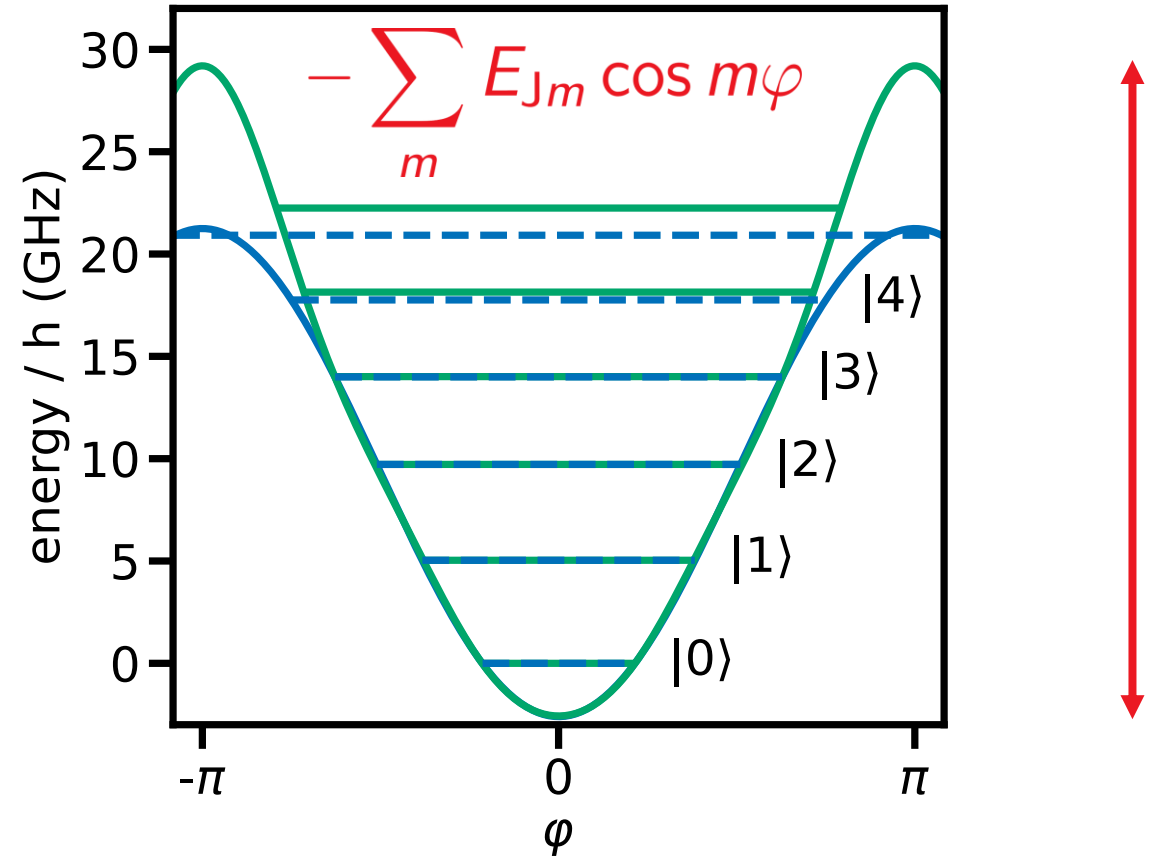
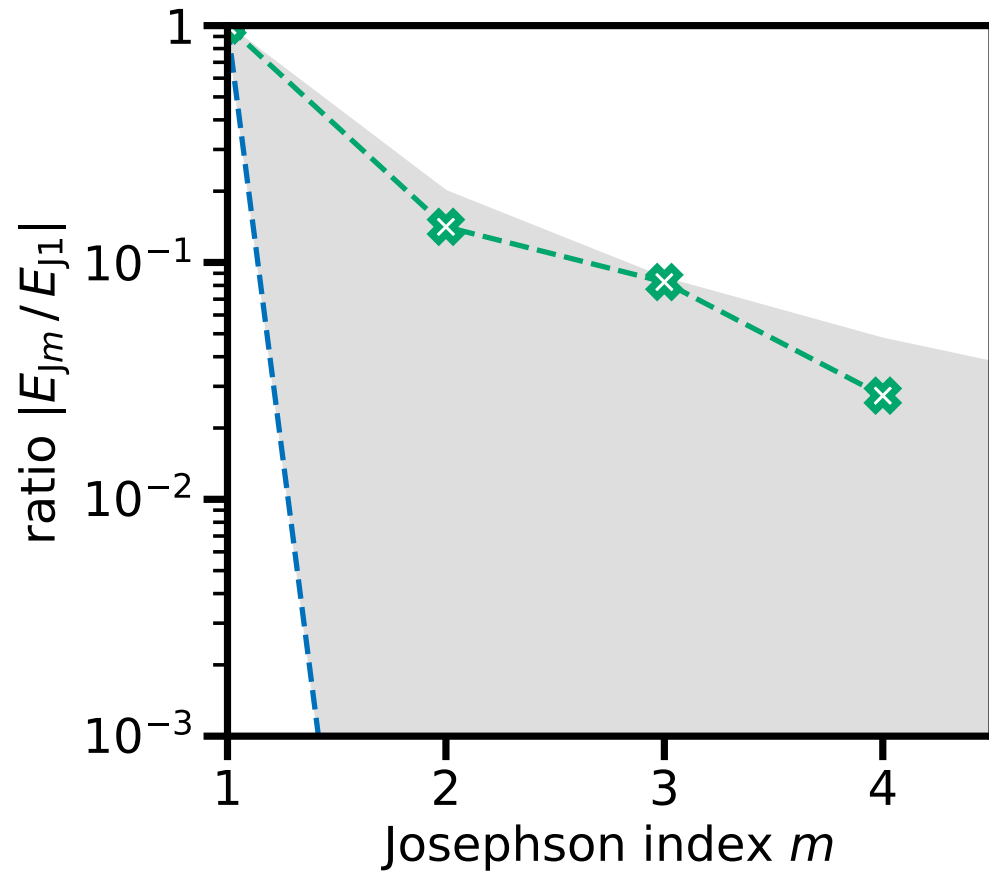
Reason for Reduced Charge Dispersion



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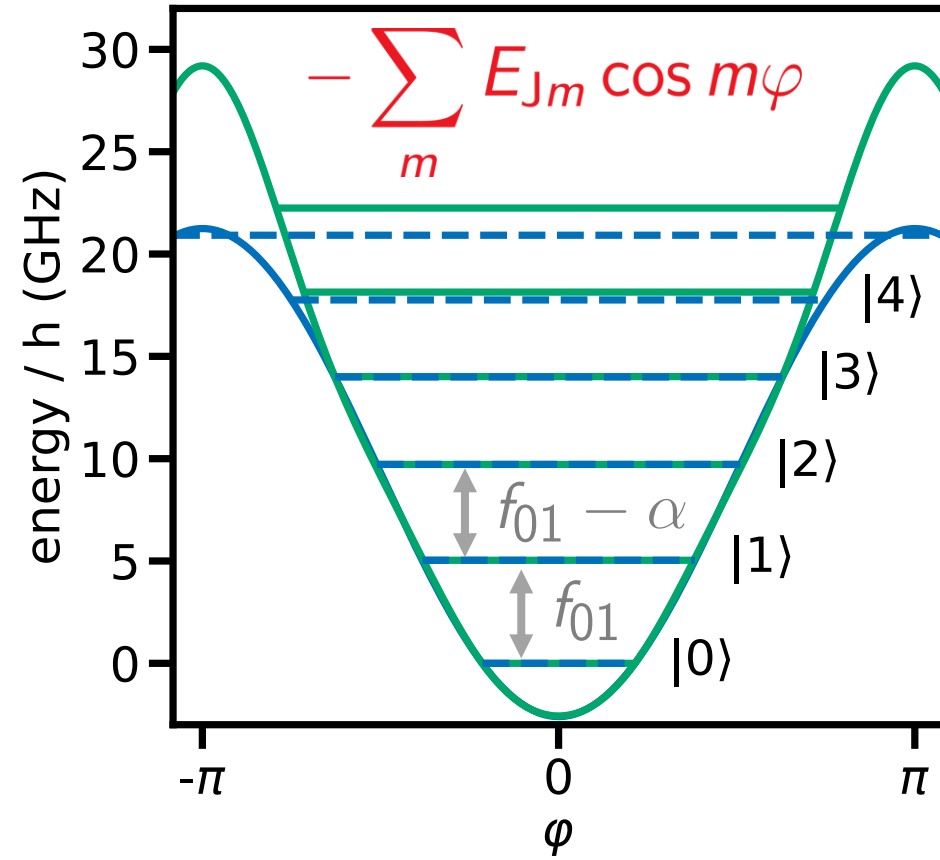
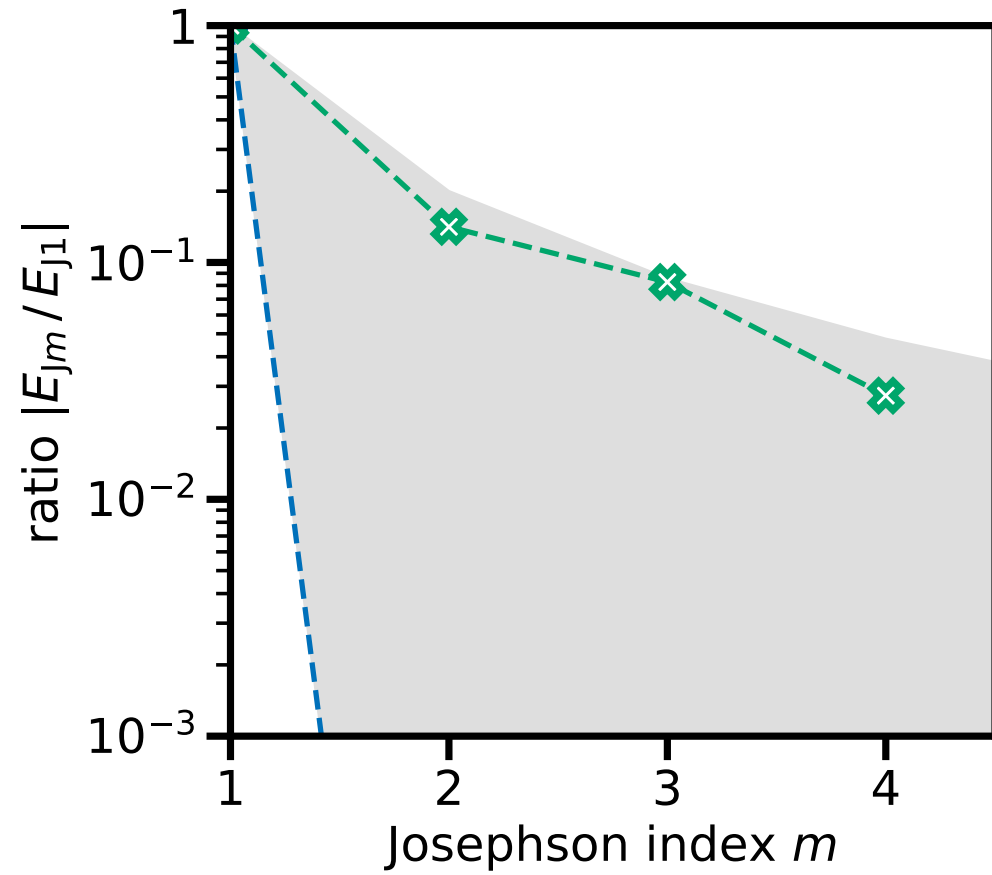


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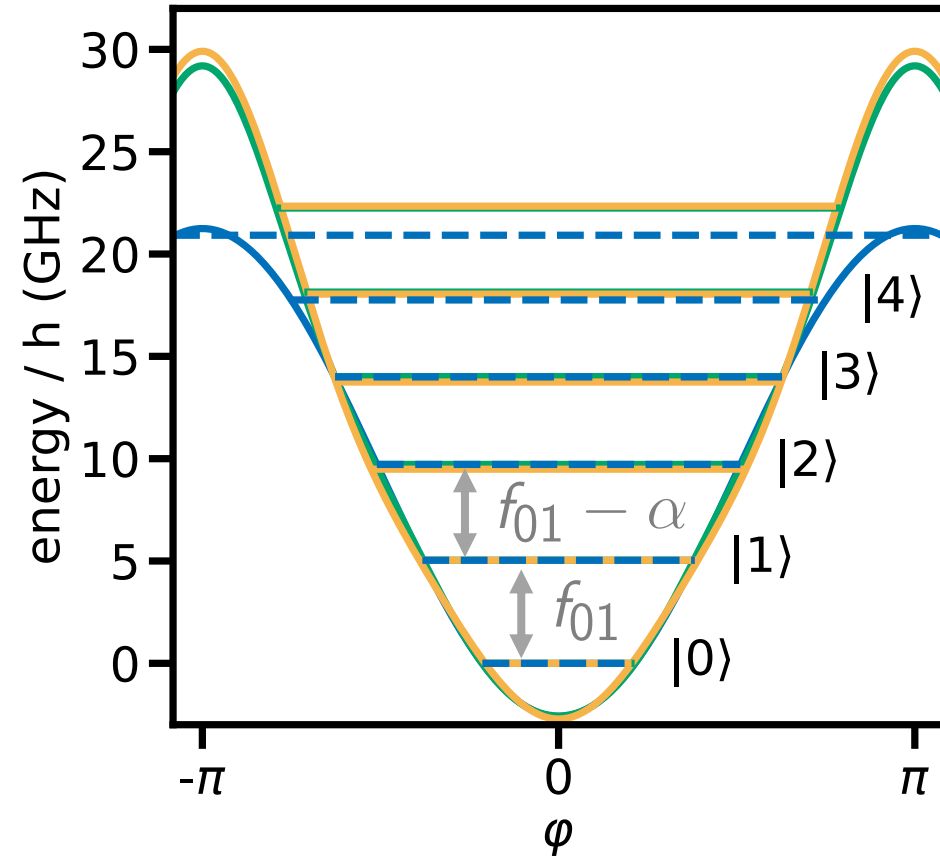
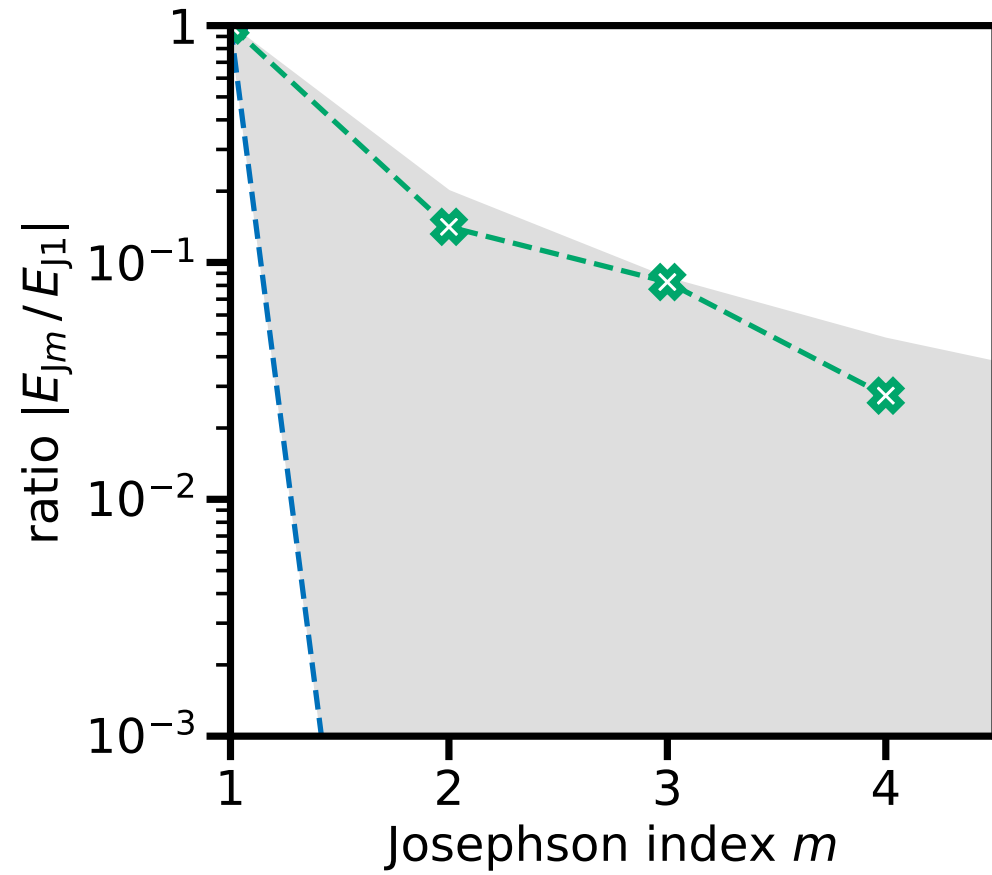


Height: $2(E_{J1} + E_{J3} + E_{J5} + \dots)$

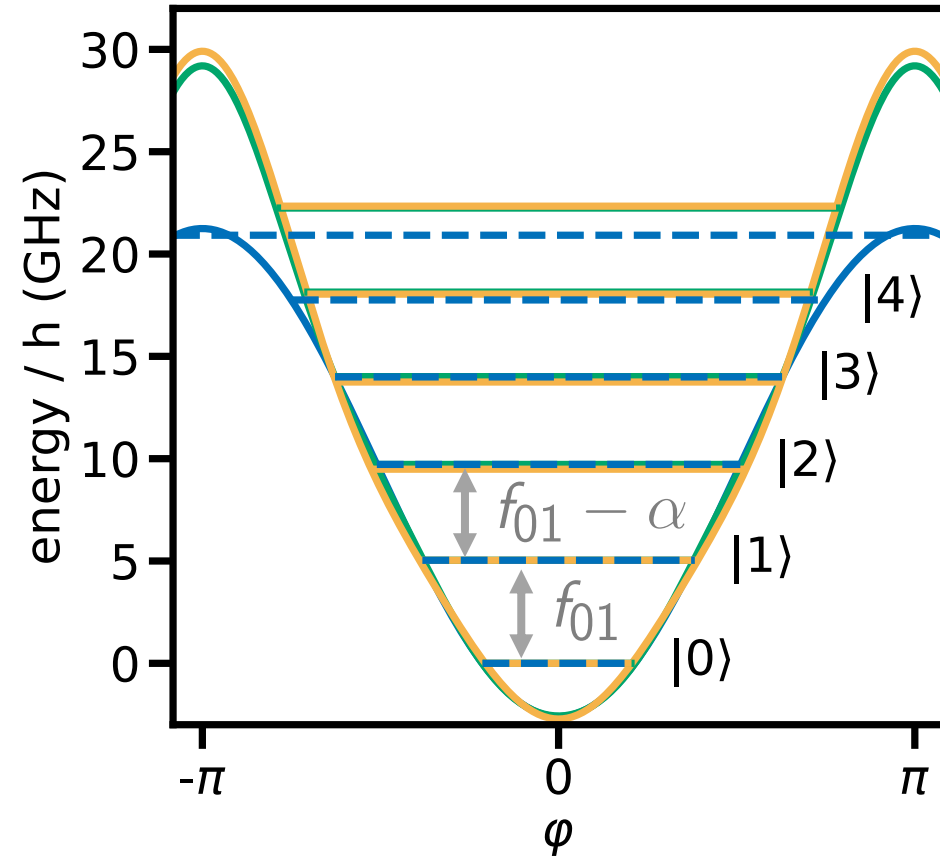
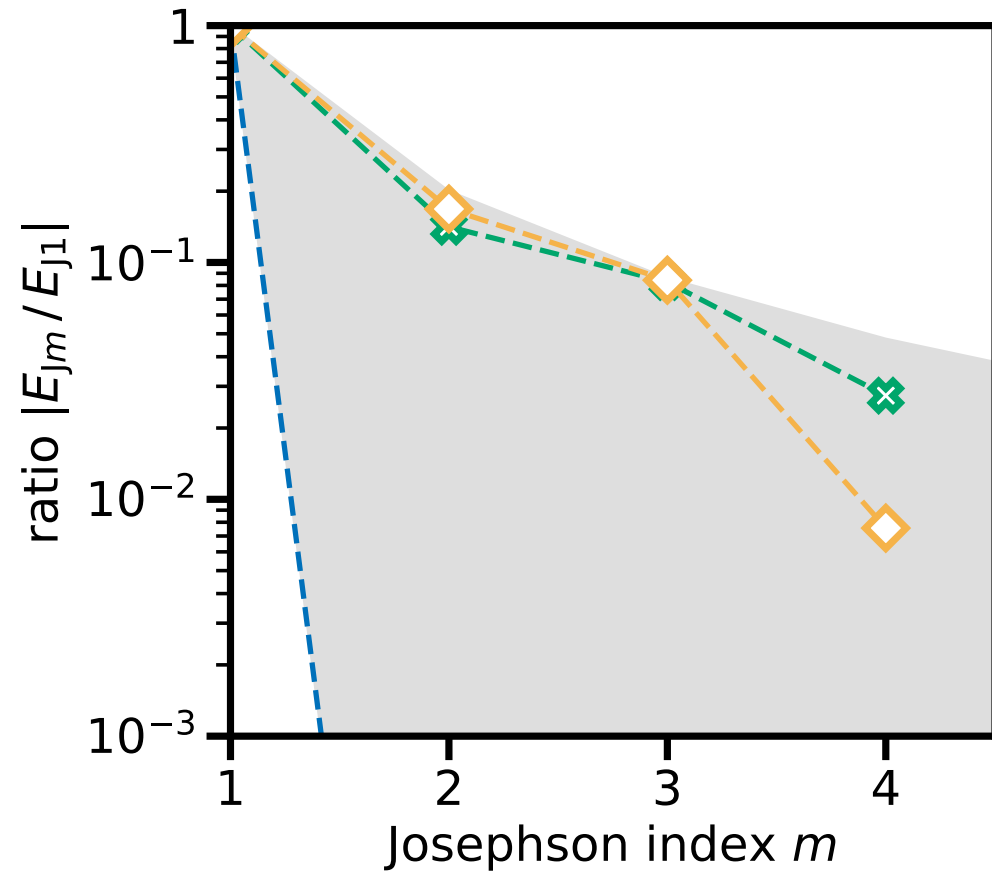
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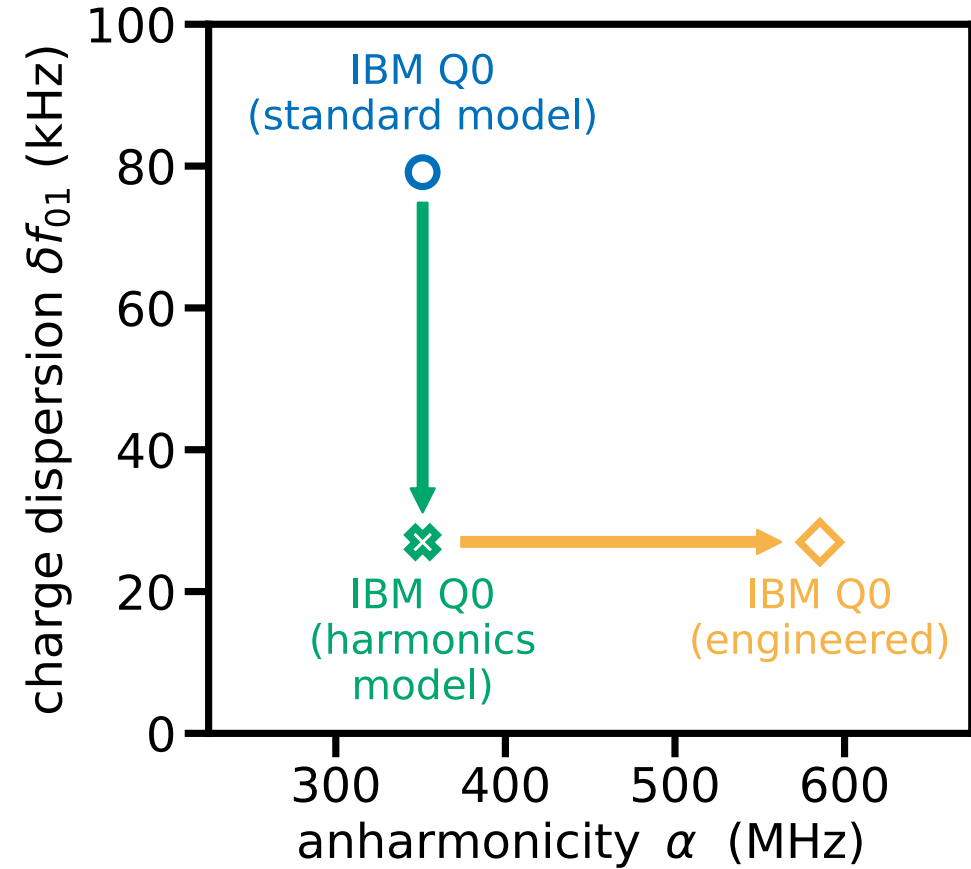
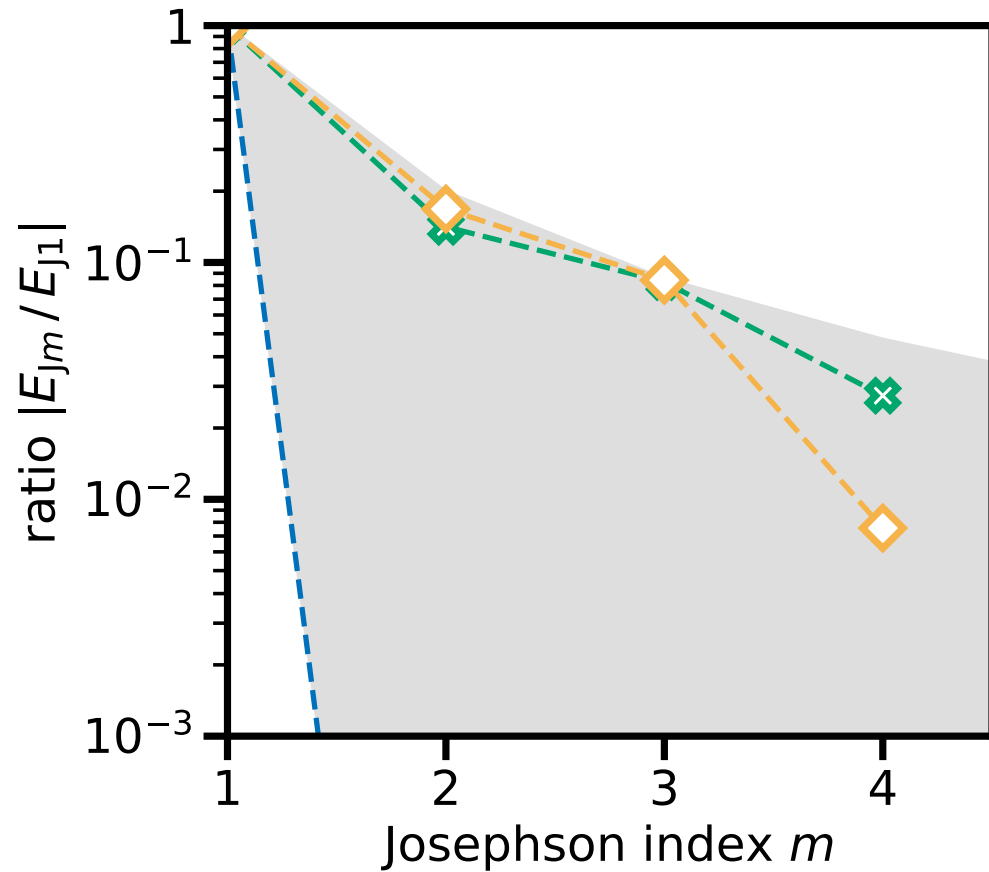
Engineering Harmonics: Can We Go Further?



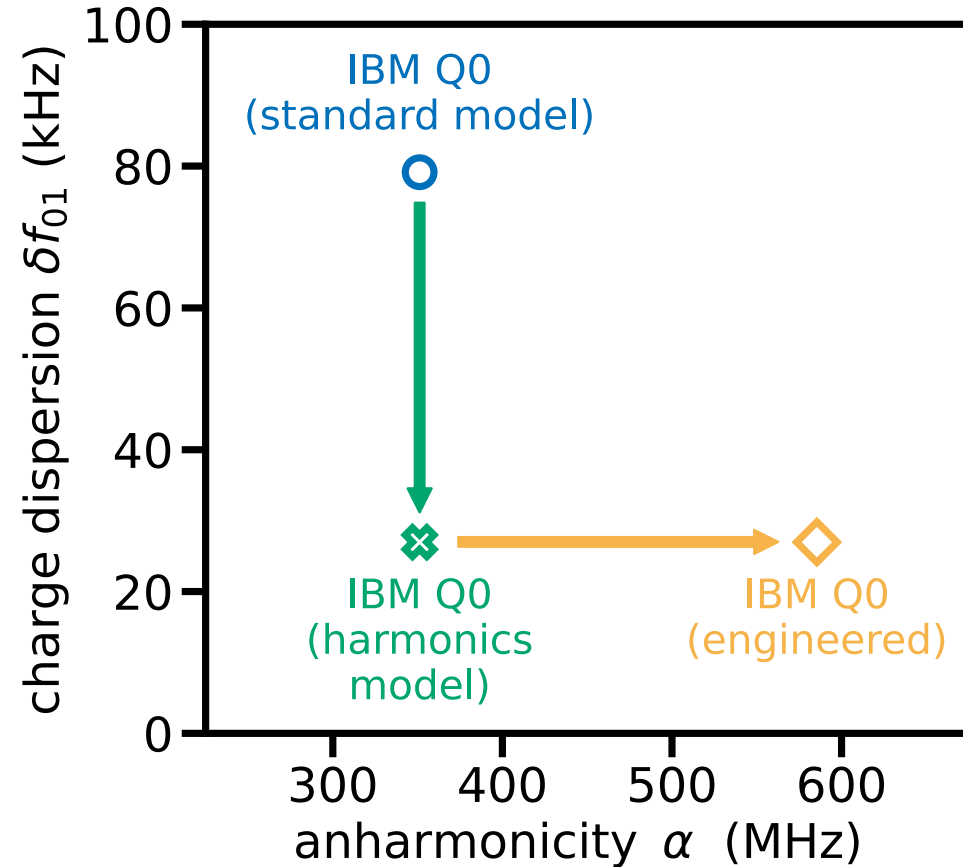
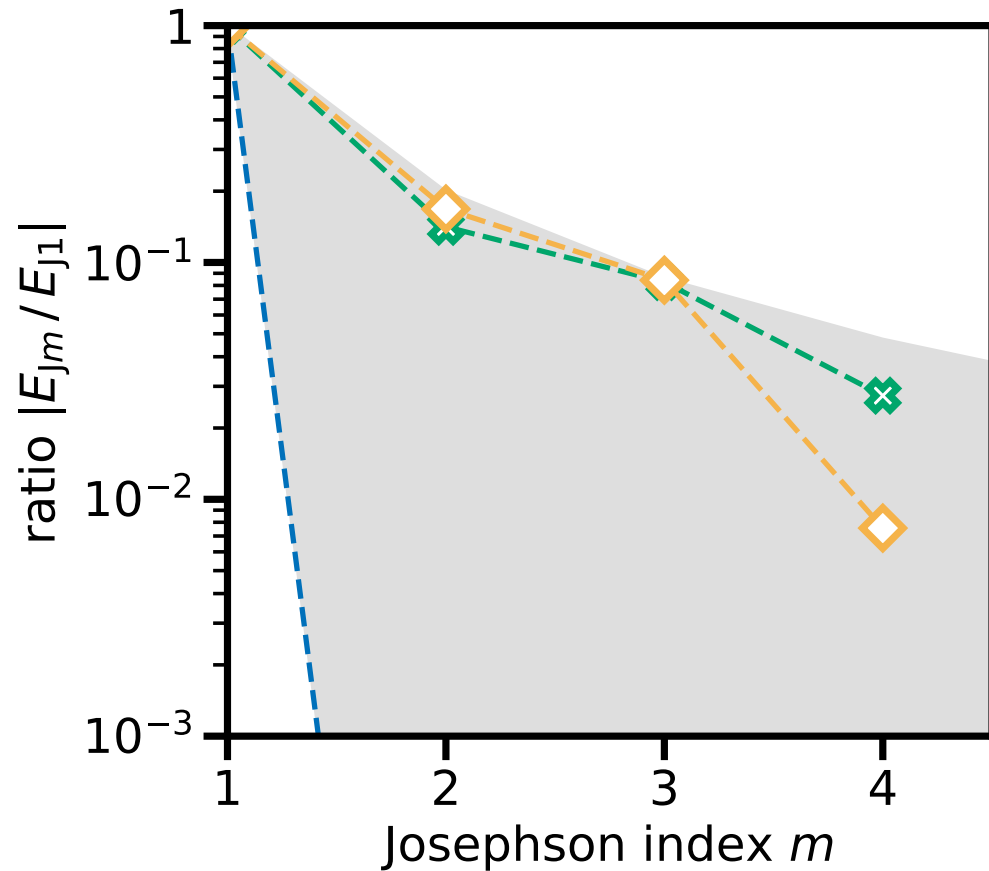
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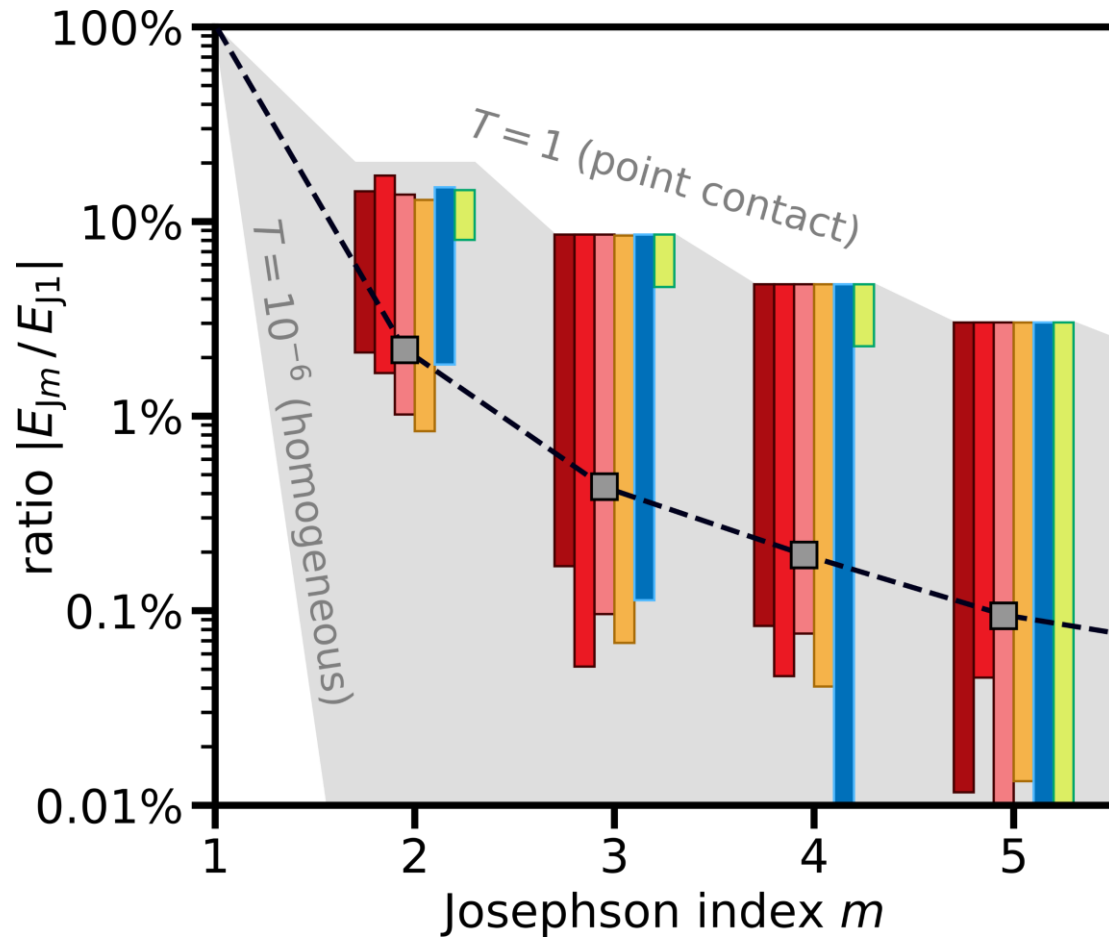


Engineering Harmonics: Can We Go Further?



How? → shaping transparencies, adding inductive elements, flux bias, JJ networks, ...

Observation of Josephson Harmonics in Tunnel Junctions



Inclusion of harmonics in
established models

Engineer and harness
Josephson harmonics