# Possible Field Dependence of Superconducting Properties in N-Doped Cavities

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# Outline

- Deconvolution of $R_{res}$ and $R_{BCS}$
- Fitting of field dependent data:
  - Exponential fitting
  - BCS fitting with SRIMP
  - Fitting with Xiao code
- Magnetic Field Studies
- Conclusions

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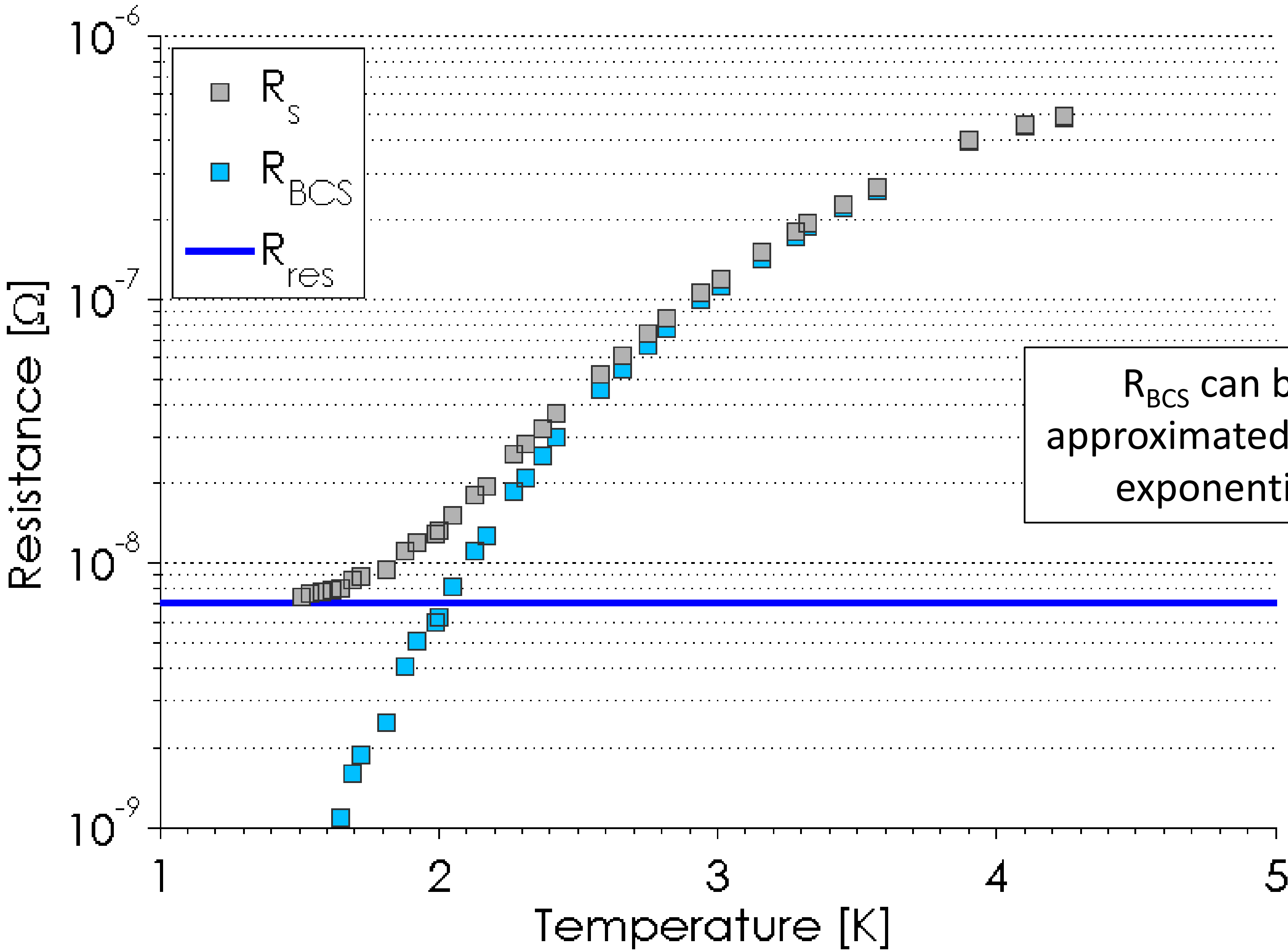
# Surface Resistance



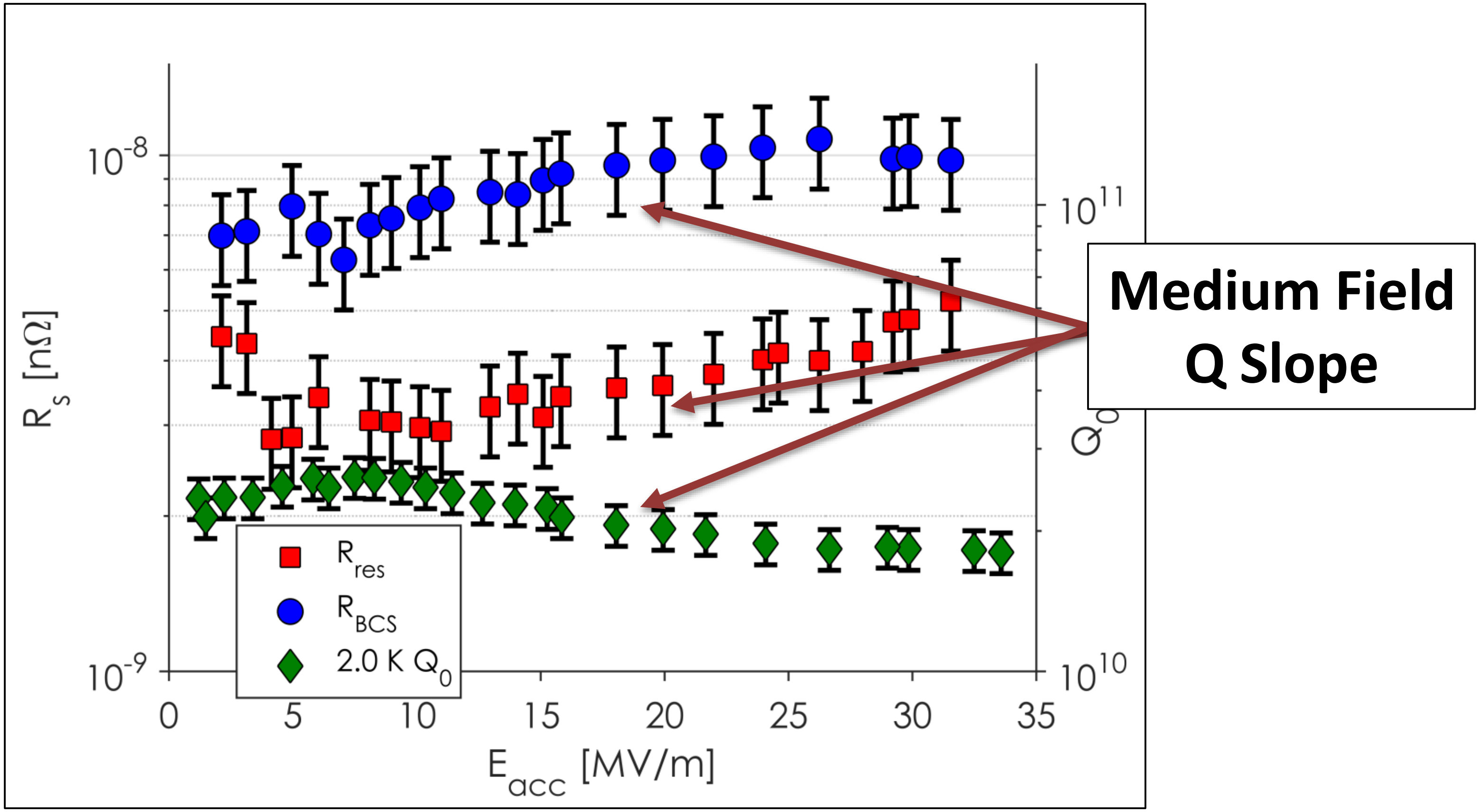

$R_{BCS}$ can be approximated as an exponential

# Deconvolution of $R_{res}$ and $R_{BCS}$

Both $R_{res}$ and $R_{BCS}$ have been shown to be field dependent:

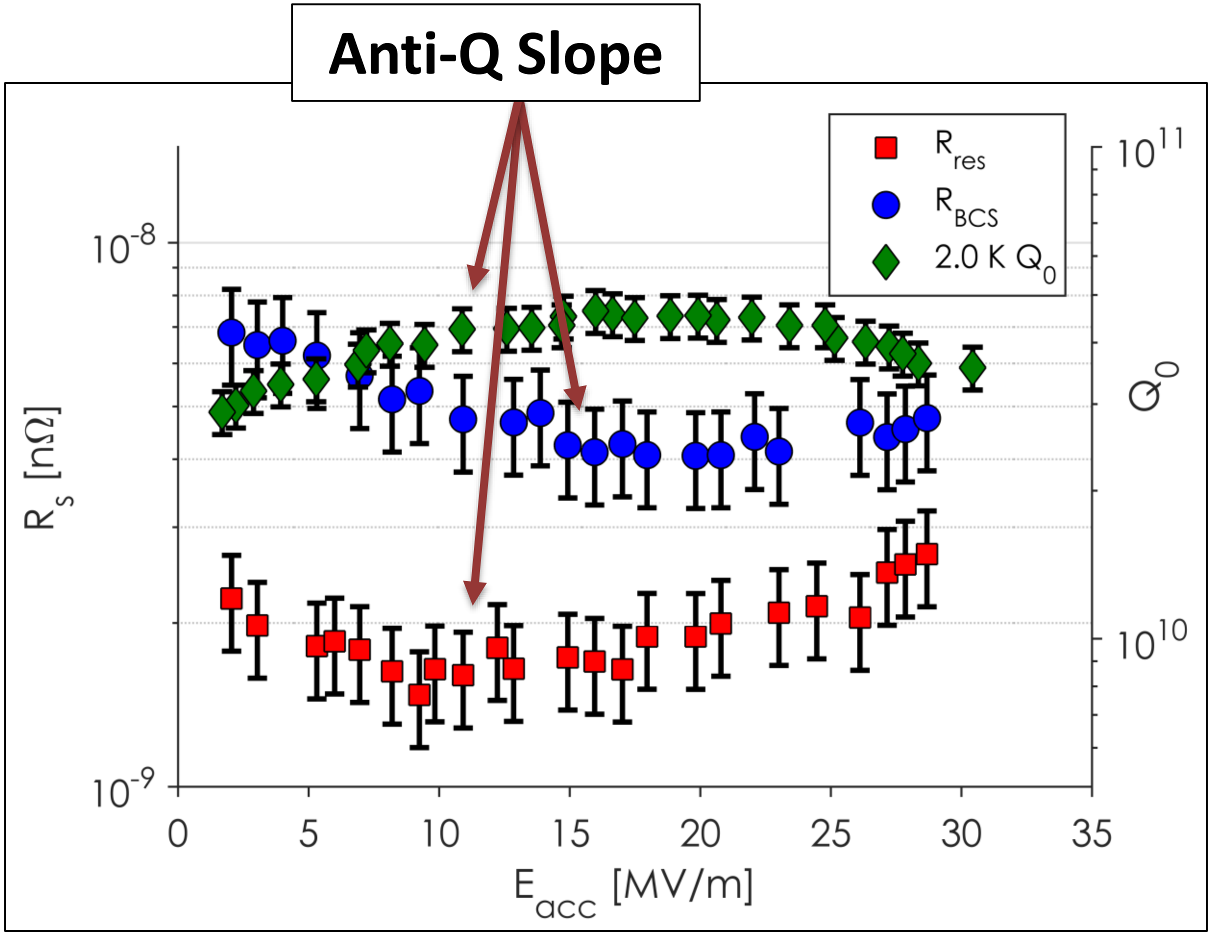
$$R_s = R_{res}(E_{acc}) + R_{BCS}(E_{acc}, T)$$

# Deconvolution in 120°C Cavities




**Medium field Q slope caused by a combination of increasing residual and BCS resistances in 120°C baked cavities**

# Deconvolution in N-Doped Cavities




**Anti-Q slope caused by a decreasing BCS resistance in N-Doped Cavities**

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# Exponential Fitting

The usual BCS equation for fitting:

$$R_{BCS} = \frac{A}{T} e^{-\epsilon/k_B T}$$

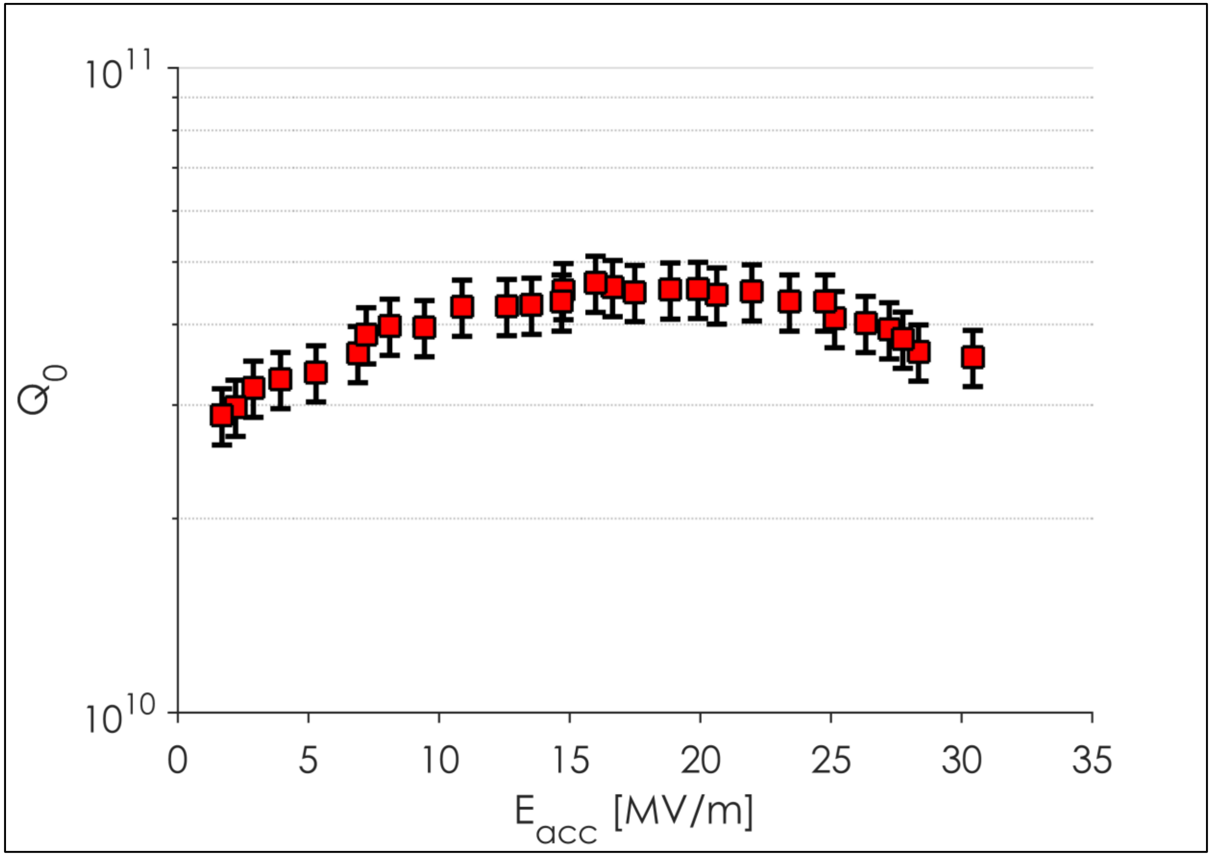
Both A and ε can vary with $E_{acc}$ however fitting both together leads to sloppy fitting.

$$R_{BCS} = \frac{A(E_{acc})}{T} e^{-\epsilon/k_B T}$$

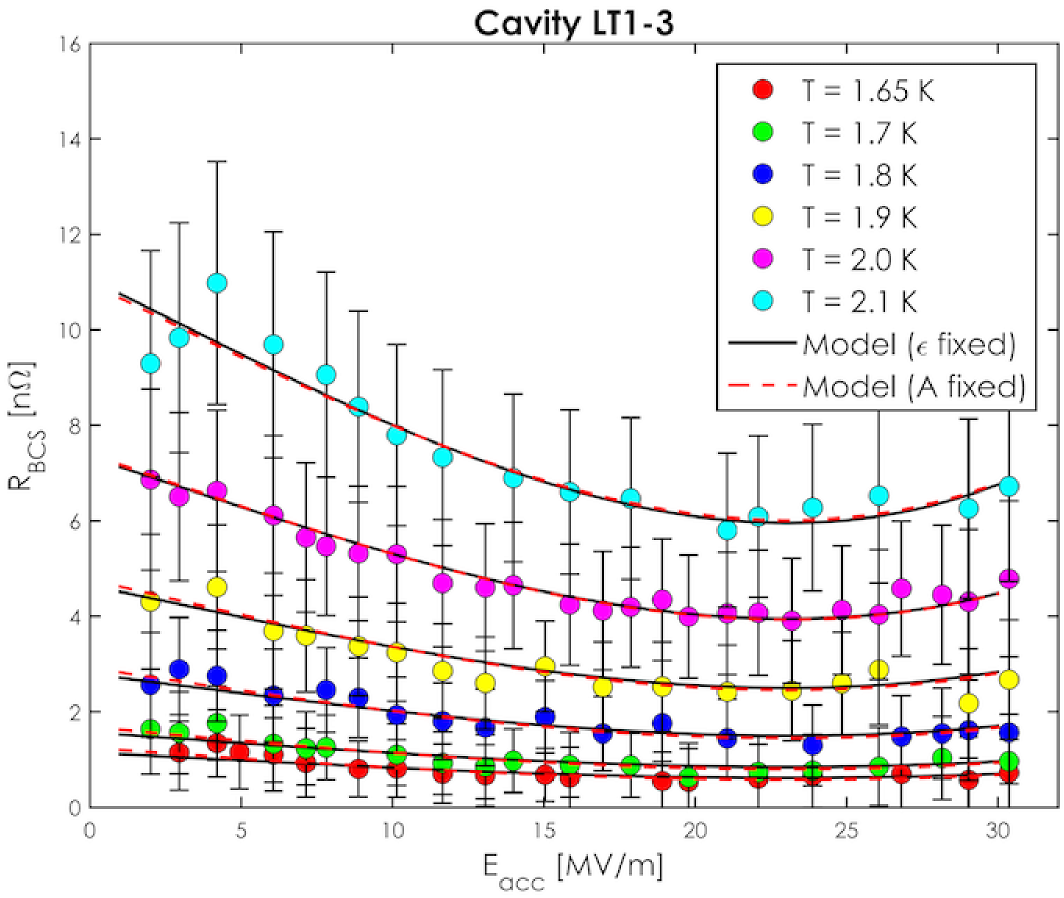
$$R_{BCS} = \frac{A}{T} e^{-\epsilon(E_{acc})/k_B T}$$

# Cavity LT1-3

1.3 GHz Single Cell ILC shaped cavity: bulk VEP, 800°C bake in vacuum for 3 hours, 20 min in 60 mTorr of $N_2$ for 20 minutes, 30 minute anneal, 12 μm VEP

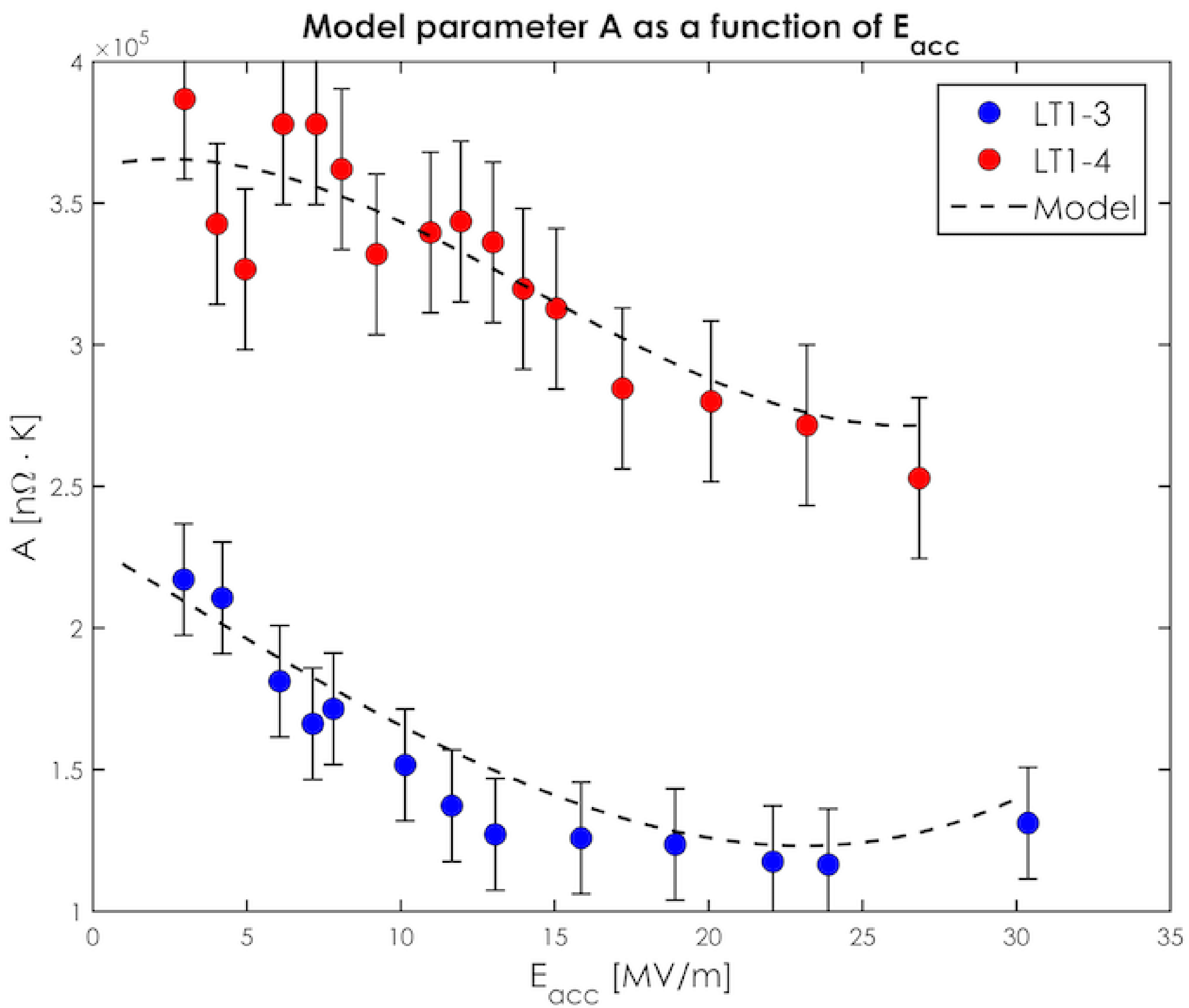


# Exponential Fitting

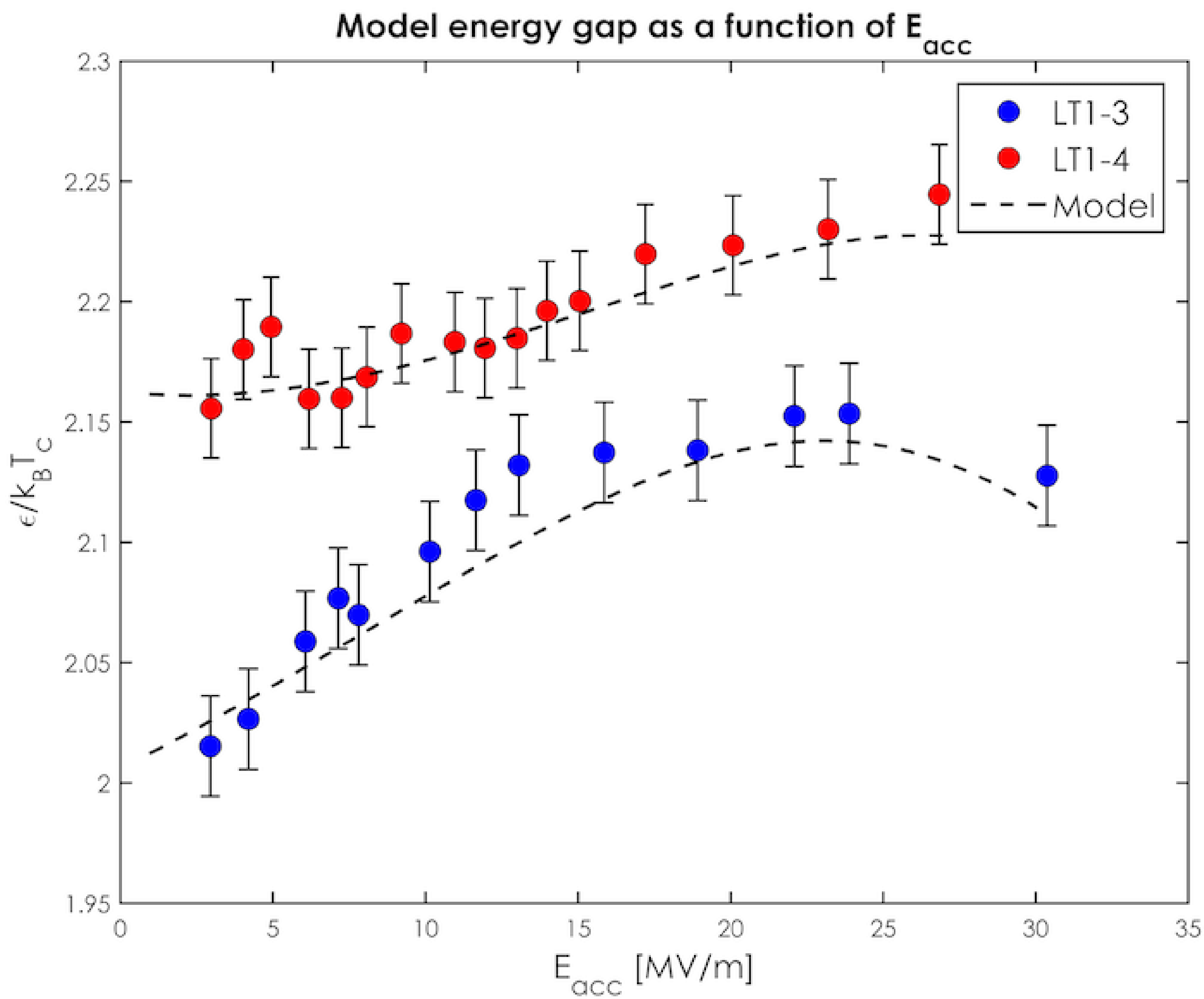



Both models can fit the $R_{BCS}$ data well in the anti-Q slope region

# Exponential Fitting



# Exponential Fitting



# Exponential Fitting

- Fits with both A and ε field dependent are sloppy
- Individual fits however can fit $R_{BCS}$ vs $E_{acc}$ data very well
- A decreasing A with field or an increasing ε can explain the anti-Q slope observed in N-doped cavities

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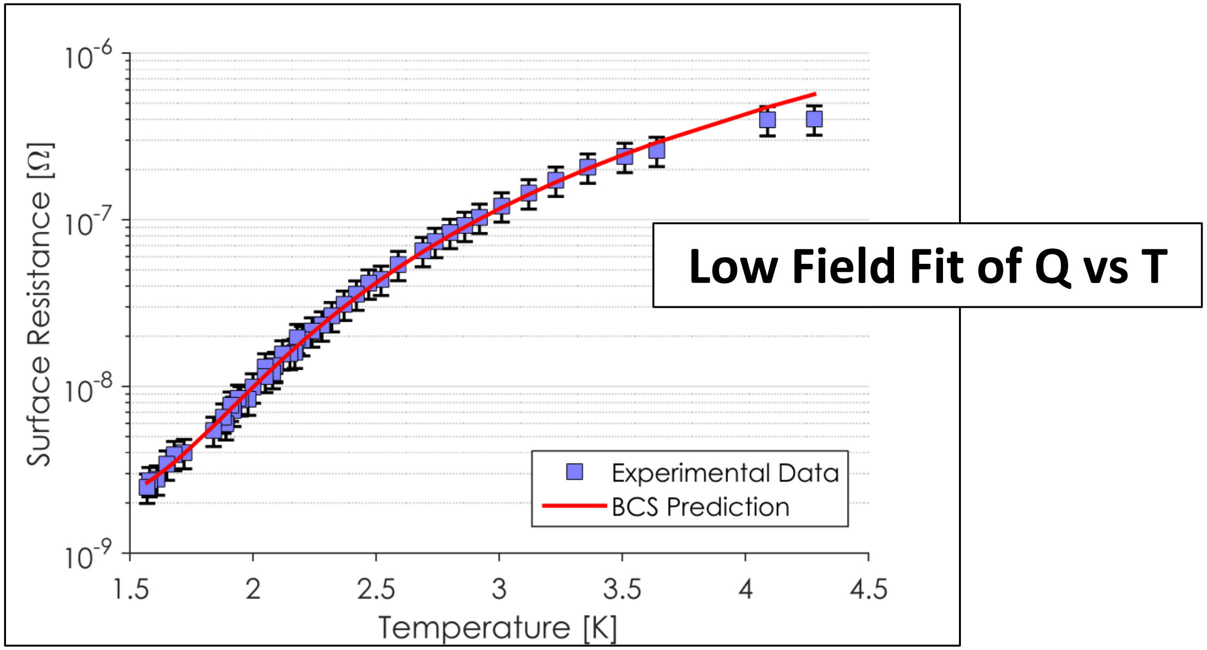
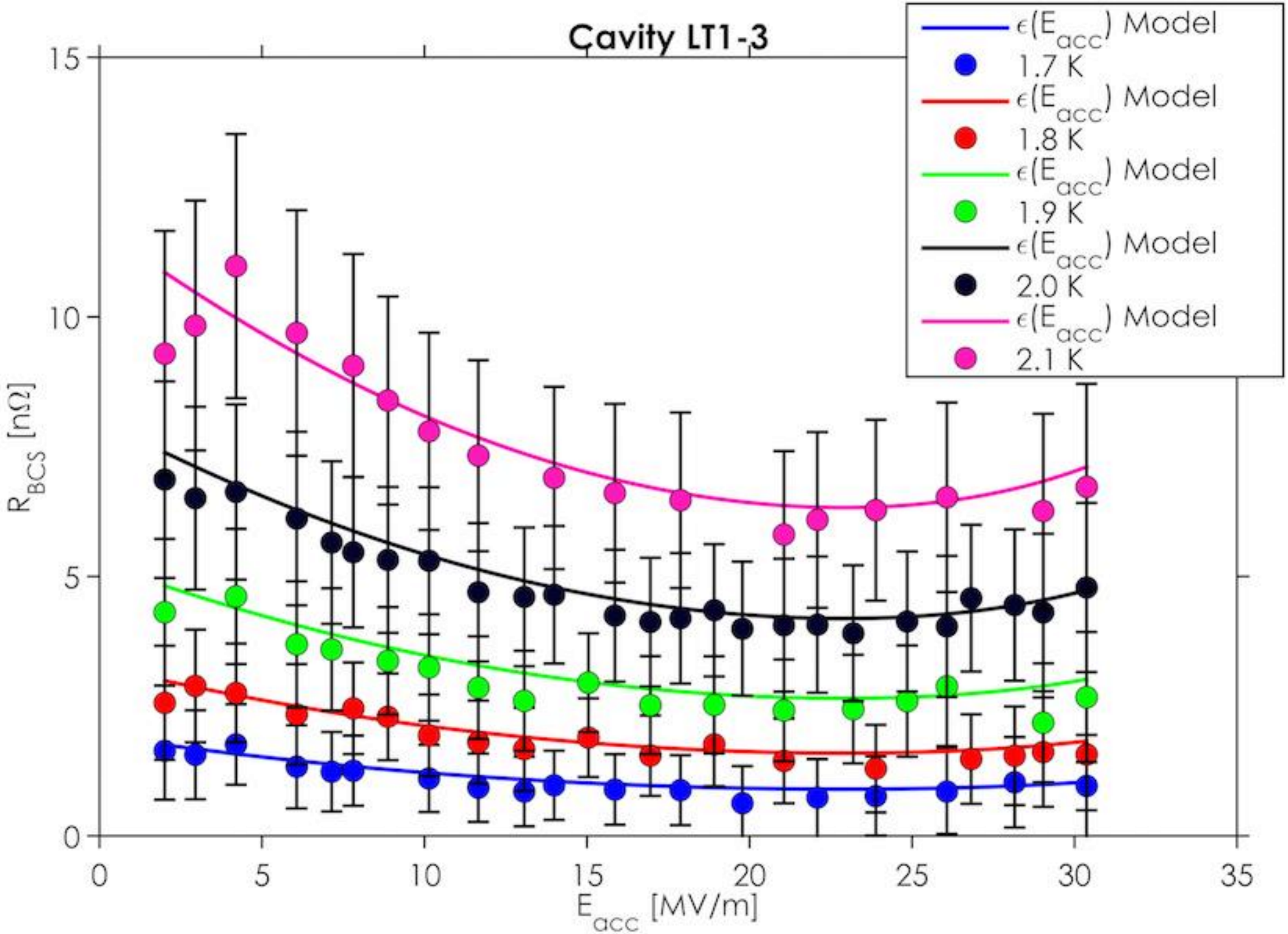
# BCS Fitting with SRIMP

- SRIMP, a code written by Halbritter, can be used to calculate $R_{BCS}$ based on material parameters
  - $T_c$, Mean Free Path, $\varepsilon/k_BT_c$, coherence length, and penetration depth

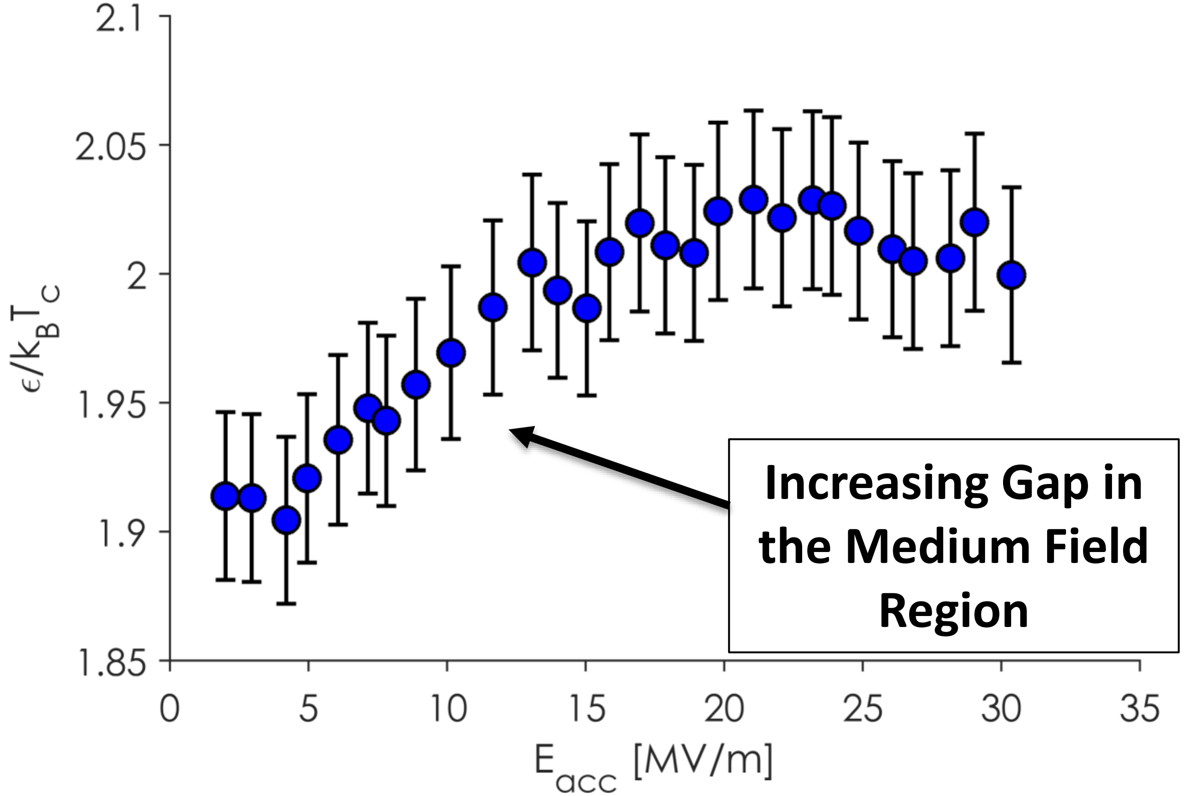


# BCS Fitting with SRIMP



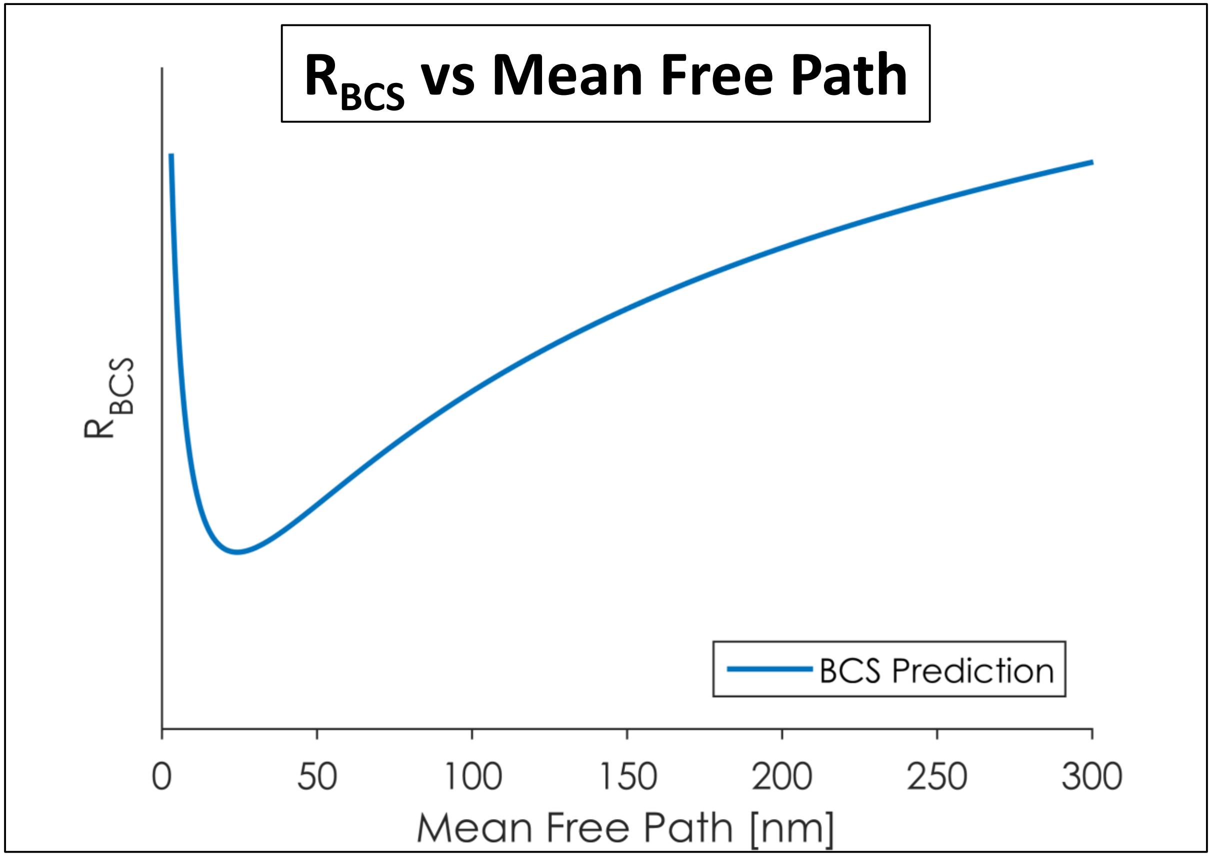
# BCS Fitting with SRIMP

**Energy Gap vs $E_{acc}$**

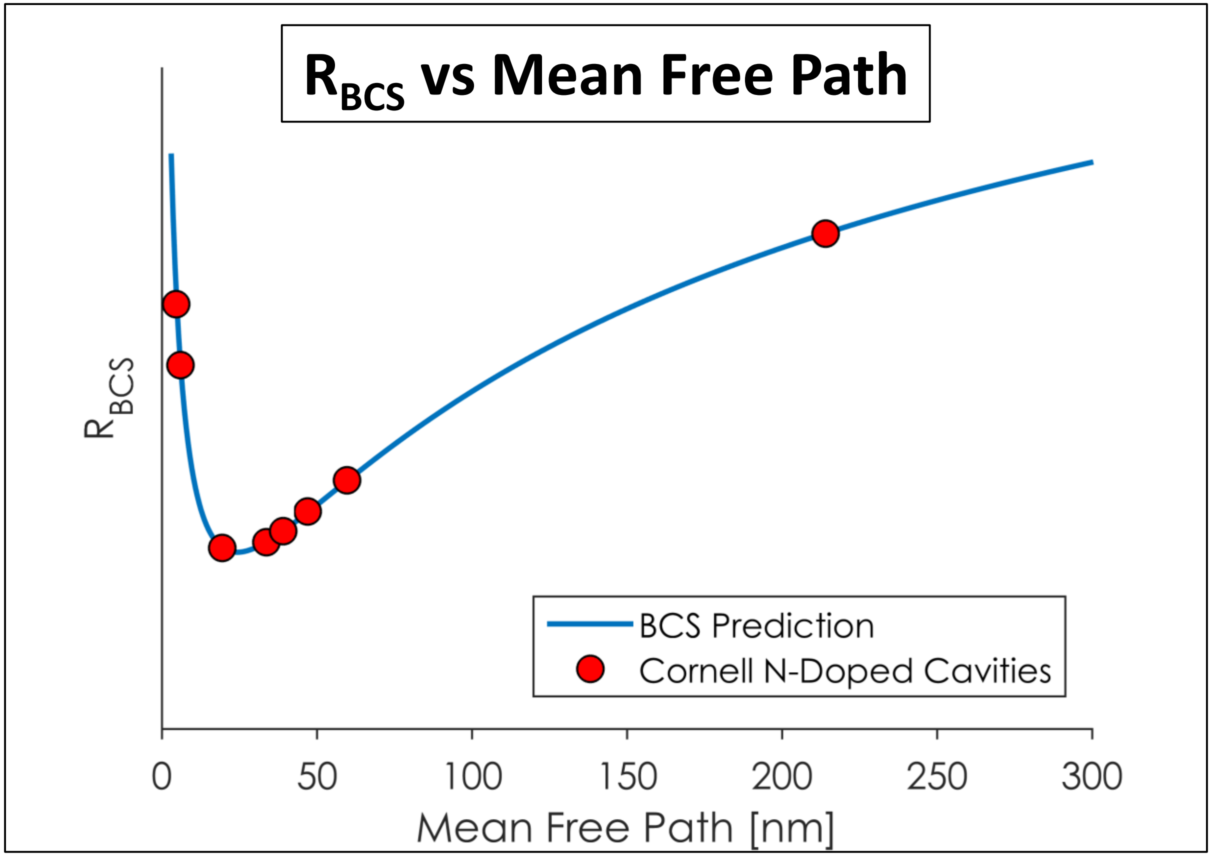



**Increasing Gap in the Medium Field Region**

# BCS Fitting with SRIMP



# BCS Fitting with SRIMP




- N-Doped cavities are on both sides of the $R_{BCS}$ vs Mean free path minimum
- Increasing or decreasing mean free path with field alone cannot explain the anti-Q slope

# BCS Fitting with SRIMP

- Field dependence of BCS resistance in N-Doped cavities is related to the energy gap
- Nitrogen-doped cavities have mean free paths that are on both sides of the $R_{BCS}$ vs mean free path minimum
  - An increasing or decreasing mean free path with accelerating field cannot explain a decreasing BCS resistance in all cavities

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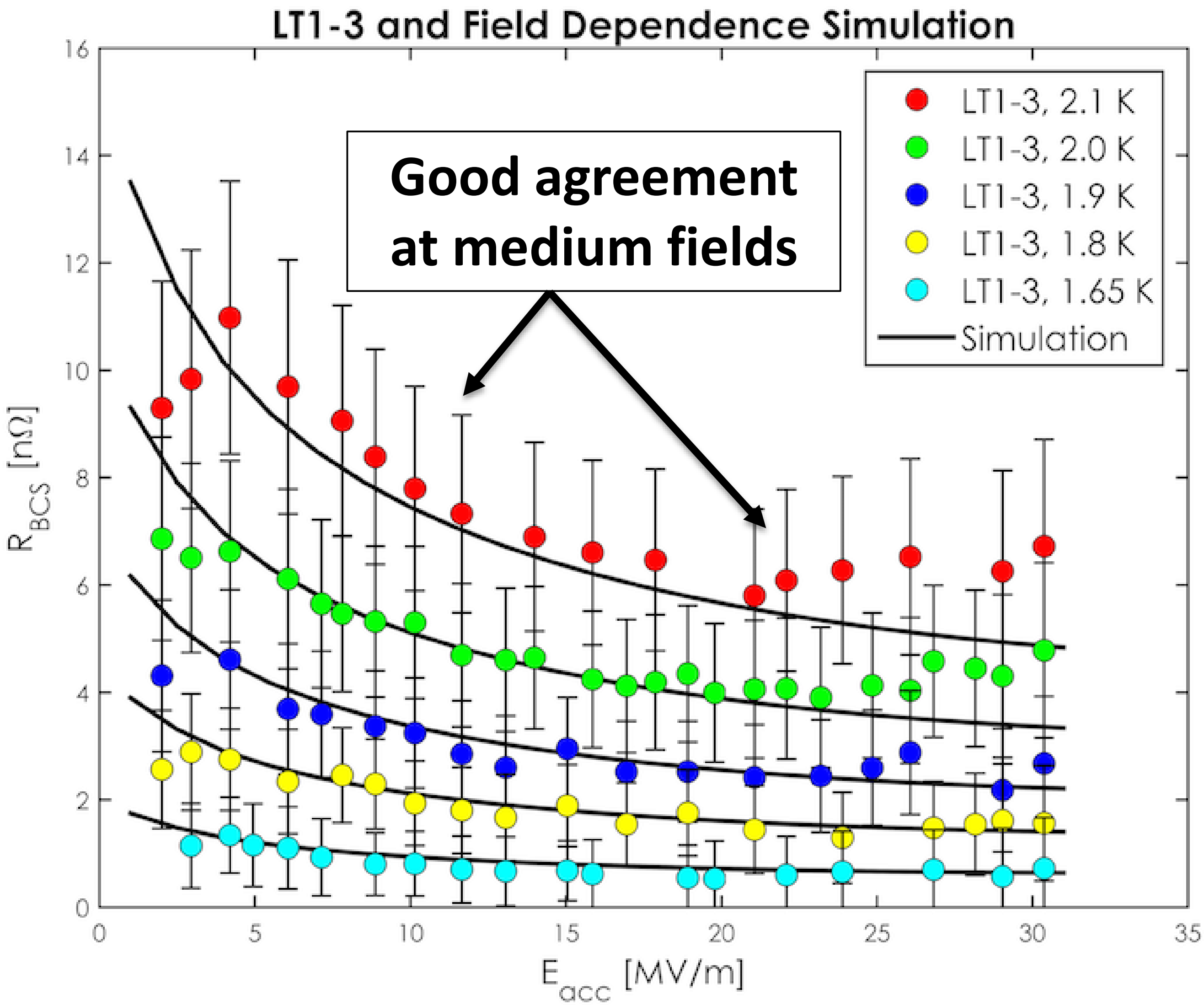
# Fitting with Xiao Code

- Xiao et. al. developed a code to include field dependence in BCS theory using an extension of Mattis-Bardeen theory
- Using low field material parameters obtained from SRIMP fitting, the full field dependence of the BCS resistance can be computed at different temperatures

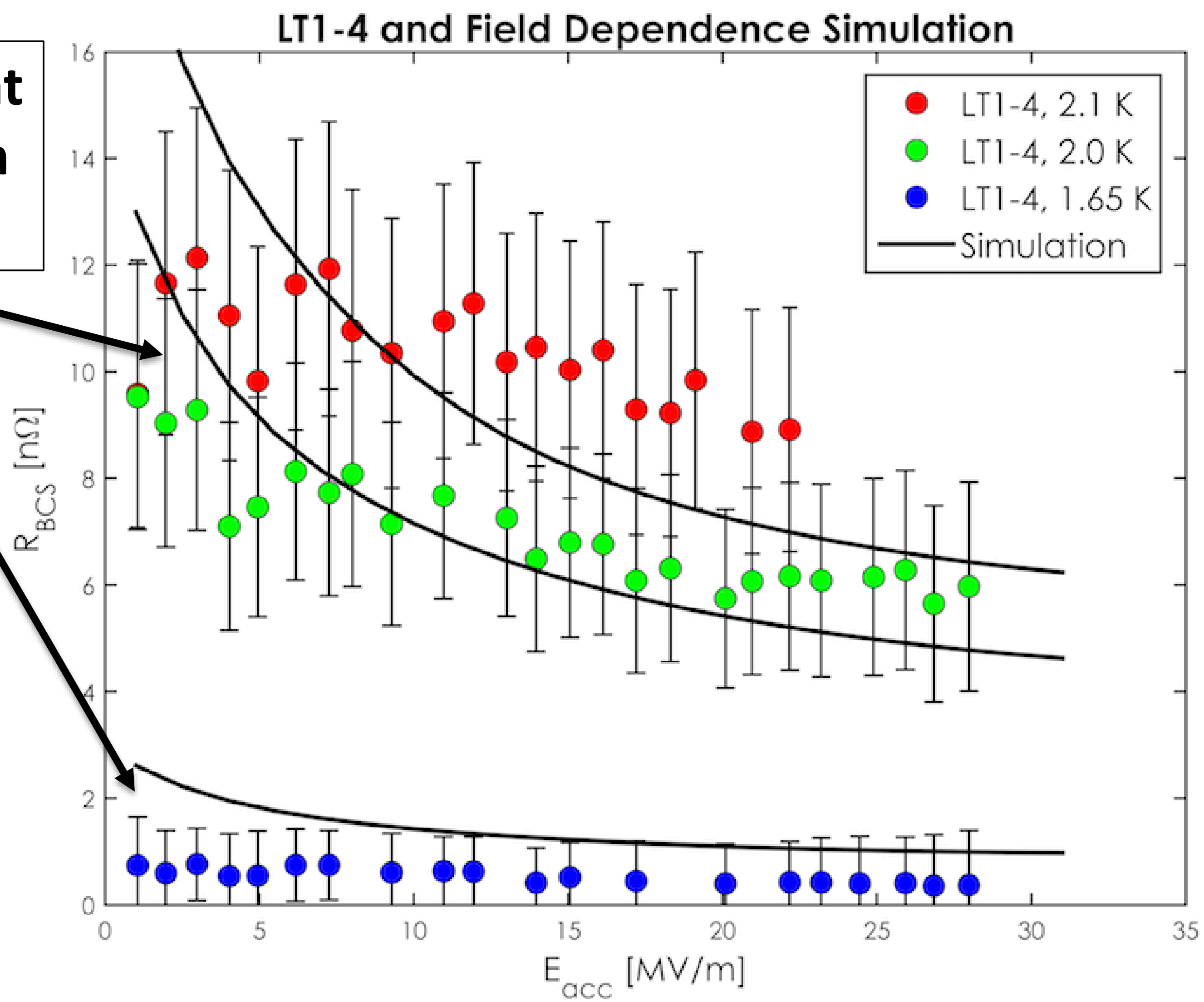
B. P. Xiao et. al. Superconducting surface resistance under radiofrequency field. Physica C, 490(0):26–31, 2013.

# Fitting with Xiao Code



# Fitting with Xiao Code

**Poor agreement at medium and high fields**



# Fitting with Xiao Code

- Xiao code can accurately predict behavior of BCS resistance at medium fields in Nitrogen-doped cavities
- Theory deviates from observed behavior at low fields:
  - The theory predicts a much more drastic increase in BCS resistance than we observe

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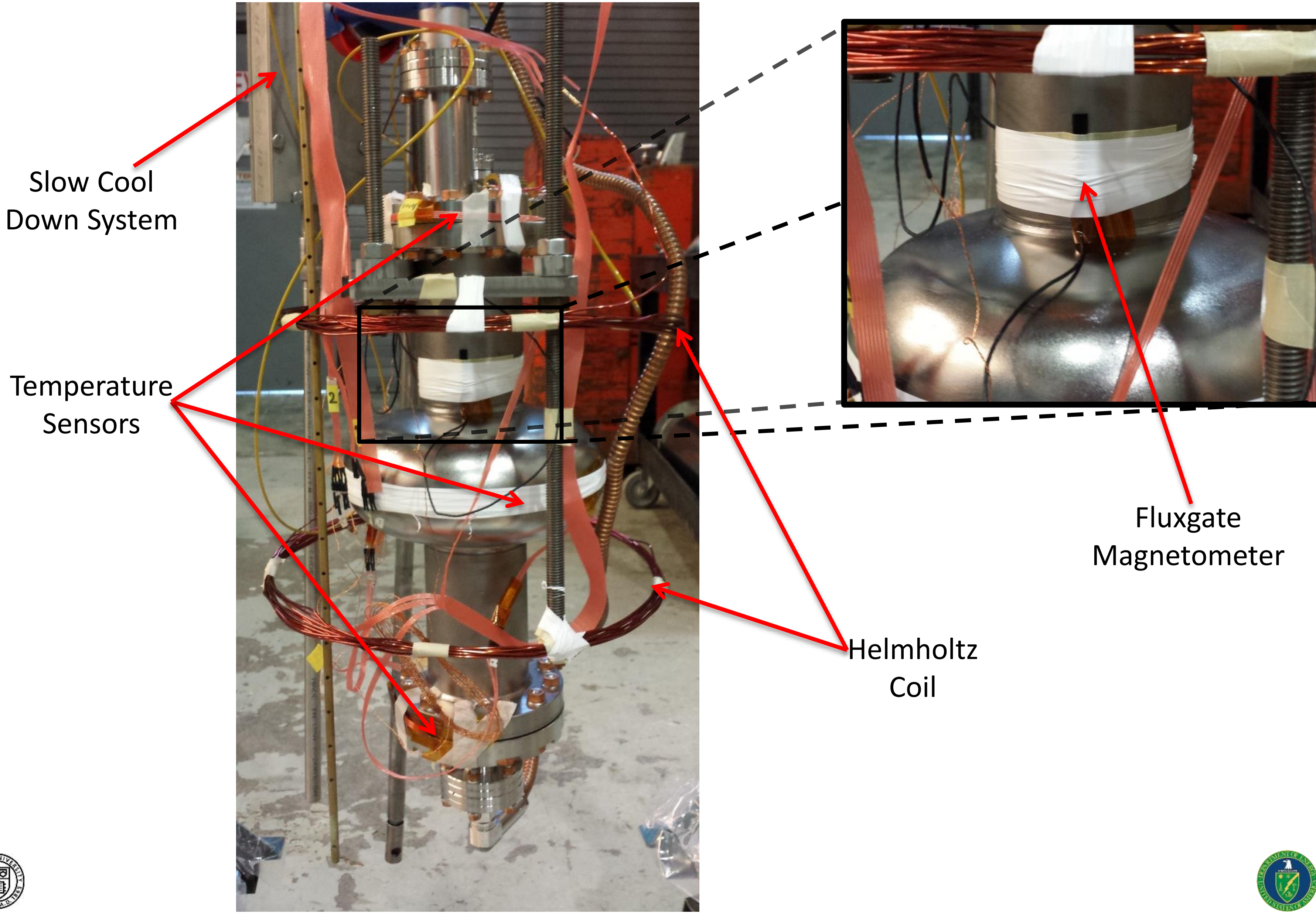
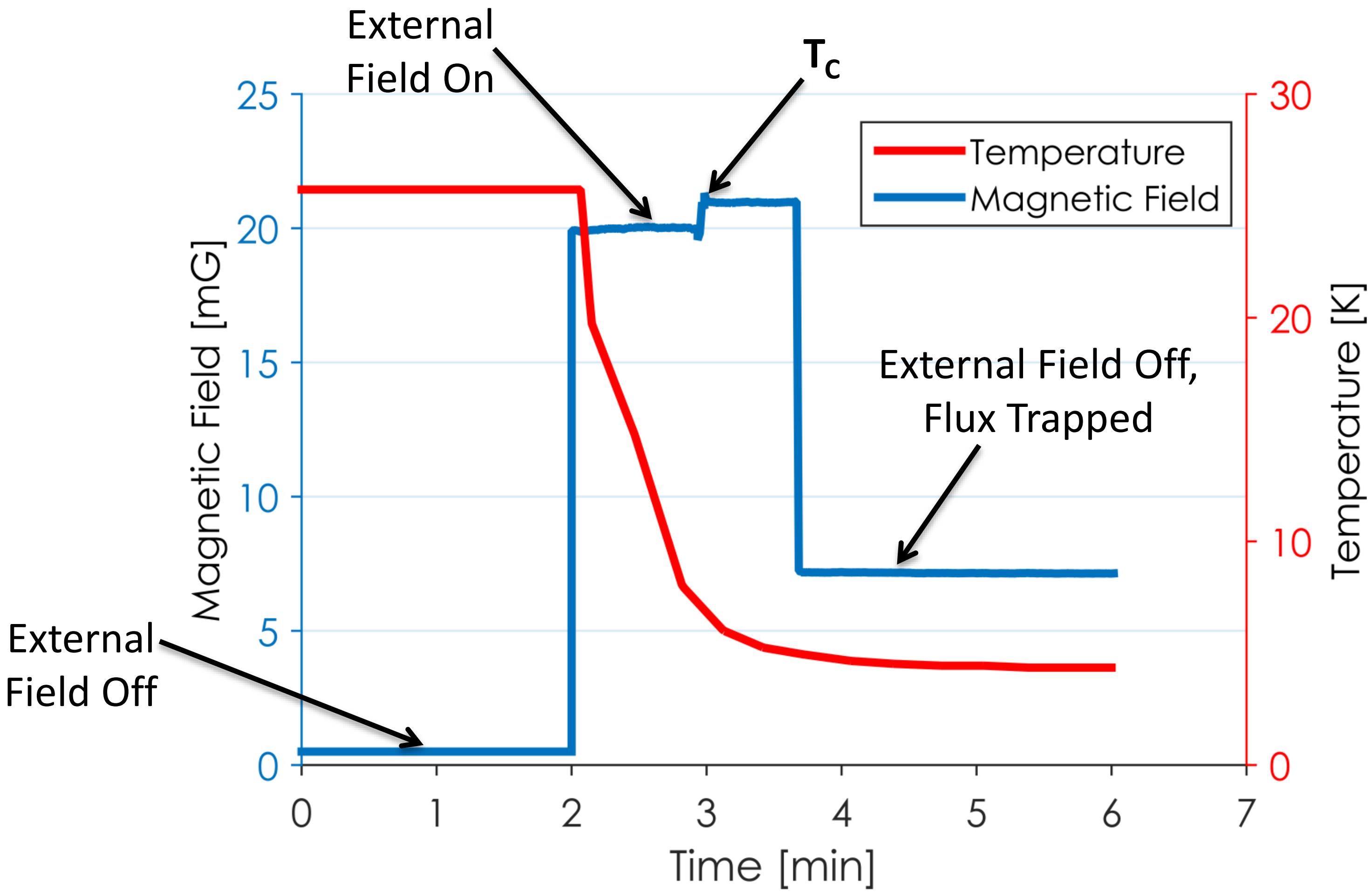
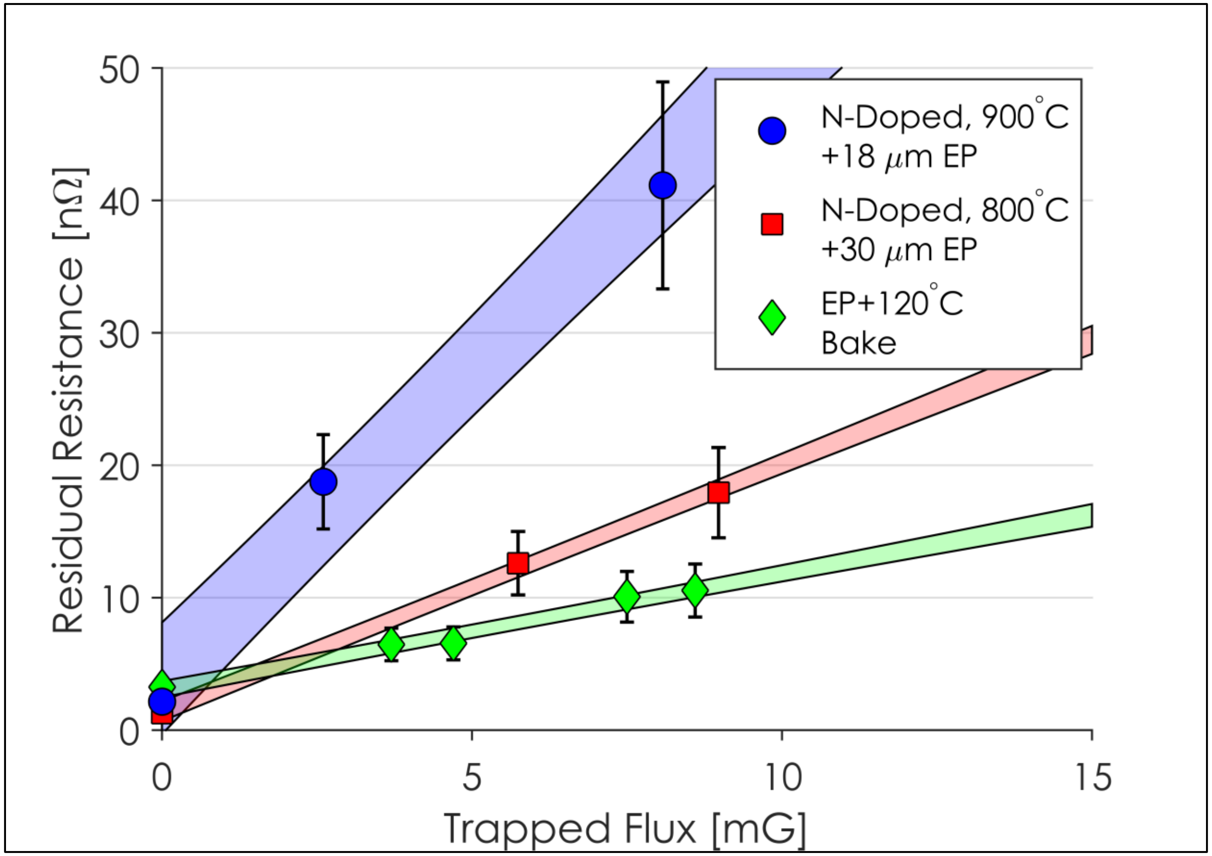
# Flux Trapping Studies



# Fluxgate Measurements

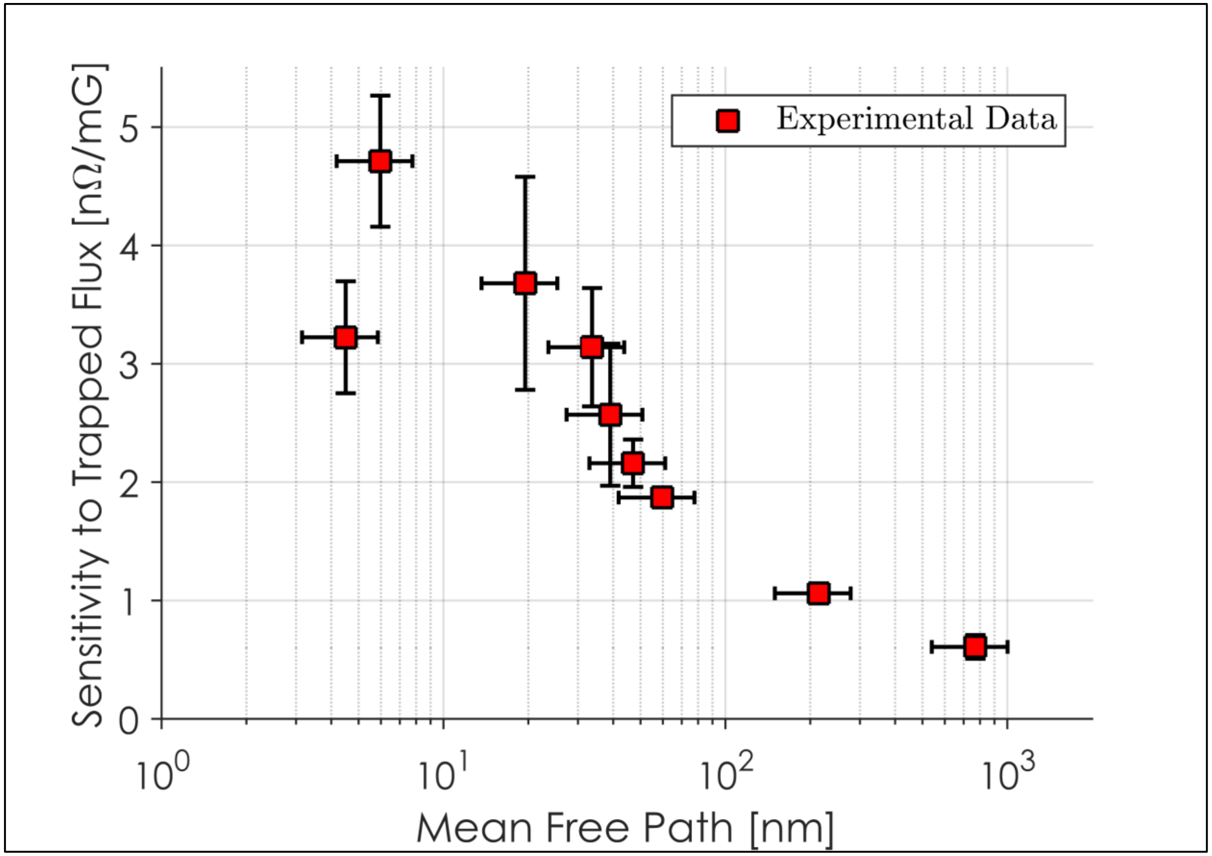


# Sensitivity to Trapped Magnetic Flux




A total of 10 cavity preparations were tested, each with different mean free paths – N-doping gives us the tools needed to finely tune the mean free path

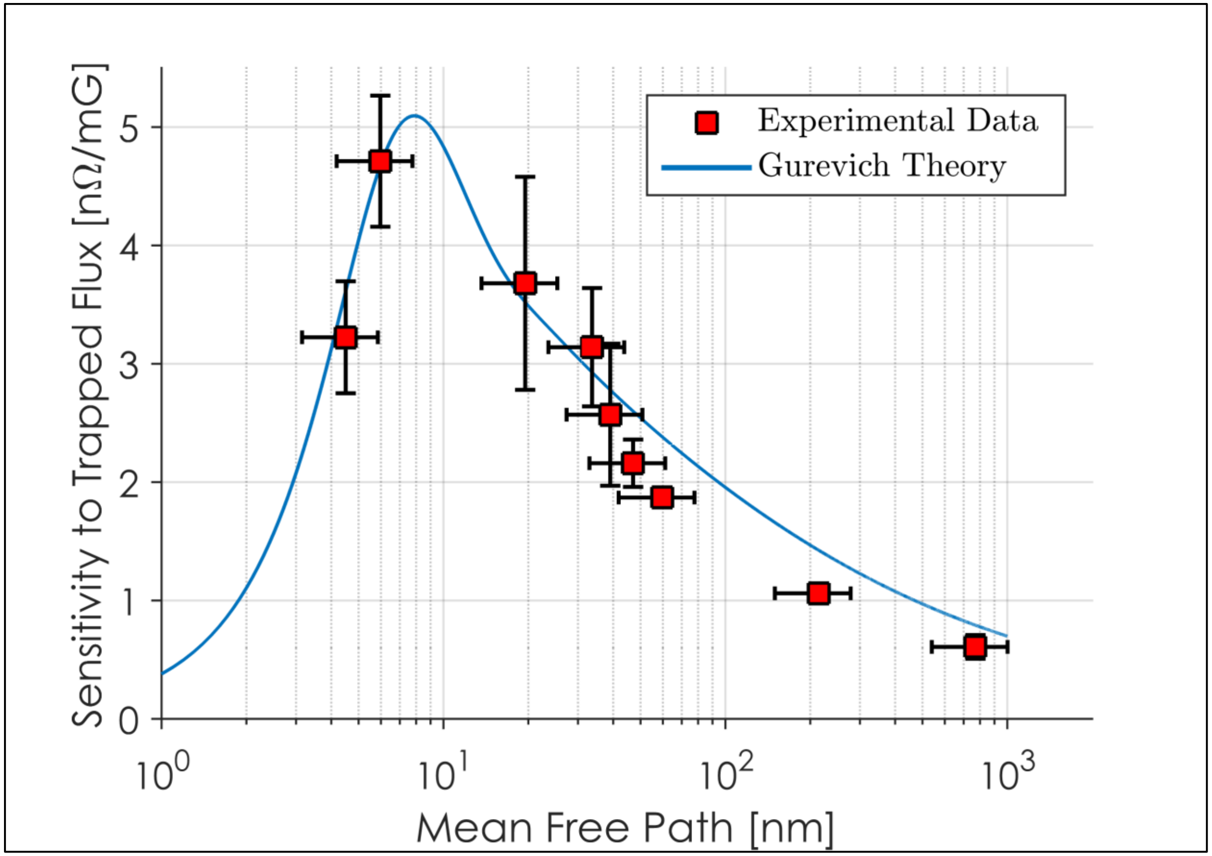
# Sensitivity to Trapped Magnetic Flux

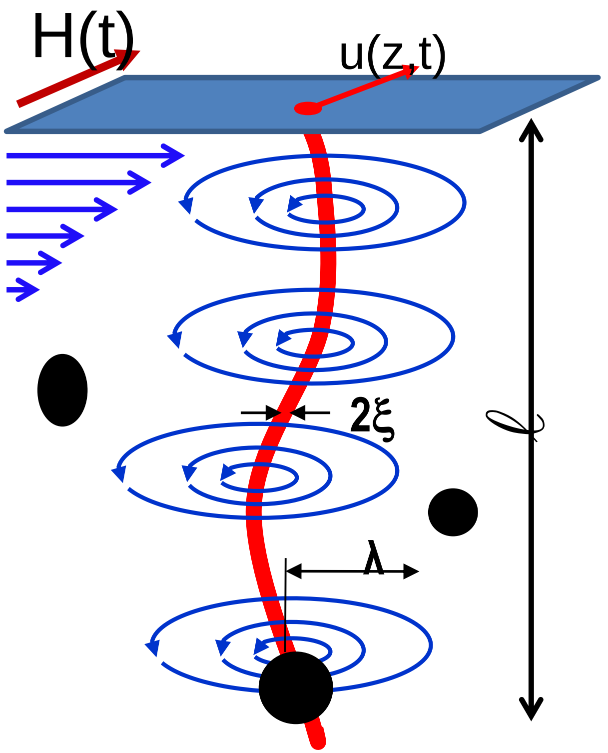



- In the clean limit, longer mean free path leads to lower sensitivity of $R_{res}$ to trapped magnetic flux
- In the dirty limit, shorter mean free path leads to lower sensitivity

See our paper on ArXiV for full details:
Gonnella et. al. arXiv:1509.04127

# Sensitivity to Trapped Magnetic Flux

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- This is well described by theoretical predictions proposed by Alex Gurevich (*Physical Review B*, 87(5):054502, 2013.)
- This model is heavily dependent upon mean spacing between pinning sites: we assume a linear relationship between this mean free path

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# Conclusions

- Medium field Q slope in 120$^{o}$C cavities is caused by a combination of increasing BCS and residual resistances
- Anti-Q slope in Nitrogen-doped cavities is caused purely by decreasing BCS resistance
- This anti-Q slope can be explained in a variety of ways: decreasing A or increasing ε in exponential fitting and increasing $\varepsilon/k_B T_c$ in full BCS fitting
  - Changing mean free path cannot solely explain the anti-Q slope since low field mean free paths are on either side of the minimum in N-Doped cavities

# Conclusions

- Xiao code, a field-dependent derivation of Mattis-Bardeen theory can accurately predict BCS resistance at medium fields from low field material parameters but fails at low fields
- Losses due to ambient magnetic fields are heavily dependent on mean free path and are very well explained by Gurevich's theory of vortex oscillations