# Overview of Flux Trapping at Cornell

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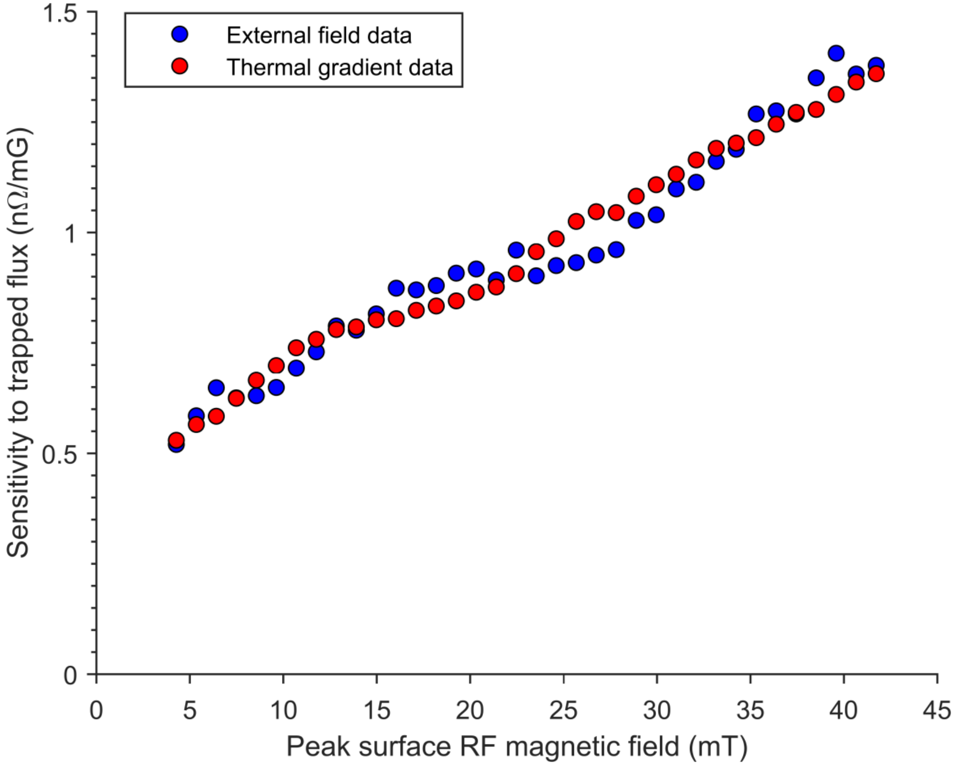
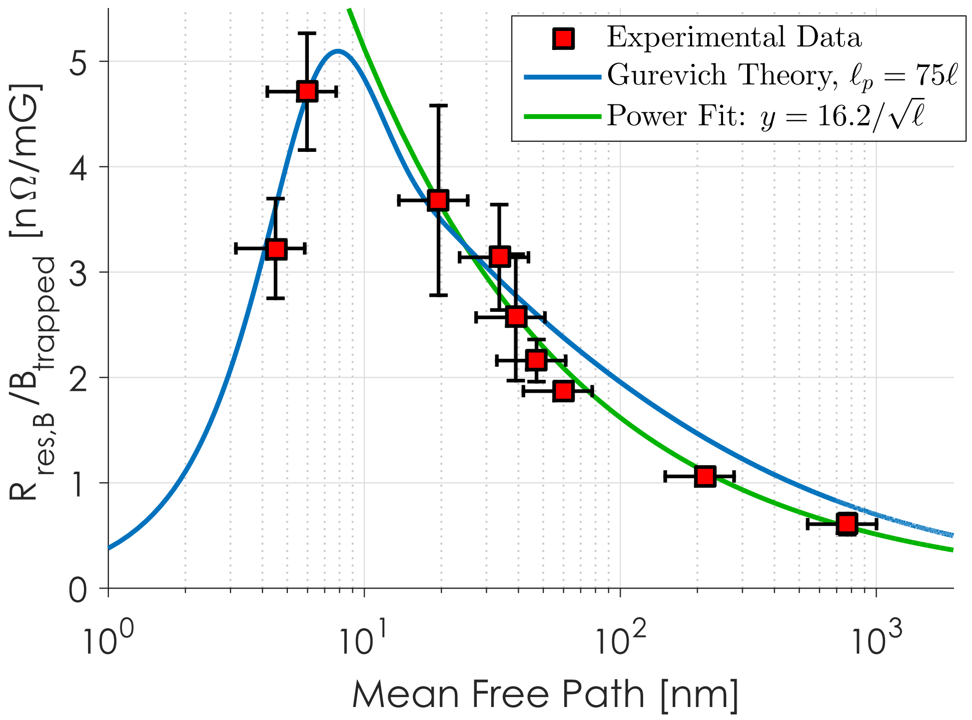
# Introduction / Teaser Slide

- In general ***linear sensitivity*** with an “offset” (y-intercept) parameter and a “slope” parameter. Linear slope predicted by “collective weak pinning” (see D. Liarte’s talk later today!)
- Parameters dependent on **cavity treatment** and **material parameters**, especially the **electron mean free path**, **doping depth**, and **frequency**.
- All Cornell cavities made from the same Nb stock

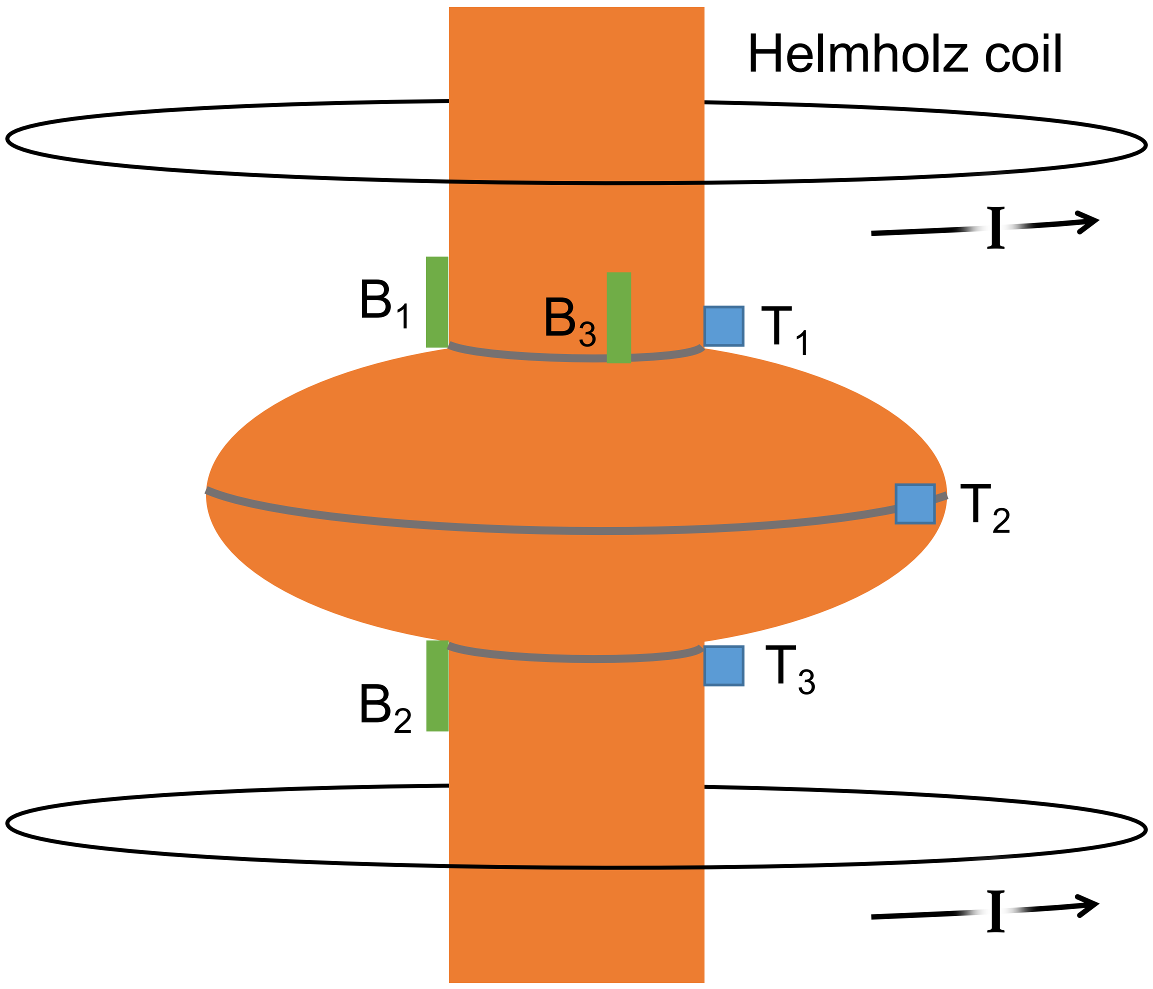




# Outline

- Overview of flux sensitivity measurement procedure @ Cornell
- Results for doped niobium
  - **1.3 GHz** high-T (**800 ºC**) **N-doping** (including **“2/6”** recipe)
  - **1.3 GHz 160 ºC impurity doping**
  - **2.6 GHz “2/6” N-doping**
- Results for $Nb_3Sn$
  - **1.3 GHz** cavities

# Flux Sensitivity Test Procedure

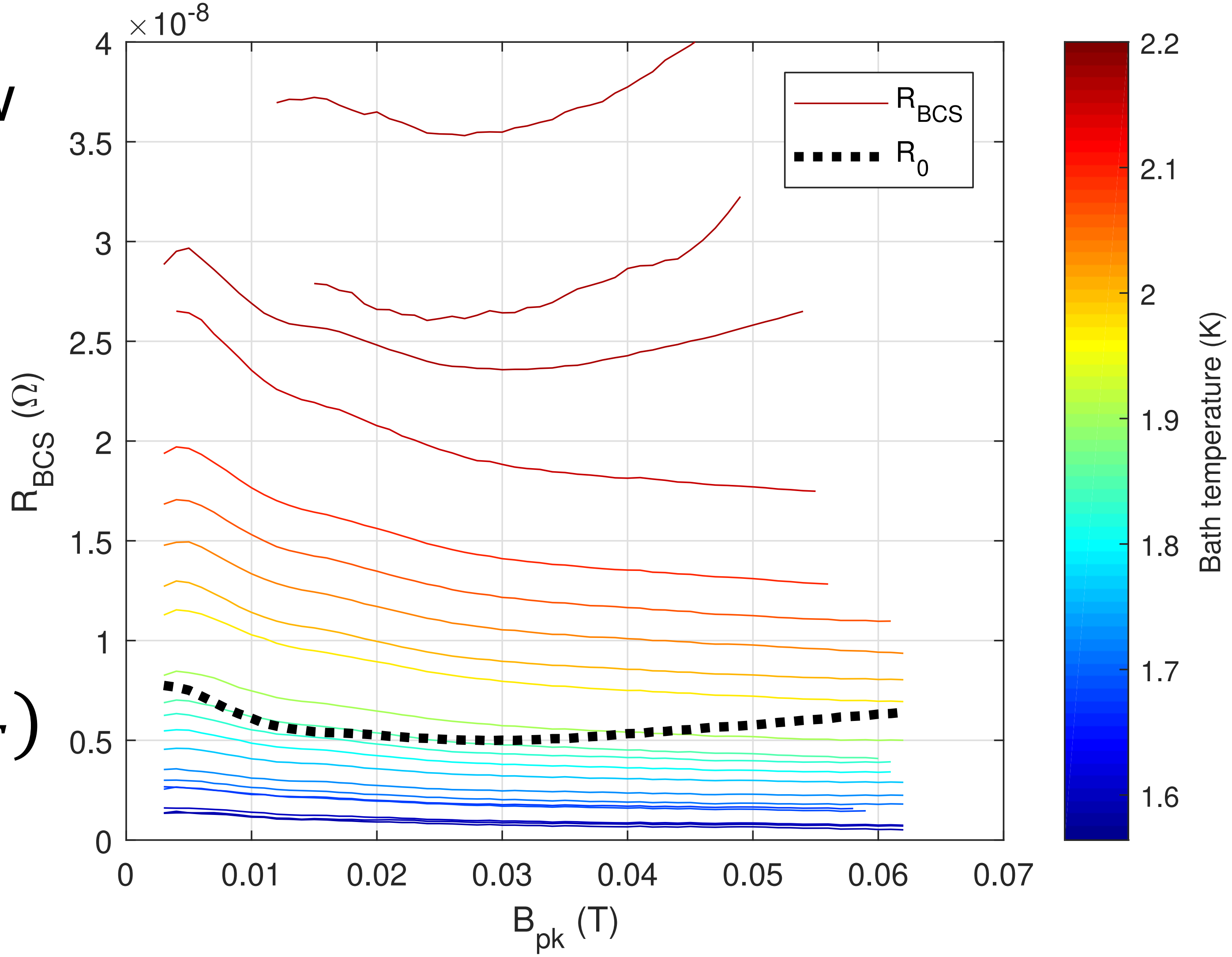


- Fast cool to expel mag. flux; slow cool to trap it
- Temperature sensors (Cernox) to measure $\Delta T$ at $T_c$
- Flux gate magnetometers to measure ambient field, applied field, expulsion, trapping
- Note: dT/dx across cell matters, not dT/dt
  - Though cooling quickly is an easy way to get a large dT/dx.

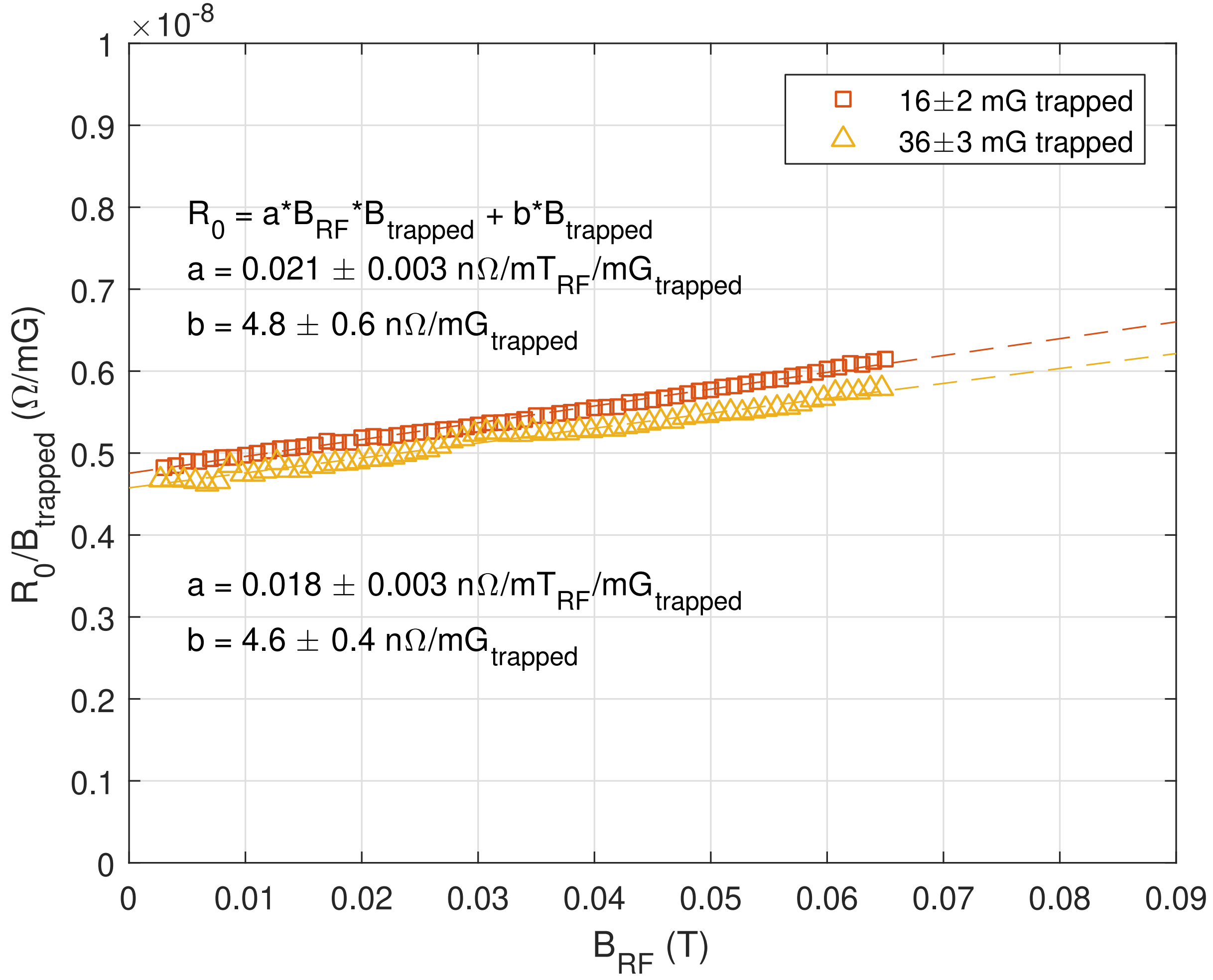
# Flux Sensitivity Test Procedure

- One test with fast cool
- One or more tests with slow cools, varying trapped flux
- Collect RF test data: $R_s(B_{RF}, T) = G / Q_0$
- Exponential fitting (SRIMP algorithm) to separate $R_s$:

$$R_s = R_{BCS}(B_{RF}, T) + R_0(B_{RF})$$



# Flux Sensitivity Test Procedure



Multiple cooldowns, same sensitivity!

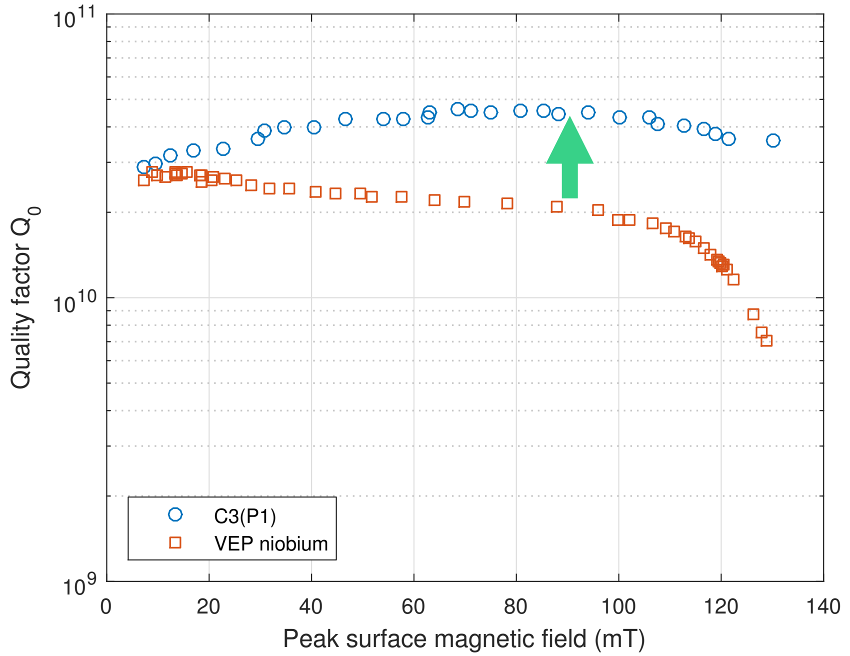
- Compare $R_0$ from different cooldowns to determine sensitivity:

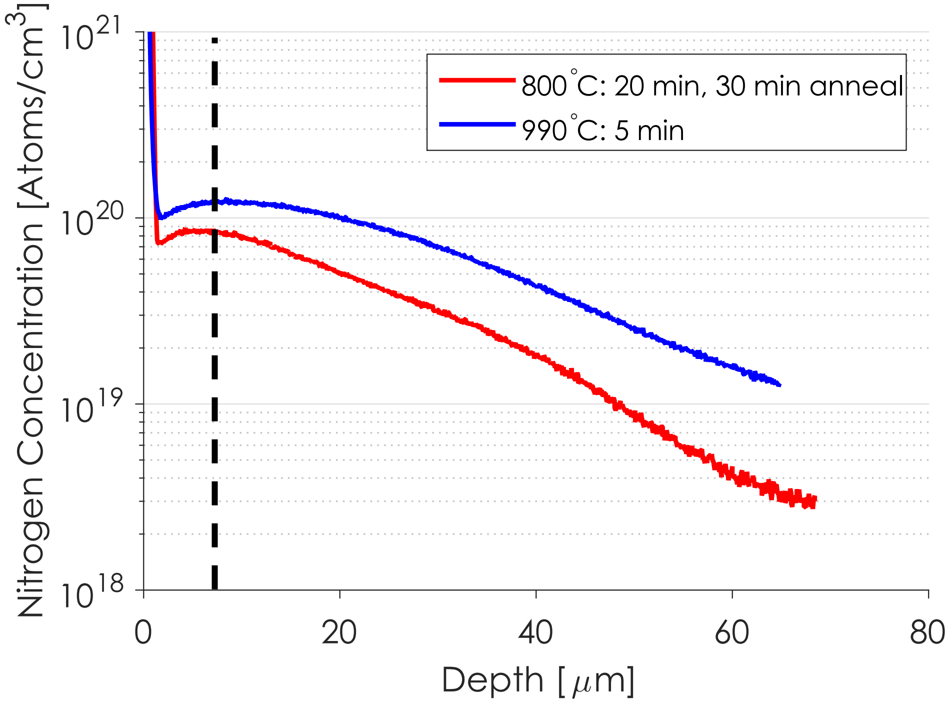
$$R_0\left(B_{\text{trapped}}\right) = R_0(\text{slow cool}) - R_0(\text{fast cool})$$

$$S = R_0\left(B_{\text{trapped}}\right)/B_{\text{trapped}} = a \cdot B_{RF} + b$$

# 1.3 GHz high-T N-doping

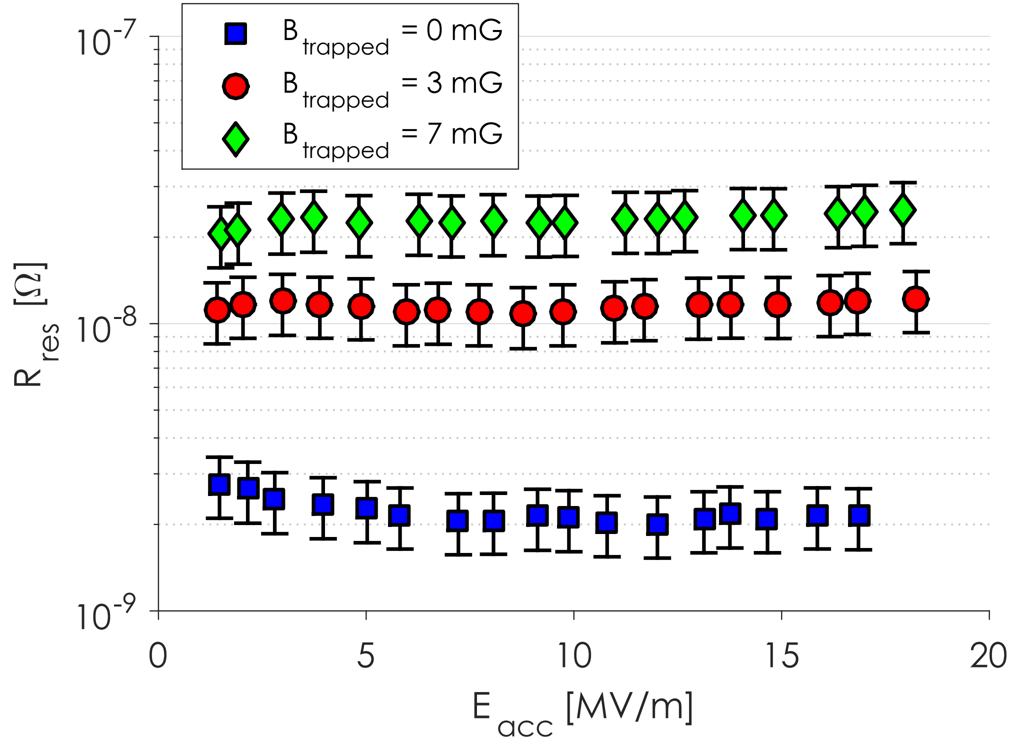
- Treatment protocol:
  - **800 ºC UHV** degas bake (5-8 hr)
  - **800 ºC 40 mTorr (6 Pa) $N_2$** doping bake (2-60 minutes)
  - **800 ºC UHV** anneal bake (0-60 minutes)
  - Final VEP (2-20 µm)



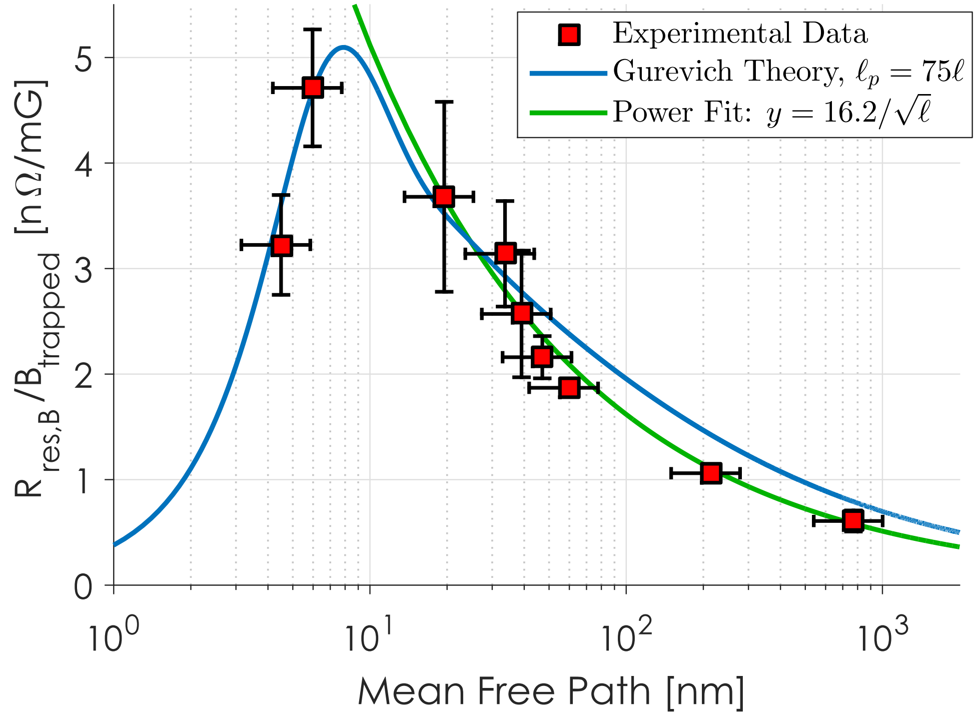


# 1.3 GHz high-T N-doping

## Strong “offset”, no slope in $B_{RF}$



## “offset” highly sensitive to $\ell_e$

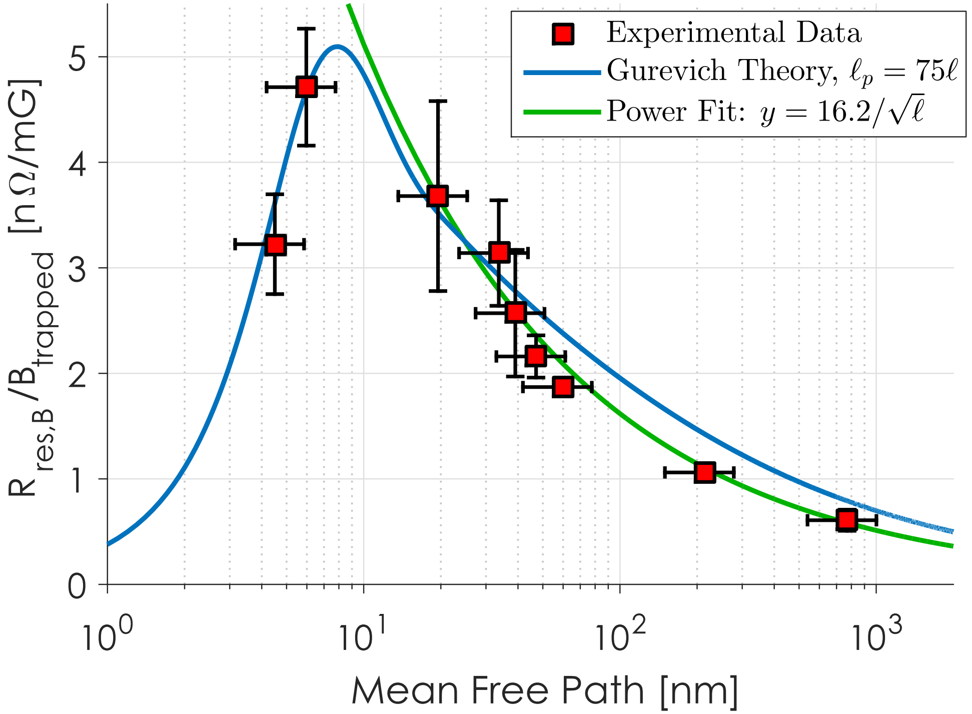


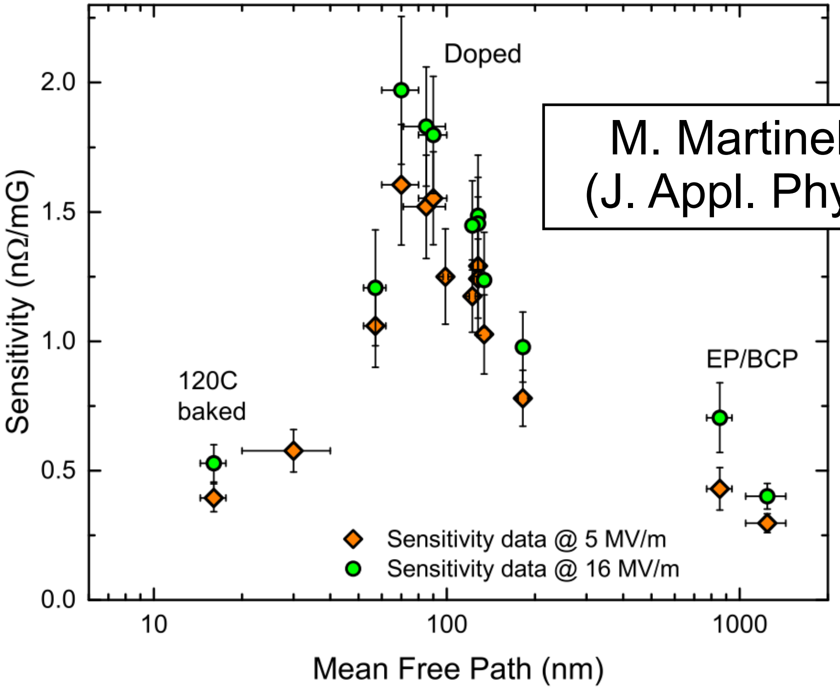
See D. Gonnella *et al.* (J. Appl. Phys. 2016)
and J. T. Maniscalco *et al.* (J. Appl. Phys. 2017)

# 1.3 GHz high-T N-doping

## Sensitivity also likely dependent on properties of bulk Nb!

(different cavity material at different labs)





M. Martinello *et al.*
(J. Appl. Phys. 2016)

## Flux expulsion also linked to material stock in doped cavities!

see D. Gonnella *et al.* (NIM-A 2018), S. Posen *et al.* (J. Appl. Phys. 2016)

# 1.3 GHz high-T N-doping

Takeaway message:

**Doping** strongly impacts trapped flux losses:
1) lowers the **mean free path**, which increases losses
2) increases **pinning effects** which decrease losses

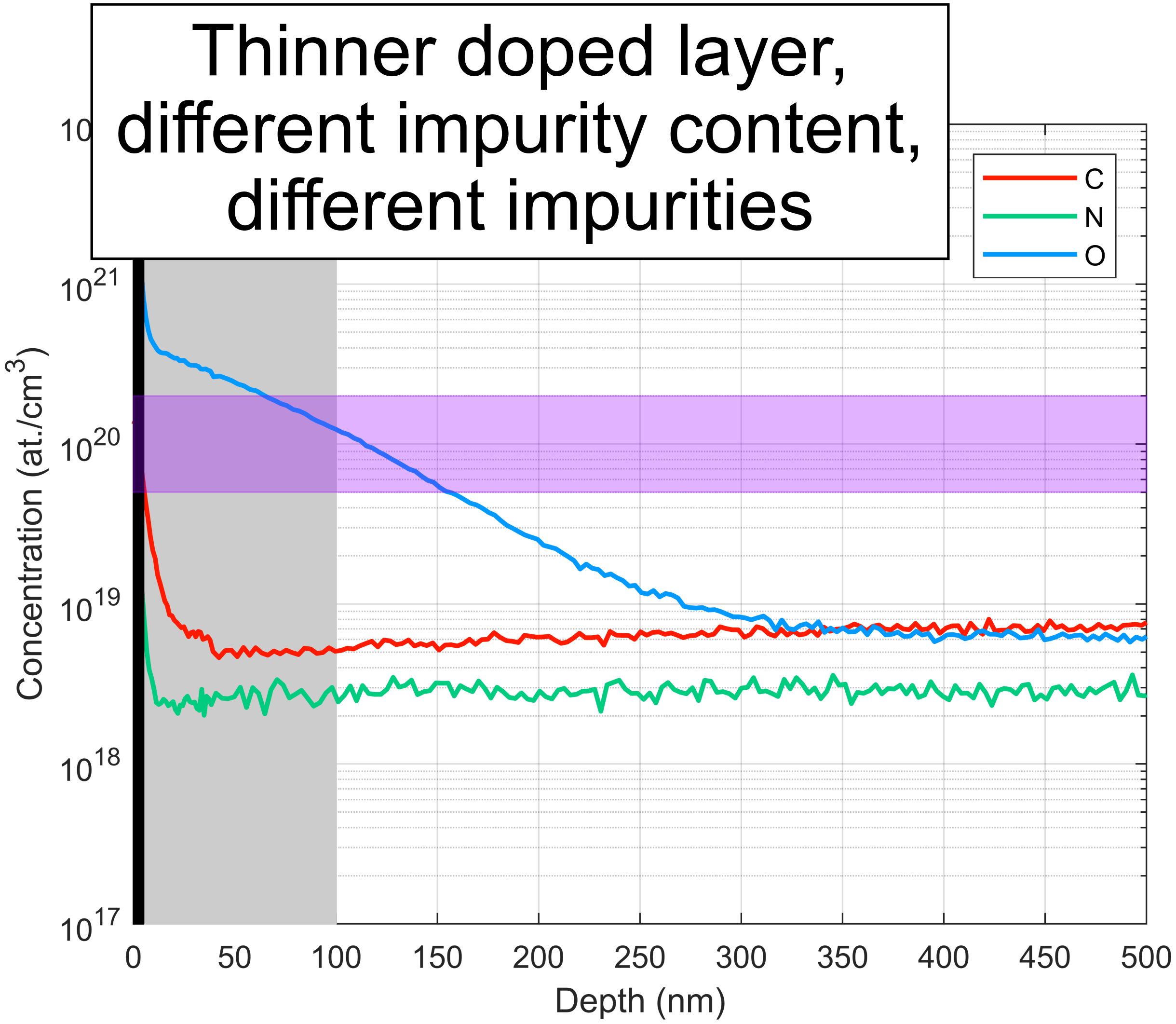
**Nitrogen's** link to pinning is still not well understood.
Other material parameters might be relevant too!

(see Danilo's work on **collective weak pinning** – how material parameters could affect pinning strength and vortex loss magnitude)

# 1.3 GHz 160 °C N-doping

- Treatment protocol:
  - **800 °C UHV** degas bake (5 hr)
  - **UHV** ramp down to **160 °C**
  - **160 °C UHV** rest (3 hr)
  - **160 °C**, **40 mTorr (6 Pa) $N_2$** doping bake (1 day for test shown here)
  - **160 °C** optional **UHV** anneal bake (not used for tests shown here)

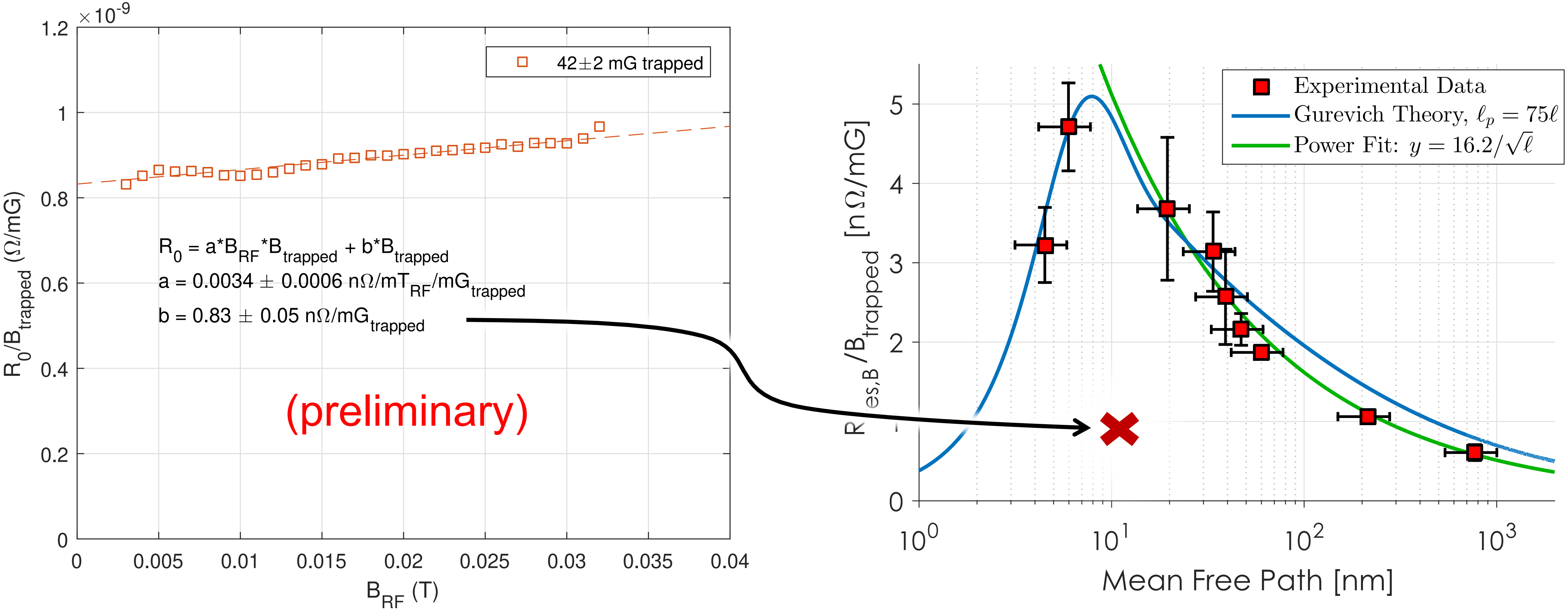
- Little/no post chemistry! Maybe HF rinse or oxypolish for light surface removal ≪ 1 µm.



Thinner doped layer, different impurity content, different impurities

# 1.3 GHz 160 °C N-doping

## Lower “offset” sensitivity, higher “slope” sensitivity compared to **800 °C**-doped cavities



$R_0 = a^*B_{RF}{}^*B_{trapped} + b^*B_{trapped}$

$a = 0.0034 \pm 0.0006$ nΩ/mT$_{RF}$/mG$_{trapped}$

$b = 0.83 \pm 0.05$ nΩ/mG$_{trapped}$

(preliminary)

# 1.3 GHz 160 ºC N-doping

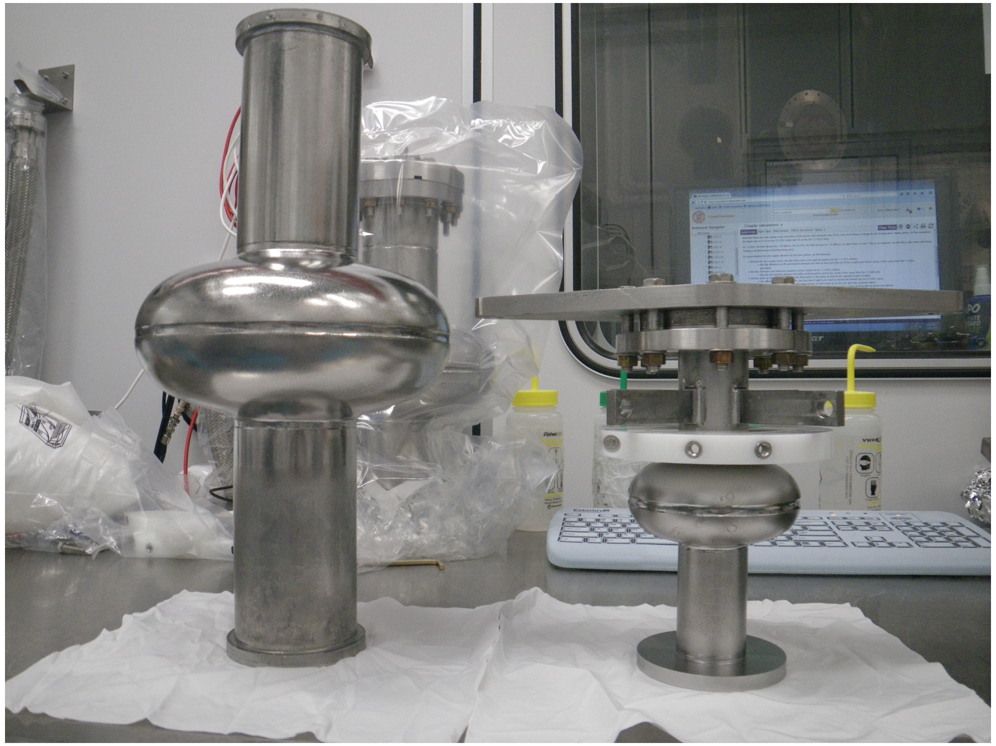
Takeaway message:

Shallow **160 ºC doping** gives lower sensitivity than **800 ºC doping**
Note: **dopant may be different**…

Results indicate **linear field dependence**
more prominent for **low-temperature dopings**
(see again Danilo's work/talk)

# 2.6 GHz “2/6” N-doping

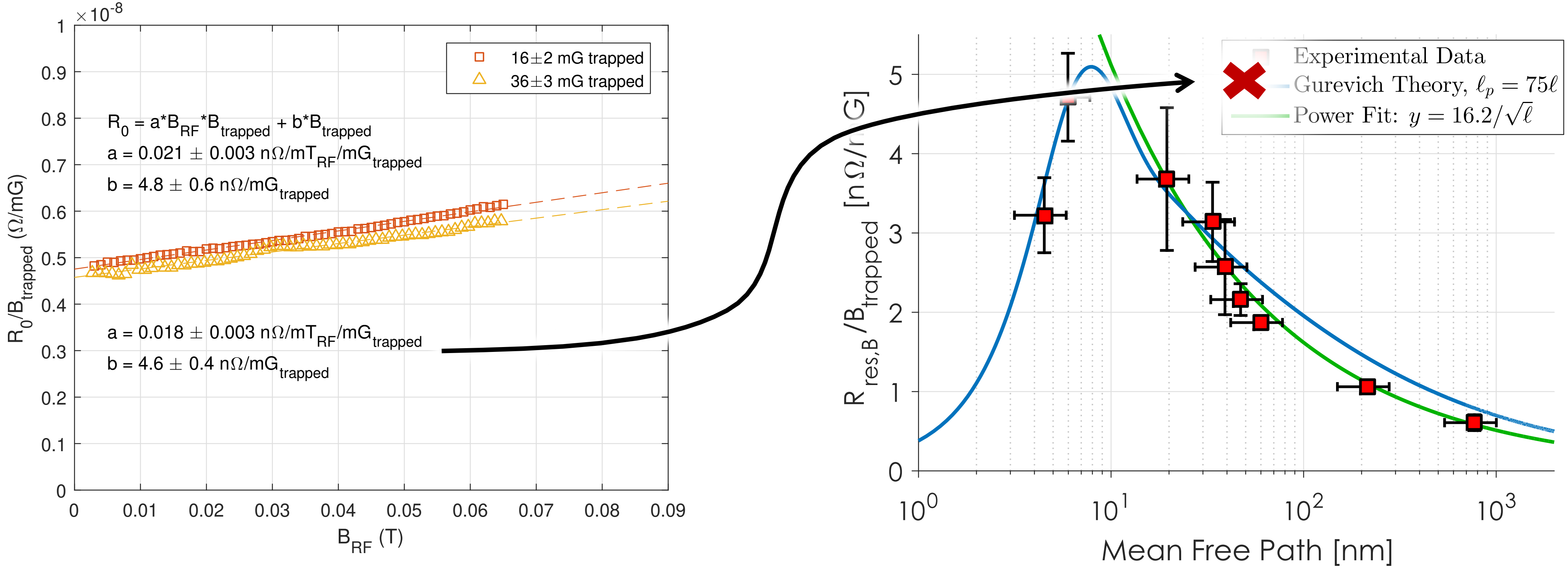
- Treatment protocol:
  - **800 ºC UHV** degas bake (3 hr)
  - **800 ºC 40 mTorr (6 Pa) $N_2$** doping bake (2 minutes)
  - **800 ºC UHV** anneal bake (6 minutes)
  - Final VEP (6 μm)



# 2.6 GHz “2/6” N-doping

## “offset” sensitivity **2x** higher than 1.3 GHz cavities with similar $\ell_e$

## $R_0/B_{trapped} \propto \omega$?



see J. T. Maniscalco *et al.* (LINAC 2018)

# 2.6 GHz “2/6” N-doping

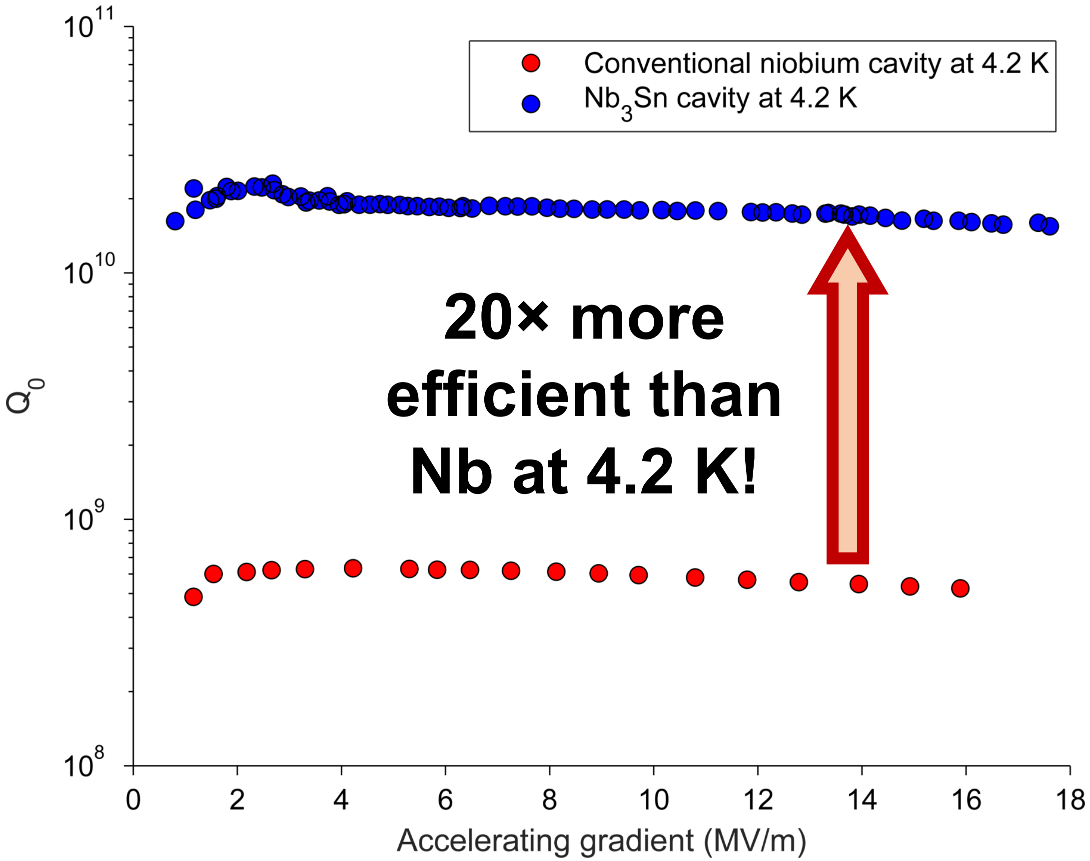
Takeaway message:

**High frequency** → stronger sensitivity

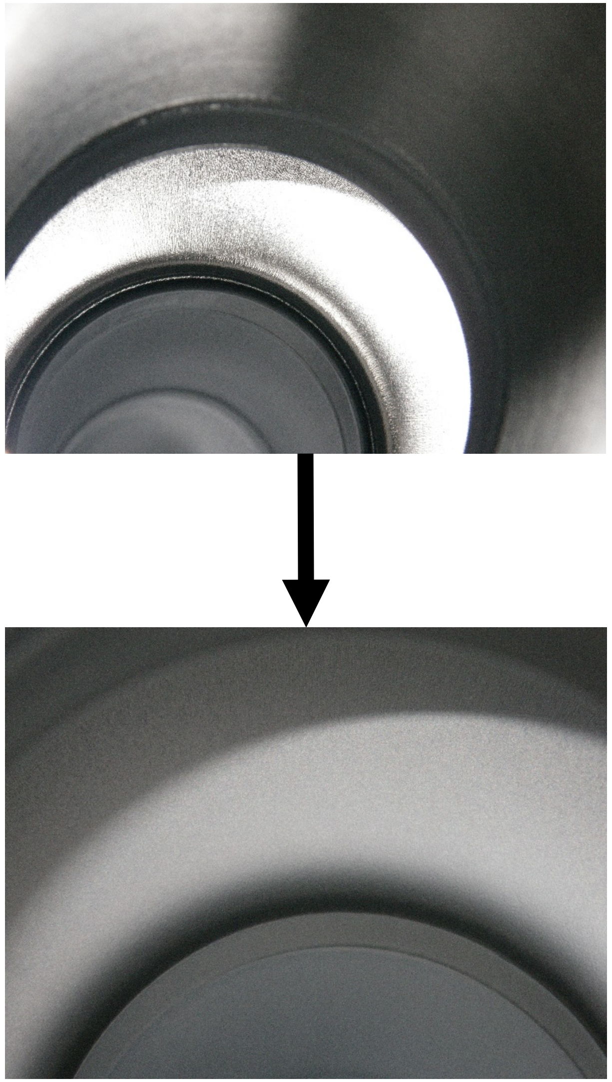
Initial results indicate linear behavior with frequency, *i.e.* $R_0/B_{trapped} \propto \omega$

# 1.3 GHz $Nb_3Sn$

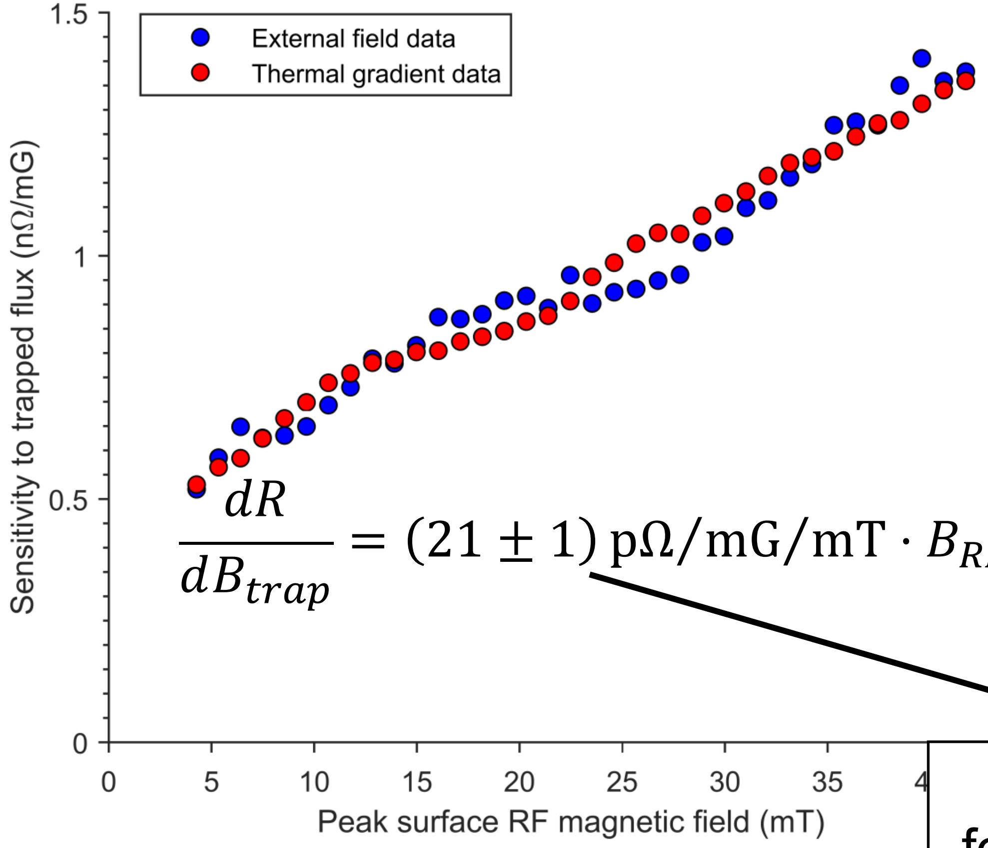
- Treatment protocol:
  - $Nb_3Sn$ grown on Nb cavity substrate by vapor diffusion



**20× more efficient than Nb at 4.2 K!**



# Typical results: **linear sensitivity**



$$\frac{dR}{dB_{trap}} = (21 \pm 1)\ \mathrm{p\Omega/mG/mT} \cdot B_{RF} + (0.47 \pm 0.02)\ \mathrm{n\Omega\ /\ mG}$$

*compare:*

$3\ \mathrm{p\Omega/mG/mT}$
for **160 ºC doping**

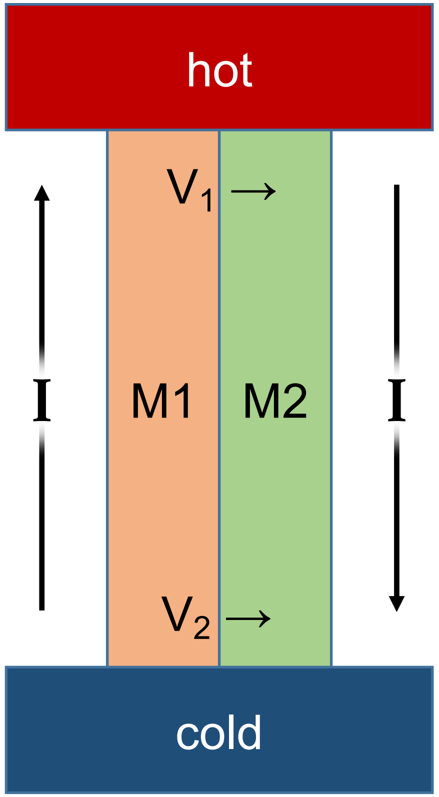
$\leq 0.5\ \mathrm{n\Omega/mG}$
for **clean Nb**

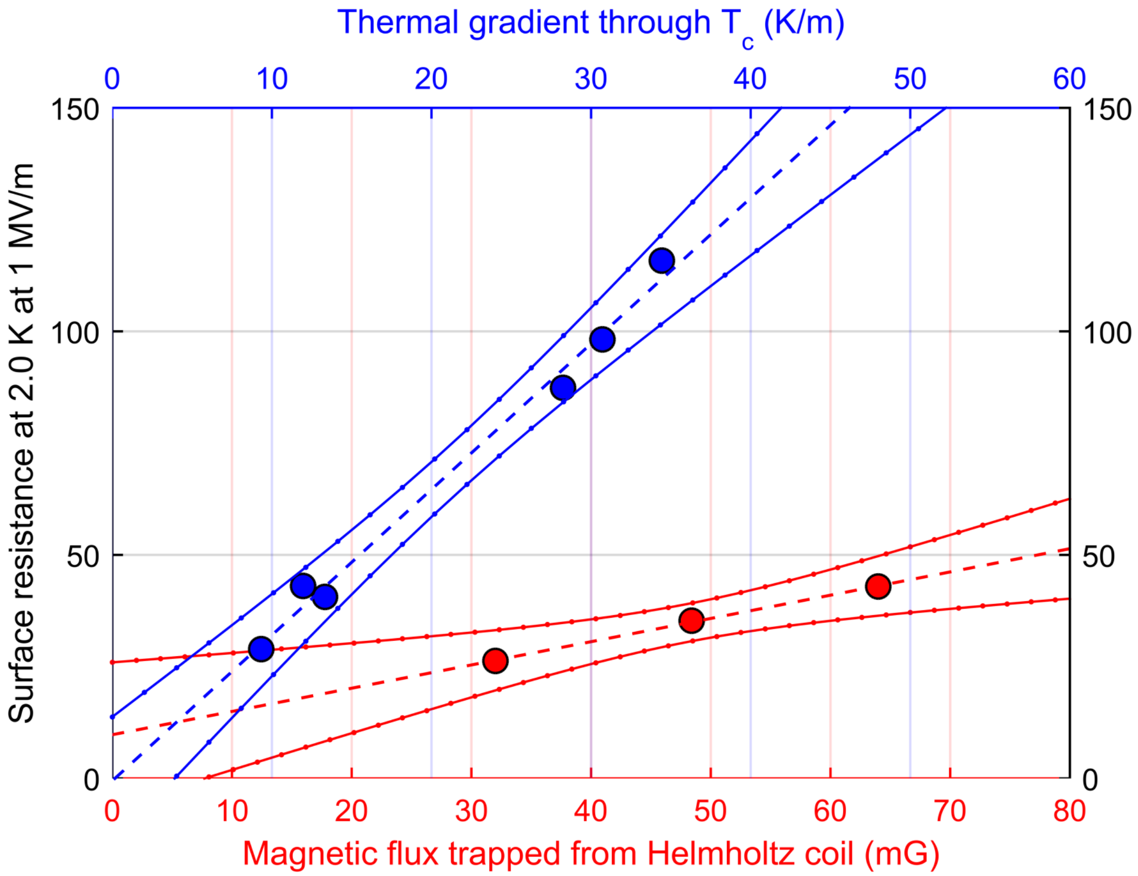
More sensitive slope than doped Nb, similar “offset” sensitivity

see D. L. Hall *et al.* (IPAC 2017)

# 1.3 GHz $Nb_3Sn$

## Also sensitive to thermoelectric currents (Seebeck effect)





Cavity must be cooled uniformly!
Need to limit flux sensitivity.

# 1.3 GHz $Nb_3Sn$

Takeaway message:

Clear **linear behavior,** strong slope

Low “offset” sensitivity – similar to undoped cavities

# Review

- Flux sensitivity typically **linear in RF field**
- Coefficients of sensitivity linked to material parameters
  - **Electron mean free path**
  - **Doping depth**
  - **Impurity species**
  - **Frequency**
  - Niobium stock
  - **$Nb_3Sn$** vs. **doped Nb** vs. **clean Nb**
    (vs. Nb/Cu films not addressed here)
- $Nb_3Sn$: $R_0$ from trapped flux important because $R_{BCS}$ is so small!
  - Higher "slope" sensitivity than doped Nb
  - Bimetallic interface necessitates slow, uniform cooling and good magnetic shielding/hygiene

# Thanks for your attention!

See also:

D. B. Liarte’s talk later today (11h59):
“Vortex dynamics and hysteretic flux losses due to pinning”