

**Inelastic Electron Tunneling
Spectroscopy
and the
Zero Bias Anomaly
In
Carbon Nanotubes**

**Jacob Alldredge
Jorg Janssen
Serge Lemay
Cees Dekker**

Outline

Introduction

1. STM Spectroscopy
2. What is Inelastic electron tunneling spectroscopy (IETS)

Our Data

1. IETS Data
2. Problems with Data

Zero Bias Anomaly

1. Old Data
2. New Data

Conclusions

What We Want to Measure

From theory:

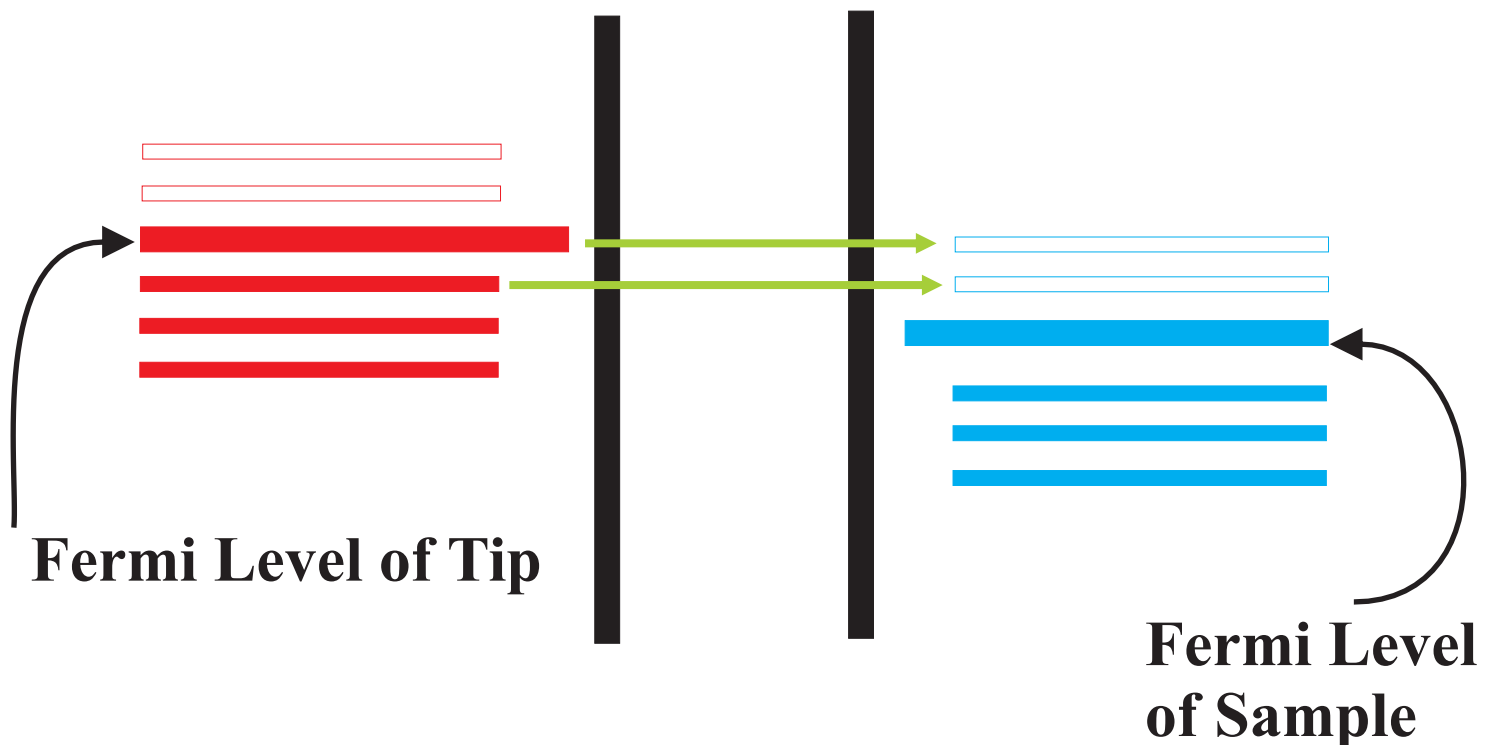
$$I(V) \propto \int_0^{eV} \rho_s(E) \rho_t(E-eV) T(E) dE$$

In our case:

$$I(V) \propto \int_0^{eV} \rho_s(E) dE$$

It follows that:

$$dI/dV (V) \propto \rho_s(V)$$



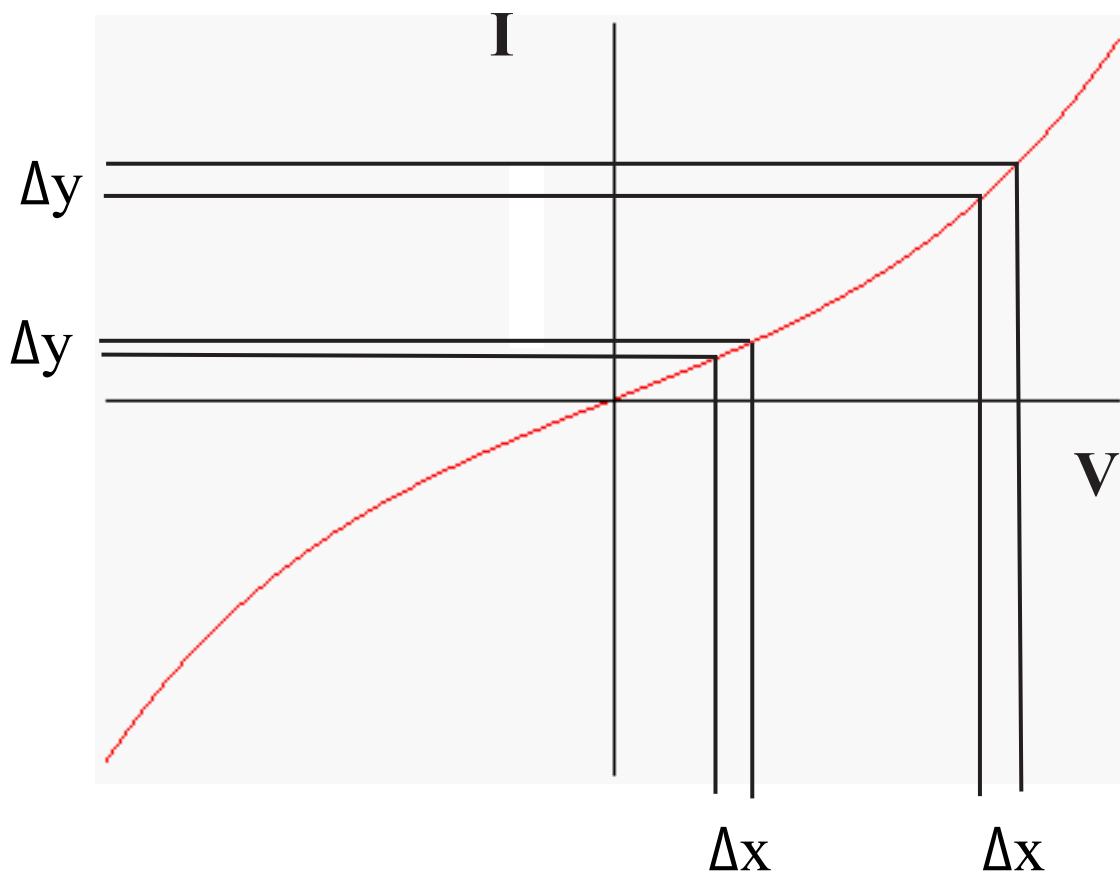
What We Actually Measure (And how we do it)

Current (I)

1st derivative (dI/dV)

2nd derivative (d^2I/dV^2)

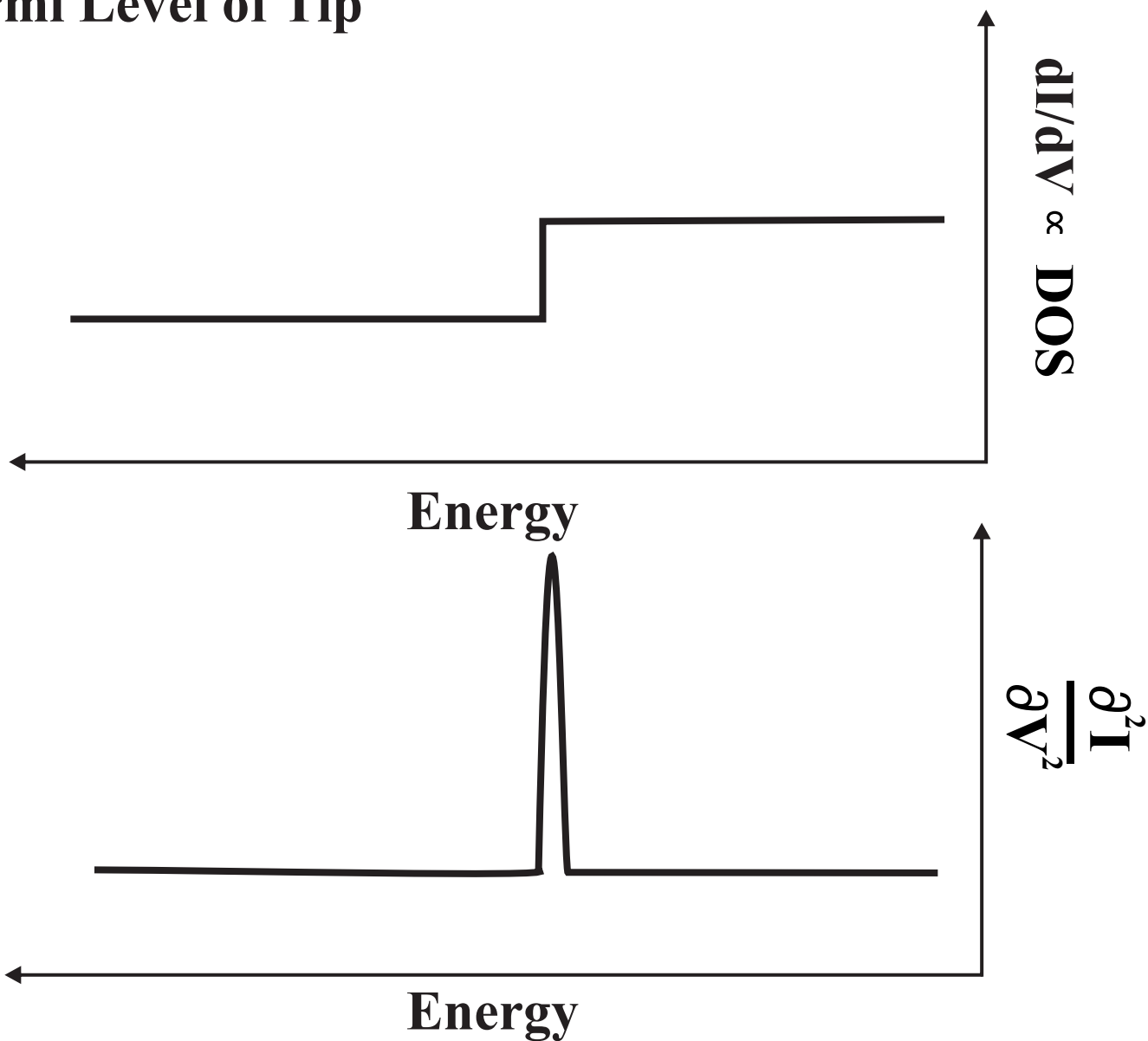
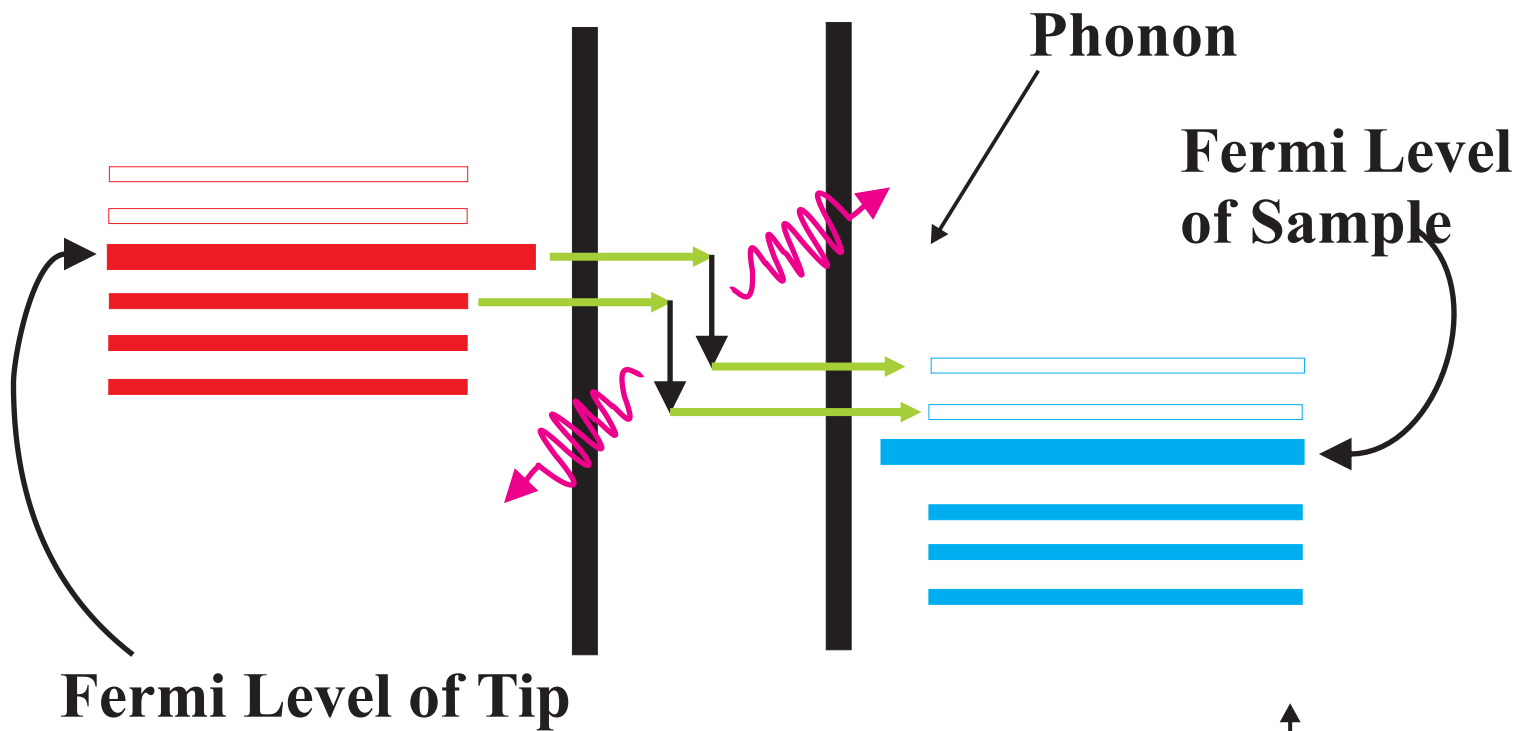
Using a lock in:



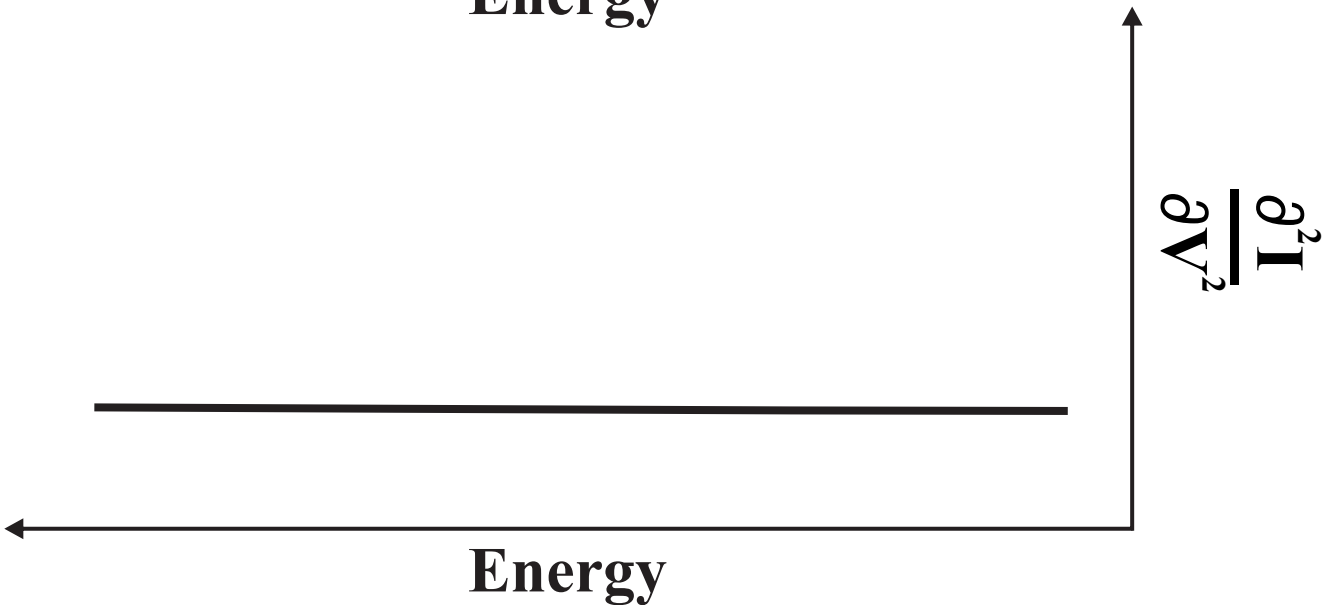
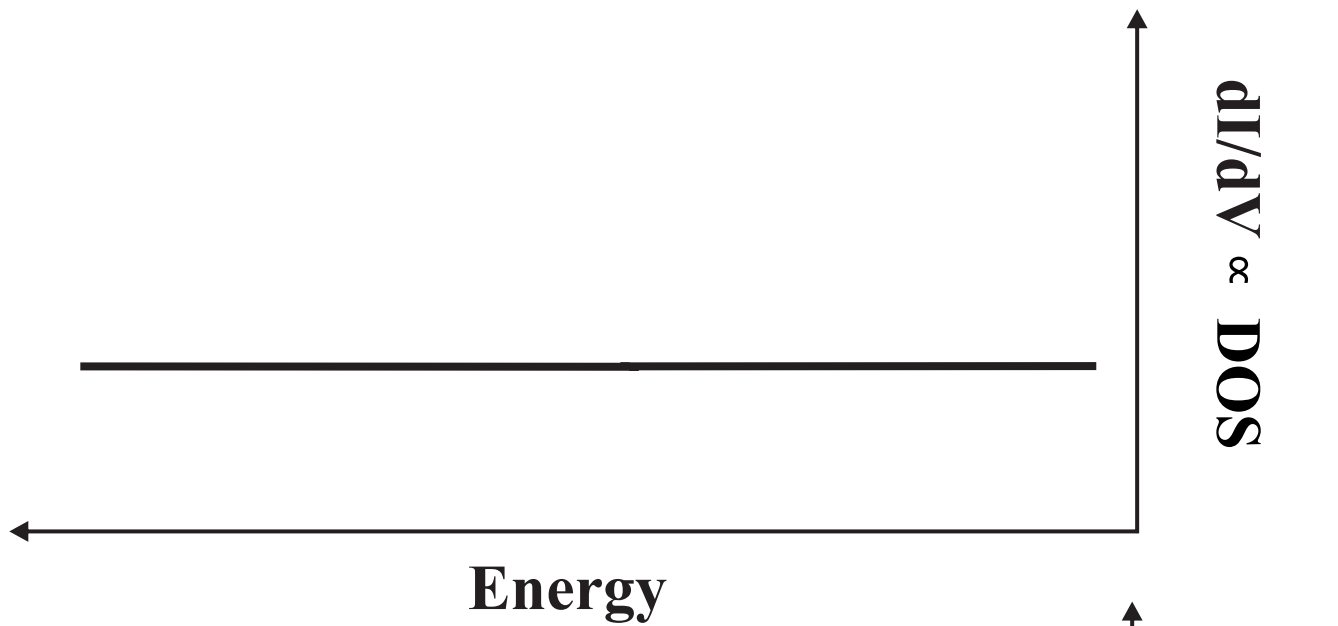
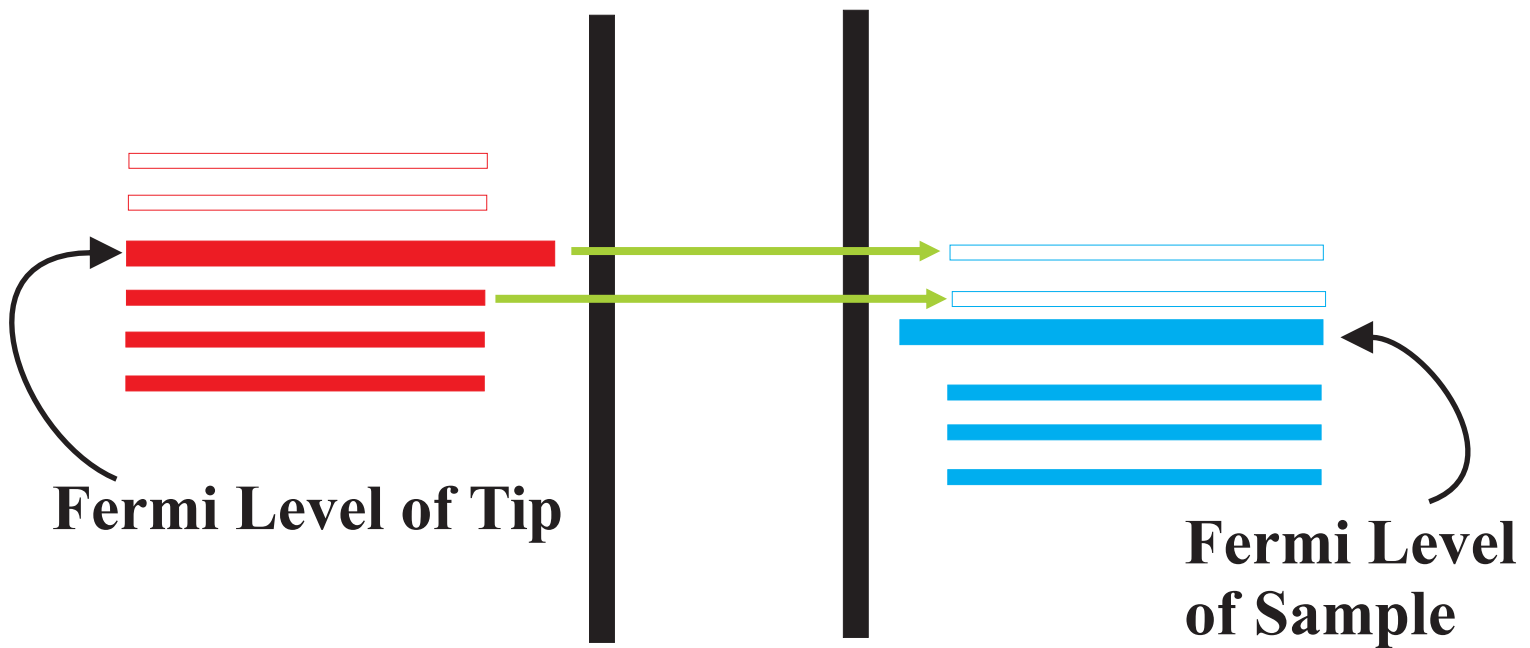
$$I_t(V) = I[V_{dc} + V_{ac} \cos(\omega t)]$$

$$I(t) = I(V_0) + \frac{\partial I}{\partial V} V_{ac} \cos(\omega t) + \frac{1}{4} \frac{\partial^2 I}{\partial V^2} \cos(2\omega t)$$

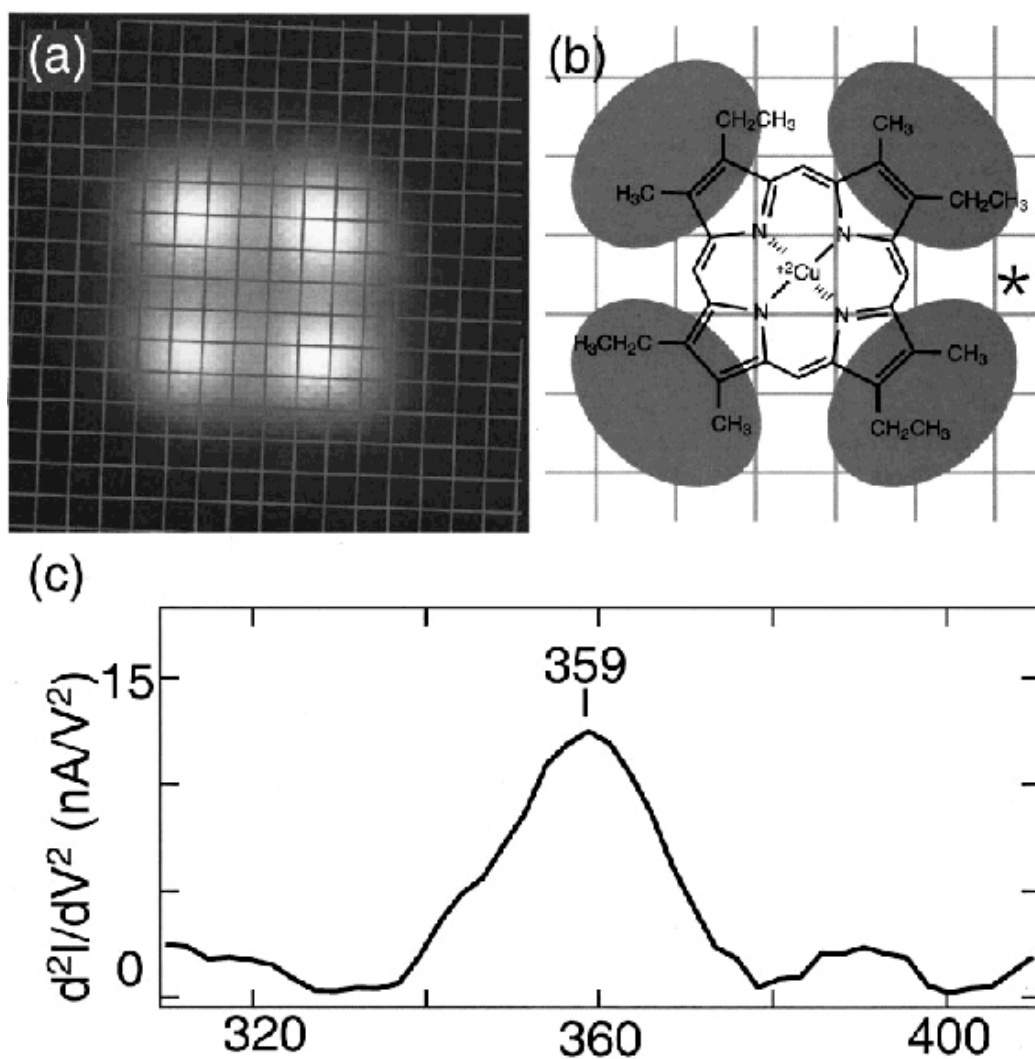
What is IETS?



Normal Tunneling

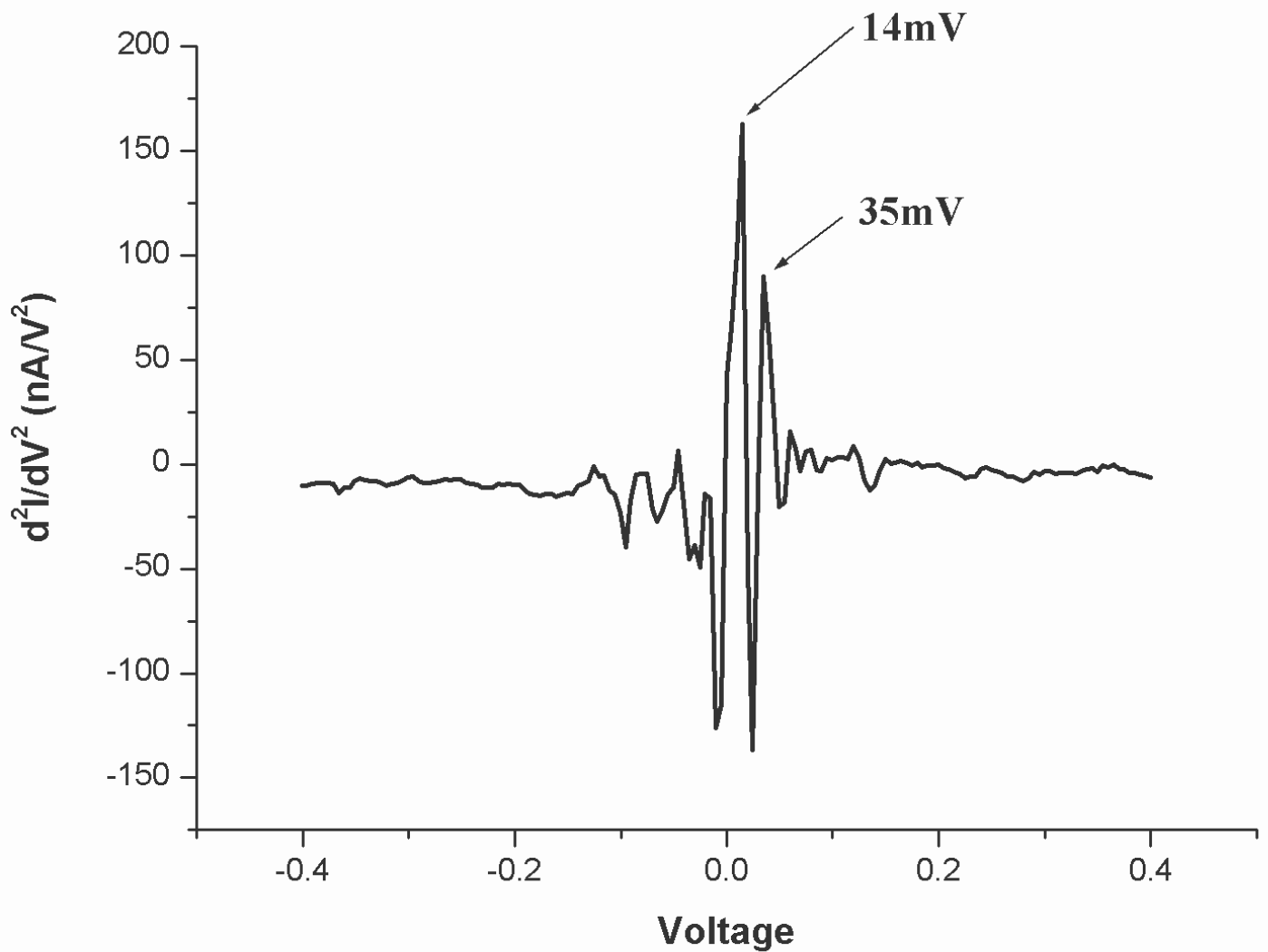


An Example of IETS



T. M. Wallis, X. Chen, and W. Ho, *J. Chem. Phys.*,
Vol. 113 Number 12, 22 September 2000 pp. 4837-4839

Our Data

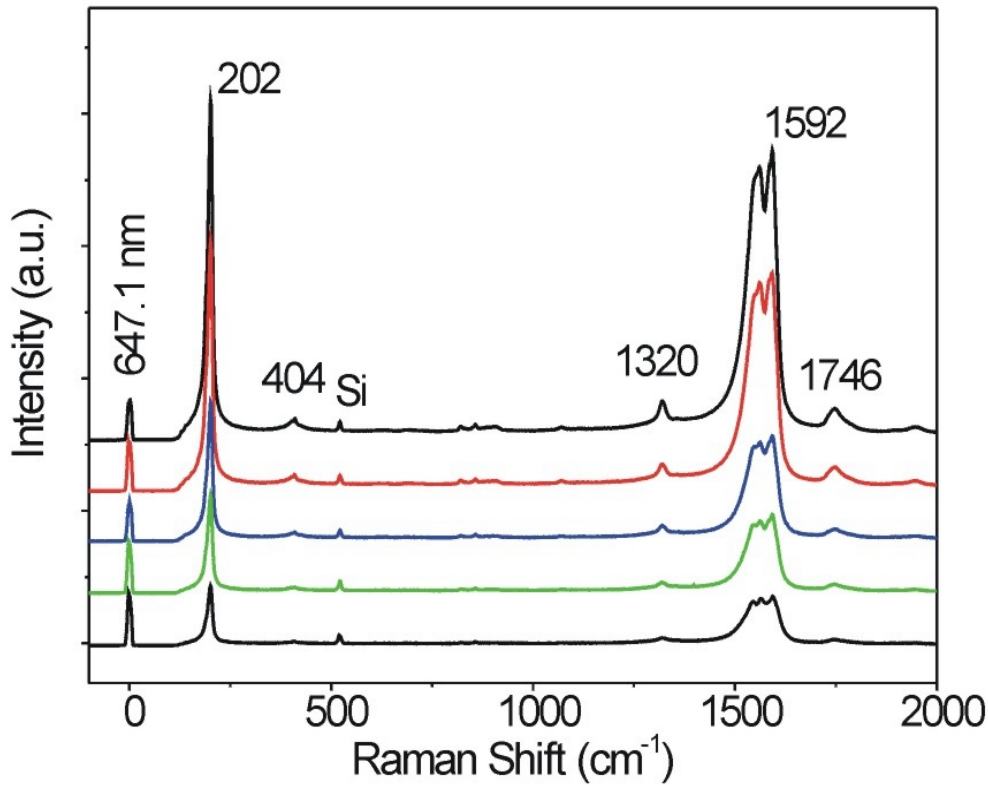


Tube Diameter = 1.6-1.7nm

Breathing mode expected $E = 17mv$

Where our States Lie

Can Determine Through Raman and Theory

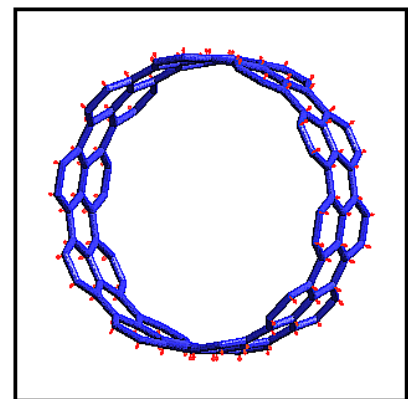


For the Breathing mode:

$$E = \frac{27.7 \text{ meV}}{d_0 \text{ (nm)}}$$

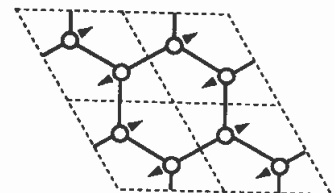
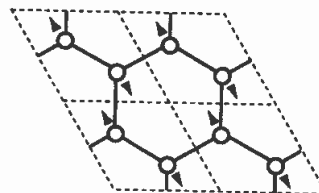
For Our Tubes:

$$E = 15\text{-}35 \text{ meV}$$

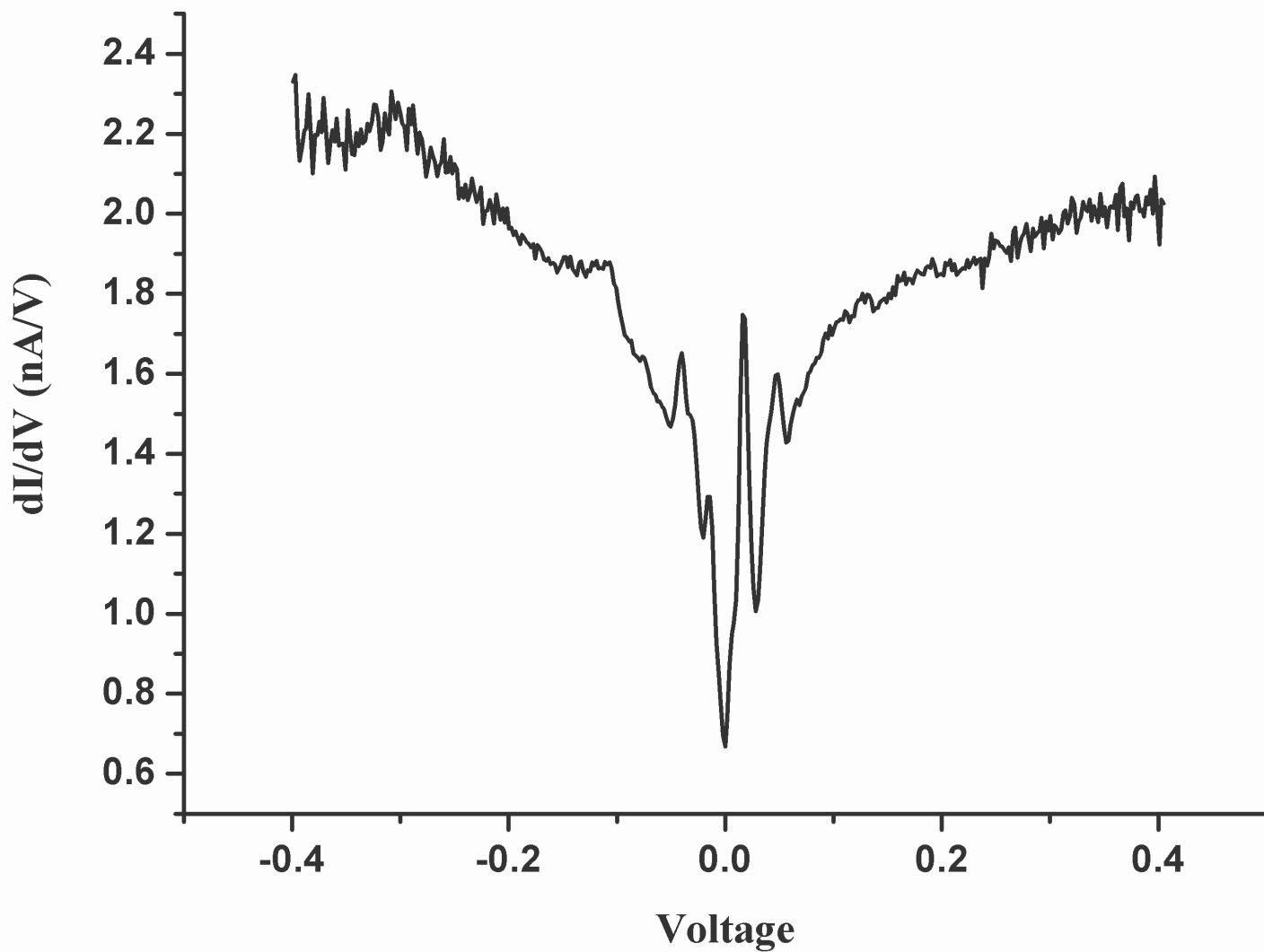


For The 1592 cm⁻¹ Peak

$$E = 197 \text{ meV}$$



An Explanation?



The Zero Bias Anomaly

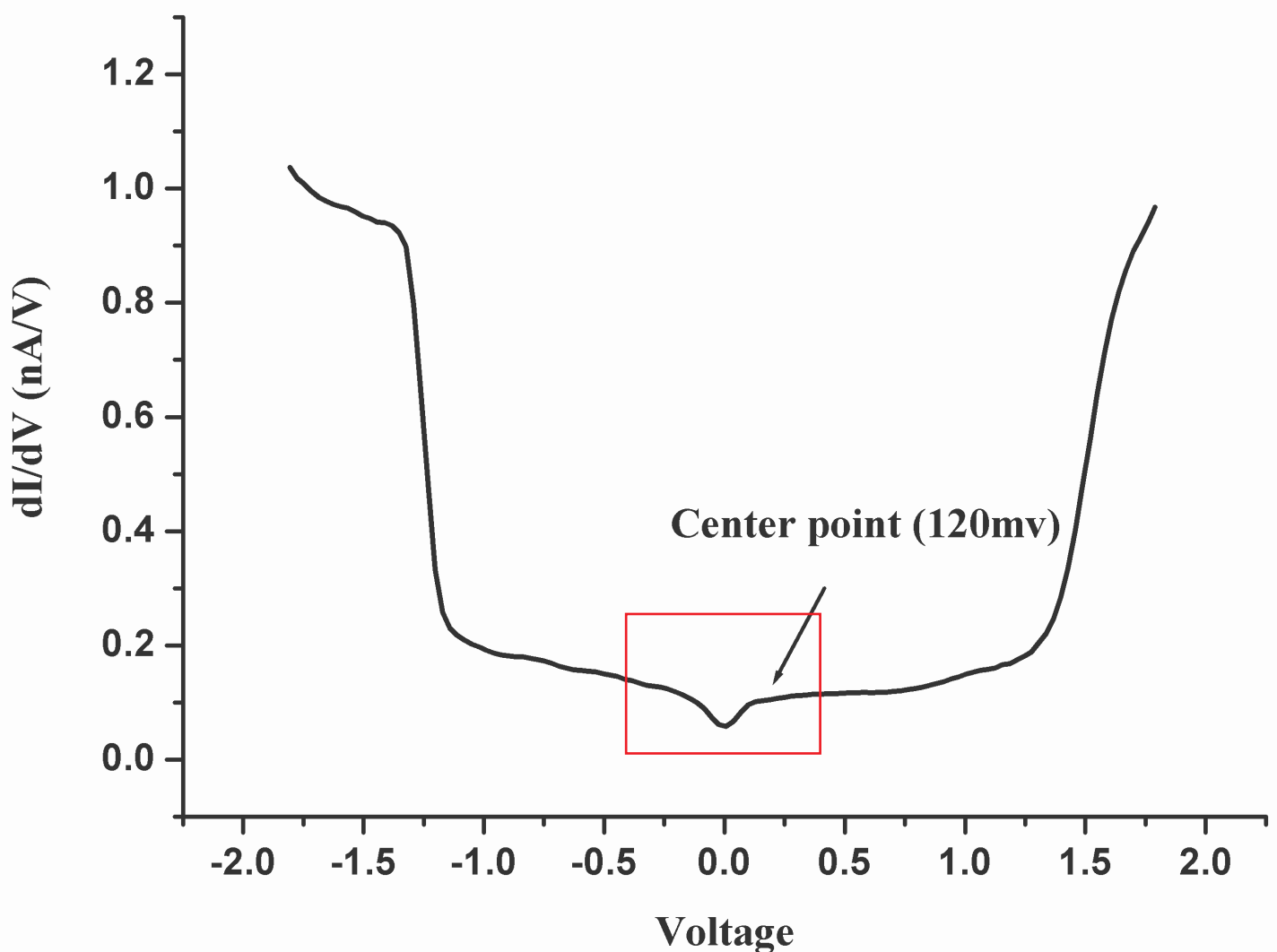
Theory:

A dip at the midpoint of the Van Hove singularities

Experiment:

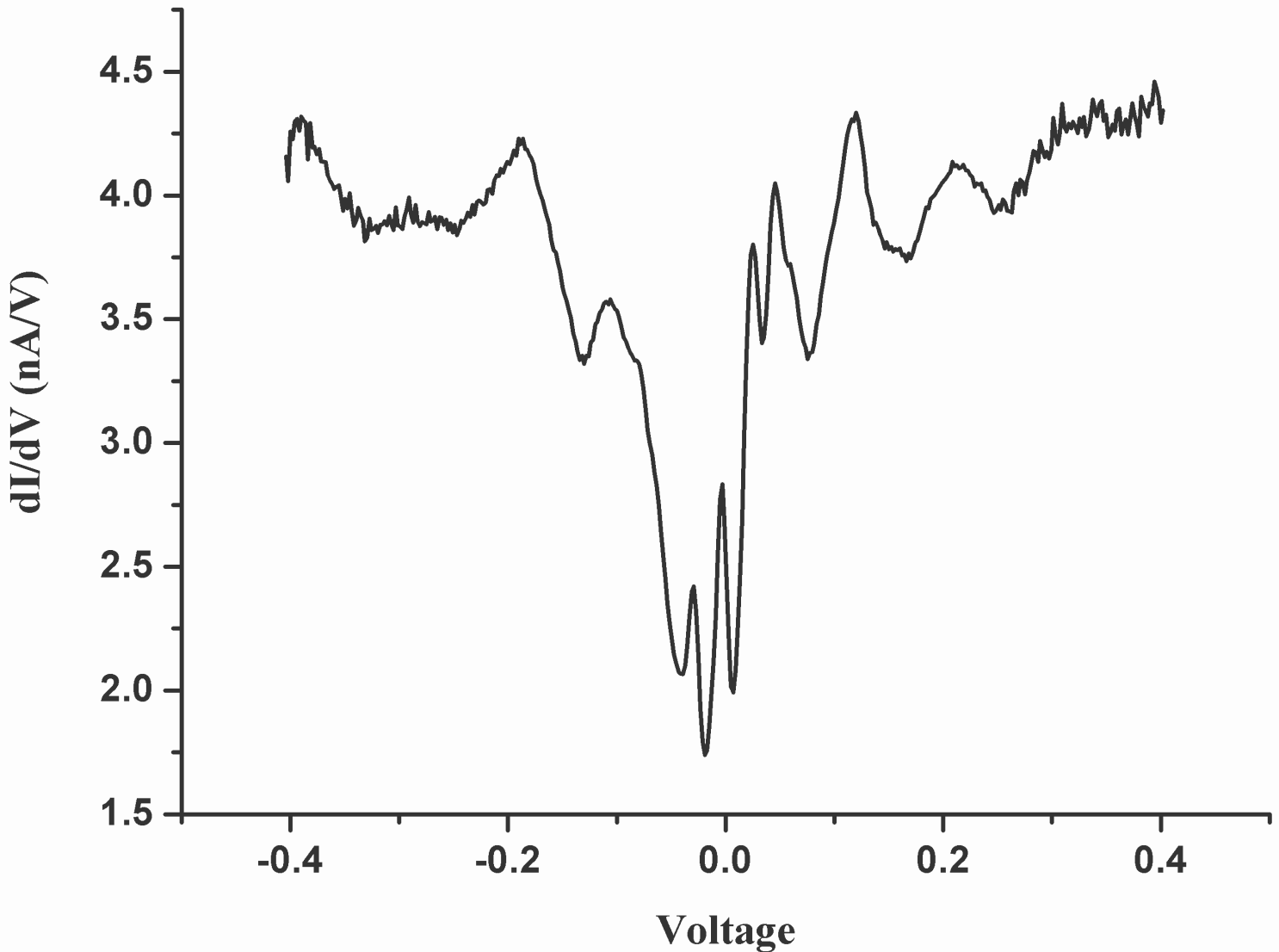
See a Dip at Zero Bias instead

Old Data Showed a smooth dip at Zero Bias



New Data

With Increased Resolution ($\approx 2\text{mV}$)

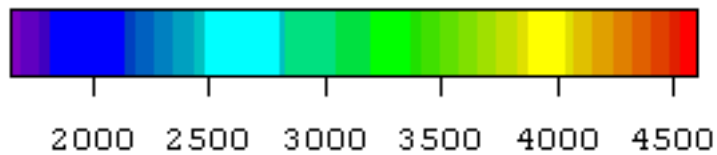
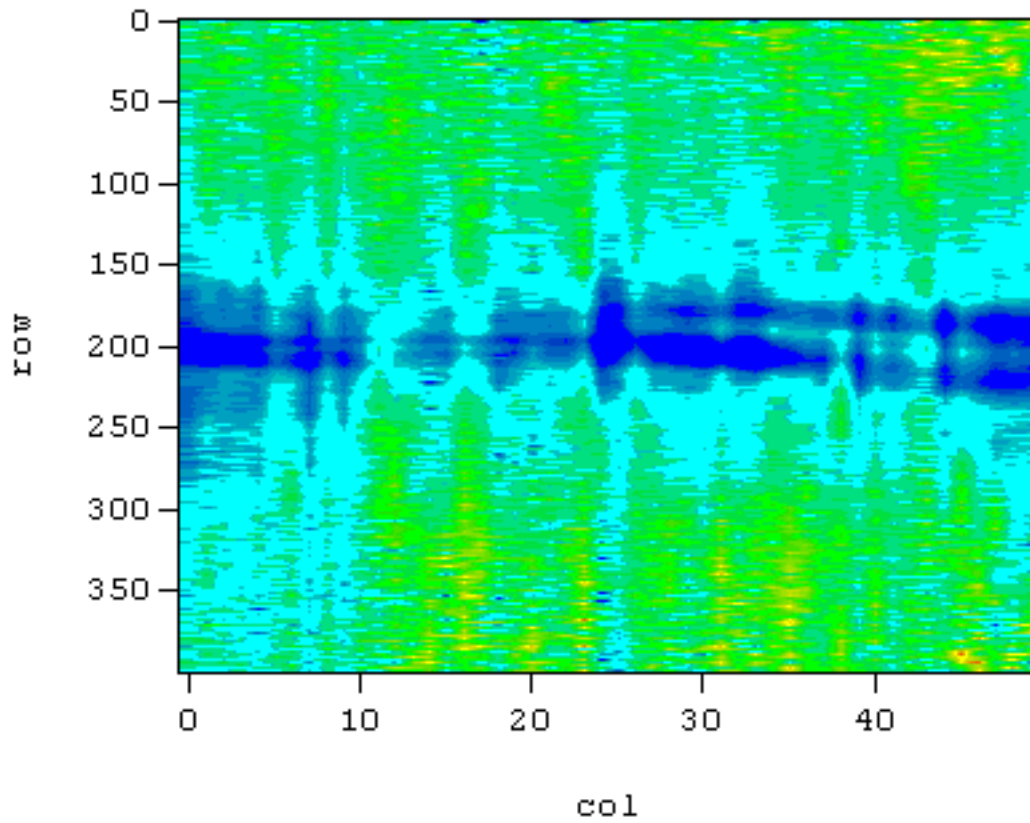


3-6 Peaks

10mV-50mV Spacing

Average of 20mV

Spatially Resolved Structure



m179_213_sf1_dat

Conclusions

The STM has the Resolution Needed to See IETS

**There exists a lot of fine structure that still
defies an explanation**

Future Work

IETS may need to be done at 77K

**A better Spatial resolution of small gap
peak structure**

Coulomb Blockade

