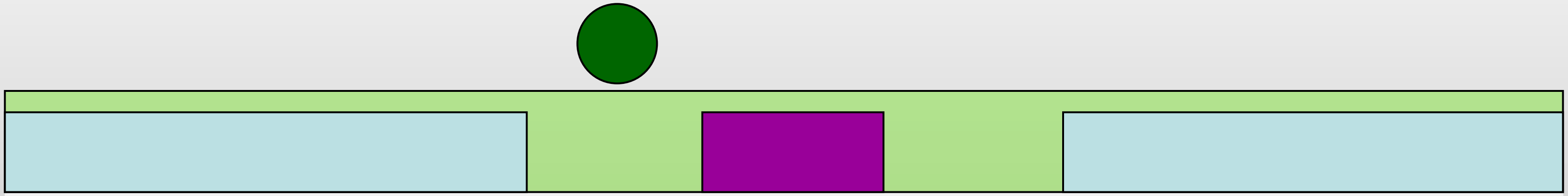
Circuit QED with electrons on helium:

What's the sound of one electron clapping?



David Schuster
Yale (soon to be at U. of Chicago)

Yale:
Andreas Fragner
Rob Schoelkopf

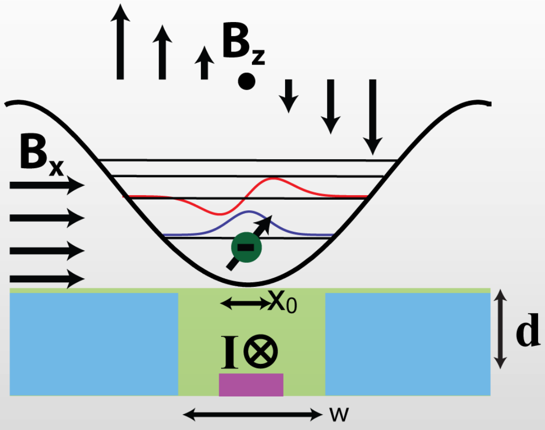
Princeton:
Steve Lyon

Michigan State:
Mark Dykman

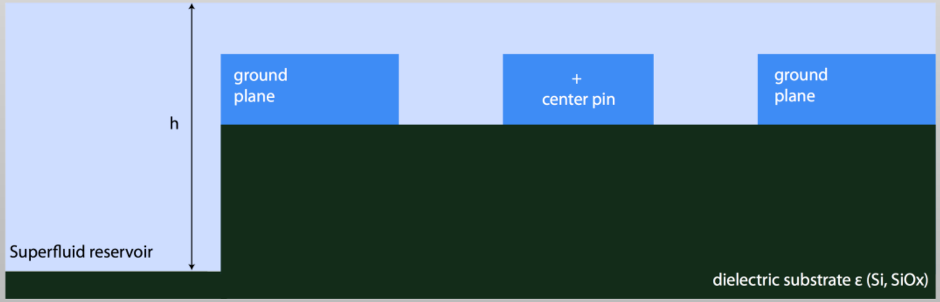
Useful cryogenics discussions: Mike Lea / David Rees

Outline

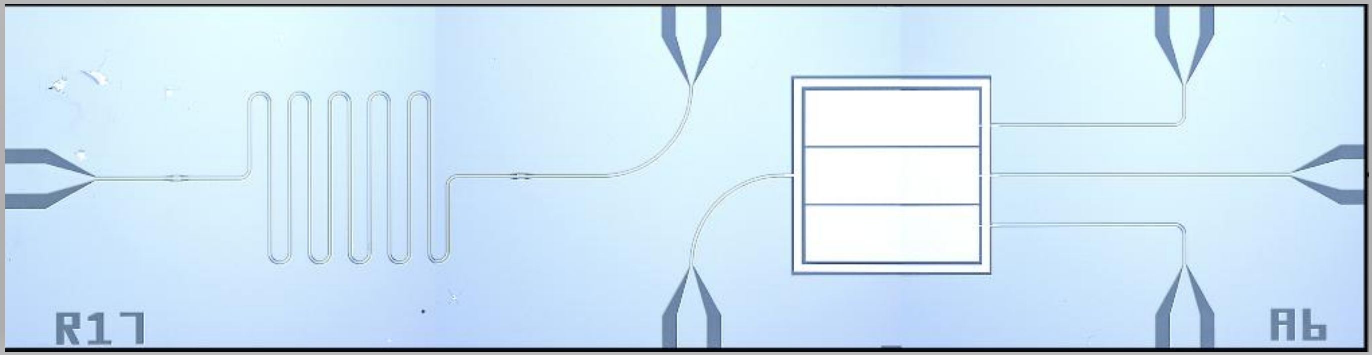
- Circuit QED with electrons on helium



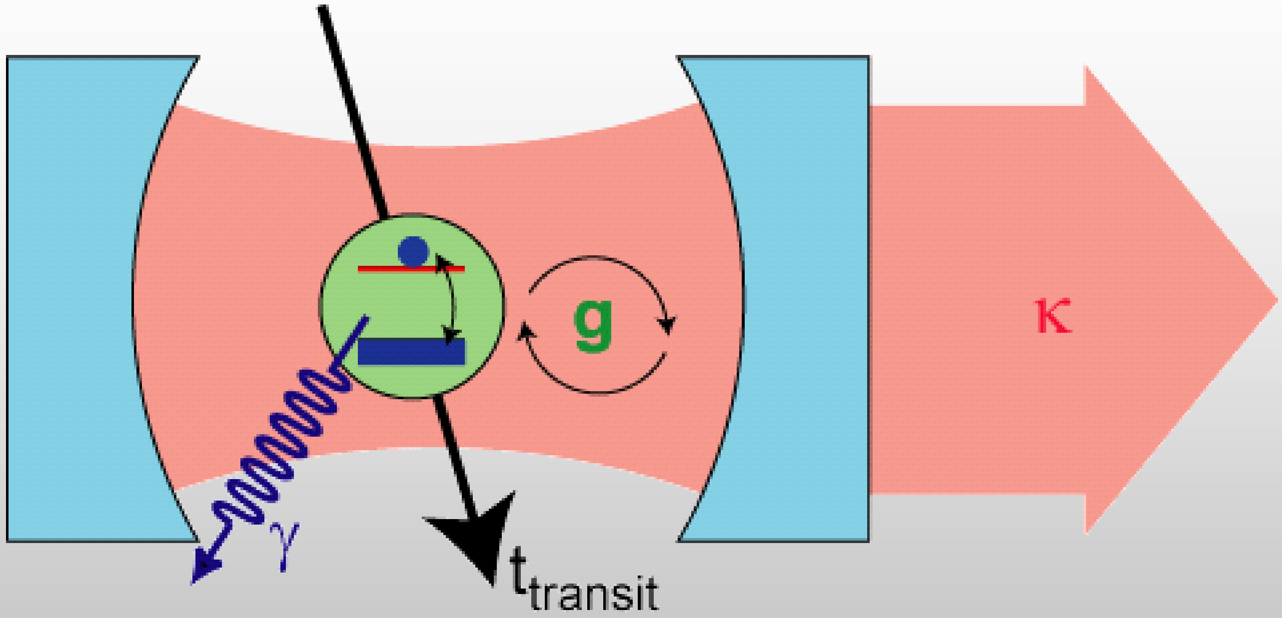
- Super-sensitive level meter



- Some preliminary measurements



Cavity Quantum Electrodynamics (CQED)



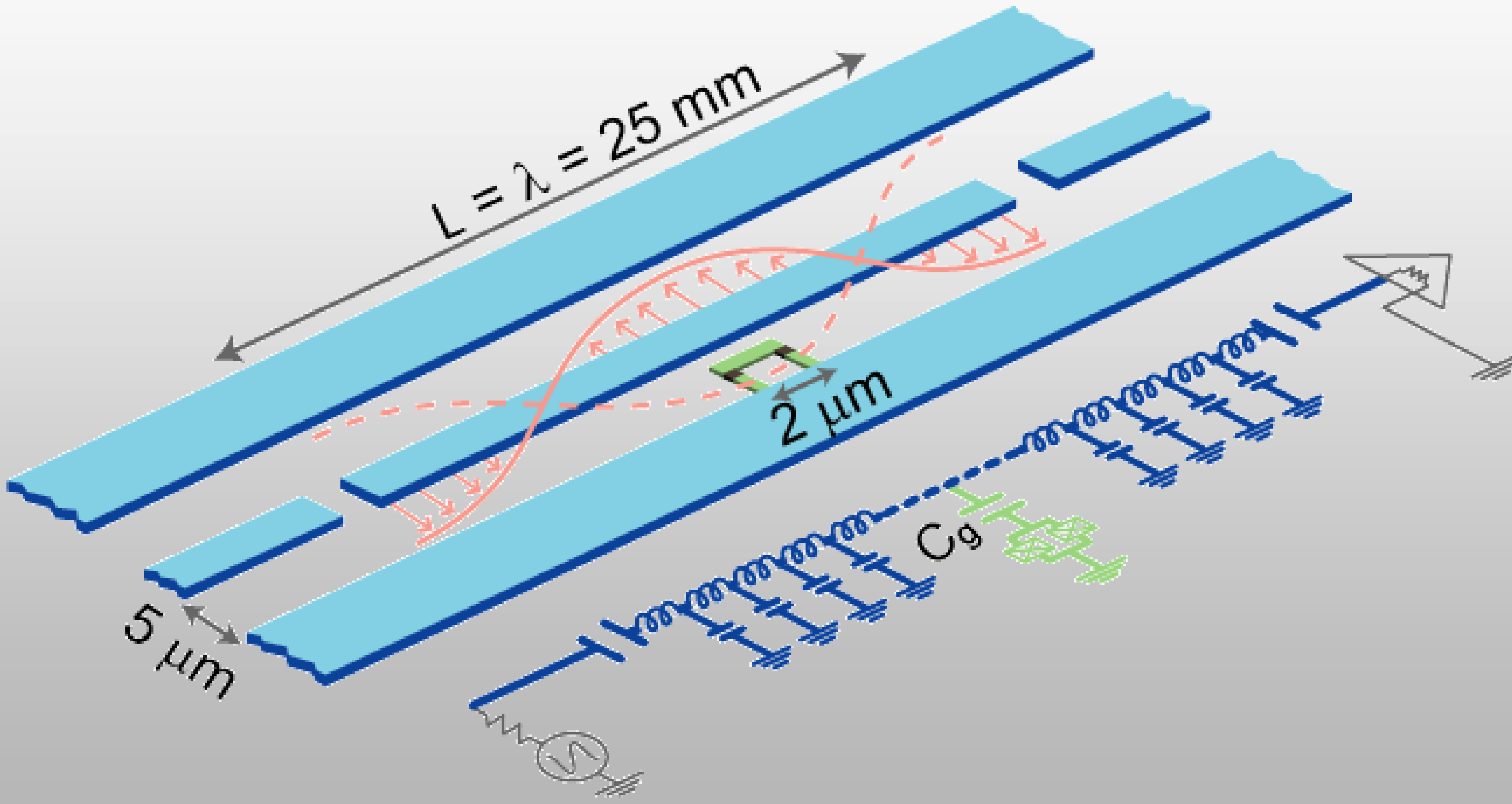
Jaynes-Cummings Hamiltonian

$$H = \hbar\omega_r \left(a^\dagger a + \frac{1}{2} \right) + \frac{\hbar\omega_a}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + a\sigma^+) + H_\kappa + H_\gamma$$

strong coupling limit $(g = dE_0/\hbar > \gamma, \kappa, 1/t_{\mathrm{transit}})$

D. Walls, G. Milburn, Quantum Optics (Spinger-Verlag, Berlin, 1994)

Circuit Quantum Electrodynamics

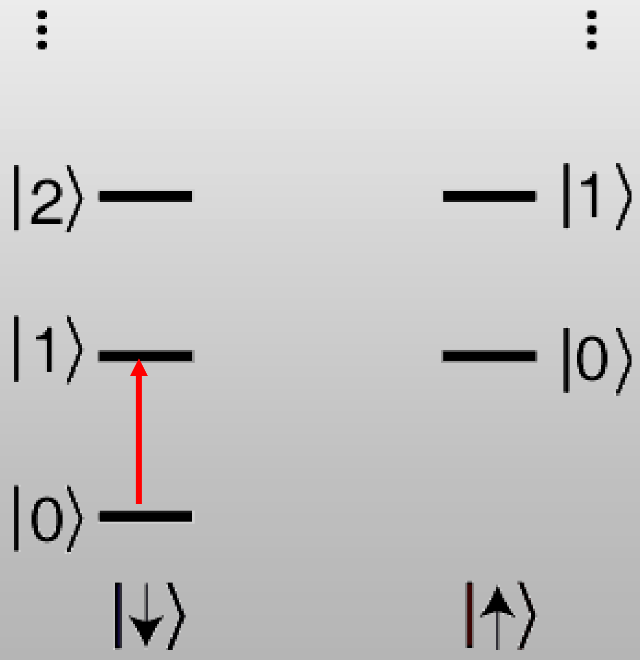


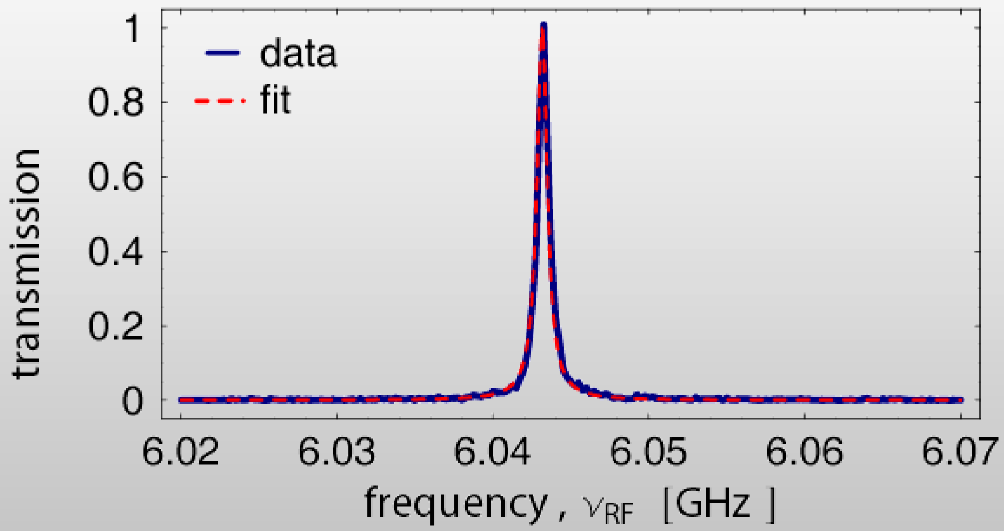
elements

- the cavity: a superconducting 1D transmission line resonator (large E_0)
- the artificial atom: a Cooper pair box (large d)

A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, *PRA* **69,** 062320 (2004)

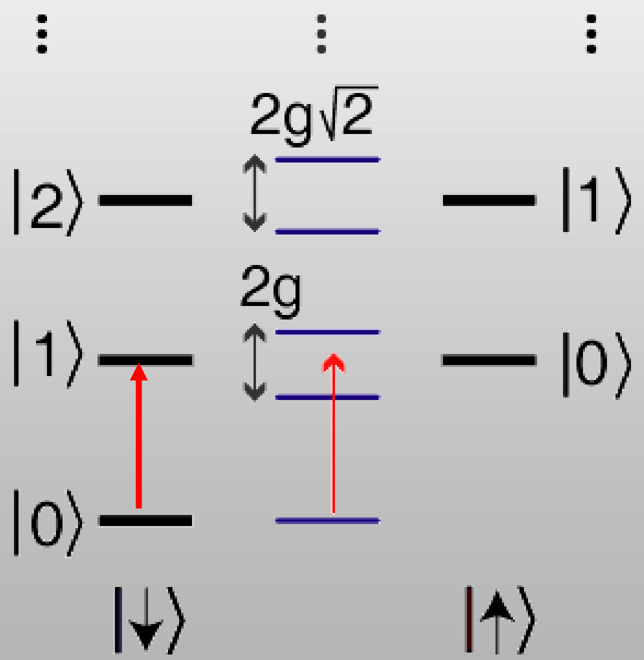
Strong coupling cavity QED!

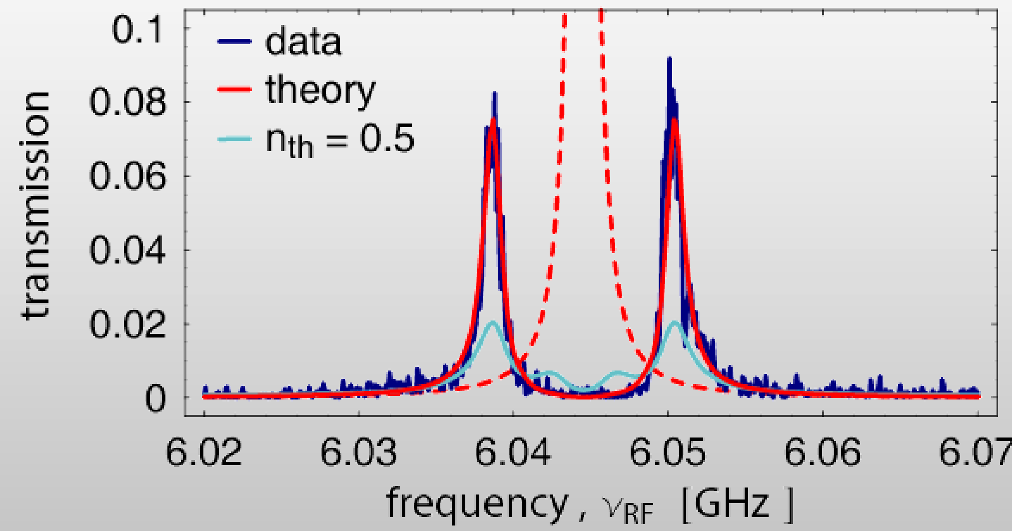




Strong coupling cavity QED!

$$\omega = \omega_r \pm g$$





$$\omega / 2\pi = 6 \text{ GHz}$$

$$2g / 2\pi = 12 \text{ MHz}$$

$$\kappa / 2\pi \approx \gamma / 2\pi = 200 \text{ kHz}$$

$$C = \frac{g^2}{\kappa\gamma} = 3600$$

Wallraff, ***DIS***, et. al. **Nature** 431 162 (2004)

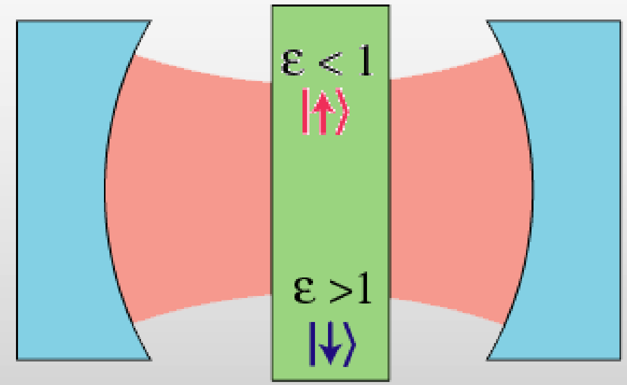
Non-Resonant Qubit Read-Out

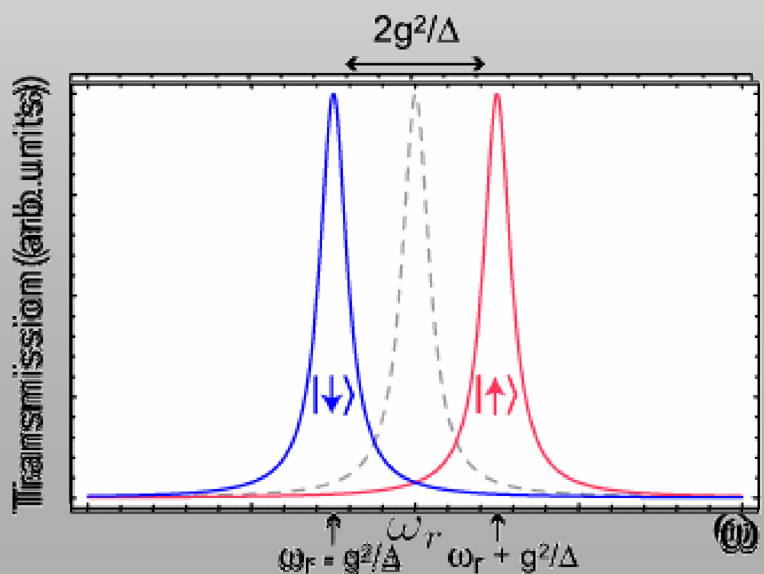
approximate diagonalization for $|\Delta| = |\omega_a - \omega_r| \gg g$

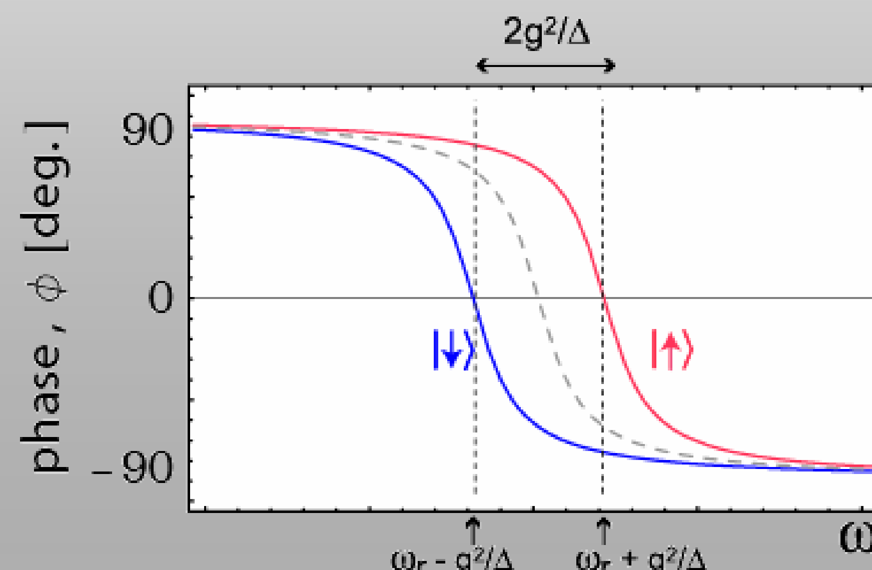
$$H \approx \hbar \left(\omega_r + \frac{g^2}{\Delta}\sigma_z \right) a^\dagger a + \frac{1}{2}\hbar \left(\omega_a + \frac{g^2}{\Delta} \right) \sigma_z$$

// cavity frequency shift *and* qubit ac-Stark shift

// Lamb shift





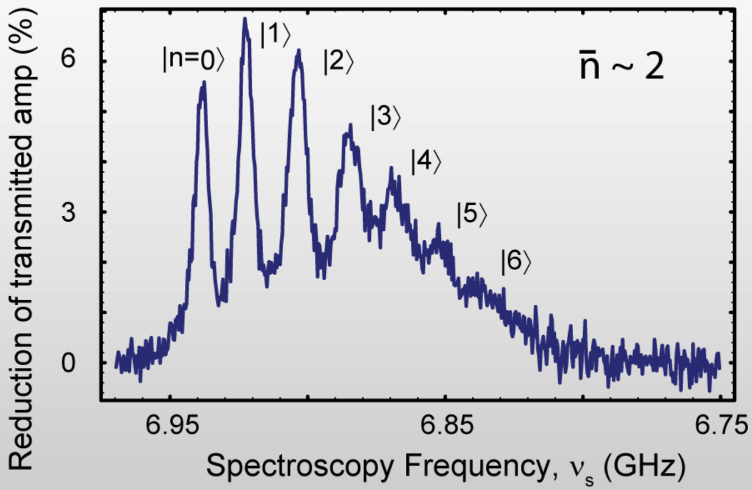


A. Blais, R.-S. Huang, A. Wallraff, S. M. Girvin, and R. J. Schoelkopf, *PRA* **69,** 062320 (2004)

Circuits make good atoms/qubits

Photon number detection

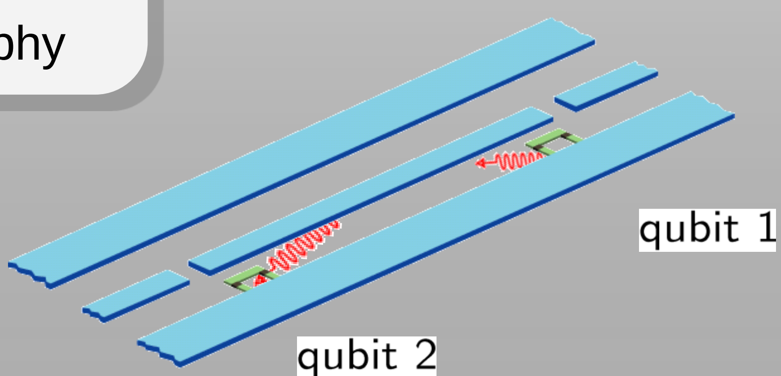
- ✧QND detection of photons
- ✧Qubit / photon gates
- ✧Non-linear optics

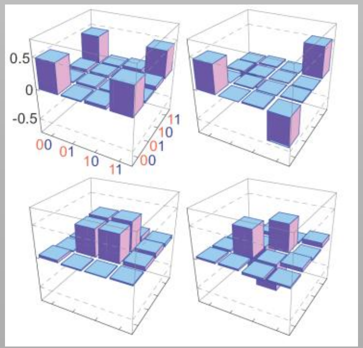


Schuster, Houck, et al., **Nature**, 2007

Coupled qubits

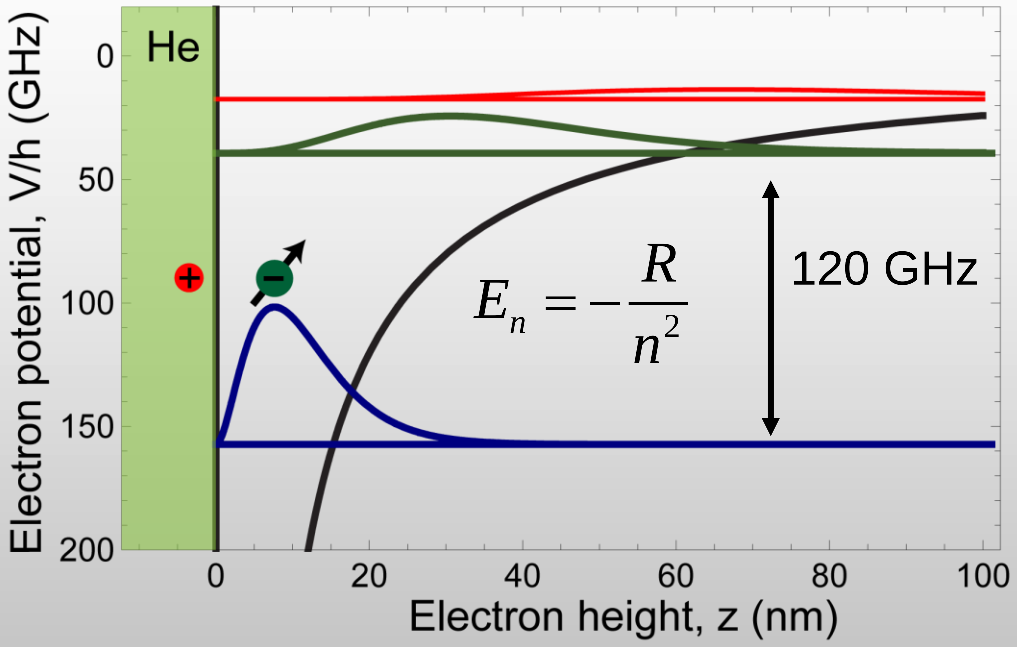
- ✧ Two qubit gates
- ✧ Quantum algorithms
- ✧ Process tomography





DiCarlo, Chow, et. al., **Nature**, 2009

Electrons on helium

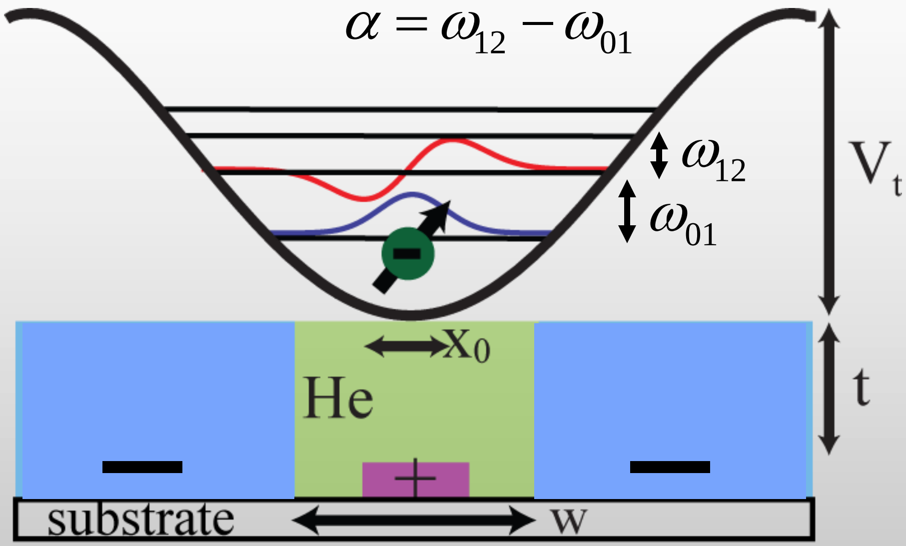


- ✧ Reduced H spectrum
- ✧ Potential well depth ~ R = 8 K
- ✧ “Bohr” radius 8 nm above surface

- ✧ Clean 2DEG (Mobility = 10^{10} cm^2/Vs)
- ✧ Bare electron: m_{eff} = 1.005 m_e, g = 2
- ✧ <1 ppm ^3He nuclear spins
  Bulk spin coherence time > 50 ms*

QC Proposal w/ vertical states: Dykman, Science 1999

An electron in an anharmonic potential



$$\frac{eV_t}{h} = 150 \text{ GHz}$$

$$w = 1\ \mu\text{m}$$

$$t = 1\ \mu\text{m}$$

$$\frac{\omega_{01}}{2\pi} \sim 10 \text{ GHz}$$

$$\frac{\alpha}{2\pi} \sim 100 \text{ MHz}$$

$$x_0 \sim 30\text{nm}$$

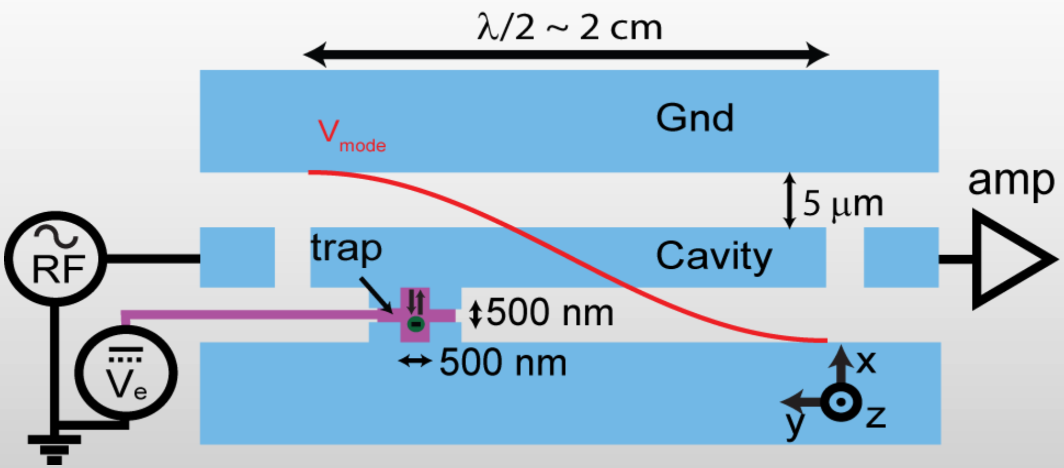
Big dipole moment! $\sim 1000D$

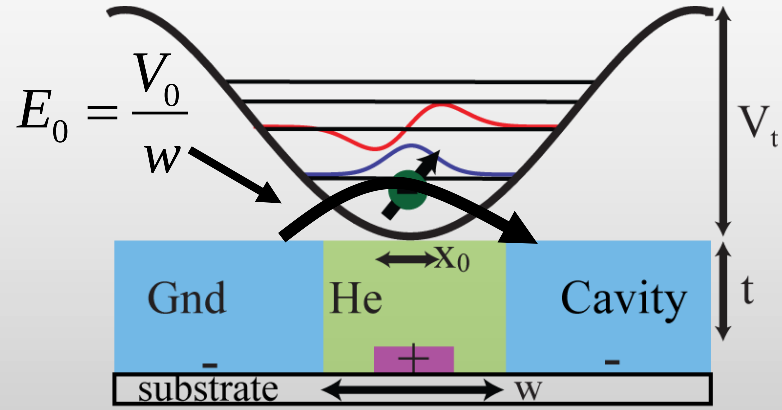
✧ DC electrodes to define trap for **lateral** motion

✧ Nearly harmonic motion with transitions at ~ GHz

✧ Anharmonicity from small size of trap (~ 1μm)

An electron in a cavity





✧ Electron motion couples to cavity field

✧ Can achieve strong coupling limit of cavity QED

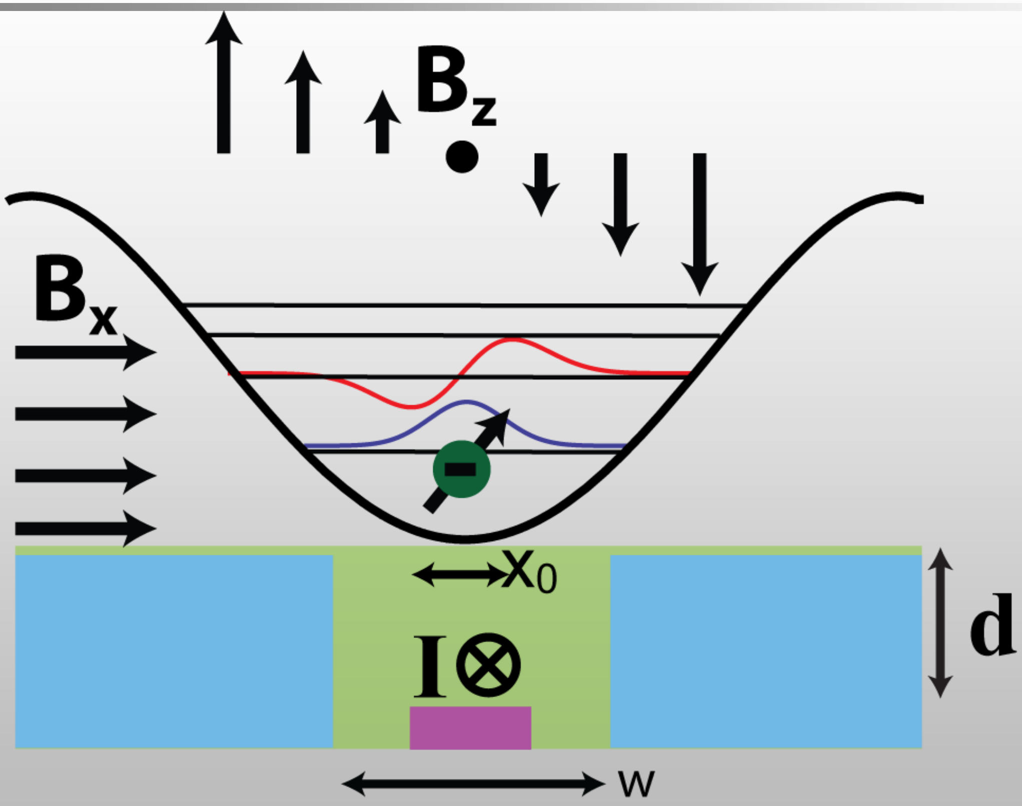
✧ Couple to other qubits through cavity bus

Cavity-electron coupling

$$\hbar g \sim e x_0 \frac{V_0}{w} \sim h \times 25\text{MHz}$$

Schuster, Dykman, et. al. arxiv:0912.1406 (2009)

Accessing spin: Gradient method



$$H_{sb} = -\mu_B \nabla \vec{B} \cdot \vec{s} \sim -\mu_B \Delta B_z \hat{\sigma}_x \hat{s}_x$$

- ✧ Electricaly tunable spin-motion coupling!
- ✧ With no flux focusing and current geometry: 100 kHz/mA

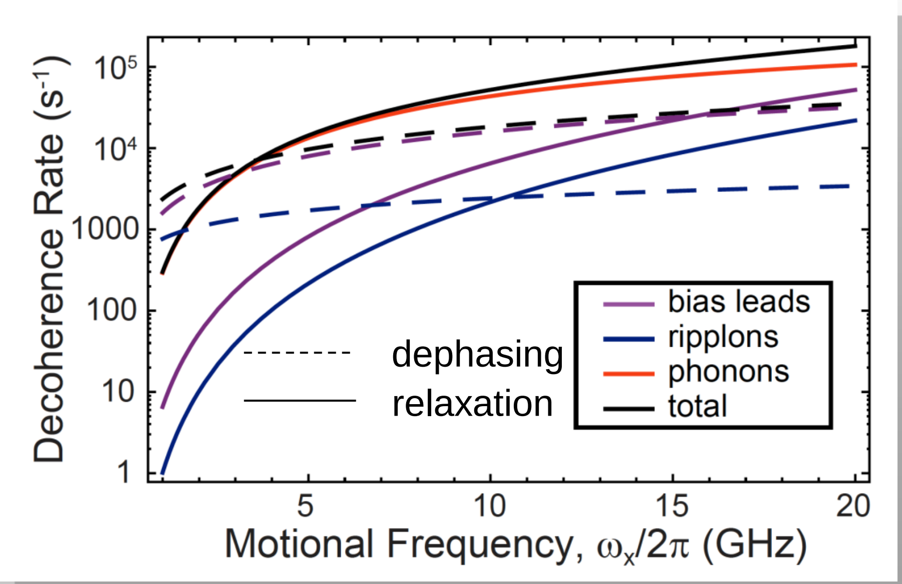
Decoherence Mechanisms

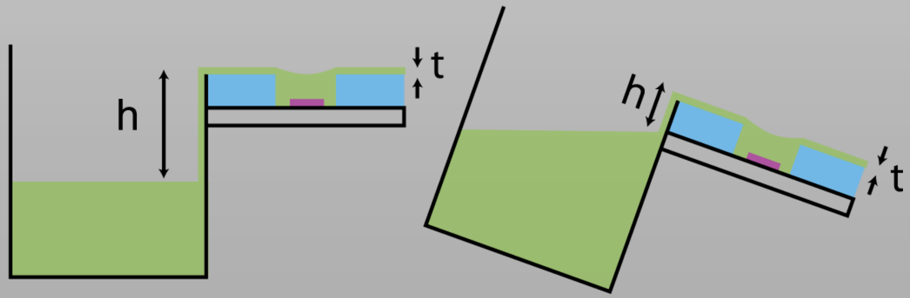
- **Motional Decoherence**

✧ Relaxation through bias electrodes

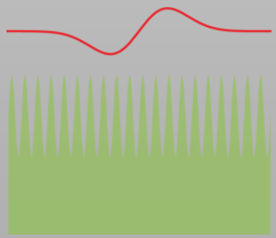
✧ Emission of (two) ripplons

✧ Emission of phonons

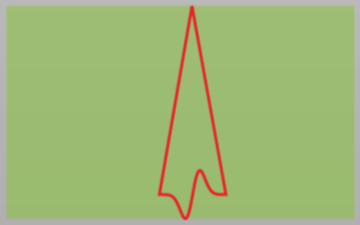




Classical helium fluctuations

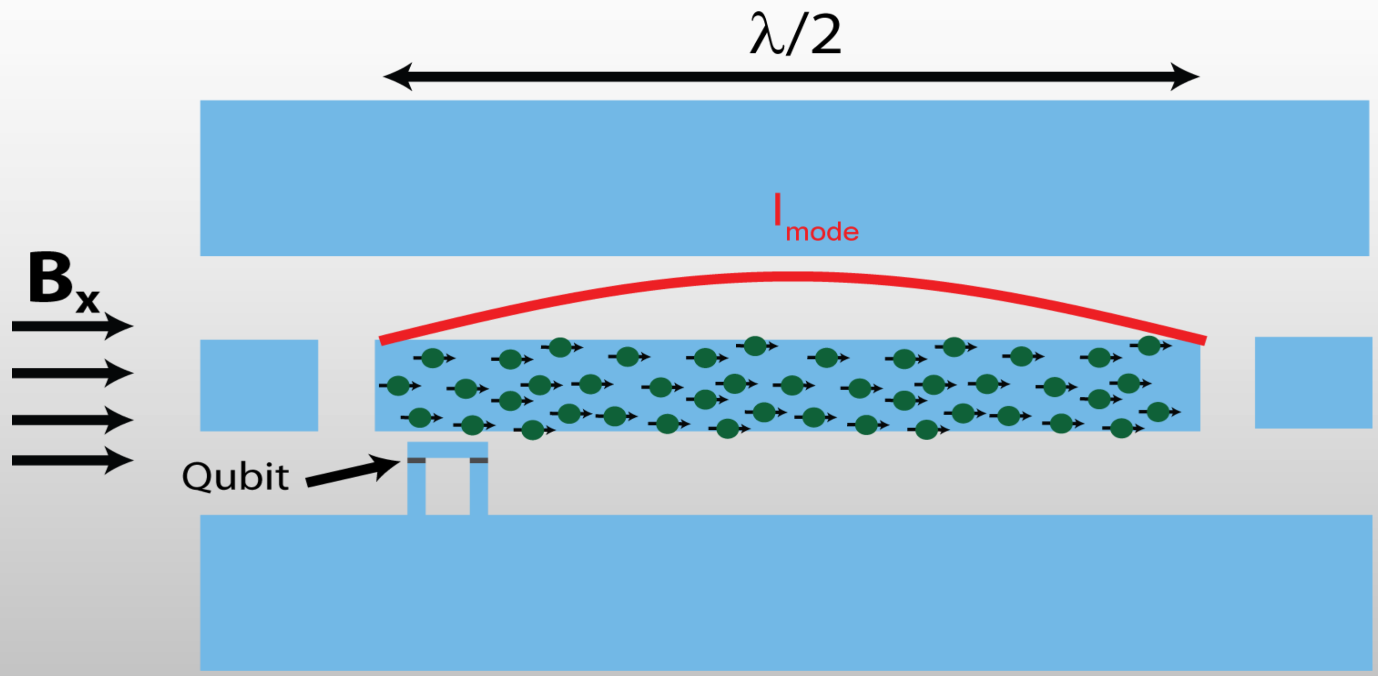


Ripplons



Phonons

eOnHe spin memory



✧Put many electrons on top of the resonator.

✧Spins coupled to resonator magnetic field.

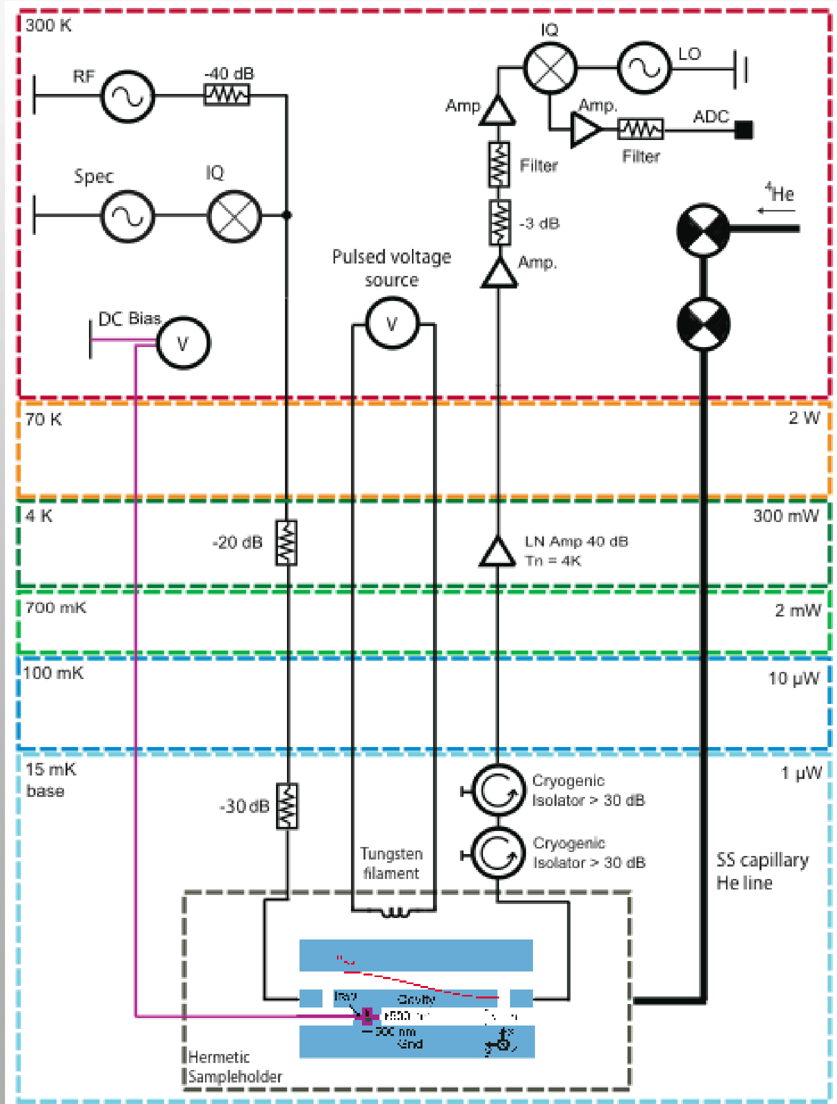
$$\frac{g}{2\pi} \sim 100\text{Hz} - 1\text{kHz}$$

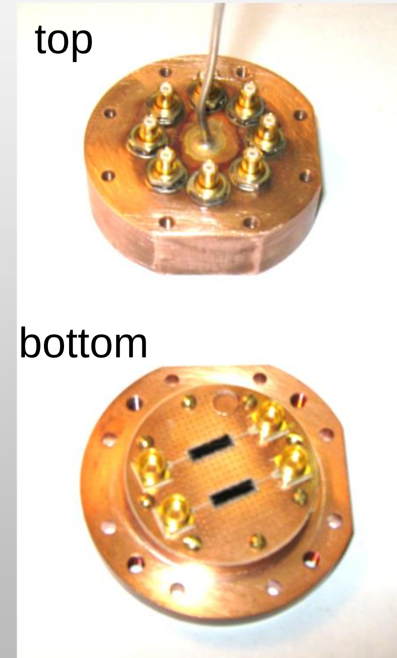
$$\frac{g}{2\pi}\sqrt{M} \sim 10\text{kHz} - 100\text{kHz}$$ with ~10^4 spins

Even basic ESR has never been done on eOnHe 2DEG!

Experimental Setup

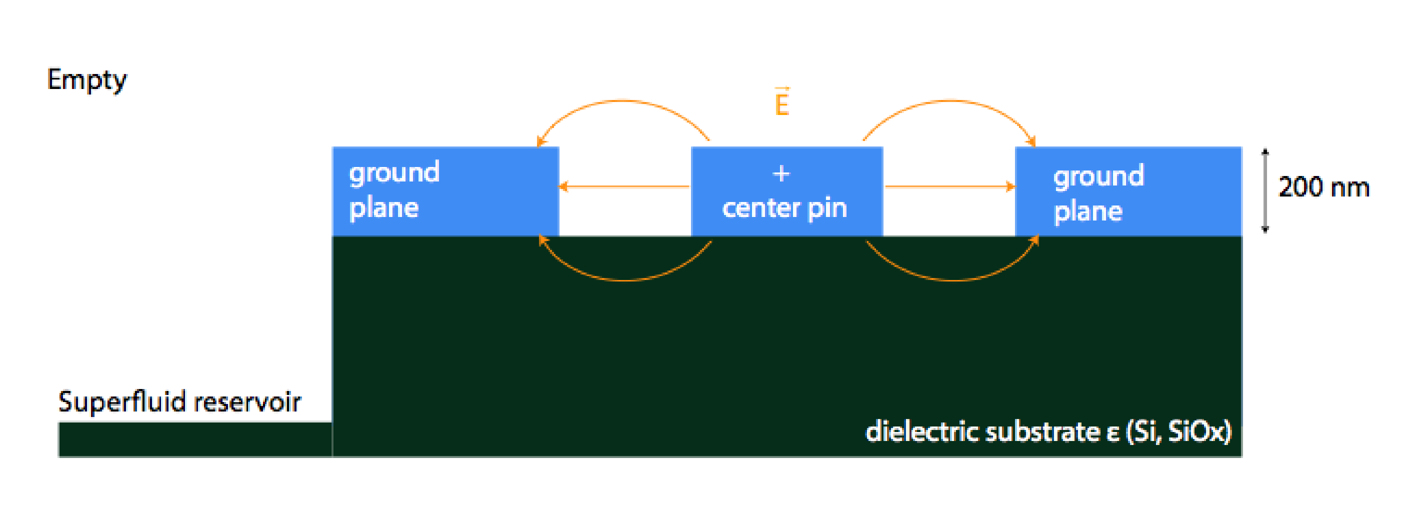
- **Pulse-tube cooled dilution refrigerator**



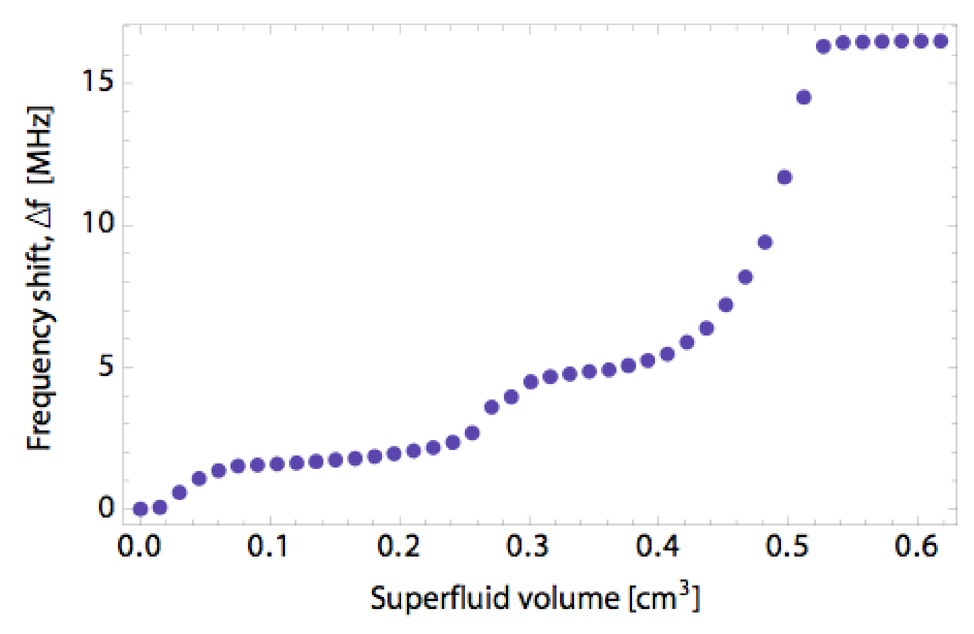


- hermetic sample holder with Indium sealing & stainless steel capillary
- no superfluid leaks down to 10mK

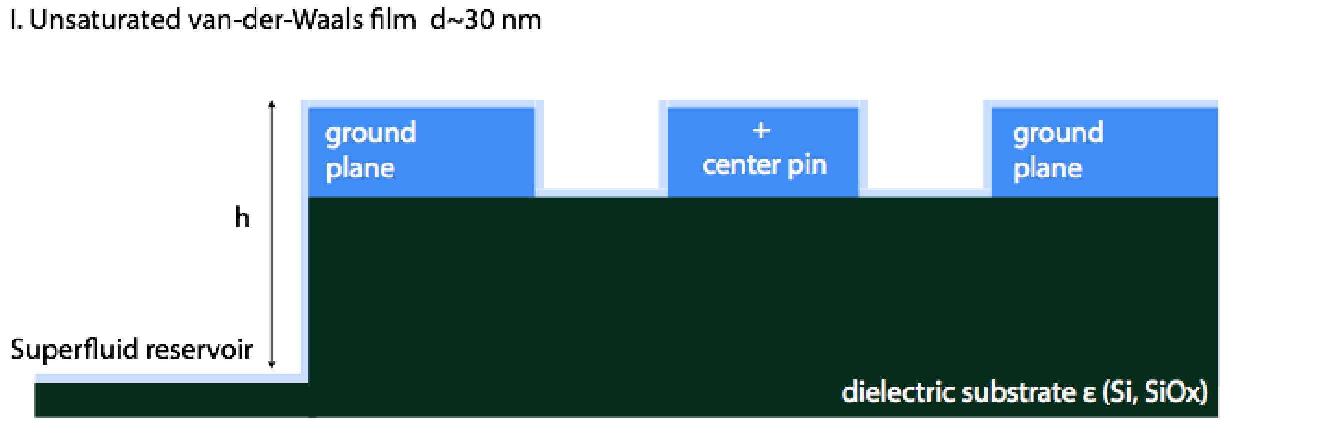
Superconducting Cavities as liquid He-Meters



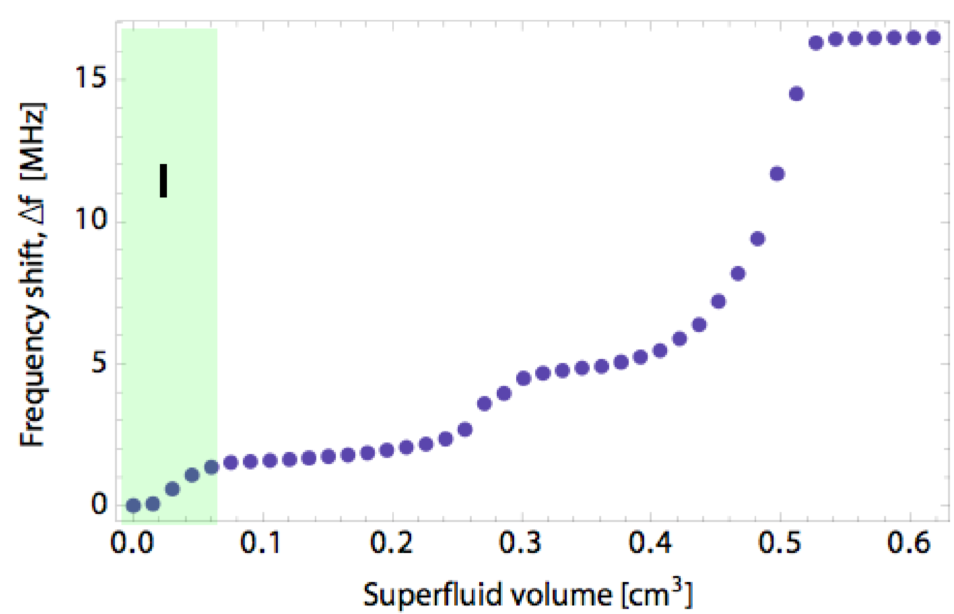
Experiment



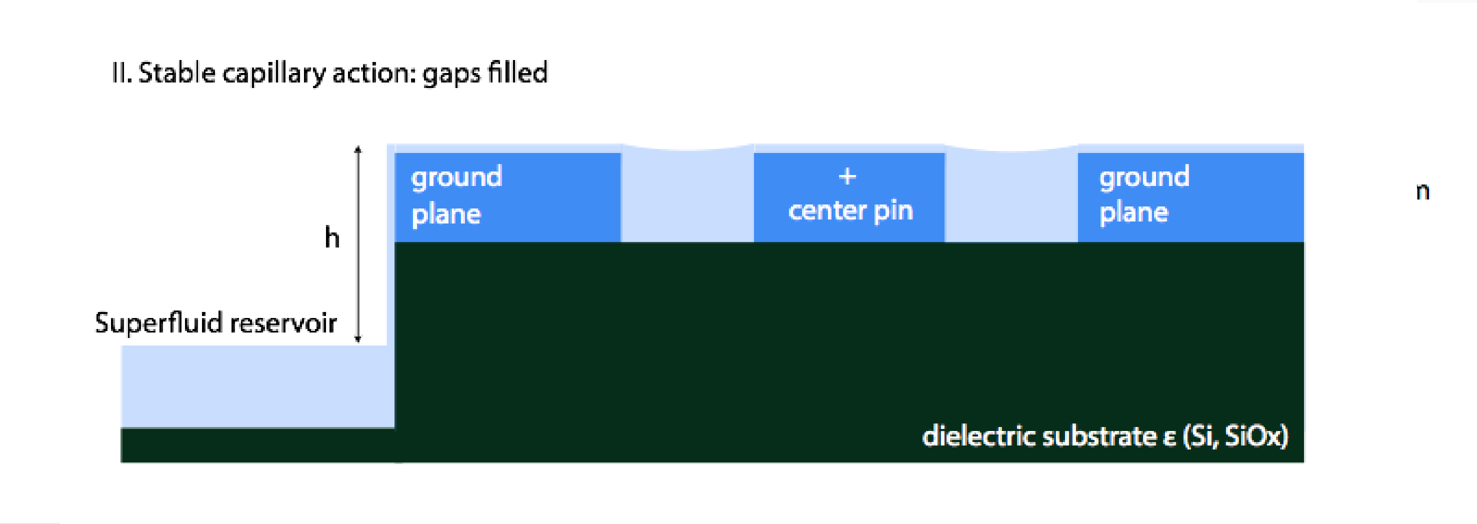
Superconducting Cavities as liquid He-Meters



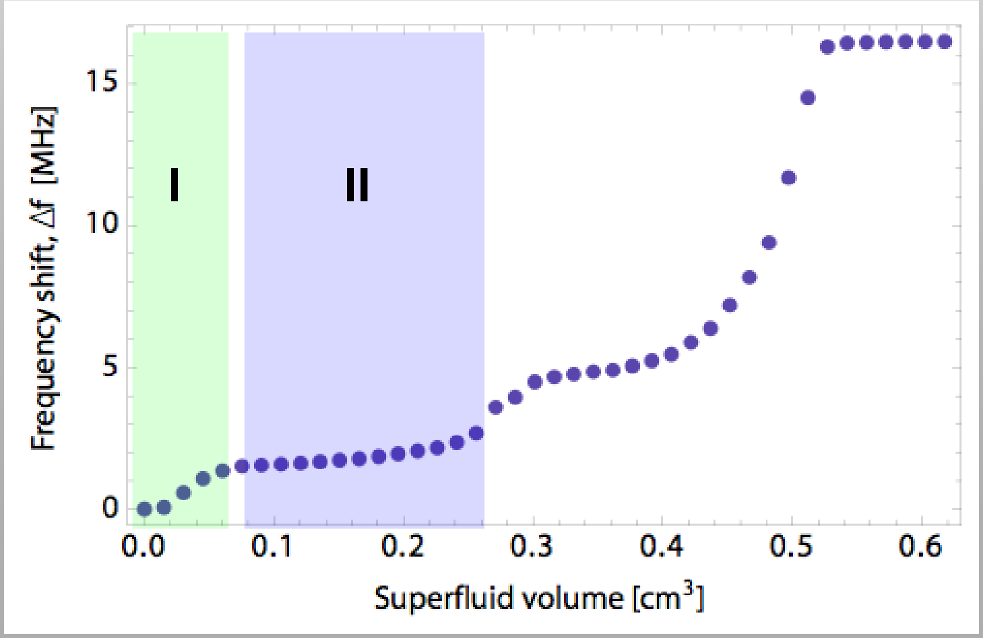
Experiment



Superconducting Cavities as liquid He-Meters

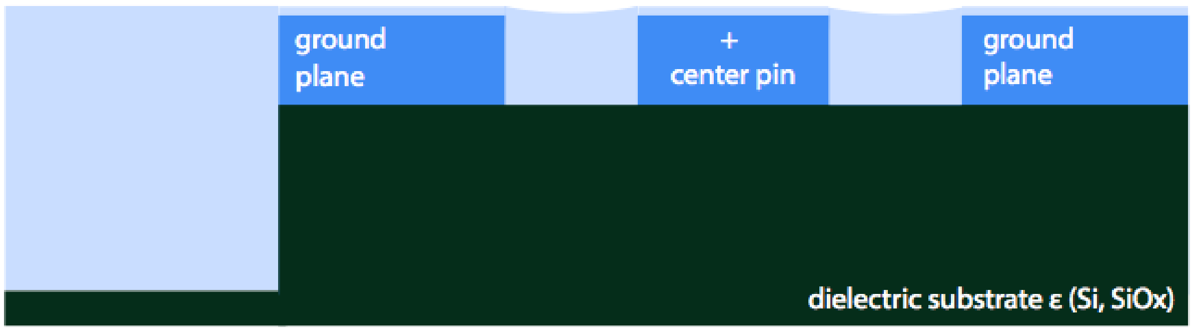


Experiment

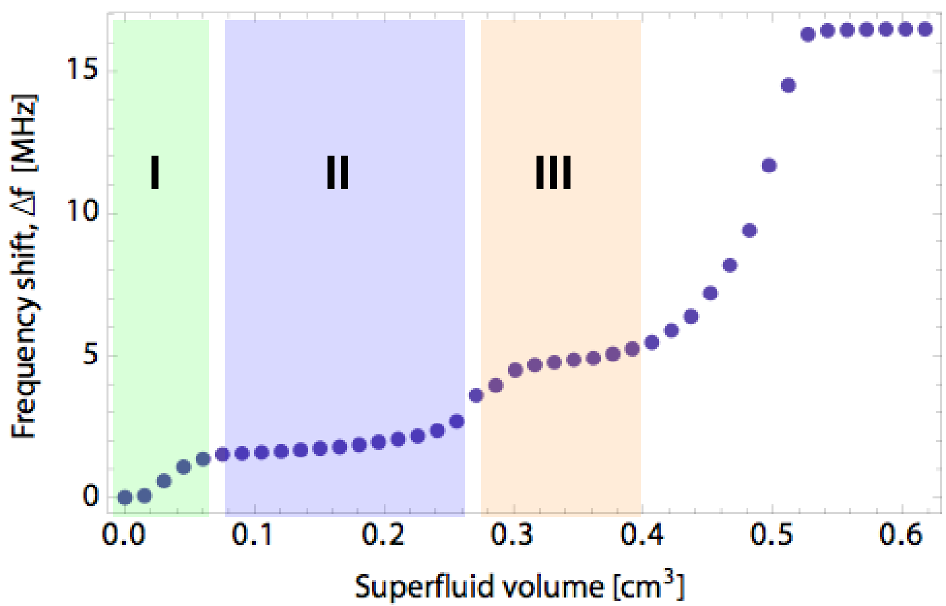


Superconducting Cavities as liquid He-Meters

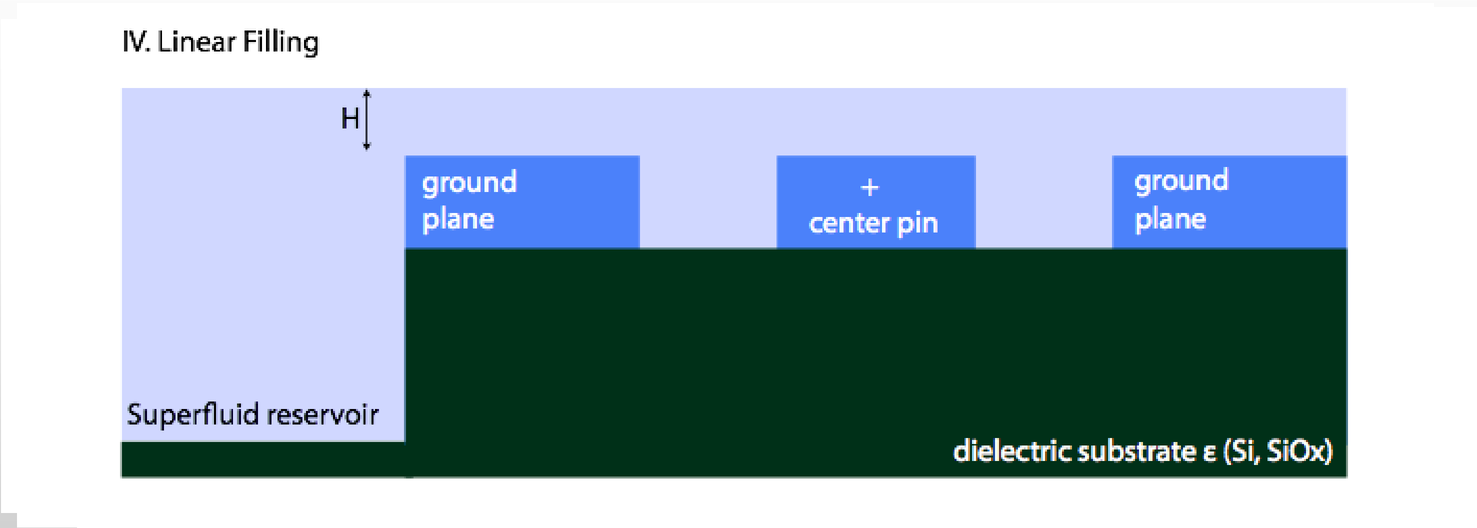
III. Unstable capillary action



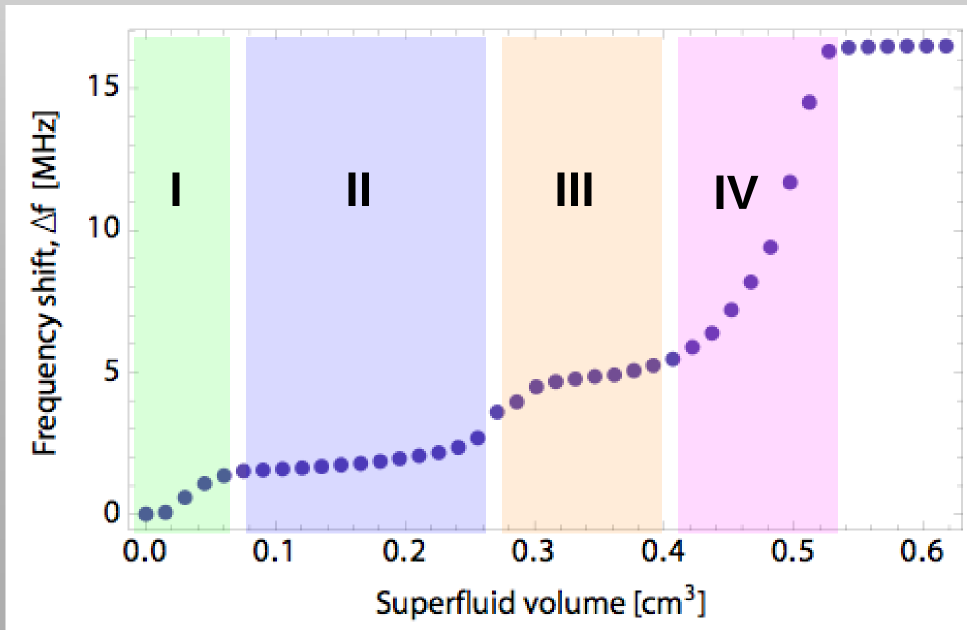
Experiment



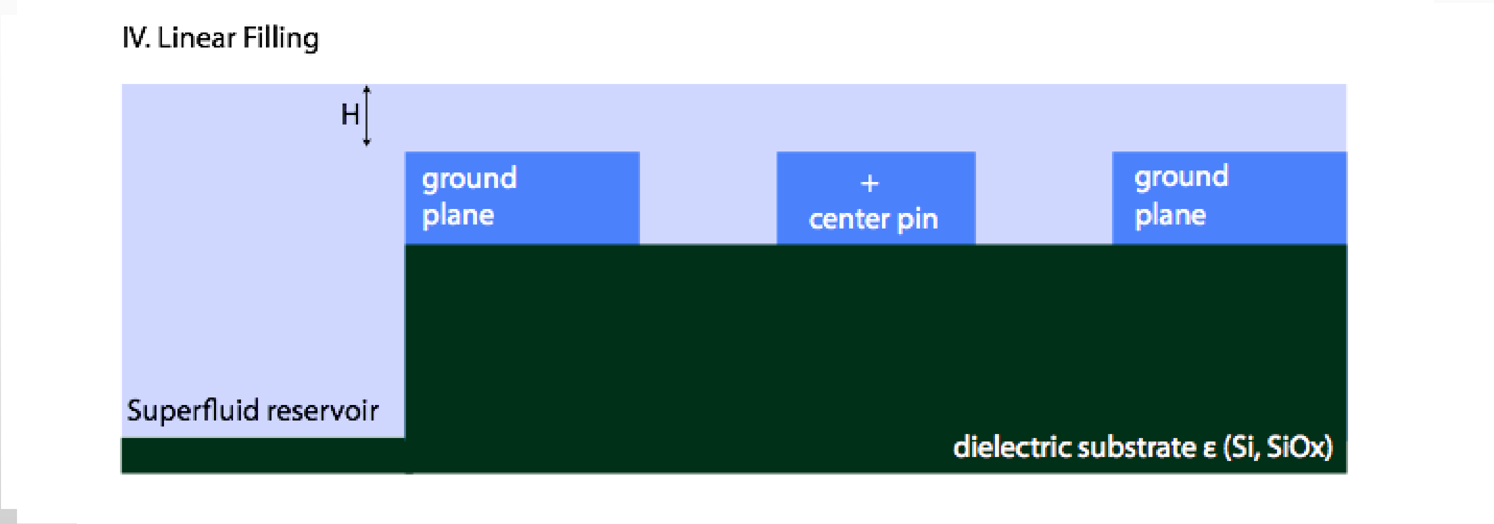
Superconducting Cavities as liquid He-Meters



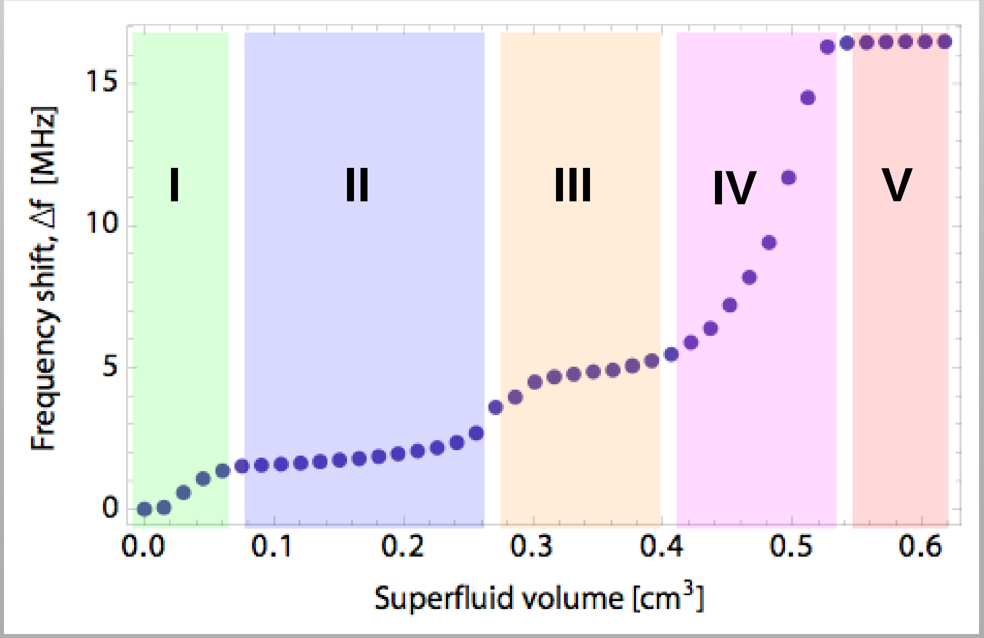
Experiment



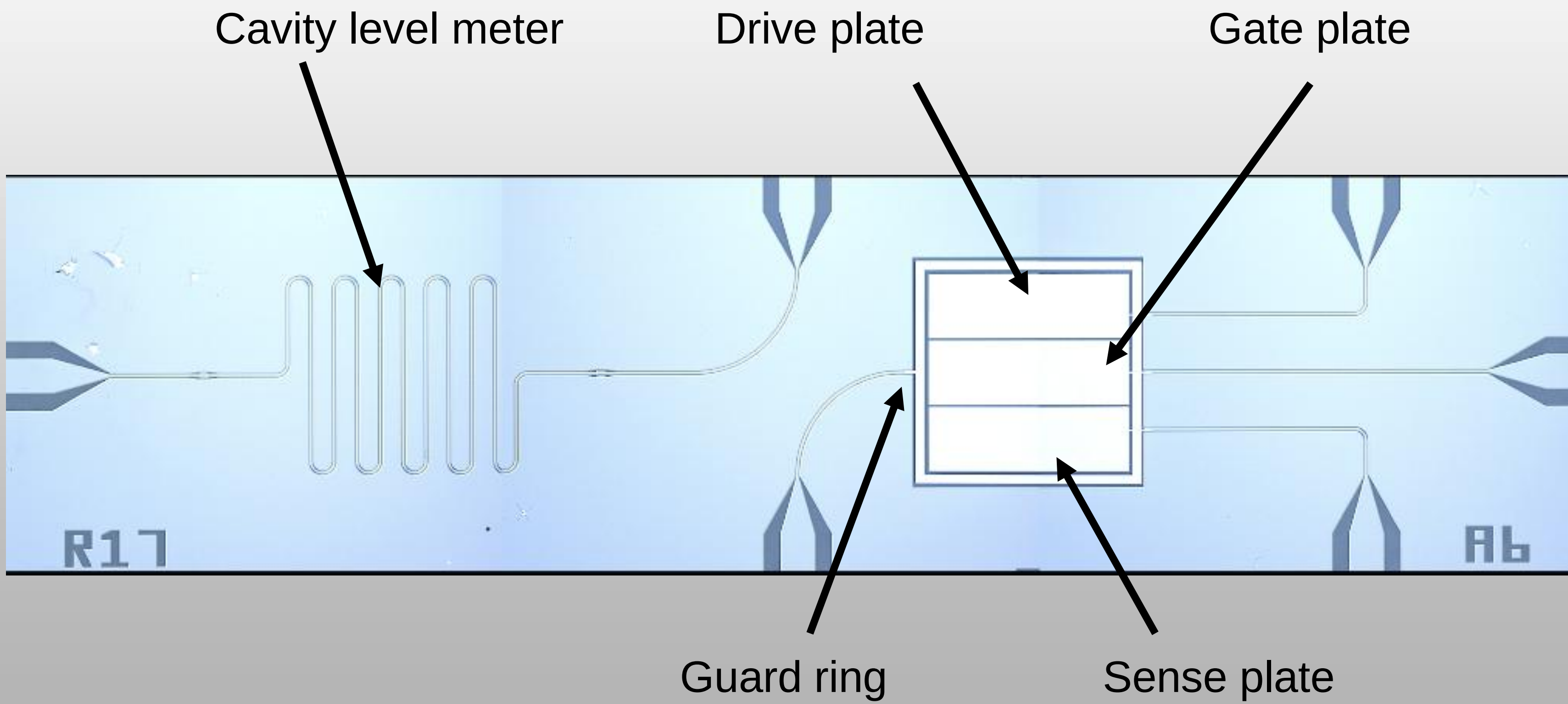
Superconducting Cavities as liquid He-Meters



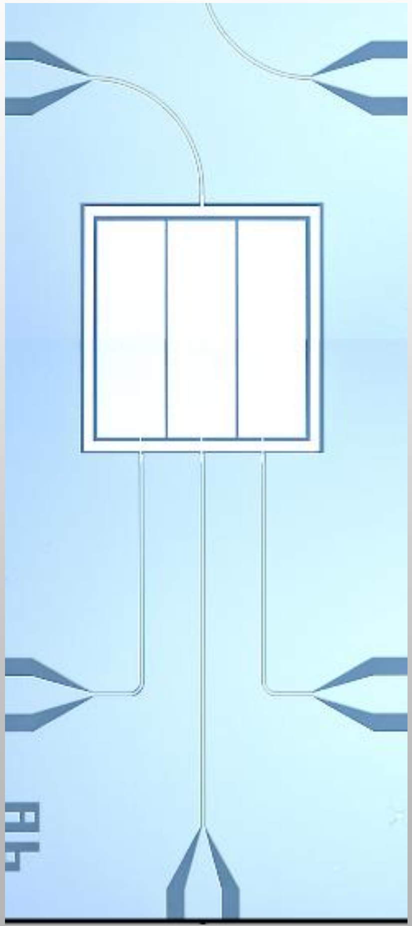
Experiment

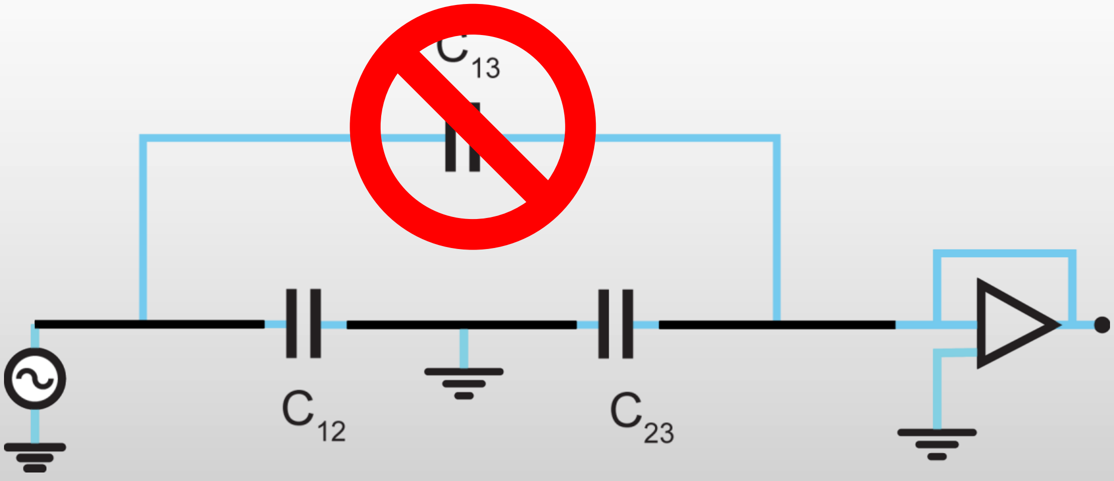


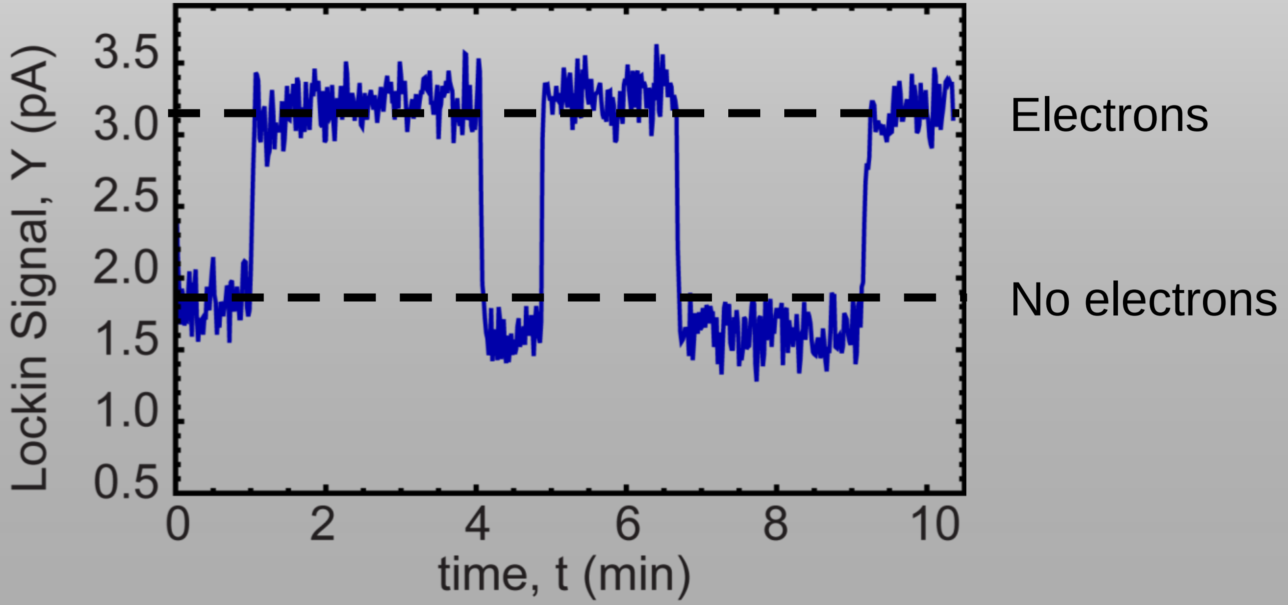
Anatomy of an "eon" trap



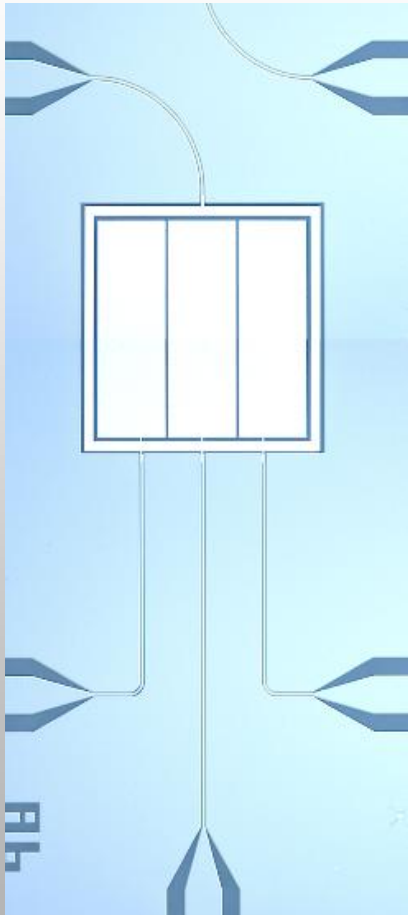
Detecting trapped electrons on helium

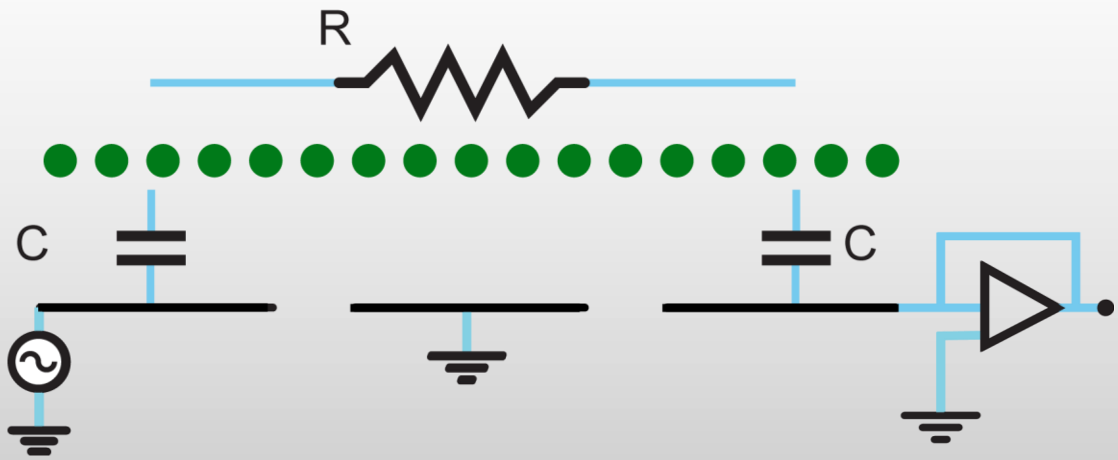


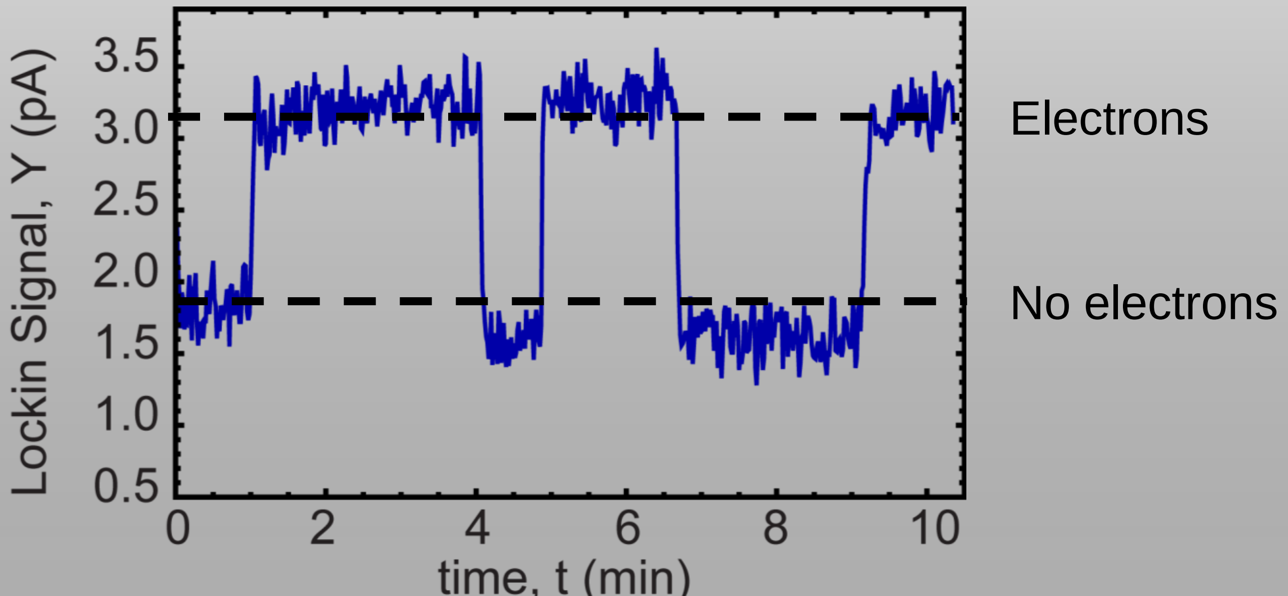




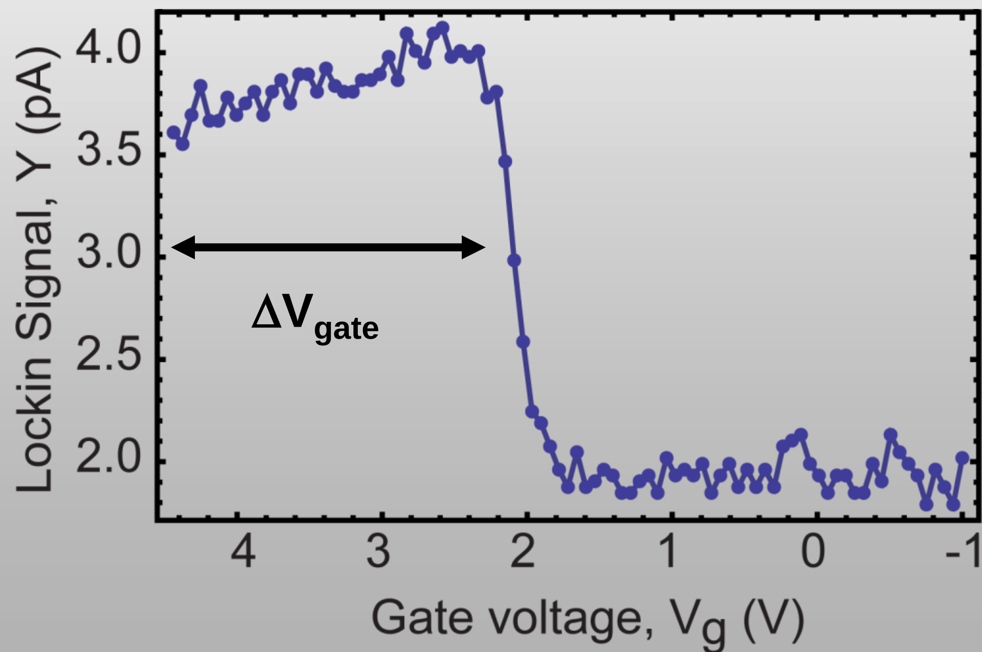
Detecting trapped electrons on helium







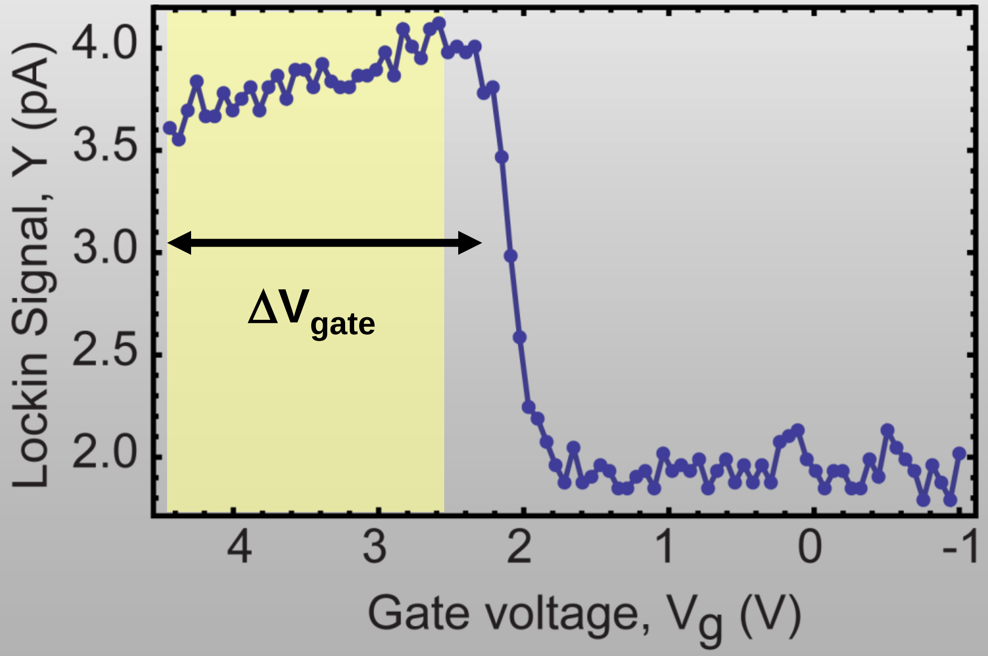
Making an eonhe transistor (eonFET)



✧ Modulate density without losing electrons

✧ Measure density ~10^9 e/cm^2 (~few e/um^2)

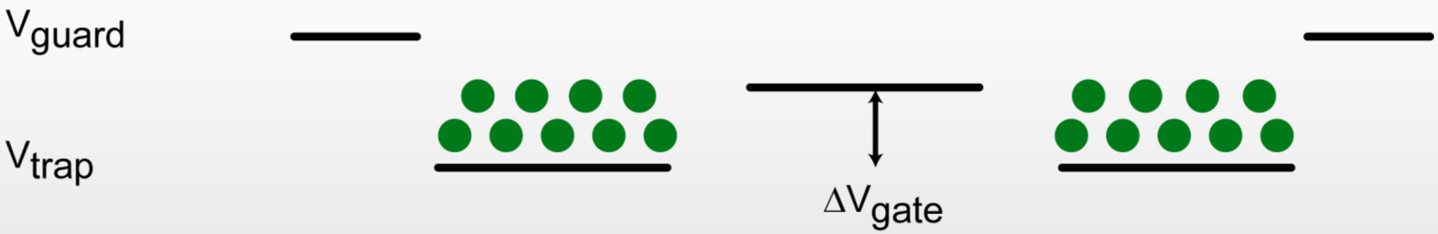
Making an eonhe transistor (eonFET)

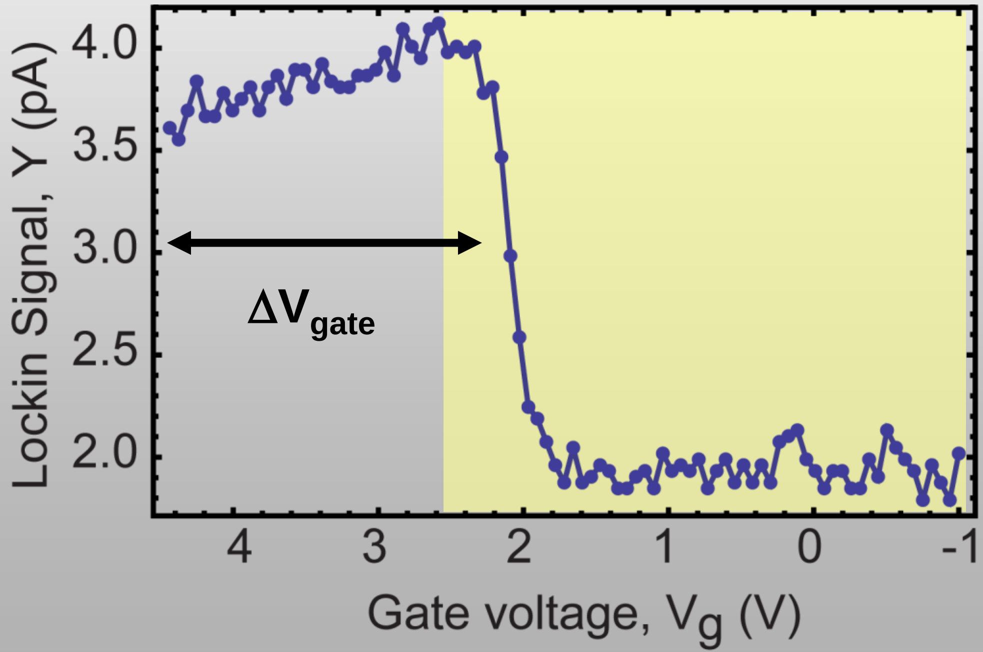


✧ Modulate density without losing electrons

✧ Measure density ~10^9 e/cm^2 (~few e/um^2)

Making an eonhe transistor (eonFET)





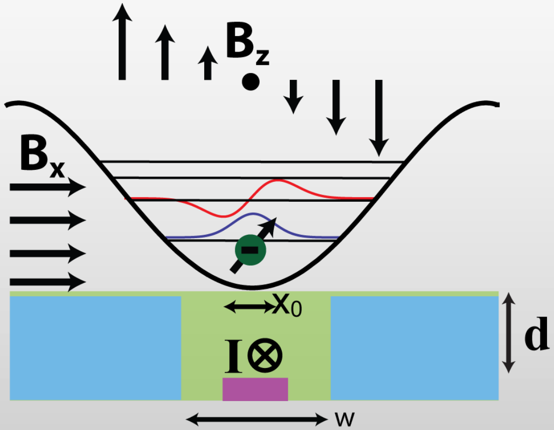
✧ Modulate density without losing electrons

✧ Measure density ~10^9 e/cm^2 (~few e/um^2)

Conclusions

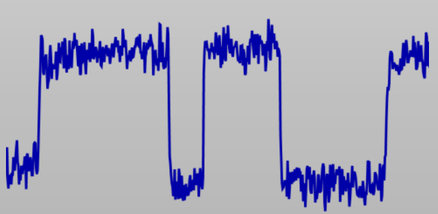
Electrons on Helium:

- Strong coupling limit easily reached
- Good coherence times for motion and spin
- Rich physics - single electron dynamics, motional and spin coherence, superfluid excitations, etc.



We see electrons on helium!!

- Can trap at 10 mK without much heating (~100mK)
- Can hold them for hours



Next up: Trapping single electrons