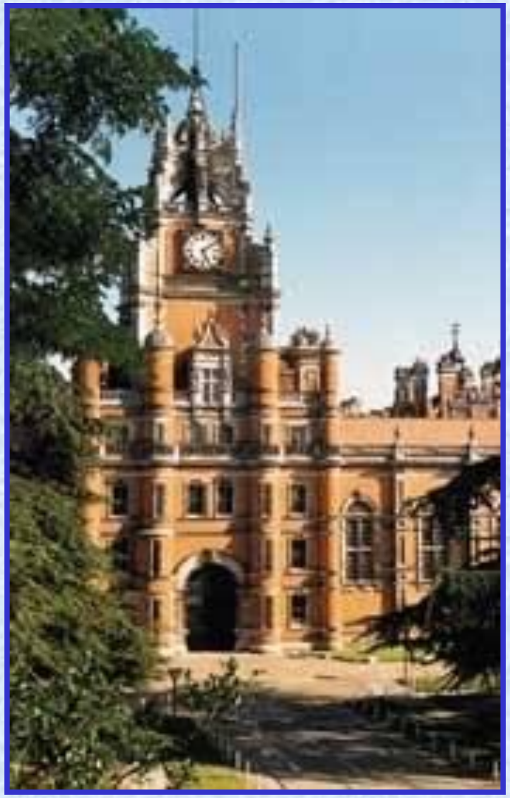
Royal Holloway University of London

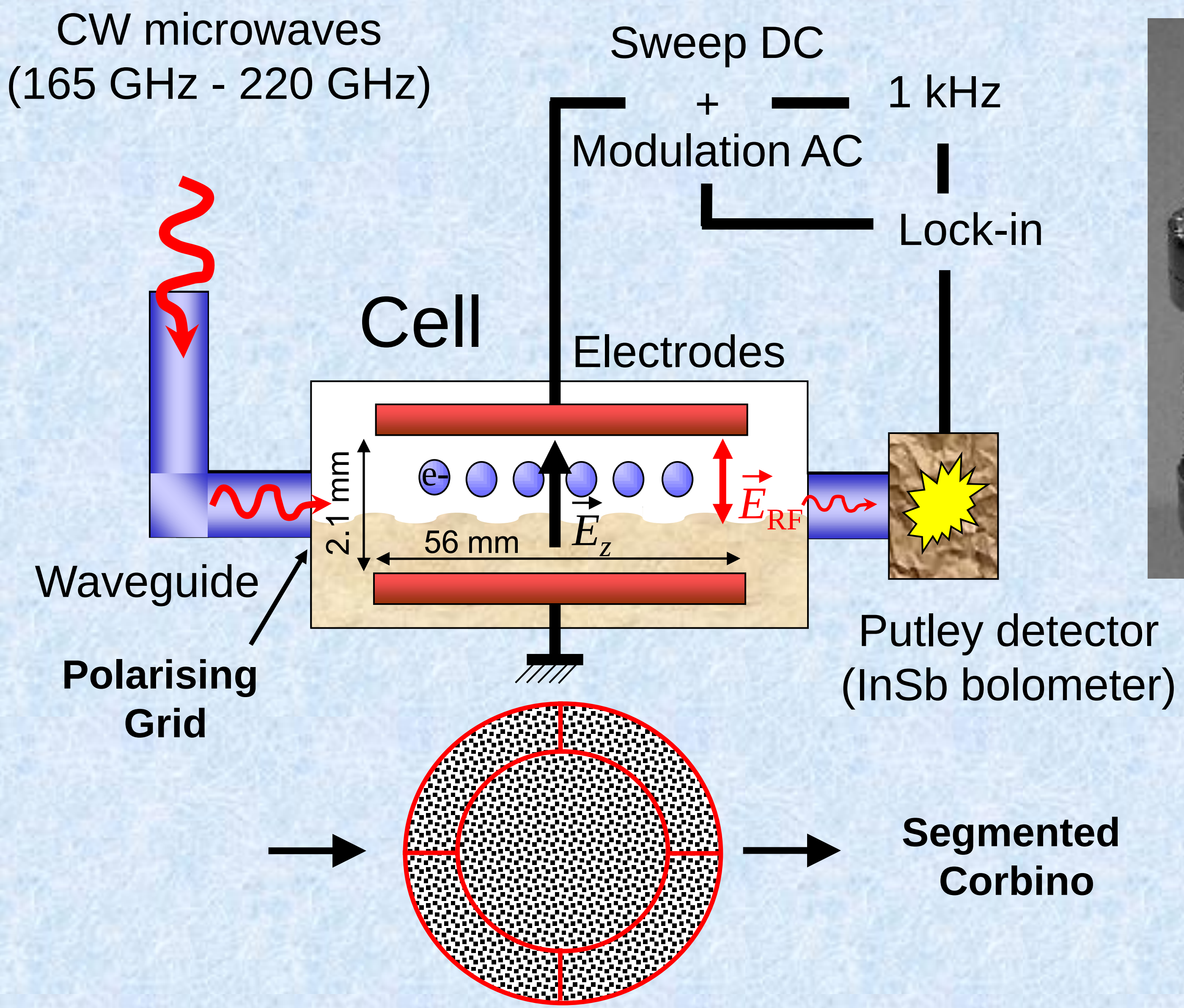
EPSRC



Temperature Dependent Energy Levels of Electrons on Liquid Helium

Bill Bailey, Parvis Fozooni, Phil Glasson, Peter Frayne,
Khalil Harrabi, Mike Lea.
+ Eddy Collin, Grenoble

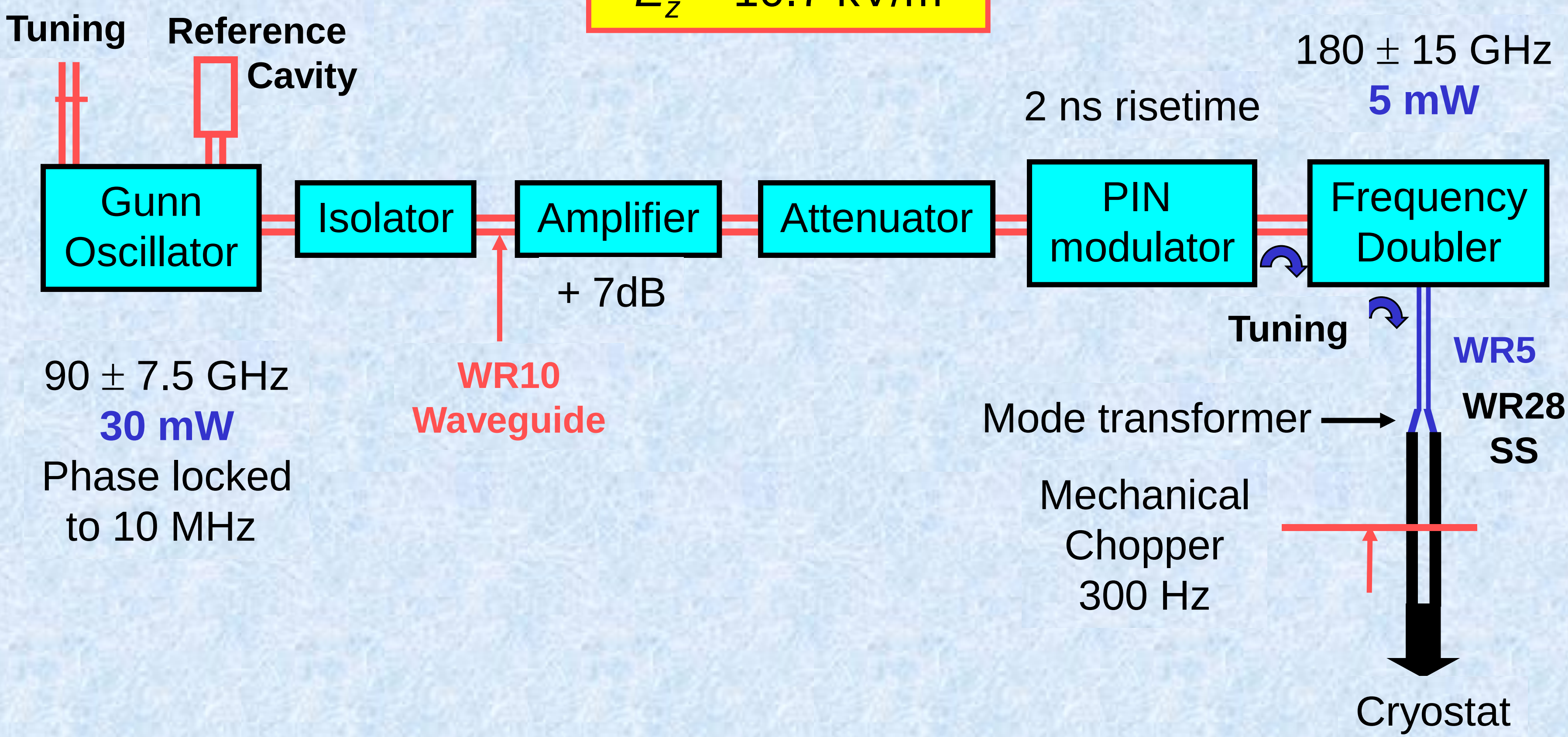
Microwave absorption

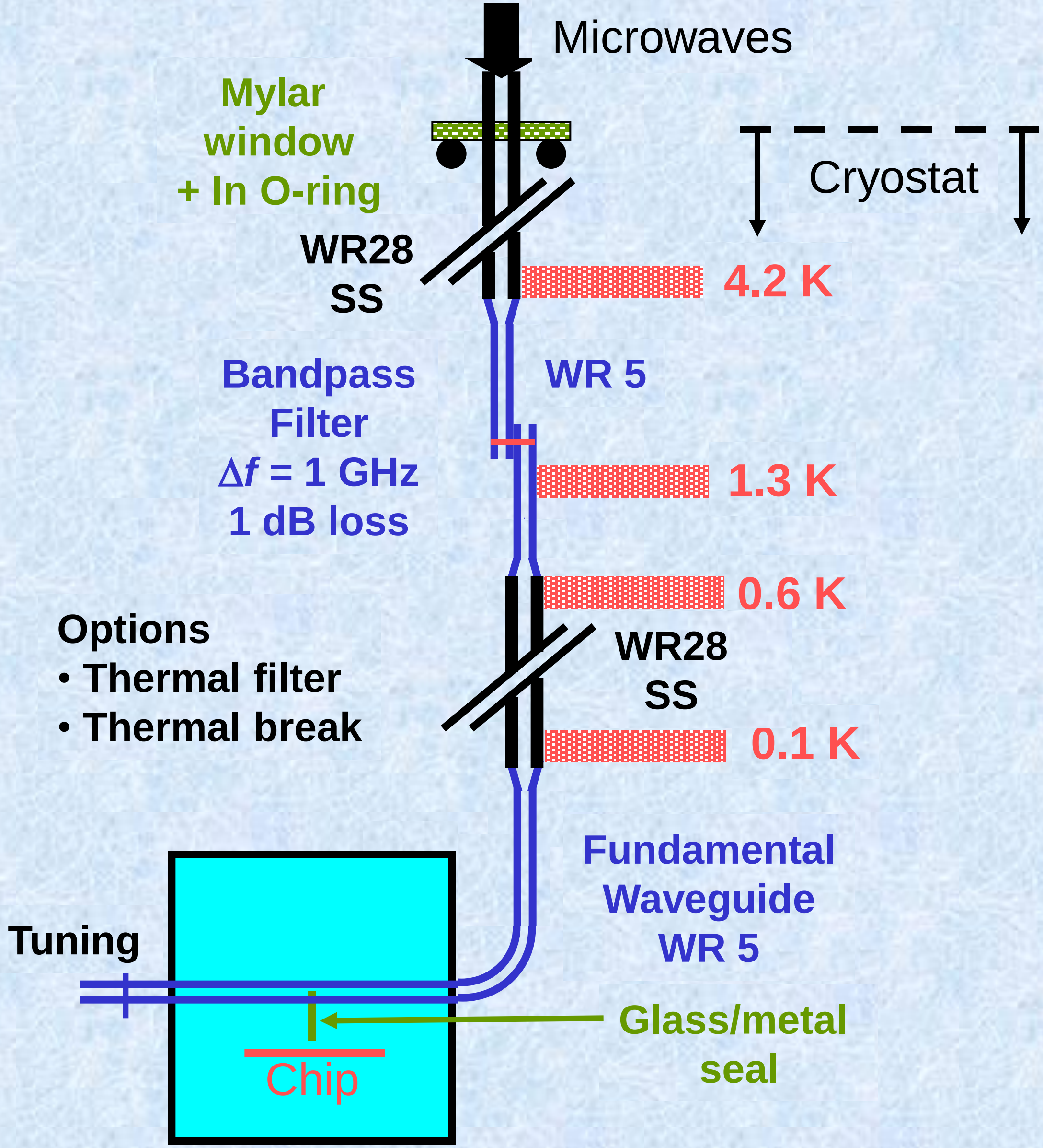


Cell

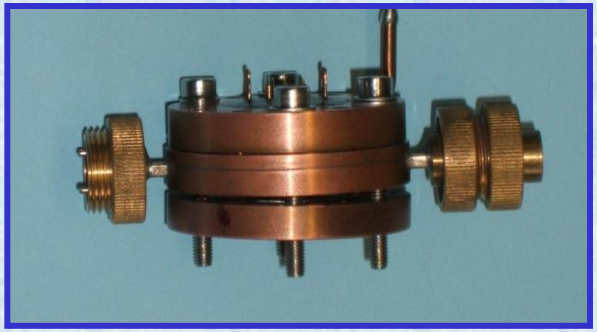
Peter Frayne
Royal Holloway

Rydberg resonance
190 GHz
$E_z = 10.7$ kV/m




Microwaves
Mylar window + In O-ring
Cryostat
WR28 SS
4.2 K
Bandpass Filter
Δf = 1 GHz
1 dB loss
WR 5
1.3 K
0.6 K
Options
• Thermal filter
• Thermal break
WR28 SS
0.1 K
Fundamental Waveguide WR 5
Tuning
Glass/metal seal
Chip

Cell



Rydberg states – liquid ^{4}He

Image charge $U_0(z) = \dfrac{-Ze^2}{4\pi\varepsilon_0 z}$ for $z > 0$

$Z = \dfrac{\varepsilon - 1}{4(\varepsilon + 1)}$

$$E_m = \frac{-R_e}{m^2}$$

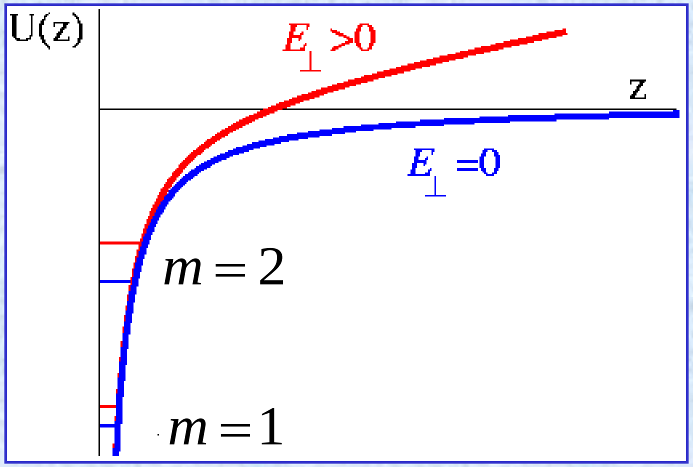
$f_{12} = 119.3$ GHz

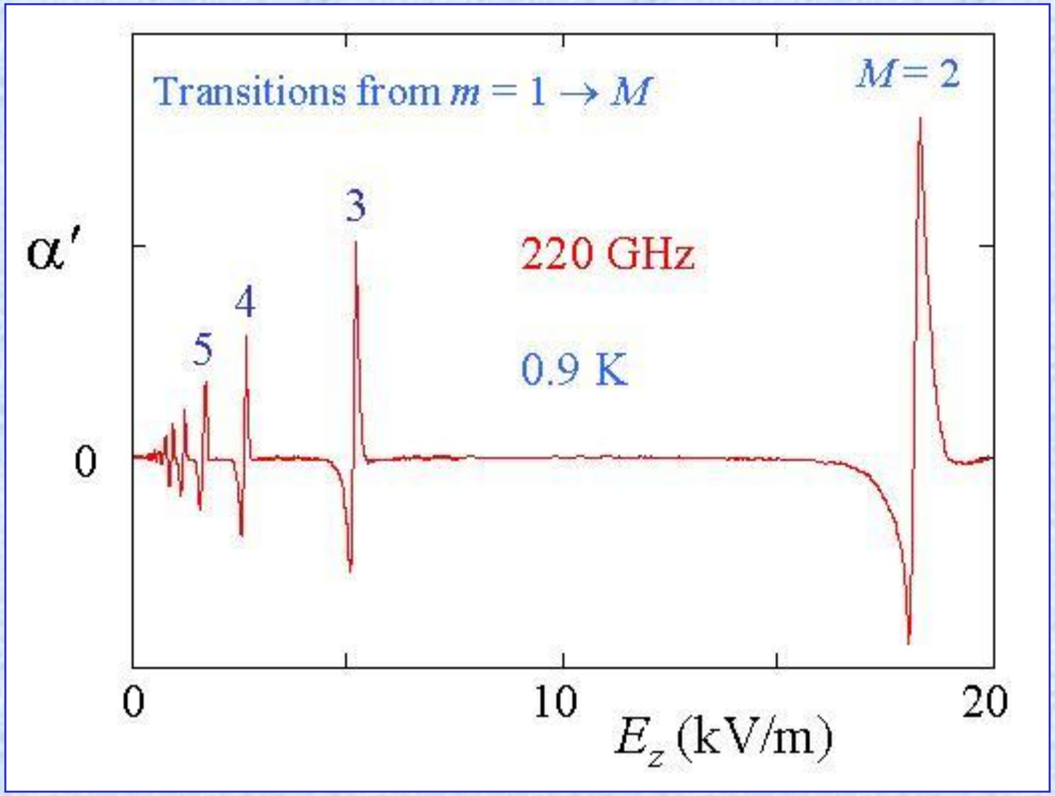
Grimes et al:

$$U_0(z) = \frac{-Ze^2}{4\pi\varepsilon_0 (z+b)} \quad \text{for } z > 0$$
$$= V_0 \quad \text{for } z \le 0$$

Experiment for $E_z = 0$:
f_{12} = 125.9 GHz at 1.2 K

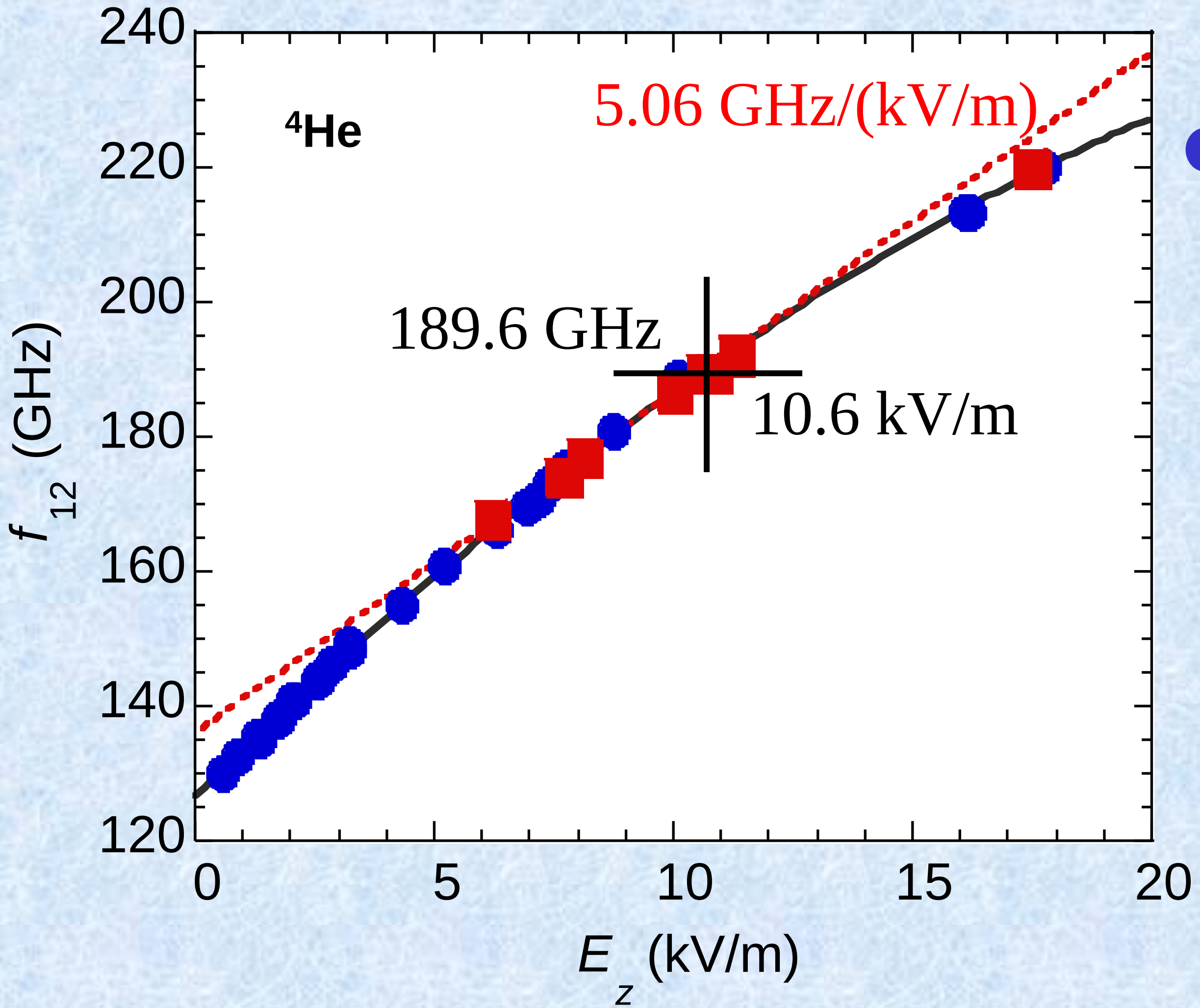
Stark tuning $U(z) = U_0(z) + eE_z z$





Ground state to first excited Rydberg state

Resonant frequency f_{12} increases with E_z



Brown, Grimes, Zipfel, 1976

1.5 K
Low power

Temperature dependent resonance

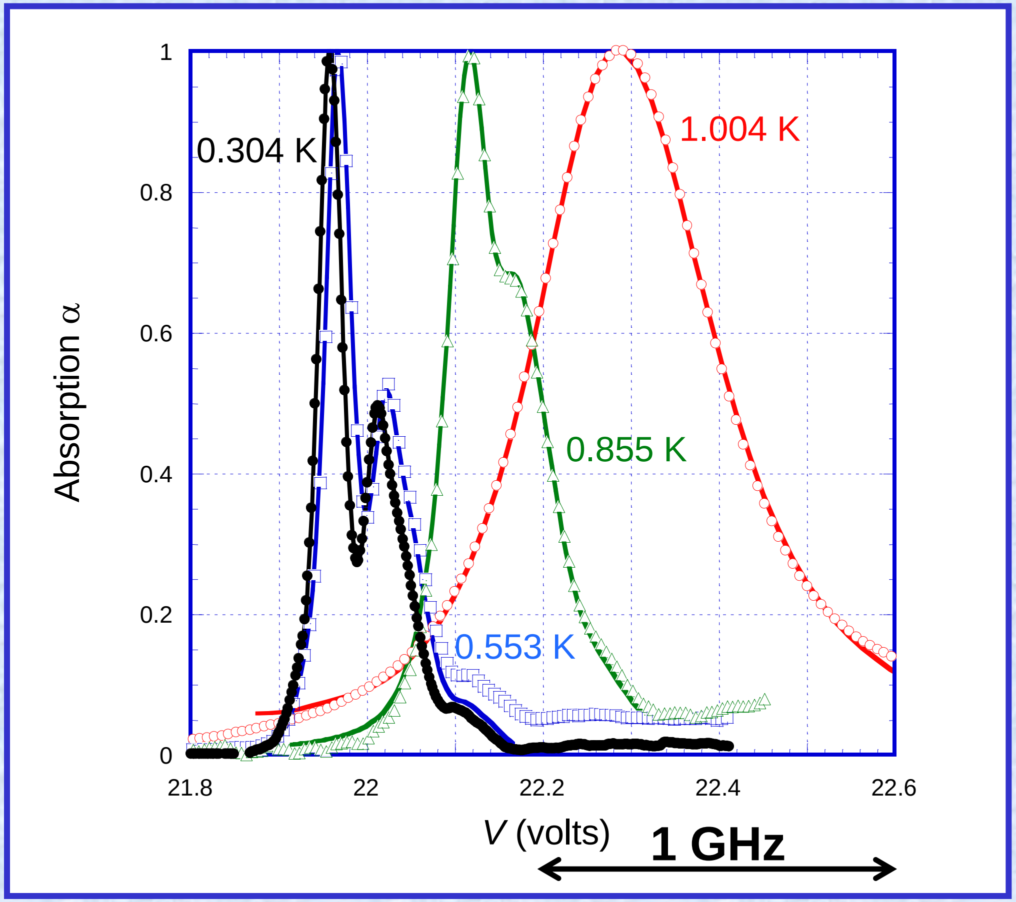
Low temperatures
Inhomogenous broadening

Medium temperatures
Inhomogenous broadening convoluted with a Lorentzian

High temperatures
Lorentzian

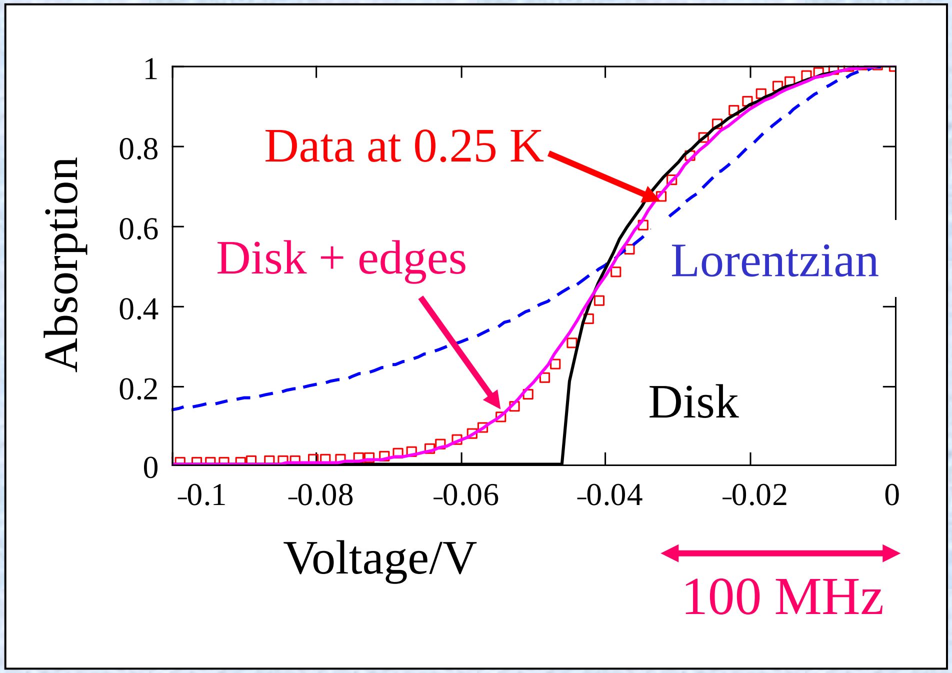
Resonance frequency *decreases* as the temperature *increases*

189.6 GHz



Non-parallel electrodes

- Lineshape independent of $T < 0.5$ K
- Inhomogeneous broadening Peaks from E_z variation (0.3%)?
- Non-parallel disk electrodes: Parabolic lineshape
- 8 μm across 50 mm
- θ = 0.17 mrad = 35" arc
- Lorentzian contribution small?

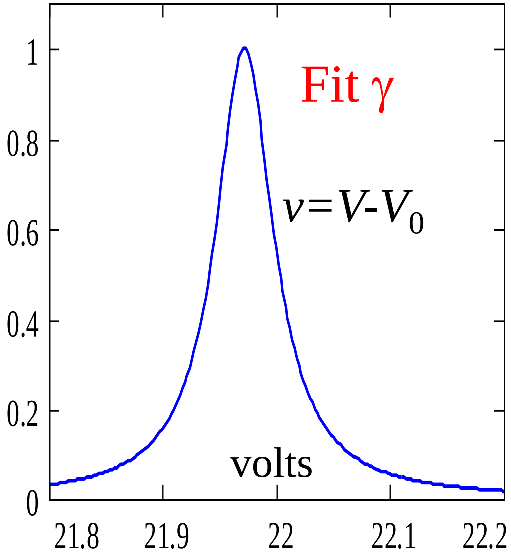


Use lineshape at 0.3 K as a template

Convolute with a Lorentzian

Fit linewidth γ to data ⇒ γ(*T*)

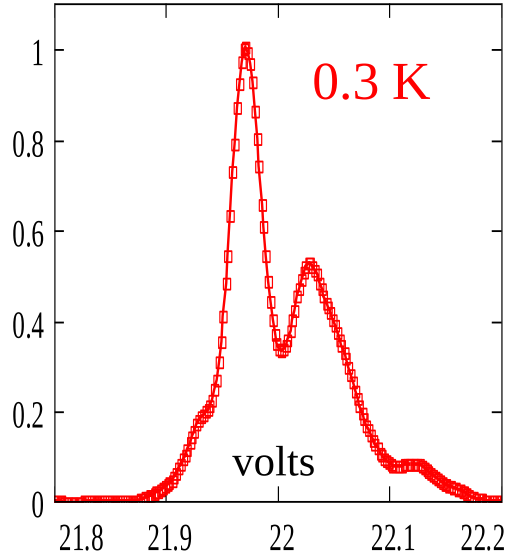
Lorentzian



⊗

Cell

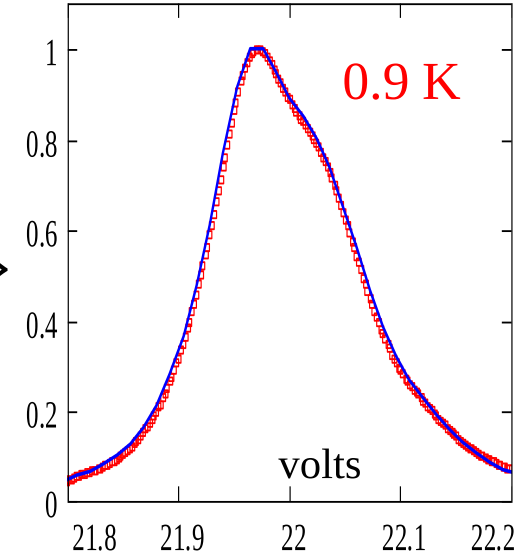
≡ δ-response



⇒

Measured

Fit γ = 106 MHz



$$L(v,\gamma) = \frac{\gamma/\pi}{v^2+\gamma^2}$$

Intrinsic linewidth

G(V)

Inhomogeneous broadening

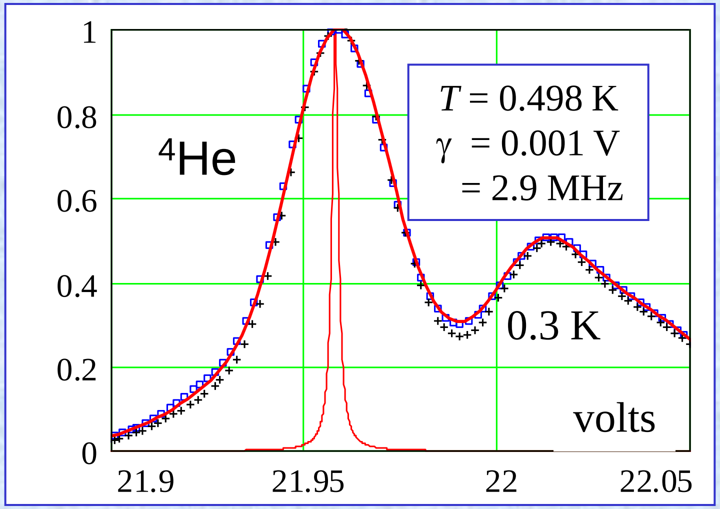
$$S(V) = \int G(V-v)L(v,\gamma)\,\mathrm{d}v$$

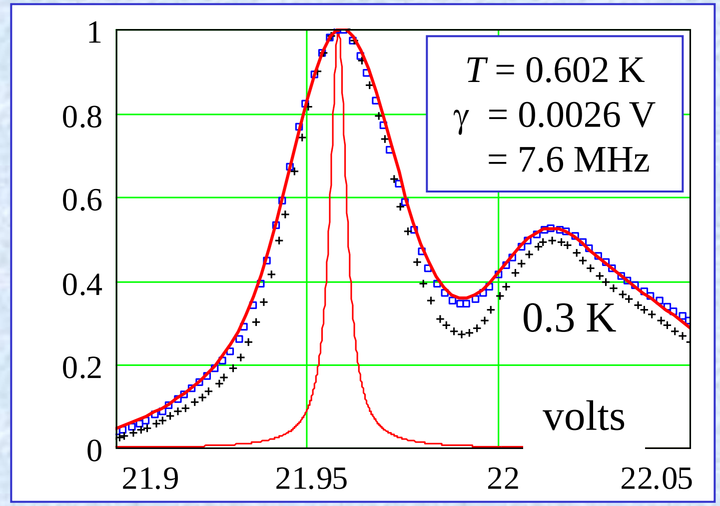
Convolution

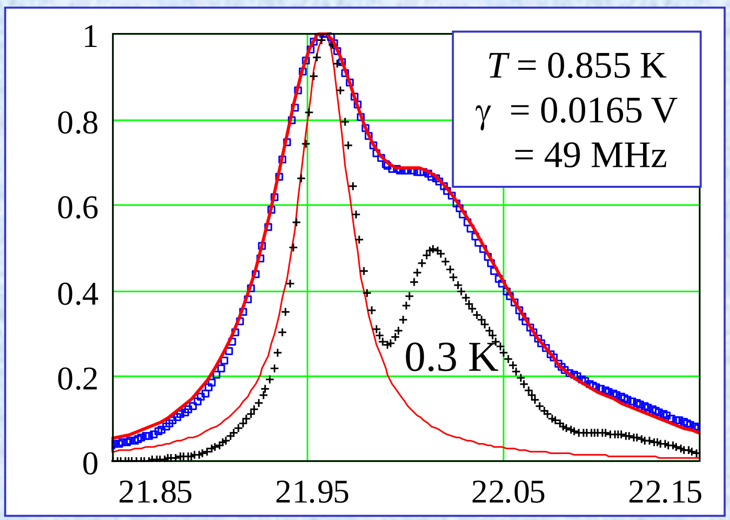
Output = Lorentzian ***L(V)*** ⊗ Cell response ***G(V)***

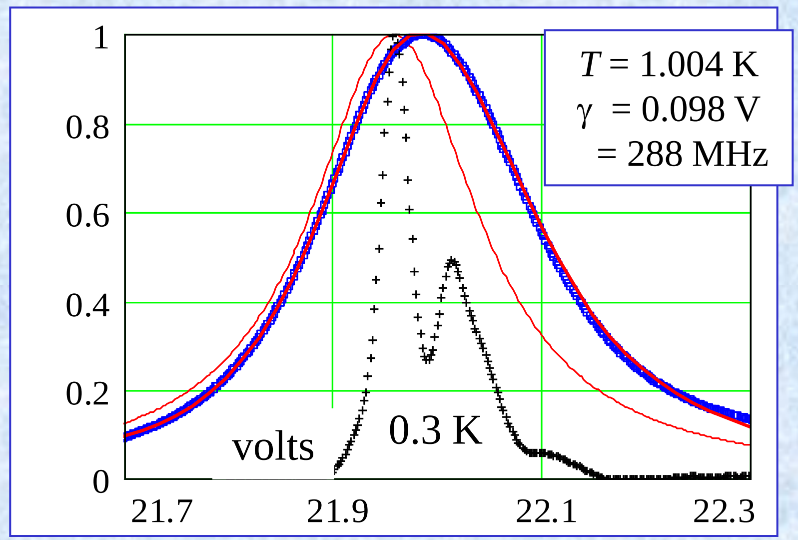
Microwave absorption at 189.6 GHz

Convolution

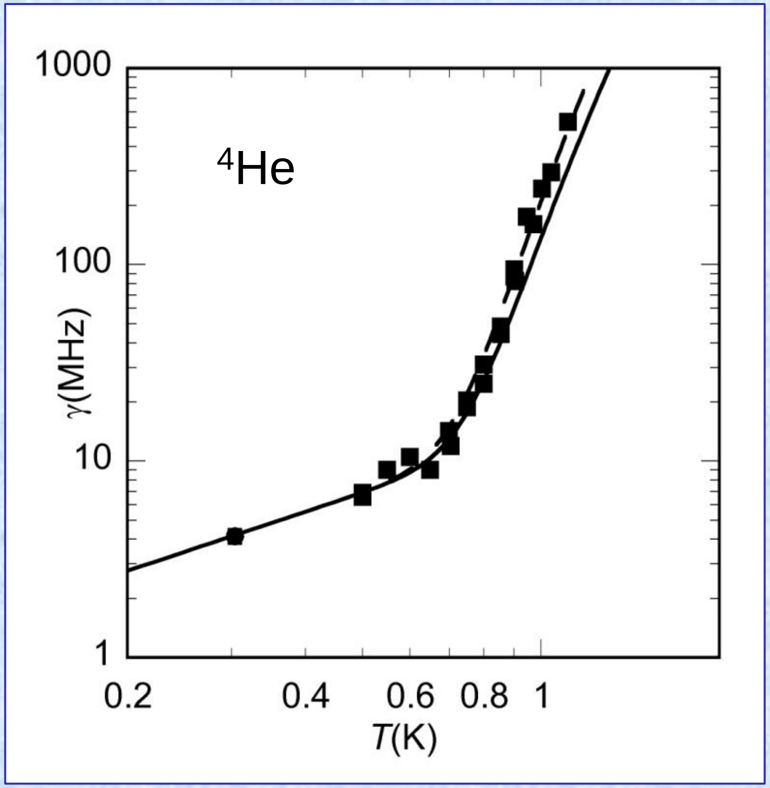


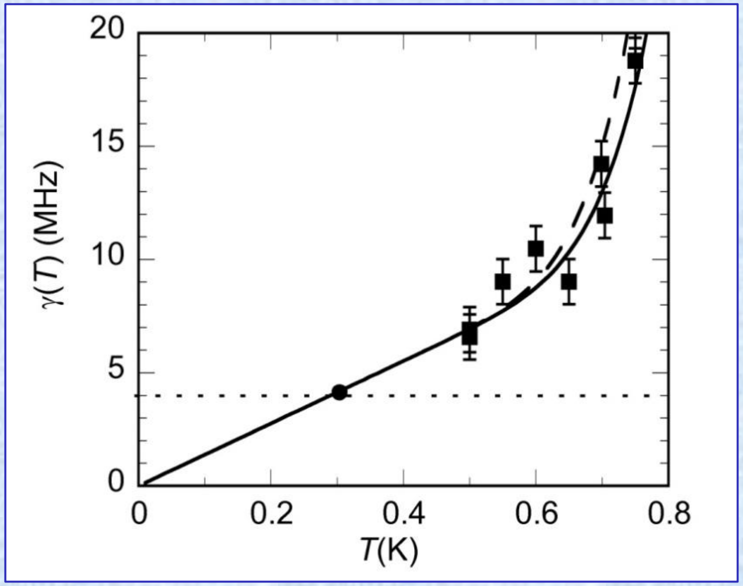


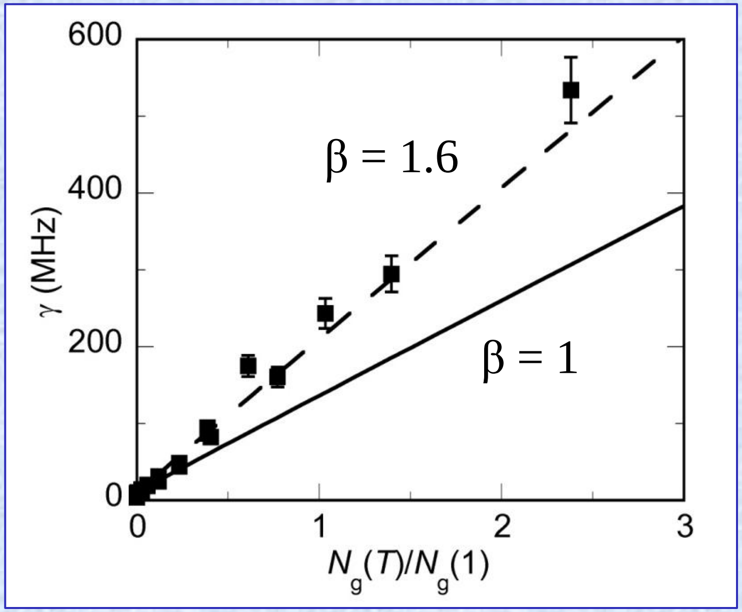




Microwave linewidth $\gamma(T)$







Theory:

T. Ando, J.Phys.Soc Japan, 44,765 (1976)

$$\gamma = aT + \beta b N_{gas}$$

Ripplon Gas atom

Scattering

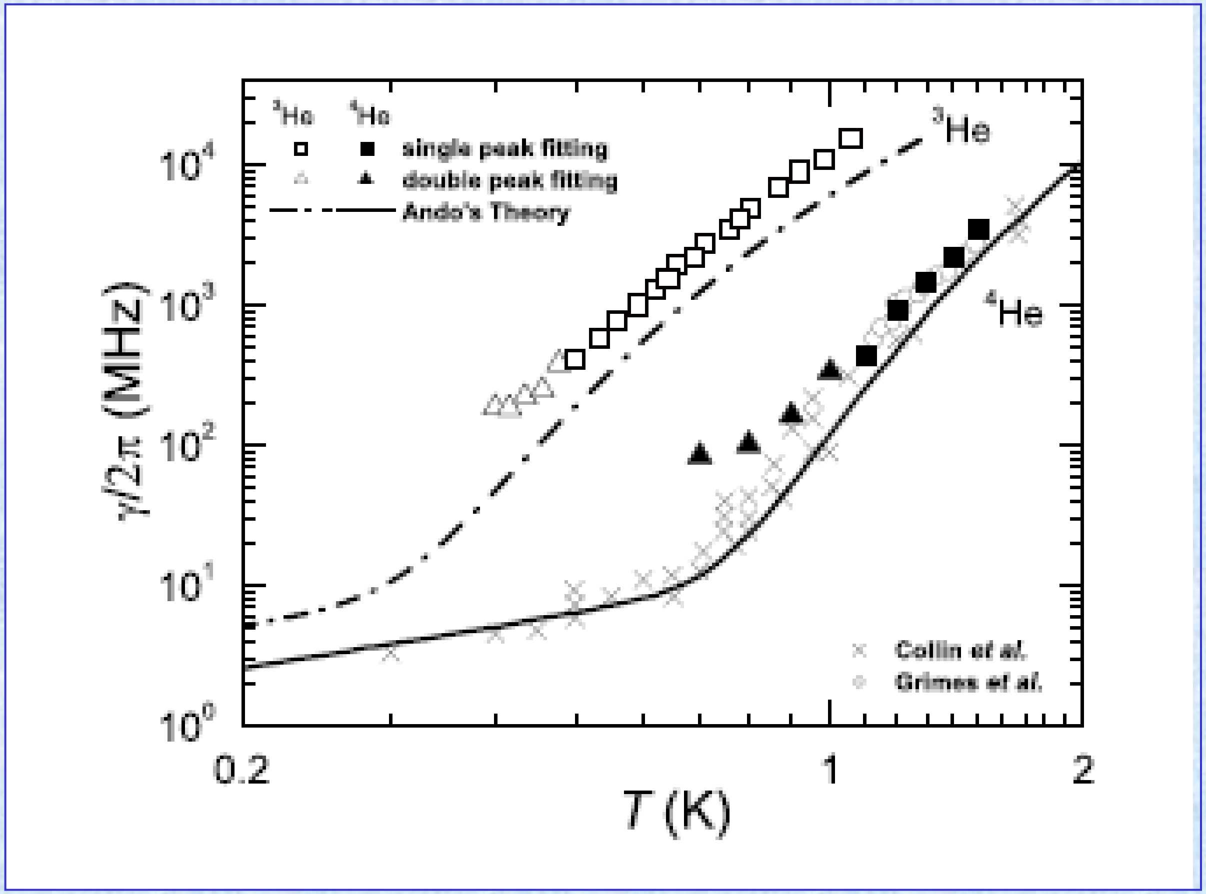
[H. Isshiki *et al*.J.Phys.Soc Japan (2007):
β = 2.1 (^{3}He); 1.6 (^{4}He)]

Temperature dependent linewidth

H. Isshiki *et al*.J.Phys.Soc Japan 76, 094704 (2007)

β = 2.1 (^3He); 1.6 (^4He)

$$\gamma = aT + \beta b N_{gas}$$



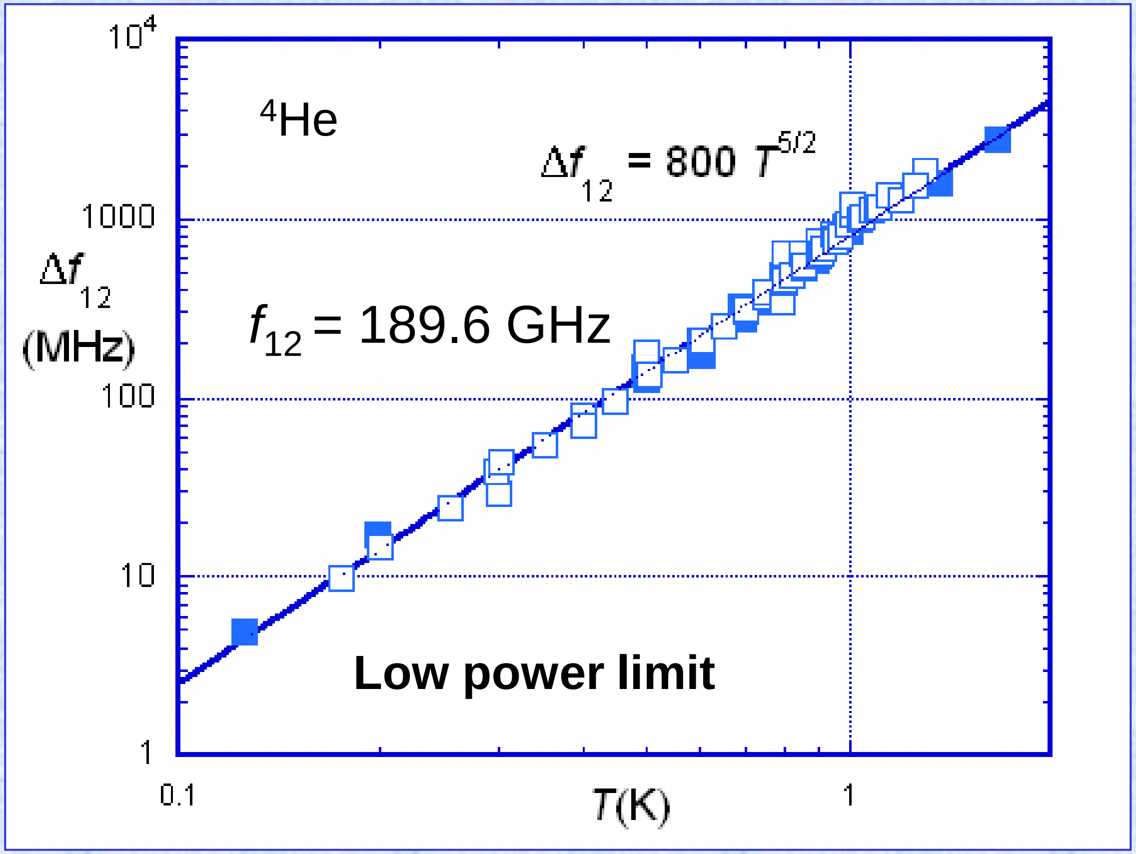
$\Delta f_{12}(T) = f_{12}(0) - f_{12}(T)$

$\approx$ 800 MHz at 1 K

$\Delta f_{12}(T) \propto T^{5/2}$ or

$\propto T^{7/3}$

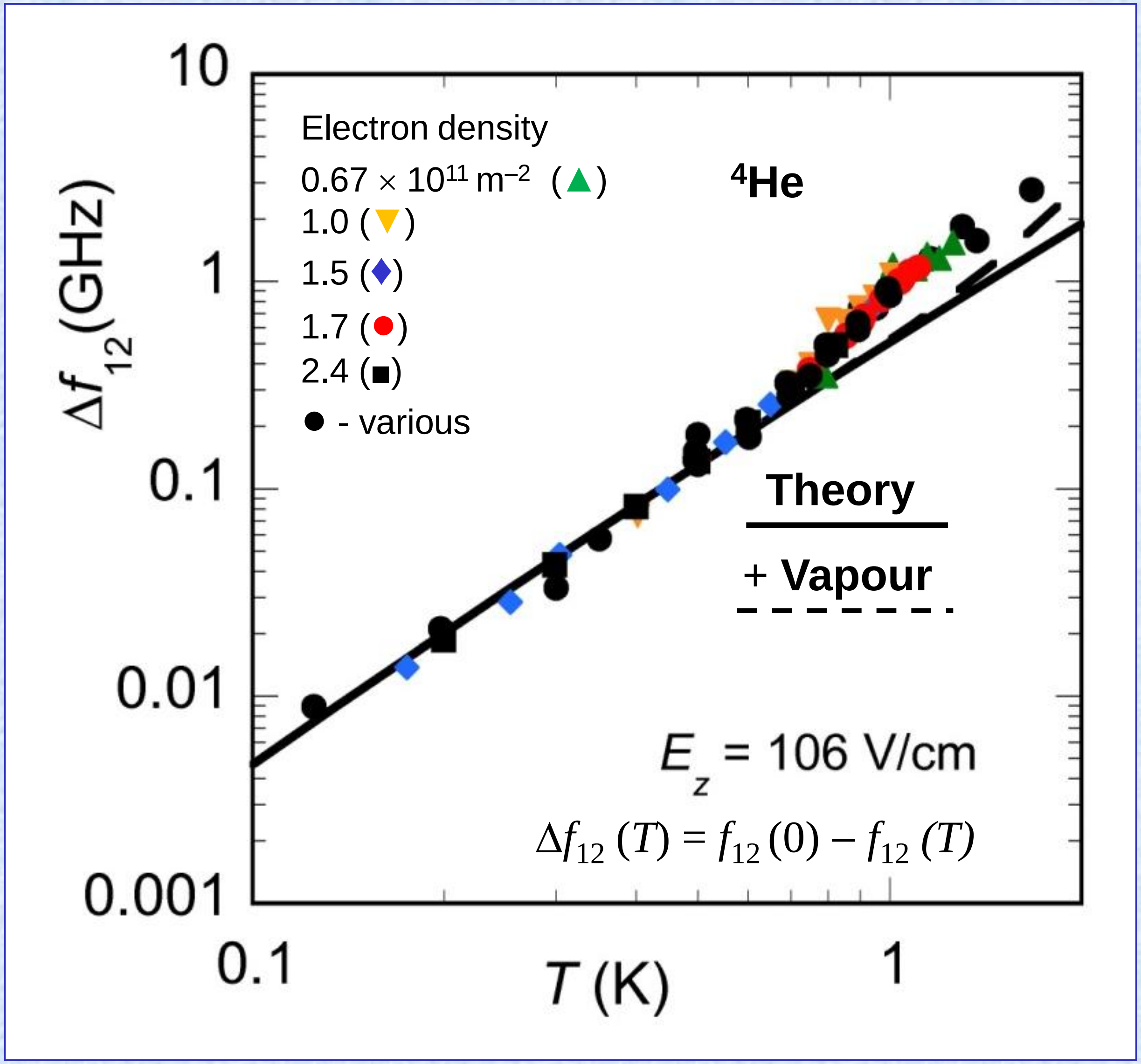
Ripplons?



Temperature dependent resonance

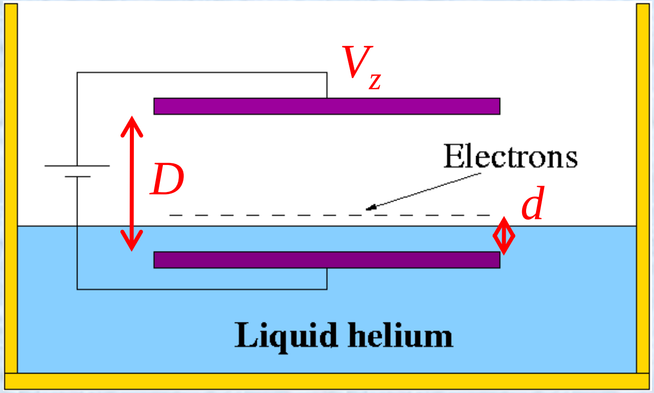
Theory:
Mark Dykman,
Denis Konstantinov
***et al* (2010)**

2-ripplon processes:
Lamb shift

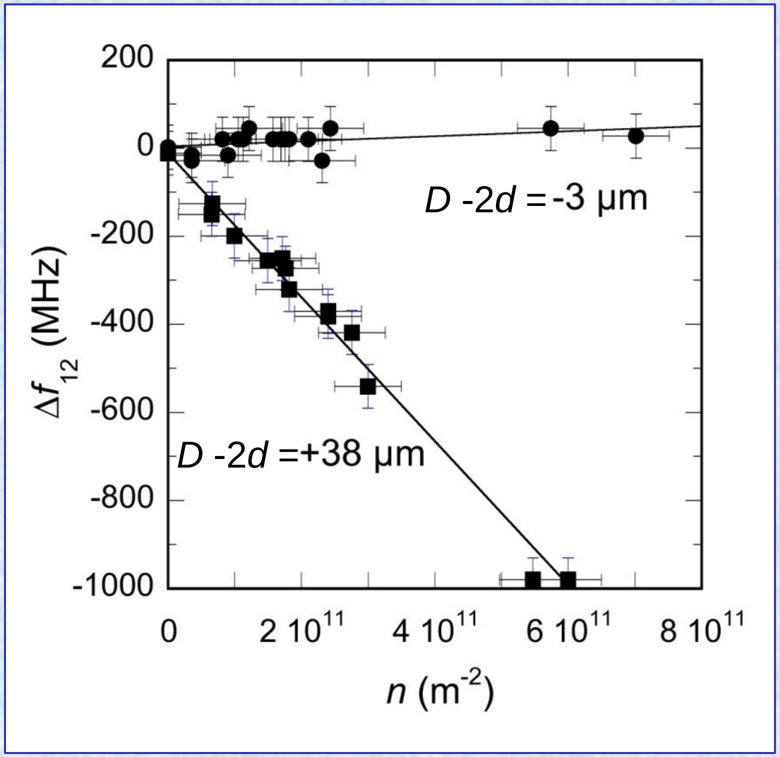


Density dependence of holding field

$$E_z = \frac{-V_z}{(D-d+d/\varepsilon)} + \frac{ne}{\varepsilon_0(\varepsilon+1)}\frac{(D-2d)}{(D-d+d/\varepsilon)}$$



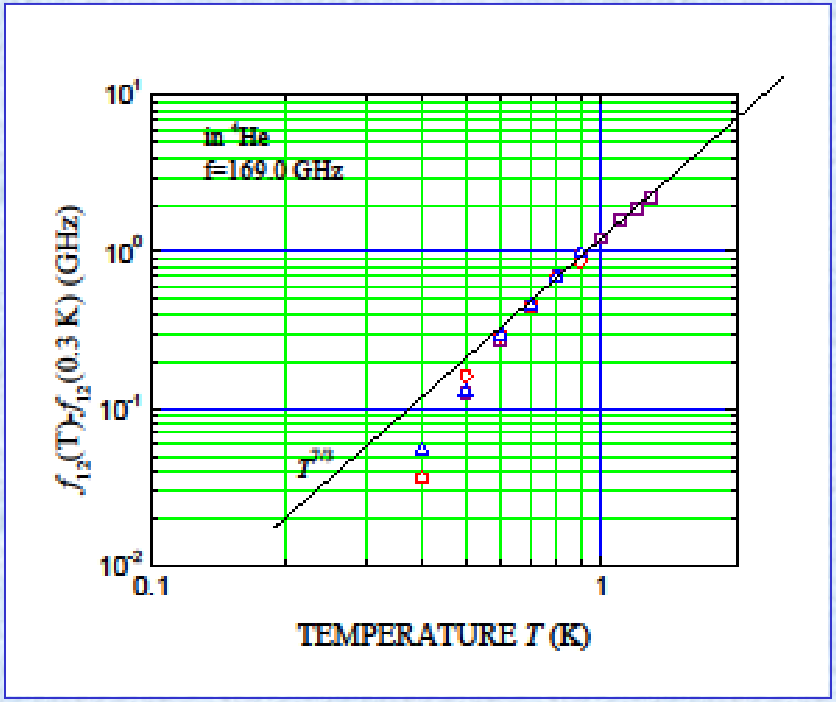
Extrapolated to $T = 0$



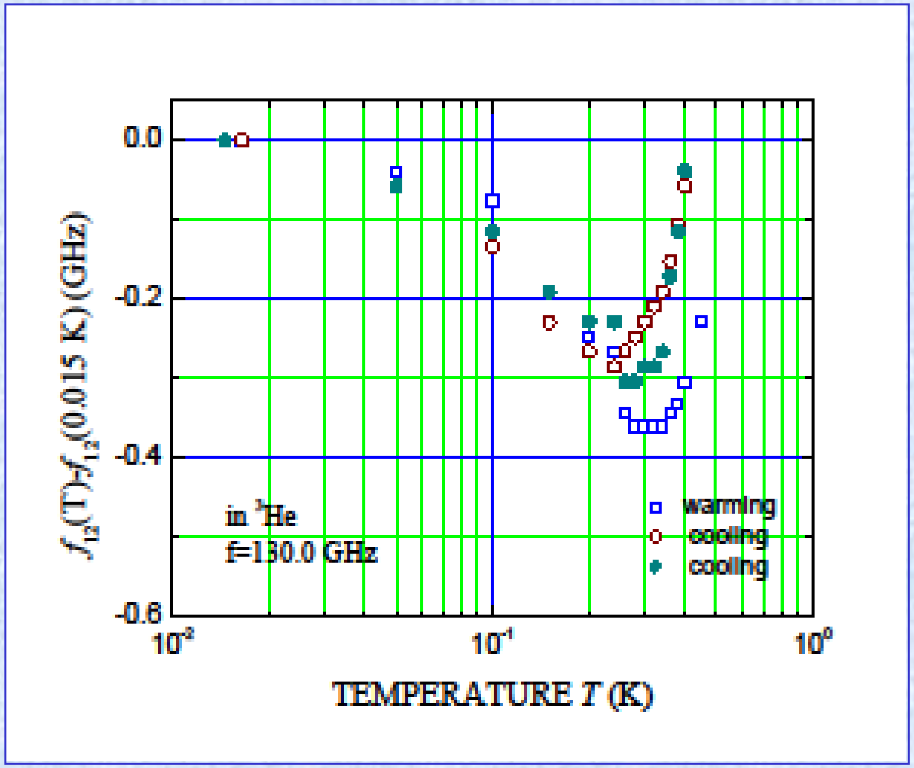
Temperature dependence of f_{12}

RIKEN

^{4}He



^{3}He



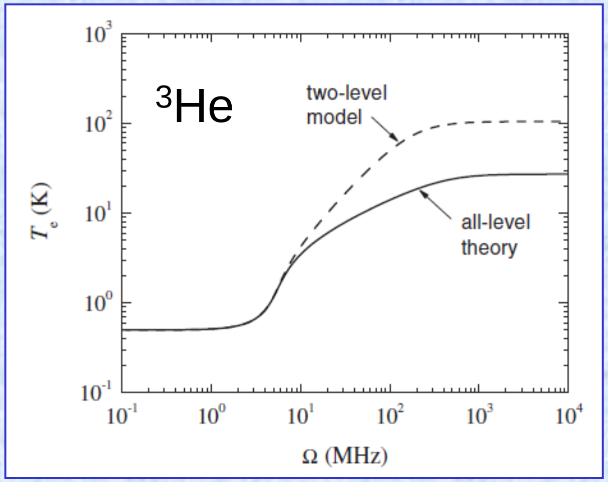
Microwave absorption - Coulomb shift

D. Konstantinov *et al.* PRL 98, 235302 (2007)

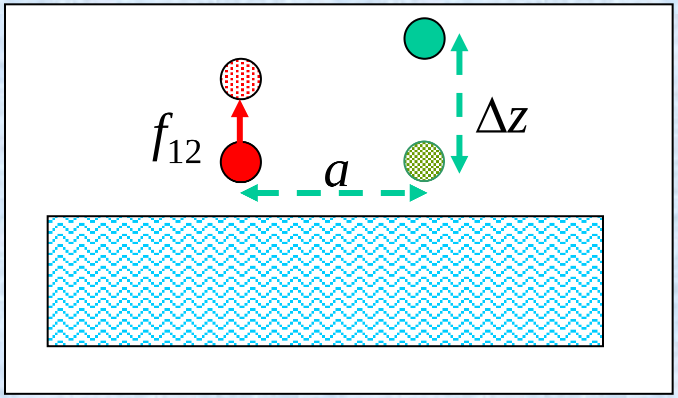
Ultra-hot Electrons on Liquid ^{3}He: T_e < 27 K

Resonance frequency shifts with

- **Power absorbed**
- **Excited state population**
- **Electron temperature T_e**
- **Electron density**

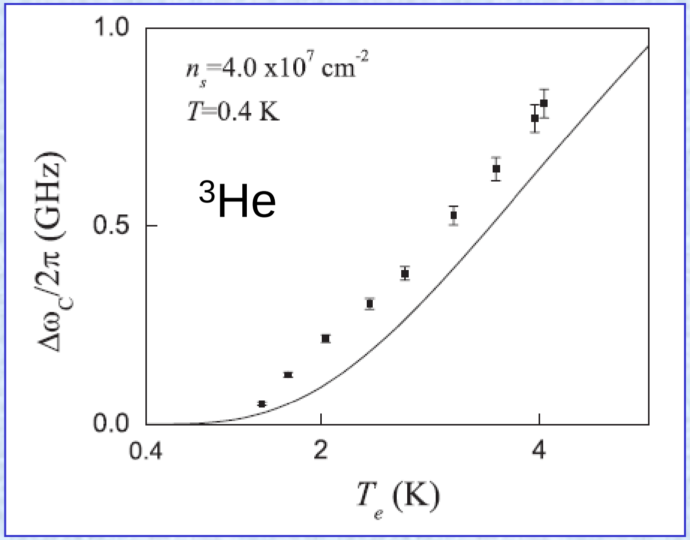


Rabi frequency $\Omega \propto \sqrt{\text{Power}}$



$$\Delta\omega_{21} = \frac{Fe^2 n_s^{3/2}}{2\hbar}\Big[(z^2)_{11} - (z^2)_{22} - 2(z_{11} - z_{22}) \times \sum_l z_{ll}\rho_{ll} + 2|z_{12}|^2(\rho_{11} - \rho_{22})\Big],$$

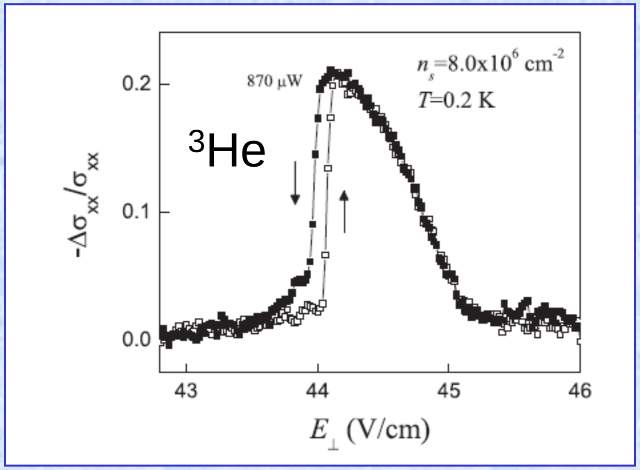
D. Konstantinov *et al.* PRL 103, 096801 (2009)

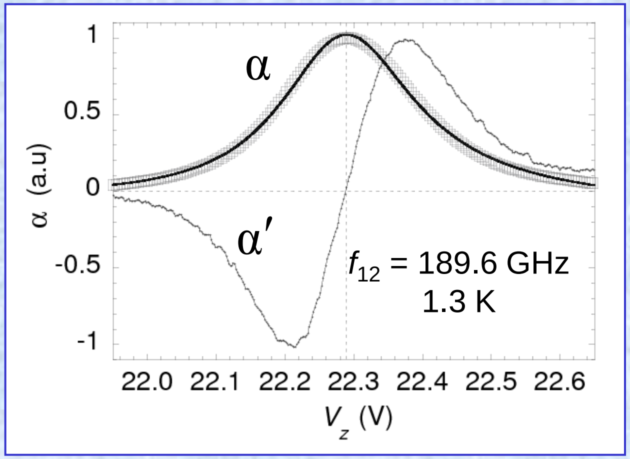


Optical bistability in microwave absoprtion

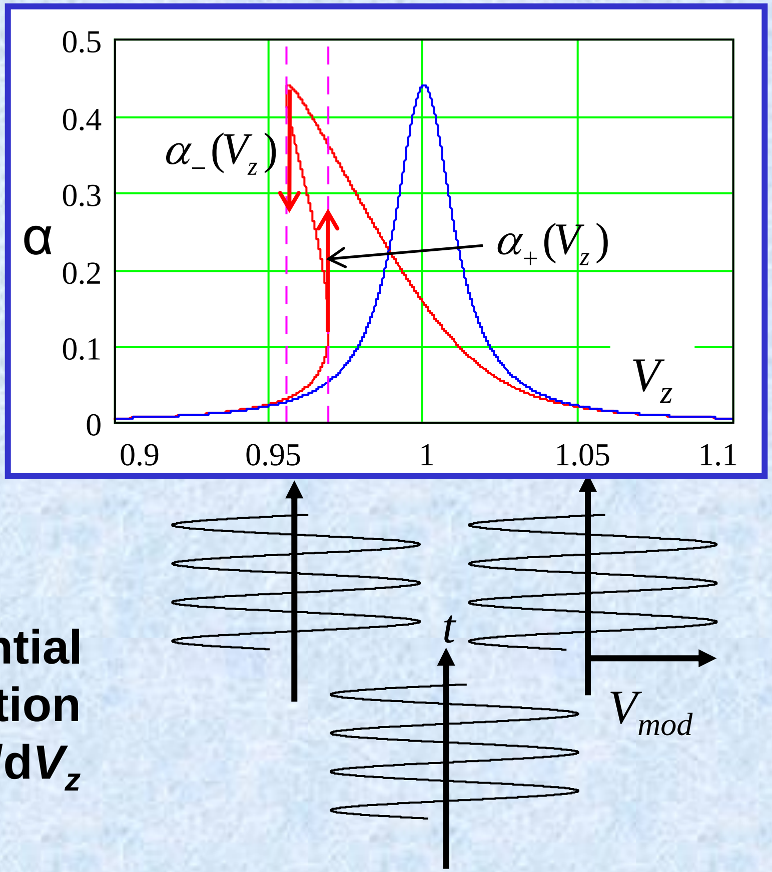
D. Konstantinov *et al.* PRL 103, 096801 (2009)

High-powers:
Hysteresis in conductivity





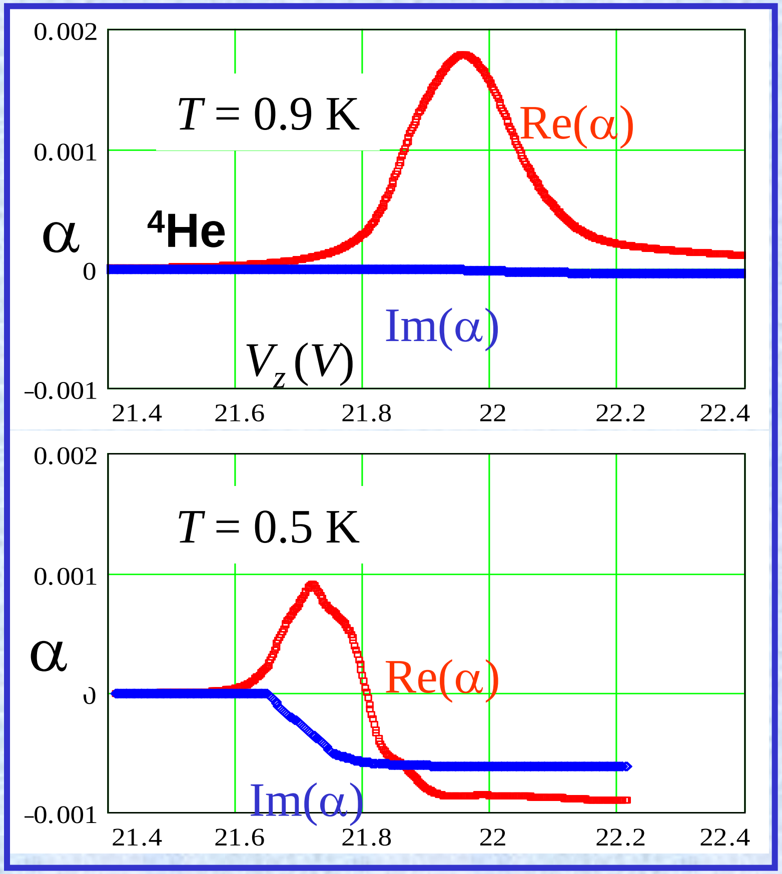
High-powers:
A.C. modulation (10 mV at 1 – 10 kHz)
Complex microwave lineshape



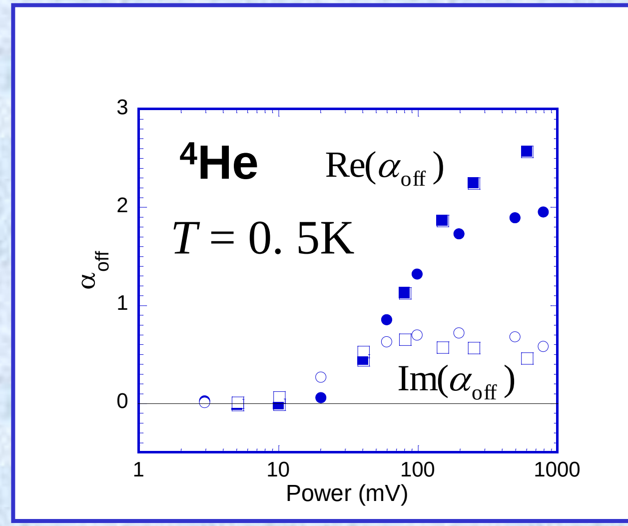
Differential absorption
α' = dα/dV_z

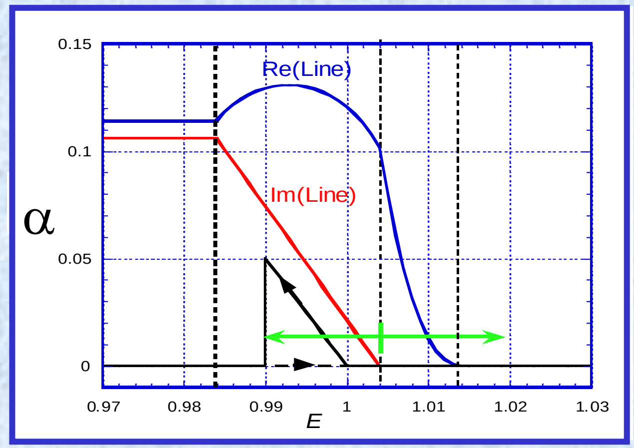
$$\mathrm{Im}(\alpha') = \frac{1}{\pi V_m}\int \left(\alpha_-(V_z) - \alpha_+(V_z)\right) dV_z$$

Hysteresis ≡ Complex Lineshape



$$\mathrm{Im}(\alpha_{\mathrm{off}}) = \frac{2}{\pi}\left(1 - \frac{\Delta V}{2V_m}\right)\int\left(\alpha_-(V_z) - \alpha_+(V_z)\right)dV_z$$





$$\mathrm{Im}(\alpha_{\mathrm{off}}) = \frac{\alpha_{\max}\Delta V}{\pi}\left(1 - \frac{\Delta V}{2V_m}\right)$$

$$2V_m \approx 20\,\mathrm{mV} \equiv 50\,\mathrm{MHz}$$

Inhomogeneous power broadening
Inhomogeneous Coulomb broadening

Conclusions

- Temperature dependent Rydberg levels
- Inhomogeneous broadening
- Enhanced Ando linewidth
- Microwave absorption bistability (hysteresis)