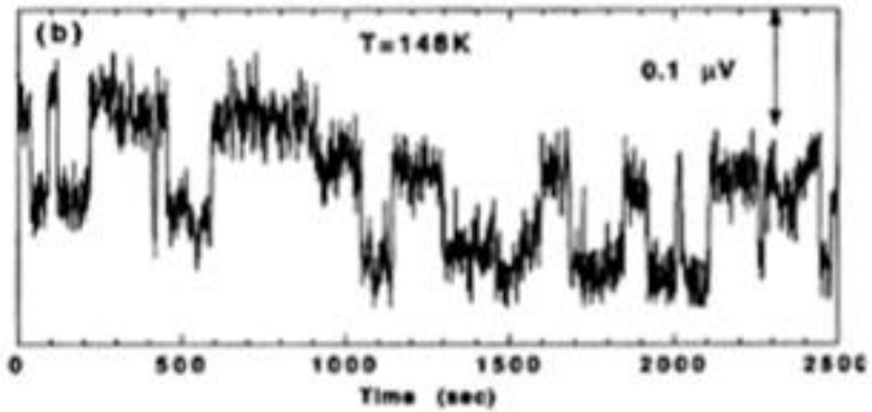
# Noise

*Michael B. Weissman*




**Physics 403, Fall 2019**

# Noise : Nuisance and Tool

Outline:

***Broad categories***

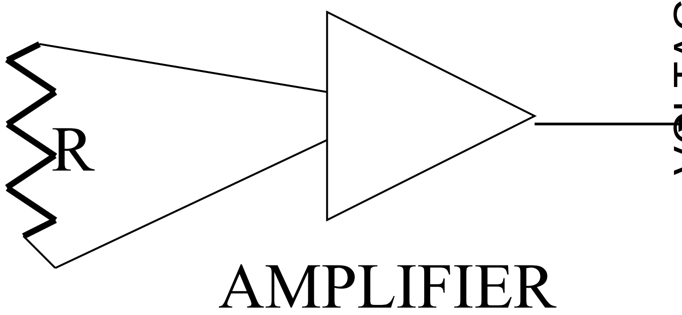
fundamental equilibrium noise
noise reflecting system physics
bad contacts, etc.

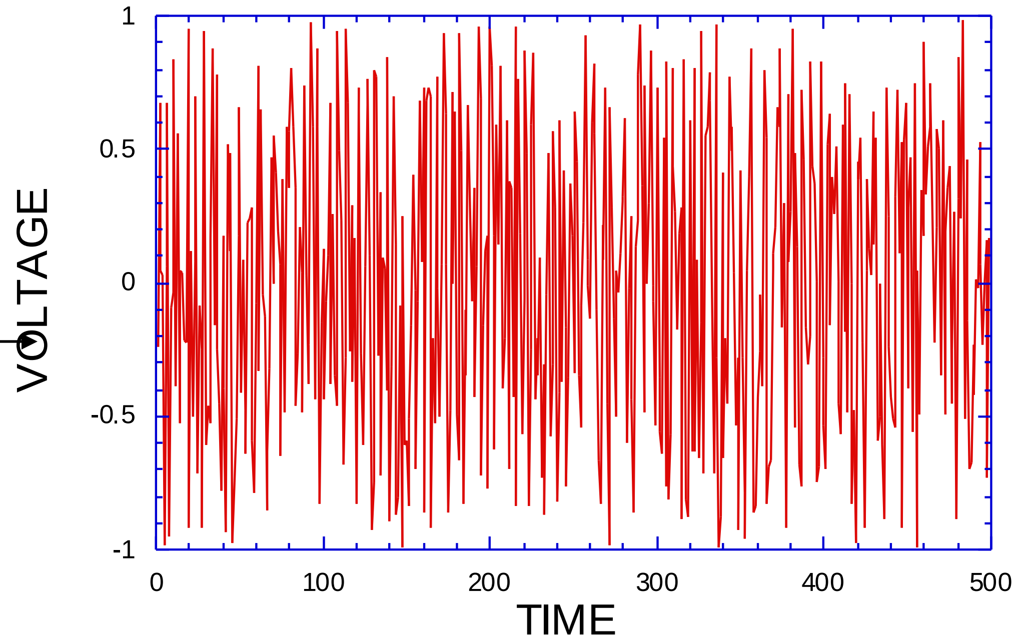
***Case studies in applications:***

Noise and extraneous dirt: defects in $SiO_2$ etc.
Noise and dirty thermodynamics: e.g. manganites
Noise out of equilibrium: ferroelectric Barkhausen

# Where does noise come from?

- White noise (often not a mystery):
  - Look at a resistor in an amplifier circuit

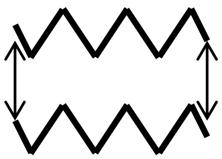



The voltage (or air pressure, etc) changes quickly from one random value to a new, independent random value. ***Why?***

# Noise and the laws of thermodynamics

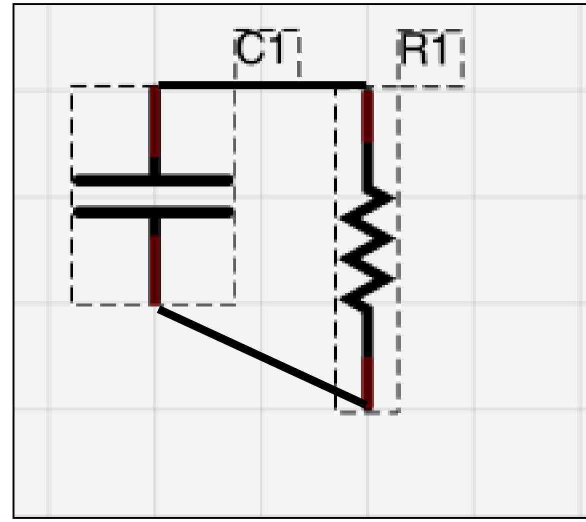
- ANY two resistors with the same resistance at the same temperature MUST have the same sort of noise *before a current is applied to them*, even if one is made of gold and one of salt water! ***Why?***
- Let's say one was noisy and the other quiet. Then when hooked together, the noisy one would drive more currents



  through the quiet one than vice versa. Currents heat up resistors. So the quiet one would heat up and the noisy one would cool down. But a basic law of thermodynamics says that two objects at the same temperature don't spontaneously go to different temperatures. Therefore they must have the same amount of noise.
- But no law like that applies when current is forced through them. (Refrigerators work.)

# Equilibrium basics

The magnitude of the noise is given by equipartition.
$<(\delta V)^2> = kT/C$




The time course is just exponential decay, with RC time constant.

So the autocorrelation function is
$<(\delta V(t)\ \delta V(t+\tau))> = (kT/C)e^{-\tau/RC}$

The spectrum S(f) is just the Fourier transform of the autocorrelation function: $\omega$

$S(f) = 4kTR$ (up to $f \sim 1/RC$)

Similar Fluctuation-dissipation relations hold for magnetism, dielectrics, mechanical systems etc.
Limited new info from noise

# Frequency spectra: S(f)

$$V(t) = a_1 \cos(2\pi t \bullet 1Hz) + a_2 \cos(2\pi t \bullet 2Hz) + etc$$

$$S(1Hz) = a_1^2 \qquad S(2Hz) = a_2^2 \qquad etc$$

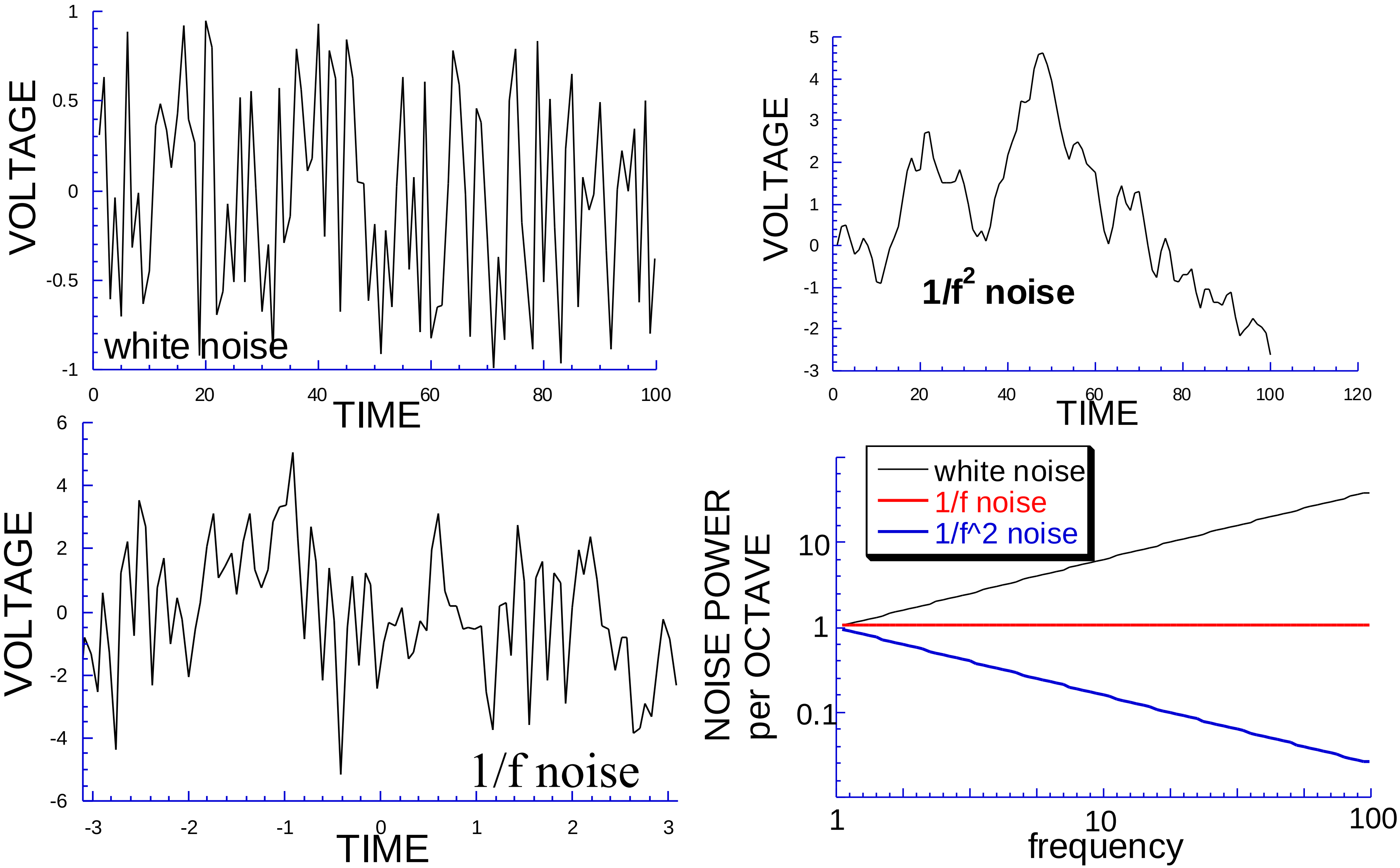
Write the signal as a sum of waves at a set of equal spaced frequencies.
S(f) gives how the *square* of the size of the components depends on f.

White noise: same amount of power in each equal frequency range 20Hz-30 Hz, 30 Hz-40 Hz, etc (like white light, except different range)

1/f noise: same amount in each OCTAVE:
20 Hz-40 Hz, 40 Hz-80 Hz, etc

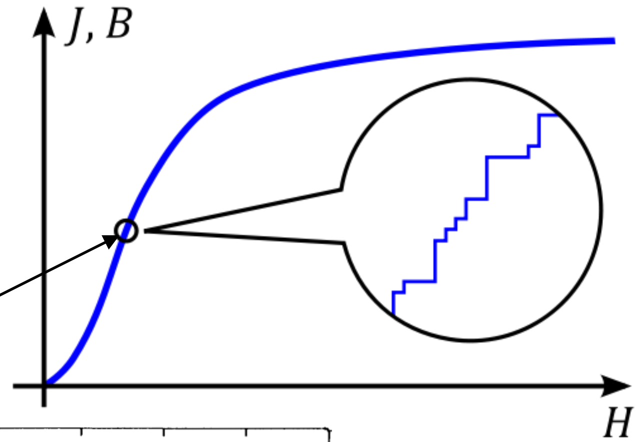
Playing the tape back at double speed doesn't change the sound!
Another fact to intrigue to theorists.

# Noise pictures



# Non-equilibrium basics

- **Some noise is intrinsically non-equilibrium, driven. e.g.**
  – Shot noise (photons, electrons,..)
    - $S_I(f)=2Iq$ for current, in simple case
  – Barkhausen domain flips in magnets
  – Sliding charge density waves




S. Bhattacharya et all. Phys. Rev. Lett **54**, 2453, (1985)

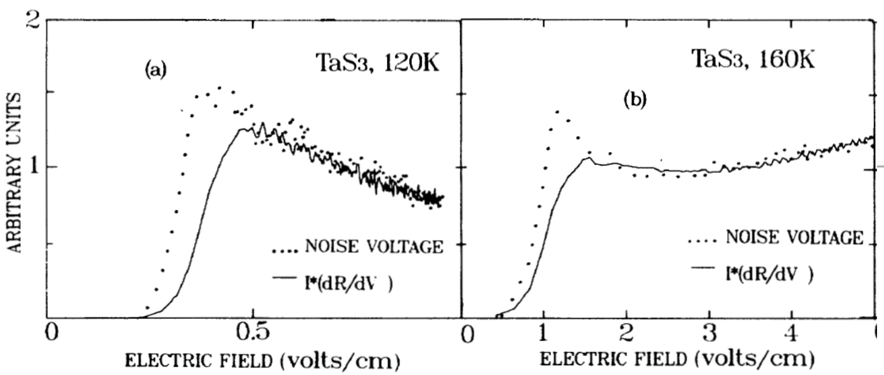
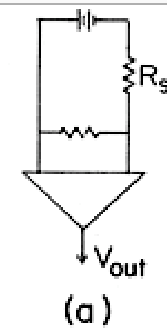
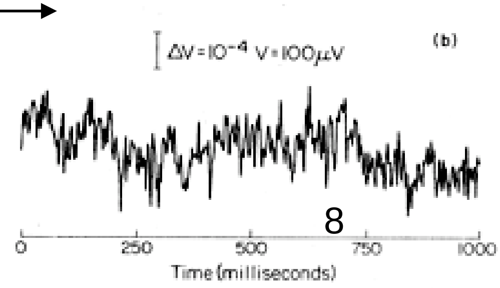



Fig.1; Field dependence of the broadband noise $\langle \delta V^2 \rangle$ measured at 300 Hz and I2 $(\partial R/\partial V_T)^2$.

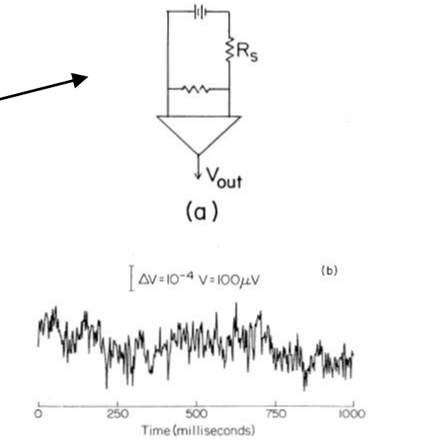



- **Some is just sampled by non-equilibrium means. e.g.**
  – most 1/f noise in resistors
  – Particle density fluctuations in fluids (via light scattering)

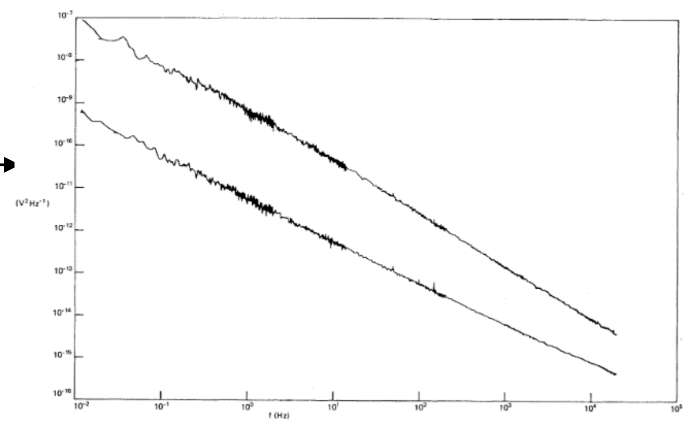


# 1/f noise basics

- δR almost always measured out of equilibrium
  - but that rarely matters, as confirmed by
    - Linearity of δV in I
    - Independence of ac or dc measurements
    - Occasional equilibrium measurements via δ(kTR)




- Other variables (magnetic μ, capacitor V) are measured in equilibrium.
- Spectra are often remarkably close to 1/f, but not usually exactly so
- The deviations from 1/f often shift around like simple thermally activated kinetics (Dutta-Horn)



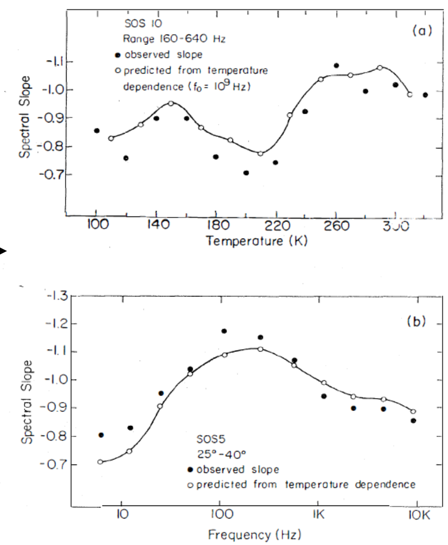



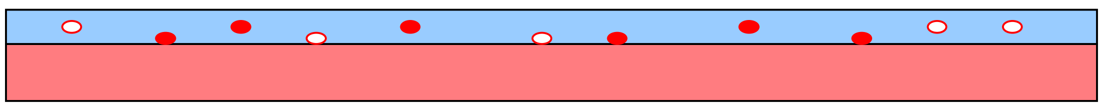

FIG. 8. Two forms of the Dutta-Horn relation for silicon-onsapphire resistors. (a) A plot of the spectral slope [∂lnS (f) ; ∂lnf] vs temperature for an SOS sample.

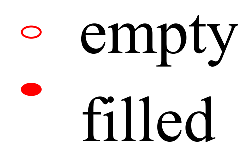
FIG. 1. (a) The basic experimental configuration and typical observations of 1/f noise. Schematic diagram of the simplest measuring apparatus for 1/f noise. $R_s$ is a large, constant resistor.

M. B. Weissman, Rev. Mod. Phys, 60, 537, (1988)

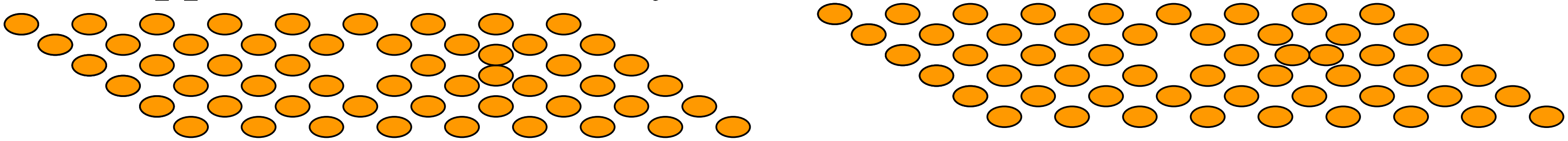
# So what's rattling?

In silicon with an oxide layer electrons jump in and out of traps in the oxide.






In copper, defects in the crystal structure move around.



In chromium, domains of a type of magnetism change their alignment back and forth.

And all give the same shape of spectrum: 1/f.

# 1/f noise: the simplest ingredients

- electron traps in amorphous $SiO_2$
- collection of simple parallel noise sources
- equilibrium thermodynamics and kinetics
- random trap depths
- random trap positions
- random barrier heights
- No important correlations among those random variables
  - Measurable from E and T dependences

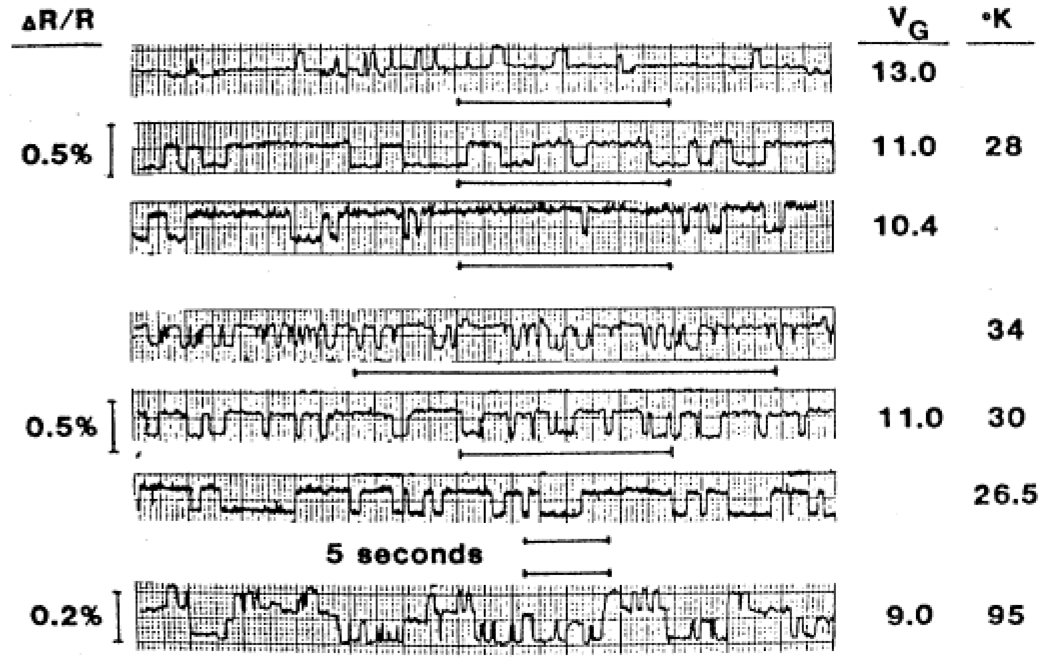



FIG. 5. Two-state switching in the voltage on small gated Si resistors, observed by Ralls et al. (1984). Va is the gate voltage,

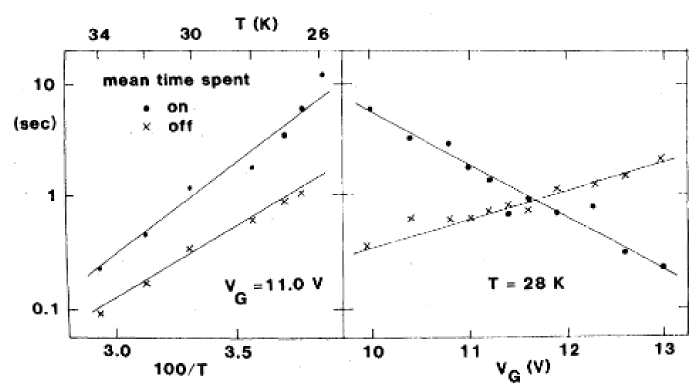



FIG.2. Exponential dependence of mean lifetimes on inverse temperature and gate voltage for a particular switching sequence.

**Why 1/f?**

K.S. Ralls et all, Phys. Rev. Lett., 52, 228 (1984)

# Could 1/f noise just come from summing the switchers?

- It sure looks that way
  - E.g in silicon-on-sapphire resistors (1983):

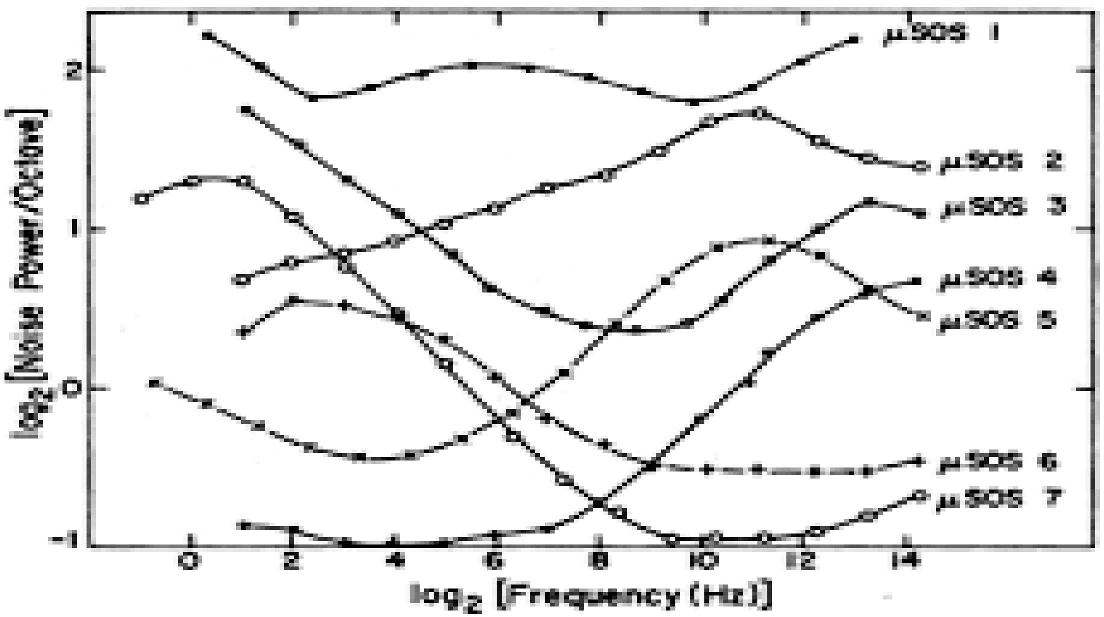



FIG. 4. Power spectra at room temperature for seven different samples having approximately the same size and geometry.

# Quantum noise

- At low temperatures, you still get 1/f noise, but the rattles don’t occur by getting enough thermal energy to go over the barrier. Things tunnel through, quantum mechanically.
  (electrons in and out of traps in $Nb_2O_5$, Rogers and Buhrman, Phys. Rev. Lett., 55, 859 (1985)

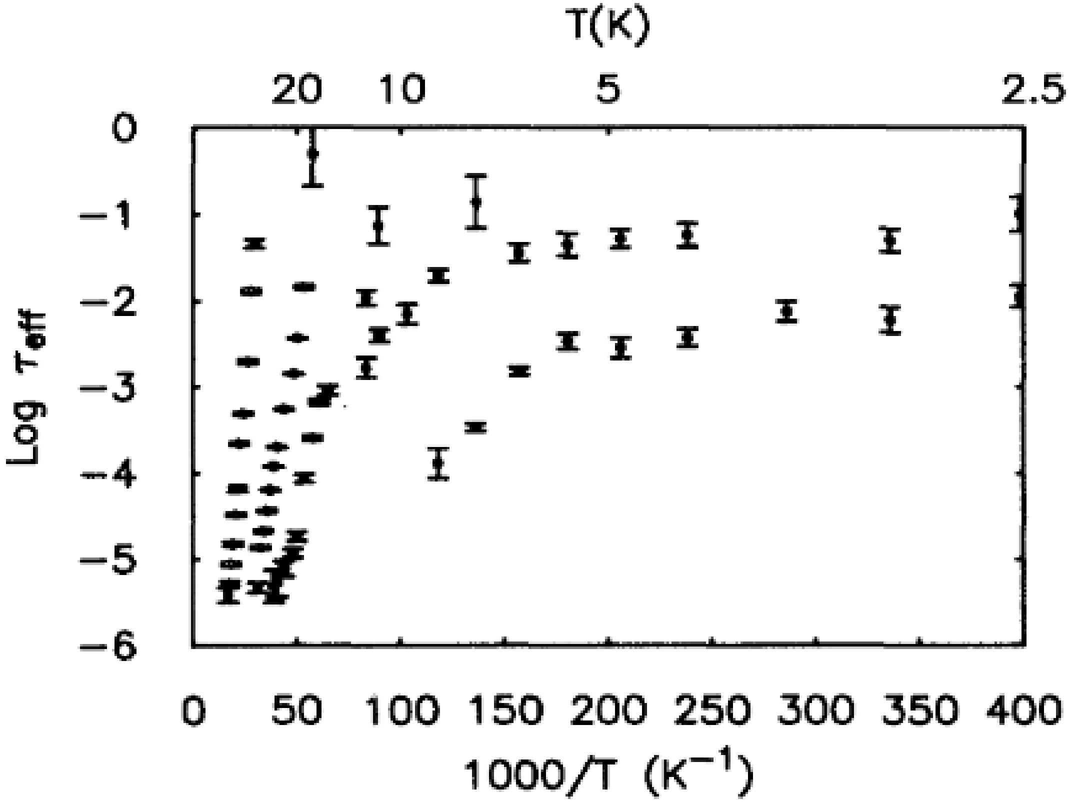



FIG. 2. Typical data set for $\tau_{eff}$ showing the abrupt change from thermally activated behavior above to nonactivated behavior below T ~15 K.

# The secret of 1/f noise

- Ingredient (e.g. two-state)

$$S(f) = \int \frac{s\left(f/f_c\right)}{f_c}\rho(f_c)\,df_c \qquad \textbf{e.g.}\; s\left(f/f_c\right) = \frac{4}{1+\left(f/f_c\right)^2}$$

$$f_c = f_A e^{-E_A/kT} \qquad f_A \approx 10^{12}\,Hz$$

$$\rho(f_c) = \frac{kT\rho(E_A)}{f_c} \qquad \textbf{i.e.}\; \boxed{\frac{d\ln(f)}{df} = \frac{1}{f}}$$

$f_c$ depends *exponentially* on a *distributed* energy, tunneling distance, etc.
Change variables
Bernamont, 1939; McWhorter, 1951

$$S(f) \approx \frac{kT\rho\left(kT\ln\left(f_A/f\right)\right)}{f}$$

1/f with log corrections

# Where does the 1/f 'secret' that apply?
# Quasi-equilibrium systems

- (Almost?) all 1/f noise in metals
  - [2]Defect motions (~all metals) –
  - [1,2]Domain motions (SDW, FM,
  - [2]Glassy TLS
  - [1,2]Spinglassy collective modes
- [2]1/f noise in semiconductors
  - (especially traps in $SiO_2$ )
- [2]disordered phase transitions
  - Manganites…..
- [1]Dielectric 1/f noise
  - Relaxor ferroelectrics

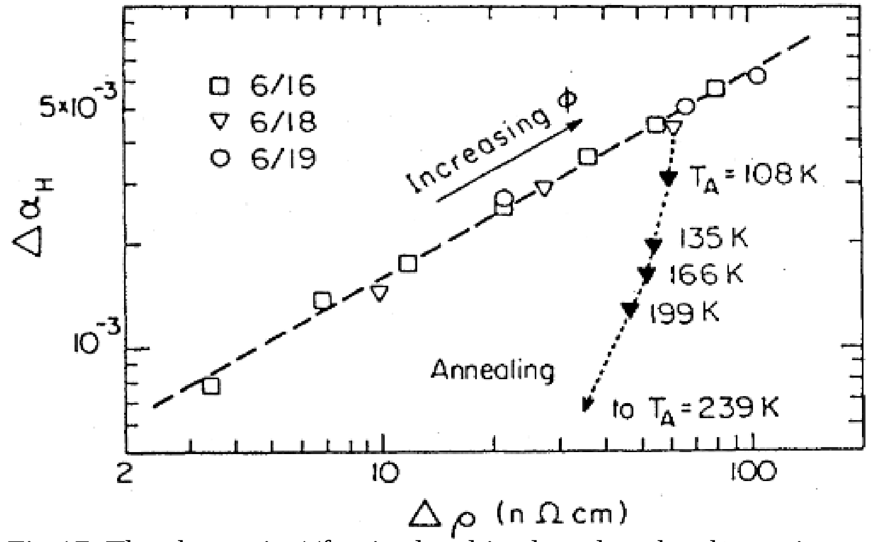



Fig.17. The change in 1/f noise level is plotted vs the change in resistivity for Cu samples irradiated with electrons and subsequently annealed

Strongly *driven* systems e.g. depinned CDWs or vortex lattices, usually show big deviations from $1/f^{1.0}$

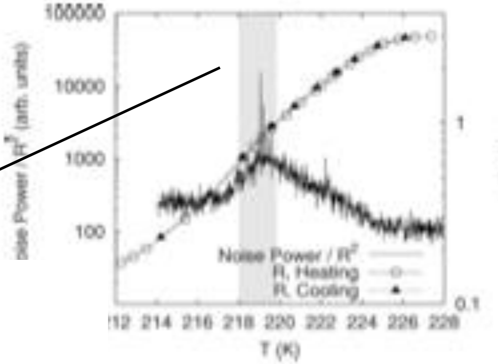
[1] direct equilibrium fluctuation-dissipation: $S_V(f) \sim kT\varepsilon''/Cf$, $S_\mu(f) \sim kTV\chi''/f$

[2] indirect $\delta V = I\delta R$, I is non-equilibrium probe of *equilibrium* noise

# Manganites: inhomogeneity and thermodynamics

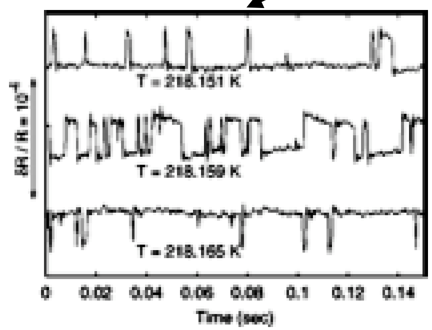
- Thermodynamics not clear from macro-measurements of R(H,T) and M(H,T)
  - Disorder messes things up
  - Noise shows what's up: little pieces of $1^{st}$-order transition

LCMO-0.3 doping




power and resistance vs temperature. Noise power
nitude squared of the Fourier transform. In this

Well defined
ΔE, ΔS, Δμ
between states




. 2. Resistance (ac coupled) vs time at different temperat
of the switchers.

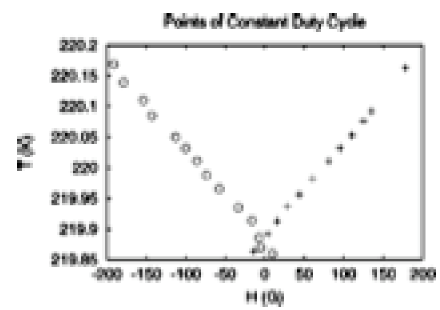



FIG. 4. Temperature and field combinations that produced a ratio $r=1$ for the switcher $b5$ of Table II. The open circles were taken sweeping field from negative to positive and the crosses were taken sweeping from positive to negative. Linear fits give slopes whose absolute value agree to about 1% between the two sweep directions. Note that this plot is analogous to a phase diagram for the mesoscopic domain under observation. The data from the two sweep directions overlap somewhat, showing an odd (as opposed to even) dependence on applied fields smaller than the coercive field. This indicates the local effective fields produced by neighboring ferromagnetic domains are larger than the coercive field (roughly 20 G).

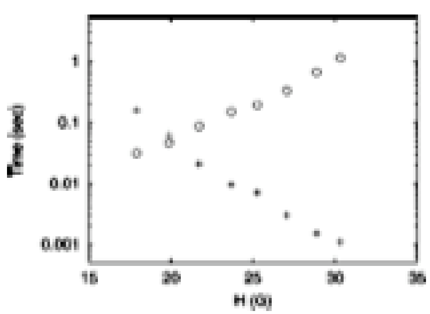
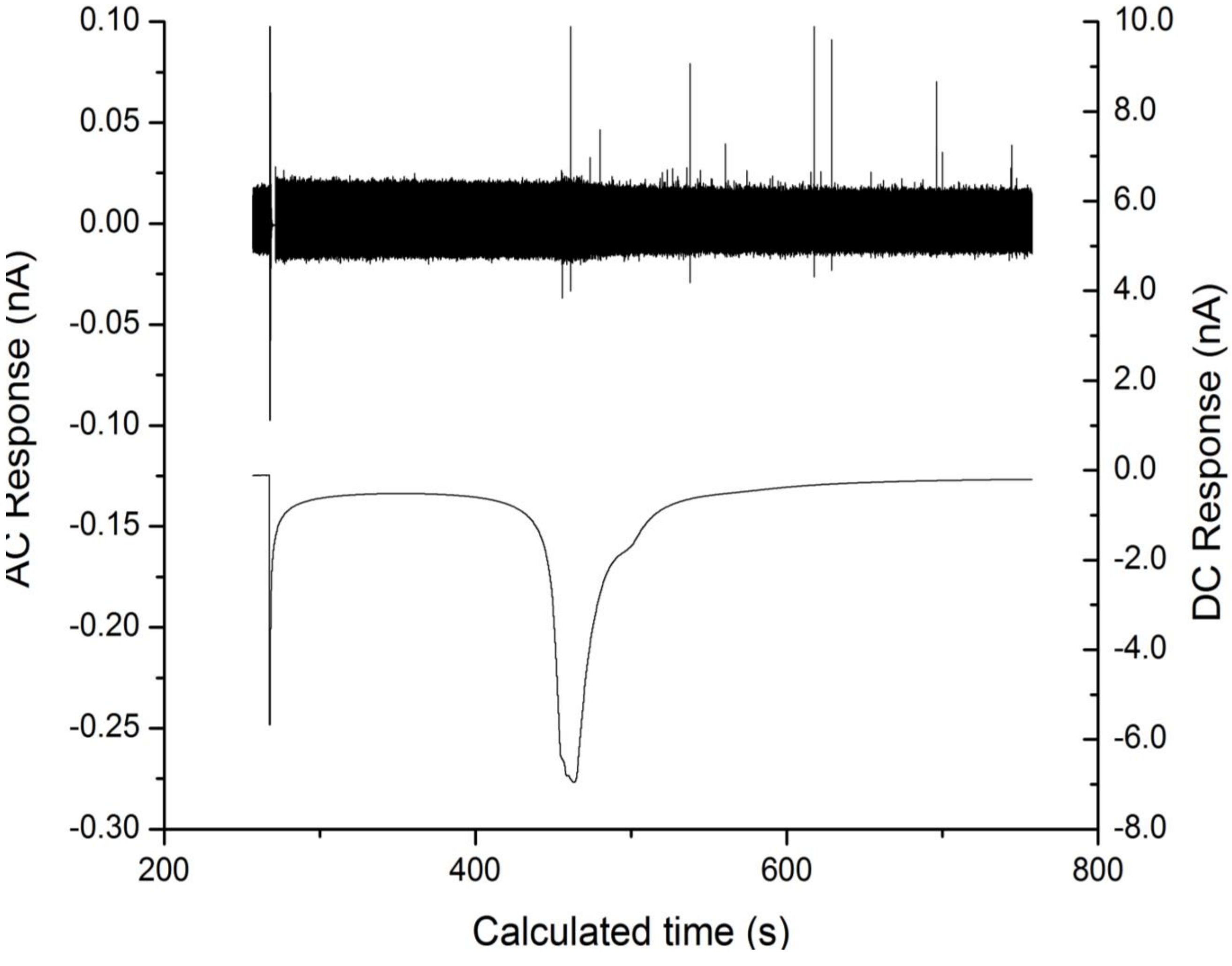


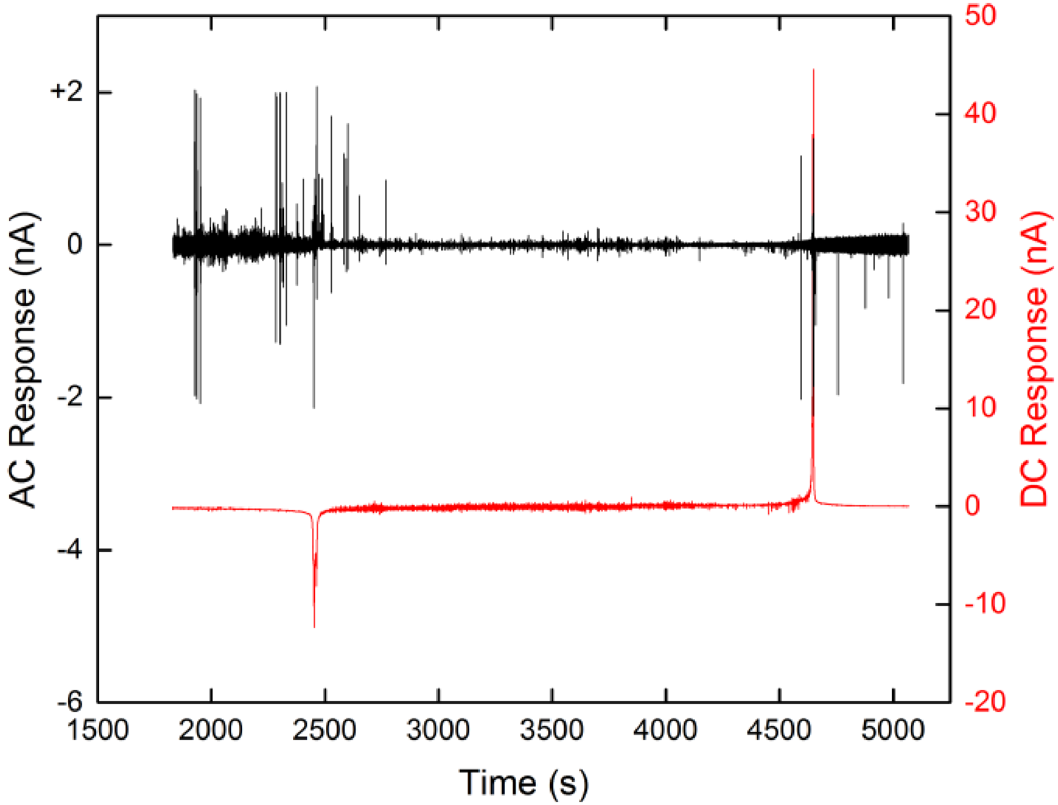

FIG. 5. The average time spent in the high (crosses) and low circles) resistance states are plotted individually vs field. The opposite signs of slope vs field indicate that the transition state has a magnetic moment intermediate between the end states. Similar results are obtained when plotting vs temperature, giving an intermediate entropy for the transition state as well.

# Barkhausen Noise in Ferroelectrics




Noise shows size of units involved in different stage of conversion of glassy state to ferroelectric state

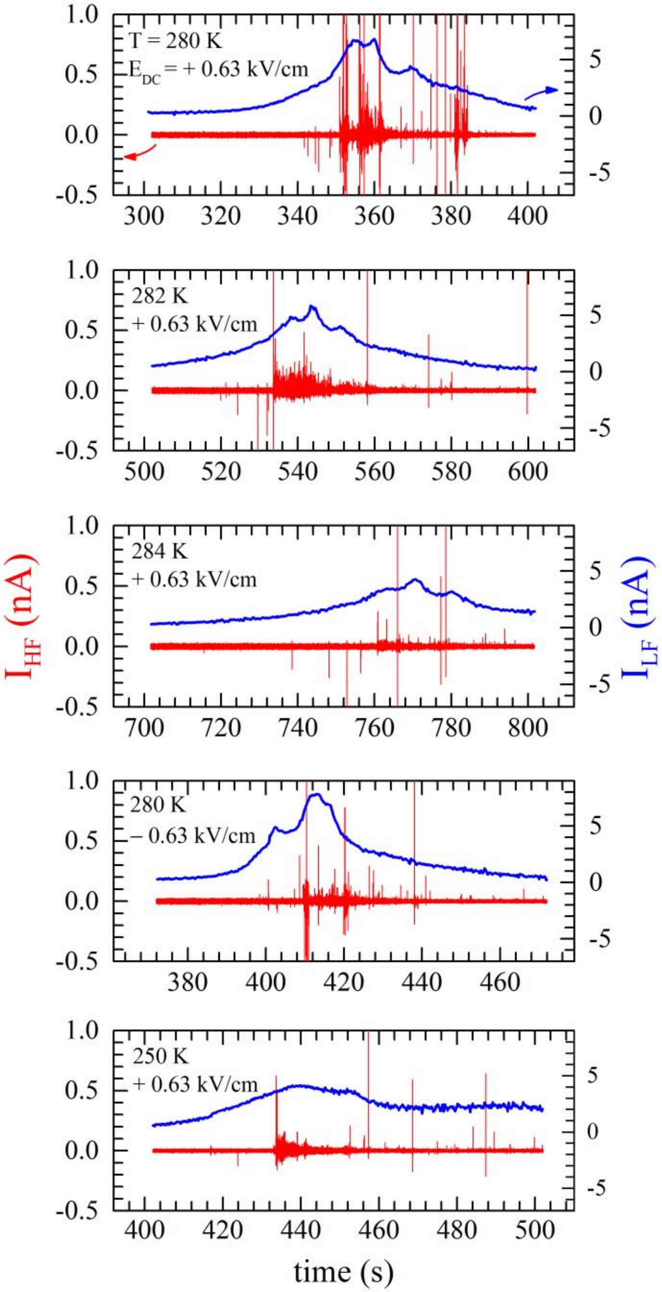
# Xinyang's Barkhausen




Big domains form before most of sample goes FE. Rates *not* limited by nucleation.

Some domains melt *after* main melting→ important heterogeneity.

# Xinyang's data: notice anything?



# Summary

- Noise provides a good probe of
  - Conduction mechanisms (shot noise)
  - Domain dynamics (Barkhausen)
  - Defect dynamics (1/f noise in metals)
  - Subtle phase transitions (CR films,…)
  - Hidden order (spinglasses)
  - Charge density wave dynamics ($TaS_3$)
  - …….