Noise : Nuisance and Tool

Outline:

Broad categories

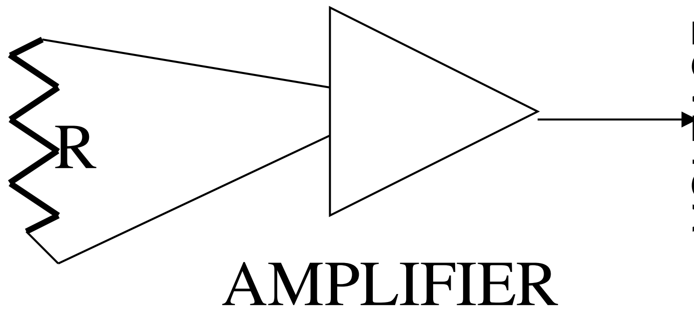
- fundamental equilibrium noise
- noise reflecting system physics
- bad contacts, etc.

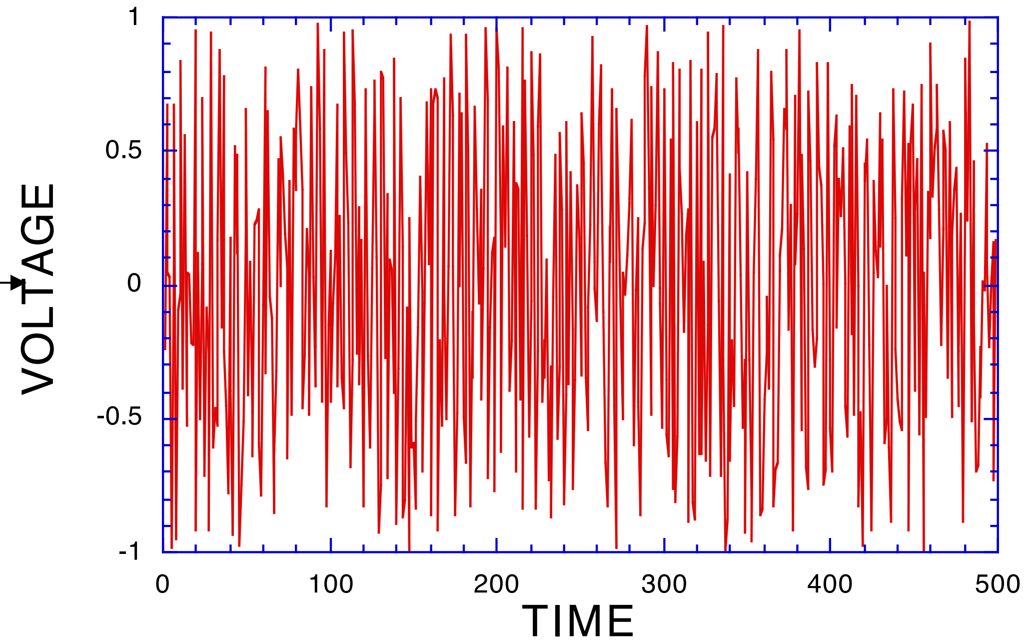
Case studies in applications:

- Cr: a case study in diversity
- Noise and extraneous dirt: defects in SiO_2 etc.
- Noise and dirty thermodynamics: e.g. manganites
- Noise and thermodynamics of dirt: cold glasses
- Noise and intrinsic disorder: spinglasses

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?*

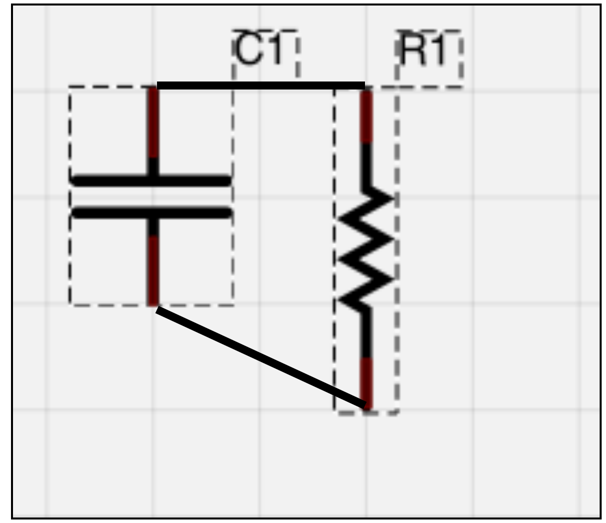
Noise and the laws of thermodynamics

- 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.
$\langle(\delta V)^2\rangle = kT/C$



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

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

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

$S(f) = 4kTR$ (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)

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

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

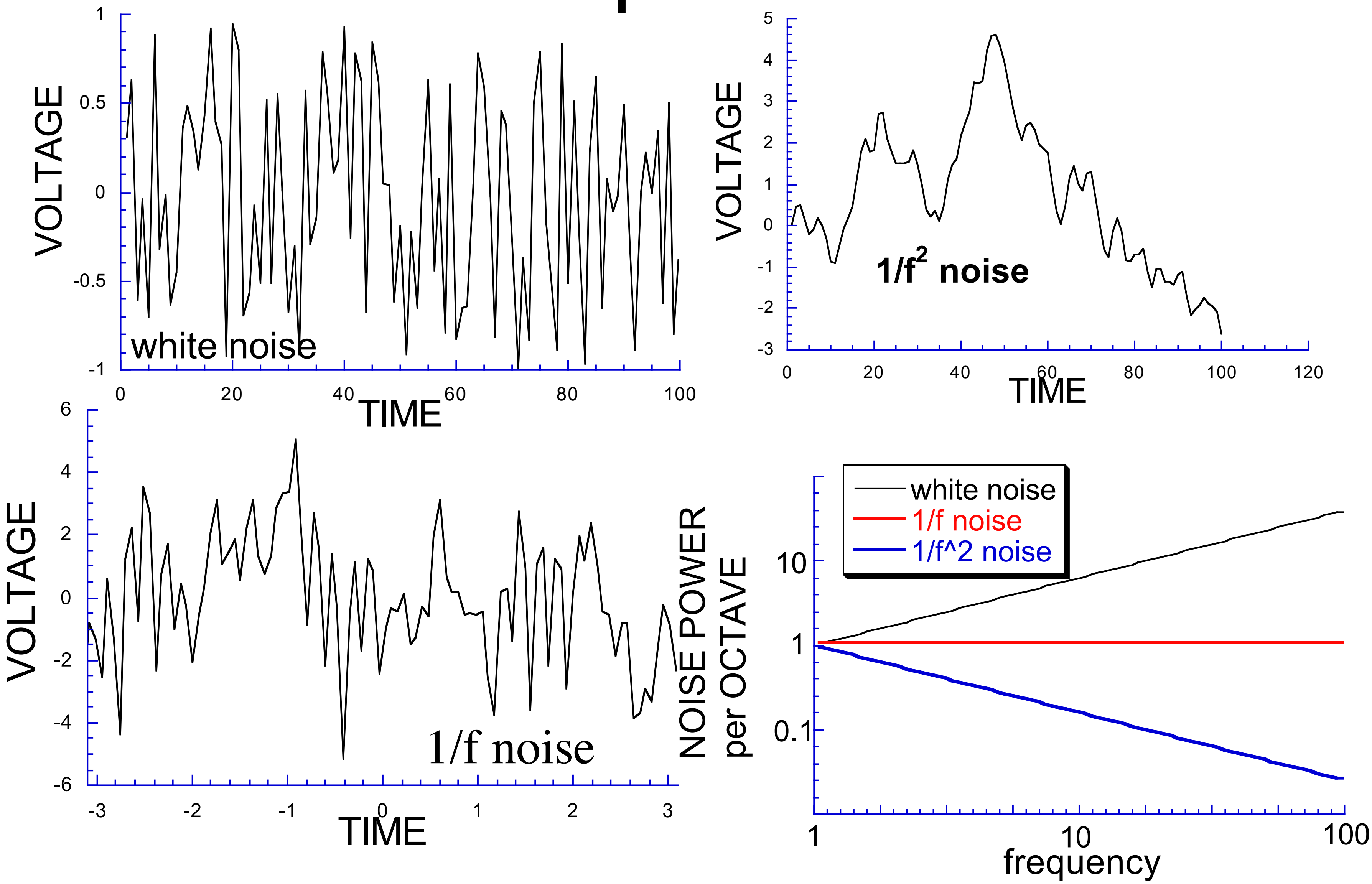
Write the signal as a sum of waves at a set of equal spaced frequencies.
S(f) gives how the *square* of the size of the components depends on f.

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

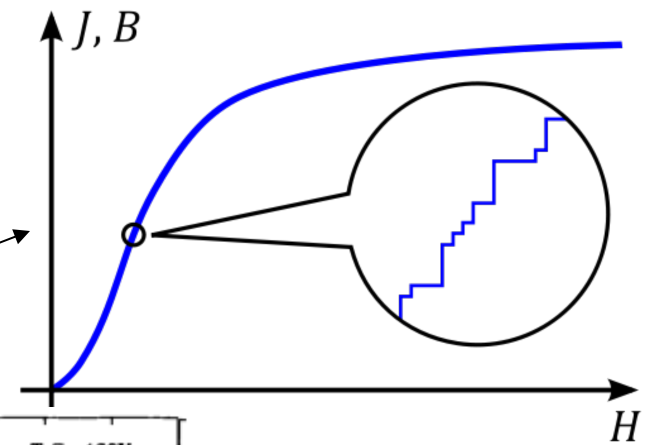
Playing the tape back at double speed doesn't change the sound!
Another fact to intrigue to theorists.

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



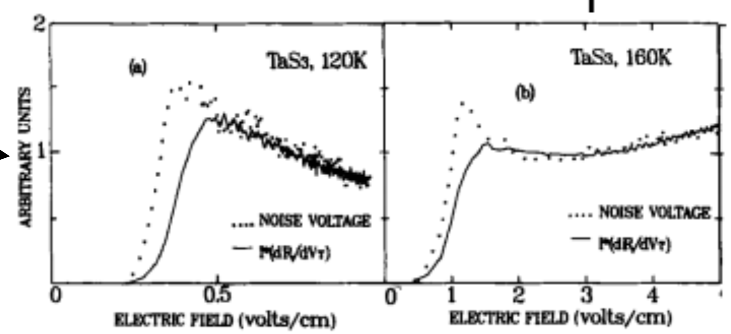
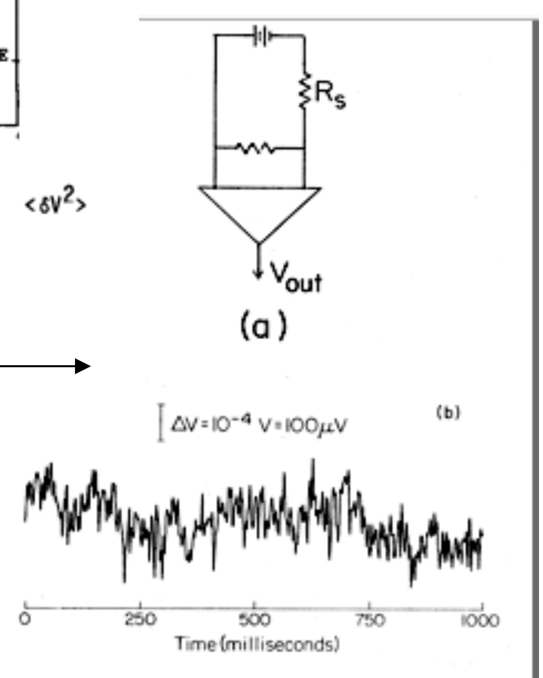


FIGURE 1 Field dependence of the broadband noise $\langle\delta V^2\rangle$ measured at 300 Hz and $I^2(\partial R/\partial V_T)^2$.

- 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 $\delta(kTR)$
- 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)

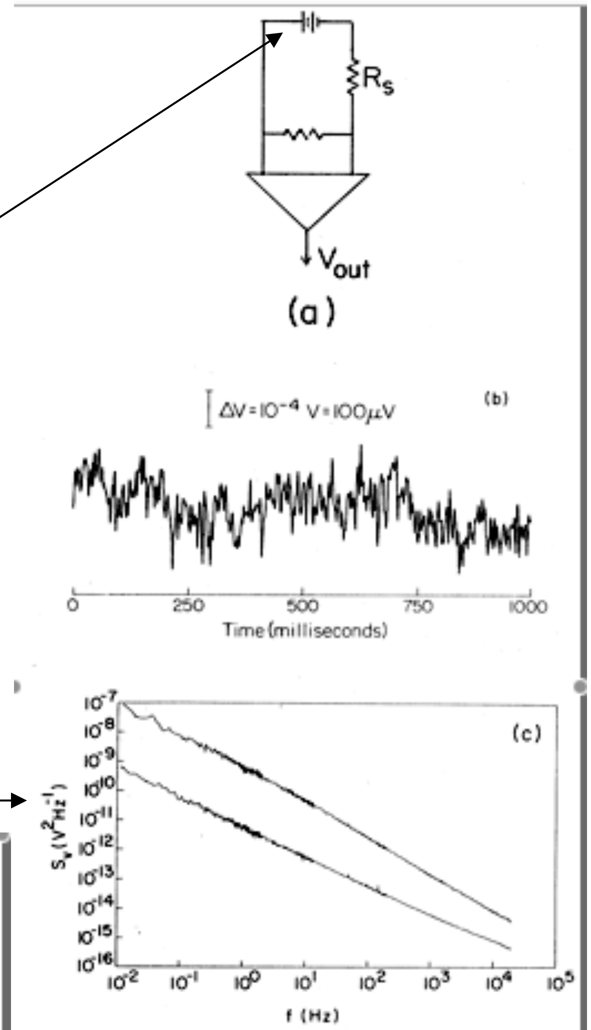


FIG. 1. (a) The basic experimental configuration and typical observations of $1/f$ noise. Schematic diagram of the simplest measuring apparatus for $1/f$ noise. R_s is a large, constant resistor. The unlabeled resistor is the sample. Various modifications, such as the use of ac currents with phase-sensitive detection, bridge circuits, and multiprobe samples, are common. (b) An actual fluctuating voltage from a silicon resistor with about 100 μA of current (1 V average bias), measured in a setup like that shown in part (a). (c) Noise spectra from two thick-film resistors, shown over a very broad range of frequencies. The upper plot is taken from an IrO_2-based film at $T=556$ K, the lower from a ruthenate-based film at $T=300$ K. Each point in each spectrum represents the average square of the Fourier transforms of 1200 1024 point traces, such as that in part (b). Several such spectra, taken at different sampling rates, are stitched together for each broad-band spectrum shown (from Pellegrini, Saletti, Terrini, and Prudenziati, 1983).

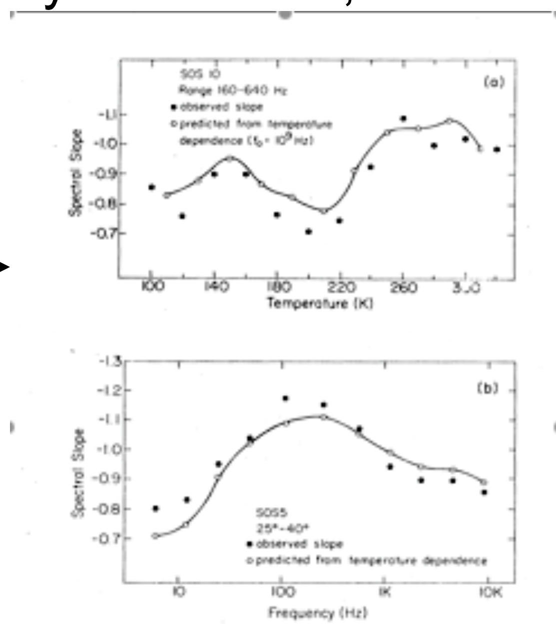
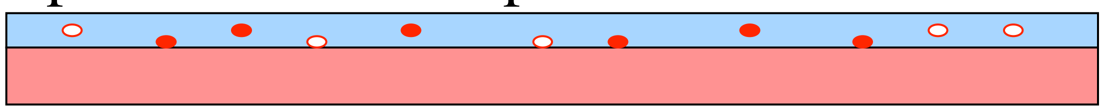
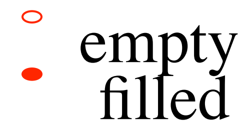


FIG. 8. Two forms of the Dutta-Horn relation for silicon-on-sapphire resistors. (a) A plot of the spectral slope $[\partial \ln S(f)/\partial \ln f]$ vs temperature for an SOS sample. The pre-

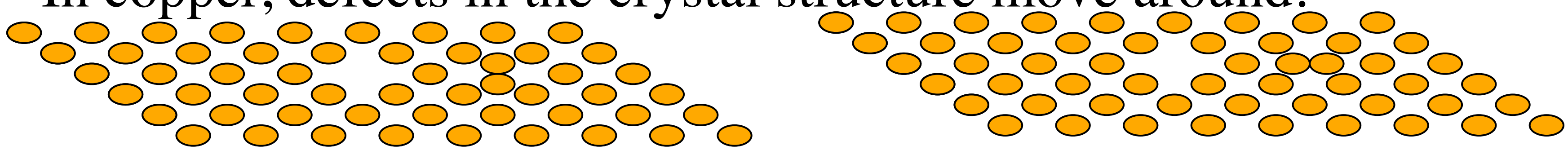
So what's rattling?

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

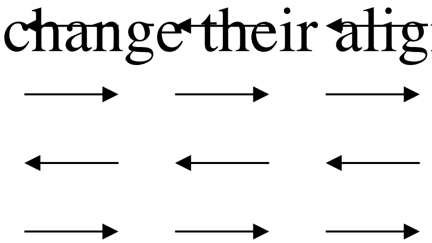


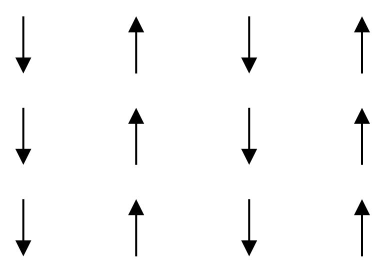


In copper, defects in the crystal structure move around.



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

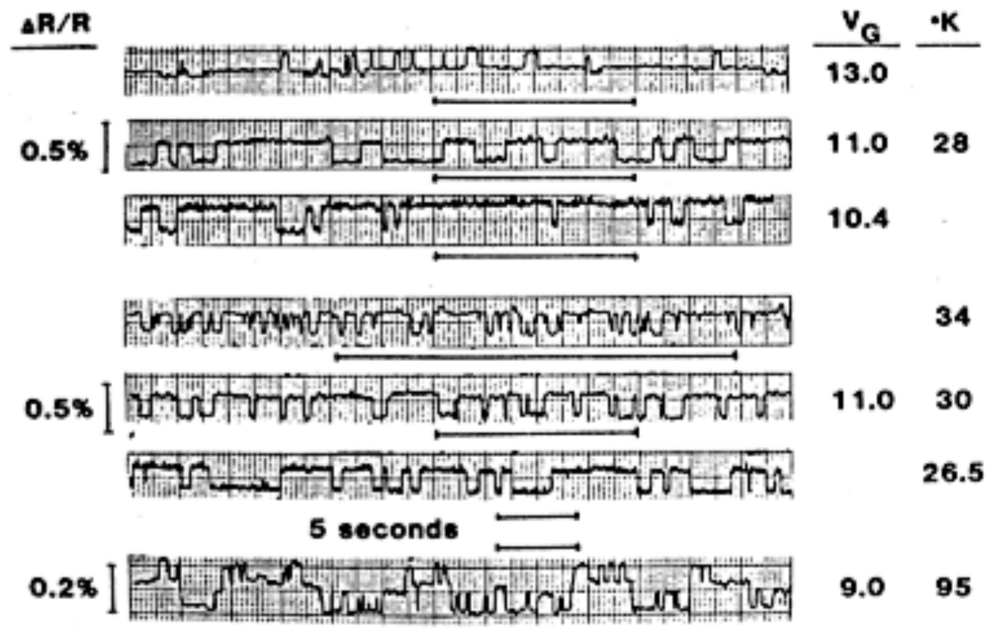


FIG. 5. Two-state switching in the voltage on small gated Si resistors, observed by Ralls *et al.* (1984). V_G is the gate voltage,

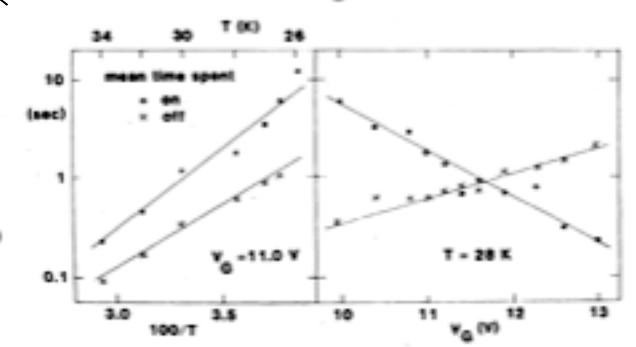


FIG. 2. Exponential dependence of mean lifetimes on inverse temperature and gate voltage for a particular switching sequence. These are identified with capture and emission rates at a single interface trap.

Why 1/f?

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

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

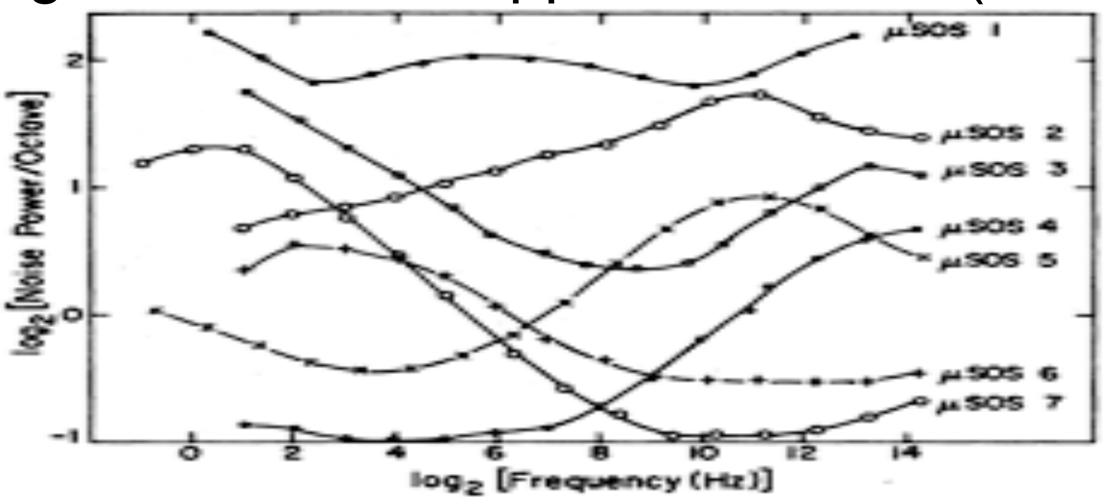


FIG. 4. Power spectra at room temperature for seven different samples having approximately the same size and geometry.

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, 1985)

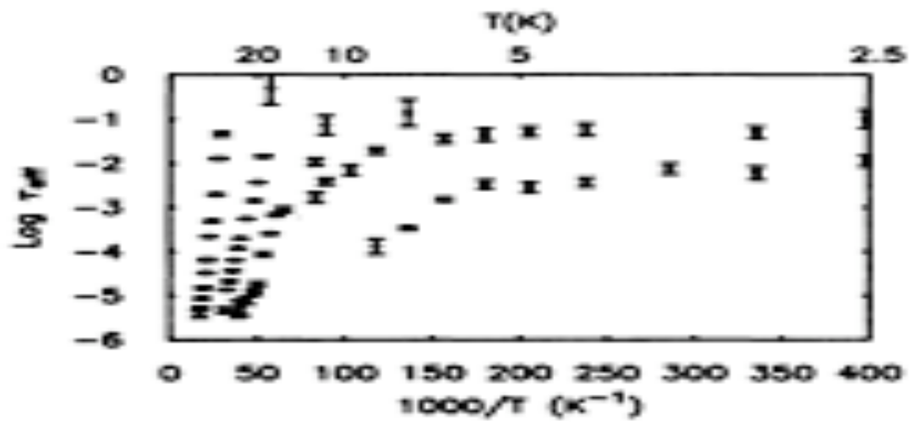


FIG. 2. Typical data set for τ_{eff} showing the abrupt change from thermally activated behavior above to nonactivated behavior below $T \sim 15$ K.

The secret of 1/f noise

- Ingredient (e.g. two-state)

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

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

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

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 ‘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

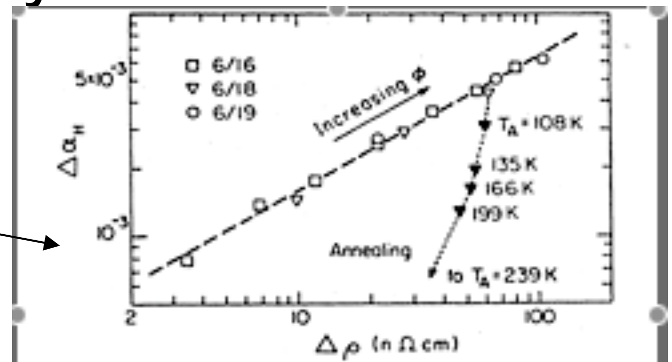


FIG. 17. The change in $1/f$ noise level is plotted vs the change in resistivity for Cu samples irradiated with electrons and subsequently annealed: dashed line [$\Delta\alpha_H \propto (\Delta\rho)^{0.6}$], irradiated samples, for which the resistance changes as the square root of the dose, ϕ; dotted line, the recovery of both variables at increasing annealing temperatures T_A. For $T_A = 239$ K (not shown), $\Delta\rho \approx 11.6$ nΩ cm and $\Delta\alpha_H \approx 7\times10^{-5}$. Clearly the defects mainly responsible for the resistance change and those mainly responsible for the noise are not the same (Pelz and Clarke, 1985).

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

Fluctuation-dissipation

usually quasi-equilibrium, but rarely have accessible dissipation

Some exceptions:

Spinglass magnetization
(Reim…, PRL)

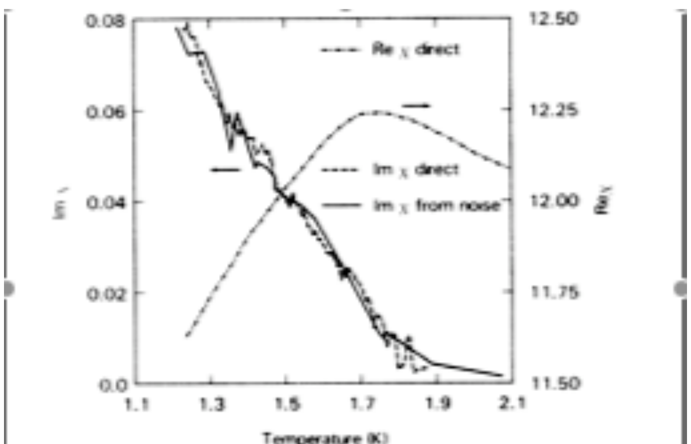
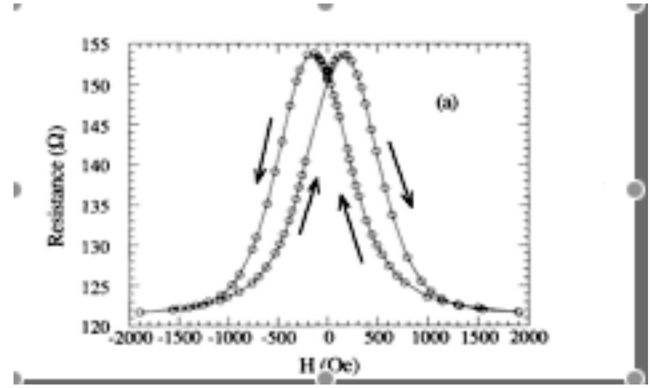


FIG. 3. Calculated imaginary part of the ac susceptibility $\chi''(T, 50\ \mathrm{Hz})$ from Eq. (1) compared with the directly measured ac susceptibility at 50 Hz. The units for the susceptibility are arbitrary.

In GMR, R fluctuations come mainly from M fluctuations via dR/dM.

Ordinary defect 1/f noise corresponds to internal friction, (strain noise) but not with uniform coefficient of R vs. strain

GMR resistance



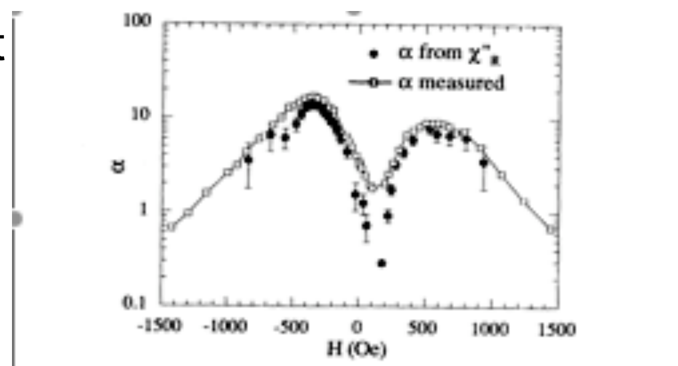


FIG. 5. The measured $\alpha(H)$ [Fig. 3(a)] is compared to that ılculated via Eq. (5) from the χ''_g data in Fig. 4.

1/f noise in Cr: a diverse example

SDW polarization rotation

Defect motions:
See works by Ralls, Scofield, Pelz, Kogan… on standard metals

SDW q-vector rotation

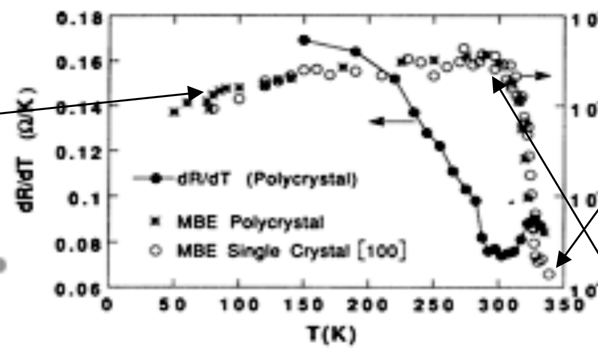


FIG. 2. The Hooge noise parameter, α increases by two orders of magnitude near the bulk Néel temperature. MBE polycrystal Cr and MBE single-crystal show the same behavior. The resistance anomaly is also observable in the same polycrystal sample, indicating the rise in the noise is a result of the magnetic ordering.

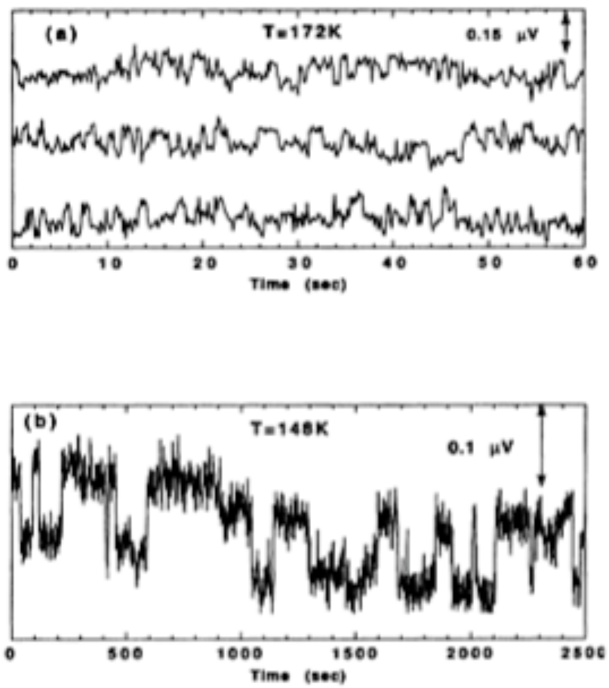


FIG. 8. Voltage vs time records for sample D at $T=172$ K, with an applied voltage of 10-mV rms are shown in (a). At this temperature, the sample resistance is 12 Ω. Switching events are visible, but obscured by the background of other events. In (b) an extremely slow but clearly visible switcher is active at $T=148$ K. The switchers represent fractional resistance changes of 1.1×10^{-5} and 1.3×10^{-5}, respectively.

Techniques:
Magnitudes vs.crystal axes
Sizes of steps
T-dependence of steps

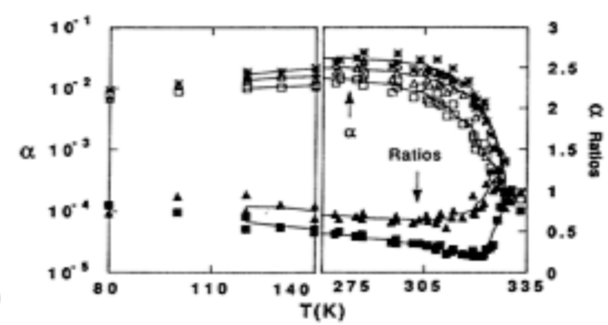


FIG. 3. The anisotropy in the noise along the different axes qualitatively reflects the underlying crystal symmetry. However, the quantitative values deviate significantly from the expected relationship. (a) The symbols represent the noise in the directions shown. The anisotropy persists down to 80 K as shown in (b). A fit to the data is shown to help guide the eye.

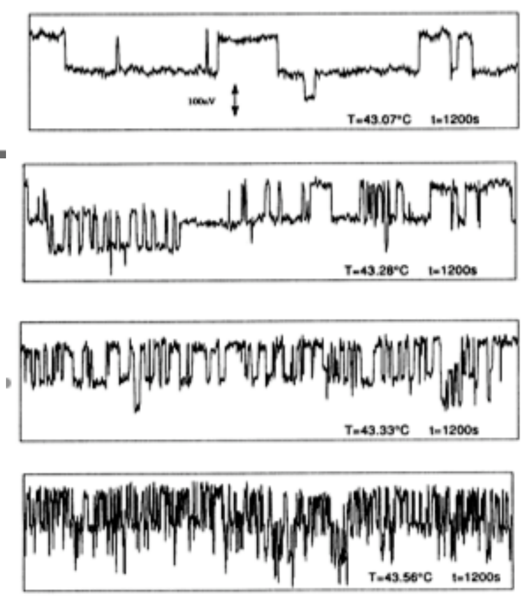


FIG. 4. In a single-crystal sample with volume 2×10^{-13} cm^3 (sample A) switching behavior in the voltage near the transition could be tracked over about 1 K at 316 K. Voltage as a function of time is shown for 1200 sec at four temperatures. The arrow represents a 100 nV change in voltage, or fractional change of $(\delta V/V)\simeq10^{-5}$. The temperature dependence of the characteristic relaxation rates for the different levels is highly non-Arrhenius.

A closer look at defects in metal nanobridges

(Ralls and Buhrman)

Simple to complicated

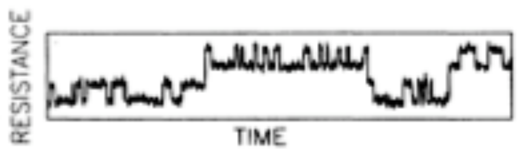


FIG. 15. Apparently noninteracting defect fluctuations.

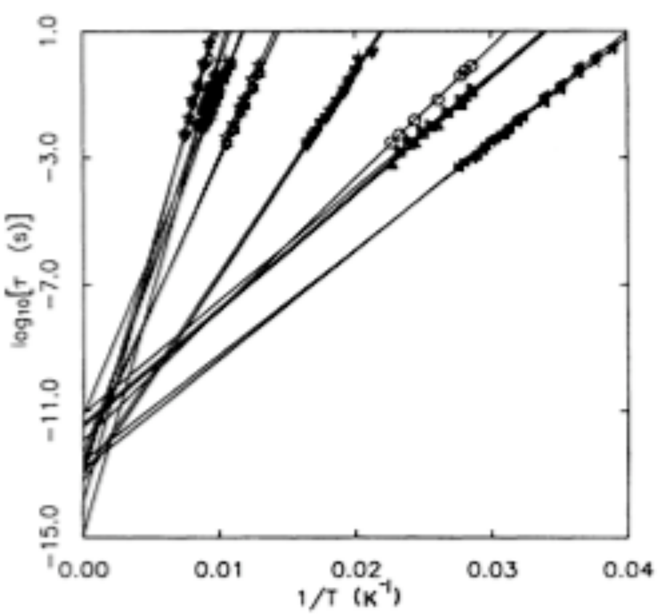


FIG. 8. Summary plot of thermally activated behavior for many different defect fluctuations. Attempt times range from 10^{-11} to 10^{-15} s, as shown by the *y* intercept. Activation energies come from the slopes of the lines, and tend to increase with increasing temperature.

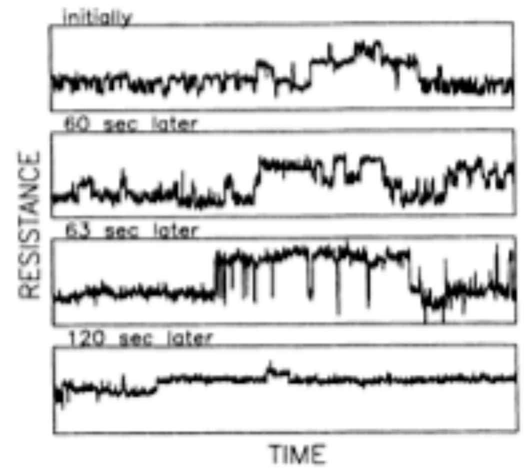
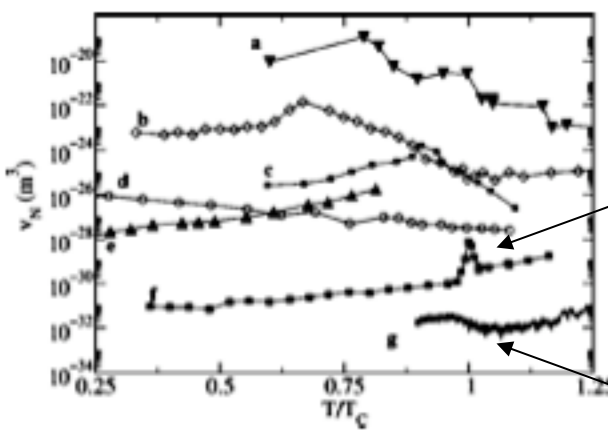


FIG. 19. Fluctuating noise behavior in a 90-Ω copper nanobridge at 300 K characteristic of the high-temperature noise seen in the smaller nanobridges. Independent TLF's are never seen above about 150 K, telling us that all the active defects are interacting strongly with other active defects.

Noise and phase transitions: manganites

We learn to expect fluctuations at 2nd order, not 1st.

but in the low frequency regime:



Clean LCMO (1st order)

Clean LSMO (2nd order)

FIG. 4. Comparison of noise magnitude v_N (suitable for comparisons between samples of different geometries) from several other samples described in the literature. (a) laser ablatedLCMO (Ref. 16), (b) laser ablated $La_{0.6}Y_{0.07}Sr_{0.33}MnO_3$ (Ref. 15), (c) ALL LCMO on STO (Ref. 10), (d) LSMO with grain boundaries (Ref. 23), (e) laser ablated LSMO (Ref. 22), (f) MBE LCMO on NGO (Ref. 20) and (g) ALL LSMO on STO.

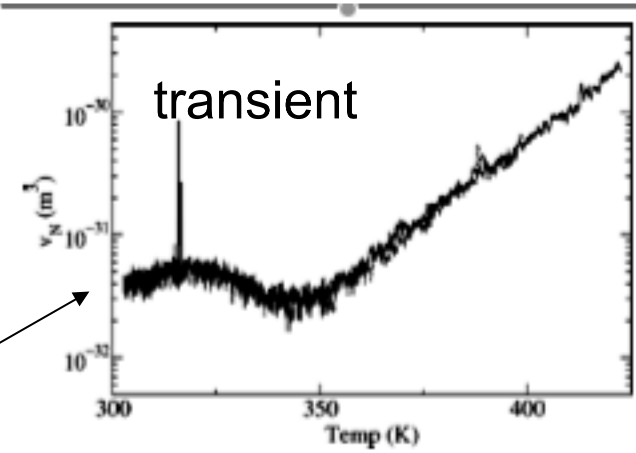


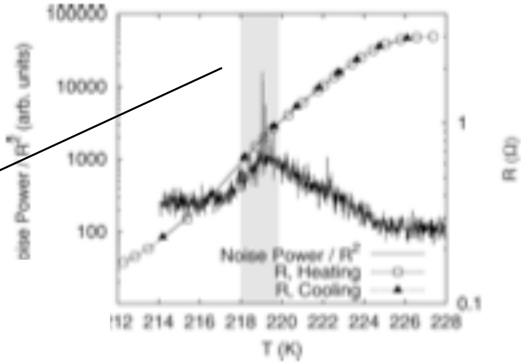
FIG. 5. Normalized noise magnitude v_N shown vs descending T for two different sweeps. The data overlap very well, except for the large spike, which occurs only in one of these two sweeps. These data were taken from a different sample than those shown in the other figures, but with a similar $R(T)$.

Disorder limits critical scaling, breaks up 1st order

Manganites: inhomogeneity and thermodynamics

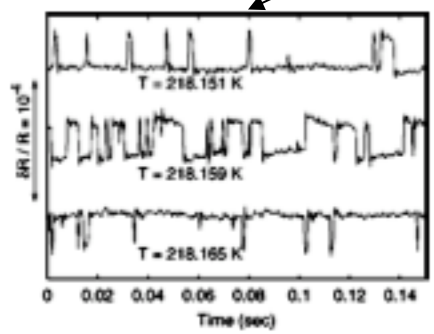
- Thermodynamics not clear from macro-measurements of R(H,T) and M(H,T)
  - Disorder messes things up
  - Noise shows what's up: little pieces of 1st-order transition

LCMO-0.3 doping



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

Well defined
ΔE, ΔS, $\Delta \mu$
between states



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

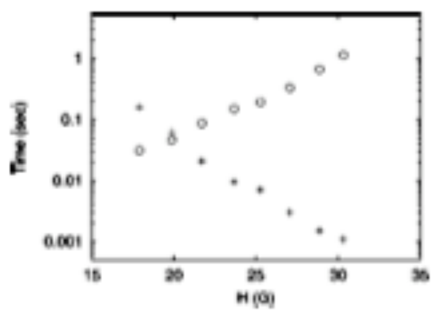


FIG. 5. The average time spent in the high (crosses) and low circles) resistance states are plotted individually vs field. The opposite signs of slope vs field indicate that the transition state has a magnetic moment intermediate between the end states. Similar results are obtained when plotting vs temperature,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

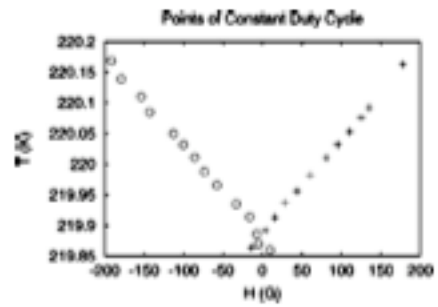
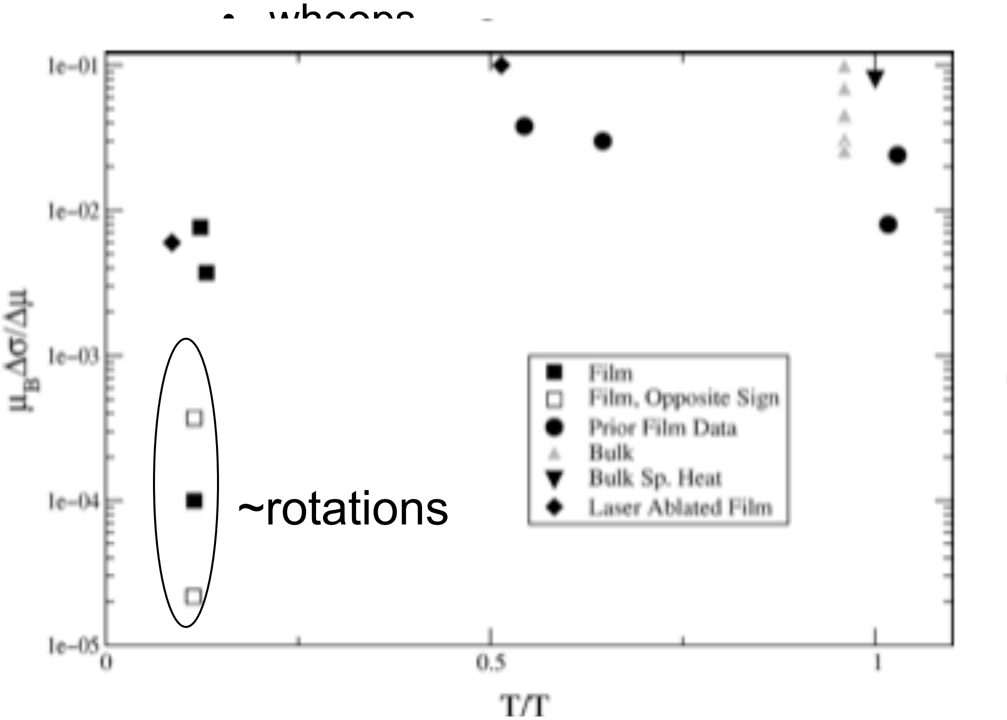


FIG. 4. Temperature and field combinations that produced a ratio $r \approx 1$ for the switcher b5 of Table II. The open circles were taken sweeping field from negative to positive and the crosses were taken sweeping from positive to negative. Linear fits give slopes whose absolute value agree to about 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).

Manganites: inhomogeneity and thermodynamics

- But why does a smallish region (~10^6 u. c.) in a biggish (~10^{17} u. c.) sample give a big $\Delta R/R$ (~10^{-4})?
- Requires *major* current inhomogeneity
  - ~expected near transition, but not deep ~~in metallic~~ phase
    - whoops



Still ~percolating?
Tunneling across domain walls?

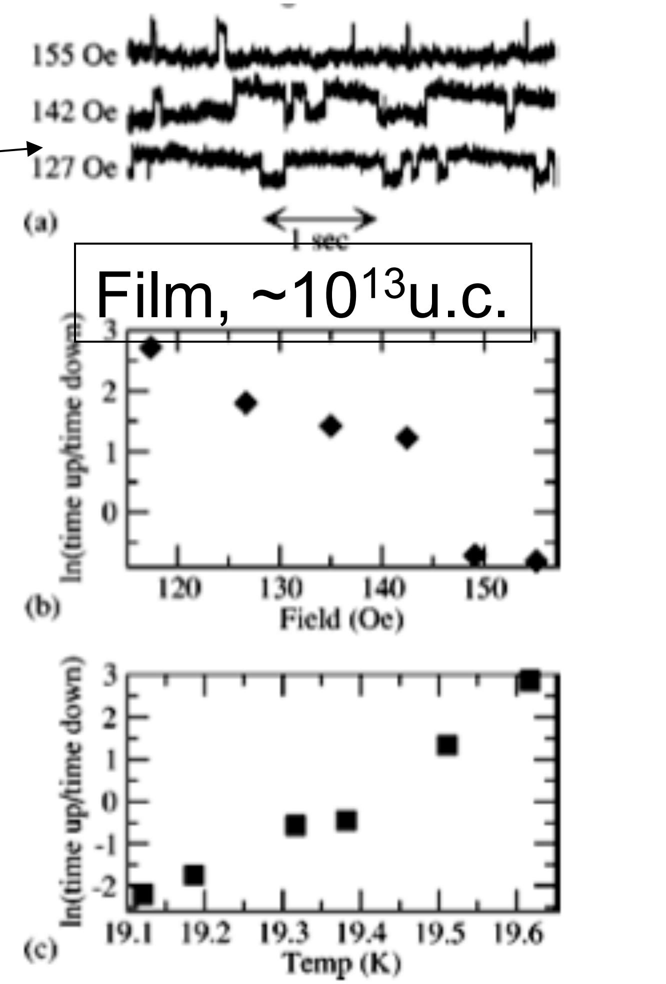


FIG. 3. Part (a) shows time traces of voltage with a fluctuator at 18.5 K at several fields. The resistance steps are 6×10^{-4} of the total R. Parts (b) and (c) show $\ln(r)$ vs H and T.

Two-state systems in glasses

account for low-T heat capacity, control thermal conductivity

- In amorphous metals, noise (via Universal Conductance Fluctuations) reveals actual TSS, as hypothesized.

- They show activated and tunneling kinetics.

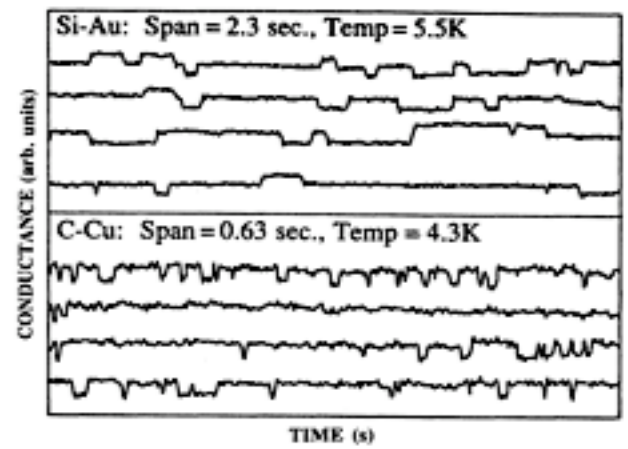
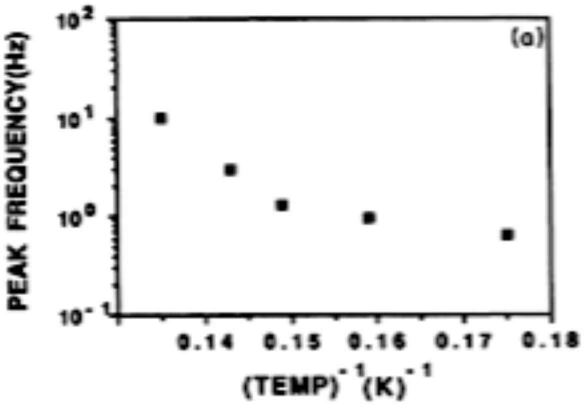


FIG. 2. Conductance traces as a function of time are shown for two samples. The top traces show a Si-Au sample illustrating three-state switching in the third trace and perhaps in the first two traces. Comparison of the traces weakly illustrates the variability of the switching rate. The C-Cu data show drastic variability in the switching rate between traces and within the third trace.



The density is roughly as expected from C_V. They often deviate from simple TSS form, indicating larger interactions than expected.

Spinglasses: $Cu_{0.91}Mn_{0.09}$

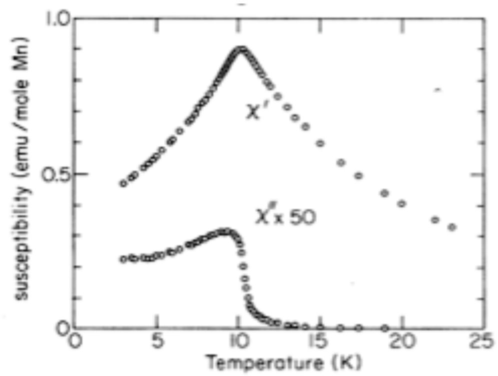


FIG. 1. The susceptibility components $\chi'(f,T)$ and $\chi''(f,T)$ shown for a typical spin glass, $Au_{1-x}Mn_x$ with $x \approx 0.03$ and $f \approx 200$ Hz (from Mulder *et al.*, 1981).

χ" in glass phase -> M noise via FDT

Known spin disorder scattering (from T_G)
+UCF theory ->
predicted R noise

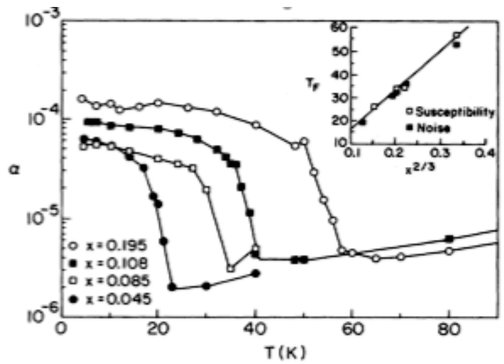
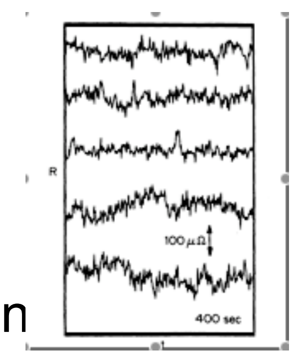


FIG. 3. Values of $\alpha(T)$, a dimensionless measure of the size of the resistance noise (Weissman, 1988), shown for several concentrations, x, of $Cu_{1-x}Mn_x$ in macroscopic samples. The inset shows that the magnetic transition temperatures and the noise-increase temperatures closely track each other as a function of x.

But these predicted spectra tell little
about how to describe the SG state
e.g. dynamics from
Isolated droplets in frozen matrix
vs. collective hierarchy of rearrangemen



Mesoscopic noise
(non-Gausian higher moments) can help

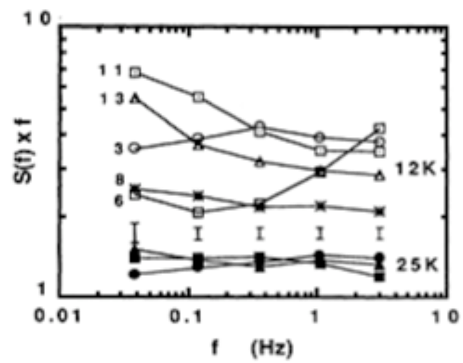


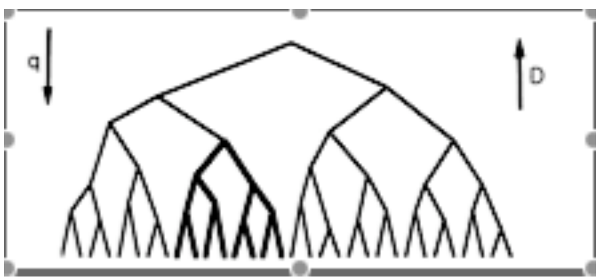
FIG. 4. Measurements of the resistance noise spectrum at $T = 25$ K and at about 12 K for a $Cu_{0.91}Mn_{0.09}$ sample containing about 2×10^6 spins with $T_G \approx 24$ K. Each spectrum is a 40-minute average derived from 100 Fourier transforms. A $1/f$ spectrum appears as a horizontal line in this representation. The set of error bars shows the calculated Gaussian standard deviation. The 12-K spectra are labeled by the order in which they were taken, with many omitted to avoid clutter.

Spinglass statistics: CuMn

Take the spectrum of the time series of powers in some octave (2nd spectrum)

Here $f_2S_2(f_2,f_1)$ is shown for different f_1 vs. f_2/f_1.

These data fit a hierarchical picture, not a droplet picture.



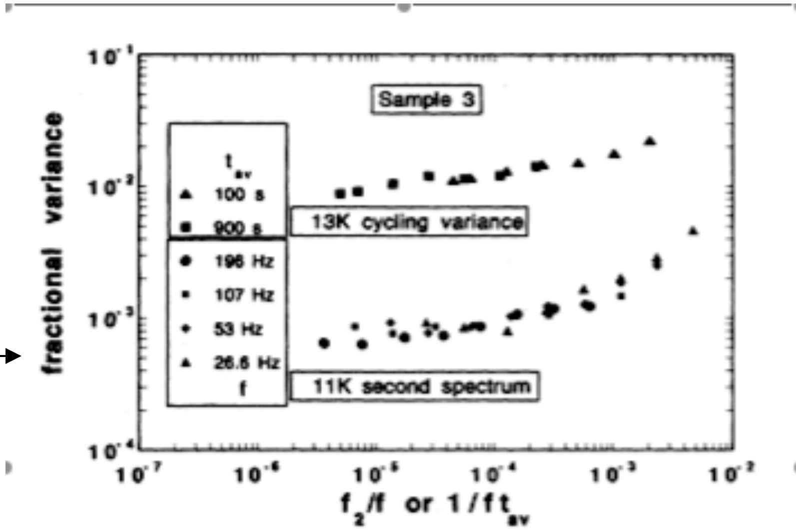
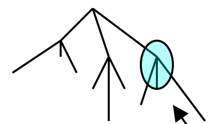


FIG. 6. The ratio $\langle(\delta S_1(f))^2\rangle/\langle S_1(f)\rangle^2$, nearly scale invariant, i.e., independent of f for fixed ft_{AV} or fixed f/f_2 (t_{AV} is the averaging time for a given data set). Top: $\langle(\delta S_1(f))^2\rangle/\langle S_1(f)\rangle^2$ from each of seven different octave bands of $S_1(f)$, measured at 13 K (with $T_G \approx 28$ K) by comparing spectra taken after 12 thermal cycles above T_G. Different groupings of the same data give $t_{AV}=900$ sec and $t_{AV}=100$ sec. Bottom: $S_2(f_2,f)$ at 11 K obtained as cross spectra between power fluctuations in adjacent octaves (to nearly eliminate Gaussian effects), plotted as $\langle(\delta S_1(f))^2\rangle/\langle S_1(f)\rangle^2$ per octave of f_2.

In each frequency range, the spectrum wanders as lower-f events change the detailed active branch.

Magnitudes of higher moments give fluctuators of $\sim 10^4$ spins interacting over volumes of $\sim 10^6$ spins.

CuMn Spinglass: what sort of hierarchy?



Correlations in low-f_2 cross-second spectrum between widely separated f_1's show that the spectral units coming and going are broader than Lorentzians, i.e. are multi-state. There's a high-f_2 component with weak inter-octave correlations, expected for internal dynamics of single multi-state vertex.

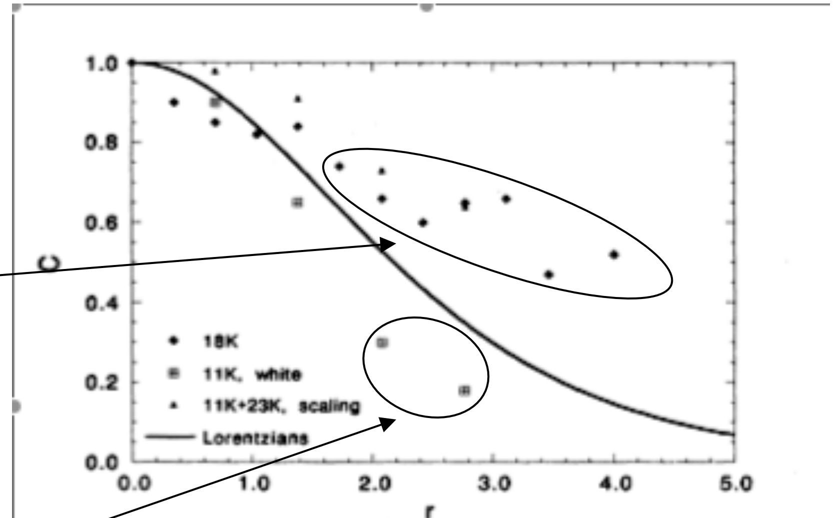
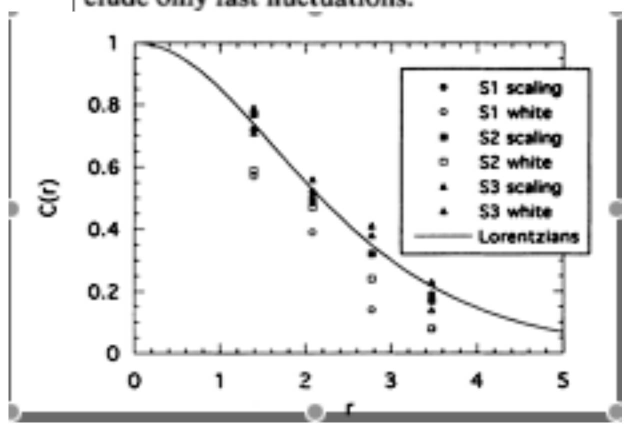


FIG. 8. Correlation coefficient C for fluctuations of the noise power at two frequencies, f_a and f_b, with $\ln(f_a/f_b)=r$. The solid curve, $r/\sinh(r)$, is predicted for independent Lorentzian contributions to S_1. The "18 K" points include mainly slow fluctuations in the noise power, and the "11K+23K, scaling" data include only slow fluctuations. The "11 K, white" data include only fast fluctuations.

More Ising-like AuMn
Looks different



AuMn: spinglass with strong random anisotropy

- Switchers: and switchers in switchers

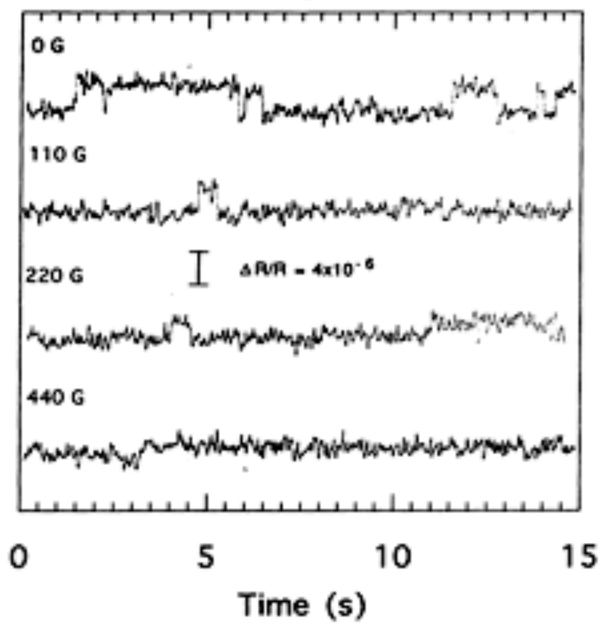


FIG. 10. Sample resistance vs time in $S2$ at 4.7 K at different applied magnetic fields.

Bifurcating hierarchy?

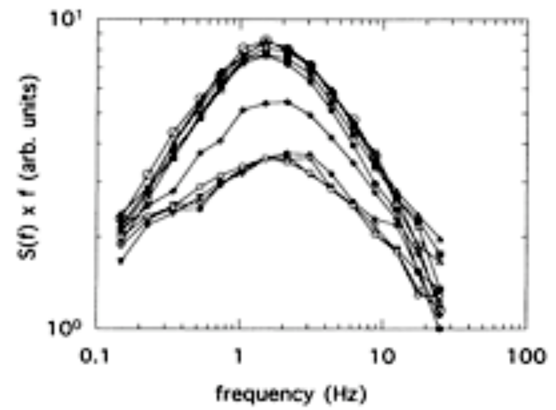


FIG. 7. Noise spectra for several sequential runs in $S2$ at 6 K. The larger peak was stable for 20 h before changing to the smaller peak and then staying stable for 13 h. Each spectrum represents 200 min of data.

Ordinary activated kinetics, contrary to expectations

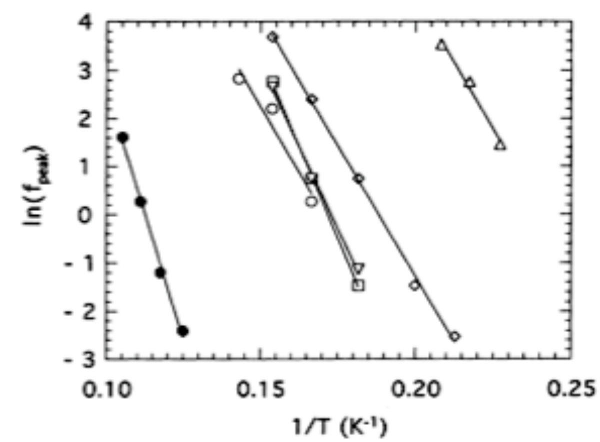


FIG. 12. Arrhenius plot of spectral features in $S1$ (ope points) and $S2$ (filled points). The fits are used to calculate a activation energy and attempt rate for each feature.

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)
  - …….