Measurement of Spontaneous Flux Generated During a Rapid *Inhomogeneous* Quench of Superconducting Films

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Outline

1. Background
2. Experimental system
3. Results with homogenous heating
4. Results with inhomogeneous heating
5. Possible scenarios
6. Conclusions

Motivation

- Ideally, phase transitions take an infinite long time - in reality the system goes through the transition over a finite time!

- This means the system is out of thermodynamic equilibrium in the temperature range near the transition temperature.

- The **Kibble-Zurek scenario** states that the outcome of an order - disorder phase transition depends on the dynamics. If the dynamics are fast enough **topological defects** will be created in the system. This scenario assumes the system is quenched through the phase transition ***uniformly***.

Question: What happens if the transition is ***not uniform*** ? Does it change the final state of the system ?

Theoretical background

Dynamical changes in the order parameter of a superconductor are described using 2 parameters:

1. Ginzburg - Landau coherence length: $\boxed{\xi_{GL}(T) = \dfrac{\xi_0}{\sqrt{\varepsilon}}}$

2. TDGL time decay: $\boxed{\tau = \dfrac{\tau_0}{|\varepsilon|}}$

Both diverge near T_c !

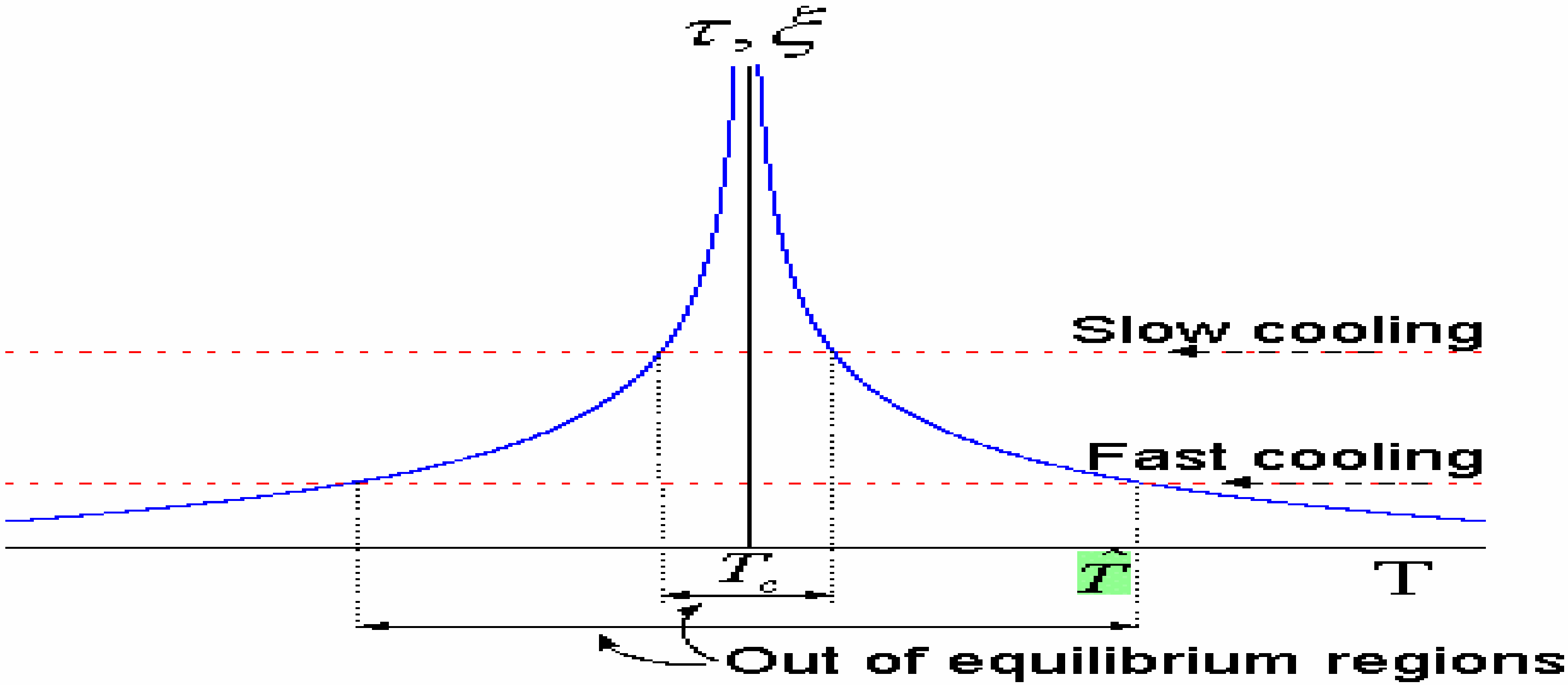
ξ_0 BCS coherence length

$\varepsilon = \dfrac{T - T_c}{T_c}$ Effective temperature

τ_0 GL decay time

The Kibble-Zurek mechanism

Basic assumprion of the Kibble Zurek model: The system is out of thermodynamic equilibrium in the temperature range $\left|T - T_c\right| < \hat{\varepsilon} \cdot T_c$:



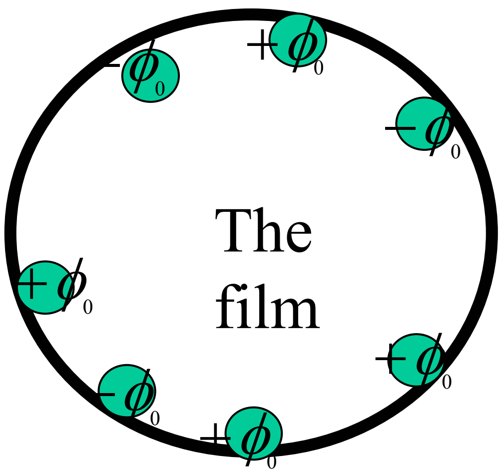
The density of domains created in a quench $\sim \hat{\xi}^{-2}$

The number of domains **increases** with the quench rate through the transition

Theoretical Predictions

- In the boundary separating several ordered domain topological defects can be created.
- In superconductors, topological defects are flux lines.
- Our experiment system can measure net flux , which equals the difference between flux and anti-flux lines.
- The predicted *net* flux scales with the cooling rate according to the following relation:

$$\boxed{n_{net} \sim \sqrt{\frac{l}{\hat{\xi}}} \sim \left(\frac{dT}{dt}\right)^{1/8}}$$



l- sample perimeter

<u>The net flux prediction is based on:</u> S. Rudaz et al., Int. J. Mod. Phys. A **14**, 1605 (1999).

The Homogenous Approximation

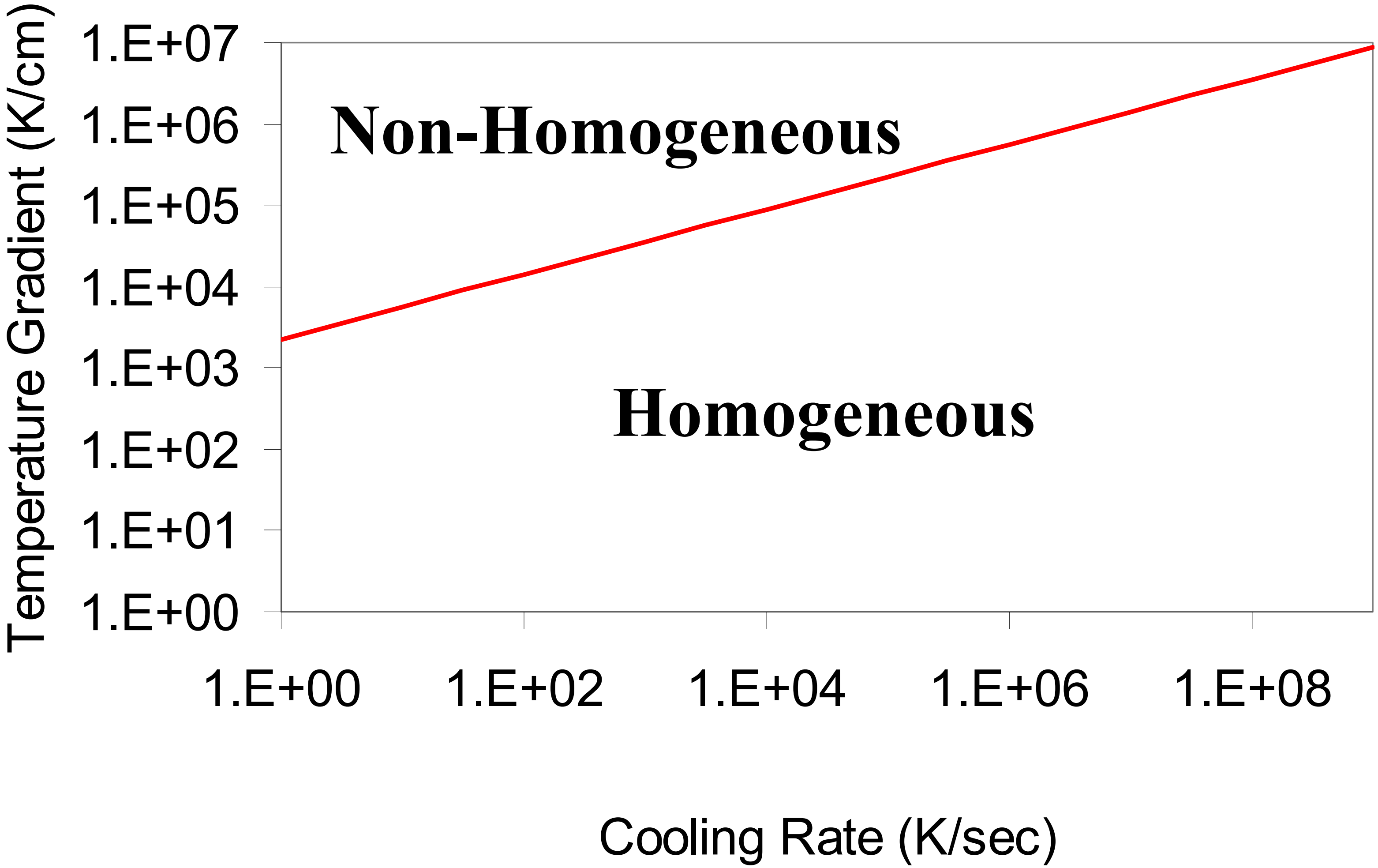
Kibble – Zurek mechanism assumes a homogenous temperature of the sample during the transition.

In order to created spontaneous flux, the experiment should be in the

Homogenous approximation limit: $\boxed{v_T > \hat{s} \Rightarrow \frac{\partial T}{\partial x} < T_c \frac{\hat{\varepsilon}}{\hat{\xi}}}$

v_T	Speed of temperature front
$\hat{s}$	Speed of fluctuations in order parameter
$\hat{\varepsilon}$	Reduced temperature at freezing point
$\hat{\xi}$	Freezed fluctuation length

Using the XY model critical parameters we get for YBCO :

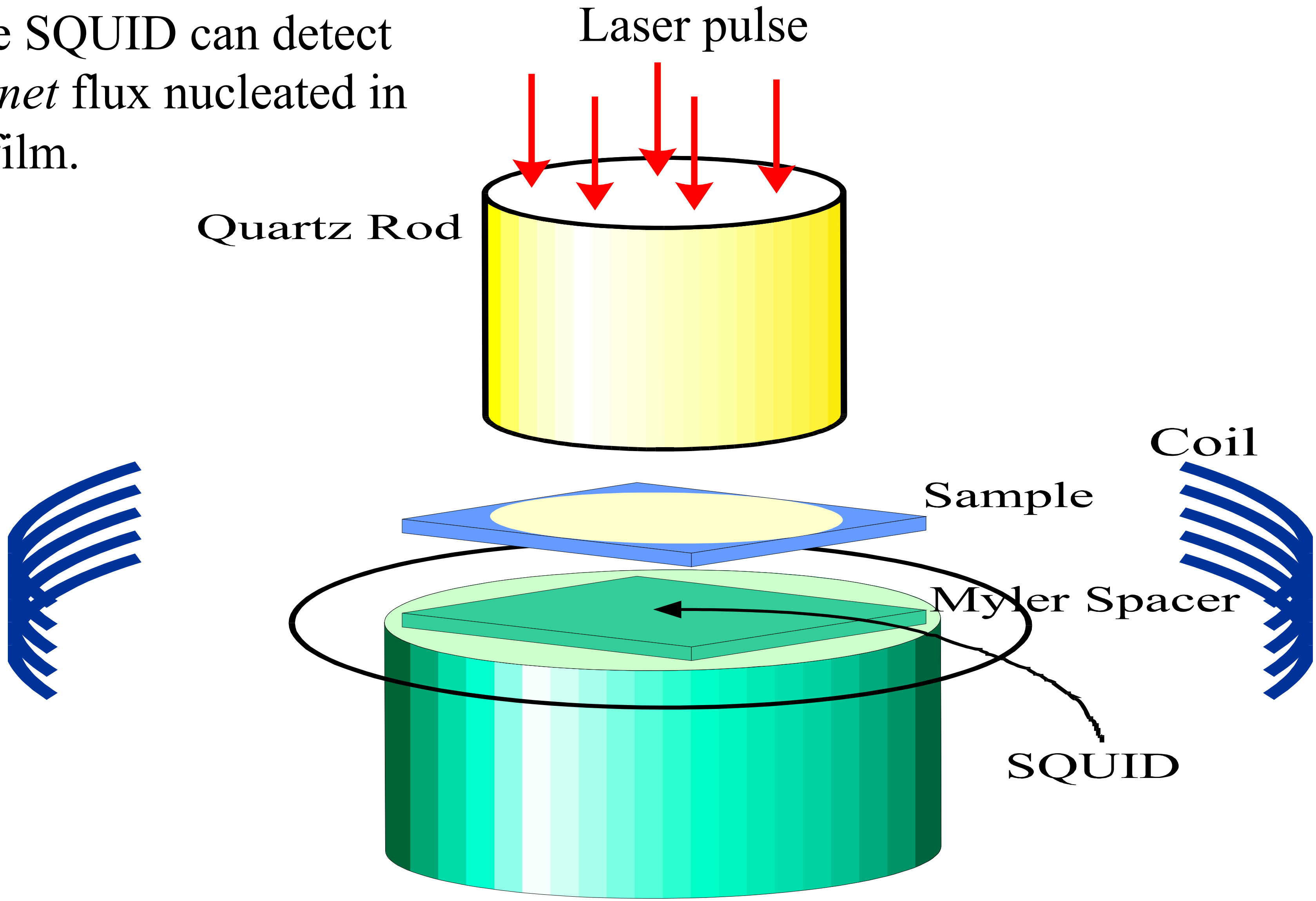


In our experiment, under homogeneous illumination, temperature gradients across the film are ~ 1 K/cm. Therefore for the cooling rates used in the experiment (> 1 K/sec) , the homogeneous approximation holds

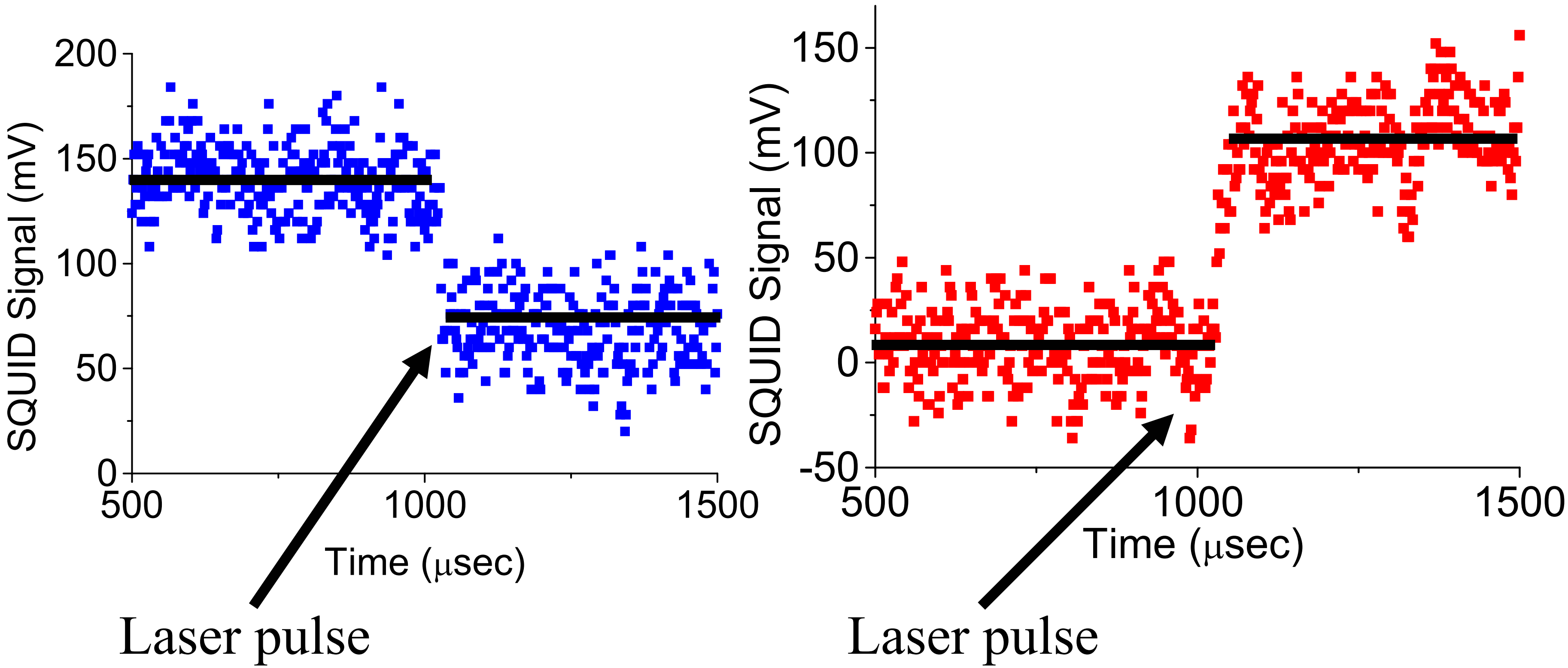
Experimental Setup

- Detection of the magnetic flux is done using a high- T_c SQUID.

- The SQUID can detect *only net* flux nucleated in the film.



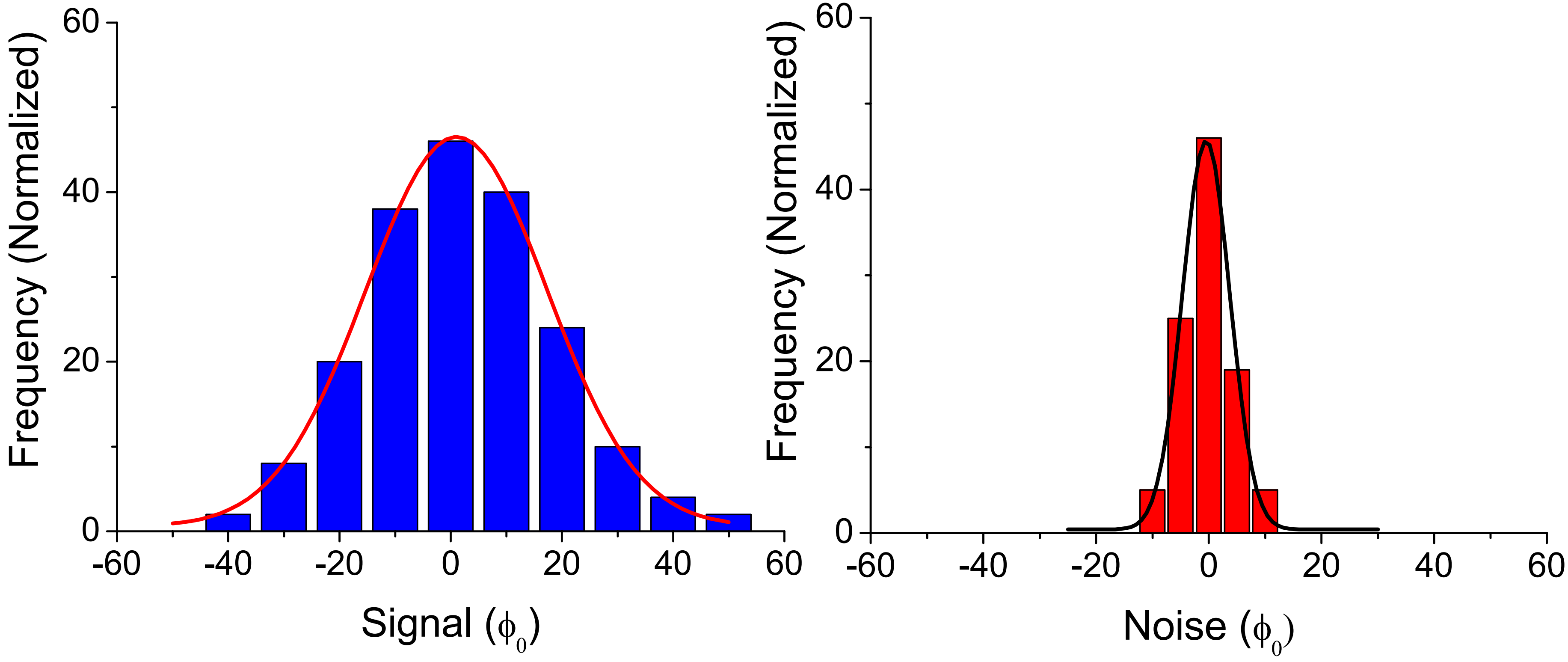
Typical Traces - Homogeneous Illumination



• The dashed lines show the average flux level before and after each measurements.

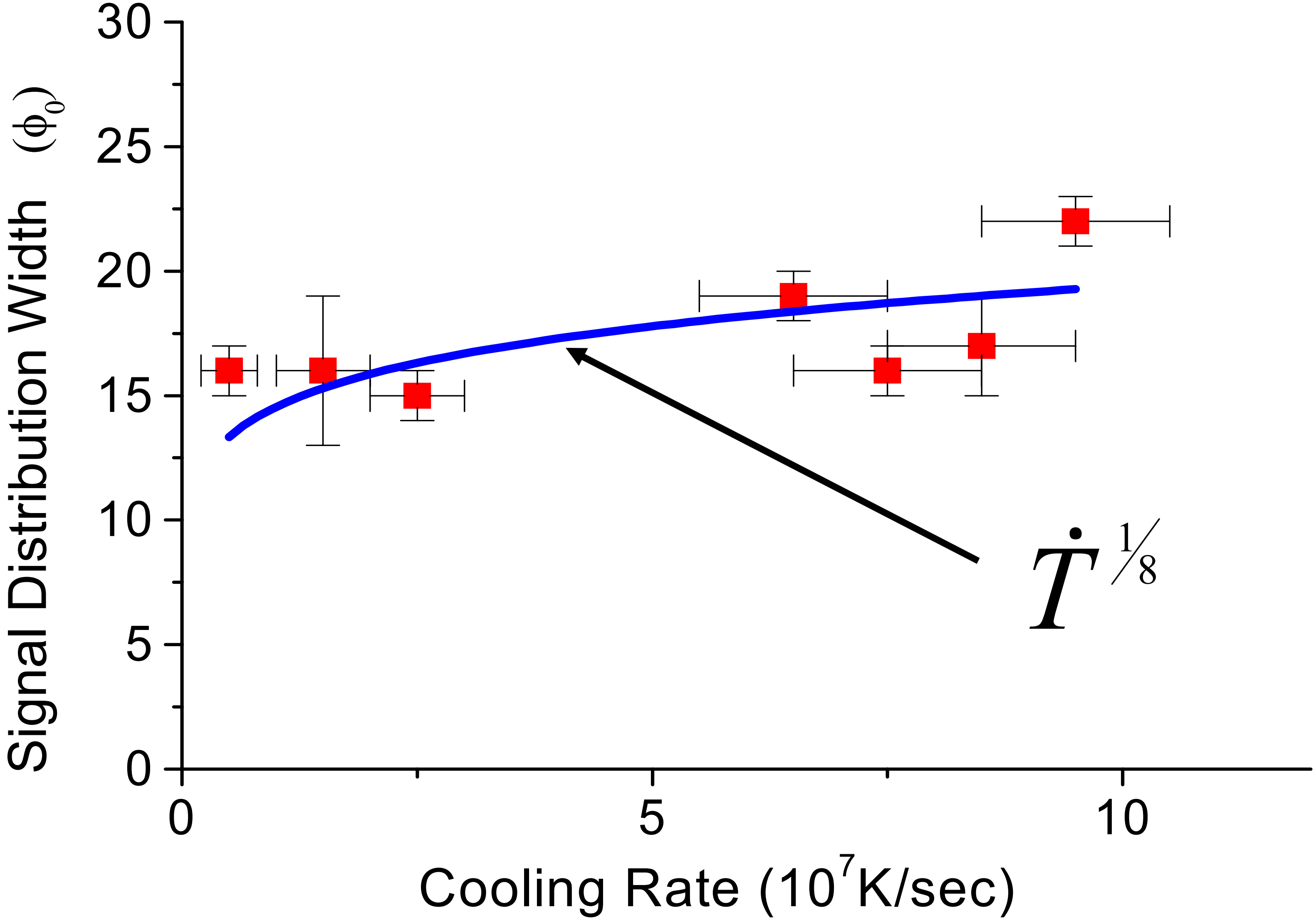
• The measured signal is the difference between the two dashed lines in each trace.

Histograms of typical data



The **signal** histogram is **wider** than the **noise** histogram, and is Gaussian in profile, as expected from the Kibble-Zurek scenario.

Signal dependence on Cooling Rate

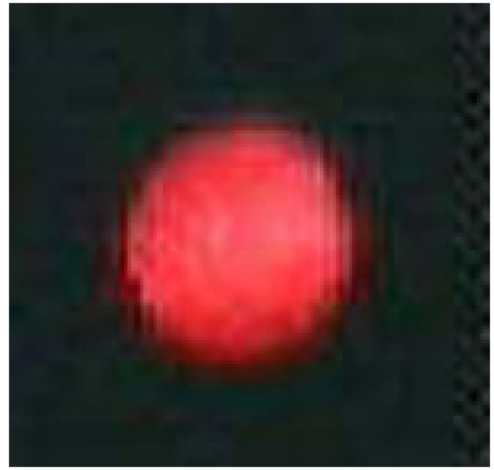


The dependence of the measured signal on the cooling rate is consistent with that given by the cosmological scenario.

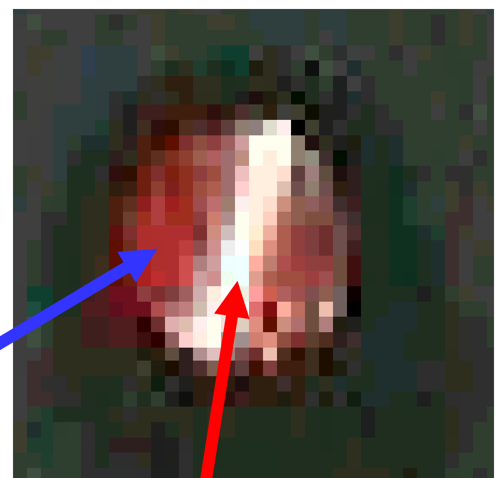
The prediction is scaled down by a factor of 8 to fit the experiment.

Non Homogeneous Illuminated Samples

Homogenous Illumination:



Hot stripe:



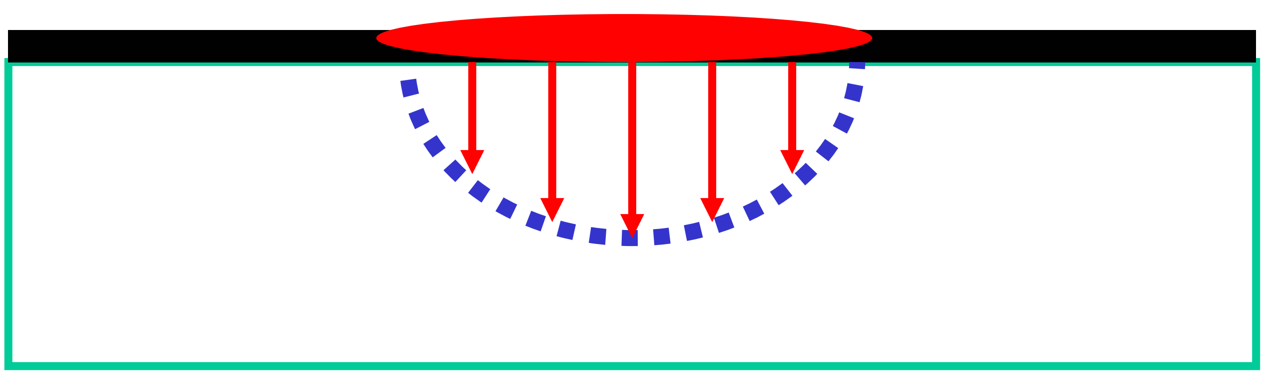
Cold part

Hot part

Non-Homogeneous Cooldown - Schematic Description

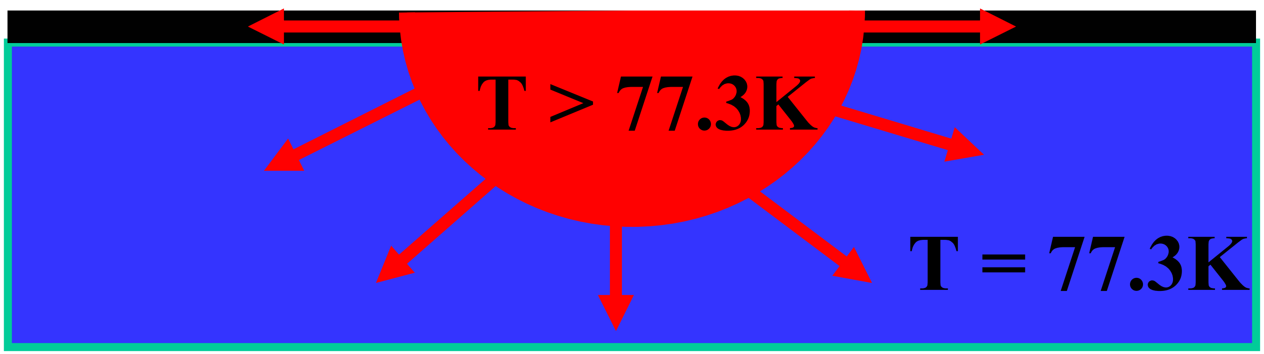
After heating the sample with a non- uniform laser pulse, the cooldown of the sample proceeds through 2 sequential steps:

First, the hot part of the film cools rapidly, transferring heat to the substrate. Part of the substrate heats up to some intermediate temperature $T_B > 77.3K$



In the second step, the hotter part of the substrate transfers heat to the outer (cold) part of the substrate.

It should be noted that the film is strongly coupled thermally to the substrate, hence the temperature distribution in the film follows that of the substrate as they ~~cool~~ dwn together.



Cooling Rate Estimation

Typical thermal time is given by: $\tau = \dfrac{U}{q}$

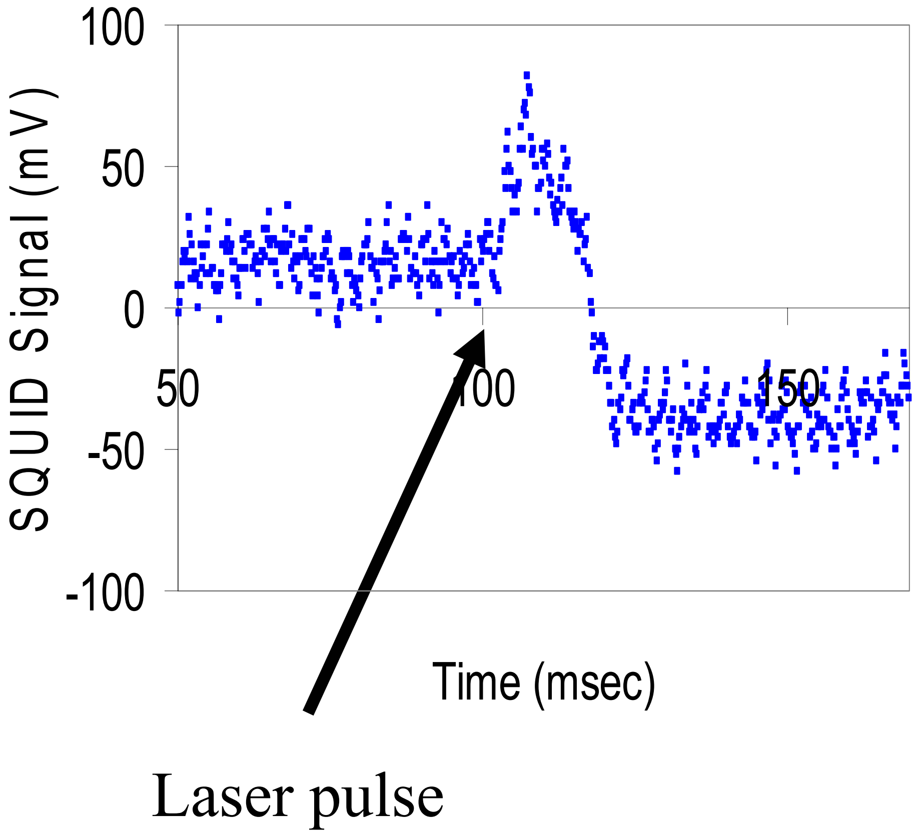
U- Internal energy

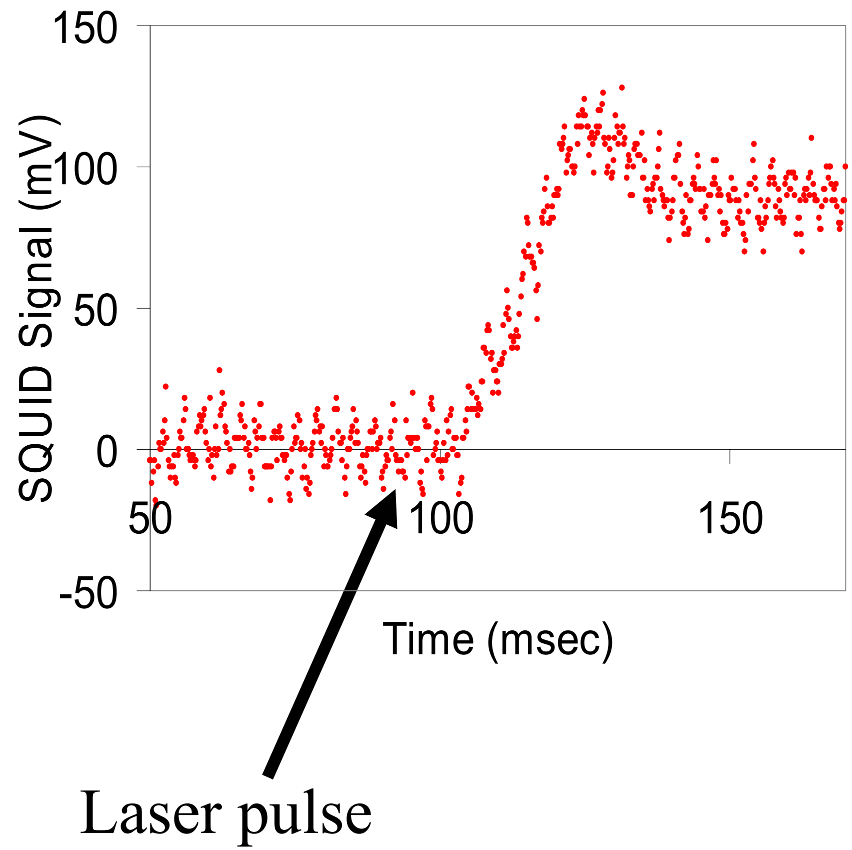
q- Heat exchange rate

For the initial stage: $\boxed{\tau \sim 10^{-6}\sec}$

For the final stage: $\boxed{\tau \sim 100 m\sec}$

Typical traces - Hot stripe in a film





• Contrary to the case of homogenous ilumination, in the hot spot experiments the time scale for the appearance of spontaneous flux is now msec (as compared to μsec).

Estimating the Typical Signal Buildup Time

- We would like to estimate the typical time on which the signal evolves, termed the **signal buildup time**

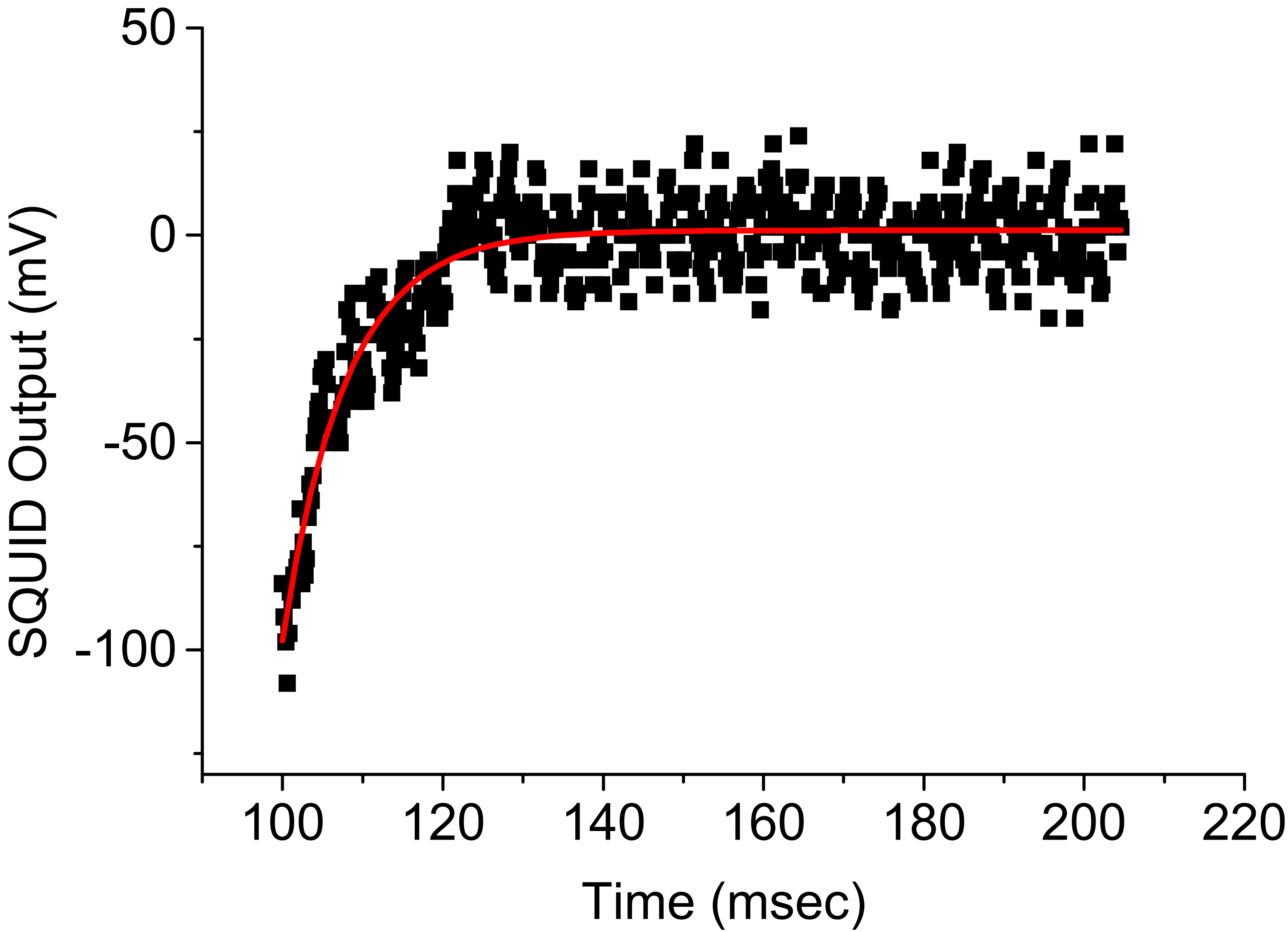
- For that task, we fitted an exponential decay function to the measured signal, of the form: $$S = S_0 + Ae^{-t/\tau}$$

S- SQUID's output

t- time

τ- signal buildup time

Exponential Fit to a Non-Homogeneous Signal



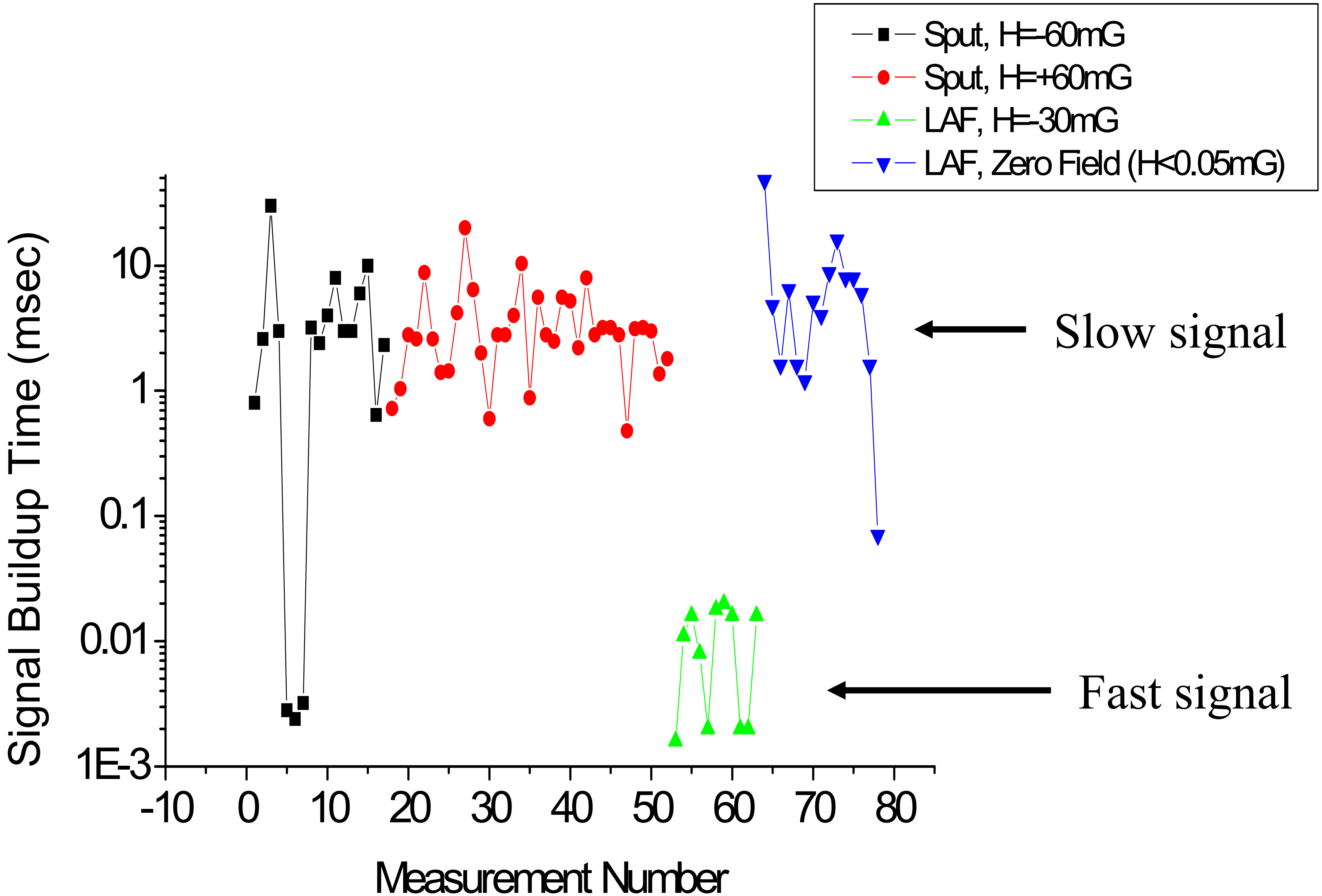
Some comments:

1. Only some of the measurements could be reasonably fitted with an exponential decay function, so the time constant involved is a rough estimate of the time scale.

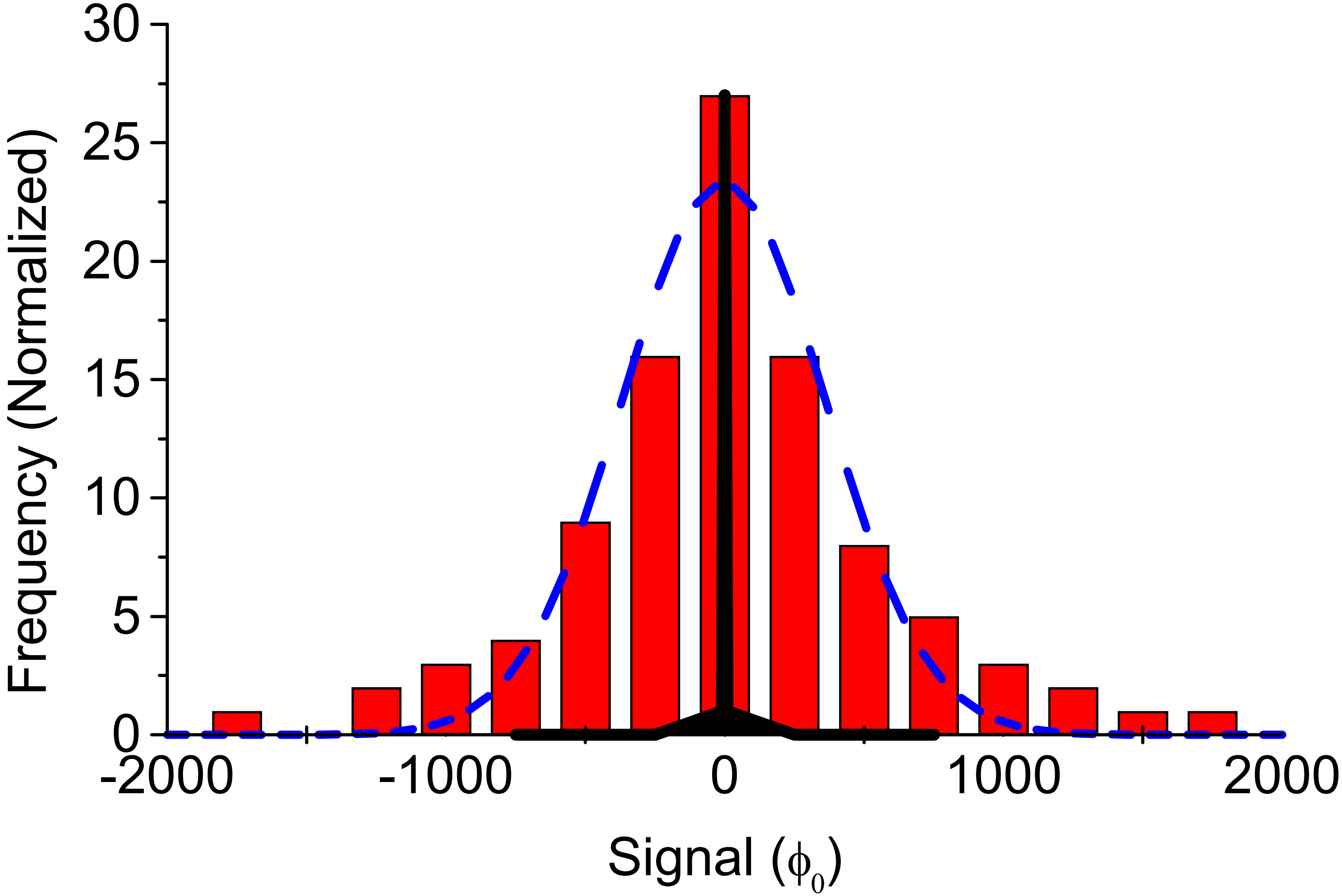
2. The non- homogenous signal was usually, but not always, made of a fast signal accompanied by a slow signal.

3. Measurements were conducted at zero field (<0.05mG) and in the presence of external magnetic field, up to 60mG.

Signal Buildup Time for Different Measurements

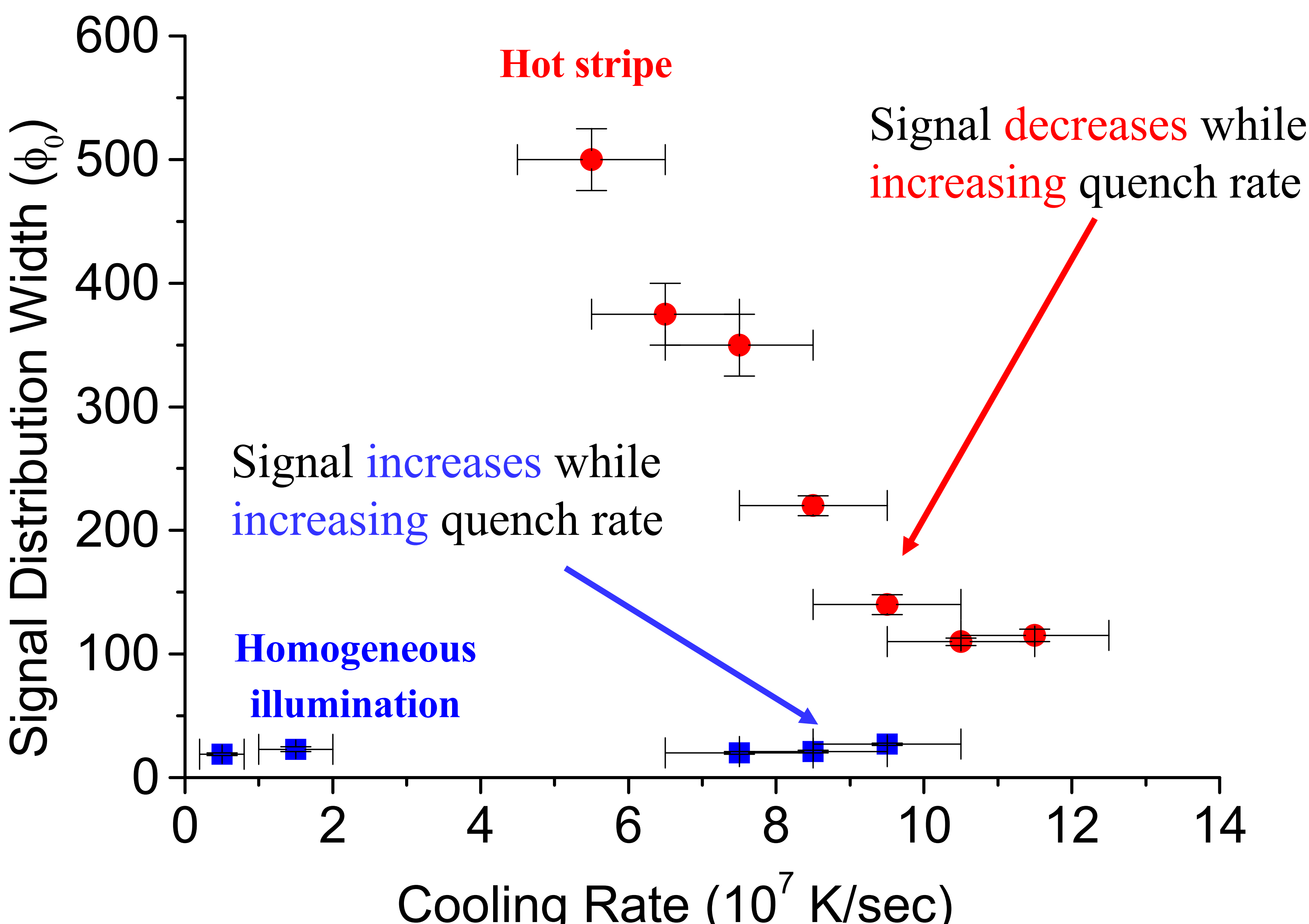


Distribution of Spontaneous Flux Values

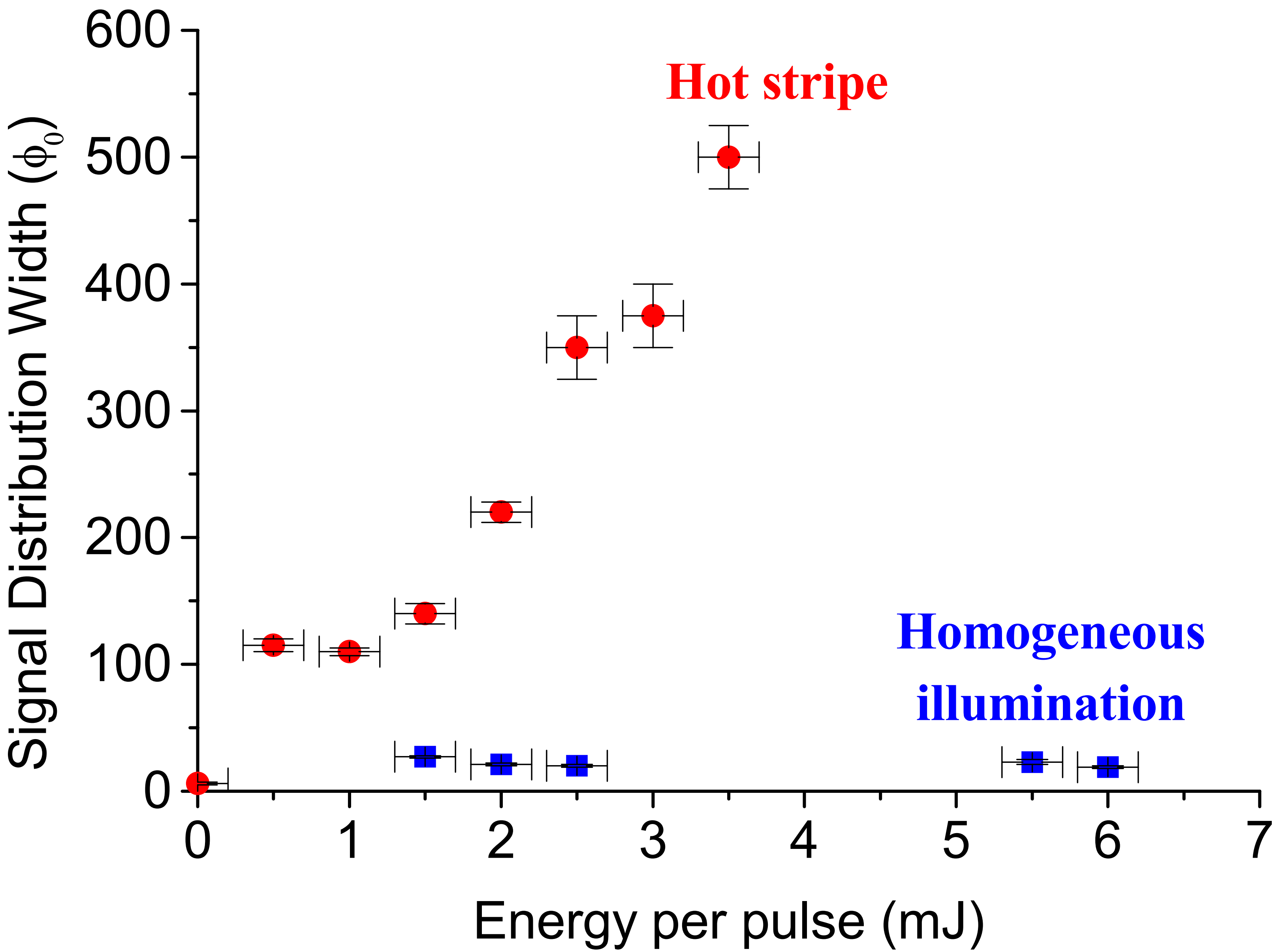


- Gaussian fit to the signal histogram is shown with a blue doted line
- The black solid distribution represents the noise

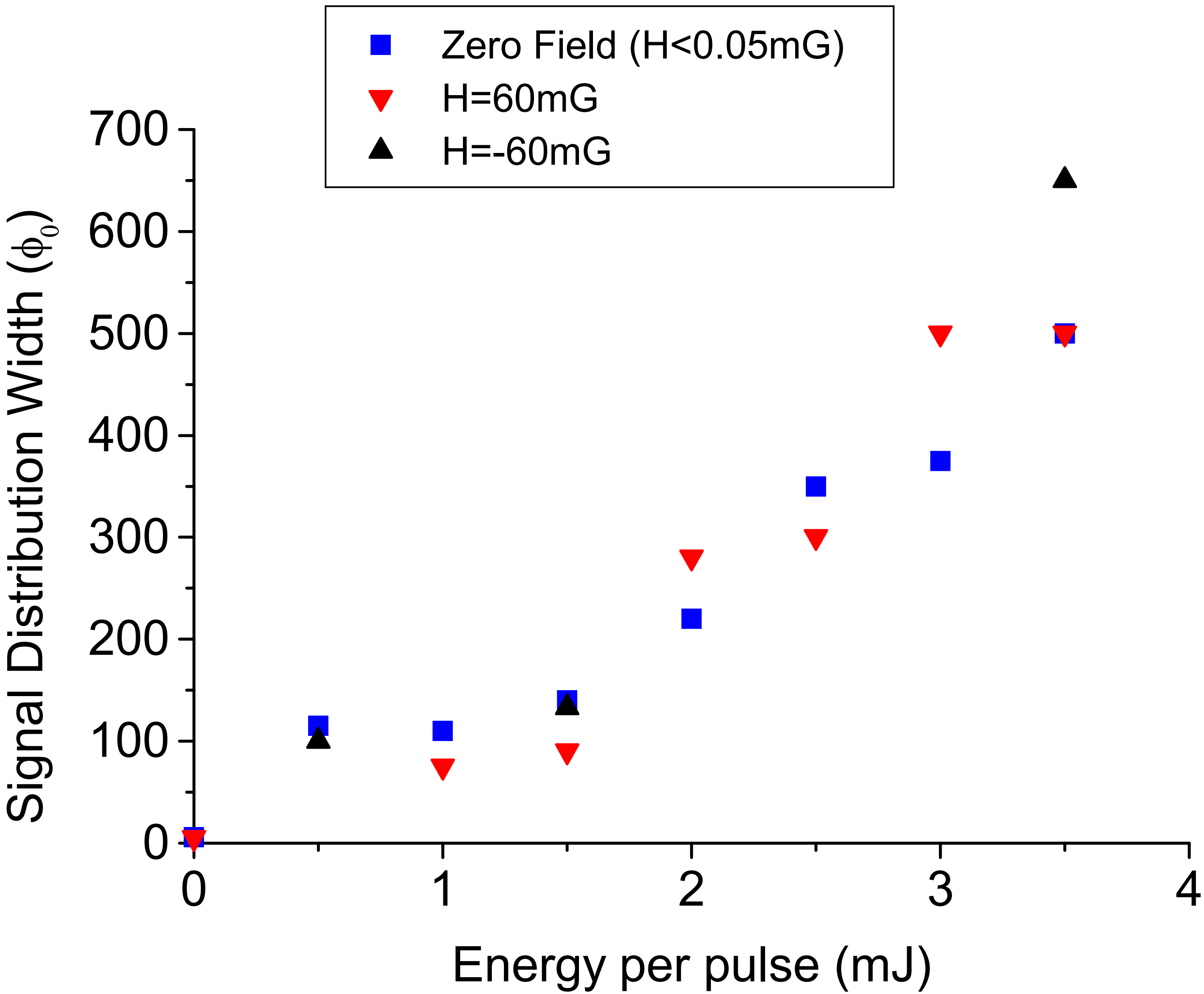
Hot Stripe Signal Vs. Cooling Rate



Hot Stripe Signal Vs. Energy per pulse



Signal Dependence on Magnetic Field



Preliminary Conclusions: Hot Stripe Illumination

1. The dependence of the measured signal on the cooling rate is opposite to its dependence in the case of homogenous illumination.

2. The time constant for formation of the flux is very long - msec. The flux is formed long after the film became superconducting (about $1\mu\mathrm{sec}$ after the quench). Note that *this time scale is the same as the typical slow thermal time scale!*

3. The signal does not depend on the external magnetic field.

Question: **What is the mechanism that generates the signal ?**

Possible Mechanisms

The non-homogeneous signal can be due to the following scenarios:

1. Thermal fluctuations: Hindmarsh-Rajantie model

2. Magnetic field redistribution

3. Magnetic field instability

4. Thermo-electric effects

Thermal Fluctuations : Hindmarsh-Rajantie Model

- This model is based on the transfer of thermal fluctuations to magnetic field fluctuations, generating magnetic flux.

- Model predictions- in the context of the our experiment, we can distinguish between two possibilities*:

For $R > {}^{1}\!/_{k_c}, N \approx \sqrt{E}$ - signal N depends on pulse energy E, not on cooling rate.

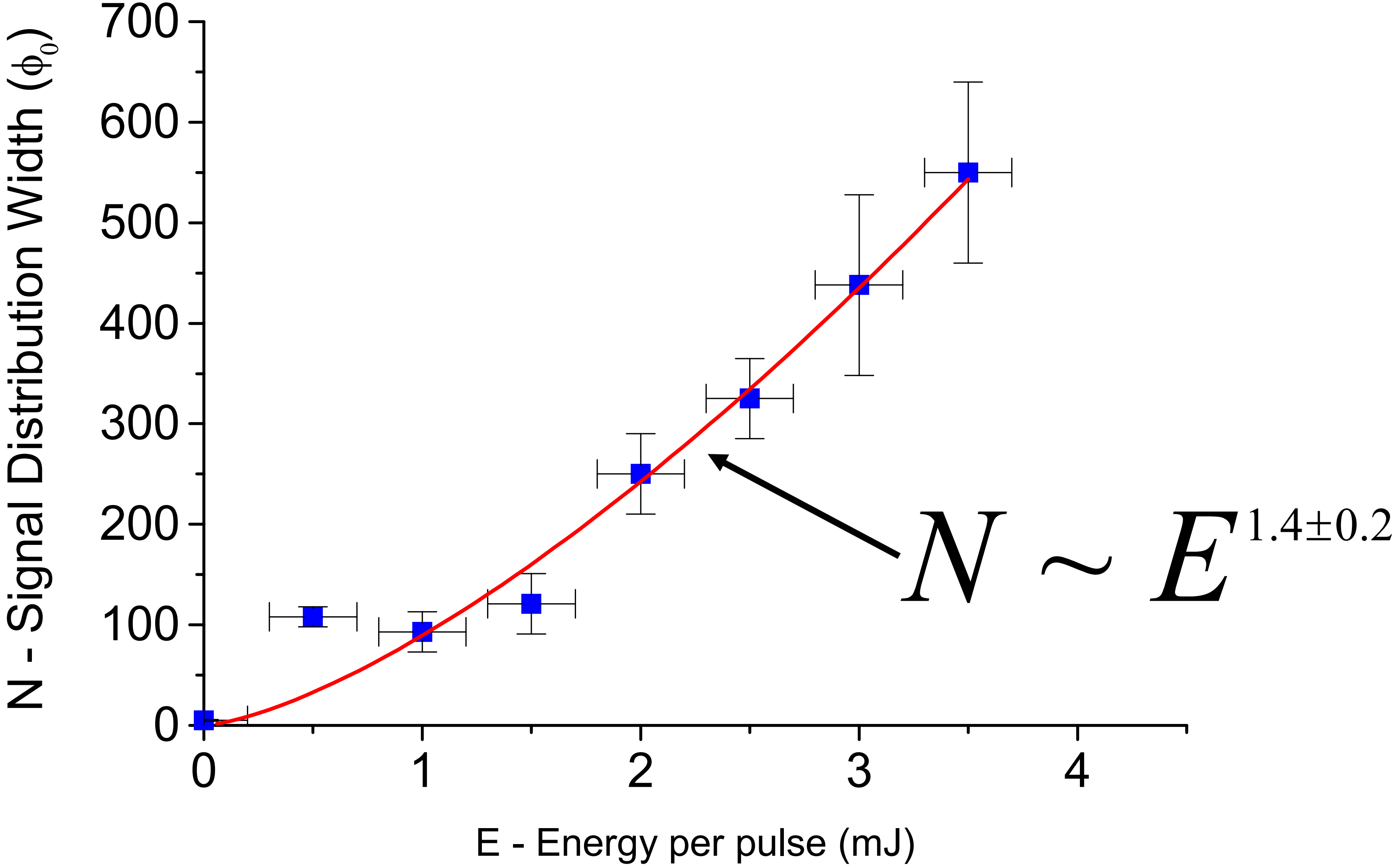
For $R < {}^{1}\!/_{k_c}, N \approx \sqrt{E}\left(\dfrac{dT}{dt}\right)^{3/4}$ - signal N depends both on pulse energy E, and on cooling rate dT/dt.

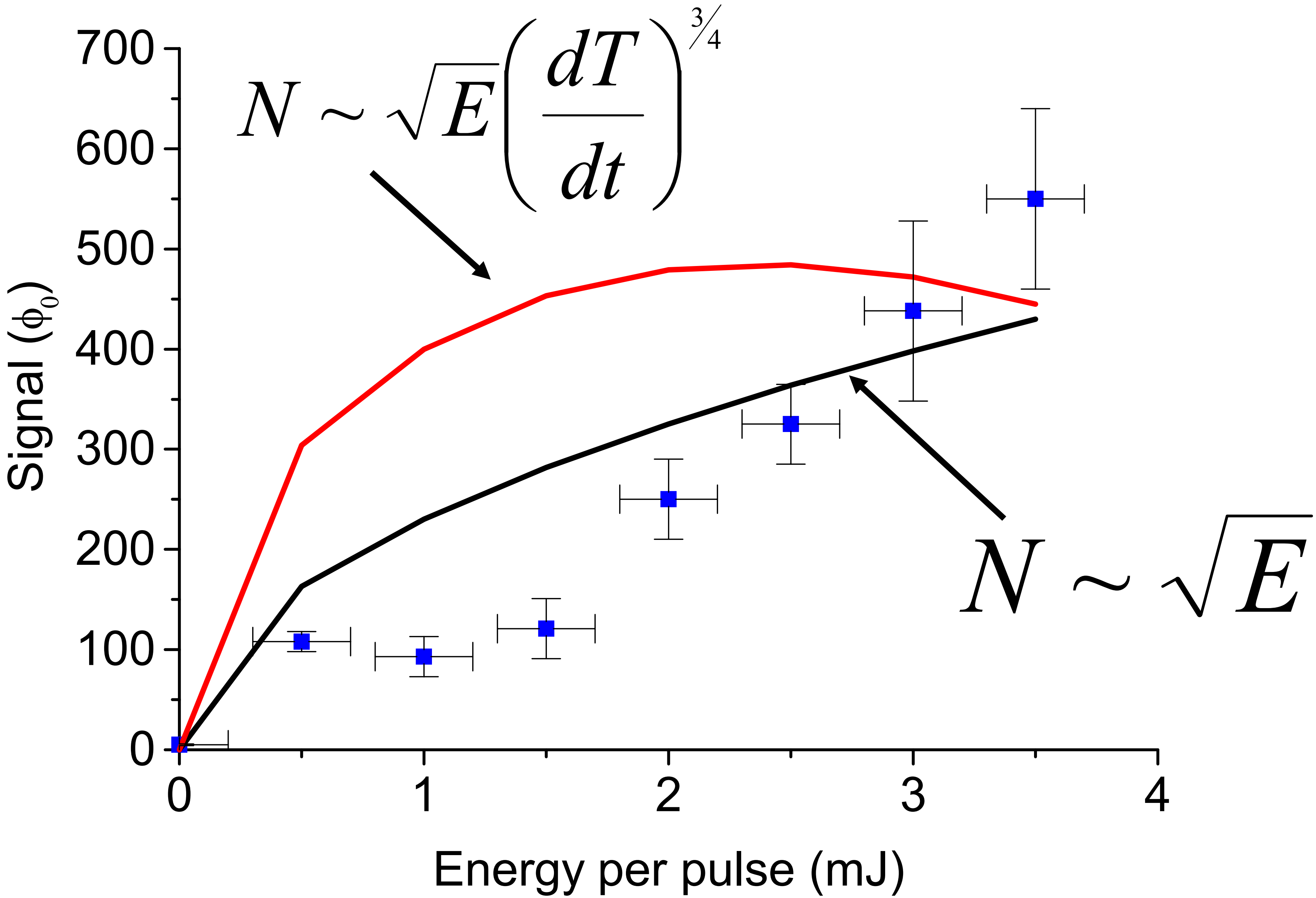
N - net flux, R - sample size, k_c freeze-out wave number

* T.W.B. Kibble and A. Rajantie, PRB, **68**, #174512 (2003)

Problems with this Scenario

1. Although the signal increases with pulse energy, but the increase seems much more rapid than a square root dependence.





$N \sim \sqrt{E}\left(\frac{dT}{dt}\right)^{3/4}$
$N \sim \sqrt{E}$
Signal (ϕ_0)
Energy per pulse (mJ)
0
100
200
300
400
500
600
700
0
1
2
3
4

2. Most importantly - the time scale does not fit !

Thermal fluctuations can create or destroy flux lines only inside the Ginzburg interval. In our experiment, this system passes this interval after less than $1\mu\,\mathrm{sec}$

The Hindmarsh-Rajantie scenario should occur on a this time scale.

The measured signal develops on a time scale 3 to 4 orders of magnitude slower, 1 - 10 msec !

So, this scenario does not fit with our observations.

Redistribution of Magnetic Flux

- Non-uniform illumination heats up only part of the film above the transition temperature.

- Residual magnetic flux can move in or out of the heated area, hence changing the magnetic flux distribution inside the film.

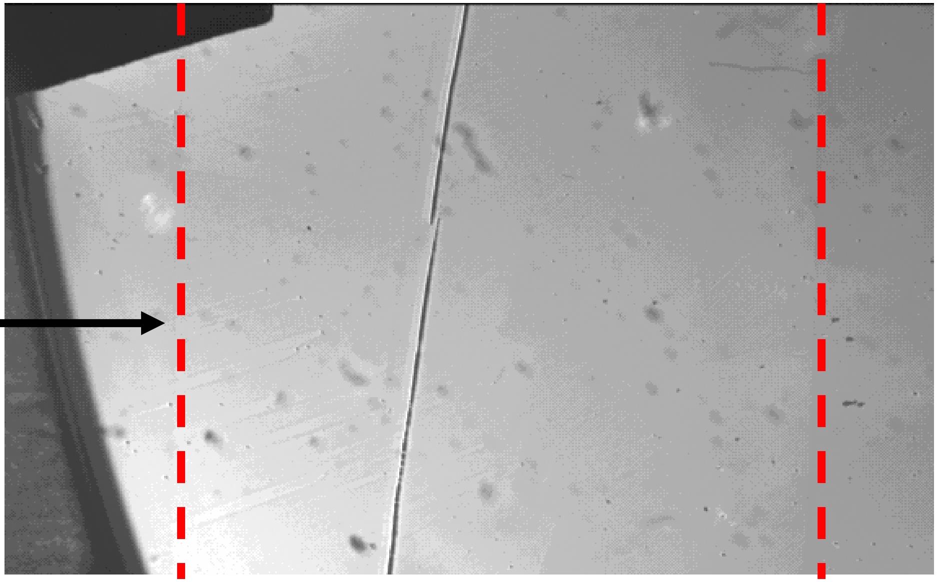
- Re-distribution of magnetic flux can then change the actual amount of flux coupled to the SQUID - hence the SQUID will indicate a change of the flux, even though the net change was zero.

- We did magneto-optical experiments in collaboration with the Konstanz group to clarify this issue

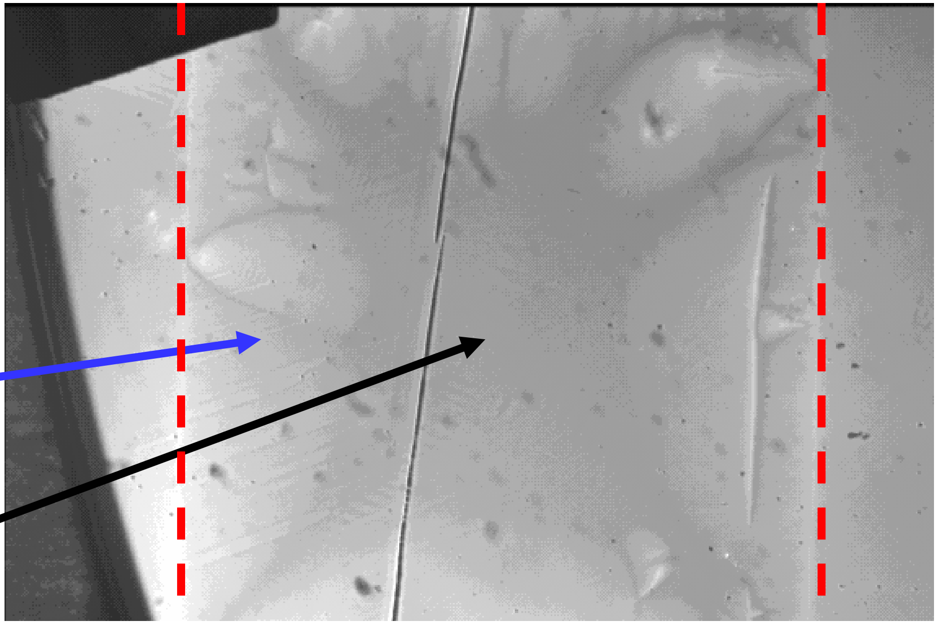
Magneto-Optical Measurements

External field ~ 0G :

Film edge

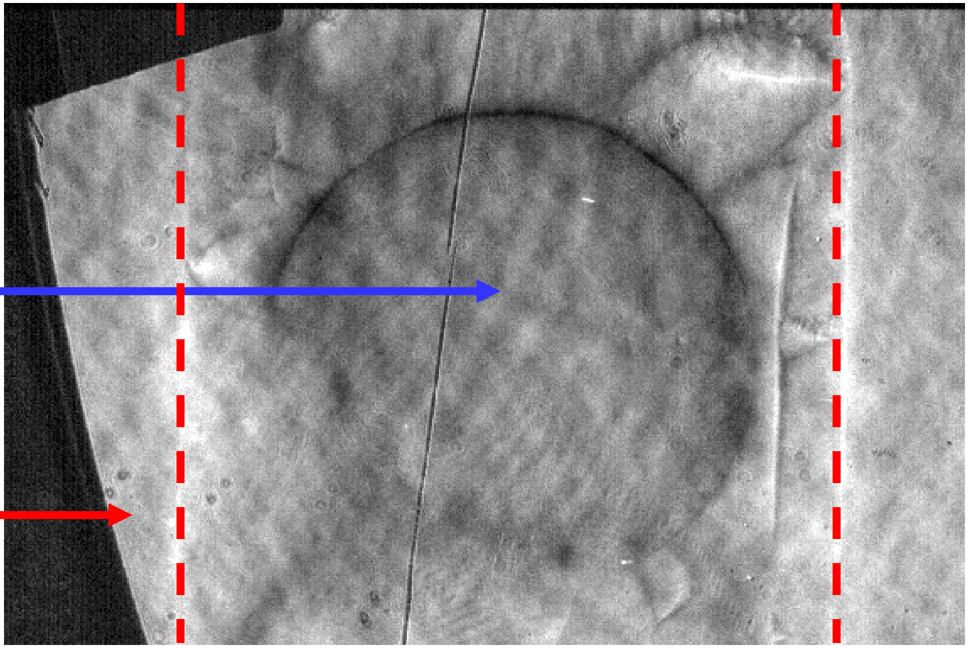


After applying a magnetic field of ~ 65G :



Magnetic field penetrates into the sample. The central region remains field free.

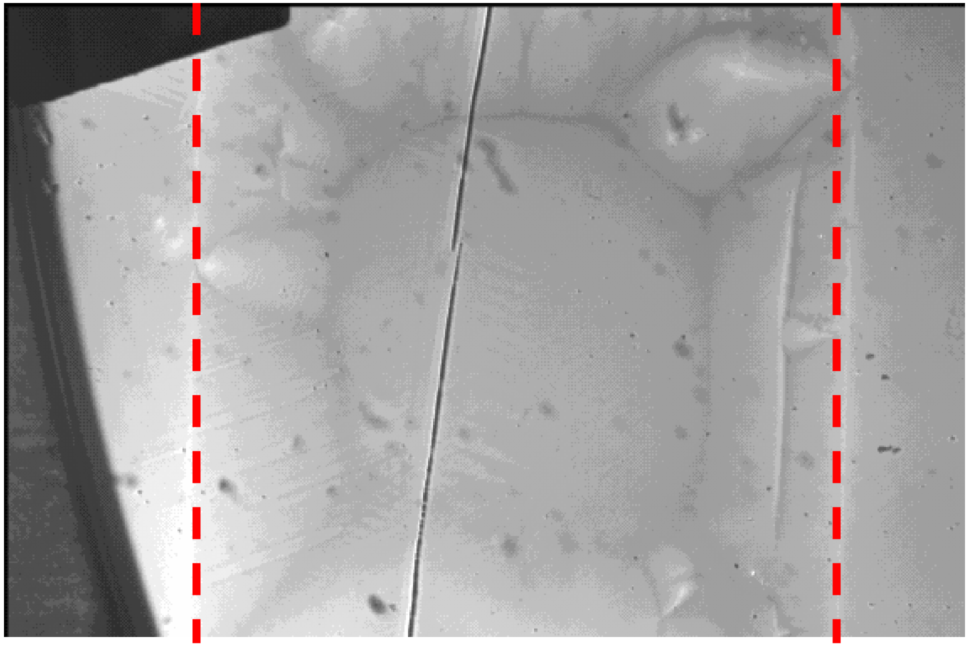
2 nsec after heating pulse :



Magnetic field penetrates into the heated region.

Film edge

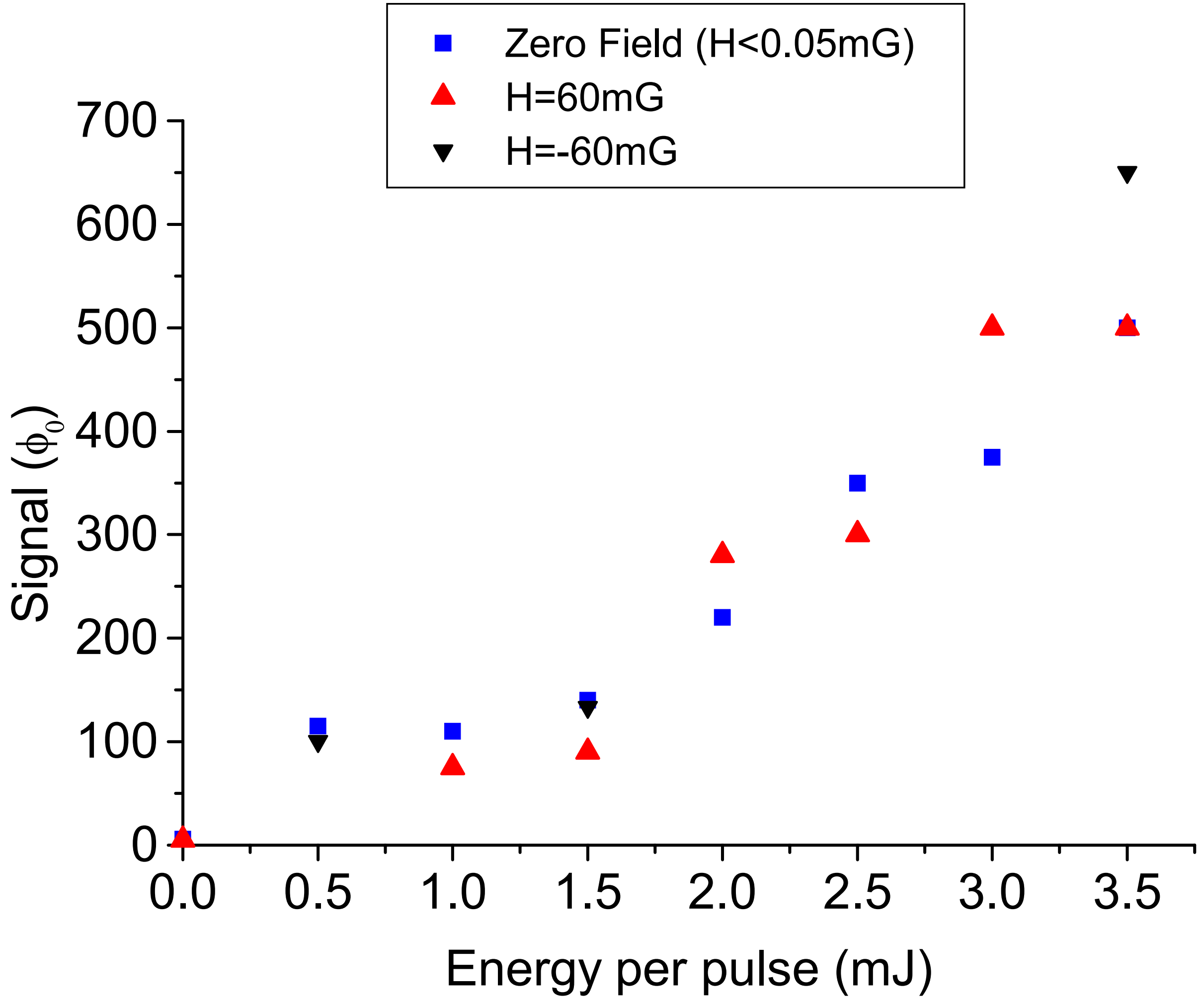
1 sec after heating pulse:



No significant difference between pictures taken 2nsec and 1sec after heating pulse.

Problems with this Scenario

1. The spontaneous flux in our experiment does not change with external field, which in any case is very small in relation to that used in the magneto-optic work.



2. Again - the time scale does not fit !

Flux lines can move only as long as the pinning forces are weak. This is true as long as T > Tc - 2K at most. In our experiment, the system passes this temperature interval after no more than $1\mu\sec$

Hence, the signal due to this mechanism should be a fast one !

In contrast, the "inhomogeneous" flux develops on a relatively slow time scale ~ 1 - 10 msec !

Magnetic Instability

Magnetic flux can form due to an instability of a propagating normal-superconducting phase boundary, which happens after a non-homogeneous heating pulse.

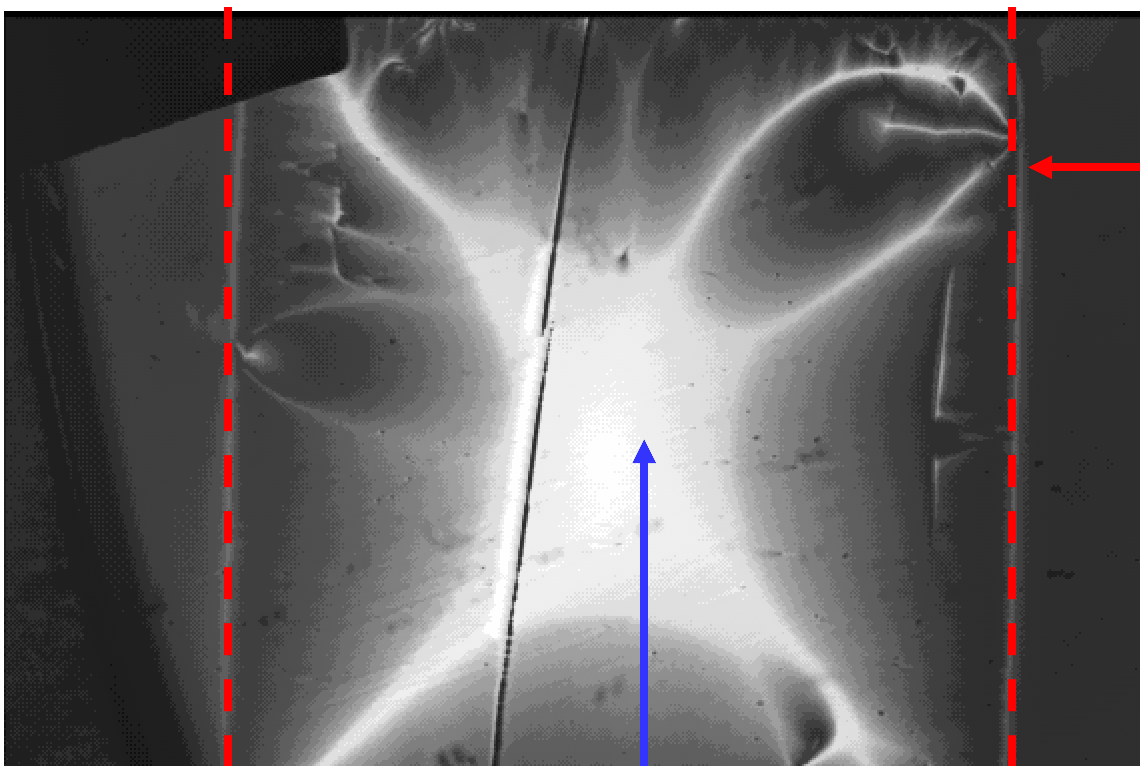
This idea was proposed in several theoretical papers:

1. I.S. Aranson, N.B. Kopnin, and V.M. Vinokur, PRB, **63**, #184501 (2001)

2. I. Shapiro, E. Pechenik and B. Ya. Shapiro, PRB, **63**, #184520 (2001)

Example of a Magnetic Instability: Flux Avalanche

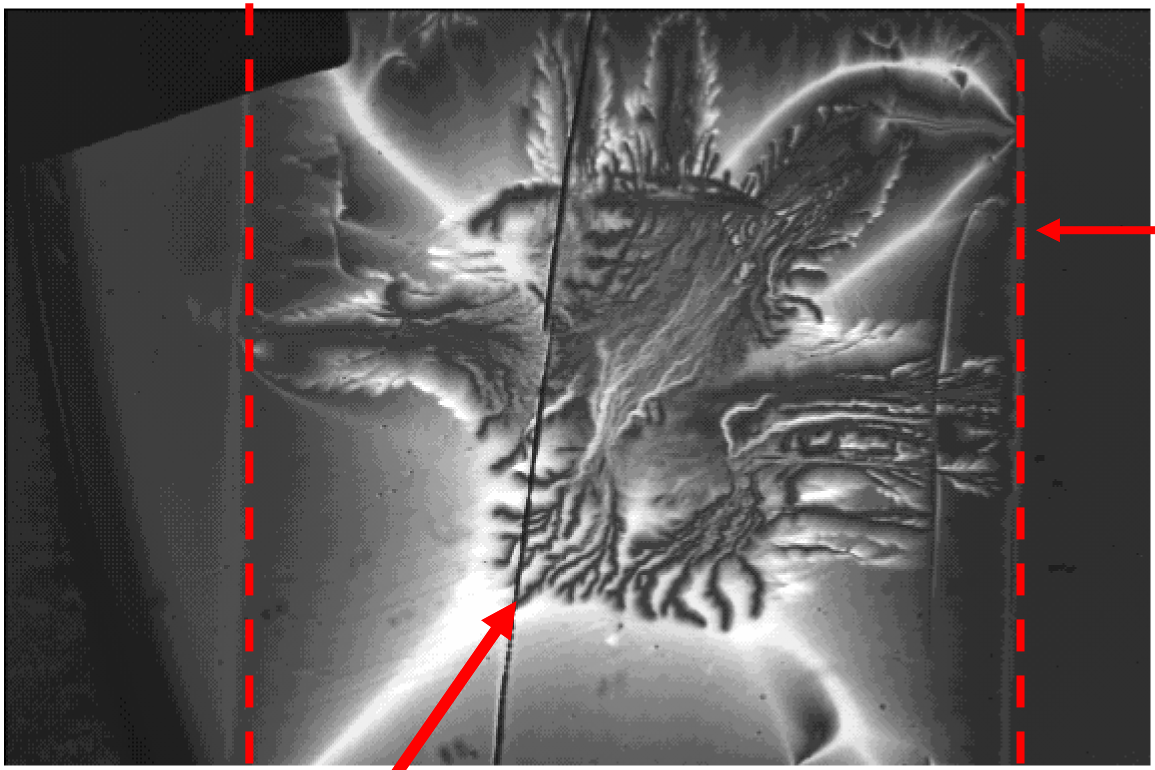
Residual field ~1G, after lowering from 600G : The central region has a trapped field of about 600G



Sample edge

High concentration of magnetic flux trapped inside the film

Remanent flux after a short heating pulse:



Sample edge

Flux Avalanche

Problems with this Scenario

Time scale problem :

The instability of the moving front separating the normal and superconducting phases should occur within no more than about 1 microsecond after the heating pulse, since at later times all the film returns to the superconducting state and this front disappears.

Again, this is 3 order of magnitude faster than the time after which we observe spontaneous flux.

The above conclusion is strengthened also by the magneto-optics measurements, in which magnetic instability (flux avalanche) was shown to exist only for high fields (>100G), which are not present in our experiment.

Thermo-Electric Effect

Thermo-electric effects arise when a thermal gradient produces electric fields. The electric fields can then drive currents, which in turn generate magnetic fields*. There are two main effects:

1. **Seebeck effect** - due to a different diffusion time of holes and electrons down the thermal gradient, an electric field is produced along the thermal gradient.

2. **Nernst effect** - motion of flux lines along the thermal gradient induces an electric field.

* Based on: D. J. Van Harlingen, Physica **109 and 110 B**, 1710 (1982)

Problems with this Scenario

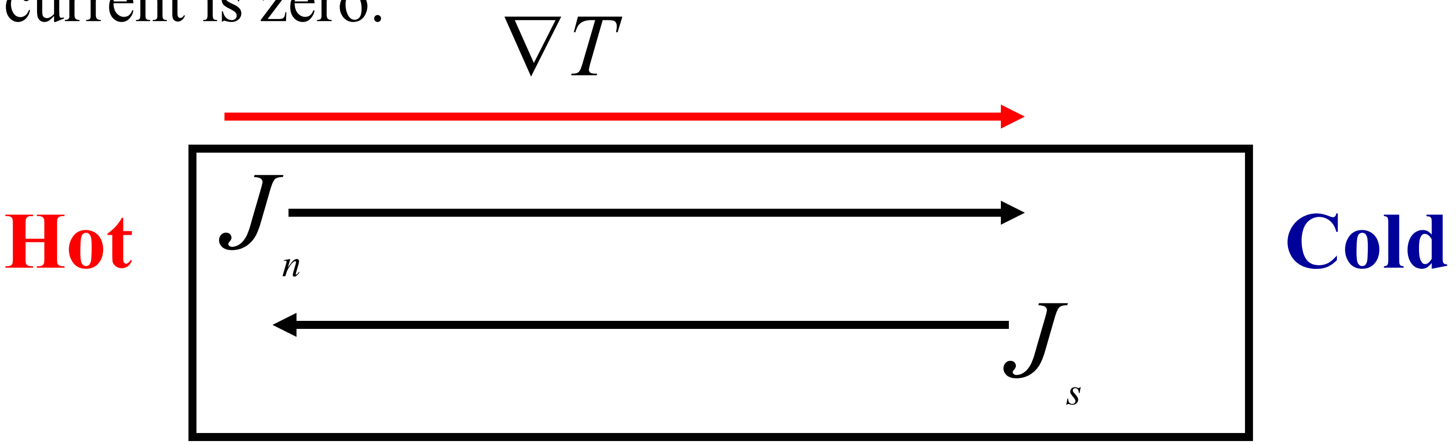
1. For the Nernst effect, the time scale does not fit !

Again, to show the Nernst effect, flux lines have to move. Flux lines can move only as long as the pinning forces are weak. This is true as long as T > Tc - 2K at most. In our experiment, the system passes this temperature interval after no more than 1μsec

→ So, after several msec this effect is zero. In other words, from the Nernst effect we would expect a fast signal, which is not the case.

Seebeck Effect in Superconductors

In superconductors, thermal gradient produces a counterflow of normal quasiparticles and superconducting pairs, so the net electric current is zero.



As noted by Ginzburg, in some case such thermo-electric currents can generate magnetic flux. One example is the Anisotropic Thermo-Electric Effect.

Anisotropy in Superconducting materials

The thermoelectric normal current is given by: $\vec{J}_n = -L_T \vec{\nabla} T$

where L_T is the transport coefficient, which equals: $L_T = \dfrac{S_B}{\rho}$

S_B Seebeck (thermopower) coefficient

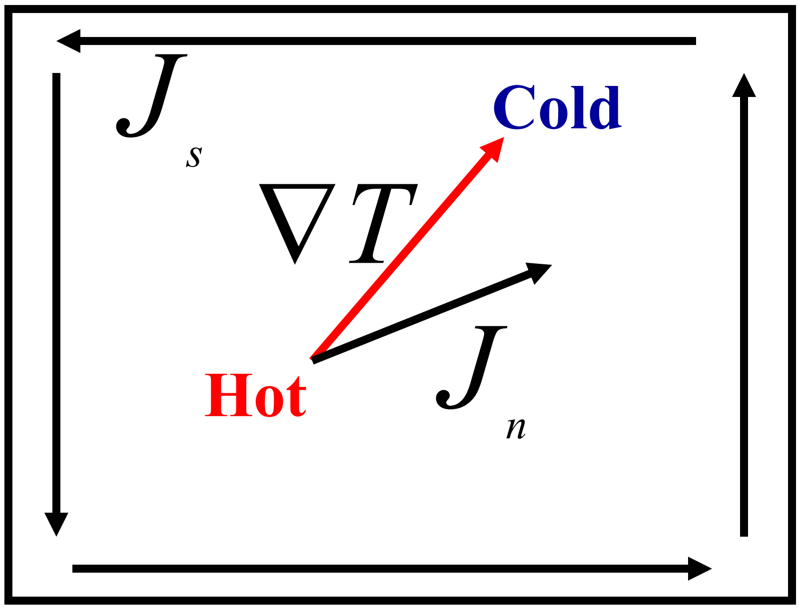
ρ Film's electrical resistivity

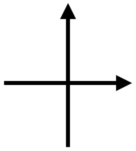
As noted by Van-Harlingen, the transport coefficient is predicted to be continuous through the transition temperature. Hence the normal state transport coefficient can give a good estimate to the transport coefficient in the superconducting state.

Anisotropic Thermo-Electric Effect

For a superconductor with an anisotropic thermal transport properties, thermal gradient applied in a direction that is not parallel to one of the superconductors symmetry axes can generate flux.

Flux is generated since the superconducting countercurrent J_s does not exactly cancel the normal current J_n at every point of the film.



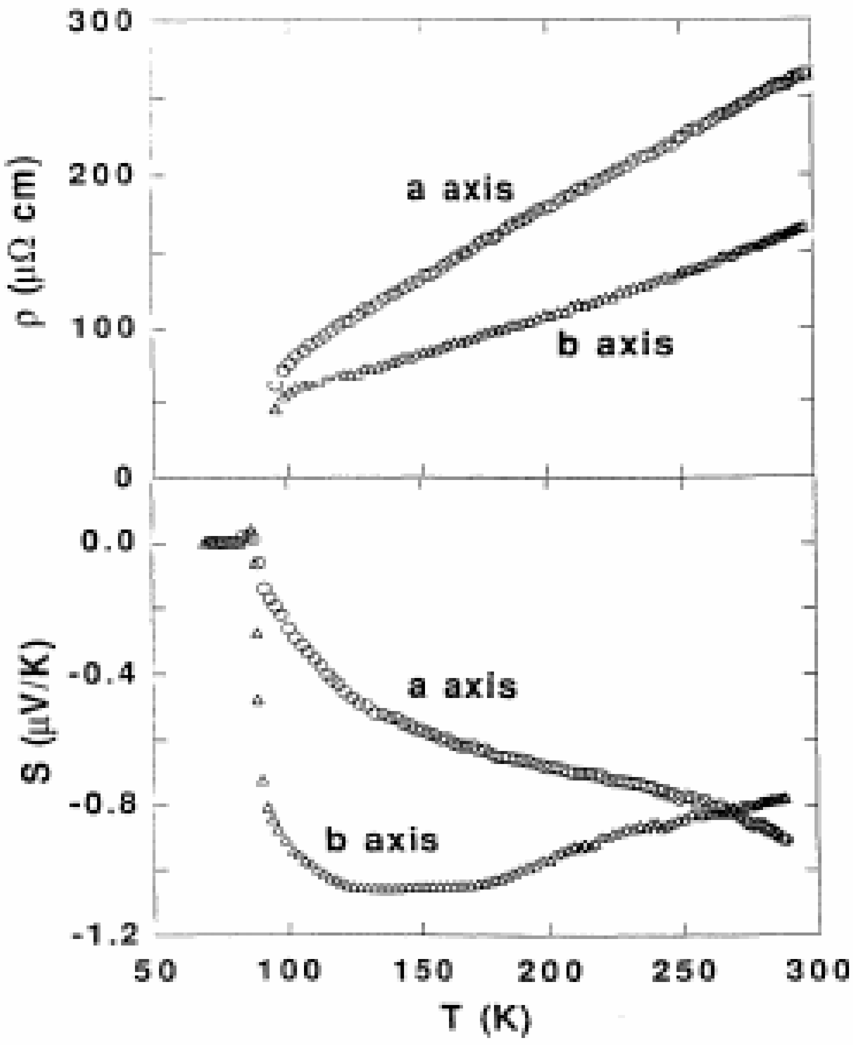


Symmetry axis

Measurements done by Subramaniam et al.* show that for untwinned YBCO crystals, the transport coefficients are anisotropic in the normal state :

$$\begin{cases} \rho_a > \rho_b \\ |S_b| > |S_a| \end{cases}$$

$$\Rightarrow \quad |L_T|_b > |L_T|_a$$



However, our films are twinned, and there is no anisotropy between the **a** and **b** directions.

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* C. K. Subramaniam et al., PRB, **51**, 3116 (1995)

Onset of Turbulence

If the current associated with the counterflow generated by a thermal gradient increases above some critical value, then the two fluid laminar counterflow becomes unstable, in a way analogous to superfluid Helium. In superfluid Helium, the flow becomes turbulent and vortices appear. In our case, flux lines may be formed.

This scenario is consistent with the amount of detected flux increasing with the energy injected, which sets up the temperature gradients.

Summary

- After non- homogeneous illumination, a change in magnetization is also measured .

- Contrary to what is seen under homogeneous illumination, the signal after a non- homogeneous quench appears after a long (~msec) delay, and its magnitude increases with the energy delivered to the sample. The signal does not depend on external field.

- The time scale over which the signal develops is the same as the slow thermal relaxation time of the sample.

- Most related scenarios such as magnetic instability, thermal fluctuations and magnetic field redistribution can not explain the origin of the signal.

- We suggest one possibility, that flux may be generated through an instability arising from a too large superconducting- normal quasiparticle counterflow current which is thermo- electric in origin.

- Such a transition may is similar to the laminar- turbulent transition in thermal counterflow of superfluid Helium, in which a tangle of vortices is formed.