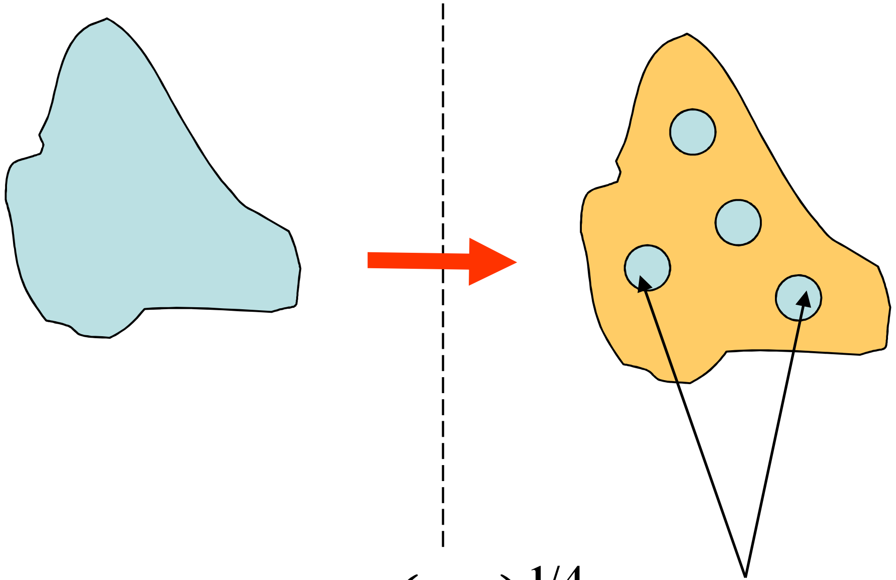
Testing of the Kibble-Zurek Mechanism in Superconductive Analogs

TA Girard

Nuclear Physics Center
University of Lisbon

Topological Defects

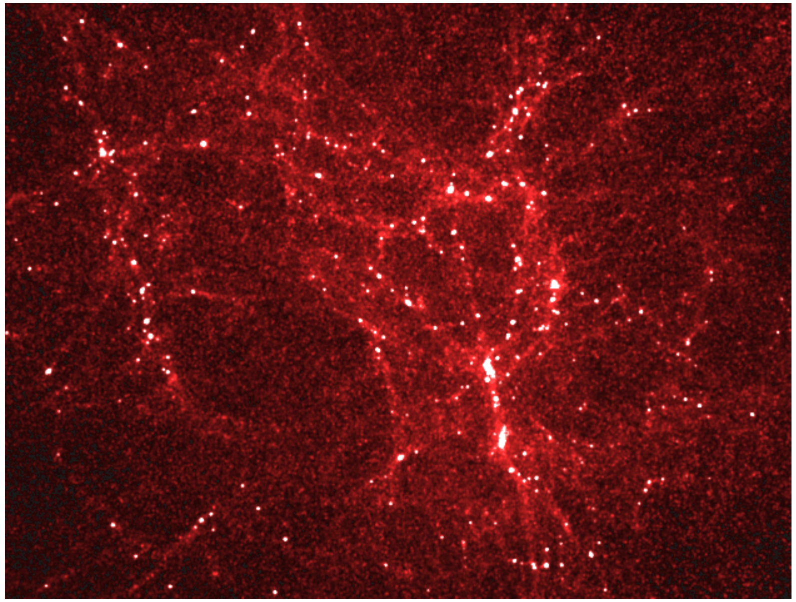
phase transition



$$N \sim \frac{1}{\xi_0^2}\left(\frac{\tau_0}{\tau_Q}\right)^{1/4}$$

defects

Kibble – Zurek mechanism



defect type depends on the symmetry broken in the phase transition

cosmological defects:

- cosmic strings
- monopoles
- domain walls
- textures

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.

cosmology in the laboratory

$$N = f \frac{1}{\xi_0^2}\left(\frac{\tau_0}{\tau_Q}\right)^{\sigma}$$

phase transitions are GENERIC:

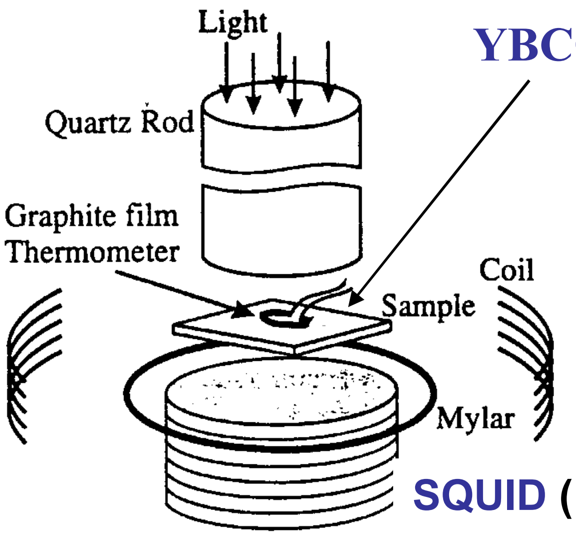
(QFT) $$\mathbf{F}(\varphi) = \frac{1}{2m_e} \,|\, ih\nabla\varphi - (e/c)\mathbf{A}\,\varphi \,|^2 + \alpha\varphi^2 + \frac{\beta}{2}\varphi^4 + \gamma\varphi^3,$$

(G-L) $$f(\varphi) = \frac{1}{2m_e} \,|\, ih\nabla\varphi - (e/c)\mathbf{A}\,\varphi \,|^2 + \alpha\varphi^2 + \frac{\beta}{2}\varphi^4 - \frac{1}{2}\mu\cdot\mathbf{H},$$

low energy tests	CM defect
• **liquid Xstals (maybe)**	**domains**
• **He4 (yes, no...)**	**vortices**
• **He3 (yes)**	**vortices**
• **Type-II superconductors (no, yes, maybe)**	**vortices**

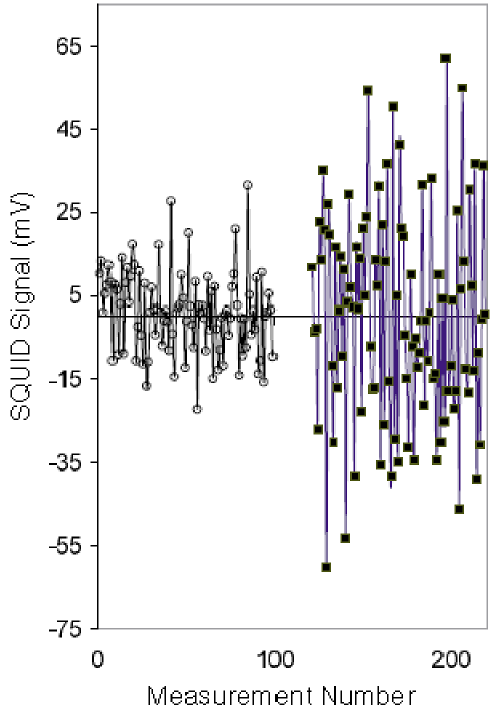
Type-II superconductors

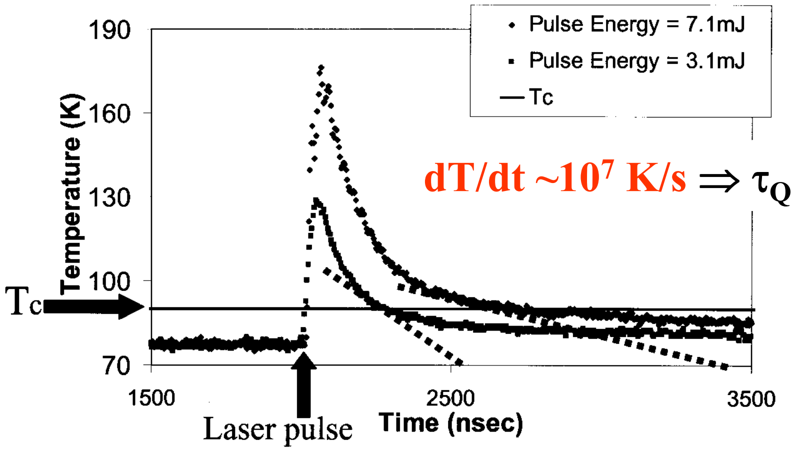
Carmi, Polturak : Phys. Rev. B60 (1999-II) 7595
Maniv, Polturak, Koren: PRL 91 (2003) 197001



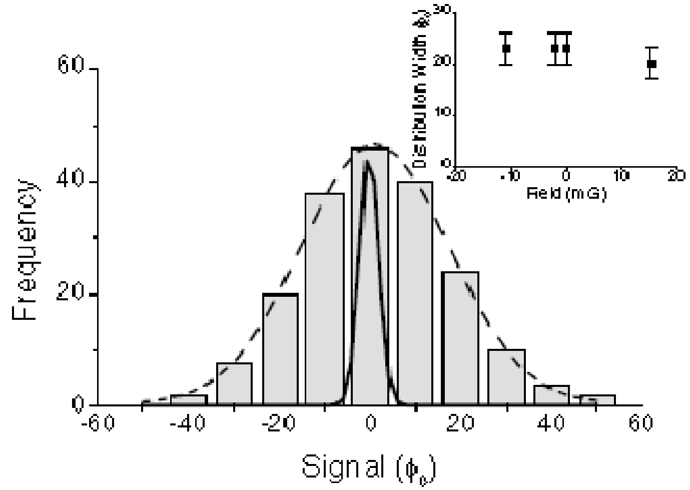
YBCO (ξ_0 =1.6 nm)

SQUID (5 ϕ_0/cm^2, τ ~ 10 μs)





dT/dt ~10^7 K/s $\Rightarrow$ τ_Q ~ 10^{-6} s



$5 \cdot 10^{-12}$ s

$$N = n_+ + n_- \sim \frac{1}{\xi_0^2}\left(\frac{\tau_0}{\tau_Q}\right)^{1/4} \sim 10^{10}\ \phi_0/\text{cm}^2 \quad ??$$

1.6 nm

10^{-6} s

PROBLEM : " pair production"

PROBLEM : defect dissipation

[Ghinovker, Shapiro & Shapiro: PL A260 (1999) 112]

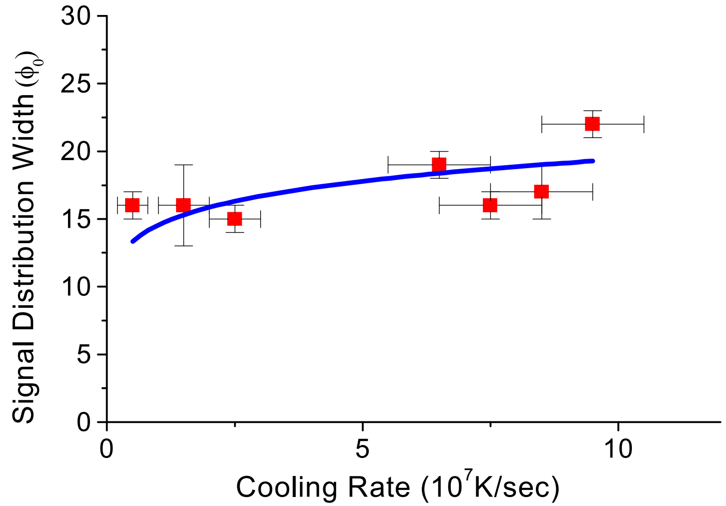
$\tau_{defect} \sim 10^{-9}$ s << SQUID sensitivity

$$\Delta N = n_+ - n_-$$

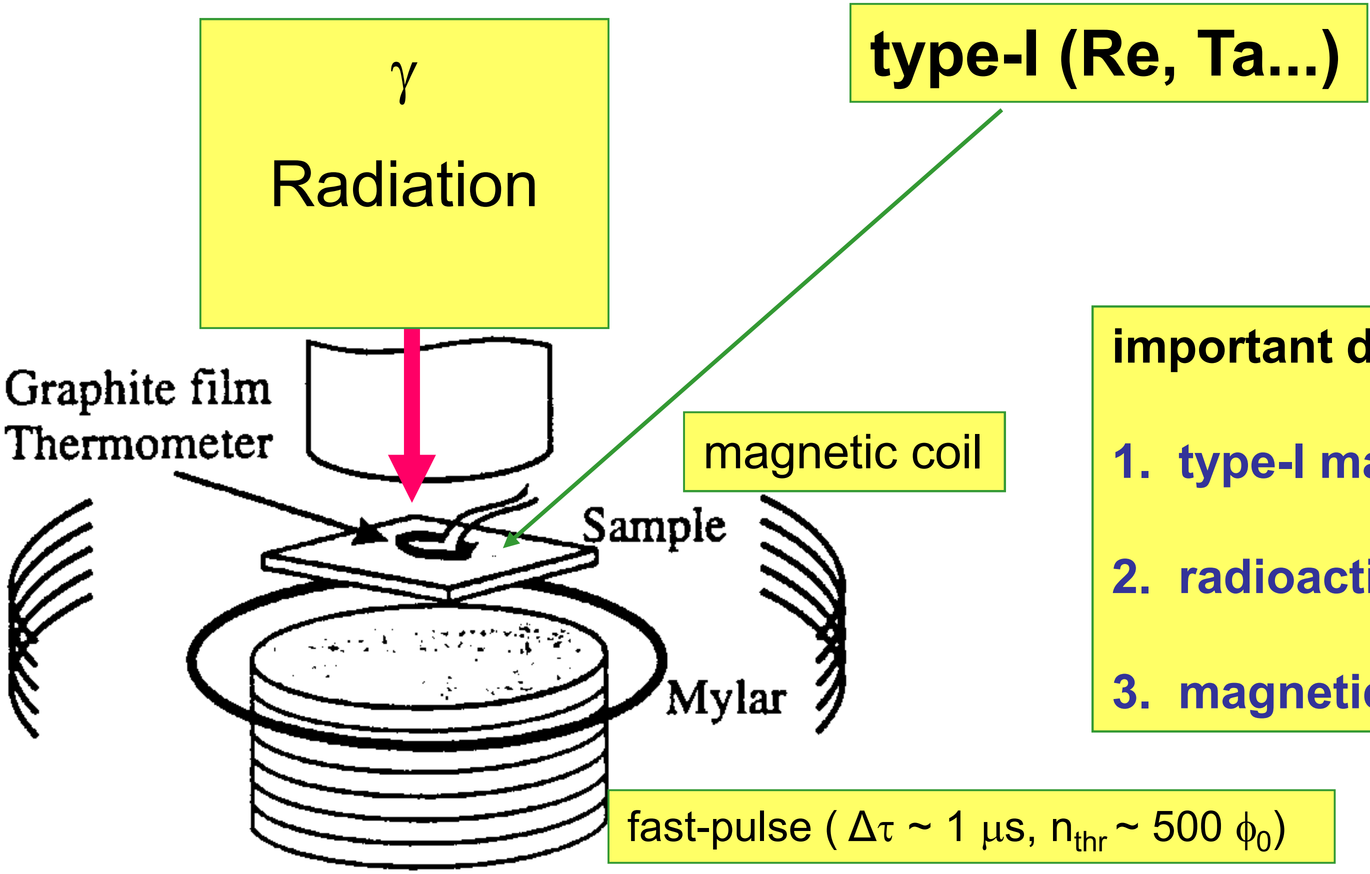
$$\sim \frac{1}{\pi}\sqrt{\ell/\xi_{Zurek}} \sim 140\ \phi_0/\text{cm}^2$$

$$\sim N^{1/4}$$

$$\sim \left| dT/dt \right|^{1/8}$$



soooo..... the Lisbon story



important differences:

1. **type-I material**
2. **radioactive source**
3. **magnetic field**

1. type-I materials

Hindmarsh & Rajantie: PRL 85 (2000) 4660

dissipation estimates* suggest a type-I defect population stability

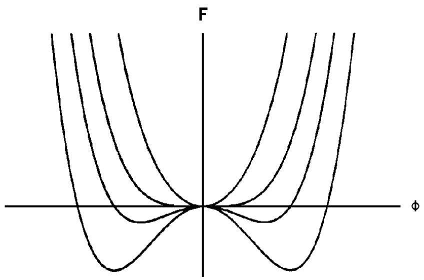
~ 10^5 longer than type-II, or order 10^{-4} s

* M. Ghinovker, I. Shapiro and B. YA. Shapiro : Phys. Lett. A260 (1999) 112; Journ. Low Temp. Phys. 116 (1999) 9

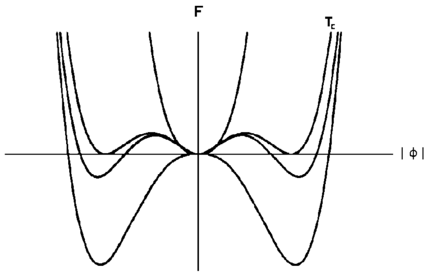
BUT *a priori* yield a 10^2 - 10^4 lower defect density because of generally larger ξ_0.

and....

Type-II [global]



Type-I [local]



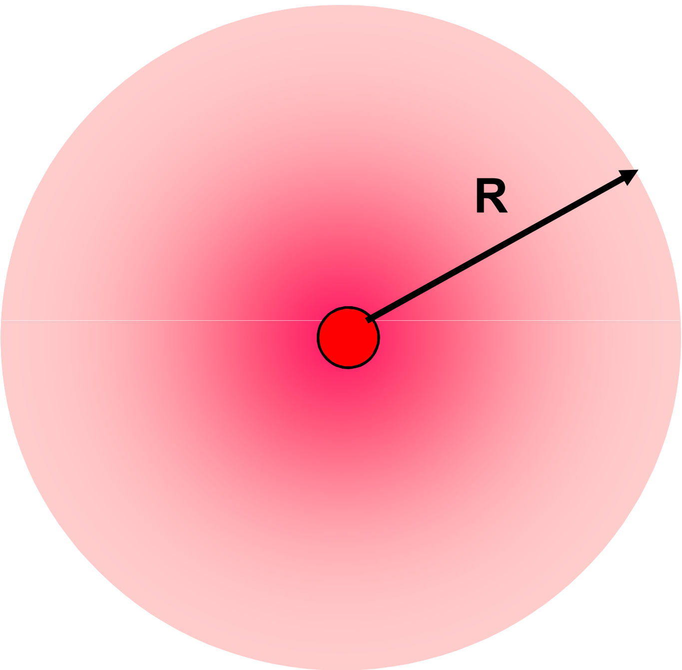
sample superconducting properties

	ξ_0 (μ)	λ_L (μ)	T_D (K)	H_c (G)	T_c (K)	κ
rhenium	0.15	0.06	415	205	1.7	0.4
vanadium	0.047	0.038	383	1408	5.4	0.8

2. Radioactive source = "hotspot"

D.J. Goldie, N.E. Booth, R.J. Gaitskell and G.L. Salmon
in Proc. SQUID'91 (Springer-Verlag, Berlin, 1992) 27.

energy deposited in ∅ $\leq$ 1 μm



hotspot rapidly expands:

$R \sim [6D/\Gamma_{qp}]^{1/2} \sim 8 - 80\ \mu m$

with $D \sim 0.1\text{-}10\ m^2/s$
$\Gamma_{qp} \sim 10\ ns^{-1}$

hotspot decay:

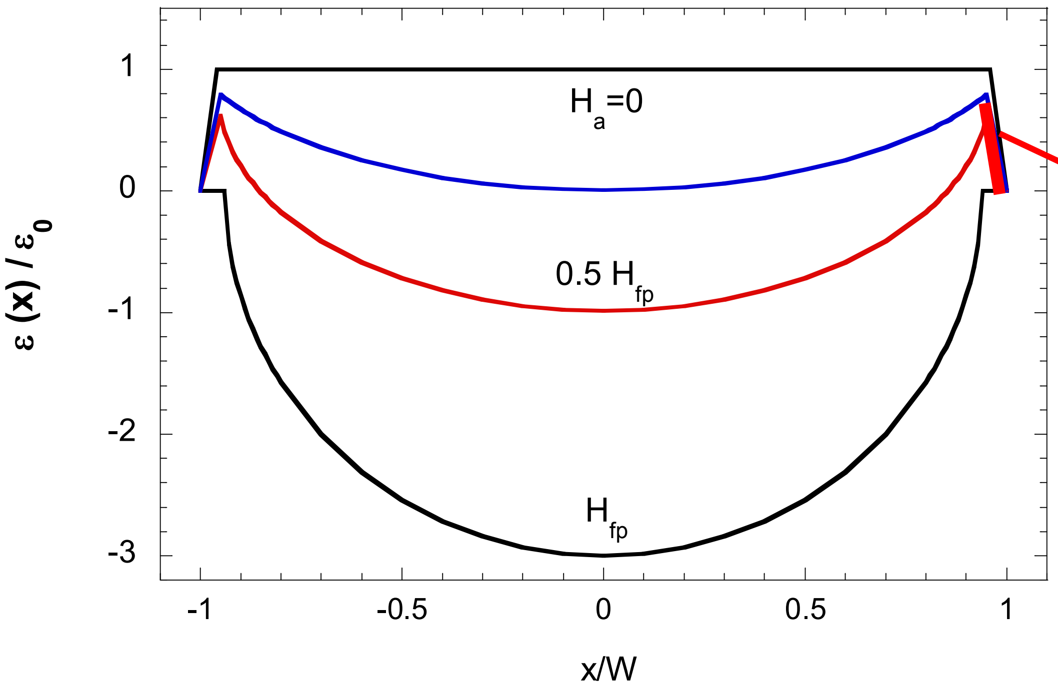
qp diffusion when phonon and qp scattering rates become equal at a few times the gap energy:

estimated $\tau_Q < 10^{-9}$ s

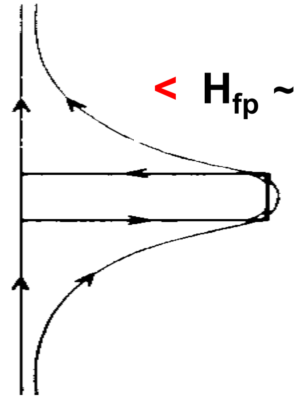
$$\frac{\Delta E}{V} = \frac{4 \cdot 10^{-2}\,\mathrm{fJ}}{< 1\,\mu\mathrm{m}} = \int_T^{T+\Delta T} C_S\,dT \sim 1.5\ \frac{\mathrm{MeV}}{\mu\mathrm{m}^3} \Rightarrow \Delta T = 1.4\ \mathrm{K}$$

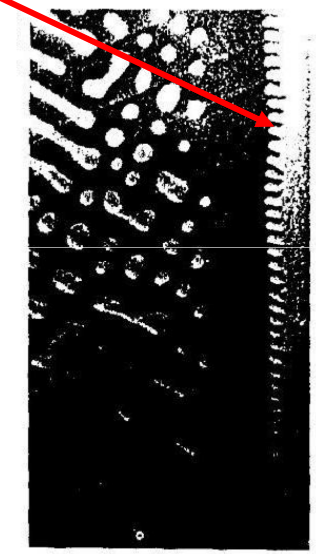
(locally)

3. Magnetic field => geometric barrier



< H_{fp} ~ 0.2 H_c

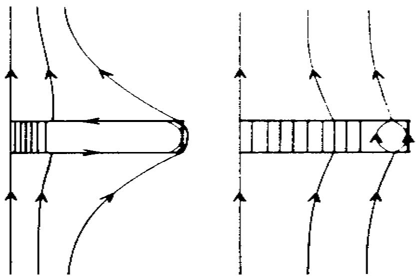




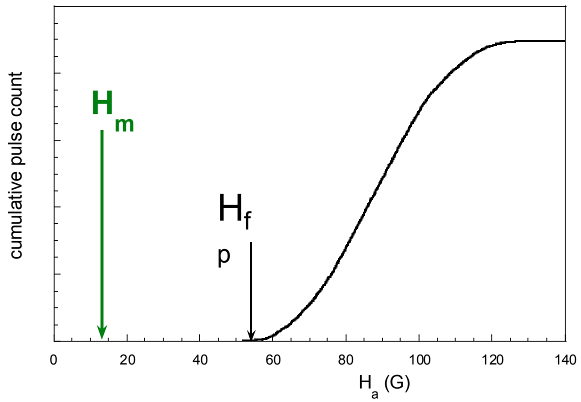
barrier presence :

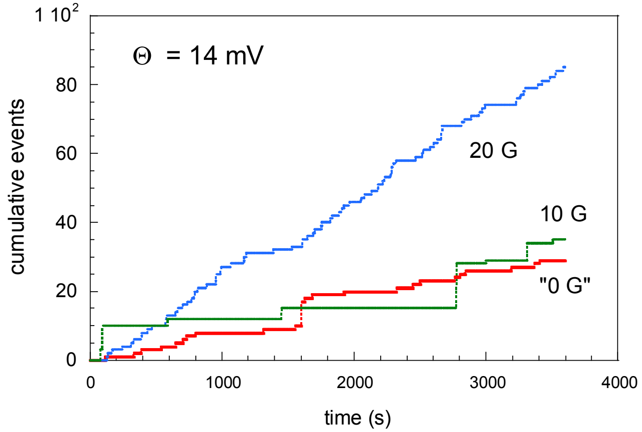
- ***traps spontaneous flux formation***
- ***purges antivortex population***

> H_{fp}

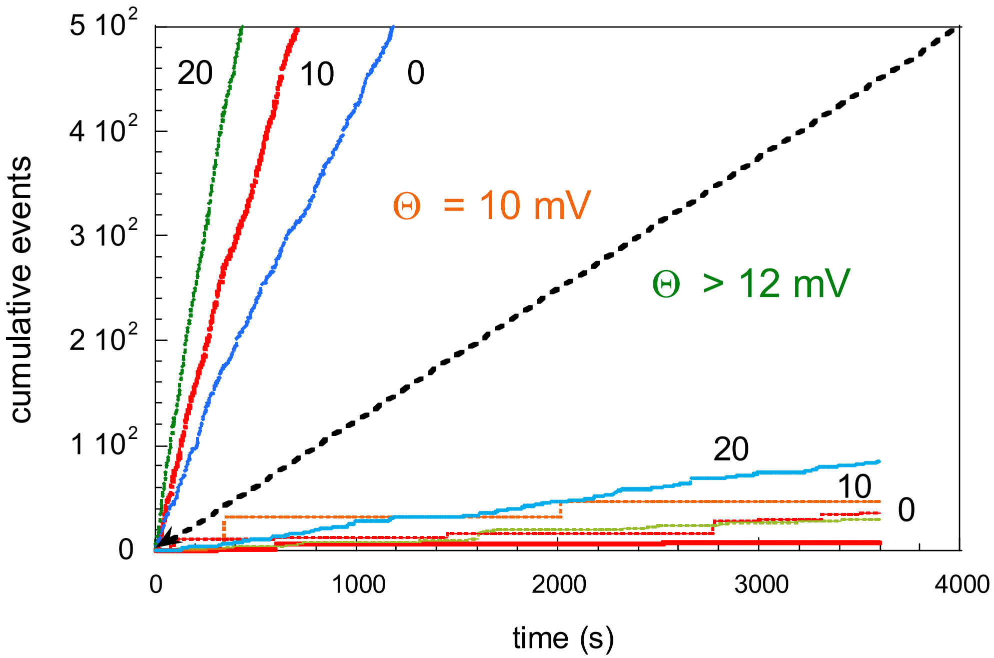


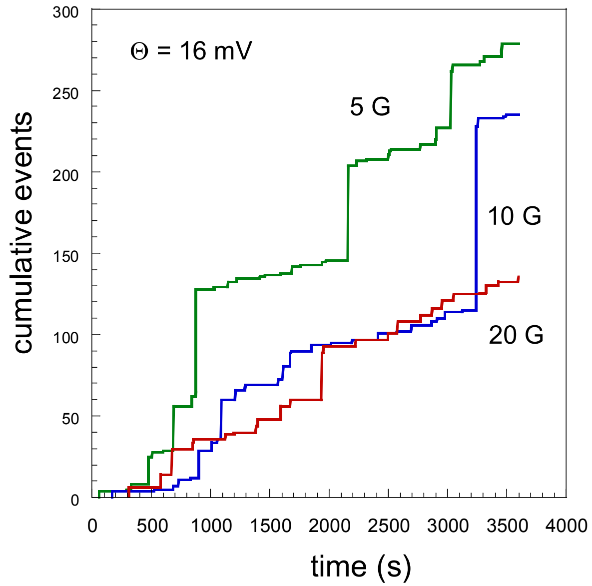
signal validation





ZFC -> H_m -> 1 hr measurement -> 0





rhenium [12.5 μm, 330 mK]

assume:

- complete purging of ϕ_- population
- nominal hotspot diameter of 40 μm

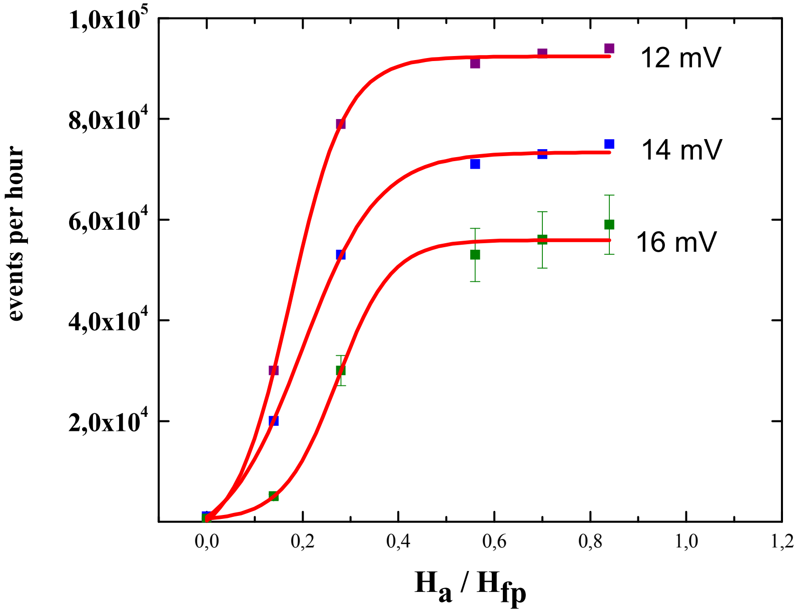
K-Z mechanism : $N \sim 12\ \phi_0\ \mu m^{-2}$

⇒ each quench = S > $10^3\ \phi_0$,

ie. corresponds to one recorded signal event

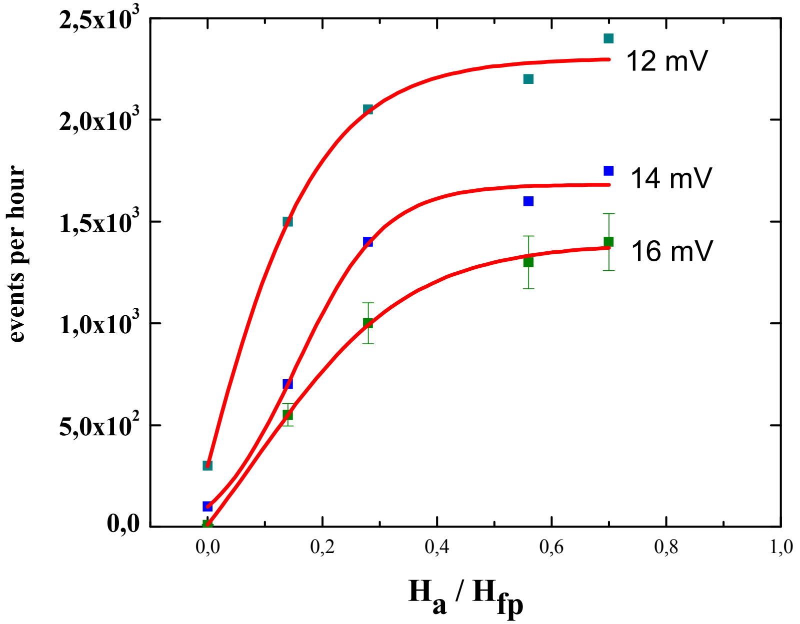
6 keV (^{55}Fe) source

114 events/s, or ~2 x 10^5 events per hour after correction for geometry (0.48) and X-ray absorption (0.99).



60 keV (^{241}Am) source

141 events/s, or ~ 2 x 10^4 events per hour after correction (0.48 and 0.08, respectively).



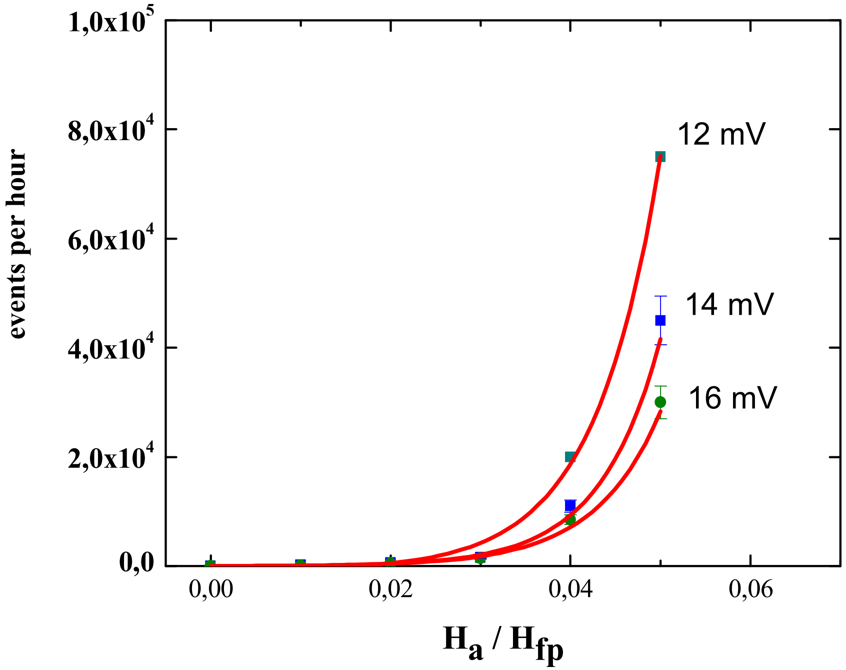
vanadium [10 μm, 4.2 K]

	ξ_0 (μ)	λ_L (μ)	T_D (K)	H_c (G)	T_c (K)	κ
vanadium	0.047	0.038	383	1408	5.4	0.8

K-Z mechanism : N ~ 120 ϕ_0 μm^{-2}

6 keV (^{55}Fe) source

114 events/s, or ~1 x 10^5 events/hour after correction for geometry (0.48) and X-ray absorption (0.51).



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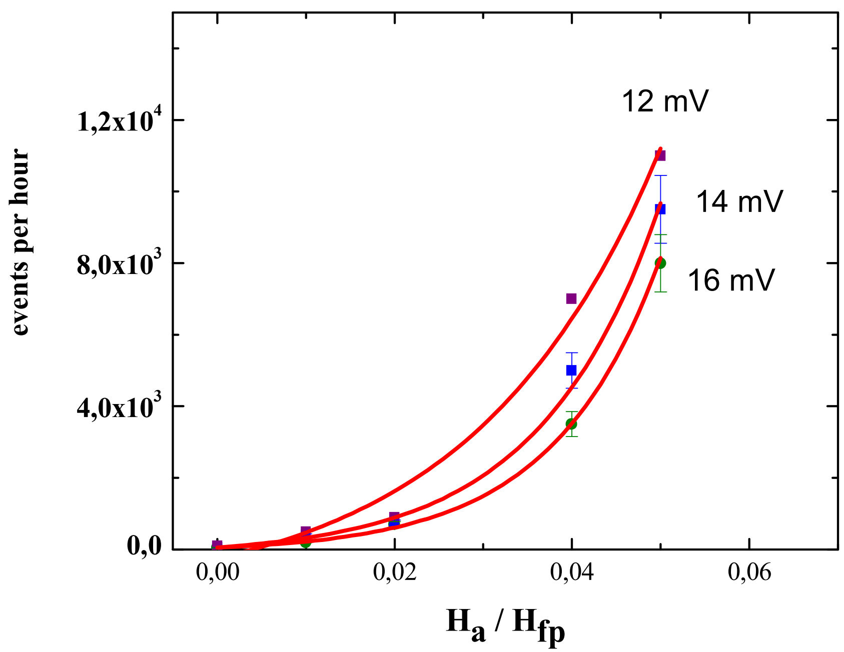


OBSERVATIONS

> S is generally above any ΔN estimate by $10 - 10^3$

> S is generally below any KZ – based prediction by $10 - 10^2$

Since only events with $n > 500\ \phi_0$ measured,

=> some events with less than $500\ \phi_0$

=> incomplete purging of ϕ- and/or evaporation

SUMMARY

- **“new” type-I experiments with geometric barrier & locally-induced quenches observe anomalous flux generation**

  * = **NOT** predicted “classically”

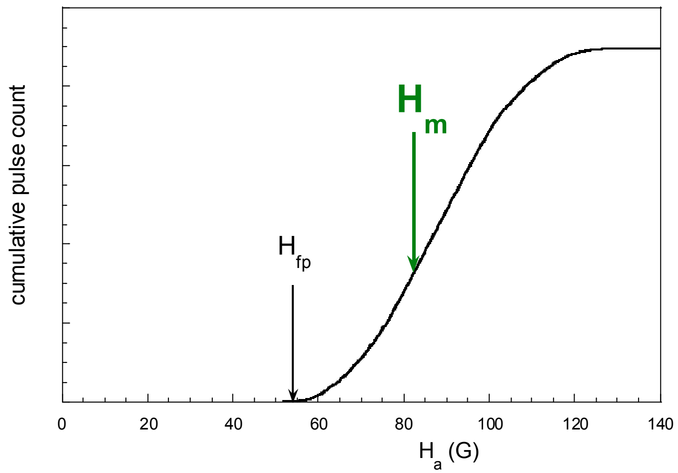
  * but, **IN**consistent with Kibble-Zurek N or ΔN prediction

- **next phase :**

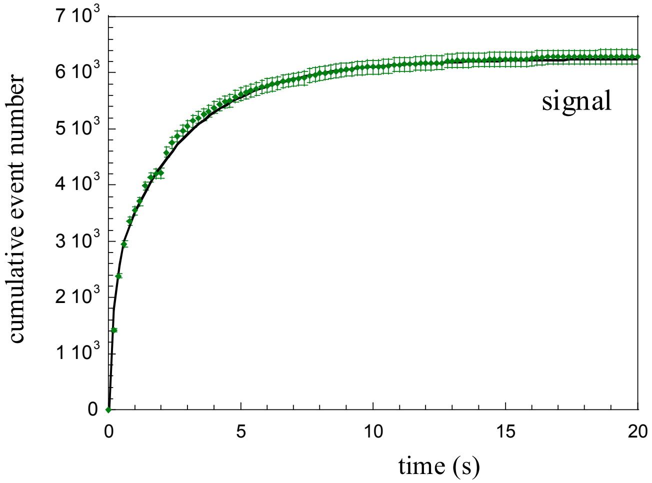
  * replace fast-pulse with fast SQUID

  * increase irradiation sources

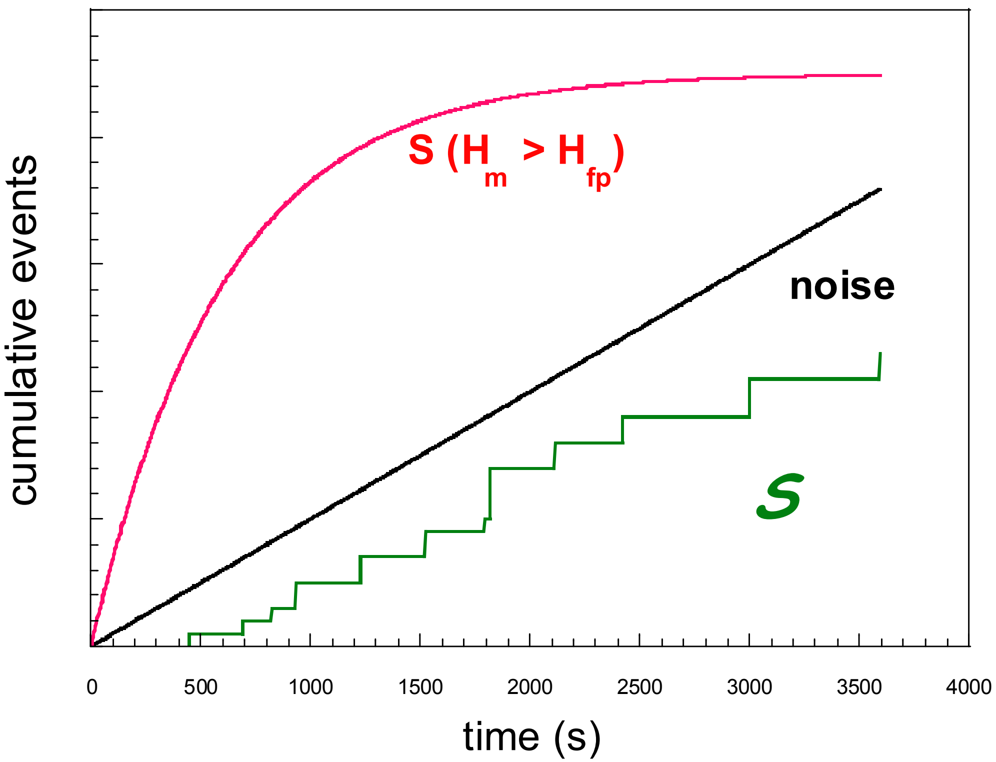
$H > H_{fp}$



cumulative pulse count
H_m
H_{fp}
0
20
40
60
80
100
120
140
H_a (G)

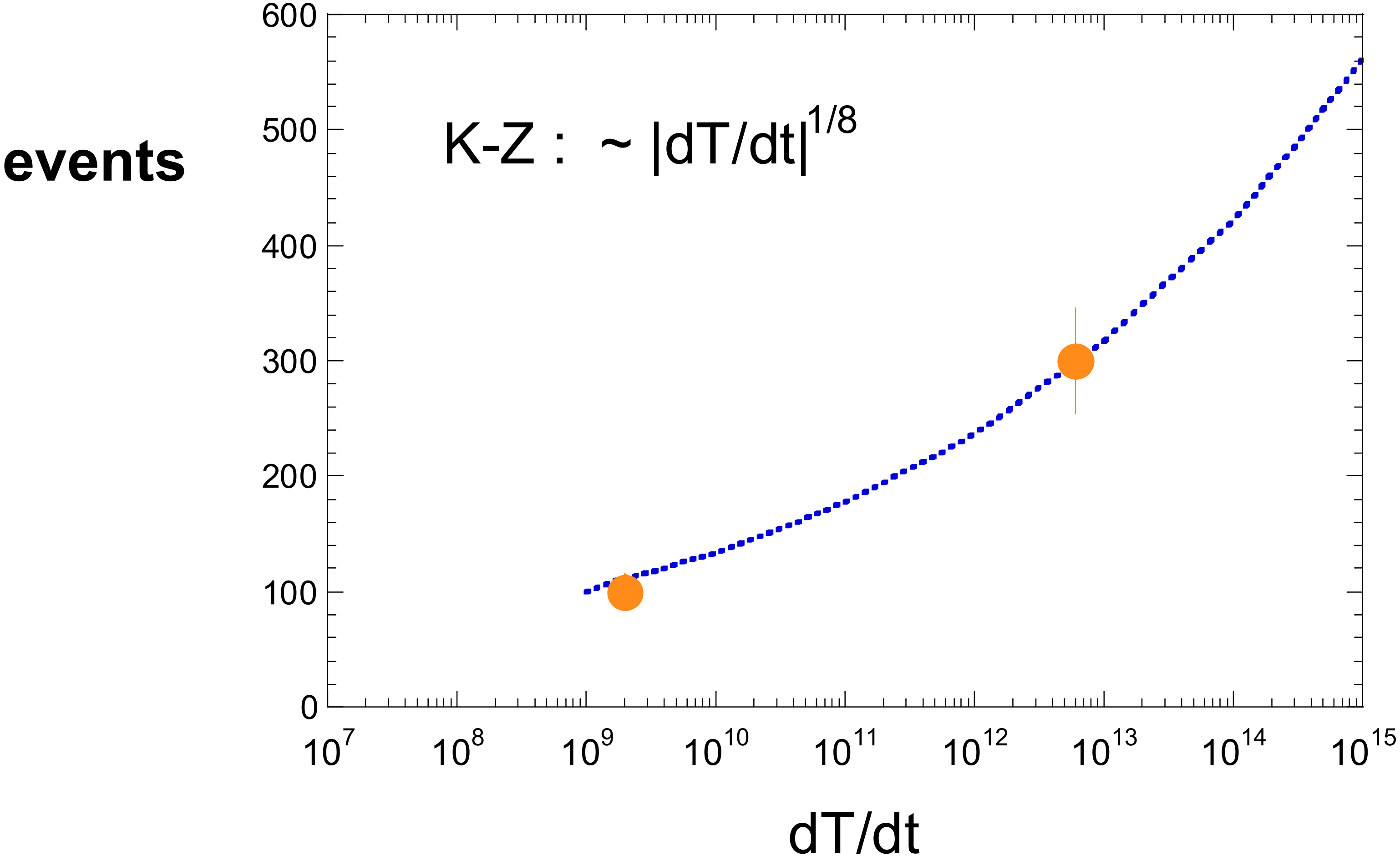


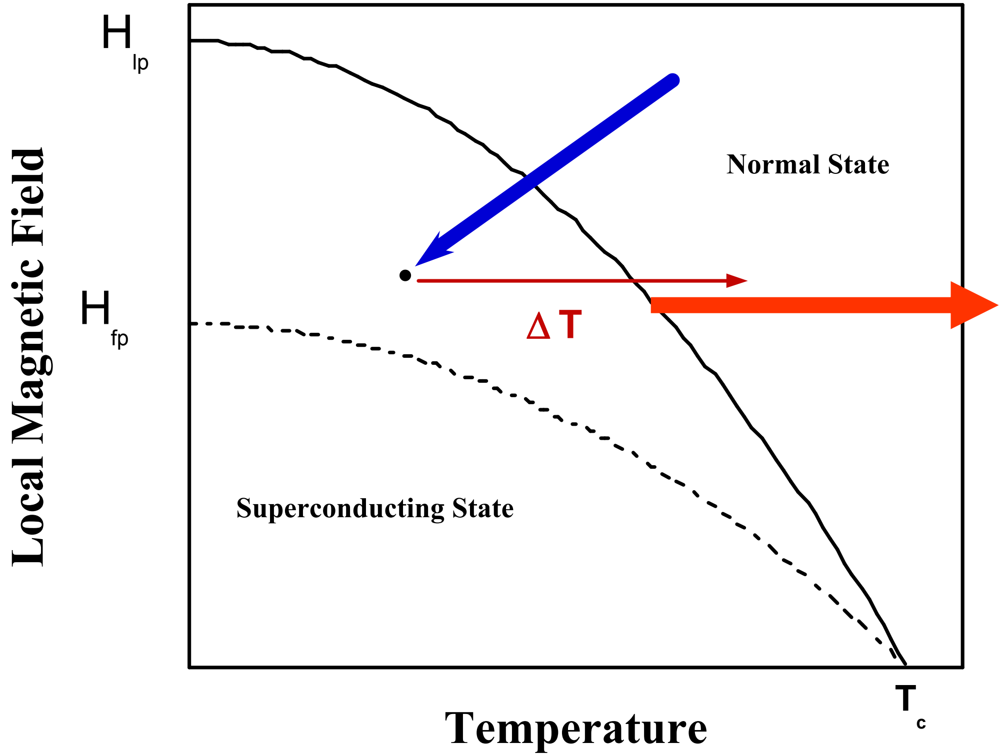
cumulative event number
7 10³
6 10³
5 10³
4 10³
3 10³
2 10³
1 10³
0
signal
0
5
10
15
20
time (s)



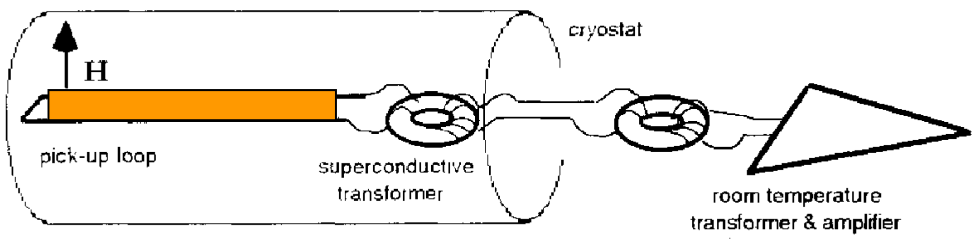
cumulative events
S (H_m > H_{fp})
noise
S
0
500
1000
1500
2000
2500
3000
3500
4000
time (s)

quench dependence





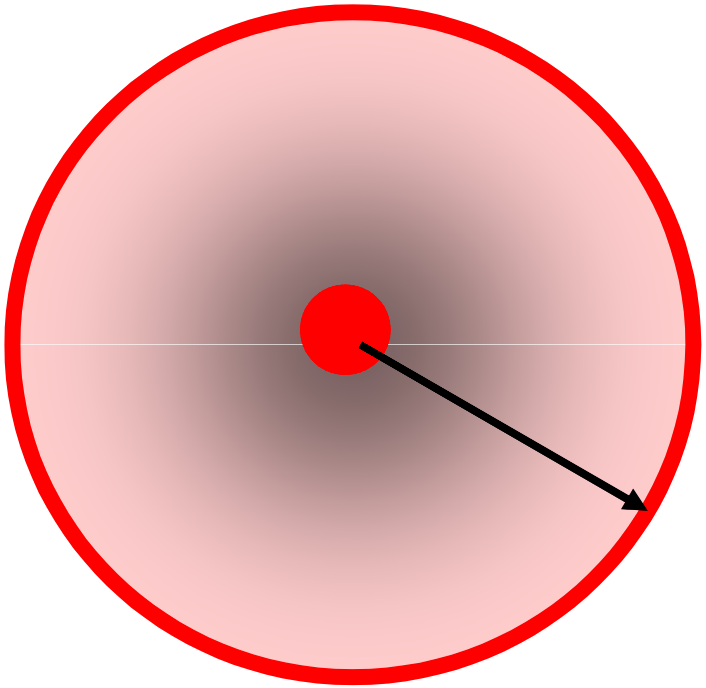
H
lp
H
fp
Local Magnetic Field
Normal State
Δ T
Superconducting State
Temperature
T
c



cryostat
H
pick-up loop
superconductive
transformer
room temperature
transformer & amplifier

“ Baked Alaska “

A. Leggett: Phys. Rev. Lett. 53 (1984) 1096



heat carried outwards in rapidly expanding shell at ~ Fermi velocity

(interior remains ~ base temperature)

$dT/dt \sim 2 \times 10^{13}$ K/s