

# Observation of Majorana fermions in superfluid $^3\text{He}$ .

**Yury Bunkov**

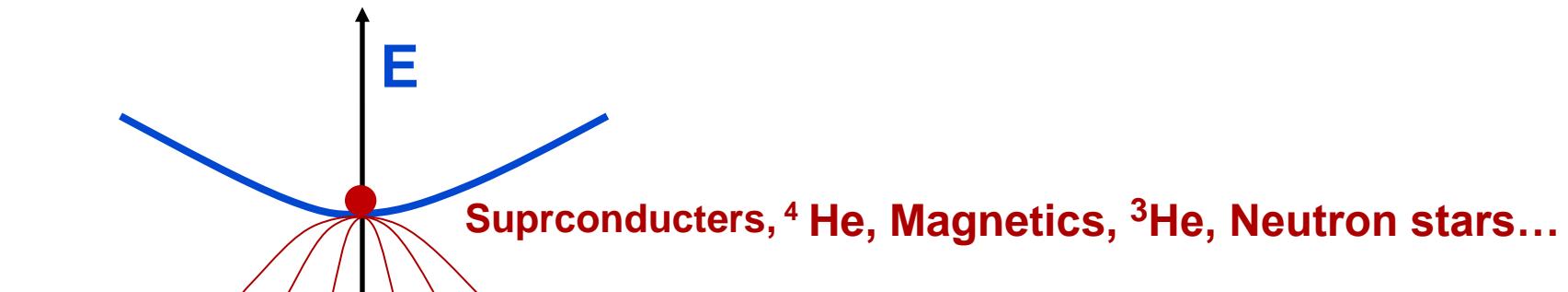
**Institut Neel, Grenoble, France**

**Kazan Federal University, Russia**



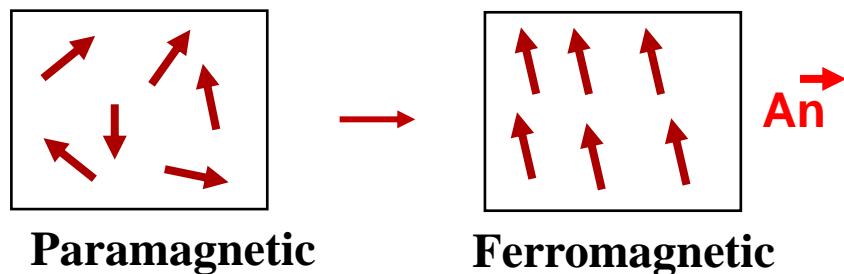
**XV-Международная Молодежная Научная Школа  
"Актуальные проблемы магнитного резонанса"**  
**Казань 22 - 26.10.2013**

# Symmetry breaking phase transition



Universe

$$A_{25} e^{i\phi}$$



$^4\text{He}$

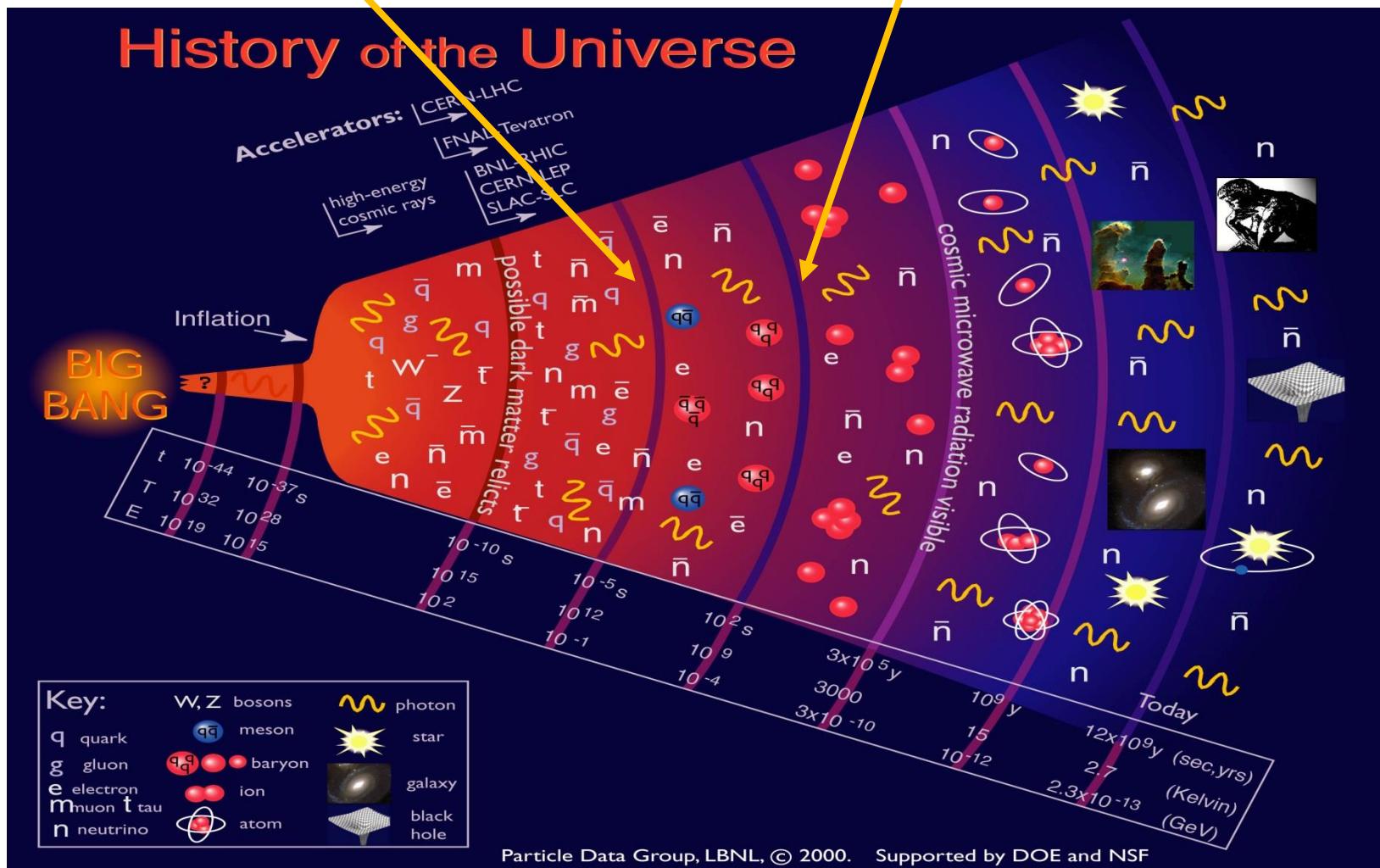
$$a_i e^{i\phi_i} \rightarrow A e^{i\phi}$$

$^3\text{He}$

$$a_i e^{i\phi_i} \rightarrow A_9 e^{i\phi}$$

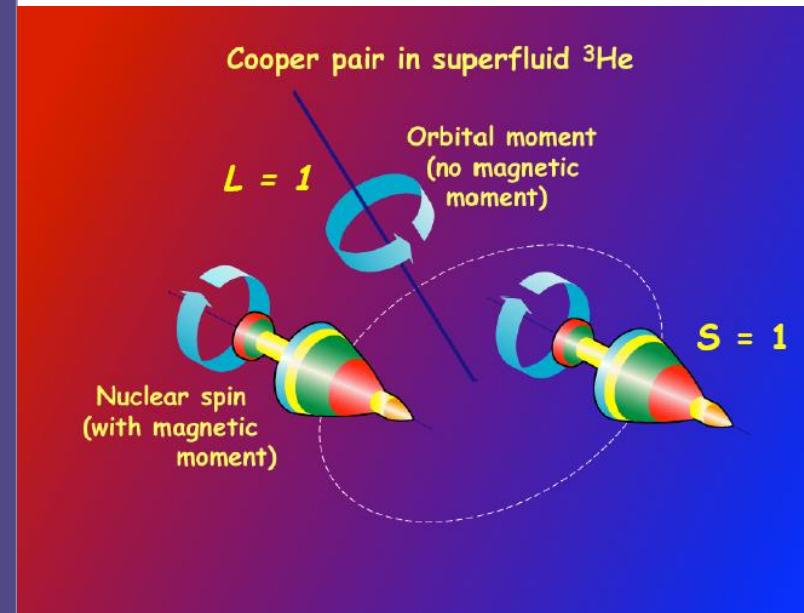
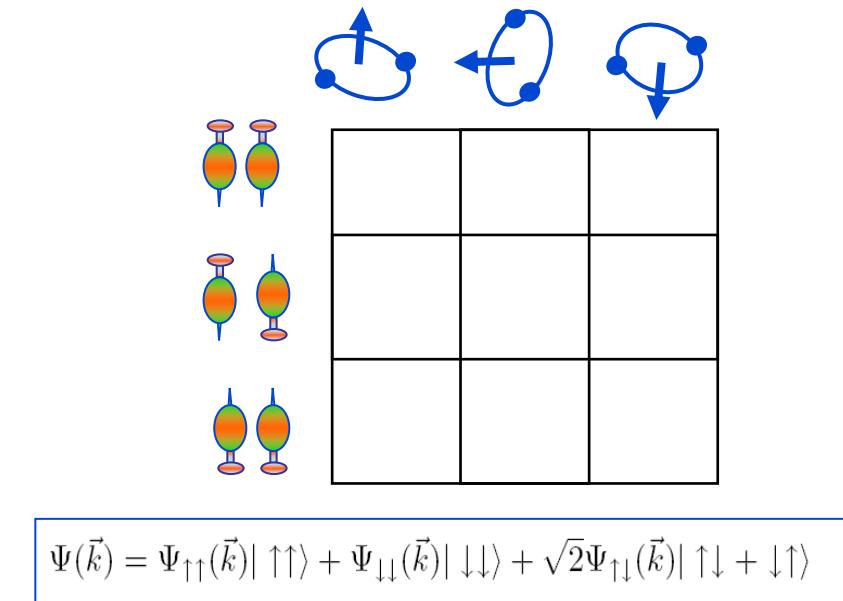
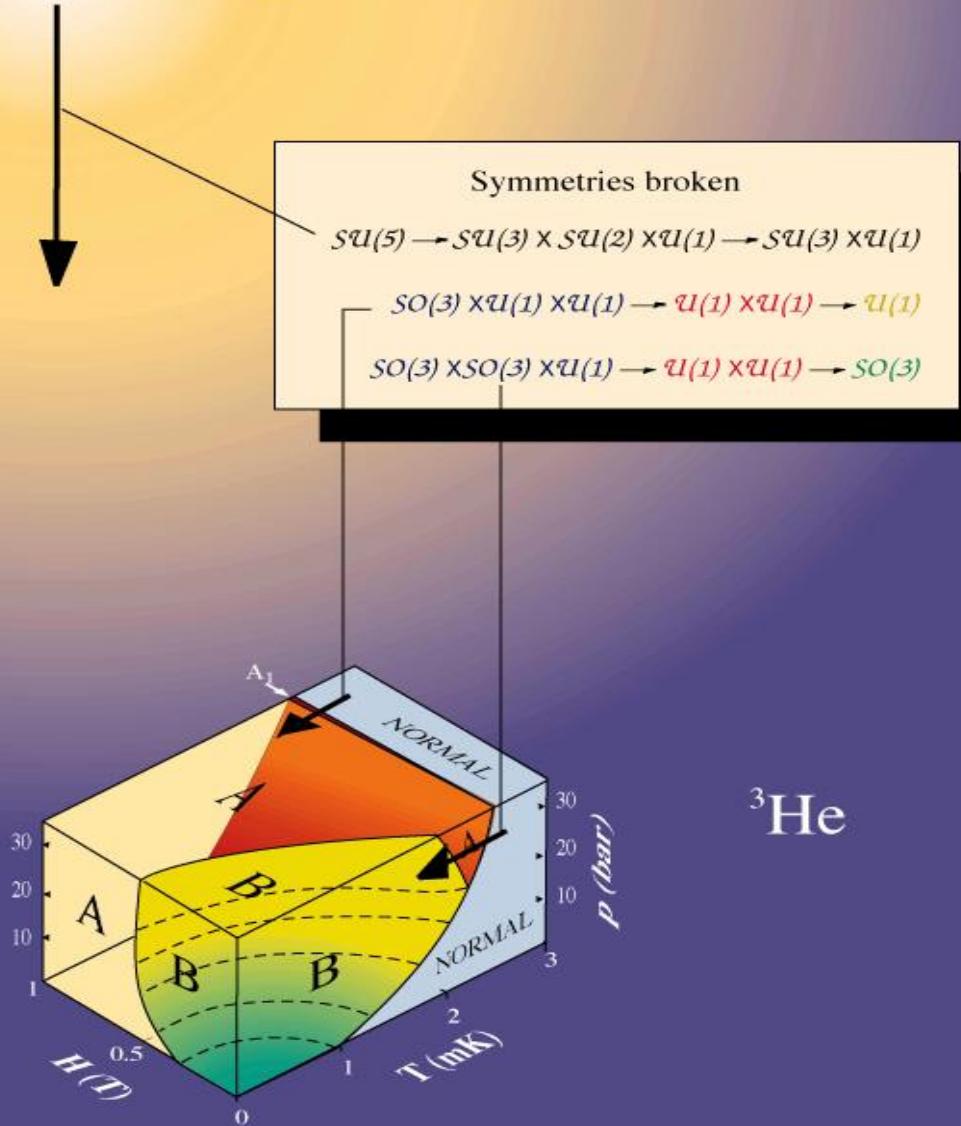
# GUT in Standard Model

$$SO(10) \rightarrow SU(3) \times SU_L(2) \times U(1) \rightarrow SU(3) \times U_Q(1)$$



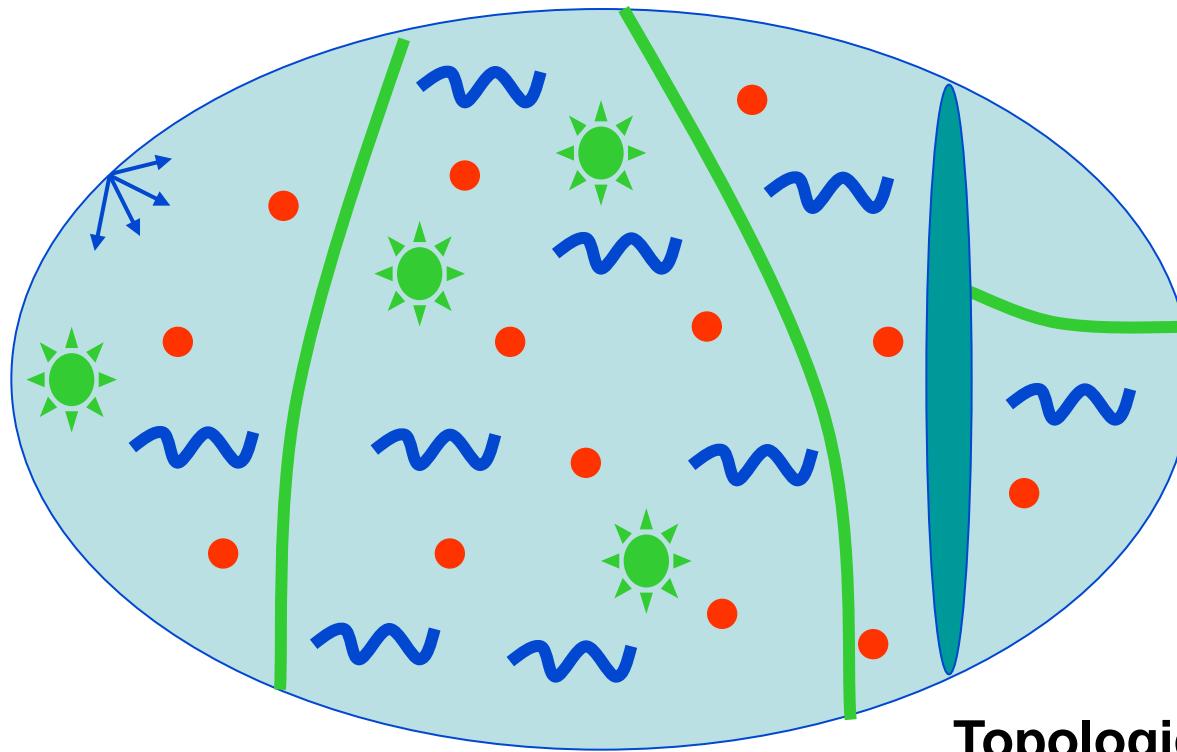
# Quantum field theory

## Big Bang



# Superfluid $^3\text{He}$

Quantum vacuum, characterized by  
 $\Psi$  (phase)  $\mathbf{S}$  (magnetization)  $\mathbf{L}$  (orbital momentum)

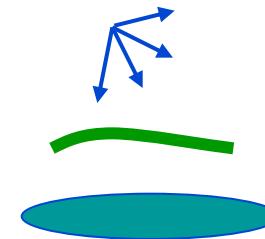


## Particles:

- Quasiparticles
- ~~~~ Magnons
- ~~~~ Acoustic modes

## Topological defects:

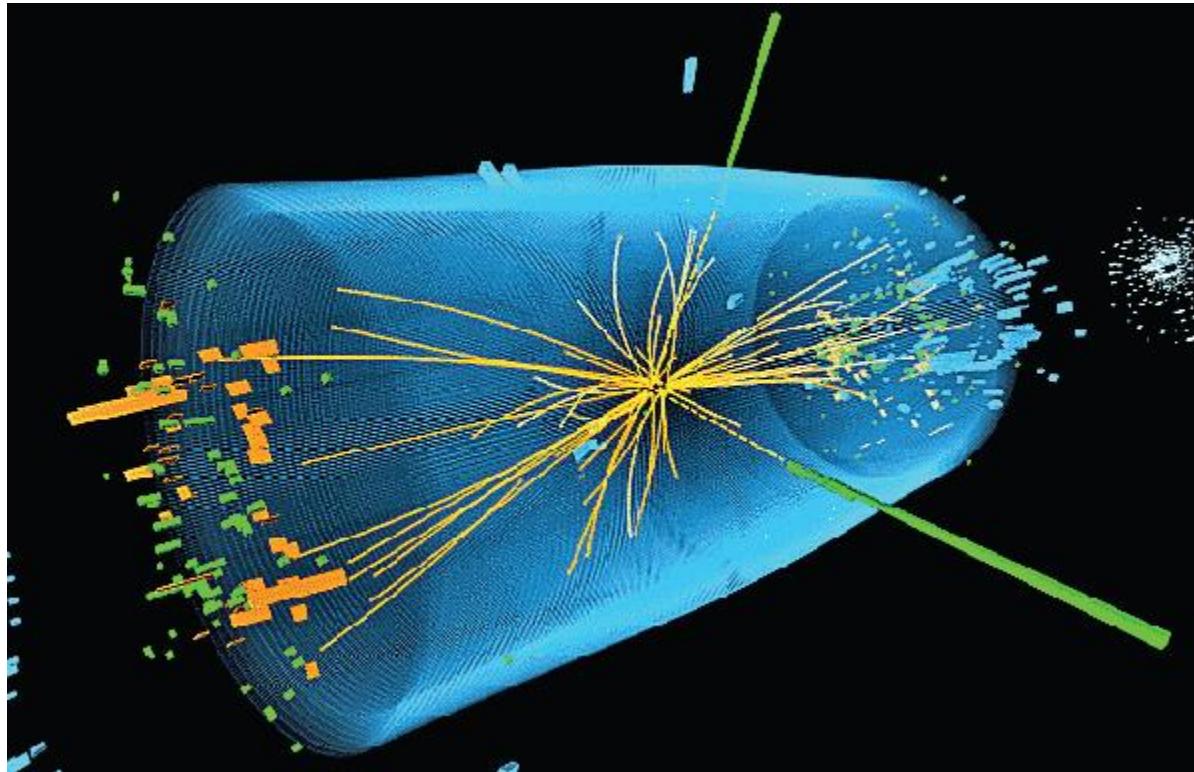
- Fields:  
Texture of orbital momentum



- Boojum
- Vortex
- Brane

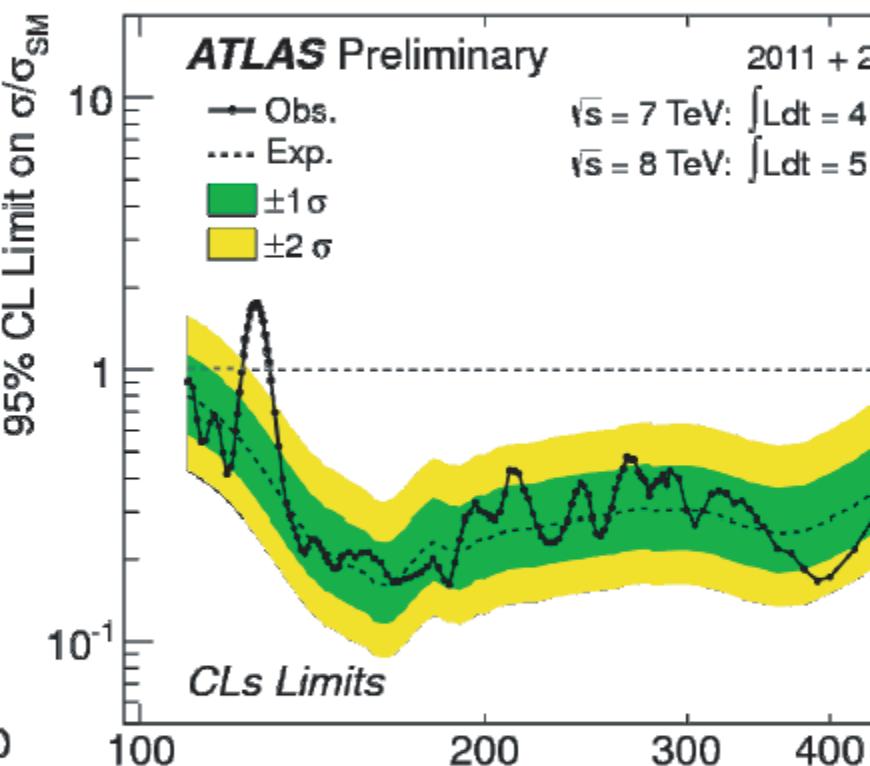
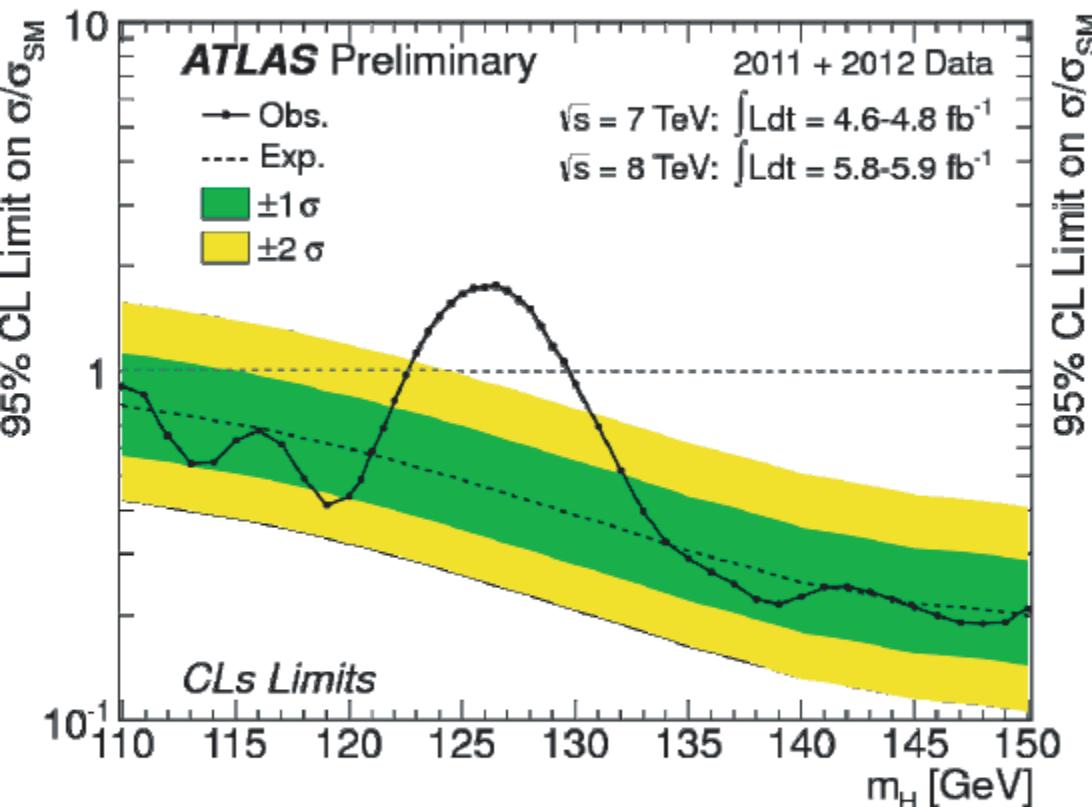
**Superfluid  $^3\text{He}$  is the most complex system  
of quantum fields, experimentally accessible,  
for which we already have  
“The Theory of Everything”**

## Multiple Higgs bosons from superfluid $^3\text{He}$



# Updated combined SM Higgs exclusion

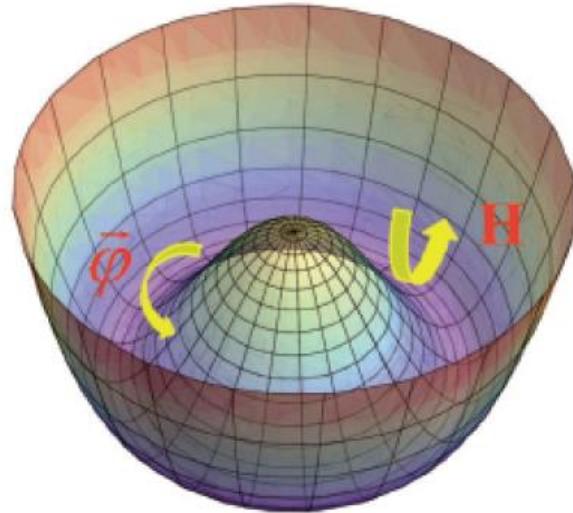
- Combining updated 2011+2012  $\gamma\gamma$  and 4-lepton analysis with others as before



- Expected exclusion with this dataset from 110-582 GeV
  - Observed exclusion from 110-122.6 GeV and 129.7-558 GeV
    - 111.7-121.8 GeV and 130.7-523 GeV excluded at 99% CL
  - Region around 126 GeV cannot be excluded

# How many Higgs bosons ?

amplitude H-modes of Higgs field



P. W. Higgs, PRL **13** (1964) 508:

“The model of the most immediate interest is that in which the scalar fields form an **octet** under **SU(3)**... There are **2** massive scalar bosons ... (**2 Higgs bosons**) ... ; the remaining **6** components of the scalar octet combine with the corresponding components of the gauge-field octet to describe massive vector bosons (**6 massive gauge bosons**).”

**Standard Model requires only one Higgs boson**

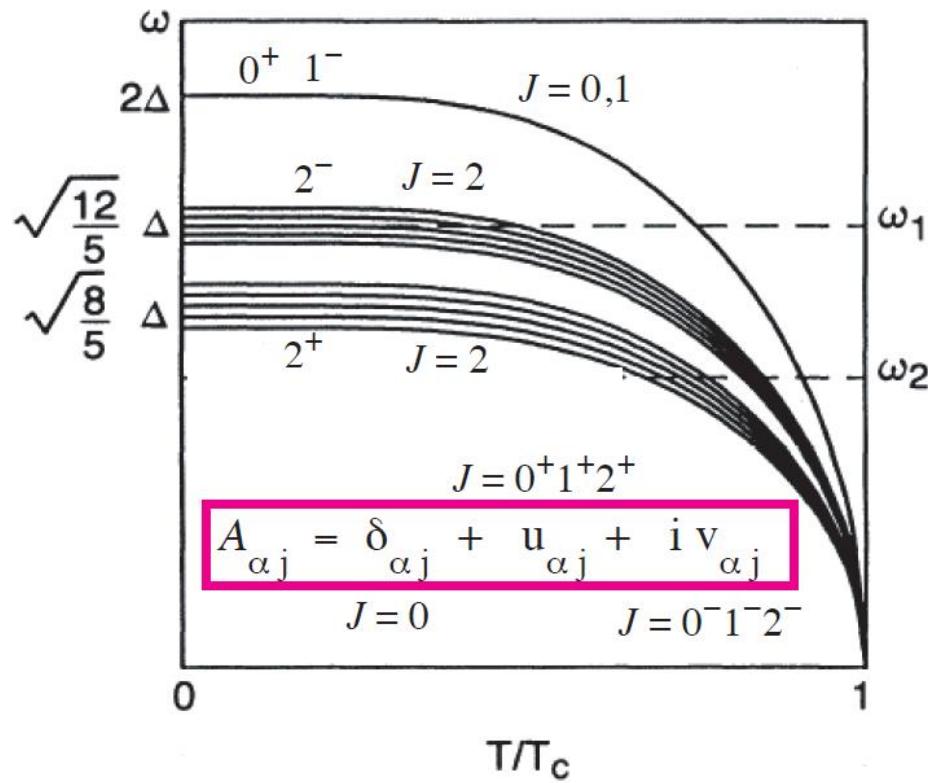
3 NG modes are absorbed into longitudinal  
modes of 3 massive vector bosons  
(charged  $W^+$ ,  $W^-$  and neutral  $Z$ )  
this is called **Higgs mechanism**

**Bosons in superfluid  ${}^3\text{He-B}$ :** collective modes of order parameter

**9-plet  $A_{\alpha i}$  under  $\text{SO}(3) \times \text{SO}(3) \times \text{U}(1)$**

**14 Higgs bosons + 4 NG modes (4 massive gauge bosons in gauged  ${}^3\text{He-B}$ )**

# Multiple Higgs bosons from superfluid $^3\text{He}$



14 Higgs bosons

$$E_{1-} = E_{0+} = 2\Delta$$

$$E_{2-} = (12/5)^{1/2}\Delta$$

$$E_{2+} = (8/5)^{1/2}\Delta$$

## Nambu sum rule: from 3He-B to Standard Model

relation between energies  $E_B$  &  $E_F$  of bosonic & fermionic excitations in BCS type theories

$$E_{B1}^2 + E_{B2}^2 = 4 E_F^2$$

3He-B       $E_{B1} = (8/5)^{1/2}\Delta$        $E_{B2} = (12/5)^{1/2}\Delta$        $E_F = \Delta$   
 real squashing mode      squashing mode      gap in quasiparticle spectrum

Application of Nambu rule to masses of Higgs fields and top quarks

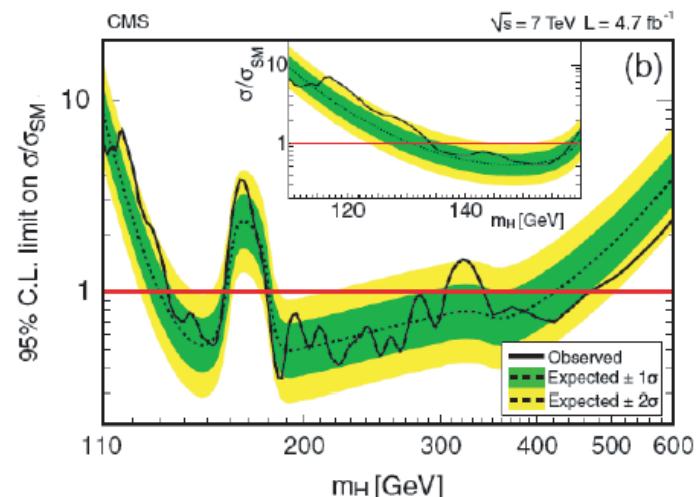
$$m_{H1}^2 + m_{H2}^2 = 4 m_t^2$$

125 GeV      325 GeV      174 GeV  
 discovered Higgs      Nambu partner Higgs      top quark

\* Search for the Standard Model Higgs Boson in CMS Collaboration @ LHS (Compact Muon Solenoid))

PRL 108, 111804 (2012)

"Small excesses of events are observed around masses of 119, 126 & 320 GeV!"

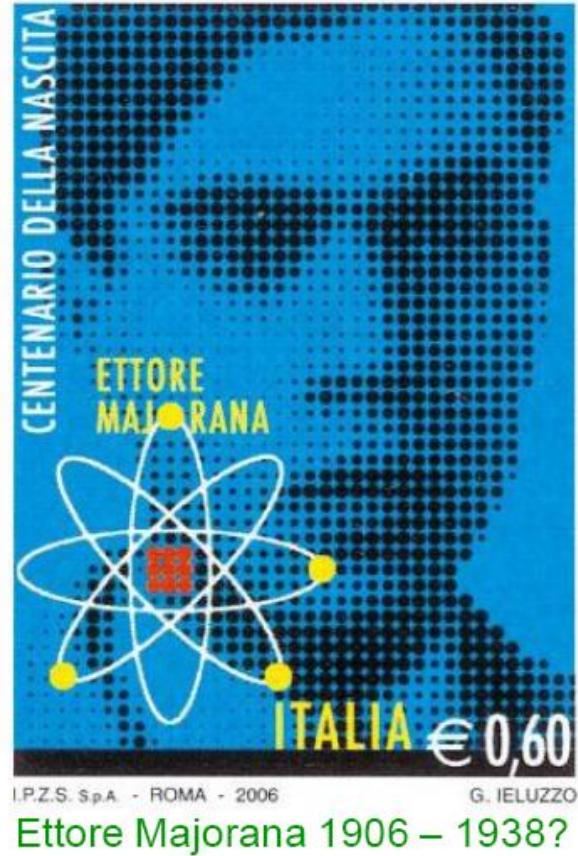


# In Search of Majorana

1937 : Majorana publishes his modification of the Dirac equation of relativistic quantum theory

Spin  $\frac{1}{2}$  particle = antiparticle :  $\psi = \psi^\dagger$

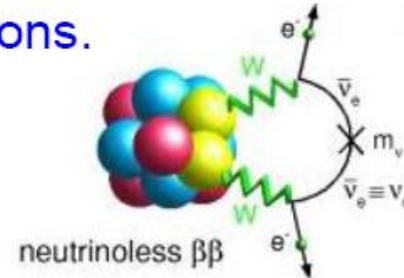
1938 : Majorana mysteriously disappears at sea



Observation of a Majorana fermion is among the great challenges of physics today.

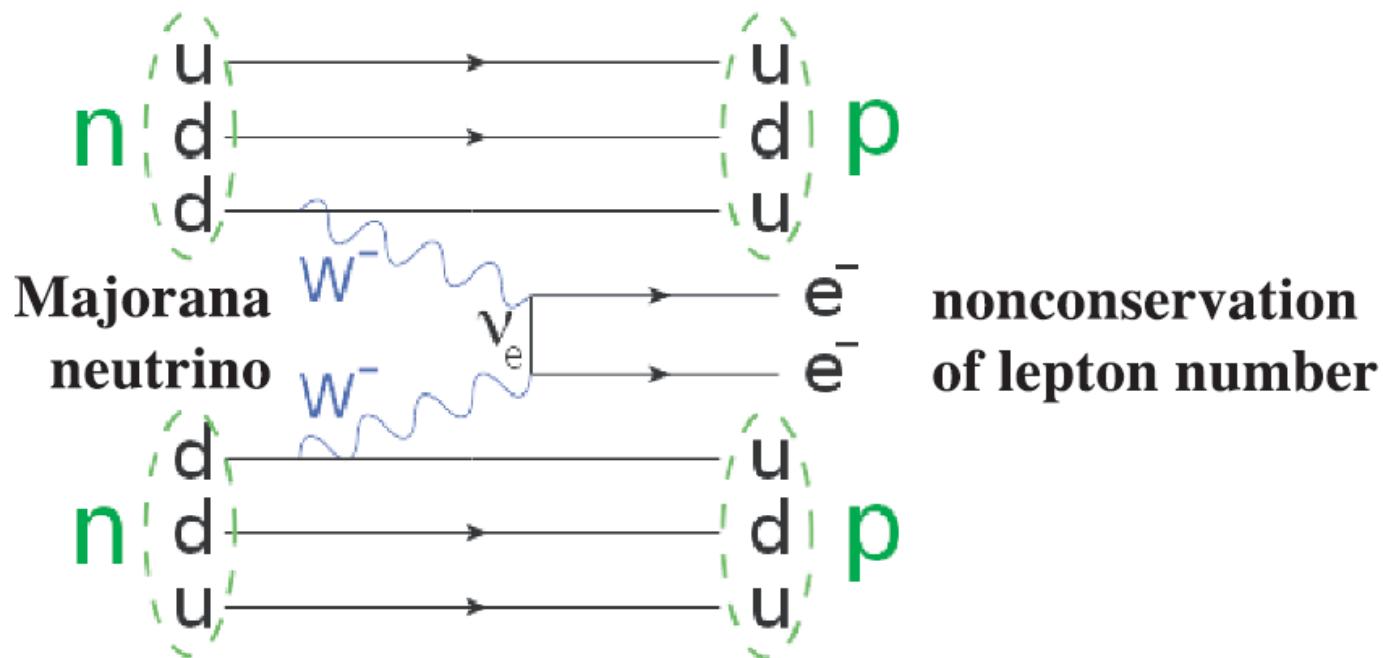
Fundamental Particles might be Majorana fermions.

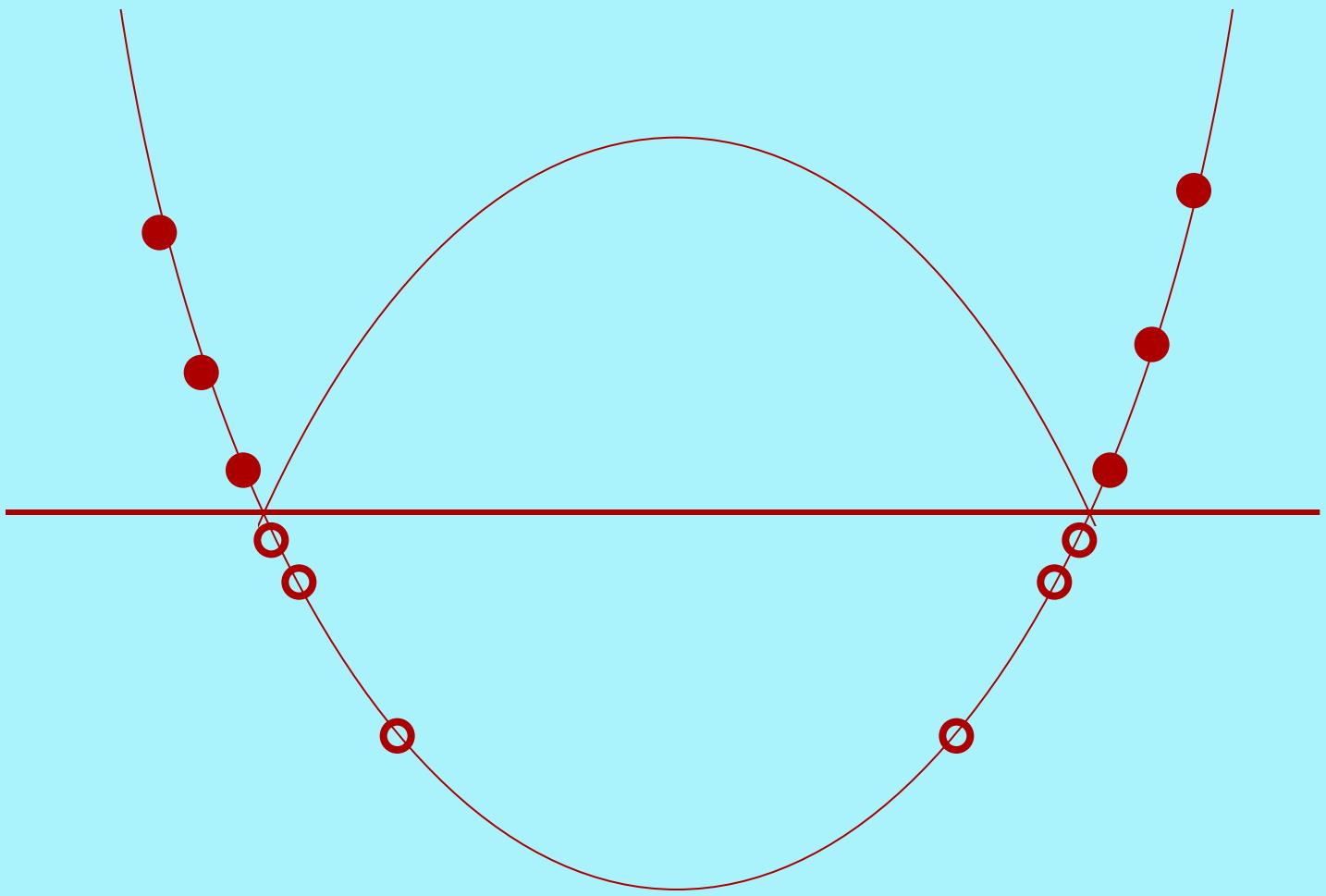
- e.g. neutrino
- Allows neutrinoless double  $\beta$ -decay.
- Candidate for Dark matter



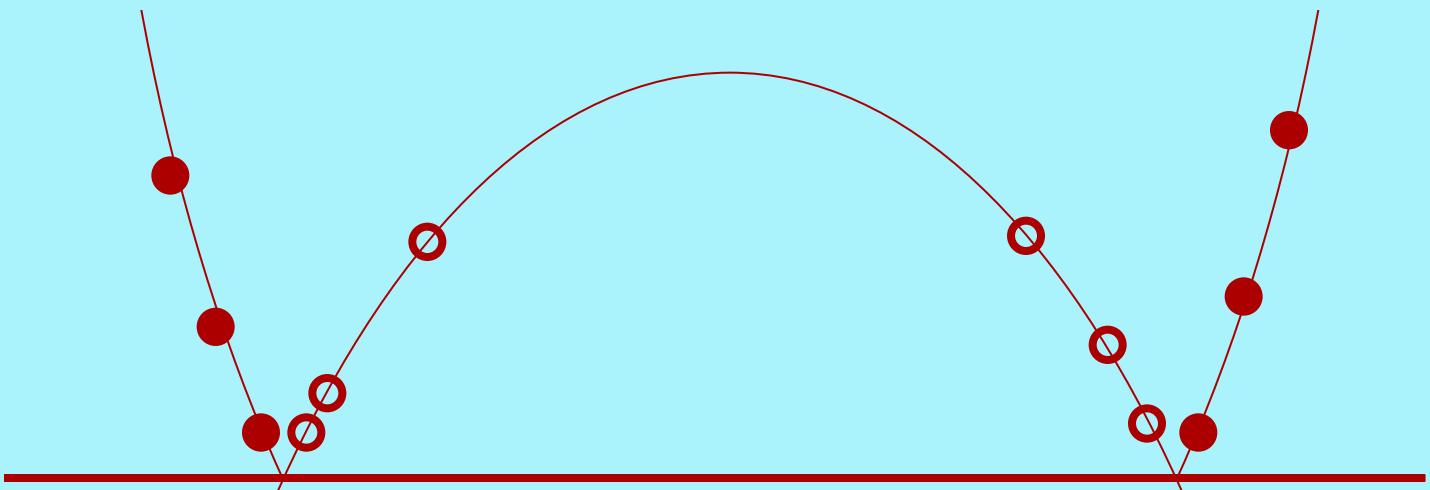
## neutrinoless double beta decay

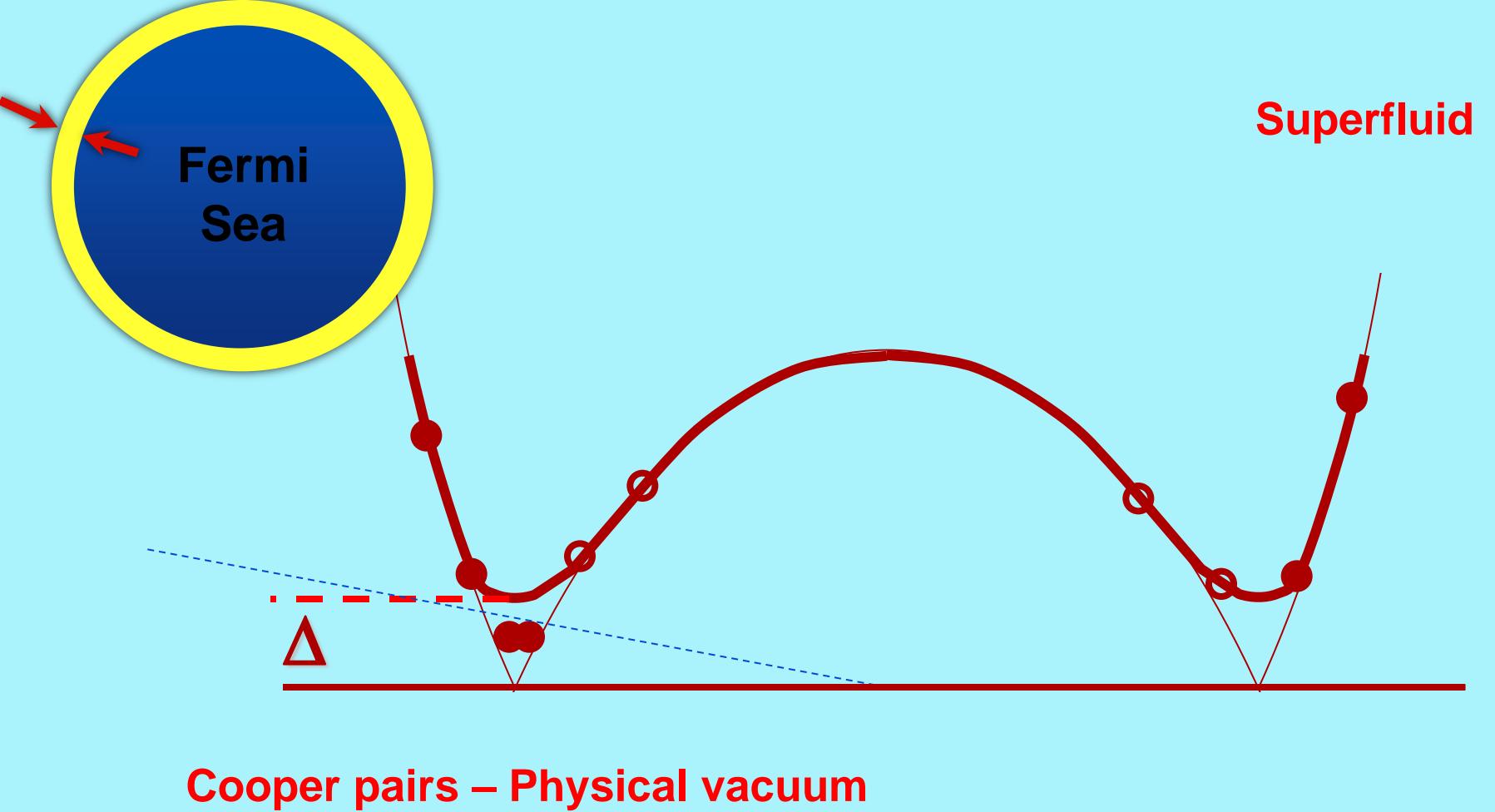
observation of neutrinoless double beta decay  
necessarily implies Majorana nature of neutrinos





Fermi liquid





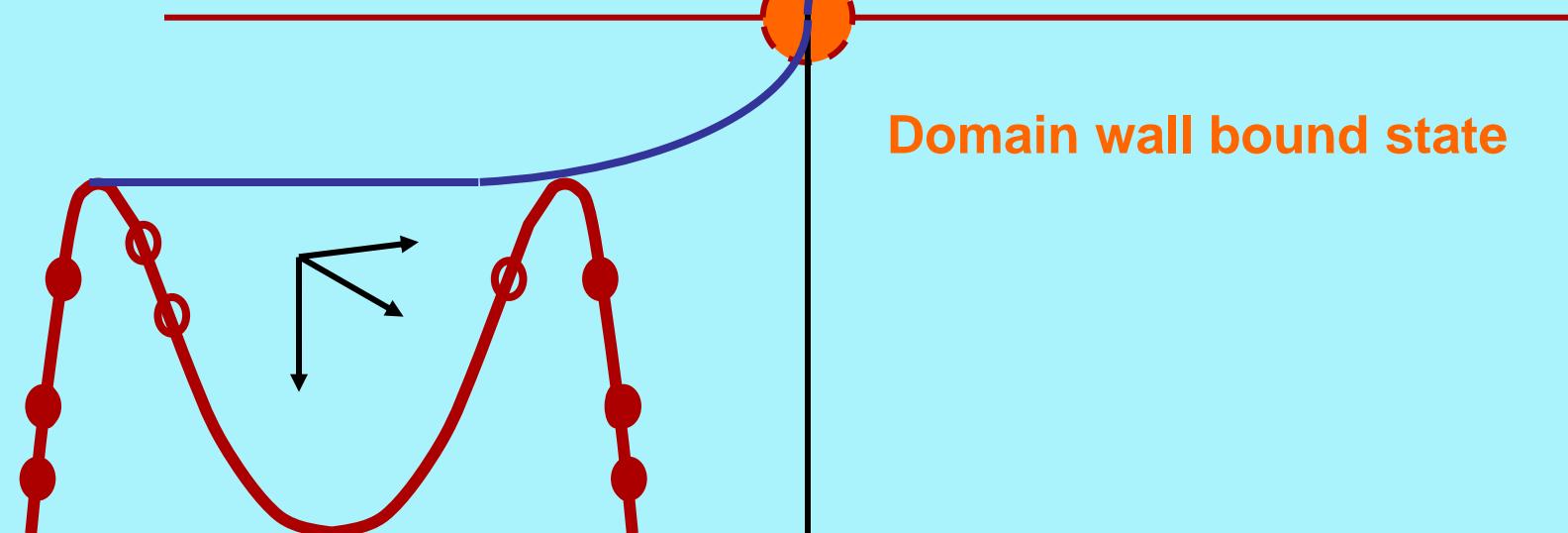
**Mass**

$$\Delta = g\Phi_0$$

$$\varepsilon_{\pm} = \pm\sqrt{c^2|\mathbf{p}|^2 + |\Delta|^2}$$

**Degenerate Vacuum States:**

$$\Phi = \pm\Phi_0$$



**Domain Wall**

**Superfluid  $^3\text{He}$**

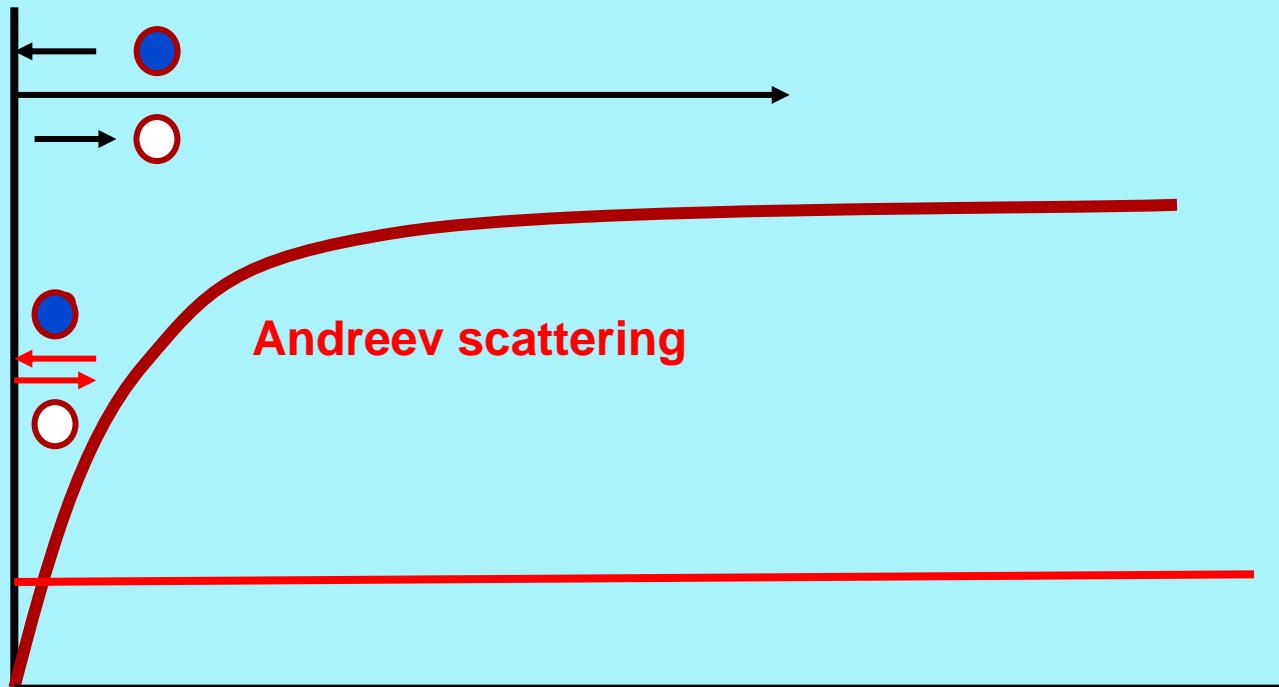
# Majorana fermions

Pis'ma v ZhETF, vol. 90, iss. 5, pp. 440–442

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Fermion zero modes at the boundary of superfluid  ${}^3\text{He-B}$

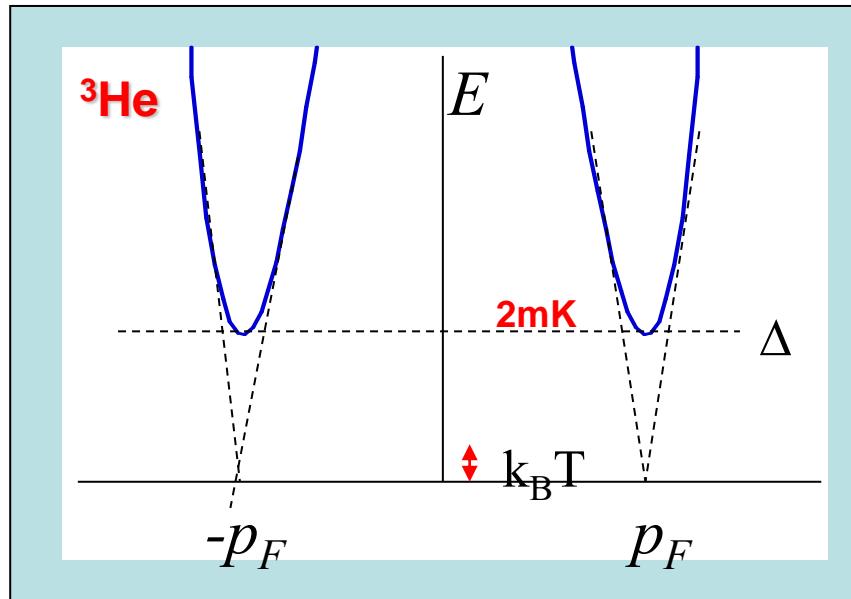
G. E. Volovik<sup>1)</sup>

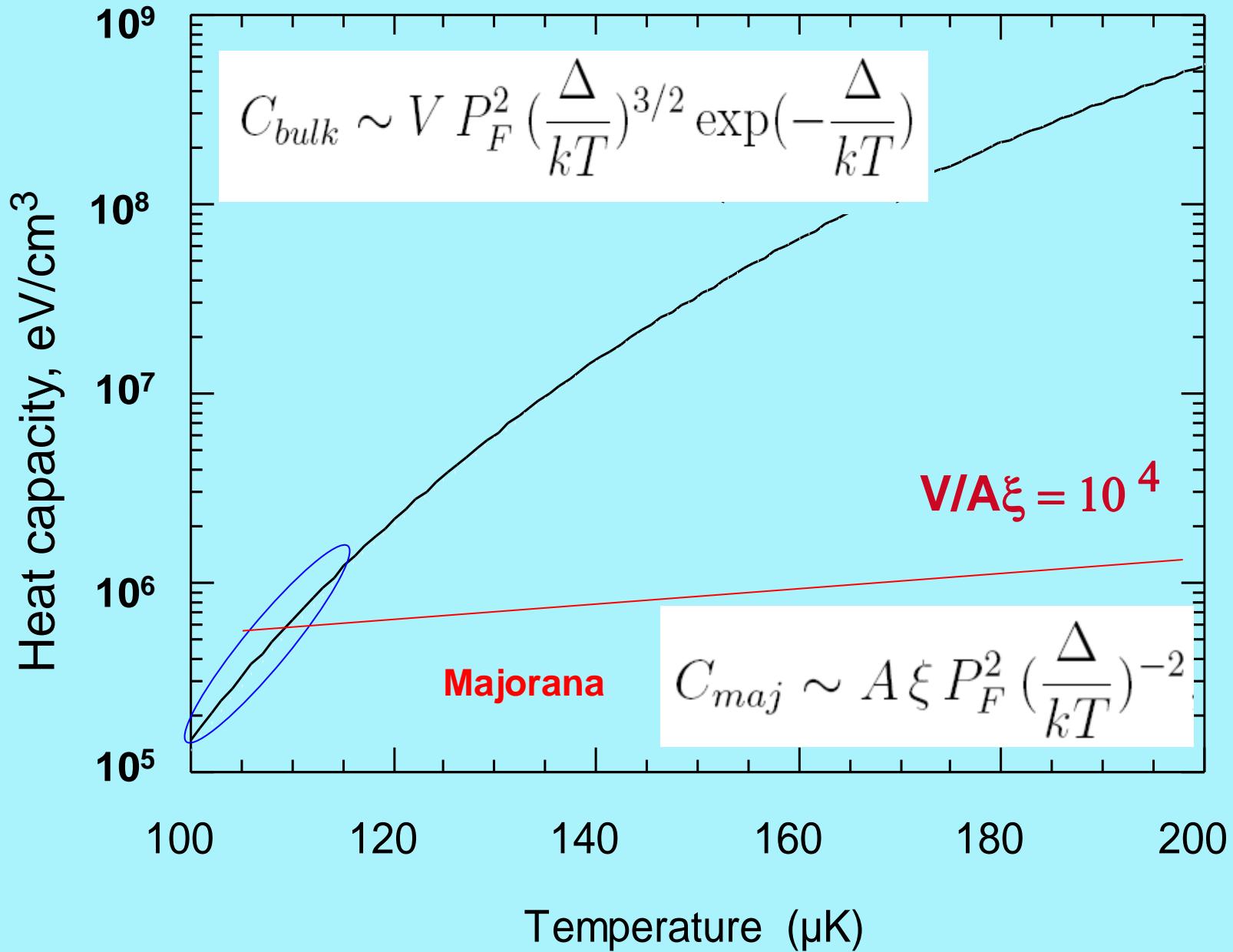


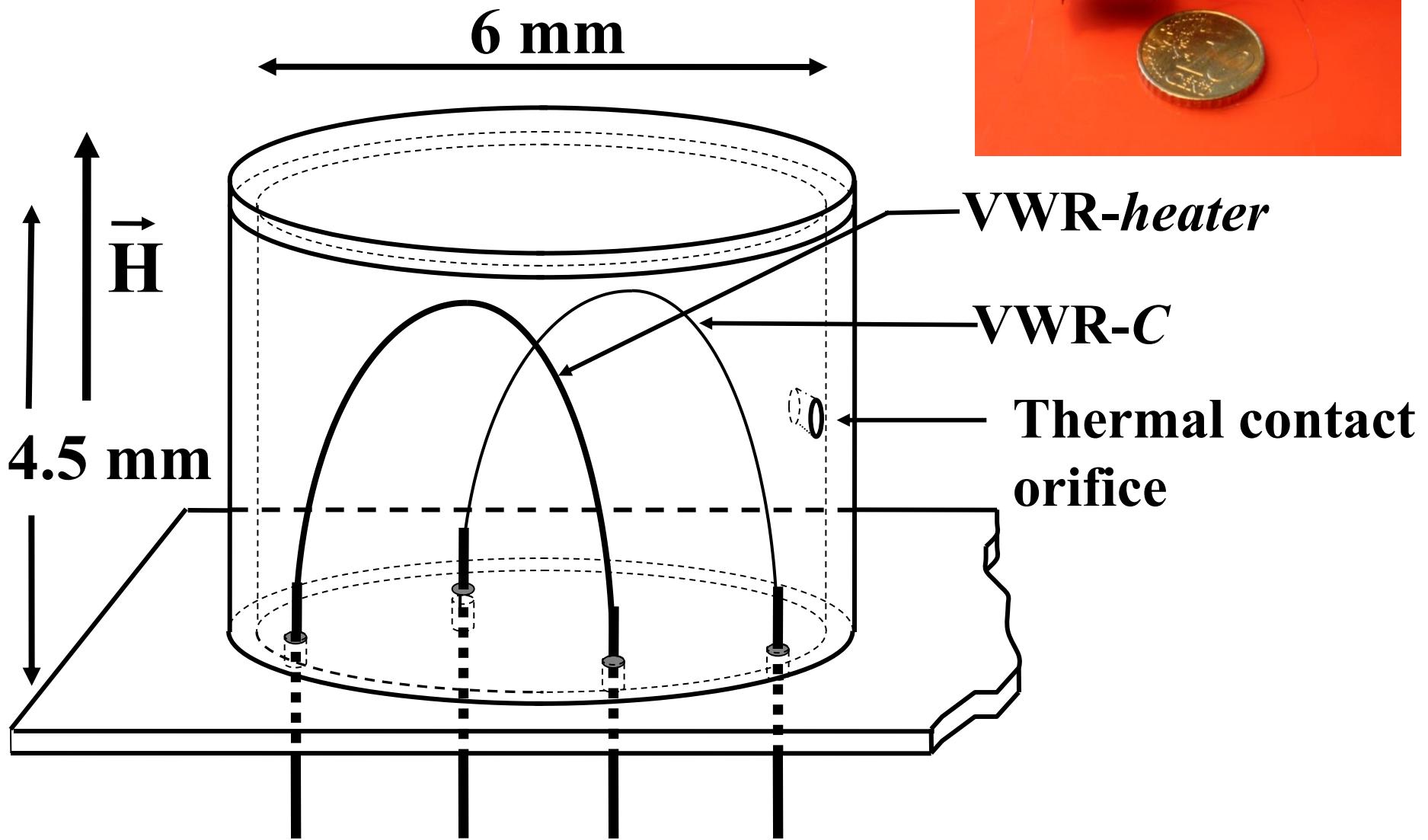
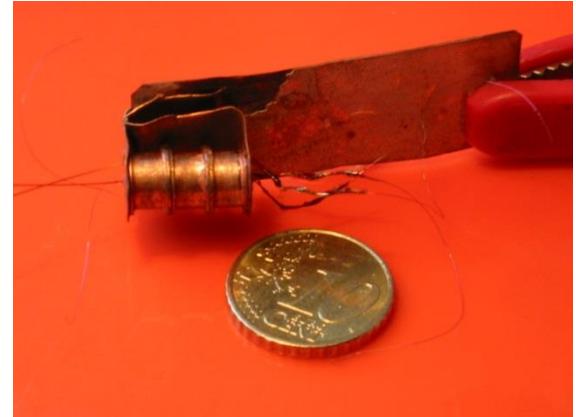
## Majorana heat capacity experiment.

C. B. Winkelmann, J. Elbs, Yu. M. Bunkov, E. Collin, H. Godfrin and M. Krusius “Bolometric calibration of a superfluid  $^3\text{He}$  detector: direct measurements of the quenching factor for neutron, electron and muonevents “Nucl. Instrum. Meth. A574, 264-271 (2007)

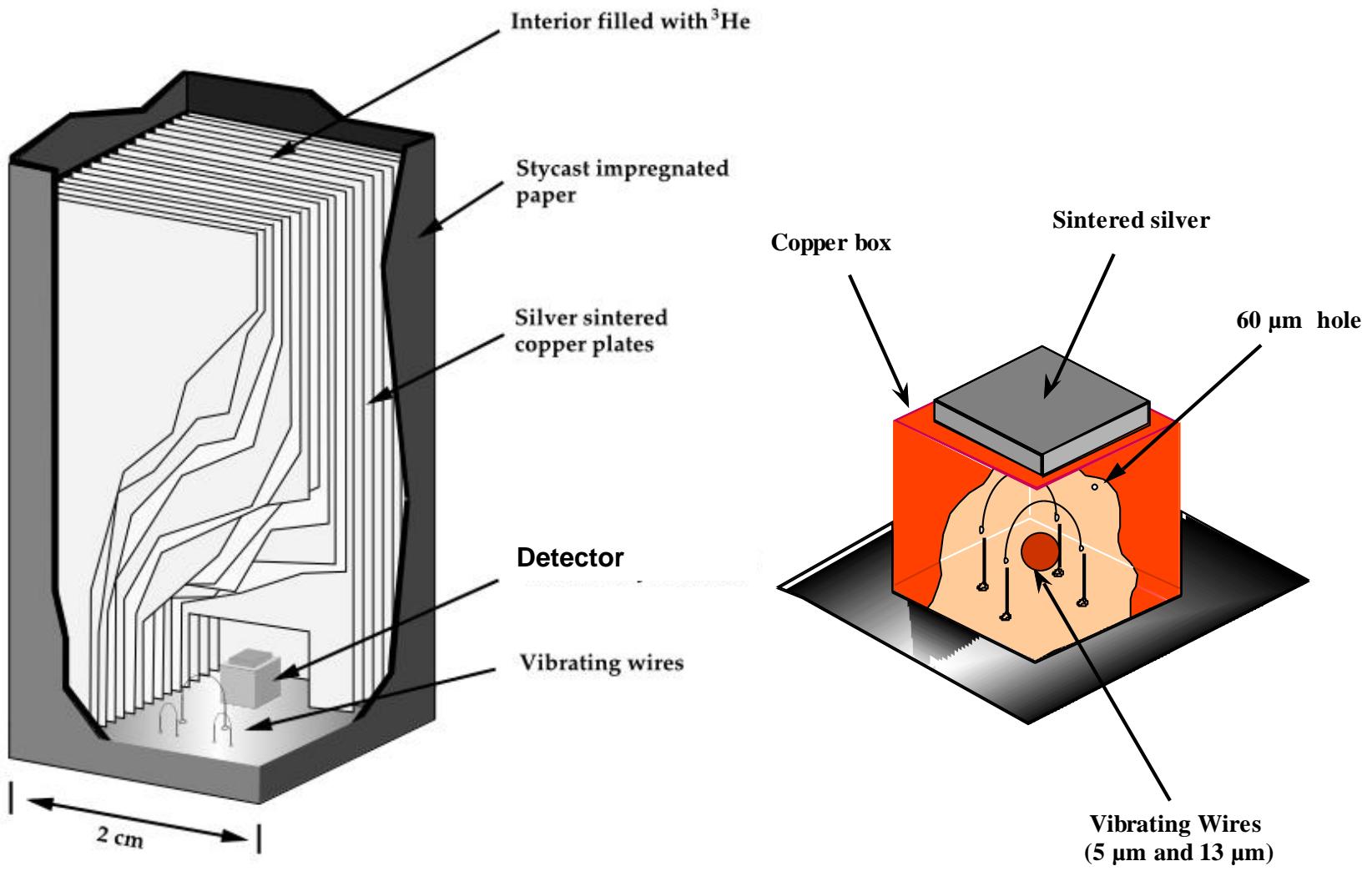
J. Elbs, Yu. M. Bunkov, E. Collin, H. Godfrin, O. Suvorova  
Electron- nuclear recoil discrimination by pulse shape analysis.  
J. of Low Temp. Phys.. 150, 536, (2008)

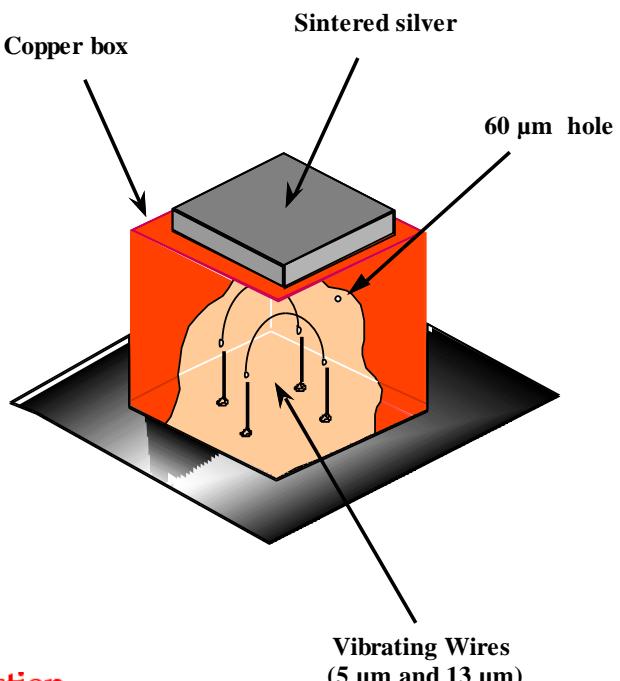




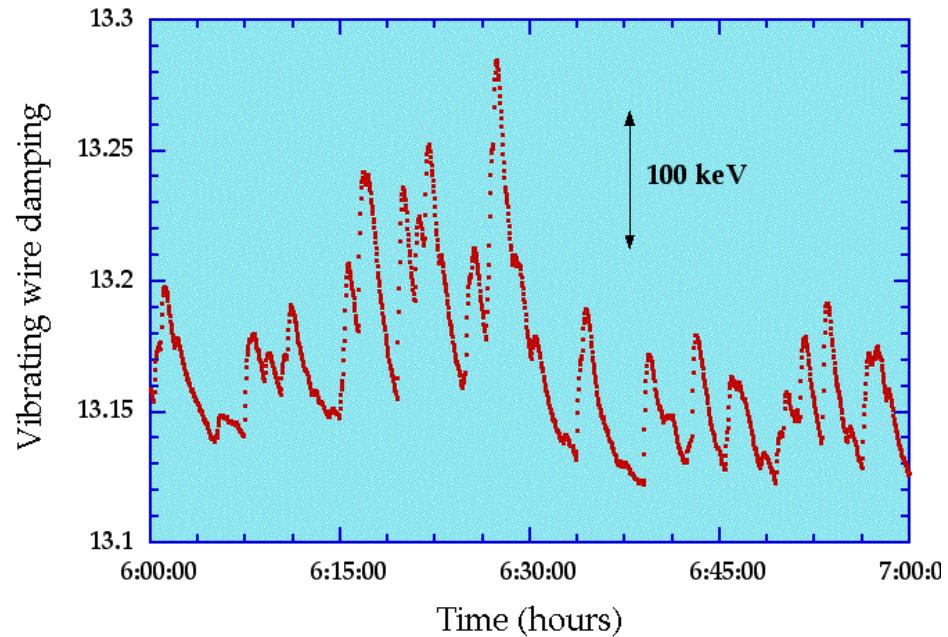


# Superfluid ${}^3\text{He}$ bolometry

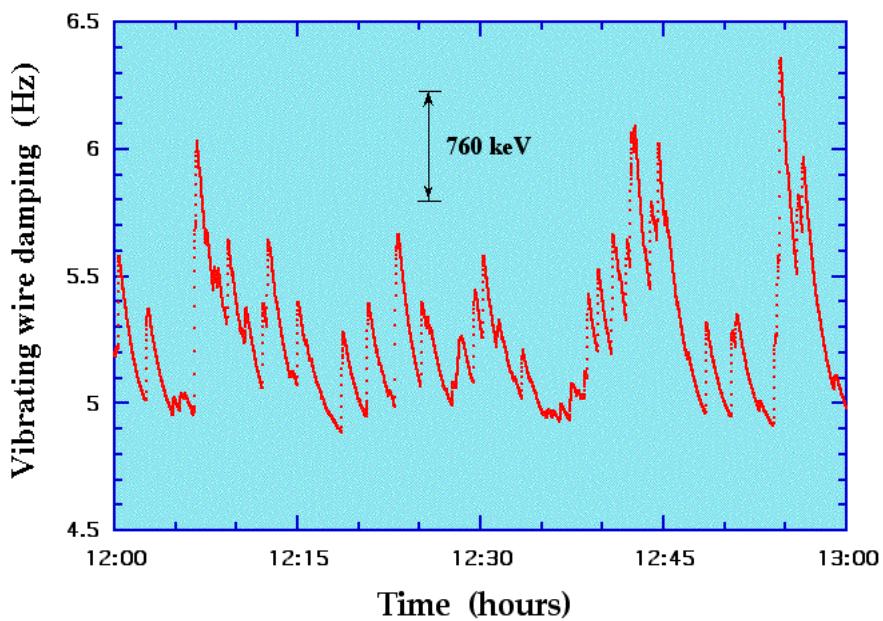




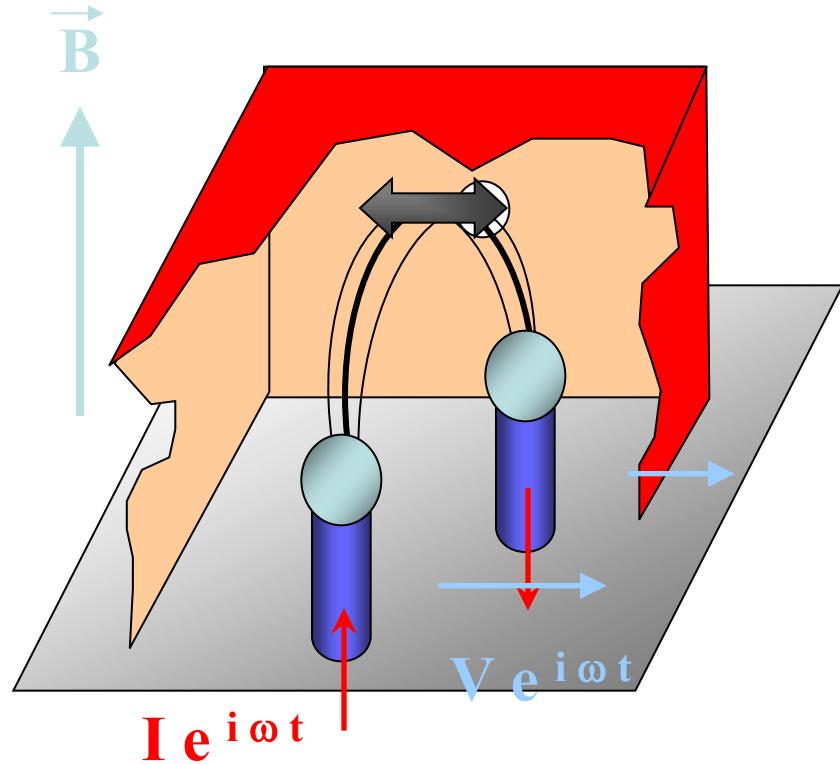
**Cosmic rays detection**



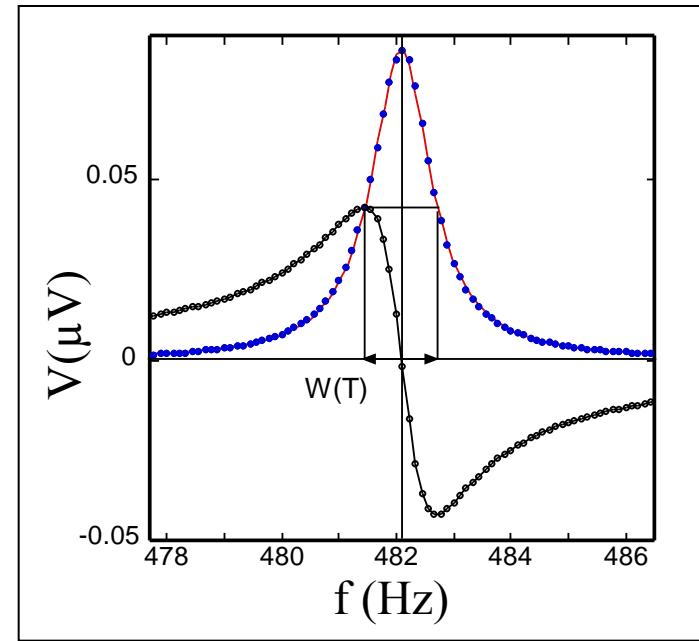
**Detection of neutrons**



# Self-calibration of ${}^3\text{He}$ bolometer

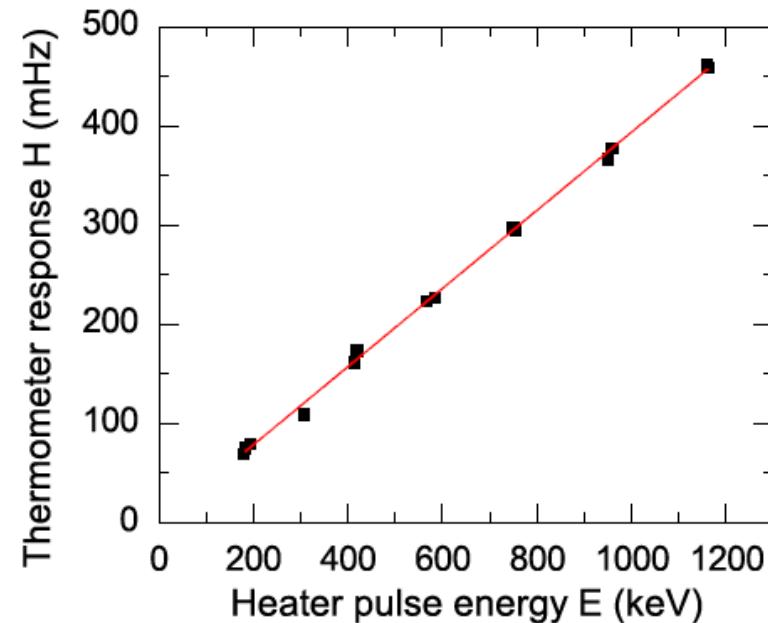
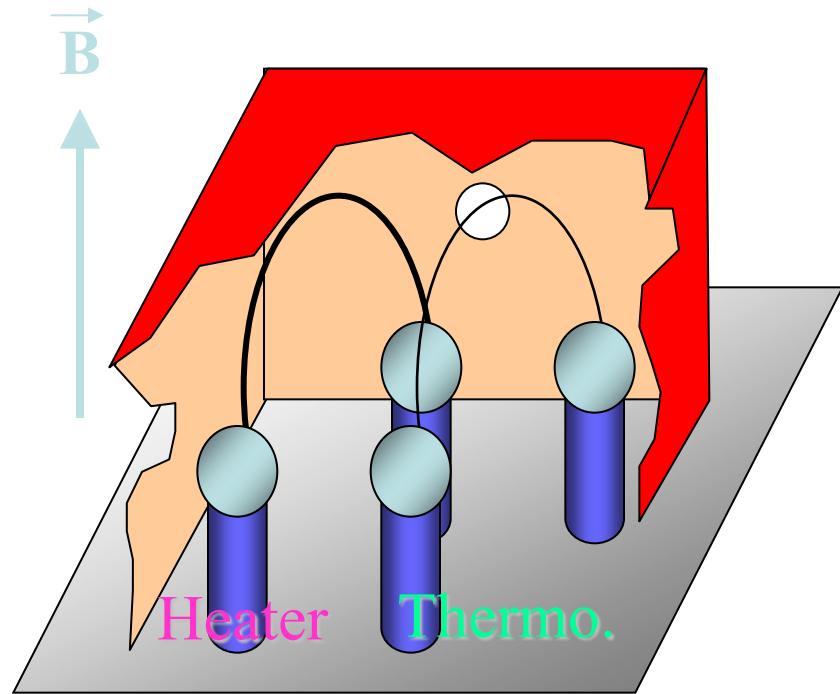


Lorentz force  
Induced voltage



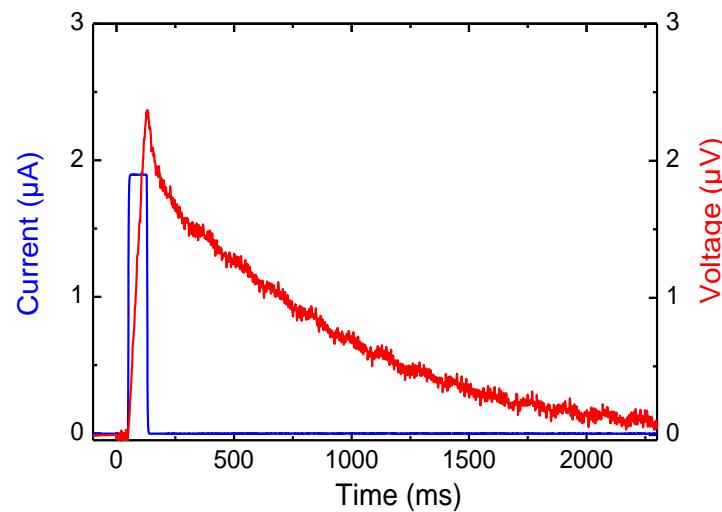
Width  $W(T)$  measures  
damping by quasiparticles  
 $H \propto 1/W$

# Self-calibration of ${}^3\text{He}$ bolometer



$$\bar{v}_g \approx \sqrt{\frac{2}{\pi}} v_F \sqrt{\frac{k_B T}{\Delta}}$$

$$\tau_b = 4 \frac{V}{S} \frac{1}{\bar{v}_g} \left( 1 - \frac{5}{16} \frac{k_B T}{\Delta} \right)$$



# Bolometric calibration by pulsed heating

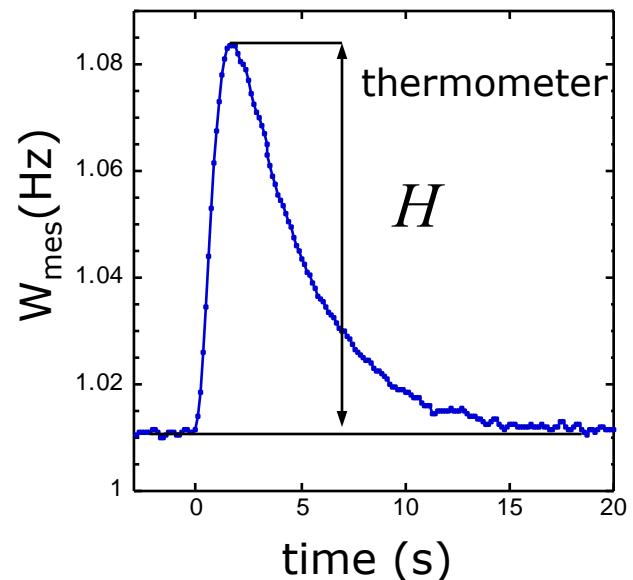
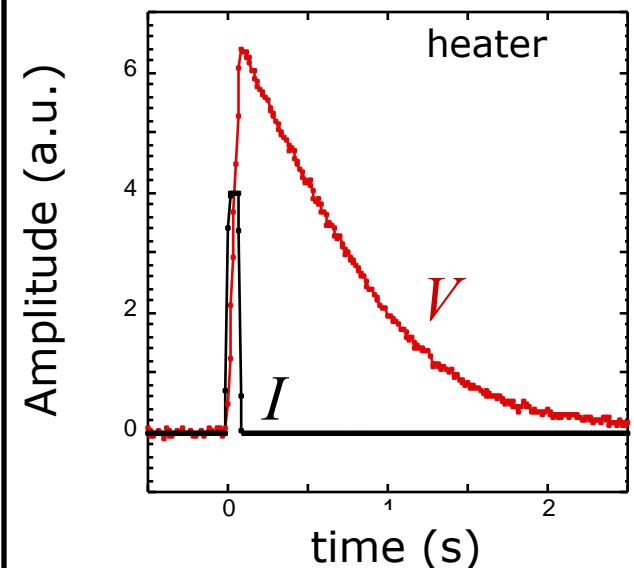
Energy injection by heater-VWR

$$\Rightarrow \text{linear dependence } H(U_{puls})$$

Bradley et al., PRL 1995; Bäuerle et al., PRB 1998

$$U_{puls} = \int V \cdot I dt$$

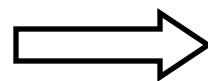
$$W_{heater} = W_{heater}^{\text{int}} + W_{heater}^{\text{ther}}$$



# Bolometric calibration coefficient

Specific heat of quasiparticle gas

$$C_{qp} = C_0 \left( \frac{T_c}{T} \right)^{3/2} \exp(-\Delta / k_B T)$$



Calibration coefficient

$$\sigma = \frac{dW}{dU} \left( = \frac{A}{\delta U} \right) \propto \frac{1}{\sqrt{T}}$$

Total enthalpy count from zero absolute

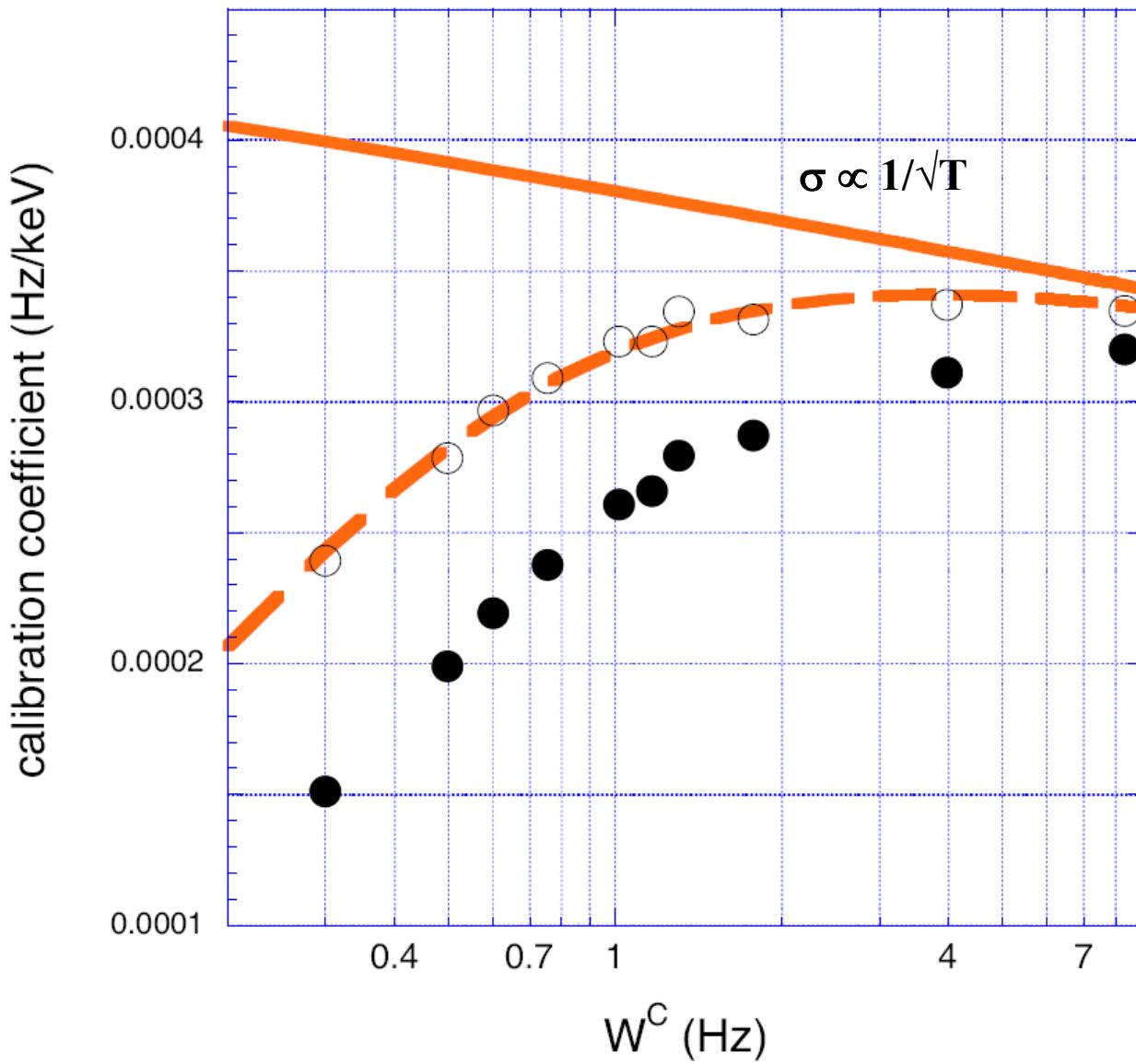
$$U \approx U_0 \left( \frac{T}{T_c} \right)^{\frac{1}{2}} \exp \left( -\frac{\Delta}{k_B T} \right)$$

$$U_0 = 1.05 \mu\text{J cm}^{-3}.$$

Vibrating Wire damping

$$W \propto \exp(-\Delta / k_B T)$$

# Bolometric calibration by pulsed heating



# Response to an instantaneous heat release

Thermal equilibrium time

$$\tau_{eq} \approx 1 \text{ ms}$$

Relaxation time of the bolometer

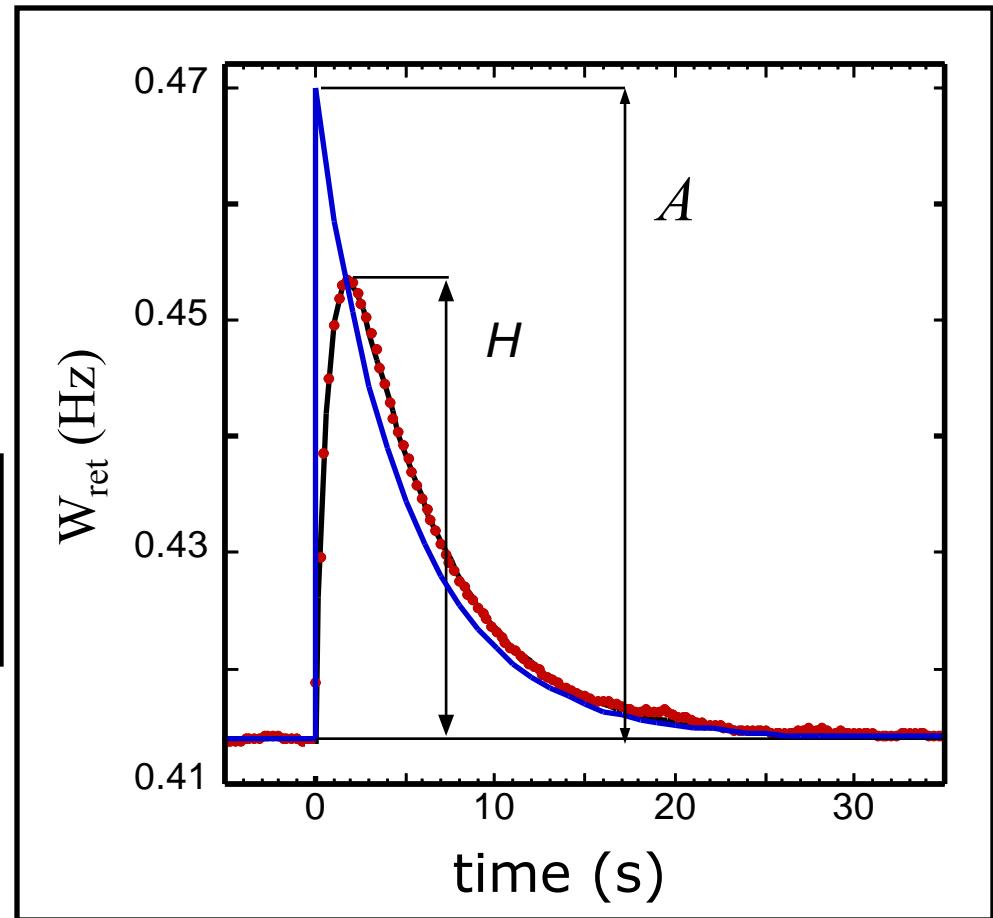
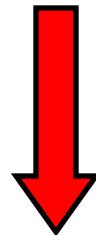
$$\tau_b \propto 1/S_{\text{orifice}} \approx 5 \text{ s}$$

Instantaneous heat release

$$W_0(t) = W_{base} + A \exp(-t/\tau_b) \theta(t)$$

Response time of the thermometer

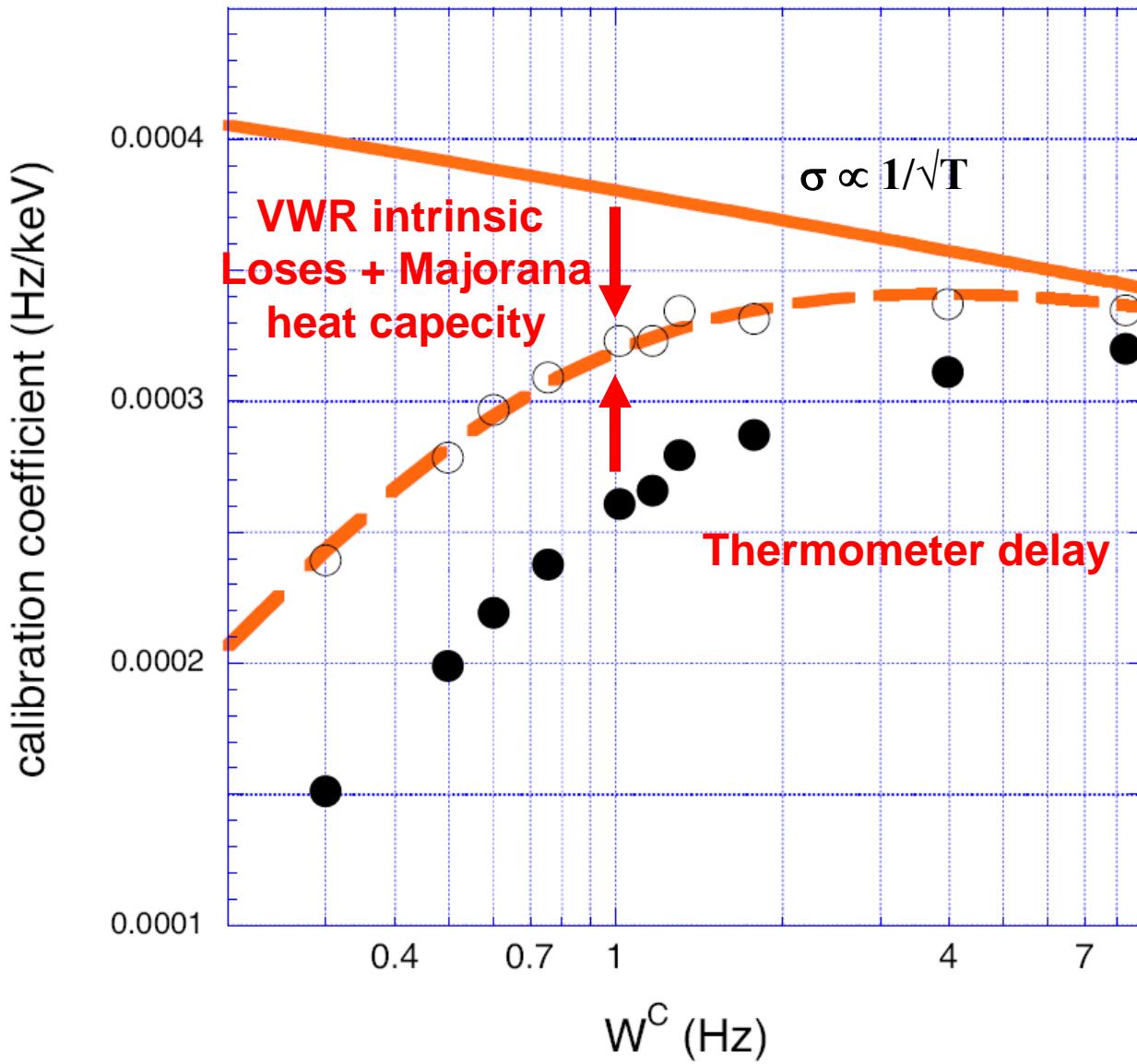
$$\tau_w = 1/\pi W$$



Dynamical response of the thermometer

$$W_{ret}(t) = W_{base} + A \frac{\tau_b}{\tau_b - \tau_w} [\exp(-t/\tau_b) - \exp(-t/\tau_w)] \theta(t)$$

# Bolometric calibration by pulsed heating



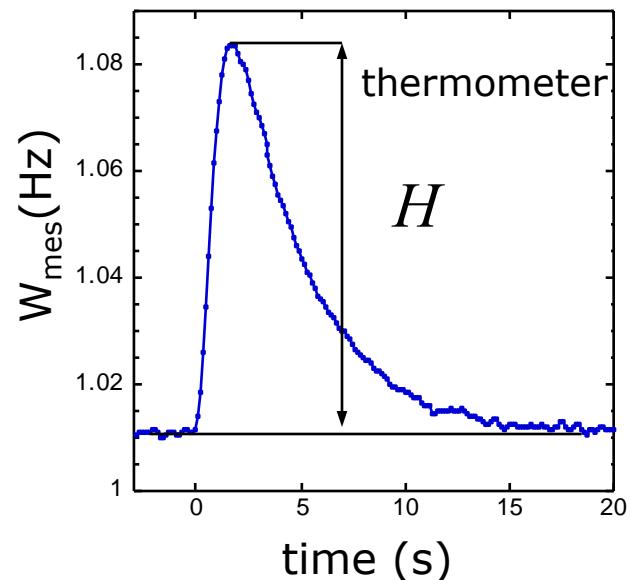
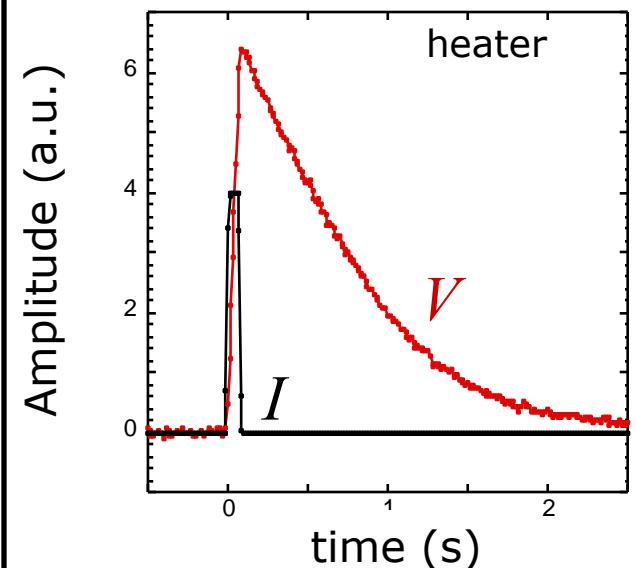
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Energy injection by heater-VWR

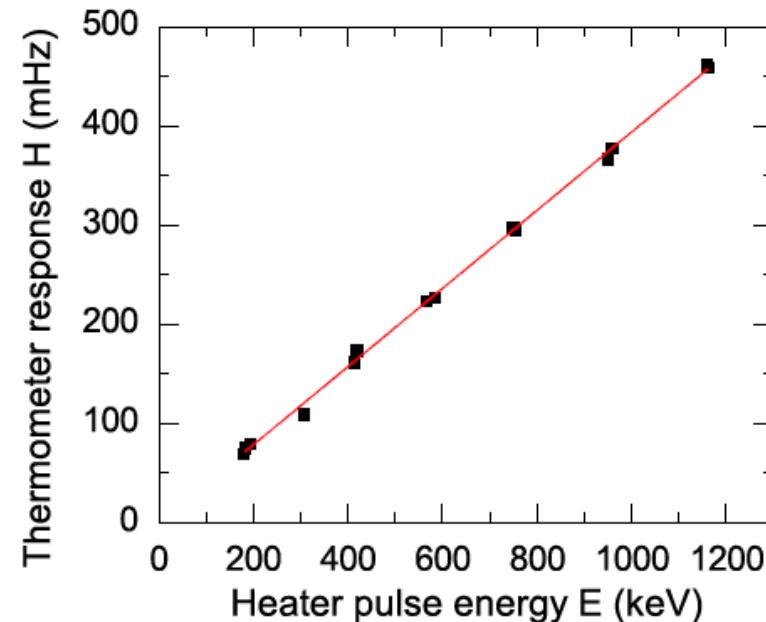
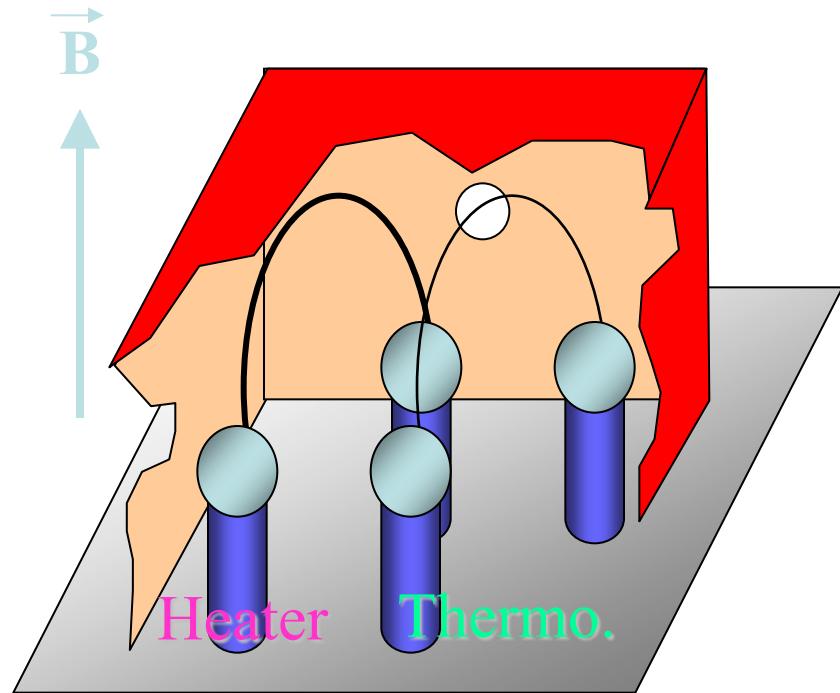
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⇒ linear dependence  $H(U_{puls})$   
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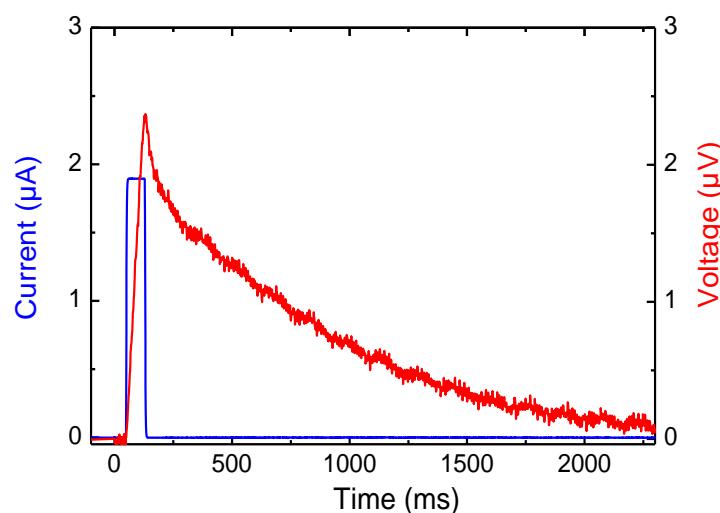


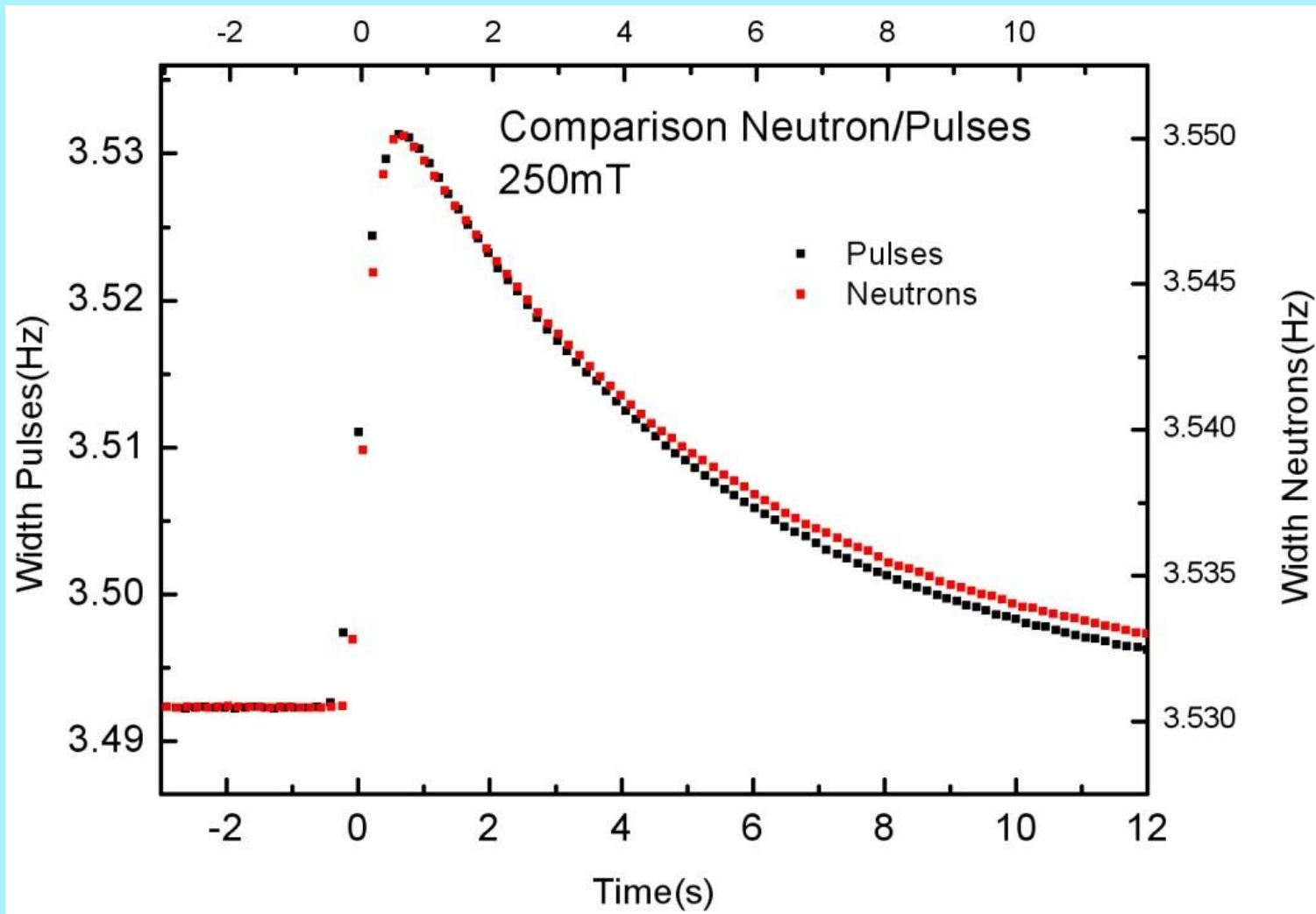
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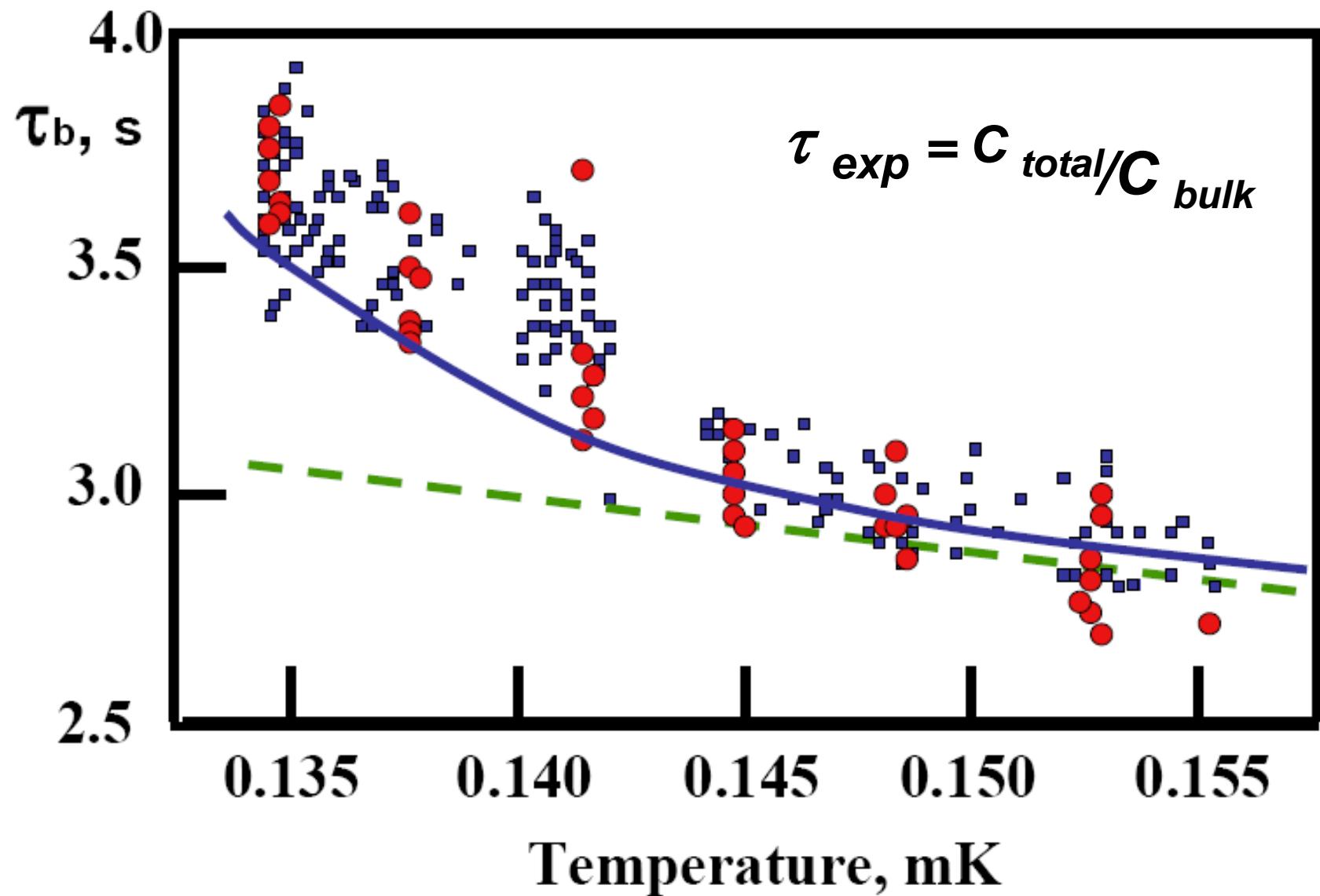


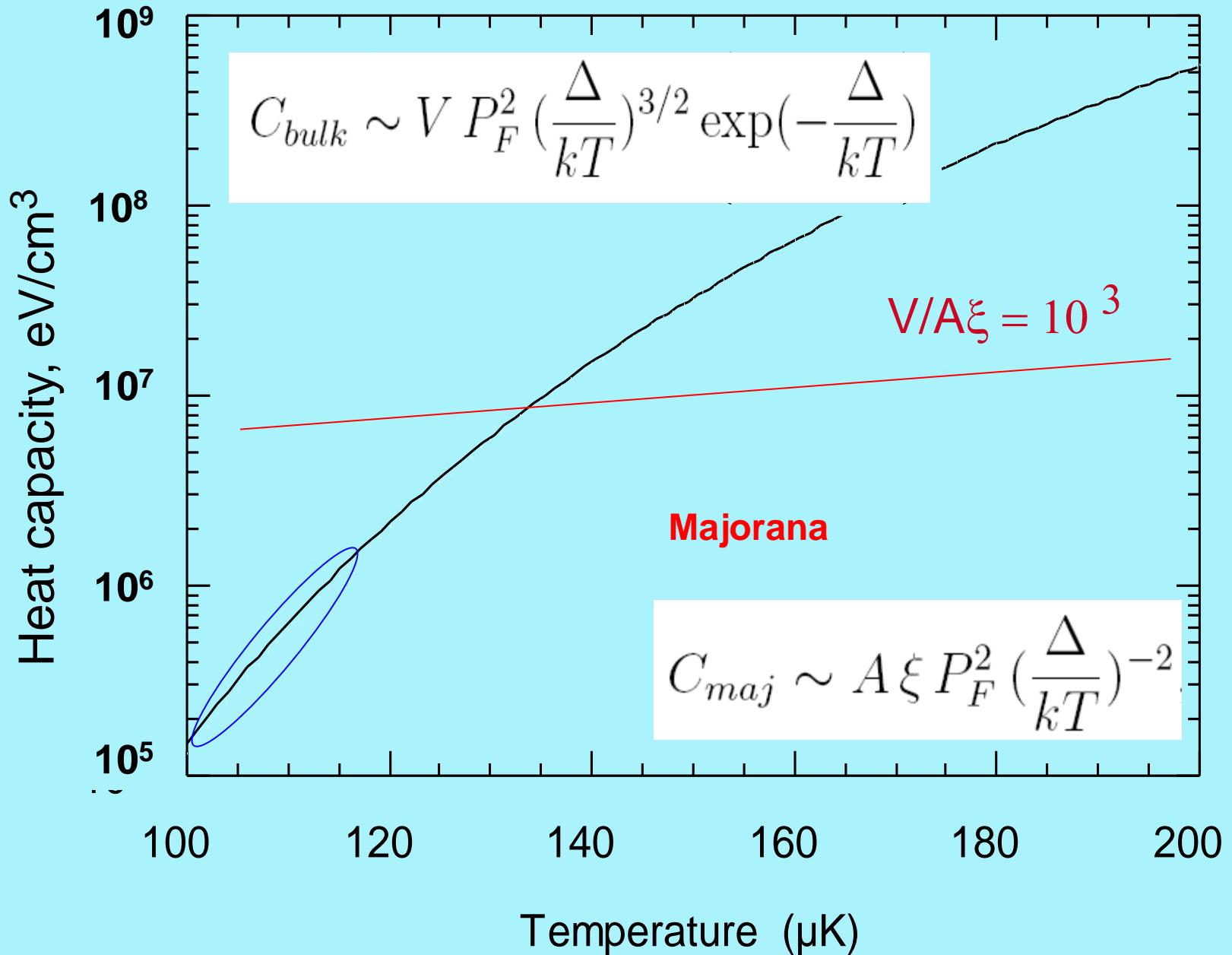
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$$\tau_b = 4 \frac{V}{S} \frac{1}{\bar{v}_g} \left( 1 - \frac{5}{16} \frac{k_B T}{\Delta} \right)$$









# Conclusions

Message from 3He-B to Standard Model: sum rule found by Nambu in 3He-B gives a hint for extra Higgs bosons

By the considered experiment the existence of low energy gapless excitations is established and measured by its heat capacity.  
They corresponds to a prediction of gapless Majorana excitations!

The further experiments with a developed surface of the walls and with different amplitude of magnetic field are desire

Acoustic investigations Review: Okuda Y and Nomura R, J. Phys.: Condens. Matter 24 (2012) 343201,

Electron bubble probe K. Kono, RIKEN.

V. Mourik et all. "Signatures of Majorana fermions in hybrid superconductor-semiconductor nanowire devices". Science. [arXiv:1204.2792](https://arxiv.org/abs/1204.2792)