Cryogenic detector system for background-free Muonium observation at temperatures below 200 mK

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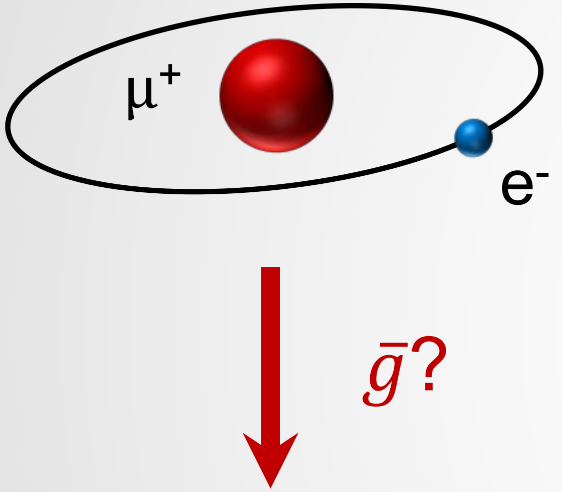
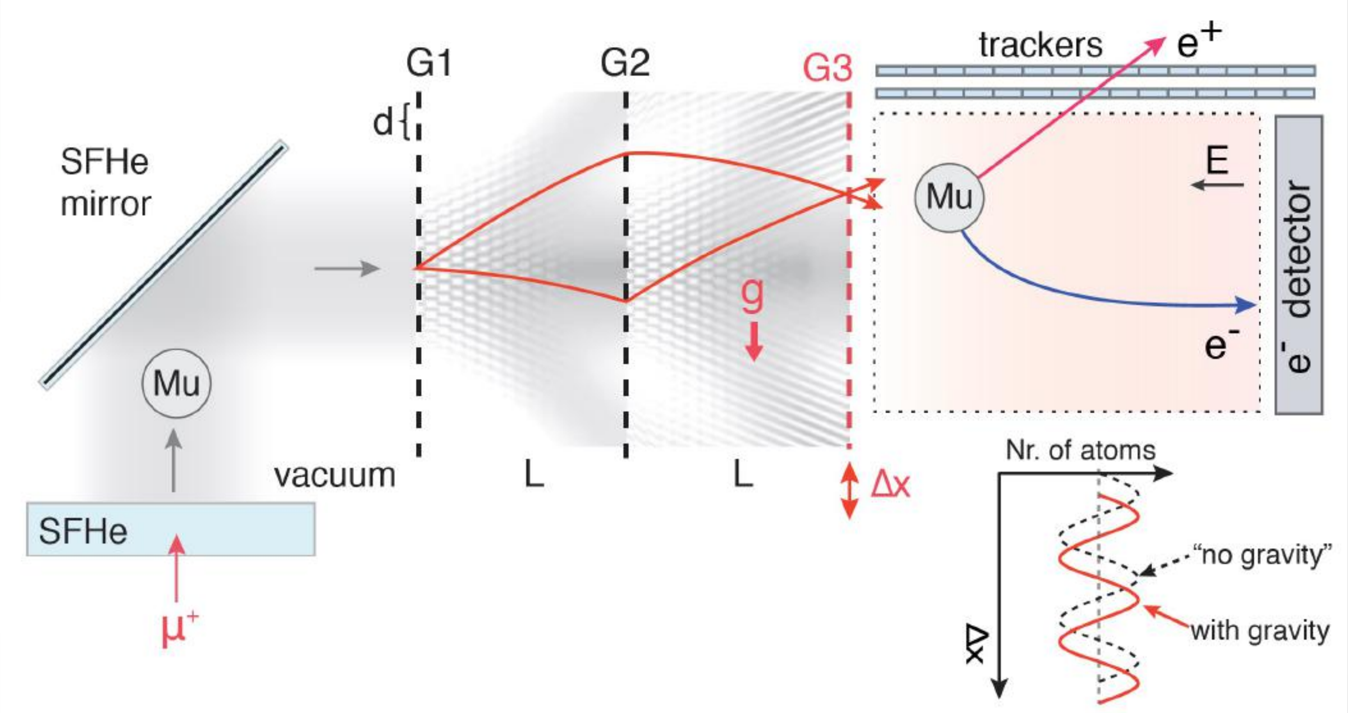
Muonium gravity experiment





Test weak equivalence principle using second generation leptonic antimatter

Mu beam

- μ^+ to vacuum Mu conversion
- low emittance
- narrow momentum distribution

Interferometry

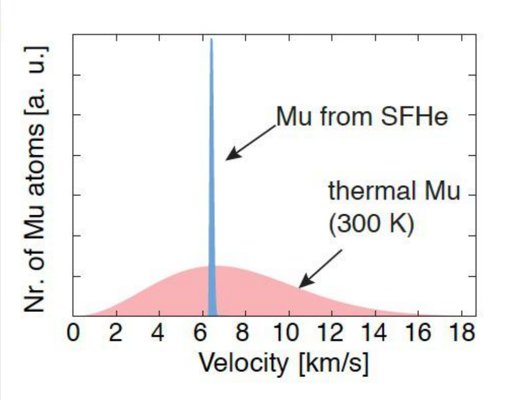
- 3-grating interferometer
- gravitational interaction shifts interference pattern

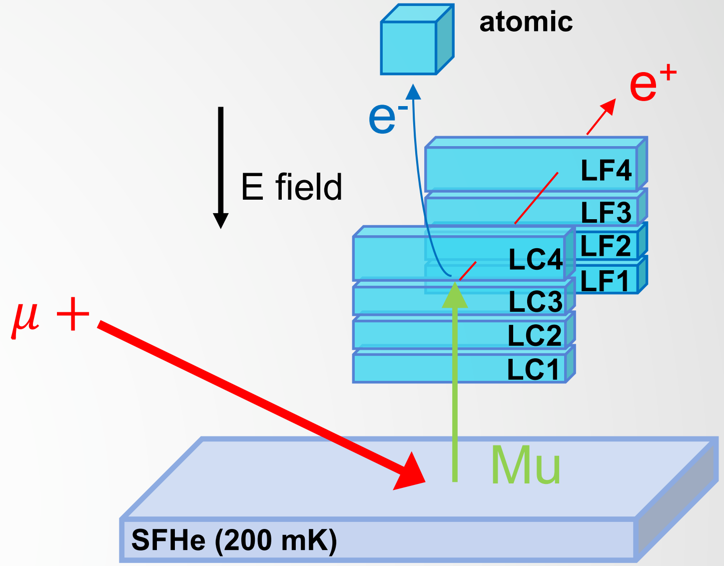
Detection

- coincidence signal of e^+ from μ^+ decay and atomic e^-

Novel atomic Mu beam from SFHe

- Mu source based on SFHe
  - Mu gravity experiment requires novel Mu beam with low emittance and narrow momentum distribution



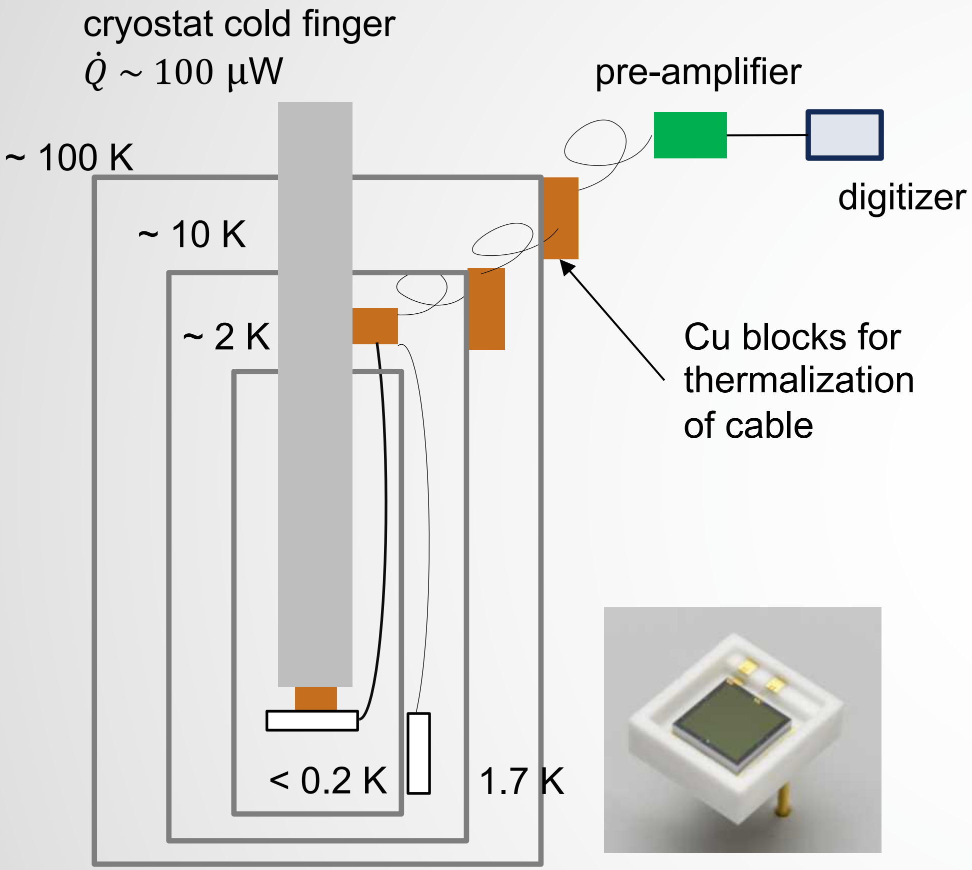


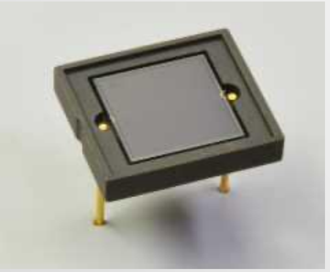
- Mu detection
  - Triple coincidence of horizontally emitted e^+ in two e^+ detectors plus signal in atomic e^- detector:
  - e.g.: LC4 && LF4 && atomic

Detector requirements:

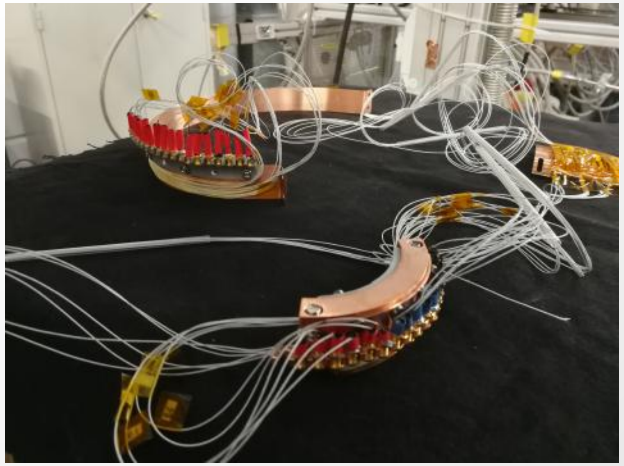
- Fast timing
- high efficiency
- high background rejection
- **Operation in cryogenic setup at T < 200 mK**

SiPM operation in dilution cryostat



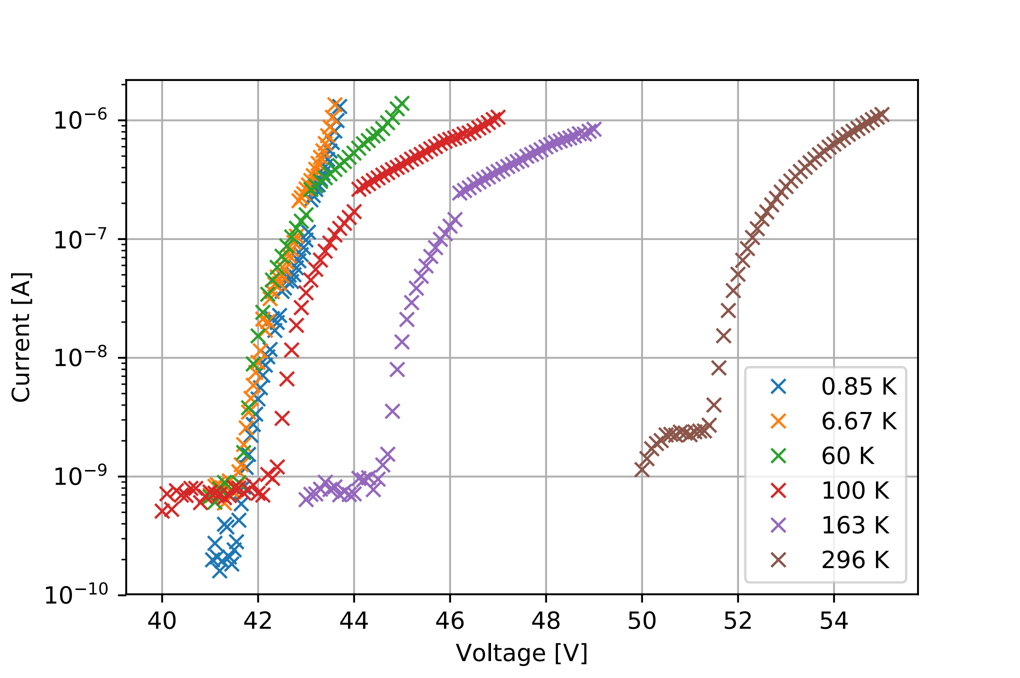


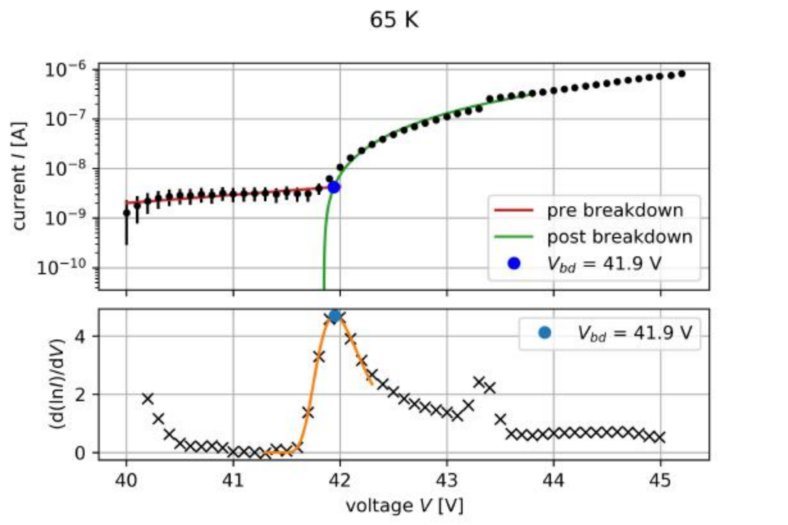
- SiPM: Hamamatsu S13370-3075CN/-6075CN
  - Pixel pitch: 75 μm, active area: 3x3 / 6x6 mm^2
  - originally for LXe, LAr scintillation (UV sensitive)
  - no window
- wiring with ~ 7 m long micro coax cable
  - AWG-38, ∅ 0.4 mm, 50 Ω
  - comprising between heat load & signal quality
  - thermalized at 3 temperature stages
  - 40dB pre-amplifier
  - DRS4 digitizer

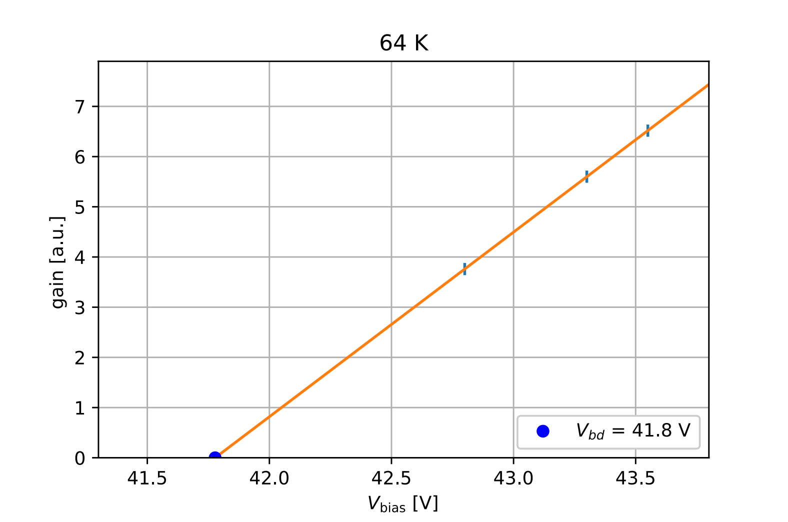


Cryogenic SiPM: Electrical characterization

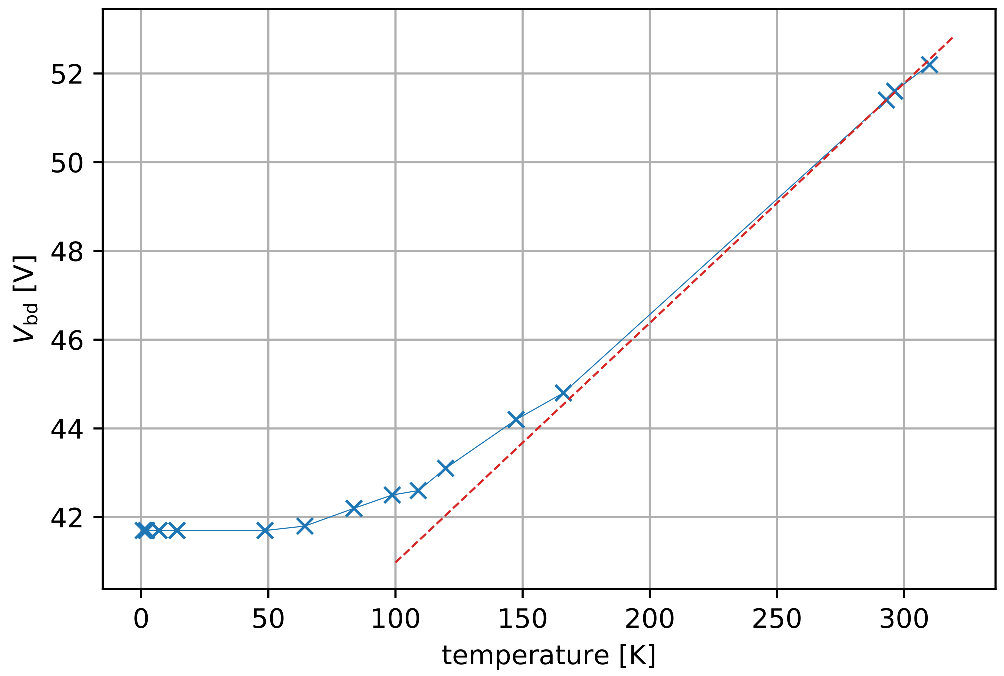
- Measure reverse IV curve under low light condition
  - linear increase up to V_{bd}, then quadratic increase
  - steeper increase after V_{bd} at low temperature
- Determine V_{bd} from
  - logarithmic derivative: Landau fit
  - gain v.s bias: linear fit

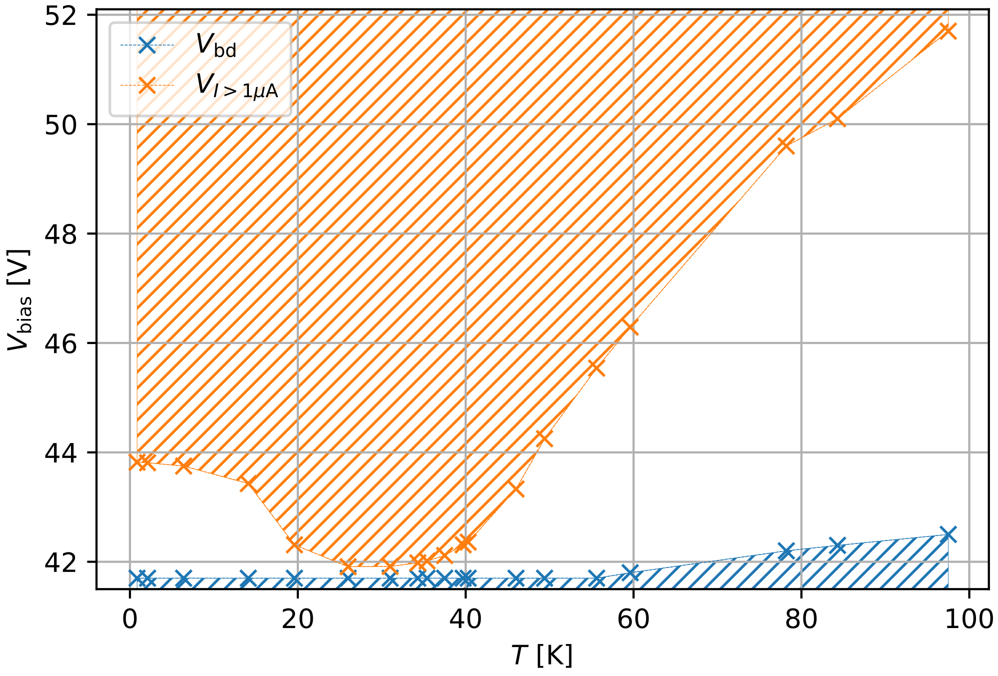






Cryogenic SiPM: Operating range

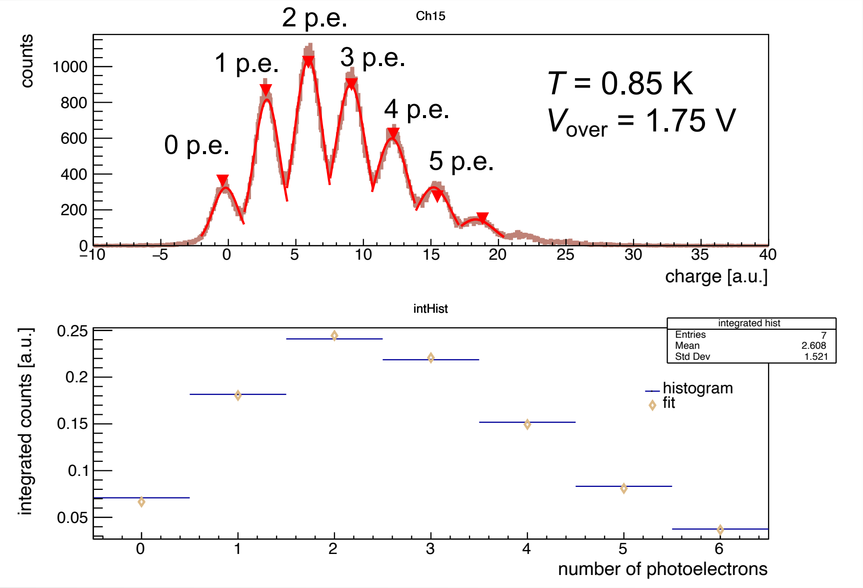




- Non-linear V_{bd} at cryogenic temperatures
- explained by Baraff's model:
  - see C. R. Crowell et al., Appl. Phys. Lett. 9, (1966)

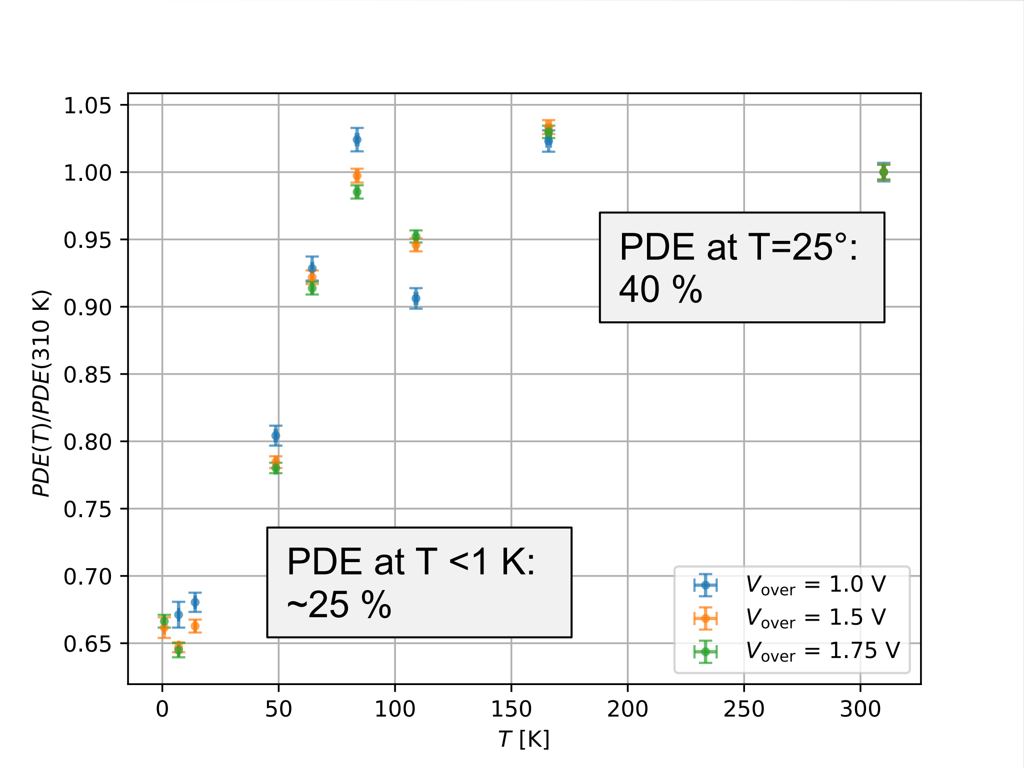
- No proper operation between 20 K and 40 K
- V_{over} limited to ~ 2 V at ultra low temperatures

Cryogenic SiPM: Single photon detection



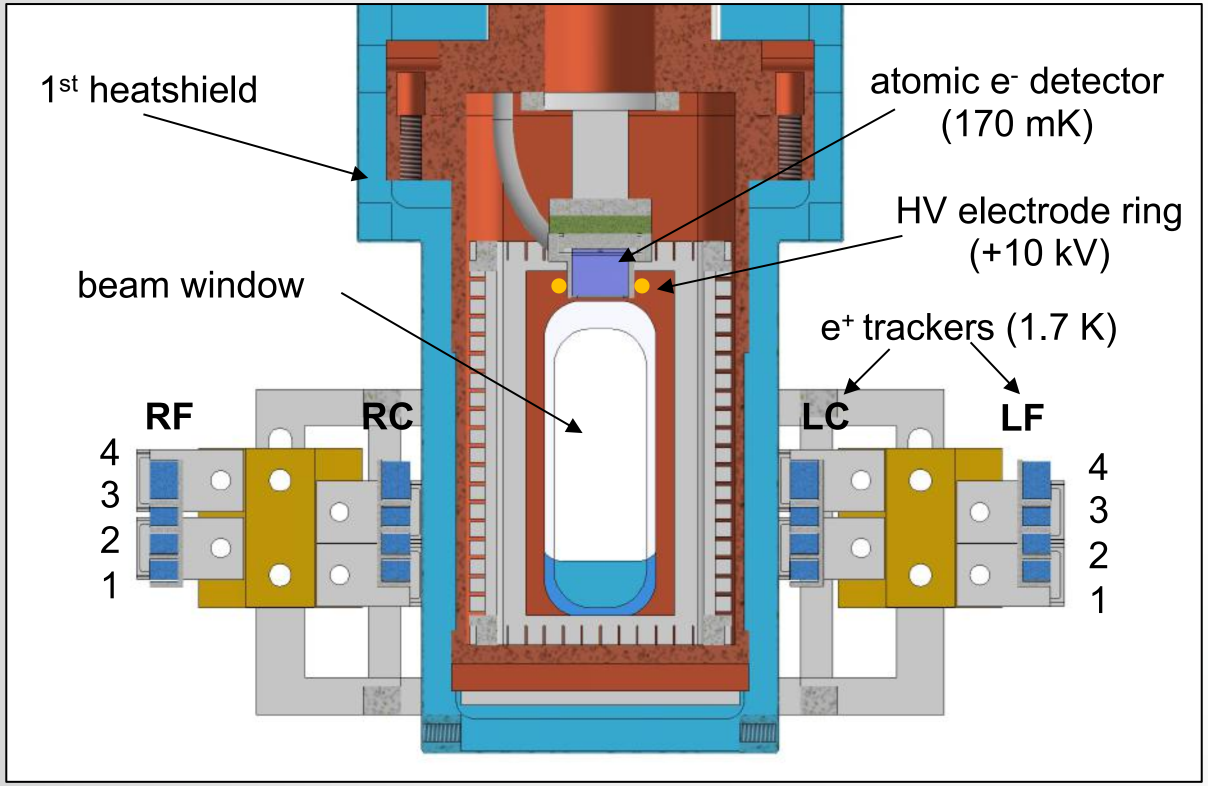
Single photon counting possible at ultra low temperatures

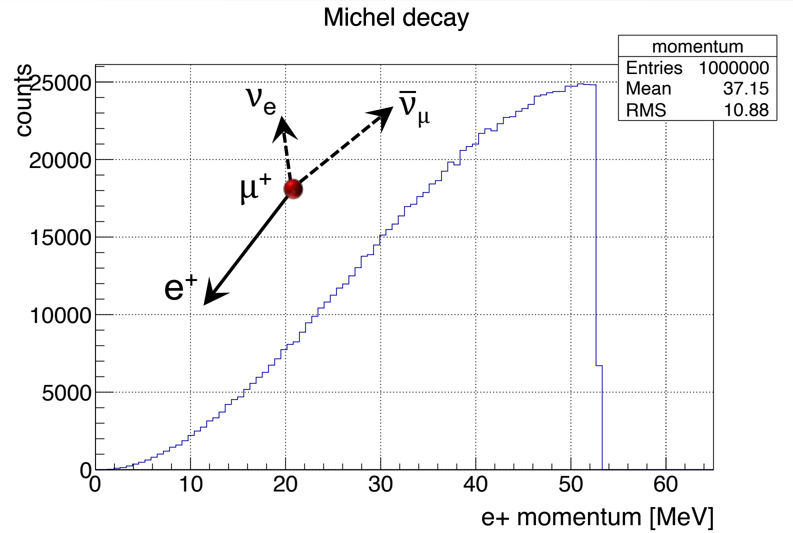
- Measure charge spectrum under low light condition
  - Photon from WLS fibre coupled to pulsed LED
- Poisson fit to estimate detected of photons
- Compare low temperature measurement to room temperature measurement



Commissioning with μ^+ beam

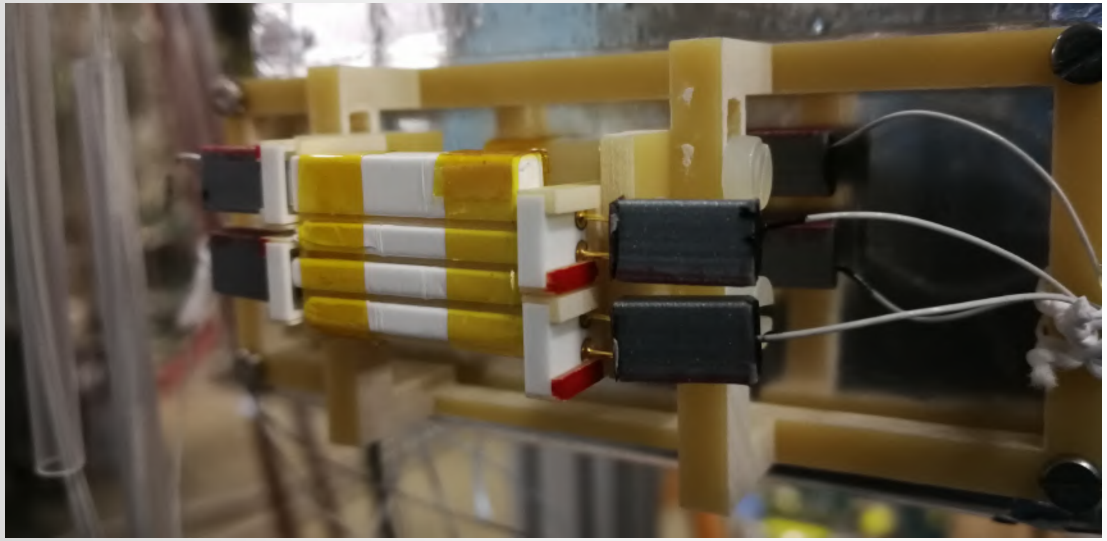
- Test detectors with muon beam at PSI
- e^+ energy from Michel spectrum



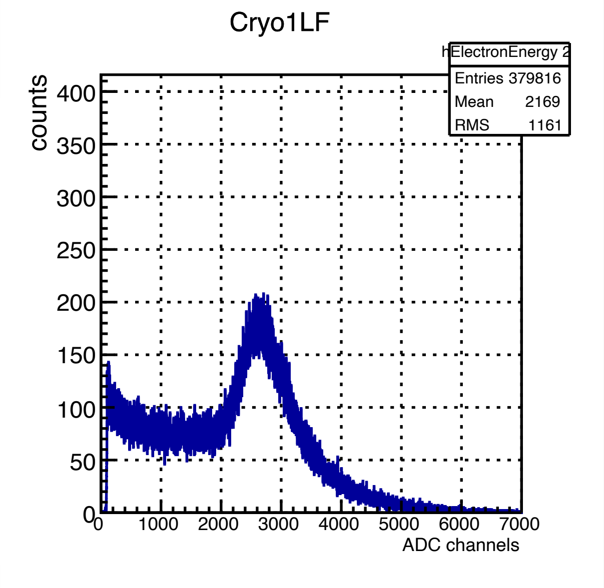


Positron detectors

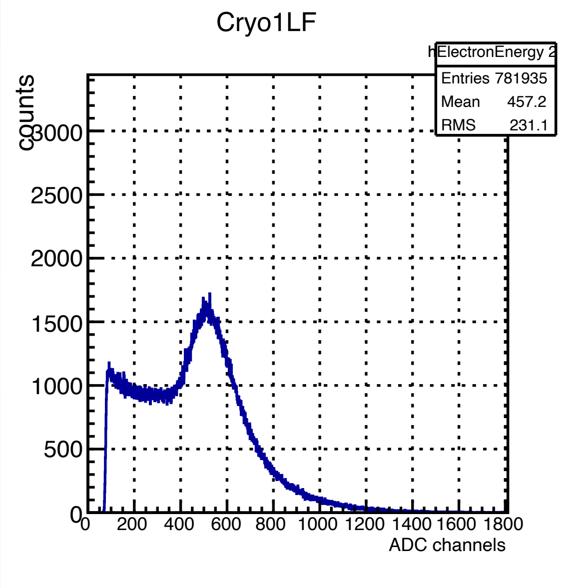
- Plastic scintillator bars
  - Eljen EJ-204, l: 20 mm, h: 3 mm, w: 2-4 mm
  - wrapped with Teflon
  - no optical cement (teared wire bonds)
  - 3D printed acrylic sleeves



296 K



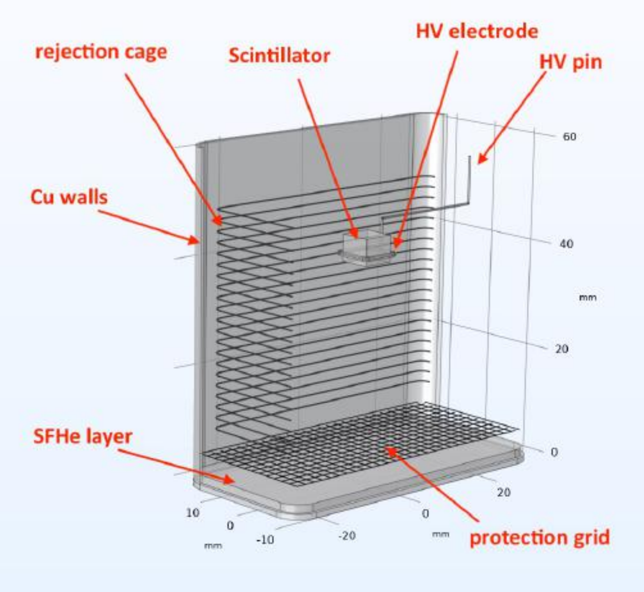
1.7 K

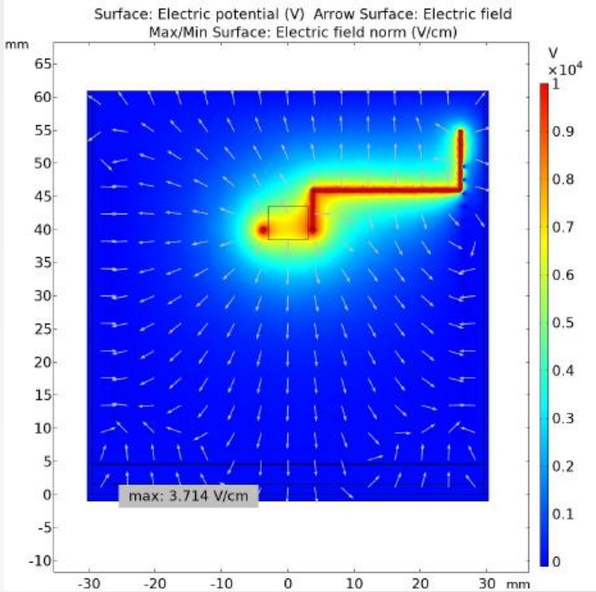


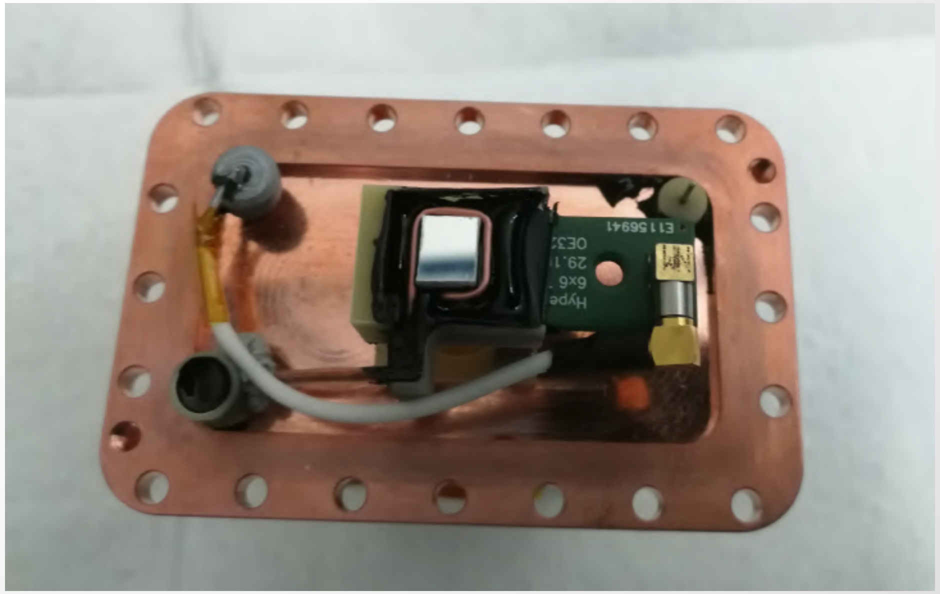
- Energy deposition in thin absorber: Landau distributed
- Lower gain in cryogenic but full peak visible

Atomic e^- detector: Design

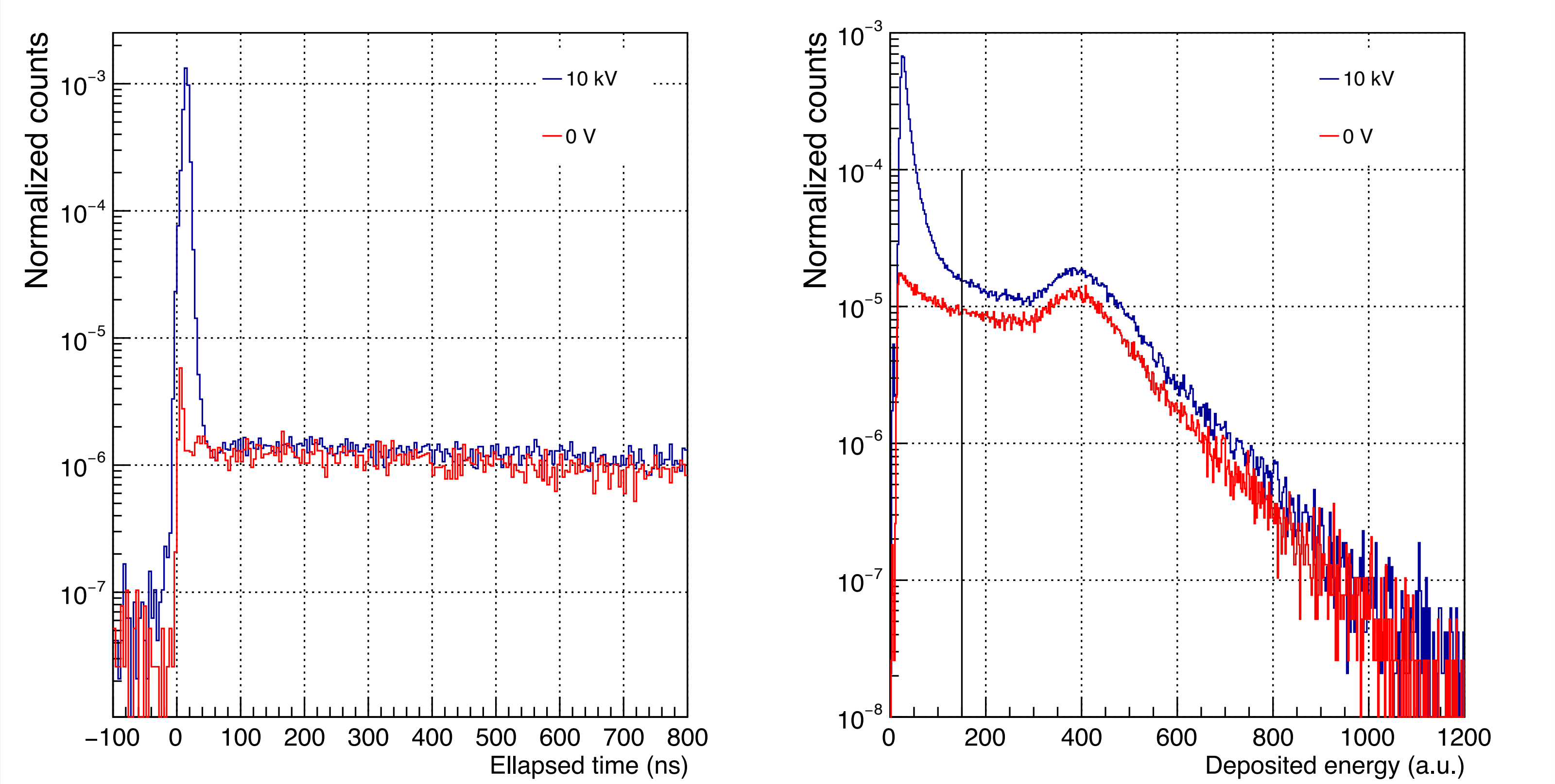
- Goal:
  - Remove muon background in positron detectors
  - coincidence detection of e^+ from μ^+ decay and atomic e^-
- Method:
  - Use HV electrode to accelerate e^- to scintillator pill
  - Detect low energy (< 10 keV) electrons







Atomic e⁻ detector: Energy and time spectrum



- Operate atomic e^- detector w/ and w/o acceleration electrode ring
- Detection of high energetic e^+ from Michel decay
- Detection of accelerated e^- liberated from Cu walls
- Atomic e^- can be detected in the cold

Michel e^+ and low energy e- detection feasible at ultra low temperatures

Summary & Outlook

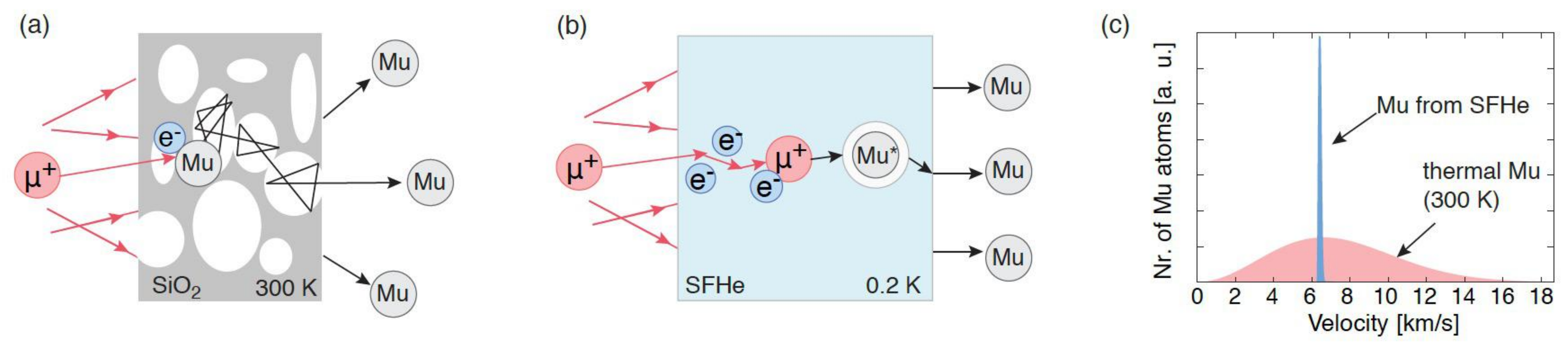
- Muonium gravity experiment aims to measure **gravitational interaction** of second generation, leptonic **antimatter**
- **Novel Mu beam** is being developed together **with cryogenic detection scheme**

- Hamamatsu VUV4 SiPMs found to be operational at T > 40 K and T < 20 K
- **SiPMs** can be **operated in dilution cryostat**, at < 200 mK temperatures
- **Single photon counting** possible at T < 1 K
- Commissioned **positron detector** with muons

- Stable operation of atomic e^- detector and physics run in September 2021

Backup

Mu formation in SFHe



present state-of-art Mu source

- porous SiO_2 structures
- 3 - 30 % vacuum Mu conversion
- thermal beam
  - large momentum distribution
  - wide angular distribution

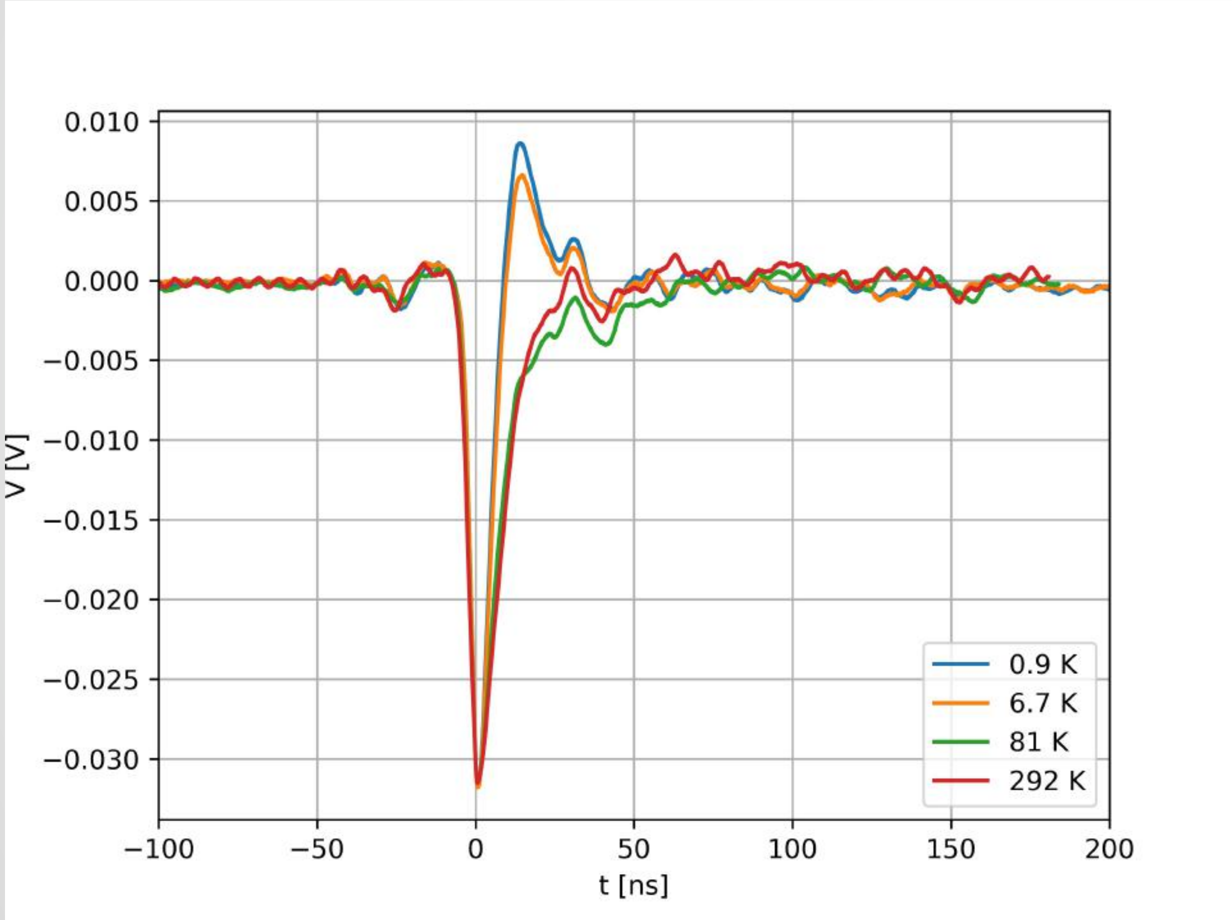
proposed SFHe Mu source

- superfluid ^{4}He
- based on high chemical potential of H isotopes Mu expected to be ejected with ~7 mm/µs velocity

high quality Mu beam

- with SFHe source: fast atomic beam with defined direction and energy

Cryogenic SiPM: Signal shape at low temperatures



- waveform has two main components
  - fast rising: cell capacitance
  - slow falling: quenching resistor R_Q
- Metallic quenching resistor with lower temperature dependence
  - Maintain pulse shape
- Increase of R_Q below 80 K leads to narrower waveform

Hamamatsu S13370 series (VUV4)

	S13370-3075 CN	S13370-6075 CN
Sensitive area / mm^2	3.0 x 3.0	6.0 x 6.0
Pixel pitch / µm	75	
Geo. fill factor / %	70	
package	ceramic	
window	unsealed	
Response range / nm	120 – 900	
Photon detection efficiency / %	40	
Operating voltage / V	V_{bd} + 4	
Dark count / Mcps	1.0 - 3.0	4.0 - 12.0
Gain	5.8 x 10^6	

see: www.hamamatsu.com,
S13370 series product datasheet (2017)