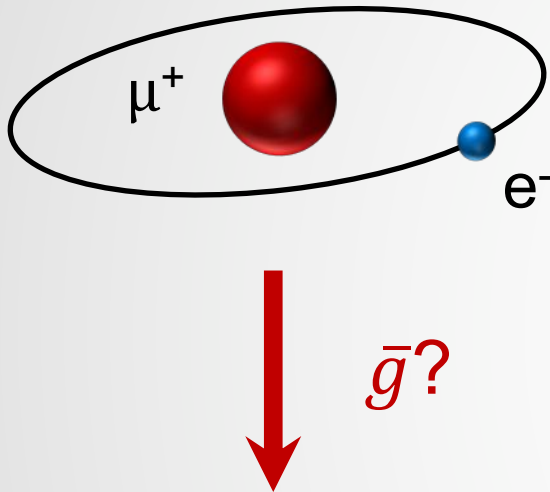


Cryogenic detector system for background-free Muonium observation at temperatures below 200 mK

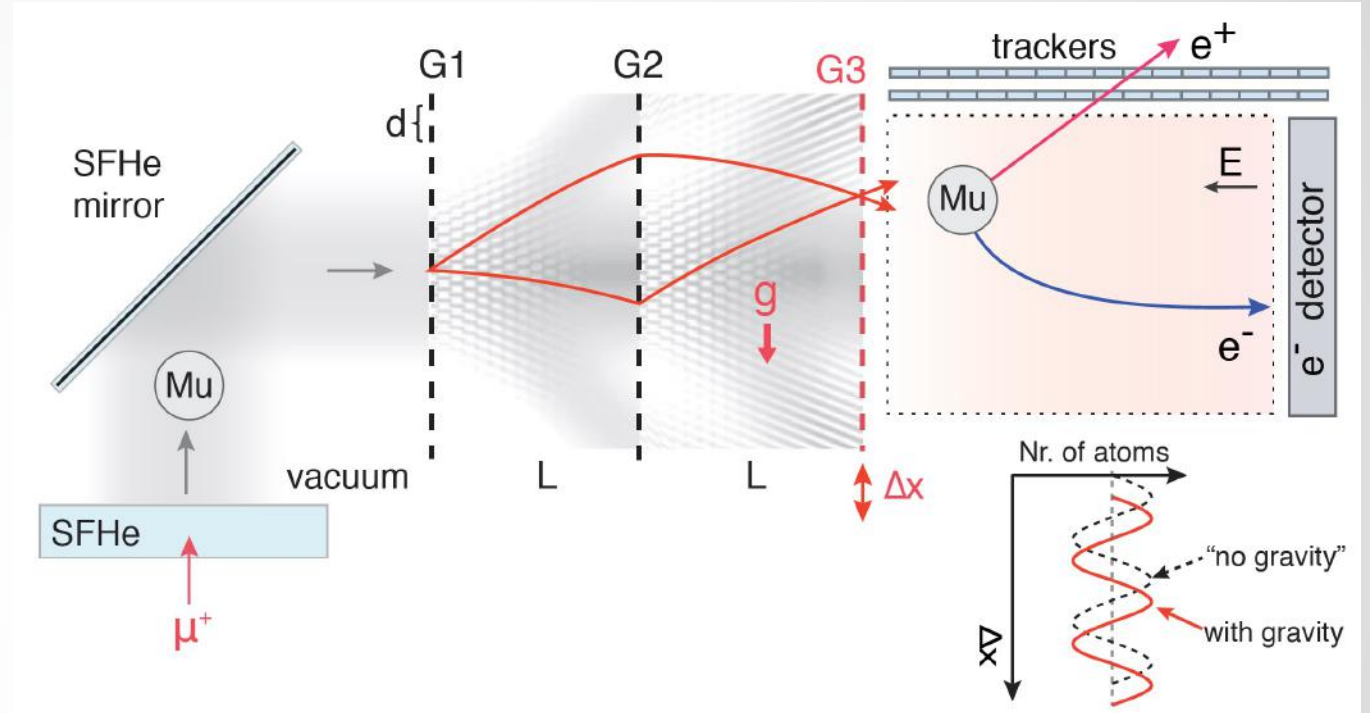
Technology and Instrumentation in Particle Physics
2021
24 – 28 May, (Virtual) Vancouver

Presented by
Jesse Zhang
Low Energy Particle Physics Group
ETH Zürich, Switzerland

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

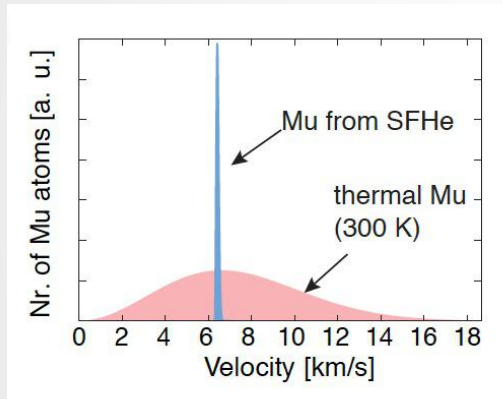
- 3-grating interferometer
- gravitational interaction shifts interference pattern

Detection

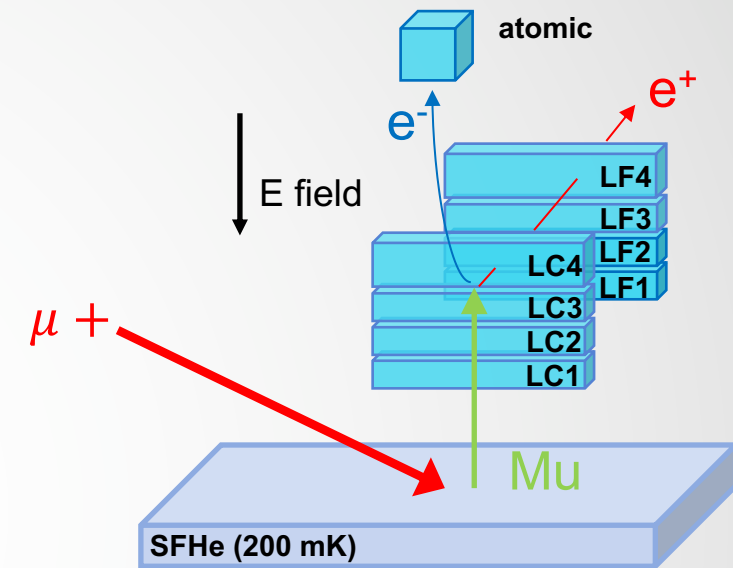
- coincidence signal of e^+ from μ^+ decay and atomic e^-

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



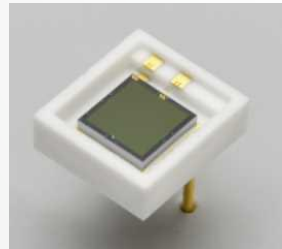
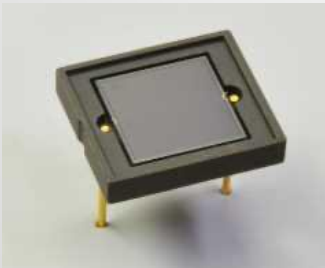
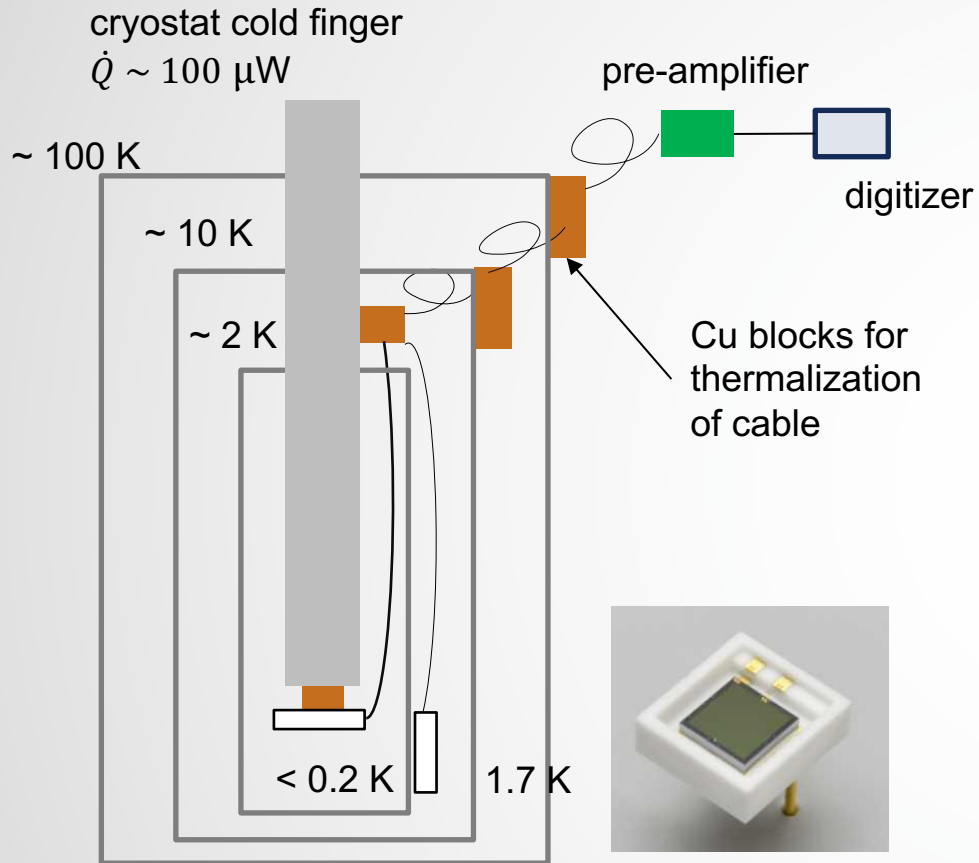
- Mu detection
 - Triple coincidence of horizontally emitted e^+ in two e^+ detectors plus signal in atomic e^- detector:
 - e.g.: LC4 && LF4 && atomic



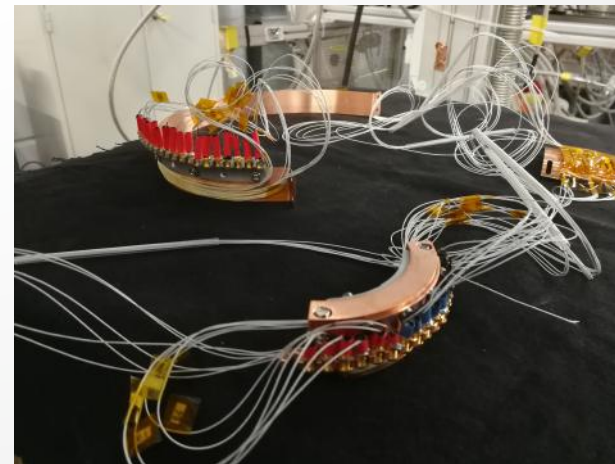
Detector requirements:

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

SiPM operation in dilution cryostat

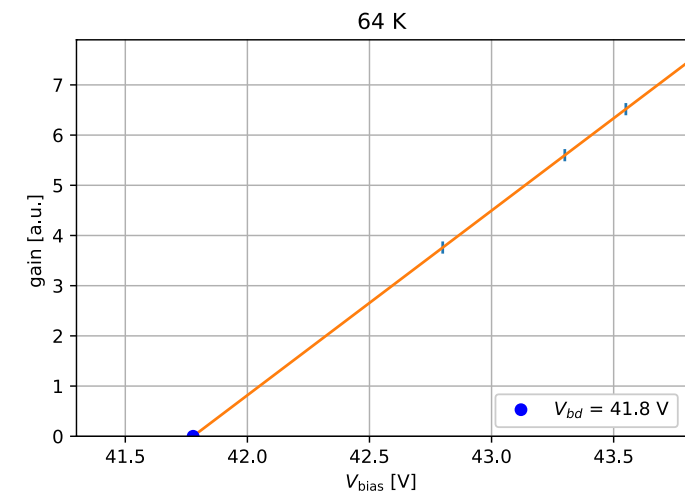
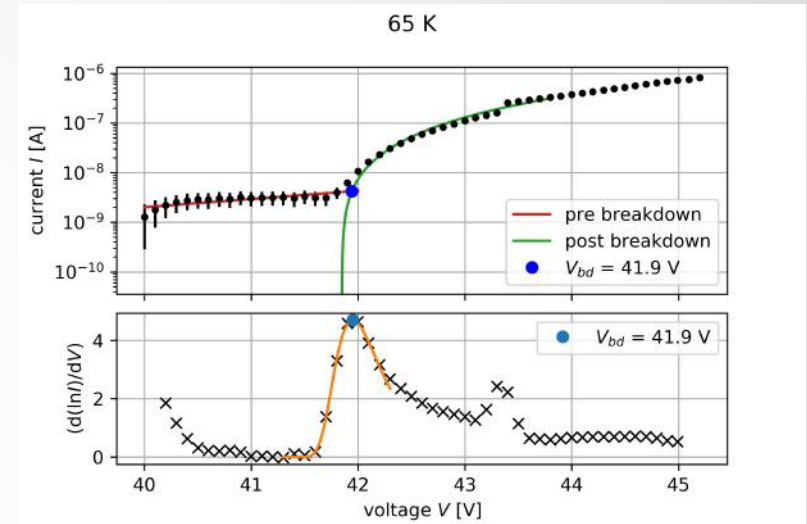
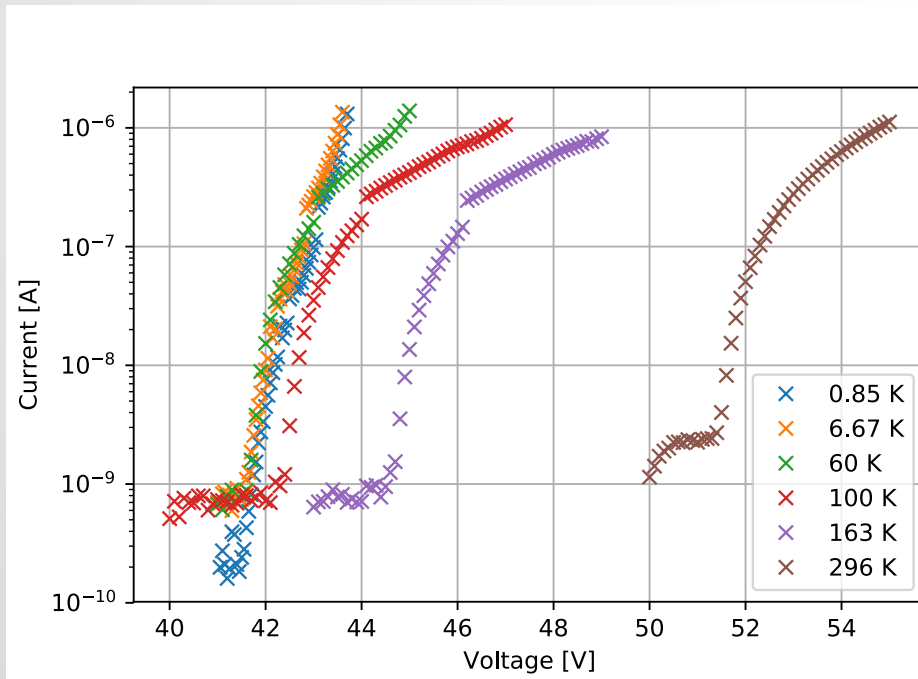


- SiPM: Hamamatsu S13370-3075CN/-6075CN
 - Pixel pitch: $75 \mu\text{m}$, active area: $3 \times 3 / 6 \times 6 \text{ mm}^2$
 - originally for LXe, LAr scintillation (UV sensitive)
 - no window
- wiring with $\sim 7 \text{ m}$ long micro coax cable
 - AWG-38, $\varnothing 0.4 \text{ mm}$, 50Ω
 - comprising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

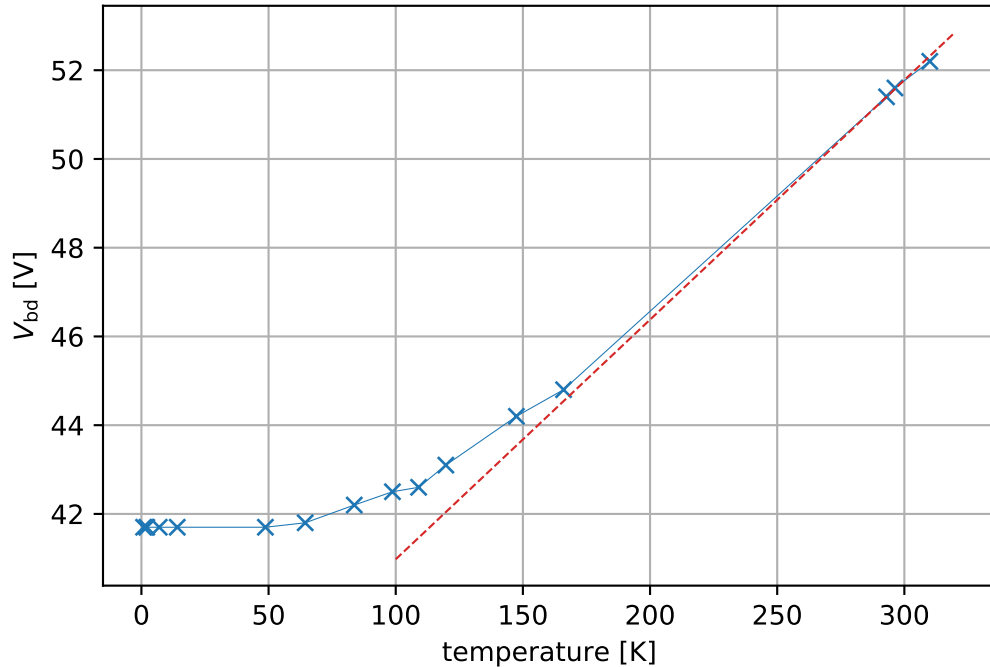


Cryogenic SiPM: Electrical characterization

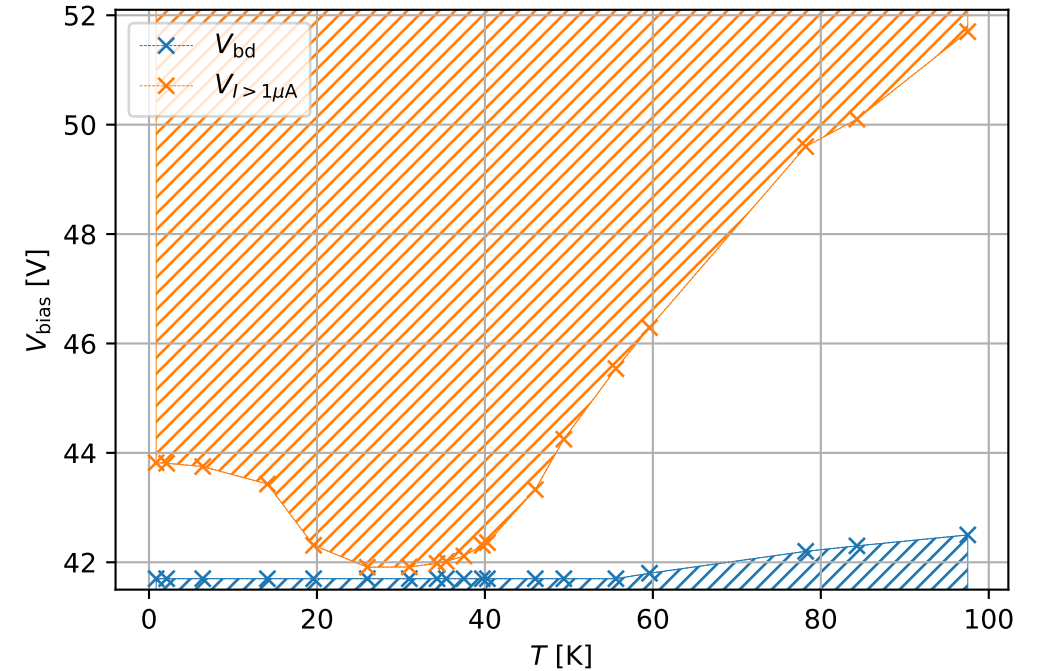
- Measure reverse IV curve under low light condition
 - linear increase up to V_{bd} , then quadratic increase
 - steeper increase after V_{bd} at low temperature
- Determine V_{bd} from
 - logarithmic derivative: Landau fit
 - gain v.s bias: linear fit



Cryogenic SiPM: Operating range

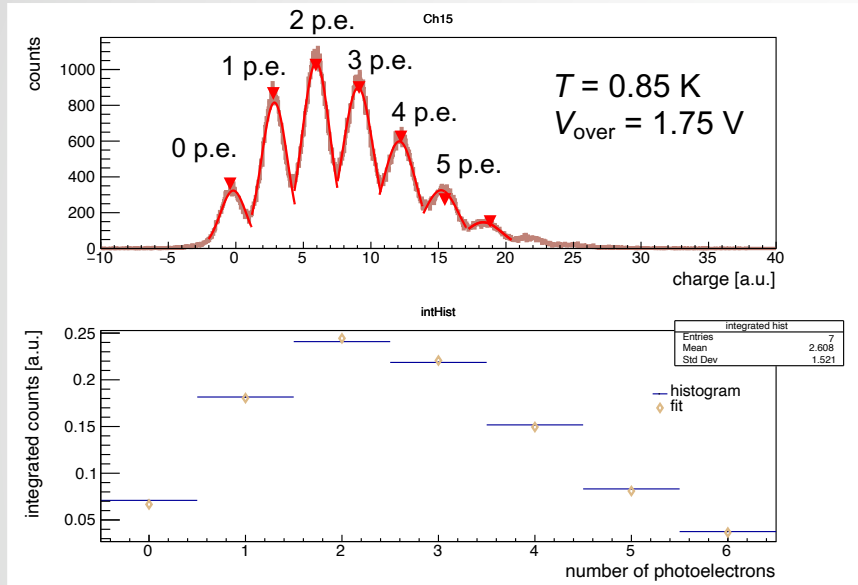


- Non-linear V_{bd} at cryogenic temperatures
- explained by Baraff's model:
 - see C. R. Crowell et al., Appl. Phys. Lett. 9, (1966)



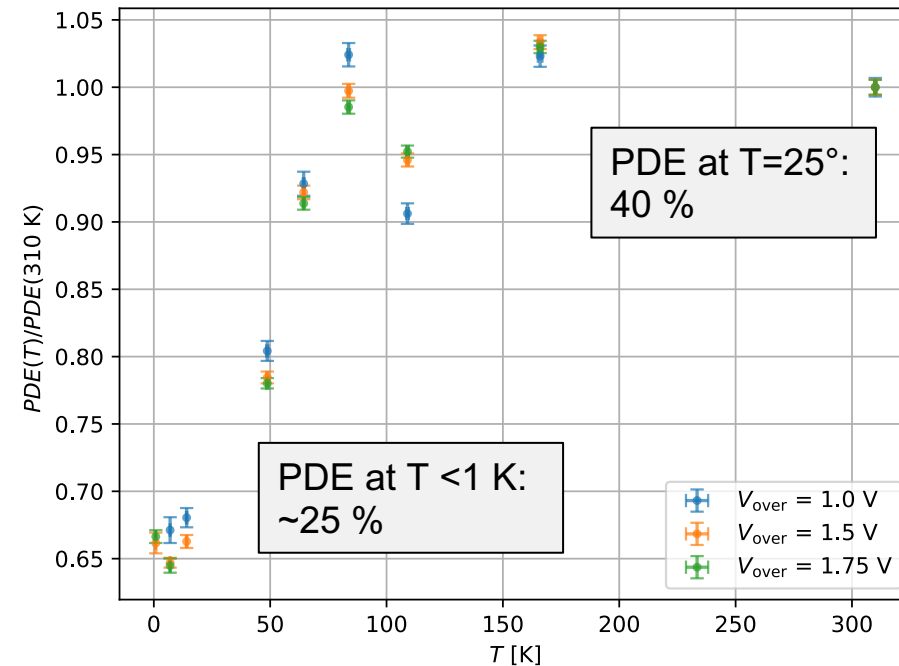
- No proper operation between 20 K and 40 K
- V_{over} limited to ~ 2 V at ultra low temperatures

Cryogenic SiPM: Single photon detection



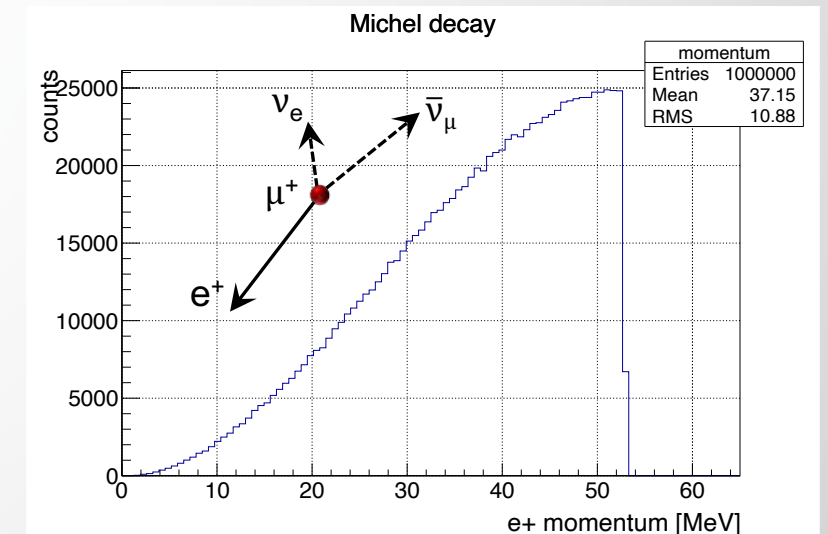
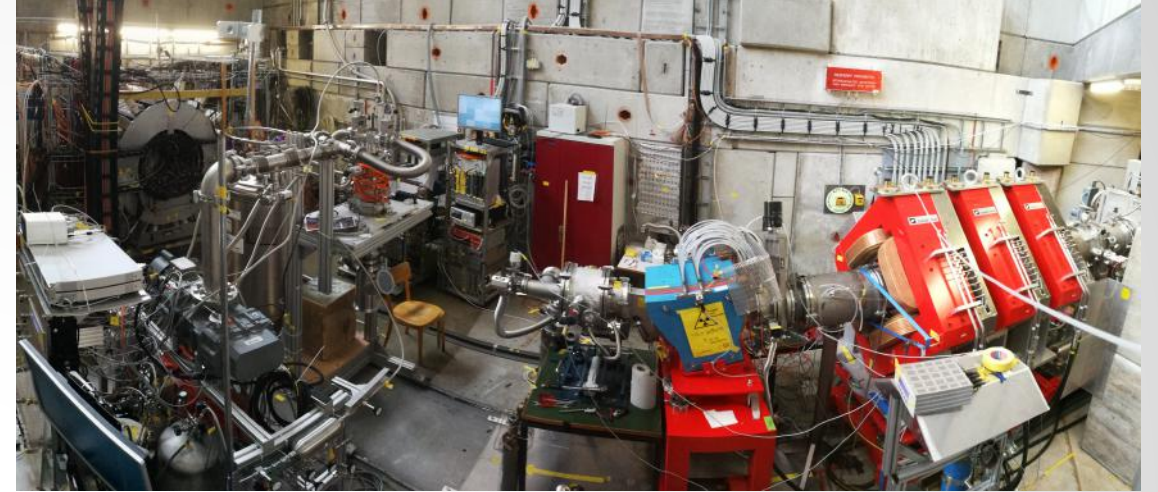
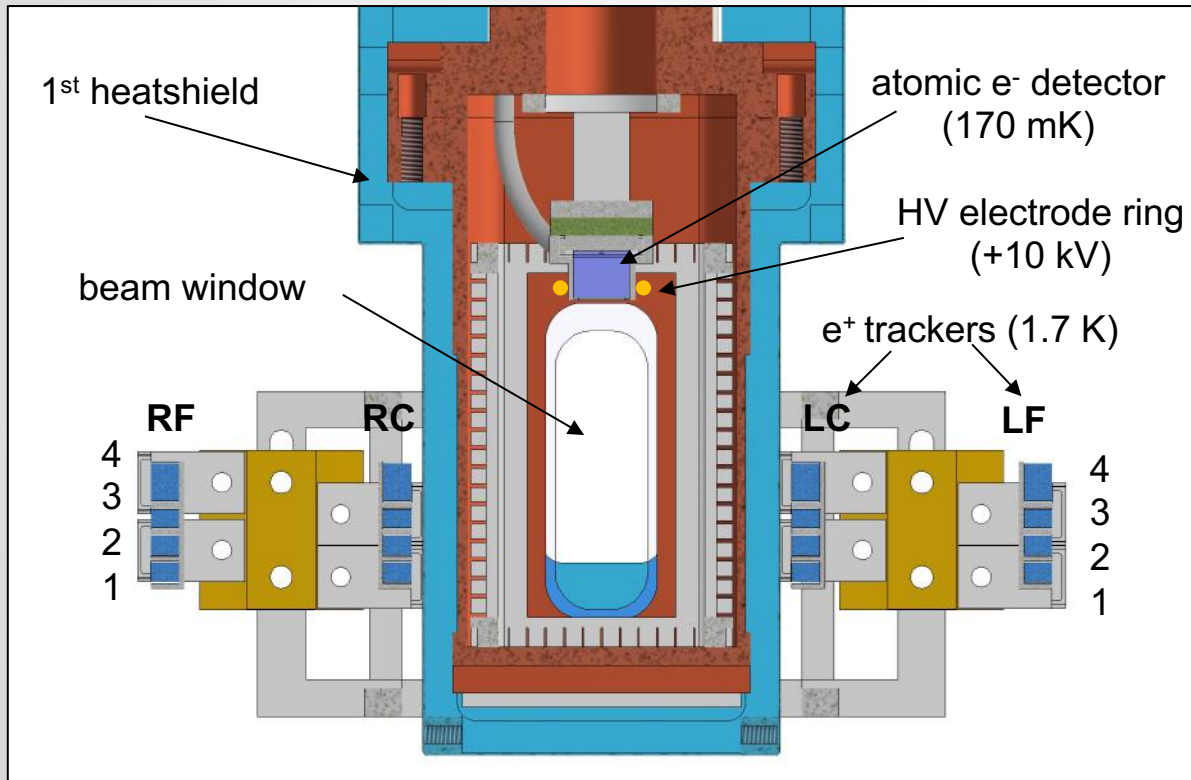
Single photon counting possible
at ultra low temperatures

- 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



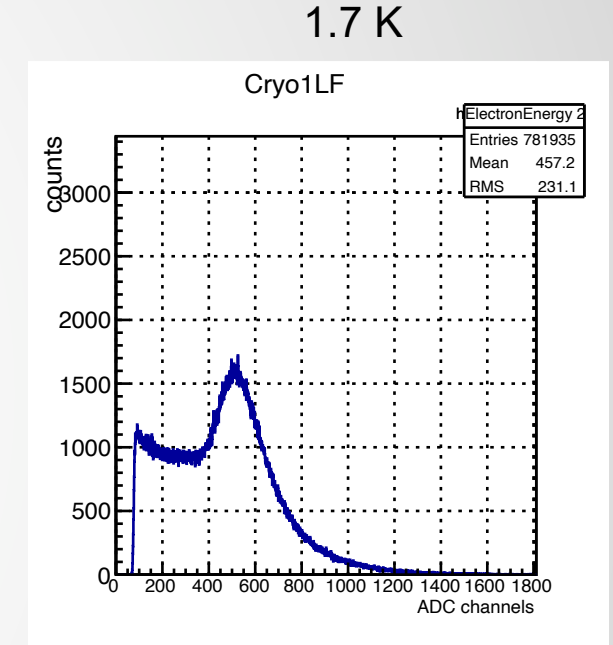
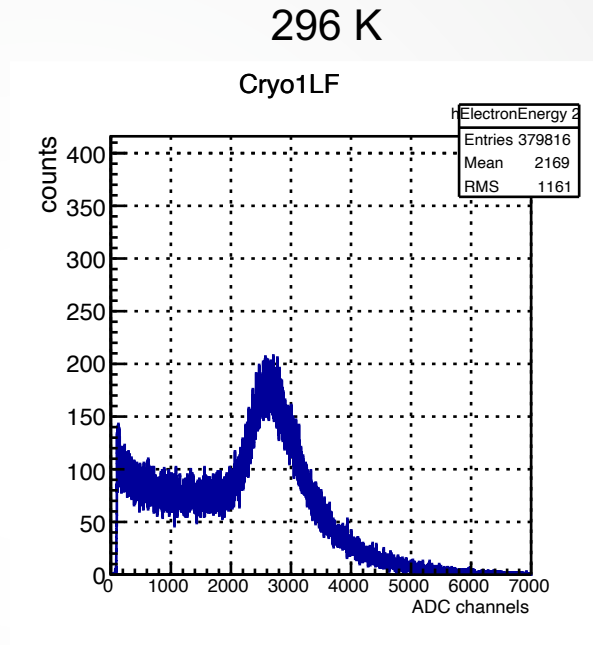
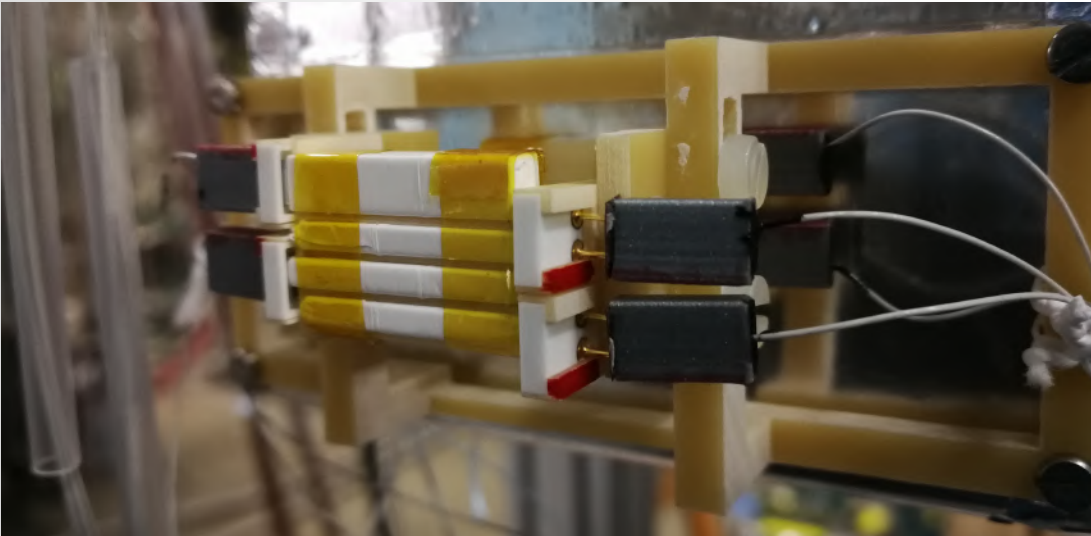
Commissioning with μ^+ beam

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



Positron detectors

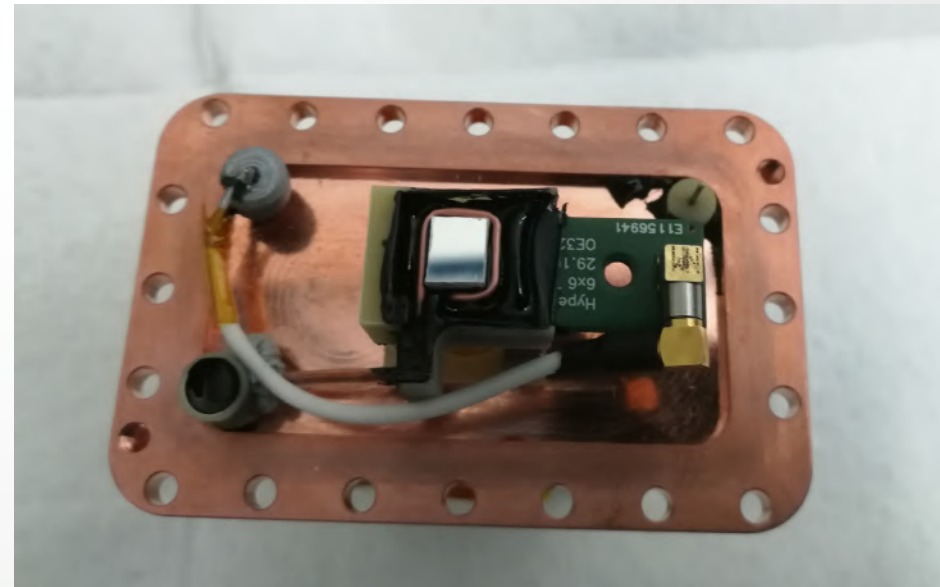
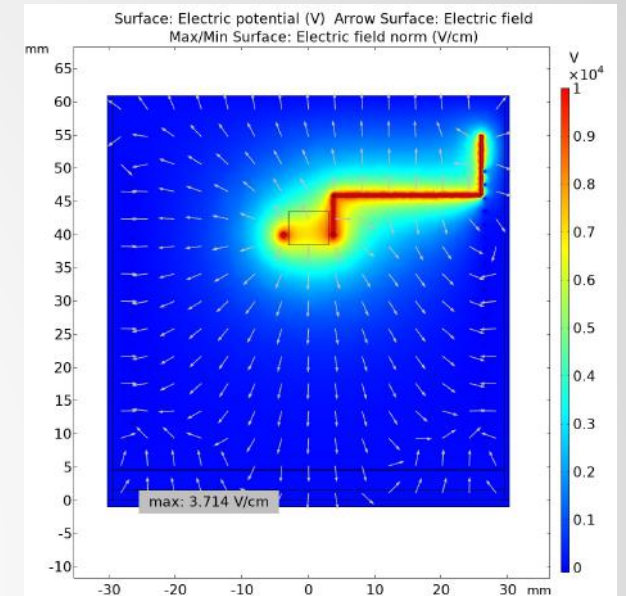
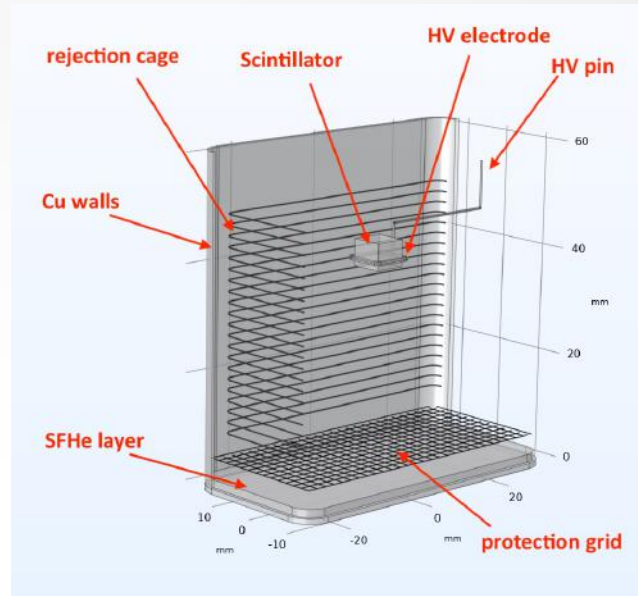
- Plastic scintillator bars
 - Eljen EJ-204, l: 20 mm, h: 3 mm, w: 2-4 mm
 - wrapped with Teflon
 - no optical cement (teared wire bonds)
 - 3D printed acrylic sleeves



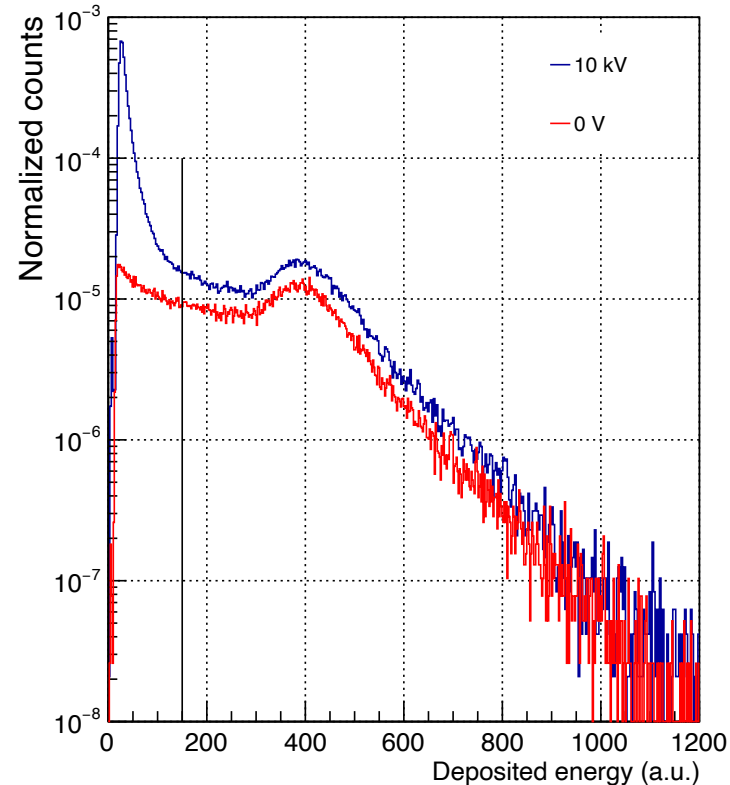
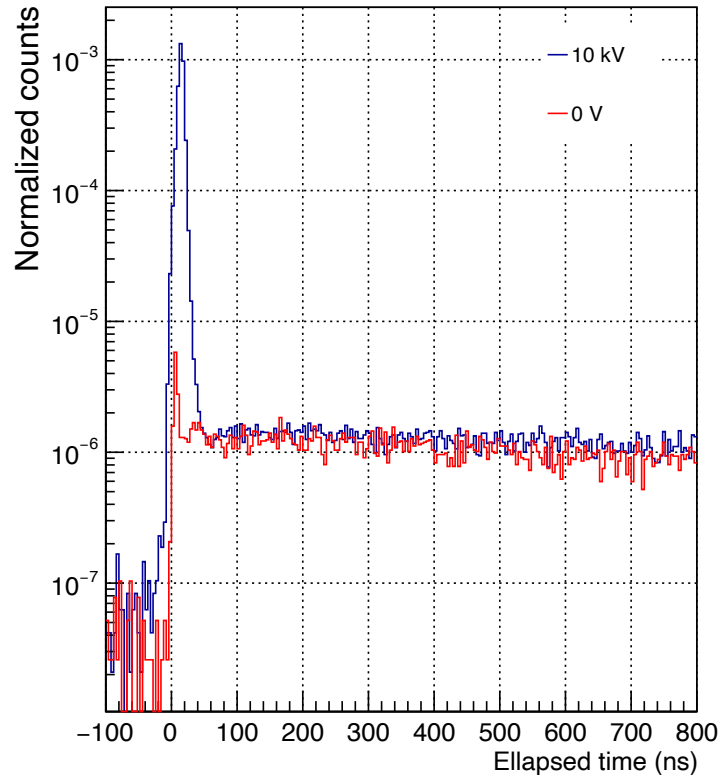
- Energy deposition in thin absorber: Landau distributed
- Lower gain in cryogenic but full peak visible

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

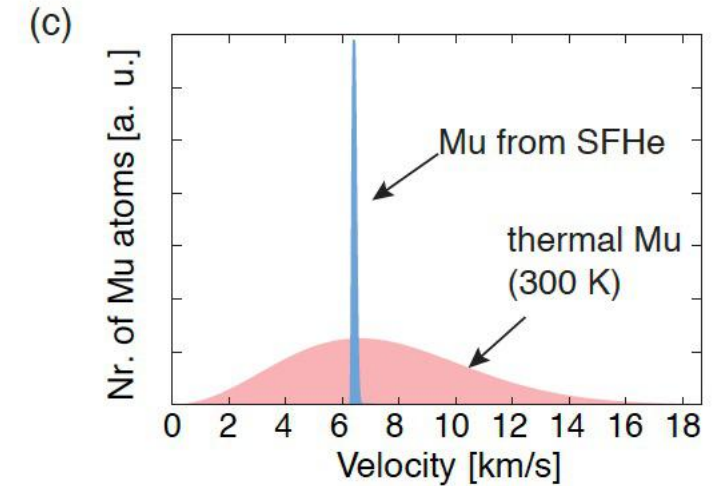
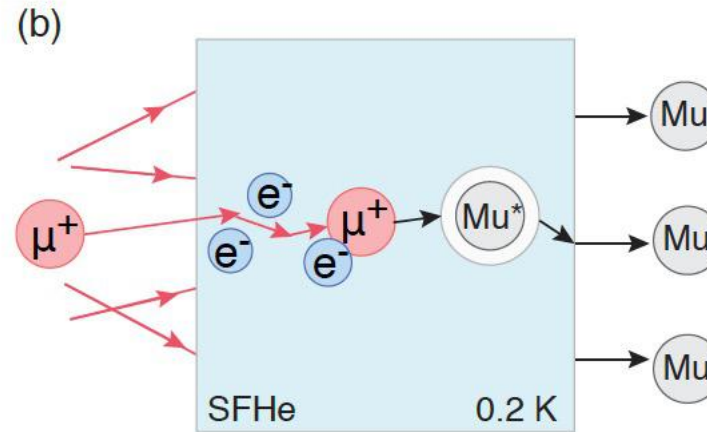
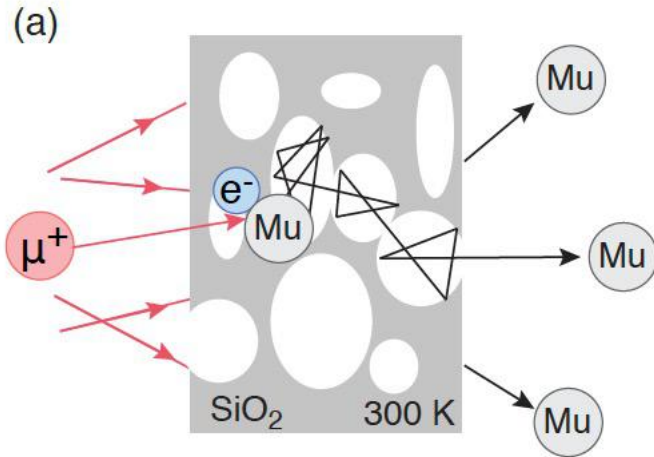
Michel e⁺ and low energy e⁻ detection feasible at ultra low temperatures

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

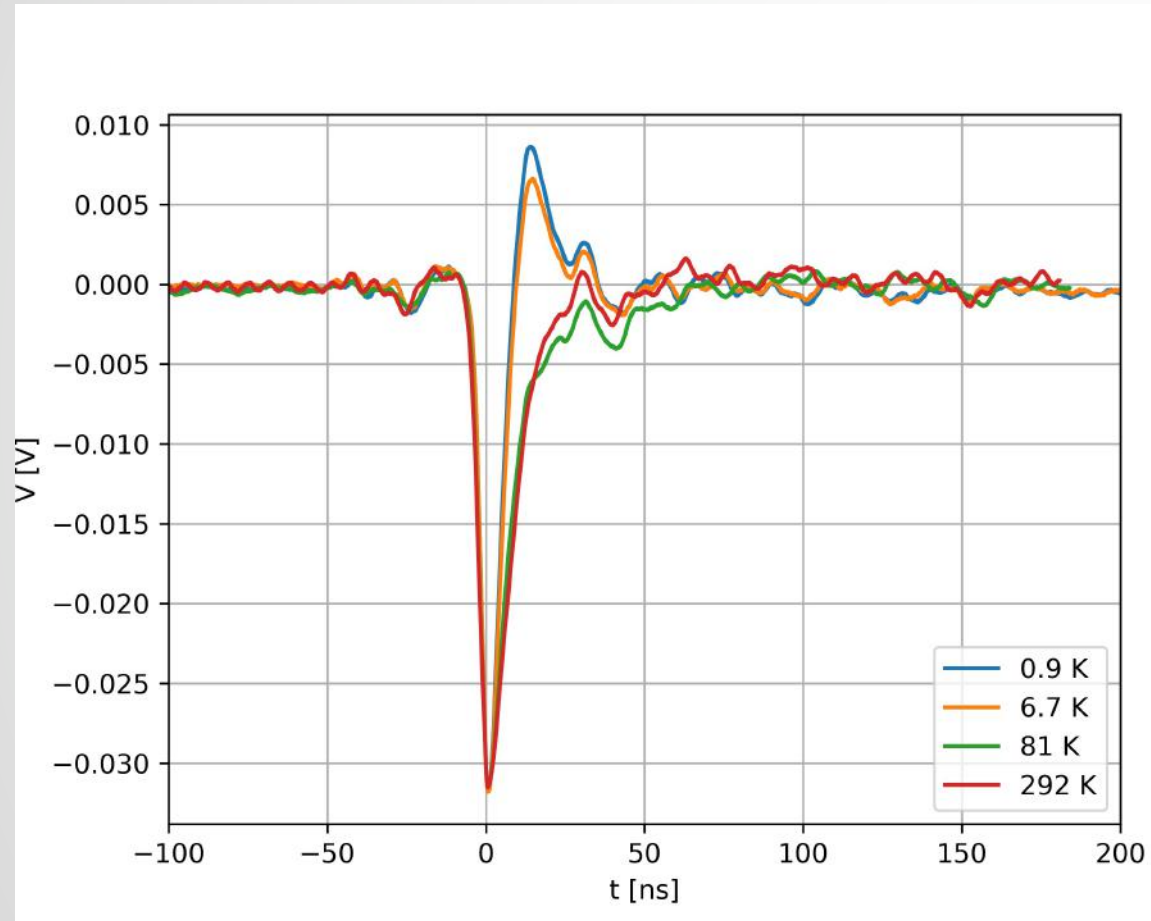
proposed SFHe Mu source

- superfluid ^4He
- 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)