Small But Not Small

GBAR (김선기, 김봉호), KAPE (김홍주, 박형우), Super-Light Dark Matter (박종철), KAEM (이세욱)

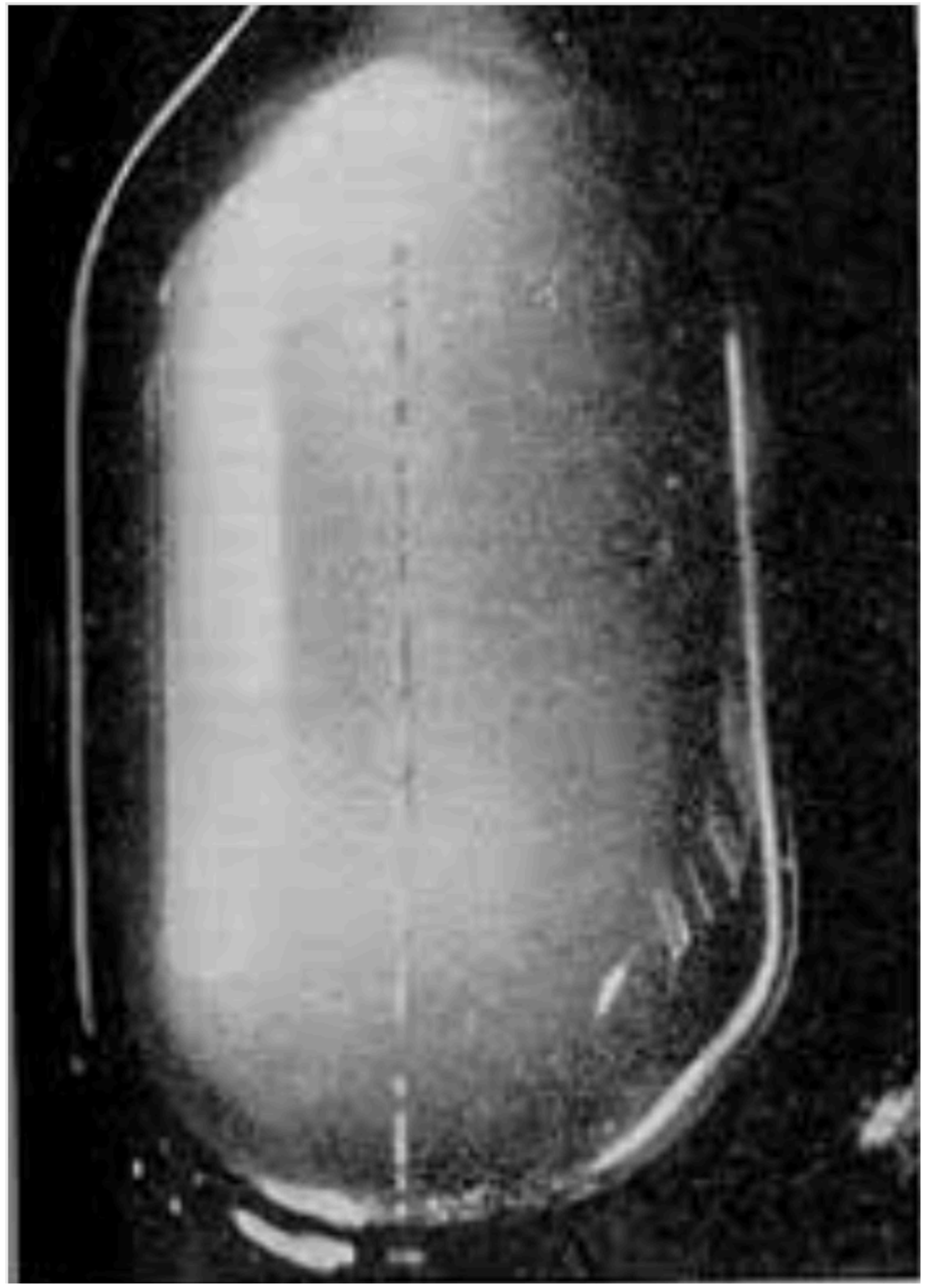
김선기, 김봉호, 김홍주, 박형우, 박종철, 이세욱
입자 및 장물리분과 2021 학술대회
Dec. 17, 2021

Creativity Diversity Innovation

Small-scale experiments

Bubble Chamber (BC)

The first bubble chamber (1 cm^3)



The first actual bubble chamber as a detector (~4 cm)

The first tracks observed in John Wood's 1.5-inch (3.8 cm) liquid hydrogen bubble chamber, in 1954.

Fig. 1. The 2", 4", 6", 10", 15" and 72" bubble chambers built at Berkeley, in the early days of the BC era.

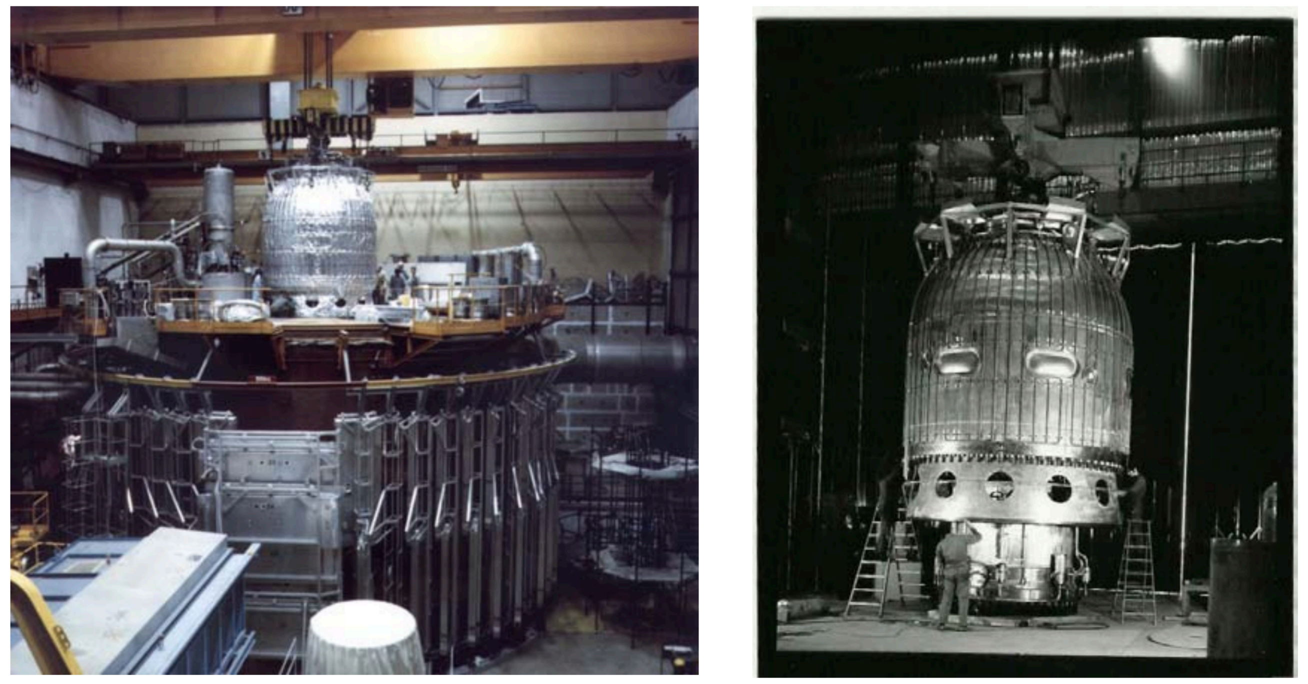


Fig. 7. The Big European Bubble Chamber (BEBC): the 3.7 m liquid container is shown at the top of the left figure, while it is being lowered into place; the right picture shows the body and in particular the expansion piston at the bottom. On the left, BEBC is shown with the external muon identifier composed of a set of electronic detectors. The superconducting coil is before the electronic detectors. BEBC, filled with H_2, D_2 or H/Neon was used mainly with neutrino beams.

Small-scale experiments

Time Projection Chamber (TPC)

The size of the first actual device

TPC for the PEP 4 experiment (6 m³)

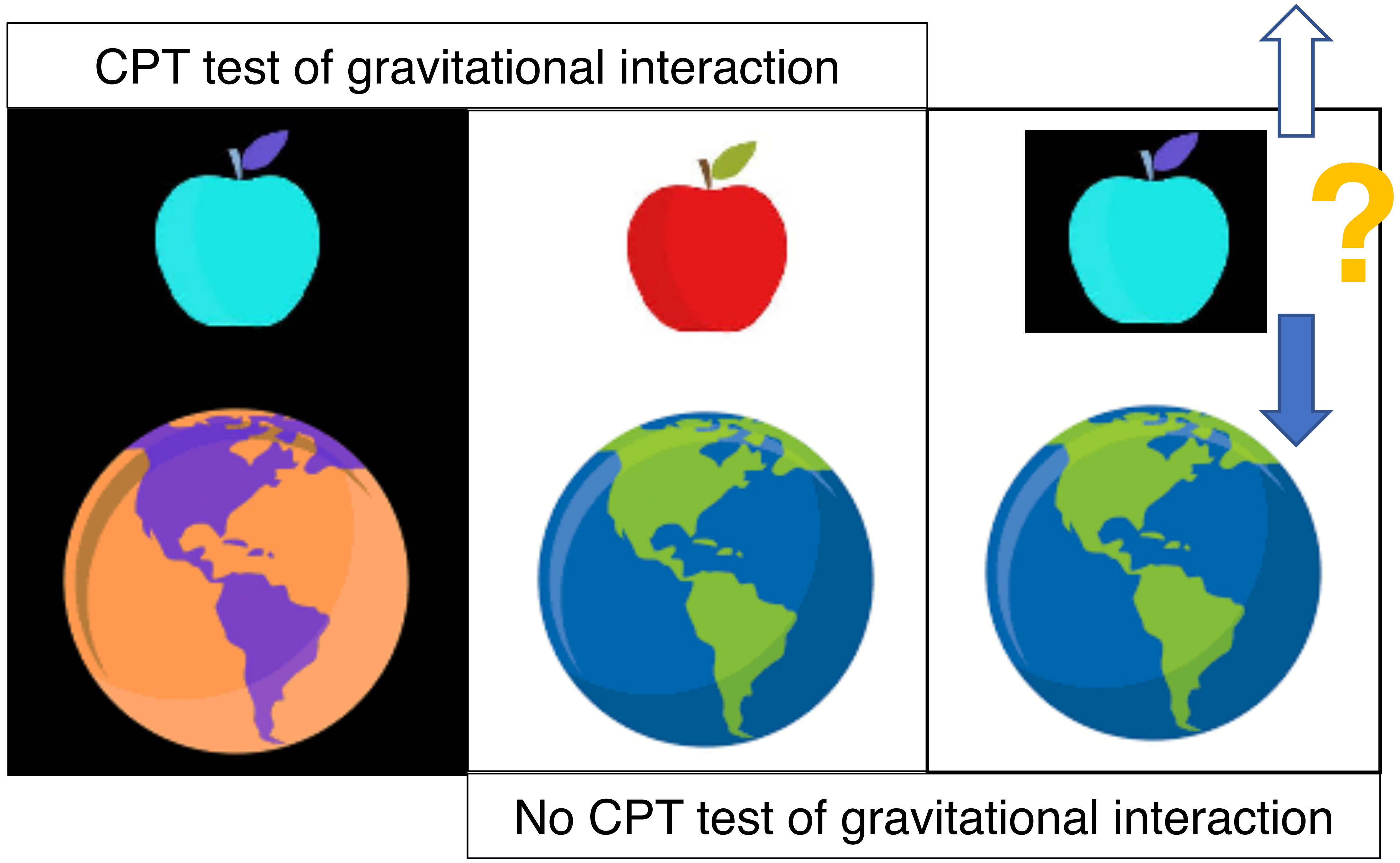
Gravitational Behavior At Rest (GBAR)

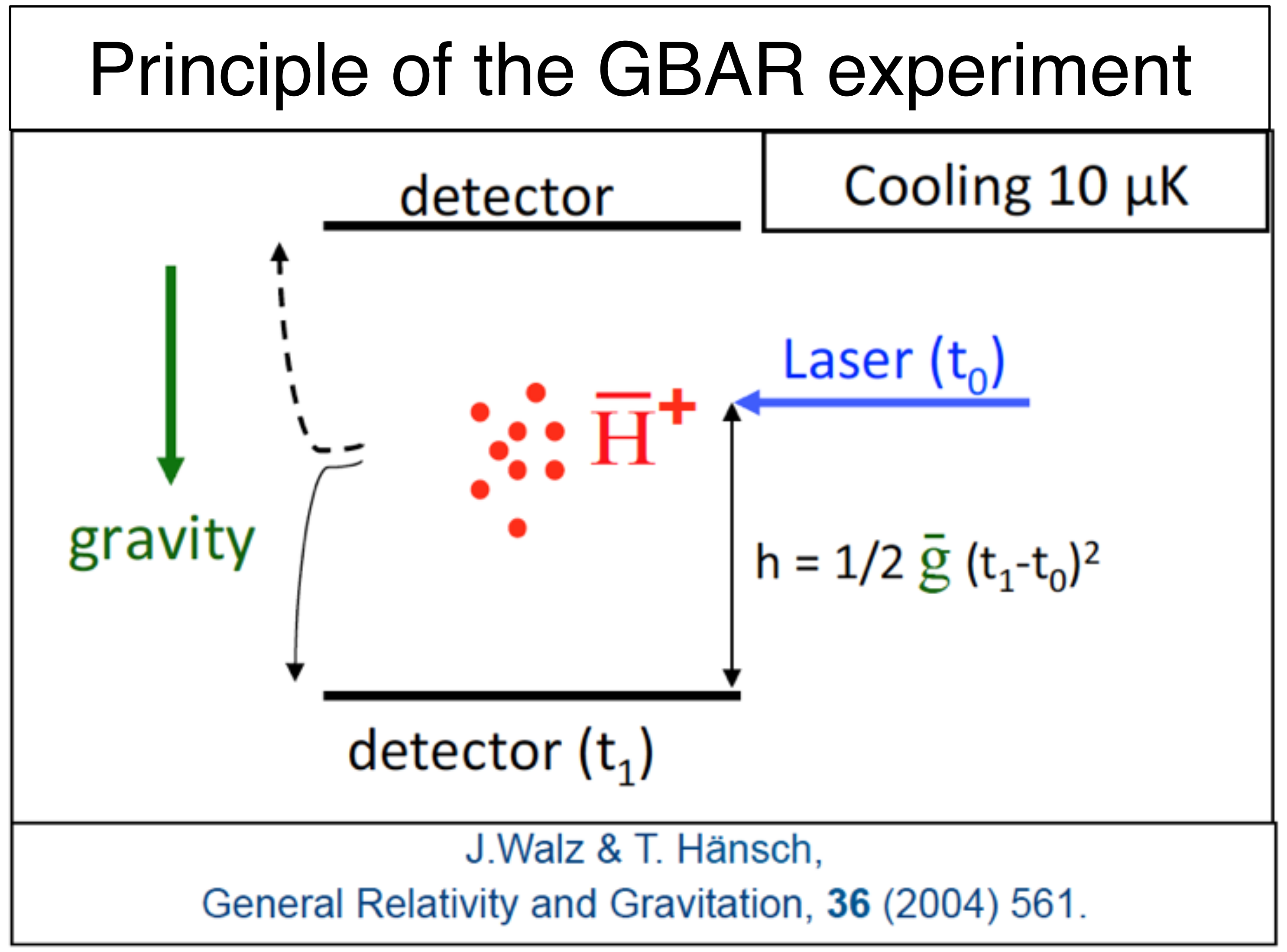
GBAR experiment

- Aim of the GBAR (Gravitational Behaviour At Rest) experiment

- Direct measurement of **ultra-cold** antihydrogen's freefall acceleration in the terrestrial gravitational field. (fundamental interaction measurement)

- Confirmation of the **weak equivalence principle (m_g=m_i)** between matter and antimatter.





- **Double charge exchange** process between antiproton beam and dense positronium cloud

$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$
$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$

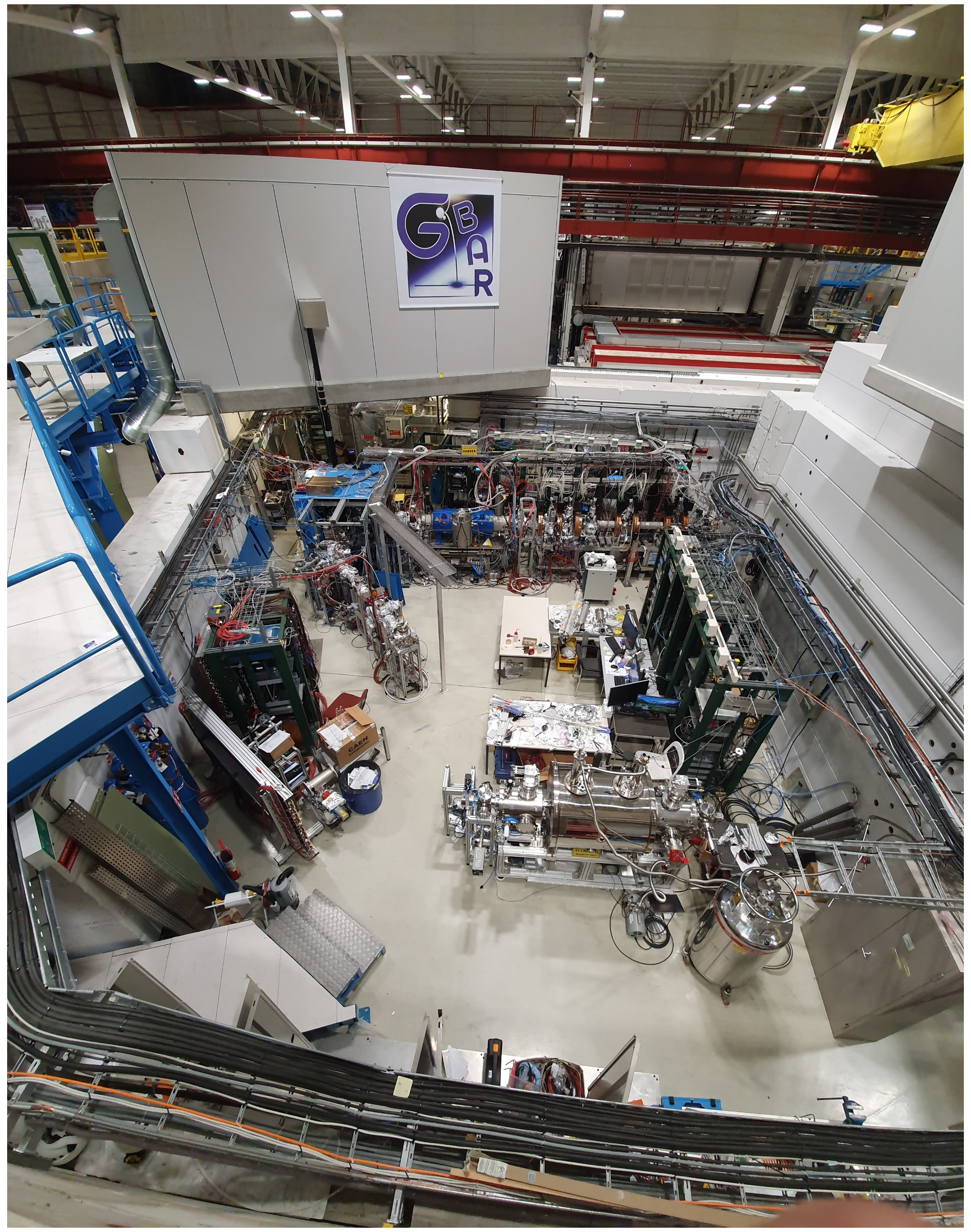
- Cooling antihydrogen **ion** down to 10 μK range (ultra-cold) to get extremely slow velocity in paul traps.
- After dropping (by **photo-detachement** laser) one positron from ion, let the ultra-cold antihydrogen freefalls.
- gravitational acceleration with 1% precision can be achieved by 1500# antihydrogen freefall test.

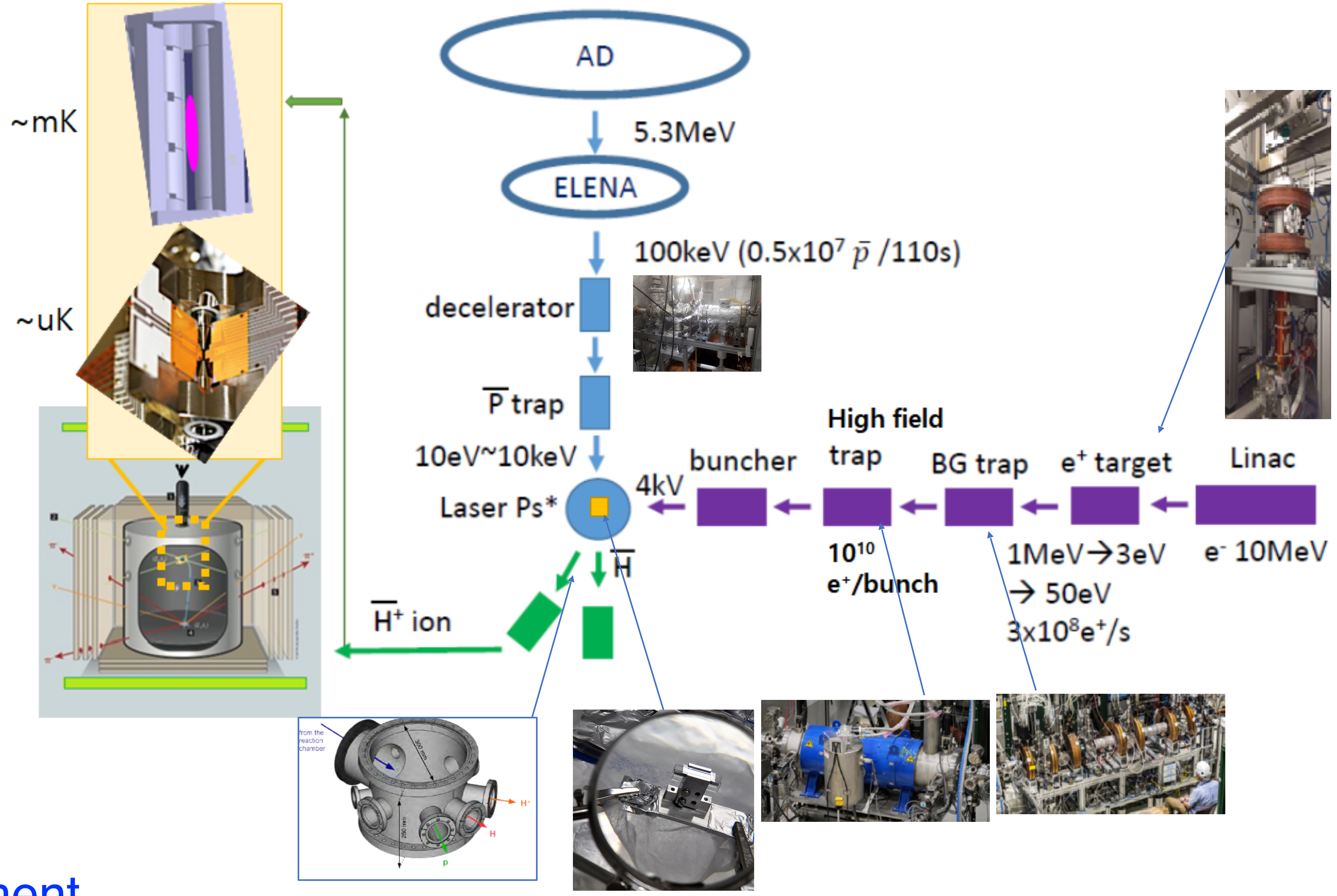
GBAR experiment

- Prepare enough beam quality

positron beam :10^{10} /bunch, positronium density 10^{12} /cm^3, antiproton : 0.4×10^7 /bunch (σ_E<10eV, σ_t<100ns)

- Antihydrogen ion(atom) production (1# ion/bunch)
- Cooling the antihydrogen to ~10uK and detect



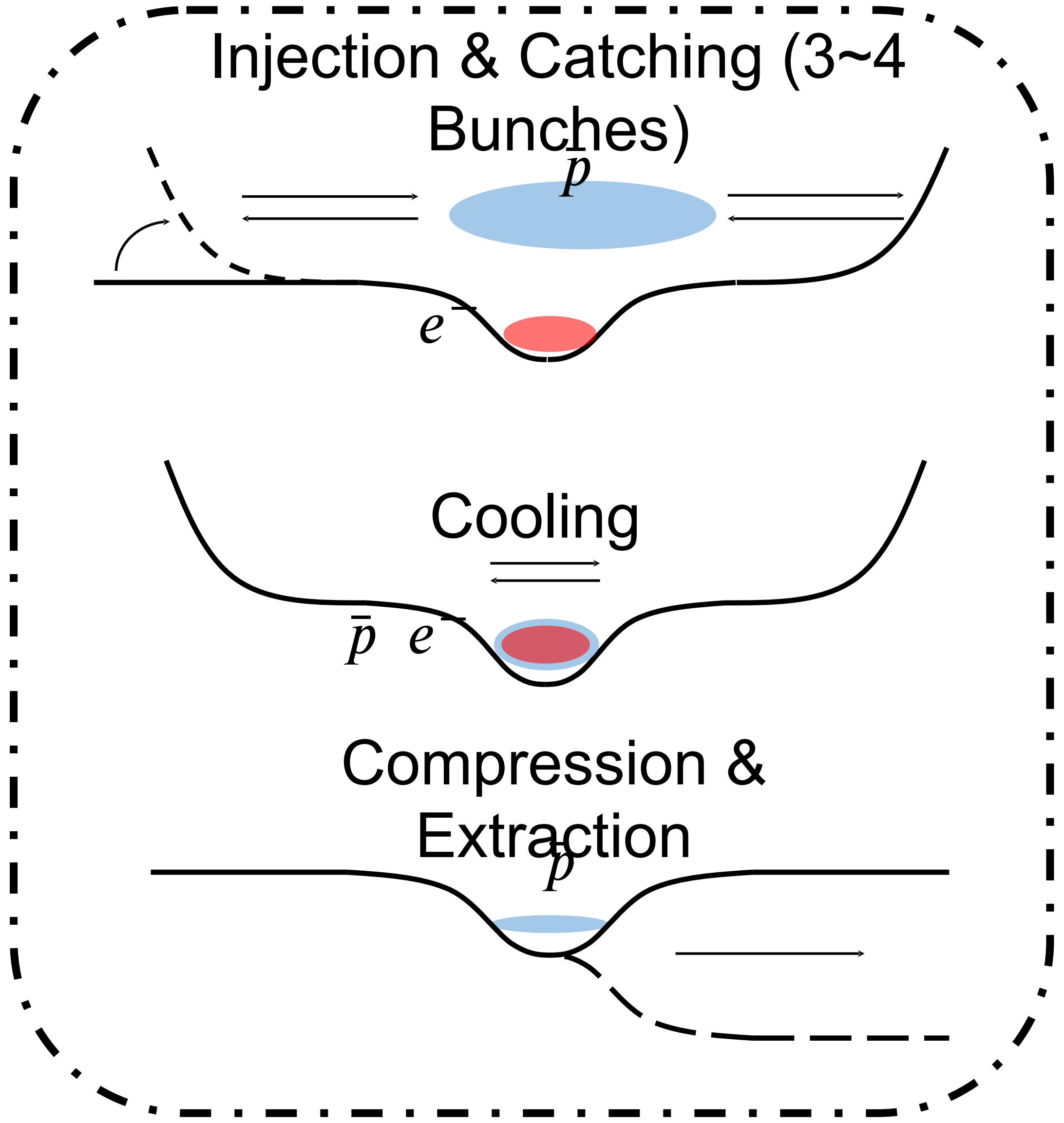


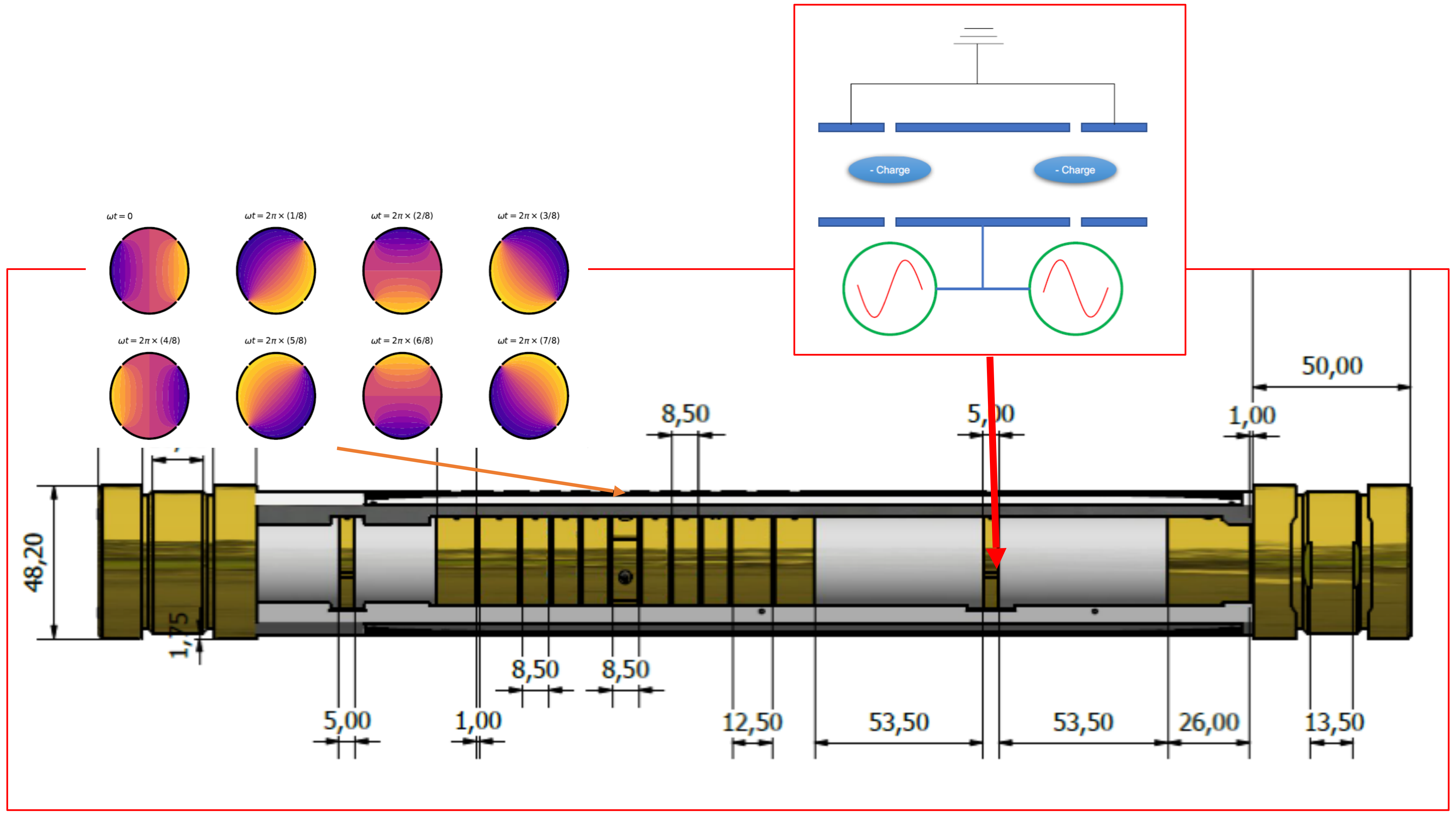
- Overview of the GBAR experiment

- Positron beam line : e⁻ linac, positron moderator, Buffer-gas trap, positron trap (penning-malmberg)
- antiproton beam line : ELENA, decelerator, antiproton trap (penning-malmberg)
- Reaction chamber : positronium target, laser for o-Ps exication
- antihydrogen ion beam line : Switchyard, guiding line
- Freefall chamber : Capture trap (paul), Precision trap (paul), freefall chamber
- Freefall detectors : Micromegas detector, TOF detector

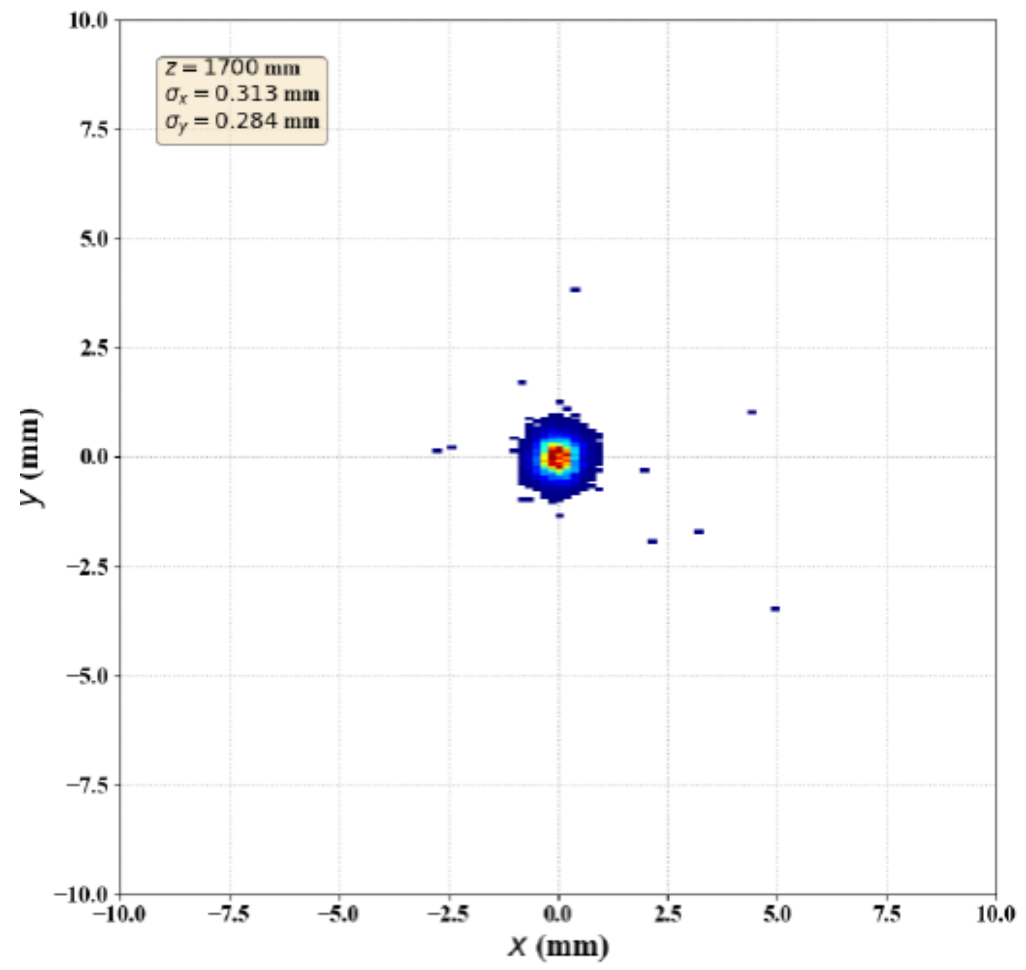
(Black : existed & currently testing, Green : not existed in the GBAR zone)

GBAR experiment





simulated beam size (preliminary)

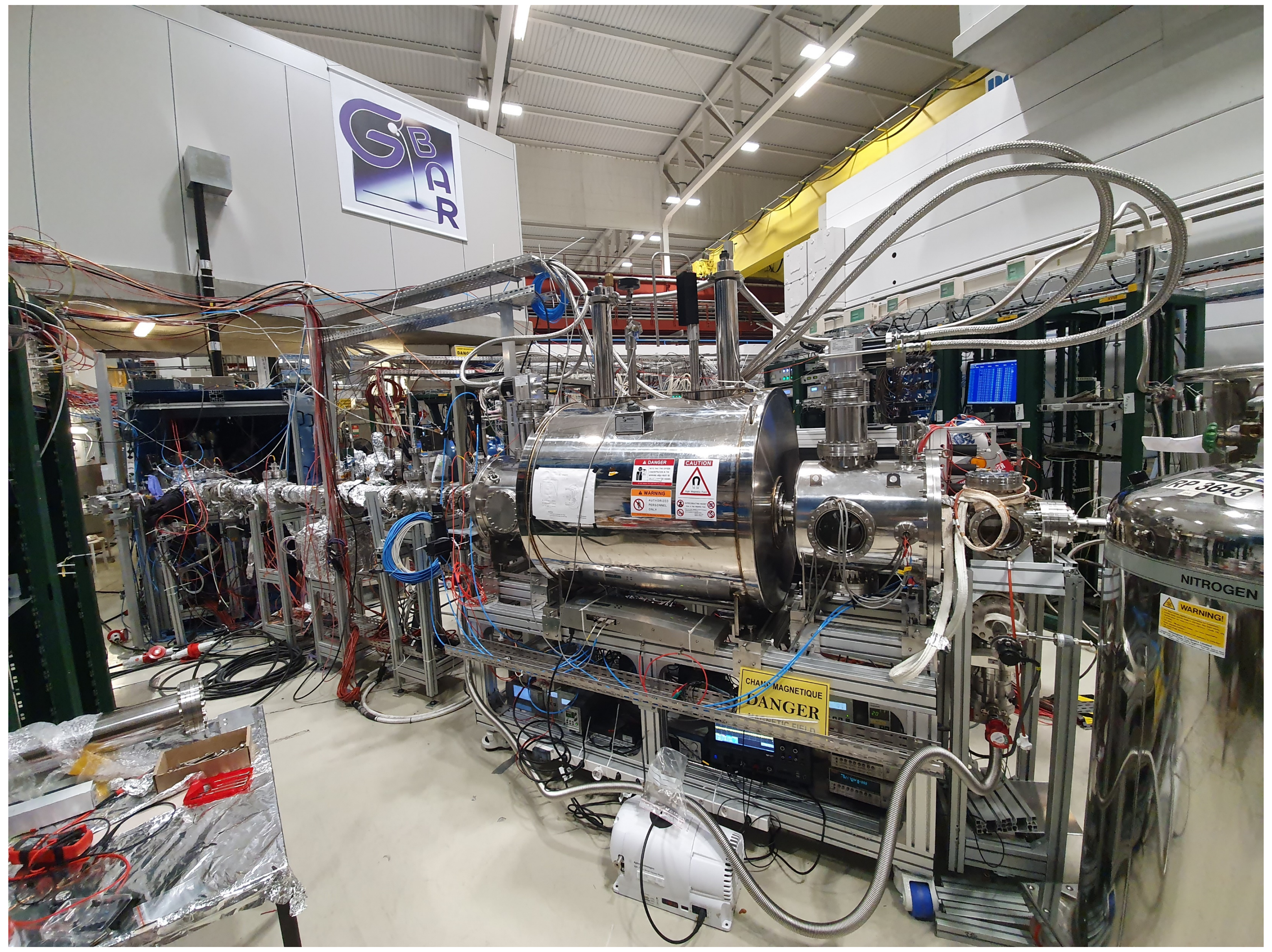


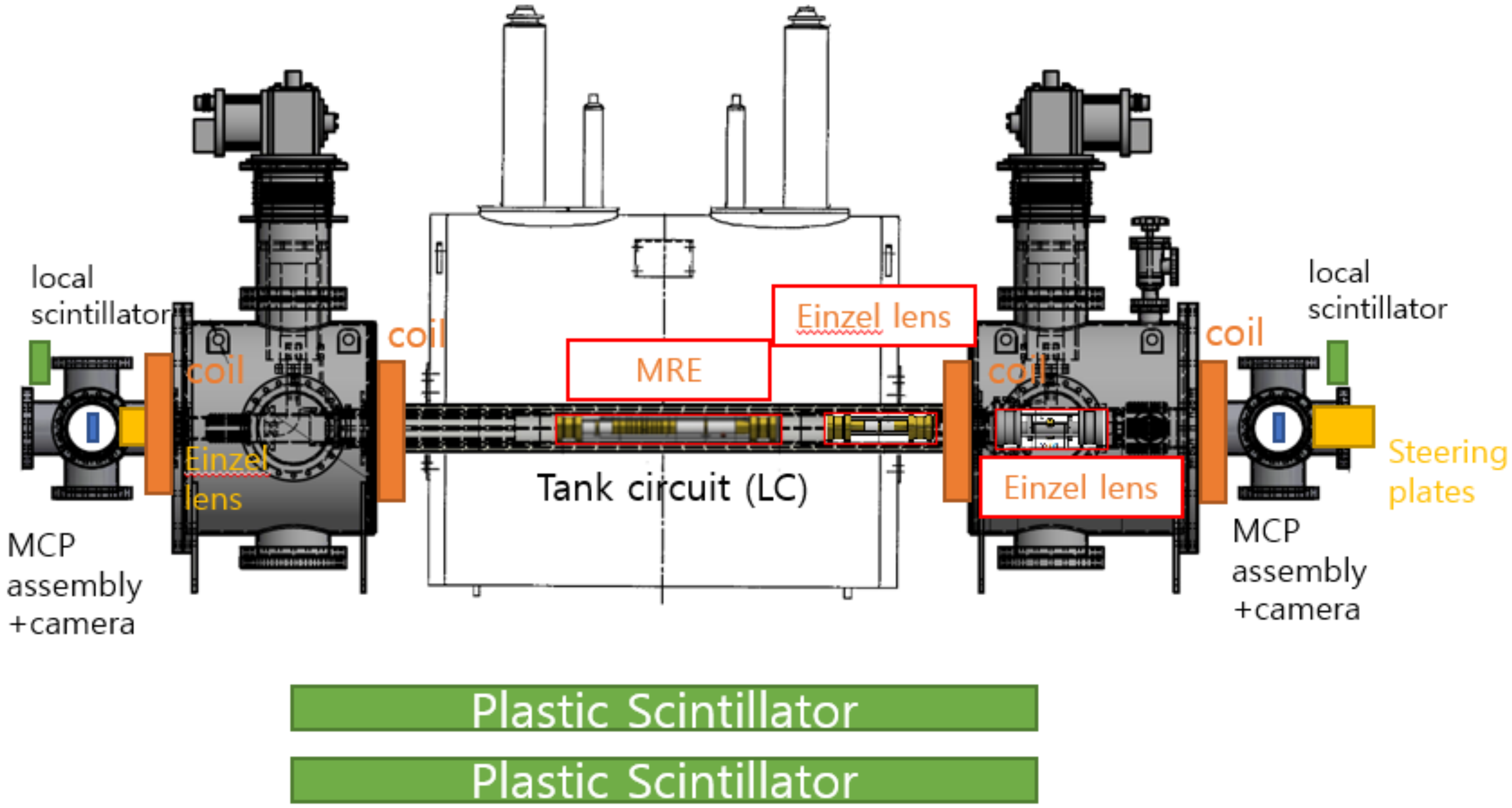
- Korean GBAR group's activity (antiproton trap)

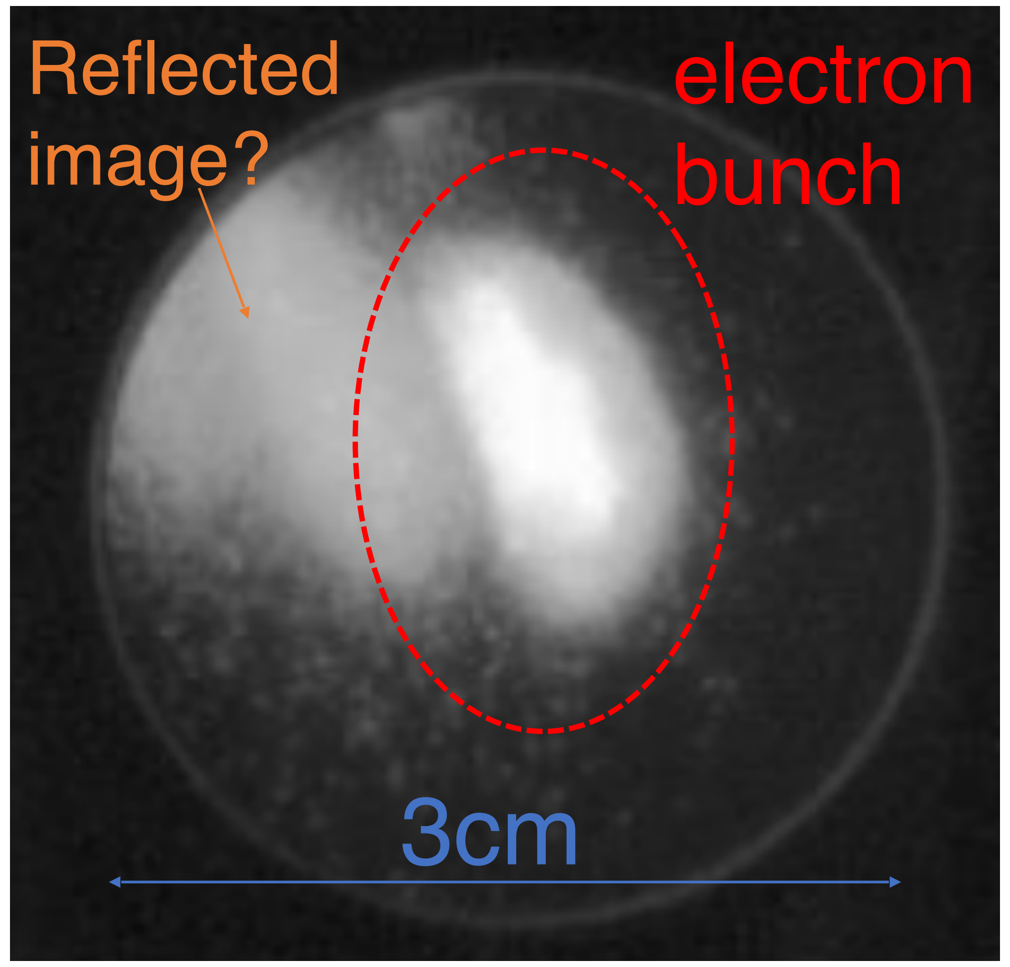
- Antiproton trap (penning-malmberg trap) is designed for cooling (sympathetic cooling by cooled electron by 7T magnet), compressing (rotating wall technique), stacking and bunching (double-gap buncher) antiproton.

- Aimed values P~10^{-10}mbar, T~10K to trap without losses are achieved.
- Simulation based on WARP for extraction of antiproton shows that simulated beam parameters are satisfied required parameters by using double-gap buncher(1x1x10mm^3 hole passing at reaction area, σ_E<10eV, σ_t<100ns).

GBAR experiment



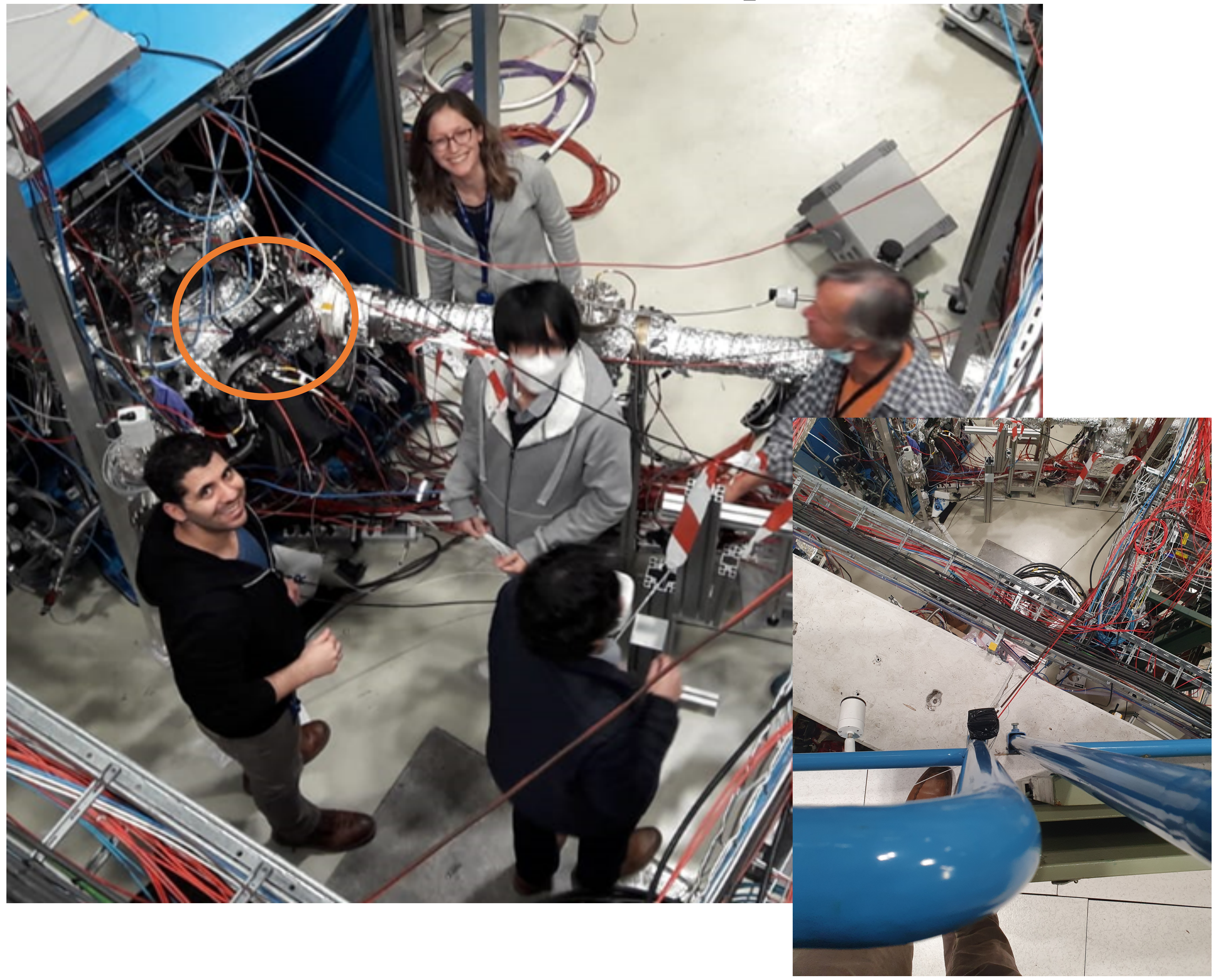


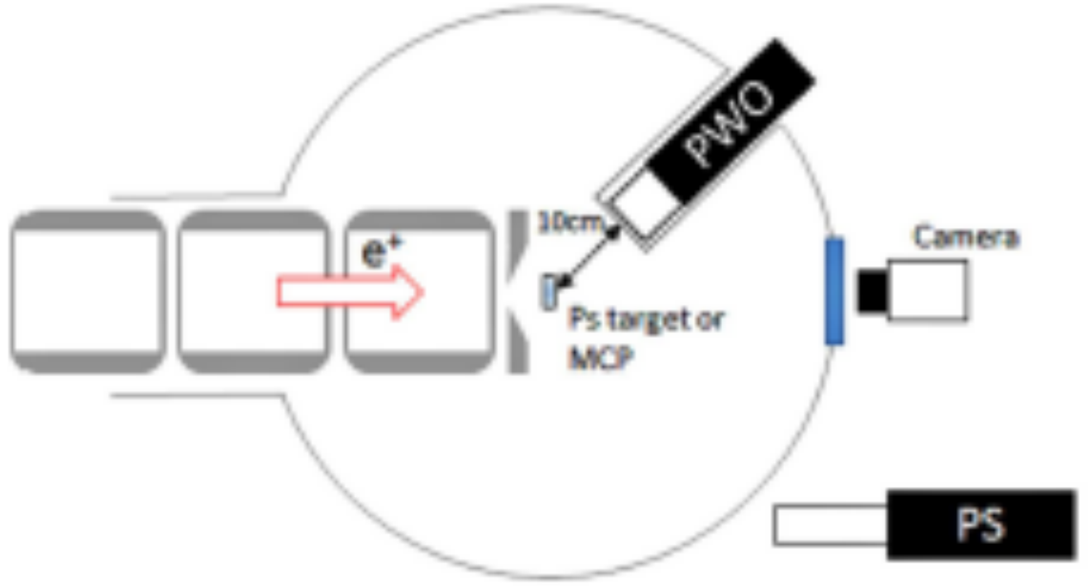


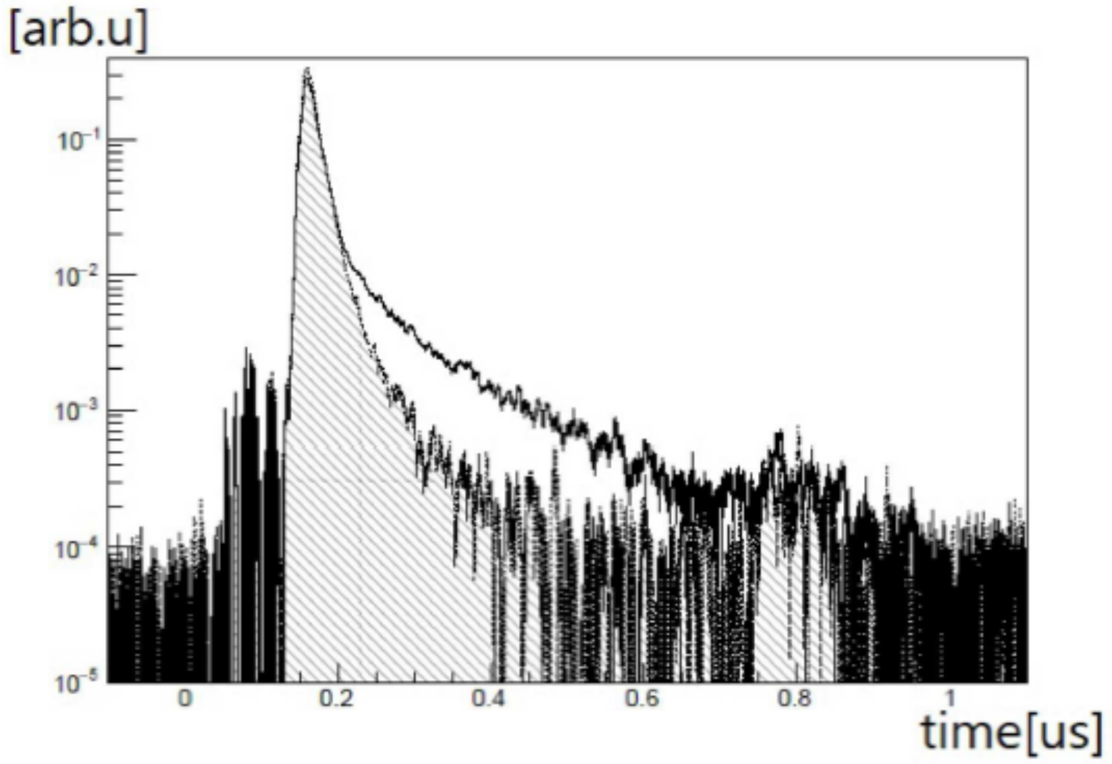
- Korean GBAR group's activity (antiproton trap)

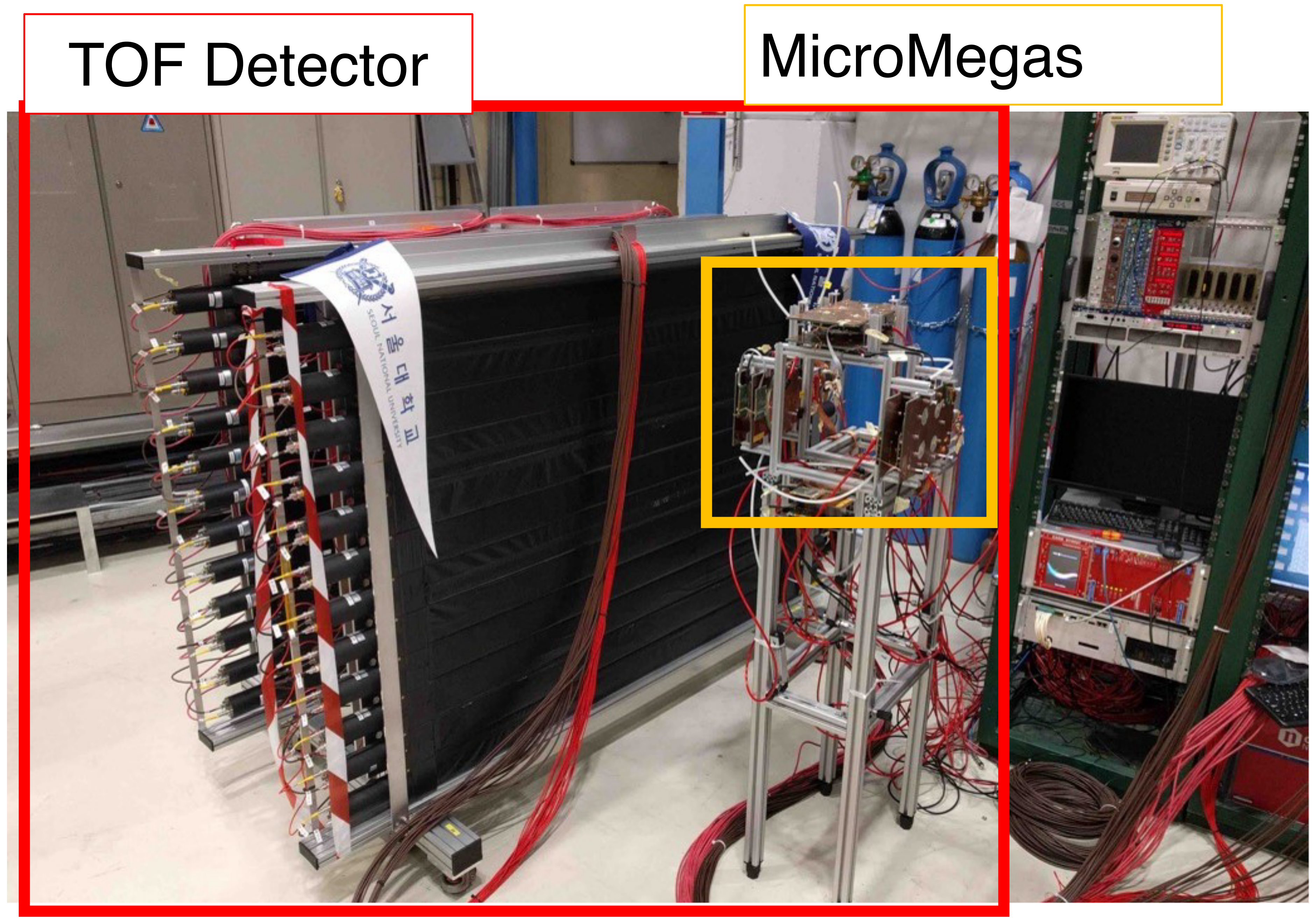
- Antiproton trap (penning-malmberg trap) is in GBAR experimental zone at AD, CERN to get antiproton beam.
- Currently, Waiting antiproton beam from decelerator(KE<10keV) for first trial of antiproton trapping. (optics and detectors are quite ready)
- Electron guiding, trapping, cooling and extraction test was done successfully.
- ion beam transmission test, electron compression, non-destructive monitor (tank circuit) test is ongoing

GBAR experiment

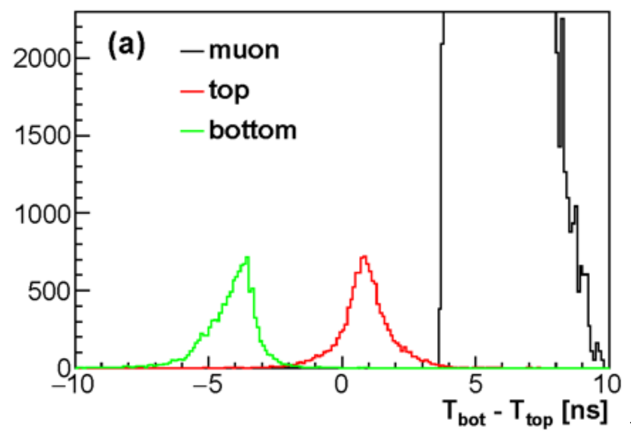


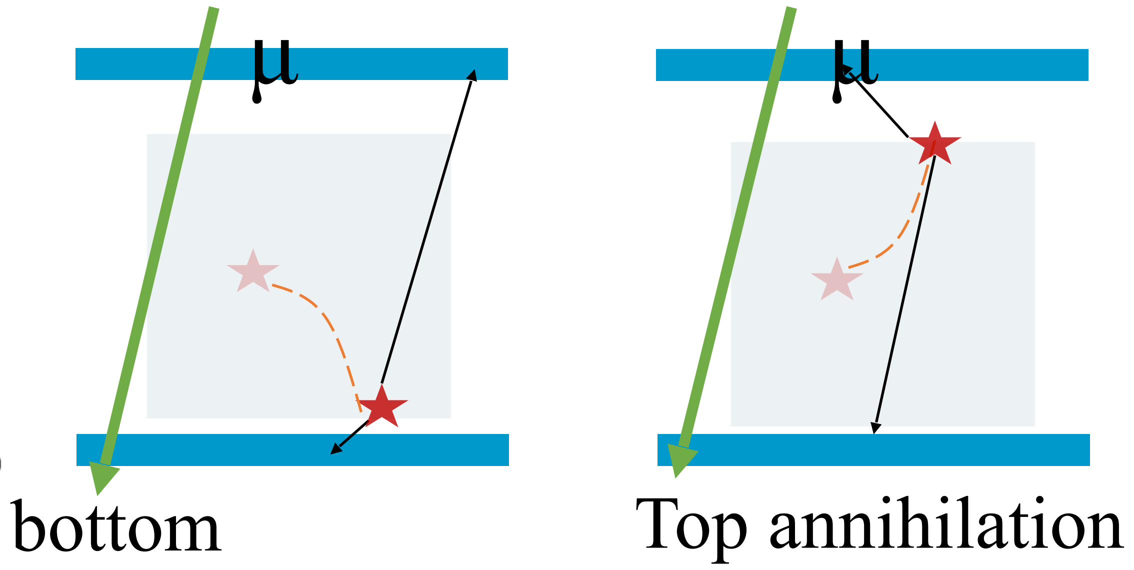






Temperature	Sign decision
10uK	~30 events
1mK	~6000 events





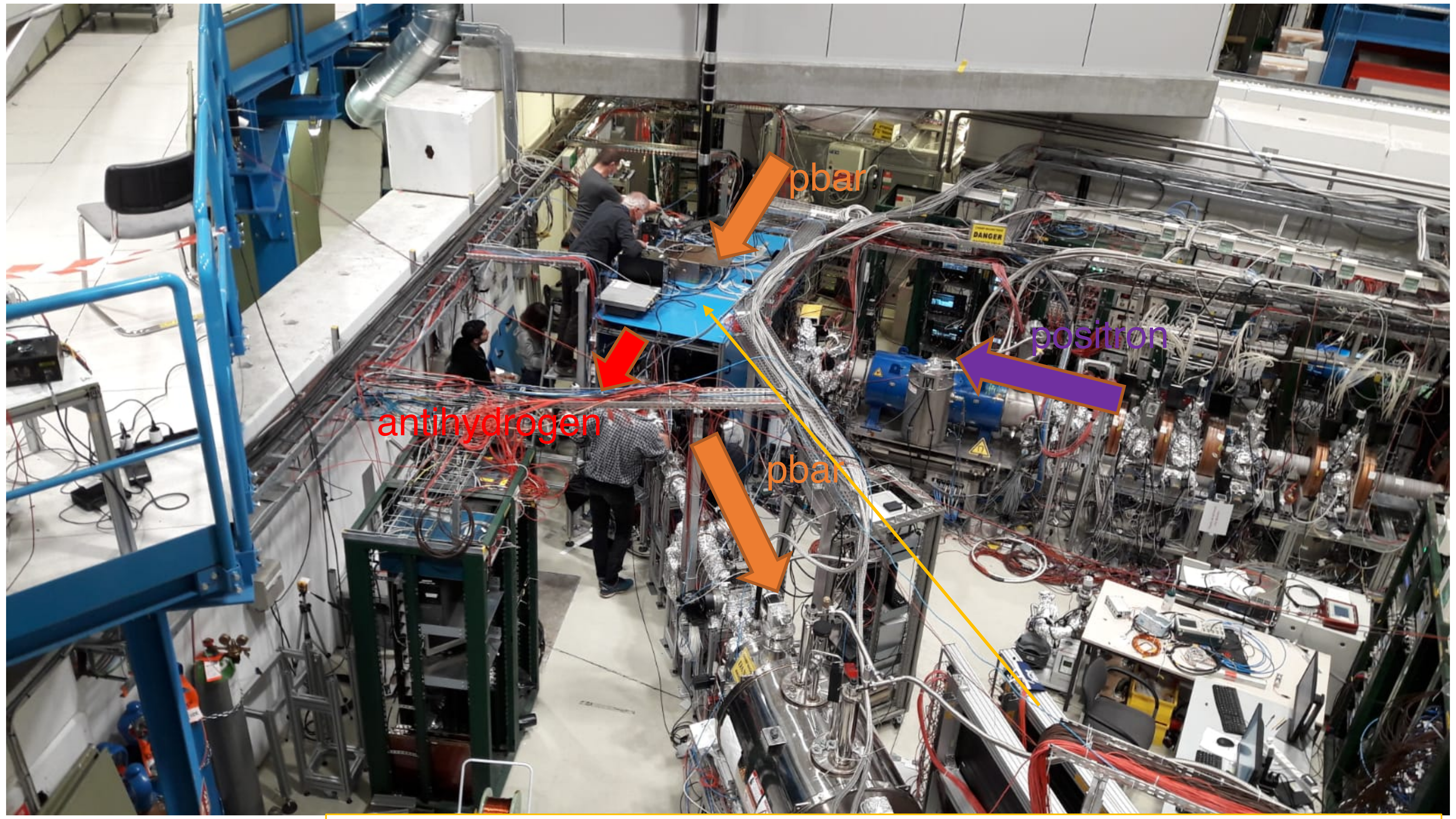
- Korean GBAR group's activity (Scintillation detector)

- All important scintillation detectors are developed (hardware & simulation) by Korean group :
- TOF detector (Freefall detection) : acceleration value and sign decision, cosmic ray background veto
- Positronium detector ($PbWO_4$ detector) :positronium amount & density detection
- Scintillators for antihydrogen production detection & beam monitoring : Antihydrogen production measurement, online monitoring for beam status.

GBAR experiment

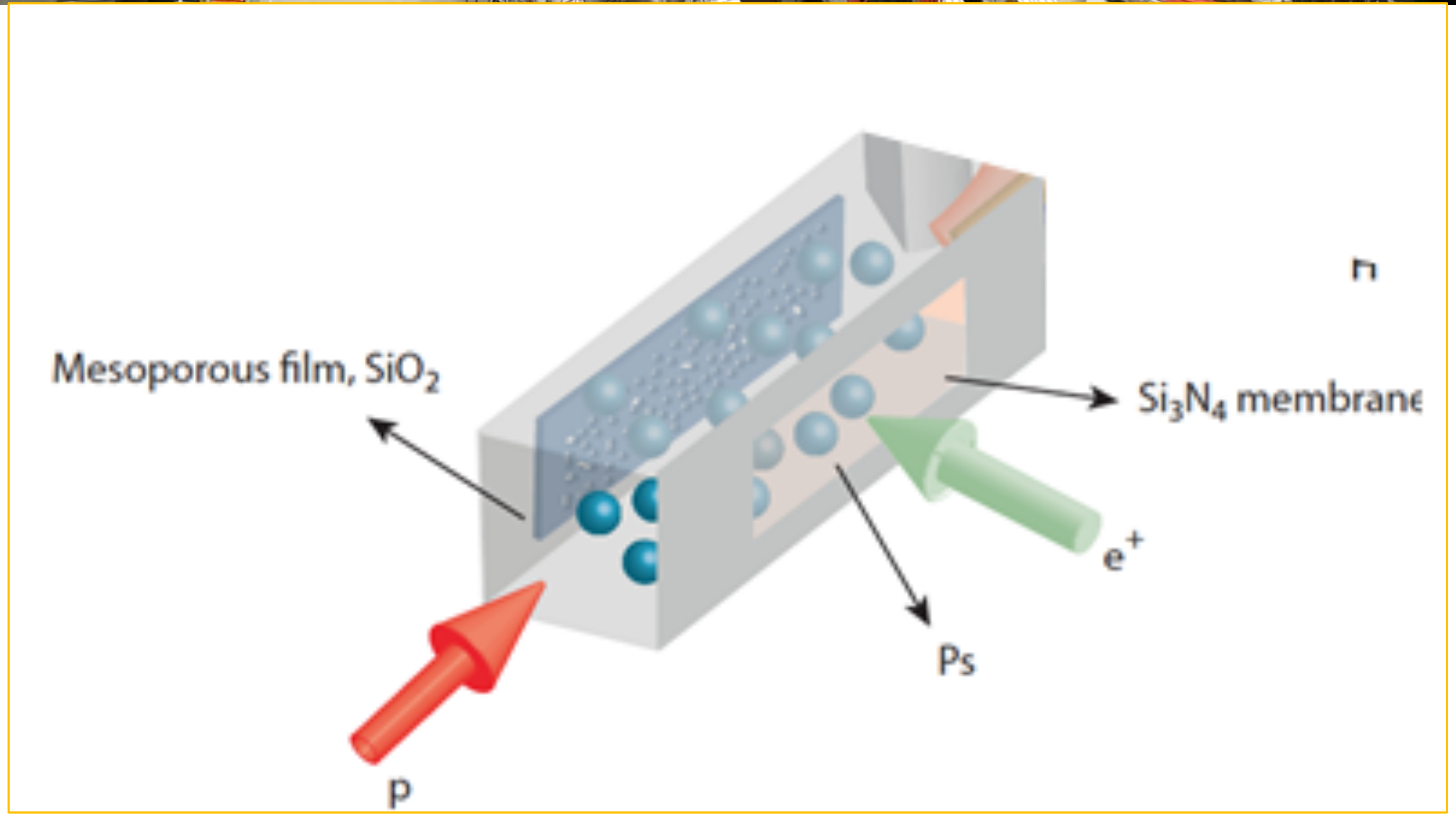
Current status

- Antiproton beam time after LS2 started from Sep. 2021.
- Antiproton decelerator performance was improved and deceleration down to 8 keV works okay.
- decelerated beam guiding to pass through reaction target (antihydrogen ion production) hole was performed.
-A demonstration of antihydrogen production & detection was performed during this year's beam time



- Plan for 2022

- Antiproton trap (currently in the end of line) will be mounted after decelerator : re-process antiproton beam which will be independent of upstream condition with better beam quality
- positron beam size at target position is bigger than target and it will be improved by reducing size at positron trap
- Antihydrogen (and ion) production can be tested after beam coming back (April. 2022)

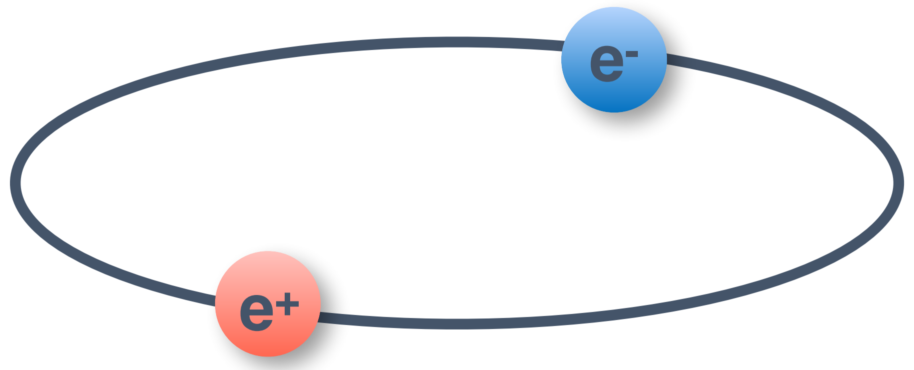


KNU Advanced Positronium Annihilation Experiment (KAPAE)

KAPAE

- KNU Advanced Positronium Annihilation Experiment (KAPAE)

Electron-Positron Pair



- Quasi-stable bound state
- Create energetic photons

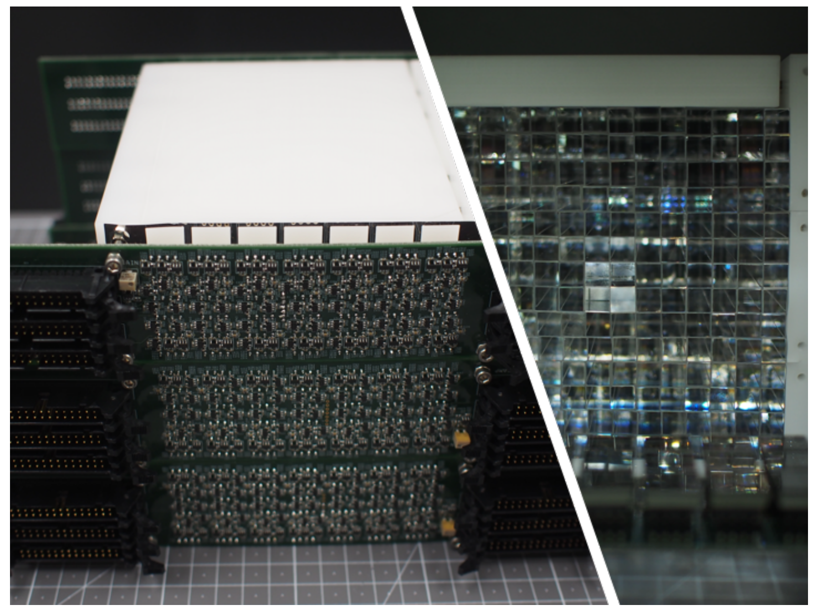
($m_{e^+} + m_{e^-}$ = 1.022 MeV)

KAPAE phase I

(State: Taking Data)

- CPT violation
- Efficient trigger part

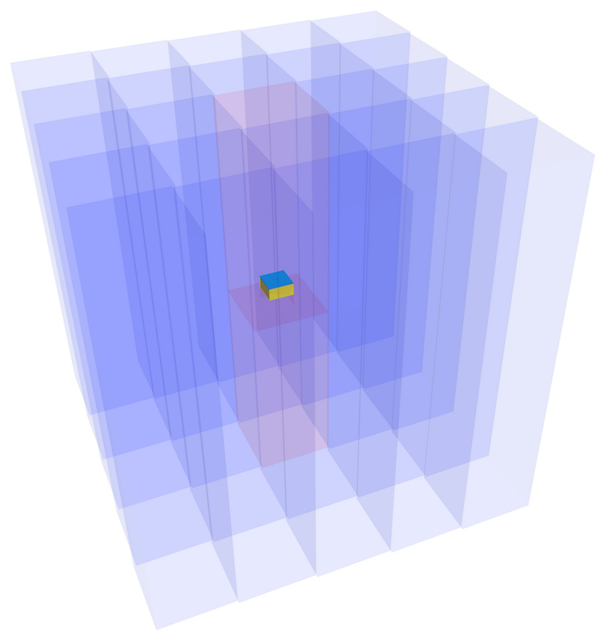
(Direct trigger signal correction)



KAPAE phase II

(State: Design & simulation)

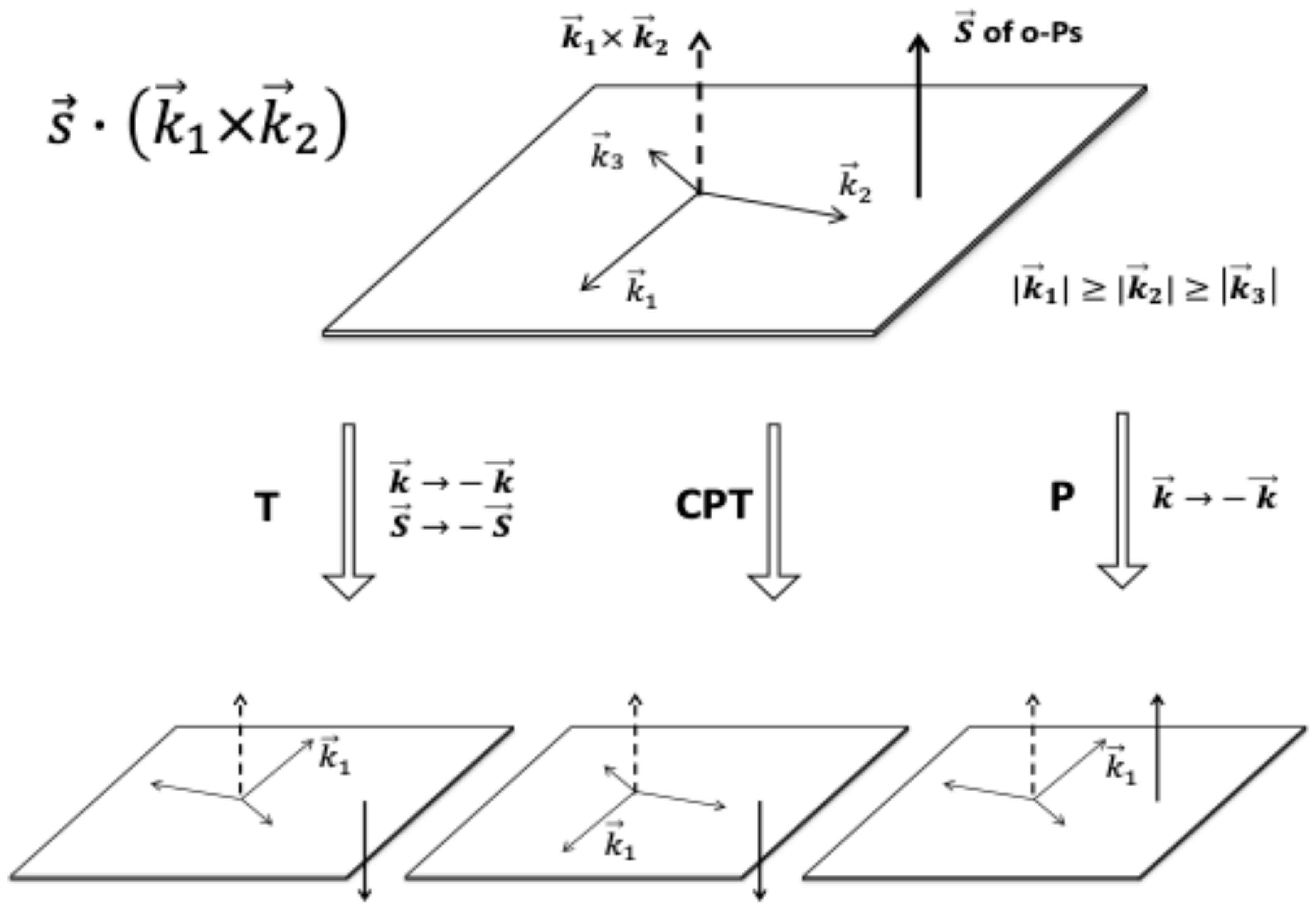
- Invisible decay
- Phoswich trigger
- Minimize dead areas



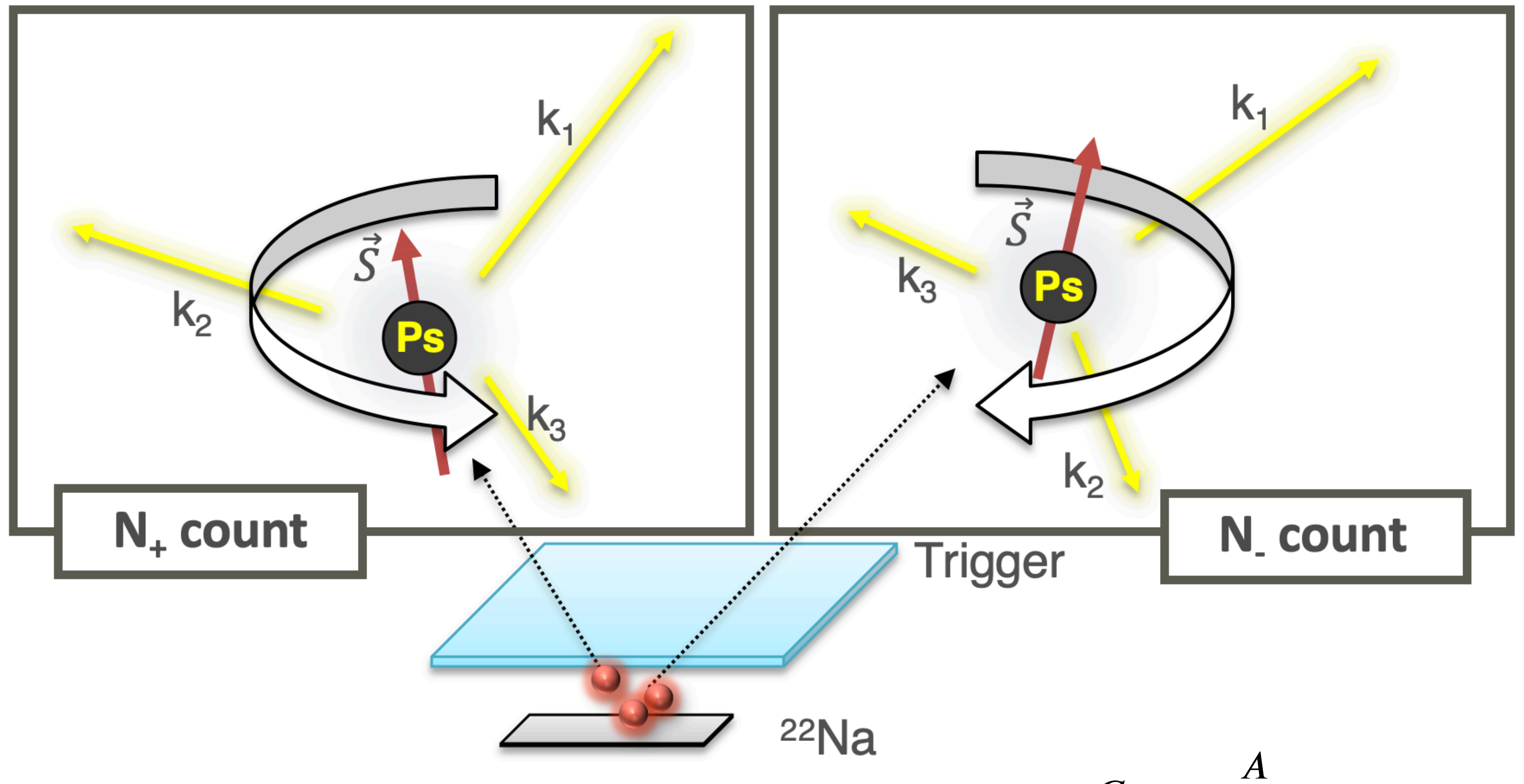
KAPAE I Goal

- Discrete symmetries of positronium
- CPT violation in lepton sector
- CPT violation forbidden

$$\vec{s}\cdot(\vec{k}_1\times\vec{k}_2)$$



The Ps rest frame



$$C_{cpt} = \frac{A}{\langle P\rangle}$$

$$A = \frac{N_+ - N_-}{N_+ + N_-}$$

$\langle P\rangle$ = 0.41 (^{22}Na)

$C_{cpt} = 0.0026 \pm 0.0031$ *

*Vetter P and J Freedman S 2003 91 263401

KAPAE II Goal

- Invisible Exotic Decay (Mirror world, Extra dimensions …)
- Visible Exotic Decay (Standard model verification, axion)

Milli-charged particles

- The grand unified theory (GUT) model

- Electric charge particles ("shadow" photon <<<< e-)

$$\Gamma(\text{o}-Ps \rightarrow X\bar{X}) = \frac{\alpha^5 Q_X^2 m_e}{6} \bullet k \bullet F(\frac{m_X^2}{m_e^2})$$

Mirror world

- The mirror universe model

- Vibration of o-Ps and mirror o-Ps

$$\text{Br}(\text{o}-Ps \rightarrow \text{ invisible}) = \frac{2(2\pi\varepsilon f)^2}{\Gamma^2 + 4(2\pi\varepsilon f)^2}$$

Extra dimensions

- k > 2.7 TeV

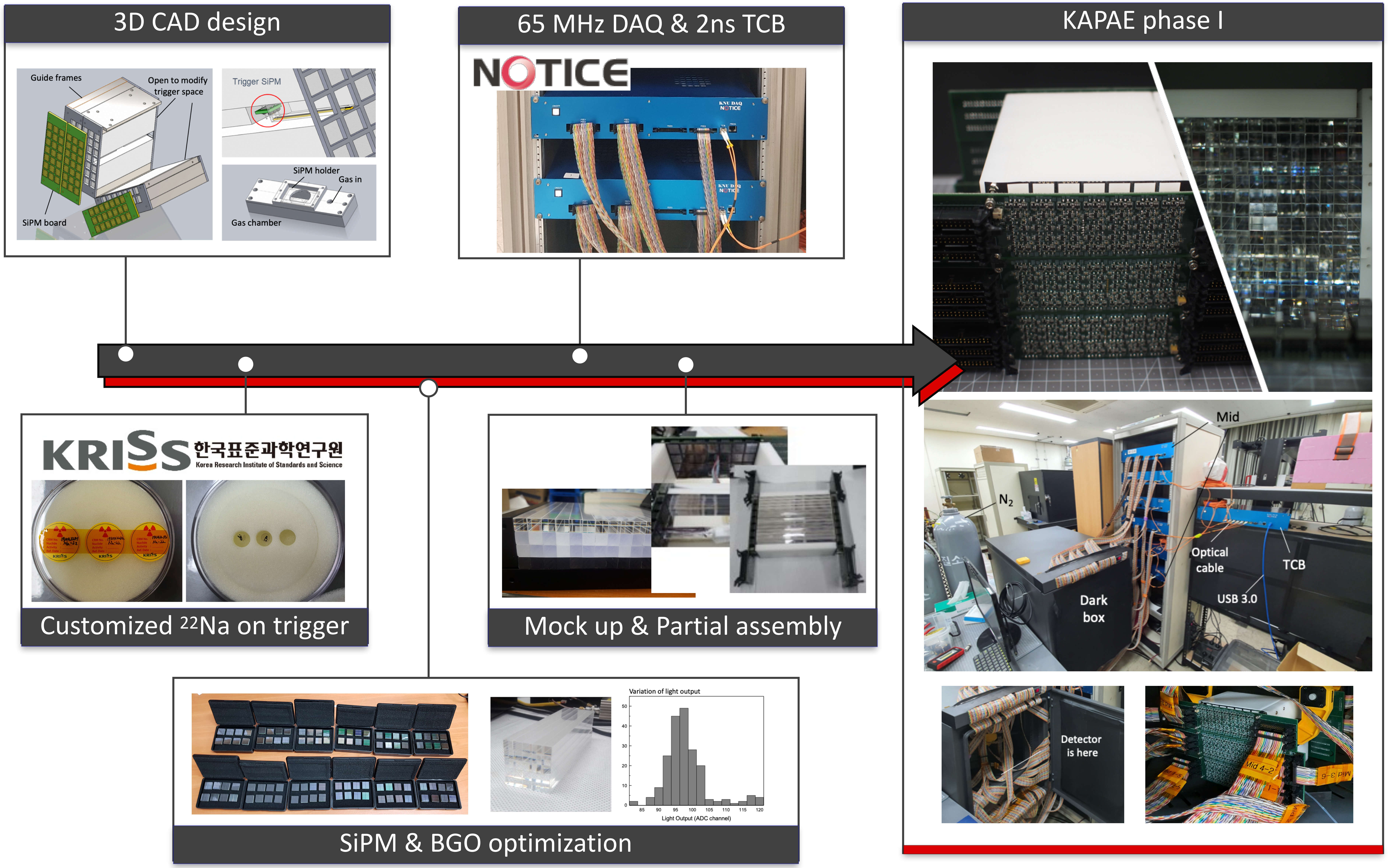
$$\text{o}-Ps \rightarrow \gamma^* \rightarrow \text{ additional dimension(s)}$$

$$\text{Br} = \frac{9\pi}{4(\pi^2-9)} \bullet \frac{1}{\alpha^2} \bullet \frac{\pi}{16}\left(\frac{m_0 - \text{Ps}}{k}\right)^2 \approx 3\times 10^4 \left(\frac{m_0 - \text{Ps}}{k}\right)^2$$

Axion

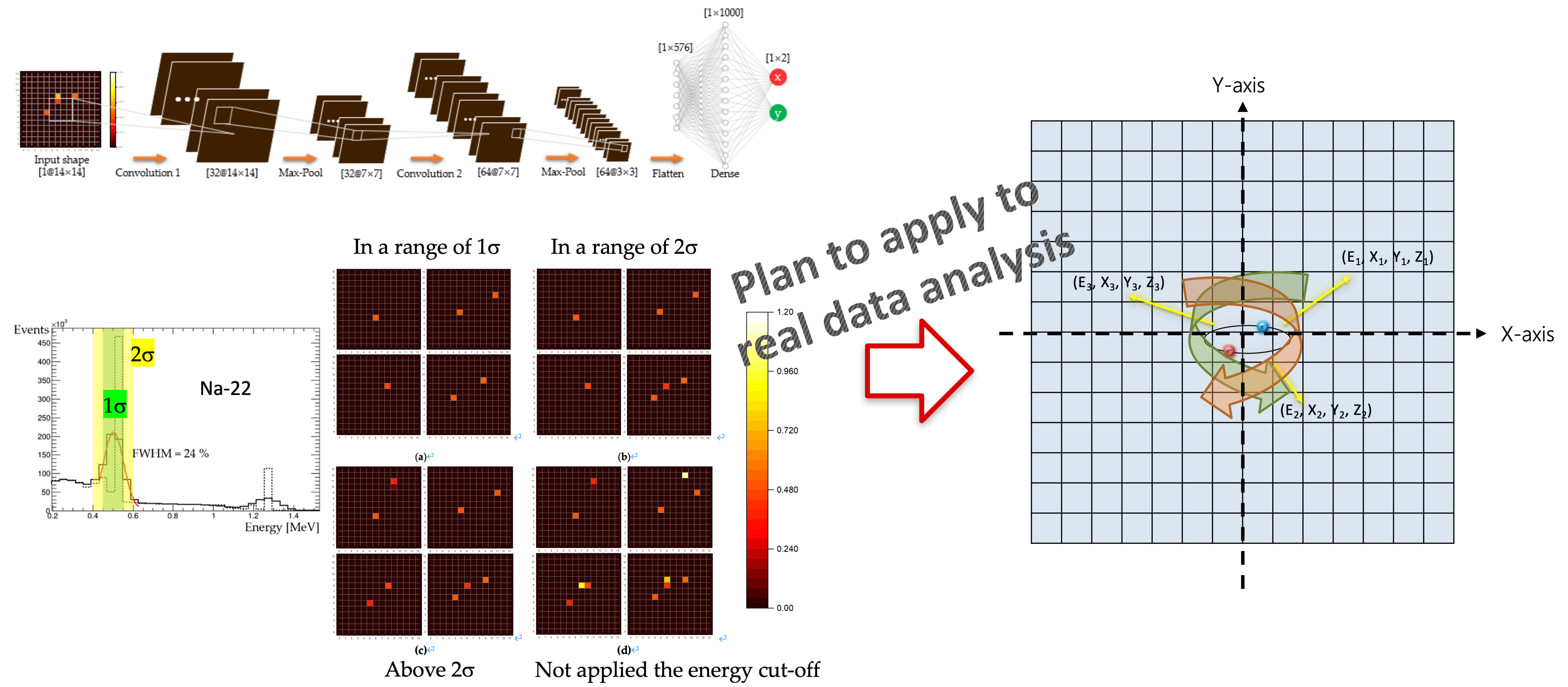
- Light pseudoscalar

$$\text{o}-\text{Ps} \rightarrow \gamma X$$


3D CAD design
Guide frames
Open to modify trigger space
Trigger SiPM
SiPM holder
Gas in
SiPM board
Gas chamber
65 MHz DAQ & 2ns TCB
NOTICE
KAPAE phase I
Mid
N2
Optical cable
TCB
USB 3.0
Dark box
Detector is here
KRISS 한국표준과학연구원
Korea Research Institute of Standards and Science
Customized 22Na on trigger
Mock up & Partial assembly
Variation of light output
Light Output (ADC channel)
SiPM & BGO optimization

Deep learning data analysis

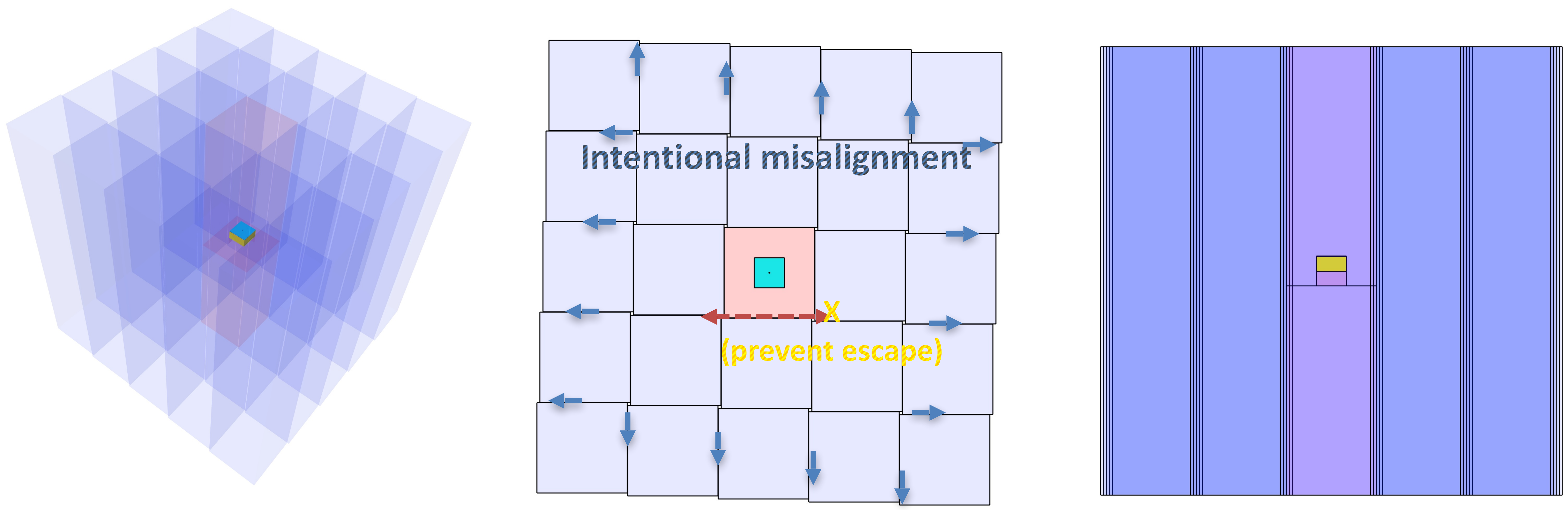
- CNN Deep learning (KAPAE Phase I Geant4 simulation data)
- Positronium annihilation reconstruction (x2 improvement in accuracy)



CNN Deep learning

Design of KAPAE II

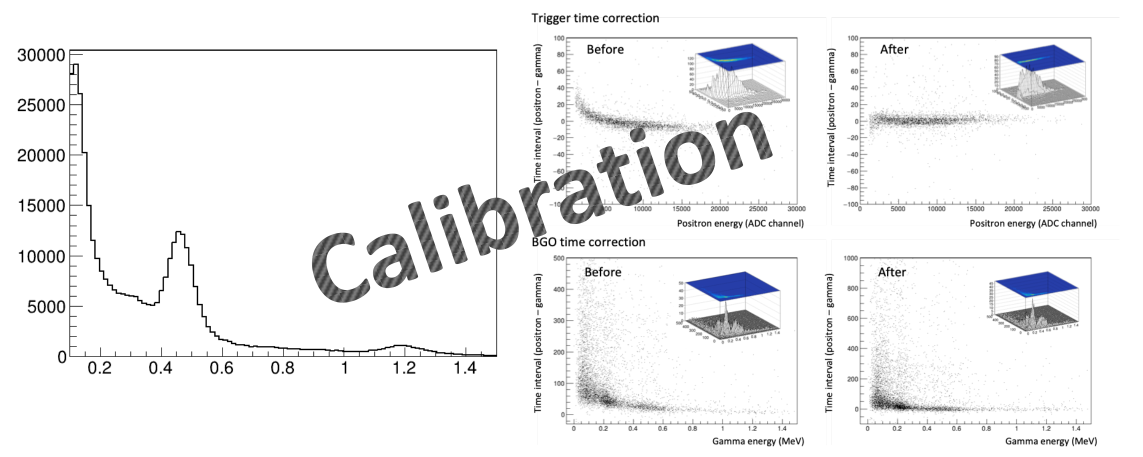
- 1st : Designed with a focus on improving zero deposit events
  → Hexagonal pillar type BGO (*Out of current funding limit*)
- 2nd : Designed to be economically upgradable
  → Changed to square pillar type BGO + Intentional misalignment (To prevent escape along the gap)



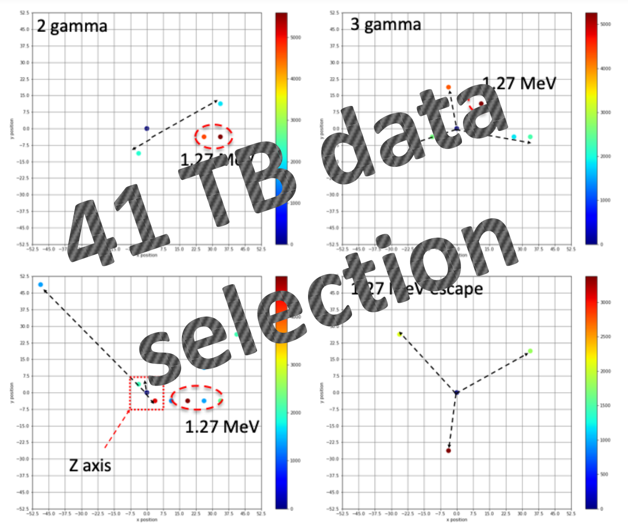
2nd Design of KAPAE II

KAPAE Phase I

Analysis of Preliminary Data



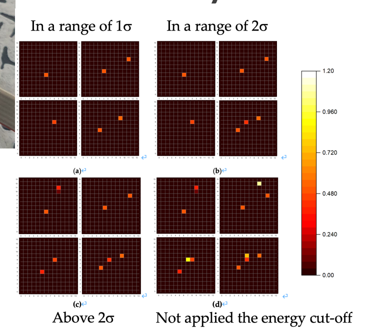
3 month data taking



Upgrade

Trigger direction modify

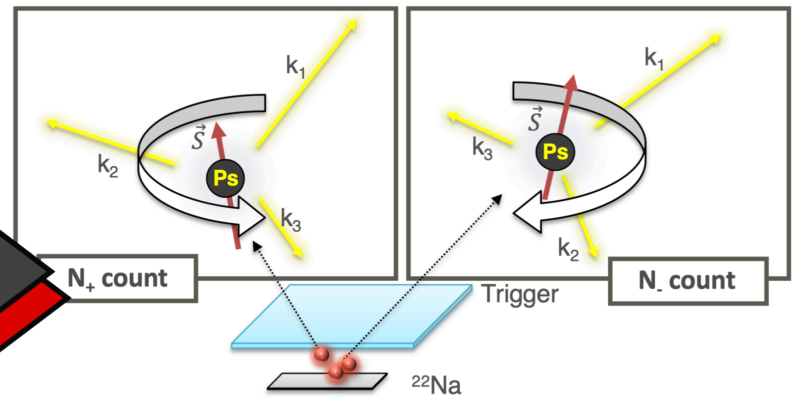
CNN data analysis

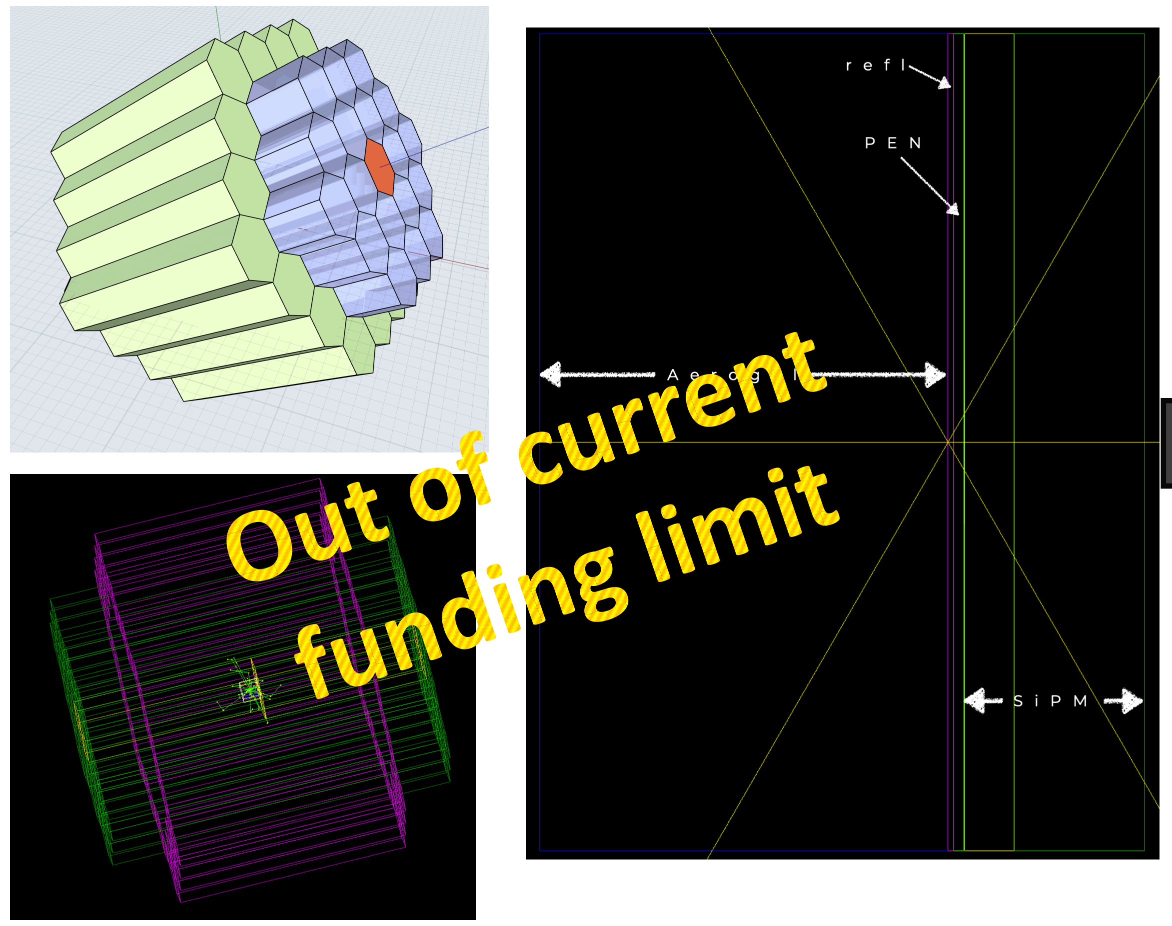


CPT Violation

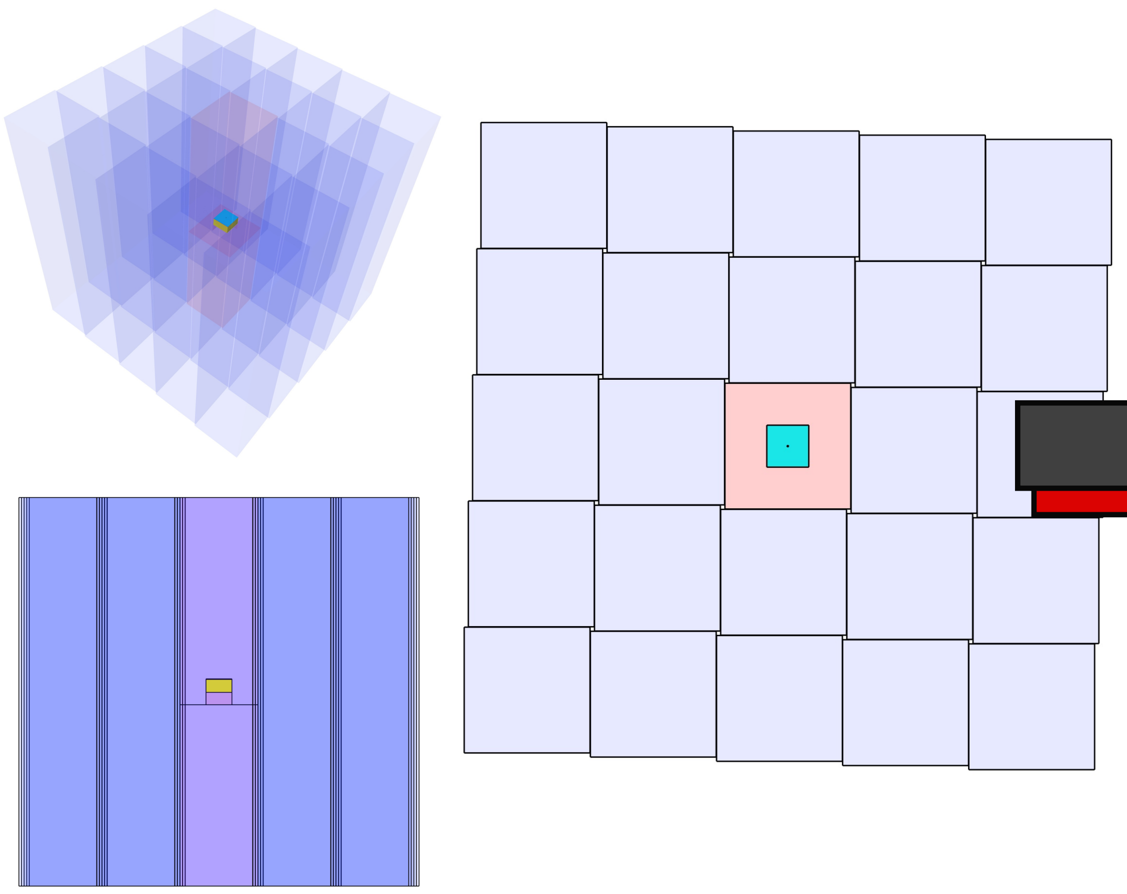
- CPT Violation sensitivity ± 0.000142 at 90%CL (5.5 times improvement)

→ ± 0.000086 at 90%CL (9.0 times improvement)





1st Design & Simulation



2nd Design & Simulation

- Invisible upper limit sensitivity

[KAPAE phase I]

1.778×10^{-8} at 90% CL

[KAPAE phase II]

→ 1.728×10^{-9} at 90% CL

0.0073 % → 0.000069%

Zero deposit events improve

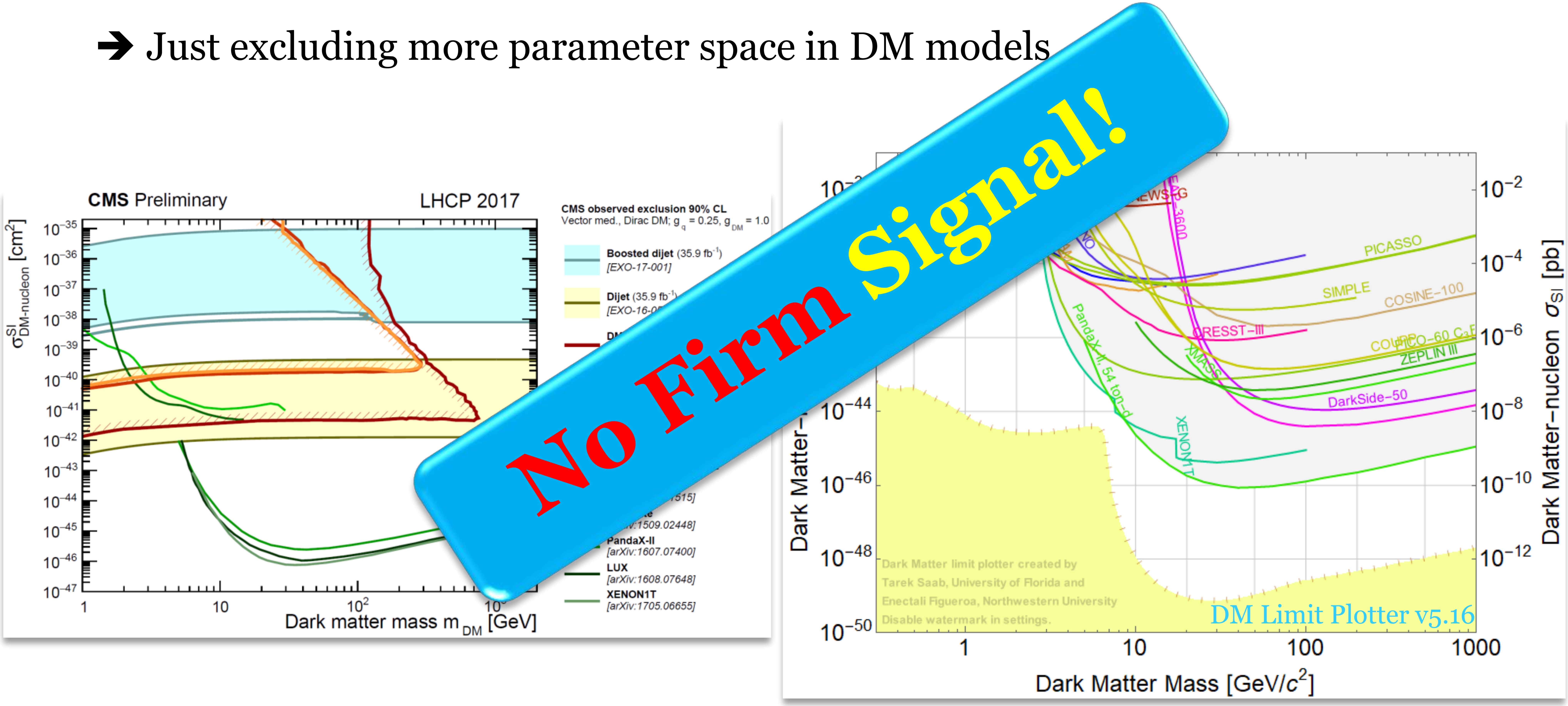
Invisible Decay

KAPAE Phase II

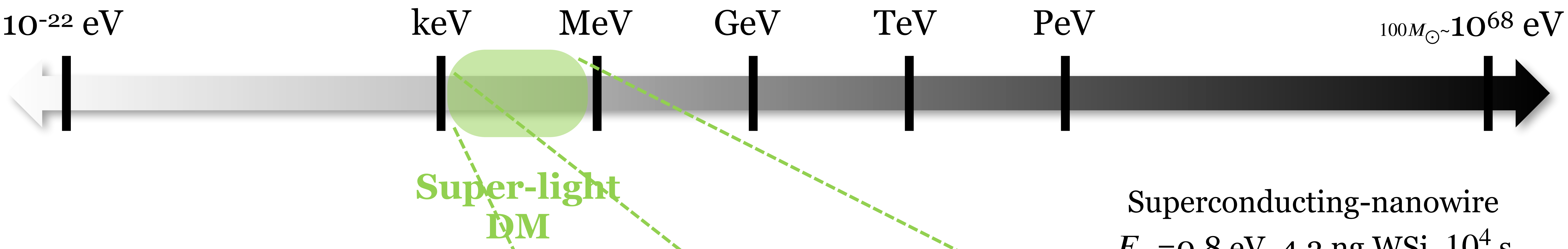
Super-Light Dark Matter

Current Status of Conventional DM Searches

- ❖ No (solid) observation of DM signatures via non-gravitational interactions
- ❖ Many searches designed under WIMP/minimal dark sector scenarios
  - ➔ Just excluding more parameter space in DM models

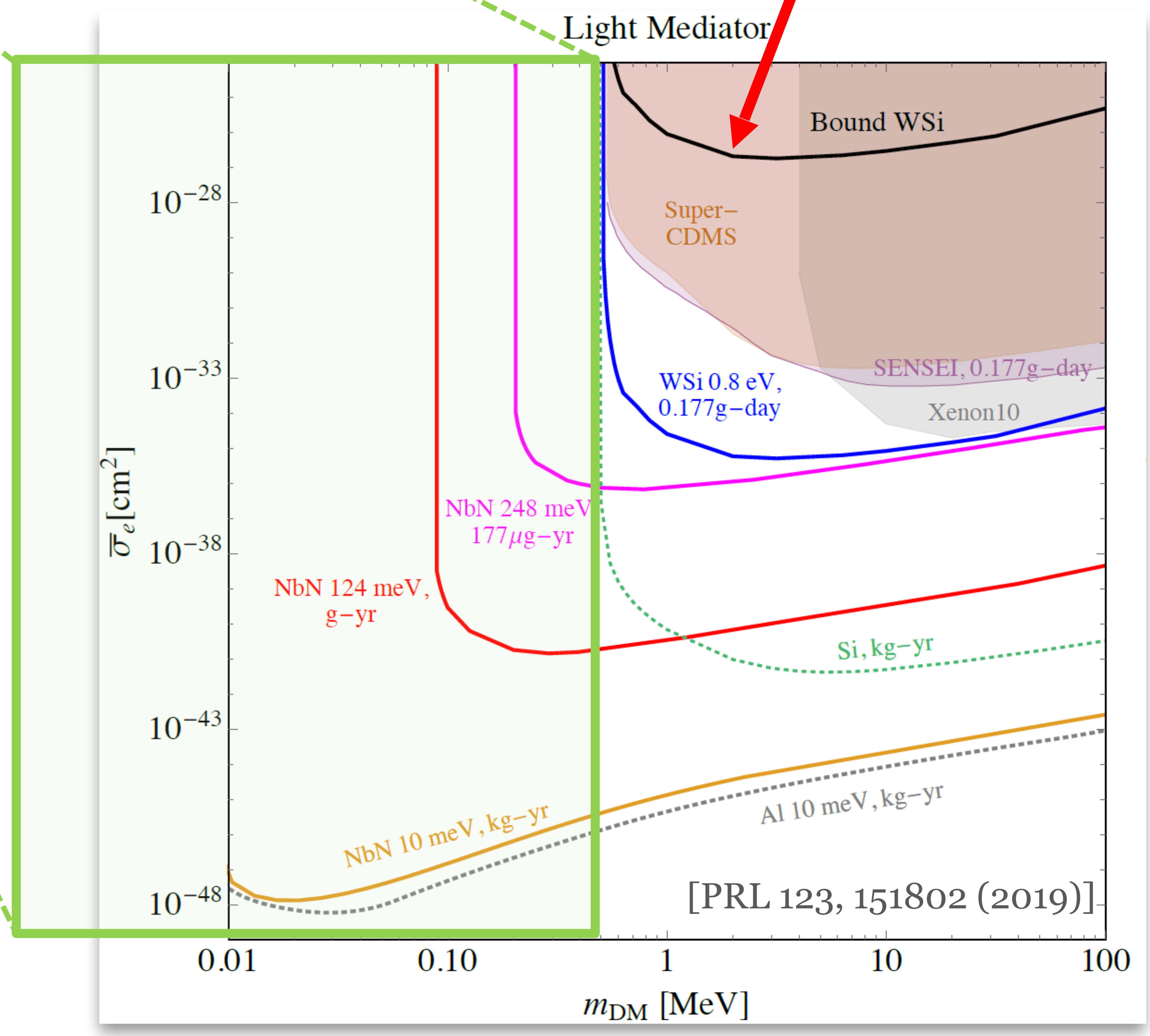


Super-Light DM: Direct Search Status



- ❖ E_k~mv^2~O(meV) with m~keV & v~10^{-3}
- ❖ **New ideas** are required!
  - ✓ Superconductor [PRL (2016)]
  - ✓ Superfluid He [PRL (2016)]
  - ✓ 3D Dirac material [PRD (2018)]
  - ✓ Polar material [PLB (2018)]
  - ✓ Superconducting-nanowire [PRL (2019)]
  - ✓ ...
- ❖ **World race** to prove **super-light DM**.
- ❖ **No experiment** for **O(keV) DM** so far.

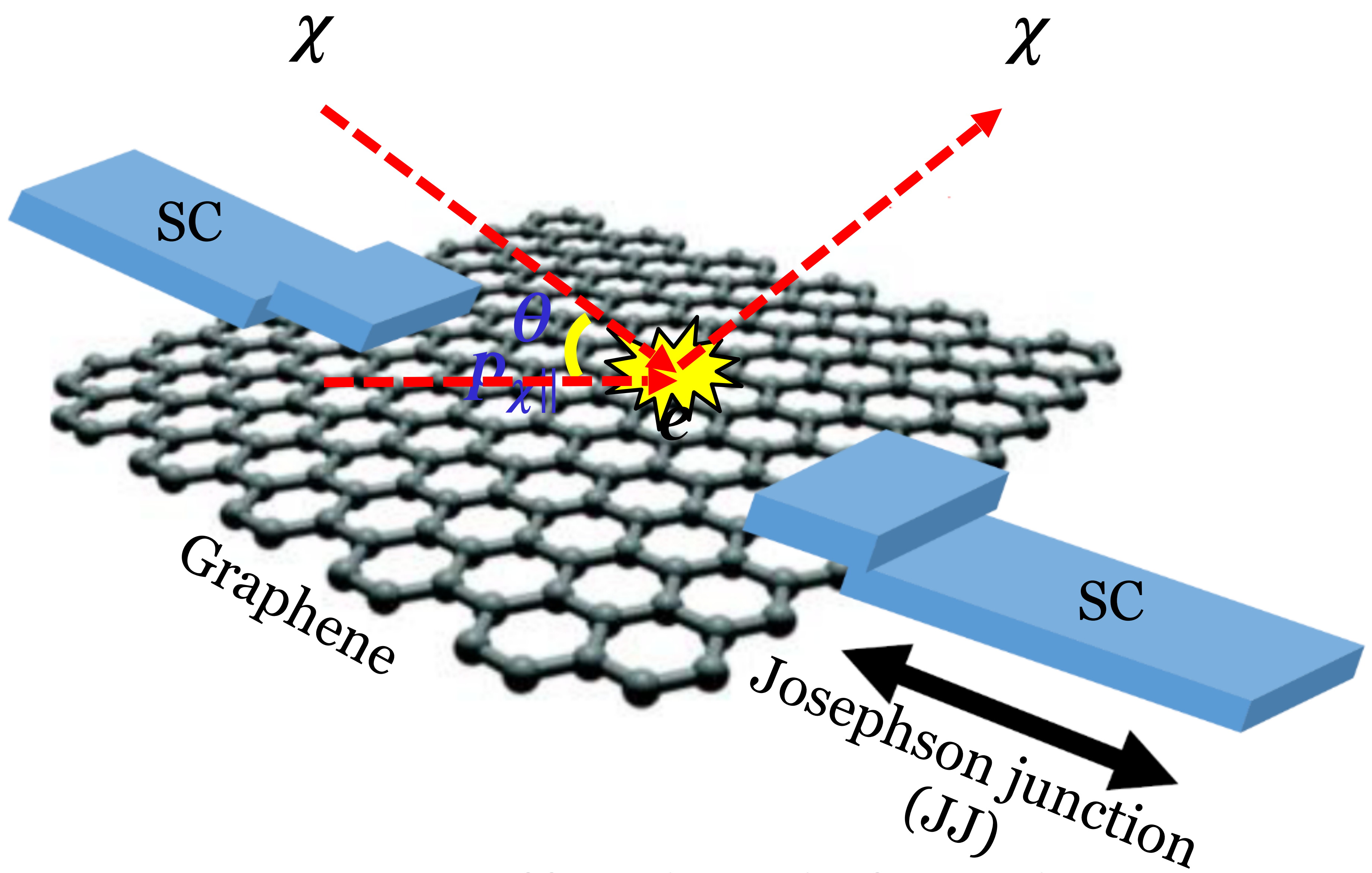
Superconducting-nanowire
E_{th}=0.8 eV, 4.3 ng WSi, 10^4 s



[PRL 123, 151802 (2019)]

Detection Principle with GJJ

D. Kim, J.-C. Park, K. C. Fong & G.-H. Lee,
[arXiv:2002.07821 & In preparation]



✓ **Scattering** between DM traveling in 3D & electrons confined in 2D graphene

✓ **Prediction**:

angular dependence of the signal rate

➔ applicable to background rejection

I. **DM scatters off (π-bond) free electrons**, transferring some fraction of its incoming E_k.

II. **The recoiling e heats up & thermalizes** with nearby e's rapidly via e-e interactions.

III. **The JJ is triggered**: the temperature rise switches the zero-voltage (non-resistive) of JJ to a **non-zero-voltage (resistive) state**.

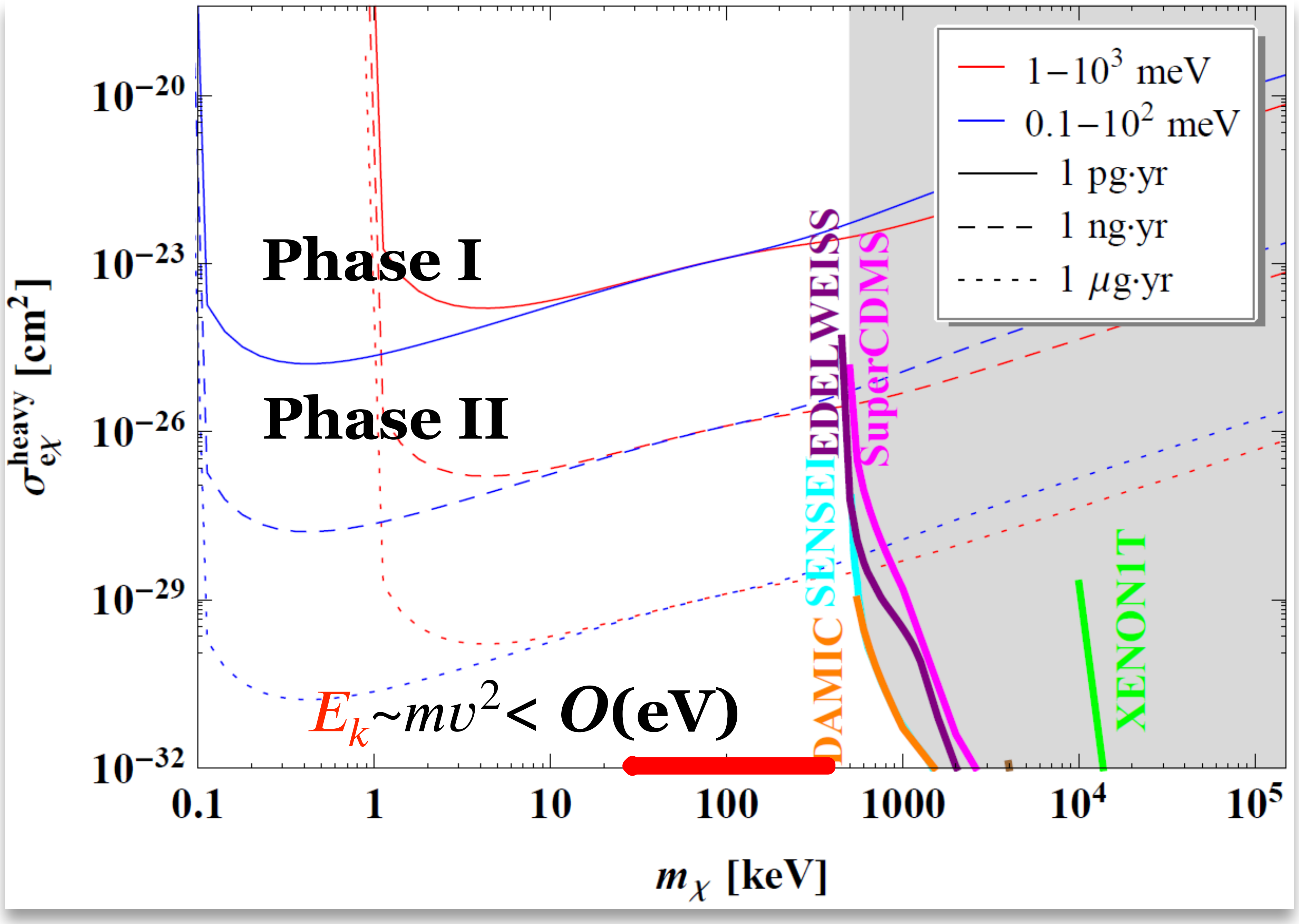
❖ **GJJ**: sensitivity to ~0.1 meV E deposit demonstrated experimentally [Nature (2020)]

❖ E_k~mv^2 & v~10^{-3} ➔ **GJJ detector: sensitivity** to the signal even by **sub-keV DM**.

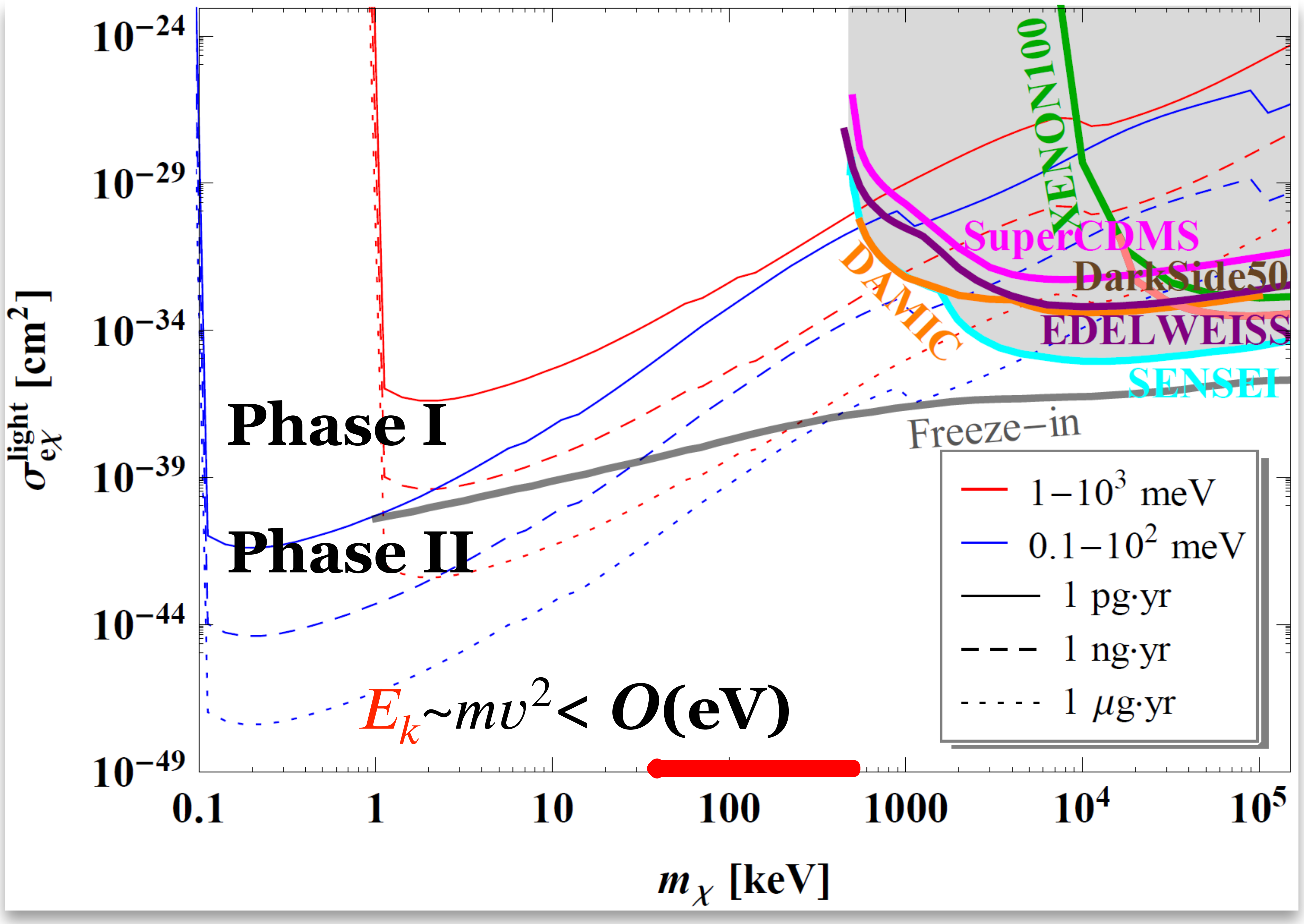
Expected Sensitivities

D. Kim, J.-C. Park, K. C. Fong & G.-H. Lee,
[arXiv:2002.07821 & In preparation]

Heavy mediator: $F_{DM} = 1$



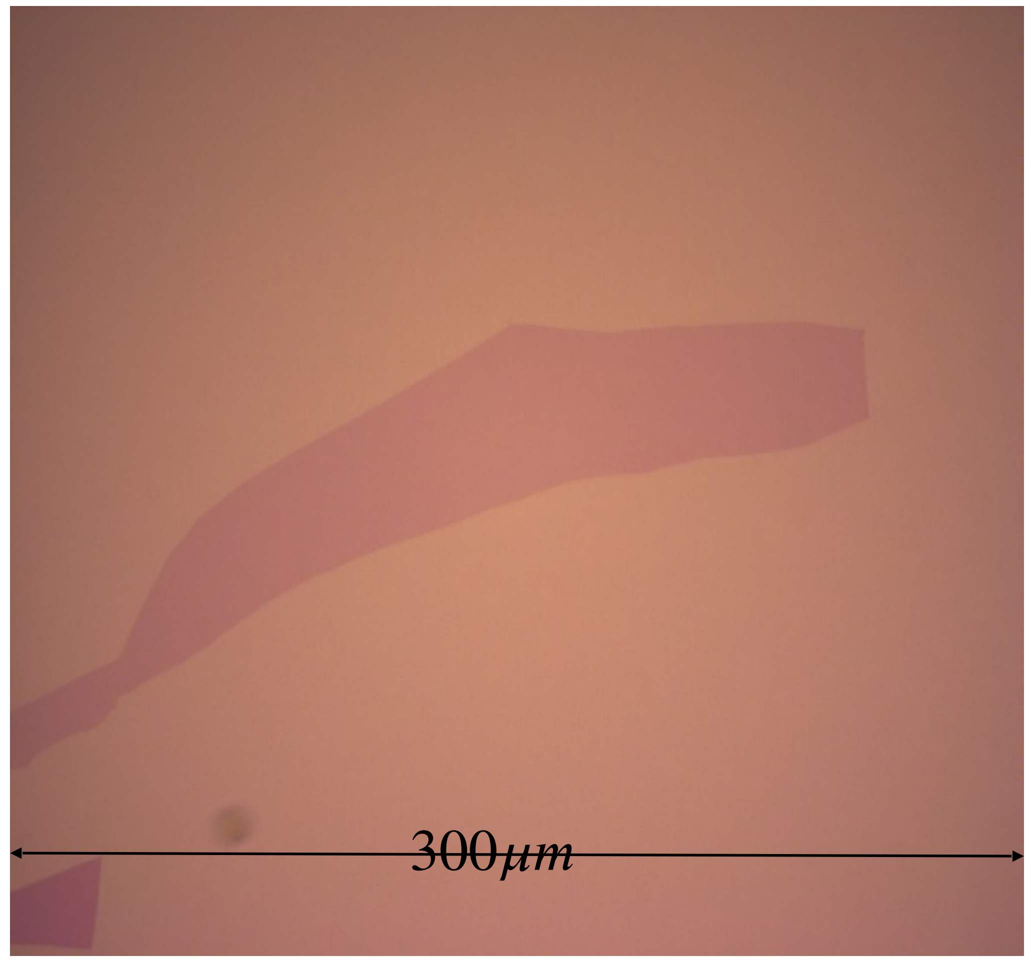
Light mediator: $F_{DM} \propto 1/q^2$ with $q_{ref} = \alpha_e m_e$



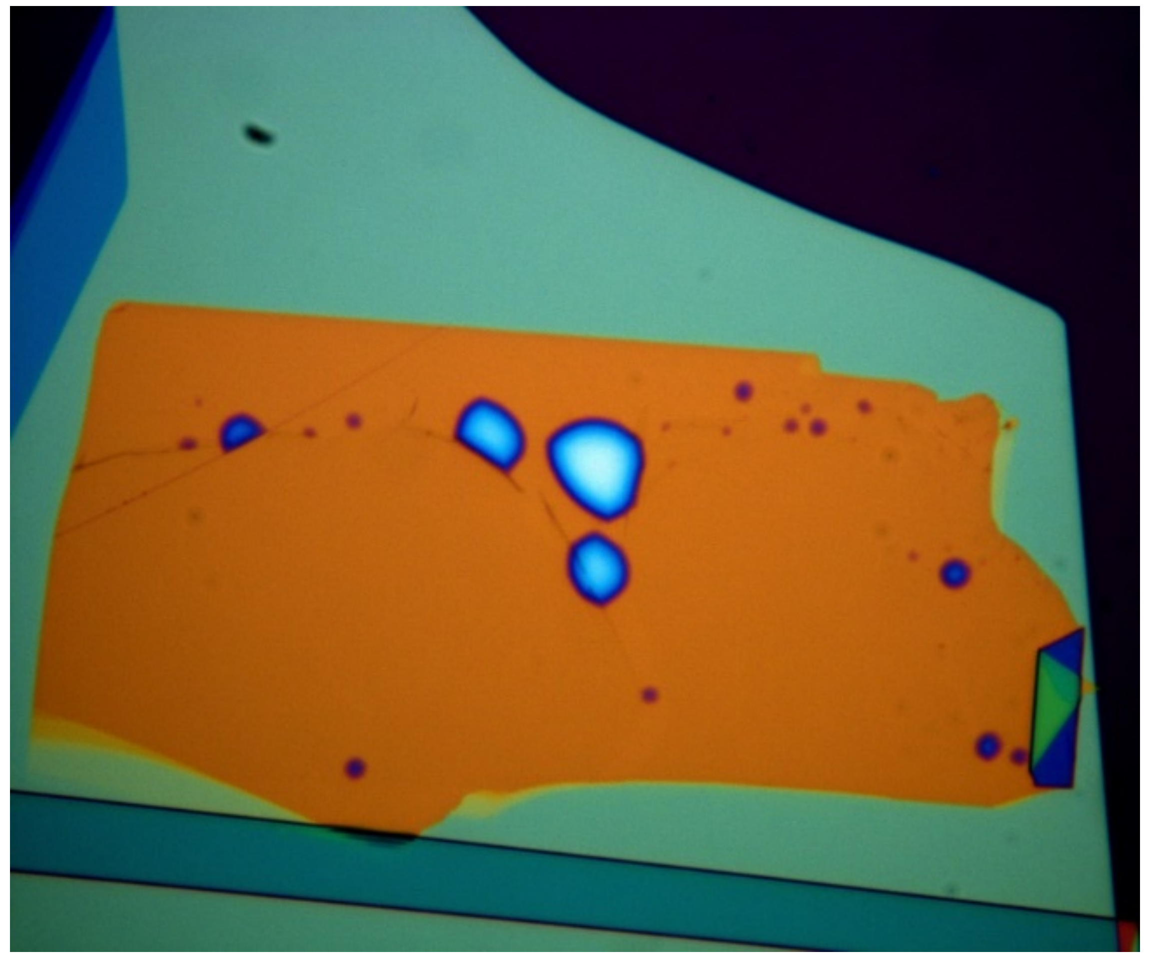
✓ The **proposed detector** can improve the minimum detectable DM mass (**$m_{DM} \sim 0.1$ keV**) by more than 3 orders of magnitude over the ongoing/existing experiments.

✓ **Capable of probing** the prediction of **freeze-in** scenarios even with a pg-scale detector.

Progress in Fabrication: ~100 GJJs in Series 1



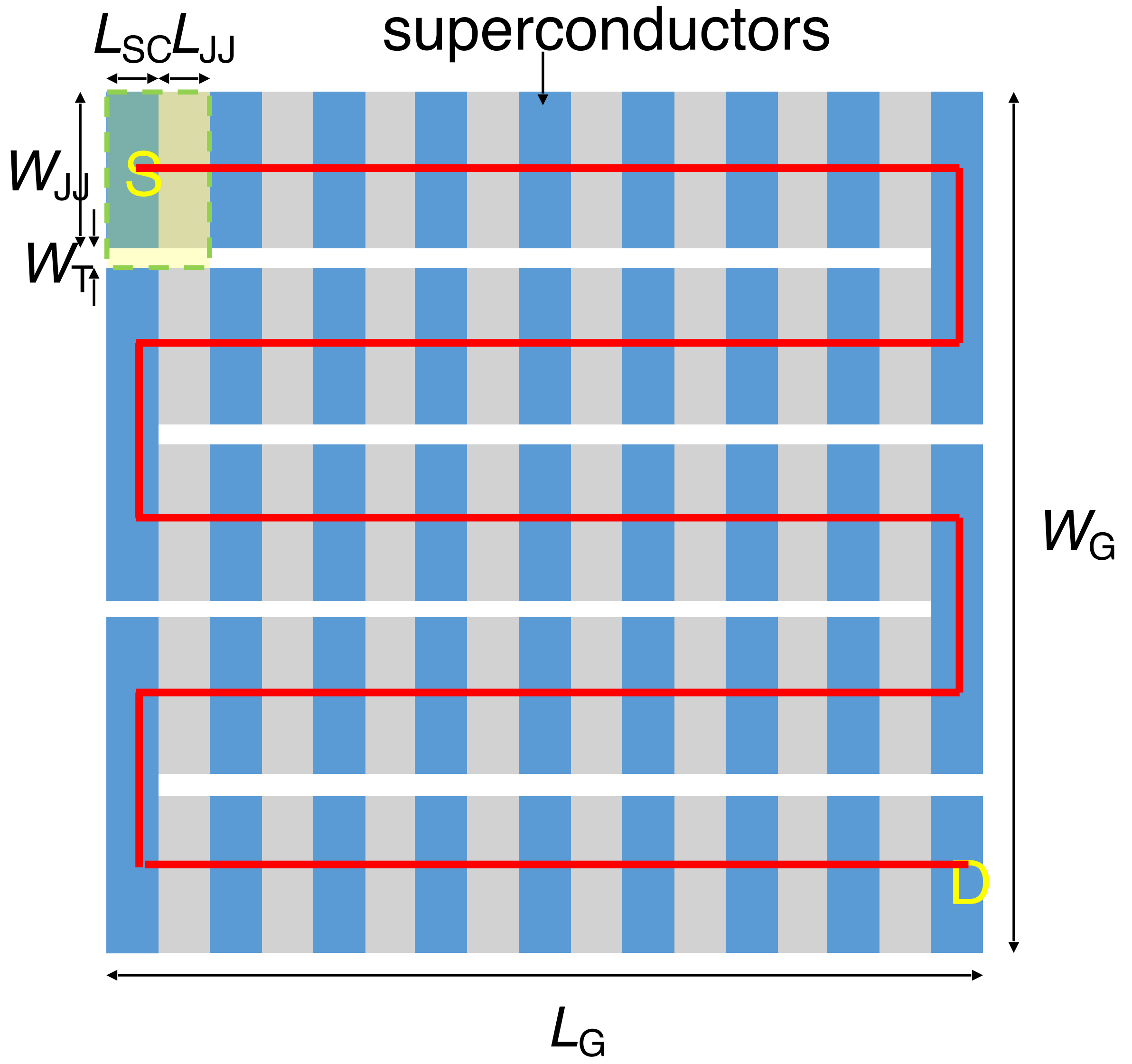
Large piece of graphene



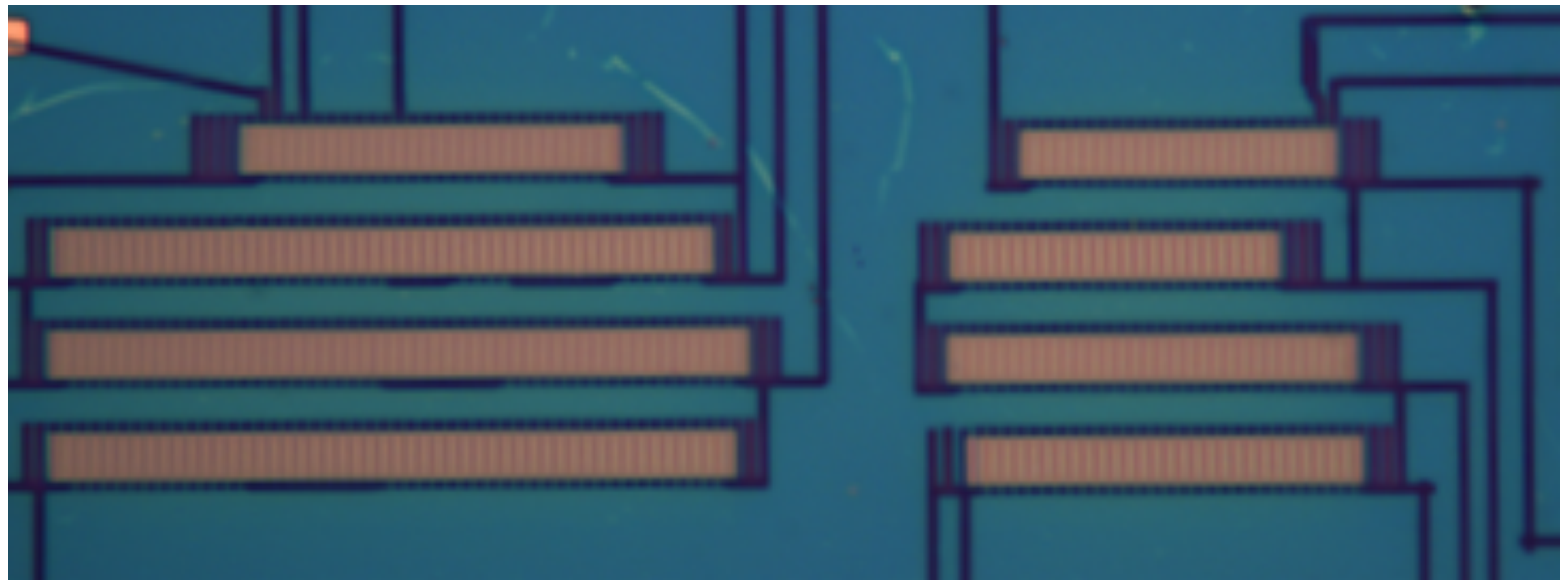
hBN-encapsulated graphene

Etched hBN/Graphene/hBN stack

Schematics

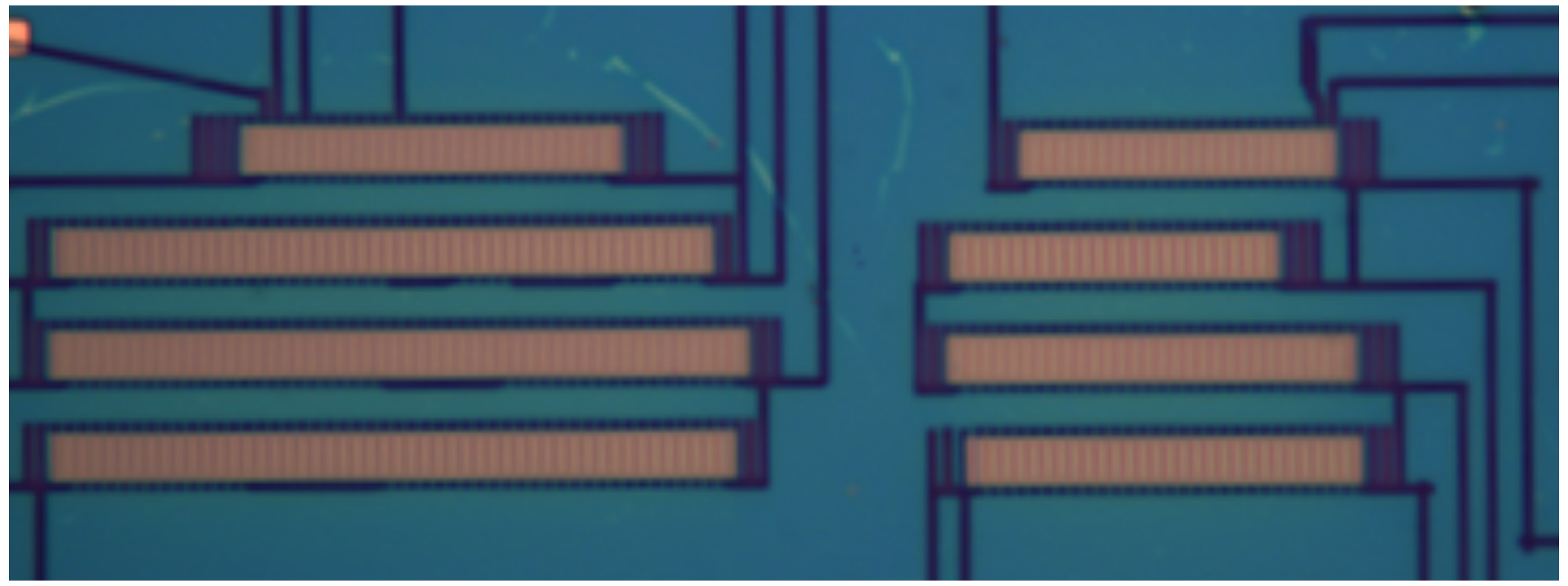


216 GJJs connected in series

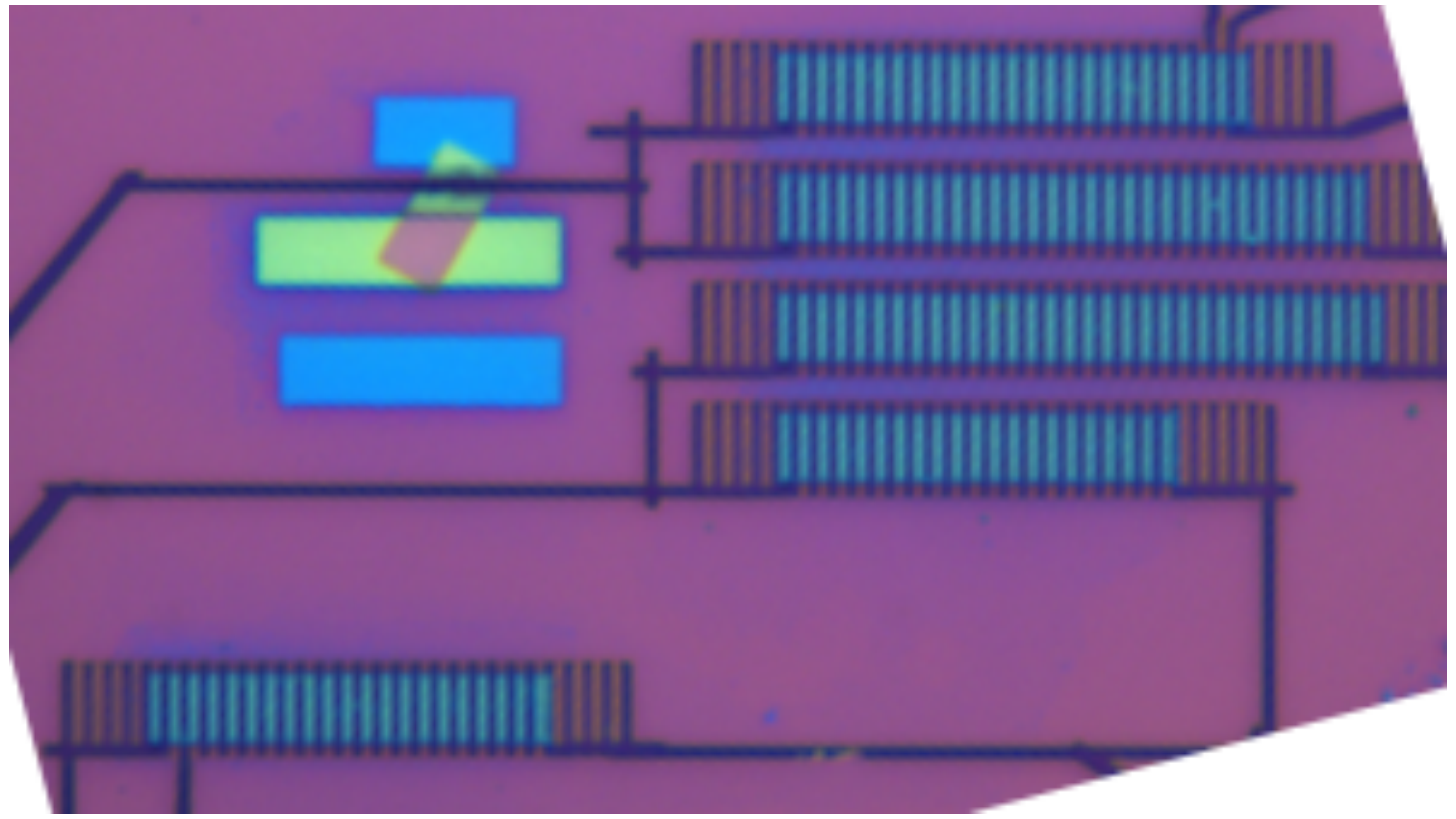


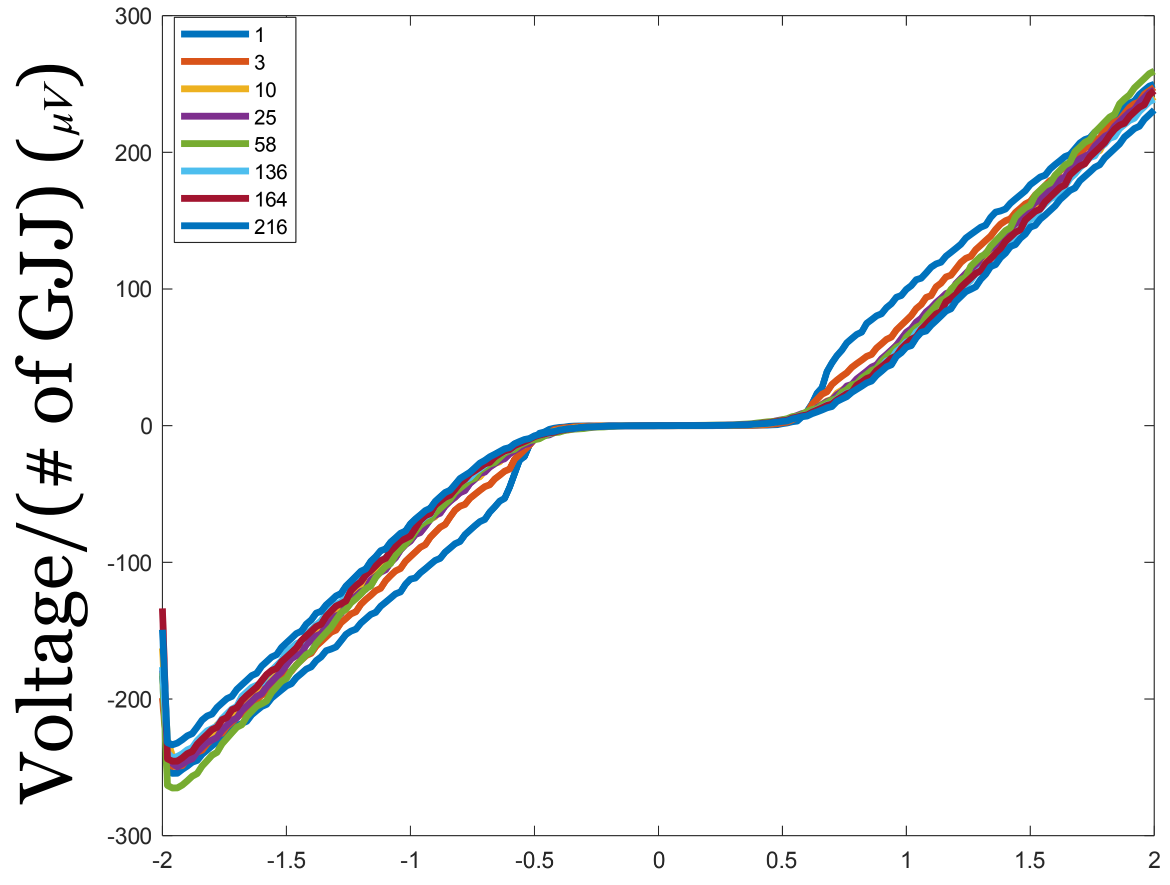
Progress in Fabrication: ~100 GJJs in Series 2

216 GJJs connected in series

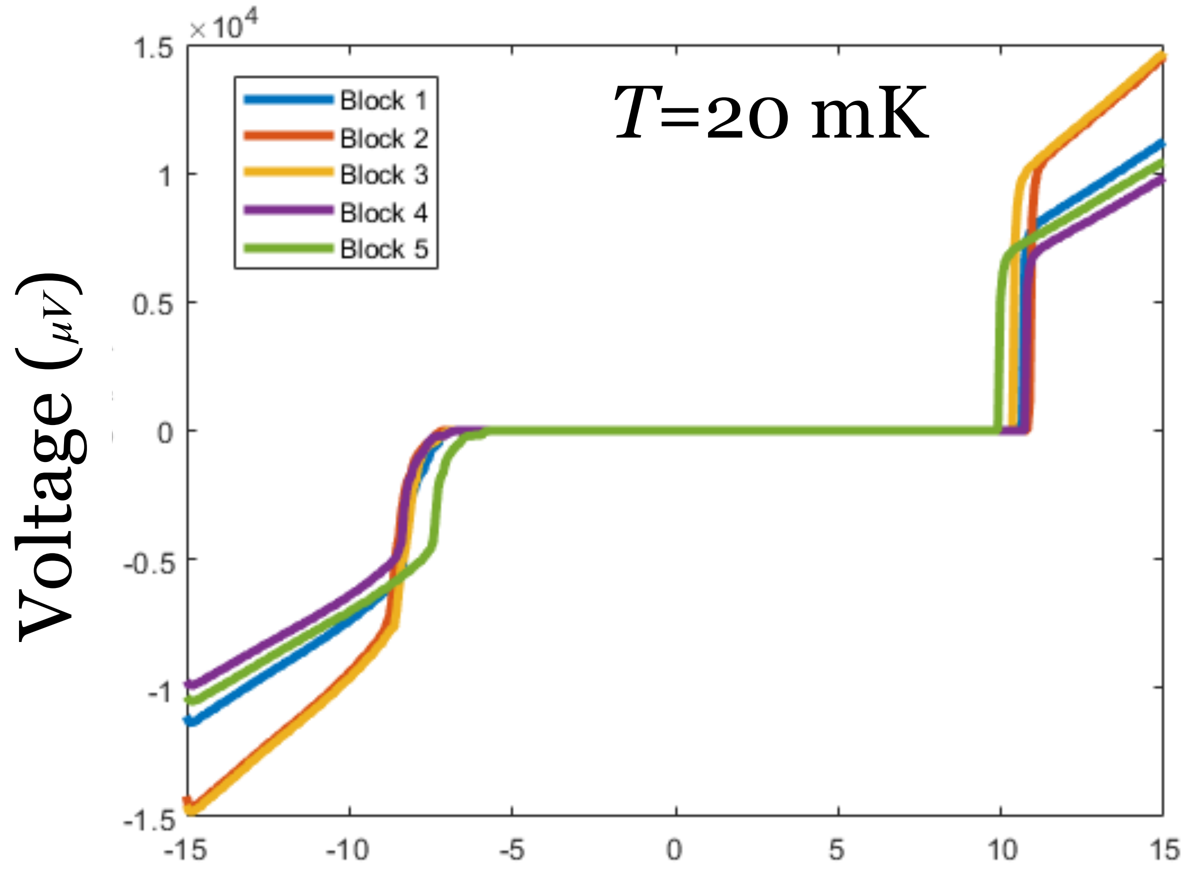


123 GJJs connected in series





I_c non-uniformity: ~ 15%

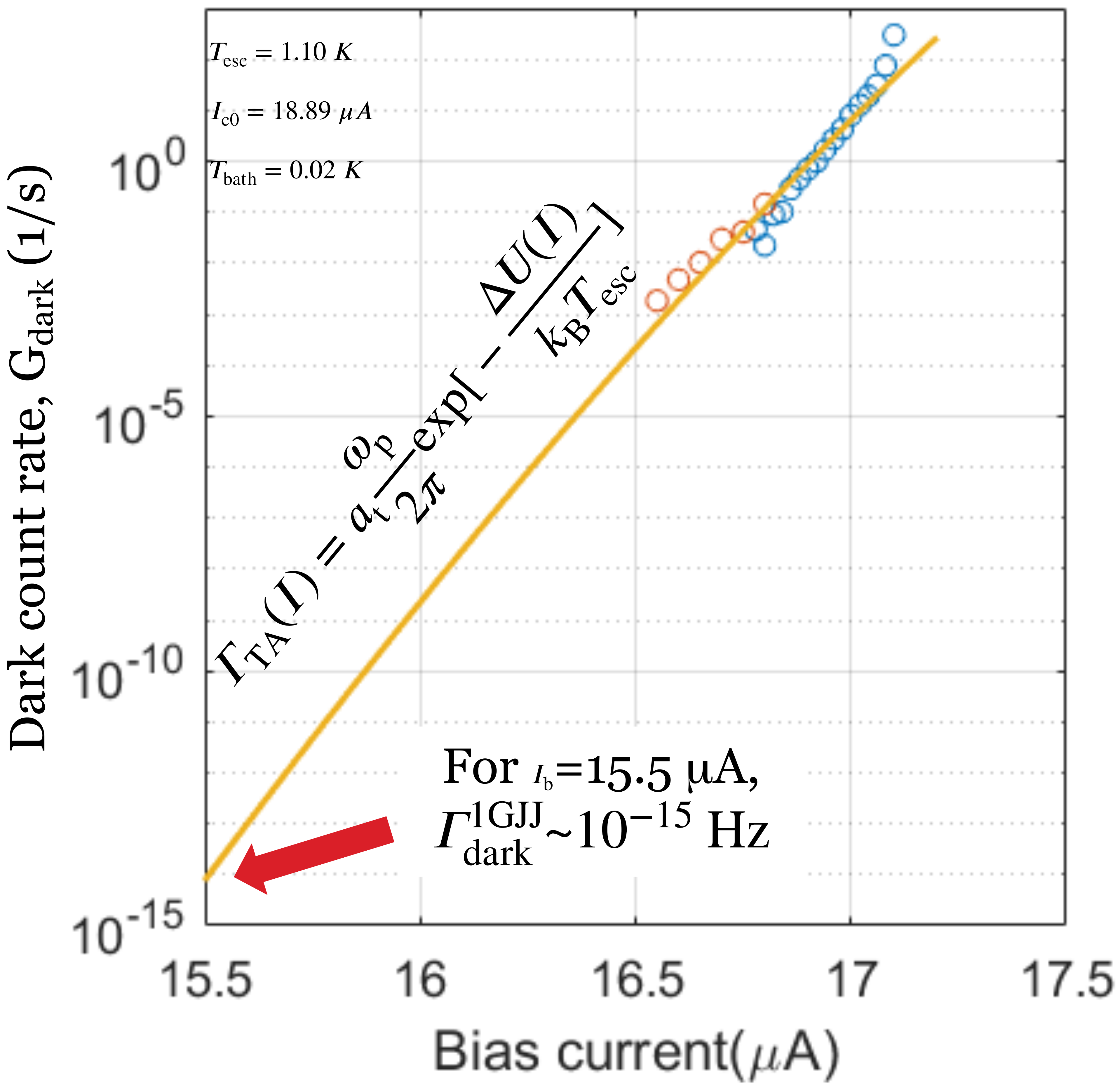


I_c non-uniformity: ~ 5%

Uniform Josephson junctions in series was fabricated.

Progress in Dark Count Rate Estimation

[Dark count rate measurement]

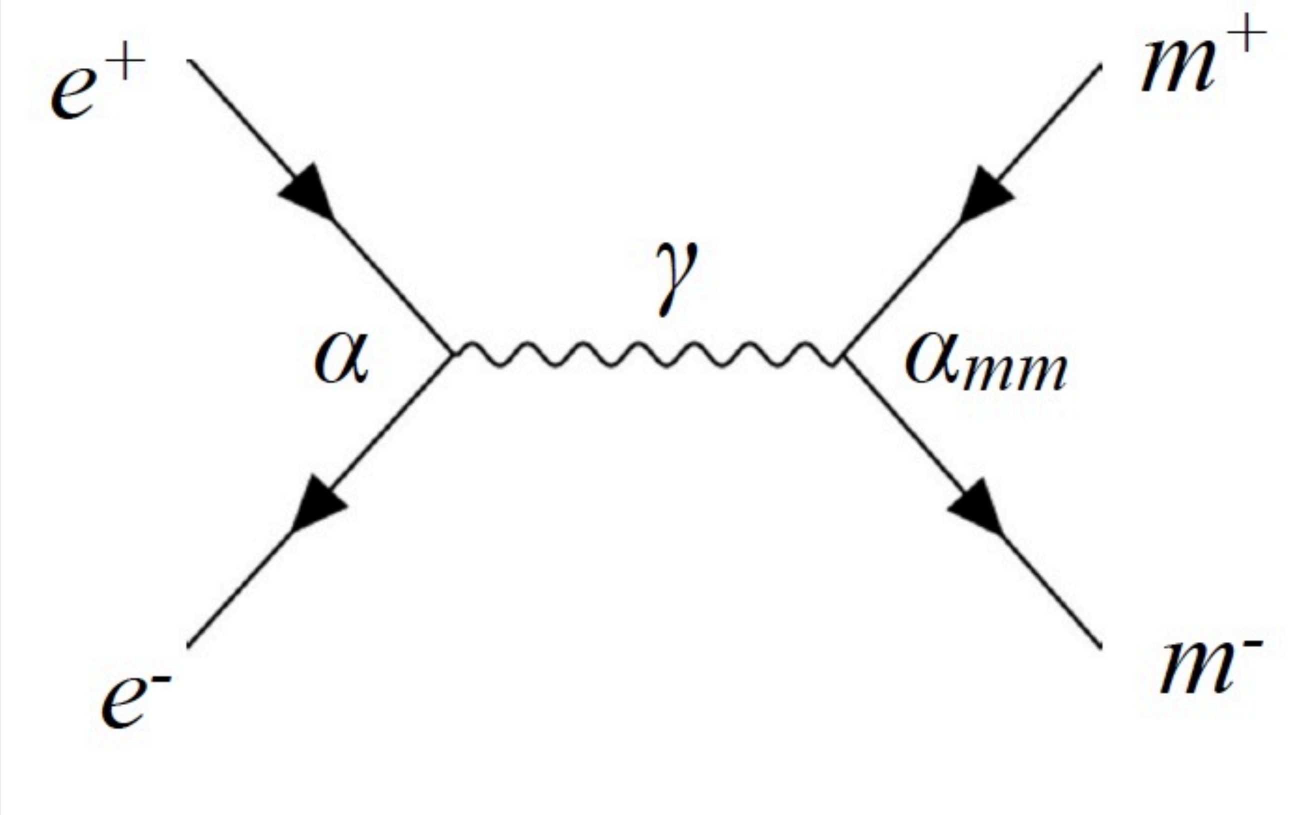


For 1-GJJ, we measured $\Gamma_{dark}^{1GJJ} \sim 10^{-15}$ Hz at I_b=15.5 μA

For uniform 10^6-GJJ array, we expect $\Gamma_{dark}^{10^6 GJJ} \sim 10^{-9}$ Hz & dark count rate~0.03/year at I_b=15.5 μA.

KoreA Experiment on Magnetic Monopole (KAEM)

Magnetic Monopole Production



$$e^+e^- \rightarrow \gamma^* \rightarrow m^+m^-$$

$$\sigma(e^+e^- \rightarrow m^+m^-) = \frac{4\pi}{3}\frac{\alpha\alpha_{m^+m^-}}{s}\sqrt{\frac{1-4m_m^2/s}{1-4m_e^2/s}}(1+2m_e^2/s)(1+2m_m^2/s)$$

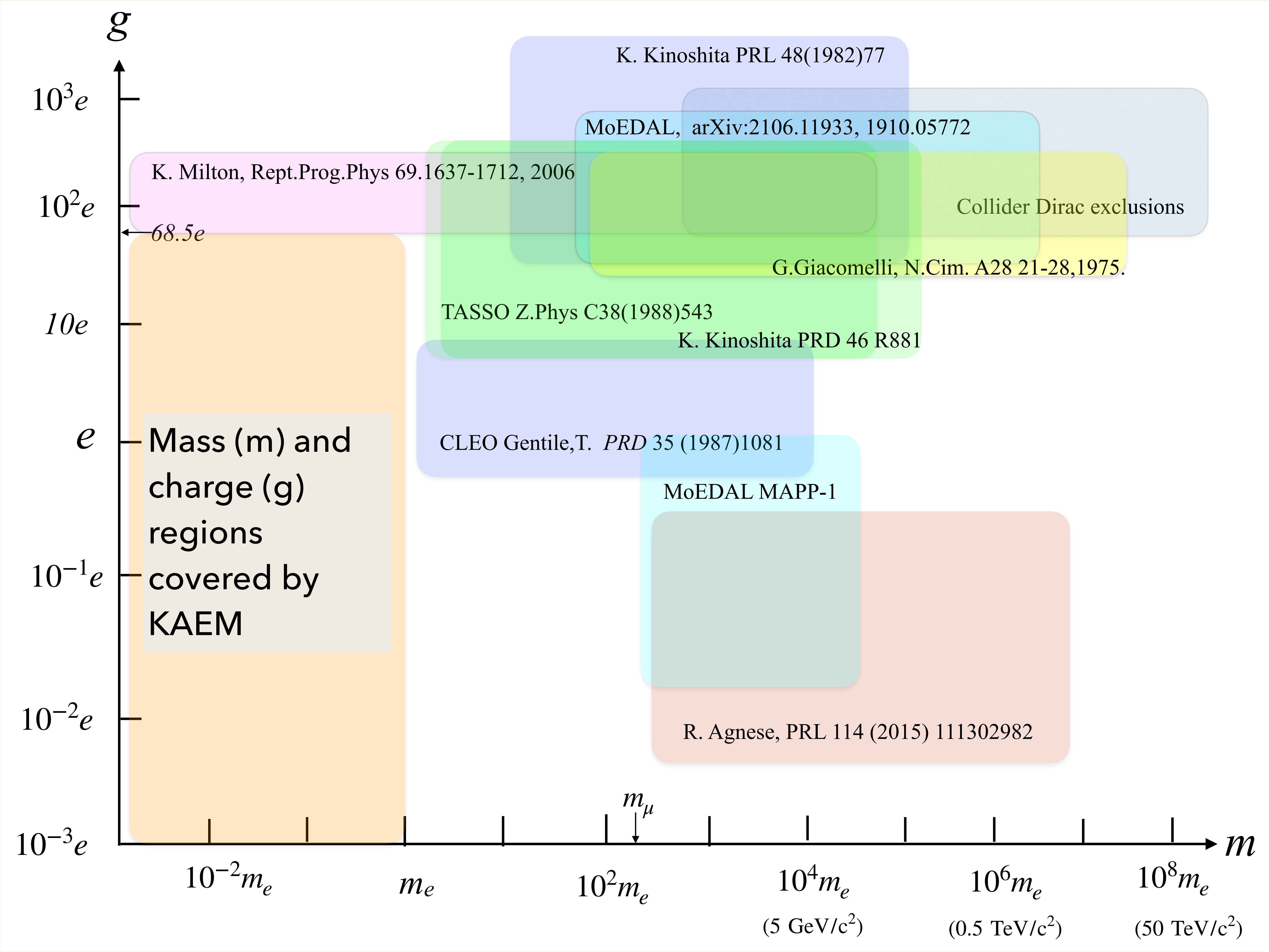
Coupling strength (or production probability)

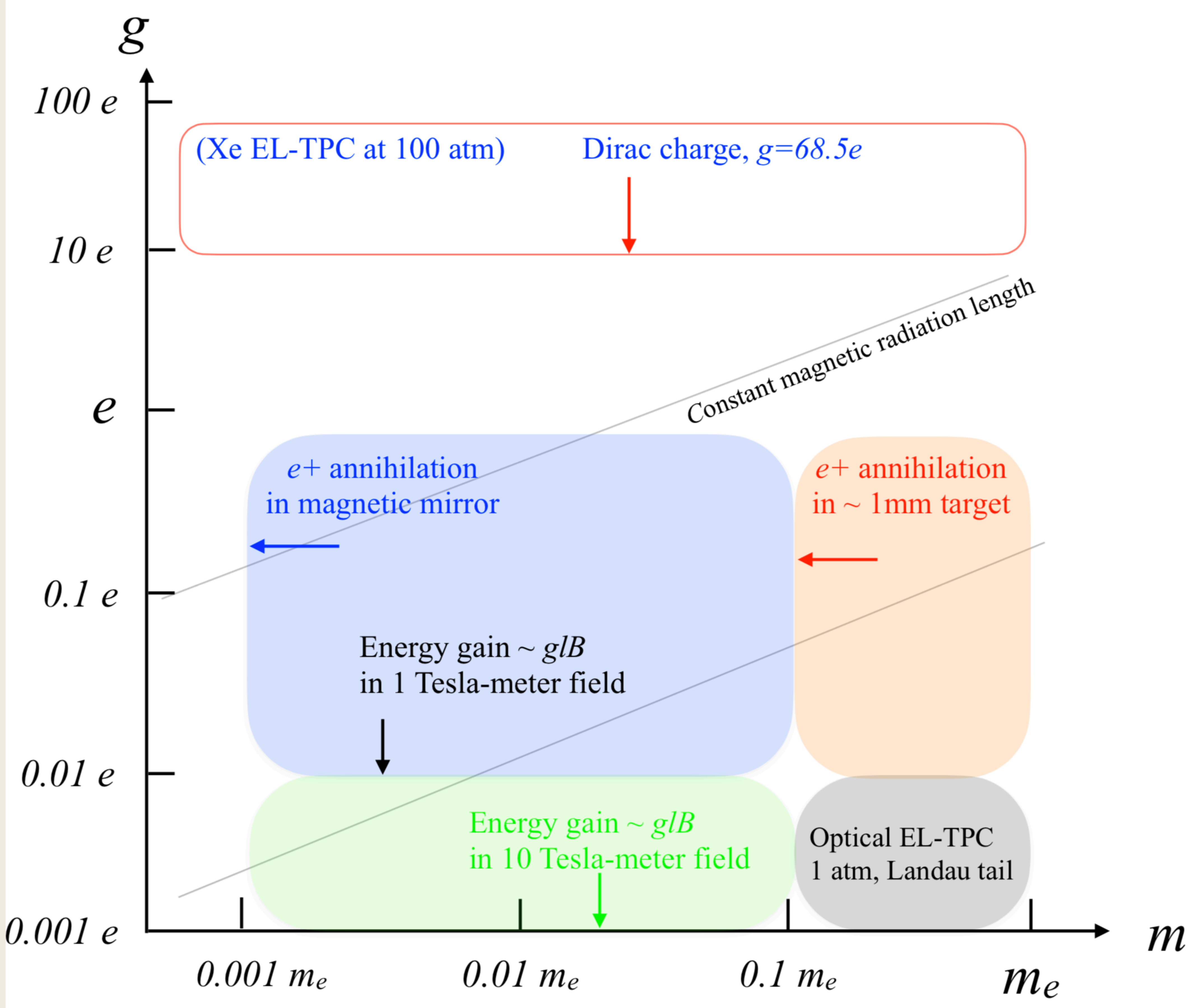
$$\alpha = e^2/4\pi\epsilon_0\hbar c \approx 1/137 \qquad \alpha_{m^+m^-} = \frac{g^2}{4\pi\epsilon_0\hbar c}$$

For small magnetic charge, g < e ➔
- **small energy transfer in ionization energy loss**
- **small radiation energy losses**
- **small magnetic Cerenkov light generation**

➔ the design of new detectors

Our Exploring Area





Target Optimization (Hyper-EM)

4. Energy loss of monopole

◈ Radiative energy loss

$$\left[\frac{dE_{rad}}{dx}\right]_{magnetic} = \frac{(g/e)^4}{(m/m_e)^2}\left[\frac{dE_{rad}}{dx}\right]_{electric}$$

◈ Ionization energy loss

$$\left[\frac{dE_{ion}}{dx}\right]_{magnetic} = \left(\frac{g\beta}{e}\right)^2\left[\frac{dE_{ion}}{dx}\right]_{electric}$$

4

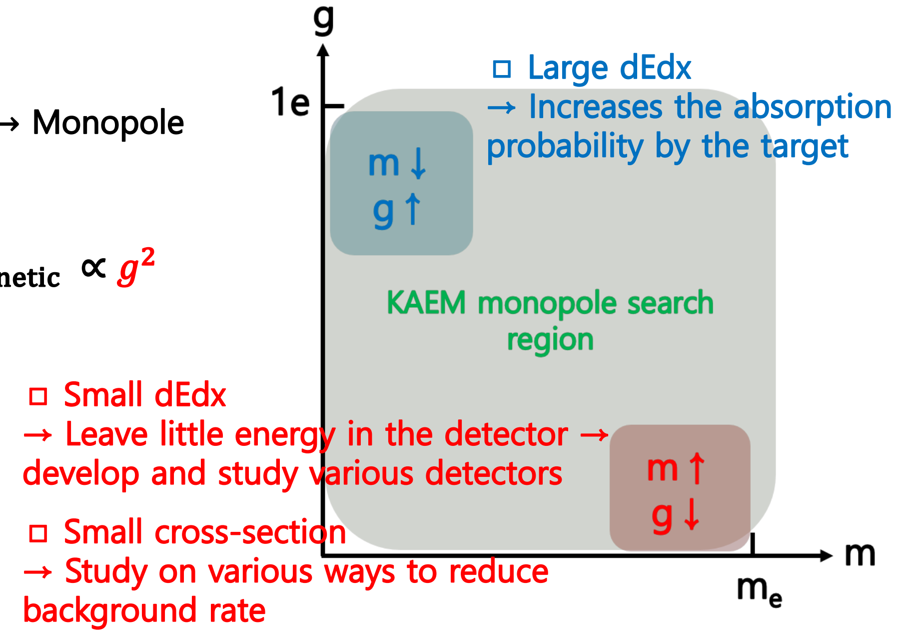
5. Various physical aspects of monopoles

• KAEM monopole process

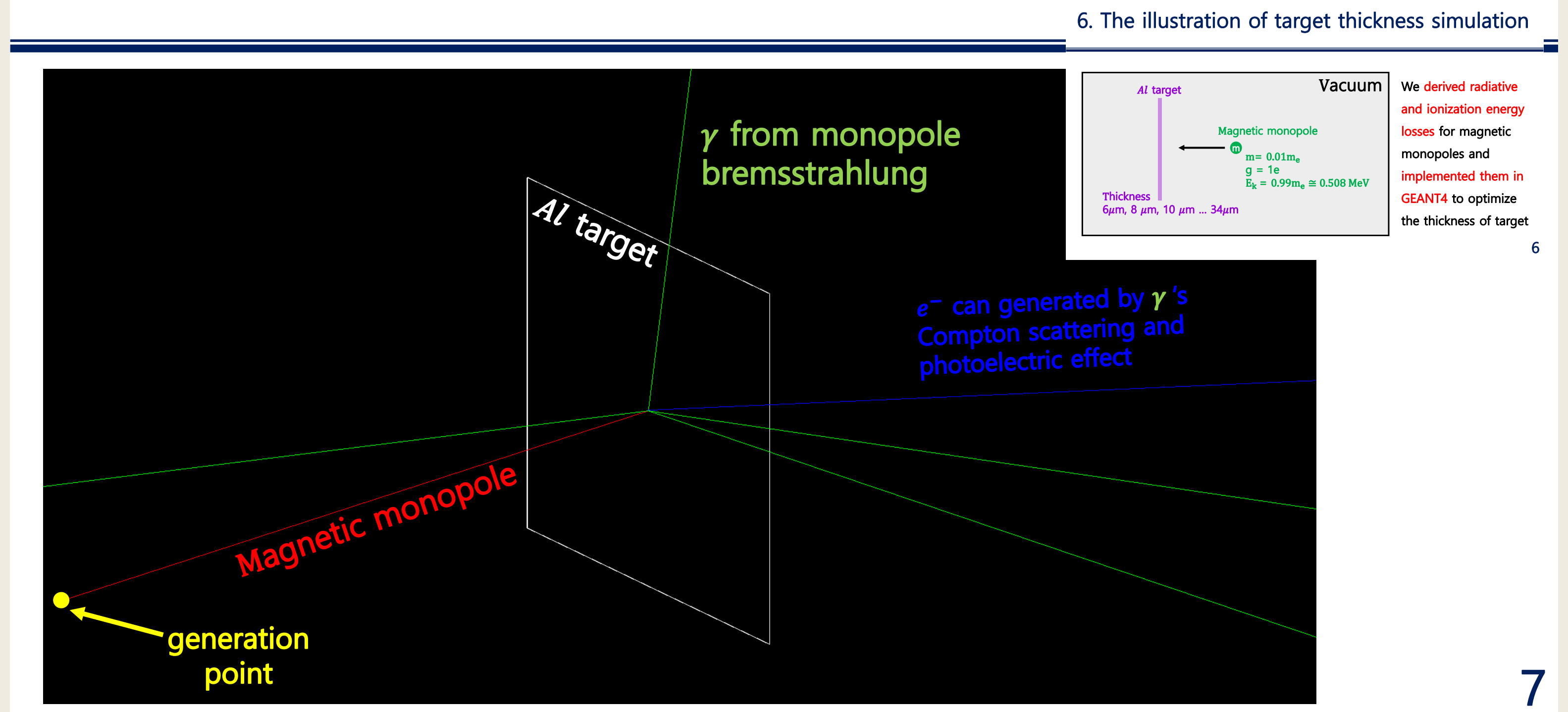
$Na^{22} \rightarrow e^{+} \rightarrow$ Annihilated in Al target → Monopole pair

◈ $\left[\frac{dE_{rad}}{dx}\right]_{magnetic} \propto \frac{g^4}{m^2}$, $\left[\frac{dE_{ion}}{dx}\right]_{magnetic} \propto g^2$

◈ $\sigma_{generation} \propto g^2$

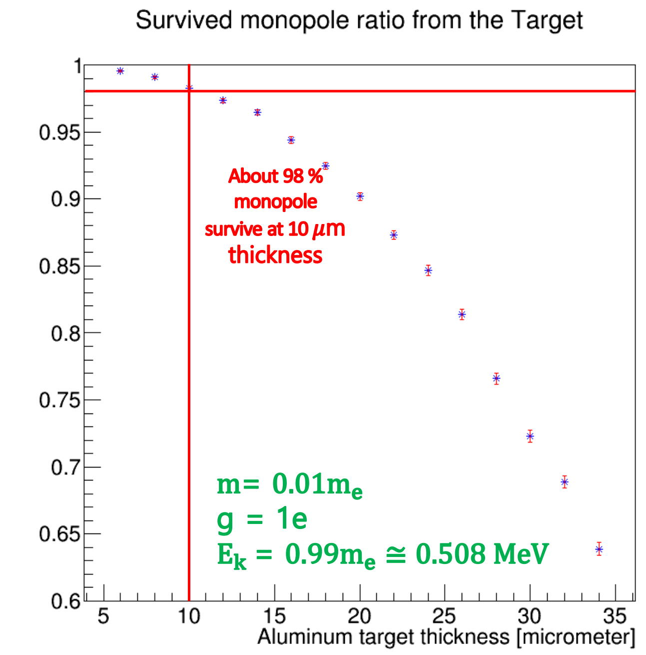


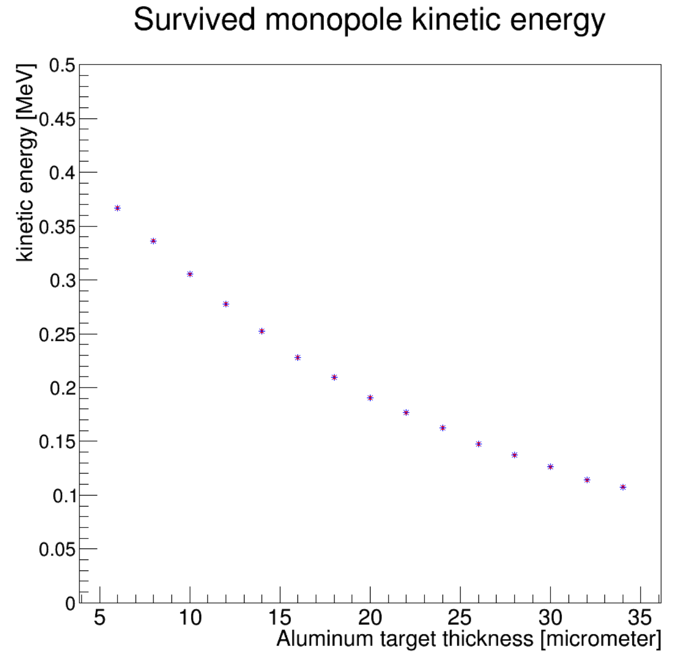
7. Visualization of target thickness simulation



7

8. Result of target thickness simulation





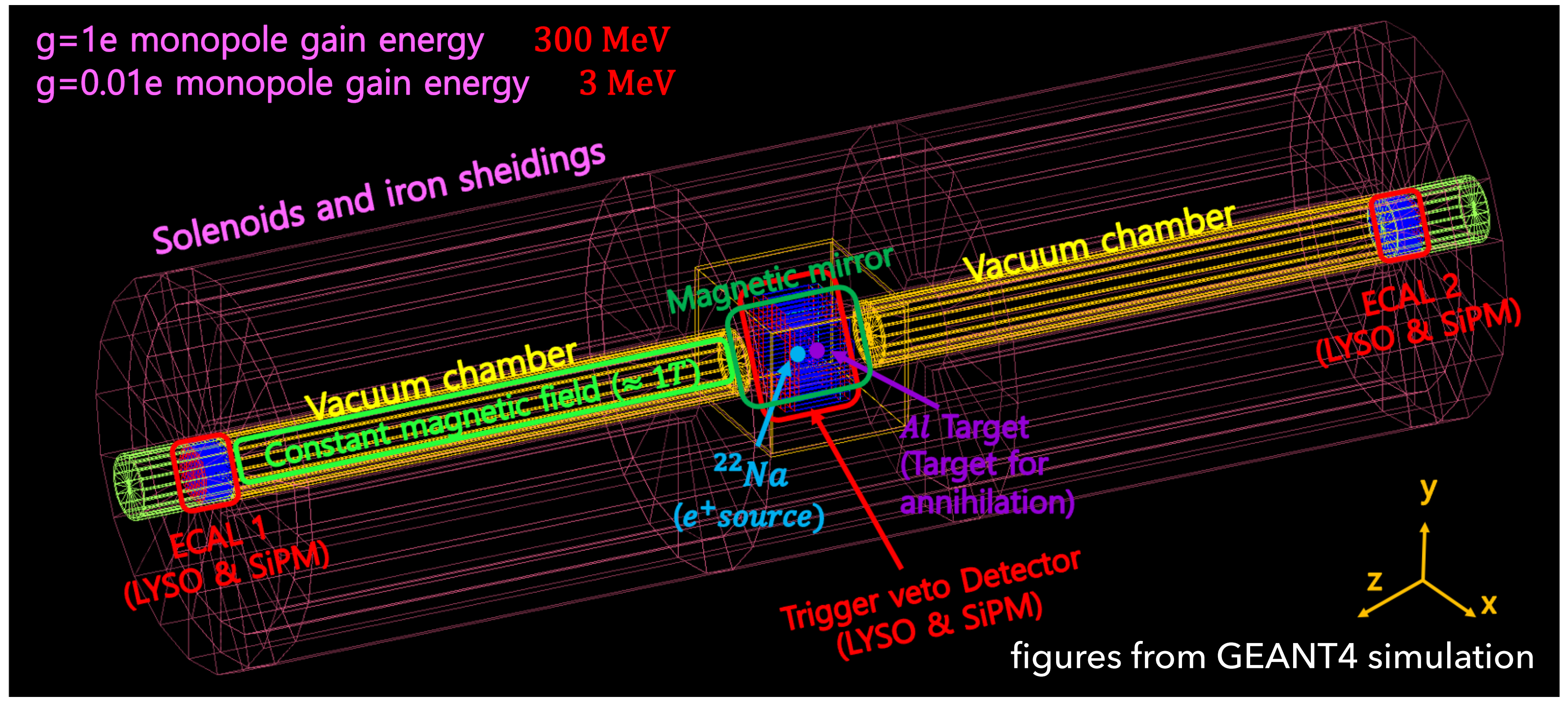
8

Background Study

4

KAEM experiments

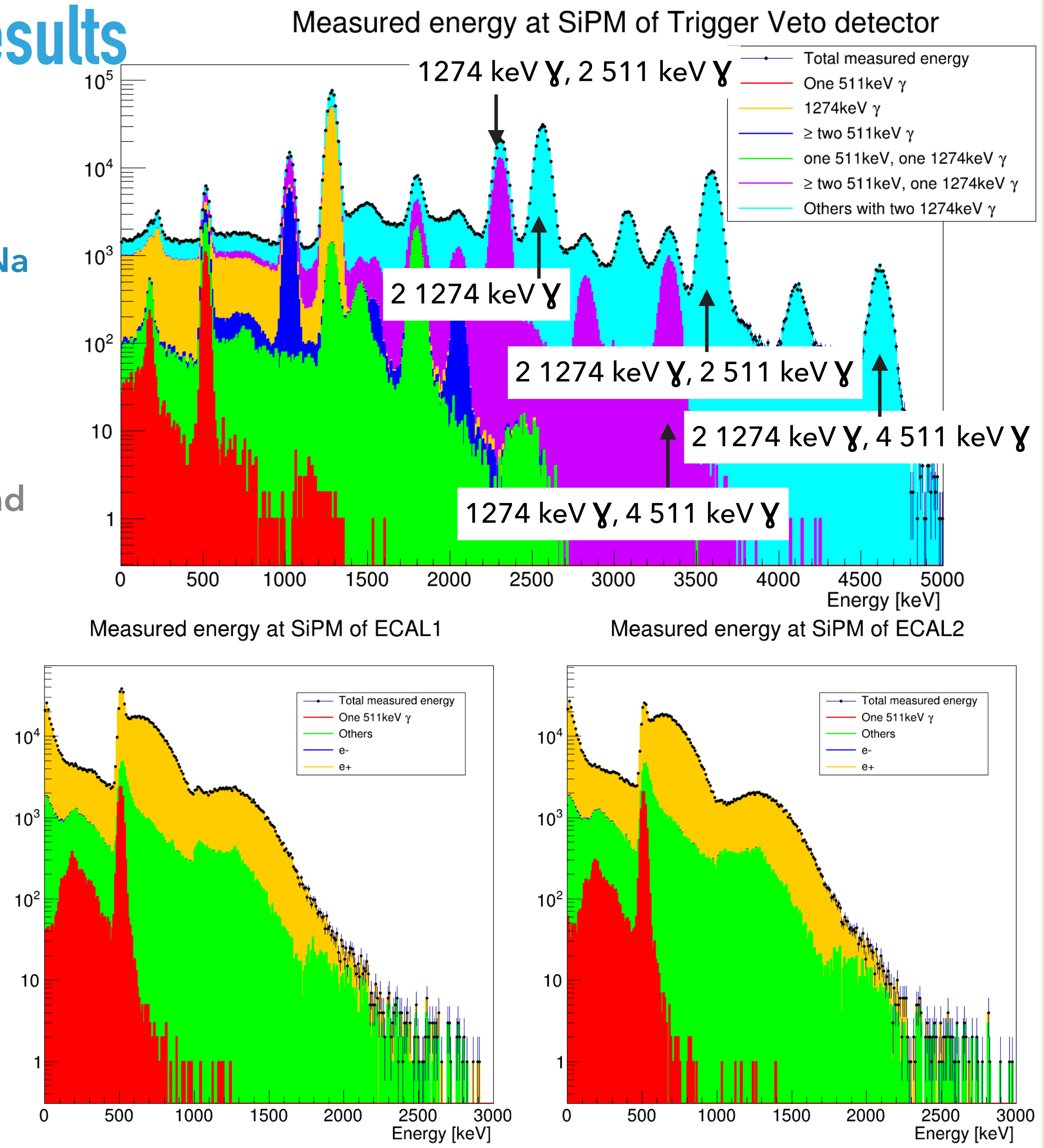
- The e^+ from ^{22}Na interacted with a thin aluminum target (10 μm) and produced the monopole pairs.
- Magnetic monopoles are accelerated under a 1 T magnetic field and measured in the ECALs.
- The 1.274 MeV ɣ-ray from ^{22}Na decay is the trigger signal in the Trigger veto detector.
- LYSO has a high light yield and good time performance.



8

Background Simulation Results

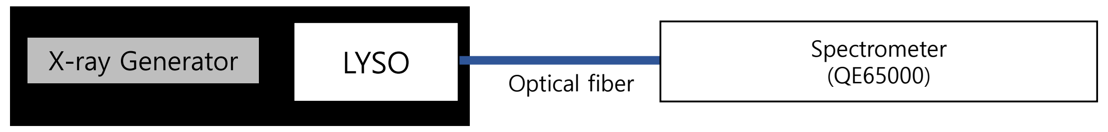
- Two near-simultaneous ^{22}Na decays :
  - Two e^+ and two ɣ-rays from the ^{22}Na source.
  - ɣ-rays from positron annihilation.
  - Interaction products from target and particles.



Test of Crystal Performance

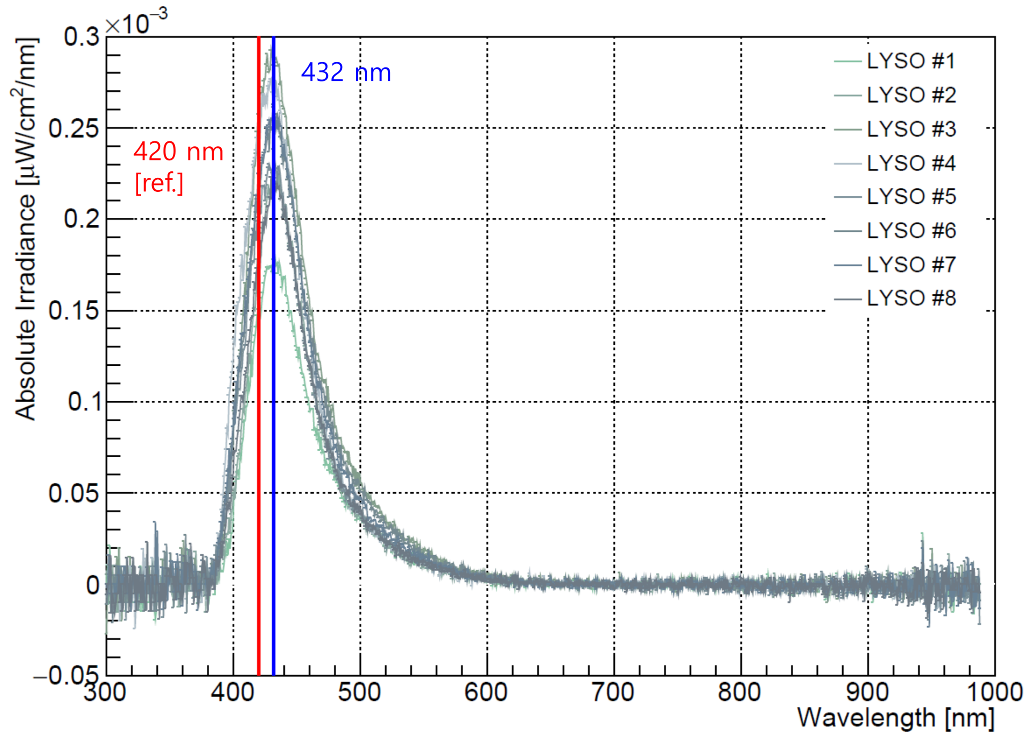
Emission Wavelength

- Set-up



- LYSO crystals: 2 cm X 2 cm X 12 cm , epic-crystal
- X-ray Generator : 2mA, 80 kV, DRGEM Co.
- Spectrometer : QE65000, Ocean optics.

- Results

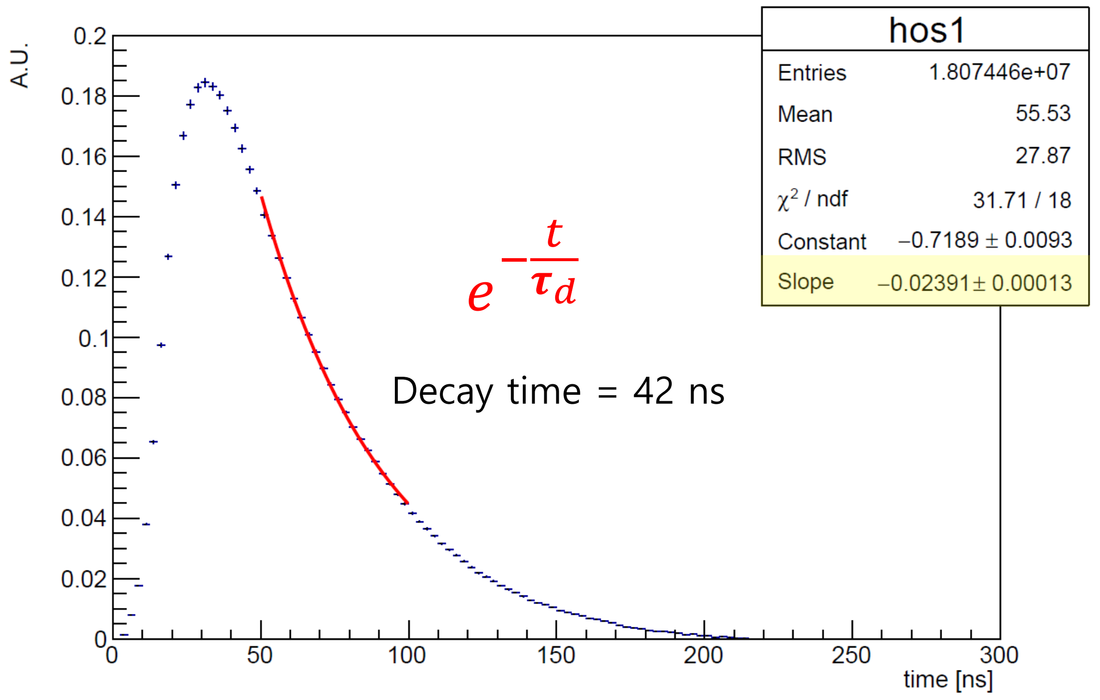


- 420 nm Emission wavelength of Reference is from epic-crystal.
- 8 LYSO crystals are measured, and average emission wavelength is 432 nm.

	Emission Wavelength [nm]
LYSO #1	433
LYSO #2	436
LYSO #3	430
LYSO #4	430
LYSO #5	431
LYSO #6	431
LYSO #7	431
LYSO #8	430
Average	432

Results: Decay Time

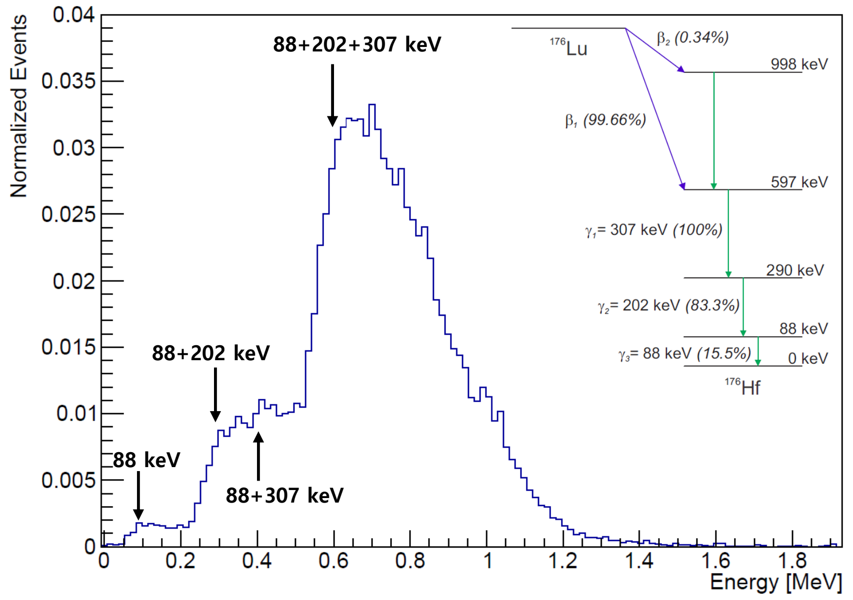
Average time structure



- Used gamma energy 1.274 MeV of ^{22}Na.
- We reproduced the decay time of LYSO crystal provided by Epic-crystal.

Results : Internal Background

- Used calibration constant calculated with 1.33 MeV of ^{60}Co



https://www.crystals.saint-gobain.com/sites/imdf.crystals.com/files/documents/lyso-material-data-sheet.pdf

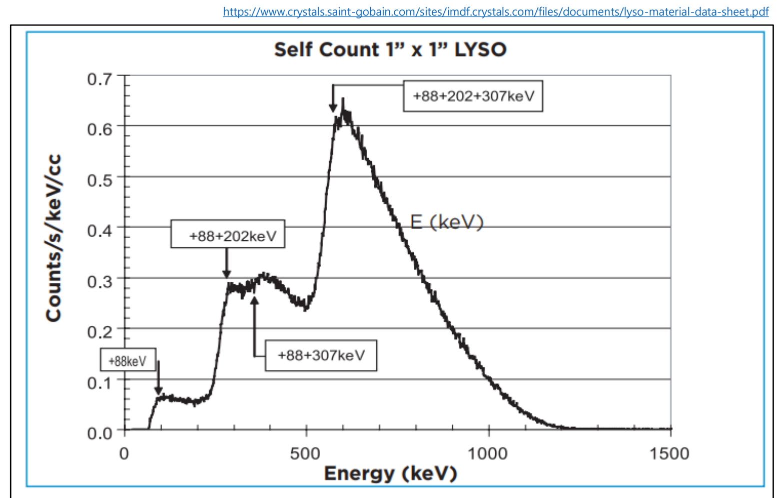
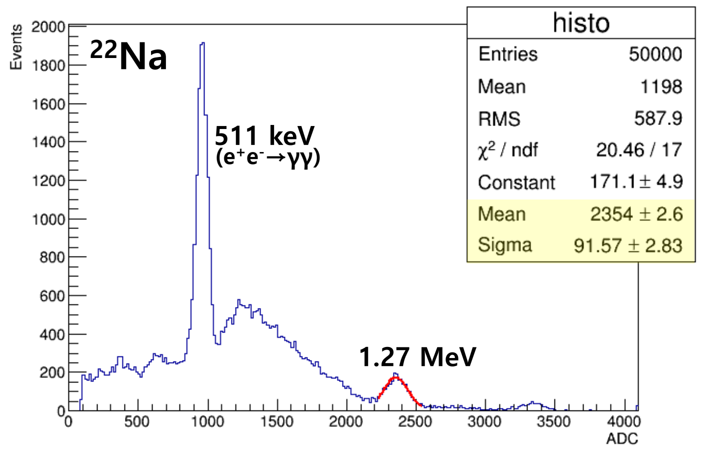


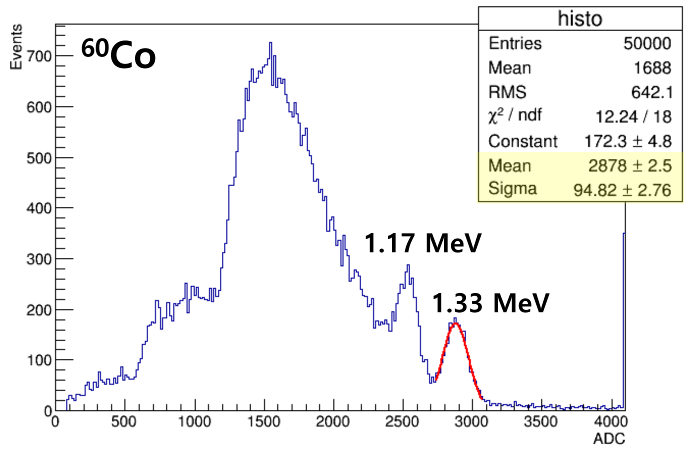
Figure 3. LYSO is a Lutetium-based scintillator which contains a naturally occurring radioactive isotope 176Lu, a beta emitter. The decay results in a 3 gamma ray cascade of 307, 202 and 88 keV, where self-absorption of these photons results in the above spectra in a 1"x1" cube. Total rate for this activity is 39 cps/g.

- Comparable results to reference from saint-gobain in spite of different size.

Results : Gamma Energy Measurement (^{22}Na, ^{137}Cs and ^{60}Co)

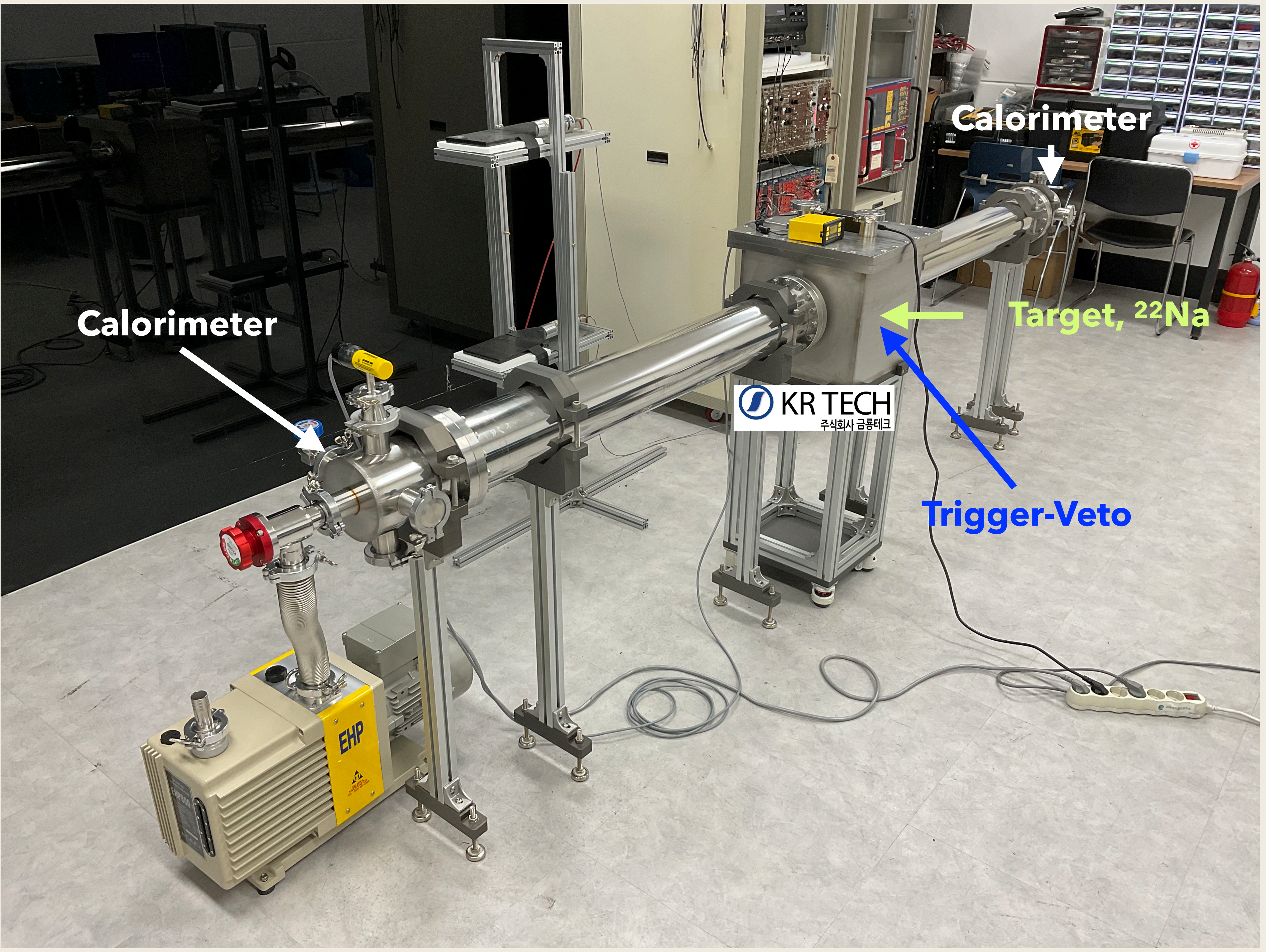
- Calibration constant is calculated using 1.27 MeV and 1.33 MeV of ^{22}Na and ^{60}Co, respectively which are hardly affected by intrinsic background.





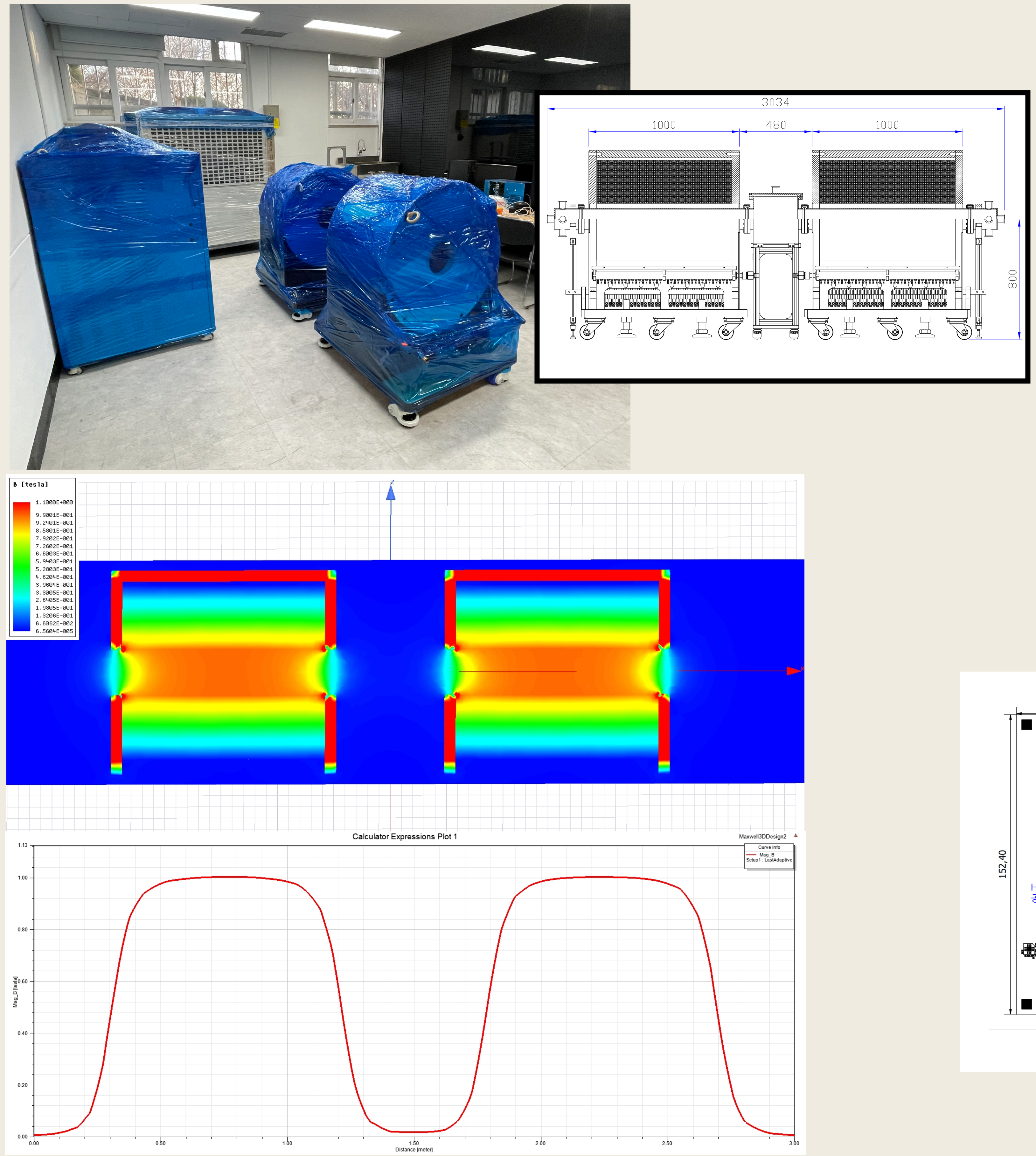
Source	Energy [keV]	Pedestal [ADC]	Raw Mean [ADC]	Mean [ADC]	Sigma [ADC]	Calibration Constant [keV/ADC]	Energy Resolution (FWHM) [%]
^{60}Co	1333	83.5	2878	2794.5	94.82	0.477	8.0
^{22}Na	1274		2354	2270.5	91.57	0.561	9.5

Vacuum Chamber



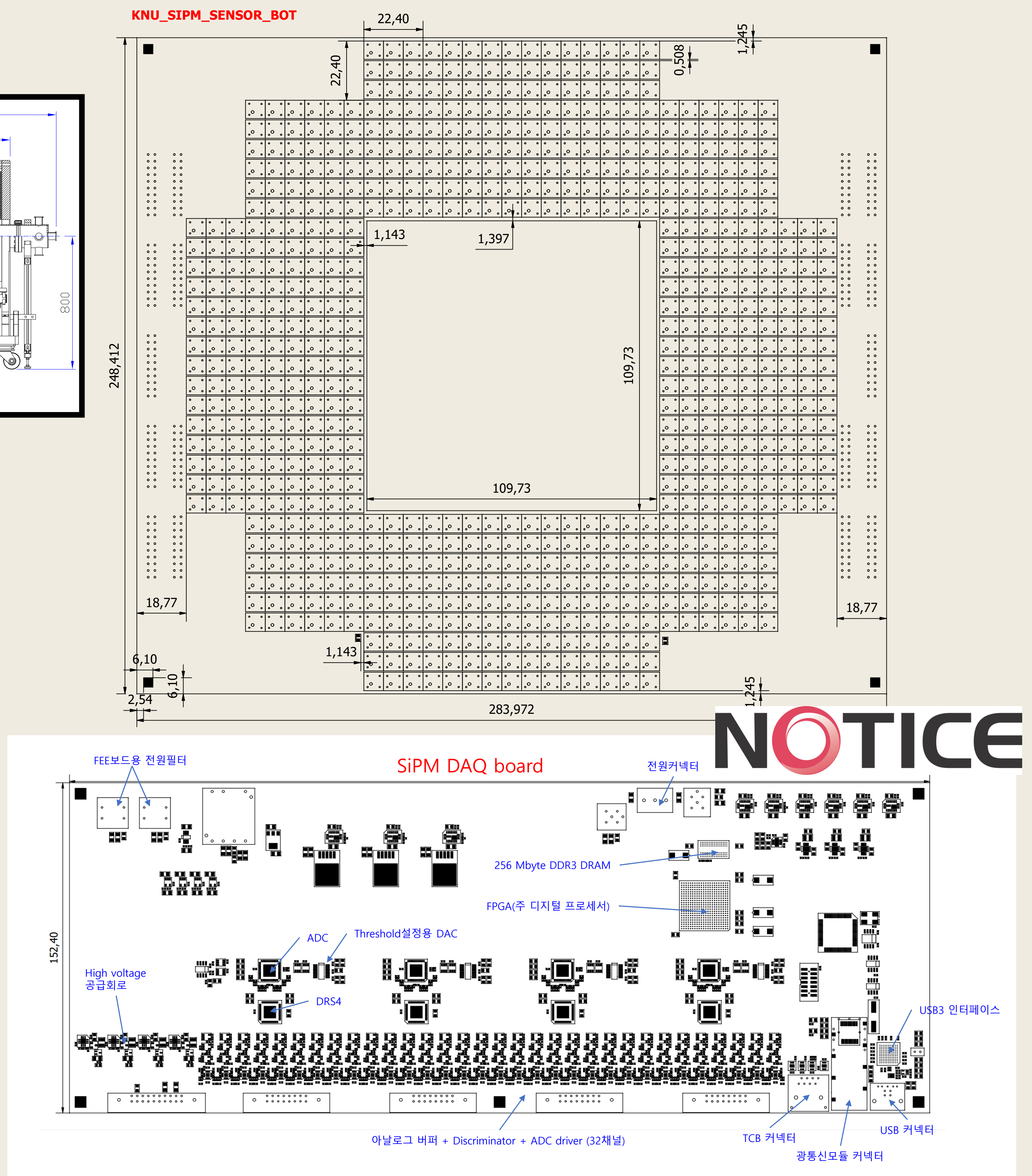
- Length: ~ 3m
- Vacuum: ~ 10^{-3} torr (prevent magnetic monopoles from interacting with air)
- Trigger-veto, calorimeters, target, and ^{22}Na source will be installed inside the chamber

Solenoids



- Uniform 1 T magnetic field in 20 cm bore and 1 m length
- Accelerate magnetic monopoles

Electronics for Trigger-Veto



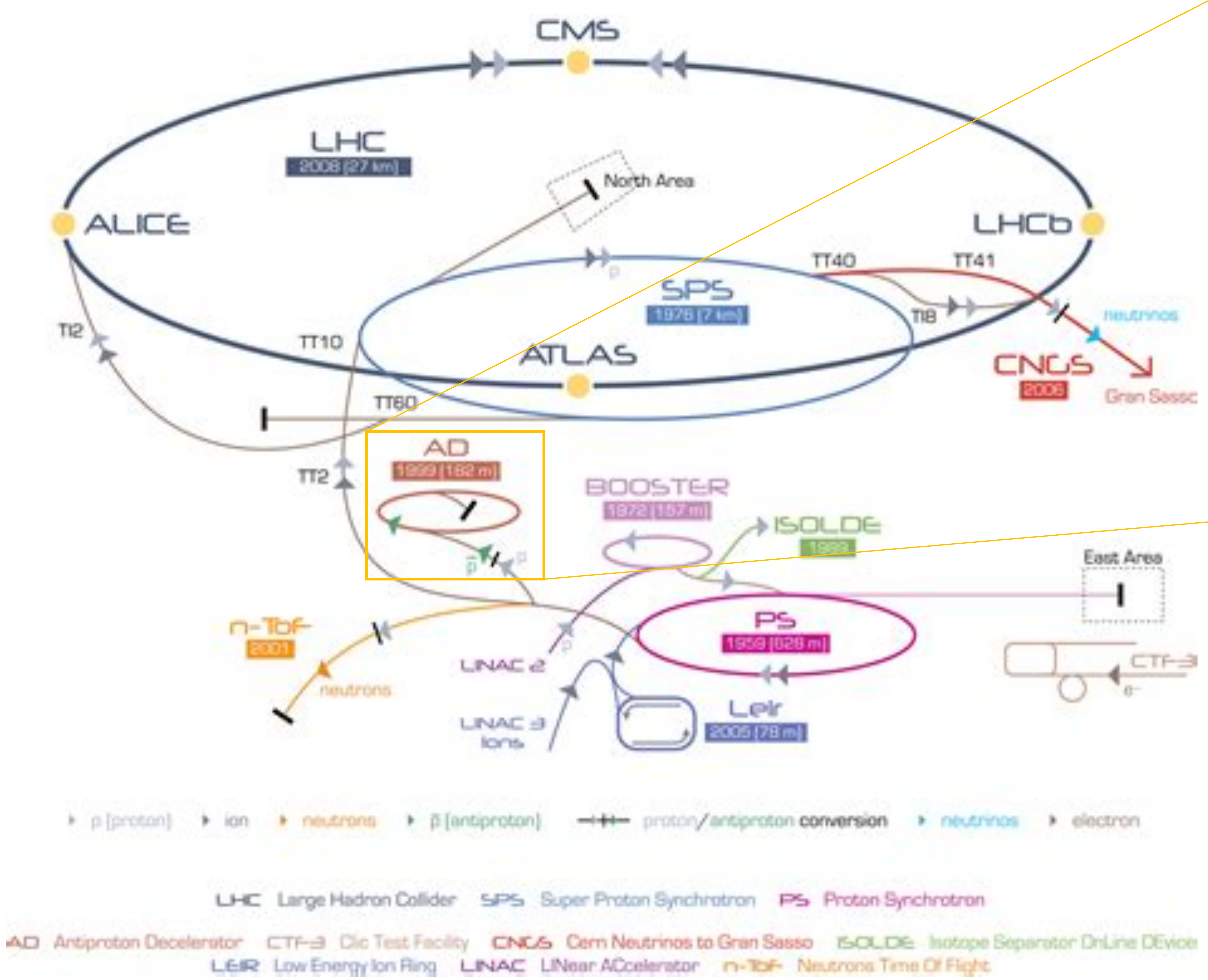
- Read scintillation light with SiPM's at both ends of crystals
- DRS (waveform digitization) +ADC+TDC
- Total 152 channels

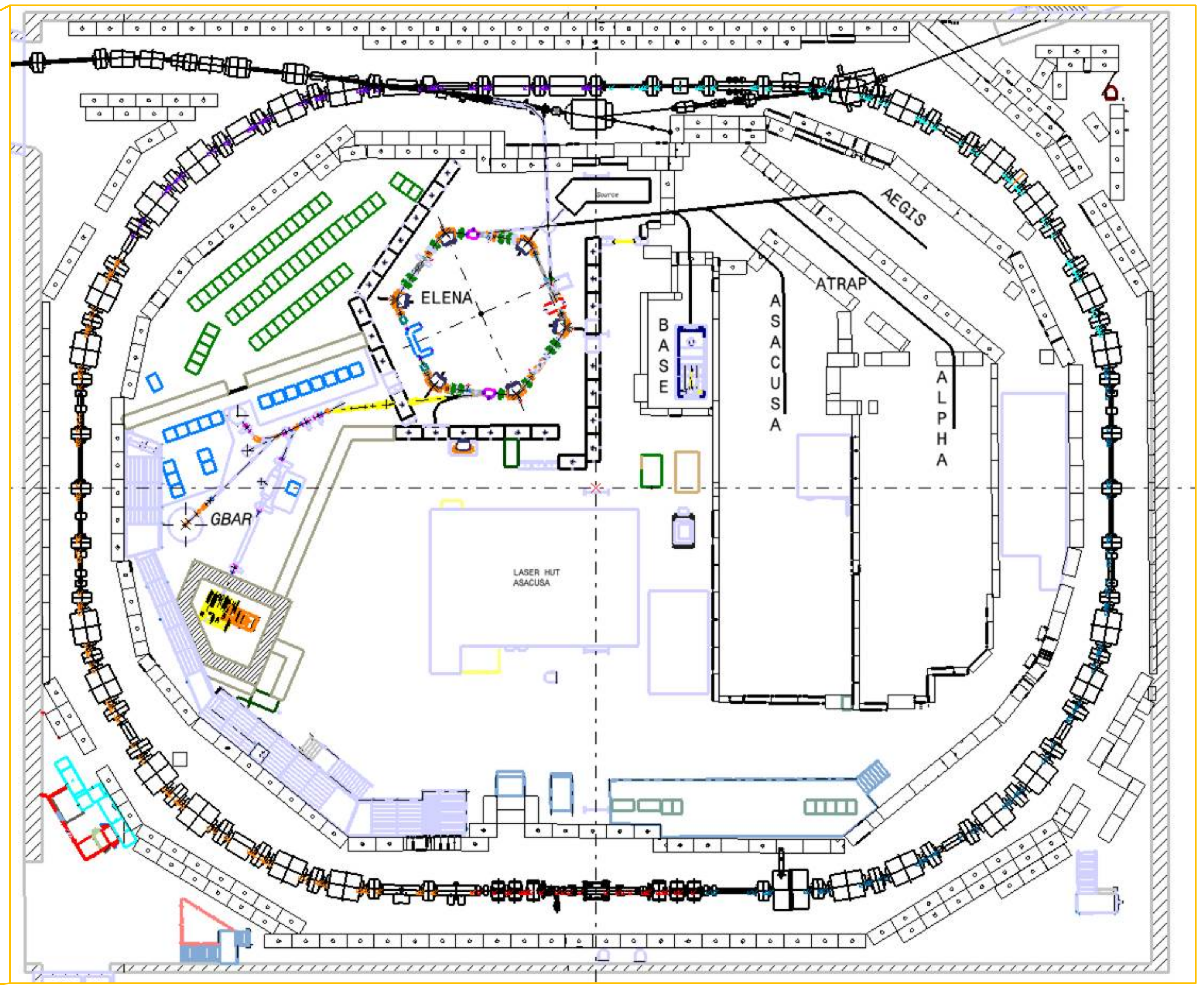
Summary

- **Creative** ideas grow into the real experiments
- **Diverse** particle physics experiments enrich particle physics opportunities from small- to large-scale experiments
- We are walking step by step toward **Innovative** physics results

Spares

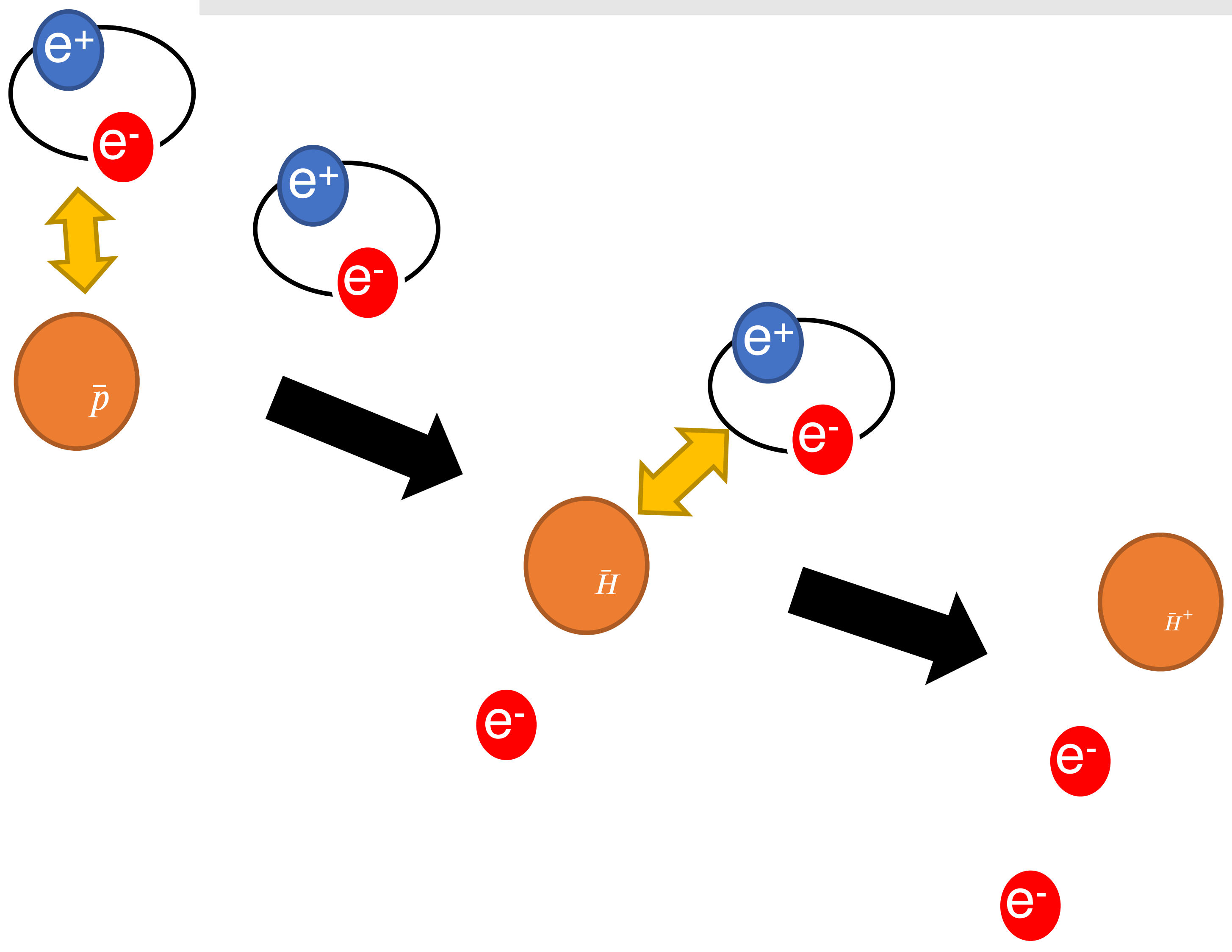
Antiproton Decelerator (AD) and ELENA

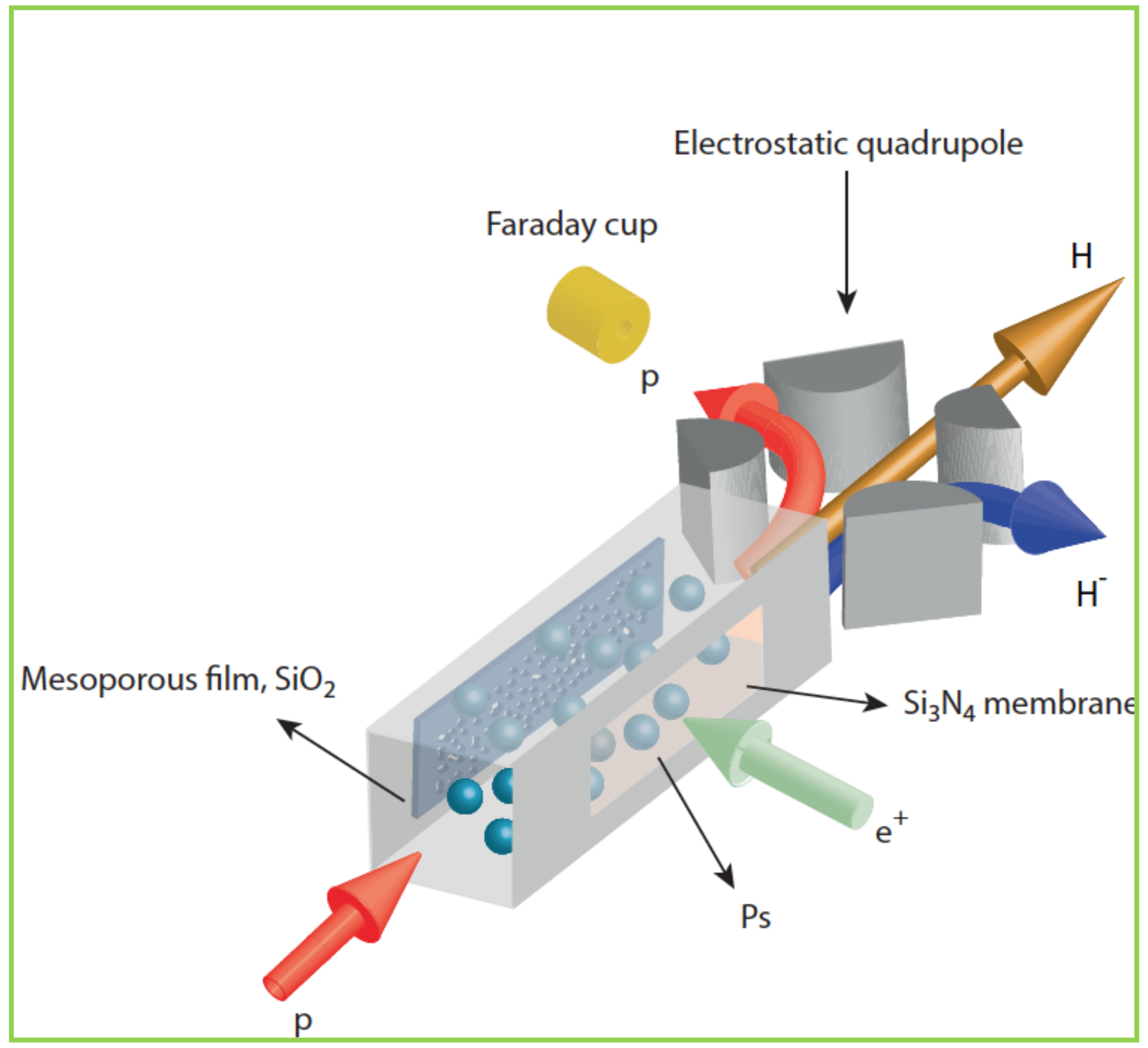


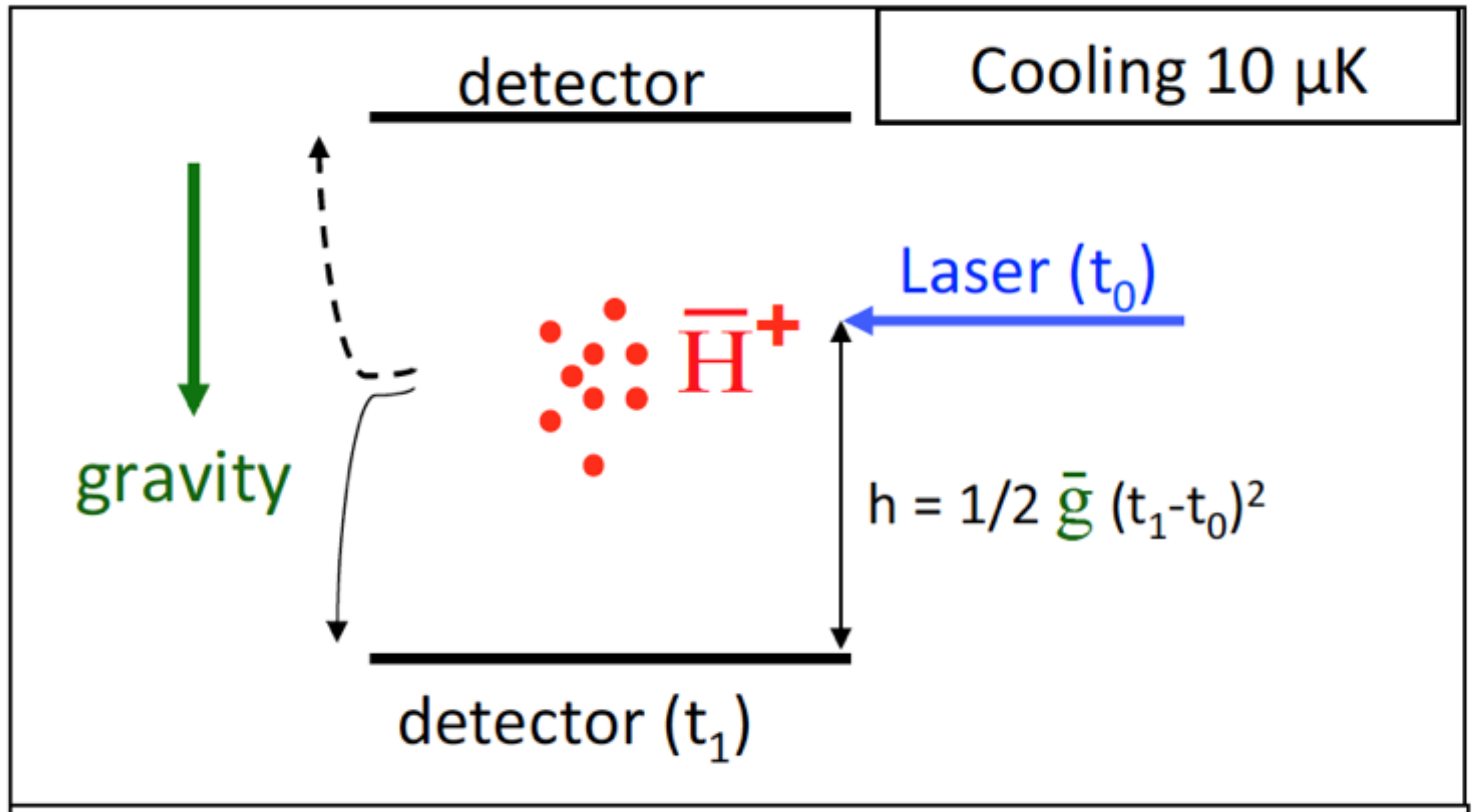


- Unique facility : low energy antiproton beam provider
- 26 GeV/c proton + Iridium target → 3.5GeV/c antiproton.
- 5.3MeV (100MeV/c) antiproton beam 3×10^7#/120s
- ELENA : 100keV antiproton beam (σ<100ns, 0.5×10^7#/120s : ¼ bunches)

GBAR 실험의 방법론







J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561.

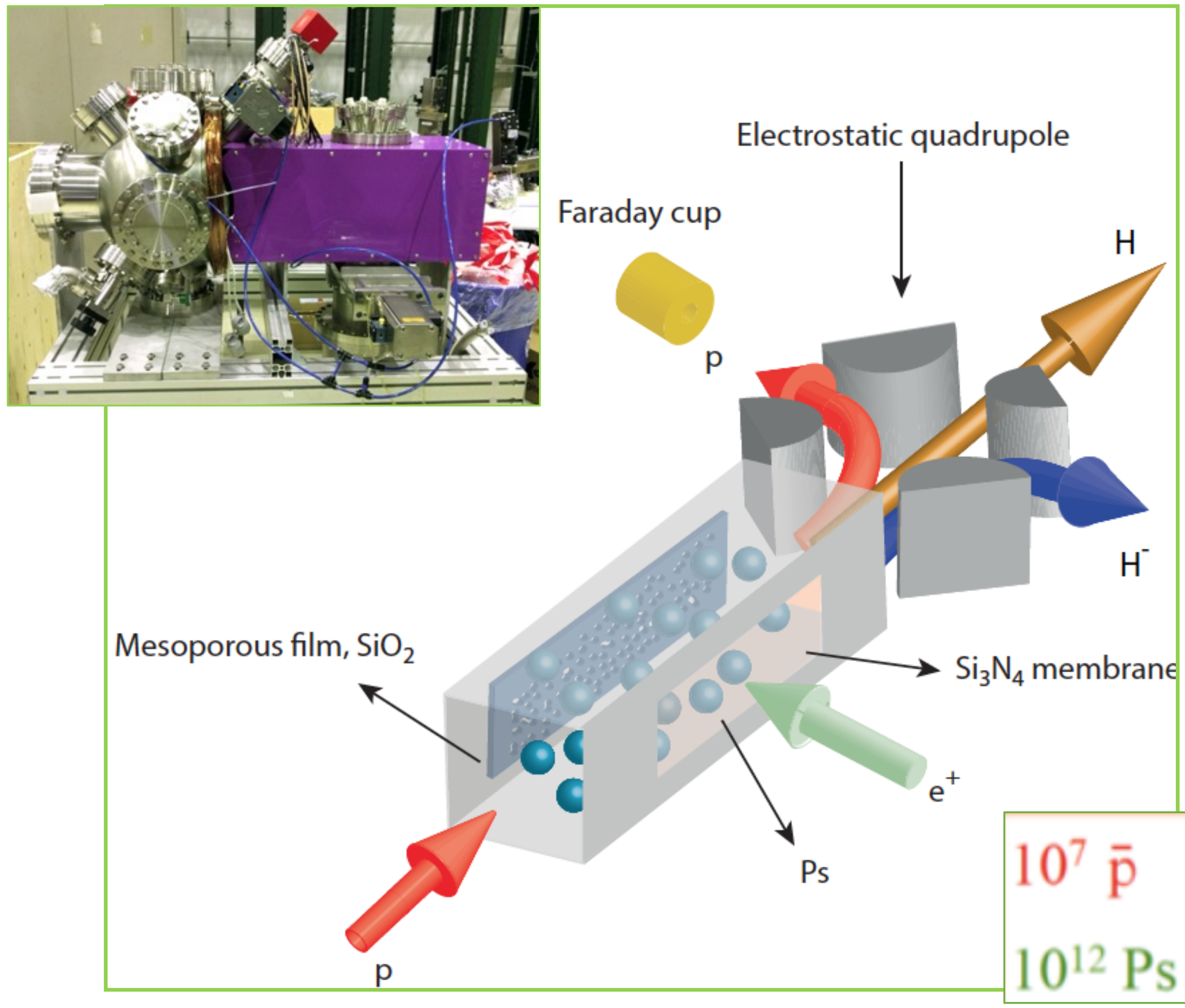
- GBAR 실험은 반수소의 온도를 초저온 수준 (uK) 으로 떨어뜨림으로서 고전적 자유낙하테스트를 가능하게 합니다.
- 초저온 반수소를 만들기 위해서 저희는 반수소 이온 만들고 이를 냉각하는 새로운 방식을 사용합니다.
- 이를 위해 반양성자와 포지트로늄 구름을 충돌 시켜 그안에서의 두번의 양전자 교환을 유도합니다.

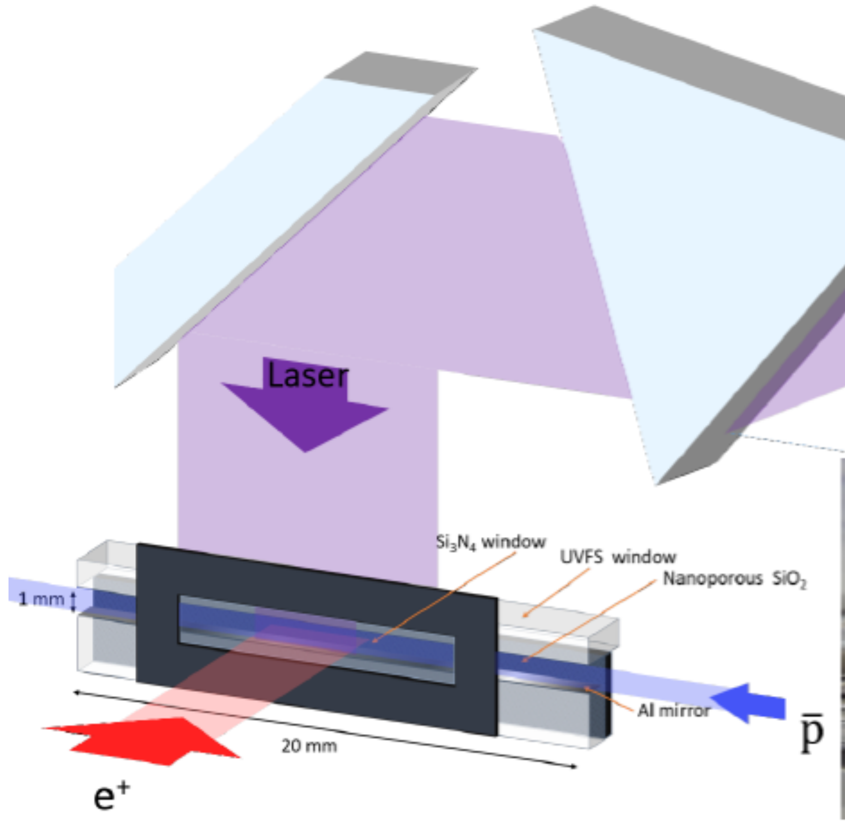
$\bar{p} + Ps \rightarrow \bar{H} + e^-$

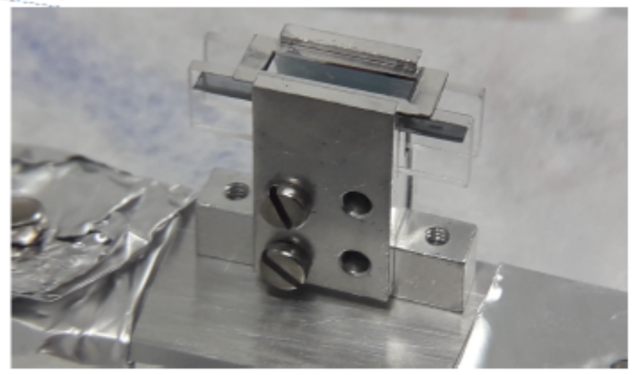
$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$

- Paul trap 에서 레이저로 냉각된 Be+ 의 sympathetic cooling 을 통해 반수소이온을 냉각시킵니다.
- 양전자를 하나 떨어뜨려(by photo-detachment laser) 반수소가 자유낙하 할 수 있도록 합니다

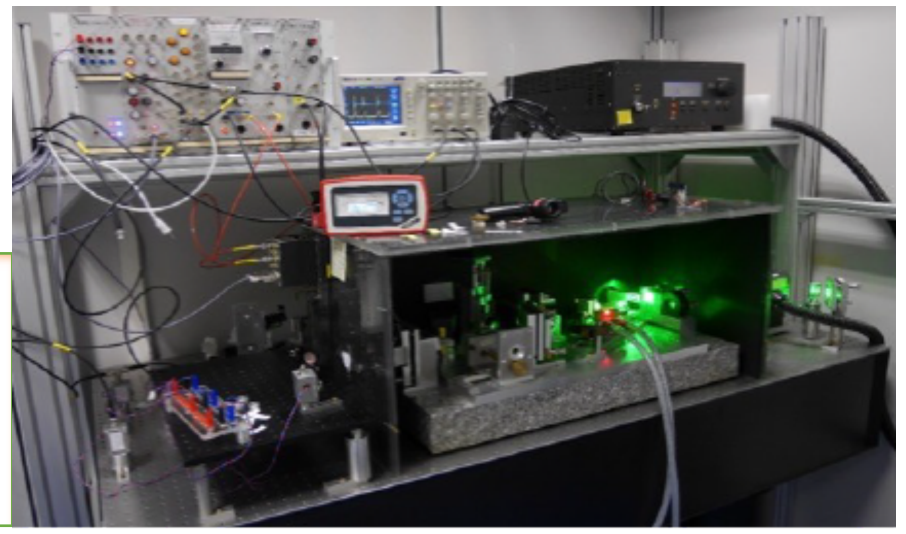
Antihydrogen production

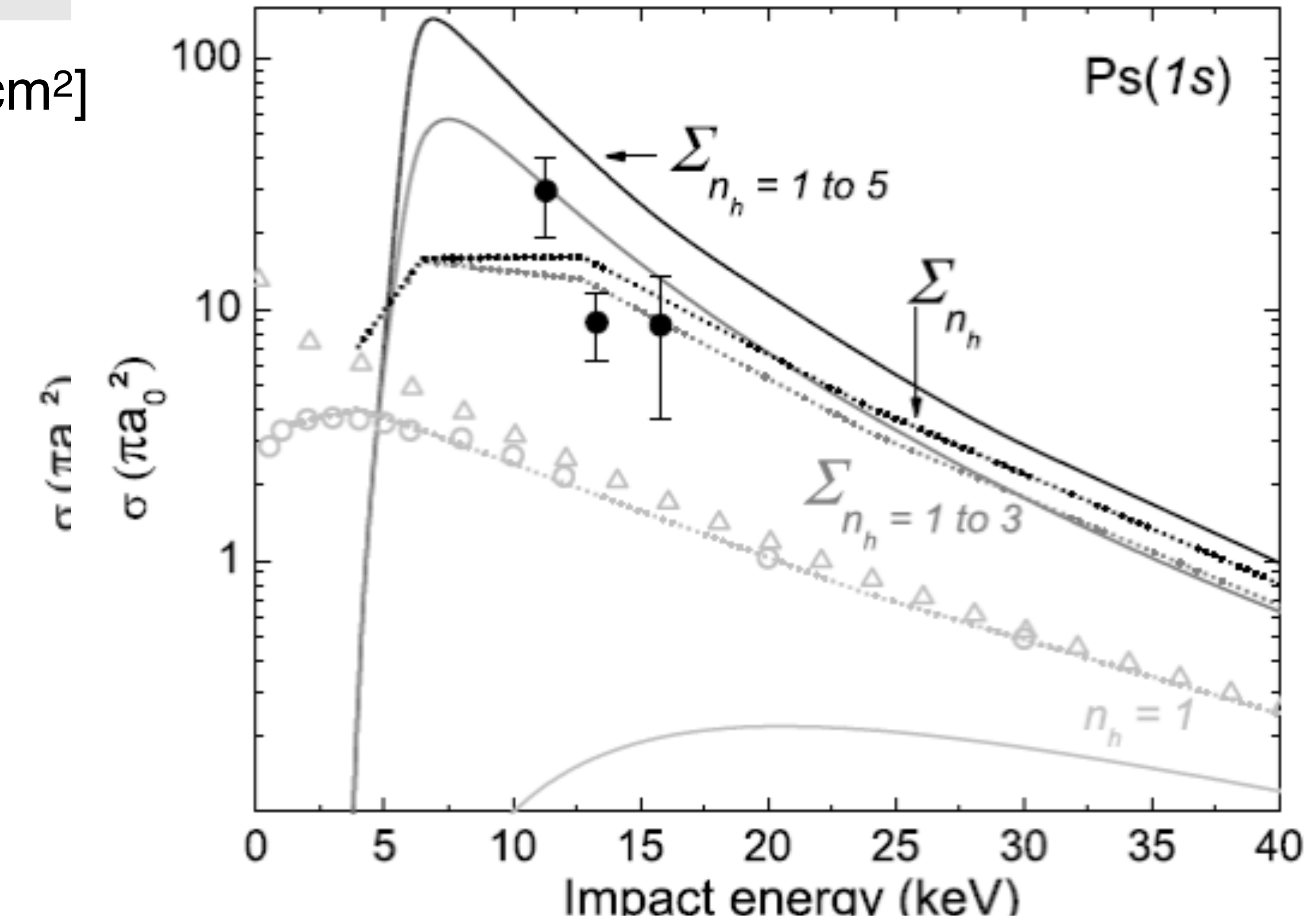


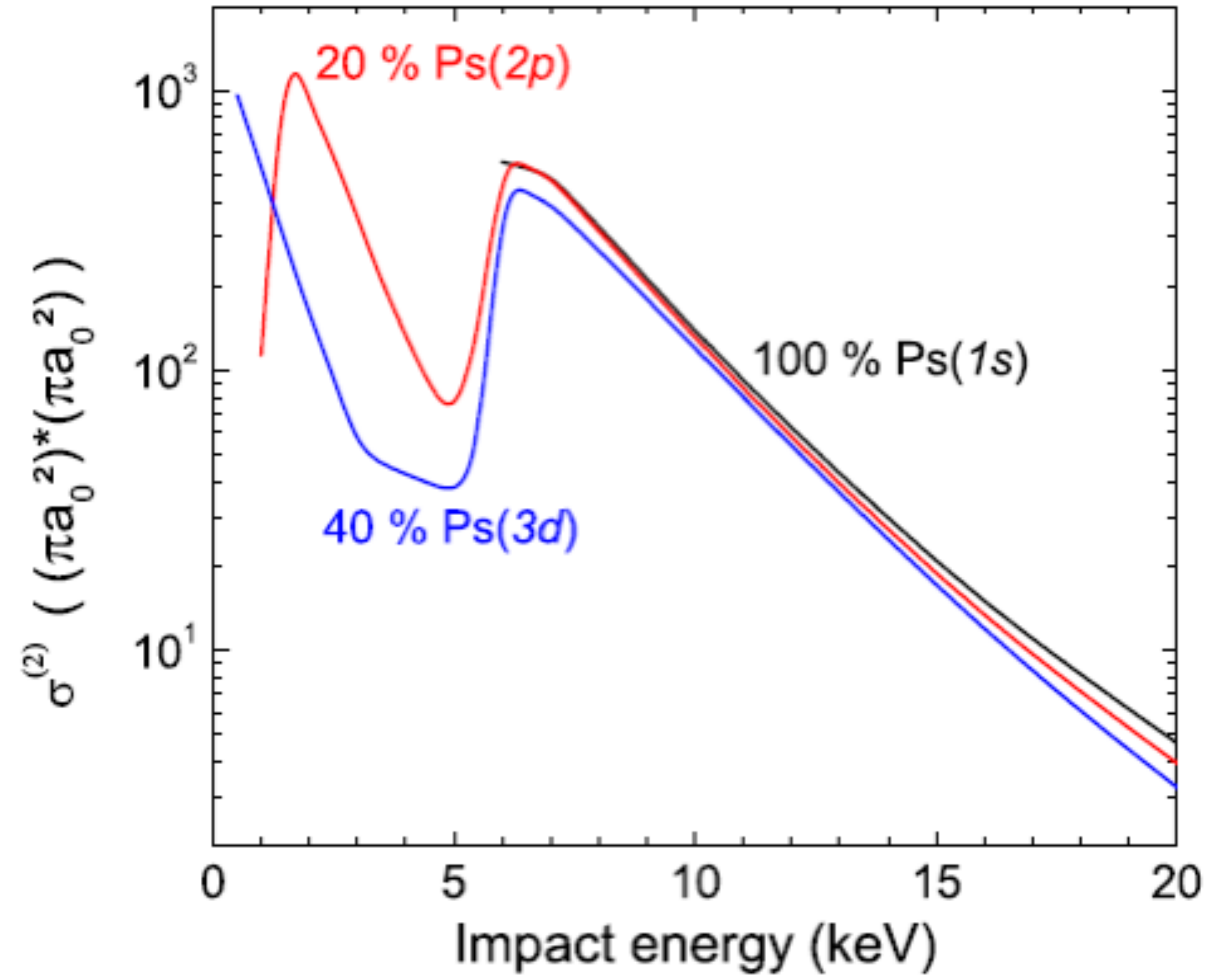




$10^7\ \bar{p}$, 10^{12} Ps at/cm² $\} \rightarrow 10^4\ \bar{H}$, $1\ \bar{H}^+$



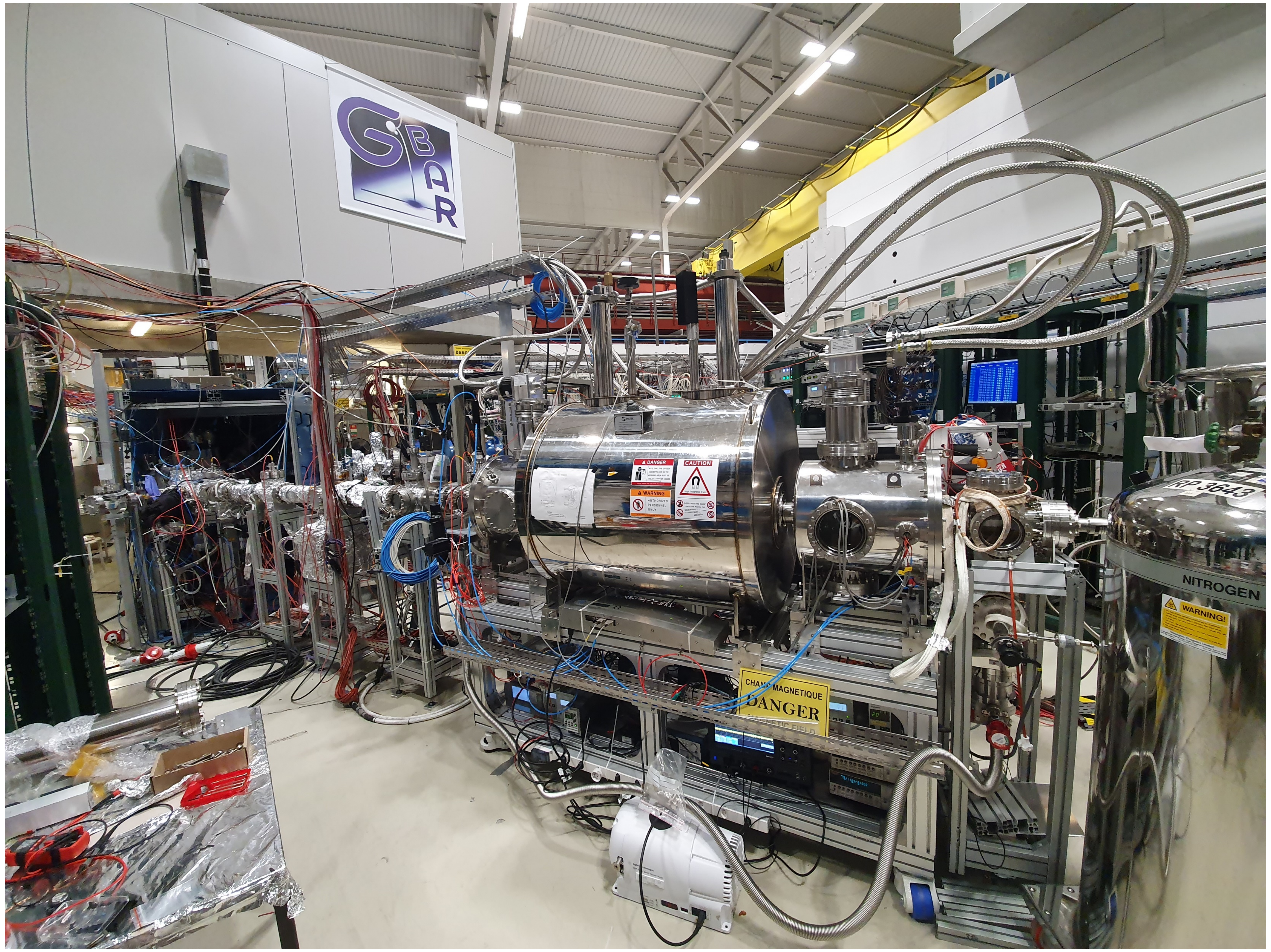




- $\bar{H}^+$ 생성량이 레이저를 사용해 증가할 수 있음 Ps(2p, 3d or 1s)
- 10^{12}Ps/cm^3 가 요구됨
- 1# $\bar{H}^+$가 2분 (1 cycle of AD) 당 기대되고 있음

P.Comini et. al, Hyperfine Interactions, 228, 159-165 (2014)

Antiproton trap 의 파라메터들

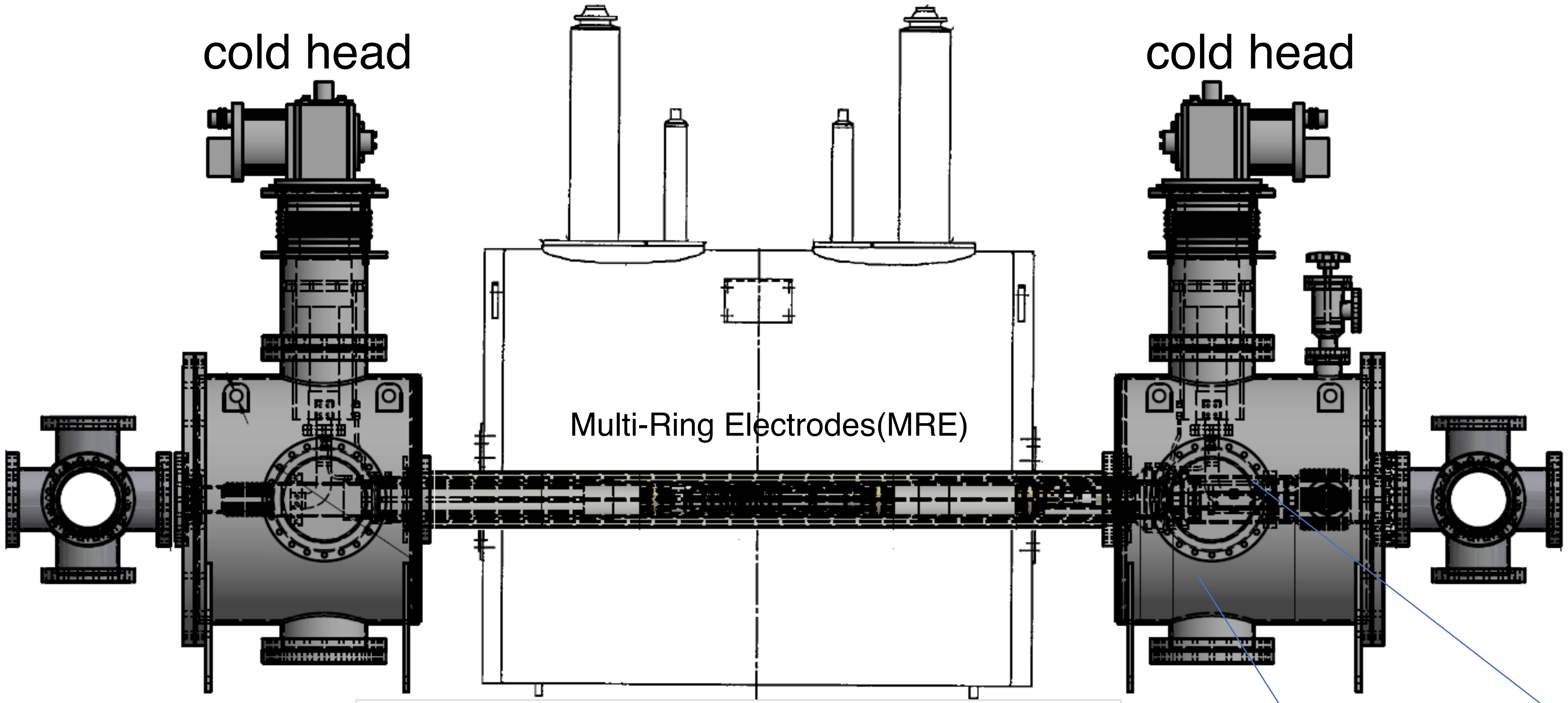


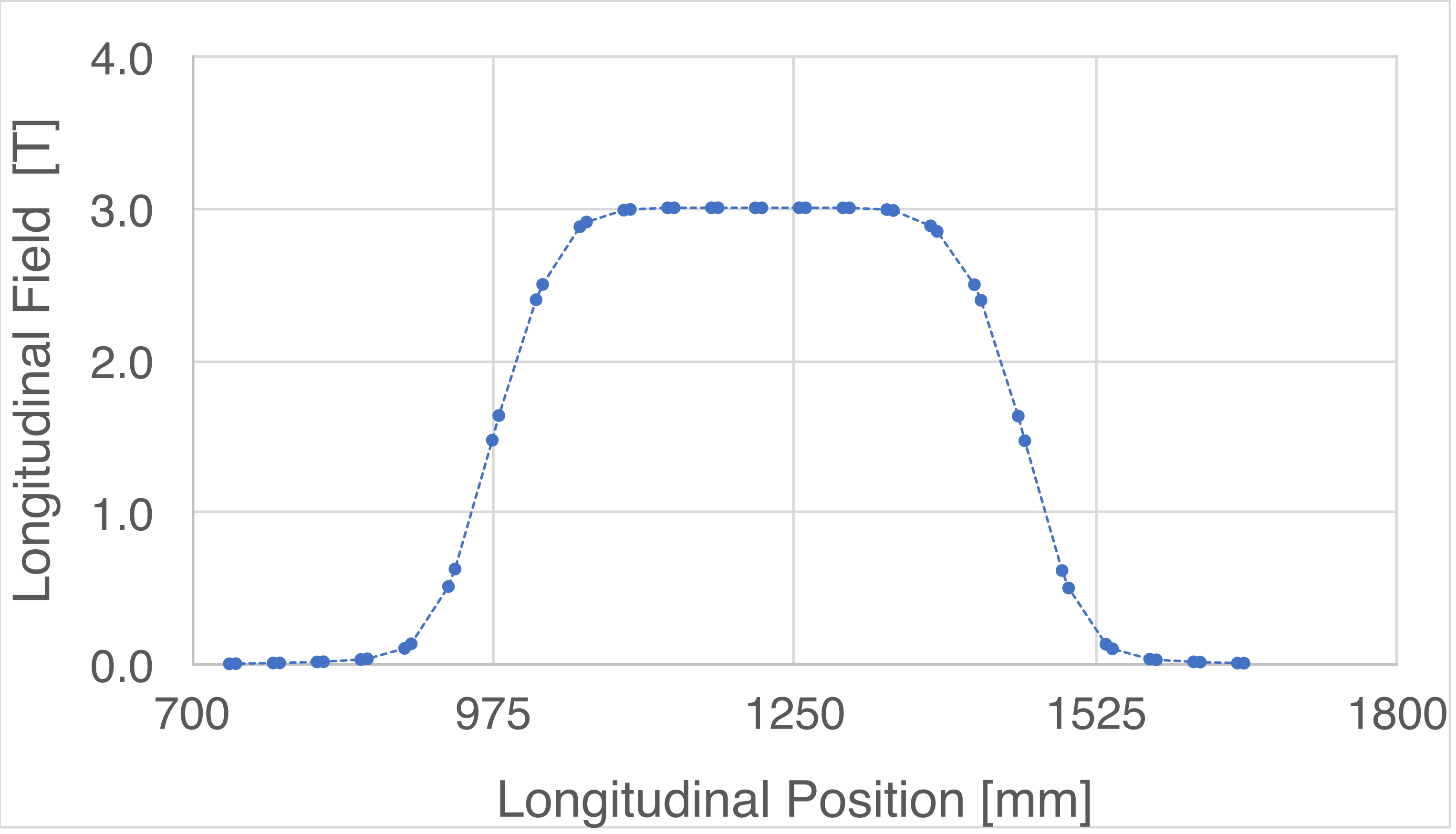
- confine pbar beam from ELENA (+decelerator)
- reprocess to better condition
- stacking if a recycler is ready

• Injection of pbar beam
- KE <10keV
- N=0.5E+7 pbar/pulse

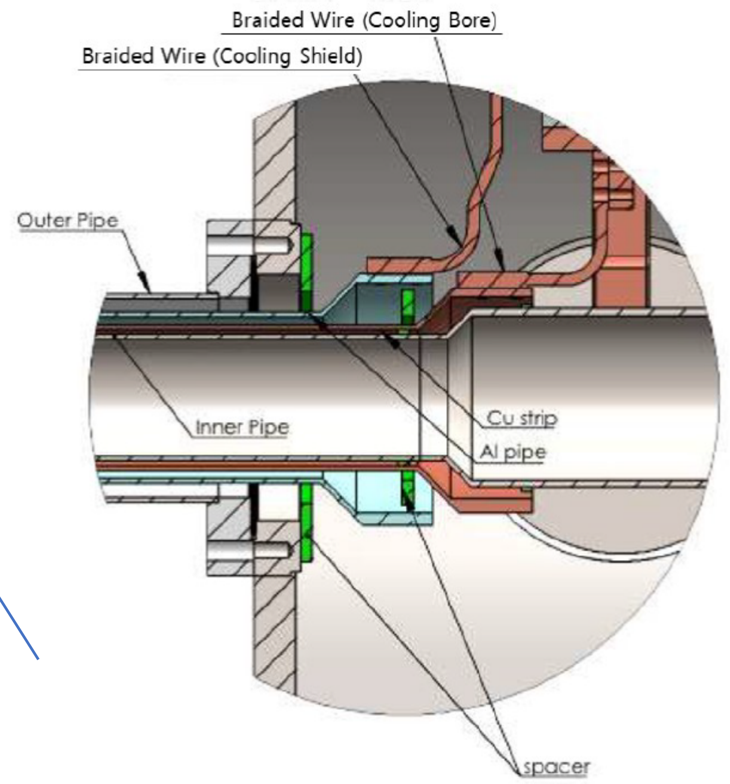
• Ejection of pbar beam
- KE : 0~10keV
- σ_E <10eV
- σ_t <100ns
- high efficiency
- small size & emittance to pass through target hole (1x1x20mm^3) at 1.5m distance

Antiproton trap 의 파라메터들

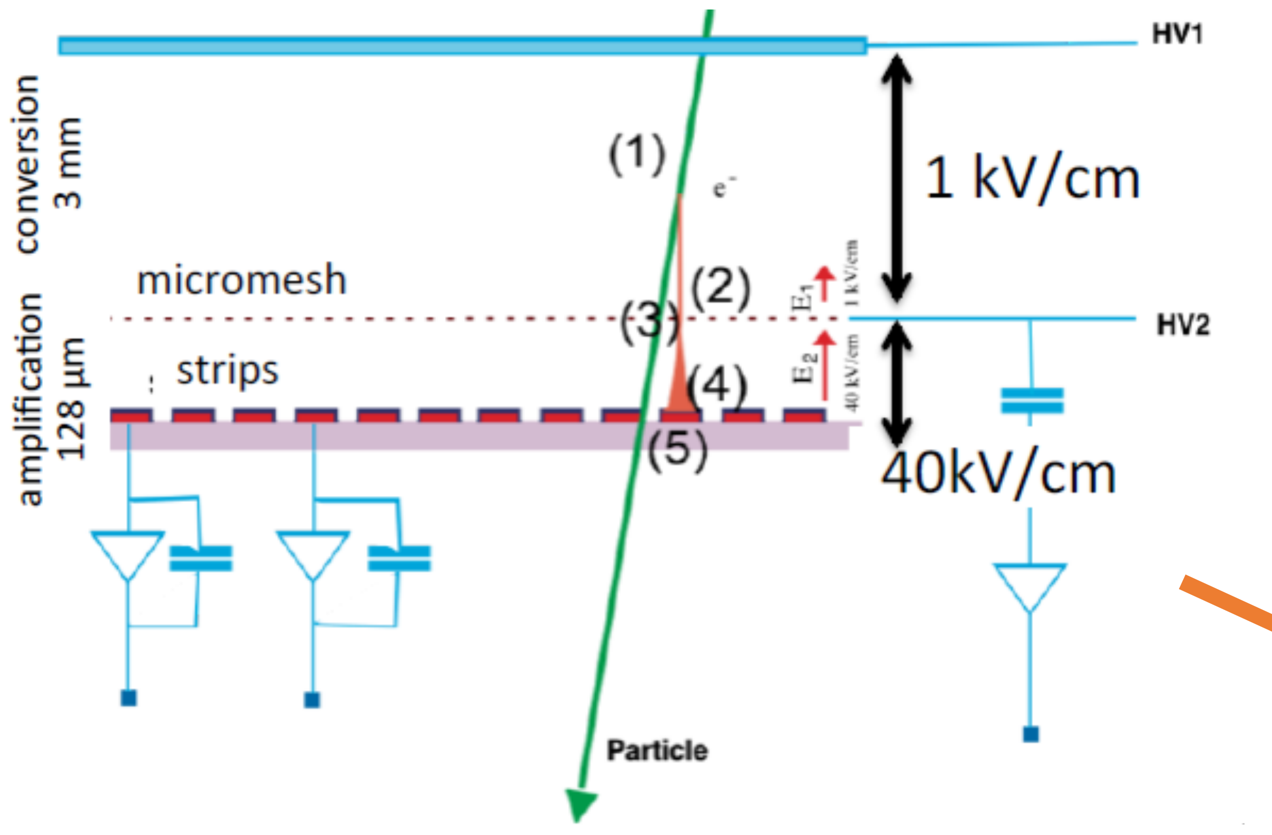


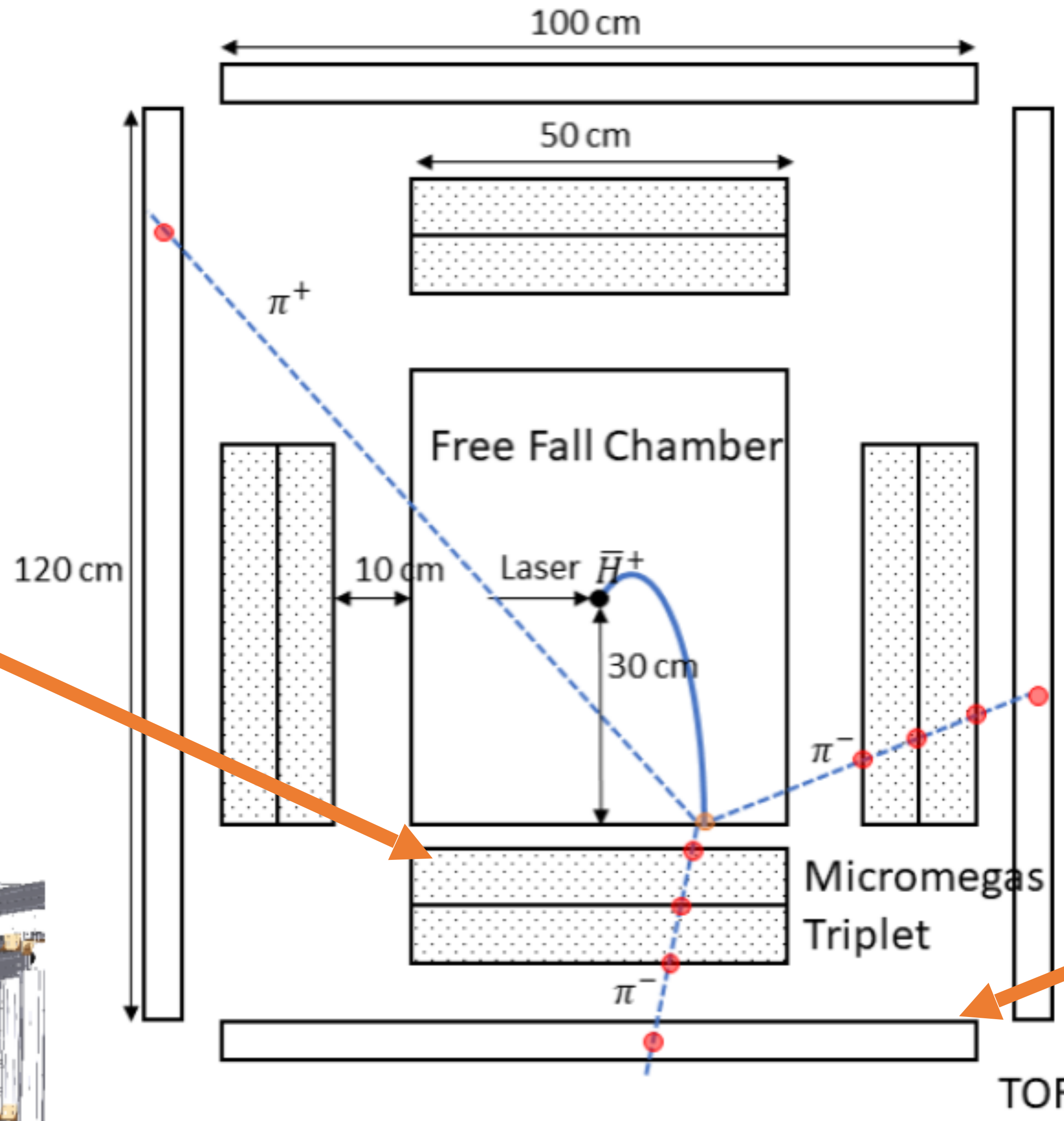


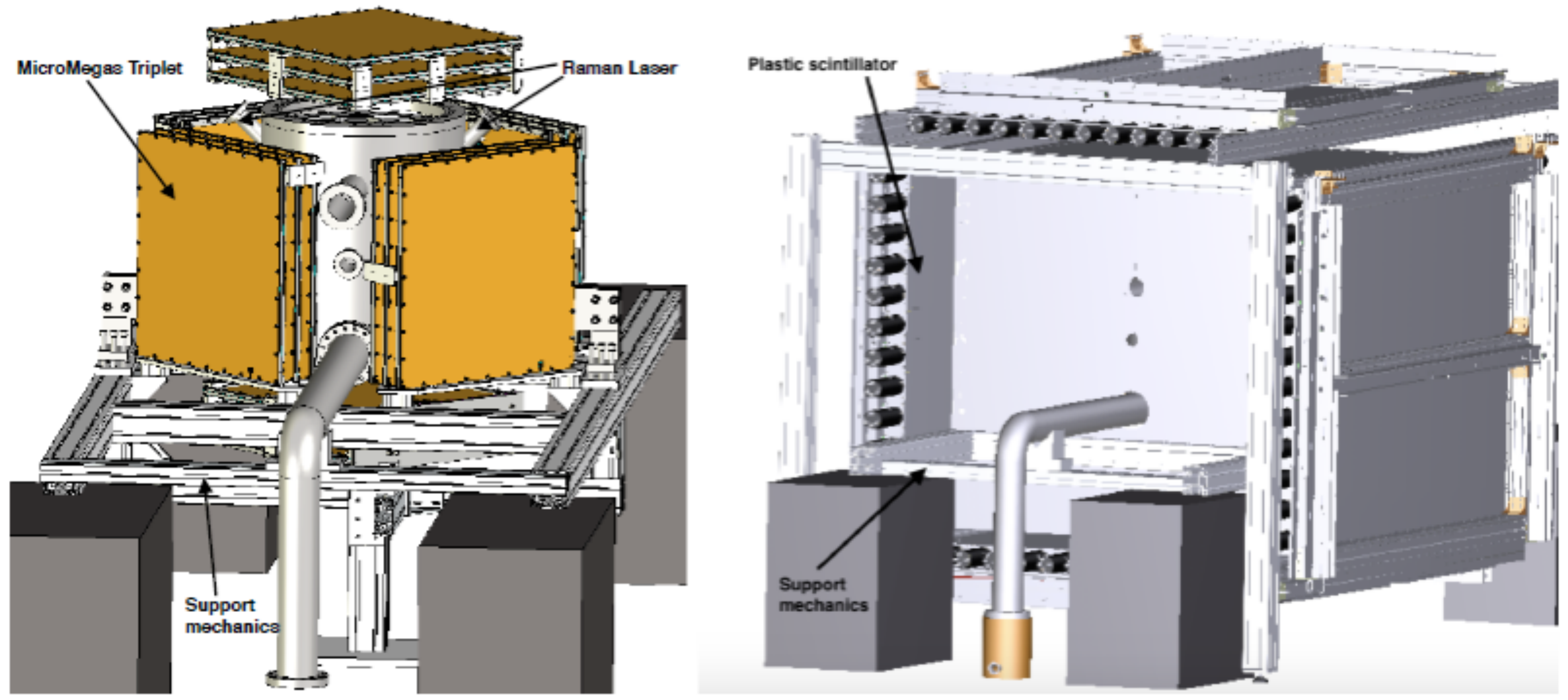
- Magnetic field : 7T
- field uncertainty : $\sigma_B/B < 1.e\text{-}3$
- Zero stary field outside of the trap : 2.3mT (55cm from center)
- Pressure : P_{MRE}<1.e-10mbar (turbo pumps (#2))
- Temperature : T_{MRE}<15K (coldheads (#2),Multi-layer insulator(MLI) layers)
- MRE Potential : V_{MRE} < 140V
- Buncher potential : V_{HV} < 10kV
- Total 11# MRE lenses (1# rotating wall) ← controlled by PXI
- HV lenses 2#(upstream, downstream) with fast switches

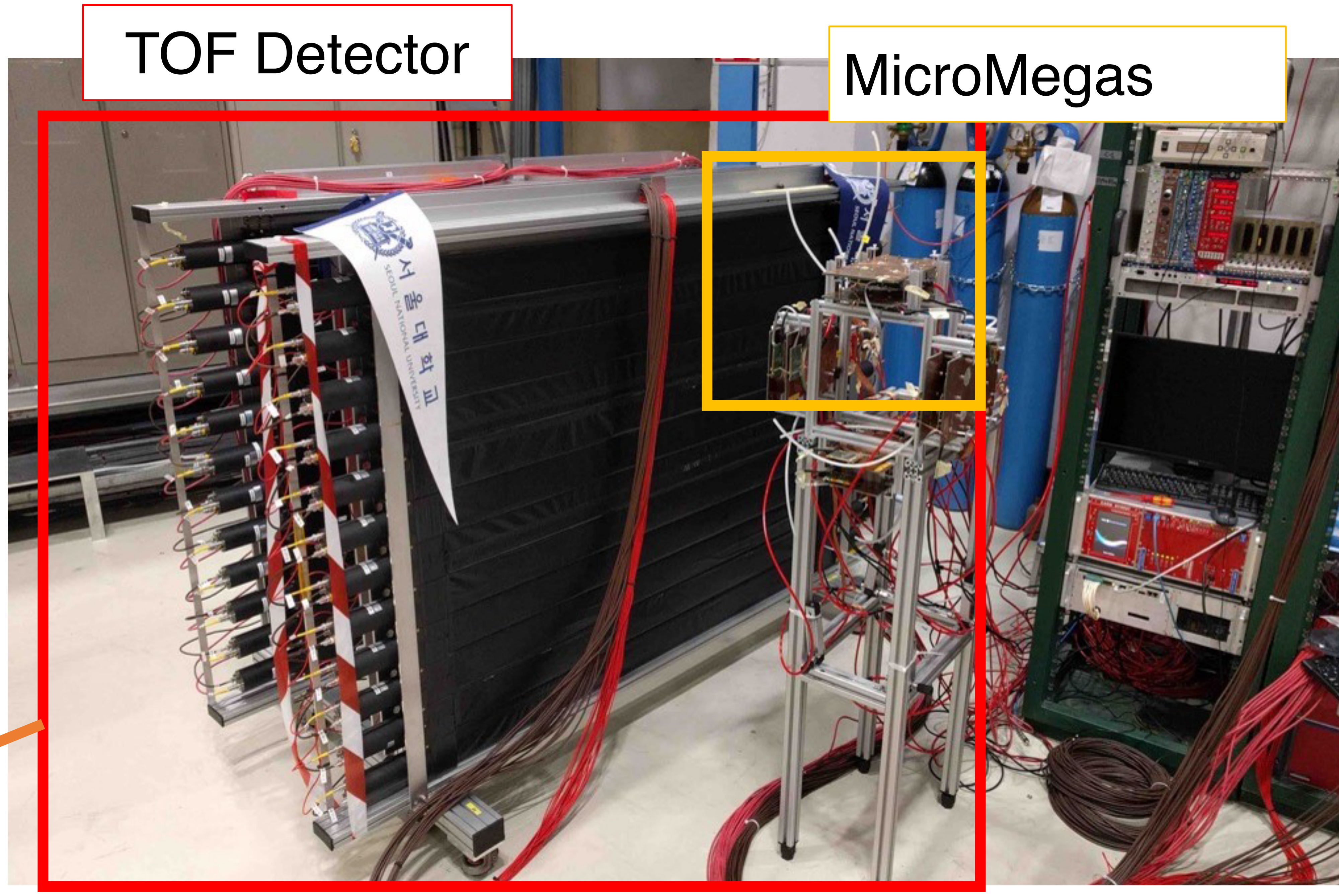


TOF 측정 장치 개발



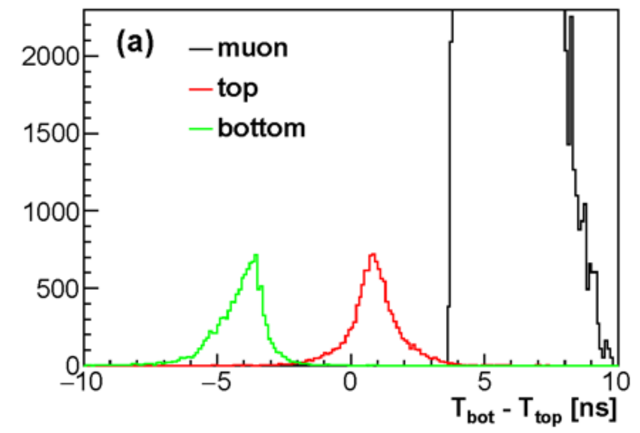


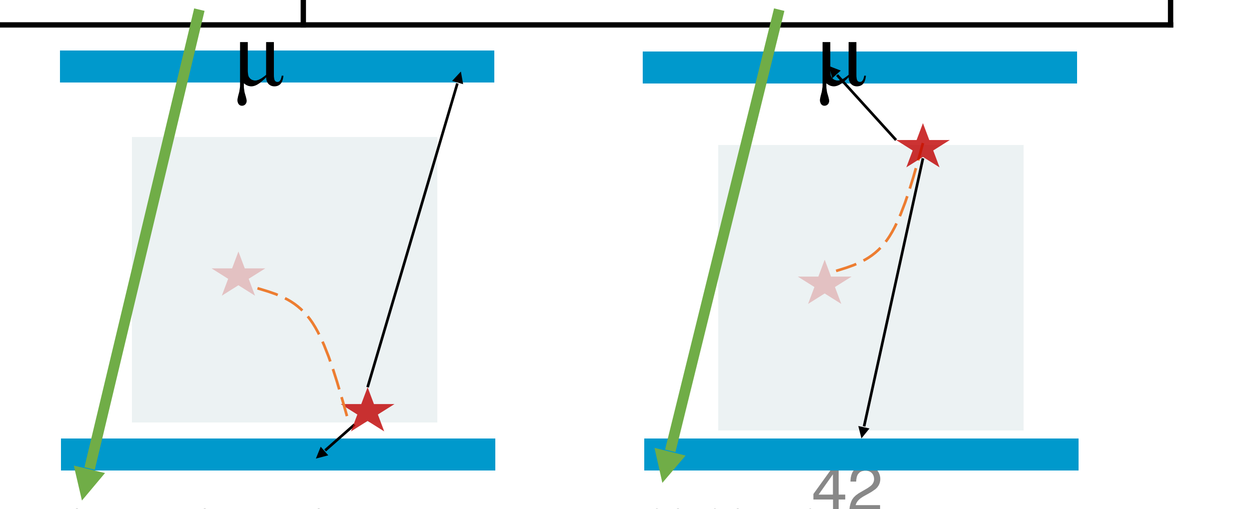




Temperature	Sign decision
10uK	~30 events
1mK	~6000 events

- 1% 정밀도는1500# 측정으로 가능할 것으로 예상됩니다(10uK)
- TOF 장치개발 되었으며 시뮬레이션 및 deep learning 스터디가 진행중입니다
- 높은 veto효율로 우주선은 TOF 장치로 제거할 것으로 기대됩니다.



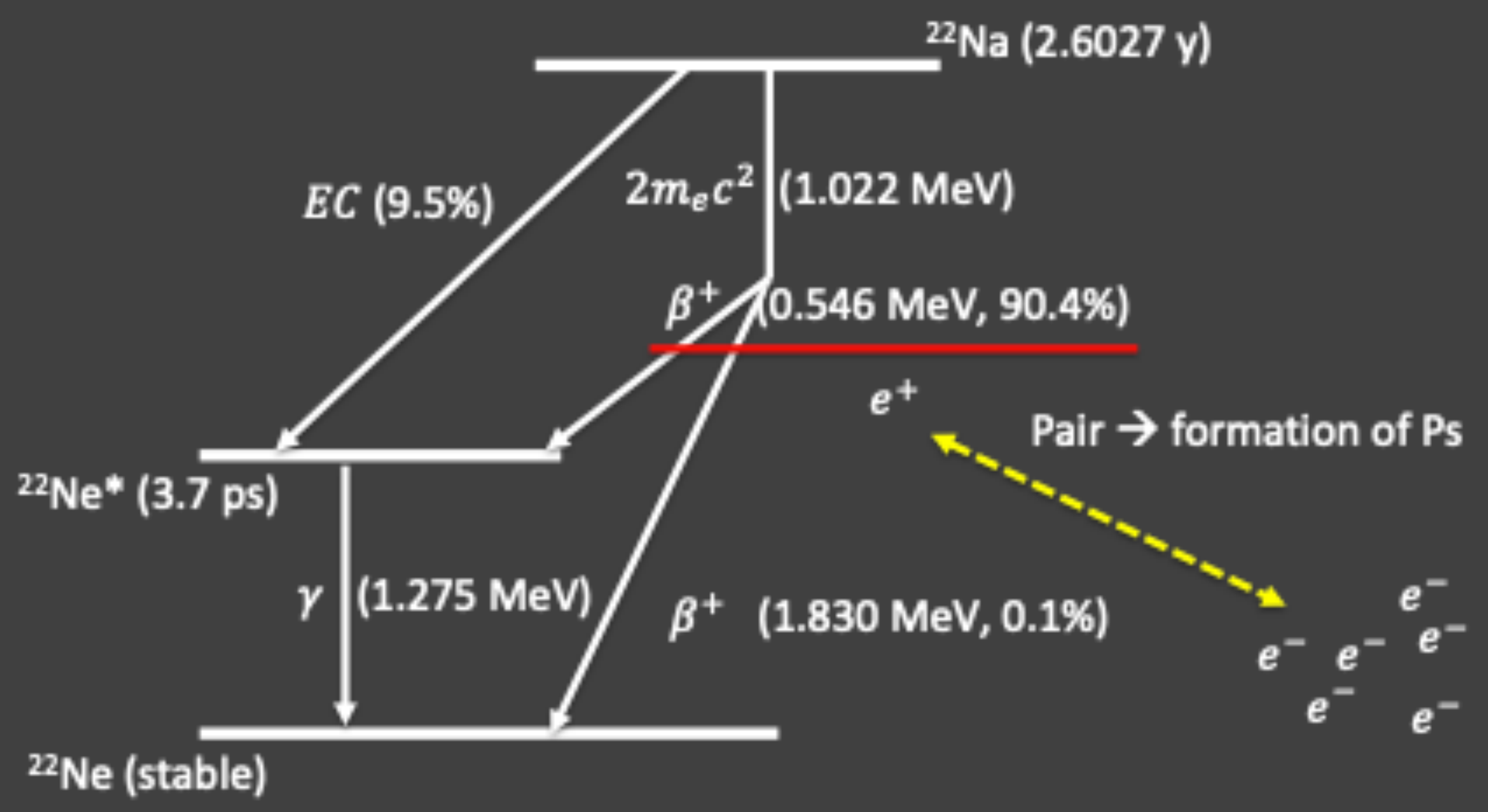


Chamber bottom annihilation Top annihilation

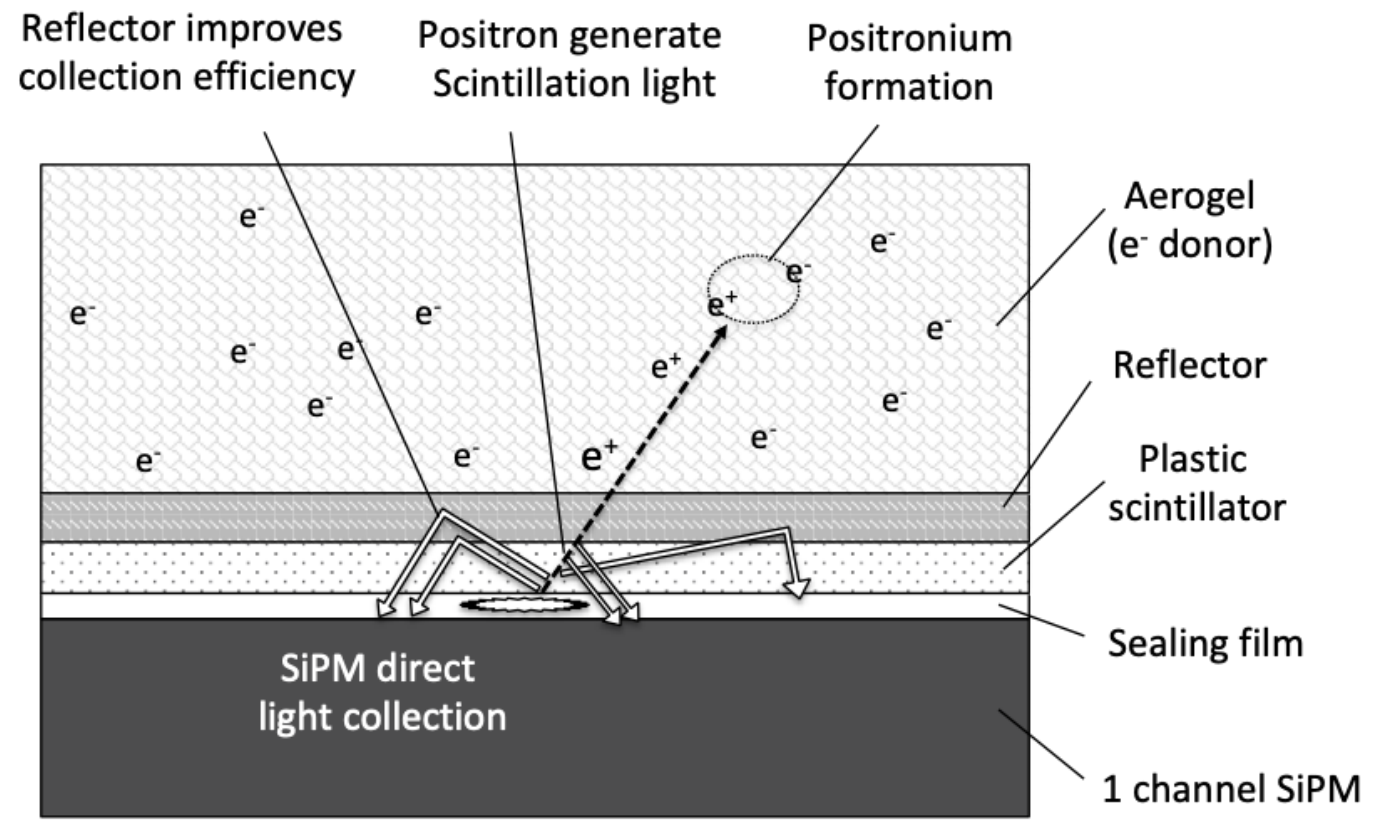
KNU KYUNGPOOK NATIONAL UNIVERSITY

The concept of detector for KAPAE

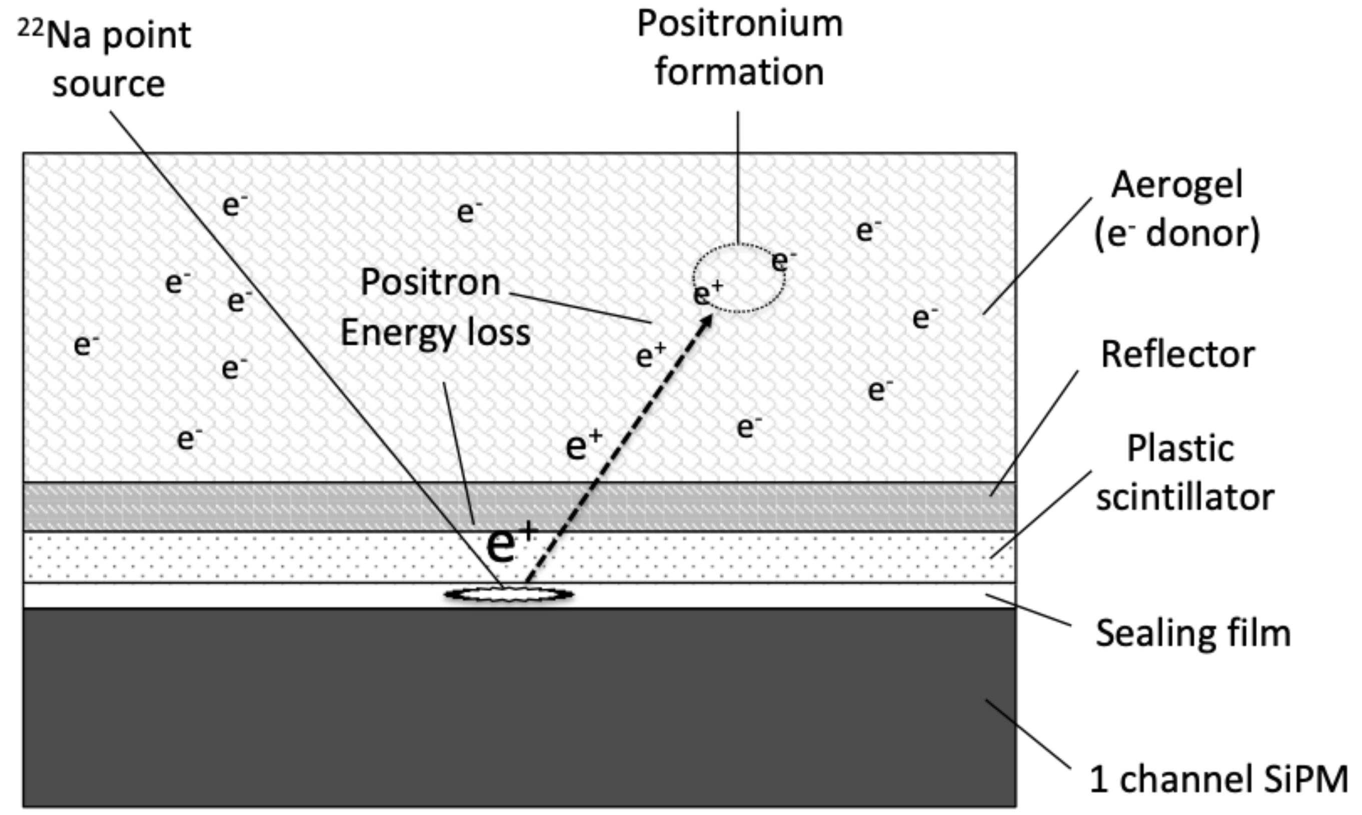
- Positronium = Electron + Positron
  - Positron → β^+ decay (^{22}Na)
  - Electron → aerogel
- Trigger signal
  → Plastic scintillator



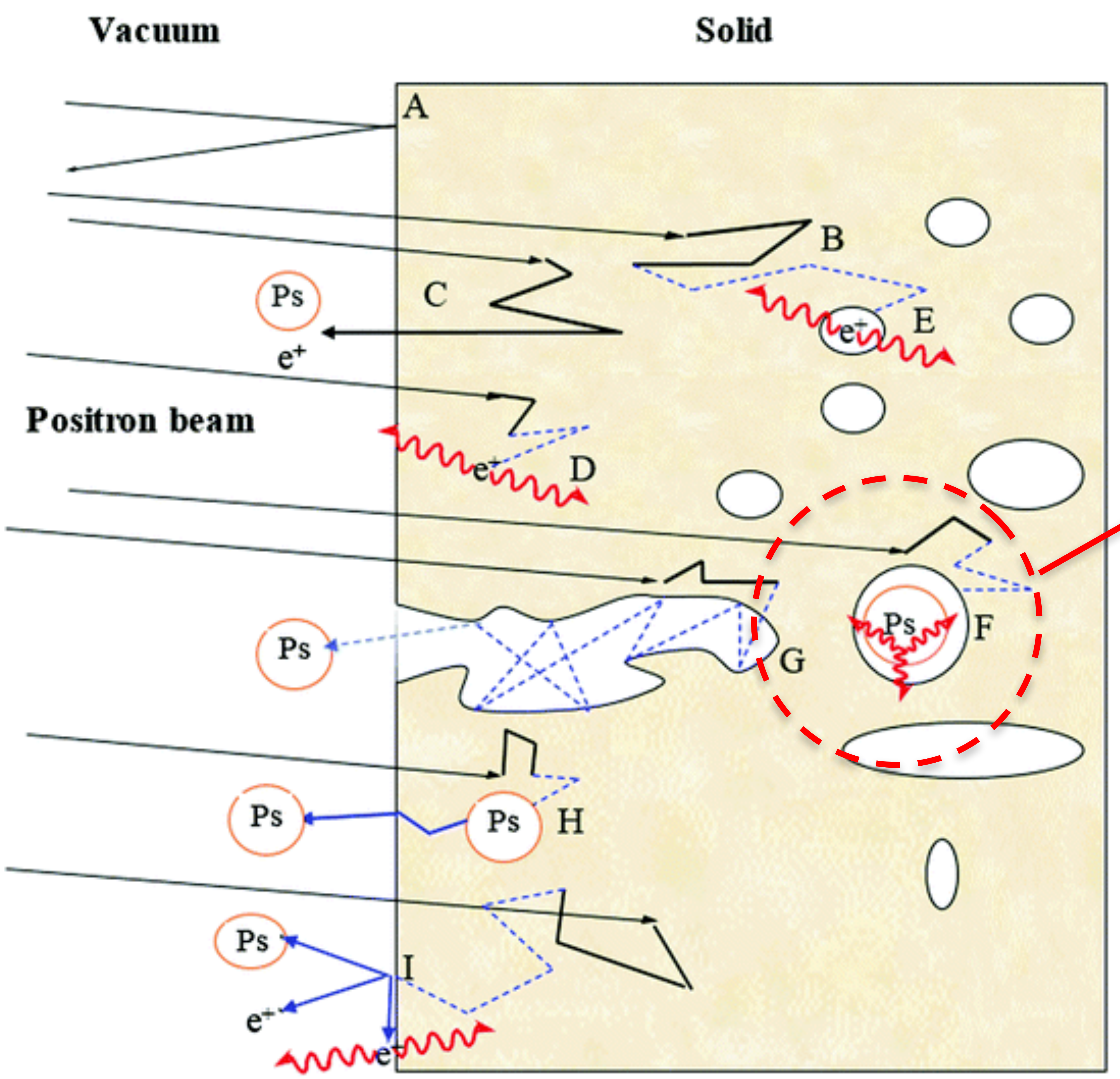
Generation of trigger signal



Positronium formation in aerogel



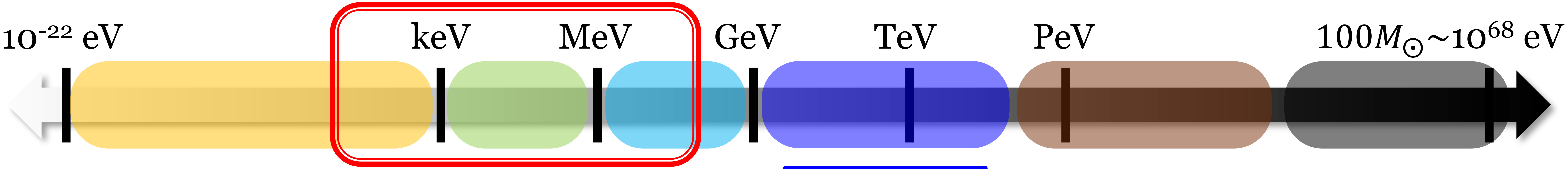
Aerogel 필요 이유



다공성 공간이 많을 수록

o-Ps 형성에 유리

Mass Scale of DM



Ultralight (QCD) axion, hidden photon, scalar field, fuzzy, non-thermal,

Superlight sterile ν, axino, warm DM, can be **thermal**

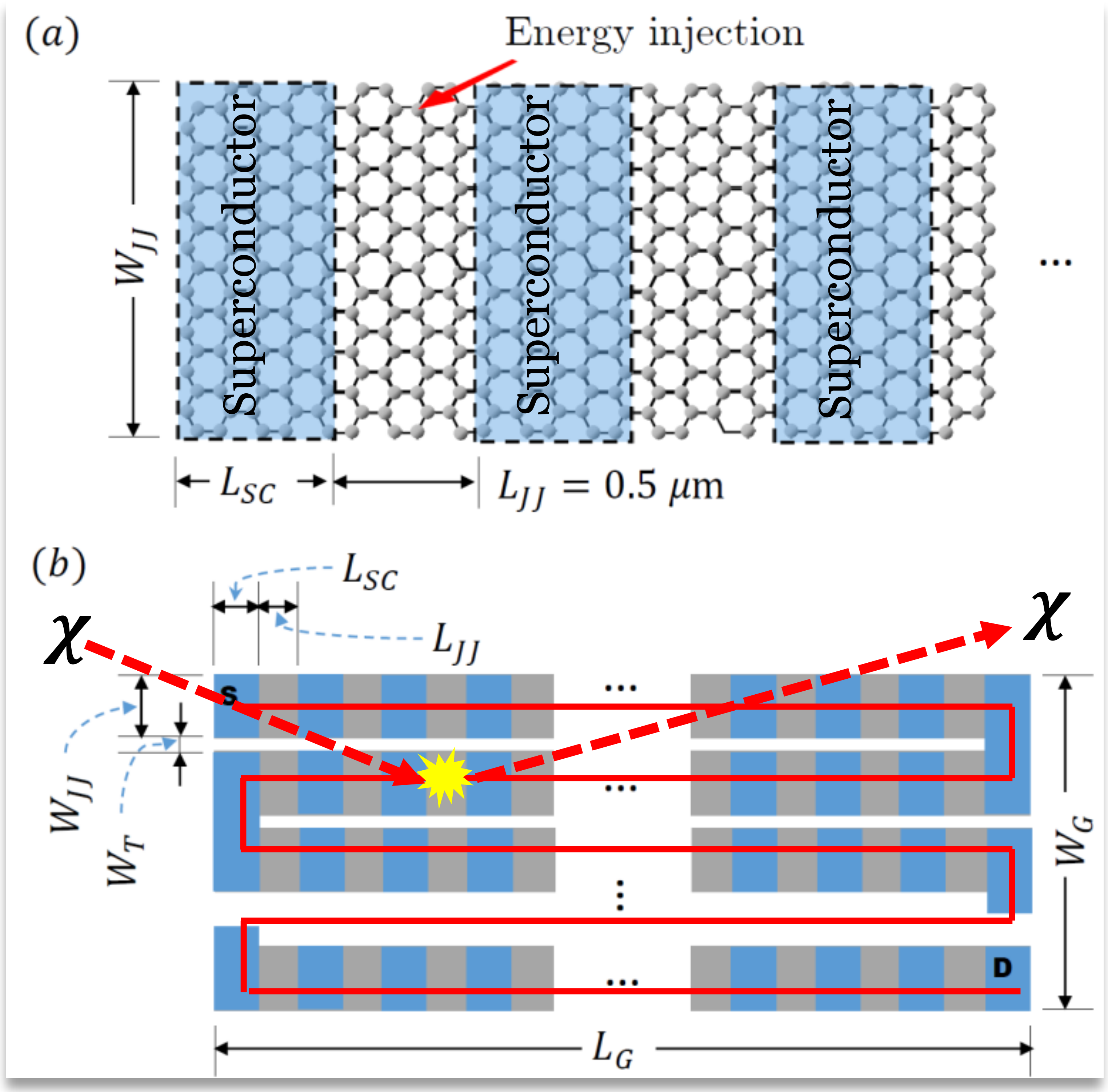
Light dark sector, can be **thermal**

WIMP well-motivated, extensively studied, thermal **No firm signal yet!**

Superheavy / Composite WIMPzilla, Q-ball, Fermi-ball, dark-quark nugget, non-thermal

MACHO / Primordial BHs non-particle

Conceptual Design Proposal



I. Single graphene strip (a): the assembly of a graphene strip & a number of superconducting material strips ➔ an array of SC-graphene-SC-graphene-SC-⋯ (SGSGS⋯).

II. Each sequence of SGS represents a single GJJ device.

III. Full detector unit (b): all GJJs are connected in series so that even a single switched GJJ allows the series resistance measured between S & D to switch from 0 to a finite value.

- ❖ E_{th} is determined by the strip width W_{JJ}: $W_{JJ} = 3\ \mu m$ ($30\ \mu m$) ➔ $E_{th} \approx 0.1$ meV (1 meV).
- ❖ A much larger-scale detector can be made of a stack of such detector units.

Maxwell's Equations with a Magnetic Monopole

Beautiful Symmetry of Maxwell's Equations

$$\nabla \cdot \mathbf{E} = \rho_e \qquad -\nabla \times \mathbf{E} = \partial \mathbf{B}/\partial t + \mathbf{j}_m$$

$$\nabla \cdot \mathbf{B} = \rho_m \qquad \nabla \times \mathbf{B} = \partial \mathbf{E}/\partial t + \mathbf{j}_e$$

Electromagnetic force law: $\mathbf{F} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) + g(\mathbf{B} - (\mathbf{v}/c^2) \times \mathbf{E})$

Magnetic Acceleration

- Main idea for experimental design

- Magnetic charges m^+m^- will be accelerated in opposites directions in a magnetic field by F=gB

$$\Delta E = gB\ell$$ the obtained energy of magnetic monopoles

$$\Delta E = 68.5e \times (1T \times c) \times 1 \text{ meter} \approx 20.5 \text{ GeV}$$

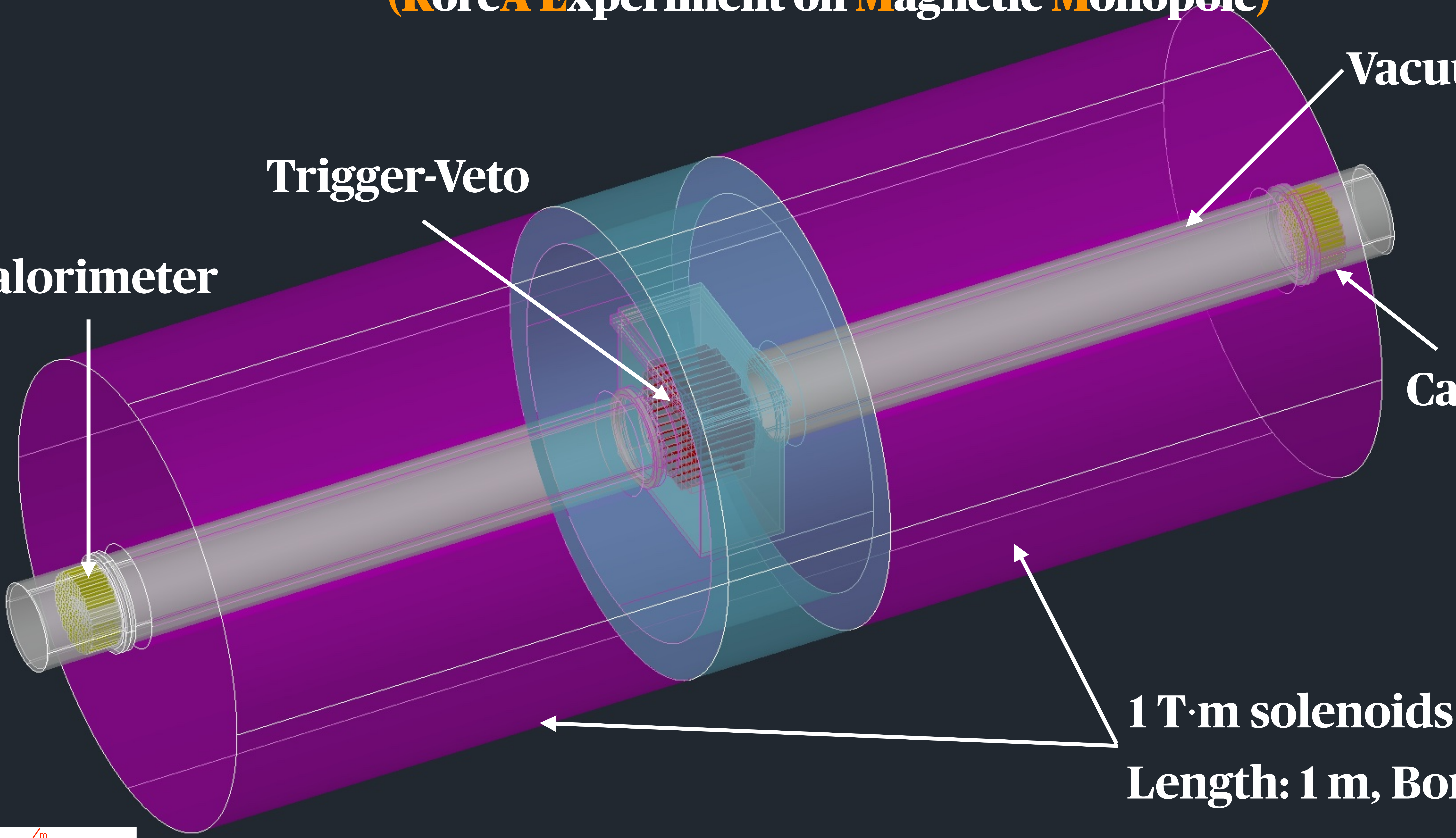
$$\Delta E = (300 \text{ MeV}) \times g/e$$ ← **the signature of monopole**

Main background: two 511 keV photons

Experimental design

KæM

(KoreA Experiment on Magnetic Monopole)



KæM
KoreA Experiment on Magnetic Monopole