Search for Sub-millicharged Particles at J-PARC

Hoyong Jeong (Korea University) on behalf of the SUBMET collaboration

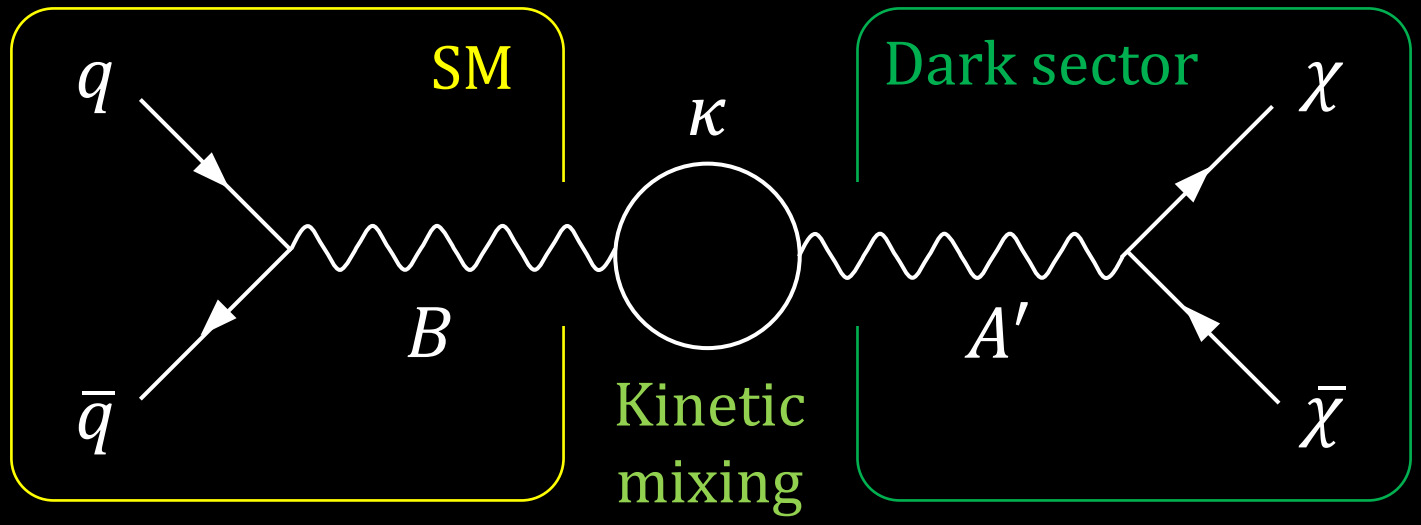
July 19th 2023

31st International Symposium on Lepton Photon Interactions at High Energies

Why milli-charged?

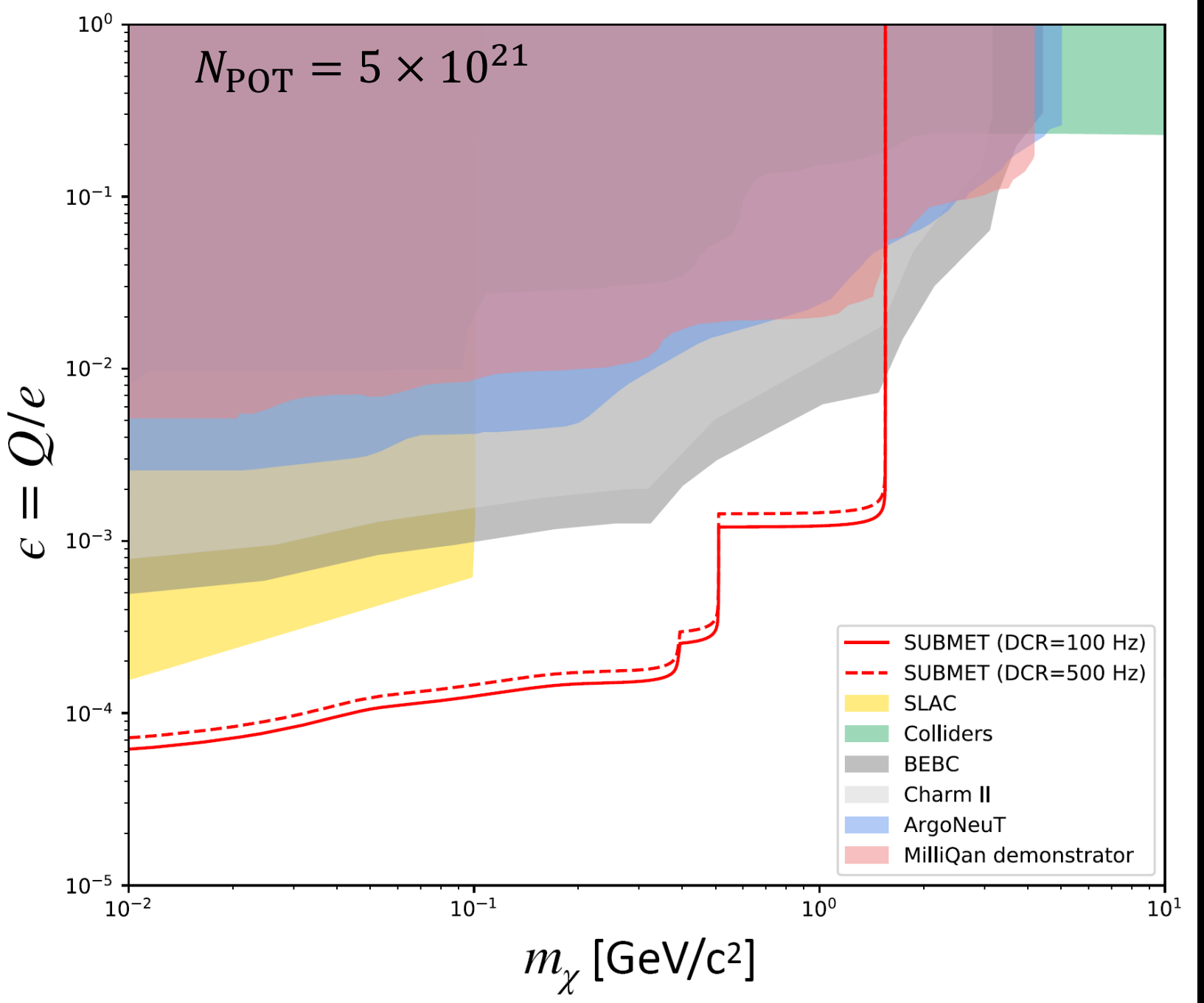
$$\mathcal{L}_{\text{dark sector}} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\chi}(\not{\partial} + ie'\not{A}' + iM_{\text{mCP}})\chi - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\chi}(\not{\partial} + ie'\not{A}' + i\boldsymbol{\kappa e'}\not{B} + iM_{\text{mCP}})\chi$$



New fermion (χ) can have a small EM charge: milli-charged particle.

"Kinetic mixing with a new massless 'dark' boson **can provide the link between SM and a hidden/dark sector**." (Holdom, 1985)



Largely yet unexplored region:

$Q < 2 \times 10^{-4} e$

and

$Q < 10^{-3} e, m_\chi > 0.1$ GeV/c²

SUBMET:

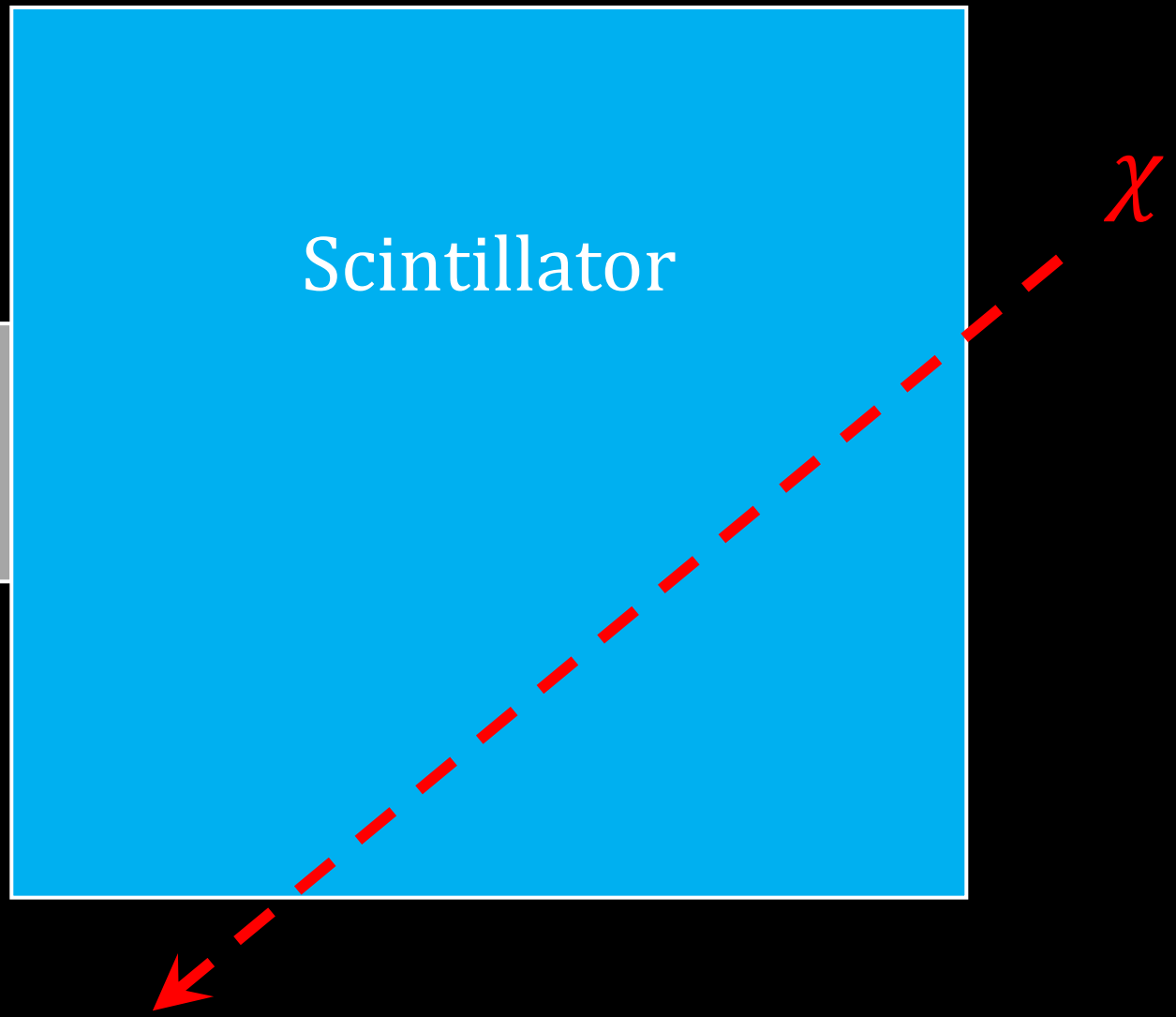
SUB-Millicharge

ExperimenT at J-PARC

$Q_\chi \neq 0$

↓

Small ionization by low-charged particles



Expected a few γs,

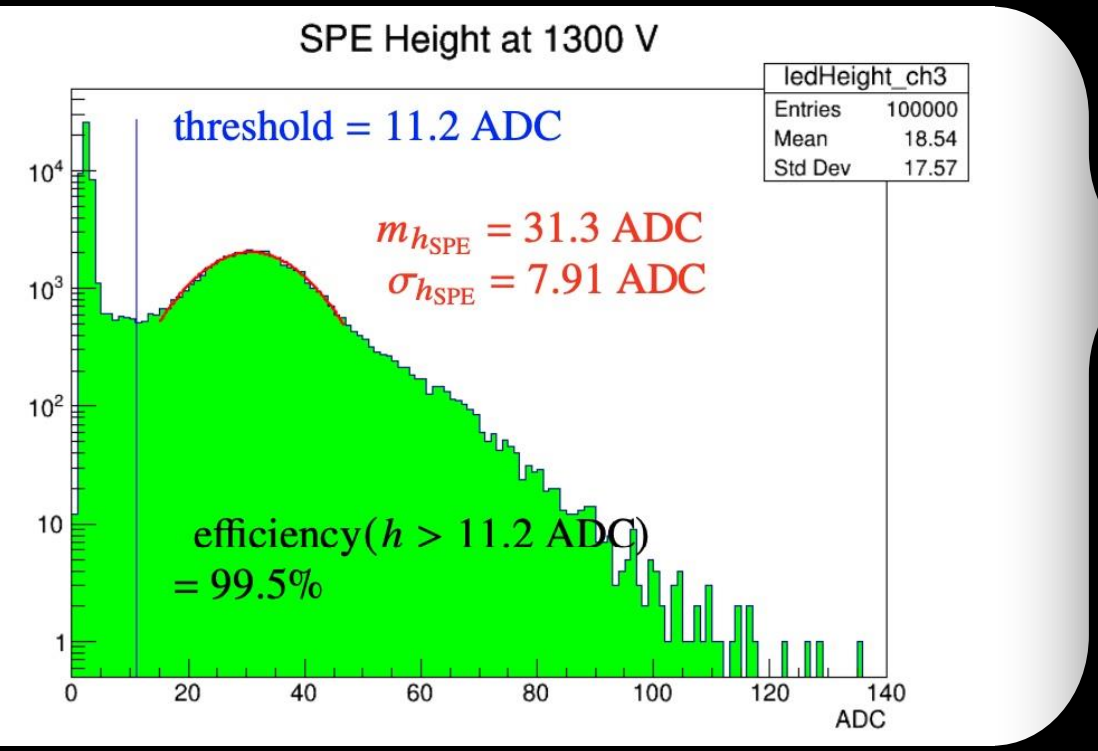
or even a single γ

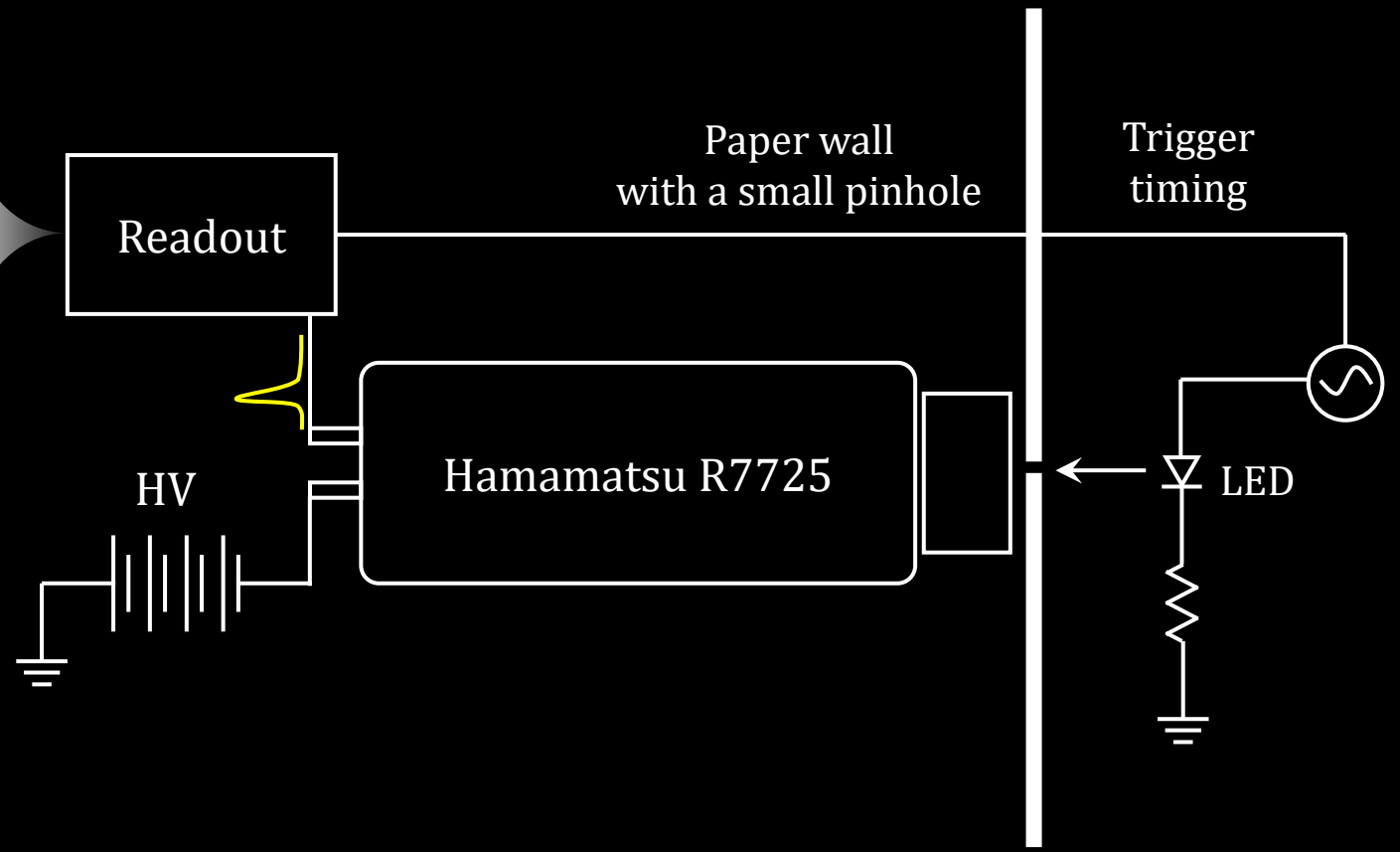
(for $Q < 10^{-3}e$,

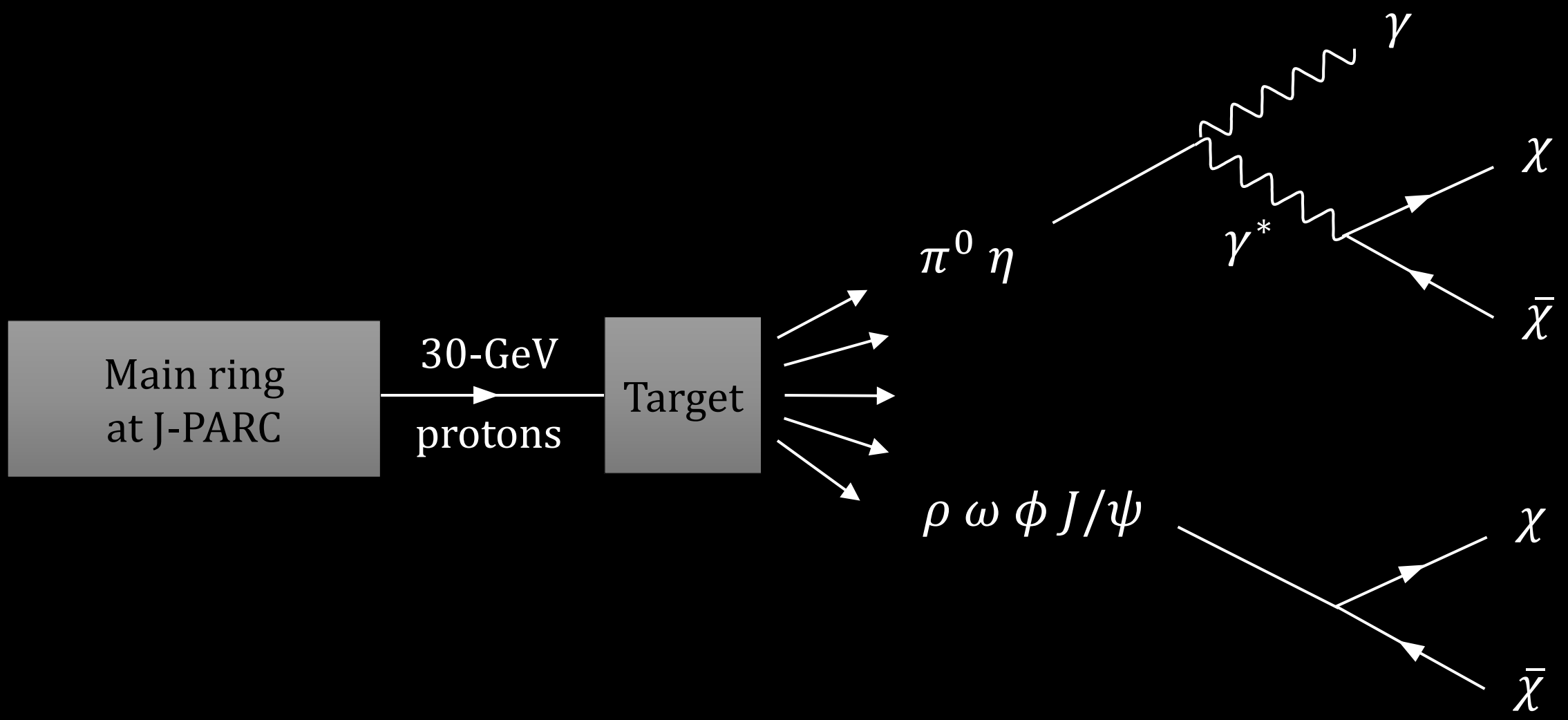
it's mostly single photon)

Q. Can PMT detect single-photoelectric (SPE) signals?

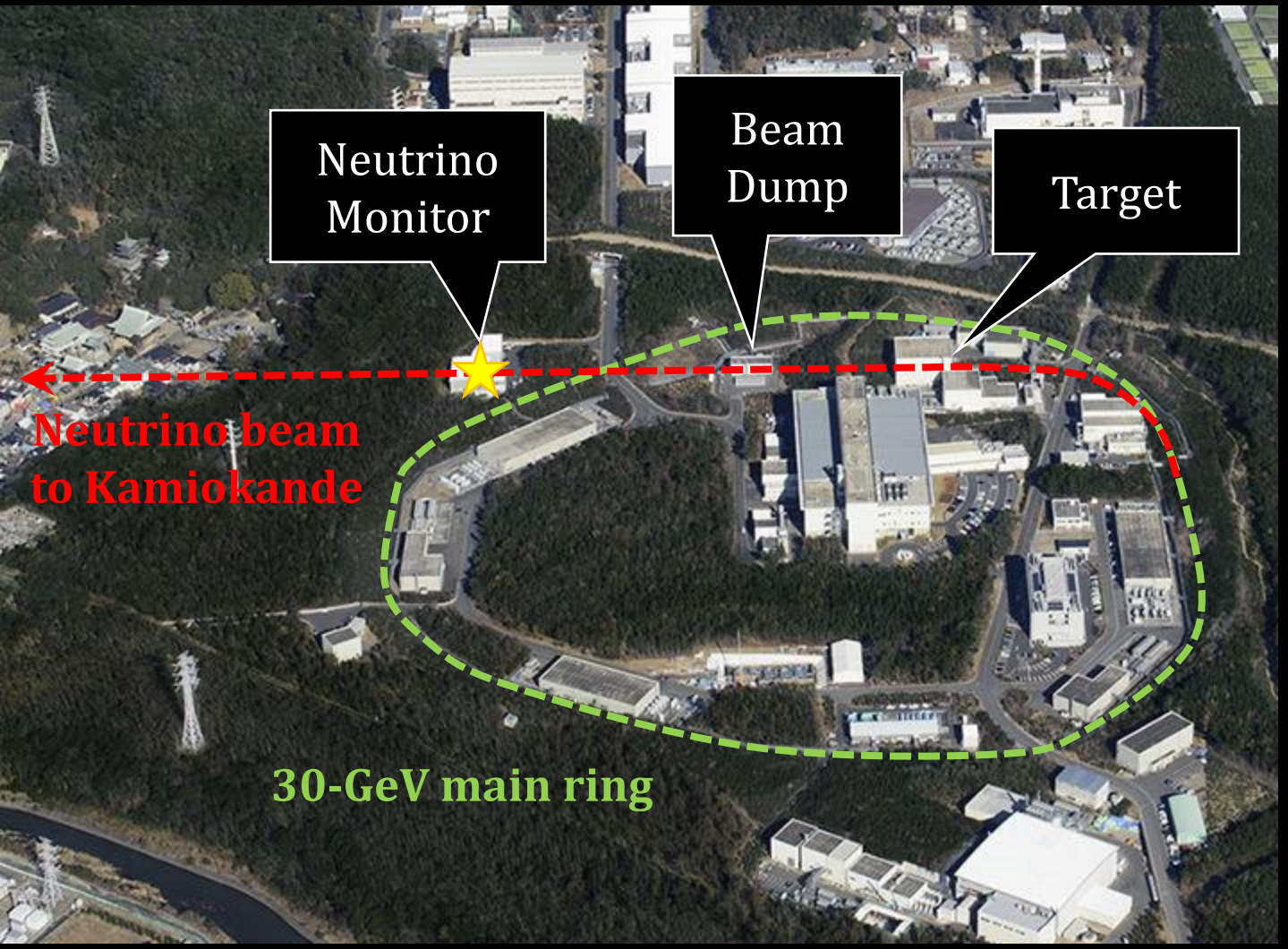
A. Yes it can.






Main ring
at J-PARC
30-GeV
protons
Target
$\pi^0\ \eta$
$\rho\ \omega\ \phi\ J/\psi$
γ
γ^*
χ
$\bar{\chi}$
χ
$\bar{\chi}$

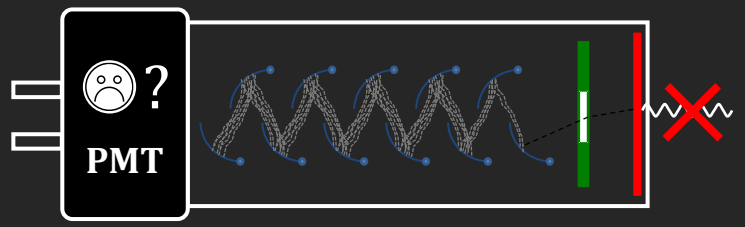
From https://j-parc.jp/c/en/about/outline.html



1 m × 4 m
is secured for the experiment.

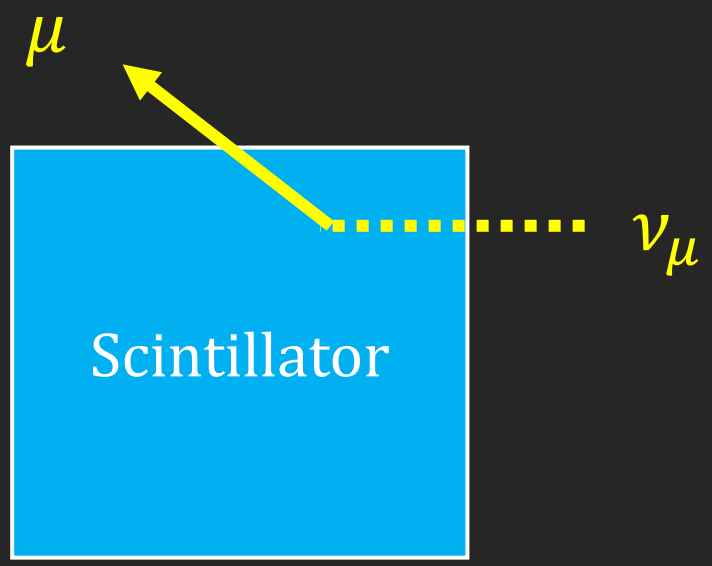
All kinds of tiny (SPE-like) pulses can be **BACKGROUNDS**

Detector itself



DCR ~ 500 Hz

Beam-induced

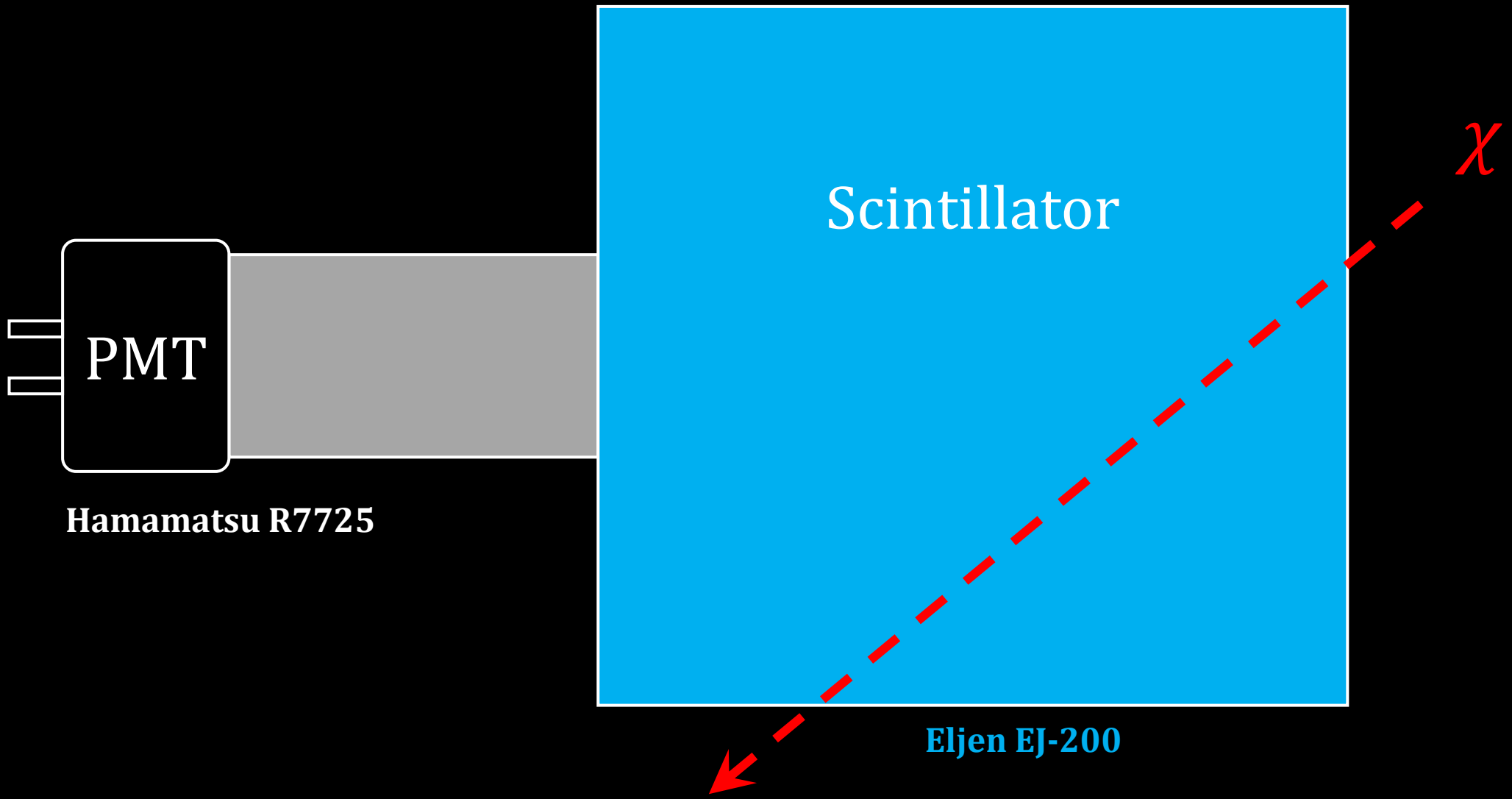


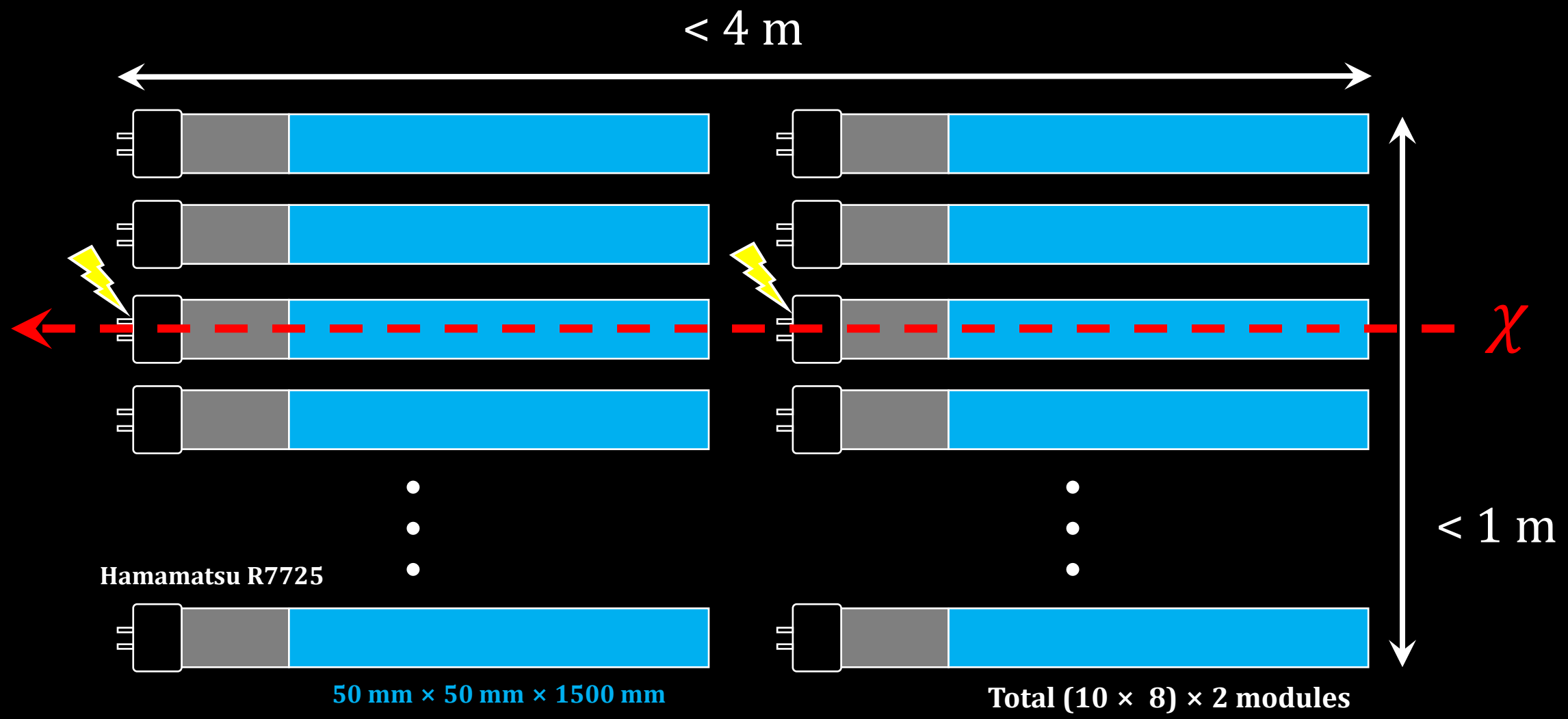
Others

Cosmic shower

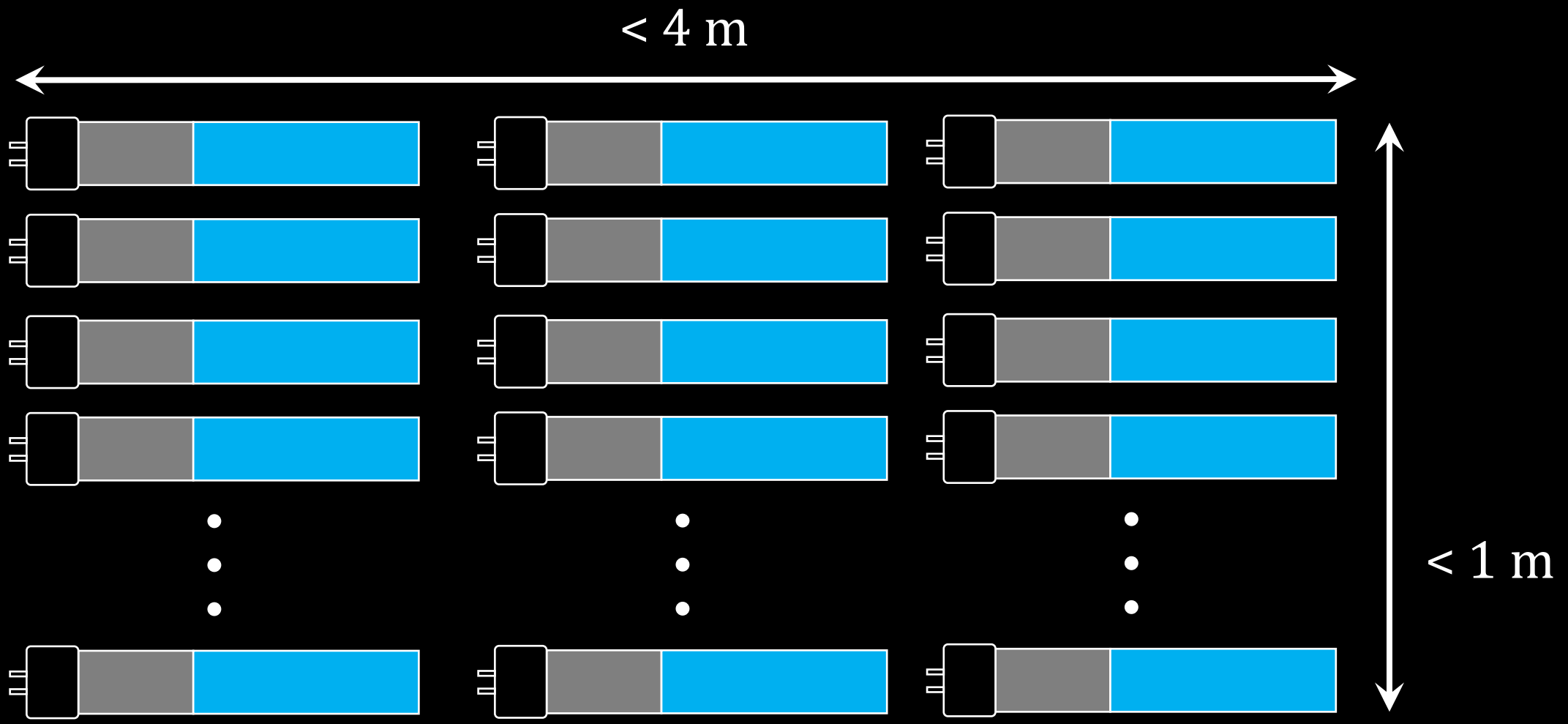
Natural radiation

…


Scintillator
χ
PMT
Hamamatsu R7725
Eljen EJ-200



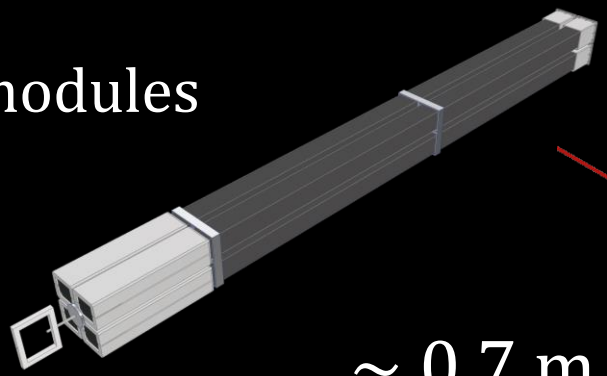
Coincidence: BG ↓



More layers? Coincidence rate ↓, signal acceptance ↓, cost ↑

Sensitivity ↓

4 sets of PMT+Scint modules

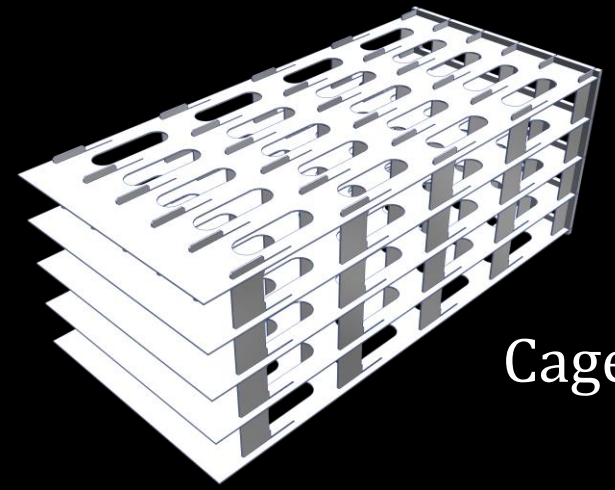


~ 0.8 m

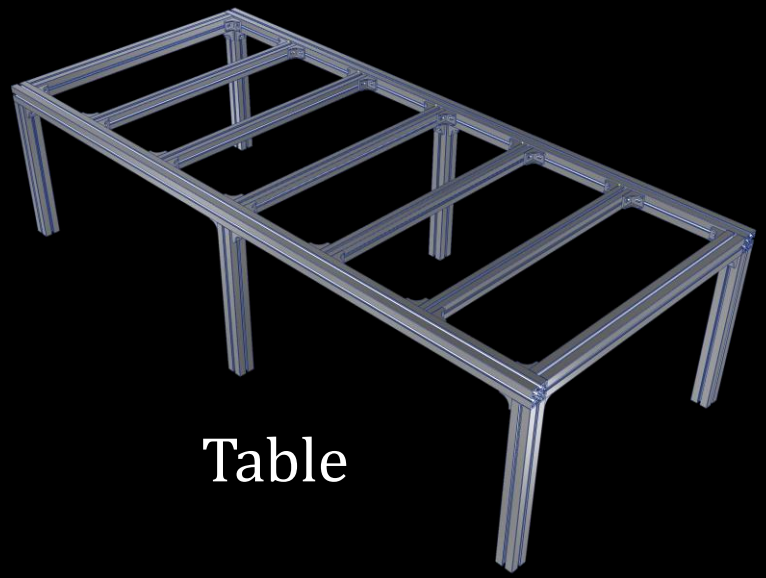
~ 4 m

~ 0.7 m

~ 0.5 m



Cage



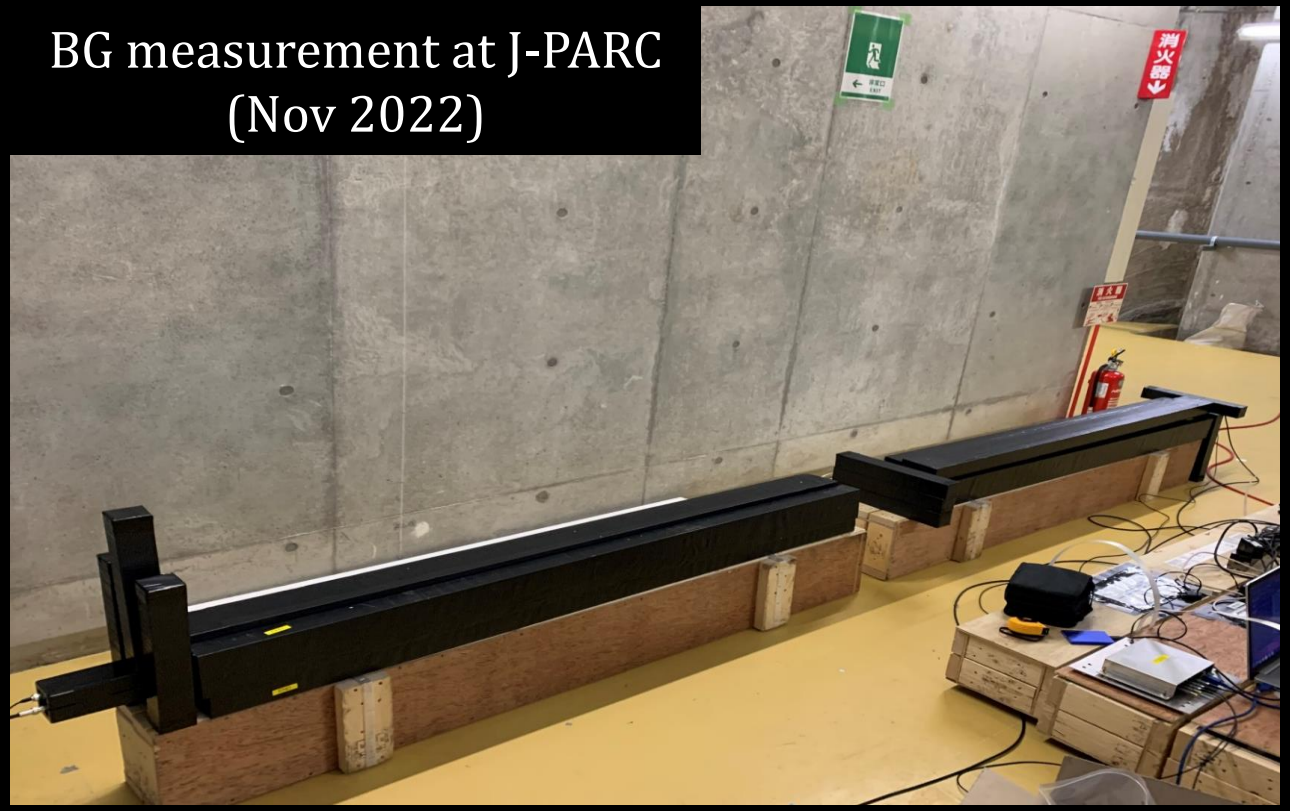
Table

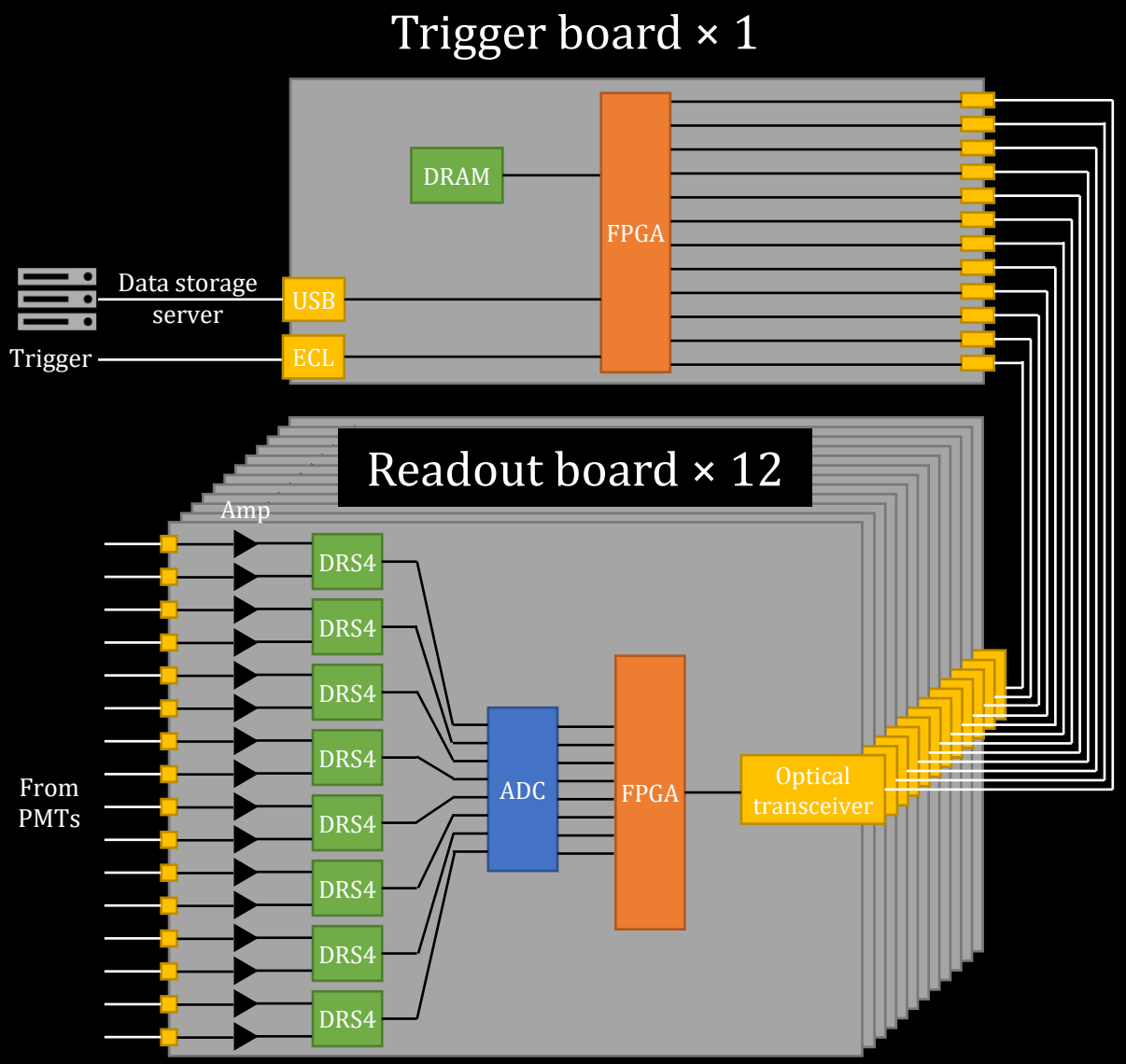
χ

2 cages
on 2 tables

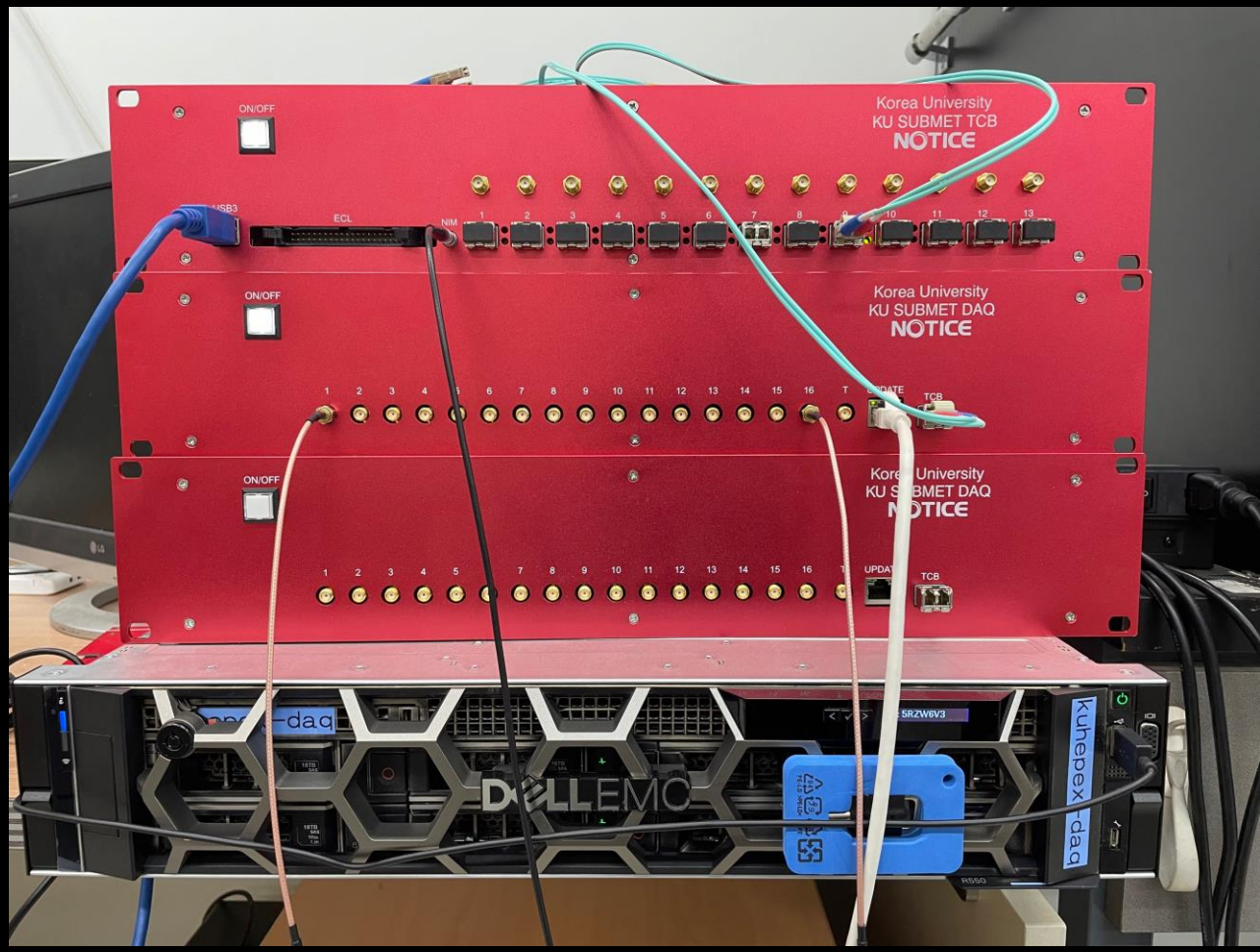
1 supermodule = 4 PMTs + 4 Scints

BG measurement at J-PARC
(Nov 2022)

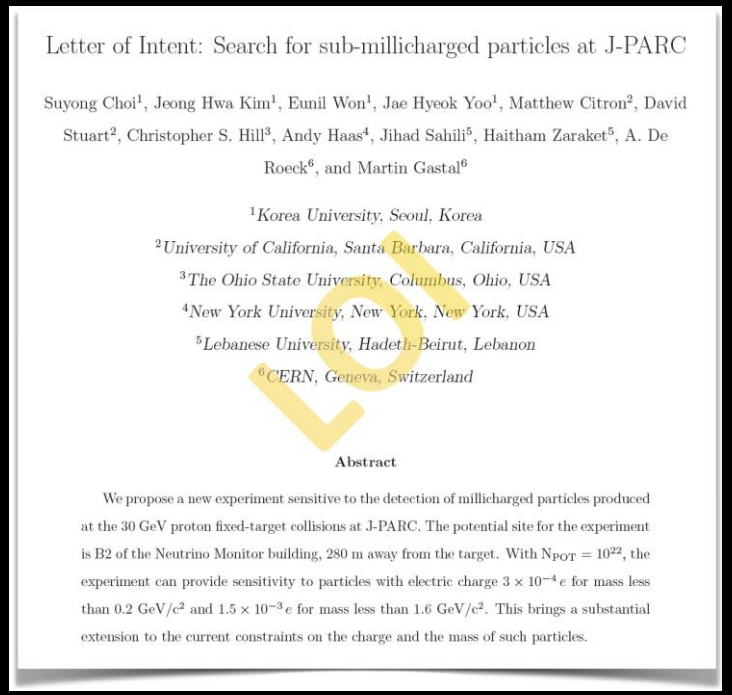




DAQ: Custom DRS4-based readout systems



Current Status, and…



Letter of Intent: Search for sub-millicharged particles at J-PARC

Suyong Choi[1], Jeong Hwa Kim[1], Eunil Won[1], Jae Hyeok Yoo[1], Matthew Citron[2], David Stuart[2], Christopher S. Hill[3], Andy Haas[4], Jihad Sahili[5], Haitham Zaraket[5], A. De Roeck[6], and Martin Gastal[6]

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[2]*University of California, Santa Barbara, California, USA*
[3]*The Ohio State University, Columbus, Ohio, USA*
[4]*New York University, New York, New York, USA*
[5]*Lebanese University, Hadeth-Beirut, Lebanon*
[6]*CERN, Geneva, Switzerland*

LOI

Abstract

We propose a new experiment sensitive to the detection of millicharged particles produced at the 30 GeV proton fixed-target collisions at J-PARC. The potential site for the experiment is B2 of the Neutrino Monitor building, 280 m away from the target. With $N_{POT} = 10^{22}$, the experiment can provide sensitivity to particles with electric charge $3 \times 10^{-4}\,e$ for mass less than 0.2 GeV/c^2 and $1.5 \times 10^{-3}\,e$ for mass less than 1.6 GeV/c^2. This brings a substantial extension to the current constraints on the charge and the mass of such particles.

Proposal: Search for sub-millicharged particles at J-PARC

SUB-Millicharge ExperimenT (SUBMET)

Sungwoong Cho[1], Suyong Choi[1], Jeong Hwa Kim[1], Eunil Won[1], Jae Hyeok Yoo[1], Claudio Campagnari[2], Matthew Citron[2], David Stuart[2], Christopher S. Hill[3], Andy Haas[4], Jihad Sahili[5], Haitham Zaraket[5], A. De Roeck[6], and Martin Gastal[6]

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[4]*New York University, New York, New York, USA*
[5]*Lebanese University, Hadeth-Beirut, Lebanon*
[6]*CERN, Geneva, Switzerland*

Proposal

Abstract

We propose a new experiment searching for sub-millicharged particles (χs) using 30 GeV proton fixed-target collisions at J-PARC. The detector is composed of two layers of stacked scintillator bars and PMTs and is proposed to be installed 280 m from the target. The main background is a random coincidence between two layers due to dark counts in PMTs, which can be reduced to a negligible level using the timing of the proton beam. With $N_{POT} = 5 \times 10^{21}$ which corresponds to running the experiment for three years, the experiment provides sensitivity to χs with the charge down to $6 \times 10^{-5}e$ in $m_\chi < 0.2$ GeV/c^2 and $10^{-3}e$ in $m_\chi < 1.6$ GeV/c^2. This is the regime largely uncovered by the previous experiments.

Technical Design Report

E83: Search for sub-millicharged particles at J-PARC

SUB-Millicharge ExperimenT (SUBMET)

Sungwoong Cho[1], Suyong Choi[1], Seokju Chung[1], Hoyong Jeong[1], Hyunki Moon[1], Eunil Won[1], Jae Hyeok Yoo[1], Matthew Citron[2], Claudio Campagnari[3], Jeong Hwa Kim[3], Ryan Schmitz[3], David Stuart[3], Christopher S. Hill[4], Andy Haas[5], Ayman Youssef[6], Ahmad Zaraket[6], Haitham Zaraket[6], A. De Roeck[7], and Martin Gastal[7]

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[7]*CERN, Geneva, Switzerland*

TDR

2020	2021	2022	2023

LOI submitted in summer 2020

Proposal submitted in summer 2021 (32nd PAC meeting)

Stage-I approval April 2022

TDR submitted Nov 2022

FIFC meeting Dec 2022

Request for stage-II approval in Jan 2023 (35th PAC meeting)

The Program Advisory Committee (PAC) of J-PARC

Stage-II

has given the final approval

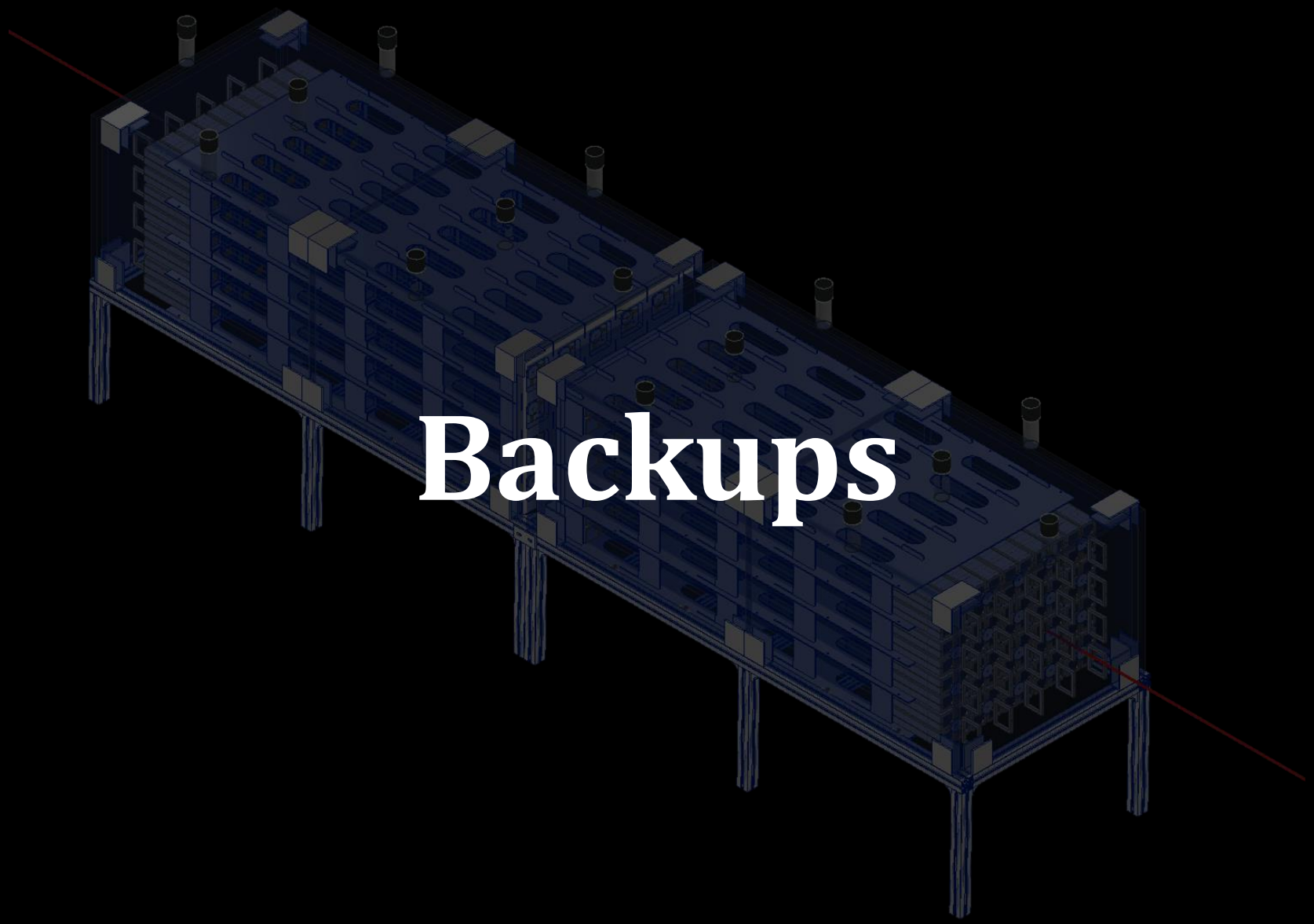
to SUBMET experiment.

Summary and Future Steps

- Current status
  - Mechanics: done
  - Modules: assembly and testing on going
  - Readout system: production and testing on going

- Plan
  - Installation: 1/2 in fall 2023 and 1/2 in spring 2024
  - Take data!

Thank you



Backups

The Team

Sungwoong Cho
Suyong Choi
Seokju Chung
Hoyong Jeong
Hyunki Moon
Changhyun Seo
Eunil Won
Jae Hyeok Yoo

Claudio Campagnari
Jeong Hwa Kim
David Stuart
Ryan Schmitz

Matthew Citron

Christopher S. Hill

Andy Haas

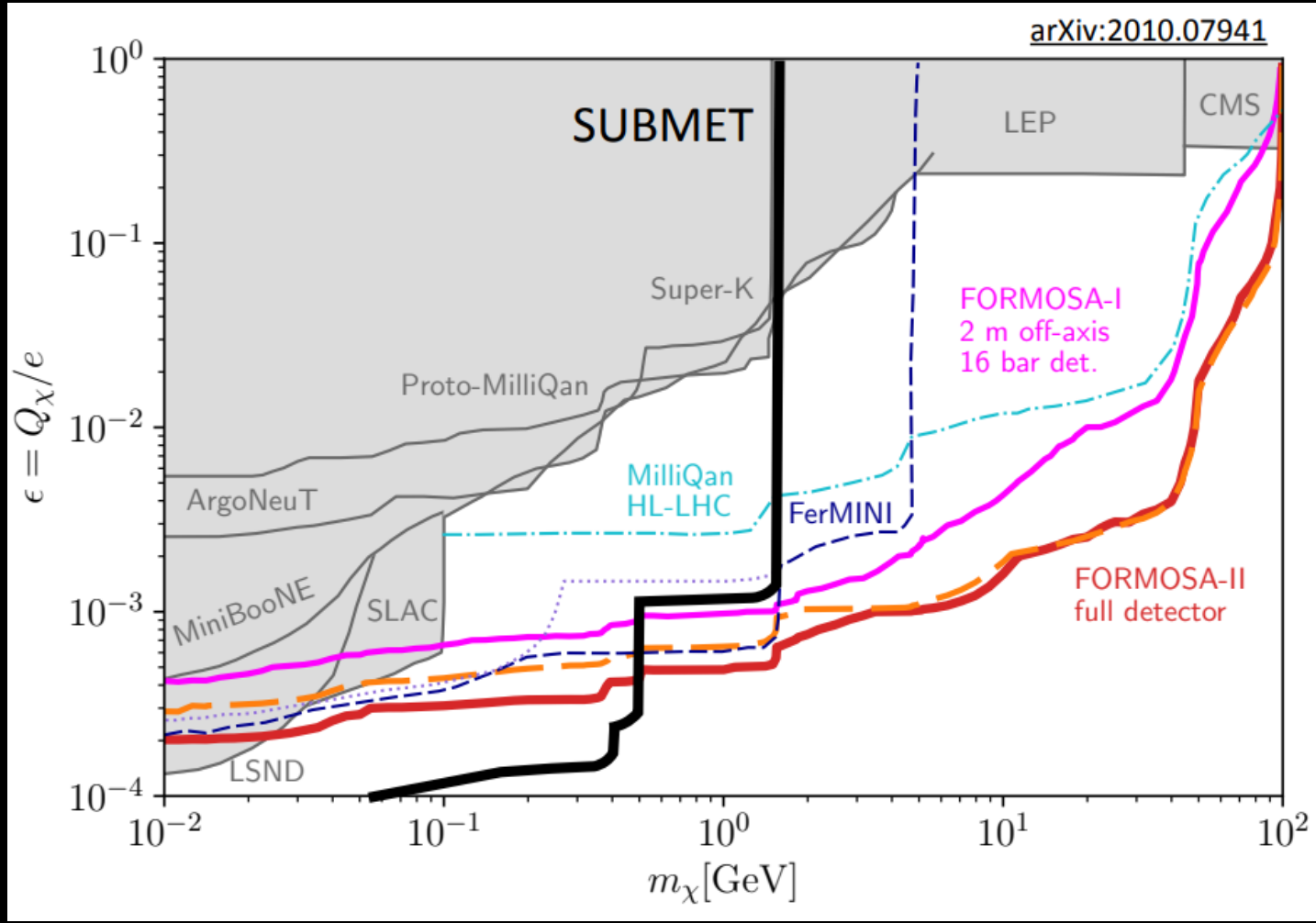
Jihad Sahili
Ayman Youssef
Ahmad Zaraket
Haitham Zaraket

Albert De Roeck
Martin Gastal

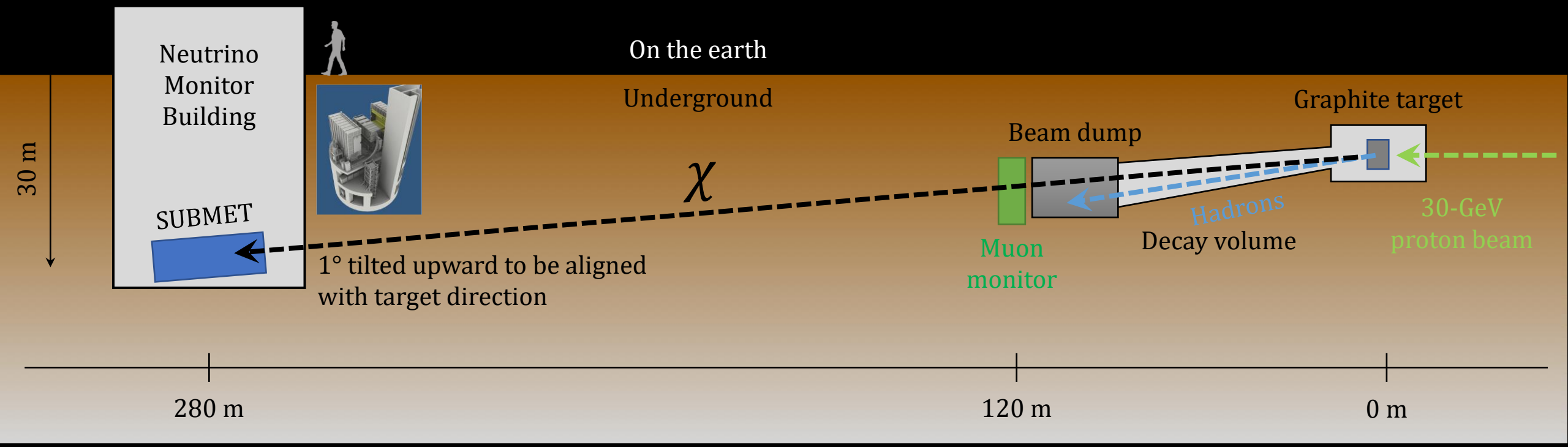
Other Proposals/experiments

There are proposals at LHC (milliQan, FORMOSA) and at FNAL (FerMINI), which are sensitive to higher mass regime

→ complimentary

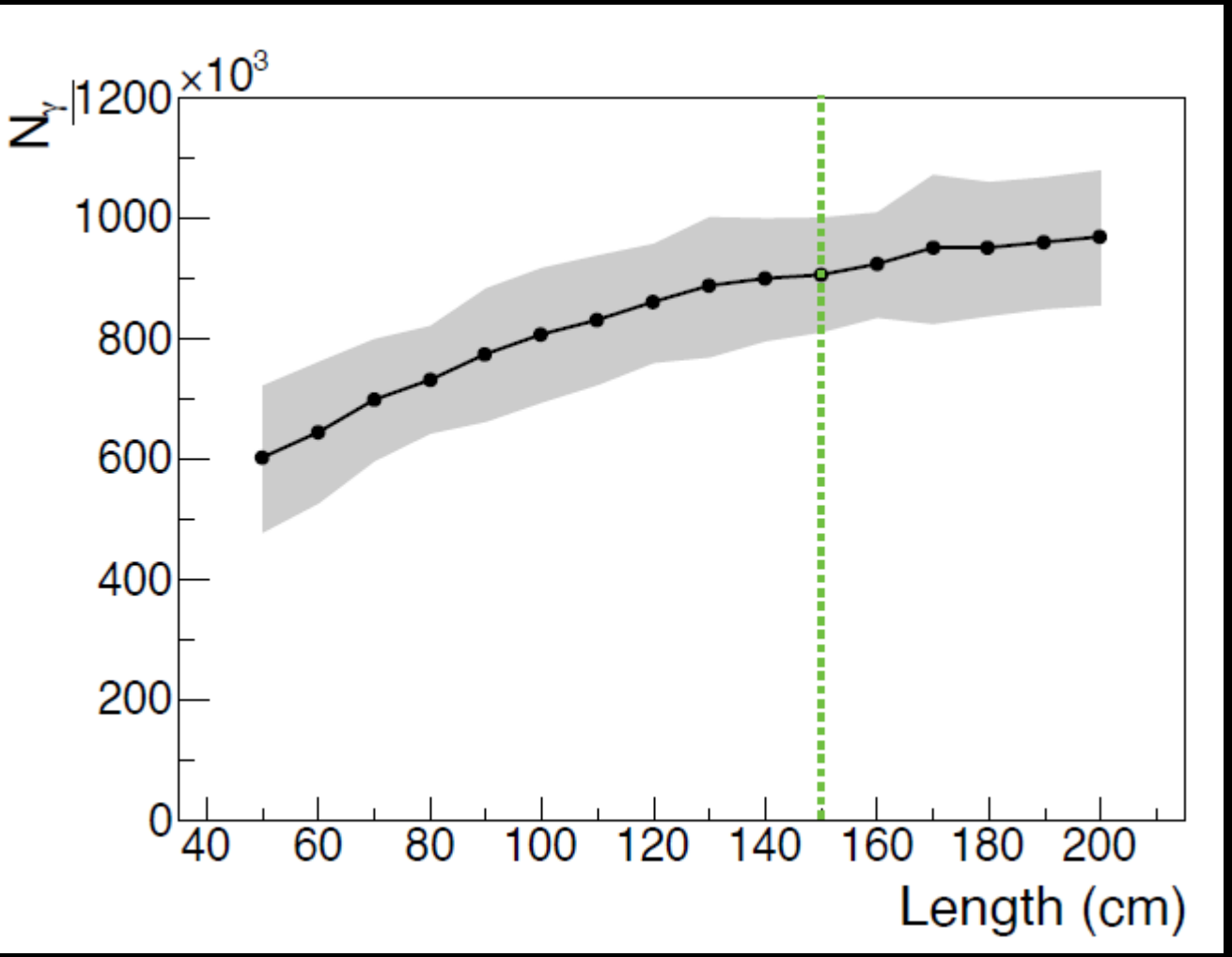


Basic Idea of Detecting χs



- Protons hit the target and hadrons are produced.
- Hadrons stop in the Beam Dump.
- Muons are identified by the muon monitor and lose the entire energy in sand (5 MeV/cm) before reaching NM building.
- χs reach the detector. (Energy loss for χs with $q = 10^{-3}e$ is < 0.1 MeV.)

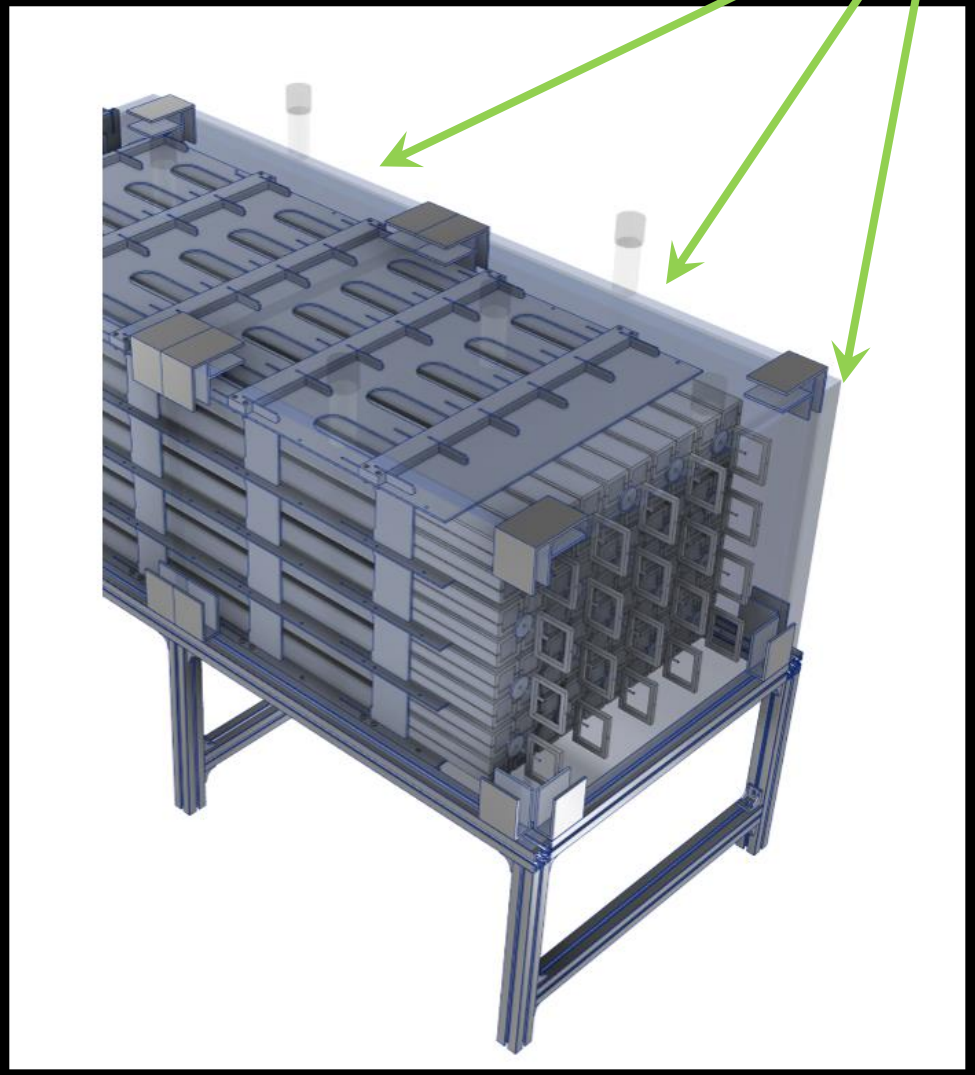
Optimization of Module Design



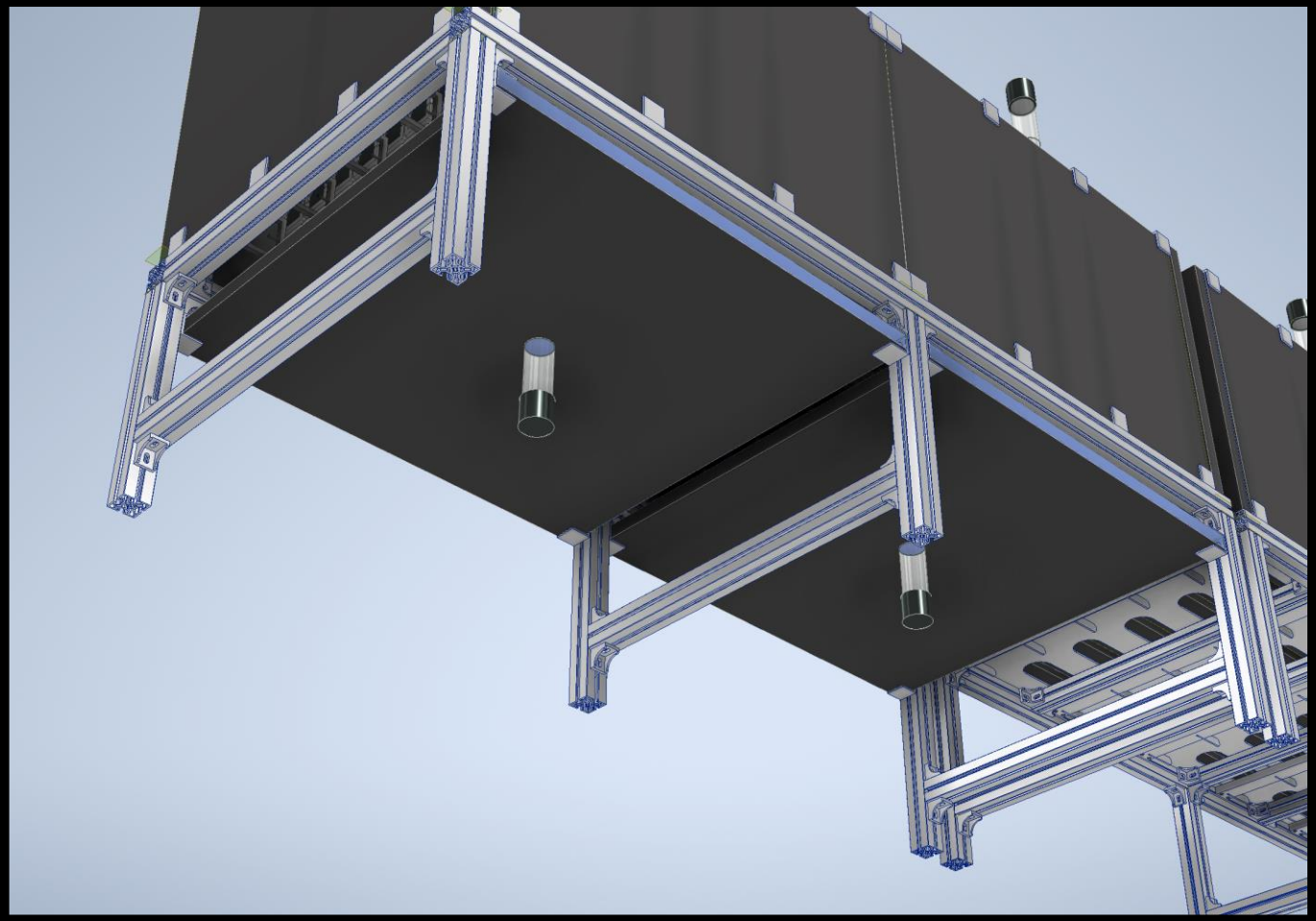
- Width of the scintillator bars (50 mm × 50 mm) determined by the size of the PMTs
- Length of the scintillator bars determined by spatial constraint and GEANT4 study
  - Due to spatial constraint, the max allowed length is about 1500 mm
  - Count the number of photons (N_γ) produced by a through-going muon as a function of bar length
  - Not much increase above 1500 mm, so 1500 mm has been chosen as the bar length

Veto Panels

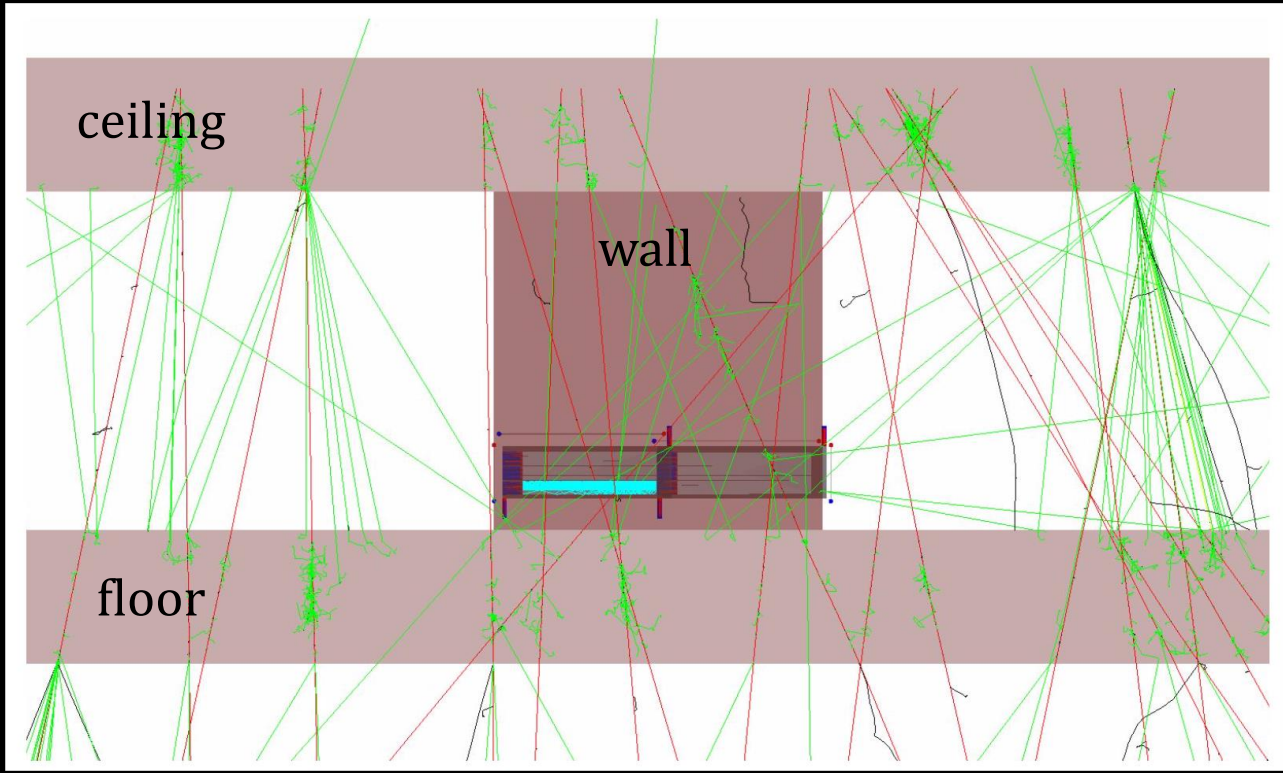
Scintillator panels
for vetoing/shielding external radiation



Bottom side covered with panels as well



Cosmic Background

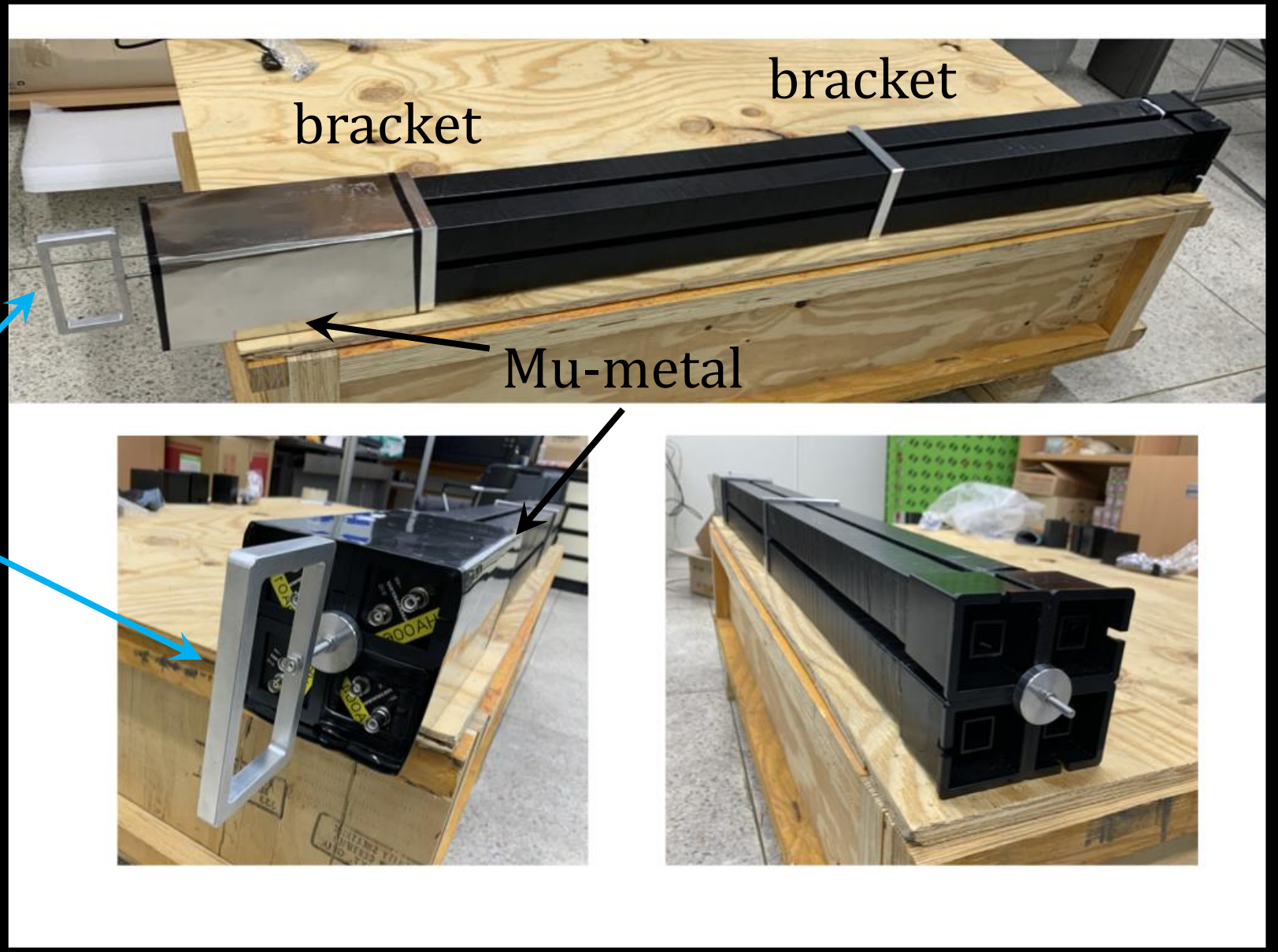


Muon
Photon
Electron

N_{PE}	Background Prediction
≤ 1	0.002
≤ 2	0.06
≤ 3	0.1
≤ 4	0.022
≤ 5	0.034

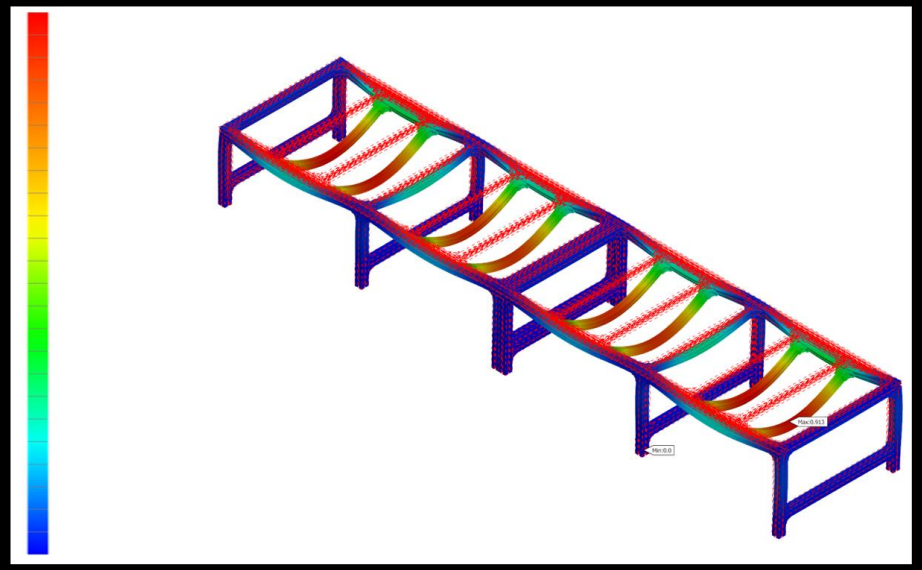
- Muons going through SUBMET can be tagged/rejected by panels
- They can interact with the material around the detector and generate shower of particles including low energy photons
  - If they hit two layers at the same time, they can mimic the signature of a χ
- Performed GEANT4 simulation to estimate this contribution
  - Used rate on the surface ($1\ /\mathrm{cm}^2 \cdot \mathrm{min}$), generated 12 m × 12 m grid of muons, number of muons corresponds to data taking for 20 years
- As the table shows, predictions is < 0.1 **for 3 years**

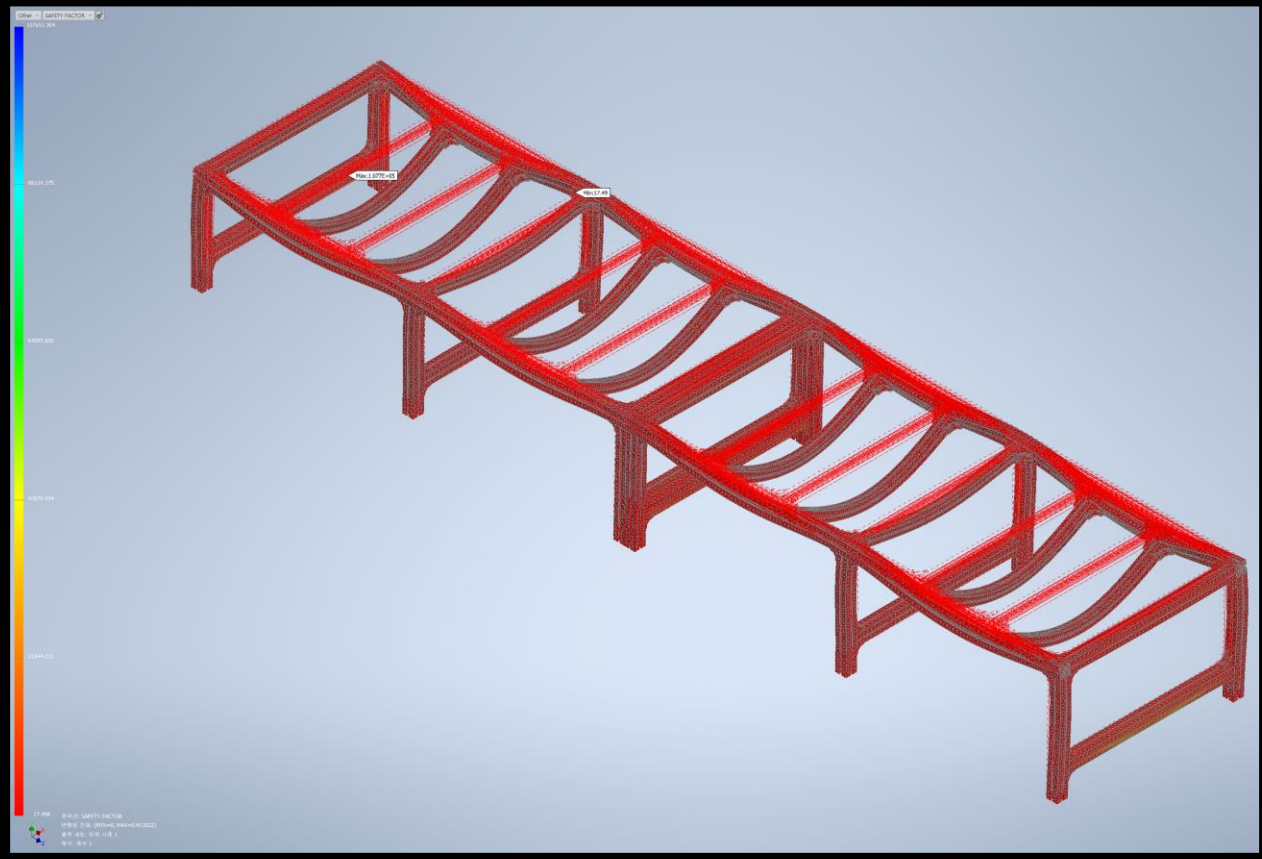
Detector components: Supermodule



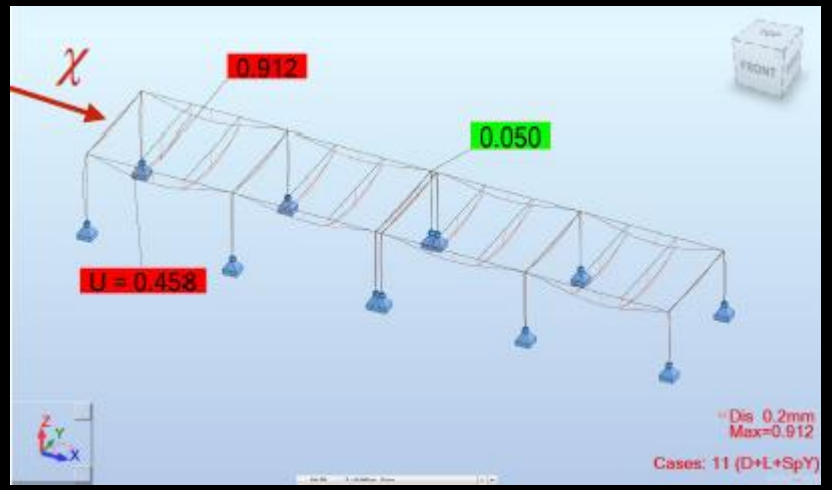
Test on the Mechanics

static





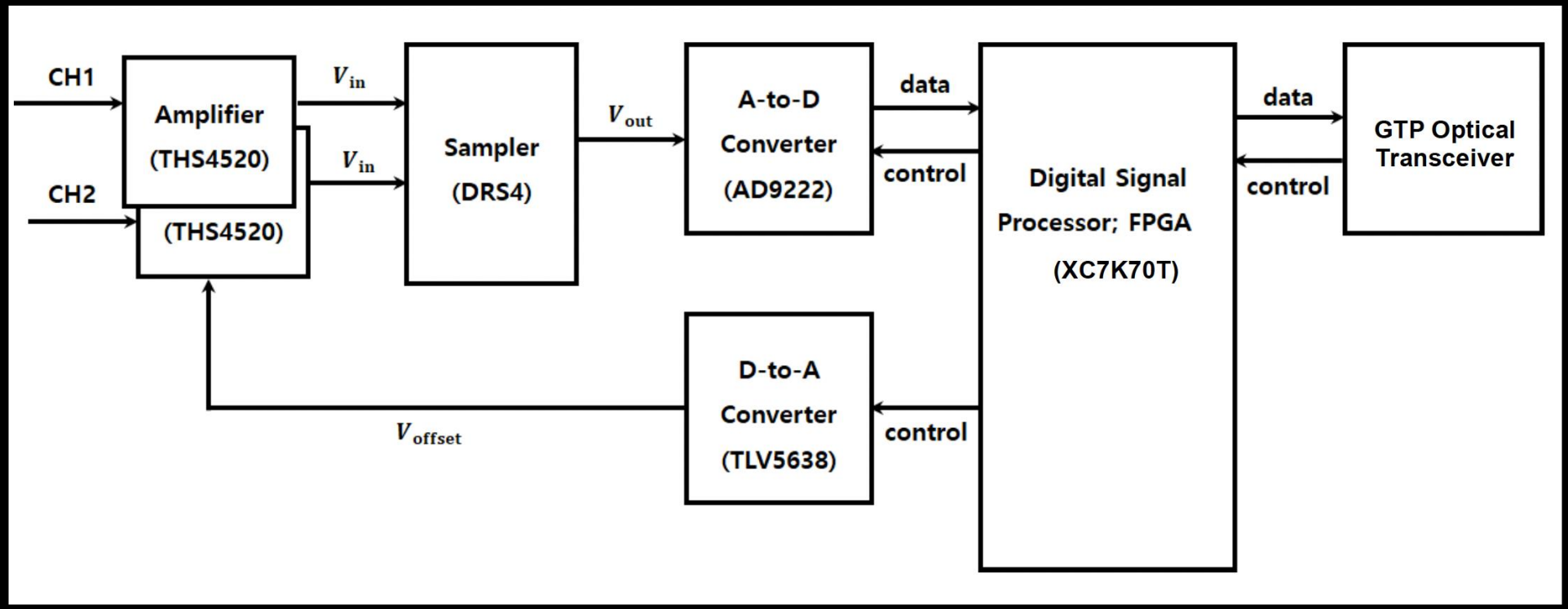
seismic



Checked stress and safety factor in FEM analysis

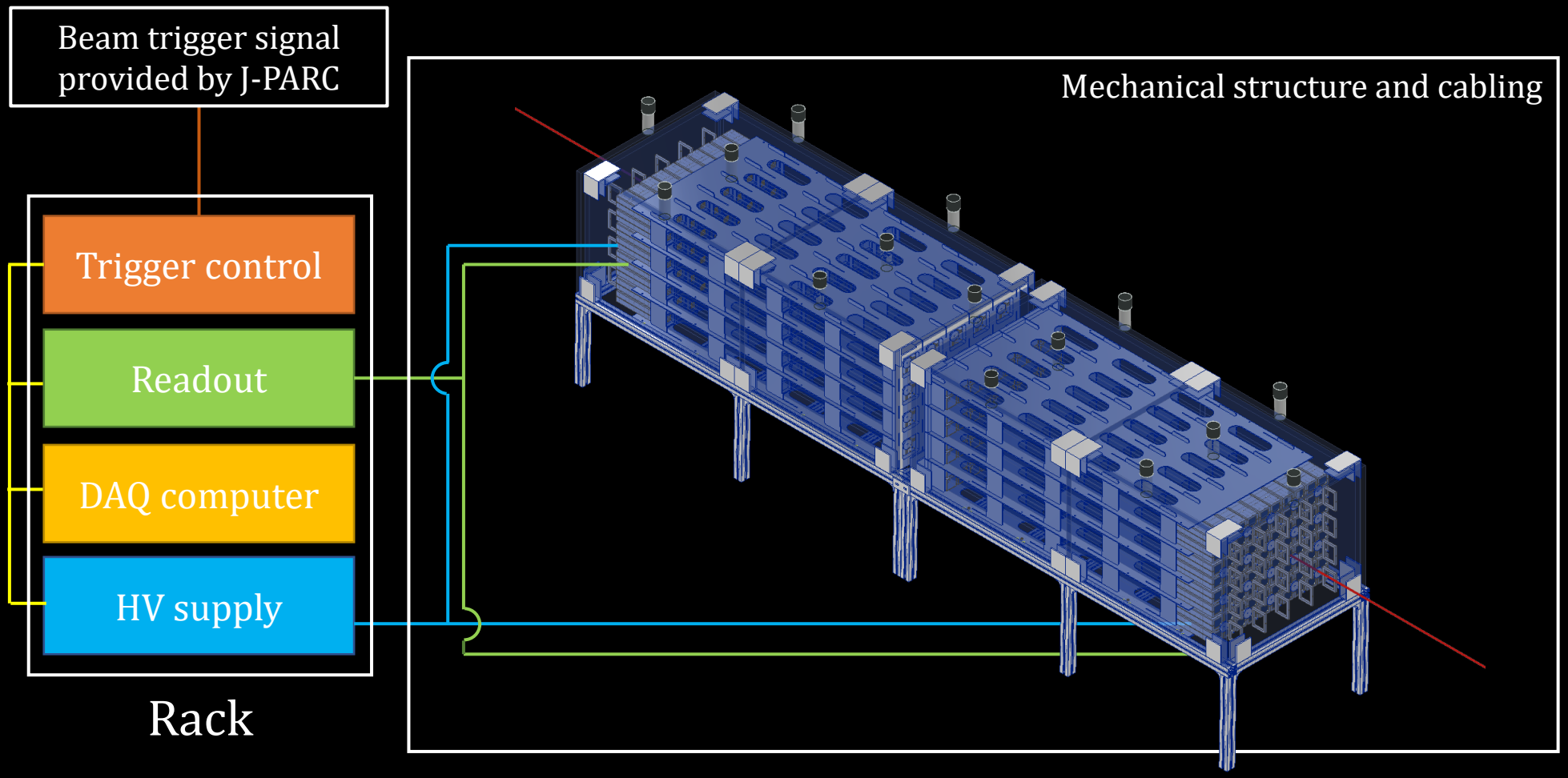
- Maximum stress: 200 MPa
- Minimum safety factor: 17.49

Test on the Mechanics

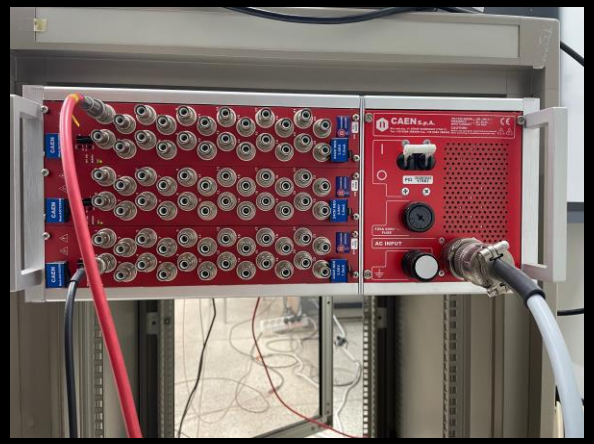


- Requirement
- $O(\sim$ mV) precision to detect SPEs
- > 0.5 GHz sampling rate to identify signals
- > 5 μs acquisition window for sampling a full spill

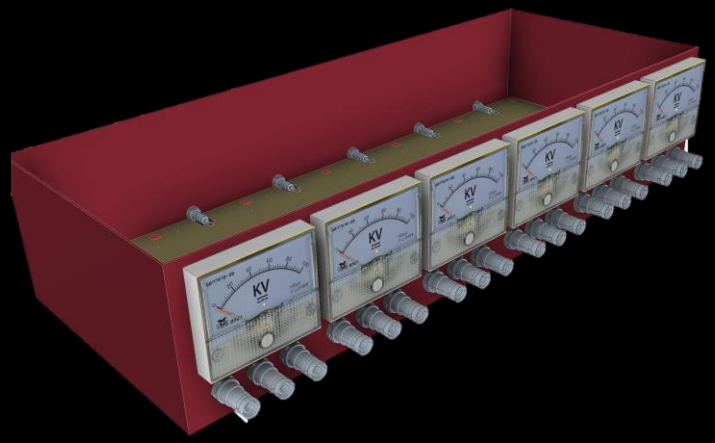
Detector System



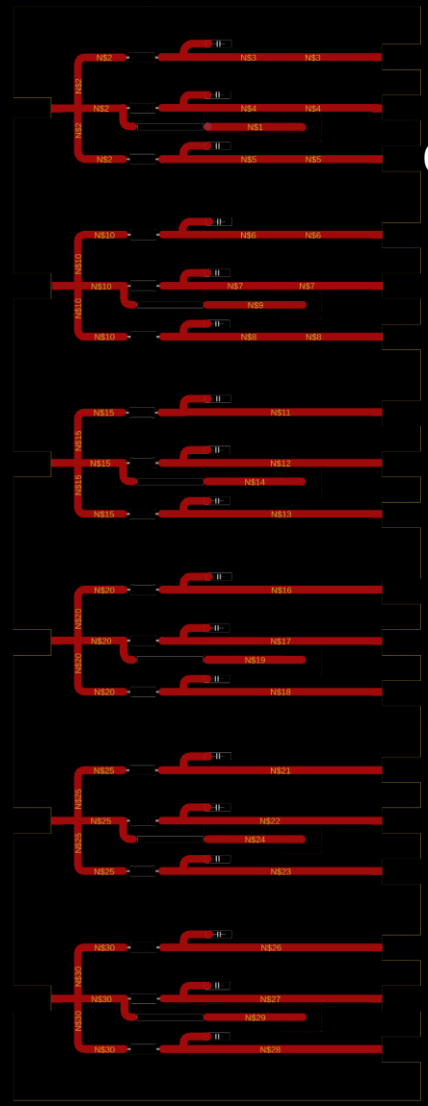
High-voltage (HV) Supply



▲ CAEN SY5527 HV supply front (left) & AG7236SN rear (right) view



▲ HV splitter



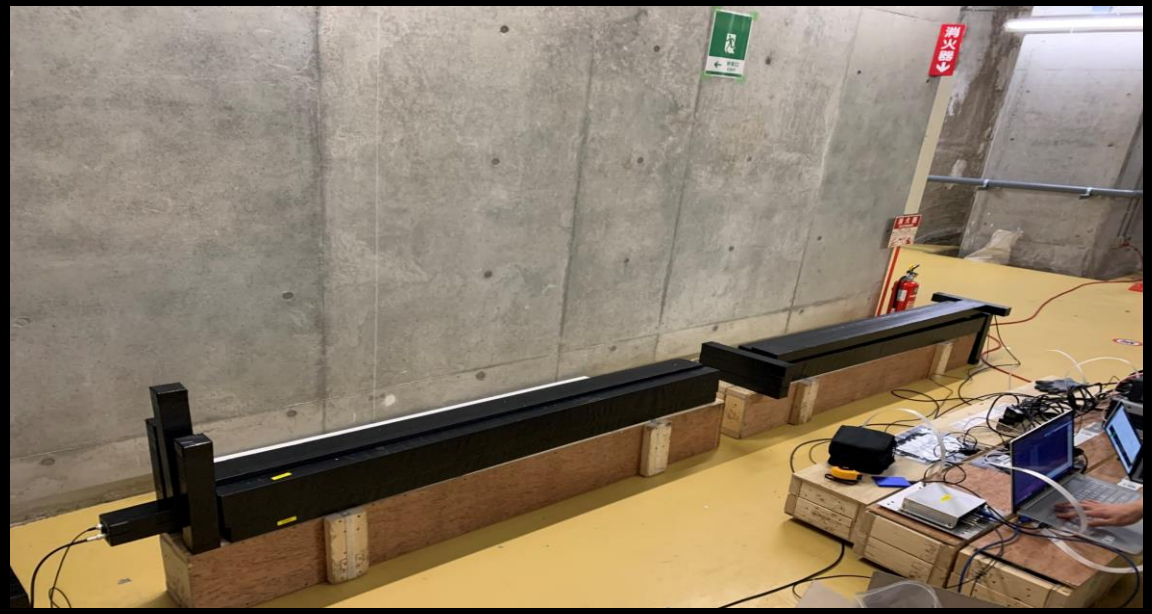
- SUBMET uses **CAEN SY5527** HV supply (72 channels) to power PMTs
- It does not have enough channels to supply HV to 192 PMTs.
- Solution: Design a splitter that can multiply number of output channels by factor of 3.

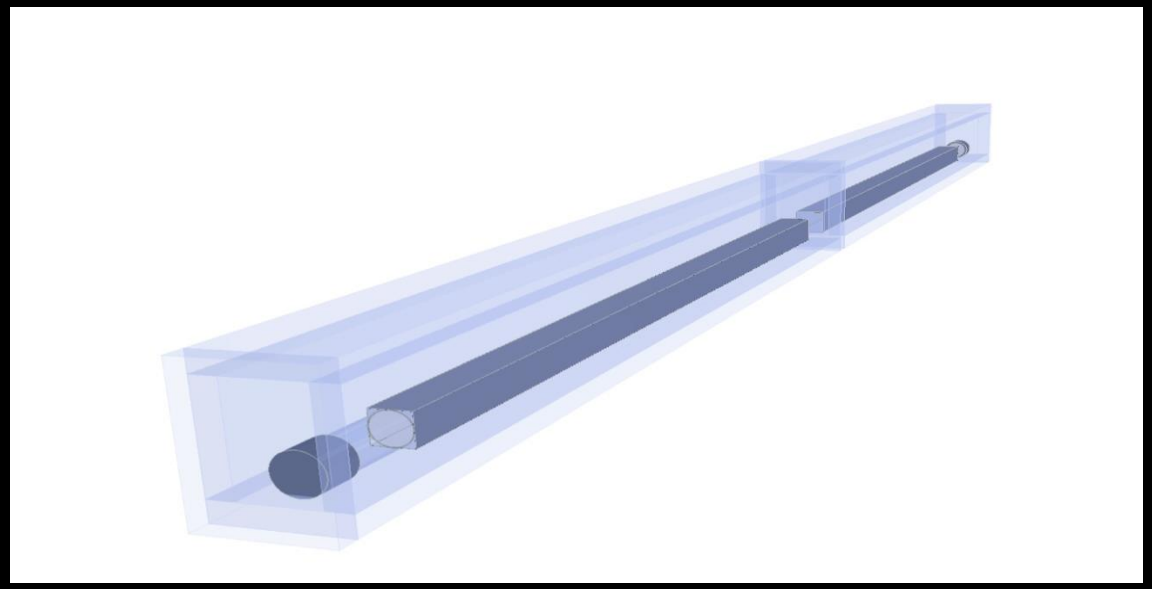
HV Supply Monitoring

▲ Web controller panel

- The voltage and current of individual channels are plotted in real-time through online.
- The numerical value of the target voltage and the channel state are combined into the upper panel, being indicated with a color palette.

Background Measurement

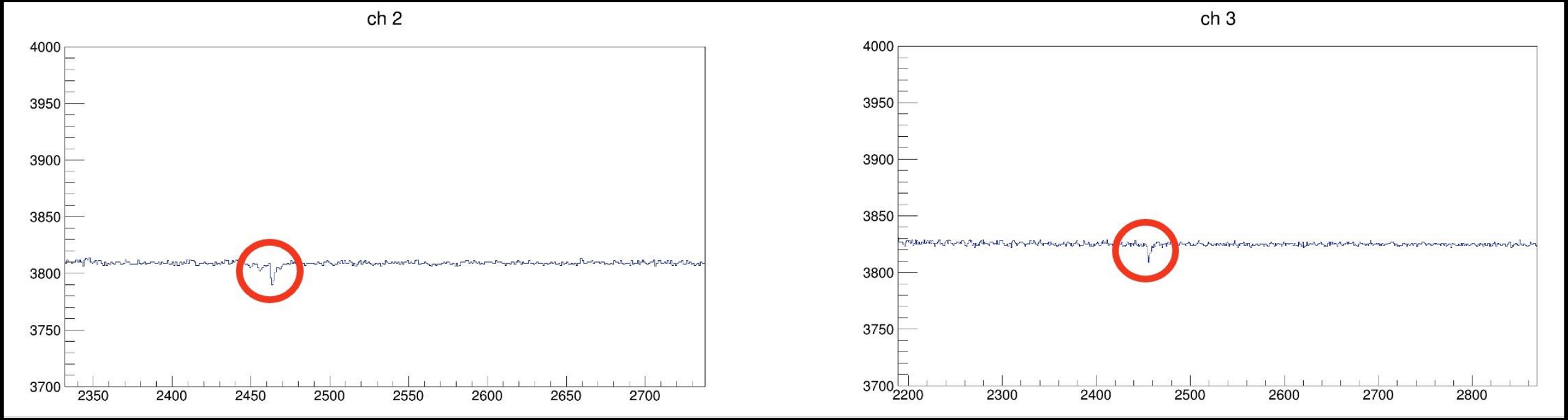




- Radiation from the structures of the building can generate pulses that are indistinguishable from the pulses due to χs
- Since the condition of such radiation strongly depends on the environment, we measured the rate at the detector site

- Pair of modules shielded by other scintillators
- Recorded total of 12M events, corresponding to ~63 s of live time (data taking for 4 years)

Background Measurement



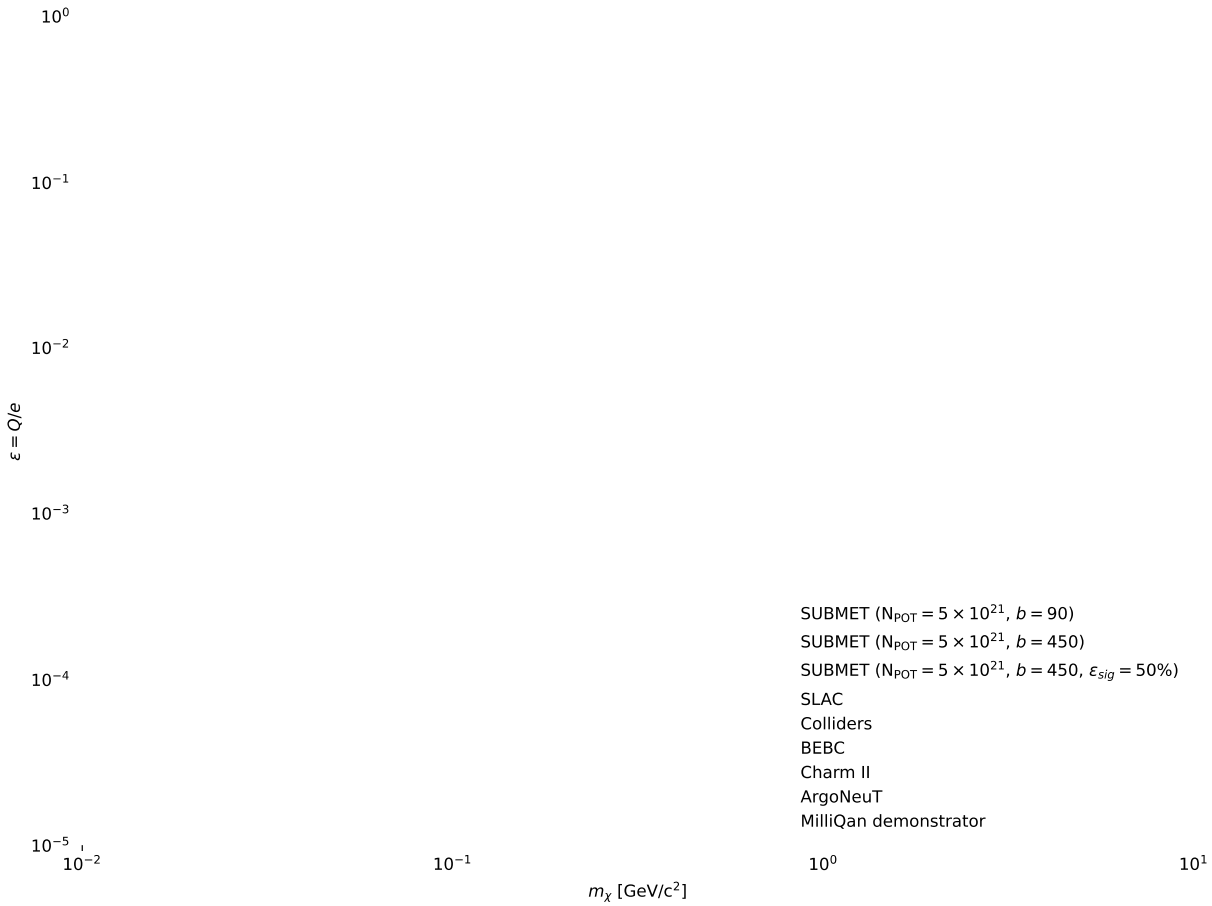
- Applied following cuts to select events
  - Pulse height : 5.8 mV < Vpulse < 30 mV
  - Pulse width : $\Delta t_{width} < 7$ ns
  - Remove events with a large number of afterpulses:

    Npulse < 3
  - Coincidence time window: $\Delta t_{pulse} < 20$ ns

- 1 background events out of 12M events
- 1×80/4 /2 = 10 background events per year

  (80 pair of modules, time ordering)

Detector Performance



- Exclusion limit using bkg = 90 and bkg =450, $N_{\mathrm{POT}} = 5 \times 10^{21}$
- Even with 5 times more backgrounds, only minor change in sensitivity due to rapid drop in signal acceptance. ($N_{signal} \propto \varepsilon^6$)

SPE Pulse Finding

[Motivation] In case of fluctuating baseline, how to estimate baseline level in spite of the presence of signals?

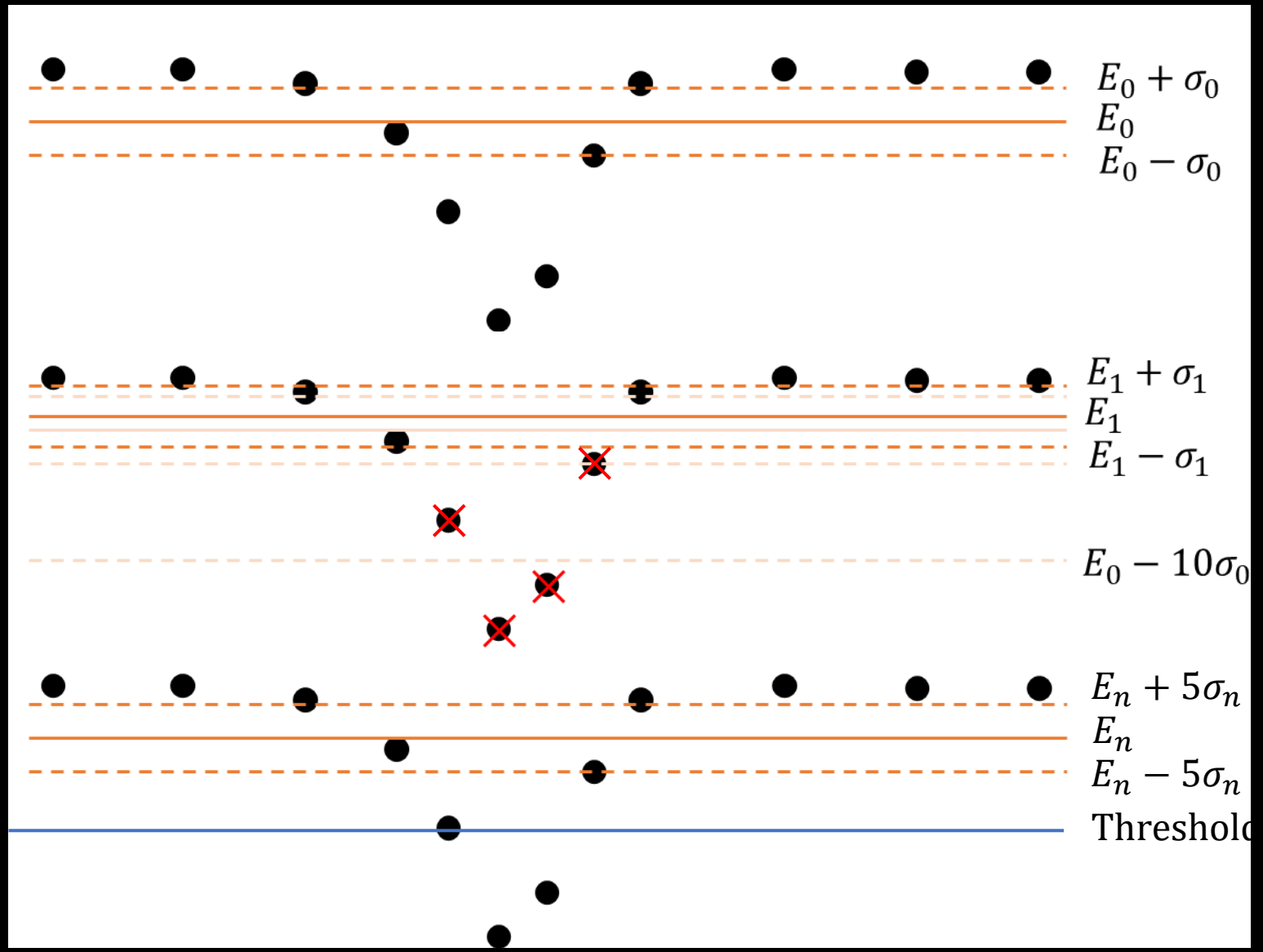
Step 1. Calculate E_0, σ_0

Step 2. Exclude points outside of $E_0 \pm 5\sigma_0$ and their neighbors when calculating E_1, σ_1.

Step 3. Iterate until every points are inside of $E_n \pm 5\sigma_n$

Step 4. Series $\{E_0\ E_1, E_2, \dots\}$ may converge to pedestal level.

Step 5. Find the point that exceeds the threshold.



Funding and Schedule

Task	2022		2023			2024				2025			
Readout system													
Mechanics													
Module production and assembly													
Installation													
Data-taking													

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