Search for millicharged particles at J-PARC

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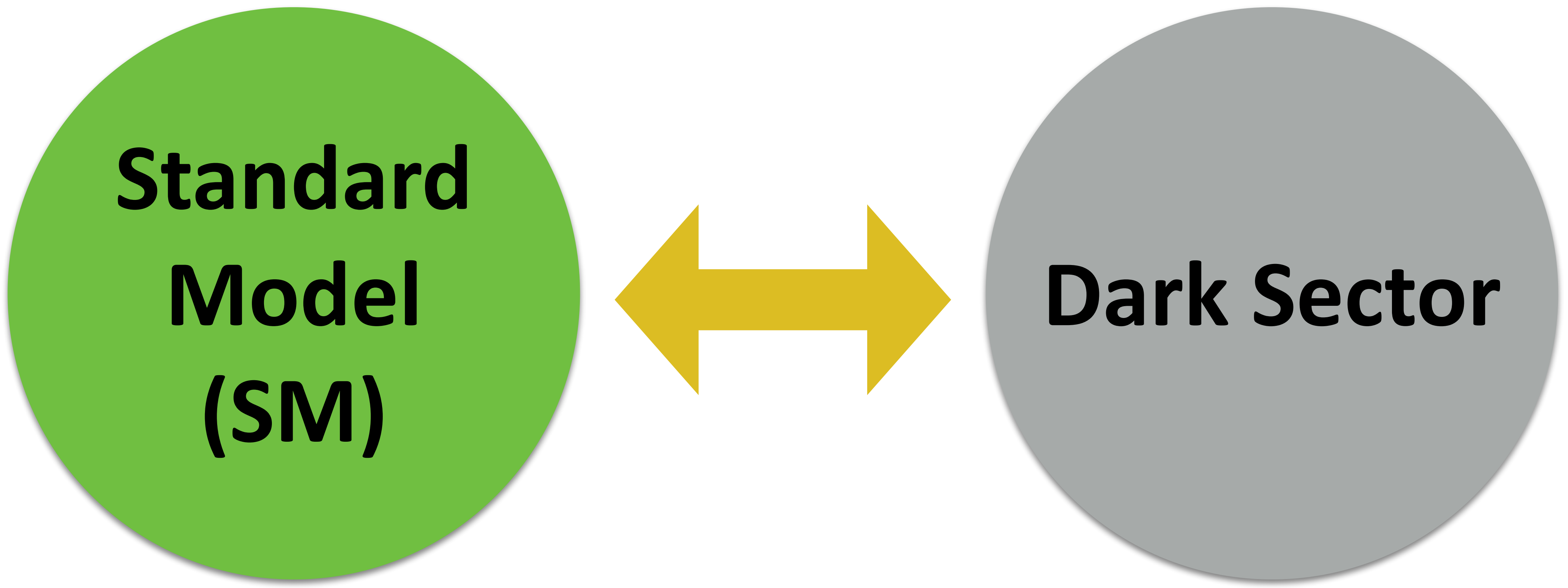
Motivation



$$\mathcal{L}_{\text{dark sector}}$$

$$= -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + i\bar{\psi}\left(\partial\!\!\!/ + ie'A\!\!\!/' + iM_{\text{mCP}}\right)\psi - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu}$$

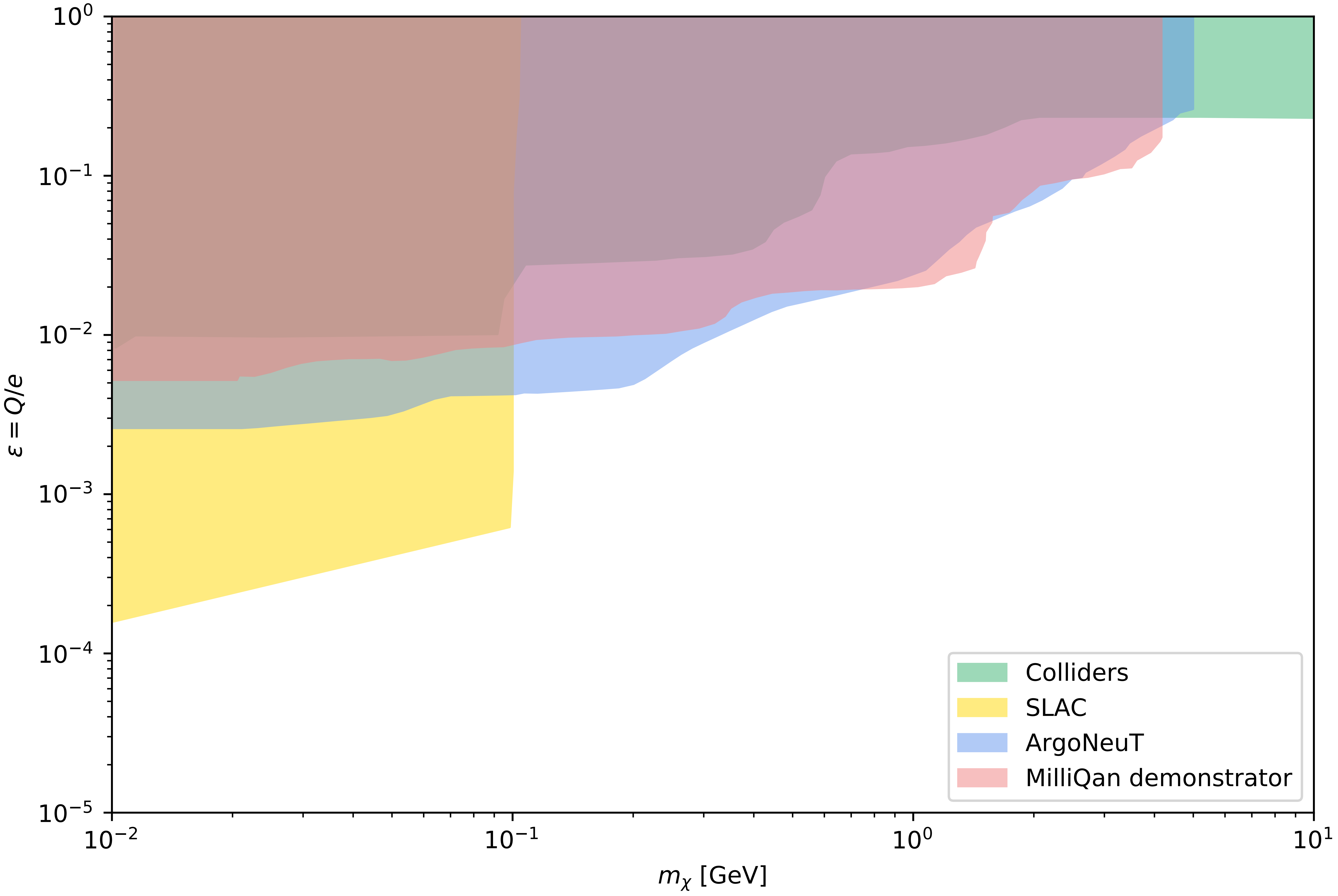
$$A'_\mu \to A'_\mu + \kappa B_\mu$$

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu}$$
$$+ i\bar{\psi}\left(\partial\!\!\!/ + ie'A\!\!\!/' + i\kappa e'B\!\!\!/ + iM_{\text{mCP}}\right)\psi$$

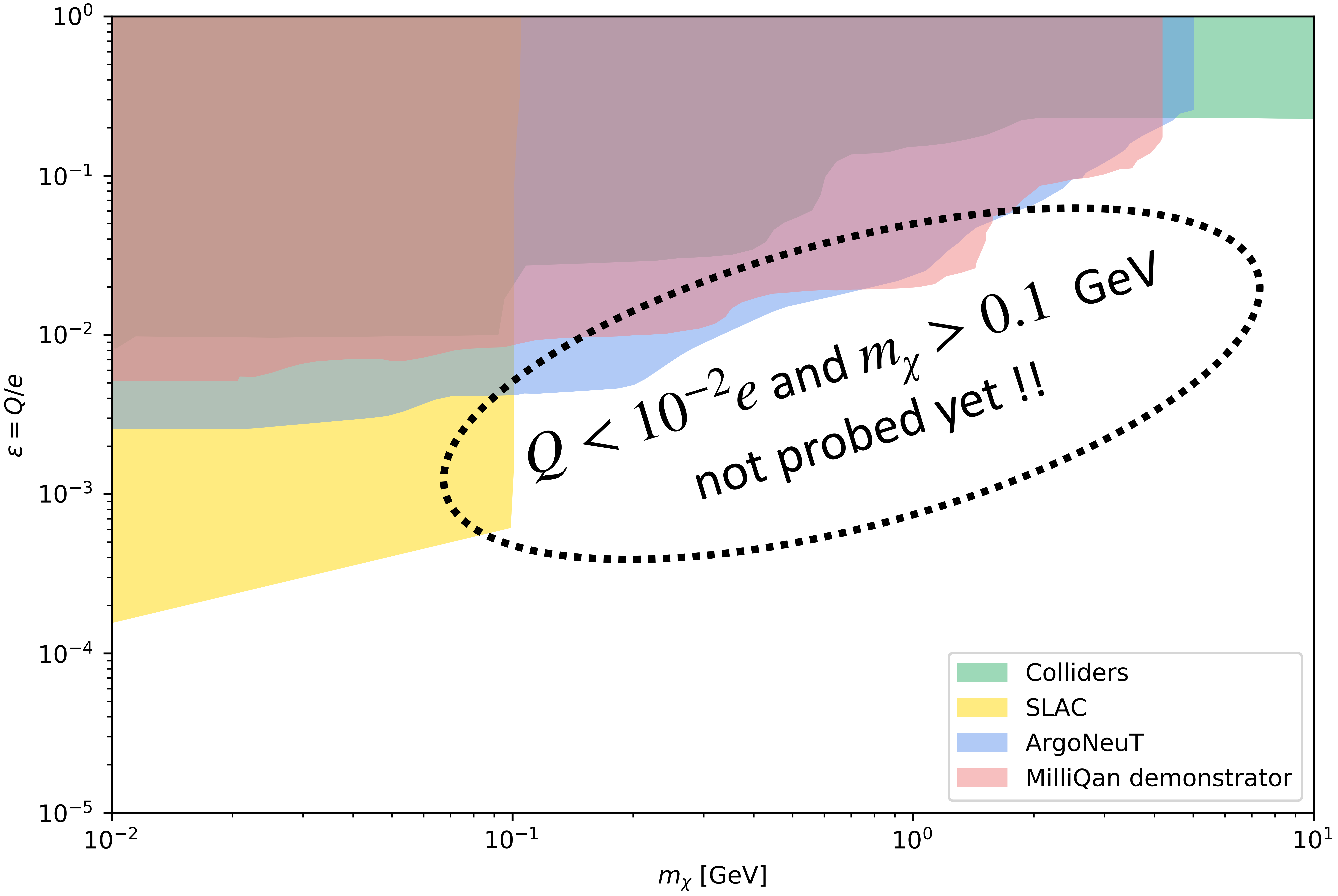
$\kappa = 10^{-3}$ - 10^{-2} : milli-charge

- Arbitrary charges are allowed in SM U(1), but only quantized charges have been found
  - Motivated Dirac quantization and considerations of GUTs => magnetic monopoles
- Well-motivated dark-sector models have been proposed to predict the existence of millicharged particles (mCPs) while preserving the possibility for unification
  - Such models can contain a rich internal structure, providing candidate particles for dark matter
- A new U(1) in dark sector with massless dark-photon (A') and massive dark-fermion (ψ)
  - A' and B kinetically mix => charge of ψ is proportional to mixing (κ)
- Results of EDGES experiment (Nature 555, 67–70 (2018)) can be explained if a fraction of DM is millicharged

Current reach



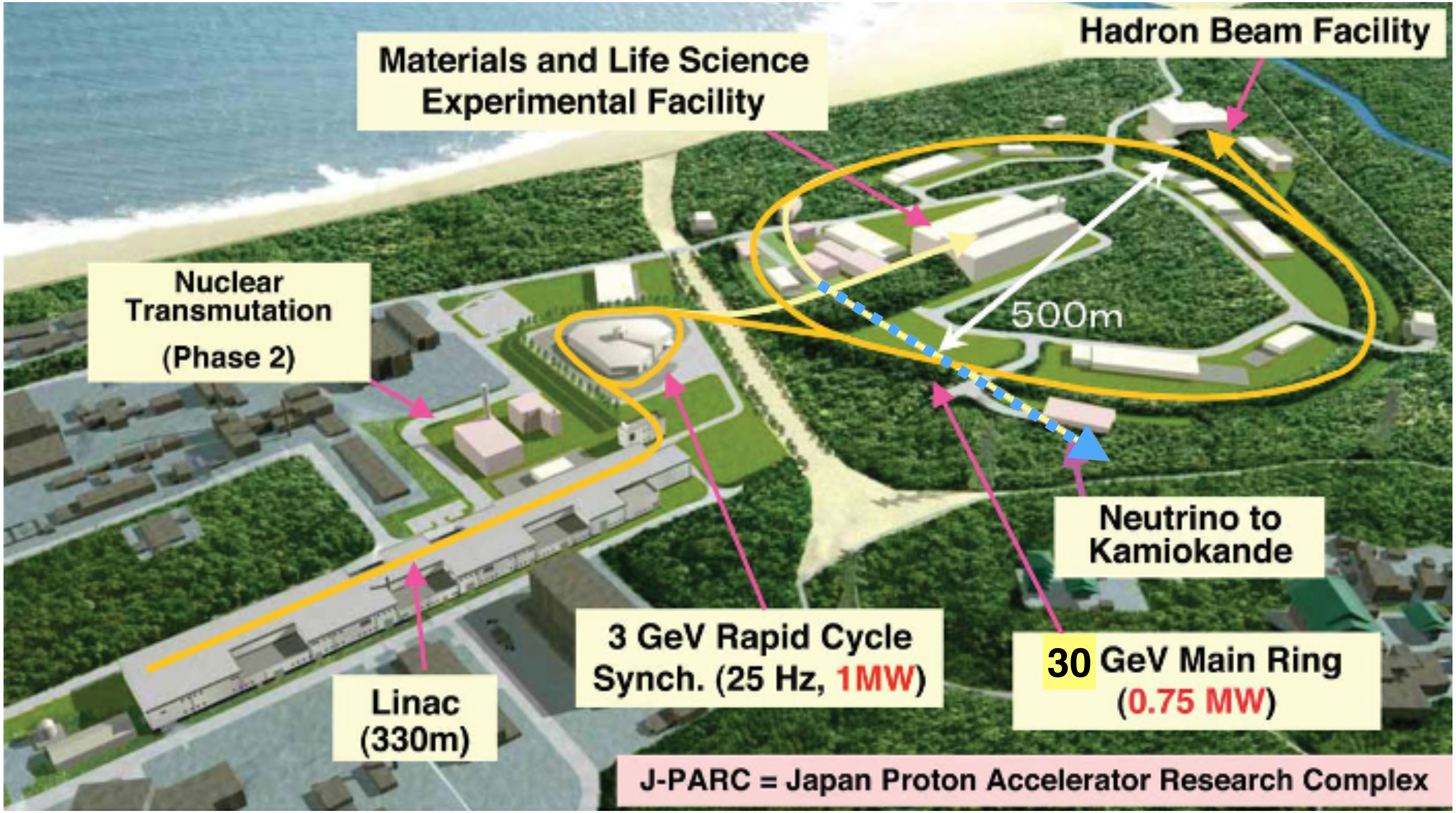
Current reach



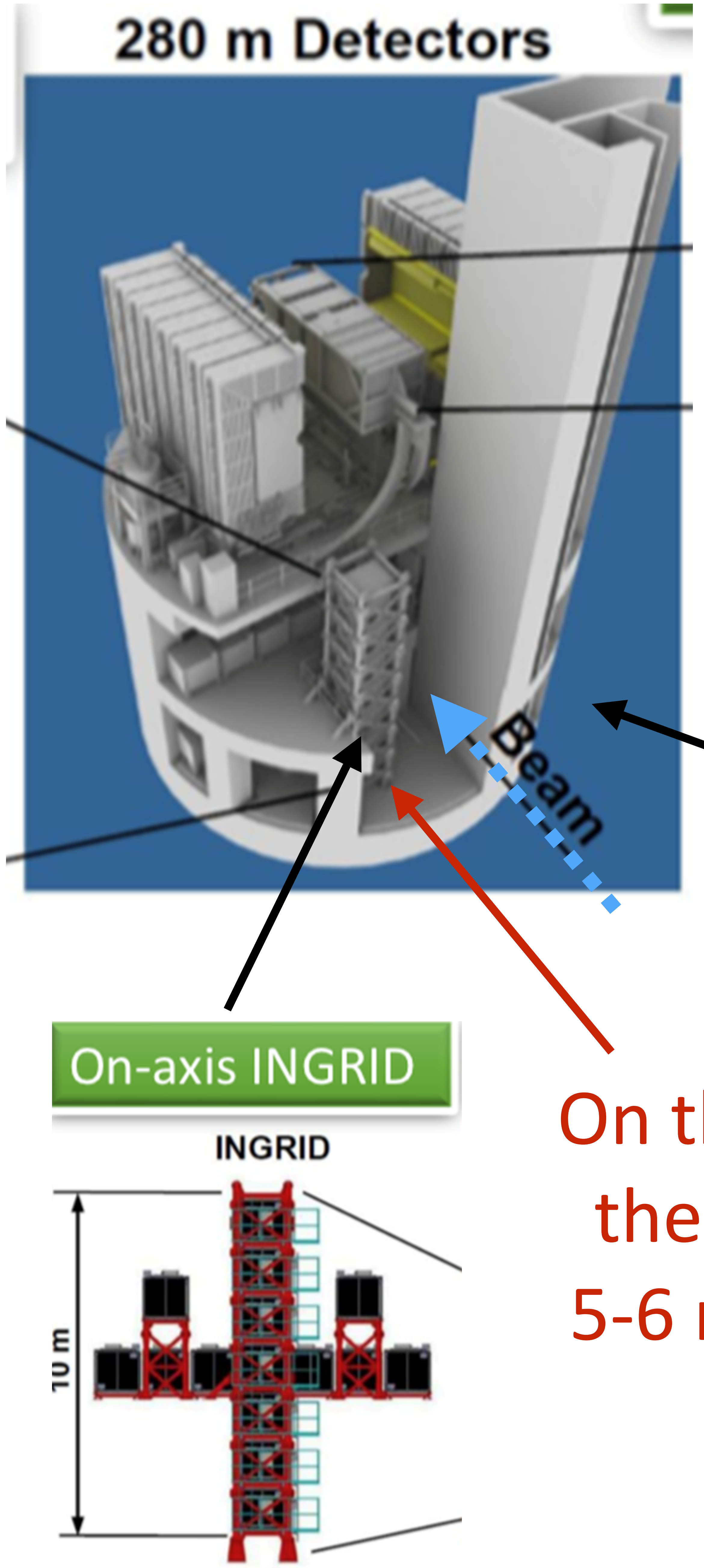
Experiment at J-PARC: **SUBMET**

- **SUBMET: SUB-Millicharge ExperimenT**
- Scintillator-based detector in pp fixed target experiment at J-PARC
  - Inspired by milliQan (LHC) and FerMINI (Fermilab) experiments
  - Similar to FerMINI experiment: with lower beam energy (30 GeV) and larger N_{POT}
- Candidate site in the existing building 280 m from the target

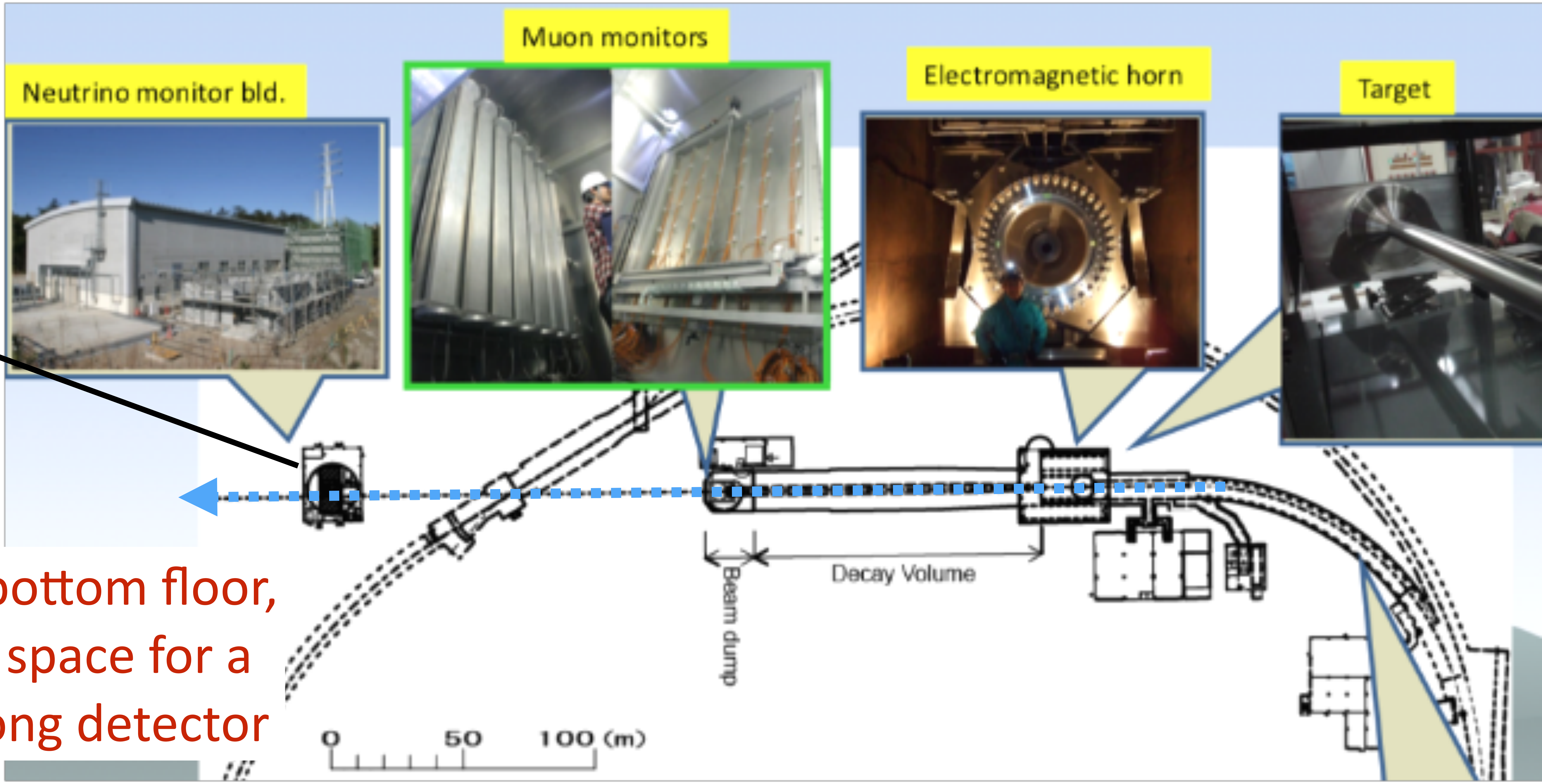
J-PARC complex



Potential detector site



On the bottom floor, there’s space for a 5-6 m long detector



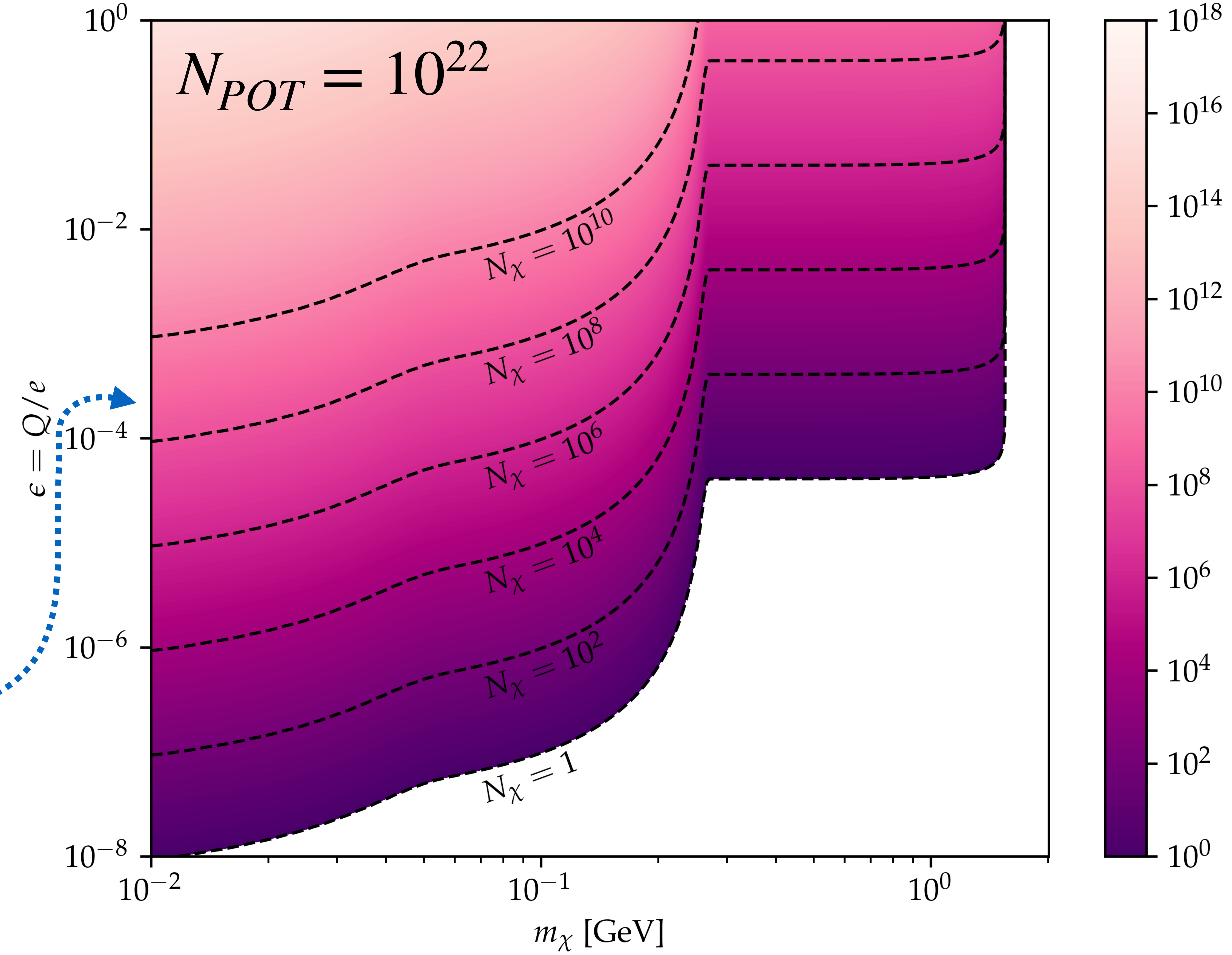
Production of mCPs

- mCP (χ) production via meson decays

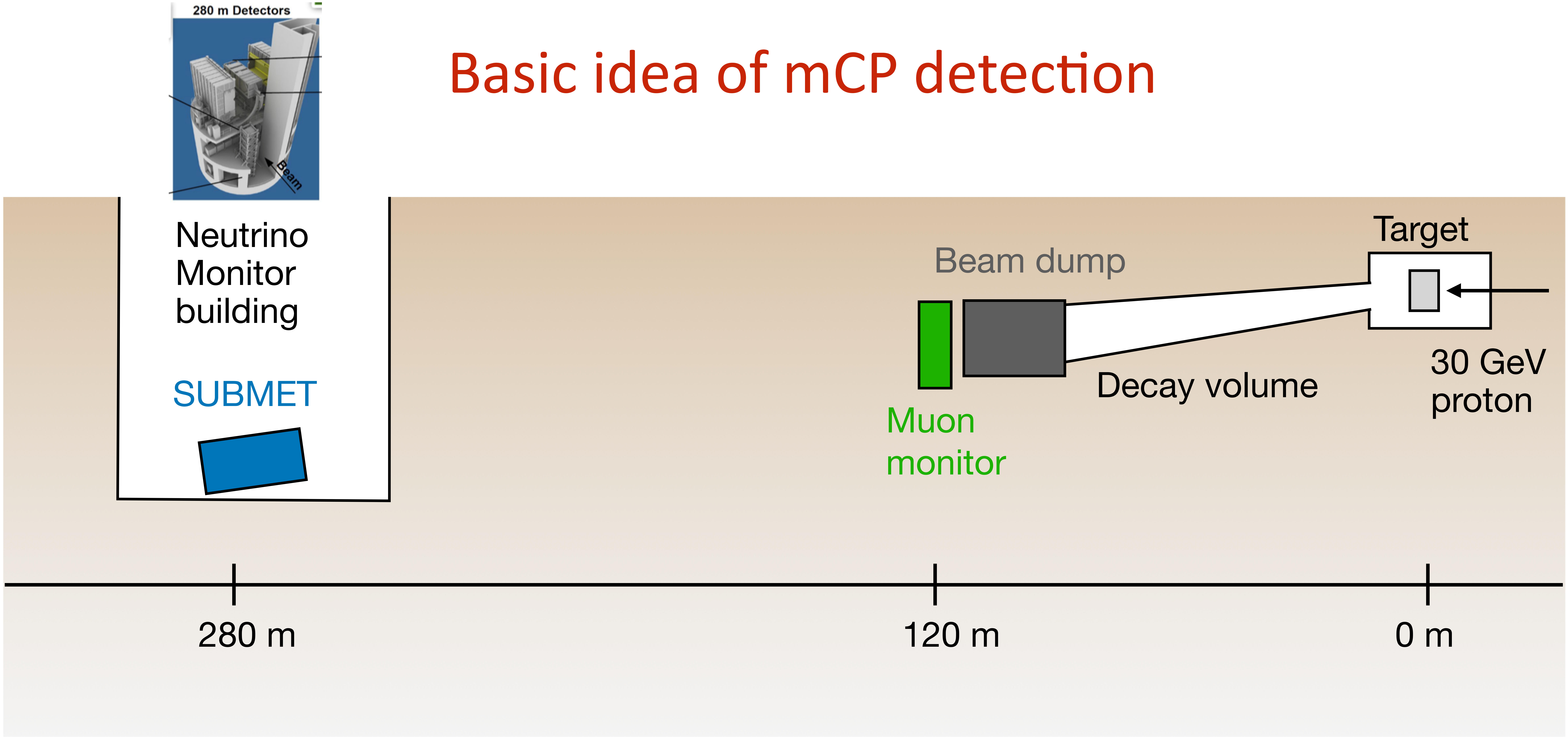
$$\pi^0, \eta \rightarrow \gamma\gamma* \rightarrow \gamma\chi\bar{\chi}$$

$$J/\psi \rightarrow \gamma* \rightarrow \chi\bar{\chi}$$

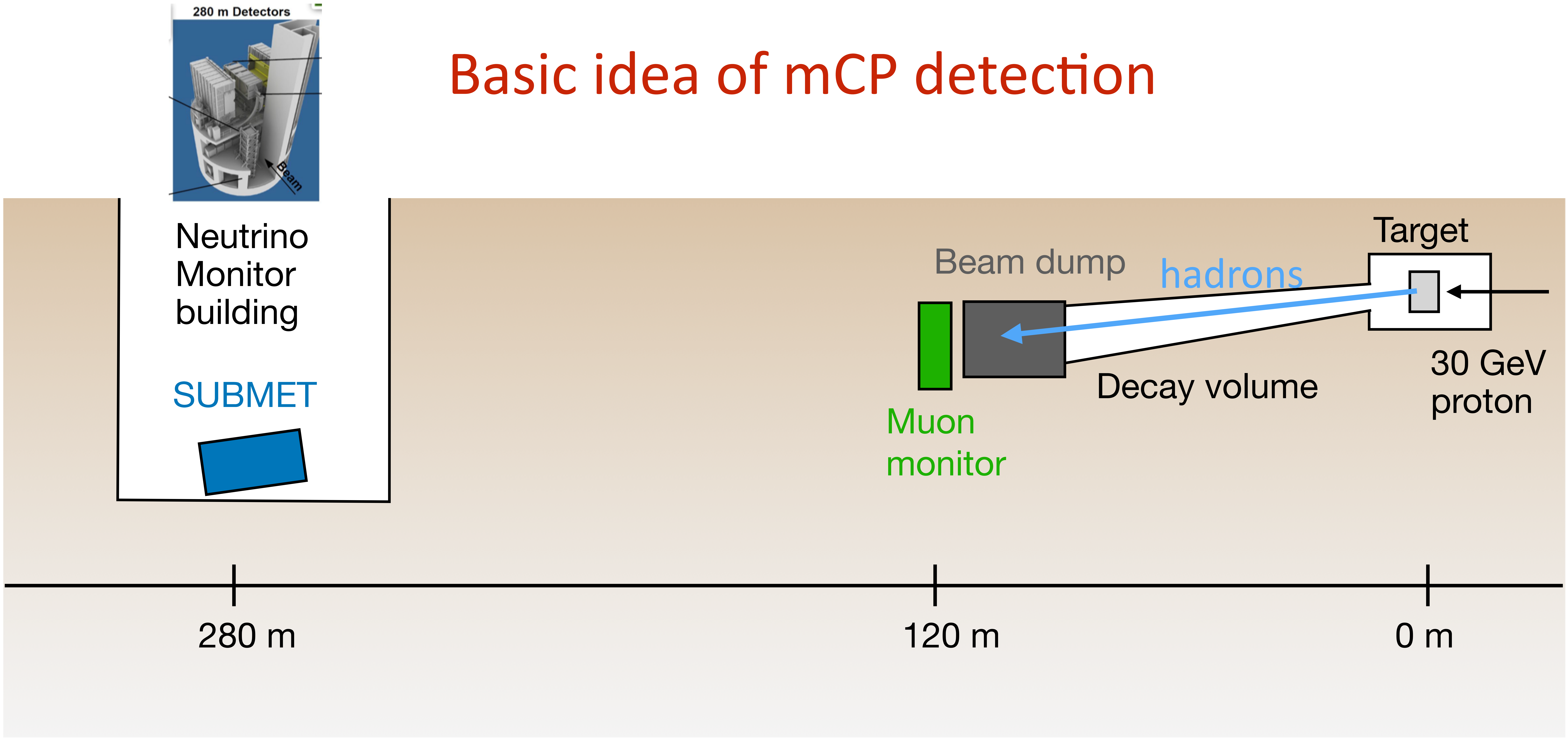
- Number of mCPs (N_χ) that reach detector
  - $O(10^9)$ where exclusion limit is



Basic idea of mCP detection

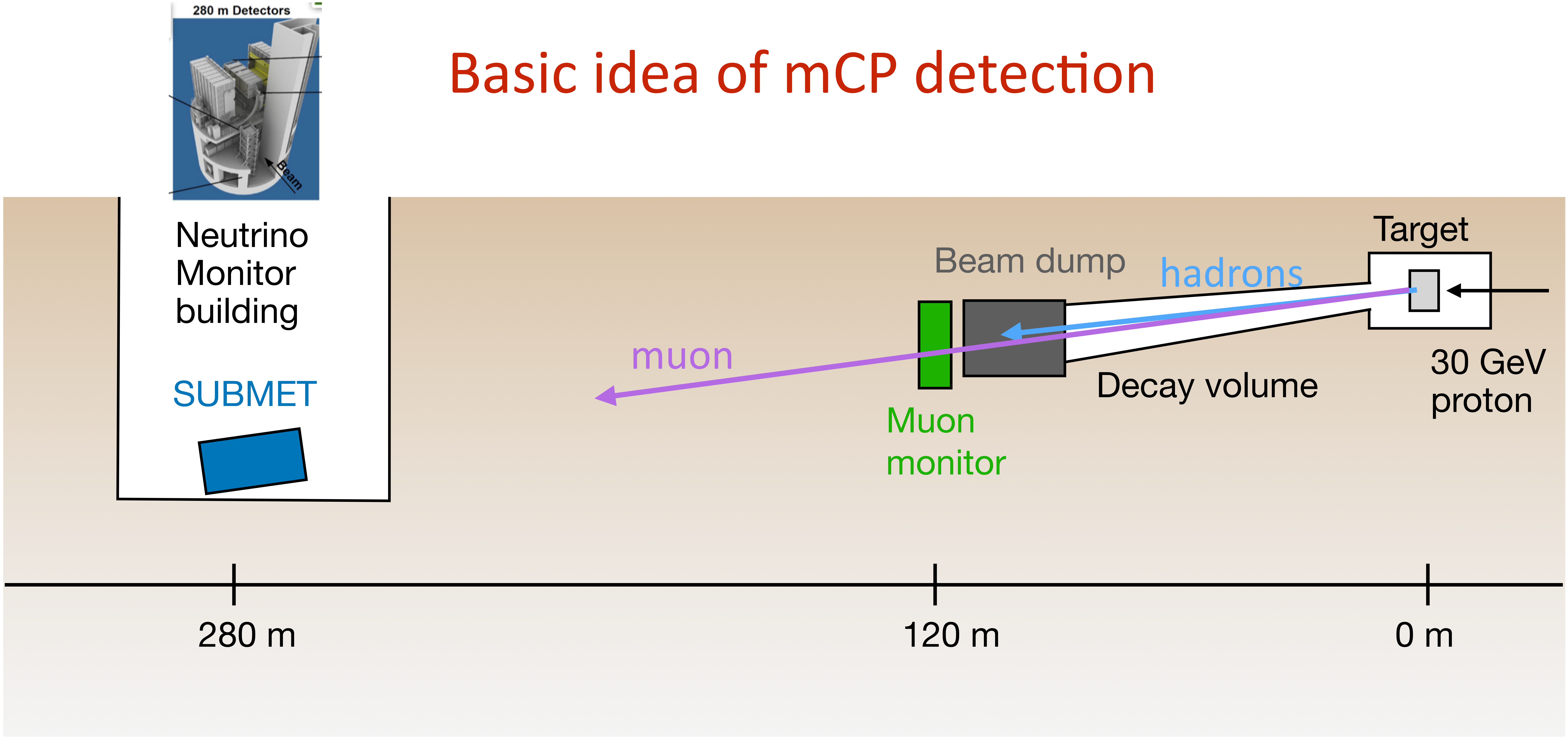


Basic idea of mCP detection



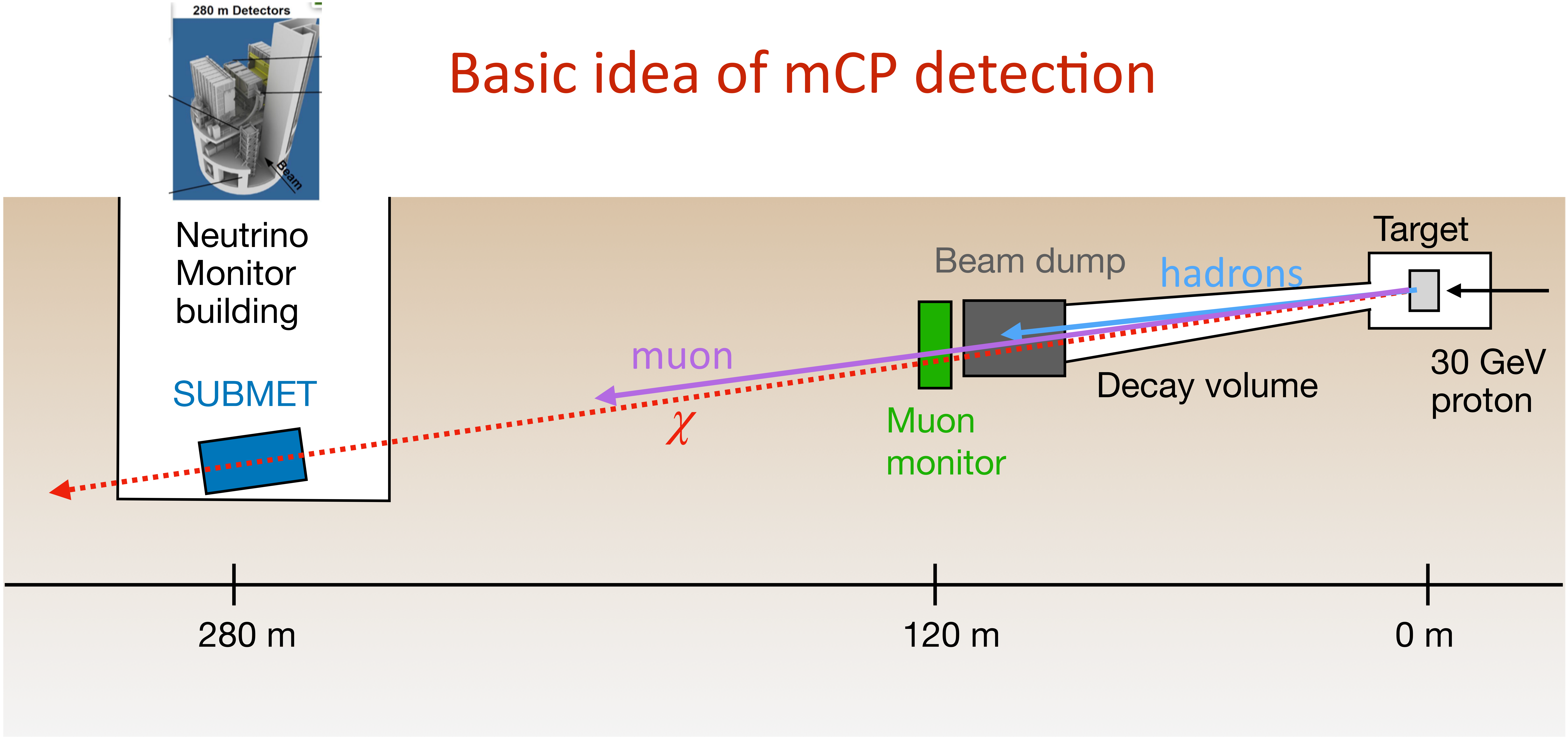
hadrons dumped in beam dump

Basic idea of mCP detection



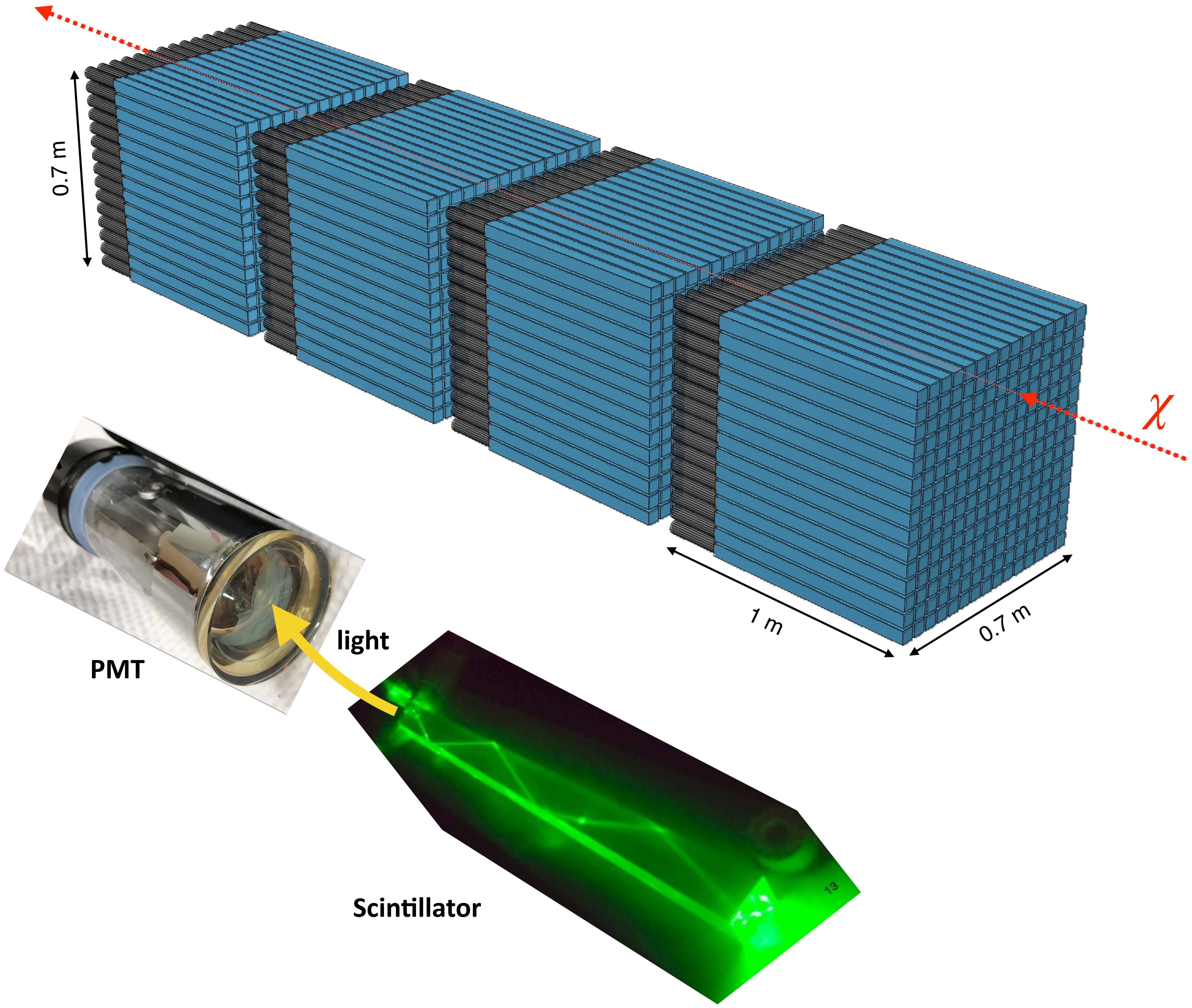
muons pass beam dump, but loose energy in sand (5 MeV/cm) neutrino monitor building

Basic idea of mCP detection



Only mCPs (and neutrinos) reach the detector
(energy loss for mCP with Q=0.001e is <0.1 MeV)

Detector concept

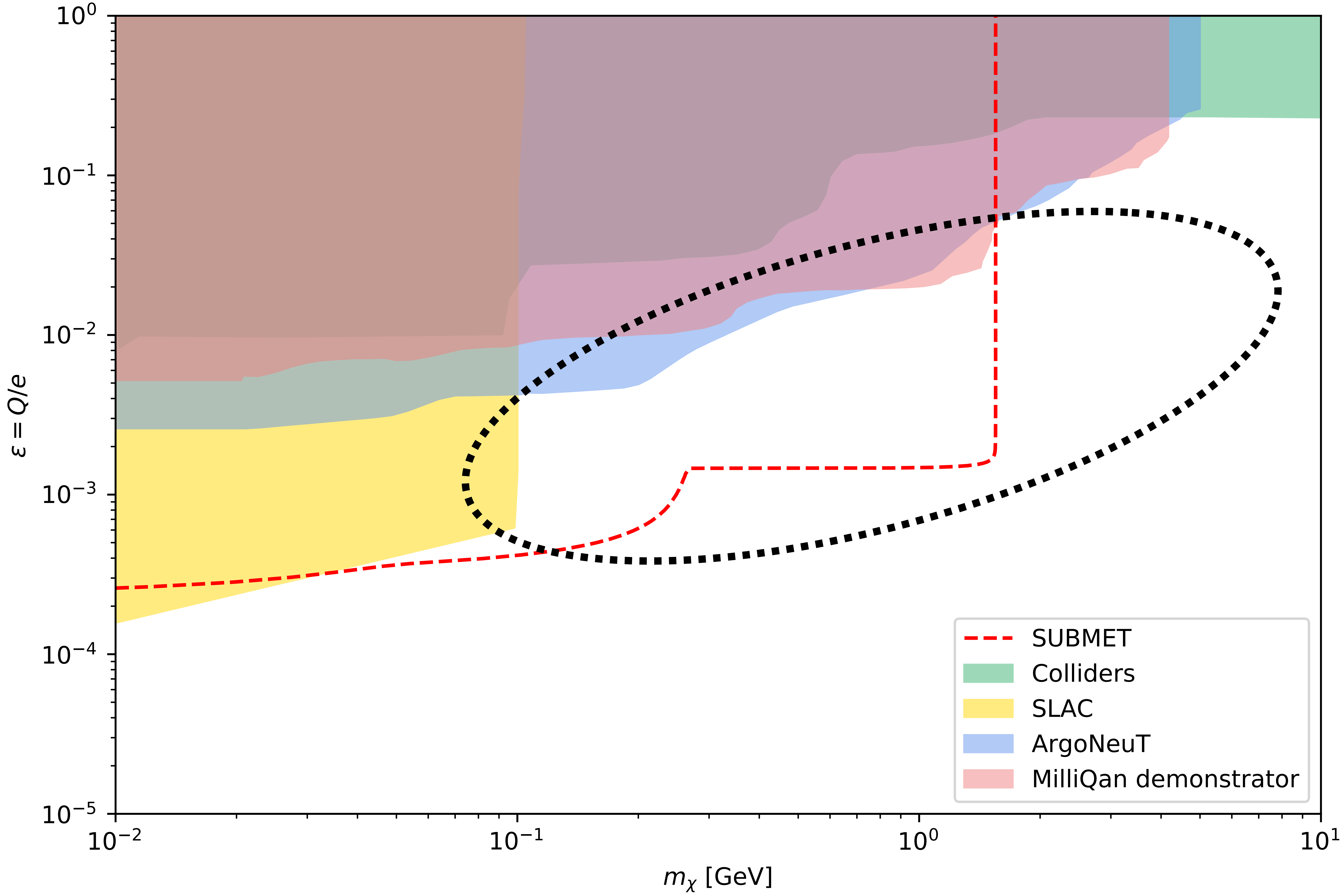


- mCPs detected by ionization which depends on Q^2
  - Need large active volume for small Q
  - In the end, the experiment becomes detecting SPEs
- 4 layers of long scintillator (BC-408, 5x5x80 cm^3) + PMT arrays
  - 4 layers to suppress backgrounds
  - PMT to cover large area (dark count rate ~ 500 Hz)
- Well-understood technology
  - Similar version of detector tested/operated by milliQan demonstrator PRD 102, 032002 (2020)
- Signal acceptance is $O(10^{-4})$
- Require 4-layer coincidence ($\Delta t \sim 20$ ns)

Backgrounds

- Beam-induced backgrounds
  - Muons from hadron decays do not reach detector due to energy loss
  - Neutrino interactions: $O(10^7)$/layer for $N_{POT} = 10^{22}$ gives $N_{bkg} \sim 0$
  - Muons from interaction of neutrinos and the material of the building can be identified/rejected by installing scintillator plates between the wall and the detector
- Detector backgrounds
  - Random coincidence expected to be negligible (thanks to using 4 layers)
- Other sources
  - Cosmic shower (needs in situ measurement)
- Non-beam-induced backgrounds can be estimated using no-beam data
- Assume $N_{bkg} \sim O(1)$ for sensitivity study

Sensitivity of SUBMET



Alternative detector configurations I

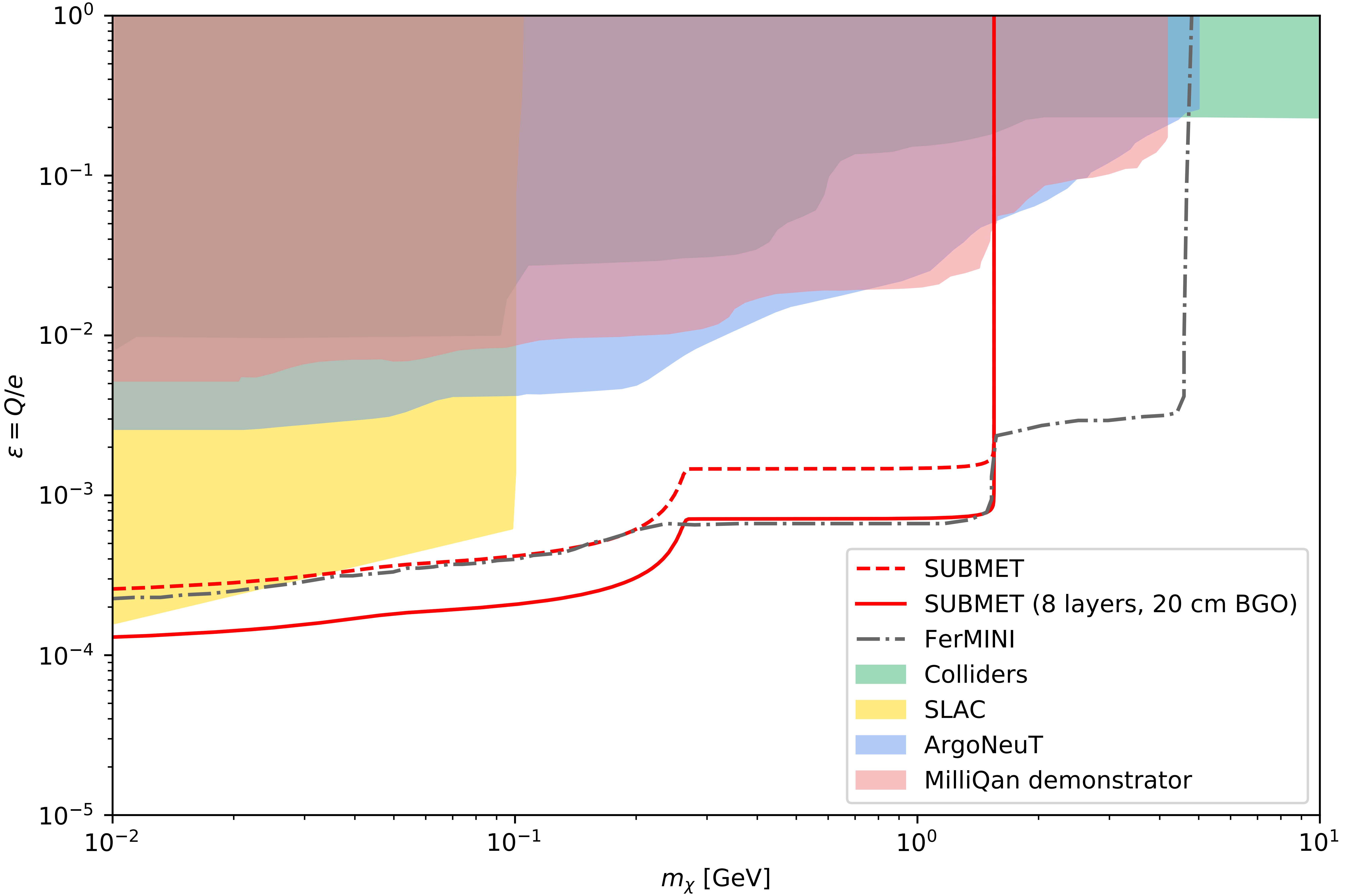
	N_χ	N_{PE}	b	Exclusion limit on ε for N_χ = 10 MeV
nominal design	x1	x1	x1	2.6 x 10^{-4}
	x2	x1	x1	2.4 x 10^{-4}
	x1/50	x1	x1	3.9 x 10^{-4}
	x1	x1	x100	3.0 x 10^{-4}
	x1	x2	x1	1.9 x 10^{-4}
	x1	x3	x1	1.7 x 10^{-4}

- Explored alternative detector configurations N_χ
- Estimated exclusion limit for 10 MeV mCP by changing 3 parameters
  - N_χ: detector volume, duration of data-taking
  - N_{PE} (number of photoelectrons): different scintillating material, length of each scintillator, different photodetectors
  - b (number of backgrounds): different photodetector, unexpected radiation
- Main driver is N_{PE}
  - N_χ and b have small impact => duration of data-taking, detector size, and backgrounds do not matter much
  - Even N_{PE} does not make a huge difference, though
- Overall, performance similar despite large variations
  - Due to steep decrease of probability to detect mCPs ($1 - e^{-N_{PE}}$)

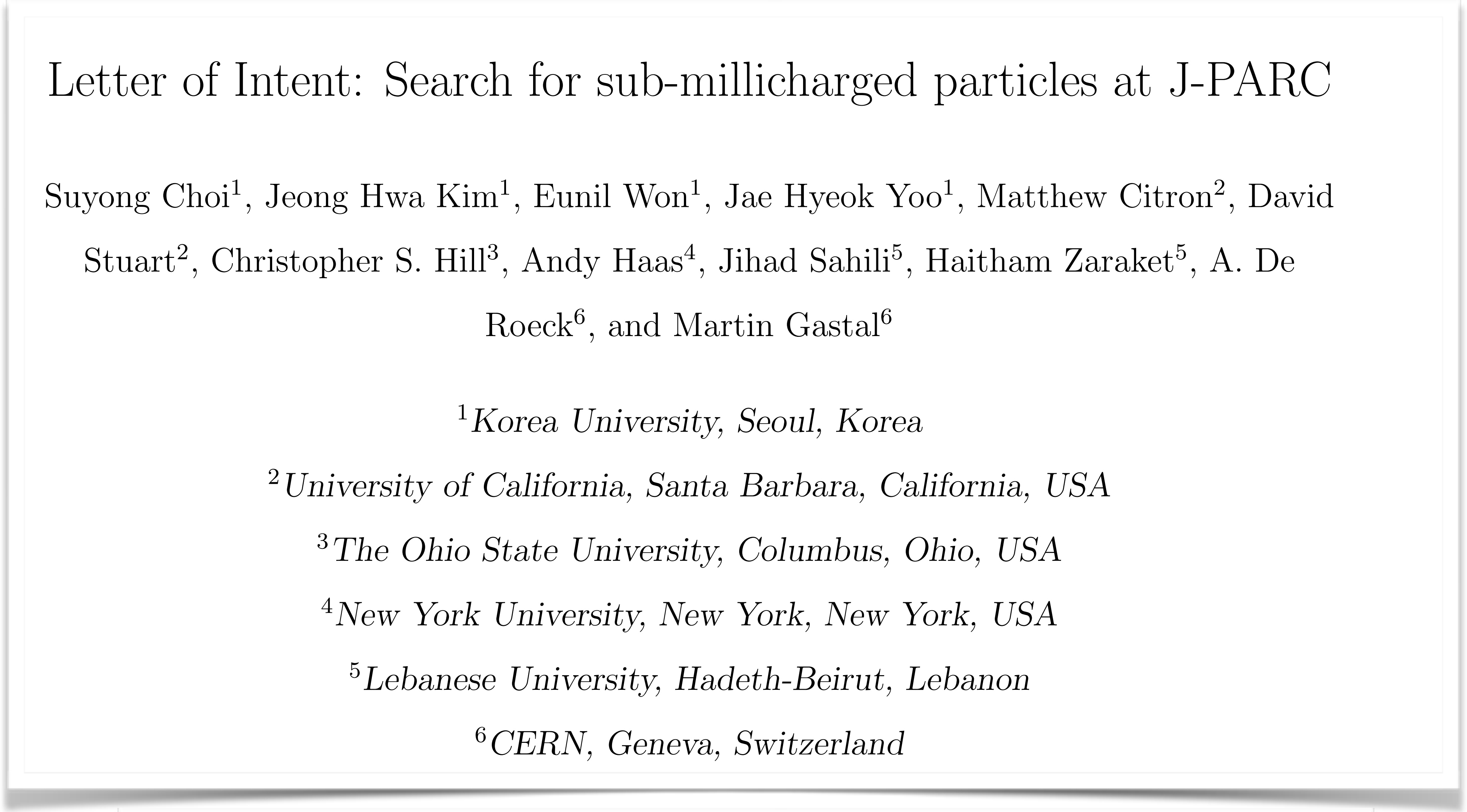
Alternative detector configurations II

- Use SiPM instead of PMT: two challenges - area coverage and DC
- Area coverage
  - SiPMs are small…
  - Use light guide + 1 cm^2 SiPM coverage
- Dark count
  - Order of MHz/cm^2 at room temperature
  - Electric cooling to -20 deg + correlation with beam timing (duration of one packet = a few μs): can reduce random coincidence to <1 per year
- Increase the number of layers, but still require 4 layer coincidence
  - Help by combinatorics, e.g., with 8 layers, N_χ becomes $\times O(100)$
  - Random coincidence still under control: a few in 3 years
- Using higher light yield scintillator, e.g. BGO, with 20 cm length and 8 layers, exclusion limit on ε for N_χ = 10 MeV can extend down to ~10^{-4} (nominal 2.6 x 10^{-4})

Sensitivity of SUBMET



Current status and plan


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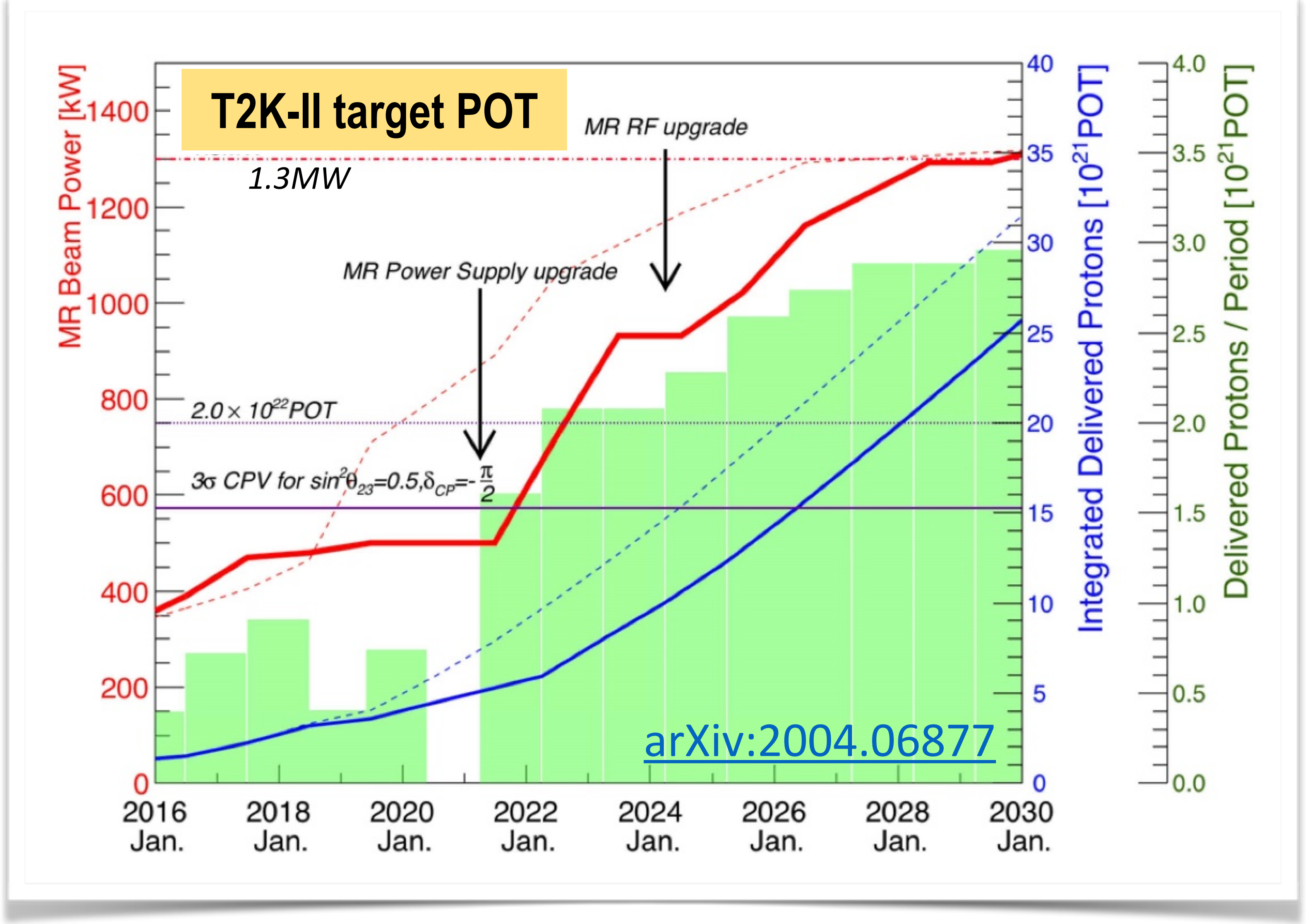
[4]*New York University, New York, New York, USA*
[5]*Lebanese University, Hadeth-Beirut, Lebanon*
[6]*CERN, Geneva, Switzerland*



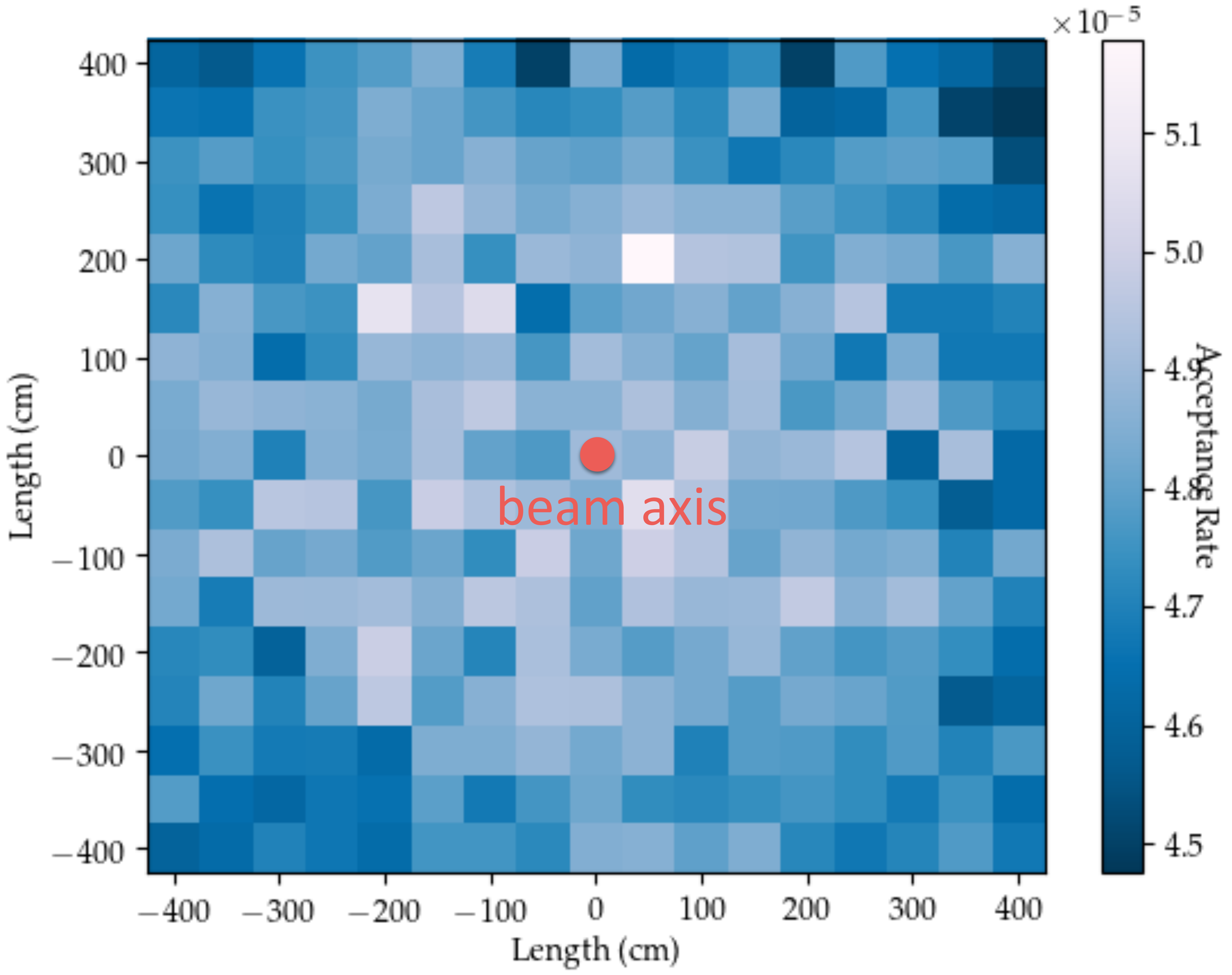
- Prepared LOI and submitted to J-PARC (arXiv:2007.06329)
  - Domestic (Korea Univ) and international collaborators (CERN, UCSB, OSU, NYU, LU)
  - Expertise from milliQan collaboration
- Next steps
  - Build/test prototype in Korea and at J-PARC
  - Get funding!
- Beam expected in 2022 after upgrade

Summary

- Designing an **experiment to search for millicharged particles** using 30 GeV proton beam at **J-PARC**
- Unique opportunity to probe **low mass (**$m_\chi < 1.6$ GeV**) millicharged particles**
  - Sensitive to mCPs with $Q/e = 3 \times 10^{-4}$ in $m_\chi < 0.2$ GeV and $Q/e = 1.5 \times 10^{-3}$ in $m_\chi < 1.6$ GeV with 3 years of data
- Other proposals at FNAL (FerMINI) and LHC (milliQan, FORMOSA)
  - These proposals are not fully funded yet and/or targeting HL-LHC (>=2027)
- **Low-hanging fruit we (Korea) should pick**
  - Well-established technology
  - Can reach the best limit in low mass region within a few months of data-taking

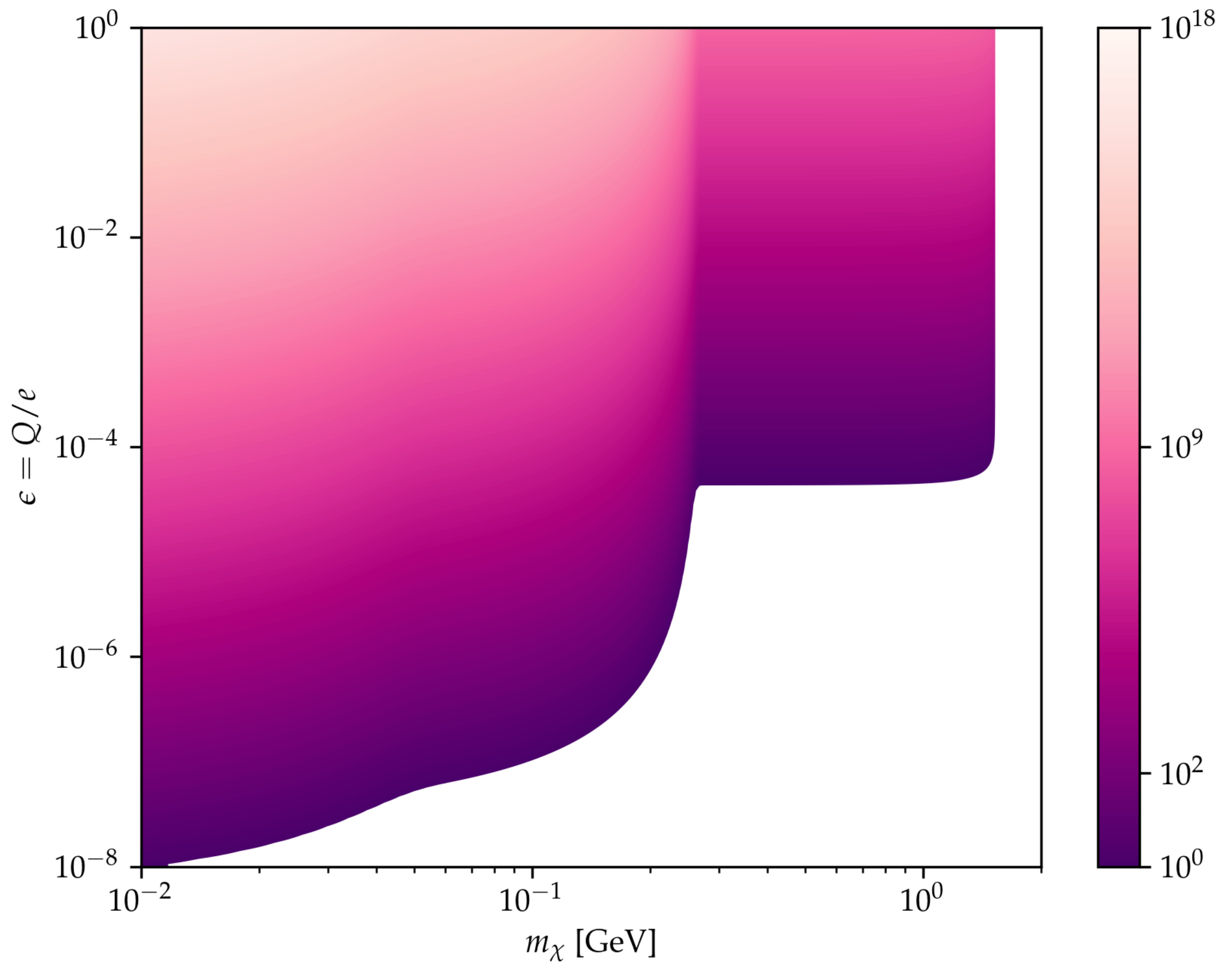
Backup

Geometrical acceptance



Production => detection

Production

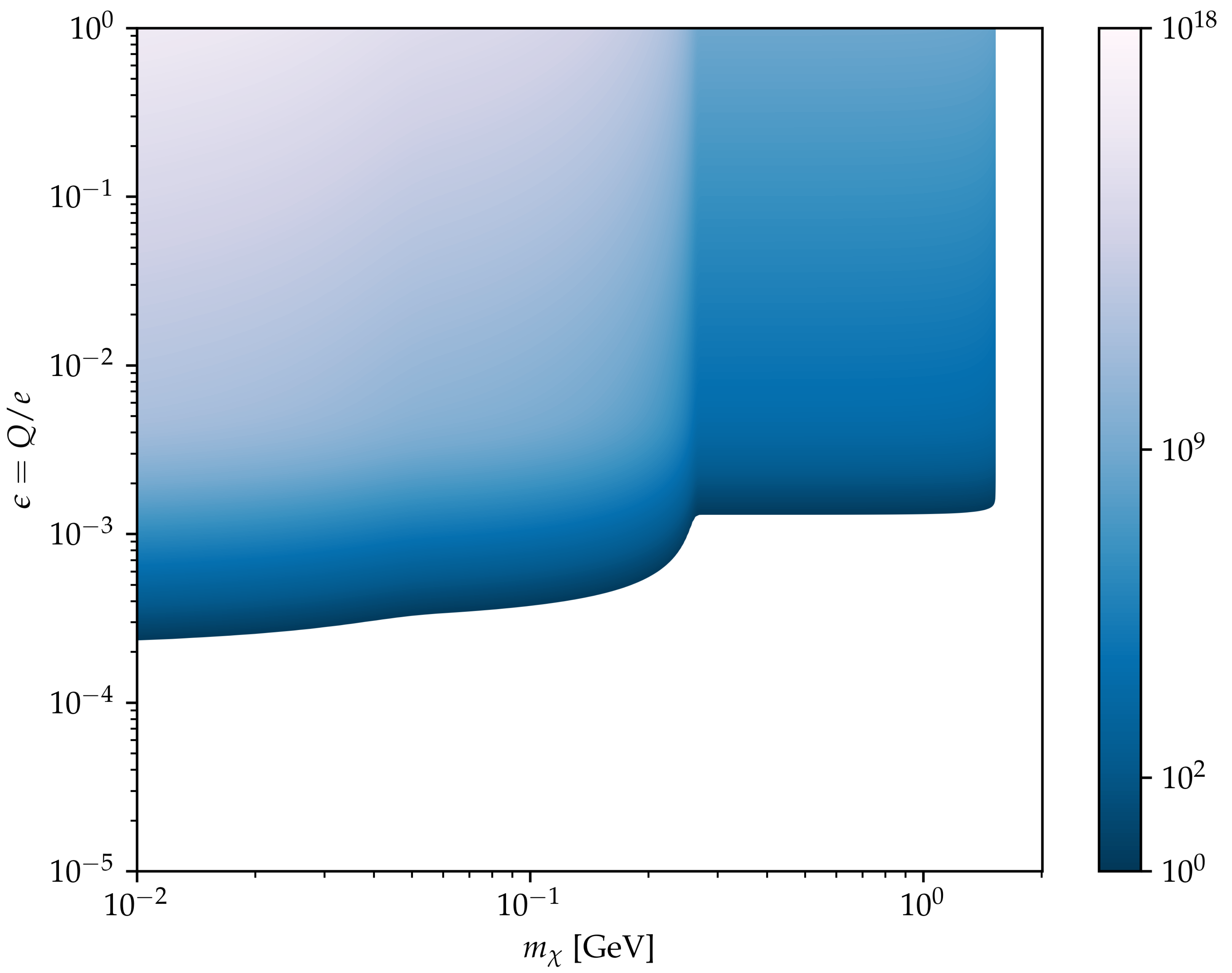


$$P = (1 - e^{-N_{PE}})^4$$

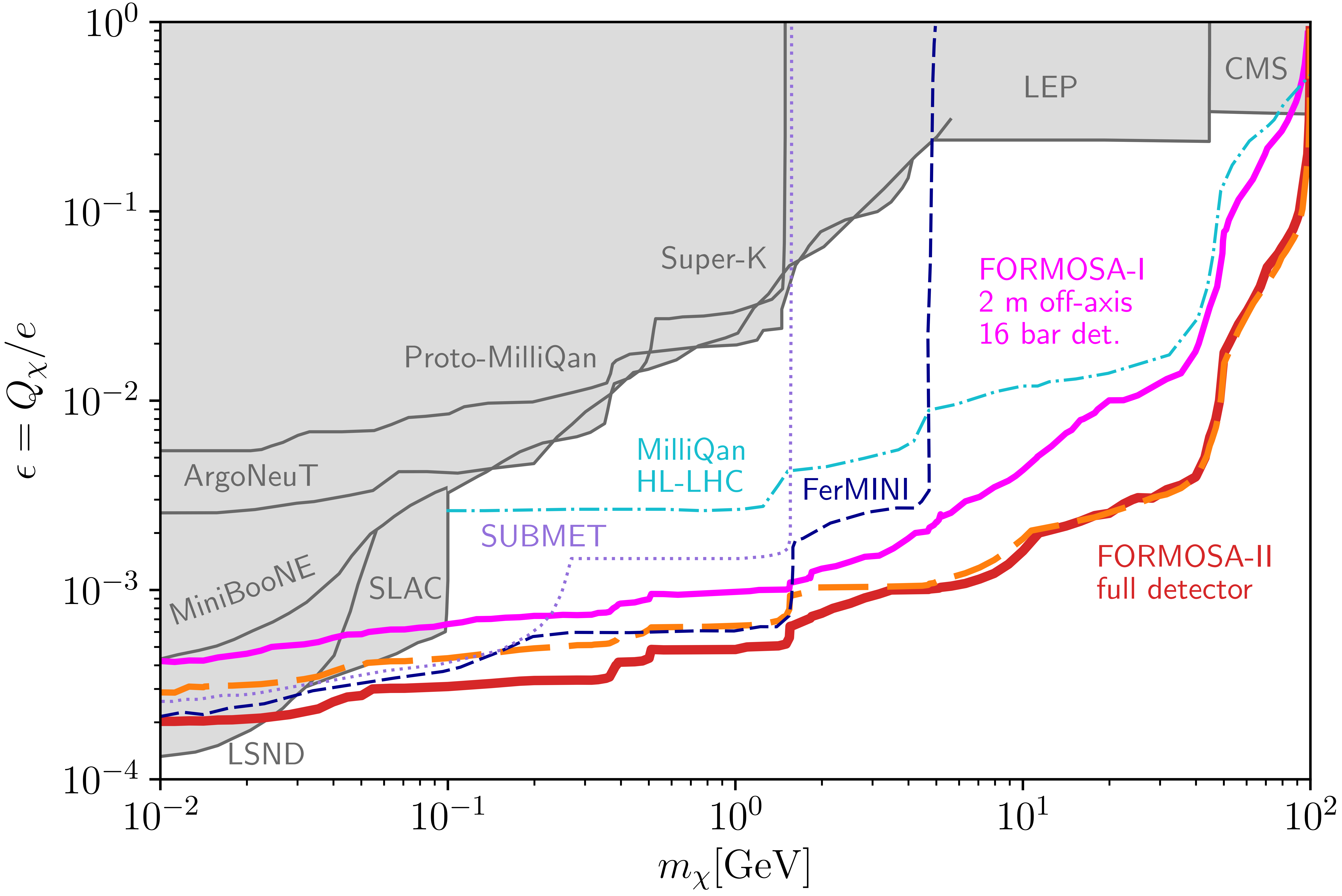
Detection efficiency

4 = number of layers

Detection

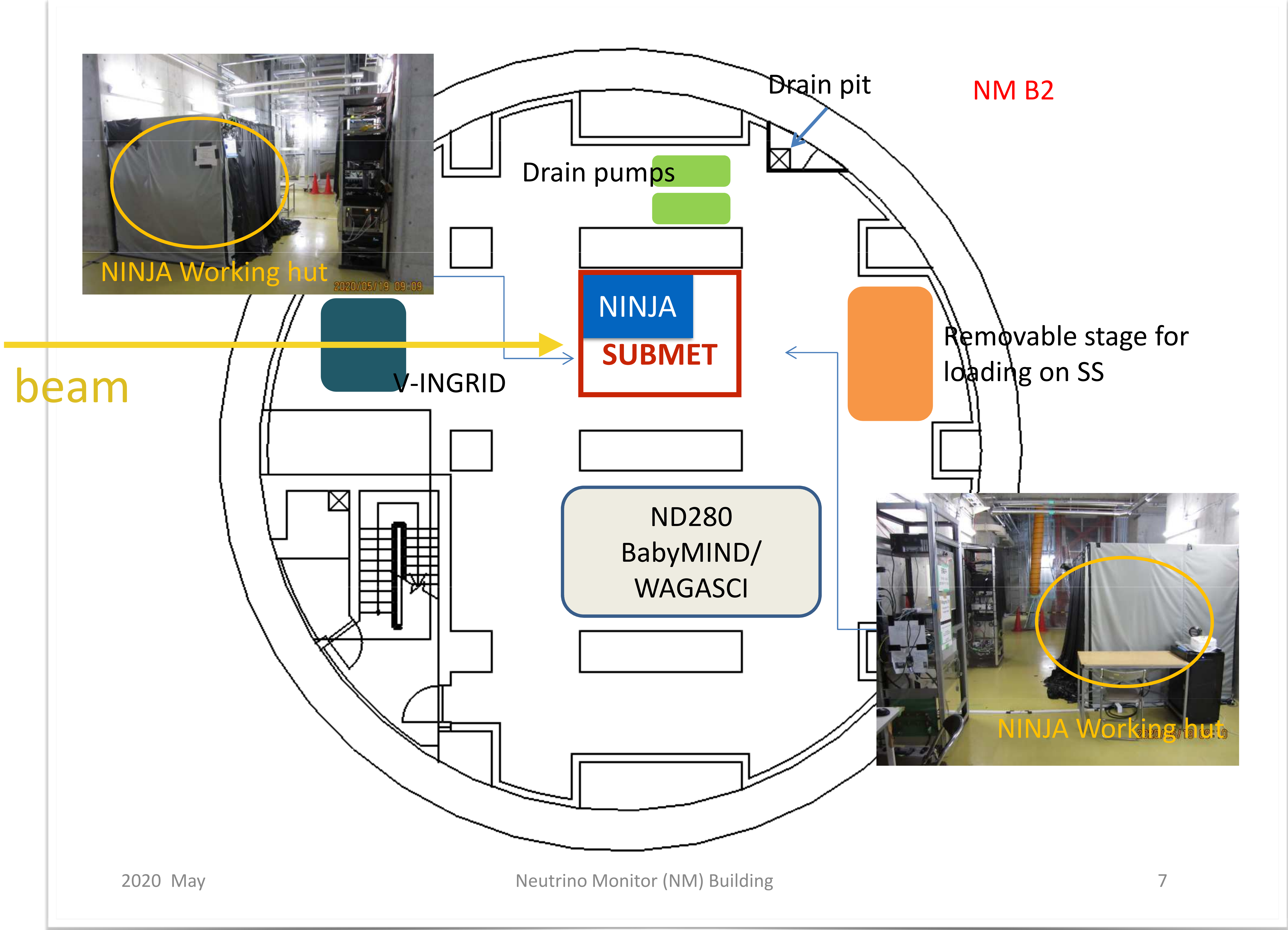


Other proposals



- MilliQan
  - full HL-LHC data
- FerMINI
  - LSNF/DUNE
- FORMOSA
  - full HL-LHC data

Potential experiment site



- Thanks to the photos, we could find a potential site for the experiment
  - On B2 where NINJA working hut is set (red box)
- It is about 5-6 m from the beam axis
  - sensitivity would not be affected much
- We will need to make sure that the experiment does not interfere with the on-going NINJA project