Beam dump experiments at PIP-II with low threshold detectors (eV).

Juan Estrada
Fermilab

the main point

- Significant progress has been done developing new technologies for detecting low energy nuclear and electron recoils for direct DM search.
- These technologies combined with high intensity proton beams provide new opportunities for dark search searches.
- Could a beam dump facility at PIP-II host a few small experiments with low threshold technologies?

a few new technologies

superCDMS calibration at 100 eV nuclear recoils with gram scale detector

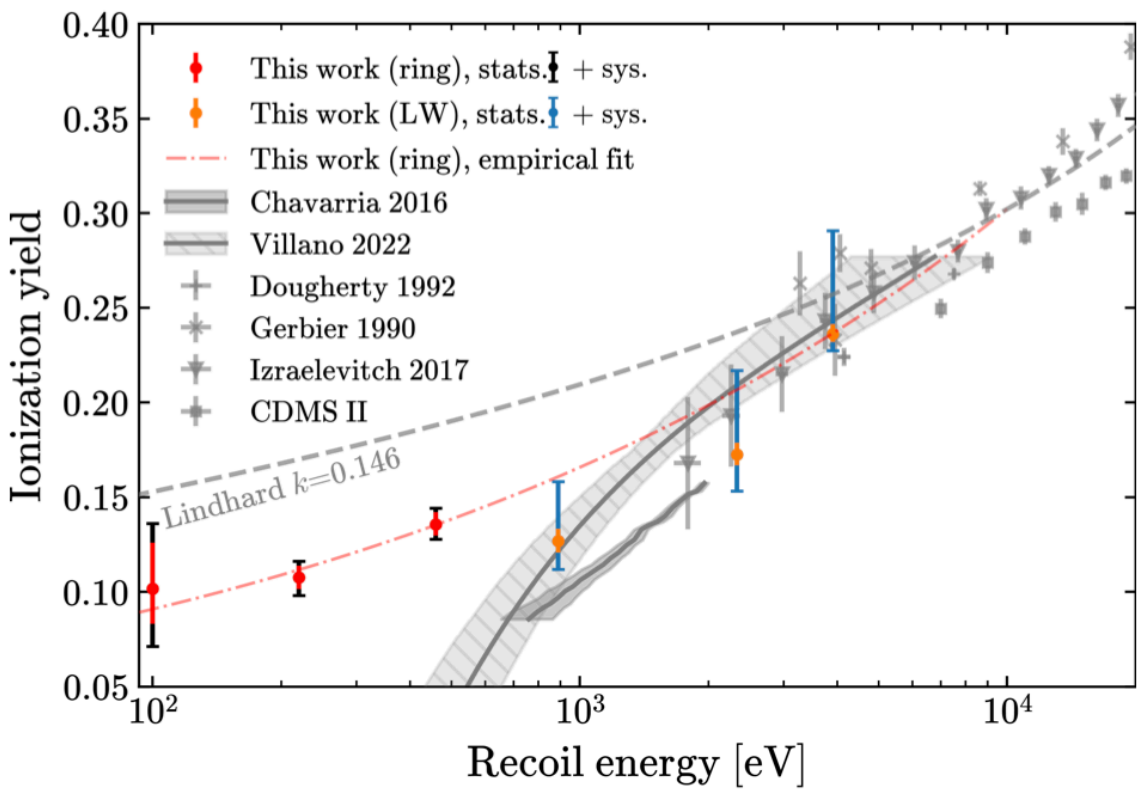
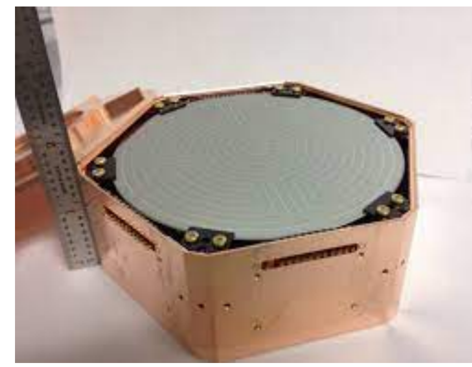


FIG. 3. The measured ionization yields, along with their statistical and total uncertainties and a fit with a power-law function. Also shown are data points from previous measurements [16, 17, 19–21, 42]. The dashed line shows the Lindhard model with k =0.146 [43].



each detector is 1.3 kg

performance on the cryogenic phonon sensitive detectors continues to improve…

NUCLEUS R. Cerulli

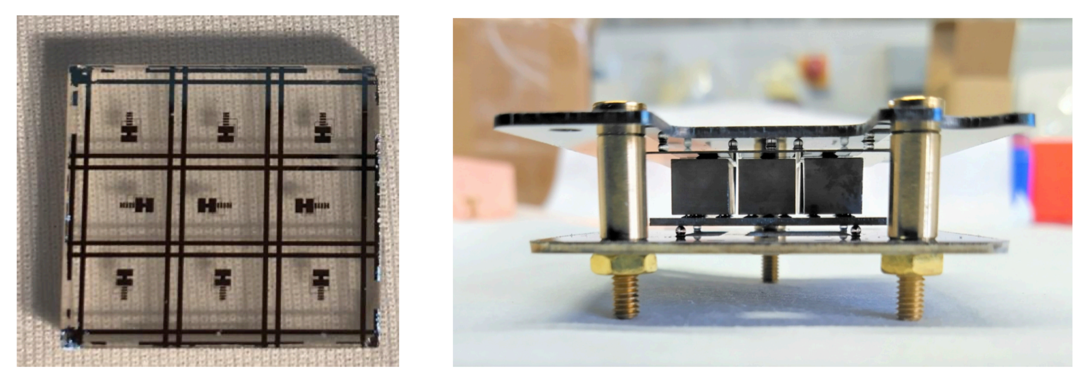


Figure 2: The picture on the left shows an array of 9 $CaWO_4$ crystals instrumented with TESs before the cut into individual crystals. The size of each crystal is $0.5 \times 0.5 \times 0.5$ cm^3. In the picture on the right the mock-up of the Inner Veto with dummy detectors is shown; the Si wafer, that pushes the crystal together, is visible with the holding plate where electrical and thermal contacts are connected. Between the holding plates and the wafer layers, sapphire balls are also present to assure mechanical stability.

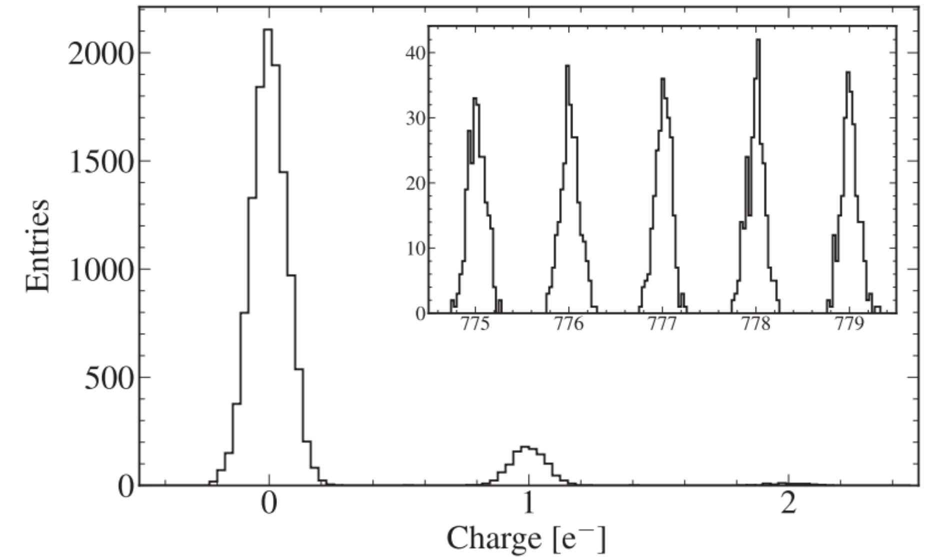
20 eV threshold NR

sub-eV threshold with quantum sensors…

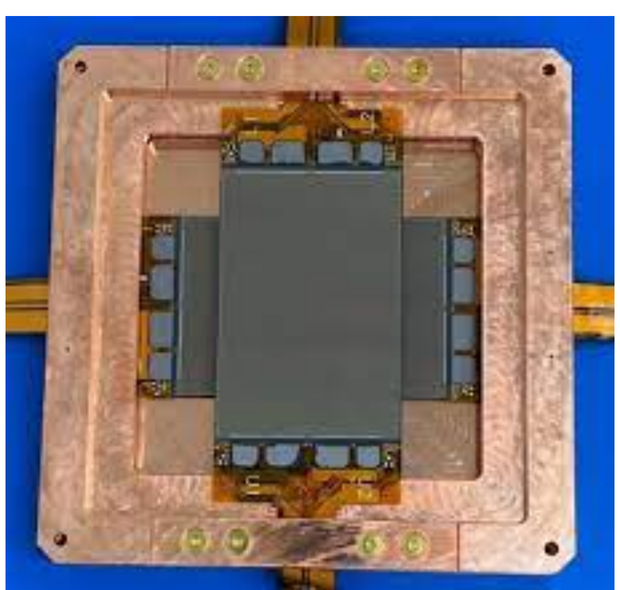
a few new technologies

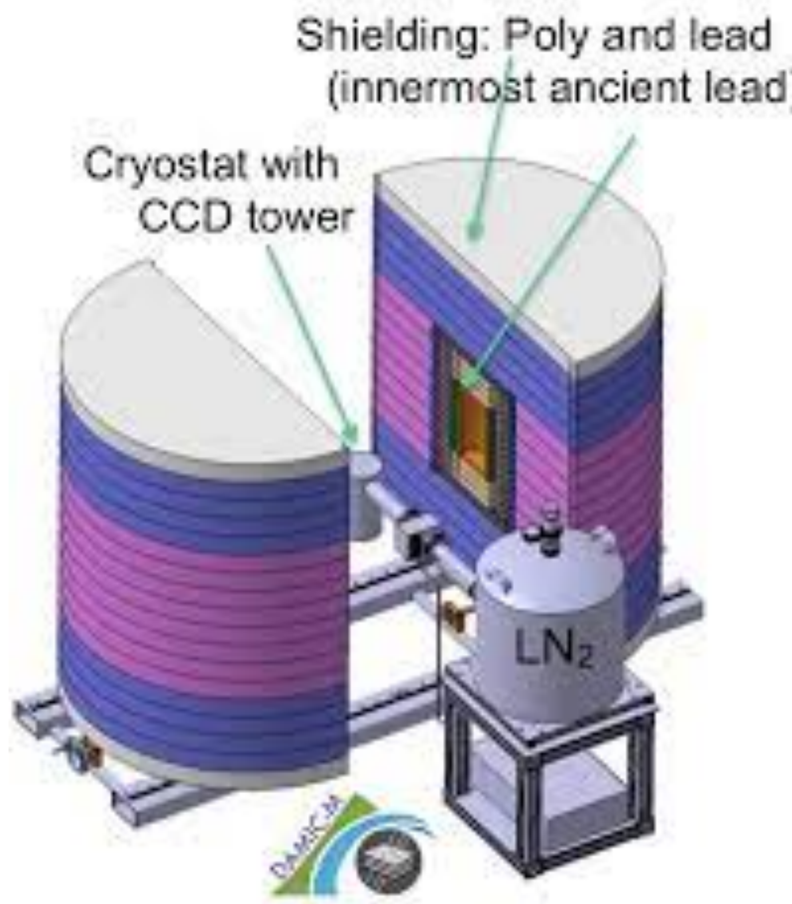
silicon CCDs : 3.7 eV threshold electron recoil

counts single electrons

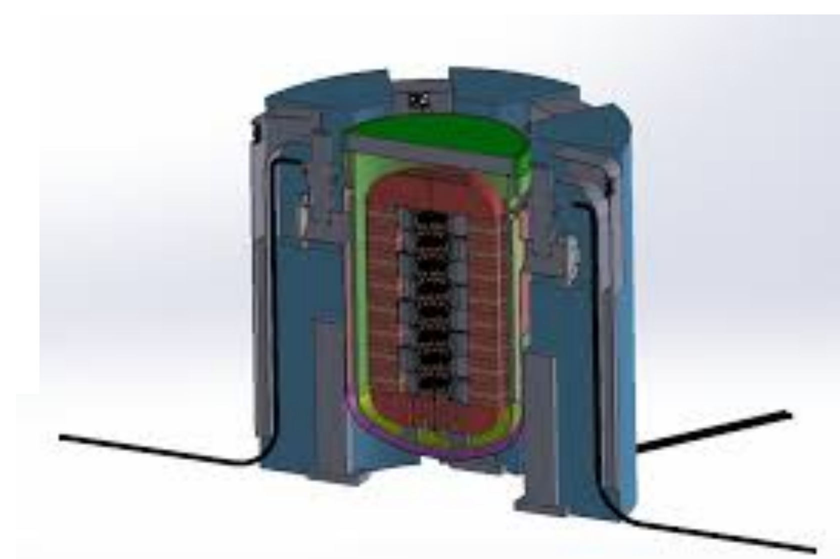


100 gram scale now (SENSEI/DAMIC)



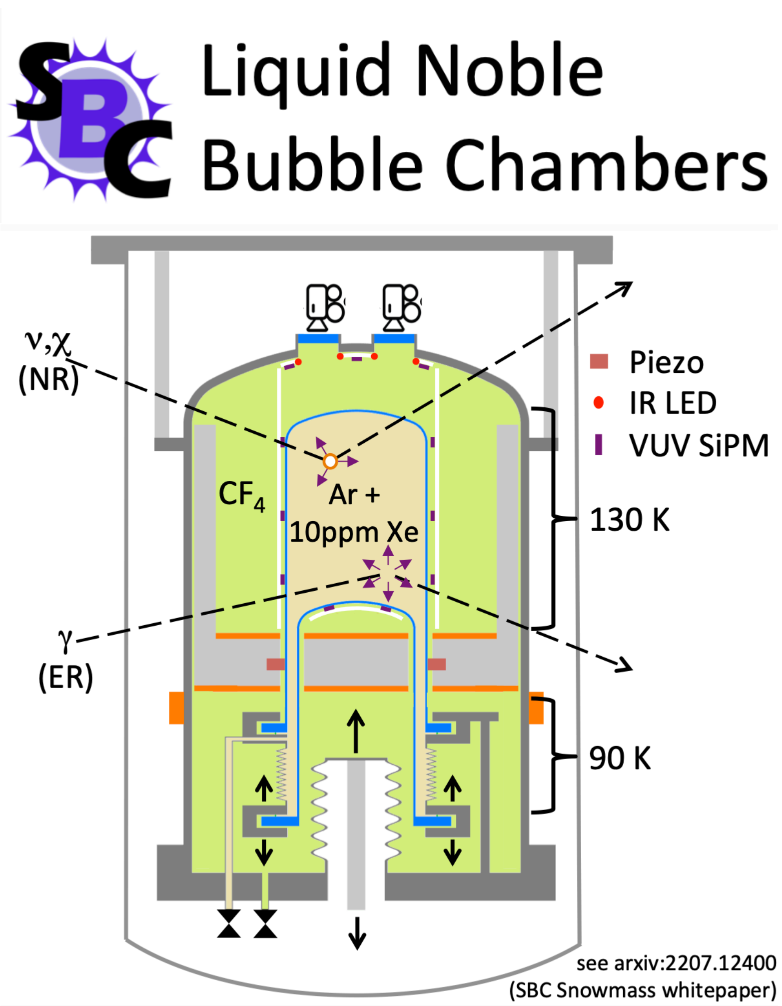


1 kg
DAMIC-M



10 kg
28 GPix camera

a few new technologies



Argon version being developed now with to demonstrate 100 eV nuclear recoil threshold.

darkside 50 calibras nuclear recoils at 0.4 keV

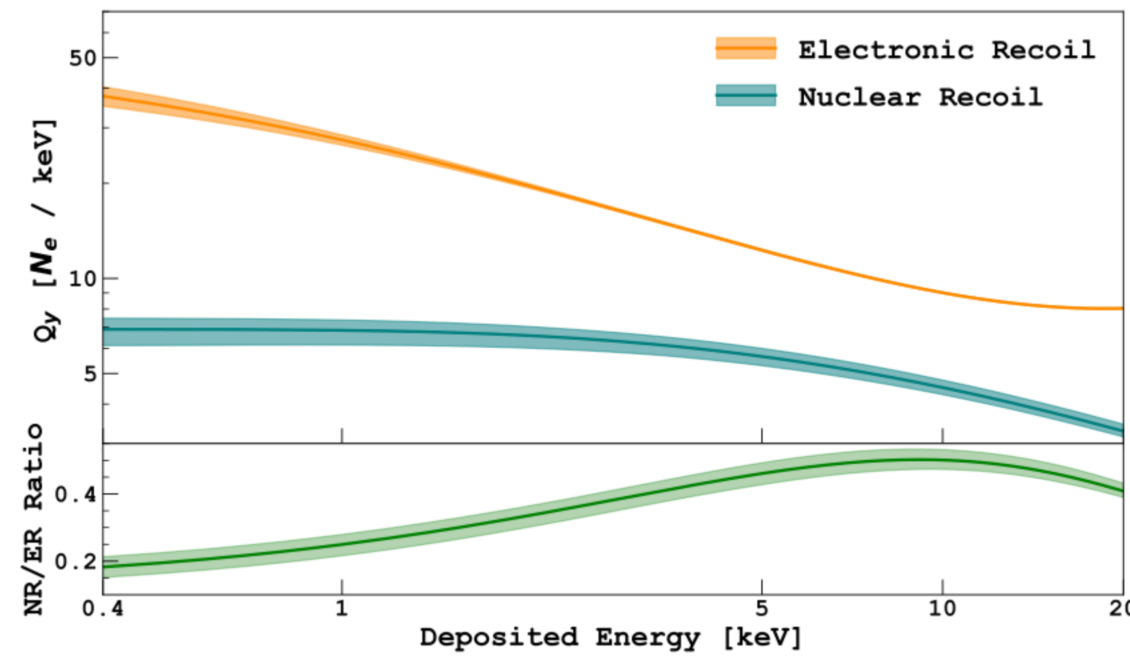


FIG. 1. Comparison and ratio between LAr ionization responses to nuclear (NR) and electronic (ER) recoils, as a function of the deposited energy. The two energy scales were measured using DarkSide-50 data and datasets from the ARIS [17] and SCENE [18] experiments, and are reported in ref. [16].

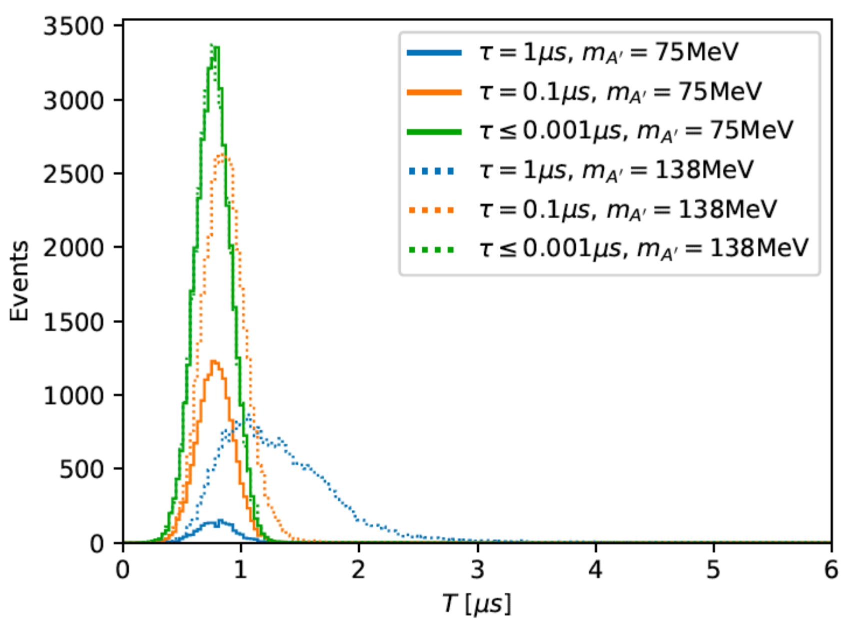
https://arxiv.org/abs/2207.11966

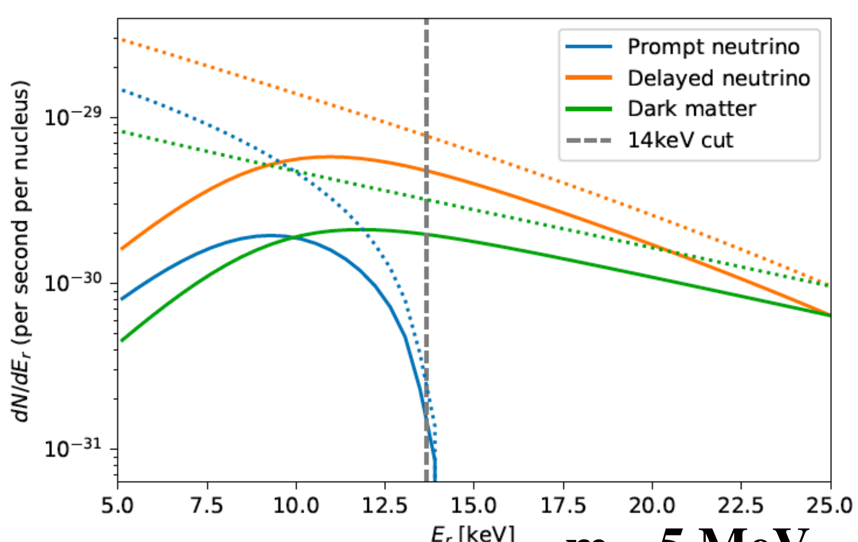
the development of new sensor technologies for low threshold experiments is fast, driven by dark matter, CEvNS, QIS.

It also helps that huge progress can be done by relatively small amounts of money.

Why are these good for dark sector searches?

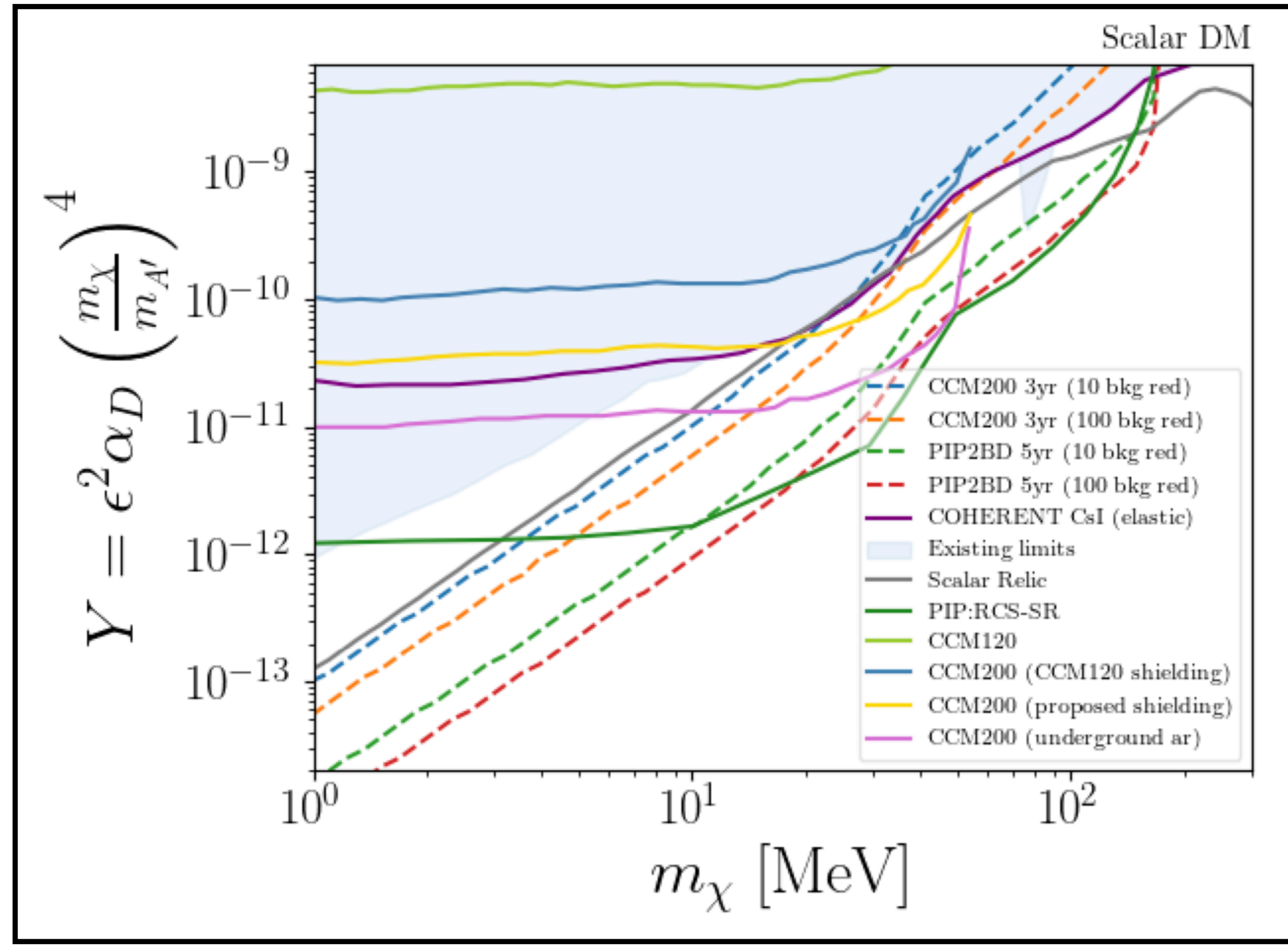
arXiv:1906.10745 Dutta et al.
Dark matter at SNS





m_χ=5 MeV

FIG. 1: Top: Timing spectra of DM signal with three different values for $\tau_{A'}$, in a relativistic A' scenario (solid) and a non-relativistic A' scenario (dashed). Bottom: Nuclear recoil spectrum produced from neutrino and DM interactions with (solid) and without (dashed) experimental efficiencies. The vertical dashed line indicates the energy cut that is used to eliminate prompt ν-induced events.



Bashkar explained to us yesterday why this threshold is important in the elastic channels

$$\sigma_{\text{elastic}} \sim 1/(2m_N E_r + m_{A'}^2)^2$$
$$\approx 1/(2m_N E_r)^2 \text{ if } m_{A'}^2 < 2m_N E_r$$

Why are these good for dark sector searches?

$$N \propto \frac{M_{det}}{E_r}$$

$$\sigma_{\text{elastic}} \sim 1/(2m_N E_r + m_{A'}^2)^2$$
$$\approx 1/(2m_N E_r)^2 \text{ if } m_{A'}^2 < 2m_N E_r$$

Going from a 10 keV threshold to a 10eV threshold es equivalent to increasing the mass of the detector by 1,000. This point was also mentioned yesterday by Zhen for electron recoils produced by mCP.

How to see Millicharged Particles (Again)?

Signal scattering probability and mean free path

$$\frac{d\sigma}{dE_r} = \pi\alpha^2\epsilon^2 \frac{2E_\chi^2 m_e + E_r^2 m_e - E_r\left(m_\chi^2 + m_e(2E_\chi + m_e)\right)}{E_r^2(E_\chi^2 - m_\chi^2)m_e^2}$$

$$\left.\frac{d\sigma}{dE_r}\right|_{E_\chi \gg m_\chi, m_e, E_r} \simeq \frac{2\pi\alpha^2\epsilon^2}{E_r^2 m_e}.$$

$$\lambda(E_r^{\min}) \simeq \left(\frac{10^{-2}}{\epsilon}\right)^2 \left(\frac{E_r^{\min}}{1 \text{ MeV}}\right) \text{ 1 km}$$

Dominated by low recoil energy scattering

Compared to LAr, Skipper CCD increases signal efficiency by 10^5 (1 MeV v.s. 10 eV)

Zhen Liu MCP@PIP-II PIP-II Opportunities 05/10/2023 22

How does this work for mCPs at PIP-2?

Ask Santiago Perez (Universidad de Buenos Aires, Argentina).

how does this work for mCP

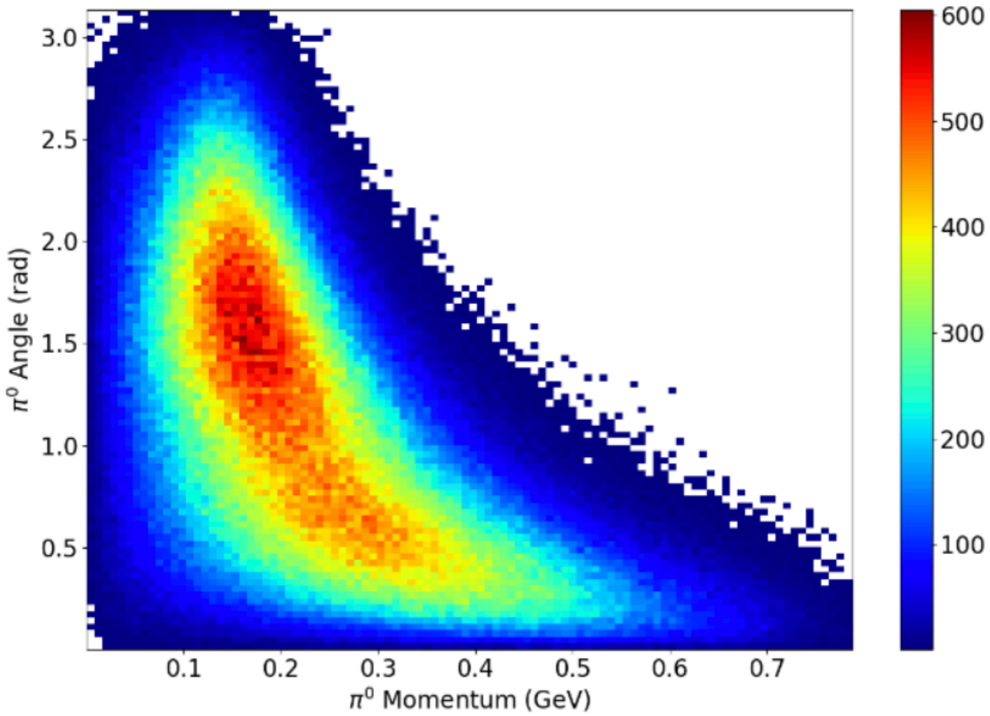


Figure 1: Momentum-angle distributions for π^0 being produced by a 800 MeV proton beam hitting a fixed Carbon target. The color scale is a relative measure of how many pions have the corresponding angle and momentum.

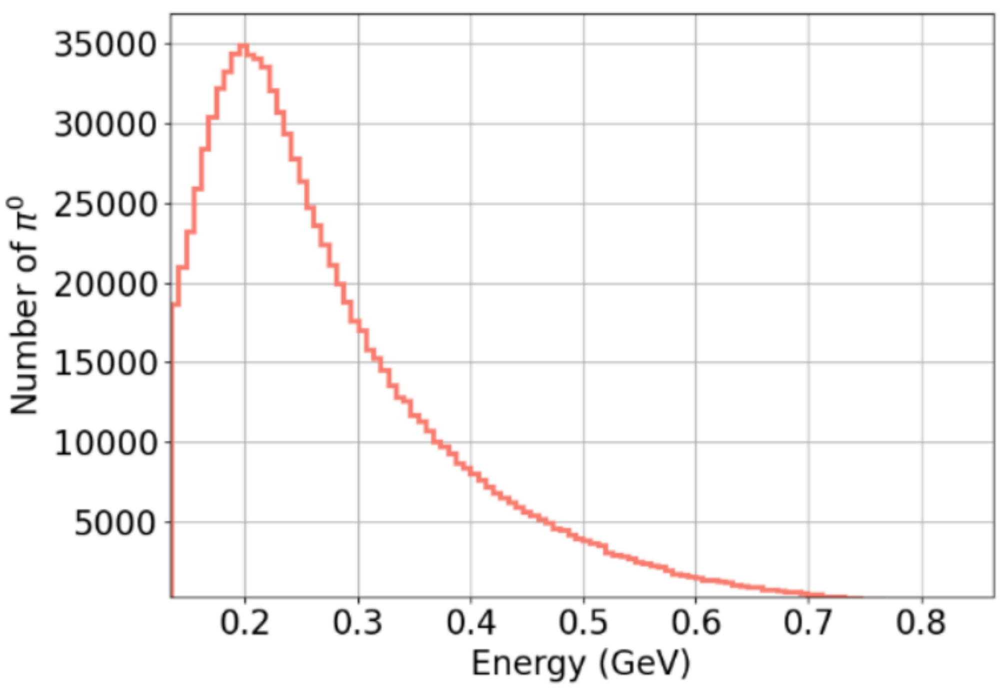


Figure 2: Energy spectra for neutral Pions coming out of the beam dump.

how does this work for mCP

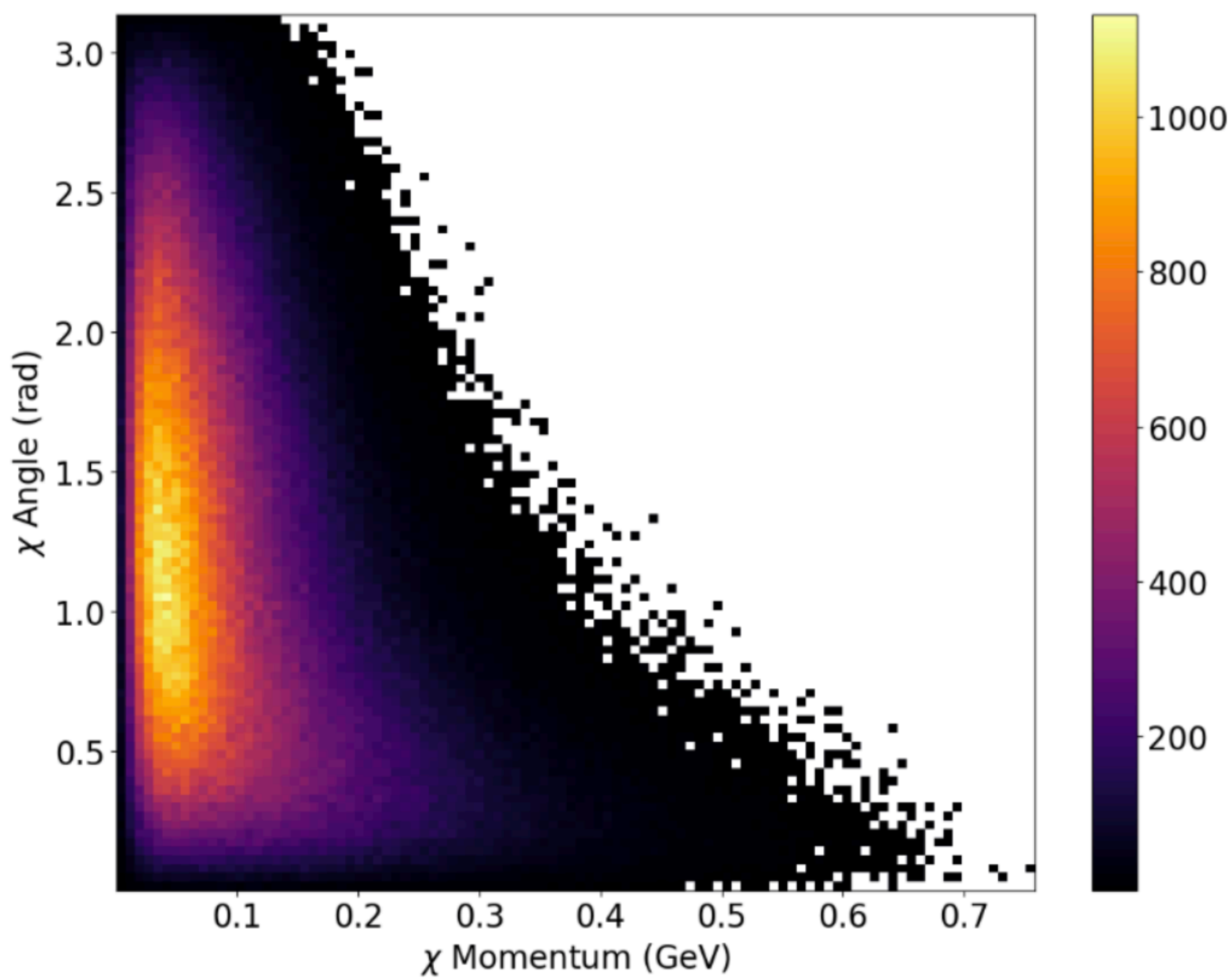


Figure 3: Momentum-angle distributions for mCPs χ after pion decays, the angle is measured relative to the beam axis. The color scale is a relative measure of how many particles have the corresponding angle and momentum.

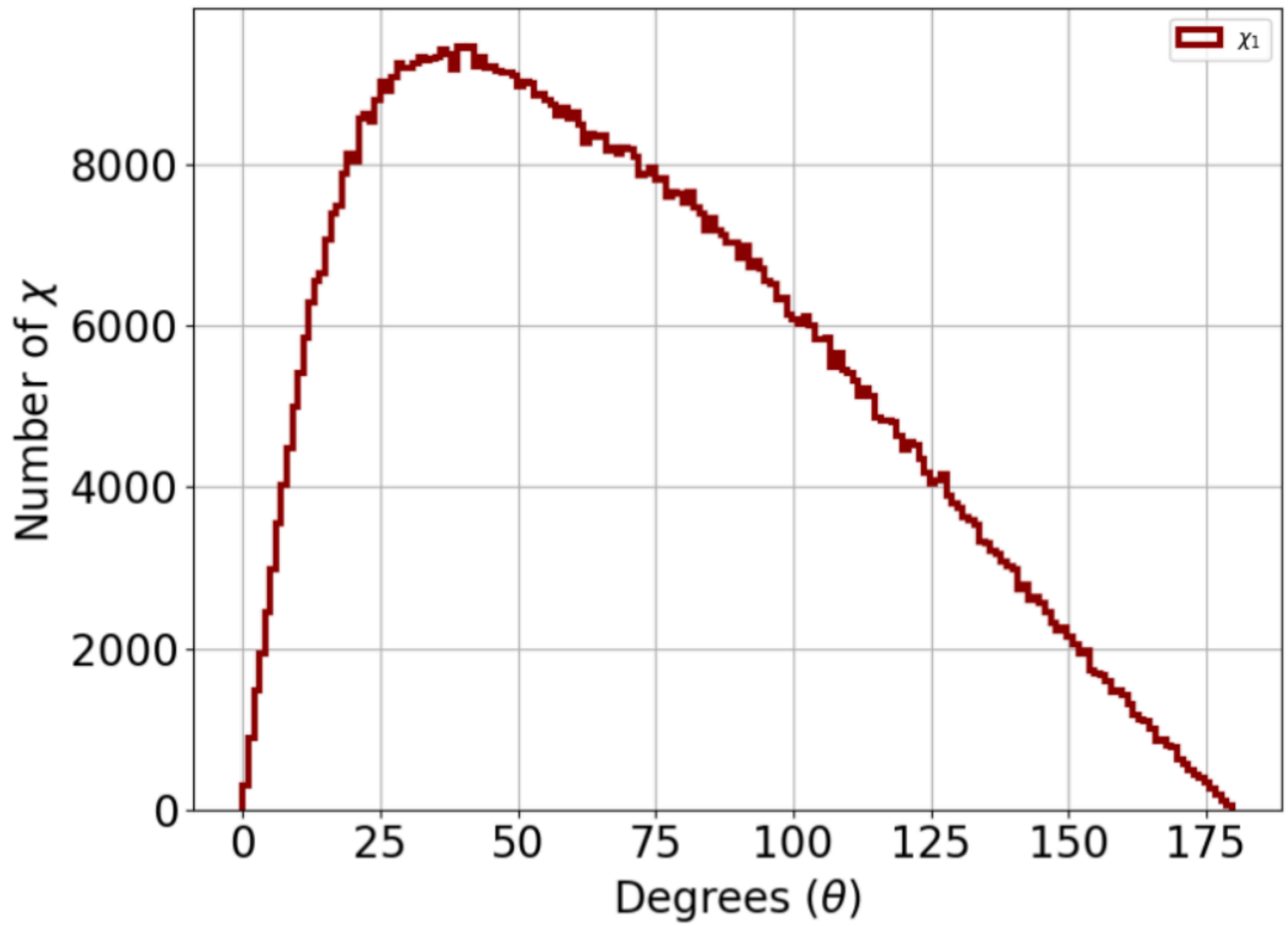


Figure 4: Angle distribution for generated mCPs. The peak in the number of mCPs is found to be around 35 to 36 degrees

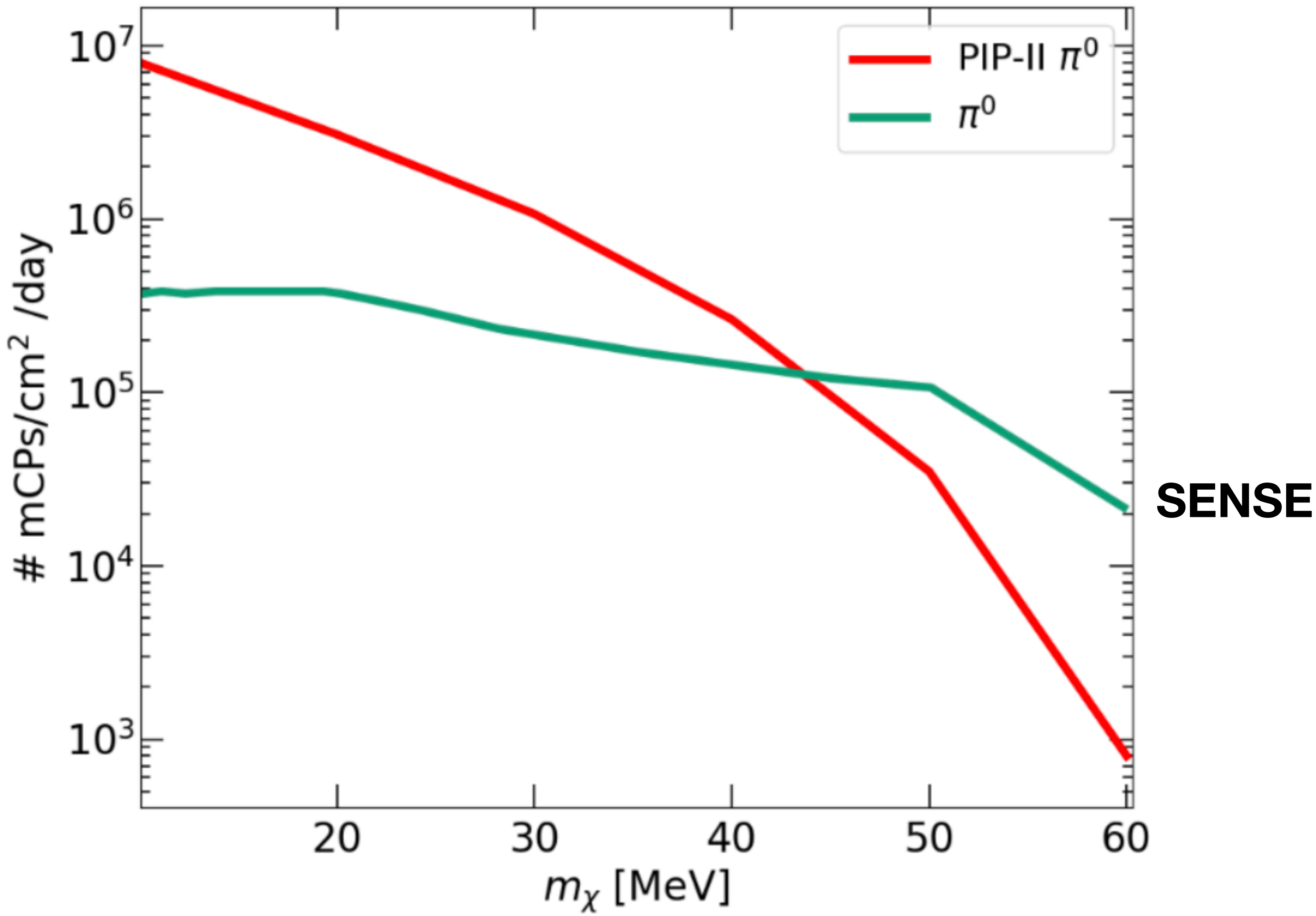


Figure 5: Millicharged flux arriving to a detector placed 10m away from a fixed Target at PIP - II, compared with the amount of mCPs arriving to the SENSEI detector placed in the NuMI beamline.

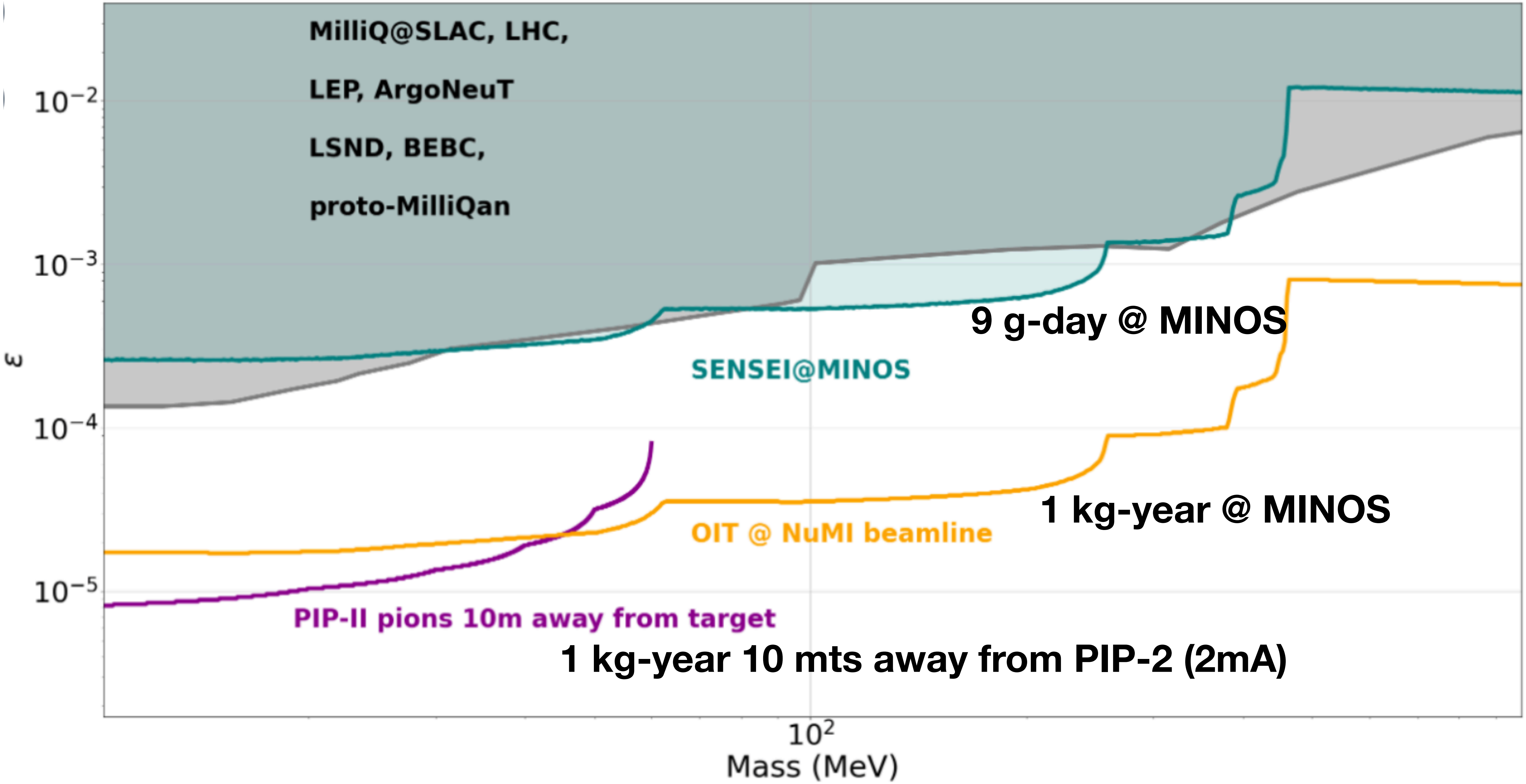
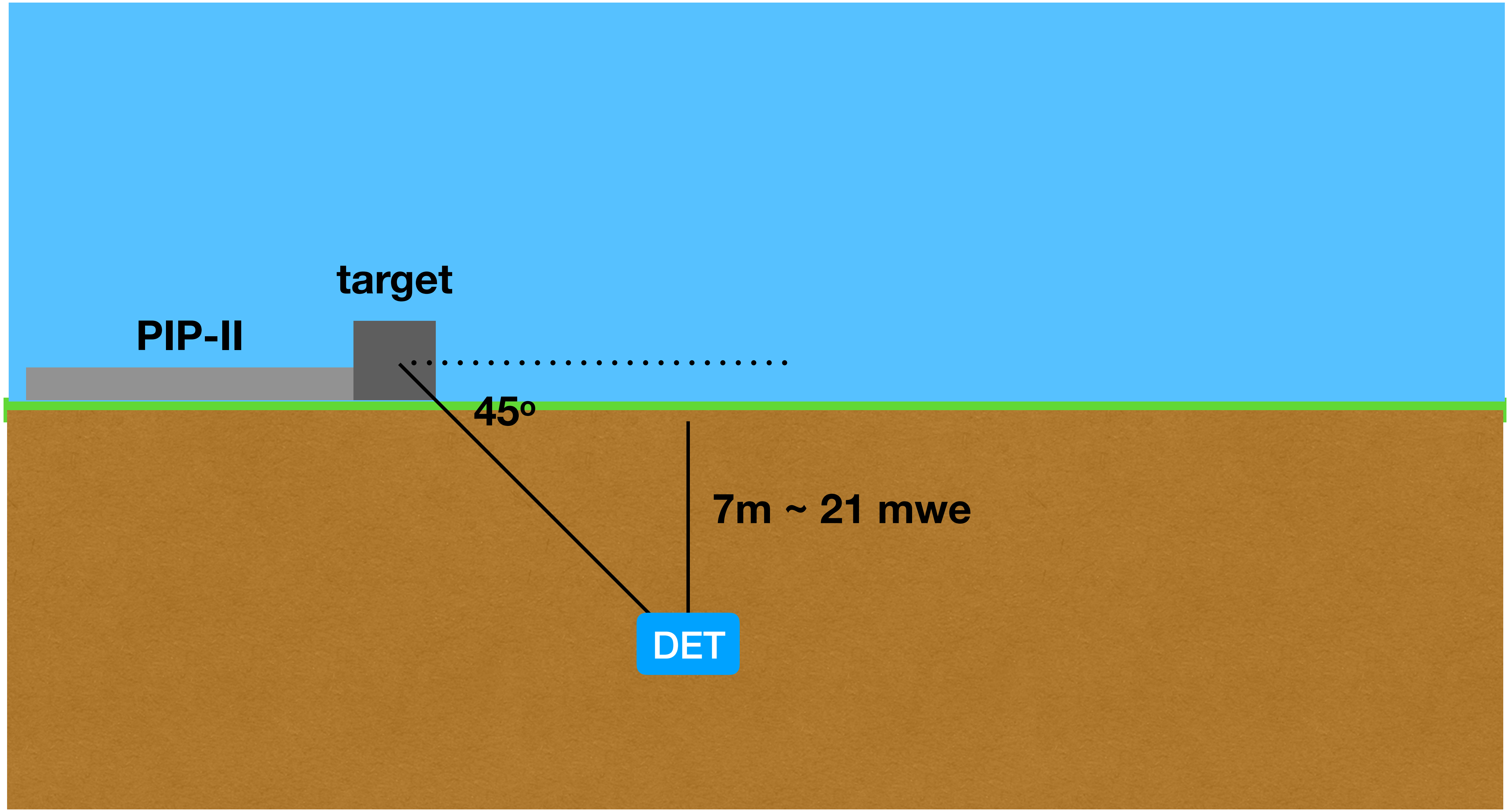


Figure 6: Projected constraints for millicharged and mass of mCPs with a 90% C.L comparing with previous experiments, and the projections for the Oscura early science at the NuMI beamline. Both projections are assuming zero background.

Backgrounds are important:

- need shield to reach levels comparable with SENSEI@MINOS (shallow underground is better).
- as Brenda will discuss (and also Zhen yesterday) in some cases tracking detectors can use position resolution to control background
- Beam background need better understanding


target
PIP-II
45o
7m ~ 21 mwe
DET

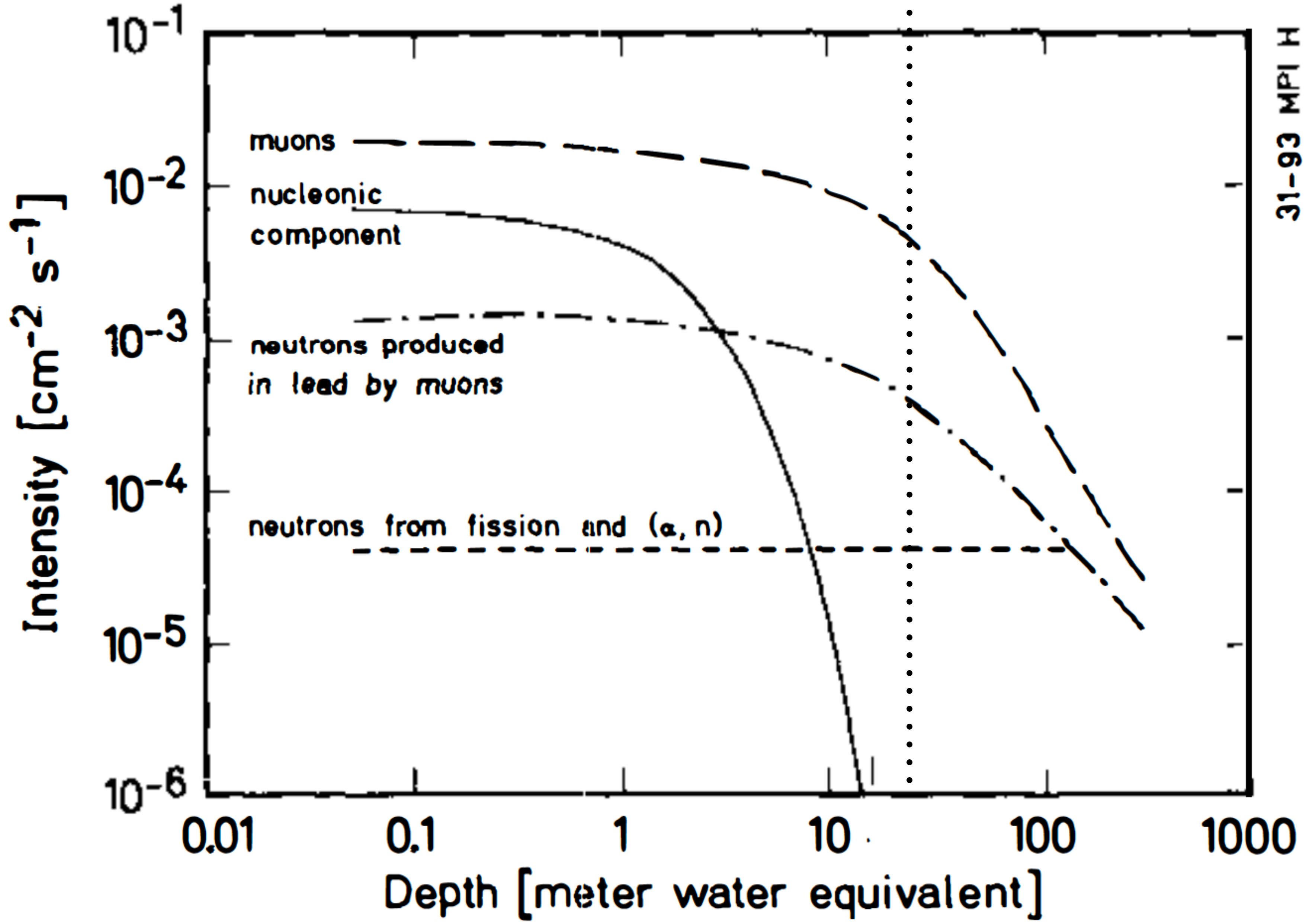
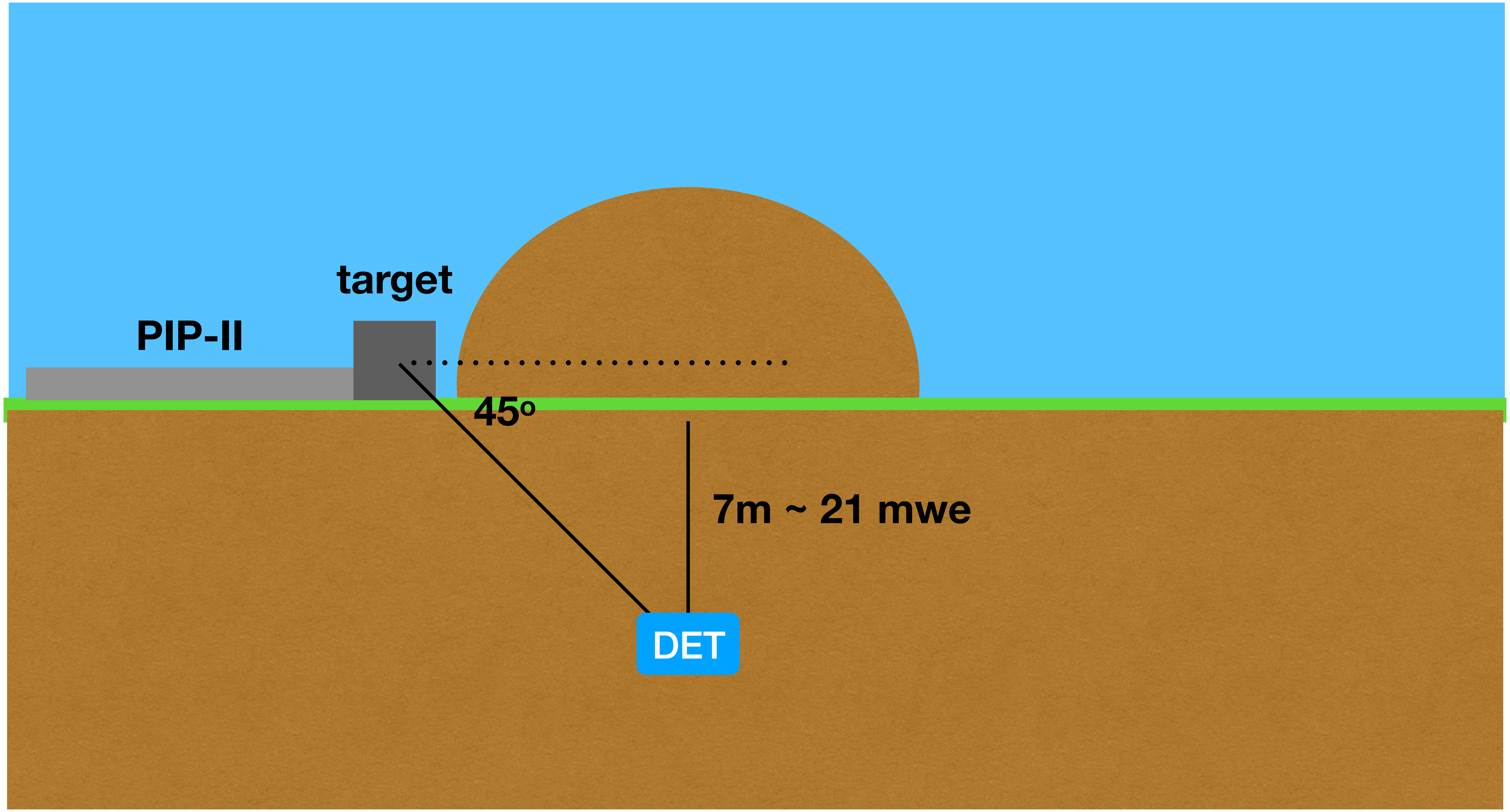


Figure 2 Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth. Neutron flux from natural fission and (α, n) reactions is also shown. The nucleonic component is more than 97% neutrons.


target
PIP-II
45o
7m ~ 21 mwe
DET

- Low threshold detectors at PIP-2 beam dump could explore new region of the dark sector parameter space.
- The accumulator ring always helps (timing), but seems like we could start before that is ready.
- to consider for this workshop:
  - a shielded experimental hall about ~10m away from a beam dump at the end of 0.8 GeV PIP-2, using the 2 mA. Off-axis.
  - If it goes to 2 GeV… maybe things get better, less angular spread.
  - a community of small experiments (thanks to low thresholds) that can be supported by next iteration of DMNI efforts, LDRDs or smaller private grants…
  - lots of work needed to fully understand this…