Nuclear Recoil Imaging in Argon

8th CYGNUS workshop - Sydney, Australia

David Caratelli [UC Santa Barbara] - December 12th 2023

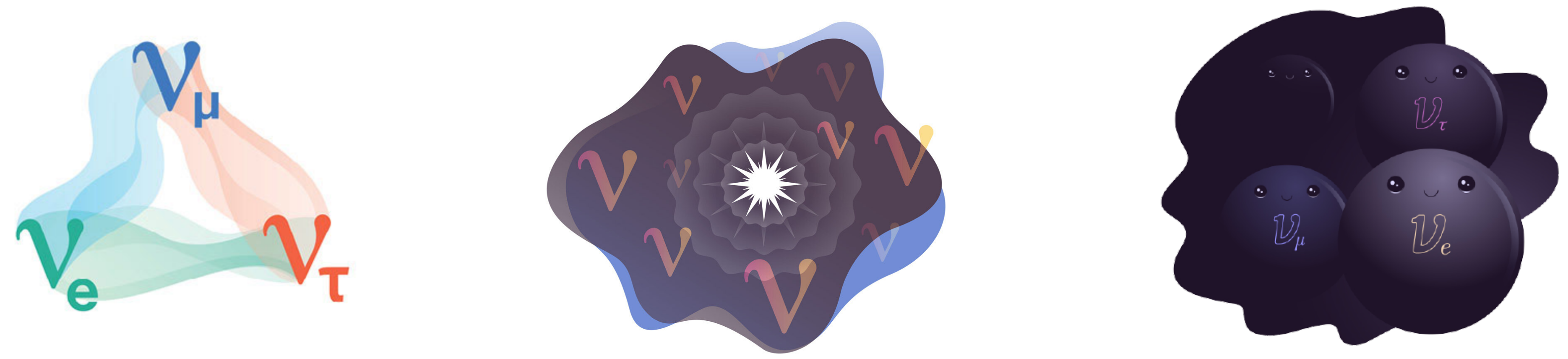
Outline

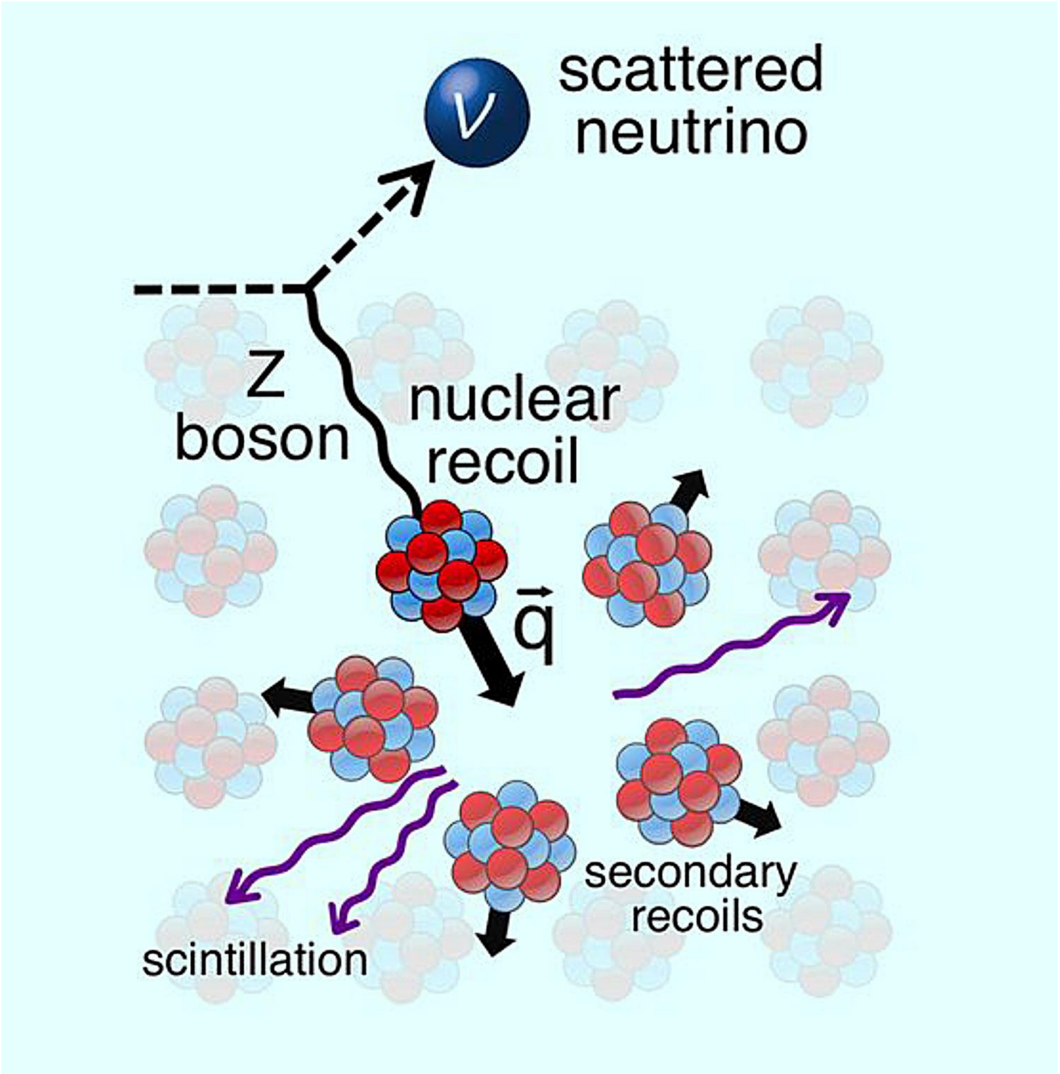
- Experimental Neutrino physics program @ Fermilab
- Liquid Argon Time Projection Chambers
- Imaging NRs in Argon:
  - LArCADe: Liquid Argon Charge Amplification Devices
  - NR Tracking in GAr
  - TRANSLATE: TRANSport in Liquid Argon of near-Thermal Electrons

NR Directionality for Neutrinos

Directional detection of Nuclear Recoil signature in CEvNS:

- neutrino spectroscopy

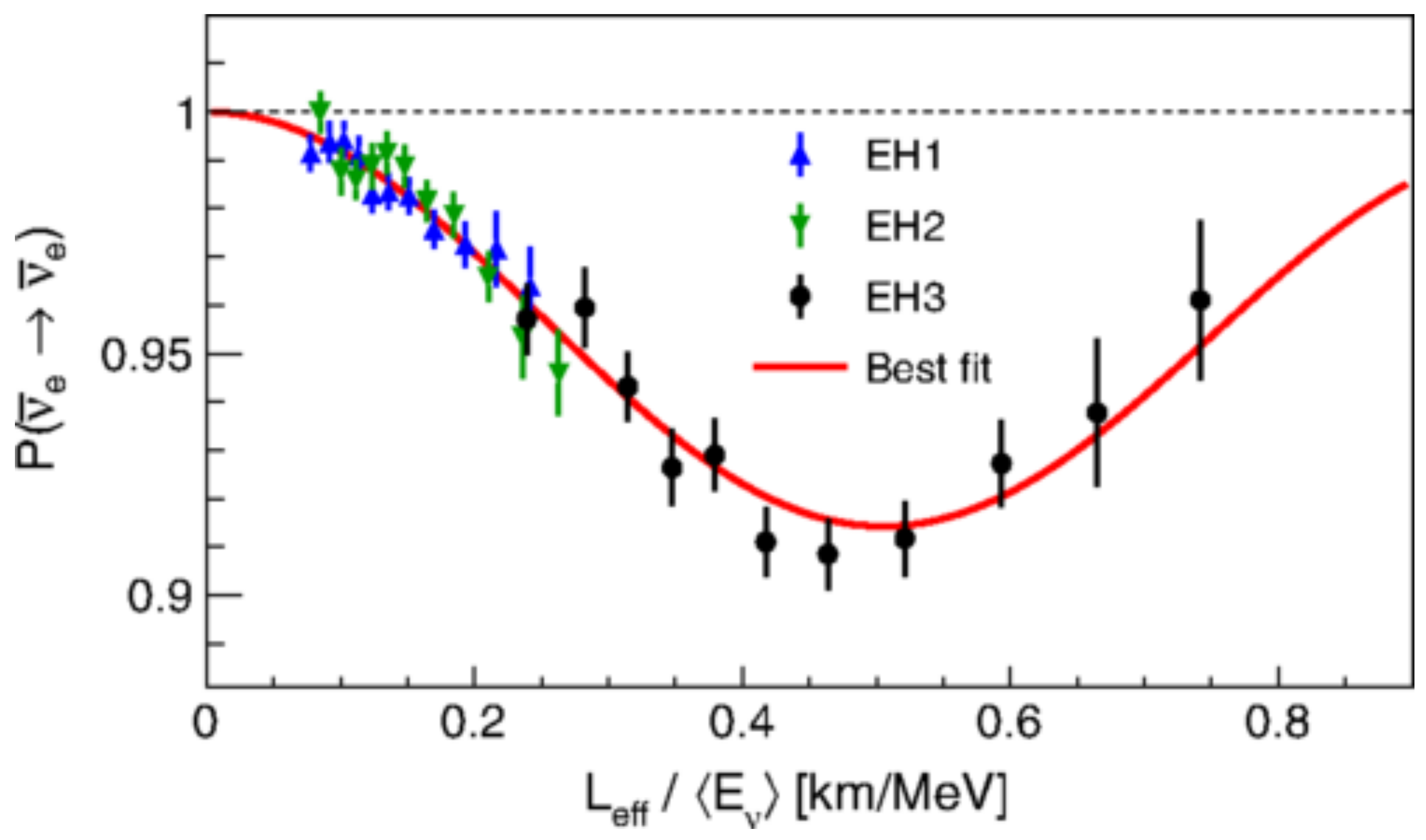




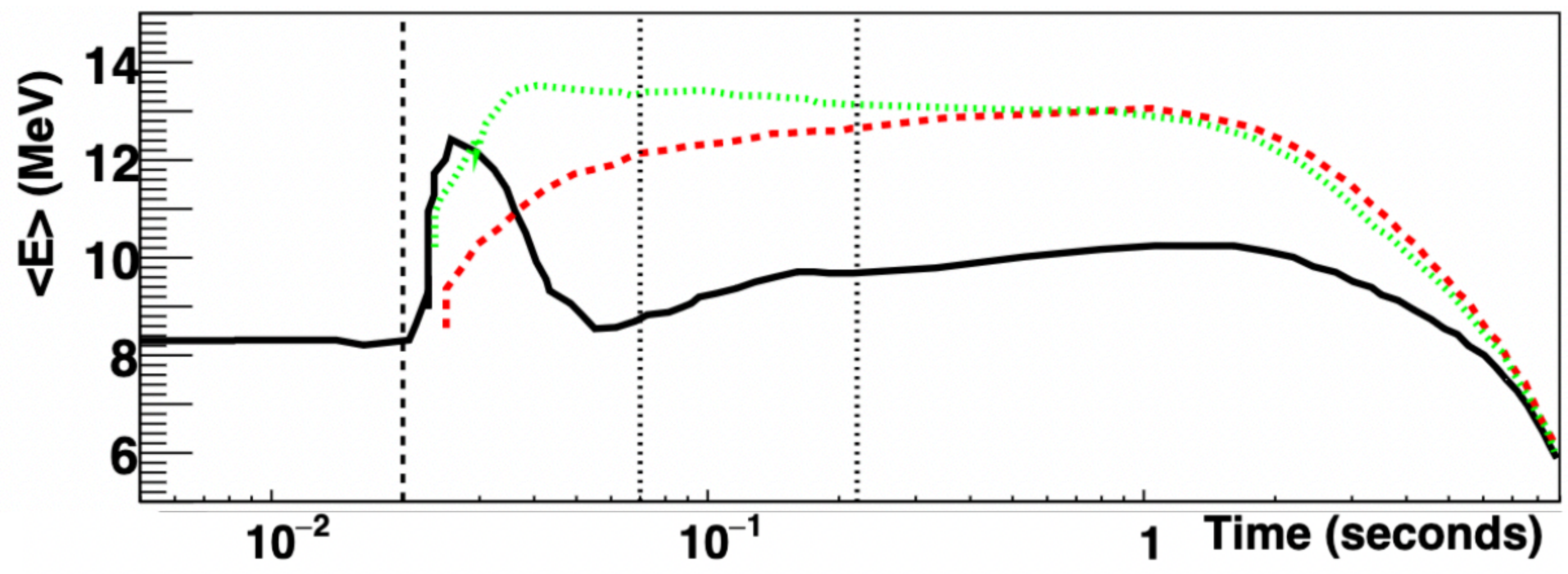
$$E_r = \frac{2m_N E_\nu^2 \cos^2\theta_r}{(E_\nu + m_N)^2 - E_\nu^2 \cos^2\theta_r}$$

"Coherent elastic neutrino-nucleus scattering with directional detectors"
PRD 102 (2020) 1, 015009
M. Abdullah, D. Aristizabal Sierra, B. Dutta, L. Strigari

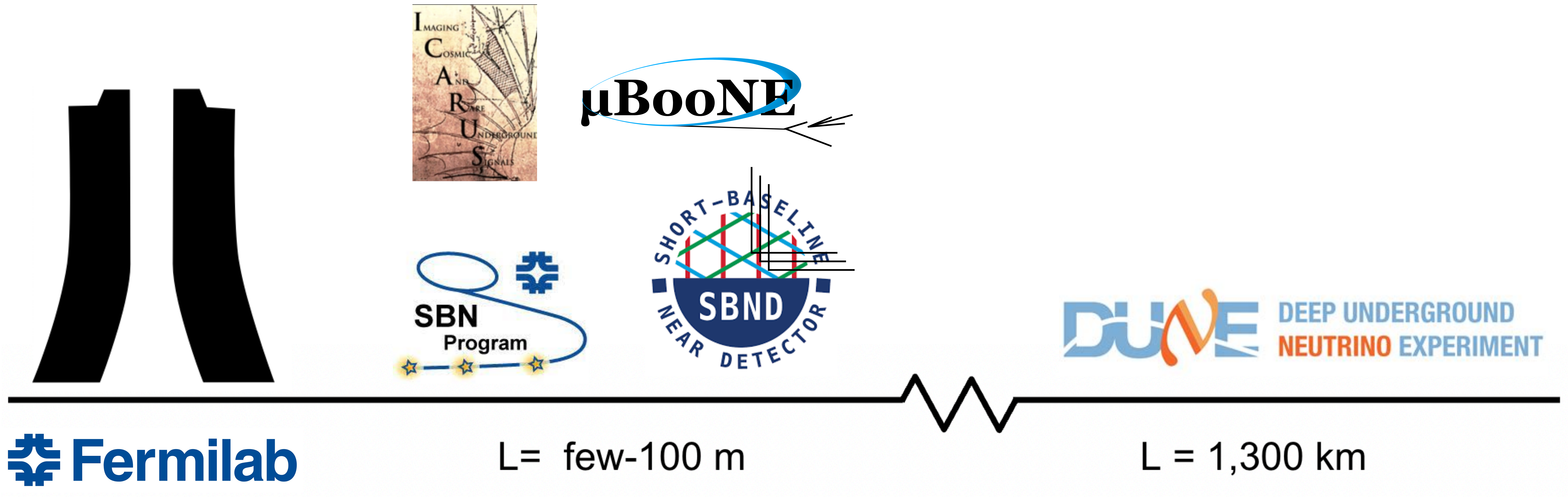
Oscillations (e.g. from Daya Bay [PRL115.111802])



DUNE supernova physics [EPJC 81 (2021) 5, 423]

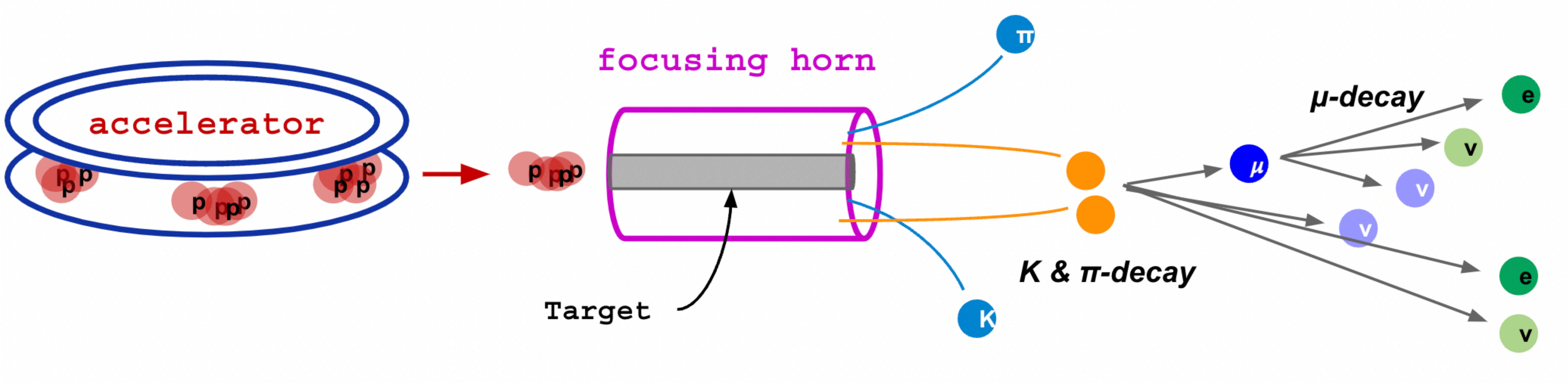


Short- and Long-Baseline Neutrinos @ FNAL



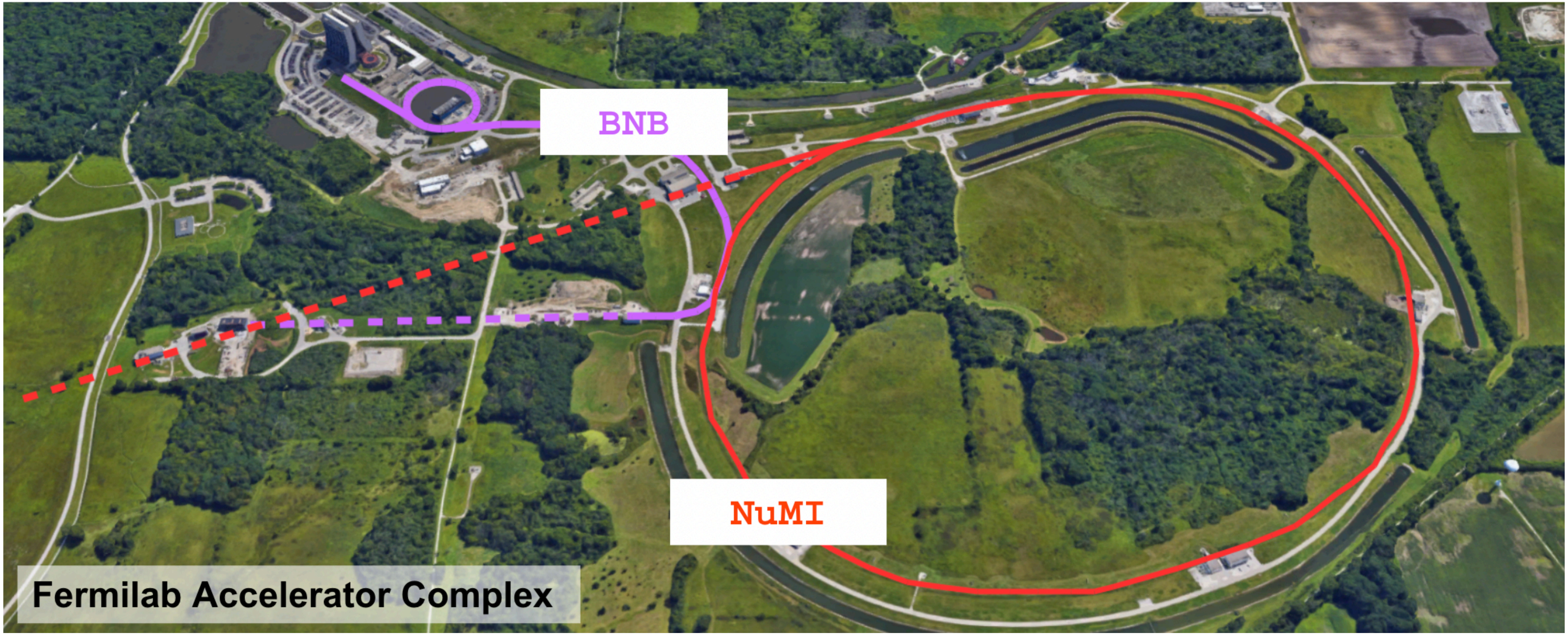
Accelerator Neutrinos

Decay in Flight neutrino beam line



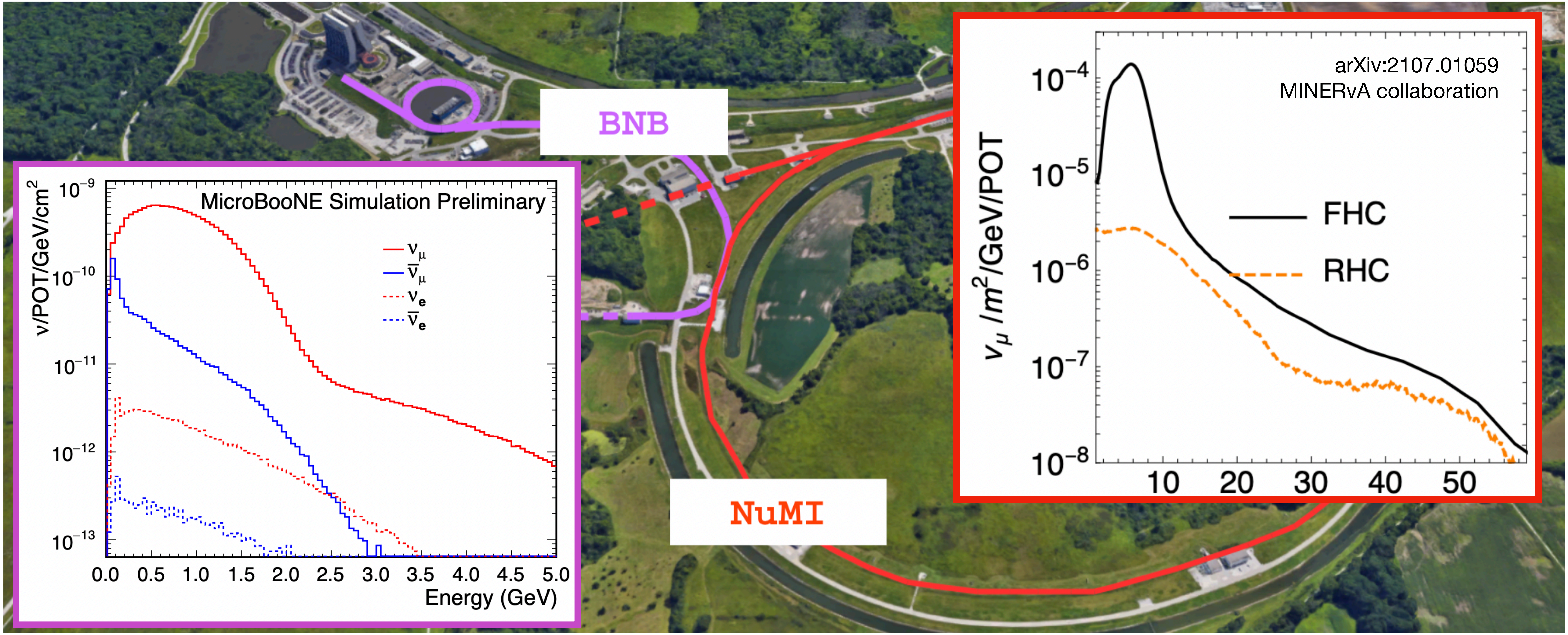
Accelerator Neutrinos

Fermilab Neutrino Campus



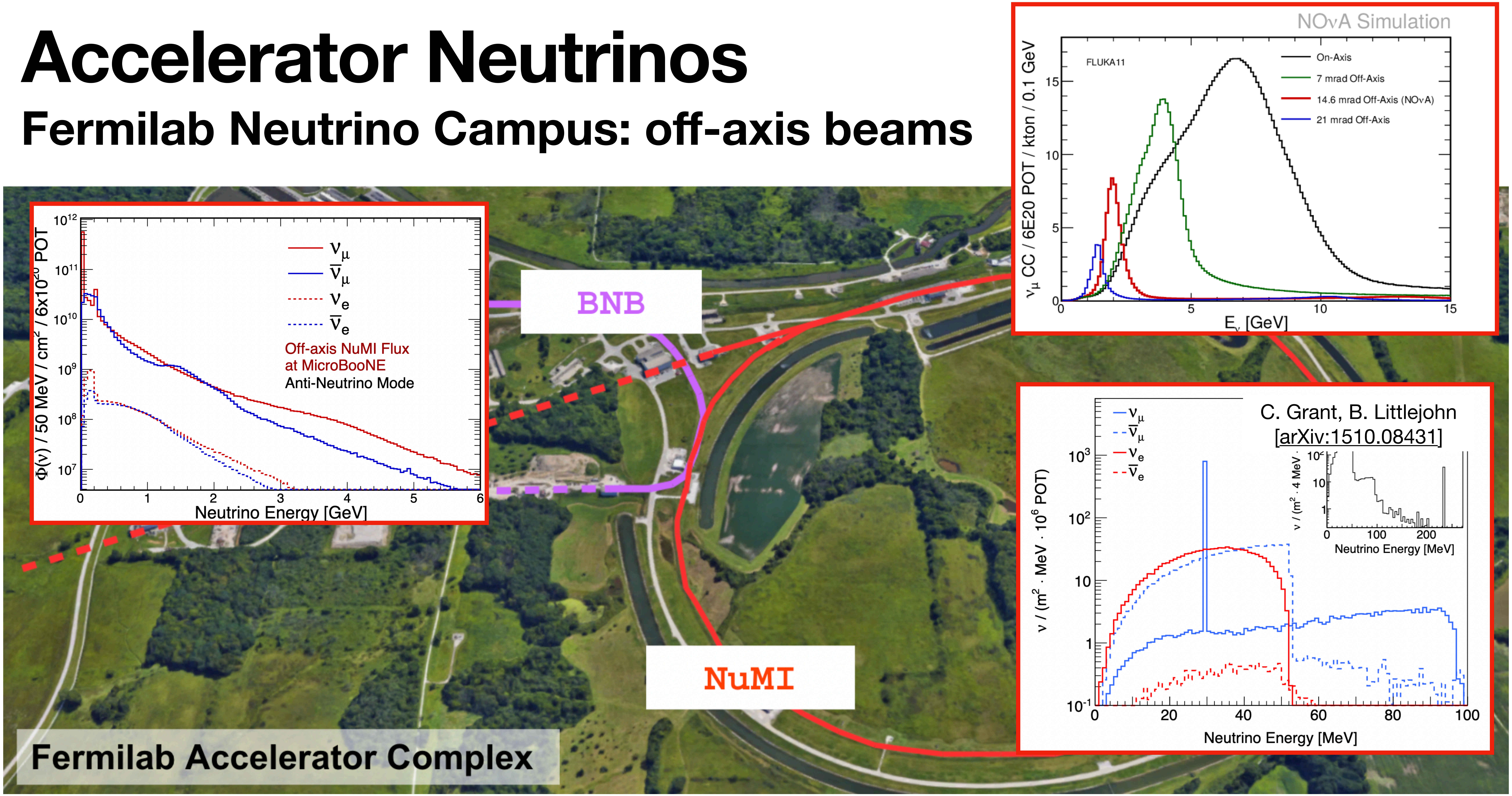
Accelerator Neutrinos

Fermilab Neutrino Campus: on-axis beams



Accelerator Neutrinos

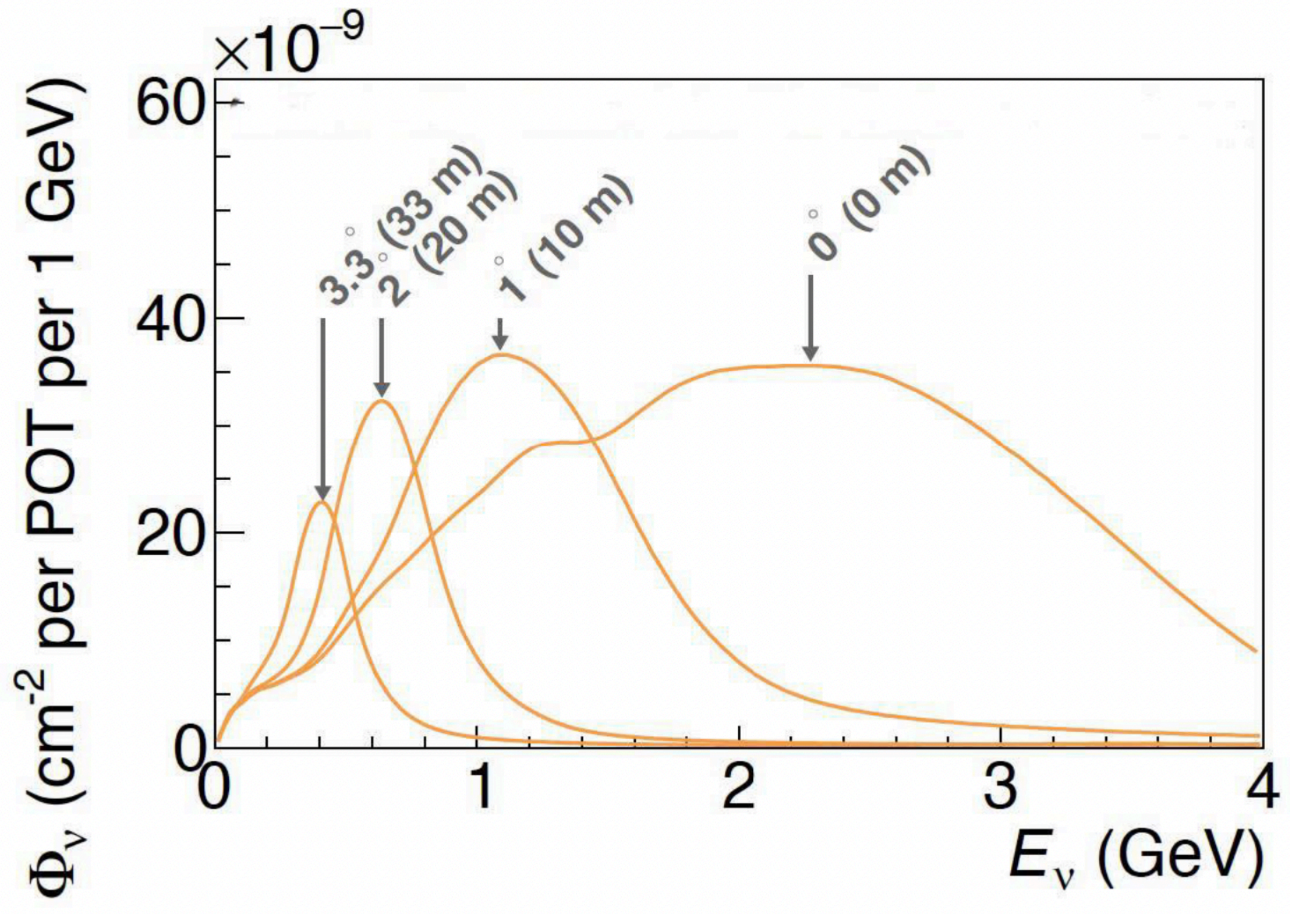
Fermilab Neutrino Campus: off-axis beams

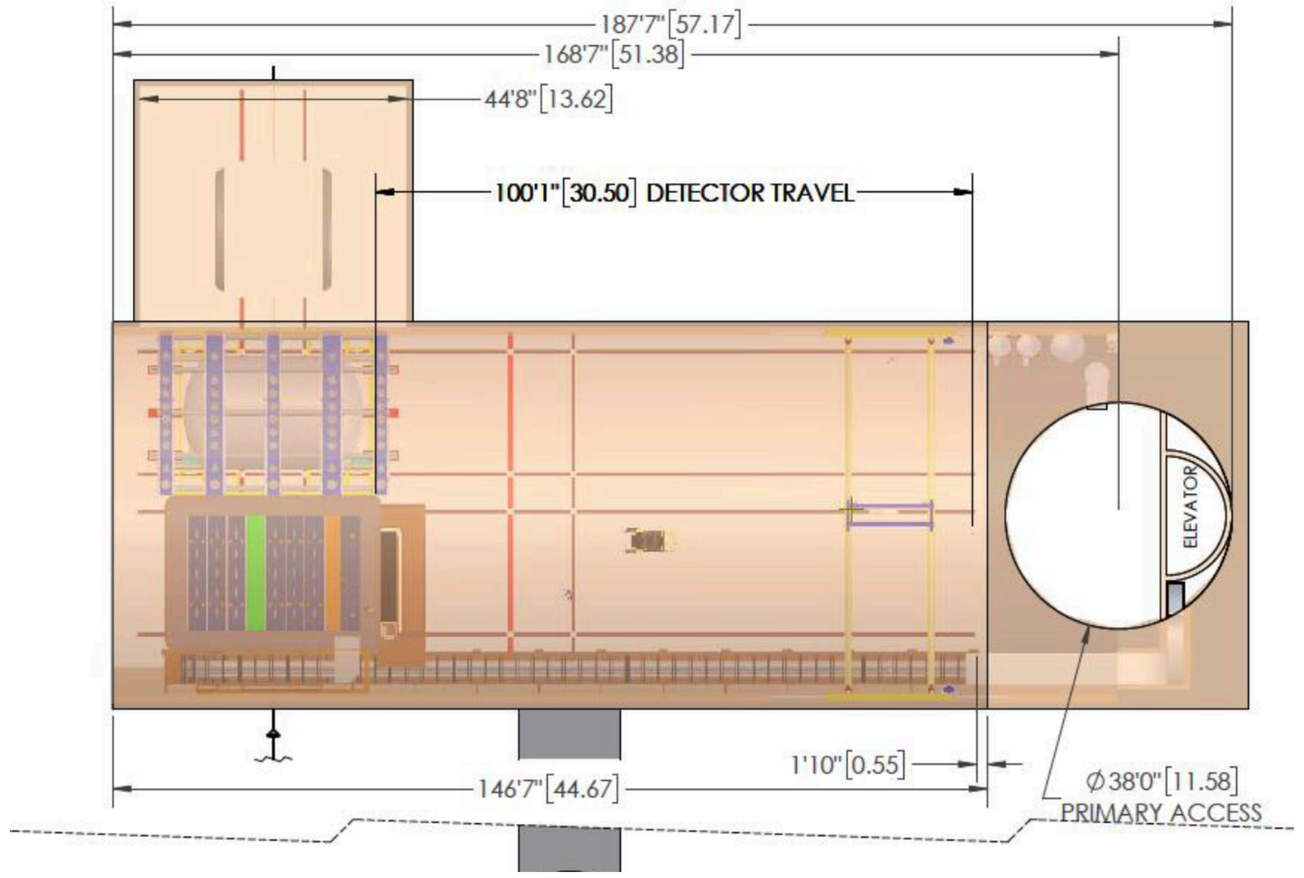


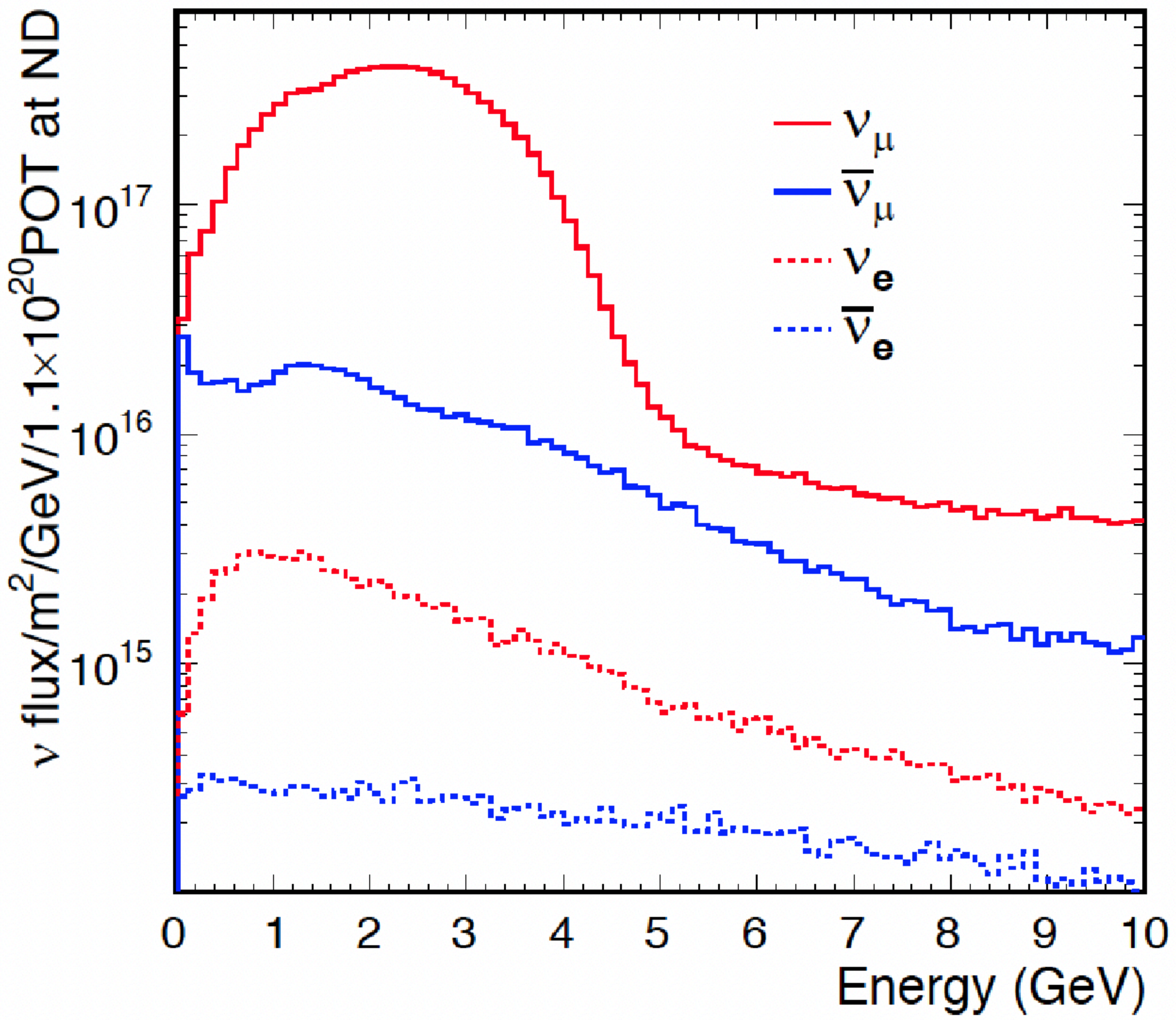
Accelerator Neutrinos

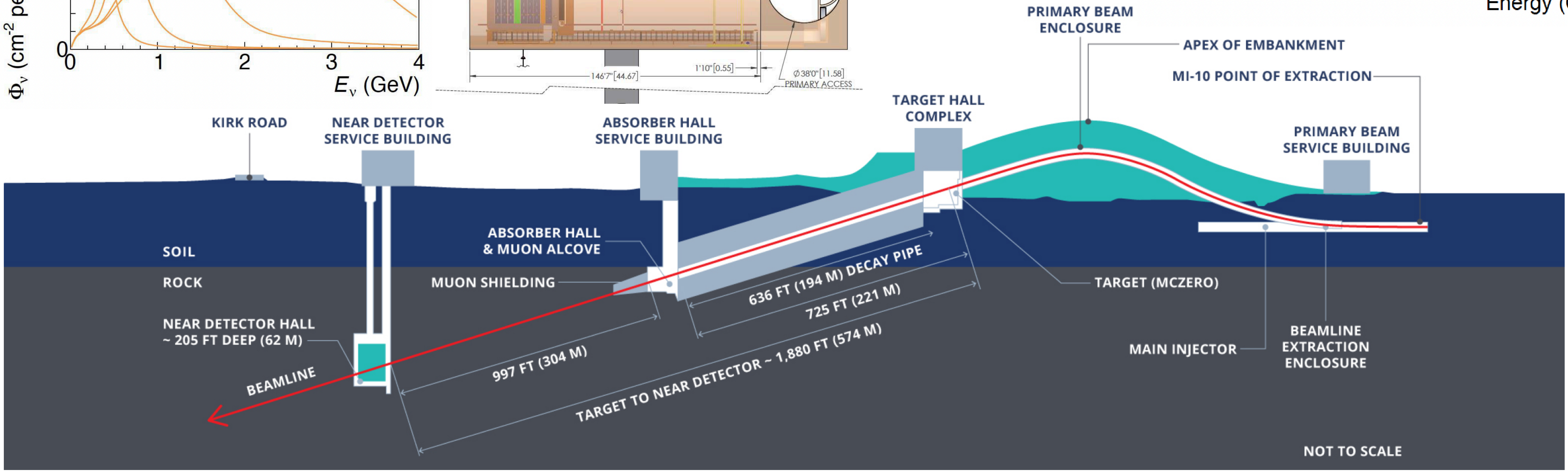
DUNE neutrino beam

figures from A. Weber (indico)







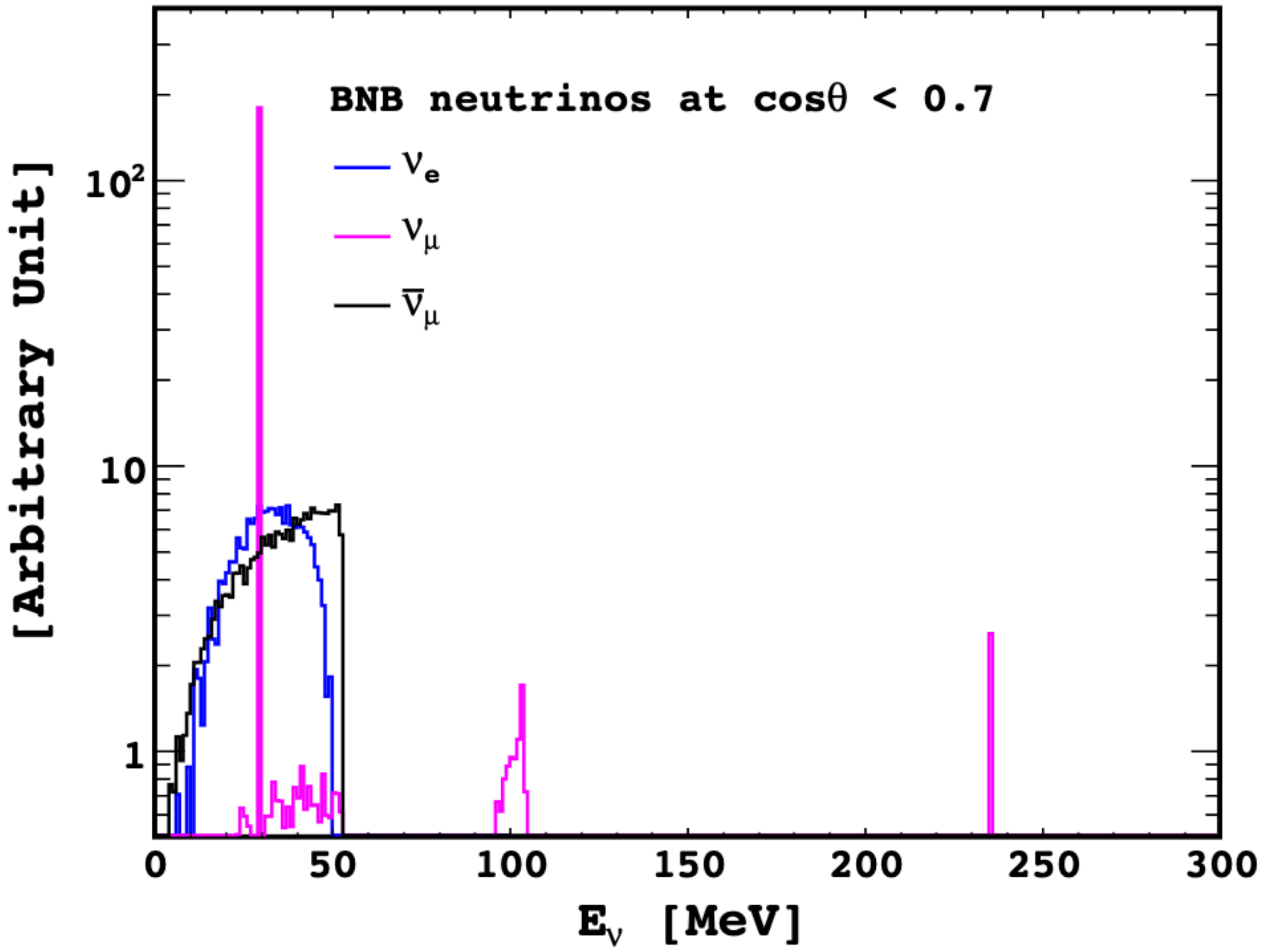


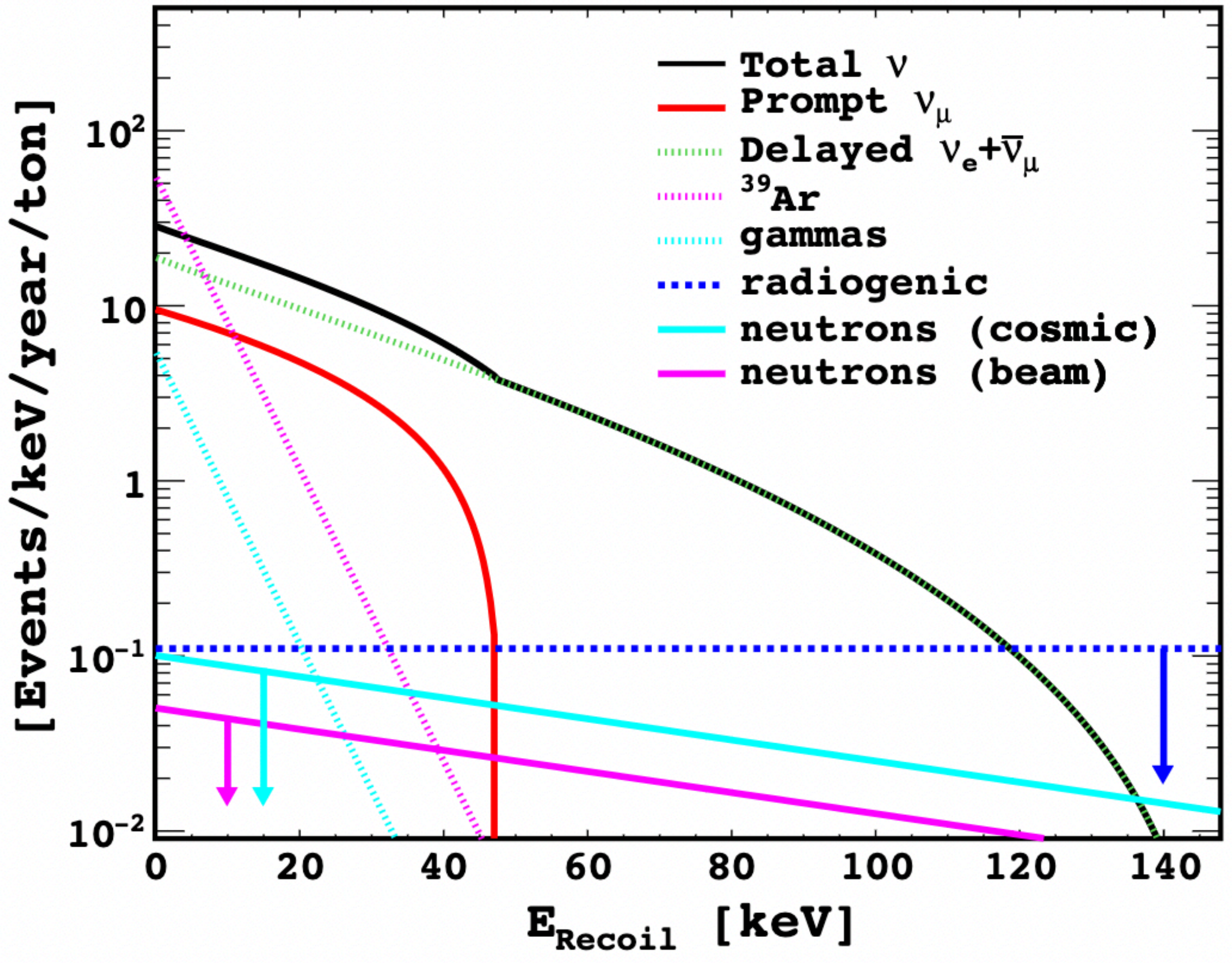
CEvNS @ Fermilab

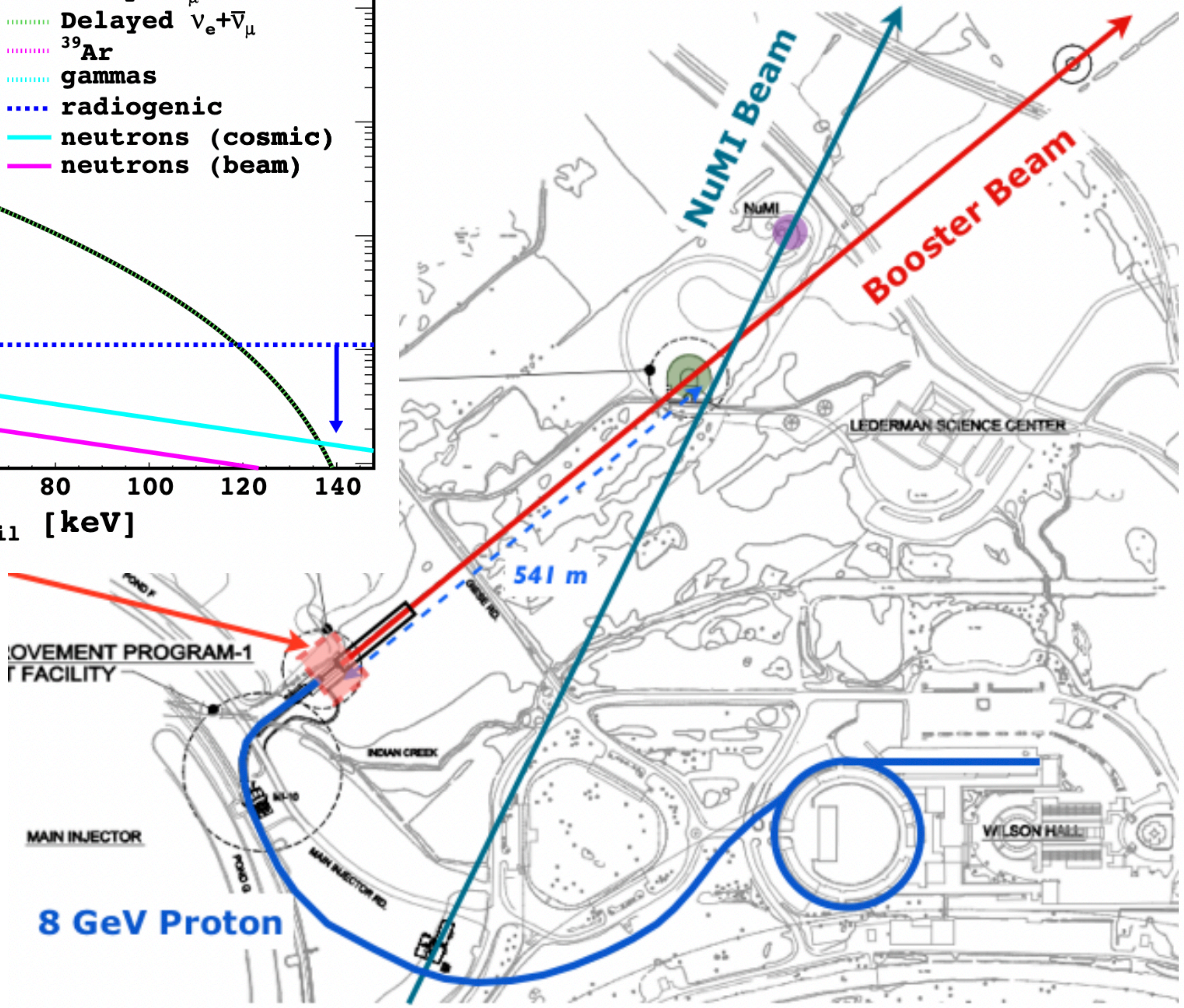
A New Method for Measuring Coherent Elastic Neutrino Nucleus Scattering at an Off-Axis High-Energy Neutrino Beam Target

S.J. Brice,[1] R.L. Cooper,[2] F. DeJongh,[1] A. Empl,[3] L.M. Garrison,[2] A. Hime,[4] E. Hungerford,[3] T. Kobilarcik,[1] B. Loer,[1] C. Mariani,[5] M. Mocko,[4] G. Muhrer,[4] R. Pattie,[6] Z. Pavlovic,[4] E. Ramberg,[1] K. Scholberg,[7] R. Tayloe,[2] R.T. Thornton,[2] J. Yoo,[1] and A. Young[6]

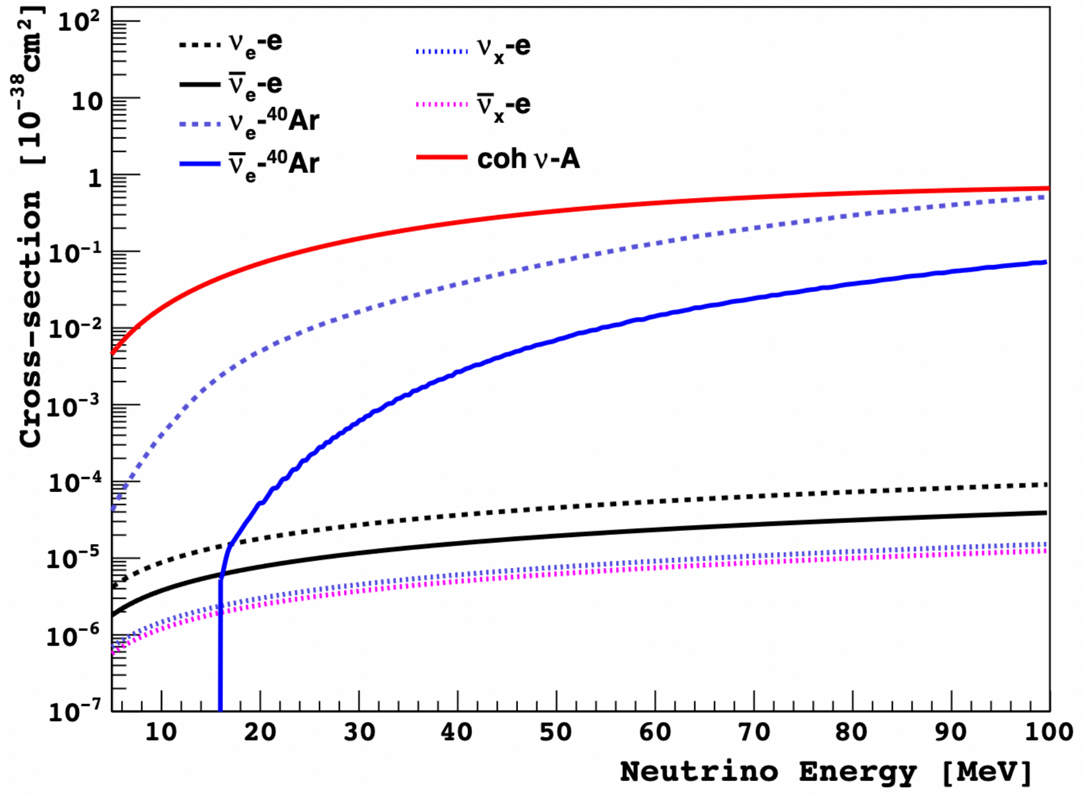
PRD 89 (2014) 7, 072004



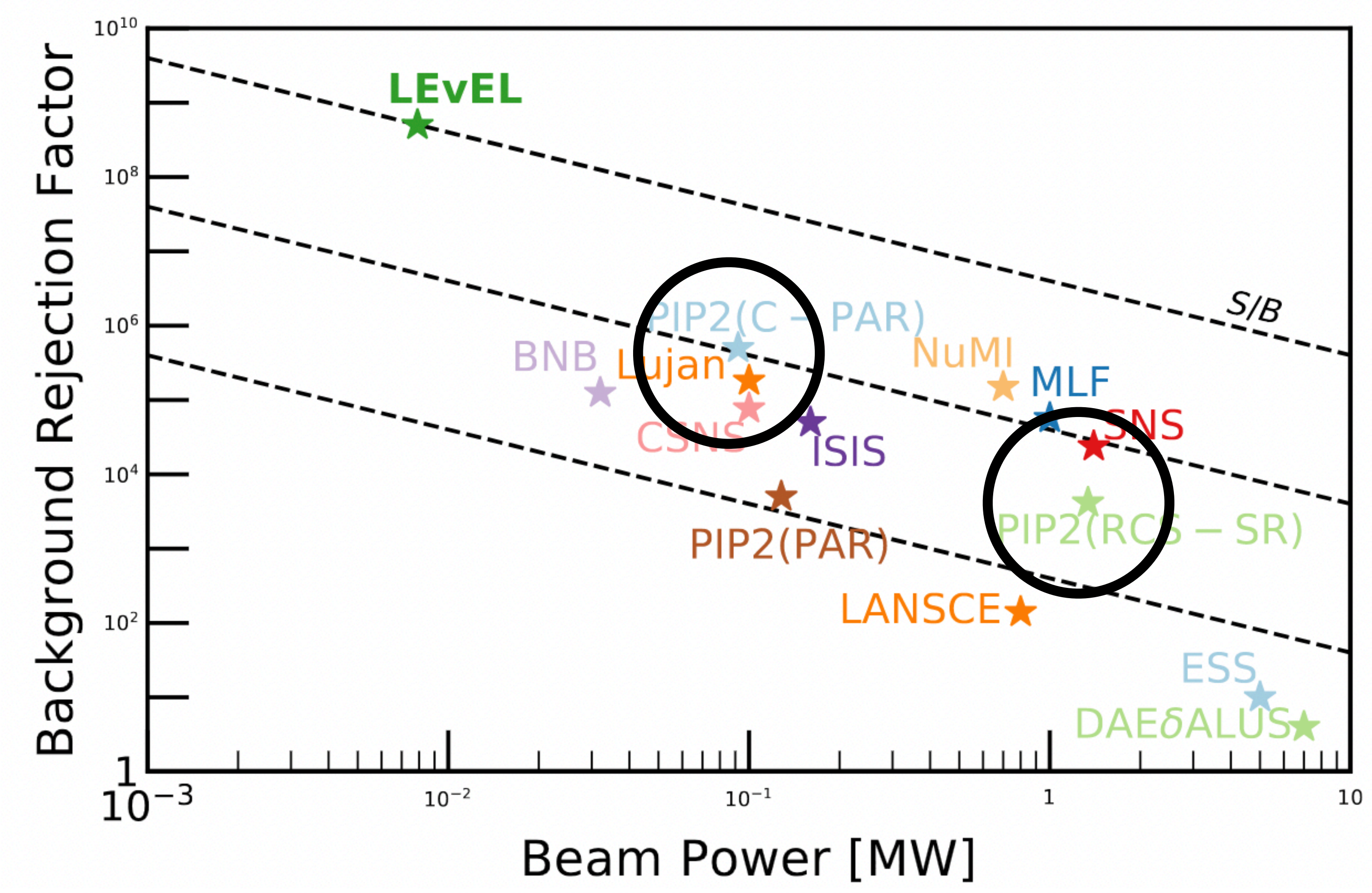




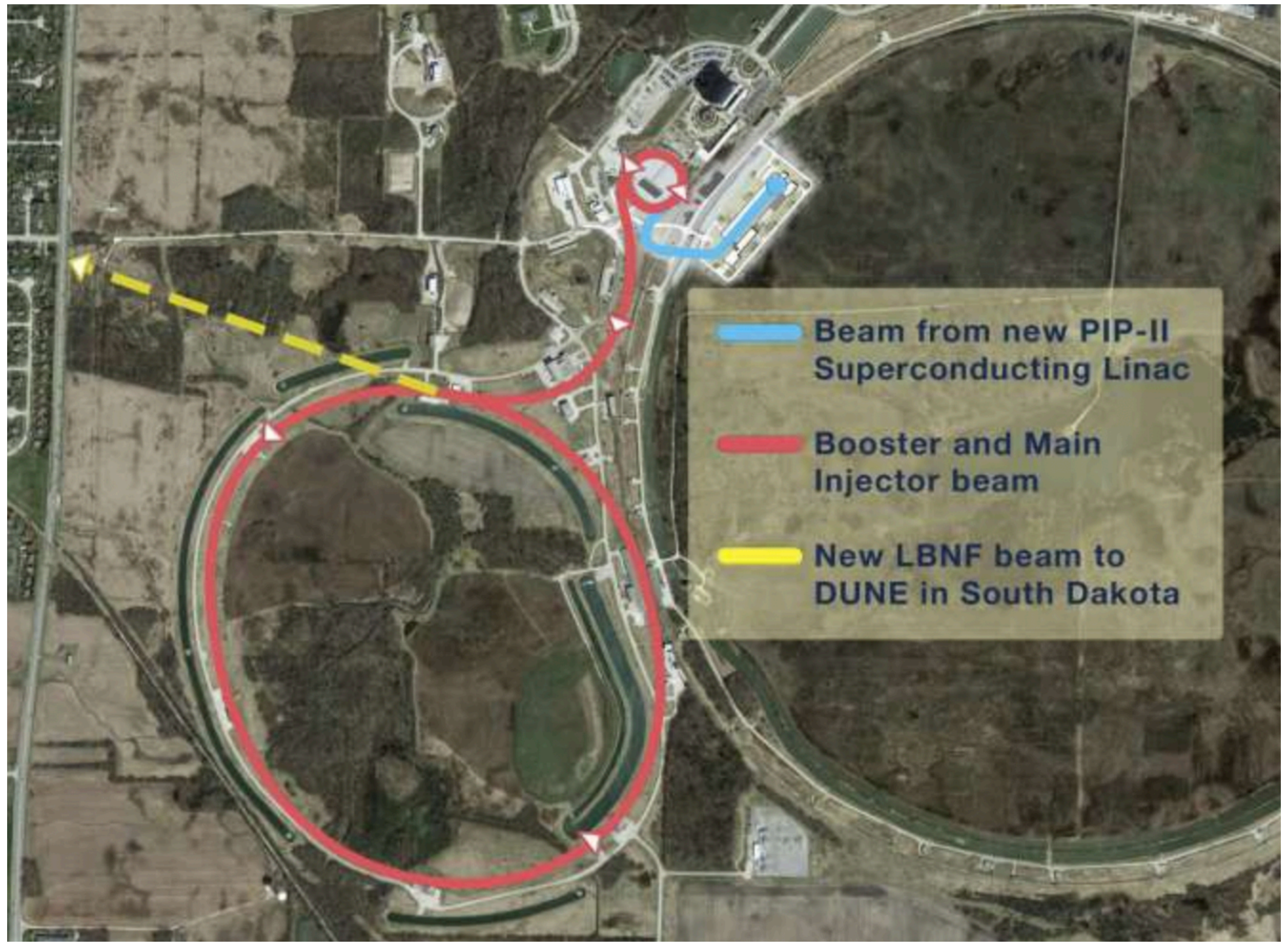
- Off-axis for pion DAR
- Enhanced CEvNS XSEC



More opportunities @ FNAL



opportunities for beam upgrades may have particularly beneficial impact to CEvNS searches



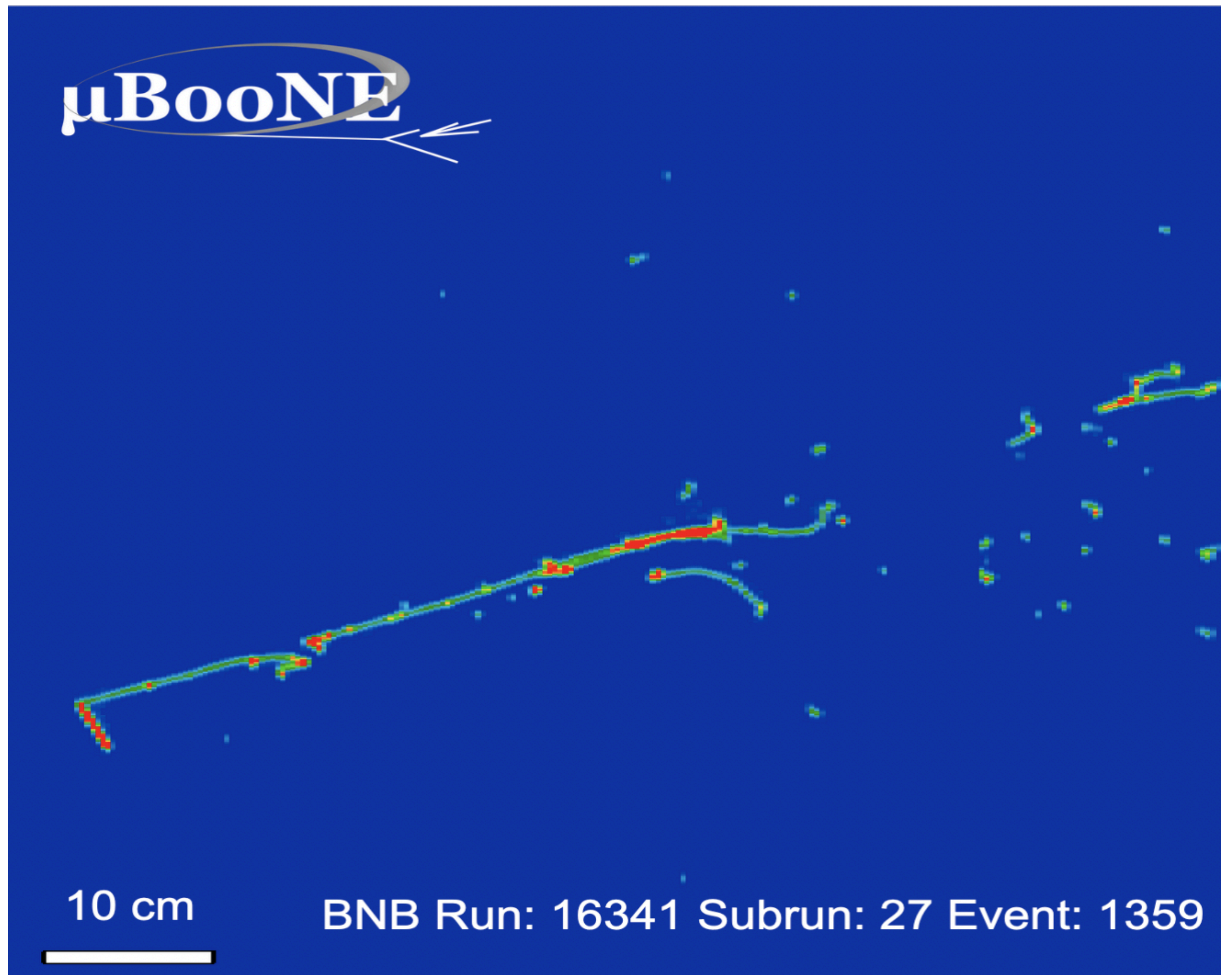
PIP2-BD: GeV Proton Beam Dump at Fermilab's PIP-II Linac [arXiv:2203.08079]

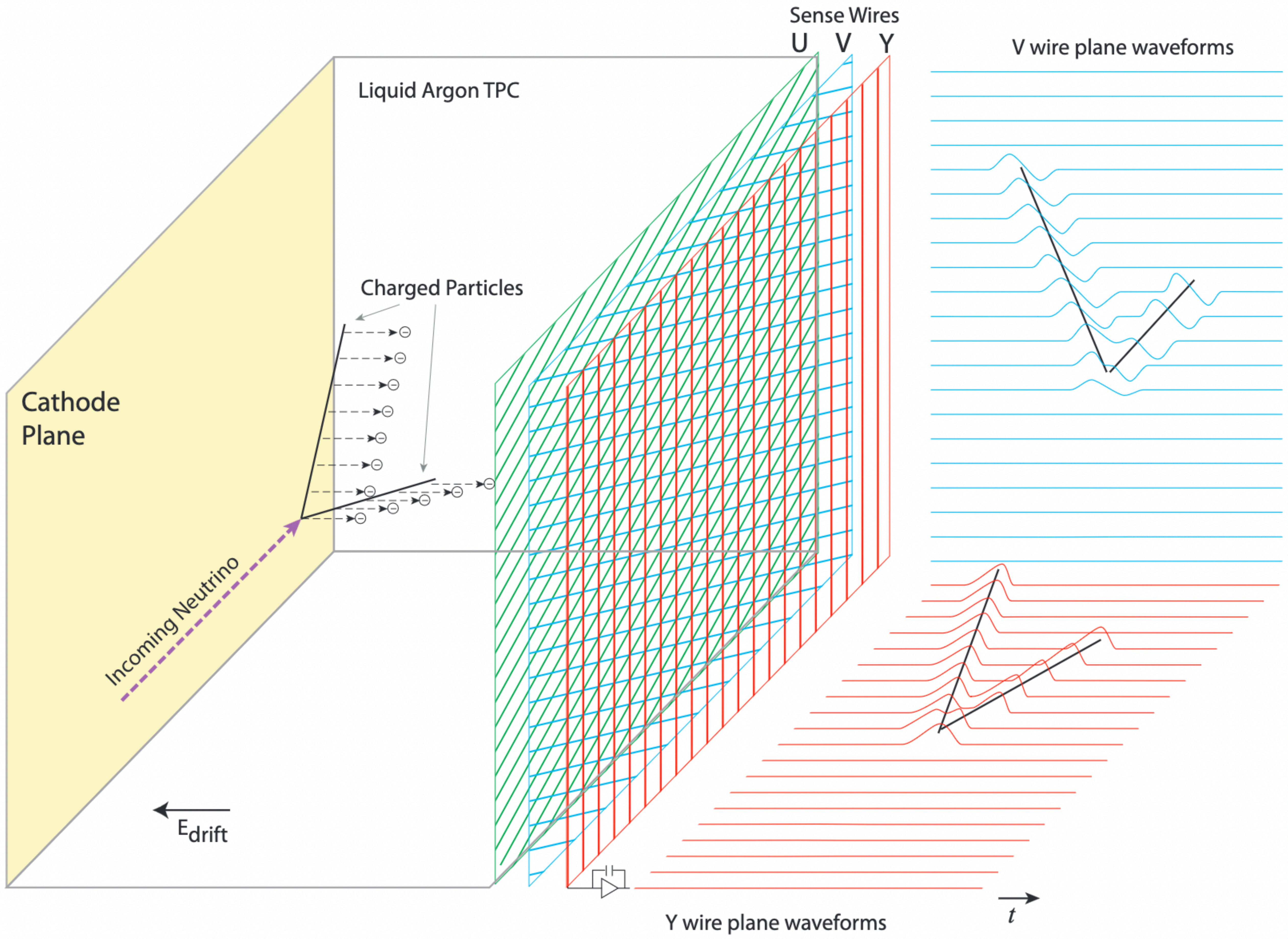
Two recent developments in particle physics clearly establish the need for a GeV-scale high energy physics (HEP) beam dump facility. First, theoretical work has highlighted not only the viability of sub-GeV dark sectors models to explain the cosmological dark matter (DM) abundance but also that a broad class of these models can be tested with accelerator-based, fixed-target experiments, which complement growing activity in sub-GeV direct DM detection [1–3]. Second, the observation of coherent elastic neutrino-nucleus scattering (CEvNS) [4, 5] by the COHERENT experiment [6, 7] provides a novel experimental tool that can now be utilized to search for physics beyond the Standard Model (SM) in new ways, including in searches for light DM [8] and active-to-sterile neutrino oscillations [9], which would provide smoking-gun evidence for the existence of sterile neutrinos.

Also "Physics Opportunities at a Beam Dump Facility at PIP-II at Fermilab and Beyond", arXiv:2311.09915

Matt Toups, Jacob Zettlemoyer @ FNAL (and many others!)

Liquid Argon Time Projection Chambers



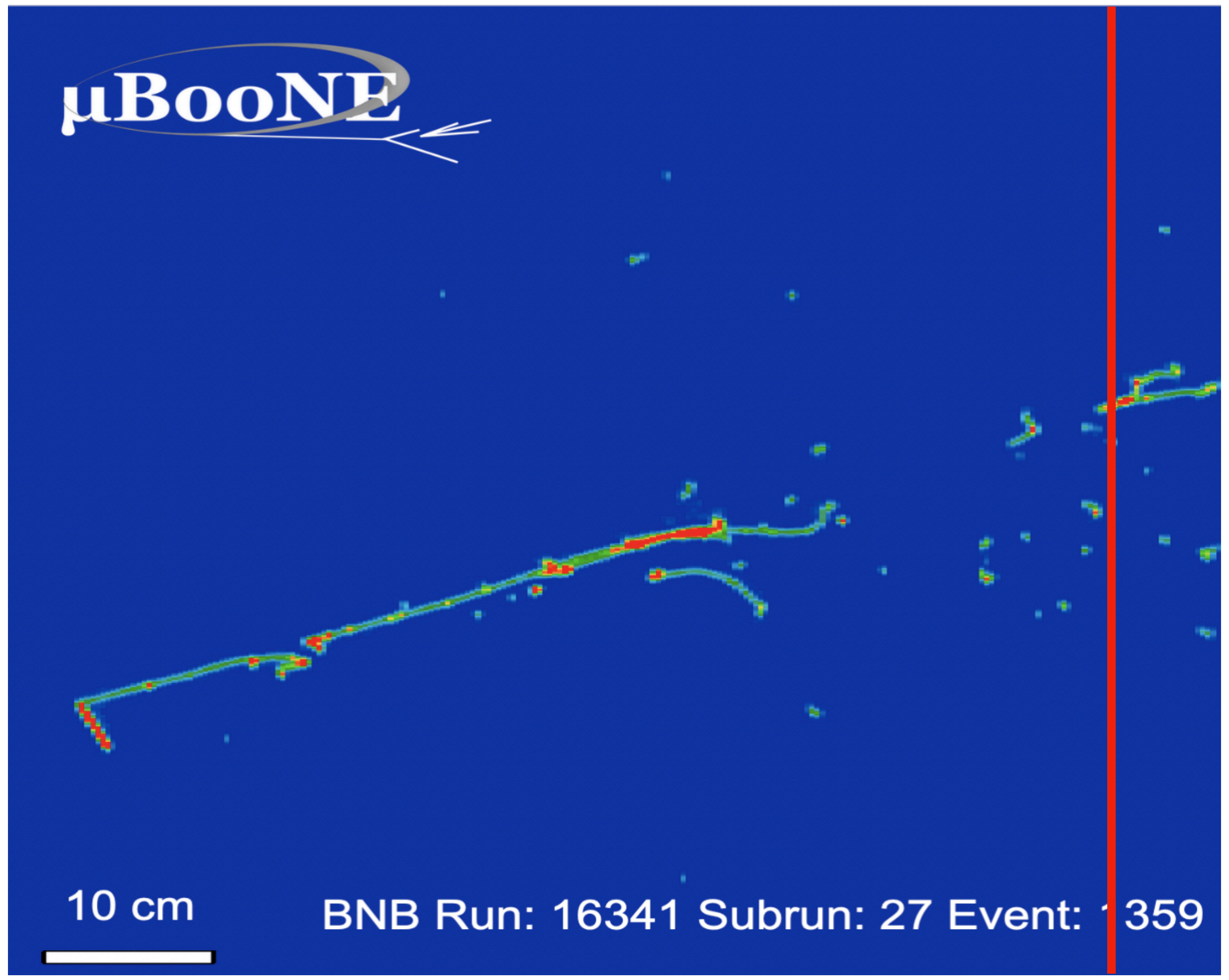


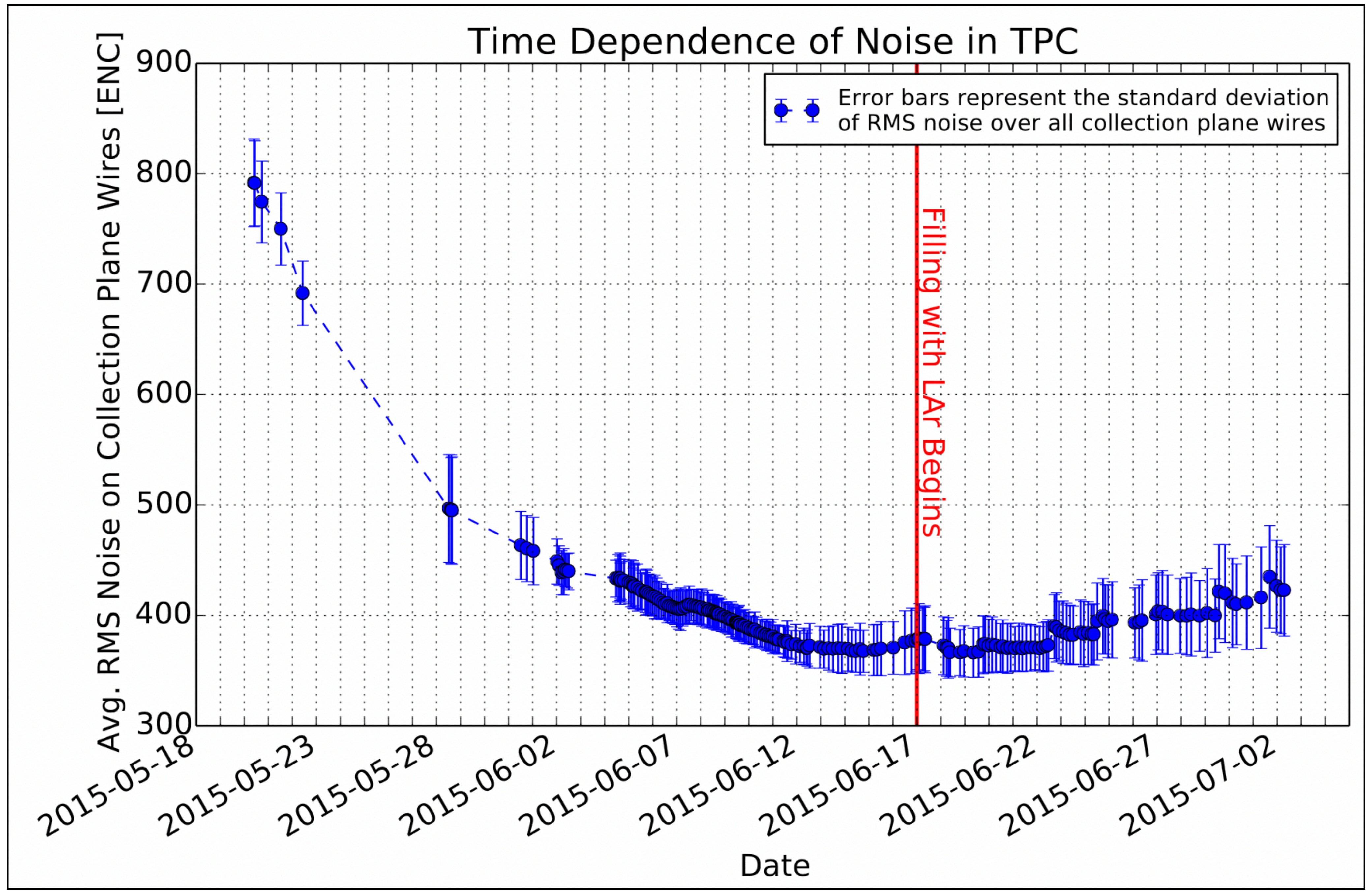
kiloton scale detectors (10^3 meters)

Noble element: efficient charge / photon transport across meter-scale volumes

O(mm) tracking resolution with sub-MeV thresholds for energy deposits → excellent for GeV neutrino physics program!

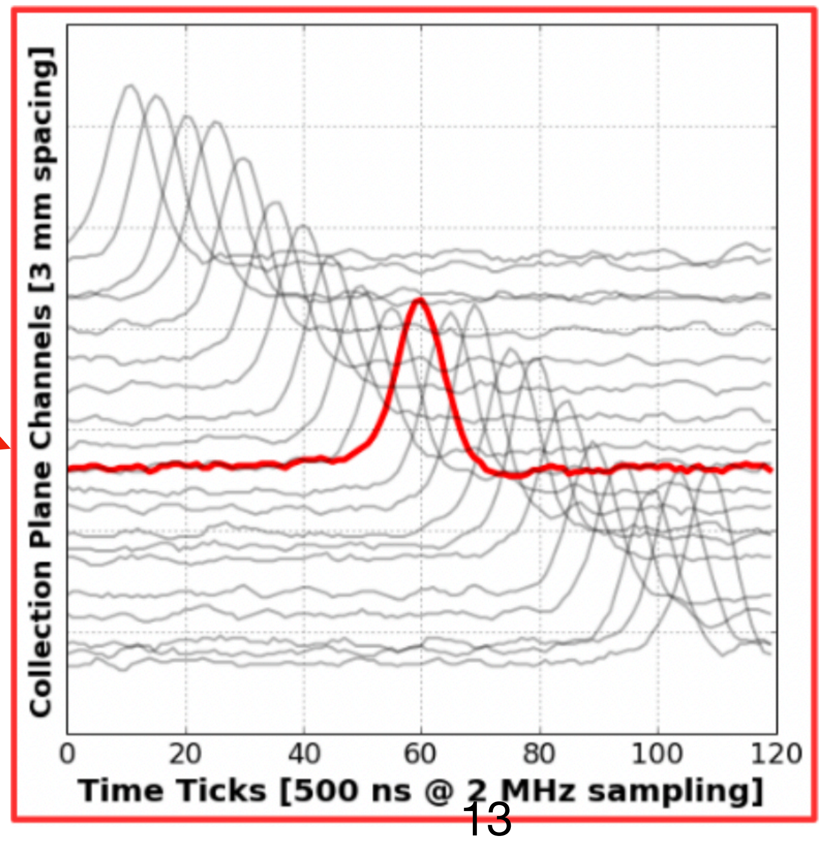
LArTPC noise levels and thresholds

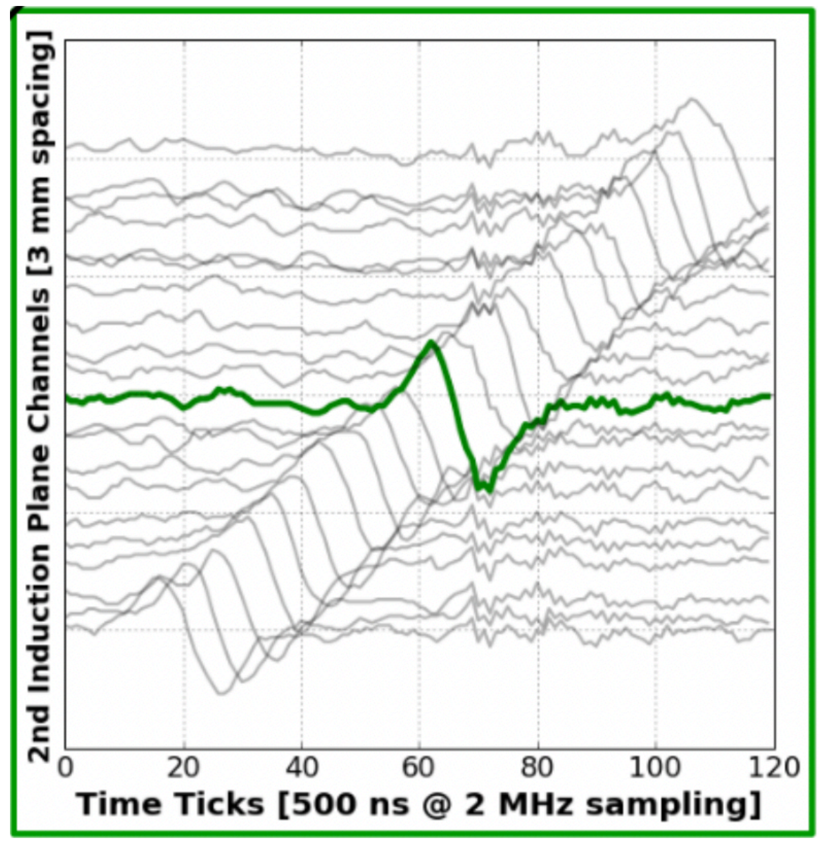


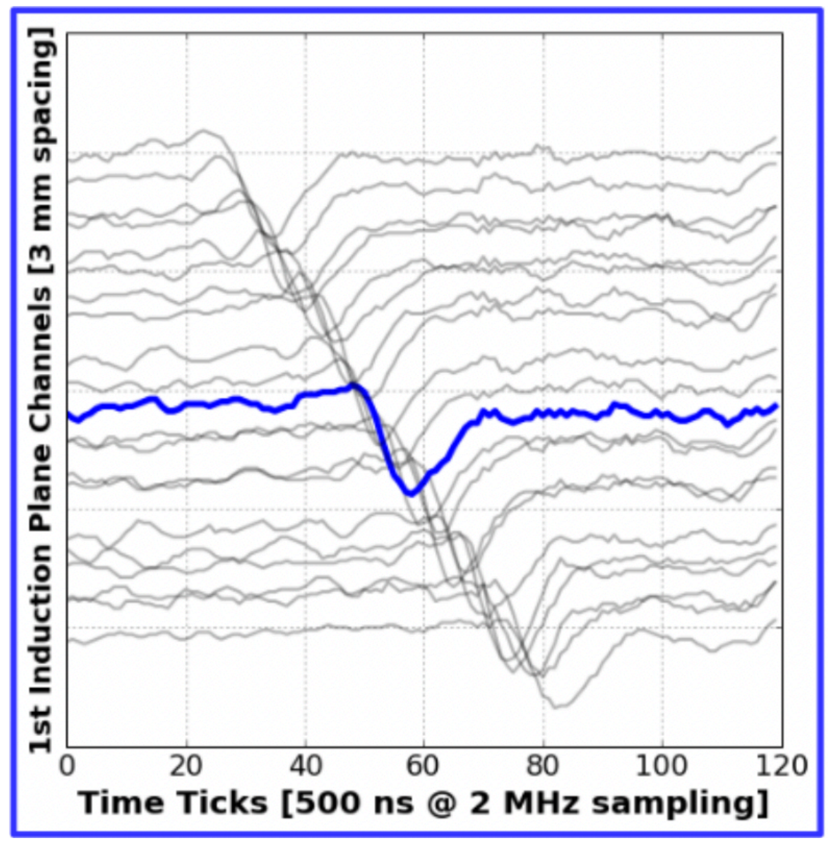


- W_{ion} = 23.6 eV/e^-
- 50% quenching
  (more if heavily ionizing particle)
- 2 MeV/cm w/ 3 mm spacing

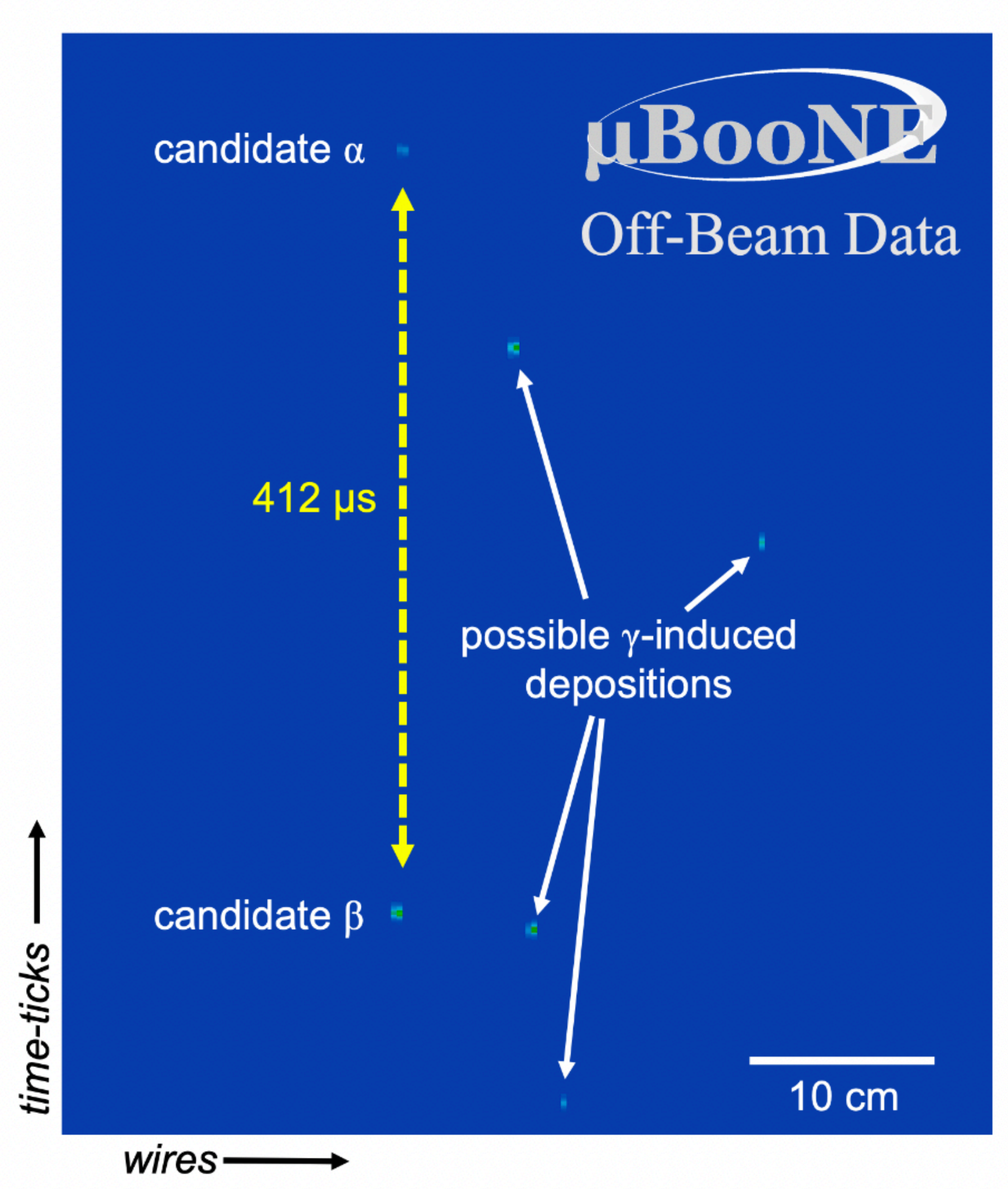
= $O(10^4)$ electrons collected





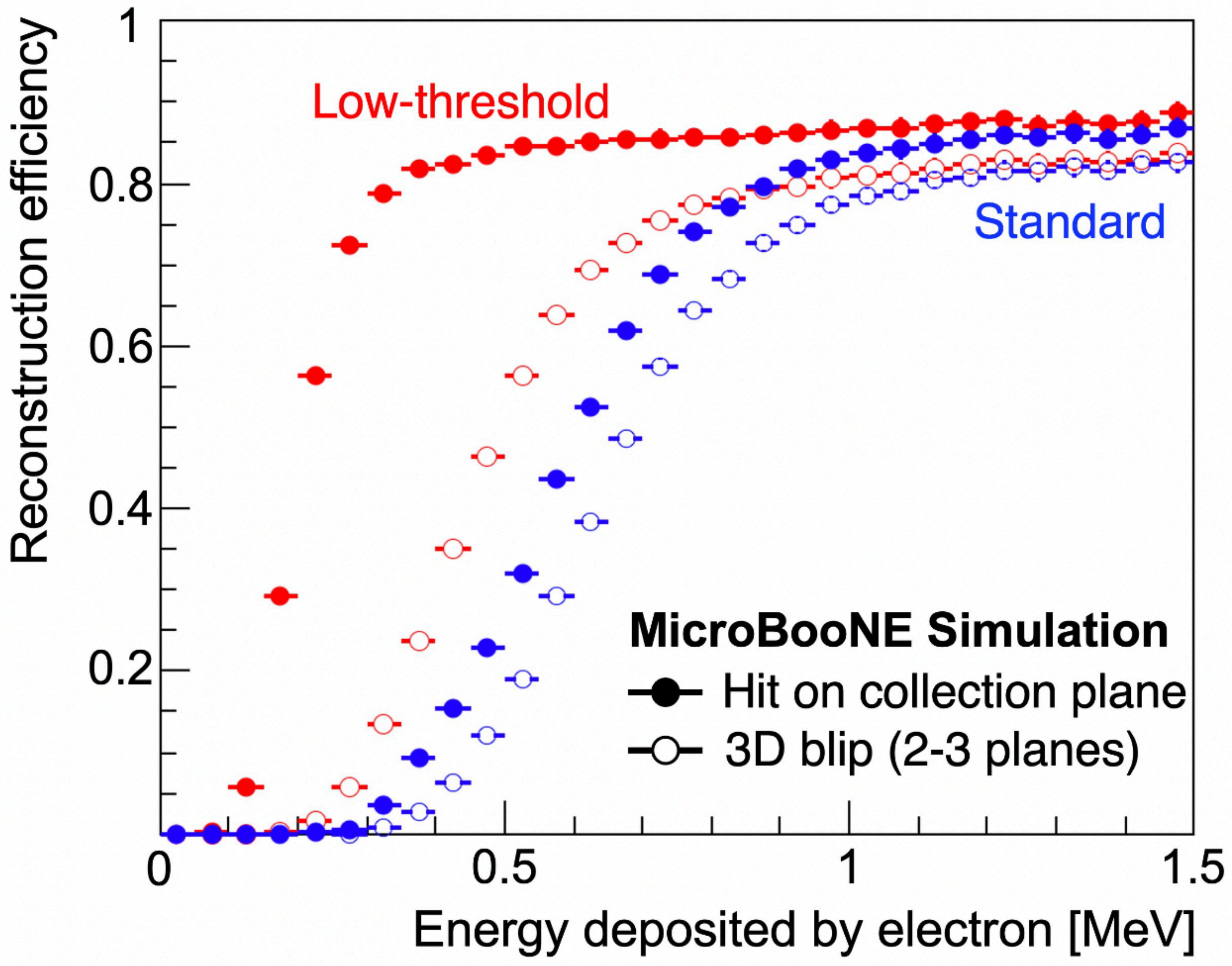


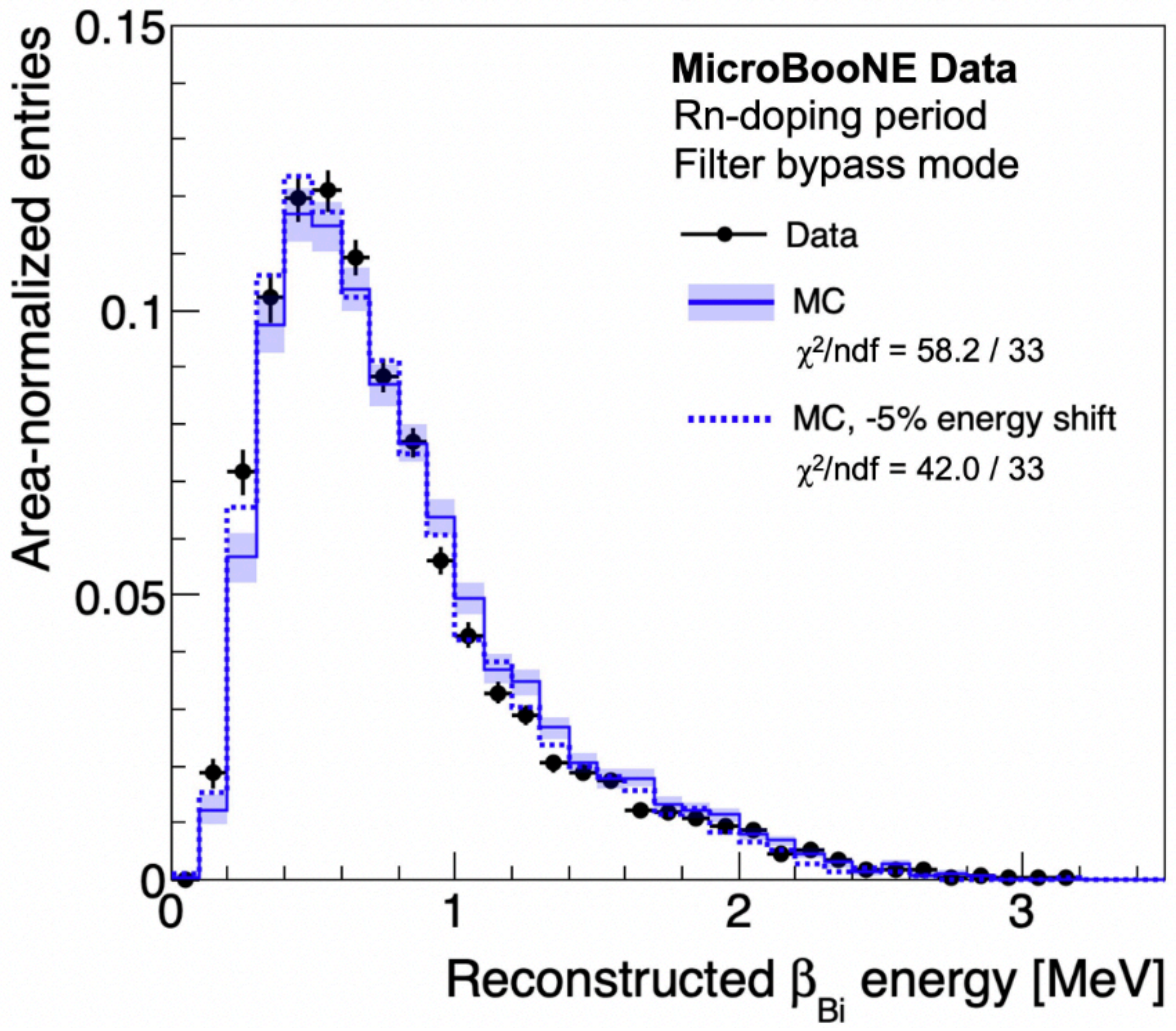
sub-MeV scale physics with LArTPCs



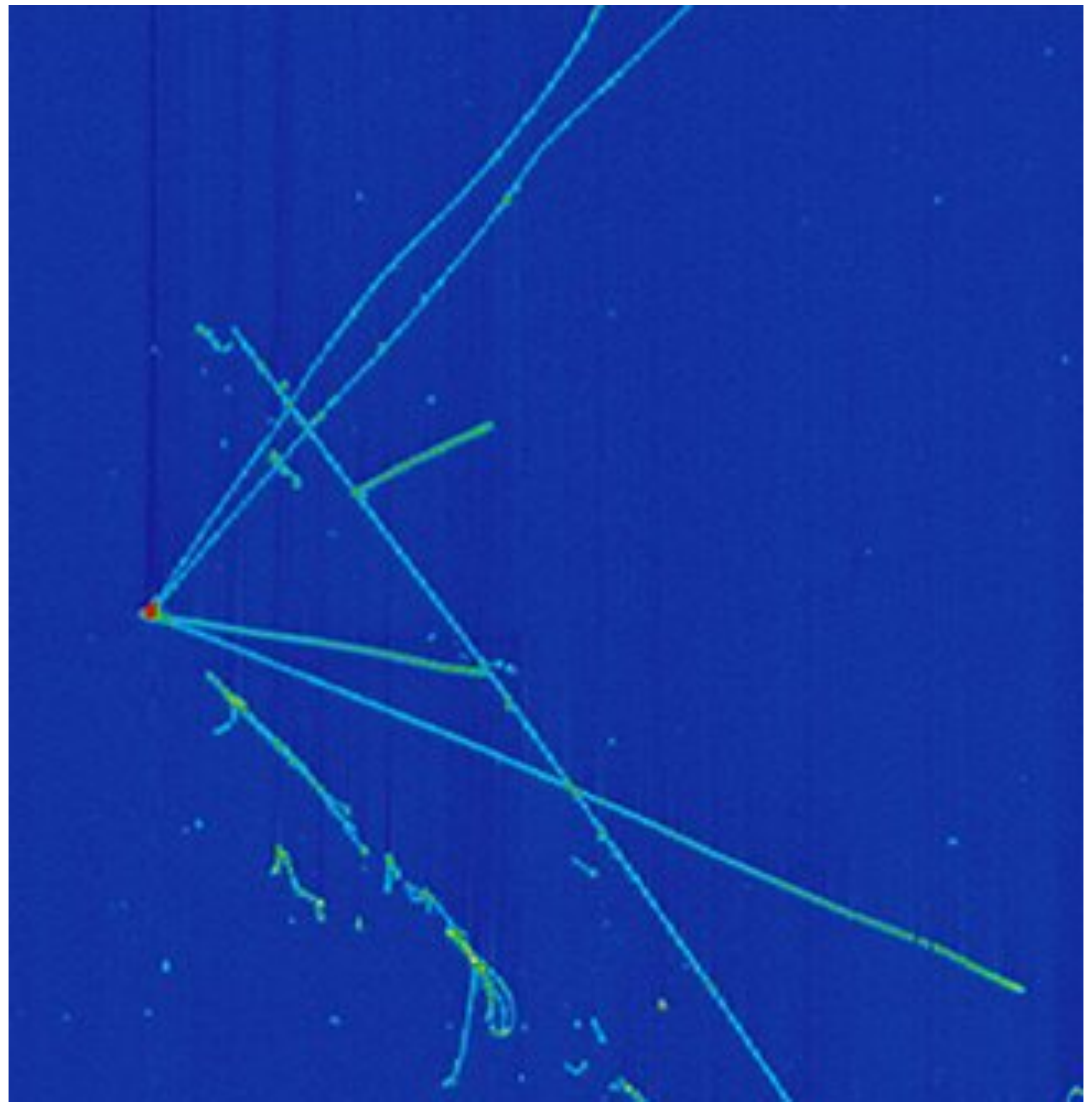
MicroBooNE arXiv:2307.03102 "MeV-scale physics" paper

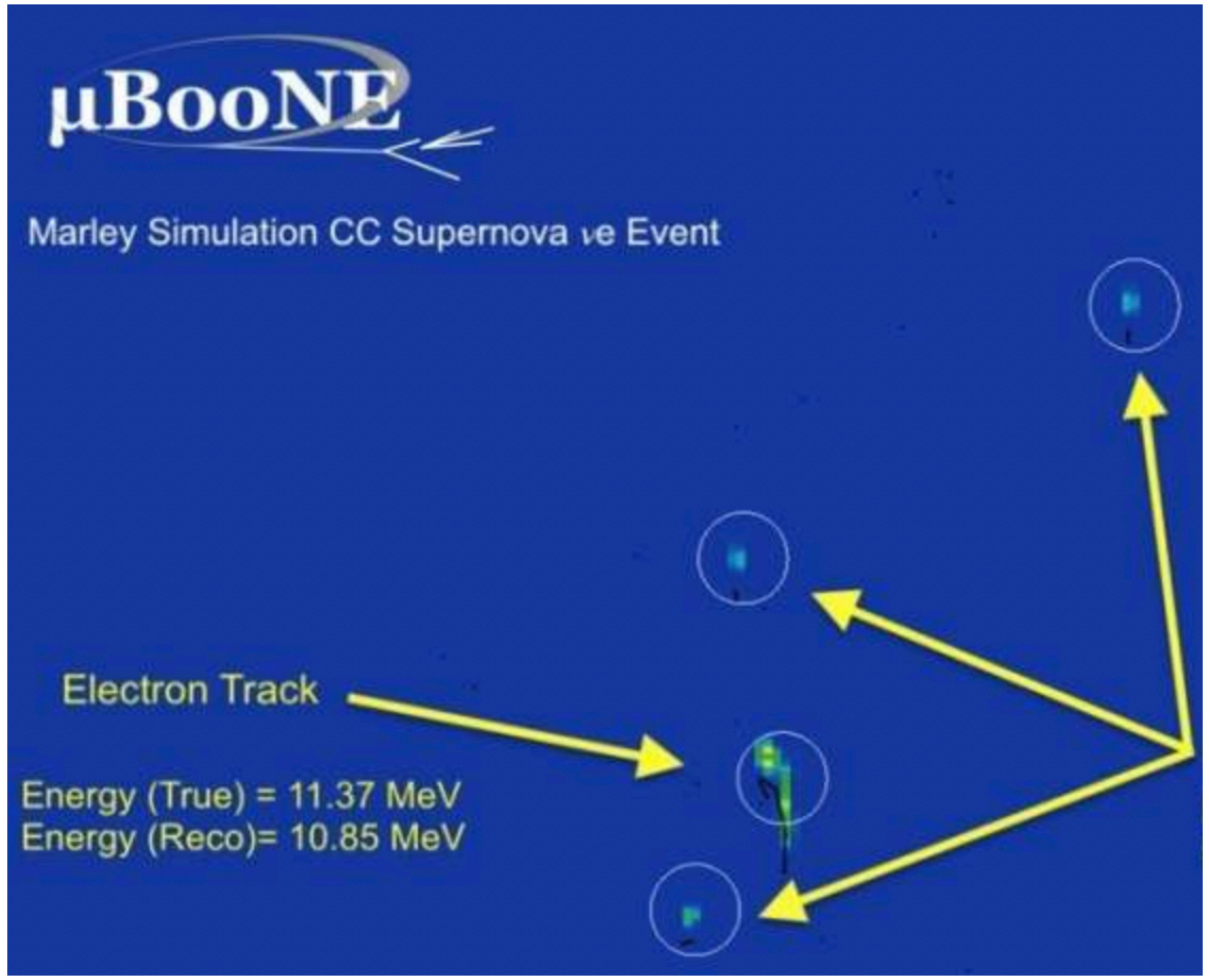
Closely tied to DUNE's astrophysics (supernova and solar) neutrino program

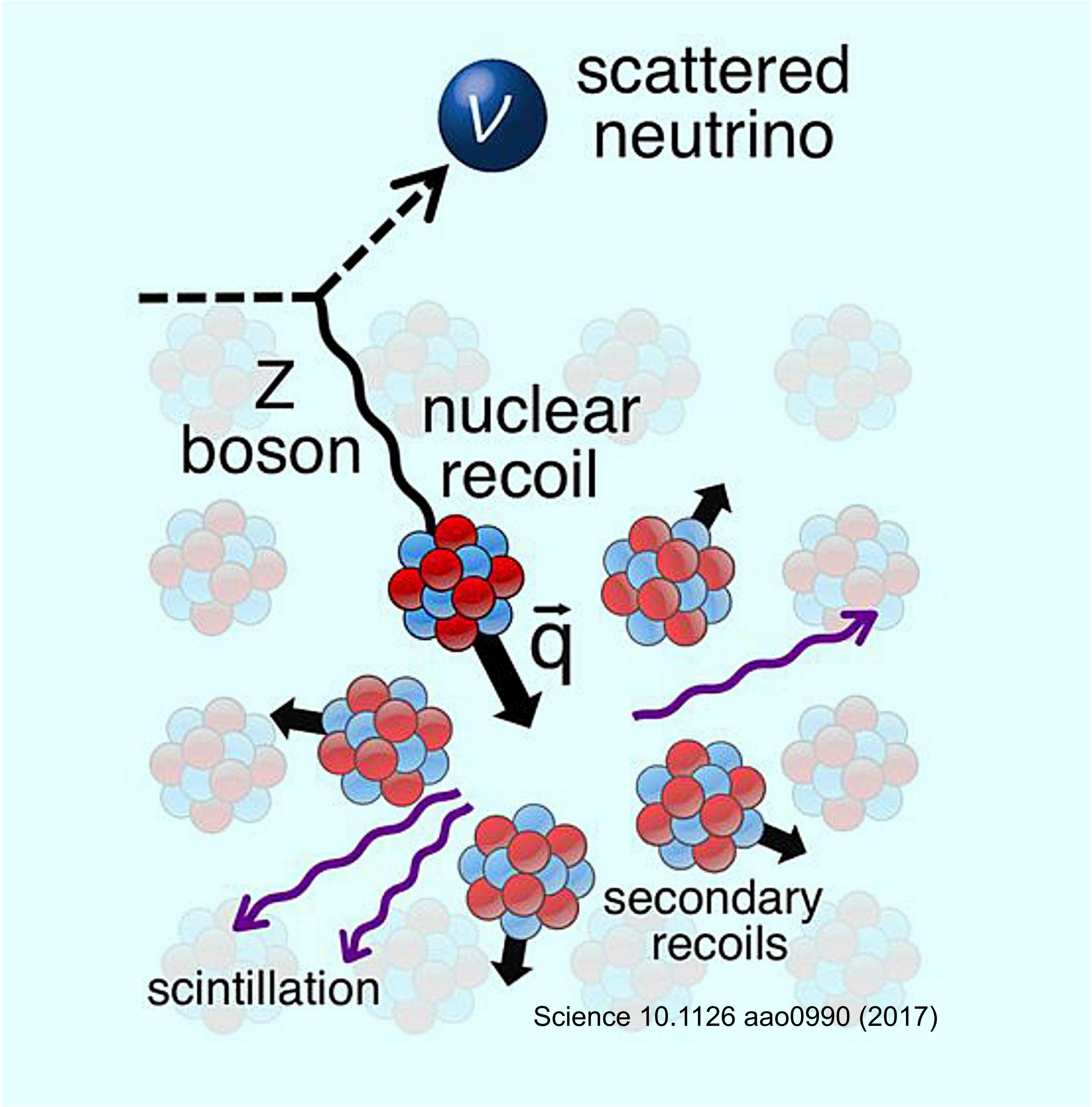




keV-scale imaging in argon-based detectors

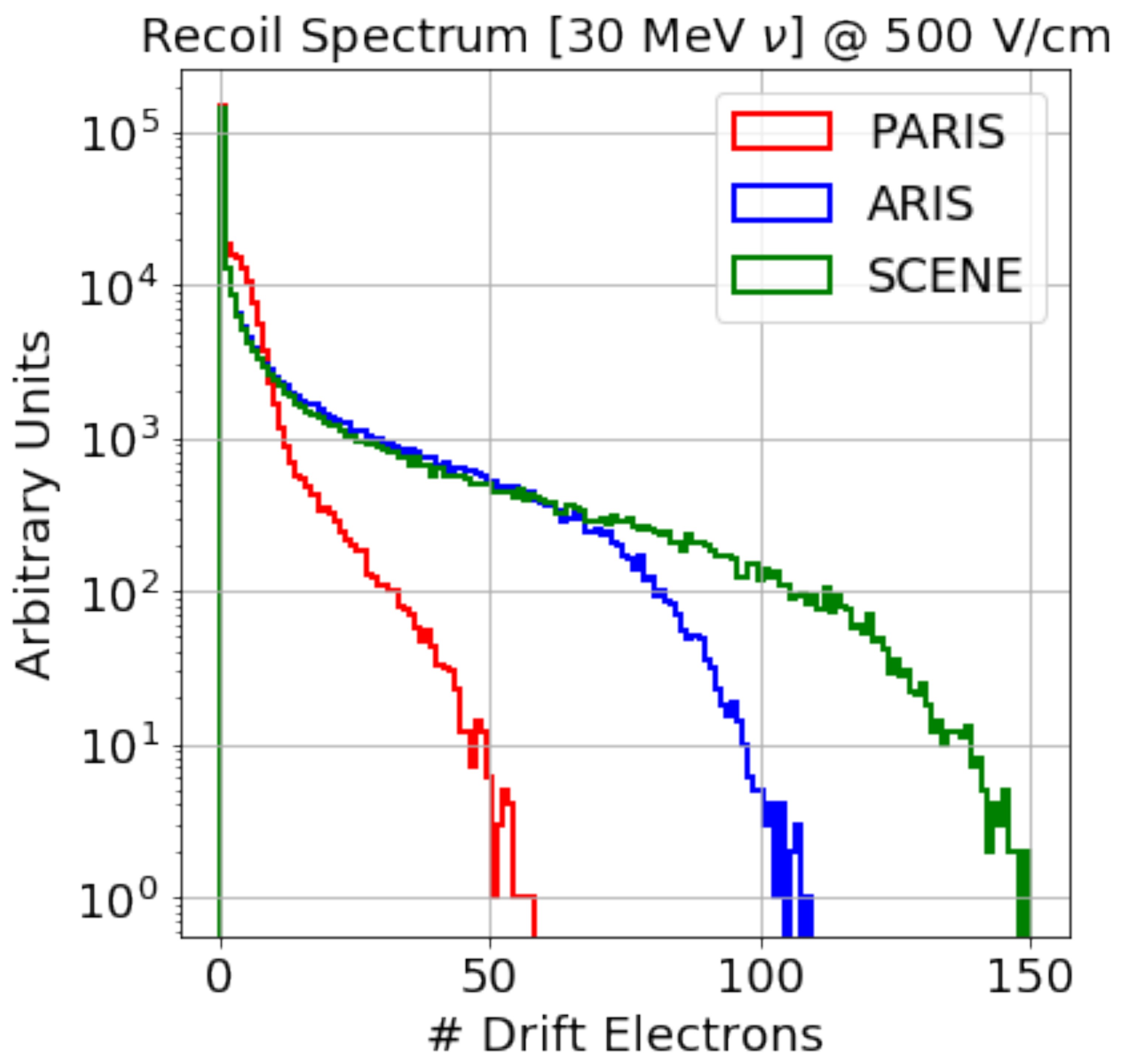




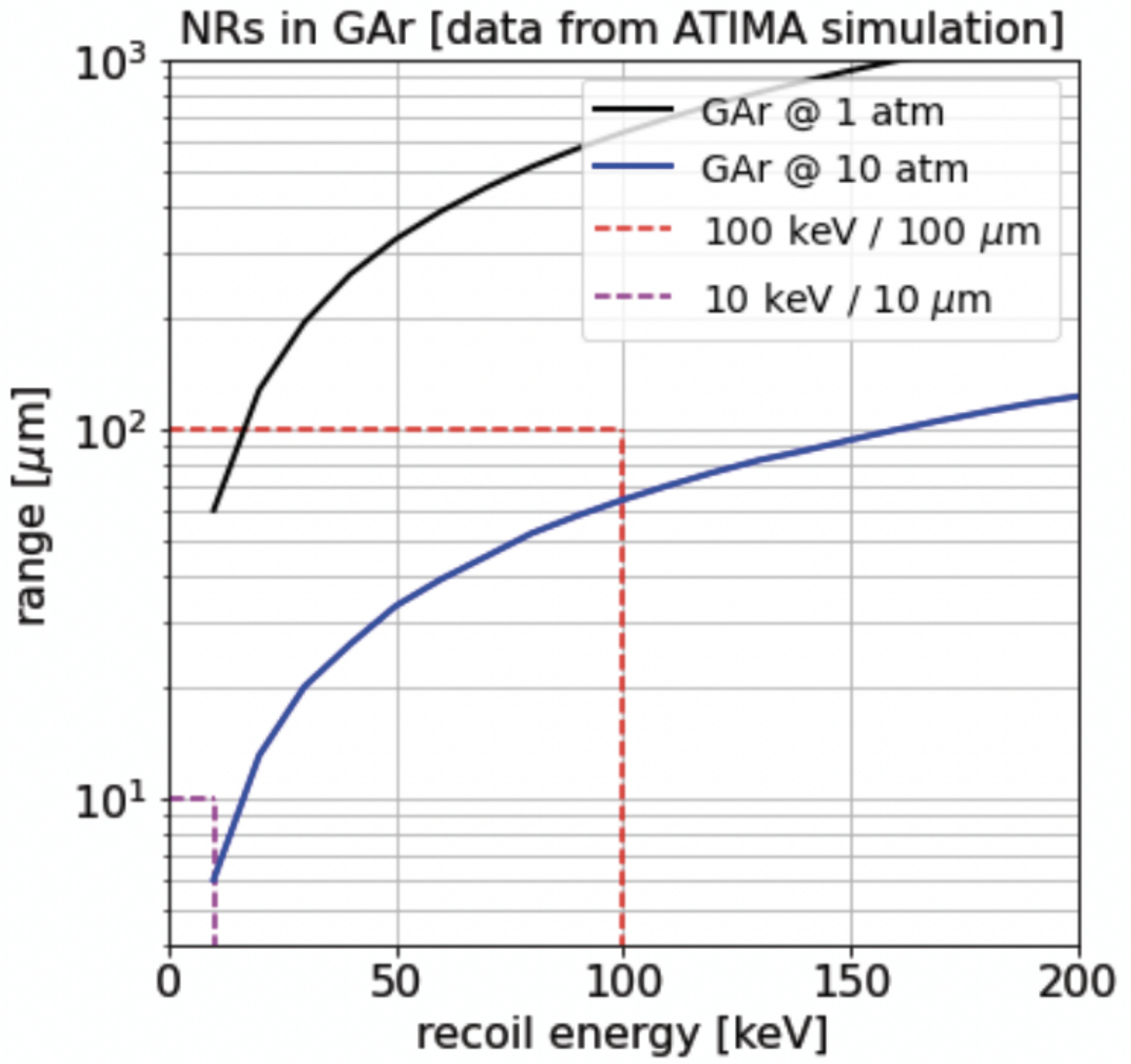


GeV MeV keV

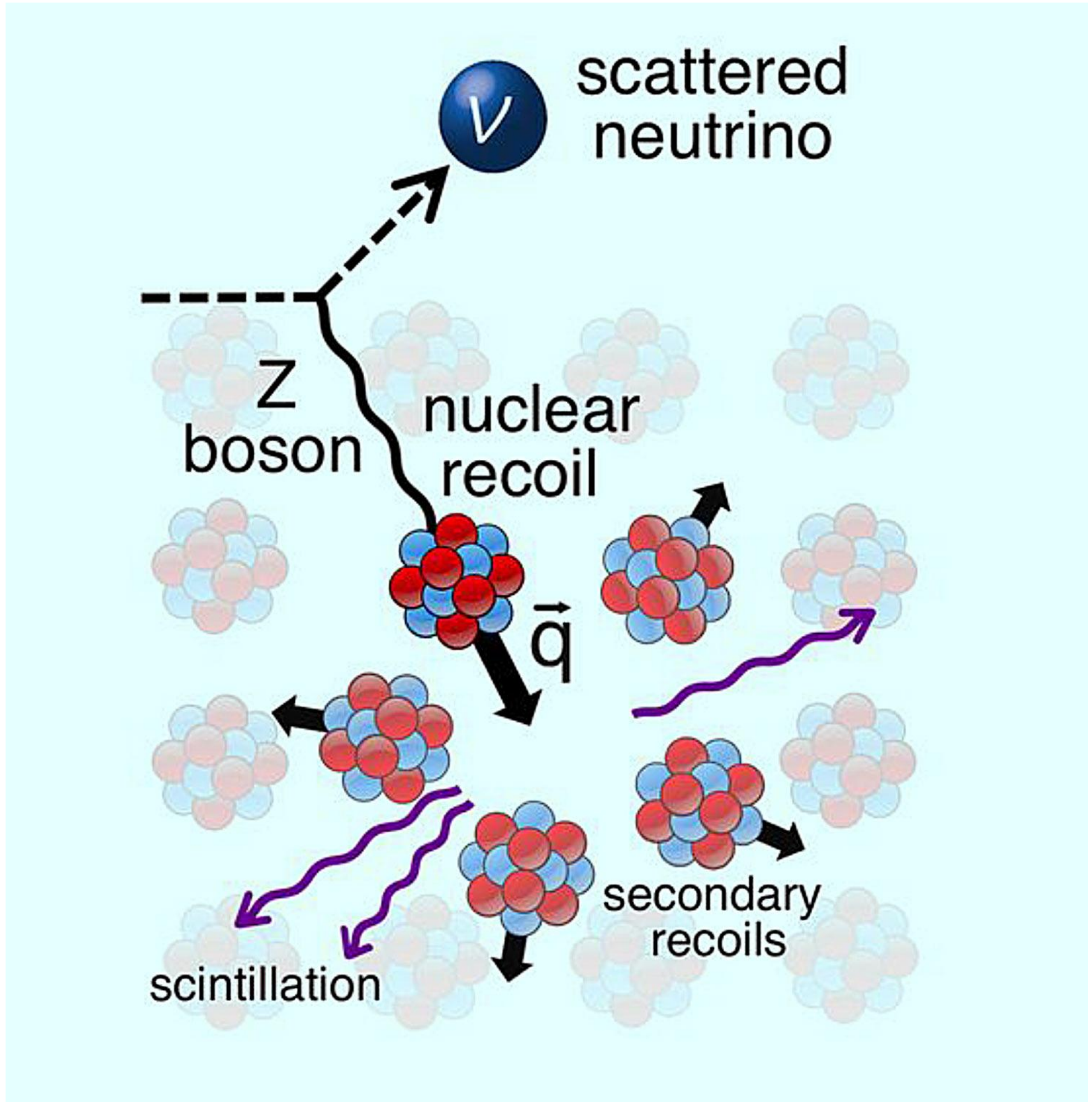
keV-scale imaging in argon-based detectors



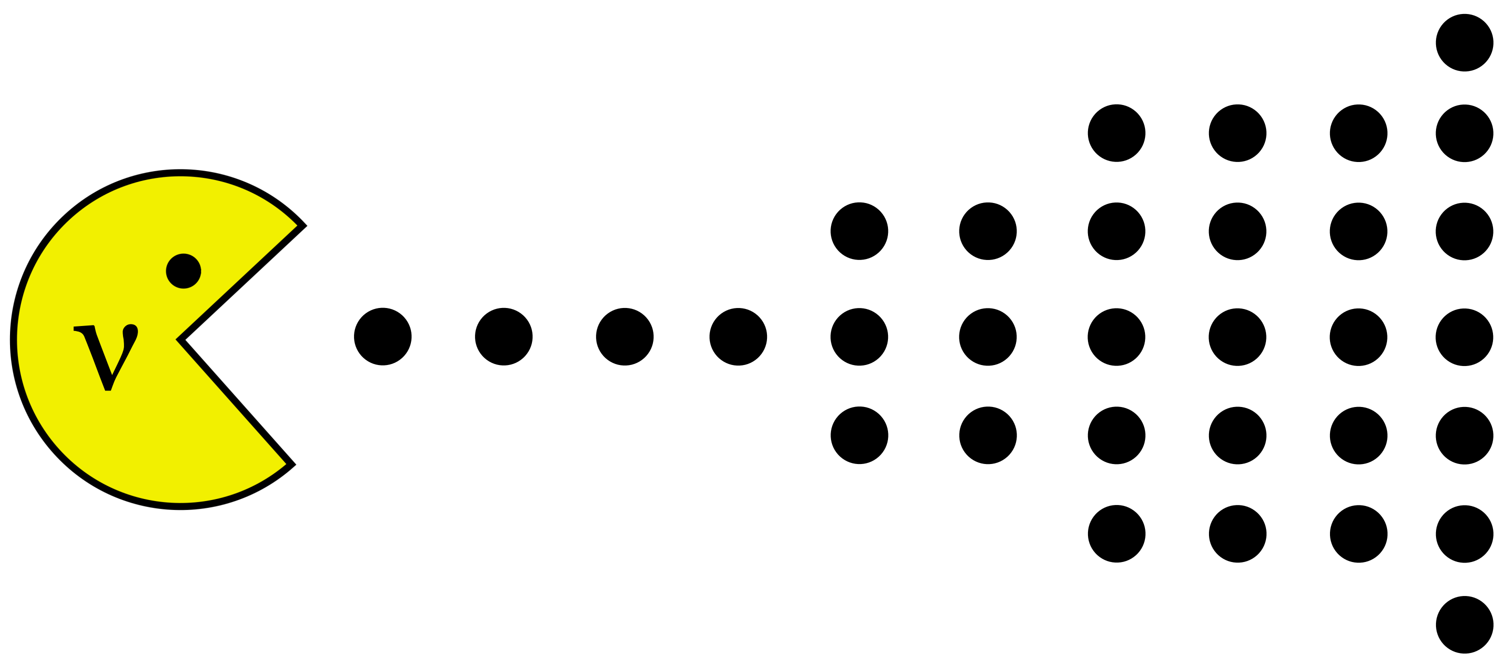
~few hundred "ENC" noise for LArTPC vs. ~tens of e- for NR signature



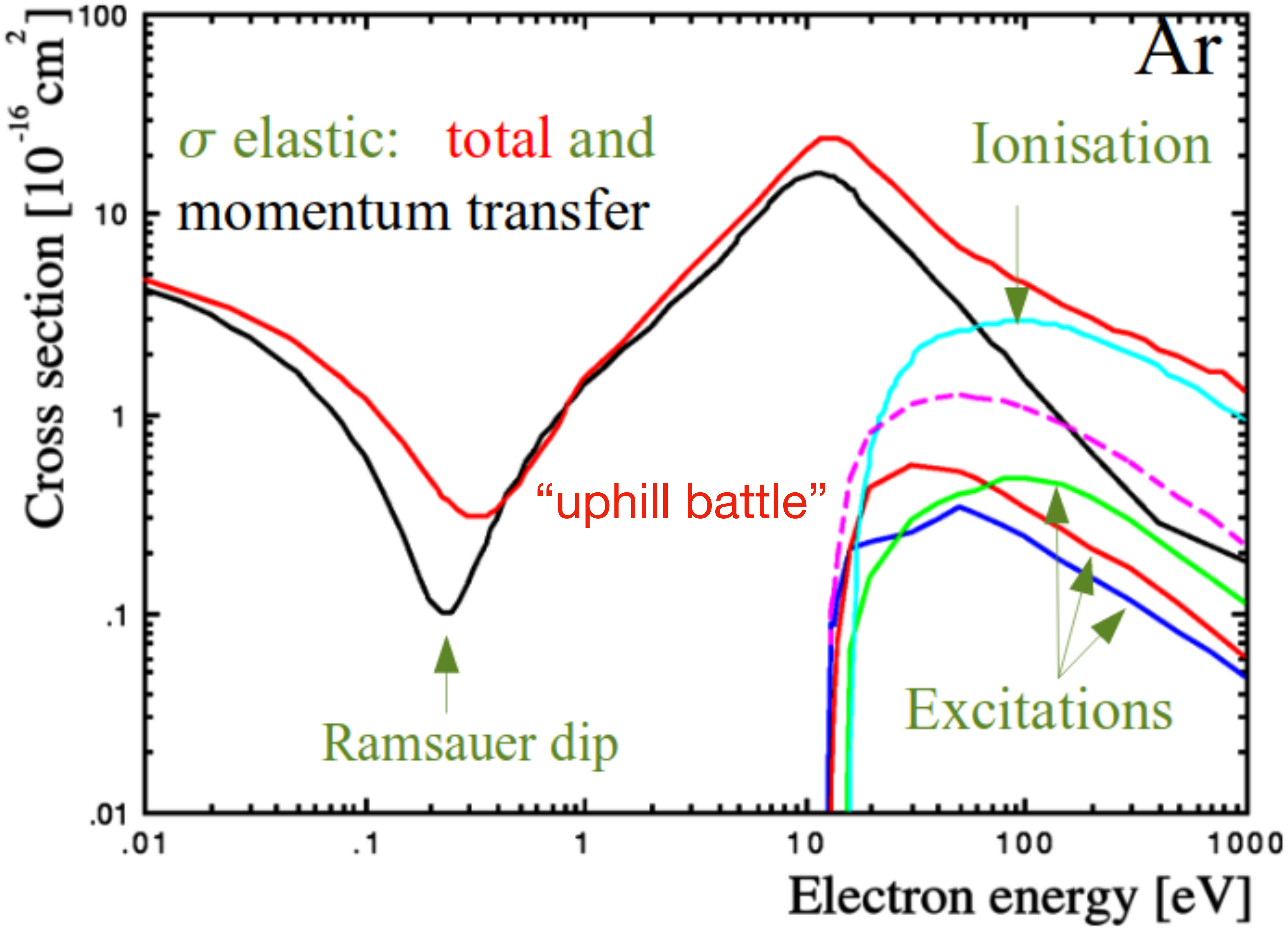
O(mm) resolution in LAr vs. O(10s um) NR range in GAr



LArCADe: Liquid Argon Charge Amplification Devices



Charge Amplification in LAr



Charge amplification in argon:

Take ~thermal electrons and accelerate to ~10 eV in order to ionize

OK in gas where inter-atomic distance is large

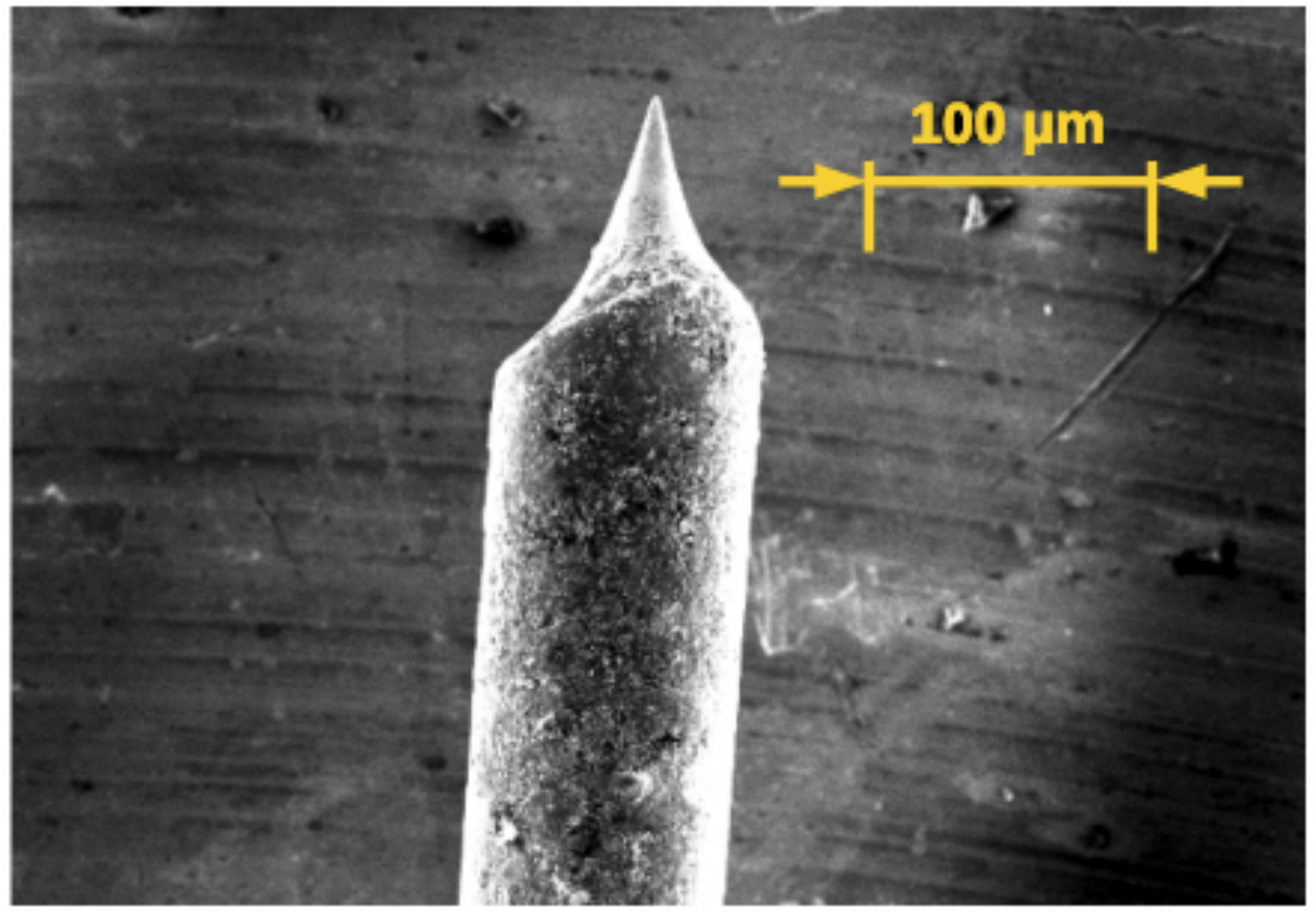
In LAr: re-scatter (and lose energy) well before reaching 10 eV

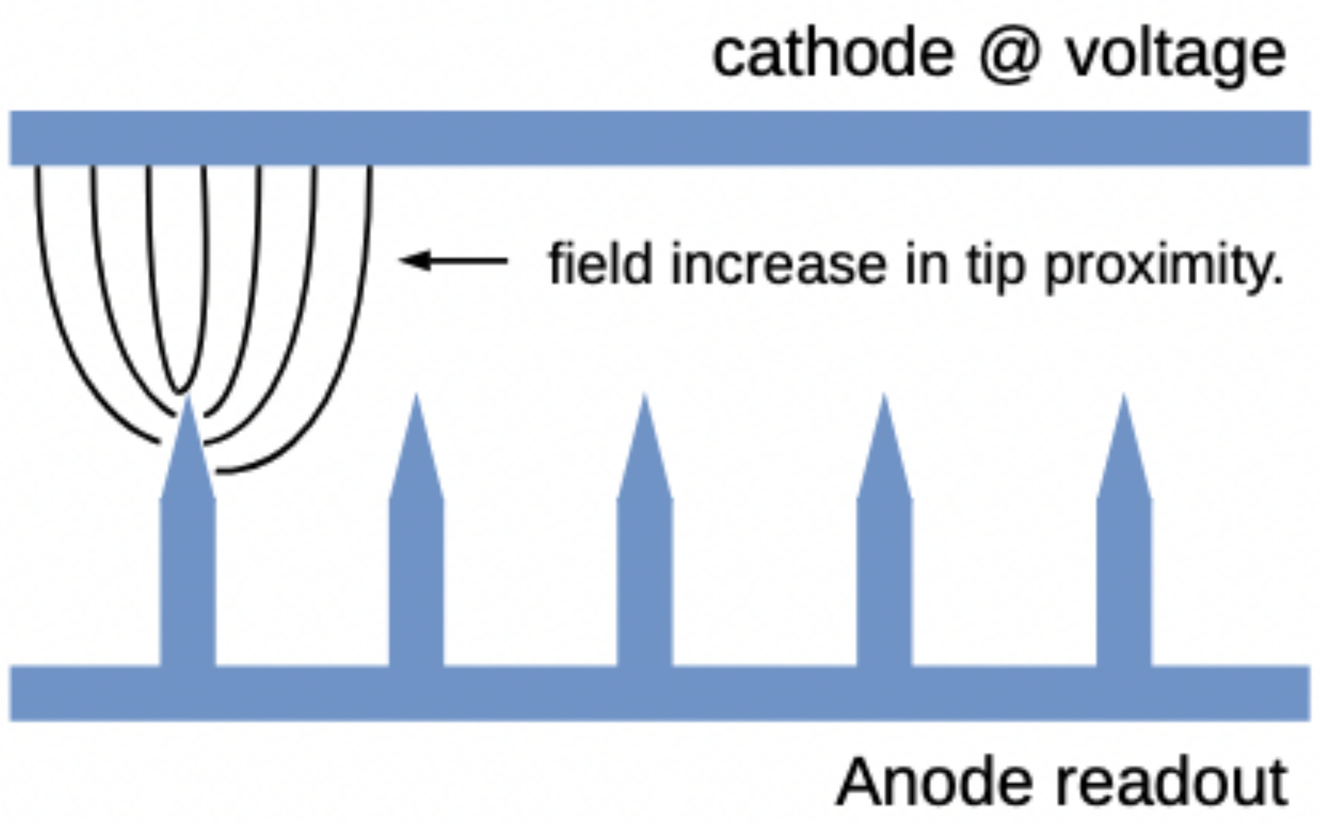
Need incredibly strong E-field (10^6 V/cm)

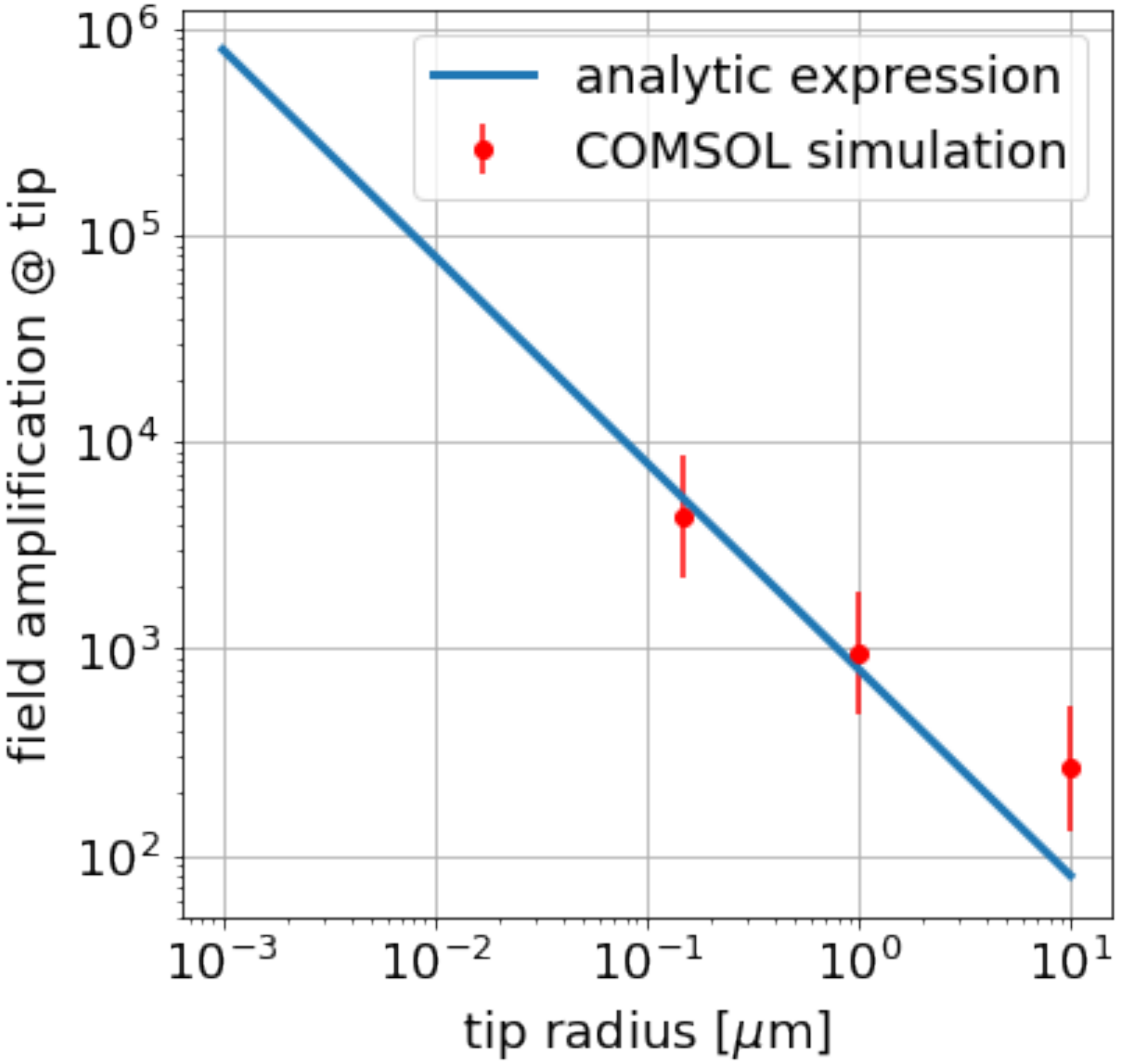
<u>"Tip" anode geometries to achieve high field</u>

LArCADe: “tip” geometries

R&D effort launched by Angela Fava (FNAL) with LDRD



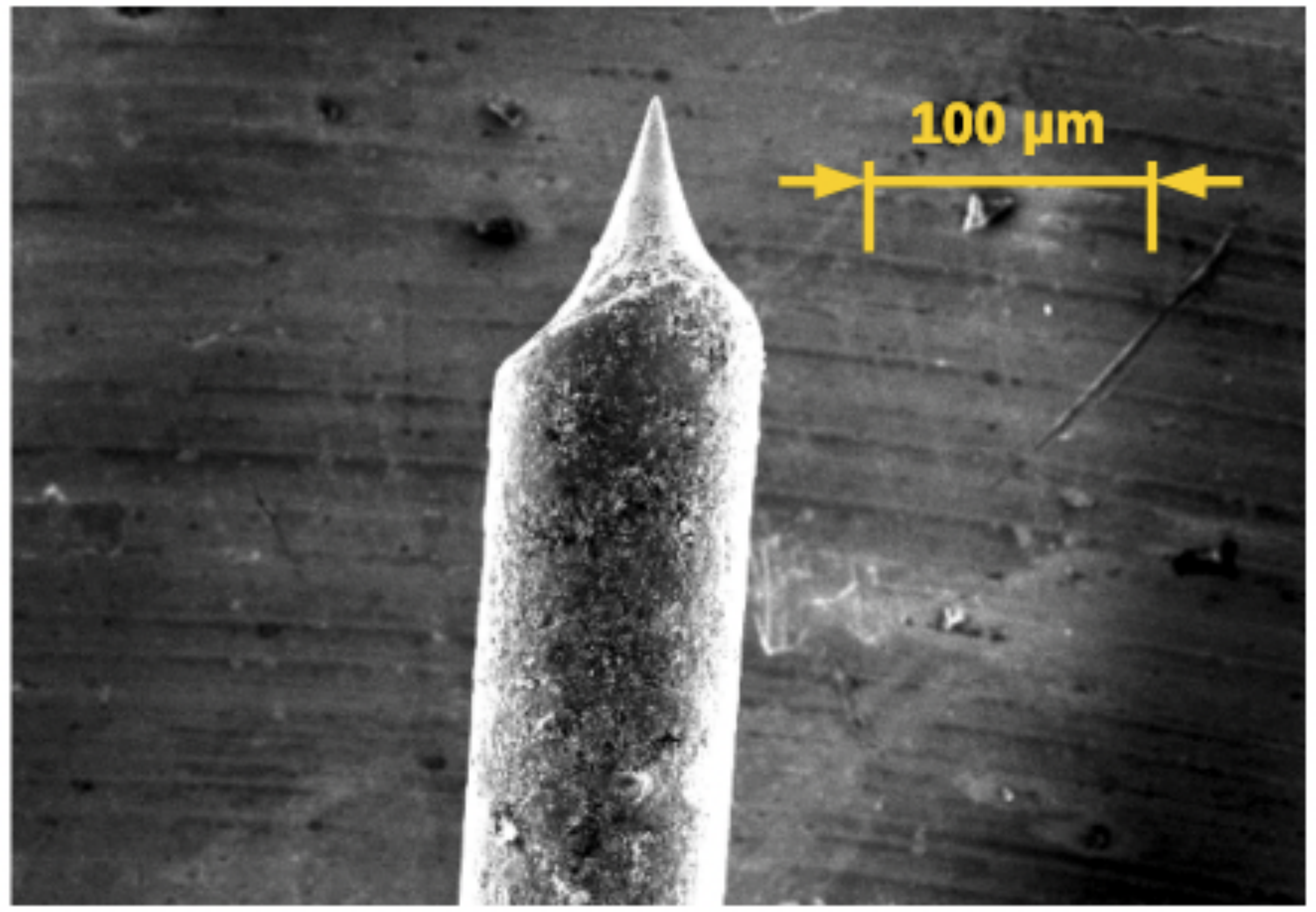


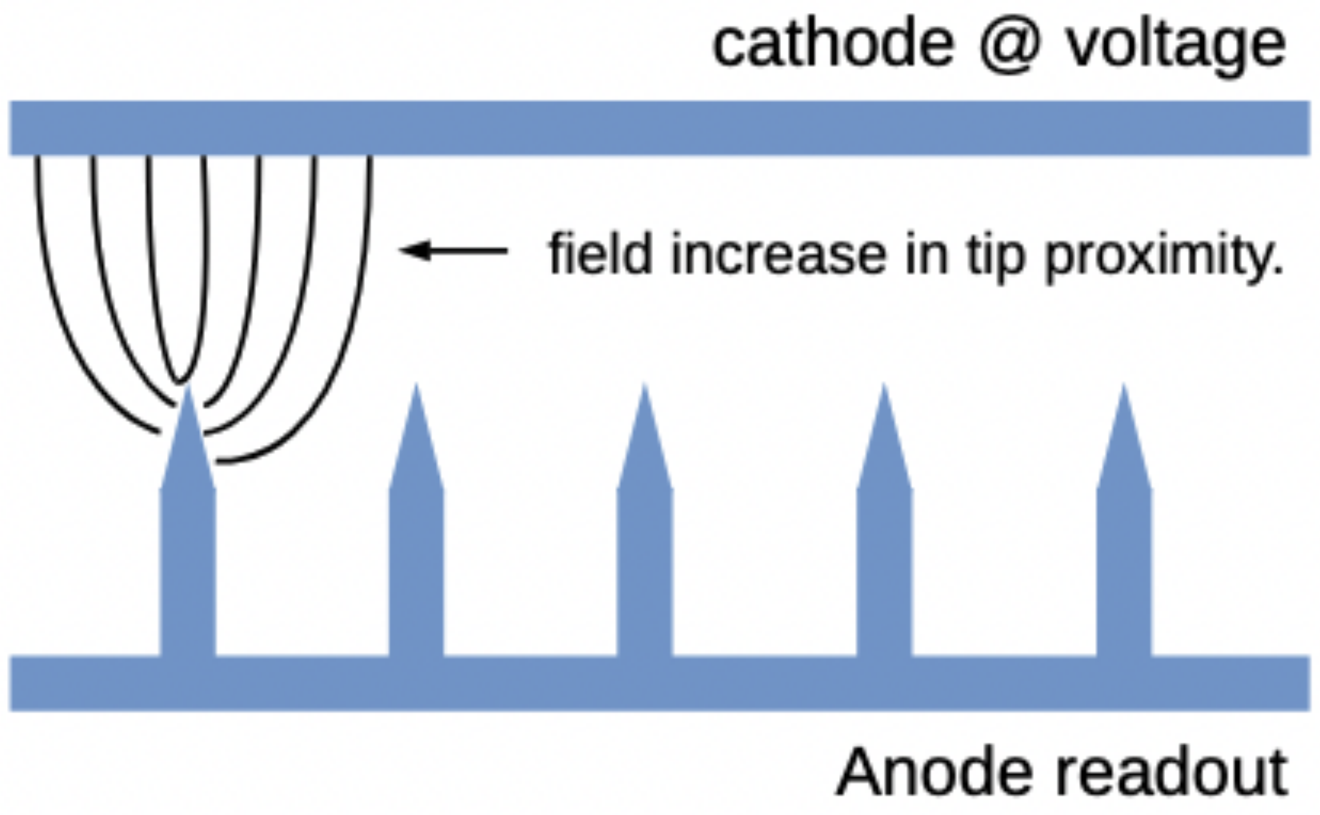


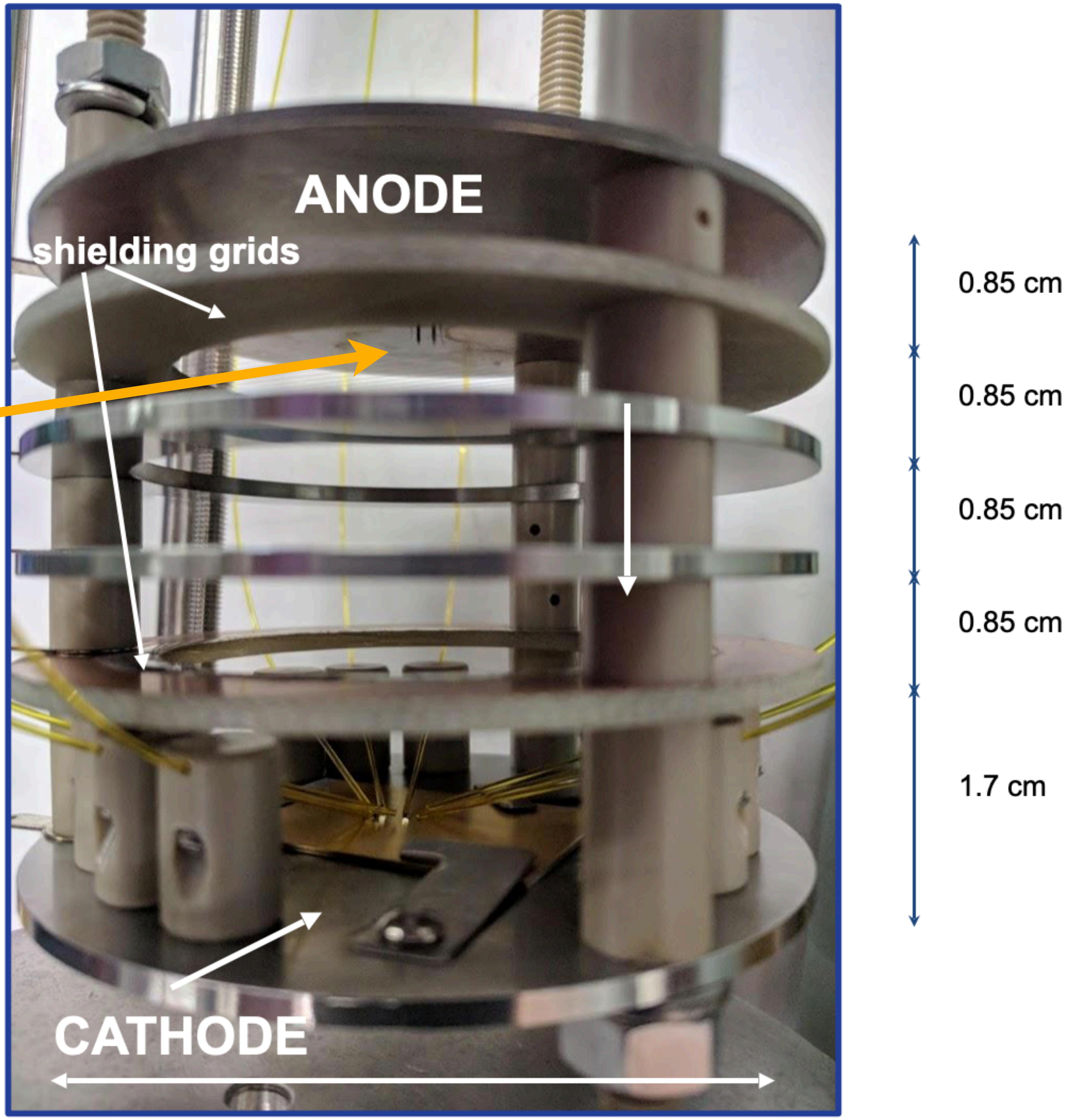
source for analytic expression: NIM A 534 (2004) 376-396

Tip geometry provides potential for amplification in bulk fields of O(100s V/cm)

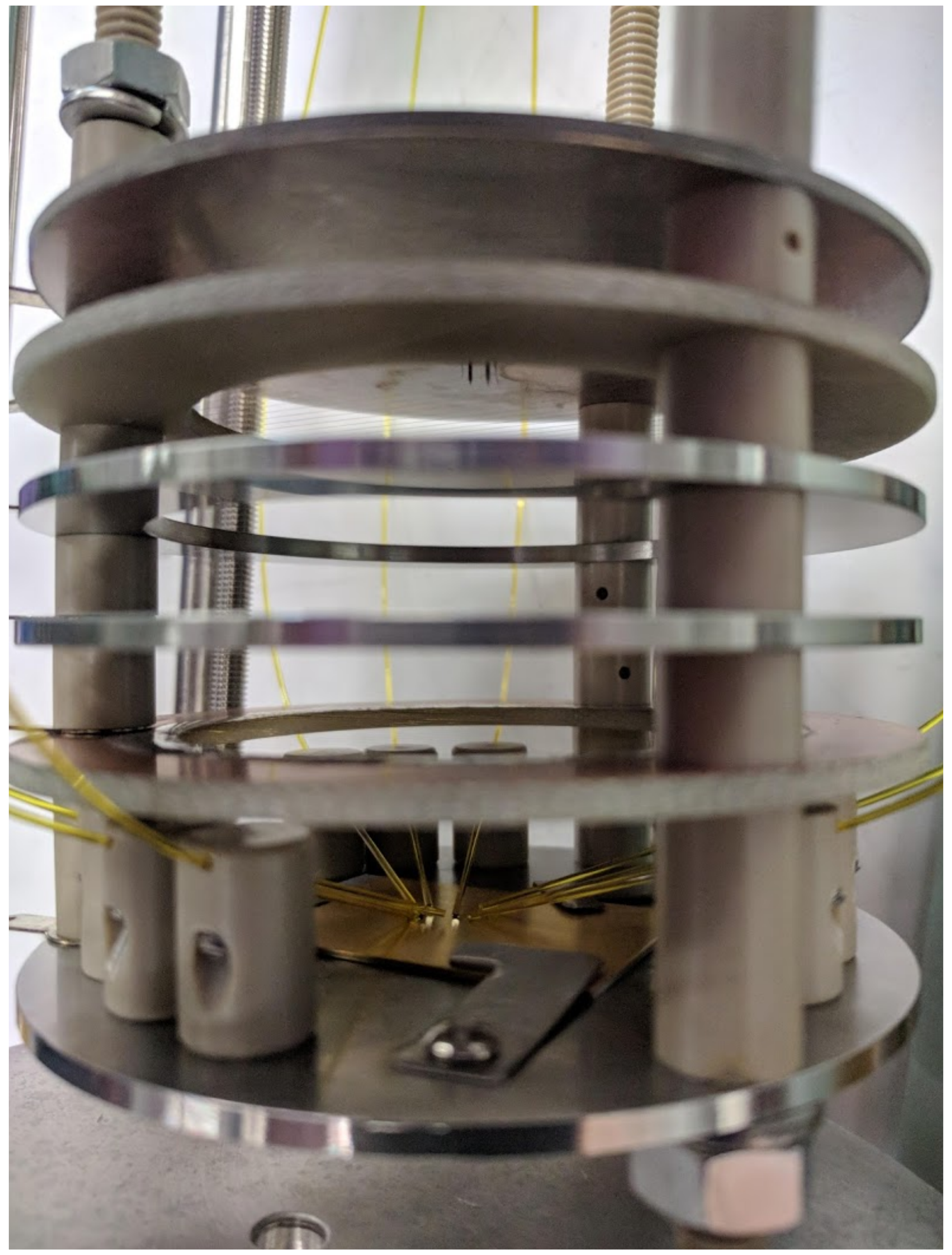
LArCADe: R&D setup

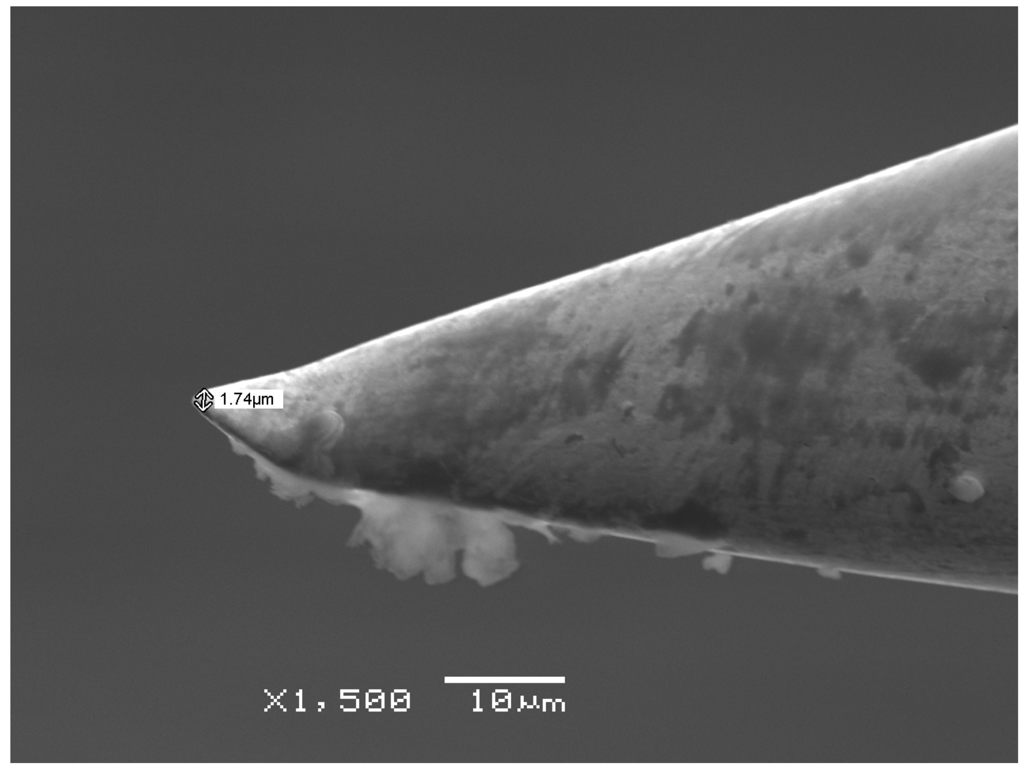




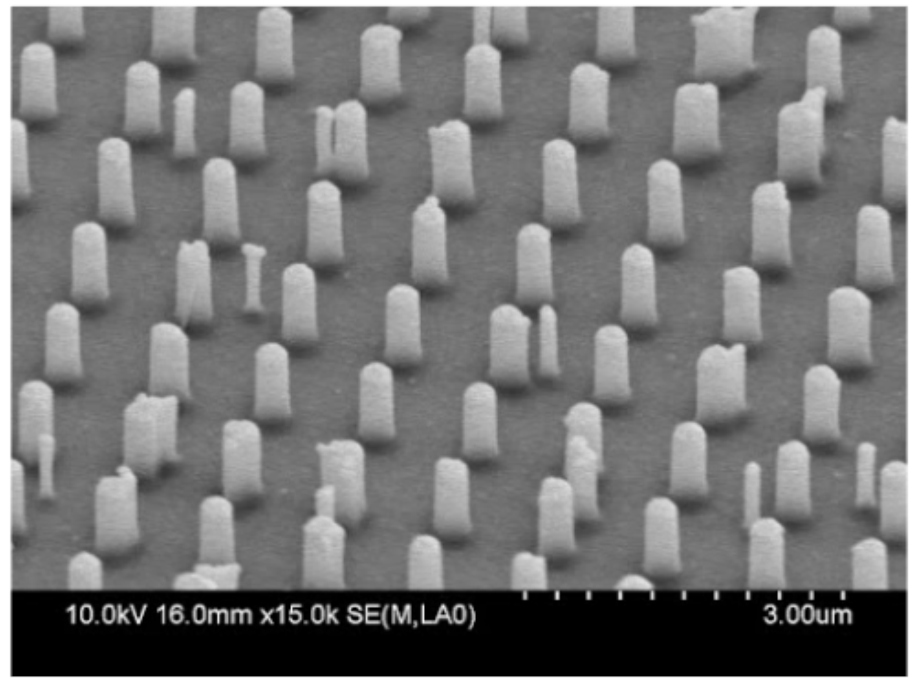


LArCADe: R&D runs at Fermilab





tip-array with sub µm apex produced @ BNL



LArCADe R&D program at Fermilab

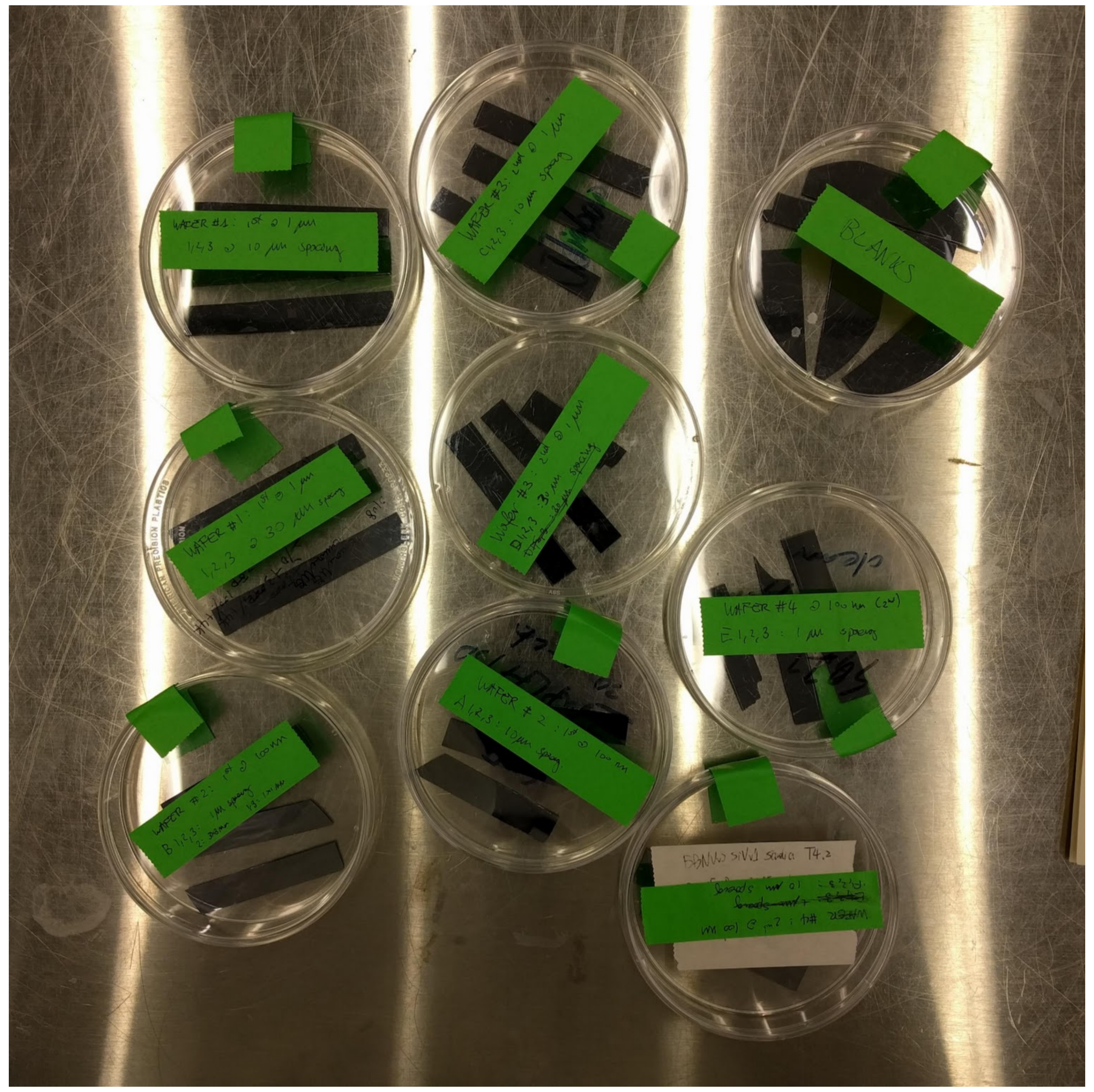
Utilize Fermilab's "PAB" (now "Noble Liquid Test Facility") for cryogenic setup with purified LAr

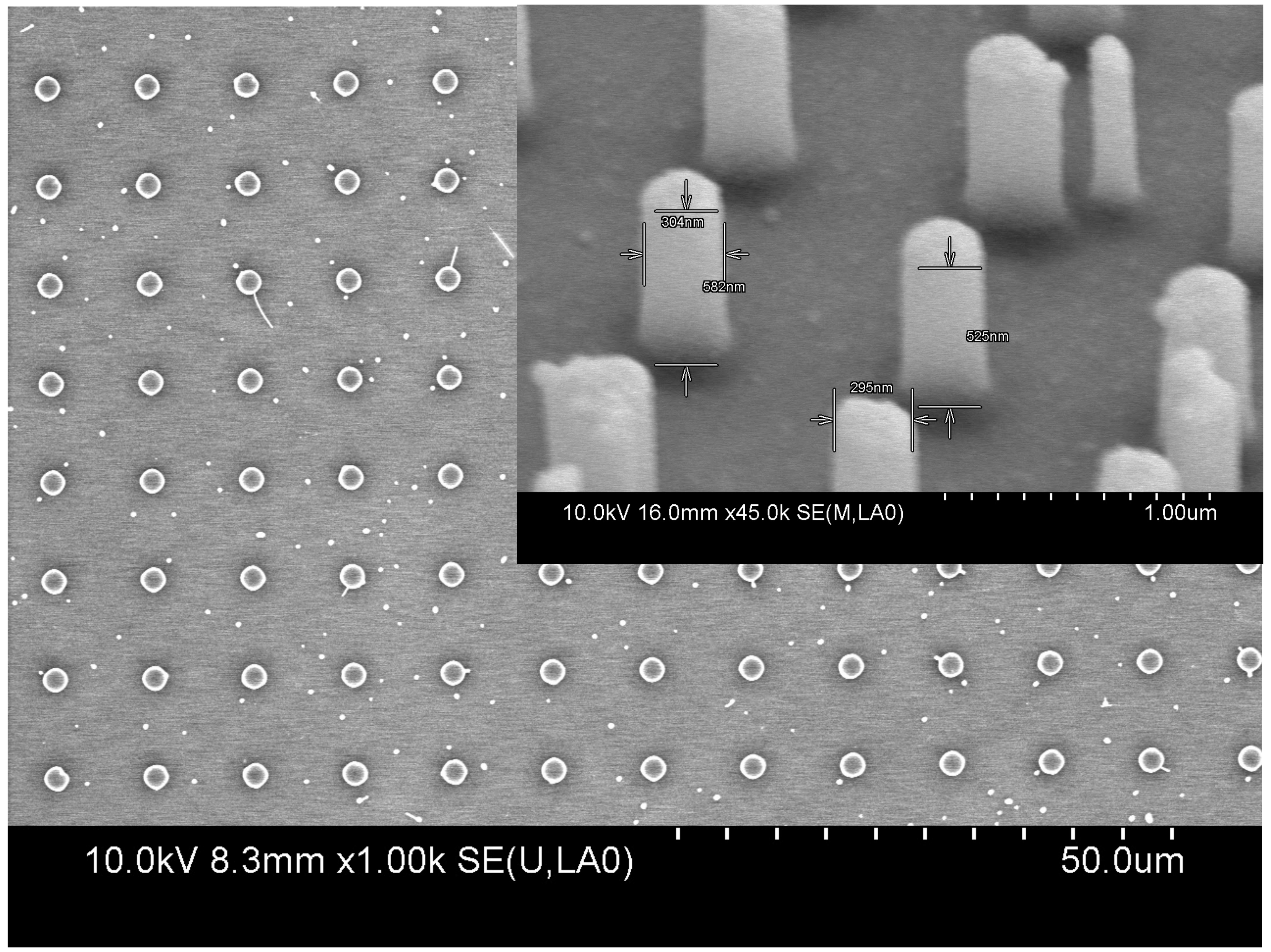
"Purity monitor": single-pixel TPC for charge transparency / attenuation measurements

Work with different tip geometries / arrays

Collaborating with materials experts @ Padova, FNAL, BNL

LArCADe: tip-array fabrication



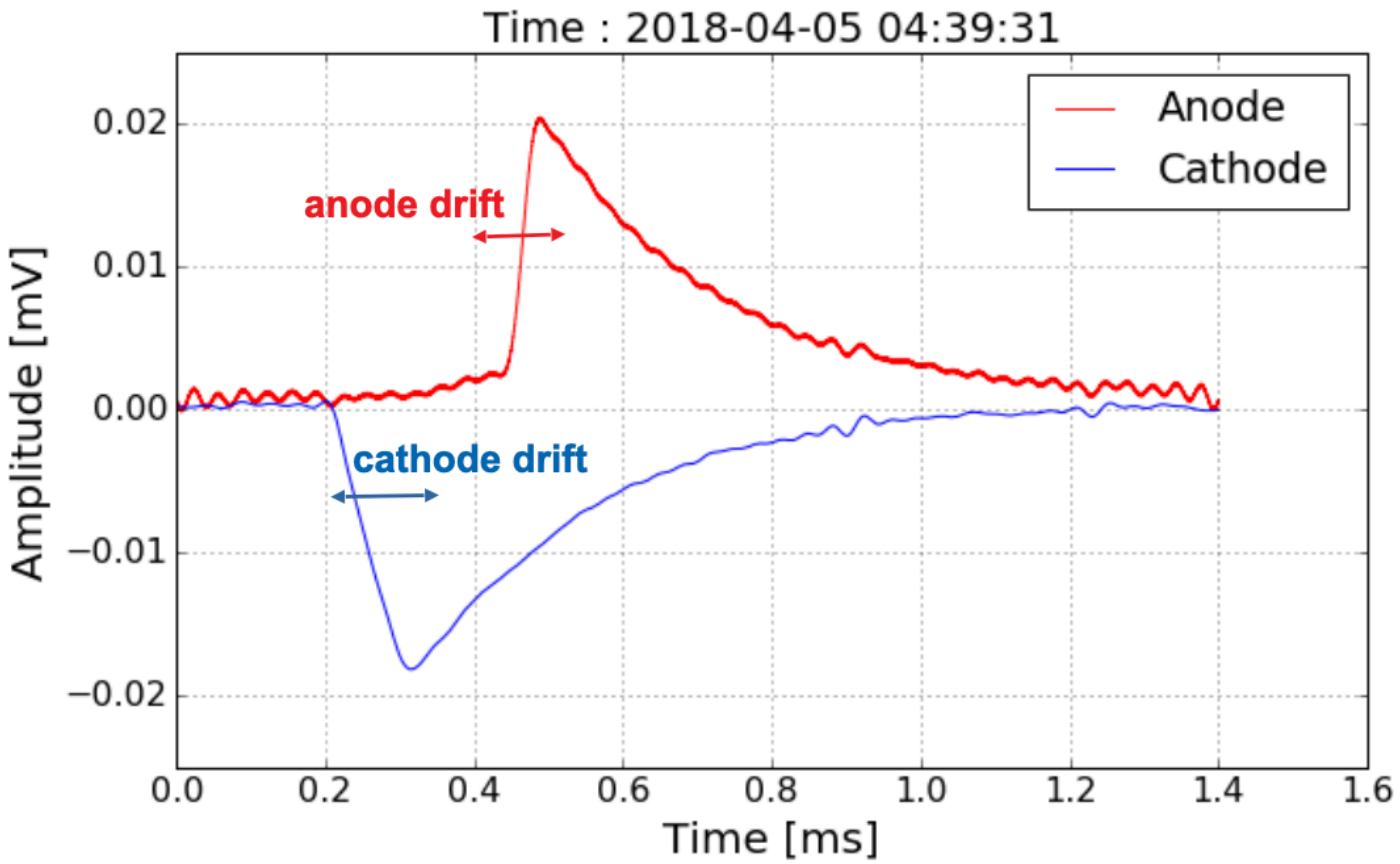


Launched development of tip-arrays @ BNL's Center for Functional Nanomaterials (CFN)

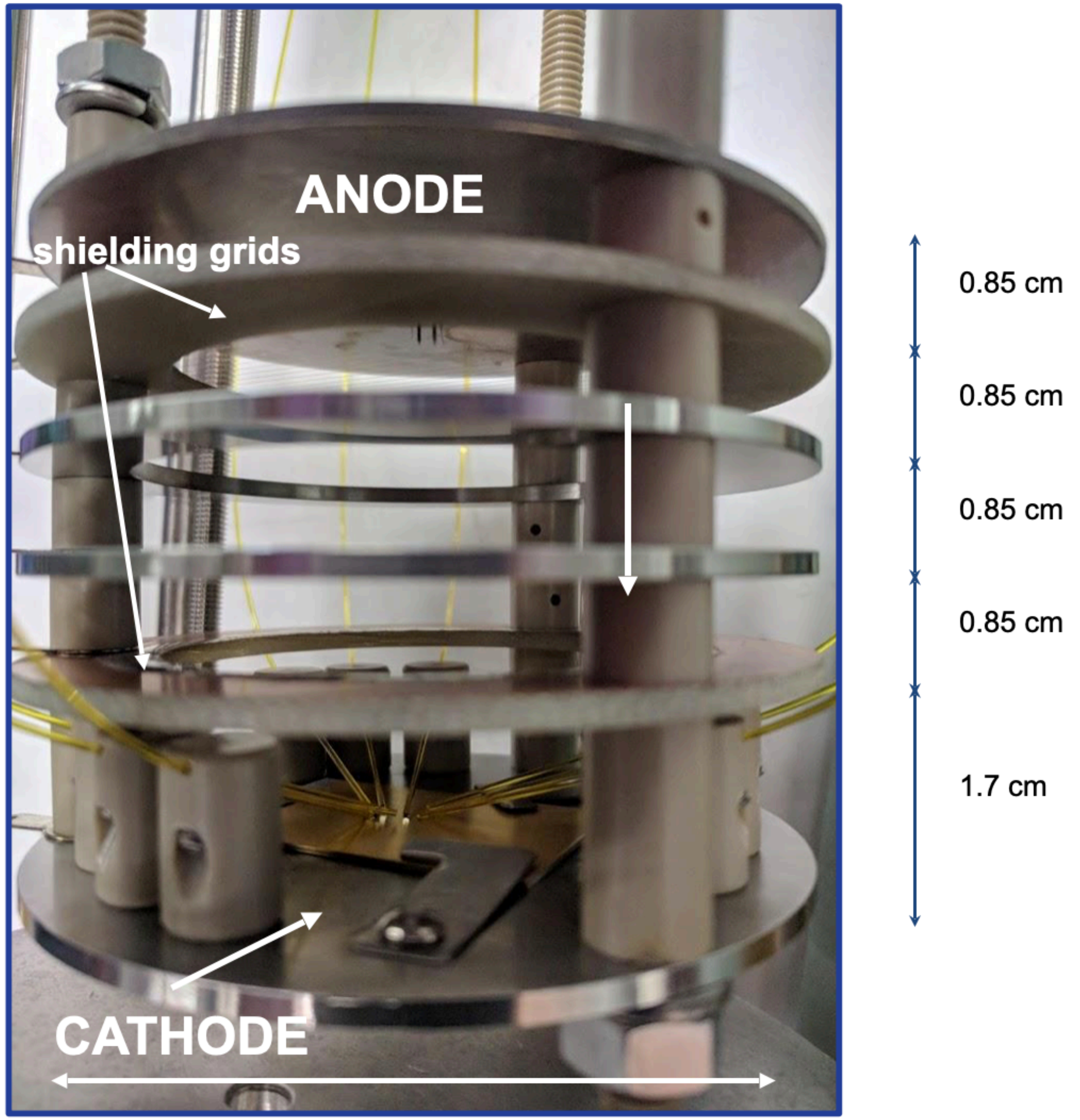
User facility with resources for design, etching, sputtering, imaging

Tip-arrays allow for optimized and scalable design

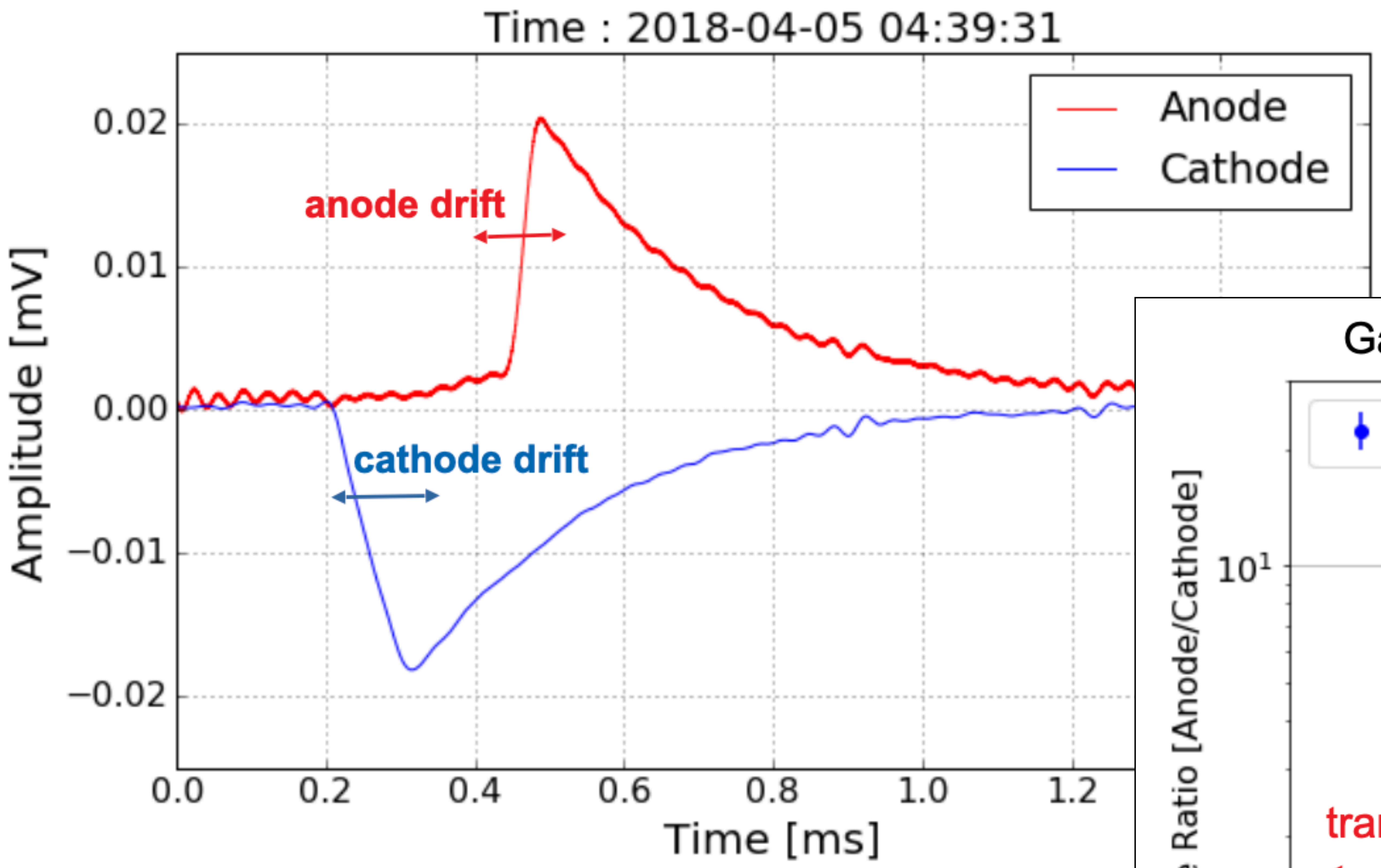
LArCADe: data-taking and analysis

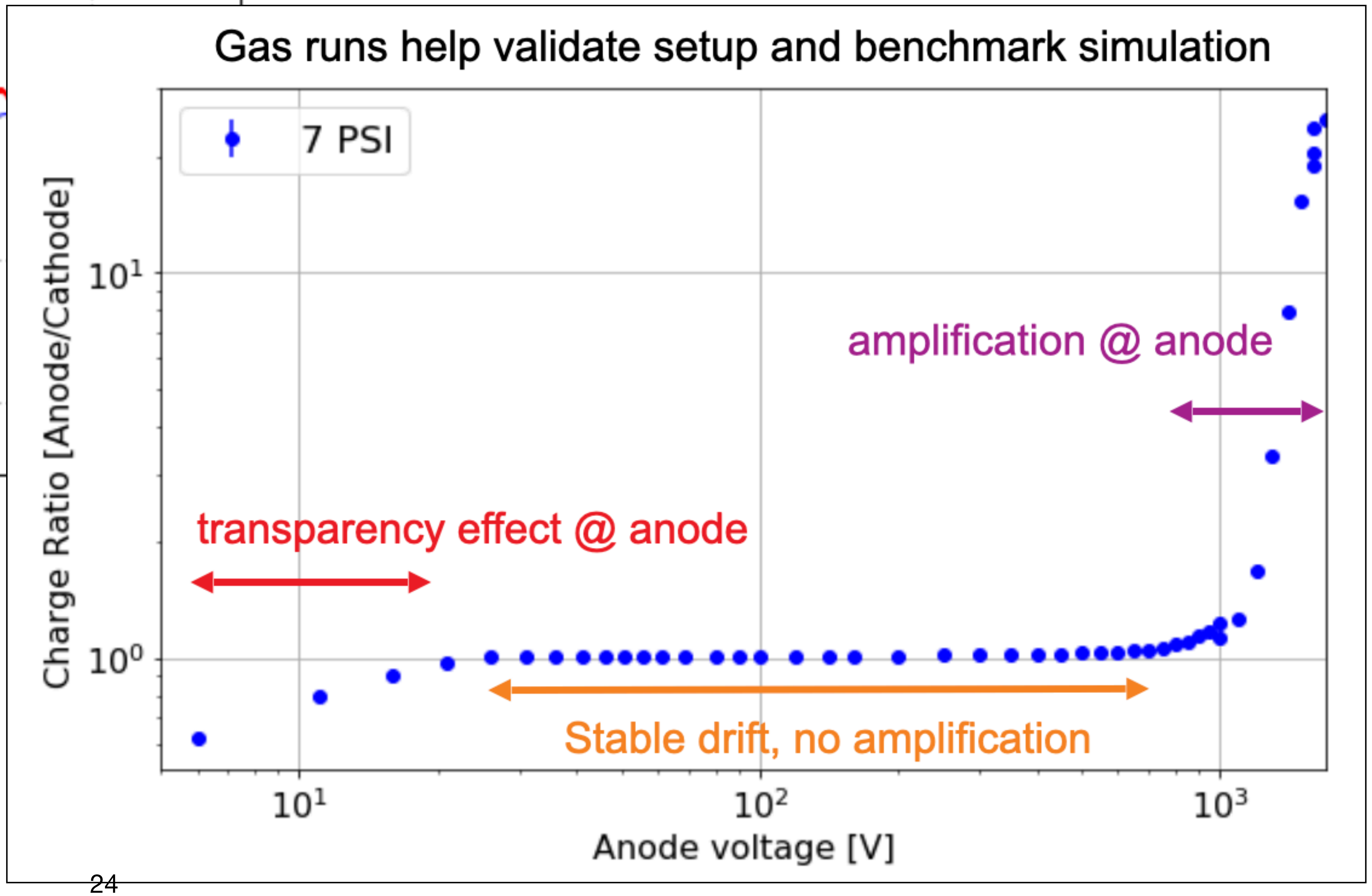


Measure charge induced at Cathode and Anode

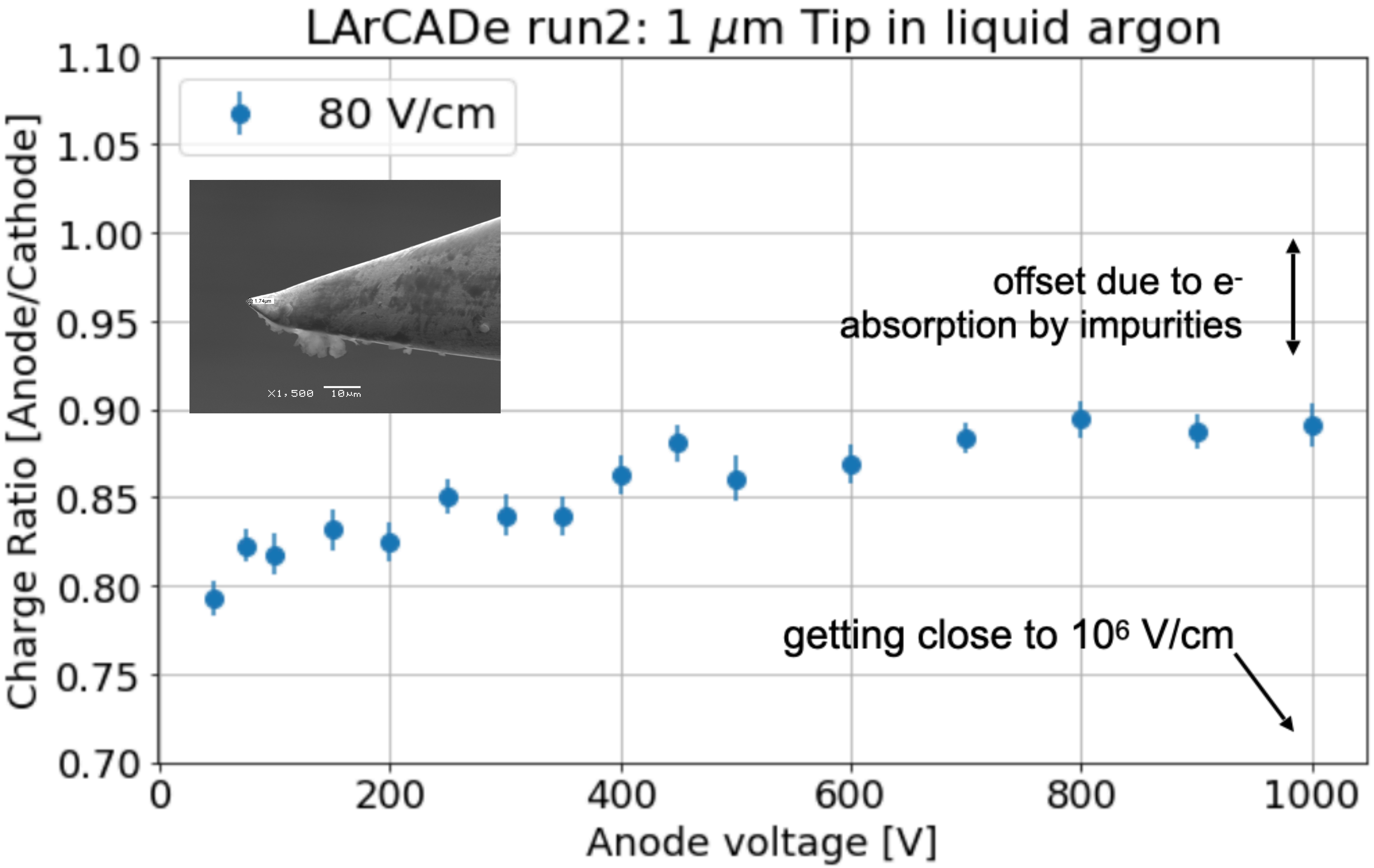


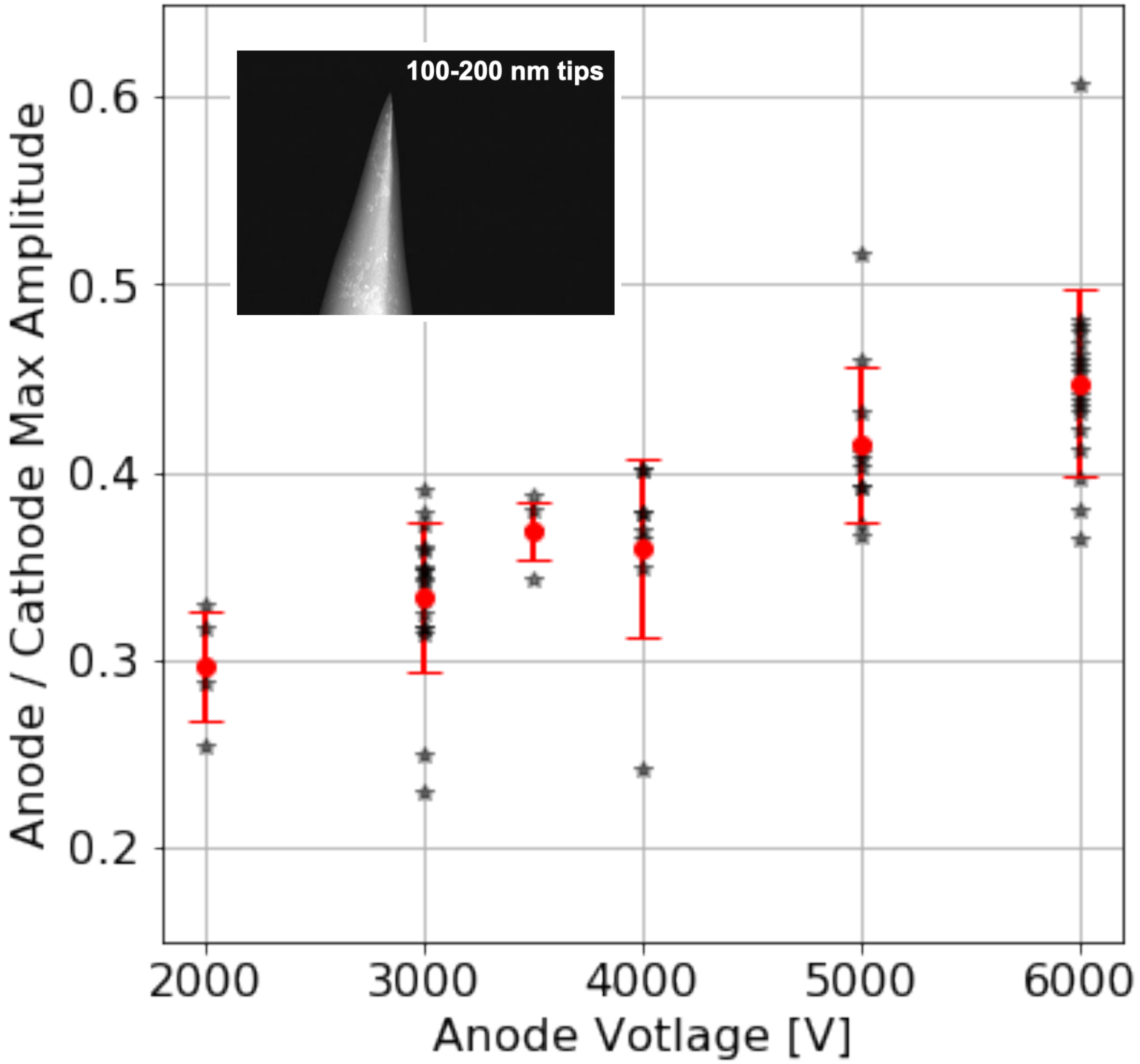
LArCADe: data-taking in GAr





LArCADe: data-taking in LAr





LArCADe: progress and R&D next-steps

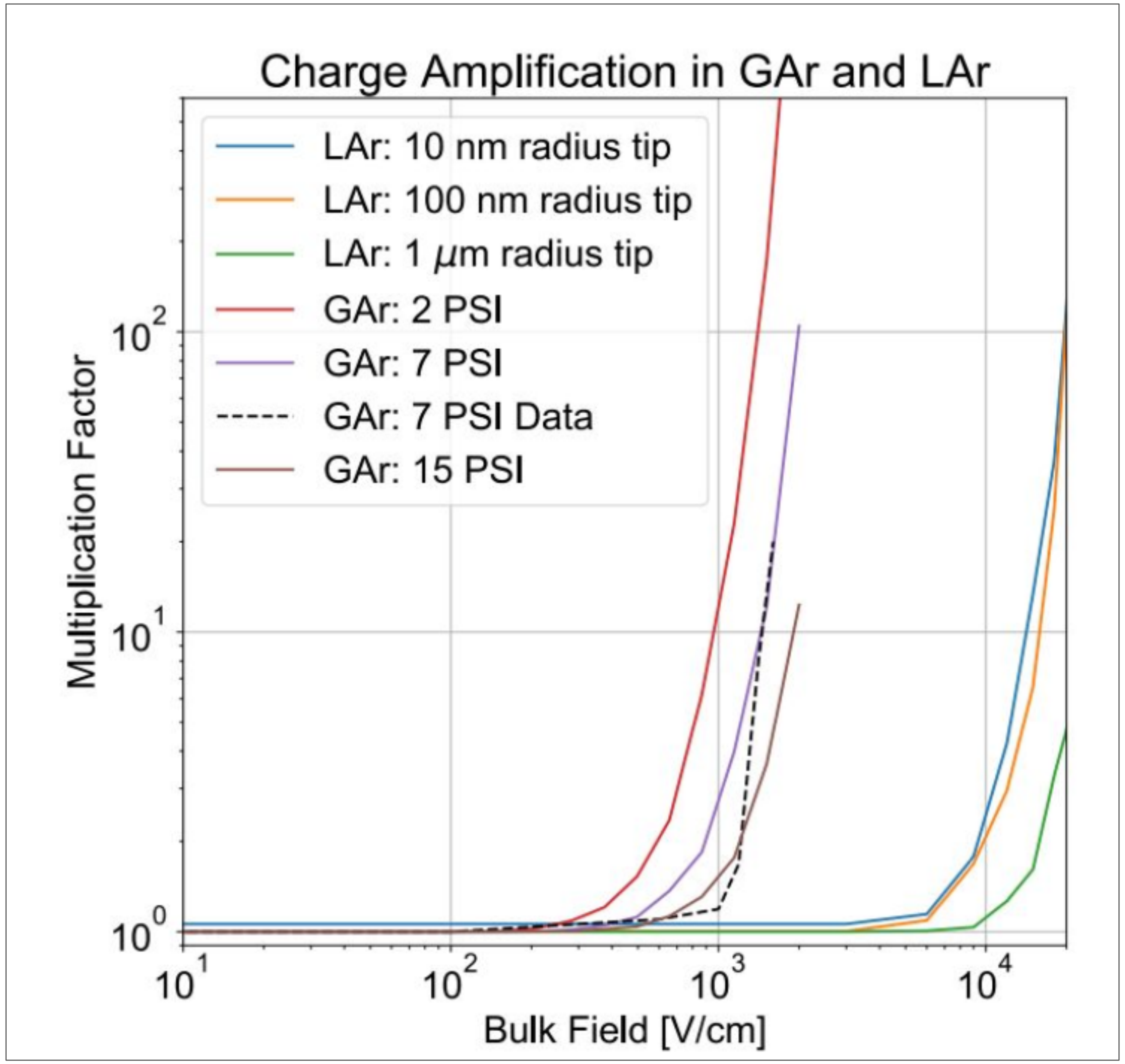
Several runs at Fermilab 2018-2020

Successful operation in gas.

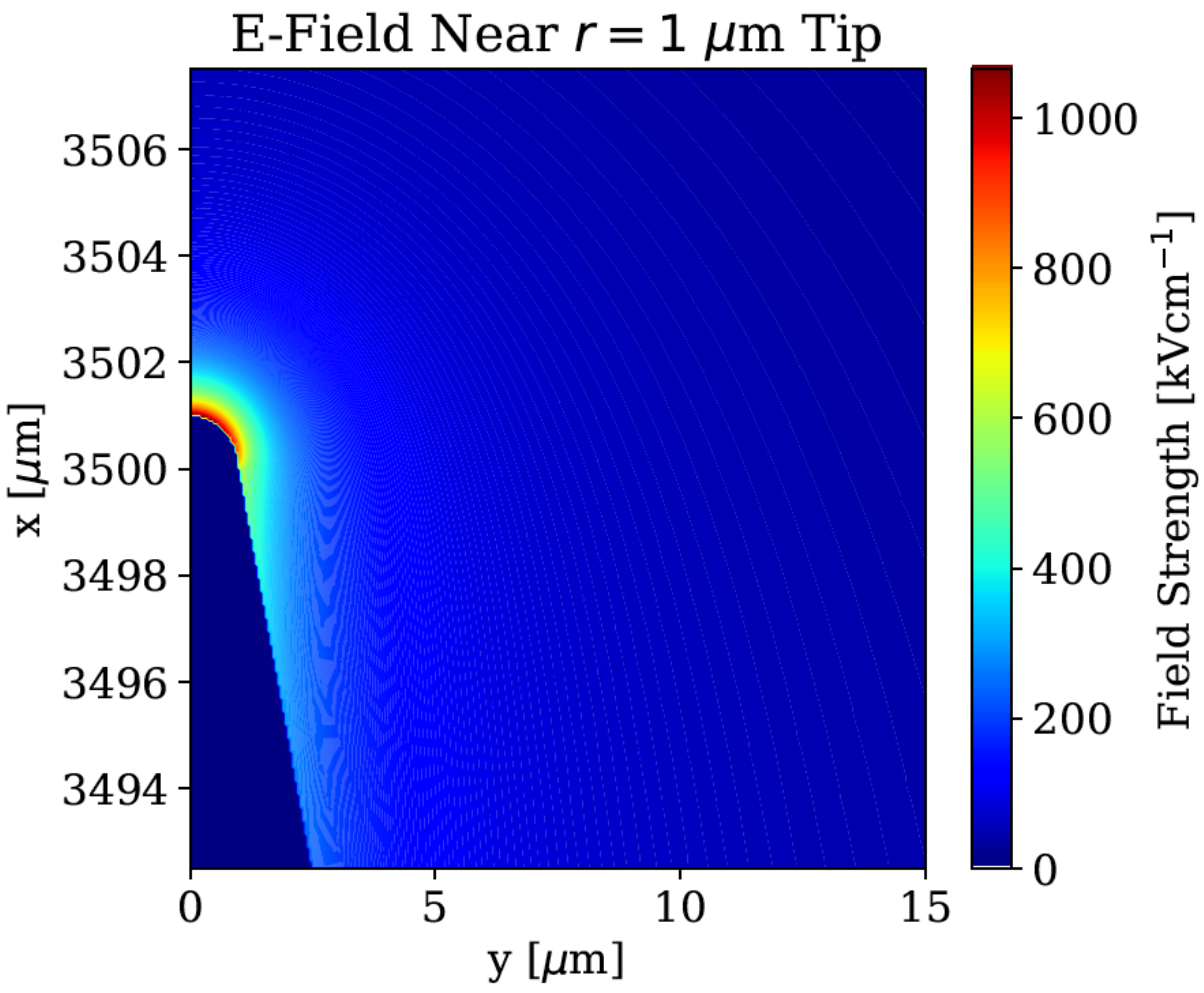
Were not able to draw clear conclusions on amplification from few kV operations in LAr

- Hardware (power supply, electronics)
- Investigations on tip geometry

Opened new R&D effort towards understanding ideal geometries for charge amplification



LArCADe: tip-array simulation



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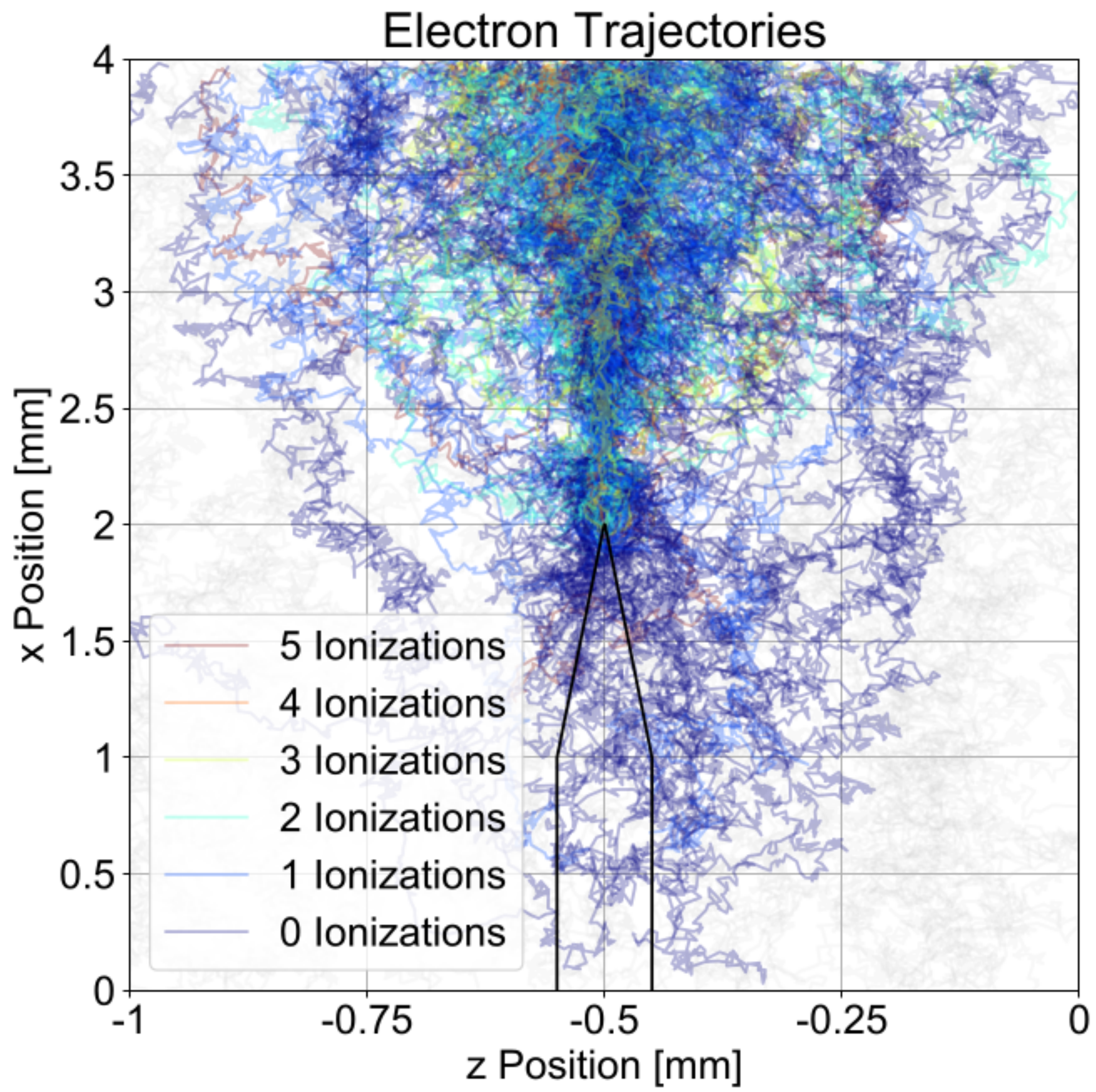
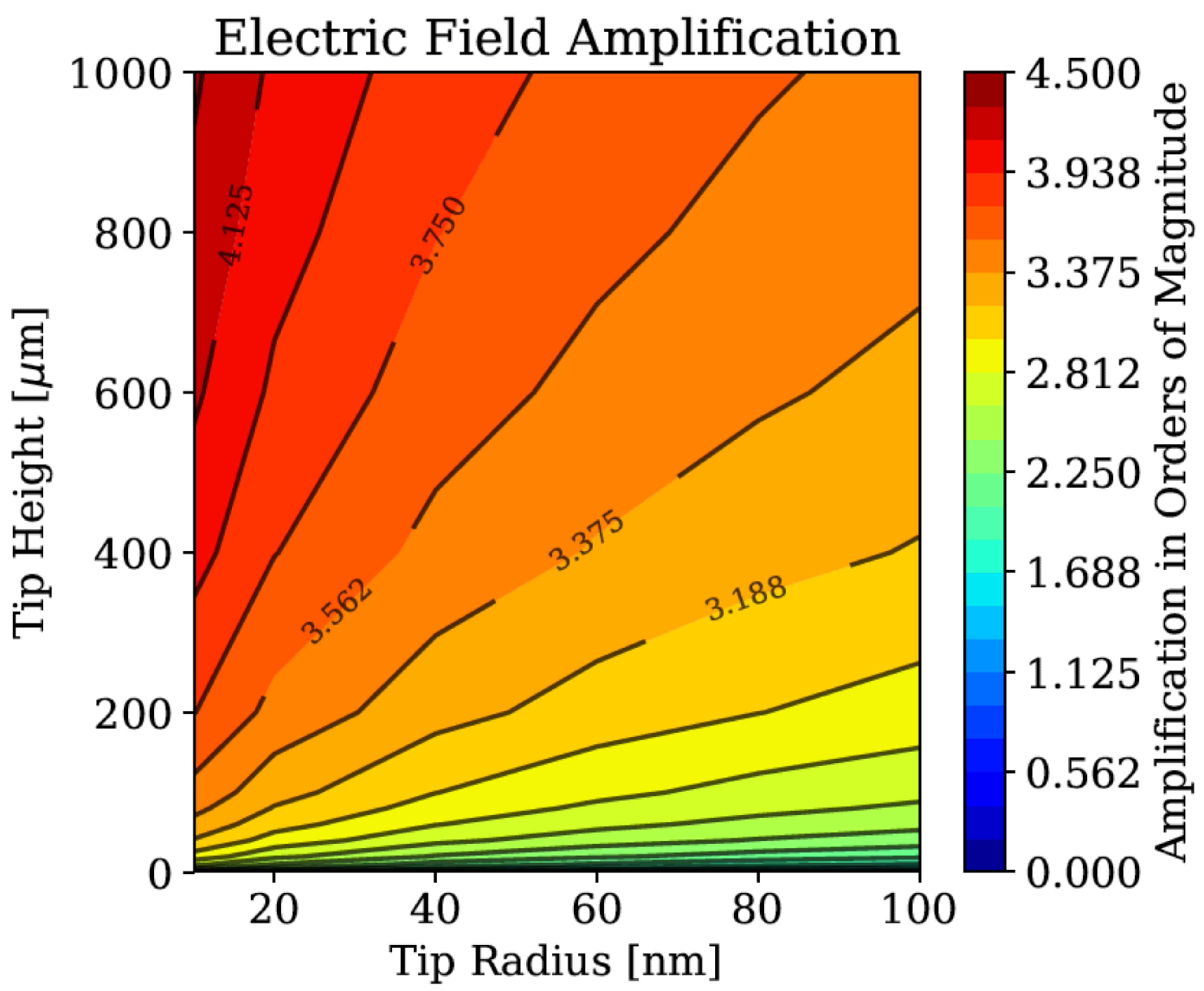
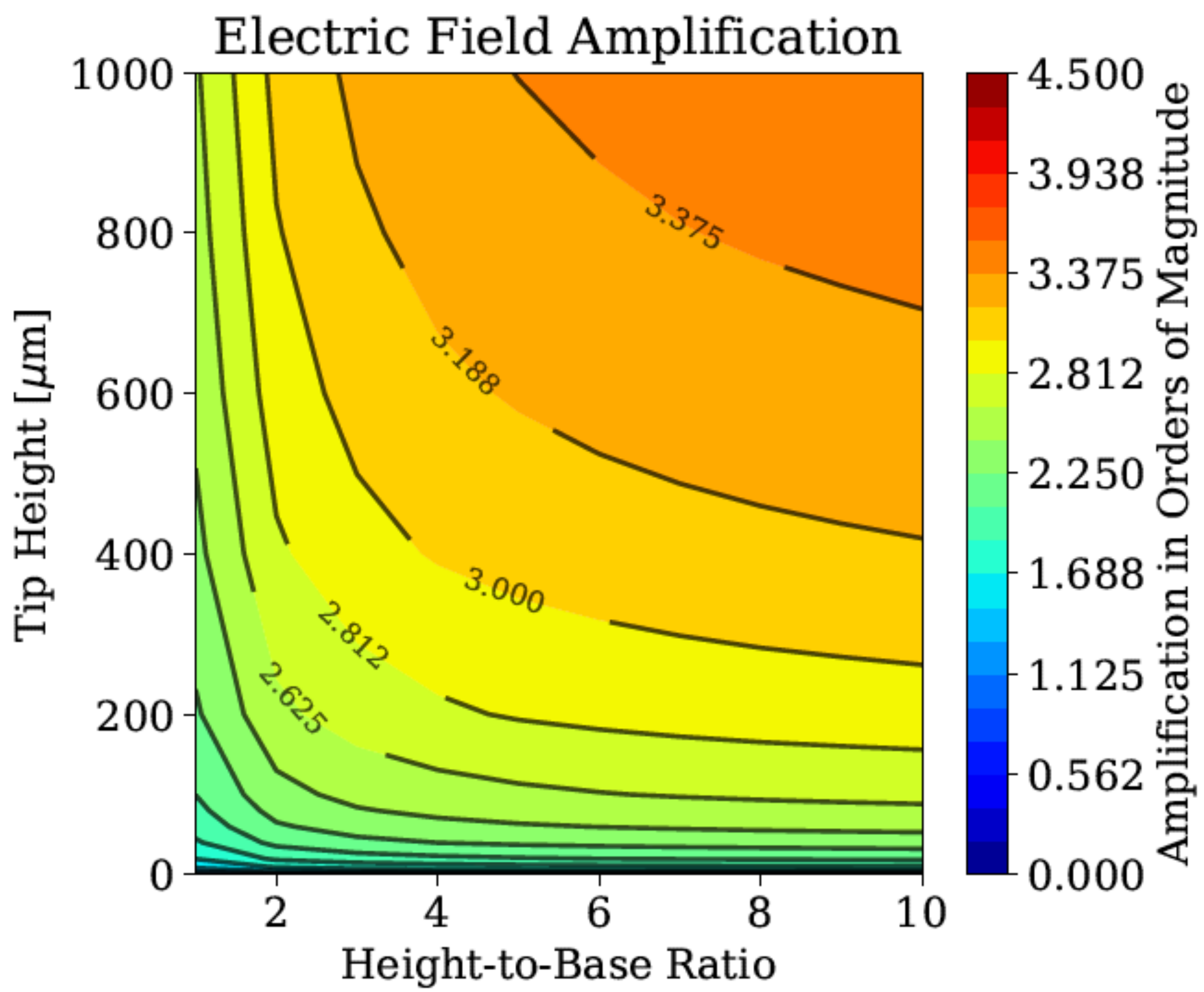


LArCADe: tip-array simulation





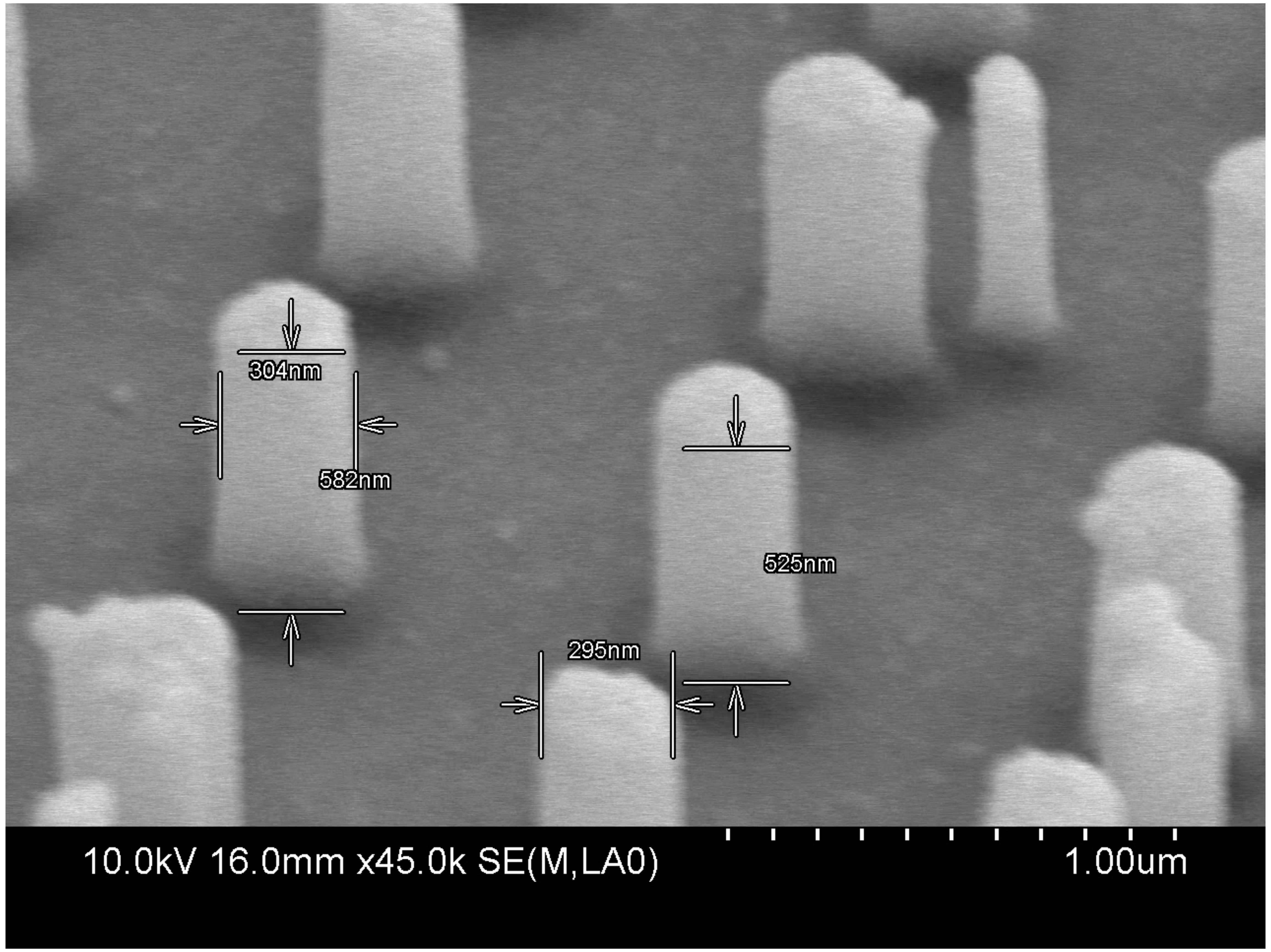
optimize tip geometry and provide input for quantitative analysis:
O(100) μm height, O(10s) nm tip radius.

LArCADe: tip-array nano fabrication

Tip-array geometries:

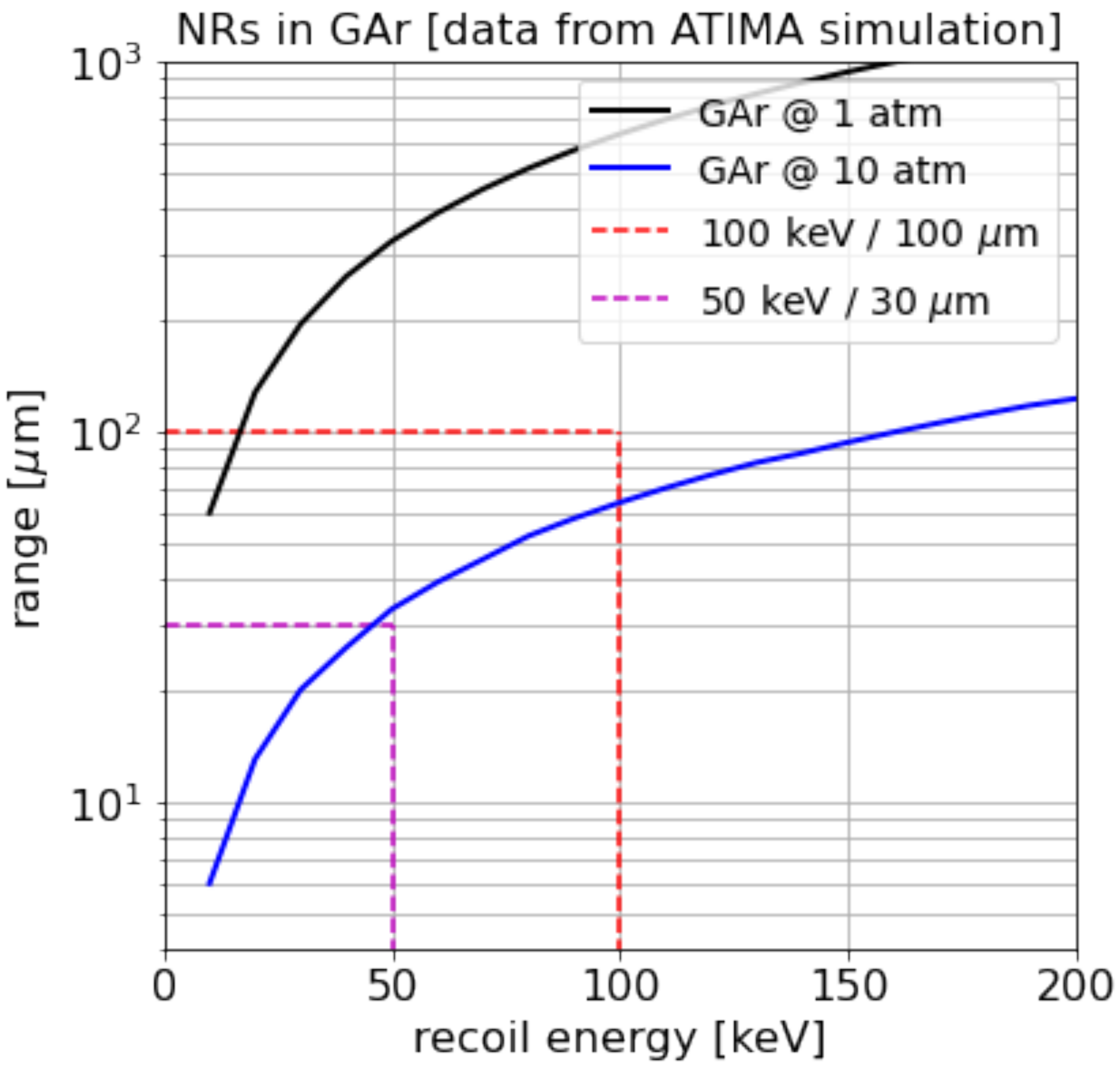
- can help achieve charge amplification
- Scalable technology
- May be leveraged for tracking capabilities

Tip-array geometries for NR tracking in GAr a possible new direction for R&D. Requires collaboration with materials and electronics for potential development.



Nuclear Recoil Tracking in GAr

Simulations and feasibility



$$E_r = \frac{2m_N E_\nu^2 \cos^2\theta_r}{(E_\nu + m_N)^2 - E_\nu^2 \cos^2\theta_r}$$

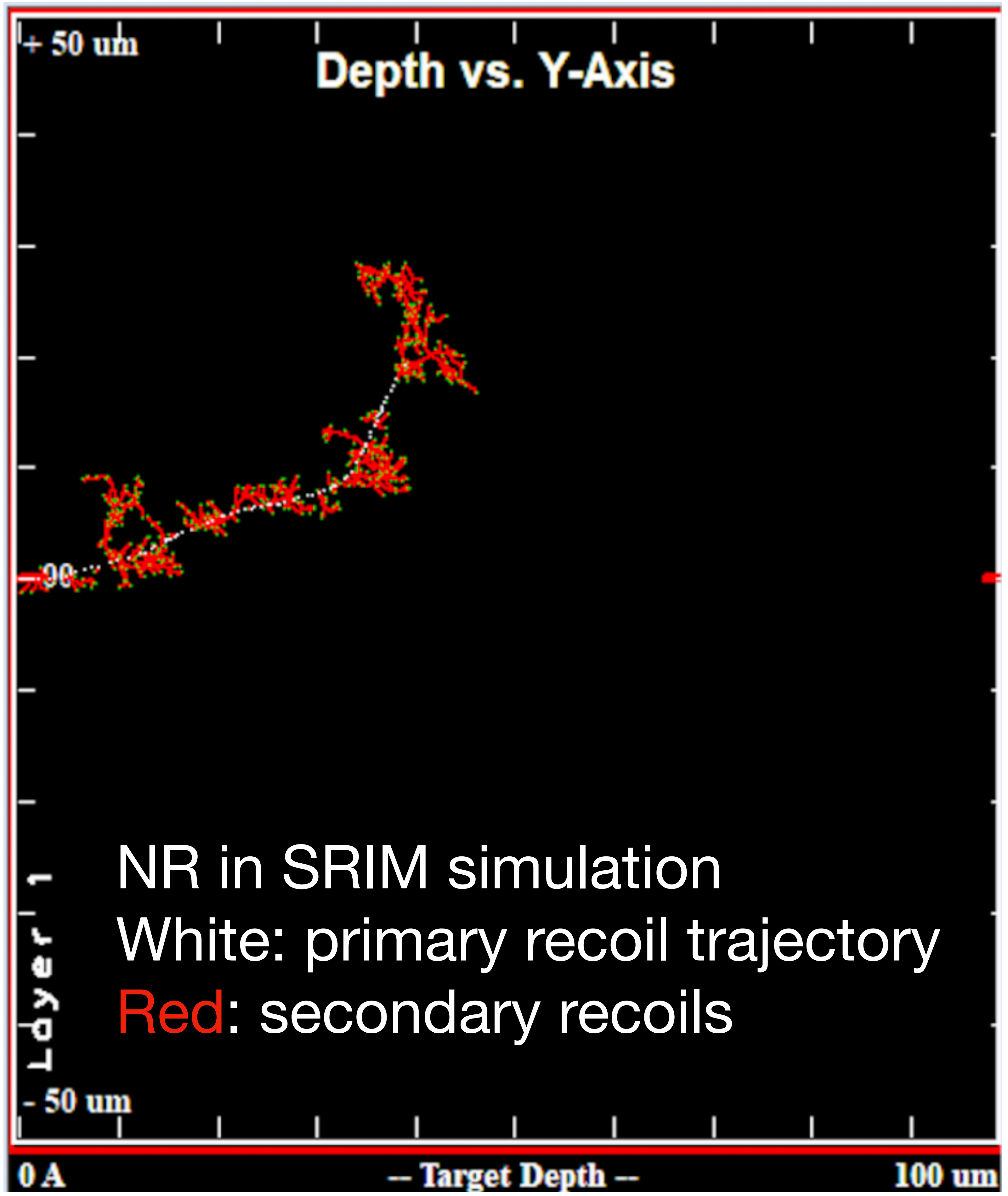
"Coherent elastic neutrino-nucleus scattering with directional detectors"
PRD 102 (2020) 1, 015009
M. Abdullah, D. Aristizabal Sierra, B. Dutta, L. Strigari

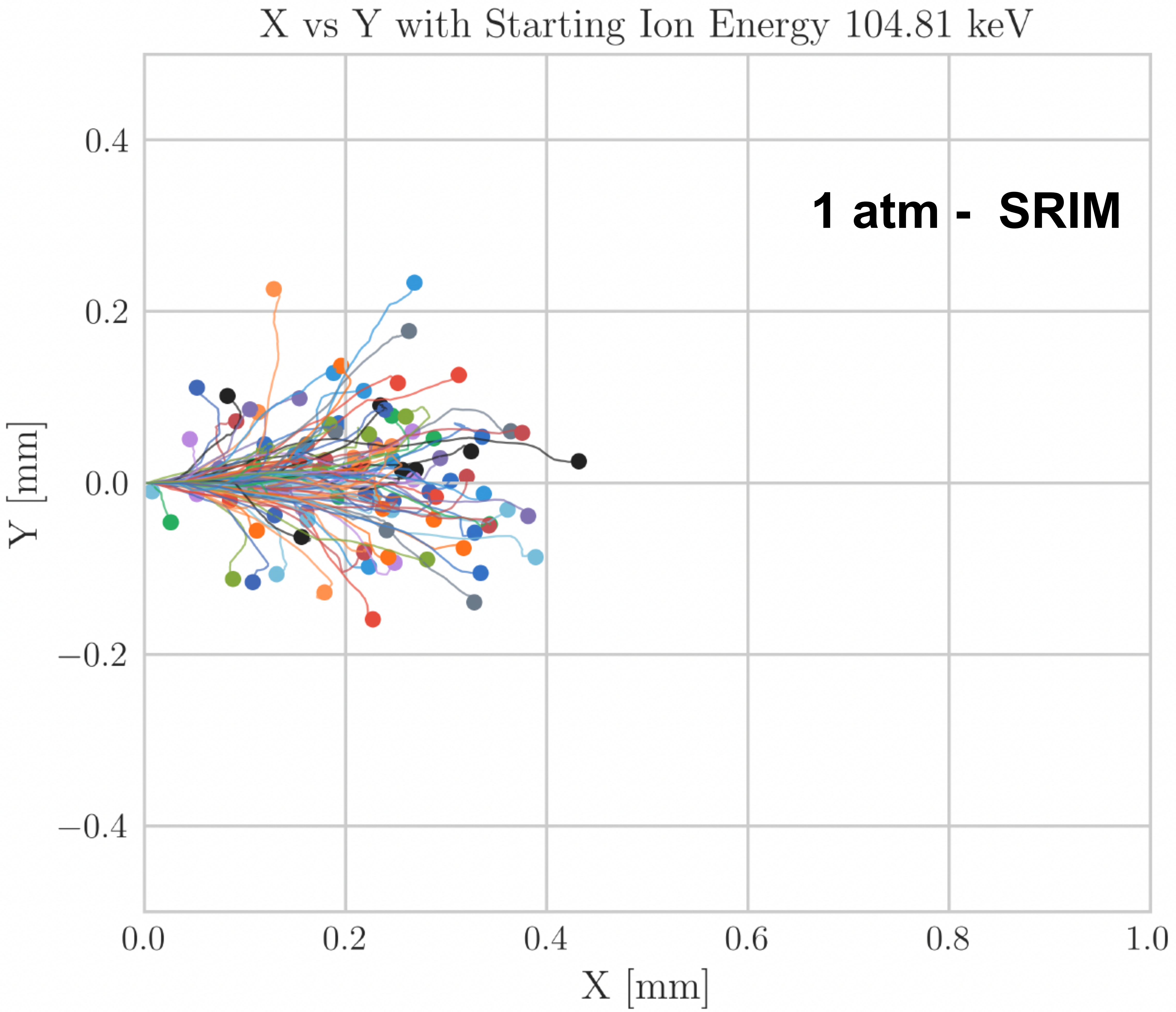
Snowmass Instrumentation Frontier IF08 Topical Group Report: Noble Element Detectors

[https://arxiv.org/abs/2208.11017]

Nuclear Recoil Tracking in GAr

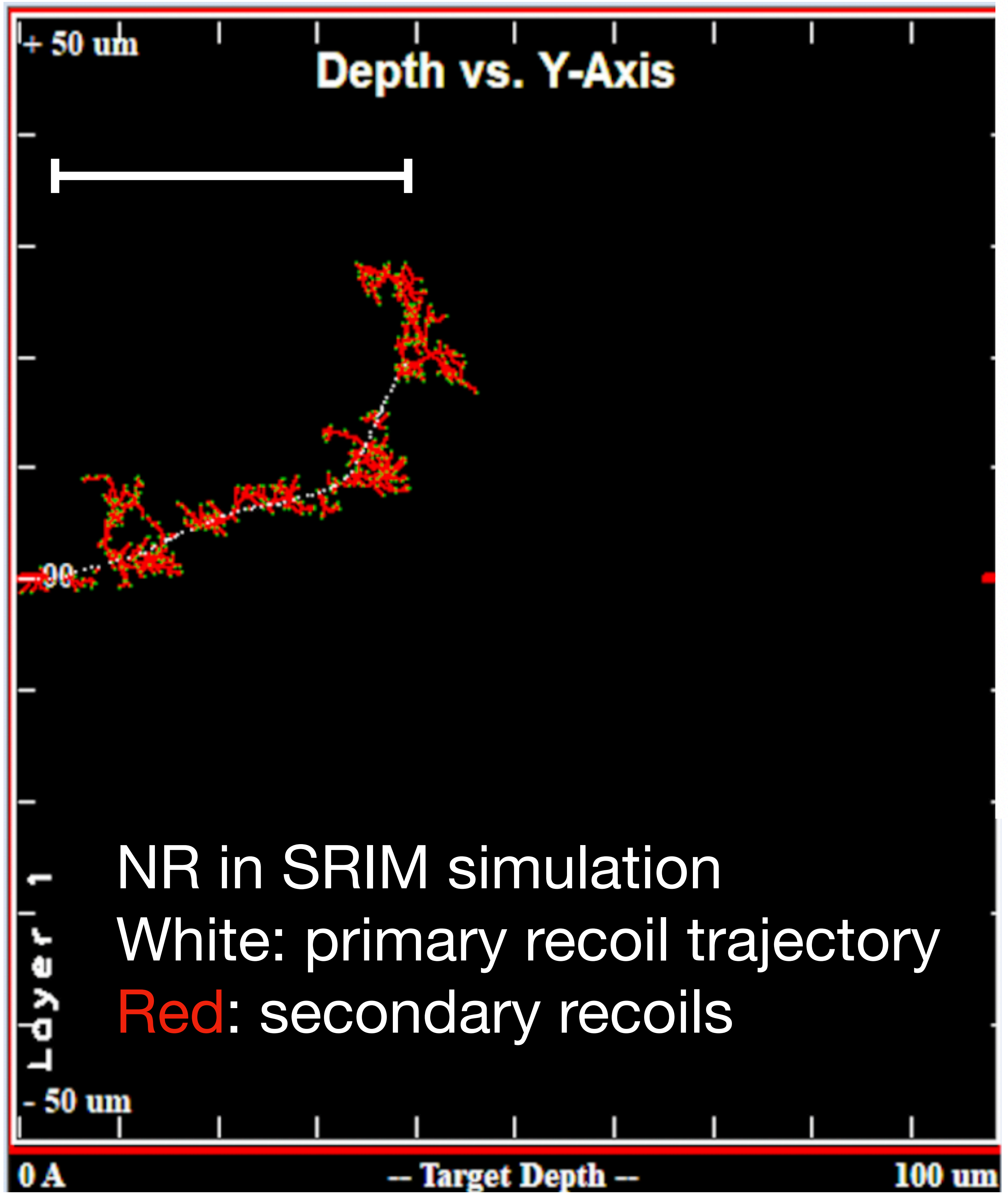
Simulations and feasibility

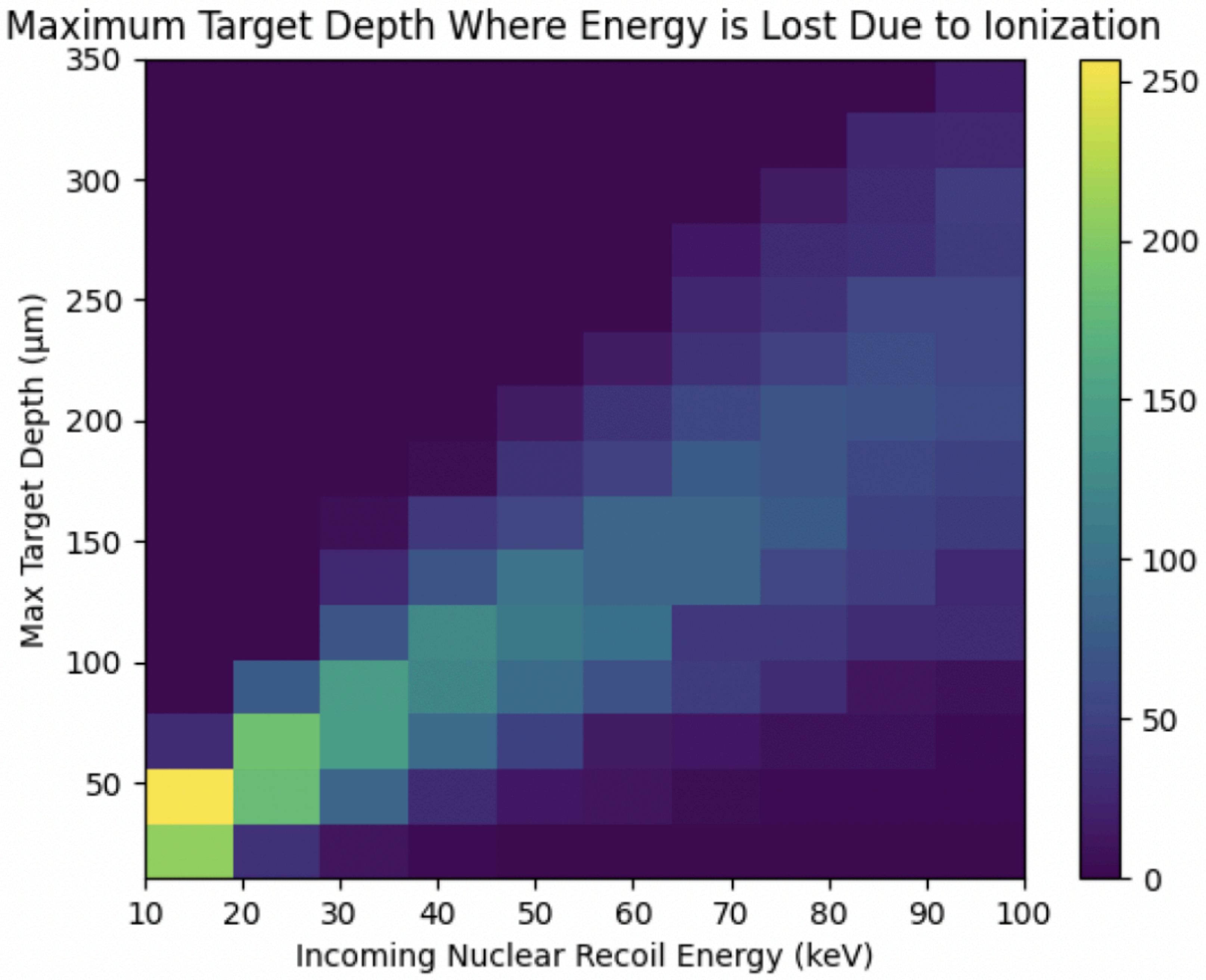




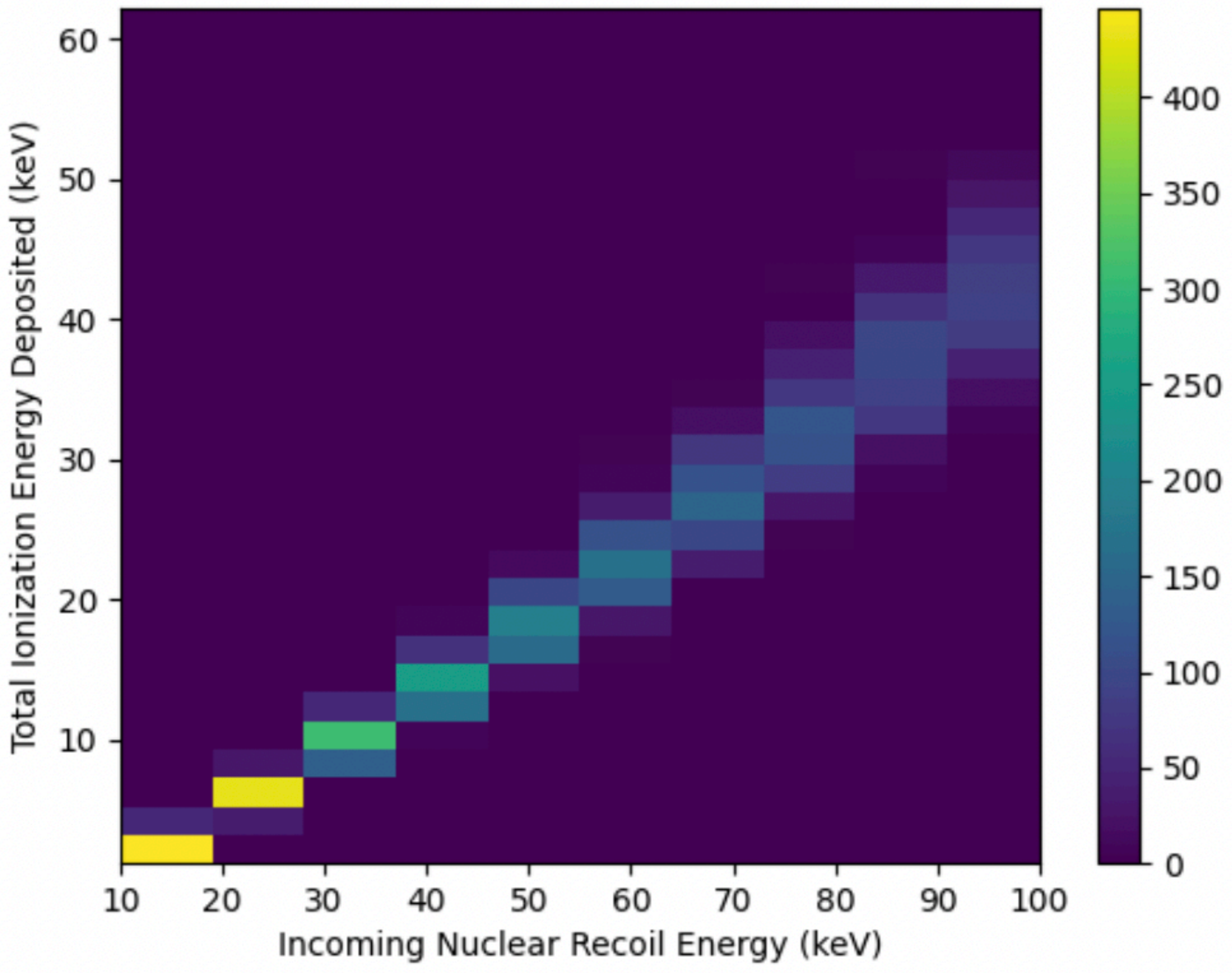
Nuclear Recoil Tracking in GAr

Simulations and feasibility





simulations run at 1 atm



Nuclear Recoil Tracking in GAr

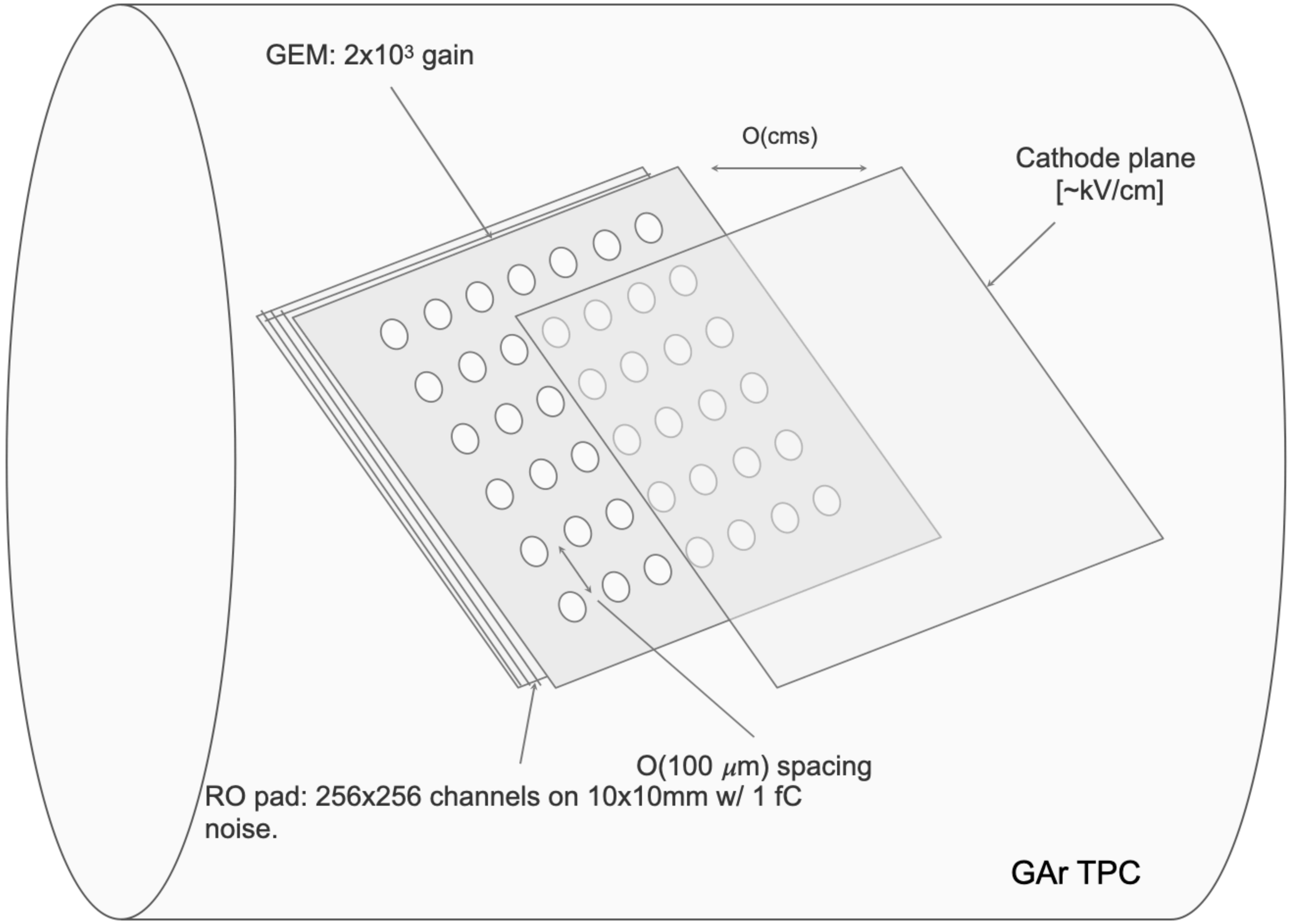
R&D program

Aim to ramp-up gaseous argon TPC development instrumented with GEM

- setup GAr operations @ UCSB
- Acquire and operate GEM
- Proof of principle tracking resolution measurements

This work will in part be supported by HEPCAT “High Energy Physics Consortium for Advanced Training” HEPCAT program

https://hepcat.ucsd.edu/



Nuclear Recoil Tracking in GAr

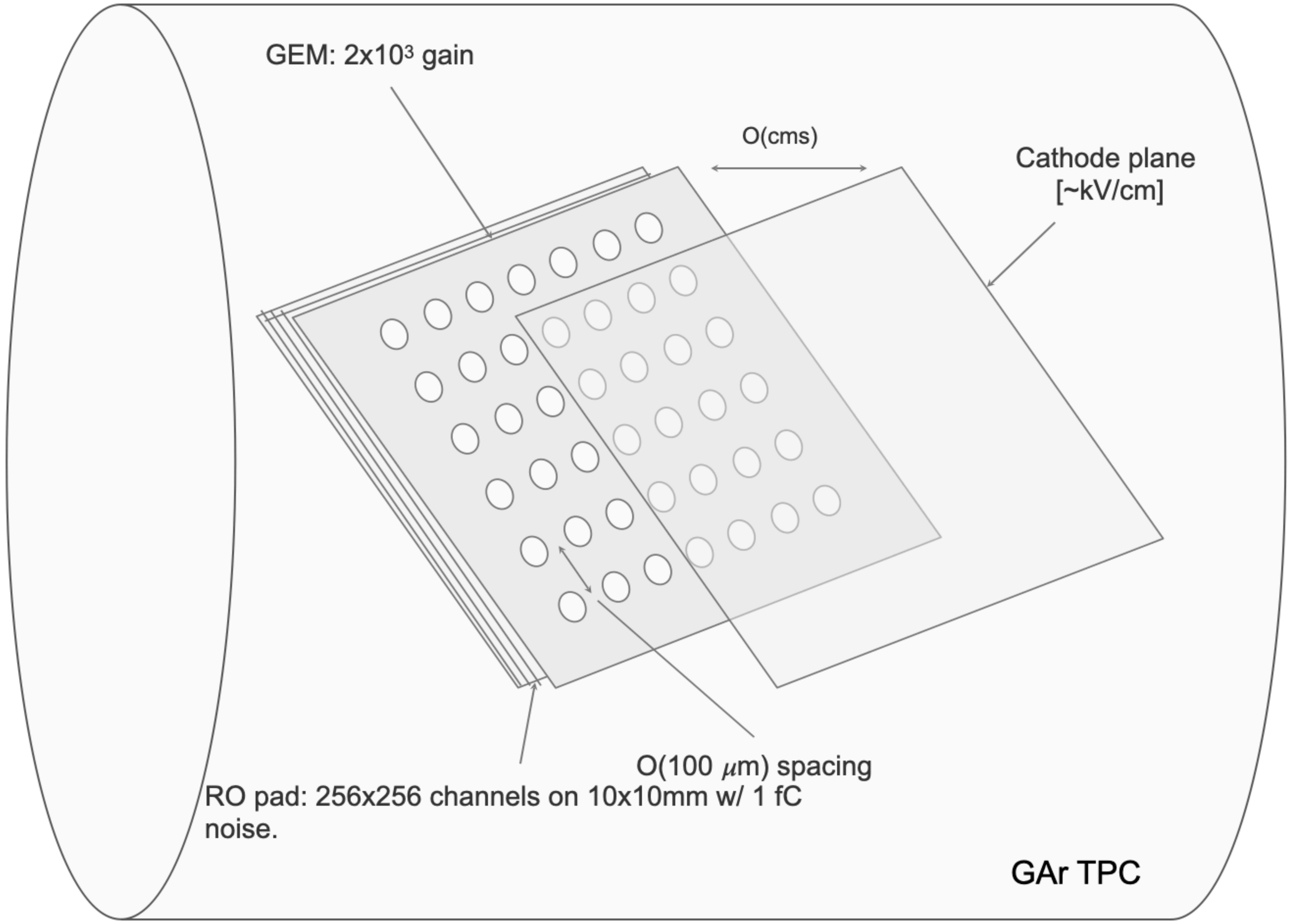
R&D program

Longer-term development

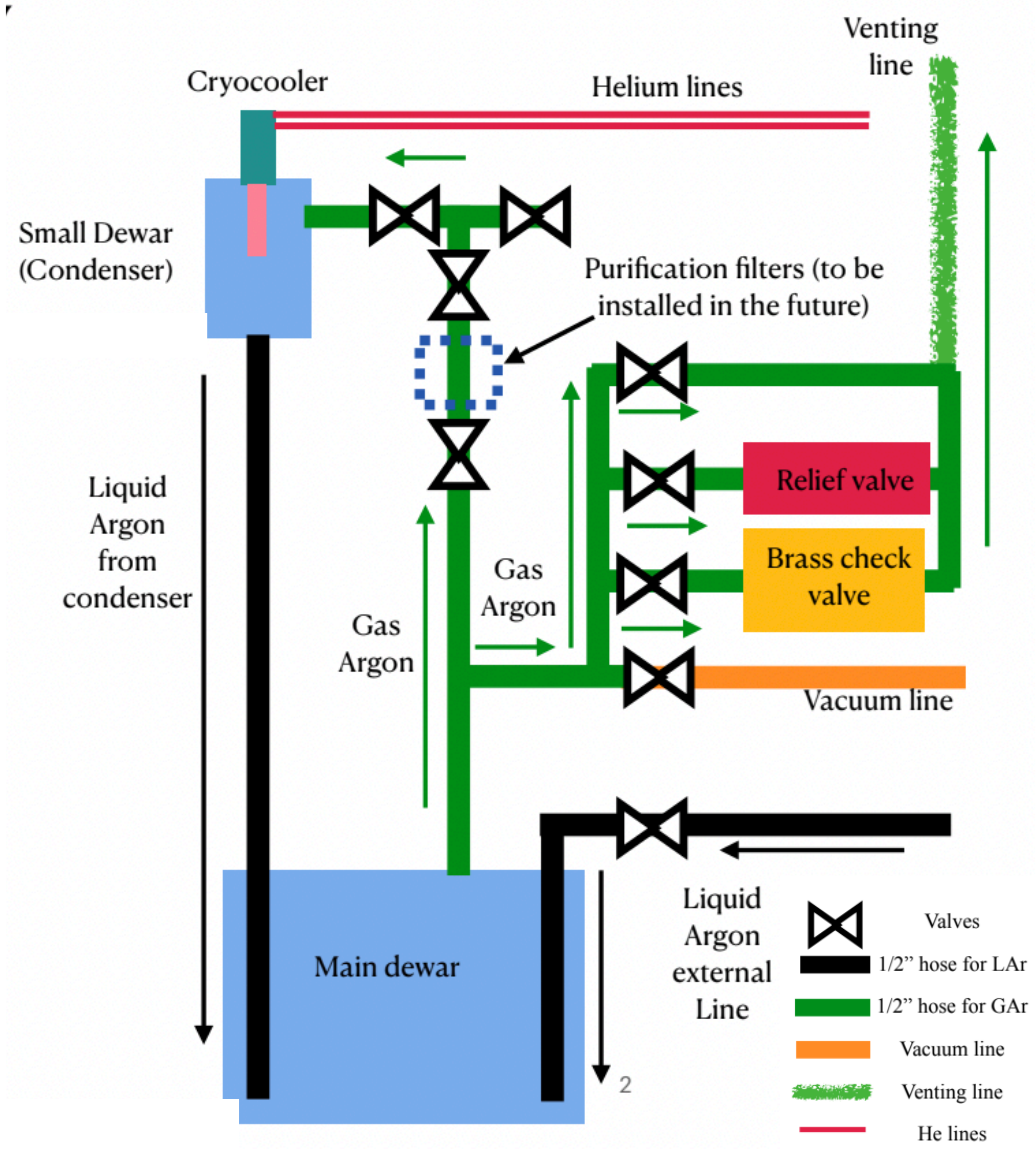
- Tracking proof of principle with Neutron source
- Investigate RO / electronics and GEM upgrades needed for tracking @ 10 atm
- Explore dopants for reduced diffusion

This work will in part be supported by HEPCAT “High Energy Physics Consortium for Advanced Training” HEPCAT program

https://hepcat.ucsd.edu/



Argon R&D @ UCSB

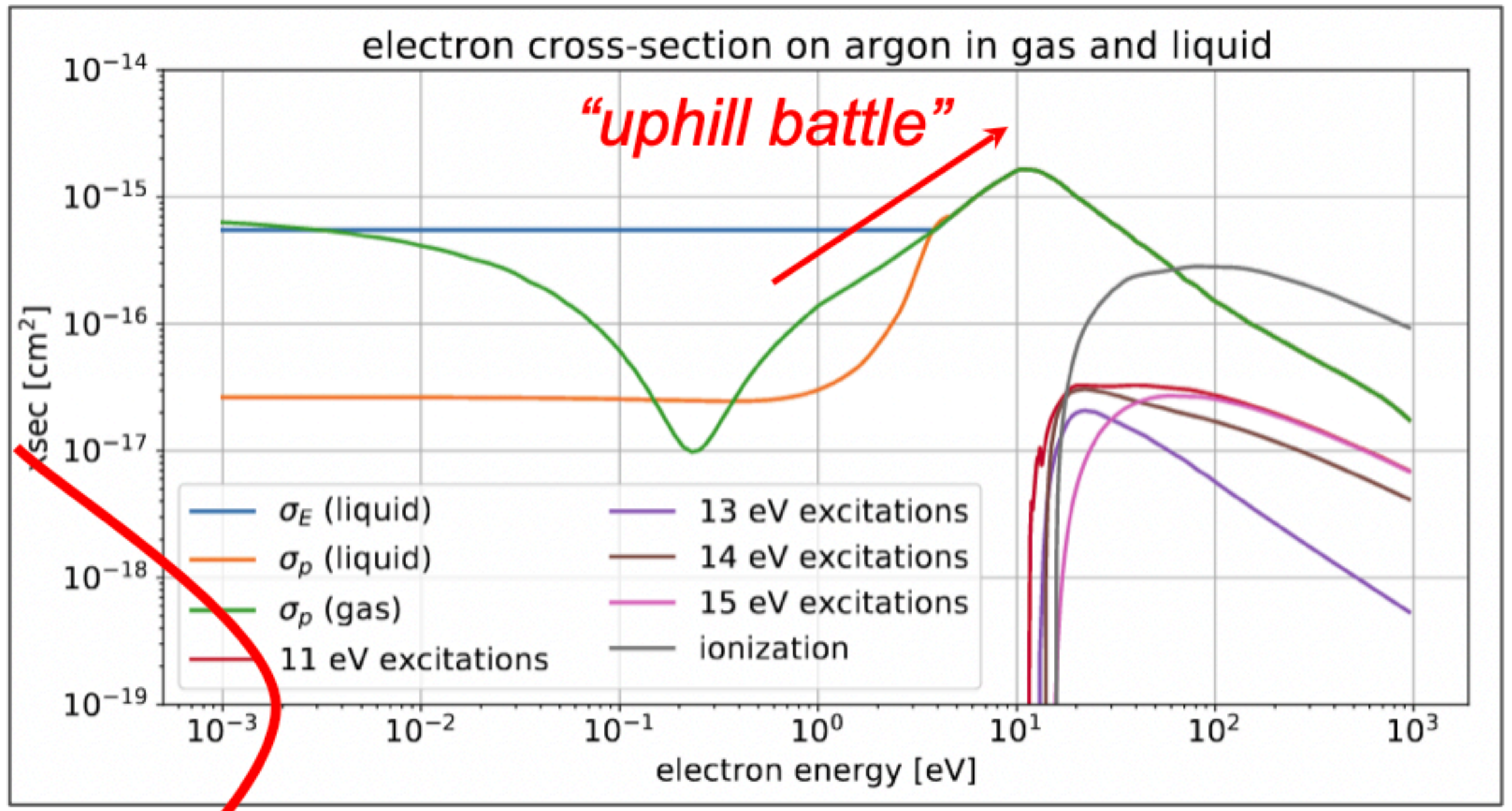


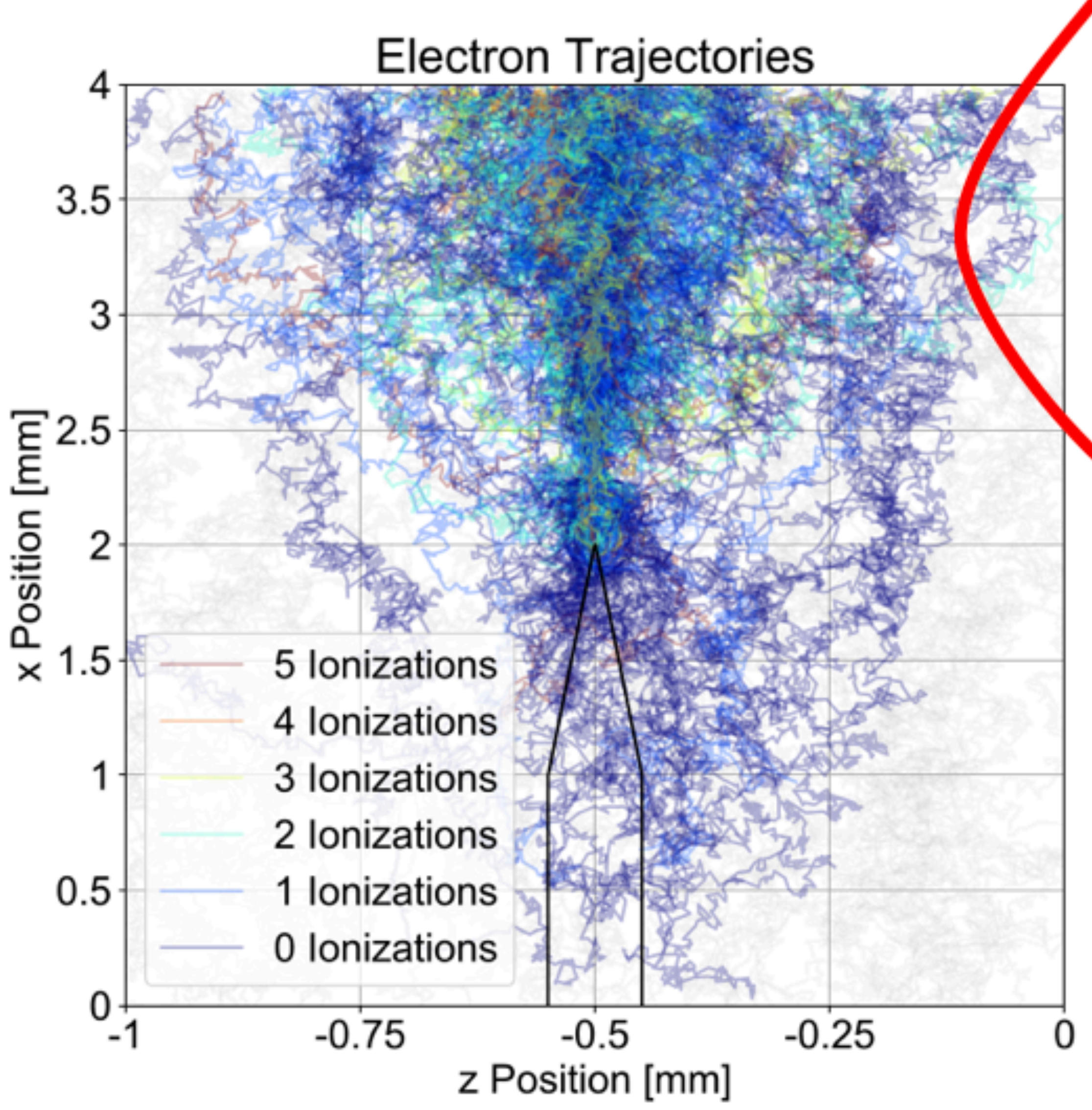
Argon R&D @ UCSB

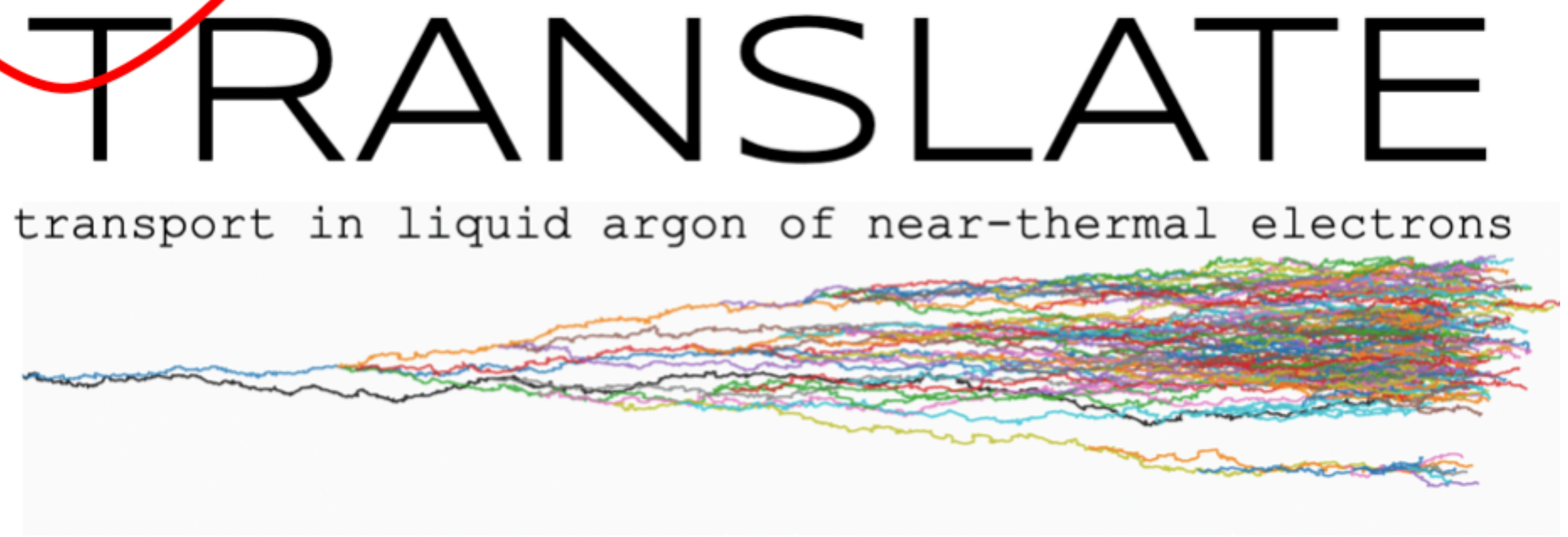
TRANSLATE

TRANSport in Liquid Argon of near-Thermal Electrons

LArCADe







arXiv:2211.12645

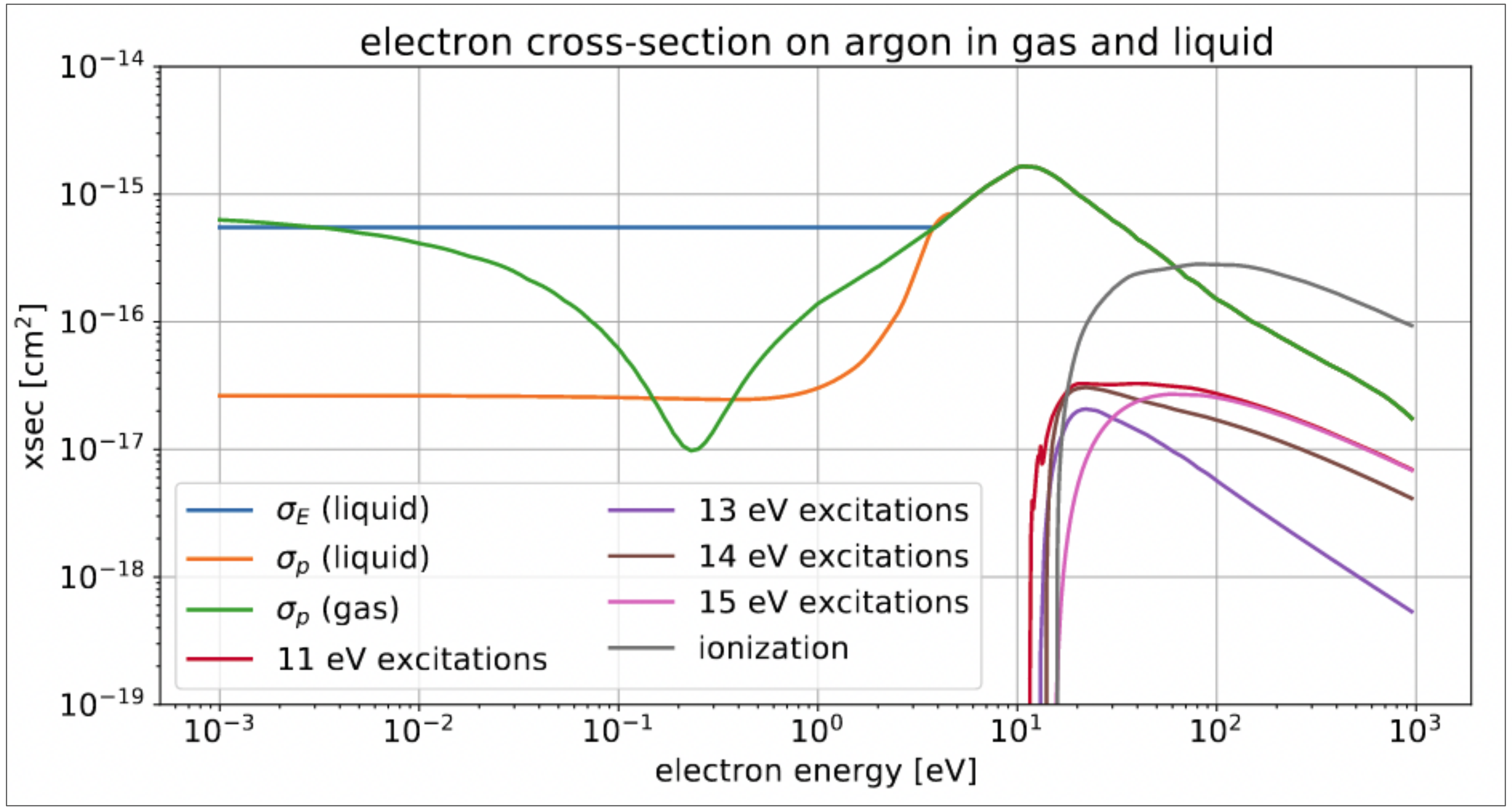
TRANSLATE -- A Monte Carlo Simulation of Electron Transport in Liquid Argon

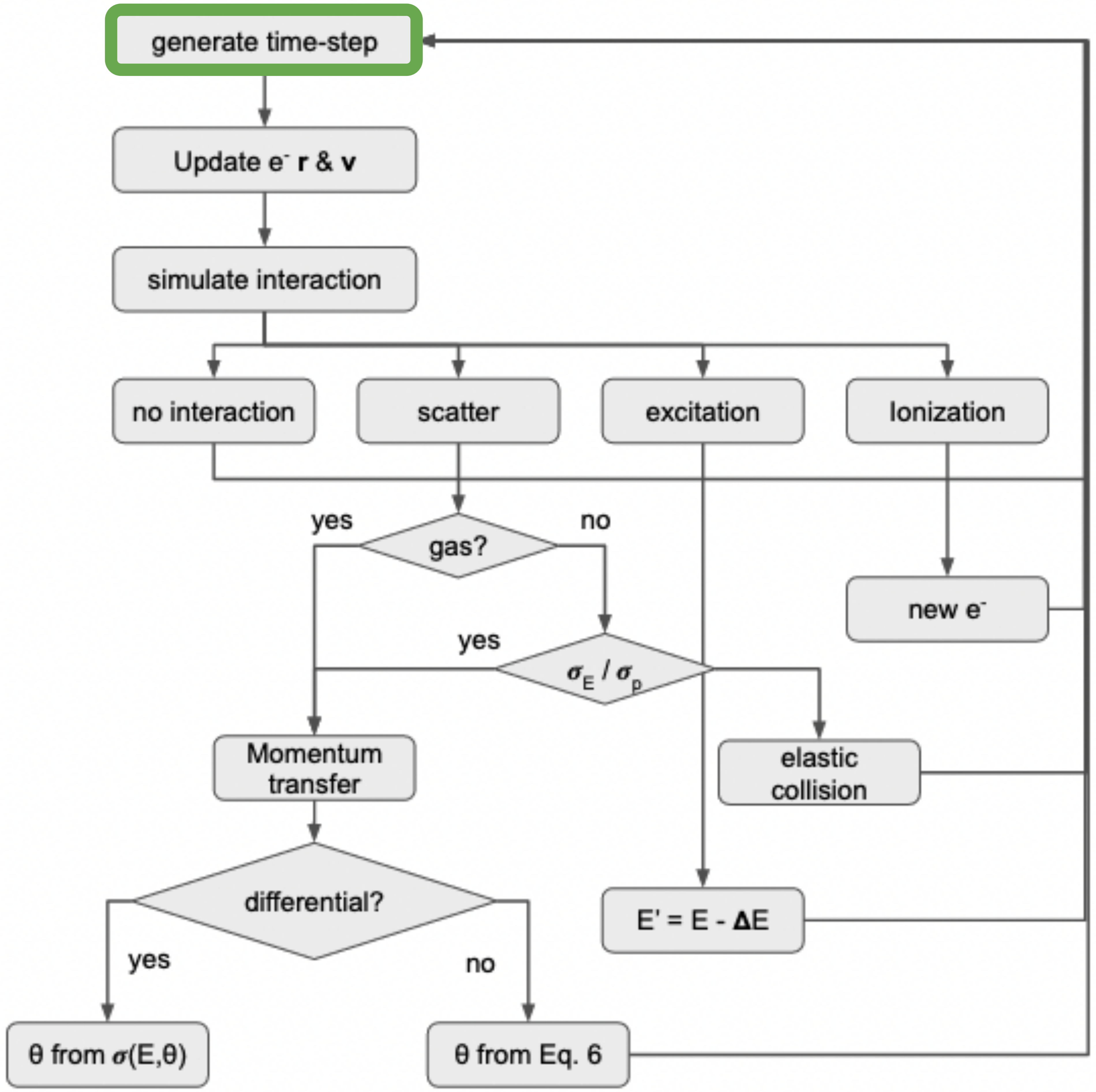
Zach Beever, David Caratelli, Angela Fava, Francesco Pietropaolo, Francesca Stocker, Jacob Zettlemoyer

TRANSLATE: Monte Carlo simulation

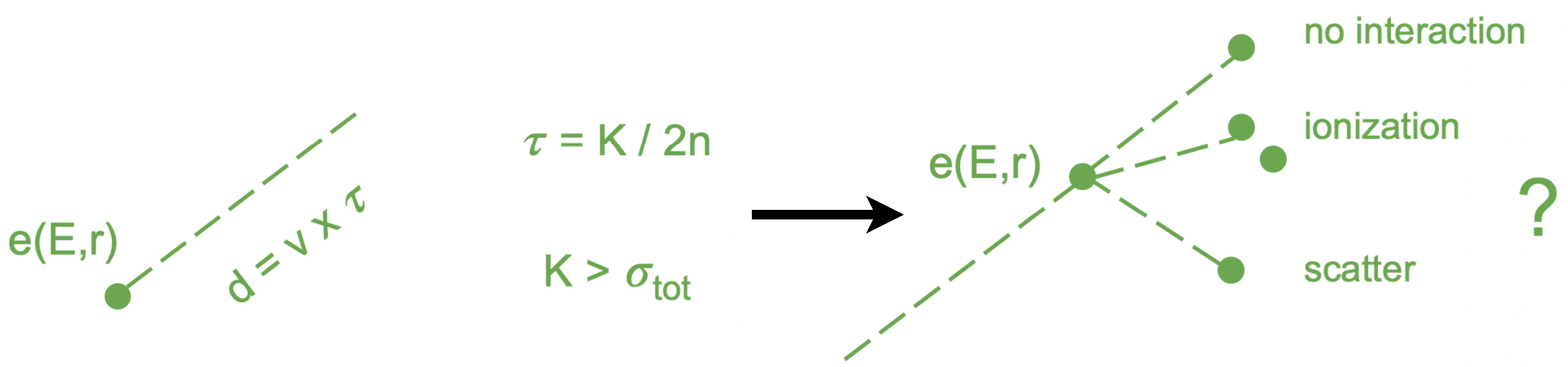
$\tau = K / 2n$

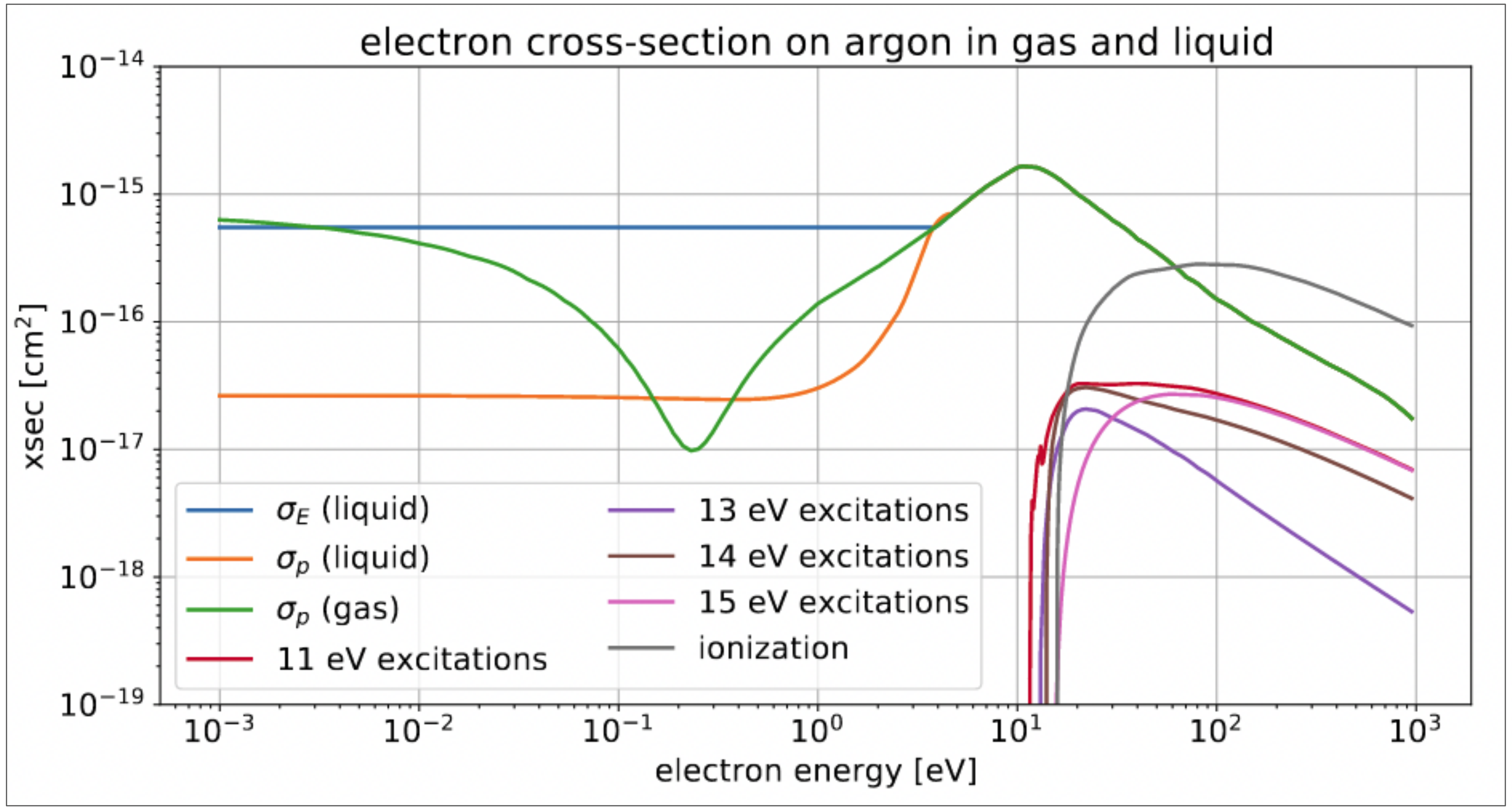
$K > \sigma_{tot}$

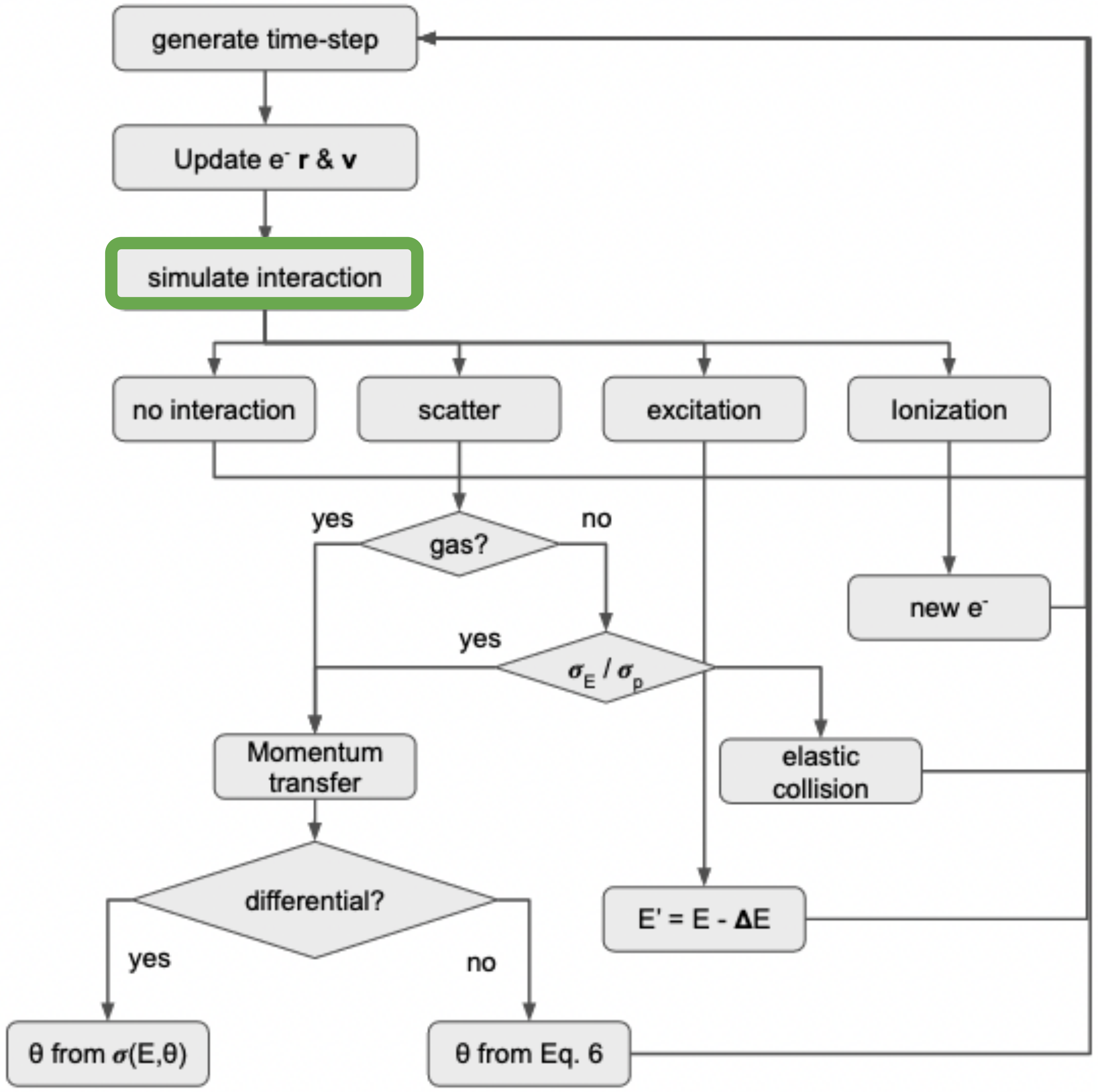




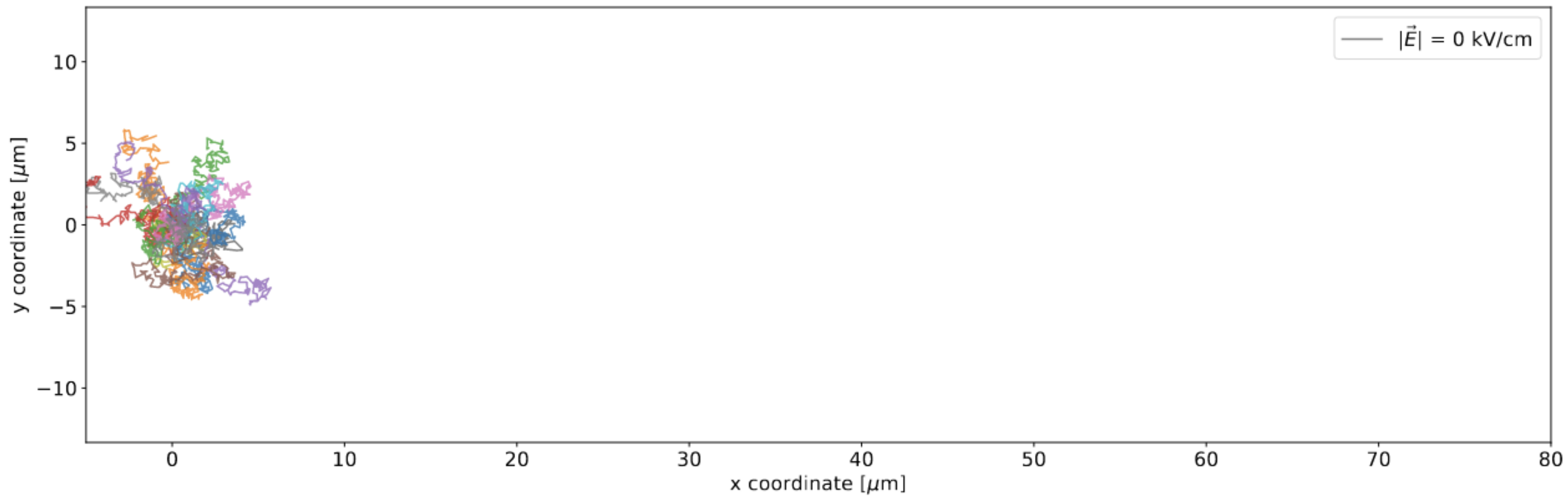
TRANSLATE: Monte Carlo simulation

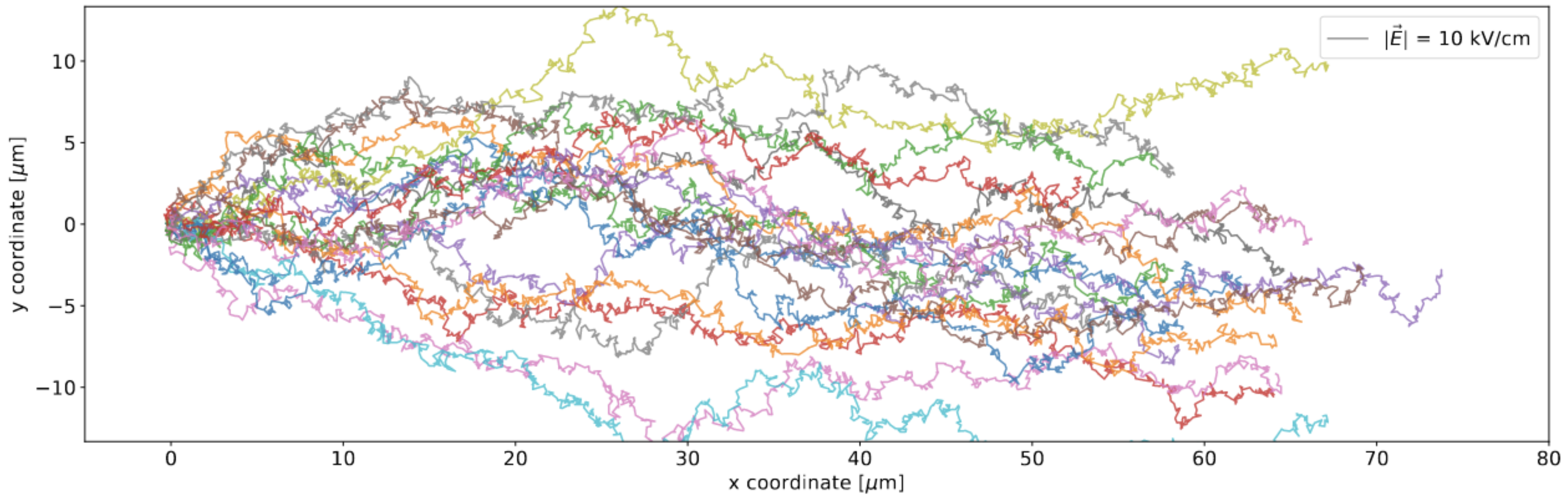






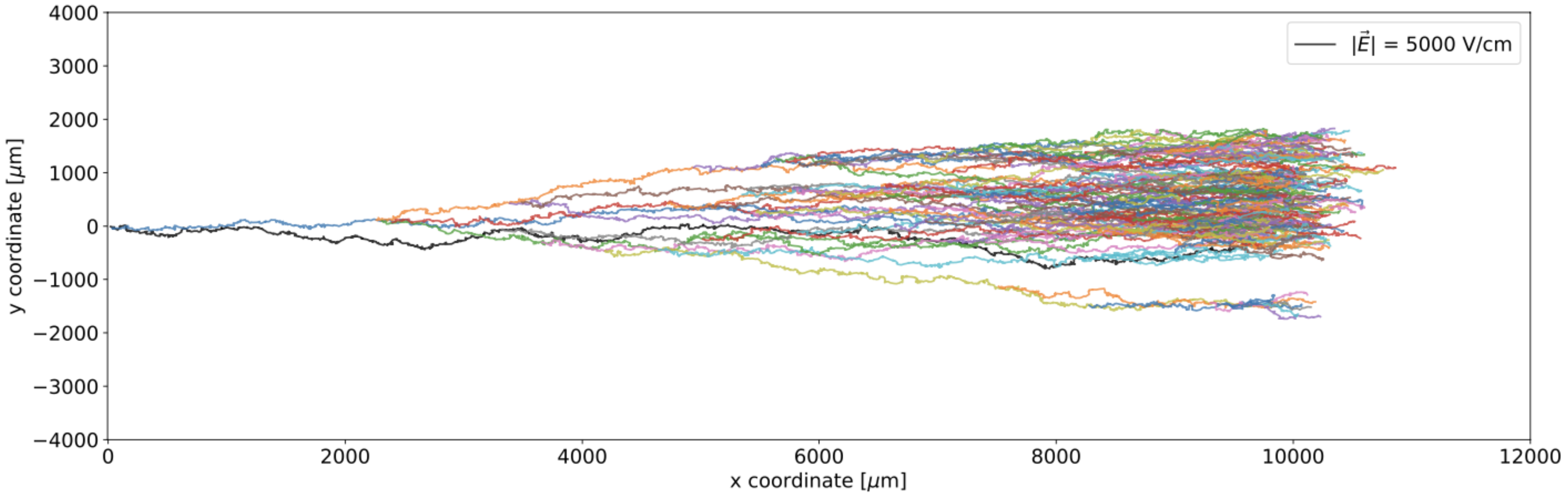
TRANSLATE: simulation output

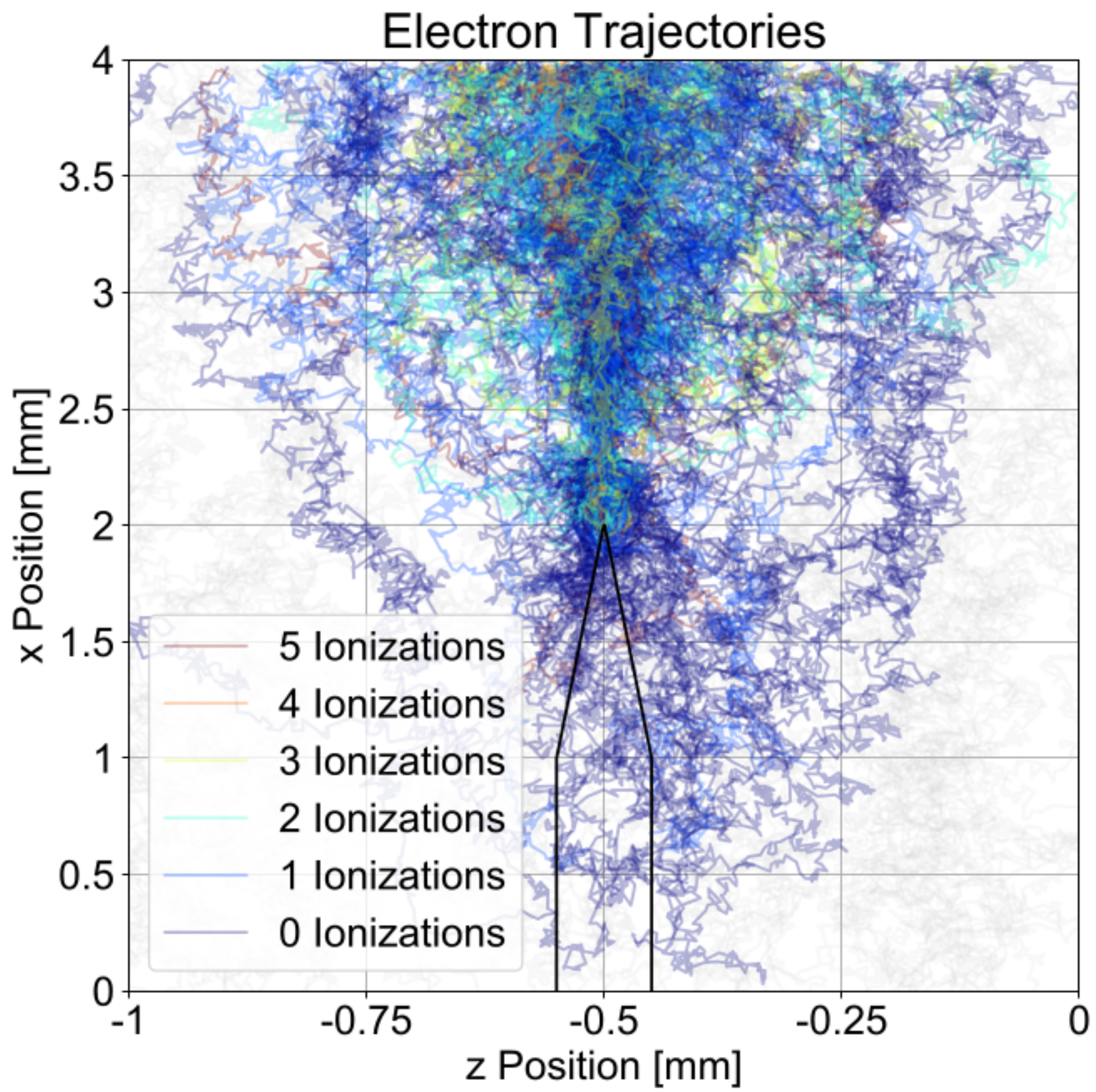




TRANSLATE: simulation output

Simulation of electron amplification in complex geometries



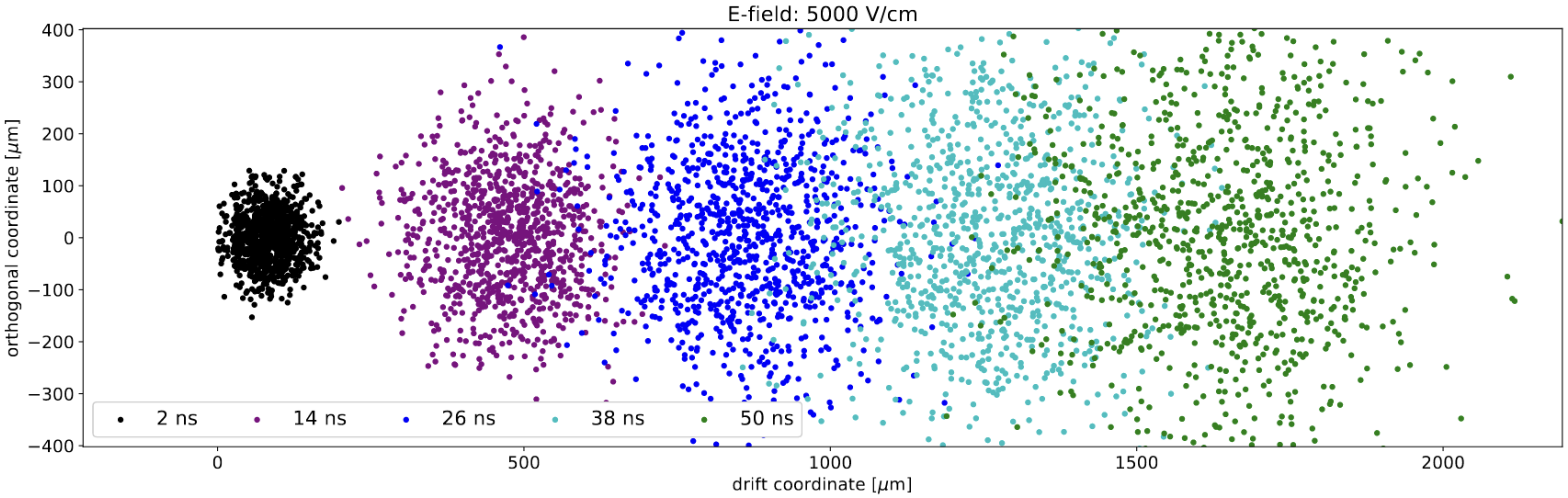


TRANSLATE: simulation validation

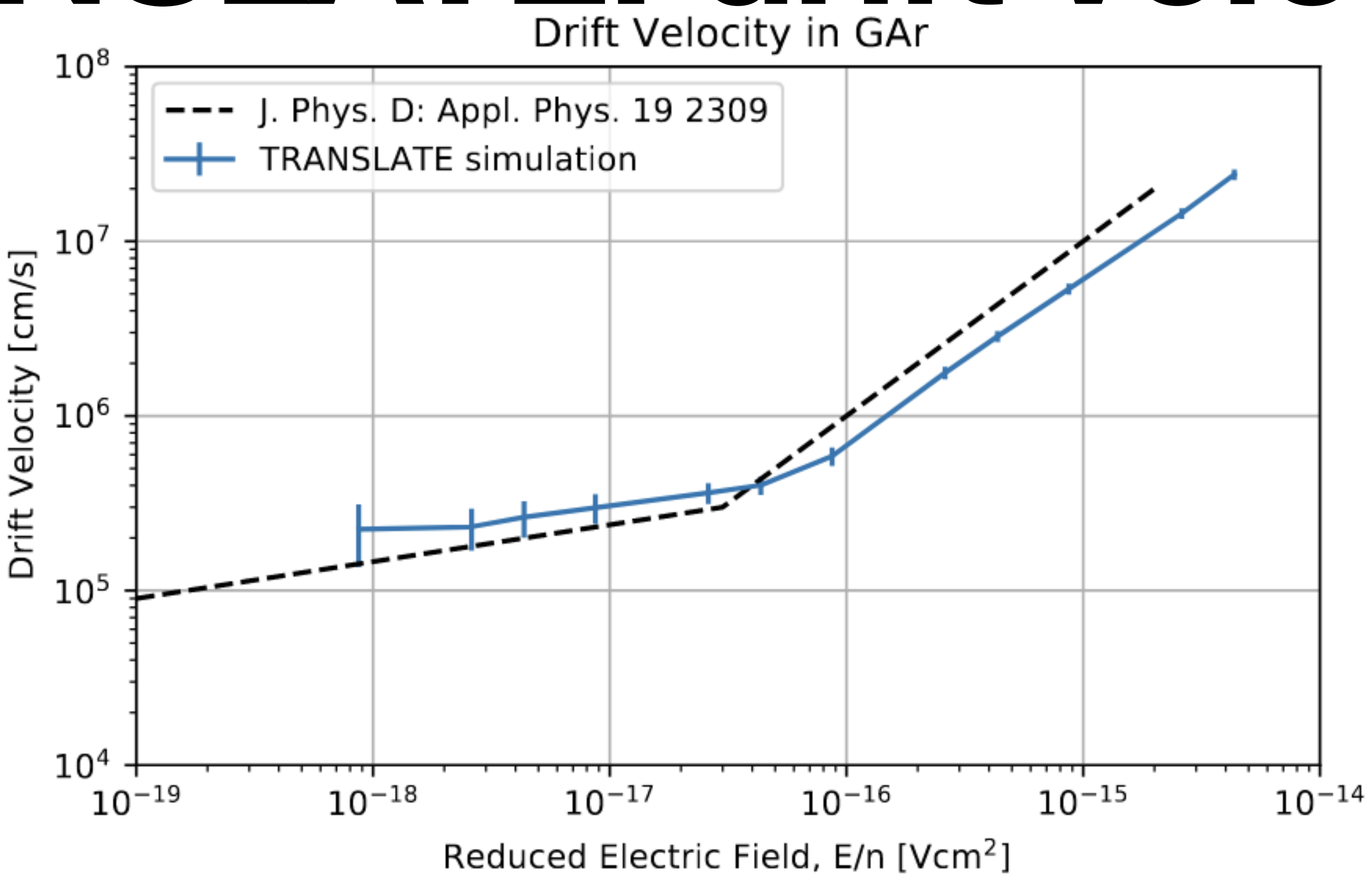
Track O(10^2 – 10^3) electrons over time intervals of 10^{-9} – 10^{-6} seconds.

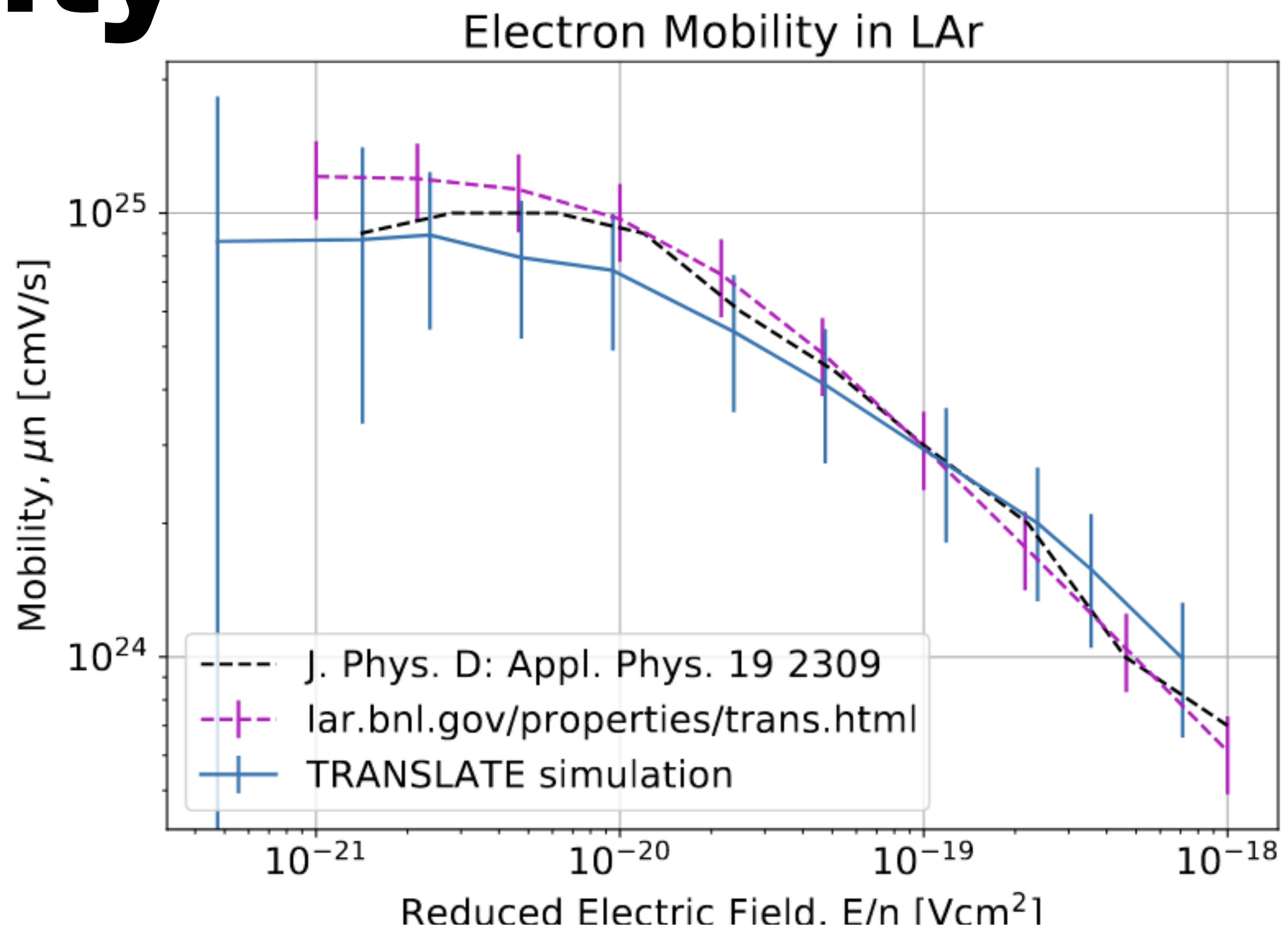
Track as a function of E-field:

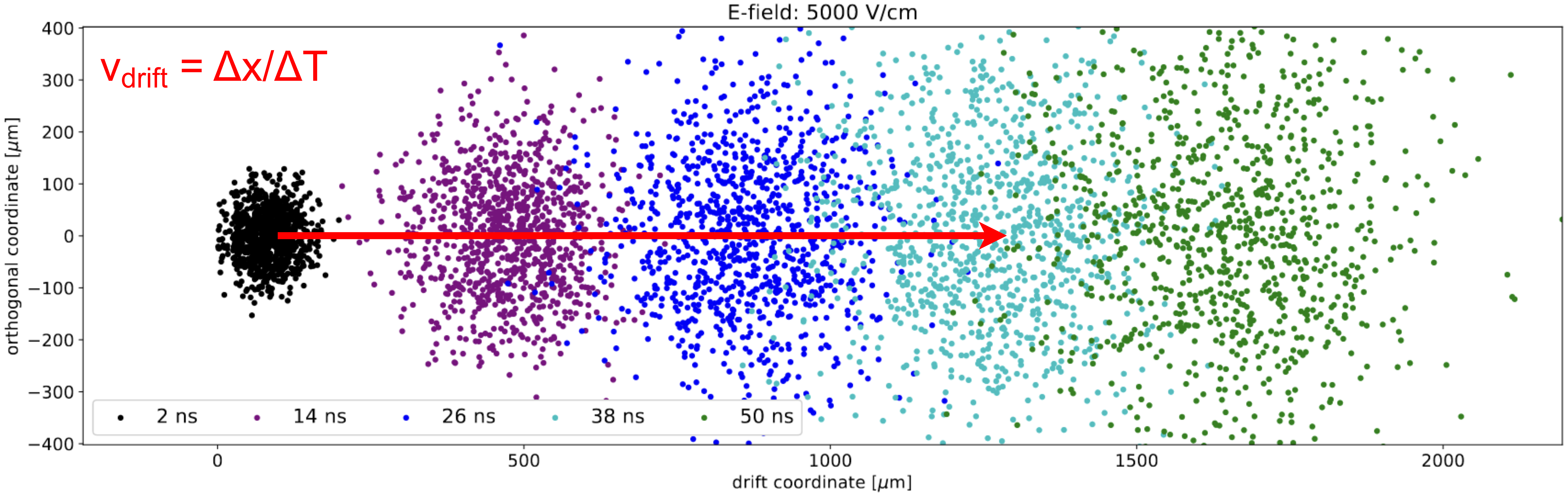
1. Average distance traveled → drift velocity [GAr & LAr]
2. Spread in electron clouds → diffusion [GAr & LAr]
3. Amplification [GAr]



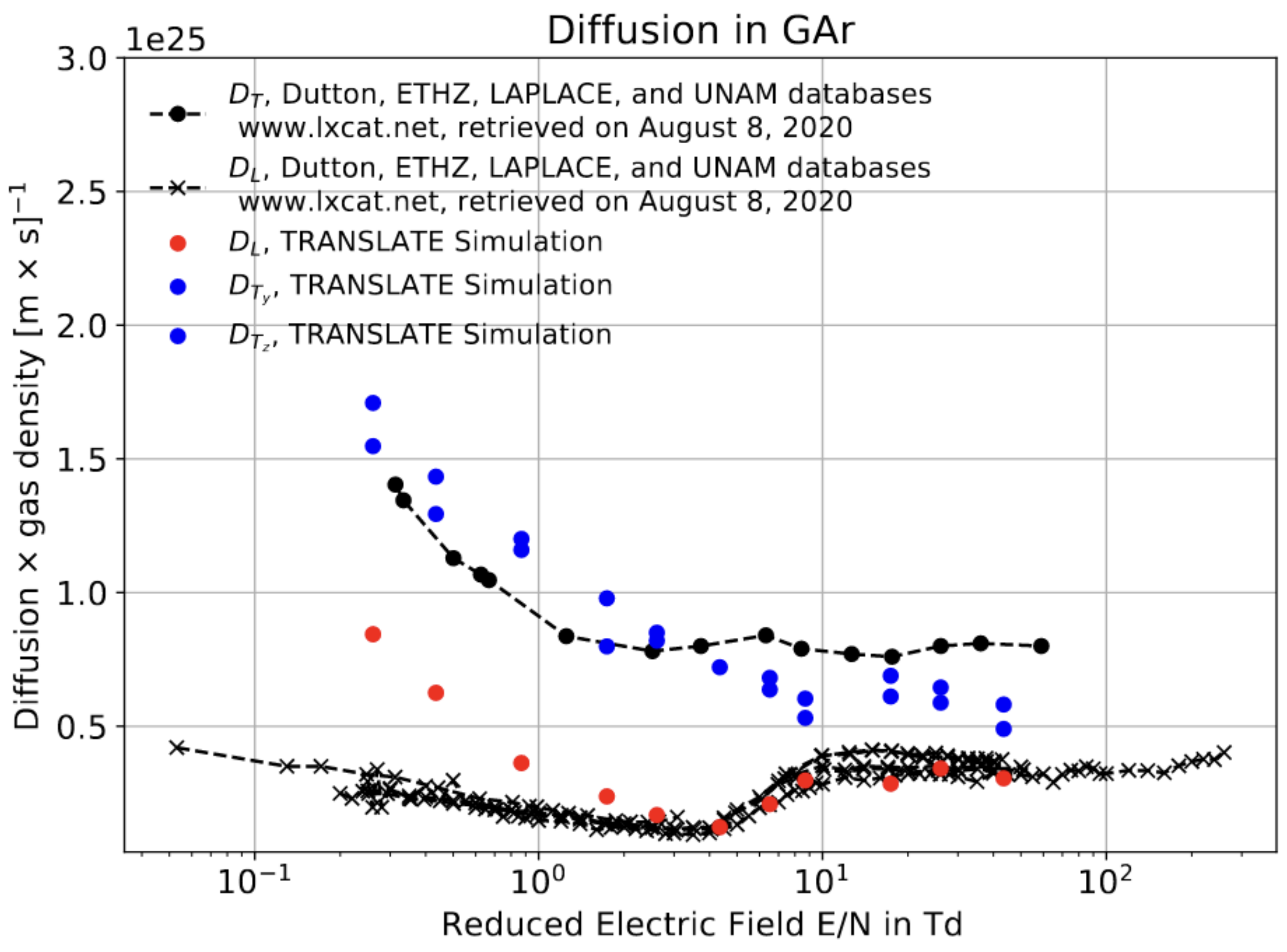
TRANSLATE: drift velocity

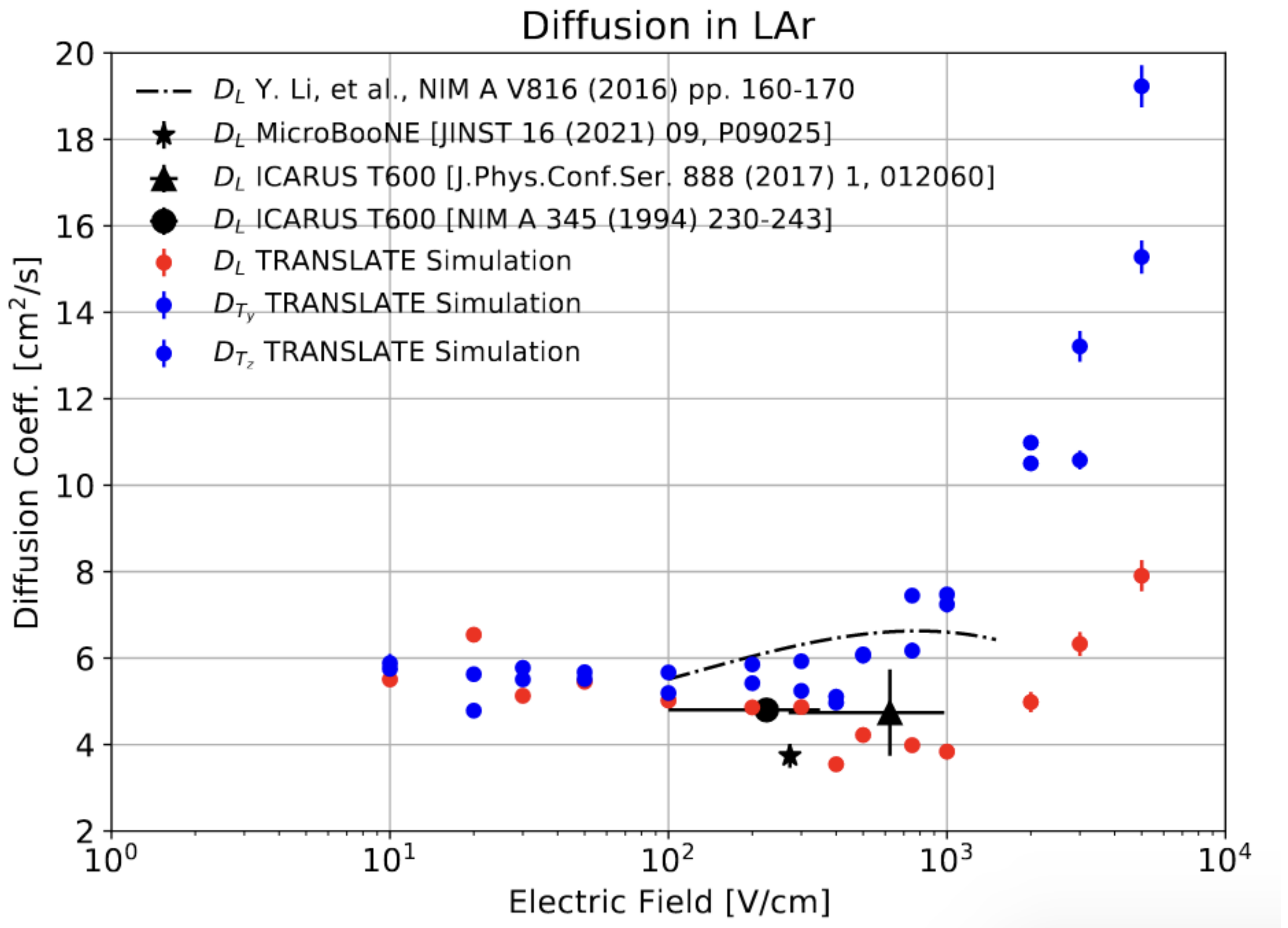


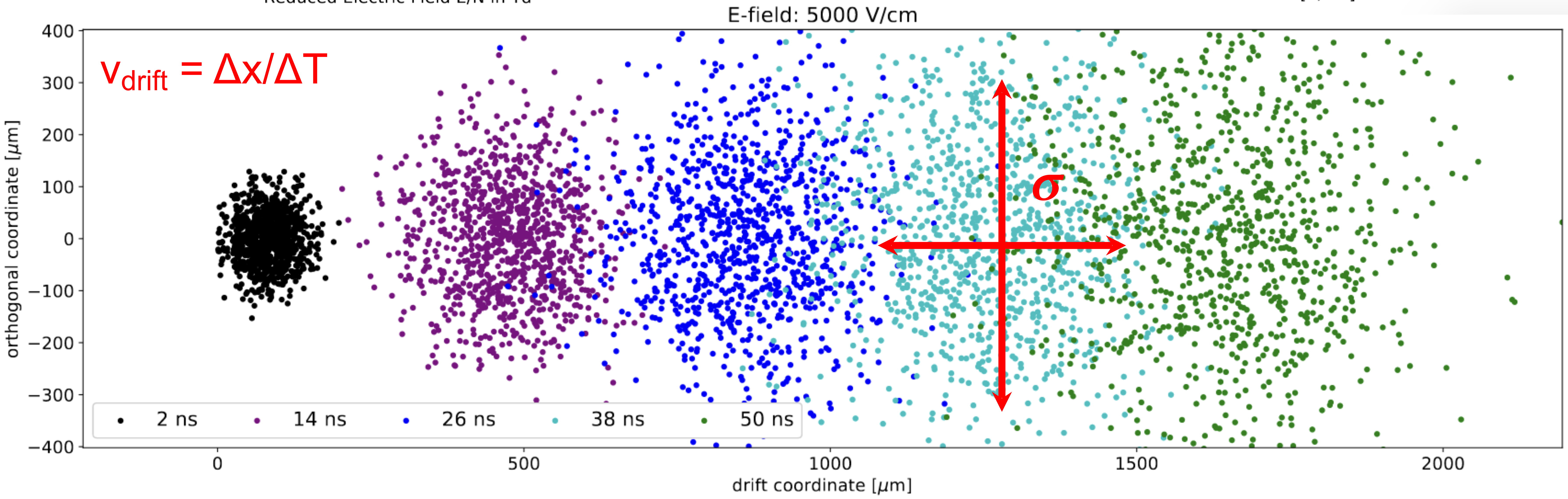




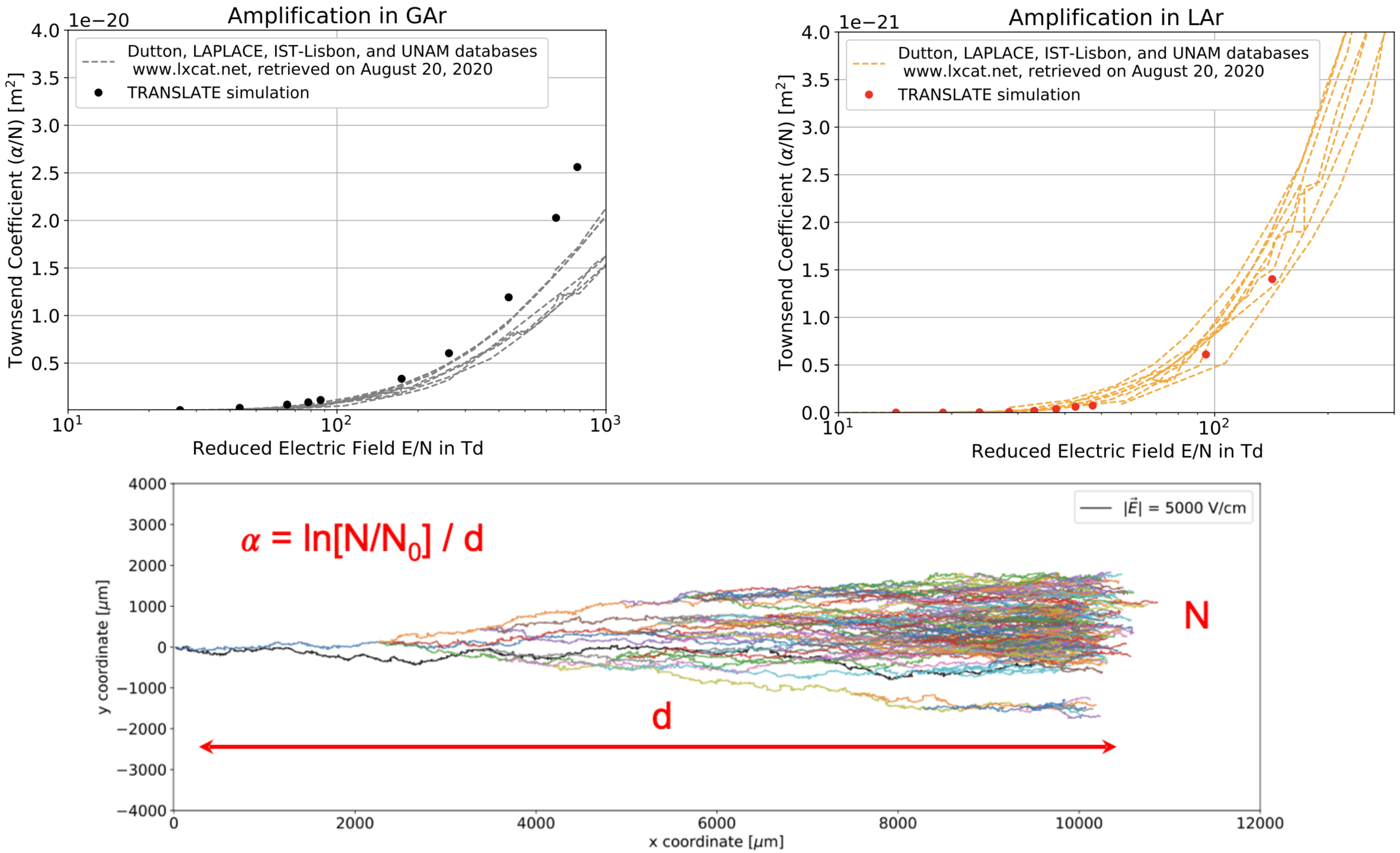
TRANSLATE: ion diffusion







TRANSLATE: charge amplification



Summary

- Measurement of CEvNS by COHERENT brings a new exciting tool to neutrino physics
- Nuclear Recoil imaging "next frontier" for CEvNS
- Strong synergy and complementarity with existing neutrino program
  - Oscillations, astrophysics, BSM searches all benefit from E_ν measurements!
- Involved in two specific R&D efforts aligned with CYGNUS' goals
  - LArCADe + GAr TPC for NR development. Eager to collaborate!

Backup