Nuclear Recoil Imaging in Argon

Magnificent CEνNS 2024 - Valencia, Spain

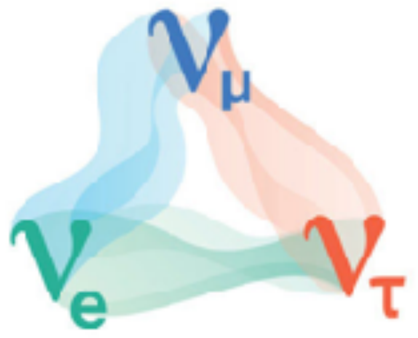
David Caratelli[1], Angela Fava[2], Jacob Zettlemoyer[2], Alexander Antonakis[1] - June 14th 2024

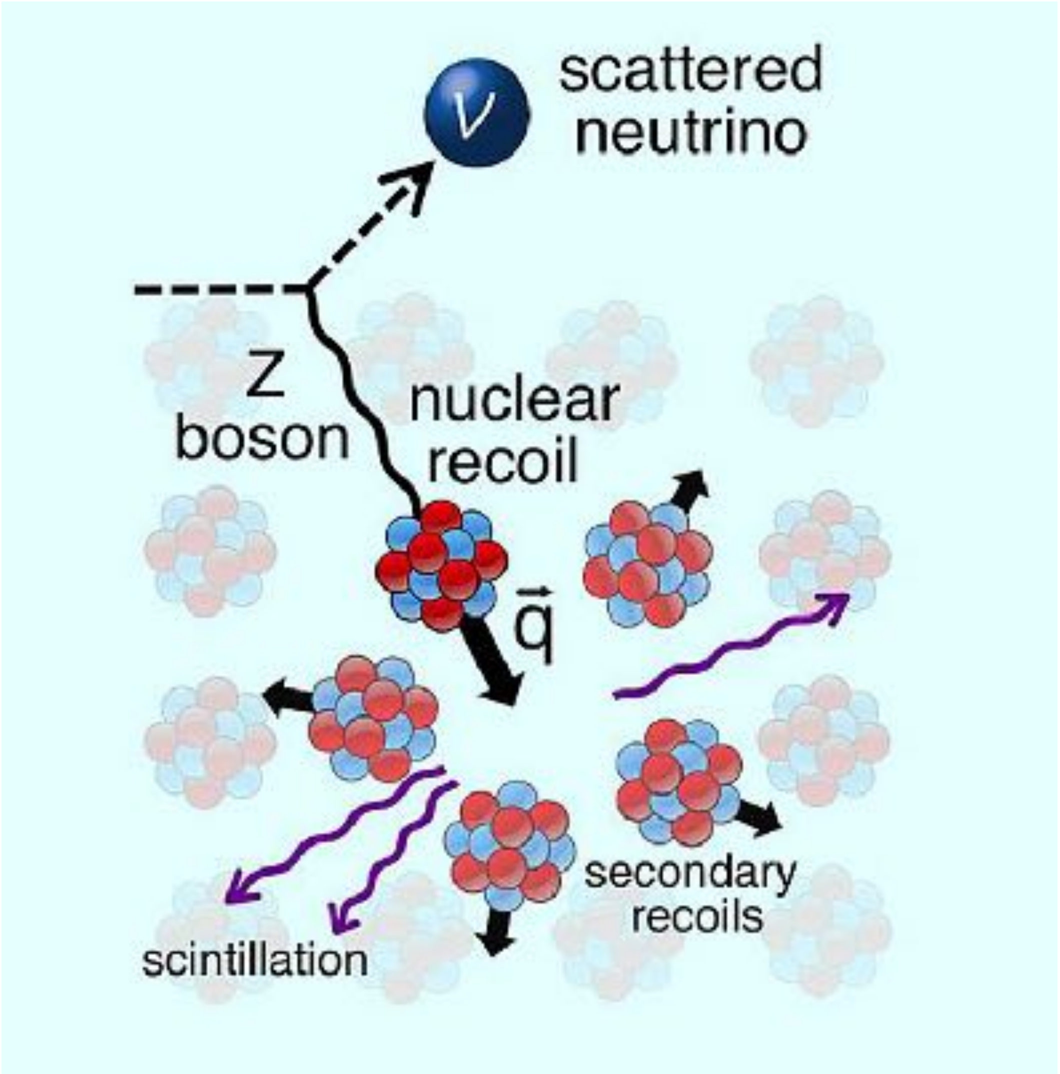
[1] UC Santa Barbara
[2] Fermilab

NR Directionality for Neutrinos

Directional detection of Nuclear Recoil signature in CEvNS:

- neutrino spectroscopy

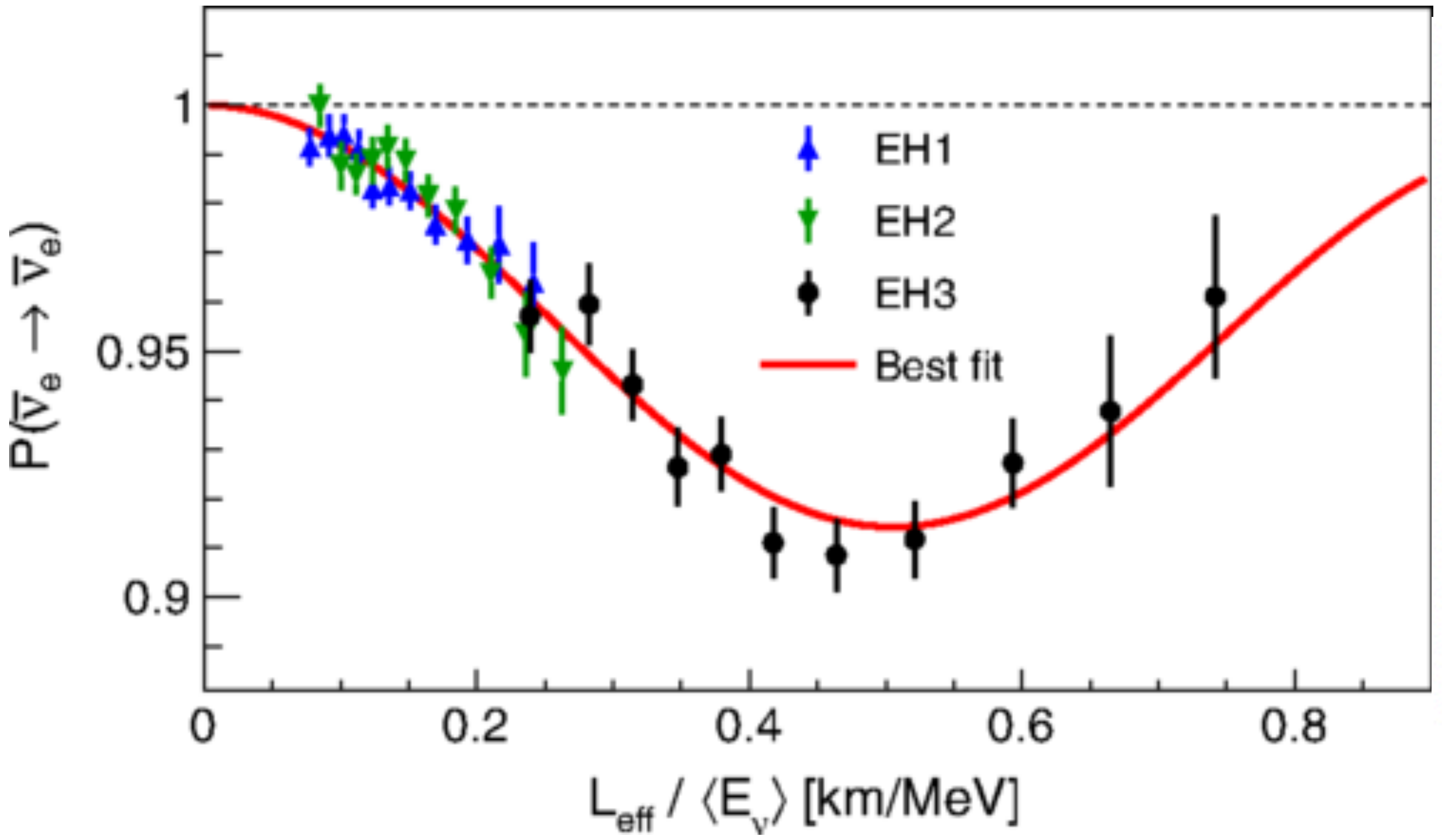




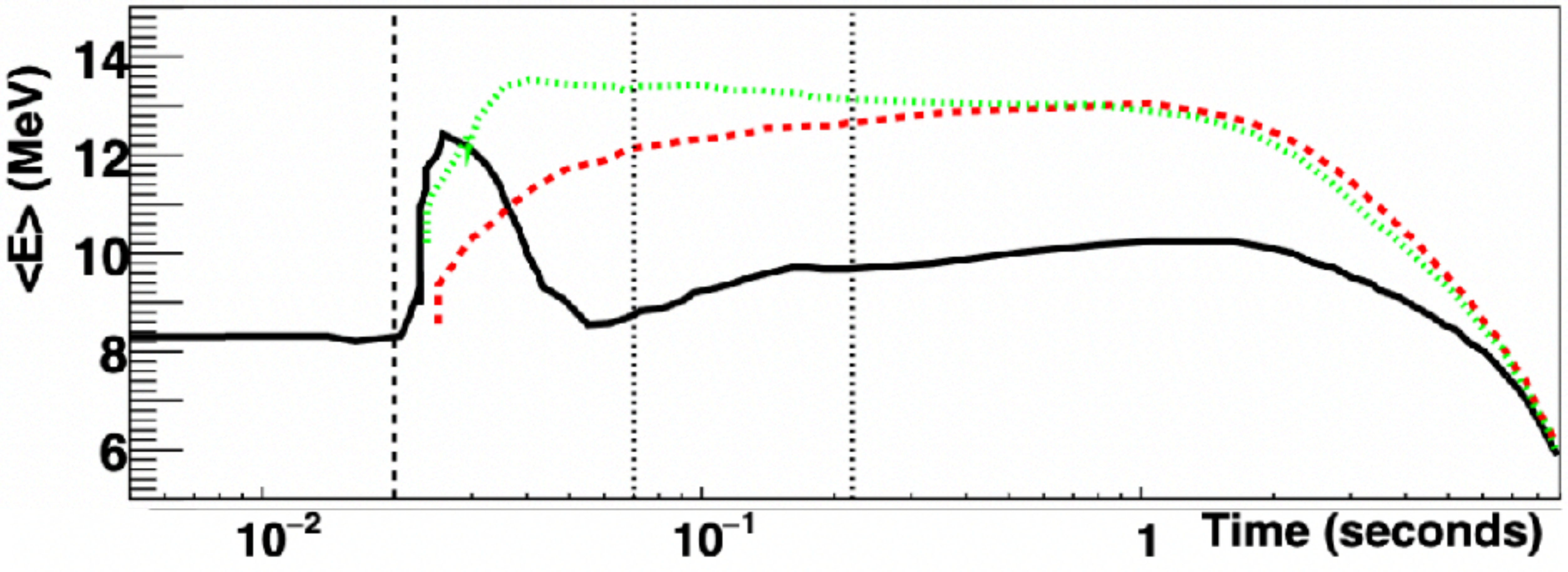
$$E_r = \frac{2m_N E_\nu^2 \cos^2\theta_r}{(E_\nu + m_N)^2 - E_\nu^2 \cos^2\theta_r}$$

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

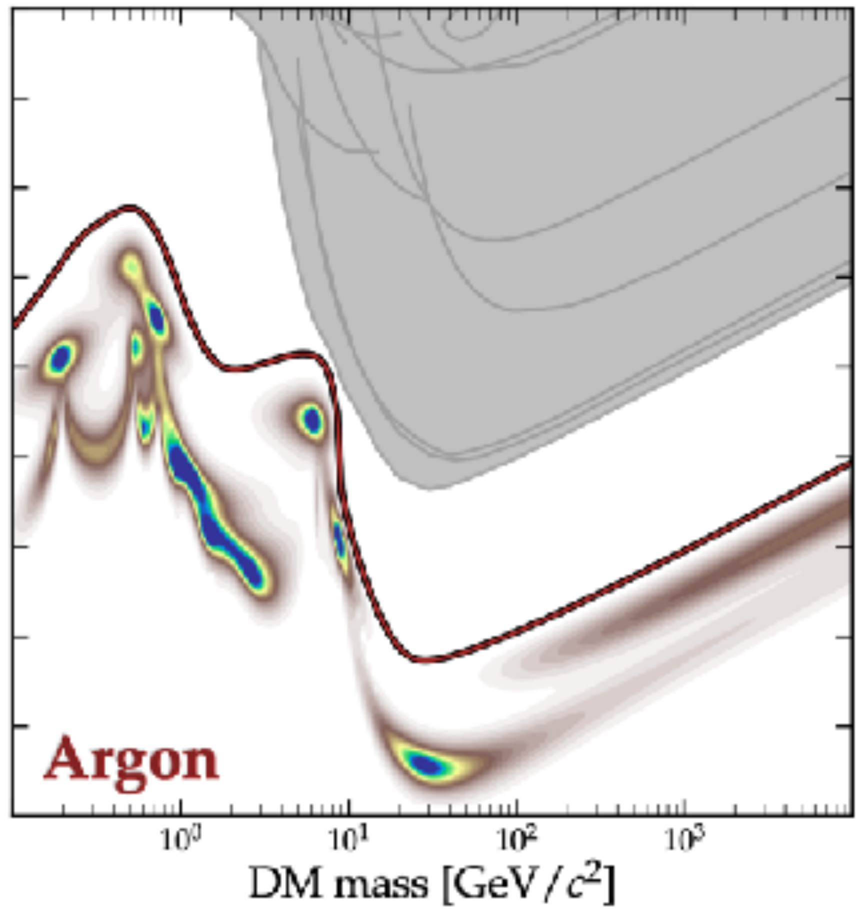
Oscillations (e.g. from Daya Bay [PRL115.111802])



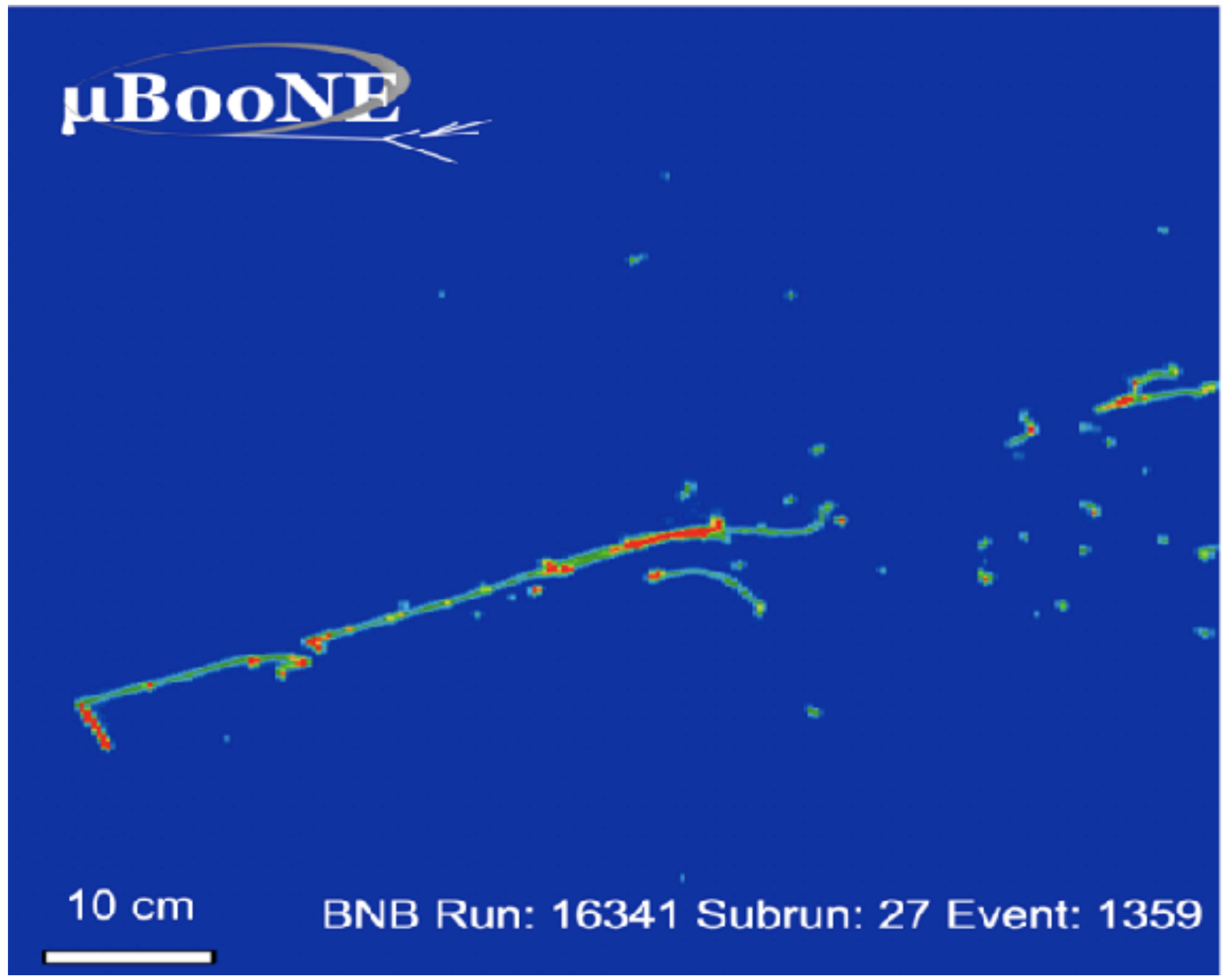
DUNE supernova physics [EPJC 81 (2021) 5, 423]

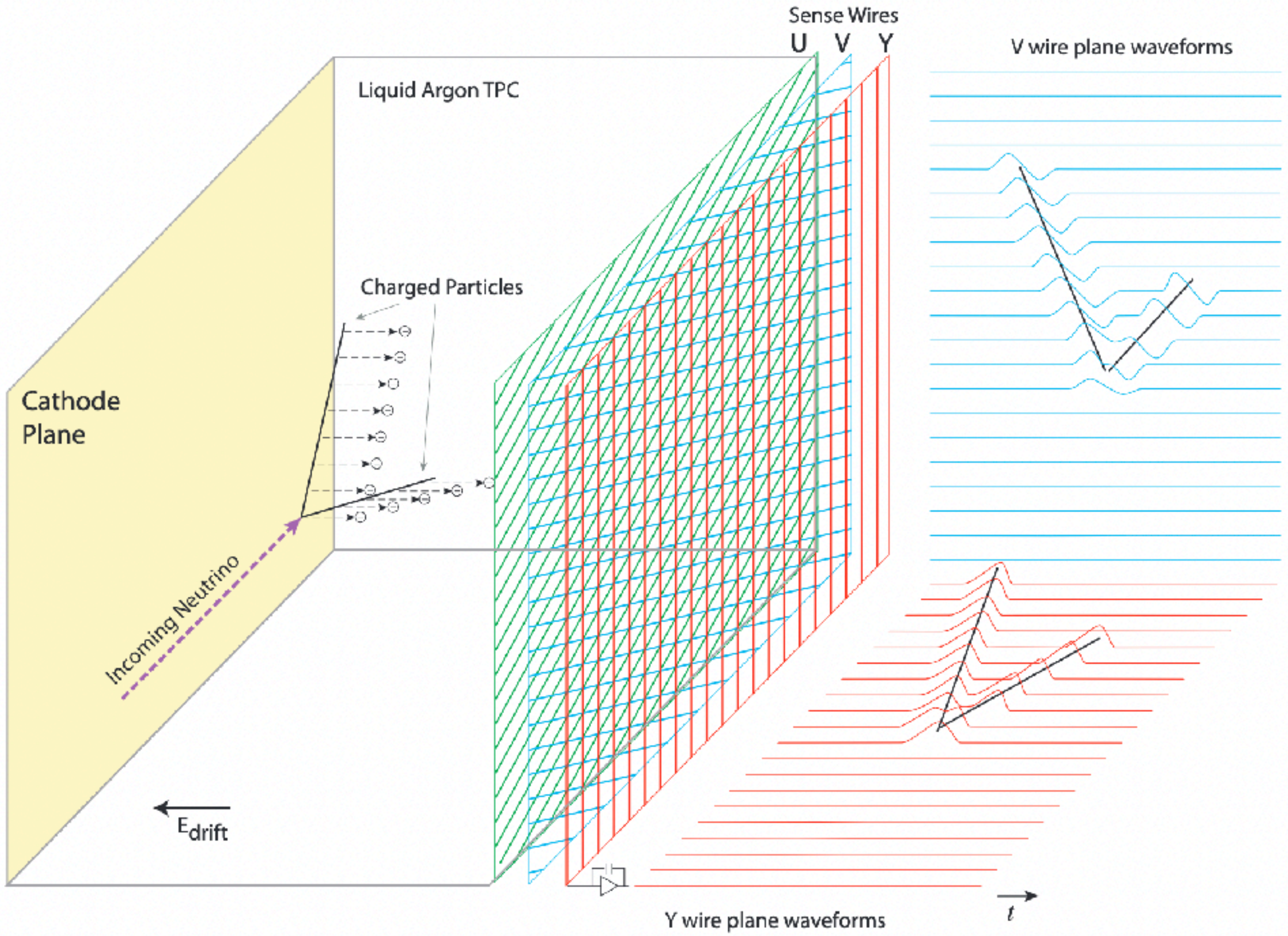


Cairan O'Hare



Liquid Argon Time Projection Chambers



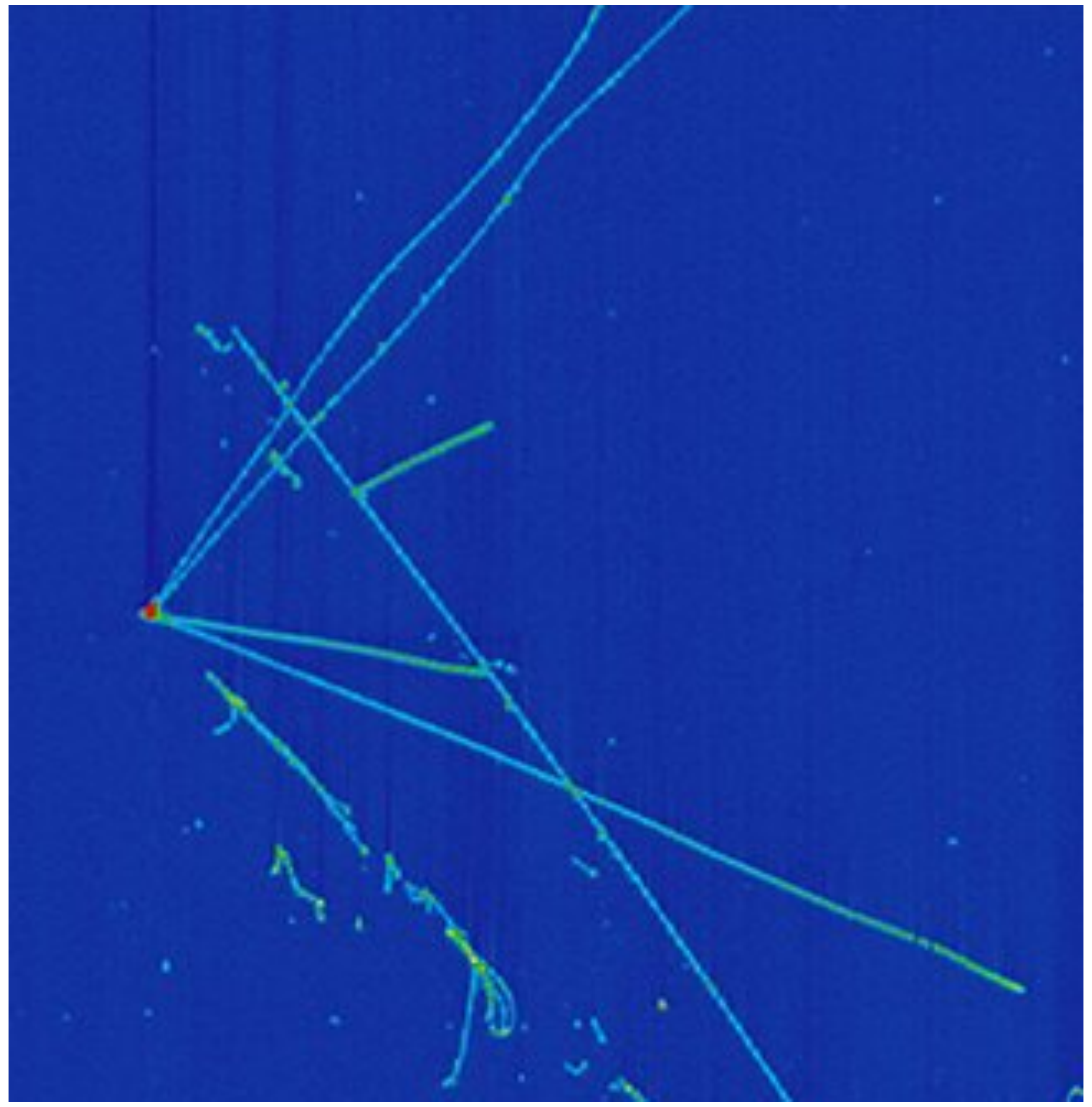


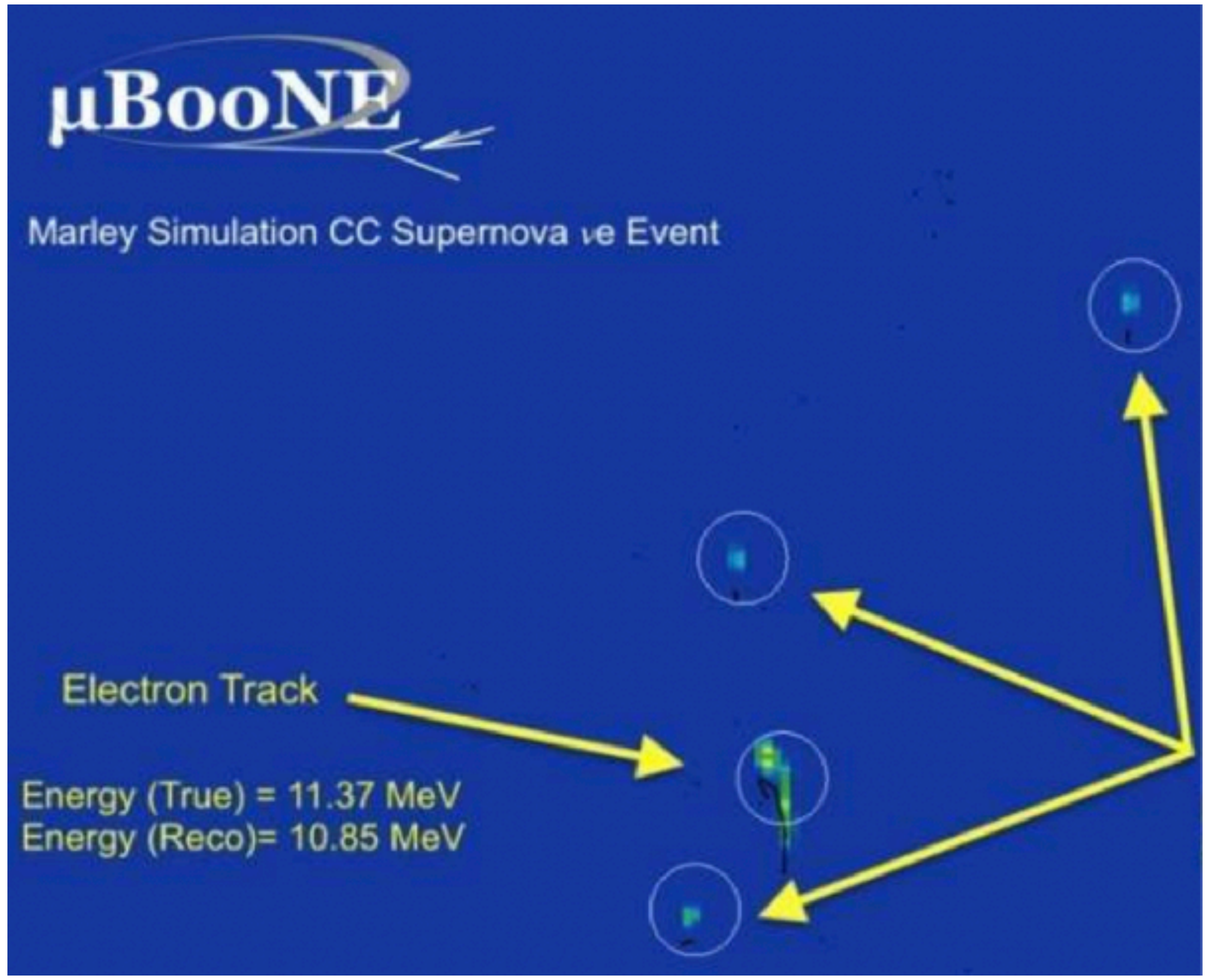
kiloton scale detectors (10^3 meters)

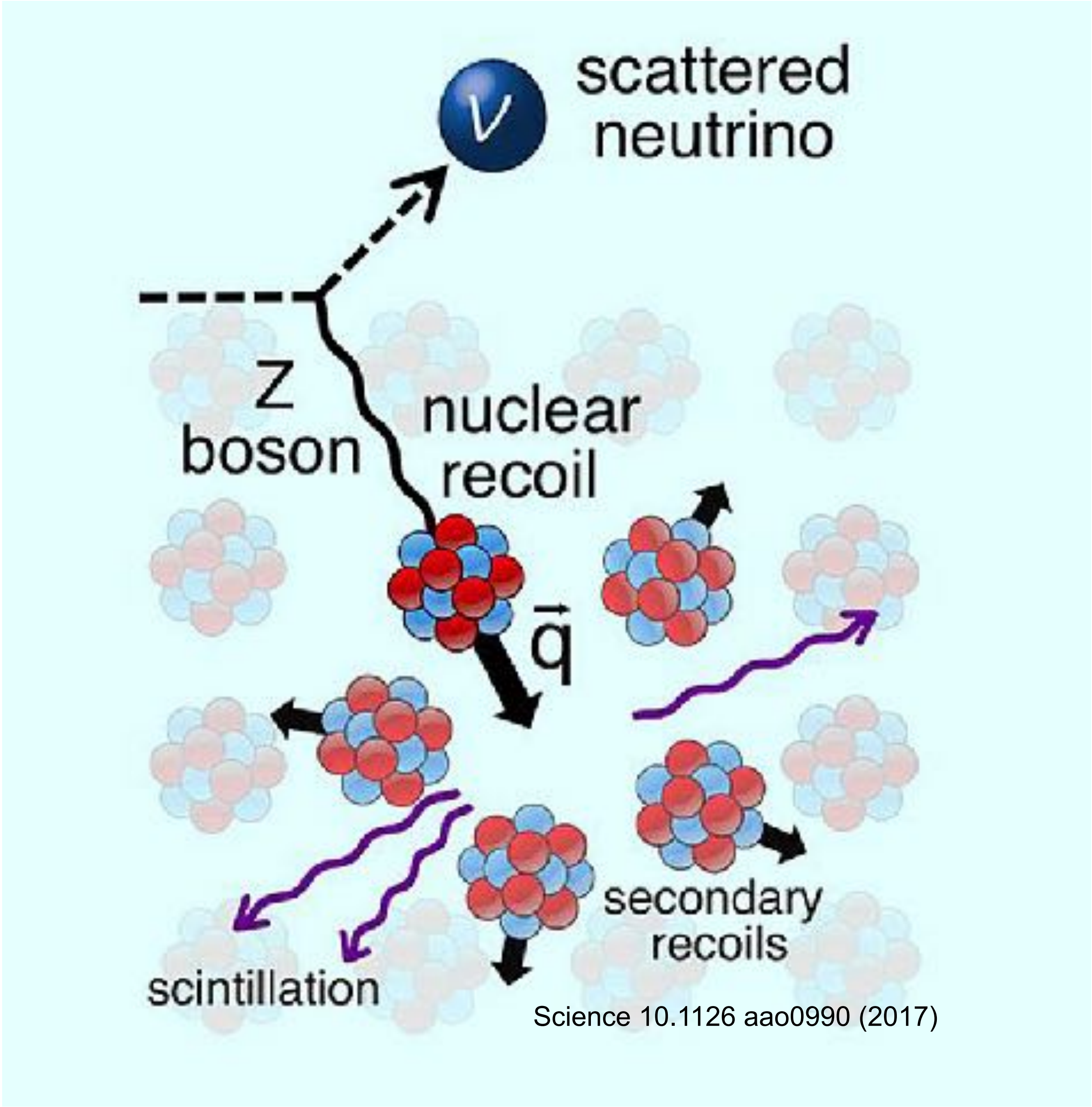
Noble element: efficient charge / photon transport across meter-scale volumes

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

Tracking in Argon-based TPCs

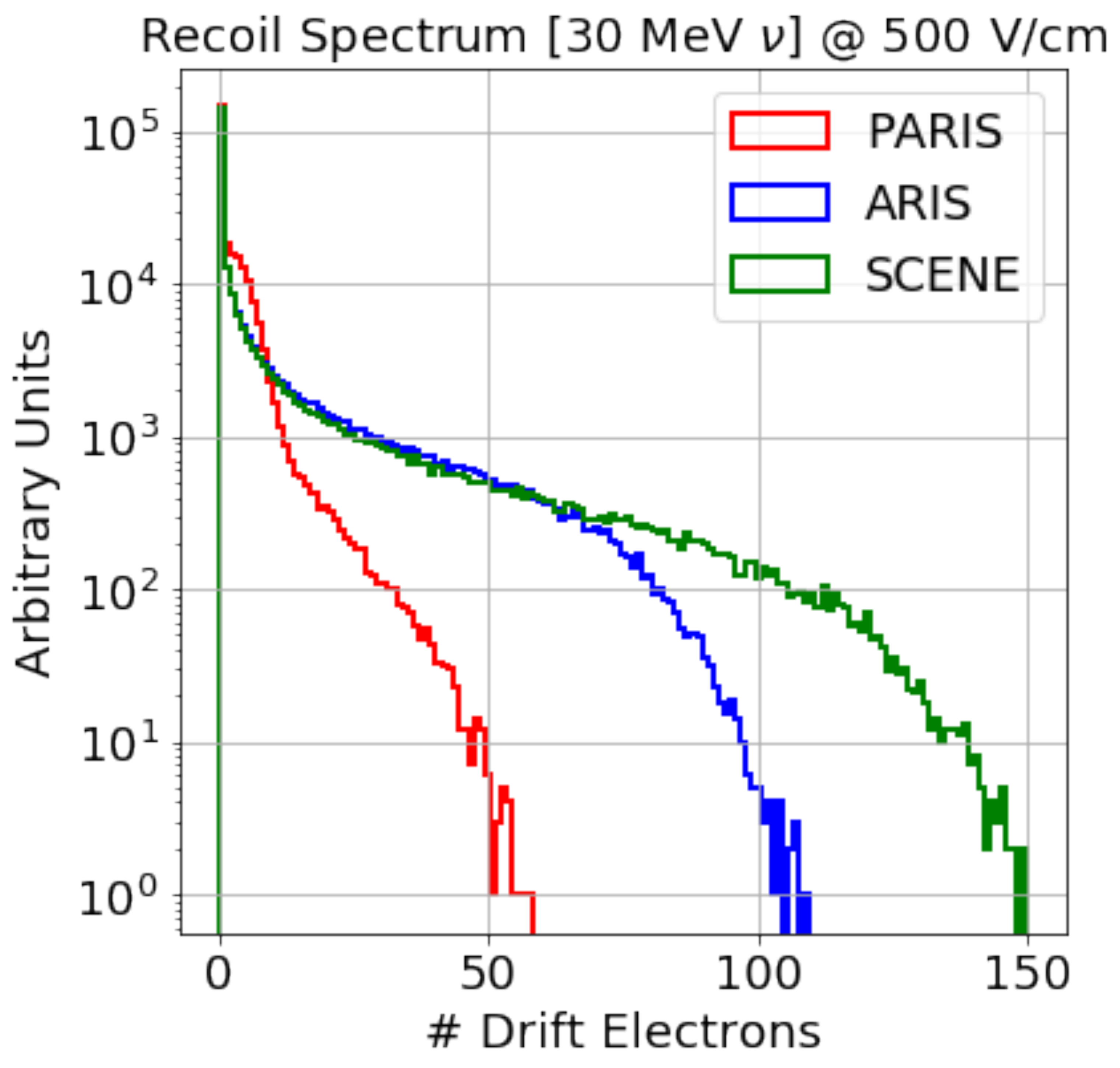




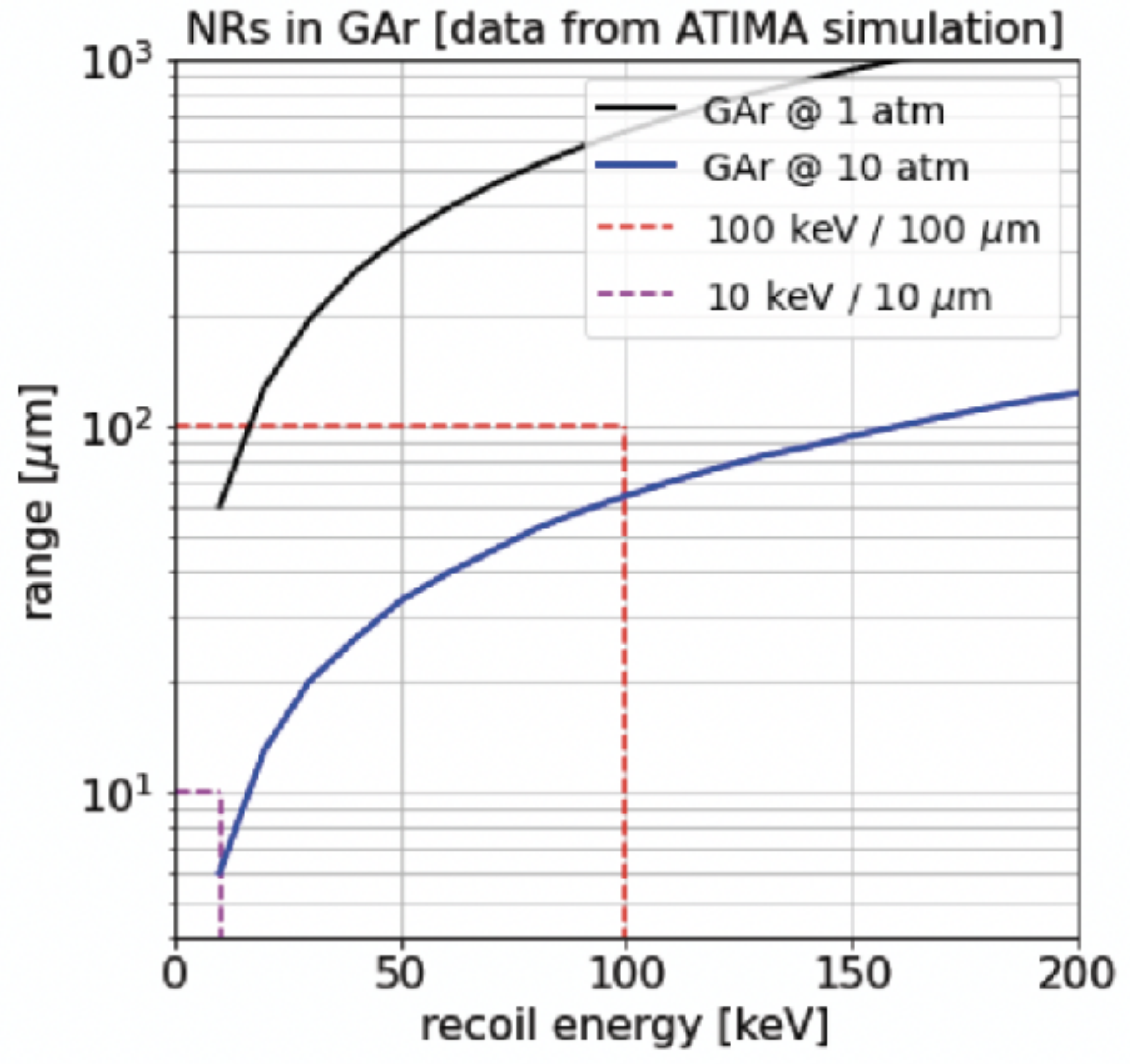


GeV MeV keV

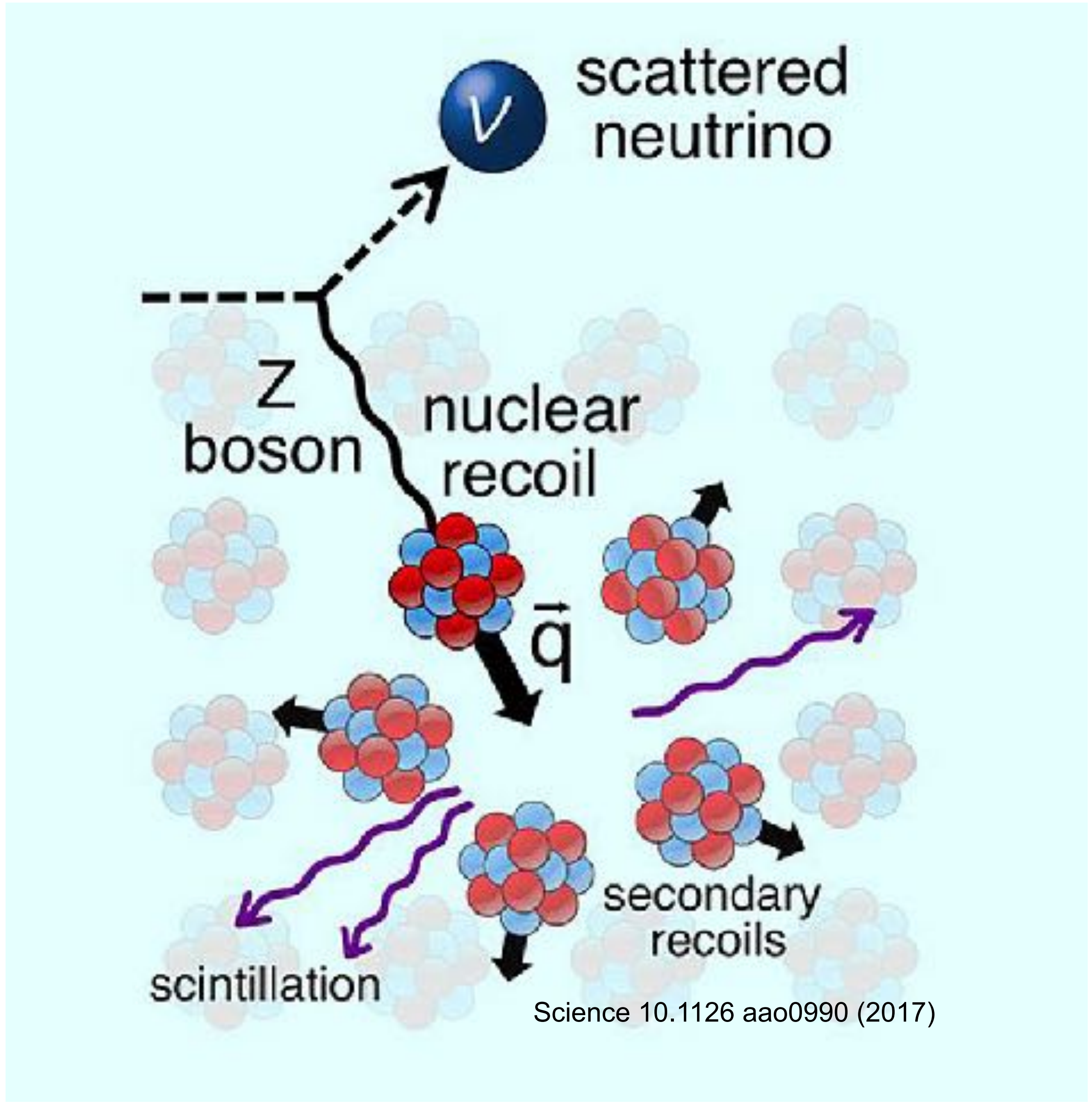
keV-scale imaging in argon-based detectors



tens of e- for NR signature

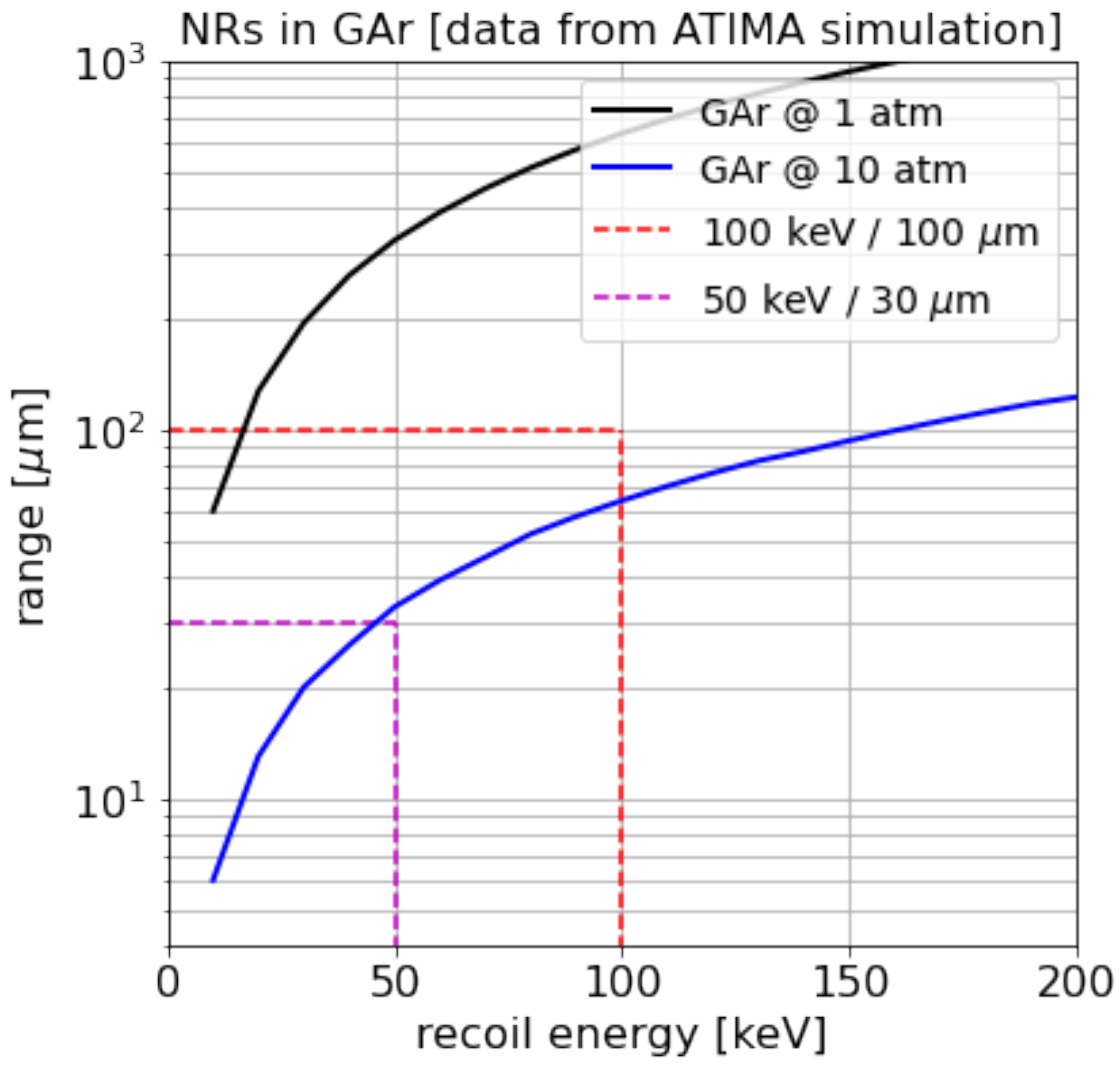


O(10s um) NR range in GAr



Nuclear Recoil Tracking in GAr

Simulations and feasibility



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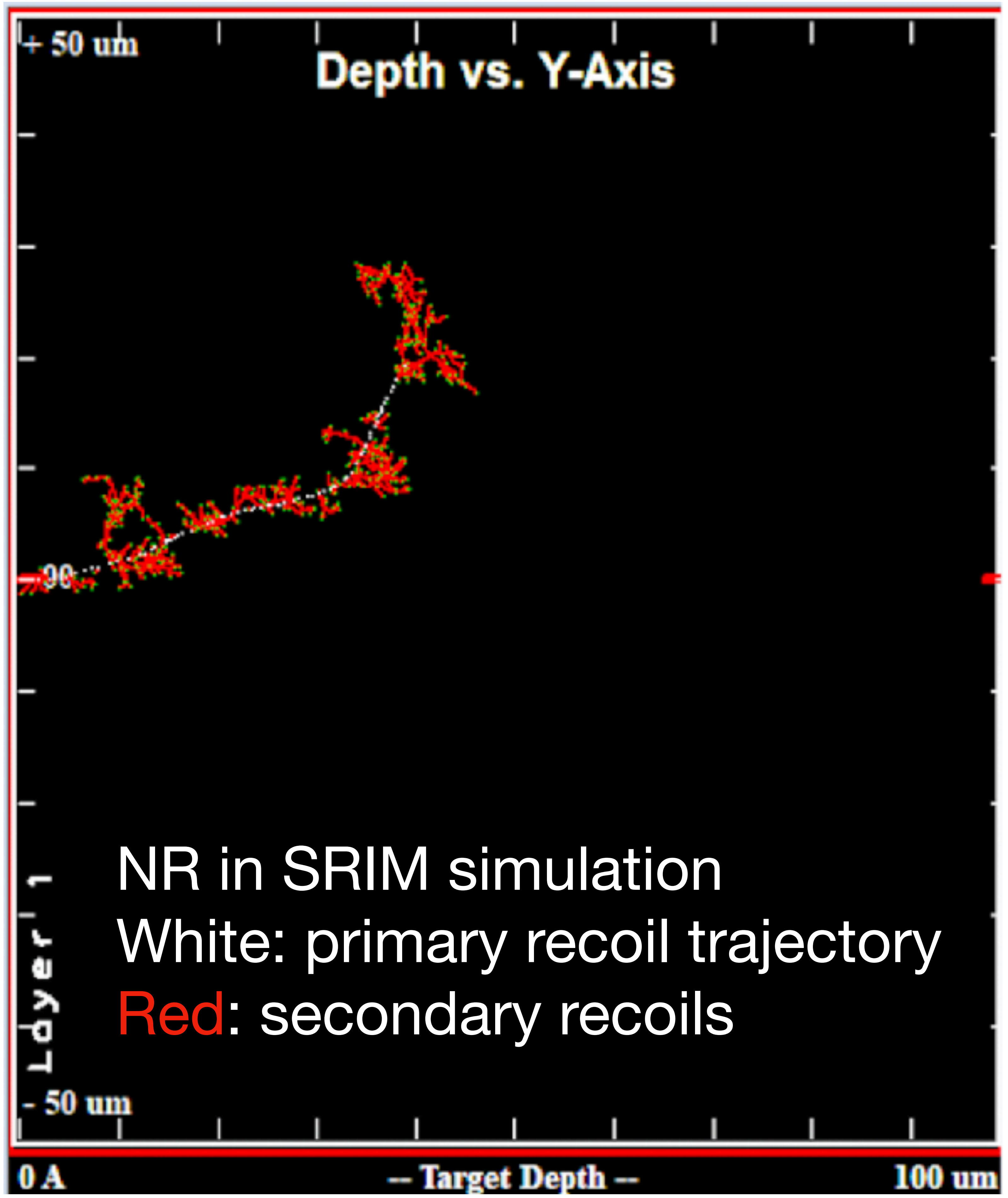
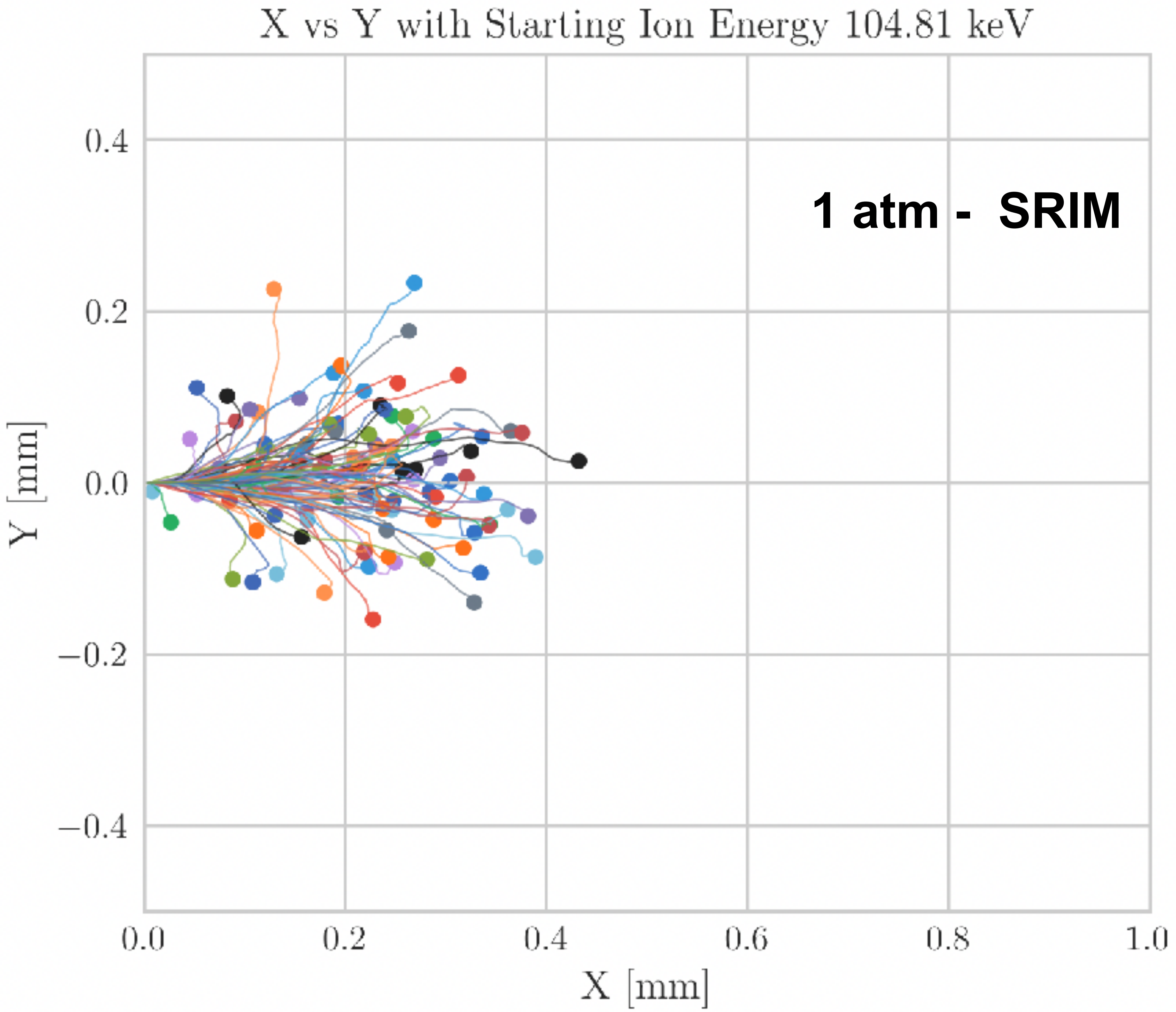
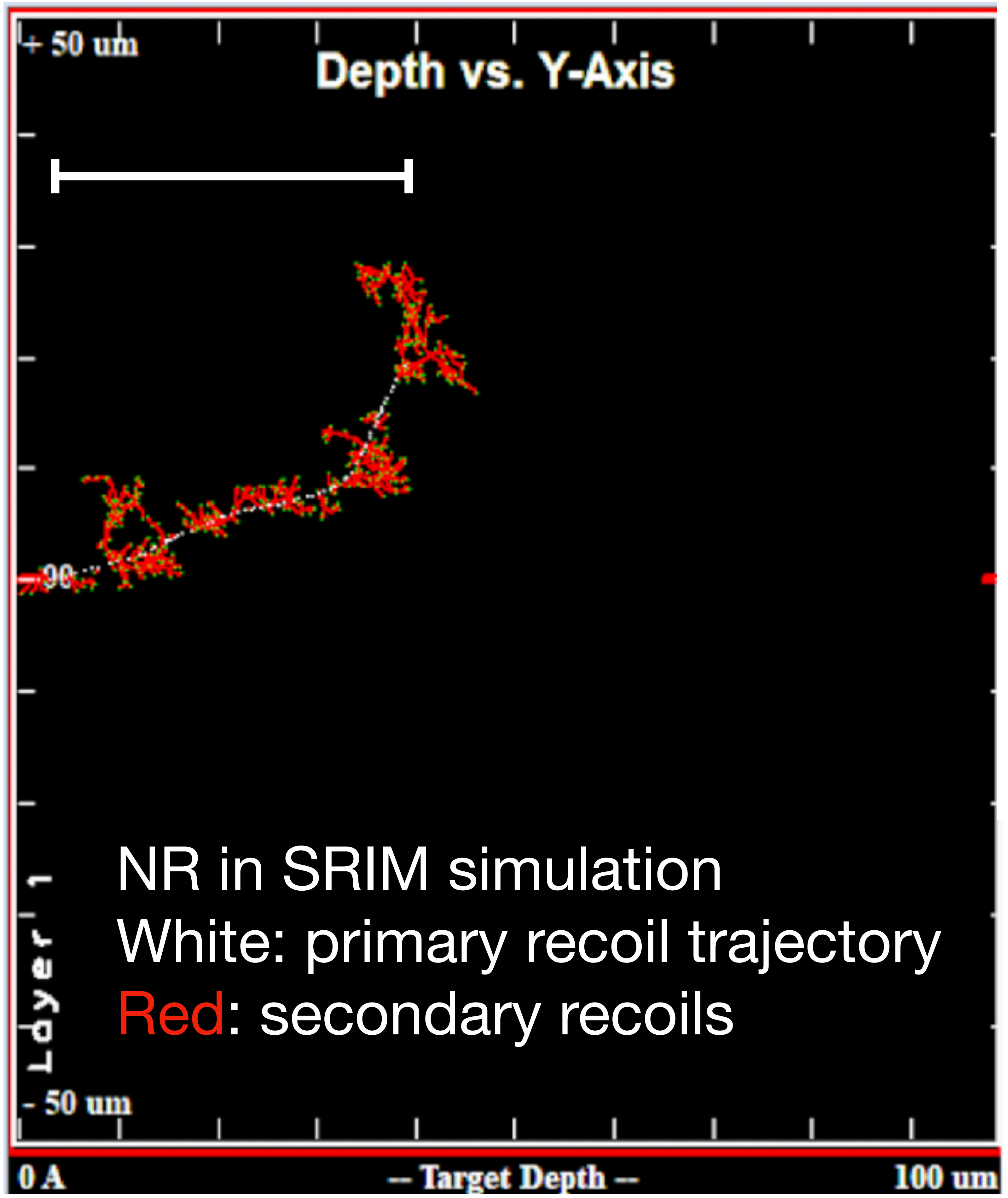


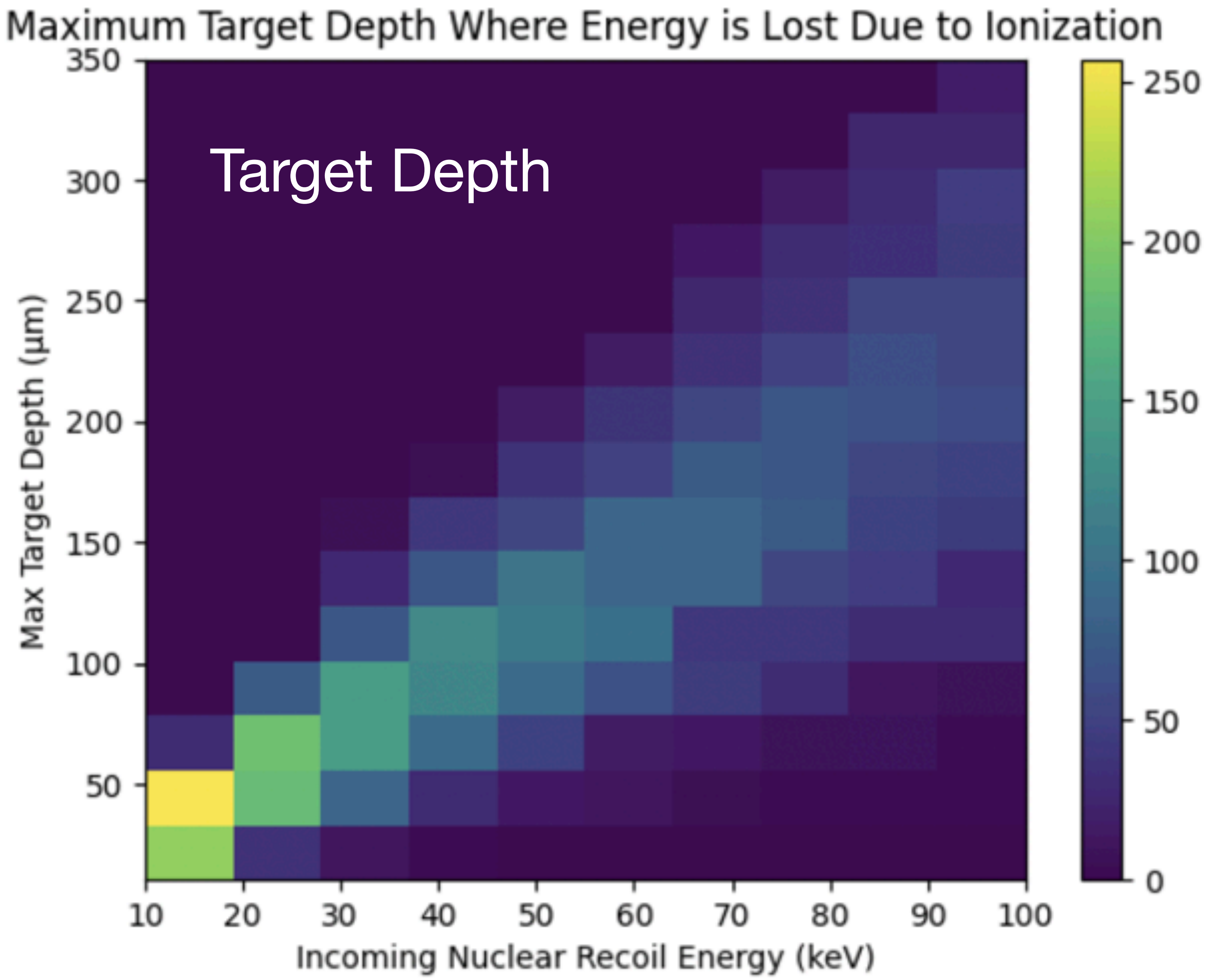


Nuclear Recoil Tracking in GAr

Simulations and feasibility



NR in SRIM simulation
White: primary recoil trajectory
Red: secondary recoils



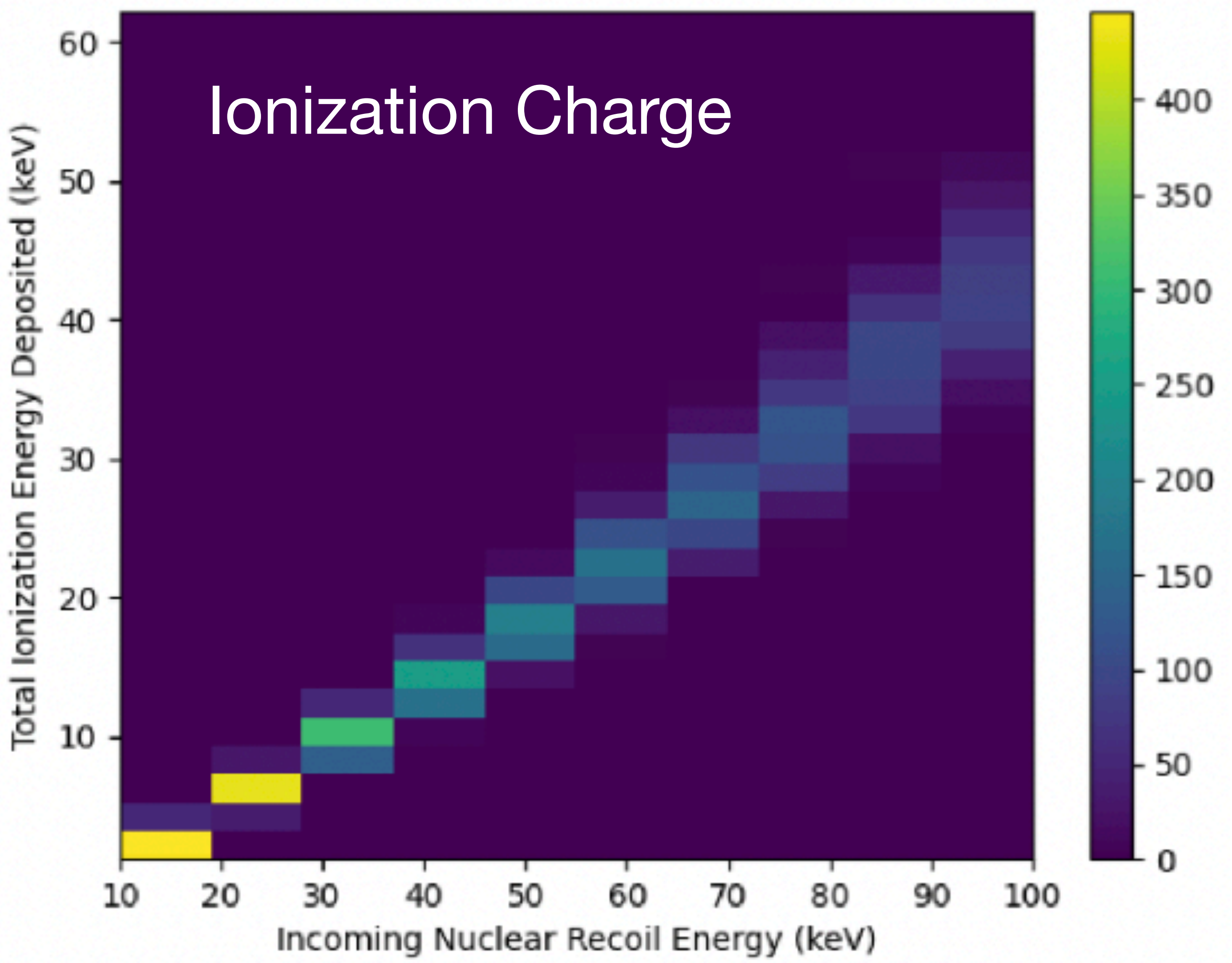
simulations in GAr at 1 atm

diffusion → smearing

Intrinsic resolution at 10s of %

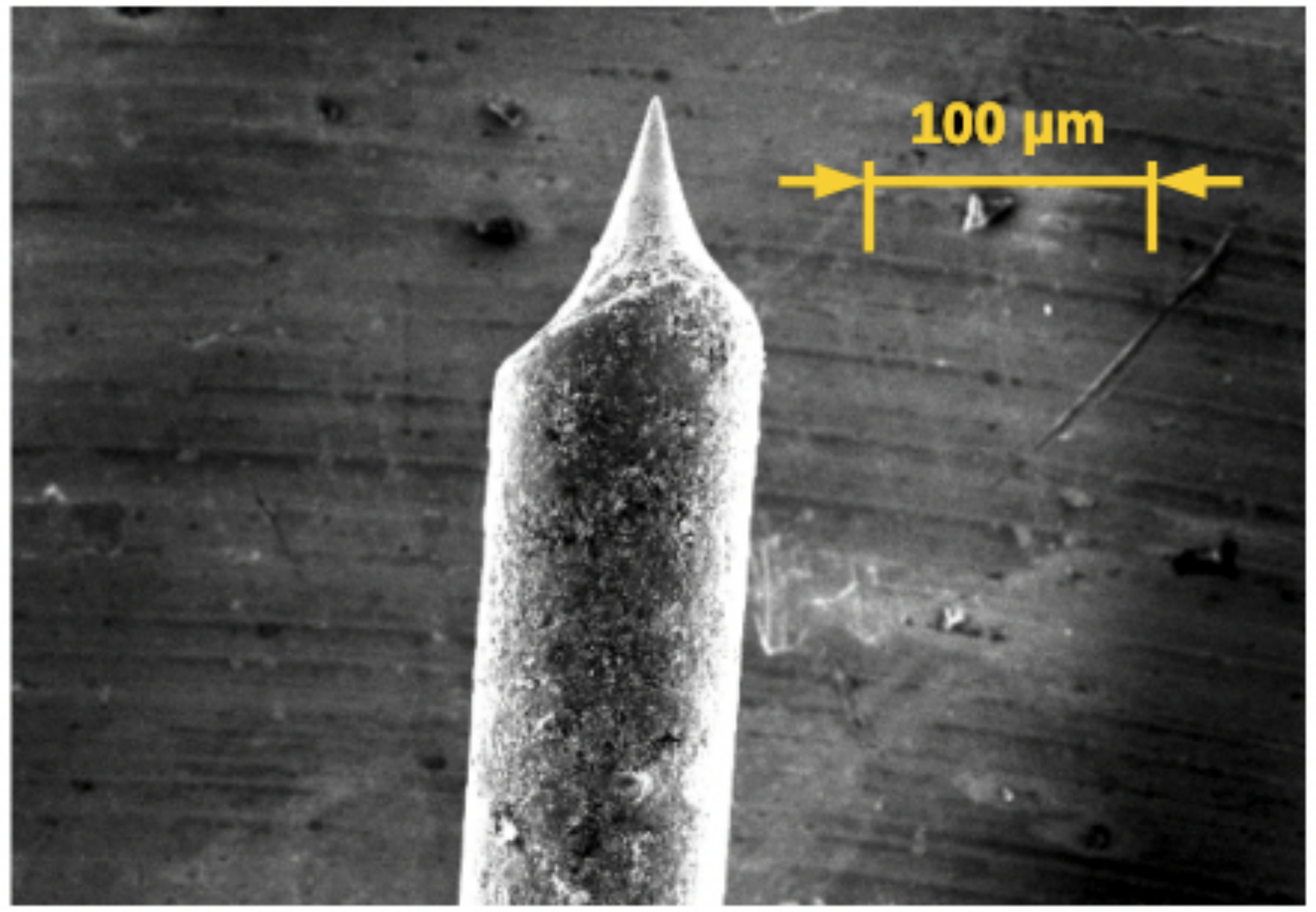
→ O(10) μm spatial resolution

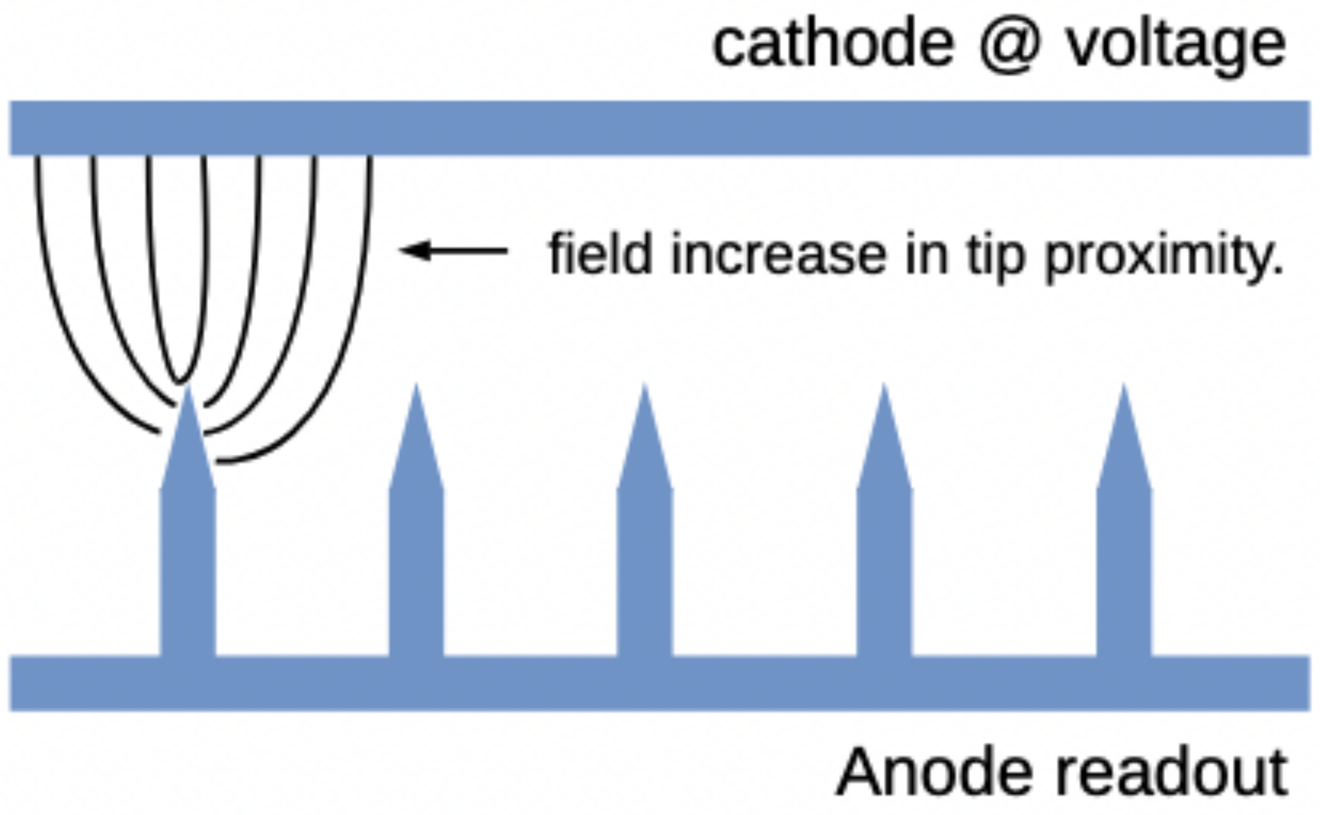
Requirements grow at higher pressures.

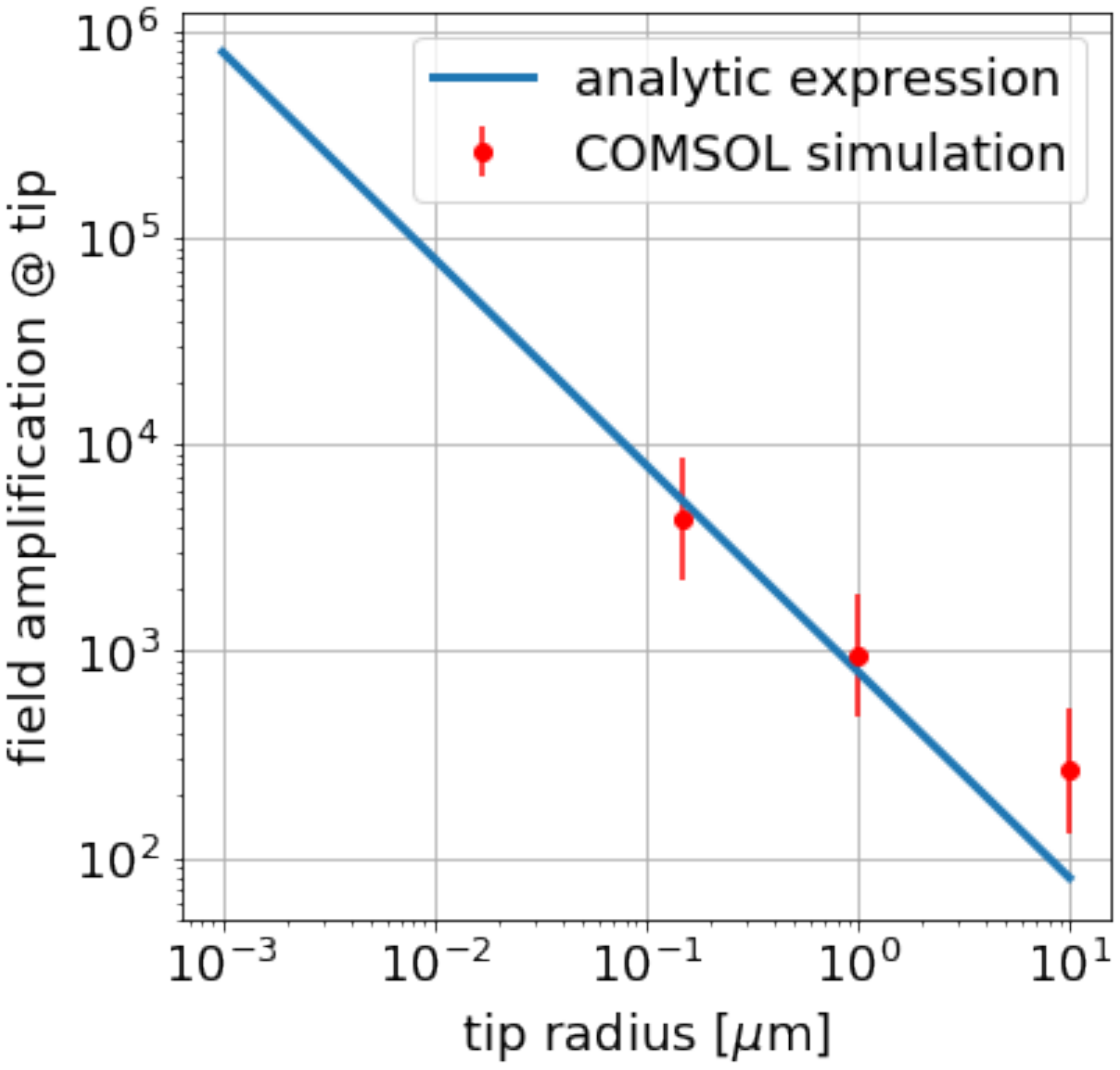


LArCADe: "tip" geometries

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







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

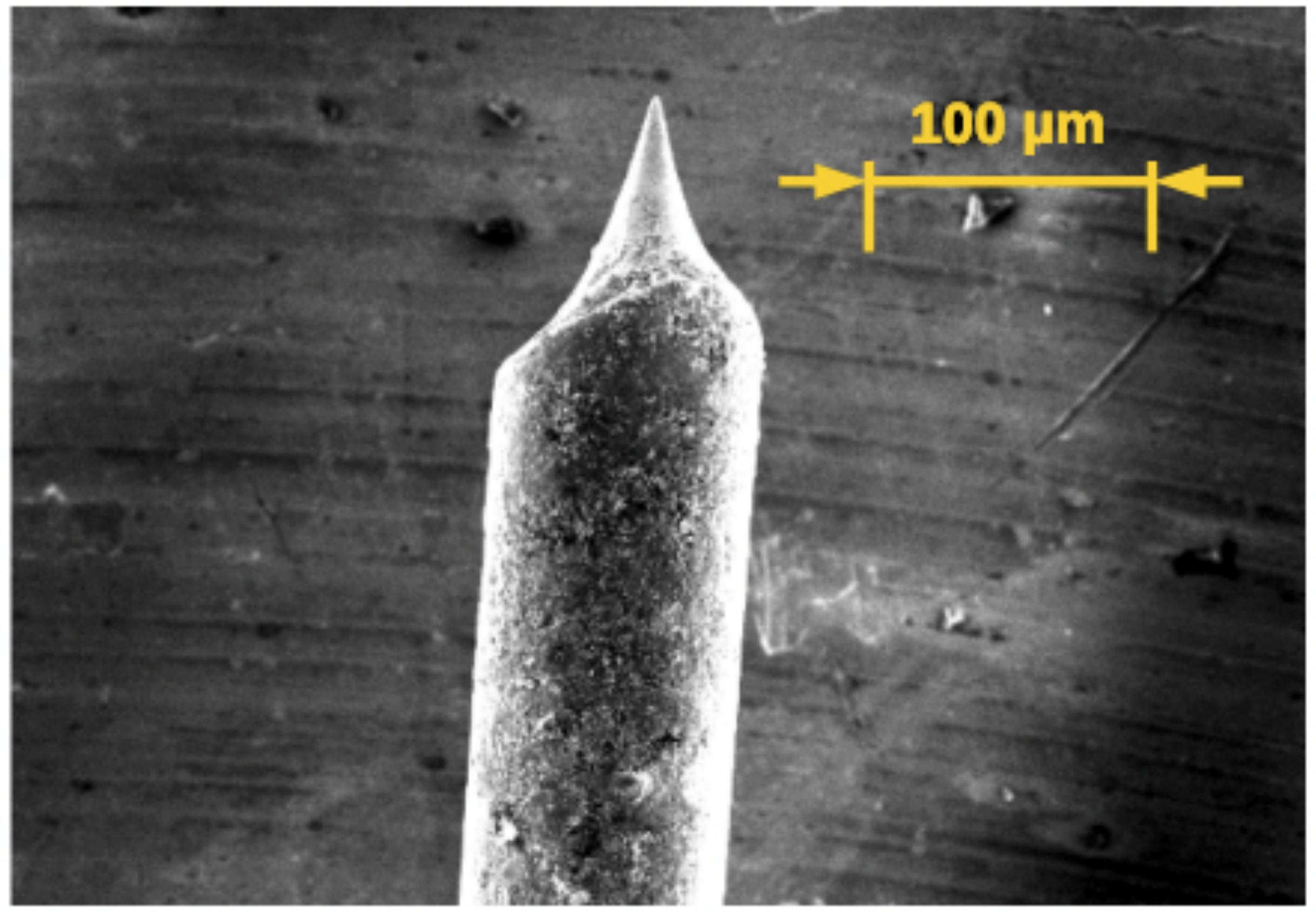
(1) Tip geometry provides potential for amplification in bulk fields of O(100s V/cm)

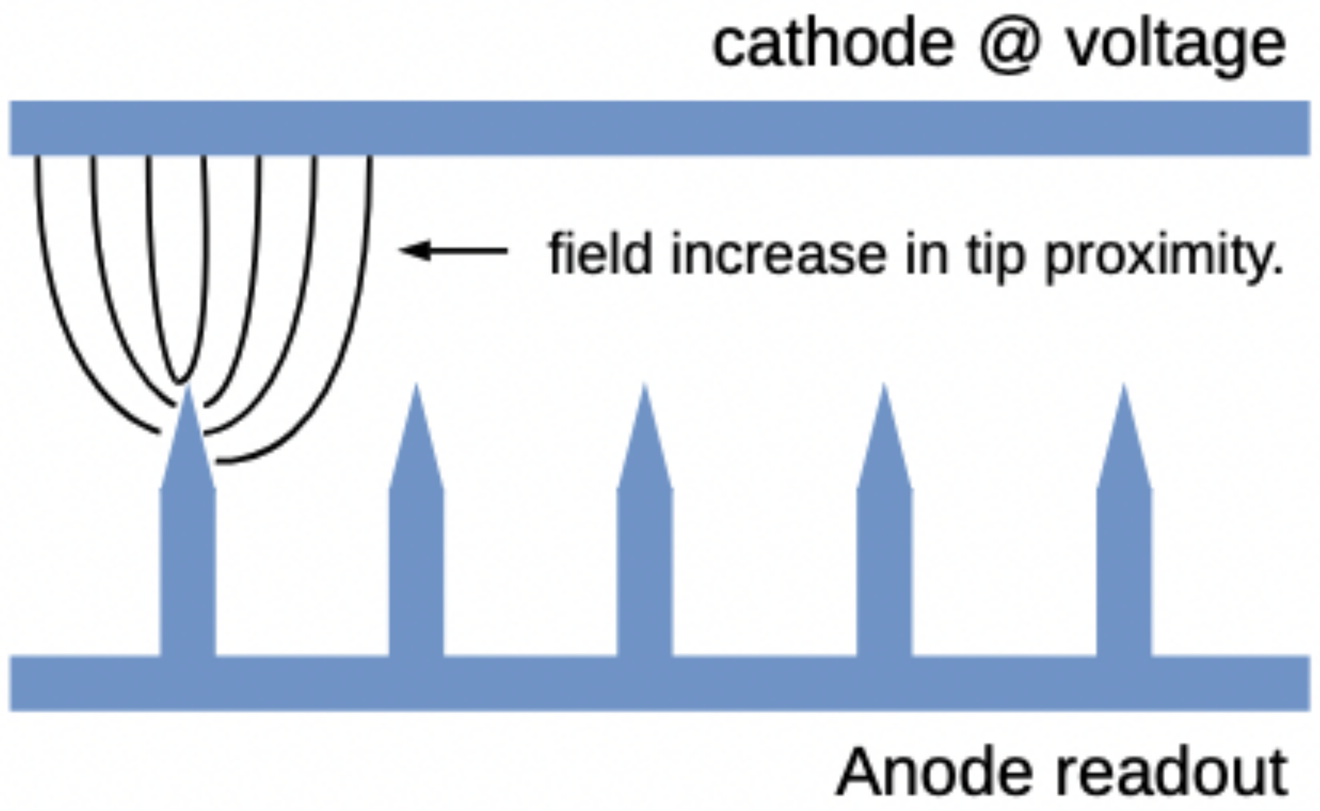
LAr amplification

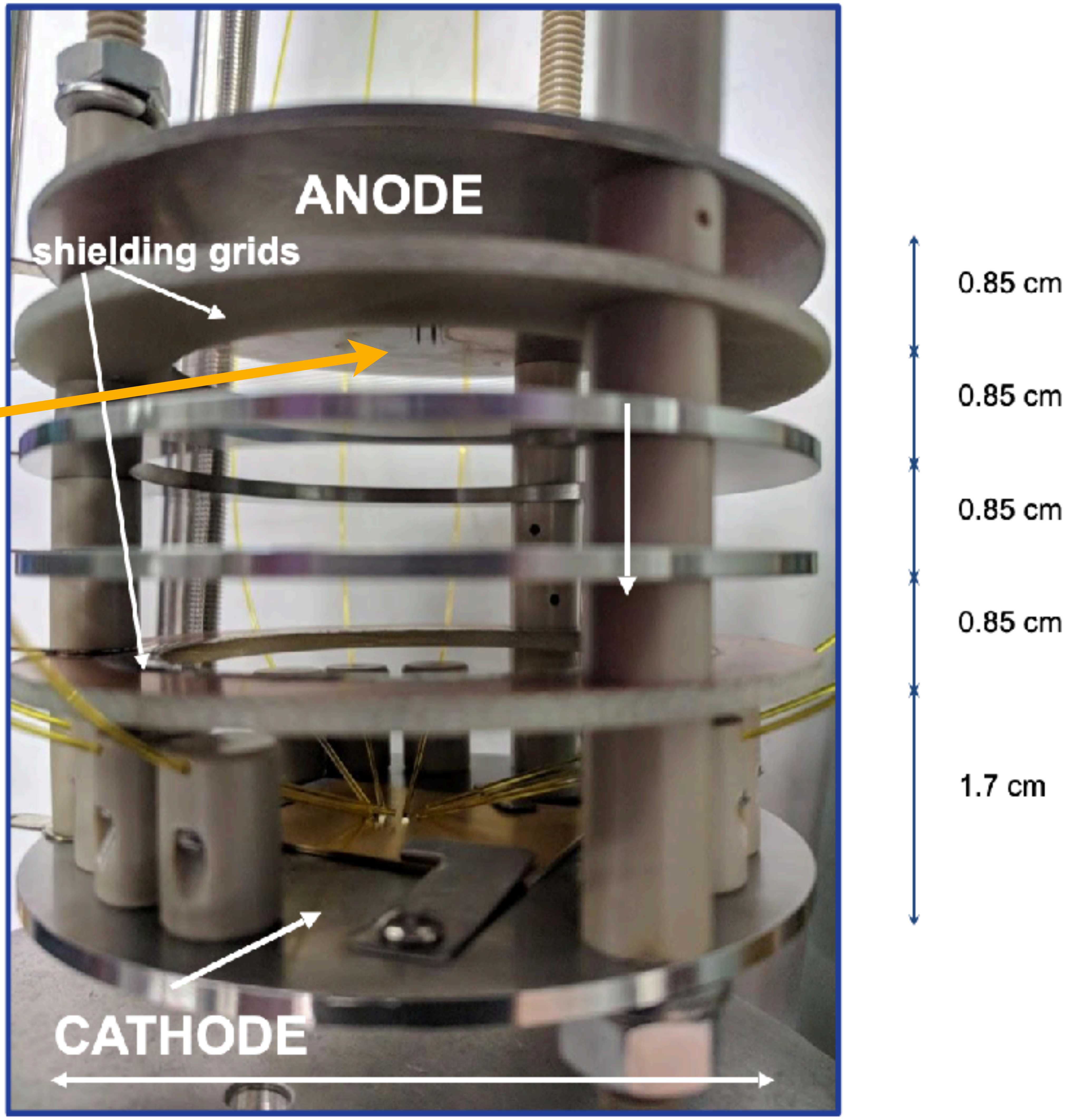
(2) Tip "arrays" may enable NR tracking in gas medium

GAr NR tracking

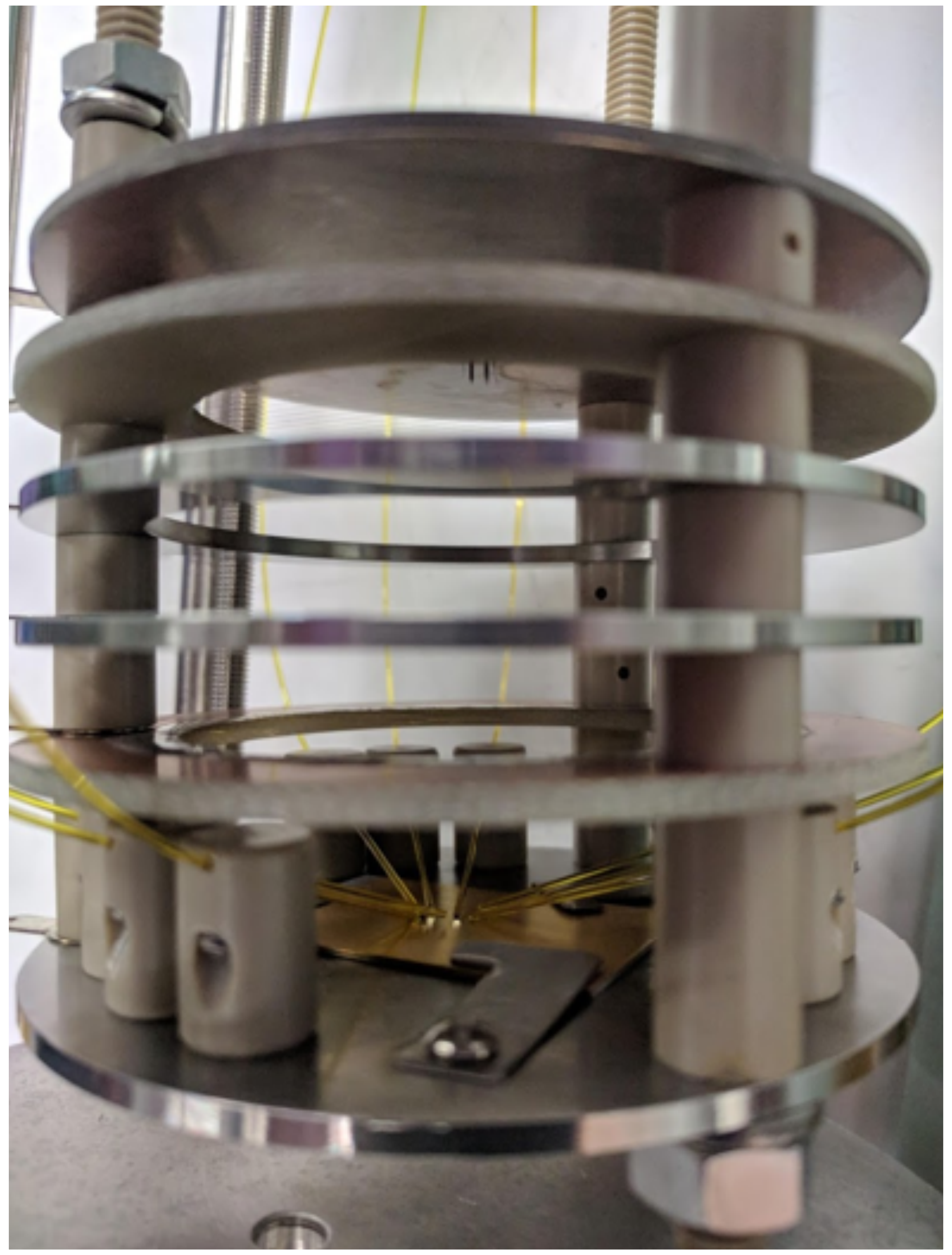
LArCADe: R&D setup

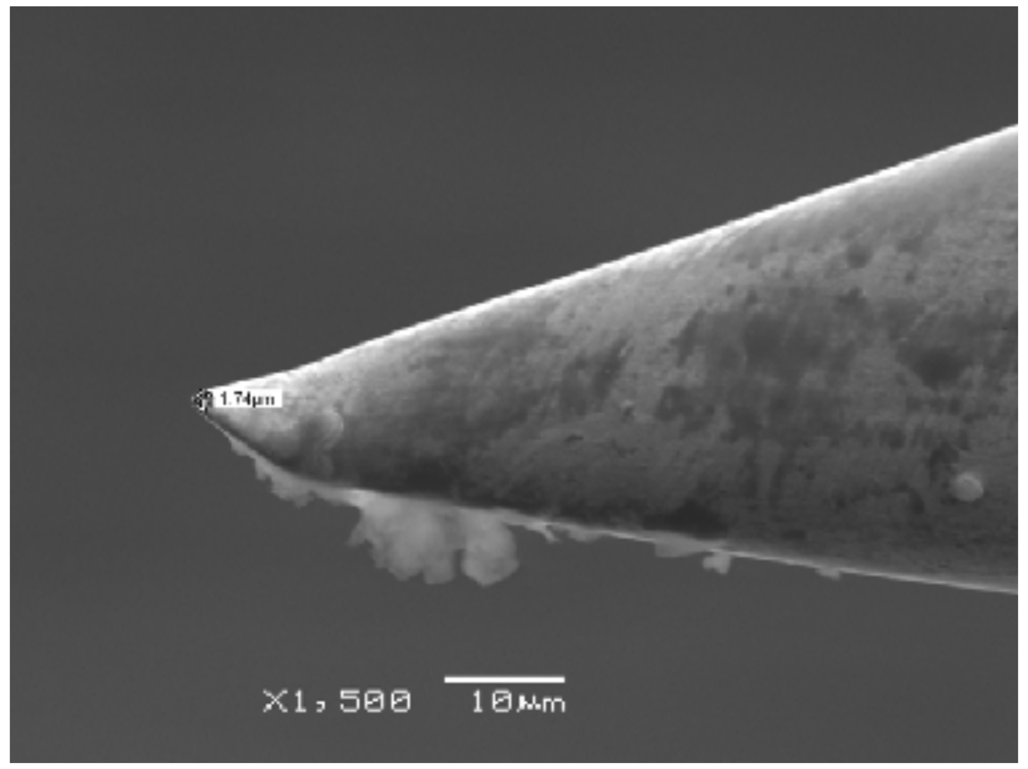




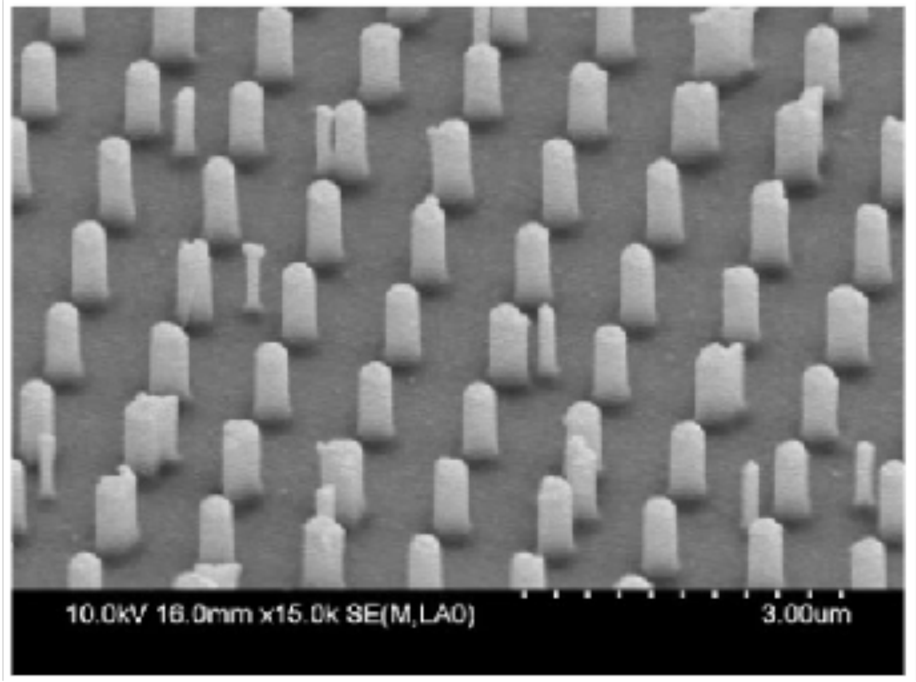


LArCADe: R&D runs at Fermilab





tip-array with sub µm apex produced @ BNL



LArCADe R&D program at Fermilab

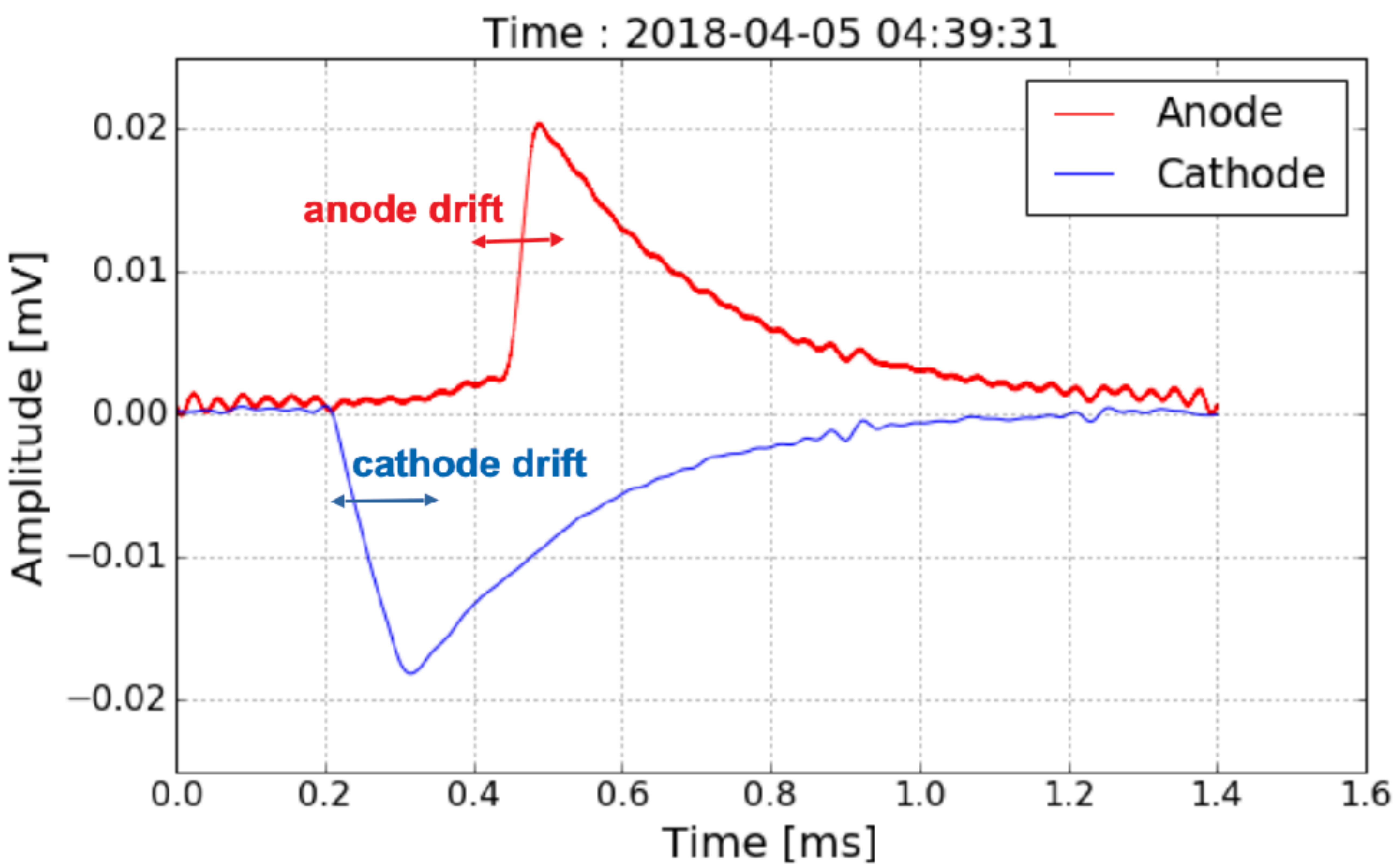
Utilize Fermilab's "PAB" (now "Noble Liquid Test Facility") for cryogenic setup with purified LAr

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

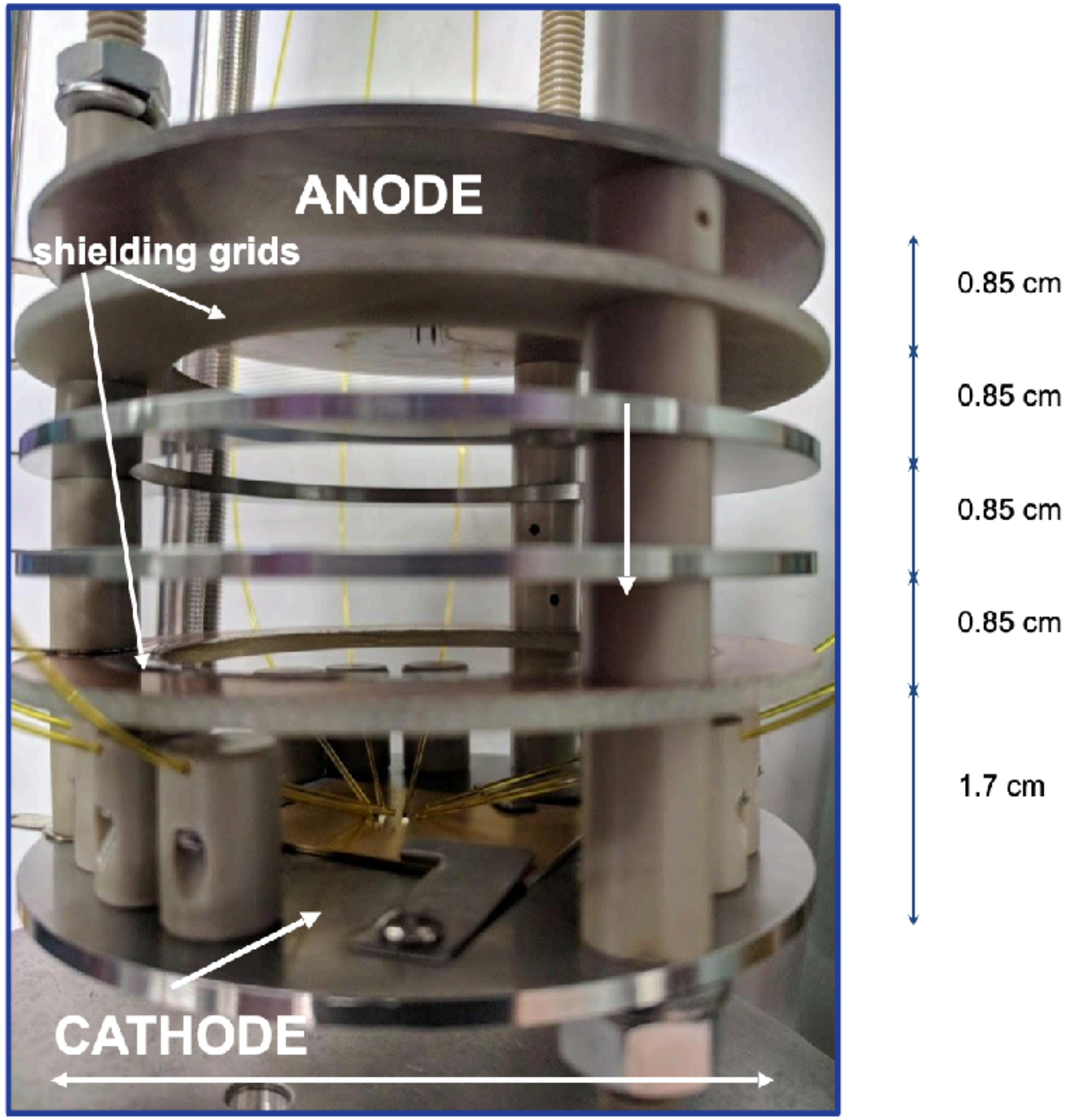
Work with different tip geometries / arrays

Collaborating with materials experts @ Padova, FNAL, BNL

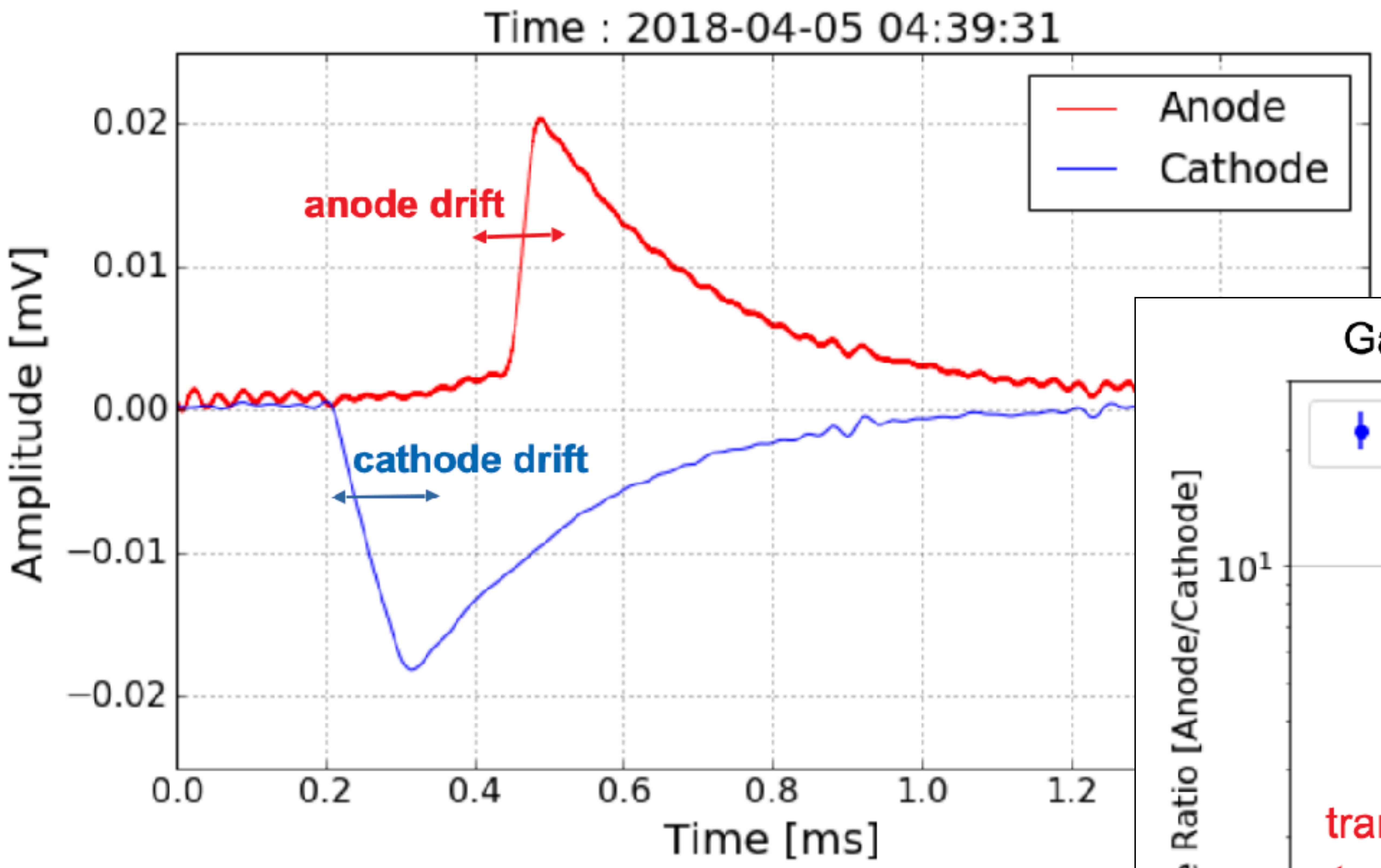
LArCADe: data-taking and analysis

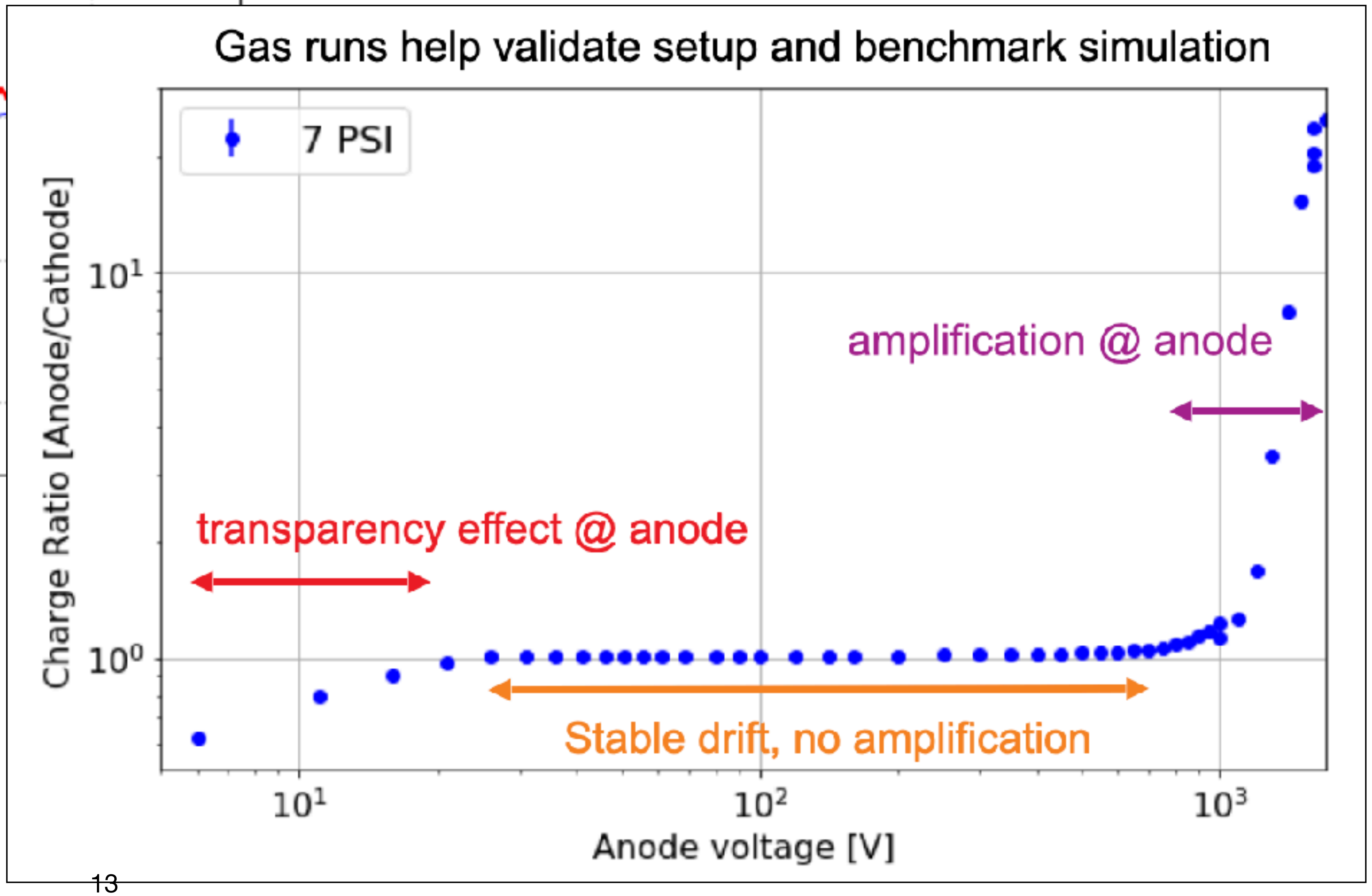


Measure charge induced at Cathode and Anode



LArCADe: data-taking in GAr





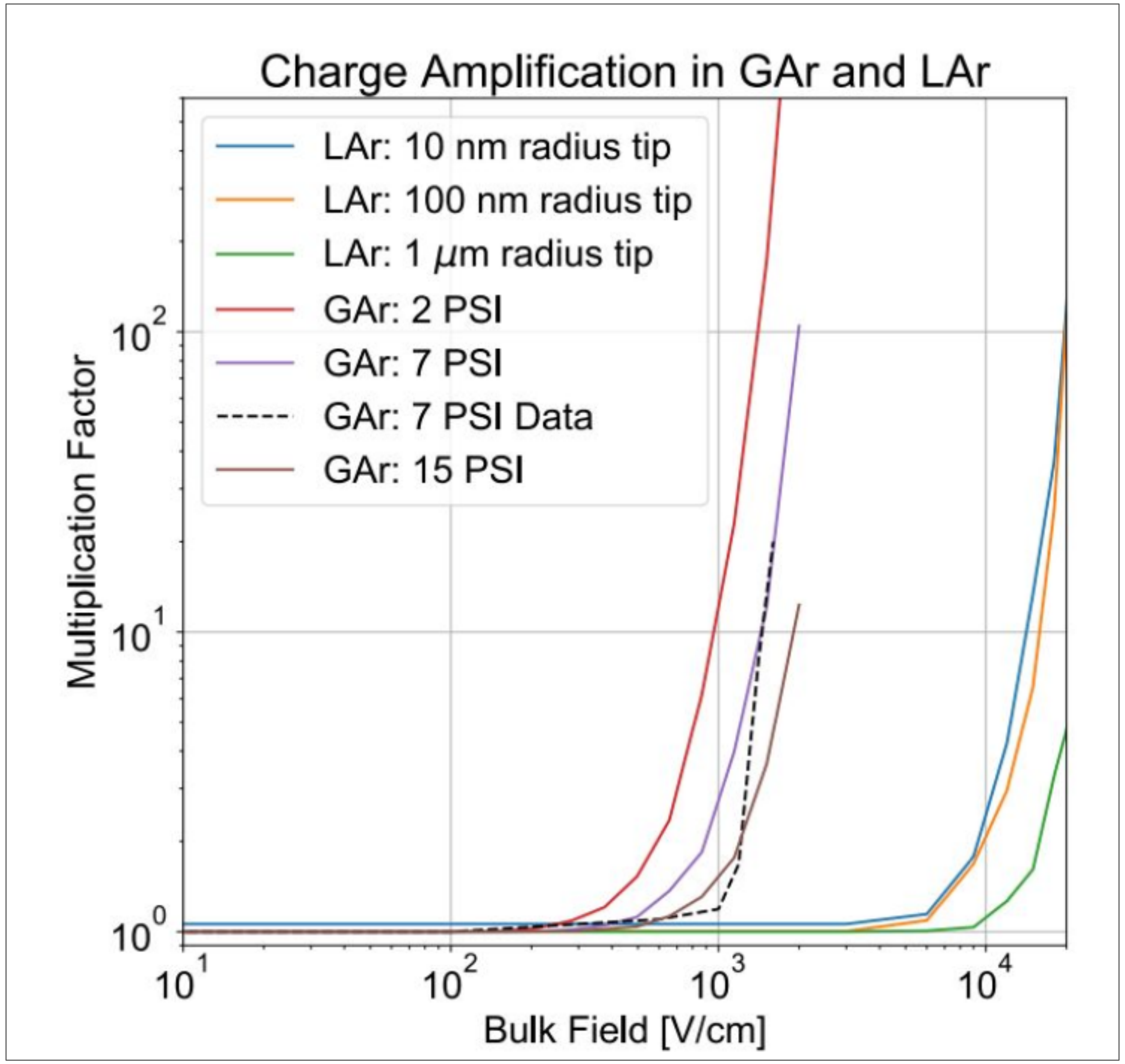
LArCADe: progress and R&D next-steps

Several runs at Fermilab 2018-2020

Successful operation in gas.

Continuing effort to obtain charge amplification in LAr at few kV operations

Launched new effort towards understanding ideal geometries for charge amplification



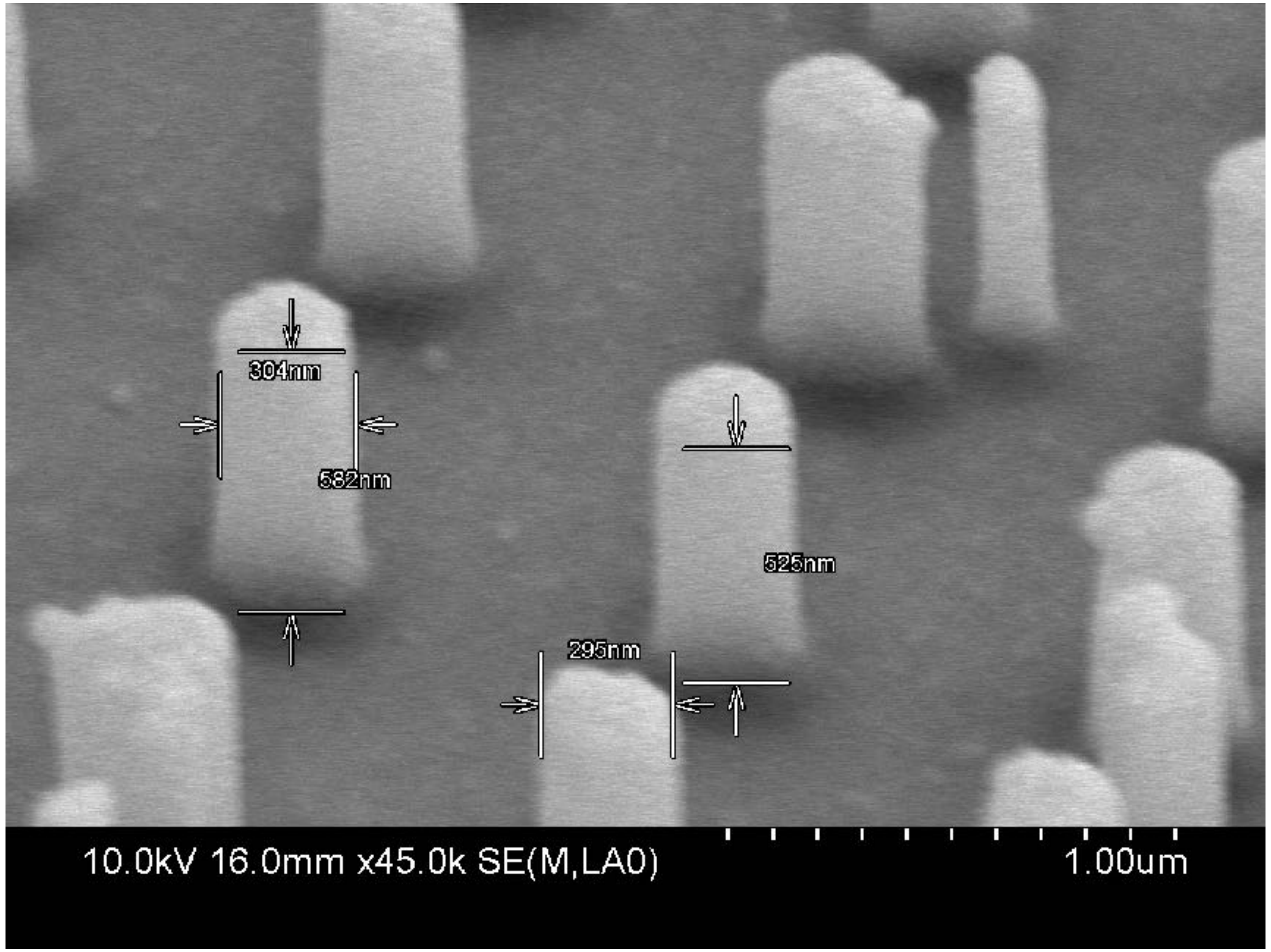
Tip-array nano fabrication

Tip-array geometries:

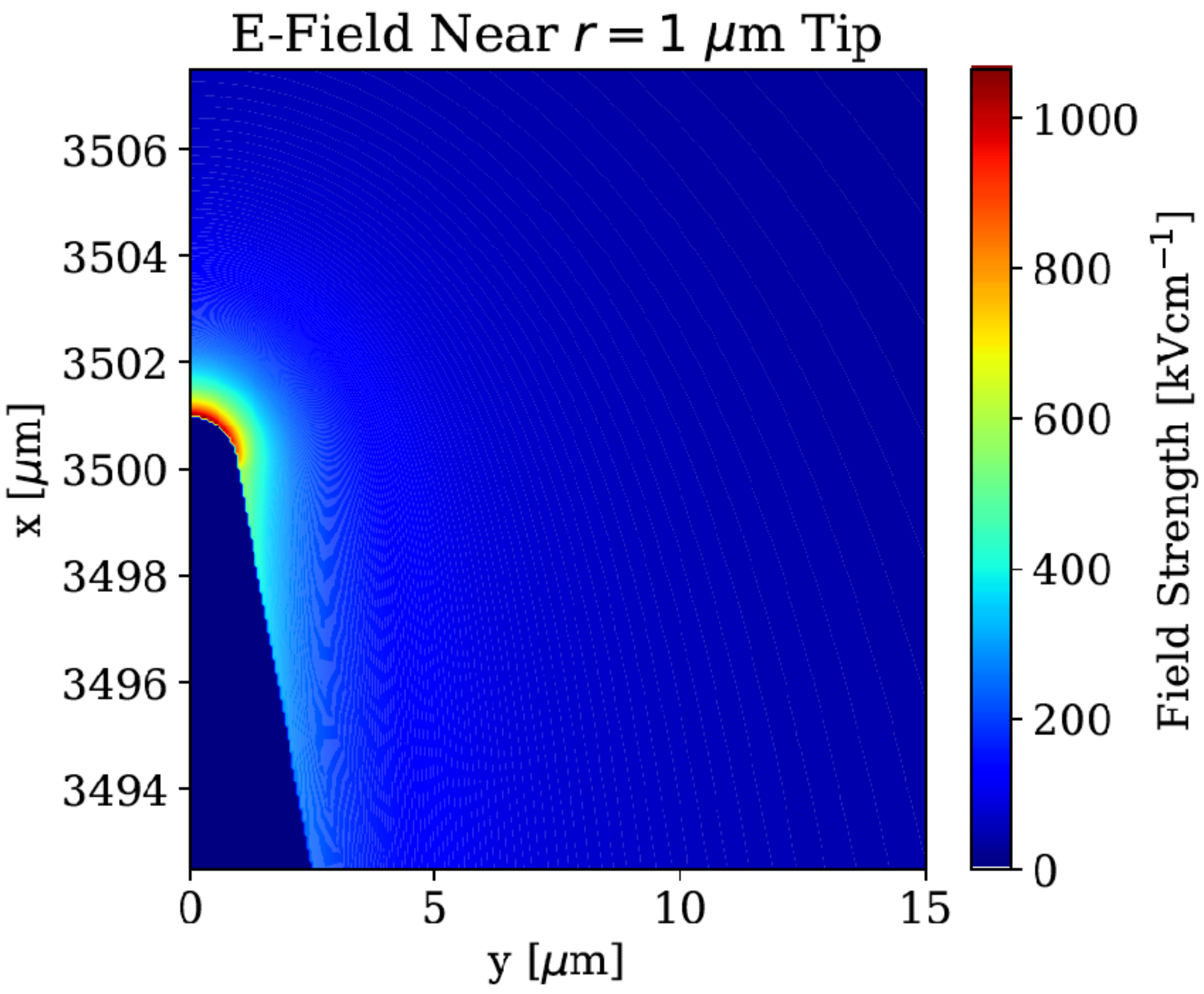
- can help achieve charge amplification
- Scalable technology
- May be leveraged for tracking capabilities

Tip-array geometries for NR tracking in GAr a possible new direction for R&D.

GEM-based designs also an attractive option



LArCADe: tip-array simulation



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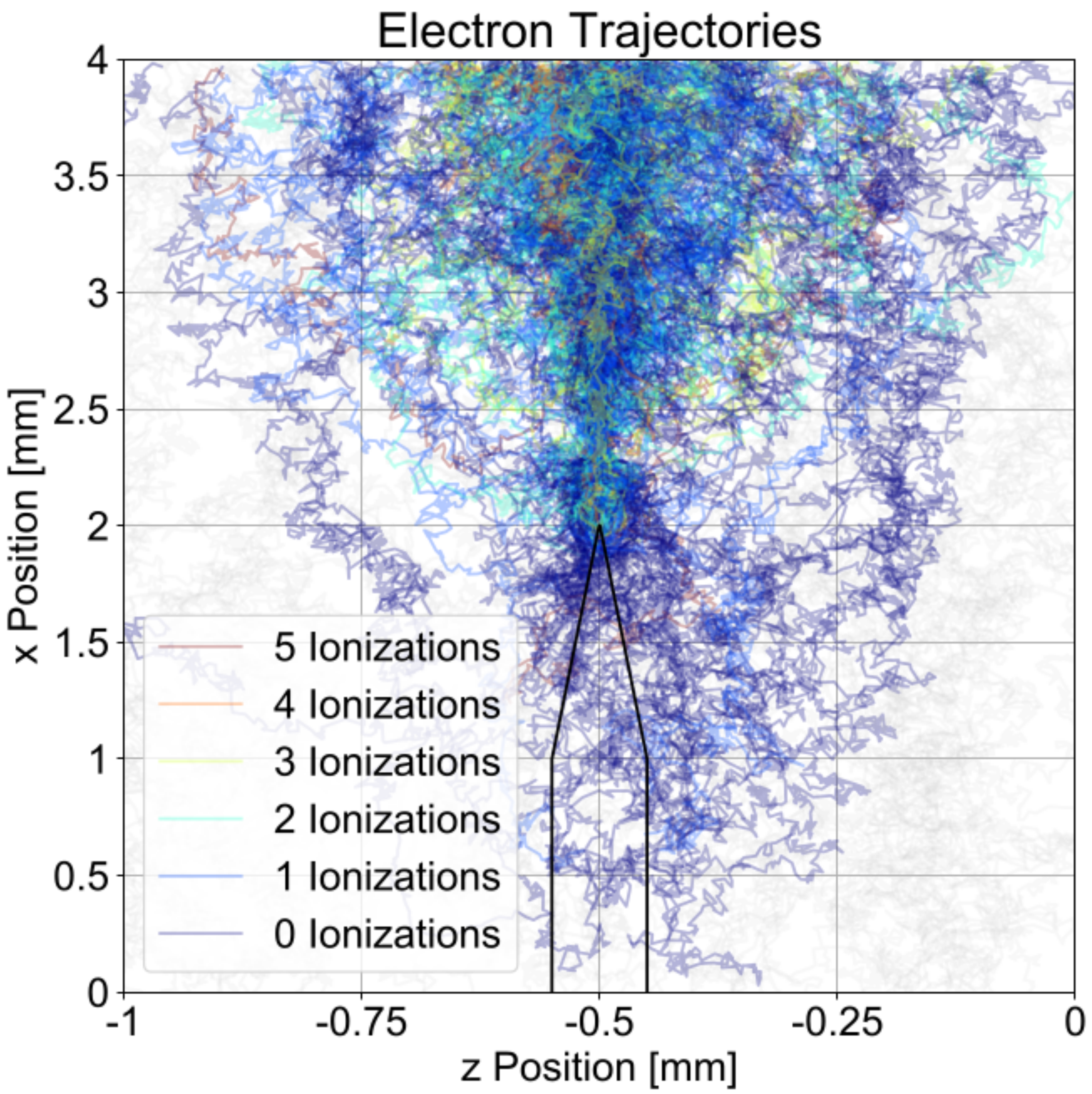
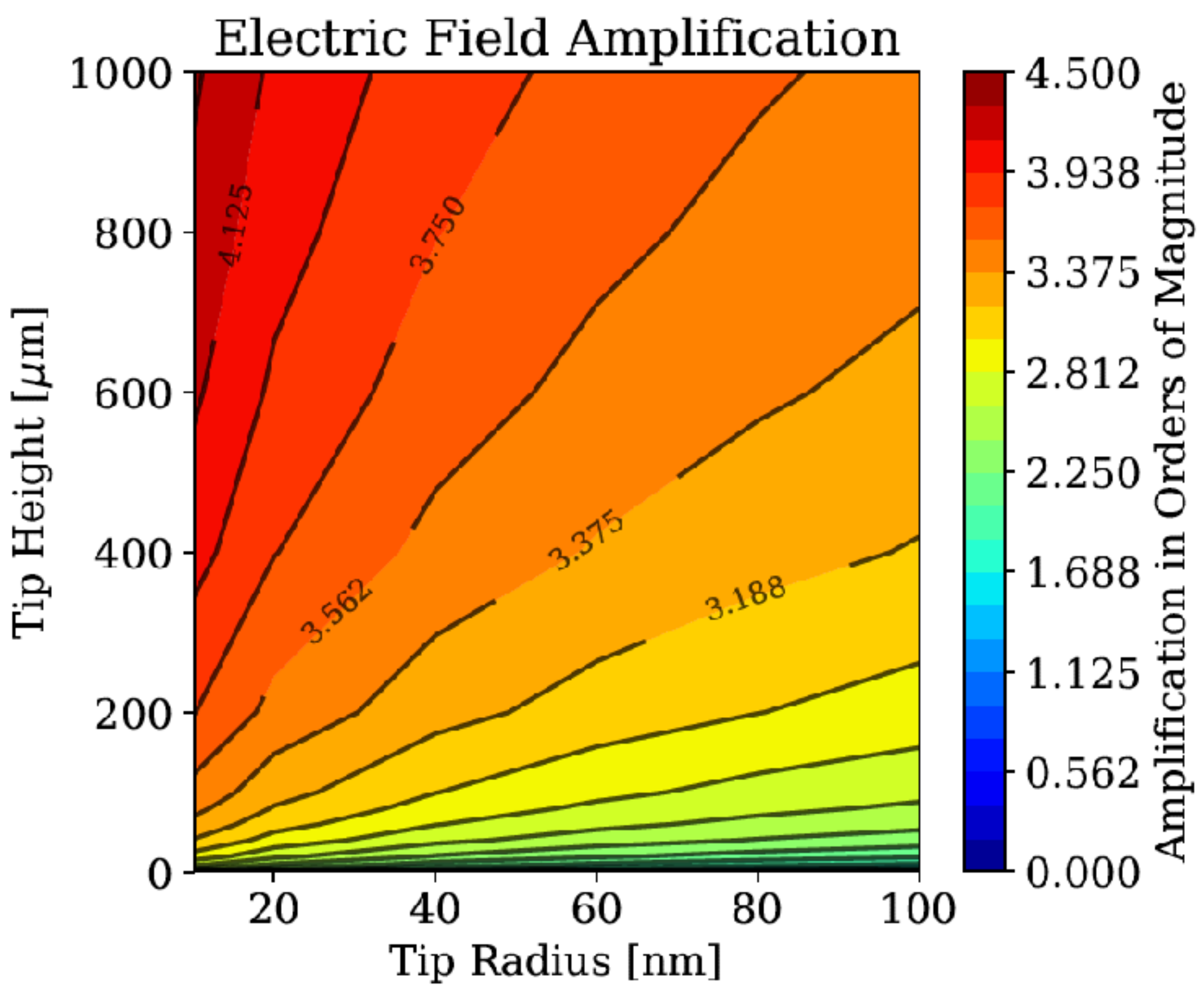
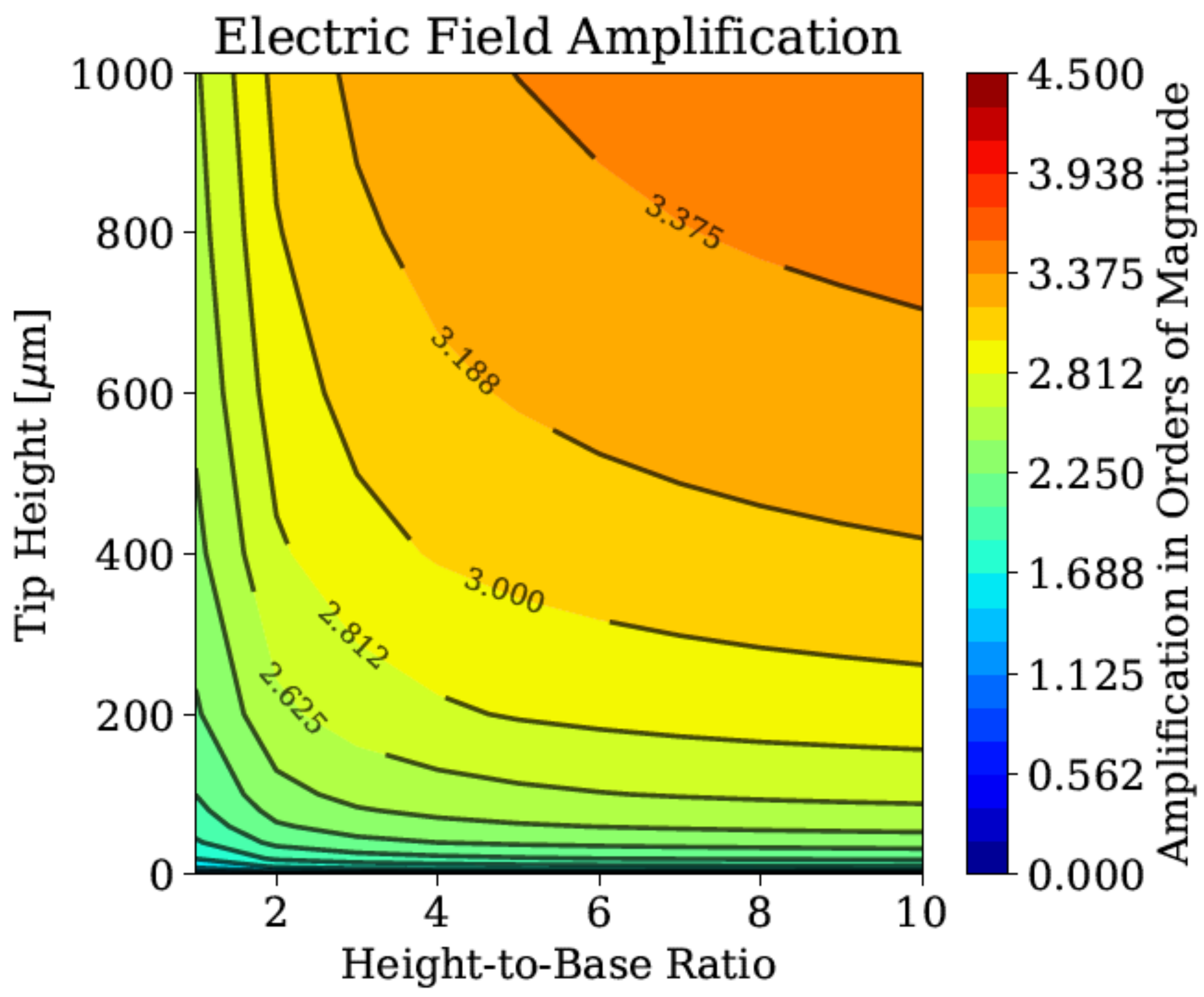


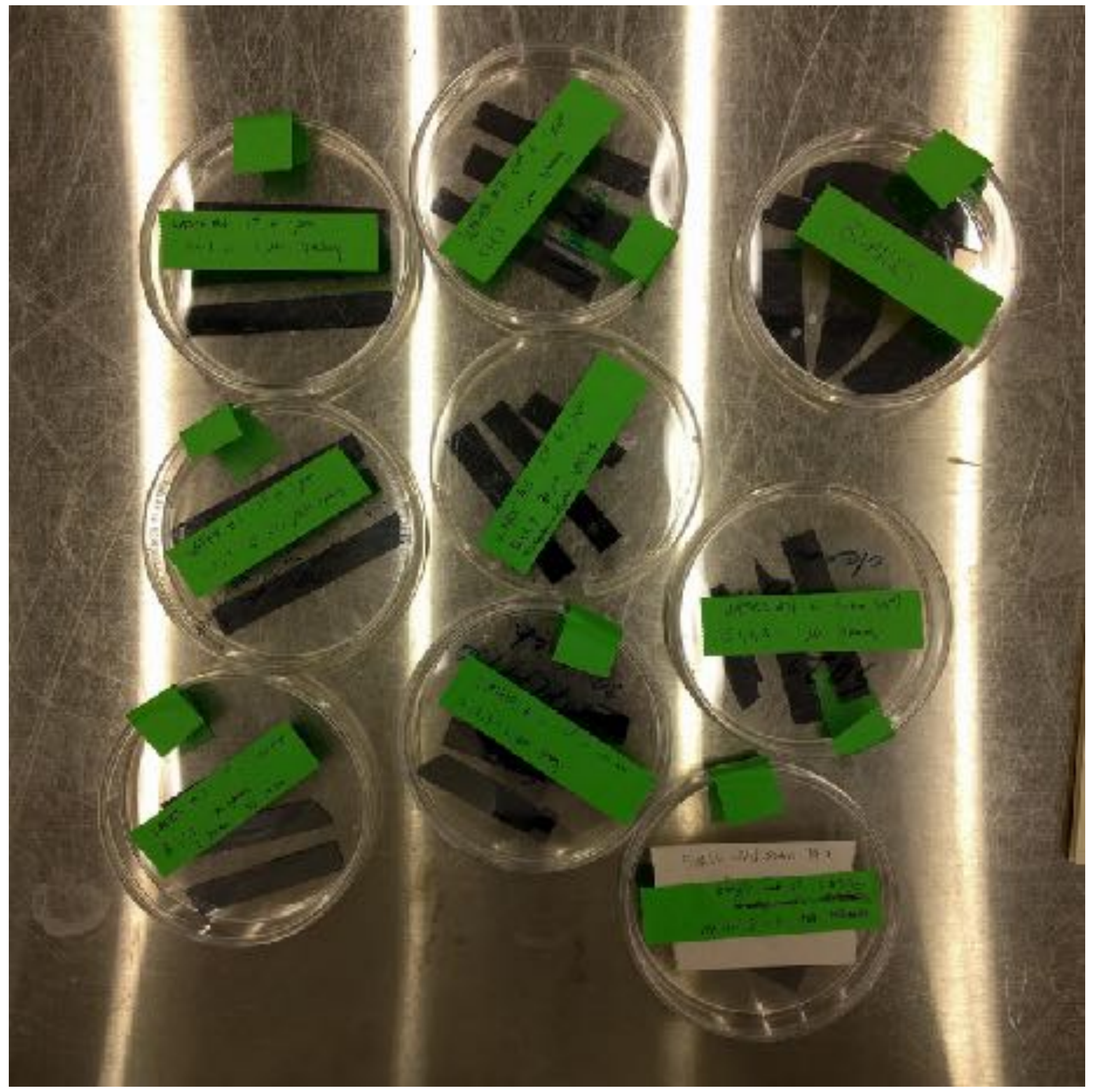
LArCADe: tip-array simulation

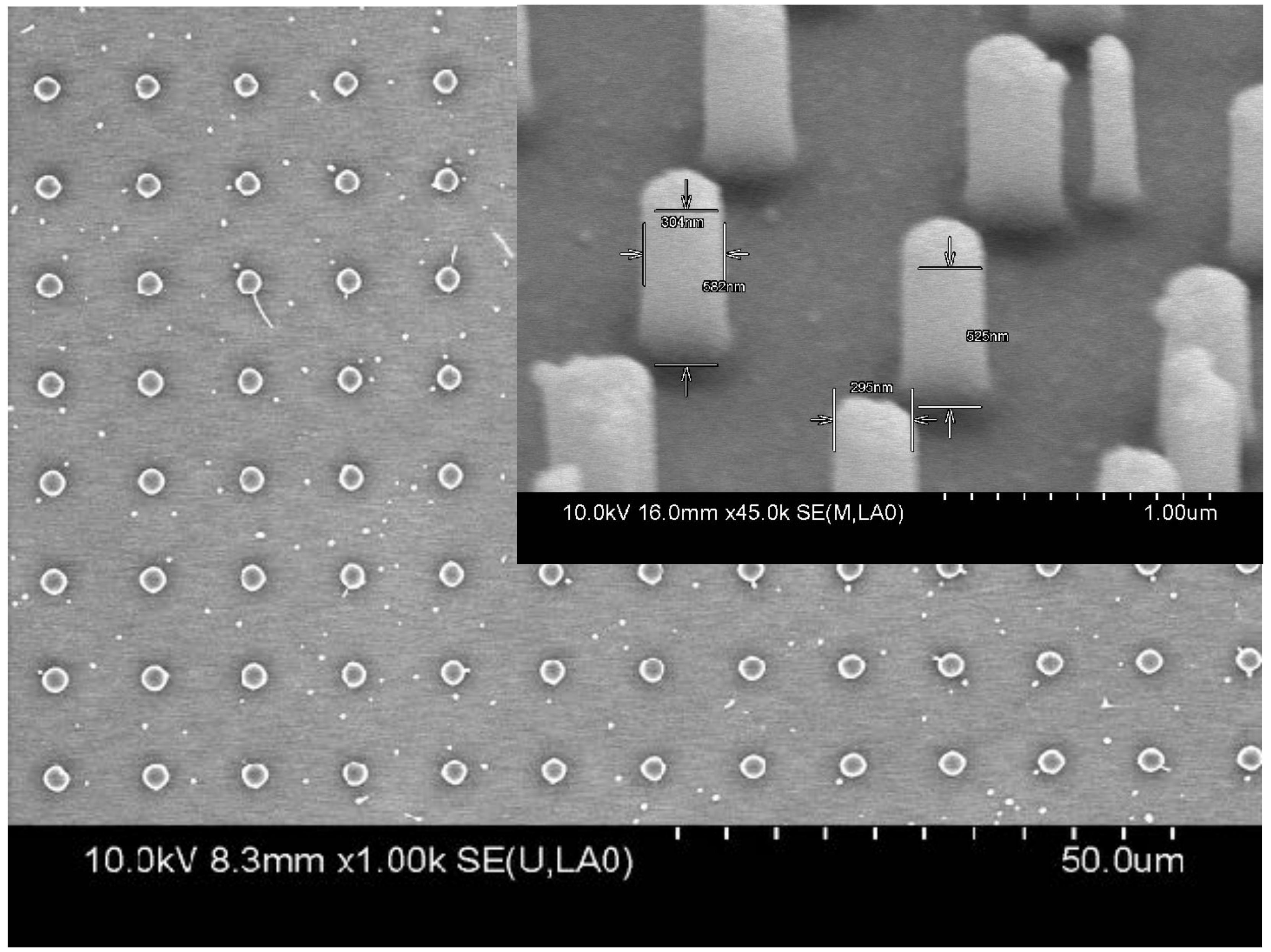




optimize tip geometry and provide input for quantitative gain assessment:
O(100) μm height, O(10s) nm tip radius.

LArCADe: tip-array fabrication

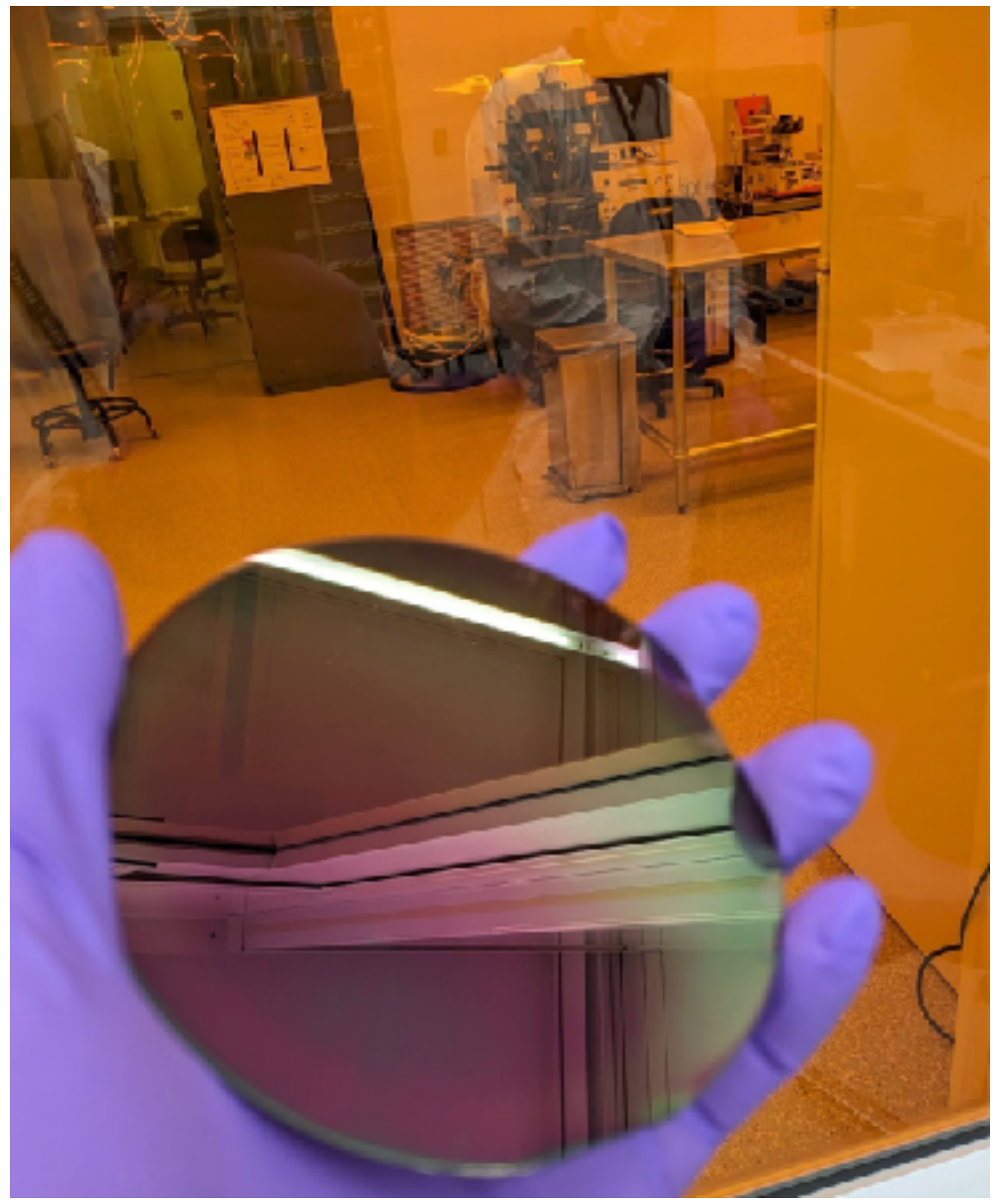


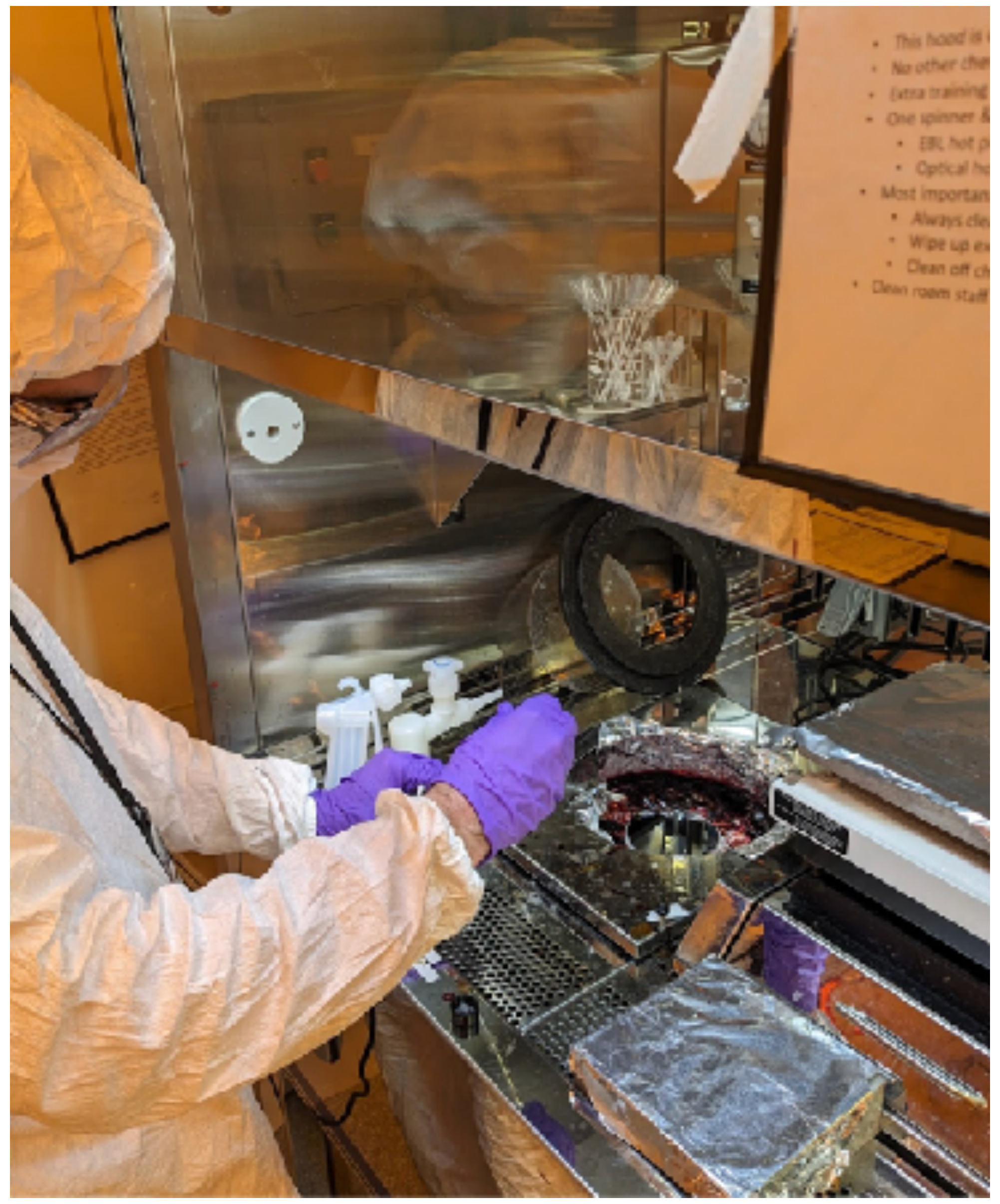


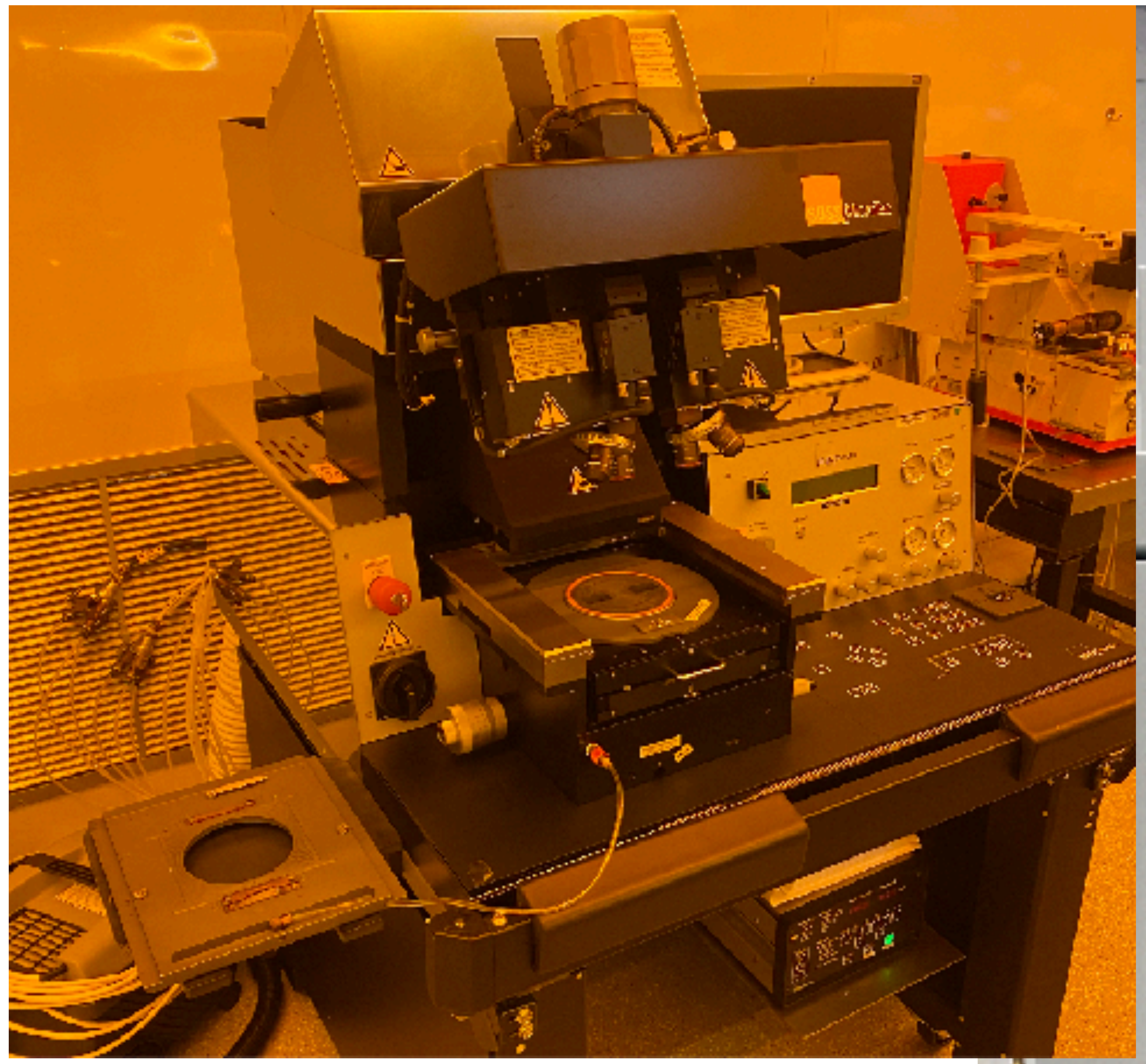
Launched development of tip-arrays @ BNL’s Center for Functional Nanomaterials (CFN)

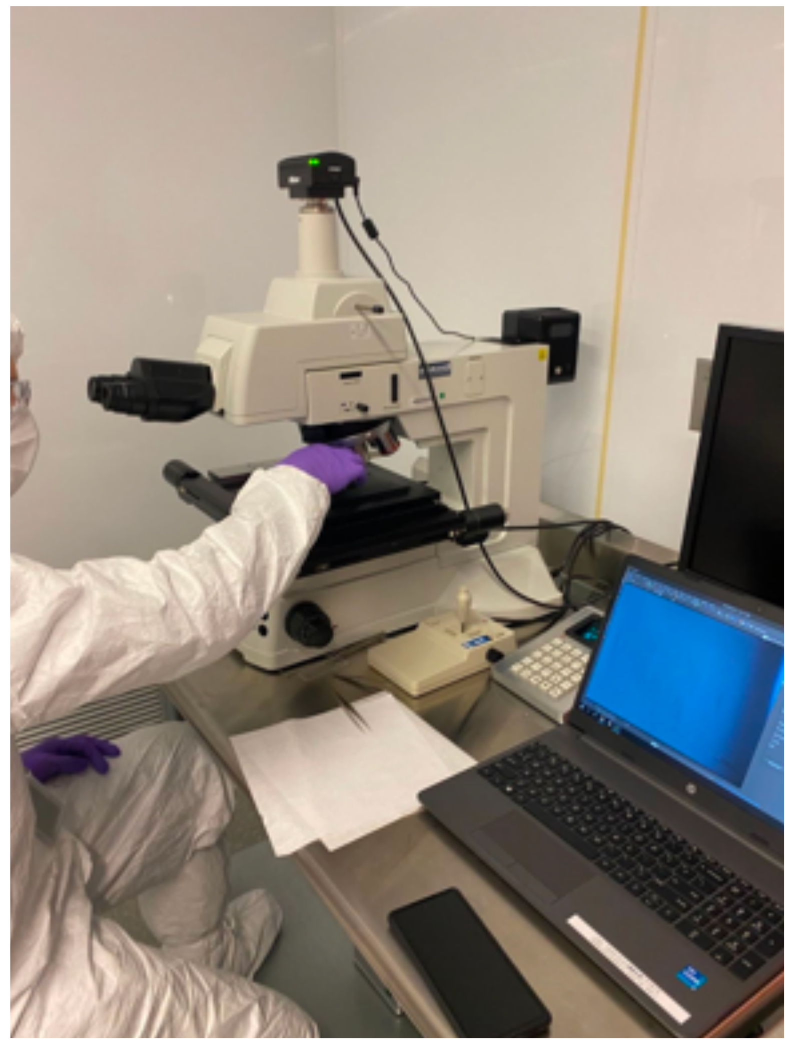
User facility with resources for design, etching, sputtering, imaging

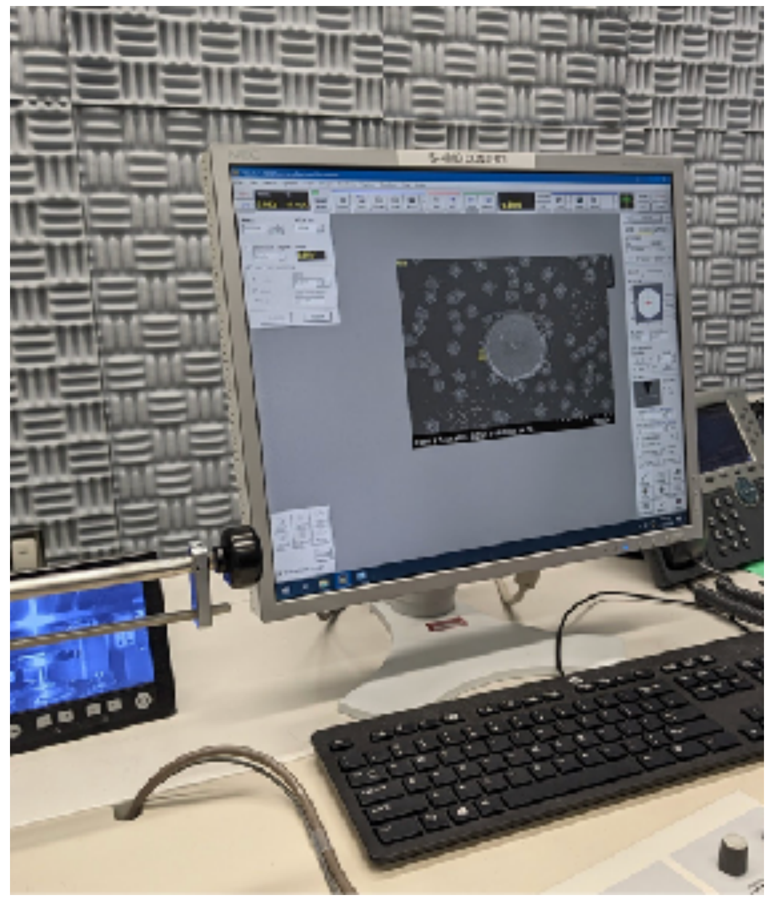
LArCADe: tip-array nano fabrication

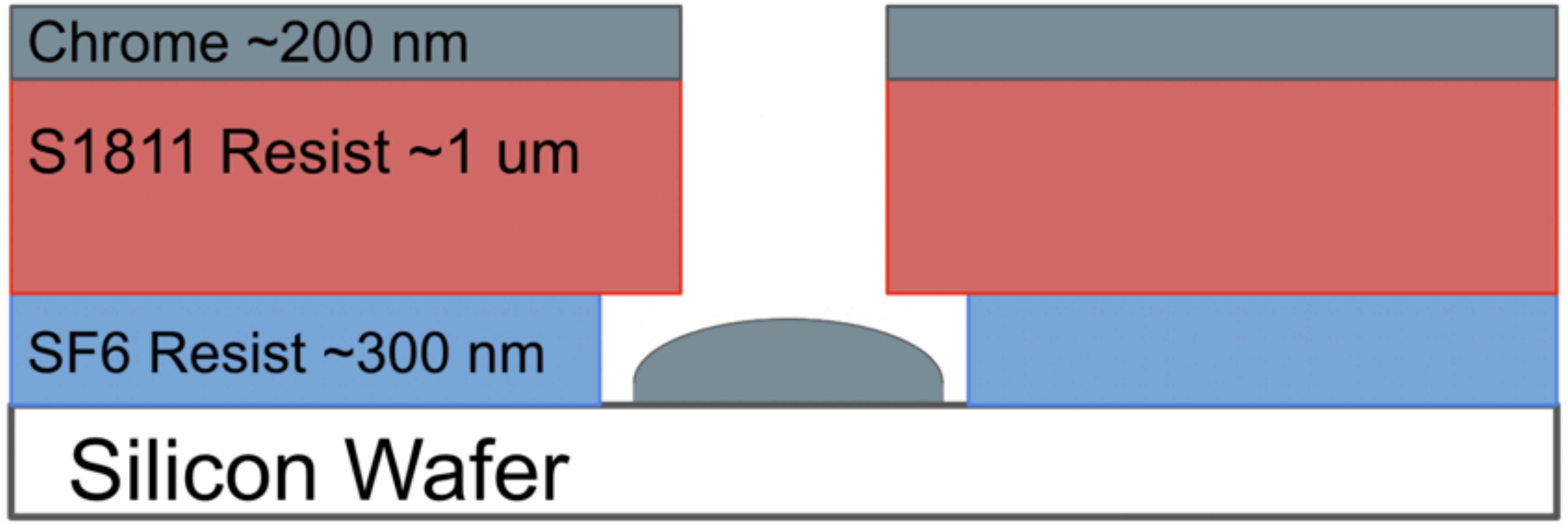




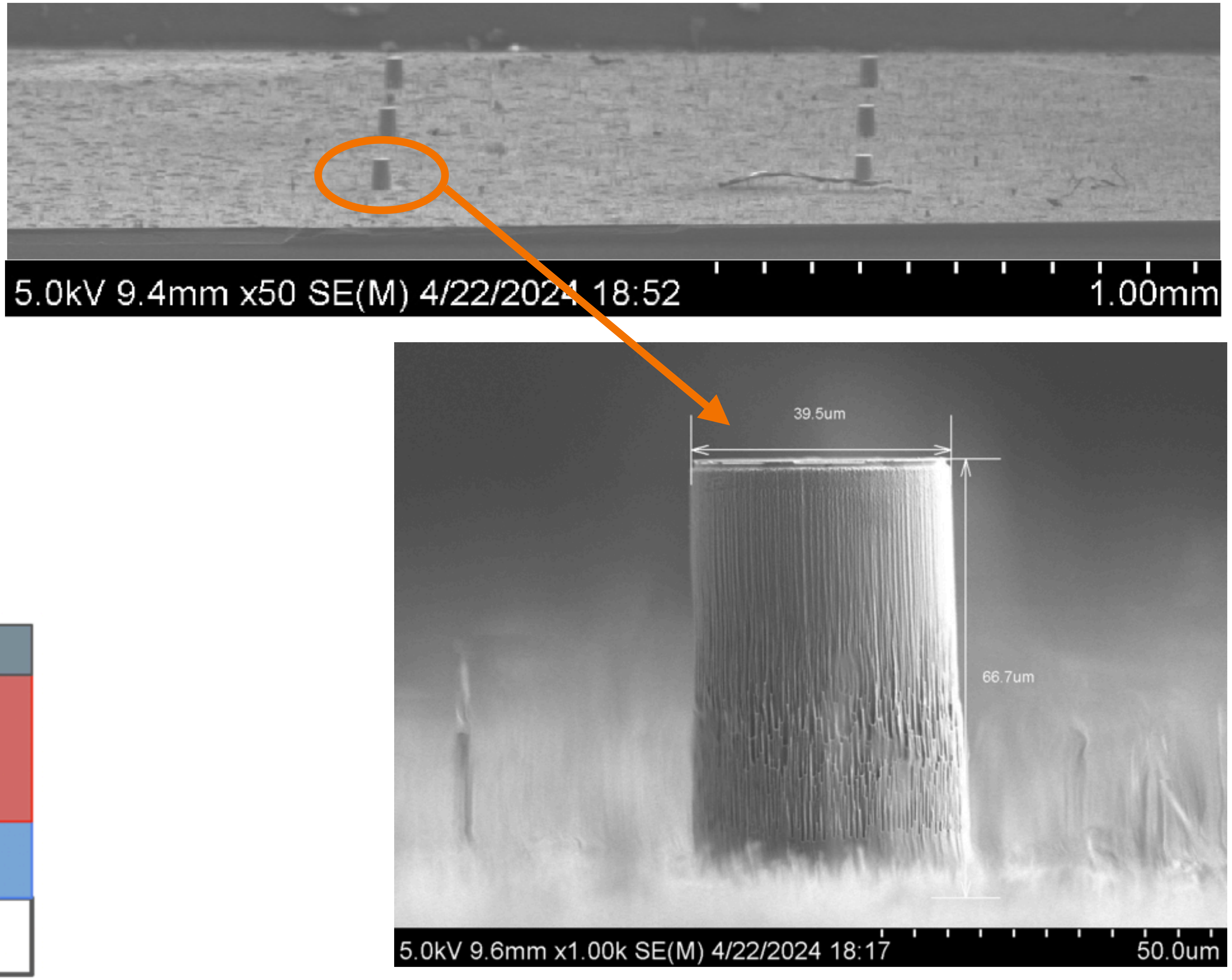








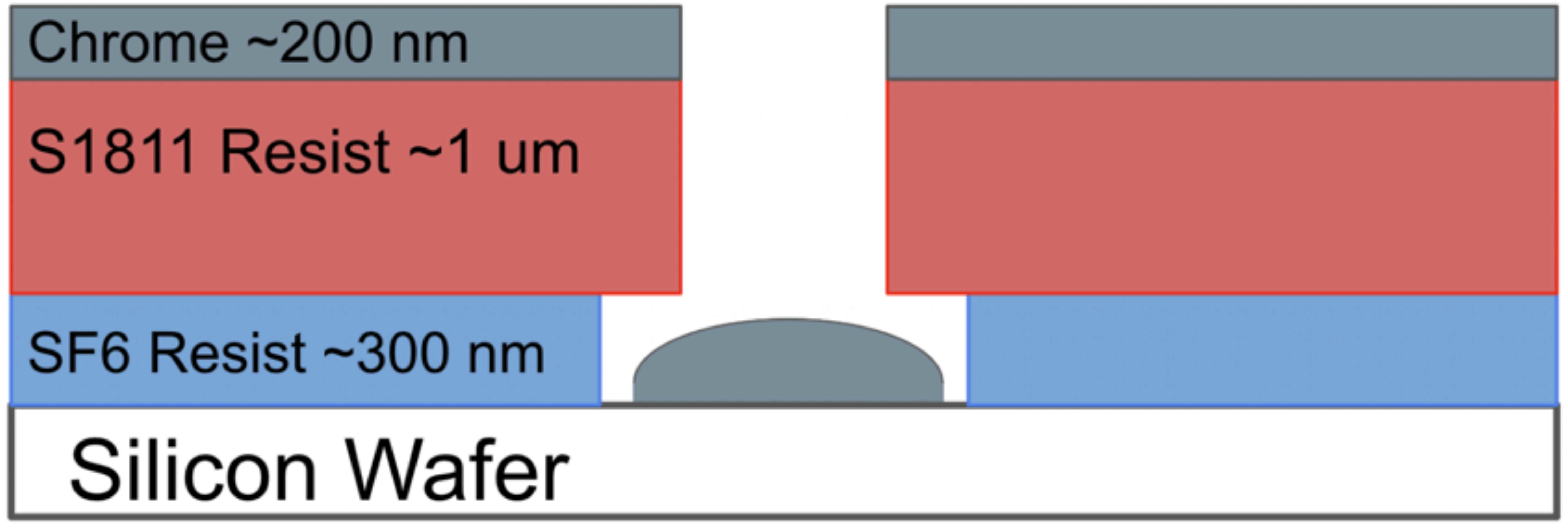
LArCADe: tip-array nano fabrication



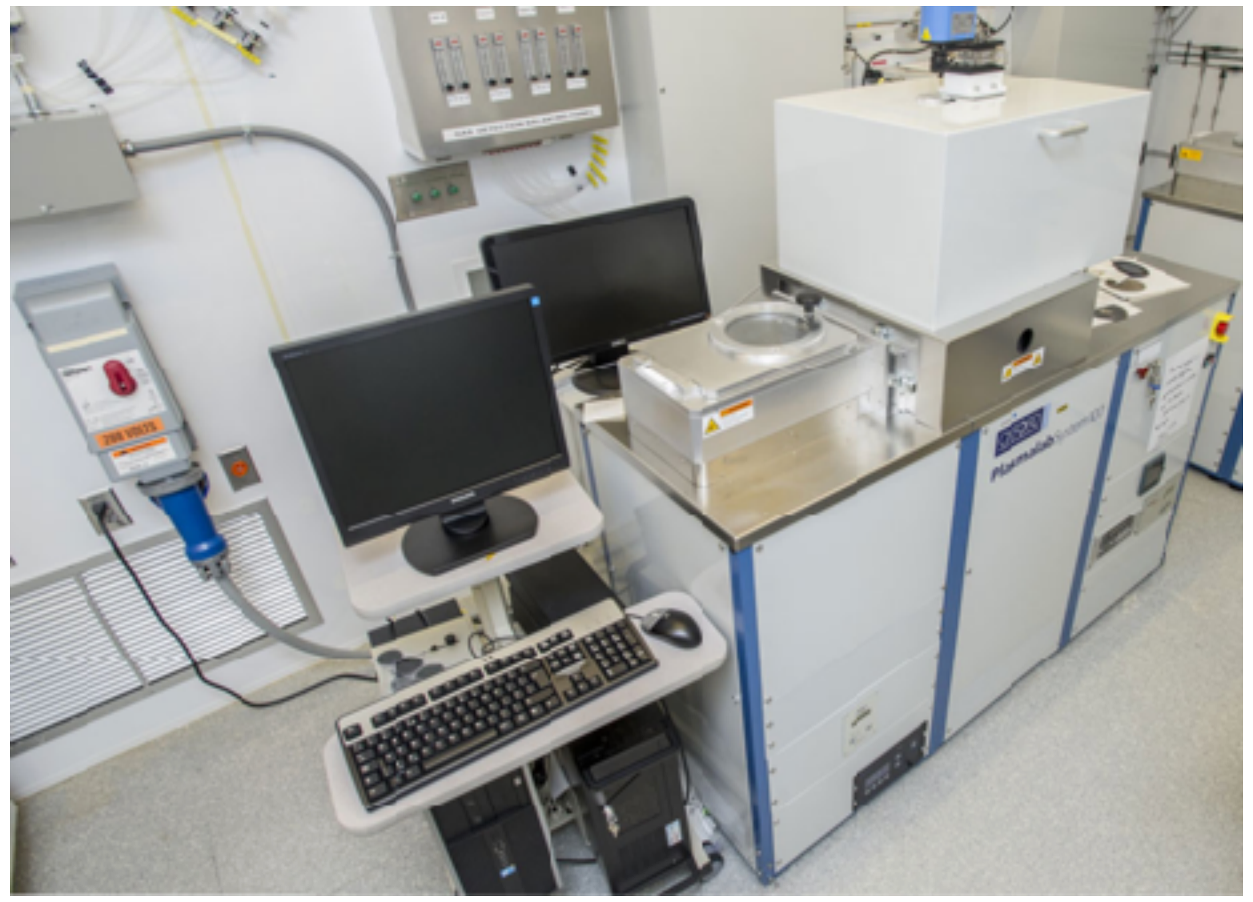
Tip-array geometries:

- can help achieve charge amplification
- Scalable technology
- R&D towards micron-scale tracking

Tip-array geometries for NR tracking in GAr a possible new direction for R&D.

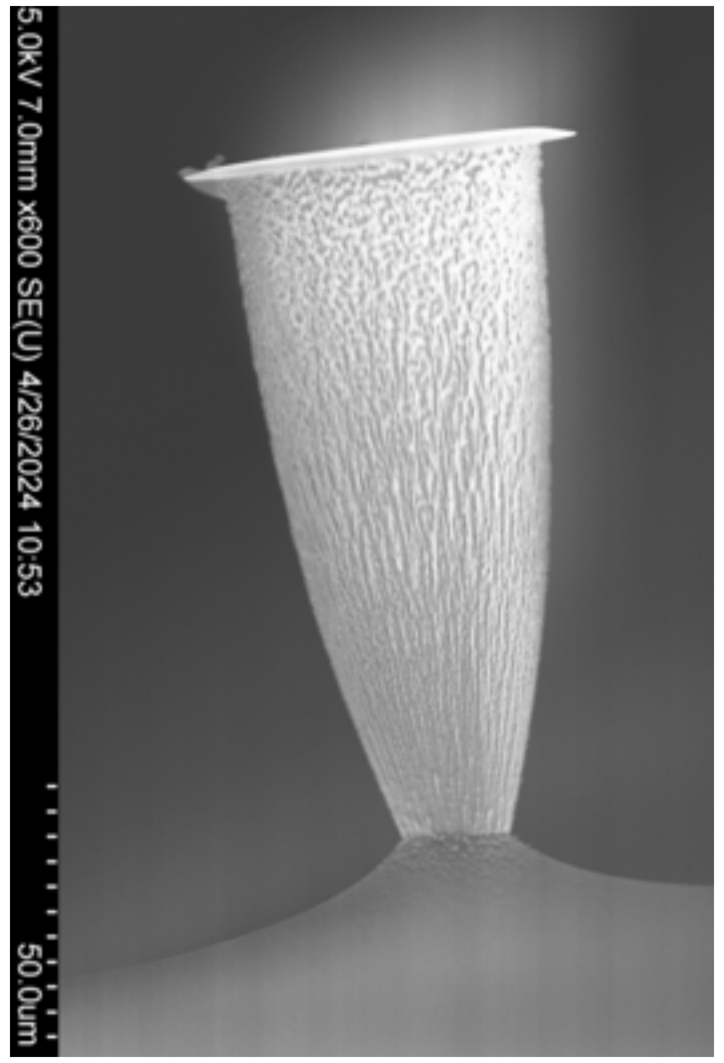


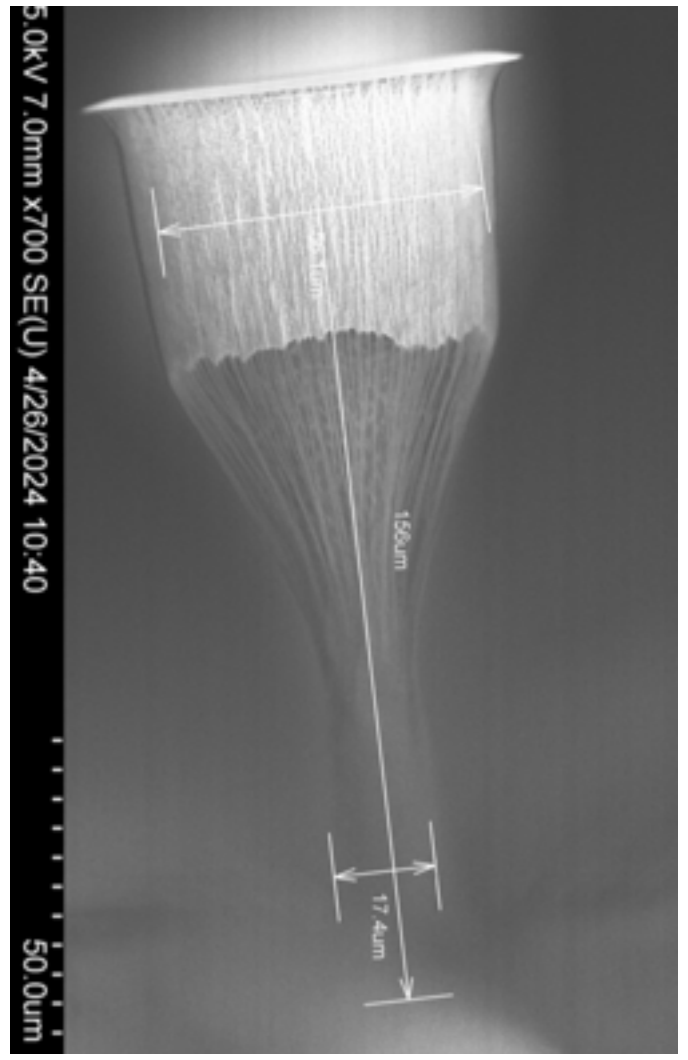
Tip geometry optimization

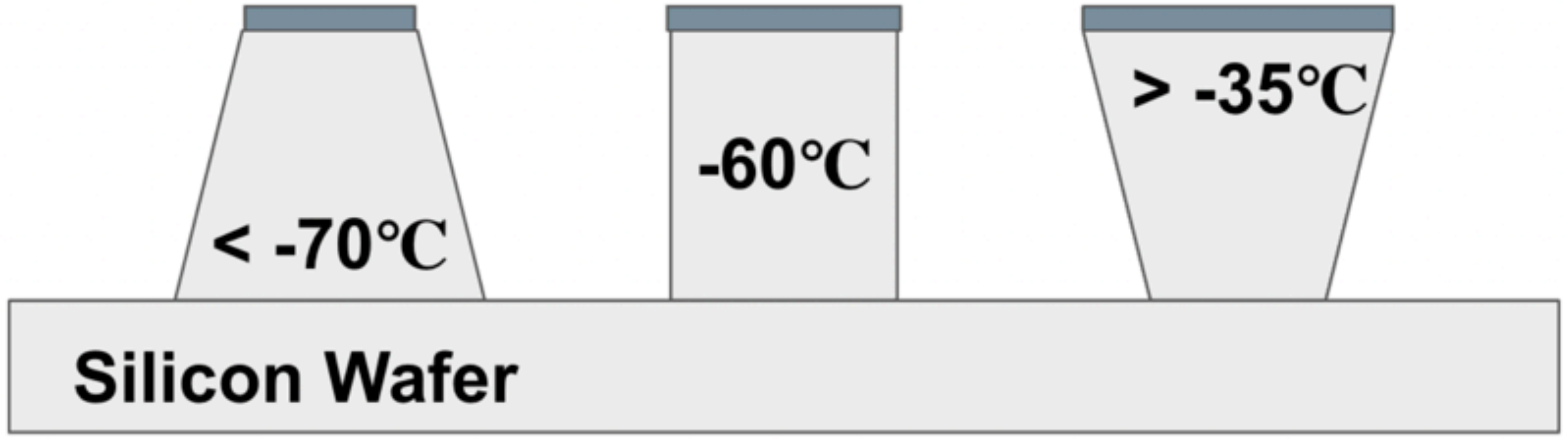


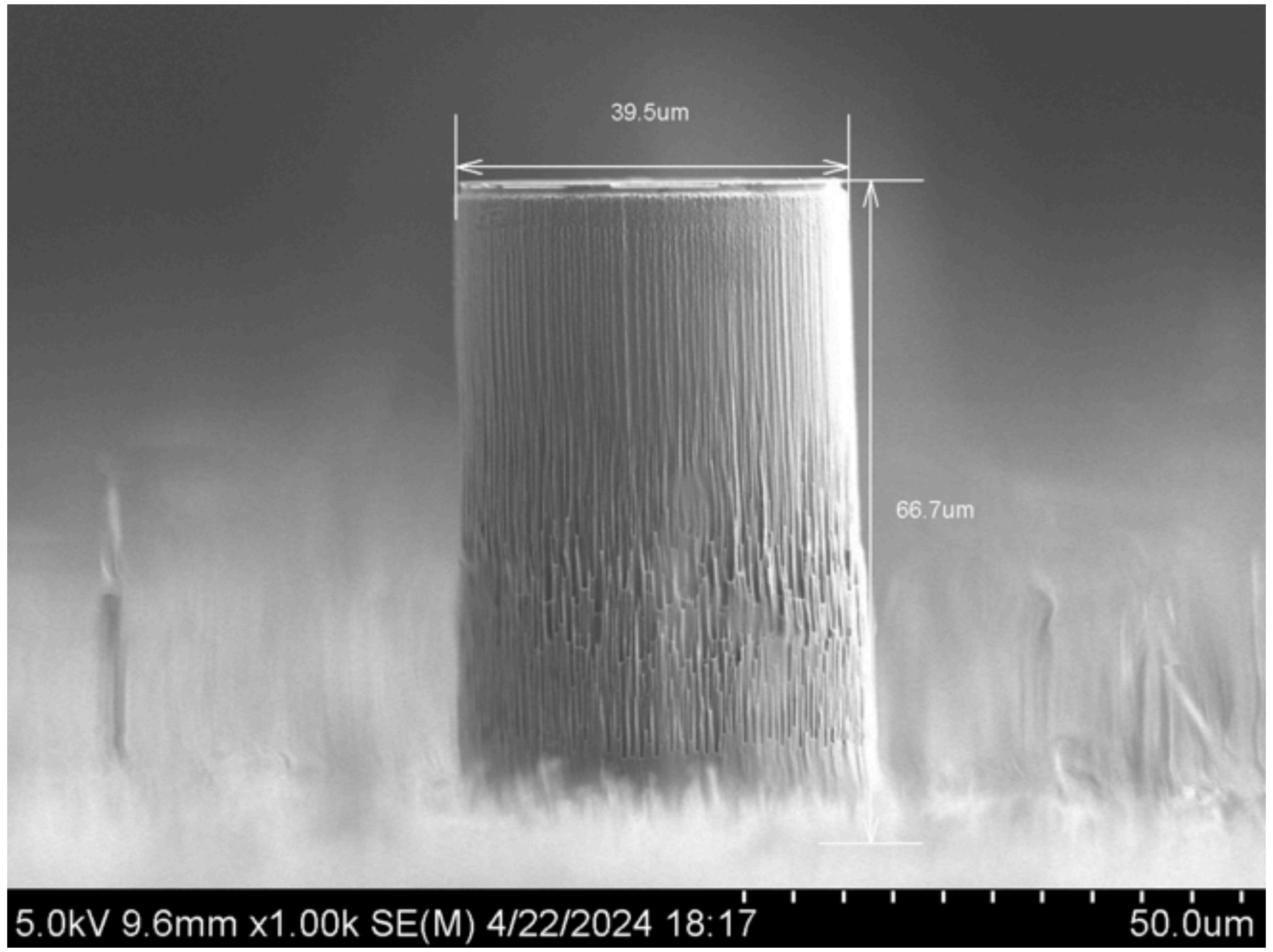
Oxford etching machine @ BNL

Bombard substrate with different gas mixtures at different temperatures to “eat” away silicon







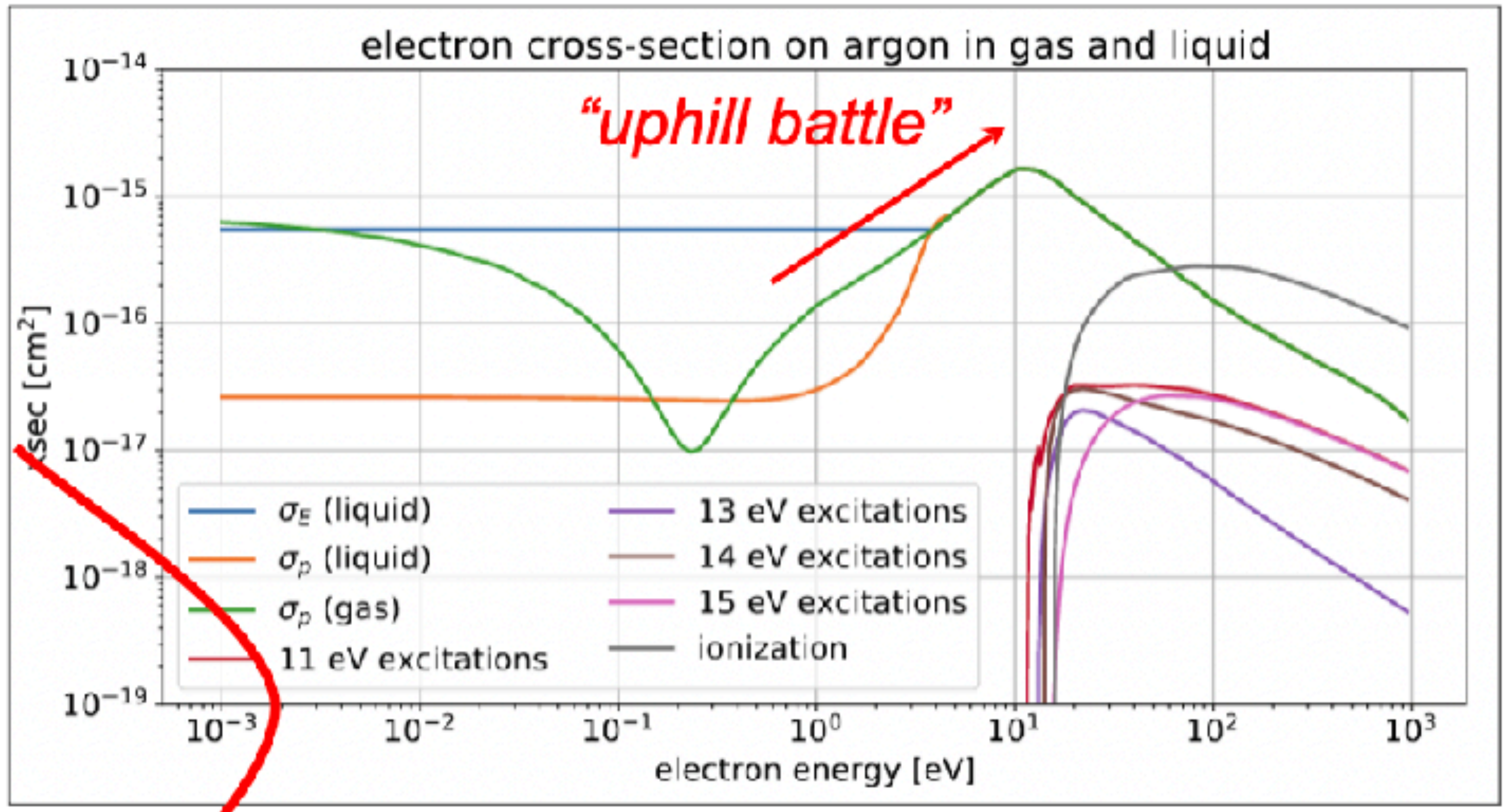


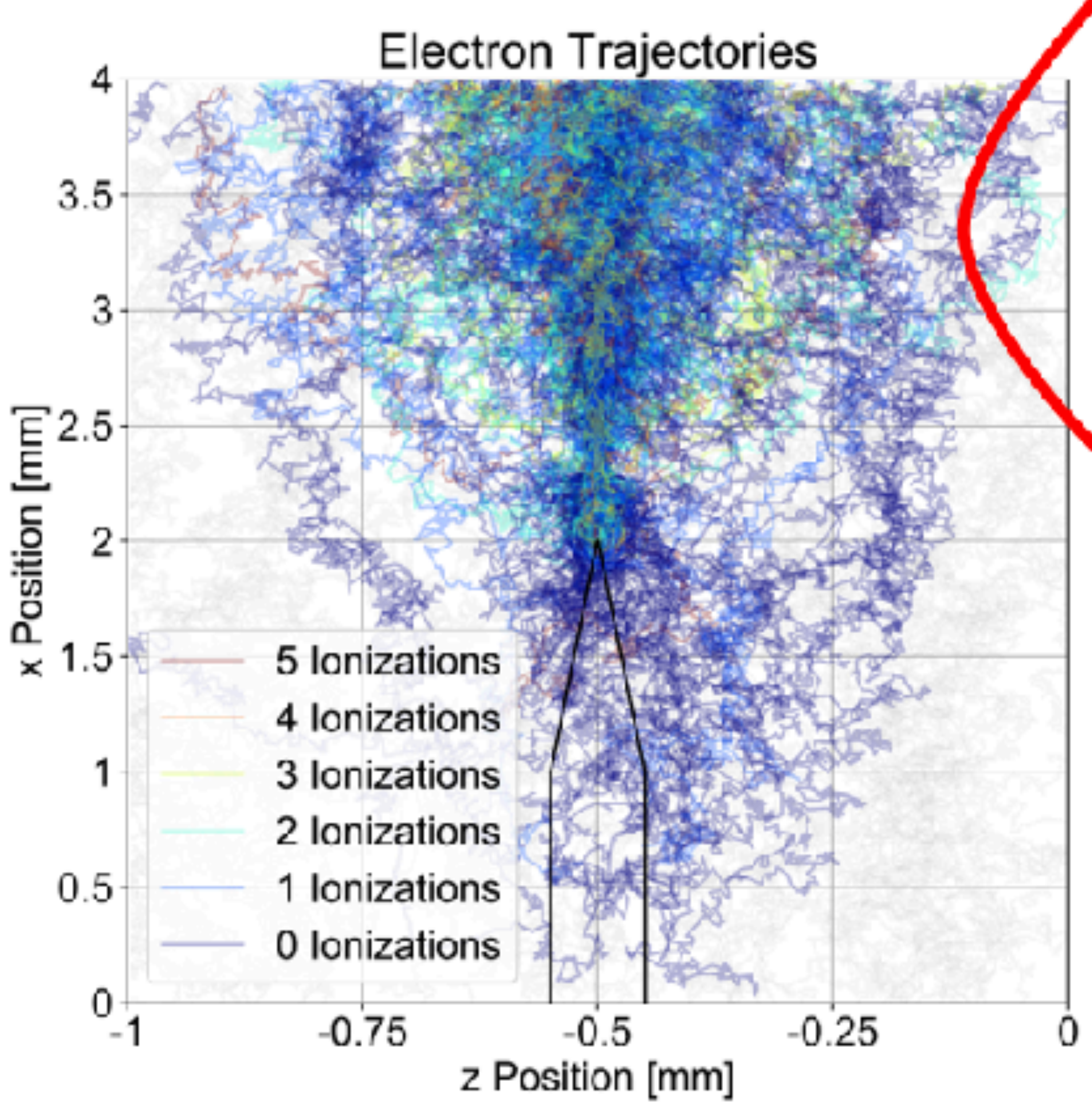
Tip “etching” key to tip geometry. Scale of structures being built large compared to standard uses for this equipment. Active R&D

TRANSLATE

TRANSport in Liquid Argon of near-Thermal Electrons

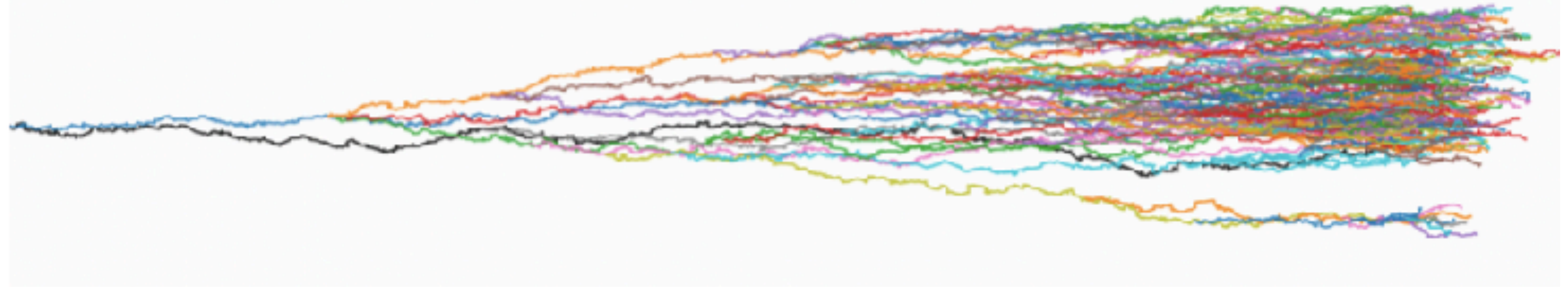
LArCADe





TRANSLATE

transport in liquid argon of near-thermal electrons

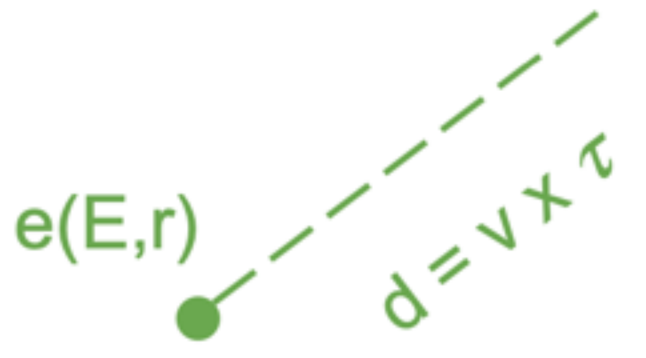


[CPC 297 (2024) 109056](#)

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

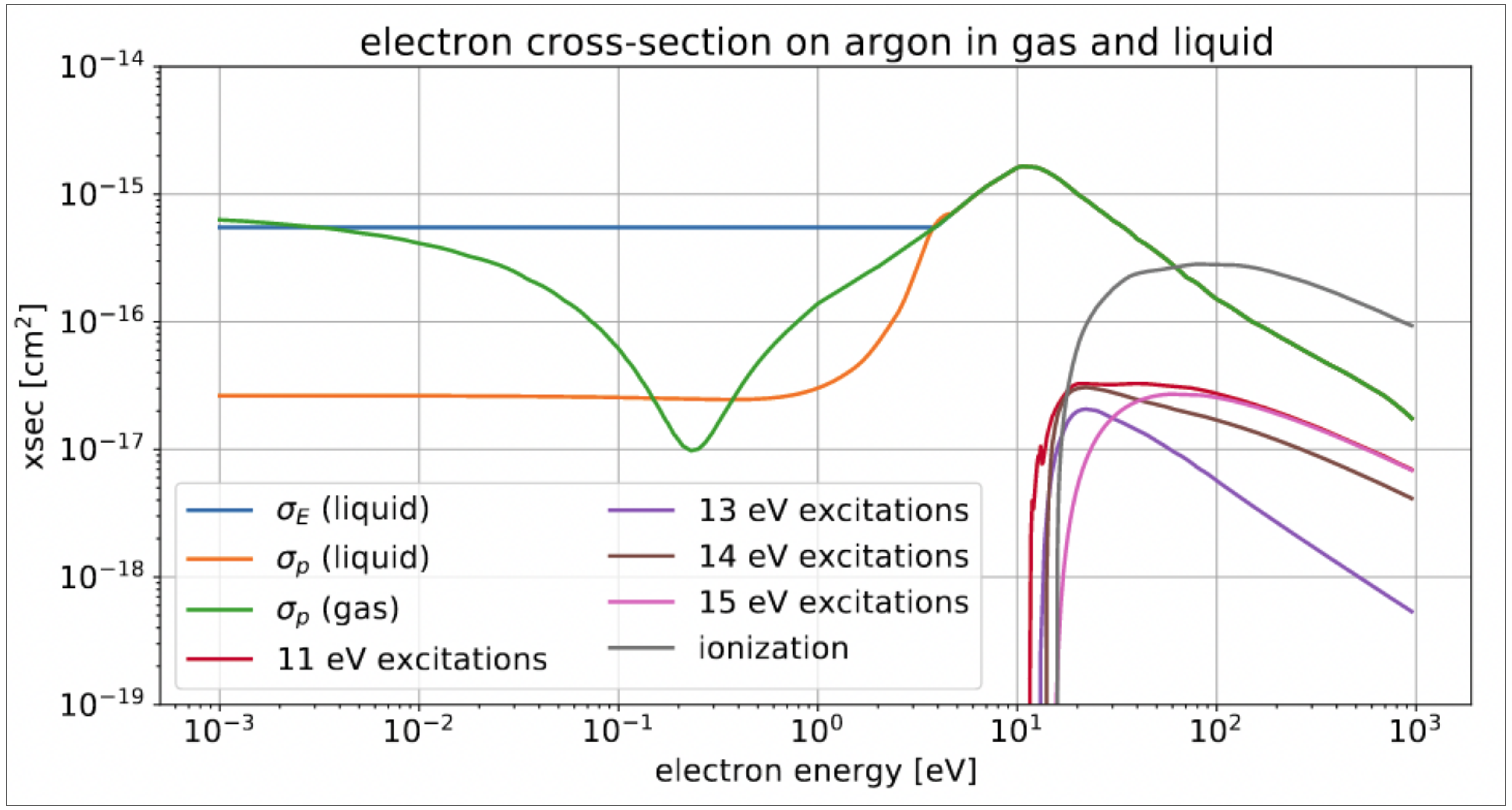
Zach Beever, David Caratelli, Angela Fava, Francesco Pietropaolo, Francesca Stocker, Jacob Zettlemoyer

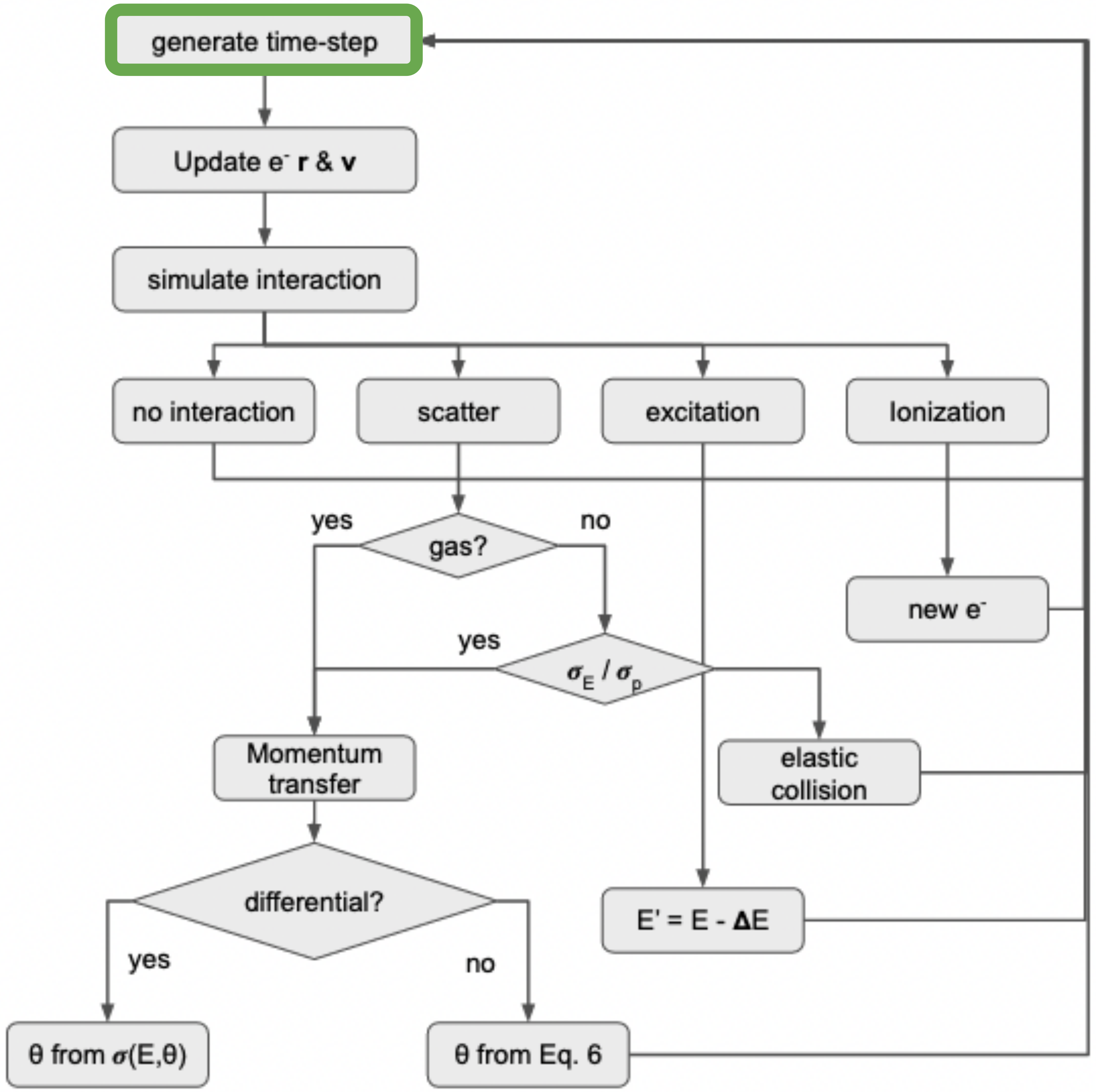
TRANSLATE: Monte Carlo simulation



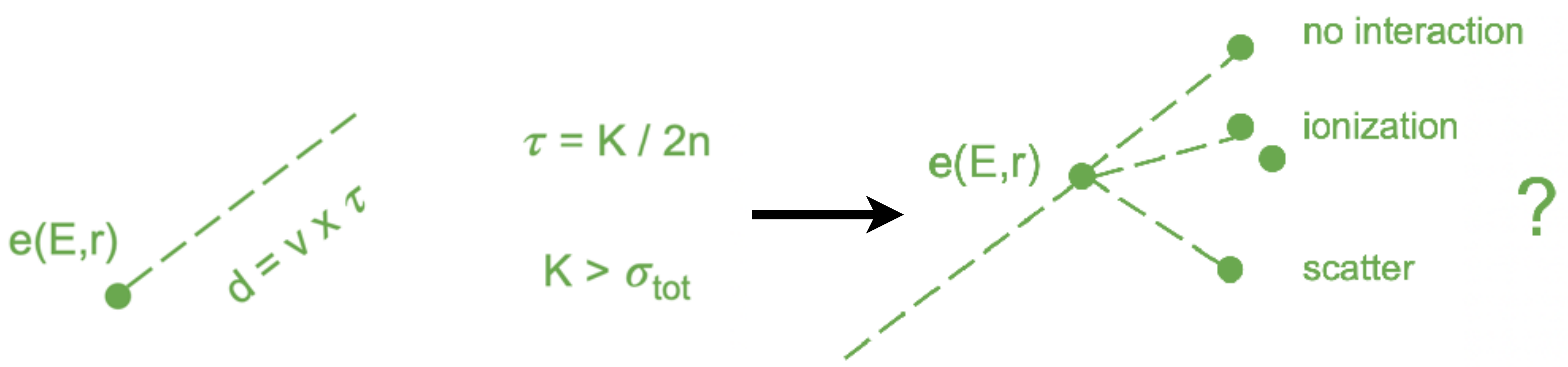
$\tau = K / 2n$

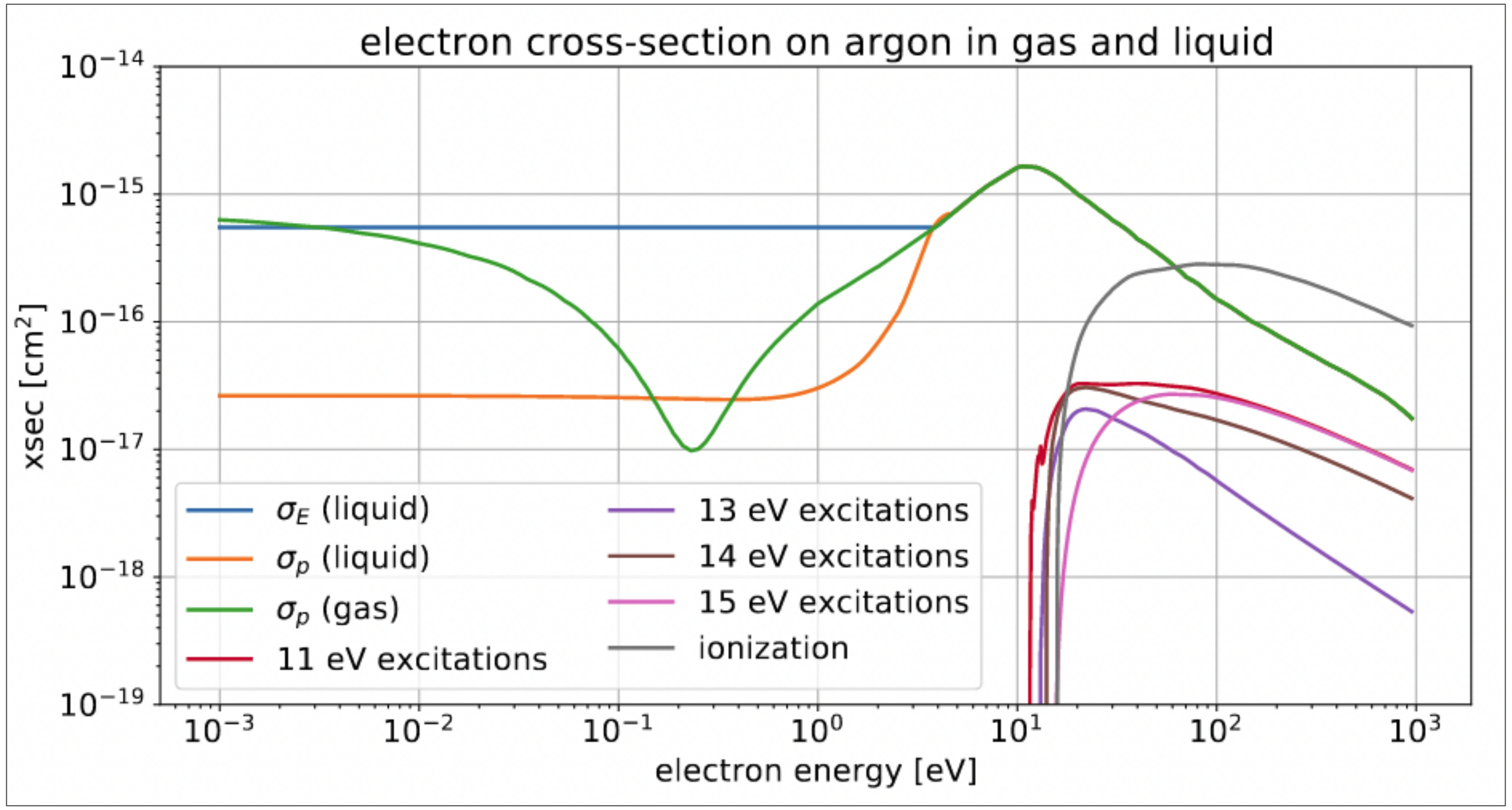
$K > \sigma_{tot}$

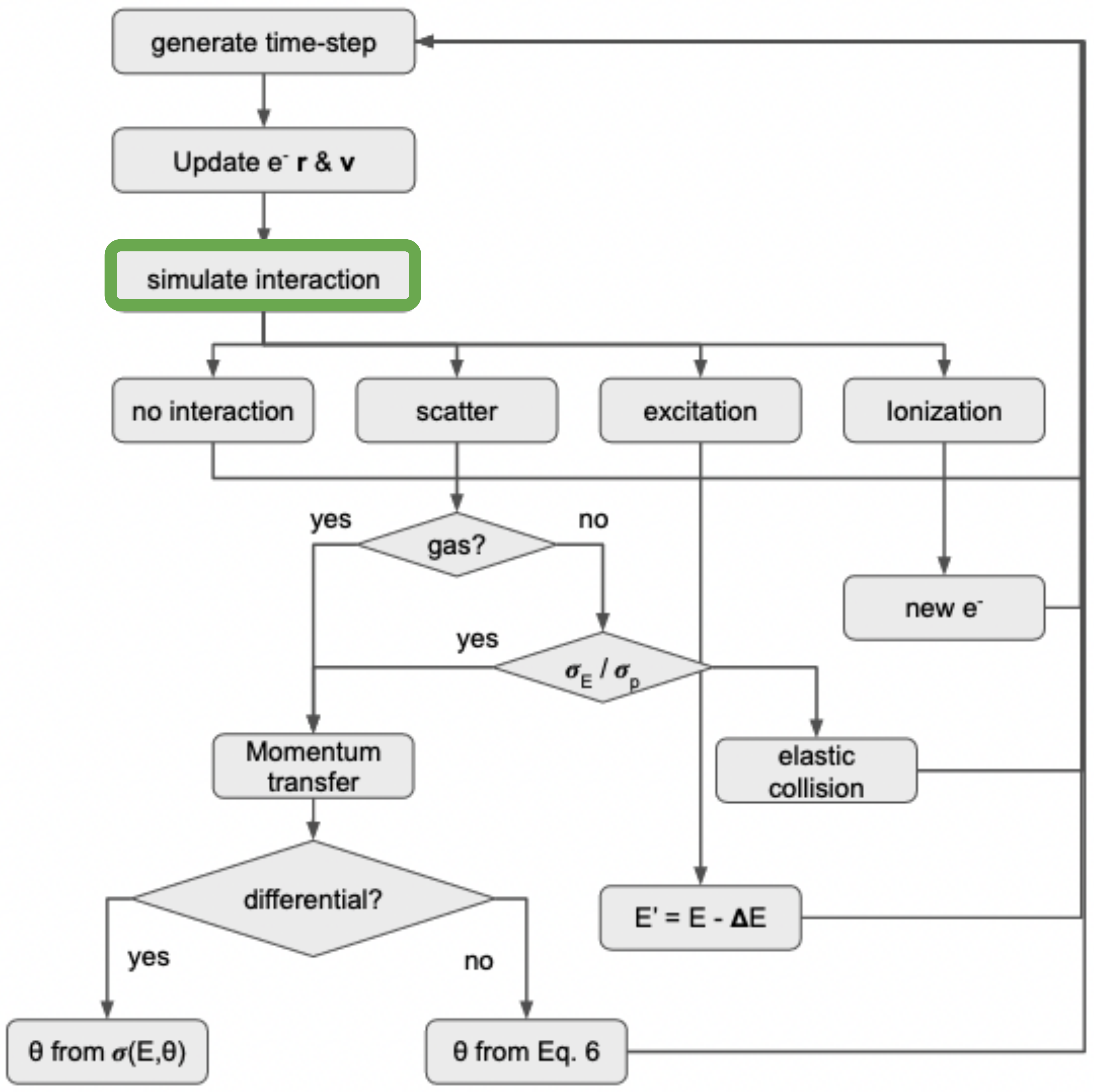




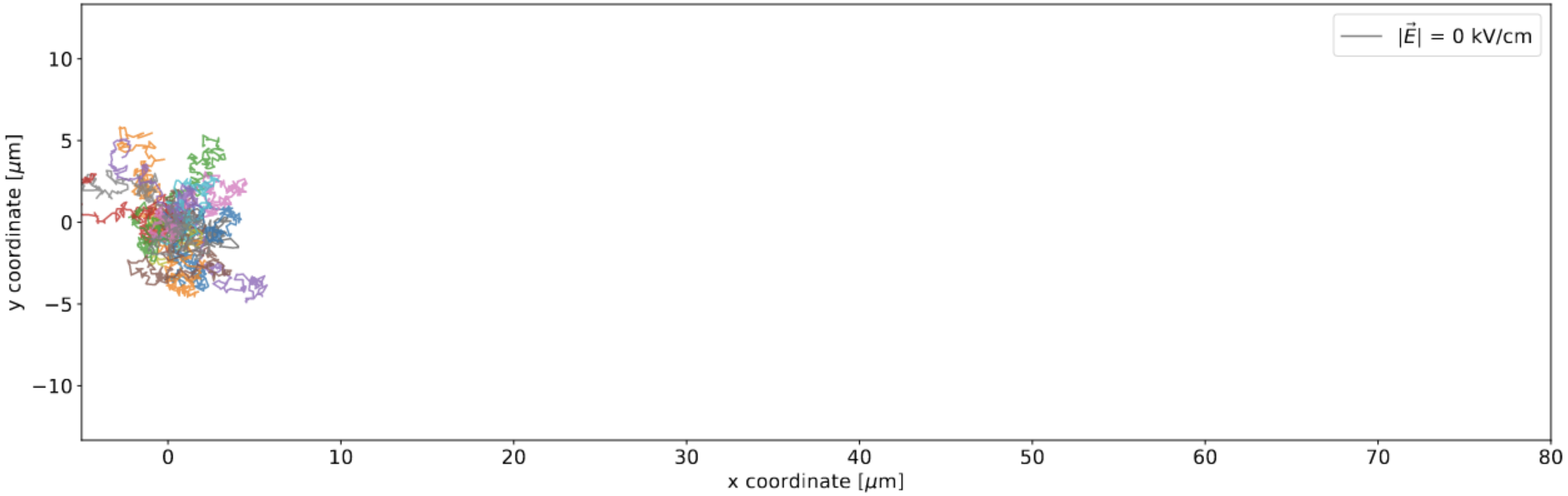
TRANSLATE: Monte Carlo simulation

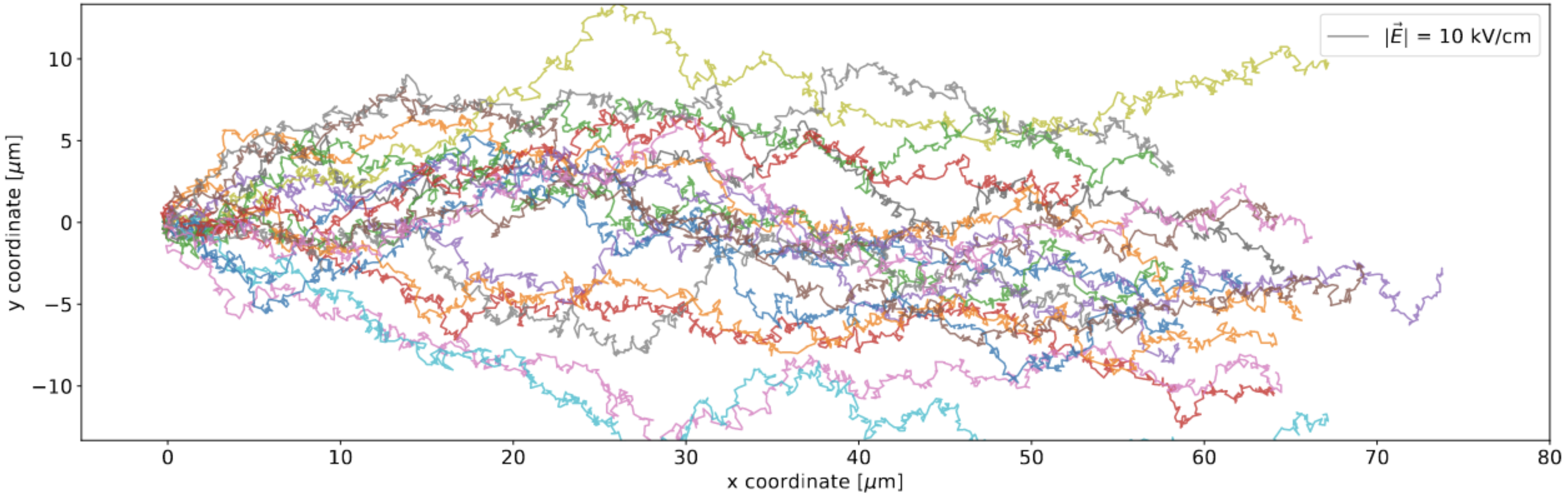






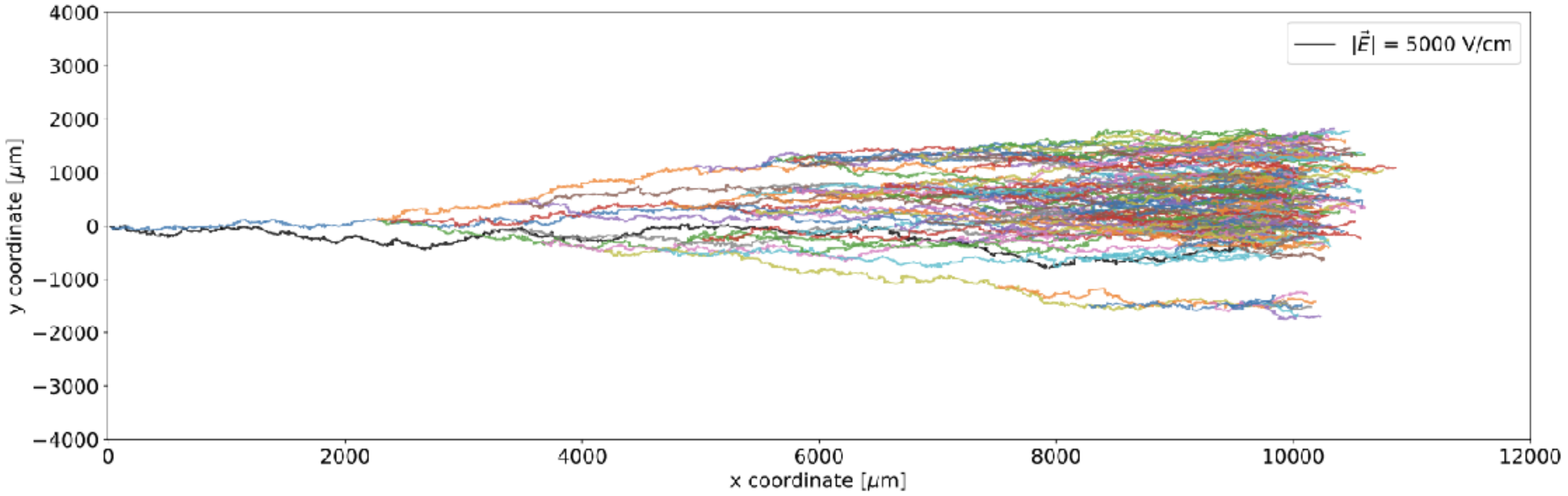
TRANSLATE: simulation output

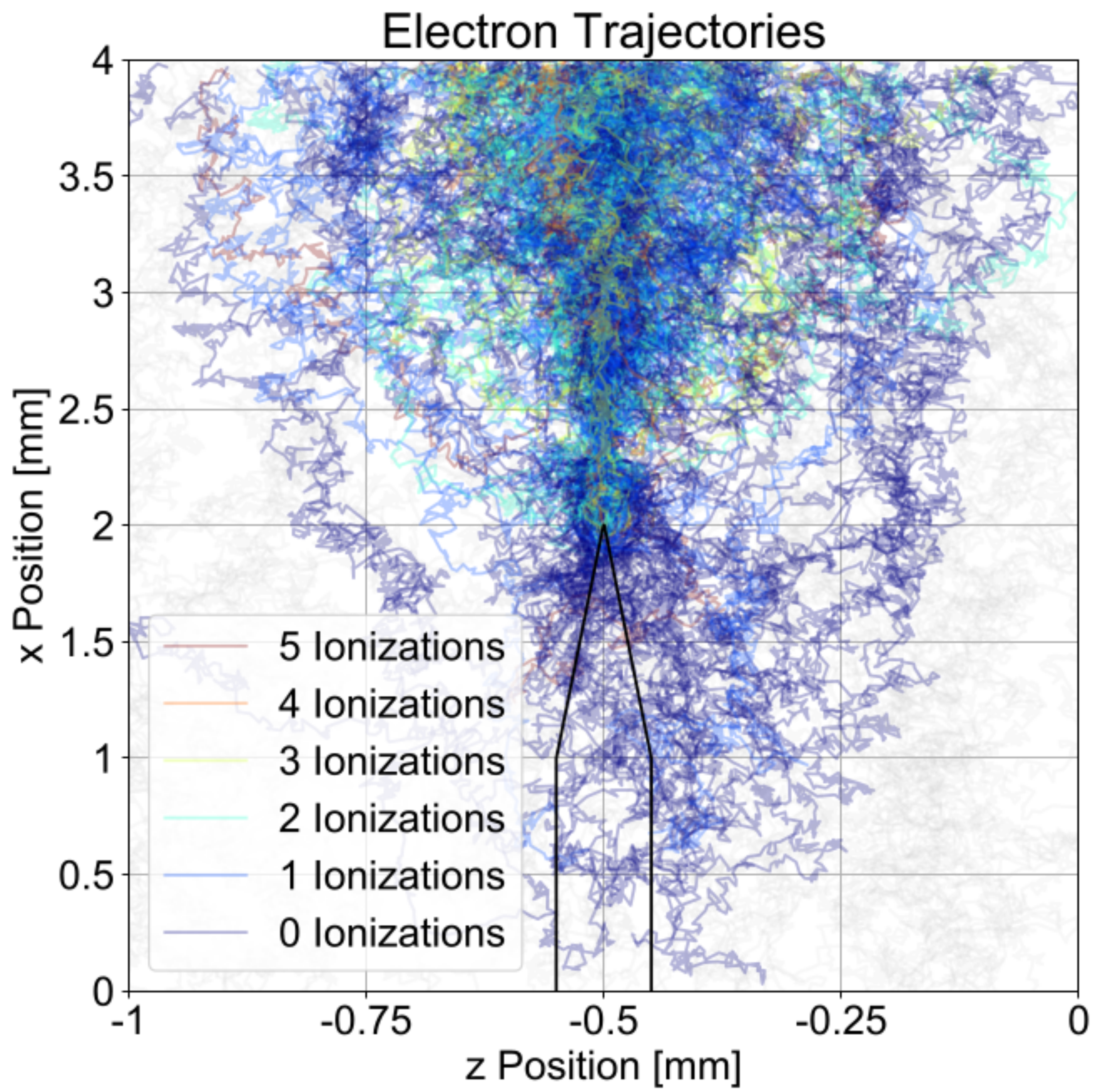




TRANSLATE: simulation output

Simulation of electron amplification in complex geometries



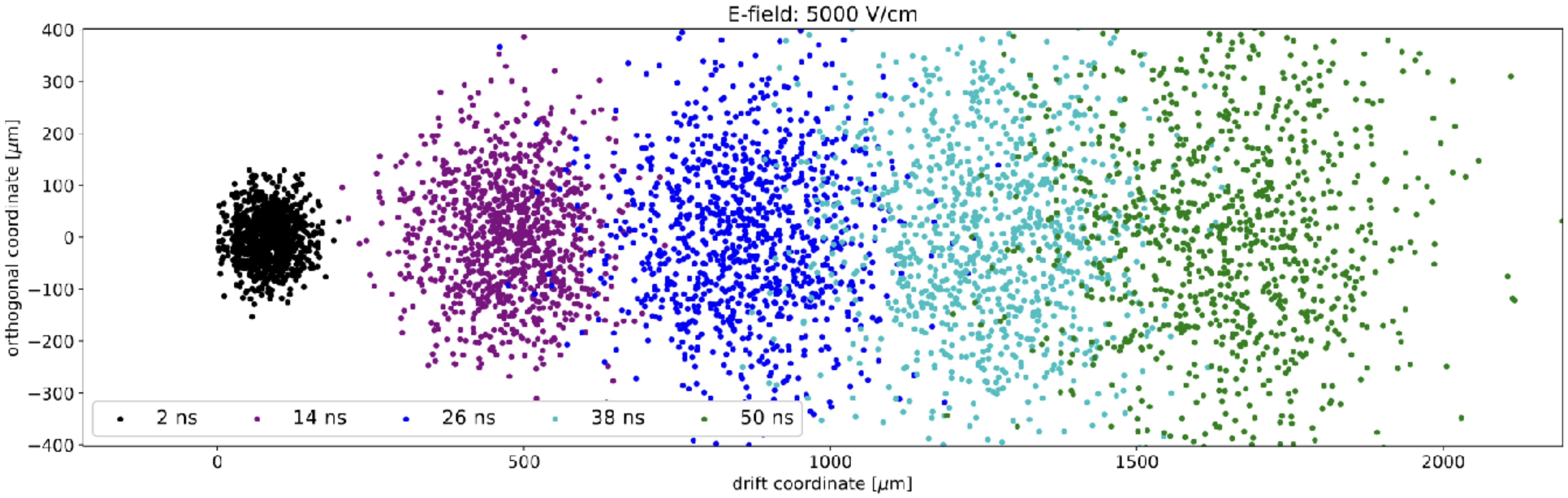


TRANSLATE: simulation validation

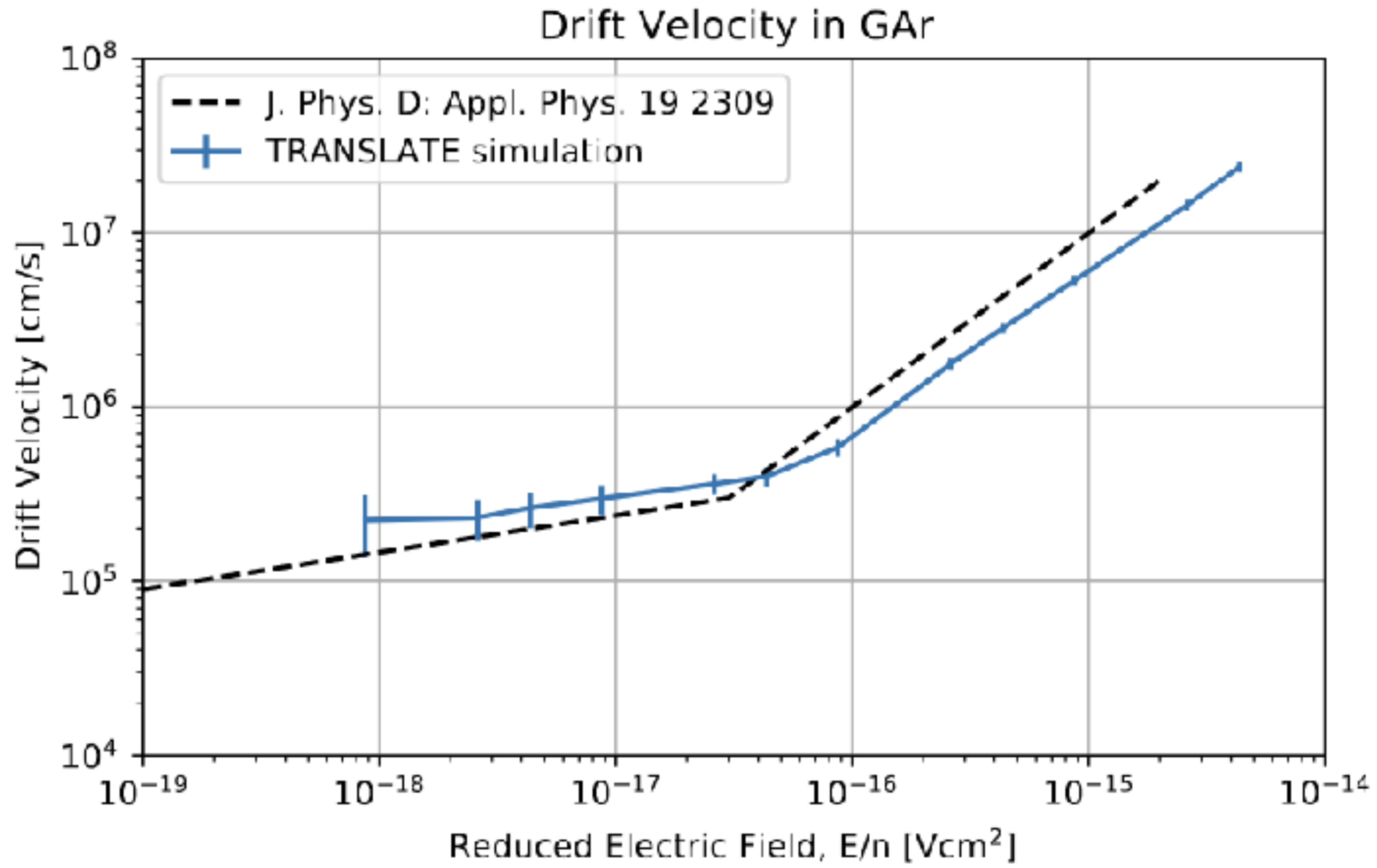
Track $O(10^2 – 10^3)$ electrons over time intervals of $10^{-9} – 10^{-6}$ seconds.

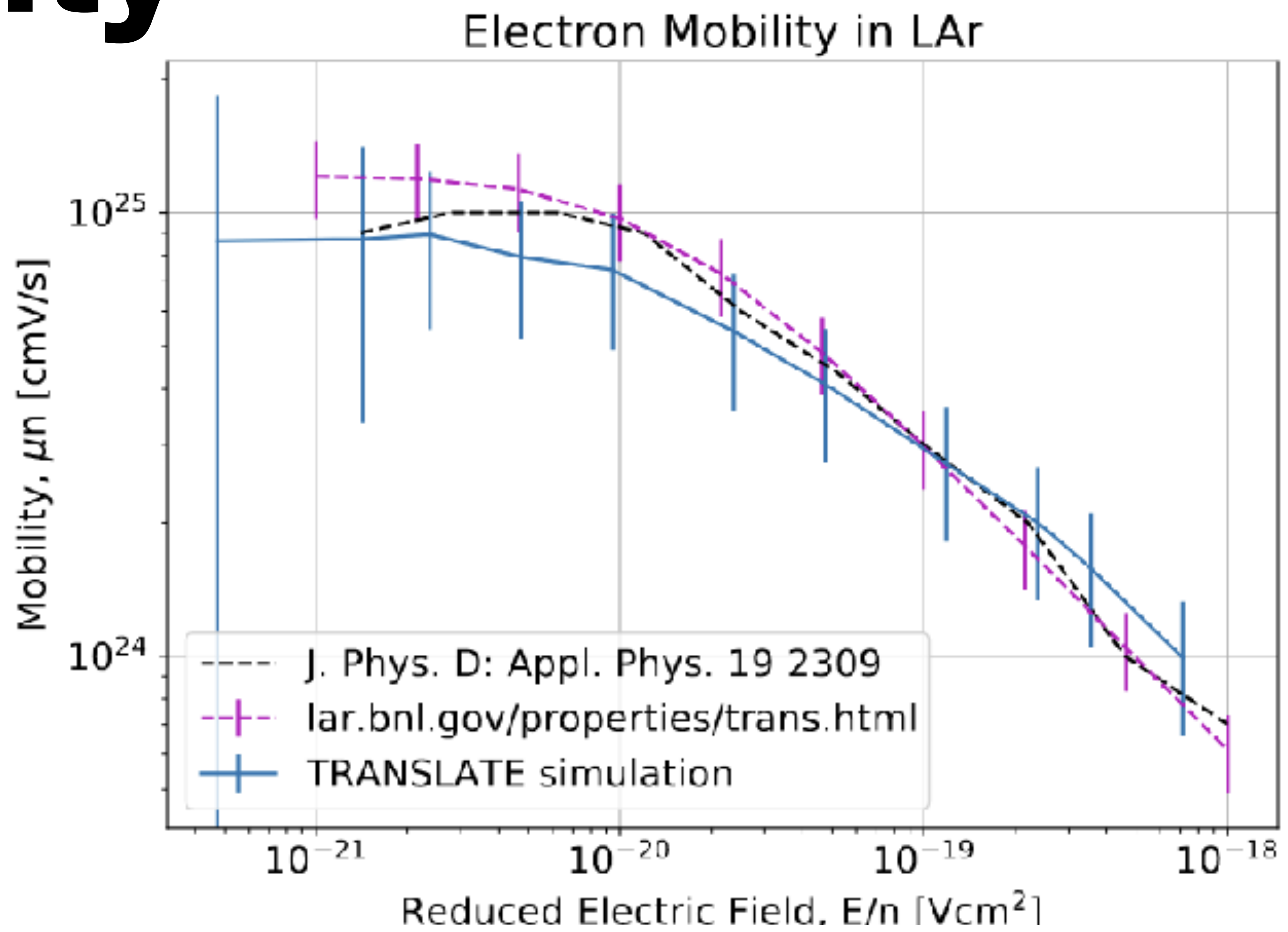
Track as a function of E-field:

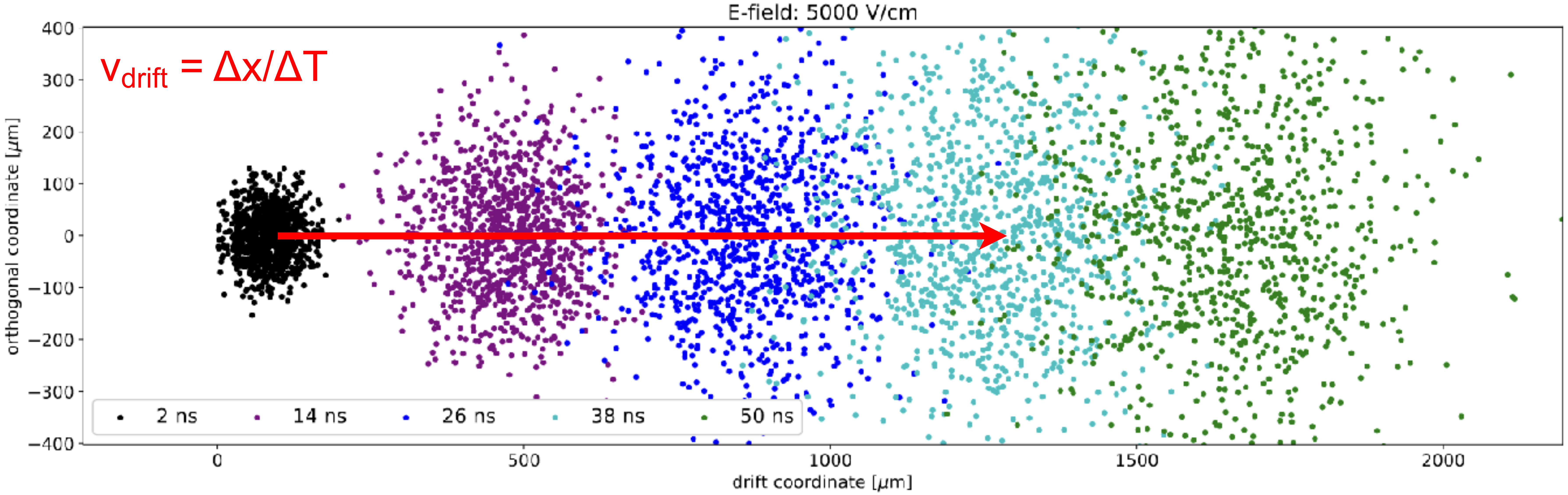
1. Average distance traveled → drift velocity [GAr & LAr]
2. Spread in electron clouds → diffusion [GAr & LAr]
3. Amplification [GAr]



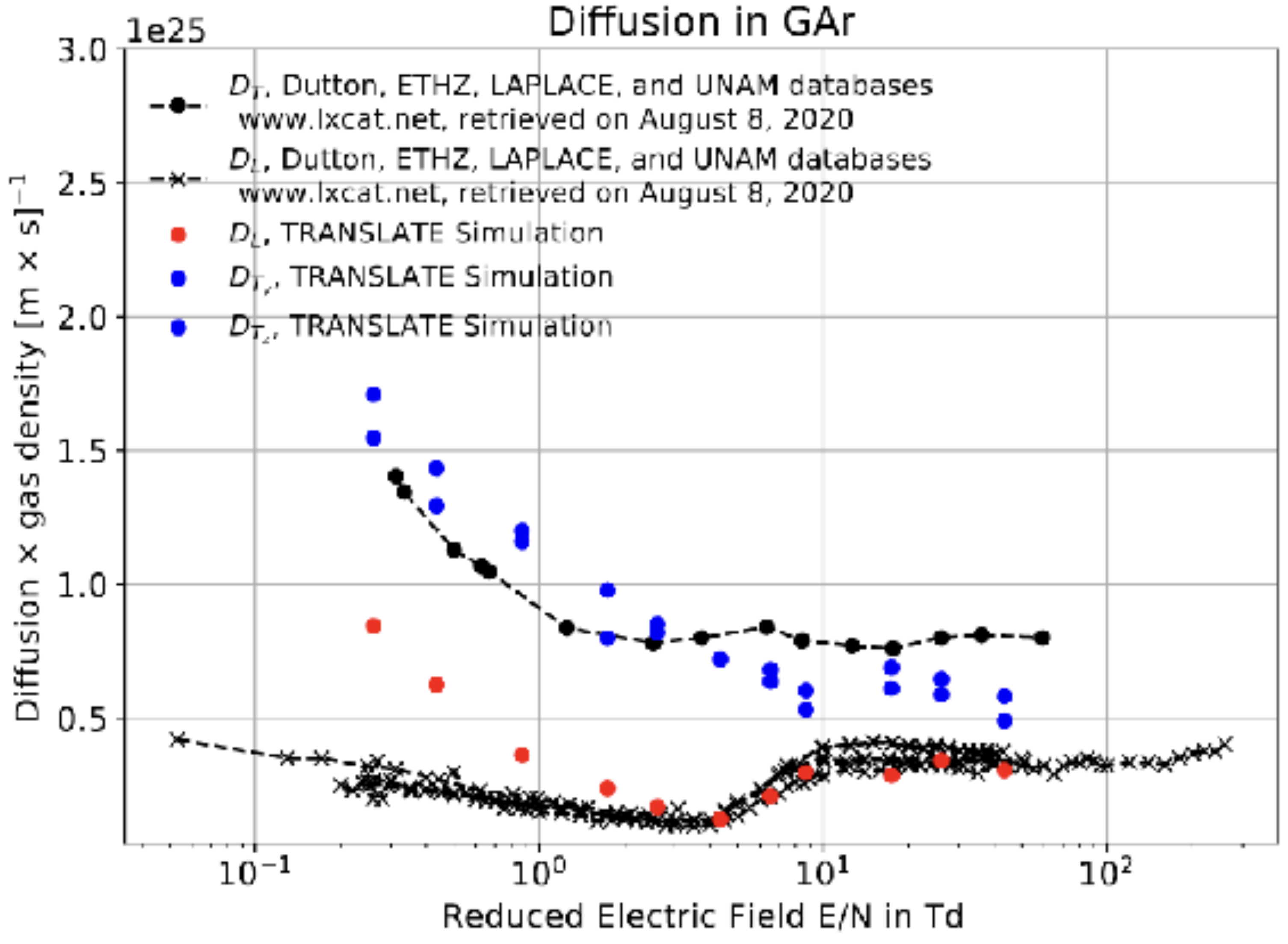
TRANSLATE: drift velocity

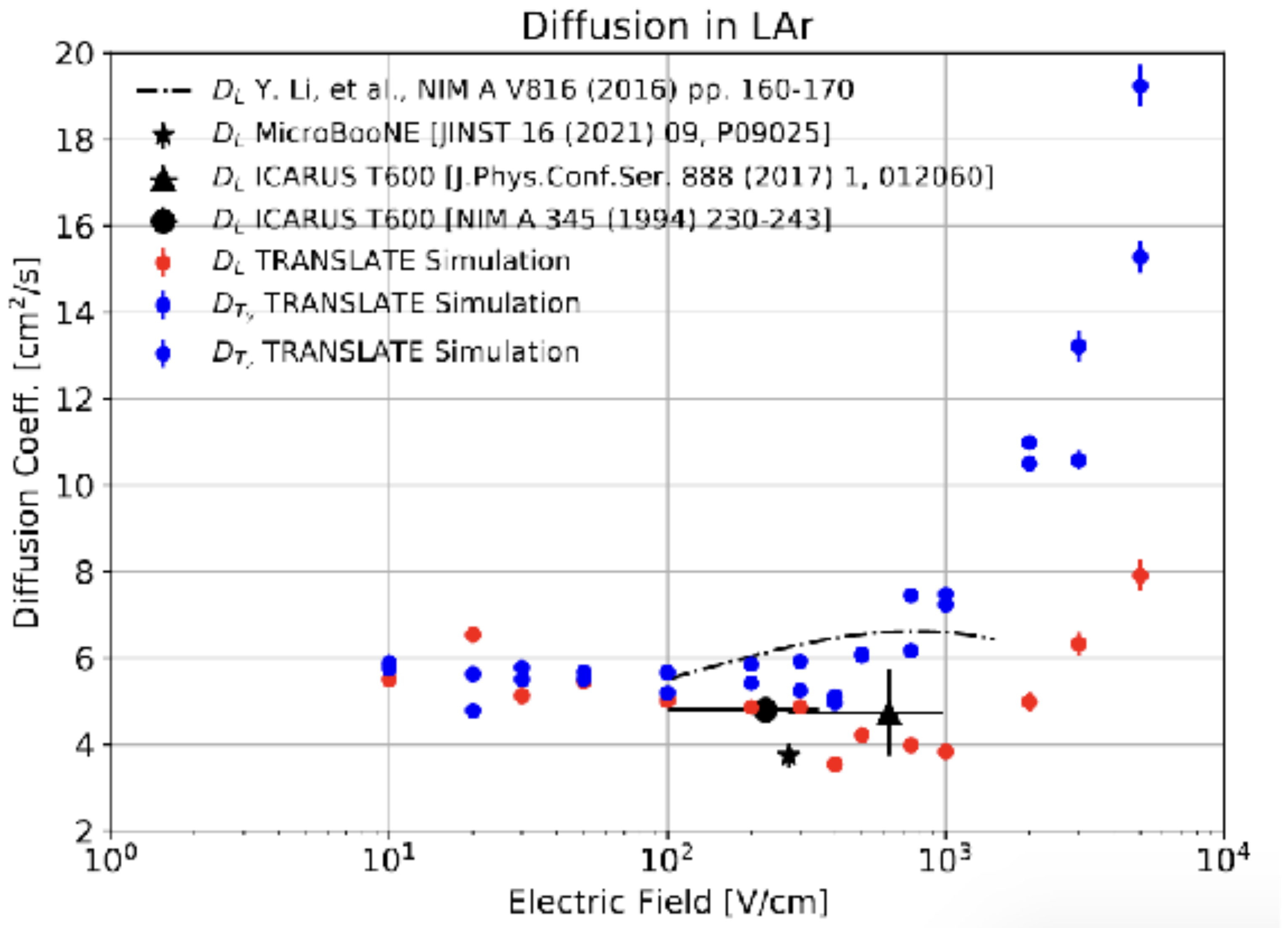


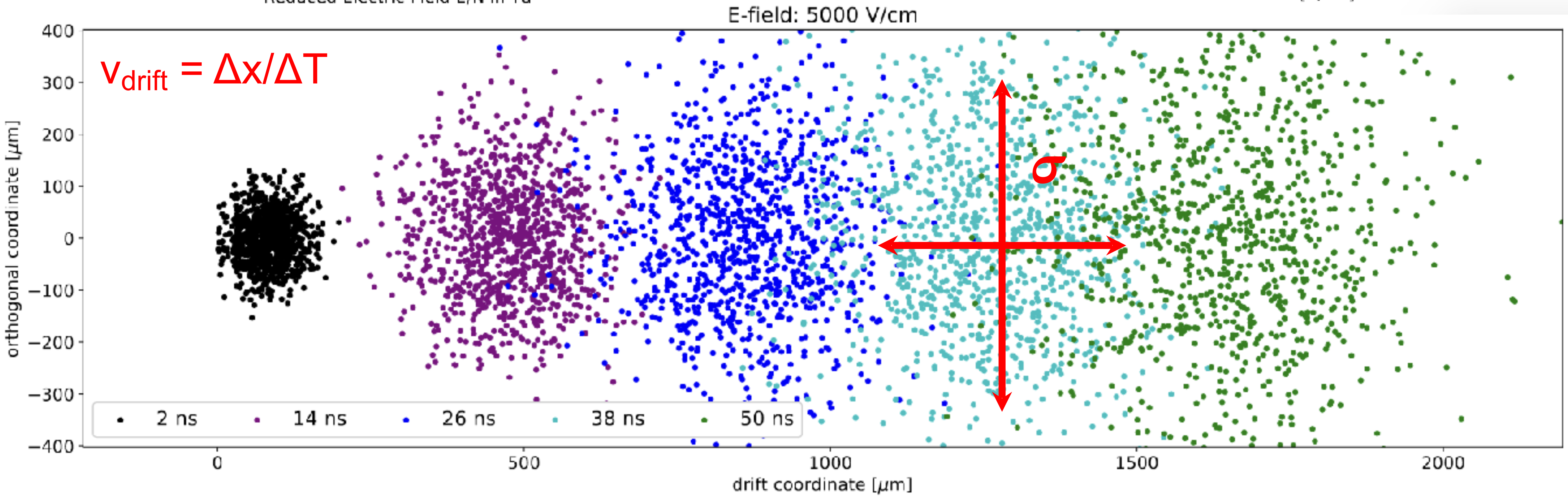




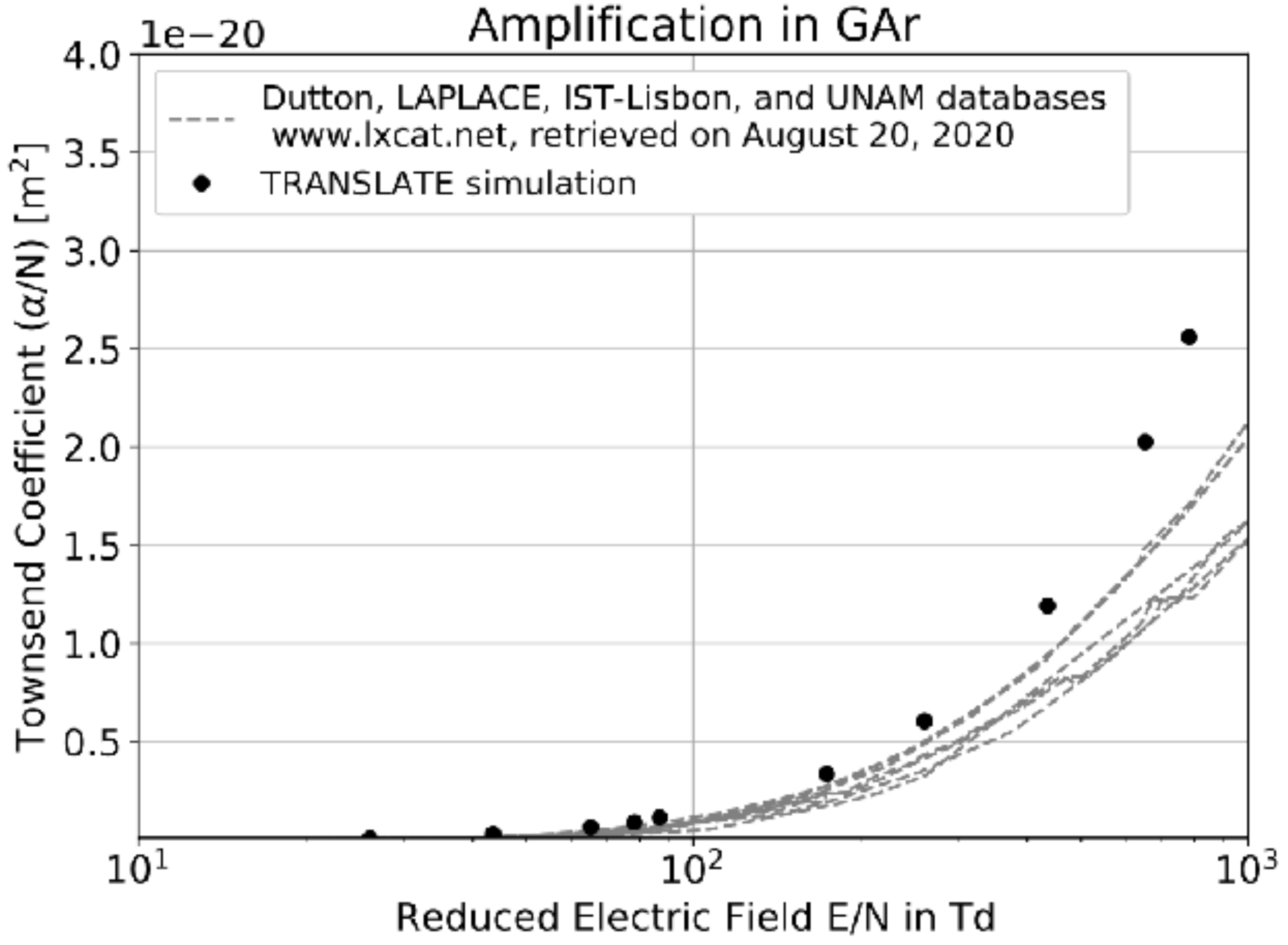
TRANSLATE: ion diffusion

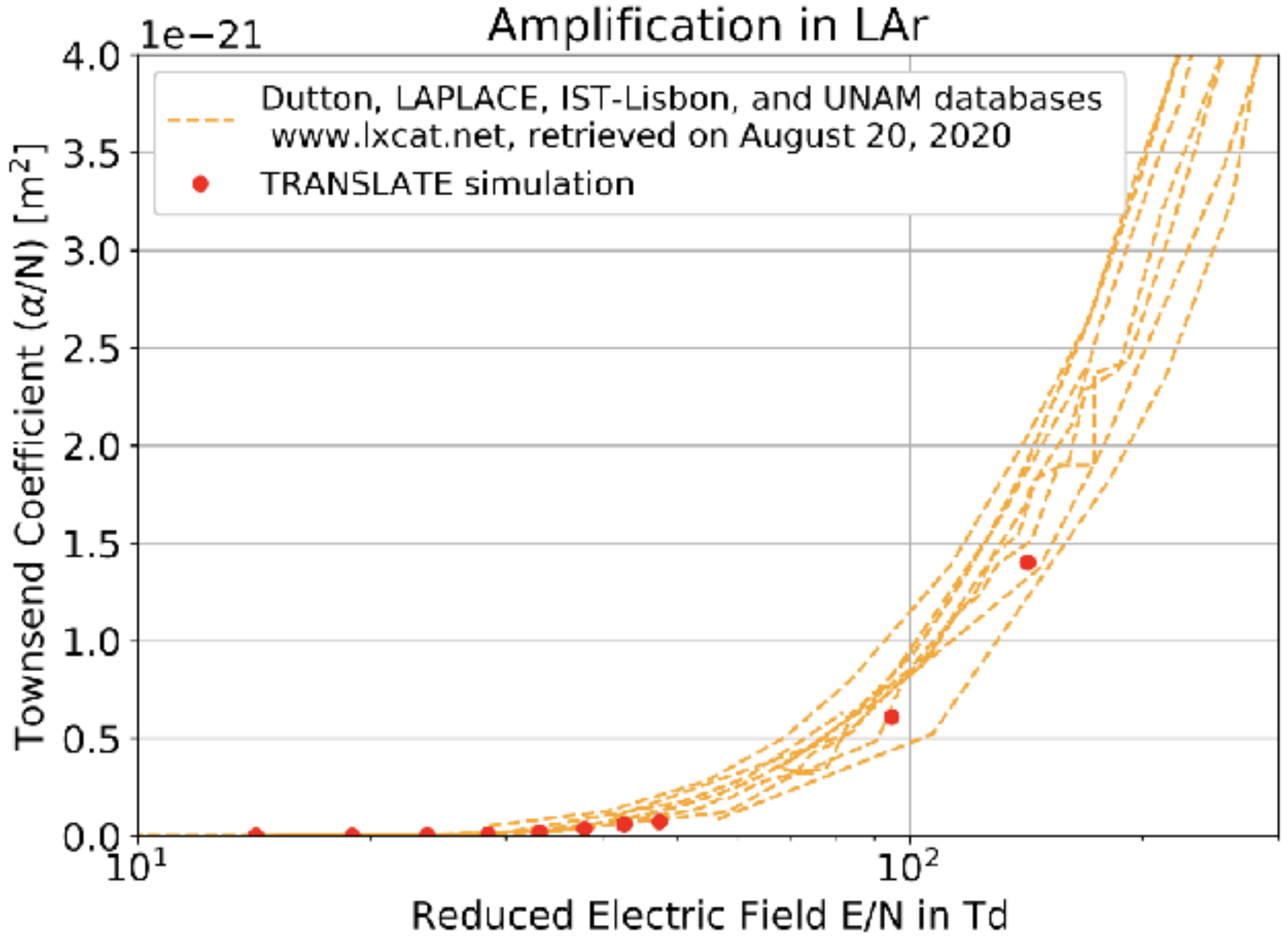


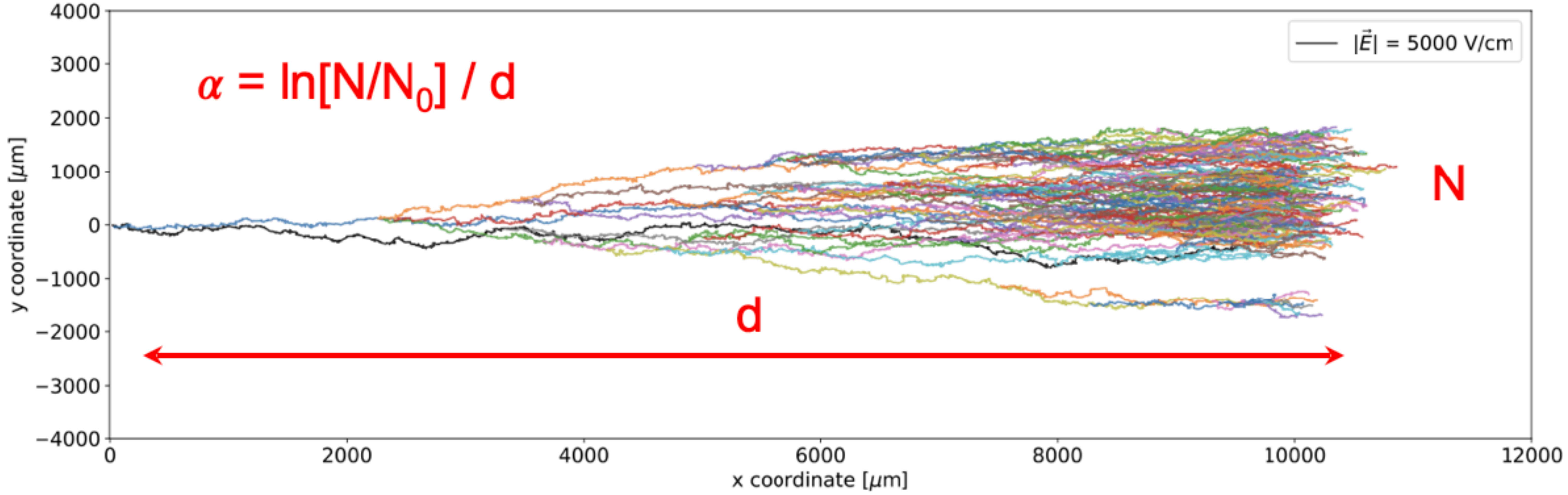




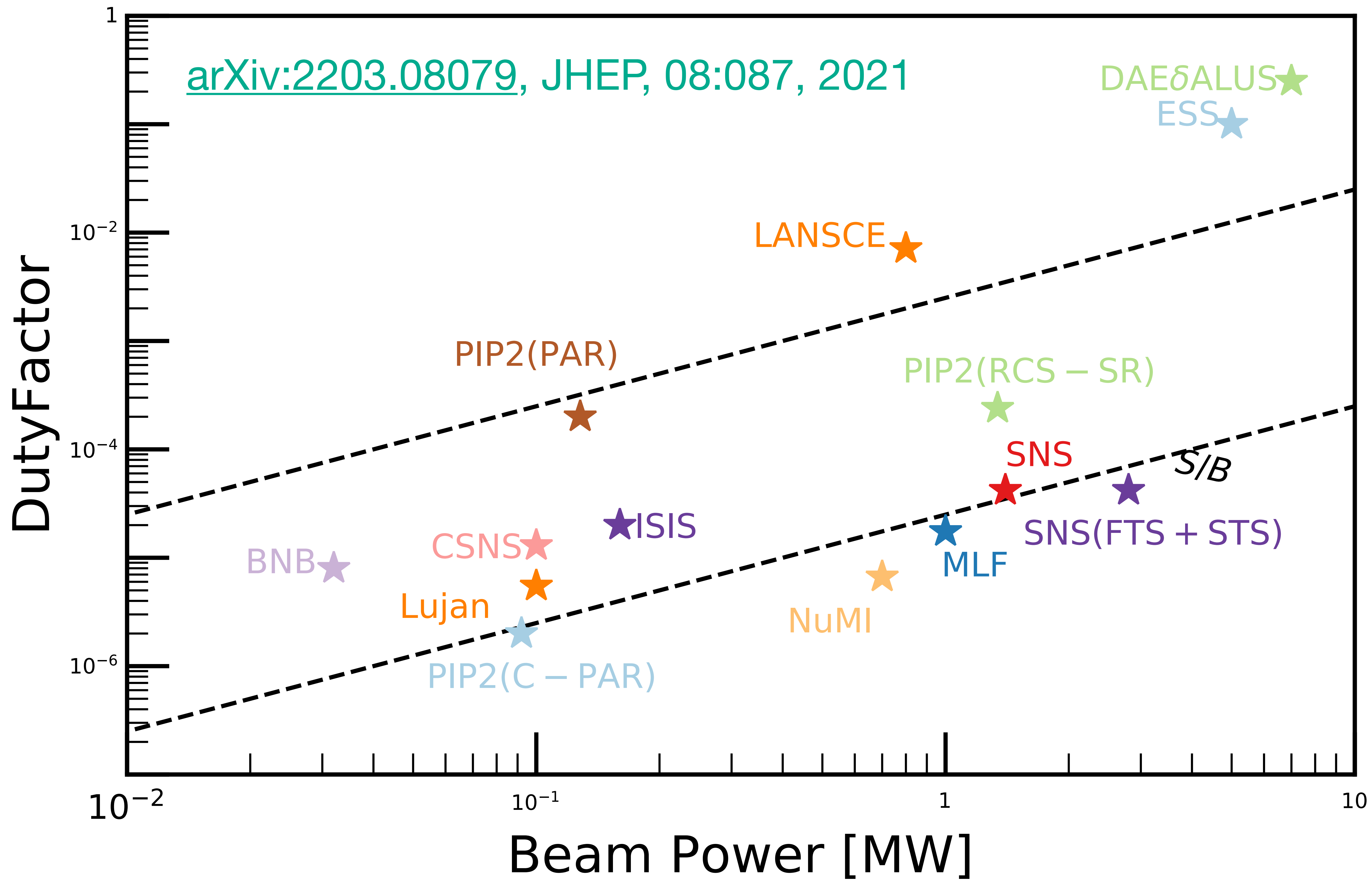
TRANSLATE: charge amplification







CEvNS NR Tracking @ Accelerator ν Sources



Several locations offer a sizable flux of 10s of MeV neutrinos for CEνNS detection.
Work ongoing to study different options for the purpose of NR tracking.

Summary

- Nuclear Recoil imaging can expand applications for CEvNS
- Strong synergy and complementarity with existing neutrino program
  - Oscillations, astrophysics, BSM searches all benefit from E_ν measurements!
- LArCADe: active R&D on tip-array charge amplification and GAr NR tracking