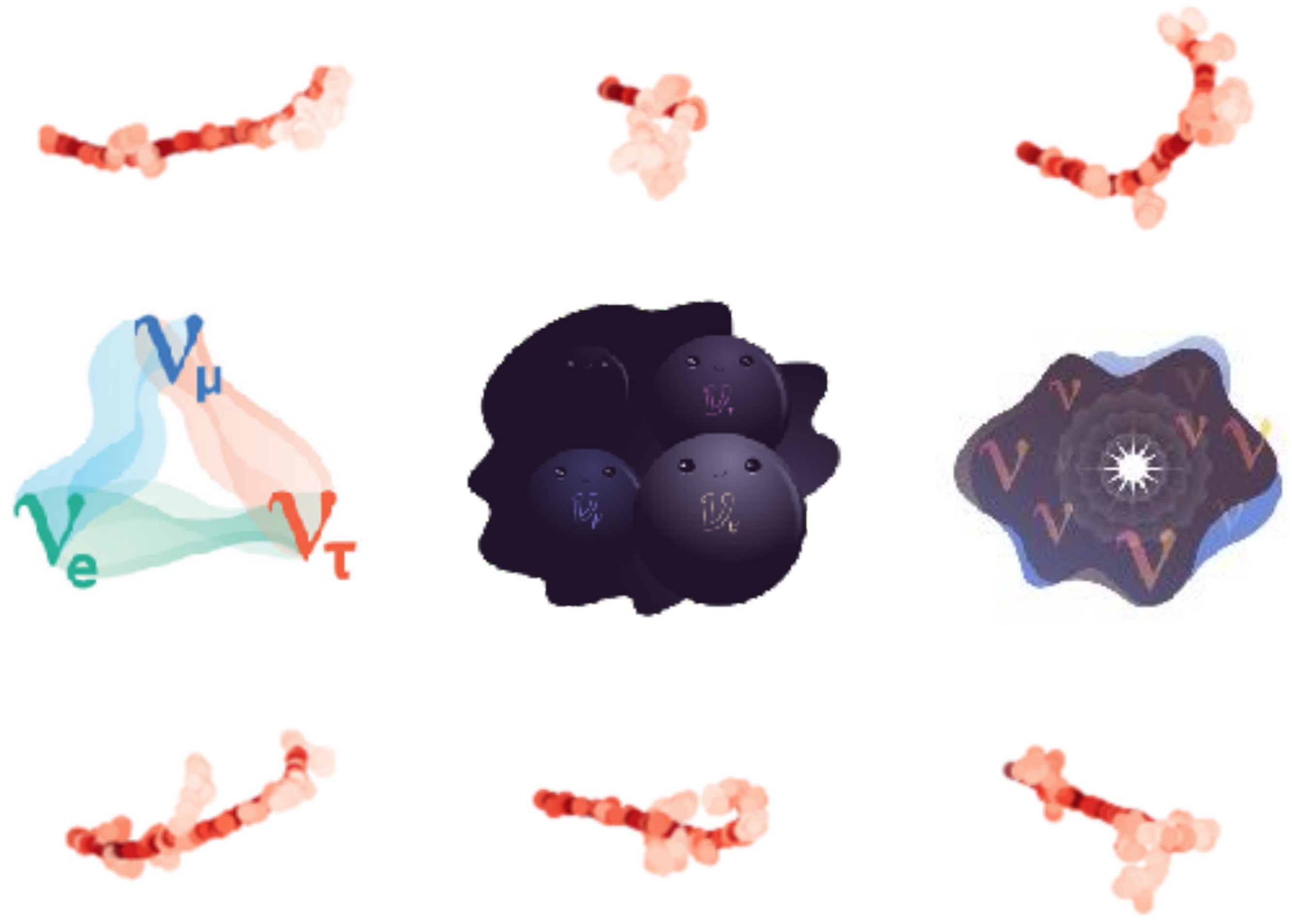
Nuclear Recoil Tracking for Directional CEvNS with π-DAR Sources

TAUP 2025 - Xichang, Sichuan, China

August 27th, 2025



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Outline

Motivation for Directional NR CEvNS detectors

NRs in CEvNS with a π-DAR source

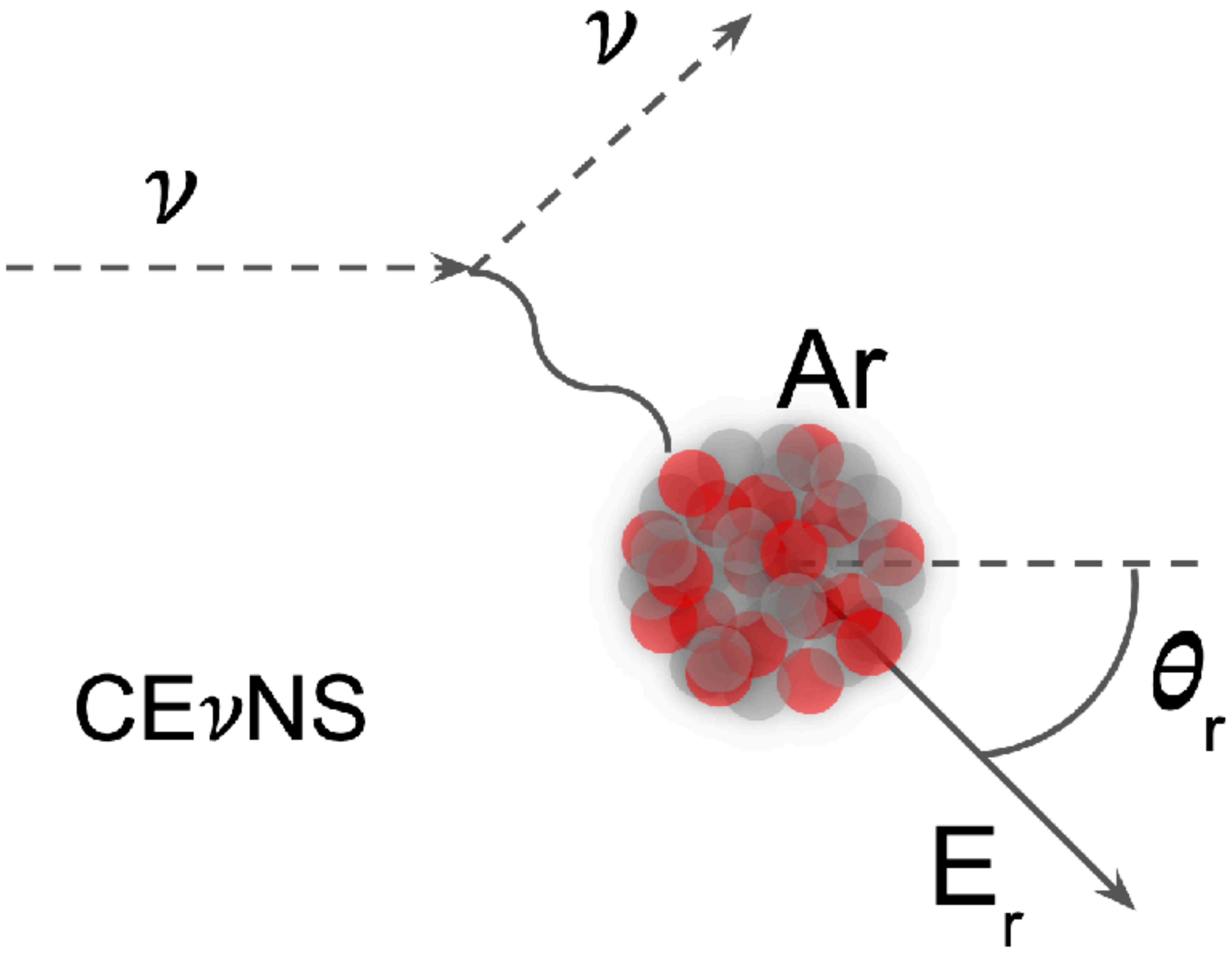
Characterization of NR propagation (in argon)

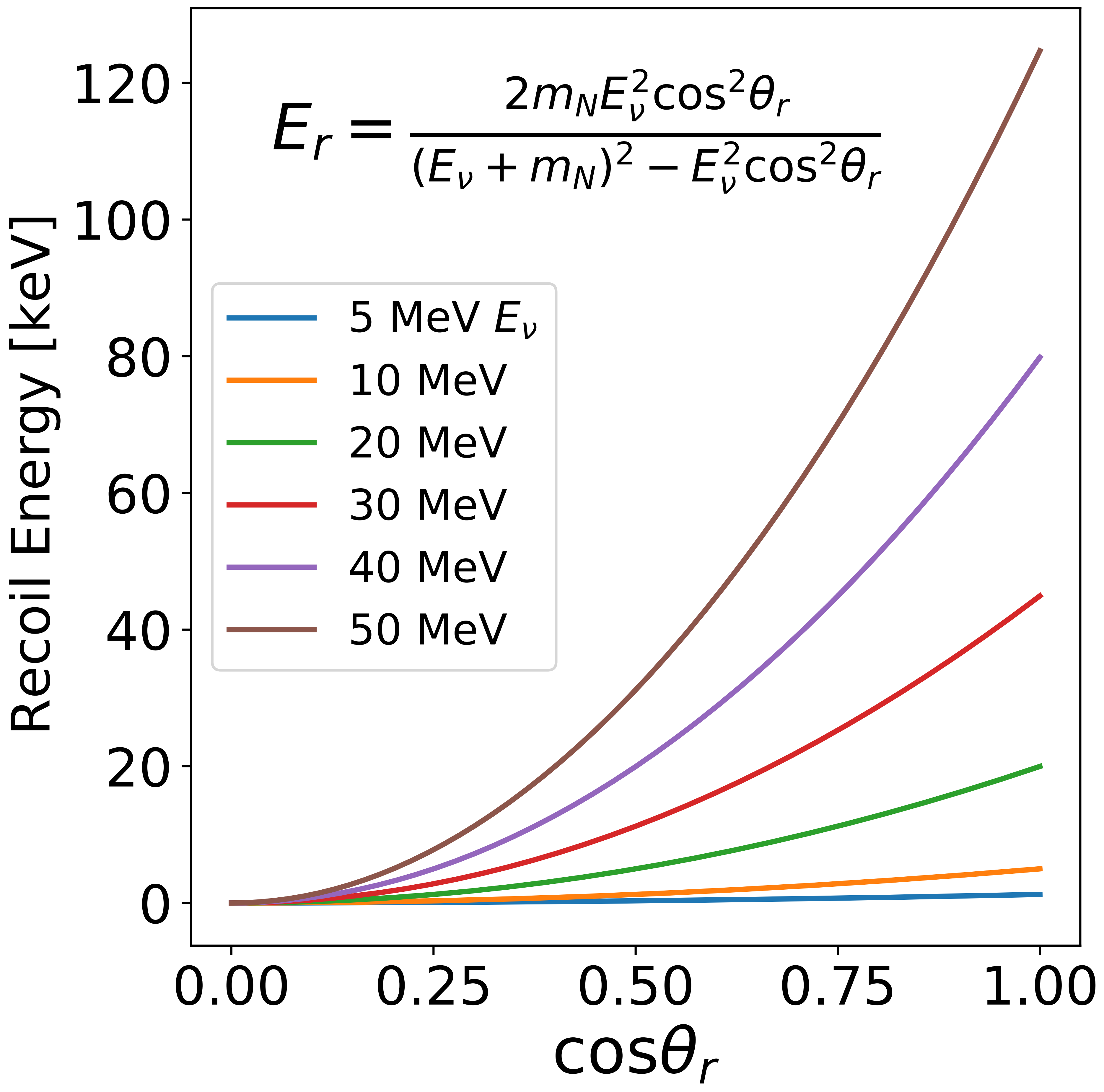
Detector response simulation + R&D

TRANSLATE: electron transport modeling in argon

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

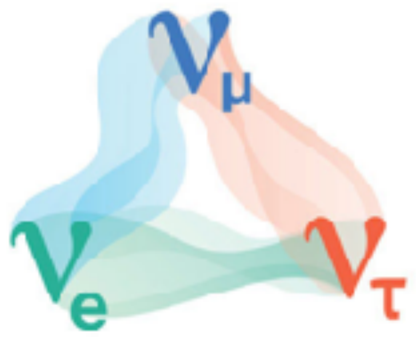
NR Directionality in CEvNS





Physics Reach of NR Directionality

- event-by-event ν energy reconstruction
- Background rejection
- Increased sensitivity in BSM searches
- CEvNS cross-section and SM physics: $\frac{d^2\sigma}{dE\,d\cos\theta}$
- Astrophysical νs: solar / supernova / DM “neutrino fog”

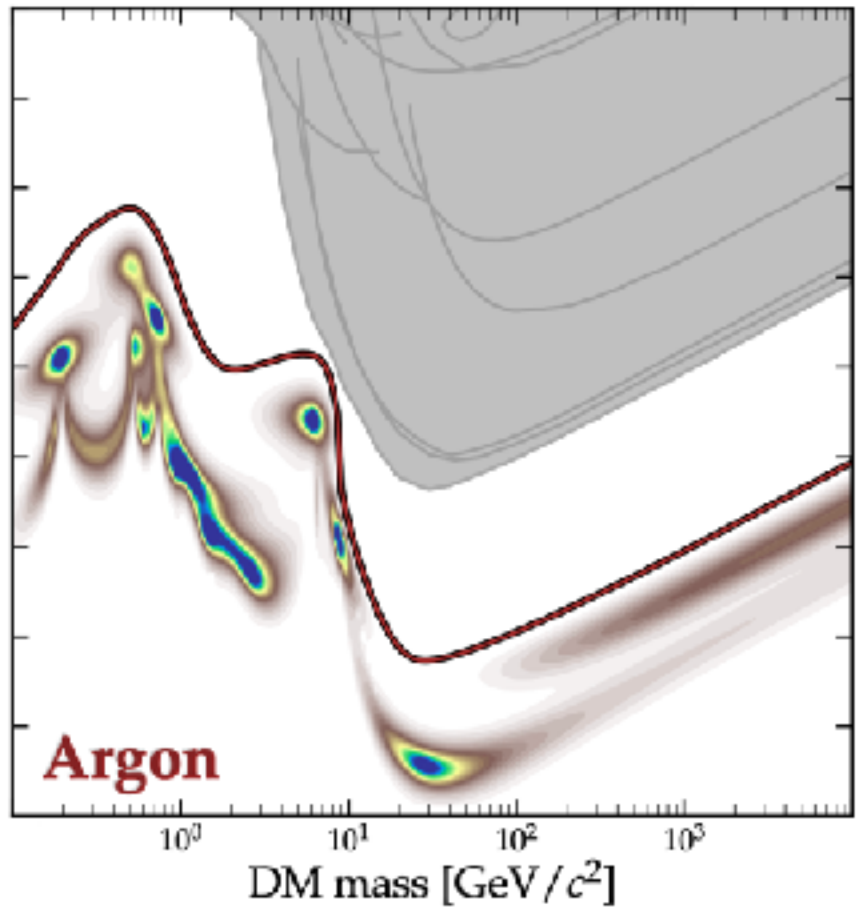


oscillations

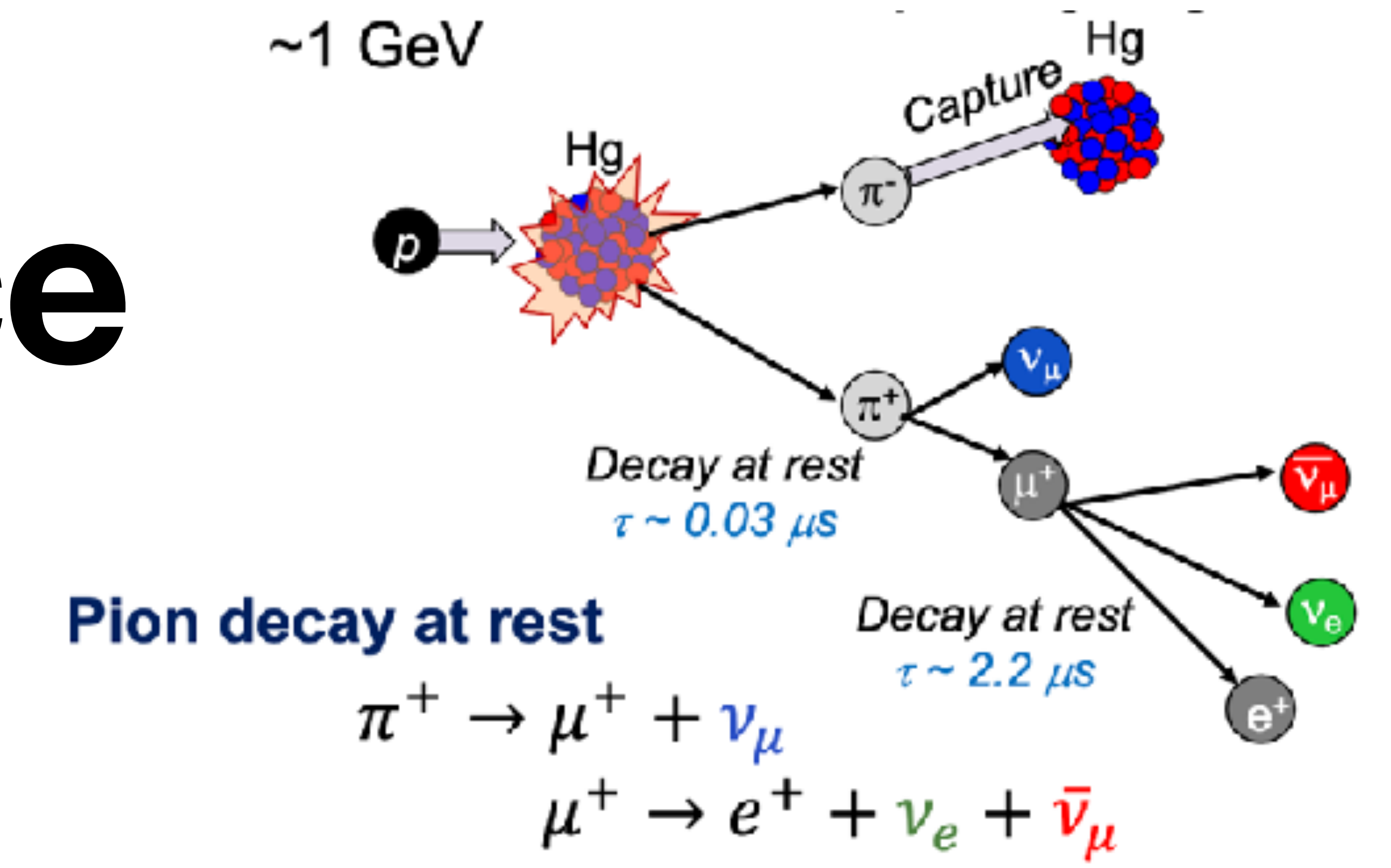
astrophysics

BSM

Cairan O’Hare

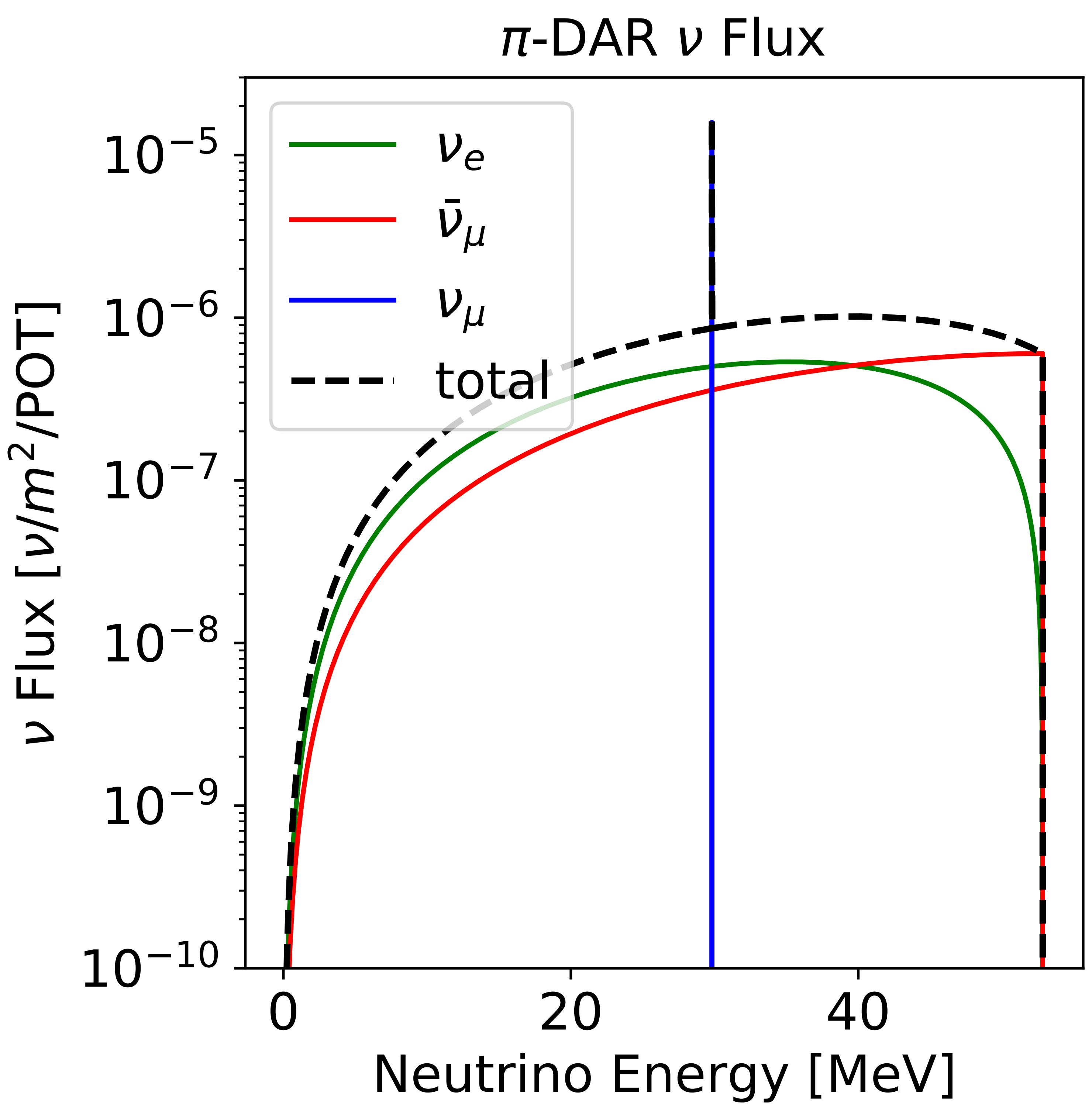


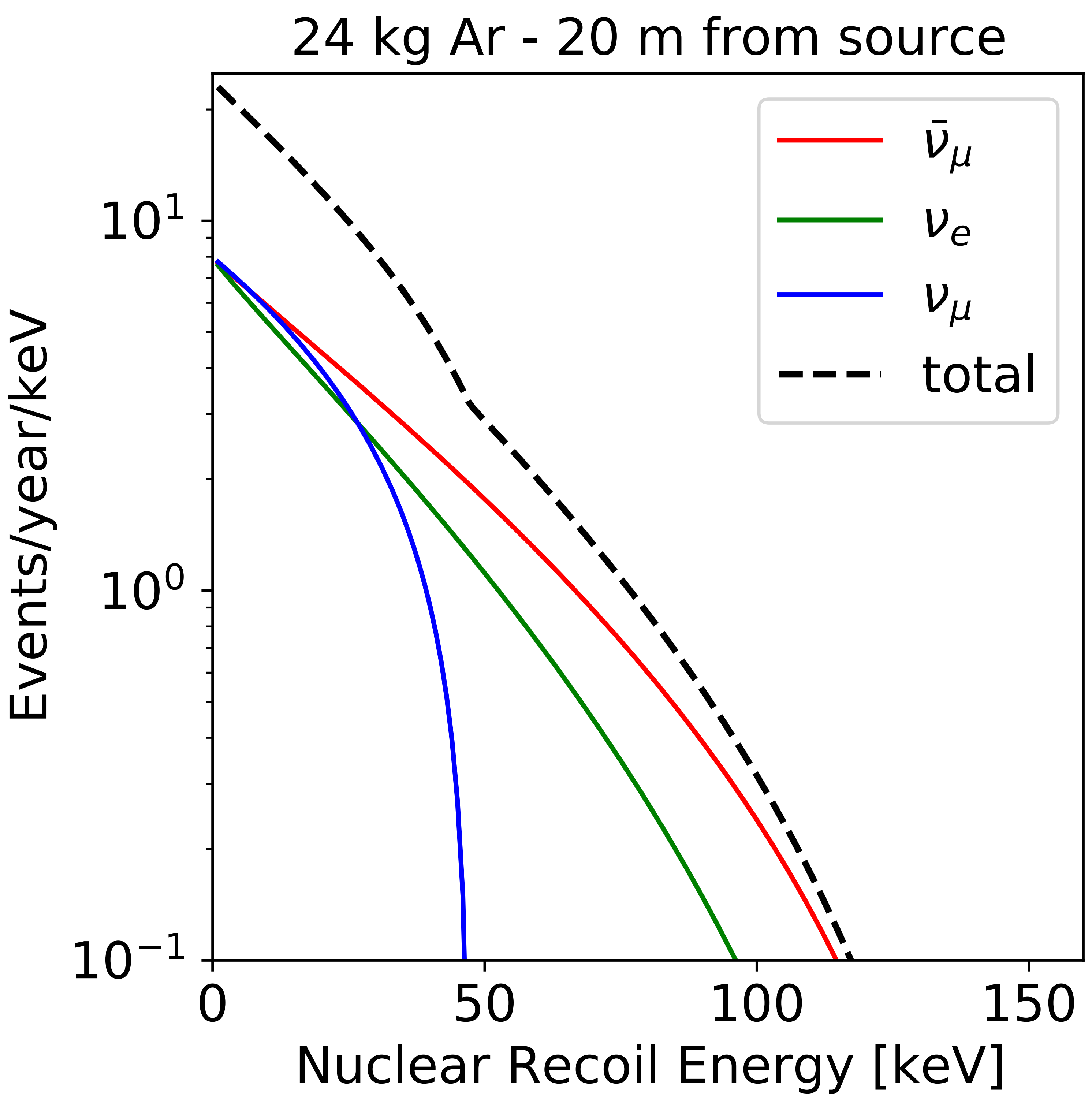
NRs from CEvNS in π-DAR Source

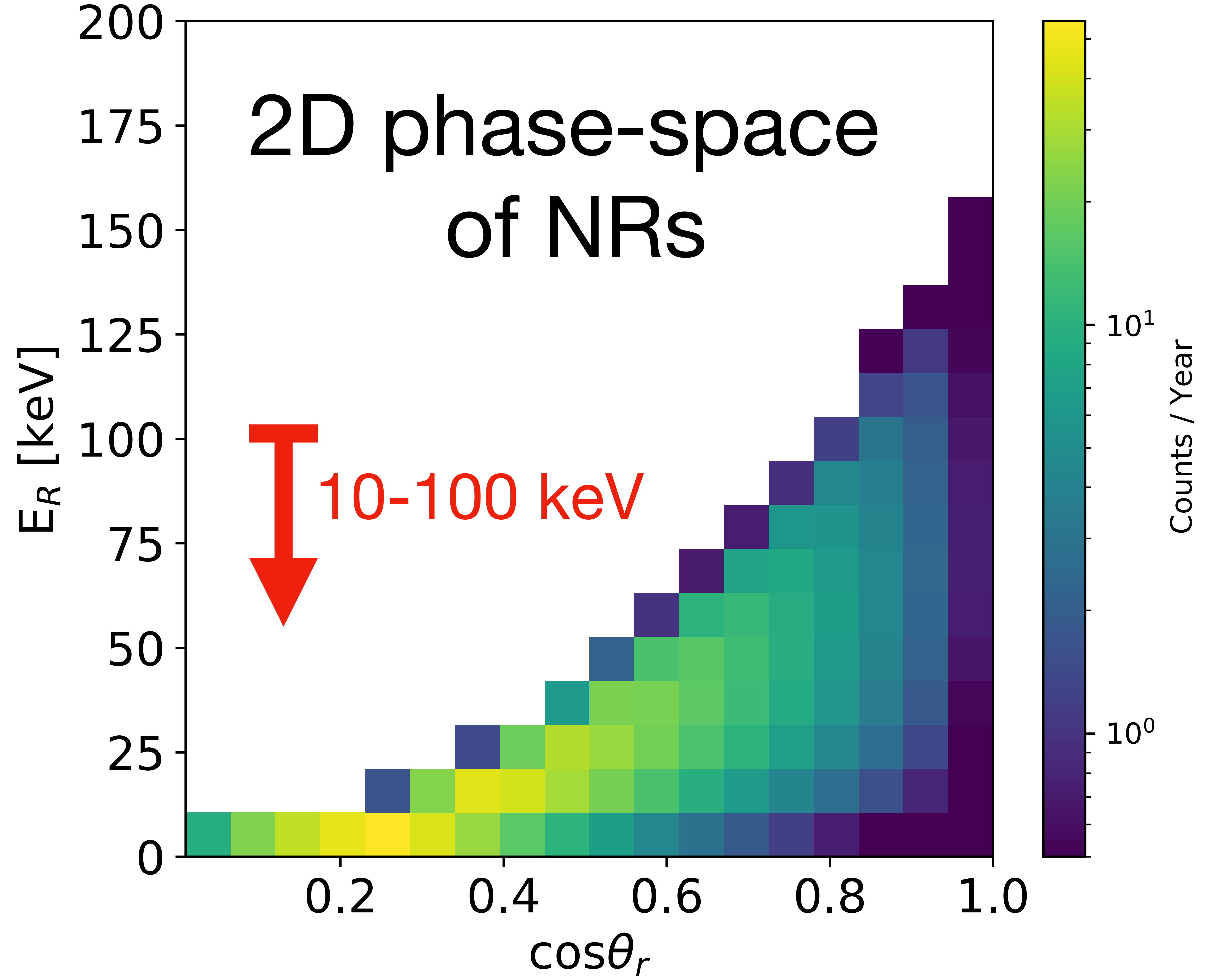


$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

SNS flux: PhysRevD.106.032003



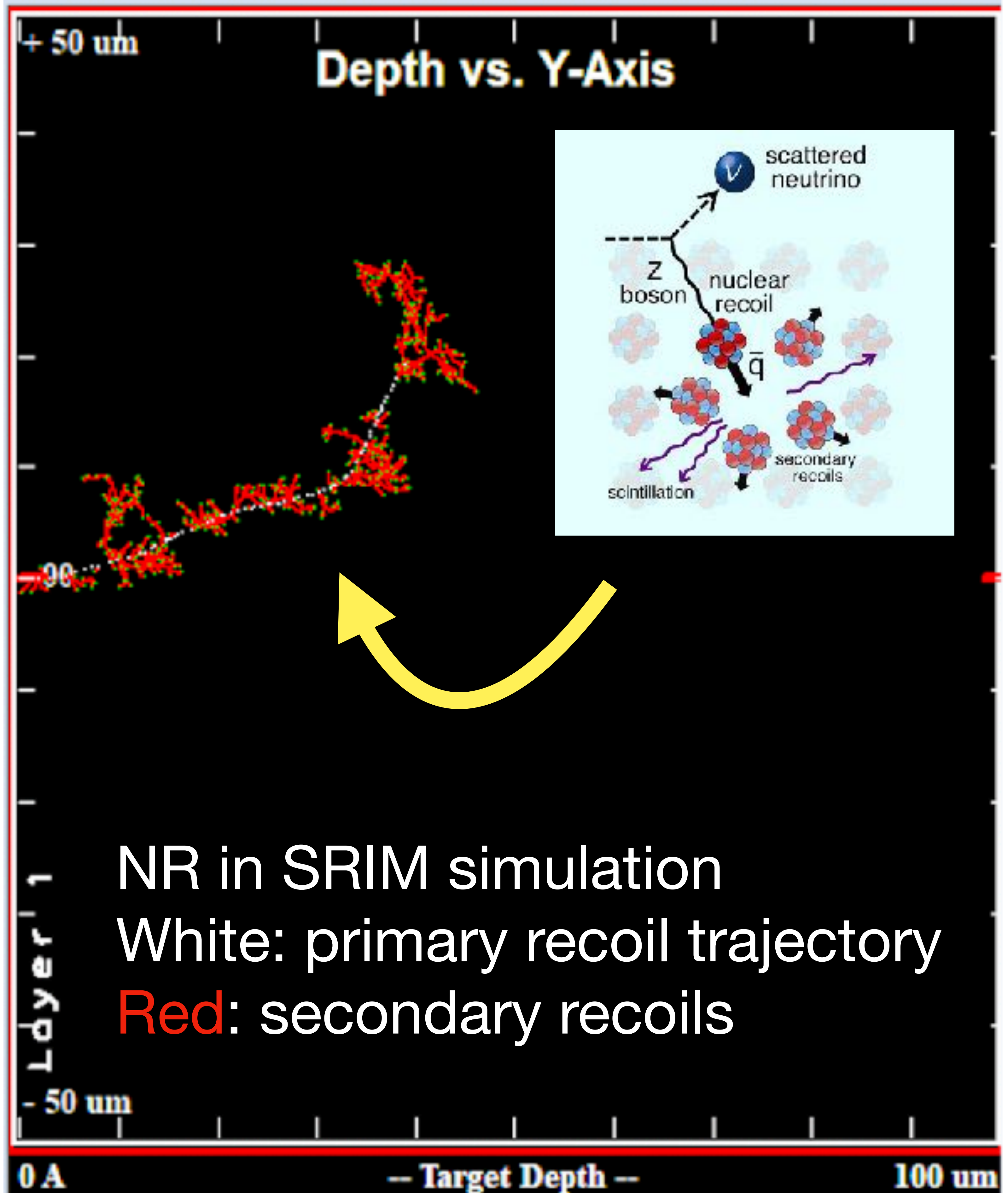




$$E_{NR\,max} = 2E_\nu^2/M_{\text{target}}$$

10s-100s keV NRs

Characterization of NR Propagation (in Ar)



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

NRs measured through thermal, ionization, and scintillation signatures.

Current experiments measure “point-like” signature

NR leaves a tiny track-like feature.

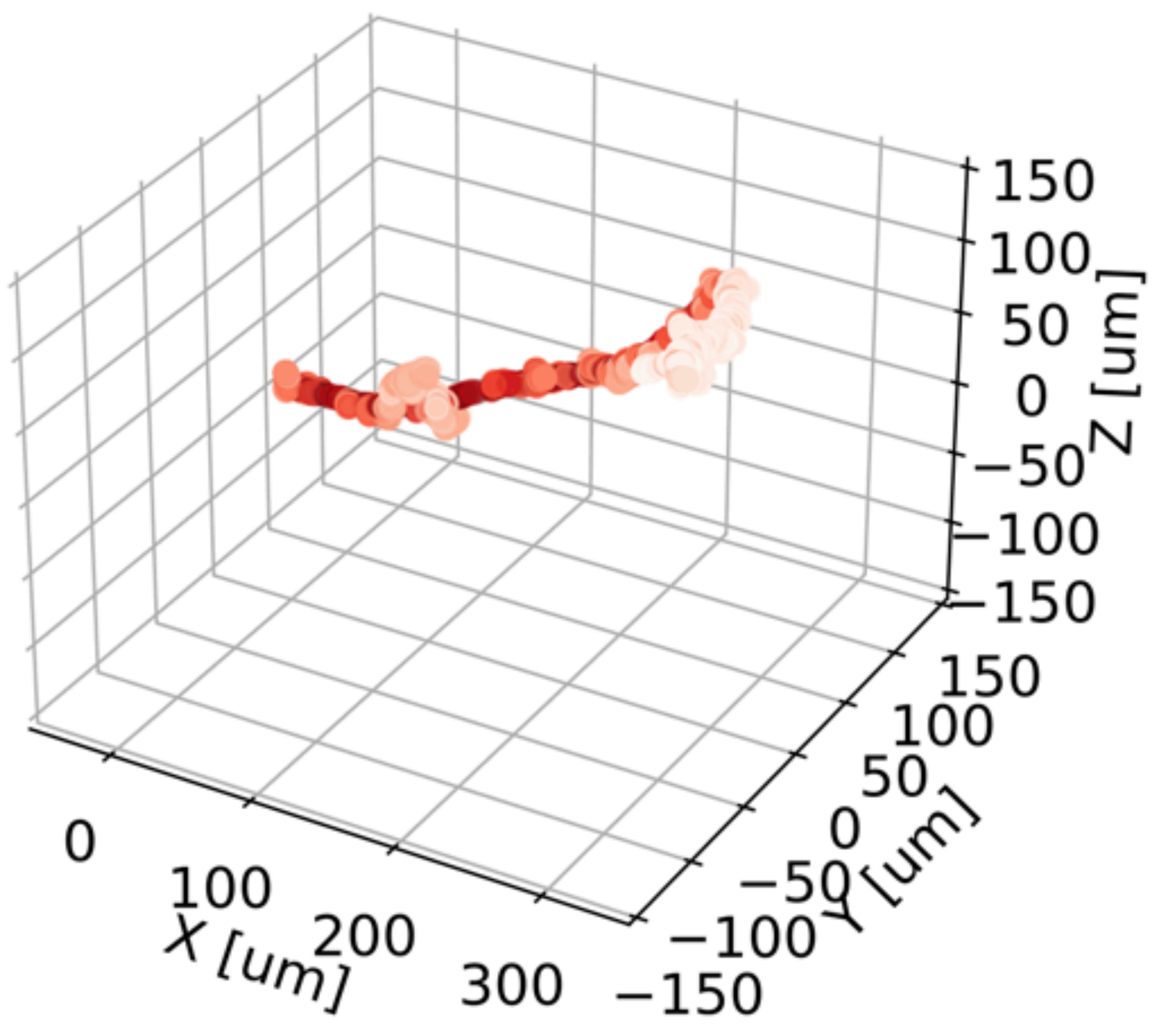
Scale: 100 μm / 100 keV @ 1 atm GAr

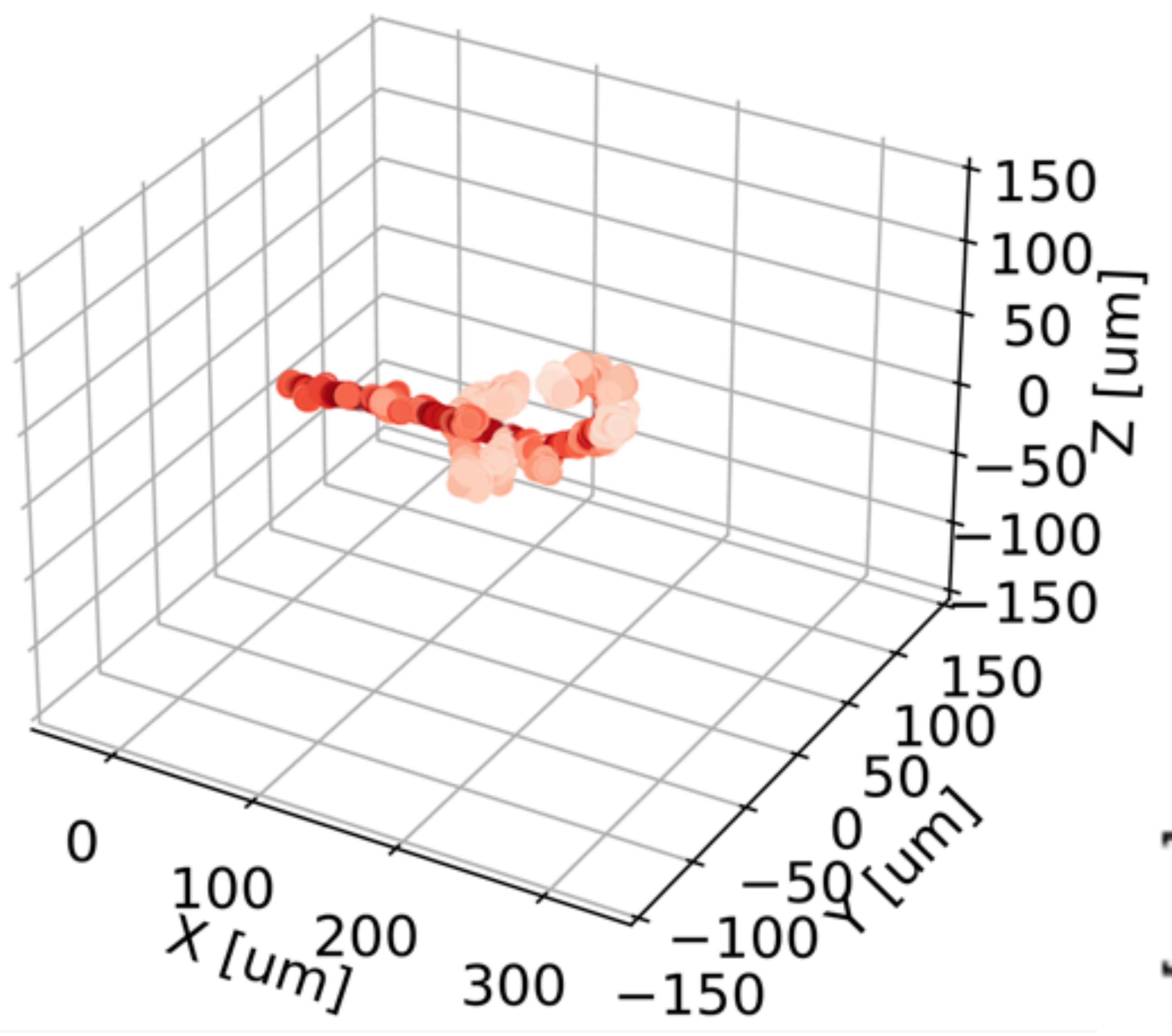
Imaging NRs from π-DAR CEvNS requires O(10-100 μm) spatial resolution depending on target / pressure.

We use SRIM simulation to study these tiny signatures.

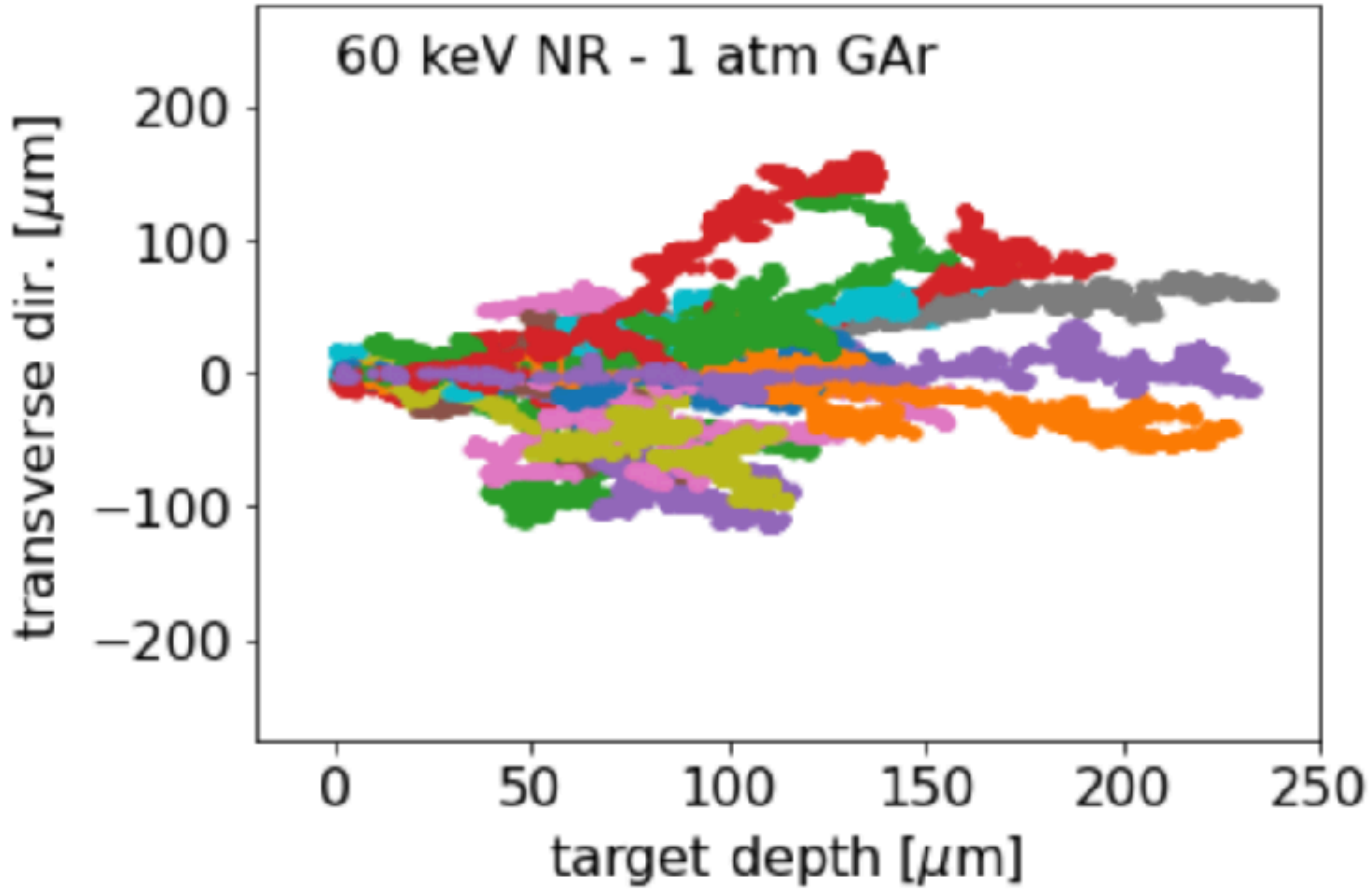
http://www.srim.org/ - Nucl. Instrum. Meth. B, 268:1818–1823, 2010

Characterization of NR Propagation (in Ar)





25 simulations with same initial conditions



Simulated 60 keV NRs in 1 atm GAr

Complex propagation: scattering in target material, secondary recoils

Characterization of NR Propagation (in Ar)

How does the spread in Edep, range, and angular deflections impact the intrinsic resolution of a possible directional CEvNS detector?

- O(20%) energy / range intrinsic smearing
- < 20 degree angular deflection

(this is comparable to resolution on E_ν in GeV-scale interactions due to complex nuclear physics of interactions)

CEvNS Signature w/ Intrinsic Detector Smearing

Assumed resolution:

- 20% energy resolution
- 20 degree angular smearing

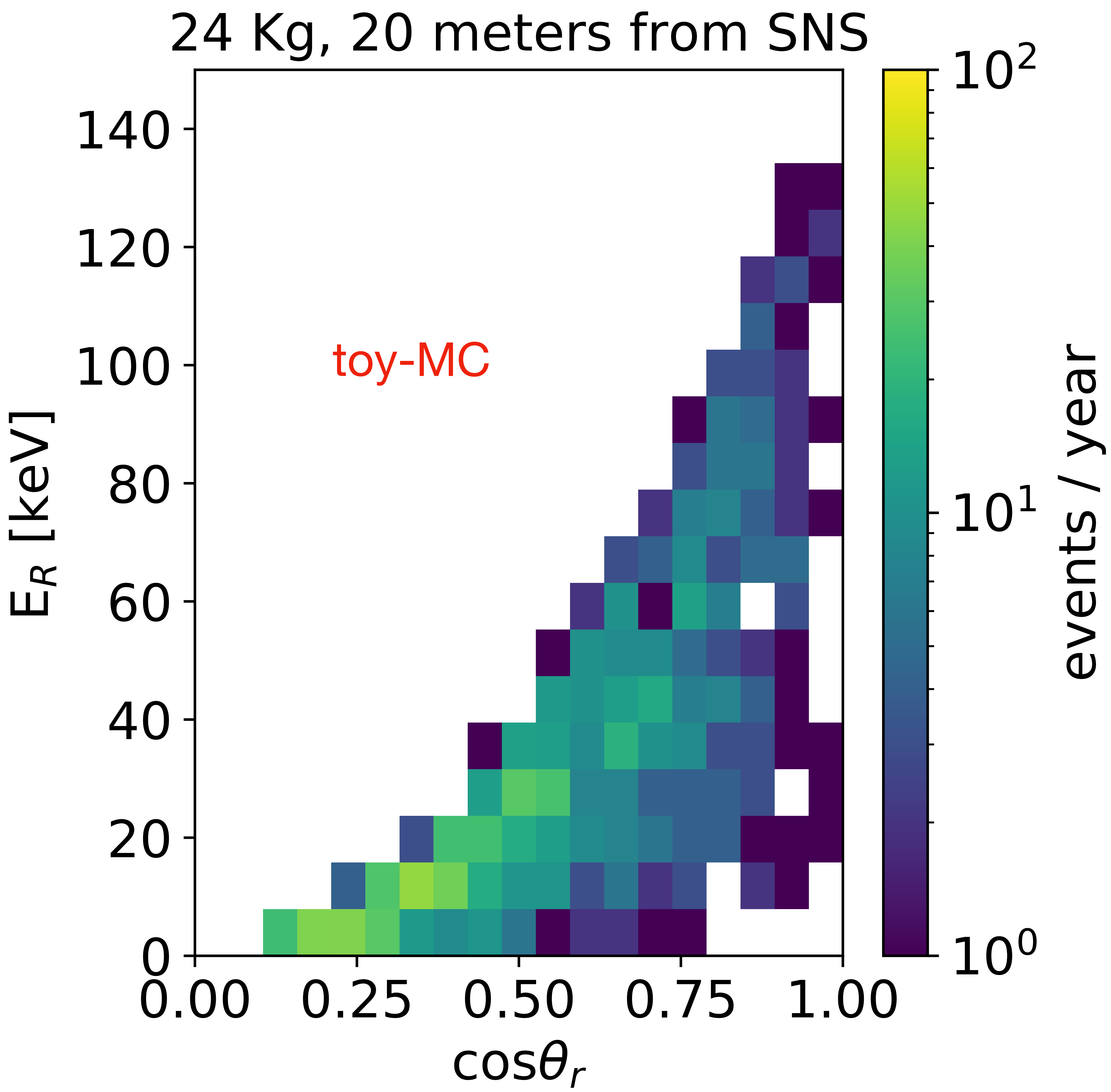
SNS exposure w/ 24 kg Ar @ 20 meter

(Same target/distance as COHERENT CEvNS-10 LAr measurement)

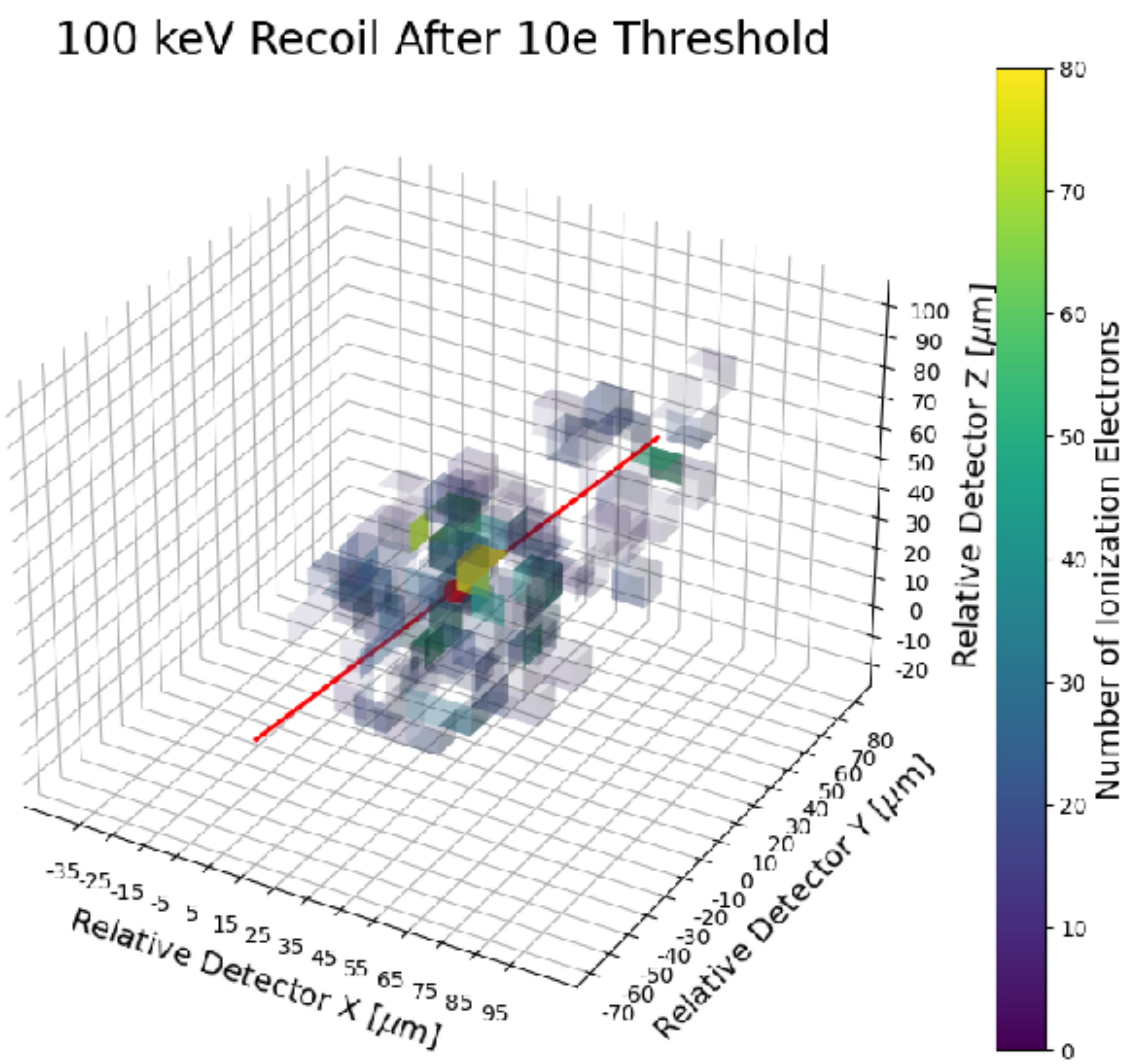
O(10^3) events / year

Conceivable detector concept…

Helps set goal for detector performance.
Intrinsic smearing sets performance.



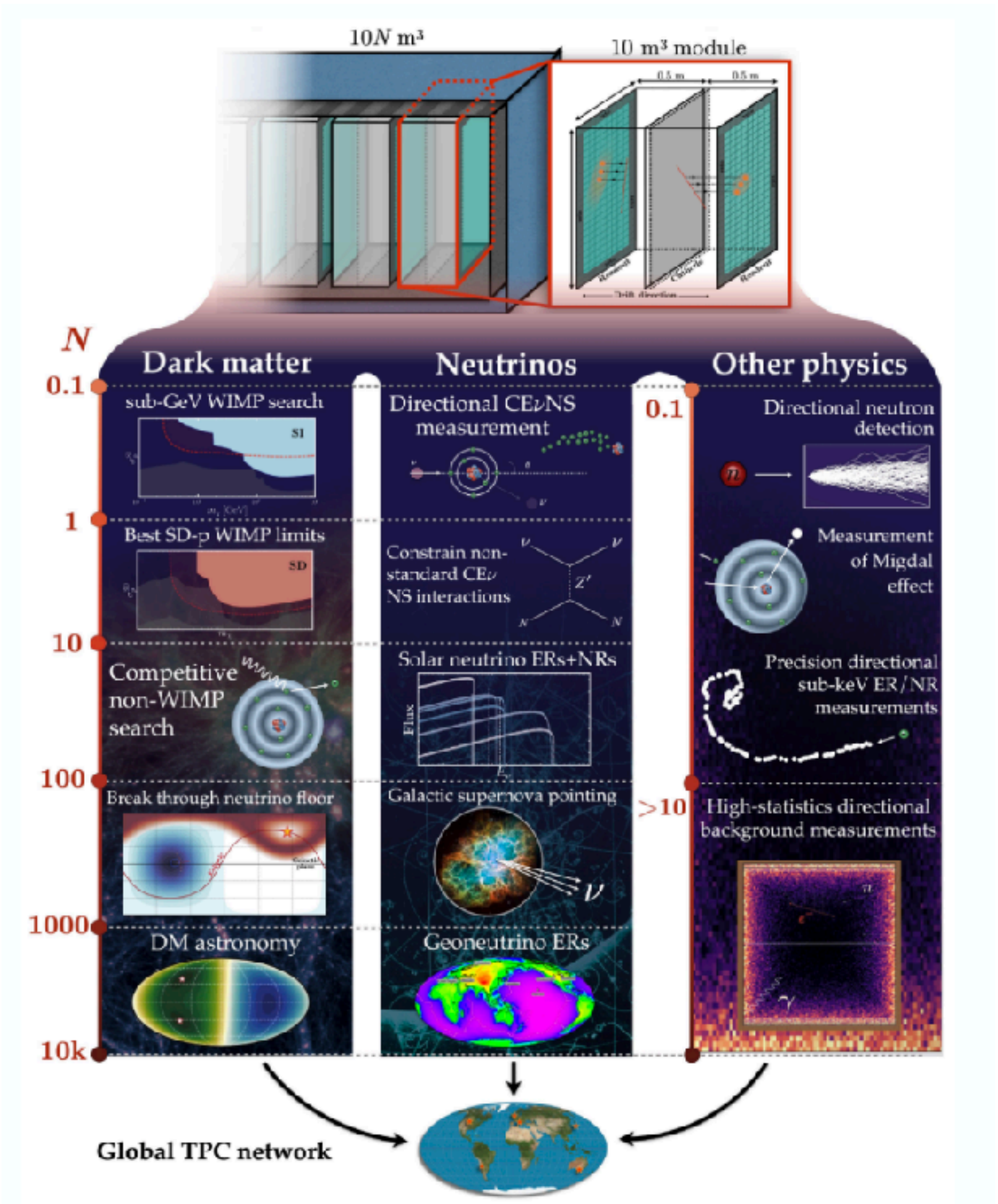
Detector R&D



Which experimental setup to use for NR "imaging"?

Experimental Directional NR Community

CYGNUS: arXiv:2203.05914



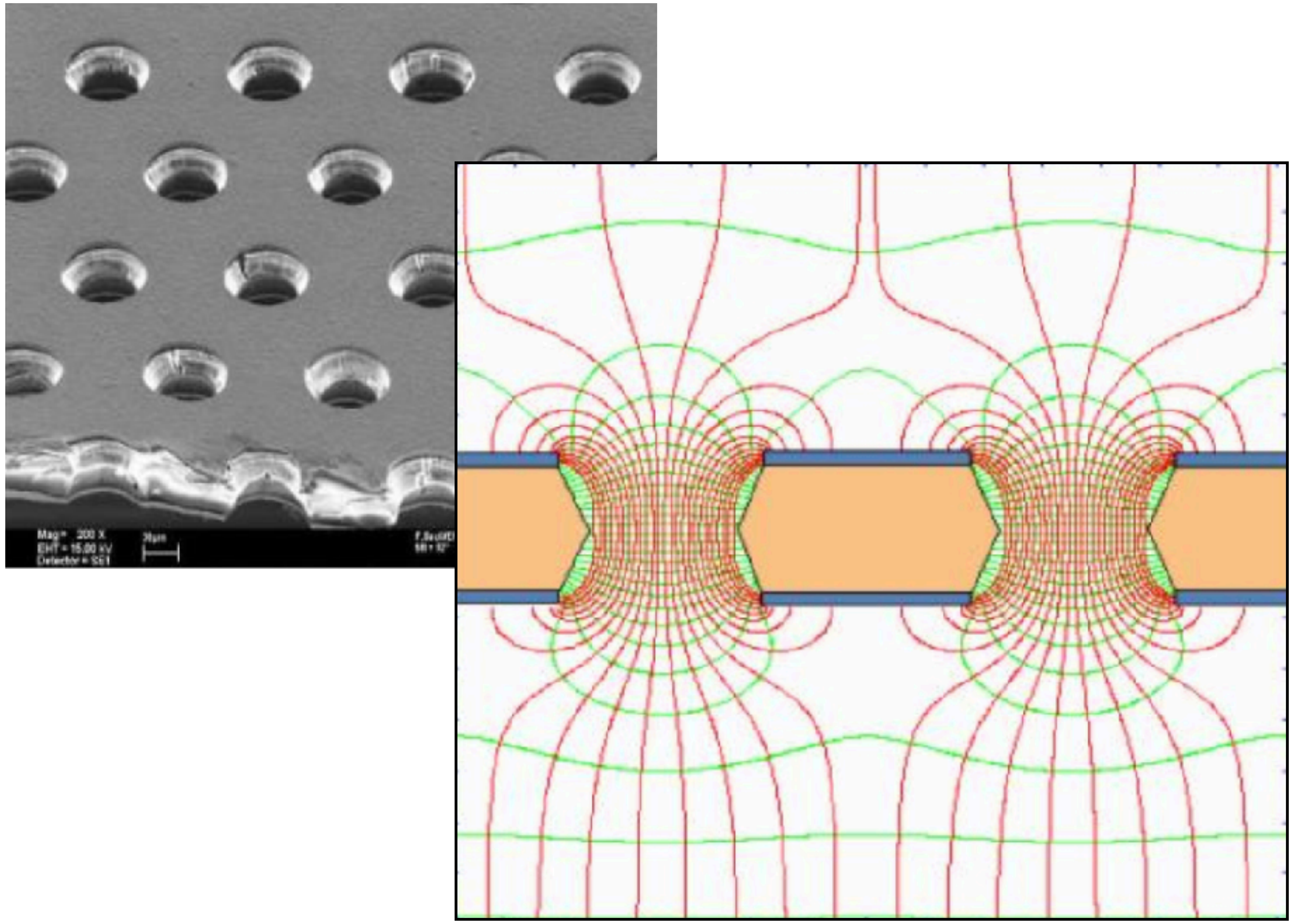
Large community approaching NR directionality with broad physics interest (DM, ν, Migdal effect, neutron detection) and technology approaches.

Our work focuses on gas-based TPC for NR imaging.

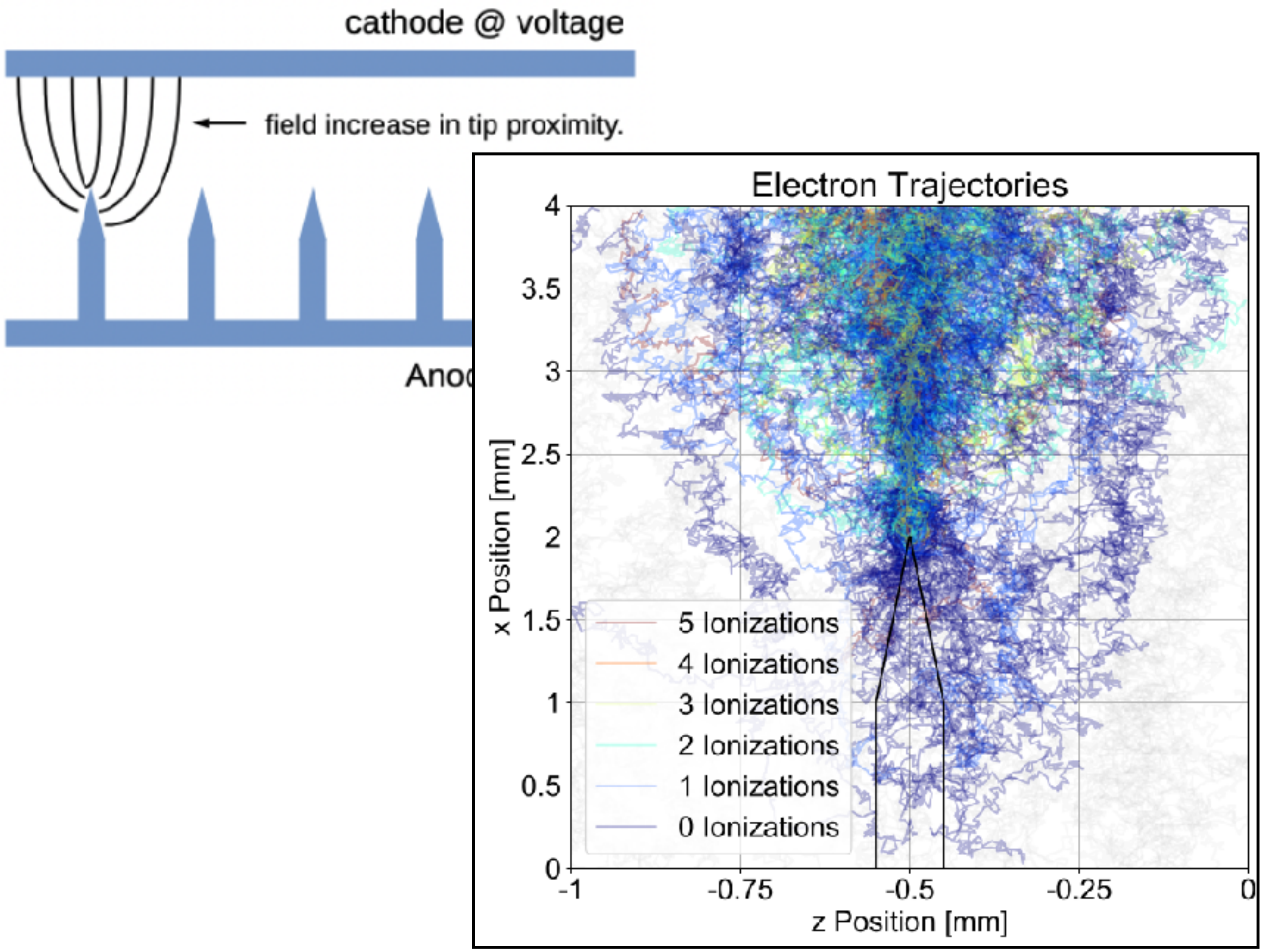
- Measure ionization signal with "pixelated" sensors.
- Optimization between density/volume and position resolution.
- Here focus on argon target (personally more familiar)

e.g. see talk by Samuele Torelli on solar neutrino w/ directional NRs [link]

GAr-TPC Design

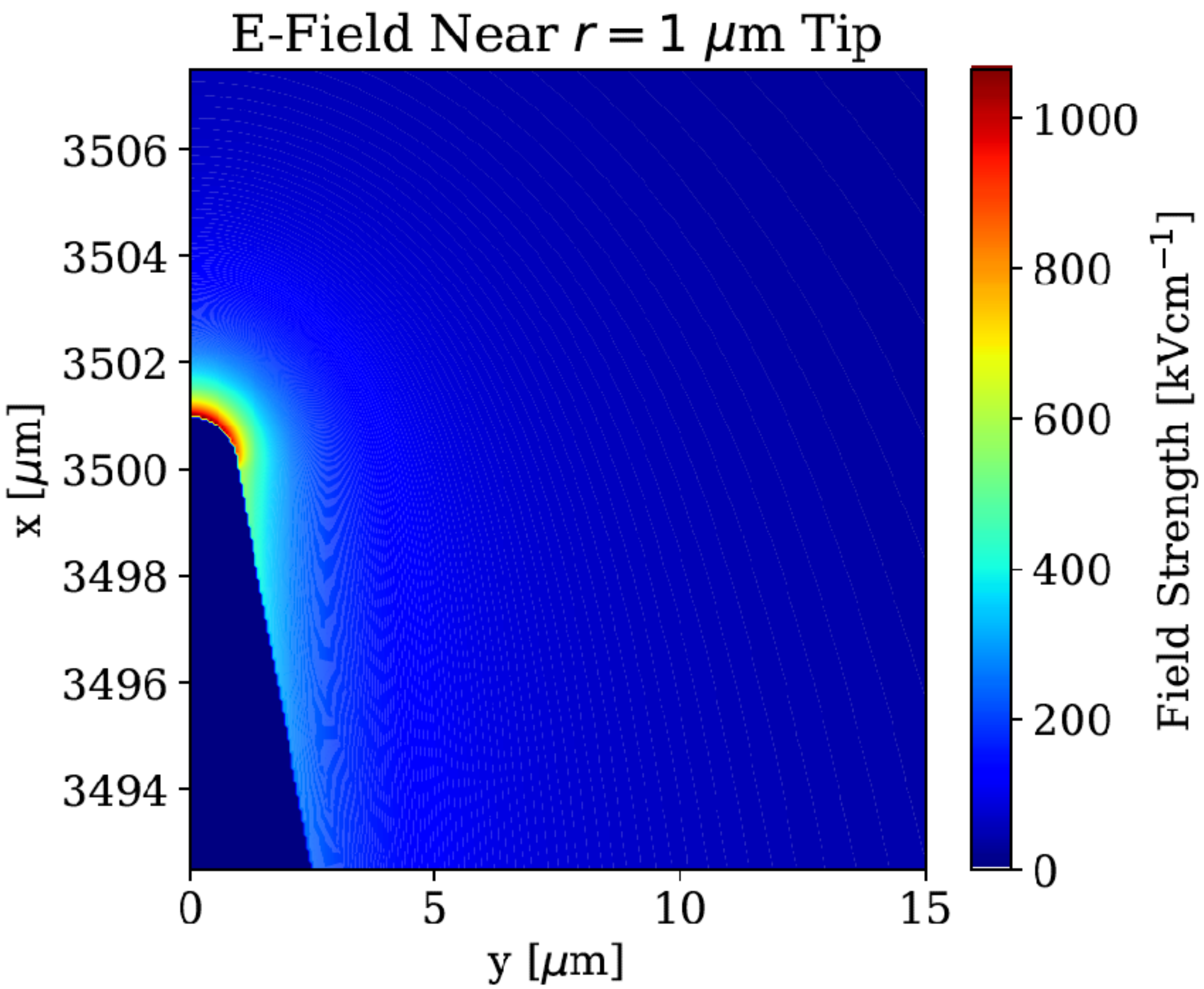


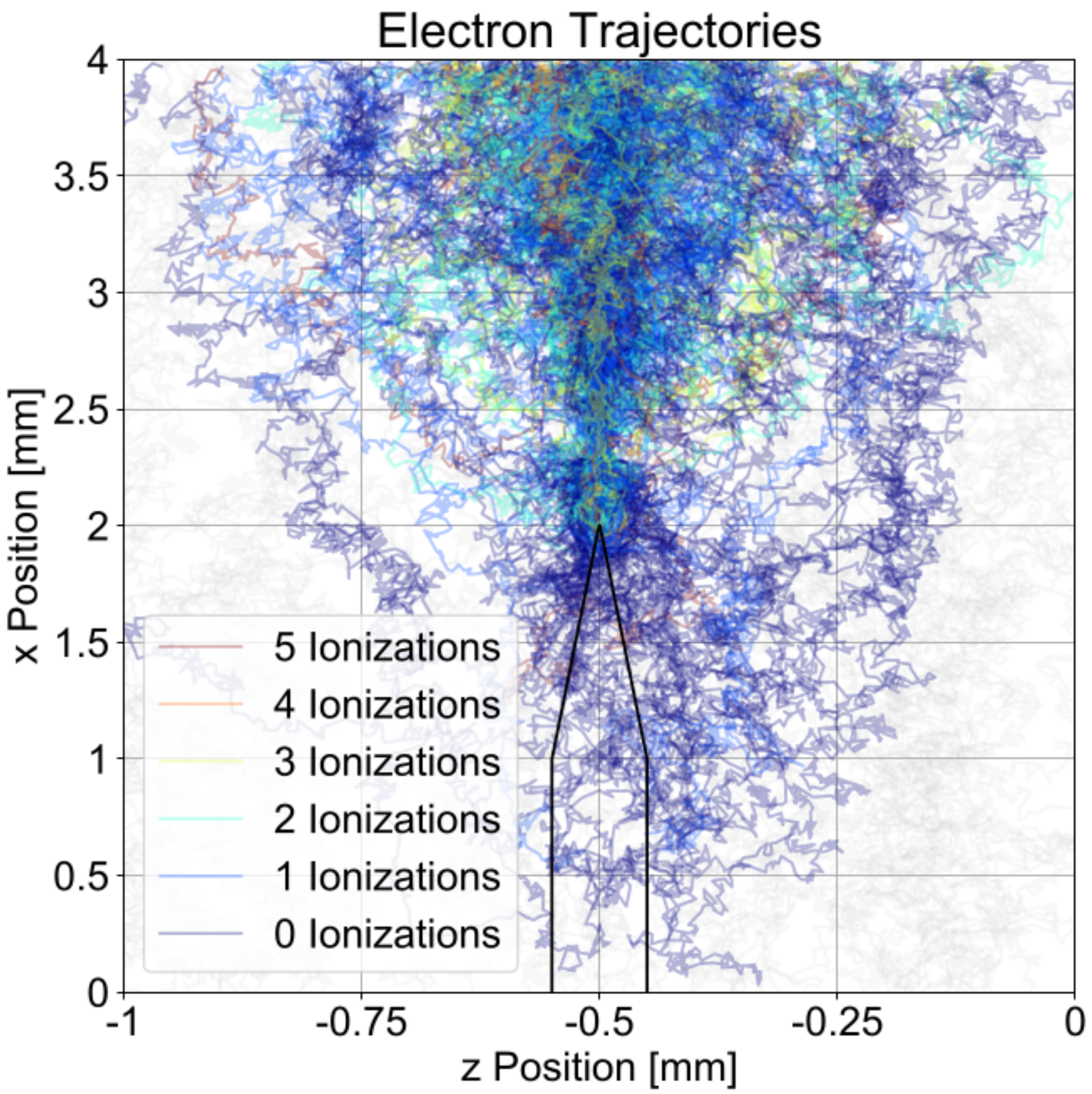
GEM-based detectors



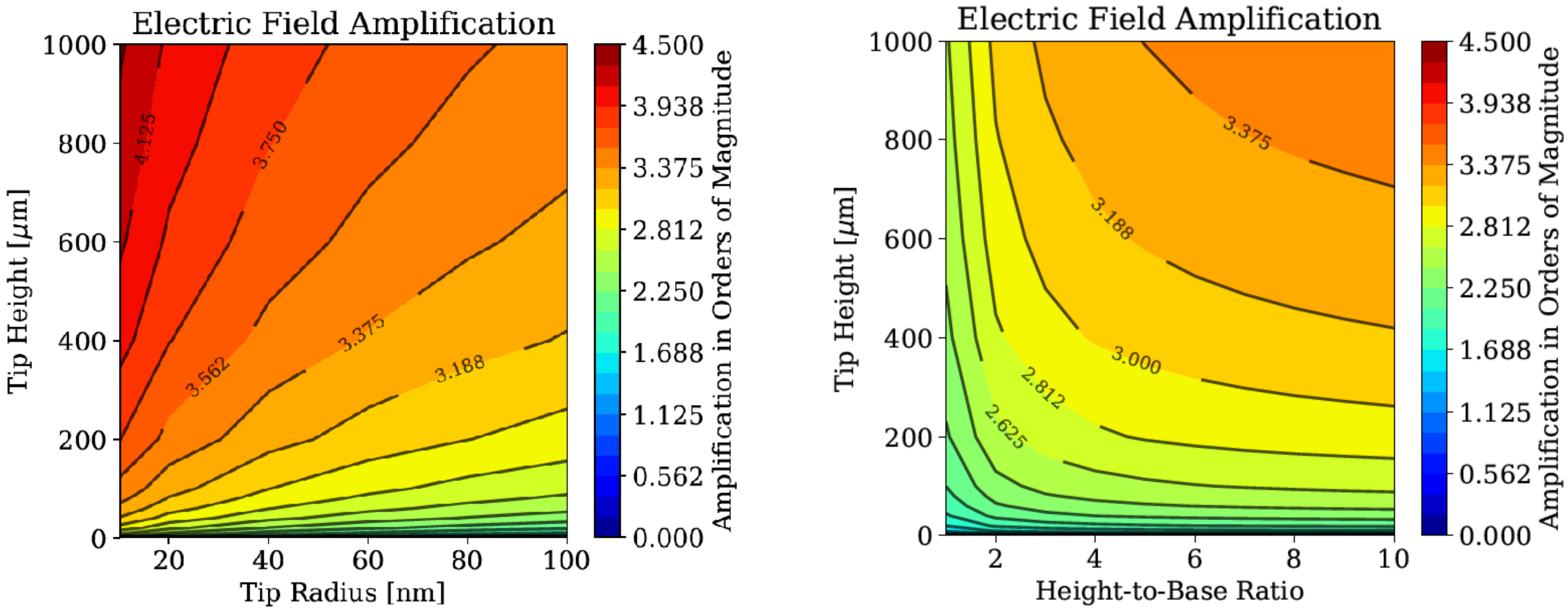
tip-based sensors: detector R&D

LArCADe: tip-array simulation



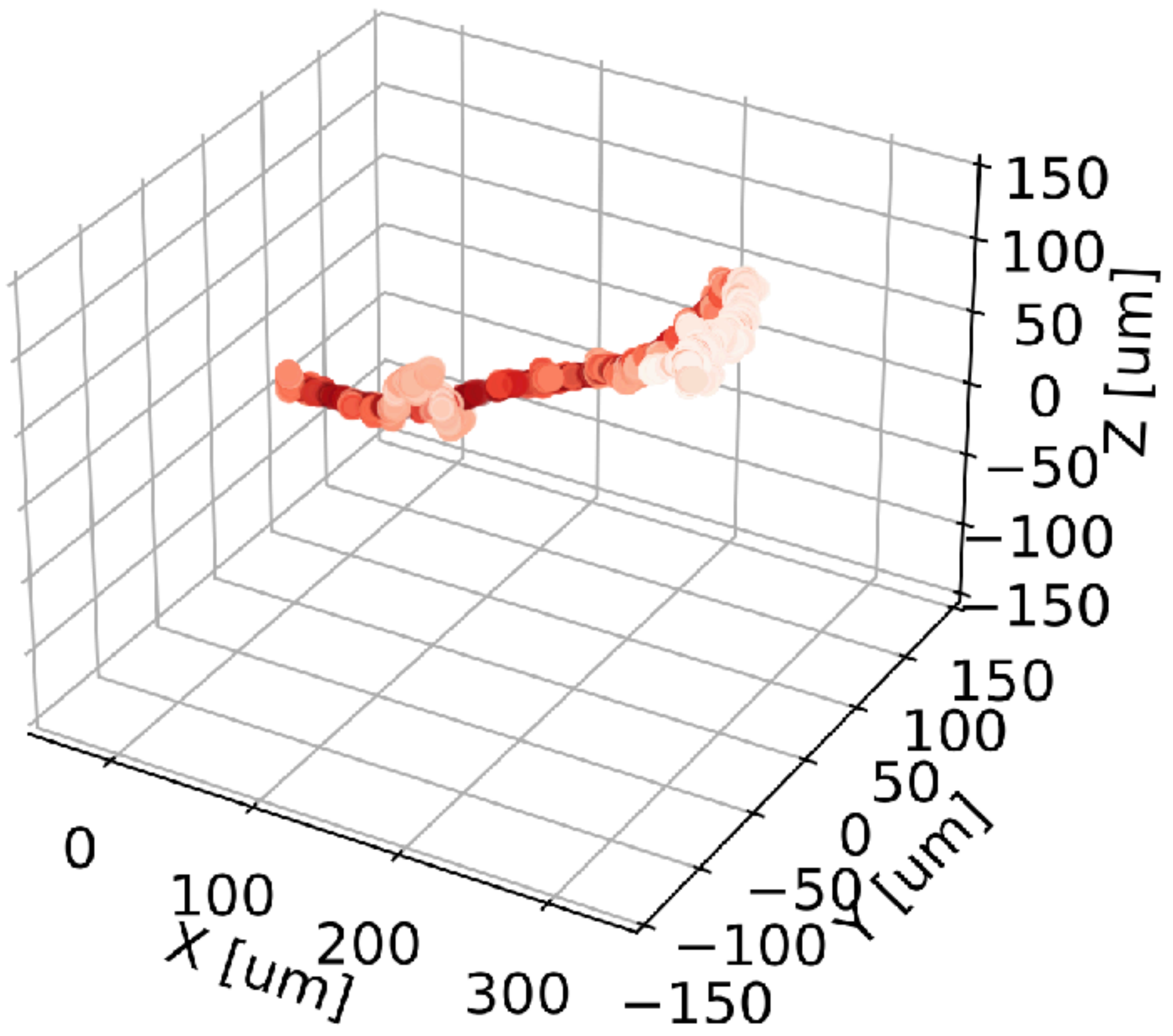


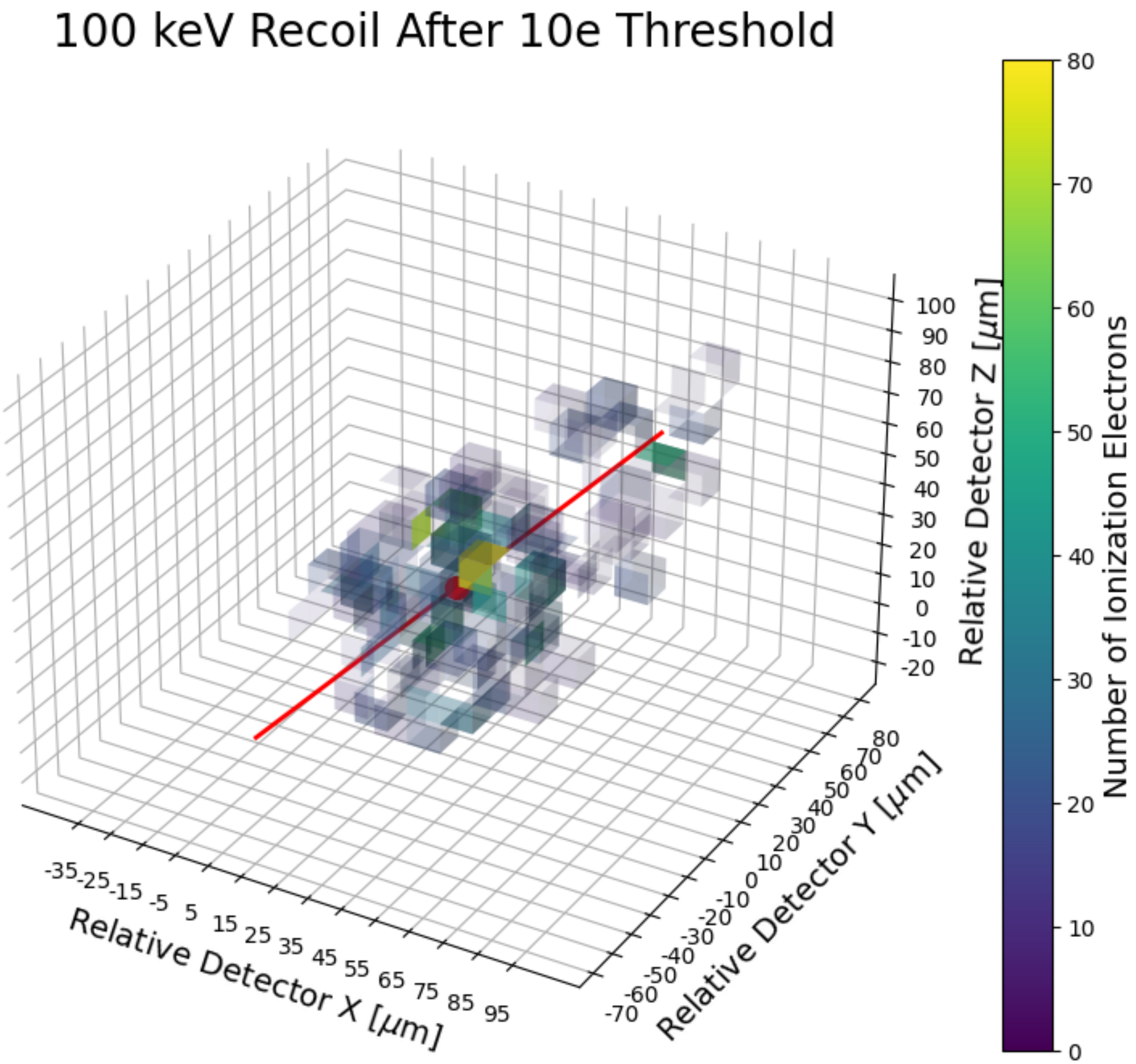
LArCADe: tip-array simulation



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

Detector Response Simulation





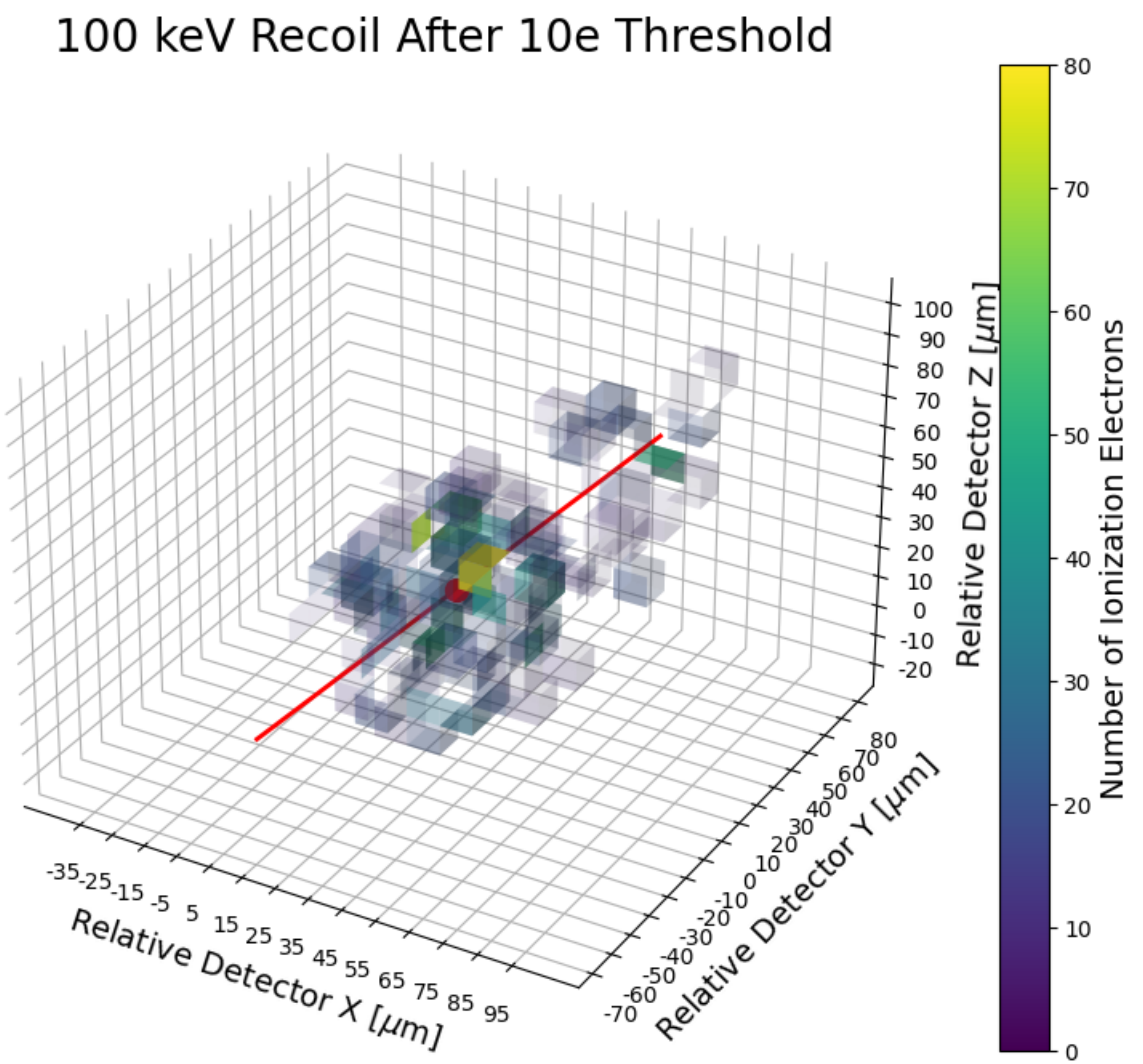
Detector Response Simulation

Implement reasonable detector modeling in order to:

- Optimize target detector configuration
- Compile realistic physics-reach studies

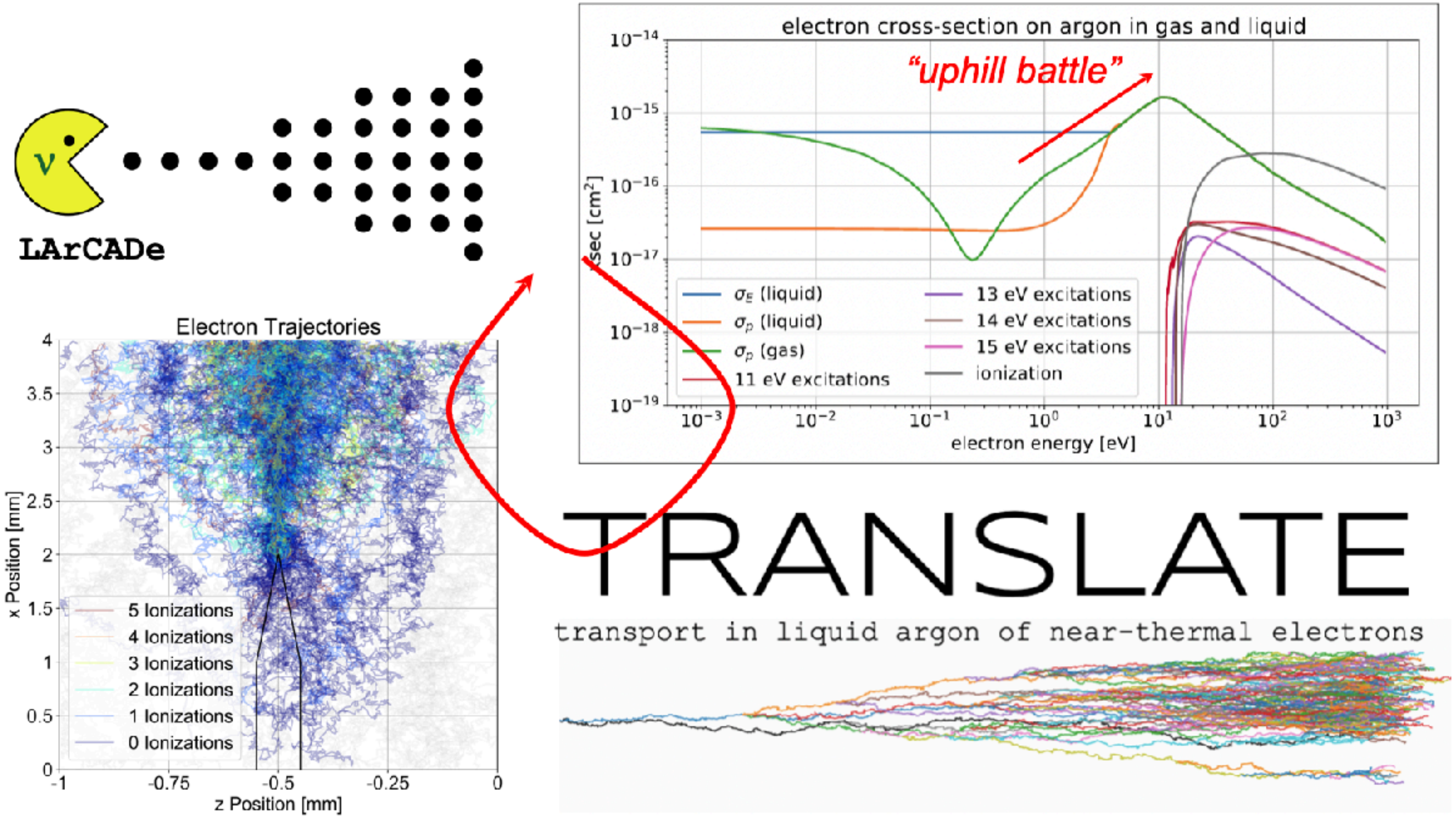
Effects to account for:

- Ionization track simulation [SRIM]
- Ion recombination / quenching
- Electron transport: diffusion
- Charge sensor response



TRANSLATE

TRANSport in Liquid Argon of near-Thermal Electrons



CPC 297 (2024) 109056

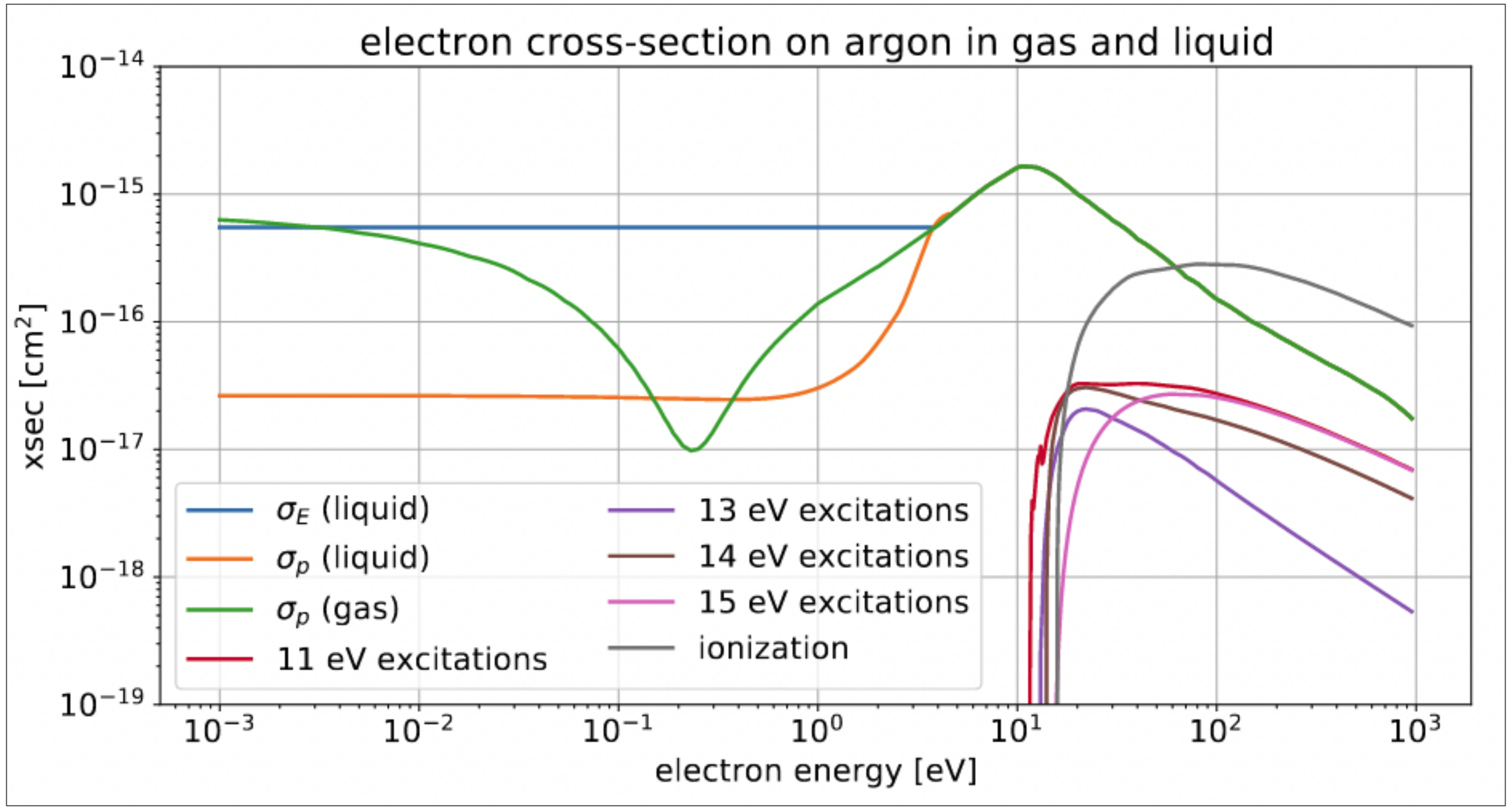
TRANSLATE -- A Monte Carlo Simulation of Electron Transport in Liquid Argon

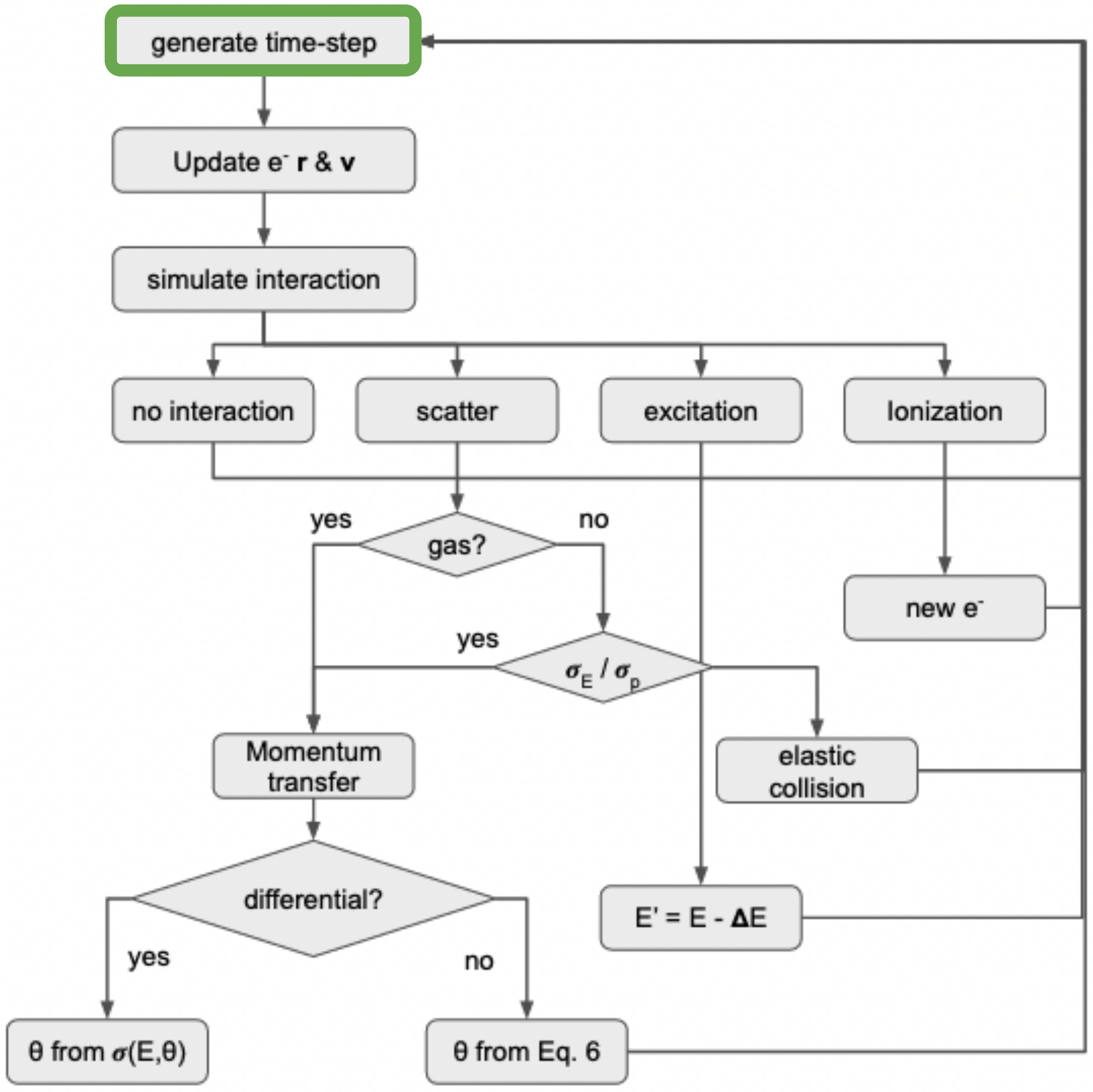
Zach Beever, David Caratelli, Angela Fava, Francesco Pietropaolo, Francesca Stocker, Jacob Zettlemoyer

TRANSLATE: Monte Carlo simulation

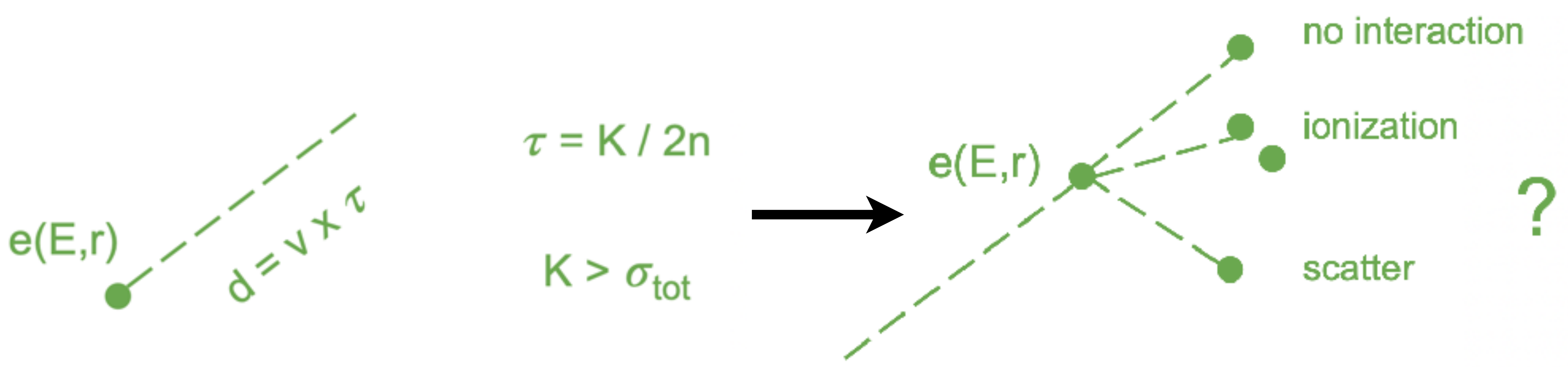
$\tau = K / 2n$

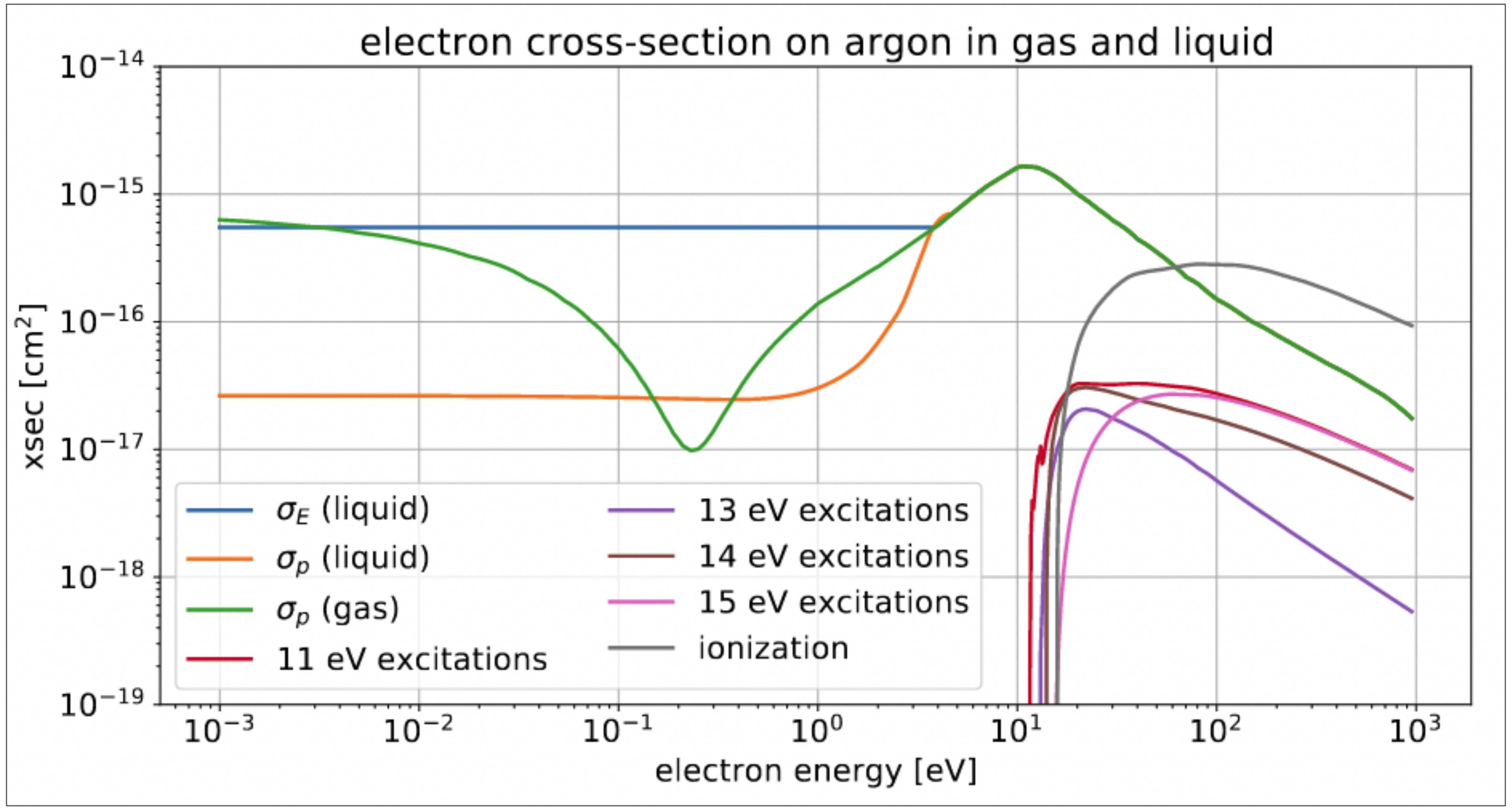
$K > \sigma_{tot}$

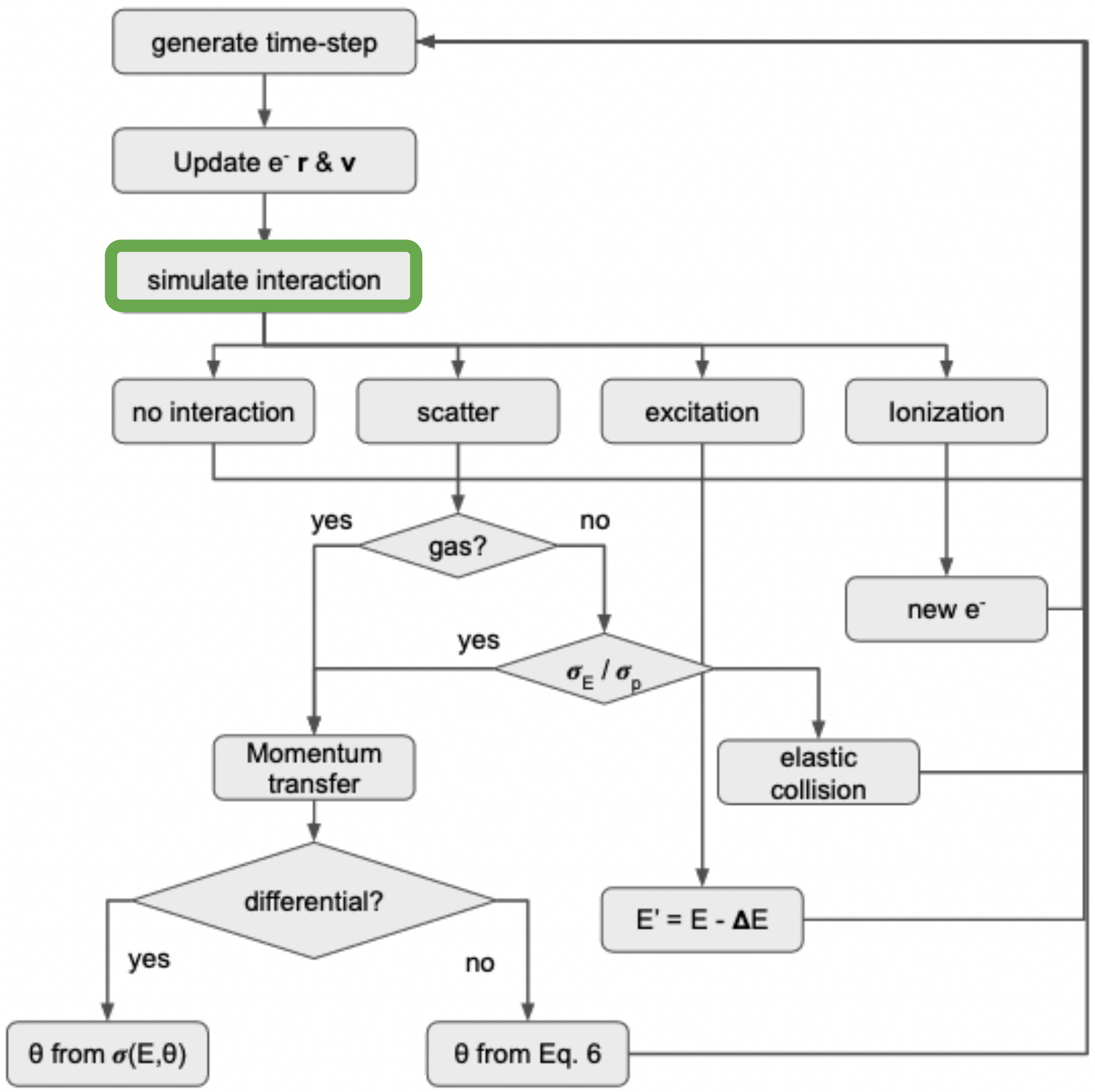




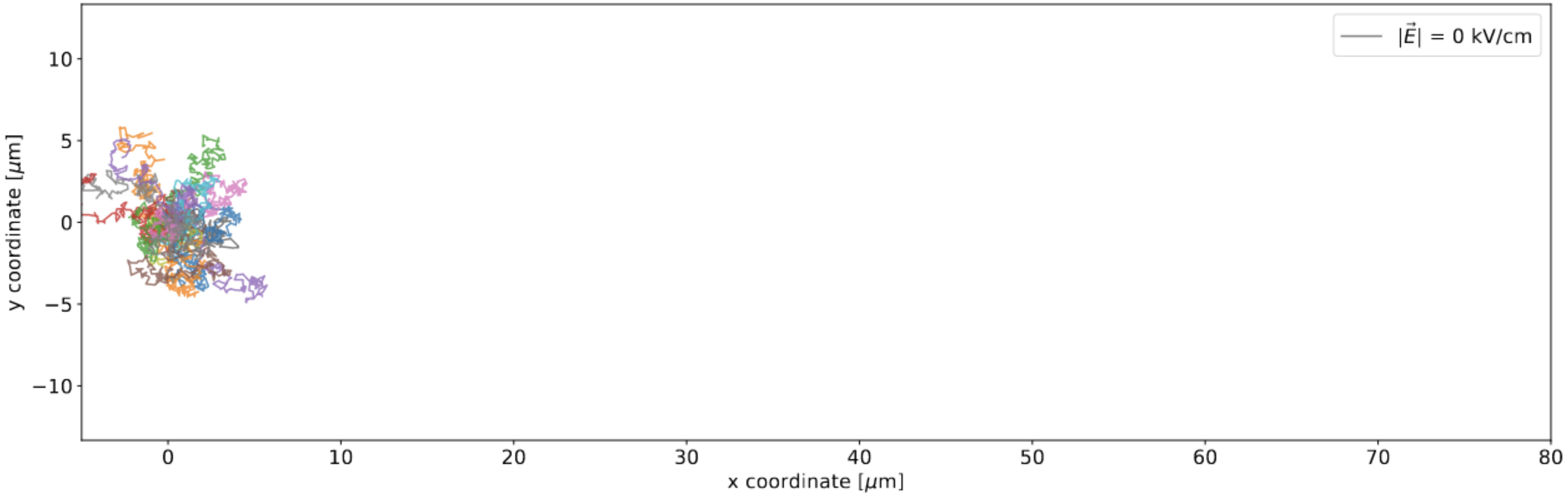
TRANSLATE: Monte Carlo simulation

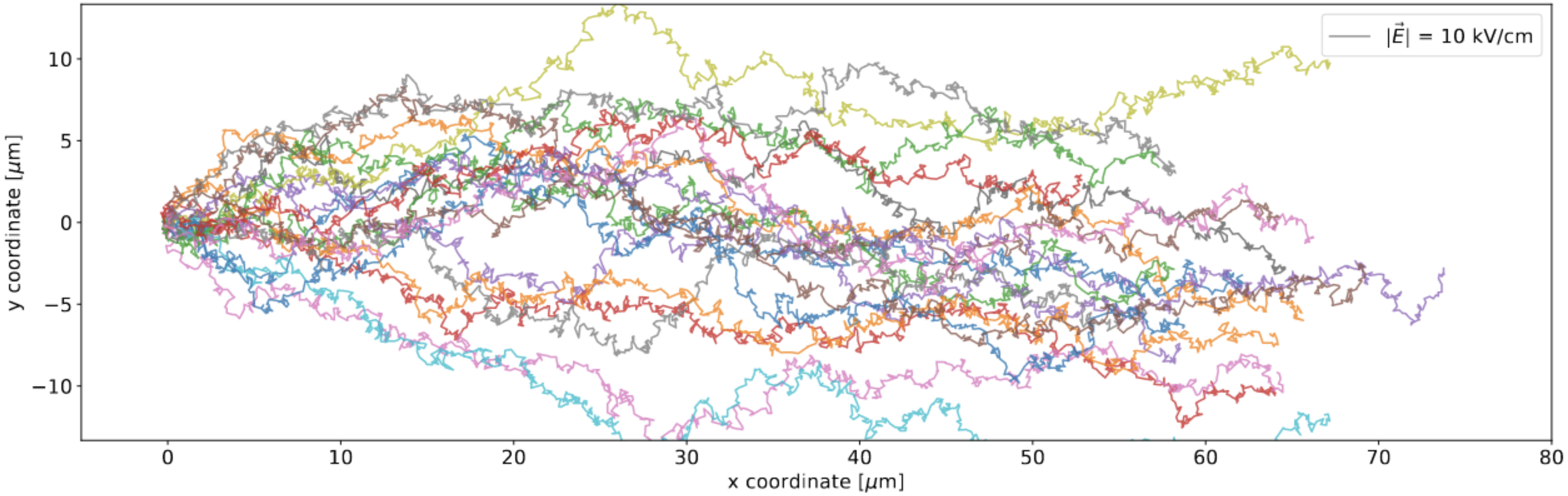






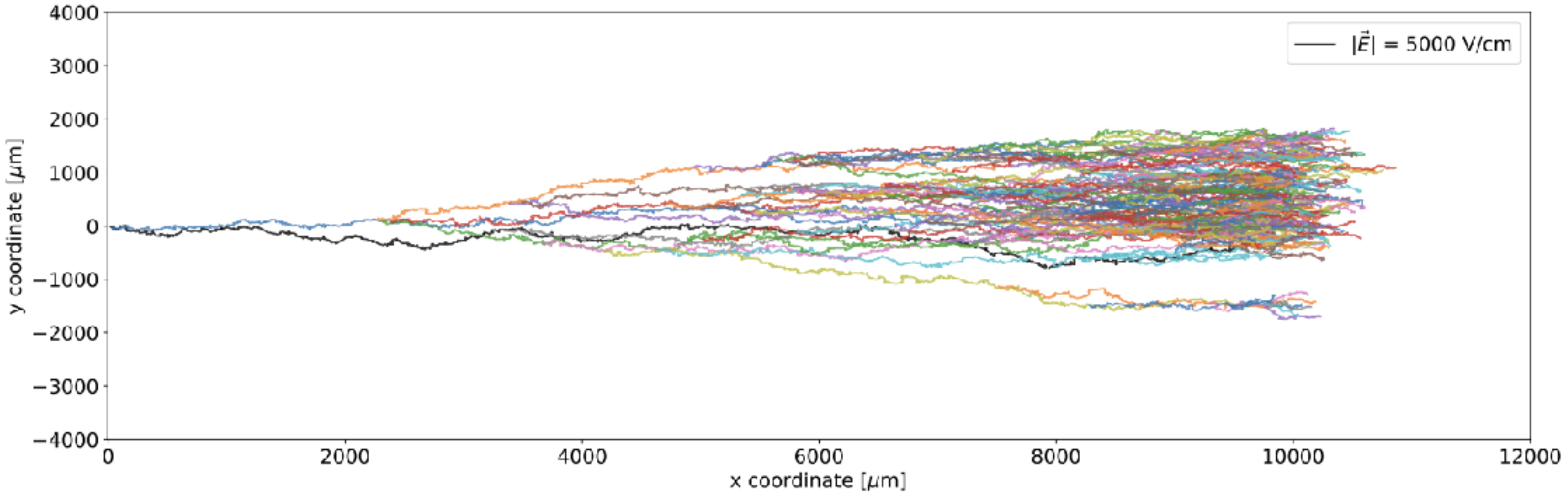
TRANSLATE: simulation output

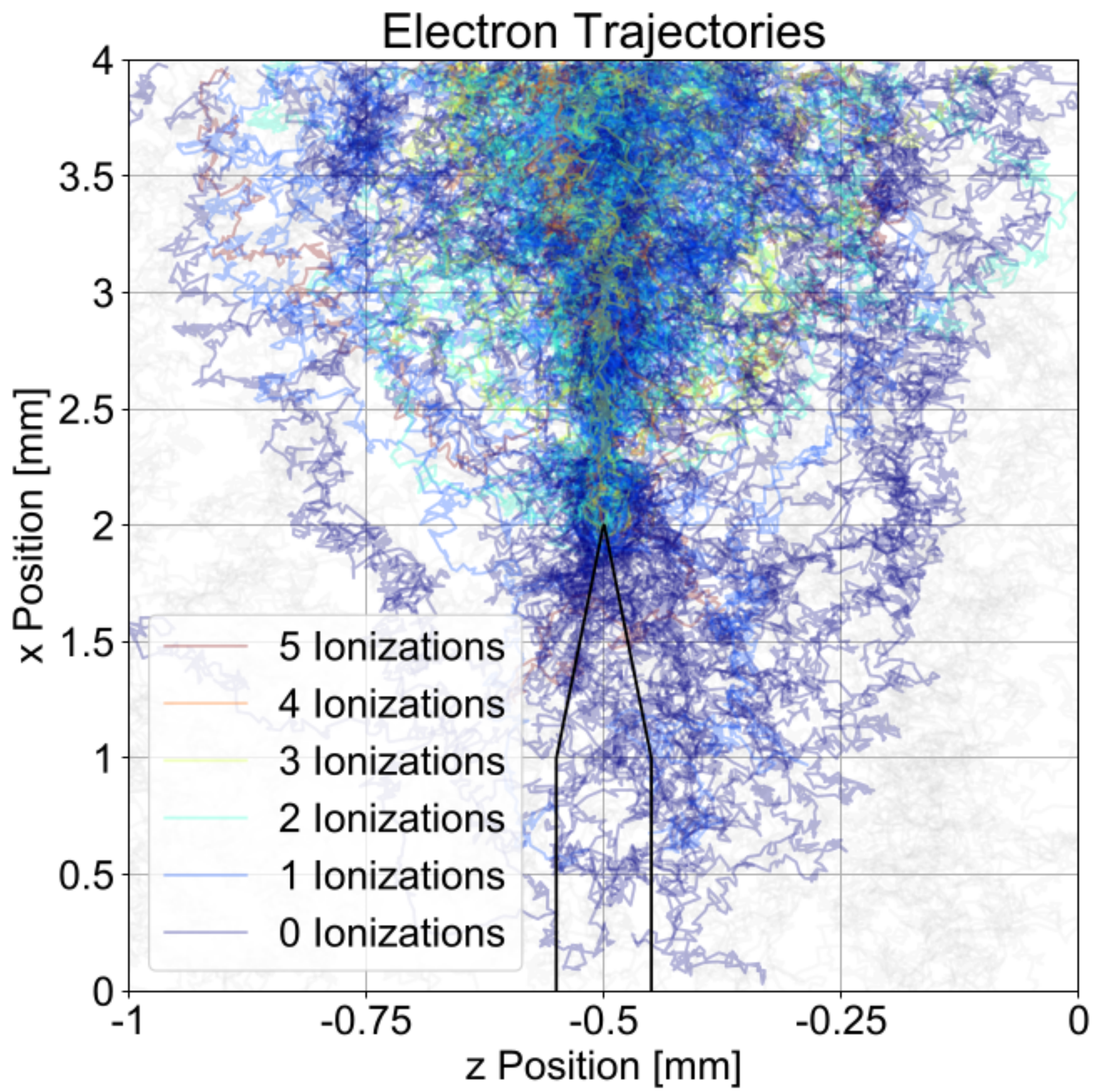




TRANSLATE: simulation output

Simulation of electron amplification in complex geometries



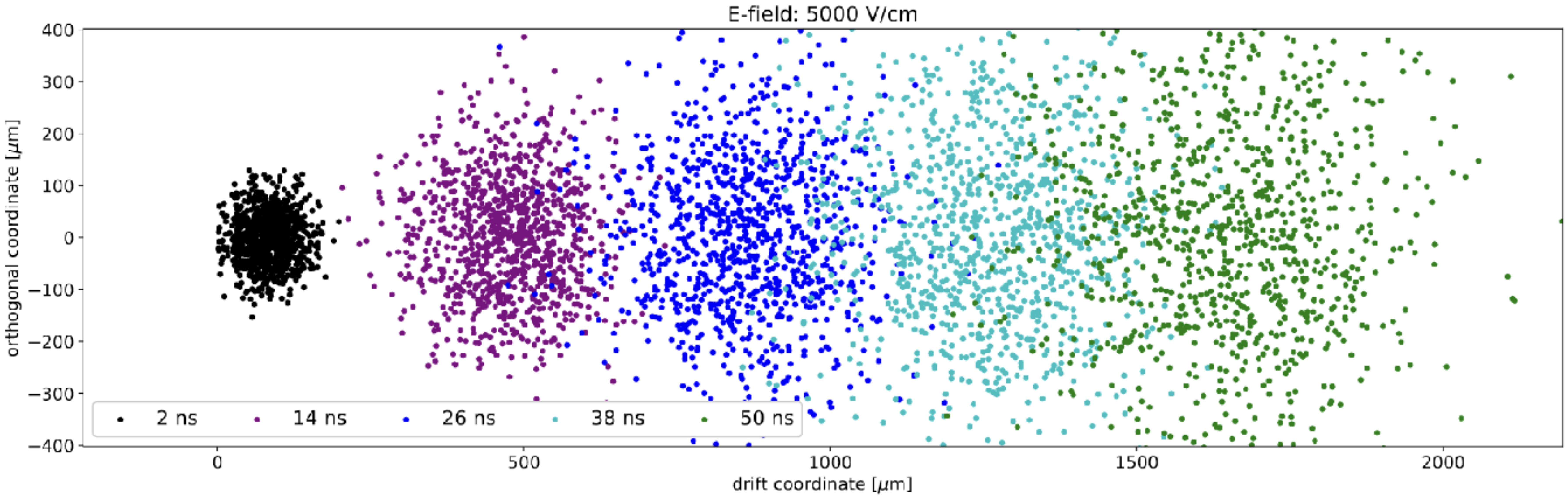


TRANSLATE: simulation validation

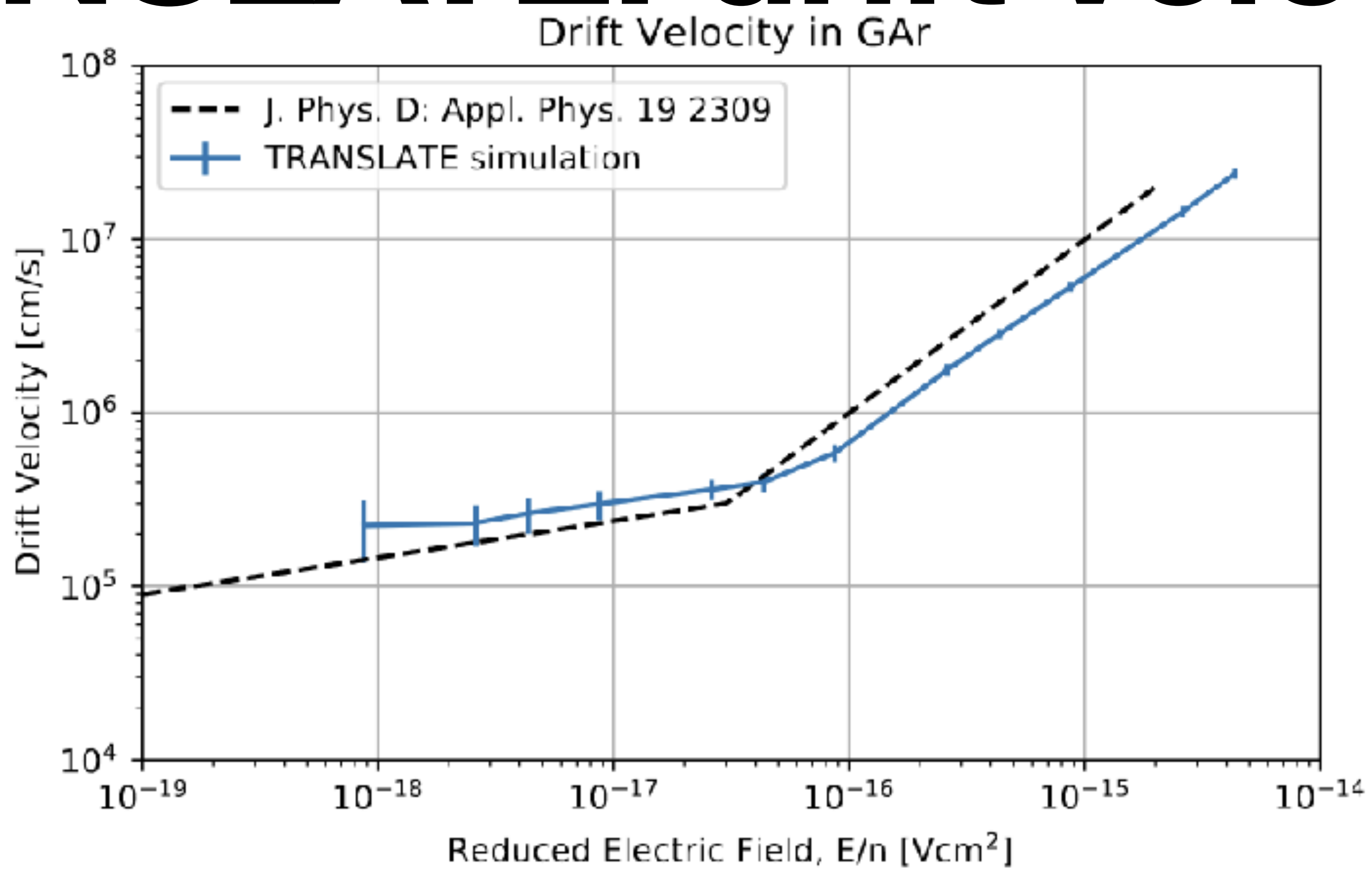
Track O(10^2 – 10^3) electrons over time intervals of 10^{-9} – 10^{-6} seconds.

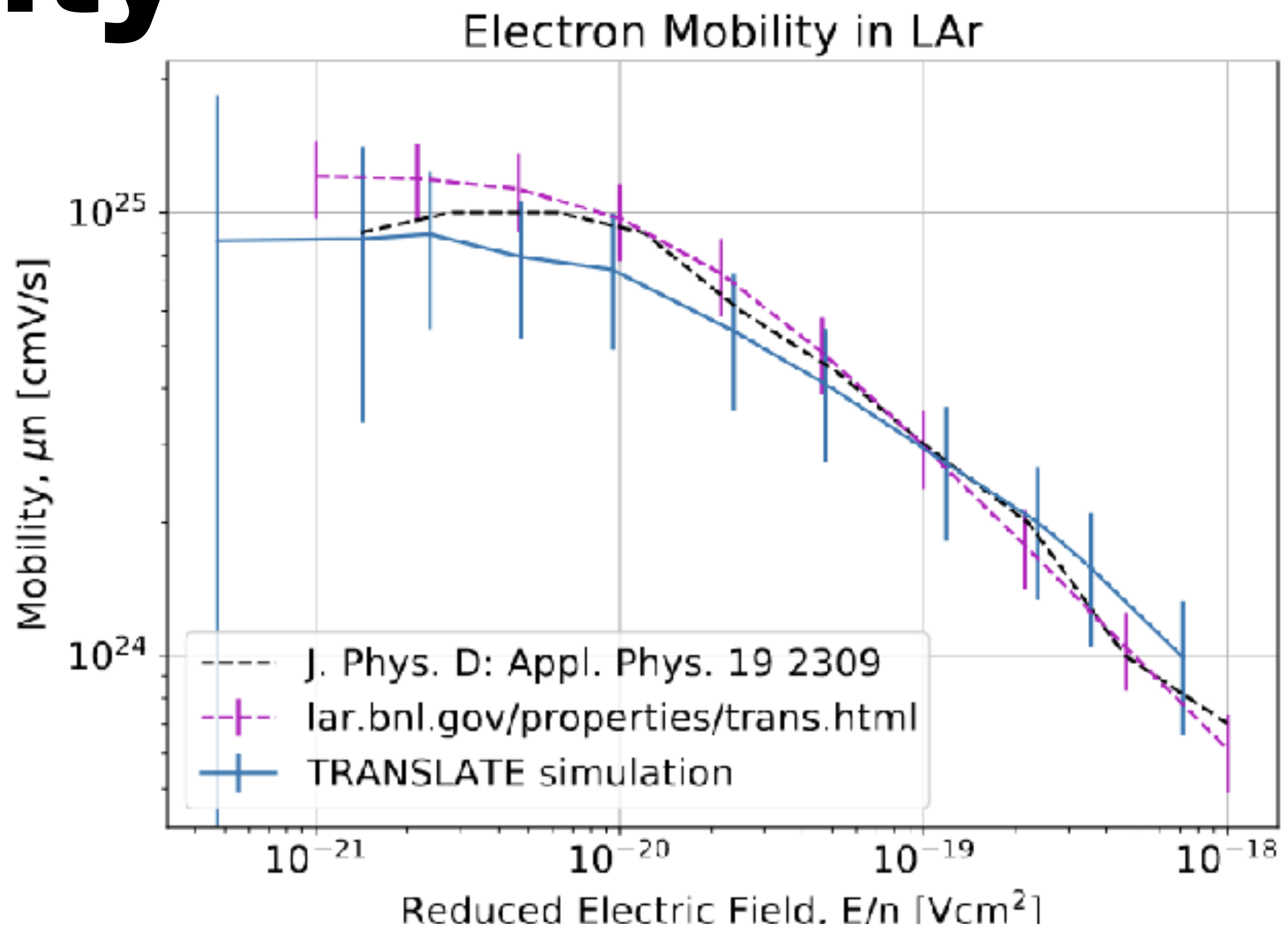
Track as a function of E-field:

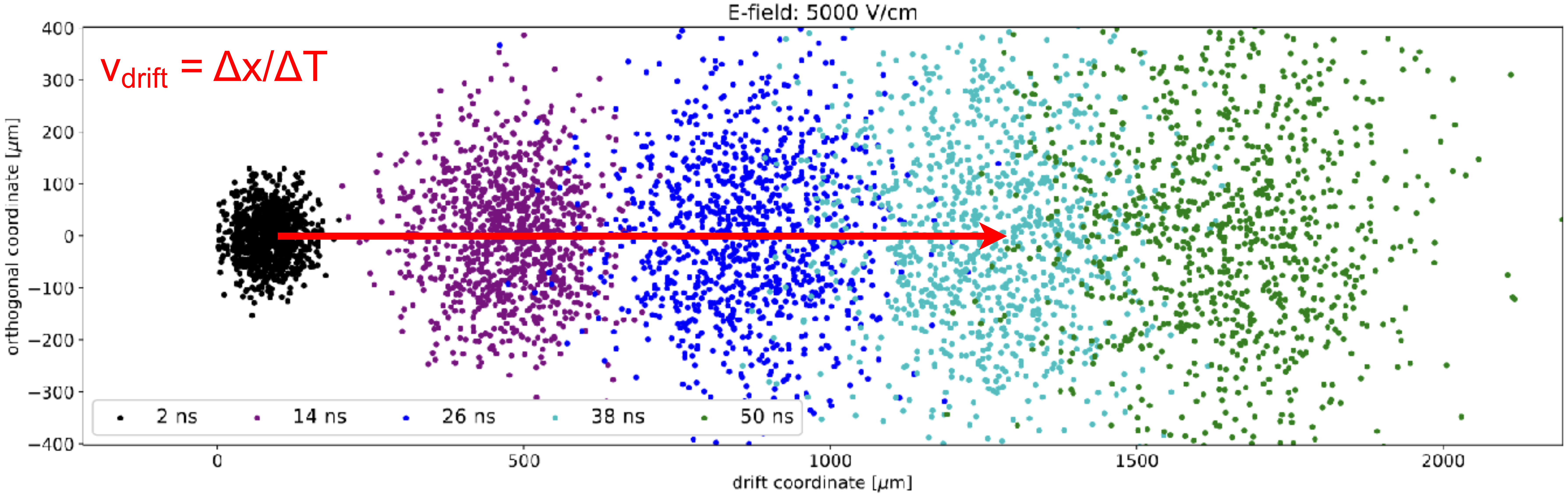
1. Average distance traveled → drift velocity [GAr & LAr]
2. Spread in electron clouds → diffusion [GAr & LAr]
3. Amplification [GAr]



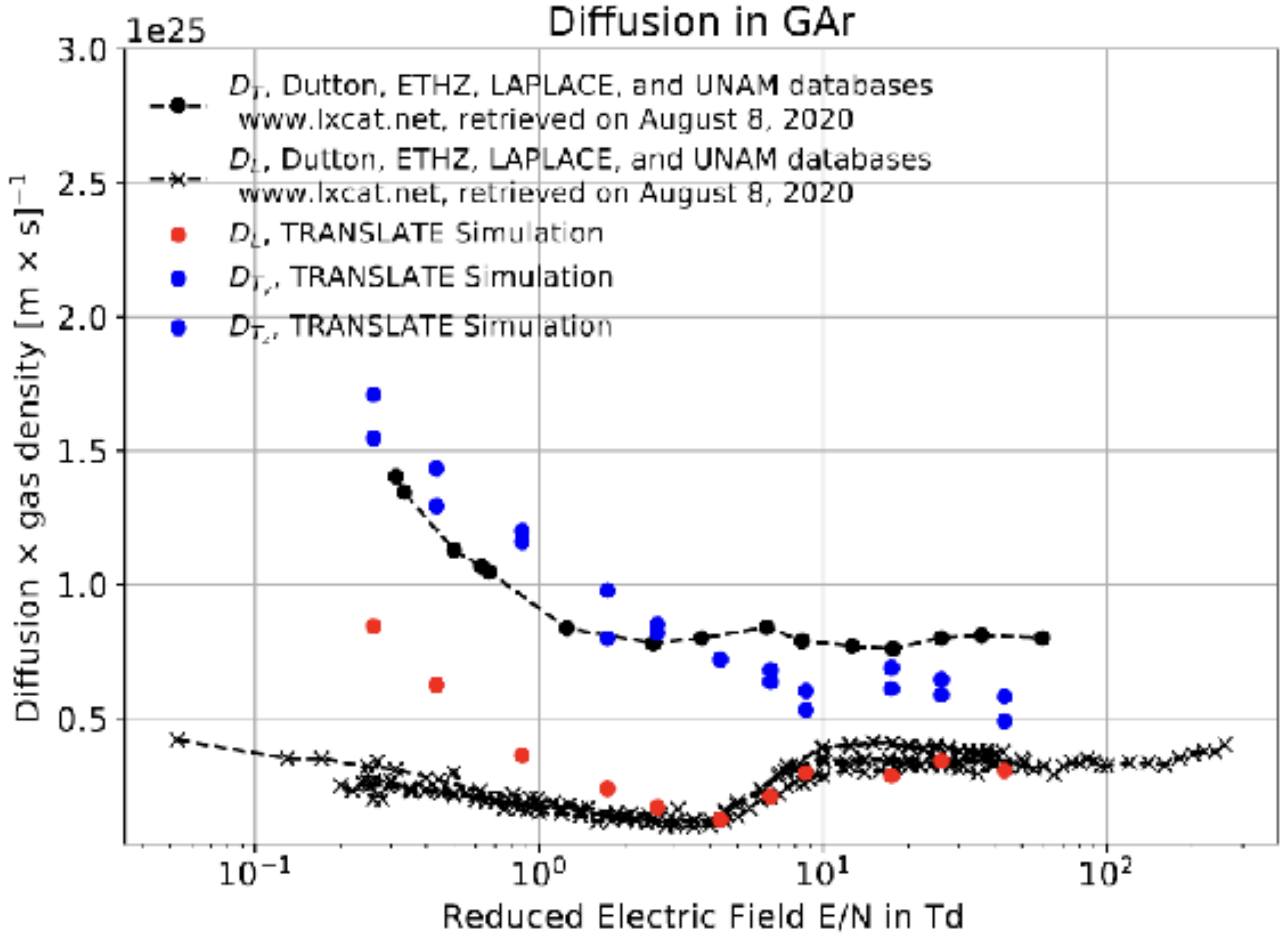
TRANSLATE: drift velocity

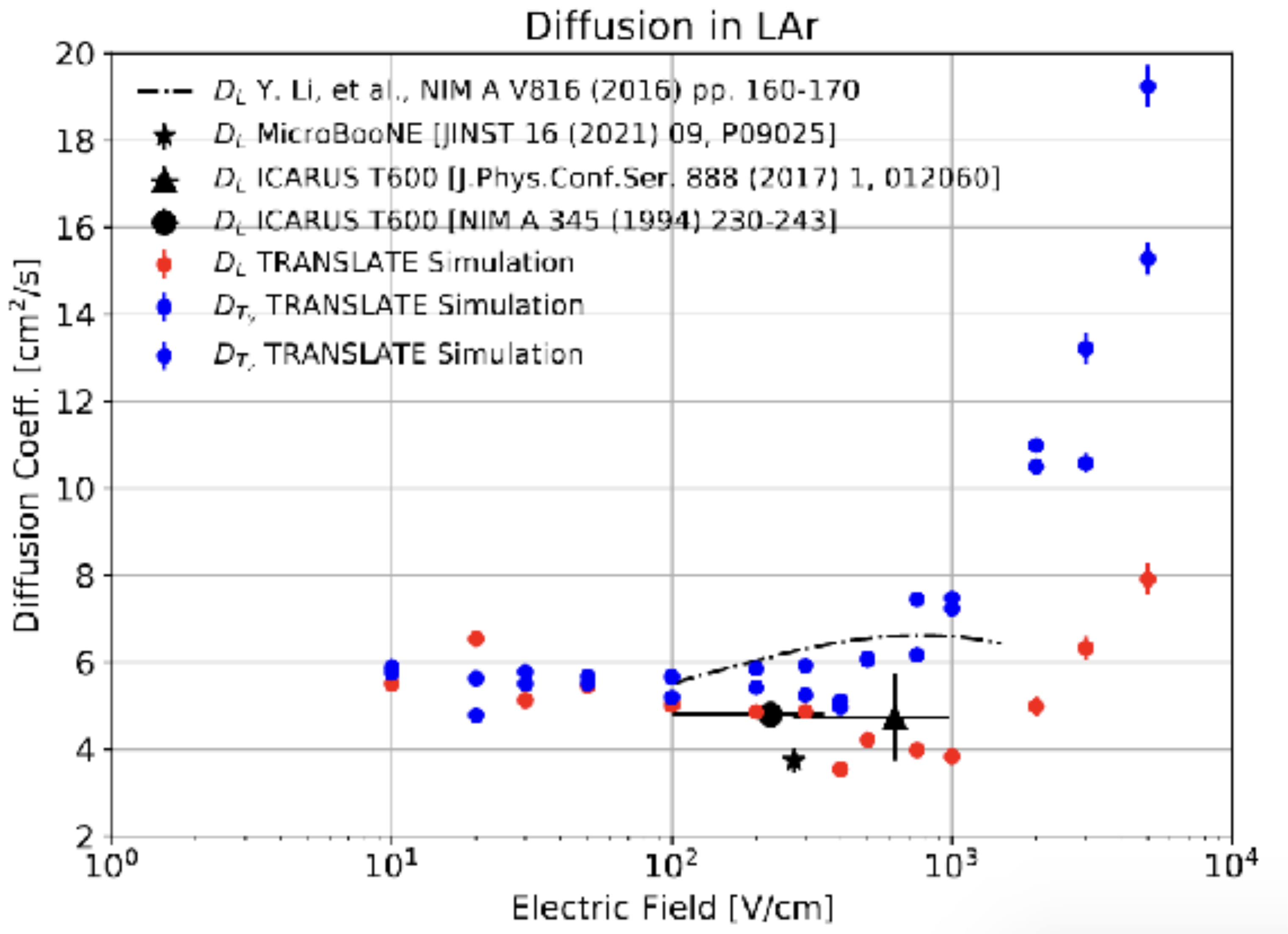


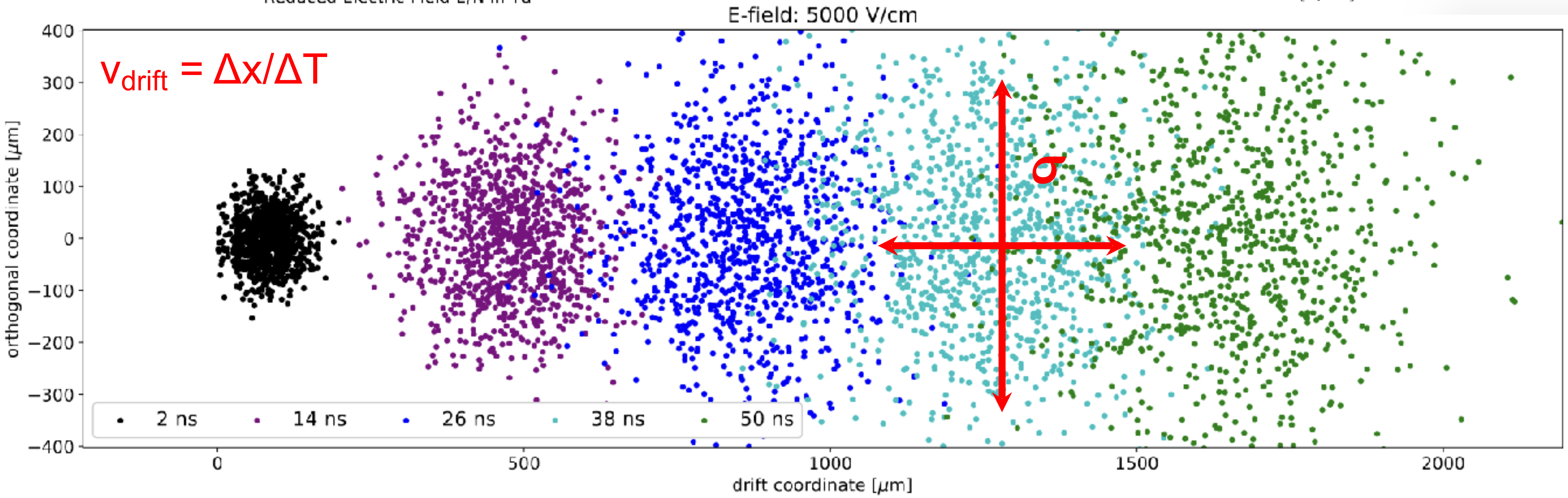




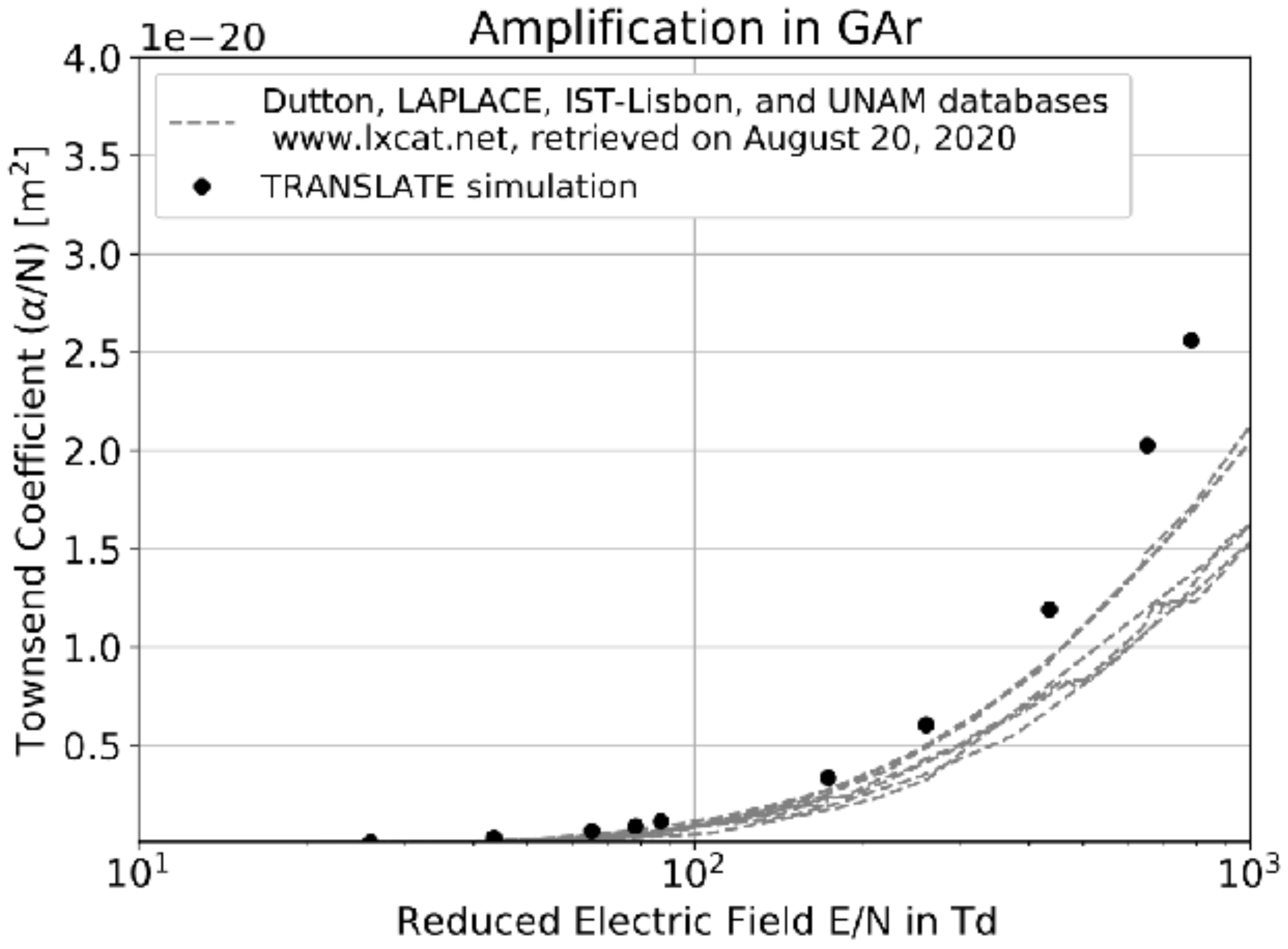
TRANSLATE: ion diffusion

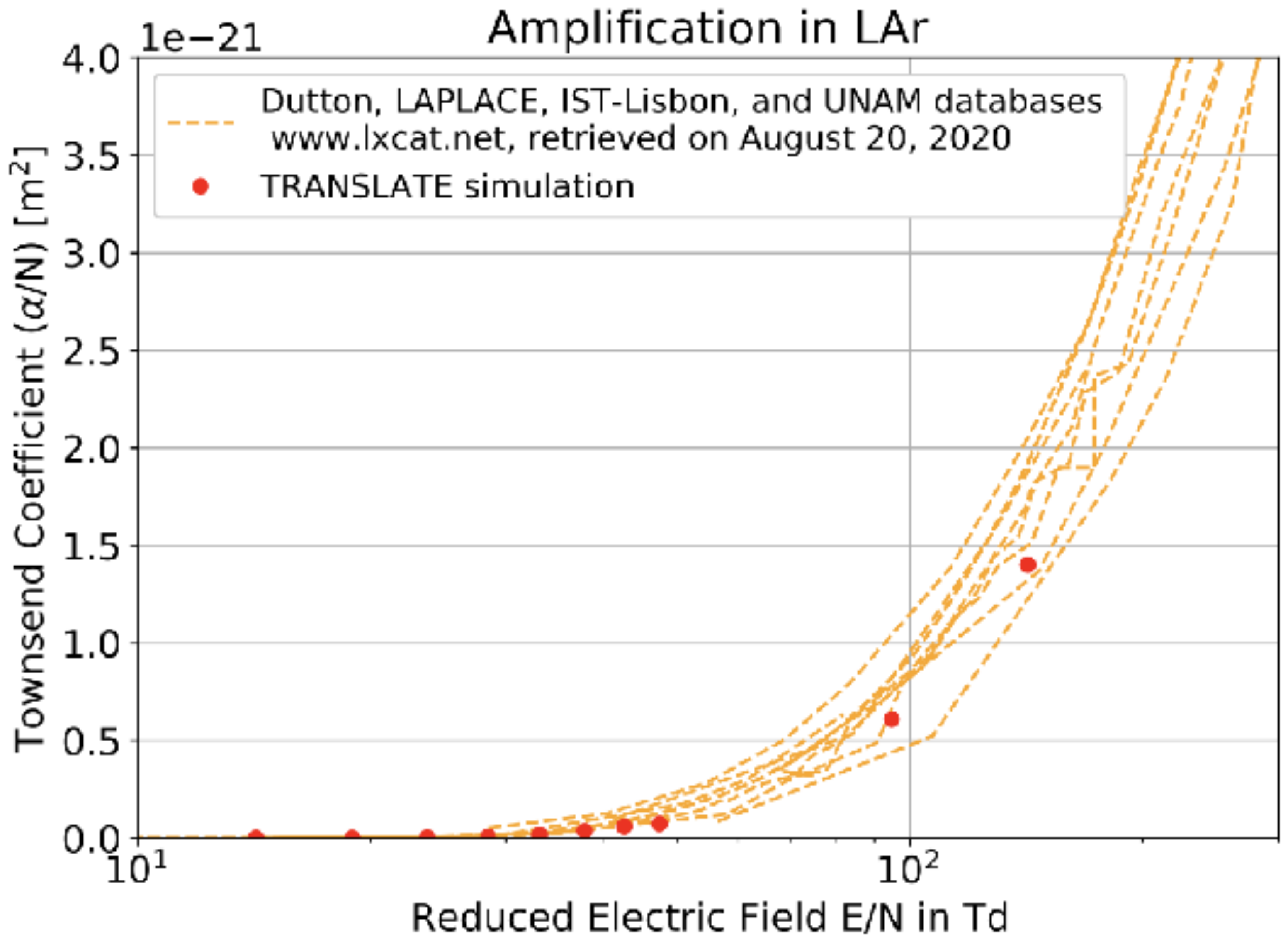


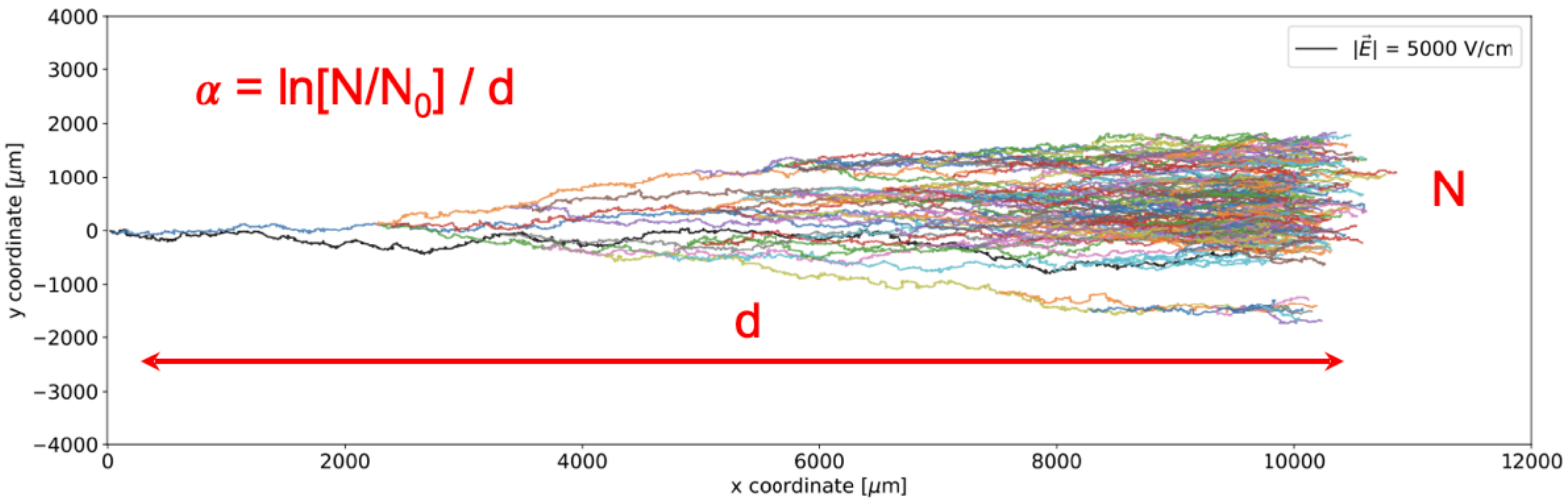




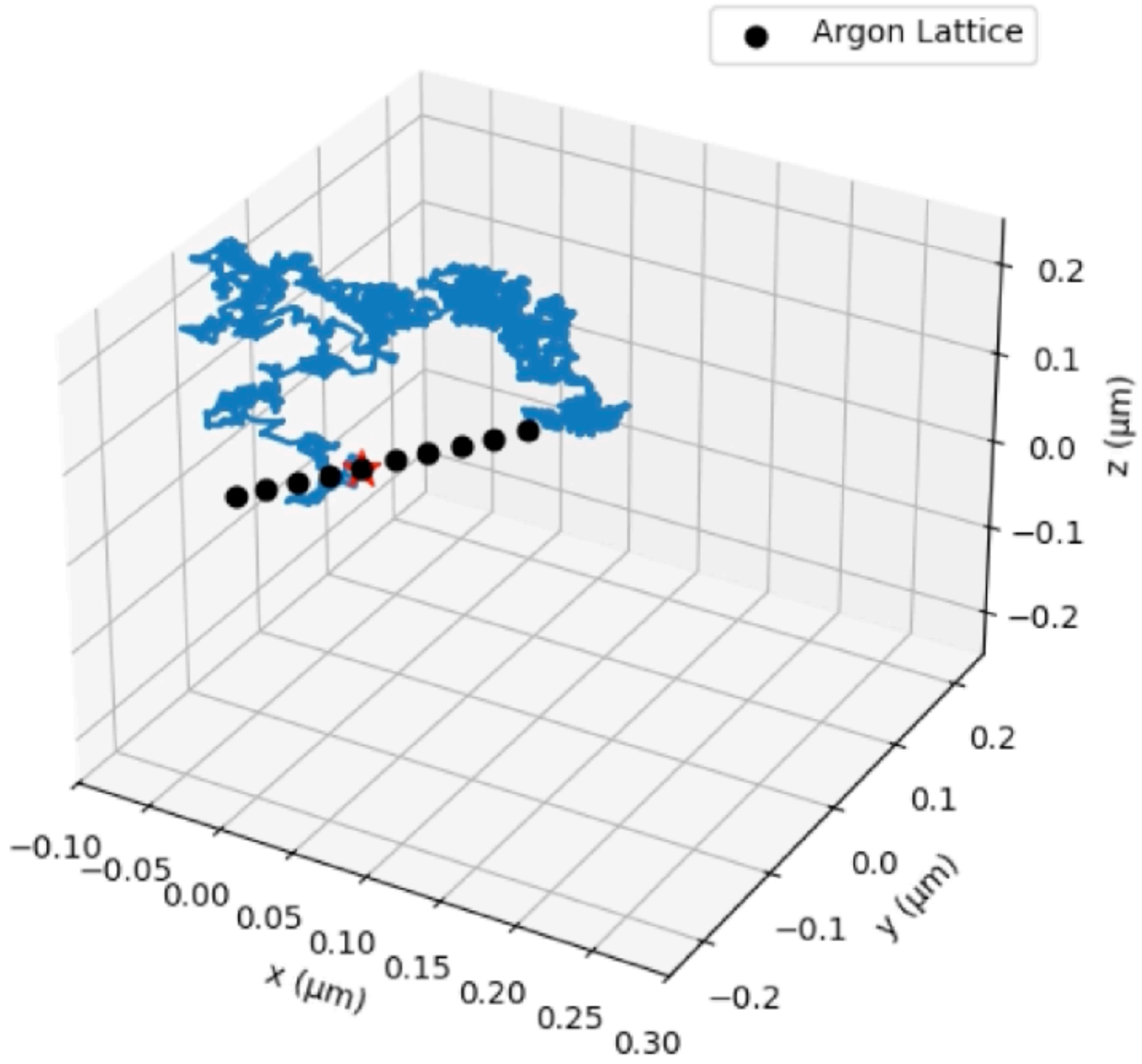
TRANSLATE: charge amplification

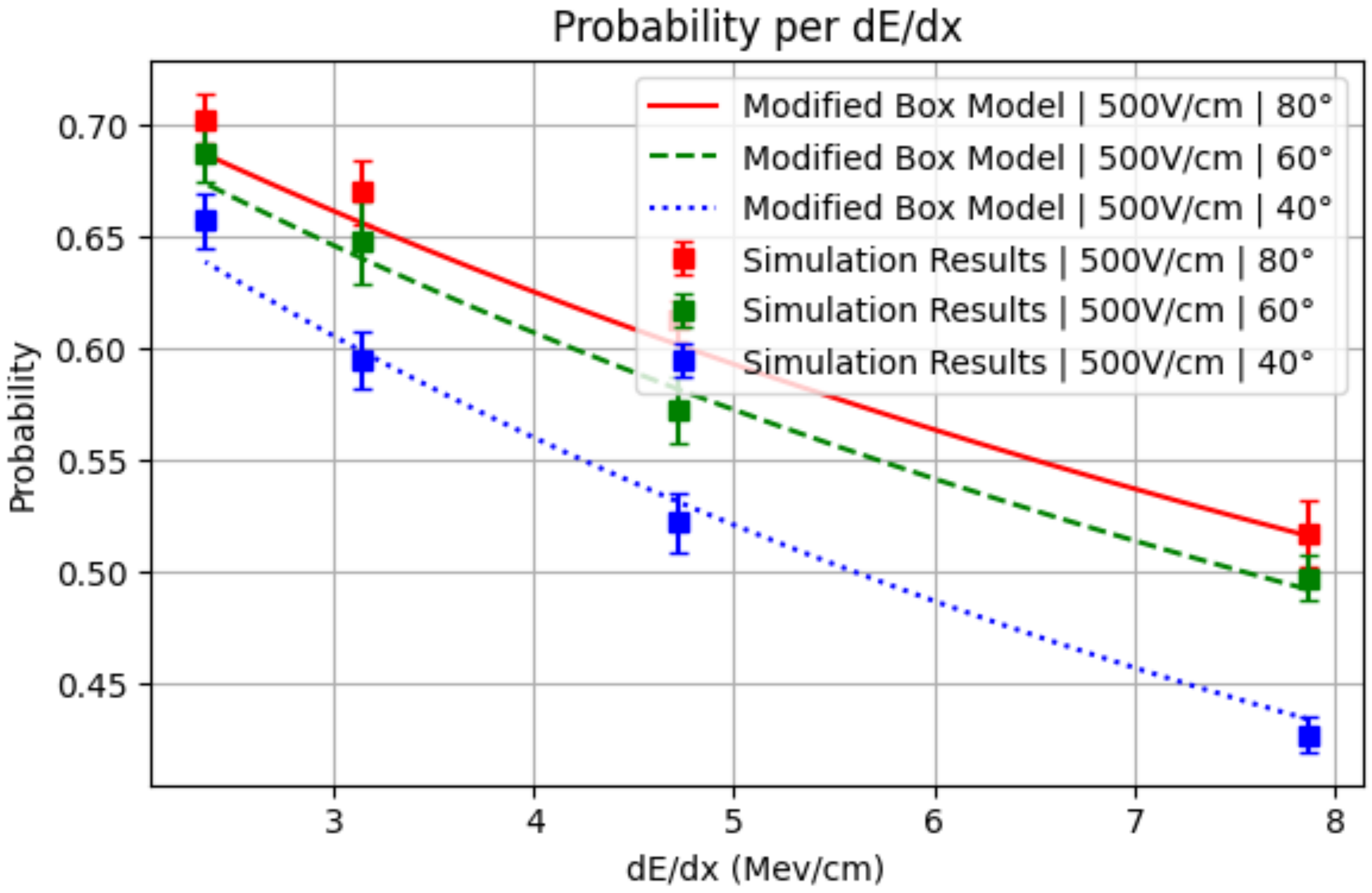






TRANSLATE: ion recombination





Curves from ICARUS: JINST 20 P01033 (2025)

Conclusions

Gas-based TPC for directional NR detection from π-DAR CEvNS is challenging but worth exploring.

Broad physics program:

- E measurement: oscillations / precision xsec
- Kinematics boost BSM sensitivity
- Neutron background rejection

Developing more refined sensitivity studies. Working with GAr, but much broader community active in many directions.