

Novel Paths to Charge Collection in Argon TPCS

| CPAD 2026



LArCADE · TRANSLATE · MOSAIC



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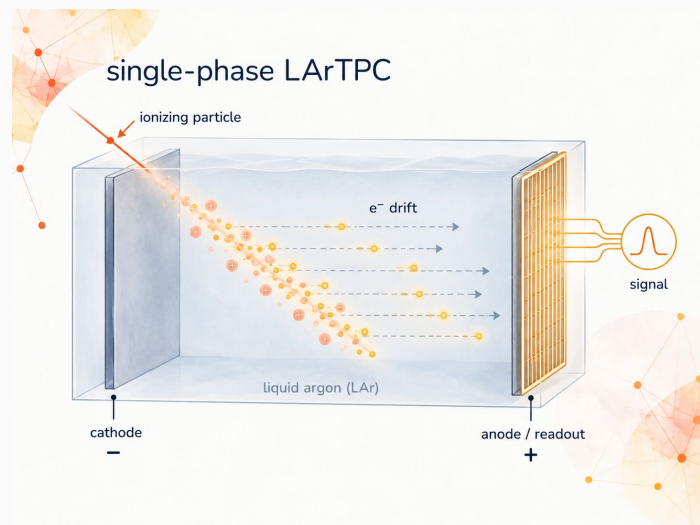
³ Fermi National Accelerator Laboratory

Towards few-electron sensitivity in liquid argon

- LArTPCs provide **scalable active targets** and **3D imaging** for neutrino and rare-event experiments.
- Low-energy nuclear recoils, including **CEvNS¹** signatures, can produce typically only a few to tens of surviving ionisation electrons.
- The **readout threshold** therefore becomes a **limiting factor** even when the argon target itself provides excellent charge transport.

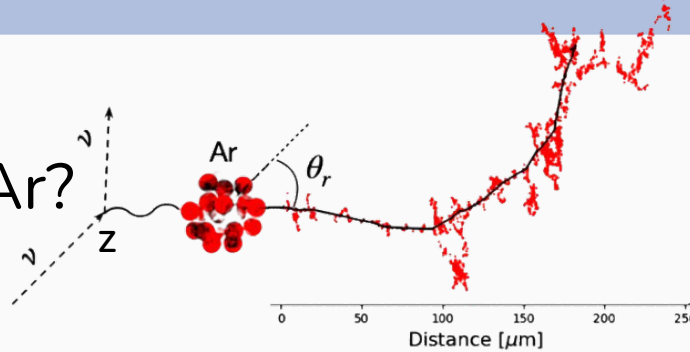


→ **Local charge amplification near the anode** could improve sensitivity while preserving spatially resolved charge collection.



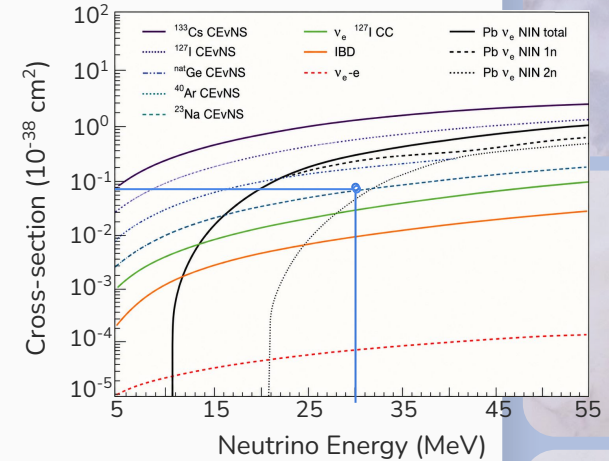
¹C. O'Hare et. al. [arXiv:2602.19618](https://arxiv.org/abs/2602.19618)

Why CE ν NS in LAr?



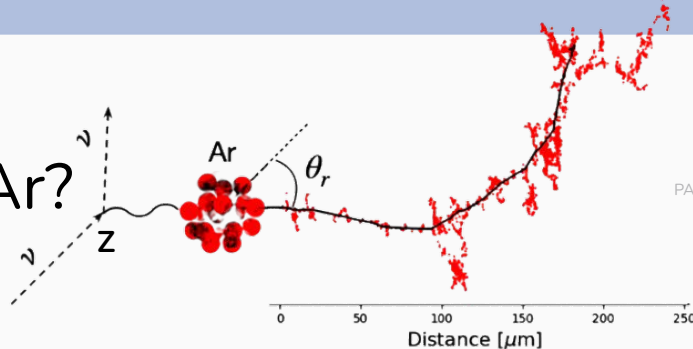
- **CE ν NS is a clean neutral-current probe** of neutrino and BSM physics
- To fully exploit it we need the **recoil energy and direction**

AIM



Expand reach of large-scale single-phase LArTPCs to be sensitive to nuclear recoil ionisation signatures

Why CE ν NS in LAr?



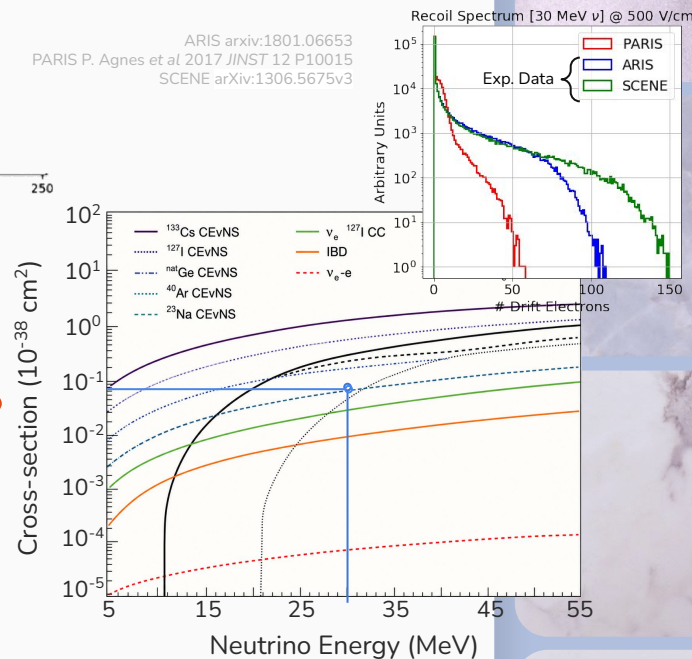
ARIS arxiv:1801.06653
PARIS P. Agnes et al 2017 JINST 12 P10015
SCENE arXiv:1306.5675v3

- CE ν NS is a **clean neutral-current probe** of neutrino and BSM physics
- To fully exploit it we need the **recoil energy and direction**
- In argon, CE ν NS recoils are **short and weakly ionising**, producing only $O(10\text{s}-100) e^-$
- This pushes signals toward current LArTPC **electronics-noise limits** $O(100\text{s}-1\text{k})$

CHALLENGE

AIM

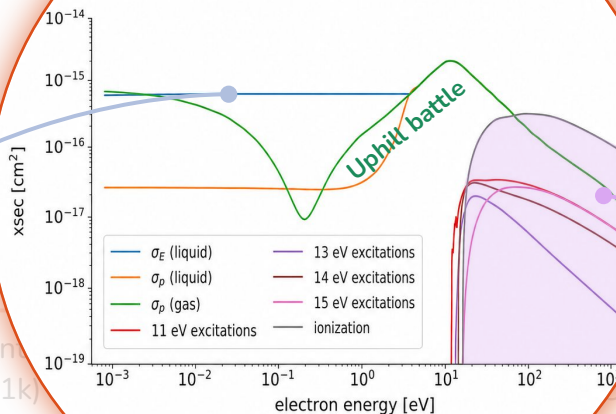
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Why CEνNS in LAr?

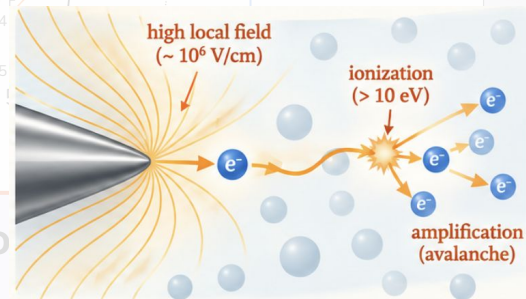
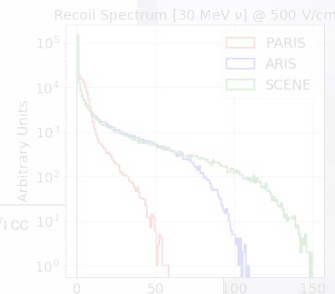
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electron cross-section on argon in gas and liquid



CHALLENGE

Electrons must reach **$O(10)$ eV** to **ionise** and produce an **avalanche**.
In dense liquid argon, frequent scattering and **inelastic energy losses** make this challenging, requiring exceptionally strong local fields of **$\sim 10^6$ V/cm**.

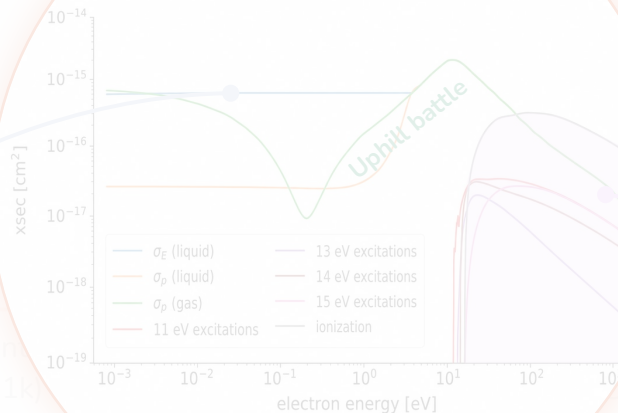


e-scale single-phase LArTPCs to
near recoil ionisation signatures

Why CEνNS in LAr?

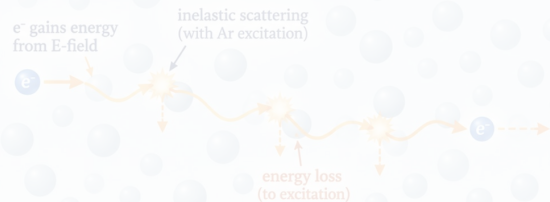
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electron cross-section on argon in gas and liquid



CHALLENGE

dense liquid Ar



HOW??

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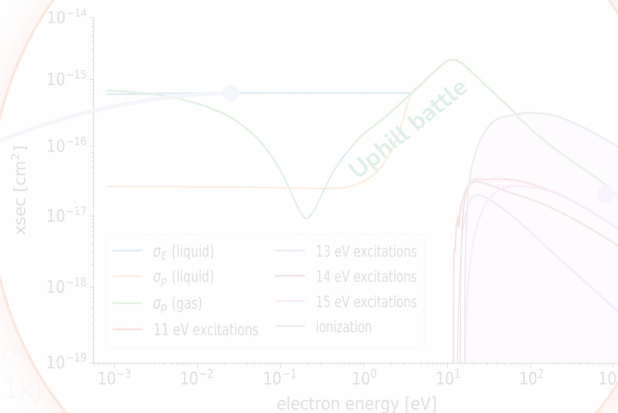


e-scale single-phase LArTPCs to hear recoil ionisation signatures

Why CEvNS in LAr?

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- To fully exploit it we need the recoils
- In argon, CEvNS recoils are short producing only $O(10s-100)$ e^-
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electron cross-section on argon in gas and liquid



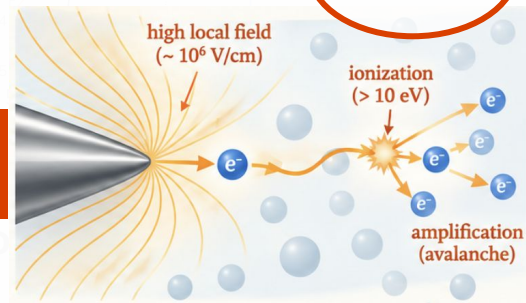
HOW??

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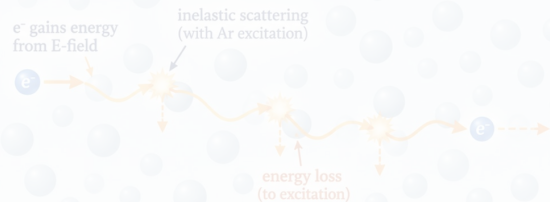
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CHALLENGE

SPOILER:
MAKE REALLY POINTY TIPS!



dense liquid Ar



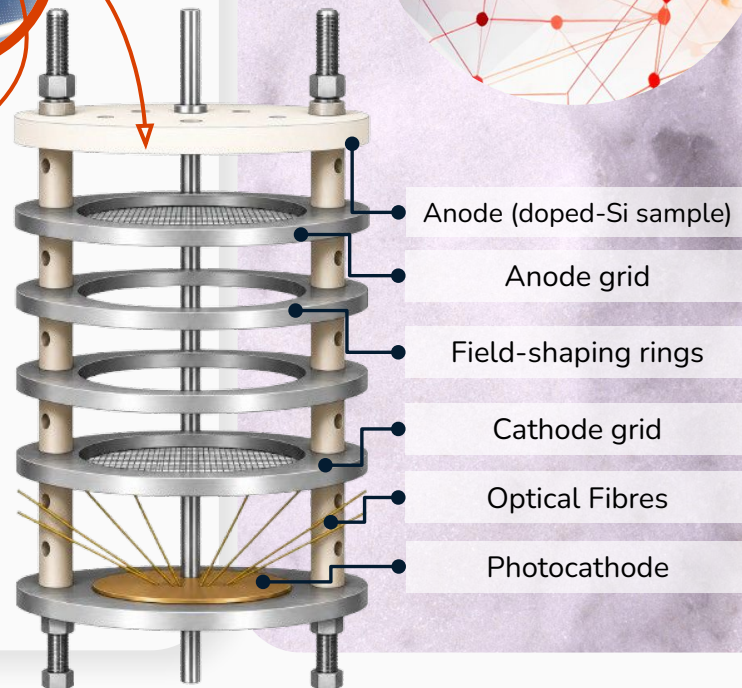
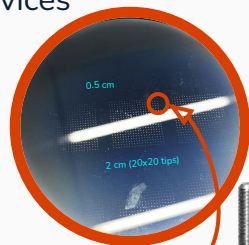
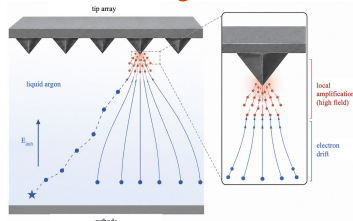
LArCAdE

Liquid Argon Charge Amplification Devices

- A biased tip or array concentrates the **applied field** into a very small region near its surface.
- Photoelectrons launched from the cathode drift towards the collection electrode in gas or liquid argon.
- Cathode and anode waveforms allow charge collection and possible multiplication to be investigated.

CHALLENGE #2

→ The long-term target is **stable, repeatable** amplification in liquid argon.





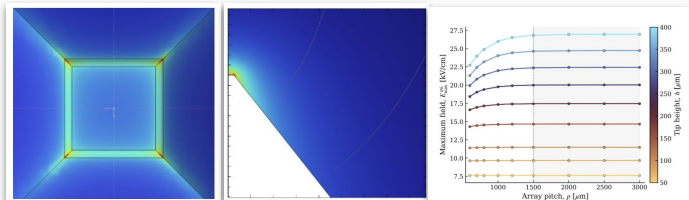
Simulation-informed design $\leftrightarrow$ Experimental Validation



Before we create the tips, we must understand the kind of geometries capable of producing amplification

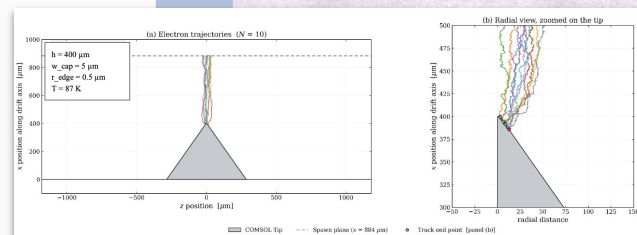
COMSOL solves for the electrostatic potential and field distribution around candidate tip geometries.

Field enhancement is controlled by tip height, cap width, edge rounding and the surrounding electrode configuration.



The interface connects fabrication-informed geometries to microscopic charge-transport trajectories in nonuniform fields.

TRANSLATE² propagates individual electrons through exported field maps using a time-domain Monte Carlo treatment of transport and collisions.



A Brief Historical Context

Earlier
the BN

Blanche @Fermilab

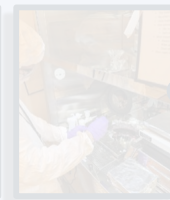
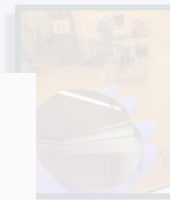
... needles and silicon-based tip structures developed with
... materials Chlorine-based reactive-ion etching (RIE)



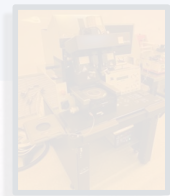
5.0kV 3.0mm x2.00k SE(M) 20.0um



LArCADE



Photolithography



Chromium deposition & lift-off
deposited by electron-beam evaporation

Metal
sputtering



Dry Etching &
Sputtering

For conductivity
but adds
fabrication
complexity

... model predictions and motivated
... informed route.

A Brief Historical Context

Earlier
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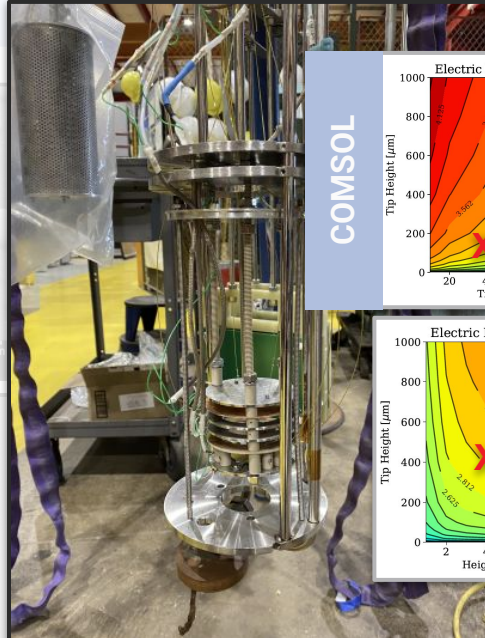
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Photolithography

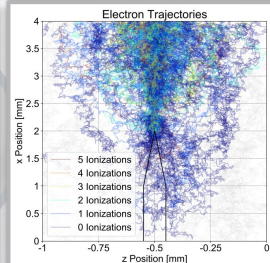
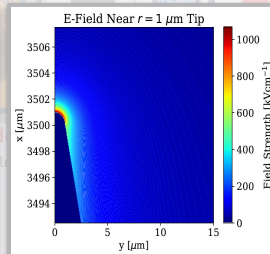
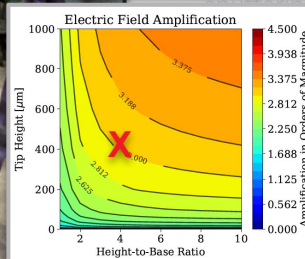
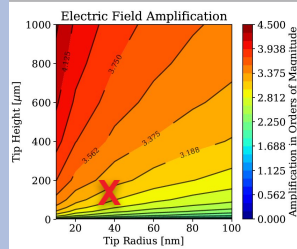


5.0kV 3.0mm x2.00k SE(M)

20.0um



COMSOL



TRANSLATE

LArCADE

model predictions and
informed route.

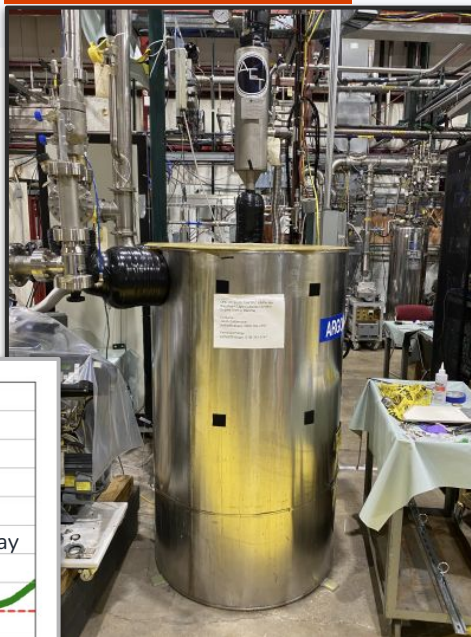
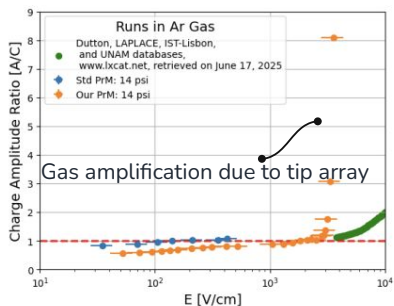
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Earlier
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Blanche @Fermilab

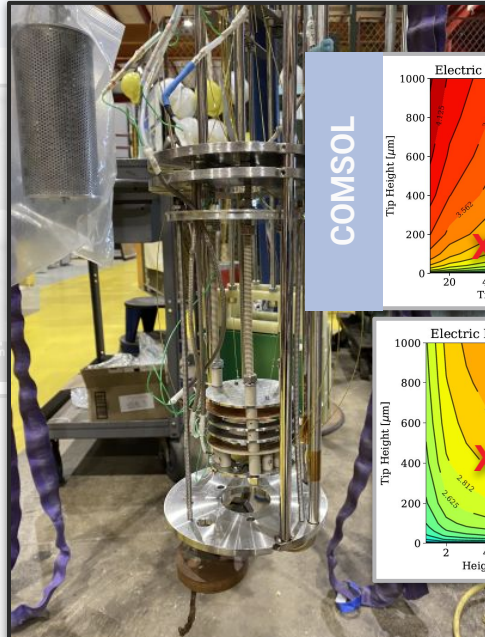
silicon-based tip structures developed with
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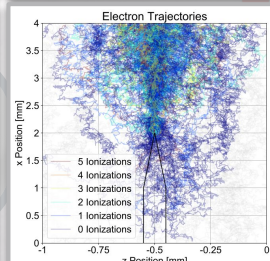
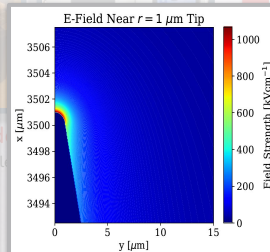
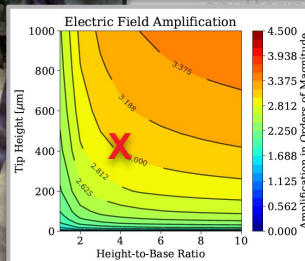
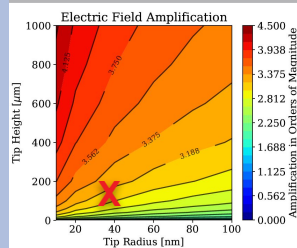


5.0kV 3.0mm x2.00k SE(M)

20.0um



COMSOL



TRANSLATE

a search

LArCADE

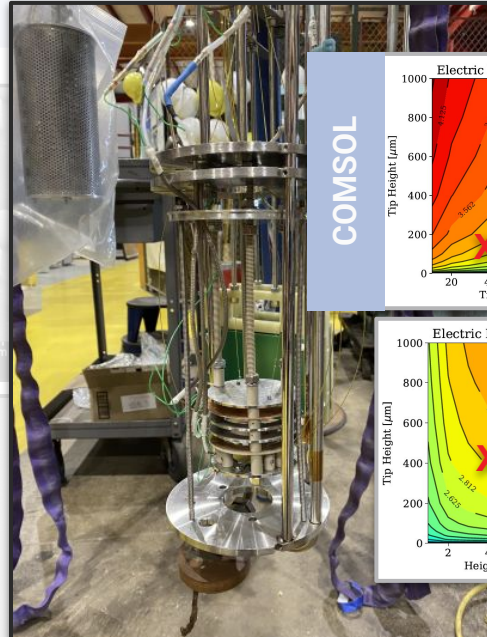
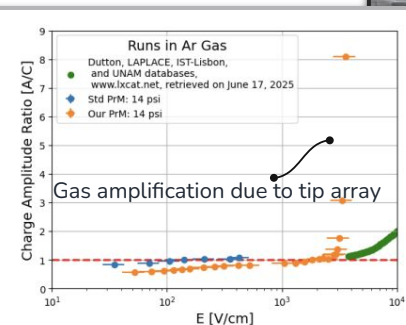
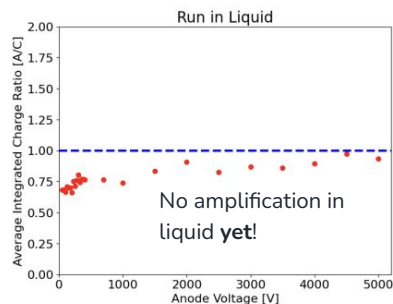
model predictions and
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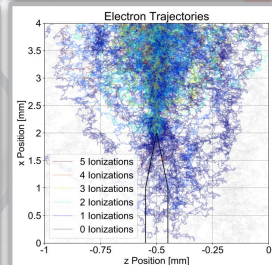
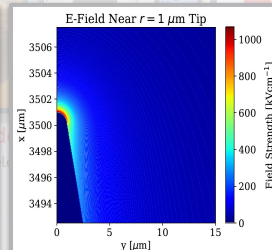
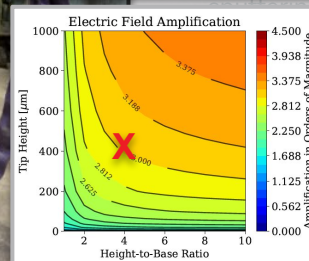
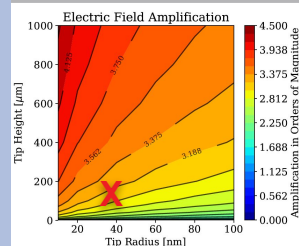
Blanche @Fermilab

Earlier needles and silicon-based tip structures developed with materials Chlorine-based reactive-ion etching (RIE)

Photolithography



COMSOL



TRANSLATE

LArCADE

A Brief Historical Context

- Earlier LARCADE studies explored metal needles and silicon-based tip structures developed with the BNL Center for Functional Nanomaterials using Chlorine-based reactive-ion etching (RIE)



Photolithography

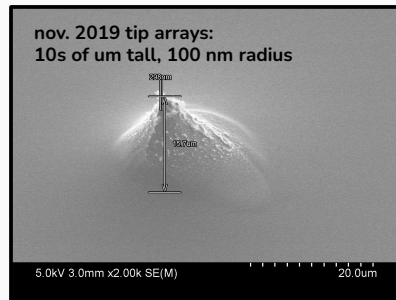
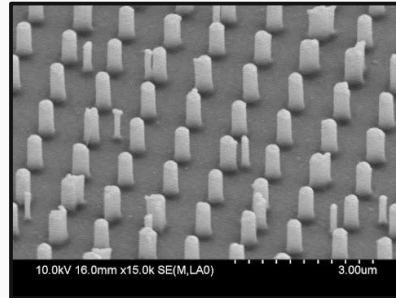
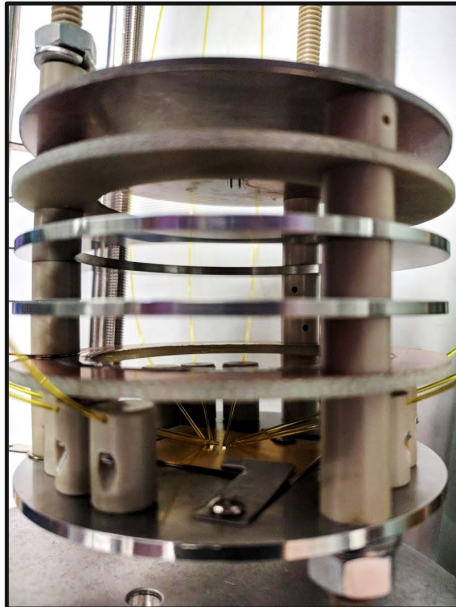


Chromium deposition & lift-off

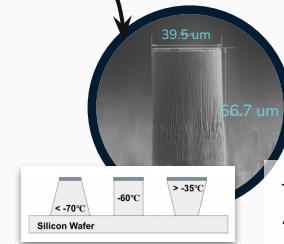
Metal sputtering

Etching & Sputtering

For conductivity but adds fabrication complexity



The realised tip shapes and dimensions varied across devices and could differ substantially from idealised simulation geometries.

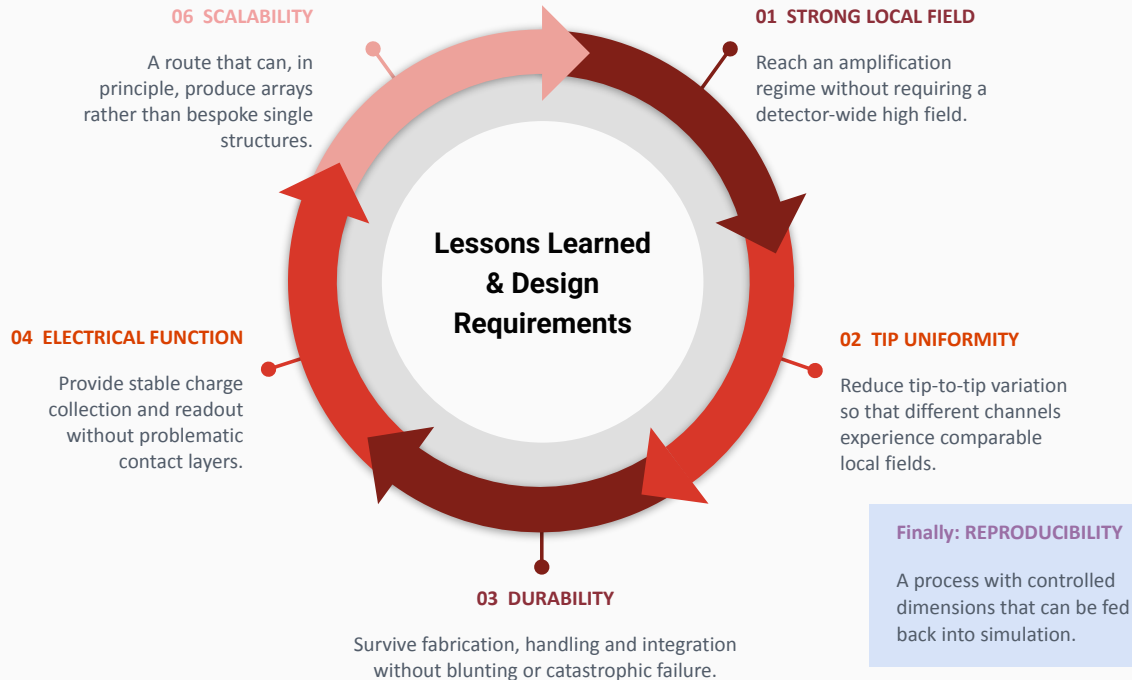


doped-Si substrate

Target: $\geq 100 \mu\text{m}$ | Achieved: $\sim 40 \mu\text{m}$

This limited direct comparisons with model predictions and motivated a search for a more uniform, fabrication-informed route.

What must a next-generation electrode deliver?



These requirements motivate two coupled changes:

- (1) using **doped silicon** as the **electrode material** itself, and
- (2) exploiting **silicon crystallography** to obtain more controlled faceted tip geometries.

Finally: REPRODUCIBILITY

A process with controlled dimensions that can be fed back into simulation.

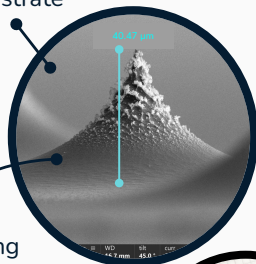
From Metallised Tips to Doped-Si Electrodes

EARLIER

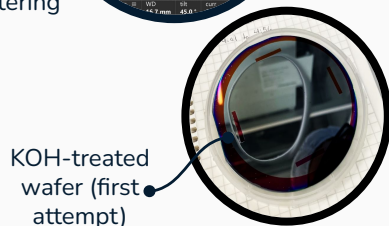
Metal needles / Si + sputtered metal

Extra metallisation and variable tip morphology introduced practical challenges.

doped-Si substrate

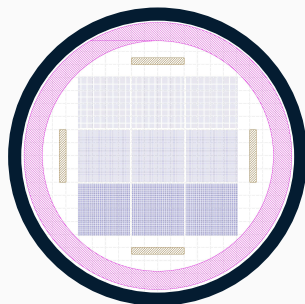


Metal sputtering



KOH-treated wafer (first attempt)

Mask design before etching

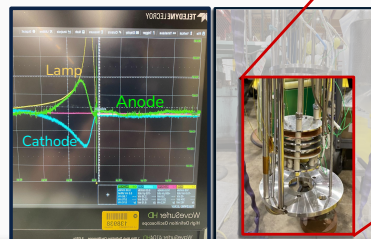
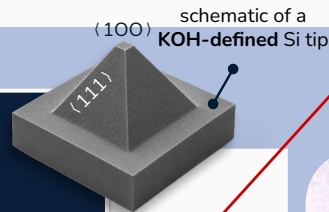


- $h = 100 \mu\text{m}$
20 x 20
1 mm tip-tip
- $h = 100 \mu\text{m}$
100 x 100
200 μm tip-tip
- $h = 400 \mu\text{m}$
25 x 25
800 μm tip-tip

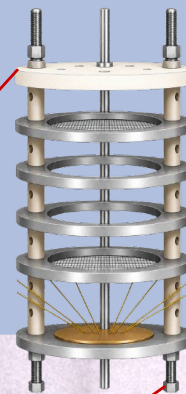
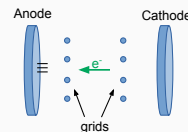
NEW DIRECTION

Doped Si as tip + electrode

Use the silicon itself as both structure and electrical collection surface.



Doped Si alone can produce clean, stable, reproducible photoelectron signals in vacuum!



- The initial signal test used a **500 μm-thick** p-doped wafer with nominal resistivity **0.001-0.005 Ω·cm**.
- This was a **feasibility observation** rather than a systematic characterisation or amplification measurement.
- It nonetheless motivates **removing the sputtered metal layer** and **treating doped Si itself as the collection electrode**.



Crystal-guided KOH Etching at UCSB

01 PROTECT THE WAFER

Deposit a thin silicon nitride (SiN) coating on BOTH sides of doped Si using PECVD.

The SiN film protects areas that must not be dissolved in KOH.

02 PRINT THE TIP PATTERN

03 DEVELOP THE PATTERN

04 OPEN THE HARD MASK

05 REMOVE THE RESIST

06 SCULPT THE SILICON

07 REVEAL & MEASURE

Crystal-guided KOH Etching at UCSB



02 PRINT THE TIP PATTERN

Spin on light-sensitive photoresist, then expose the tip-array pattern through a mask (MA6 aligner).

The mask determines where the future tips will be located.

03 DEVELOP THE PATTERN

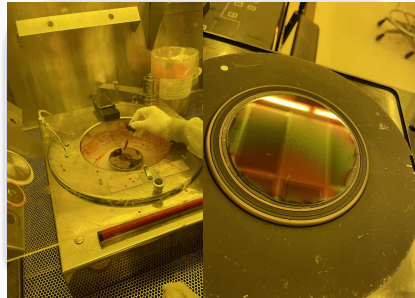
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Crystal-guided KOH Etching at UCSB



03 DEVELOP THE PATTERN

Wash away the exposed photoresist using AZ300MIF, revealing selected regions of SiN.

The remaining resist protects the SiN underneath.

04 OPEN THE HARD MASK

Use CF_4/O_2 plasma to remove exposed SiN; check the opening with Filmetrics.

Only these openings allow KOH to reach the silicon.

05 REMOVE THE RESIST

06 SCULPT THE SILICON

07 REVEAL & MEASURE

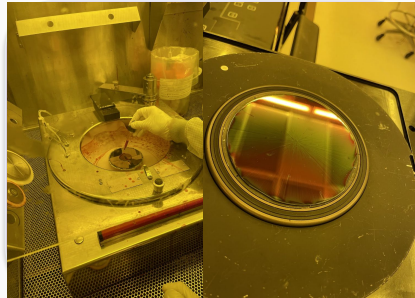
Crystal-guided KOH Etching at UCSB



05 REMOVE THE RESIST

Use a brief O_2 plasma clean, then acetone / IPA rinses to strip photoresist and residues.

The patterned SiN remains as the durable etch mask.



06 SCULPT THE SILICON

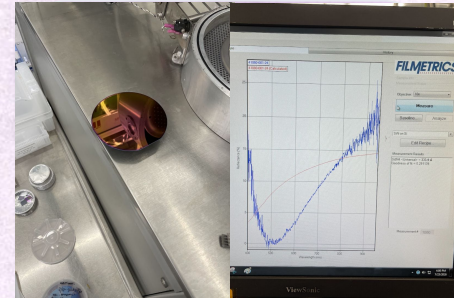
Immerse in 45% KOH at 87°C . Exposed Si dissolves; slow-etching $\{111\}$ planes define the sloped facets.

Rinse and inspect during etching; repeat if needed.

03 DEVELOP THE PATTERN

Wash away the exposed photoresist using AZ300MIF, revealing selected regions of SiN.

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07 REVEAL & MEASURE

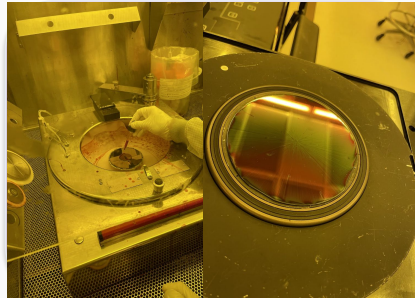
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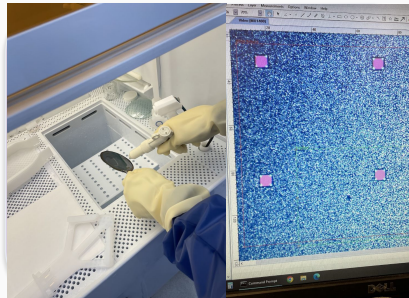
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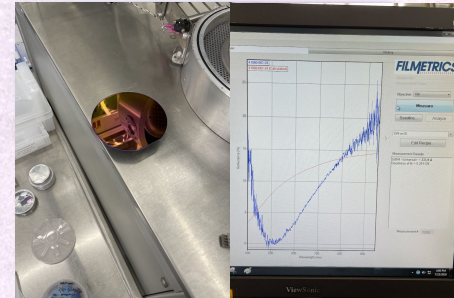
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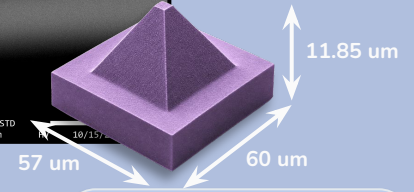
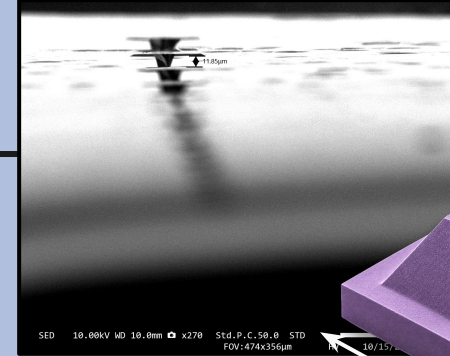
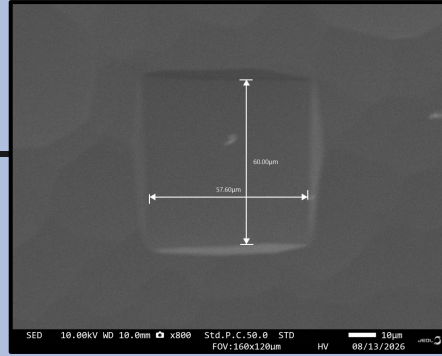
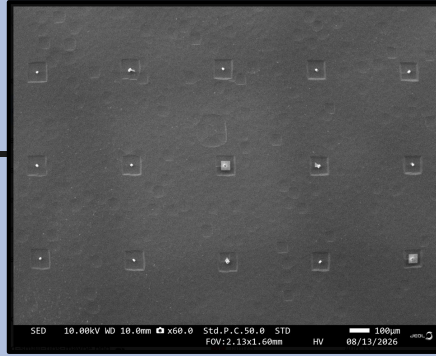
07 REVEAL & MEASURE

Rinse and dry; the traveller specifies a final buffered-HF SiN strip. Use microscopy / profilometry / SEM.

Measure height, cap width and uniformity before device testing.



Recent Fabrication Progress & Experimental Next Steps



NEW STRUCTURES

SEM geometry /
reproducibility



LArCADE TESTS

Charge collection /
possible gain /
stability



SIMULATION

COMSOL +
TRANSLATE
comparison

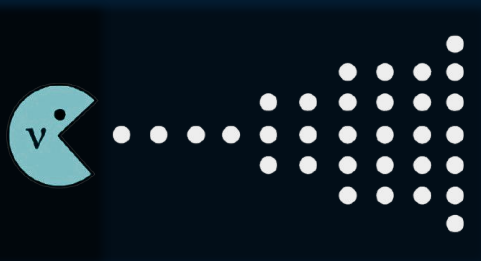


ITERATE

Geometry and process
refinement

- Early process development exposed **lithography**, **mask-integrity** and **etch-uniformity** challenges; the latest SEMs demonstrate progress!
- The **as-fabricated dimensions** have not yet been rerun in simulations → that is a natural next step once dimensional metrology is consolidated.

Closing the loop between geometry, microphysics and materials



GEOMETRY

COMSOL benchmarks
↔ fabrication-informed
tip arrays

MICROPHYSICS

TRANSLATE transport
↔ gain and
recombination

MATERIAL

MOSAIC doped-Si studies
↔ relaxation and pulse
formation

- Historical simulations and measurements **support the amplification concept**
 - Also show how **sensitive performance** is to the realised **geometry**.
- Crystallographically defined **KOH fabrication** provides a **more controlled** route to silicon tip arrays
 - Encouraging SEM evidence
- **Next steps** are to **mount** the new **electrodes**, measure **collection** / possible **gain** in the **LArCAdE** testbed and feed those results back into COMSOL + TRANSLATE.
- In parallel, **MOSAIC** extends the programme by asking whether **tunable semiconductor material properties** can themselves **shape signal formation**.



MOSAIC
Material-Oriented Signal Architecture
in Cryogenic Detectors

Backup

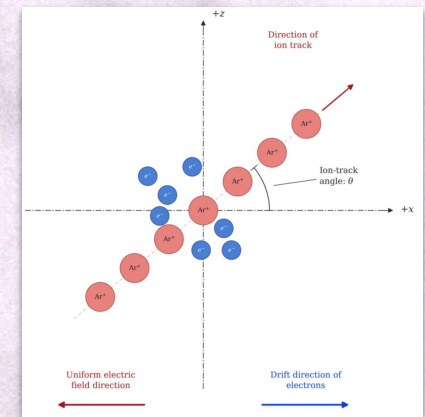
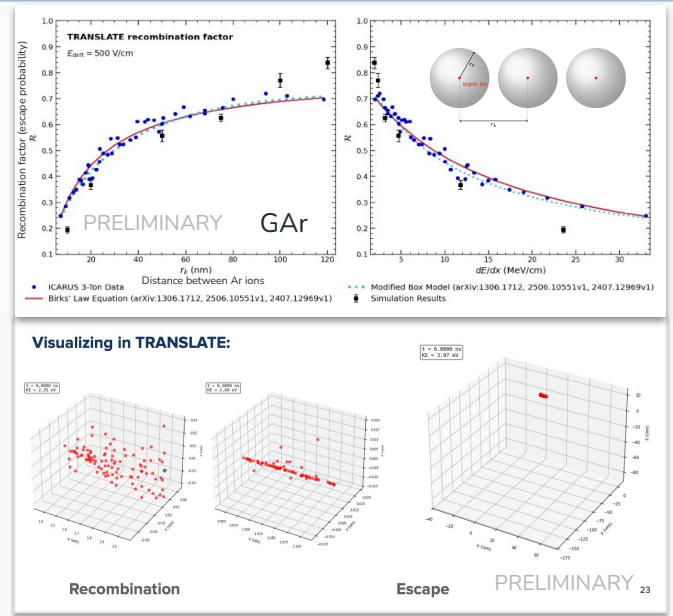
| CPAD 2026



More Recent TRANSLATE Updates



- **New microphysics:** TRANSLATE now includes the Coulomb fields of positive argon ions, allowing microscopic electron-ion recombination to be simulated.
- **Electron fate:** Individual electrons are propagated through collisions and classified as escaping the ionisation region or recombining.
- **Dependences:** The electron escape fraction depends on ionisation density (ion spacing), applied drift field and initial conditions.
- **Initial validation:** Comparisons with ICARUS 3-ton data reproduce the qualitative trends, but quantitative discrepancies remain.



Next steps:
 Refine the microphysics,
 investigate systematic effects and
 extend the treatment to realistic
 low-energy ionisation topologies.



Crystal-guided KOH Etching at UCSB

01 PROTECT THE WAFER

Deposit a thin silicon nitride (SiN) coating on BOTH sides of doped Si using PECVD.

The SiN film protects areas that must not be dissolved in KOH.

02 PRINT THE TIP PATTERN

Spin on light-sensitive photoresist, then expose the tip-array pattern through a mask (MA6 aligner).

The mask determines where the future tips will be located.

03 DEVELOP THE PATTERN

Wash away the exposed photoresist using AZ300MIF, revealing selected regions of SiN.

The remaining resist protects the SiN underneath.

04 OPEN THE HARD MASK

Use CF_4/O_2 plasma to remove exposed SiN; check the opening with Filmetrics.

Only these openings allow KOH to reach the silicon.

05 REMOVE THE RESIST

Use a brief O_2 plasma clean, then acetone / IPA rinses to strip photoresist and residues.

The patterned SiN remains as the durable etch mask.

06 SCULPT THE SILICON

Immerse in 45% KOH at 87°C . Exposed Si dissolves; slow-etching {111} planes define the sloped facets.

Rinse and inspect during etching; repeat if needed.

07 REVEAL & MEASURE

Rinse and dry; the traveller specifies a final buffered-HF SiN strip. Use microscopy / profilometry / SEM.

Measure height, cap width and uniformity before device testing.