Critical Measurements & Technological Advancements on the path to DUNE

Elena Gramellini, Lederman Fellow

Sept 23rd, 2021

Rising Star Symposium

Warning!!!

Warning!!!

This talk contains ghosts…

Warning!!!

This talk contains ghosts… and potatoes?!?

Warning!!!

This talk contains ghosts… and potatoes?!?

… it may get a bit weird...

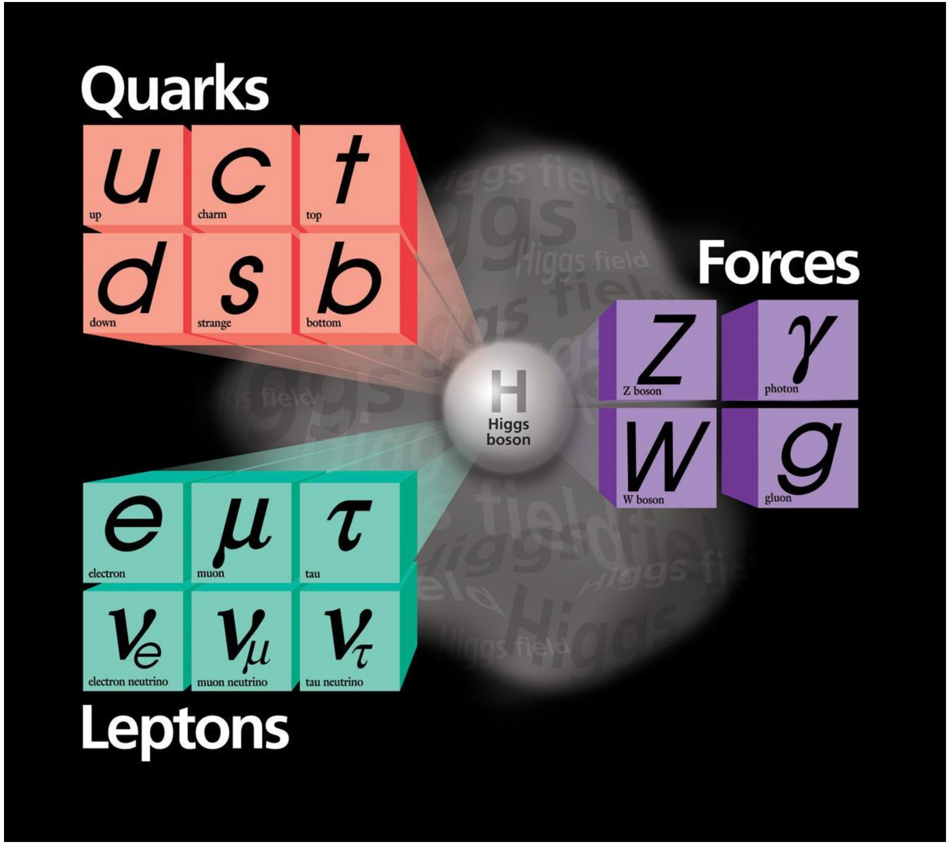
Why do we study neutrinos?

[The spoilsports of the Standard Model]

What’s the Standard Model?

The **Standard Model** is the theory describing the “micro-cosmos”:
the **building blocks of the universe** (particles!) and **their interactions** via the three fundamental forces.

The SM explains most of what we see, it works great: we have probed SM predictions with countless experimental tests, and they always passed with flying colors, until…



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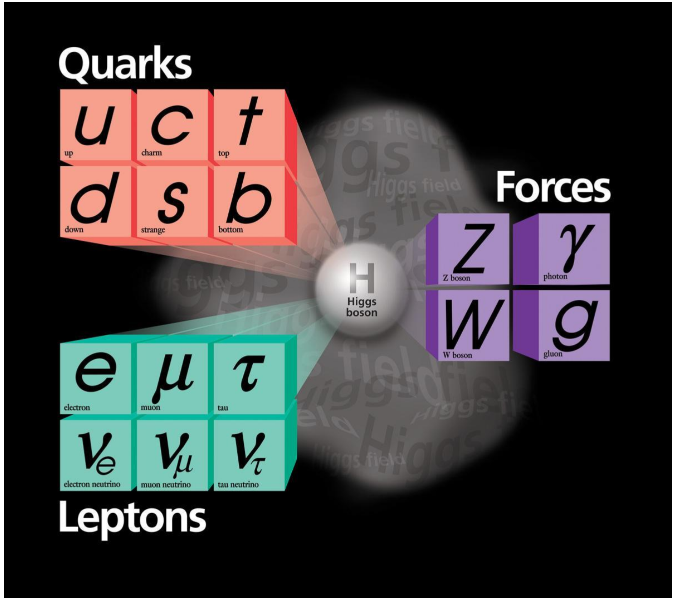

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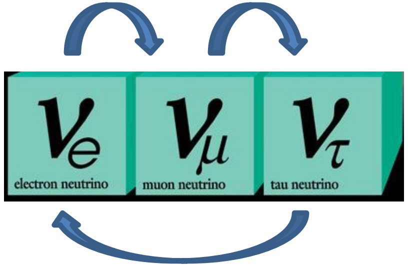
… neutrino oscillations.



Can happen only if ν are massive: first lab-based evidence of physics beyond the standard model

The Standard Model: that’s NOT all, folks!

Why do neutrinos have masses?
And why are they so surprisingly small?!?

Why is our universe made of matter?
CP-violation → matter-antimatter asymmetry

What’s Dark Matter? We know it exists...

Why do we have copies of the first family?

Is baryon number conservation even… a thing?

We know the Standard Model is not the end of the story, and yet
Beyond Standard Model Physics
has been very elusive...

… but we know what we don’t know:
we are pretty ignorant about neutrinos…
… and for good reasons: neutrinos are experimentally very challenging to study!

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They are **neutral**: we can’t directly detect them.
We can study them only if they interact, but…
neutrinos **don’t really like to interact**!
14 orders of magnitude less likely than a pion interaction!

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(shameless plug LArIAT’s latest paper on π interactions arxiv.2108.00040 submitted to PRD)

ν physics: what we know…

$\theta_{12}, \theta_{13}, \theta_{23}$ ✓

$\Delta m^2, \delta m^2$ ✓

$$\left.\begin{array}{l}\theta_{12}, \theta_{13}, \theta_{23} \\ \Delta m^2, \delta m^2\end{array}\right\}$$ Precision era (< 10%)

N_ν ✓ · · · · ▶ N Active: 3 ν

δ_{CP}

$\mathrm{sign}(\Delta m^2)$

α_1, α_2

m_x

p ∞?

ν physics: … and what we don't!

$\theta_{12}, \theta_{13}, \theta_{23}$	✓	Precision era (< 10%)
$\Delta m^2, \delta m^2$	✓	
N_ν	✓ ✗	N Active: 3 ν N sterile?
δ_{CP}	✗	Only hints
$\text{sign}(\Delta m^2)$	✗	
α_1, α_2	✗	No information
m_x	✗	Upper limits
p ∞?	✗	Upper limits

ν physics: … and what we don't!

$\theta_{12}, \theta_{13}, \theta_{23}$	✓	Precision era (< 10%)
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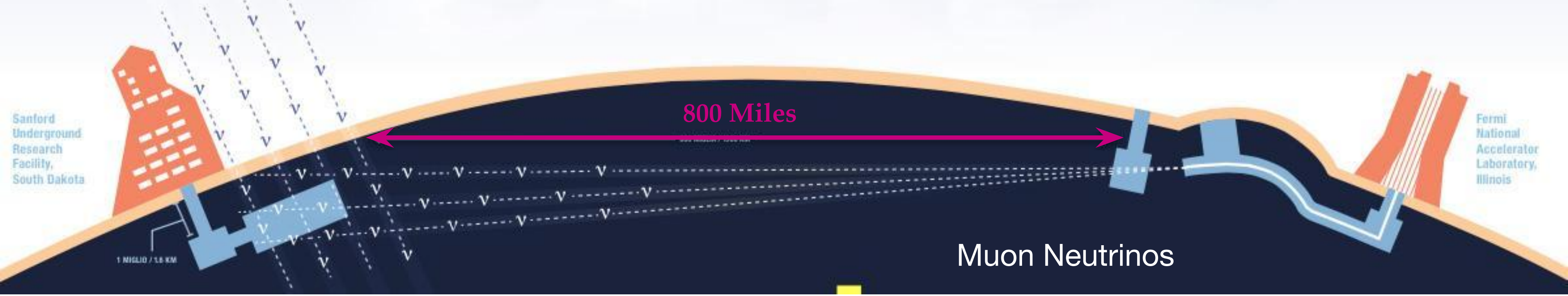
$\text{sign}(\Delta m^2)$		
α_1, α_2		
m_x		
p ∞?	✗	Upper limits

The detailed study of neutrino oscillations
in BIG UNDERGROUND DETECTORS
is
an extremely promising portal for new physics!

DUNE: the next big thing in neutrino physics



Burning Questions in ν Physics

- $\theta_{12}, \theta_{13}, \theta_{23}$
- $\Delta m^2, \delta m^2$
- N_ν
- δ_{CP}
- sign(Δm^2)
- α_1, α_2
- m_x
- p ∞?

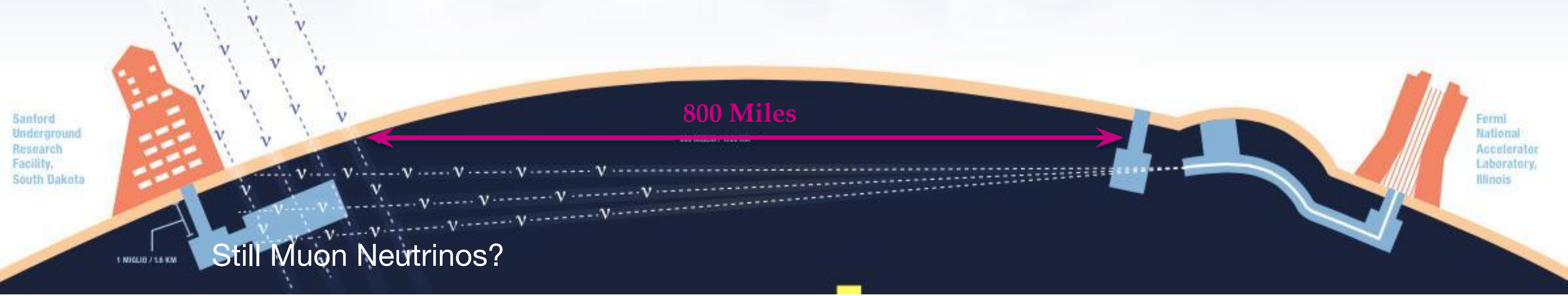
US flagship project in the HEP panorama:

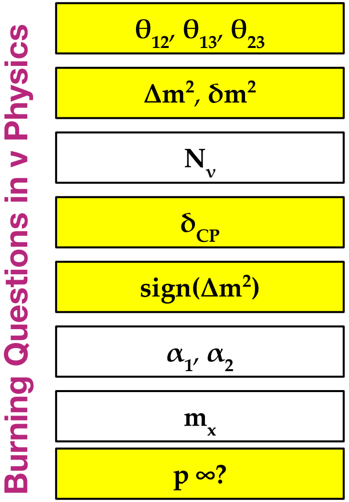
- → Precision Measurements of Neutrino Mixing
- → Explore CP violation in lepton sector
- → Neutrino Mass Hierarchy
- → Rare BSM processes & Low Energy physics (pdk, nnbar oscillations, SN)

Set to run for 10+ years starting in the late 2020s

Far Detector: 4 Gigantic Modules (10 kTon total) 1 mile underground

DUNE: the next big thing in neutrino physics





$\theta_{12}, \theta_{13}, \theta_{23}$

$\Delta m^2, \delta m^2$

N_ν

δ_{CP}

$\text{sign}(\Delta m^2)$

α_1, α_2

m_x

$p\ \infty?$

US flagship project in the HEP panorama:

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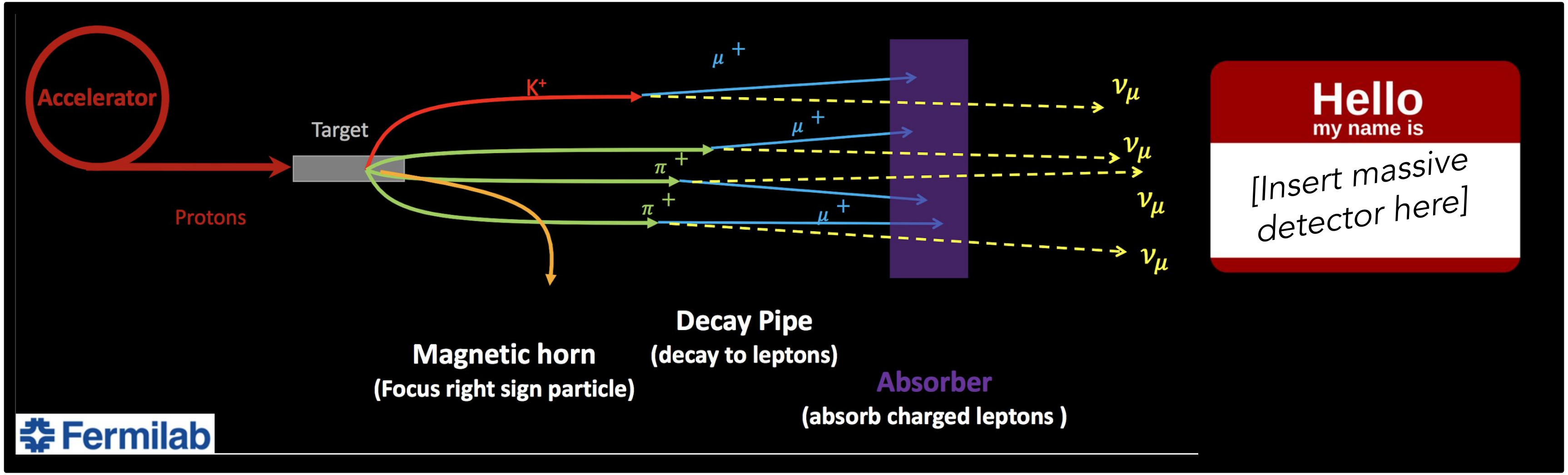
Main search: neutrino oscillations

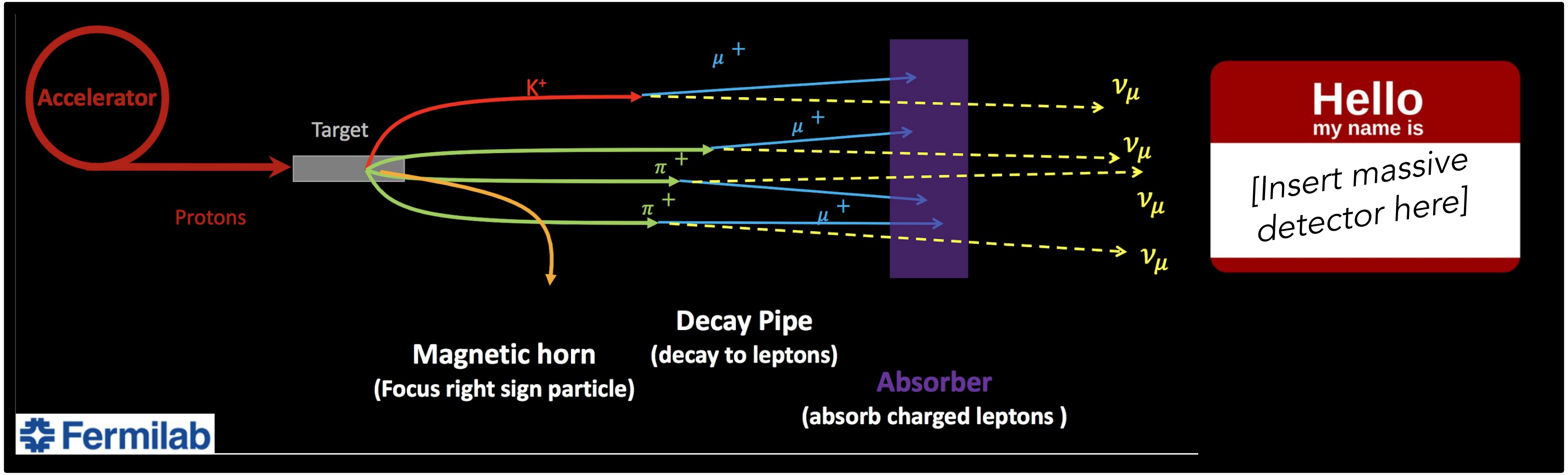
seeing electron (anti)neutrino appearing in a beam of muon (anti)neutrinos

Ingredients for a successful on-beam neutrino experiment



1. Know your neutrino flux → How many neutrinos were produced initially?
2. Know your detector → Understand well what your detector sees (and doesn't see)
3. Know you neutrino cross section → How many neutrinos were expected to interact w/o osc?

Ingredients for a successful on-beam neutrino experiment



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How do you catch a ghost? Who you gonna call?

For DUNE: Liquid Argon Time Projection Chambers!

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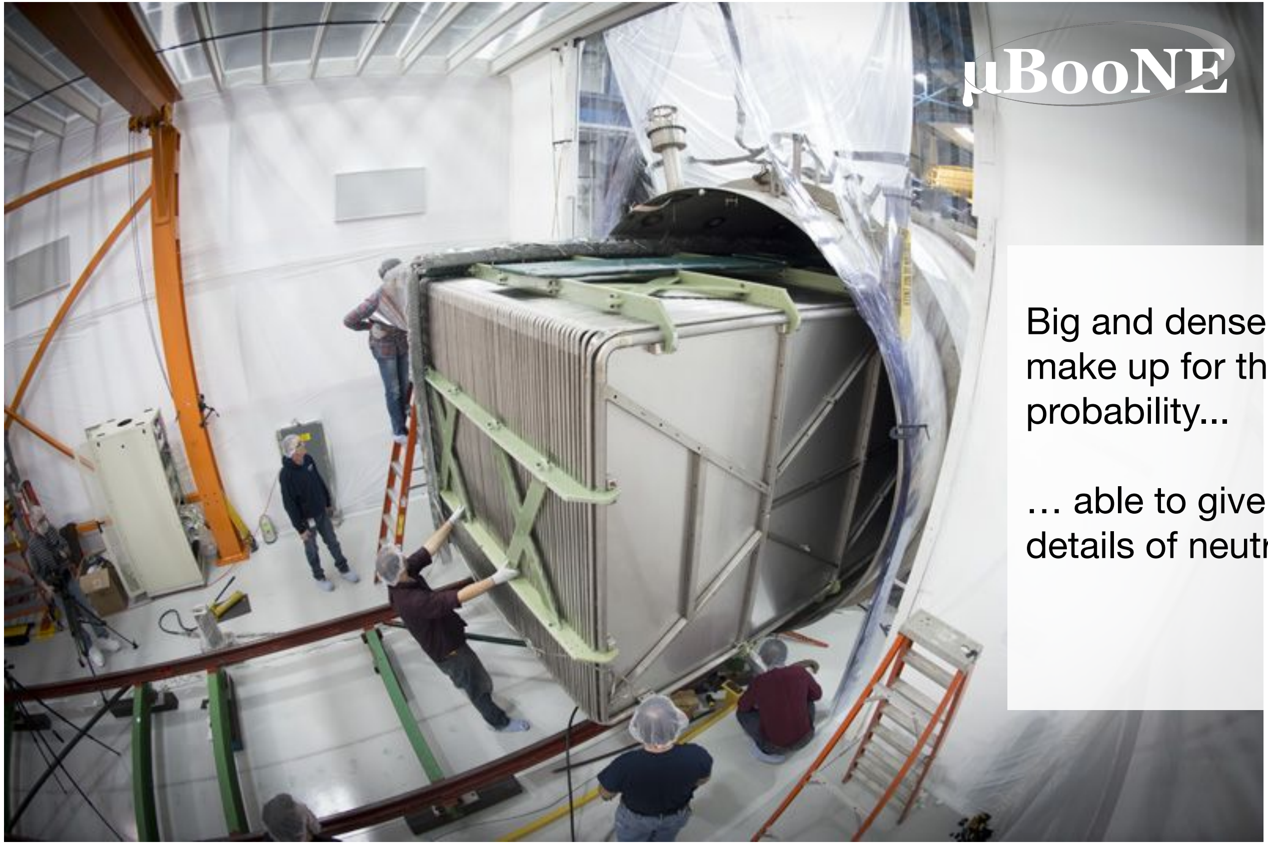
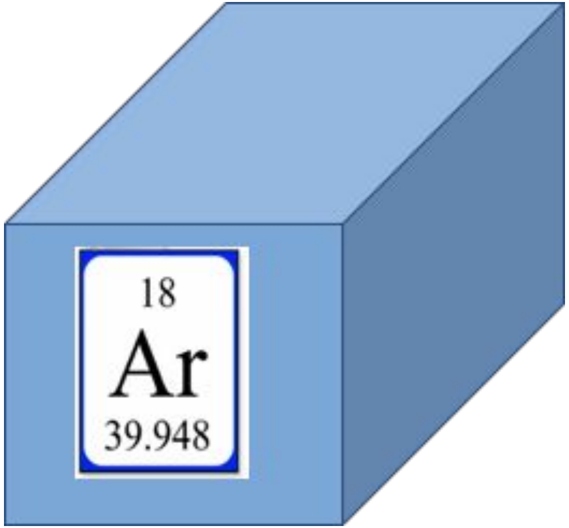


Big and dense detectors to make up for the small interaction probability...

… able to give unprecedented details of neutrino interactions.

Liquid Argon Time Projection Chamber: a crash course

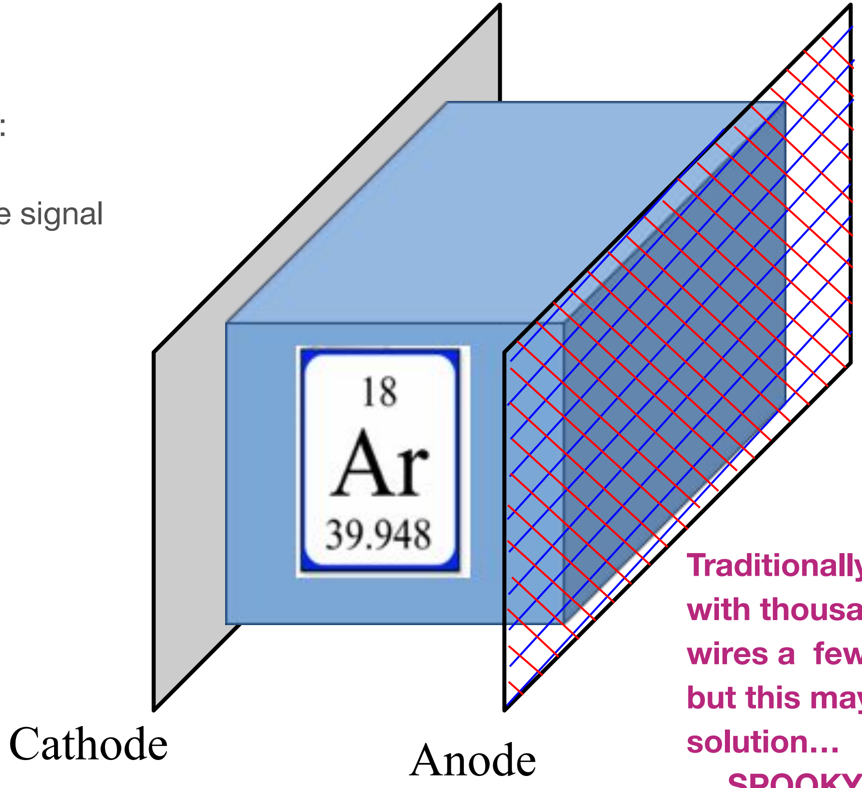
→ A block of Ar



Liquid Argon Time Projection Chamber: a crash course

→ A block of Ar

→ Sandwich it in a parallel planes capacitor:
  - Cathode at negative HV
  - Segmented anode to see the charge signal



Traditionally, 2 or more planes with thousands of parallel wires a few millimeters apart… but this may not be the best solution…

… SPOOKY foreshadow

Liquid Argon Time Projection Chamber: a crash course

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→ Sandwich it in a parallel planes capacitor:
  - Cathode at negative HV
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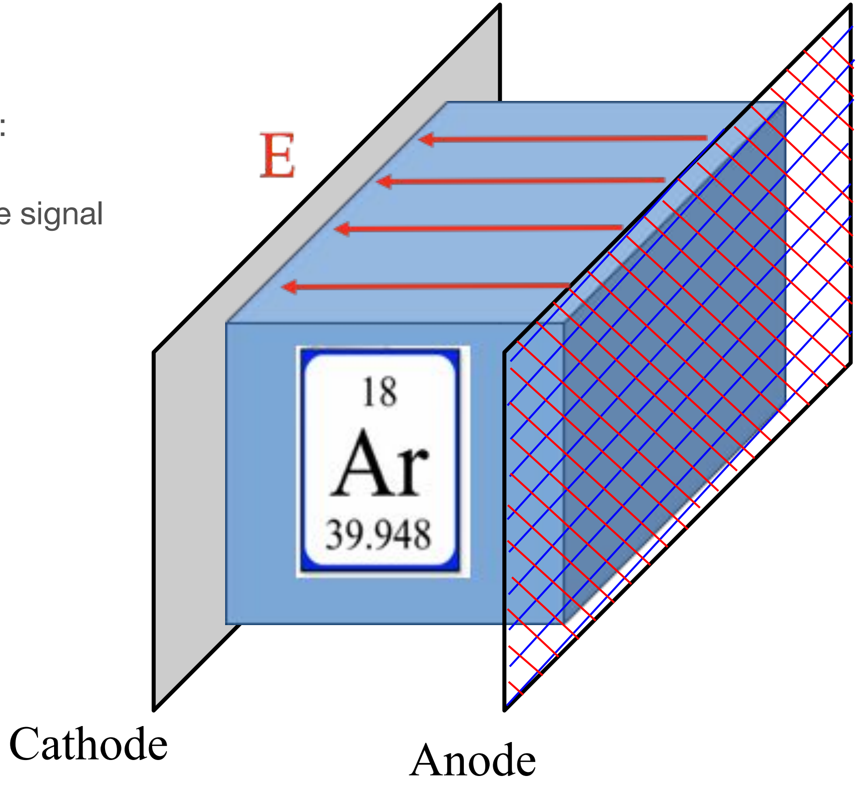
→ Create an electric field as uniform and as constant as possible



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→ A block of Ar

→ Sandwich it in a parallel planes capacitor:
  - Cathode at negative HV
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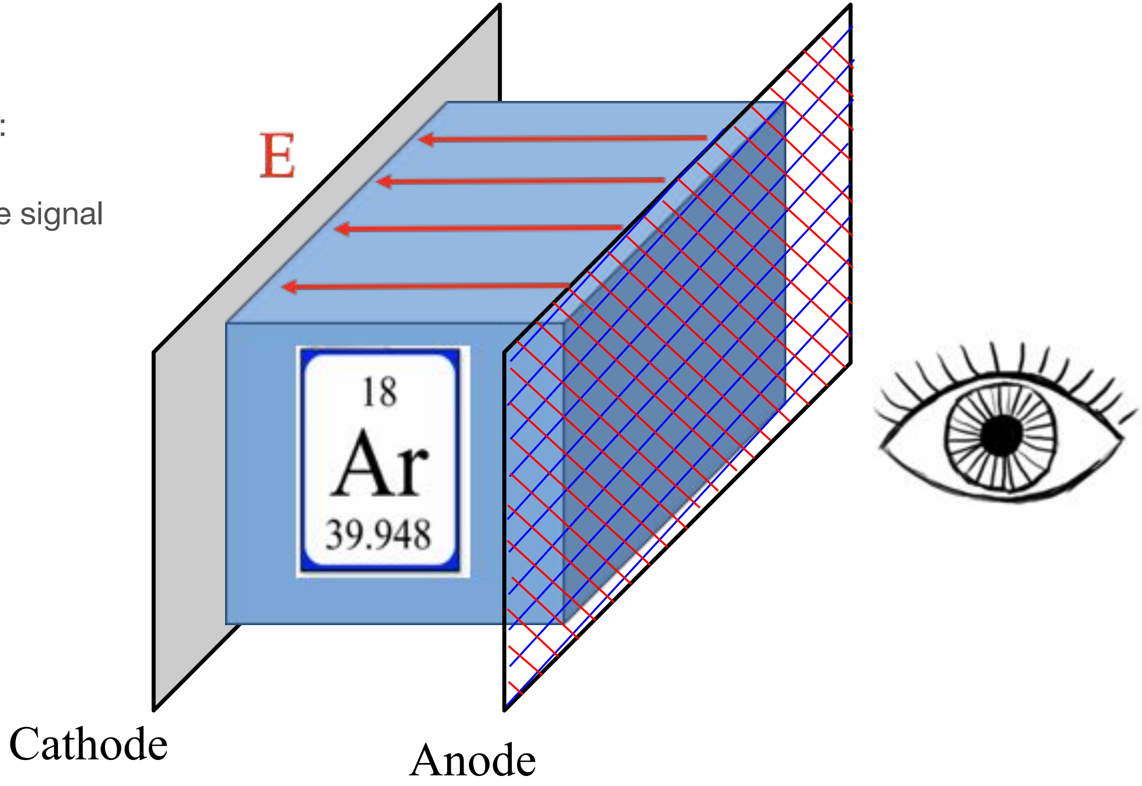
→ Create an electric field as uniform and as constant as possible

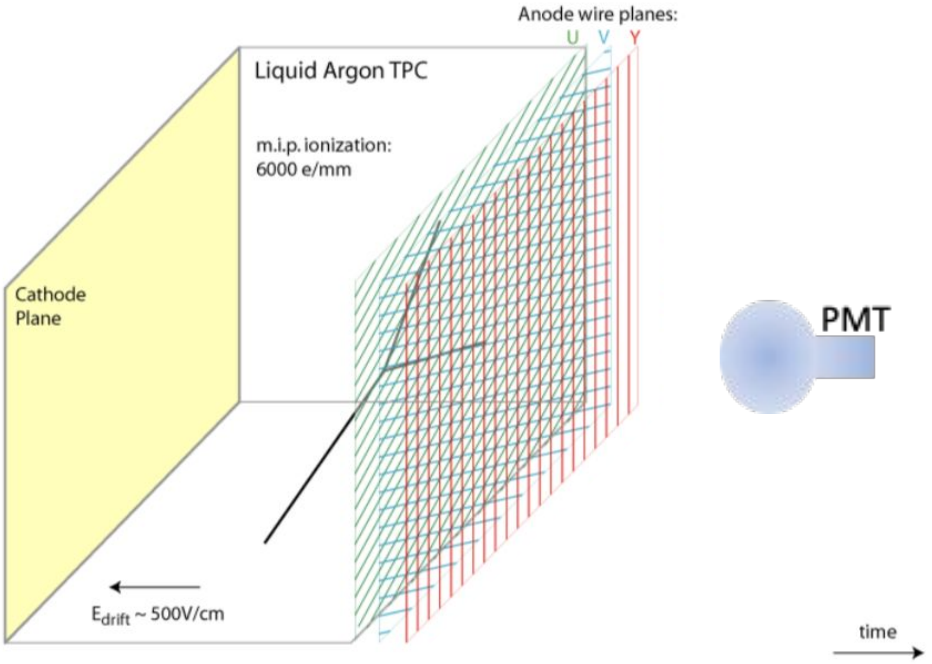
→ Equip with a light collection system (usually mounted behind the anode)



Liquid Argon Time Projection Chamber: Working Principles

1. Energy loss by charged particles:
   Ionization and
   Excitation of Ar

2. Prompt scintillation light emission by Ar_2^+ starts clock: the light arrives to the light collection system in matter of ns



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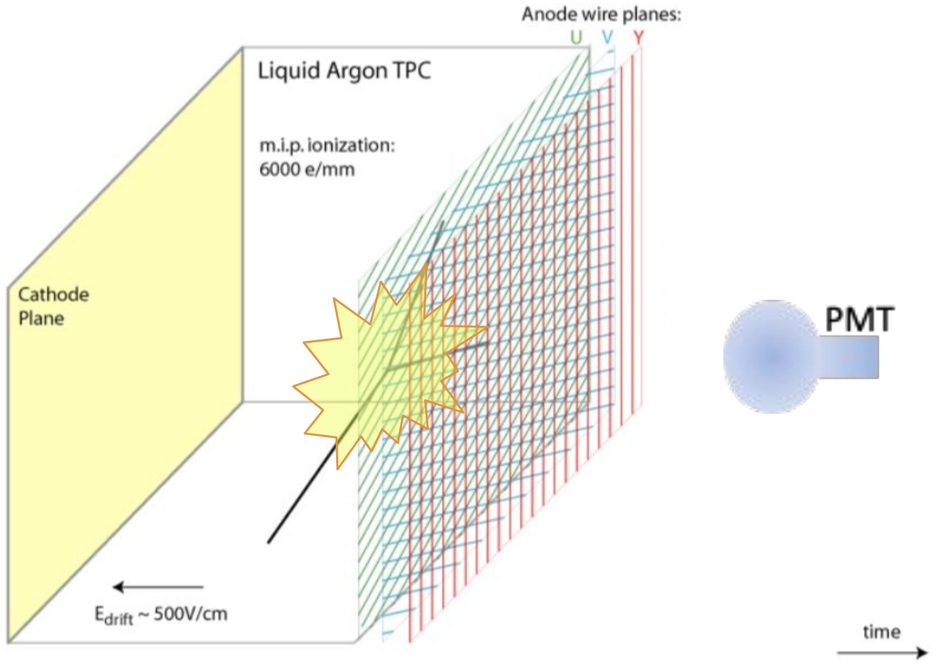

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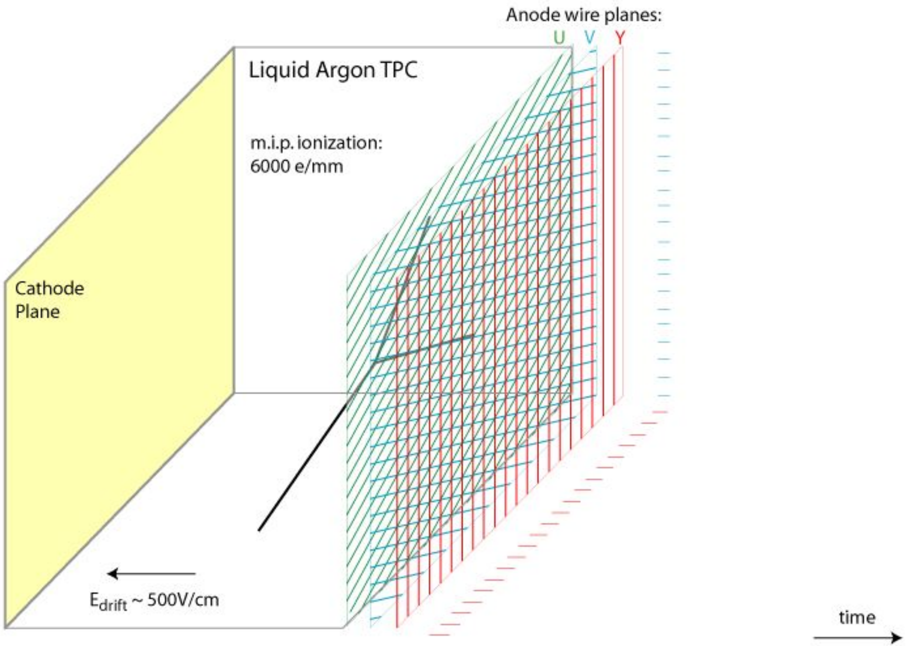
3. Electrons drift to anode: the charge arrives to the anode in matter of ms depending on detector size.
   (Ar^+ ions drift to cathode)

4. Moving electrons induce currents on wires

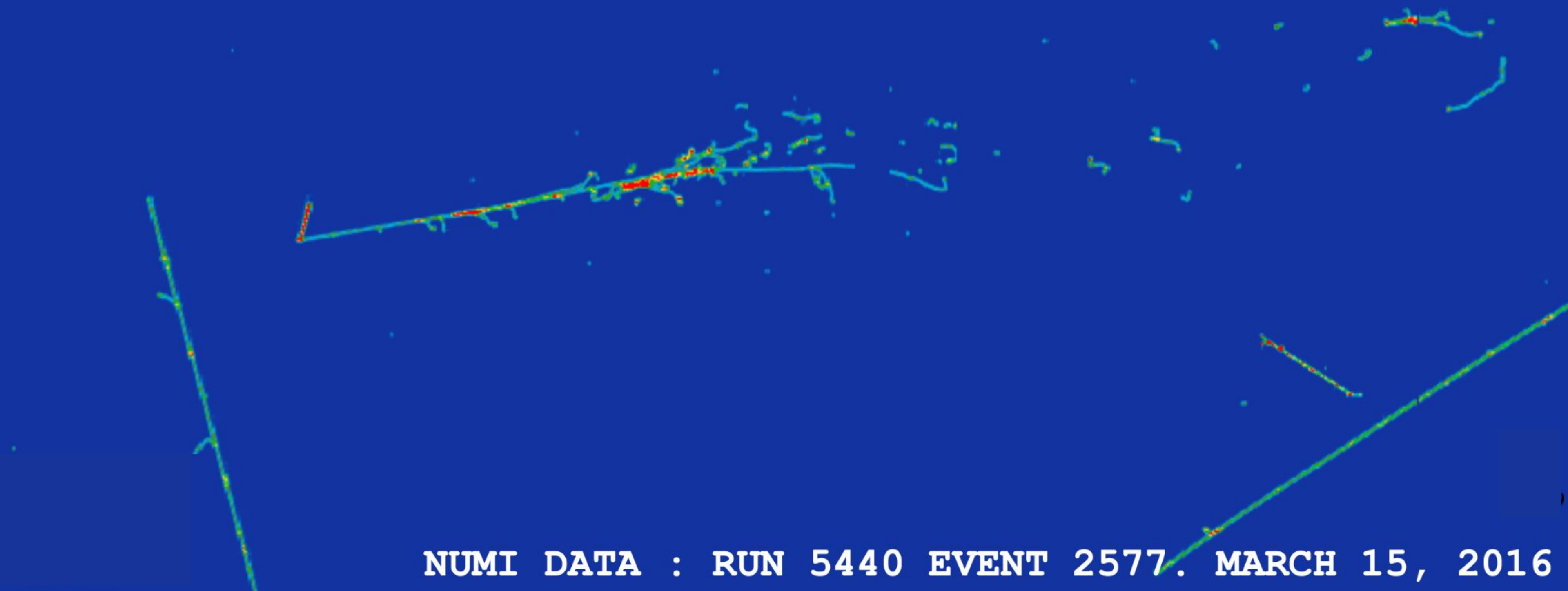
5. Tracks are reconstructed from wire signals and matched to form 3D images



LArTPC in action

Extremely detailed 3D images + calorimetry + PID:

unprecedented tool for neutrino interaction & BSM physics



µBooNE

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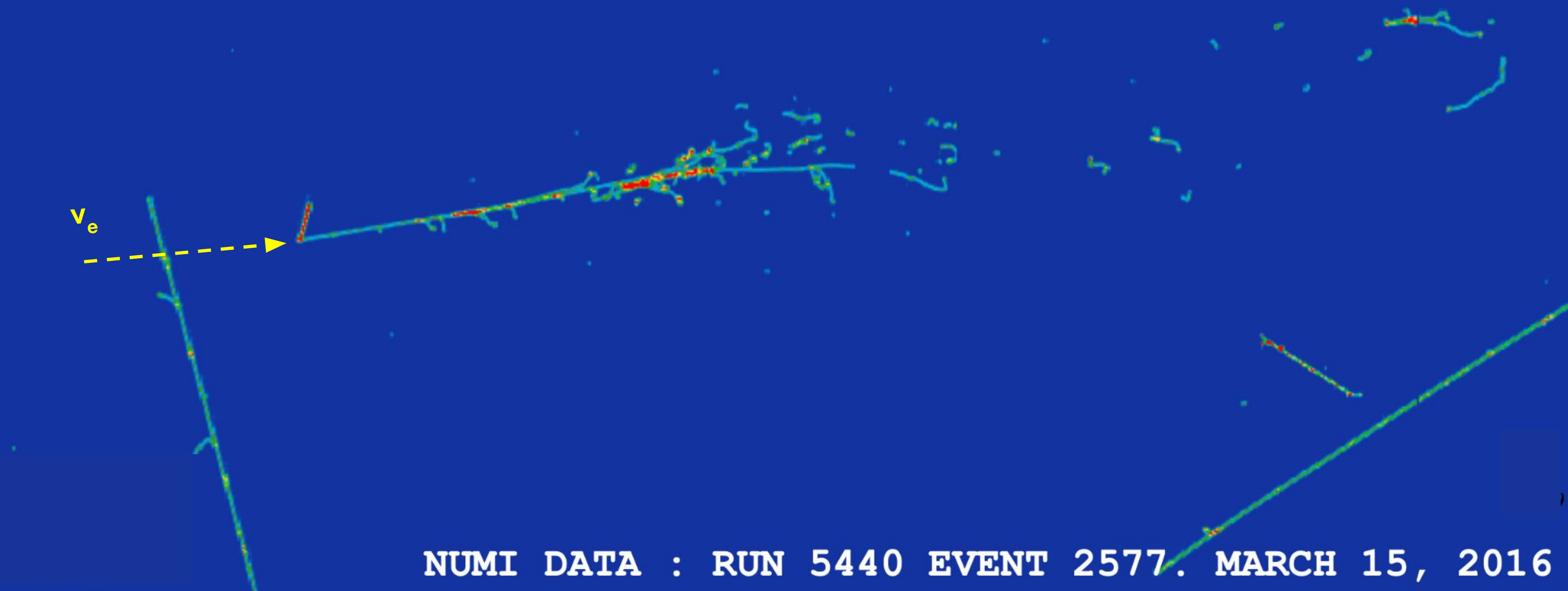

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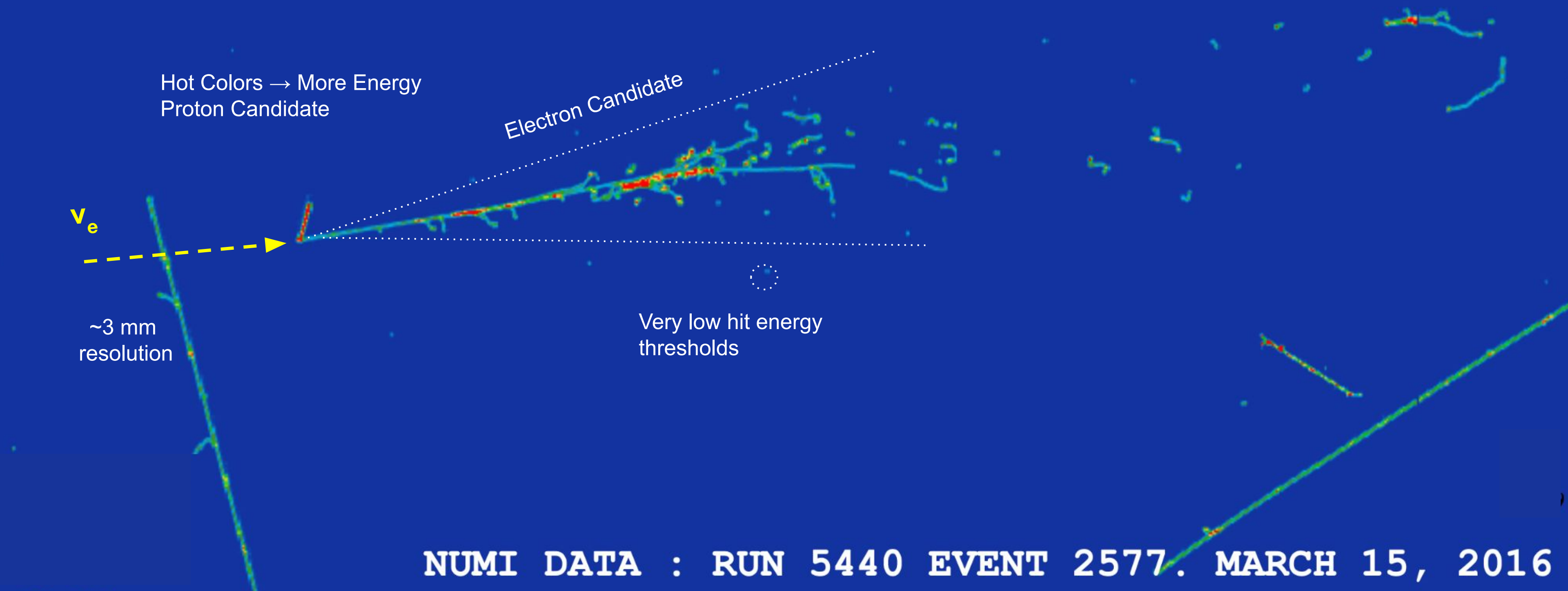


Hot Colors → More Energy
Proton Candidate

~3 mm
resolution

Very low hit energy
thresholds

MicroBooNE & SBN: physics on the path to DUNE

We are testing the detector capabilities by performing physics analyses in **Liquid Argon Time Projection Chambers** at FNAL.

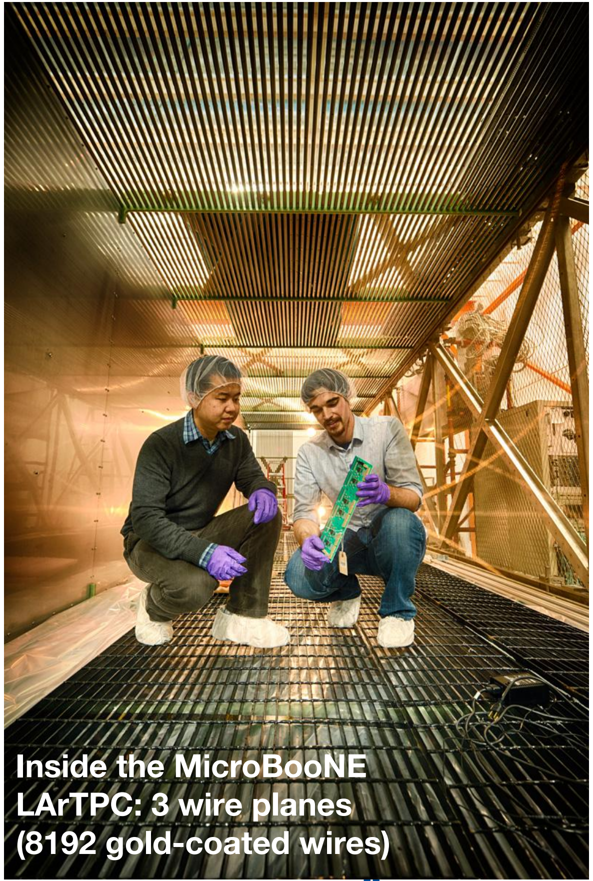
MicroBooNE collects neutrinos 2 beams: BNB and NuMI.

Completed 5 years physics runs: 2015-2021.

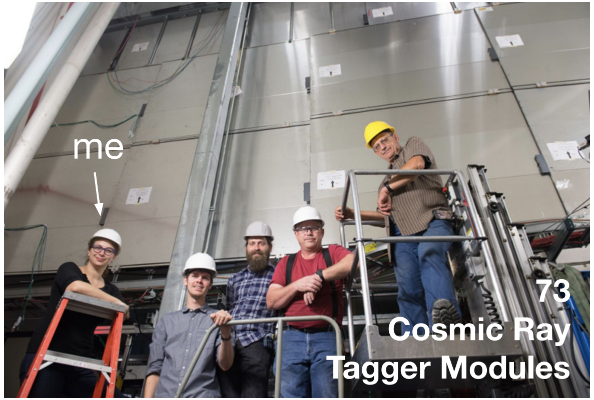
Largest neutrino-argon dataset available to date!

→ Do sterile neutrino exist?

→ Neutrino interactions: how do neutrinos look in a LArTPC?



Inside the MicroBooNE LArTPC: 3 wire planes (8192 gold-coated wires)



73 Cosmic Ray Tagger Modules

32 Photomultipliers

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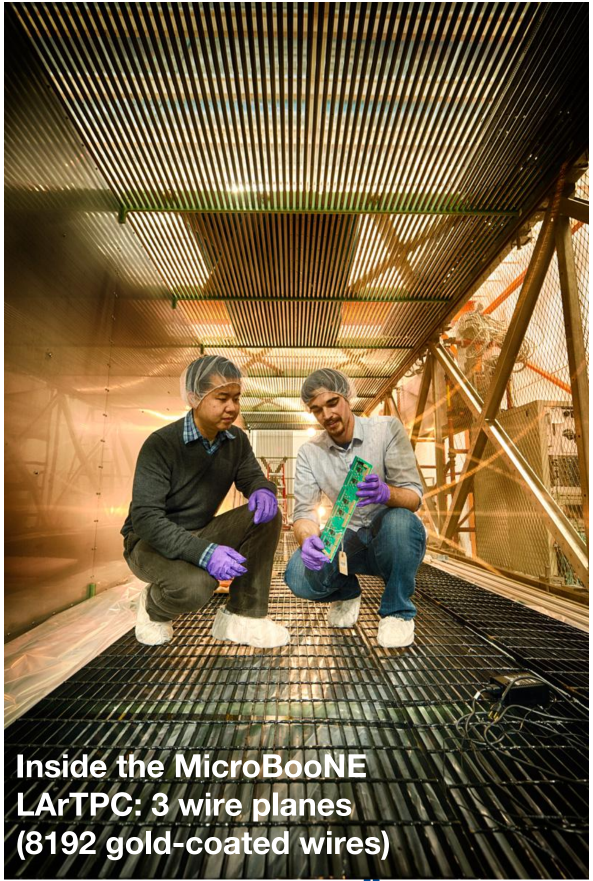

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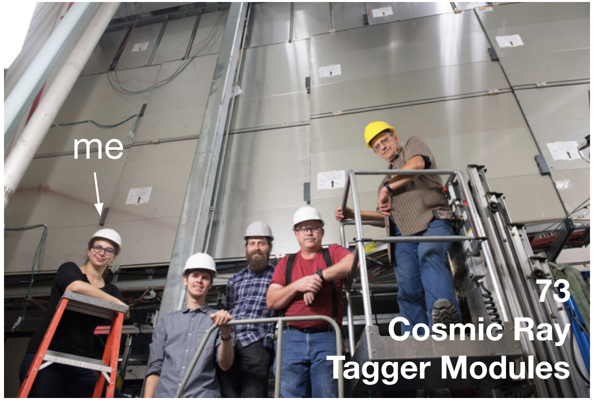

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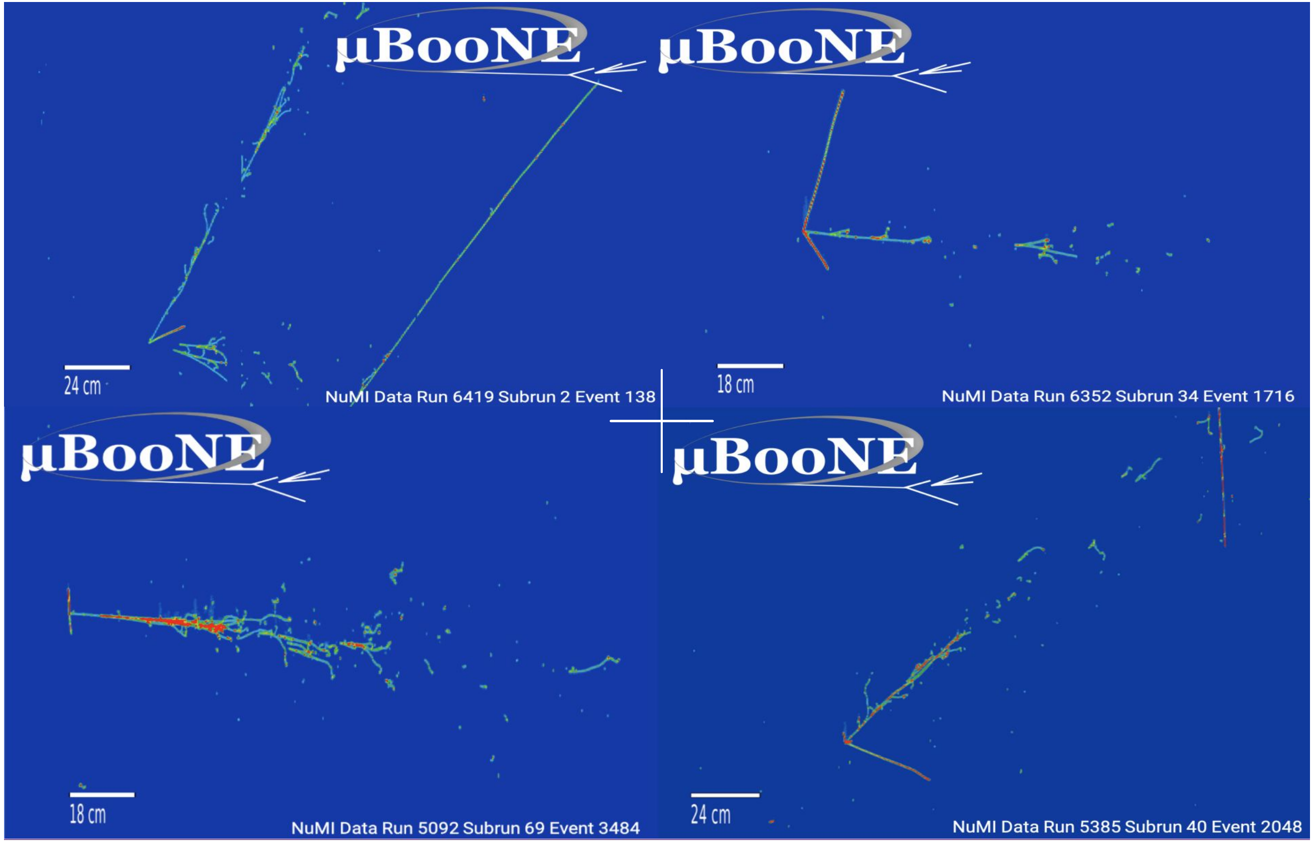
Key to DUNE & SBN Appearance Searches: See Electron Neutrinos



… and distinguish them from muon neutrino. This is not an easy task for 2 reasons:

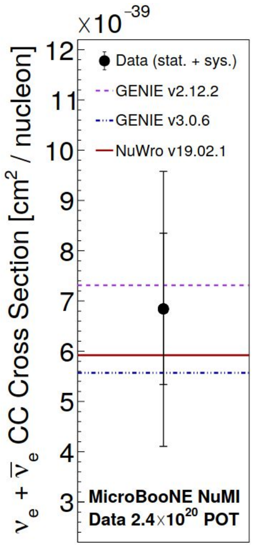
1. Neutrinos don’t interact in a vacuum!
They interact on the complex argon nucleus!
Counting correctly the number of ν_e interactions relies on the **nuclear model** adopted by the experiment.

We characterize this by performing crucial cross section measurements...

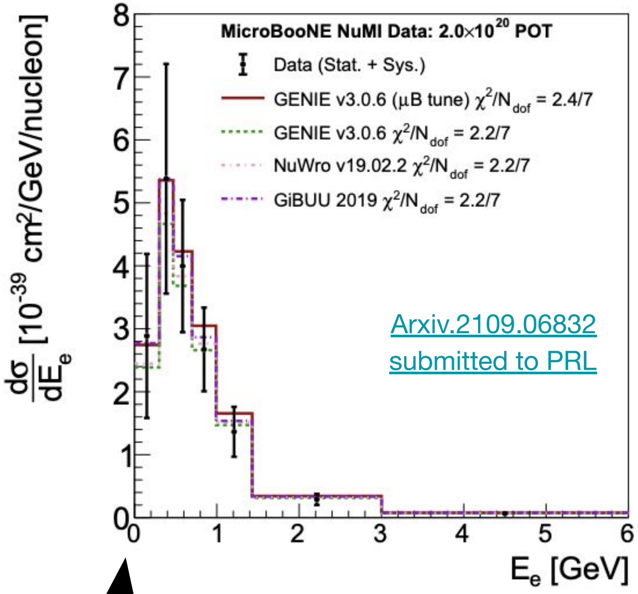
A Campaign to Scrutinize Electron Neutrino Interactions

The **NuMI group at MicroBooNE** is performing world-leading ν_e Cross Section Measurements on Ar

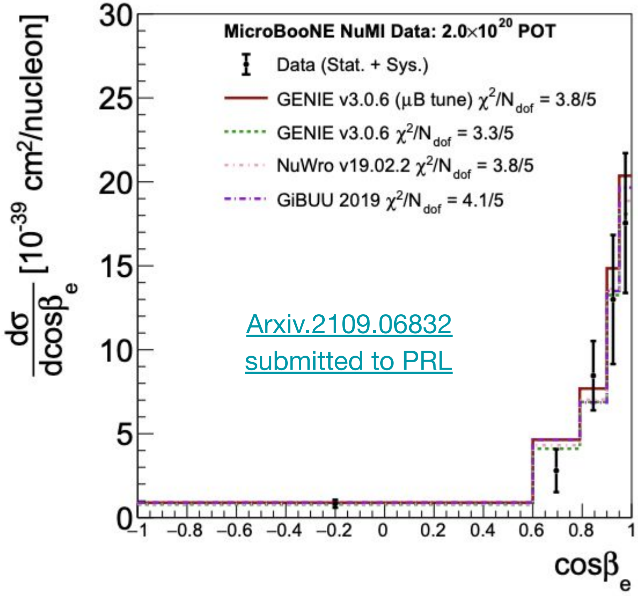
My team's 1st measurement: Flux Averaged Total ν_e Cross Section. Highest statistics sample to date.



[Phys. Rev. D.104.052002](https://doi.org/10.1103/PhysRevD.104.052002)



Arxiv.2109.06832
submitted to PRL



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Follow up: 1st Measurement of Inclusive ν_e and $\overline{\nu}_e$ CC differential in lepton energy and full angle coverage on Argon.

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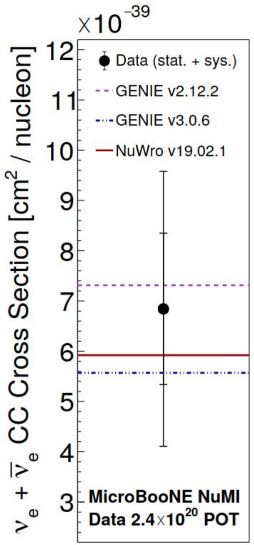

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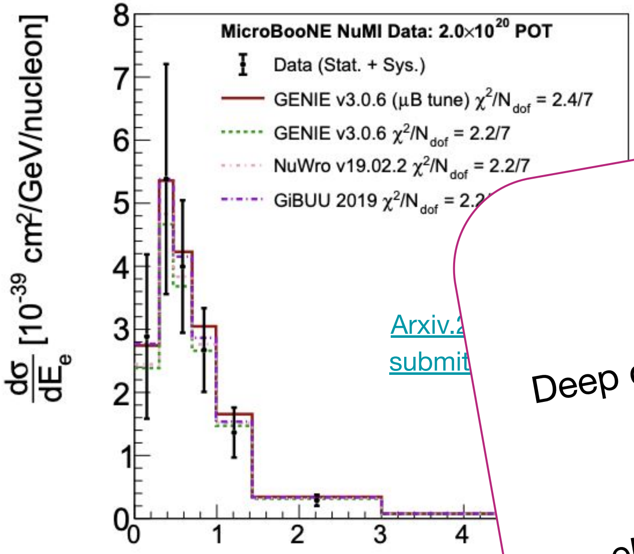
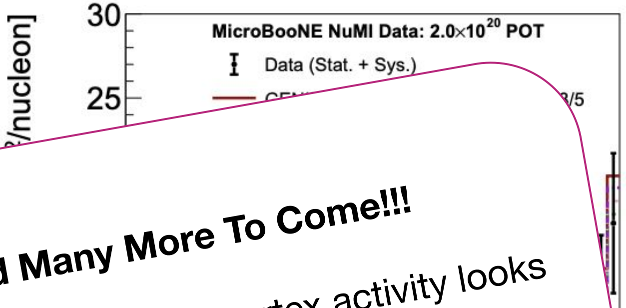


Arxiv.2
submit

Follow up: 1st Mea



erential in
angle coverage on Argon.

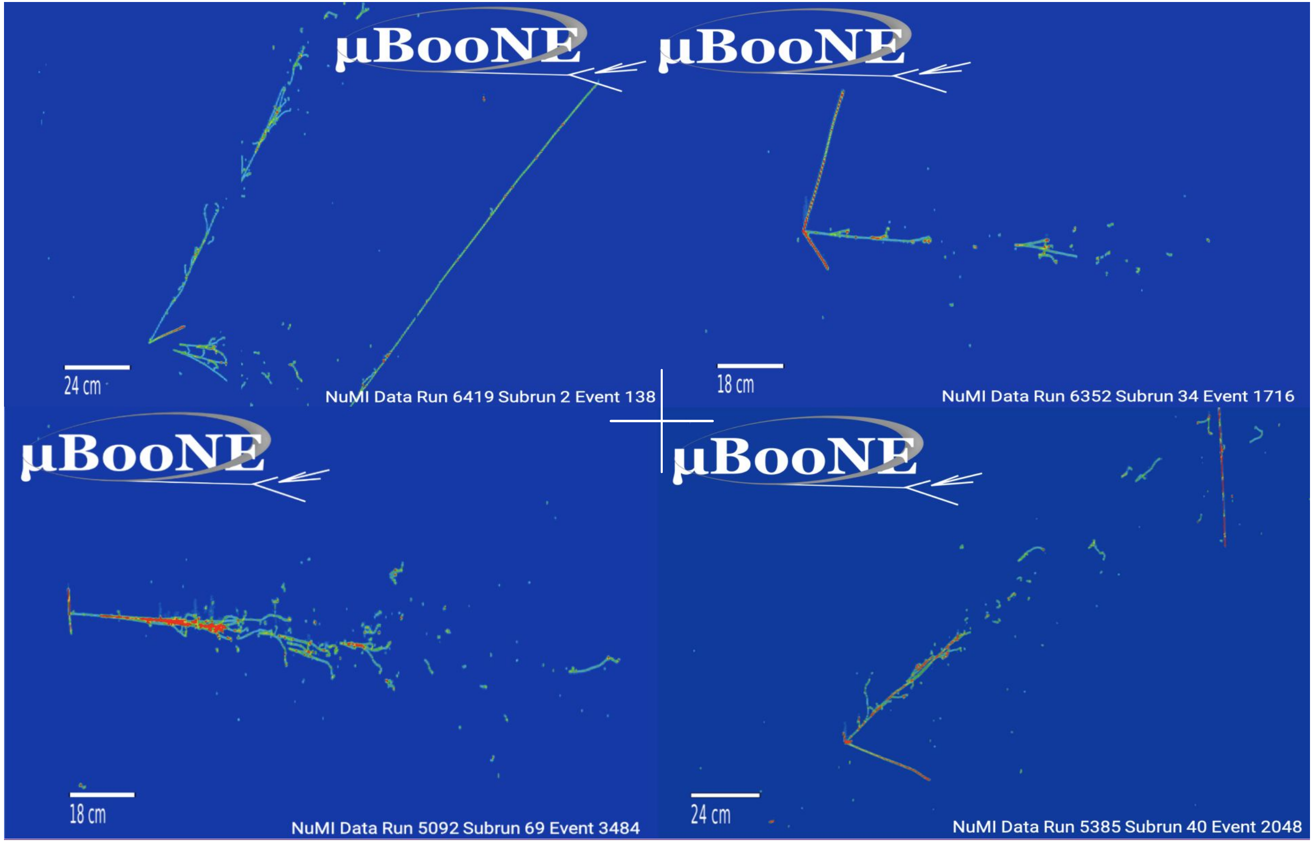
And Many More To Come!!!

Deep dive into how the vertex activity looks like (**exclusive channels**)

and

into the relationship between electron neutrinos and muon neutrino interactions in absence of oscillations.

Key to DUNE & SBN Appearance Searches: See Electron Neutrinos



… and distinguish them from muon neutrino. This is not an easy task for 2 reasons:

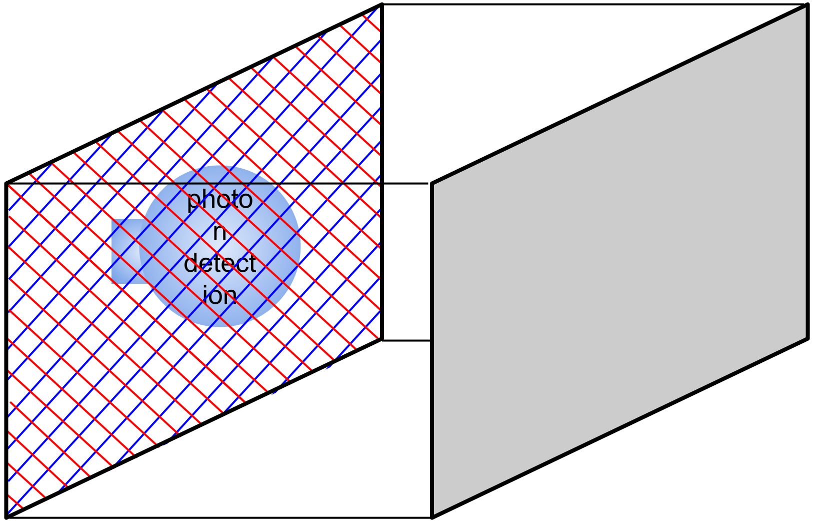
2. Event Reconstruction in traditional LArTPCs (made of wires) is a very complicated, and subject to ambiguities coming from the **projection task.**

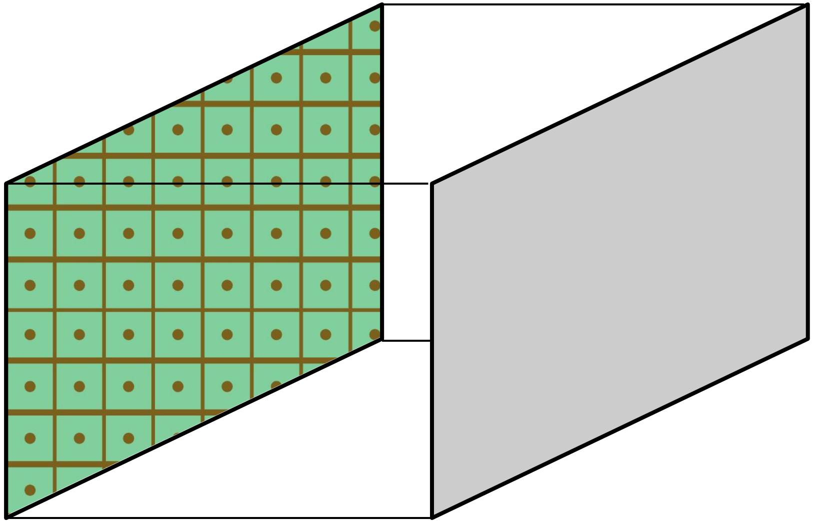
Can we improve on the LArTPC technology while keeping all its benefits?

Substitute Wires with Pixels!!!

Traditional LArTPC
2+ planes of meters long wires

Pixelated LArTPC
Millimeters^2 pixel elements





Same Granularity, Much Less Ambiguities

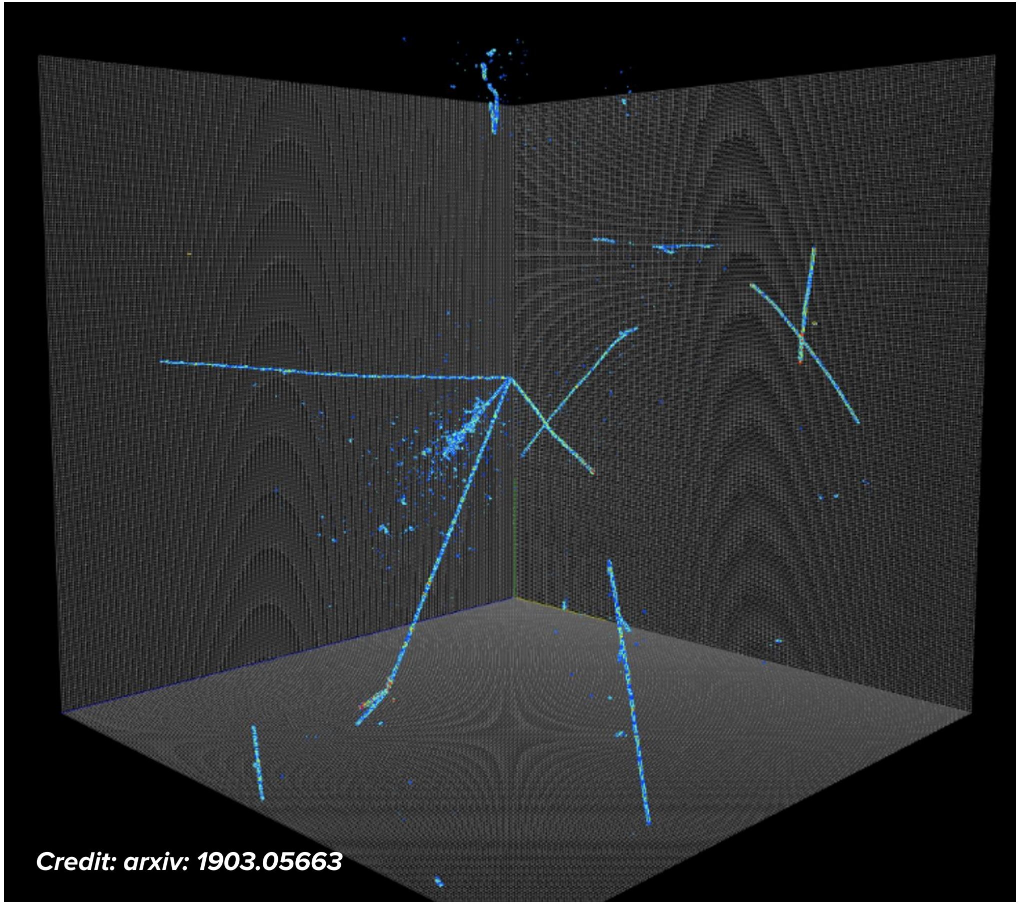
Substitute Wires with Pixels!!!

Pixel TPCs are at the forefront of noble element detector R&D even for kiloton scale neutrino detectors.

They offer a number of competitive advantages wrt traditional wire readouts

The **readout space coincides w/ the physical projected space**:
→ native 3D reconstruction w/ same spatial resolution
→ abated ambiguities (mm vs m projections)

Simulation work shows superior performances in all reconstruction parameters for osc search. Appealing technology for future DUNE's modules.



Credit: arxiv: 1903.05663

Important Pixel Drawback: how can we collect the scintillation light?

In traditional wire readouts, a rather coarse light collection system is mounted behind the wires of the anode plane:

→ VUV light from products of neutrino interaction can reach the light collection system

Ar scintillation light λ = 128 nm

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Pixels are embedded in PCB: **opaque boards** to the VUV light!

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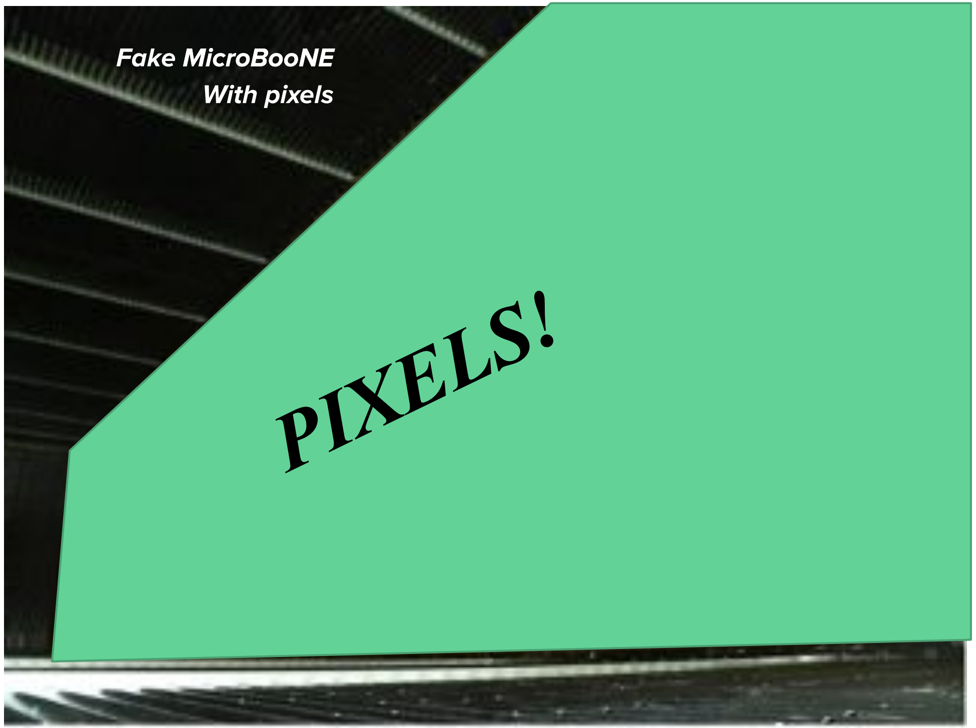

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A pixel sensitive to **BOTH LAr detection handles**: VUV photons and ionization charge simultaneously would be a **major breakthrough**

Ar scintillation light λ = 128 nm

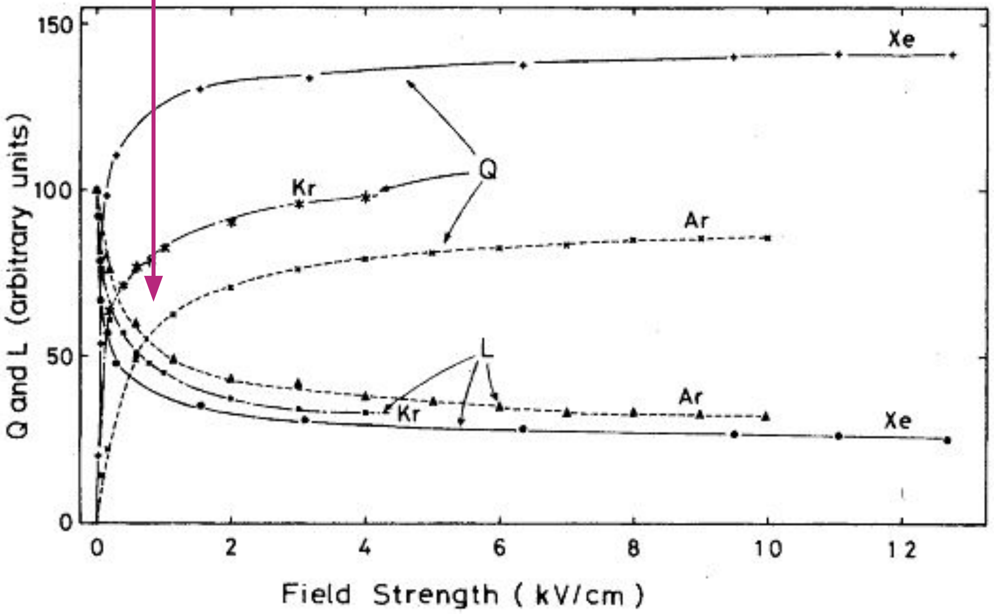
Charge and Light in Noble Elements

At E = 500 V/cm (typical LArTPC field)
½ of half of energy released by charged particles in LAr goes in **scintillation light**

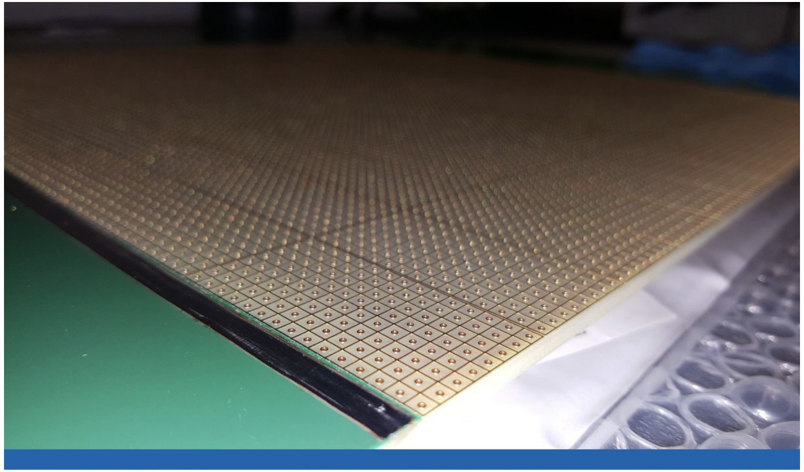
→ Light holds ½ of the information boost detection capabilities especially at low E with light and charge combination.

DUNE LIVES HERE!

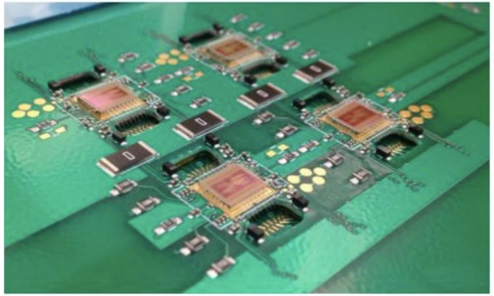
Phys. Rev. B, vol. 20, no. 8, p. 3486, 1979



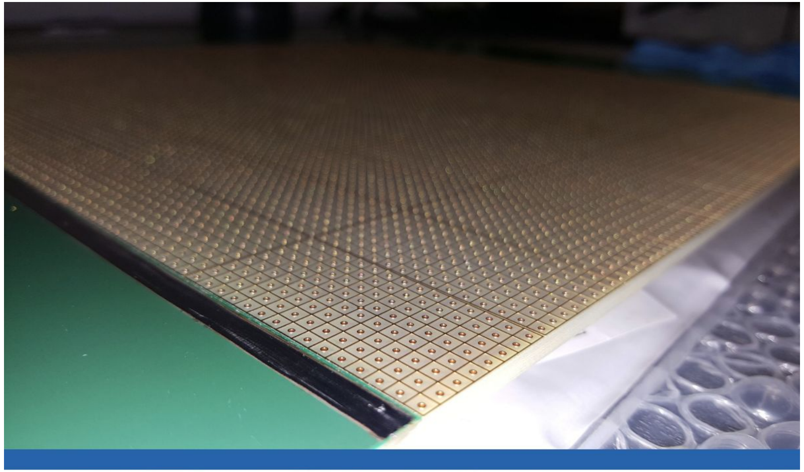
What do pixels look like? Regular Pixels



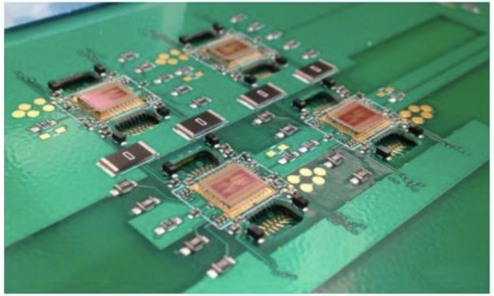
LArPix Readout
JINST 13 P10007



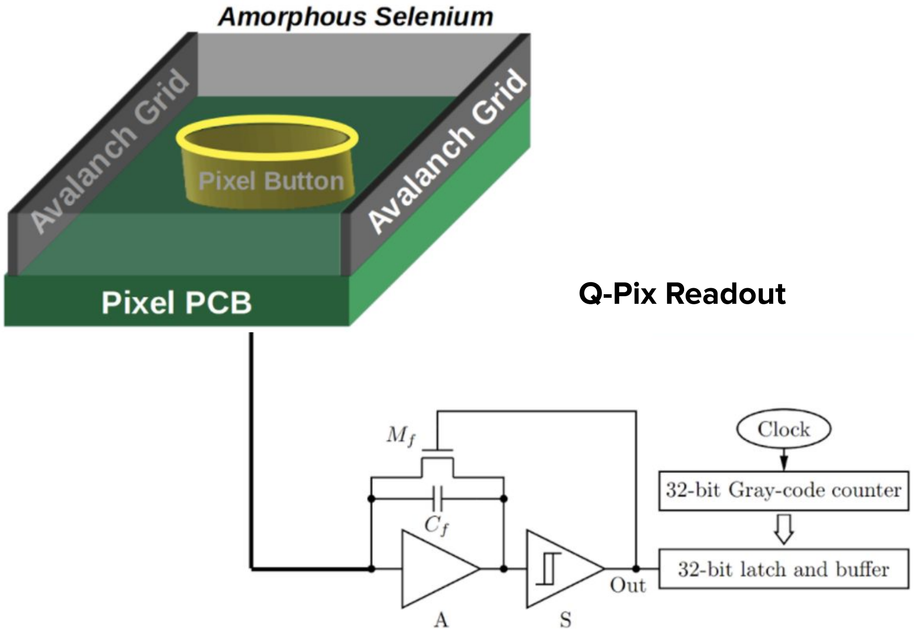
What do pixels look like? Light Sensitive Pixels



LArPix Readout
JINST 13 P10007



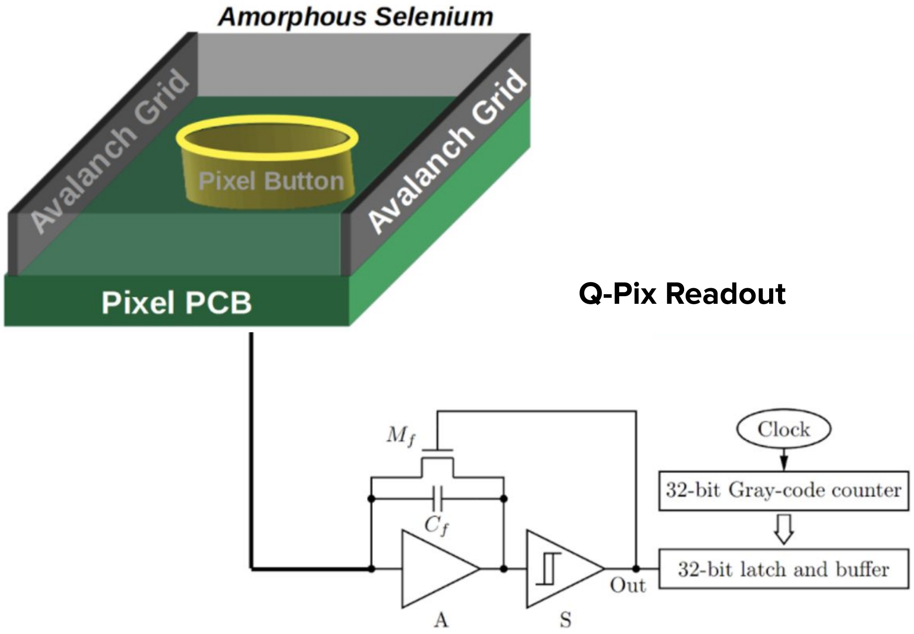
Pixels **coated with photo-conducting** material.
“3D view”



Q-Pix Readout

What do pixels look like? Light Sensitive Pixels

Pixels **coated with photo-conducting** material.
“3D view”



First material choice for coatings:
Amorphous Selenium.

→ Widely used in X-Ray medical imaging
→ Se (SeO) is fairly toxics if inhaled
→ An element commonly found in…

What do pixels look like? Light Sensitive Pixels

Pixels **coated with photo-conducting** material.

First material choice for c

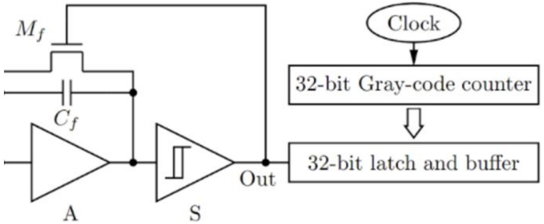
Amorphous Selenium.

→ Widely used in X-Ray

→ Se (SeO) is fairly toxic

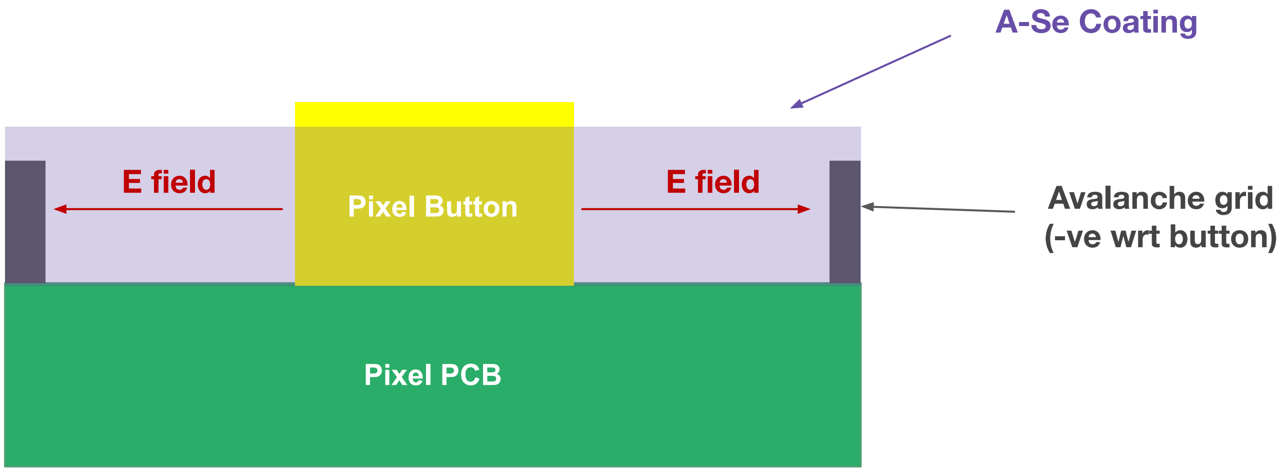
→ An element commonly

Q-Pix Readout



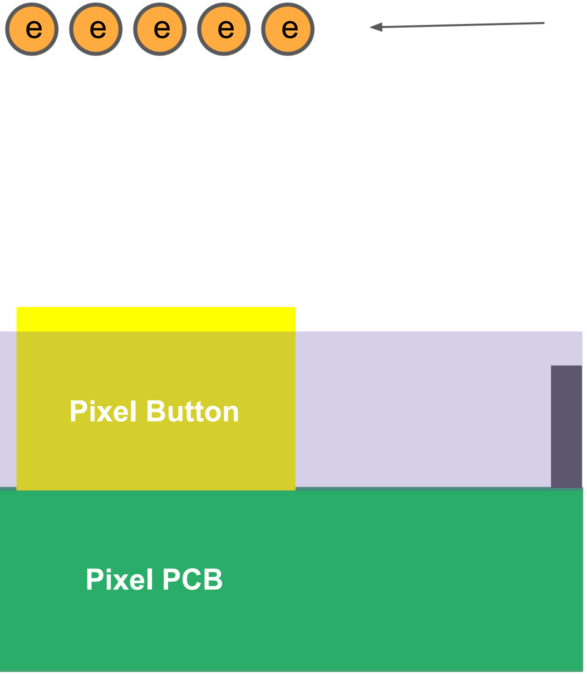
Light Sensitive Pixels: Working principles

Side view of my ~~potato-coated~~ **A-Se coated** pixel



Light Sensitive Pixels: Working principles

Side view of my **A-Se coated** pixel
What happens to the **charge**?
Same as regular pixels...



**Drifting Charge,
gets to the pixels
on LONG times scales
[drift times ~ ms]**

Light Sensitive Pixels: Working principles

Side view of my **A-Se coated** pixel
What happens to the **charge**?
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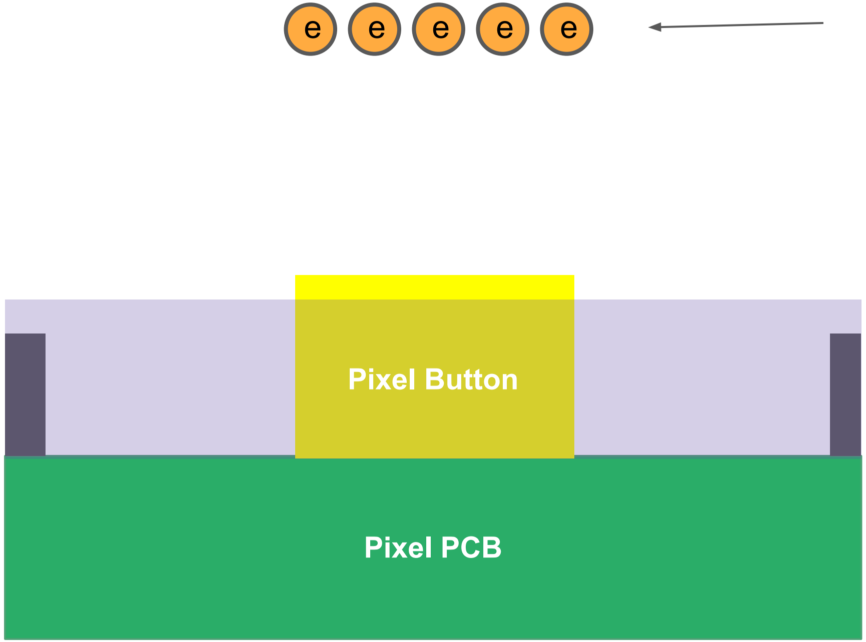

**Drifting Charge,
gets to the pixels
on LONG times scales
[drift times ~ ms]**

Light Sensitive Pixels: Working principles

Side view of my **A-Se coated** pixel
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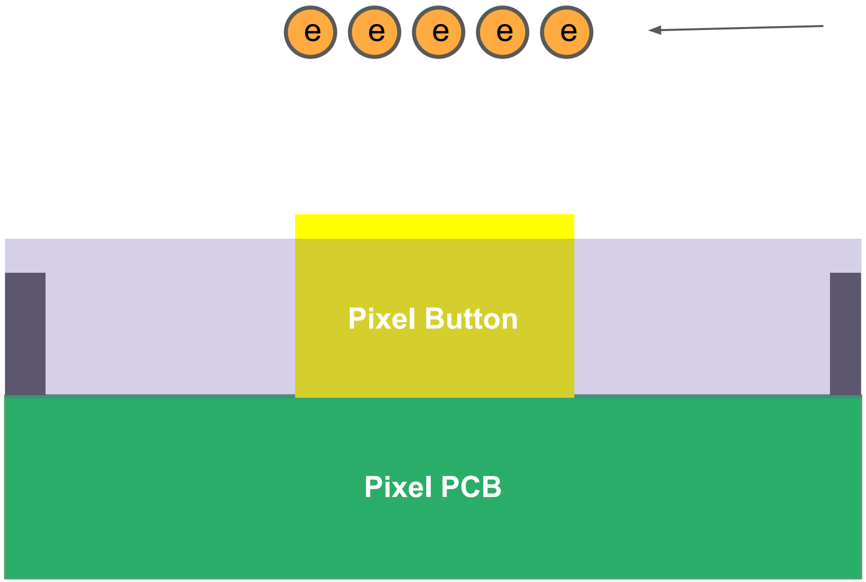
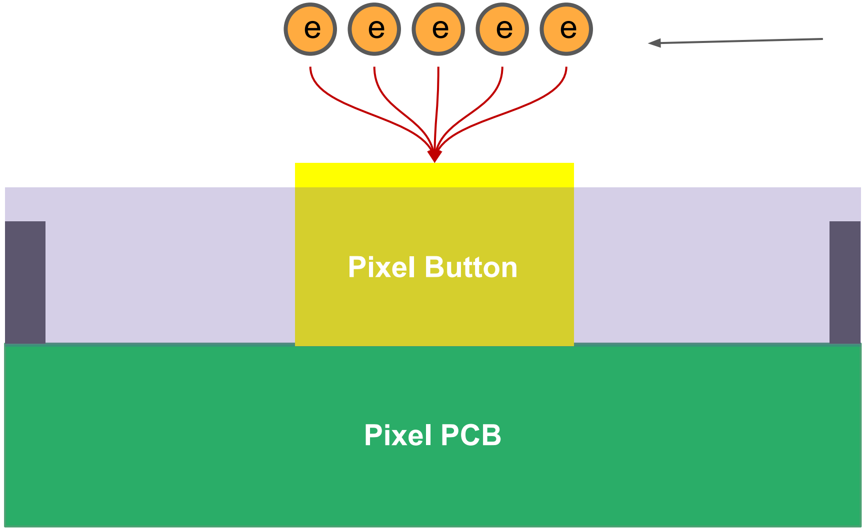


Drifting Charge,
gets to the pixels
on LONG times scales
[drift times ~ ms]

Light Sensitive Pixels: Working principles

Side view of my **A-Se coated** pixel
What happens to the **charge**?
Same as regular pixels...

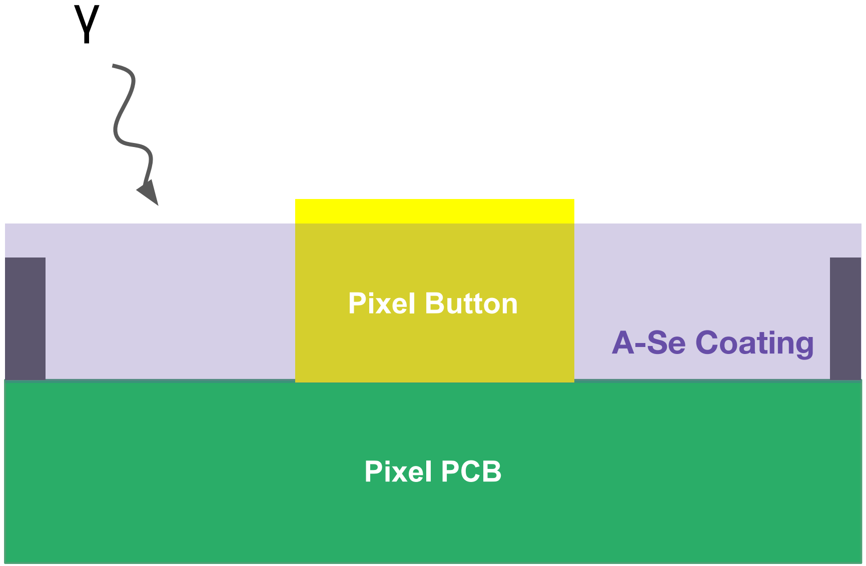


**Drifting Charge,
is collected by the button**

Light Sensitive Pixels: Working principles

Side view of my **A-Se coated** pixel
What happens to the **light**?

Scintillation light:
gets to the pixels in ns!

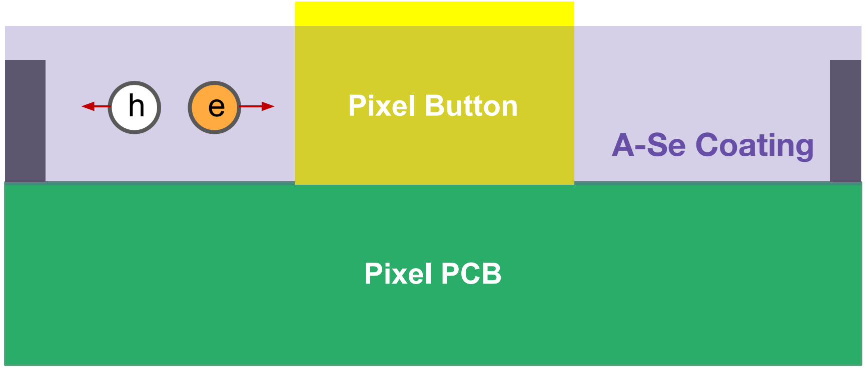


Light Sensitive Pixels: Working principles

Side view of my **A-Se coated** pixel
What happens to the **light**?

γ is absorbed and creates 1.3 electron-hole pairs (on average)

These “carriers” start moving in the A-Se

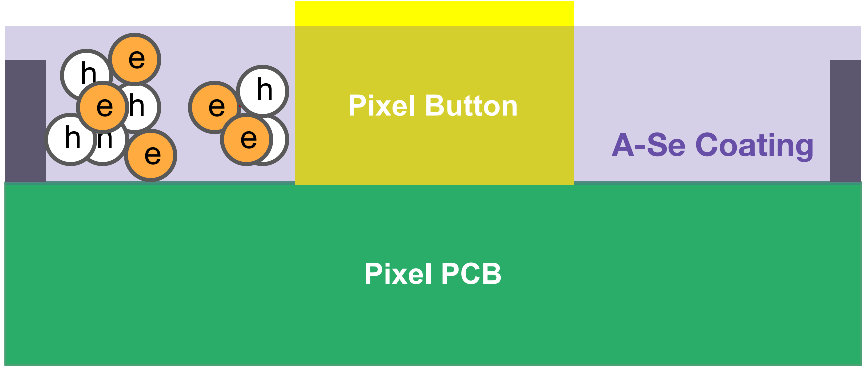


Light Sensitive Pixels: Working principles

Side view of my **A-Se coated** pixel
What happens to the **light**?

If the E field in the A-Se is high enough (80 V/µm):
AVALANCHE MULTIPLICATION!!!

~ 10^3 pairs per γ
Signal readable by the same electronics



Light Sensitive Pixels: Working principles

Side view of my **A-Se coated** pixel
What happens to the **light**?

Where's the catch?

If the E field in the A-Se is high enough (80 V/μm):
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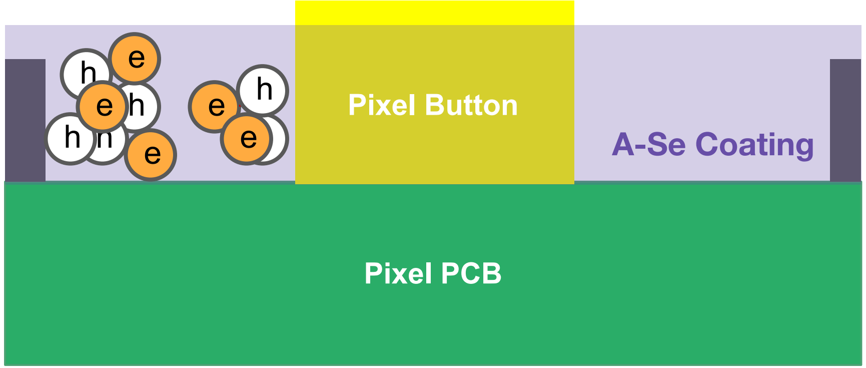
Signal readable by the same electronics



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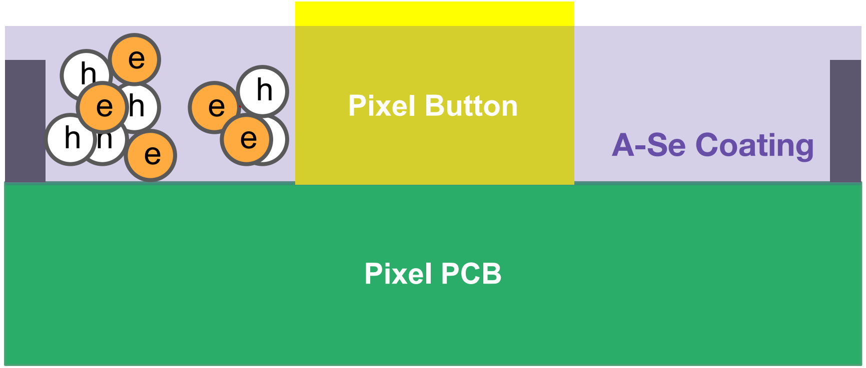

This is a very high field: need to find smart ways to reduce it.

We plan to use A-Se in **extreme conditions**: Argon is liquid at 87k!

Light Sensitive Pixels: Working principles

Side view of my **A-Se coated** pixel
What happens to the **light**?

Prototype, Test & Repeat

If the E field in the A-Se is high enough (80 V/µm): AVALANCHE MULTIPLICATION!!!

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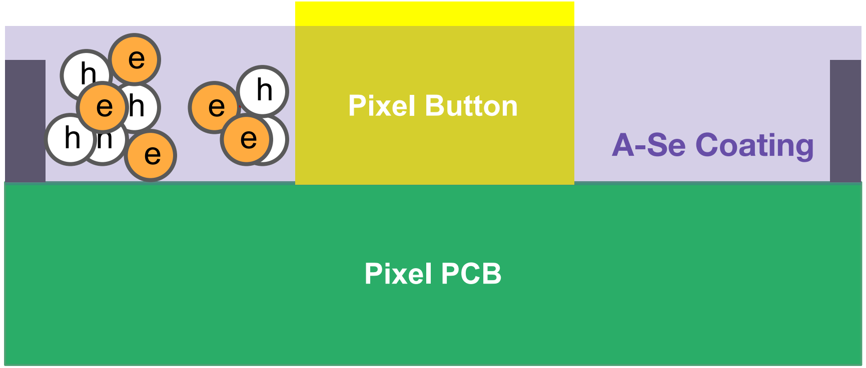
Signal readable by the same electronics

This is a very high field: need to find smart ways to reduce it.

We plan to use A-Se in **extreme conditions**: Argon is liquid at 87k!



Fermilab

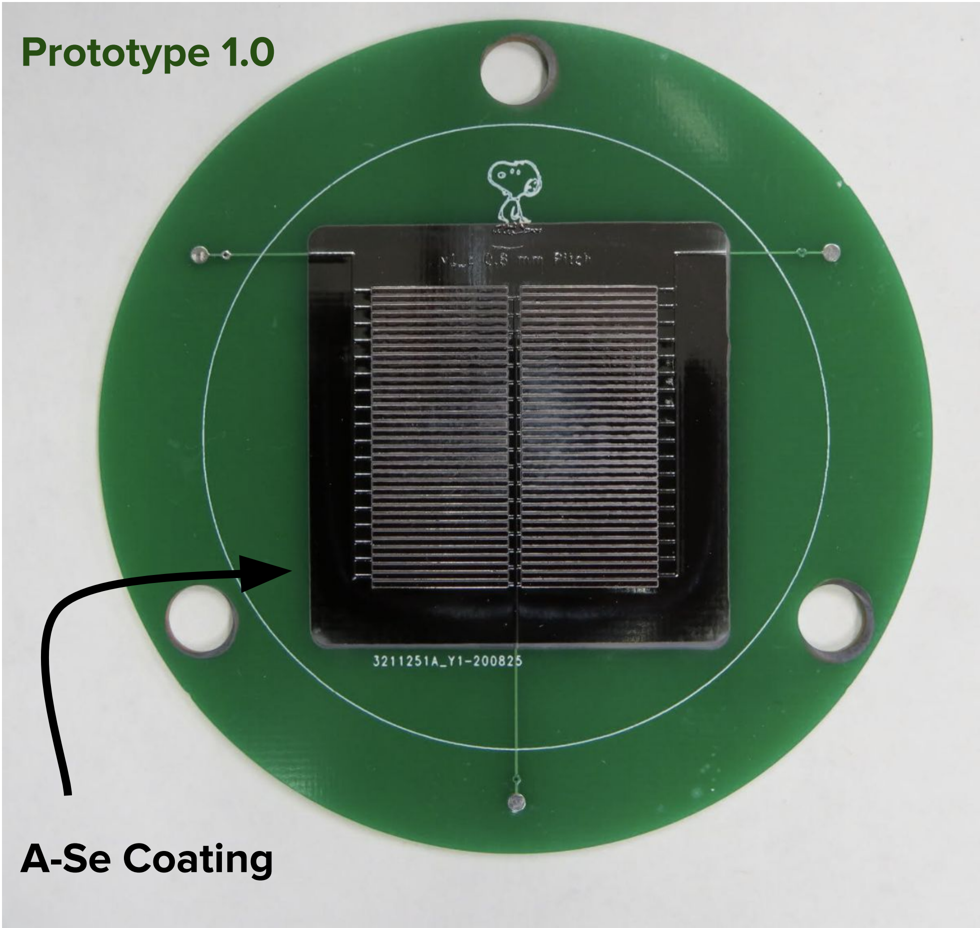
First Prototypes and Tests

A-Se deposited through thermal evaporation on commercial printed circuit board…
(same base device as your motherboard)

First prototypes: 200 µm & 127µm spacing.

UTA & ORNL tests: source Xe light (178 nm), data taken at different voltage & temperature points.

And with these very simple prototypes…


Prototype 1.0

A-Se Coating

First Prototypes and Tests: 1^{st} demonstration of VUV sensitivity in Cold!!

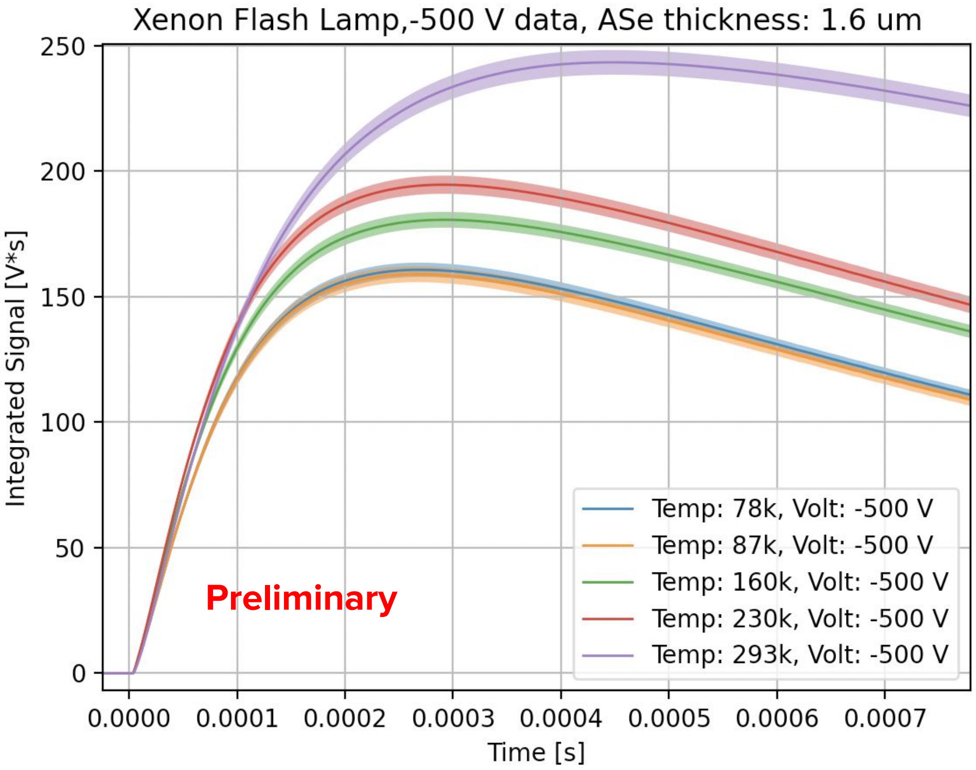
A-Se deposited through thermal evaporation on commercial printed circuit board…
(same base device as your motherboard)

First prototypes: 200 µm & 127µm spacing.

UTA & ORNL tests: source Xe light (178 nm), data taken at different voltage & temperature points.

And with these very simple prototypes…

… WE SAW SIGNAL IN COLD!

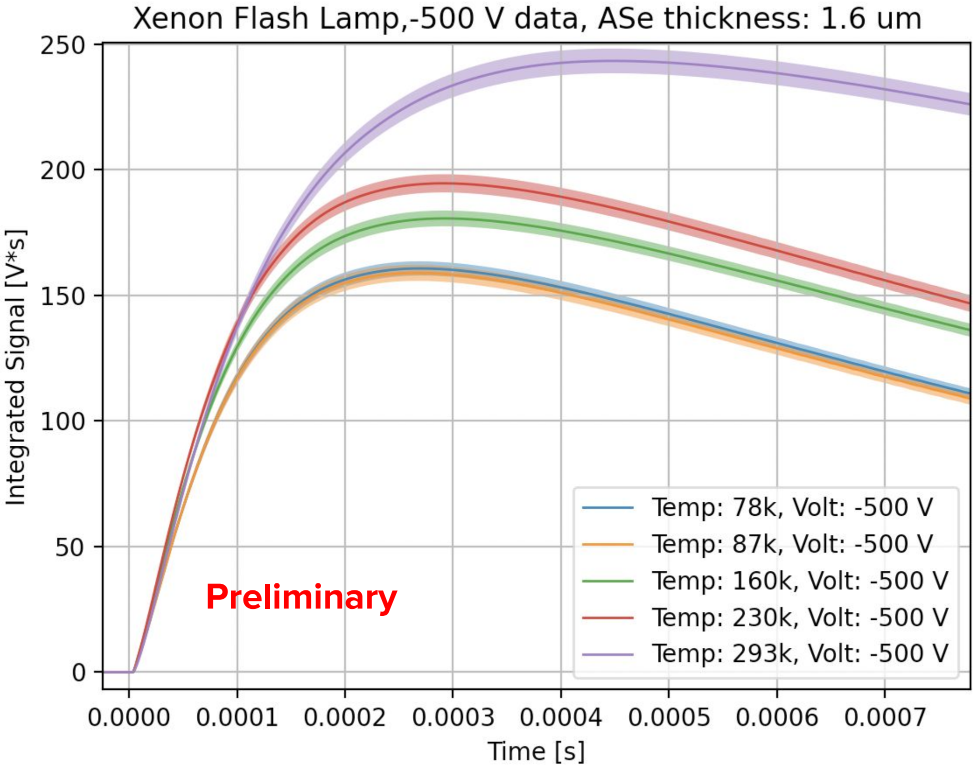


First Prototypes and Tests: 1st demonstration of VUV sensitivity in Cold!!

Why is this a big deal???

A-Se is commonly used in medical physics: we knew it was sensitive to **X-rays** (**0.01-10 nm**) at room temperature, but we need sensitivity at **128-178 nm** and at **87 K**!

1. Light absorption can **change** as a function of the light wavelength:
   No guarantee it would work with **VUV light**
2. Transportation properties in semiconductors (i.e. how well e-h travel in the A-Se) are sensitive to the **temperature**.



What’s next? Prototype 3.0 & Simulation

With new prototypes we’re **targeting avalanche regime!**
Increasing the E field by diminishing the spacing:
→ 25 µm pitch: **bleeding edge of commercial high density PCB**


Prototype 3.0 cross section: 25 µm

Simulation of the opto-electrical properties of the A-Se using newly developed simulation in collab with condensed matter theorists (arxiv.org 2104.14455)
→ Optimize Semiconductor Mixture (not only ASe, dopants as well!)
→ Updated sensor geometry

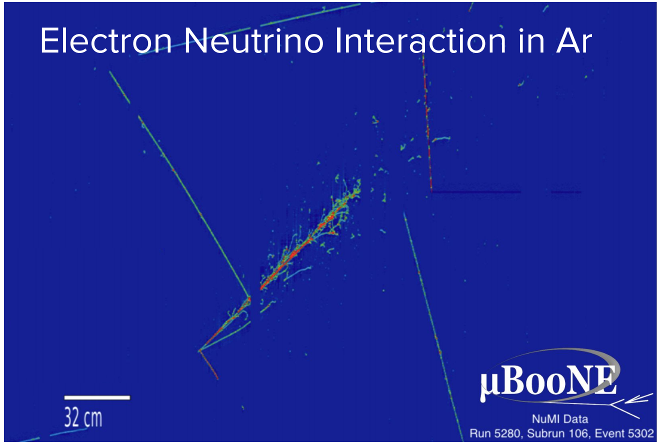
… our Selenium adventure continues!!

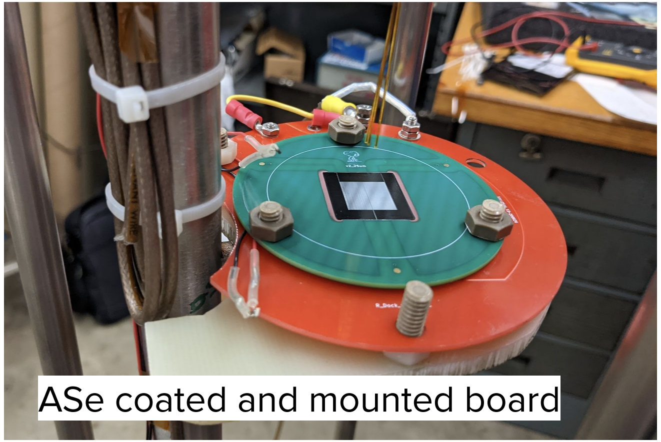
Summary

DUNE is going to answer many of the burning questions in neutrino physics today: to ensure DUNE's success, a multidisciplinary approach is needed.

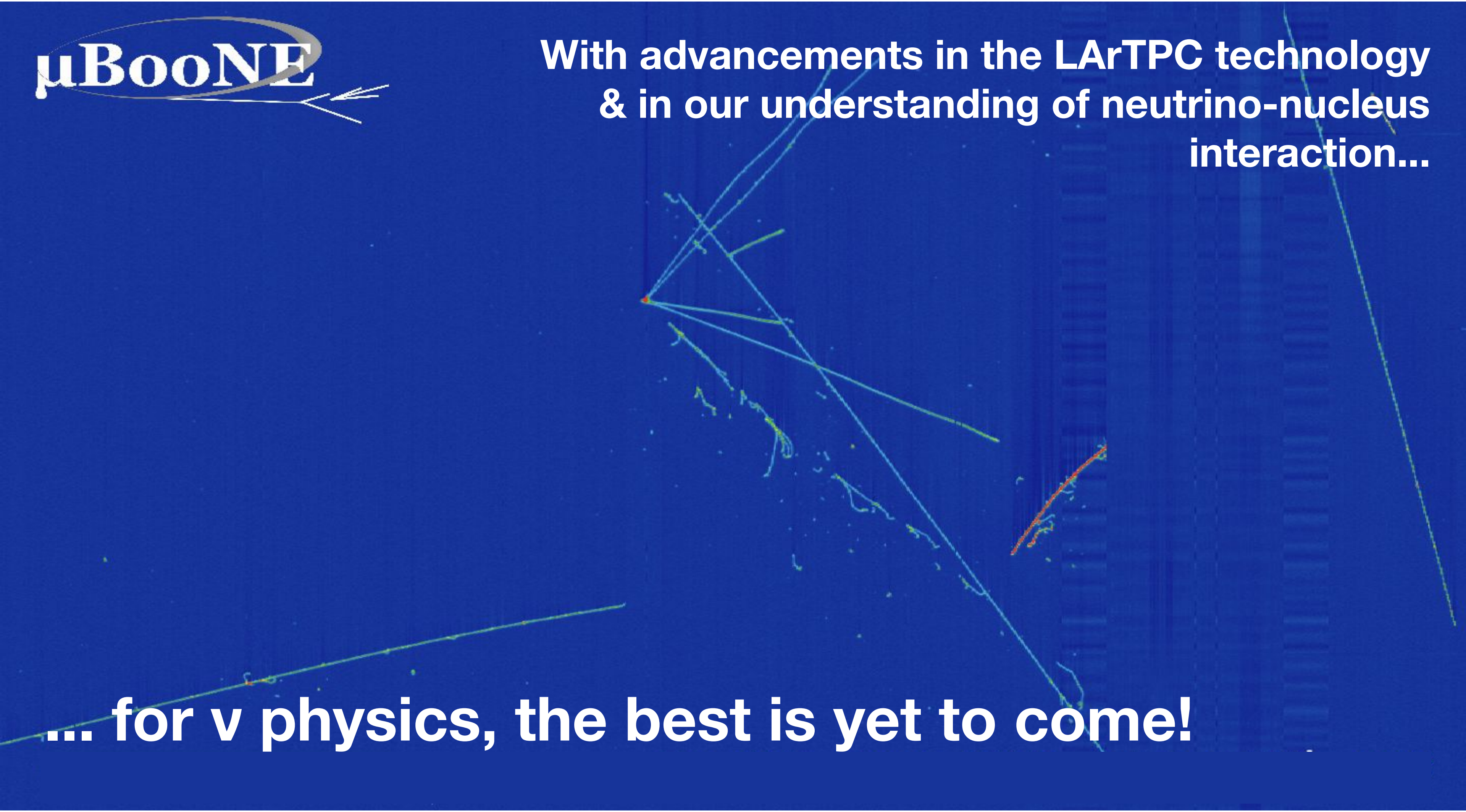
On one hand, **current Liquid Argon Time Projection Chambers** are the perfect place to advance our understanding of the **nucleus** and abate systematics related nuclear modelling (while exploring **new BSM physics** in the meanwhile).

On the other, **new technologies** such as **pixelated TPCs with a powerful light collection system** offer opportunities to boost DUNE's sensitivity to its main searches and for physics at low energy...



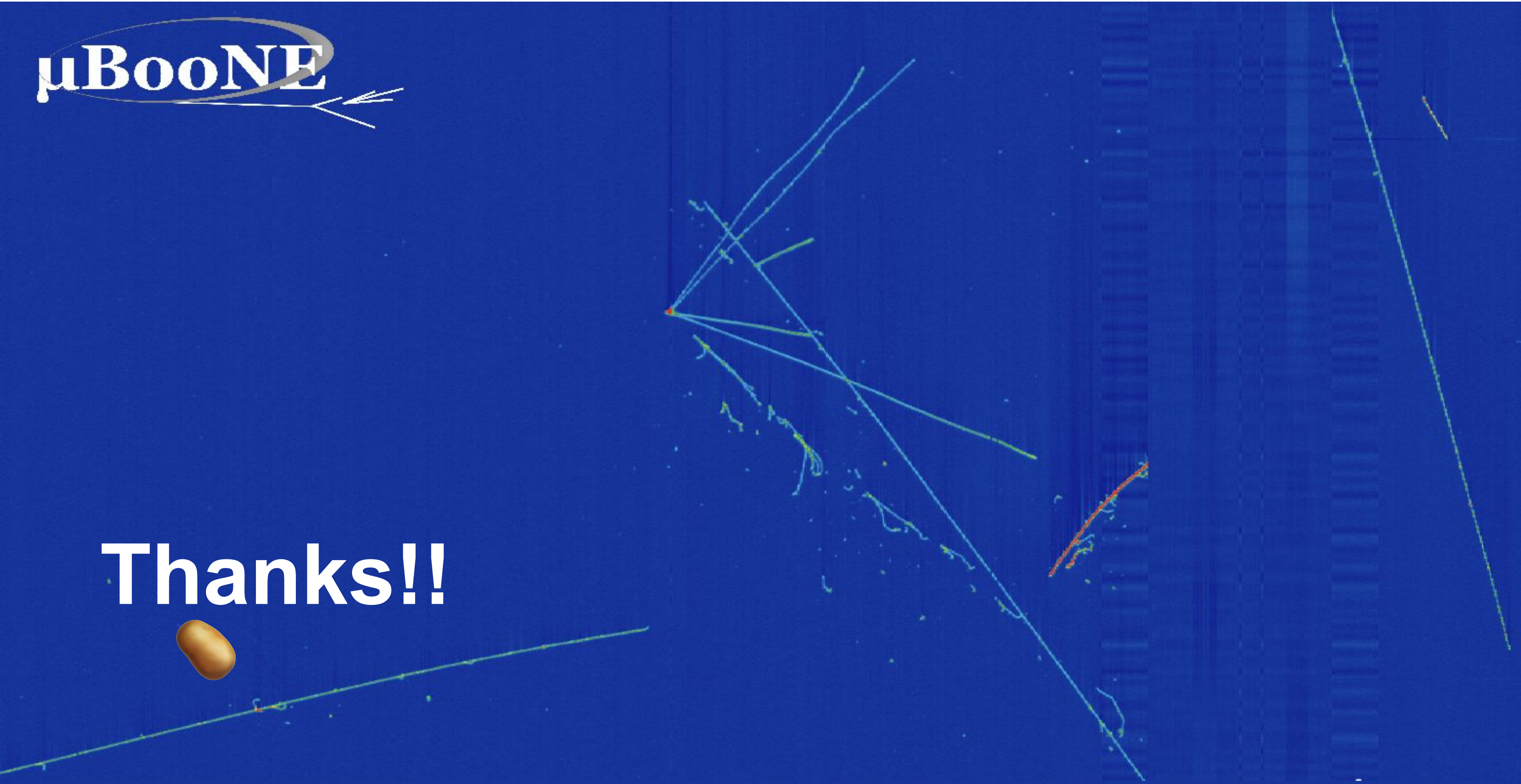

ASe coated and mounted board

With advancements in the LArTPC technology & in our understanding of neutrino-nucleus interaction...



With advancements in the LArTPC technology & in our understanding of neutrino-nucleus interaction…

… for ν physics, the best is yet to come!

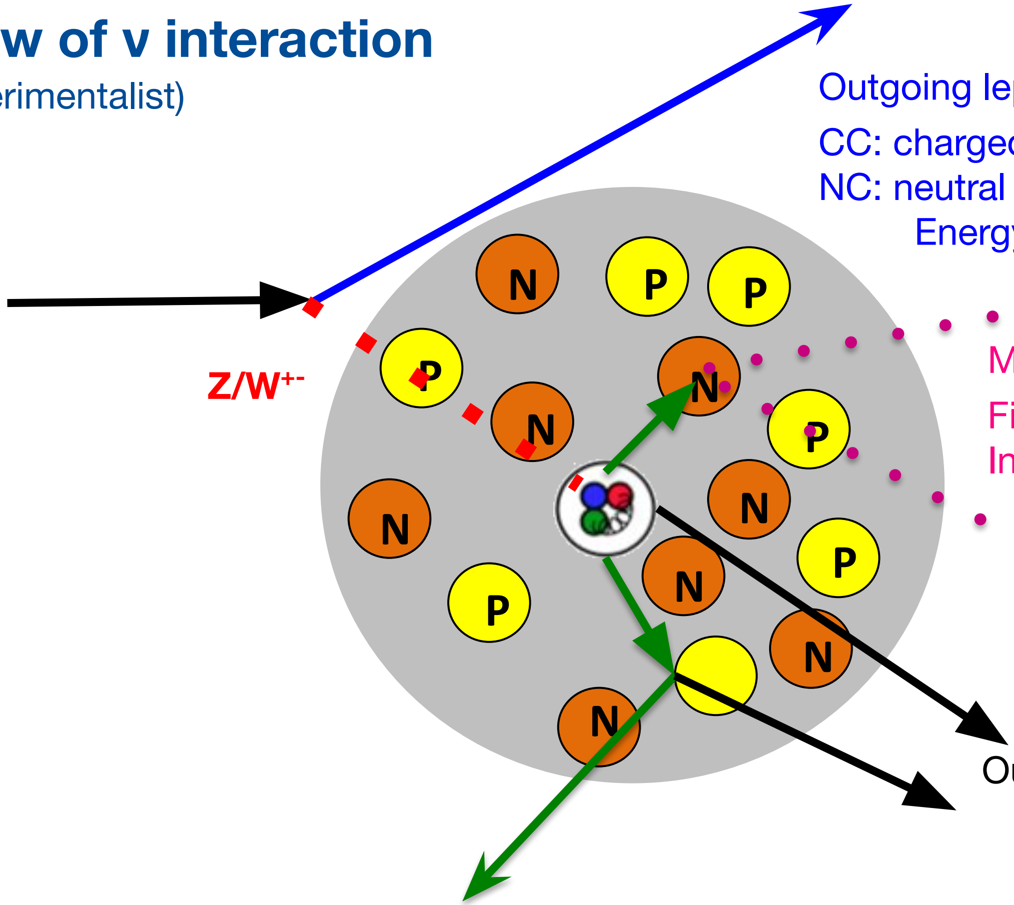


Thanks!!

🥔

A simplified view of ν interaction

(and of our job as experimentalist)



Incoming ν:

Flavor unknown

Energy unknown

Outgoing lepton:

CC: charged lepton
NC: neutral lepton
Energy: measure

Mesons:

Final State Interactions

Energy? Identity?

Outgoing nucleons:

Visible?

Energy?

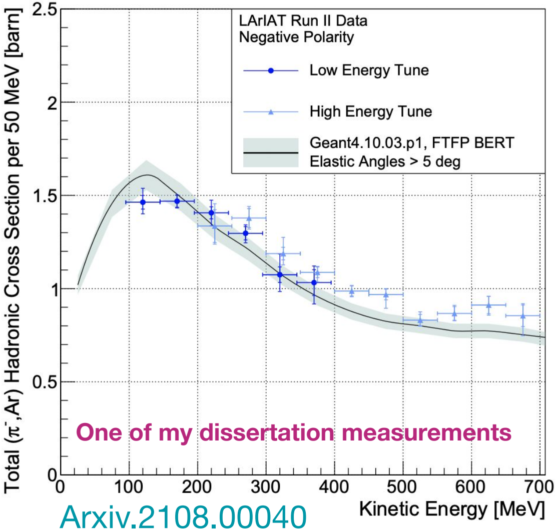
A simplified view of ν interaction

(and of our job as experimentalist)

{ Parenthesis }

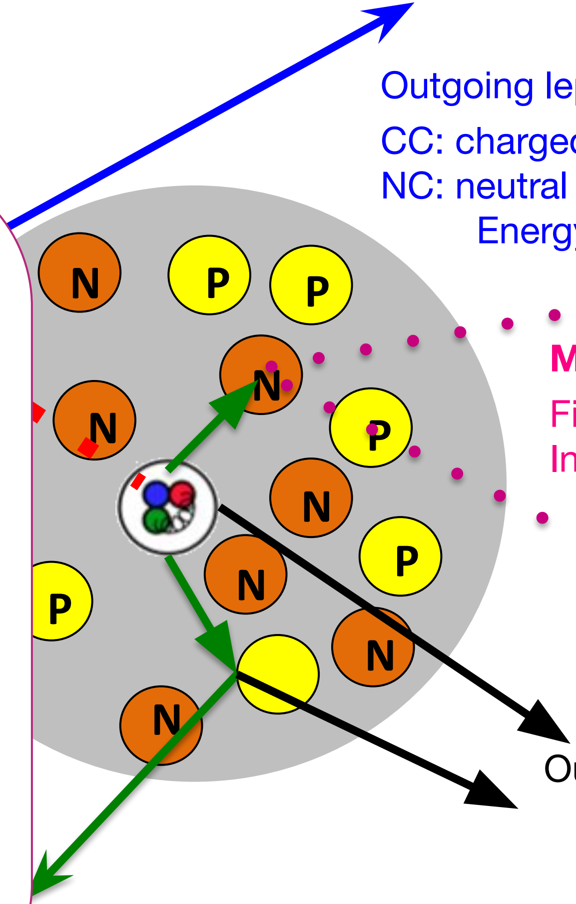
Independently characterizing hadronic interactions of pions, kaons and protons is important for ν!

1^{st} measurement of π-Ar hadronic Total XS



One of my dissertation measurements

[Arxiv.2108.00040
submitted to PRD](https://arxiv.org/abs/2108.00040)



Outgoing lepton:

CC: charged lepton
NC: neutral lepton
Energy: measure

Mesons:

Final State Interactions

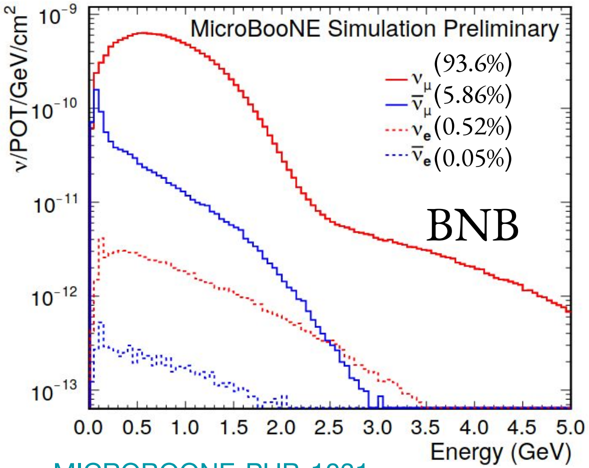
Energy? Identity?

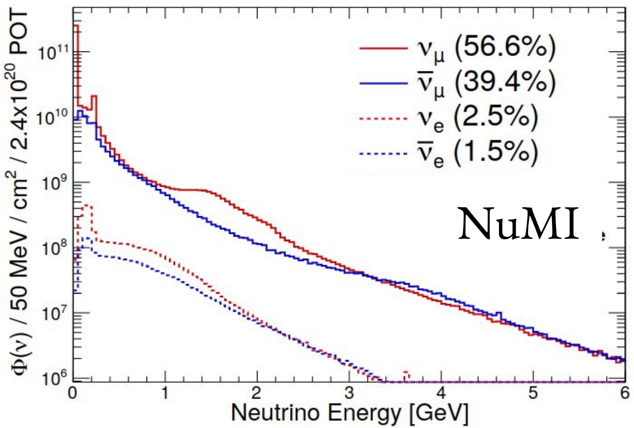
Outgoing nucleons:
Visible?
Energy?

MicroBooNE at a glance

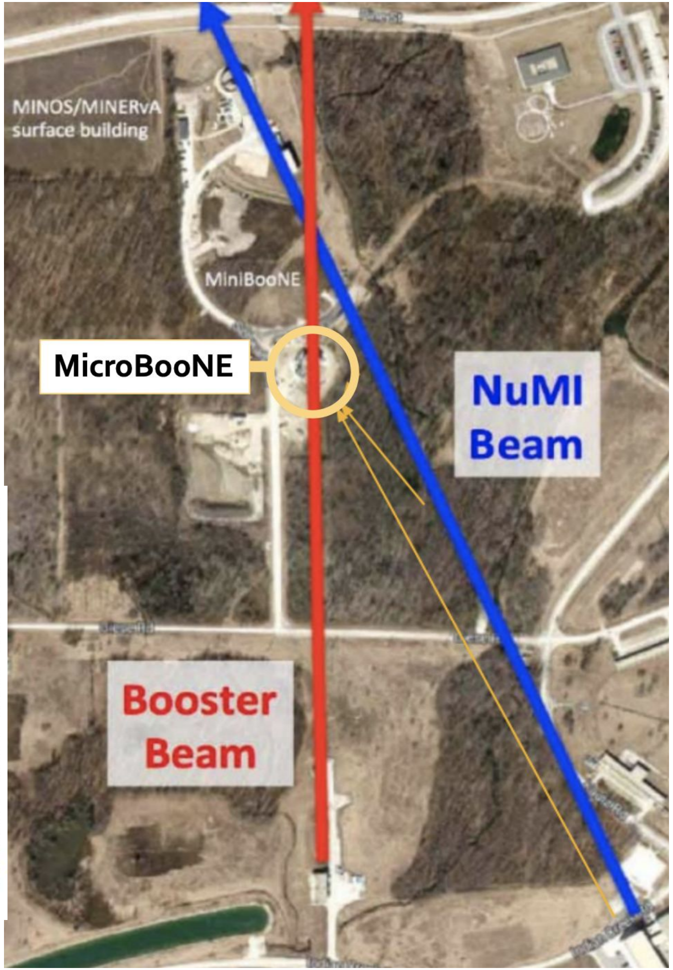
MicroBooNE is the longest running **Liquid Argon Time Projection Chamber** at FNAL. With 85 ton active volume, MicroBooNE collects neutrinos on-axis from the BNB and highly off-axis from NuMI.

Completed 5 years physics runs: 2015-2021.
Largest neutrino-argon dataset available to date!





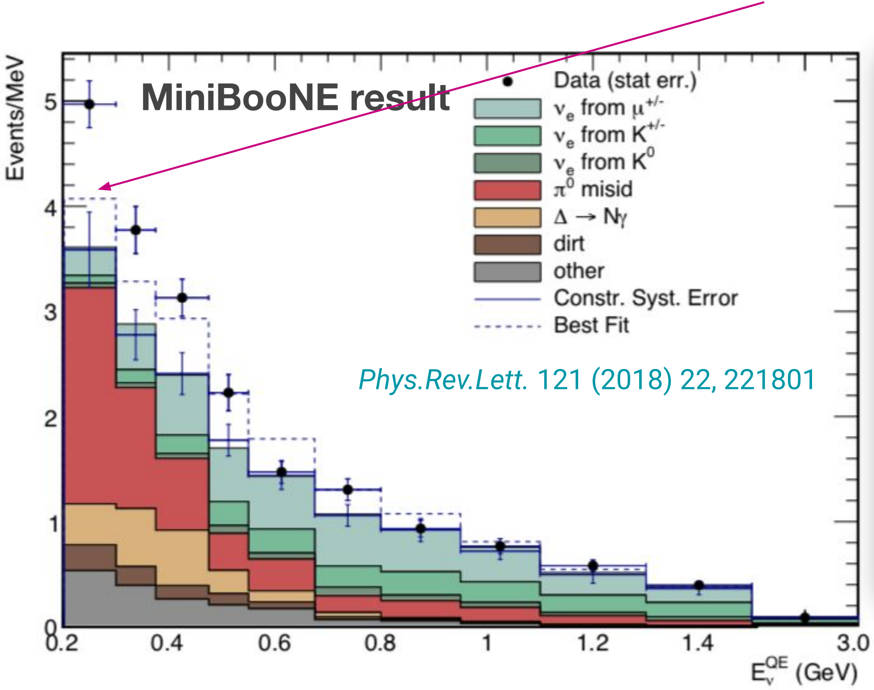
MICROBOONE-PUB-1031



A bit of BSM physics, before our DUNE homework...

Primary scope using BNB neutrinos:

Investigate the nature of the MiniBooNE excess of low energy electromagnetic events. **Is it electrons? Is it photons?**



Phys.Rev.Lett. 121 (2018) 22, 221801

$\theta_{12}, \theta_{13}, \theta_{23}$

$\Delta m^2, \delta m^2$

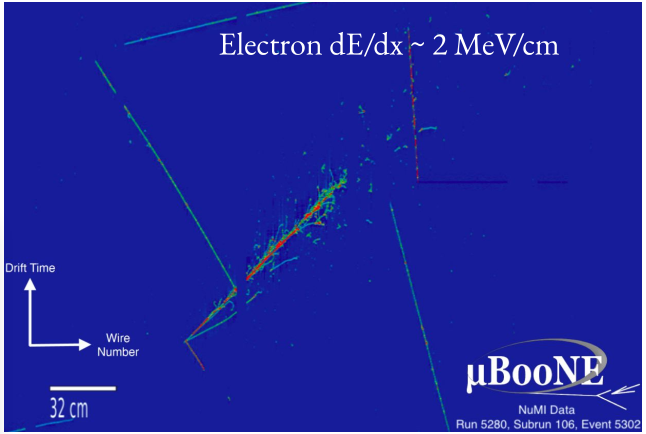
N_ν

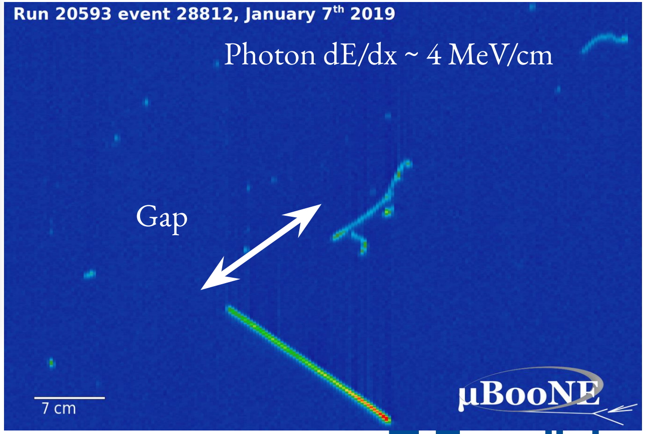
δ_{CP}

$\text{sign}(\Delta m^2)$

α_1, α_2

m_x





Exploring the MiniBooNE LEE @ MicroBooNE

Appearance of low energy ν_e:

- → MiniBooNE-like final state (Pandora, 1eNp, 1e0p)
- → Restricting to quasi-elastic kinematics (Deep Learning , 1e1p)
- → All ν_e final states (Wire-Cell, 1eX)

Single photon analysis:

- → targeting Delta radiative decay hypothesis (Pandora, 1γ1p, 1γ0p)

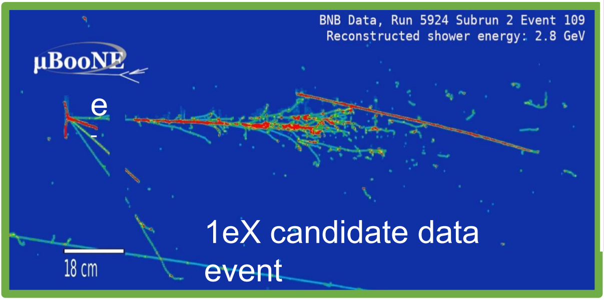
3 reconstruction paradigms, 6 complementary channels


1eNp candidate data event

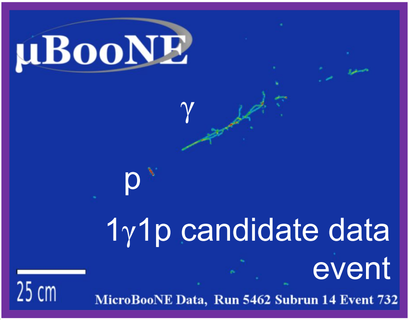

1e0p candidate data event


1e1p candidate data event

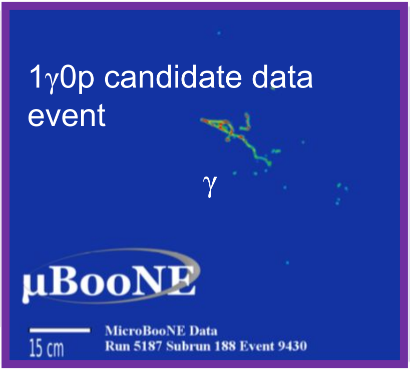
RUN 8617 SUBRUN 46 EVENT 2328


BNB Data, Run 5924 Subrun 2 Event 109
Reconstructed shower energy: 2.8 GeV

1eX candidate data event



1γ1p candidate data event
MicroBooNE Data, Run 5462 Subrun 14 Event 732


1γ0p candidate data event

MicroBooNE Data
Run 5187 Subrun 188 Event 9430

Exploring the MiniBooNE LEE @ MicroBooNE

Appearance of low energy ν_e:

- → MiniBooNE-like final state (Pandora, 1eNp, 1e0p)
- → Restricting to quasi-elastic kinematics (Deep Learning , 1e1p)
- → All ν_e final states (Wire-Cell, 1eX)

Single photon analysis:

- → targeting Delta radiati
  (Pandora, 1γ1p, 1γ0p

3 reconstruction paradigms, 6

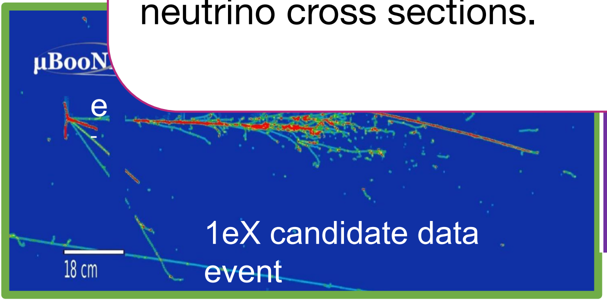
My contribution (results coming soon!):

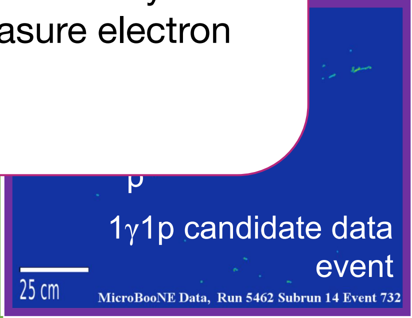
Characterizing ν_e interactions using the second neutrino beam available at MicroBooNE (NuMI) both as a direct application of the BNB search and by directing a campaign to measure electron neutrino cross sections.

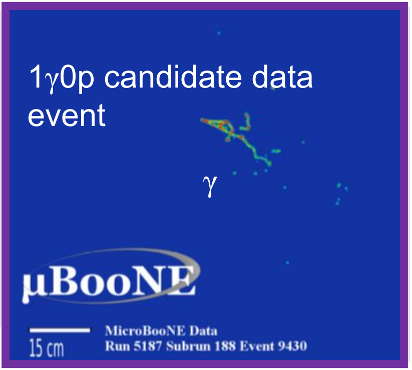

1eNp candidate data event


e0p candidate data event


1e1p candidate data event


1eX candidate data event

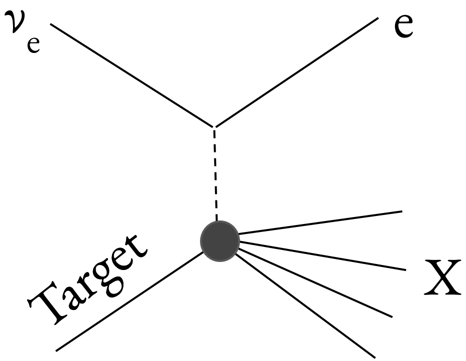

1γ1p candidate data event

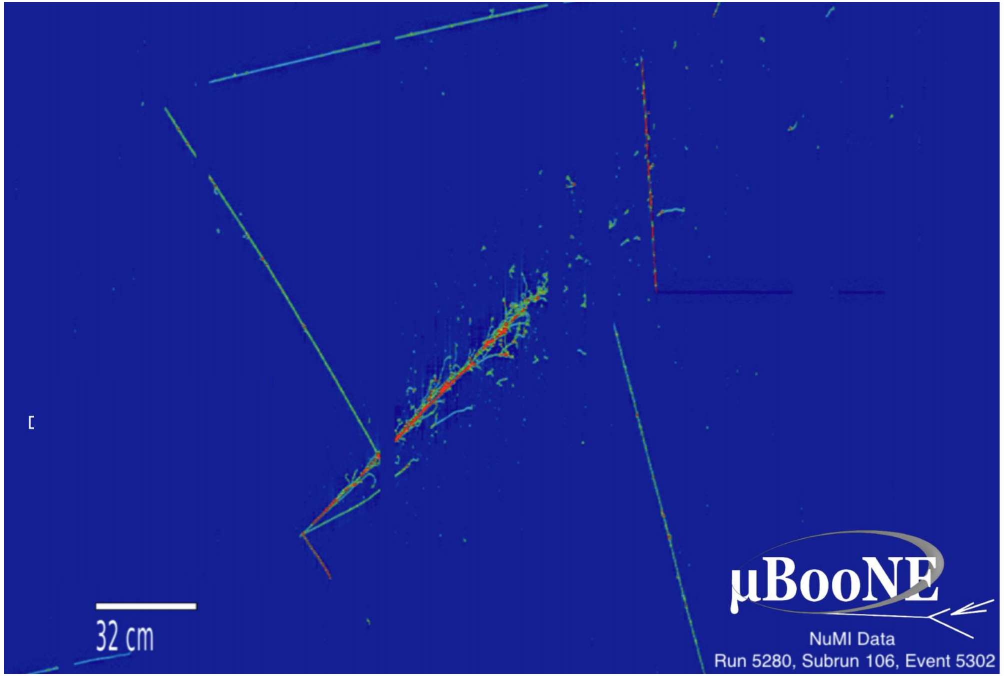

1γ0p candidate data event

In a Nutshell: Electron Neutrino Cross Section Campaign @ NuMI

Neutrino cross sections measure the probability of a ν_e to interact with the nucleus via a certain channel → essential to benchmark neutrino-nucleus interaction theory and help improve it!

Inclusive cross sections are standard candles to probe the model overall. **Exclusive states** hone into features of the underlying interaction.



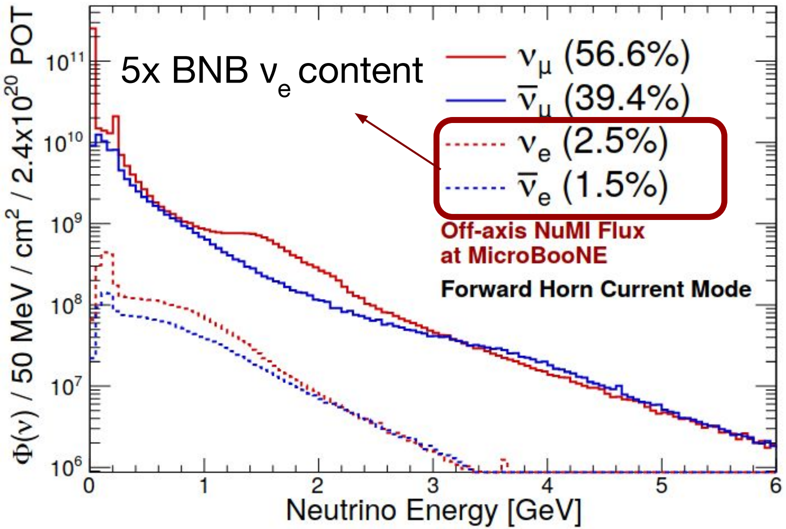


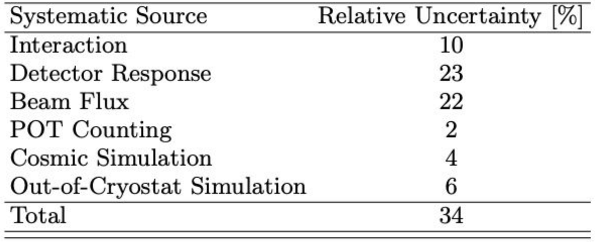
NuMI Data
Run 5280, Subrun 106, Event 5302

First measurement: total $\nu_e + \bar{\nu}_e$ CC Inclusive @ NuMI

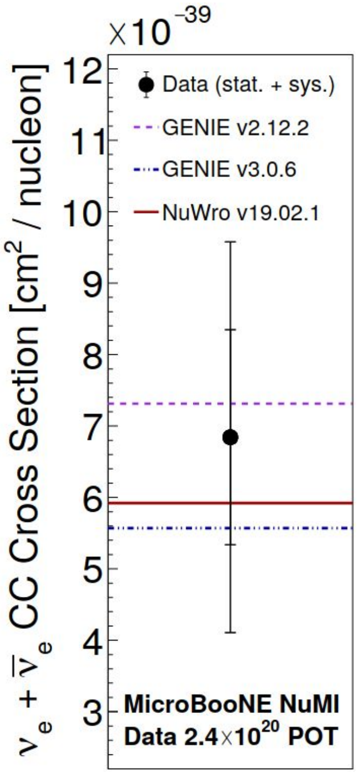
Flux averaged inclusive cross section. 214 selected events
Selection main requirement: at least one shower consistent with electron hypothesis: Purity ~40%, Efficiency ~10%.

In good agreement with models


5x BNB ν_e content



Systematic Source	Relative Uncertainty [%]
Interaction	10
Detector Response	23
Beam Flux	22
POT Counting	2
Cosmic Simulation	4
Out-of-Cryostat Simulation	6
Total	34



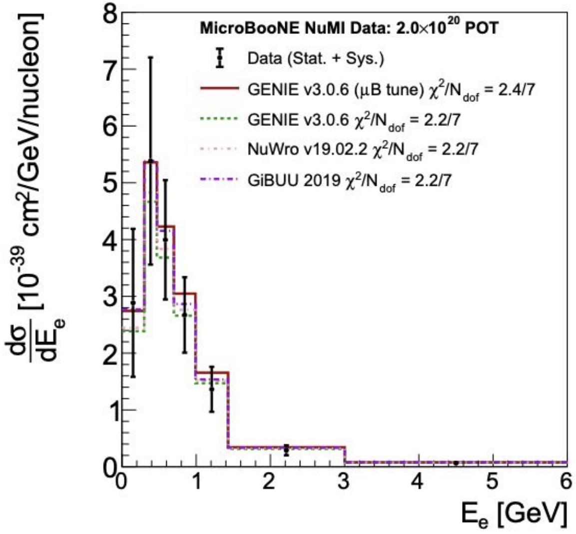
Phys. Rev. D.104.052002

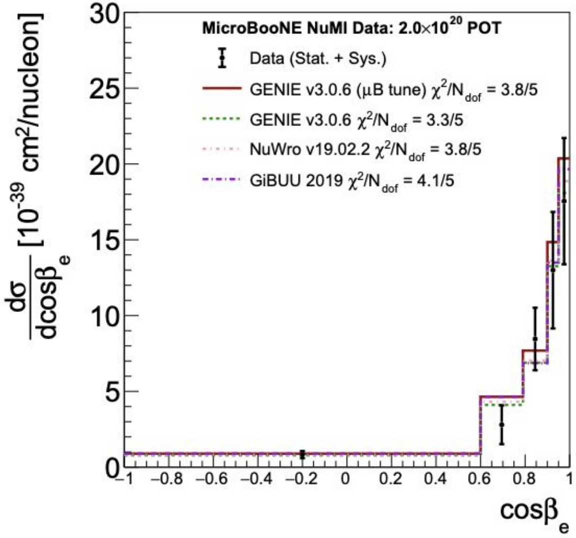
Differential $\nu_e + \bar{\nu}_e$ CC Inclusive @ NuMI

Arxiv.2109.06832
submitted to PRL

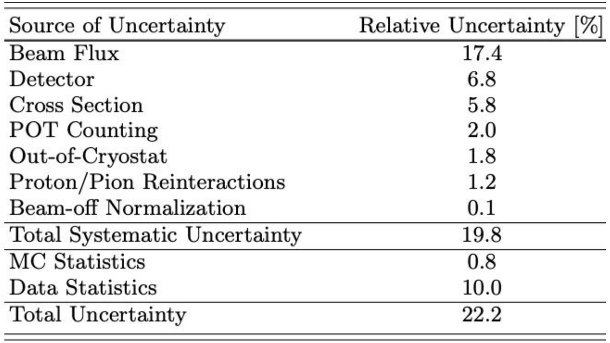
First Measurement of Inclusive ν_e and $\bar{\nu}_e$ CC differential in Lepton Energy on Argon.

Selection main requirement: at least one shower consistent with electron hypothesis.
Biggest sample of selected ν_e CC interaction on Argon to date: 243 events.
Purity ~70%, Efficiency ~20%. Extracted cross section in good agreement with models.





Total cross section compatible with previous measurement, a factor of 2 reduction in uncertainties



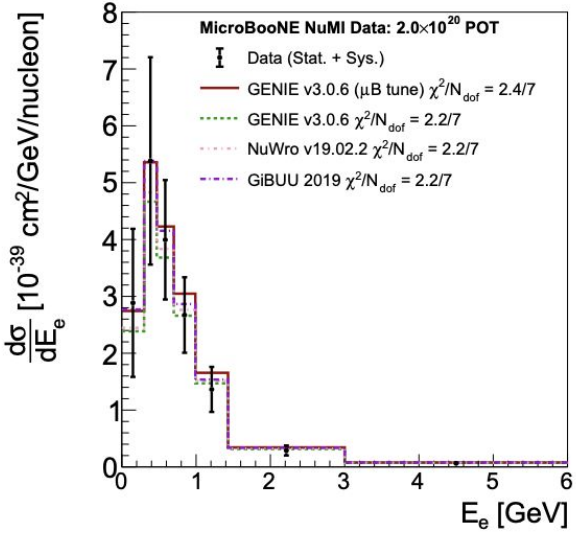
Source of Uncertainty	Relative Uncertainty [%]
Beam Flux	17.4
Detector	6.8
Cross Section	5.8
POT Counting	2.0
Out-of-Cryostat	1.8
Proton/Pion Reinteractions	1.2
Beam-off Normalization	0.1
Total Systematic Uncertainty	19.8
MC Statistics	0.8
Data Statistics	10.0
Total Uncertainty	22.2

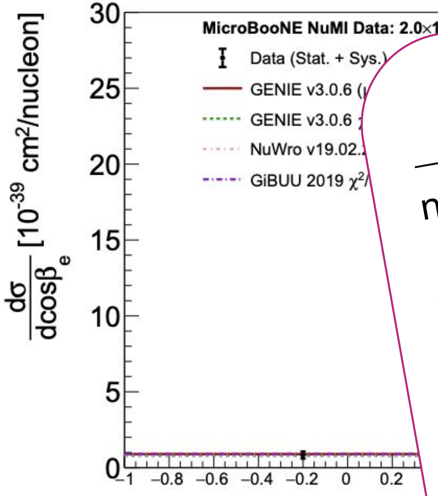
Differential $\nu_e + \bar{\nu}_e$ CC Inclusive @ NuMI

Arxiv.2109.06832
submitted to PRL

First Measurement of Inclusive ν_e and $\bar{\nu}_e$ CC differential in Lepton Energy on Argon.

Selection main requirement: at least one shower consistent with electron hypothesis.
Biggest sample of selected ν_e CC interaction on Argon to date: 243 events.
Purity ~70%, Efficiency ~20%. Extracted cross section in good agreement with models.





In the works from NuMI ν_e:

→ ν_e CC inclusive differential in neutrino energy

→ ν_e CC 1eNp exclusive

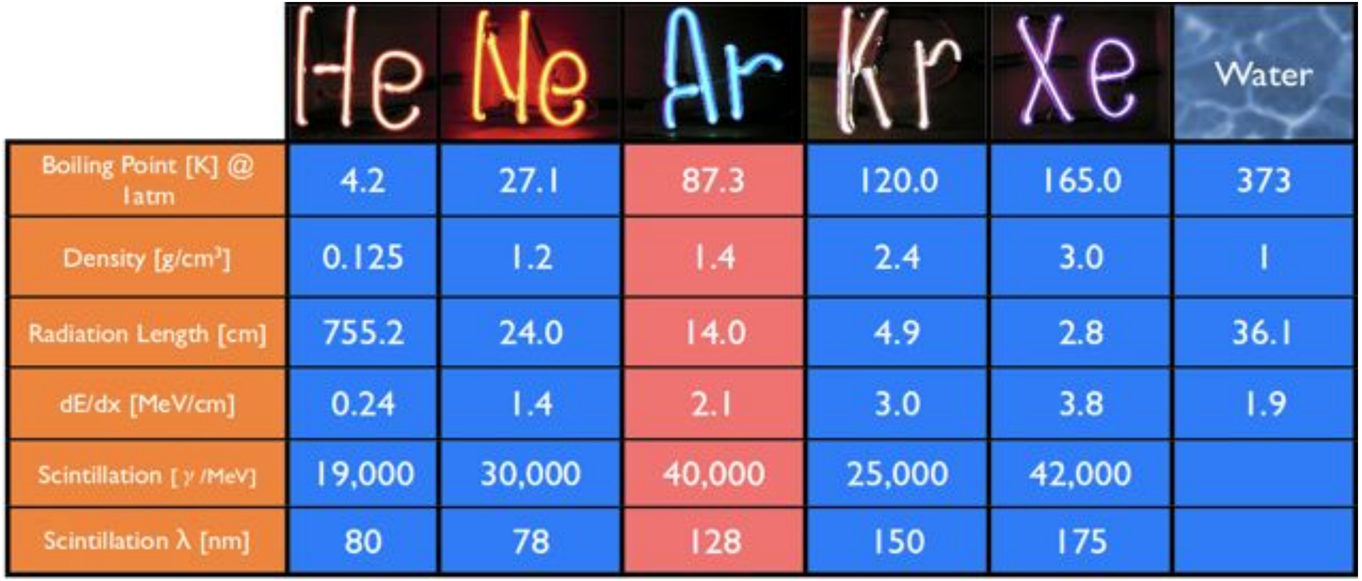
→ ν_e/ν_μ ratios

→ Anti ν_e inclusive

Why Argon? And Why Liquid?

Dense 40% more dense than water → many nuclear centers for interaction
Abundant 1% of the atmosphere → “cheap”, we can build big detectors!
Ionizes easily 55,000 electrons / cm
High e^- lifetime Noble liquid!

Standard ionization mechanism:
energy transferred from charged particle to the medium knocks off ionization electrons if the energy is high enough
(LAr work function 23.6 eV).



	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

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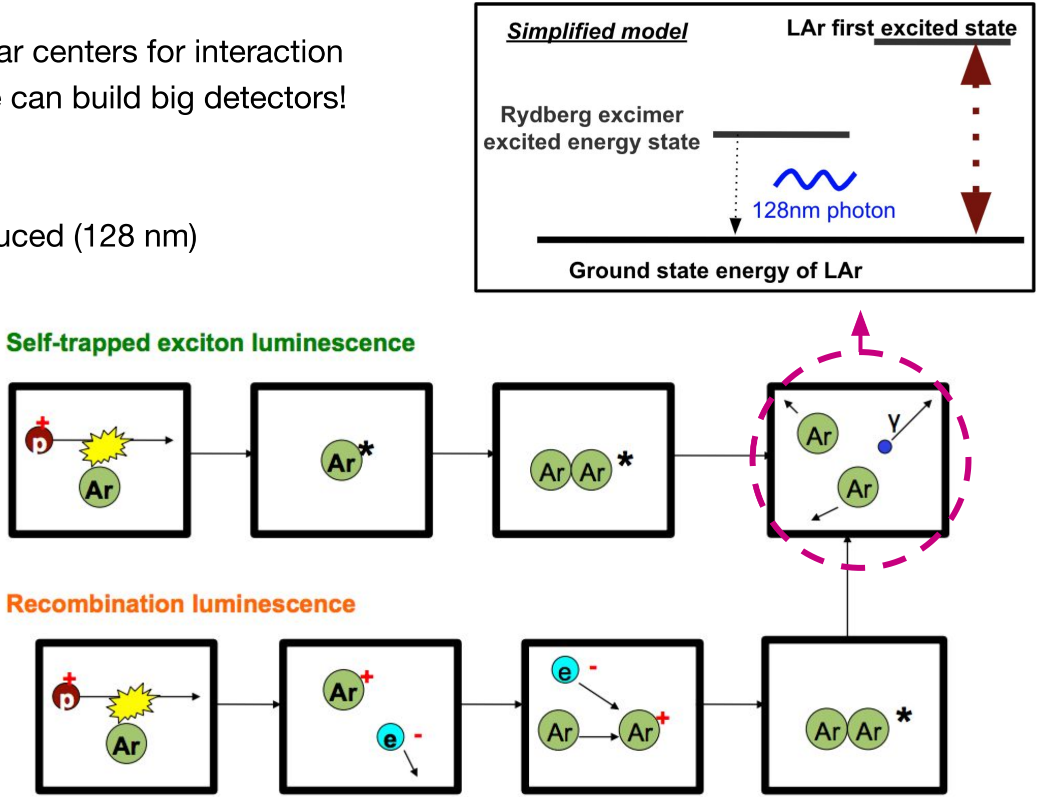
Ionizes easily 55,000 electrons / cm
High e^- lifetime Noble liquid!
Lots of scintillation light Transparent to light produced (128 nm)



Two detection mechanisms:
Ionization Charge and
Scintillation Light

Exploring the Sterile Neutrinos @ SBN

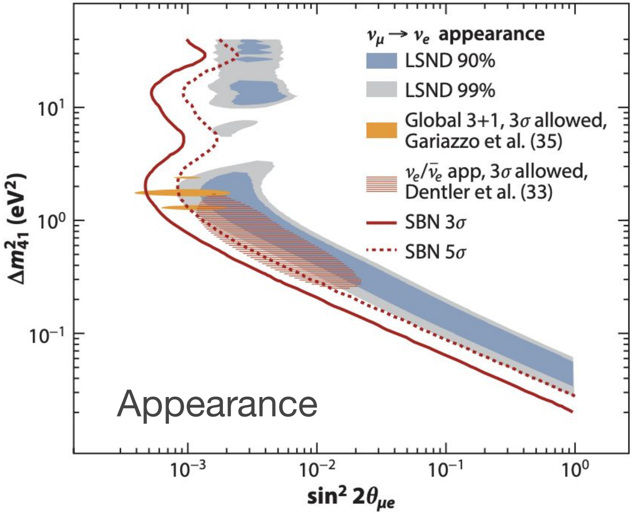
SBN will provide a **conclusive verification** of the **sterile neutrino** hypothesis

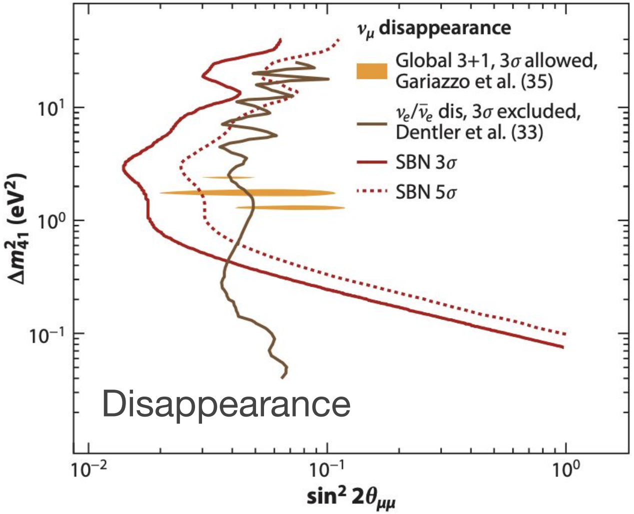
In 3 years of data-taking (6.6 10^{20} pot):

→ Same detector technology will greatly reduce the systematic errors:

SBND (near detector) will characterize the un-oscillated beam composition and spectrum.

→ Combined analysis of SBND and ICARUS data expected to cover the currently allowed parameter region with 5σ sensitivity both in appearance and disappearance channels





Annual Rev. Nucl. Part. Sci. 2019.69:363-387

A glance at the Neutrino Cross Section Panorama at LArTPCs

ν_μ CC inclusive cross section

ArgoNeuT: Single-differential cross section

ArgoNeuT: Updated single-differential cross section

MicroBooNE: Double-differential cross section

ν_μ CC exclusive channels

MicroBooNE: νμ CCQE-like scattering

ArgoNeuT: νμ and Anti-νμ CC2p production

MicroBooNE: νμ CCπ0 production

ArgoNeuT: νμ and Anti-νμ NCπ0 production

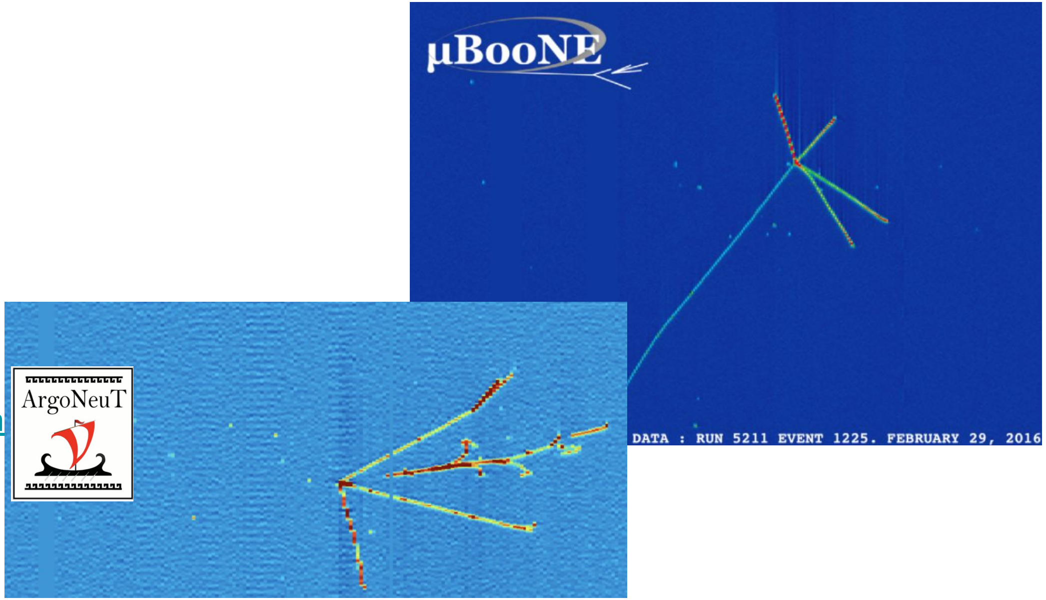
ArgoNeuT: νμ and Anti-νμ CCπ+ production

ArgoNeuT: νμ and Anti-νμ Coherent CCπ+ production

ν_e + Anti-ν_e CC inclusive cross section

ArgoNeuT: ve and Anti-ve Inclusive in lepton angle

MicroBooNE: Total ve and Anti-ve CC Inclusive



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ArgoNeuT: νμ and Anti-νμ CCπ+ production

ArgoNeuT: νμ and Anti-νμ Coherent CCπ+ production

And many more to come!

Extensive Cross Section campaigns for the SBN program,

MicroBooNE: public notes

SBND: ~ 7 million ν_μ and ~ 50,000 ν_e in 3 years

ICARUS: high-stat ν_e from NuMI off axis, ~ 10^5 events/yr

as well as DUNE Near Detectors

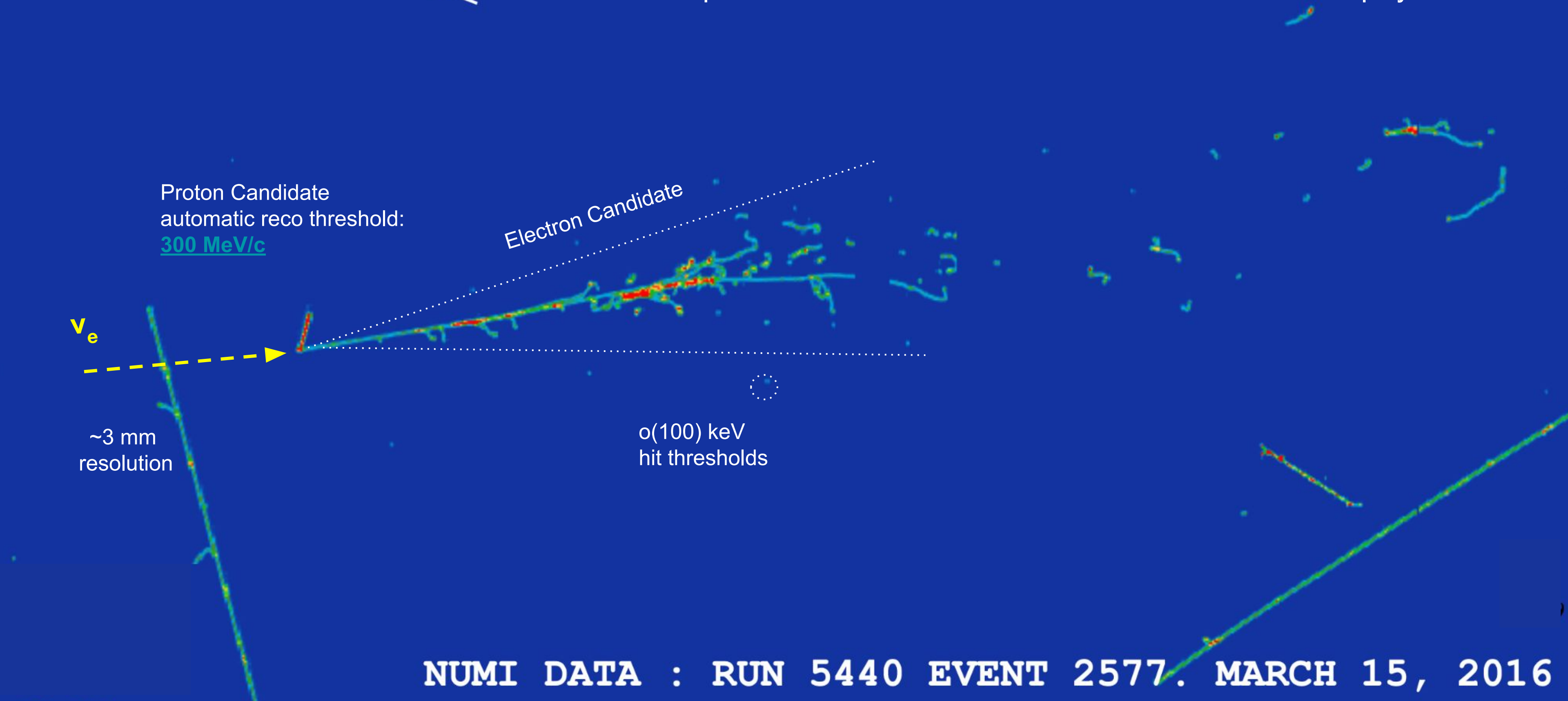
Fermilab

µBooNE

LArTPC in action

Extremely detailed 3D images + calorimetry + PID:

unprecedented tool for neutrino interaction & BSM physics



Proton Candidate
automatic reco threshold:
300 MeV/c

Electron Candidate

ν_e

~3 mm
resolution

o(100) keV
hit thresholds

μBooNE

LArTPC in action

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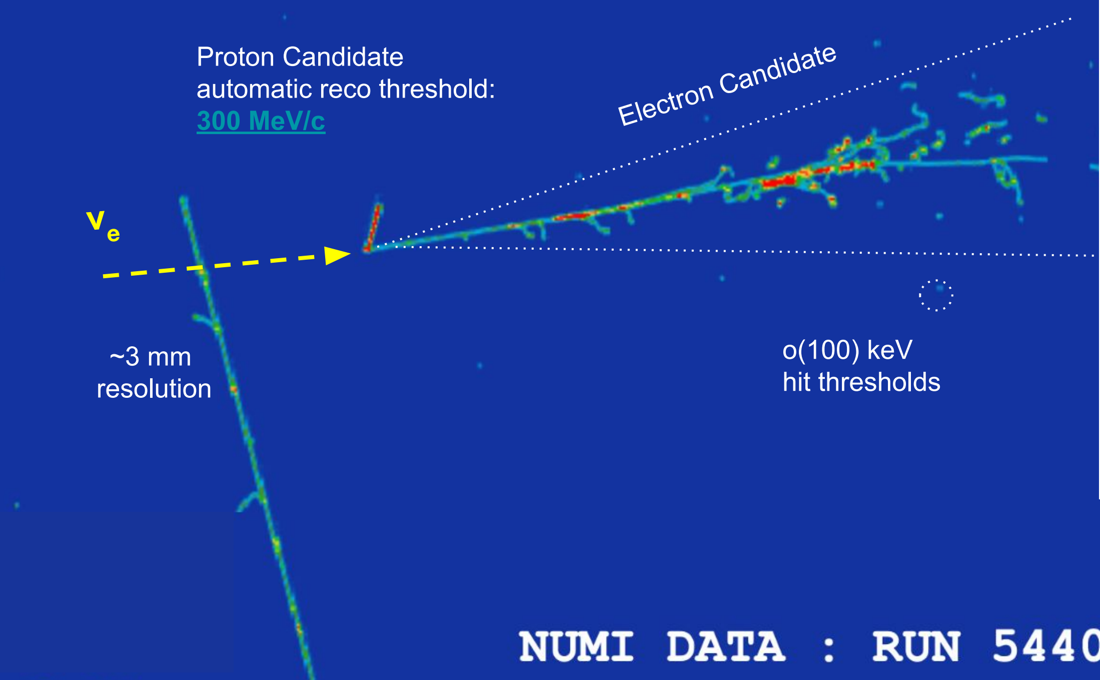

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automatic reco threshold:
300 MeV/c

Electron Candidate

~3 mm
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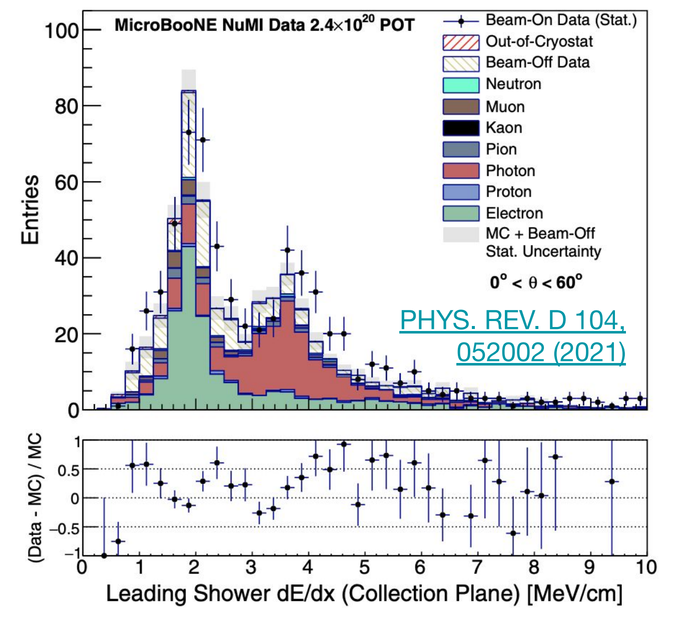
o(100) keV
hit thresholds

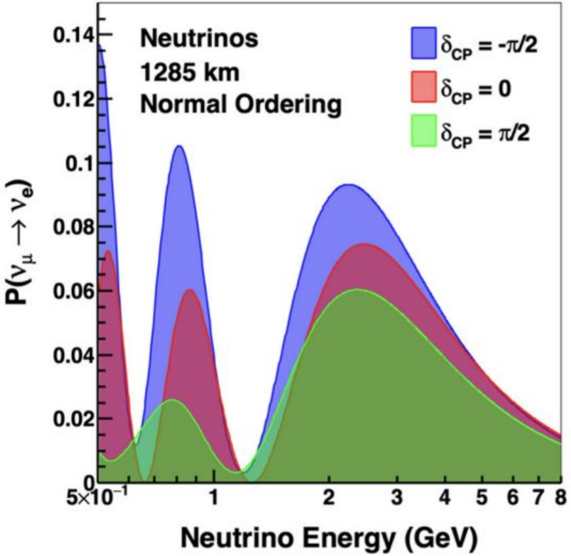
NUMI DATA : RUN 5440 EVENT 2577. MARCH 15, 2016

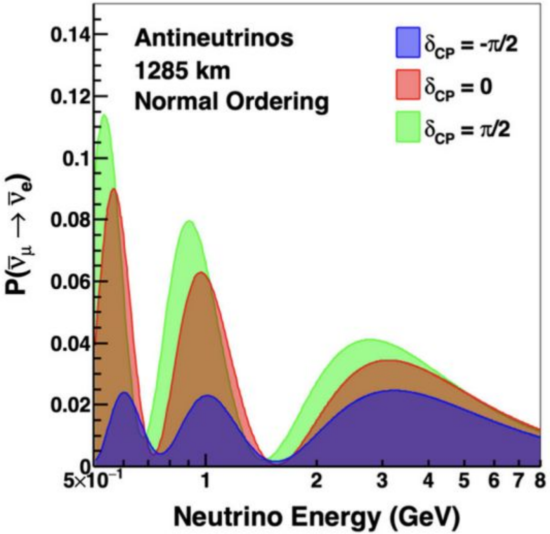


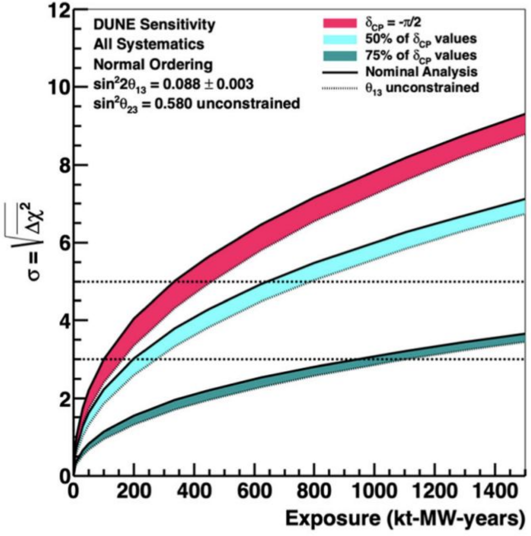
PHYS. REV. D 104, 052002 (2021)

DUNE Long Baseline Oscillations

On long baseline, DUNE will leverage oscillations to measure δ_{CP}, mass ordering, θ_{23} octant.
The 1300 km baseline → powerful handle: **sensitivity to the matter effect**
a large asymmetry in the $\nu_\mu \rightarrow \nu_e$ vs Anti-$\nu_\mu \rightarrow$ Anti-ν_e oscillation probabilities (±40% at peak flux)
More than allowed by max CP-violation: mass ordering and δ_{CP} can be determined at the same time.
Epjc 10052 020 08456





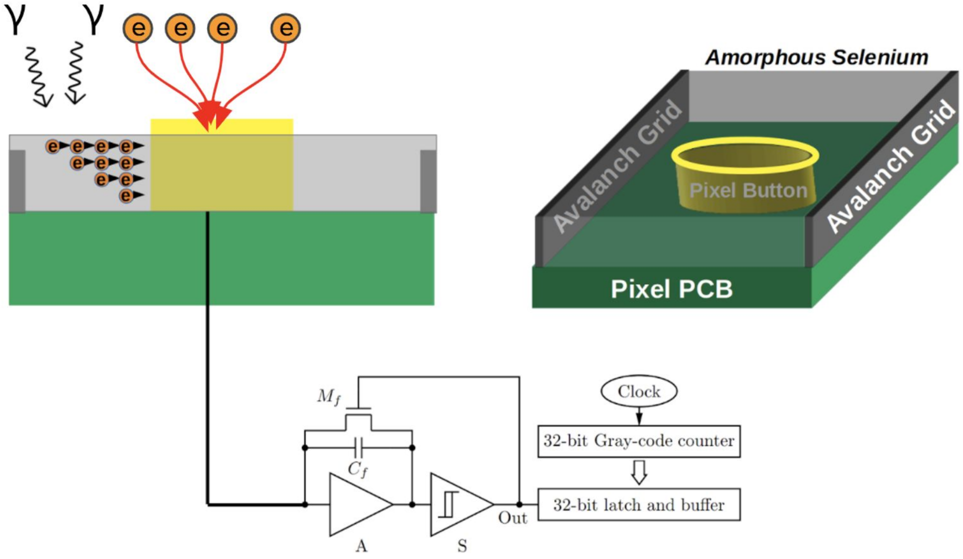


Amorphous Selenium Coatings

Multiple modality pixel: develop pixel **coatings with photo-conducting** material.

First material:
Amorphous Selenium
→ Commonly used in
X-Ray digital radiography devices
→ Never used in cold: LAr ~ 87k!
(Big “make it or break it” challenge)

When VUV γ strikes the A-Se,
the γ is absorbed and a e-h pair is created
with an extremely high probability
if the A-Se layer is thick enough.



Q-Pix Readout

Short Baseline Neutrino Anomalies

Four main anomalies have been observed in neutrino experiments at short baseline in the last 20 years.

Appearance of v_e/anti-v_e in v_μ/anti-v_μ beams at particle accelerators (LSND & MiniBooNE).

Disappearance of anti-v_e detected from nuclear reactors (reactor anomaly).

Disappearance of v_e from intense calibration sources in solar v experiments (gallium anomaly)

Experiment	Type	Channel	Significance
LSND	DAR accelerator	$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	3.8 σ
MiniBooNE	SBL accelerator	$\nu_\mu \rightarrow \nu_e$ $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$	4.5 σ 2.8 σ
GALLEX/SAGE	Source – e capture	ν_e disappearance	2.8 σ
Reactors	β decay	$\overline{\nu}_e$ disappearance	3.0 σ

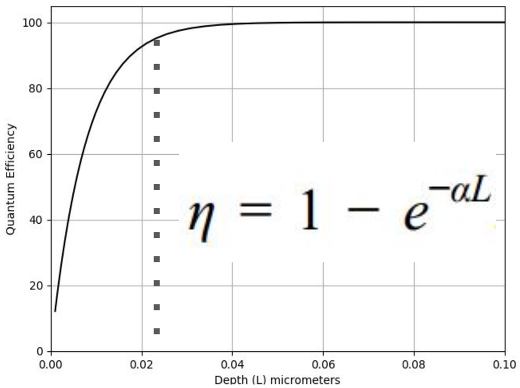
While independent explanations are not excluded, a unifying hypothesis exists:
mixing of the standard neutrinos with a fourth, **non–weakly interacting sterile species**,
with mass splittings $\Delta m^2{}_{43} \approx \Delta m^2{}_{42} \approx \Delta m^2{}_{41} \sim O(1\ eV^2)$: main search for SBN experiments.

What’s special about selenium?

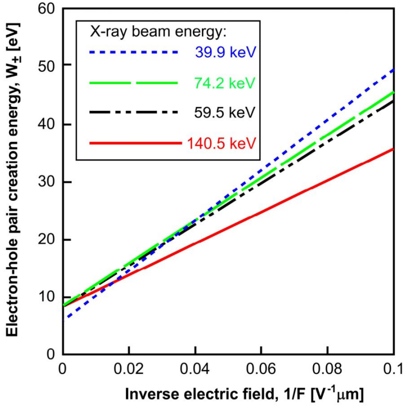
The literature on amorphous selenium reports an attenuation coefficient α ~130 μm^{-1} for photons at 128 nm, resulting in a **QE than 99% for thin coatings (> 1 μm)**

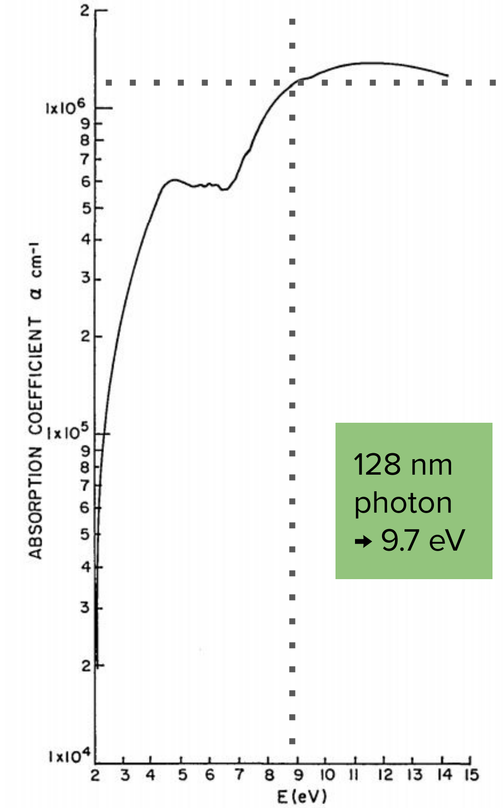
1 γ results on avg in ~ 1.3 e-h pairs: single photon sensitivity not excluded.

At the theoretical break down voltage (90 V/μm) the gain factor is ~ 1.5 10^3
Electron yield for 2+ γ is compatible w/ Q-Pix readout [1800-6000 e]



$$\eta = 1 - e^{-\alpha L}$$





128 nm photon → 9.7 eV

FIG. 6. The spectral dependence of the absorption coefficient, α, of amorphous selenium.

What’s special about selenium?

The literature on amorphous selenium reports an attenuation coefficient α ~130 um^{-1} for photons at 128 nm.

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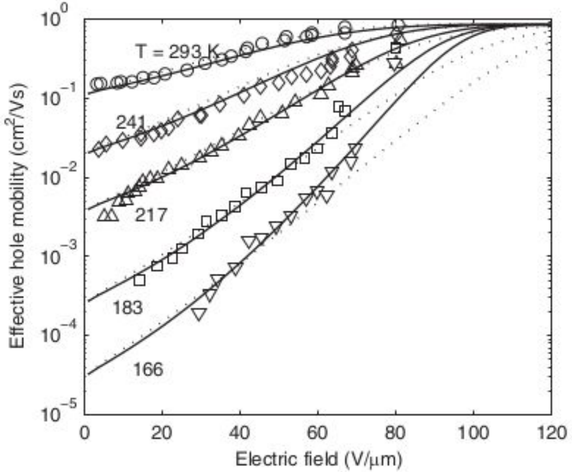
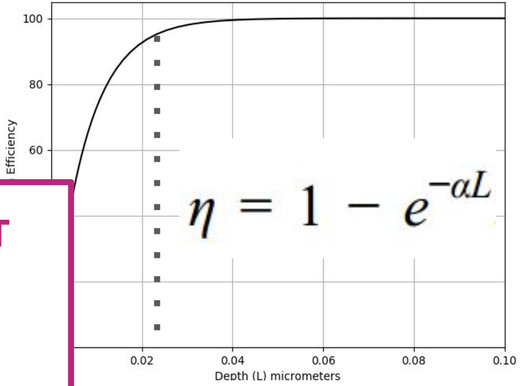
Mobility of carriers might drop at low T needed for the Ar to be Liquid





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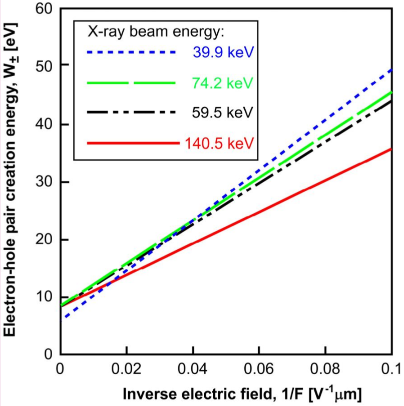

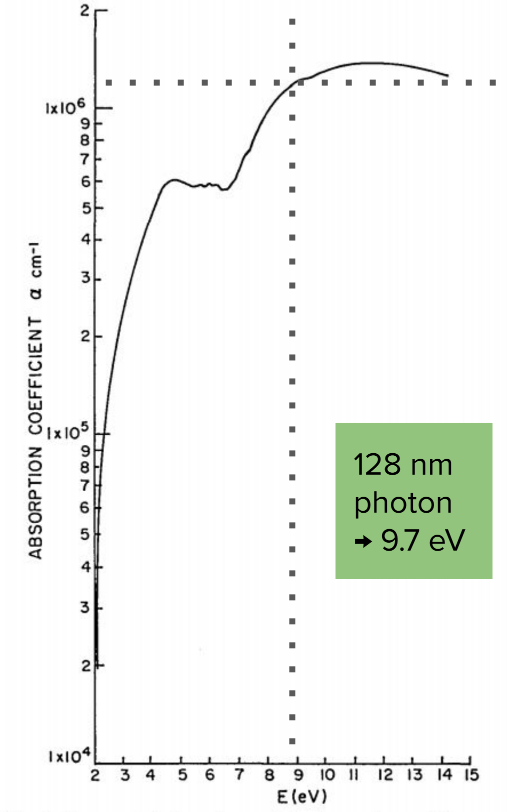

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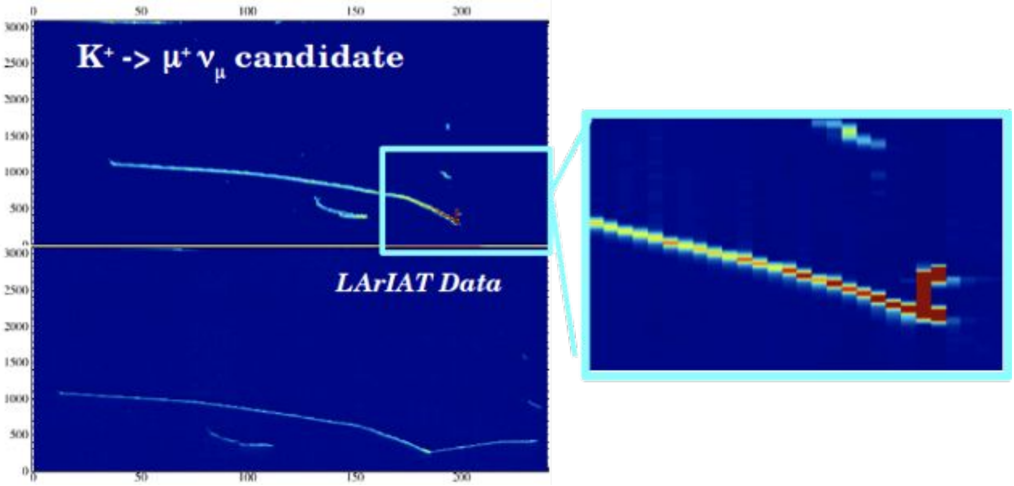
FIG. 6. The spectral dependence of the absorption coefficient, α, of amorphous selenium.

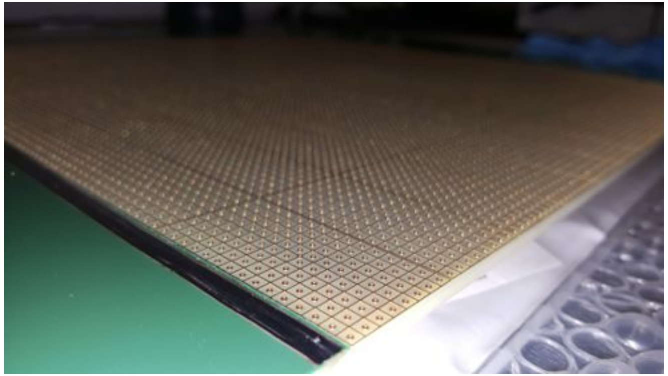
Making the LArTPC better

A fundamental issue with LArTPC w/ projective readouts (wires): highly **anisotropic detectors**... the readout **affects the possibility of maintaining the intrinsic 3D quality of the events.**

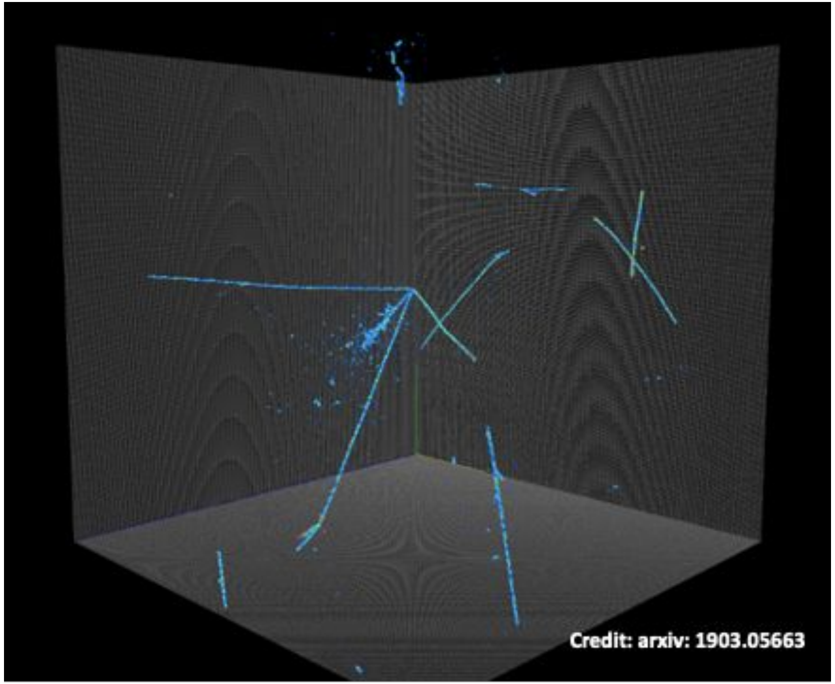
In 2D projective readouts, the readout space **DOES NOT coincide w/ the physical space:** traditional LArTPCs use sets of wire planes at different angles to reconstruct the transverse position → automatic plane matching is difficult, especially for complex topologies.

Constructing anode planes with pixels instead of wires can **solve a number of shortcomings** of 2D projective readouts.





Pixels!


Credit: arxiv: 1903.05663

More resilient against single point failure and simpler to construct.

Small pixels sizes (4x4 mm^2) provide **comparable spatial resolution**, but the **readout space coincides w/ the physical projected space**:
→ native 3D reconstruction
→ abated ambiguities (mm vs m projections)

Shortcomings: massive amounts of readout channels “Pixelizing”
→ a massive detector such as a 10kTon DUNE module requires **O(130.0 million) pixels vs O(1.5 million) wires.**

→ PCB is opaque to light: need innovative solutions to light collection system.

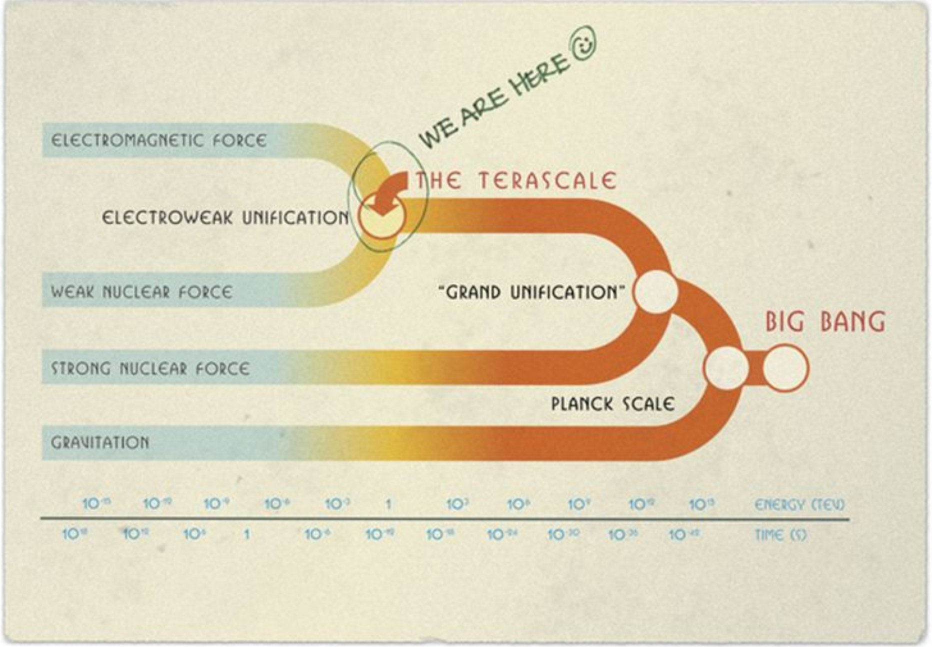
DUNE non-accelerator physics: Baryon Number Violating Processes

Every interaction in the SM **conserves baryon number**, yet this conservation is “accidental”: no underlying symmetry

Proton or bound neutron **decay, or nnbar oscillation** can occur only as a **violation of baryon number** and it’s predicted by almost every Grand Unified Theory.

The detection of even **one** rare process event would open a window on GUTs exploration.

Possible in DUNE FD given the sheer mass of the detector



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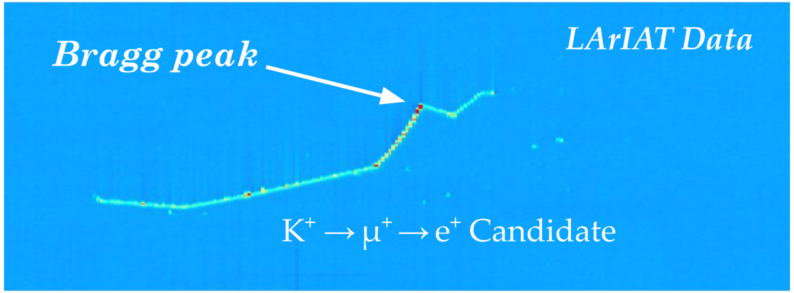
Possible in DUNE FD given the sheer mass of the detector

What would the signatures of such processes be in a LArTPC?

Signal for proton decay (golden mode):

p → K^+ + Anti-ν



My thesis