Improving LArTPC Performance With Photosensitive Dopants

Joseph Zennamo,
Fermilab

Based on Snowmass LOI by A. Mastbaum, F. Psihas, J. Zennamo

Snowmass Summer Study 2022
March 19th, 2021

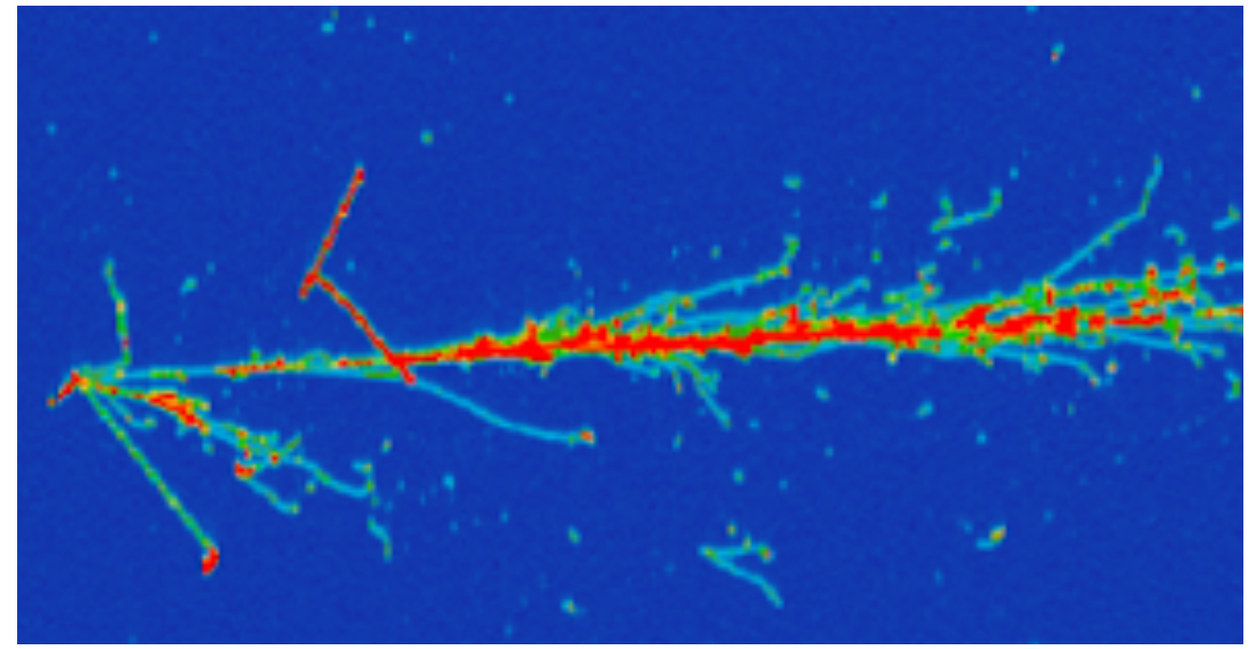
Fermilab

Publication in preparation

Physics With LArTPCs

- LArTPCs are highly capable neutrino detectors
  - Cheap, scalable, dense, high-resolution readout (spatial and calorimetric)
- Traditionally, used to study GeV-scale neutrino interactions
- Significant interest to enhance MeV-scale LArTPC performance with an eye towards future DUNE detectors

GeV-scale ν_e interaction in LArTPC



arxiv:2203.00740

Low-Energy Physics in Neutrino LArTPCs

Contributed Paper to Snowmass 2021

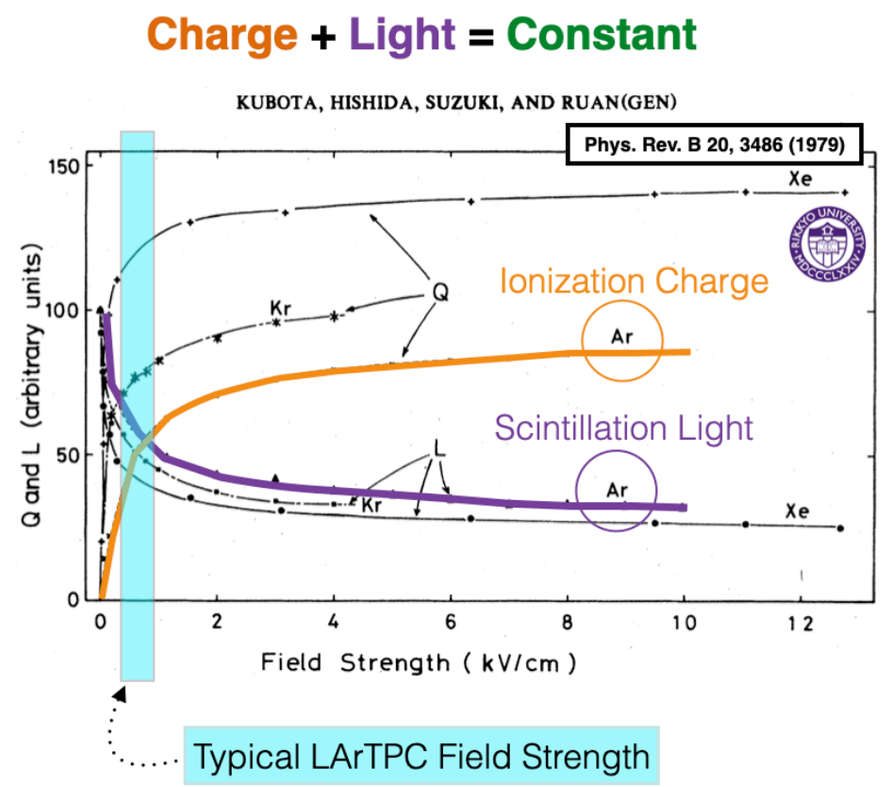
D. Caratelli,[17,*] W. Foreman,[44,*] A. Friedland,[99,*] S. Gardiner,[33,*] I. Gil-Botella,[21,*] G. Karagiorgi,[26,*] M. Kirby,[33,*] G. Lehmann Miotto,[20,*] B. R. Littlejohn,[44,*] M. Mooney,[27,*] J. Reichenbacher,[100,*] A. Sousa,[23,*] K. Scholberg,[29,*] J. Yu,[108,*] T. Yang,[33,*]

How LArTPCs Work

Charge readout

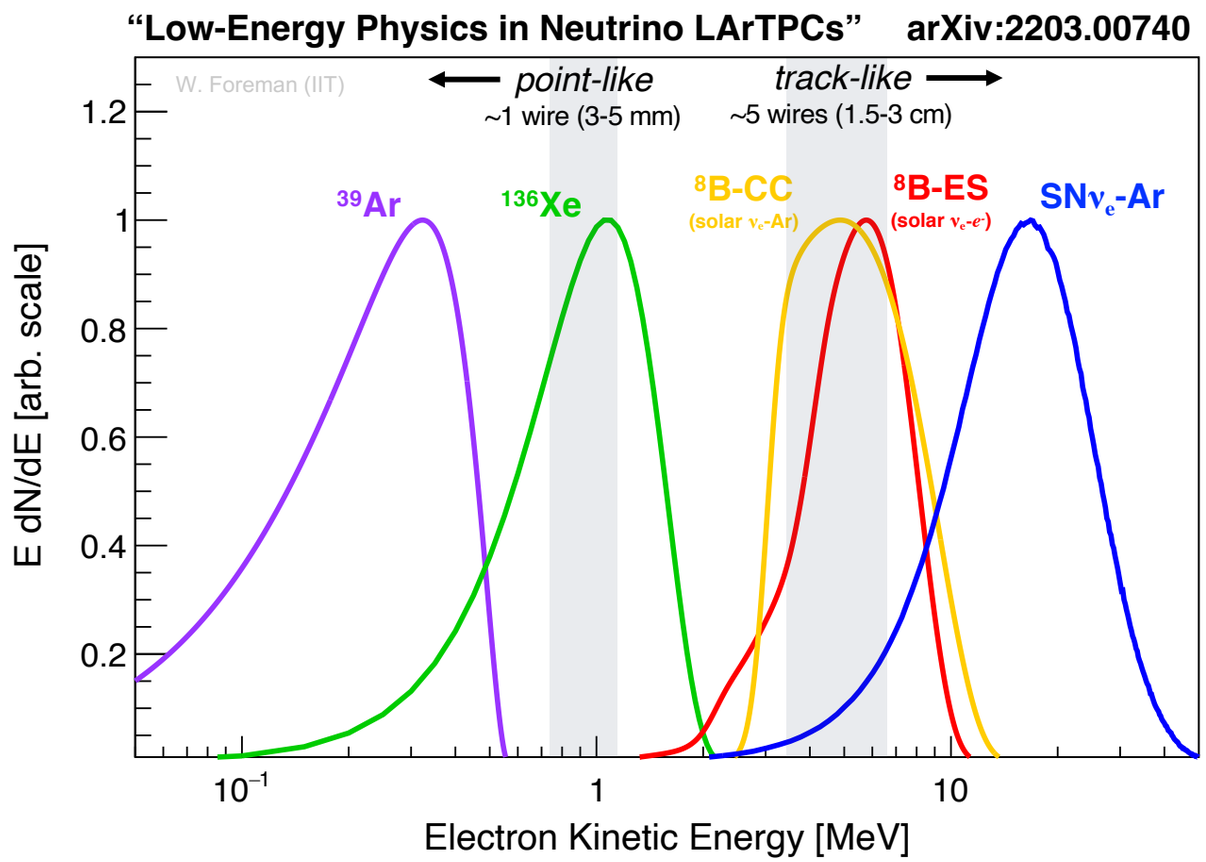
Electric Field

Applied voltage

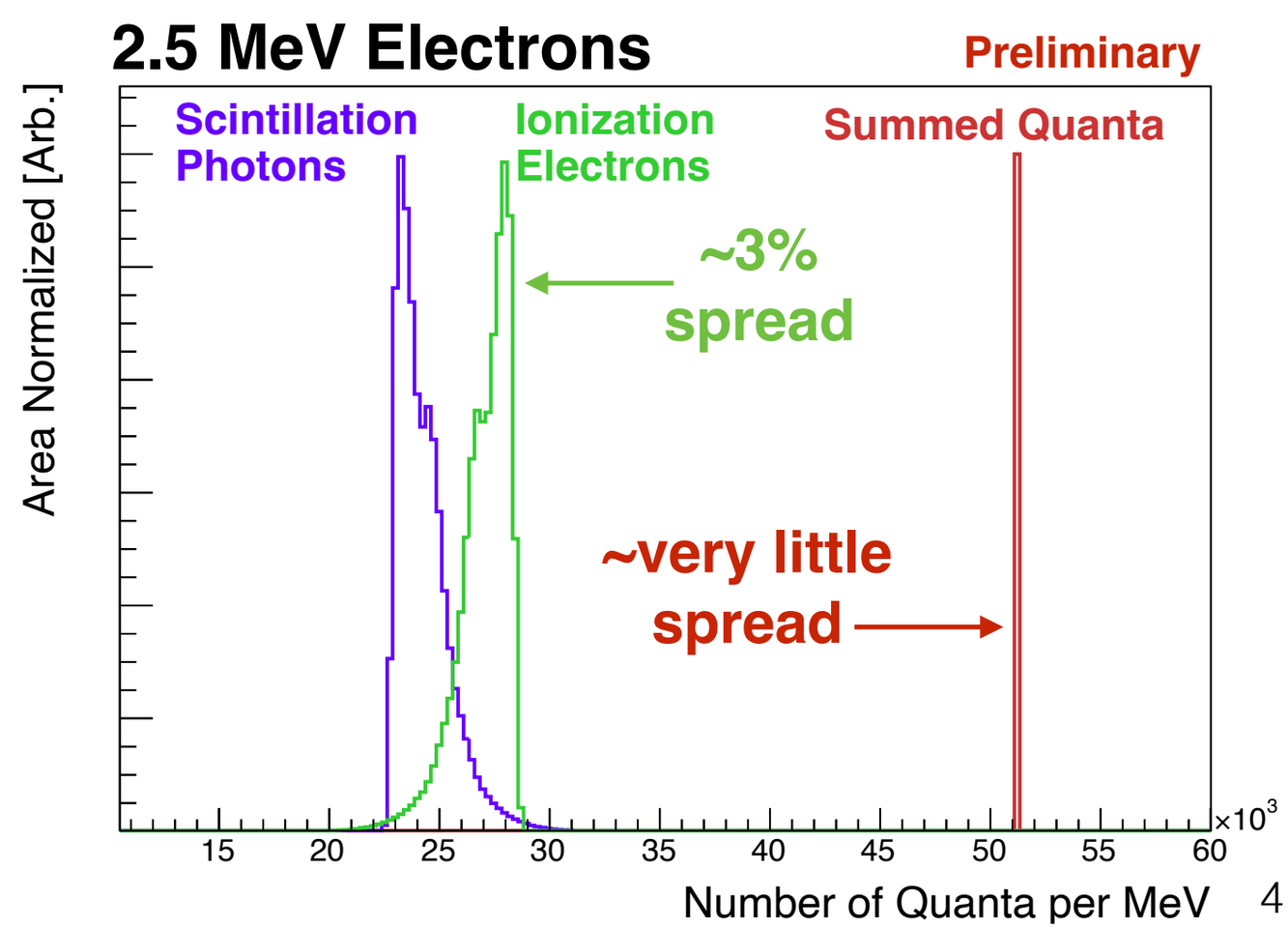


Using charge <u>or</u> light one could measure the energy deposited

MeV-Scale Energy Deposits

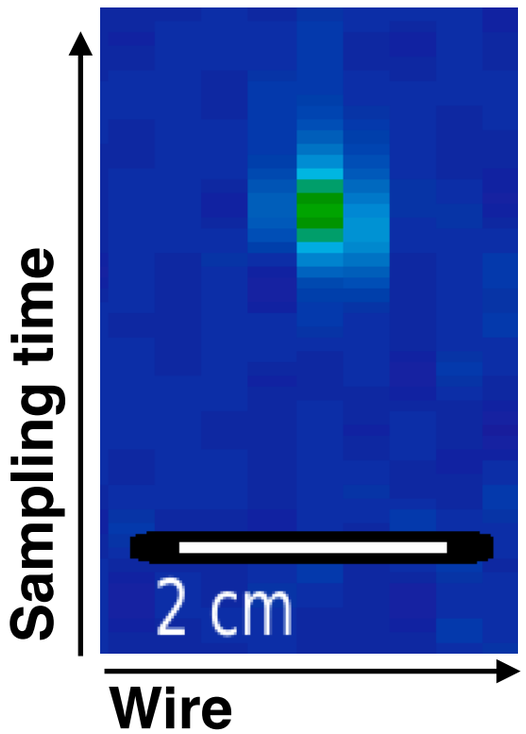


- MeV-scale signals generally fall on 1-2 channels in LArTPC
  - **Energy measurements via range are unreliable, instead need to focus on calorimetry**



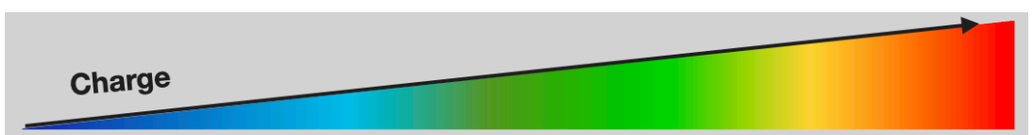
- In pure LAr, energy measurement is degraded when only charge is used
  - Charge and light are correlated
  - **Summing these signals leads to reduced spread**

MeV-Scale Energy Deposits



Simulated 2.5 MeV electron raw data

0.001% of the total readout surface area



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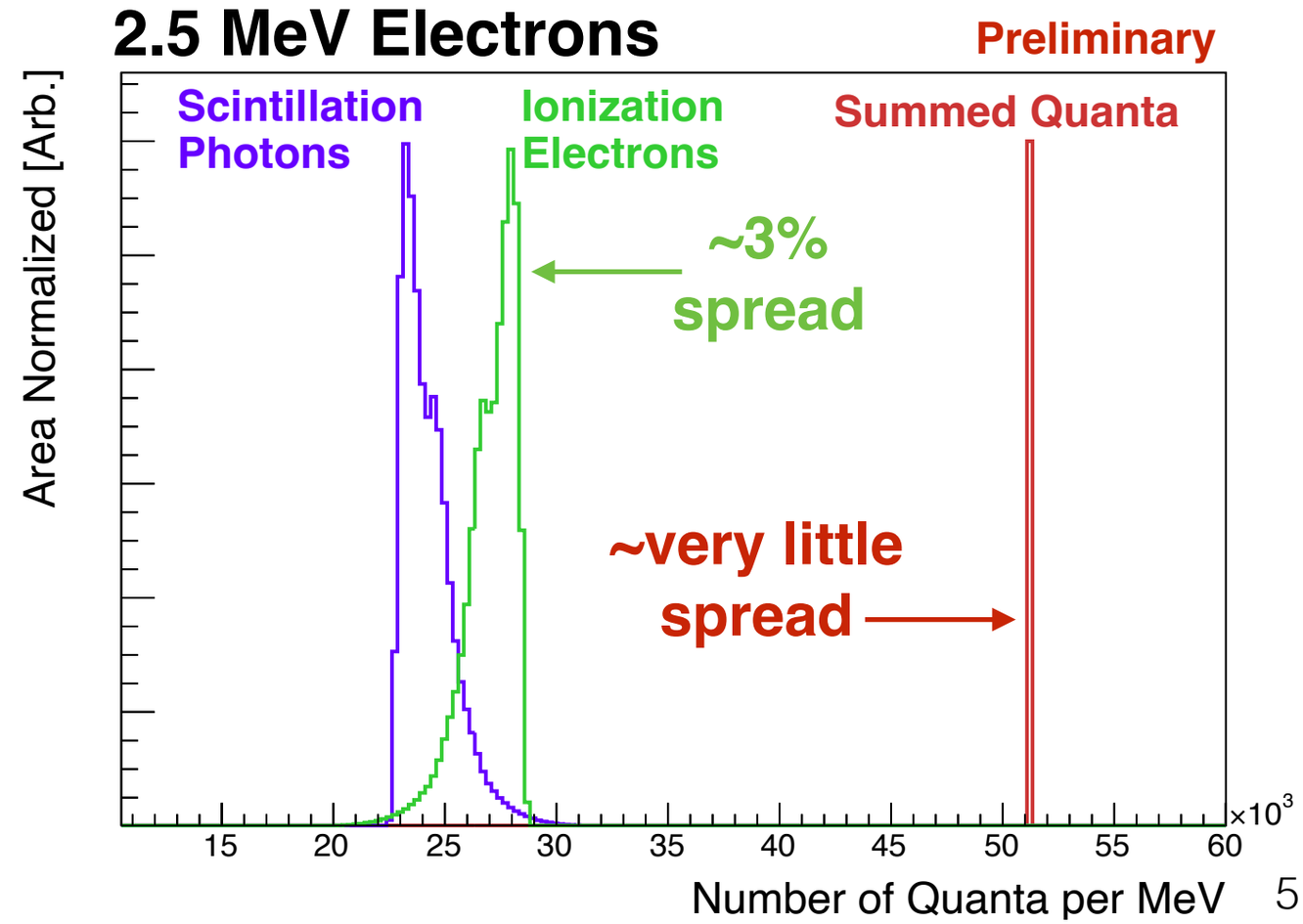
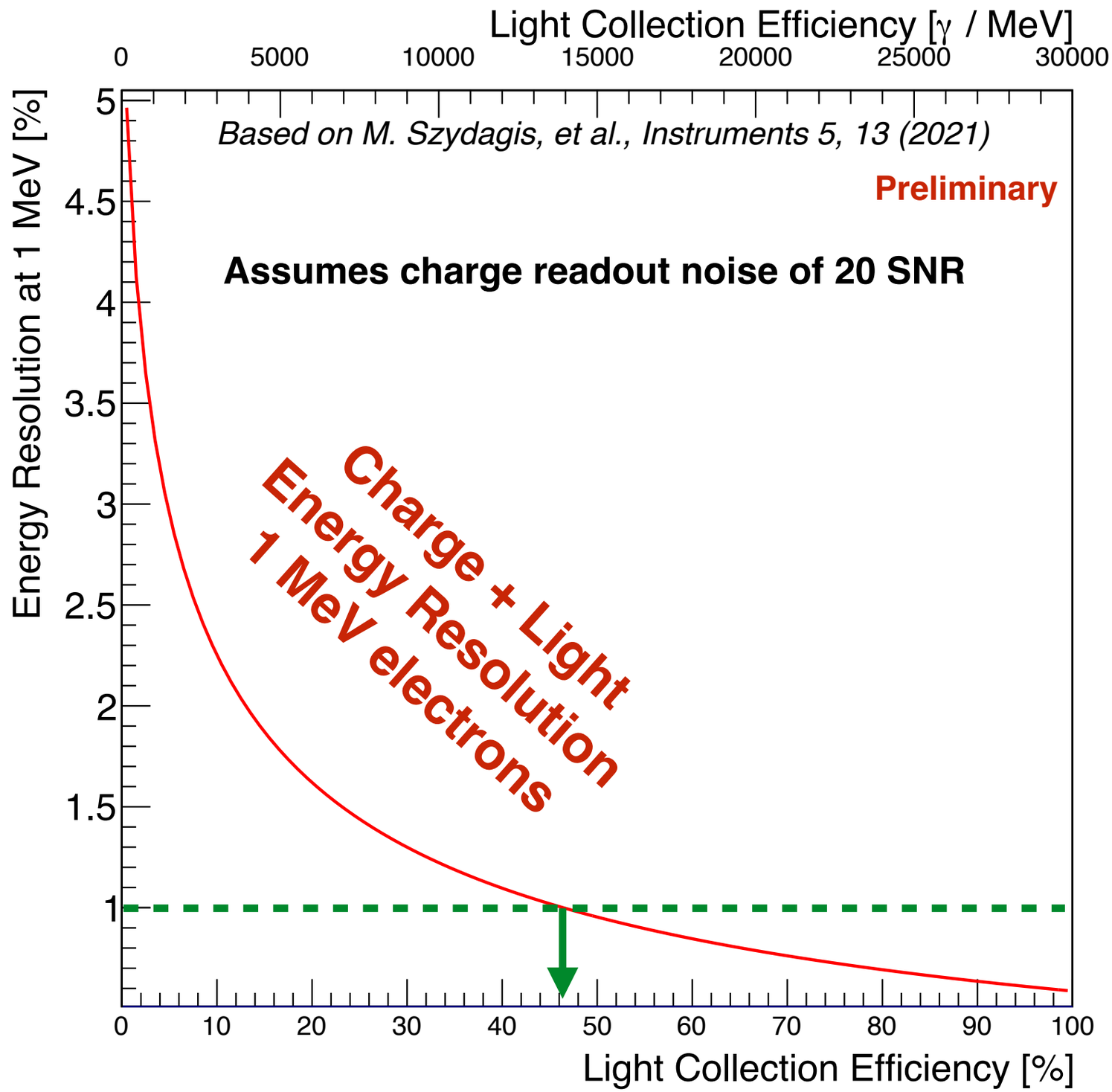


Combining Light and Charge

- Energy measurements improved by combining **<u>light & charge</u>**
- The NEST collaboration studied resolution vs. light collection
  - Results based on only on microphysical simulation
- **1%-level resolution can be achieved by collecting ~50% light**



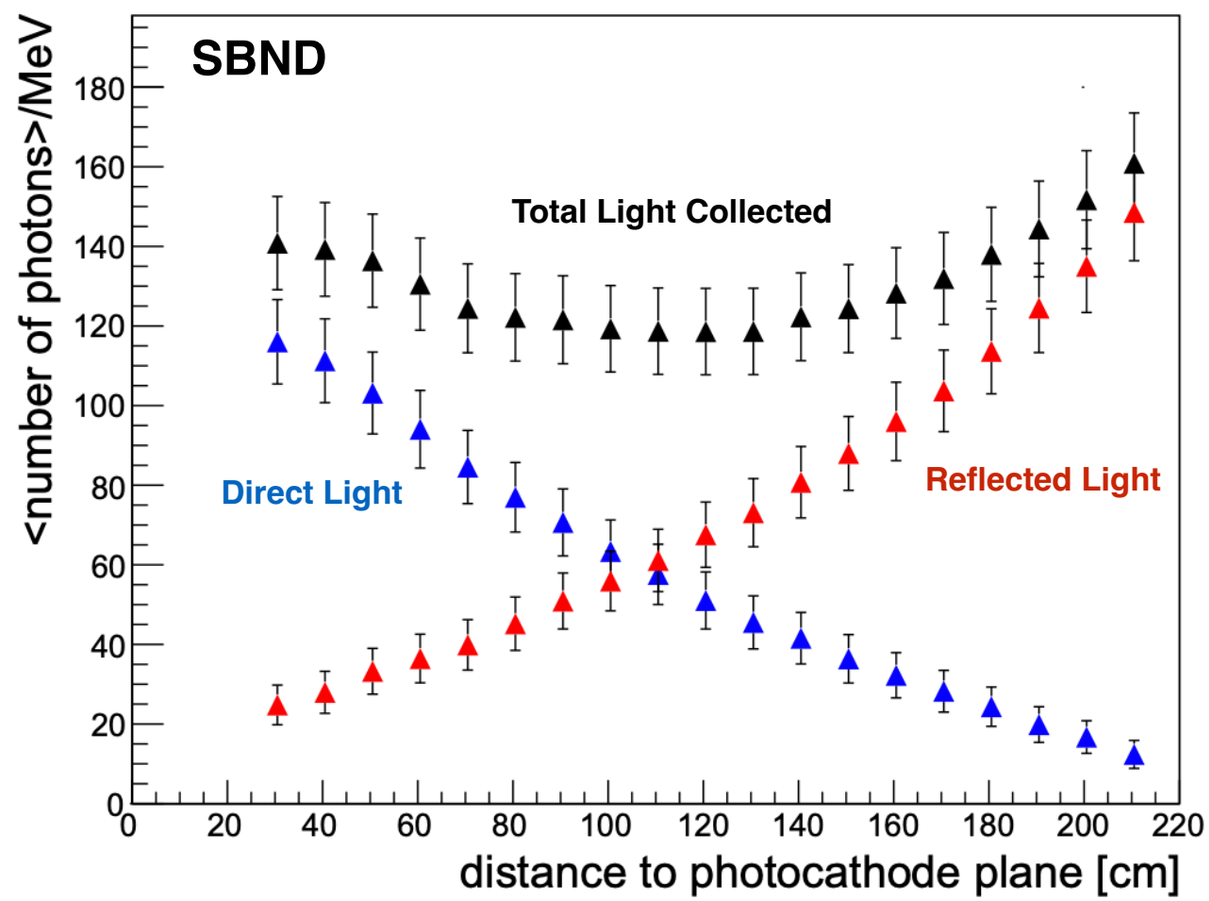
Light Collection in LArTPCs

- Efficient collection of light is challenging in large LArTPCs
  - **Light is radiated isotropically** and photon detectors generally sit on the LArTPC surfaces

- With substantial effort SBND has the highest light collection efficiency of any large LArTPC
  - **Collects ~1% of the light**
  - **Sufficient for GeV-scale program**

Journal of Physics: Conf. Series 888 (2017) 012094

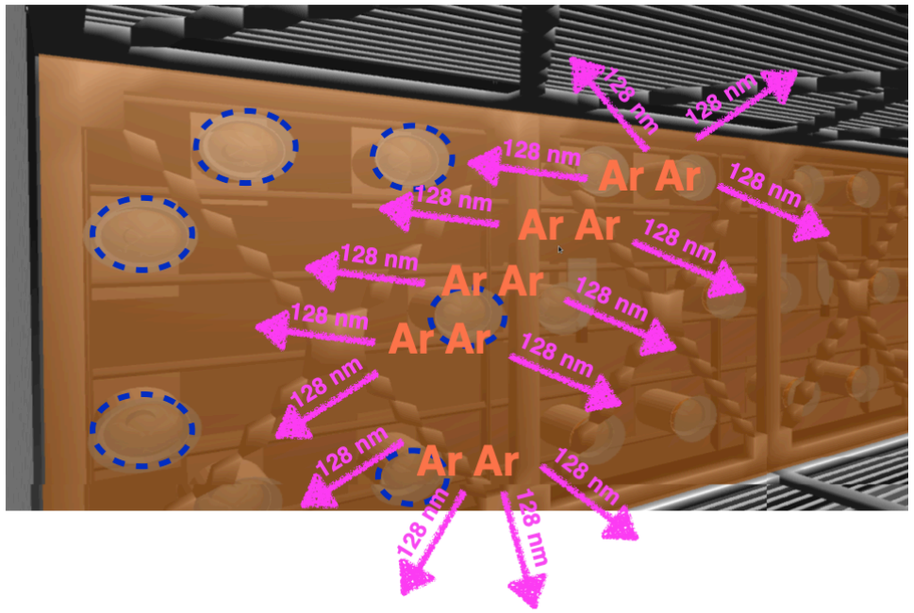
D. Garcia-Gamez

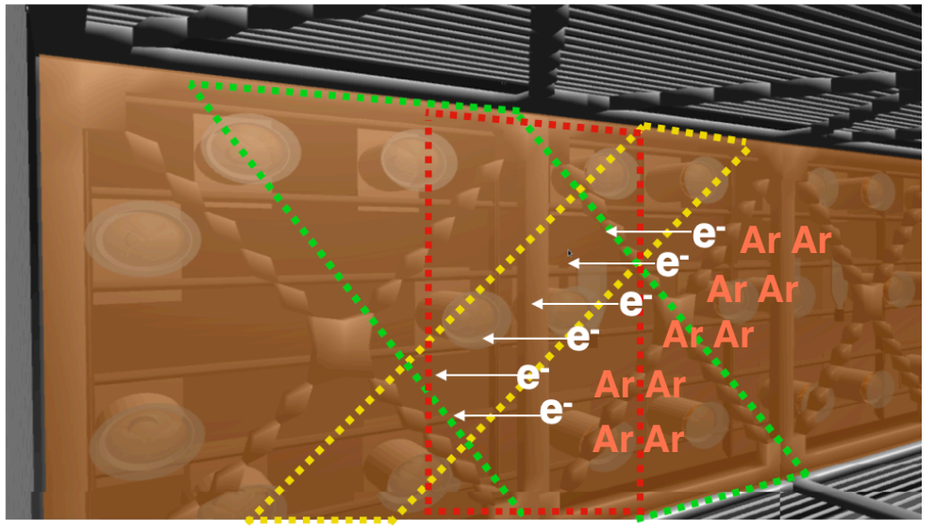


For MeV-scale measurements a solution that increases the light collected by 100x is needed

Another Way? Photo-conversion

- To collect the largest possible fraction of the deposited energy we could **convert the light to charge**
- This would take the isotropic, short wavelength light and convert it into directional electrons that are already efficiently collected
  - **This would allow us to collect the most information about the scintillation signal** and enable a higher precision measurement of the energy deposited
- This conversion can be achieved through doping with a special class of hydrocarbons





Photosensitive Chemicals

- These chemicals work by having an ionization energy near the scintillation photon energy
  - Convert scintillation light into ionization charge
- Literature has explored many potential choices (*), the most commonly used:
  - Tetramethylgermane (**TMG**), $(CH_3)_4Ge$
  - Trimethylamine (**TMA**), $N(CH_3)_3$
  - Triethylamine (**TEA**), $N(CH_2CH_3)_3$

Scintillation γ Energy

LAr	9.6 eV
LAr+Xe	7.0-9.6 eV

Ionization Energies

TMG	9.2 eV
TMA	7.8 eV
TEA	7.5 eV

(In LAr these drop by ~0.7 eV)

- **These chemicals have a long track record of demonstrations in the literature starting back in the early 1970s**

(*) D.F. Anderson, Nucl. Instr. and Meth. A 242 (1986) 256

Studies for Collider LAr Calorimeters

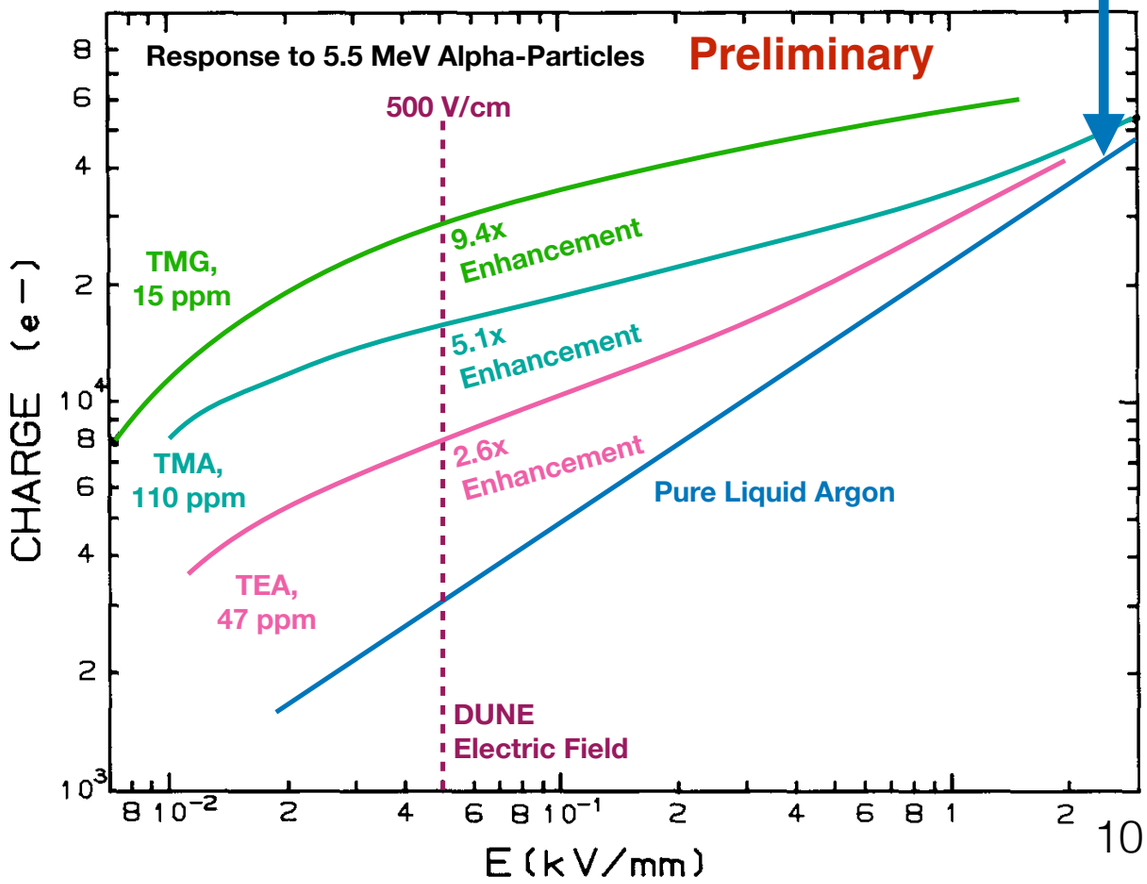
- In the 1980s various dopants were tested and found to lead to large increase of charge for highly scintillating particles
  - Using 5.5 MeV α-source they found that **TMG** increased charge collected by a factor of 9.4 at 500 V/cm
  - **Equivalent to collecting 60% of the light**
- These exciting results don't address our fundamental questions:

Would this work in a LArTPC?

Improve MeV-scale energy resolution?

Pure LAr @ 276 V/cm

Courtesy of Ivan Lepetic

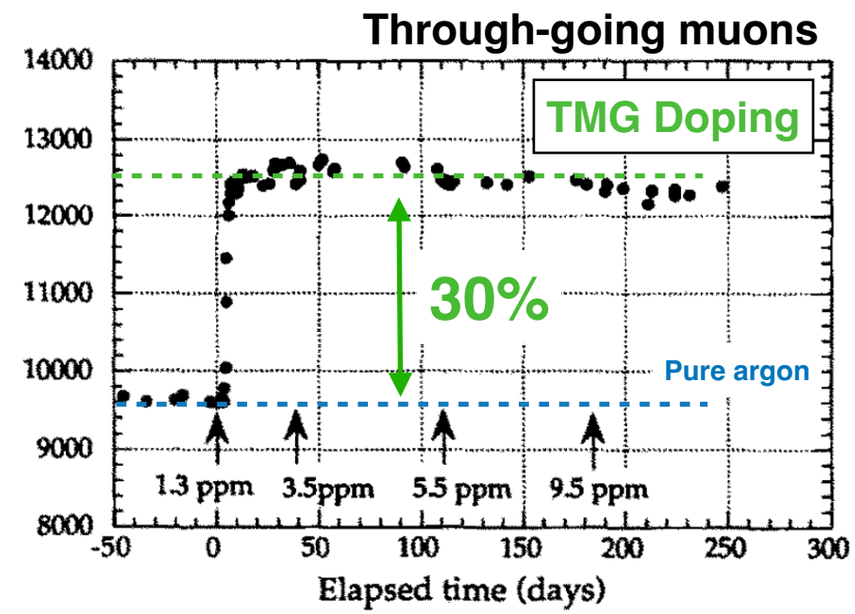


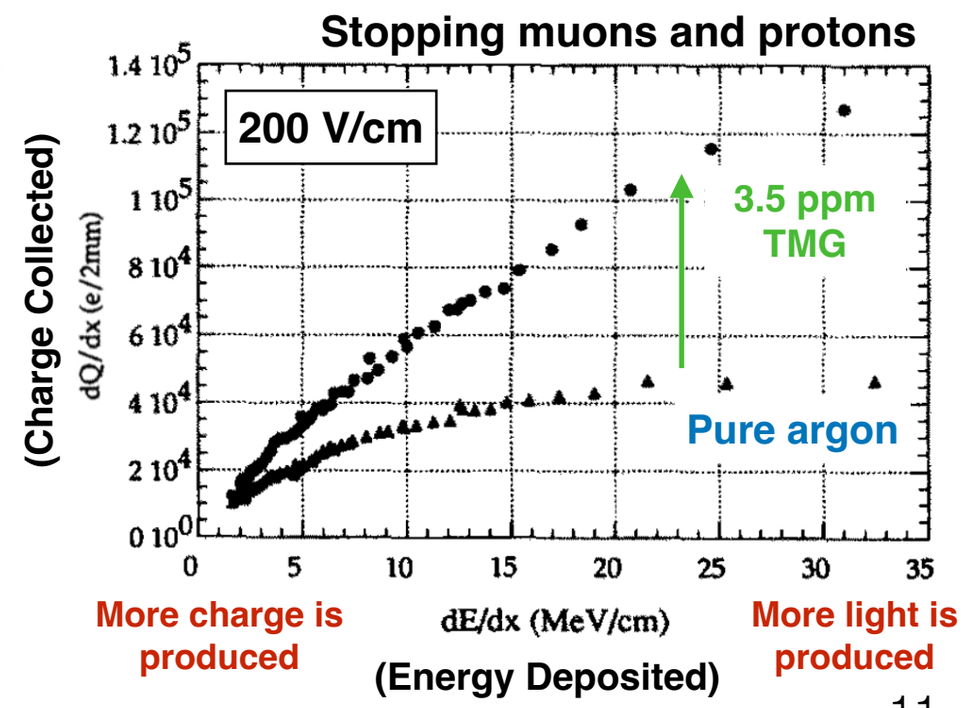
Would this work in a LArTPC?

- ICARUS doped their 3-ton prototype detector with TMG to the few ppm level
  - TMG worked with their filters and easily purified
- **After doping observed:**
  - **30% increase in muon charge signals**
  - **No degradation of electron lifetime**
  - **Stable operation over 250 days**
  - **Found a more linear detector response for highly ionizing particles**
- Would improve the LArTPC performance for the GeV-scale physics program

Nucl. Instrum. Methods. Phys. Res. B 355, 660 (1995).

ICARUS Collaboration





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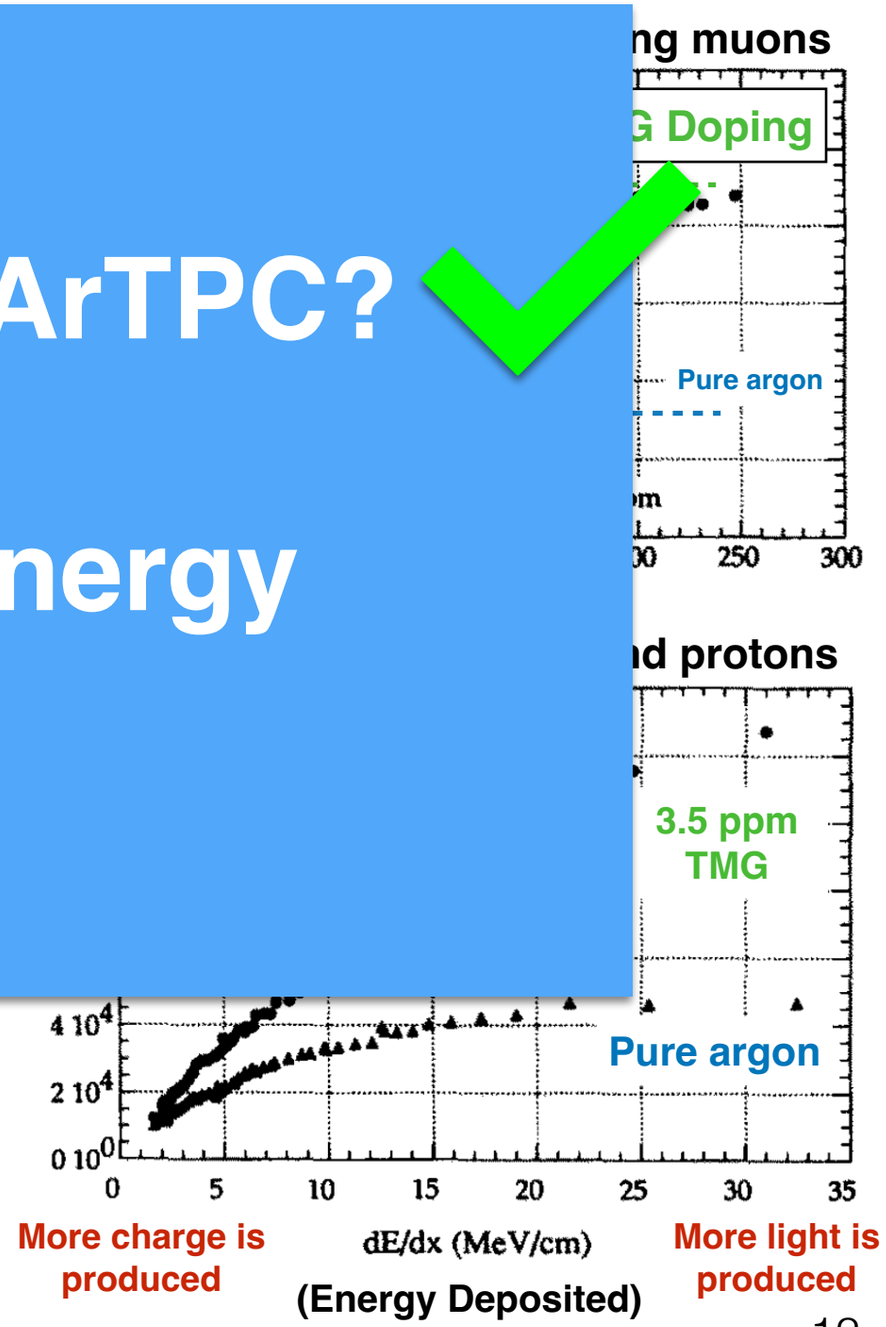
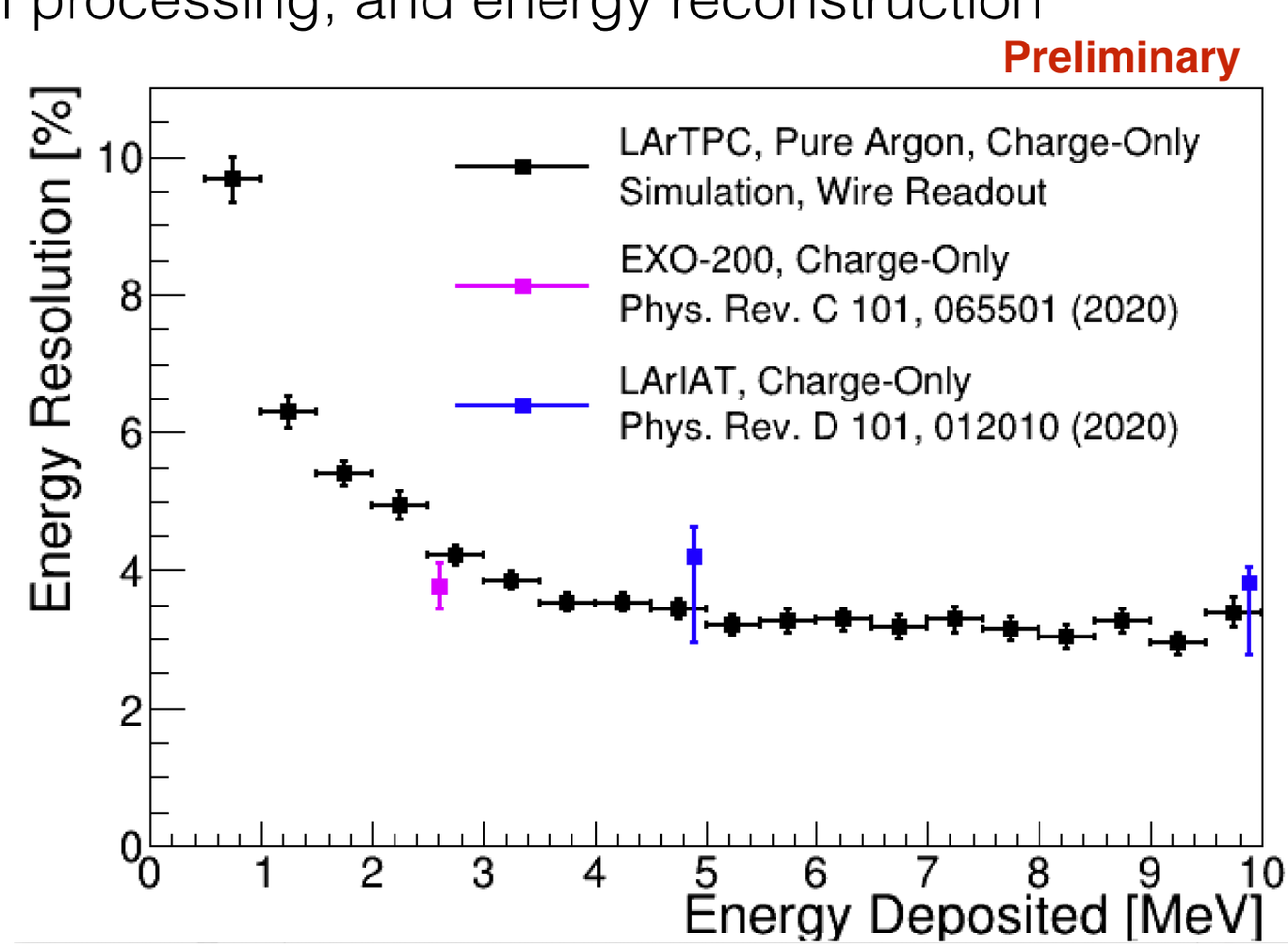


MeV-Scale Energy Resolution

- **Studied improved electron response with simulation of dopants**
  - Converts scintillation light to ionization charge, fully integrated into LArSoft
  - Does not simulate any smearing from dopants (open R&D question)
- Performed a full large LArTPC detector simulation
  - Included wire noise (~350 ENC, ~40 SNR for MIPs), microphysical effects, detector response, noise filtering, signal processing, and energy reconstruction
- First, we study summed charge without any doping and compare to experiments



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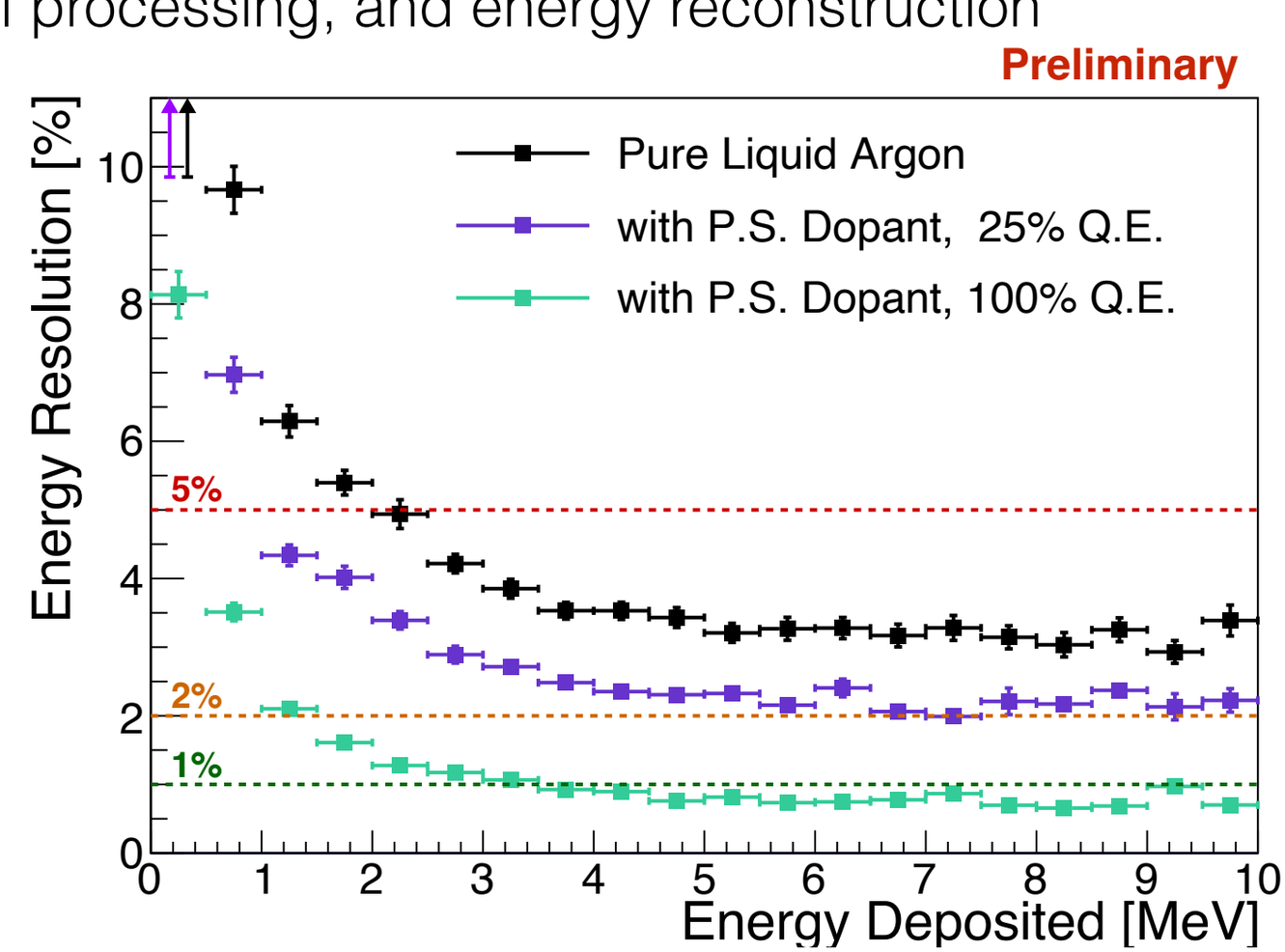
- First, we study summed charge without any doping and compare to experiments
- Then, add dopant simulation see improved energy Reco
  - **High QE dopants can enable 1%-level energy resolution**



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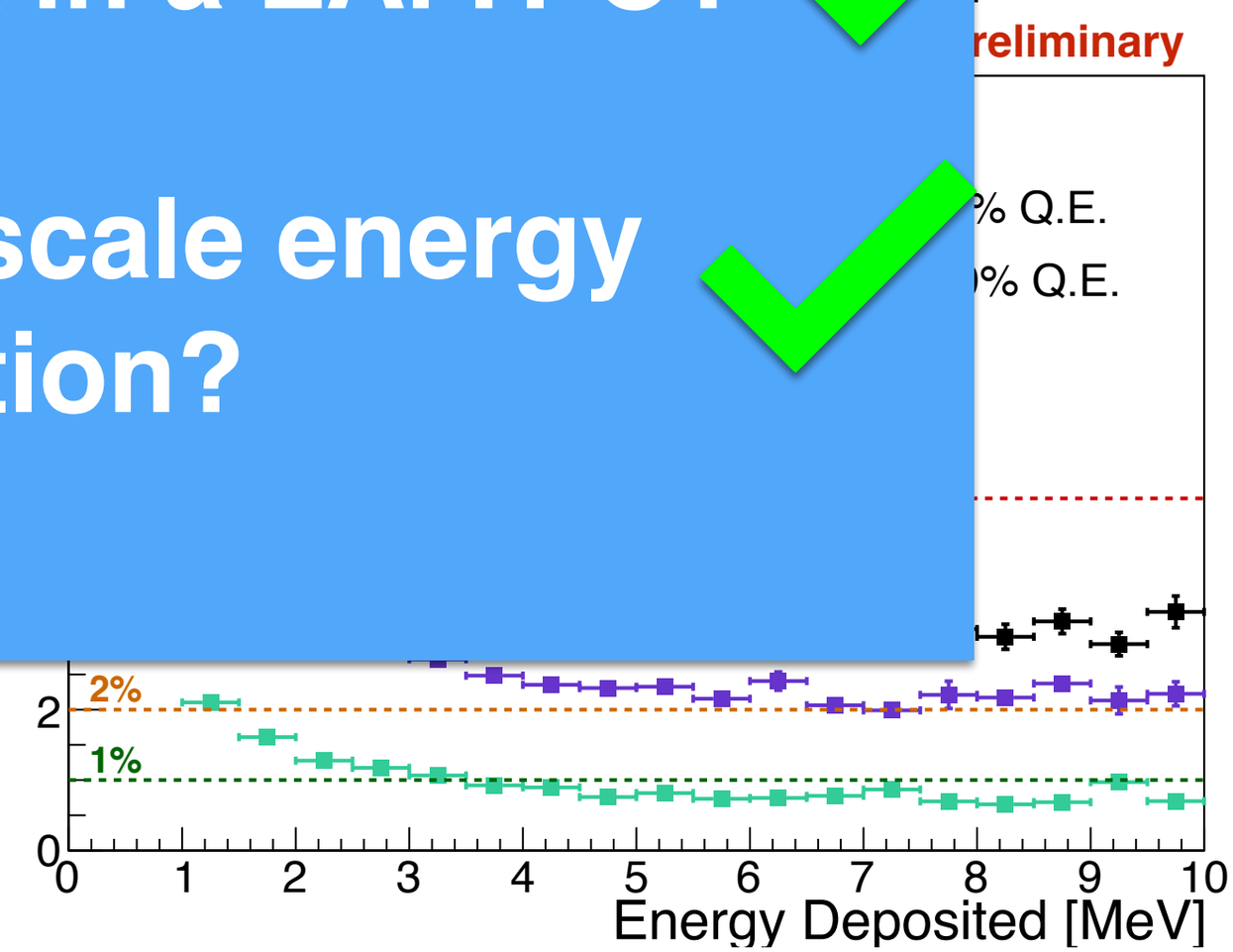
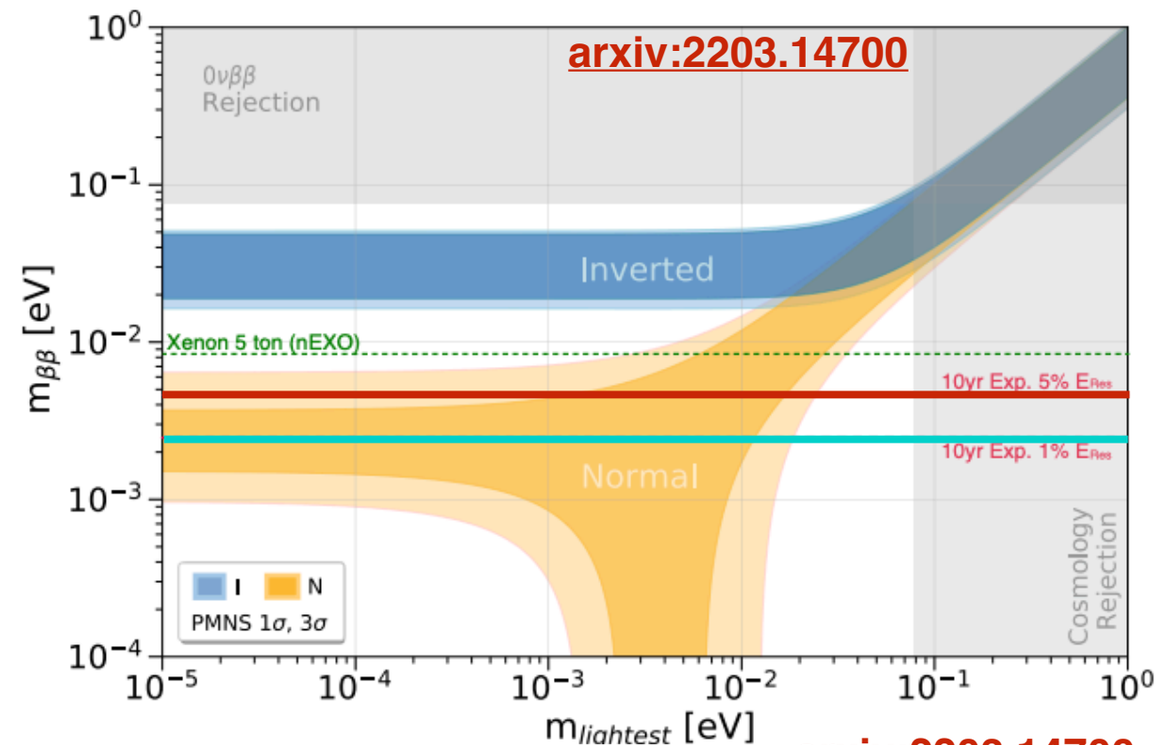
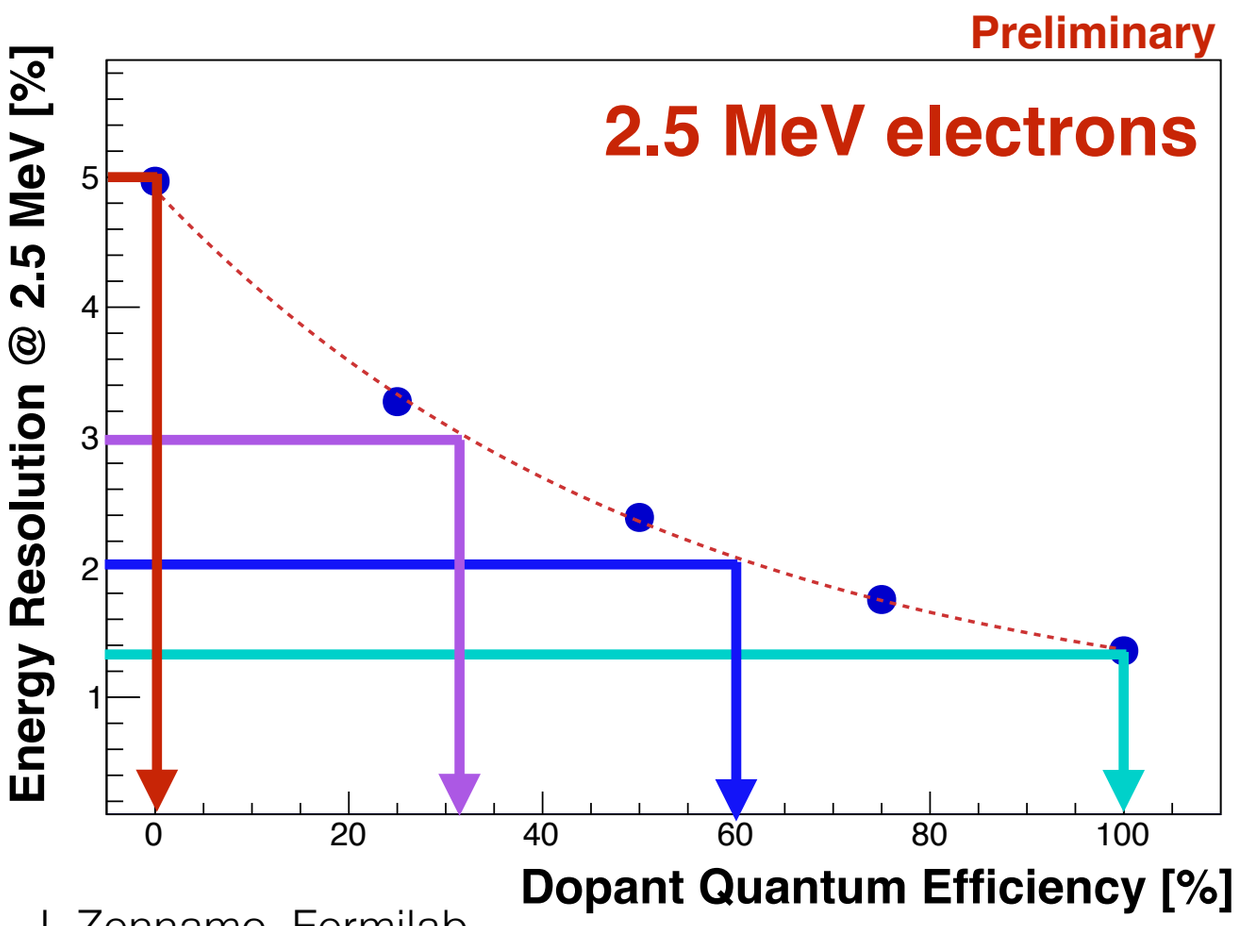
Improve MeV-scale energy resolution?

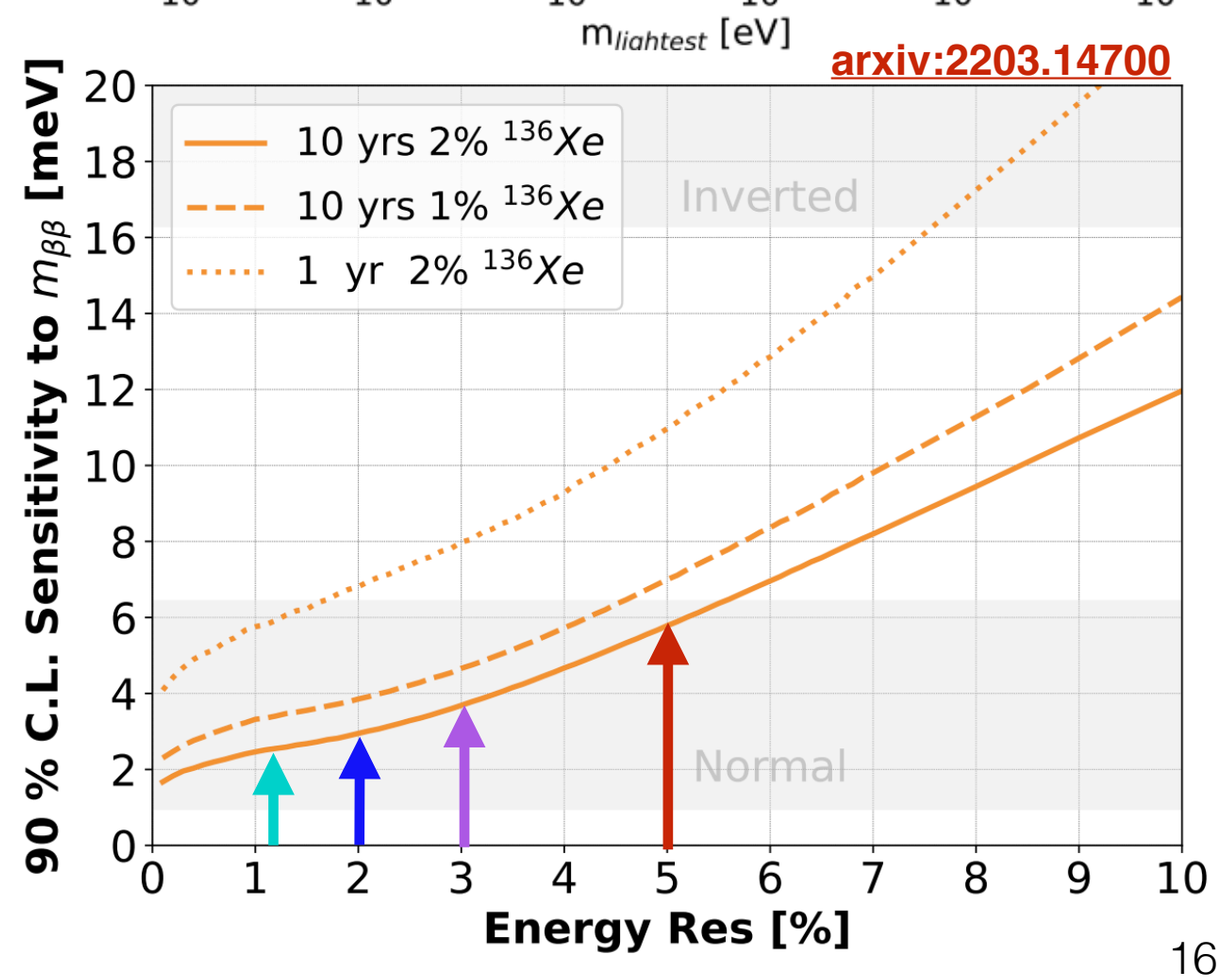


Game Changing Applications

- **Dopants could enable large LArTPCs, like a future DUNE module, doped with ^{136}Xe to search for 0νββ**
  - **Search with 100 ton of >target**
  - **Option for DUNE 3rd or 4th module**



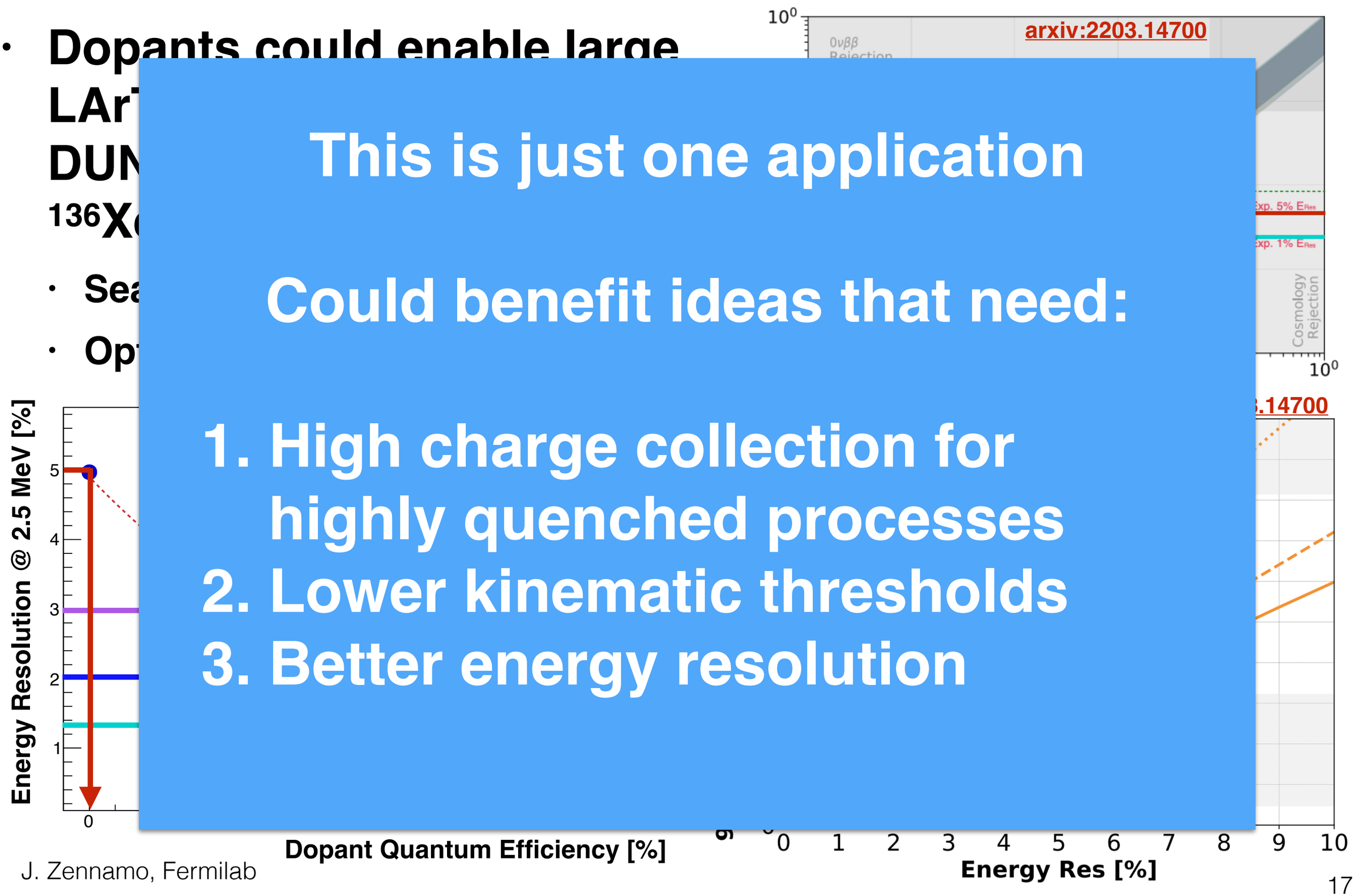




J. Zennamo, Fermilab

Game Changing Applications

- **Dopants could enable large**
  LAr
  DUN
  ^{136}X
  - **Sea**
  - **Op**



This is just one application

Could benefit ideas that need:

1. **High charge collection for highly quenched processes**
2. **Lower kinematic thresholds**
3. **Better energy resolution**

Conclusions

- **Photosensitive dopants provide an exciting opportunity** to enhance the GeV and MeV reach of massive LArTPCs

- Past experiments and simulations provided us with tantalizing hints of what these dopants can offer
  - **A rich R&D program is needed to validate the simulated gains and demonstrate viability at the multi-kiloton scale and beyond**

- These dopants could remove the need for us to utilize scintillation light to enhance energy reconstruction, **revolutionizing how LArTPCs can explore the MeV-scale**
  - Including neutrinoless double beta decay searches, solar neutrinos, supernova neutrinos, and possibly more! **arxiv:2203.14700**

Backups

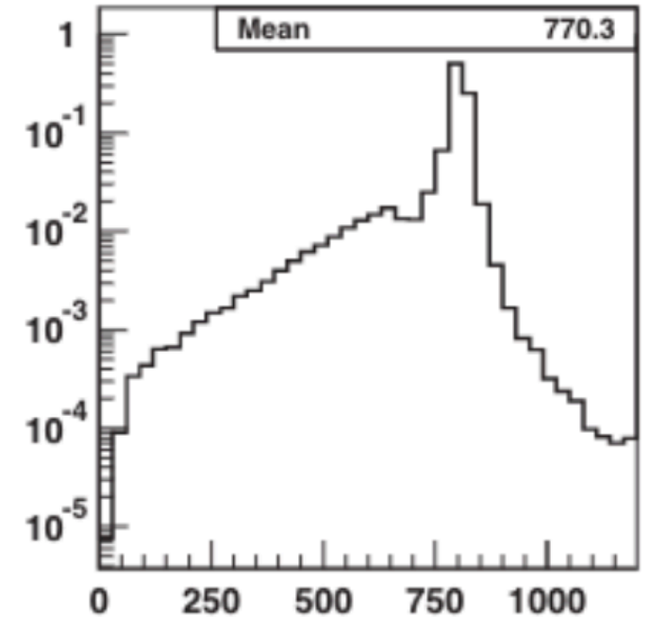
Fermilab

Locating in the Drift Direction

- LArTPCs uses the light to locate the charge in the drift direction
- Cherenkov light produced by particles produces light in the optical range
  - Easier to detect, insensitive to the dopants, and provides a prompt signal
  - Less light (~100x) is produced and is produced directionally
- As the cloud of electrons travel towards the readout they diffuse
  - The width of this charge correlates with the distance that charge has traveled

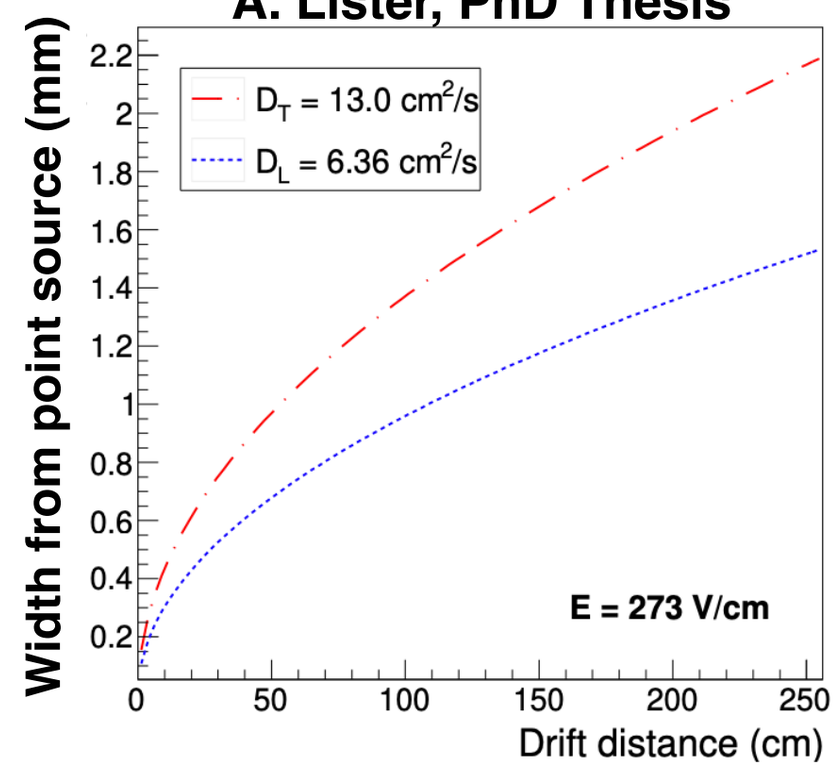
NIM A 516 (2004) 348-363

ICARUS Collaboration



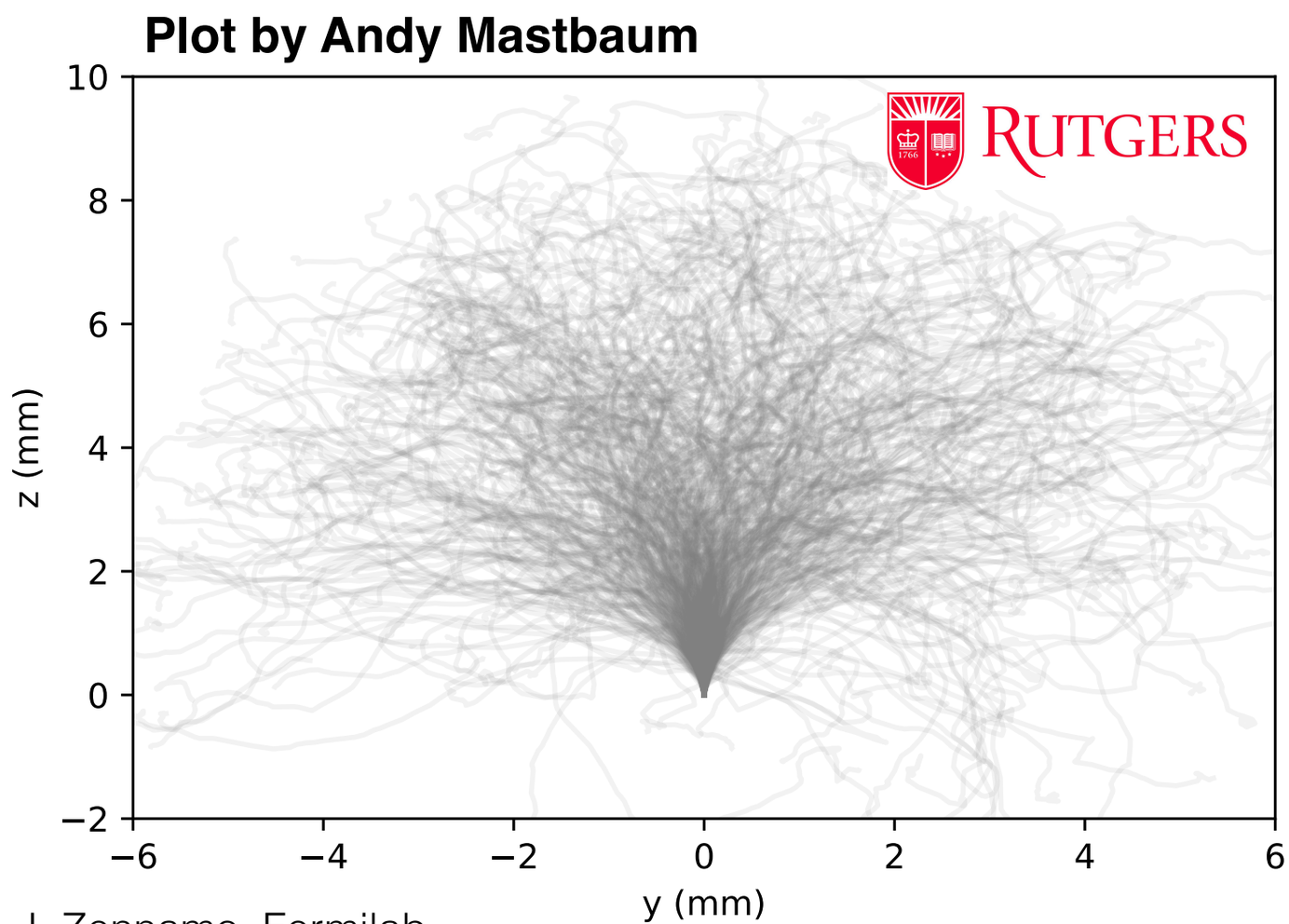
Number of Cherenkov photons (γ/cm)

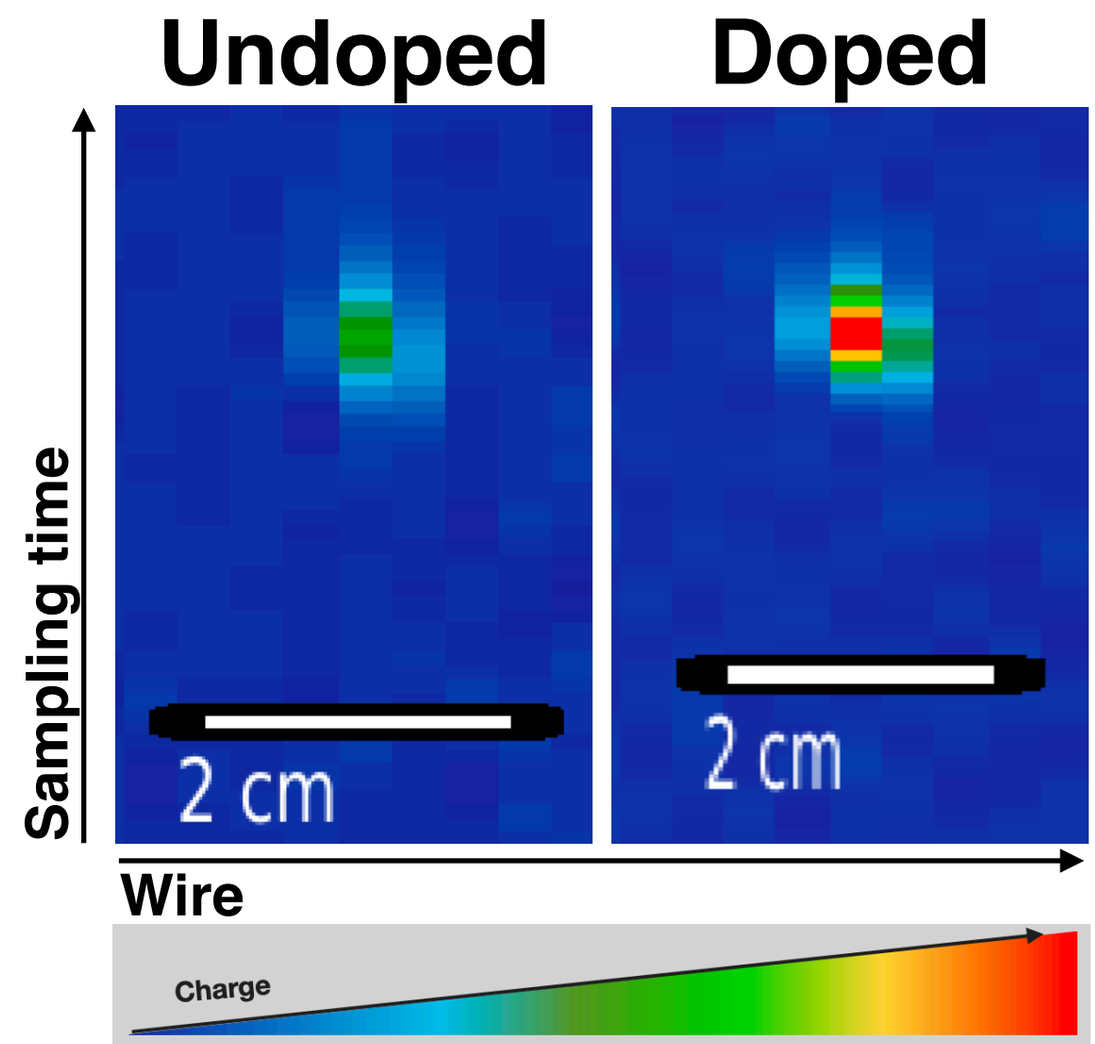
A. Lister, PhD Thesis



2.5 MeV Electrons in LArTPCs

- 2.5 MeV electrons do not follow straight trajectories in LAr
  - **Not easy to measure their range**
- In a wire-readout LArTPC these electrons will occupy 1-3 channels in the readout

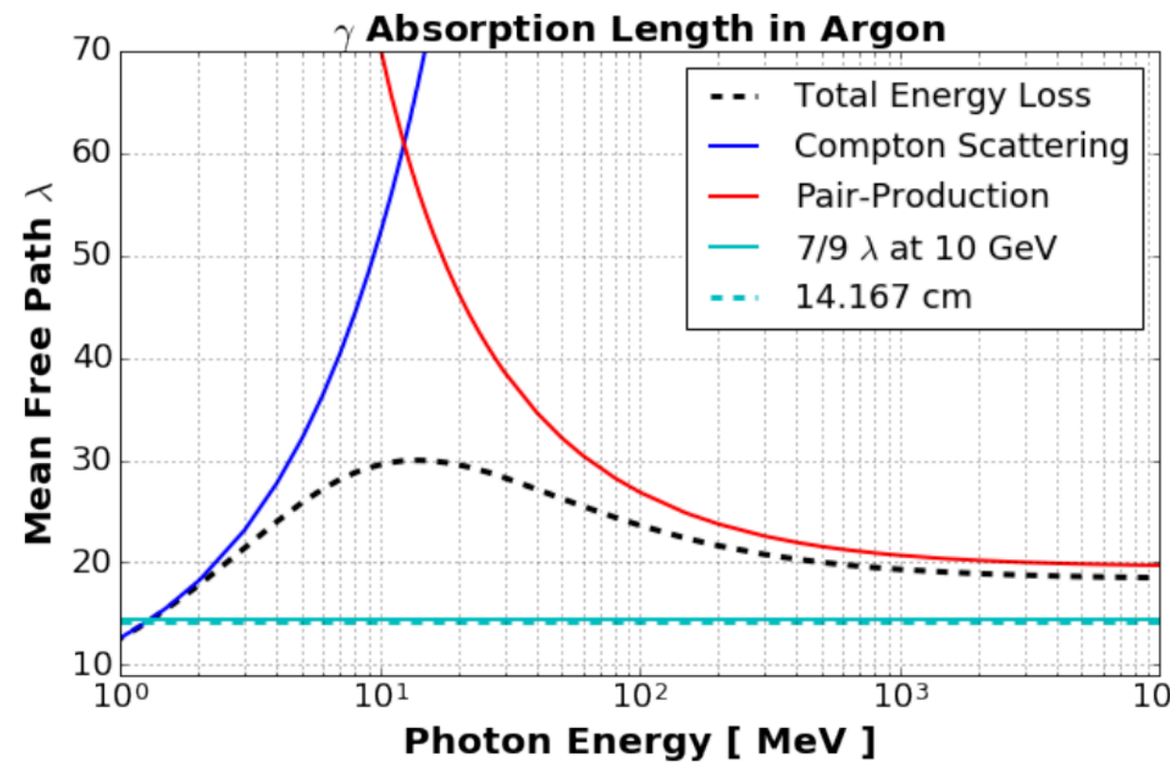


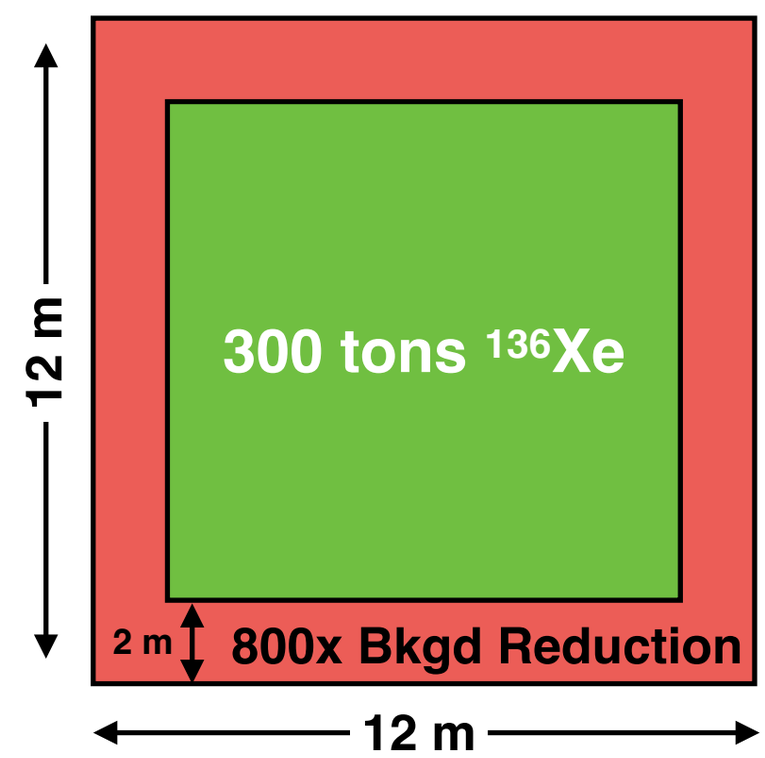


Types of Backgrounds

- A number of sources of backgrounds need to be addressed to enable 0νββ searches in DUNE
  - Environmental contamination (rock and detector), cosmic spallation, solar neutrino interactions, and intrinsic 2νββ
- The most challenging background comes from the small fraction of ^{42}Ar which is present in atmospheric argon
  - When ^{42}Ar decays it creates ^{42}K which has an energy that overlaps our energy range and, with so much LAr, swamps a 0νββ signal
  - To mitigate this we would need to use underground argon which has no ^{42}Ar
- The remaining backgrounds can be suppressed through fiducial volume cuts and β+γ coincidence tagging

D. Caratelli, PhD Thesis



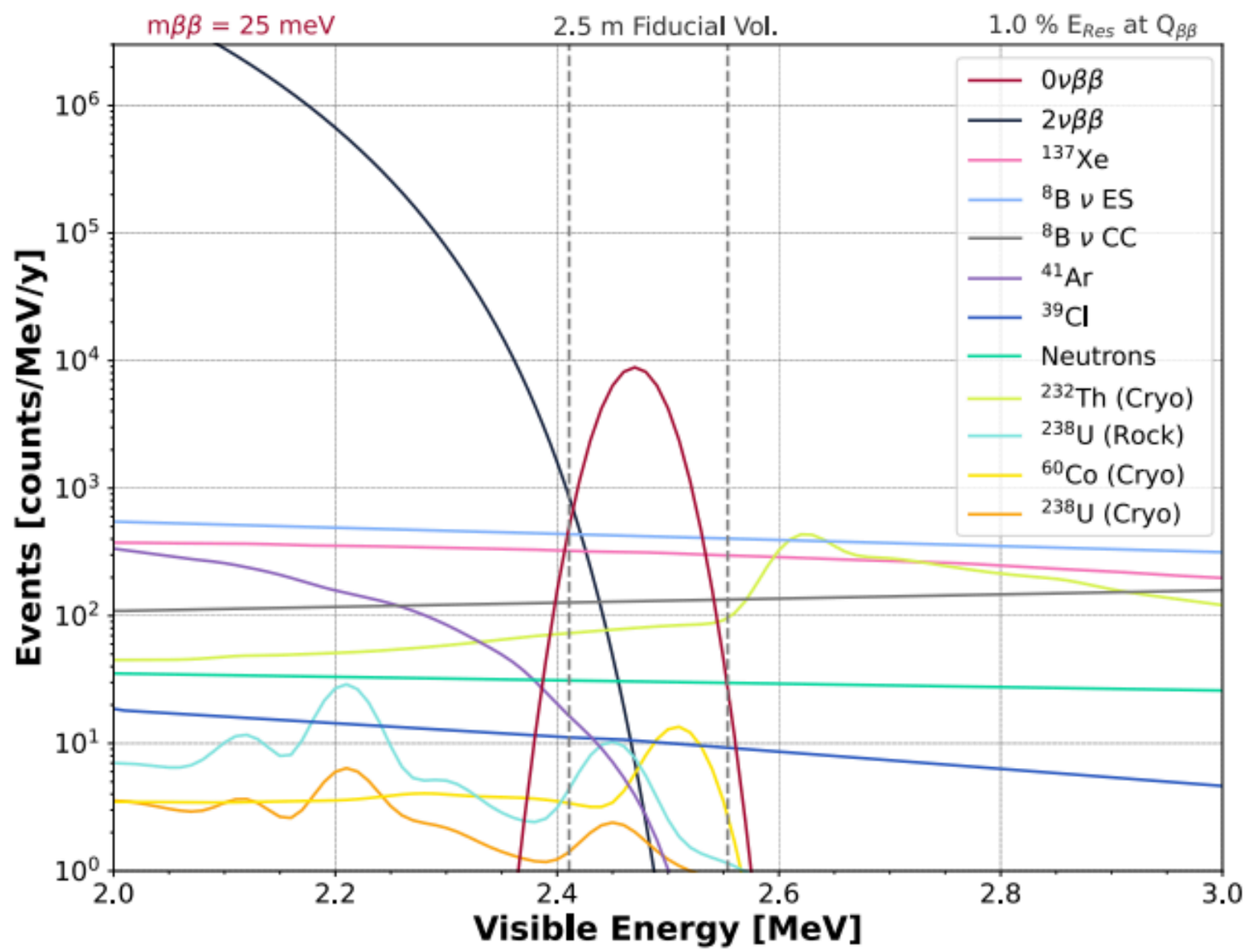


Publication pending, A. Mastbaum, F. Psihas, J.Zennamo

Backgrounds and Our Signal

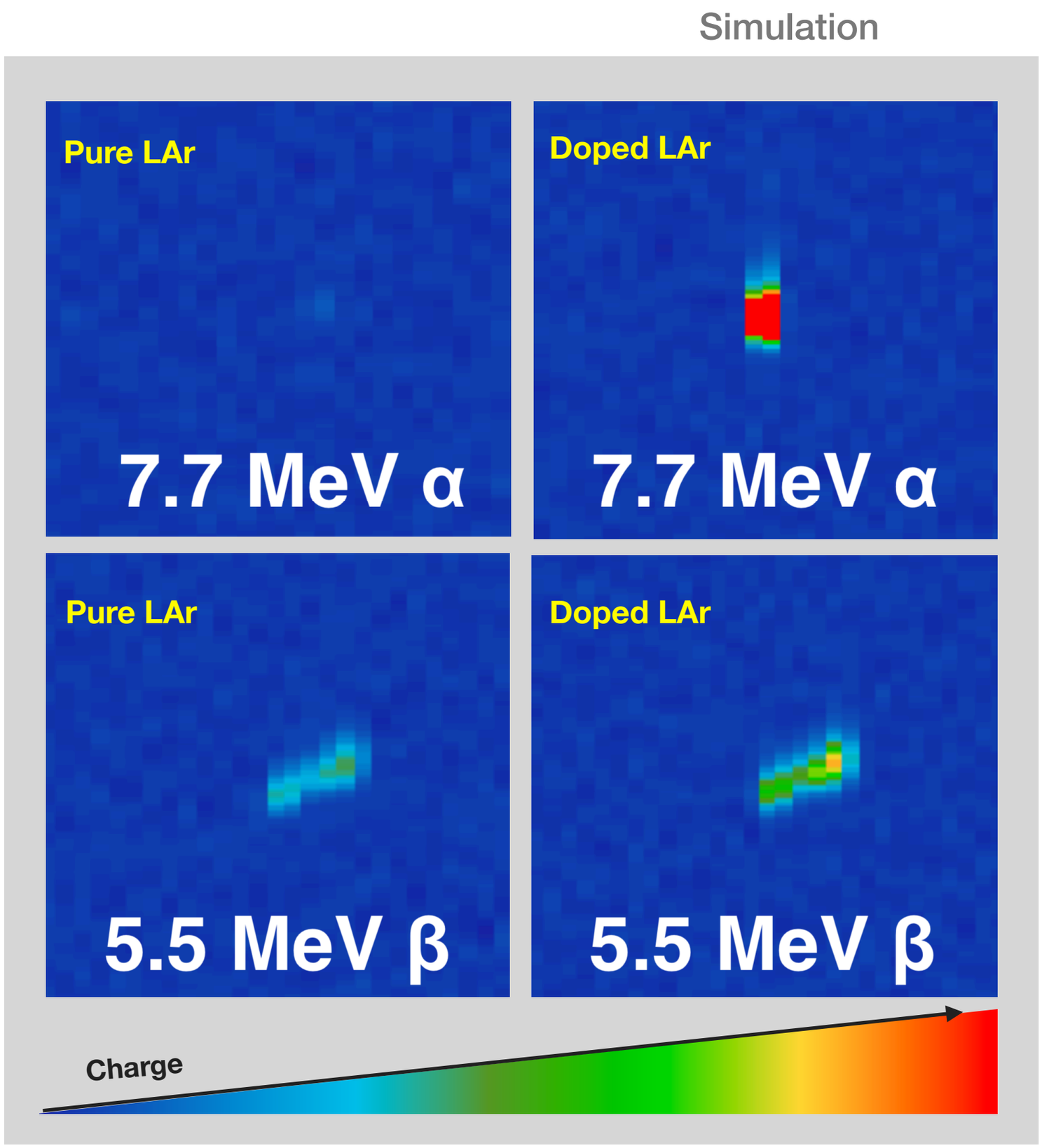
When we combine all the known source of backgrounds and integrate some simple background suppression we find the following:

- Backgrounds from environmental gamma sources are subdominant
- Spallation and solar activity form our largest backgrounds



Uses underground argon, external shielding, 2.5-meter fiducial volume, 32 cm photon coincidence cut, and veto with 2 meter and 60s of crossing muon

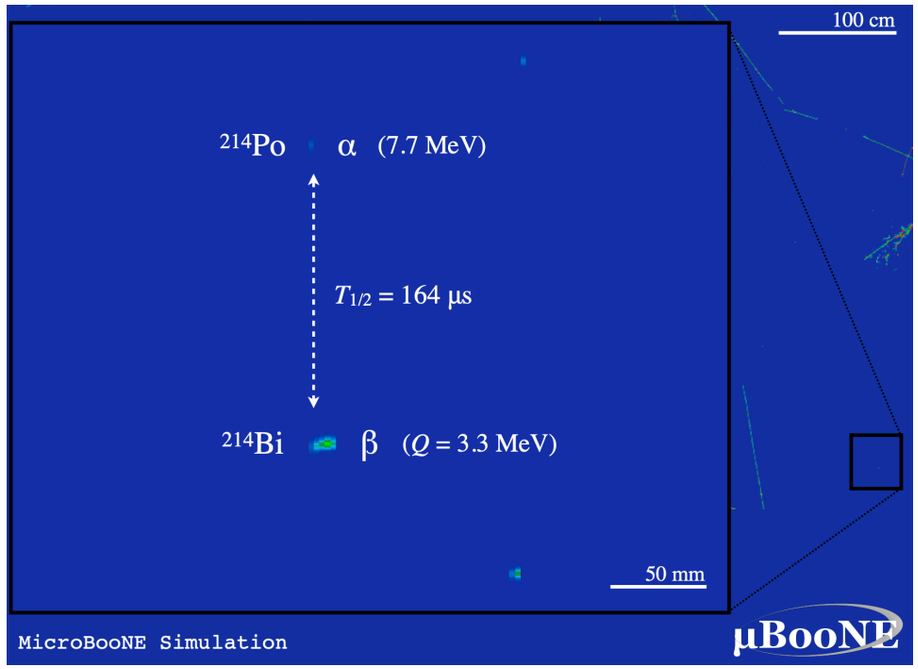
Simulated MeV-scale Signatures



LArTPC Thresholds

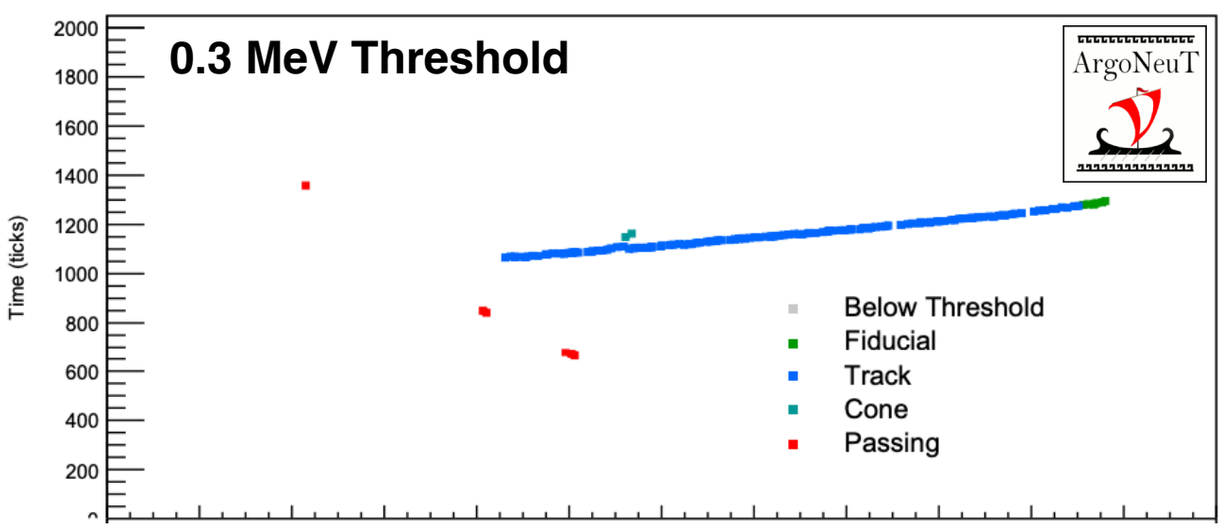
arxiv:2203.10147

^{214}Bi^{214}Po Tagging



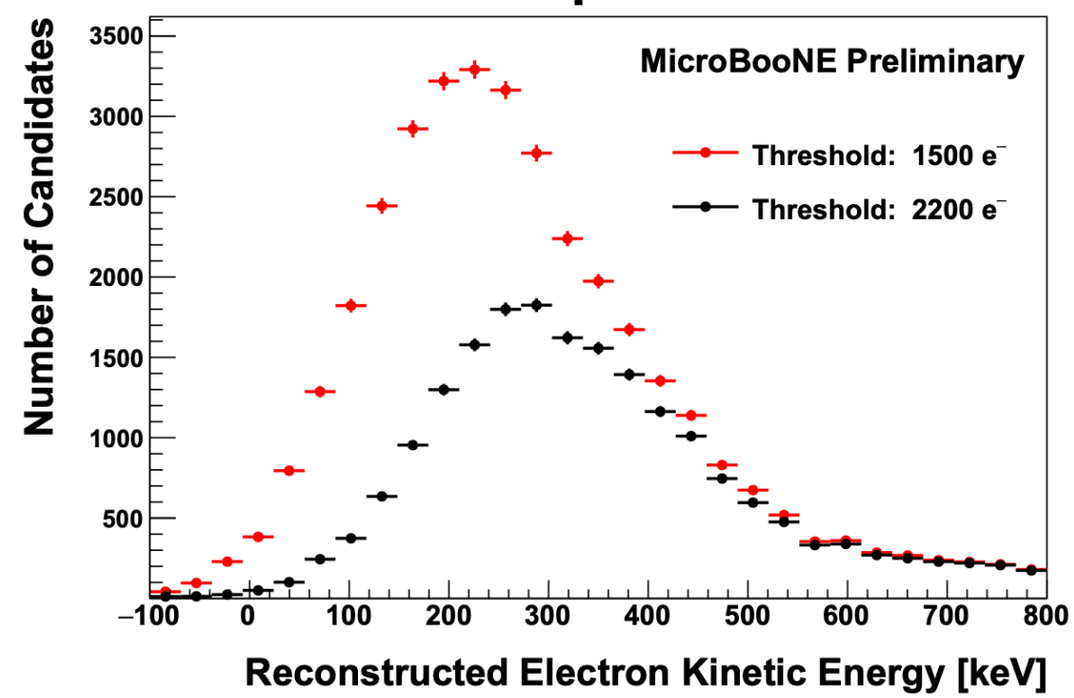
Phys.Rev.D 99 (2019) 1, 012002

First MeV-Scale Demonstrations



MicroBooNE Public Note 1050

^{39}Ar Spectrum



A. Bhat, PhD Thesis (S.U.)

Radiological decays