Using Photo-converting Dopants to Improve Large LArTPC Performance

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

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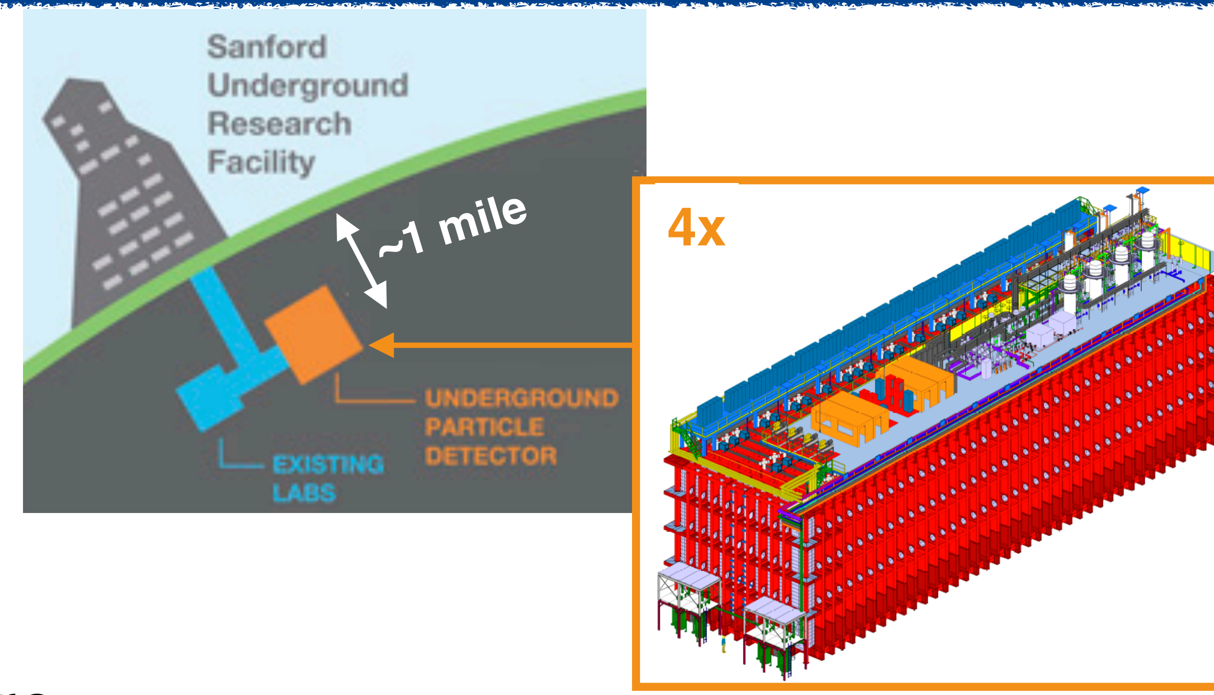
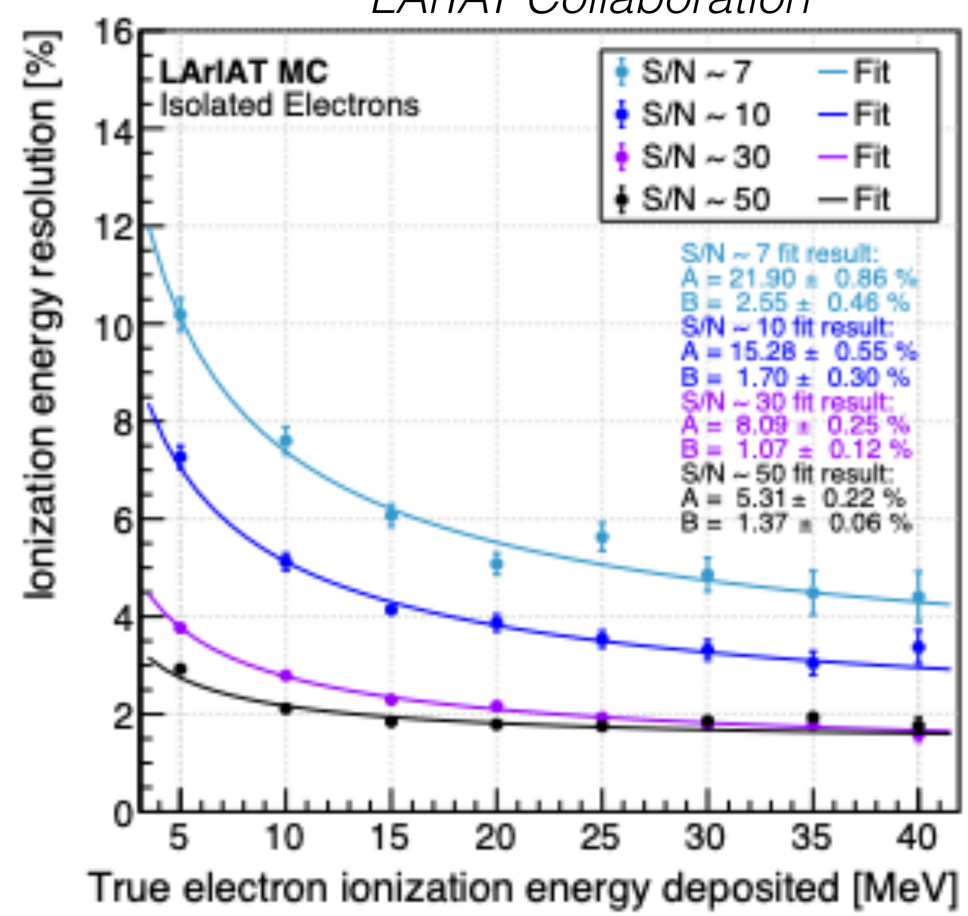
Physics at the MeV-Scale

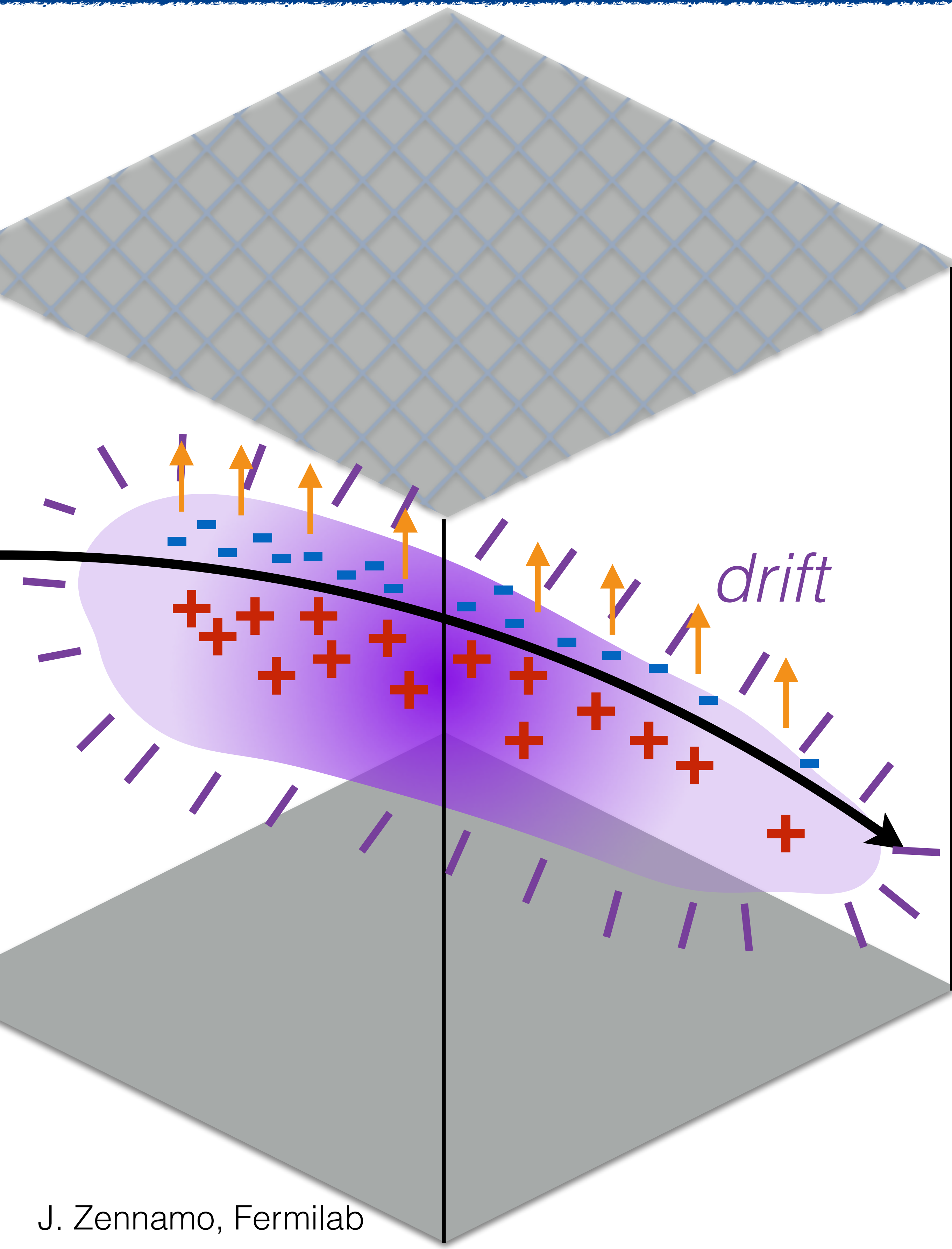
- The four massive LArTPCs of Deep Underground Neutrino Experiment (DUNE) offer us a unique opportunity for discovery at the MeV-scale
  - Solar neutrinos, supernova neutrinos, pre-supernova neutrinos, etc.
- Enhancing MeV-scale energy resolution of large LArTPCs could open new avenues for discovery
  - **If we can achieve %-level energy resolution near the MeV-scale we could enable searches for 0νββ decay in a doped LArTPC**



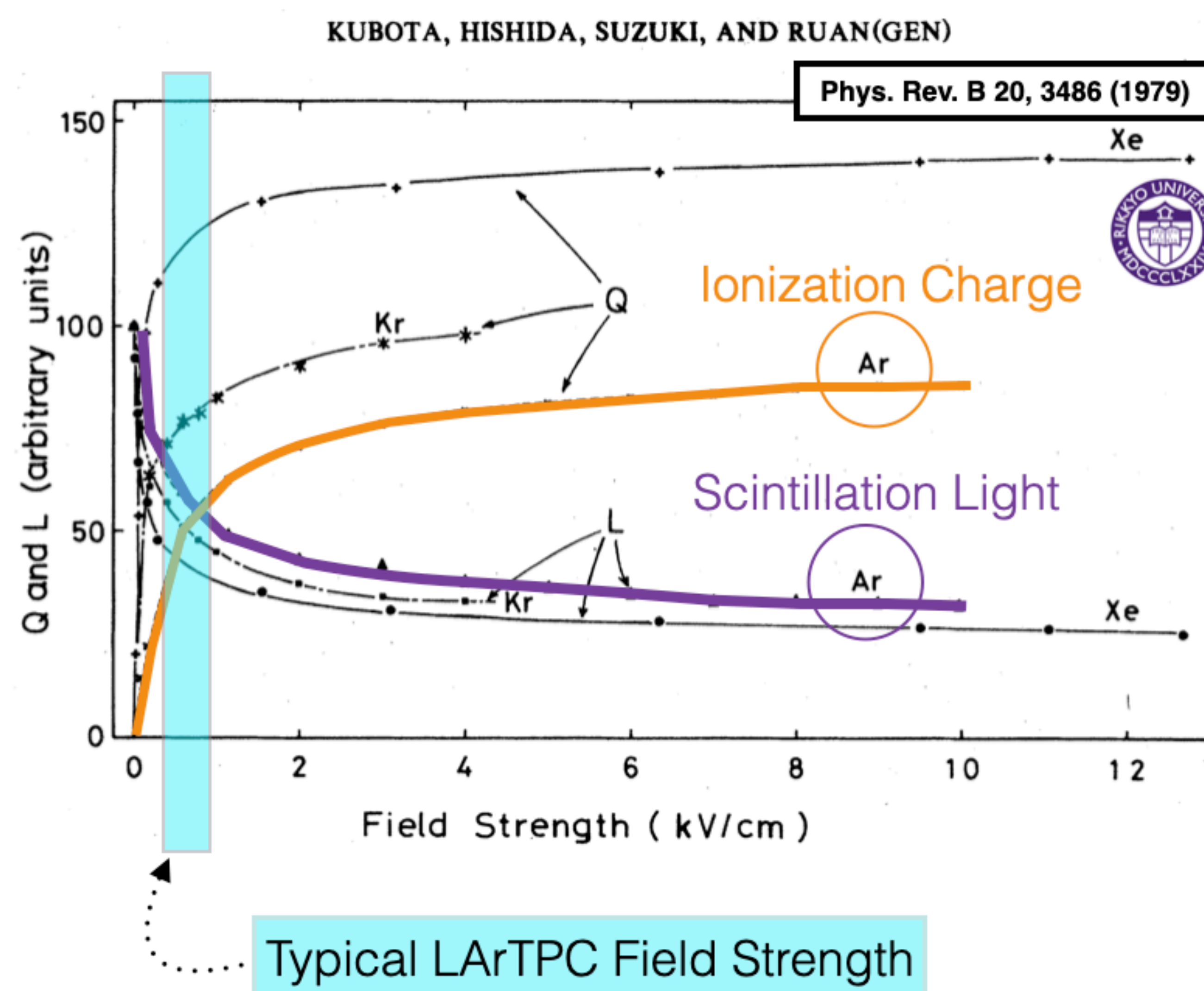
<u>PRD 101, 012010 (2020)</u>
LArIAT Collaboration



Energy Deposits in LArTPCs



Charge + Light = Constant



Using charge or light one could measure the energy deposited

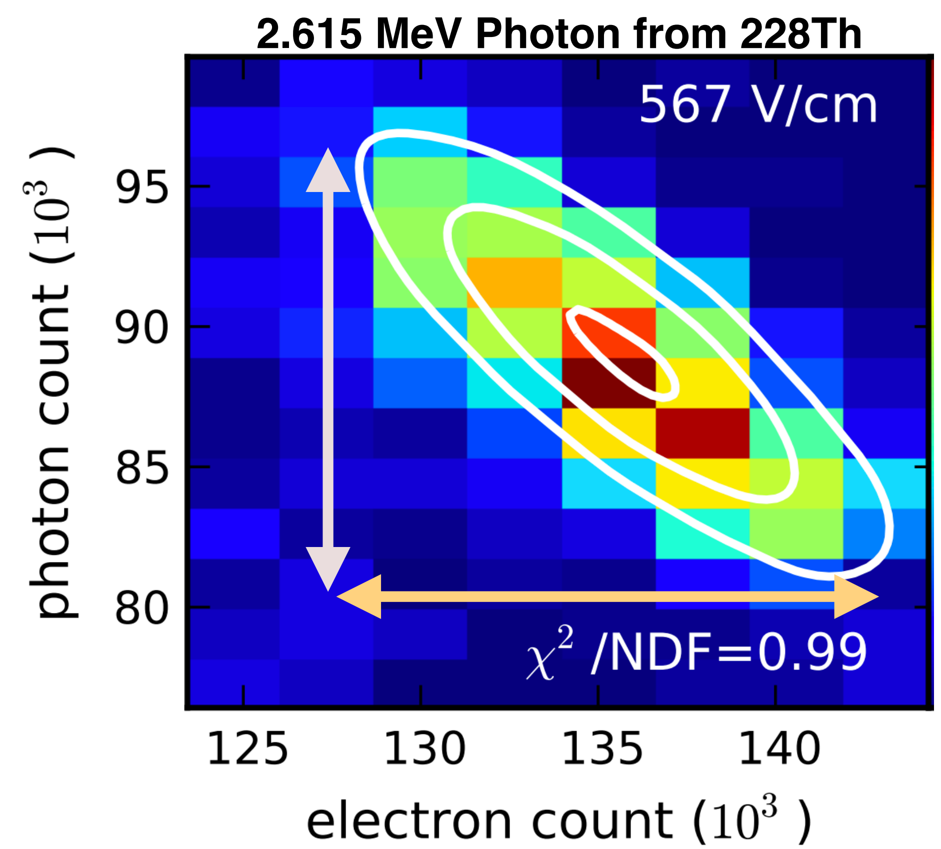
But combining them provides a more precise metric!

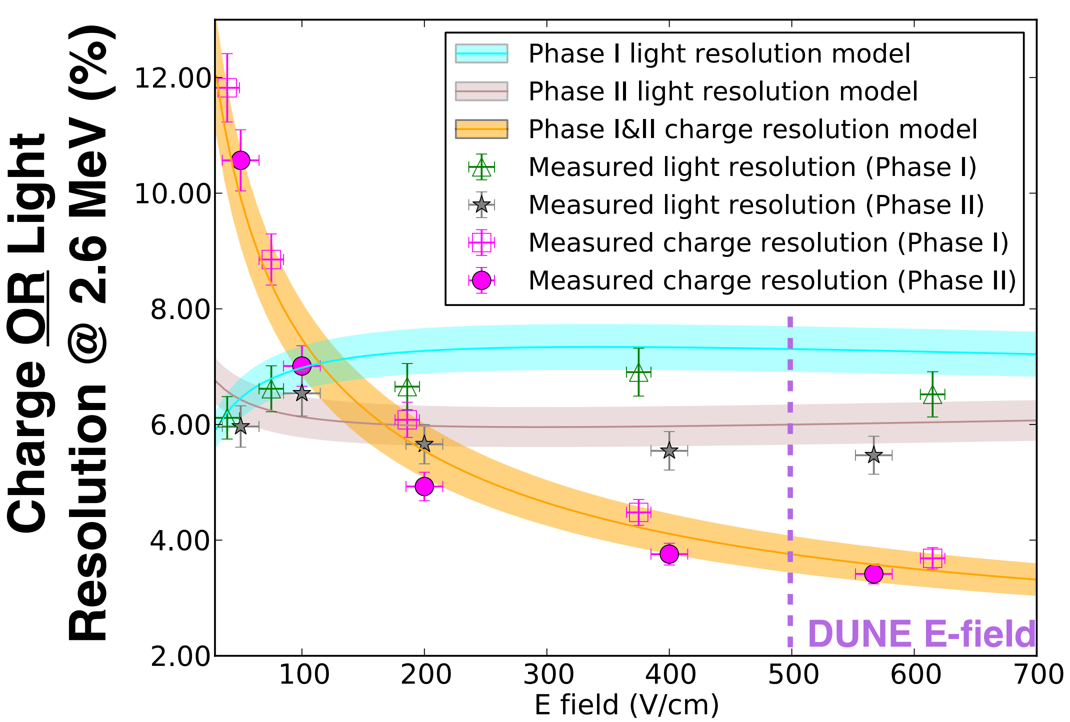
Light Augmented Calorimetry In Liquid Xe

- EXO-200, a LXeTPC searching for 0νββ, found an anti-correlation between light and charge signal
  - Two cylindrical TPCs with radius 18cmx20cm
- They found that when measuring the energy deposited in either light or change they were only able to achieve a 4% energy resolution
- By combining light and charge they were able to improve their energy resolution by 3x, to ~1%
  - **To achieve this they collected roughly 30,000 photons/MeV**

PRC 101, 065501 (2020)

EXO-200 Collaboration





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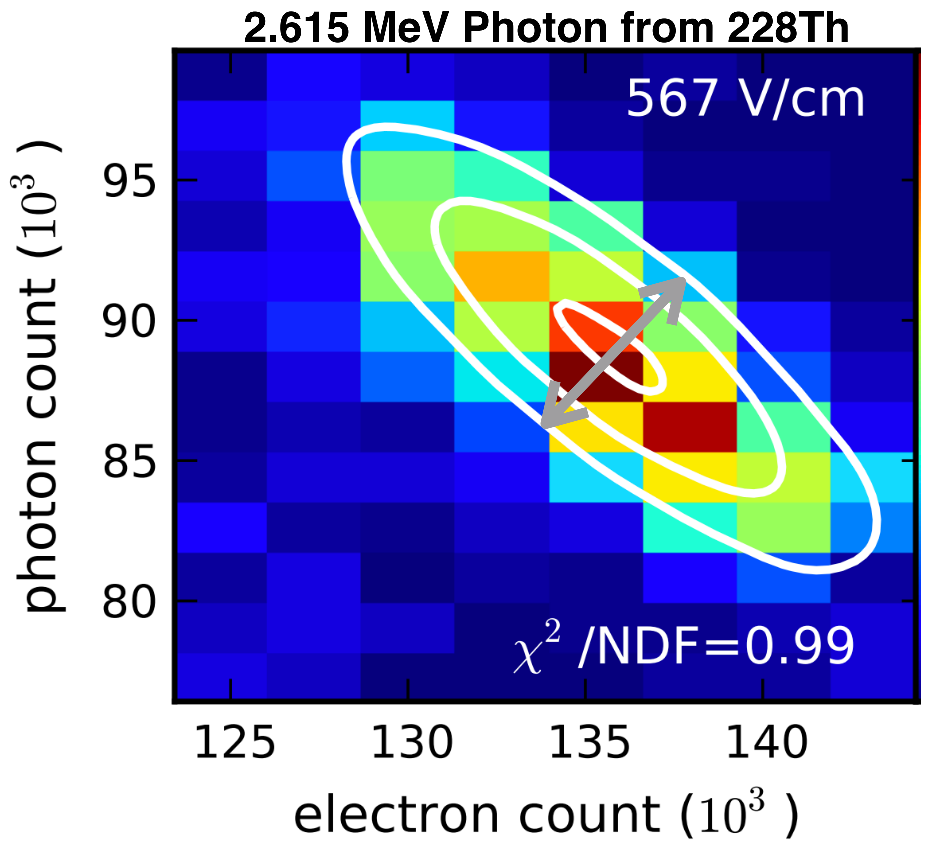
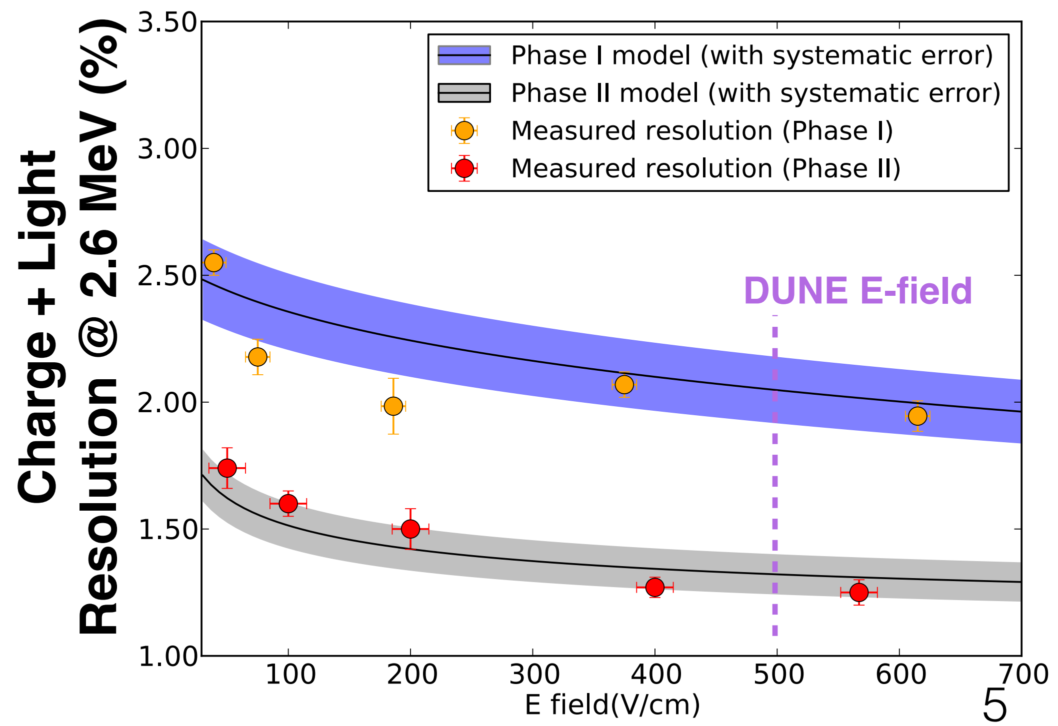
EXO-200 Collaboration



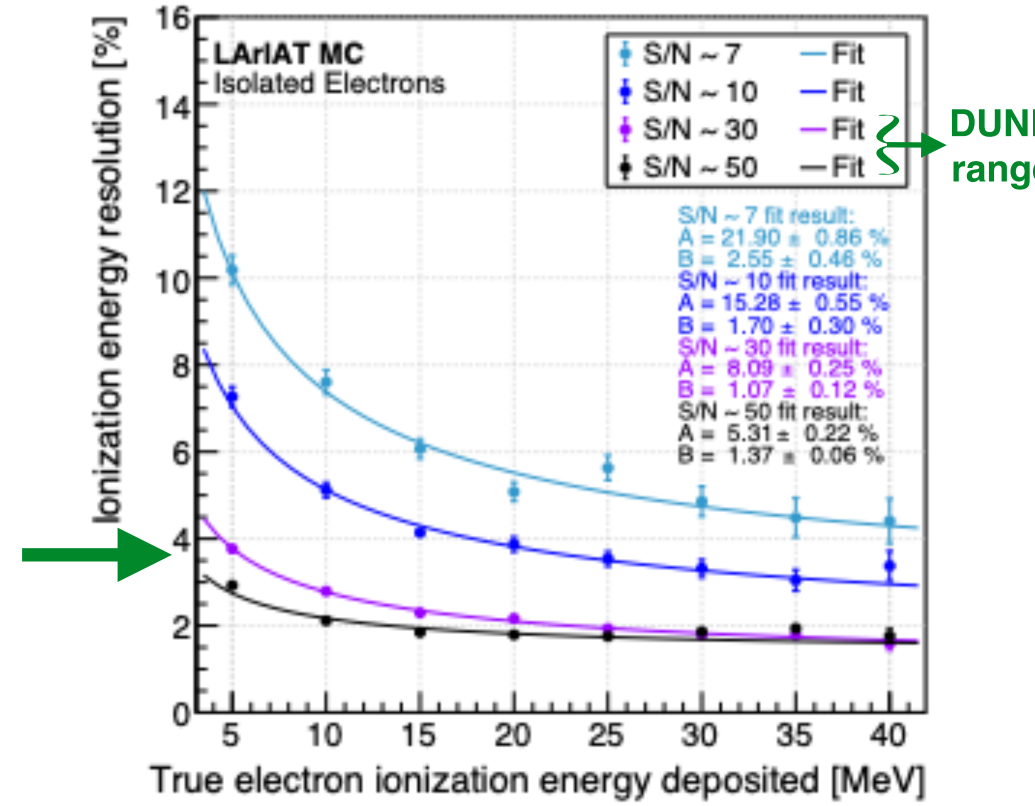


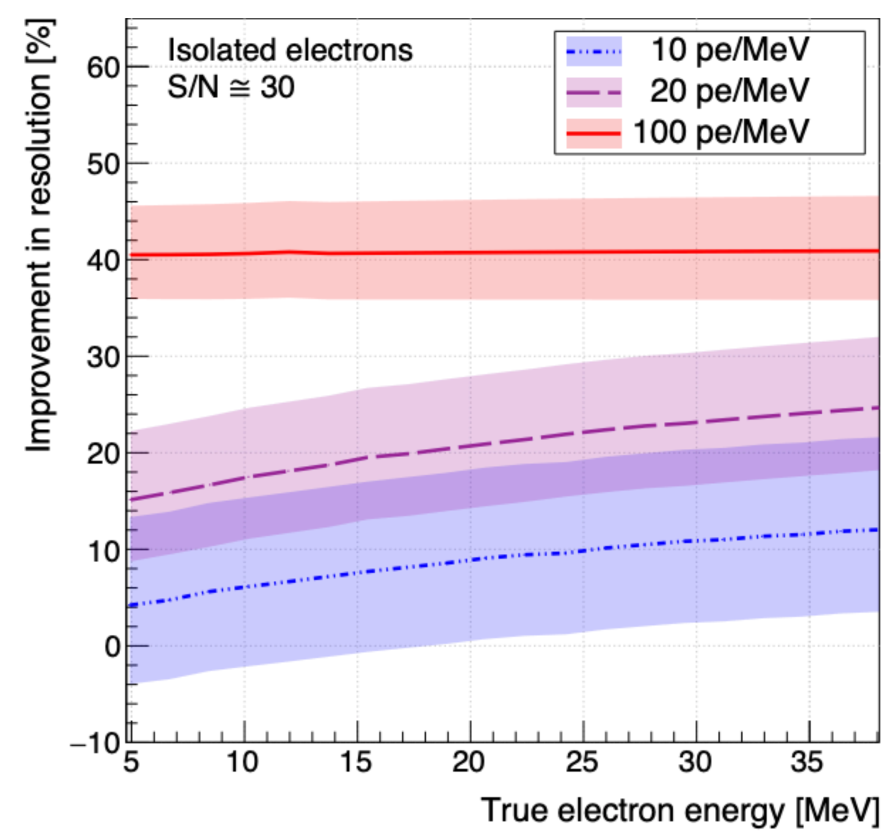
Precision Calorimetry in LAr

- The LArIAT collaboration studied precision LArTPC calorimetry with Michel electrons
- They demonstrated a ~4% charge-only energy resolution at 3 MeV
  - **On-par with what EXO-200 achieved for their charge-only measurements**
- When augmenting this measurement with light LArIAT was only able to improve this measurement by 40%
  - **LArIAT used 100 photons/MeV while EXO-200 had 30,000 photons/MeV**

PRD 101, 012010 (2020)

LArIAT Collaboration





Challenges of Light Collection in LArTPCs

- Efficient collection of light is challenging in large LArTPCs
  - **Light is radiated isotropically** and photon detectors generally sit on LArTPC surface
  - **The surface area of a DUNE detector is >4,500x larger than that of EXO-200**
- The latest generation LArTPCs, SBND, are integrating reflector foils to improve the light collection
  - This system is capable of collecting 150 γ/MeV which is well below the number that EXO-200 used
- **We would like a solution that can increases the light collected by 100x**

DUNE FD Module

5,600 cm by 1,200 cm

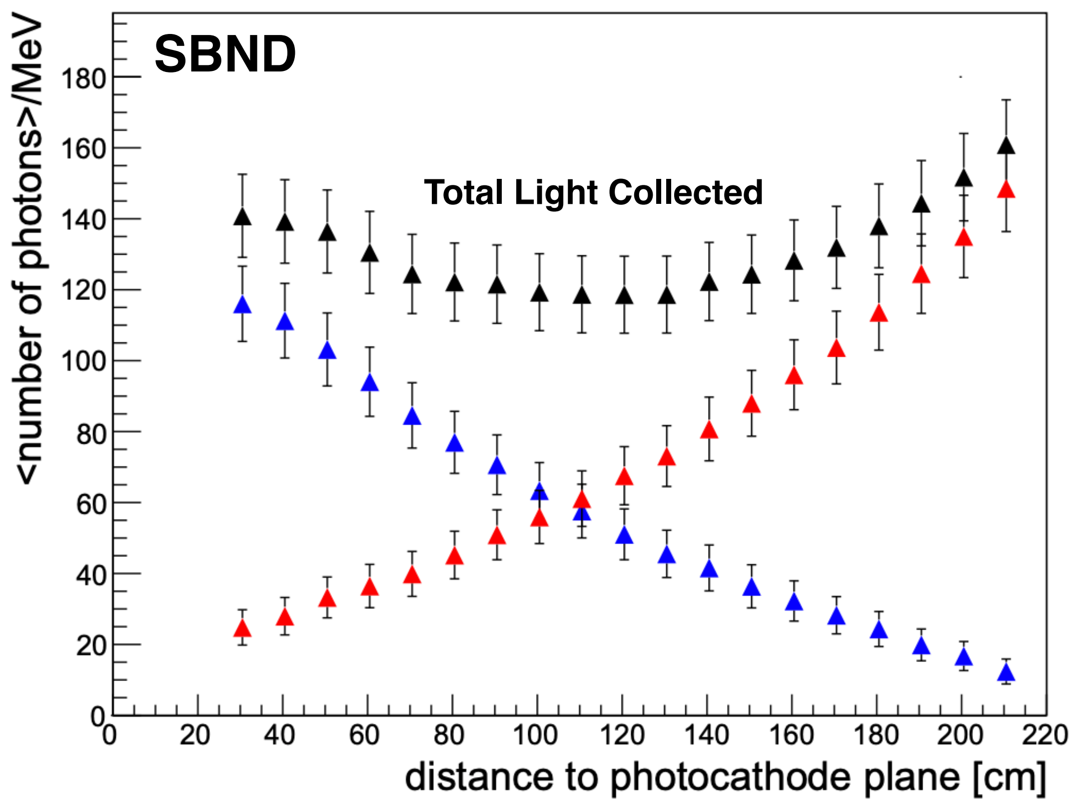
Traditionally light collected at anode plane

EXO-200 Detector

40 cm by 18 cm

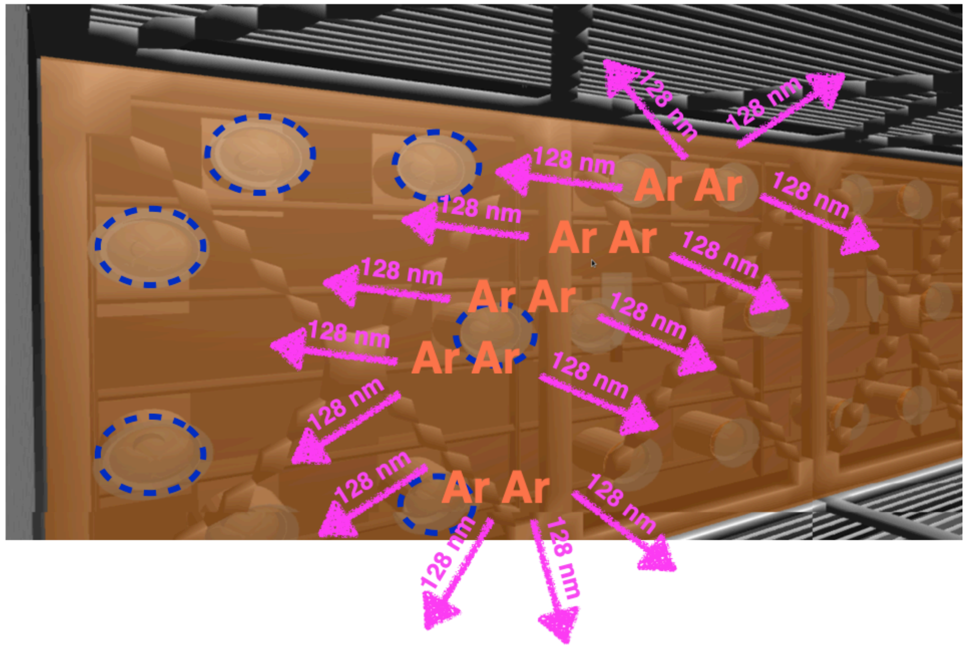
Journal of Physics: Conf. Series 888 (2017) 012094

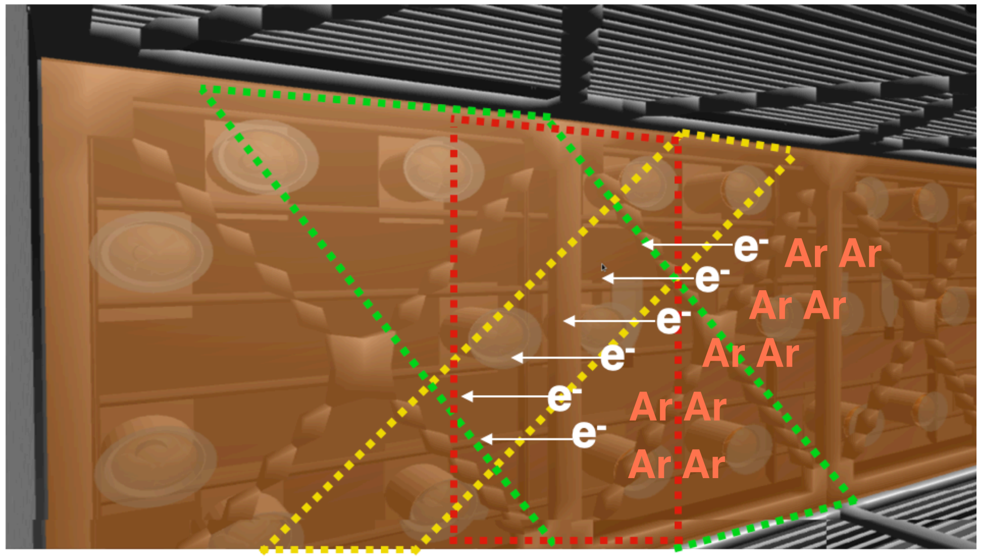
D. Garcia-Gamez



Another Way? Photo-conversion

- To collect the most energy deposited in the LAr 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





Photon Conversion

- 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)

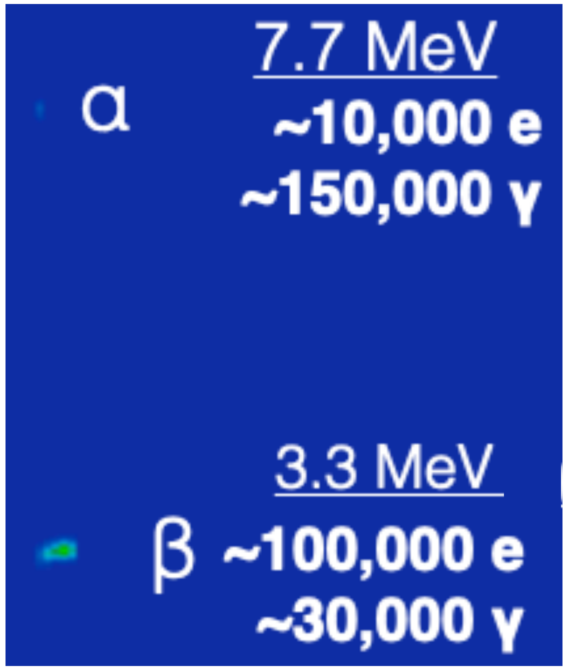
- **These chemicals have a long track record of demonstrations in the literature starting back in the early 1970s**

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

Studies for Collider LAr Calorimeters

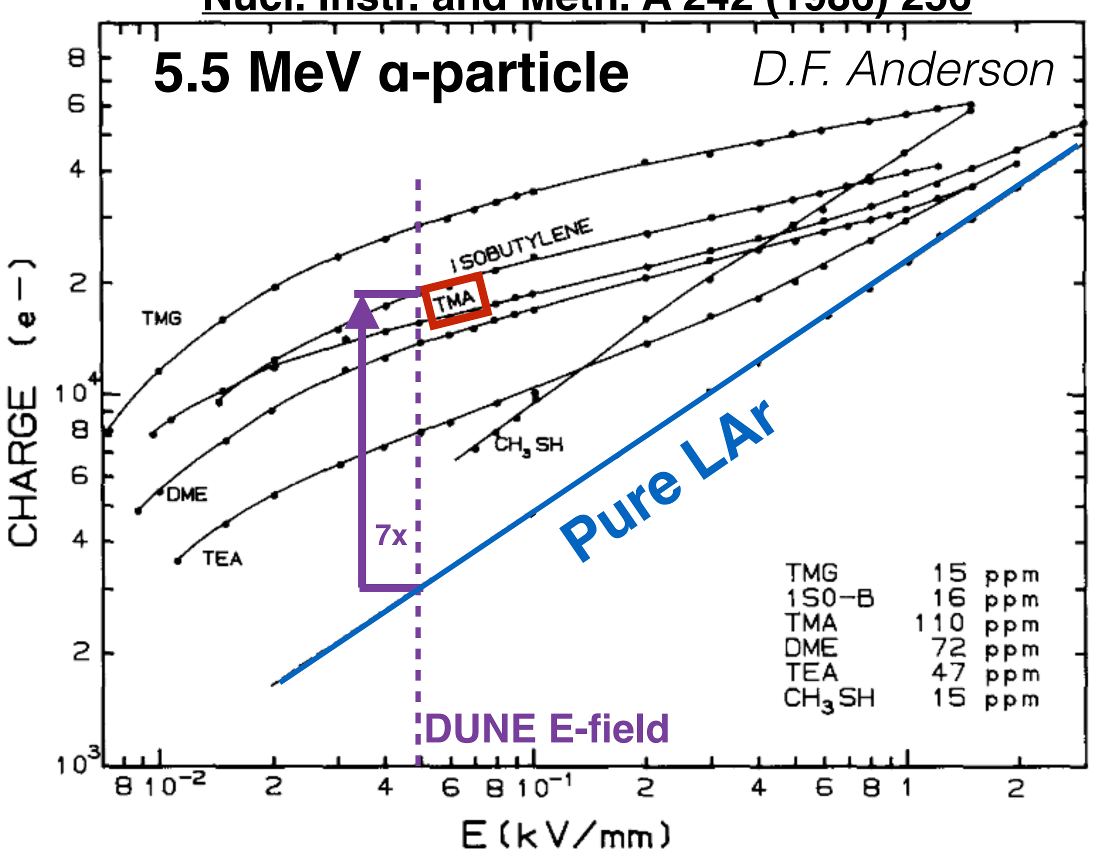
- Using small test stands a variety of different chemicals were tested and found to lead to substantial charge enhancement for highly scintillating particles
  - Charge enhancement **equivalent to collecting 40% of the light produced**
  - This would imply **10,000 photons/MeV for MeV-scale electron signals**
- They also measured significant improvements in the energy resolution for alpha particles
  - All these studies were performed in coarse test-stand detectors, it is important to see if they translate to LArTPCs

Simulated Event in Pure LAr

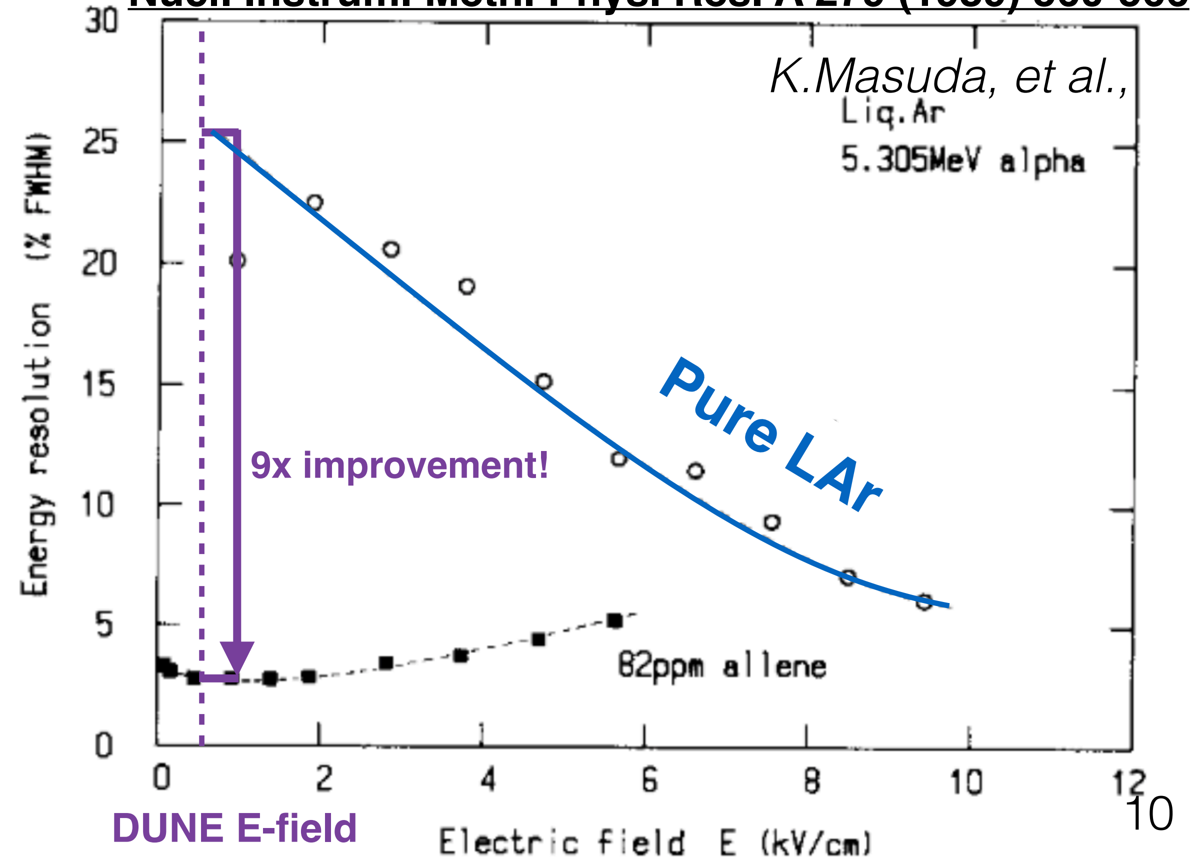


Courtesy of Ivan Lepetic

Nucl. Instr. and Meth. A 242 (1986) 256



Nucl. Instrum. Meth. Phys. Res. A 279 (1989) 560-566

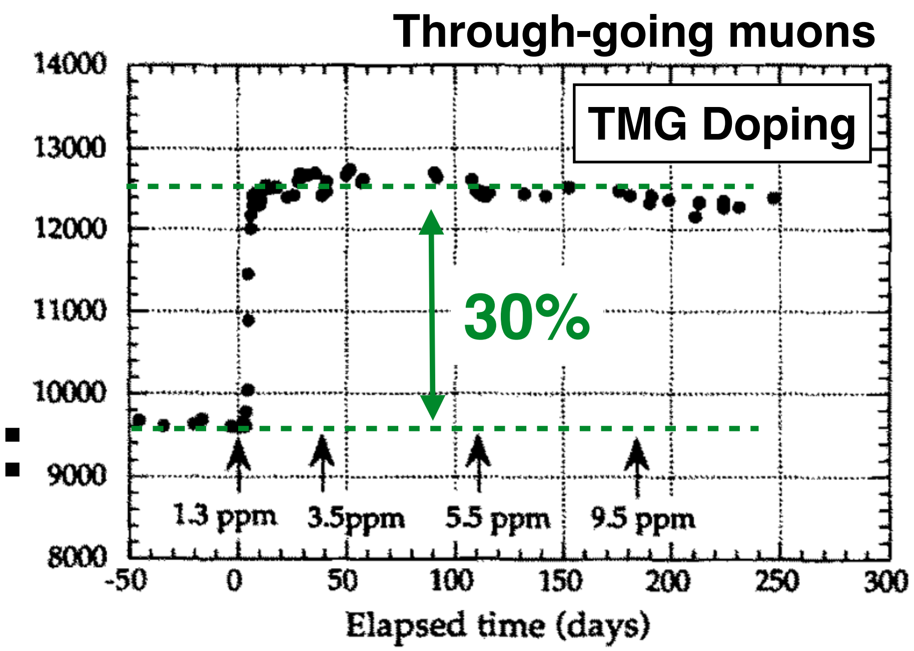


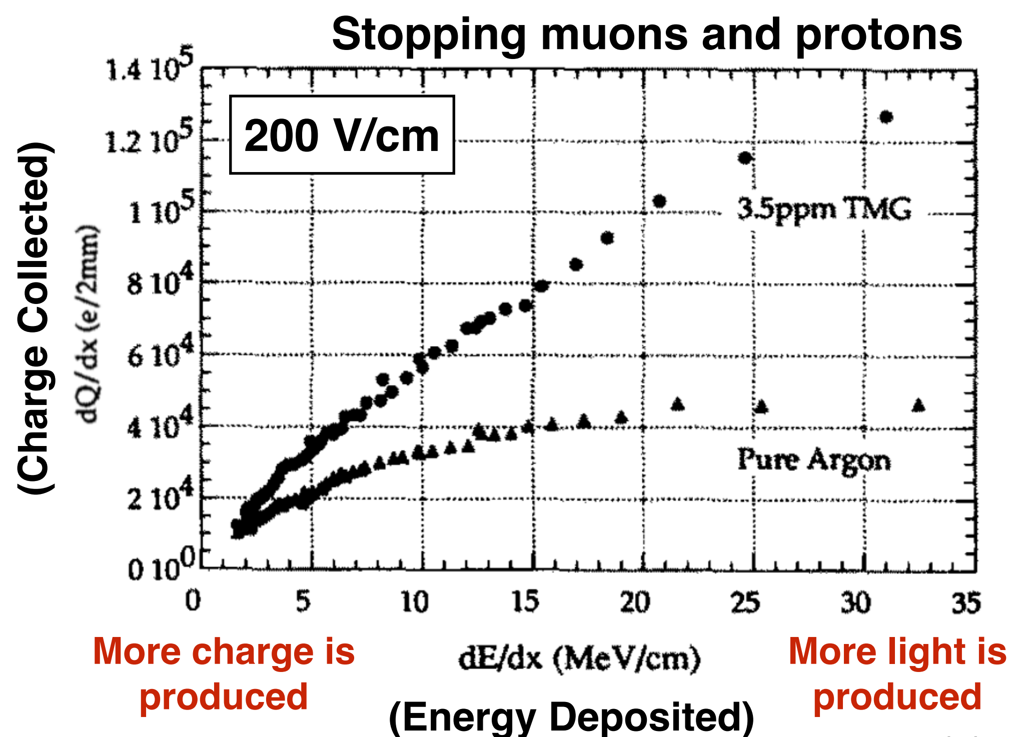
Doping ICARUS Prototype

- ICARUS doped their 3-ton prototype detector with TMG to the few ppm level
  - Selected TMG because it didn't react with filter material, had a large photo-absorptive cross section, and was easily purified
- **After introducing TMG they observed:**
  - **30% increase in muon charge signals**
  - **Stable operation for 250 days**
  - **Found a more linear detector response for highly ionizing particles**
- These features would improve the detector's performance for the GeV-scale physics program

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

ICARUS Collaboration

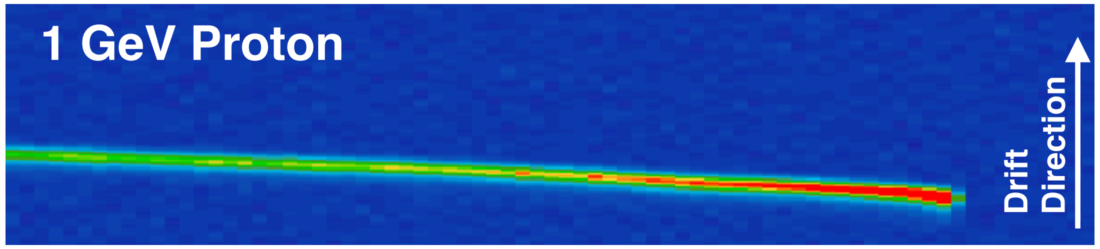




Open Questions: Mechanism

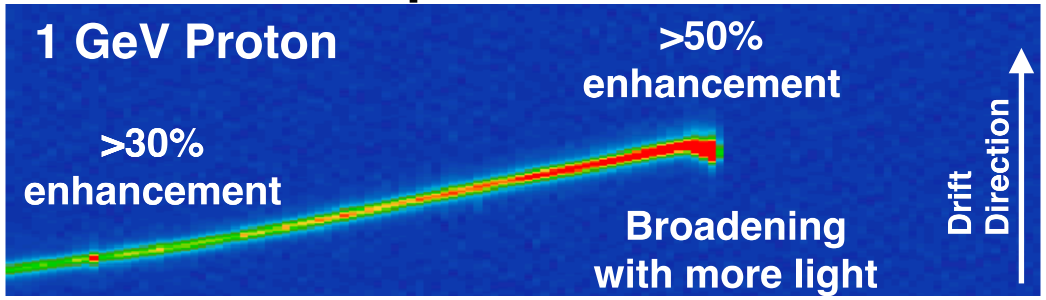
- Before we can build a detailed simulation of this process we need to know what mechanism dominates the photo-conversion:
  - **"Penning transfer":** excited argon atoms directly ionize the dopants
  - **"Photo-ionization":** photons ionize dopants, the charge signal will be impacted by scintillation time constants
- To address this we could dope with xenon which contracts the time profile
  - xenon also lower the energy of photons
- **Answering these and other open questions provides us a rich R&D pathway**

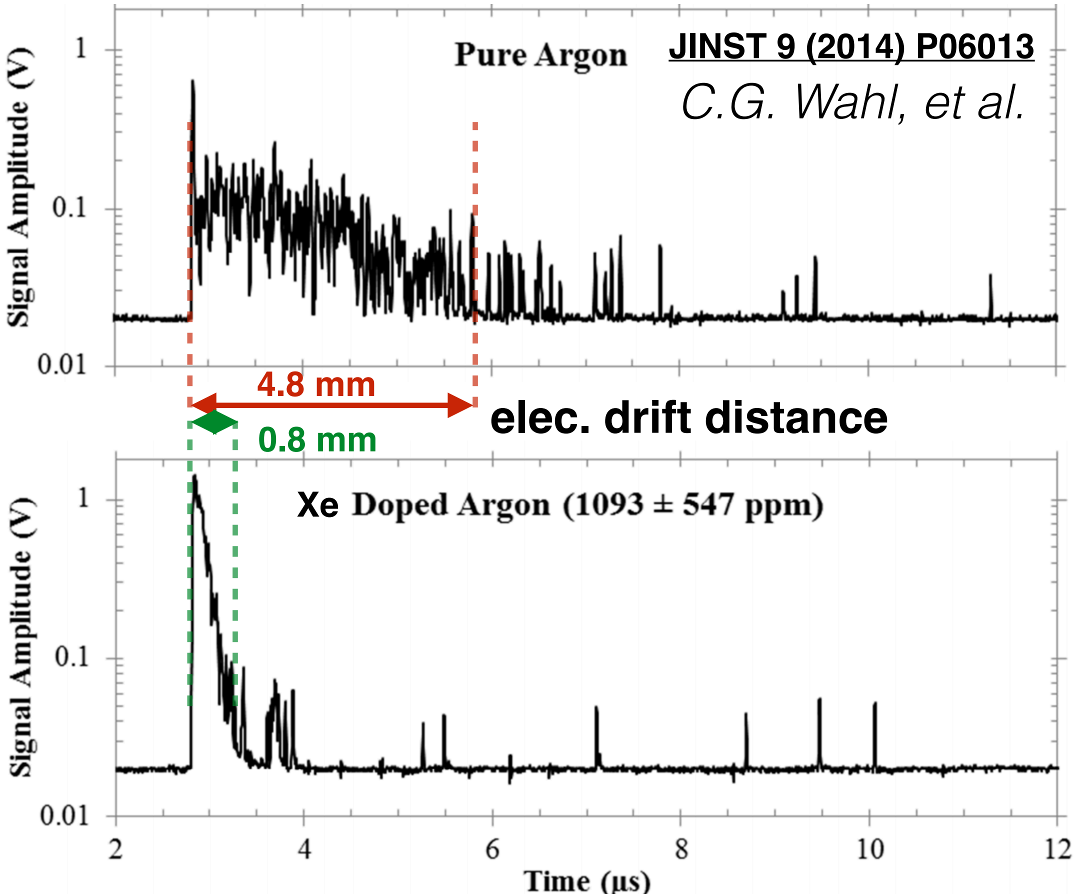
Standard LAr Simulation



TMA Simulation

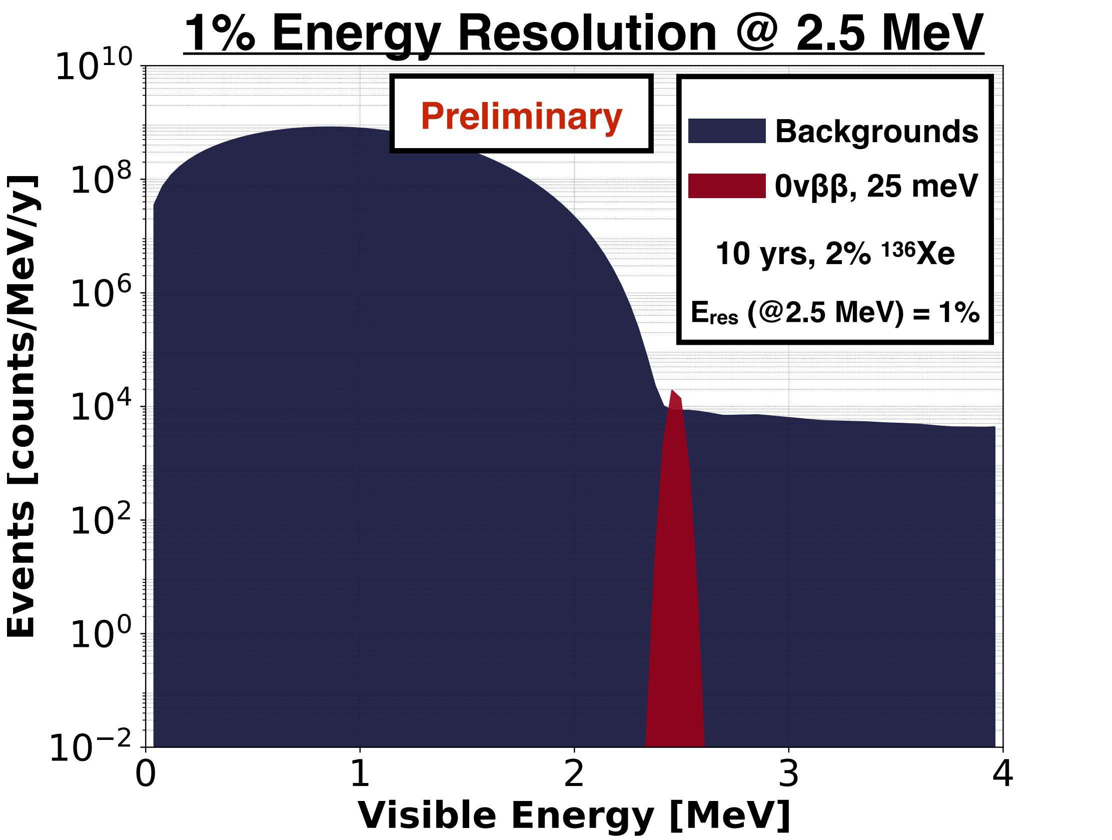
Modeled as a photo-ionization effect

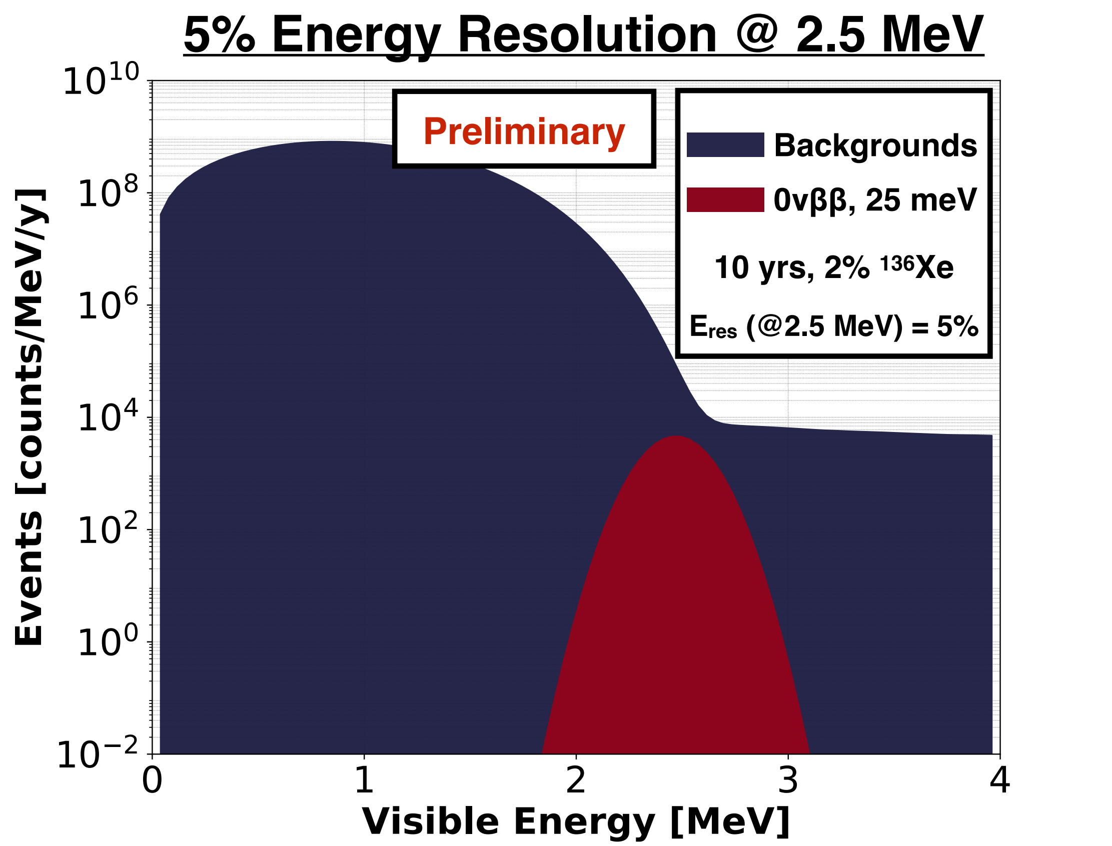




Other Benefits of Xenon-Doping

- On top of modifying the detector's performance ^{136}Xe is also a $0\nu\beta\beta$ candidate isotope
  - Doping with ^{136}Xe could enable a 100-ton scale search for $0\nu\beta\beta$
- **Concept:** Dope DUNE FD module LAr with 2% ^{136}Xe ($Q_{\beta\beta}$ = 2.5 MeV)
  - Enabling a **>300-ton** mass of xenon to sit within a 2 m fully active LAr buffer, eliminating most surface backgrounds
  - Additional background suppression comes via multisite tagging
- **To enable such a search one needs to utilize ^{42}Ar depleted LAr**

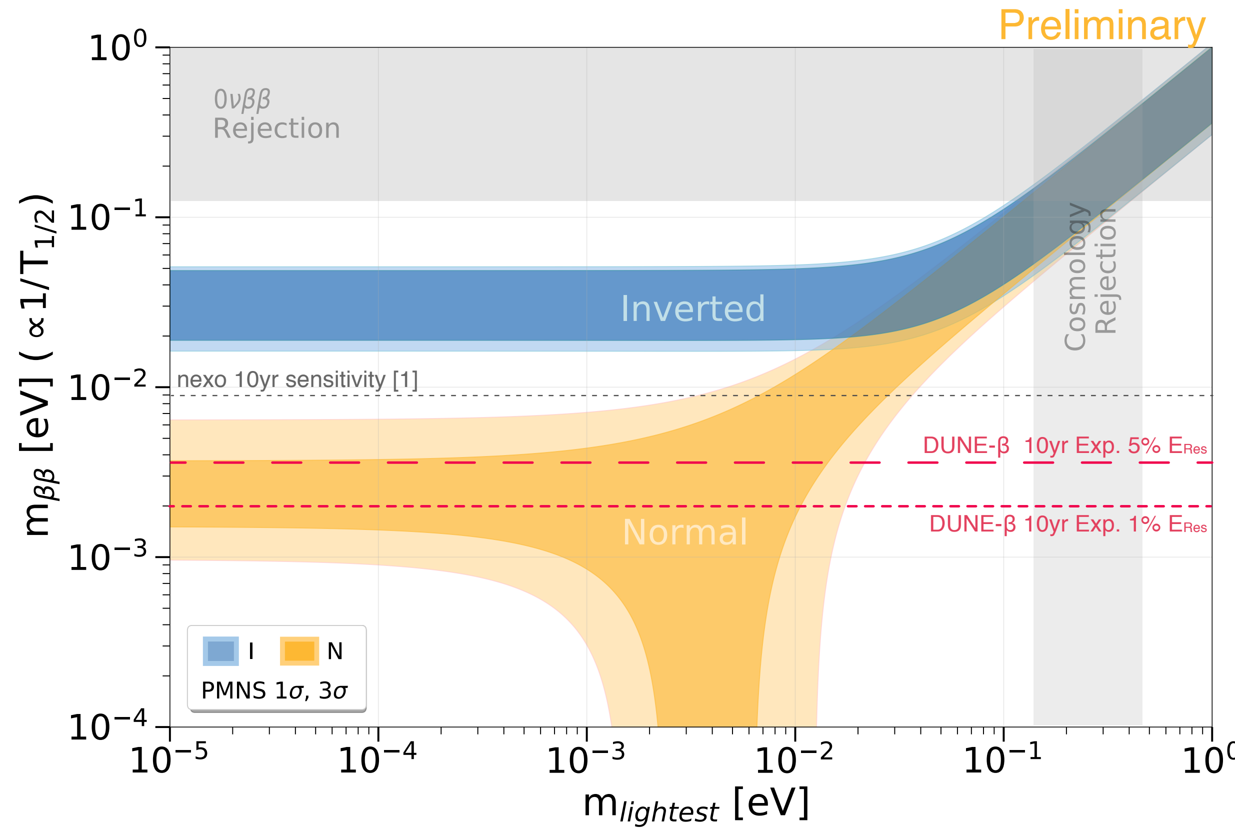


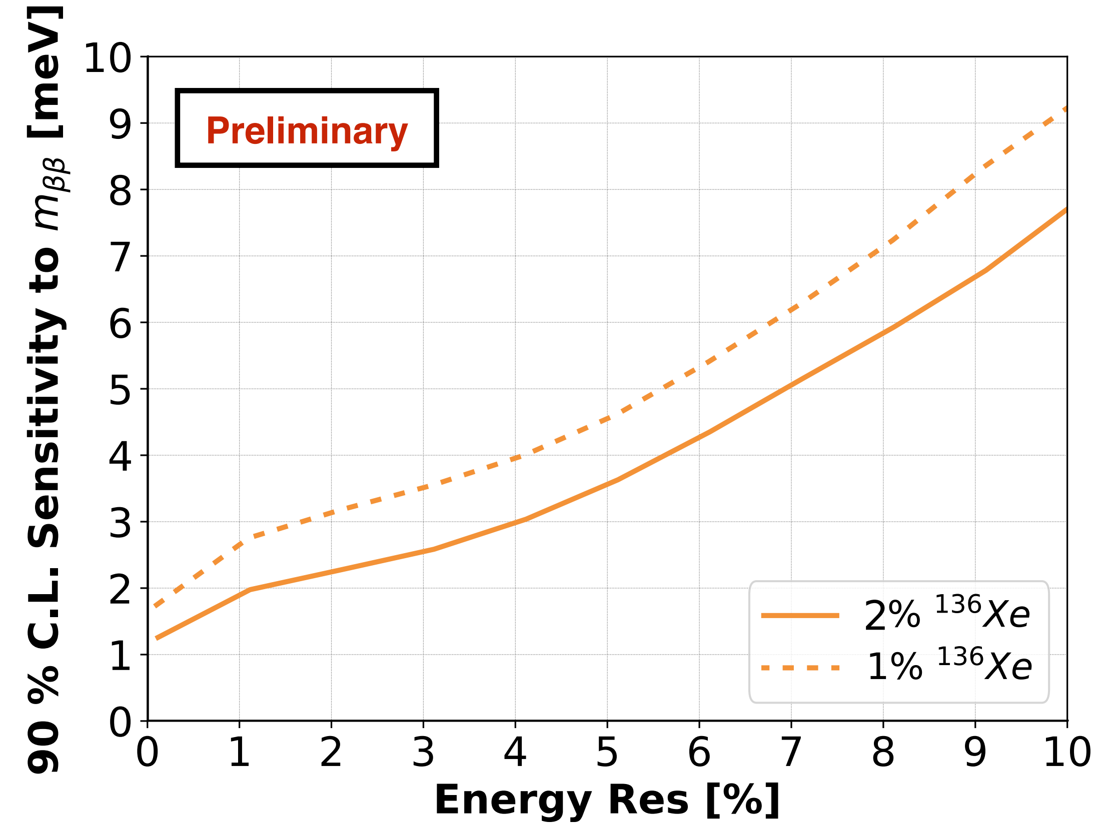


Publication pending, A. Mastbaum, F. Psihas, J.Zennamo

What Could Photoionizing Dopants Enable? Discovery!

- We can reach the normal hierarchy region by utilizing:
  - A single DUNE module for 10 years
  - Doped it with ^{136}Xe to 2% of its mass
  - Utilizing ^{42}Ar-depleted argon
  - Rudimentary background cuts
  - Keep energy resolution better than 5%
- These estimates are performed with a rudimentary counting analysis
  - Looking forward a more sophisticated statistical analysis coupled with a detailed studies of background mitigation techniques could improve this picture





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

Wrapping It Up

- **Photo-converting dopants provide an exciting opportunity** to enhance the MeV-scale reach of massive LArTPCs

- ICARUS and others have provided us tantalizing hints of the promise these dopants offer
    - **A rich R&D pathway is needed to validate these expected gains and demonstrate viability**

- These dopants could remove the need for us to utilize scintillation light to enhance energy reconstruction, **revolutionizing how LArTPCs can explore the MeV-scale**

Backups

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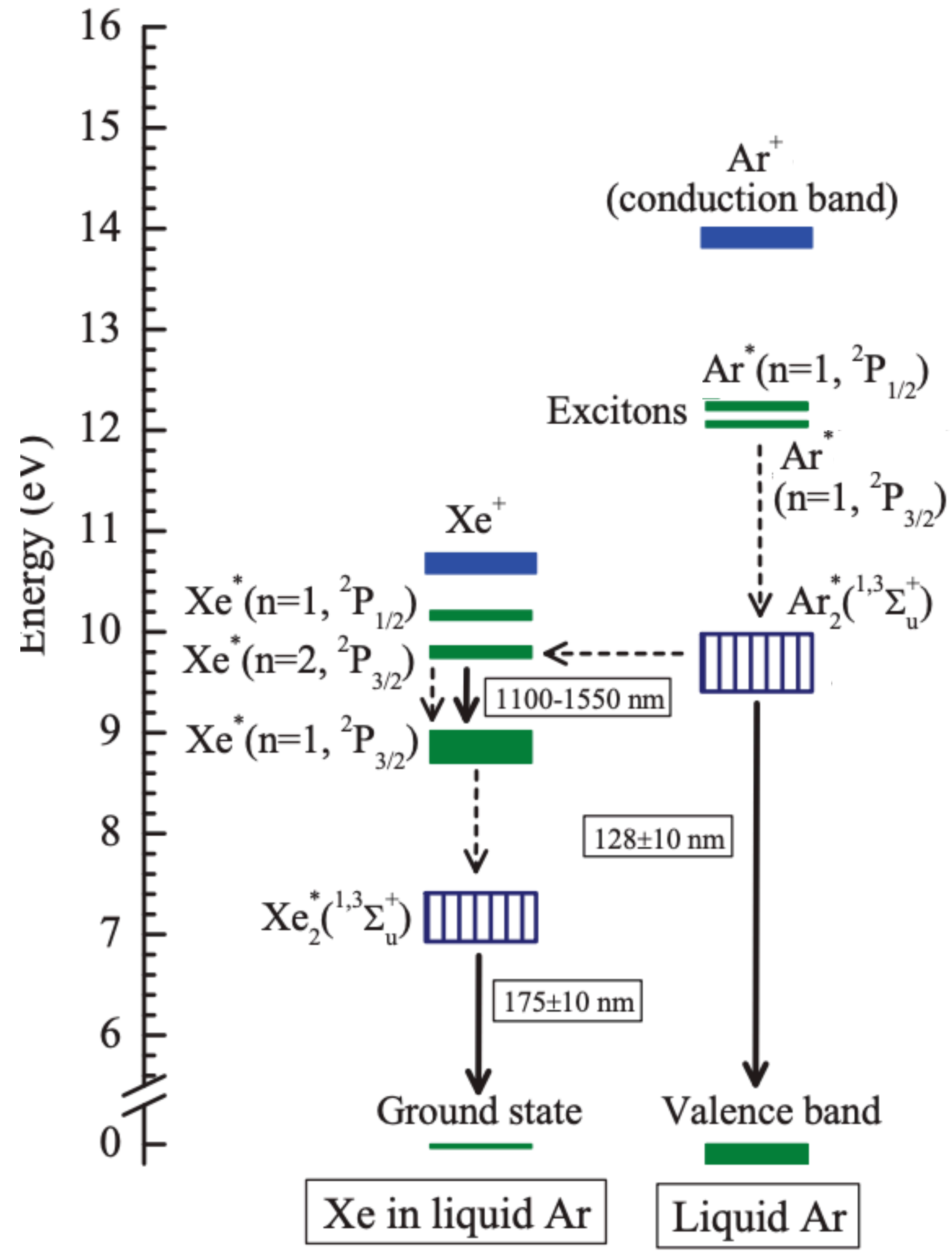
Xenon To the Rescue?

- Another way to improve the light yield is by doping the LAr with xenon
  - It is a happy coincidence that our 0νββ isotope also improves our detector's performance
- This works by the xenon atom absorbing the argon excitons energy before it can relax
  - Xenon scintillation light is at a longer wavelength, which is easier to detect and has a more compact time profile

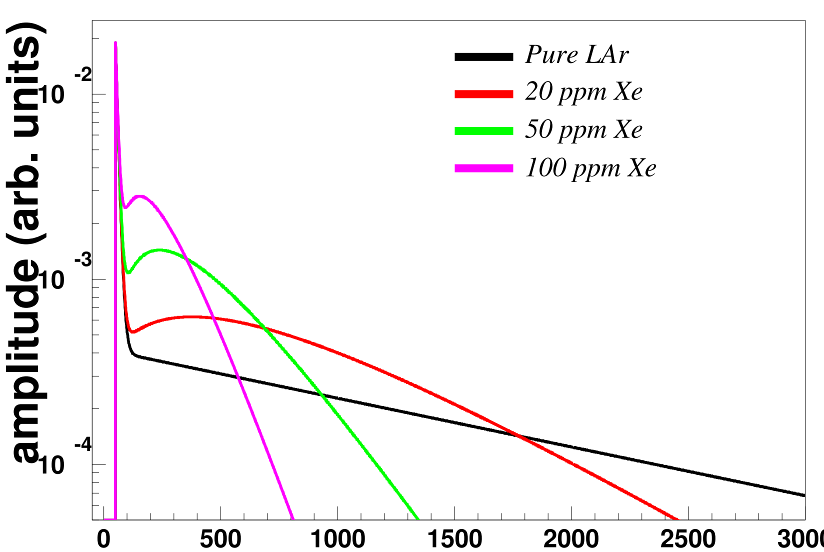
EPL 117 (2017) 3, 39002
A. Buzulutskov

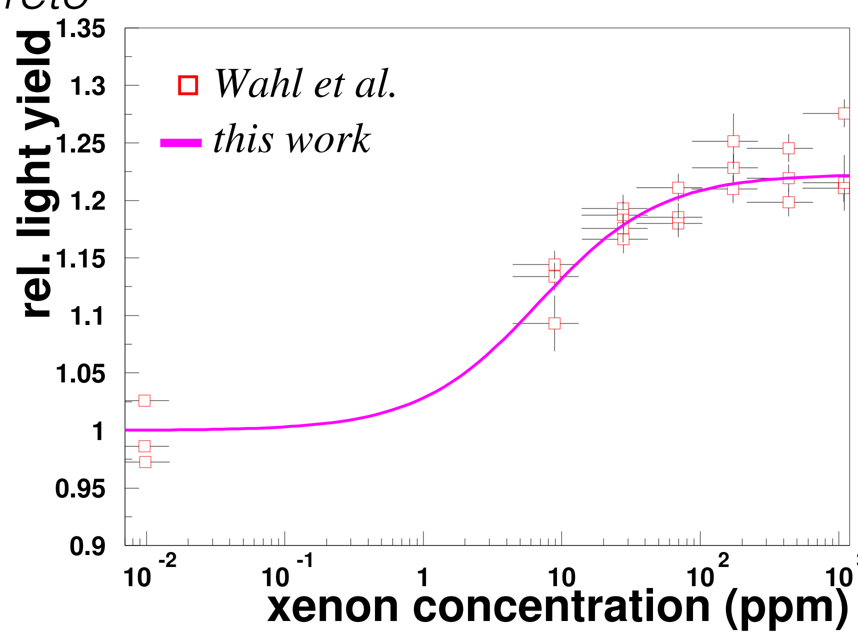


Benefits of Xenon Doping

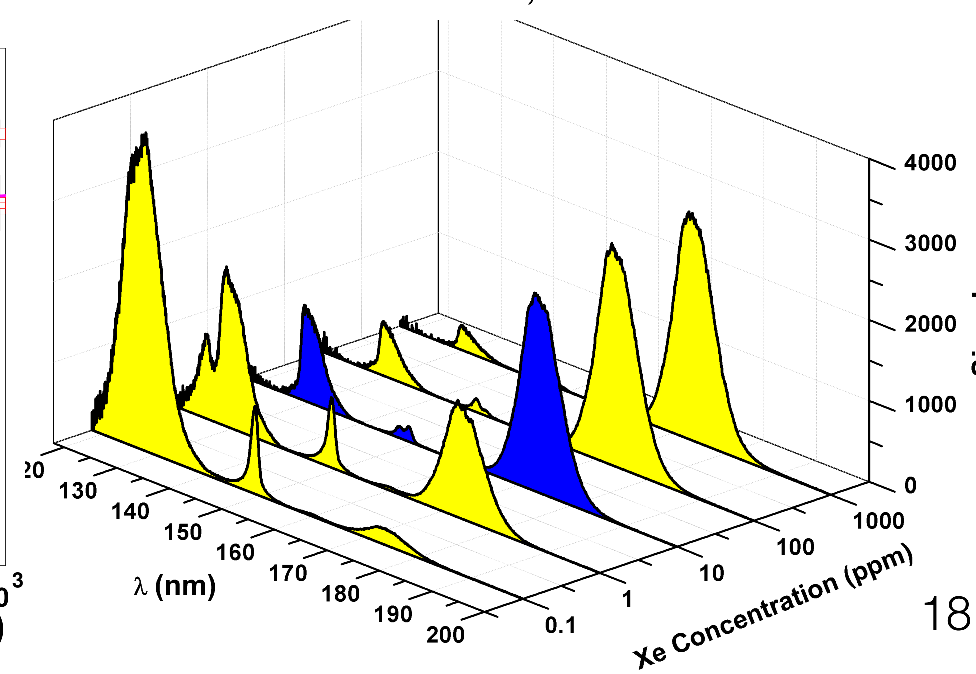
- The benefits of xenon doping have been observed with ppm levels of doping and persist at higher levels of doping
- The introduction of xeon will enhance our light collection but only at the level of O(10%)
- **Our goal is to improve our light collection by >100x**

arXiv:2012.06527
E. Segreto





EPL 109 (2015) 1, 12001
A. Neumeier, et al.

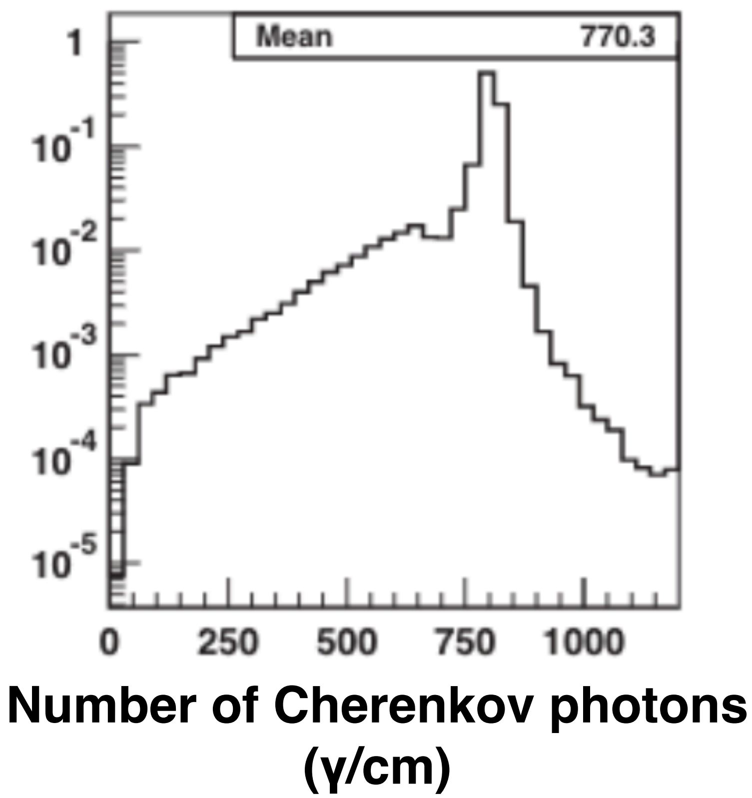


Locating in the Drift Direction

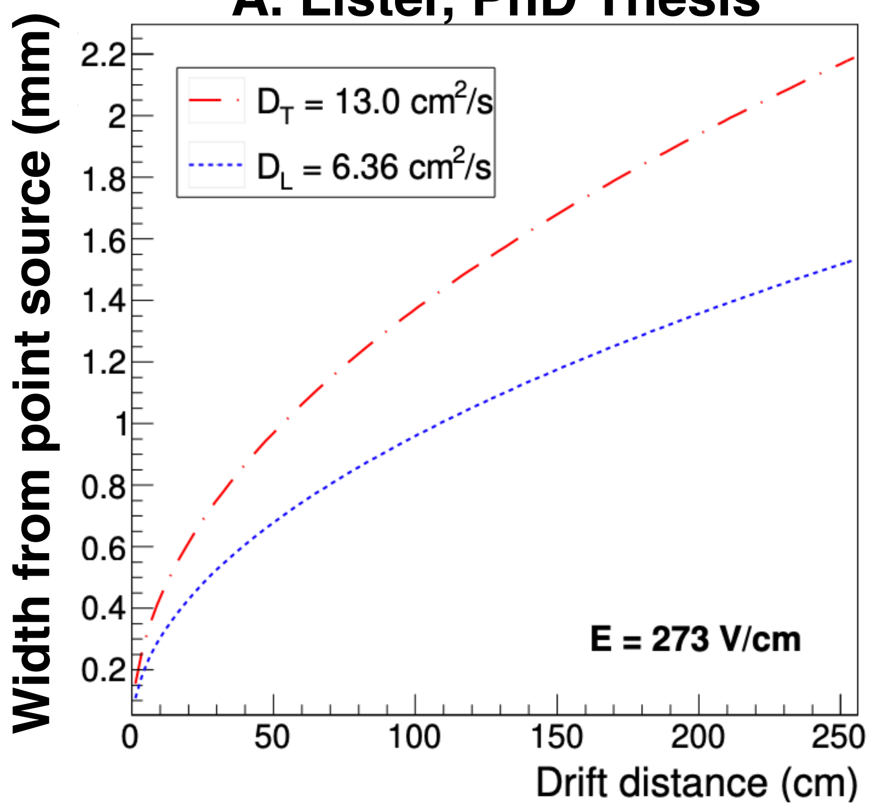
- LArTPCs uses the light to locate the charge in the drift direction
- Cherenkov light produced by particles produces light in the optical range
  - Easier to detect, insensitive to the dopants, and provides a prompt signal
  - Less light (~100x) is produced and is produced directionally
- As the cloud 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



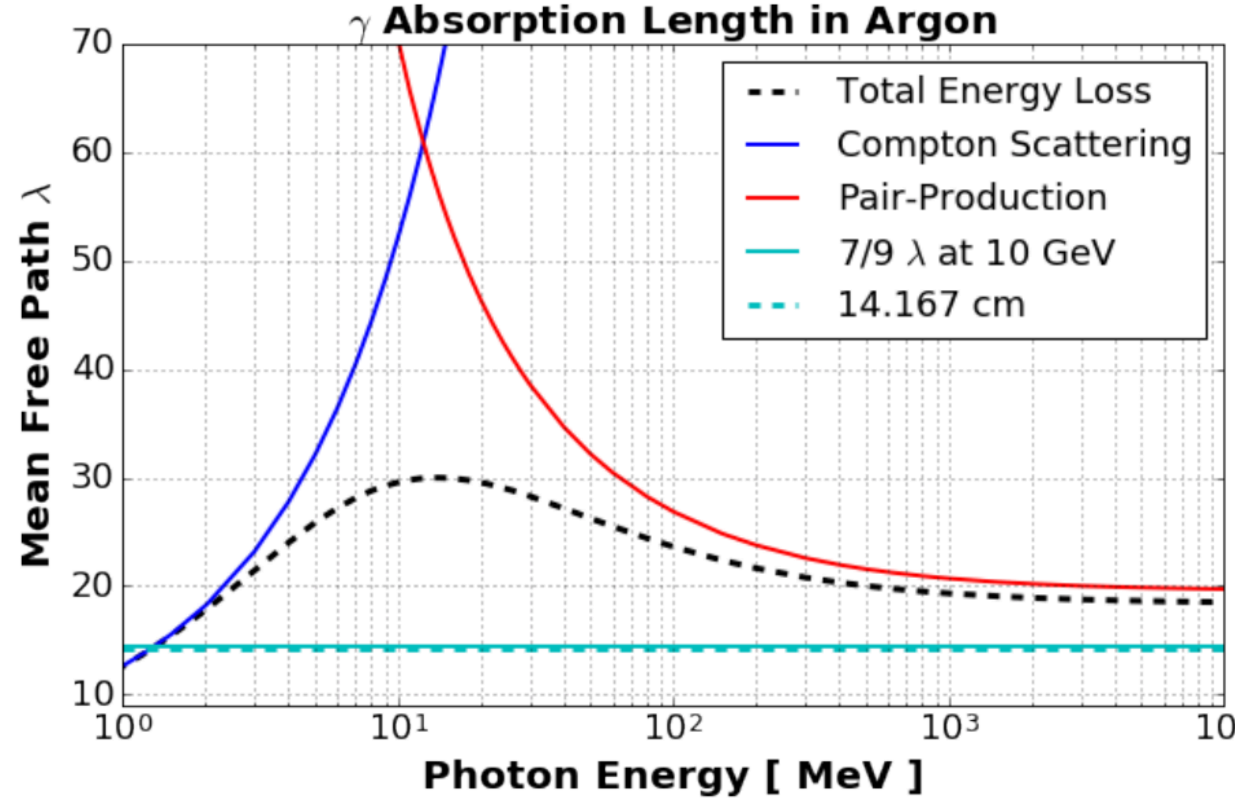
A. Lister, PhD Thesis

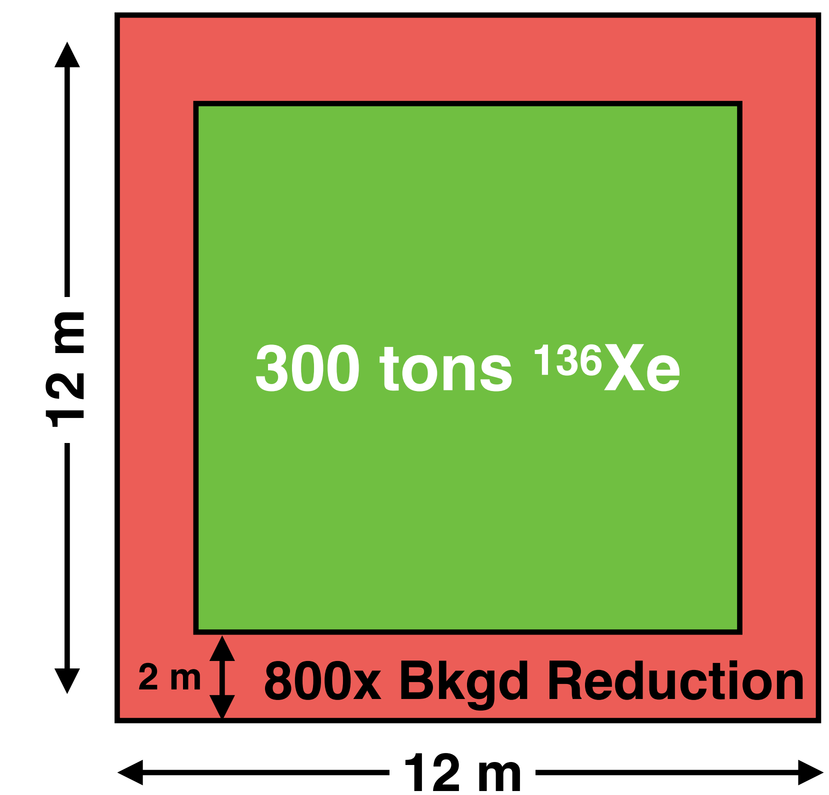


Types of Backgrounds

- 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



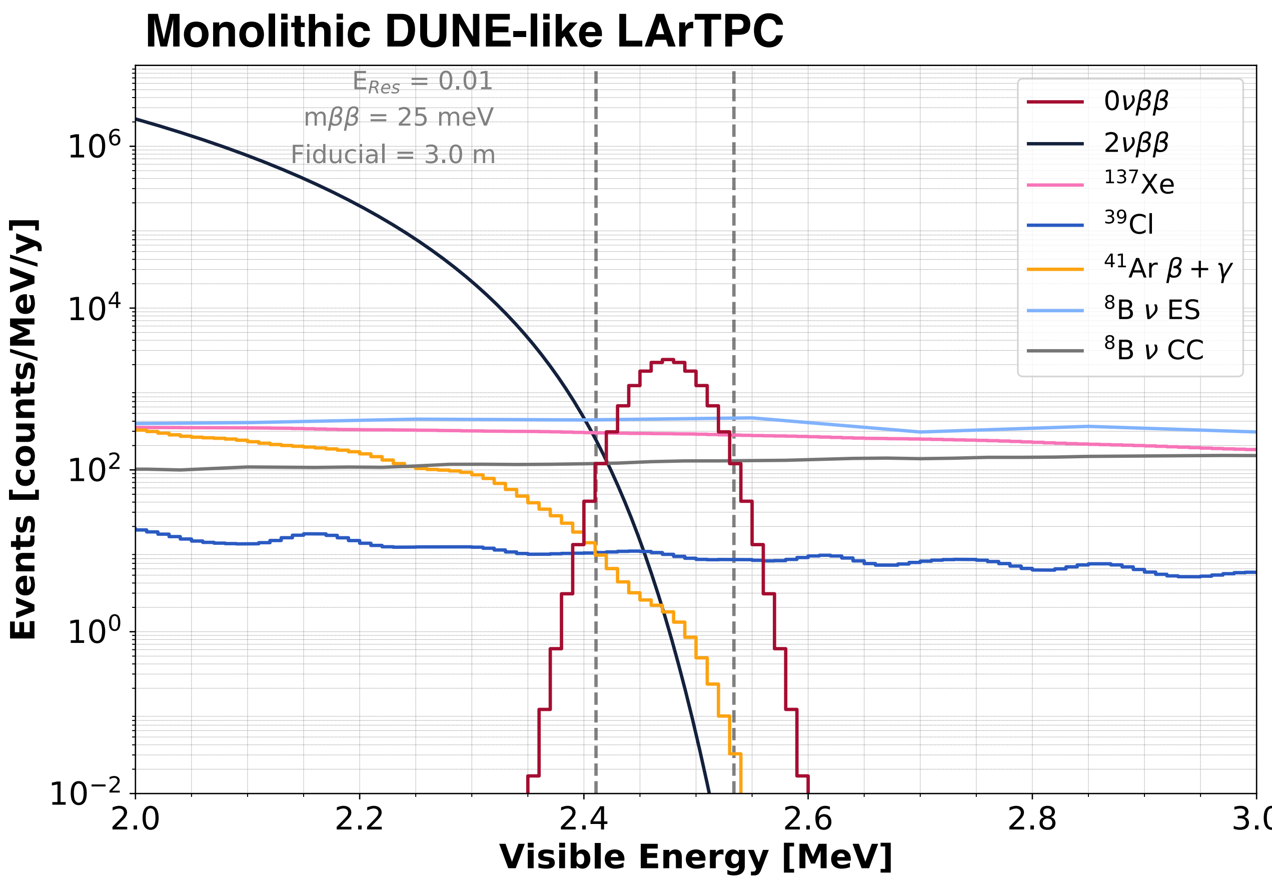


Publication pending, A. Mastbaum, F. Psihas, J.Zennamo

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



With these background estimates we can look at the possible reach of a xenon doped DUNE detector

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