Simulating Light Detection in Liquid Argon Time Projection Chambers Doped With Xenon for DUNE

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GEM Fellowship Program — Final Presentation

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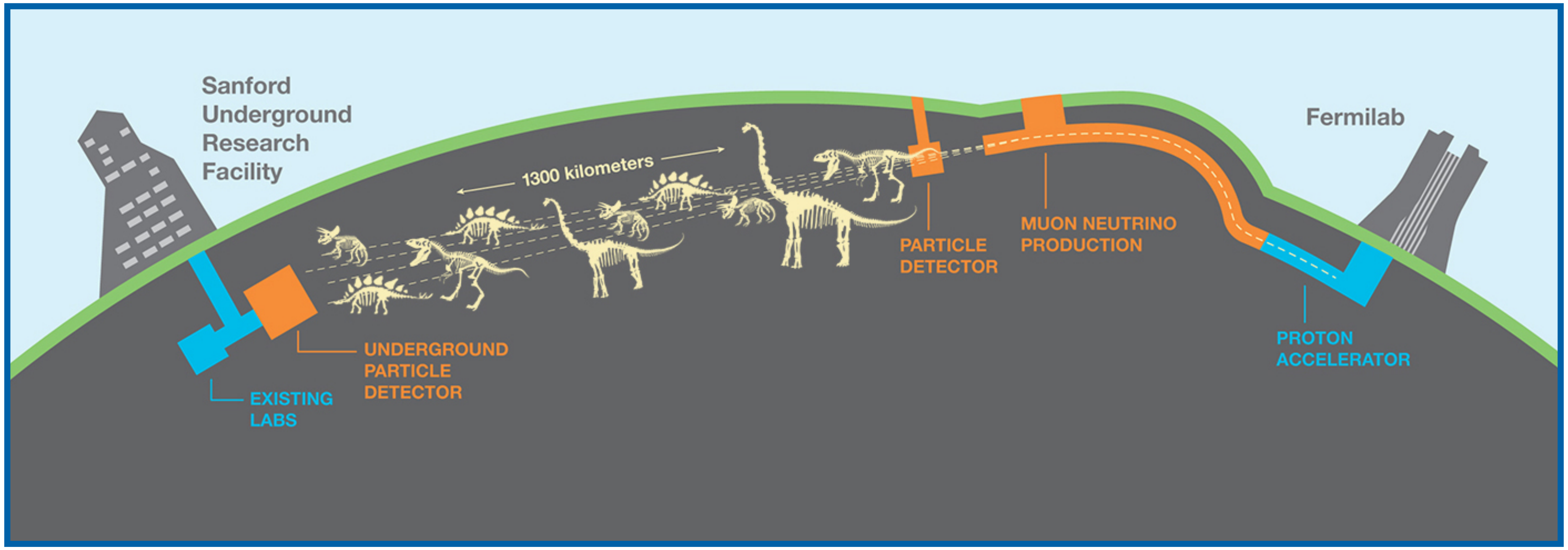
DUNE Background

- DUNE will be a neutrino observatory and nucleon decay detector that will tackle some of the most fundamental questions in physics. Some goals include:
  - Measuring proton decay
  - Measuring neutrinos from supernovae
- The detection of scintillation light is a key measurement needed to answer these questions.



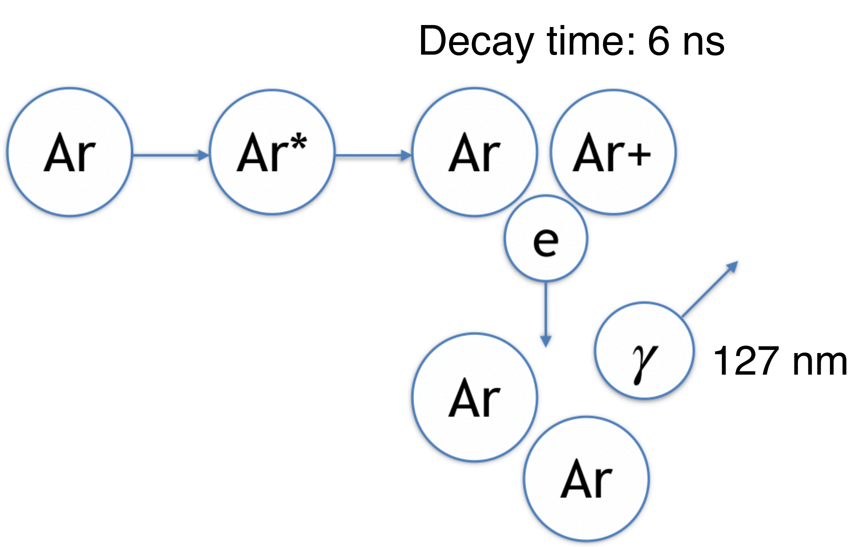
The Deep Underground Neutrino Experiment

Objective

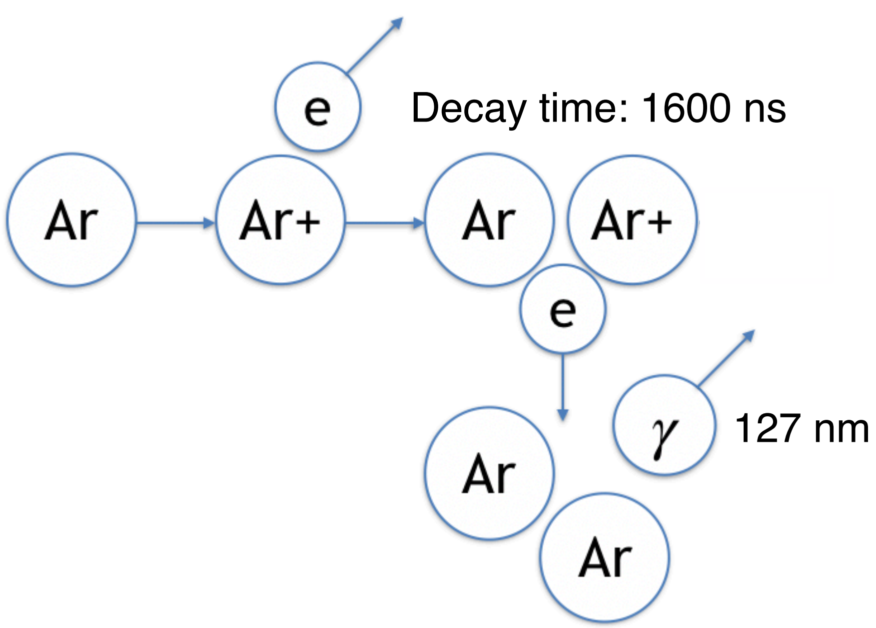
By doping the liquid argon with liquid xenon, we suspected that there would be a noticeable increase in the number of photons detected by our light detection system. Such an effect will allow for better energy resolutions and tracking efficiencies. Through simulation, we determined both the positive and potentially adverse, consequences resulting from the xenon doping.

Relevant Interactions

- The interaction of an electron transversing through liquid argon causes electron excitations and ionization.
  - The newly formed excited argon atoms bond with ground state argon atoms to form excimer states.
  - Additionally, excimer states can also form by argon ions recombining with recently liberated electrons and ground state argon atom (known as recombination luminescence).



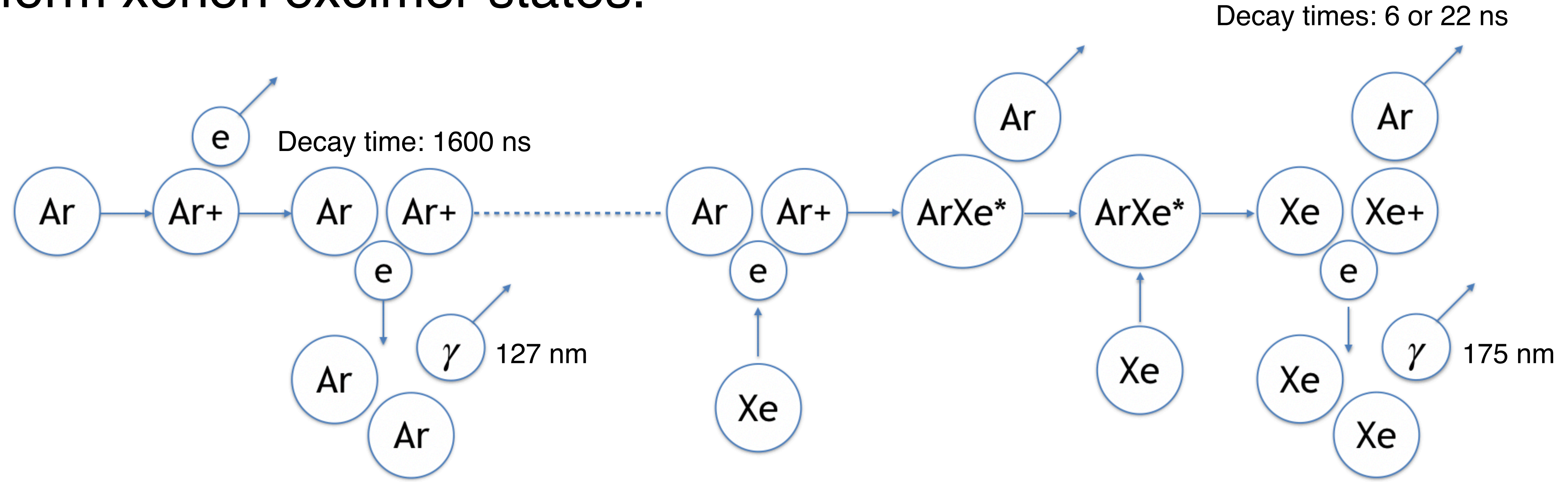
Self-trapped exciton luminescence



Recombination luminescence

Relevant Interactions Cont.

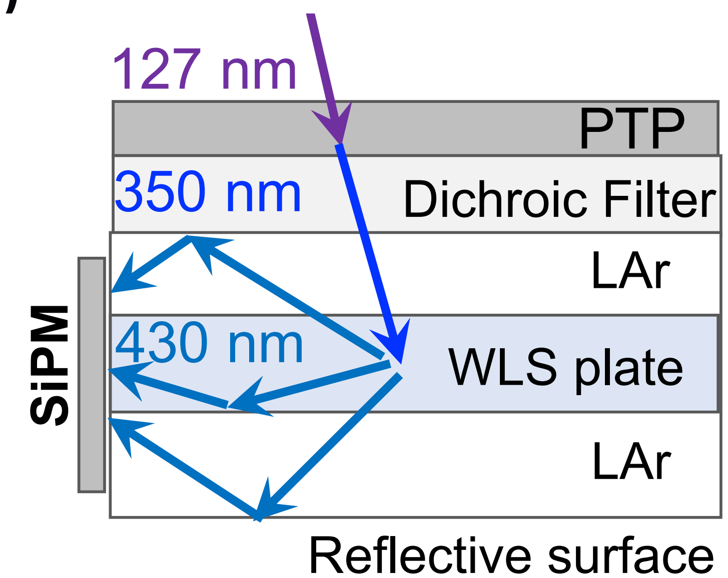
- As one would expect, when liquid xenon is added to the liquid argon there are additional and more complicated interactions that take place.
  - The decay time of the recombination state (1600 ns) is much longer than the decay time of the self-trapped exciton state (6 ns).
  - Therefore, these recombination states can interact with xenon atoms to form xenon excimer states.



Recombination luminescence

Light Detection System

- Our light detection system is comprised of X-ARAPUCAs.
  - pTP film for upshifting the wavelengths of light
  - Dichroic filter with a threshold of 400 nm (below it is transparent and above it is reflective).
  - A wavelength shifting plate that upshifts the photon and via total internal reflection traps the light
  - At the ends of the light guides there is an array of silicon photomultipliers (SiPMs)



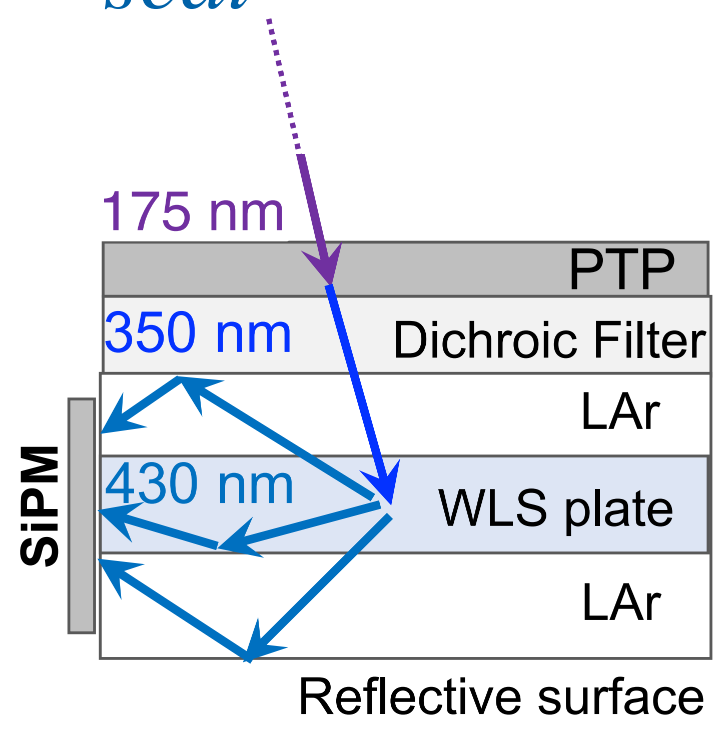
Not to scale.

Current photon detection system for DUNE (each APA has 10).

Light Detection System Cont.

- The absorption spectra of liquid xenon corresponds to the absorption spectra of argon.
- We suspected that the affect this wavelength shift has on the Rayleigh scattering will translate to less light being scattered and, as a result, increase the light detection yield.

$$I_{scat} \propto 1/\lambda^4$$



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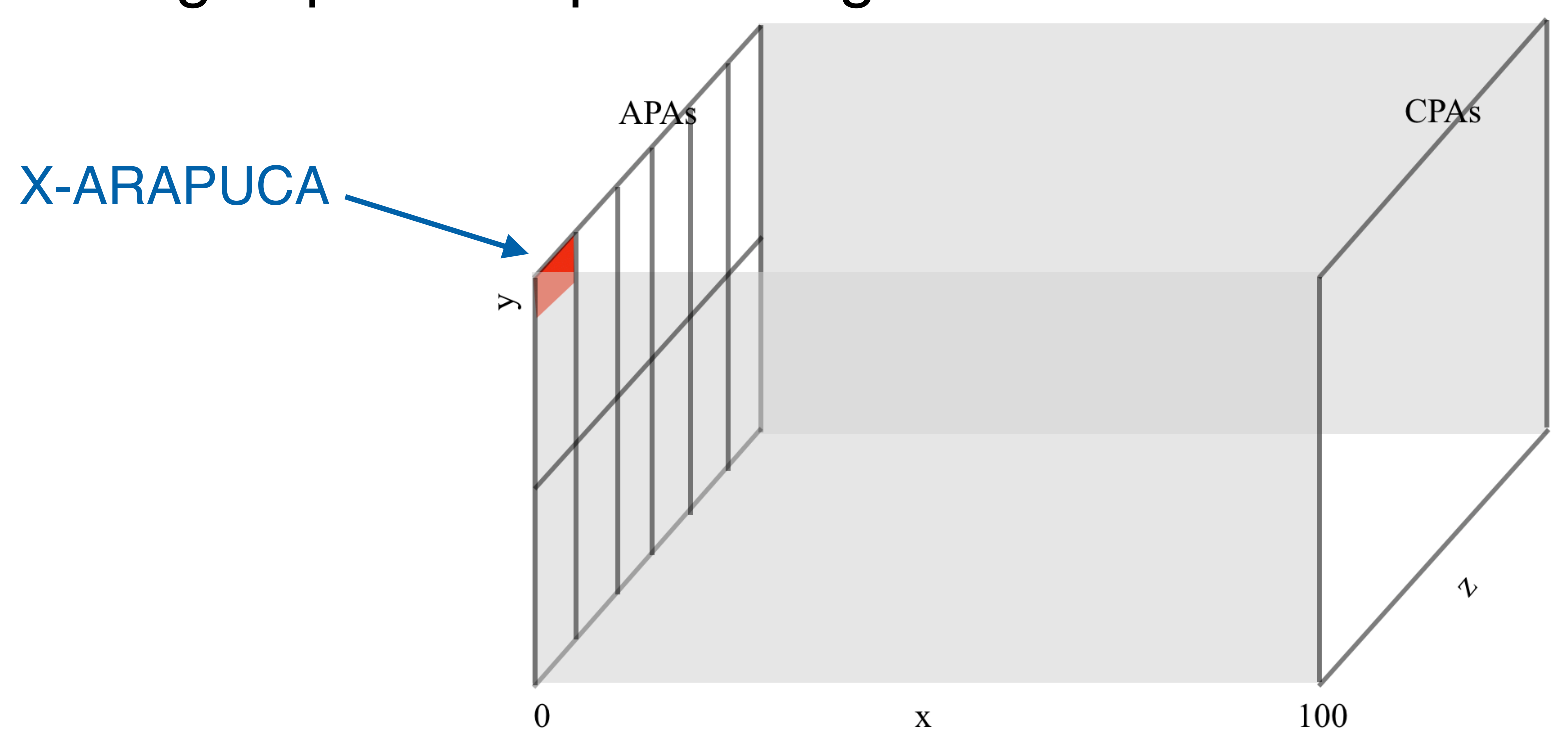
Current photon detection system for DUNE (each APA has 10).

Simulation

- The simulation required knowledge of LArSoft and ROOT. The argon and xenon datasets followed a similar procedure (similar geometries/detector properties).
  - In the electron simulation step, we consider a 1x2x6 module of the detector, as we are yet unable to simulate the entire module.
  - For an electron, many photons are produced for each simulated event. So much so that our computational limits are unable to handle them all.
- The only thing that changed between the two was the wavelength of the scintillation light. Information on the visibility of each voxel, stored in a photon library, allows us to have a better grasp on our photon signal.

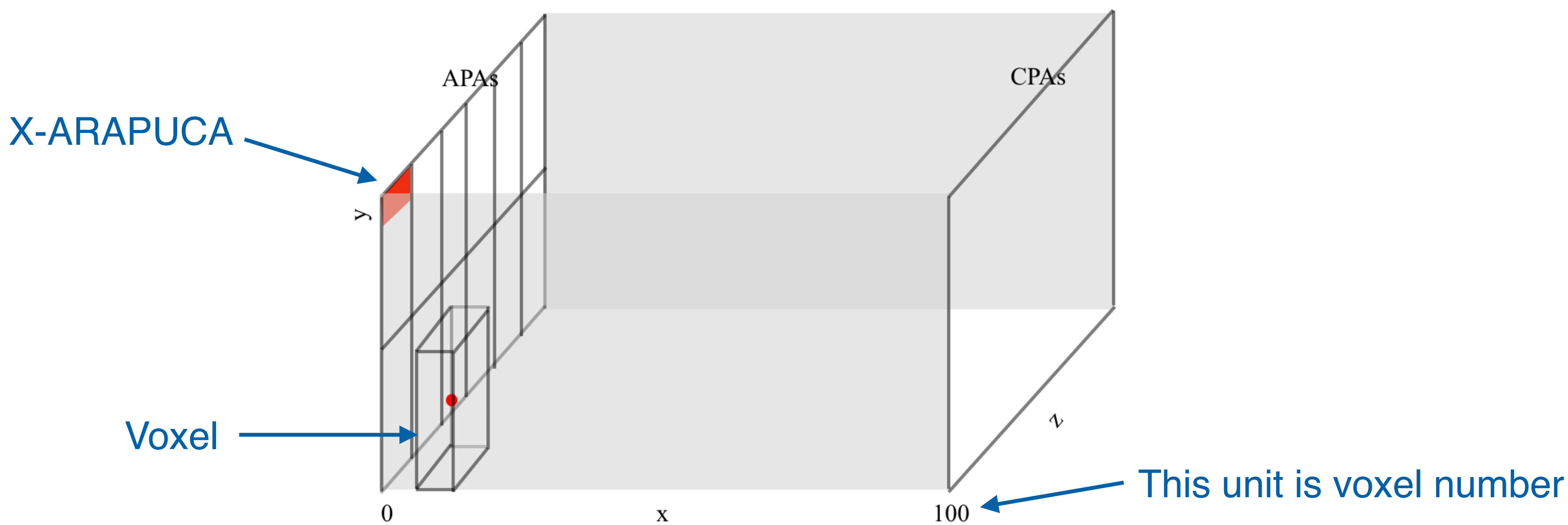


Argon library: 127 nm

Xenon library: 175 nm

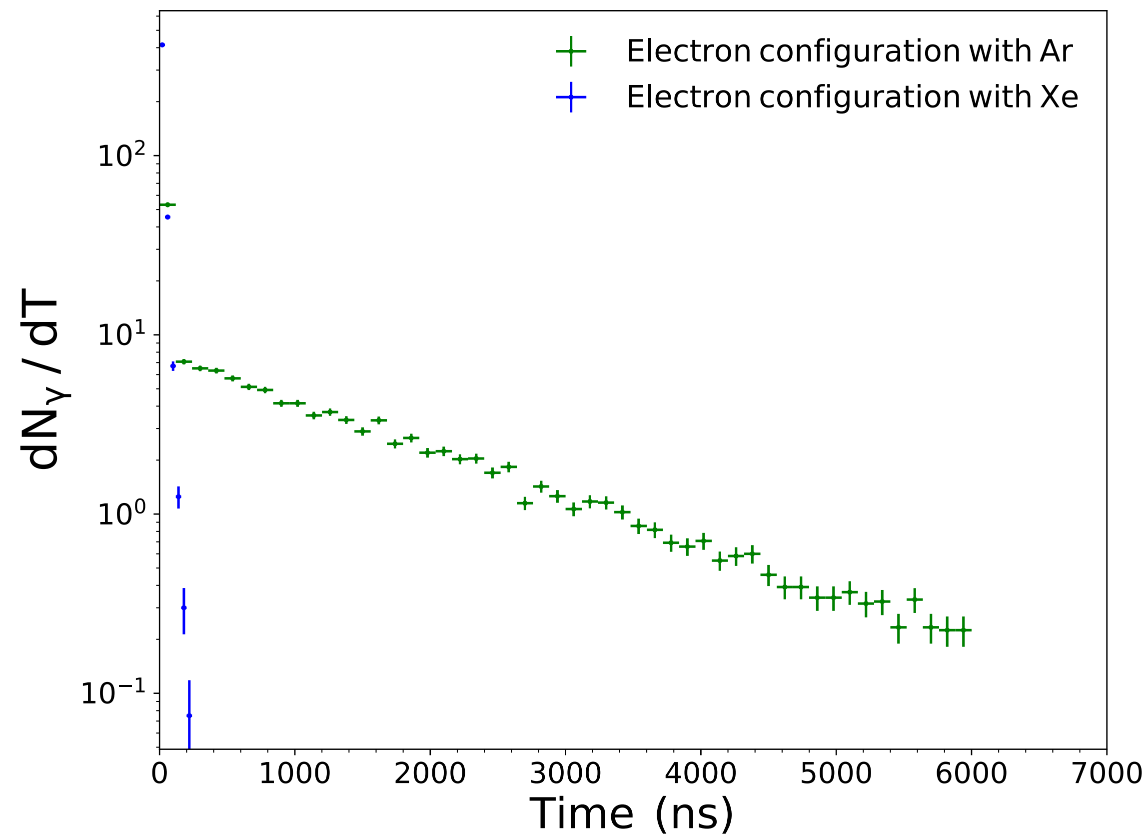
Simulation Cont.

- The photon library gives the likelihood that a photon produced within a voxel will be seen by our photon detection system.
  - The way these are generated is by splitting our detector volume into smaller 3D pixels called voxels.
  - At the center of each of these voxels, we generate an isotropic source of light. Depending on the photon library of interest, this light will have a wavelength of 127 or 175 nm. The visibility is equal to $N_{\gamma,det}/N_{\gamma,gen}$.

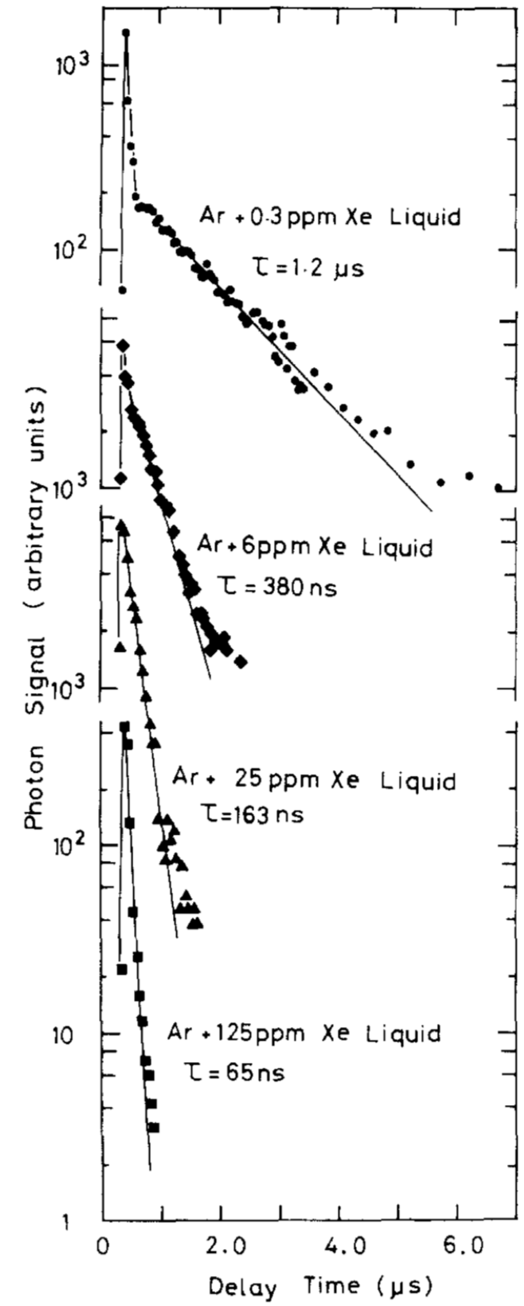


Xenon Photon Library

- A xenon photon library will influence all of the analyses that proceed. Therefore, it is imperative that we make sure that a newly made xenon photon library is thoroughly studied.
  - By making sure that we see those decay times in the results of the electron simulation step, we can see that it did reproduce what is seen in experimentation (also looked into energy deposition).

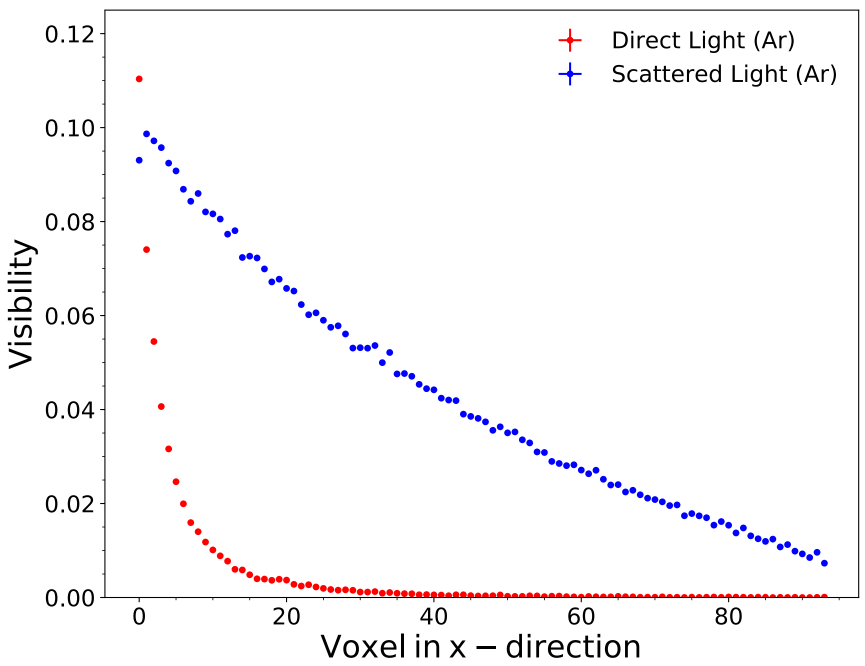


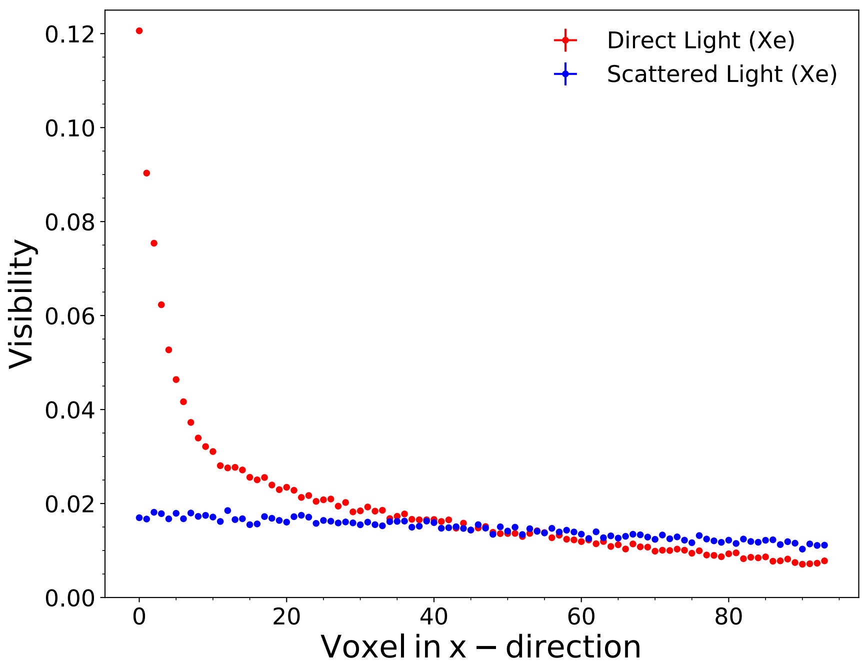
Compared to experiment

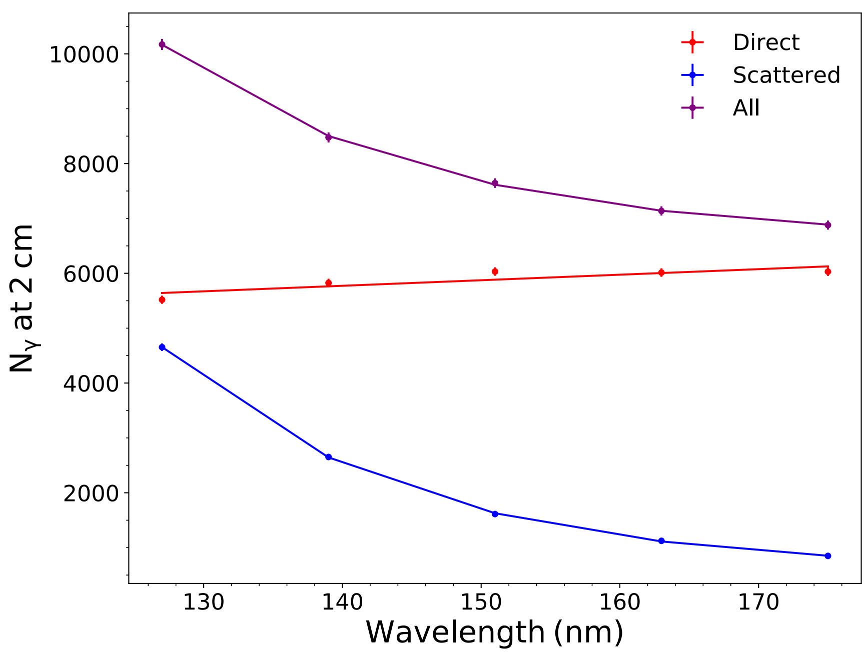


Impact of Direct vs. Scattered Light

- Now we took a step back, and looked at the photon library level for a smaller section of the detector. Looked at the contributions of scattered and direct light for xenon and argon. There are two important features to notice:
  - For the argon case, we see the importance of scattering and how it dominates our visibility as we move further away from the APAs in the X-direction.
  - We see a drop off in the scattered light contribution as we increase the wavelength. An explanation for such behavior is due to the wavelength shift.

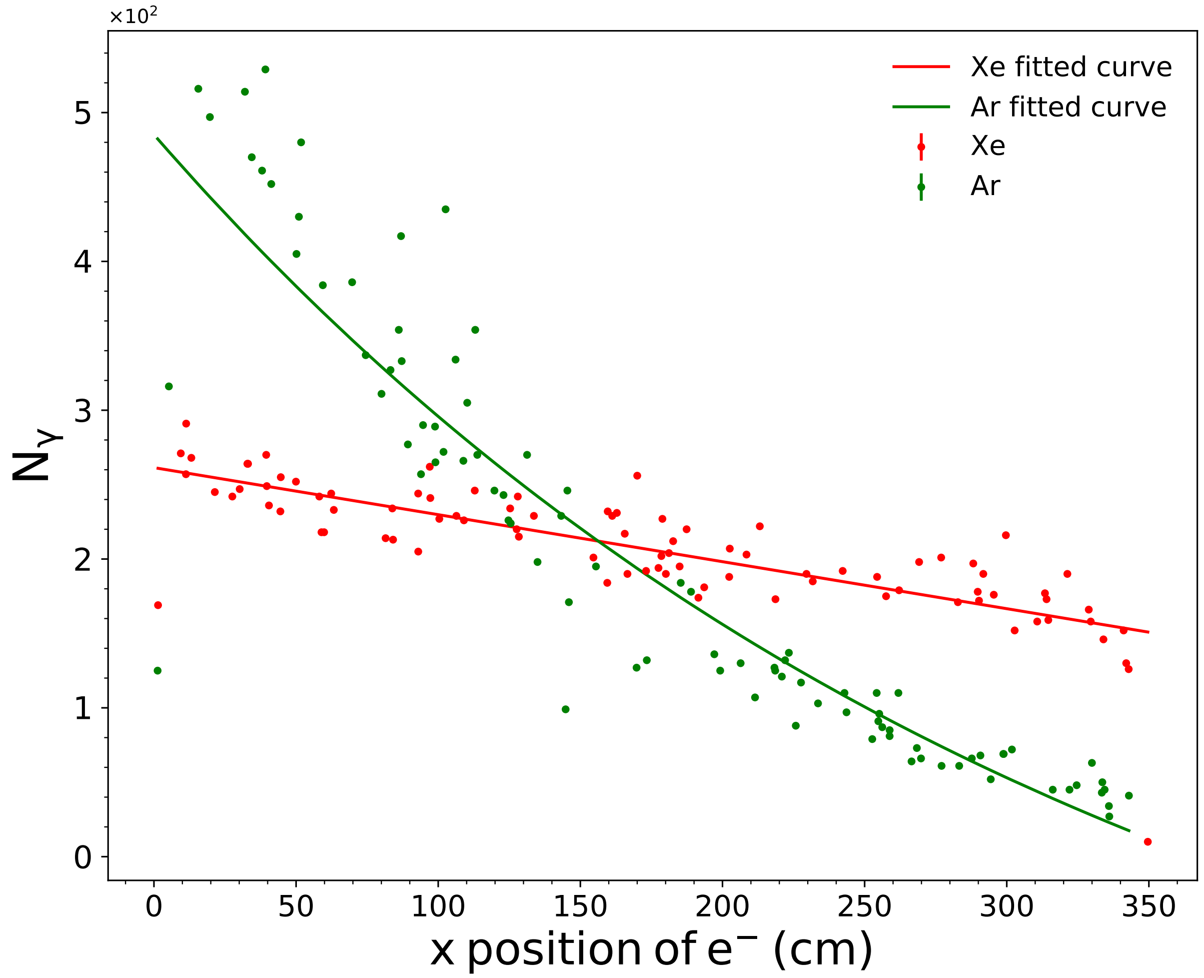






Attenuation

- The attenuation observed when 20 MeV electrons transverse through argon and xenon (using the full detector libraries).

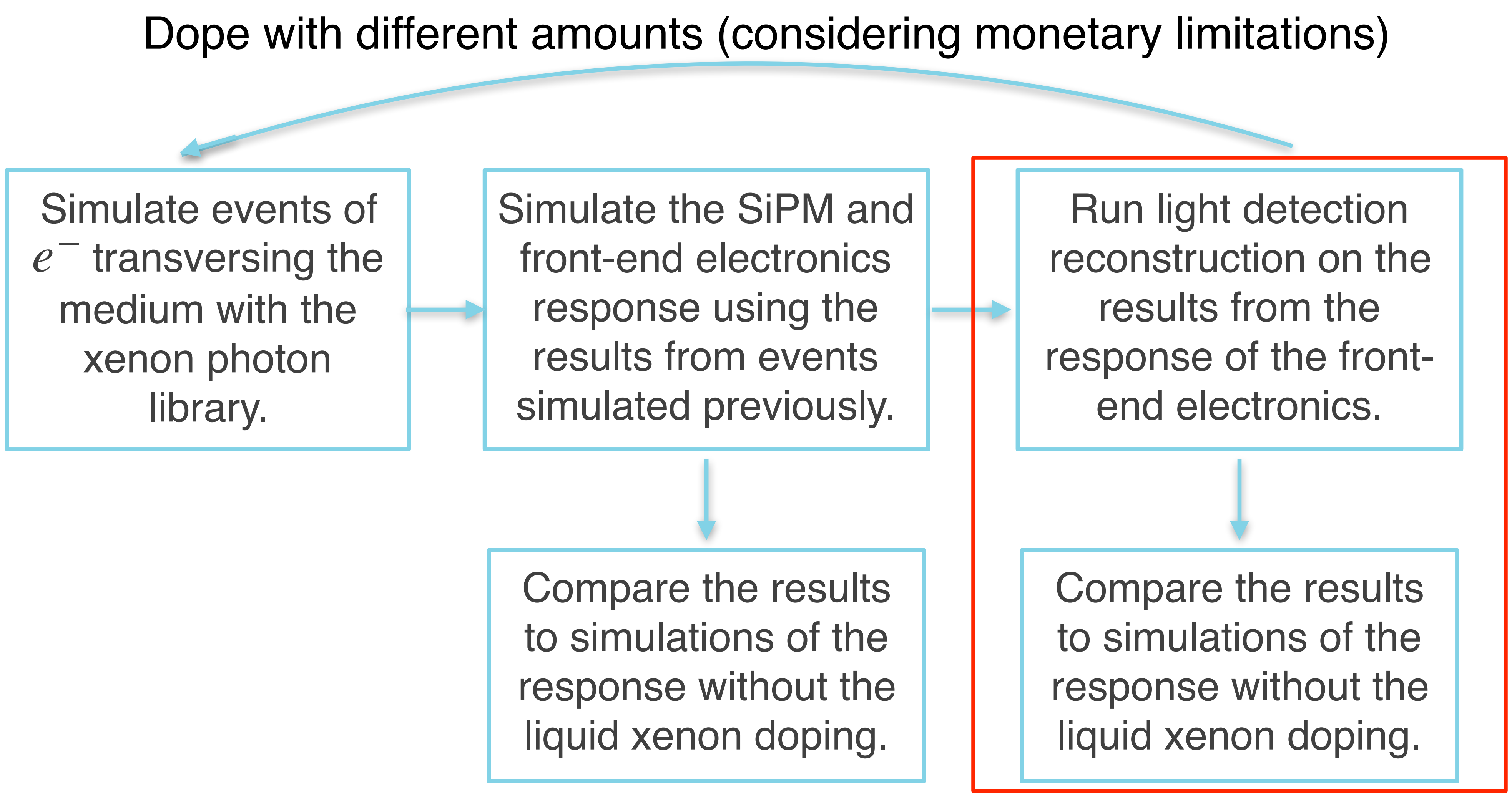


Need to think about the detector geometry/ technology.

- The benefits of doping can be seen in the uniformity of the signal yield. By having an accurate and precise photon library for xenon, we can progress to simulating doping procedures. That entails using a new version of GEANT4 and seeing the limits to when doping becomes beneficial for DUNE.

Future Work

- Once a newer version of GEANT4 is implemented, we can work towards understanding the benefits of doping at DUNE as a function of doping, or monetary cost, and get a clearer understanding of argon xenon admixtures (xenon: $2000/kg, argon: $2/kg).



Conclusions

- Concluded that Rayleigh scattering is important, but depends on detector geometries and detection technologies. We need to ask:
  - Are we giving our detector a large enough volume to see the impact of Rayleigh scattering?
  - How efficient is our PTP wavelength at shifting 175 nm light?
  - Or does including a reflective coating along the interior of the detector introduce additional unaccounted for properties?
- **Nonetheless, the signal yield for xenon is more uniform compared to argon.**
- We need to continue to the process by implementing a newer version of GEANT4 that can handle both argon and xenon photon libraries.

Acknowledgements

I would like to thank my supervisors Alex Himmel and Bryan Ramson for the help and guidance throughout the summer. Their help was pivotal in learning LArSoft and developing an understanding of the simulation. Also, I would like to thank Sandra Charles, Judy Nunez, Laura Fields, Raul Campos, Matthew Alvarez, and Alexander Martinez for their support during my stay at Fermilab.

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Backup Slides

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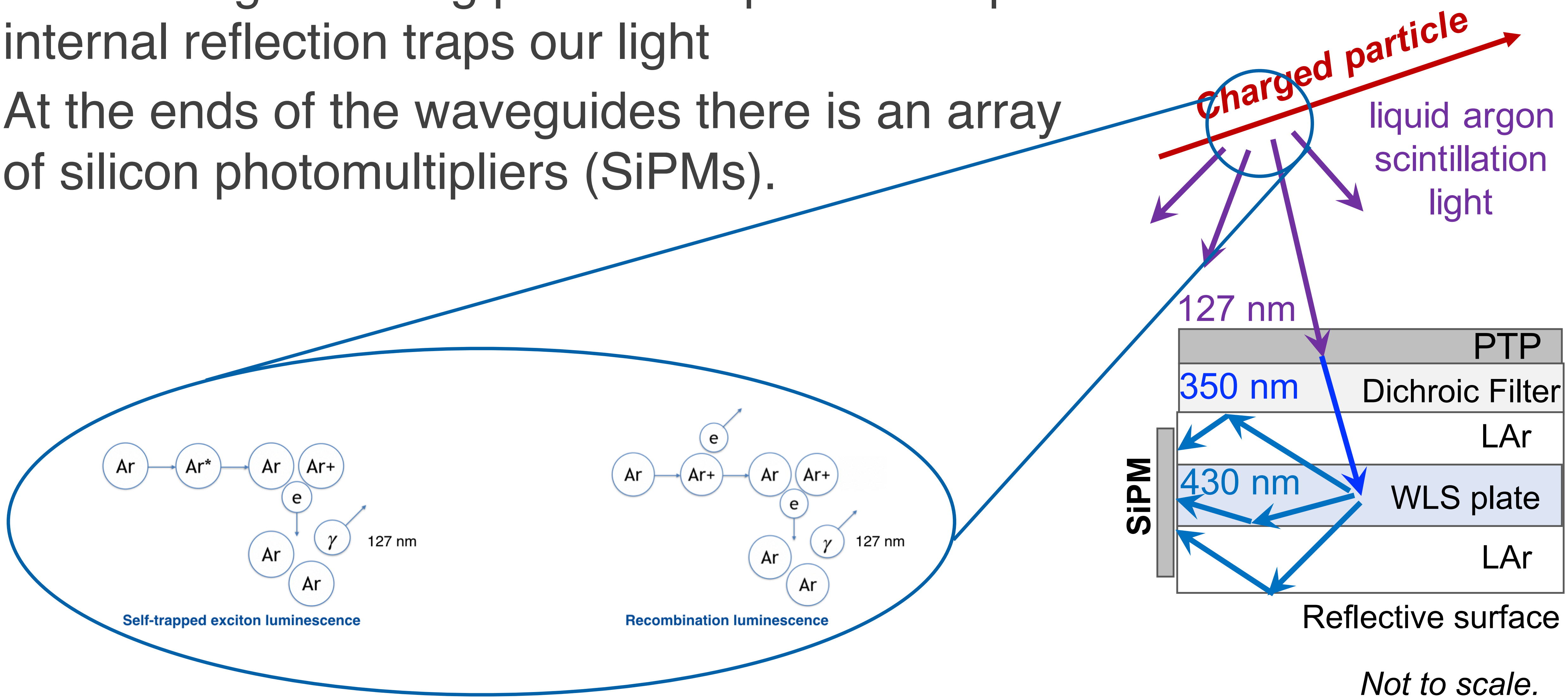

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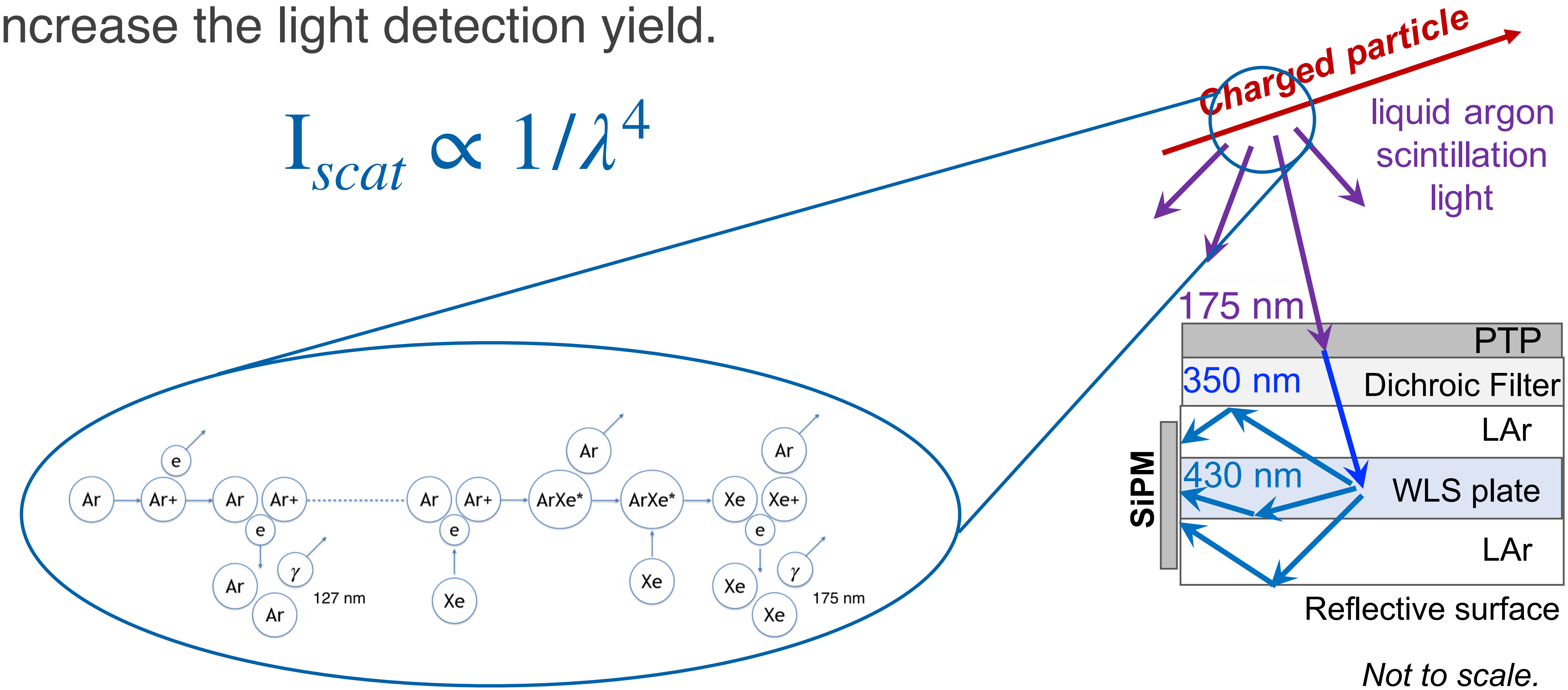

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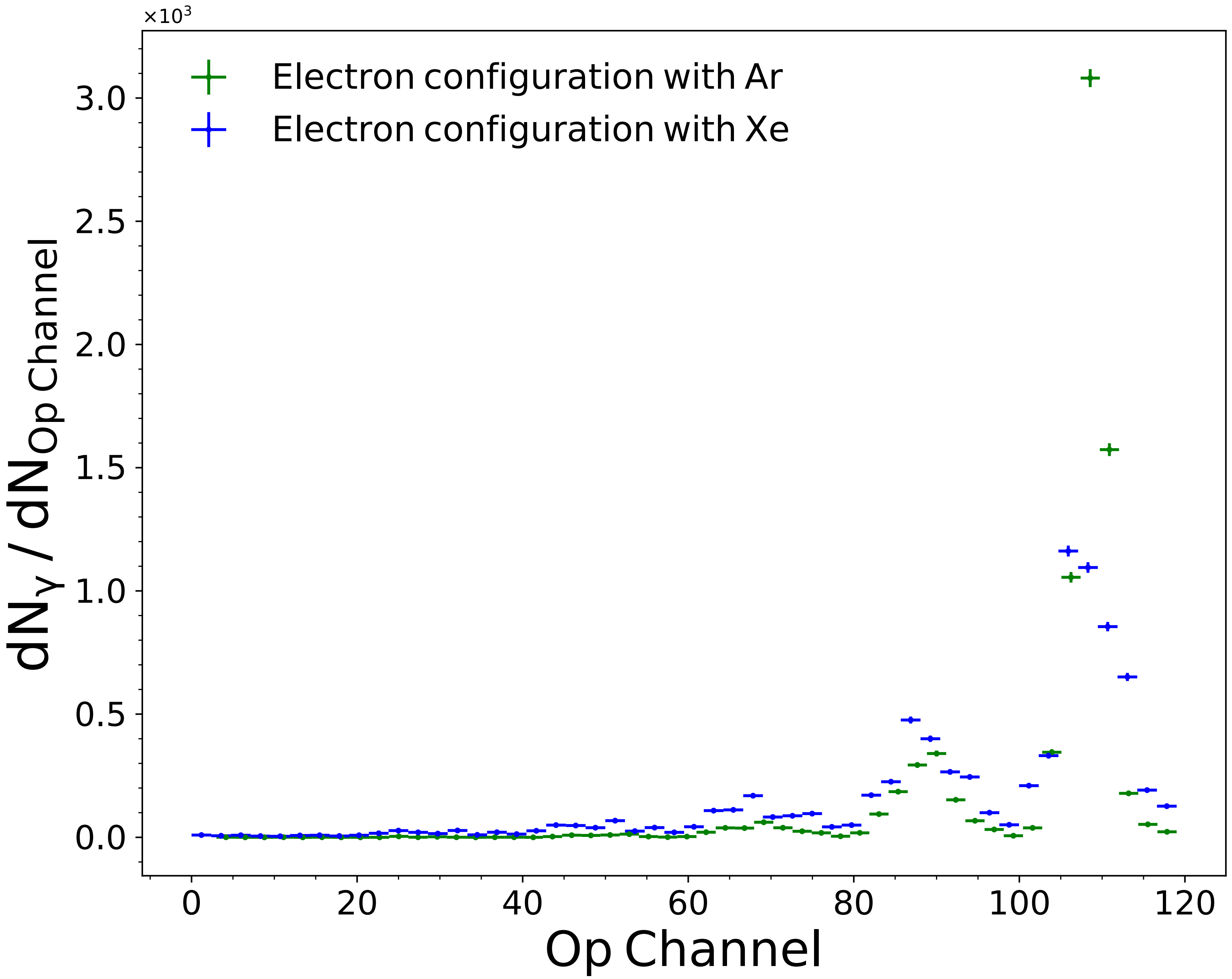
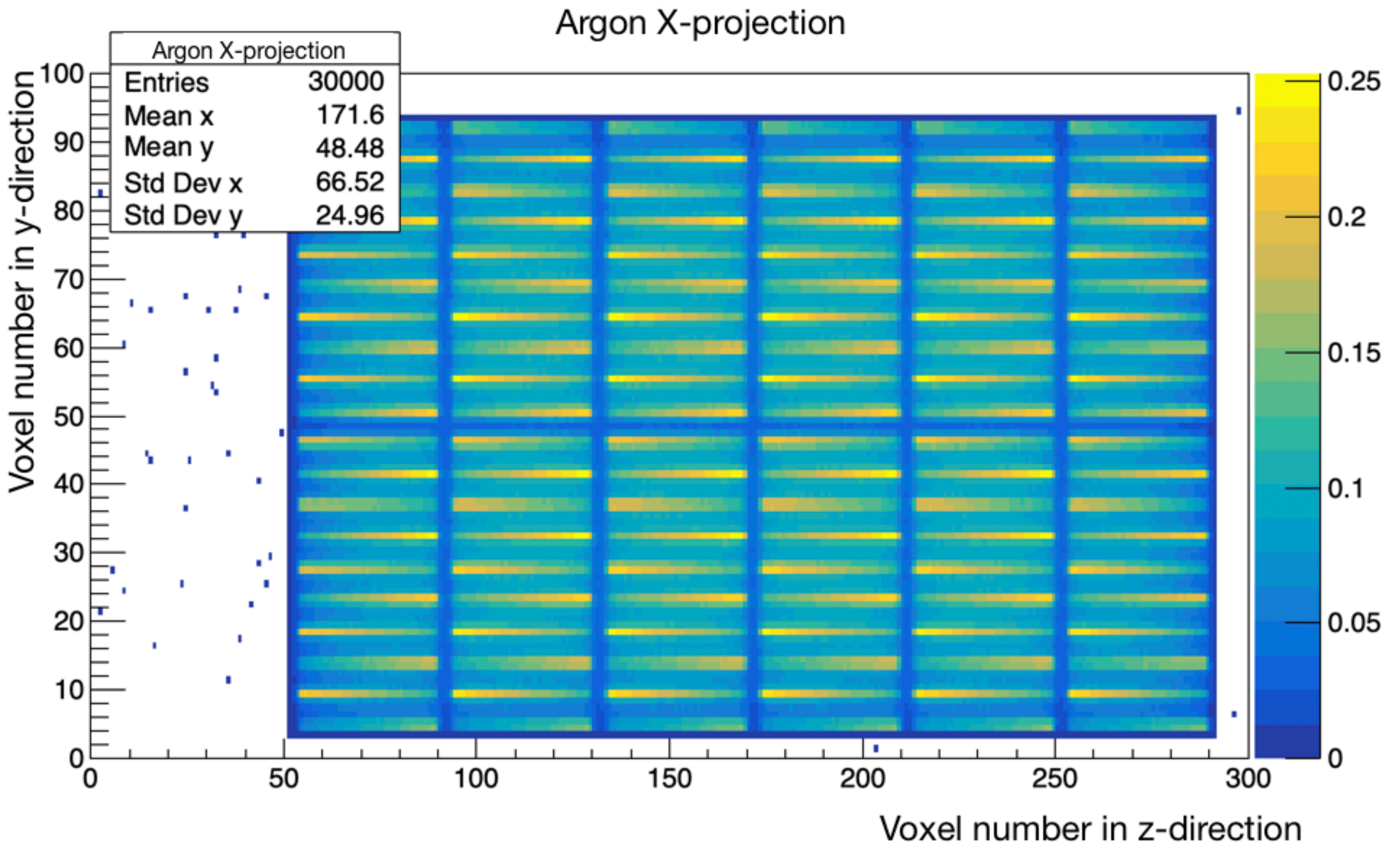
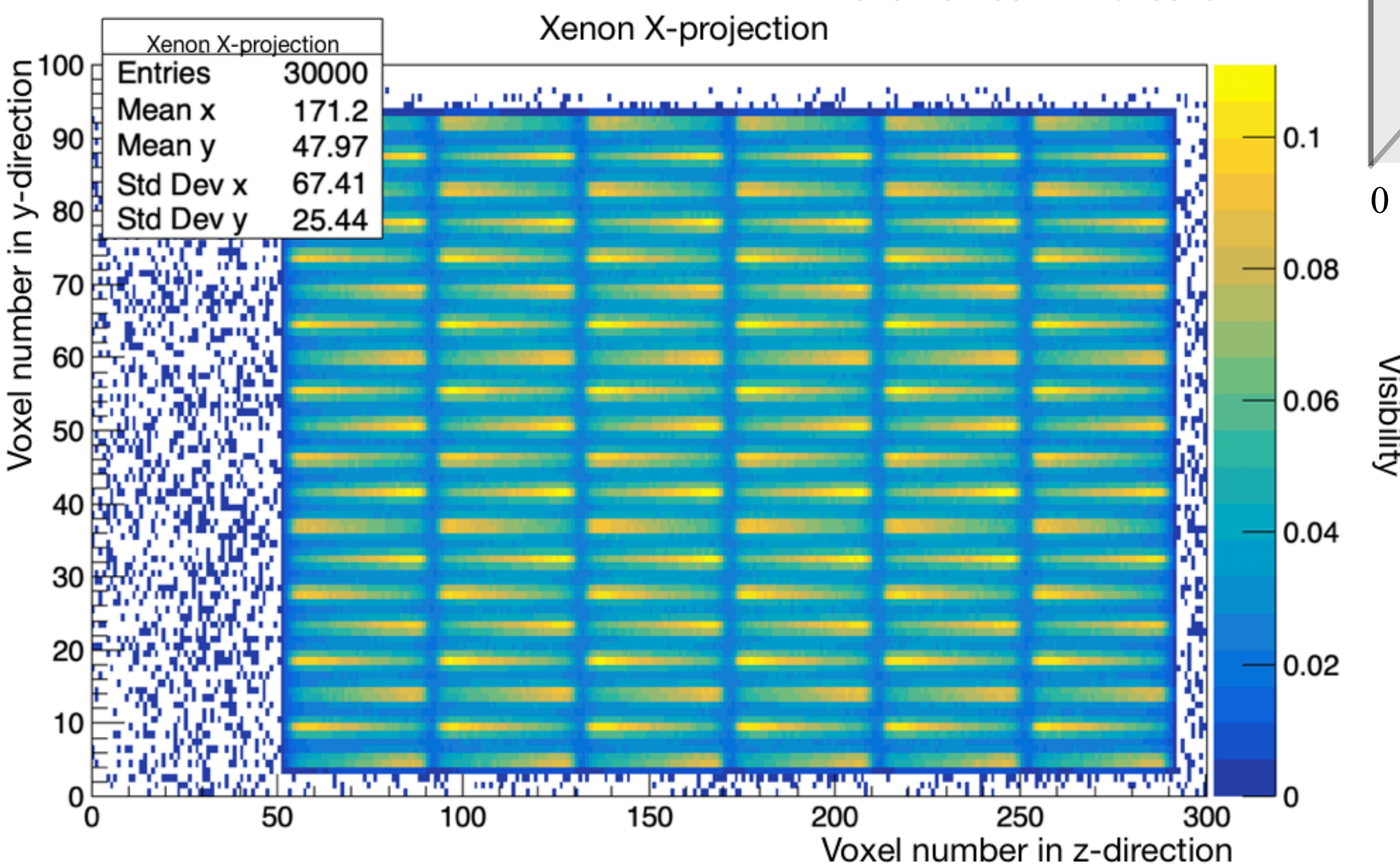


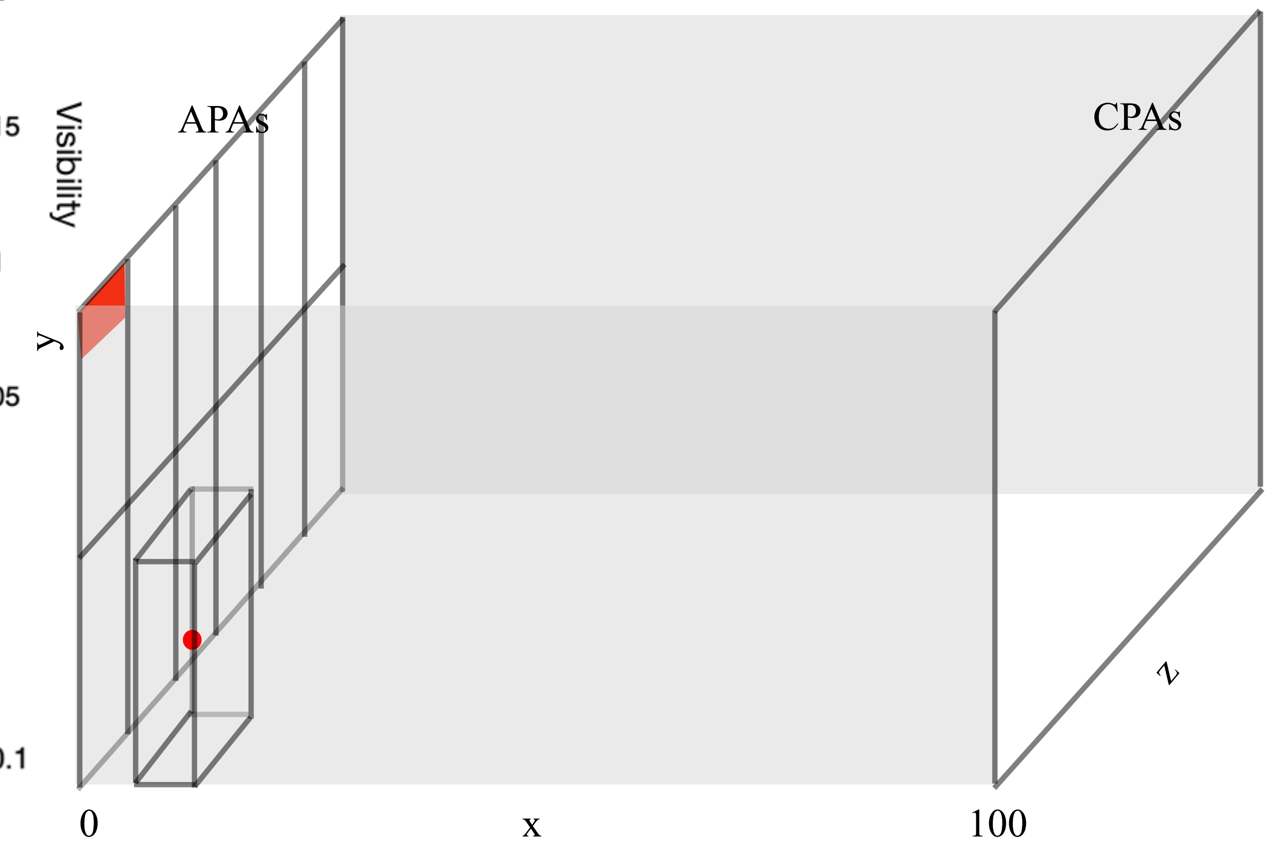
×10^3
Electron configuration with Ar
Electron configuration with Xe
3.0
2.5
2.0
1.5
1.0
0.5
0.0
dNγ / dNOp Channel
0
20
40
60
80
100
120
Op Channel



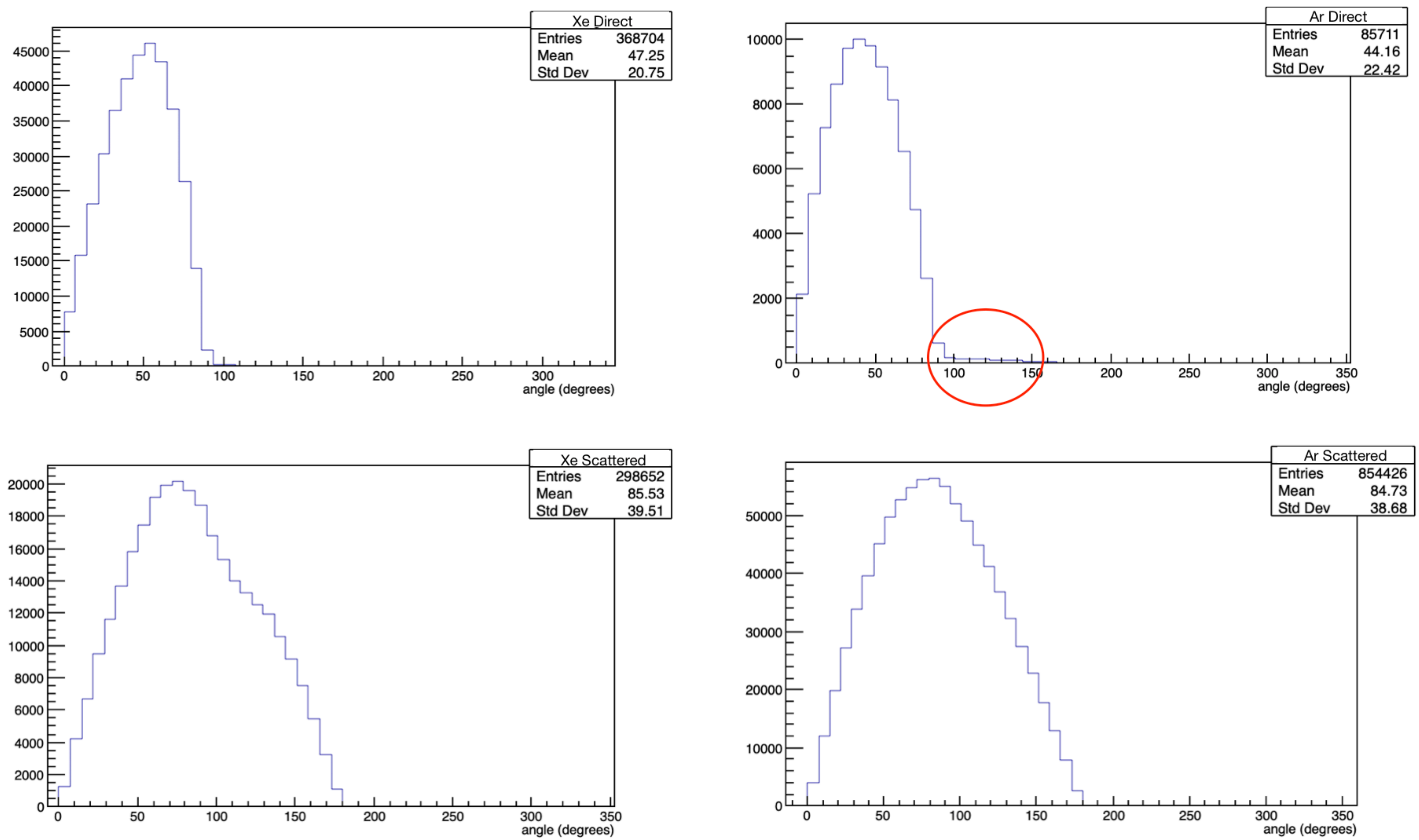
Argon X-projection
Argon X-projection
Entries 30000
Mean x 171.6
Mean y 48.48
Std Dev x 66.52
Std Dev y 24.96
Voxel number in y-direction
Voxel number in z-direction
Visibility
0 0.05 0.1 0.15 0.2 0.25
0 50 100 150 200 250 300
0 10 20 30 40 50 60 70 80 90 100



Xenon X-projection
Xenon X-projection
Entries 30000
Mean x 171.2
Mean y 47.97
Std Dev x 67.41
Std Dev y 25.44
Voxel number in y-direction
Voxel number in z-direction
Visibility
0 0.02 0.04 0.06 0.08 0.1
0 50 100 150 200 250 300
0 10 20 30 40 50 60 70 80 90 100



APAs
CPAs
y
x
z
0
100


Xe Direct
Entries 368704
Mean 47.25
Std Dev 20.75
angle (degrees)
Ar Direct
Entries 85711
Mean 44.16
Std Dev 22.42
angle (degrees)
Xe Scattered
Entries 298652
Mean 85.53
Std Dev 39.51
angle (degrees)
Ar Scattered
Entries 854426
Mean 84.73
Std Dev 38.68
angle (degrees)