Optical Simulation and Reconstruction Methods for Liquid Argon TPC Detectors

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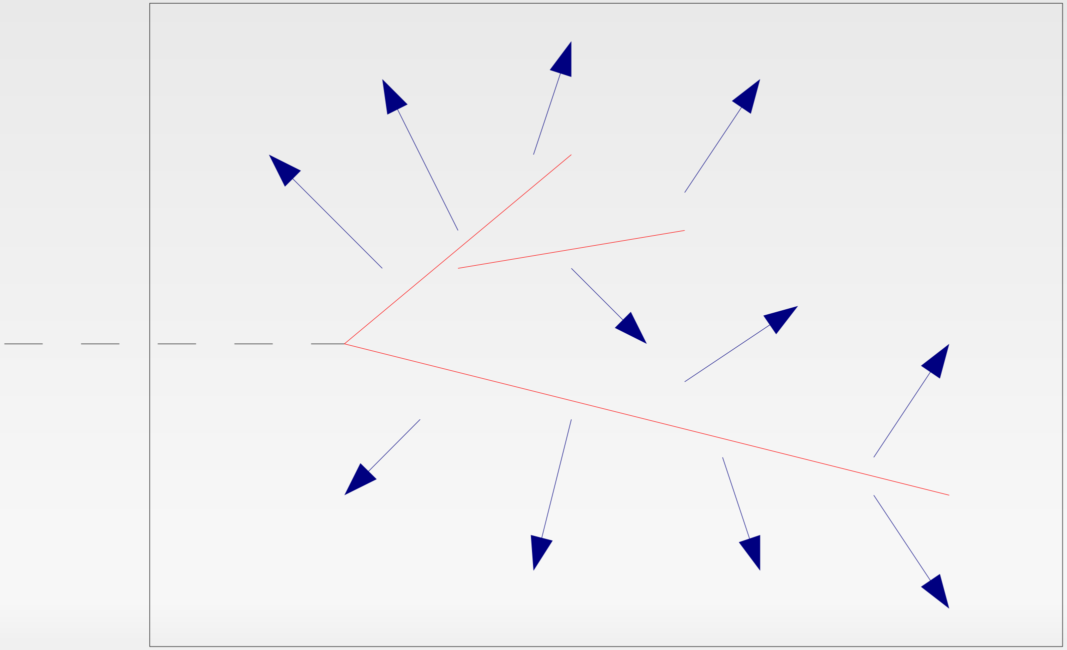
Liquid Argon and LBNO Physics Meeting
University of Durham, 11th March 2011

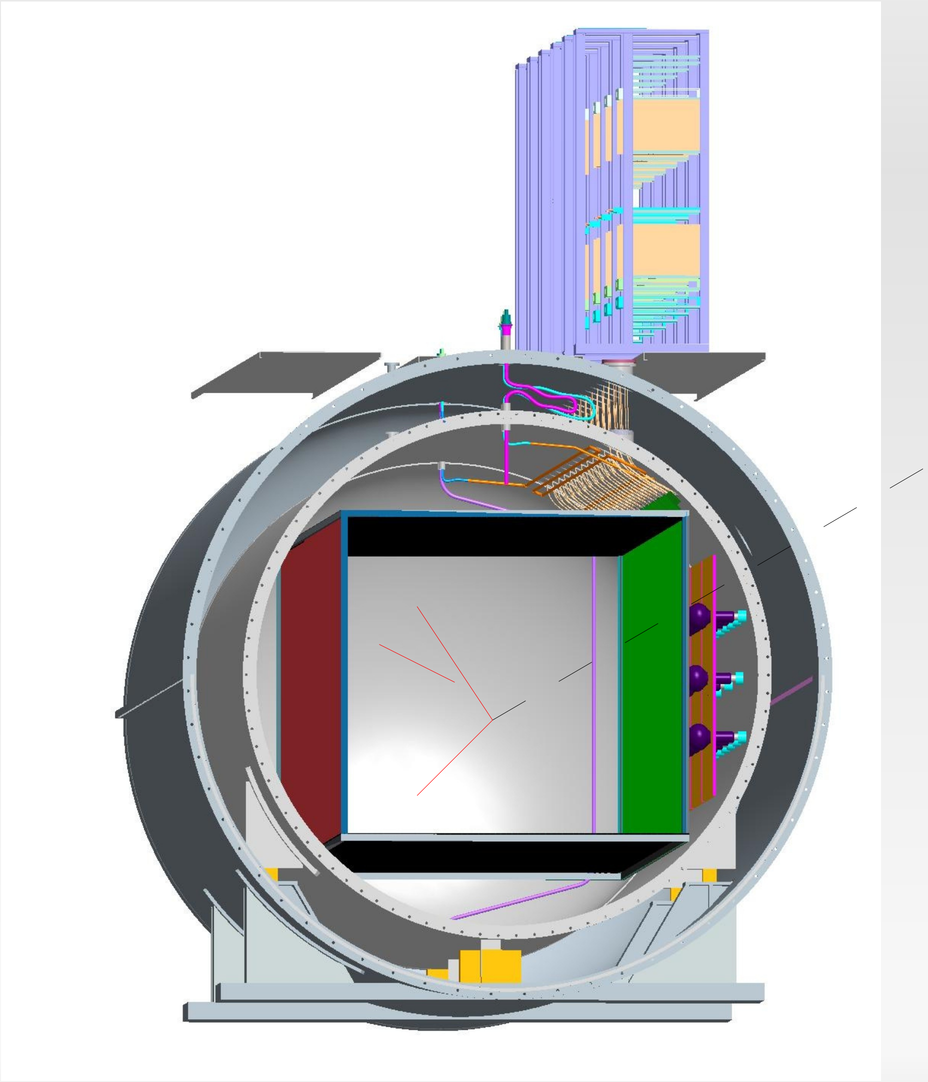
The MicroBooNE Experiment

A 170 ton liquid argon TPC in the Booster neutrino beam at Fermilab, due to run 2013

The motion of the charged particles liberates charge from the surrounding argon (**ionization**) and produces light (**scintillation**)

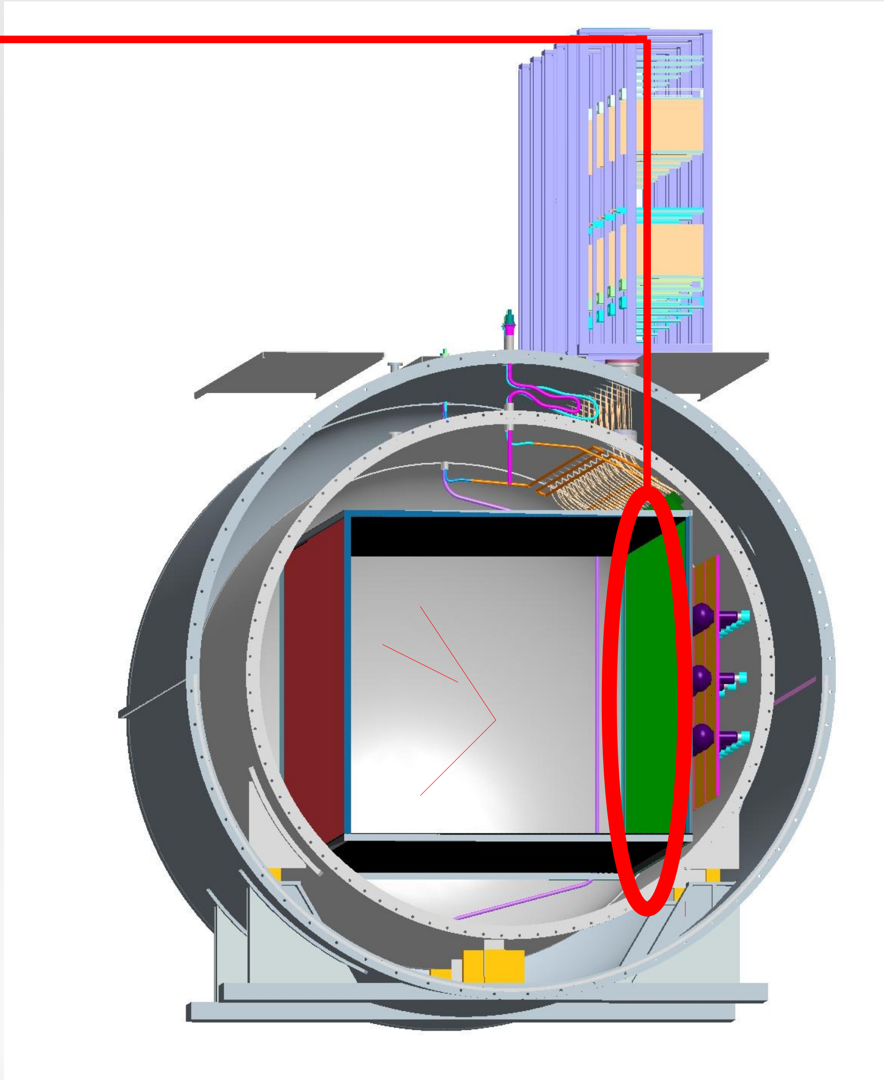
MicroBooNE measures both of these signals

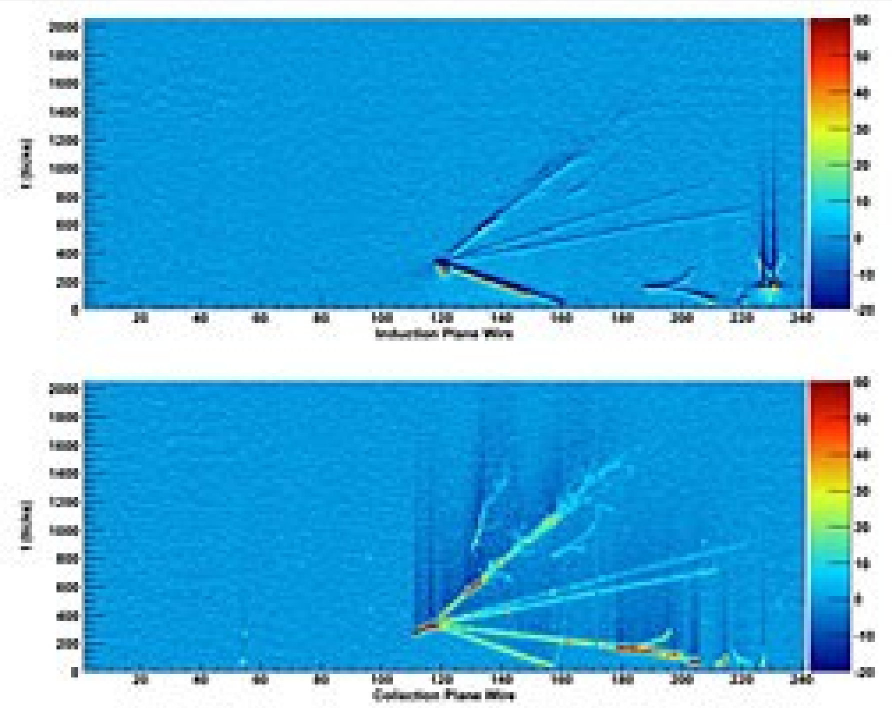




MicroBooNE Sensitive Detectors

1 – TPC System





MicroBooNE Sensitive Detectors

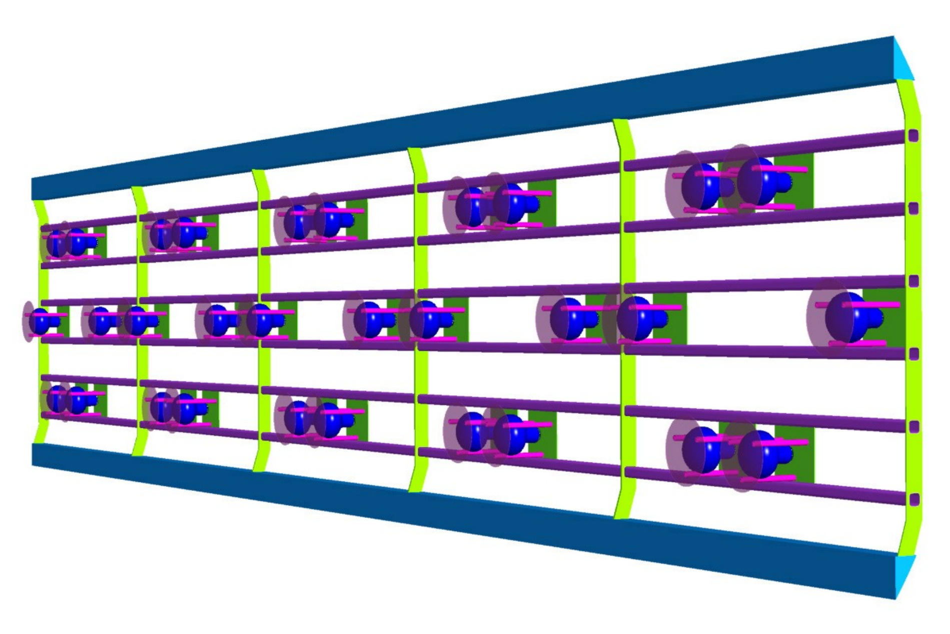
2 – Optical System

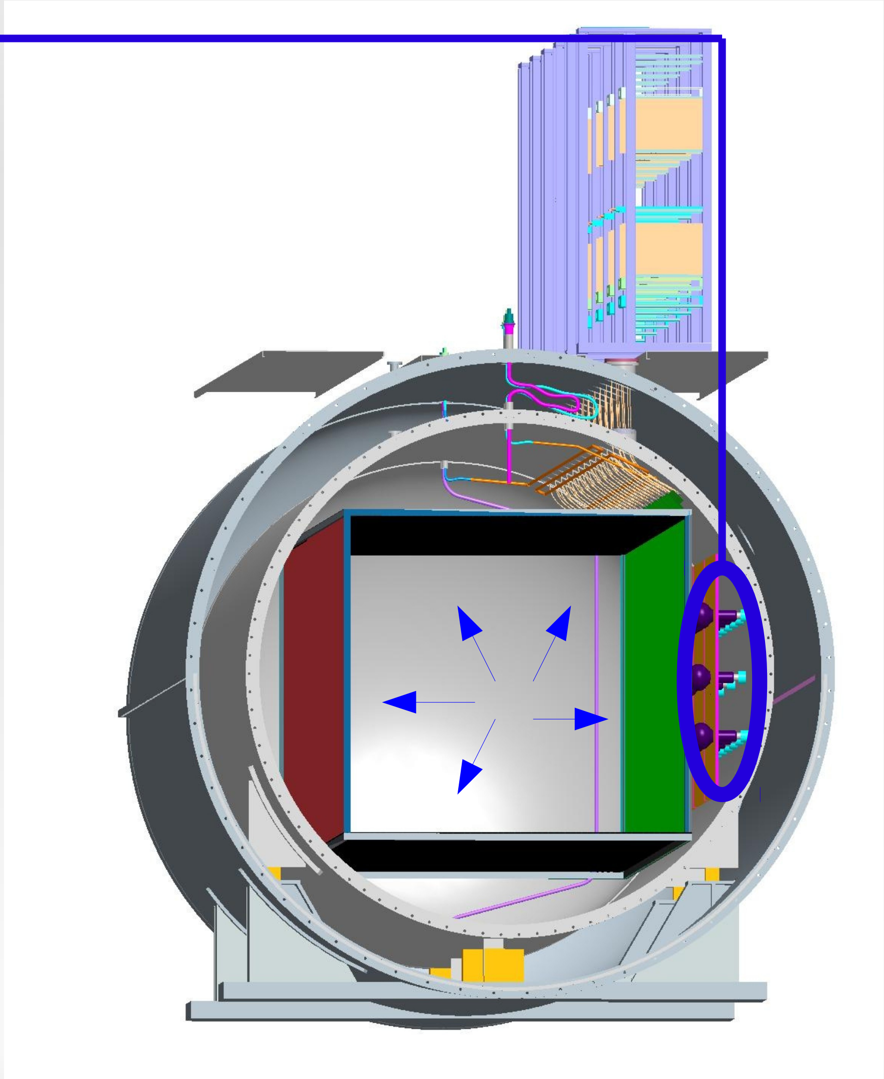
Optical systems provide

1) A simple, low data rate trigger system

2) A secondary view of the event with noise uncorelated with the TPC

3) Fine grained timing information about the event in question





PMT Assemblies

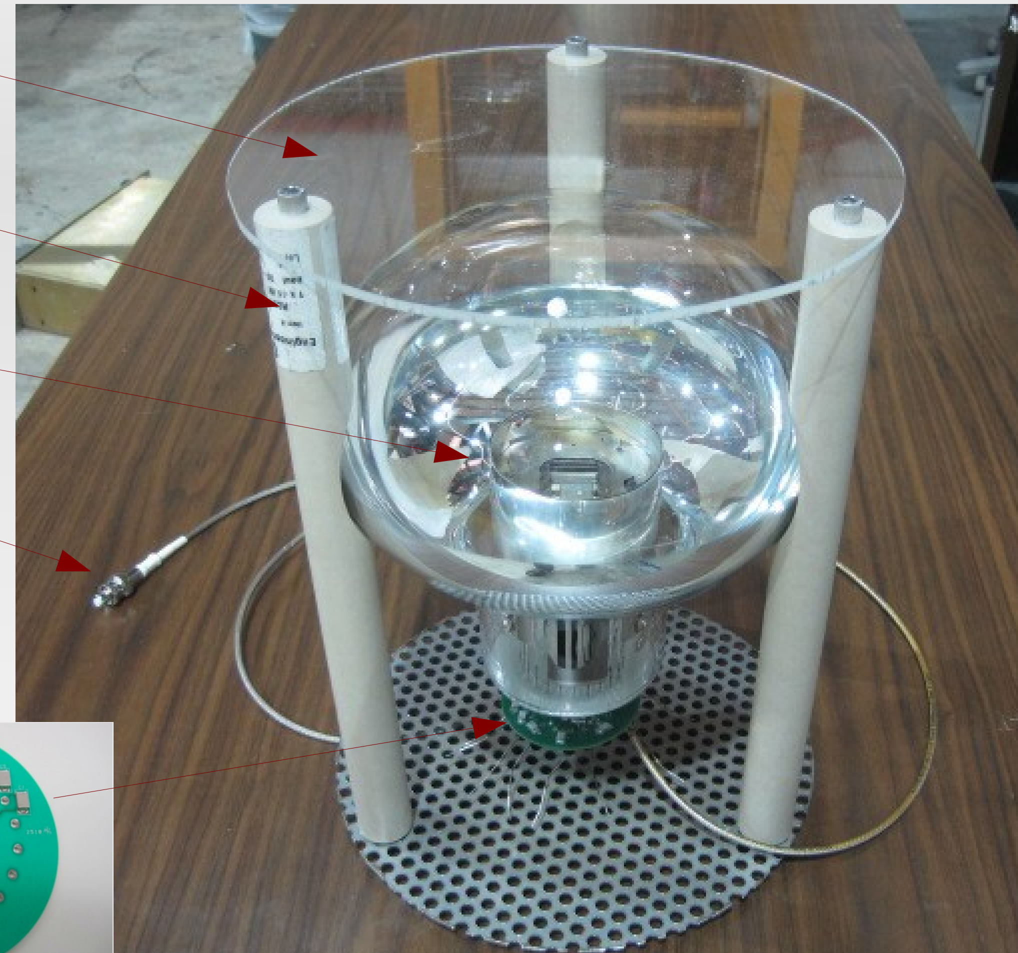
TPB coated acrylic plate

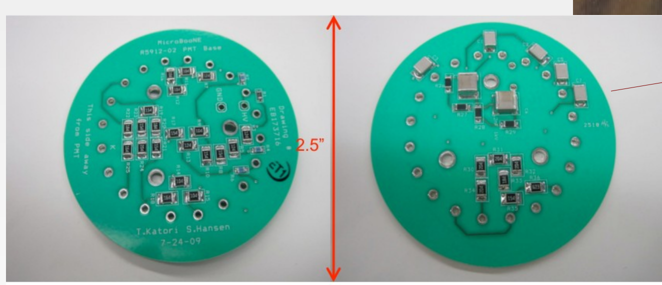
PEEK supports

8” Cryogenic PMT

Combined HV and Signal Cable

Specially designed cryogenic base

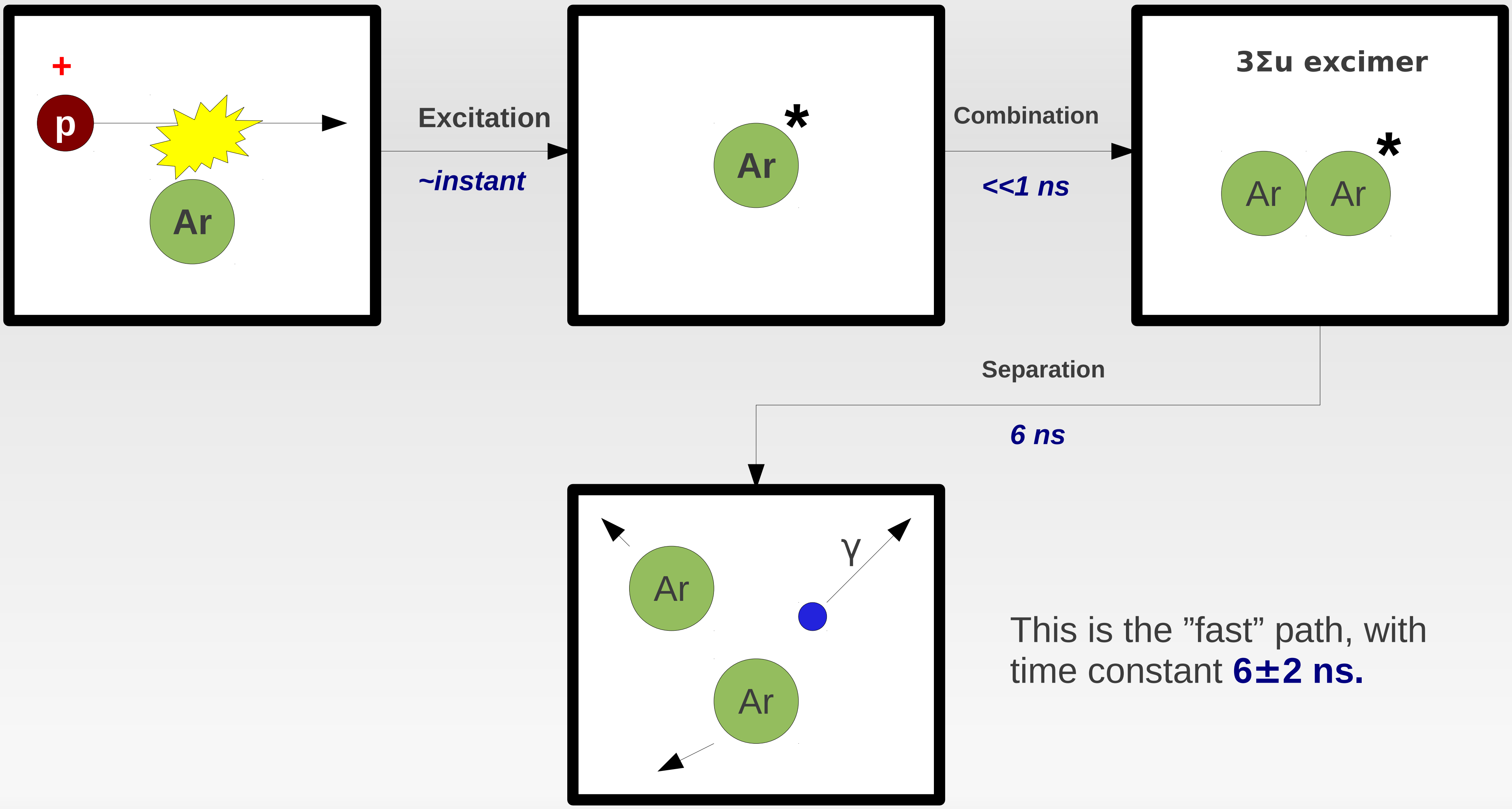




MicroBooNE base

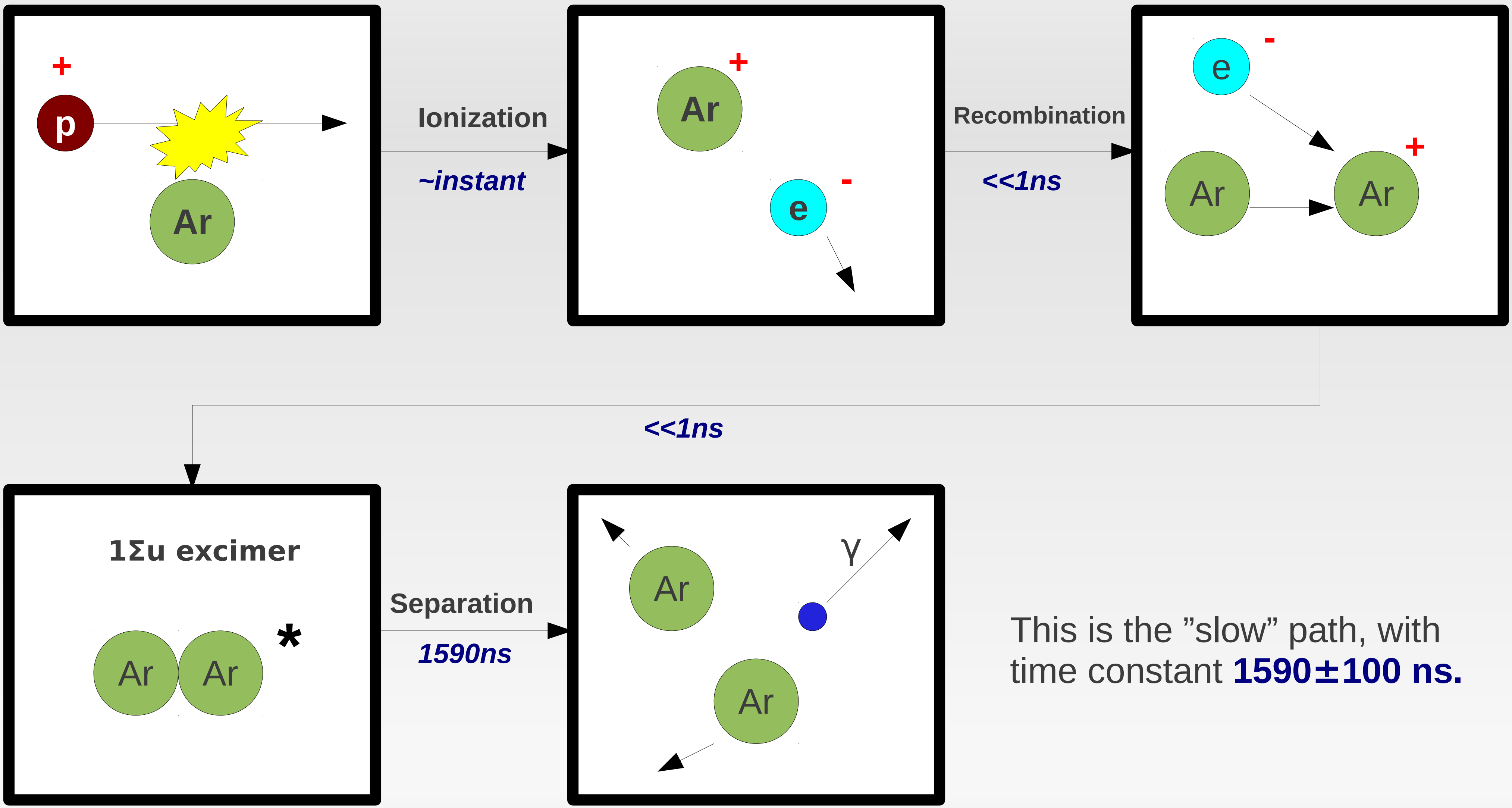
Phototubes have a platinum photocathode undercoating improve quantum efficiency at 87K
(*Hamamatsu R5912-02mod*)

LAr : The fast scintillation path



This is the ”fast” path, with time constant **6±2 ns.**

LAr : The slow scintillation path



This is the ”slow” path, with time constant **1590±100 ns.**

Light in Liquid Argon

- Liquid argon produces scintillation light via two distinct scintilation mechanisms, each of which has a different characteristic time constant
- The relevant time constants are :

  Early Light *:* **6±2 ns**

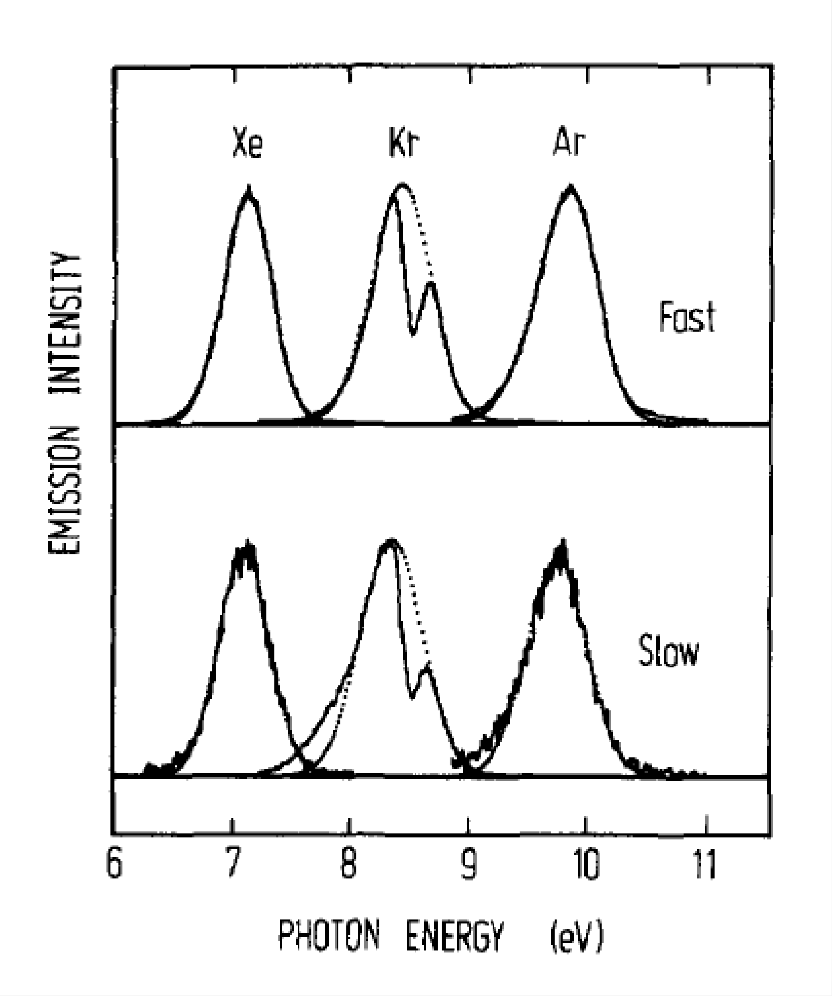
  Late Light *:* **1590±100 ns**

- Both mechanisms produce a spectrum of photons with peak energy **9.7eV (128nm)**
- Scintillation yield is E-field and particle dependent. For a proton:

  24,000 photons / MeV, **E = 500 V / cm**

  40,000 photons / MeV, **E = 0 V / cm**

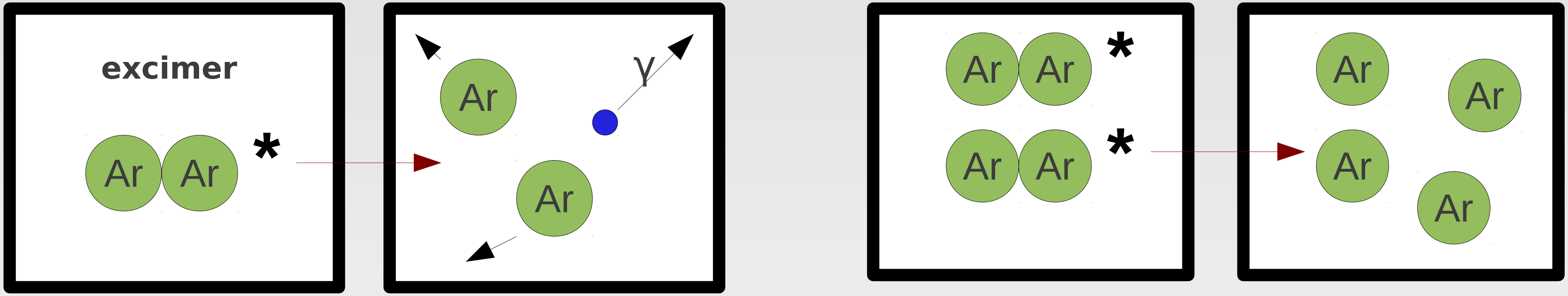
- Also present is Cerenkov light, but this is directional, primarily not towards the PMTs



J Chem Phys vol 91 (1989) 1469 E Morikawa et al

Scintillation Quenching and PSD

- Scintillation in liquid argon is quenched due to recombination effects. The competing, non light producing process is collision and dissociation of two eximers, so depends on the local excimer density.



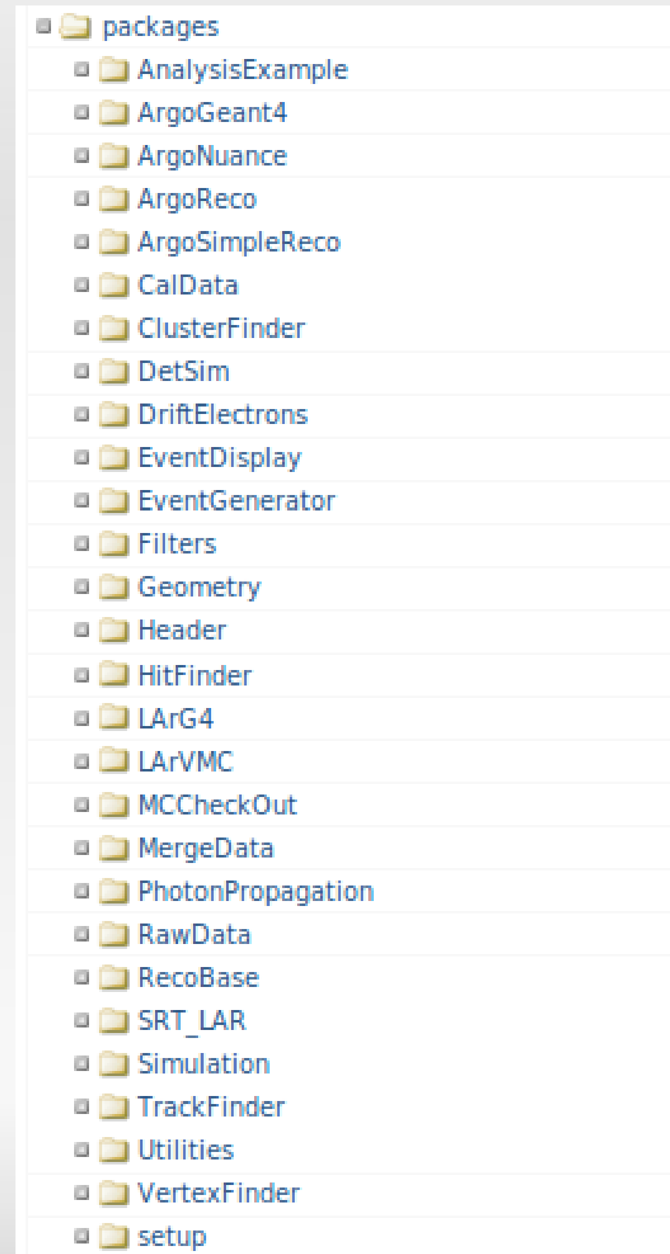
- Hence the degree of quenching depends on dE/dx, which in turn depends on particle energy and ID
- Also, the slow light component will be more strongly quenched
- Clearly pulse shape discrimination, comparing the ratio of fast to slow light, has potential to be a powerful tool for particle ID.

Simulations

- All MicroBooNE simulations are performed within the open source LArSoft simulation framework
- An open source framework which provides simulation, reconstruction and analysis tools for current and future LAr experiments
- We have developed two simulation methods within LArSoft

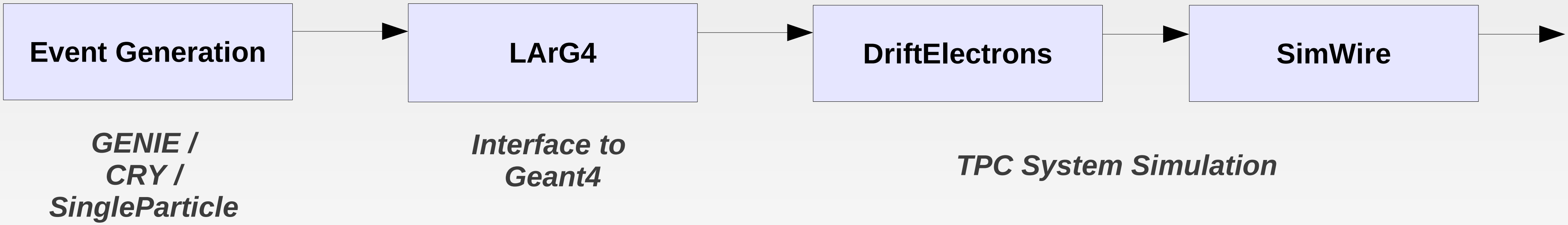
  - FULL OPTICAL SIMULATION

  - FAST OPTICAL SIMULATION

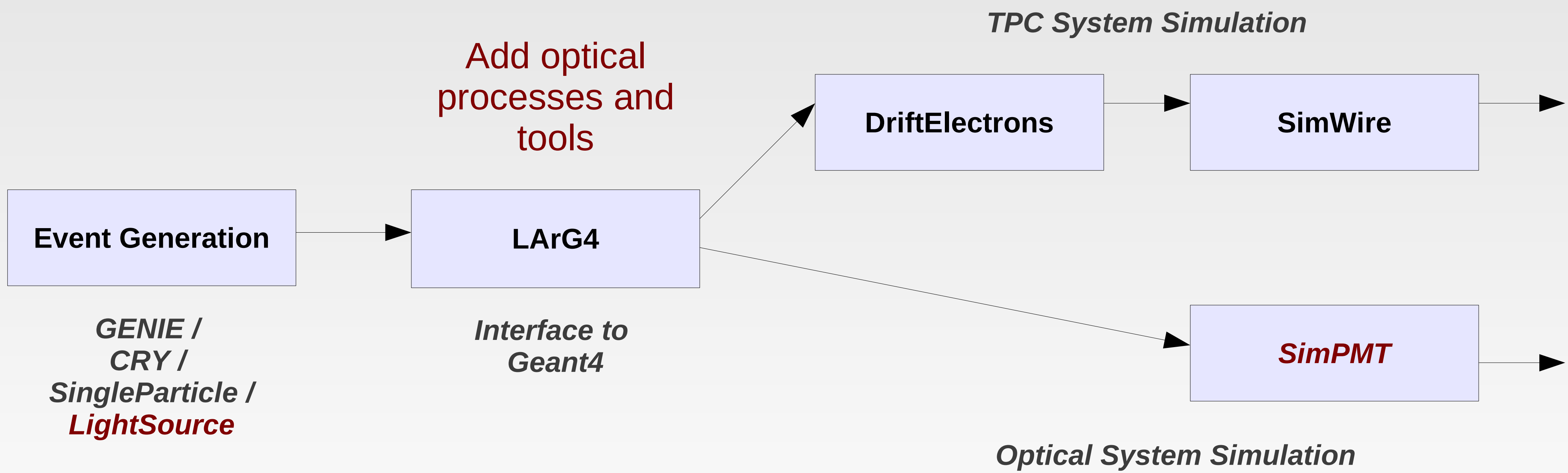


LArSoft Simulation Chain

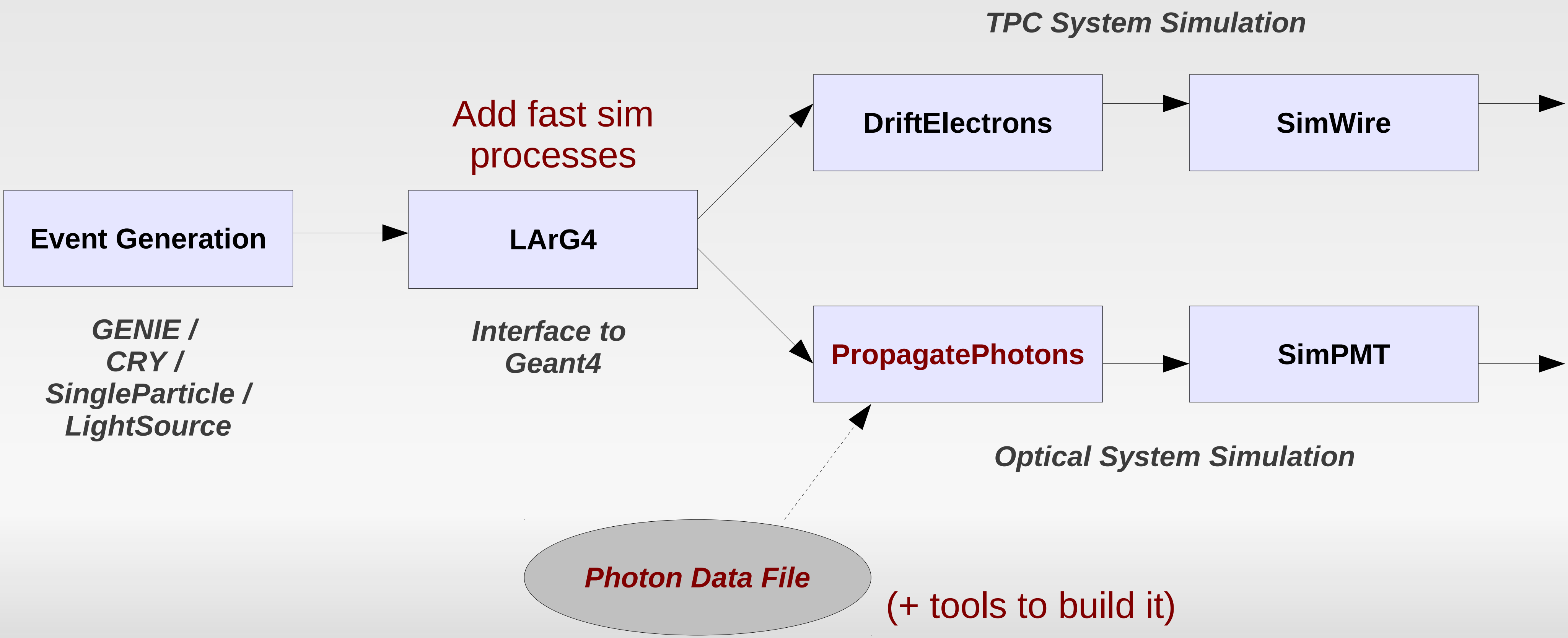
- Simulation jobs in LArSoft are broken down into discrete steps.
- A typical simulation chain for a non optical detector (eg ArgoNeuT) is shown below



LArSoft Full Optical Simulation



LarSoft Fast Sim Chain



Optical Processes in LArG4

- We wrote a configurable physics list system for LarSoft, such that both custom and built in physics constructors can be enabled / disabled on a job by job basis via job config
- Optical physics processes are loaded via the ”OpticalPhysics” GEANT4 physics constructor, which was customized to fit our needs in LarSoft.
- Optical photons step within a parallel geometry in LArG4, to optimize simulation speed

Optical Physics

- **Scintillation production** *(fast and slow)*
- **Cerenkov production**
- **Rayleigh Scattering**
- **Reflections** *(specular and diffuse)*
- **Absorption at surfaces**
- **Wavelength shifting**
- **Absorption in argon bulk** *(currently none)*

Optical Properties of Materials

- Optical properties of materials are loaded during the detector construction step using the MaterialPropertyLoader class.
- The requirement of loading wavelength dependent parameters required us to step outside the default gdml parser and implement this new class.
- Several implementations are possible (xml reading, hard coded, etc)

Per Material Type

Per Boundary Type

Scintillation

Fast component spectrum
Slow component spectrum
Scintillation yield
Fast time const
Slow time const
Proportion fast / slow
Quenching per particle

Cerenkov

- none -

Absorption

Absorption Length

Rayleigh Scattering

Scattering Length

WLS

Absorption spectrum
Emission spectrum
Time Constant
Yield out / in

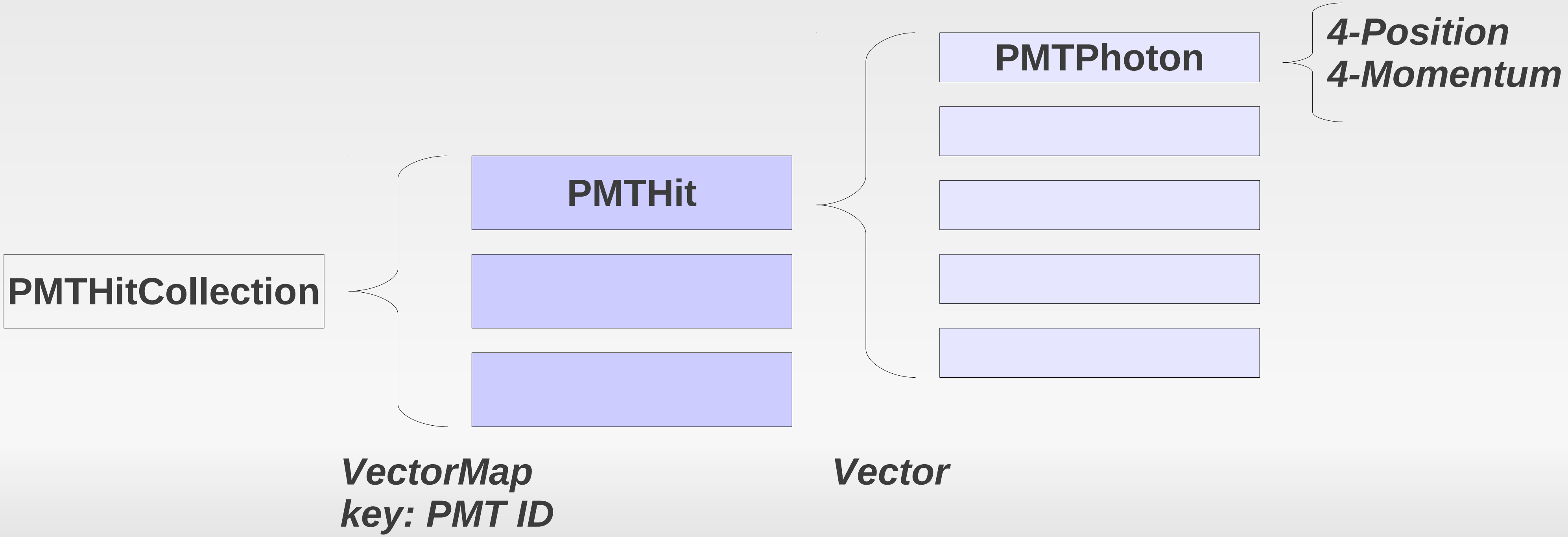
Reflections

Total Reflectivity
Fraction specular / diffuse

Wavelength dependent
Non wavelength dependent

PMTHit Data Structures

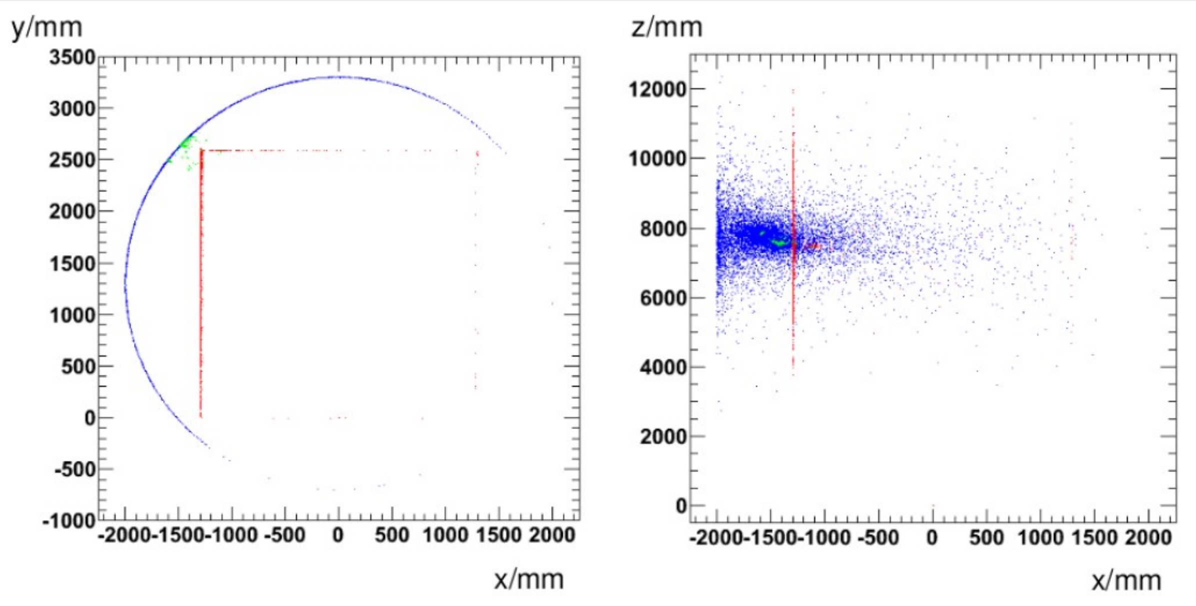
- The optical information to be passed along the simulation chain from LArG4 is contained within a PMT hit collection
- The PMTHitCollection is a set of PMTHits, one for each PMT that saw one or more photon
- Each hit is a list of 4-positions and 4 momenta of photons which stepped across the lens of the PMT

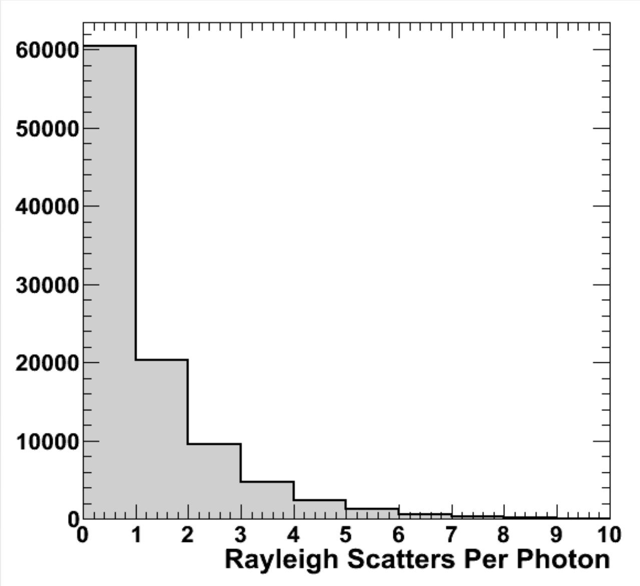


Other Components of Full Sim

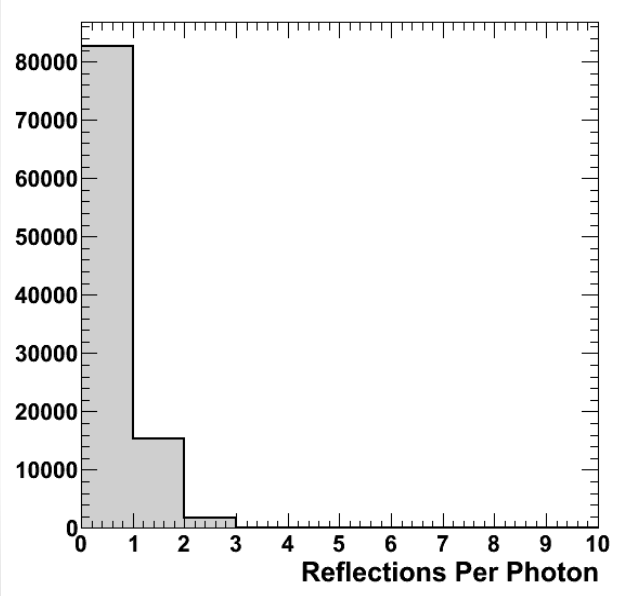
- **Geometry** – Placement of semi-reallistic PMT assemblies in desired cryostat positions can be achieved with scripts
- **LightSource event generator –** event generator representing a customizible light source, for optical system studies and fast sim library building. Can be static or mobile with positions supplied by file or stepping instructions
- **OpticalMCOutput** - photon watching module for tracking birth and death points of photons in LarG4. Helps to locate ”light leaks” (areas with no reflection properties which kill lots of photons), etc.
- **PMTResponseAnalyzer** – analyzer which extracts data to TTrees at one of four levels of detail based on the stored PMTHitCollection
- **Paralellized geometry including sensitive detector volumes –** paralellized to optimize simulation speed, and sensitive detectors have customizible quantum efficiency and wavelength windows

A Sample Neutrino Event in LArG4



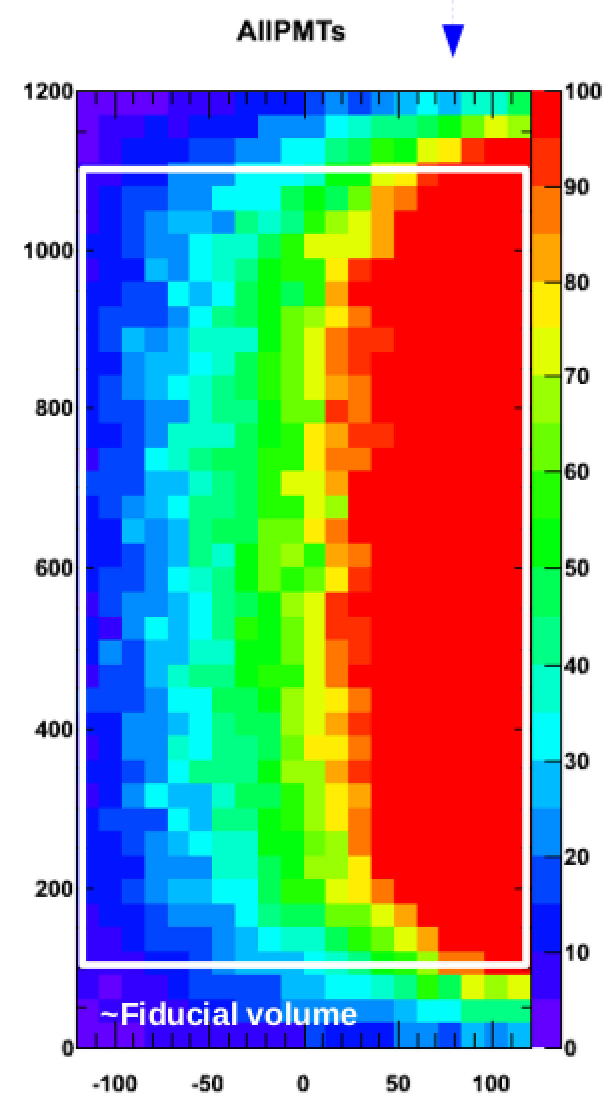


Green - Photon production
Blue - Photon absorption at surface of known reflectivity
Red - Photon absorption at surface with no reflectivity data

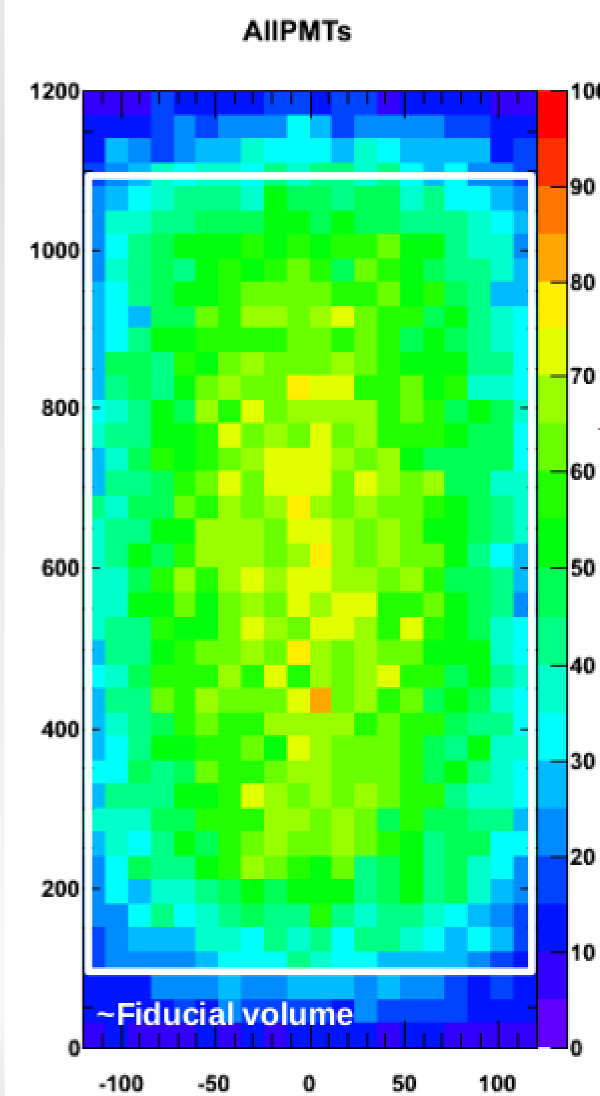


- 95161 photons were generated of which 58996 were eventually absorbed at a steel surface and 20932 were absorbed into a ”black area”
- Each photon underwent a mean of 0.76 Rayleigh scatters and 0.19 reflections

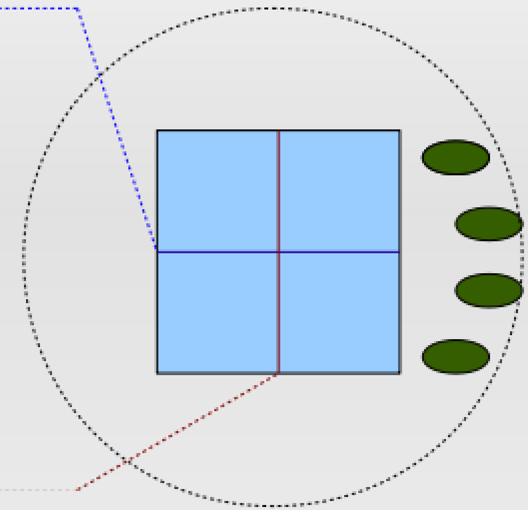
Sensitivity Maps



y=0 plane



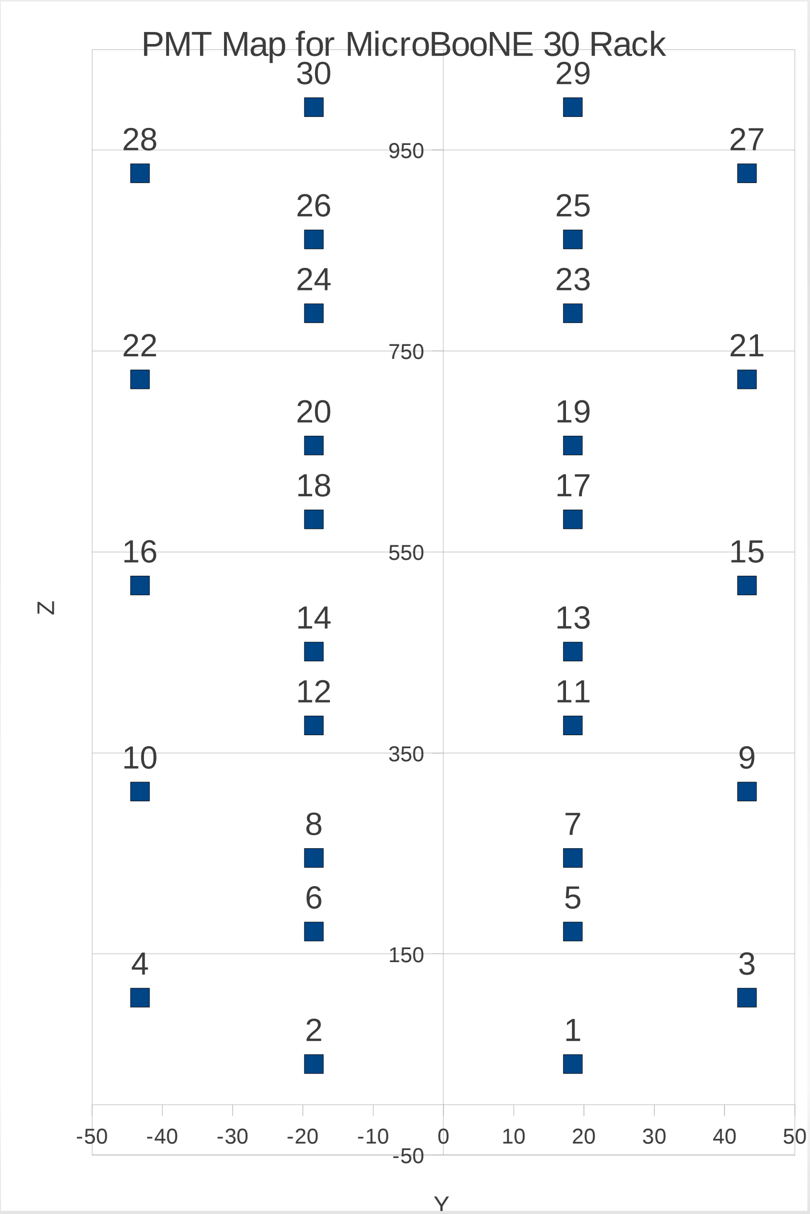
x=0 plane



Number of photoelectrons summed over all PMTs for point source of **5MeV** equivalent at different detector points

Trigger should be possible on 1 p.e. We are sensitive at all points on these plains within fiducial volume.

PMT Coverage and Redundancy Tests

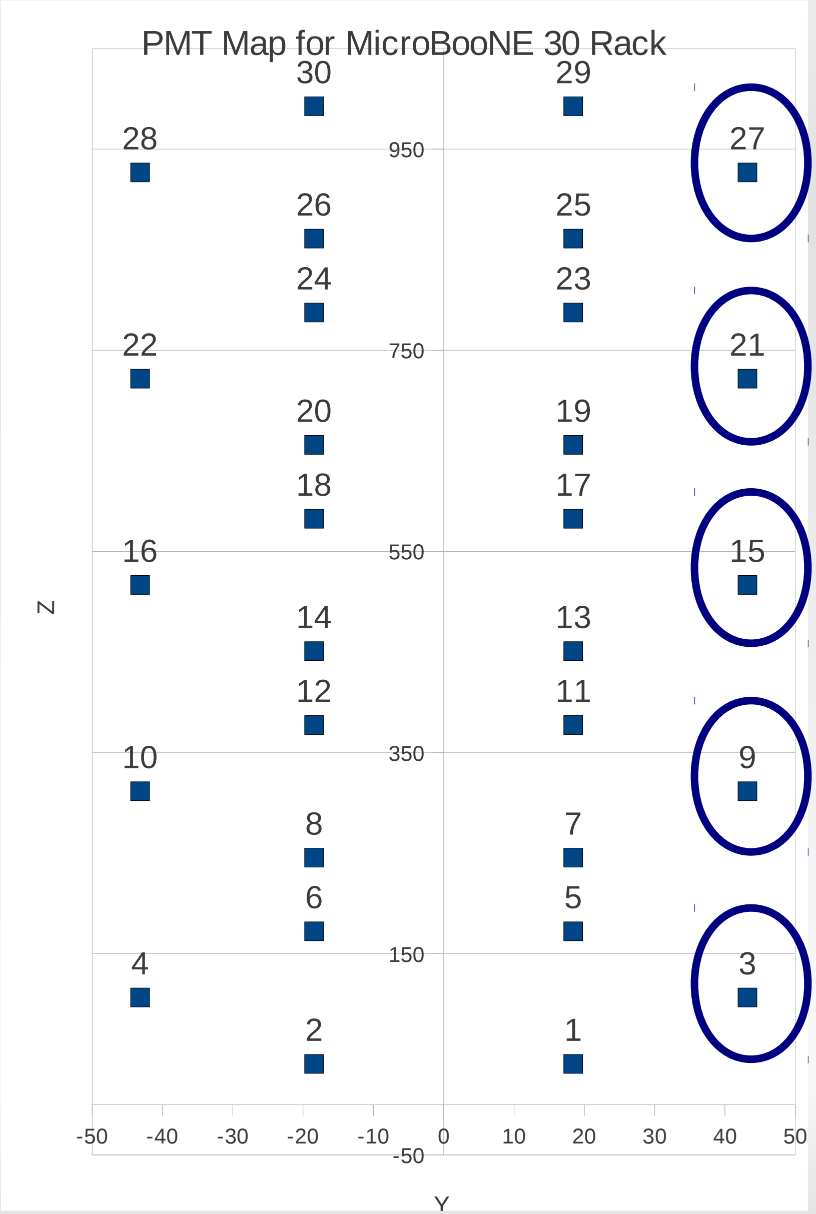


Ask two questions:

1) How wide is the coverage of each PMT?

2) How does the global coverage change if a given PMT fails?

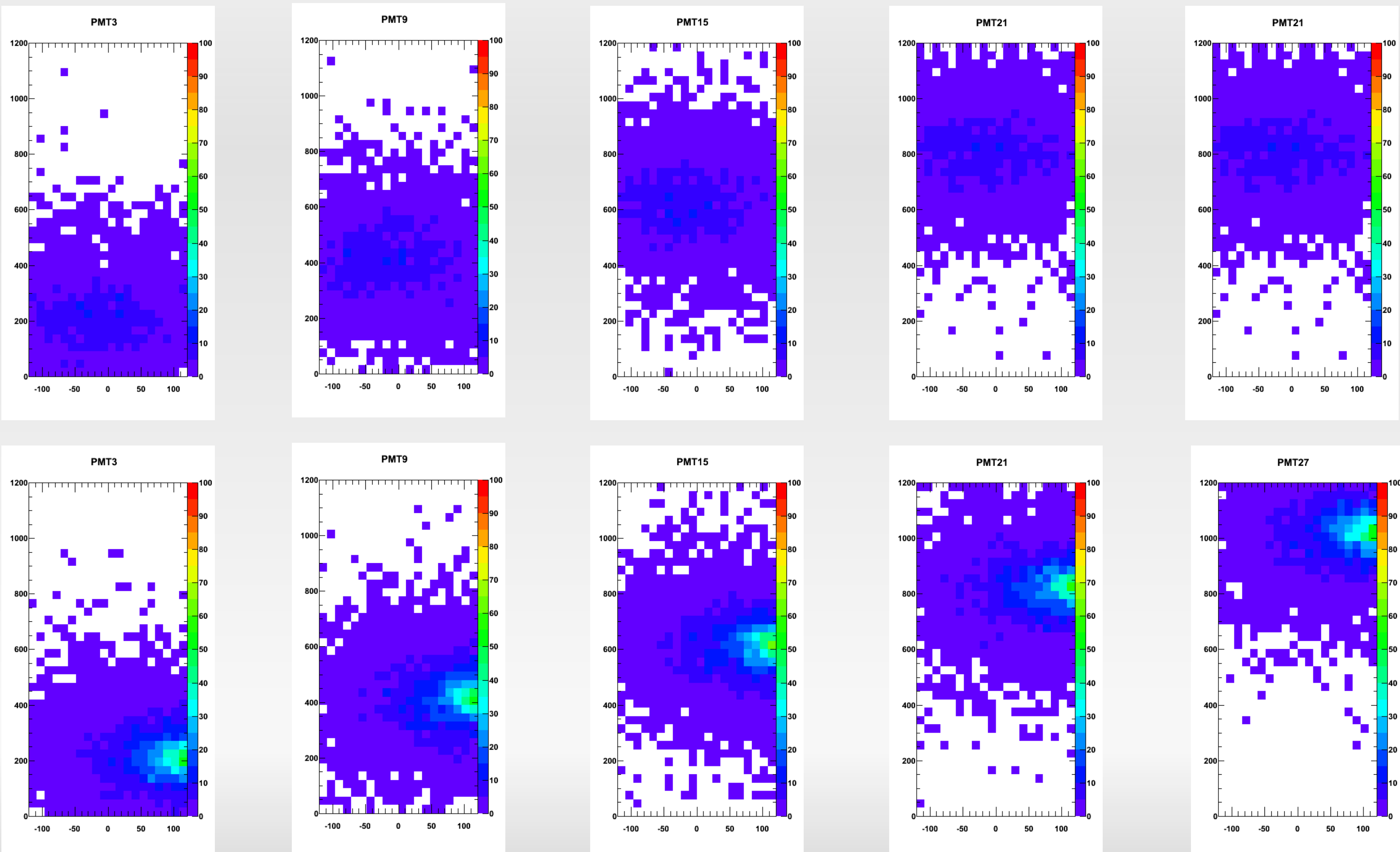
PMT Coverage and Redundancy Tests



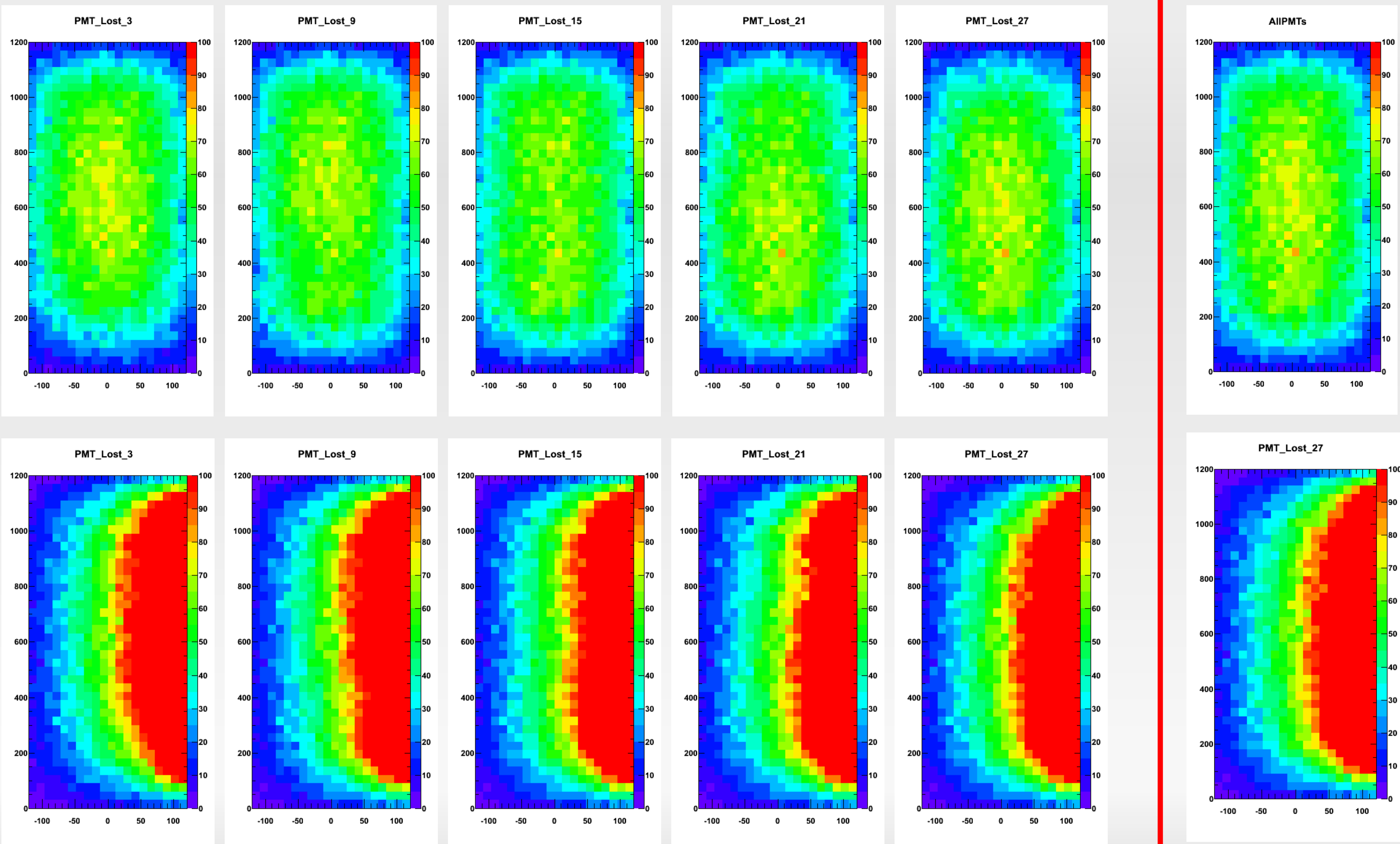
As an example:

consider a line of PMTs in Z

PMT Coverage Test



PMT Redundancy Test

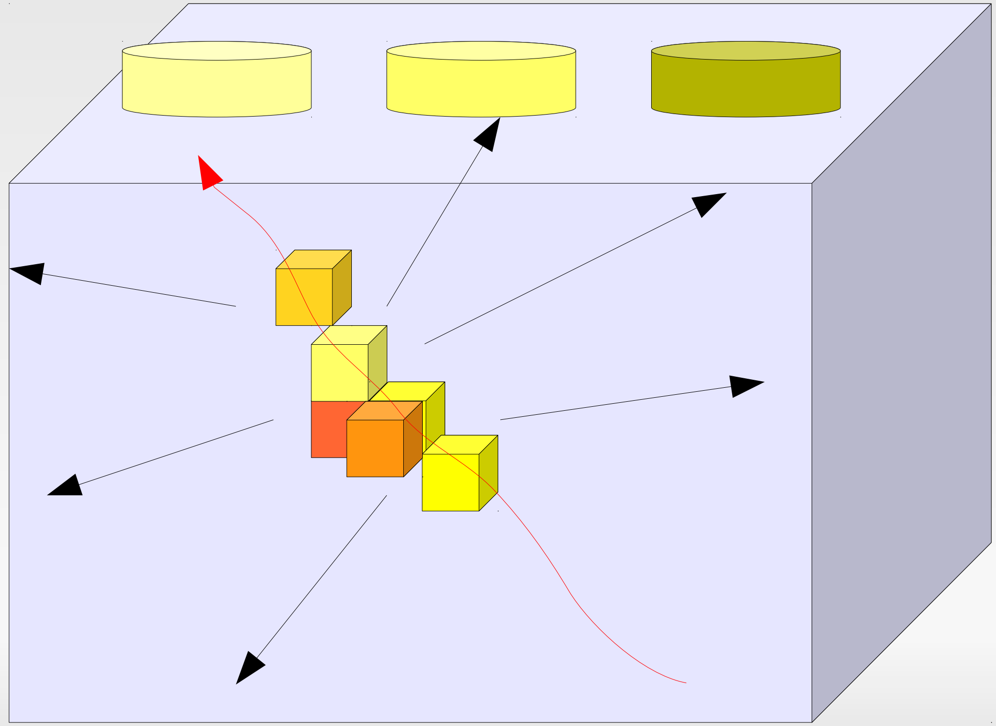


ONE PMT MISSING

ALL PMTS

Fast Simulations and Photon Library Sampling

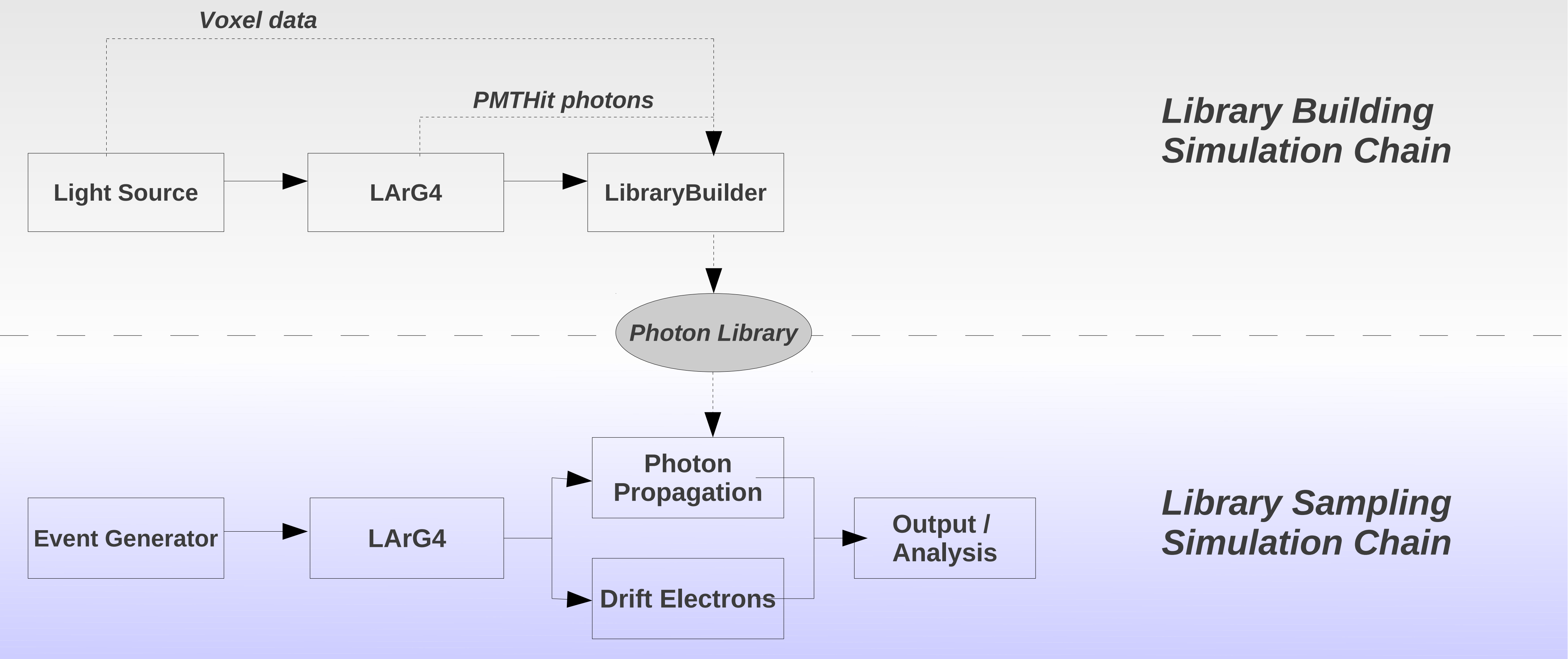
- GEANT4 simulation of 100,000s of photons per event takes a very long time – not a feasible approach for long monte carlo runs
- Scintillation photons are produced isotropically and in large numbers so we can take a different approach and sample from a library of typical responses



How many photons from each "voxel" will reach each PMT?

How will their angles of incidence and positions on the PMT face be distributed?

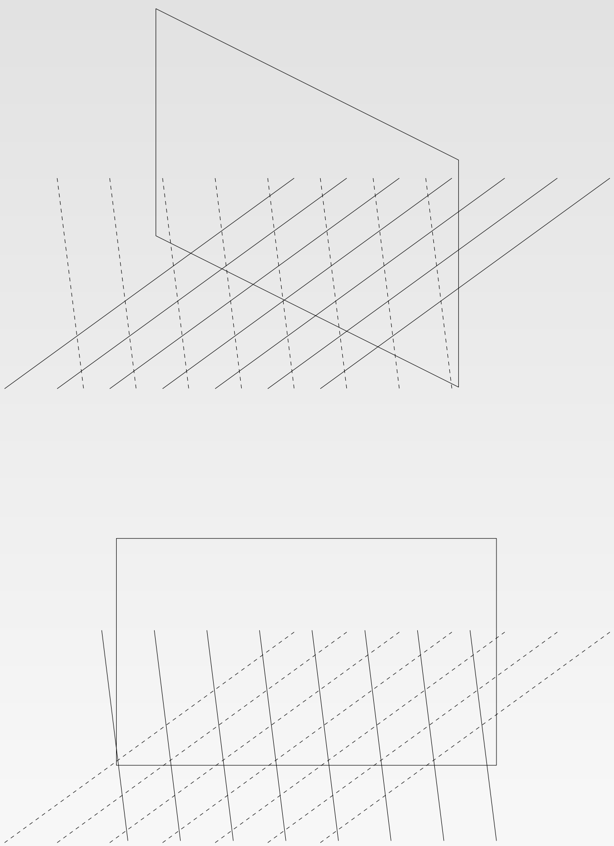
Voxelized PhotonLibrary Building And Sampling Chains

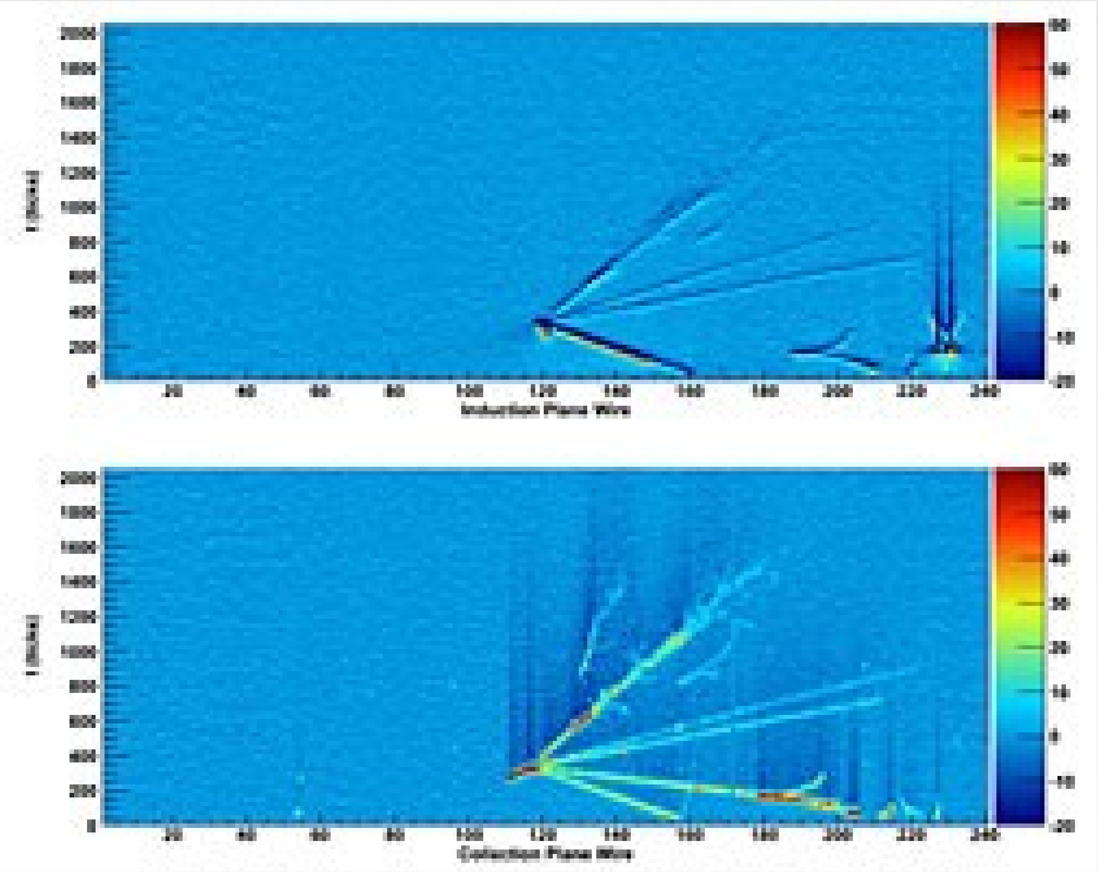


- Library is built using a light source with gaussian spectrum of **9.7 +/- 1 eV** in each voxel
- Later sampled by new module **PhotonPropagation**, which runs in parallel with DriftElectrons
- During the LarG4 step of the sampling chain, we do not step any photons, simply provide the **number produced in each voxel**

Reconstruction in LArTPCs

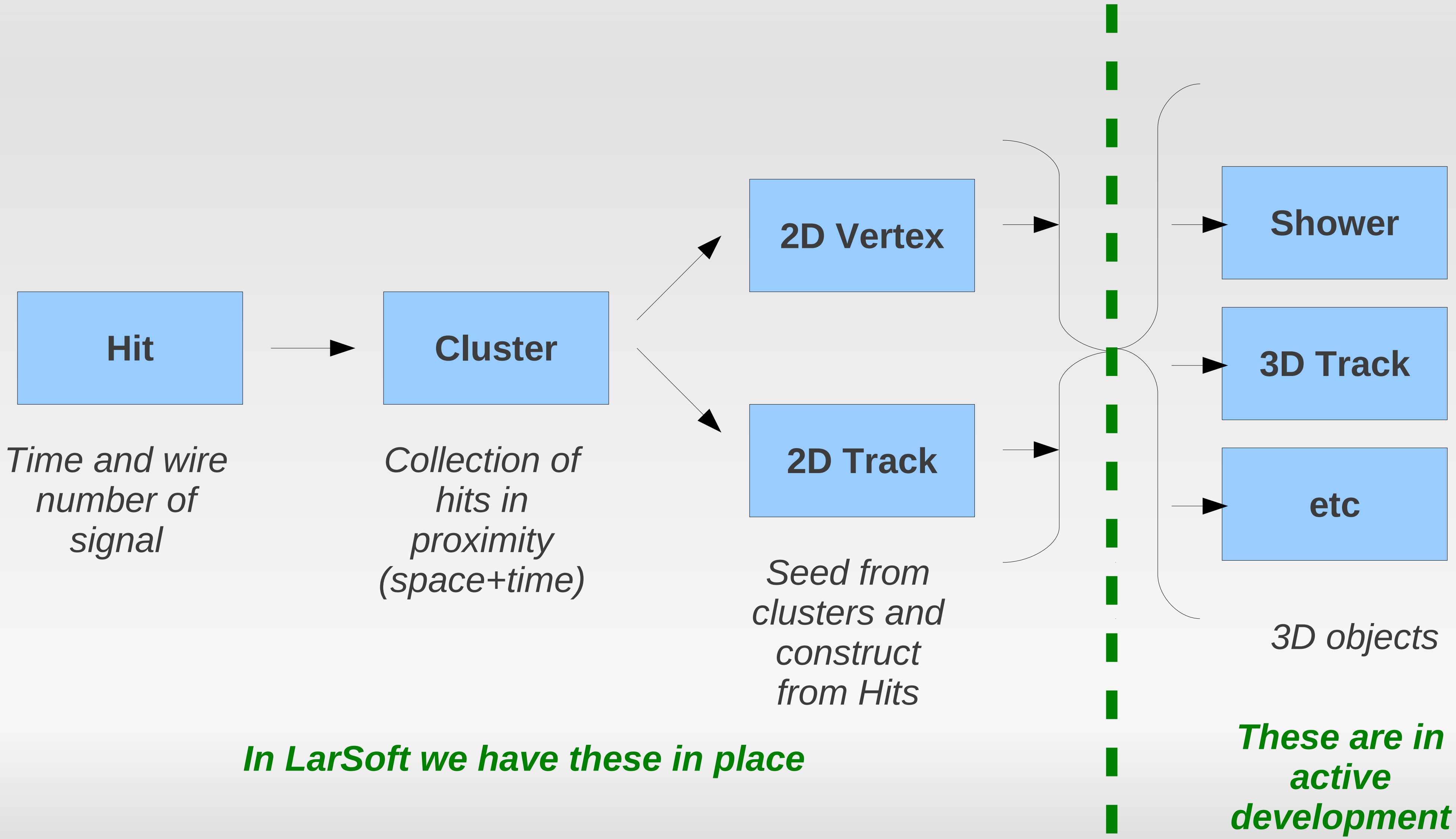
- Build one image for each wire plane, with two dimensions, time and wire number

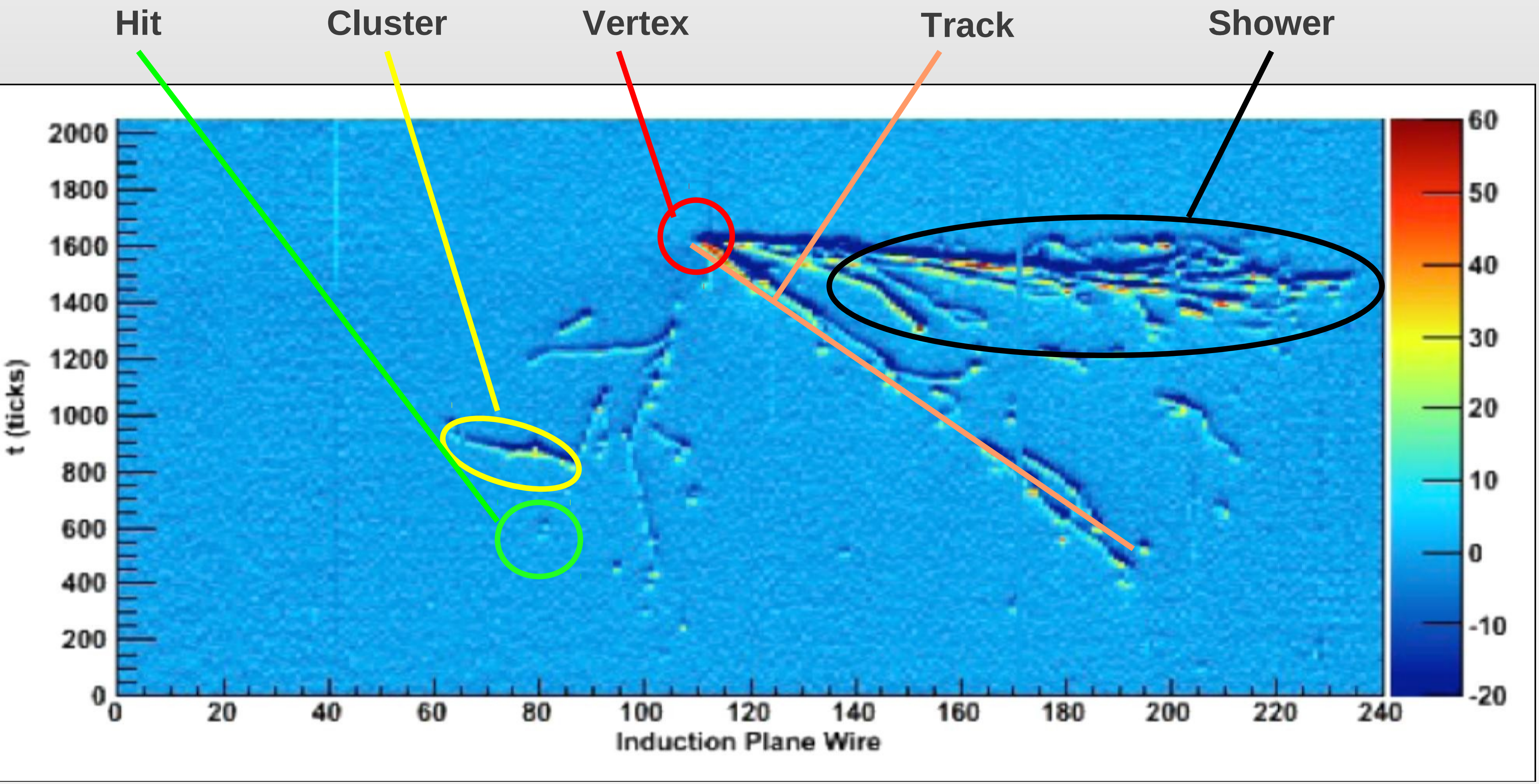




TPC Reconstruction

- 1 – Reconstruct tracks and showers in 3 dimensions

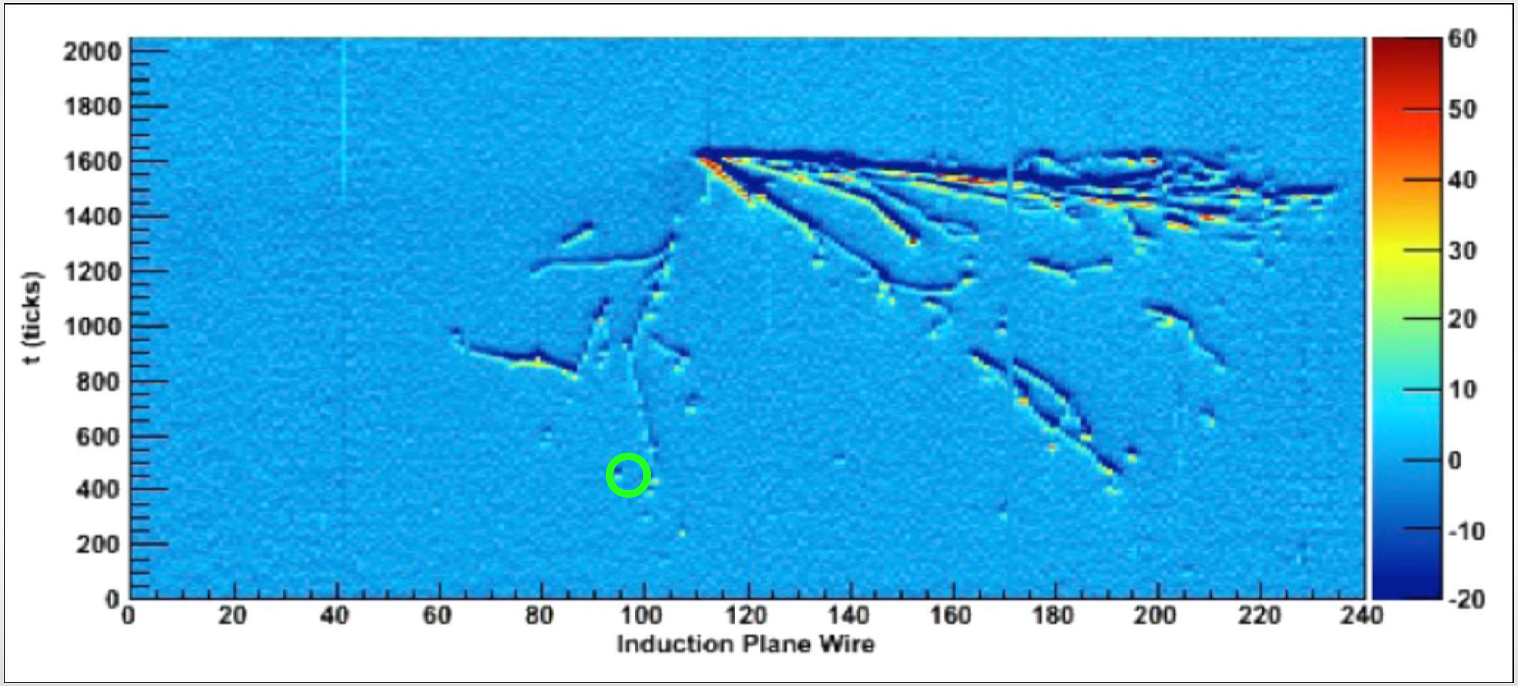




Hit
Cluster
Vertex
Track
Shower
t (ticks)
Induction Plane Wire
0
20
40
60
80
100
120
140
160
180
200
220
240
0
200
400
600
800
1000
1200
1400
1600
1800
2000
60
50
40
30
20
10
0
-10
-20

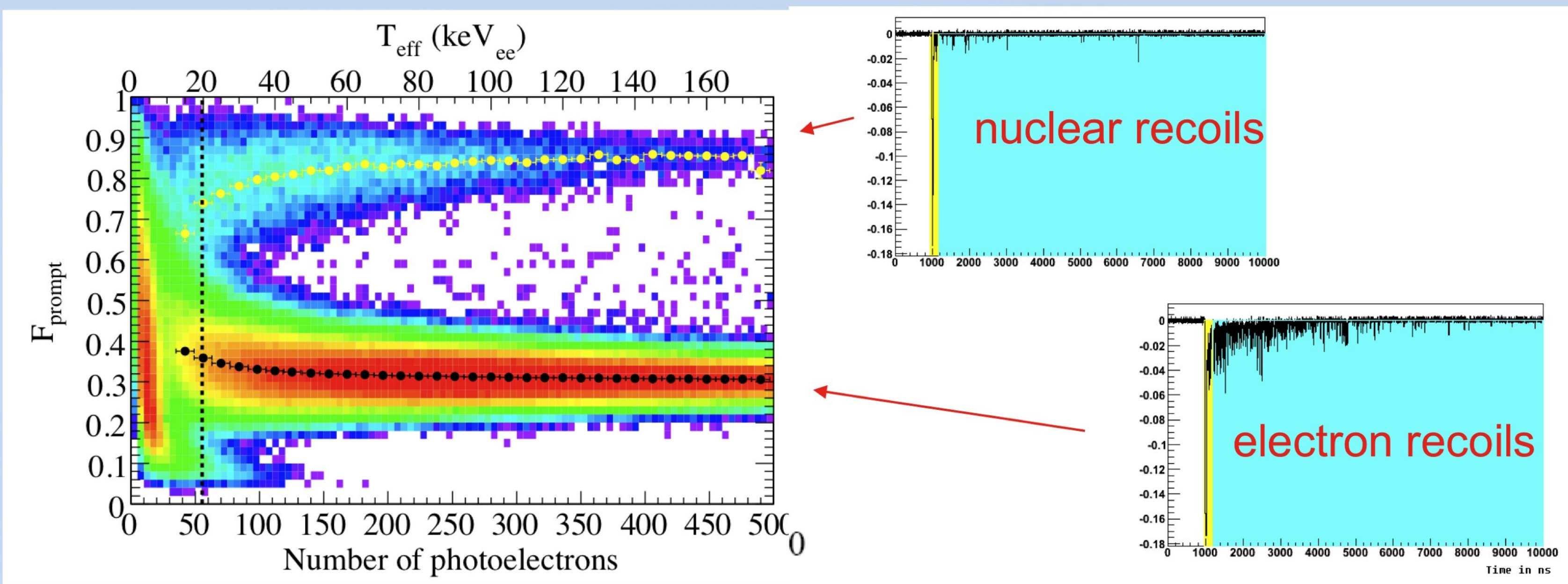
Particle ID

- Having done some pretty complicated reconstruction and identified tracks of charged particles, now have to perform particle ID
- Remember, no B field here. dE/dx is the only handle.
- Liquid argon TPCs give great 3D reconstruction, but:
  - ***Clearly easier to reconstruct tracks in some directions than others***
  - ***Short tracks give less reliable dE/dx measurement (wire pitch gives the fundamental limit, a few mm)***



PSD As Applied in Dark Matter

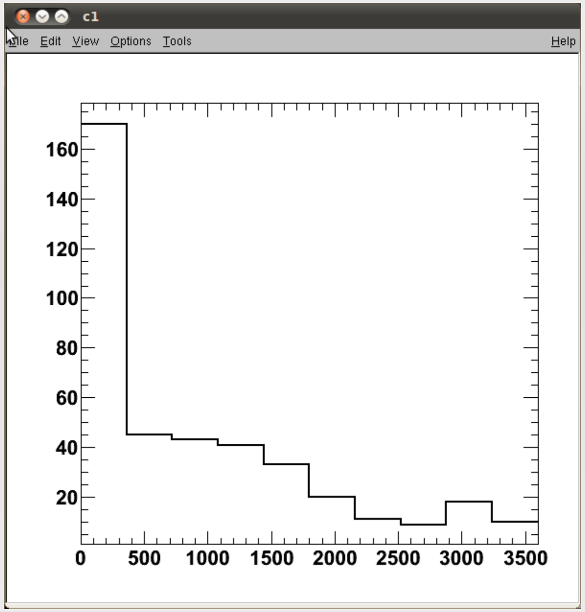
Pulse Shape Discrimination

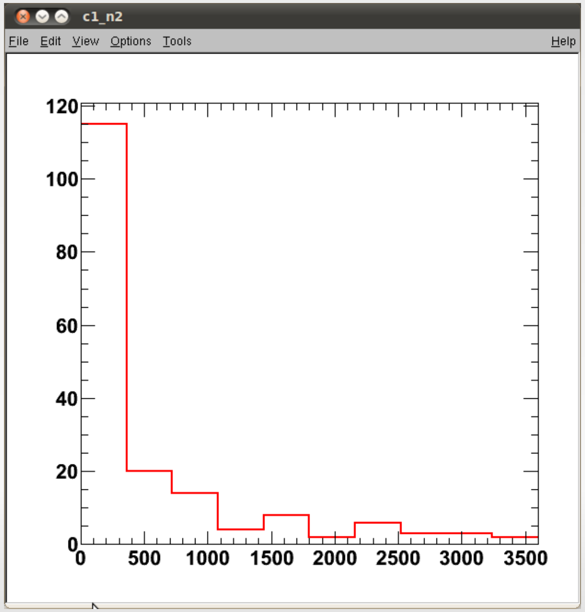


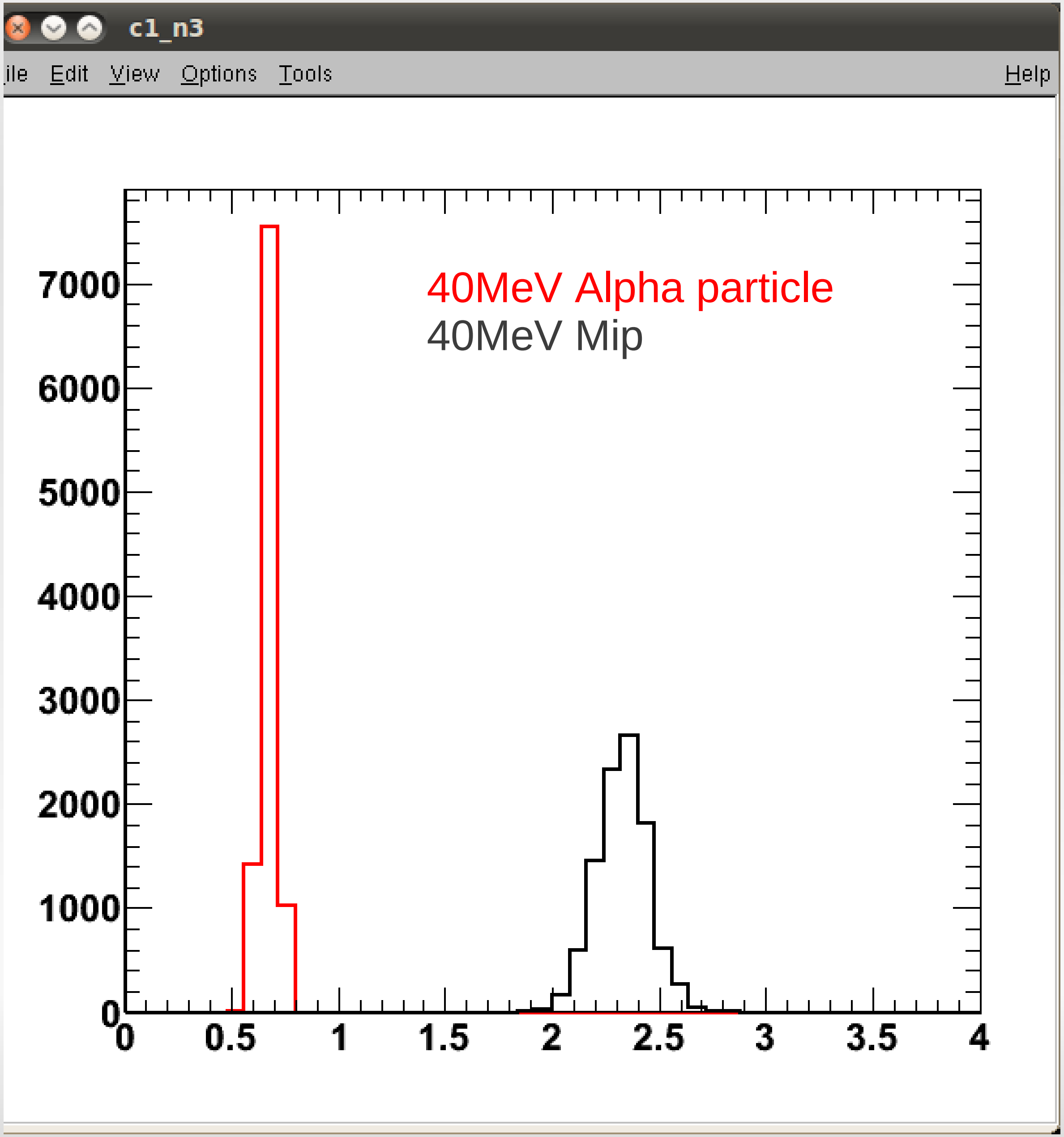
$$F_{prompt} = \frac{\text{Charge in first 150 ns}}{\text{Charge in first 10 μs}}$$

From Thomas Sonley's talk at DNP 2010 : The DEAP 3600 Experiment

An Example for MicroBooNE

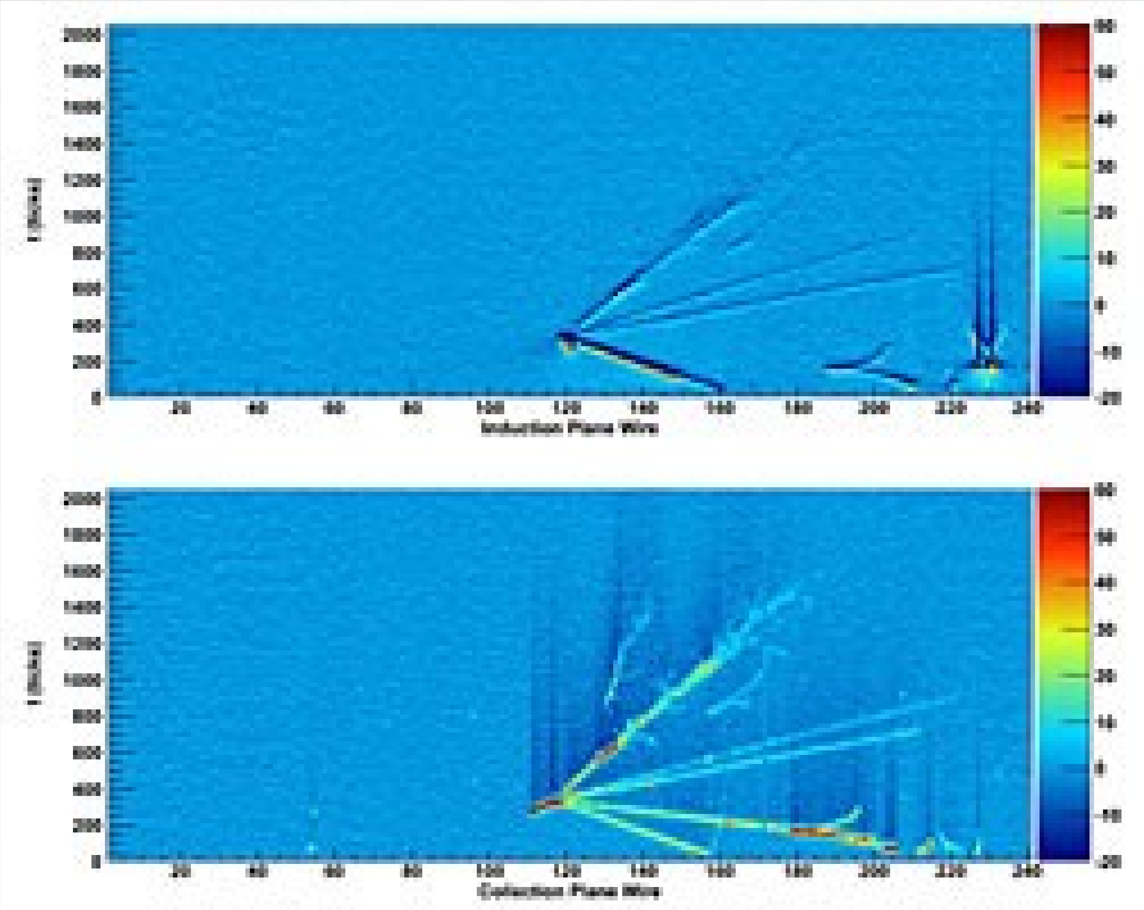






PSAR – A Step Further

- PSD appears to work great for telling the difference between a keV electron recoil and a keV nuclear recoil event
- But there are two ways in which MicroBooNE will be different to a dark matter LAr experiment
    - ***Events will often have a much more complicated structure***
    - ***Events will produce a lot more light***
    - Clearly need a more sophisticated algorithm



Pulse Shape Augmented Reconstruction

1 – Run full TPC based track reconstruction to figure out the event geometry

2 – Run TPC particle ID, which will output a list of candidates for each track, accompanied by a probability for this candidate

3 – Seek out points of confusion where several candidates are possible (hopefully rare), and run the parameterized optical sim for the event

4 – Fit each hypothesis to the measured PMT signals to determine the best fit, and resolve as many confused events as possible!

PSAR helps to:

Reduce the probability of mis-ID
Reconstruct tracks in the least reconstructable directions

PSD is VITAL for:

Obtaining information about tracks shorter than a few mm
(including supernova neutrinos, geoneutrinos?, etc)

Summary

- Optical information from events in liquid argon is complementary to TPC information, and may be used to enhance triggering and event reconstruction capabilites.
- A set of tools have been developed within the LArSoft framework, which will support the MicroBooNE optical systems
- Detailed photon by photon optical simulations can be performed and have been used to optimize detector design and understand triggering capabilities
- A fast simulation, which will allow all MicroBooNE simulation jobs to produce an expected optical system output is at an advanced stage
- We have proposals for two new reconstruction algorithms utilizing optical data, which we expect to come to fruition once TPC based particle ID becomes a reality.

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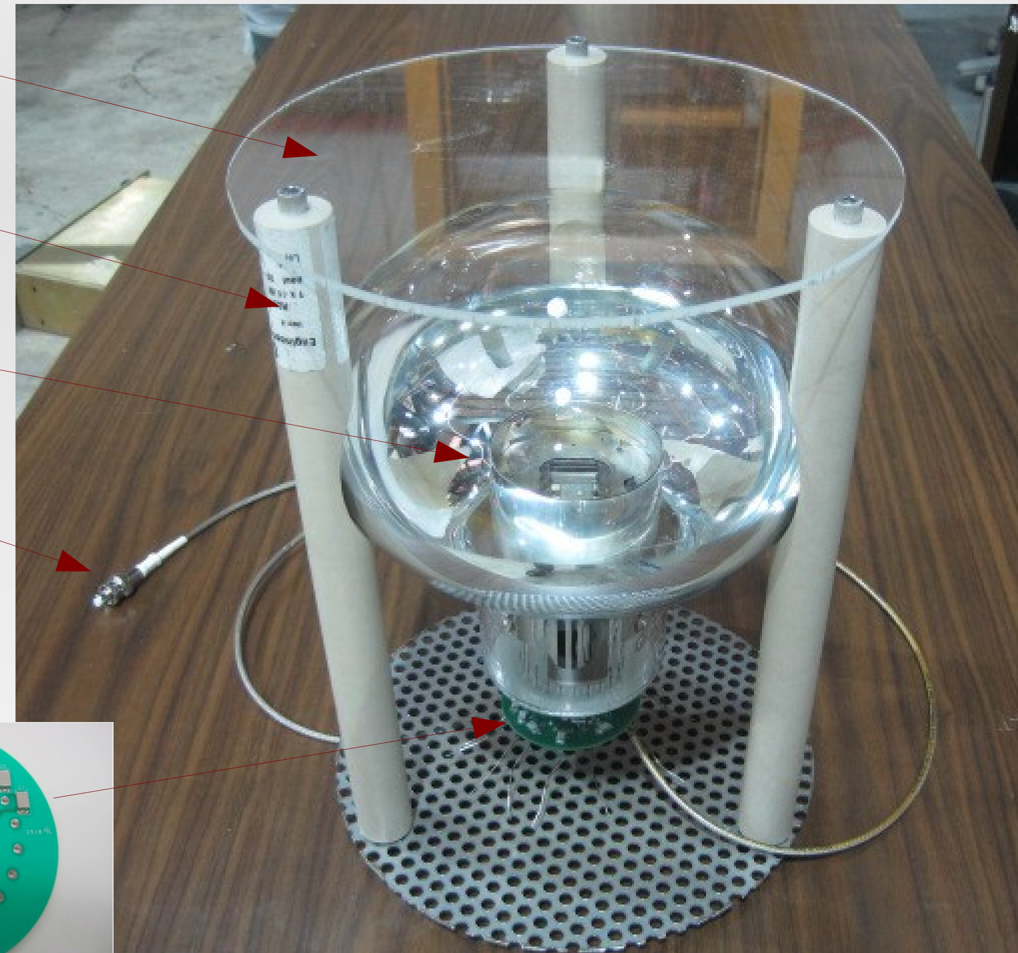
TPB coated acrylic plate

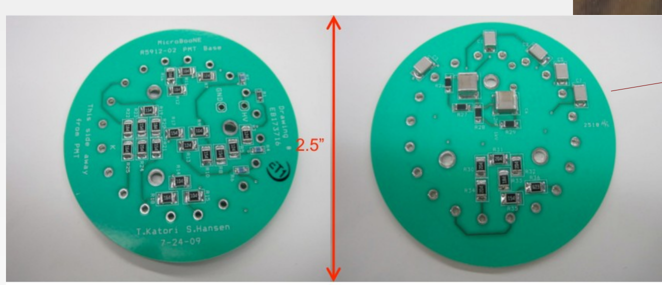
PEEK supports

8” Cryogenic PMT

Combined HV and Signal Cable

Specially designed cryogenic base



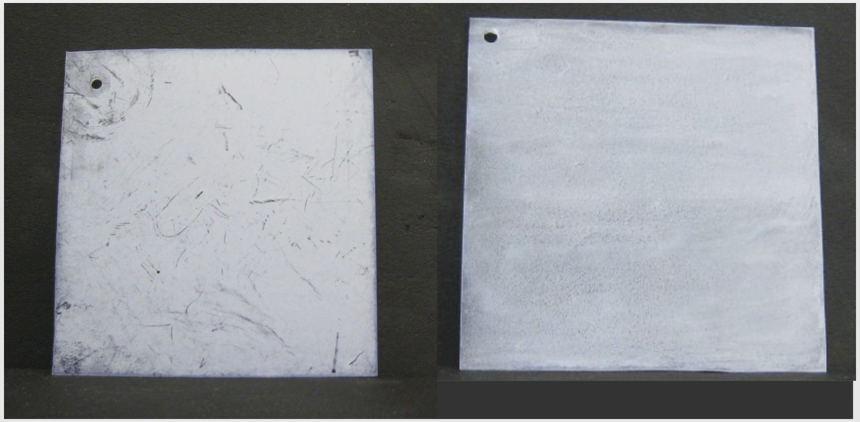


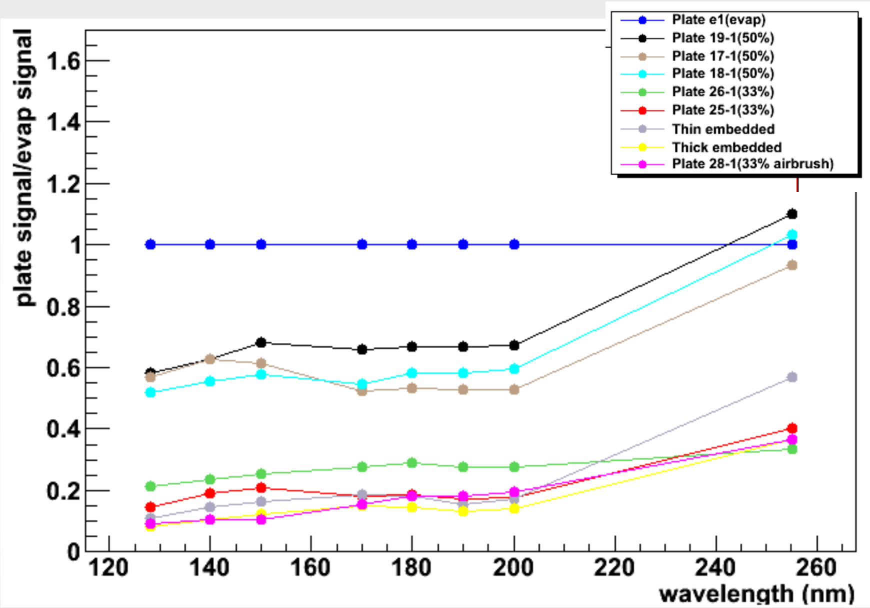
MicroBooNE base

Phototubes have a platinum photocathode undercoating improve quantum efficiency at 87K
(*Hamamatsu R5912-02mod*)

WLS Plates

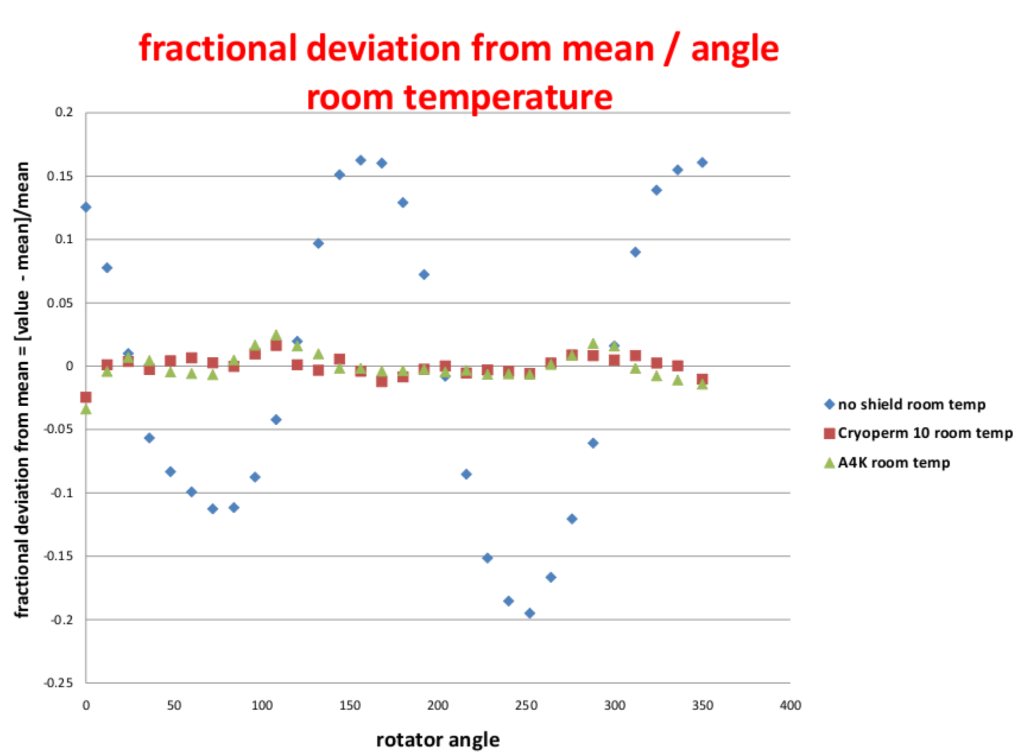
- We have performed extensive R&D into the development and optimization of the wavelength shifting plates
- Various factors at play :
  - *Coatings must be robust in liquid argon*
  - *Want to achieve a high uniformity*
  - *Even more important : high reproducibility*
  - *Water absorption into coating causes degradation of efficiency with time*
  - *Maximize wavelength shifting efficiency*
  - *Minimize cost and production difficulty*
  - *Unexplained discoloration in some batches of TPB*
  - *Etc, etc*
- Closing in on an optimal production method, but further testing and optimization is ongoing
- We will test all plates and all PMT's in a liquid argon test stand to independently measure each efficiency before installing them in the detector

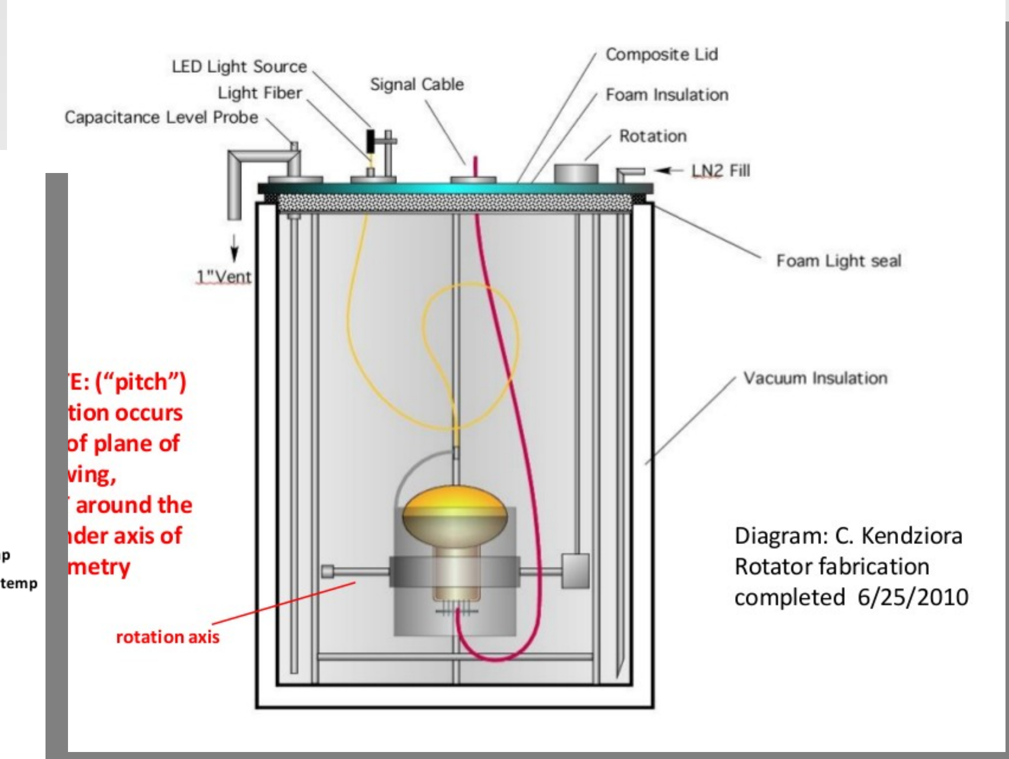




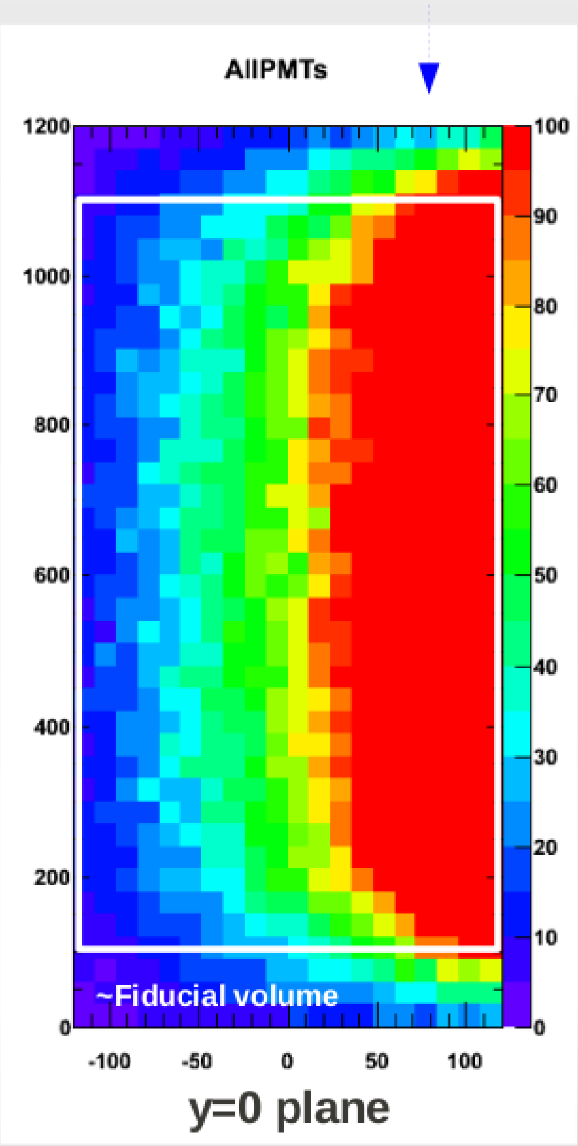
Magnetic Shielding

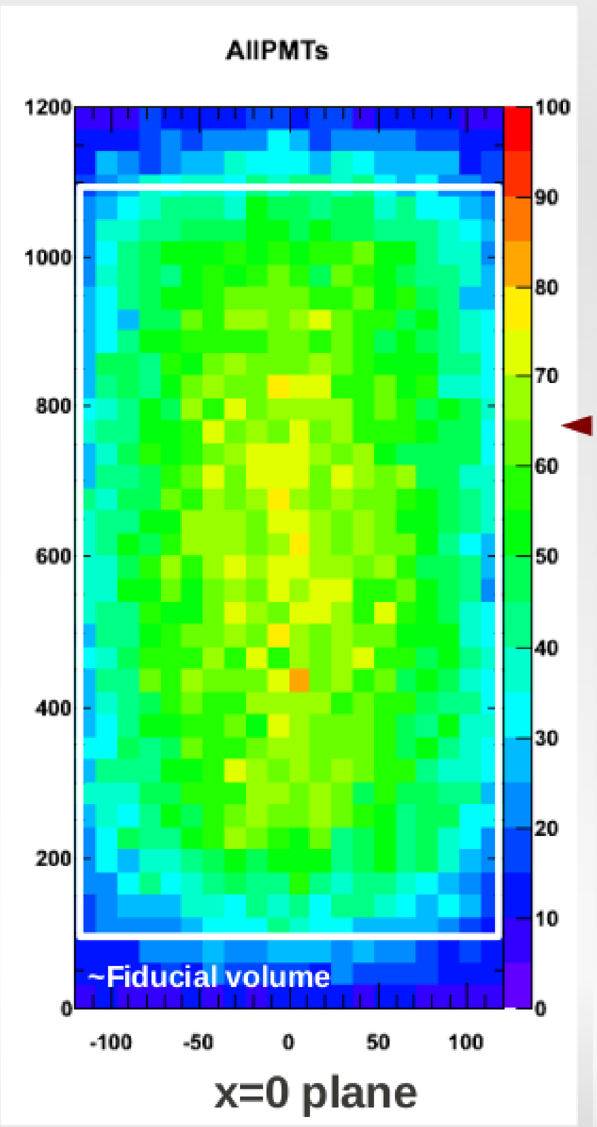
- We are also exploring the possibility of magnetically shielding the PMTs with mu-metal surrounds to reduce noise levels from external B fields
- This is a recent addition to the project and R&D is ongoing. So far results look great!





Some things we need to learn – 1 : PMT Linearity





Remember my last talk – these plots are for 5MeV of scintillation deposits.

Many interesting events will have ~100 times this energy deposit

The slow light component is not a problem – photons arrive over a long time interval

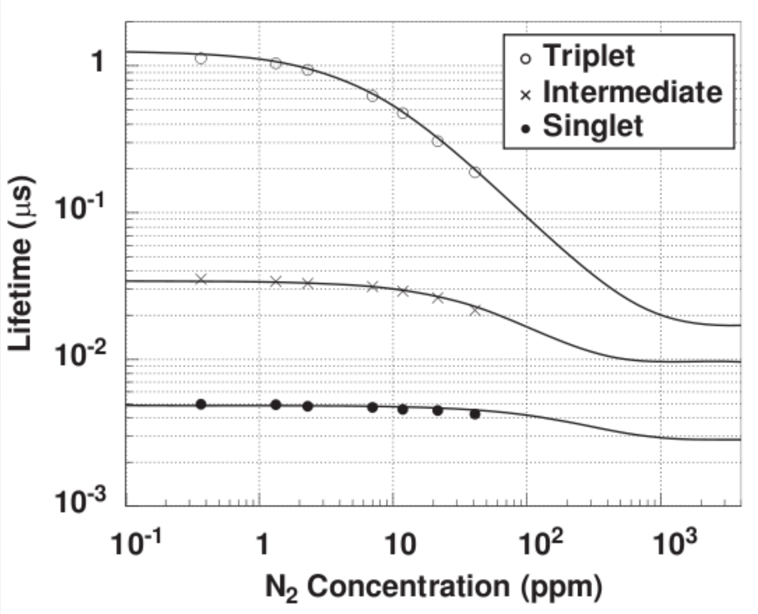
But getting a charge measurement for the fast component will require good PMT linearity for a high photon yield

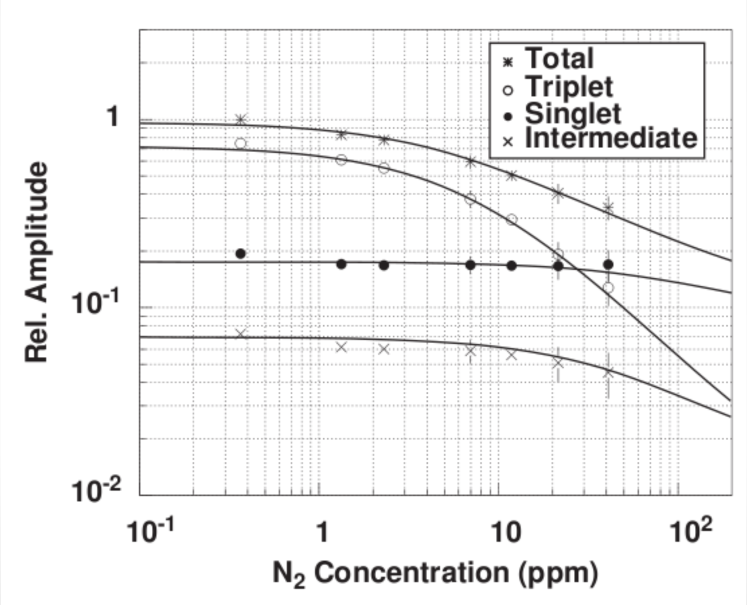
Preliminary measurements suggest good charge linearity up to 100 p.e.

To answer : how high in energy is PSR important?

Some things we need to learn - 2 : Argon purity and stability

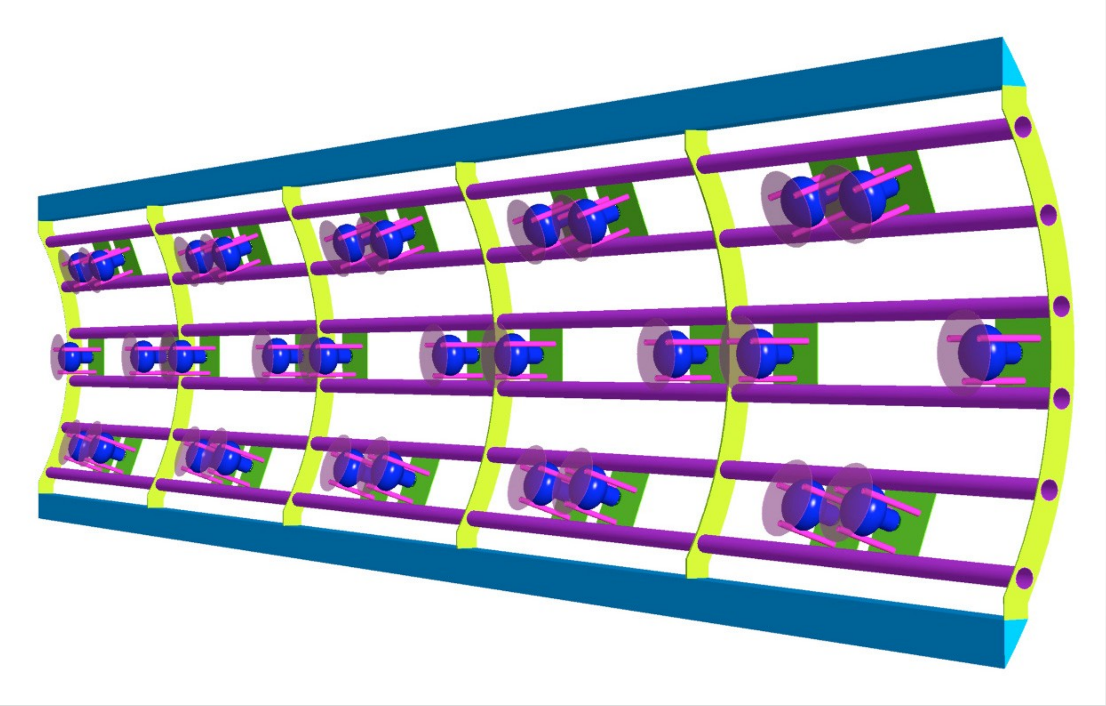
- The argon in MicroBooNE has slightly less strict purity constraints than in argon dark matter experiments
- Nitrogen and oxygen impurities both quench scintillation light. As with recombination quenching, slow light is quenched more strongly.
- Oxygen impurities are tightly controlled in MicroBooNE since they effect electron drift
- Nitrogen impurities may be larger and less stable.
- Can we callibrate out these effects in real time? How high a nitrogen purity is feasible?





PMT Placement and Geometry

- The geometry files used for LArSoft experiments are written in the **GDML** language and built using a set of geometry generation scripts
- **PMT geometry** definition and placement scripts have been added
- **microboone.gdml** has been rebuilt with coordinates from one possible 30 PMT design
- PMTs are placed by supplying the **x,y,z coordinates of the centre of the PMT lens ellipsoid** and the **direction of the lens normal**
- During geometry parsing, PMT components are used to build a **parallel world volume** and appropriate **sensitive volumes** with **PMT ID's** are assigned
- Other **PMT geometries** (30Rack-A, 30Rack-B, 40Rack) can be built and compared simply by supplying a new set of PMT coordinates and running a script



PMTs in LArSoft

2) AcrylicPlate

Shape:
Cylinder

Material:
Acrylic

4) PMTUnderside

Shape:
Ellipsoid

Material:
Solid Glass

5) PMTStalk

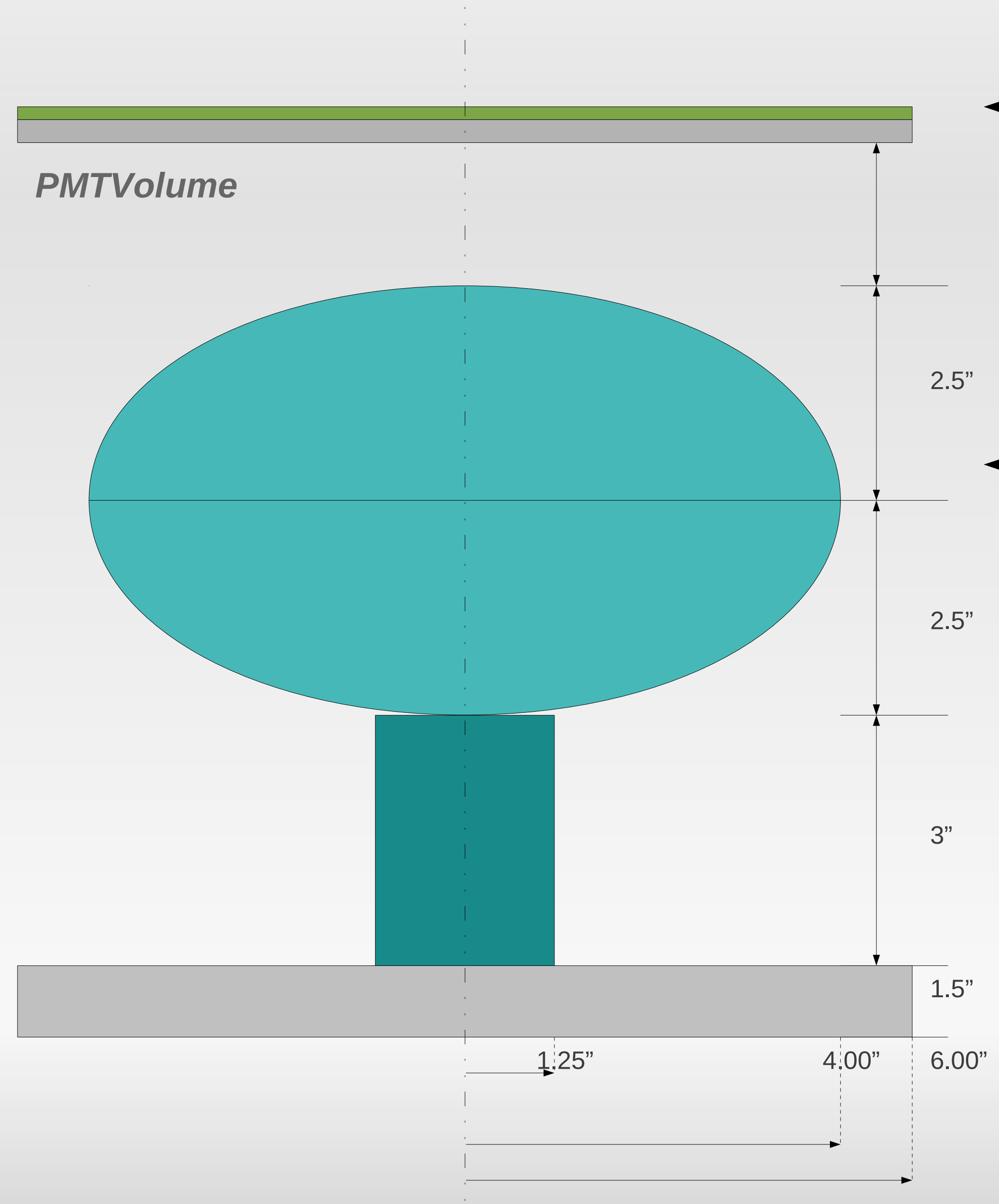
Shape:
Cylinder

Material:
Solid Glass

6) PMTSteelBase

Shape:
Cylinder

Material:
Stainless Steel



1) TPBCoating

Shape:
Cylinder

Material:
TPB

Physics:
OpWLS Process in OpticalPhysics constructor

3) PMTLens

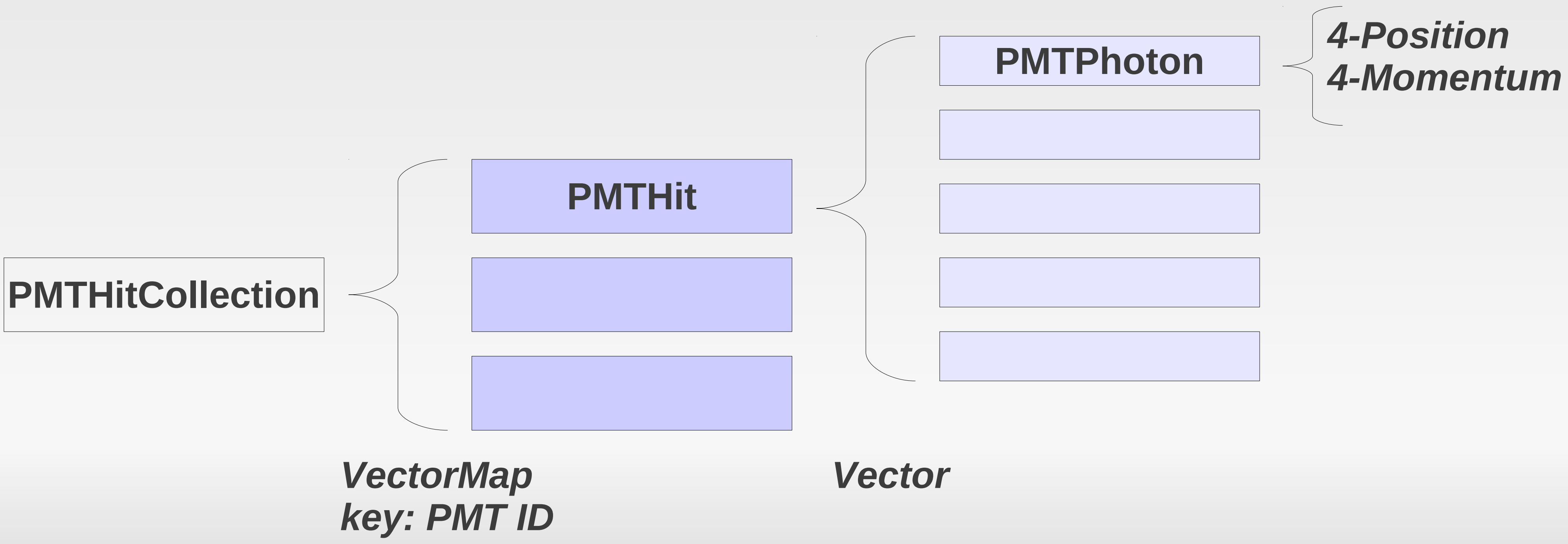
Shape:
Ellipsoid

Material:
LAr *

Physics:
PMTSensitiveDetector associated in DetectorConstruction

PMTHit Data Structures

- The optical information to be passed along the simulation chain from LArG4 is contained within a PMT hit collection
- The PMTHitCollection is a set of PMTHits, one for each PMT that saw one or more photon
- Each hit is a list of 4-positions and 4 momenta of photons which stepped across the lens of the PMT



The Light Source Event Generator

- Event generator which simulates an extended, isotropic light source at some position in the detector
- Two modes of operation:

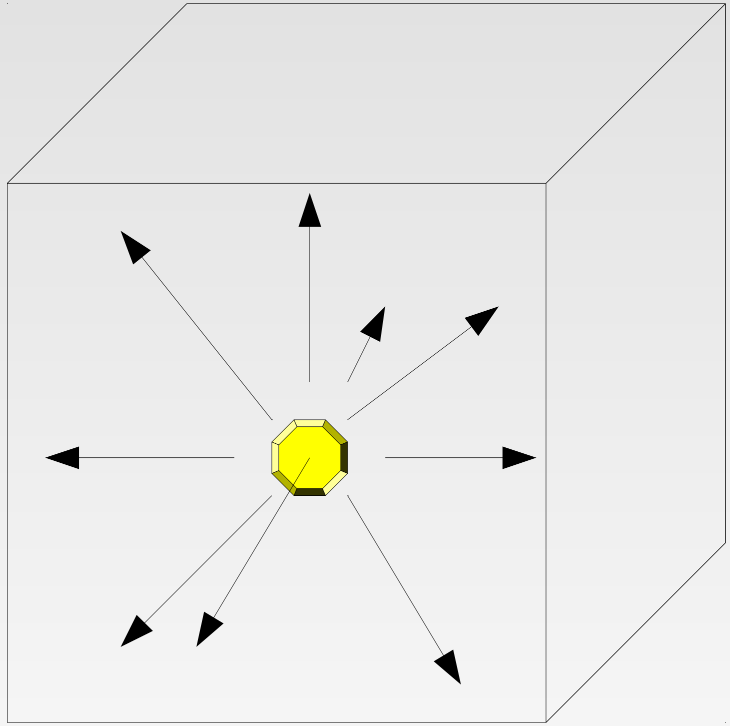
  - Scan Mode

  Voxelize the detector into cuboidal regions, and step through the volume deposititting N photons uniformly across one voxel per event.

  - File Mode

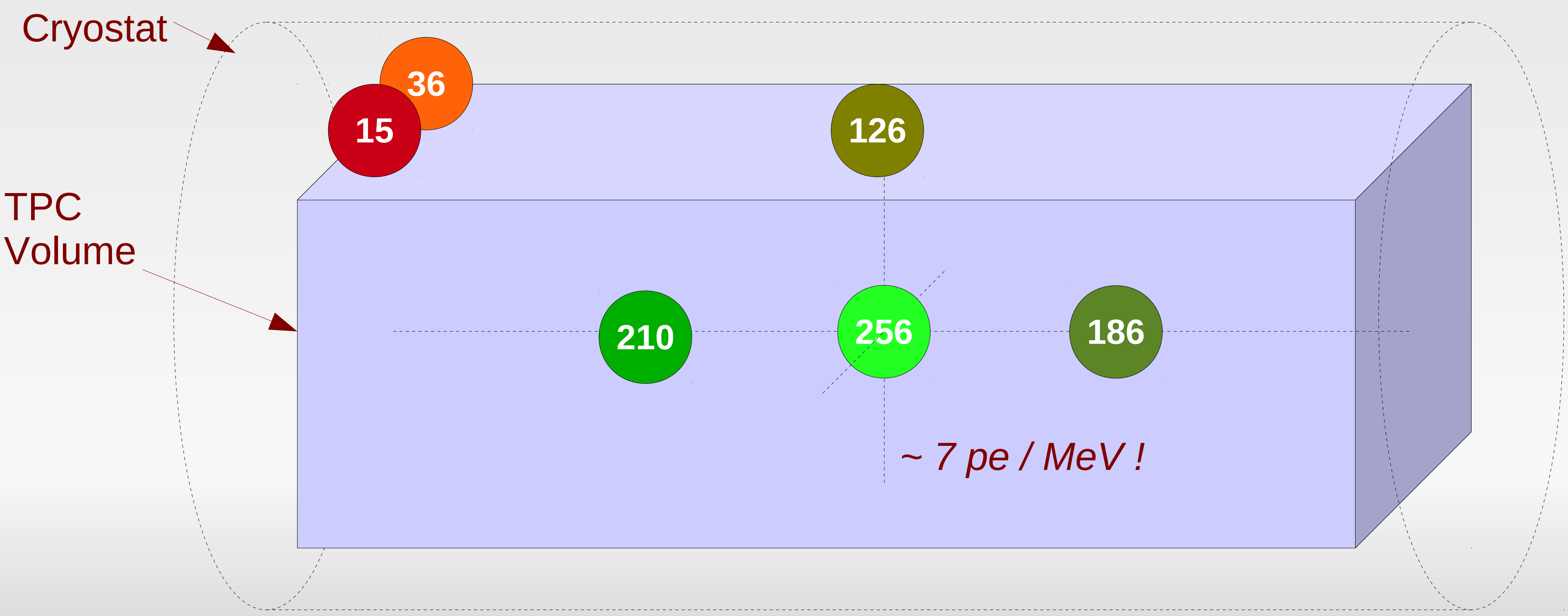
  Specify the size, intensity, shape and position of one light source for each event in a text file which is specified in the config file for the module.

- Optionally, a data structure can be stored in the event with details of the light source configuration



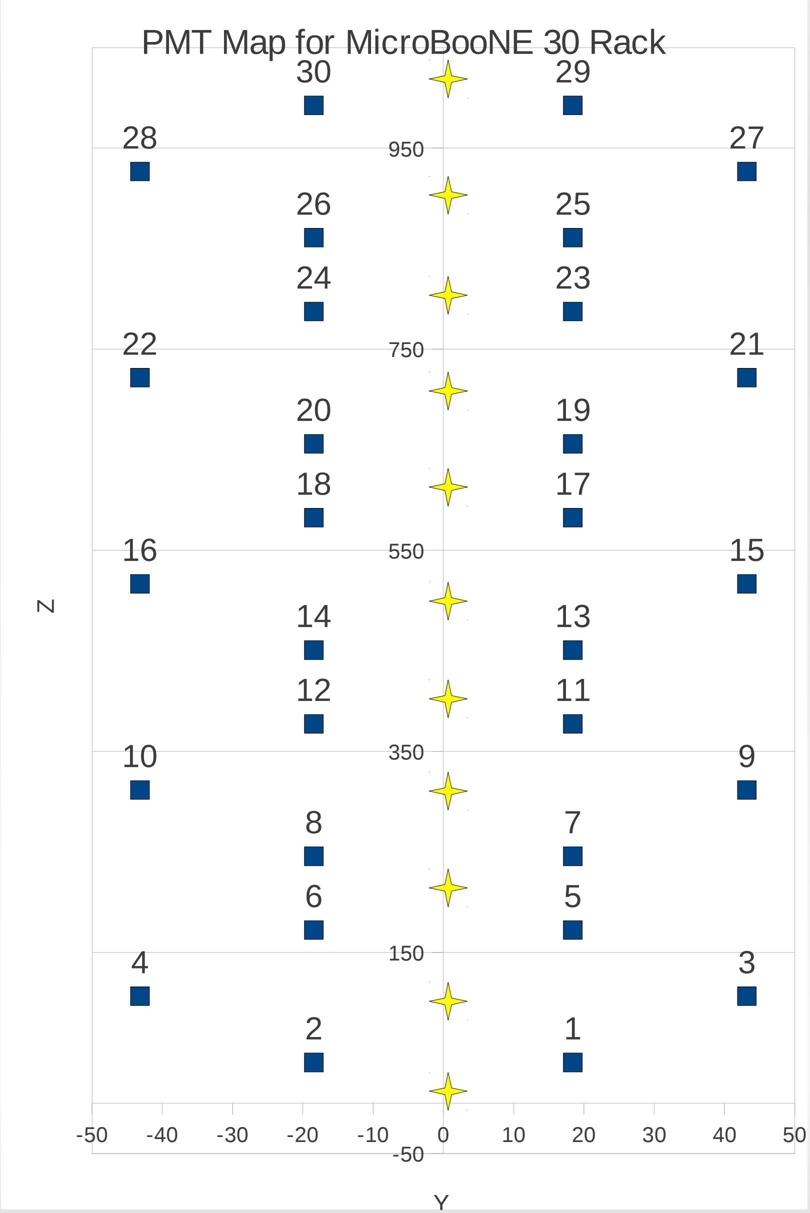
Preliminary Sensitivity Studies

- Place light sources which produce 10,000 photons per event at different points in the detector geometry. This is over a factor of 10 smaller than a scintillating 5MeV proton.
- Ask how many photons make it to a PMT lens – all reflections and scatters enabled
- Note that in this preliminary study, PMT lenses are naked - no wavelength shifting plates. Hence we still need to factor in WLS related efficiencies. We estimate a factor of 0.03 (see TDR)

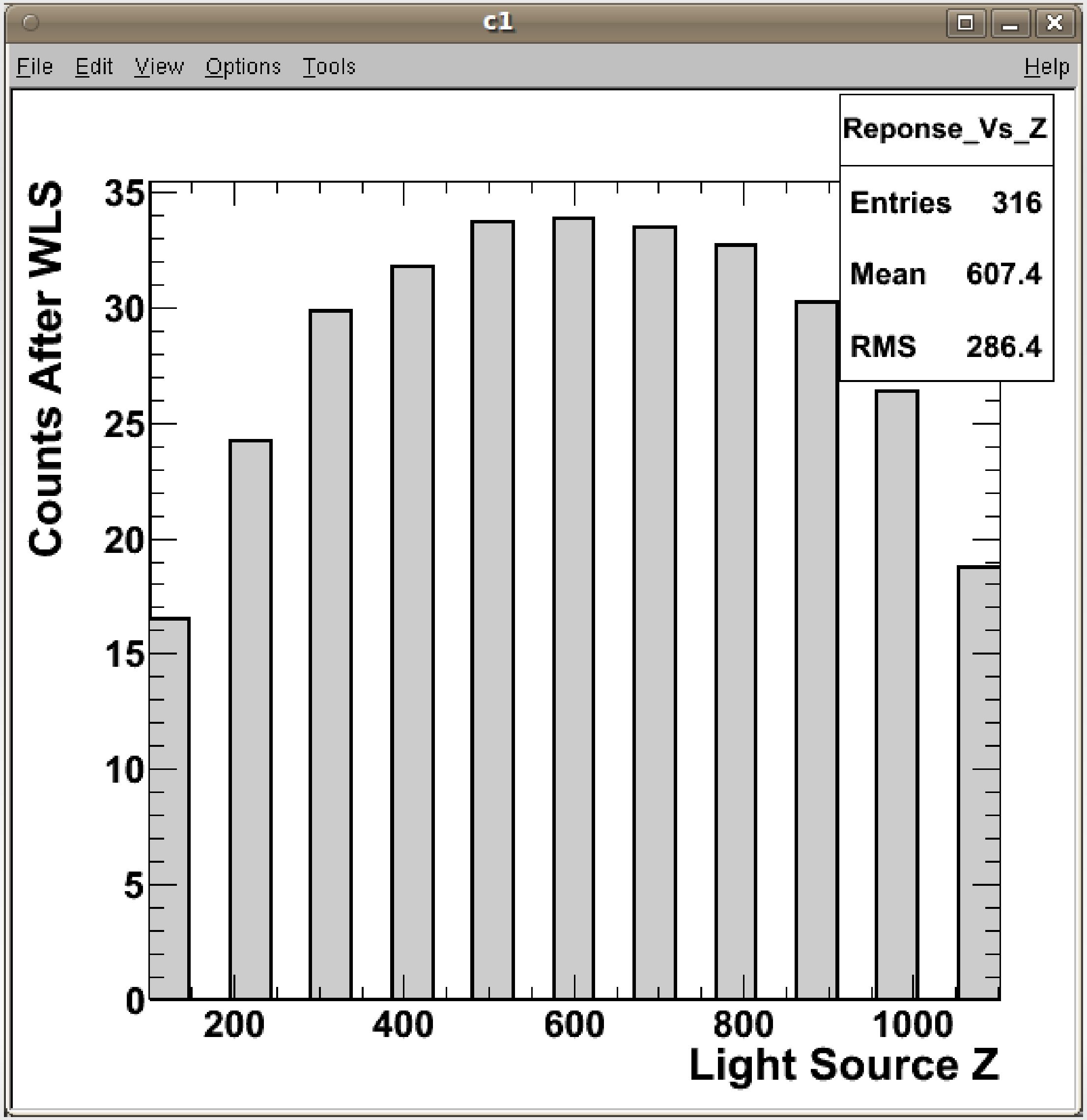


Preliminary – Point Source Test

- Place point light sources at various points in the detector
- Run full simulation with photons corresponding to **5MeV scintillation** (120,000 photons)
- Count photons reaching PMT lens
- Note – PMTs here are naked with no wavelength cut, need to include WLS efficiency. In our TDR, we estimate this to be 0.03.
- Until we have computing power to do more, we only consider on-axis points



Preliminary – Point Source Test

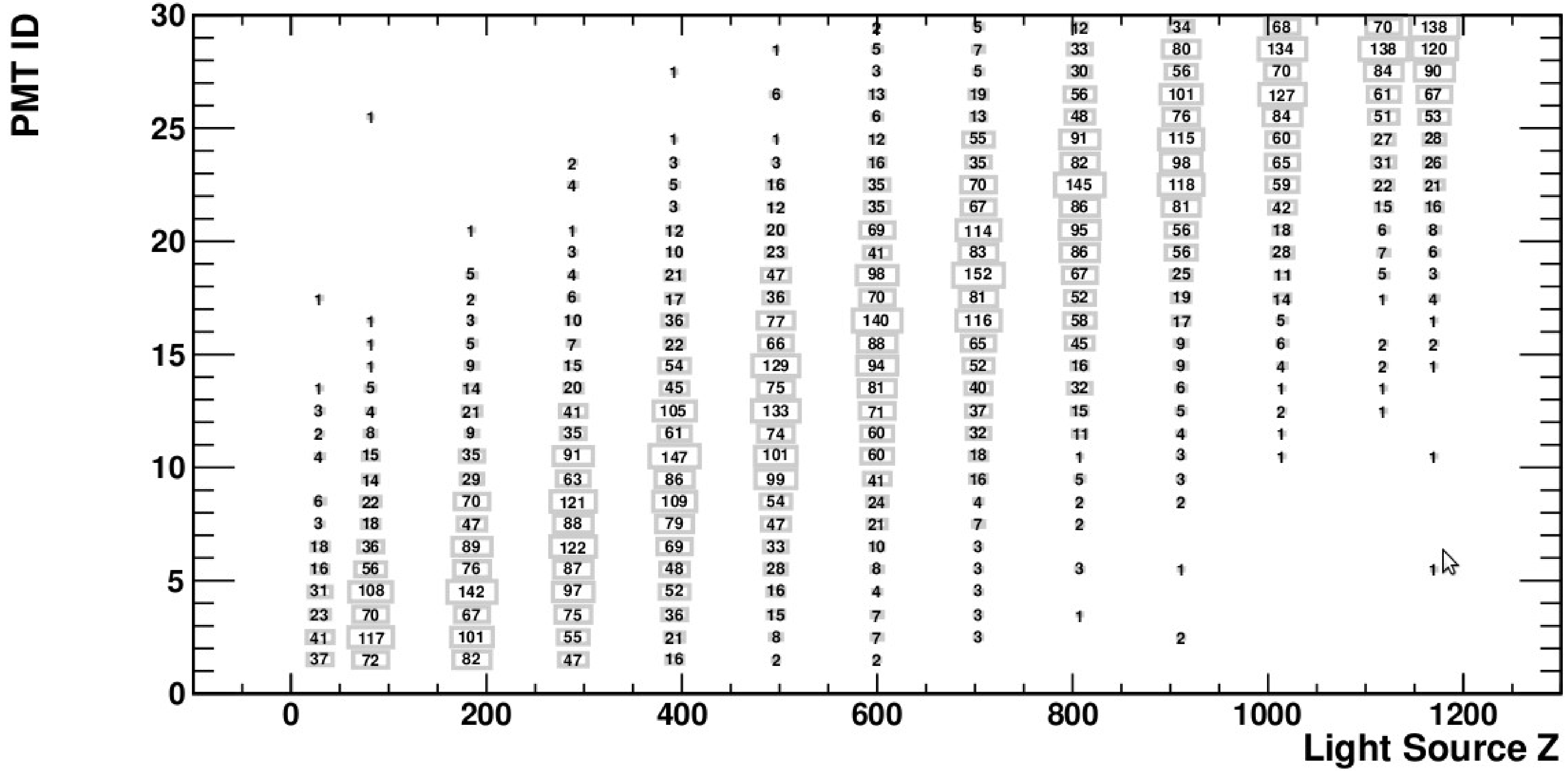


> 15 photoelectrons for each on-axis point in the fiducial volume!

Suggests we have good efficiency for even 5MeV of scintillation

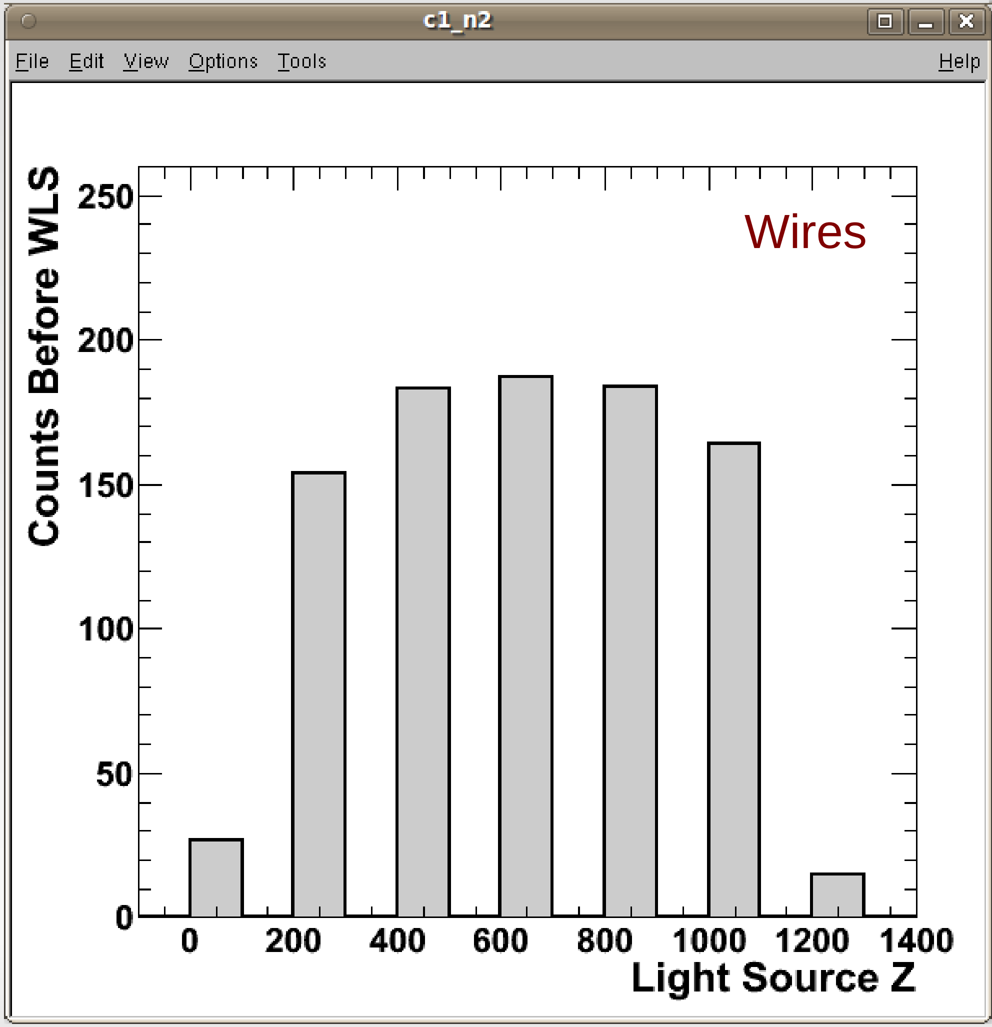
(Subject to geometry modifications)

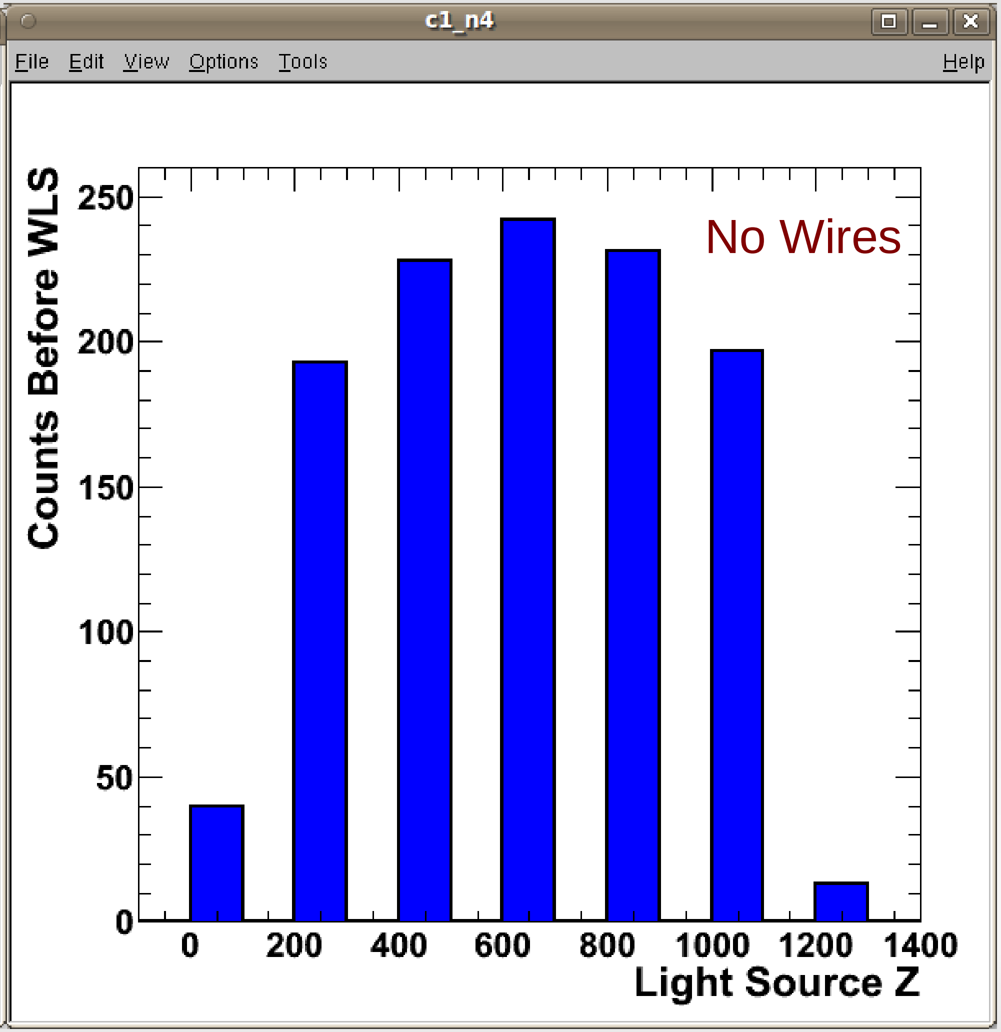
Preliminary – Point Source Test



Preliminary – Effect of Wires

- Wires block ~20% of the light. Note the flattening...





Preliminary – Effect of Wires

- Considering only one central PMT – note that the large angle light is more strongly blocked. Explains the flattening on the previous slide.