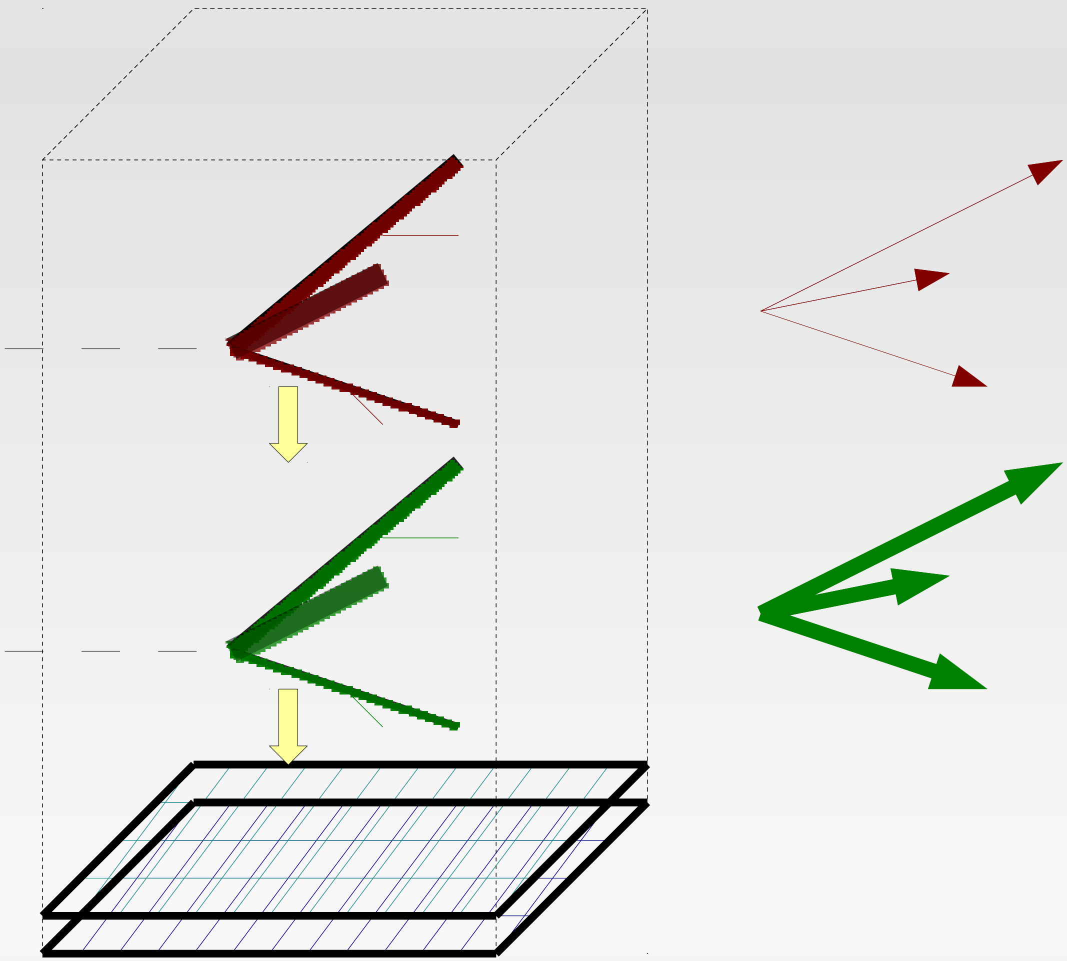
Massachusetts Institute of Technology

Lightguide Detectors
and
Optical Simulation and Reconstruction Methods
for
LArTPC Experiments

Ben Jones, MIT

GLA2011 - Wednesday 08 June 2011
University of Jyväskylä, Finland (JYFL)

Why Optical Detectors in LArTPCs?



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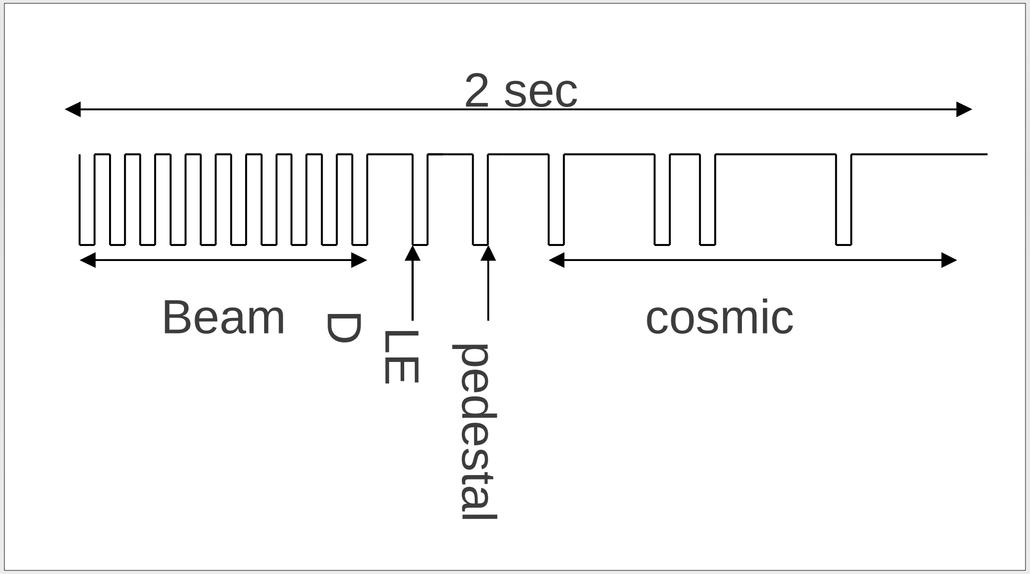

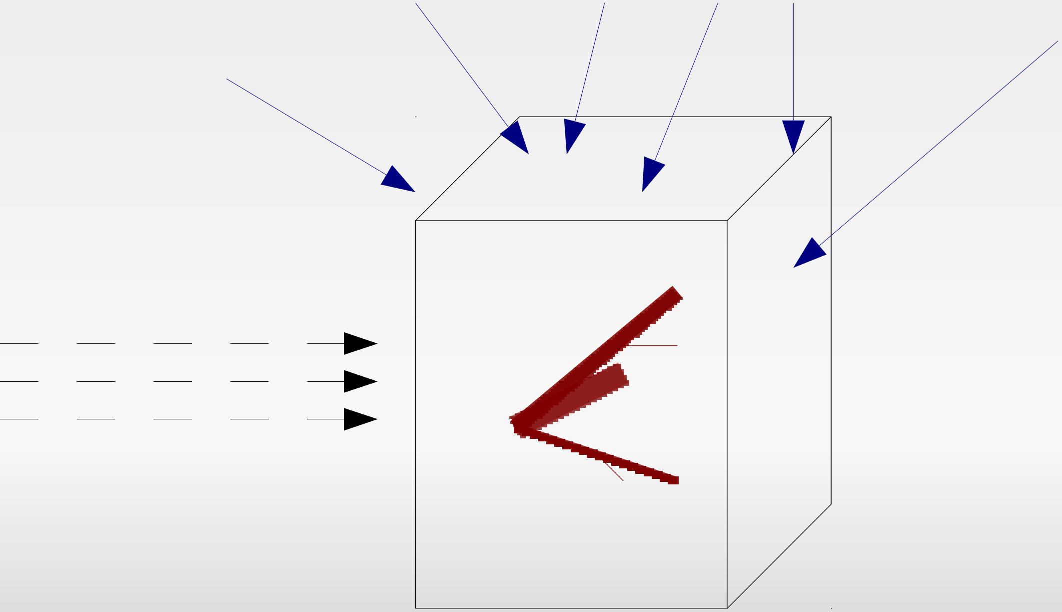

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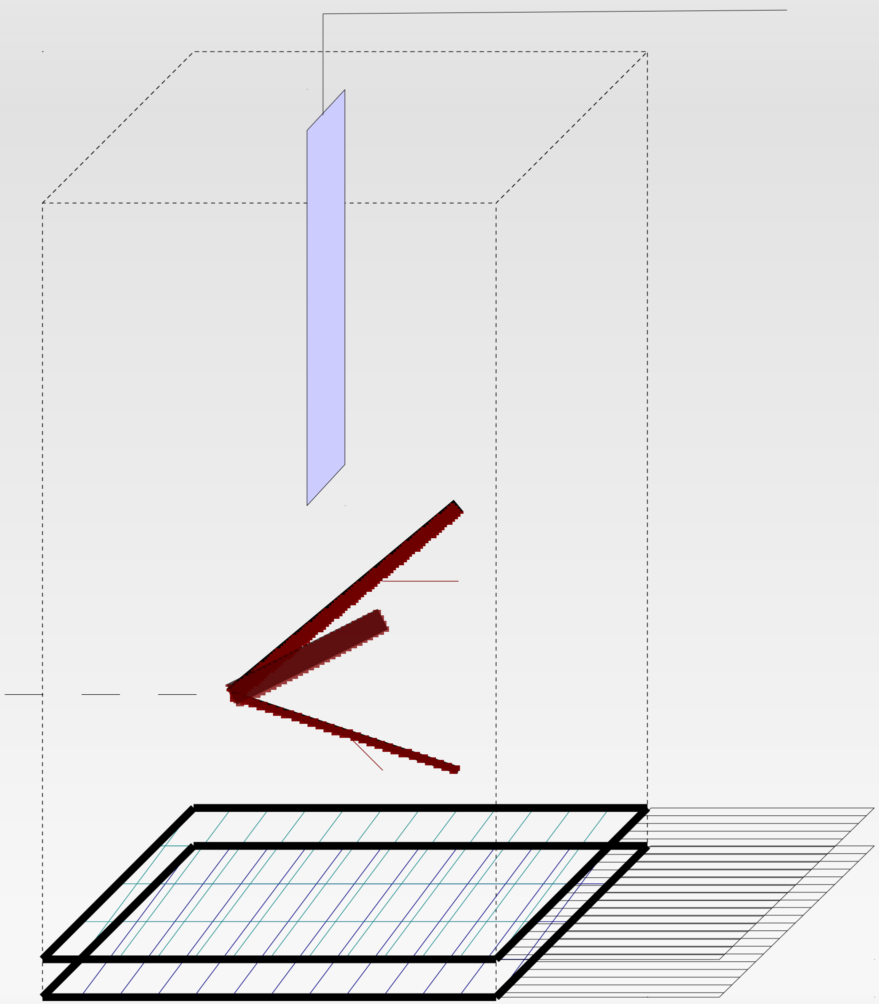

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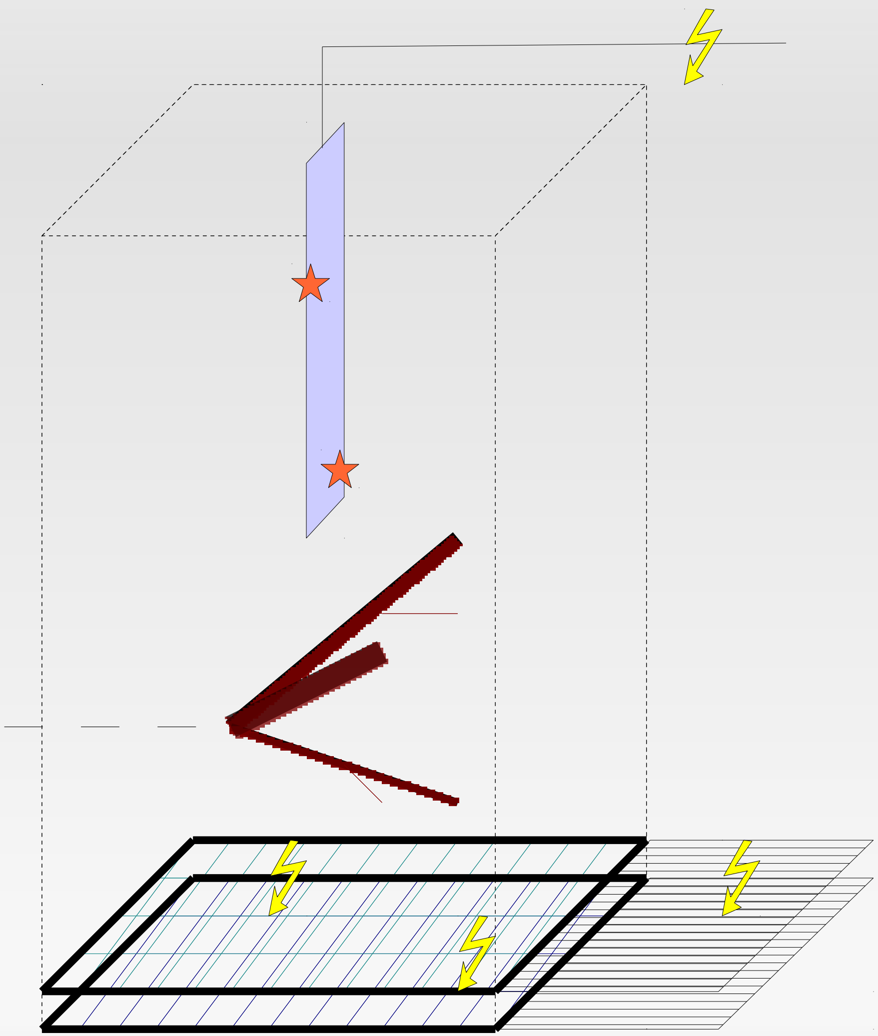

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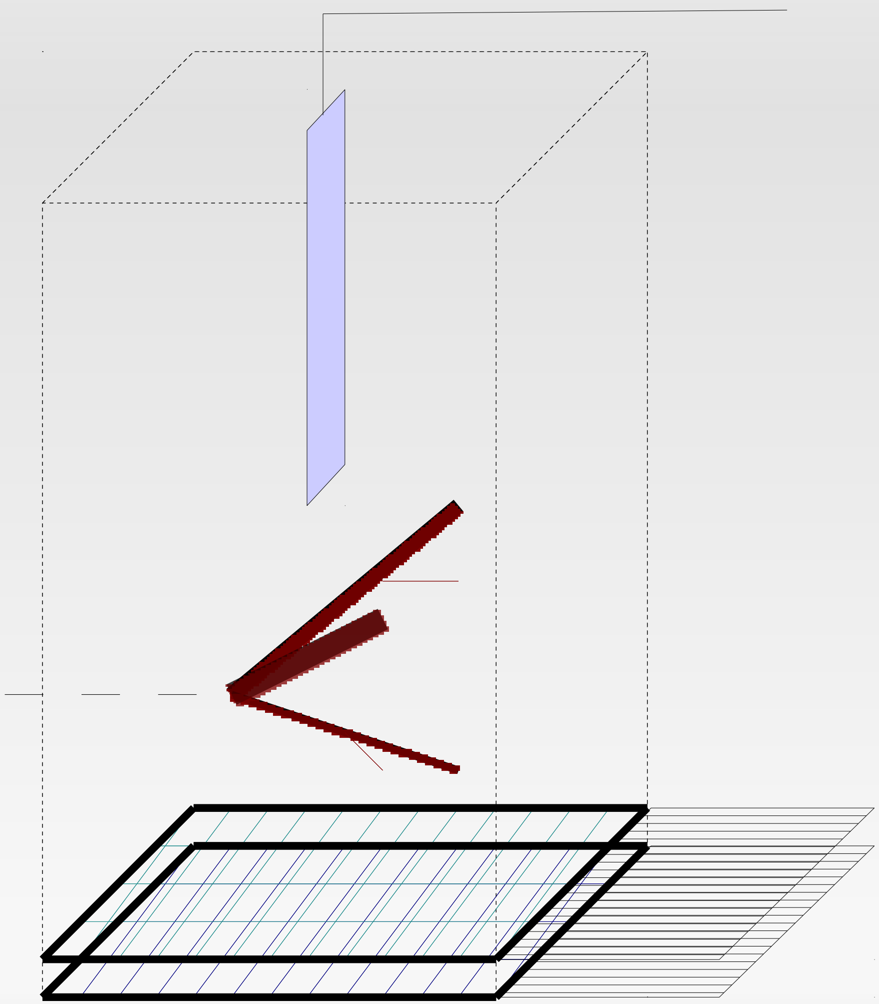

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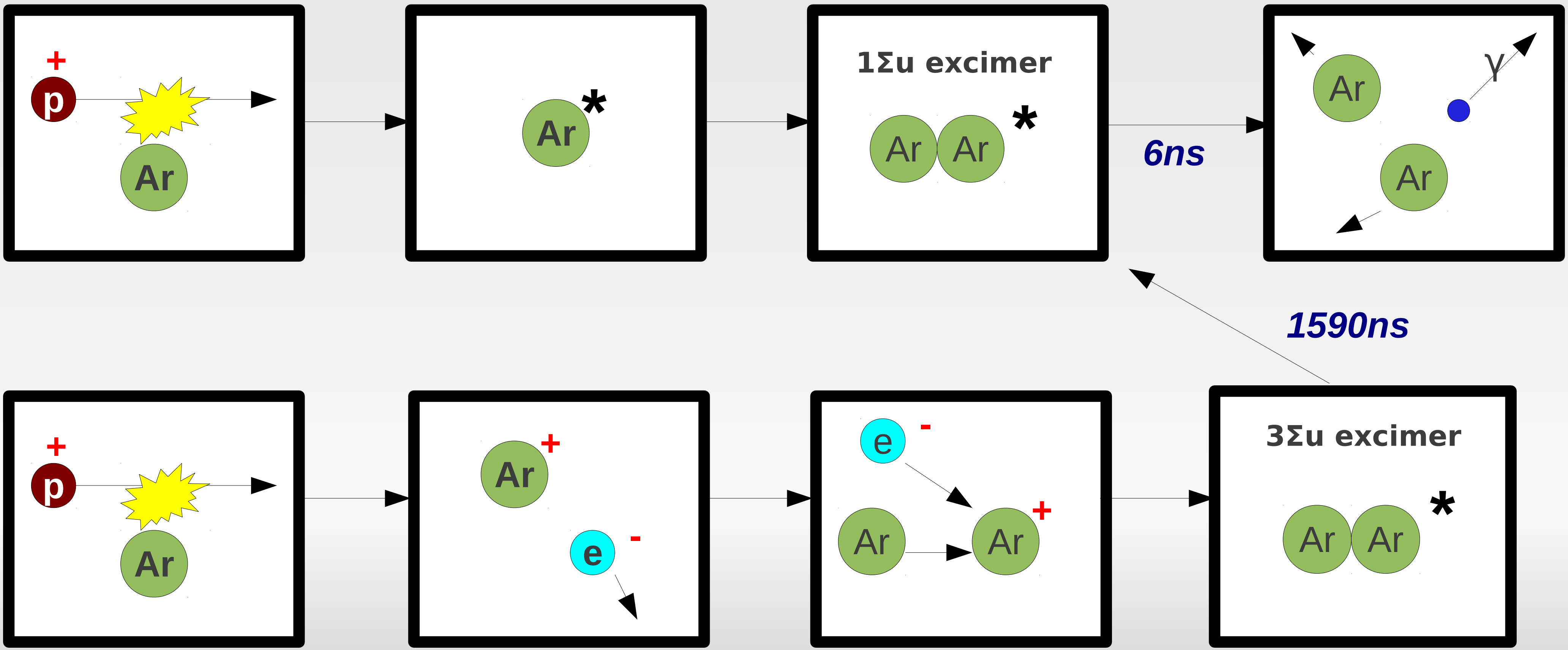
And the importance of every point increases with detector size

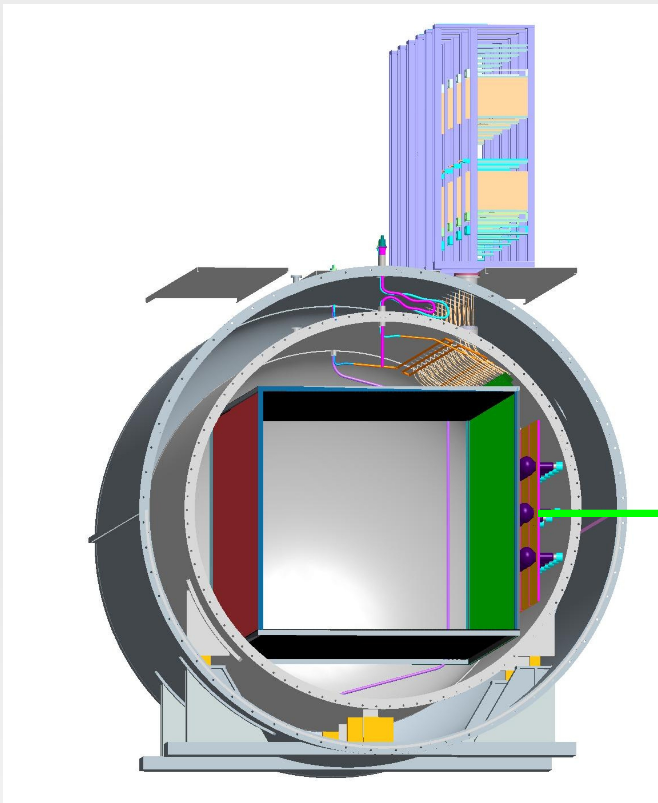
Special Bonus – PID Information

Due to dE/dx dependent yields of fast and slow scintillation light, the time profile of emitted light gives information about particle ID.

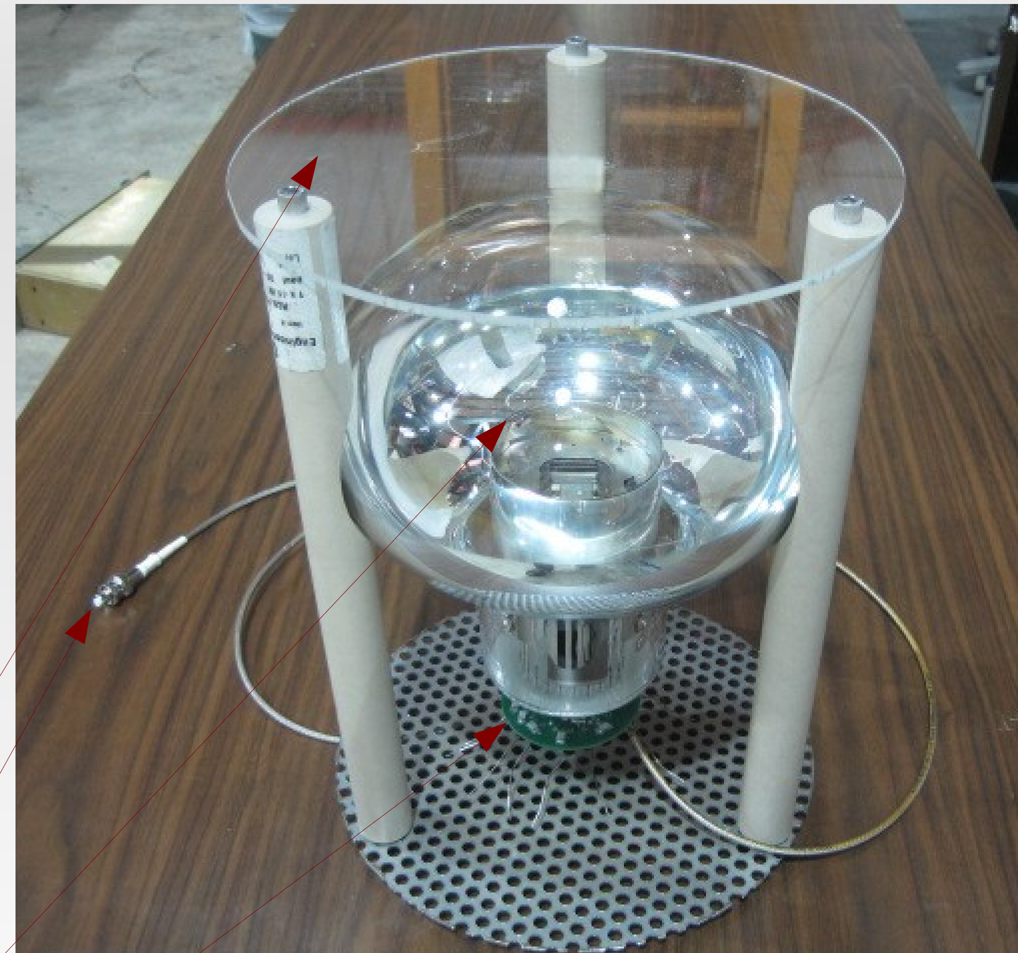
This is utlized in dark matter searches (MiniCLEAN, DEAP), and we are investigating the applications of this technique to augment TPC based particle ID in MicroBooNE.



The MicroBooNE Optical Systems



(Mechanical model)



TPB coated acrylic plate

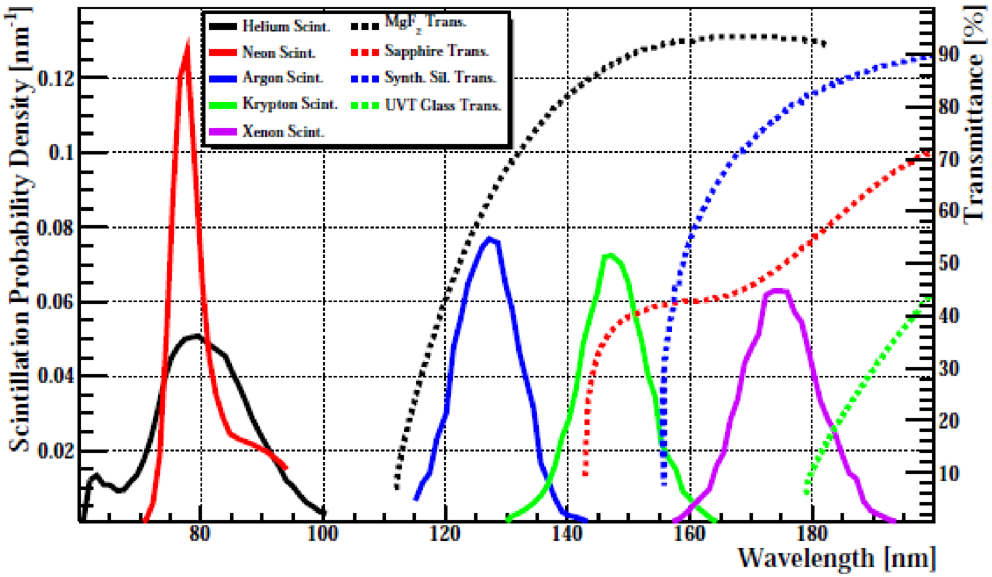
Combined HV and Signal Cable

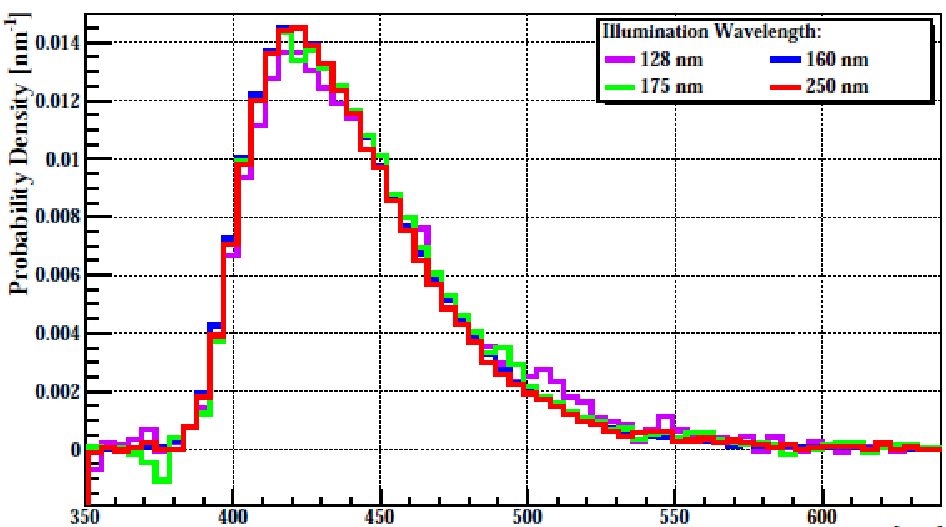
8” Cryogenic PMT

Specially designed cryogenic base

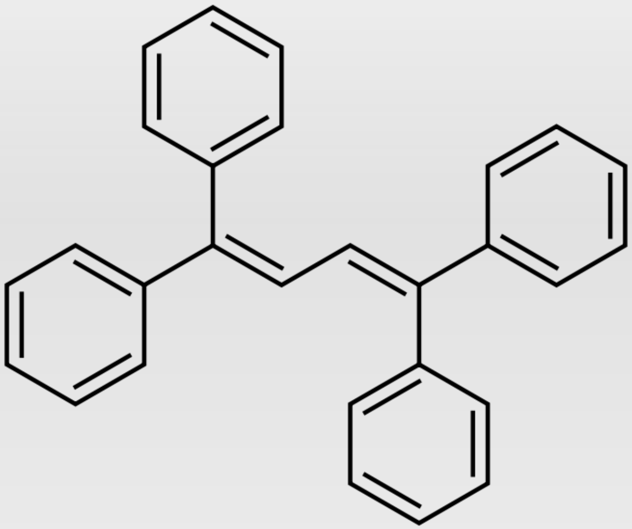
Phototubes have a platinum photocathode undercoating improve quantum efficiency at 87K (*Hamamatsu R5912-02mod*)

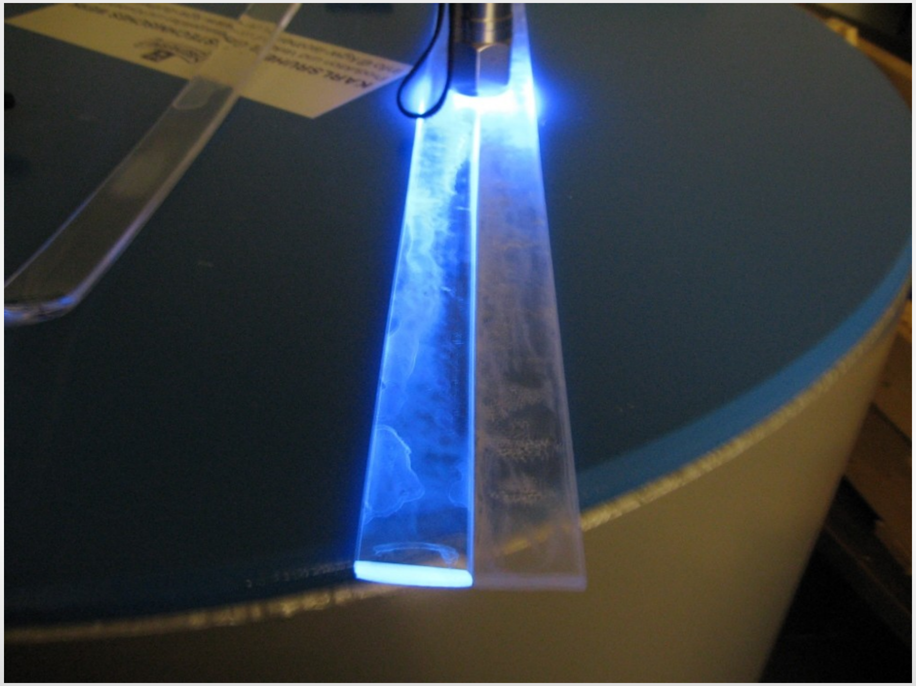
Wavelength Shifting



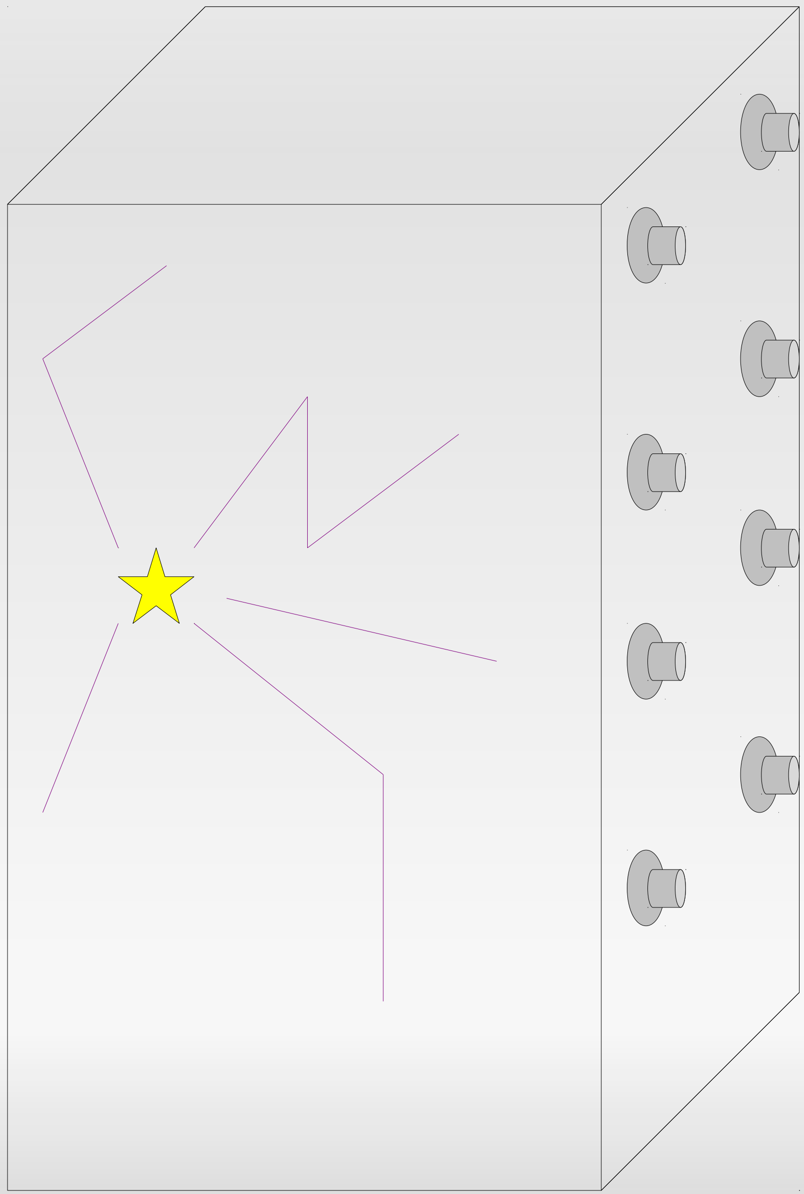


Plots from Gehman et al, arXiv:1104.3259v1





Application to a GLA detector



This is probably not a good strategy for a giant detector, since the path length from the event to the PMTs will in general be large

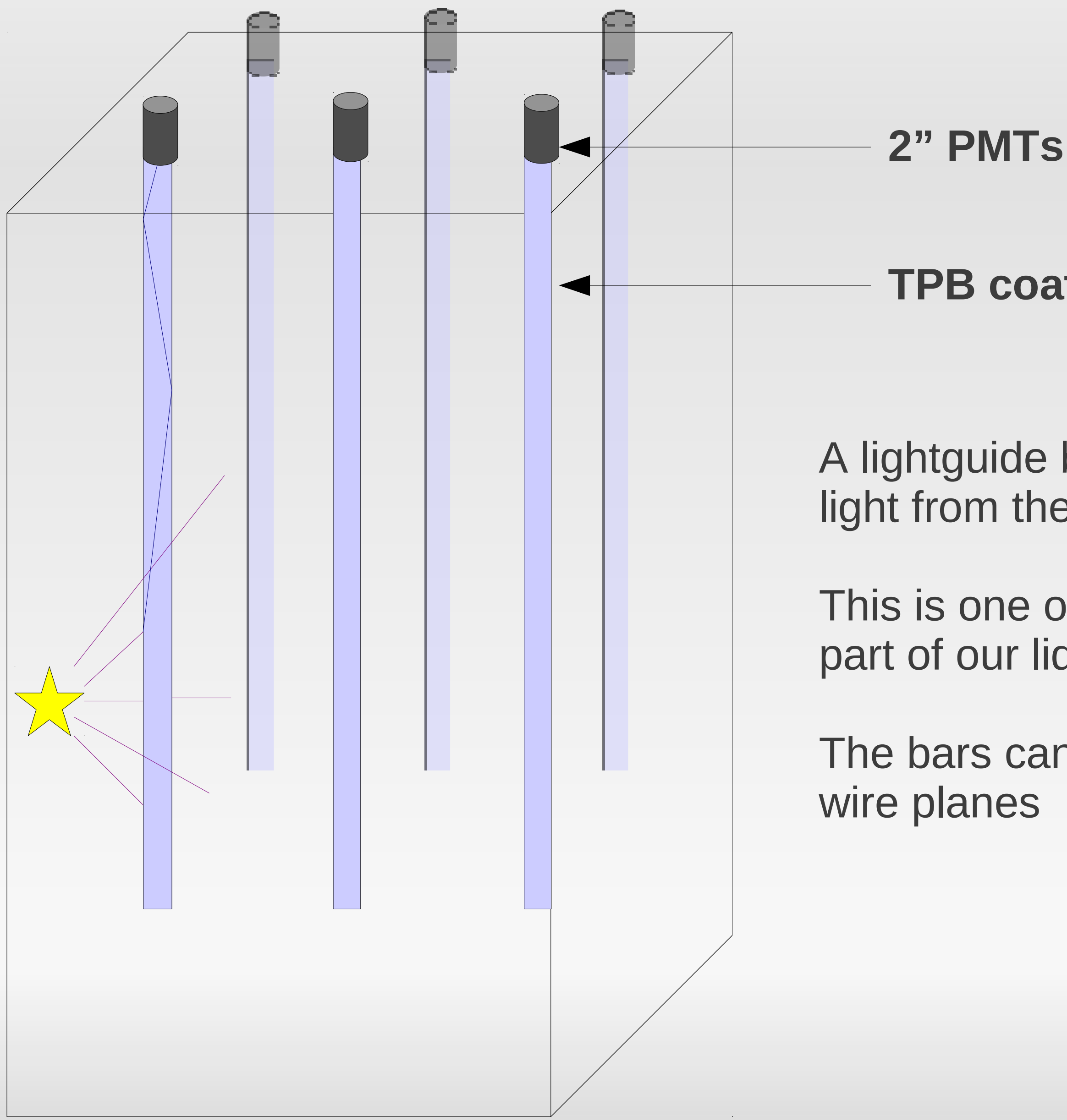
- Low solid angle
- Rayleigh scattering effects
- Bulk absorption along light path

We also cannot put PMTs inside the volume itself, as they will not work in a region of strong electric field

8” or 10” PMTs will also waste fiducial volume

Instead we require a strategy for extracting light from deep in the bulk.

A Simple Lightguide Detector

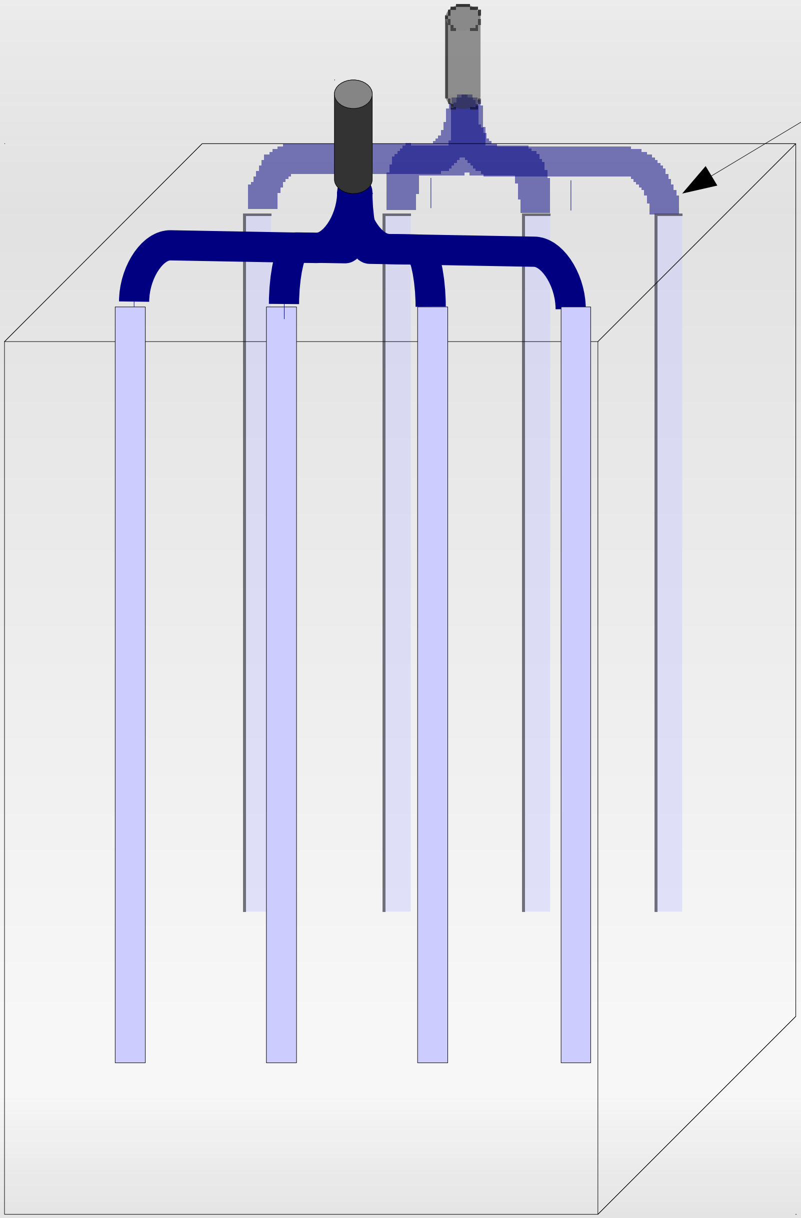


A lightguide based detector allows extraction of light from the LAr bulk.

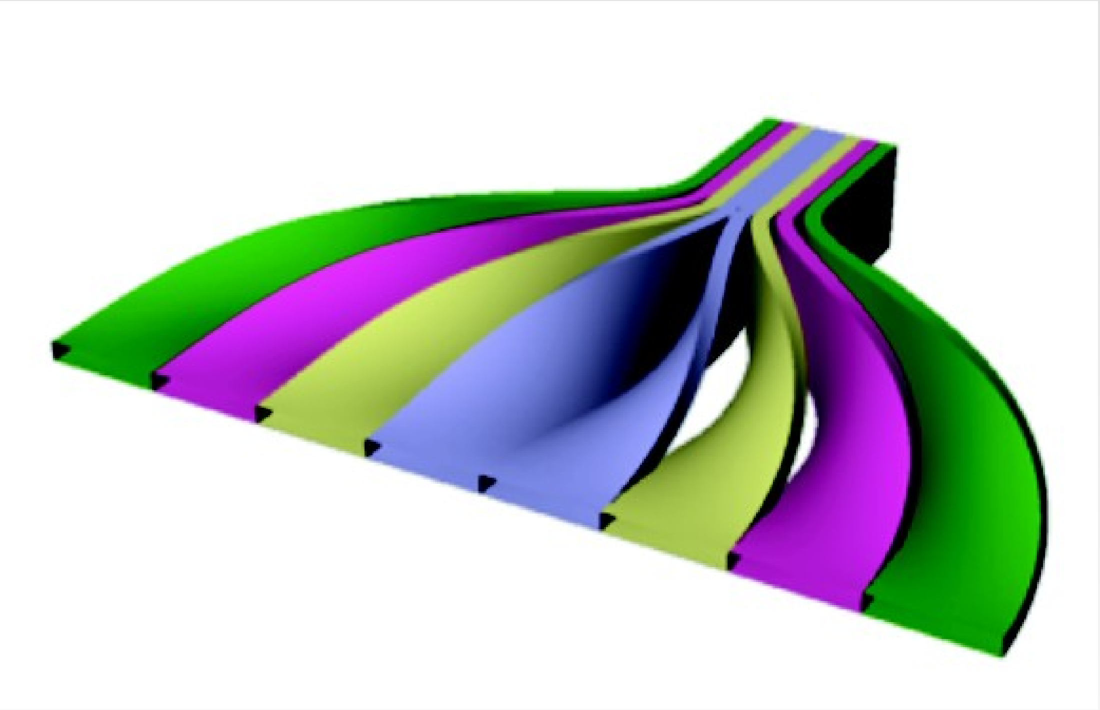
This is one of the projects we are working on as part of our liquid argon R&D work at MIT.

The bars can be slid between interspersed TPC wire planes

More Economical (Fewer PMTs)

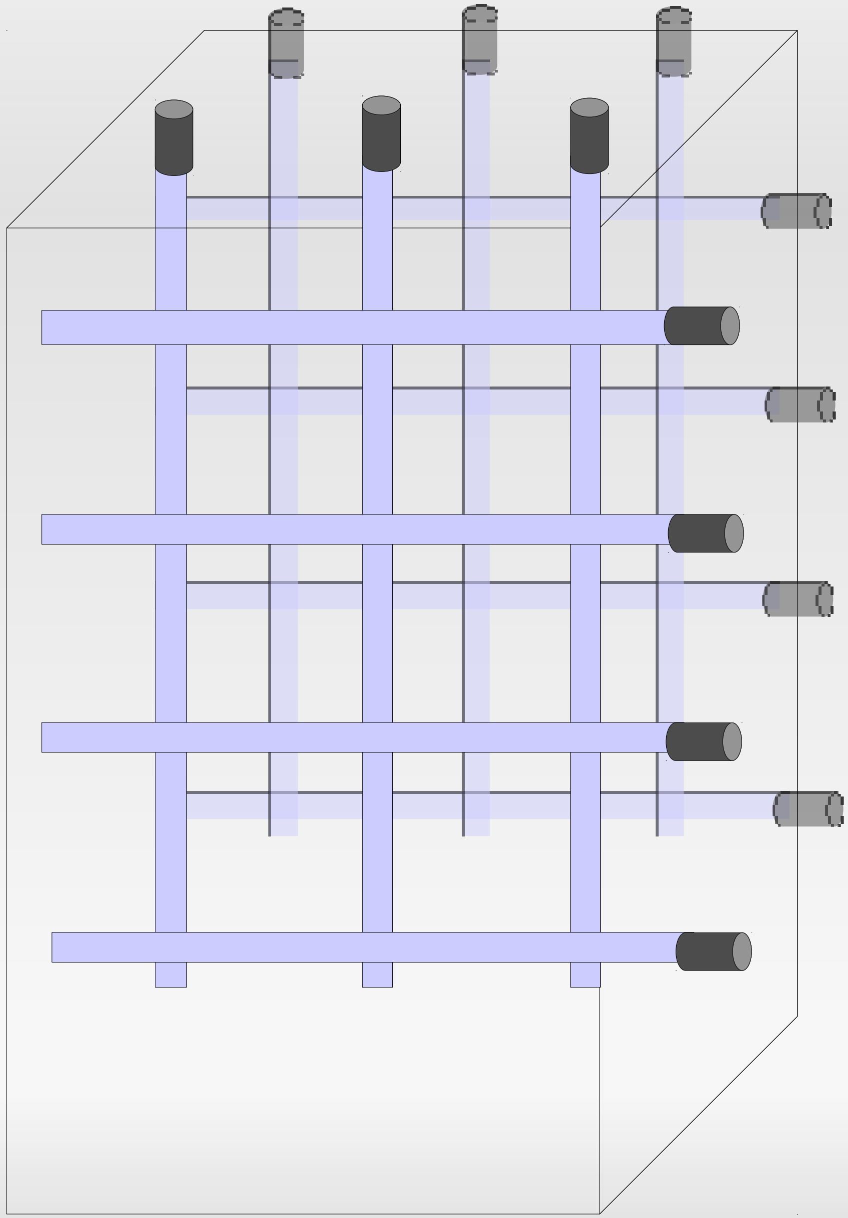


Adiabatically curved lightguides, feeding many paddles to one 2” PMT

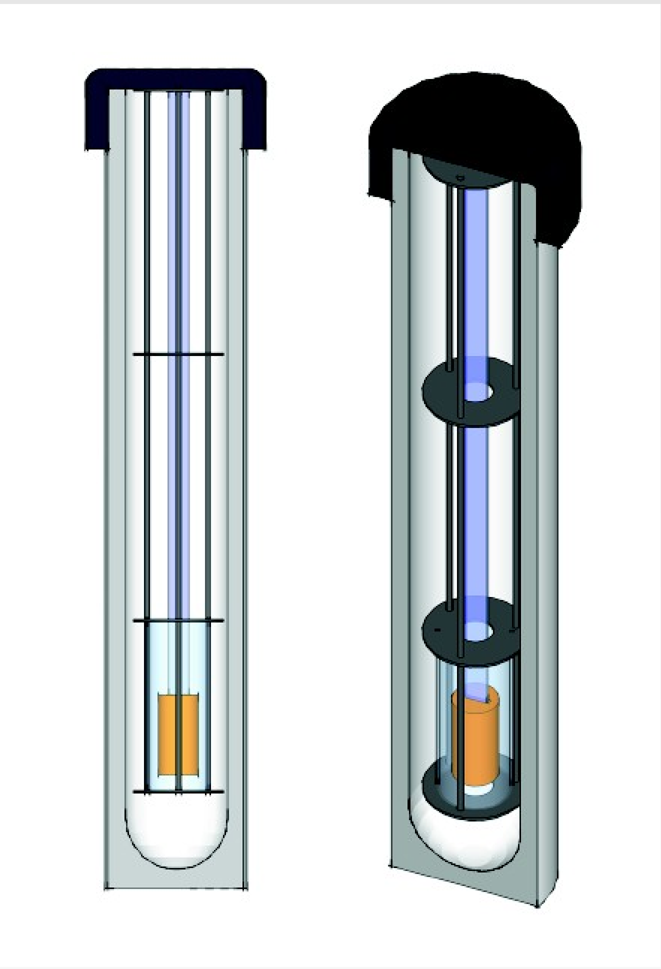


Tradeoff : less geometrical information and some light loss in curved waveguide

Etc...



The MIT Test Stand



- TPB coated acrylic rod in liquid argon filled dewar

- Movable alpha source attached a few mm from the rod. Alpha particle scintillates with a range of a few nm in LAr producing UV light.

- UV light shifted by TPB coating and transported by lightguide to the PMT at the bottom of the setup.

- A good optical connection is formed between the PMT and rod due to the natural buoyancy of the assembly in liquid argon

- No scintillation observed when LAr replaced with LN2 as expected.

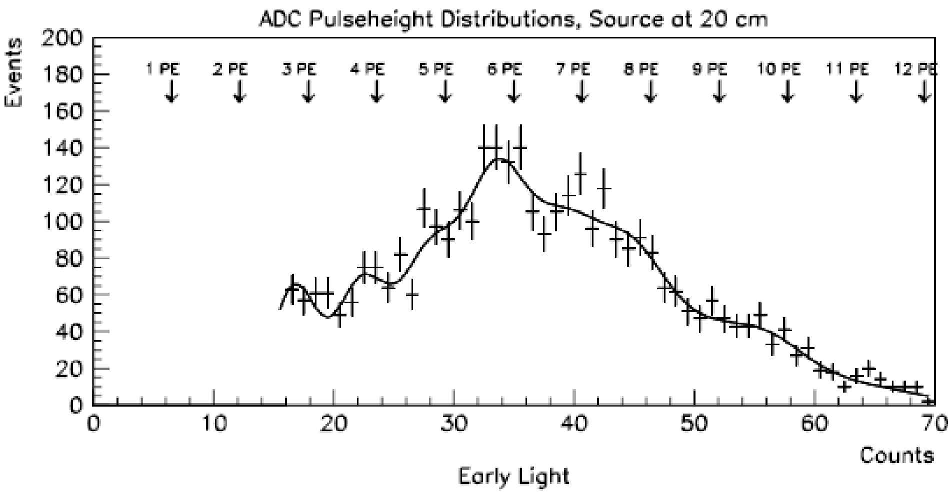
arXiv:1101.3013v1 [physics.ins-det]

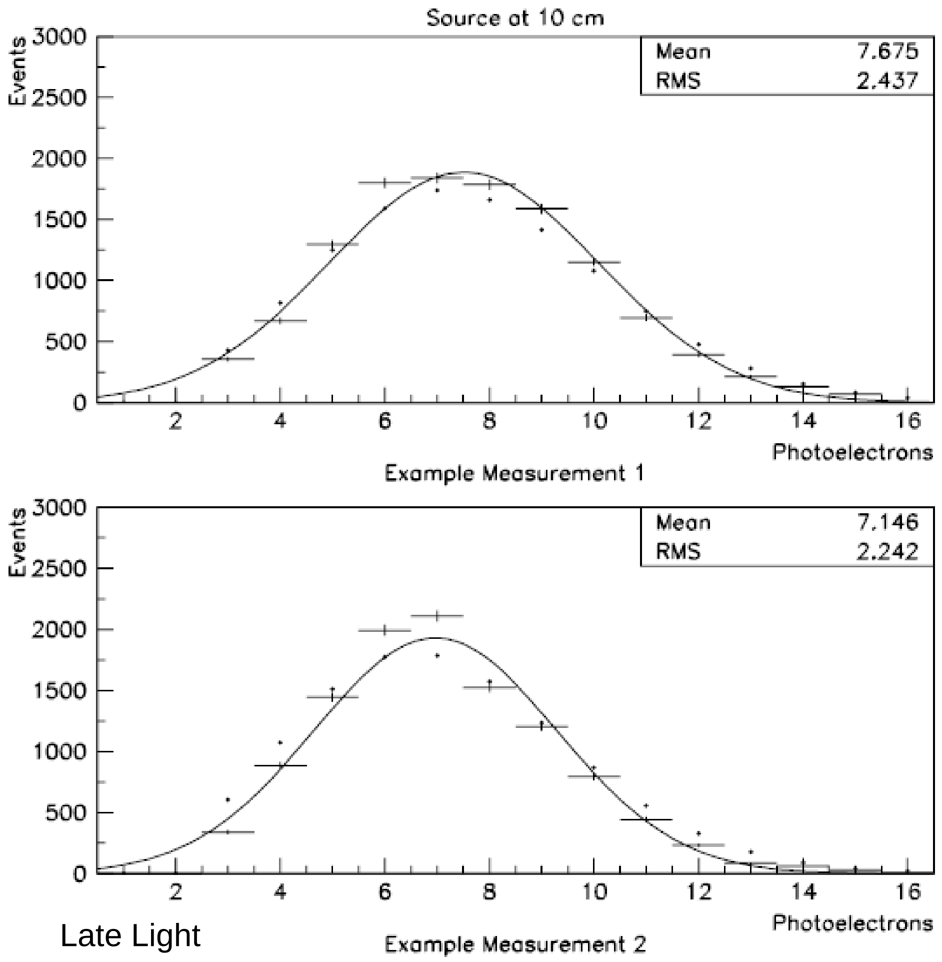
Demonstration of a Lightguide Detector for Liquid Argon TPCs

L. Bugel, J.M. Conrad, C. Ignarra, B.J.P. Jones, T. Katori, T.Smidt and H.-K. Tanaka[1]

Physics Dept., Massachusetts Institute of Technology, Cambridge, MA 02139

Test Stand Results





Late Light

- Despite using only industrial grade argon, where severe quenching of late light is expected, we see both early and late scintillation light

- By fitting gaussians to a high statistics sample, after performing pulse cleaning we can make an ADC to p.e. calibration

- Hence the number of photons striking the photocathode for each event are measured

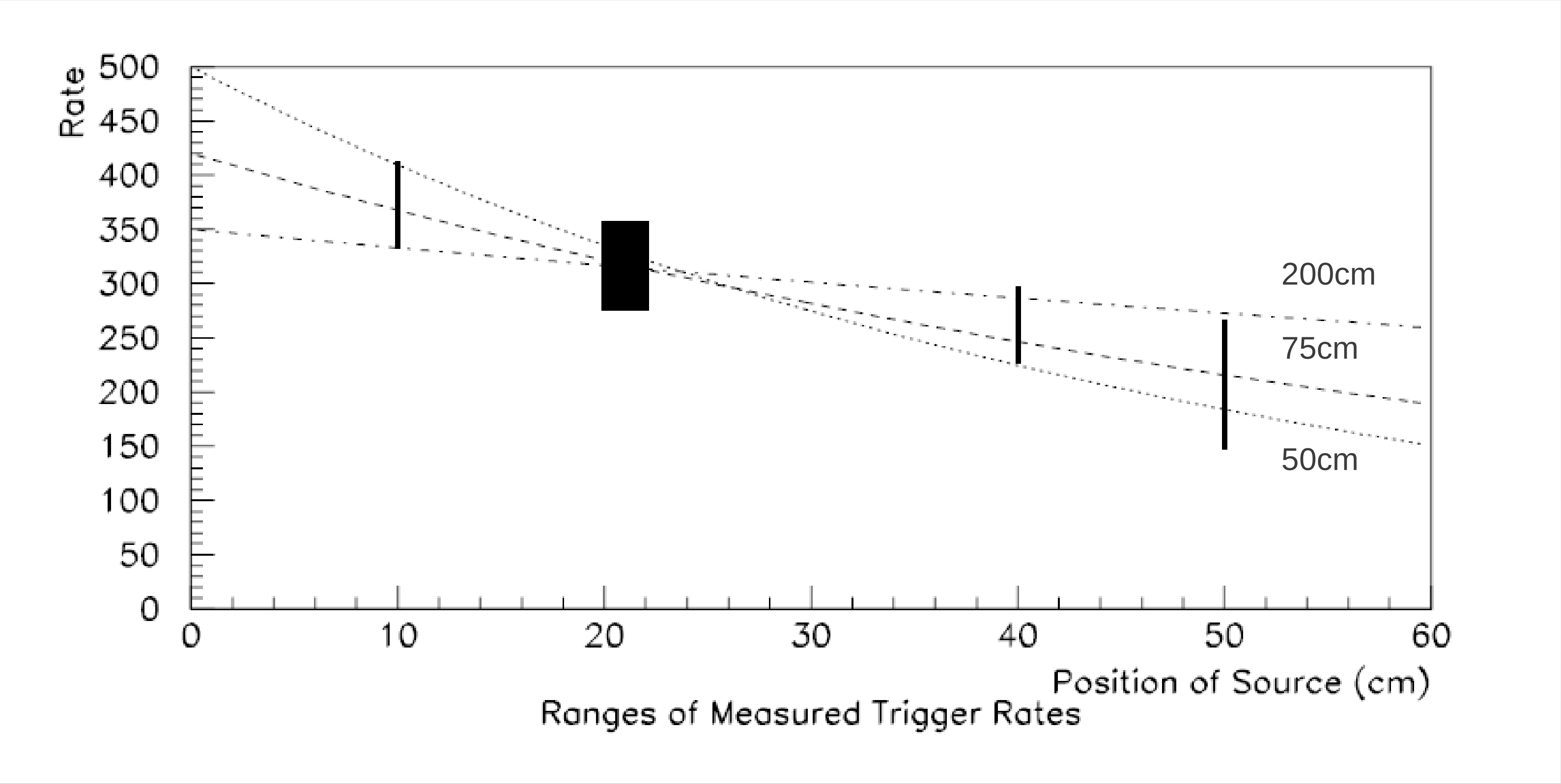
Efficiency at 10cm, and Attenuation Length

By condiering geometrical factors and various efficiencies, we can calculate the ideal performance we might expect from the system, This is **10p.e. / scintillation event**

In fact, with the source at the 10cm position, we see a mean of **7p.e. / scintillation event**

The discrepancy can be reasonably attributed to attenuation losses in the lightguide

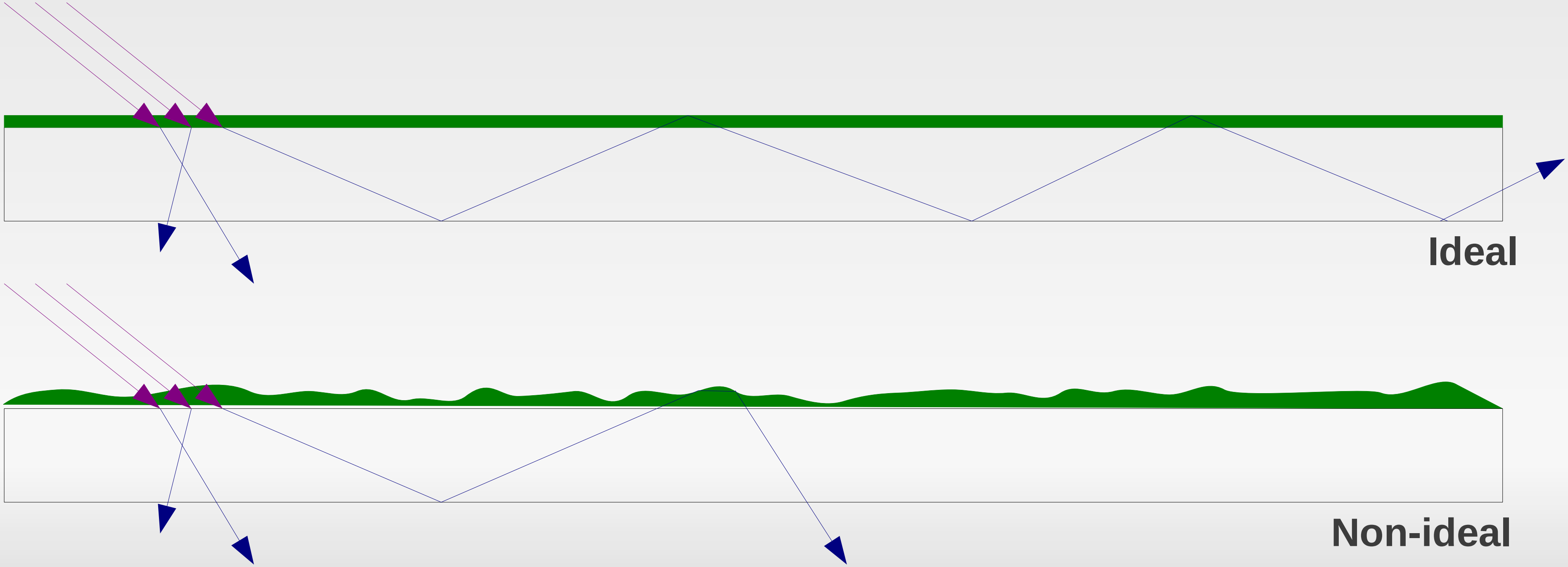
We also investigated this attenuation directly by moving the source along the bar



Areas of Development

Currently our primary focus is upon improving the optical coating quality in order to increase attenuation lenghth. We are investigating:

- Improvement of the spray method, and investigation of other surface film application methods
- Co-extrusion of TPB into the acrylic (or similar) bar at production
- Measuring and improving the uniformity of the light production along one bar, and between bars to understand coating thickness and TPB concentration flucturations



Optical Software Methods for LArTPCs

- All MicroBooNE simulations are performed within the open source LArSoft framework
- An simulation, reconstruction and analysis framework to support current and future LArTPC experiments including ArgoNeuT, MicroBooNE, LBNE, etc
- For more info, see talk on Thursday:

Studies on event reconstruction
14:30 **LArSoft** *30'*
Speaker: Dr. Eric Church (FNAL)

- We have developed two simulation packages within LArSoft

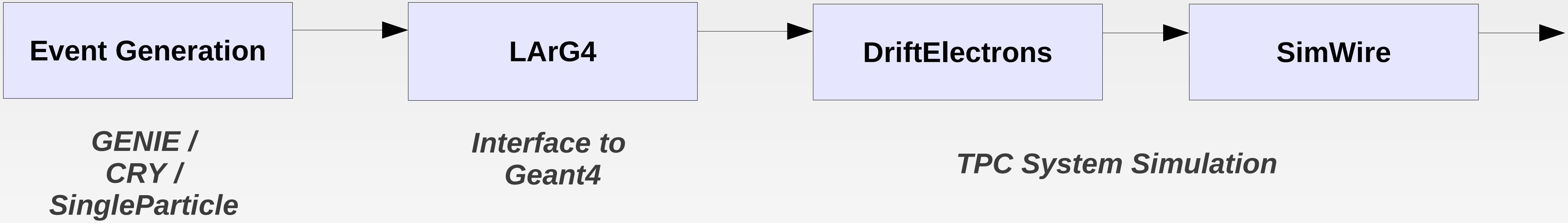
- FULL OPTICAL SIMULATION

- FAST OPTICAL SIMULATION

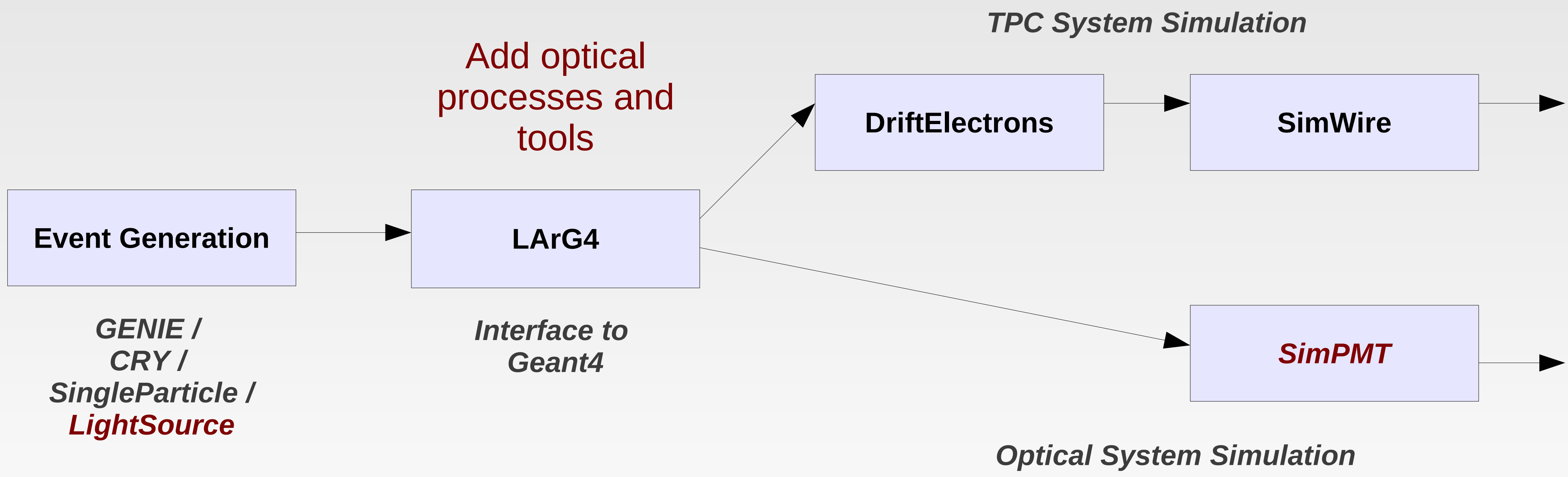
- packages
  - AnalysisExample
  - ArgoGeant4
  - ArgoNuance
  - ArgoReco
  - ArgoSimpleReco
  - CalData
  - ClusterFinder
  - DetSim
  - DriftElectrons
  - EventDisplay
  - EventGenerator
  - Filters
  - Geometry
  - Header
  - HitFinder
  - LArG4
  - LArVMC
  - MCCheckOut
  - MergeData
  - PhotonPropagation
  - RawData
  - RecoBase
  - SRT_LAR
  - Simulation
  - TrackFinder
  - Utilities
  - VertexFinder
  - setup

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



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

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

Per Boundary Type

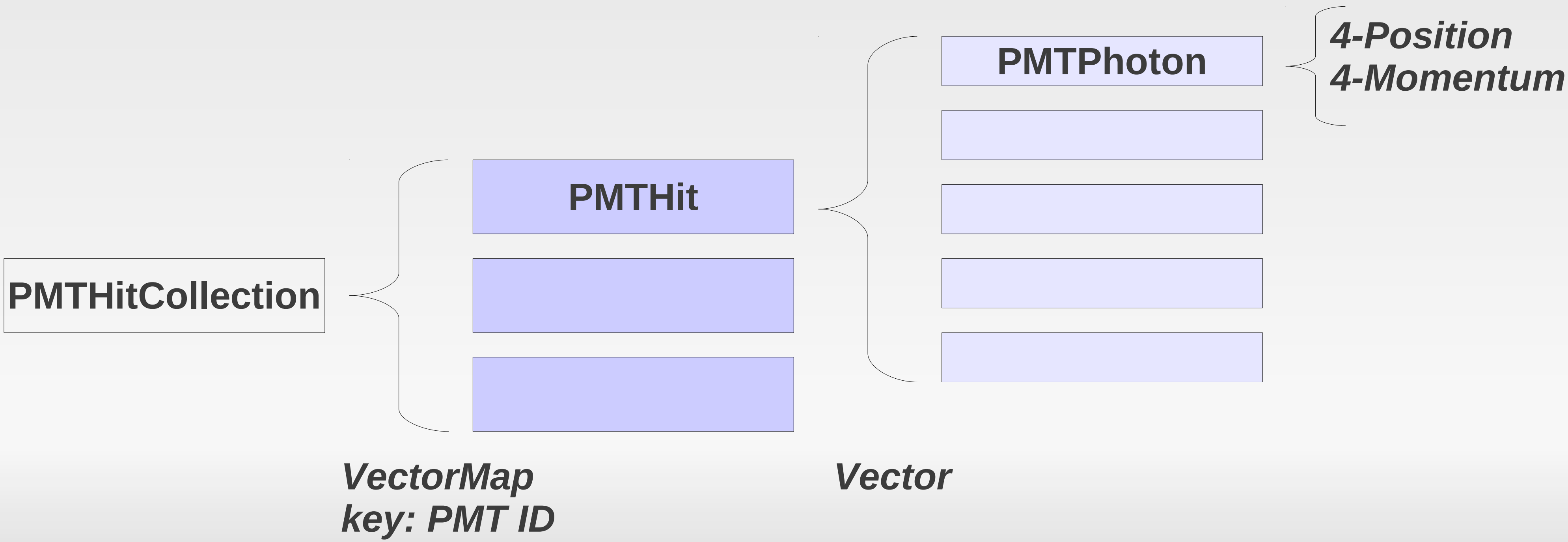
Reflections

Total Reflectivity
Fraction specular / diffuse

Wavelength dependent
Non wavelength dependent

PMTHit Data Structures

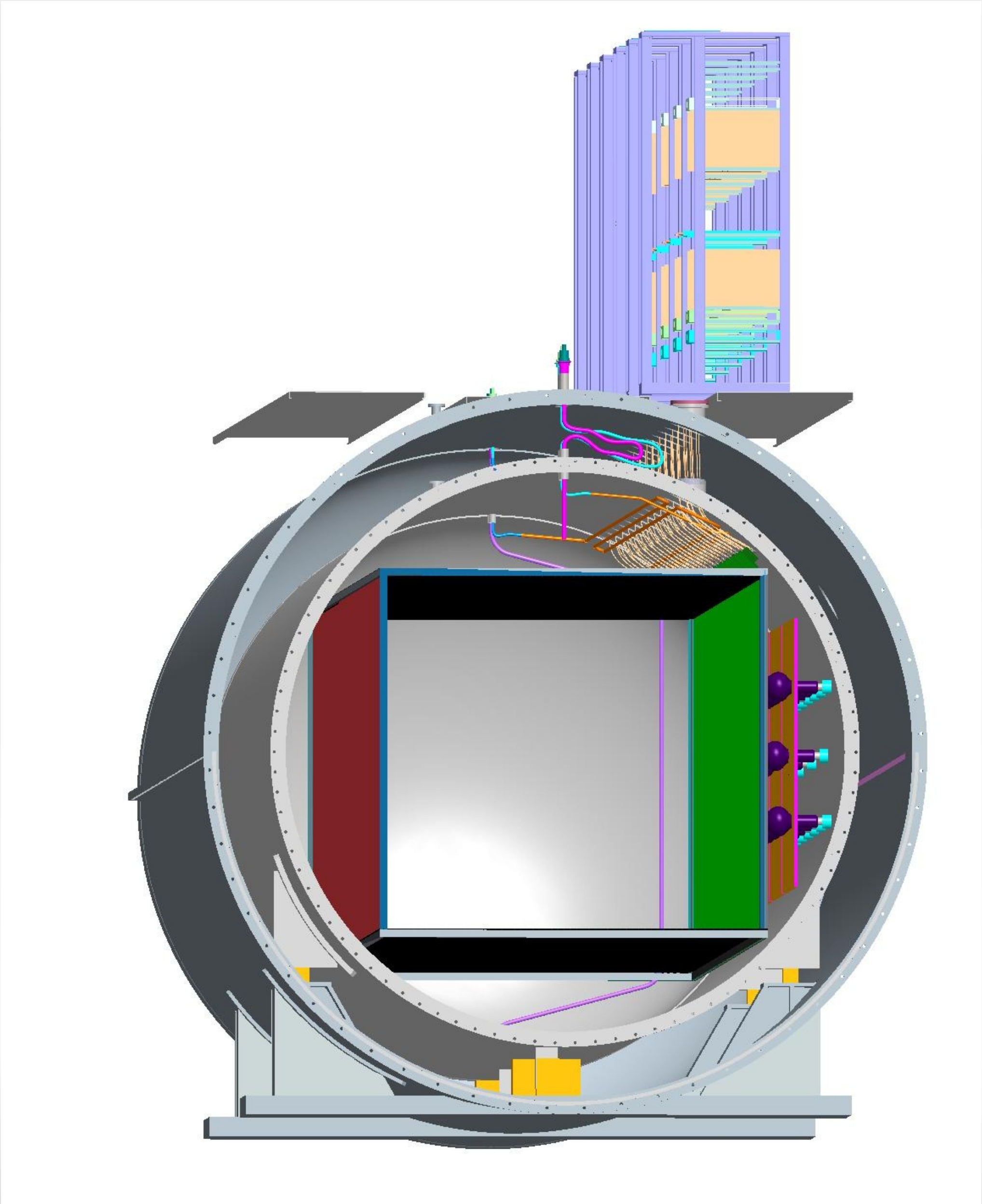
- The optical information to be passed along the simulation chain from LArG4 is contained within a PMT hit collection
- The PMTHitCollection is a set of PMTHits, one for each PMT that saw one or more photon
- Each hit is a list of 4-positions and 4 momenta of photons which stepped across the lens of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

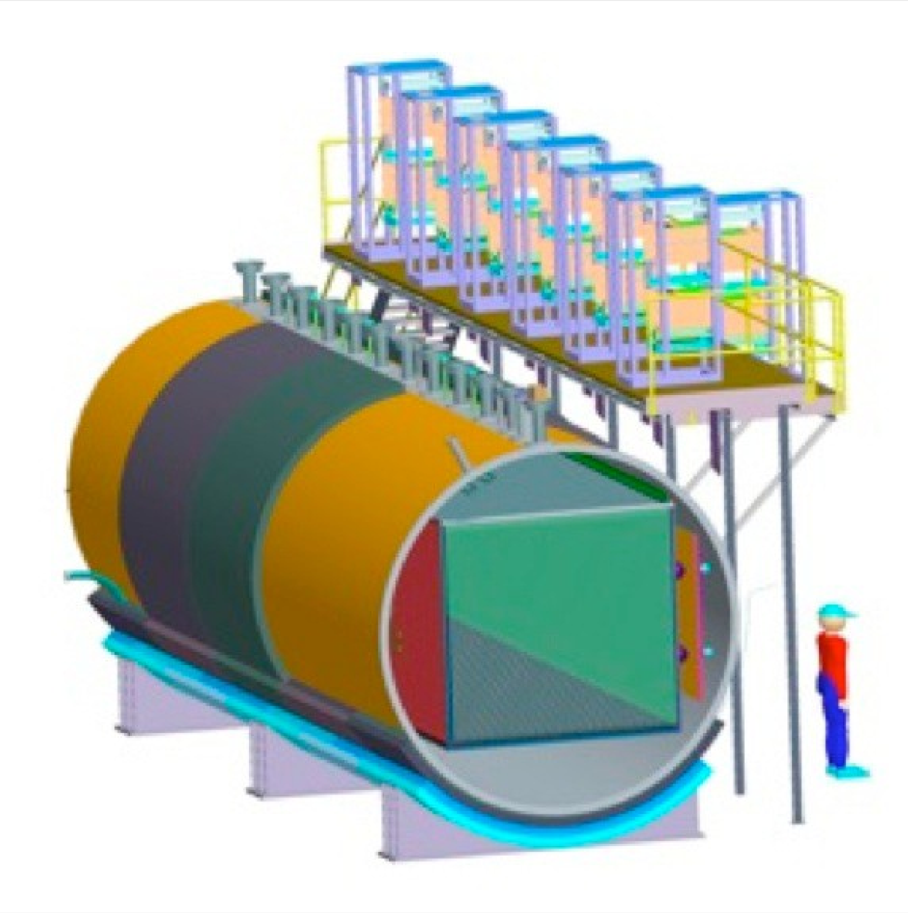


Other Components of Full Sim

- **Geometry** – Automated placement of semi-reallistic PMT assemblies in desired cryostat positions
- **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

MicroBooNE

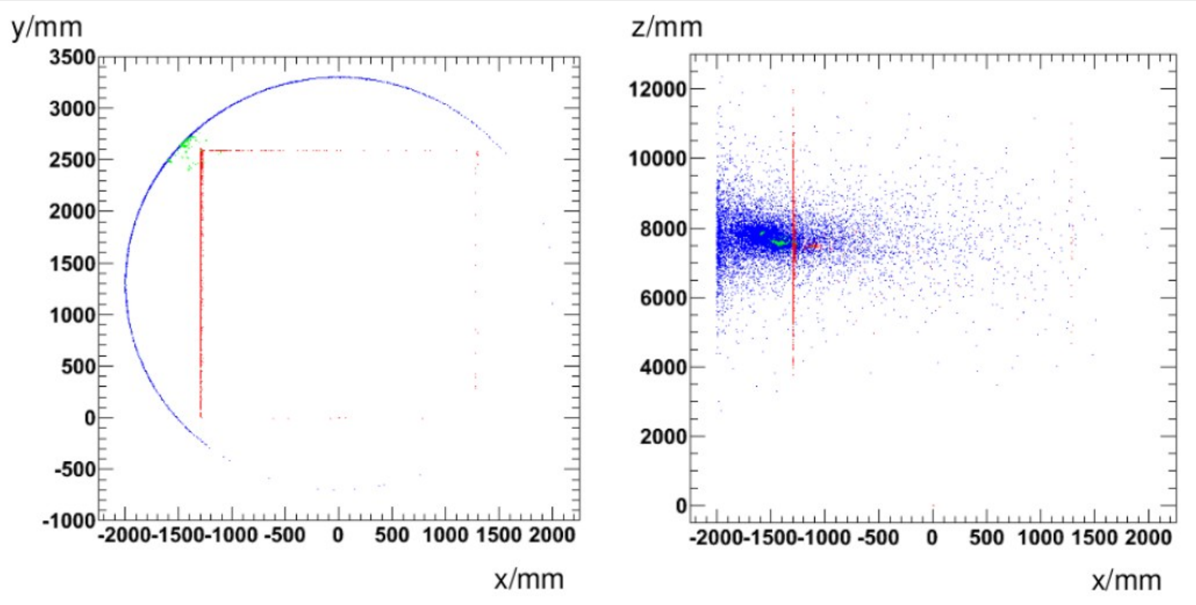


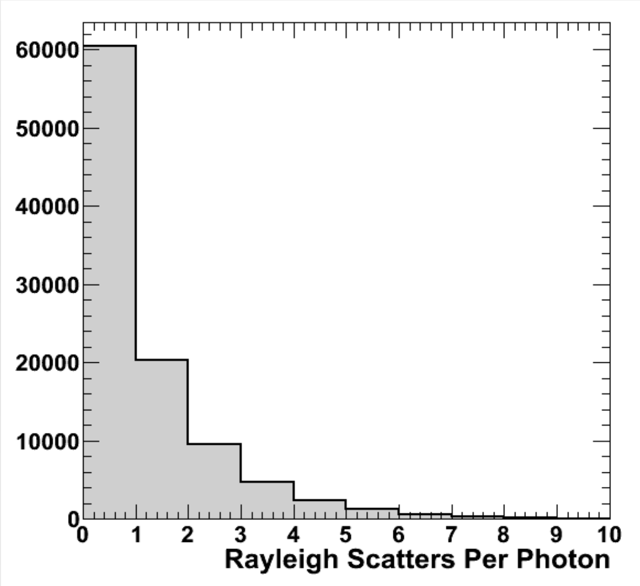


More details in this talk on Wednesday:

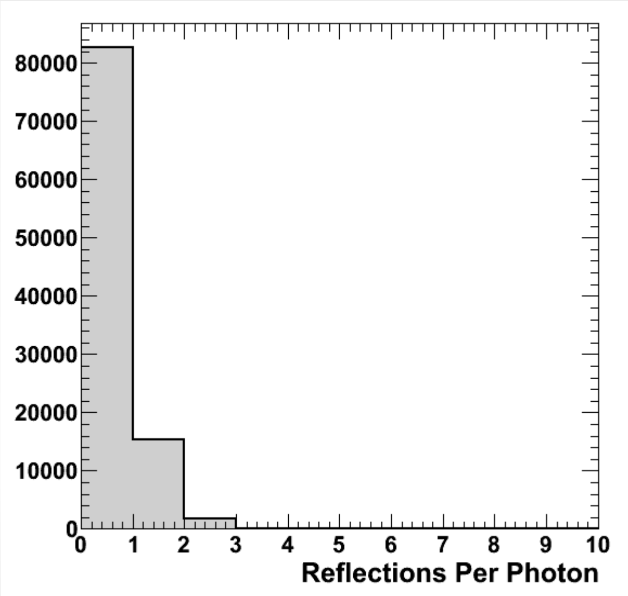
09:10	**Status of MicroBOONE** *20'*
	Speaker: Dr. Roxanne Guenette (Yale University)

A Sample Neutrino Event in LArG4



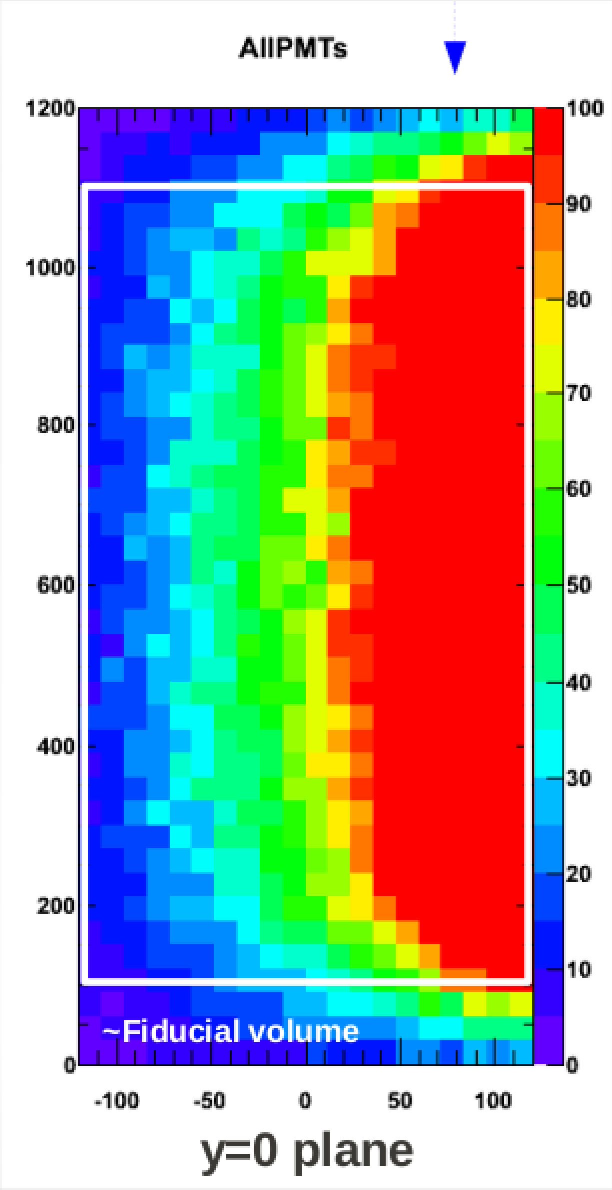


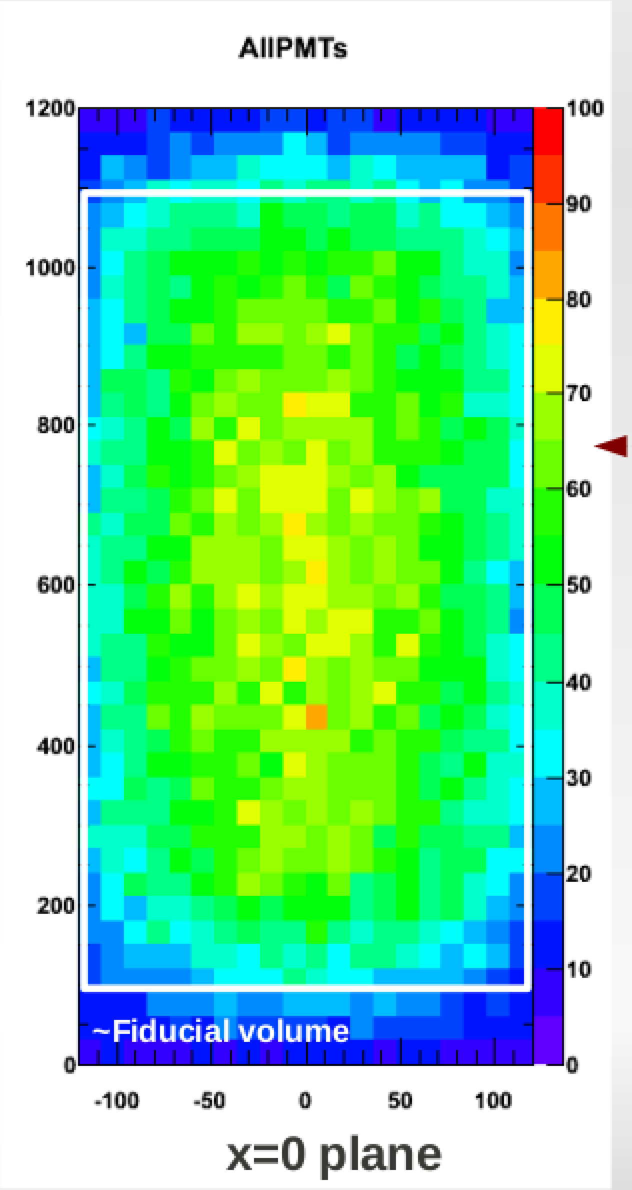
Green - Photon production
Blue - Photon absorption at surface of known reflectivity
Red - Photon absorption at surface with no reflectivity data

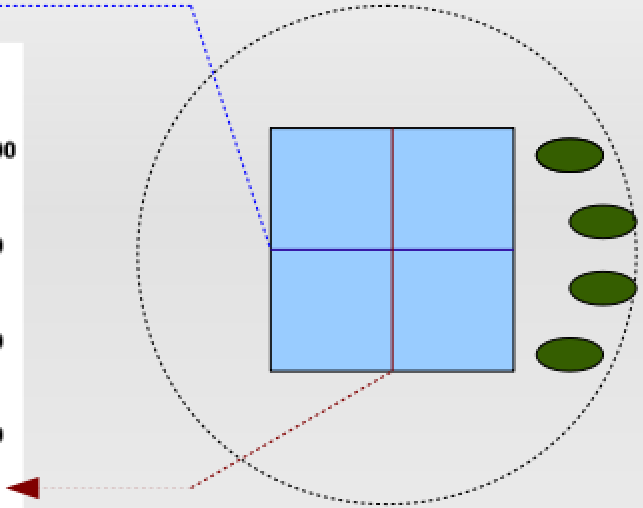


- 95161 photons were generated of which 58996 were eventually absorbed at a steel surface and 20932 were absorbed into a ”black area”
- Each photon underwent a mean of 0.76 Rayleigh scatters and 0.19 reflections

Sensitivity Maps







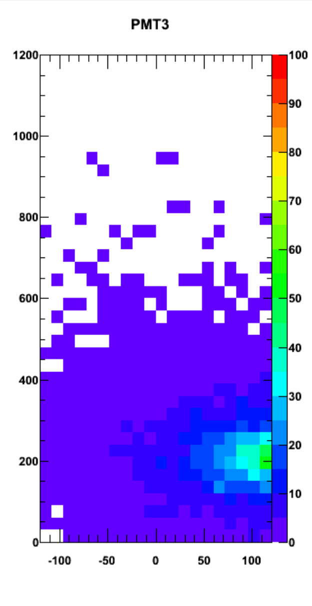
Number of photoelectrons summed over all PMTs for point source of **5MeV** equivalent at different detector points

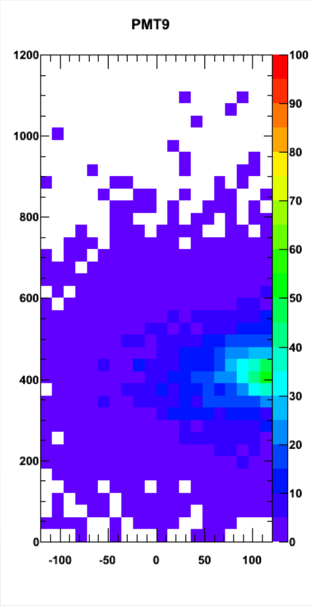
Trigger should be possible on 1 p.e. We are sensitive at all points on these plains within fiducial volume.

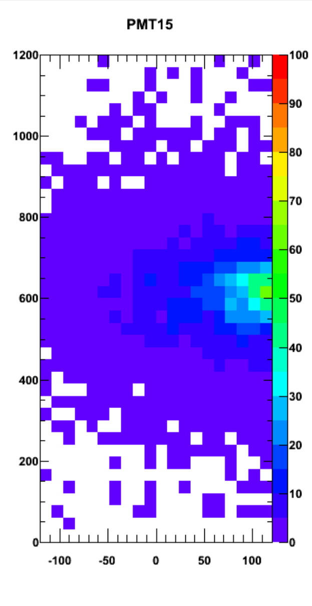
Other MicroBooNE Optical Studies in LArSoft

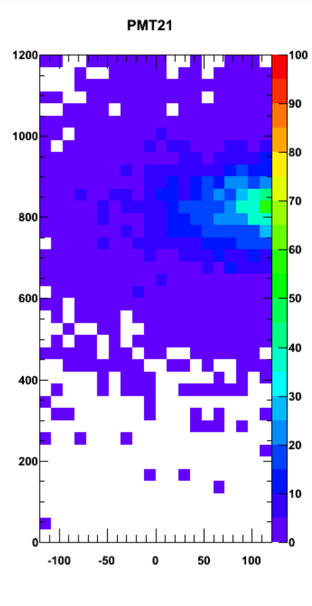
We have performed numerous other studies for MicroBooNE using the new optical modules:

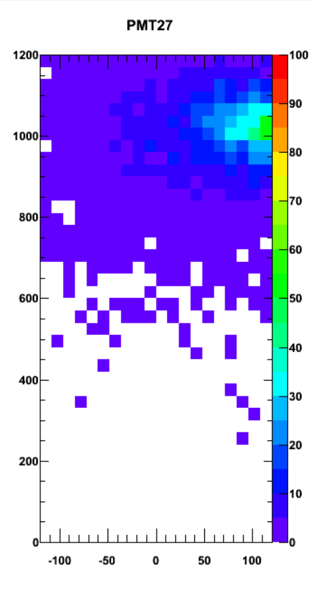
1 – PMT by PMT coverage study
2 – Optical system redundancy test
3 – Effect of wire placement upon light detection efficiency
4 – Support rack design optimization
Etc, etc...





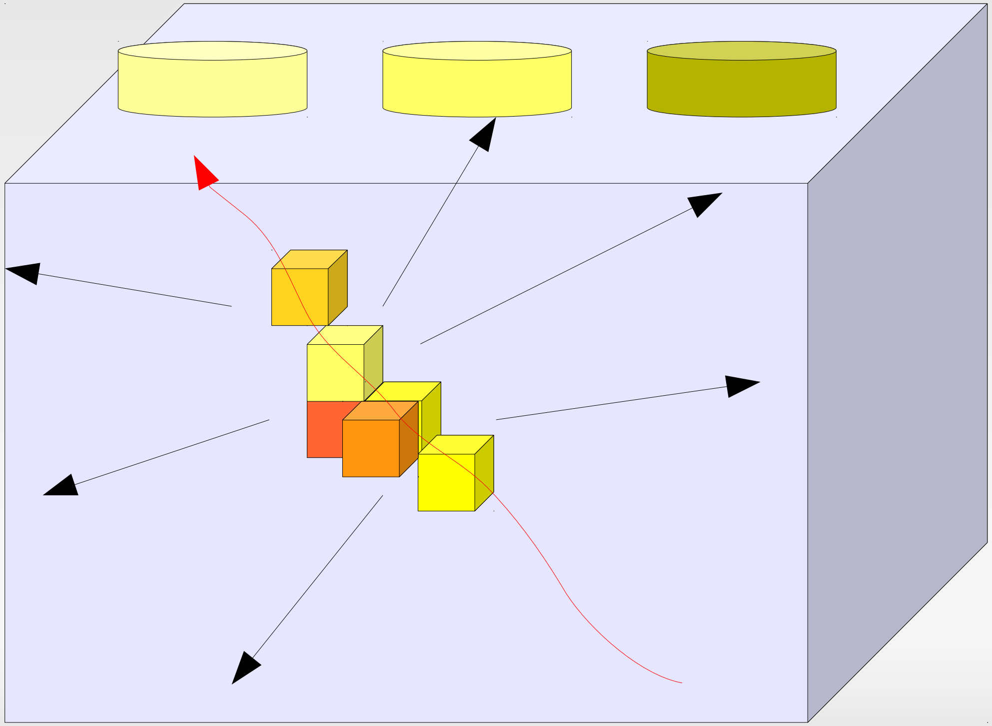






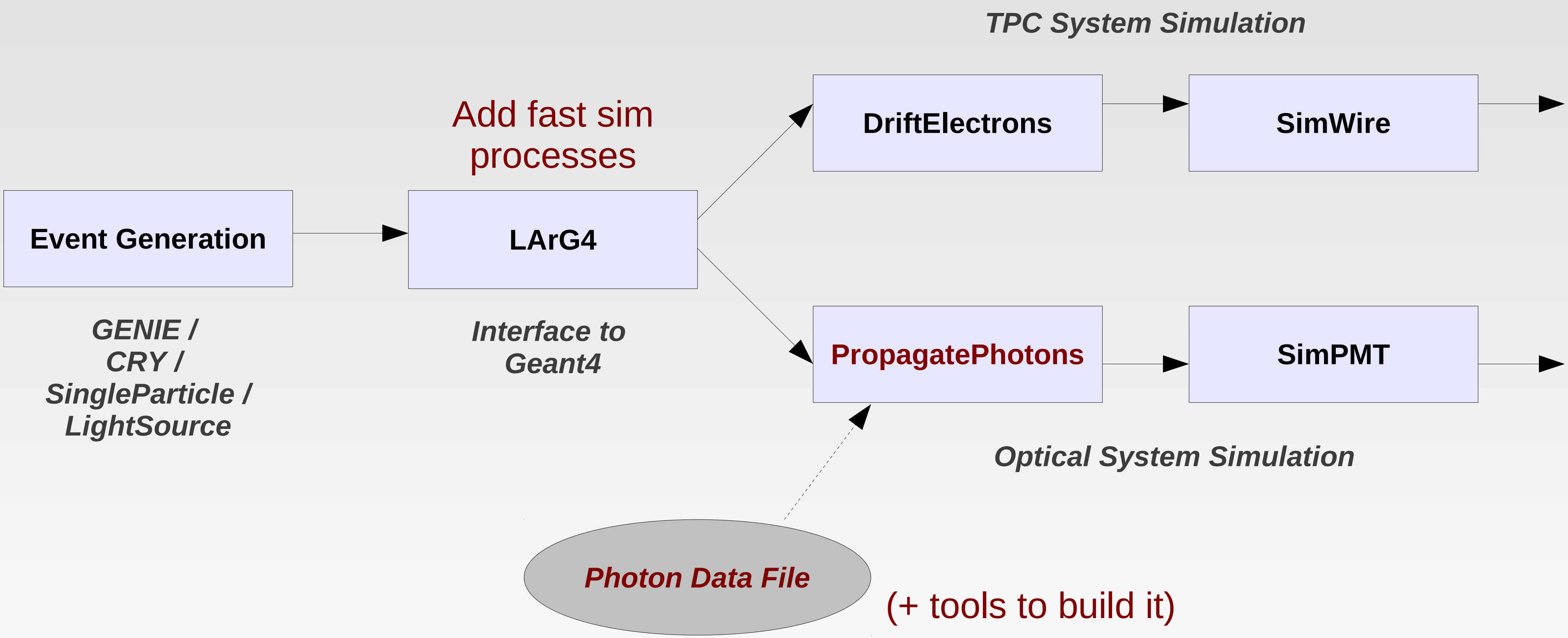
Fast Simulations and Photon Library Sampling

- 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



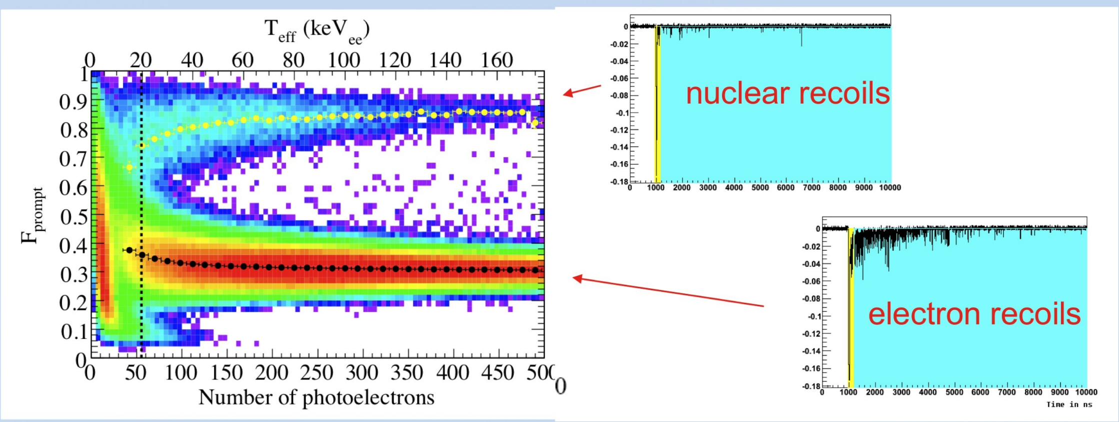
- During the standard simulation chain, we note the photon production in each volume element
- We then sample a representitive set of PMTHits, smeared by the photon production time distribution
- Library building is computationally intensive, but sampling is fast
- Both library building and sampling modules can be used for a general optical detector ”out of the box”

LArSoft Fast Sim Chain



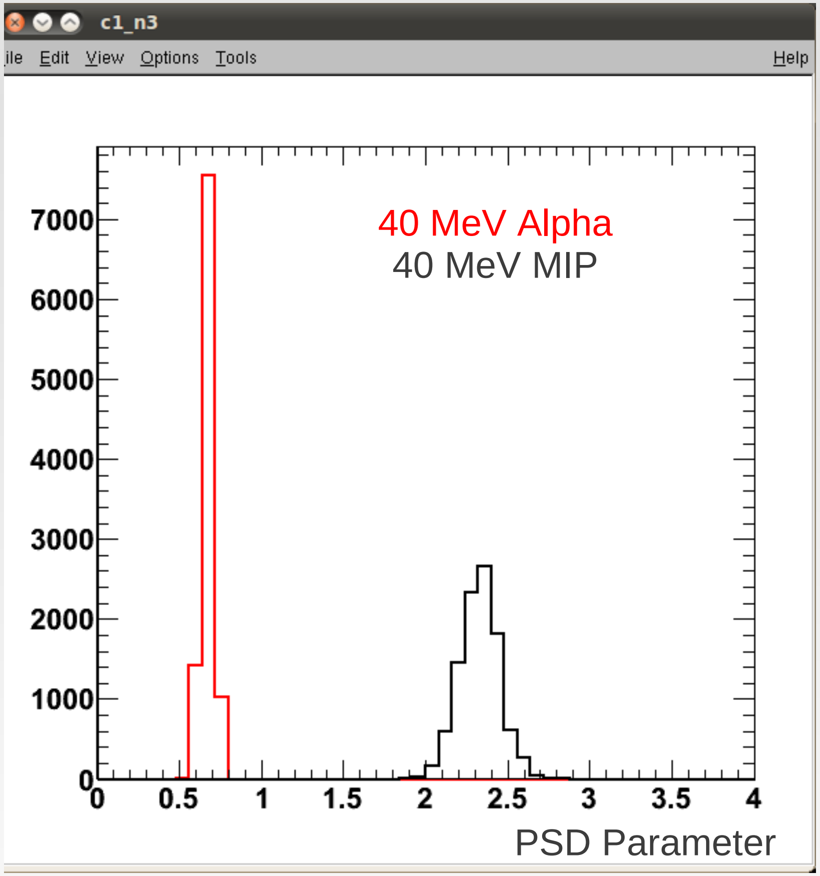
Reconstruction Applications

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



Example of PSD as applied in MicroBooNE (alpha particles vs MIPs)

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, solar neutrinos?, etc)

Summary

- Any GLA detector requires an optical system in order to correctly reconstruct charge deposits along tracks
- Such a system also helps triggering and may provide reconstruction information
- We have been developping lightguide based optical systems with a GLA detector in mind, and have performed proof-of-concept tests using our test stand at MIT
- Code to run simulations for the optical systems for the MicroBooNE experiment has been written in the open source LArSoft framework. The majority of this code is usable ”out of the box” for any optical experiment
- A fast simulation package is also available for running optical simulations during normal LArTPC sim jobs
- Reconstruction applications are under investigation – we expect to begin exploring these in a serious way this summer.

PMT Assemblies

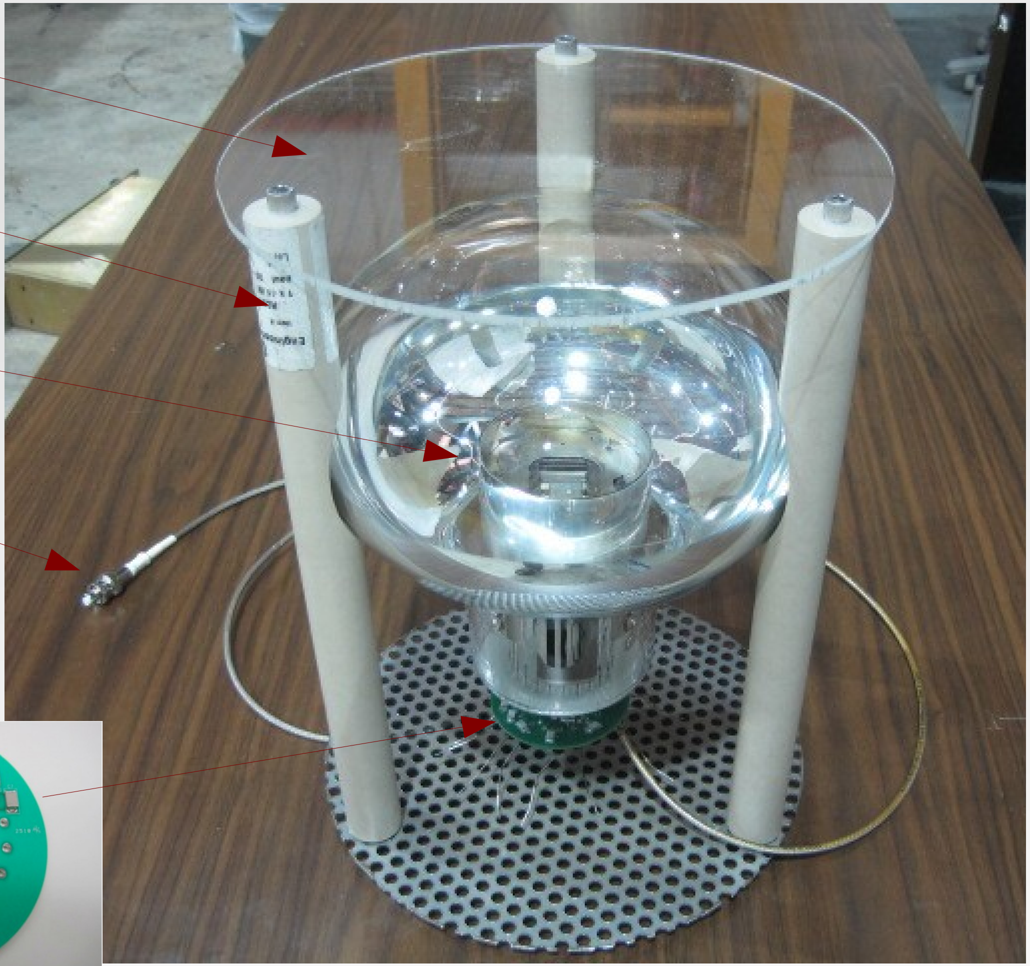
TPB coated acrylic plate

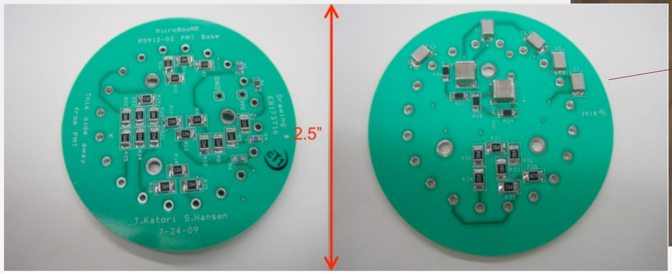
PEEK supports

8” Cryogenic PMT

Combined HV and Signal Cable

Specially designed cryogenic base



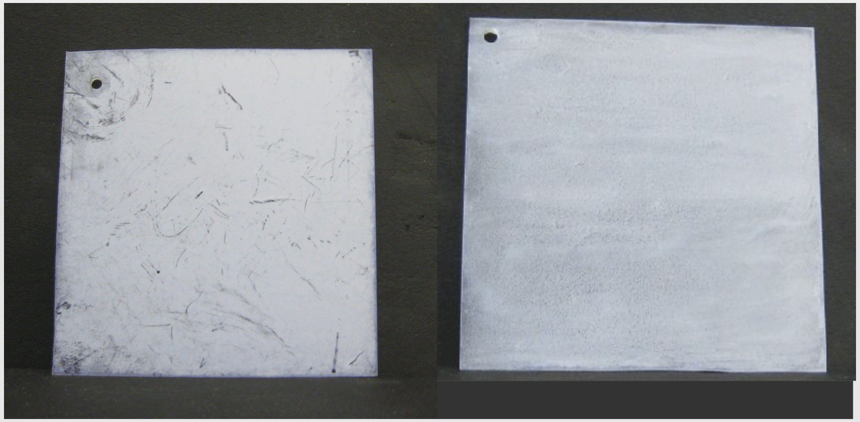


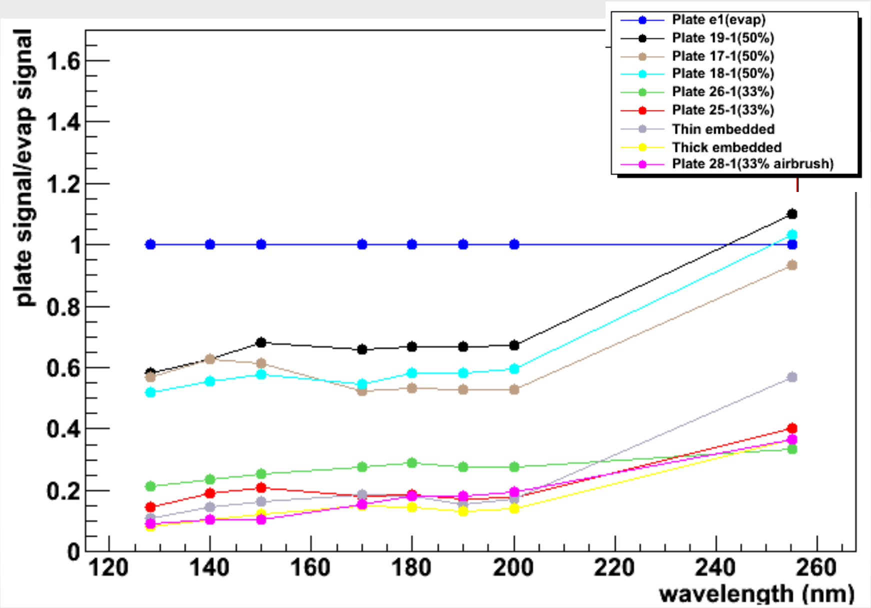
MicroBooNE base

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

WLS Plates

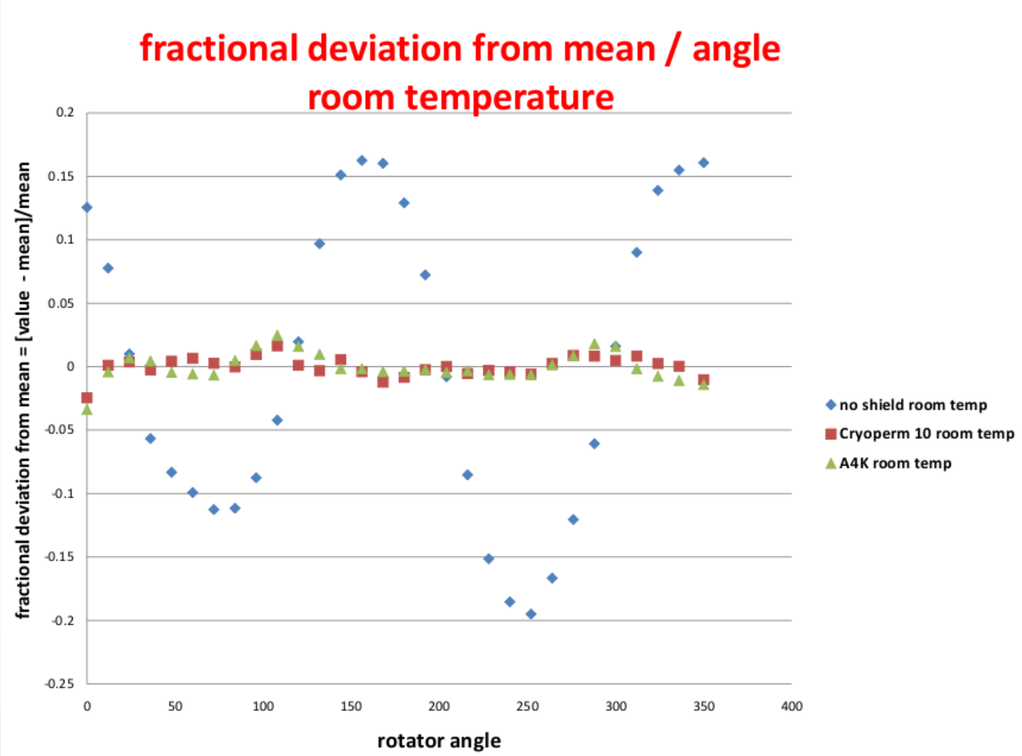
- We have performed extensive R&D into the development and optimization of the wavelength shifting plates
- Various factors at play :
  - *Coatings must be robust in liquid argon*
  - *Want to achieve a high uniformity*
  - *Even more important : high reproducibility*
  - *Water absorption into coating 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

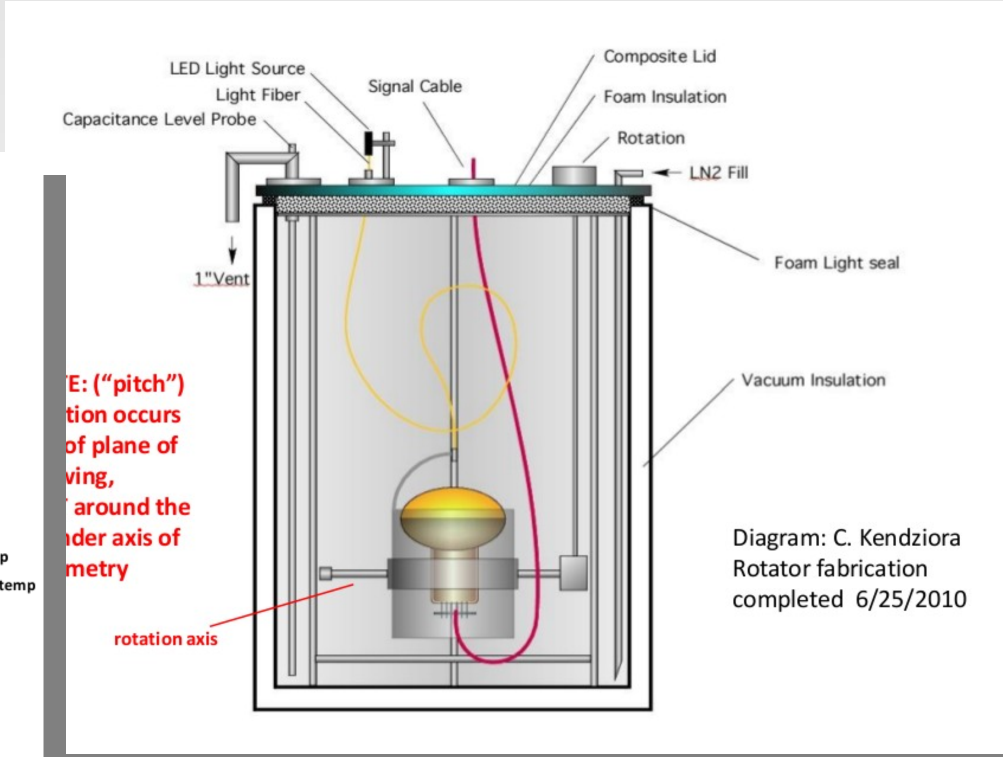




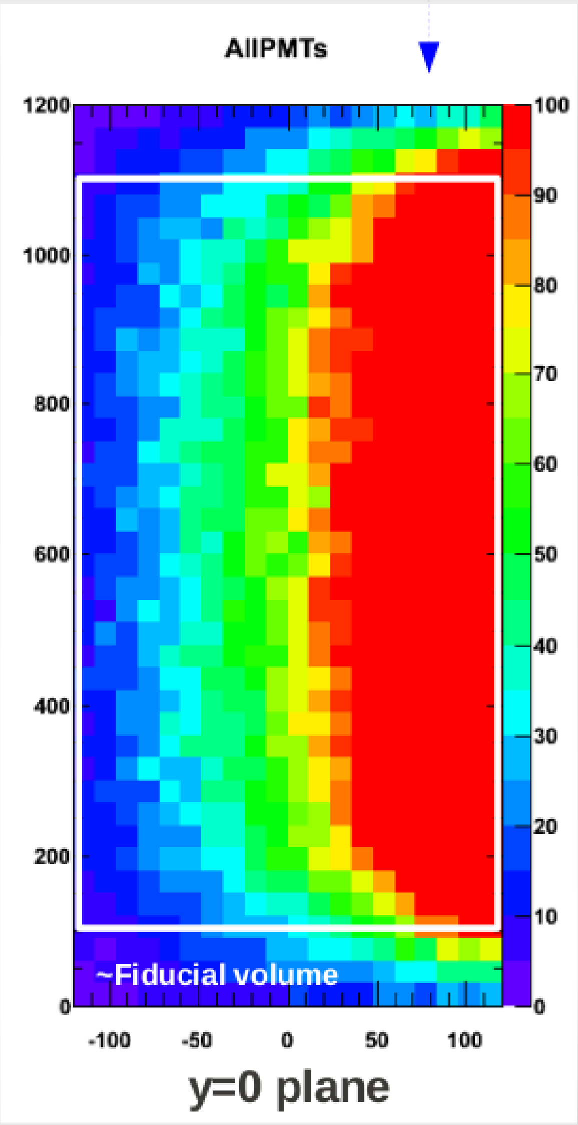
Magnetic Shielding

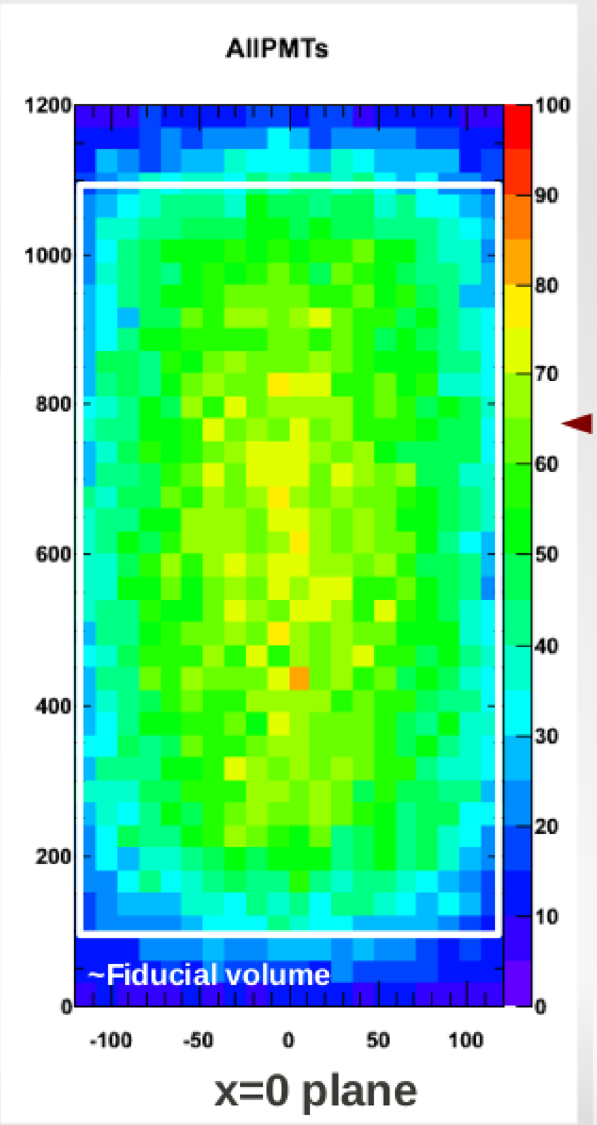
- We are also exploring the possibility of magnetically shielding the PMTs with mu-metal surrounds to reduce noise levels from external B fields
- This is a recent addition to the project and R&D is ongoing. So far results look great!





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

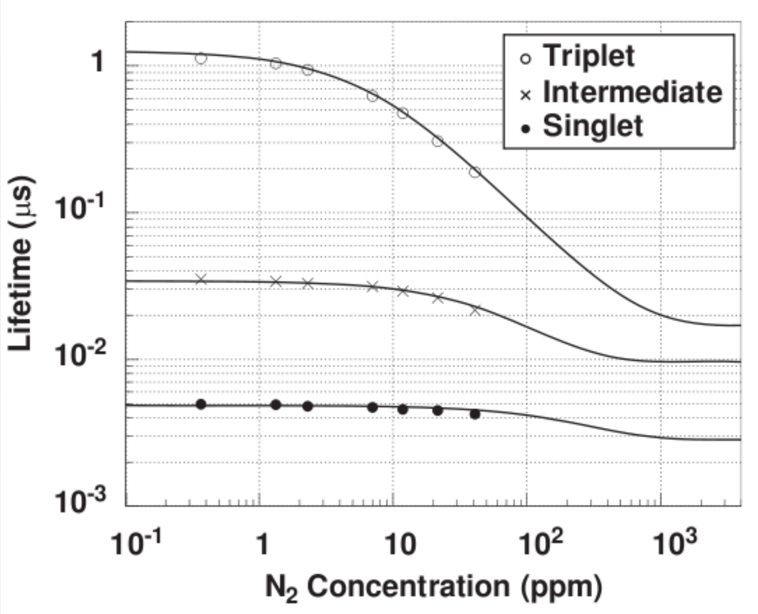
But getting a charge measurement for the fast component will require good PMT linearity for a high photon yield

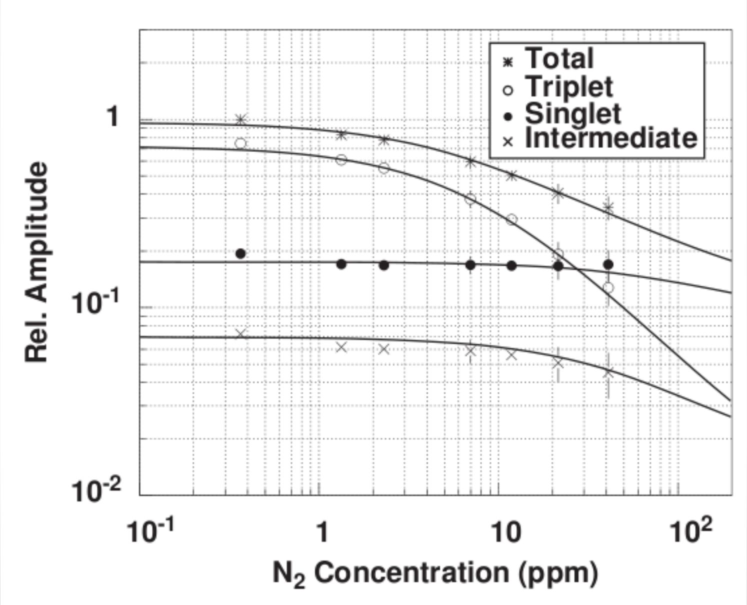
Preliminary measurements suggest good charge linearity up to 100 p.e.

To answer : how high in energy is PSR important?

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

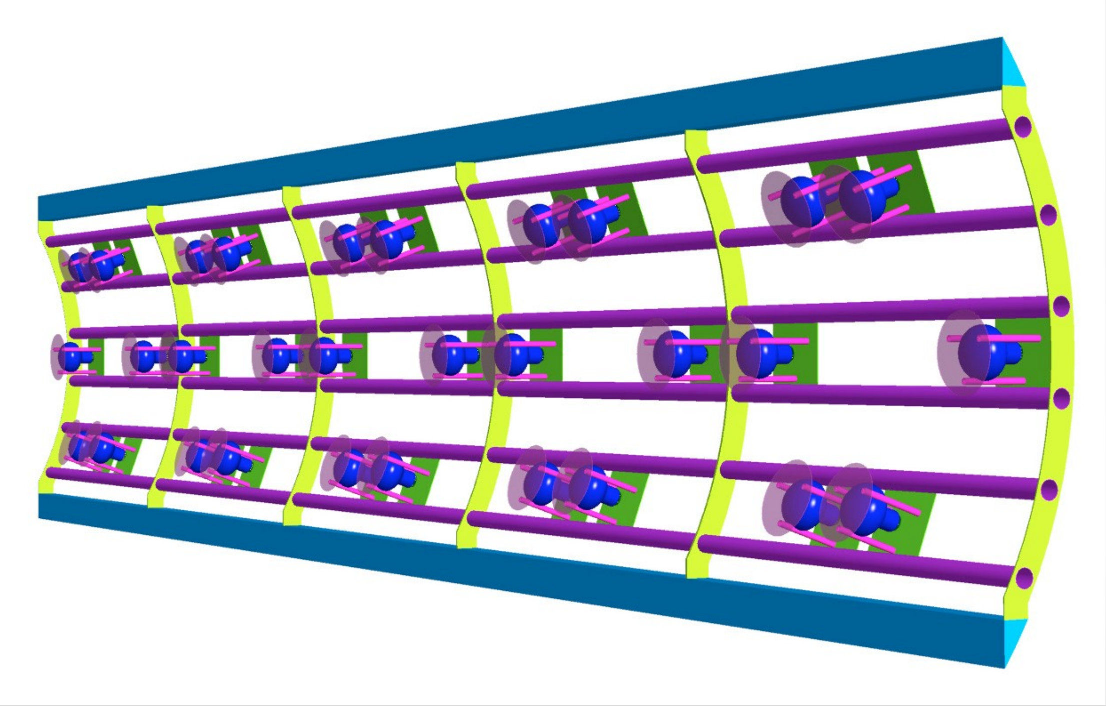
- The argon in MicroBooNE has slightly less strict purity constraints than in argon dark matter experiments
- Nitrogen and oxygen impurities both quench scintillation light. As with recombination quenching, slow light is quenched more strongly.
- Oxygen impurities are tightly controlled in MicroBooNE 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

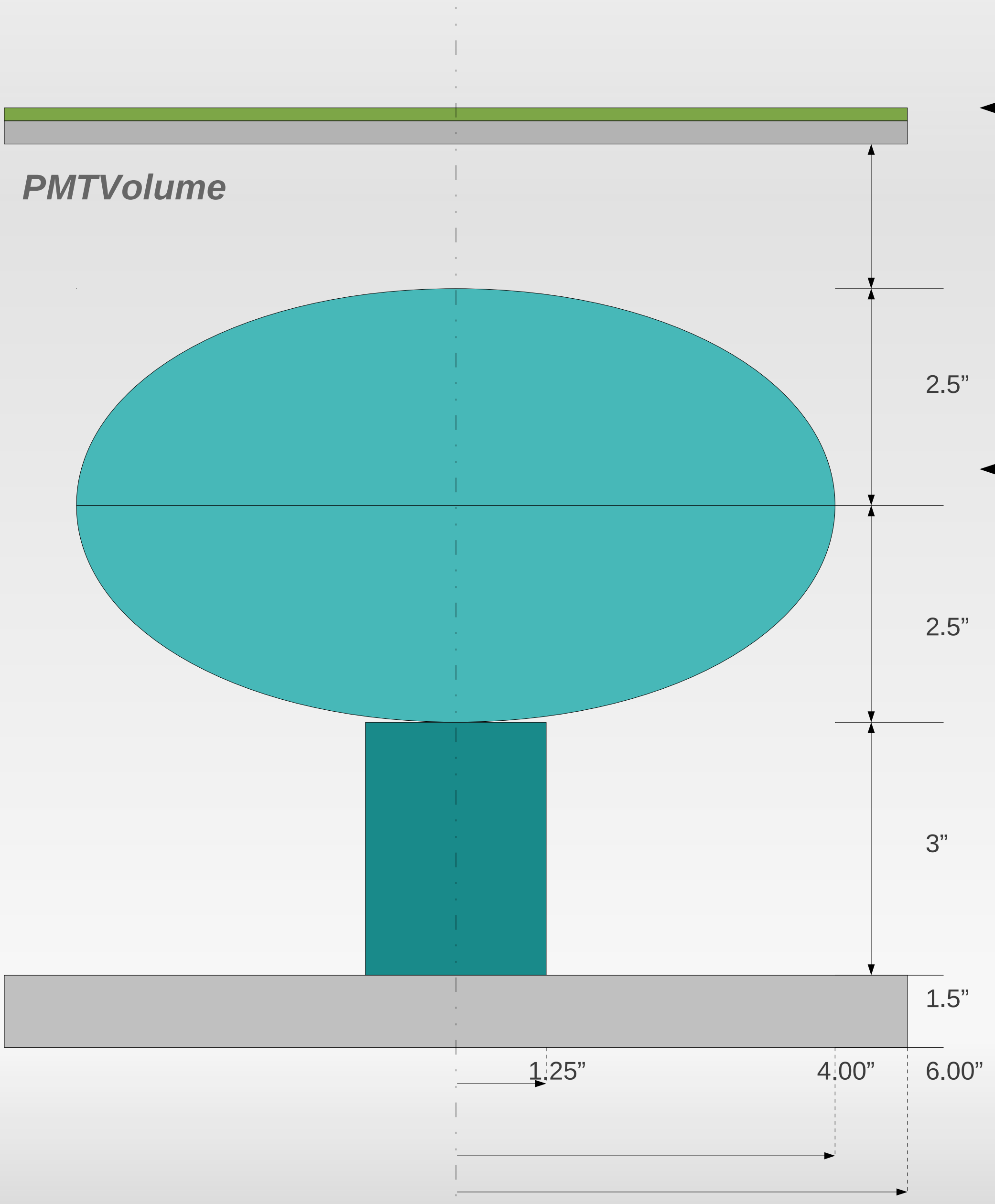
Shape:
Cylinder

Material:
Solid Glass

6) PMTSteelBase

Shape:
Cylinder

Material:
Stainless Steel



1) TPBCoating

Shape:
Cylinder

Material:
TPB

Physics:
OpWLS Process in OpticalPhysics constructor

3) PMTLens

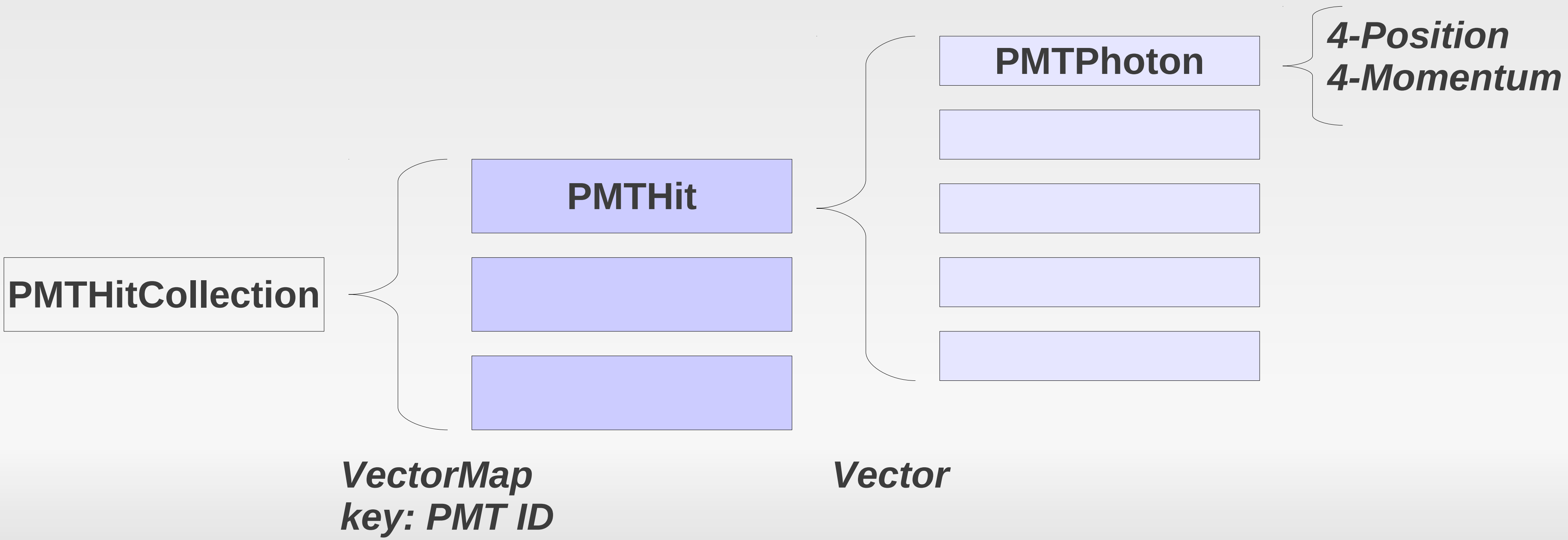
Shape:
Ellipsoid

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:

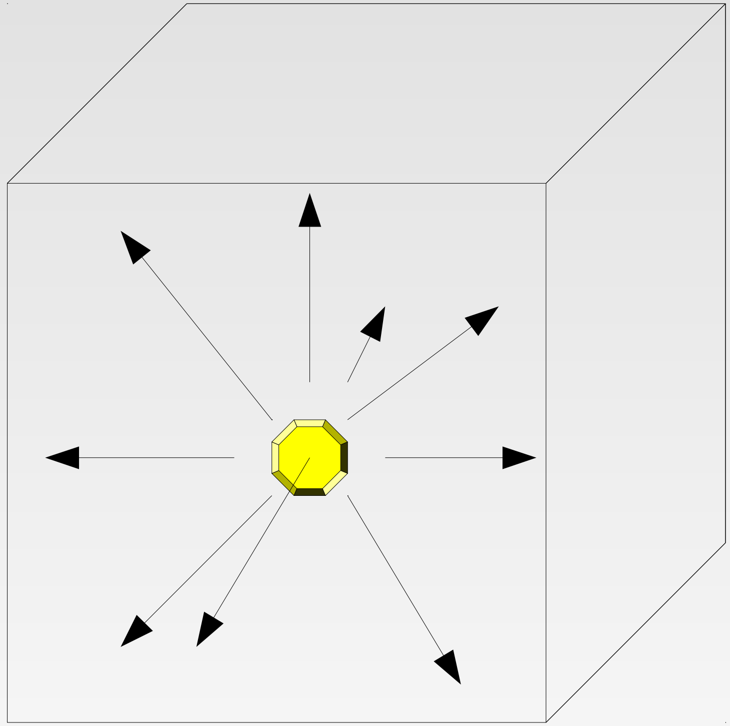
  - Scan Mode

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

  - File Mode

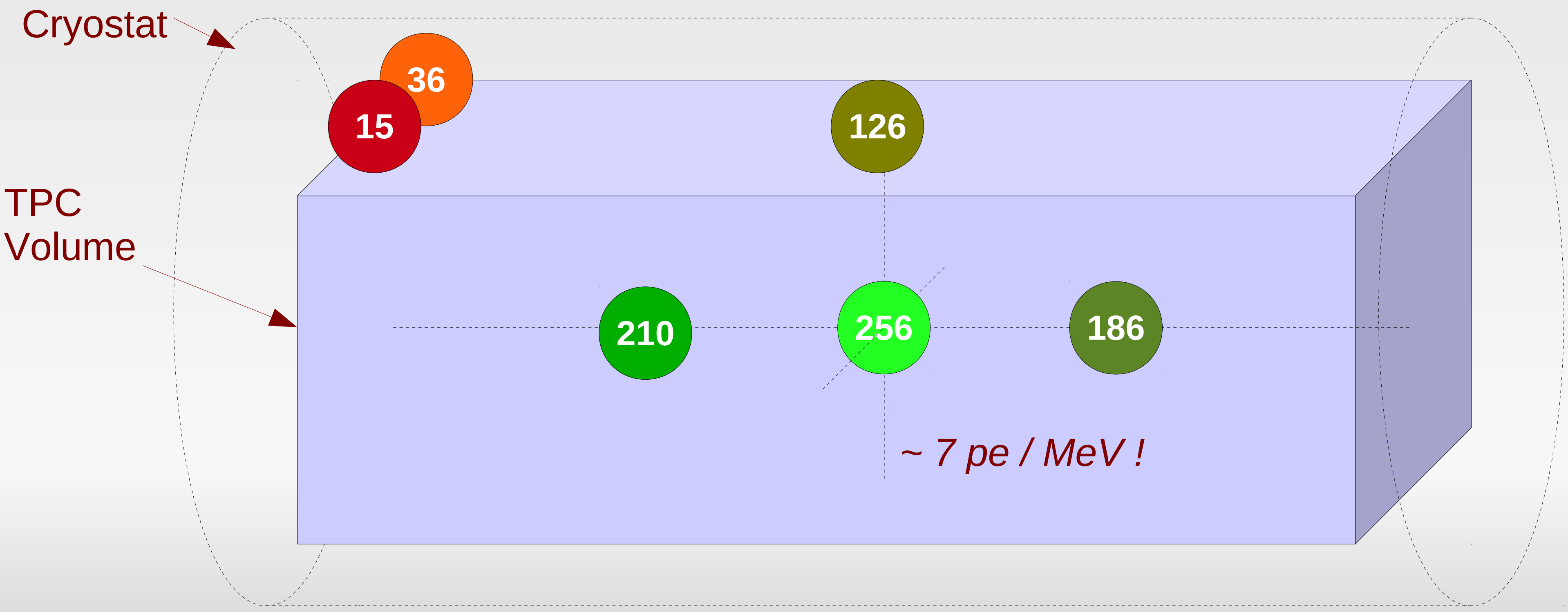
  Specify the size, intensity, shape and position of one light source for each event in a text file which is specified in the config file for the module.

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



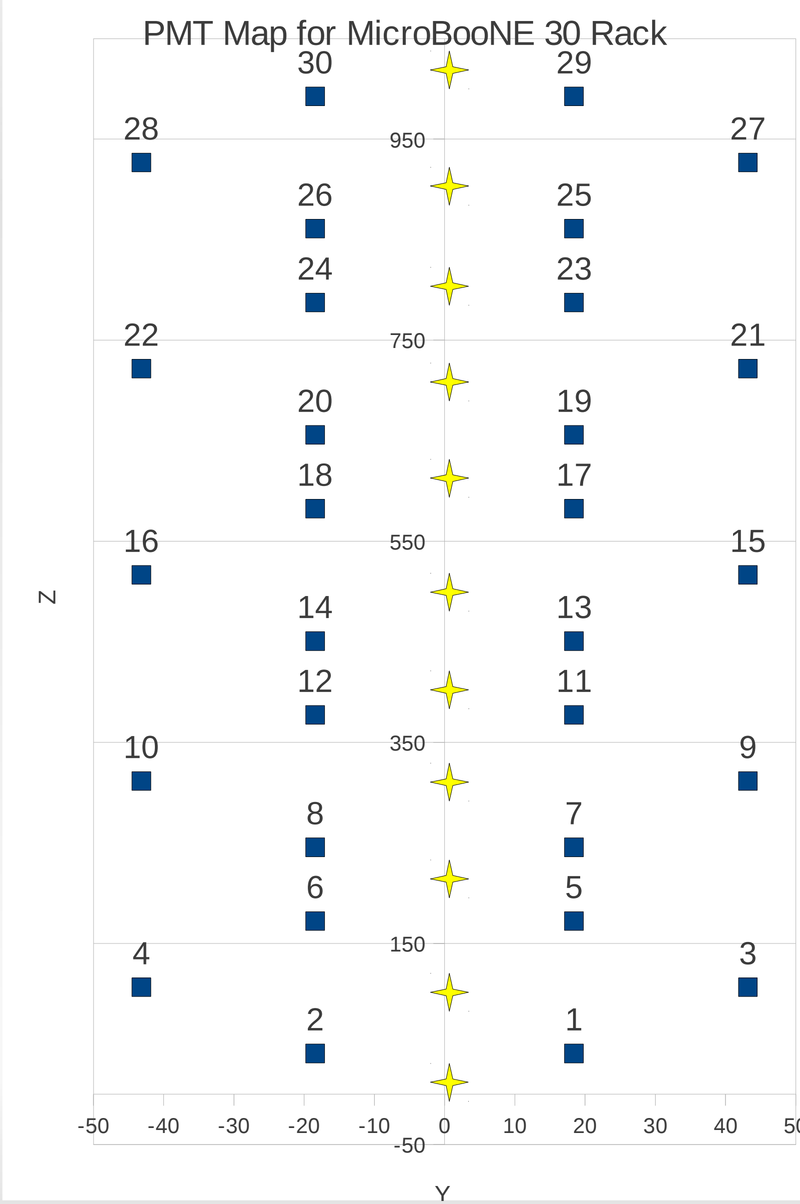
Preliminary Sensitivity Studies

- 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)

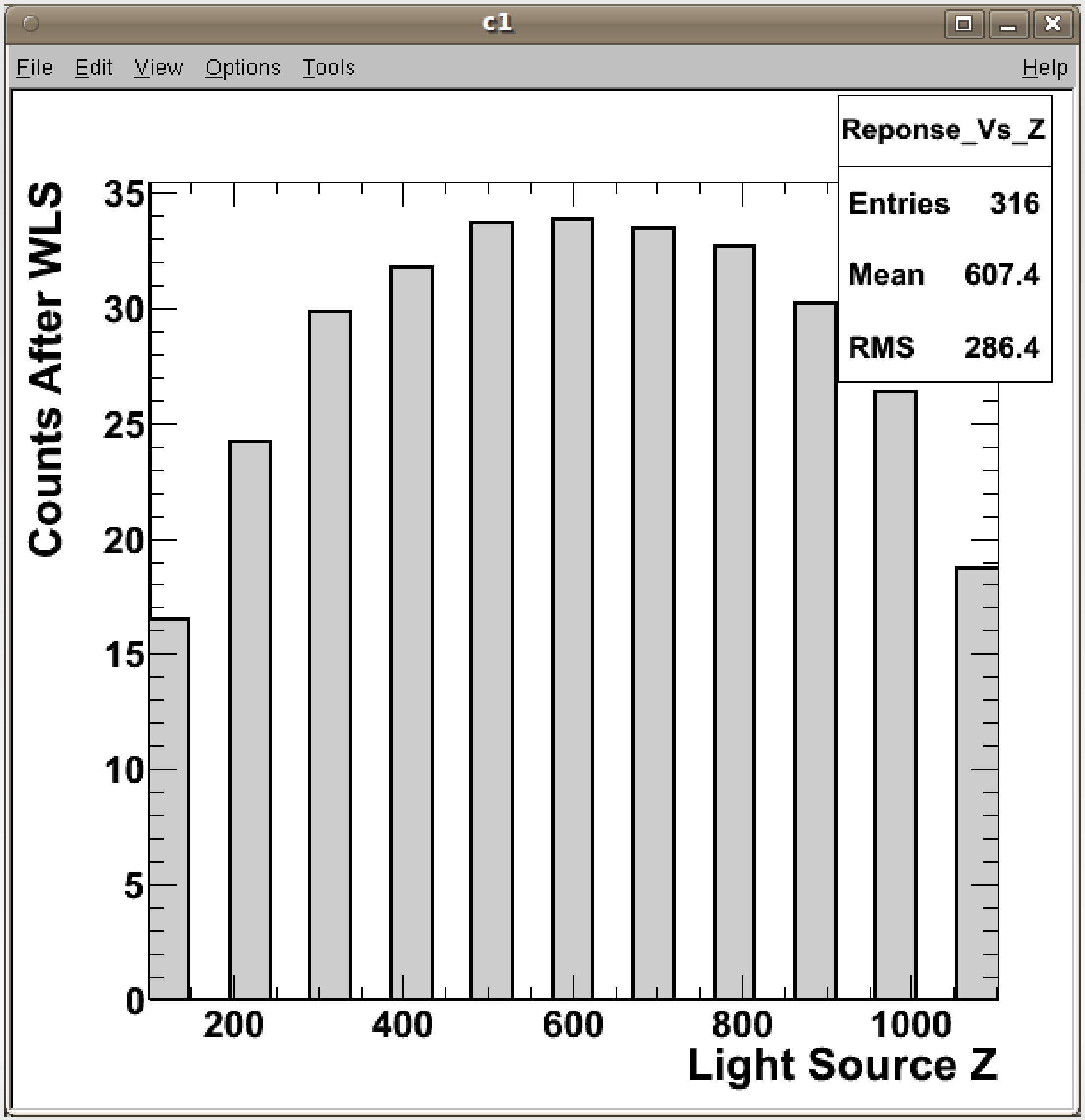


Preliminary – Point Source Test

- 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

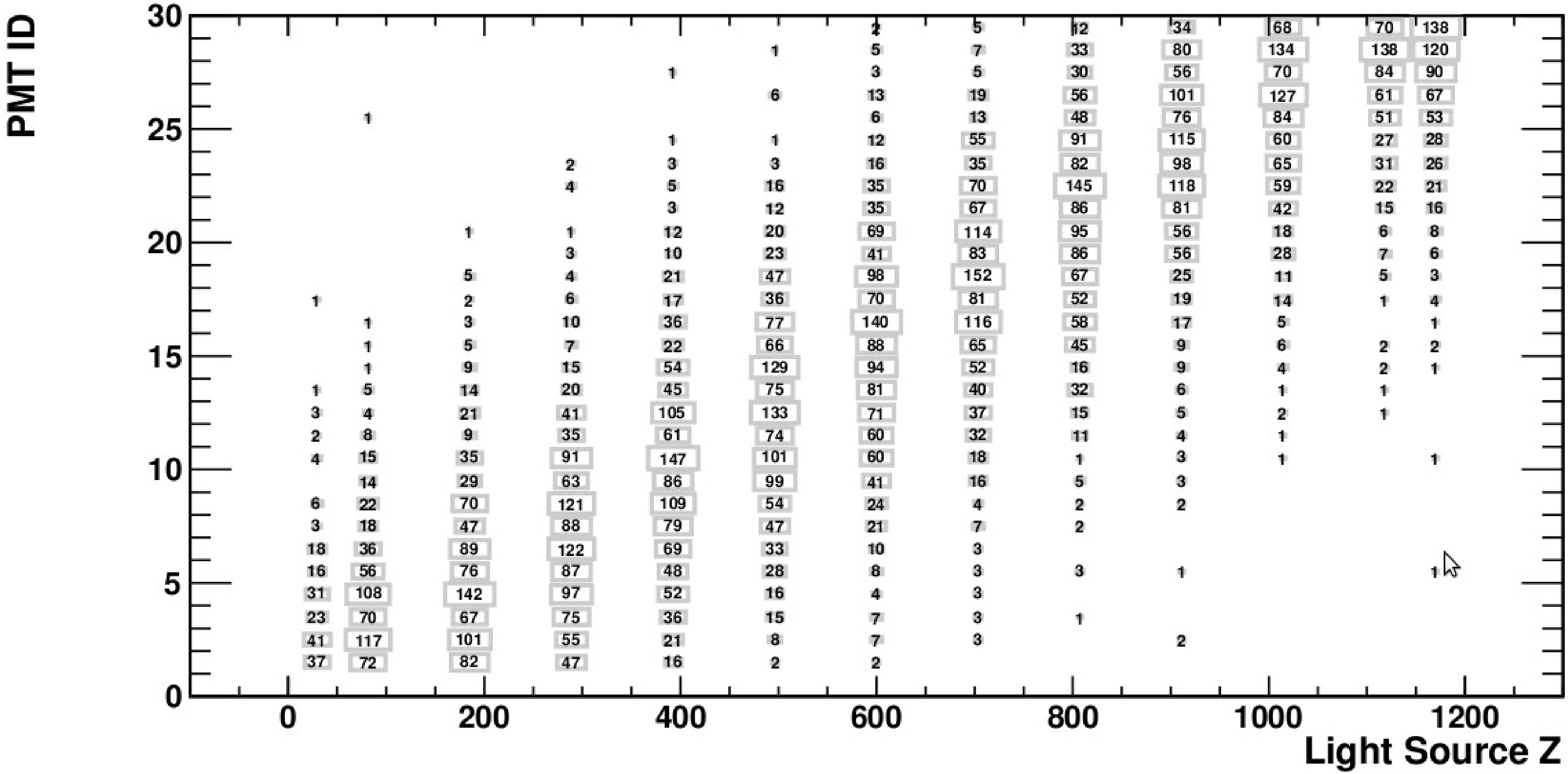


> 15 photoelectrons for each on-axis point in the fiducial volume!

Suggests we have good efficiency for even 5MeV of scintillation

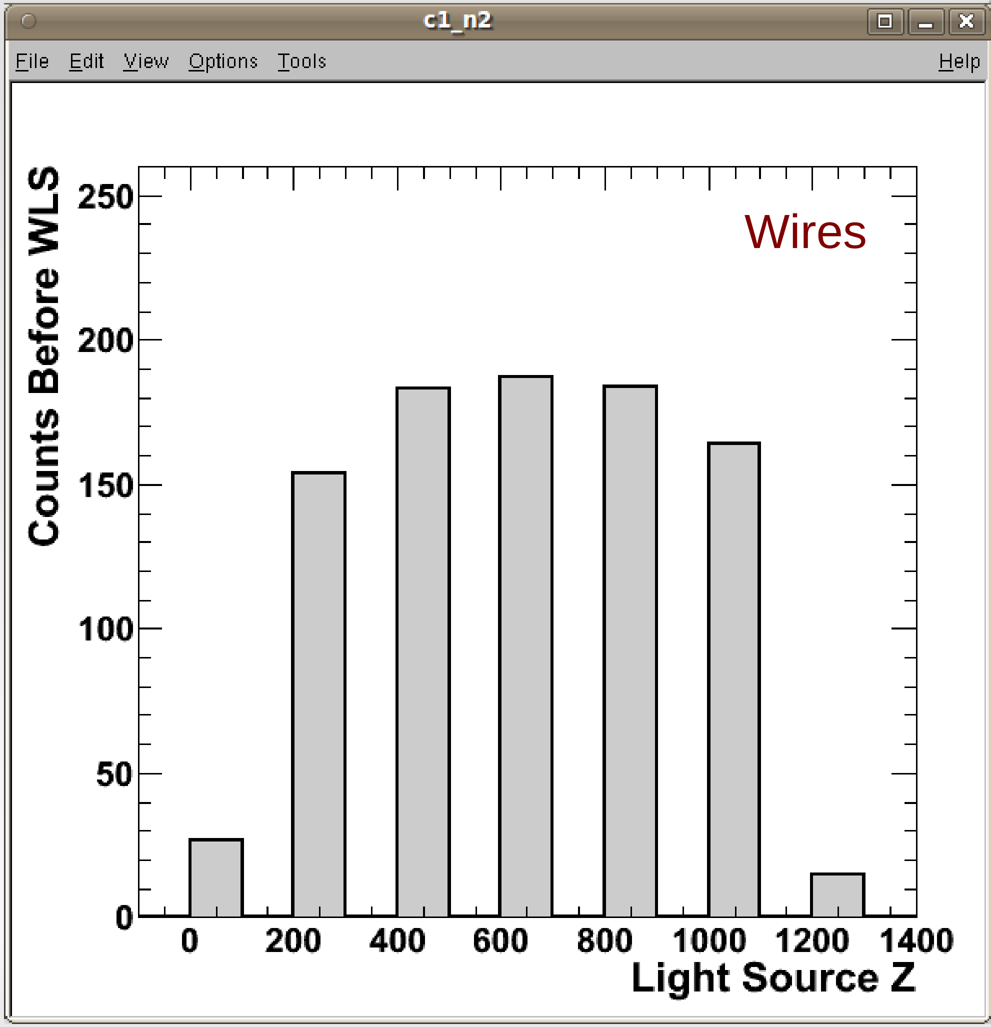
(Subject to geometry modifications)

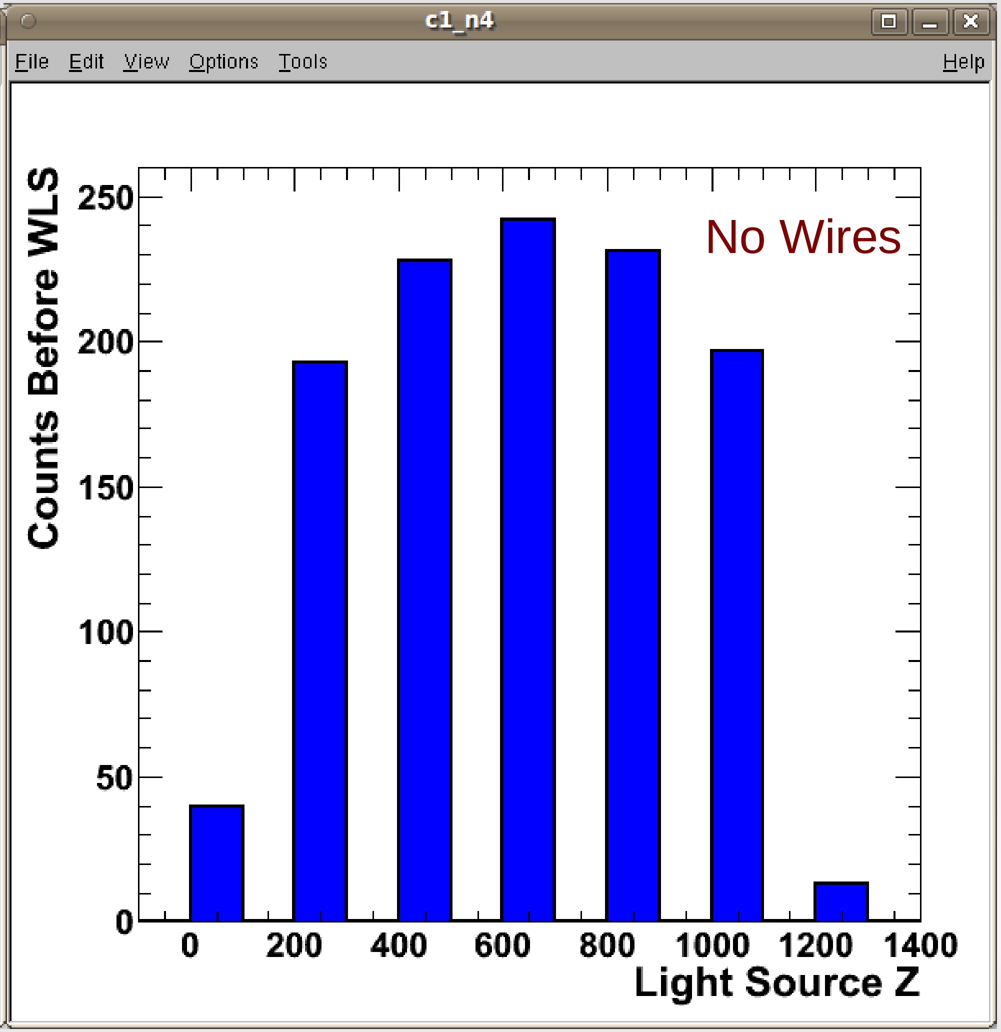
Preliminary – Point Source Test



Preliminary – Effect of Wires

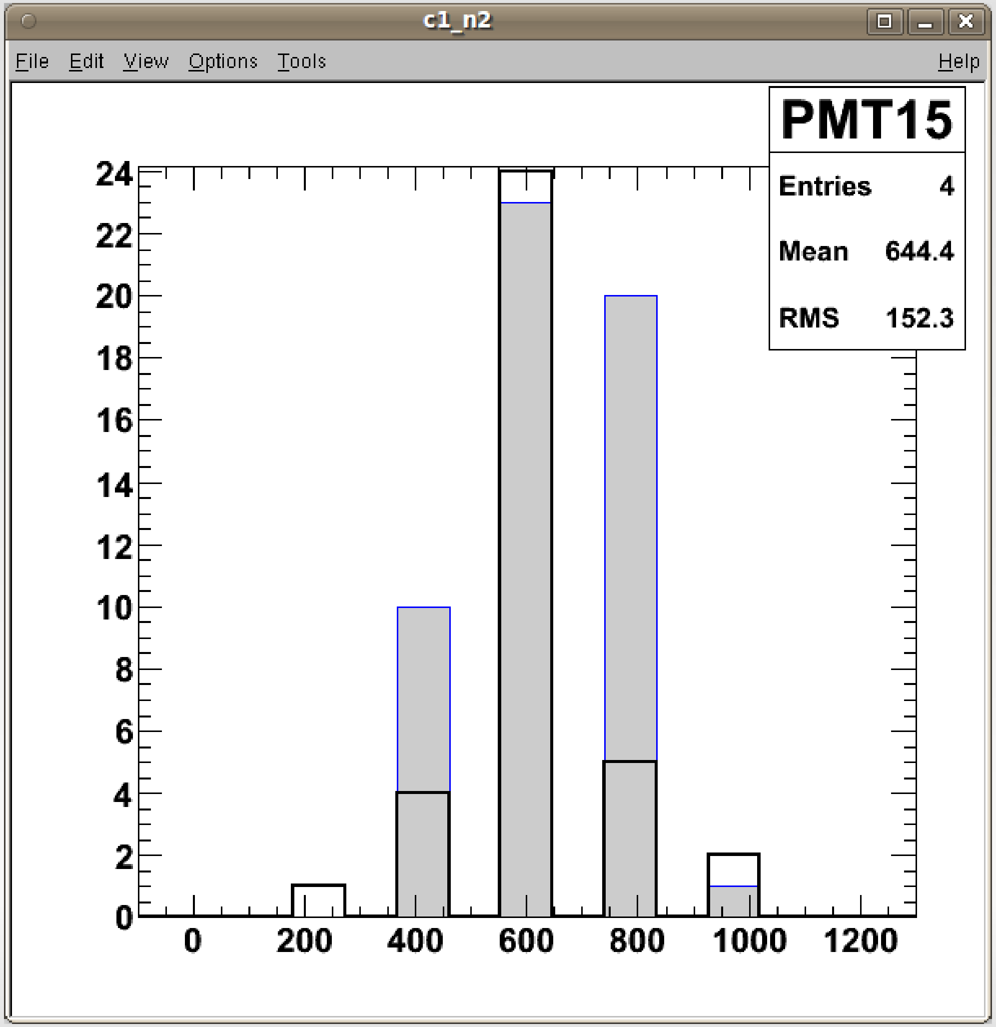
- Wires block ~20% of the light. Note the flattening...

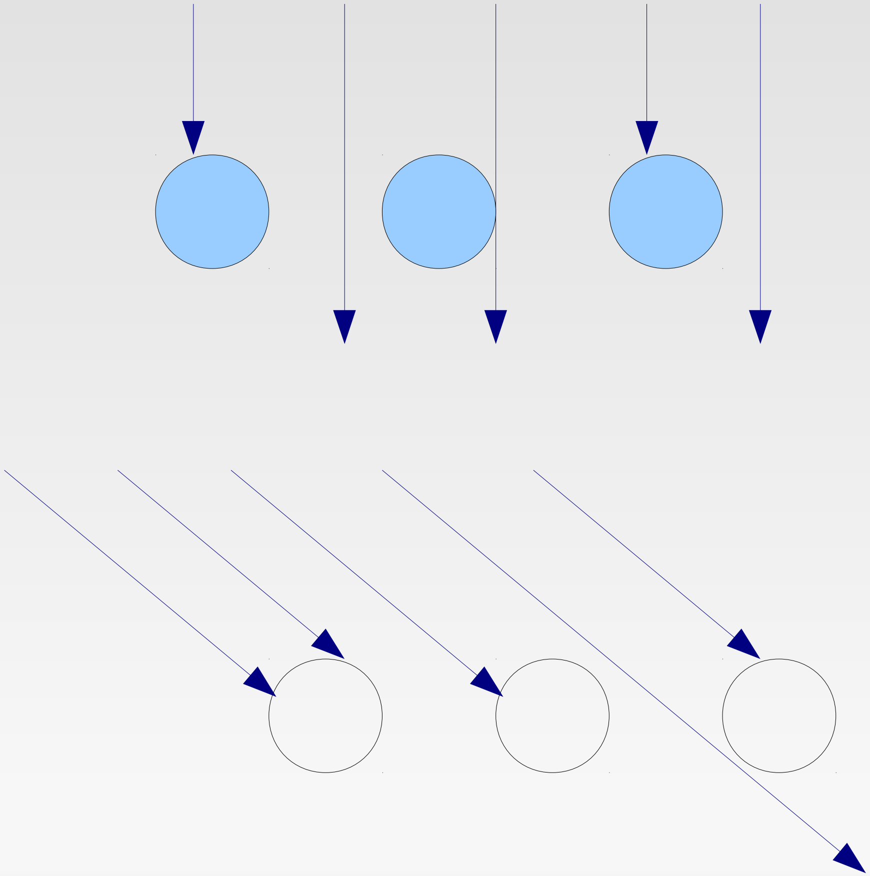




Preliminary – Effect of Wires

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





Comparison to Ideal Efficiency

Parameters Used in Ideal Calculations				
#	Parameter	Value in Calc.	Source	See Sec(s)
Related to UV light production				
1	Early (< 10 ns) UV γ/MeV (MIP)	7600	Ref. [14]	4 & 6
2	Light reduction factor for α	0.72	Ref. [14]	4
3	Light reduction factor for p	0.81	Ref. [15]	6
Related to Geometry of Teststand				
4	Acceptance of UV light	0.33	calculated	4
Conversion and Capture in the Bars				
5	UV/visible γs, evaporative coat	1.0	Ref. [16]	4 & 6
6	Response, bar coating to evap.	0.1	measured	4 & 6
7	Capture fraction	0.05	calculated	4 & 6
PMT response				
8	QE of 7725 PMT	0.25	Ref. [9]	4 & 6
9	Cryogenic modification factor	0.8	Ref. [10]	4 & 6

Combining Parameters to Calculate Efficiencies				
	Efficiency	Value	Combined Params.	See Sec(s)
10	Efficiency to convert and capture	0.005	$5 \times 6 \times 7$	4 & 6
	Total Ideal Efficiency	0.001	$8 \times 9 \times 10$	4 & 6

Ideal mean p.e. per event, no attenuation in bar : **10p.e.**
Measured mean p.e. per event, with source at 10cm : **7p.e**