UNIVERSIDAD
DE GRANADA

Scintillation Light in LArTPCs: Simulation and Reconstruction

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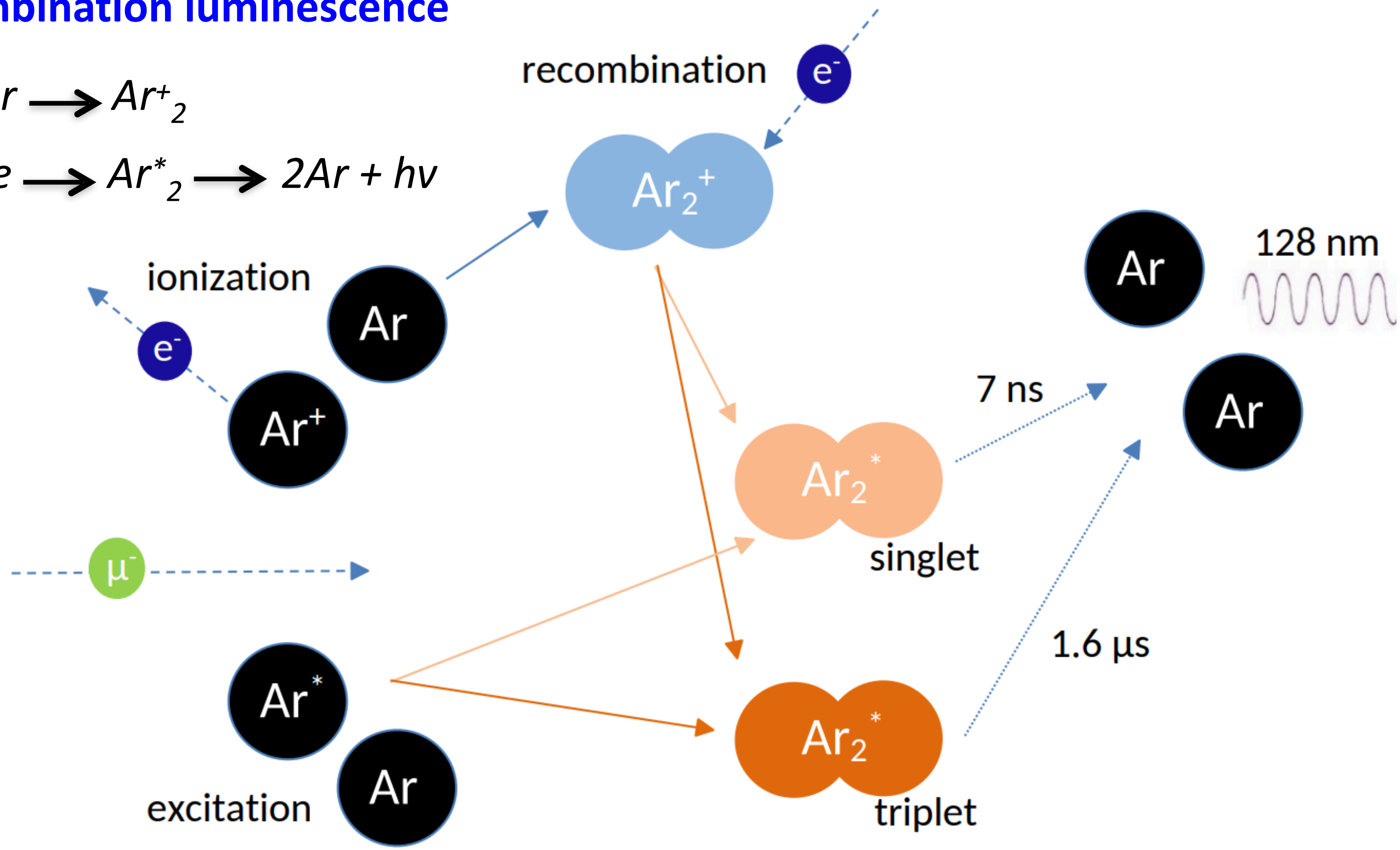
Emission

Scintillation mechanism in LAr

- **Recombination luminescence**

$$Ar^+ + Ar \longrightarrow Ar^+_2$$

$$Ar^+_2 + e \longrightarrow Ar^*_2 \longrightarrow 2Ar + h\nu$$

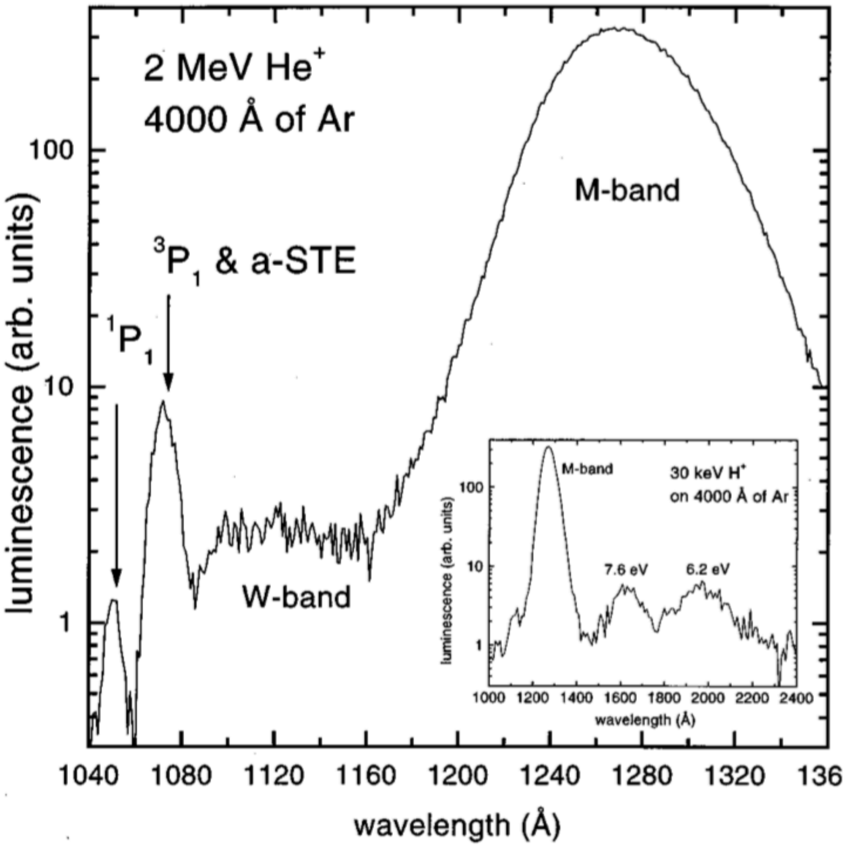


- **Self-trapped excitation luminescence**

$$Ar^* + Ar \longrightarrow Ar^*_2 \longrightarrow 2Ar + h\nu$$

Scintillation wavelength in LAr

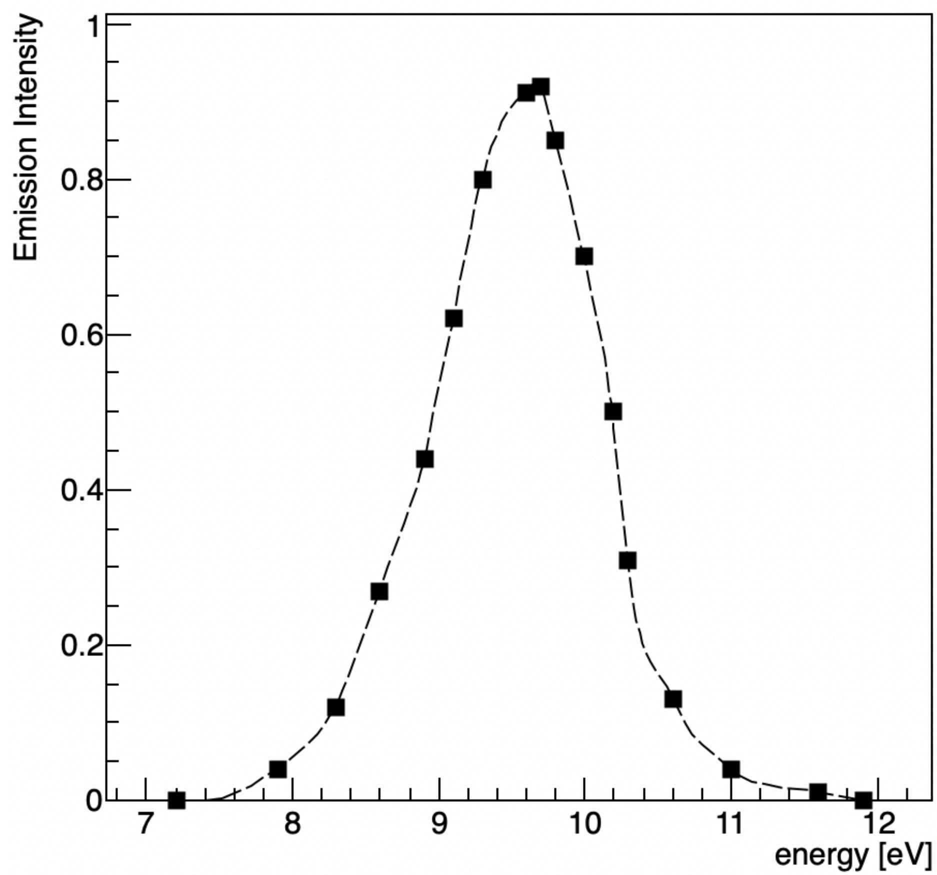
Ph. Rev. B 56 (1997), 6975



In liquid argon, the overall spectrum is well represented by a gaussian shape, peaking around λ = 128 nm (FWHM ≃ 6 nm)

lardataalg / lardataalg / DetectorInfo / larproperties.fcl

```
# Fast and slow scintillation emission spectra, from [J Chem Phys vol 91 (1989) 1469]
FastScintEnergies:    [ 7.2,  7.9,  8.3,  8.6,  8.9,  9.1,  9.3,  9.6,  9.7,  9.8,  10,  10.2,  10.3,  10.6,  11,  11.6,  11.9]
SlowScintEnergies:    [ 7.2,  7.9,  8.3,  8.6,  8.9,  9.1,  9.3,  9.6,  9.7,  9.8,  10,  10.2,  10.3,  10.6,  11,  11.6,  11.9]
FastScintSpectrum:    [ 0.0,  0.04, 0.12, 0.27, 0.44, 0.62, 0.80, 0.91, 0.92, 0.85, 0.70, 0.50, 0.31, 0.13, 0.04,  0.01, 0.0]
SlowScintSpectrum:    [ 0.0,  0.04, 0.12, 0.27, 0.44, 0.62, 0.80, 0.91, 0.92, 0.85, 0.70, 0.50, 0.31, 0.13, 0.04,  0.01, 0.0]
```



Scintillation signal shape in LAr

- In all measurements the overall scintillation light emission exhibits a double exponential decay
- These decays (at 90 K) are characterized by two very different components: *a fast component*, with a time constant of $\tau_S \approx$ 6ns, and by a slow component, with a time constant of $\tau_T \approx$ 1.3μs

lardataalg / lardataalg / DetectorInfo / larproperties.fcl

```
   ScintFastTimeConst:   6.     # fast scintillation time constant (ns)
(*)ScintSlowTimeConst:   1590.  # slow scintillation time constant (ns)
```

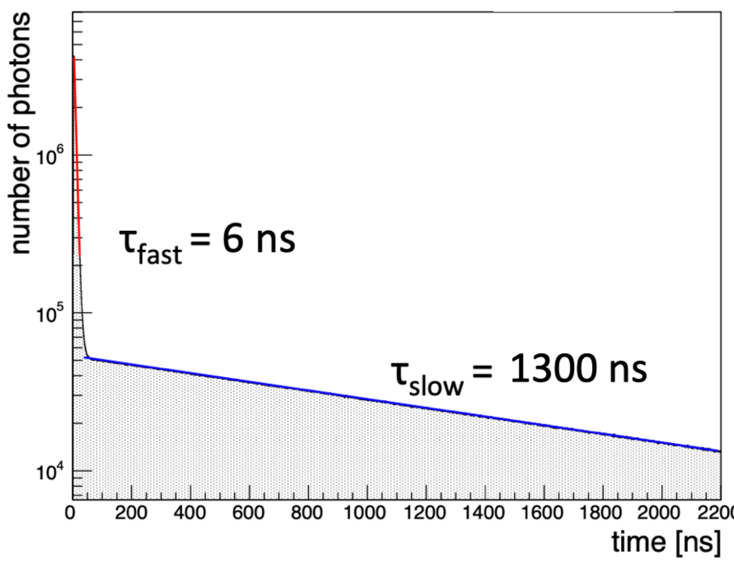
Warning: In the refactored LArG4 decay times are defined in a different place

sbndcode / sbndcode / LArSoftConfigurations / opticalproperties_sbnd.fcl

```
   # Updating the triplet decay-time (Phys. Rev. C 91, 035503). Note that in our simulations we account
   # independently for the TPB-delay time and the emission (fast and slow) decay times.
(*)ScintSlowTimeConst:   1300.  # slow scintillation time constant (ns)
```

Note:
Some experiments use a slow time constant value convolved with the WLS-delay, resulting in a larger value.

In SBND we account for both delays separately.

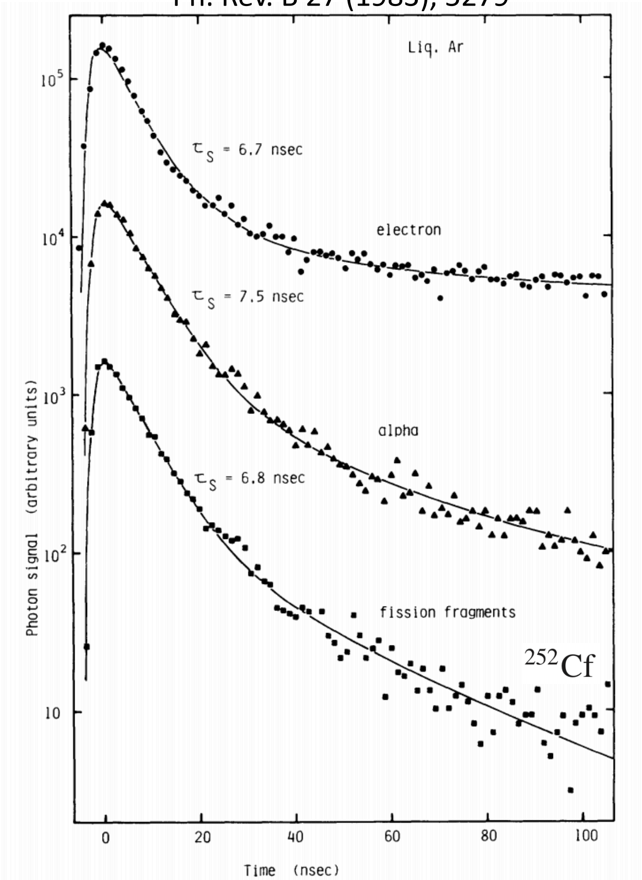


Scintillation time components

- The lifetimes of the fast and slow components agree within experimental uncertainties for different particles
- Light yield and fast/slow ratio depend on LET (the specific energy loss along the path)

Particle	τ_S	τ_T	I_S/I_T	Reference
Electron	6.3 ±0.2	1020±60	0.083	Kubota *et al.*[a]
	(5.0 ±0.2)	(860±30)	(0.045)	(E = 6 kV/cm)[a]
	4.6	1540	0.26	Carvalho and Klein[b]
	4.18±0.2	1000±95		Keto *et al.*[c]
		1110±50		Suemoto and Kanzaki[d]
	6 ±2	1590±100	0.3	This work
α	~5	1200±100		Kubota *et al.*[e]
	4.4	1100	3.3	Carvalho and Klein[b]
	7.1±1.0	1660±100	1.3	This work
F.F.	6.8±1.0	1550±100	3	This work

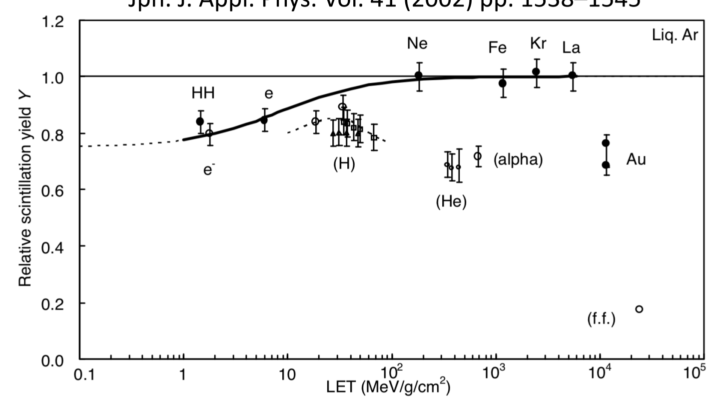
Ph. Rev. B 27 (1983), 5279



lardataalg / lardataalg / DetectorInfo / larproperties.fcl

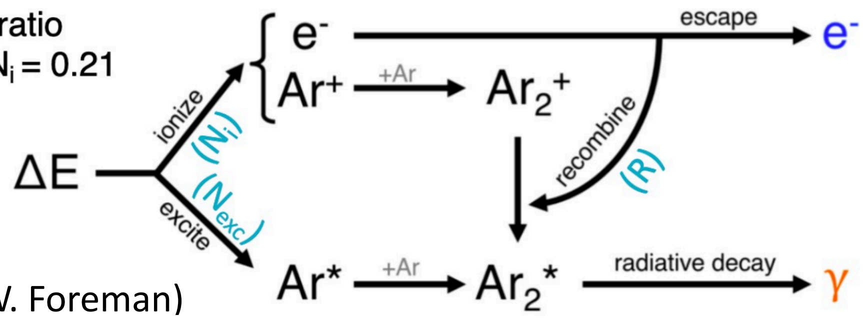
```
ScintYield:           24000. # total scintillation yield (ph/Mev)
ScintYieldRatio:      0.3    # fast / slow scint ratio (needs revisitting)
ScintByParticleType:  true   # whether to use different yields and

# Scintillation yields and fast/slow ratios per particle type
MuonScintYield:             24000
MuonScintYieldRatio:        0.23
PionScintYield:             24000
PionScintYieldRatio:        0.23
ElectronScintYield:         20000
ElectronScintYieldRatio:    0.27
KaonScintYield:             24000
KaonScintYieldRatio:        0.23
ProtonScintYield:           19200
ProtonScintYieldRatio:      0.29
AlphaScintYield:            16800
AlphaScintYieldRatio:       0.56
```

Jpn. J. Appl. Phys. Vol. 41 (2002) pp. 1538–1545



L vs Q and Electric Field

Excitation ratio
α = $N_{exc} / N_i = 0.21$



(Credit to W. Foreman)
PHYSICAL REVIEW D **101,** 012010 (2020)

$$Q = N_e = N_\mathrm{i} R$$

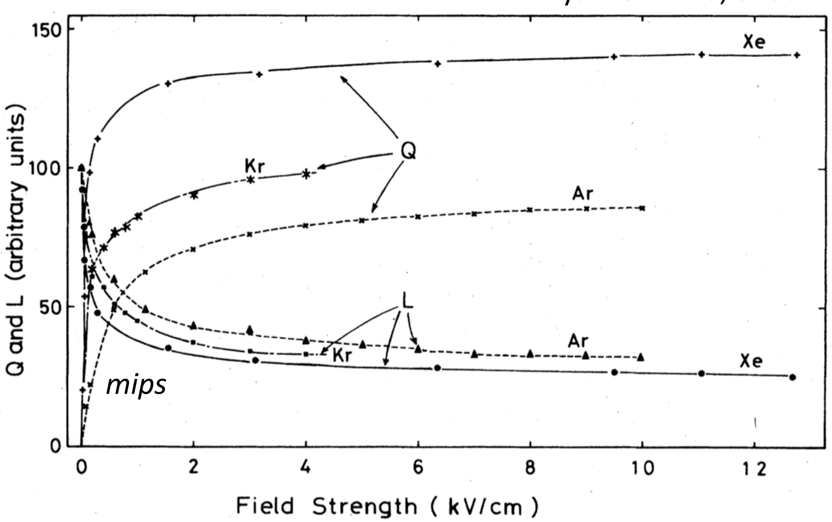
$$L = N_\gamma = N_\mathrm{ex} + N_\mathrm{i}(1 - R)$$

$$Q + L = N_\mathrm{ex} + N_\mathrm{i} = \frac{\Delta E}{W_\mathrm{ph}}$$

(19.5±1.0) eV

- Electric Fields applied to the LAr medium also affect the intensity weights of the decay components by the recombination (R)

Phys. Rev. B 20, 3486



larsim / larsim / IonizationScintillation / ISCalcCorrelated.cxx

```
// using this recombination, calculate number of ionization electrons
double const num_electrons = (energy_deposit / fWion) * recomb;

// calculate scintillation photons
double const num_photons = (Nq - num_electrons) * fScintPreScale;
```

```
// calculate recombination survival fraction
if (fUseModBoxRecomb) {
  if (ds > 0) {
    double Xi = fModBoxB * dEdx / EFieldStep;
    recomb = log(fModBoxA + Xi) / Xi;
  }
  else {
    recomb = 0;
  }
}
else {
  recomb = fRecombA / (1. + dEdx * fRecombk / EFieldStep);
}
```

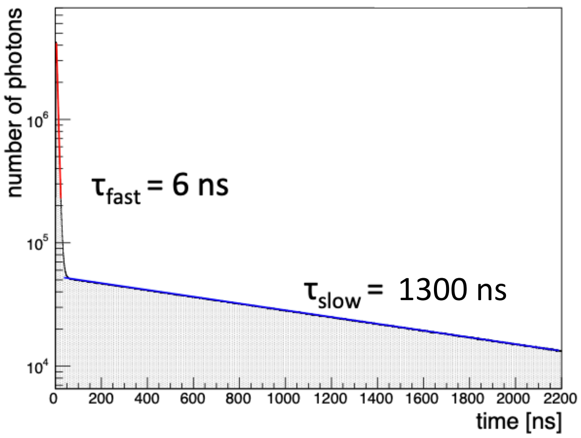
Services.LArG4Parameters.IonAndScintCalculator: "Correlated"   (available from v09_09_03)

Propagation

Scintillation light propagation

Scintillation (emission):

$0.3 \times \tau_{fast}(6\ \text{ns}) + 0.7 \times \tau_{slow}\ (1300\ \text{ns})$



$$Q = N_e = N_i R,$$
$$L = N_\gamma = N_{ex} + N_i(1 - R),$$
$$Q + L = N_{ex} + N_i = \frac{\Delta E}{W_{ph}}$$

We need how to get our number of detected photons and their arrival times ⇒ **Transport effects**

- Scintillation photons have energy lower than the first excited state of the Ar atom, therefore pure LAr is transparent to its own scintillation radiation

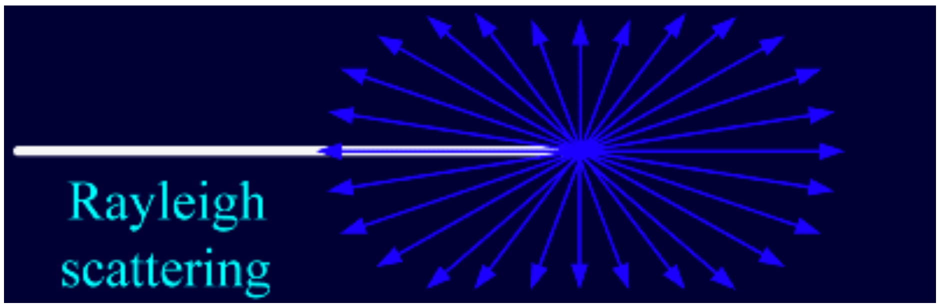
- However, during propagation through LAr VUV photons may undergo elastic interactions on Ar atoms ⇒ Rayleigh scattering

- **Rayleigh Scattering affects, in a non negligible way, the light signals in our detectors in comparison with the "pure" emitted scintillation light**

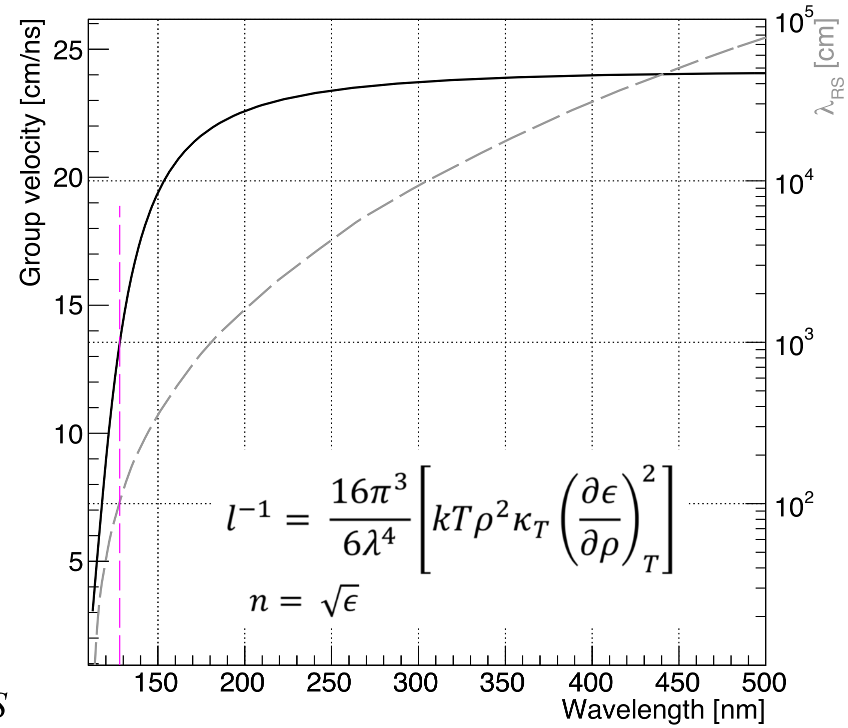
- It is important to understand/model it properly in liquid argon

Rayleigh Scattering in LArSoft

- Elastic scattering of photon with medium of particle ~1/10 size of the wavelength (change angle/direction)



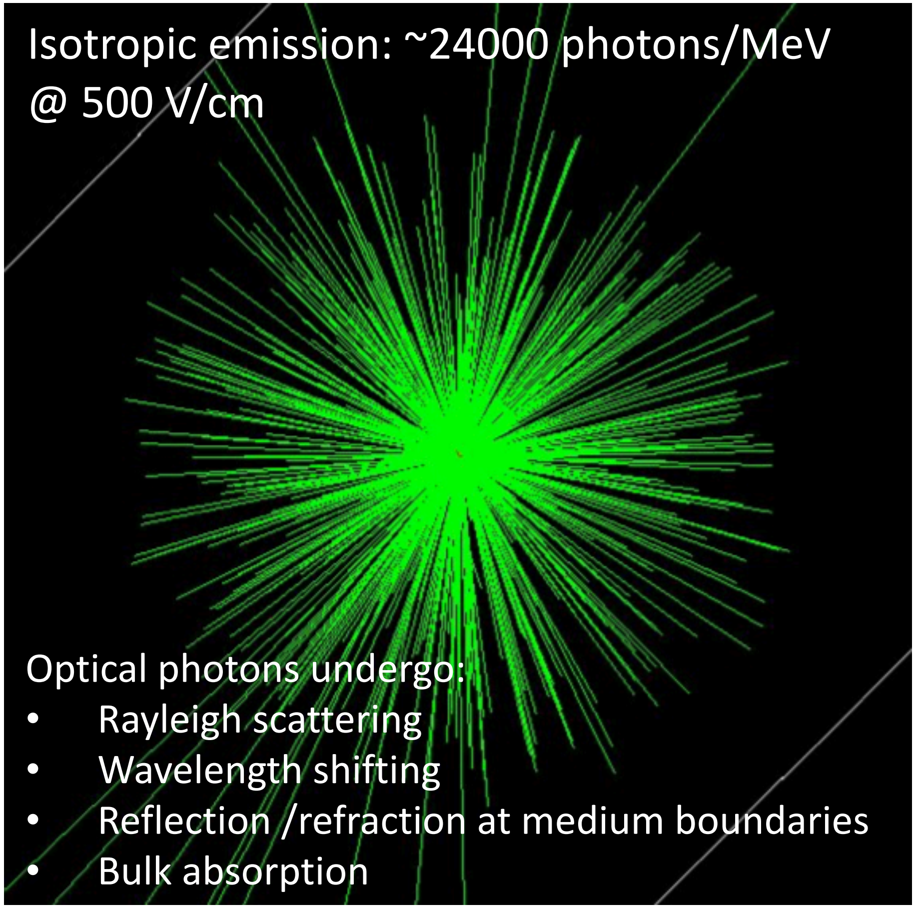
- Small uncertainties in the index of refraction can drastically change the scattering length λ_{RS}

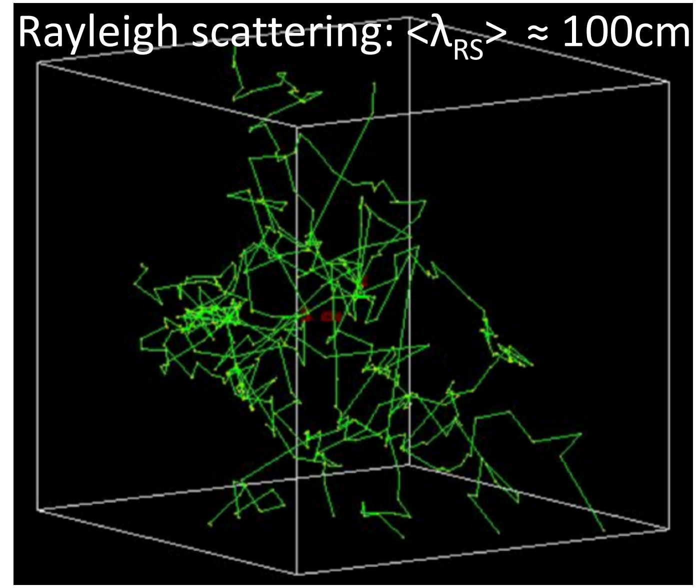


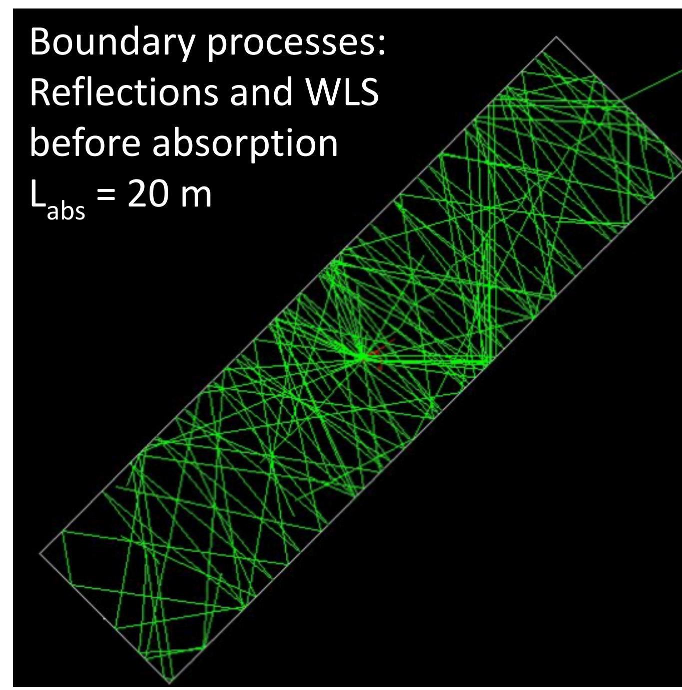
lardataalg / lardataalg / DetectorInfo / larproperties.fcl

```
# Refractive index as a function of energy (eV) from arXiv:2002.09346
RIndexEnergies: [ 1.18626, 1.68626, 2.18626, 2.68626, 3.18626, 3.68626, 4.18626, 4.68626, 5.18626,
RIndexSpectrum: [ 1.24664, 1.2205, 1.22694, 1.22932, 1.23124, 1.23322, 1.23545, 1.23806, 1.24116, 1

RayleighEnergies: [ 1.18626, 1.68626, 2.18626, 2.68626, 3.18626, 3.68626, 4.18626, 4.68626, 5.18626,
RayleighSpectrum: [ 1200800, 390747, 128633, 54969.1, 27191.8, 14853.7, 8716.9, 5397.42, 3481.37, 23
```

(Parenthesis): GEANT4 light simulation



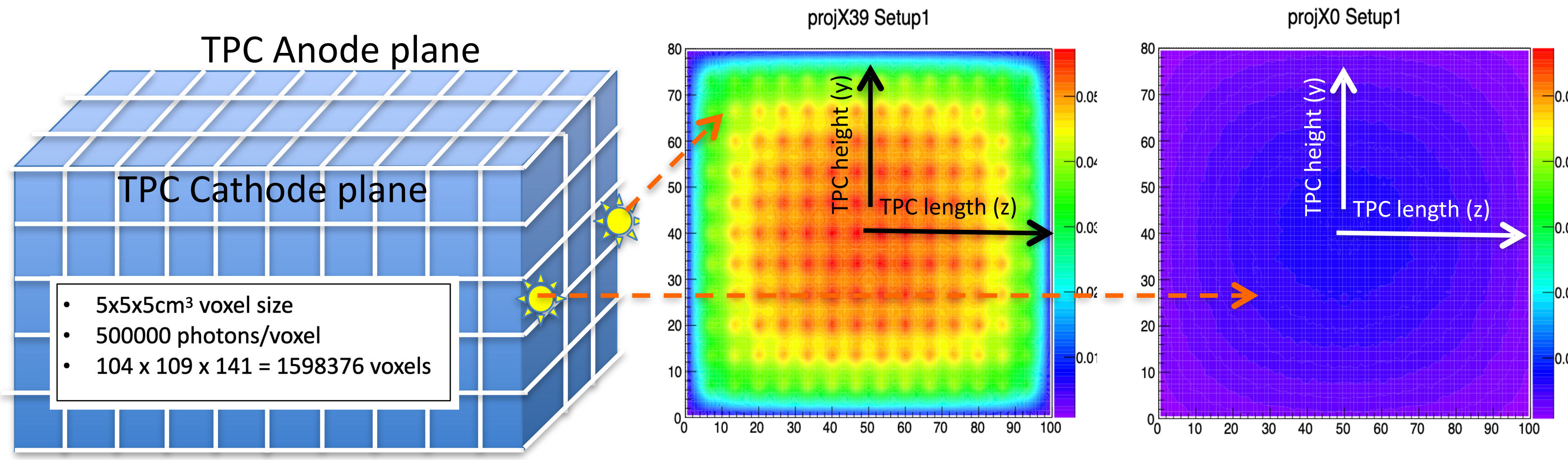




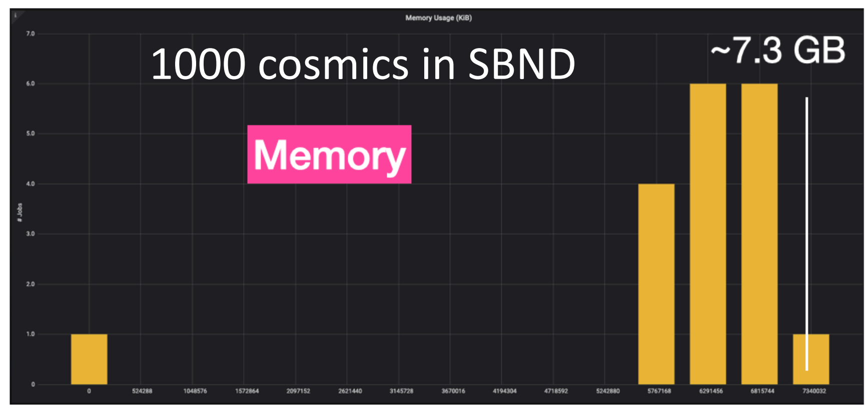
In large detectors, the tracking of each individual photon is prohibitively long: approaches need to be used →

This is what we call LArSoft fast optical mode(s)

Fast optical model: Optical Library



$$\langle N \rangle_{PMT-hits} = \left(\frac{dE}{dx}_{step} \cdot Length_{step} \right) \cdot LY \cdot visibility^{PMT}_{step}$$



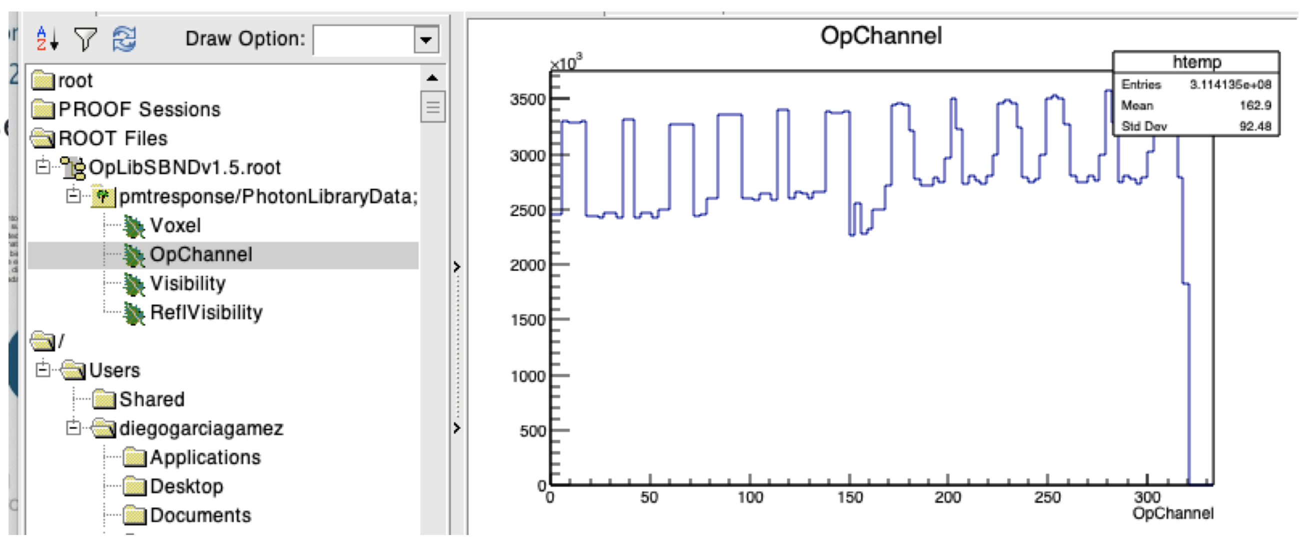
- Resolution depends on voxel sizes: granularity effects at short distances
- Optical library size scales with detector size and number of photon detectors
- Prohibitive memory use for events with large energy depositions (i.e. cosmics)
- **New approach needed!**

Optical Library parameters: voxelization scheme

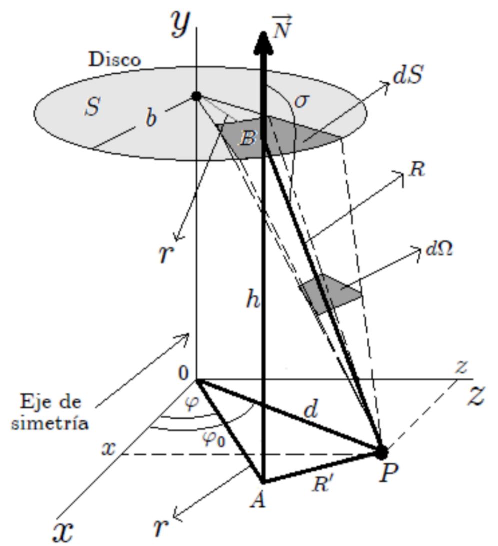
sbndcode / sbndcode / LArSoftConfigurations / photpropservices_sbnd.fcl

```
# (Re)Defining the Optical Library information/files for the PD-fast HYBRID optical mode
sbnd_library_for_hybrid_mode_photonvisibilityservice:
{
  @table::sbnd_library_vuv_vis_prop_timing_photonvisibilityservice
  LibraryFile: "OpticalLibrary/SBND_OpLibOUT_v2.00.root"
  NX: 66
  NY: 56
  NZ: 71
  UseCryoBoundary: false
  # IF UseCryoBoundary is s
  XMin:  -264
  XMax:   264
  YMin:  -280
  YMax:   280
  ZMin:  -60
  ZMax:   650
}
```

Detector specific



Fast optical model: Semi-Analytic



$$\Omega = h \int_0^{2\pi} \int_0^{b} \frac{r}{[h^2+r^2+d^2-2rd\,\mathrm{Cos}(\varphi_o-\varphi)]^{3/2}} dr d\varphi$$

- Given a dEdx in a point (x, y, z) we want to predict the number of hits in our optical detector (x_i, y_i, z_i)
- Isotropic scintillation emission makes the problem **"almost"** geometric

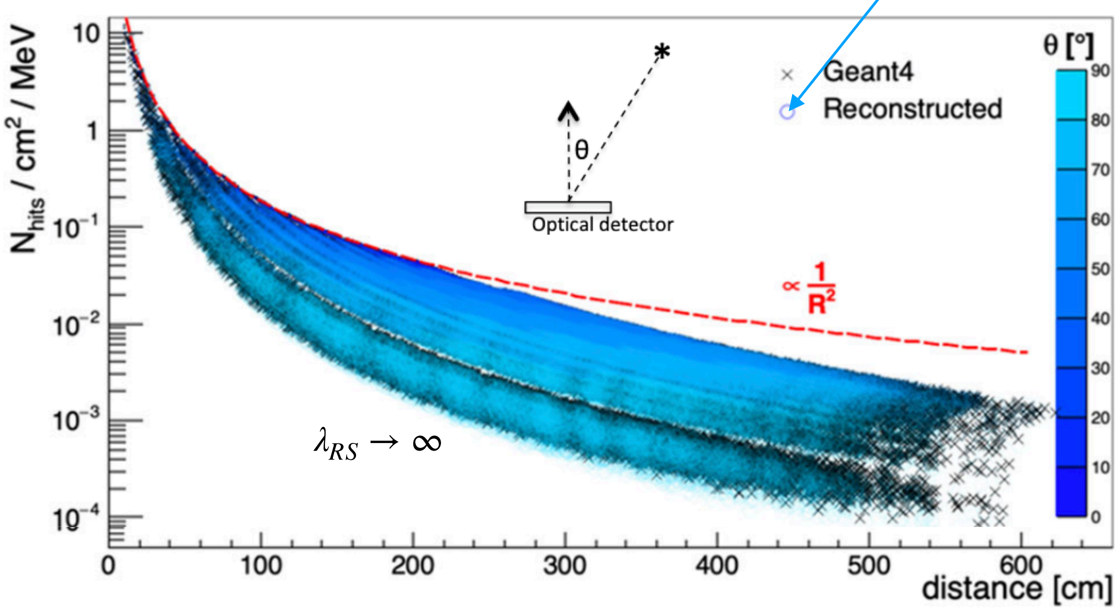
$$N_\Omega = e^{-\frac{d}{\lambda_{abs}}} \Delta E \cdot S_\gamma(\mathscr{E}) \frac{\Omega}{4\pi}$$

λ_{abs} = LAr absorption length

S_γ = Scintillation Yield

$\mathscr{E}$ = Electric Field

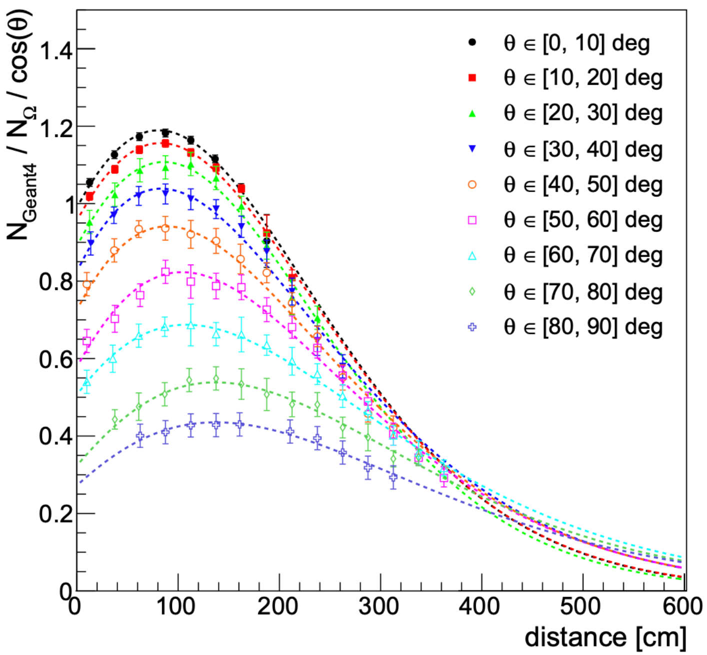
Ω = Solid angle



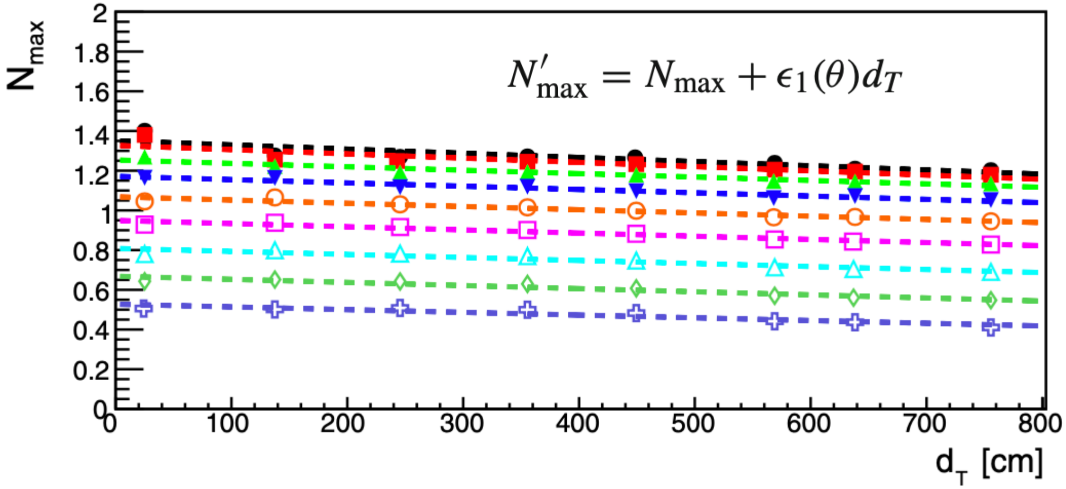
- **"Almost" because we have Rayleigh scattering**

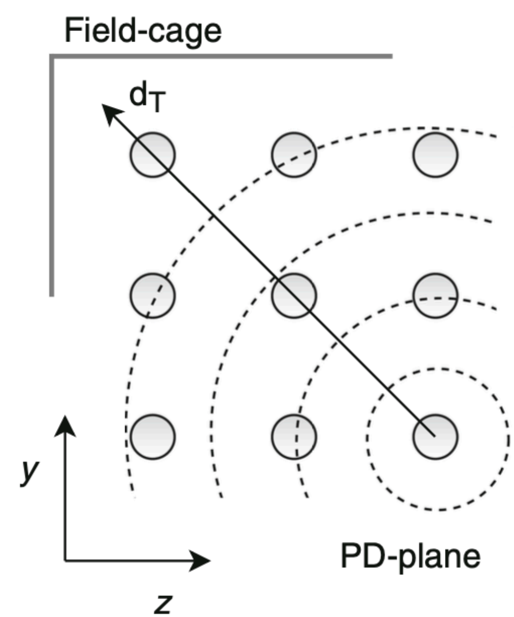
Transport corrections to light signals

Eur. Phys. J. C (2021) 81:349



Border effects:





$$GH(d) = N_{\max} \left(\frac{d - d_0}{d_{\max} - d_0} \right)^{\frac{d_{\max} - d_0}{\Lambda}} e^{\frac{d_{\max} - d}{\Lambda}}$$

$$N_\gamma = N_\Omega \times GH'(d, \theta, d_T)/cos(\theta)$$

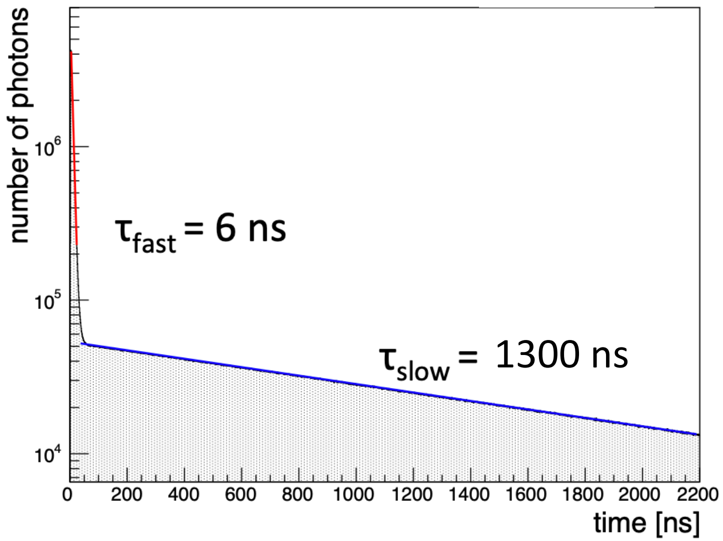
Geometric estimation

Transport correction

Time structure of detected signals

Scintillation (emission):

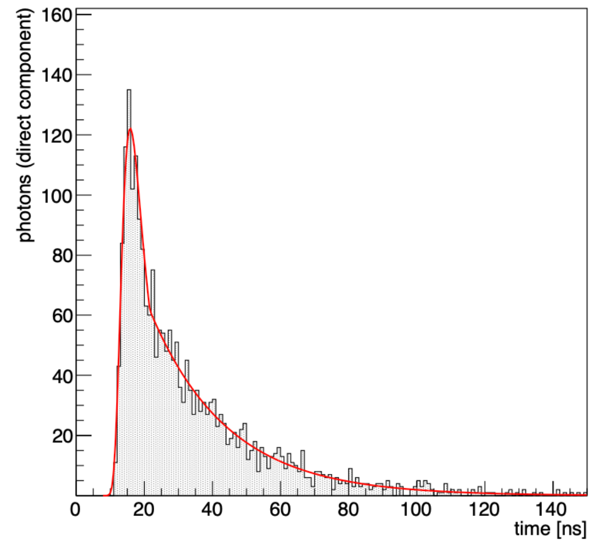
$0.3 \times \tau_{fast}(6\ \text{ns}) + 0.7 \times \tau_{slow}(1300\ \text{ns})$



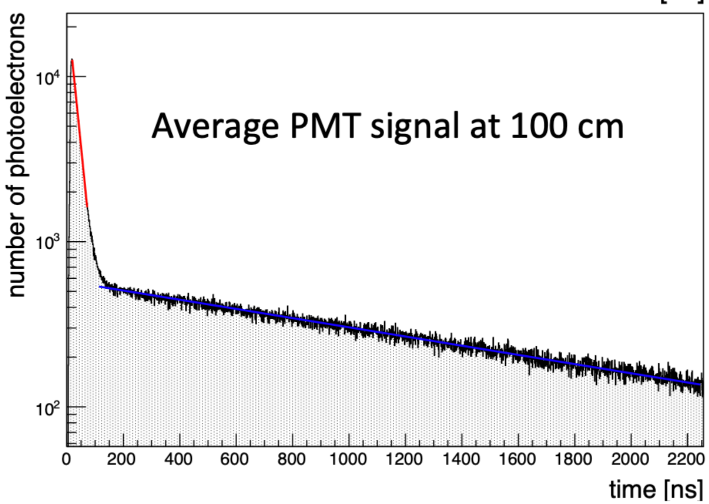
+

Propagation:

Direct transportation + Rayleigh Scattering



=

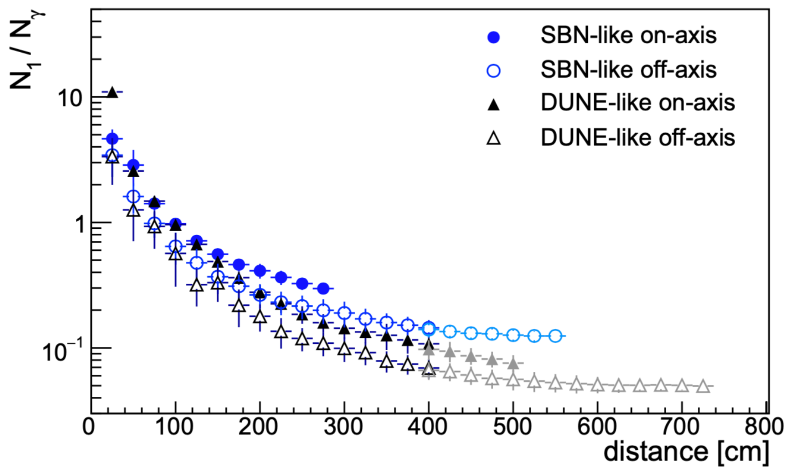


In "large" detectors transport effects will affect the effective time structure of the detected scintillation light

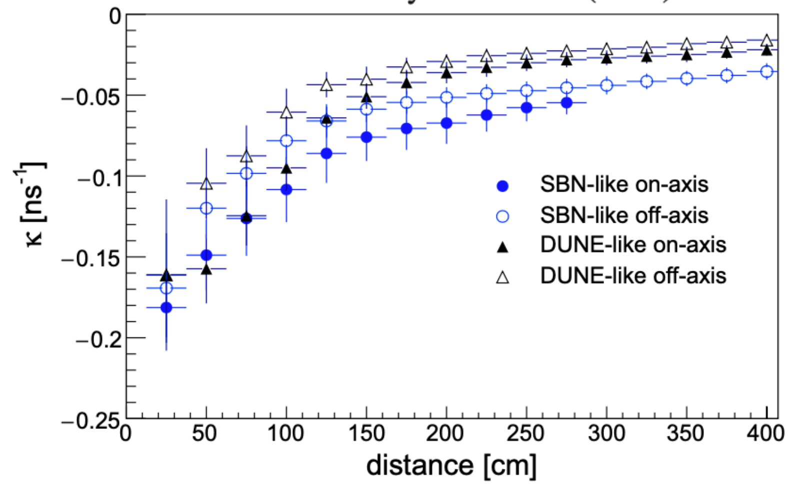
$$t_\gamma = t_E + t_t(d,\theta) + t_{WLS} + t_{det},$$

- t_E = emission time
- t_t = transport time
- t_{WLS} = WLS delay time
- t_{det} = detector time

Time structure of detected signals



Eur. Phys. J. C (2021) 81:349



$$t_t(x) = \underbrace{N_1 \frac{1}{\xi} \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} e^{\lambda s + s \log s}\, ds}_{Landau} + \underbrace{N_2\, e^{\kappa\, x}}_{Exponential} ,$$

larsim / larsim / PhotonPropagation / opticalsimparameterisations.fcl

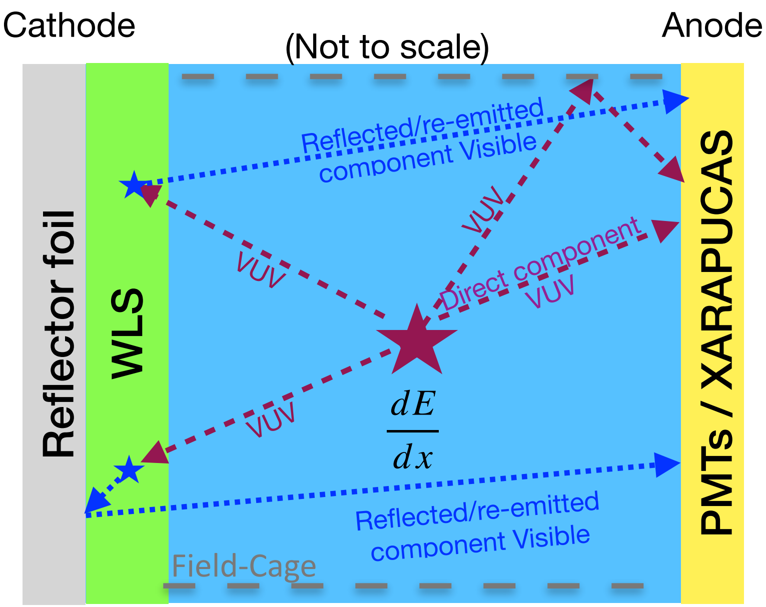
```
# VUV/DIRECT LIGHT: TIMING PARAMETERISATION
# Parameters of the Landau + Exponential (<= 350 cm) and Landau (> 350 cm) models
# Landau parameters
Distances_landau_generic: [0, 25, 50, 75, 100, 125, 150, 175, 200, 225, 250, 275, 300, 325, 350, 375, 40
Norm_over_entries_generic: [ [4.64837, 4.64837, 2.86581, 1.4143, 0.974871, 0.71311, 0.55772, 0.461078, 0
                0.297132, 0.297132, 0.297132, 0.297132, 0.297132],
                [3.43562, 3.43562, 1.61042, 0.981127, 0.64465, 0.476552, 0.369063, 0.310461, 0.264819, 0
Mpv_generic: [  [2.73373, 2.73373, 3.599, 5.80141, 7.57883, 9.56959, 11.6047, 13.6676, 15.6126, 17.5389,
                21.3254, 21.3254],
                [2.19076, 2.19076, 4.0163, 5.86531, 8.09466, 10.4547, 12.9261, 15.2731, 17.7939, 20.6664
```

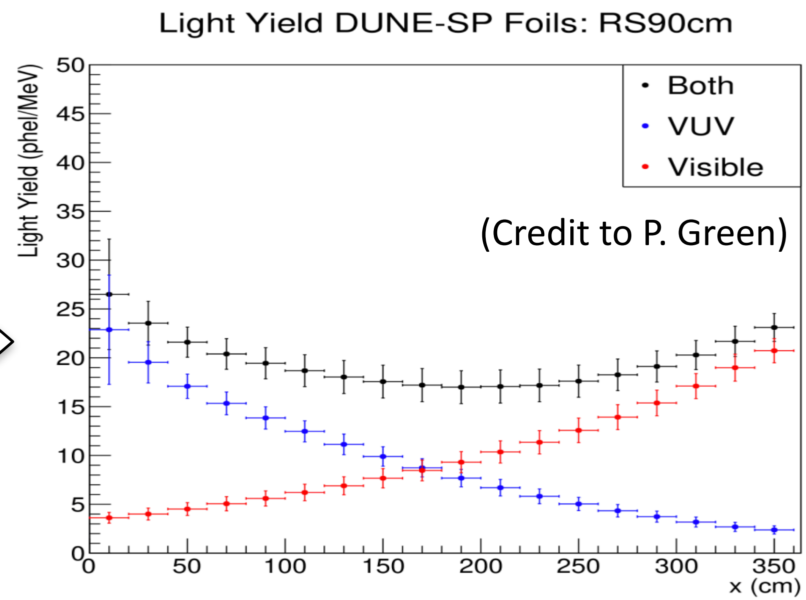
larsim / larsim / PhotonPropagation / PDFastSimPAR.fcl

```
IncludePropTime:        true
```

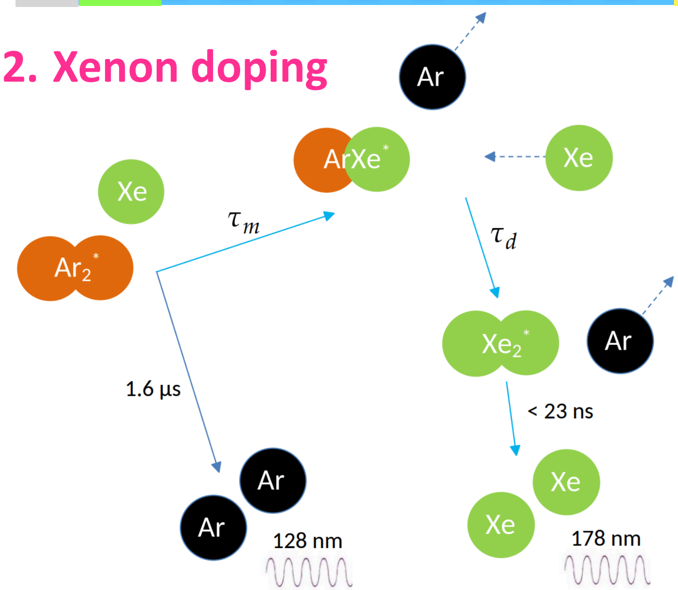
(Parenthesis): Enhancing the Light Yield in LArTPCs

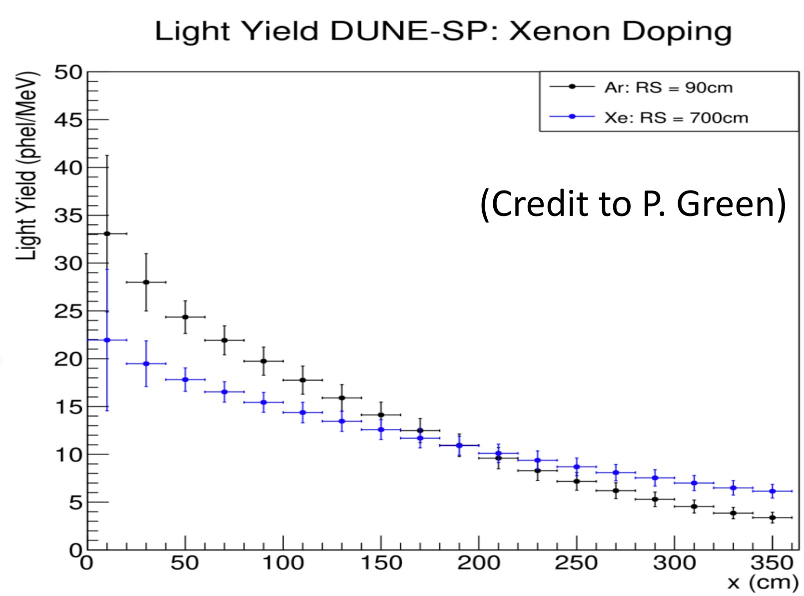
1. WLS-Coated reflector foils



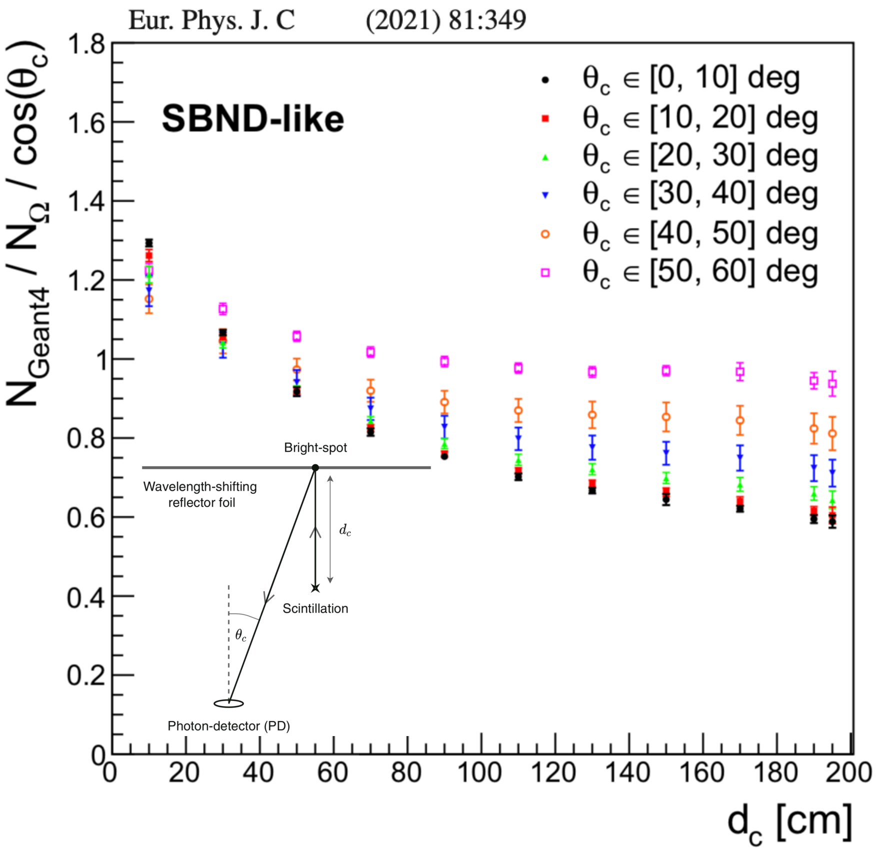


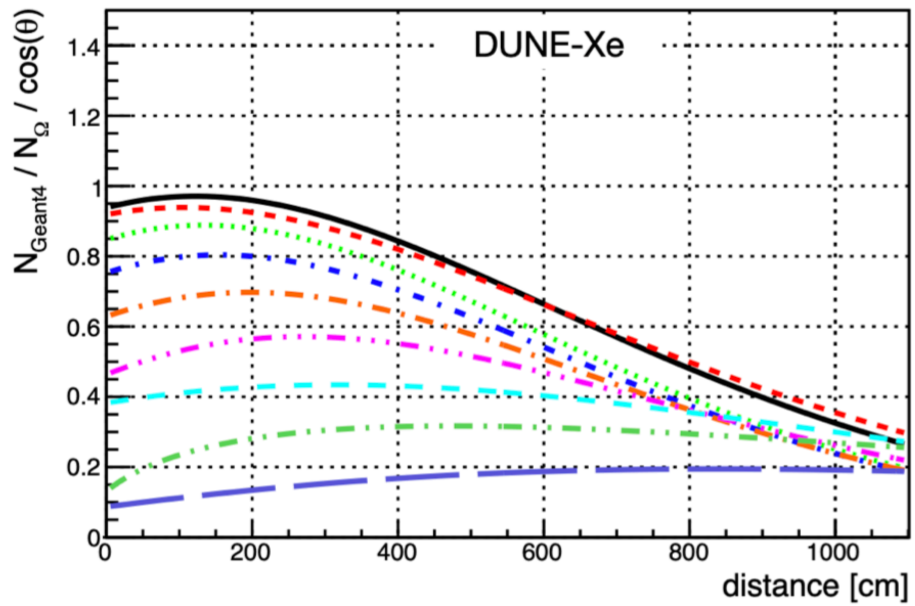
2. Xenon doping





Semi-Analytic model extensions (available)





$$N_{\Omega,reflected} = N_{\gamma,direct}(\Omega_c, d_c, \theta_c, d_T) \times Q_r \times \frac{\Omega_{PD}}{2\pi}$$

Number of photons incident on the cathode

$Q_{WLS} \times Q_{foil}$

PD aperture as viewed by the bright spot

$$N_{\gamma,reflected} = N_{\Omega,reflected} \times A(d_c, \theta_c, d_T)/cos(\theta_c)$$

PD-location + border correction

- LArSoft suits Semi-Analytic model simulation incorporating all of the extensions:
  - LAr and LXe wavelengths (doping)
  - Direct and Reflected light (foils)

Fast optical model: Semi-Analytic

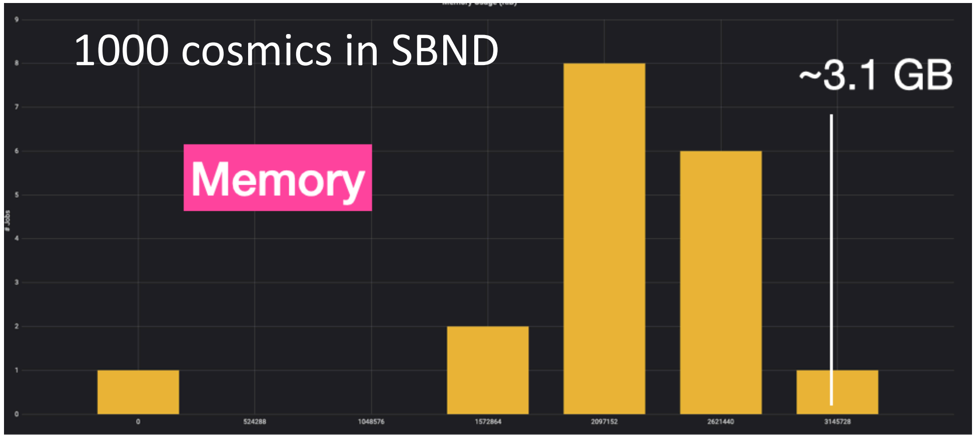
sbndcode / sbndcode / LArSoftConfigurations / opticalsimparameterisations_sbnd.fcl

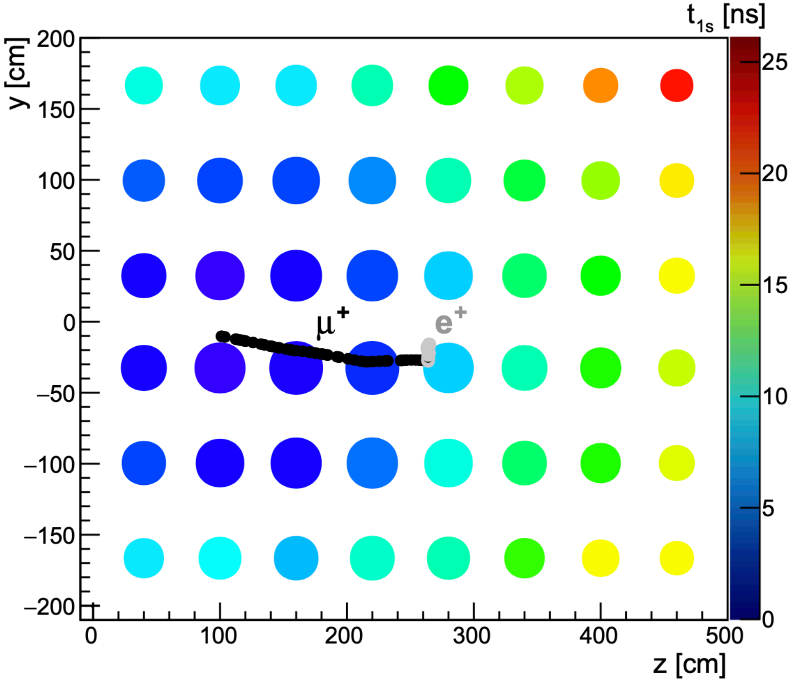
```
# ***********************************************************************************
#          PARAMETERS SETS FOR SEMI-ANALYTIC SIMULATION ARE DEFINED HERE
# ***********************************************************************************
BEGIN_PROLOG


# VUV/DIRECT LIGHT: TIMING PARAMETERISATION

# VUV/DIRECT LIGHT: NUMBER OF HITS CORRECTIONS
# SBND Gaisser-Hillas
# Includes Wires
# ***********************************************************************************
#  VIS semi-analytic model, specific to SBND
# ***********************************************************************************

# VISIBLE/REFLECTED LIGHT: TIMING PARAMETERISATION

# VISIBLE/REFLECTED LIGHT: NUMBER OF HITS CORRECTIONS
```

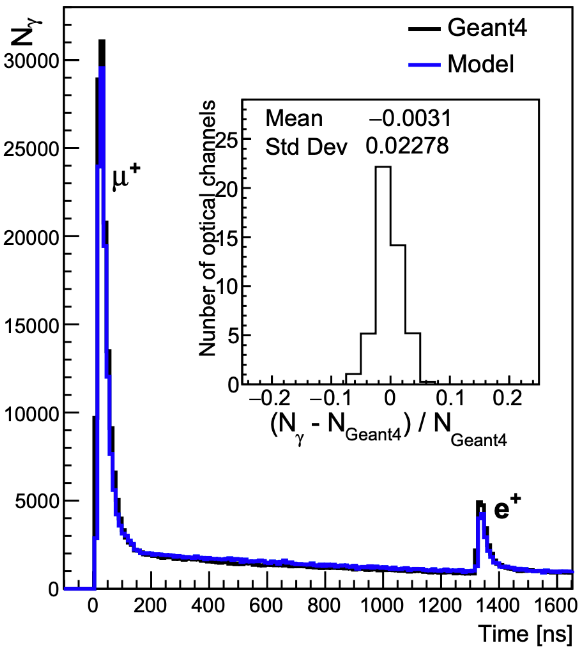
Detector specific

Semi-Analytic model performance

- **Solves the problems of other approaches**
- Photon propagation with no impact on memory (RAM) or simulation (CPU) time
- It models both (N_γ, time)
  - used in SBND and DUNE-SP simulations

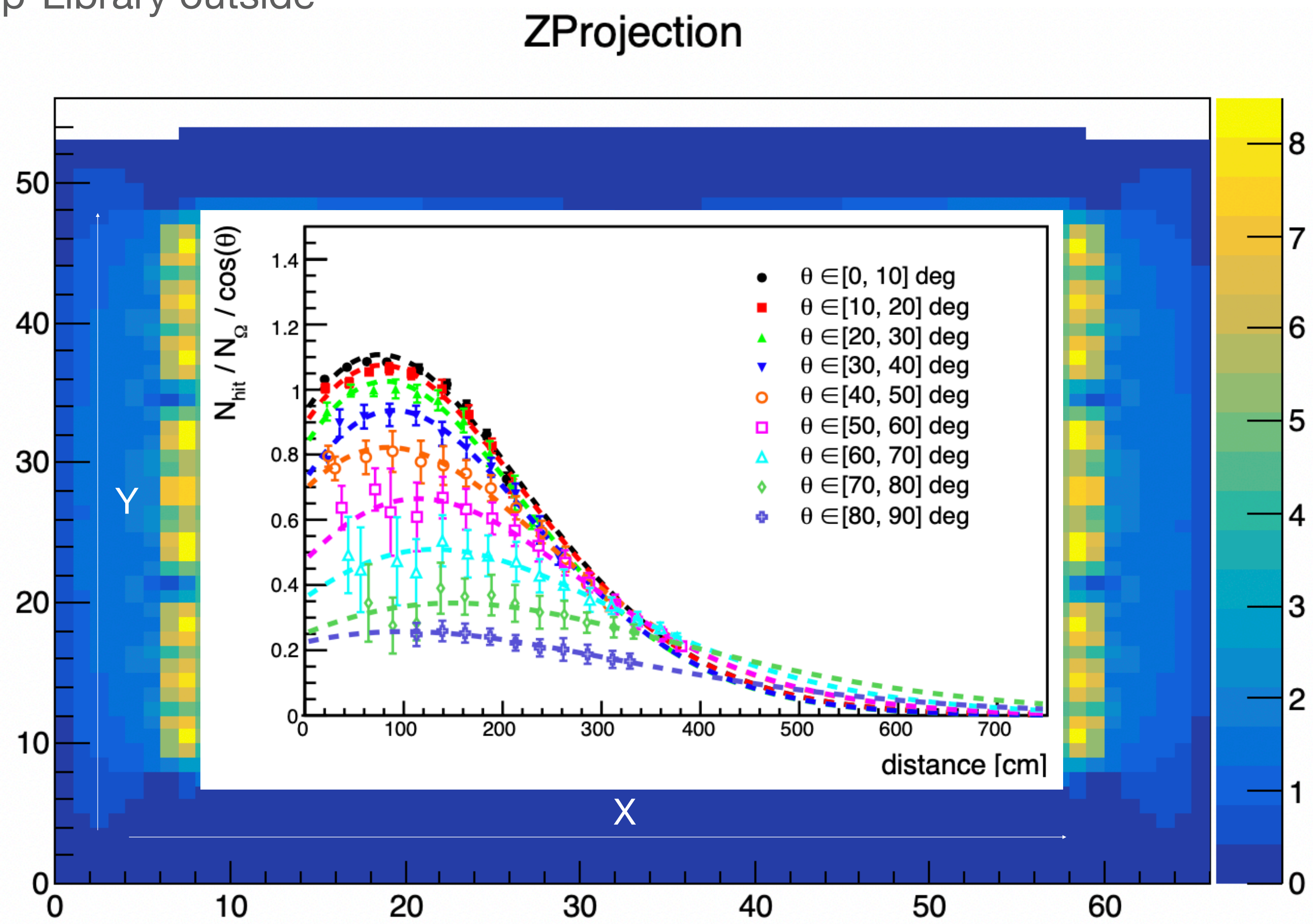






Hybrid model for the photon propagation

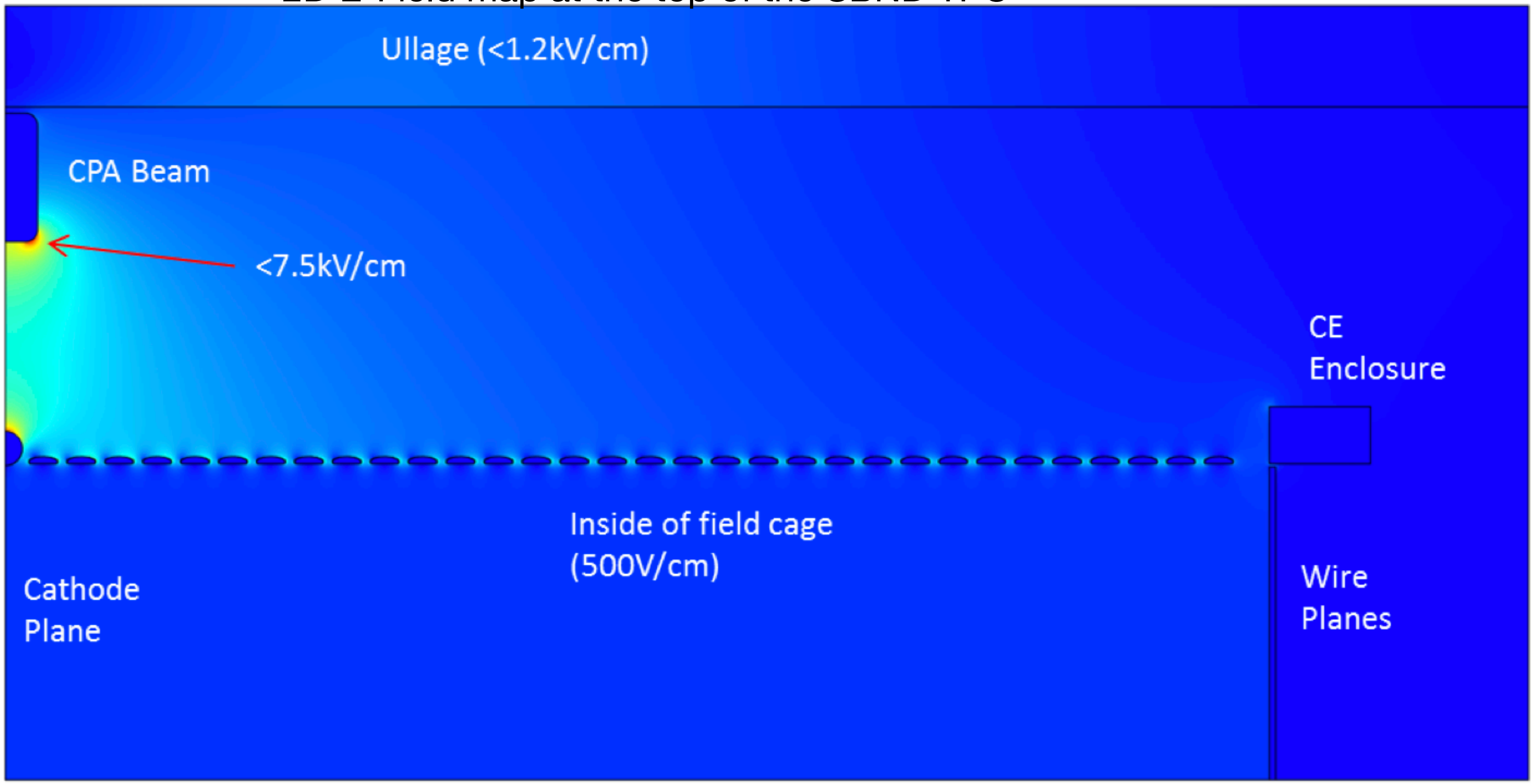
- Semi-Analytic model has a limitation: only applicable inside the active volume (geometric approach)
- Simple idea to overcome the problem ⇒ **Hybrid model**: Semi-Analytic model inside the TPC + Op-Library outside



E-Field map in a TPC (SBND case example)

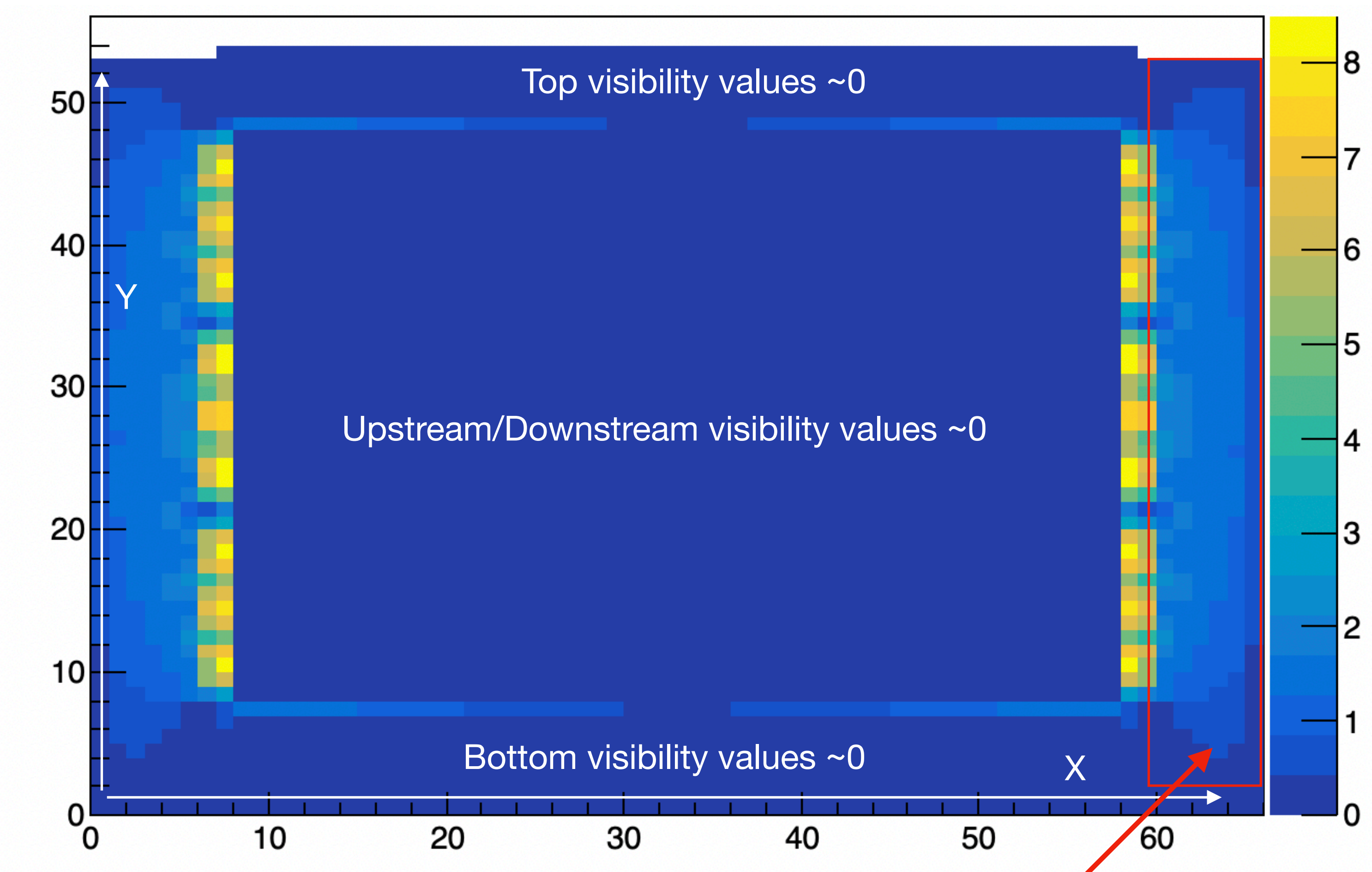
Warning: Light yield strongly depends on the Electric Filed value

2D E-Field map at the top of the SBND TPC SBN-doc-1317



- Inside the active volume EF is constant @ 0.5 kV/cm (nominal)
- In the top of the TPC EF values range from few kV/cm at the CPA location decreasing to ~0 at the APA.
- Behind APA (PD-plane) EF = 0 is a good approximation (almost constant)

E-Field x Visibility map in a TPC (SBND case example)



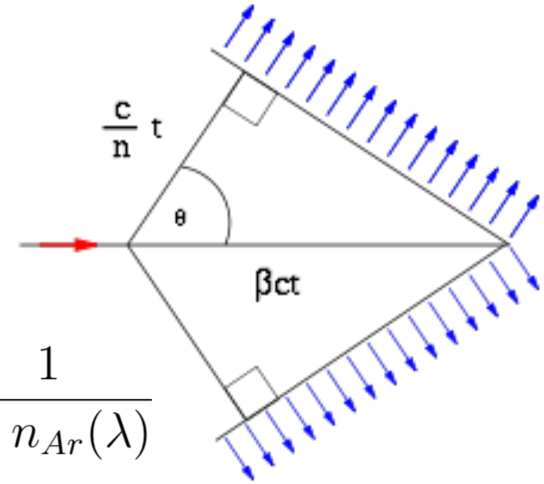
- Only behind APA visibilities are significant
- Current EF model in the hybrid approach: **500V/cm inside the TPC & 0V/cm anywhere else**

sbndcode / sbndcode / JobConfigurations / standard / standard_g4_sbnd.fcl

```
physics:
{

  producers:
  {
    rns: { module_type: "RandomNumberSaver" }

    # A dummy module that forces the G4 physics list to be loaded
    loader: { module_type: "PhysListLoader" }

    # The geant4 step
    largeant: @local::sbnd_larg4

    # Creation of ionization electrons and scintillation photons, inside the active volume
    ionandscint: @local::sbnd_ionandscint

    # Creation of ionization electrons and scintillation photons, outside the active volume
    ionandscintout: @local::sbnd_ionandscint_out

    # Light propogation inside the active volume
    pdfastsim: @local::sbnd_pdfastsim_par

    # Light propogation outside the active volume
    pdfastsimout: @local::sbnd_pdfastsim_pvs

    # Electron propogation
    simdrift: @local::sbnd_simdrift

    # Truth-level reconstruction
    mcreco: @local::sbnd_mcreco

  }
```

(Parenthesis): Cherenkov radiation in LAr

- A particle propagating in a medium with velocity greater than that of light in the medium produces an electromagnetic shock-wave with conic wavefront



- Photons are emitted with a precise angle with respect to particle direction

$$\cos\theta_{\check{C}} = \frac{1}{\beta \cdot n_{Ar}(\lambda)}$$

NIMA 516 (2004) 348–363

$$\frac{d^2N}{d\nu dx} = \frac{2\pi\alpha}{c}\sin^2\theta_{\check{C}}$$

$$\Rightarrow \int_{109\,nm\ \text{(LAr absorbed)}}^{600\,nm\ \text{(hard to detect)}} \Rightarrow \quad R_{\check{C}} = \frac{dN_{\check{C}}/dx}{dN_{scint}/dx + dN_{\check{C}}/dx} = 2.4\%$$

→ Can be considered a second order effect with respect to scintillation light emission

sbndcode / sbndcode / LArSoftConfigurations / opticalproperties_sbnd.fcl

```
EnableCerenkovLight: false # Cerenkov light OFF by default
```

Detection

Wavelength shifter in LArSoft

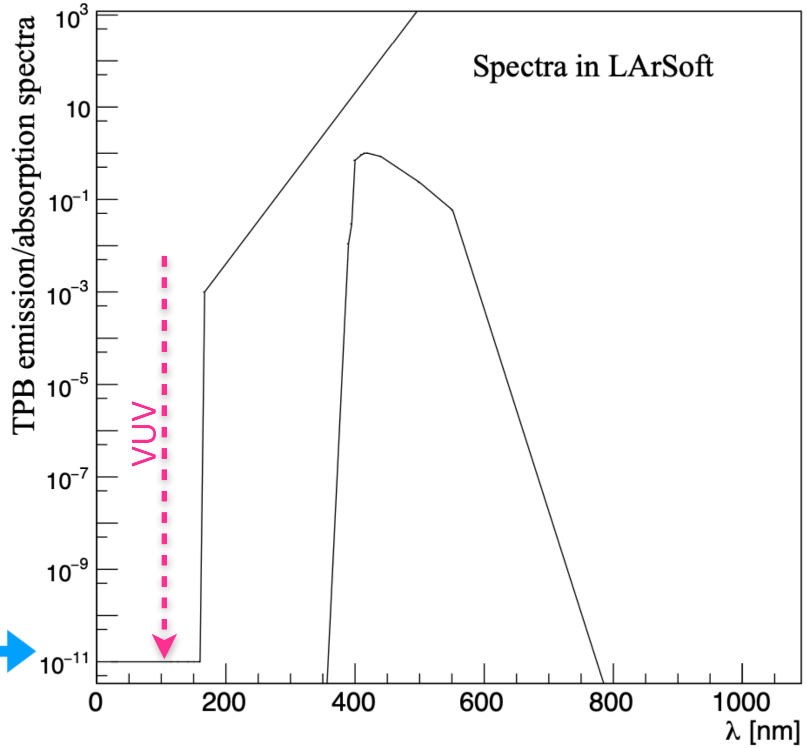
Processes handled by `G4OpWLS`:

- Initial photon killed and a new one created with different wavelength
- User must provide:

• Absorption length as function of photon energy

• Emission spectrum as function of photon energy

• Time delay between absorption and re-emission



The **WLSABSLENGTH** defines the absorption length which is the average distance travelled by a photon before it is absorbed by the TPB.

lardataalg / lardataalg / DetectorInfo / larproperties.fcl

```
# WLS - TPB properties original tpb [0.0, 0.0, 0.0, 0.0588,0.235, 0.853, 1.0,1.0,0.9259,0.704
TpbEmmisionEnergies: [0.05,1.0,1.5, 2.25, 2.481, 2.819, 2.952,2.988,3.024, 3.1, 3.14,3.1807,
TpbEmmisionSpectrum: [0.0, 0.0, 0.0, 0.0588,0.235, 0.853, 1.0,1.0,0.9259,0.704,0.0296,0.011,
TpbAbsorptionEnergies: [0.05,1.77,2.0675, 7.42, 7.75, 8.16, 8.73, 9.78,10.69, 50.39]
TpbAbsorptionSpectrum: [100000.0,100000.0, 100000.0,0.001,0.00000000001,0.00000000001, 0.000
```

Wavelength shifter time delay

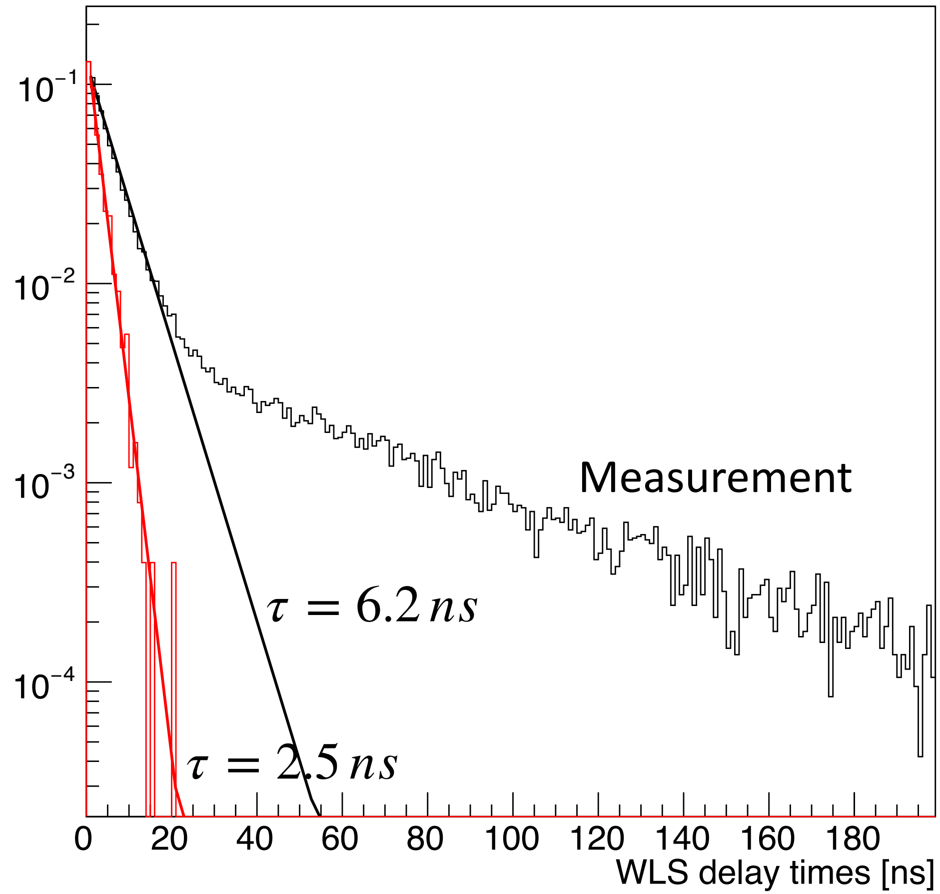
Geant4 (G4OpWLS class) only simulates Delta or Exponential model (none is the case for TPB)

PHYSICAL REVIEW C **91**, 035503 (2015)

TABLE I. Decay times and relative abundances of the components found in the decomposition into exponentials of the response function of TPB to 127 nm photons. Only statistical errors from the fit are quoted.

	Decay time (ns)	Abundance (%)
Instantaneous component	1–10	60 ± 1
Intermediate component	49 ± 1	30 ± 1
Long component	3550 ± 500	8 ± 1
Spurious component	309 ± 10	2 ± 1

- If we want to use the Geant4 class then we would have to approach it by a single exponential (~6.2 ns):
  - We know this is not what we measure
  - It would also require adding a line in OpticalPhysics (model switching not possible via .fcl).
- In SBND we don't use the Geant4 WLS time simulation.



Photon simulation output objects

lardataobj / lardataobj / Simulation / SimPhotons.h

```
// This structure contains all the information per photon
 // which entered the sensitive OpDet volume.

 class OnePhoton
 {
 public:
   OnePhoton();

   bool          SetInSD;
   TVector3      InitialPosition;
   TVector3      FinalLocalPosition; // in cm
   float         Time;
   float         Energy;
   int           MotherTrackID;
 };
```

```
class SimPhotons : public std::vector<OnePhoton>
```

```
class SimPhotonsLite
{
  public:
    SimPhotonsLite();
    SimPhotonsLite(int chan)
      : OpChannel(chan)
    {}

    int   OpChannel;
    std::map<int, int> DetectedPhotons;

    SimPhotonsLite& operator+=(const SimPhotonsLite &rhs);
    const SimPhotonsLite operator+(const SimPhotonsLite &rhs) const;

    bool operator==(const SimPhotonsLite &other) const;
};

// Define a OpDet Hit as a list of OpDet photons which were
// recorded in the OpDet volume.

class SimPhotons : public std::vector<OnePhoton>
```

- `SimPhotons` objects (collections of OnePhoton) save detailed information about each detected photon

- while `SimPhotonsLite` objects reduce memory and size at the price of keeping only the number of photons at a time-slot.

- The kind of object you want to save in your simulation is specified in the configuration file by the line:

```
services.LArG4Parameters.UseLitePhotons: true  # false to save SimPhotons
```

Detector effects

PMT digitisation: SBND case example

The PMT features included are: SER, electron transit time, transit time spread, saturation, baseline, dark noise, baseline noise, and pre-trigger.

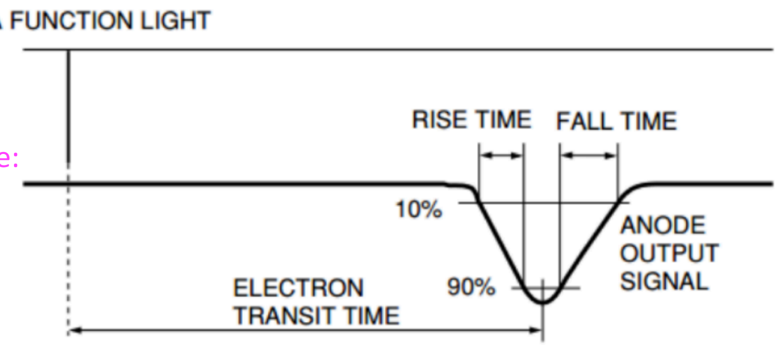
sbndcode / sbndcode / OpDetSim / **digi_pmt_sbnd.fcl**

8” Hamamatsu PMT - R5912

```
sbnd_digipmt_alg:
{
  PMTRiseTime:          3.8       #ns
  PMTFallTime:          13.7      #ns
  PMTMeanAmplitude:     0.9       #in pC
  PMTBaselineRMS:       1.0       #in ADC
  PMTDarkNoiseRate:     1000.0    #in Hz
  TransitTime:          55.1      #ns
  TTS:                  2.4       #Transit Time Spread in ns
  CableTime:            135       #time delay of the 30 m long readout cable in ns
  PMTChargeToADC:       -11.1927  #charge to adc factor
  PMTSaturation:        300       #in number of p.e. to see saturation effects in the signal
  PMTBaseline:          8000.0    #in ADC
  SinglePEmodel:          false   # false for ideal PMT response, true for test bench measured response
  PMTDataFile:            "OpDetSim/digi_pmt_sbnd.root" # located in sbnd_data

  MakeGainFluctuations: true
  GainFluctuationsParams: @local::FirstDynodeGainFluctuations
}
```

Ideal SER response: Not realistic!

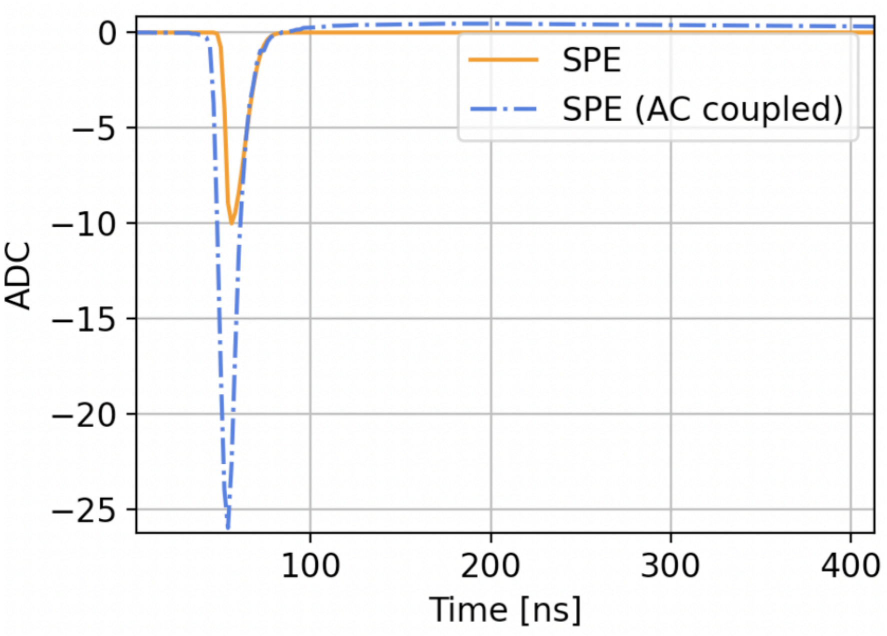
In the backup

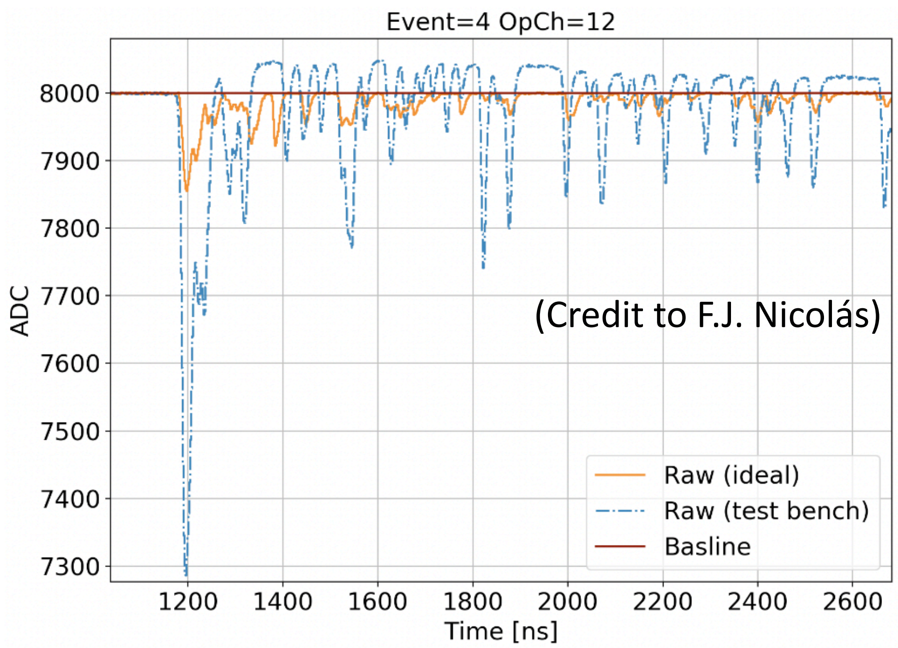


Single Electron Response (SER)

- About the single electron response, in general, there are two different cases [Left]:
  - Monopolar
  - Bipolar corresponding to an AC coupled device (to reduce the number of channels)

- Simulated waveforms using the two version of the SER are very different [Right]:
  - Bipolar signals can distort the baseline making not trivial its subtraction
  - This makes accurate light reconstruction a challenge ⇒ **Deconvolution** (Backup)





(Credit to F.J. Nicolás)

Reconstruction

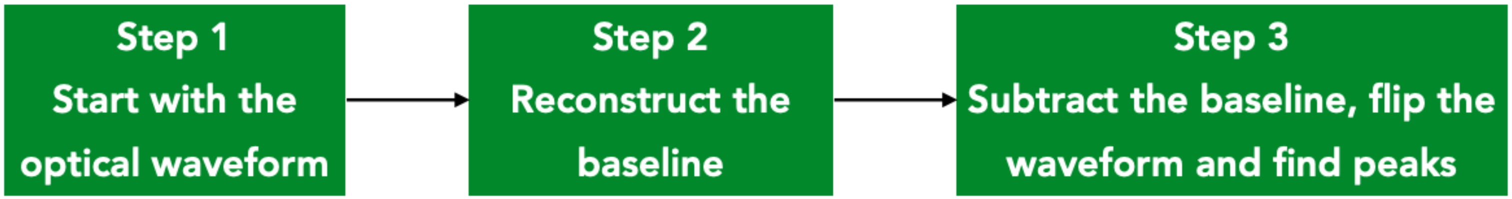
Detector specific

Same objects but algorithms might be different!

Optical signal reconstruction: OpHits

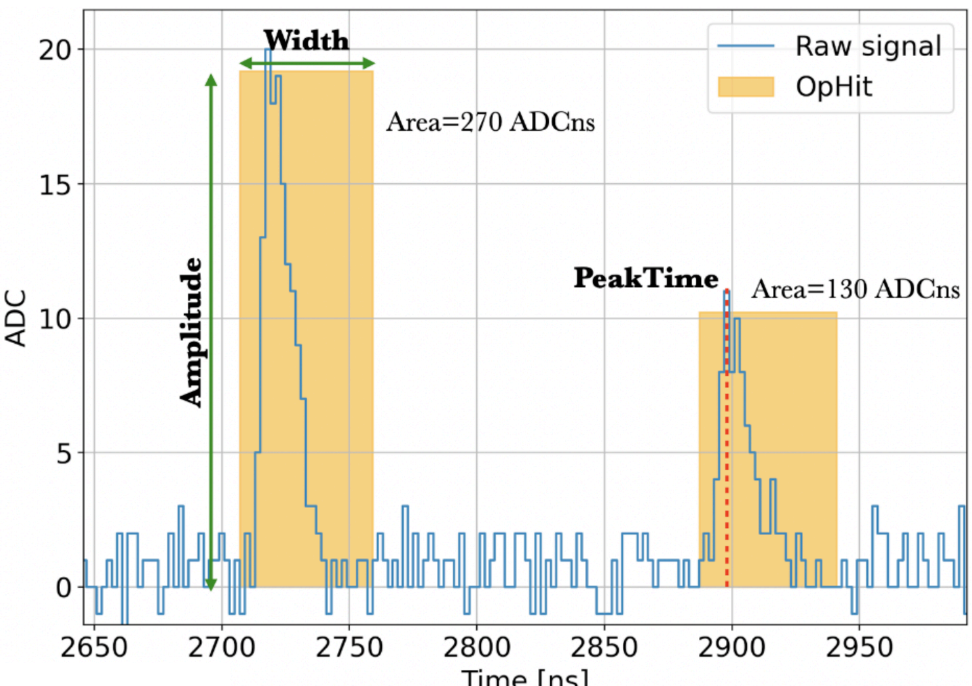
- The first stage of the optical reconstructions looks for pulses in the raw waveforms.
- The light pulses in LArSoft are stored in objects called OpHits.

(by M. Del Tutto)



(by F.J. Nicolás)

```
    OpHit(); // Default constructor

private:

    int                 fOpChannel;
    unsigned short      fFrame;
    double              fPeakTime;
    double              fPeakTimeAbs;
    double              fWidth;
    double              fArea;
    double              fAmplitude;
    double              fPE;
    double              fFastToTotal;
```

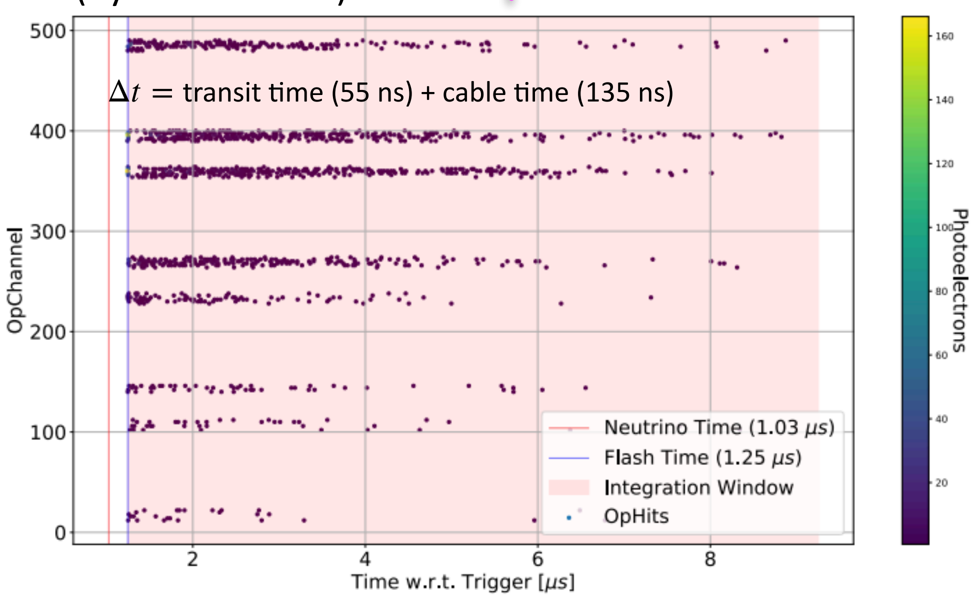


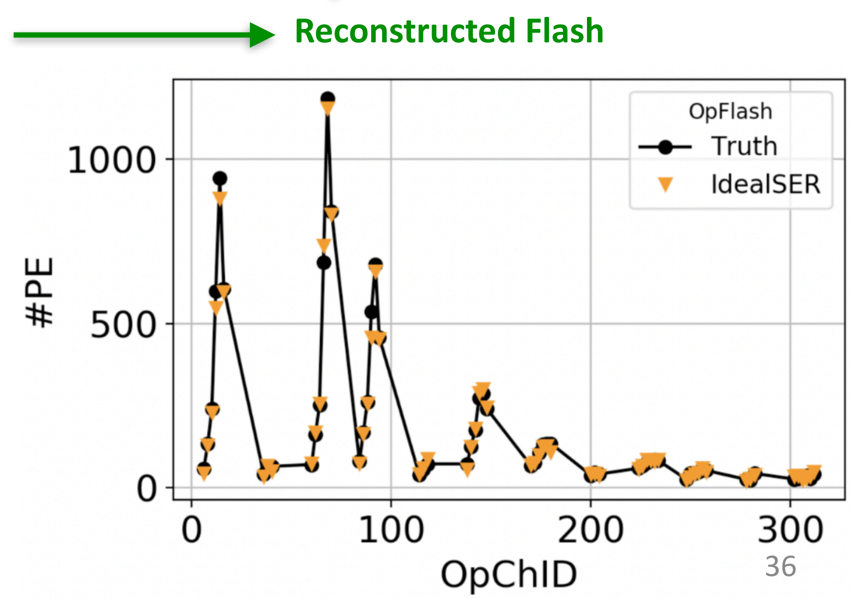
lardataobj / lardataobj / RecoBase / OpHit.h

Optical signal reconstruction: OpFlash

- **Goal of the flash reconstruction:** cluster the light that was produced by an interaction in the TPC. A flash is a cluster of PDs that see light at the same time (same interaction).
- **How it works in brief:** the algorithm clusters OpHits that are in time with each other:
  - Can configure how many PEs are required for a coincidence to be claimed (set to 6 PE), and what time resolution to use for claiming a coincidence (set to 10 ns).
  - Once the flash time is found, light is integrated for a fixed (configurable) window (set to 8 µs).
  - There is also a veto window (set to 8 µs): no other flashes can be claimed in this window.

(by M. Del Tutto)





Optical signal reconstruction: OpFlash

lardataobj / lardataobj / RecoBase / OpFlash.h

```
private:

    double                 fTime { 0.0 }; ///< Time on @ref DetectorClocksHardware
    double                 fTimeWidth;    ///< Width of the flash in time [us]
    double                 fAbsTime;      ///< Time by PMT readout clock
    unsigned int           fFrame;        ///< Frame number
    std::vector< double > fPEperOpDet;    ///< Number of PE on each PMT
    std::vector< double > fWireCenters;   ///< Geometric center in each view
    std::vector< double > fWireWidths;    ///< Geometric width in each view
    double                 fXCenter { NoCenter }; ///< Estimated center in x [cm]
    double                 fXWidth { NoCenter }; ///< Estimated width in x [cm]
    double                 fYCenter;      ///< Geometric center in y [cm]
    double                 fYWidth;       ///< Geometric width in y [cm]
    double                 fZCenter;      ///< Geometric center in z [cm]
    double                 fZWidth;       ///< Geometric width in z [cm]
    double                 fFastToTotal;  ///< Fast to total light ratio
    bool                   fInBeamFrame;  ///< Is this in the beam frame?
    int                    fOnBeamTime;   ///< Is this in time with beam?
```

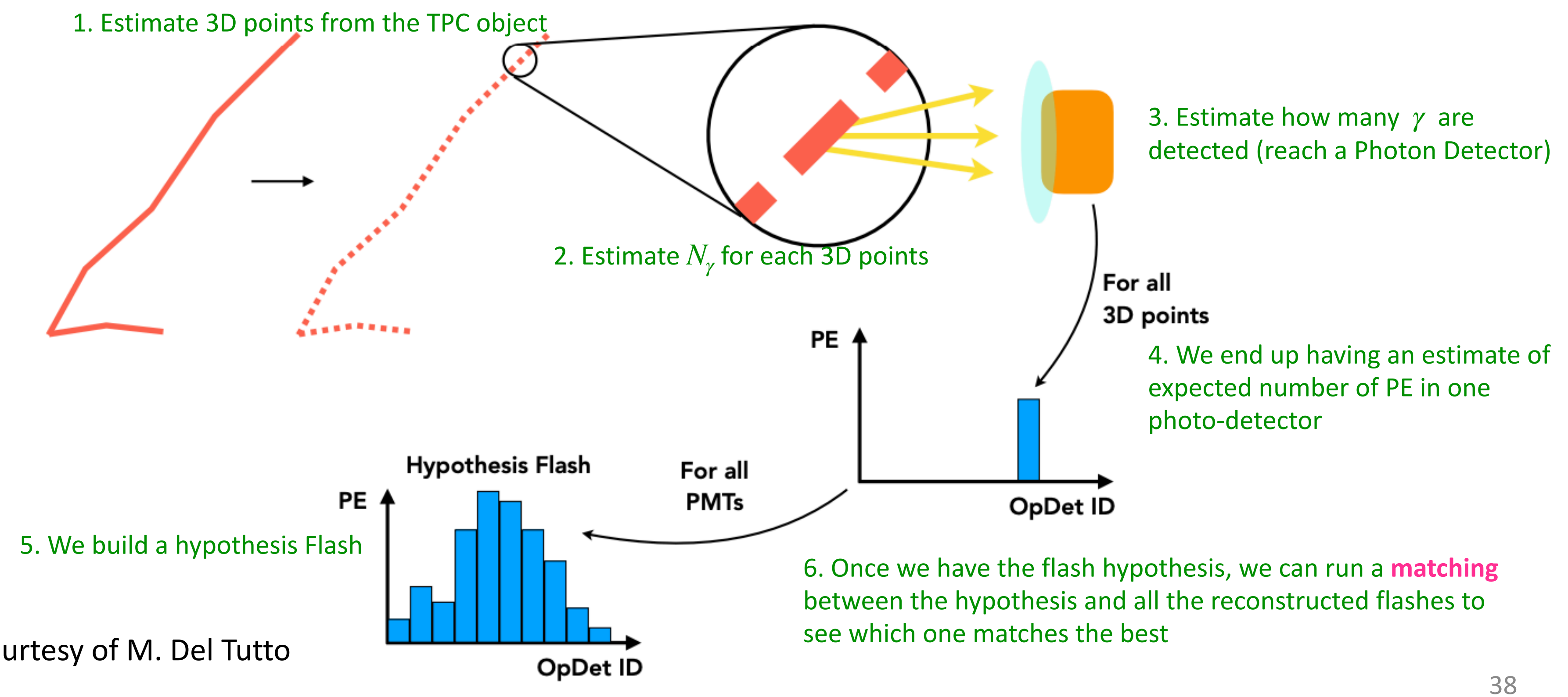
Flash Matching: `OpT0Finder` example

Flash matching goals:

- Identify a neutrino interaction from cosmic backgrounds
- Provide T_0 for each TPC interaction

The two ingredients for flash matching:

- Reconstructed Flashes
- TPC Objects (reconstructed objects in the TPC, i.e. Pandora's `recob::Slice`) ⇒ The flash matching code should match a TPC Object with its flash



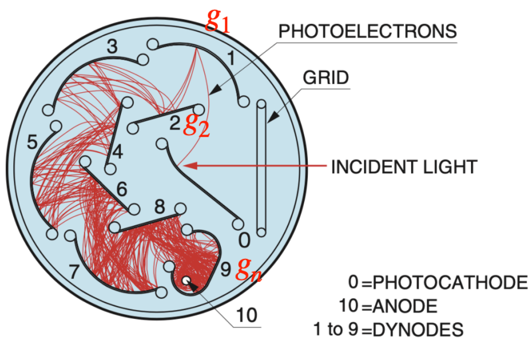
Courtesy of M. Del Tutto

Have fun!

PMT Gain fluctuation

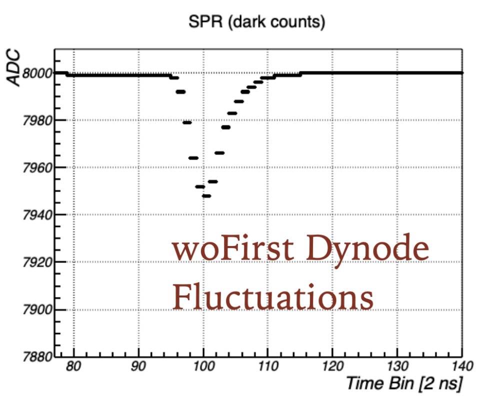
(Slide from F.J. Nicolás)

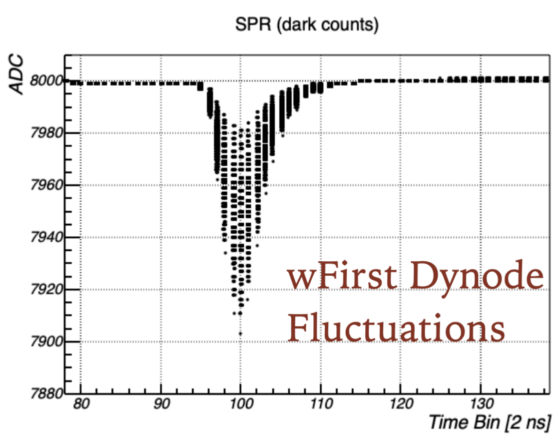
- Number of secondary electrons generated at each dynode: random variable



- Toy example:
  - Consider 1e hits one of the dynode (with gain g_i)
  - On average $< m > = g_i$ with a standard deviation $\sigma = \sqrt{g_i}$
  - This leads to fluctuations in the SER

- Approximations (approach directly taken from icaruscode) ⇒ Only takes into account fluctuations at first dynode: $\longrightarrow \frac{\sigma_N^2}{< N >^2} = \frac{1}{g_1} + \frac{1}{g_1 g_2} + \ldots \frac{1}{g_1 g_2 \cdots g_n}$
  - <N>: average number of electrons at the end of the multiplication chain (anode)
  - σ_N^2: fluctuations in the total number of electrons at the anode





sbndcode / sbndcode / OpDetSim / PMTAlg / **pmtgainfluctuations_config.fcl**

(Parenthesis): Light Signal Deconvolution

- In SBND we have PMT (and XARAPUCA) readout with **AC coupling**: bipolar SER ⇒ This makes accurate light reconstruction **a challenge**

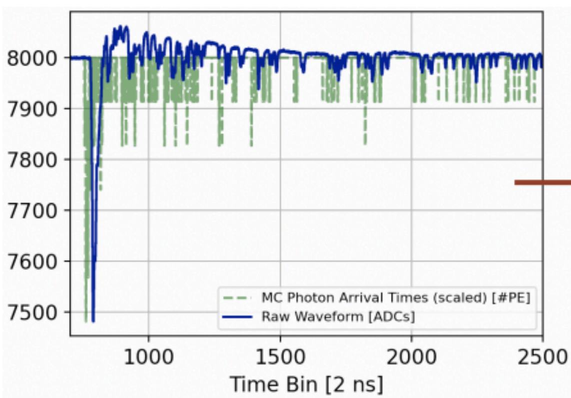
(by F.J. Nicolás)

➤ OpDeconvolution module (in brief): sbndcode / sbndcode / OpDetReco / **OpDeconvolution** /

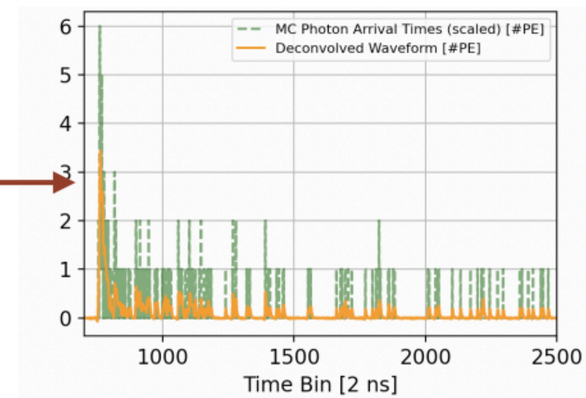
Starts with the **raw::OpDetWaveform** objects (from DetSim stage)

OpDeconvolution module

Produces deconvolved signals (also **raw::OpDetWaveform** objects) to be fed to downstream reco algorithms

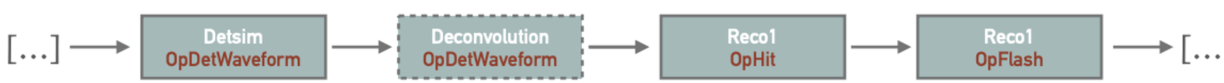


➤ Methods to:
- ➤ Perform deconvolution (using FFT)
- ➤ Baseline estimator
- ➤ Reduce noise (waveforms smoothing and filtering in the frequency domain)



Downstream reconstruction chain:

- Use standard OpHit and OpFlash finder algorithms to recover pulses ⇒ #PE, t0… using the deconvolved signals



- OpHit and OpFlash configuration file with refined parameters for deconvolved waveforms

⇒ **Performance: resolution better than ~5% and unbiased at the level of few %**