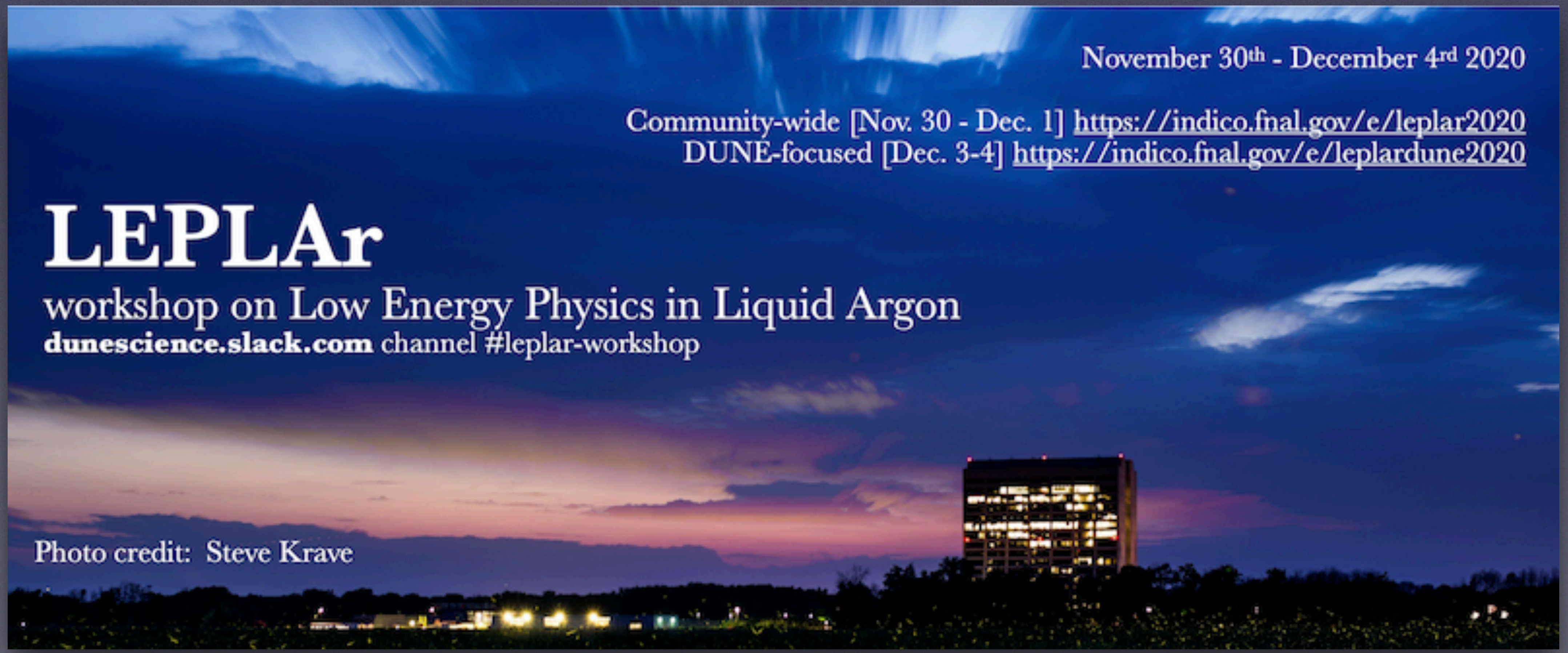
Enlarging the DUNE Physics Scope with

An Enhanced Photon Detection System in the VD layout (proposed for future DUNE FD Modules)



Flavio Cavanna - FERMILAB

LArTPC technology approaches the limits of its *full reconstruction capability** when event energy falls below the ~ten(s) MeV range:

- *This is where an important part of rare UG Physics may lie*

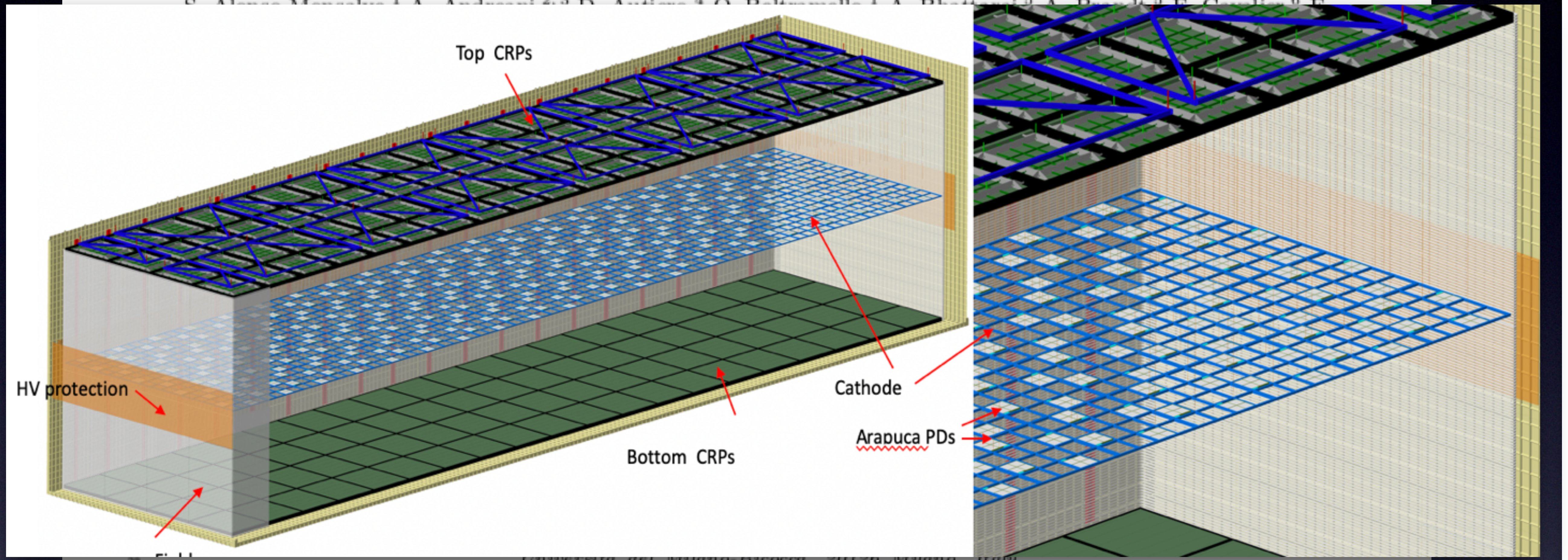
- *This is where traditional large Volume Liq. Scintillator UG experiments successfully operate - e.g. Borexino,* ***or were proposed - e.g. LENA***

While developing the (new) **VD LAr detector concept** for **DUNE FD(UG) Module** ≥ 2, exploiting abundant LAr scintillation light *(complementary to ionization charge)* appeared as a "natural" way to enhance/extend detection sensitivity for UG low-energy rare events.

The key point is to extend PD Optical Coverage as close to 4π as possible: to embed it into LArTPC layout is a big technological challenge.

* *complete Topology (vtx, energy, position, direction, ptcl. Id.) - En. Threshold in* E_{dep} *can be much lower, in the ~tens keV, depending on S/N*

Next-generation LArTPC Detector Technology for the Deep Underground Neutrino Experiment: a Vertical Drift Single-phase Solution with Perforated PCB Anode



(Dated: November 30, 2020)

This dynamic author list will be updated regularly.

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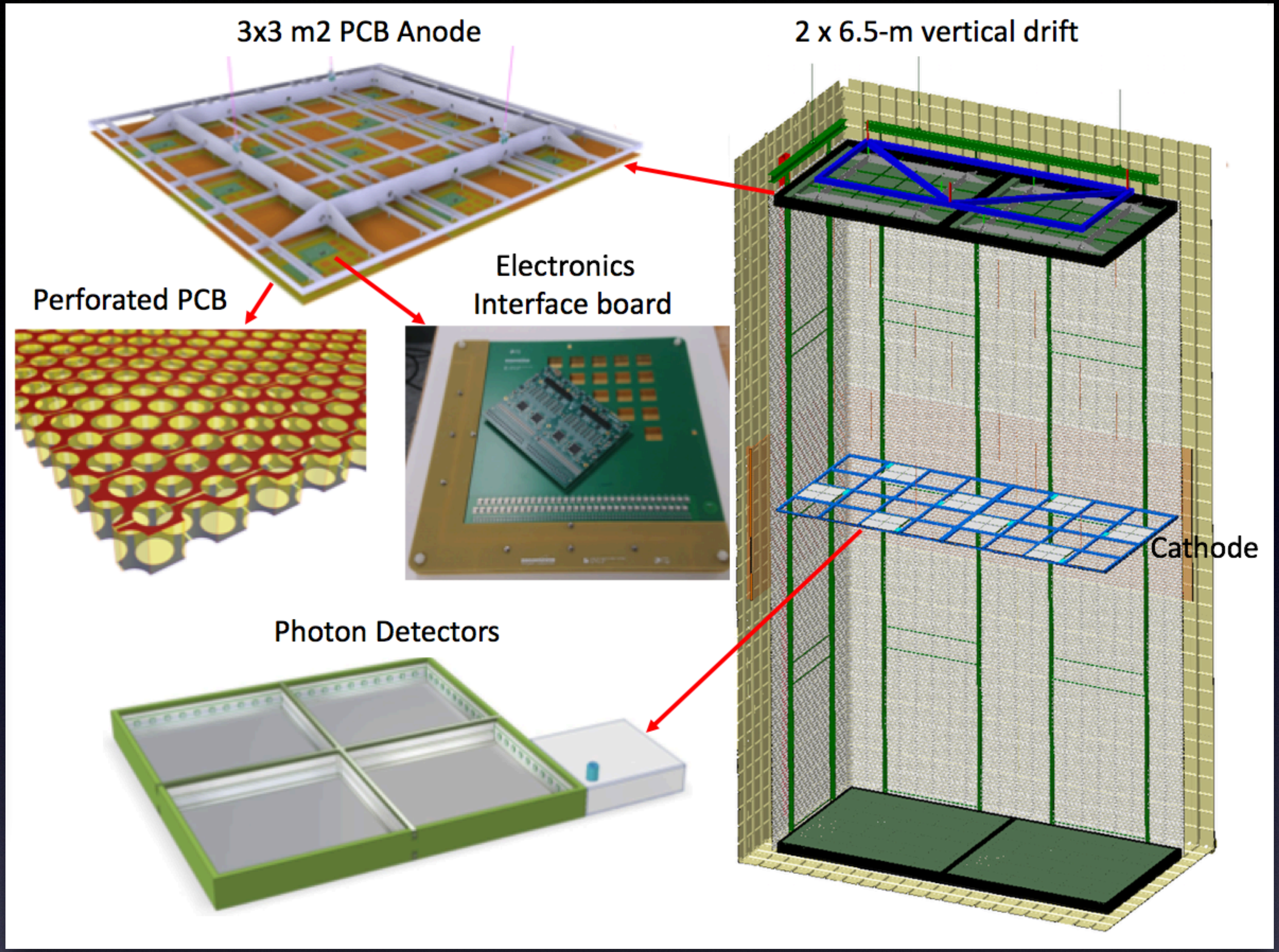


Next-generation LArTPC concept:

a Vertical Drift Solution with PCB based Charge Readout
complemented by a robust X-ARAPUCA Photon Detection System

Conceptual design for a $\sim 4\pi$ PD System for the VD LAr Volume

- ***PDS cannot be located at the Anode Plane (as in the DUNE SP Module#1) !***
- If a solution for operating a PD on HV surfaces is found:

PD Active Optical Coverage distributed onto 5 sides of the LAr Volume (Cathode side and 4 Field Cage sides)

+

PD Passive Optical Coverage (reflector) onto Anode side (laminated on perforated PCB)

+

Xe doping (minimize Rayleigh scatter for light at far distance)

*This would allow **~4π coverage**:*

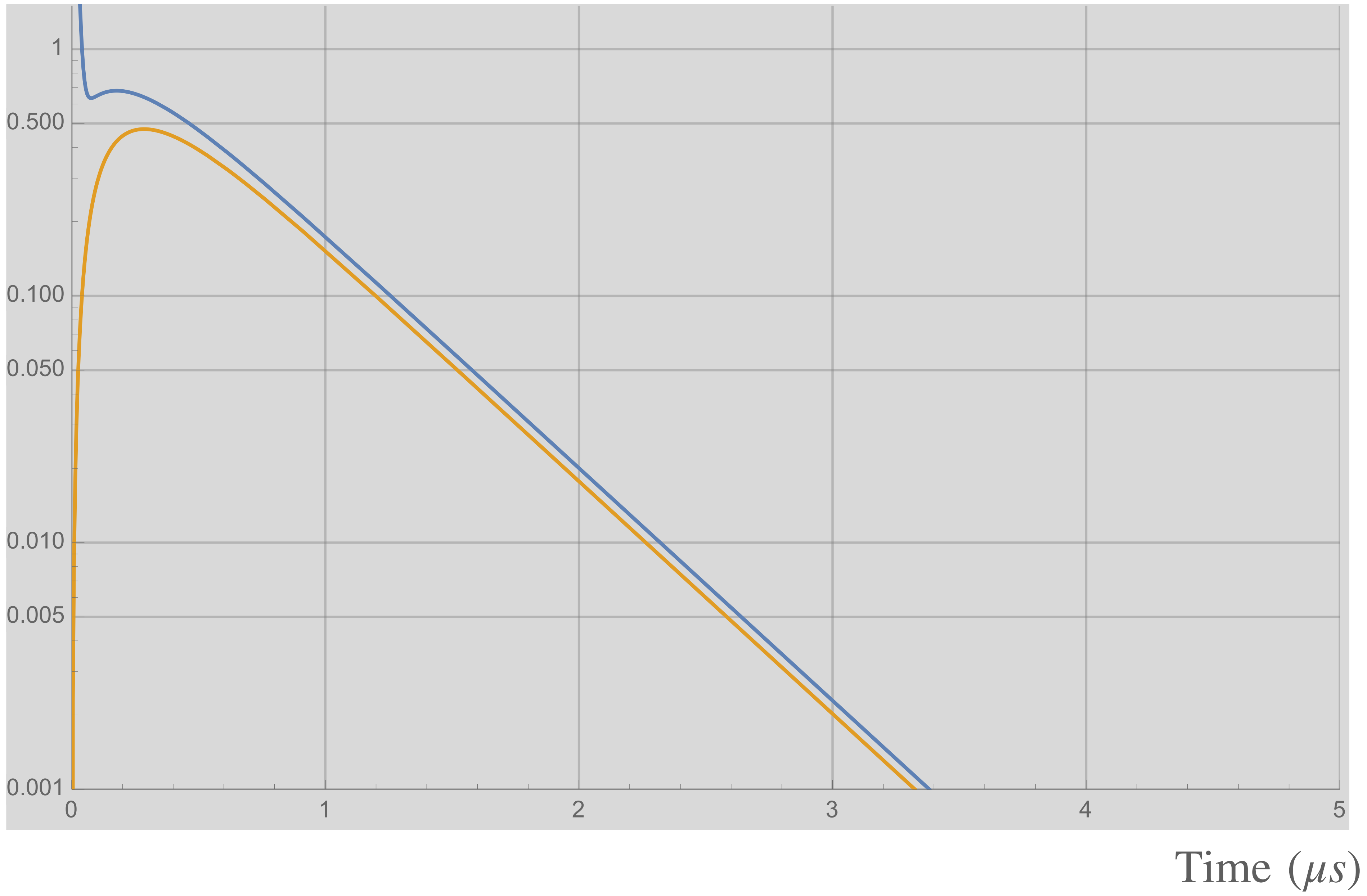
⇒ ~uniformity of response, low detection threshold, energy resolution and position resolution capability

It would be a second detector - for Ar Light Signals - complementary to LArTPC (directionality):

- *complete exploitation of LAr features (collect all energy deposited)*
- *Guarantee highest Live Time (PD active also when LArTPC may be OFF for purity drop/maintenance, HV issues/ maintenance,..) very relevant for UG Physics*
- *Start data taking (SN observer) six months/one year before LArTPC (while LAr filling)*

Baseline assumptions here are:

- Liquid Scintillator: **Ar + Xe(10 ppm)** [residual impurity: $[N_2] < 1$ ppm, $[O_2]$ negligible $\Rightarrow \lambda_{Abs} \geq 30$m]. Photon Yield (mip, nominal EF): $Y_{ph}(\mathrm{Ar}) \simeq 6k$ ph/MeV, $Y_{ph}(\mathrm{Xe}) \simeq 19k$ ph/MeV ($\lambda_R(\mathrm{Ar}) \simeq 1$m, $\lambda_R(\mathrm{Xe}) \simeq$ 7m).
- Photo-collector: **X-ARAPUCA technology** (light trapping by dichroic filters and 2-stages WLS), sensitive to both Ar VUV light (128 nm) and Xe UV light (147 and 175 nm), detection efficiency $\epsilon_D \simeq 3\%$.
- Photo-sensor: **SiPM/MPPC** Si avalanche photodiode micro-cell array, $6 \times 6\mathrm{mm}^2$ area, single-photon sensitive, PDE(430 nm)$\simeq$ 40%, SNR$\geq$ 5. Cold electronics read-out (active ganging + shape&noise filtering + digital conversion& transmission).



(Ar_S, Ar_T+ArXe+Xe) & (Xe)
detectable Light Time Distribution

Where's the challenge ??

Operating PD on HV surface

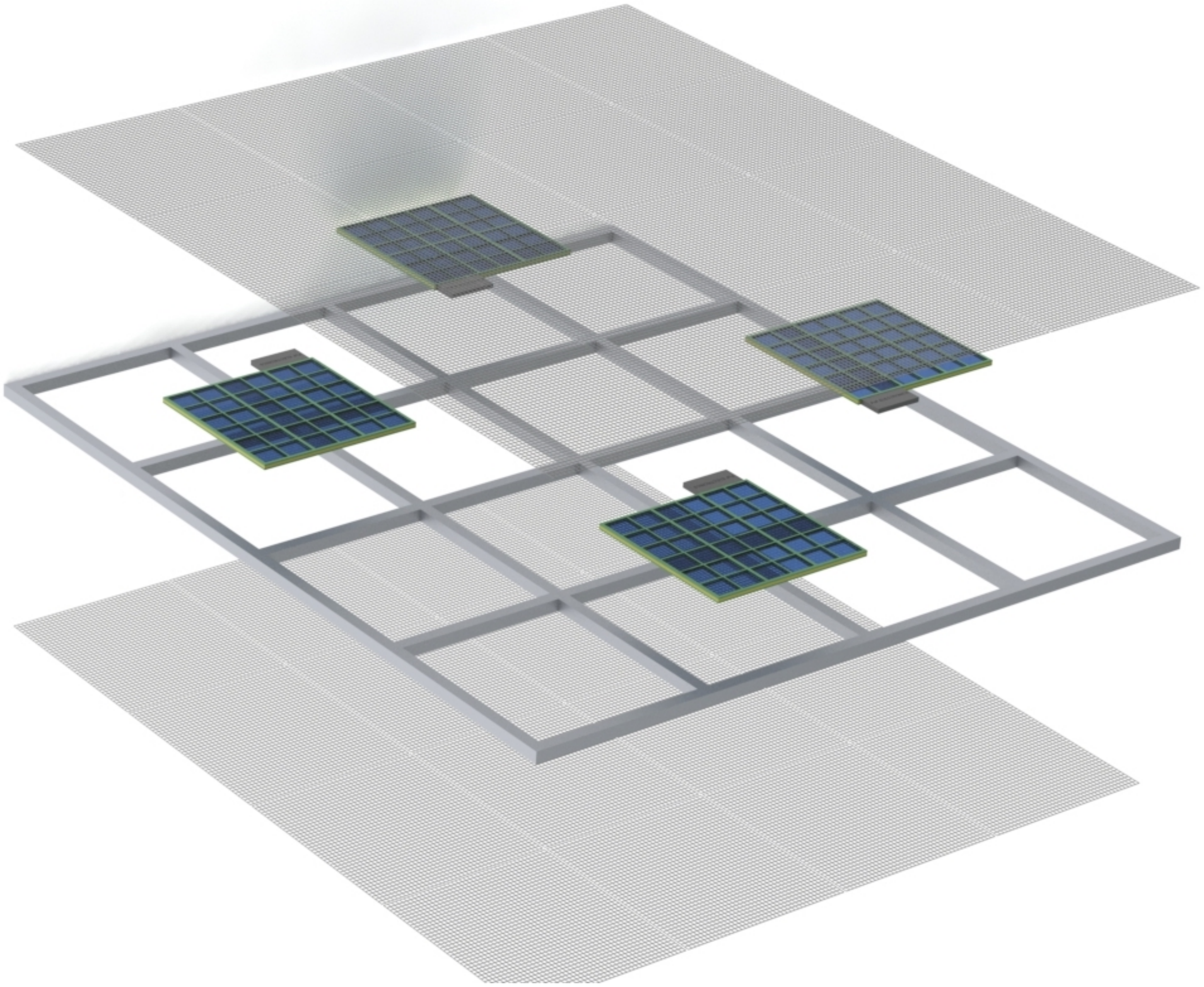
- requirements, base solutions, alternatives
  - ✳ PD based on SiPM (low Bias V, minimal occupancy)
  - ✳ SiPM Bias Voltage Supply (IN), SiPM transmit Signal (OUT)
    - ✳ **PoF (Bias V) Receiver & PoF (Signal) Transmitter**
      - ✳ **PoF Receiver (Bias V) & *WiFi/RF (Signal) Transmitter***
  - ✳ **SiPM Cold Electronics** (if used, it also requires Power => more from PoF receiver)

Major **R&D**

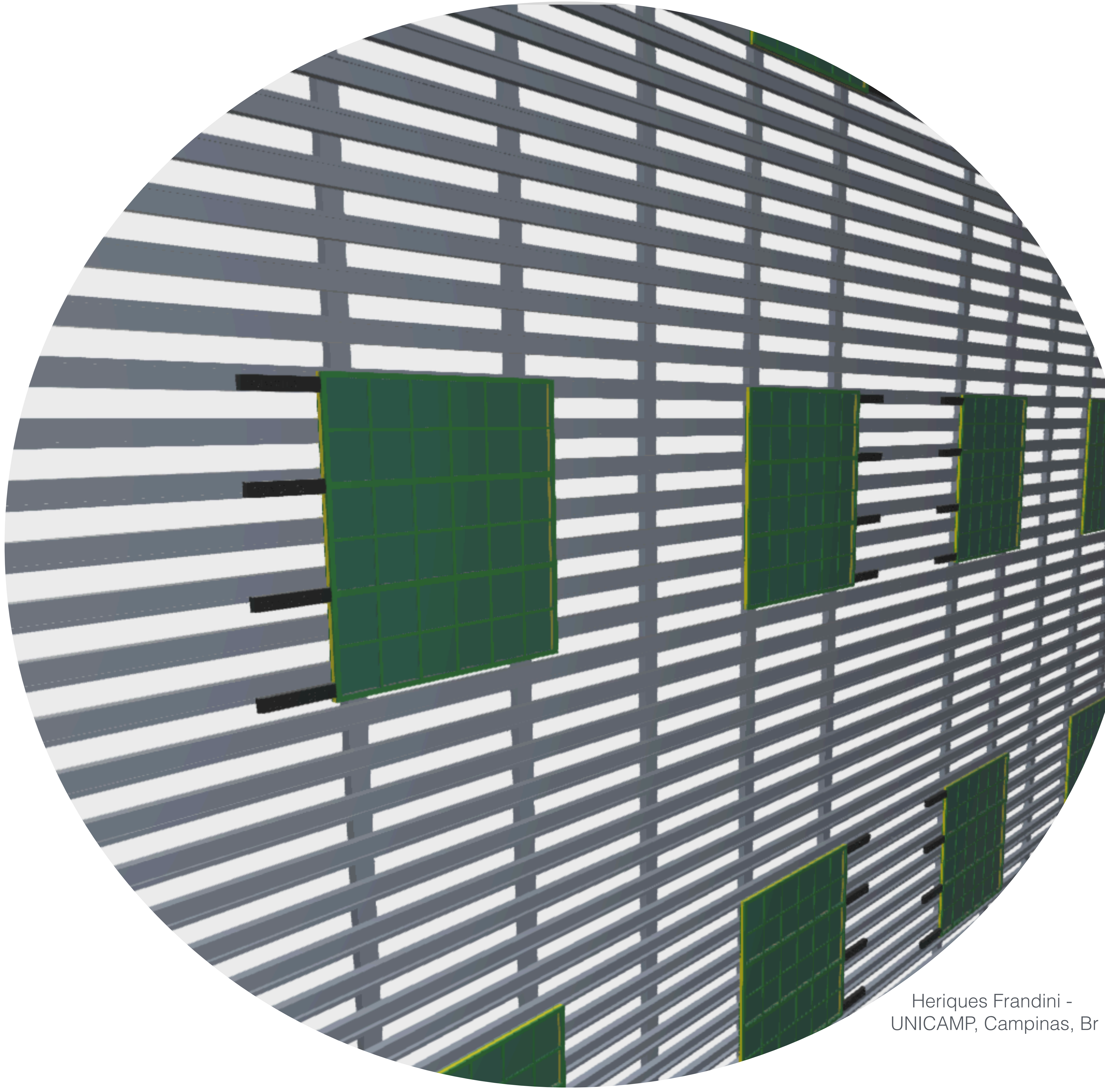
- Detector design and coverage: existing (X)ARAPUCA technology with SiPM photosensors is suitable for this application (flexible design opposite to PMT, **optimization for Xe light**)] **R&D**

- Fiber Routing (IN and OUT)] **Design Effort**

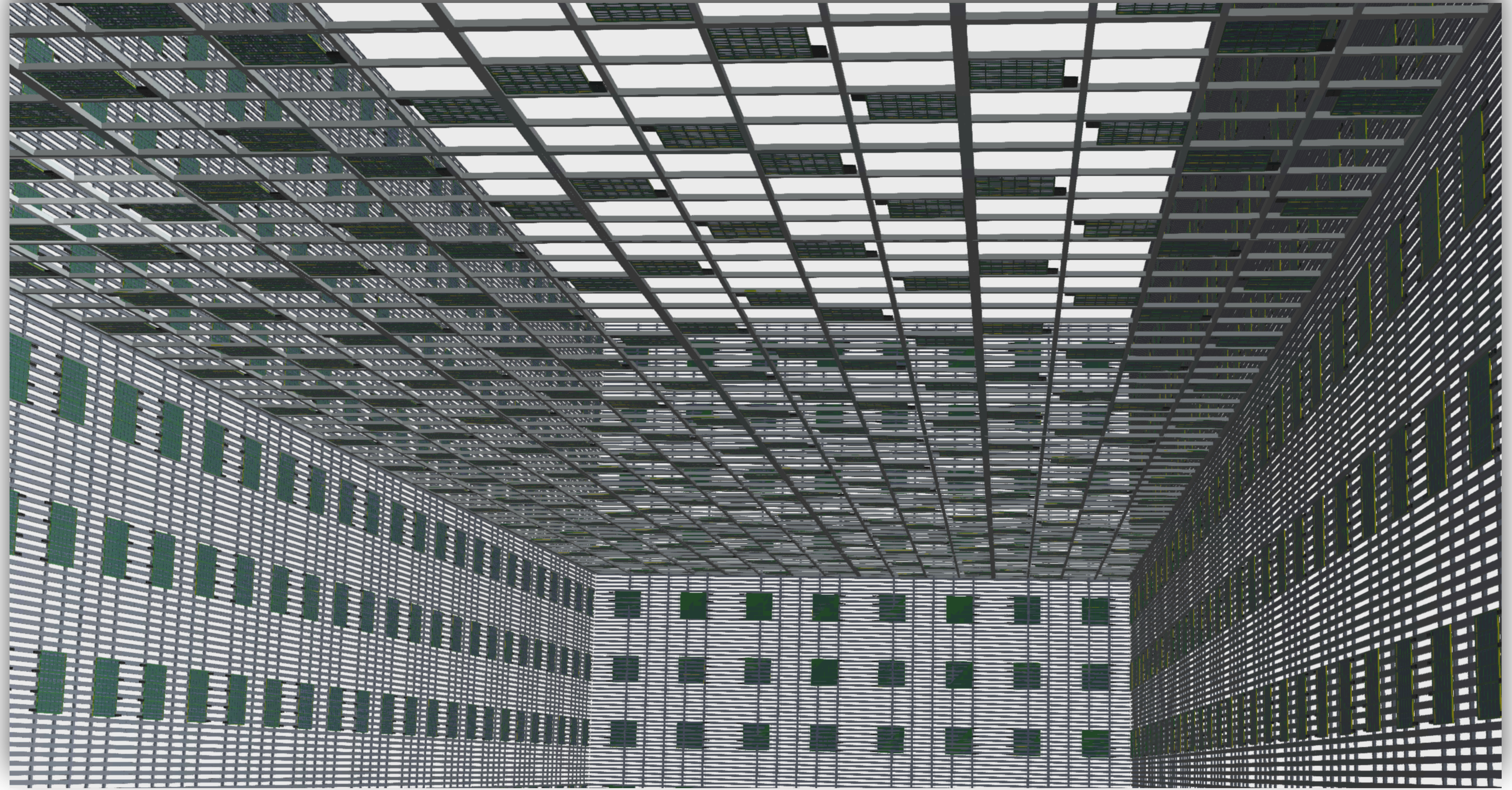
$\sim 4\pi$ PD System design for the VD LAr Volume



Photon Detector into the Cathode frame under conductor mesh (exploded view)

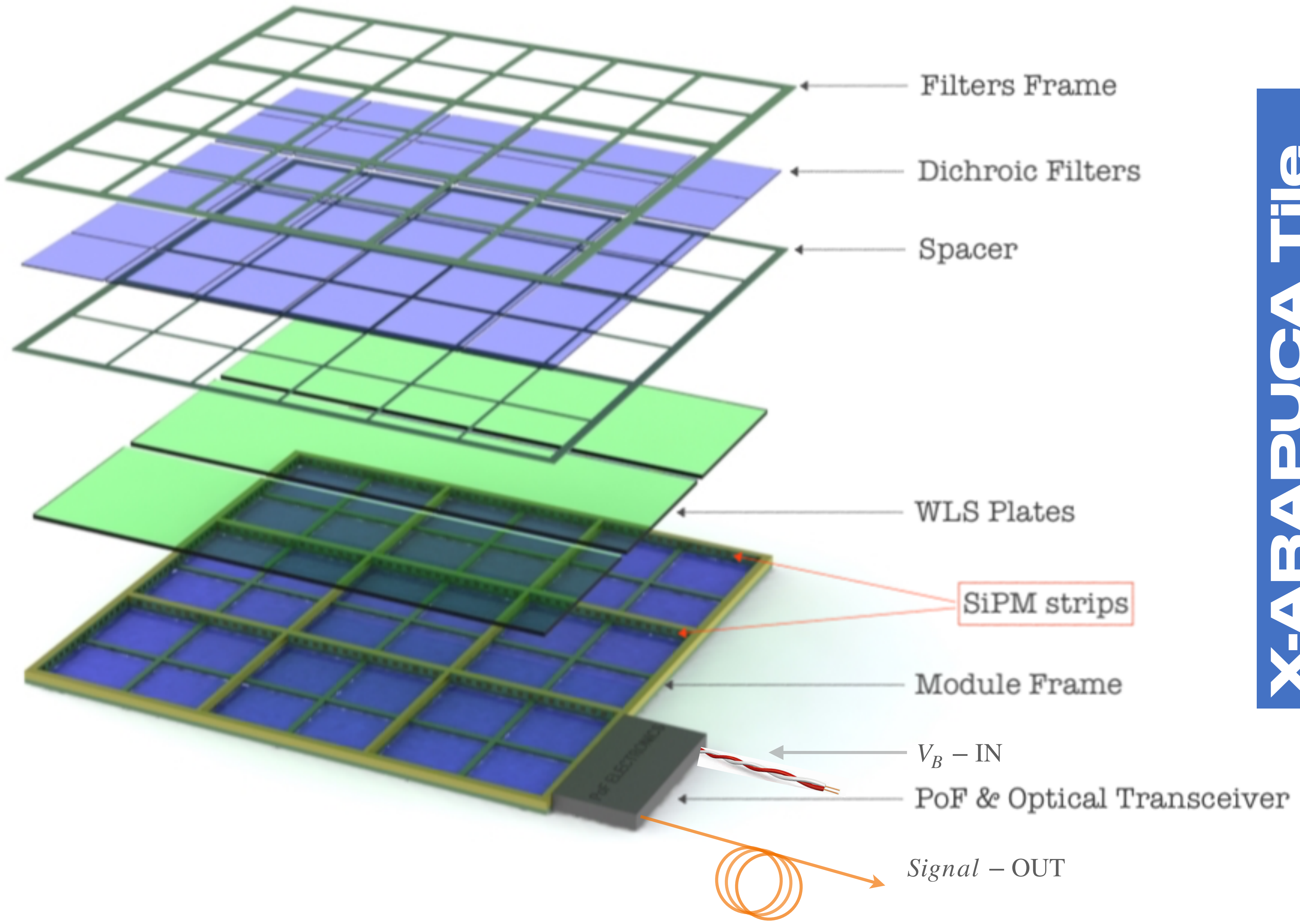


Photon Detectors hanging on Field Cage Walls



Heriques Frandini - UNICAMP, Campinas, Br

D. Totani, F.Terranova, H. Chen, M. Verzocchi, B. Yu, W. Pellco, FLC



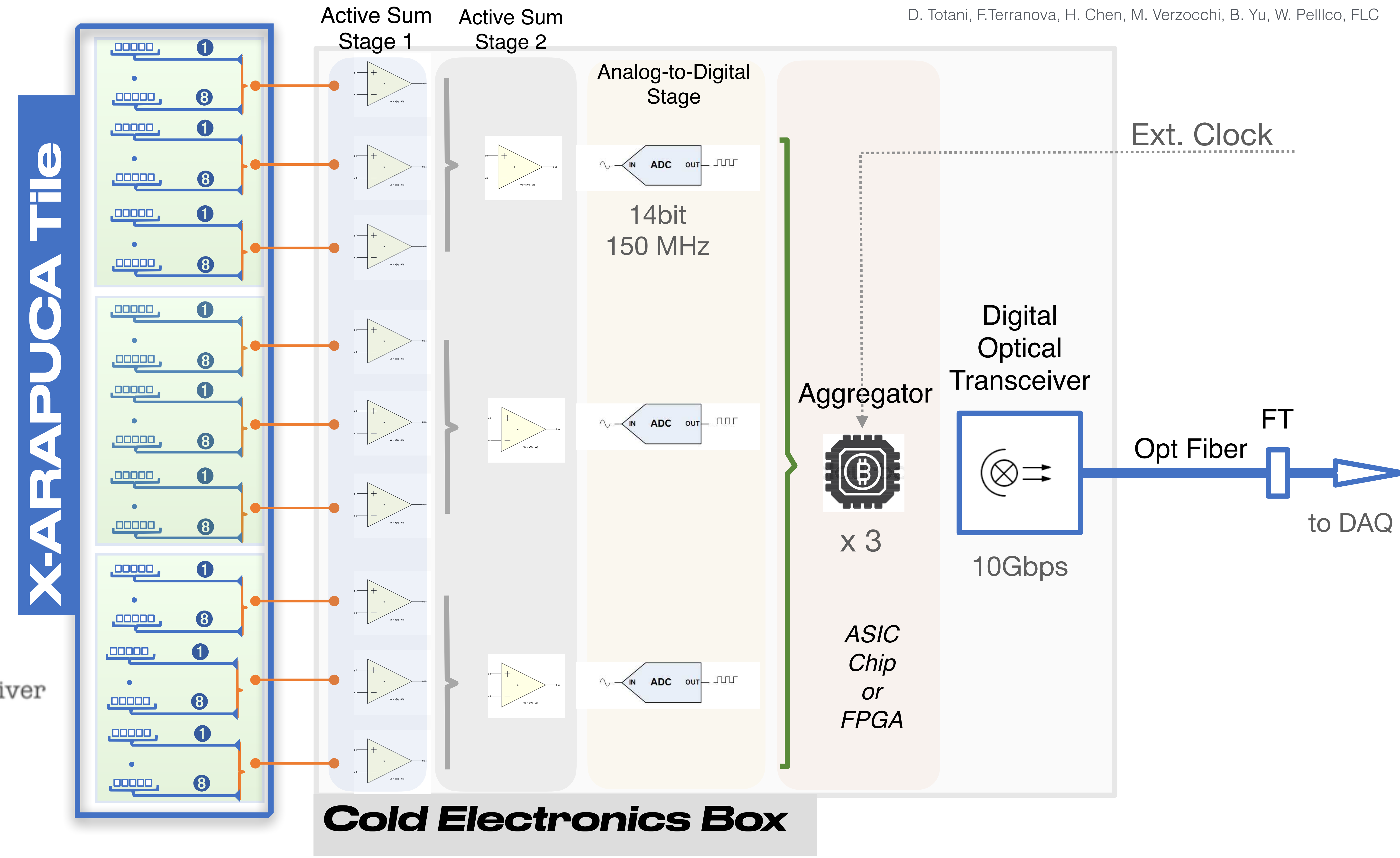
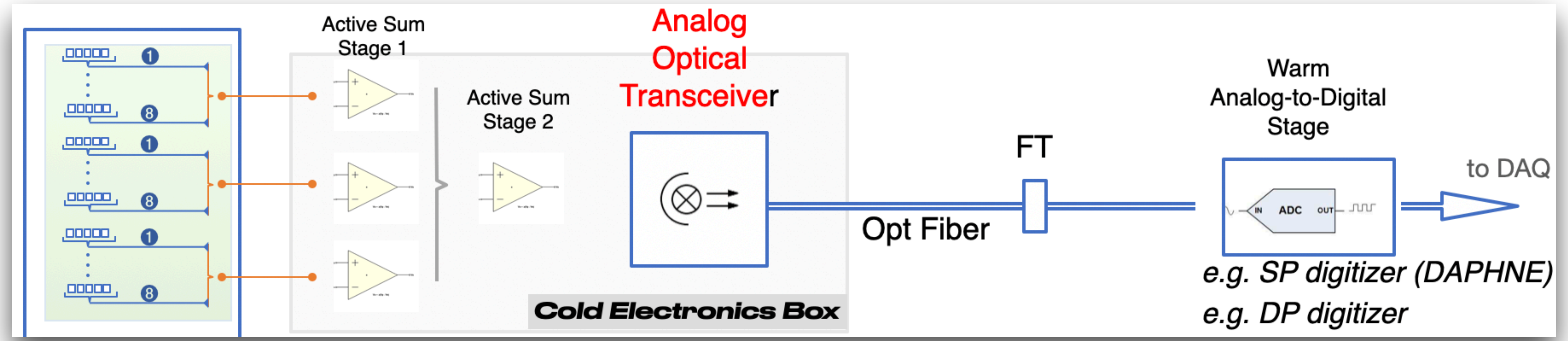


TABLE V. PD basic unit: X-ARAPUCA Tile

	Quantity	Dimensions
Area	1	630×630 mm^2 = 0.4 m^2
Thickness	1	22 mm
Weight	1	~ 4.5 kg
Optical Area	2 (two-sided)	600×600 mm^2 = 0.36 m^2
Sectors ("MegaCell")	3	600×200 mm^2 = 0.12 m^2
Dichroic Filters	36×2	100×100 mm^2
WLS plates	3	600×200 mm^2 = 0.12 m^2
PhotoSensors (SiPM)	360	6×6 mm^2
Read-out Channels	3	
SiPMs per channel	120	

OR *(alternative)*
depending on available solution for Optical Transceiver

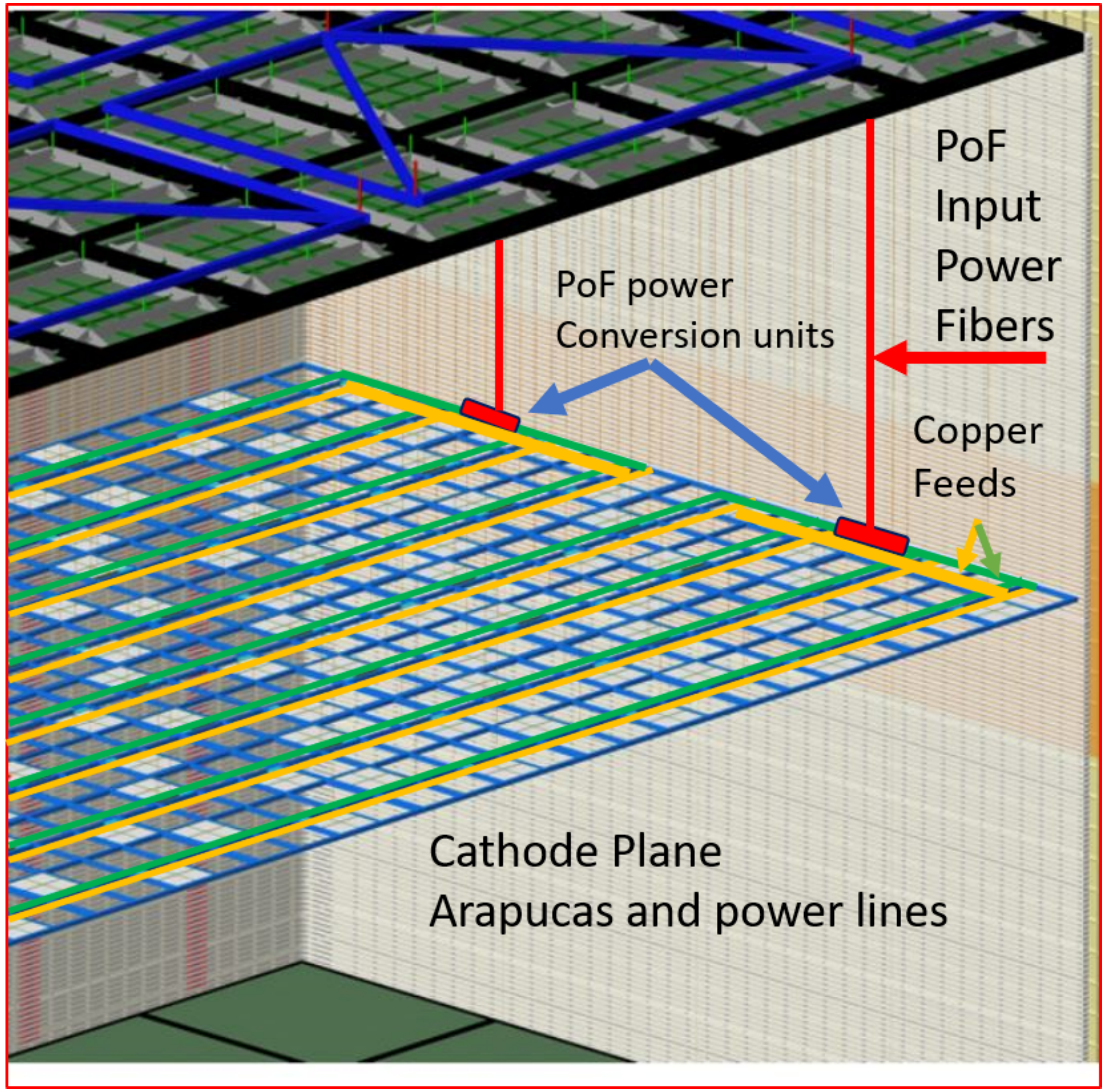


$\sim 4\pi$ PD System design for the VD LAr Volume

TABLE VI. VD PDS $\sim 4\pi$-Configuration

Item	Quantity	HV Surface	HD-Single Phase Module
X-ARAPUCA Tiles	320 double-side	Cathode plane	1500
	768 single-side	Field Cage walls	
Dichroic Filters	50,688		48,000
WLS plates	3,264		6000
PhotoSensors (SiPM)	115,200	Cathode plane	288,000
	207,360	Field Cage walls	
Signal Channels	960	Cathode plane	6000
	2,268	Field Cage walls	
Fibers (Serialized Channels)	1088		
SiPMs per channel	120	Cathode plane	
	90	Field Cage walls	48
Optical Area	$115\ m^2 + 115\ m^2$	Cathode plane	
	$277\ m^2$	Field Cage walls	(anode side only)
Active coverage	14%		12%

W. Pellico - FNAL



- The role of Xe doping

- $LY(x, y, z)$ - the detector Light Yield with a $\sim 4\pi$ Optical Coverage
- Energy Reconstruction and Energy Resolution for low-E UG events
- Position Reconstruction and Space Resolution for low-E UG events

- First evaluation of Trigger Efficiency in Fiducial VD Volume for low-E UG events

- Time Resolution study in progress (not reported today)

TABLE IV. Requirements and Physics purposes for the VD Photon Detector System - $\sim 4\pi$-configuration option

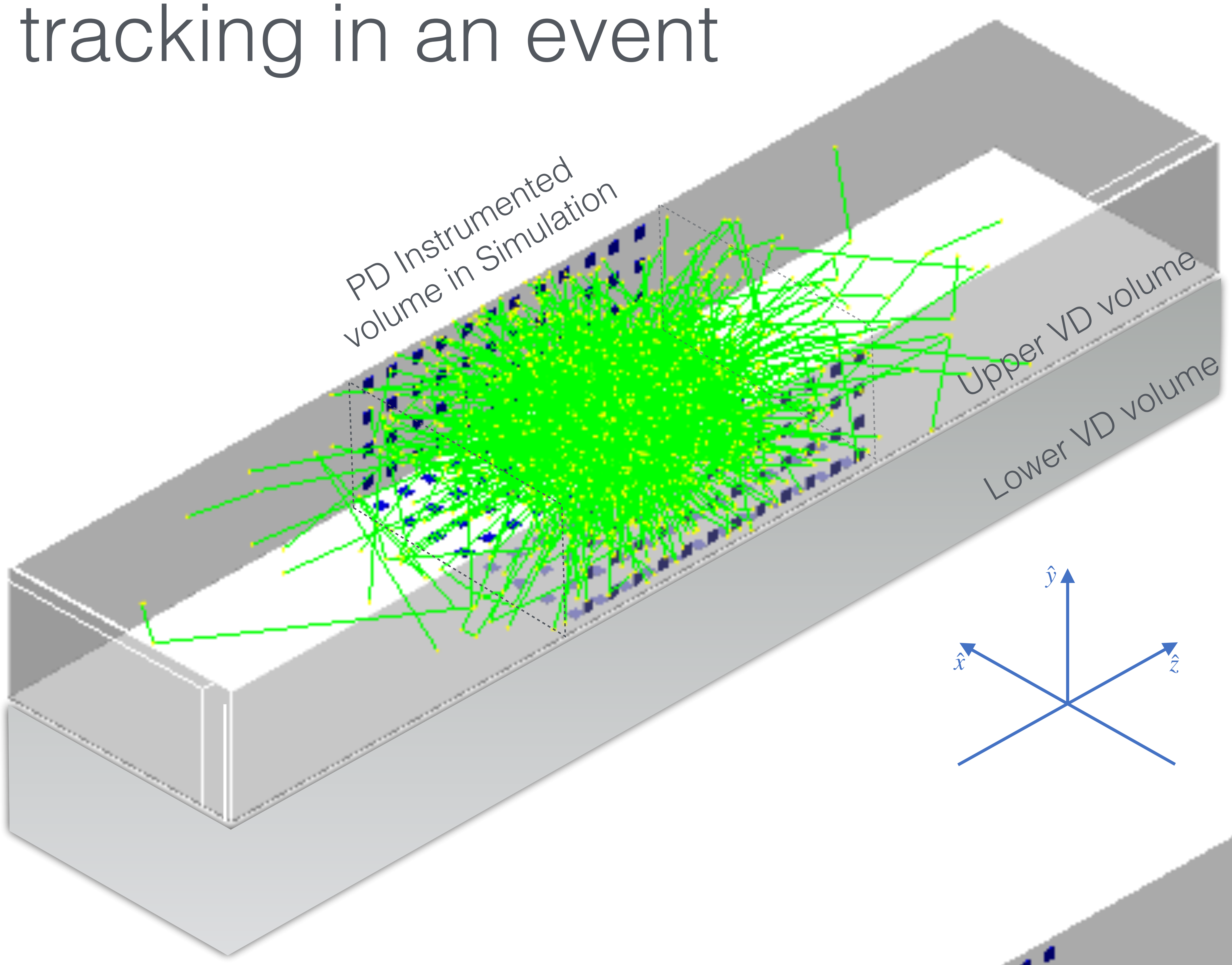
Detector Requirement	Value	Physics Purpose (*)
Trigger efficiency for interactions with energy deposit $E_{dep} \geq 5$ MeV in 100% of detector fiducial volume	$\geq 99\%$	- SN burst trigger up to the Large Magellanic Cloud (50 kpc) yielding 10 interactions in 10 kt LAr - Low-energy background rejection
Spatial resolution for interactions with energy deposit $E_{dep} \geq 10$ MeV	≤ 1 m	- Background rejection for SN, solar, nucleon decay
Energy resolution for interactions with energy deposit $E_{dep} \geq 5$ MeV	$\leq 8\%$	- Identification of SN spectrum features from different SN dynamical models
Time resolution	≤ 200 ns	- SN burst triggering - Identification of SN time features due to standing accretion shock instabilities - Identification of neutrino "trapping notch" (SN dip in luminosity)

Ph. Detector Performance: Expectation from first MC simulations of Response

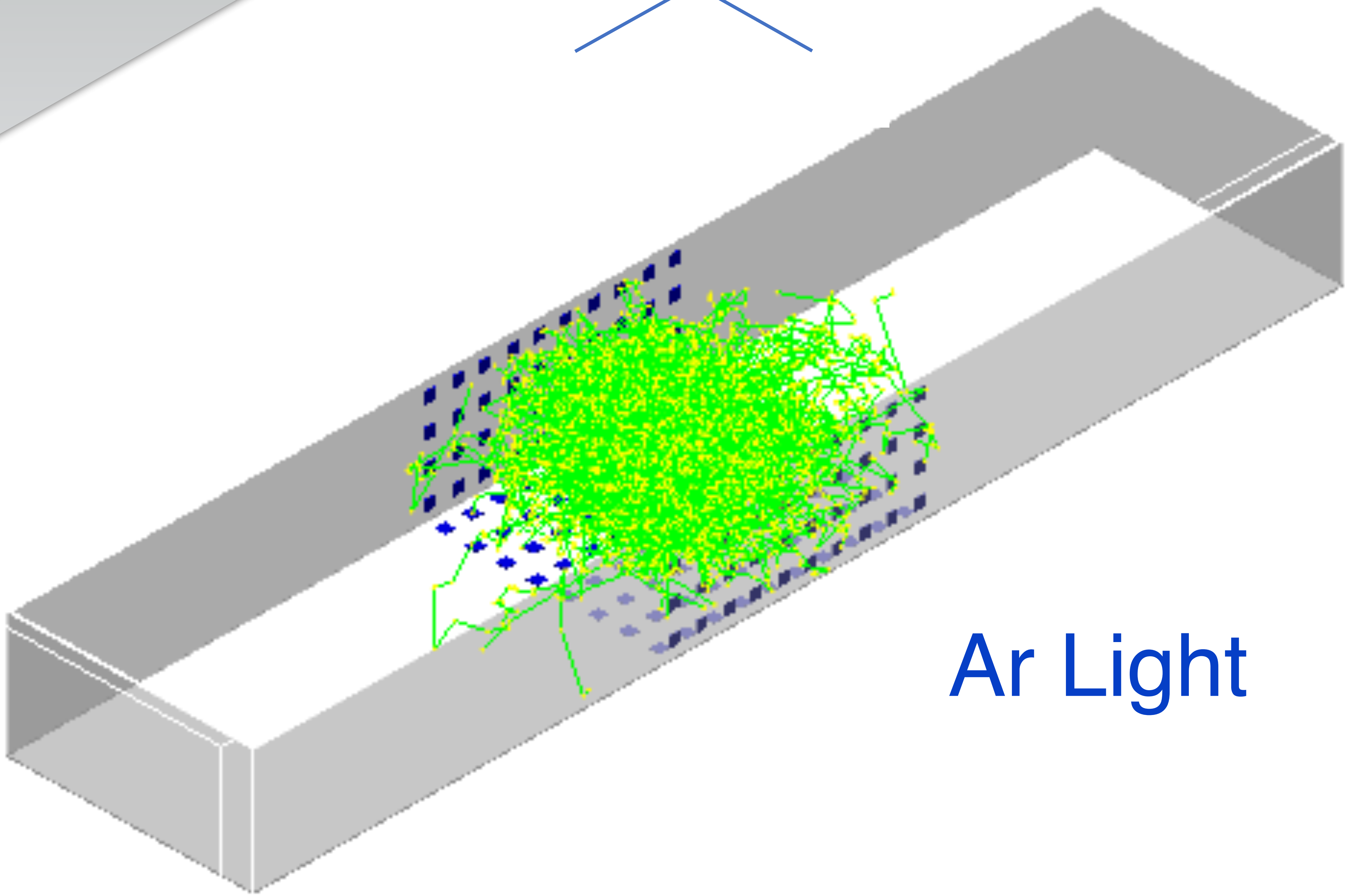
L. Paulucci, Universidade Federal do ABC, Santo André, SP, Brazil
F. Marinho, Universidade Federal de São Carlos, Brazil
D. Totani, University California Santa Barbara, USA

* I. Gil-Botella - for fundamental advice on Low-E Physics and PD concepts

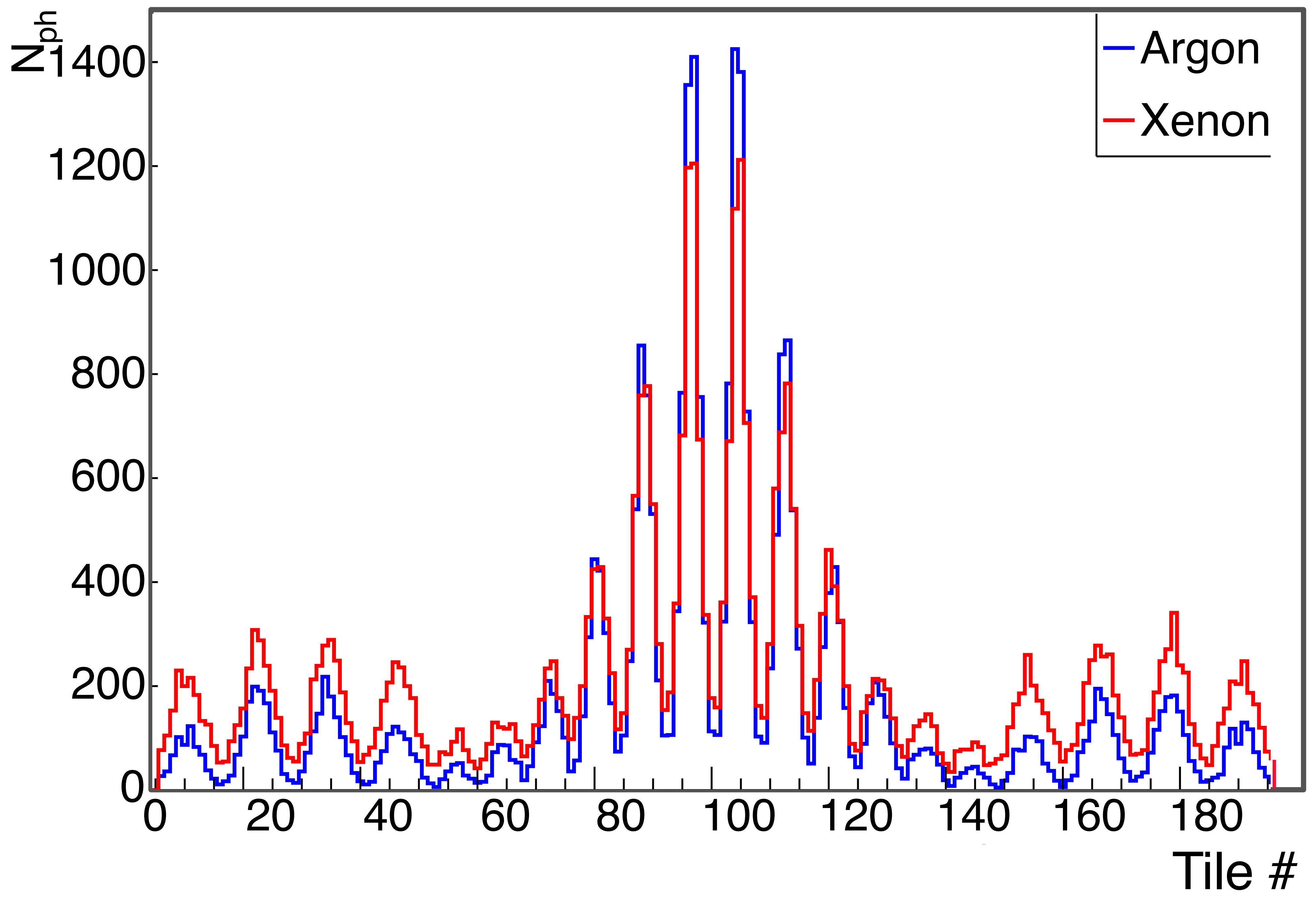
GEANT4 photon tracking in an event

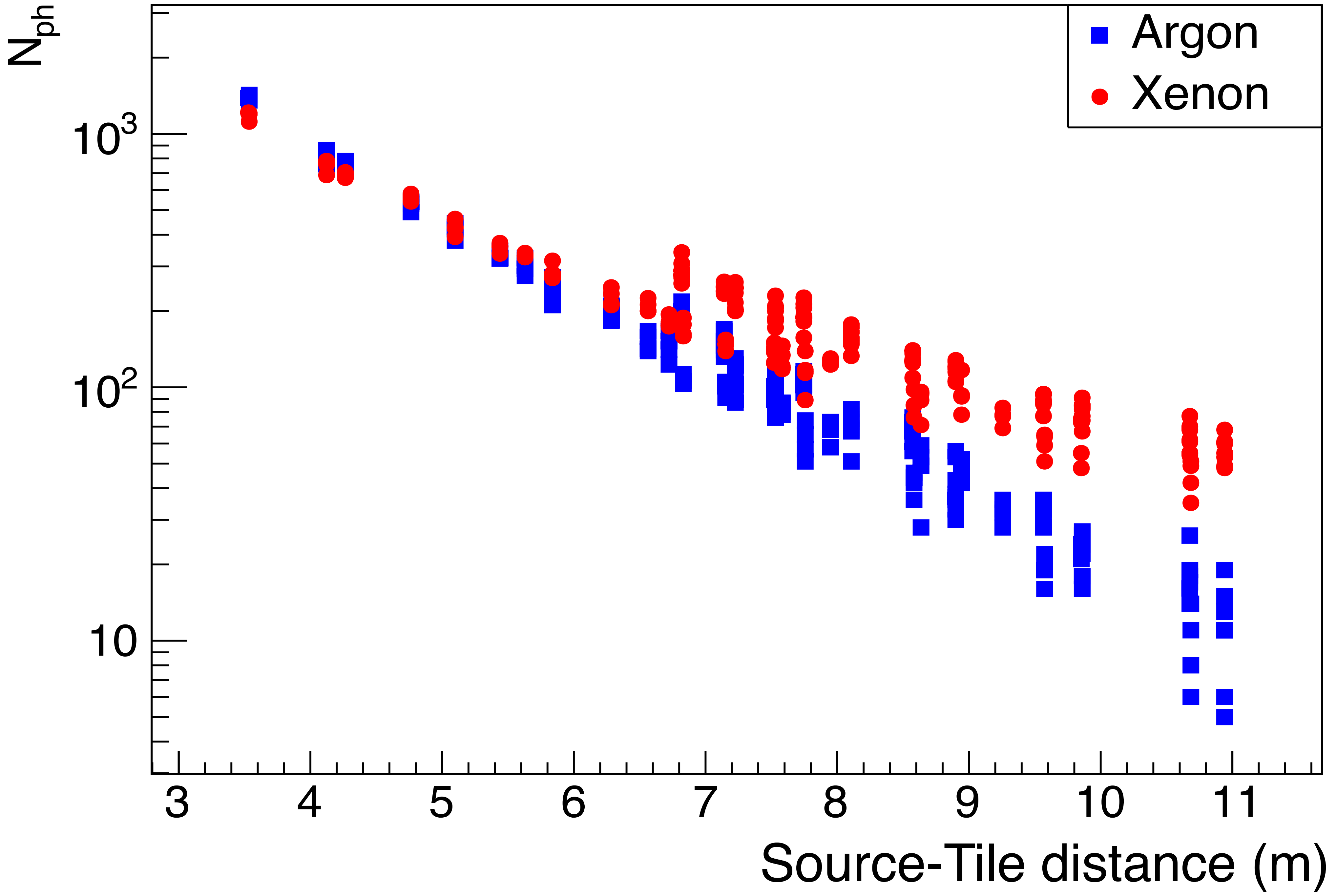


Xe Light

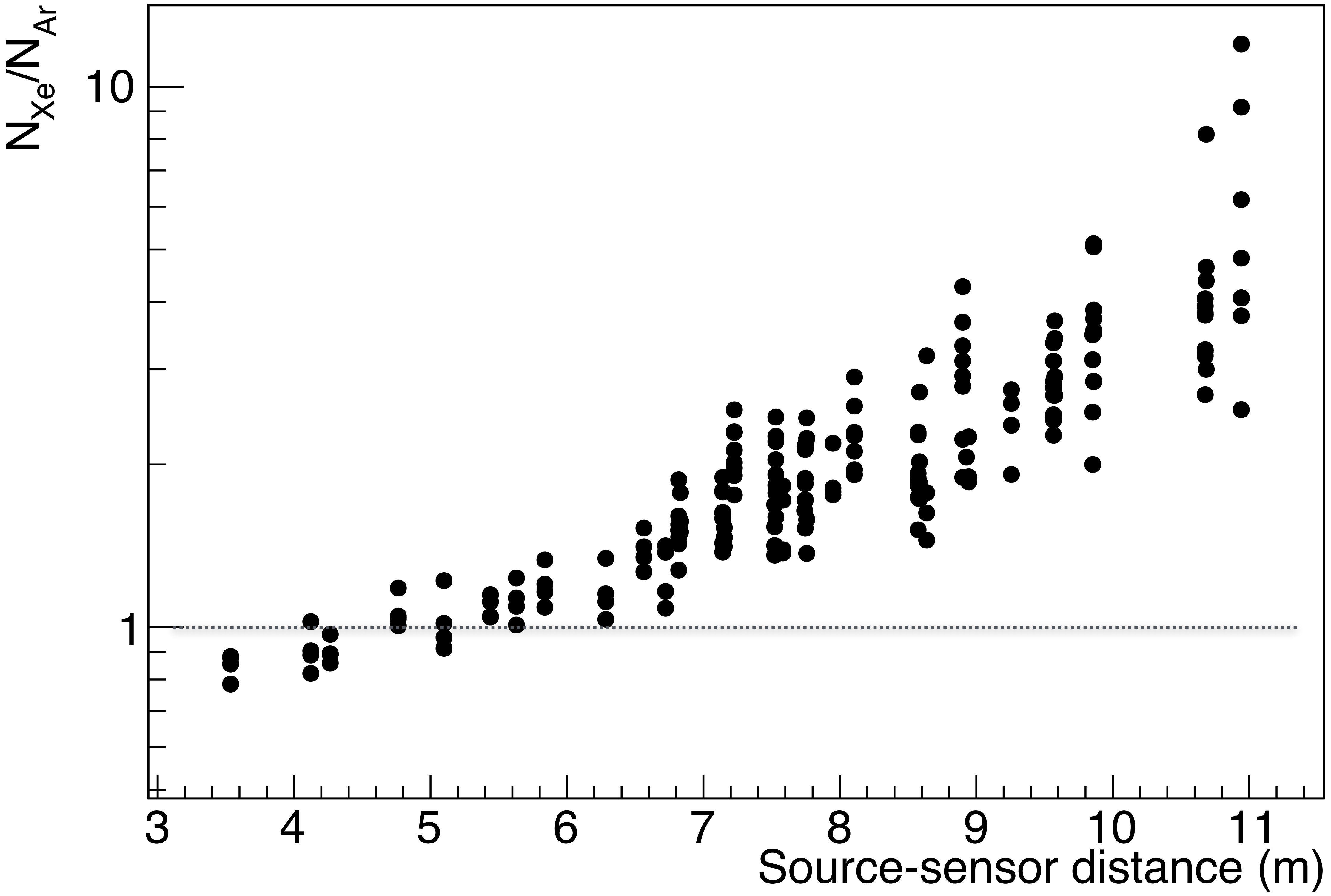


Ar Light



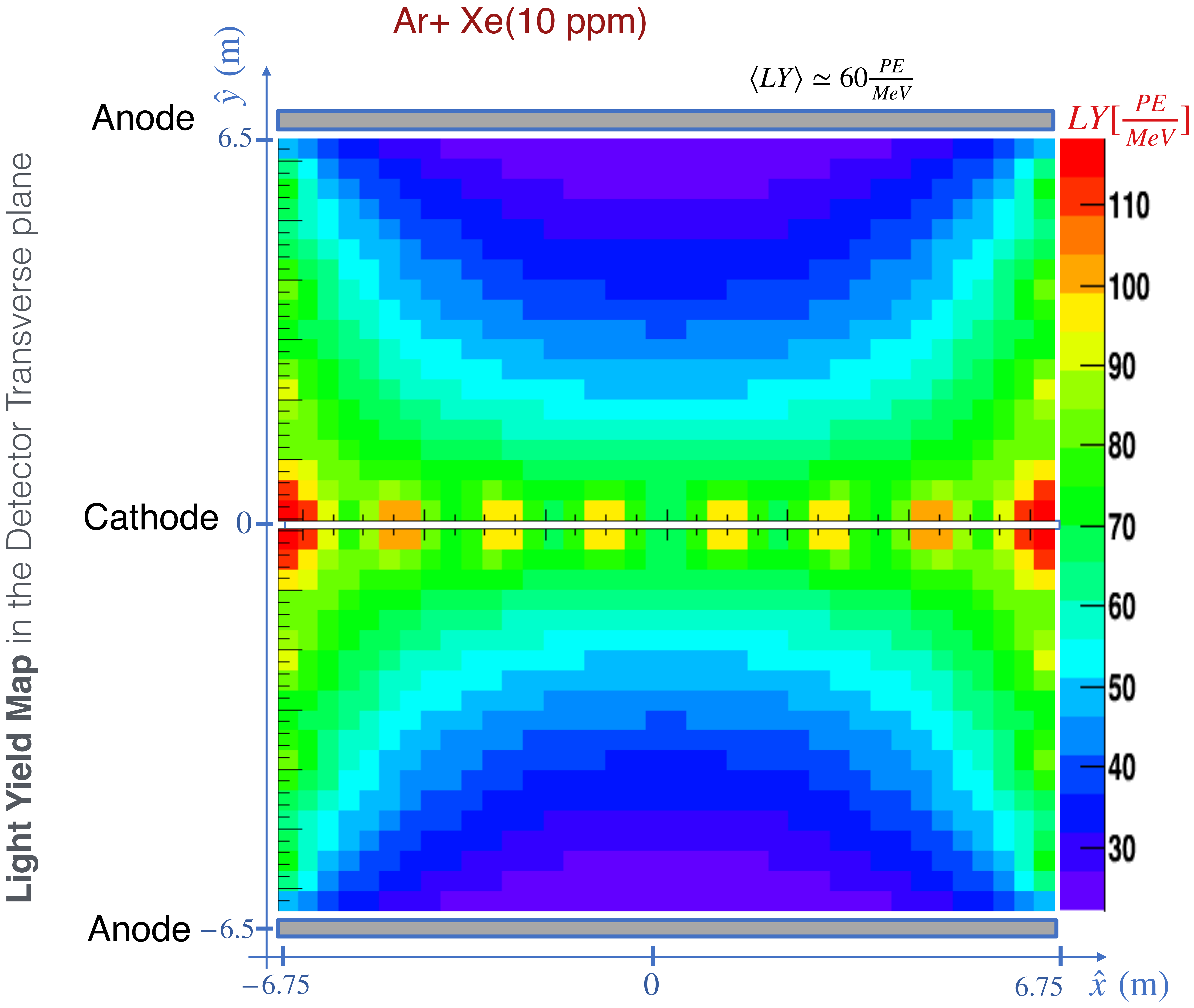


The collected light is found to be ~30% larger for Xe-doped Argon (8.2% of the total emitted photons reach the PD optical surface vs 6.3% in case of pure Ar), due to the effect of the longer Rayleigh scattering length enhancing collection probability for light emitted at longer distances from the PD-detectors



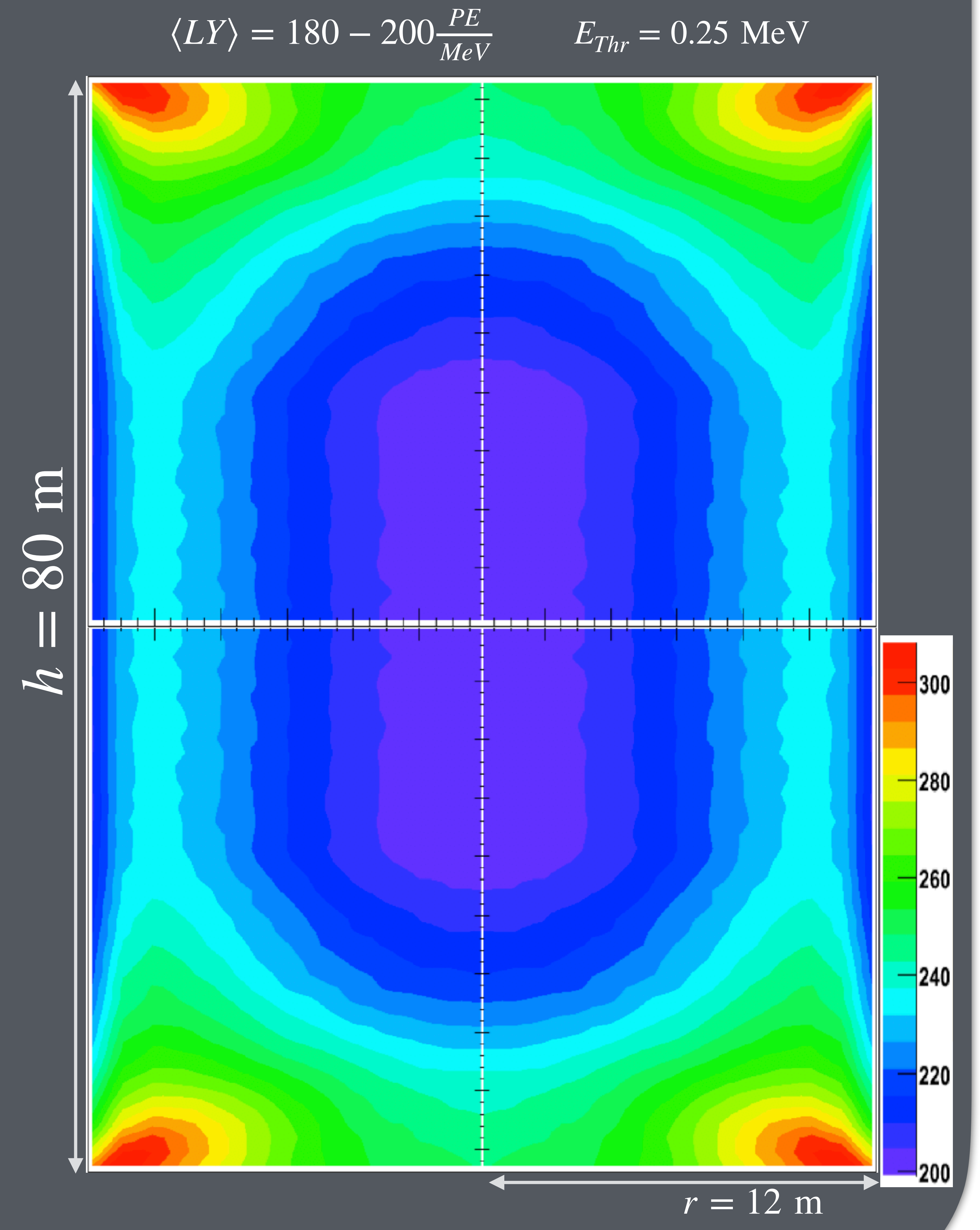
This supports the choice of Xe-doped Ar as scintillation medium.

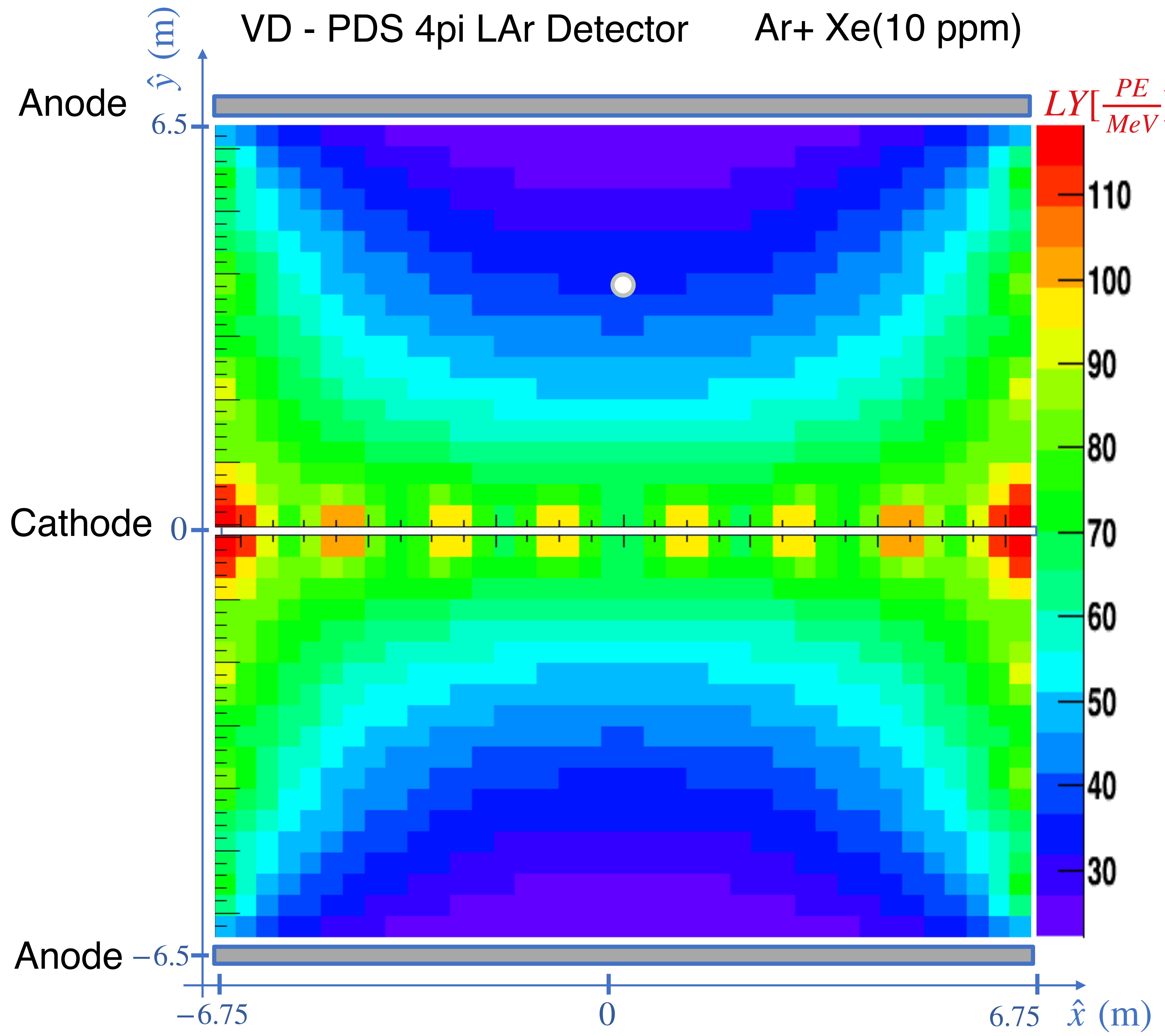
The VD $\sim 4\pi$-PD w/ $\sim 14\,\%$ Optical Coverage



LAGUNA-LBNO design study for Solar Neutrino and SN/DSNB Experiment

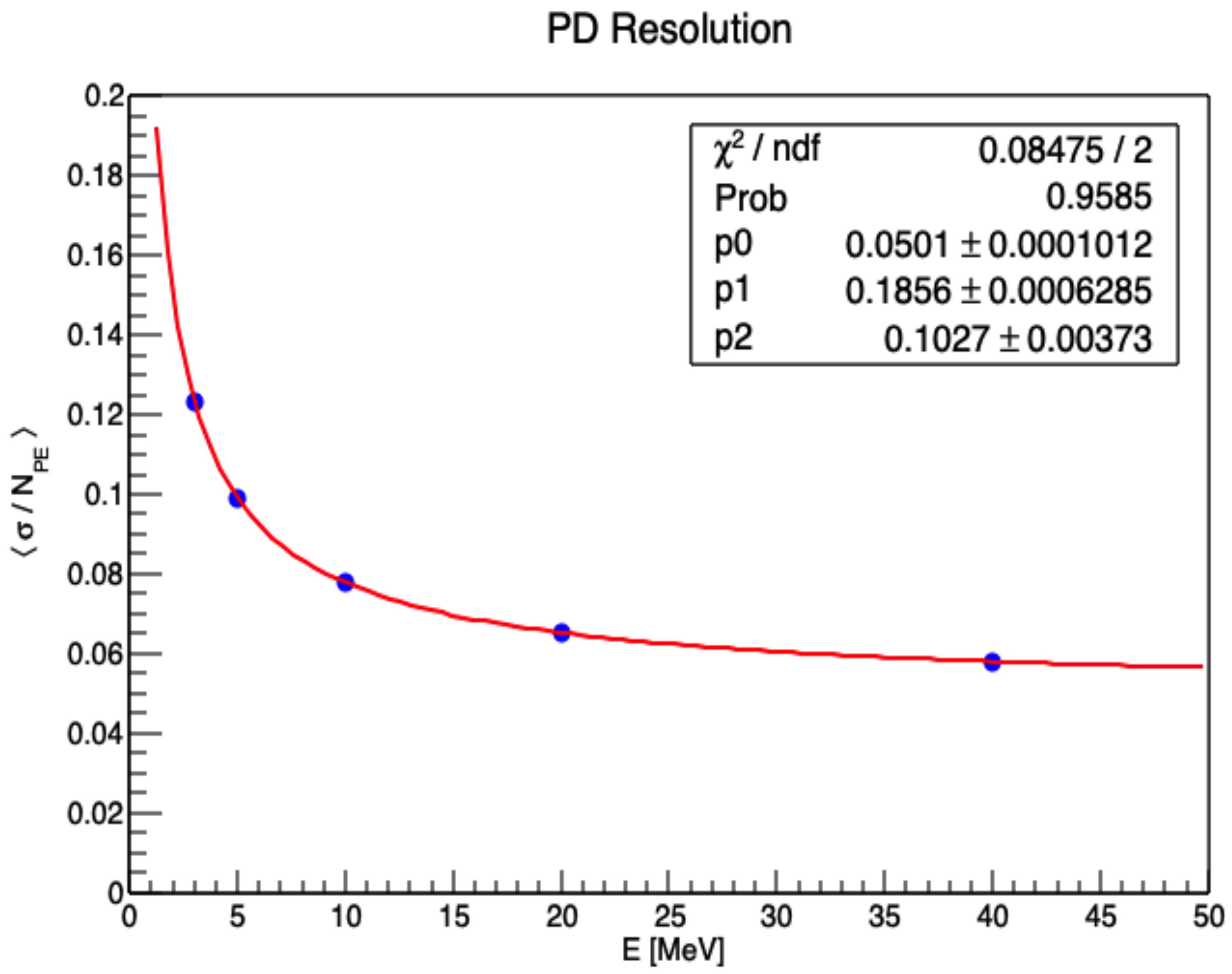
LENA - 4π LiqScint w/ 30% O.C.





Calorimetric Energy reconstruction from detected photon counting

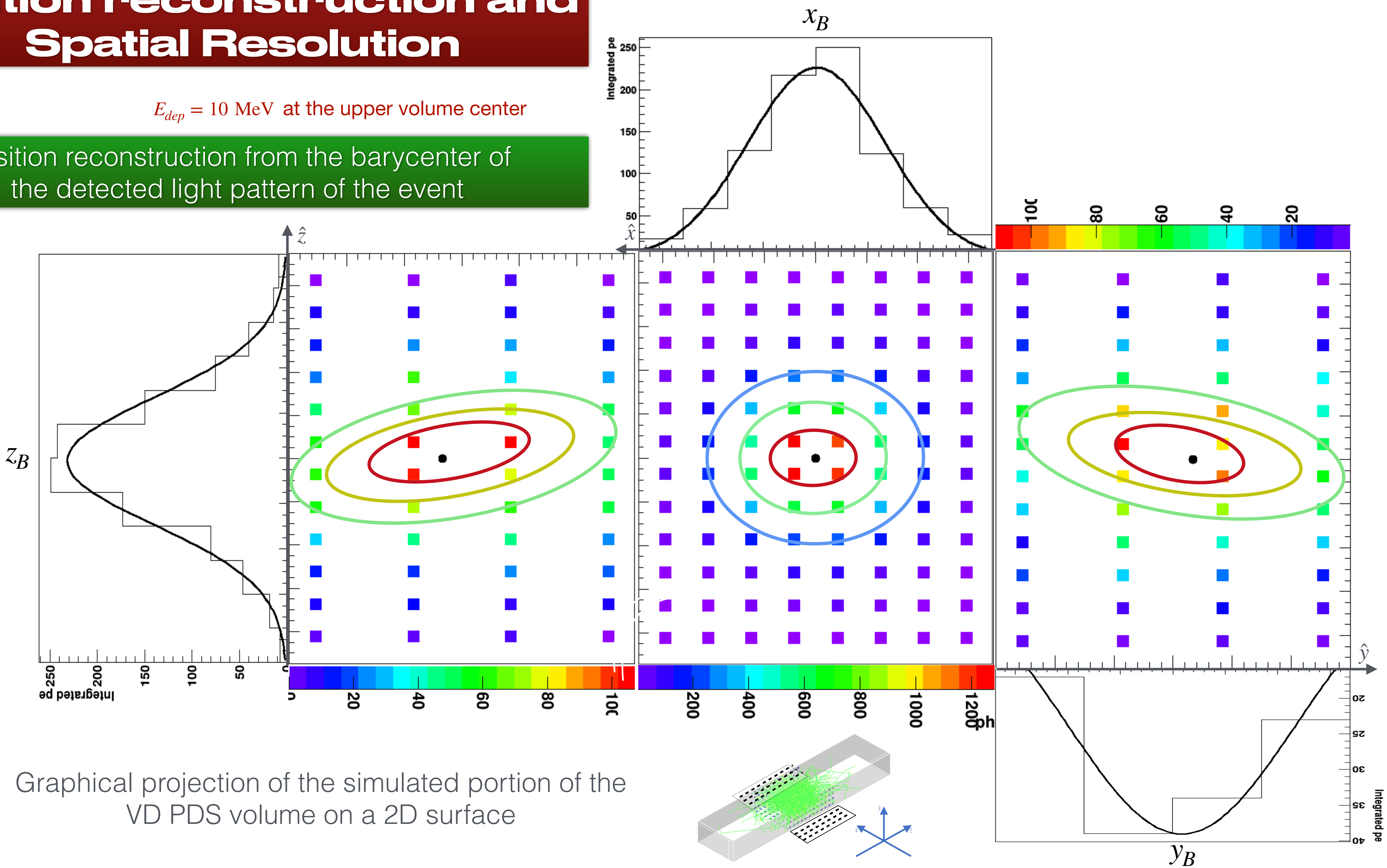
Energy Resolution
from statistical fluctuation (p1) on the number of detected PEs and to uncertainty on energy calibration (p0)



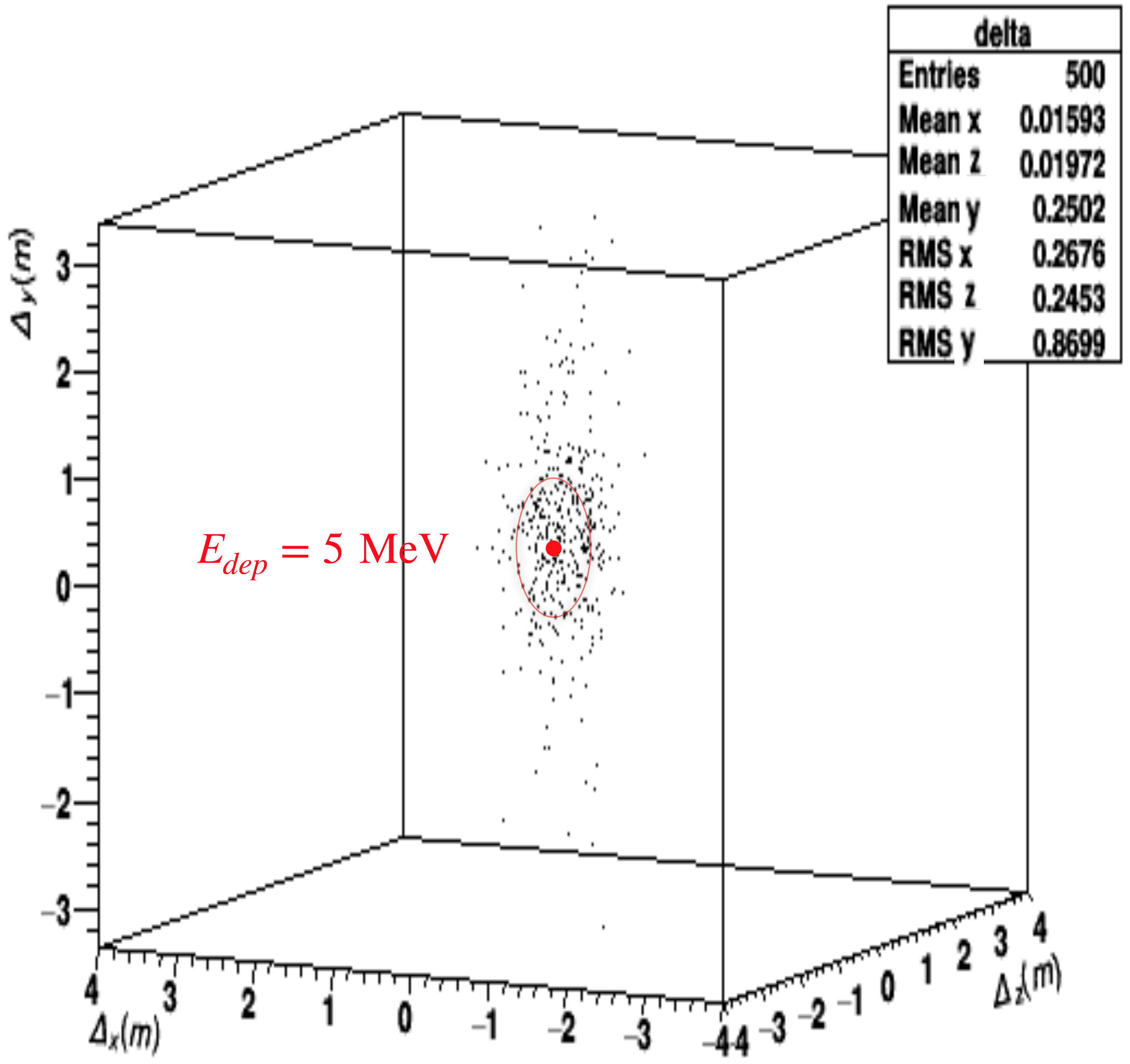
Position reconstruction and Spatial Resolution

$E_{dep} = 10$ MeV at the upper volume center

position reconstruction from the barycenter of the detected light pattern of the event



Graphical projection of the simulated portion of the VD PDS volume on a 2D surface

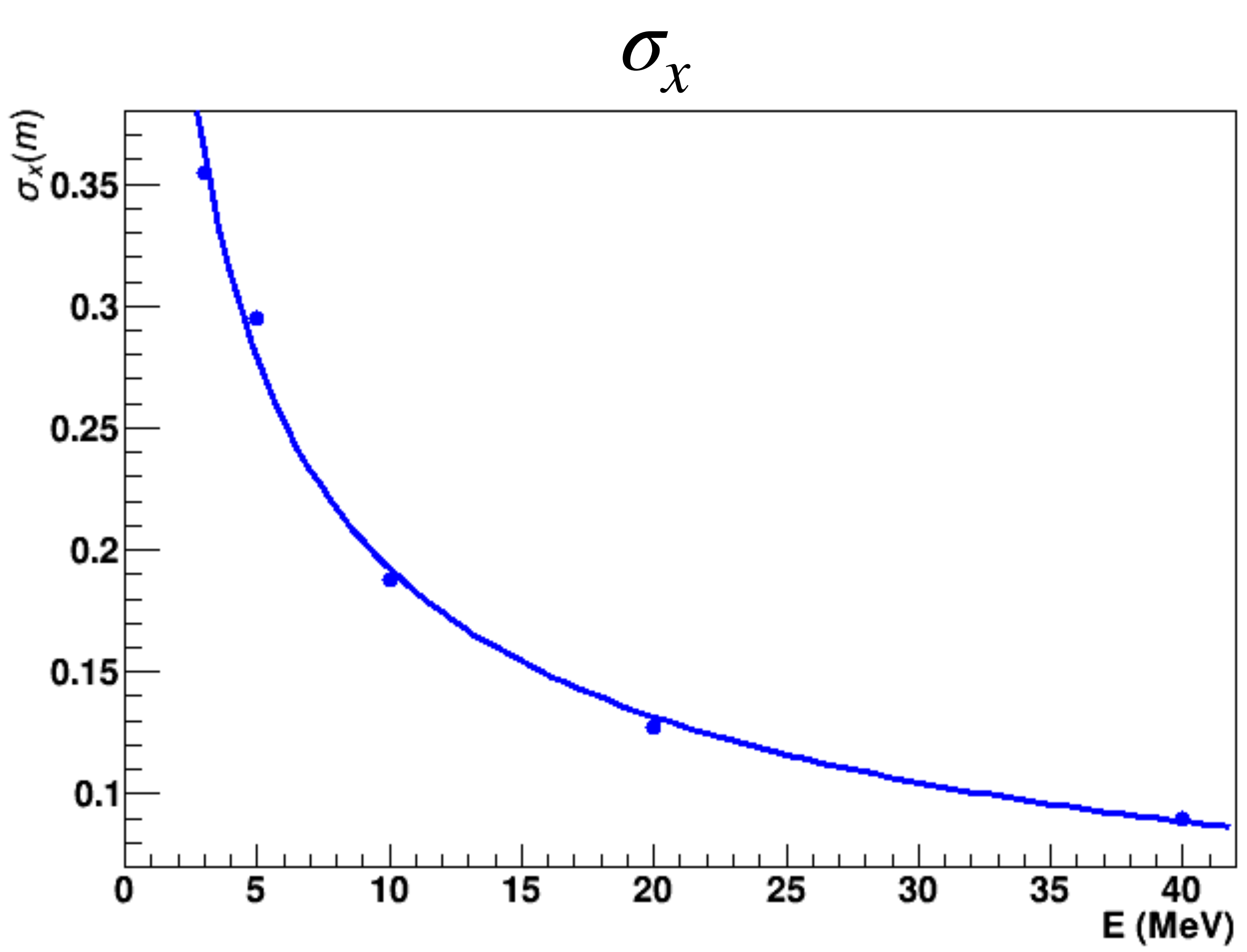


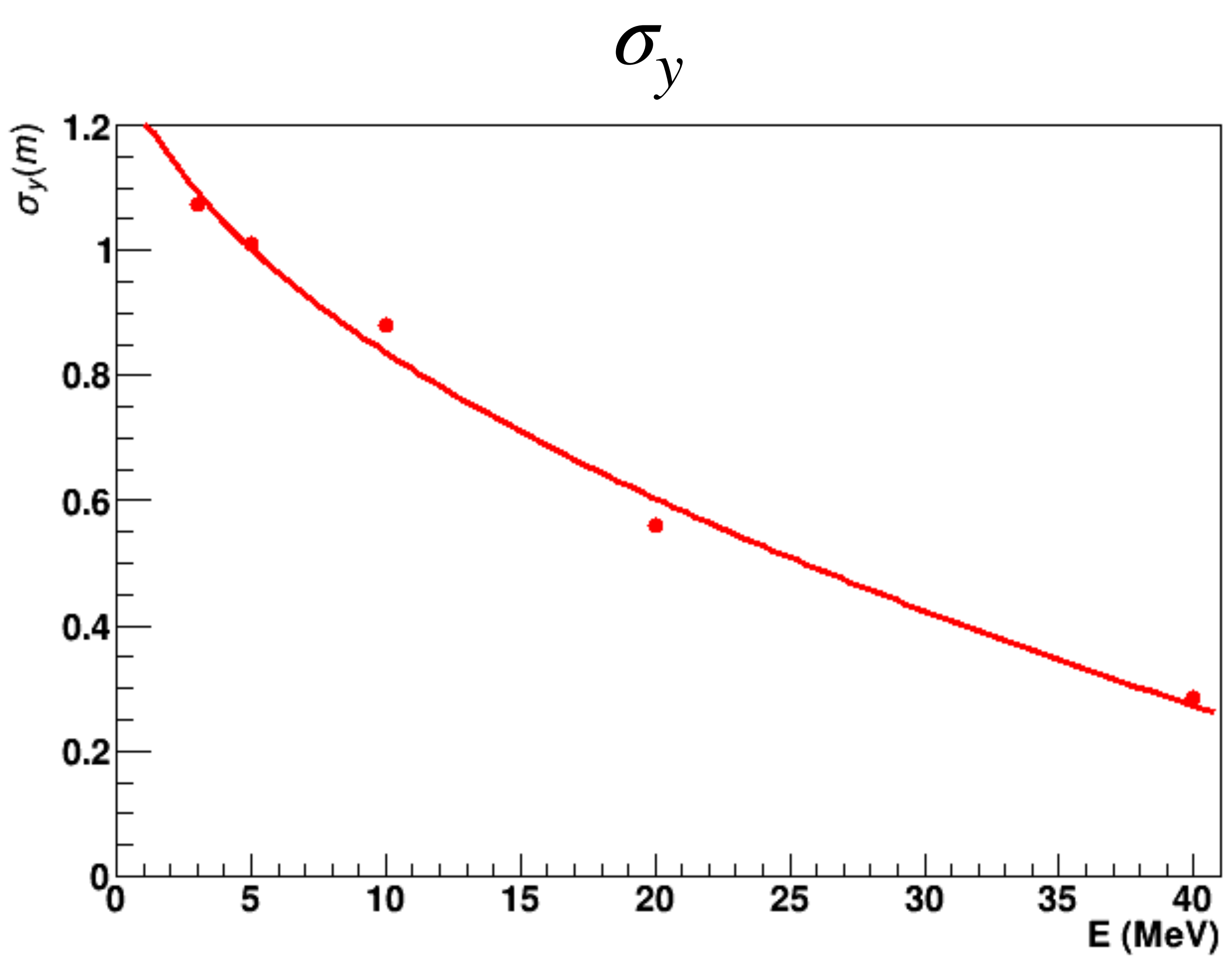
Reconstructed position in space for a sample of 5 MeV MC events generated at a fixed position

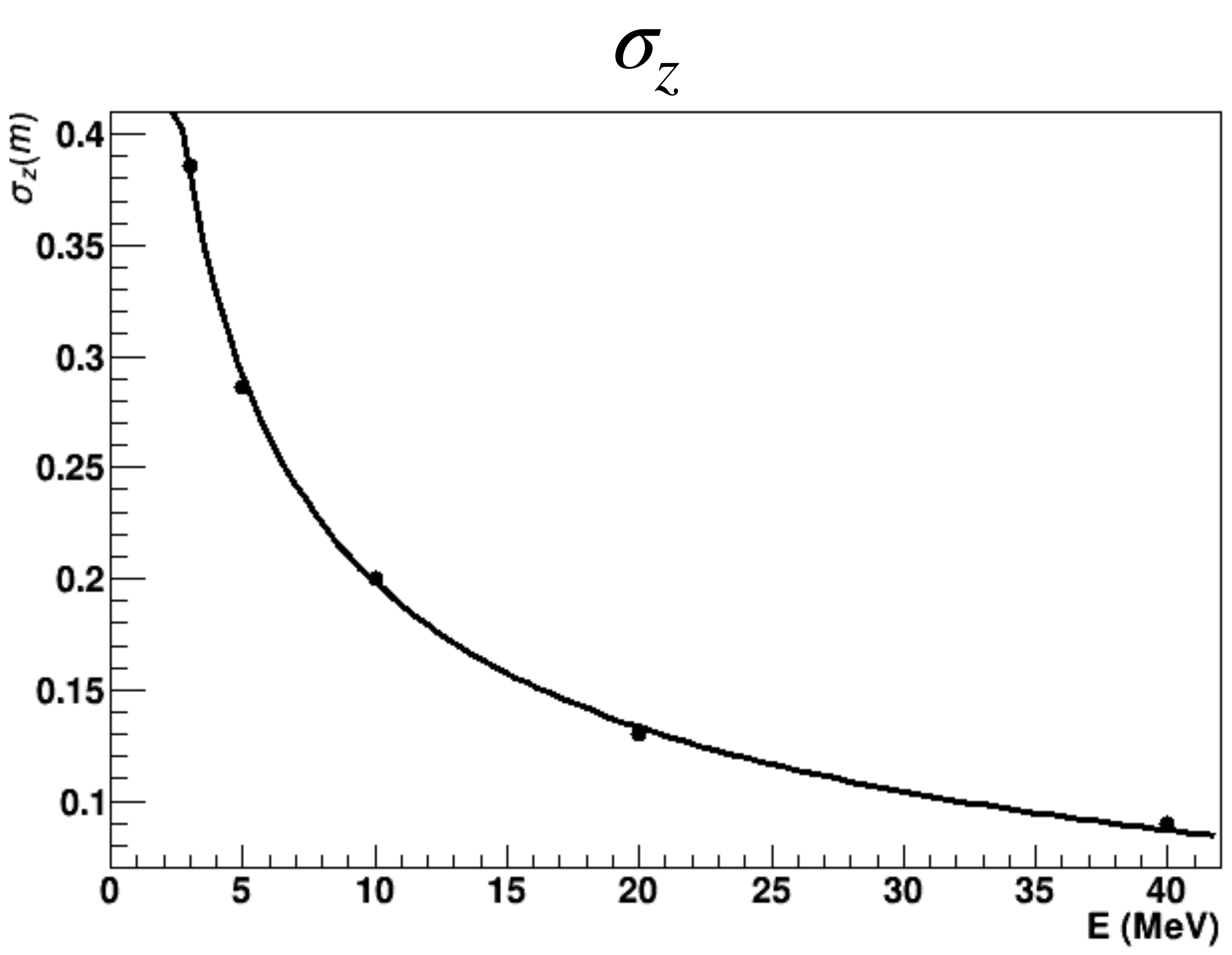
Position resolution ≈inversely proportional to the square root of the number of photons detected in the event

Good Position resolution in $\hat{x}$, $\hat{z}$ $(\sigma_{x,z} \leq 30\ \text{cm})$
worse in $\hat{y}$ $(\sigma_z \leq 1\ \text{m})$, due to less n. of PD tiles along VD direction

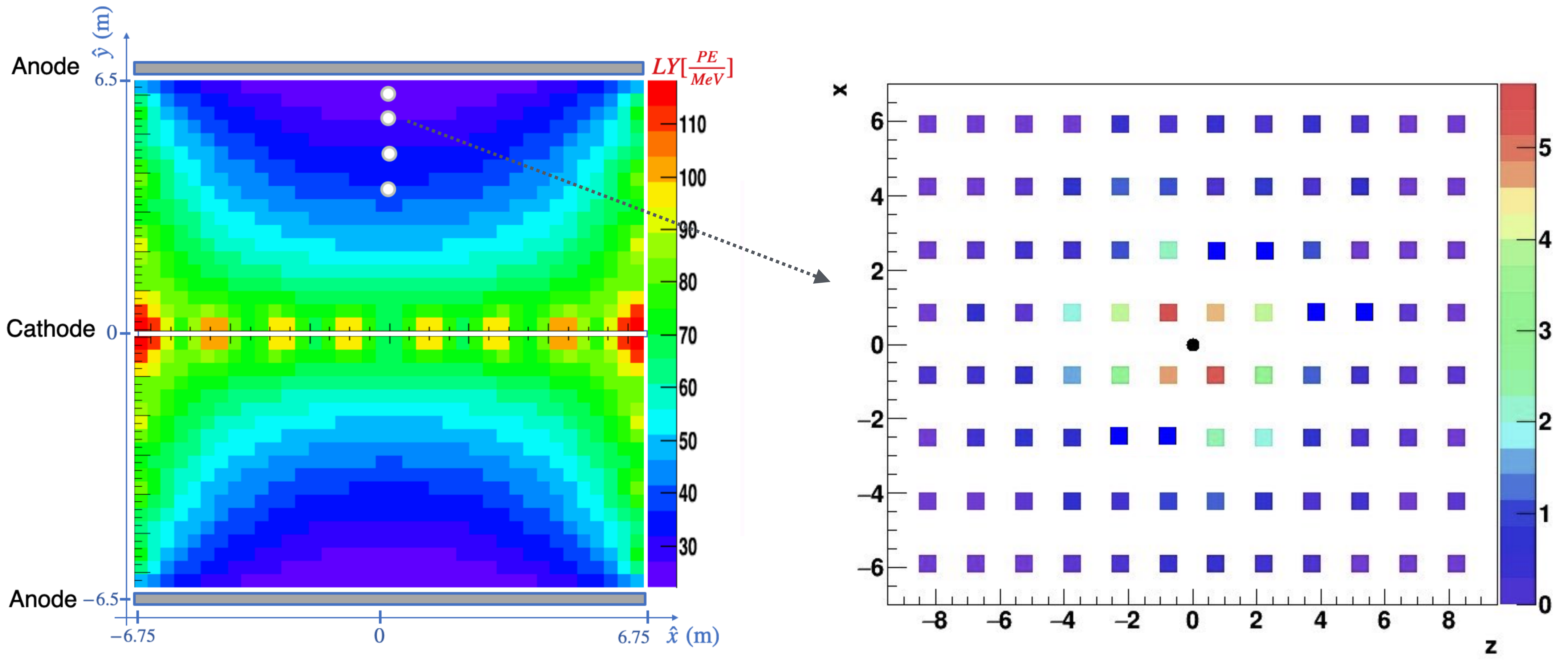
Timing in formation (not used here) should improve Space Resolution

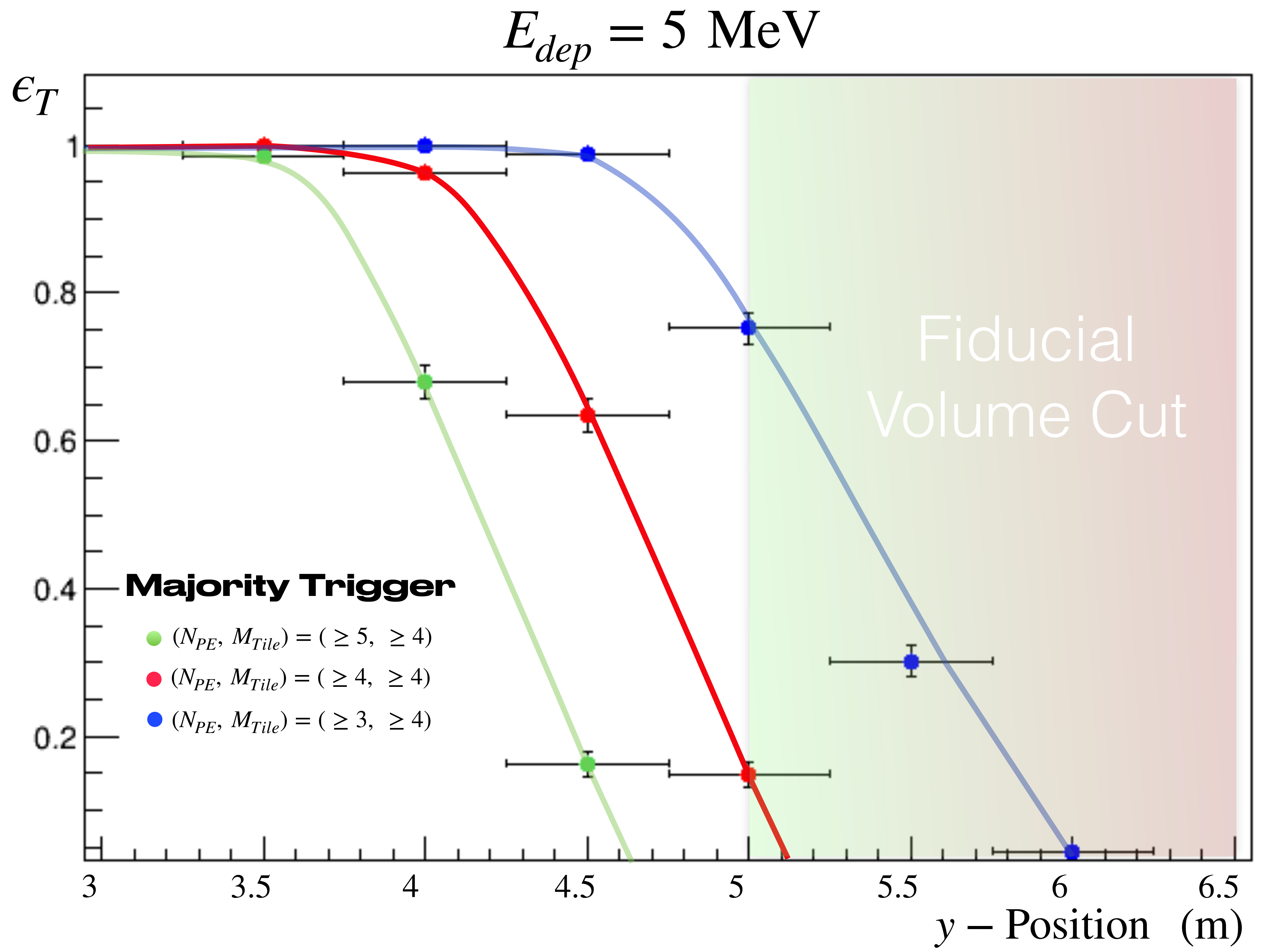


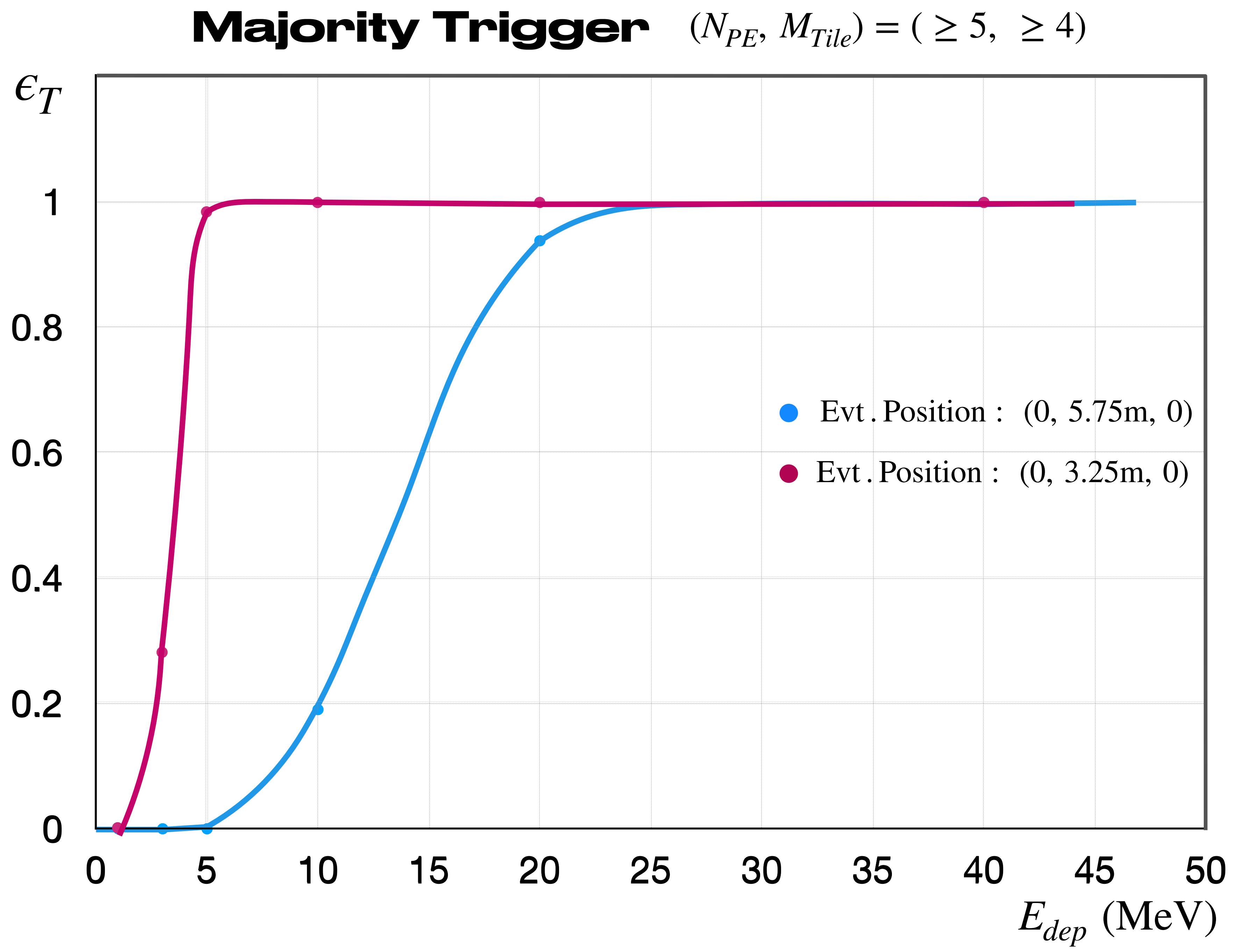




(N_{PE}, M_{Tile}) − Majority Trigger condition

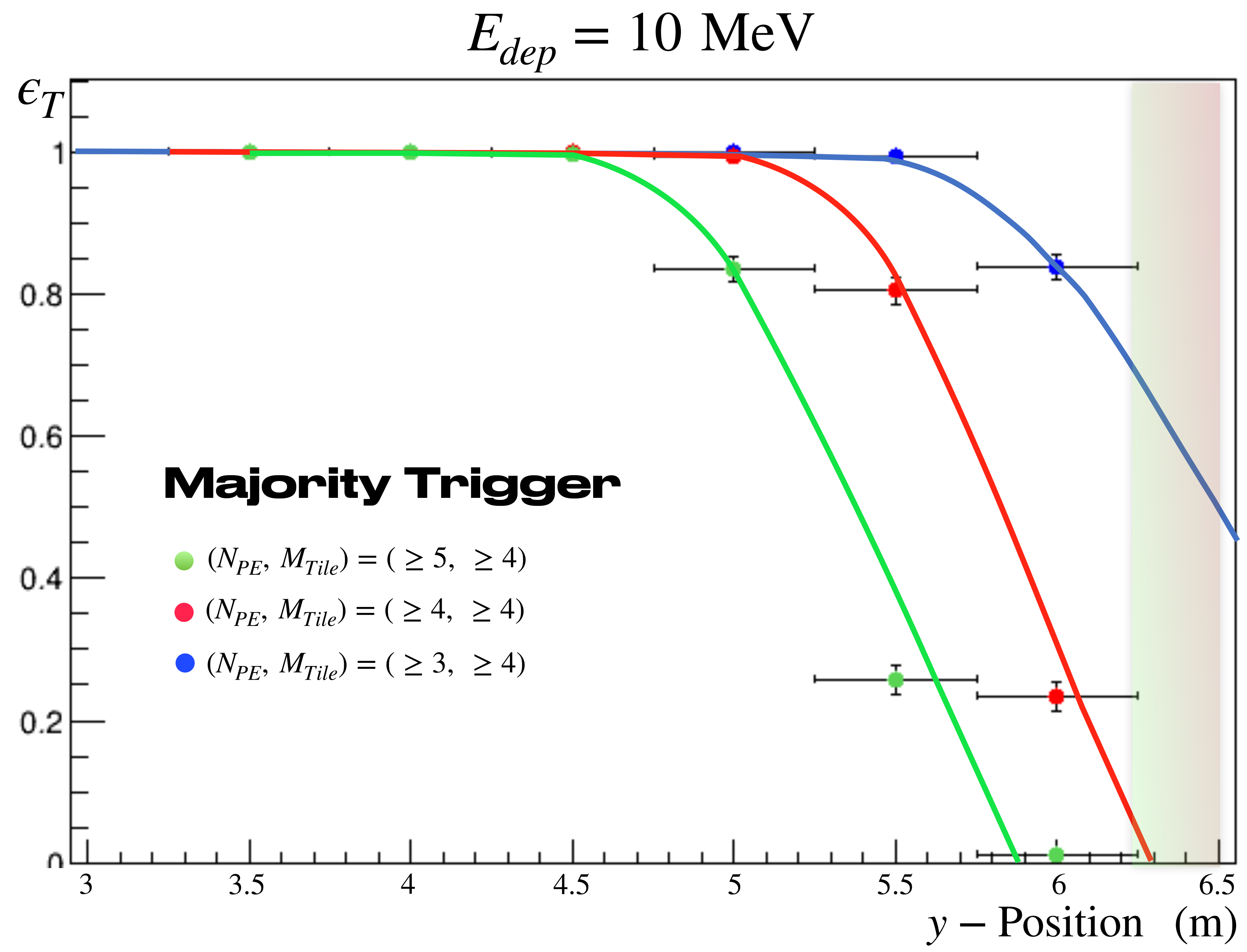




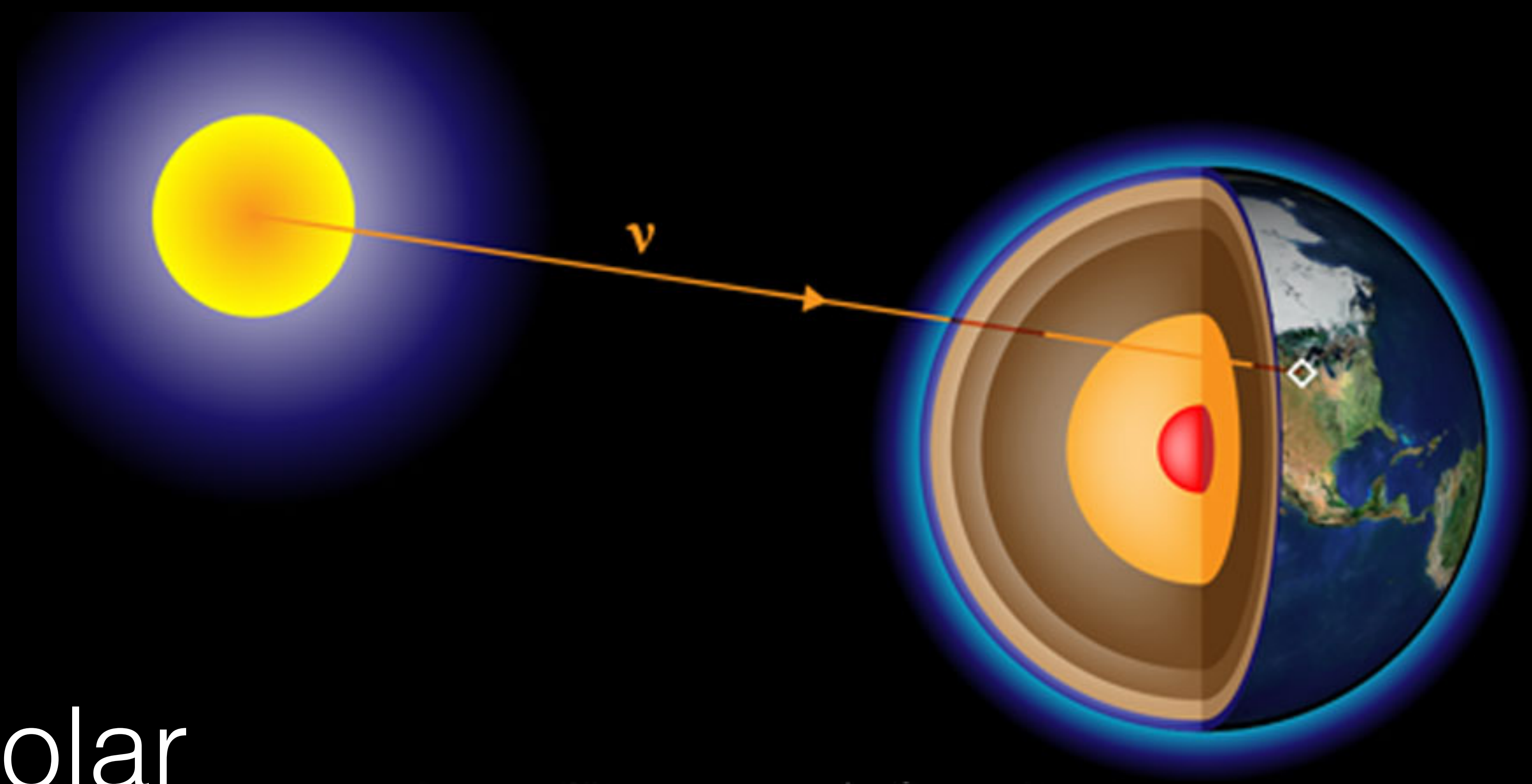


Relaxing (N,M)-Majority requirements enhance trigger efficiency, but also increase rate of false-positive triggers

Trigger Efficiency $\geq 99\%$ for interactions with $E_{dep} \geq 5$ MeV expected in 100 % of a 10 kT Fiducial Volume



Enlarging the DUNE Physics Scope



Solar

SuperNova

John Beacom **Concluding Remarks**

- With new liquid-argon detectors, we can lead exciting new solar-neutrino studies, opening substantial discovery space in particle physics and astrophysics
- It is critical to DUNE's overall science program to succeed at measuring low energies well

Summary

Evan O'Connor

- The progenitor dependence imprints itself nicely on the neutrino signal – DUNE can see this

- *It is is critical to lower Trigger E-threshold to extend range of SN detection (toward and beyond Galaxy edge).*
- *It is critical to guarantee good Time resolution and improve Energy resolution for SN-signatures in time & energy spectra*

LEPLAr
workshop on Low Energy Physics in Liquid Argon

*How to **supply bias voltage** to the photo-sensors (in the range of 50 V or less) on the HV surfaces and to **read-out the signal** out of HV surface*

POF Technology for VD application

Two Parts

W. Pellico - FNAL

Warm

- **(1) Power to fiber**
  - Convert electrical power to light
    - Four Laser modules to generate 48 V
    - Each are **4 watt** laser systems
    - Individual adjustable output power
    - Interlocked – to protect laser/personnel
  - Transmit via fiber

Cold

- Fiber optic Receivers
  - Four receivers tied in series ⇒ 48 volt for SiPM and power for LEDs for calibration
  - Typical conversion efficiency 22 %
  - 14 W dissipation (heat)

Cold

- SiPMs cold electronics module
  - Gang some number of SiPMs
  - Passive or/and Active (w/ preAmp&Shaping)
  - **(2) Signal to fiber**
    - Convert electrical to light
    - Eleds – analog light Transmitters
  - Transmit via fiber

Warm

- SiPMs warm electronics module
  - Fiber to copper
  - Signal conditioning
  - Signal processing