Next generation Photon Detector R&D Challenge for the Vertical Drift DUNE Far Detector Module

Outline:

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.

To this end

key point is to extend PD Optical Coverage as close to 4π as possible

to embed a 4π PD into LArTPC layout is a big technological challenge

Compelling (very exciting) R&D plan is taking shape

Photon Detector in VD LAr Detector layout Implementation Choices

- " $\sim 4\pi$ VD" solution for extending DUNE Physics Reach
- "SP mirror" solution *(Reference design)* for minimizing cost
- Fallback solution for minimizing technical risks

The " $\sim 4\pi$ VD" solution for LowEn Physics in DUNE

- PDS cannot be located at the Anode Plane (as in the HD-SP Module)

- If a solution for operating a PD on HV surfaces (r/o electronics and power/signal transmission in cold) is validated:

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 (PCB metallization and/or laminated on perforated PCB)

+

Xe doping (minimize Rayleigh scatter effect for light at far distance) *[Note: this feature is not VD-exclusive]*

This would allow ***~4π coverage ⇒ enhanced uniformity of response and higher Light Yield****:*

It would act as an additional detector for Ar Light Signals

with low detection threshold, good energy resolution and position resolution capability on its own

- complementary to LArTPC for Charge Signals (imaging - directionality) -

The VD PD Reference design": "SP mirror solution"

- If a solution for operating a PD on HV surfaces is validated:

PD active coverage distributed on the Cathode side only ("SP mirror solution" w/ PD into APA)

+

PD passive coverage (reflector) onto Anode side (PCB metallization, laminated on perforated PCB facing LAr)

+

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

lower fabrication cost

similar performance compared w/ HD (SP) 1st-Module (no expanded physics reach)

Where is the challenge ?

Operating PD on HV surface requires
Photo-sensors and r/o Electronics
Power (IN) and Signal (OUT) transmitted via
non-conductive cables

PoF and Optical Transceiver Technology provide solutions
via optical fibers

but

none of these (commercially available) technologies is rated
to operate in Cold (at LAr Temperature)

A highly specialized R&D is needed
to validate existing technology in Cold
or develop Cold custom technology for this application

The VD PD Fallback design

a PD scenario with no critical technological risk associated

- Operate PD on surfaces at Ground:

PD Active coverage distributed onto the 4 vertical sides of the Membrane Cryostat (outside the FC)

+

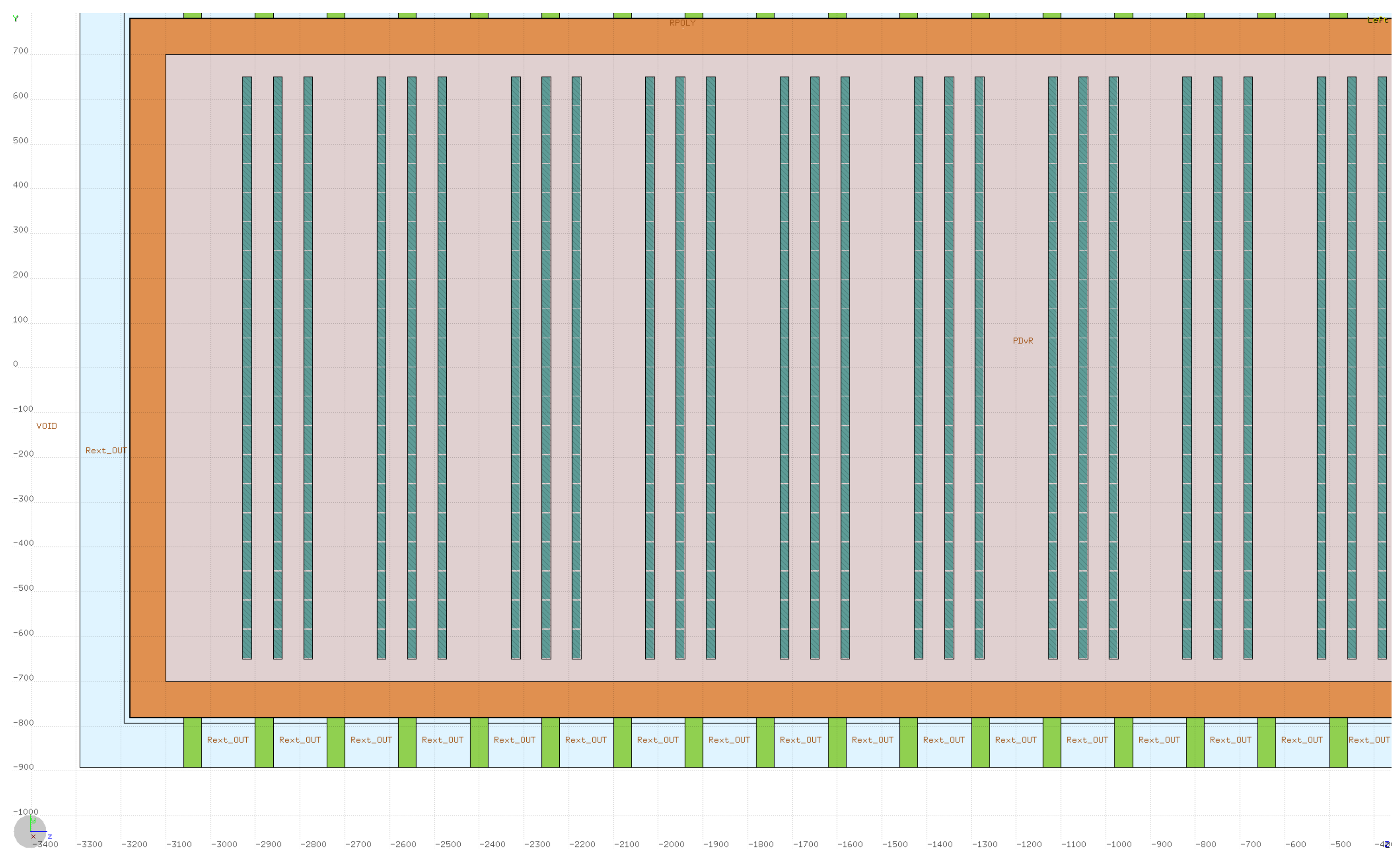
Modify Field Cage design (thinner profiles & wider gaps btw. profiles to increase FC transparency)

+

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

Simulation in progress

Implemented geometry: Megacells on the Cryo inner surface: side view



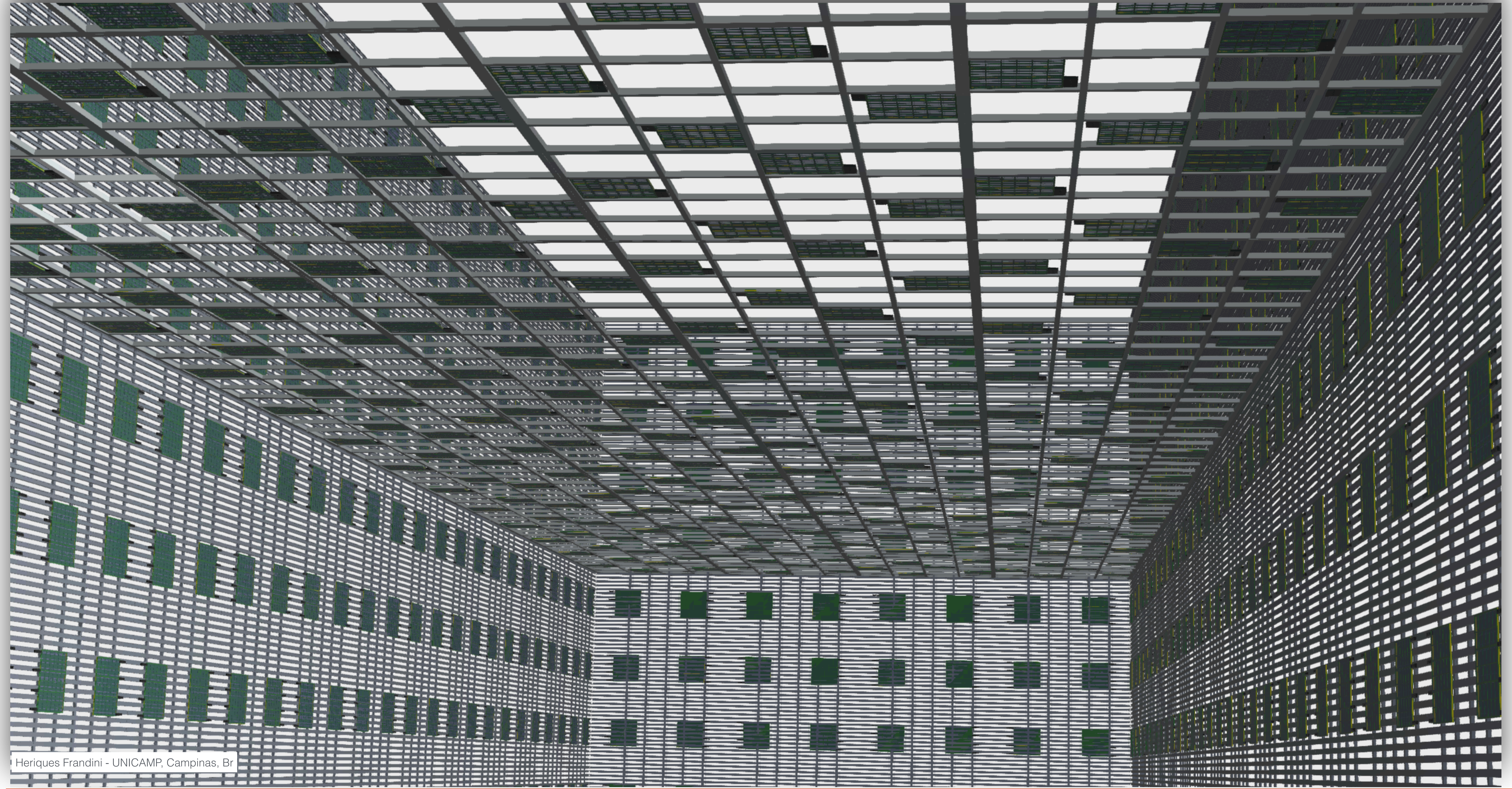
P. Sala

No critical R&D required - just re-design existing ARAPUCA Technology
no need of new electronics and power/signal transmission

On the other hand

reduced performance compared to the $\sim 4\pi$-PD is expected $\Rightarrow$
no expanded physics scope, no reduced fabrication cost

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

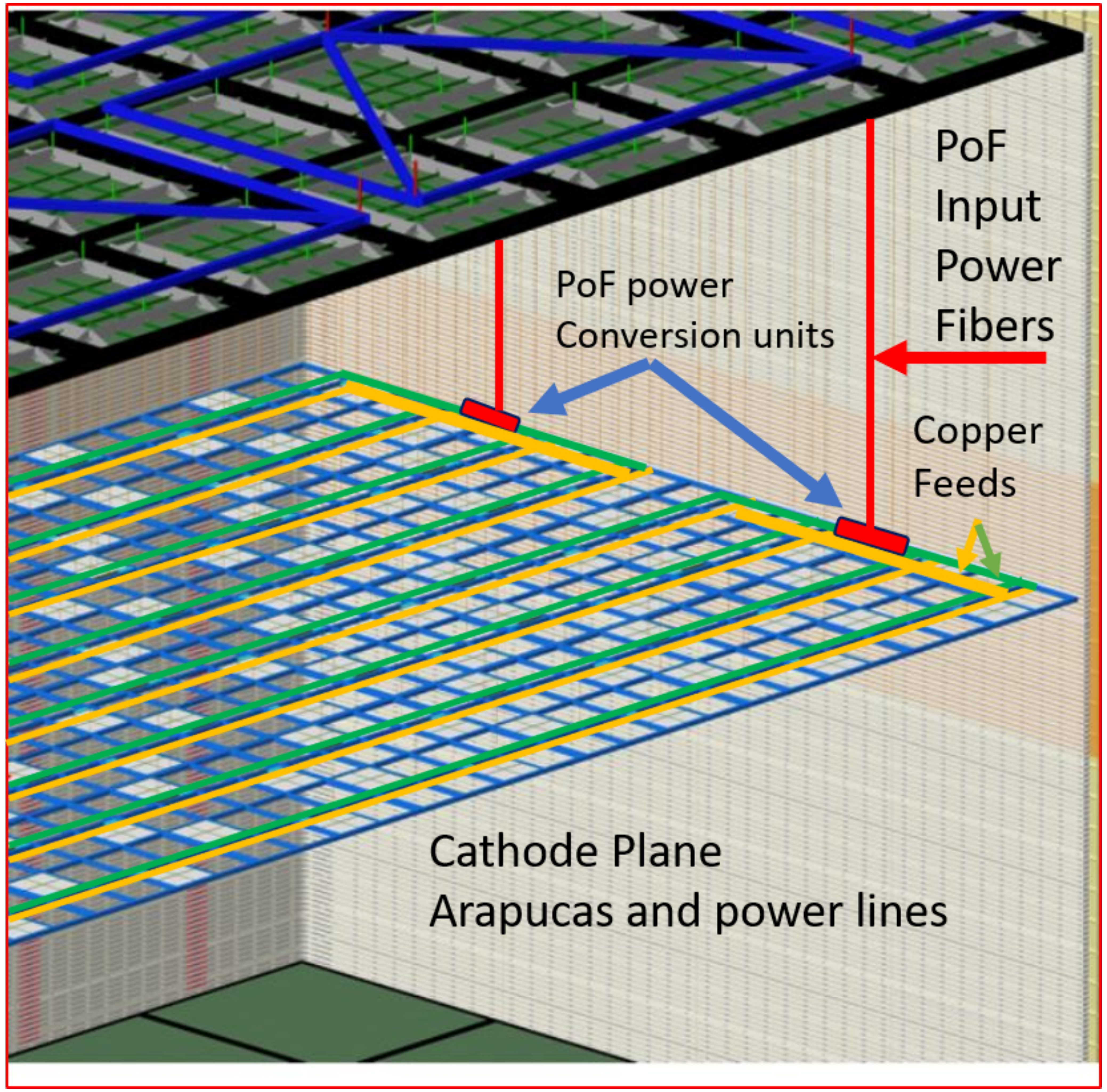


~ 4π PD System design for the VD LAr Volume

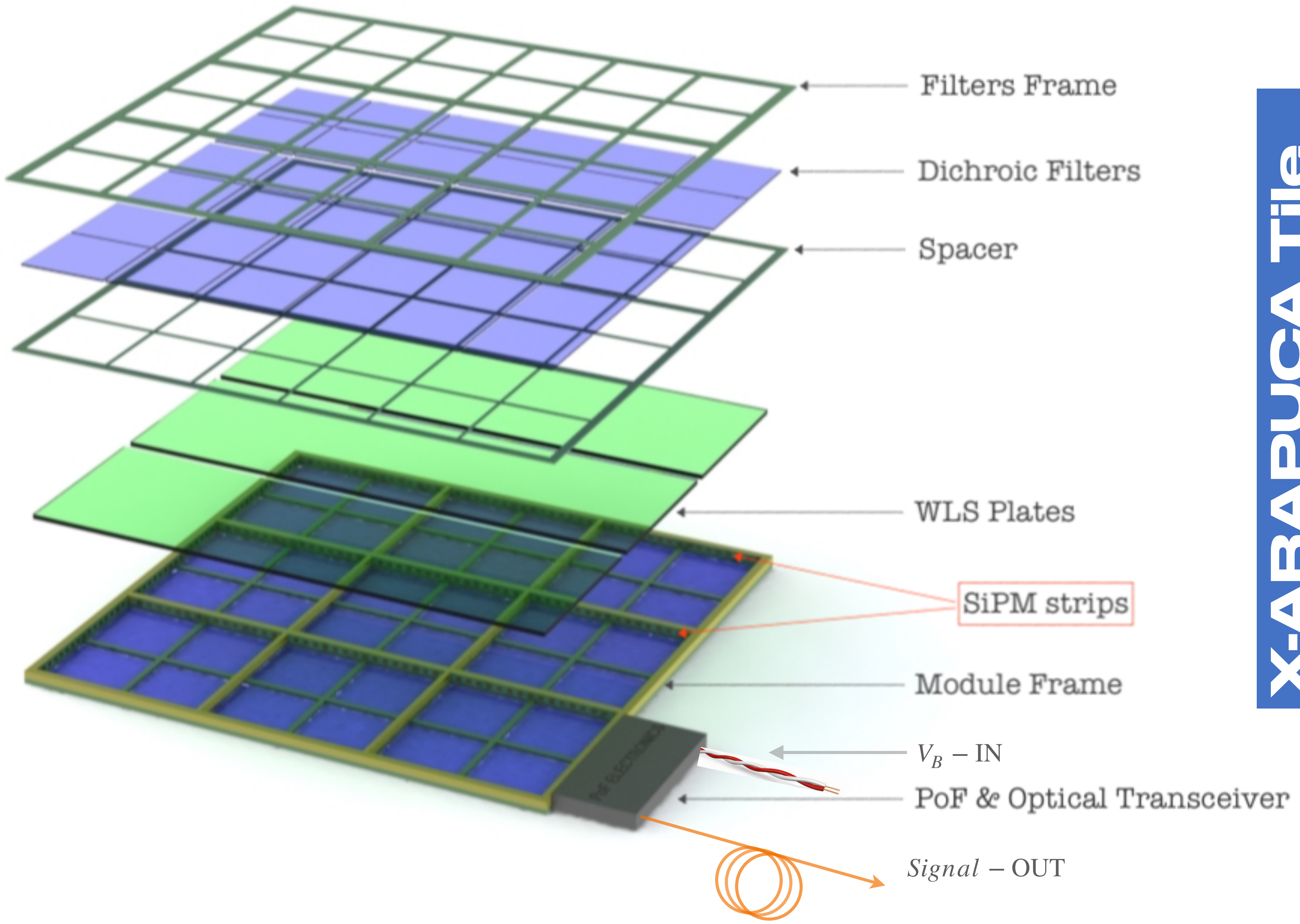
TABLE VI. VD PDS ~ 4π-Configuration

Item	Quantity	HV Surface	HD PDS
X-ARAPUCA Tiles	320 double-side 768 single-side	Cathode plane Field Cage walls	1500
Dichroic Filters WLS plates PhotoSensors (SiPM)	50,688 3,264 115,200 207,360	Cathode plane Field Cage walls	48,000 6000 288,000
Signal Channels	960 2,268	Cathode plane Field Cage walls	6000
Fibers (Serialized Channels) SiPMs per channel	1088 120 90	Cathode plane Field Cage walls	48
Optical Area Active coverage	115 m^2 + 115 m^2 277 m^2 14%	Cathode plane Field Cage walls	Anode plane ~350 m^2 12%

W. Pellico - FNAL



D. Totani, F.Terranova, H. Chen, M. Verzocchi, D. Christian, G. Cancelo, B. Yu, W. Pellico, FLC



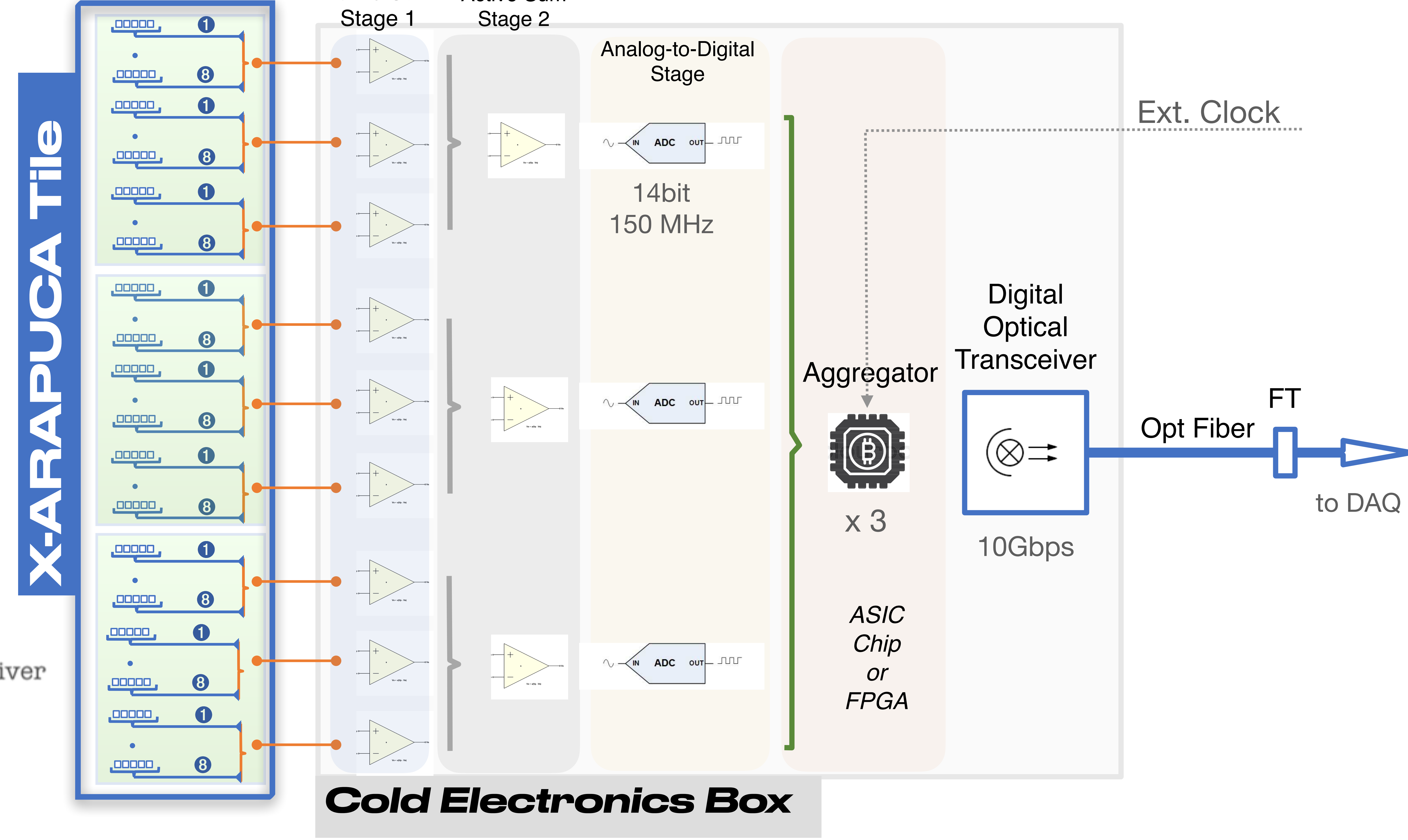
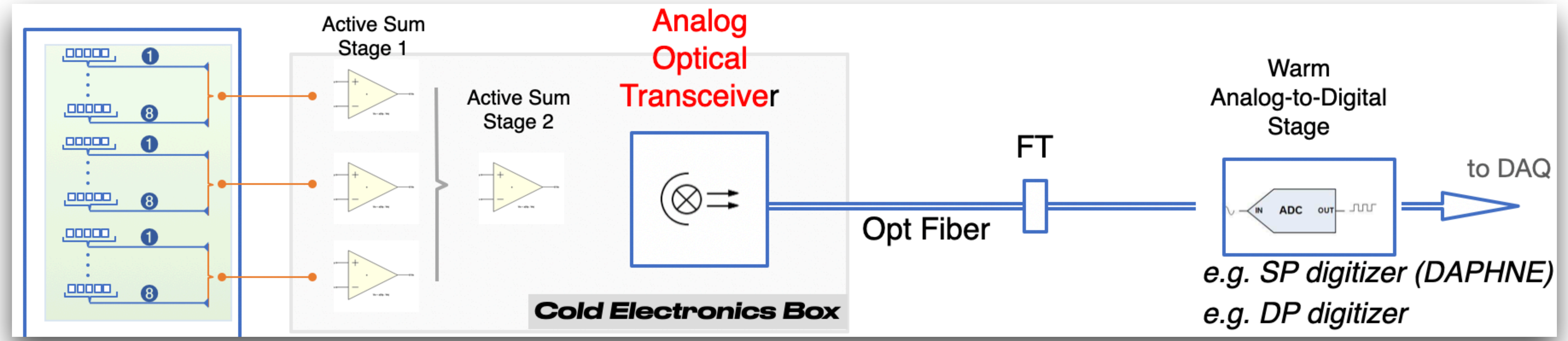


TABLE V. PD basic unit: X-ARAPUCA Tile

	Quantity	Dimensions
Area	1	630×630 mm^2 = 0.4 m^2
Thickness	1	22 mm
Weight	1	$\sim$ 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



VD PD R&D

PD Consortium re-organization to include VD and VD R&D

Very Strong Support and incoming Resources in US by DoE at FNAL and BNL

Enthusiasm form many DUNE grps (new to PD Cons.) in Eu and in US with resources being required/ allocated

Interest on $\sim 4\pi$ VD PD from (yet) non-DUNE grps & individuals in Neutrino community

Intense lab R&D is on-going at FNAL and CERN (since Feb 2020)

R&D Kick-off mtg in early Feb
Rise-up into full-steam R&D activity expected in the next weeks

- The R&D design team is tasked to design the delivery of power over fiber (PoF) to power the SiPMs in the x-ARAPUCAs. This includes bench testing at FNAL and use in LArTPCs at the 50L at CERN and in the full-scale cold box test at EHN1.
- The R&D team is tasked to demonstrate designs for readout of the SiPM signals over fiber.
- The R&D team is tasked to deliver TWO x-ARAPUCA modules for readout in the NP02 cold box test by the end of 2021.
- The R&D team is tasked to optimize the existing x-ARAPUCA designs for Xe light read-out for use in vertical drift (VD Module-0) and demonstrate with prototypes in the 50L test stand at CERN and in the NP02 cold box test in 2022.

Activity	FY21 (cold box prototype)	FY22 (Optimization, *Module-0* prep)
ARAPUCA Detector	Prototype Fabrication (2 units - standard Ar + Xe): 1 Two-sided (Cathode), 1 One-sided (FC). Component Production at UNICAMP, Mi Bicocca + … many grp.s in Eu, UK and US interested • Dichroic Glass • WLS bar • SiPM • Tile mechanics	Prototype Fabrication (2 units): optimized for Xe light • Dichroic Quartz Glass • WLS bar (cutoff) • SiPM (PDE)
PoF power transmission	Prototype Fabrication (2 units - 60 W) - pre-test at FNAL (PAB) and CERN (50l) • PPM (Photonic Power Module) • Fiber & FT • Cold Receiver • Regulator	Optimization for Power distribution to Cathode PDS • PD Calibration • Fiber & FT for NP02
Cold Electronics	Design and Prototype development - pre-test at FNAL, BNL, UCSB, Mi Bicocca + … • SiPM Passive Ganging Board • Cold Active Ganging & Shaping Stage (analog Signal) • Cold ADC Stage (digital signal) • Clock distribution • Cold Aggregator Stage (FPGA, ASIC)	CE Board Optimization • Cold ADC + Aggregator in one single stage
Electro-Opto Signal transmission	Prototype development - pre-test at FNAL, CERN, Mi Bicocca, APC Paris + … • Cold (Analog or Digital) Transmitter • RF/WiFi Transmitter • Fiber & FT	Layout optimization and DAQ interface - Bristol • Fiber & FT • Fiber Warm Interface to DAQ
PDS Performance	MC simulation - ABC, SC, TFPR (Br), NAL, Edinburg, UCSB, Syracuse, CIEMAT, Mi + … • Implement DUNE FD detailed • PDS detector simulation in standard LArG4/ LArSoft framework. • Standalone MC simulation of Arapuca Efficiency. • Xe light emission and propagation simulation.	MC simulation - optimization • CE signal processing in standard LArG4/ LArSoft framework. • Xe light emission and propagation simulation.

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

- 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

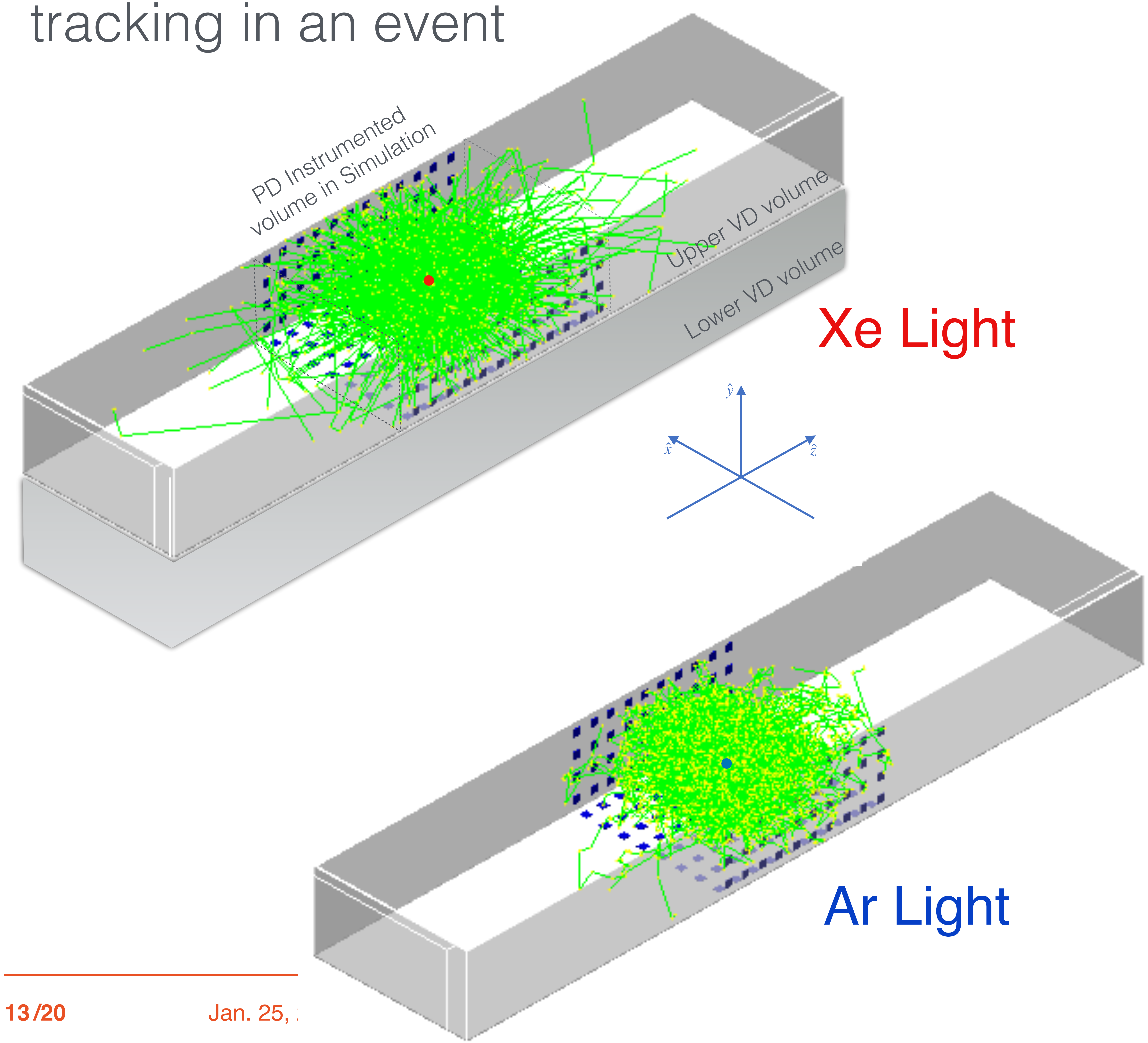
Detector Requirement	Value	Physics Purpose (*)
Trigger efficiency for interactions with energy deposit $E_{dep} \geq 5$ MeV in 100% of detector fiducial volume	$\geq 99\%$	- SN burst trigger up to the Large Magellanic Cloud (50 kpc) yielding 10 interactions in 10 kt LAr - Low-energy background rejection
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)

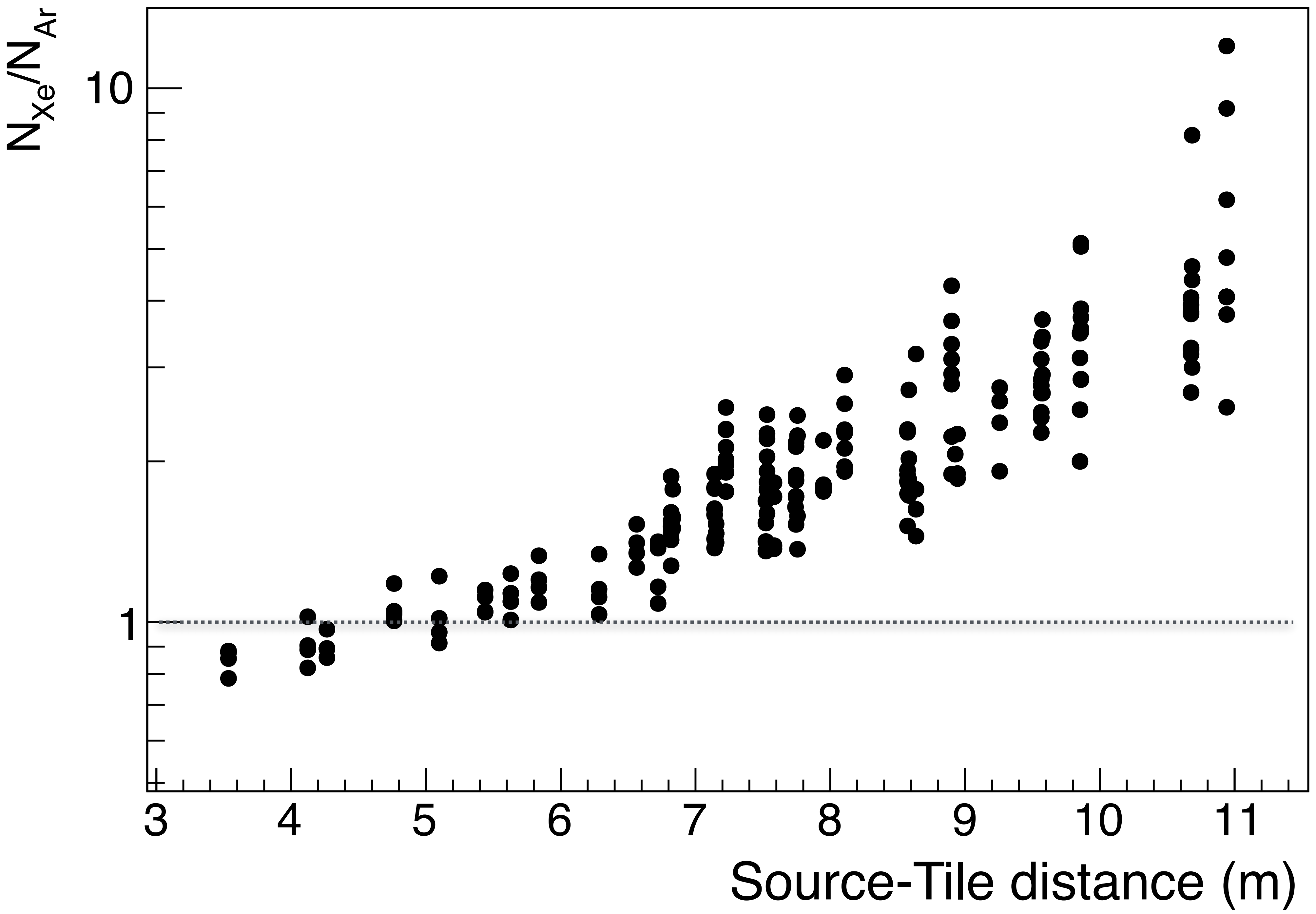
* I. Gil-Botella - Low-E Physics and PD role

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

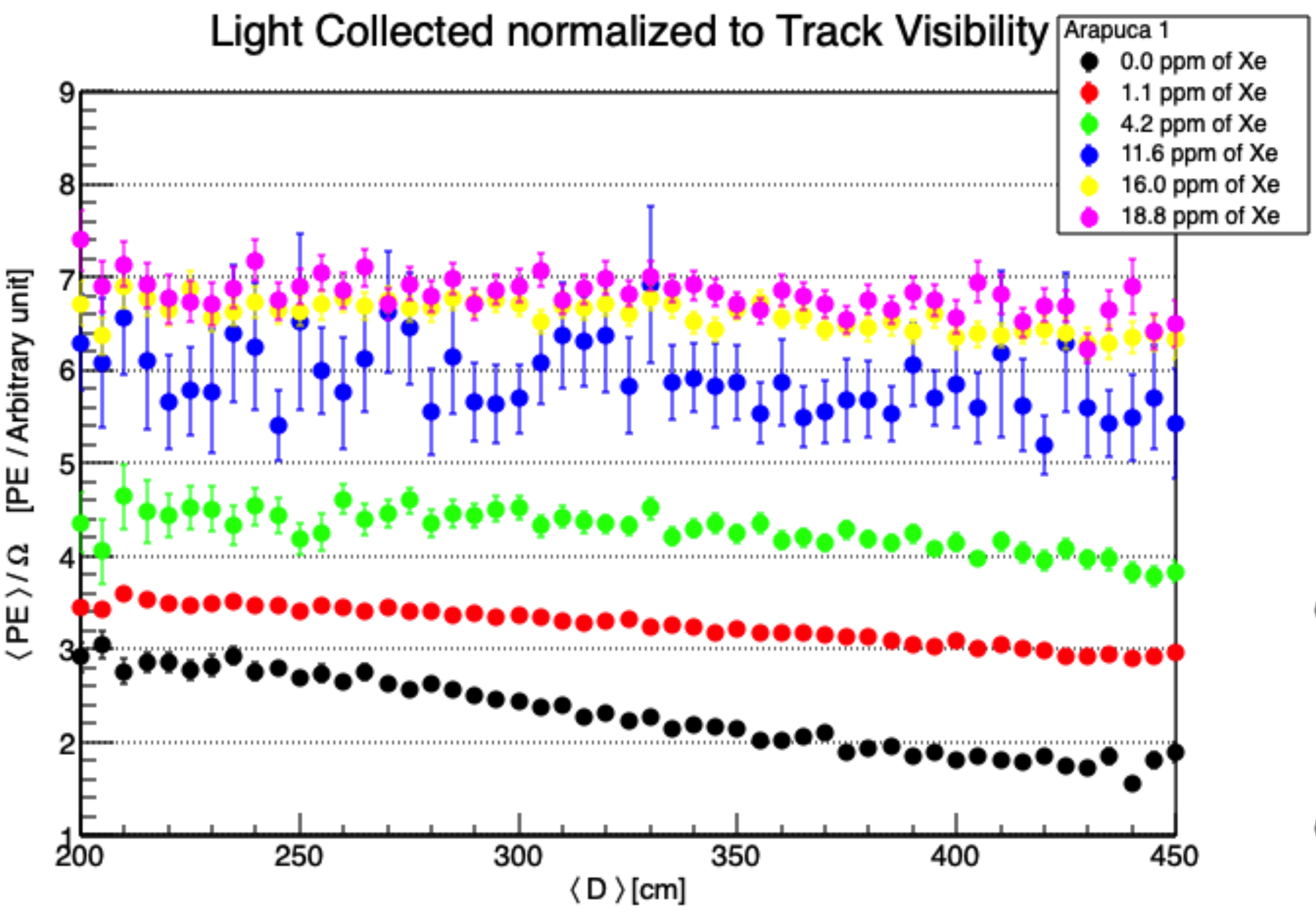
L. Paulucci, Universidade Federal do ABC, Santo André, SP, Brazil
F. Marinho, Universidade Federal de São Carlos, Brazil
D. Totani, University California Santa Barbara, USA

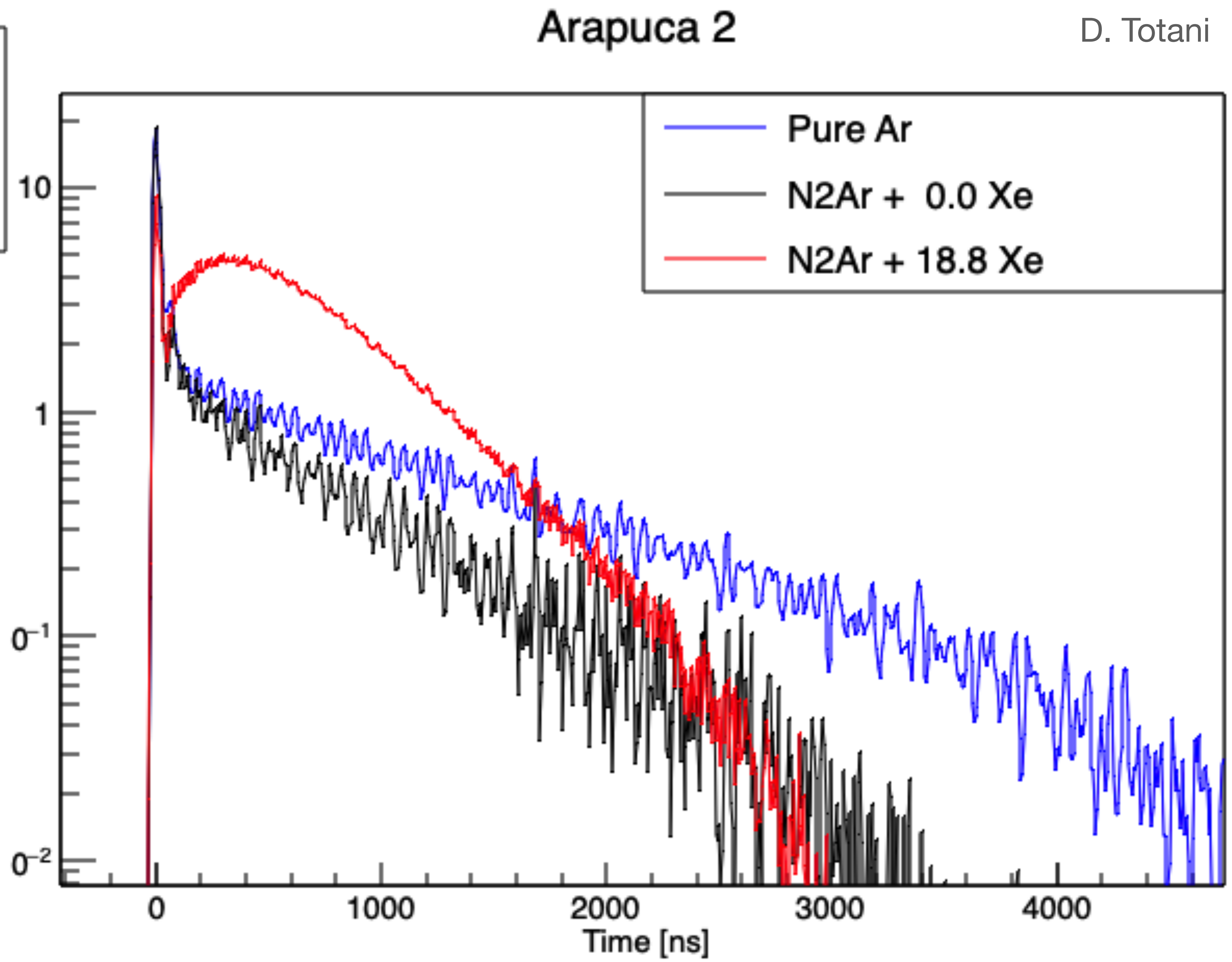
GEANT4 photon tracking in an event





Xe doping test in protoDUNE

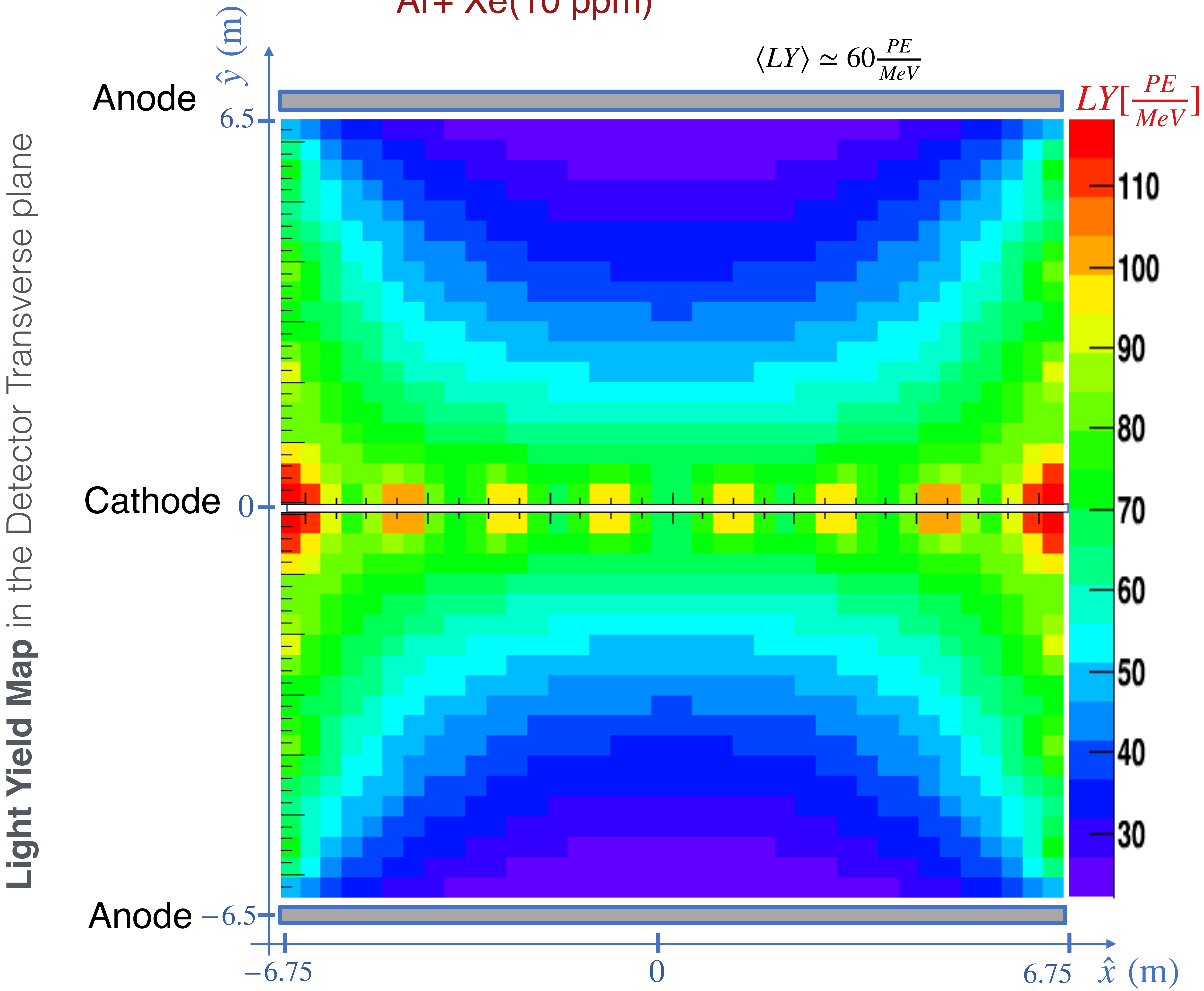




D. Totani

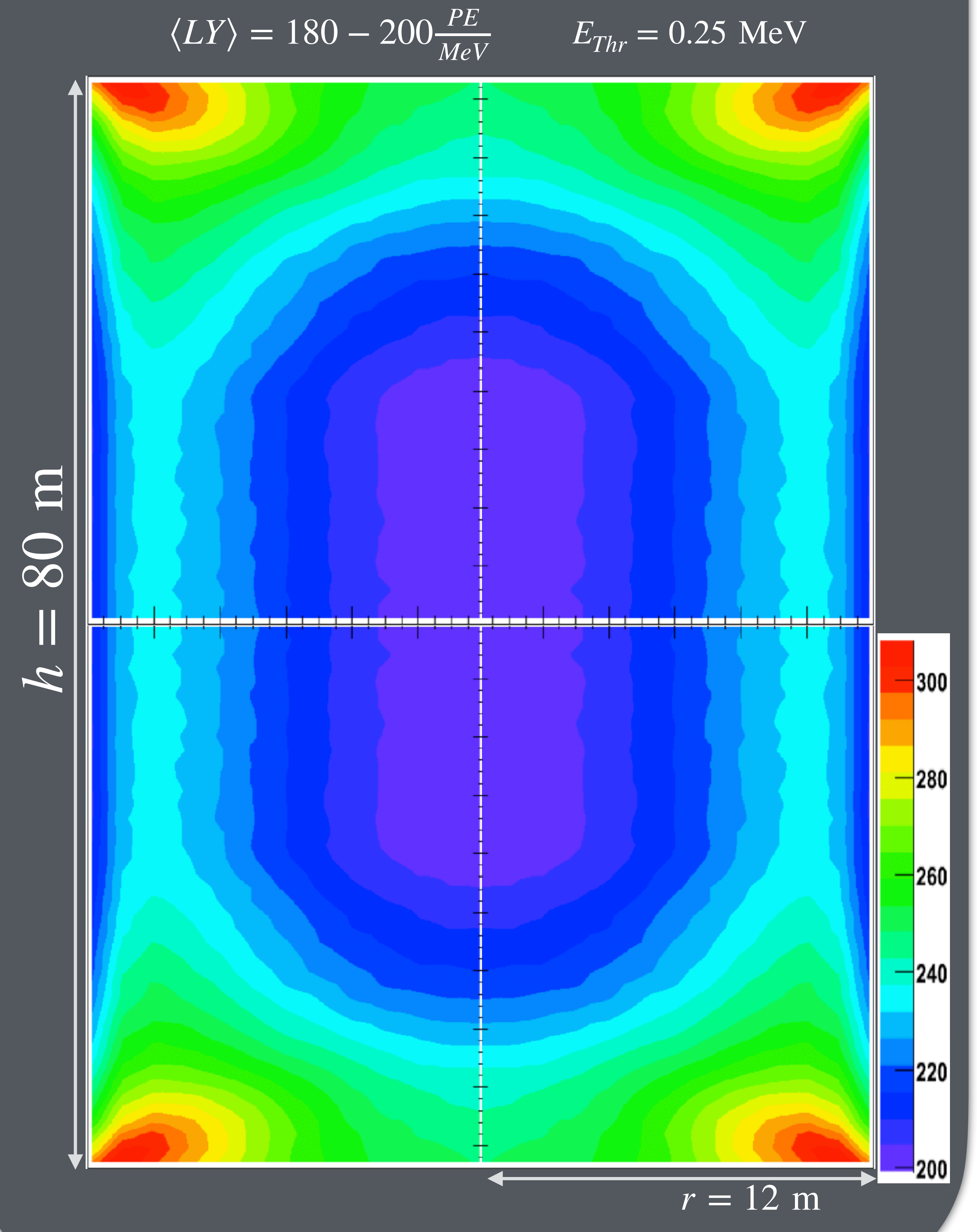
The VD $\sim 4\pi$-PD w/ $\sim 14\,\%$ Optical Coverage

Ar+ Xe(10 ppm)

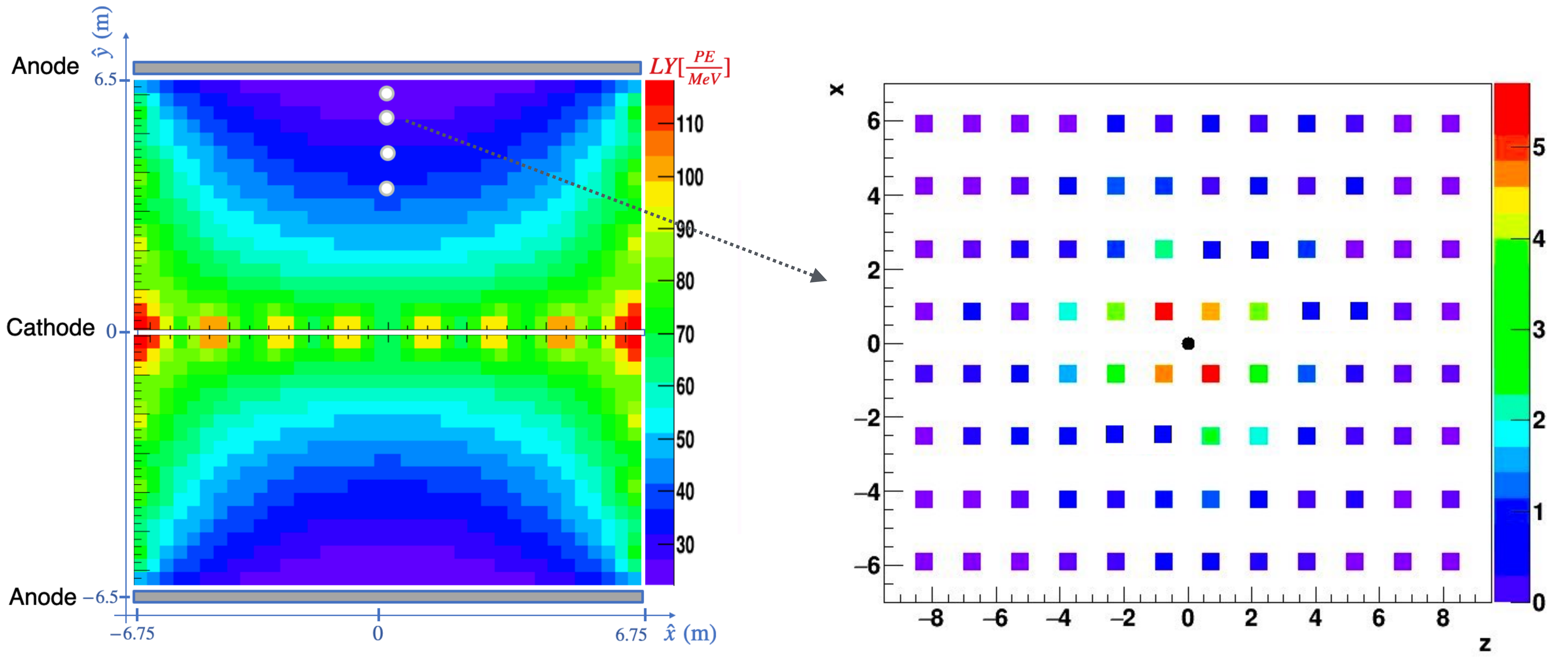


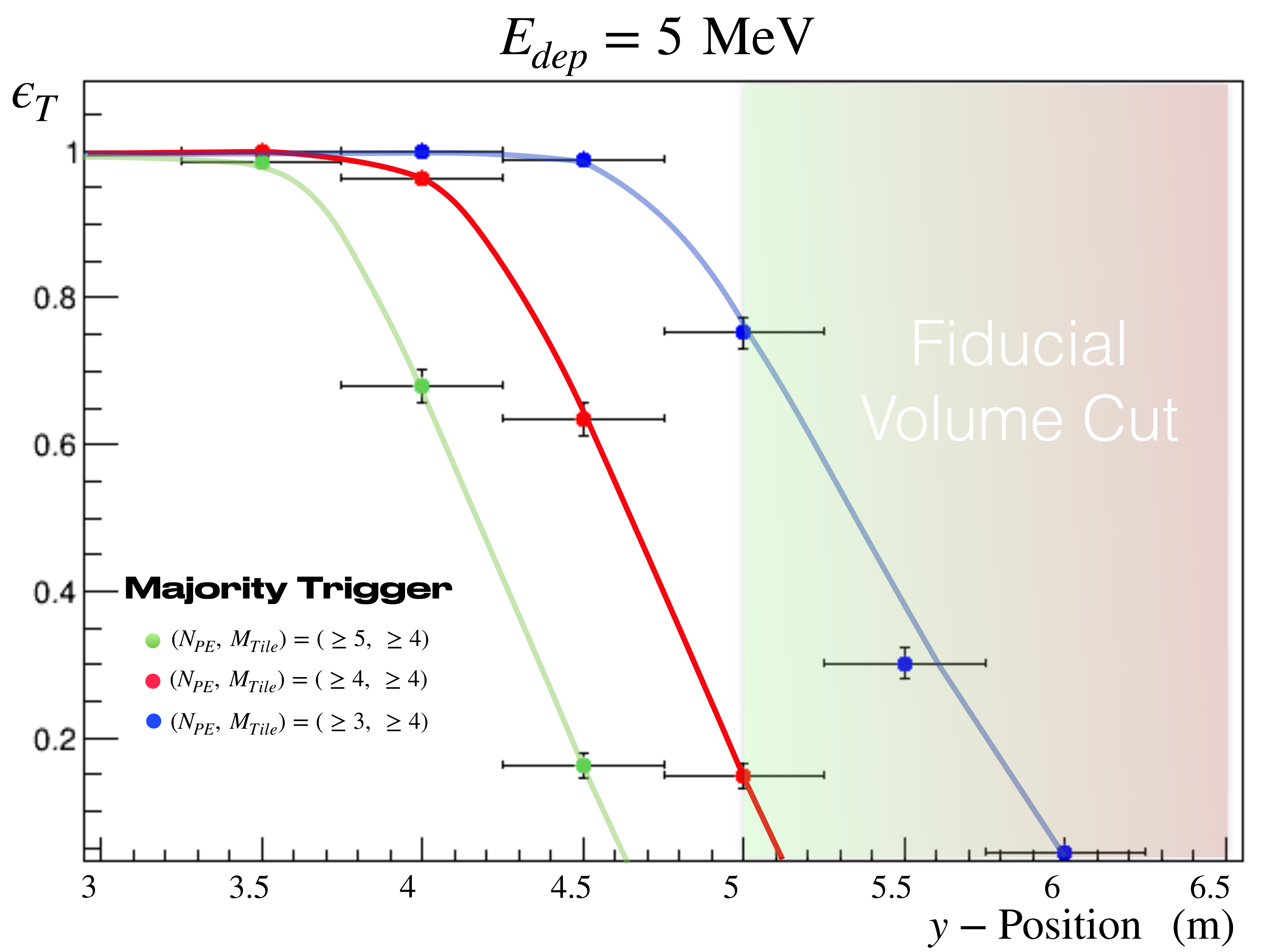
LAGUNA-LBNO design study for Solar Neutrino and SN/DSNB Experiment

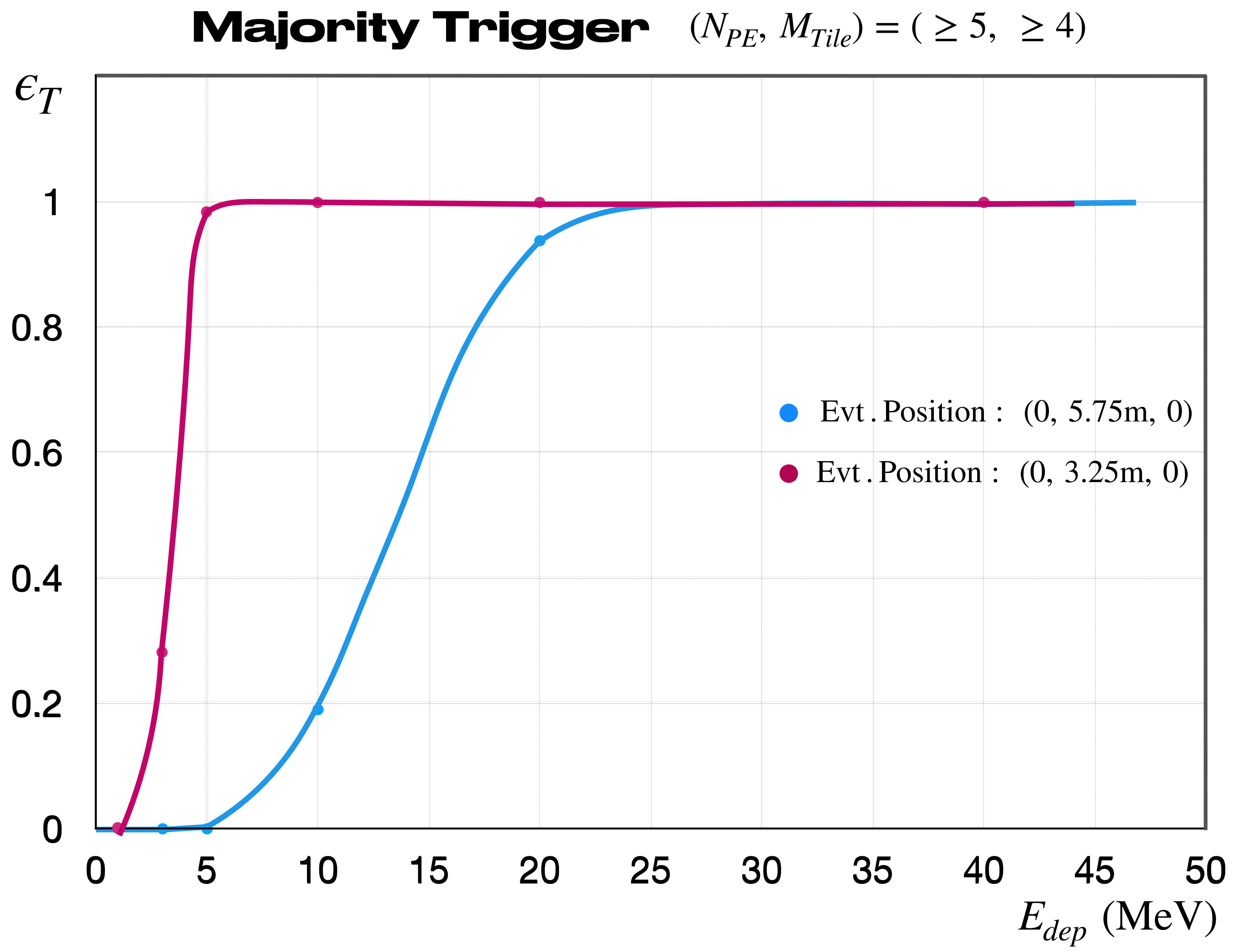
LENA - 4π LiqScint w/ 30% O.C.



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

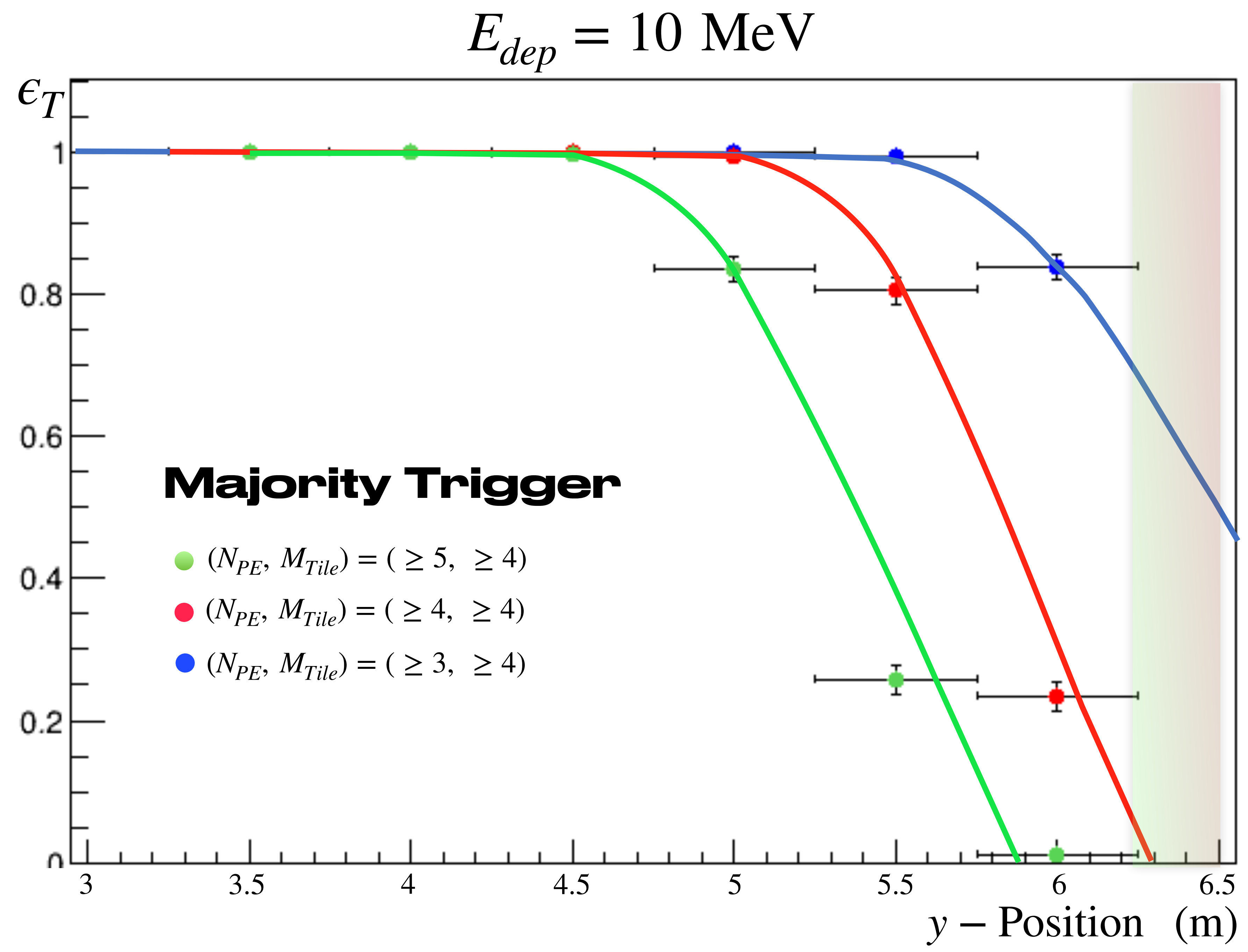






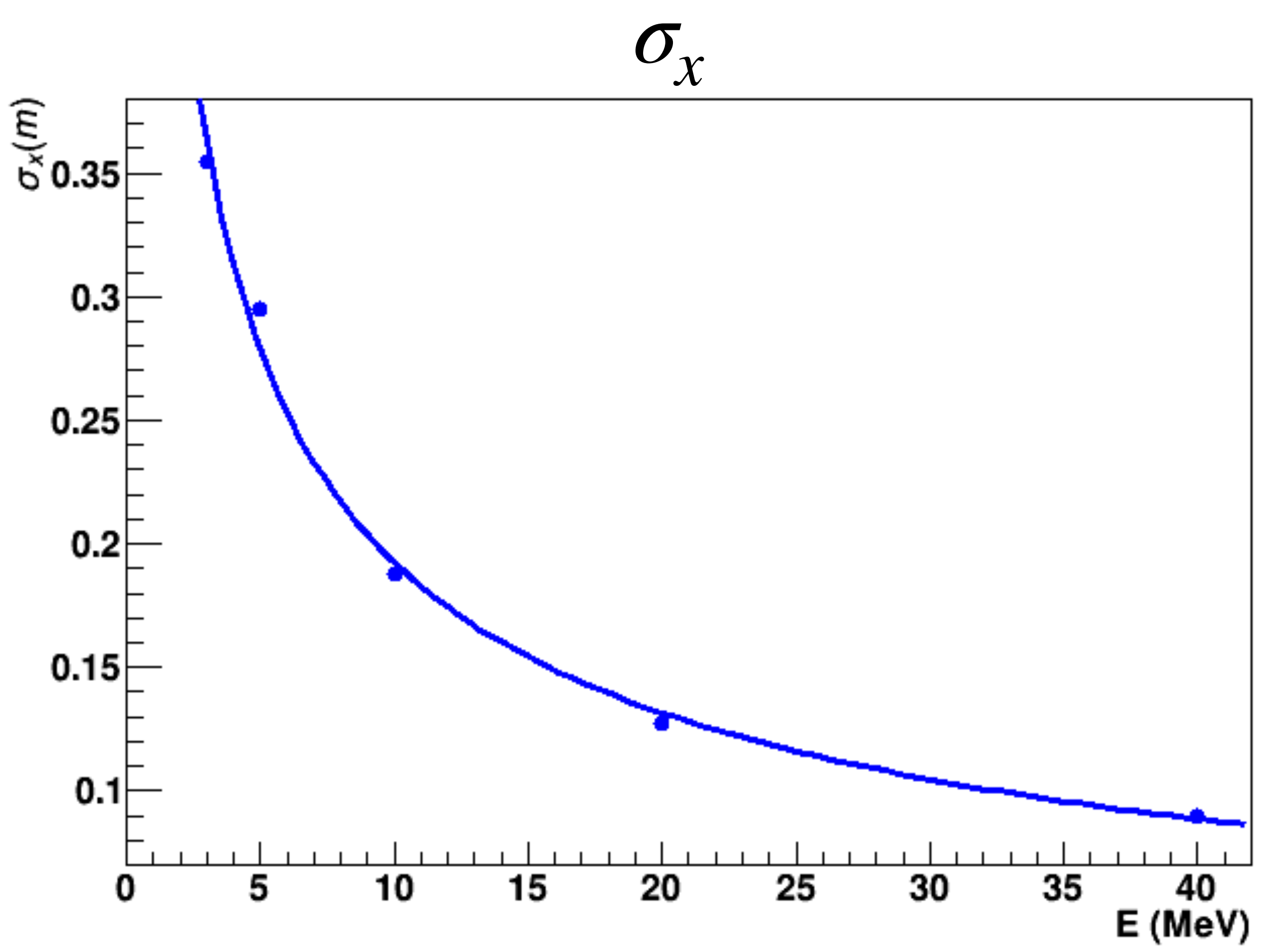
Relaxing (N,M)-Majority requirements enhance trigger efficiency, but also increase rate of false-positive triggers

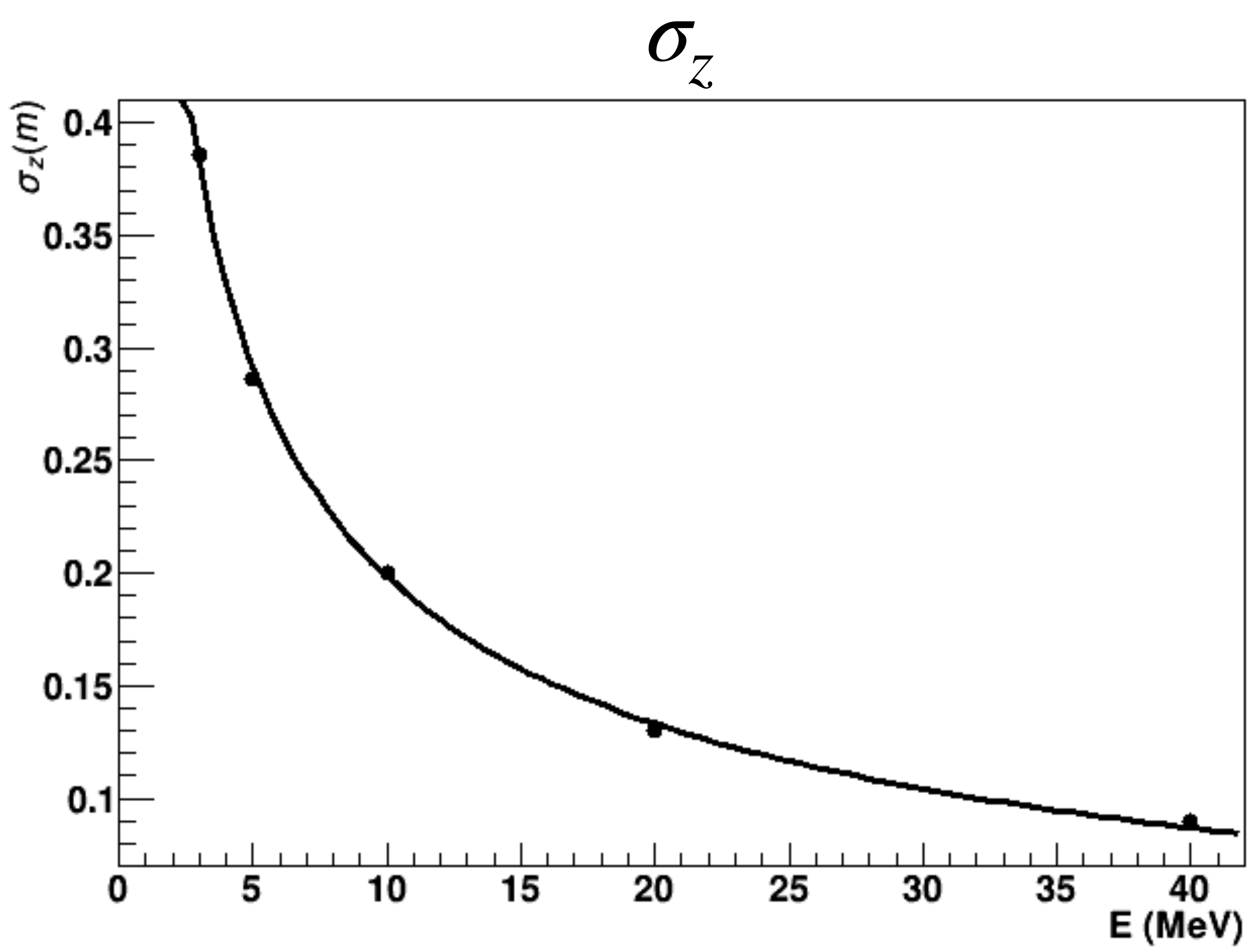
Trigger Efficiency $\geq 99\,\%$ for interactions with $E_{dep} \geq 5$ MeV expected in 100 % of a 10 kT Fiducial Volume

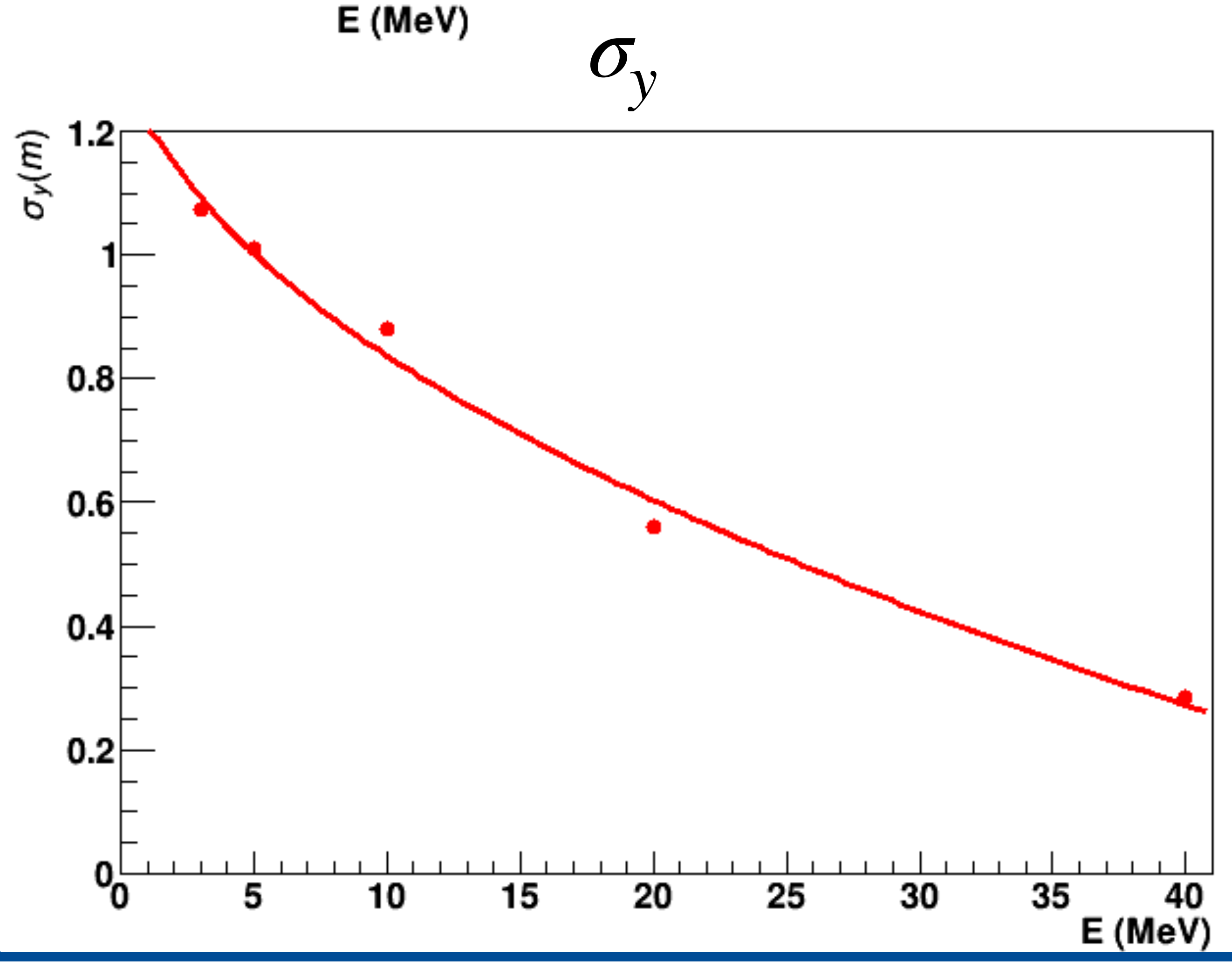


Position reconstruction from detected photon counting

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

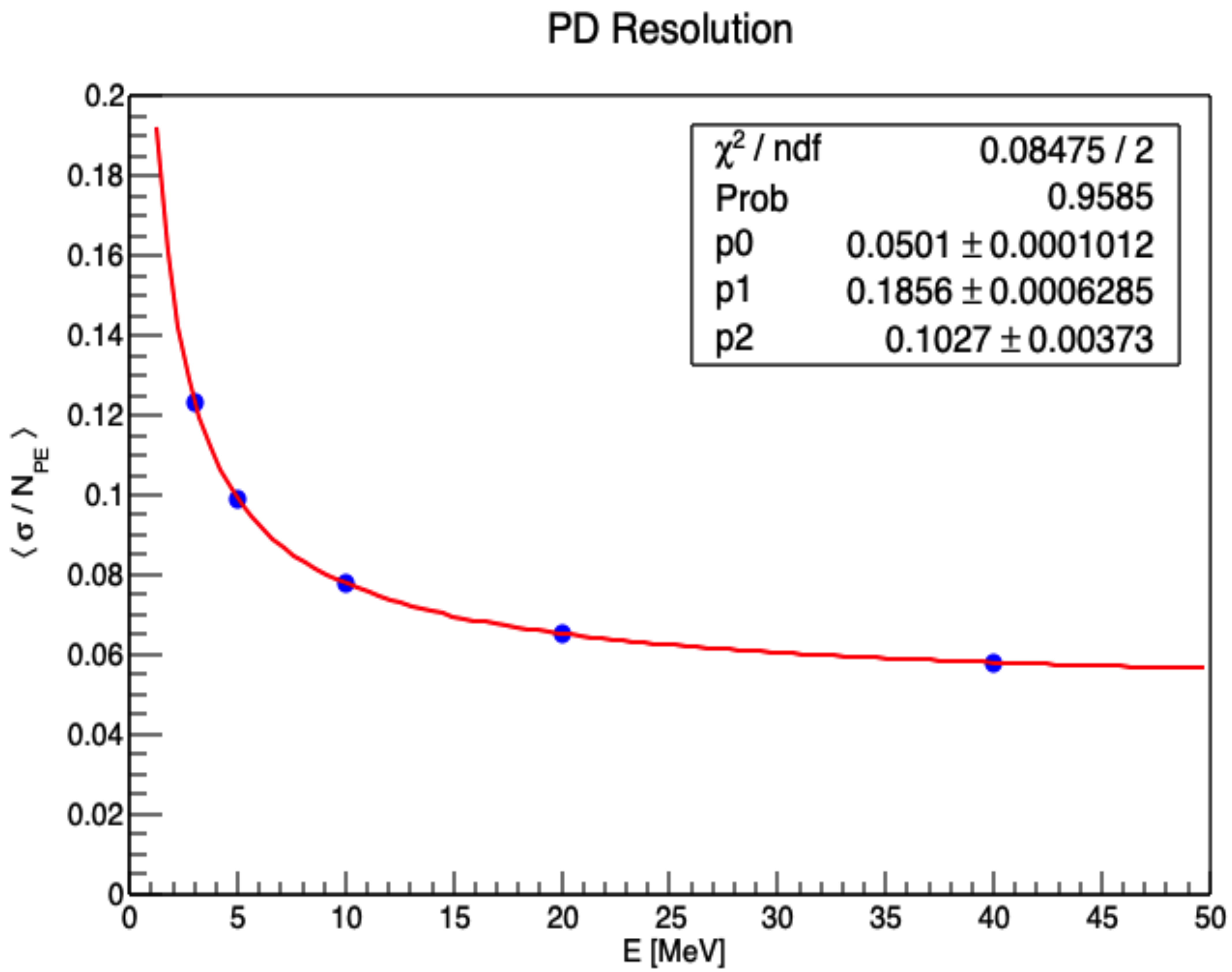






Calorimetric Energy reconstruction from detected photon counting

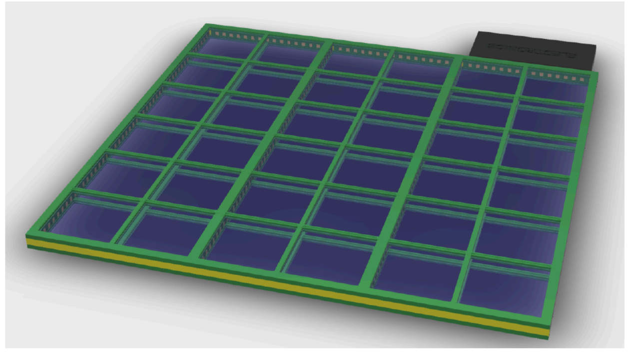
Energy Resolution
from statistical fluctuation (p1) on the number of detected PEs and to uncertainty on energy calibration (p0)



Timing information (not used here) should improve Space Resolution

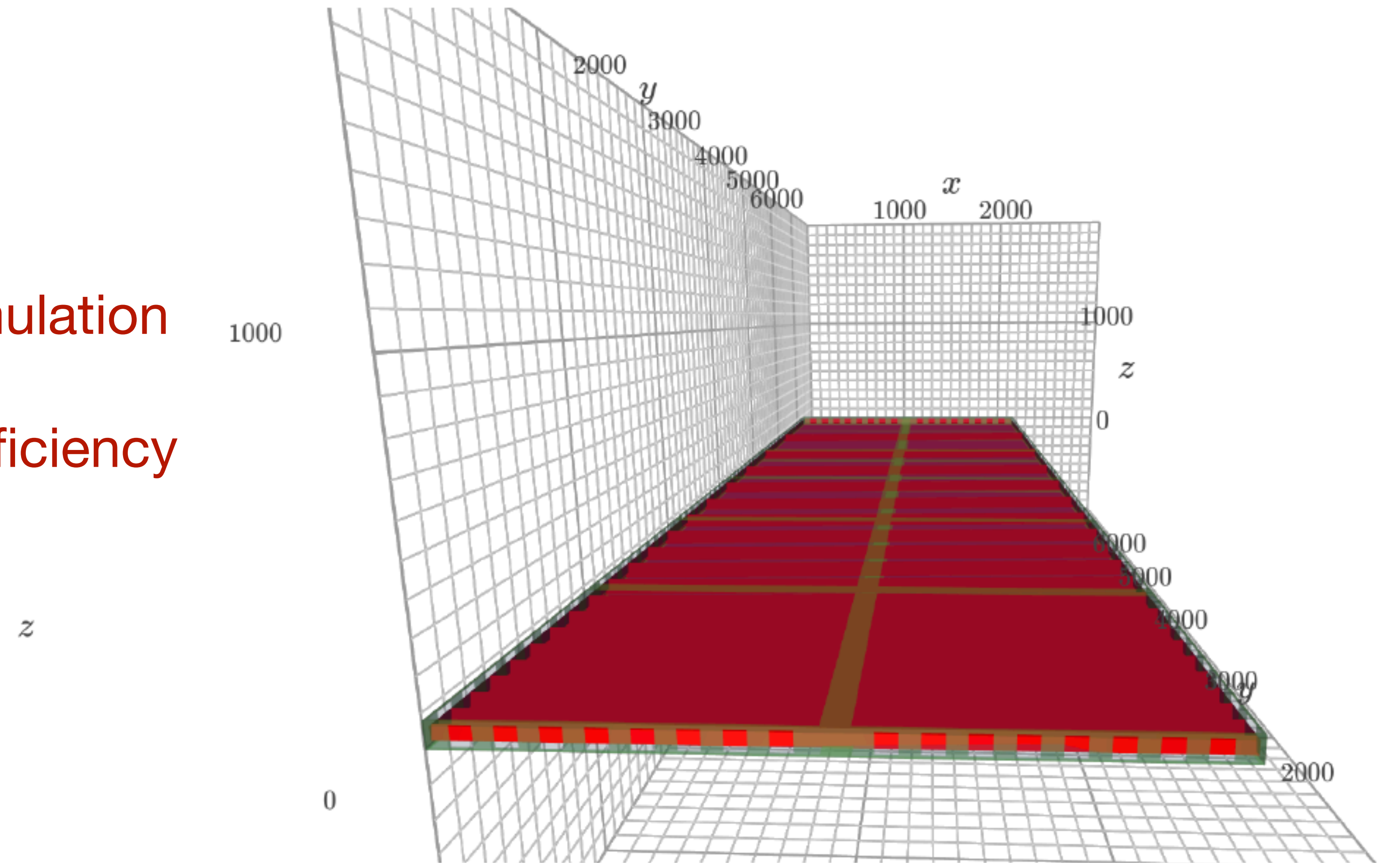
PDS vDrift: recent software developments

Arapuca-Açu (by Heriques Frandini)

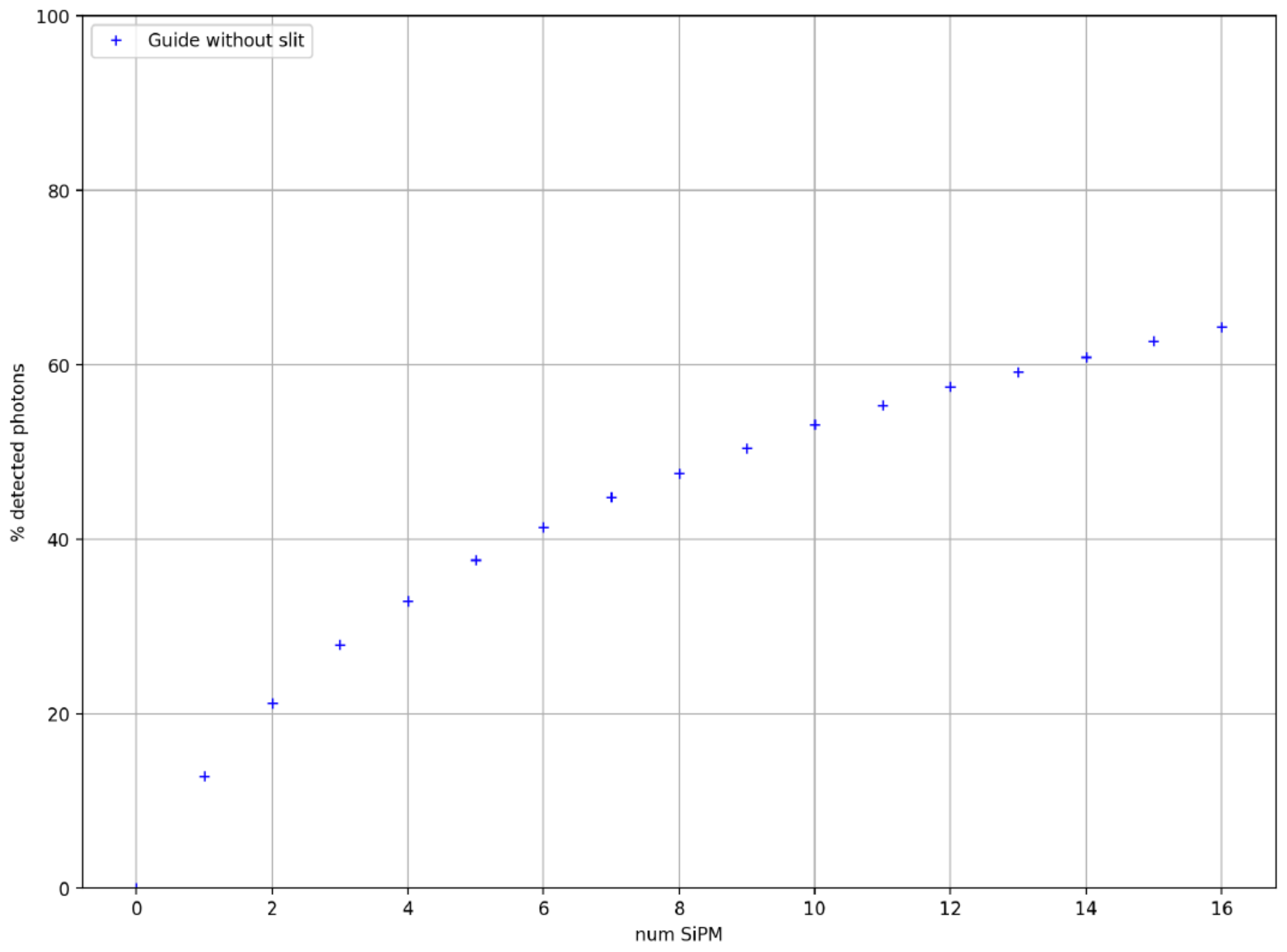


Arapuca-Açu with a 4mm thick light guide.

Standalone simulation
for
X-ARAPUCA efficiency



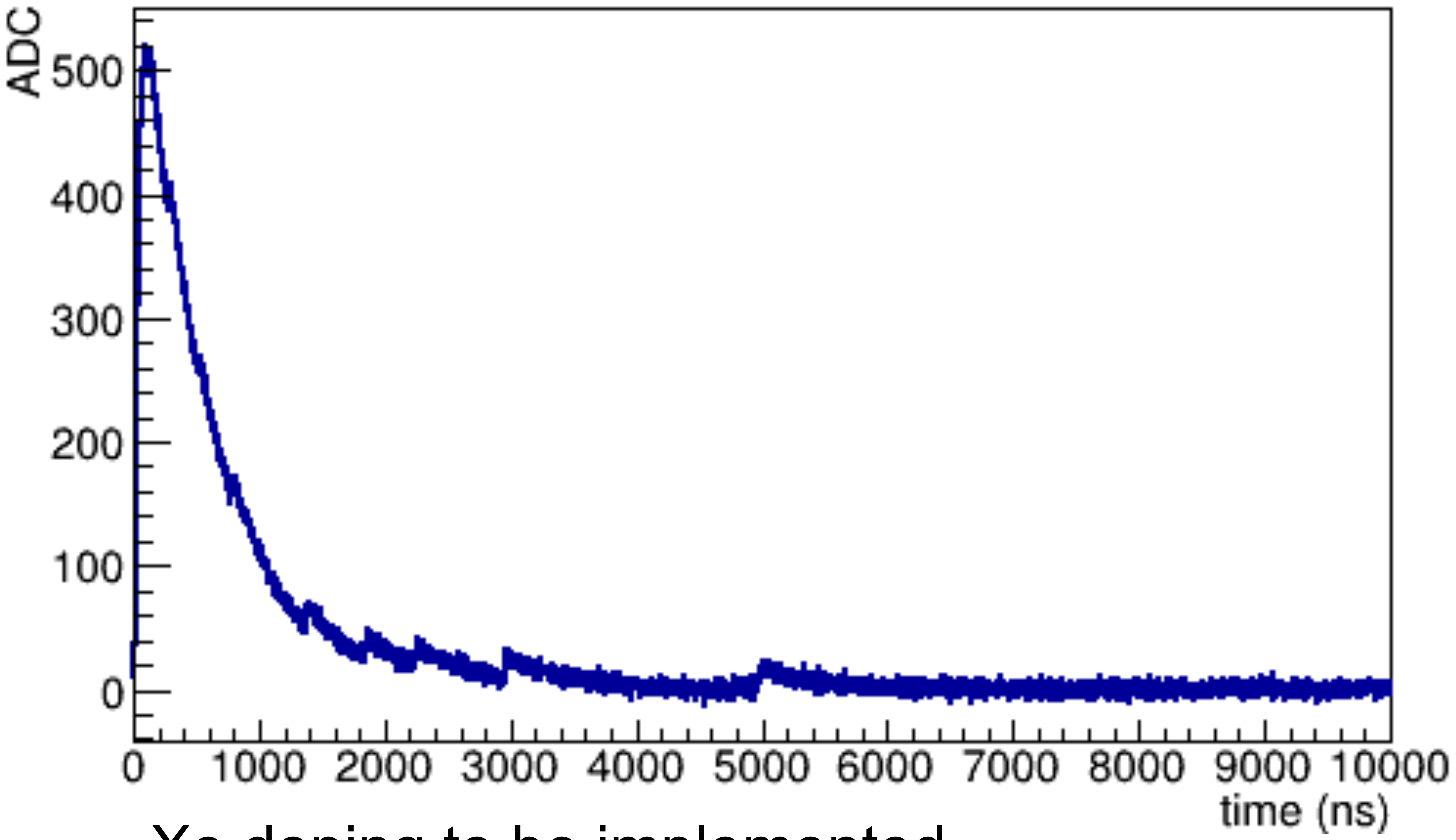
% of detected photons
vs
number of SiPM per side
of dichroic filter



M. Adames,
F.Ganacim,
A. Steklain

Standalone photon time profile simulation:

Accounts for LAr scintillation + light propagation + wavelength shifting + SiPM readout effects



Xe doping to be implemented

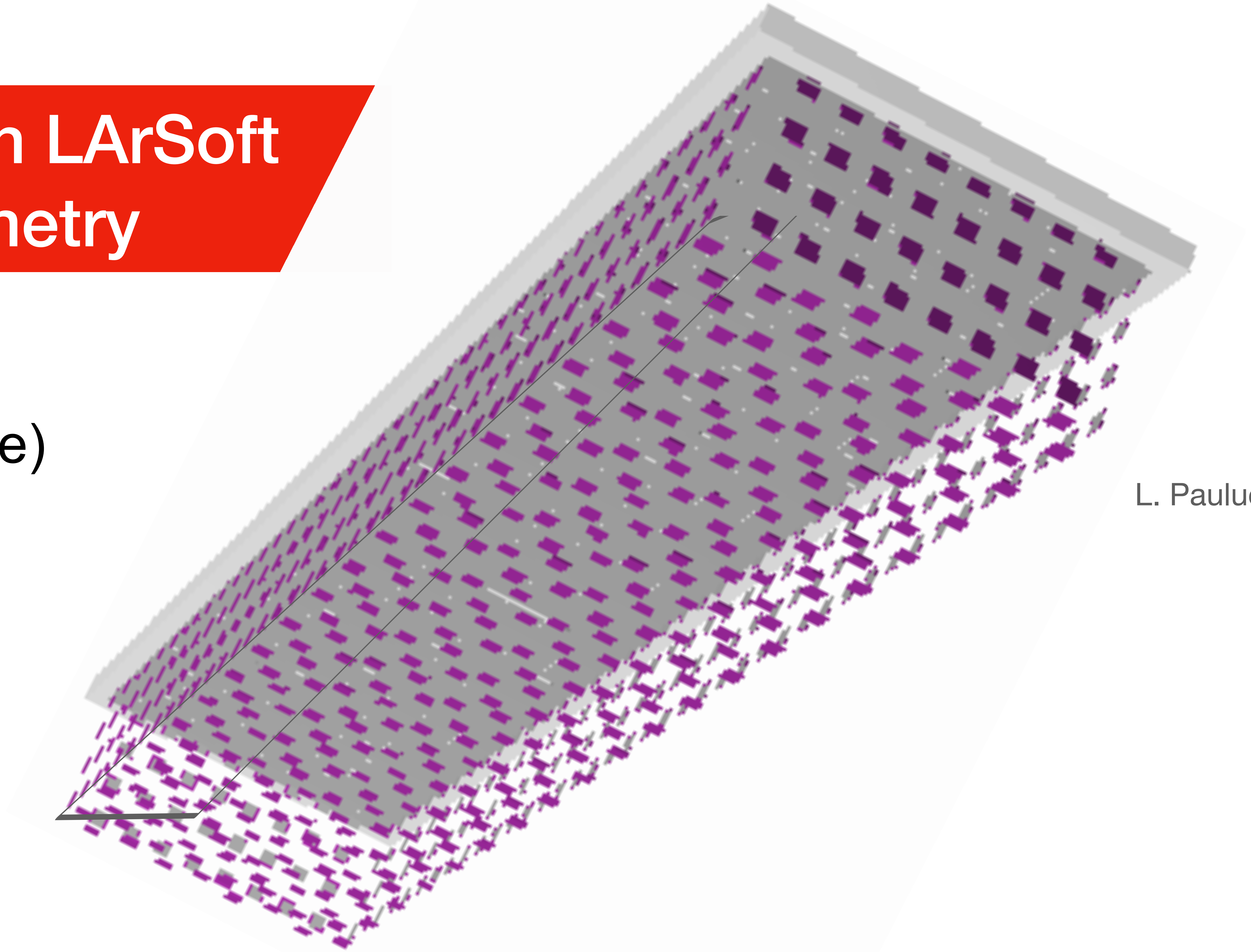
F. Marinho

VD PDS: recent software developments

VD PDS in LArSoft geometry

"VD $\sim 4\pi$" configuration (upper Volume)

"SP mirror" configuration (cathode only coverage) also available

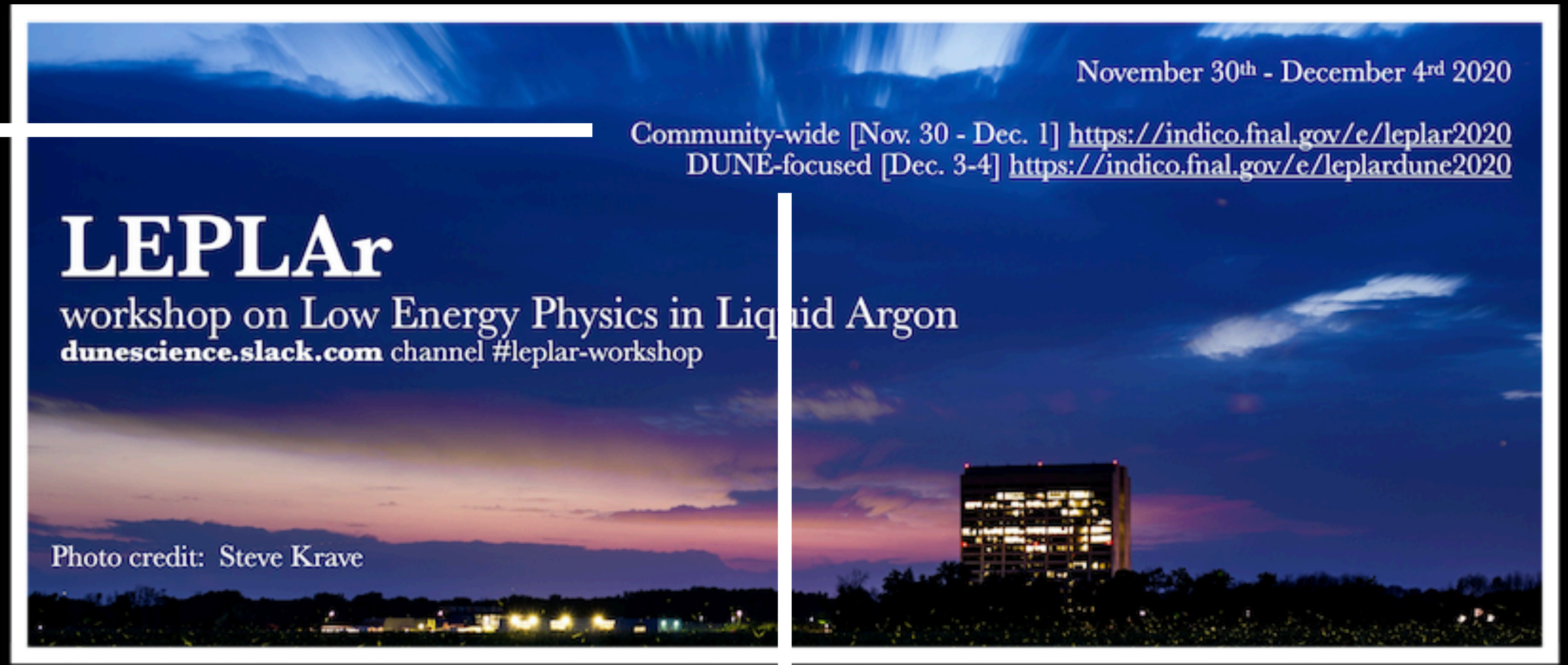


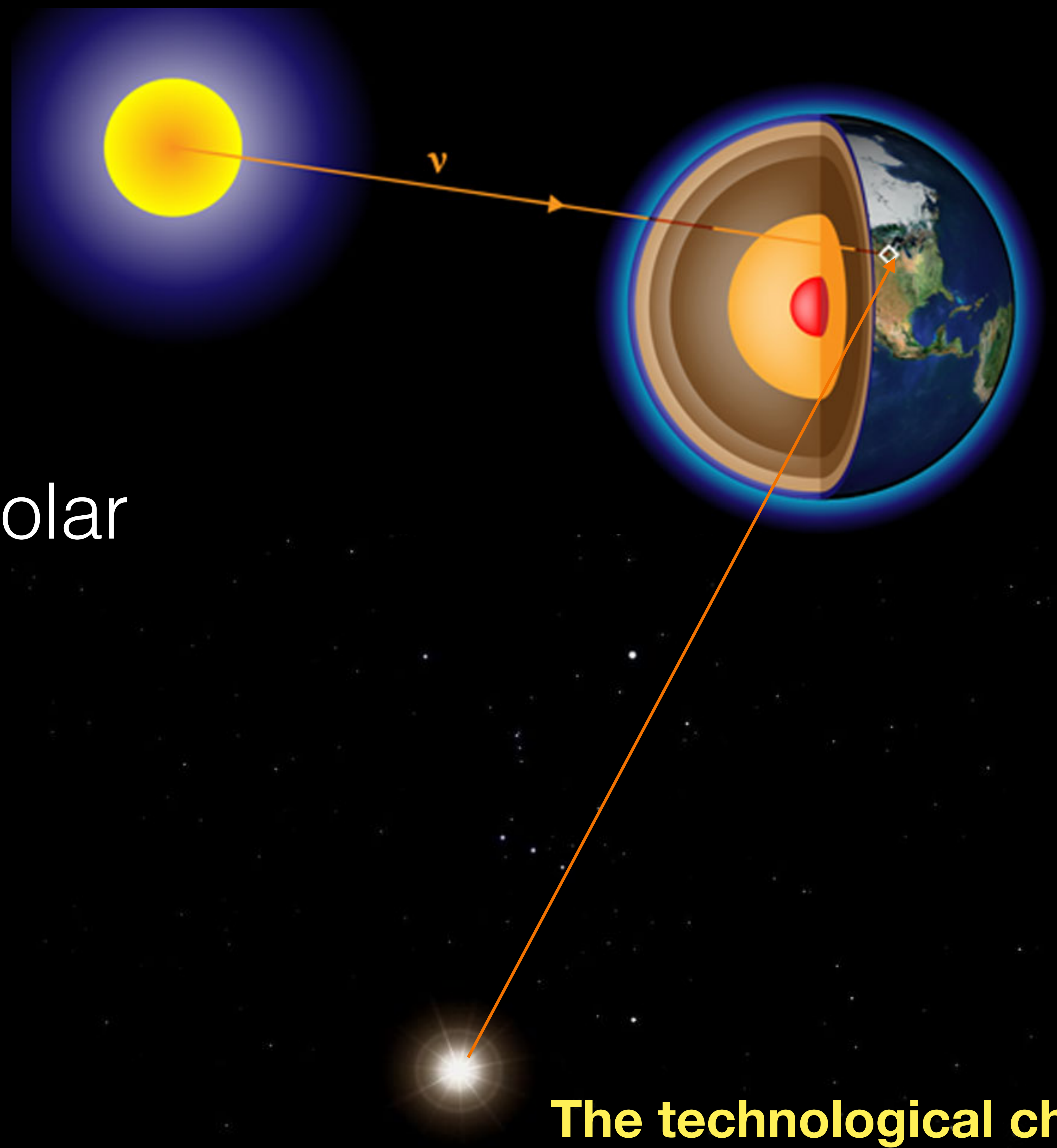
L. Paulucci

Simulation of mixed Ar and Xe light in LArSoft in progress/close, some additional technical work is needed and Xe time profile validated from experimental tests (protoDUNEs) results

A.Himmel & PD SW Grp.

- Solar neutrinos open discovery space in particle and astro-particle physics
- CoreCollapse SN is the most spectacular phenomenon in Nature and is imprinted in neutrino signal





Solar

SuperNova

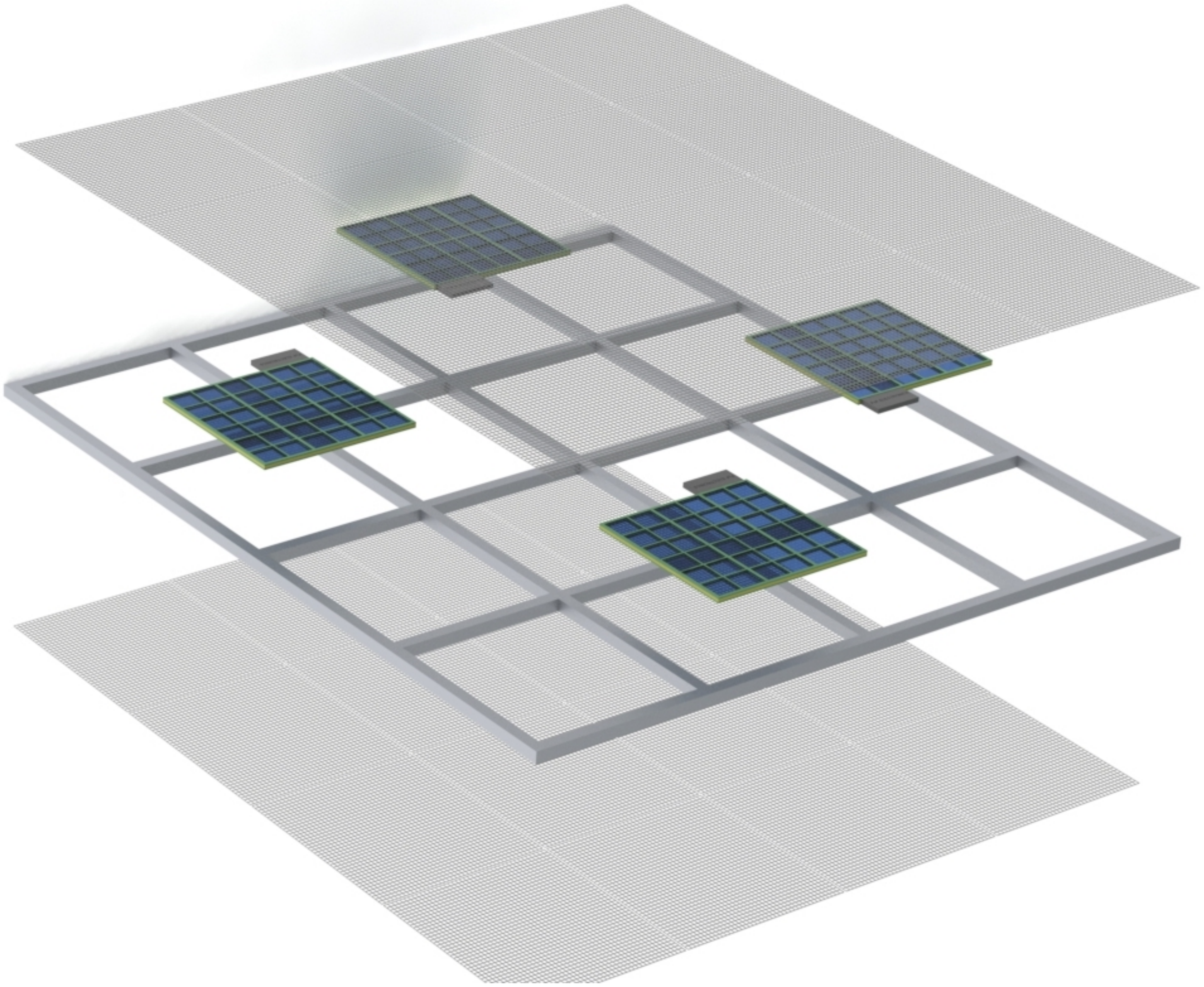
- *It is critical*
  - *to DUNE Science Program to succeed at measuring low energies from Solar and SN neutrinos*
  - *\to lower Trigger En-threshold to extend range of SN detection (toward and beyond Galaxy edge).*
  - *to guarantee good Time resolution and improve Energy resolution for SN-signatures in time & energy spectra*
- *Wide consensus on*

VD $\sim 4\pi$ PDS is a preferred technology option (in combination w/ TPC) to expand DUNE Physics reach in the lowEn UG sector

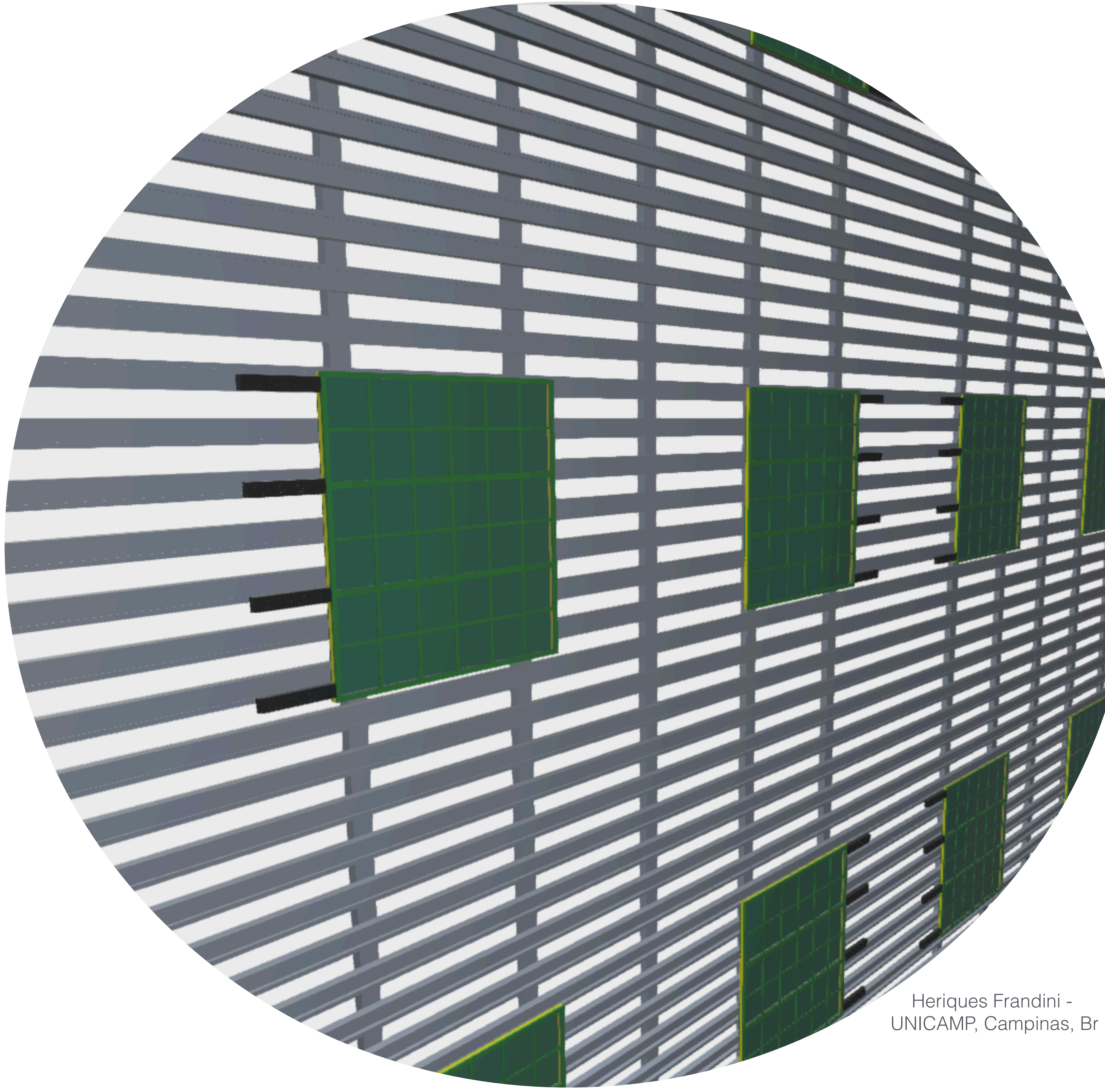
The technological challenge is high, and compelling critical R&D is now being organized
Involvement and skills of DUNE grps are essential for success

Back Up

~ 4π 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

POF Technology for VD application

Two Parts

R&D activity

PoF
Power over Fiber Optic

R&D ongoing at CERN and at FNAL

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

(8) the PDS system operating on the cathode or FC looks challenging. What is the plan for testing in a realistic environment? Will the heat load of the optical powering give rise to bubbles? (Bill Pellico)

The PDS system operating on the cathode and FC consists of three parts:

1) The ARAPUCA, which is using a design that very similar to previous operating Arapuca's

2) Delivering power via power over fiber (PoF) and distribution to cathode electronics

3) PD data collection and transmission

- The powering of the 117,000 SiPMs on the cathode has been estimated to require between 6 to 30 Watts. Although this is not significant power, the power system, including distribution and connections, require significant viability and reliability testing. The initial concept testing was completed successfully at FNAL and now moved to prototype unit testing at CERN. The prototype system will test the delivery of sufficient power for one quarter of the Arapucas on the cathode. The first part of this test, using a small dewar filled with liquid nitrogen to power a dummy load, is underway. This will provide the optimum load match and prove thermal stability.
- After reaching sufficient power levels with acceptable heat loss (minimal to no bubbles), step two of the testing will be to put the PoF prototype with an upgraded SiPM circuit board onto the cathode at voltage in the CERN argon cryo test stand. During step two, SiPM calibration and performance will be done under PoF conditions.

- Our present testing is showing very good results but more needs to be done on the prototype housing. The design is modular with a series of small PoF units summed to reach desired power. Figure1 below show the result of scanning a load using single PoF cell (sub-unit) in an argon bath. We expect each PoF power unit to use 6 to 8 PoF cells. Figure 2 shows PoF voltage at SiPM in liquid argon (with no regulation unit).
- After meeting the power needs of the SiPMs, a similar system will be built to supply power to the data processing electronics. The collection and transmission electronics is still in the planning stage. Once, chip selection is firmed up, the build up the PoF will done. The power is expected to be on the same order as the SiPMs, but will depend heavily upon data rates. Planned use of a dual 14 bit ADC at approximately 125 MHz is being planned for each FC Arapuca unit. Transmission will be via a digital-fiber link. However, the cold electronics are still in early stages and firm power numbers are not yet generated.

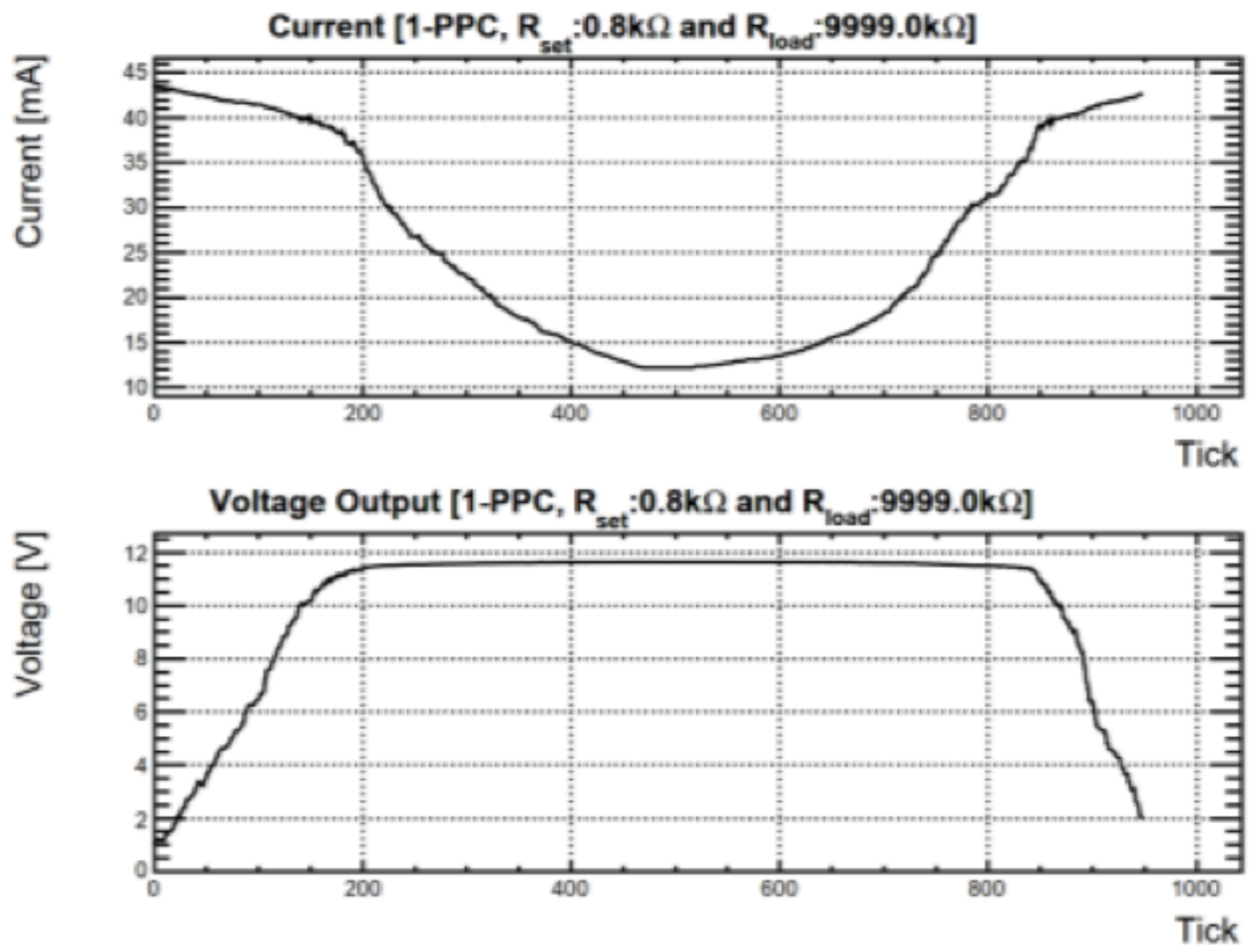


Figure 1 Power scan of PoF sub-unit

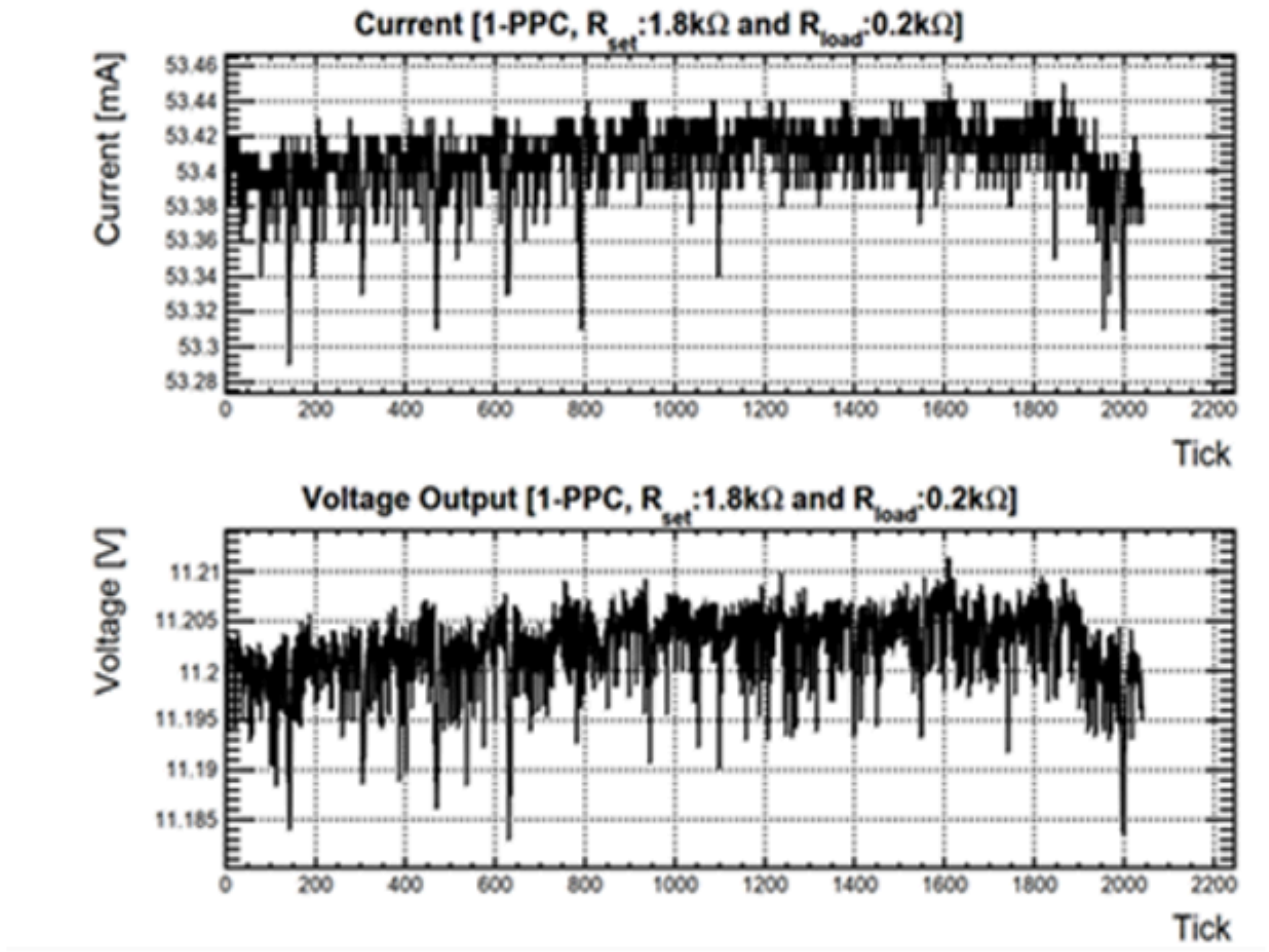


Figure 2 Voltage and current of PoF sub-unit

From tests at CERN
U. Kose, D. Totani

TABLE VIII. Power estimates for PoF cathode SiPM system.

Approx. Power Capability W* **+ STATUS**	**# of PPC modules**	**Current mA**	**Est. Voltage V****	Approx Power
< 4 **Tested**	1	80	12	4 W
20 **Testing Underway**	5	400	62	20 W
4 sets each capable of 20 **Plan**	4 sets of 5	4 sets each 400	4 sets of 62	80 Watts

* The power delivered is not all converted to usable power. Efficiency is about 22 % in LAr.
** Each PPC module voltage can vary about 3 %.

TABLE IX. Power estimates for PoF field cage SiPM system.

Number of Pof System *	**Power per PoF Unit**	**Power per field cage row**	**Total power top or bottom****
22 Top and Bottom	24 watts per unit	24 watts	528 watts
Usable power	6 watts	6 watts	116 watts

* The total number of PoF systems will depend upon how many rows of the field cage will contain ARAPUCAs
** The total power can be increased by adding additional laser power receivers. Each receiver contributes 4 watts with 1 usable watt