The DUNE VD Module#2 Enhanced Photon Detection System For

Supernova and Low-Energy Neutrinos

Feb. 18, 2021

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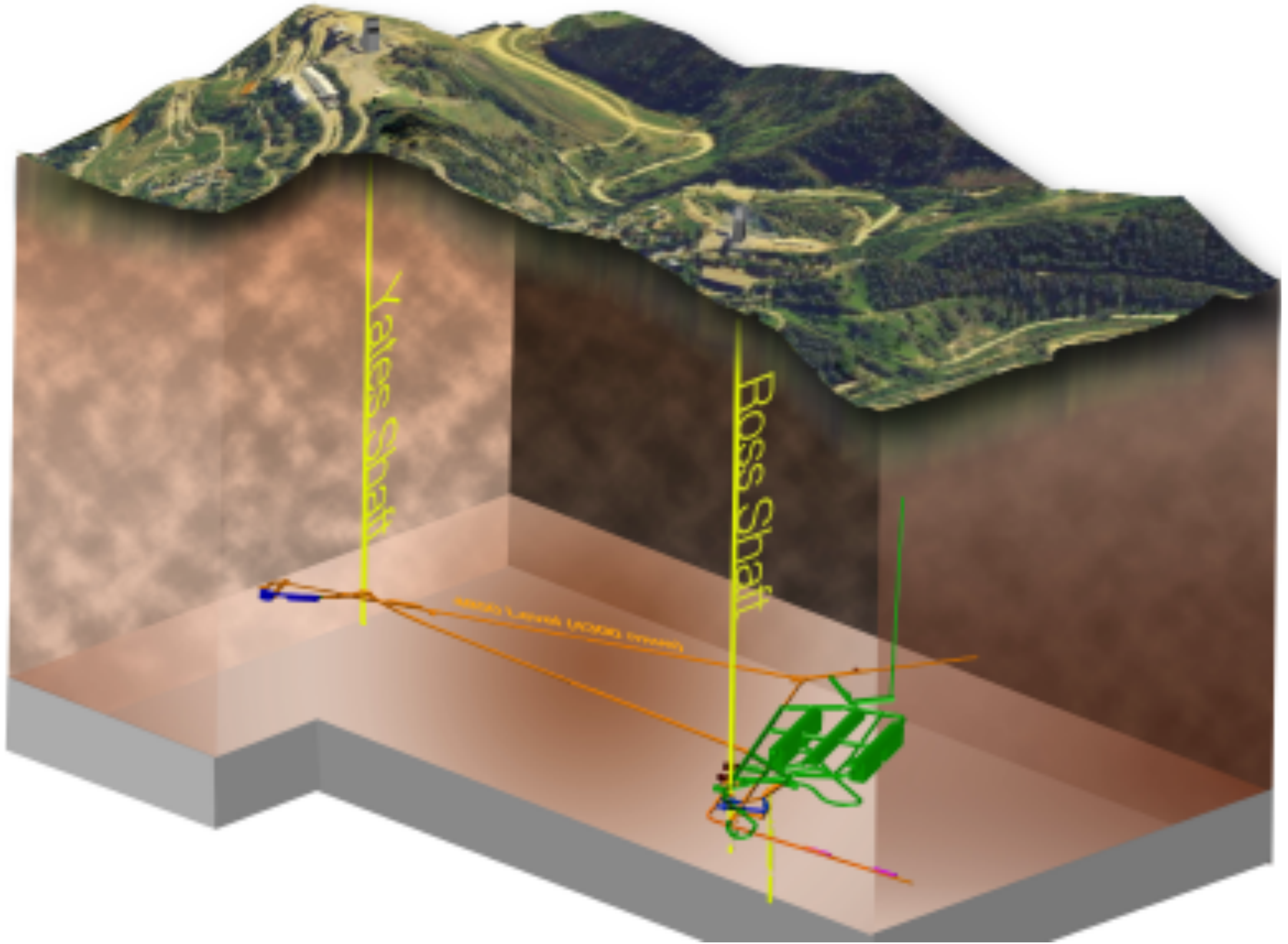
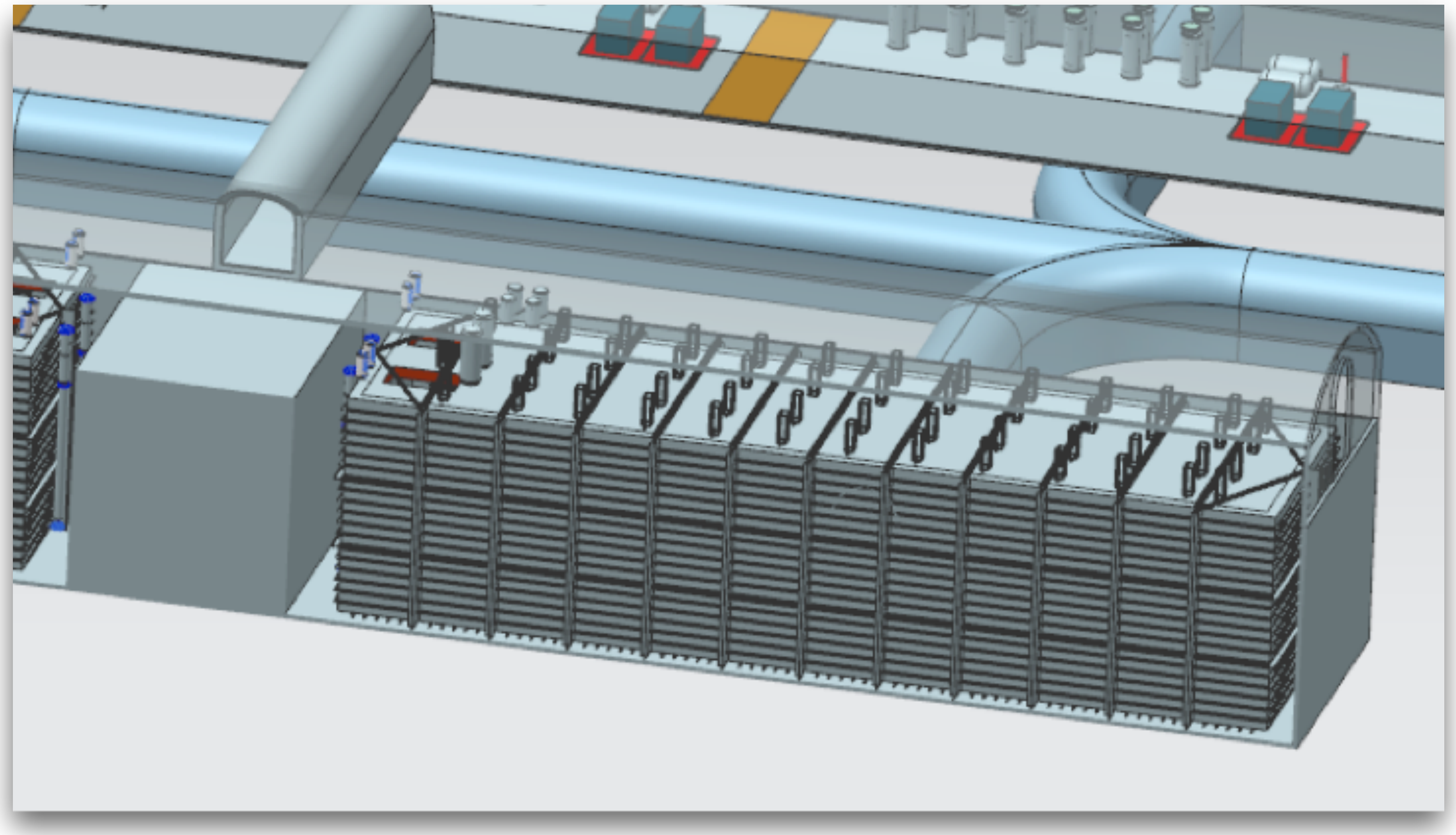
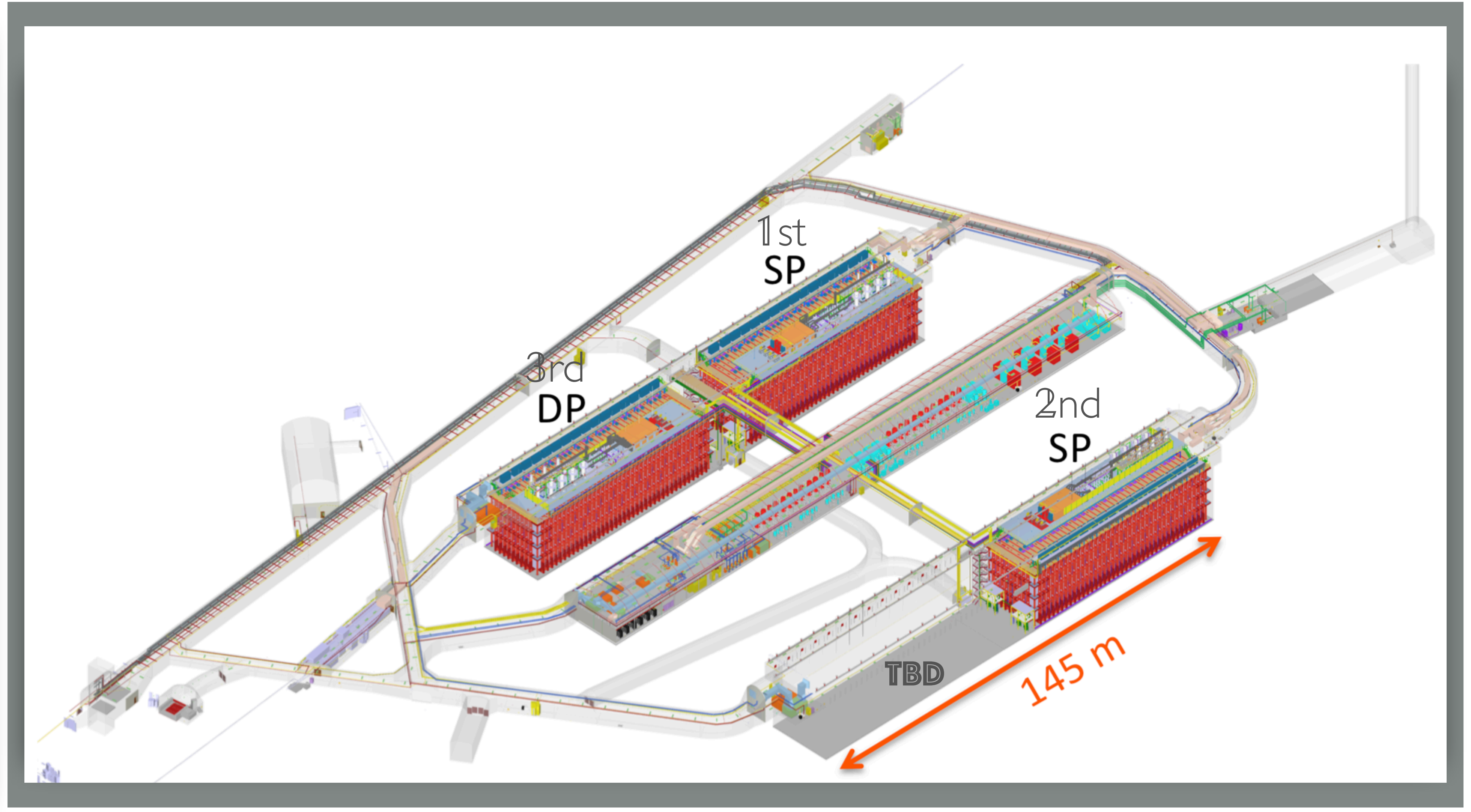
DUNE “Far Site”: @SURF 4850 Level

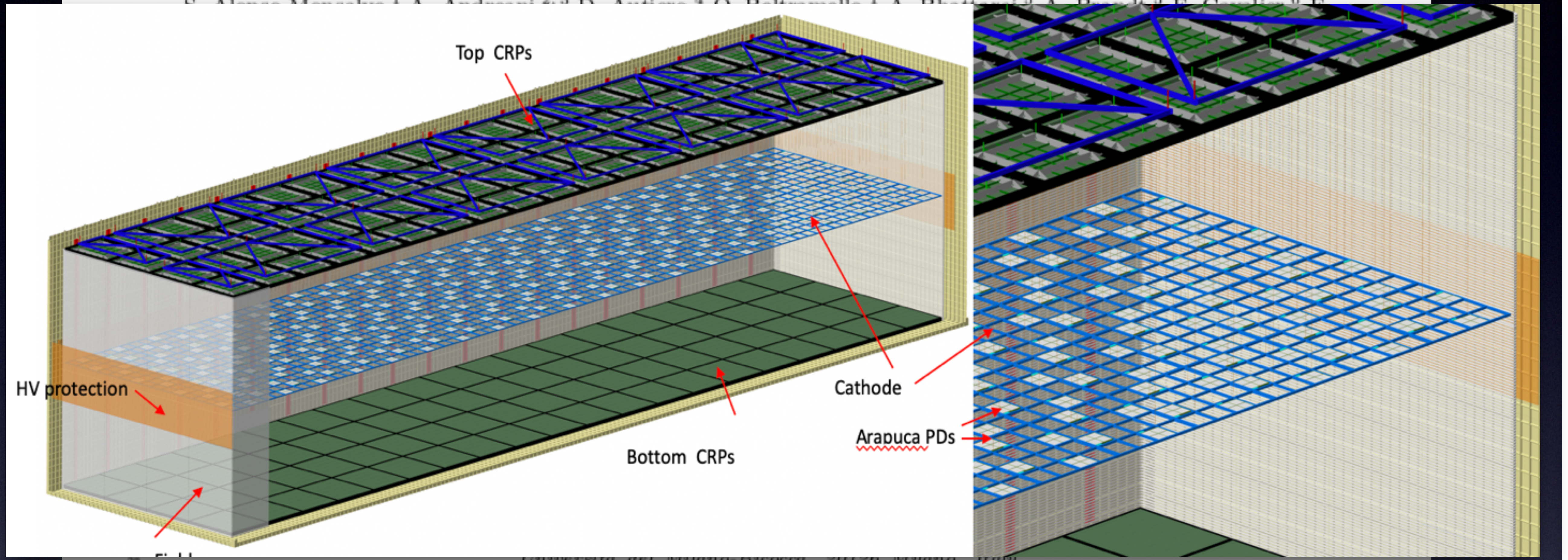
- Major underground excavation removing ~800,000 tons of rock
- Two large caverns housing **four** cryostats and a central utility space
- $4 \times 17{,}000$ **tons of LAr to fill the cryostats:** ***the target for neutrino interactions***





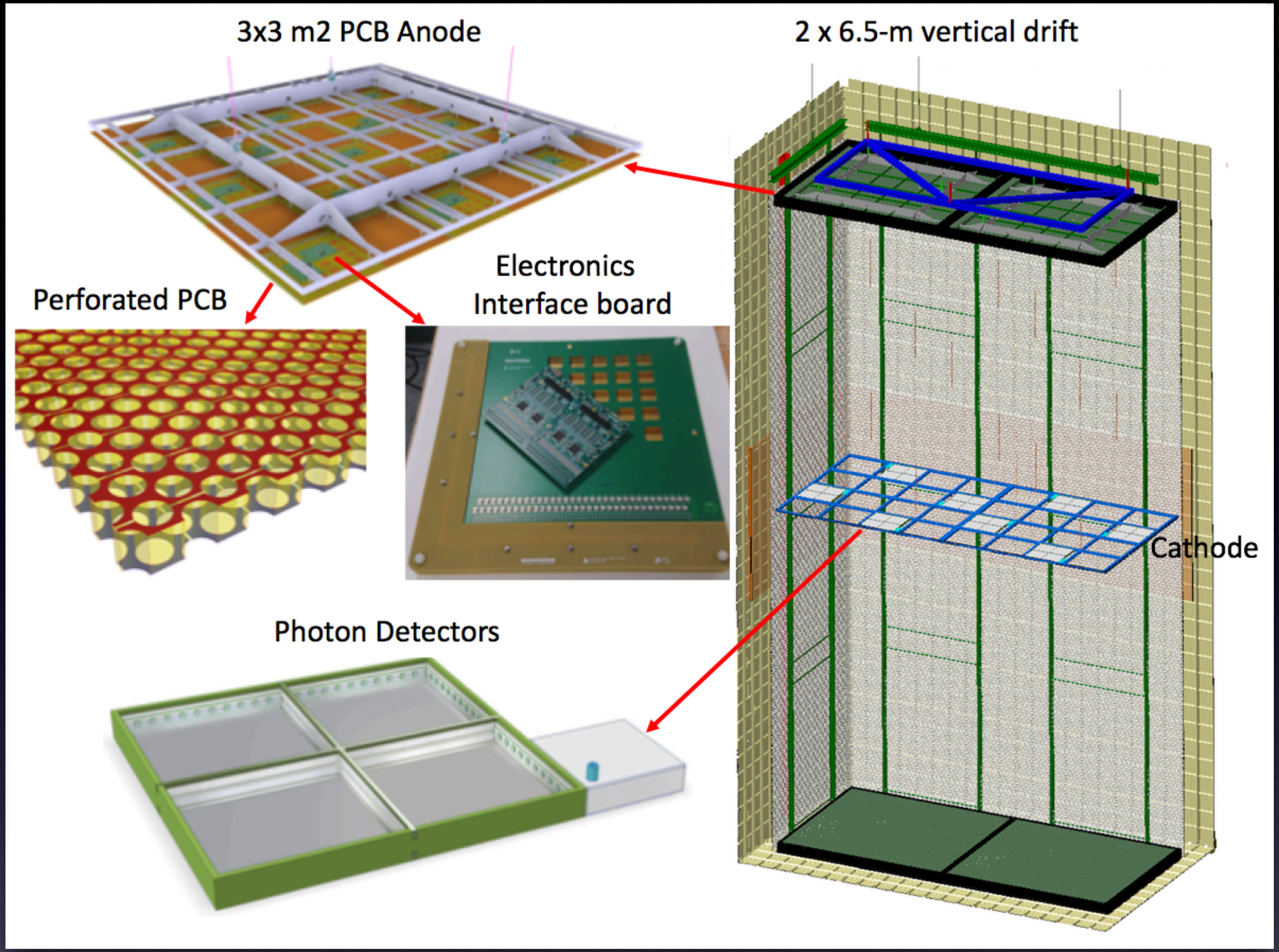


Next-generation LArTPC Detector Technology for the Deep Underground Neutrino Experiment: a Vertical Drift Single-phase Solution with Perforated PCB Anode



(Dated: November 30, 2020)

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



Next-generation LArTPC concept:

a Vertical Drift Solution with PCB based Charge Readout

complemented by a robust X-ARAPUCA Photon Detection System

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. However, to embed it into LArTPC layout is a big technological challenge.

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

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 (electrically floating) is found:

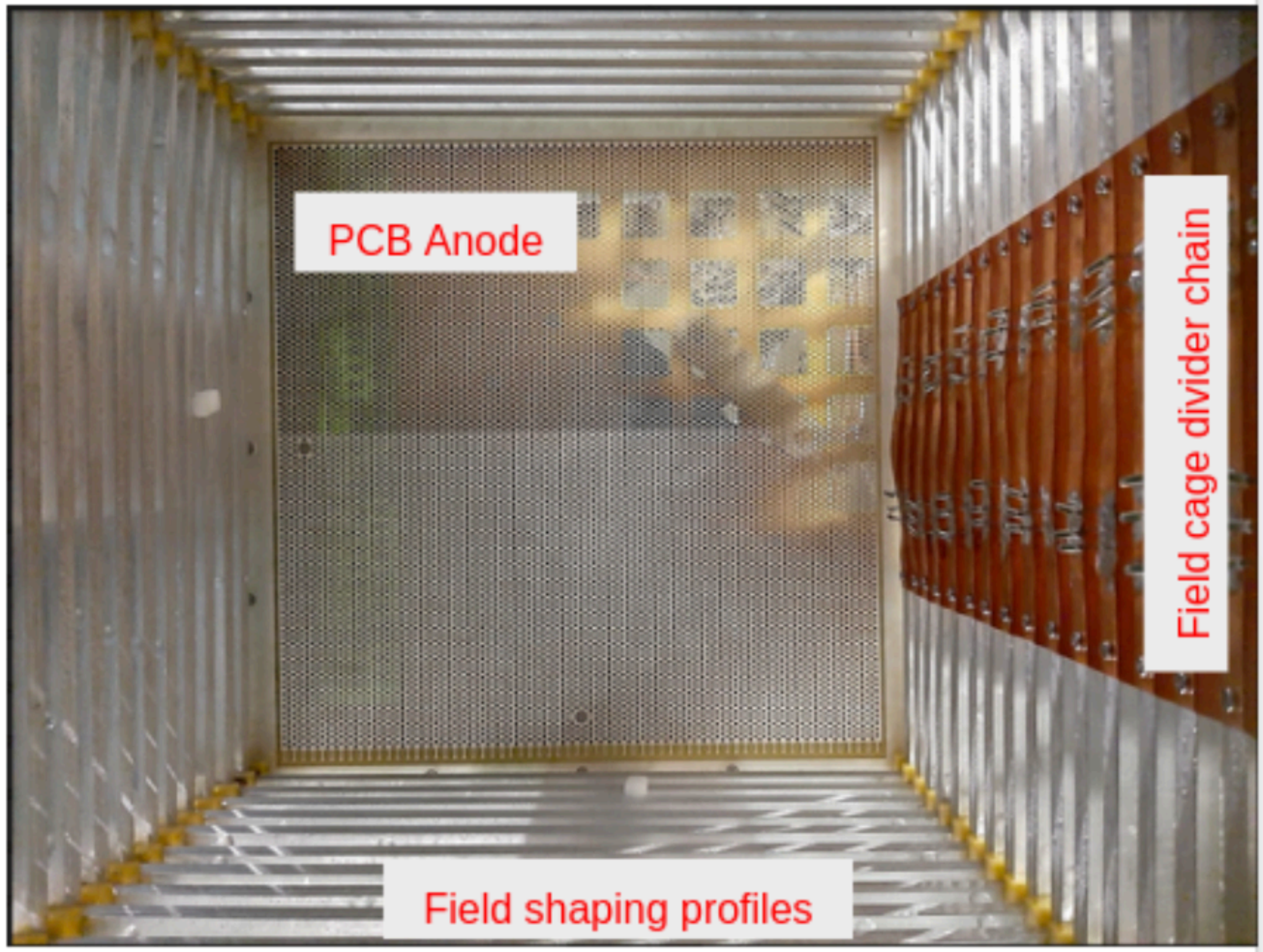
PD Active Optical Coverage distributed onto 5 sides of the LAr Volume (Cathode side and 4 Field Cage sides)

+

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

Xe do

far distance)



*This would allow ~4π **covera***

⇒ ~uniformity of re

and position resolution capability

It would be a second detecto

(directionality):

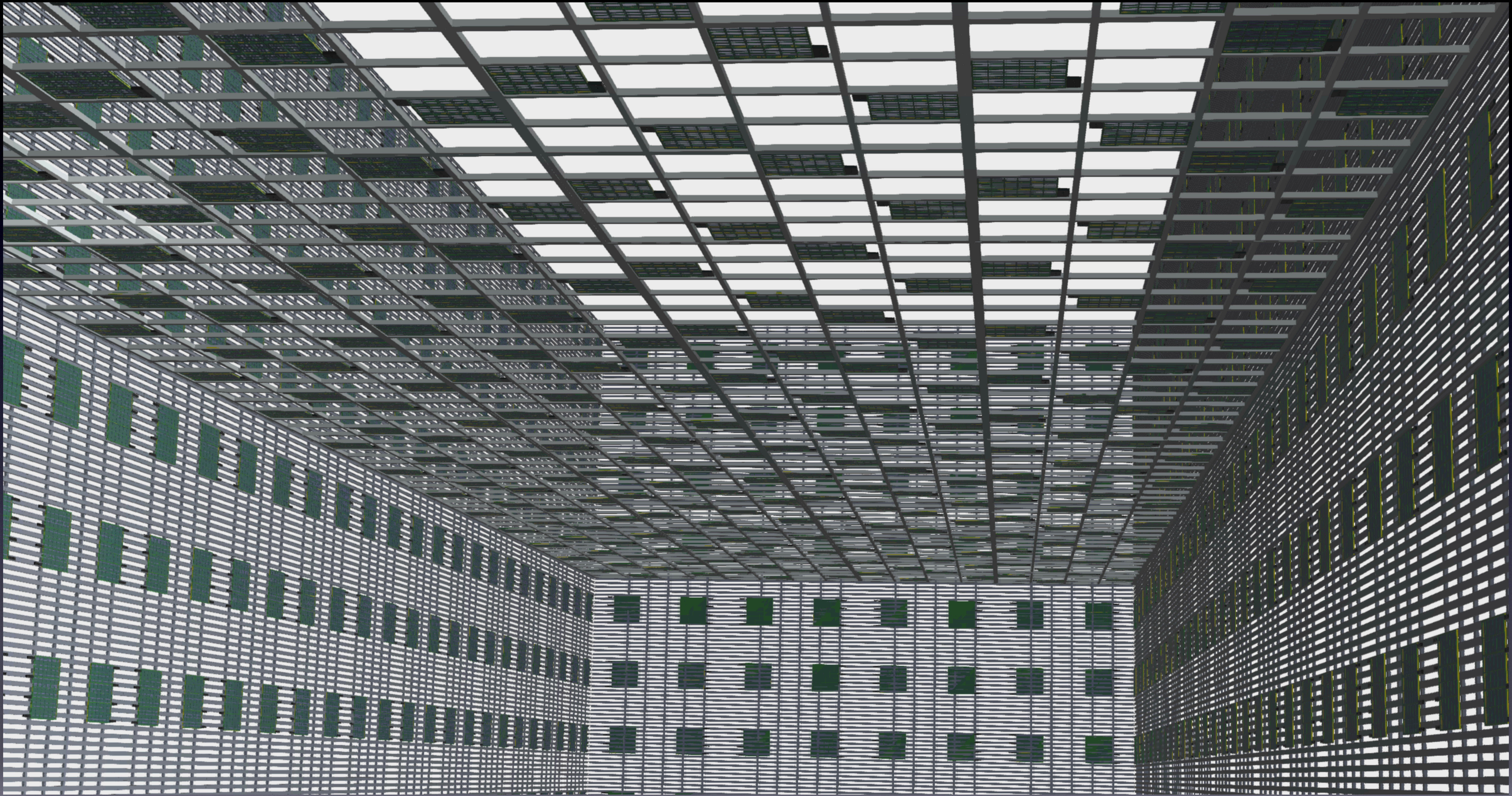
- *complete exploitation o*
- *Guarantee highest Live T*

  purity drop/maintenance, HV issues/

  maintenance,..) very rel
- *Start data taking (SN obs*

  Ar filling)

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



~ 4π PD System design for the VD LAr Volume

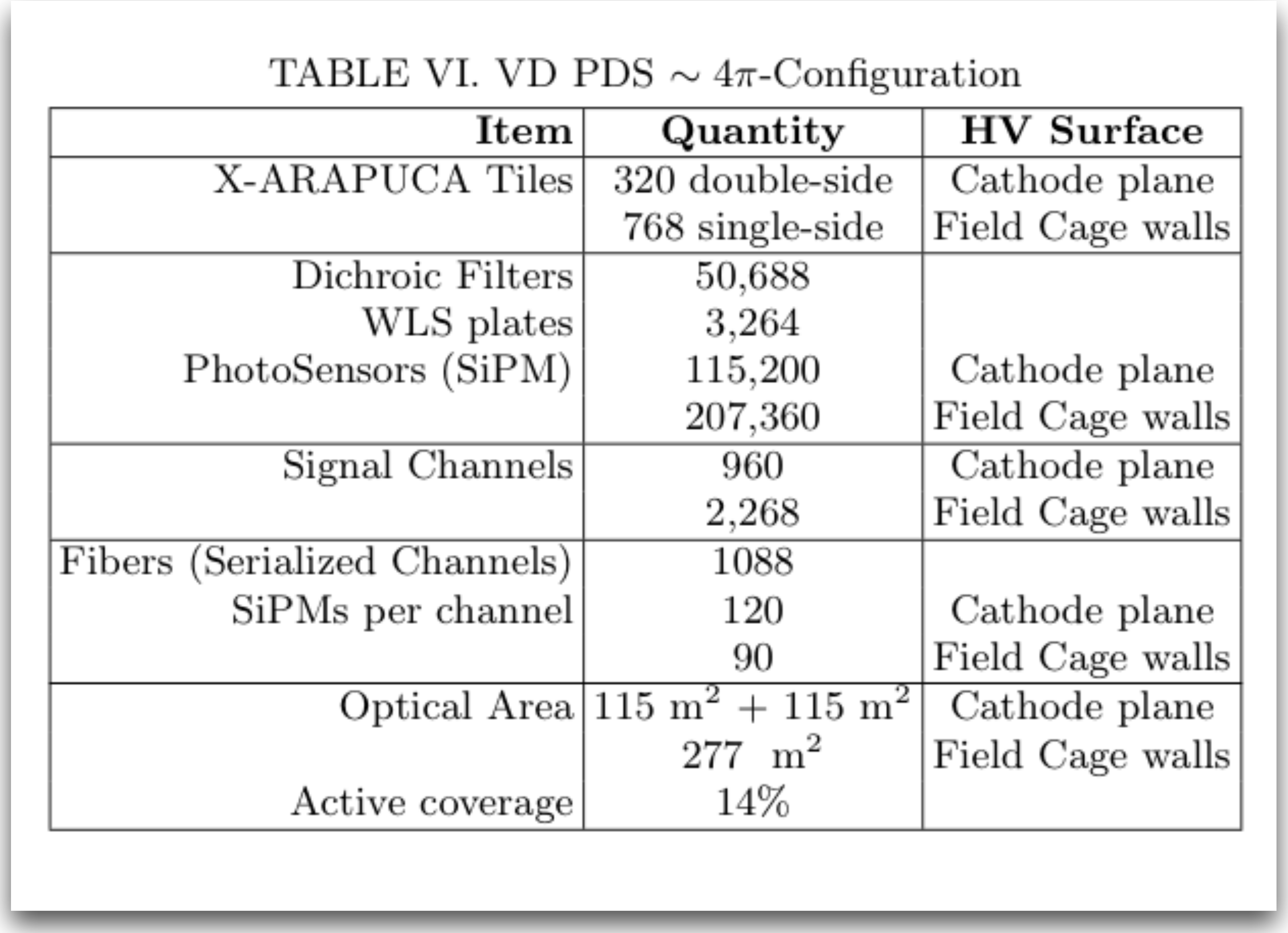
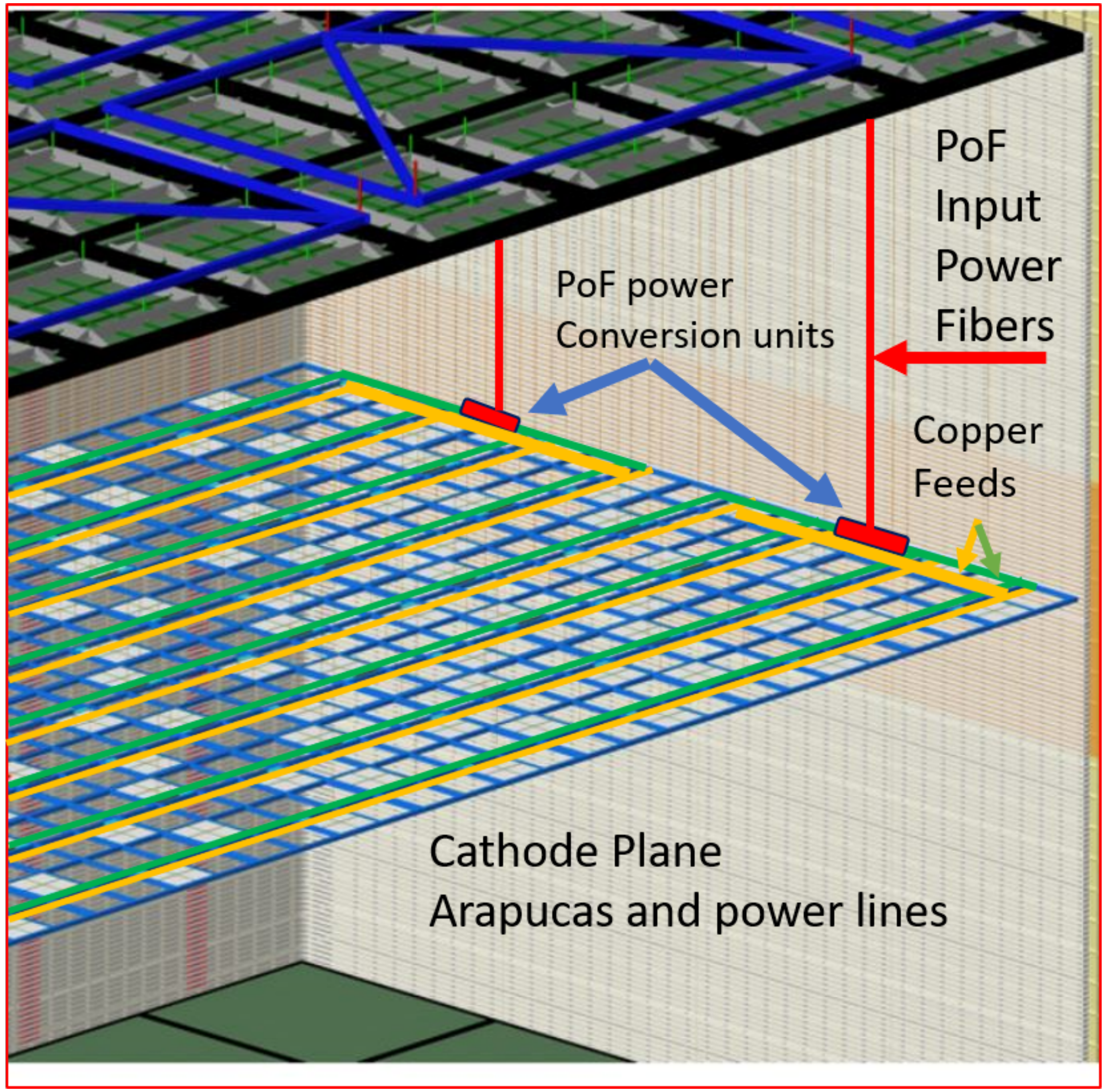
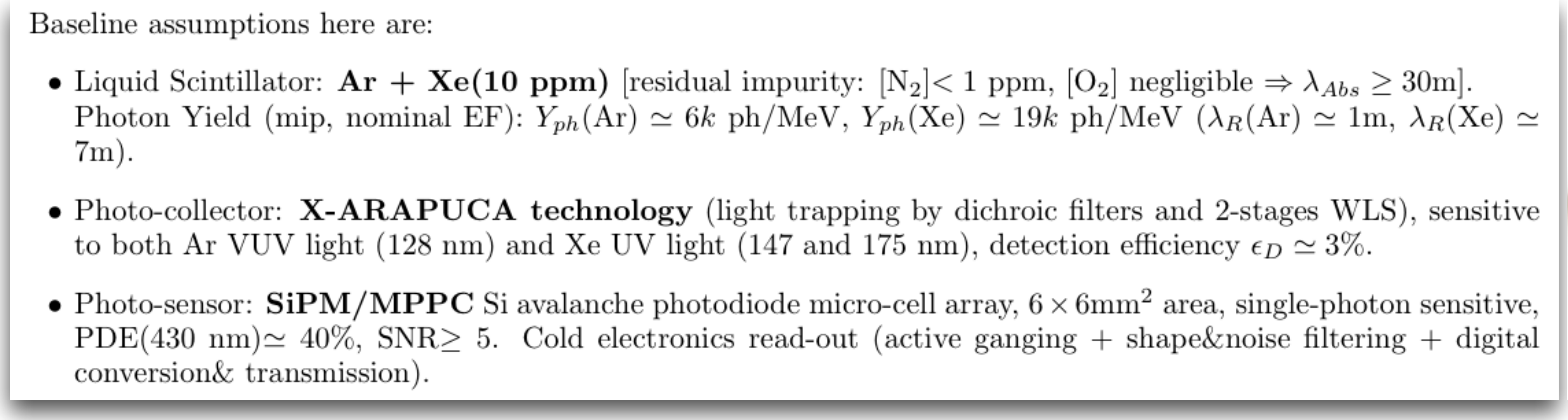


TABLE VI. VD PDS ~ 4π-Configuration

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

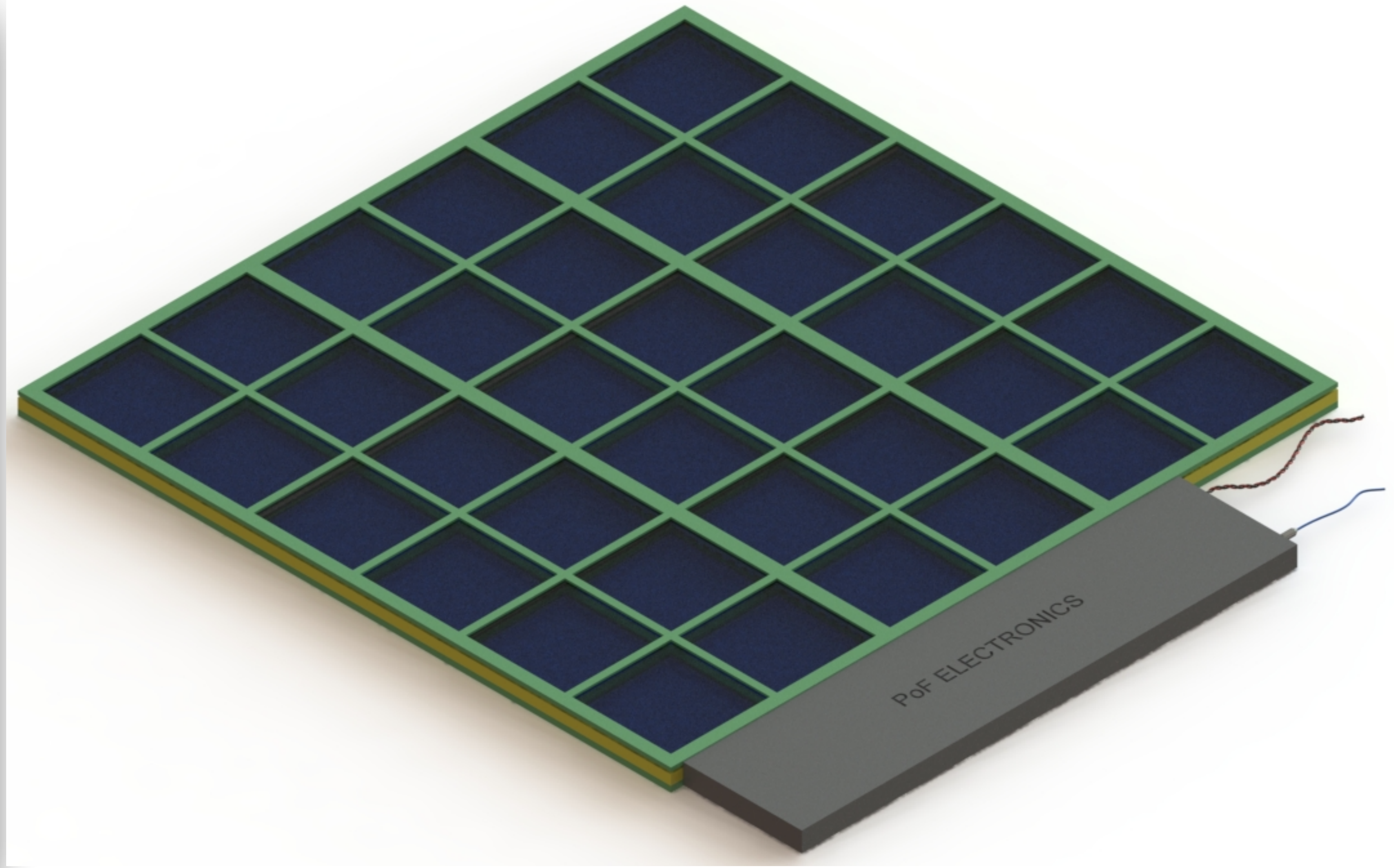
W. Pellico - FNAL

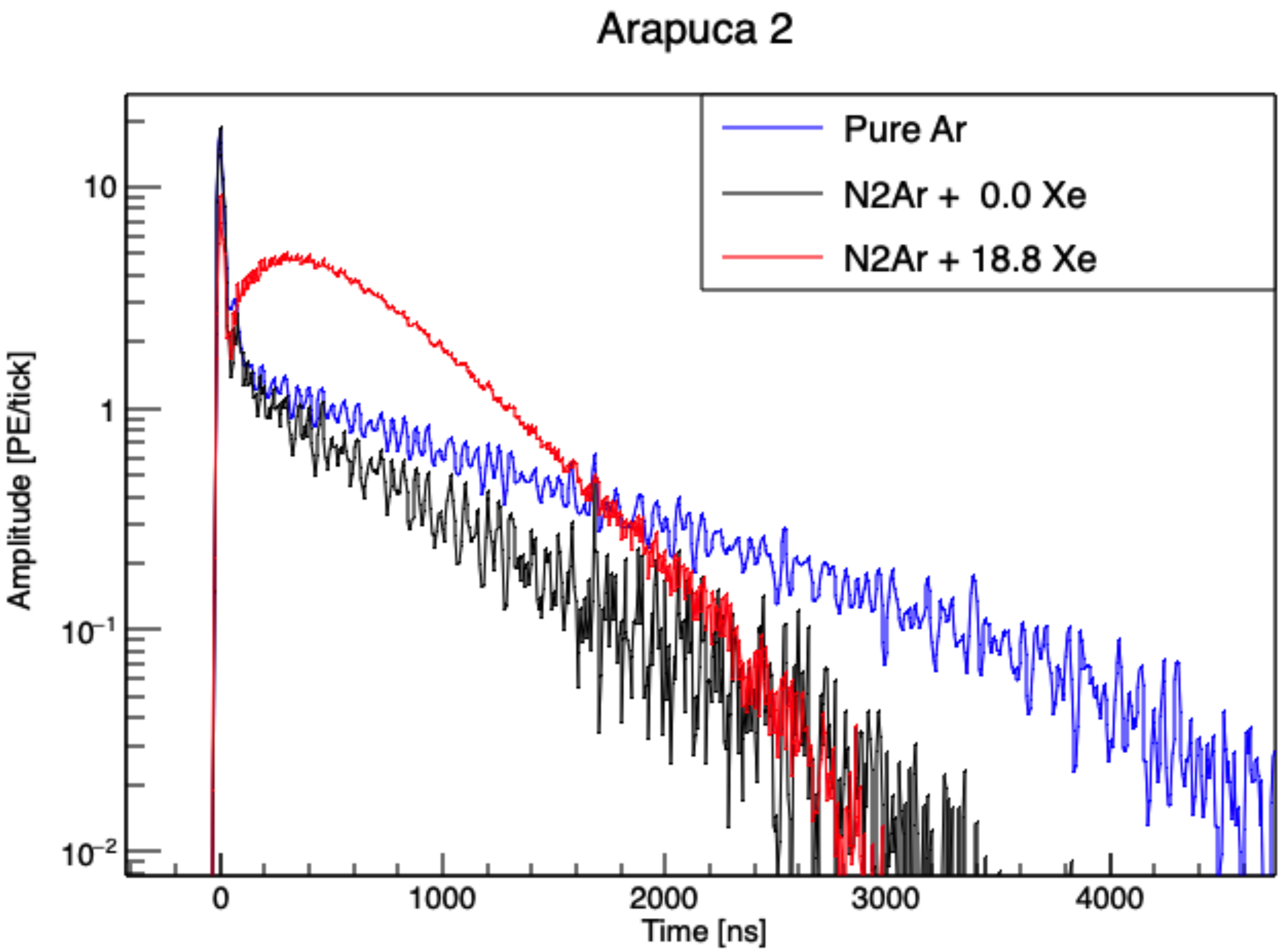




Baseline assumptions here are:

- 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, $\lambda_R(\mathrm{Xe}) \simeq 7$m).
- 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).

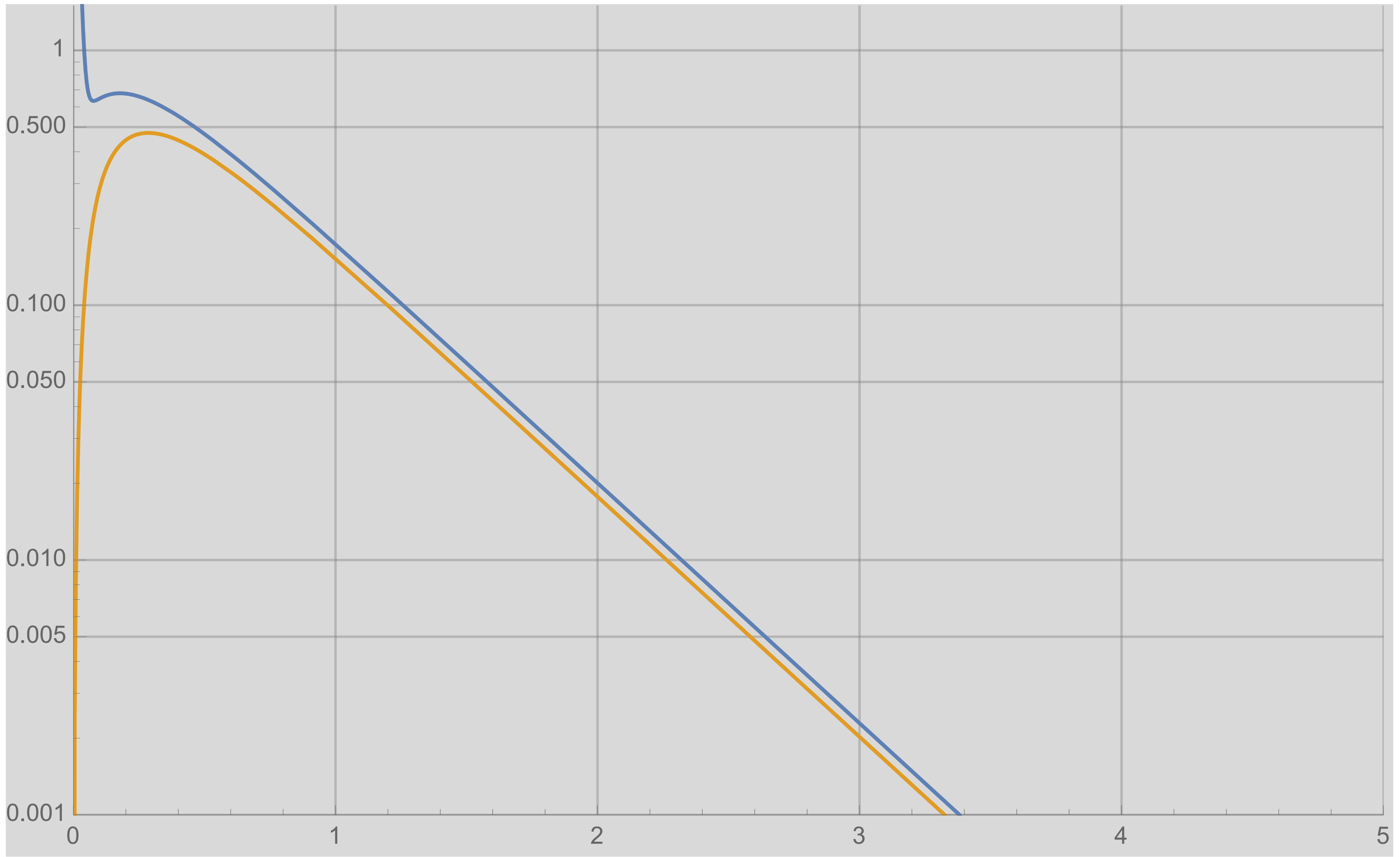




Time (μs)

(ArS, ArT+ArXe+Xe) & **(Xe)**

detectable Light Time Distribution



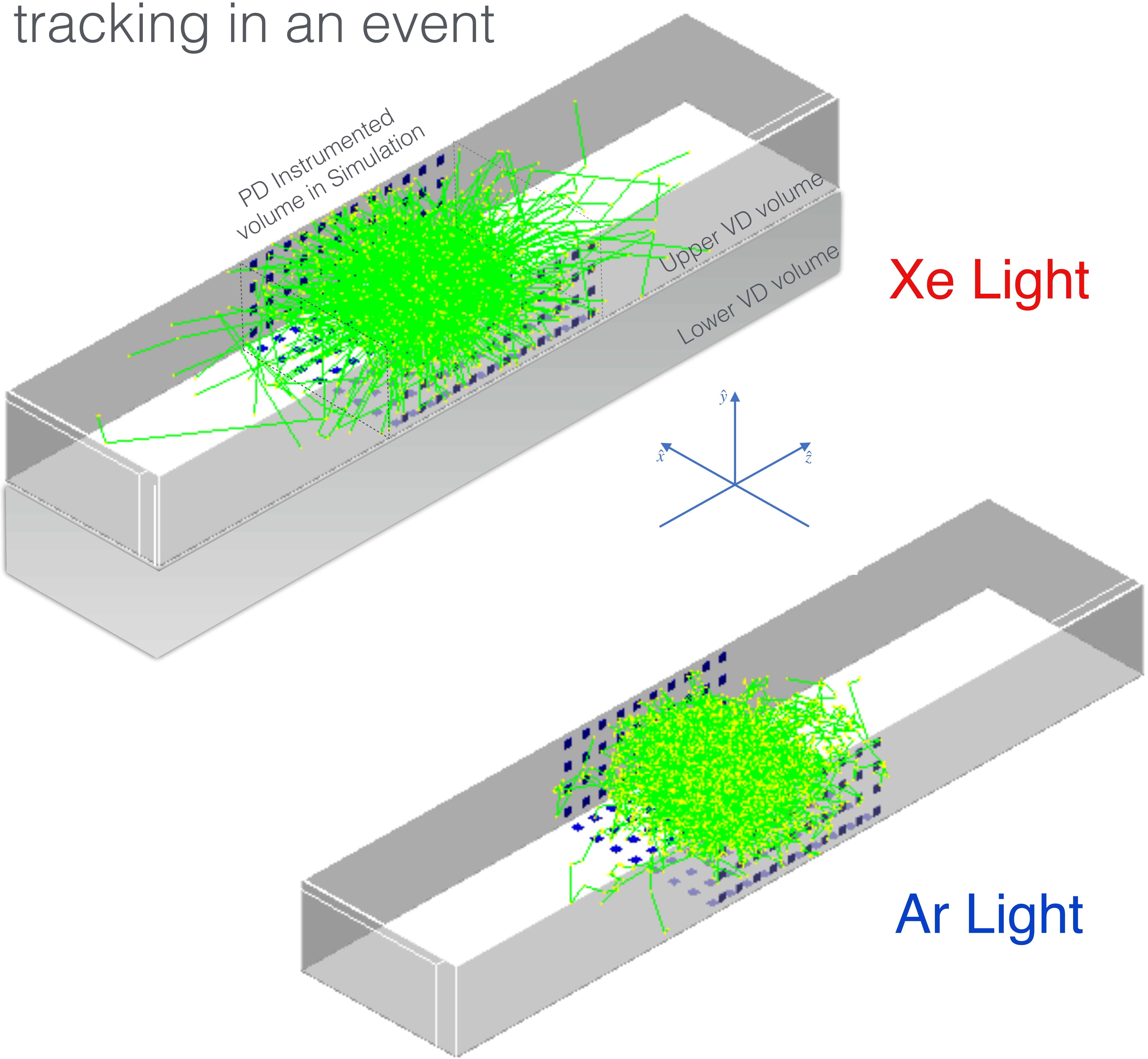
Ph. Detector Performance: Expectation from first MC simulations of Response

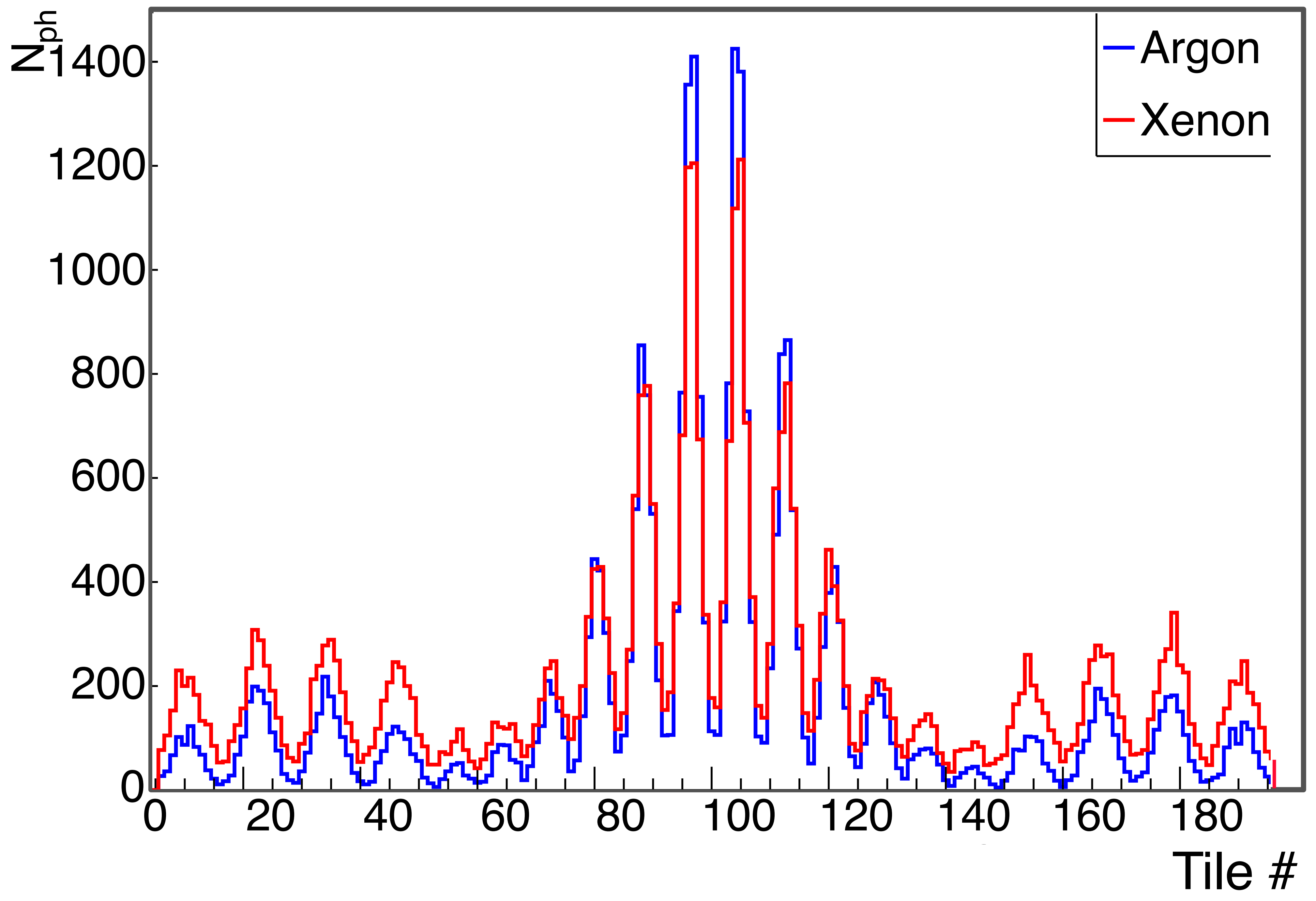
L. Paulucci, Universidade Federal do ABC, Santo André, SP, Brazil
F. Marinho, Universidade Federal de São Carlos, Brazil
D. Totani, University California Santa Barbara, USA

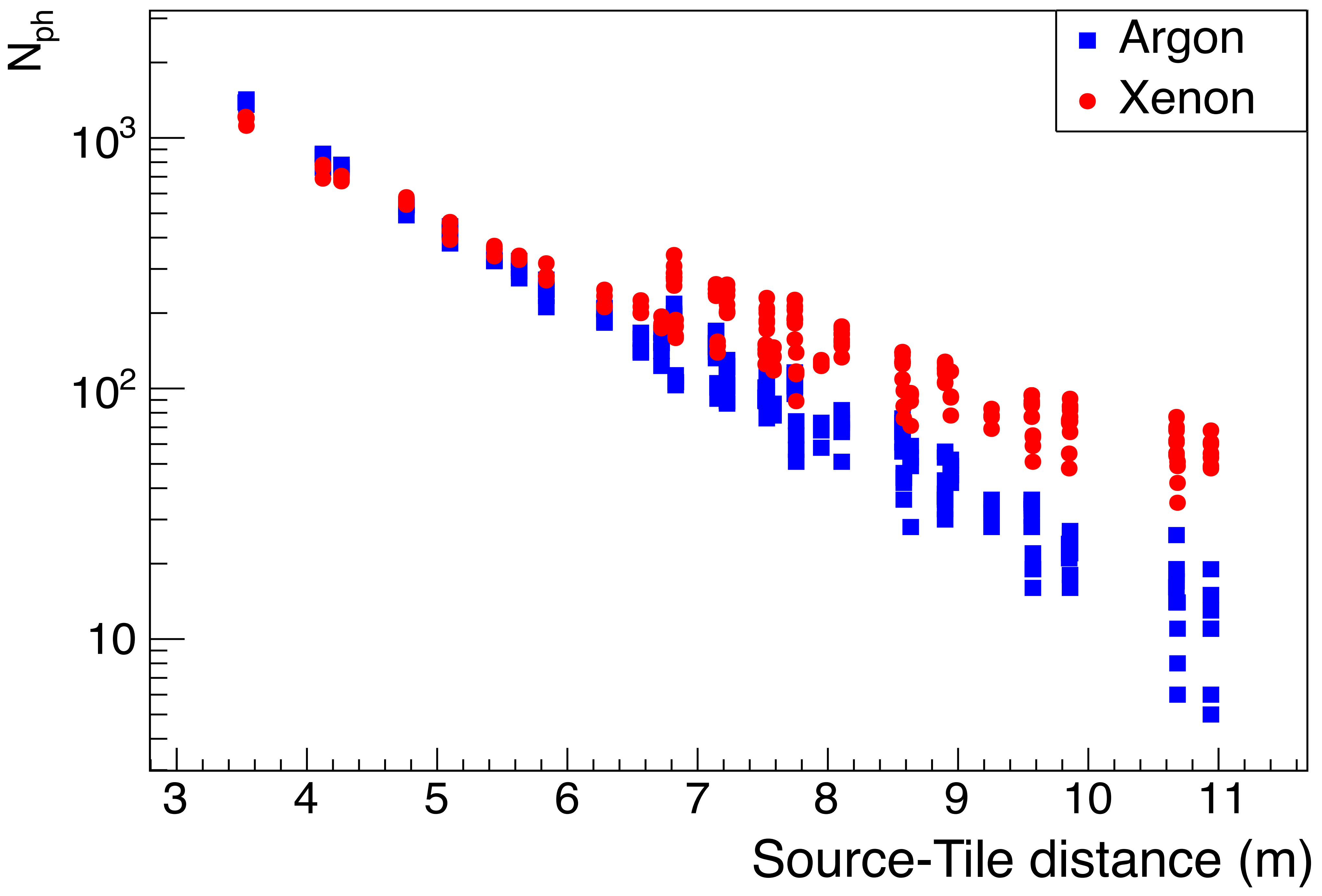
- understand the science reach
- evaluate detector parameters that meet the science needs

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

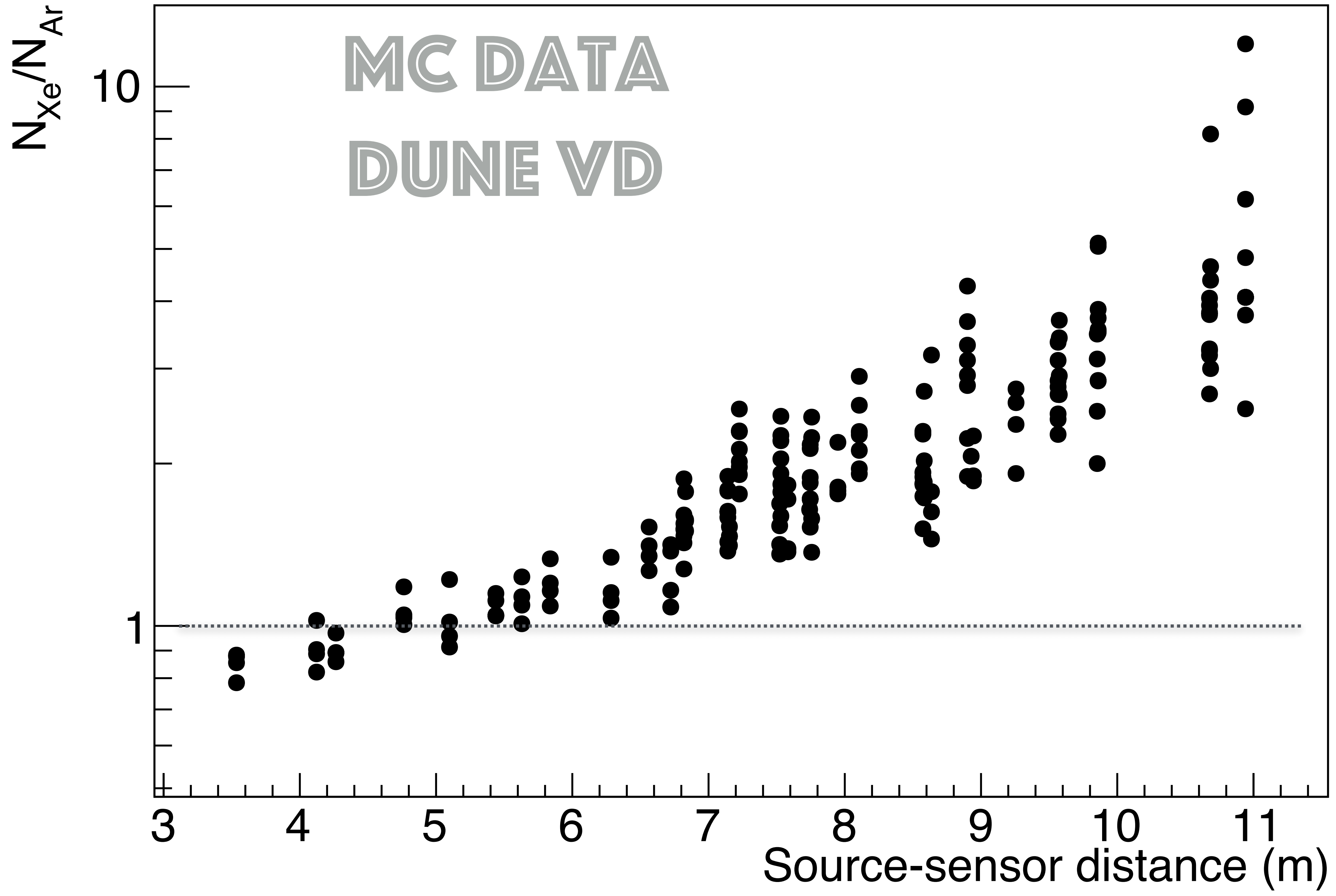
GEANT4 photon tracking in an event



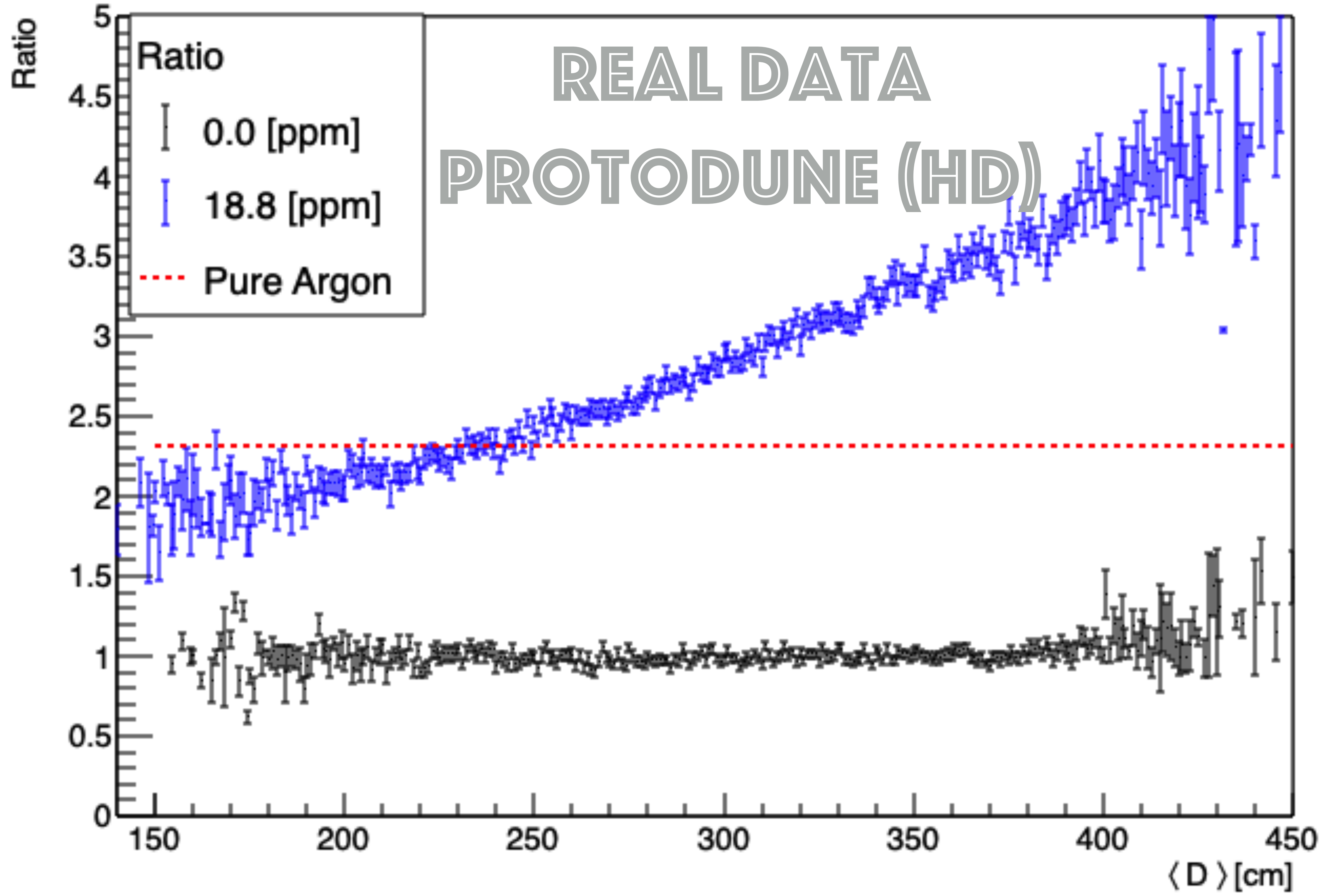




The collected light is found to be ~30% larger for Xe-doped Argon (8.2% of the total emitted photons reach the PD optical surface vs 6.3% in case of pure Ar), due to the effect of the longer Rayleigh scattering length enhancing collection probability for light emitted at longer distances from the PD-detectors



Light Recovery (at E field=0)



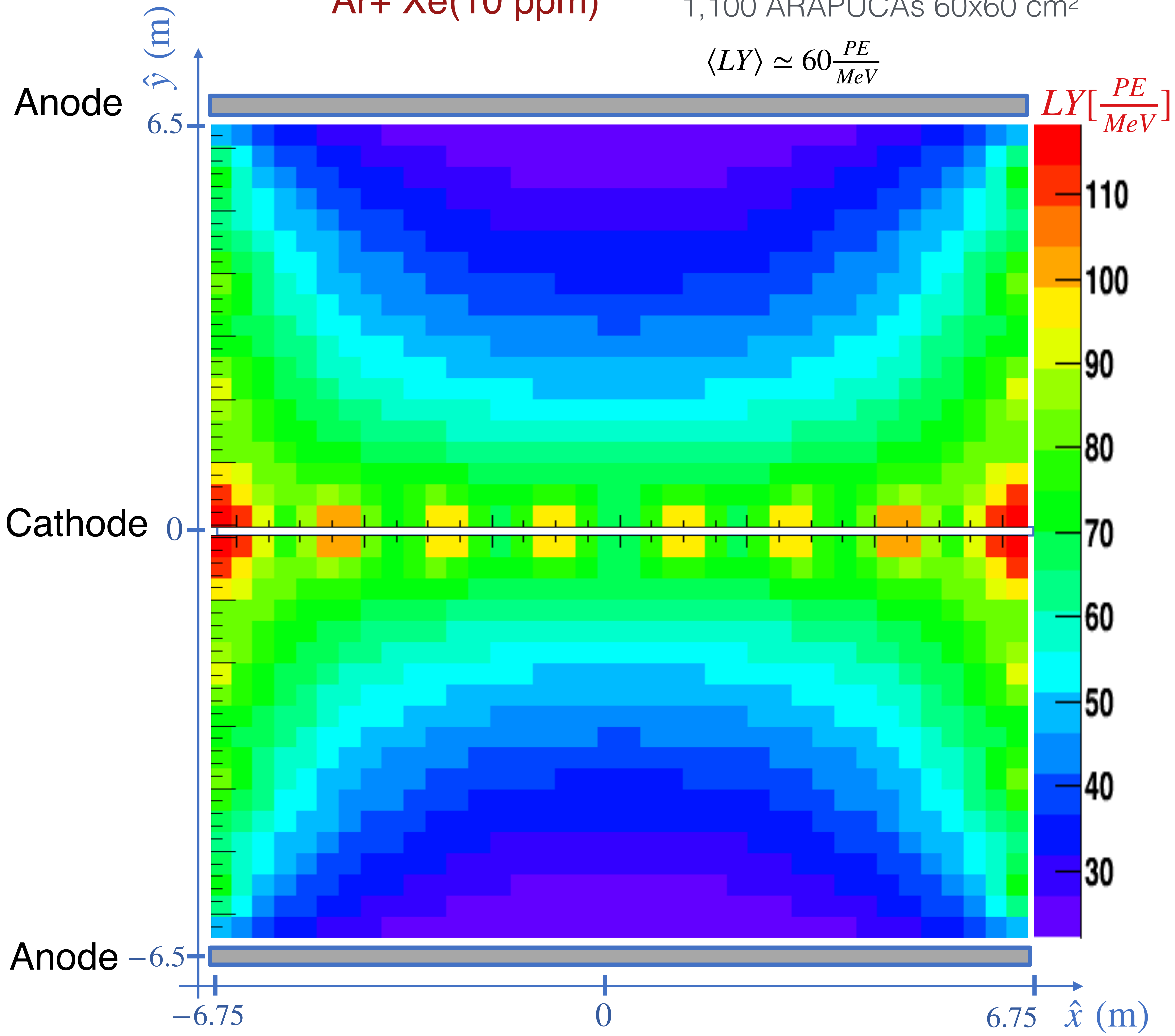
This supports the choice of Xe-doped Ar as scintillation medium.

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

Ar+ Xe(10 ppm)

1,100 ARAPUCAs 60x60 cm²

Light Yield Map in the Detector Transverse plane



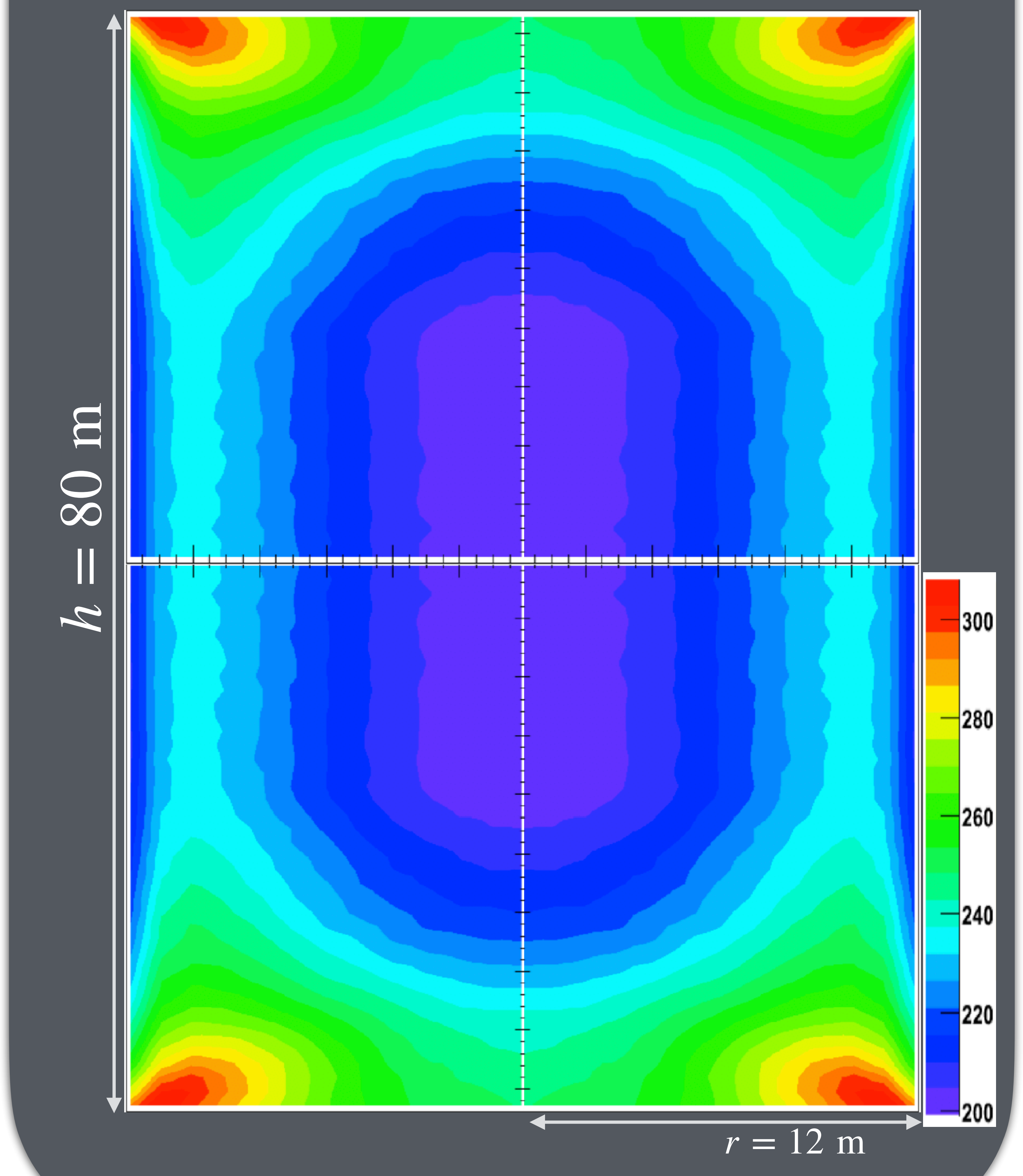
$\langle LY \rangle \simeq 60 \frac{PE}{MeV}$

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

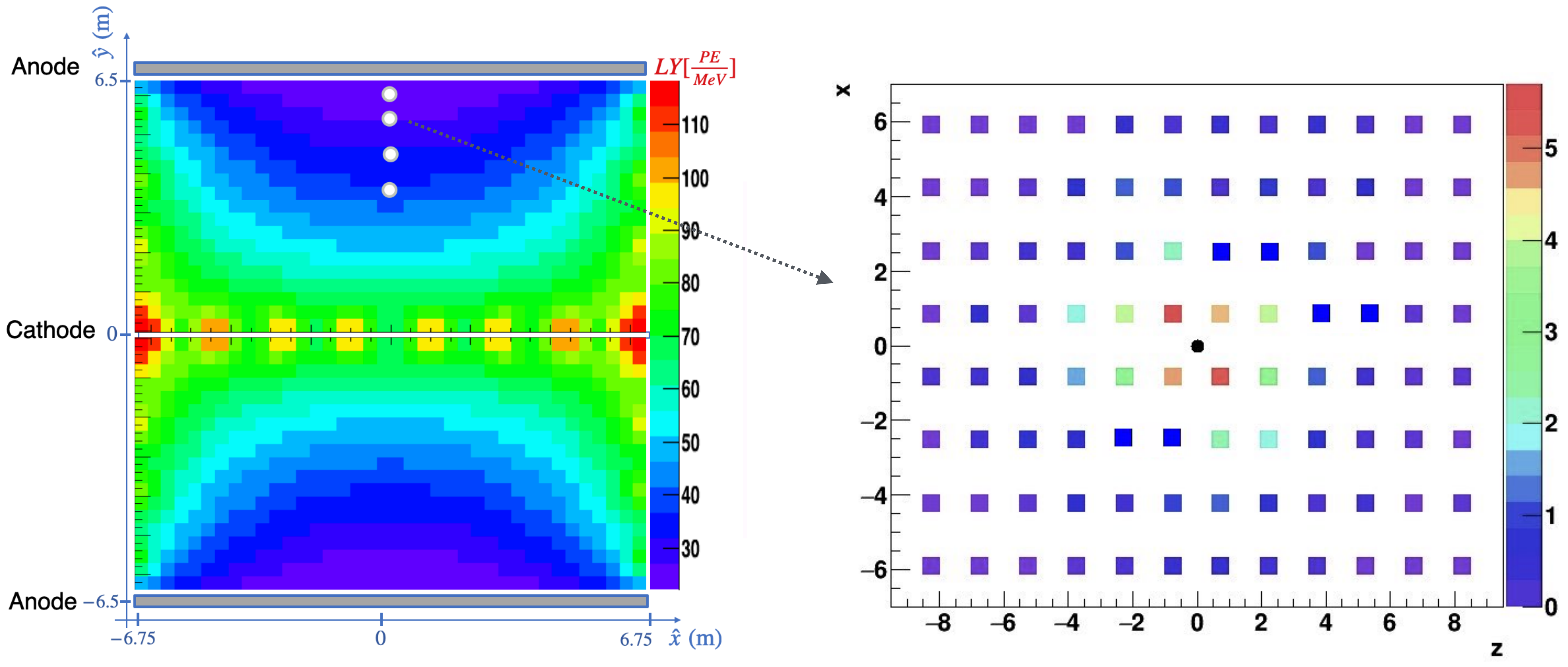
45,000 PMTs 8”

LENA - 4π LiqScint w/ 30% O.C.

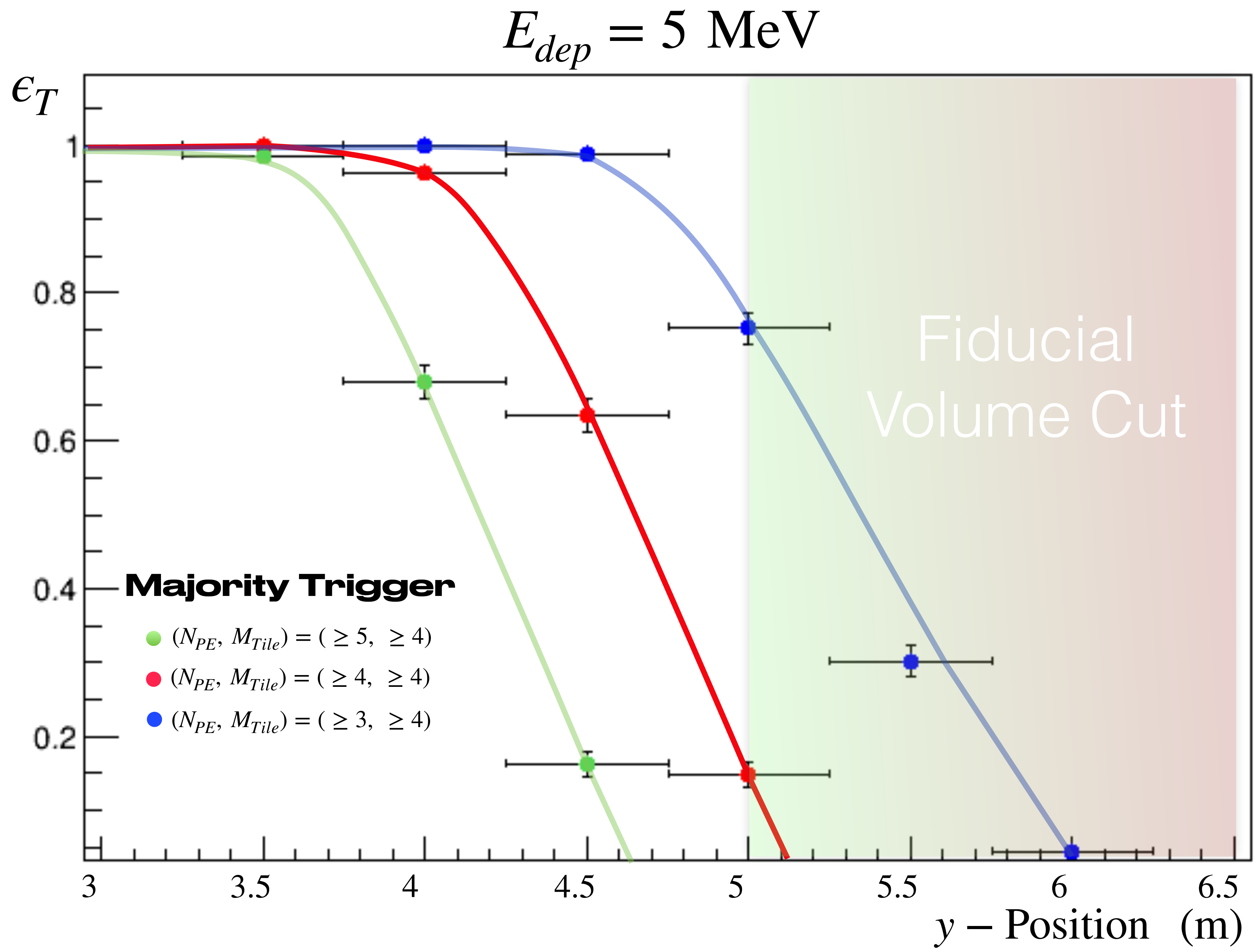
$\langle LY \rangle = 180 - 200 \frac{PE}{MeV}$ $E_{Thr} = 0.25$ MeV

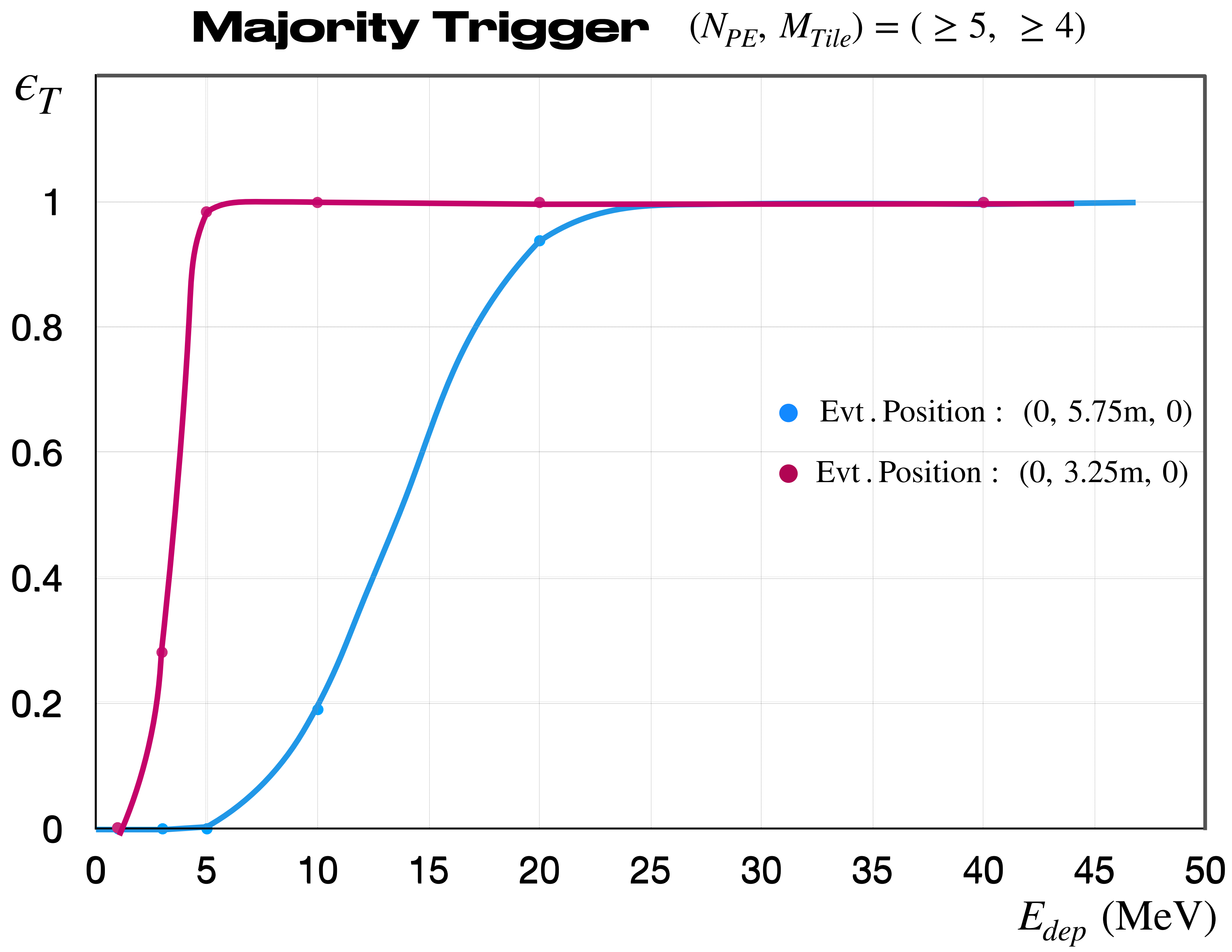


$(N_{PE}, M_{Tile})-$Majority Trigger condition



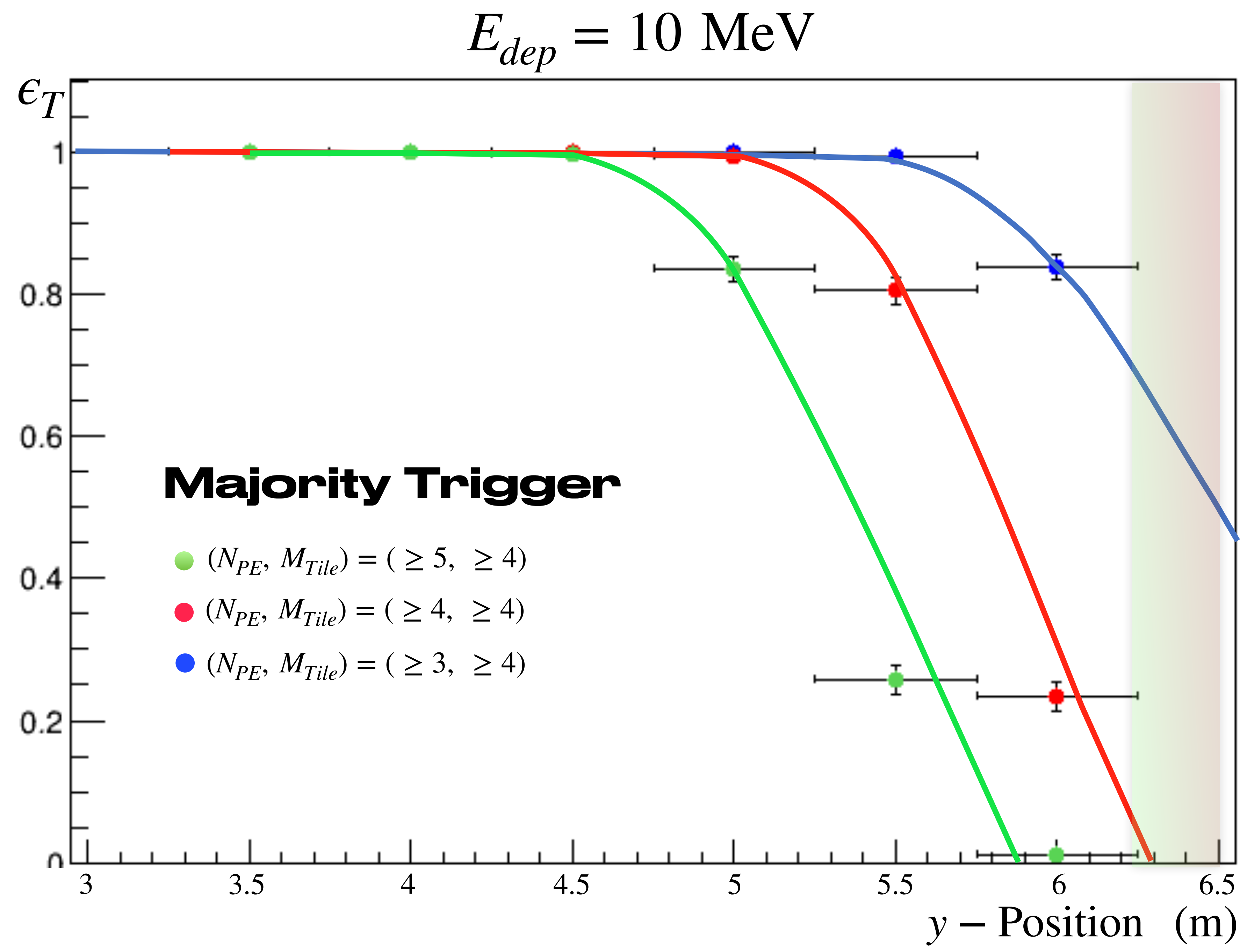
Light Response of PD tiles on the Cathode





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

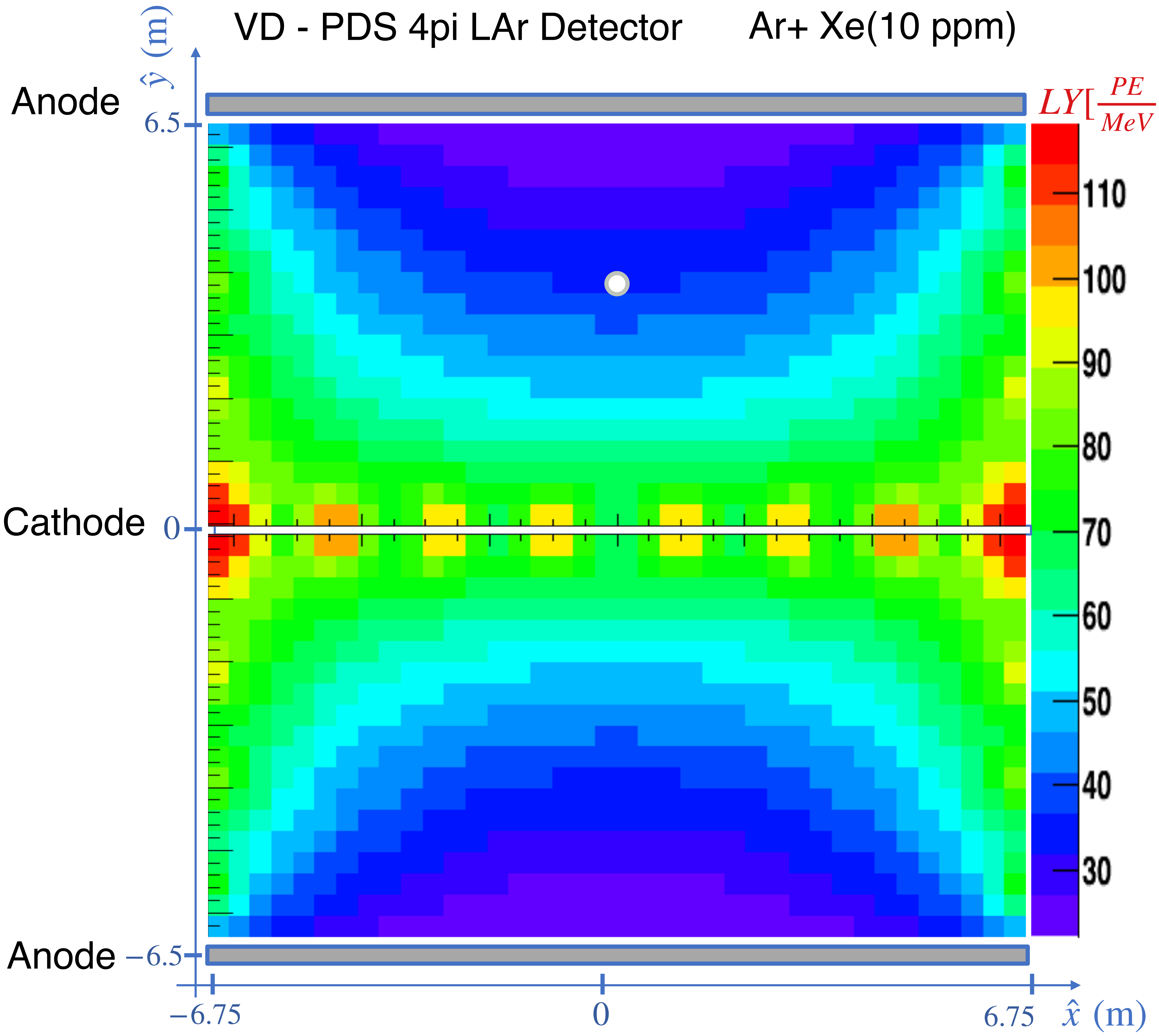
Trigger Efficiency $\geq 99\,\%$ for interactions with $E_{dep} \geq 5$ MeV expected in 100 % of a 10 kT Fiducial Volume

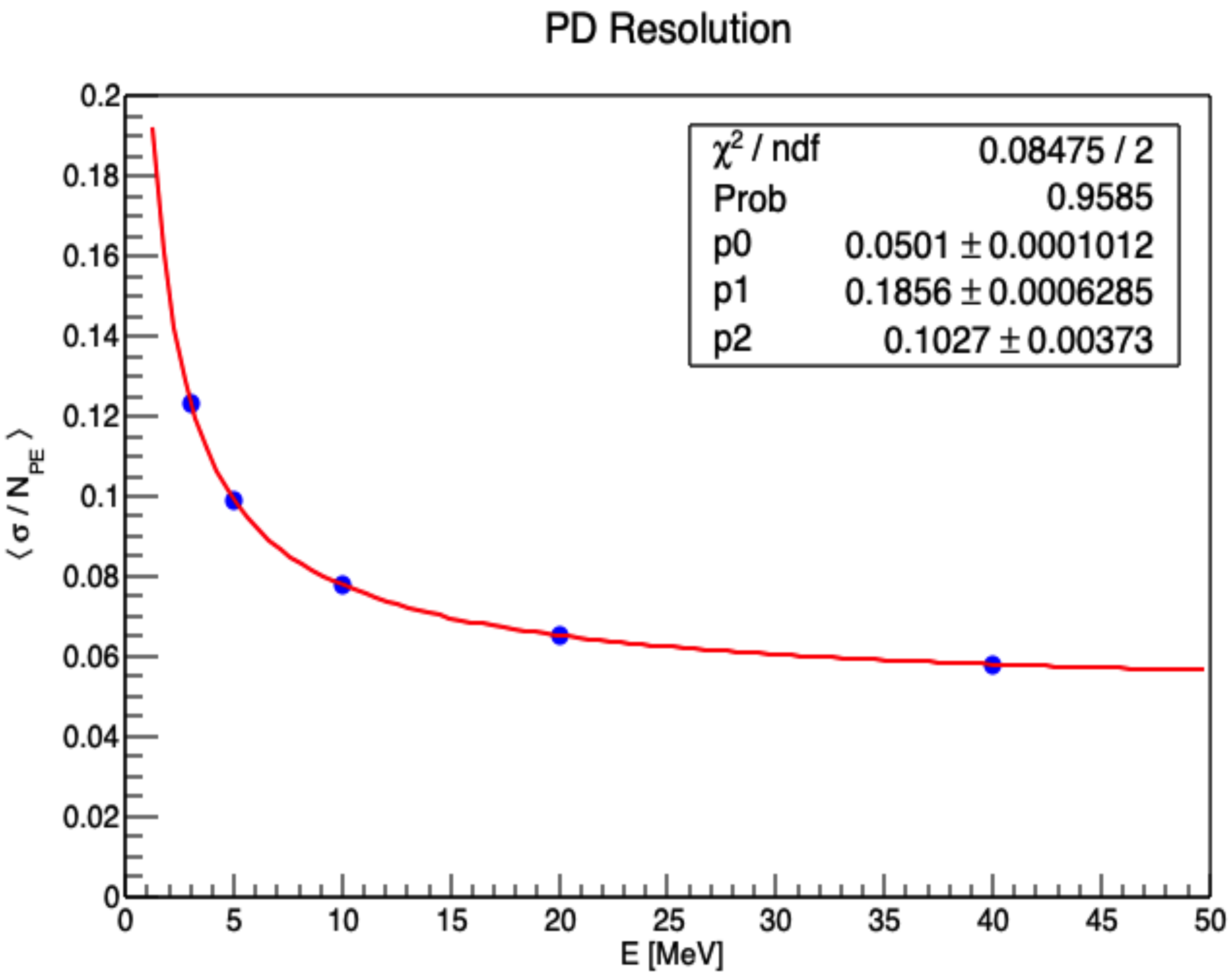


Calorimetric Energy reconstruction
from detected photon counting

Energy Resolution

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

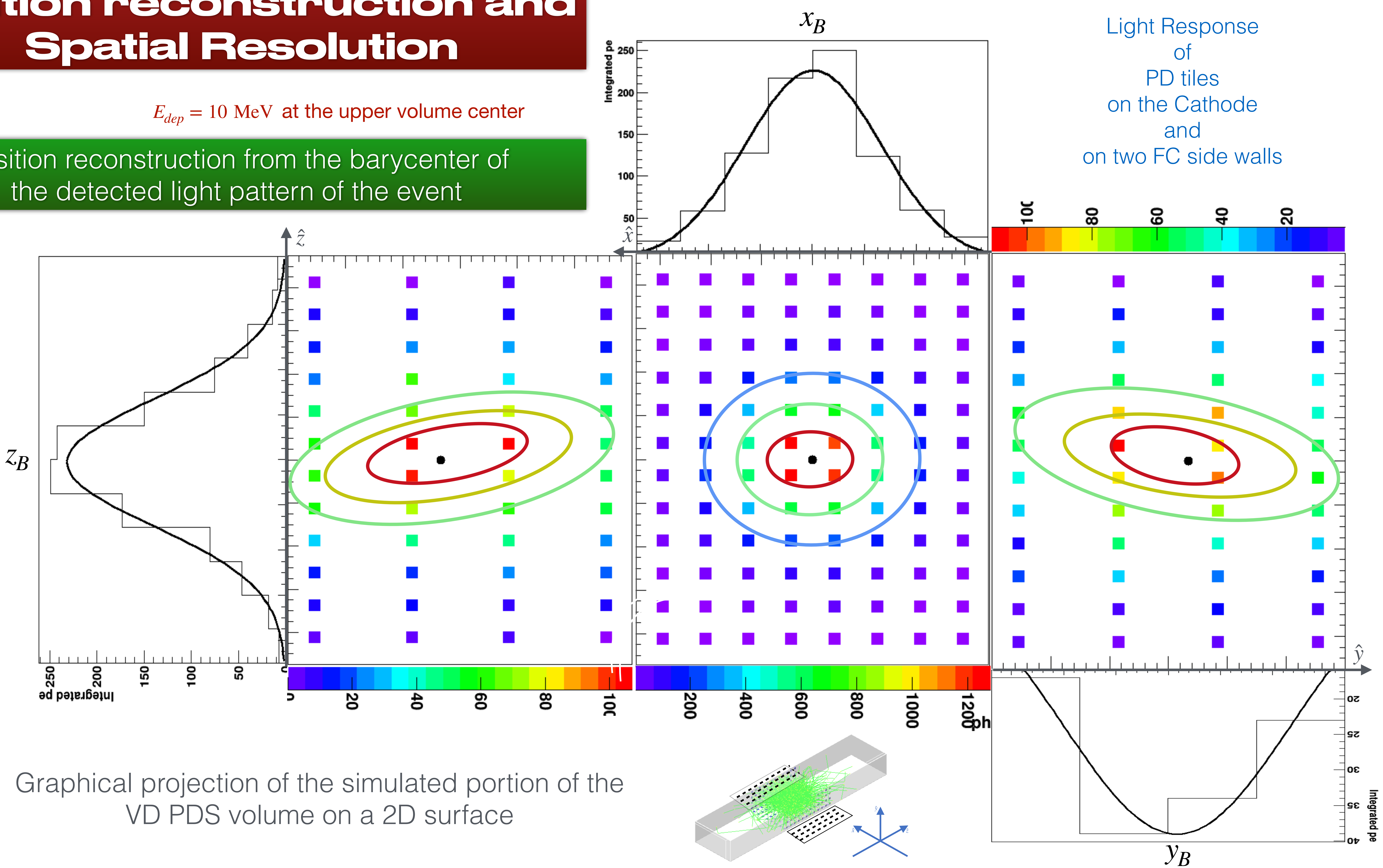




Position reconstruction and Spatial Resolution

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

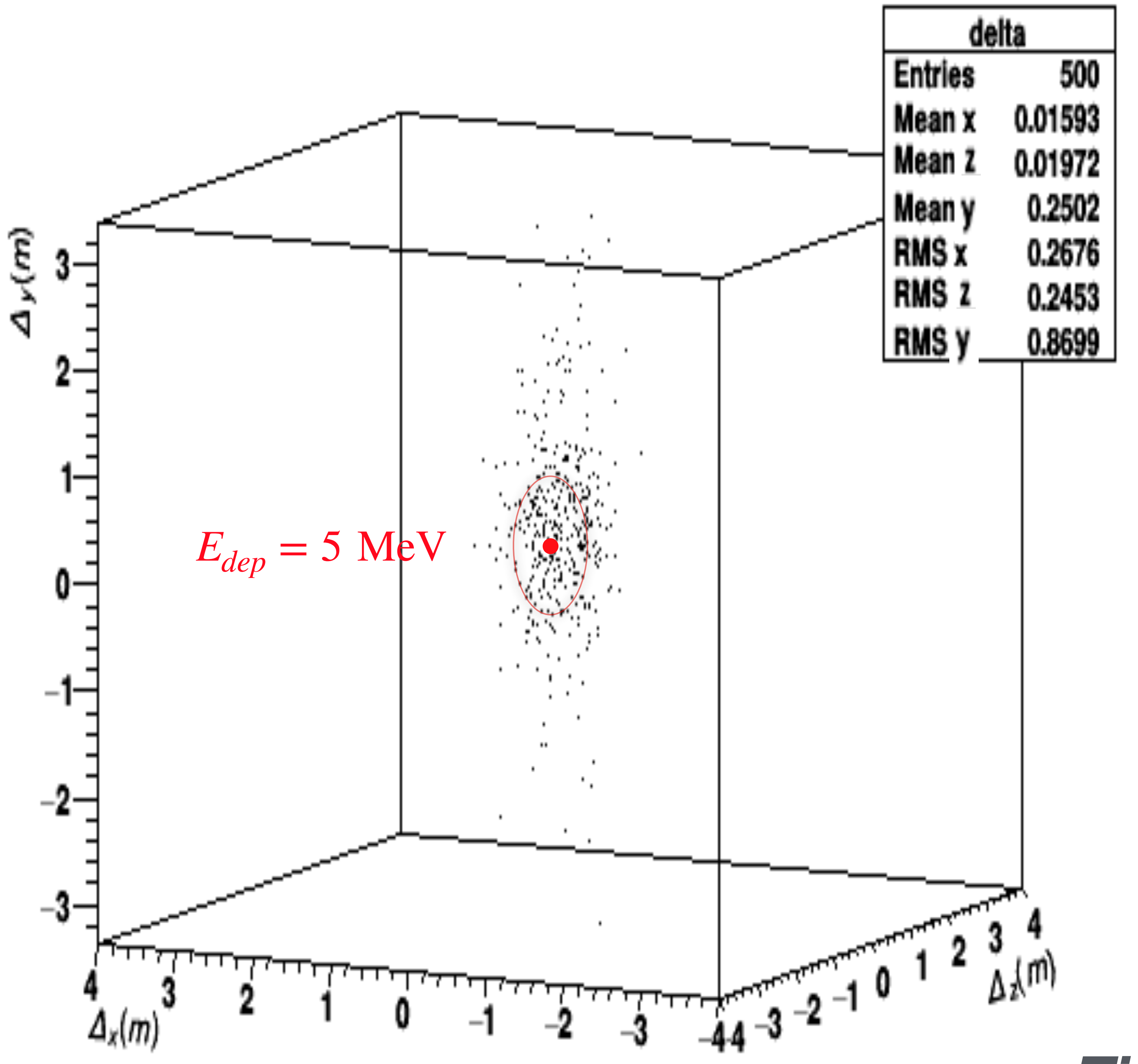
position reconstruction from the barycenter of the detected light pattern of the event



Light Response
of
PD tiles
on the Cathode
and
on two FC side walls

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

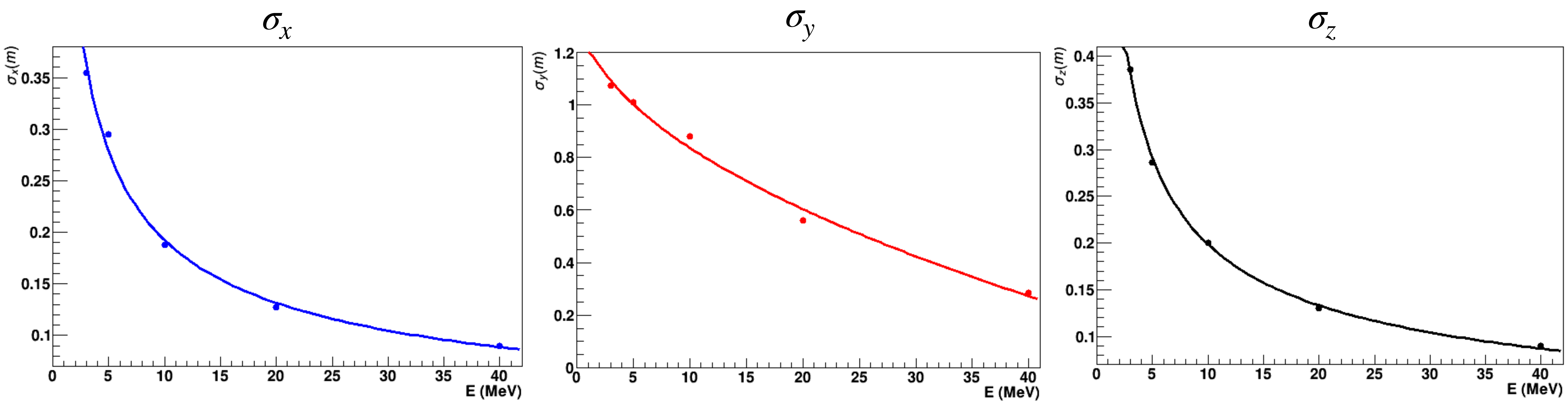
Reconstructed position in space for a sample of 5 MeV MC events generated at a fixed position



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

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

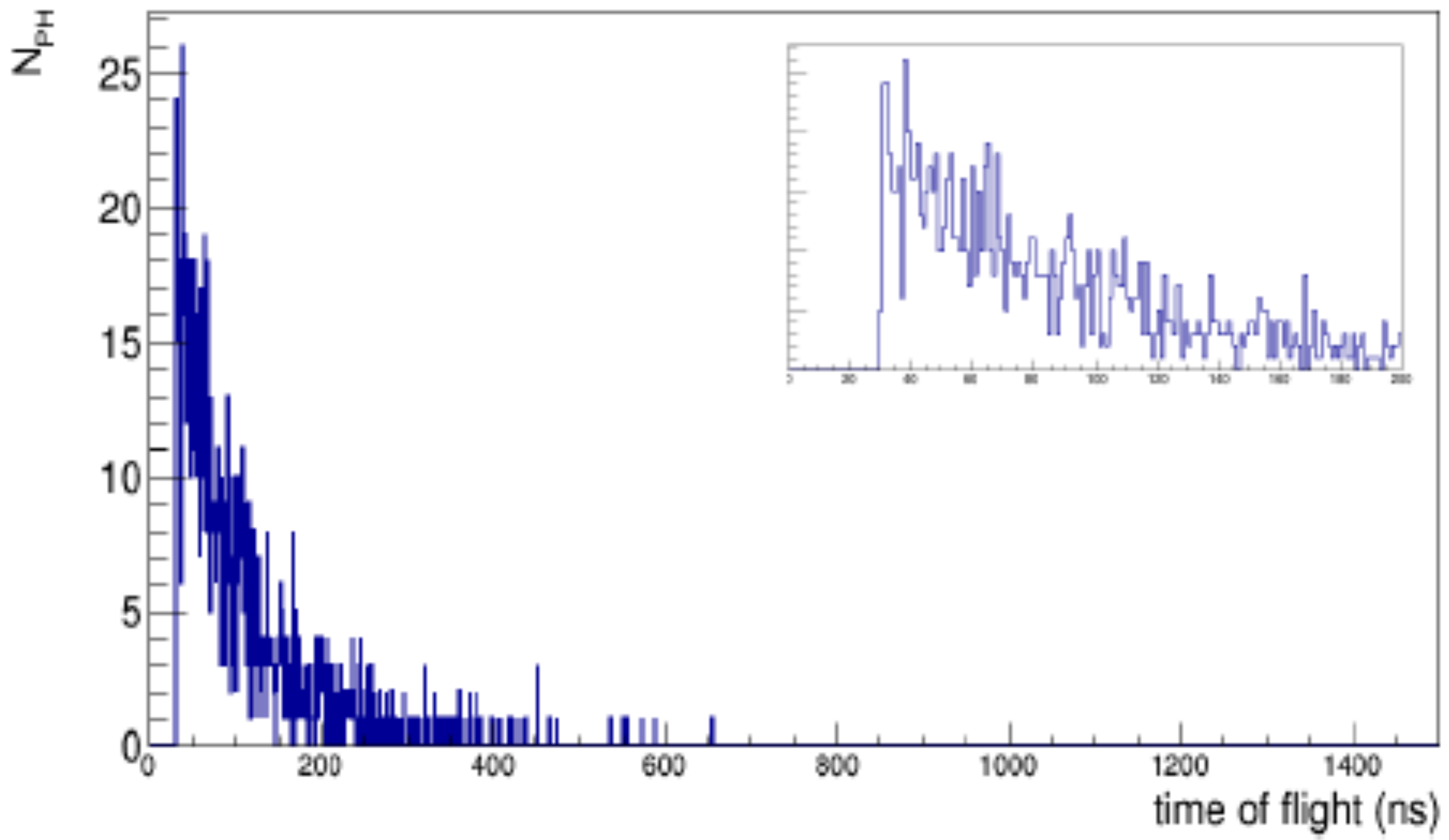
Timing in formation (not used here) should improve Space Resolution



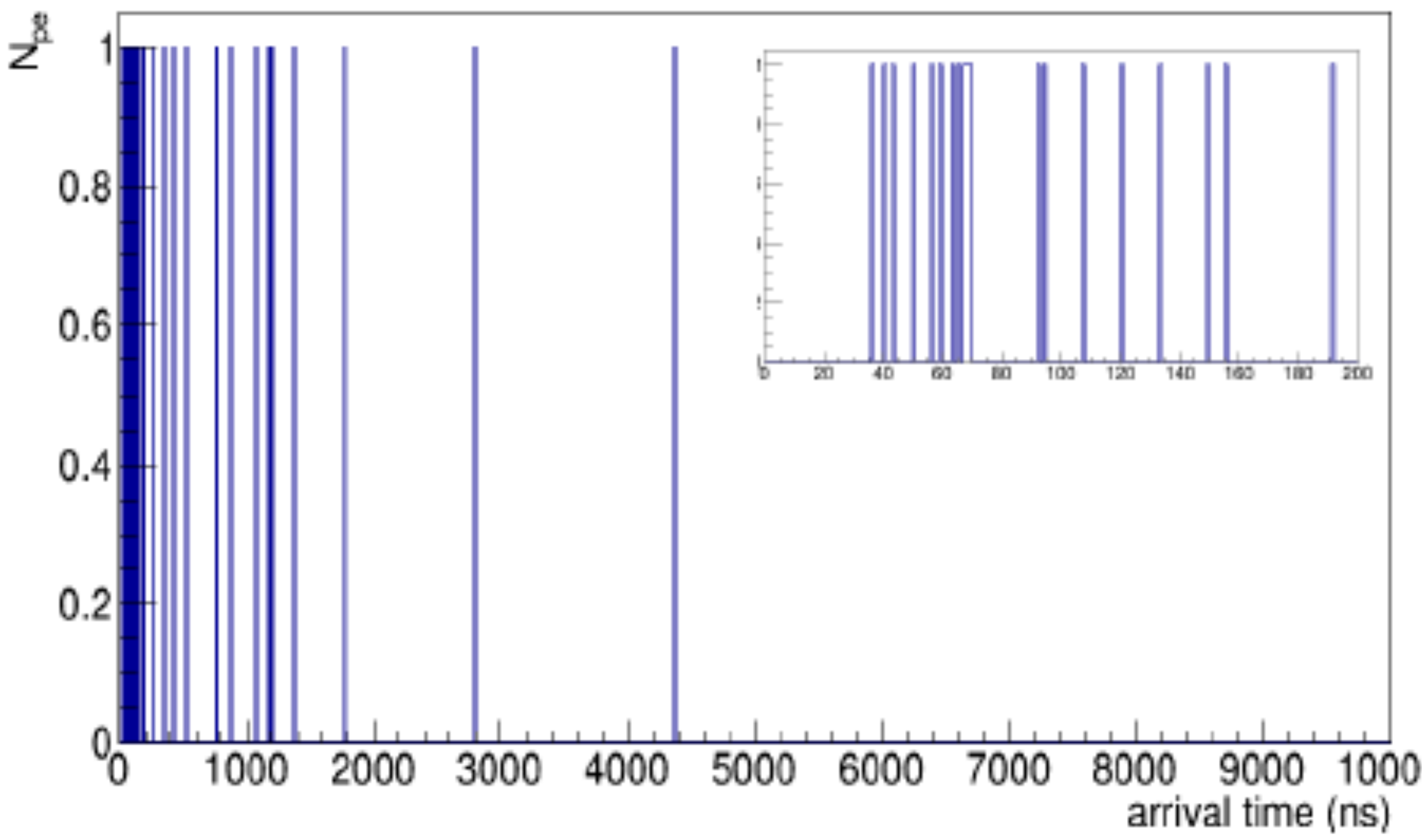
Time information

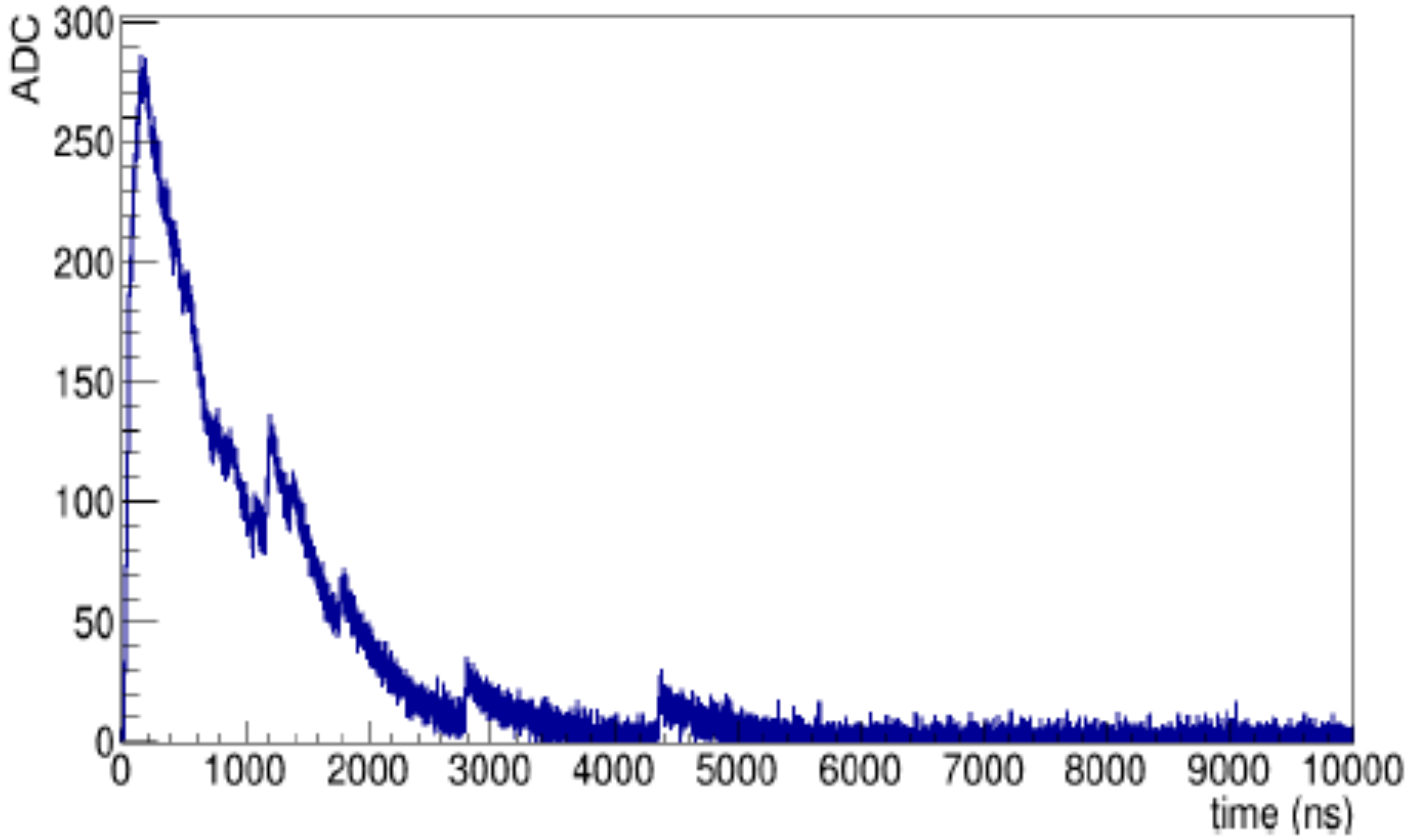
Accounts for:

- LAr scintillation
  - fast and slow components parametrization
- Light propagation (G4)
- Wavelength shifting
  - multi components emission model
- SiPM readout effects



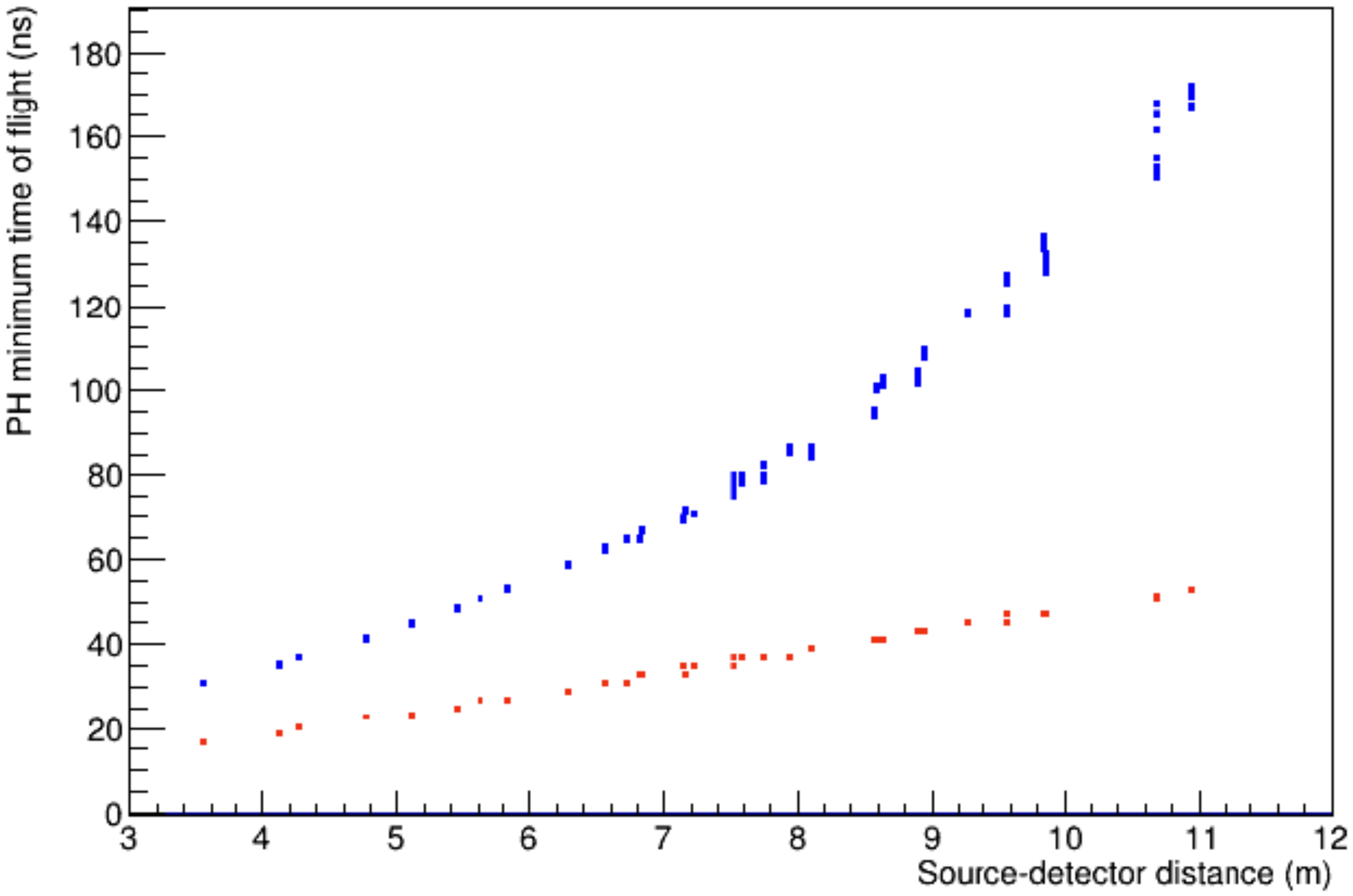
Work
in progress
(Franciole)





Time information

Argon vs Xenon comparison



Work
in progress
(Franciole)

Xe doping can be fully implemented provided scintilation model

- $LY(x, y, z)$ - the detector Light Yield with a $\sim 4\pi$ Optical Coverage

- First evaluation of Trigger Efficiency in Fiducial VD Volume for low-E UG events
- Energy Reconstruction and Energy Resolution for low-E UG events
- Position Reconstruction and Space Resolution for low-E UG events

- Time Resolution study in progress (not reported today)

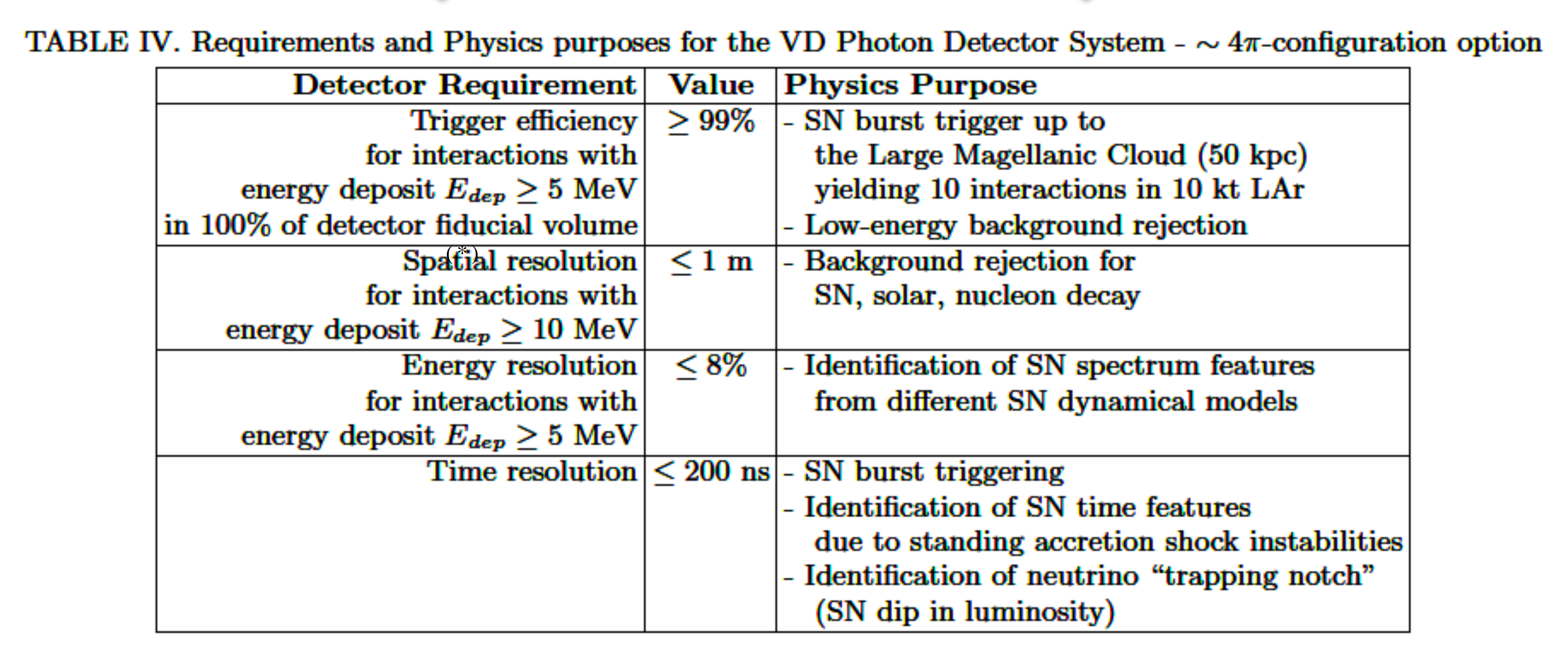


TABLE IV. Requirements and Physics purposes for the VD Photon Detector System - $\sim 4\pi$-configuration option

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)

4π LArPD and VD LArTPC
COMPLEMENTARITY

Combining

4π PDS detection features

(fast, high efficiency trigger down to VLowEn, good E Resol down to LowEn)

with LArTPC detection features

(very good position resolution, imaging=topological discrimination [ABS vs ES], some directionality)

would result in [but need full MC demonstration !!]

an unprecedented detection power - superior to any other experiment

operating in the

Few - Few-tens MeV energy range

Absorption Reaction
of
electron-neutrino on Ar

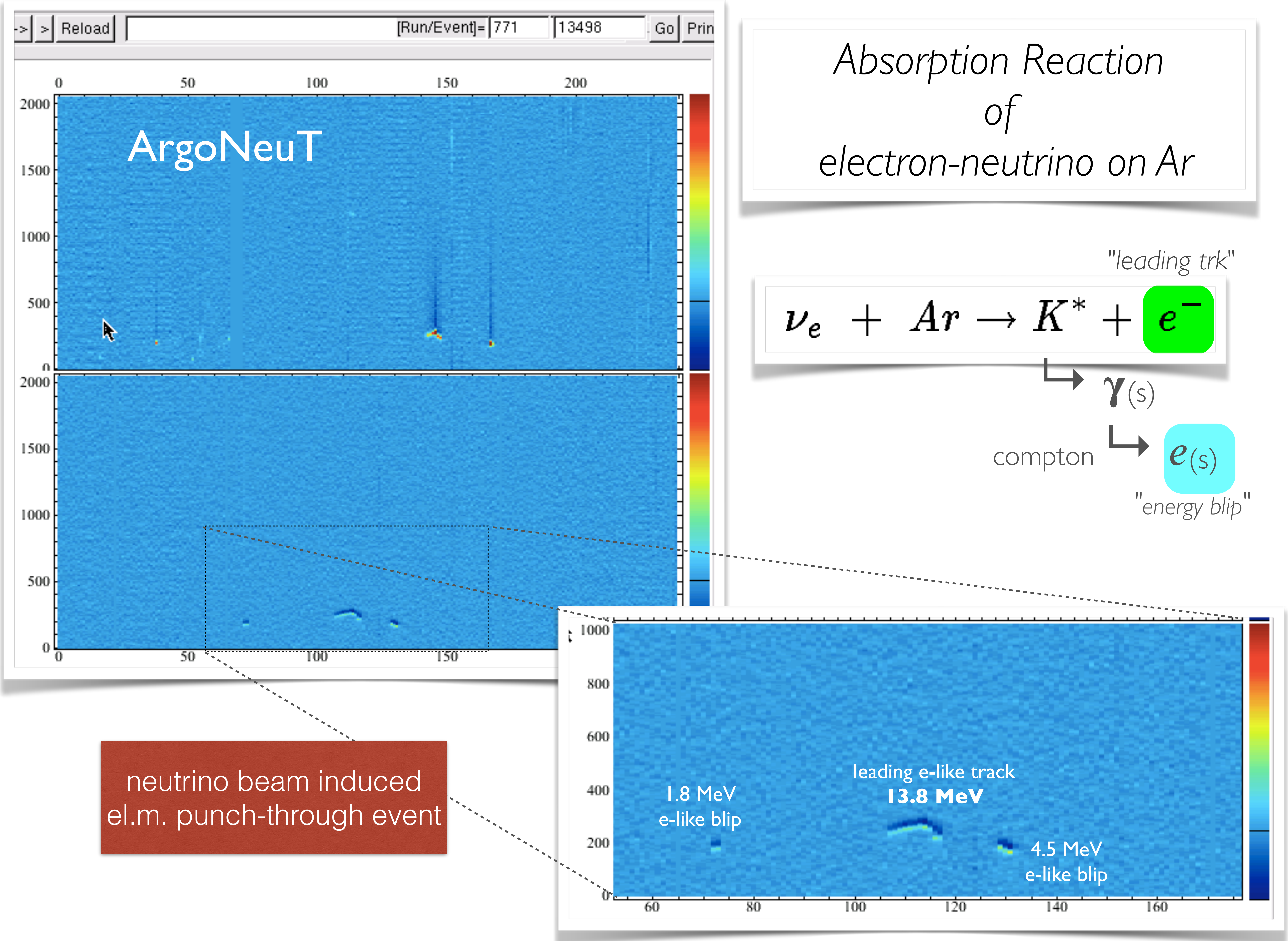
"leading trk"

$$\nu_e + Ar \rightarrow K^* + \boxed{e^-}$$

$\hookrightarrow \gamma$(s)

compton $\hookrightarrow$ e(s)

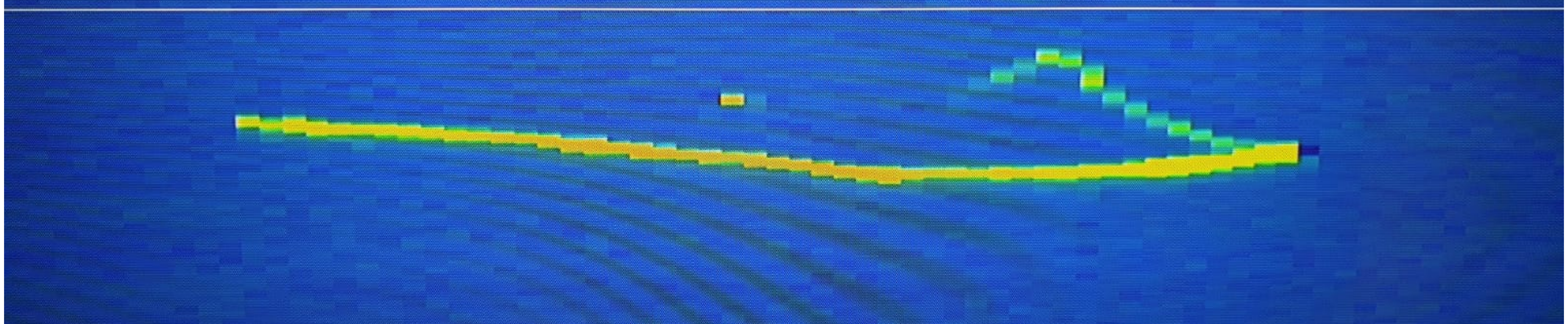
"energy blip"



neutrino beam induced
el.m. punch-through event

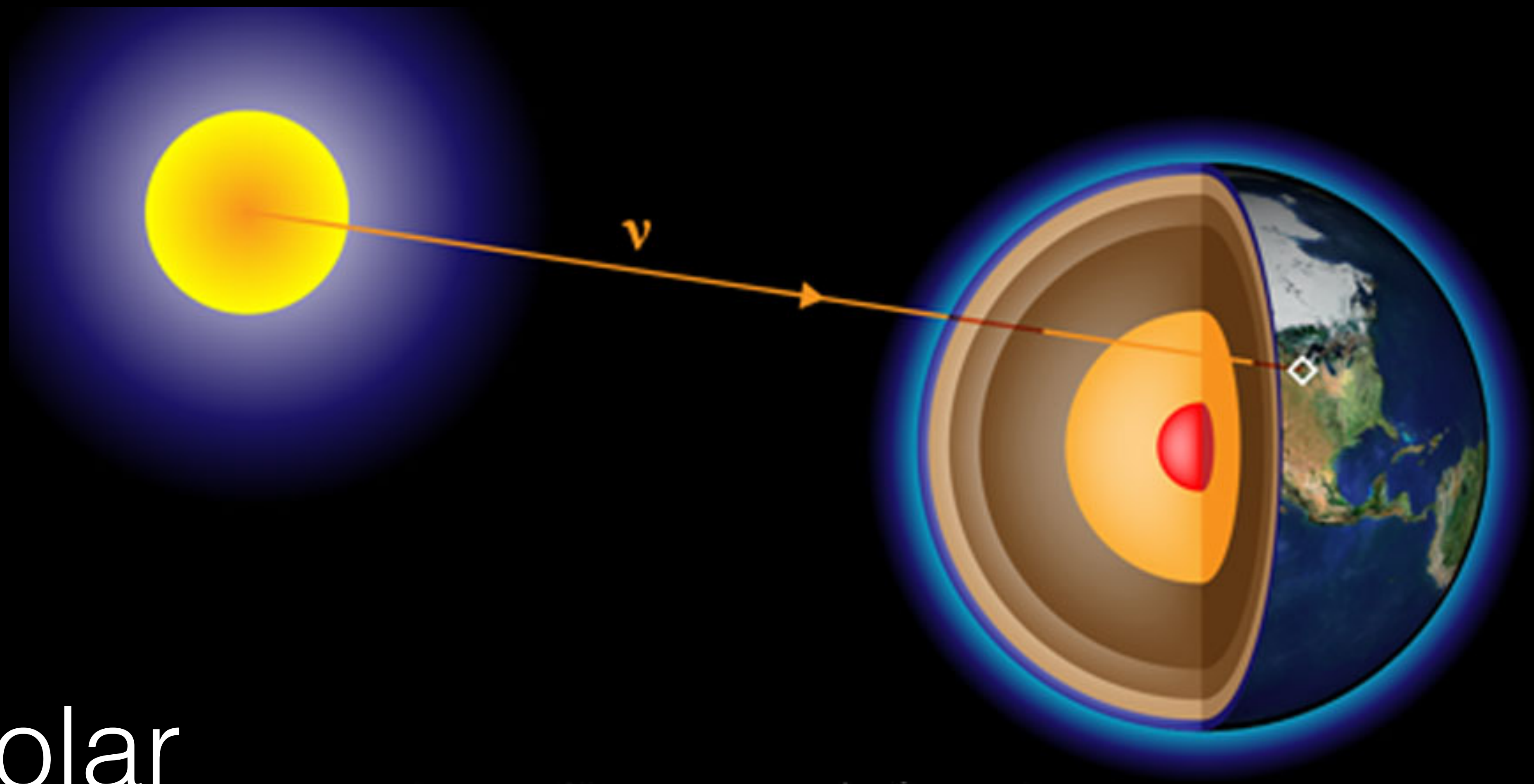
Time to Celebrate

few seconds after, from the On-Line Monitor



First track recorded at Nominal El.Field

Enlarging the DUNE Physics Scope



Solar

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**

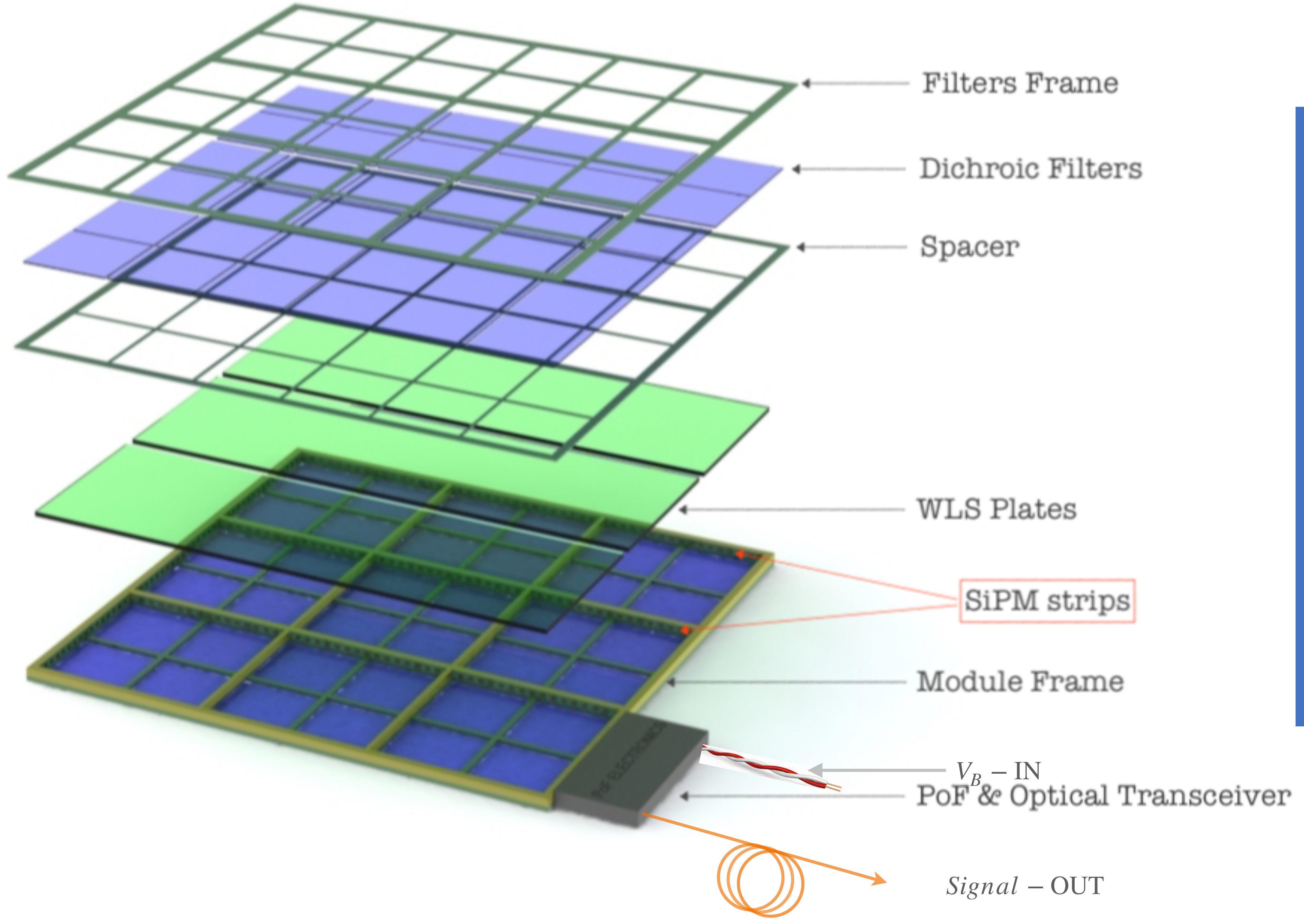
- The progenitor dependence imprints itself nicely on the neutrino signal – DUNE can see this

SuperNova

- *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



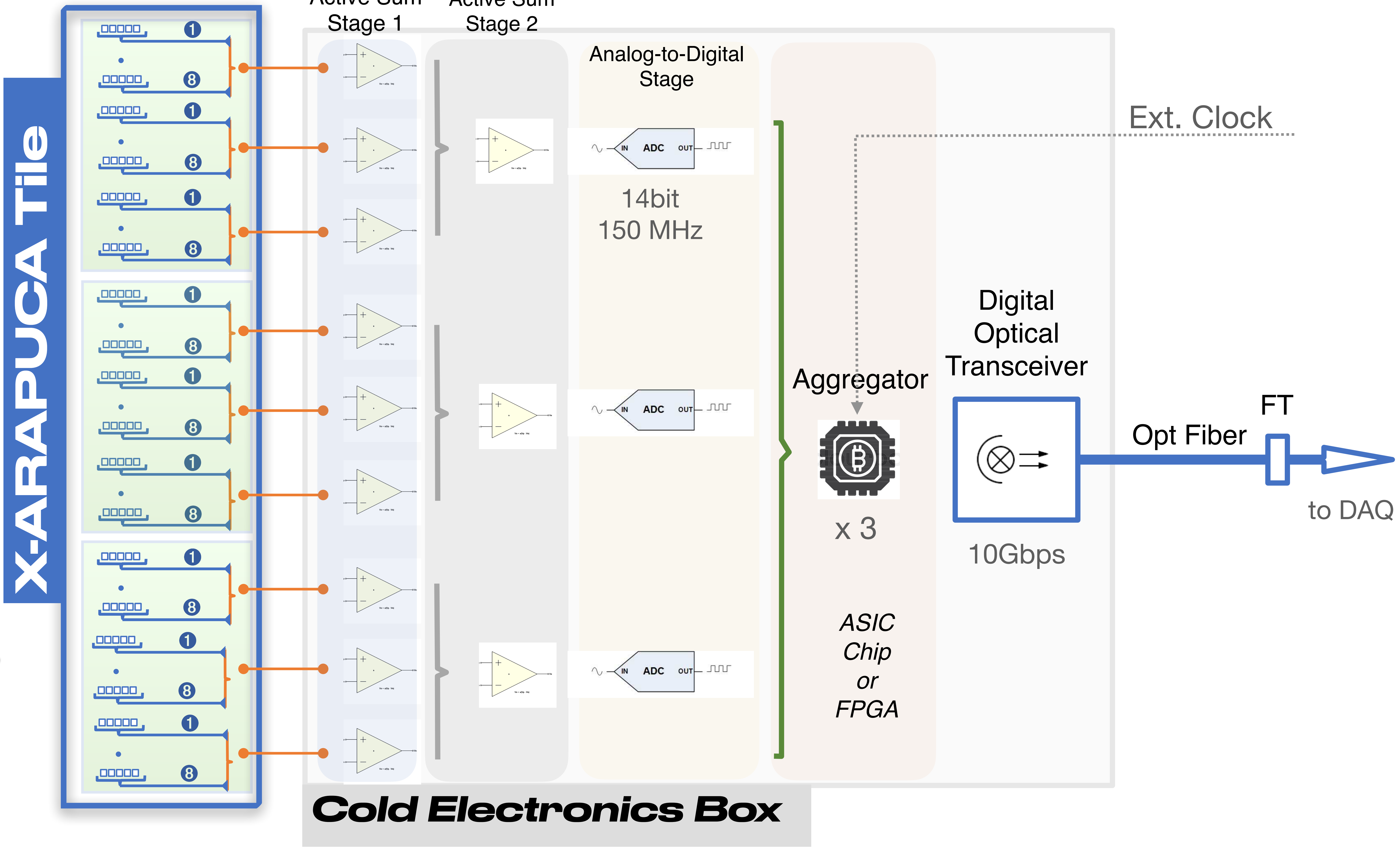
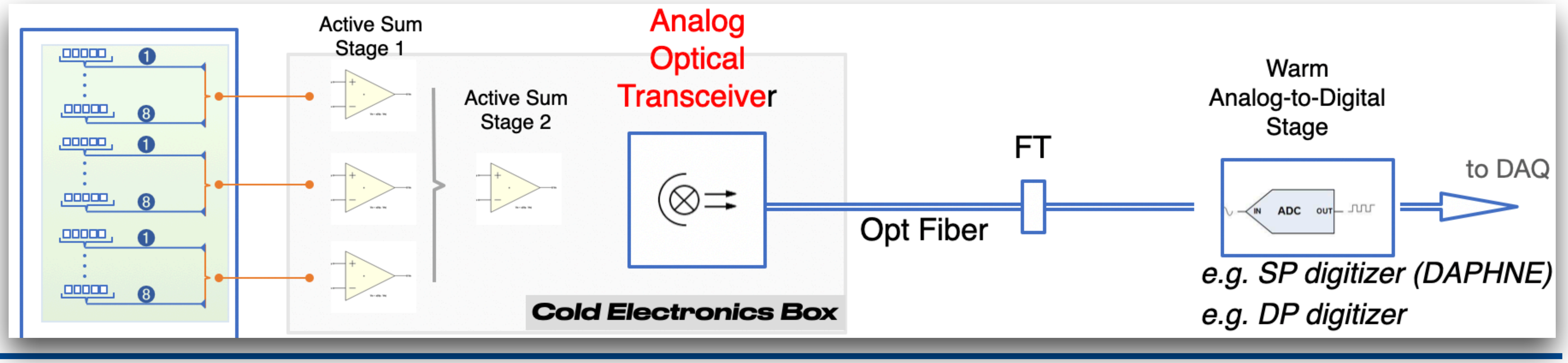


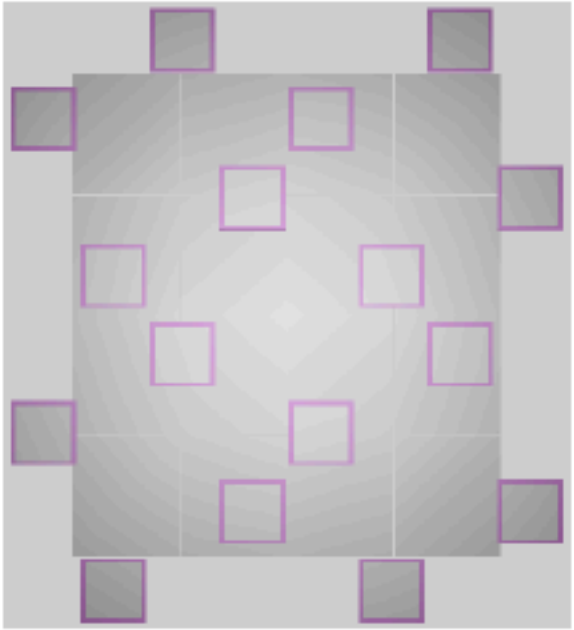
TABLE V. PD basic unit: X-ARAPUCA Tile

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

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

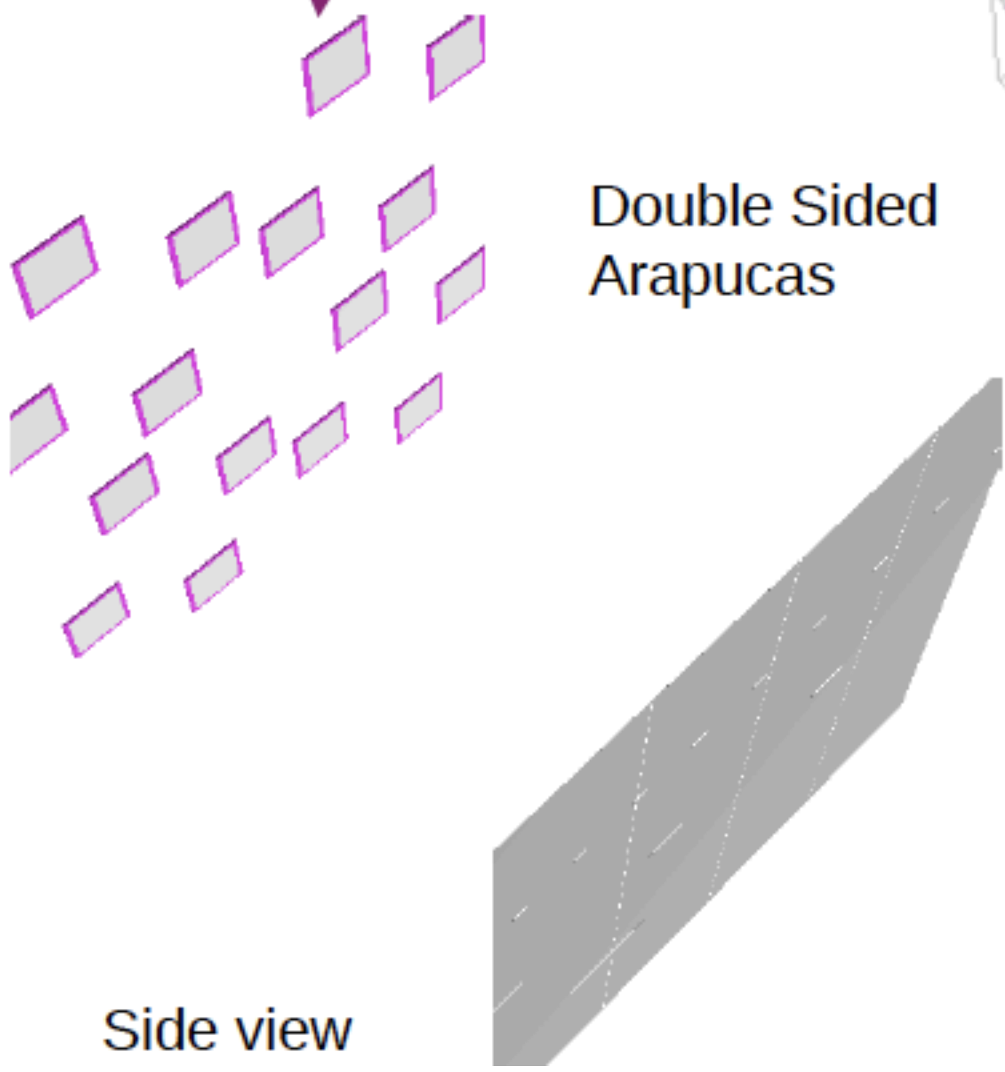


VD PDS Geometry in LArSoft



Bottom view

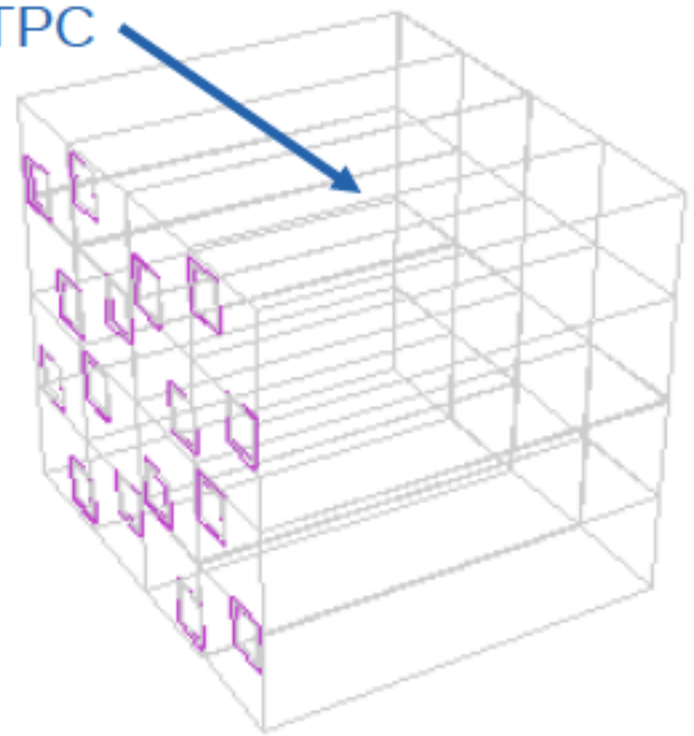
Arapuca box (not optically sensitive)



Double Sided Arapucas

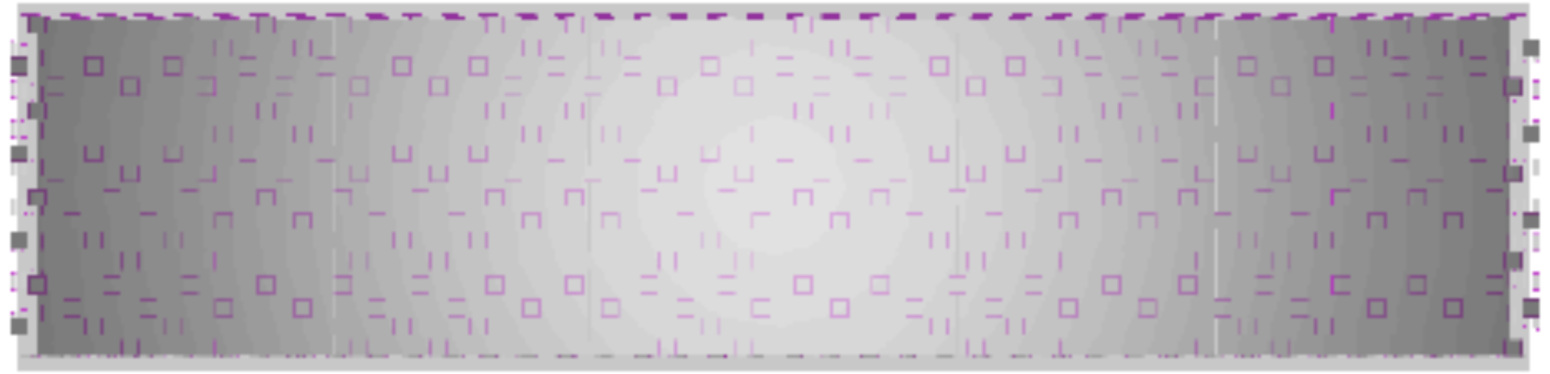
Arapuca optical window

Side view



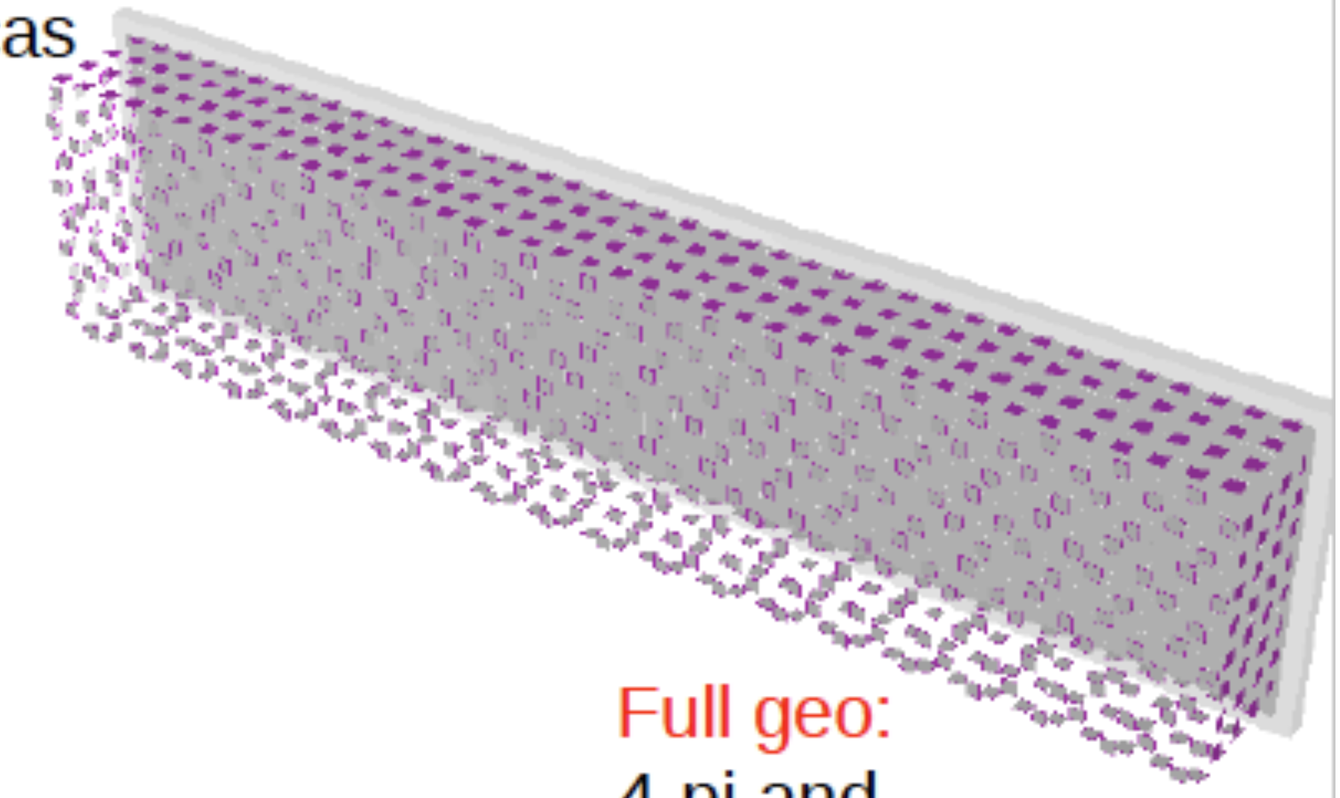
Smaller geo

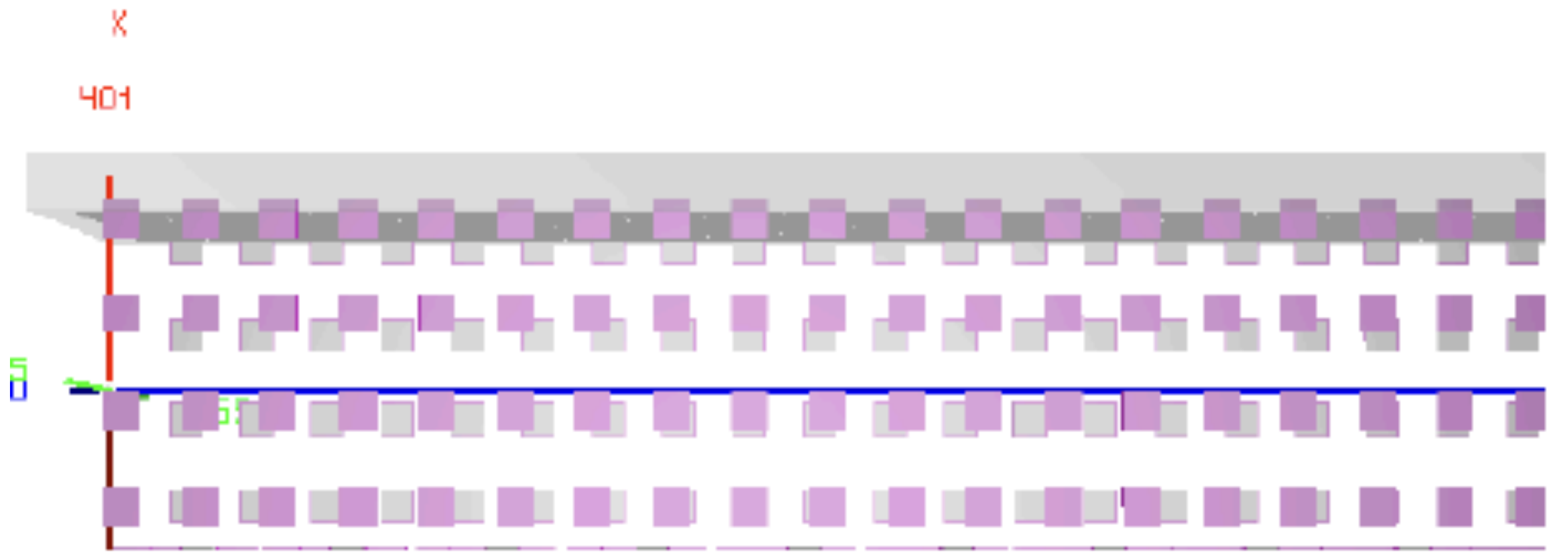
V. Galymov, L. Paulucci



Bottom view

Double Sided Arapucas





Single Sided Arapucas

Full geo:
4-pi and cathode only coverage available

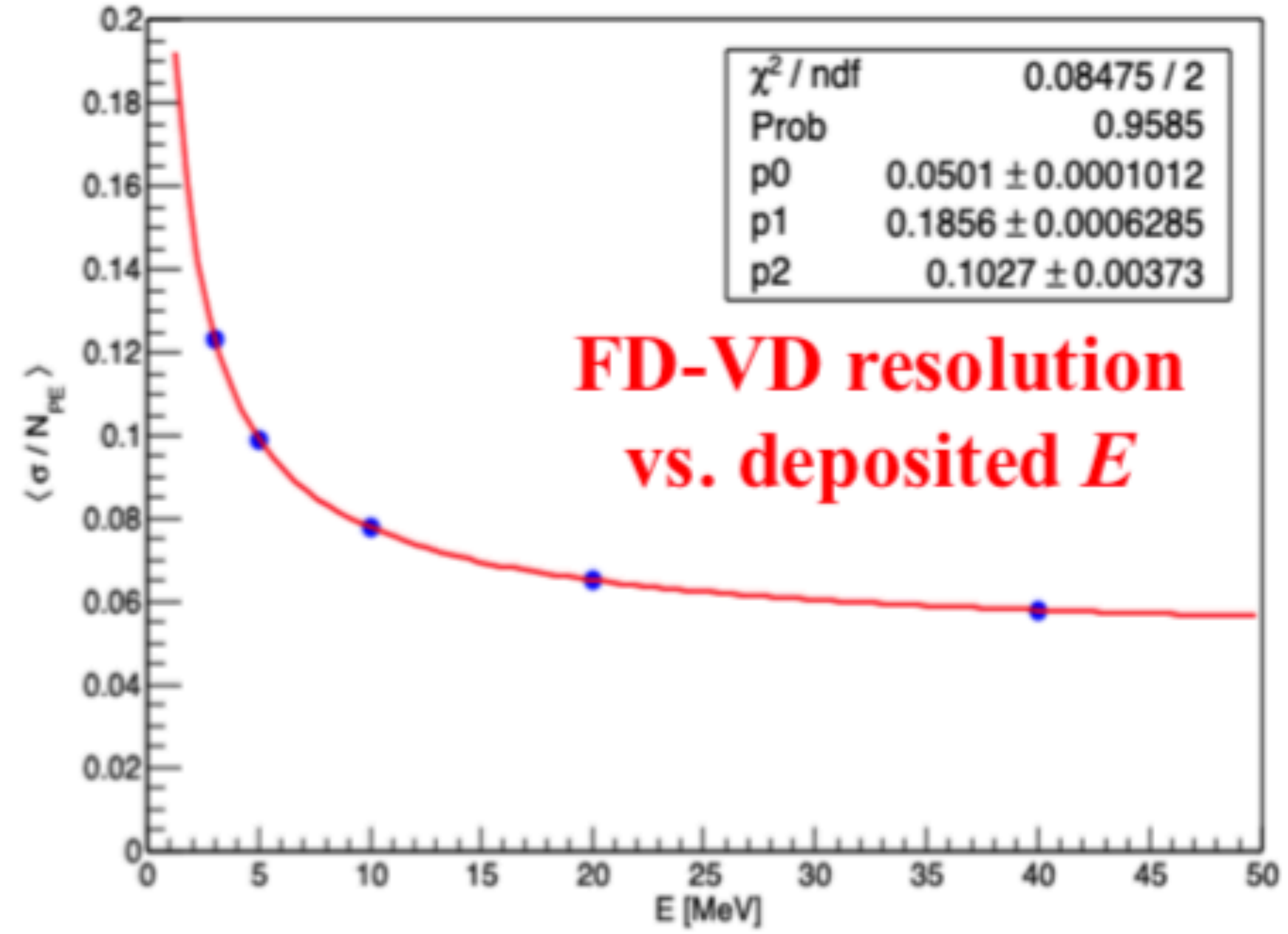
Work
in progress
(Laura)

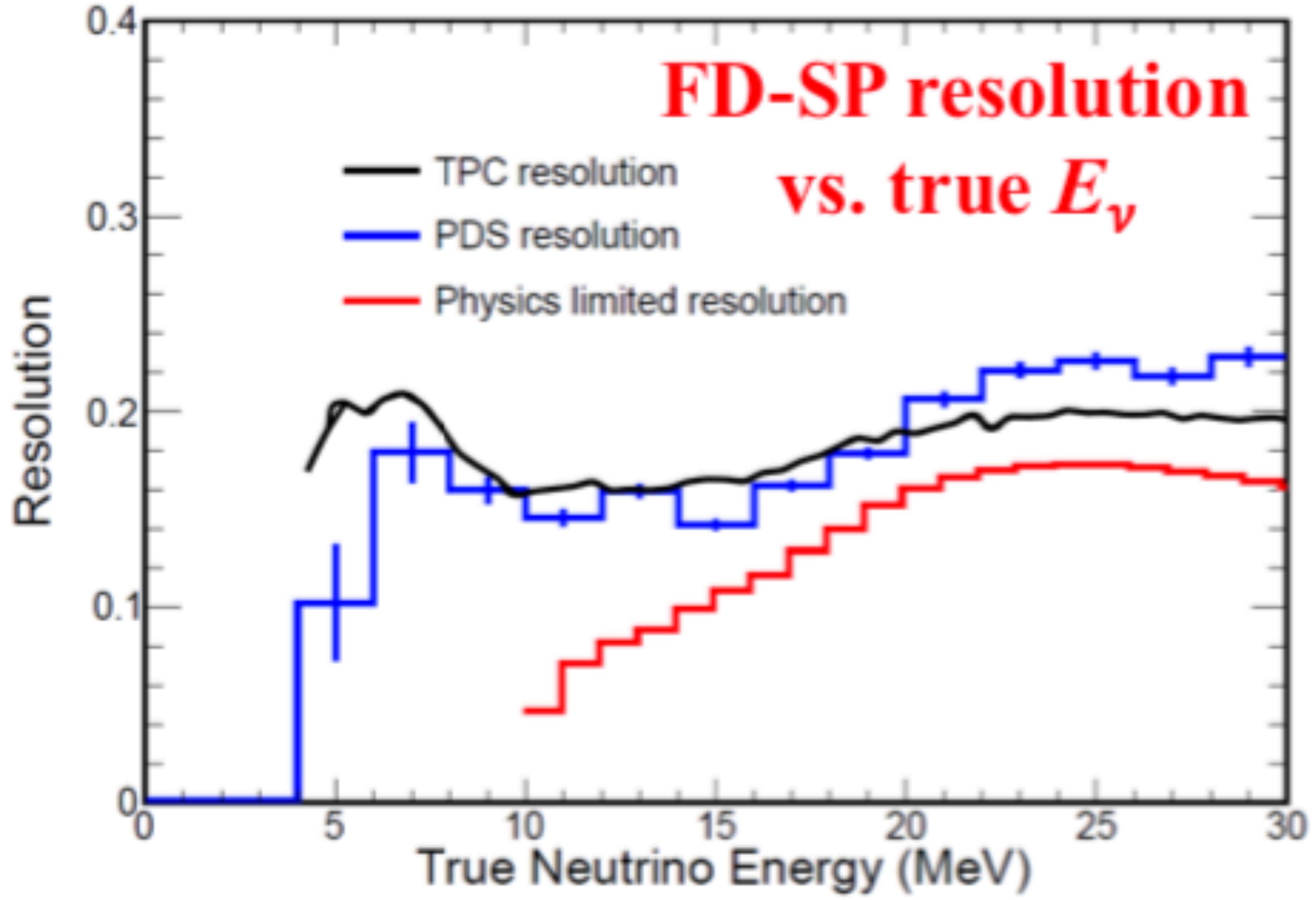
“Low-level” performance requirements: Light collection

- **From Dec 6th talk from Flavio Cavanna:**
  - Ample average light yield of ~60 PE/MeV
  - Darkest area >20 PE/MeV
- *At right:* estimate of FD-VD PDS energy resolution shows **excellent performance** compared to FD-SP.
  (Caution: *x* axes are not showing the same thing)

→ No concerns over total light collected

- **Timing and spatial resolutions; triggering:**
  - Stated FD-VD performance requirements already match physics requirements


FD-VD resolution vs. deposited *E*


FD-SP resolution vs. true E_ν

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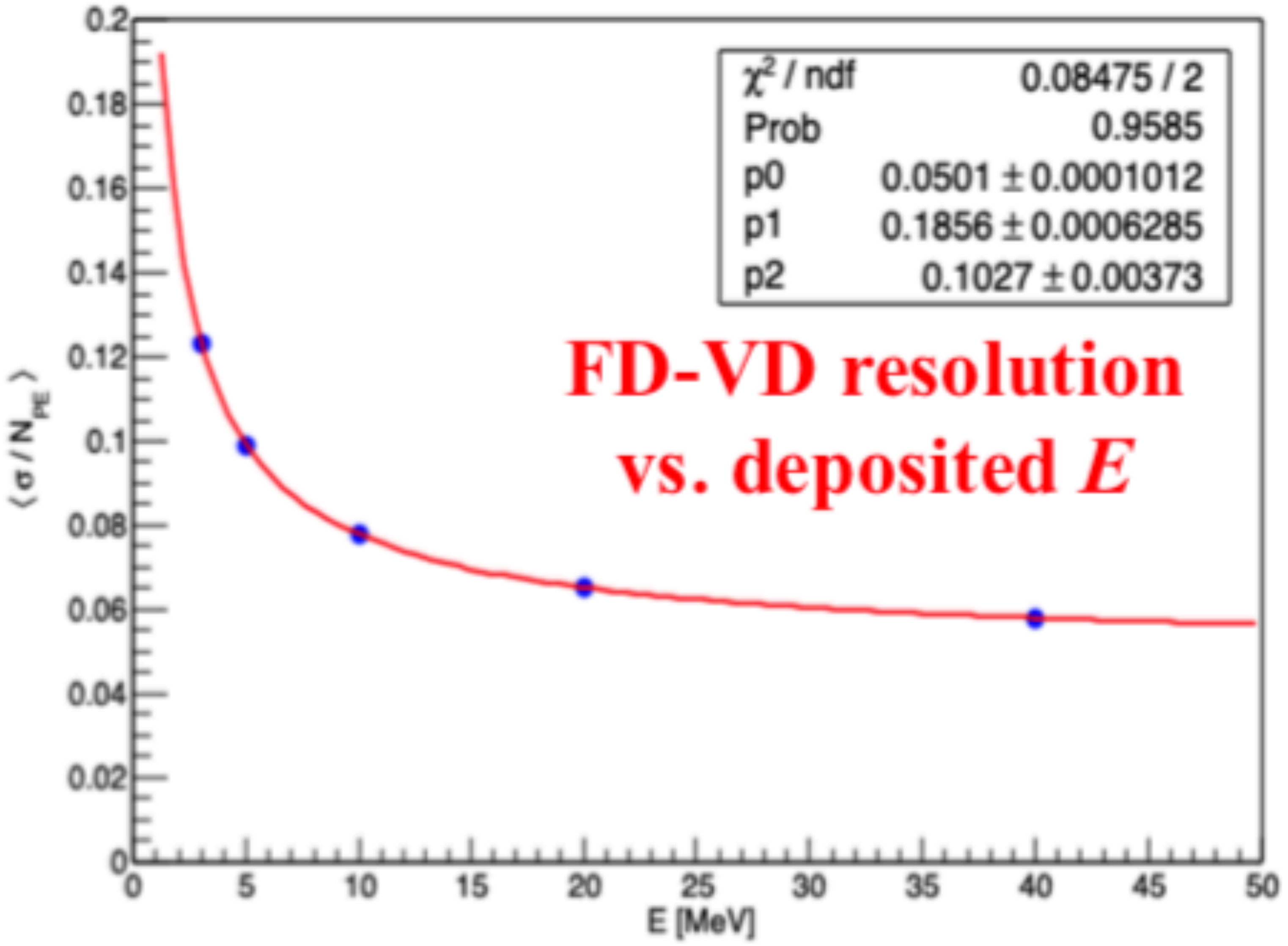
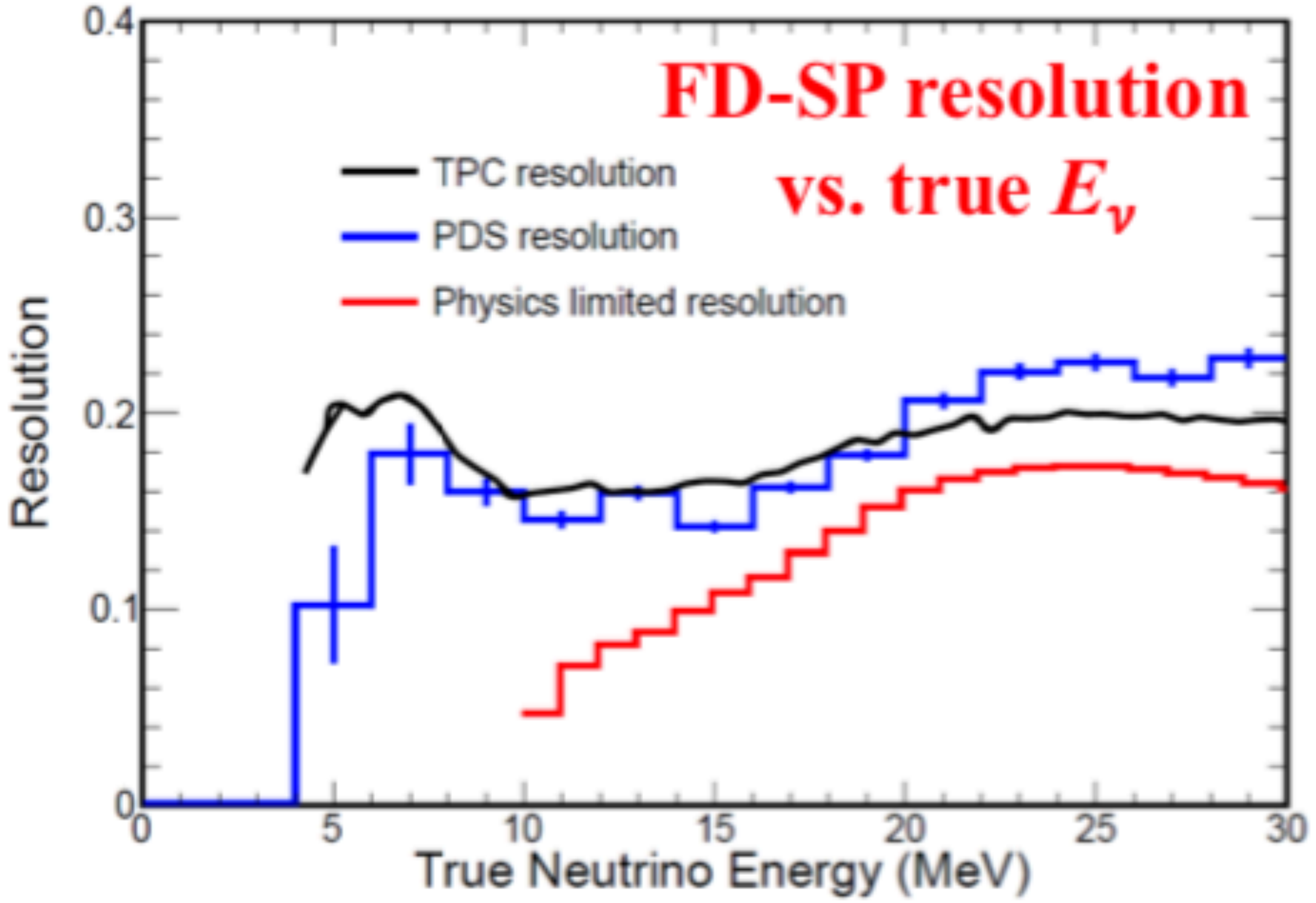




Where's the challenge ??

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)

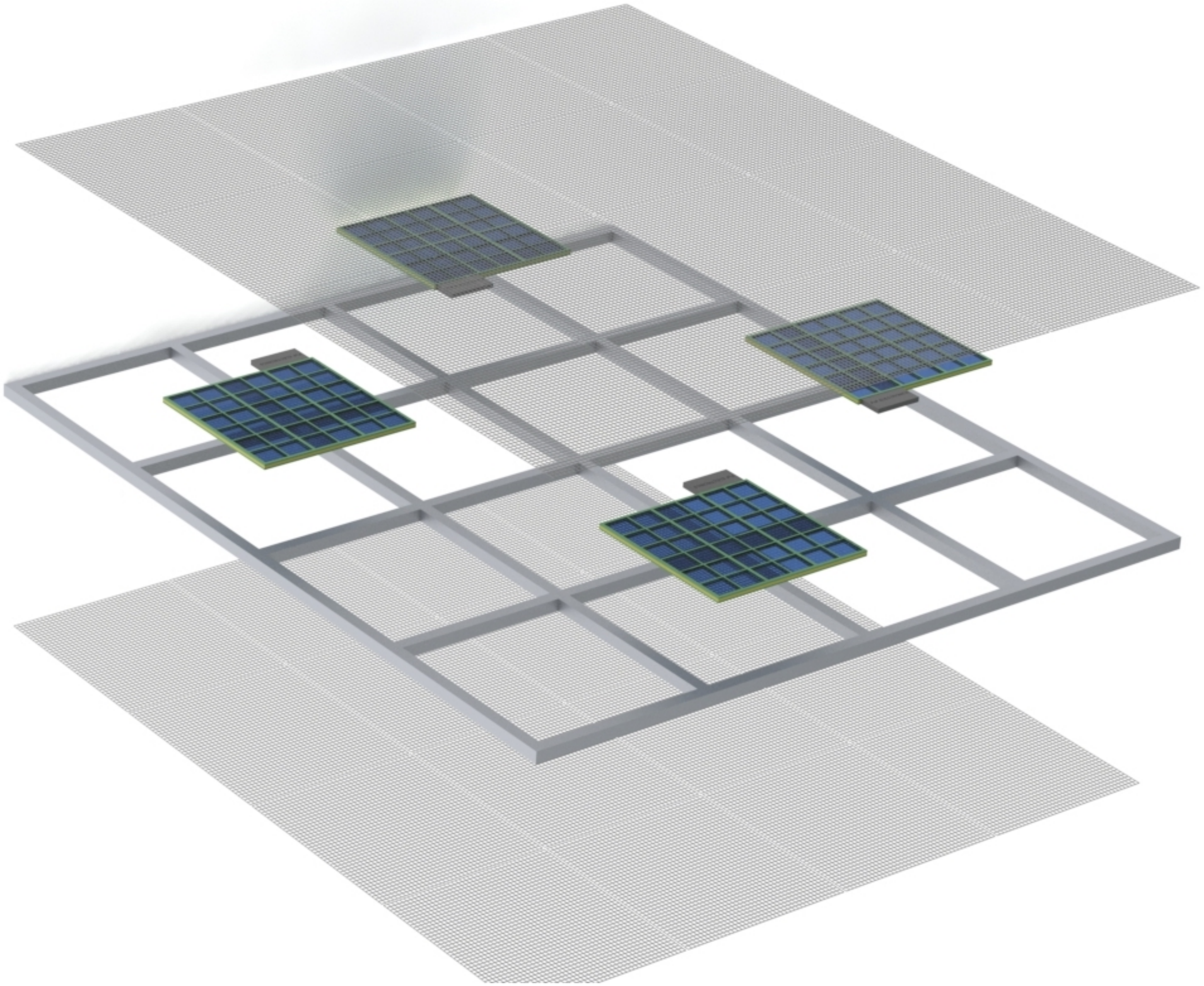
PoF
Power over Fiber Optic

Major **R&D**

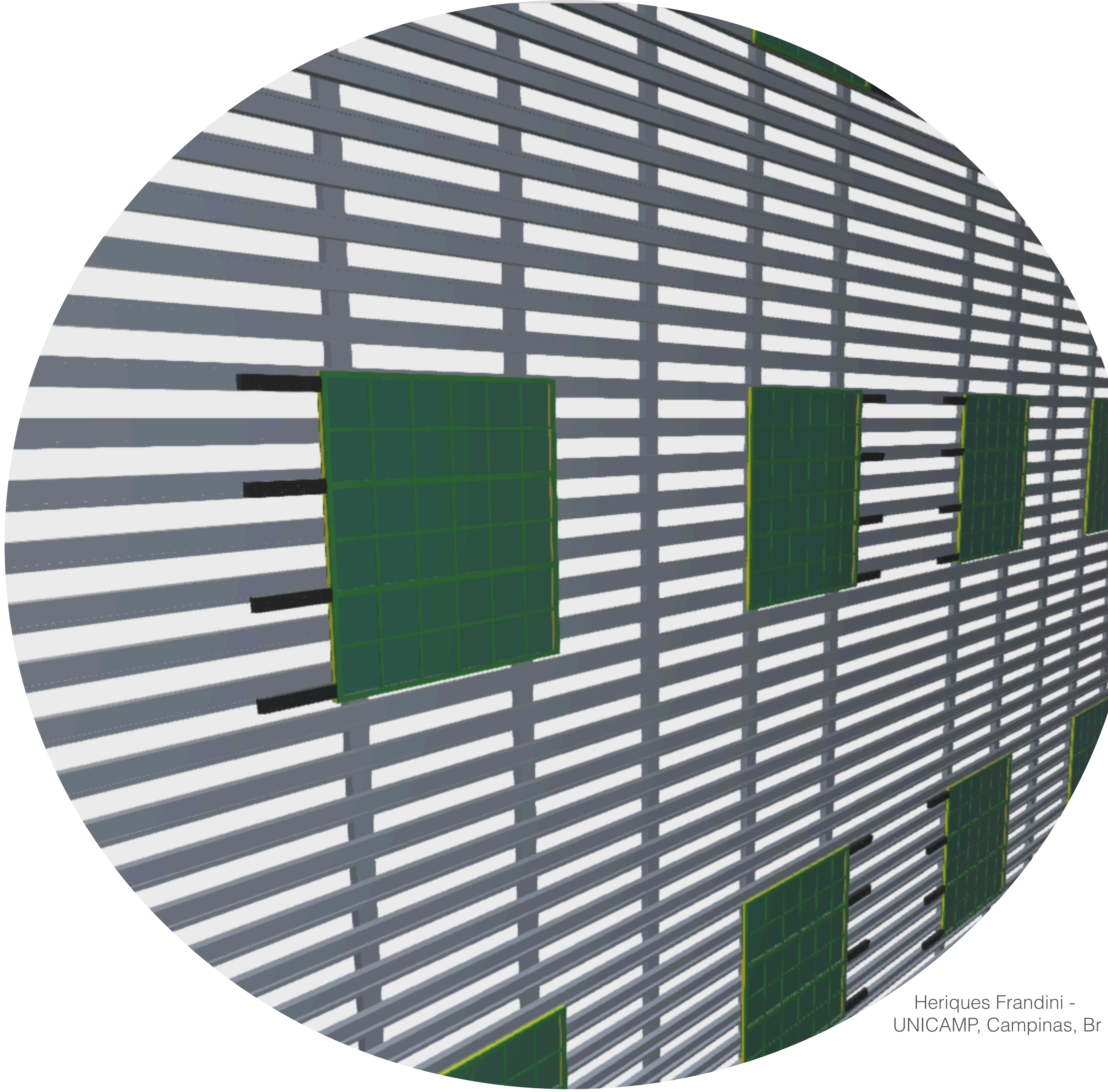
- Detector design and coverage: existing (X)ARAPUCA technology with SiPM photosensors is suitable for this application (flexible design opposite to PMT, **optimization for Xe light**)] **R&D**

- 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)



Heriques Frandini - UNICAMP, Campinas, Br

Photon Detectors hanging on Field Cage Walls

*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)

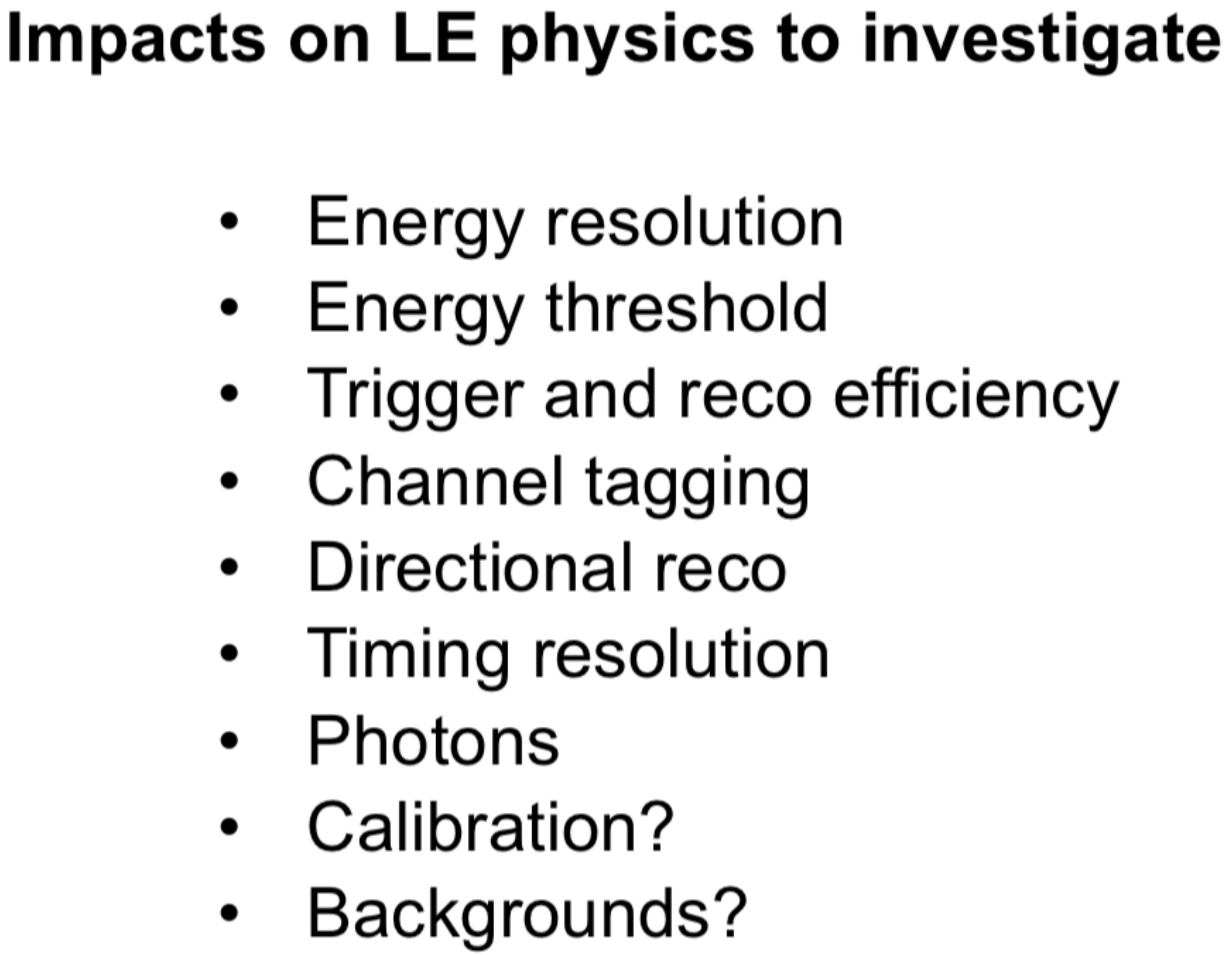
Cold

- 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

Kate Scholberg



Impacts on LE physics to investigate

- Energy resolution
- Energy threshold
- Trigger and reco efficiency
- Channel tagging
- Directional reco
- Timing resolution
- Photons
- Calibration?
- Backgrounds?