

HYBRID DETECTORS: OVERVIEW AND PATH FORWARD



JOSÉ MANEIRA
LIP, UNIV. DE LISBOA
PORTUGAL

WORKSHOP ON HYBRID CHERENKOV/SCINTILLATION DETECTORS
PHILADELPHIA, JUNE 5, 2025

- 1. Introduction
 - Detector innovations and discoveries in neutrino physics
 - Limitations of Cher/Scint detectors
 - Analysis refinements in Borexino and SNO+
- 2. Overview of hybrid technology developments
 - Technology testbeds
 - Water-based liquid scintillators
 - Slow and loaded scintillators
 - Dichroicons
 - LAPPDs and fast PMTS
 - Other ideas
- 3. Path forward
 - Integration into large scale detectors
 - What's the best compromise between low and high energy goals?

1. INTRODUCTION

- Physics discoveries are based on innovations in detector (and sources) technology

FIRST

Nuclear reactors
HE synchrotron

DISCOVERY OF

- Electron neutrinos
- Muon neutrinos

Radiochemical technique
Ultra-pure liquid scintillators

- Solar Neutrinos
- Low energy solar neutrinos

Large water Cherenkov detectors
Huge water/ice detectors

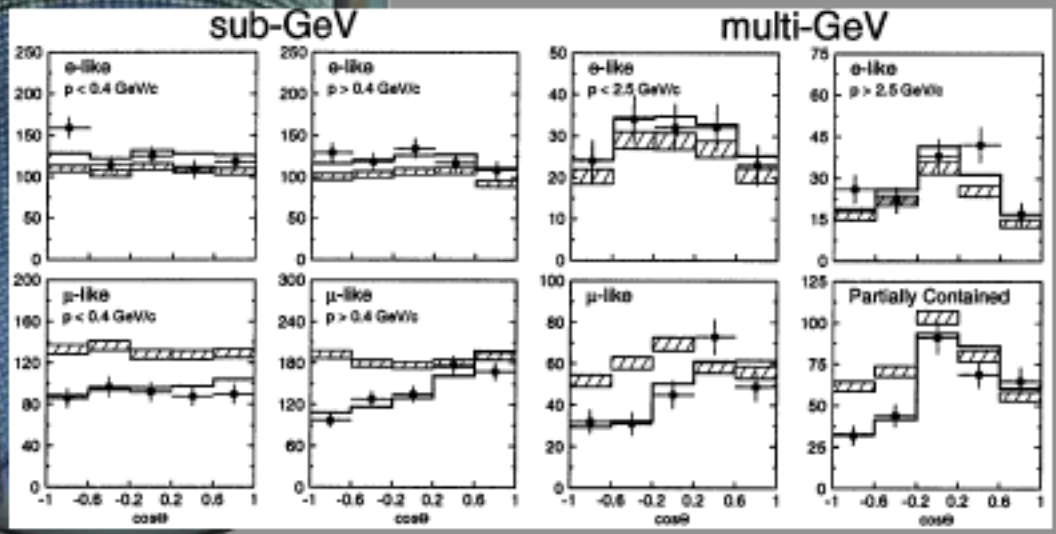
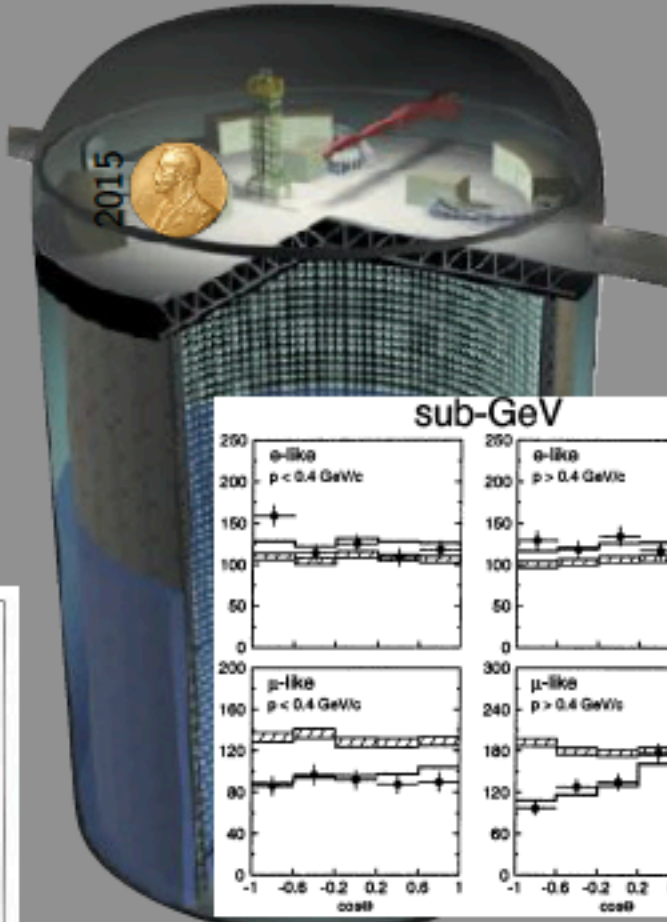
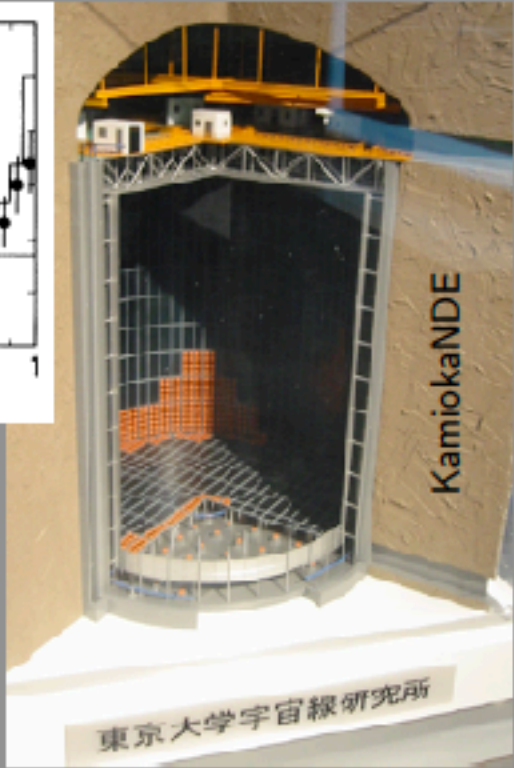
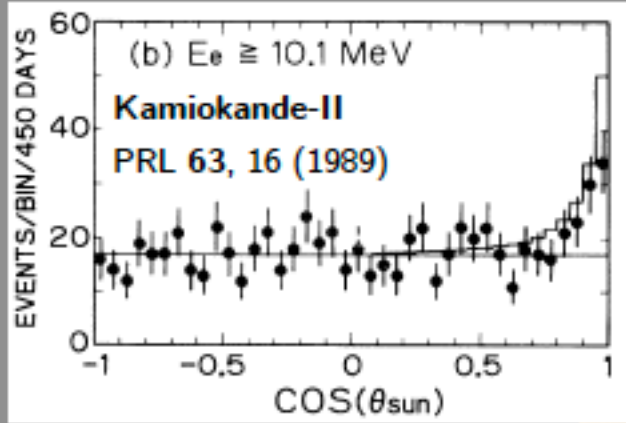
- Neutrino oscillations
- HE astronomical neutrinos

Loaded liquid scintillators

- Best double-beta decay limit

1980s–: Rise of the Cherenkov Giants Massive Directional Detectors

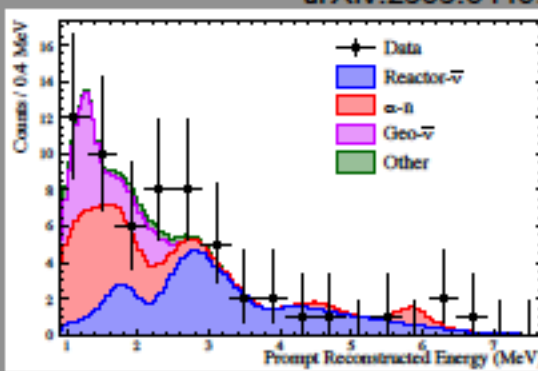
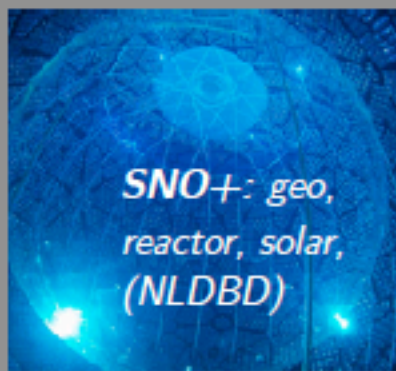
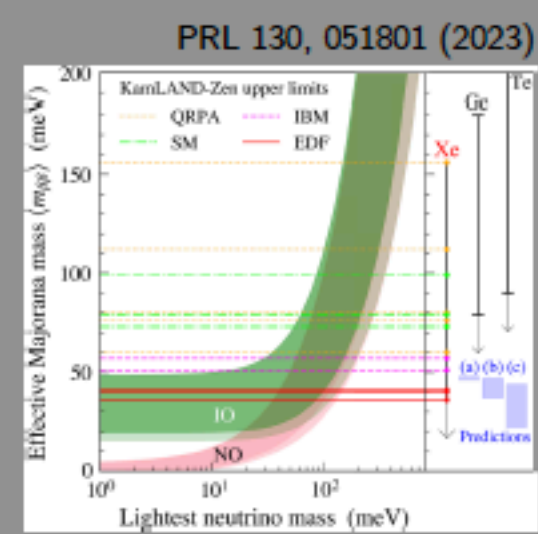
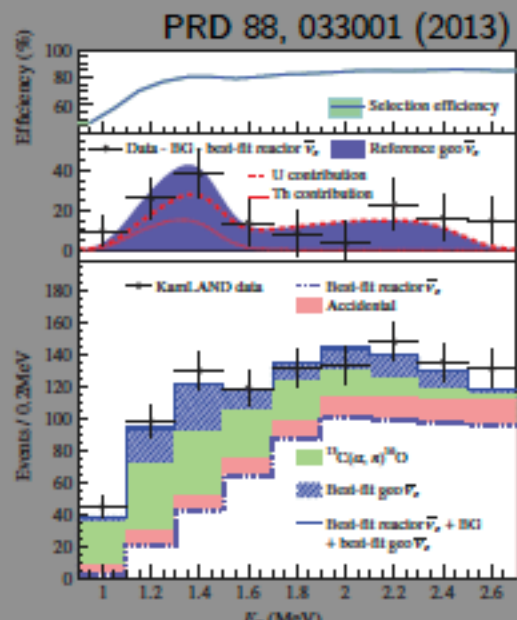
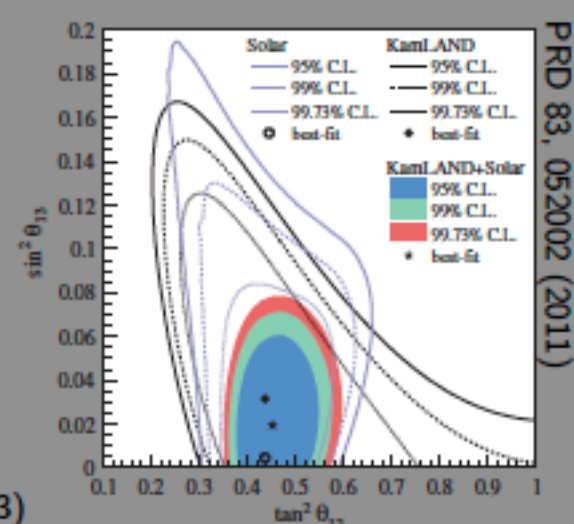
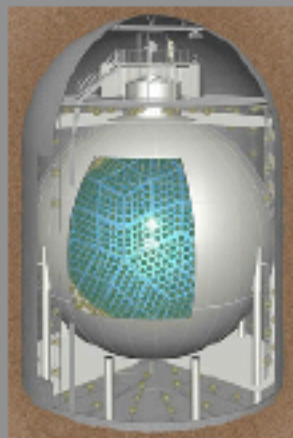
- Nucleon decay:** Strongest constraints on proton stability and baryon number symmetry, a key to GUT/SUSY physics
- Supernova ν :** The world's supernova burst neutrino dataset is from IMB, Kamiokande-II, + BUST (Baksan, LS)
- Neutrino Oscillations:** Solar and atmospheric neutrino measurements at SNO and Super-K establish neutrino oscillations and neutrino mass.



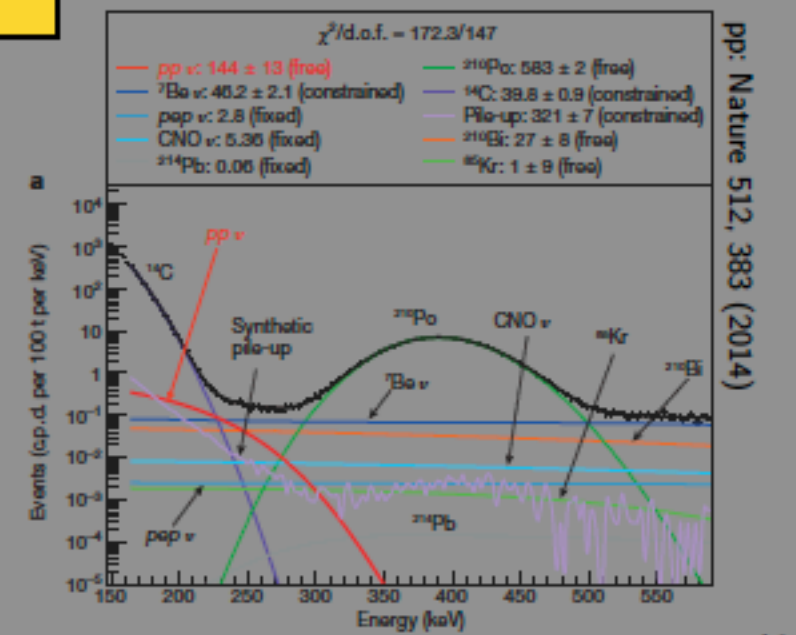
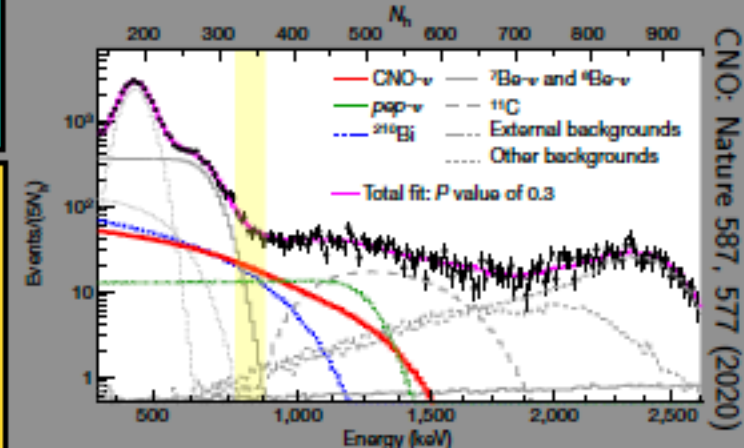
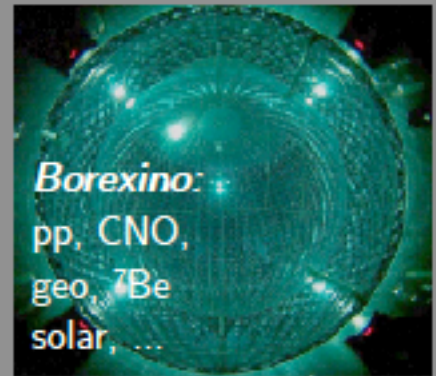
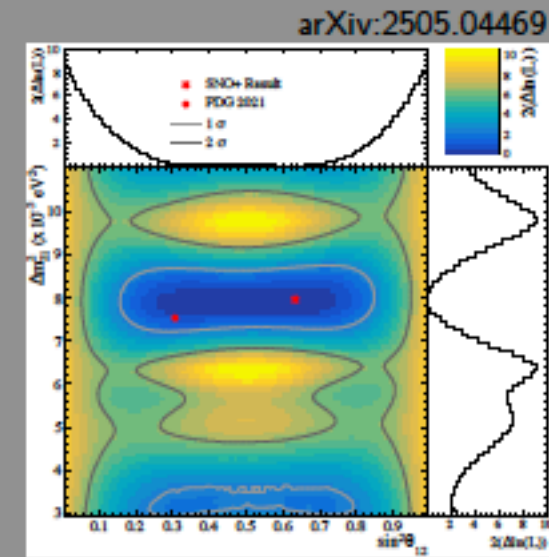
Plus: Constraints on Lorentz violation, neutrino decay, *hep* solar neutrinos, diffuse supernova neutrino backgrounds, cross sections, ...

2000s–: Pioneering Liquid Scintillator Pushing the Envelope of Threshold and Backgrounds

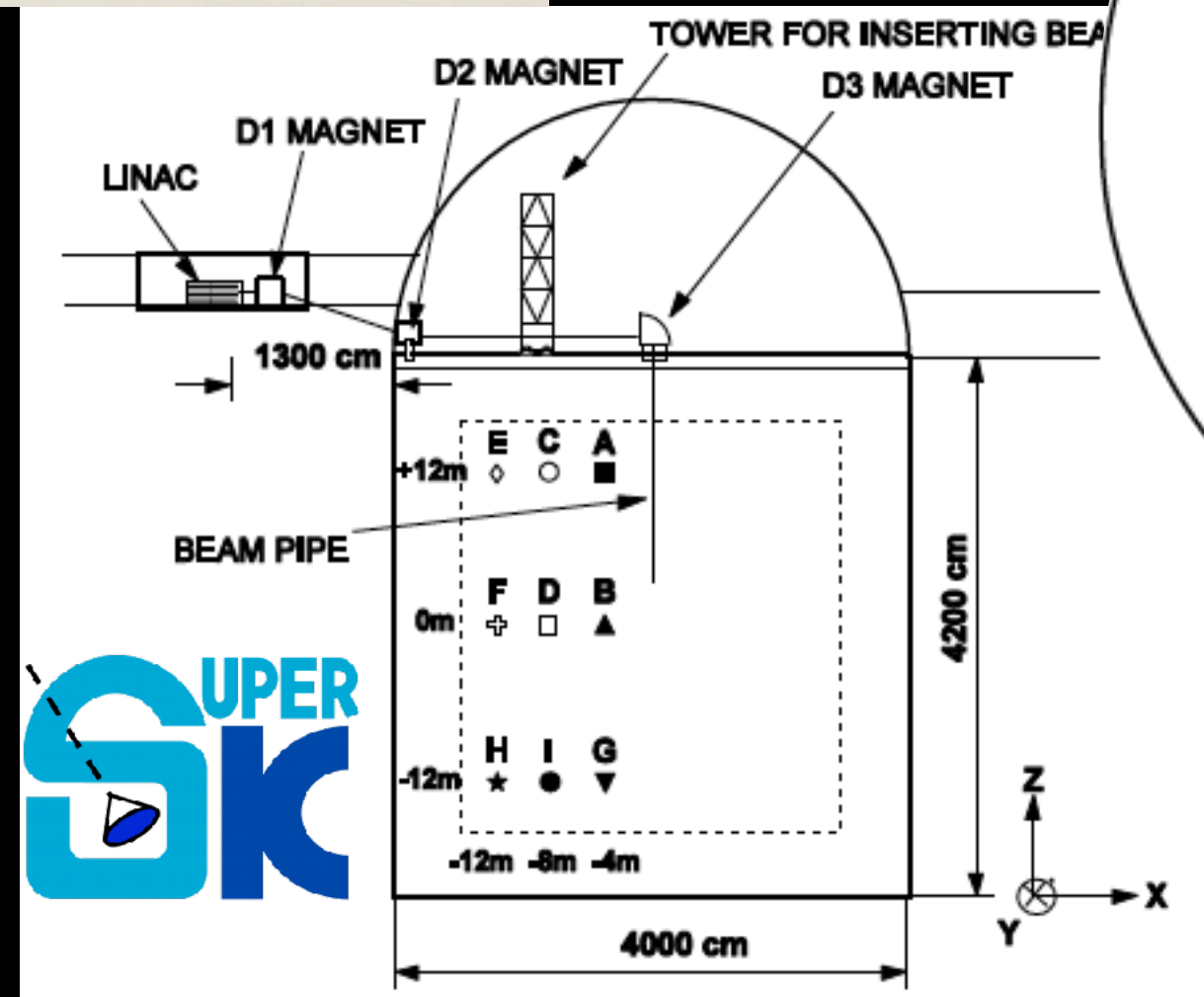
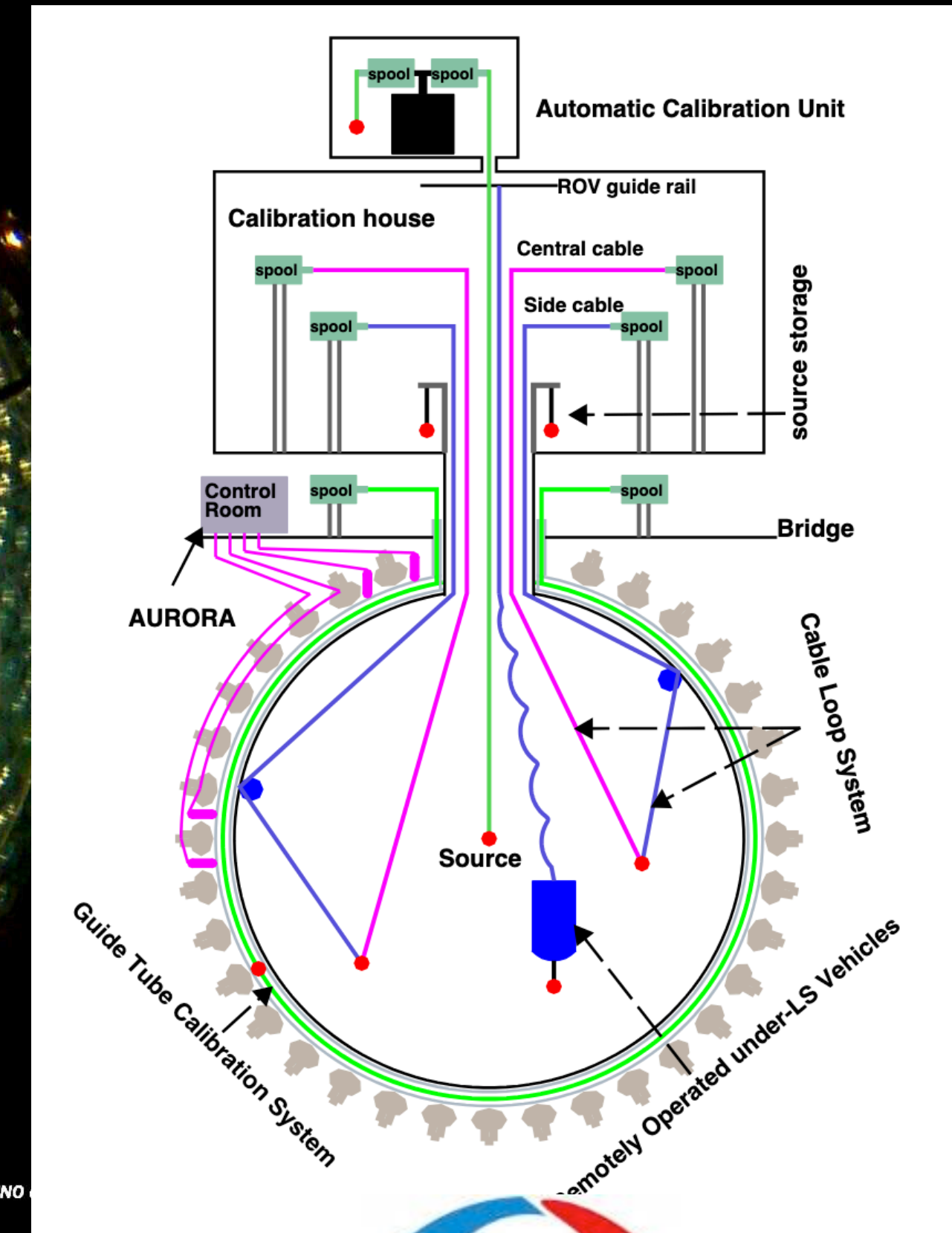
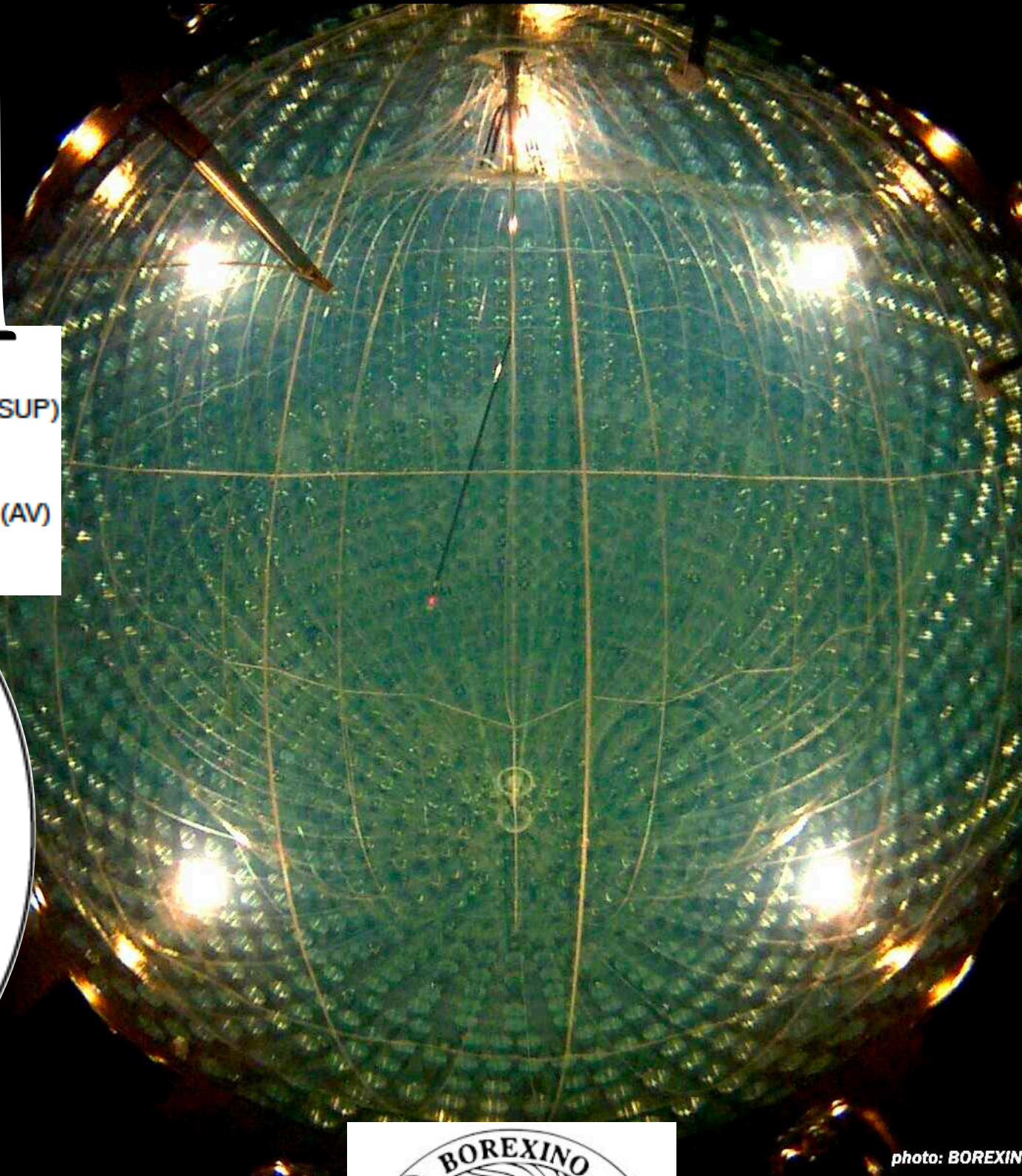
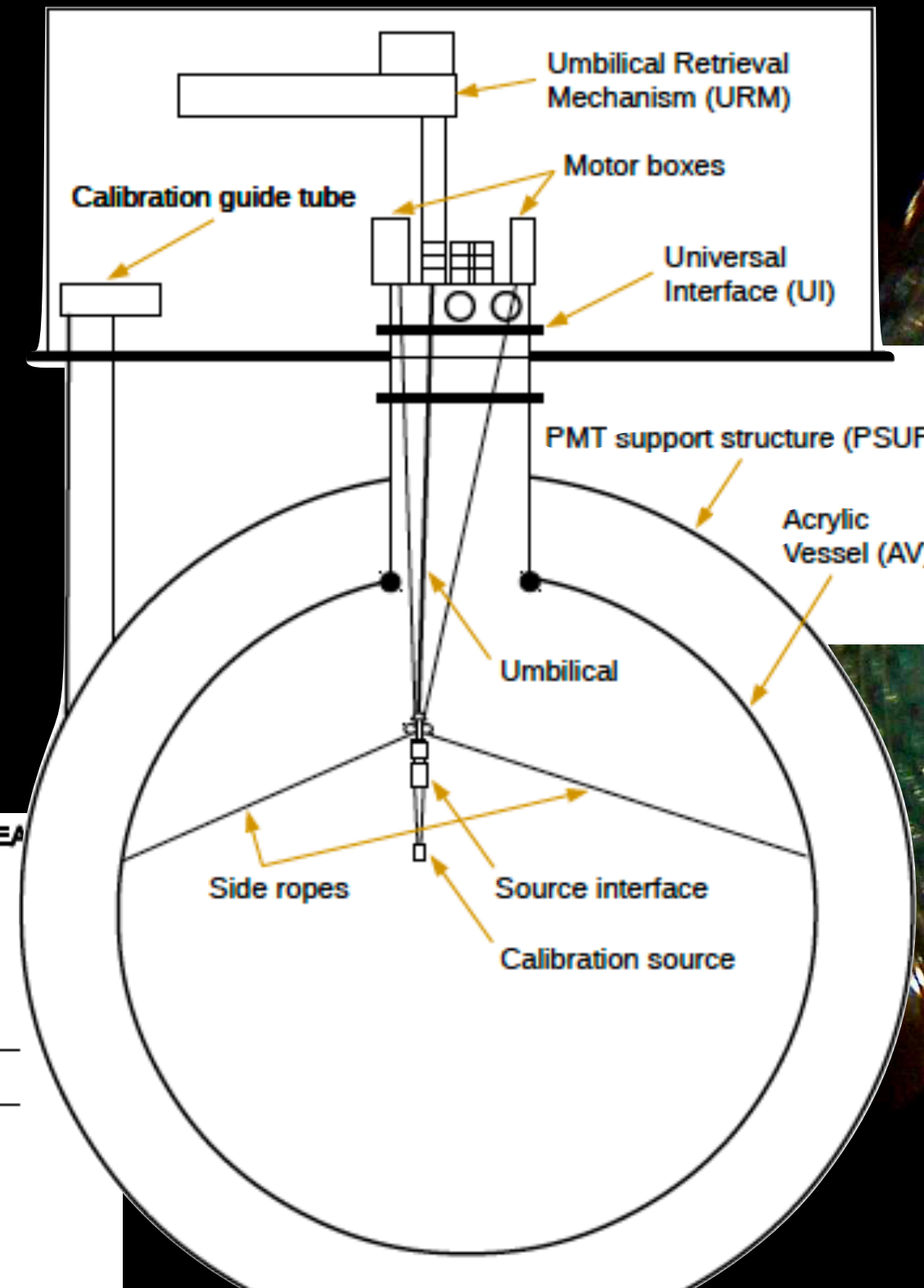
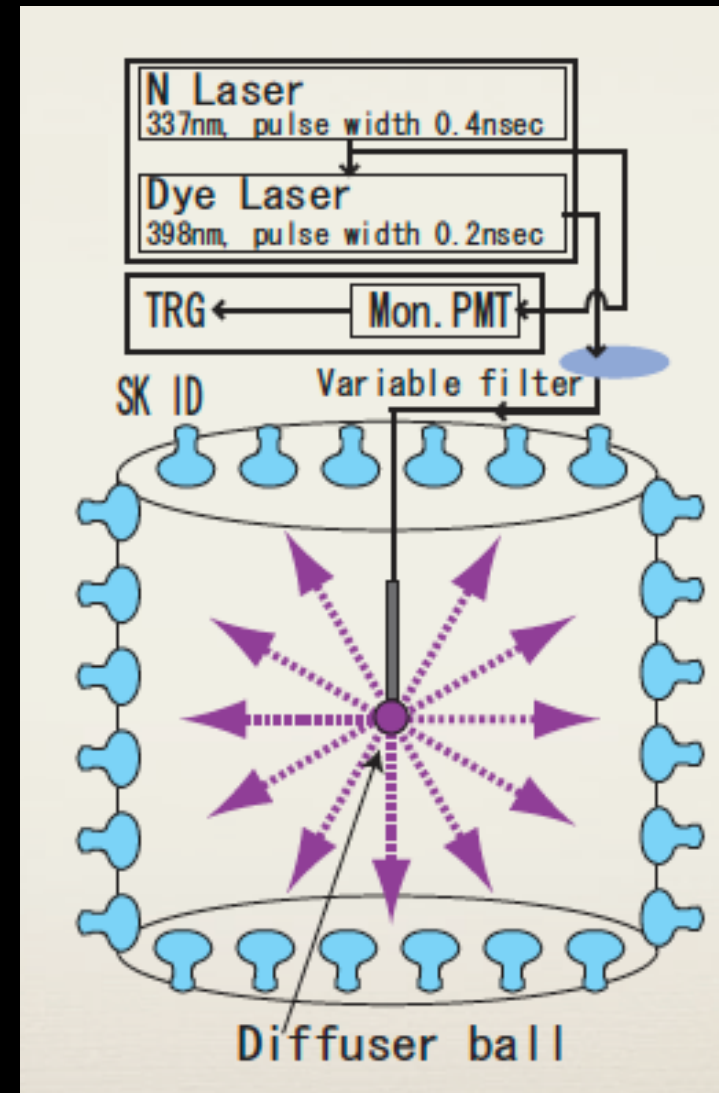
KamLAND/KL-Zen: θ_{12} , Δm_{12}^2 , geo, NLDBD, ...



- Low-energy neutrinos:** Access to the low-energy solar neutrino and geo-neutrinos.
- Oscillations:** Precise oscillation measurements, including θ_{13} which sets the stage for the global δ_{CP} program.
- Neutrino-less Double-beta Decay:** World-leading sensitivity to neutrino-less double-beta decay and lepton number violation.



CALIBRATABLE DETECTORS



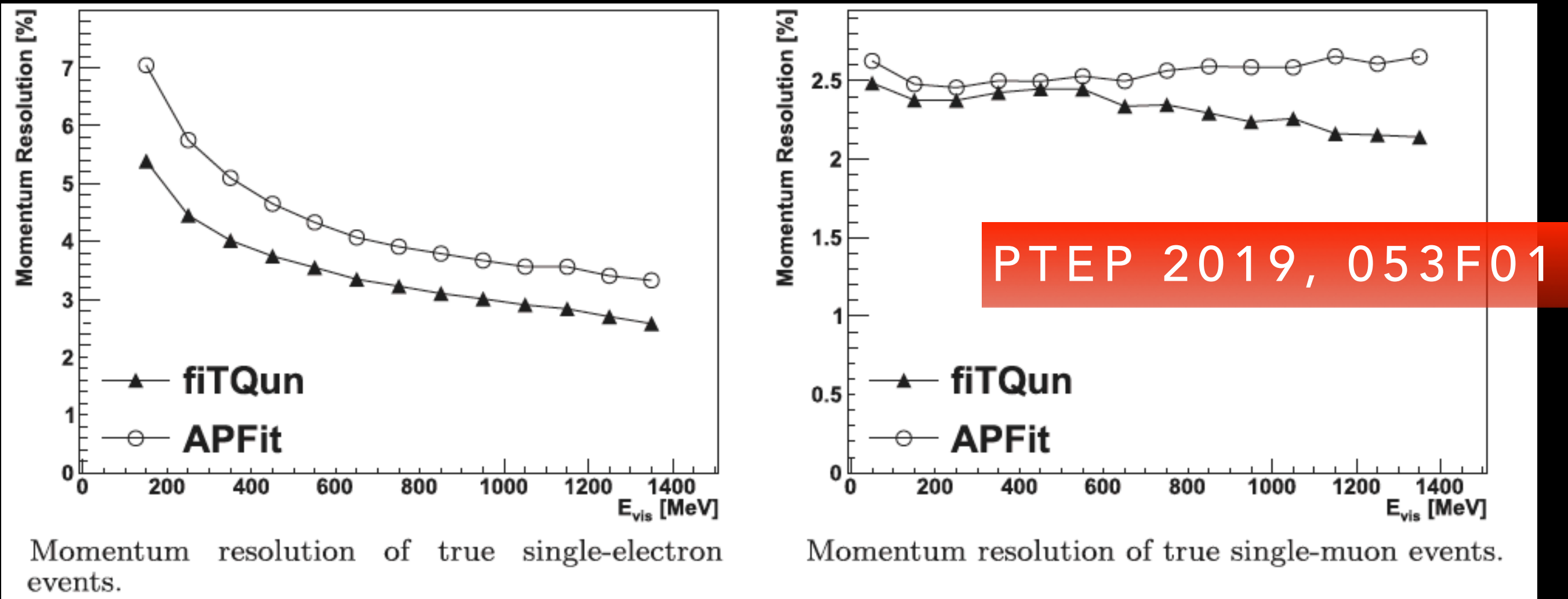
CURRENT LIMITATIONS



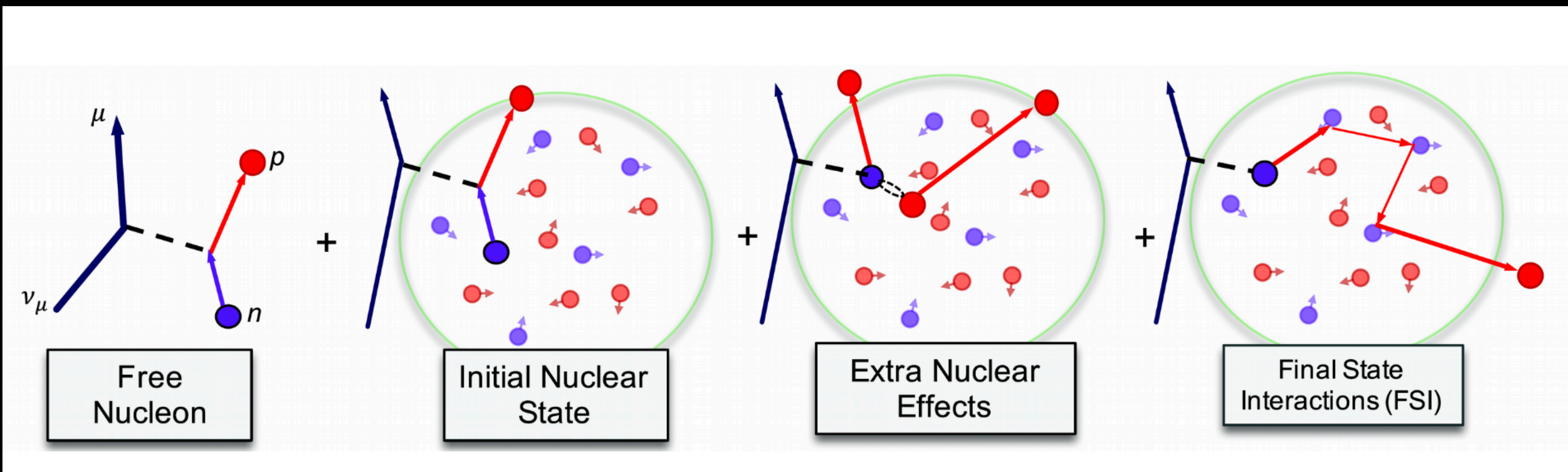
- Single tech experiments

TYPE/ENERGY	LOW ENERGY	HIGH ENERGY
CHERENKOV	LOW LIGHT YIELD. LIMITED REACH (3.5 MEV)	NOT SENSITIVE TO HADRONS OTHER THAN PIONS
SCINTILLATOR	LIMITED EVENT INFO SOME BACKGROUNDS STILL HARD TO BEAT	RECONSTRUCTION OF COMPLEX TOPOLOGIES LARGE MASS IS HARD

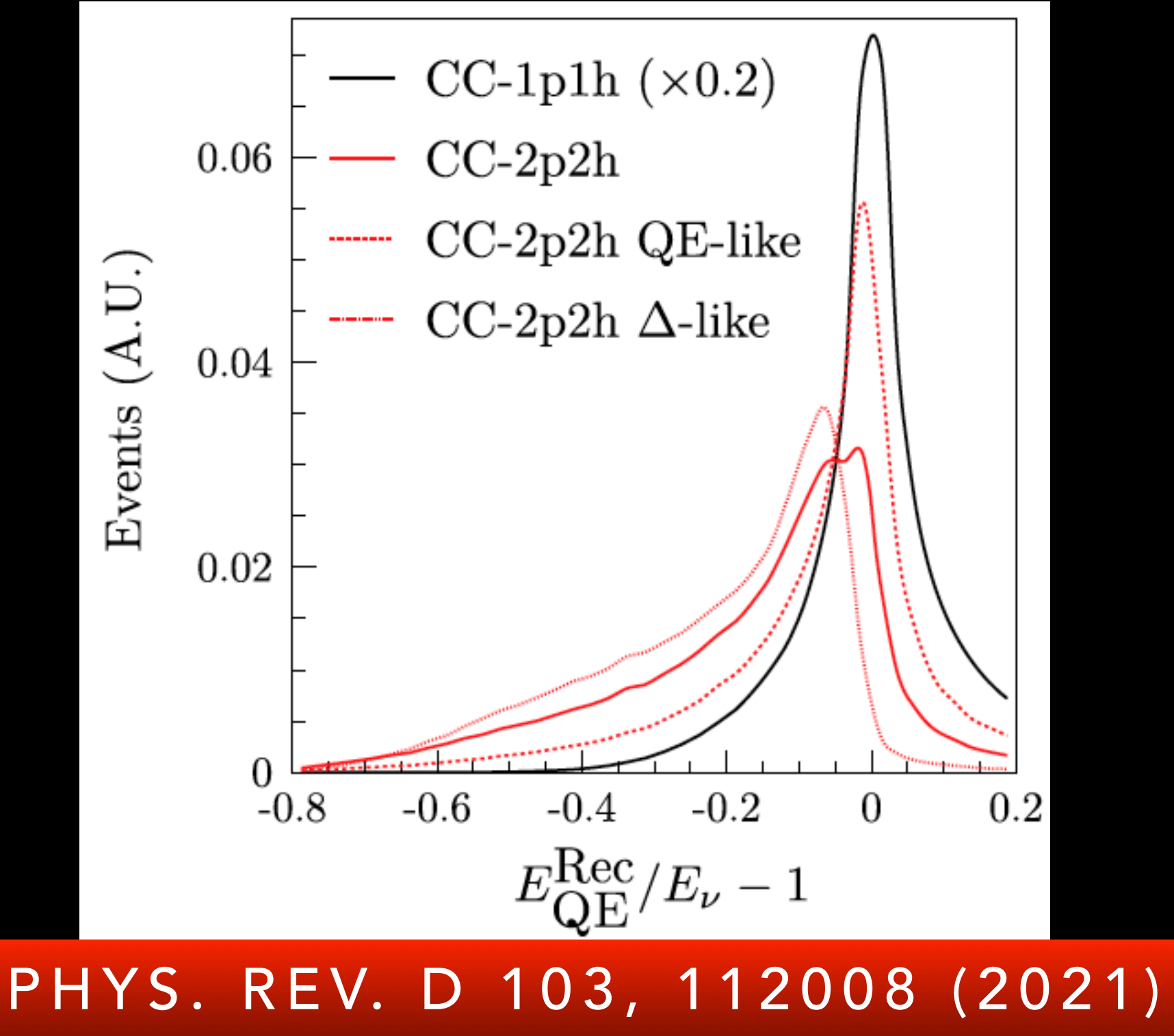
- Very good detectors for HE leptons



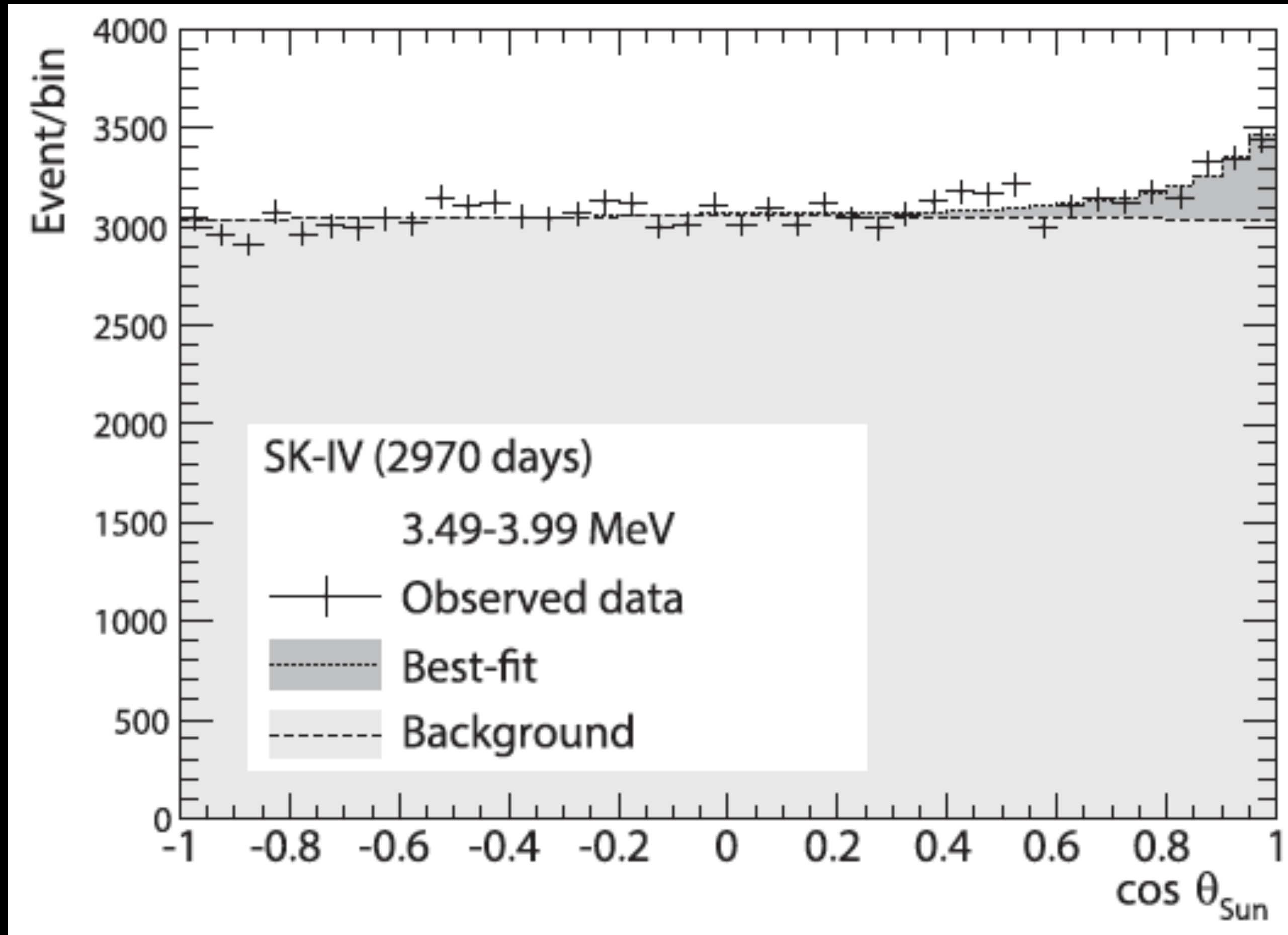
- But $E_\nu \neq E_{lepton}$



Final states involving hadrons (other than pions...) are hard for water Cherenkov detectors



NEED MORE INFORMATION TO RESOLVE COMPLEX TOPOLOGIES



- Great SK results in solar neutrinos, due to huge statistics
- Lowest threshold: 3.5 MeV
- Backgrounds rise dramatically below 4 MeV

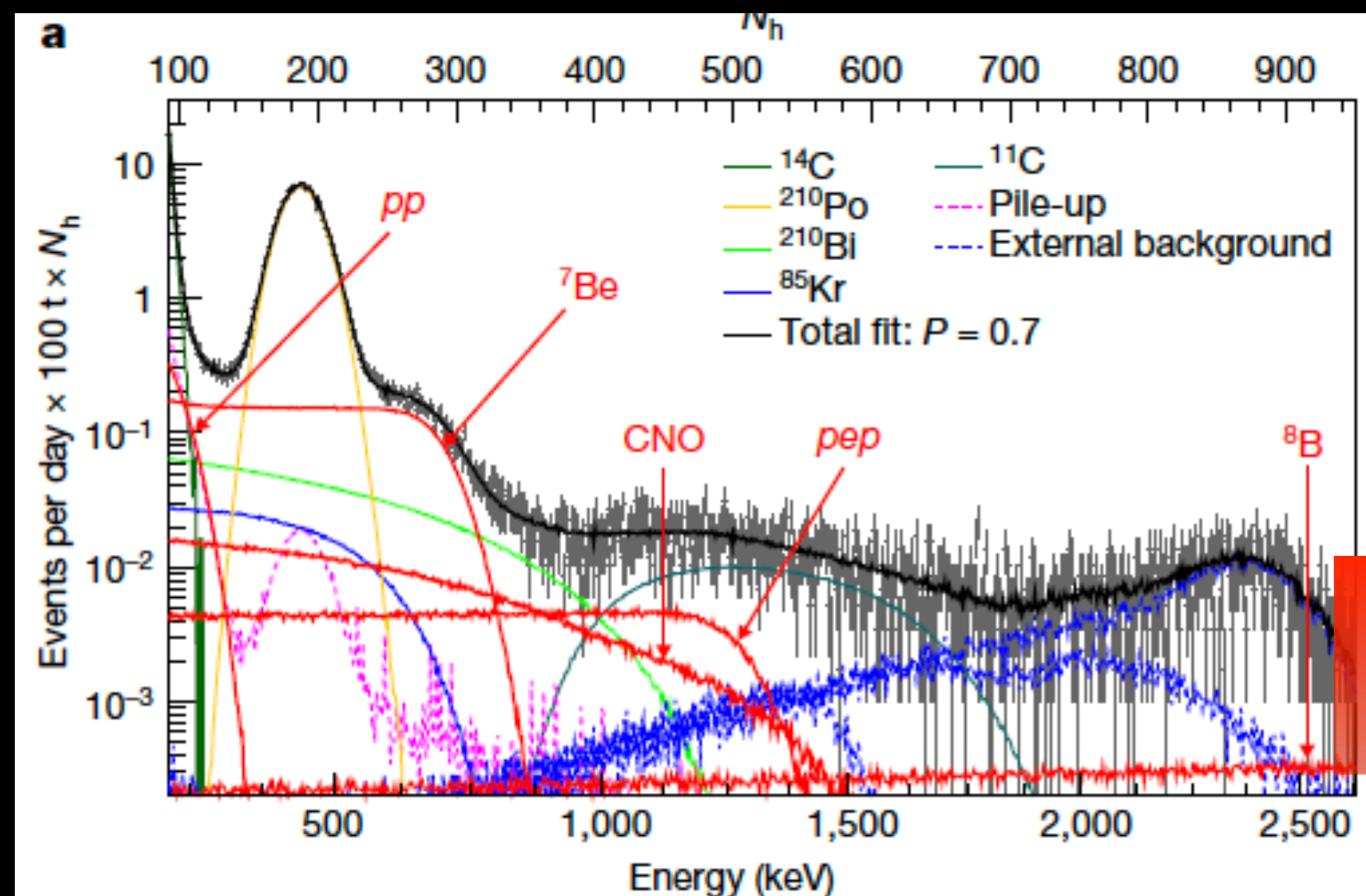
PHYS.REV.LETT 132, 241803 (2024)

DIRECTIONALITY NOT ENOUGH WHEN BACKGROUNDS TOO HIGH
NEED CLEANER MATERIALS

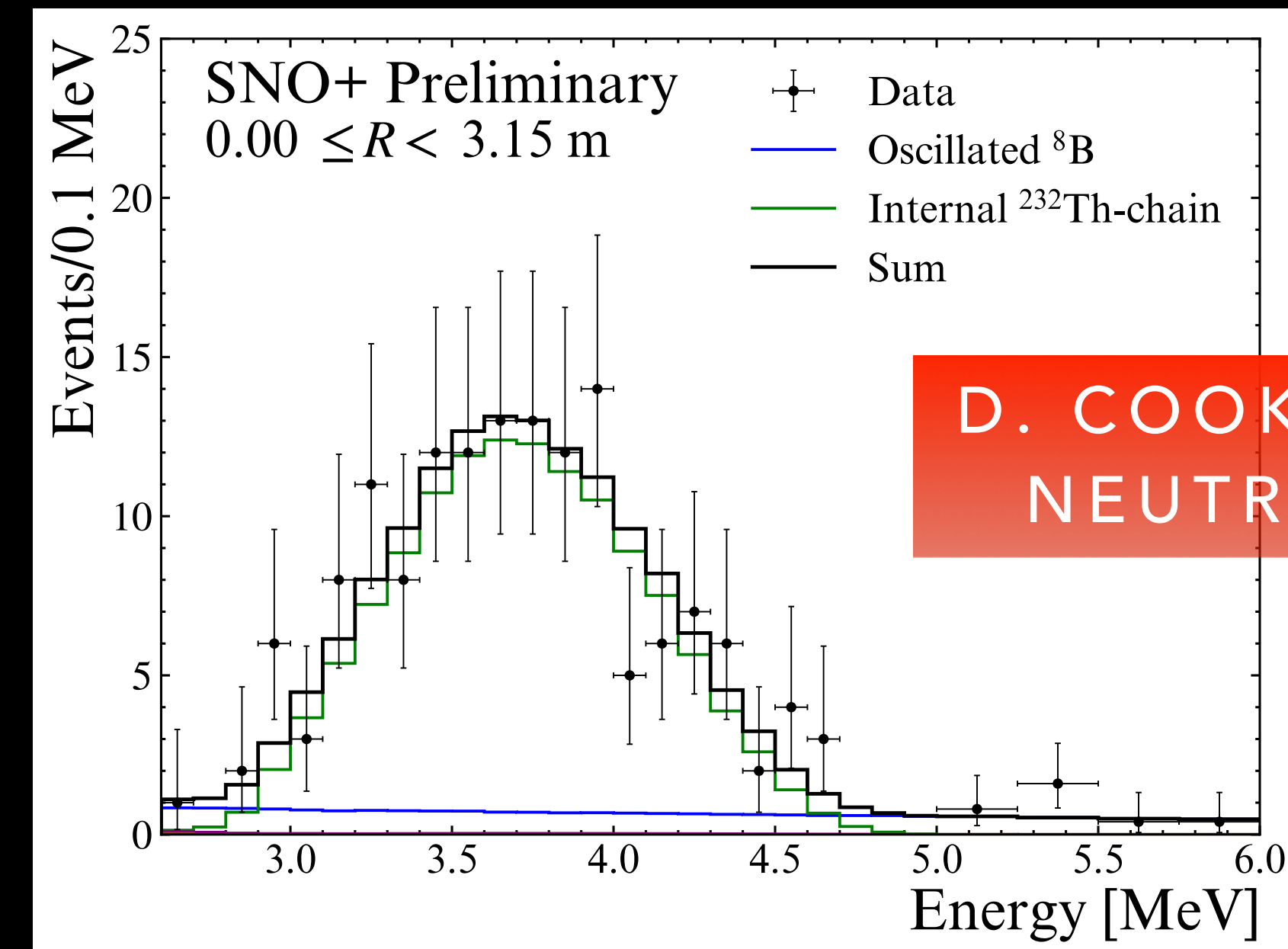
SCINTILLATOR, SOLAR



- Borexino, low energy
 - pioneering measurements using T control and Bi210 constraint
 - pep: +16% - 18%
 - CNO: +18% - 12%
- SNO+, ^8B
 - good prospects for 2.5 MeV bin, pushing into transition region
 - 3.0 MeV is not impossible but hard



NATURE V. 562,
P. 505 (2018)

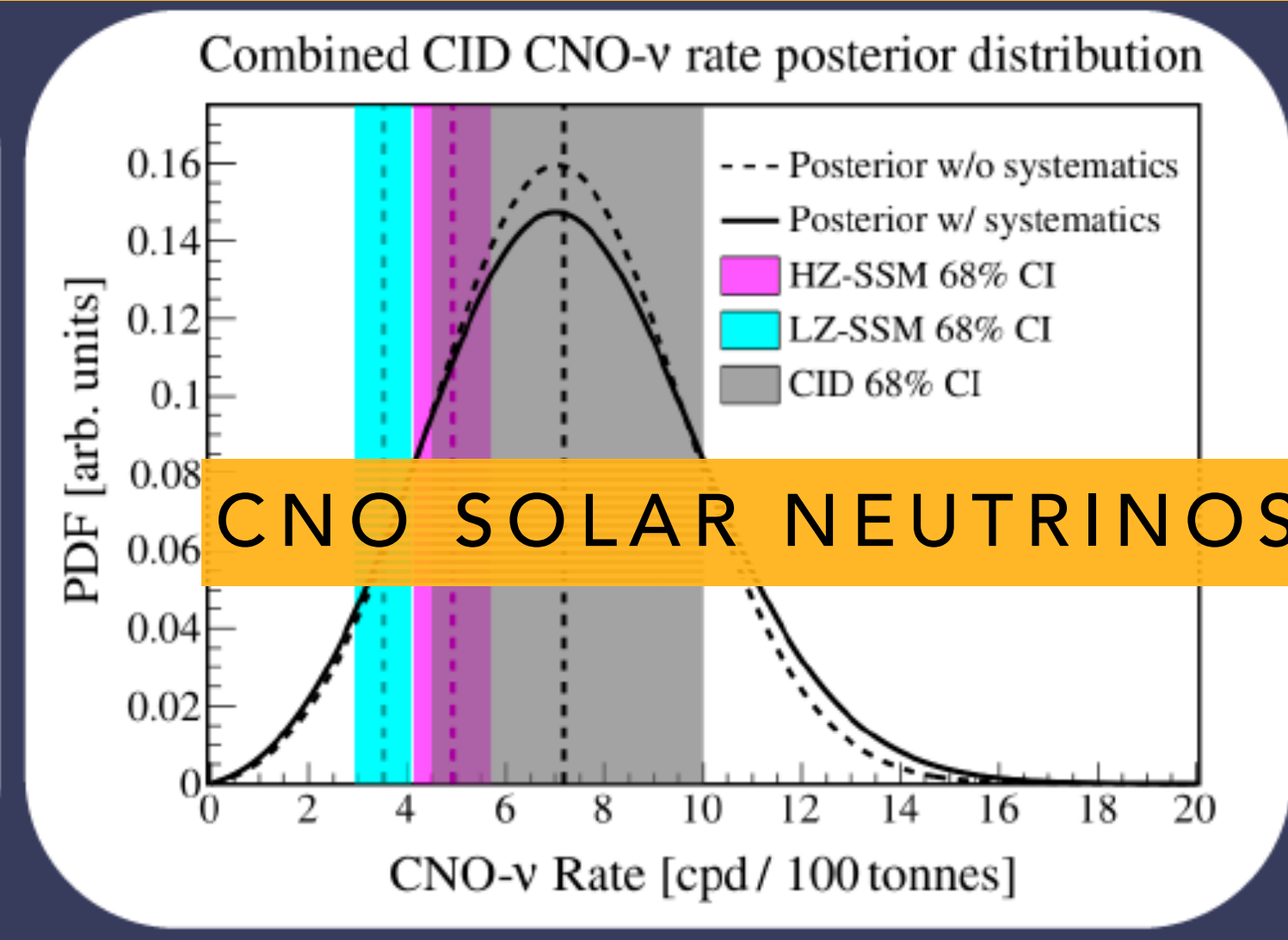
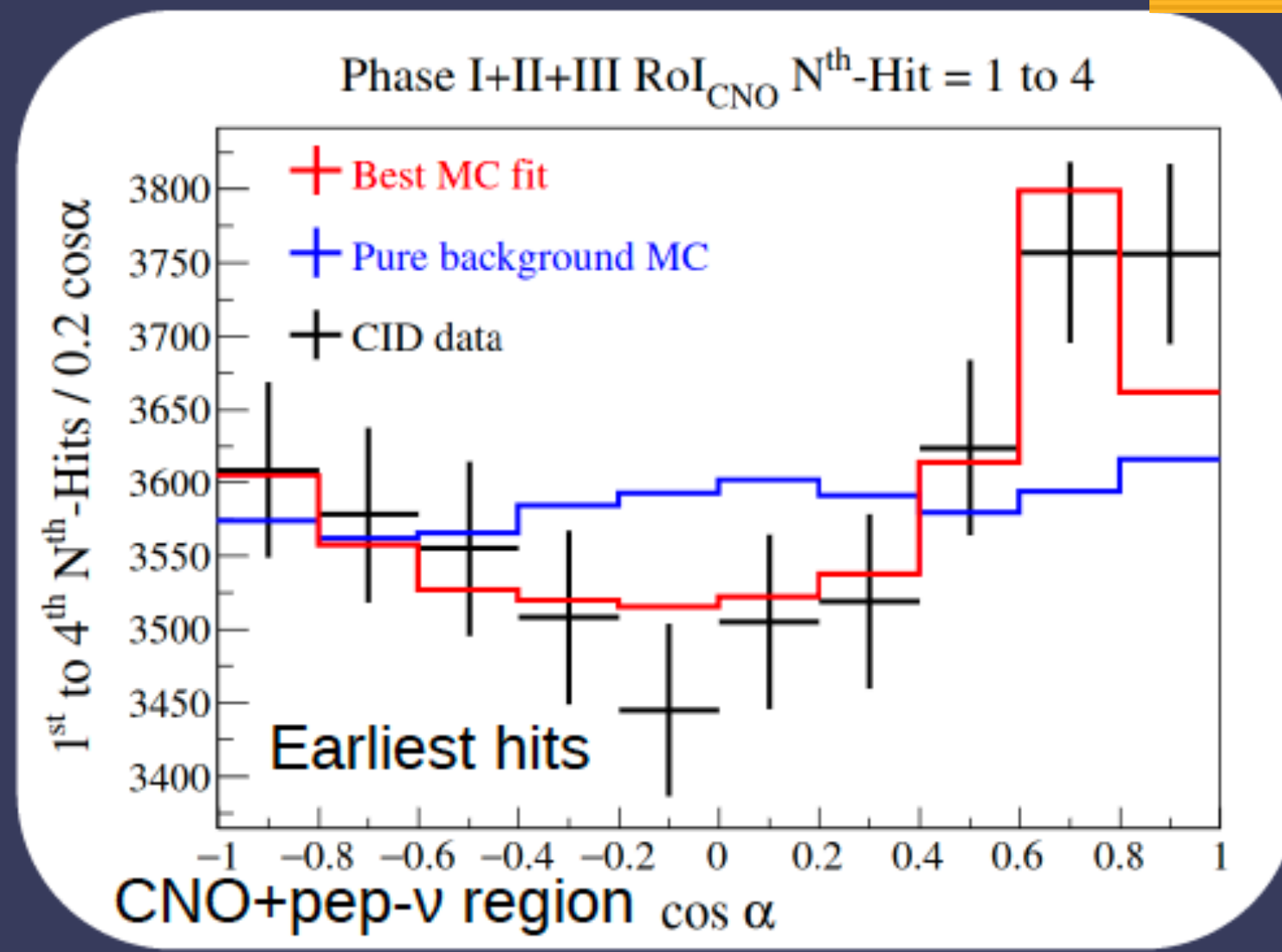


D. COOKMAN / JM,
NEUTRINO 2024

HIGH BACKGROUNDS, NEED MORE EXPERIMENTAL HANDLES
BETTER DIRECTIONALITY WOULD SURELY HELP

USE EARLIEST HITS IN BOTH CASES

J. MARTYN, T. KROUPOVA



CNO SOLAR NEUTRINOS

Borexino

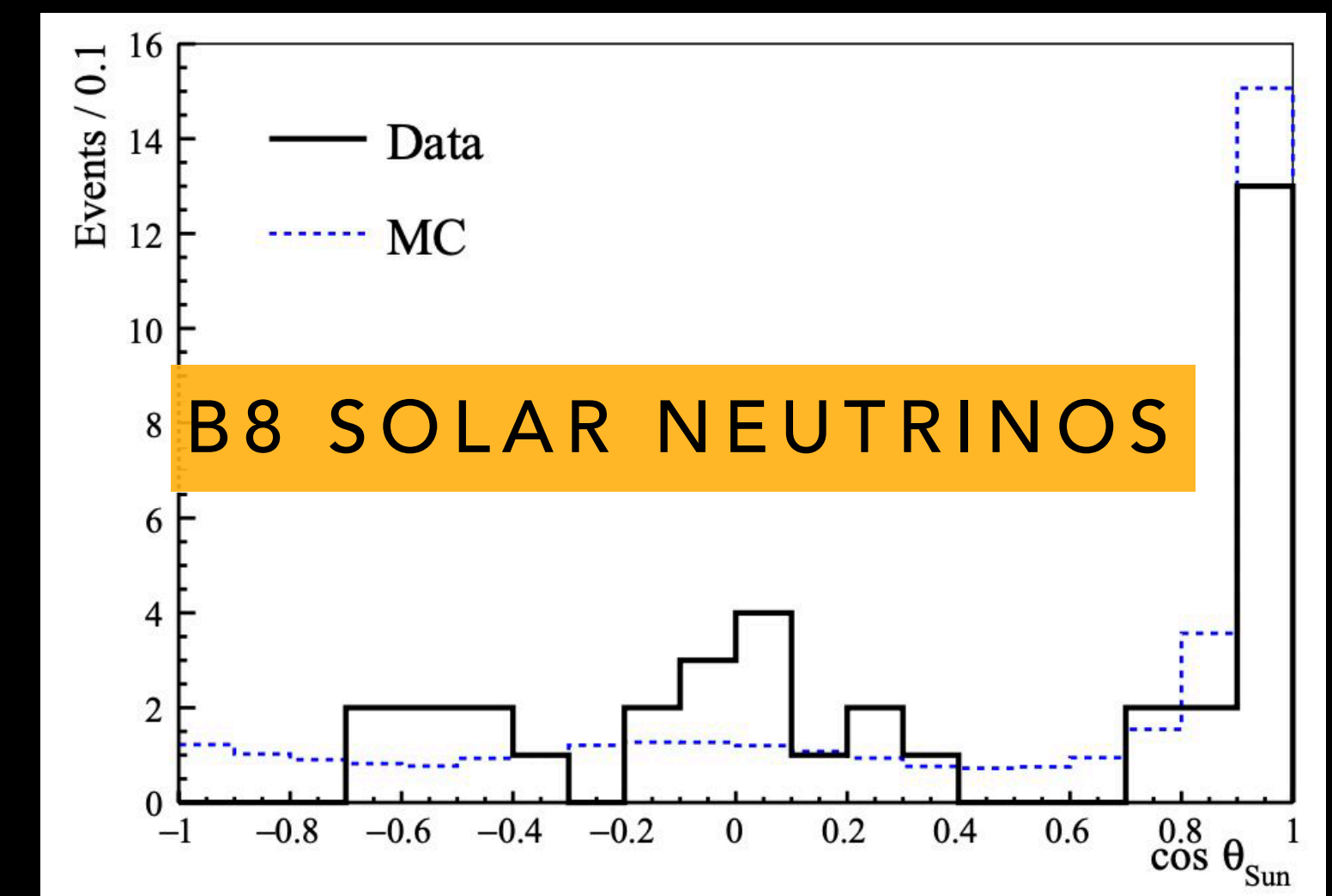
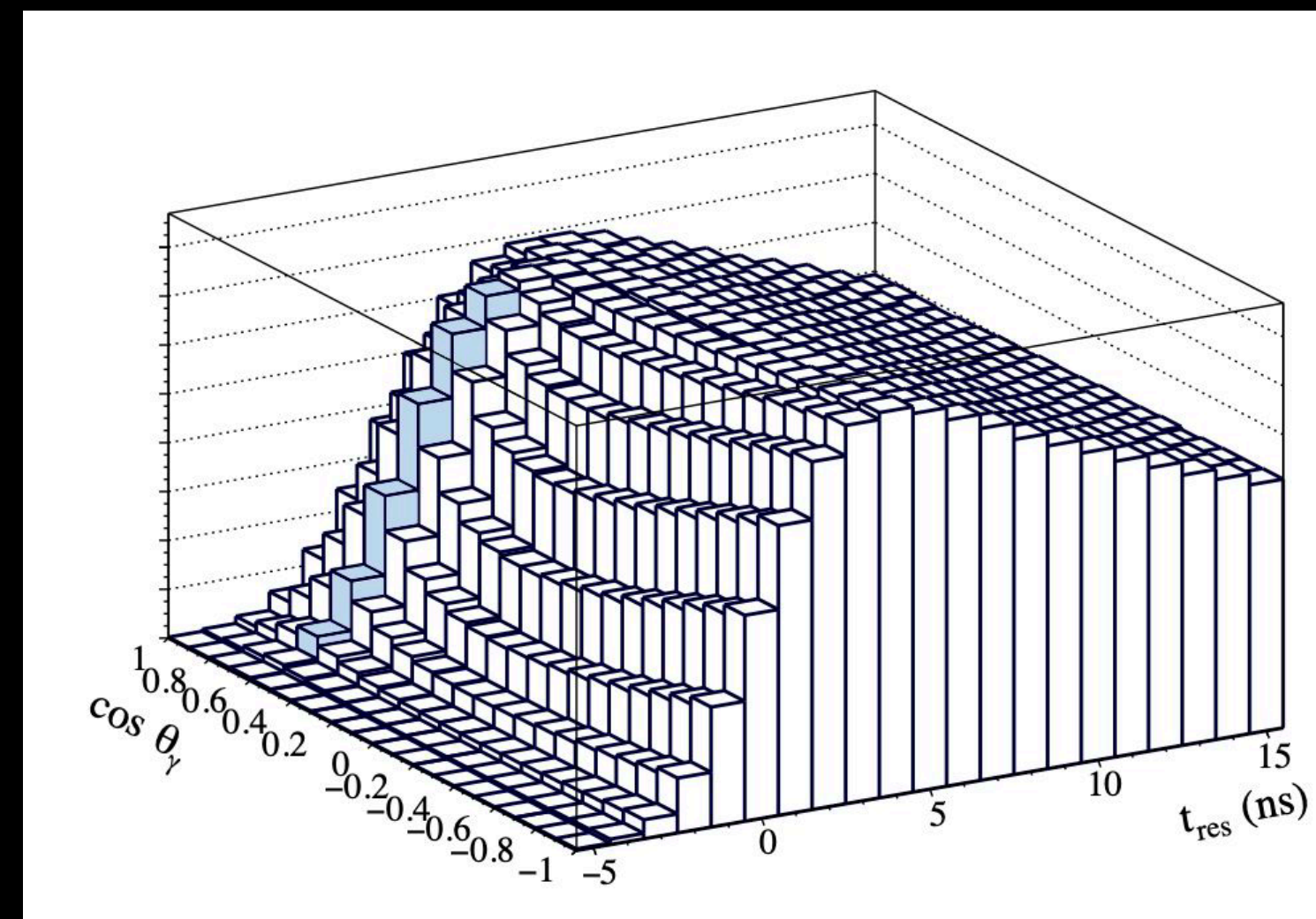
Ch. photons cause “drive” in position reconstruction

Statistically observe excess in the direction of the Sun

Improve CNO measurement

• SNO+

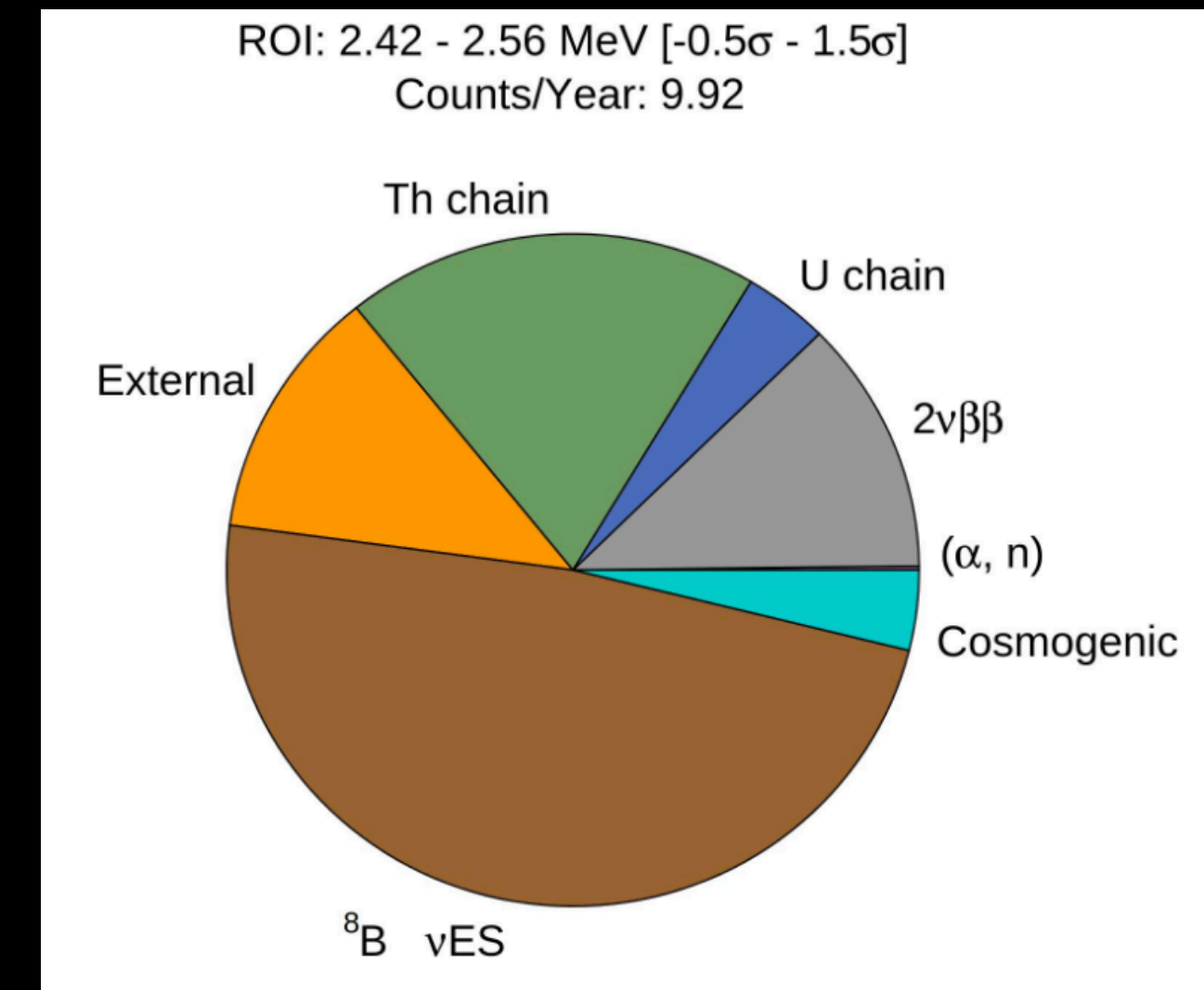
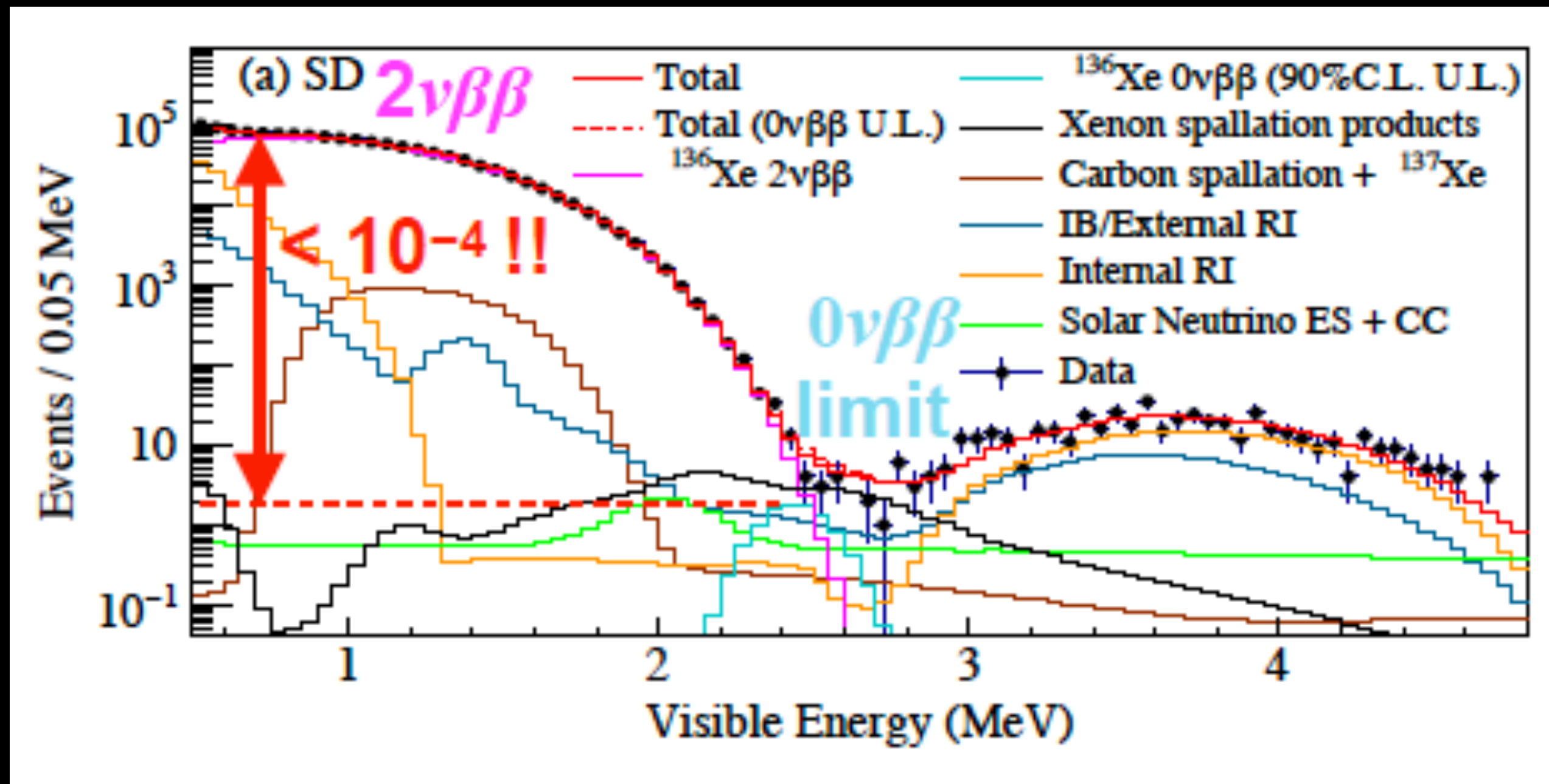
- In partial fill phase, low PPO concentration 0.6 g/l
- Slower scintillation
- **First event-by event reconstruction!**



B8 SOLAR NEUTRINOS

- KamLAND-Zen, ^{136}Xe
 - World-leading DBD sensitivity
 - Limiting background is Xe cosmogenics
 - K2-Zen can improve, but not by much

- SNO+, ^{130}Te
 - Limiting background will be
 - 0.5%: solar neutrinos
 - 1.5%: $2\nu\beta\beta$

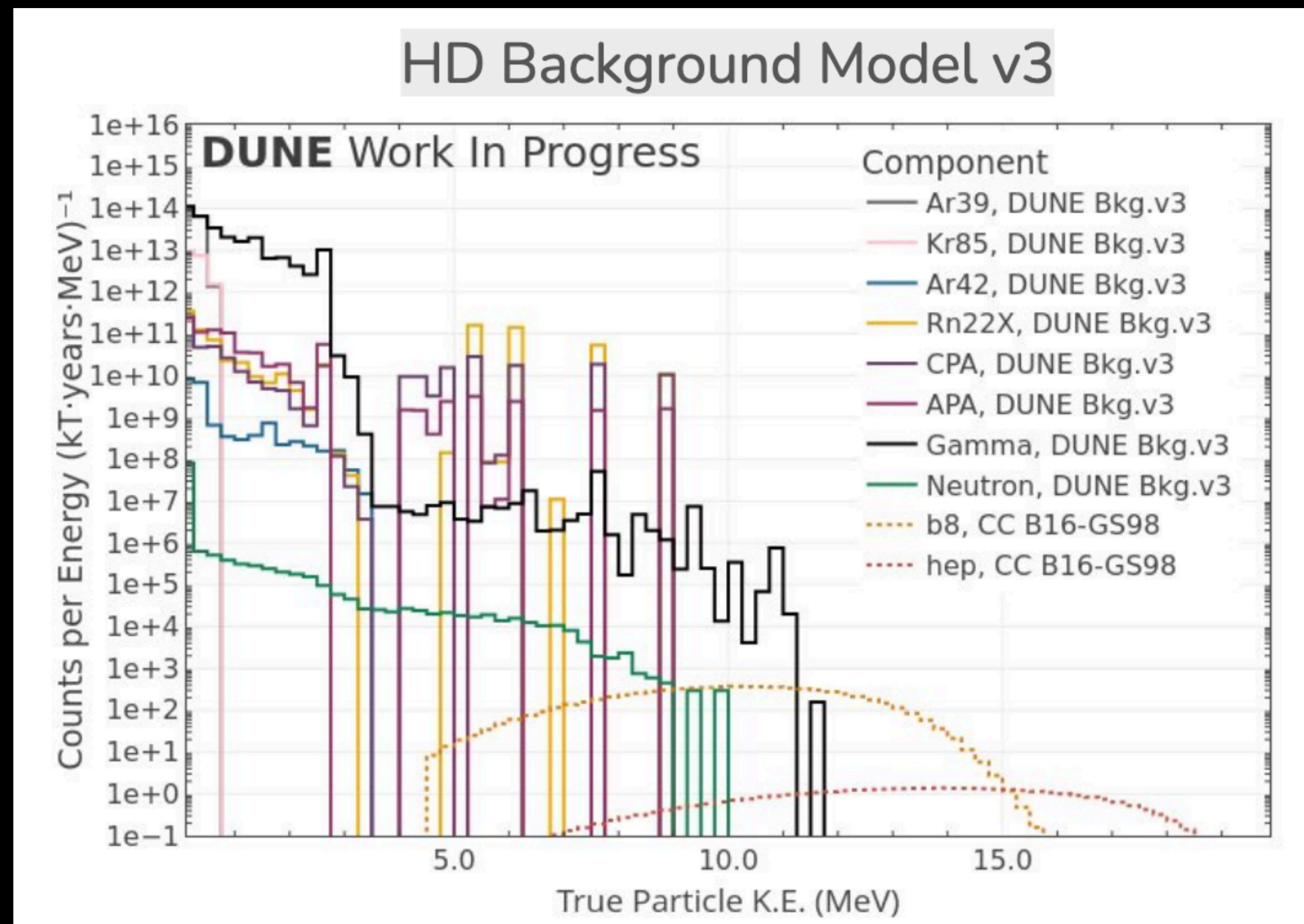


HIGH BACKGROUNDS, NEED MORE EXPERIMENTAL HANDLES
BETTER DIRECTIONALITY WOULD SURELY HELP
BETTER TIMING CAN HELP FOR MULTI-SITE REJECTION

LIQUID ARGON, LOW ENERGIES



- Solar neutrinos
 - main reaction is CC, not ES
 - that's nice in itself, can combine with SK/HK ES and make a model-independent measurement of full flux. First time after SNO
 - best detector to measure hep
 - can also see day-night
- Double-beta decay (with Xe doping)
 - Backgrounds are simply too high below 5.0 MeV...



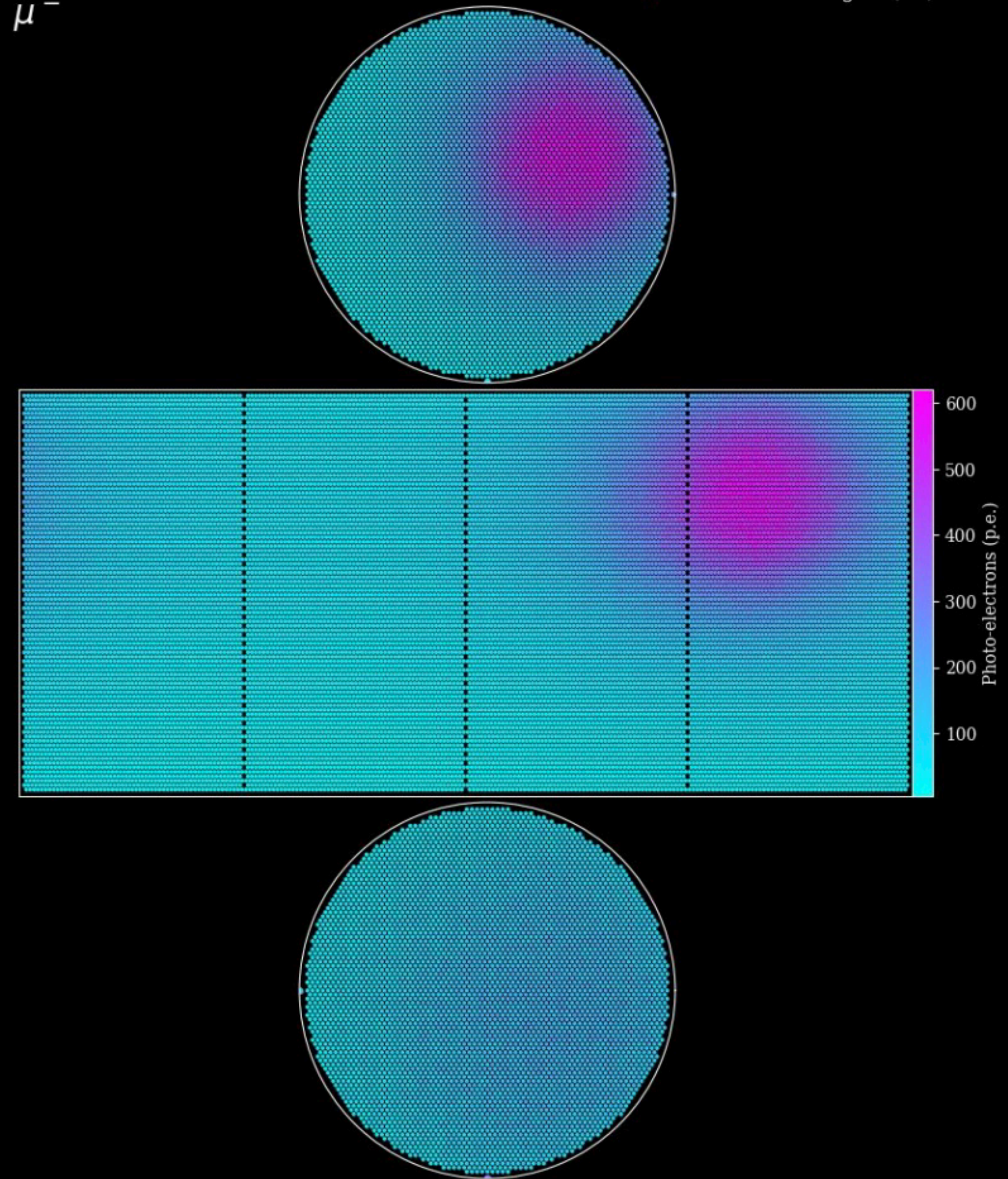
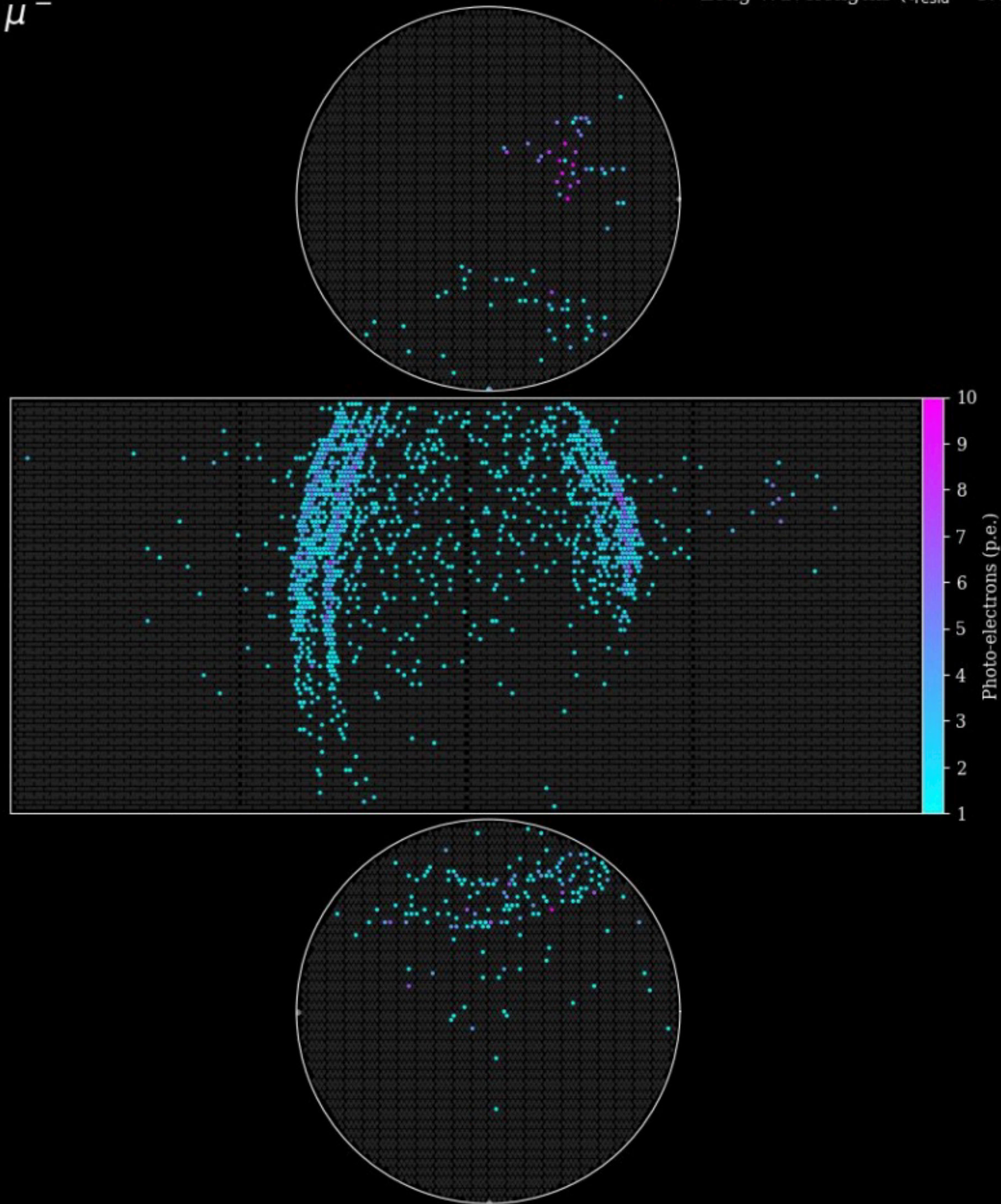
2. OVERVIEW OF HYBRID TECHNOLOGIES

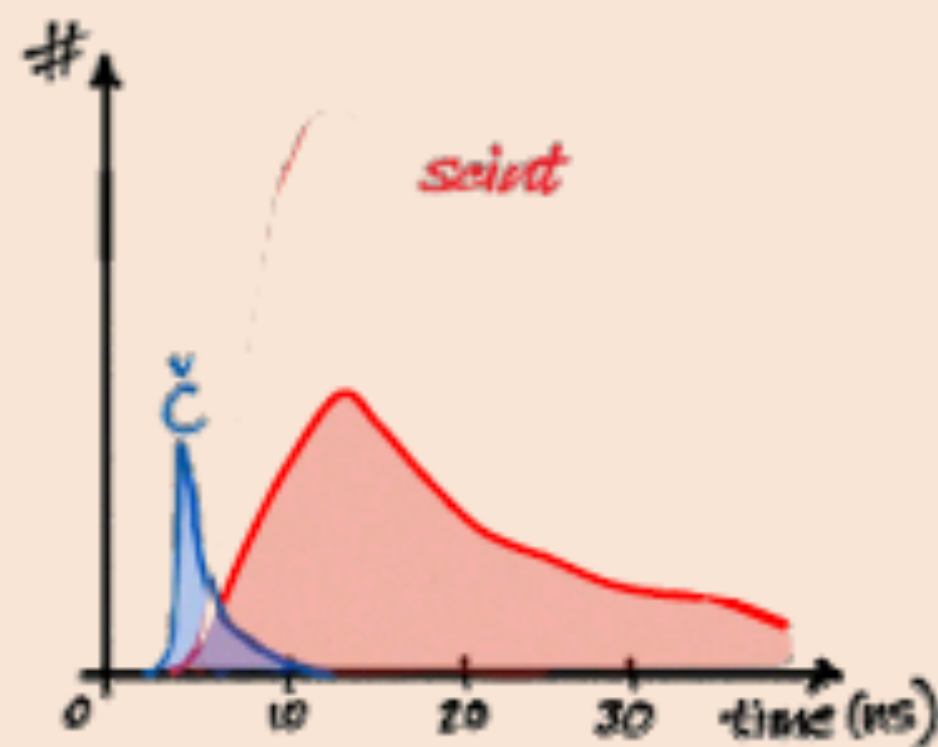
EXAMPLE: 1 GEV MUON

1 GeV
 μ^-

Long Wavelengths ($t_{\text{resid}} < 3.0$ ns) 1 GeV
 μ^-

Short Wavelengths (All)

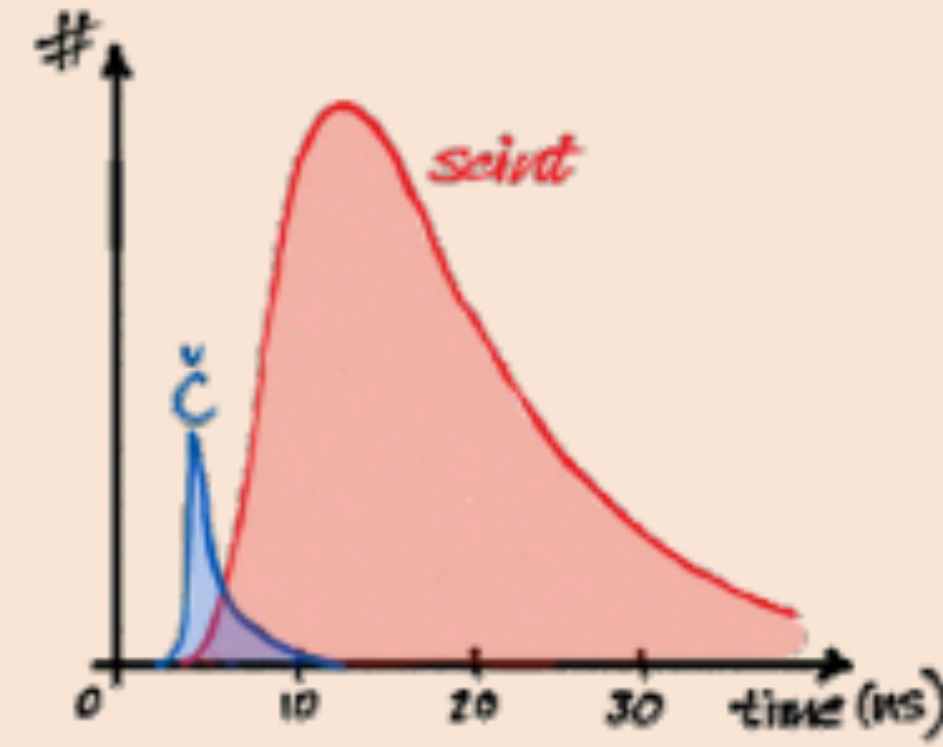




Ratio

Reduce the amount of scintillation light produced, so Cherenkov photons are a larger fraction of the total.

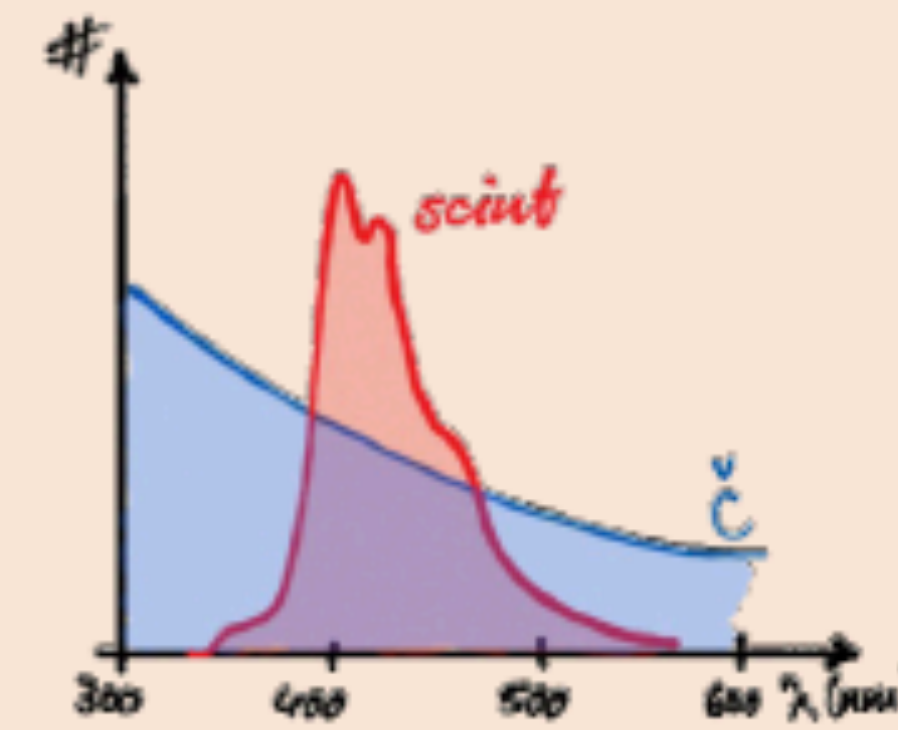
Any sample of photons is relatively Cherenkov-rich.



Timing

Cherenkov light is produced promptly, while scintillator rise times are typically on the order of nanoseconds.

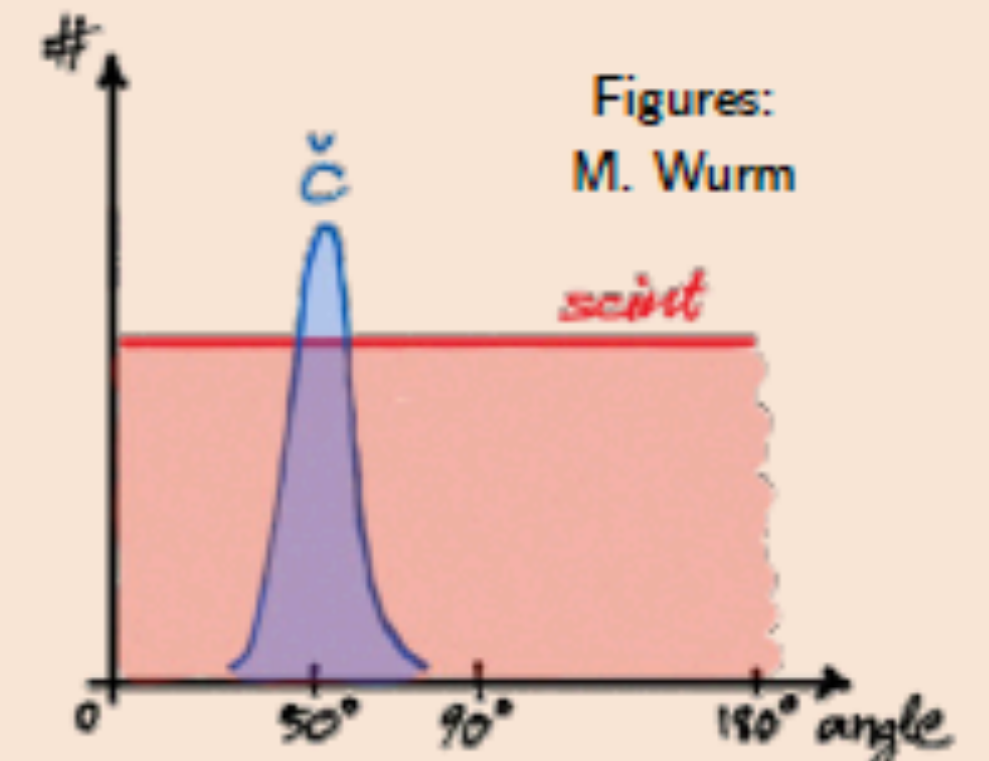
Early photons are Cherenkov-rich.



Wavelength

Scintillation light is emitted over a frequency band, while the Cherenkov spectrum is steeply falling.

Photons outside the scintillation band are Cherenkov-rich.



Angle

Cherenkov light is emitted at a specific angle with respect to the particle track, while scintillation light is isotropic.

Photons in the Cherenkov cone are Cherenkov-rich.

Figures:
M. Wurm

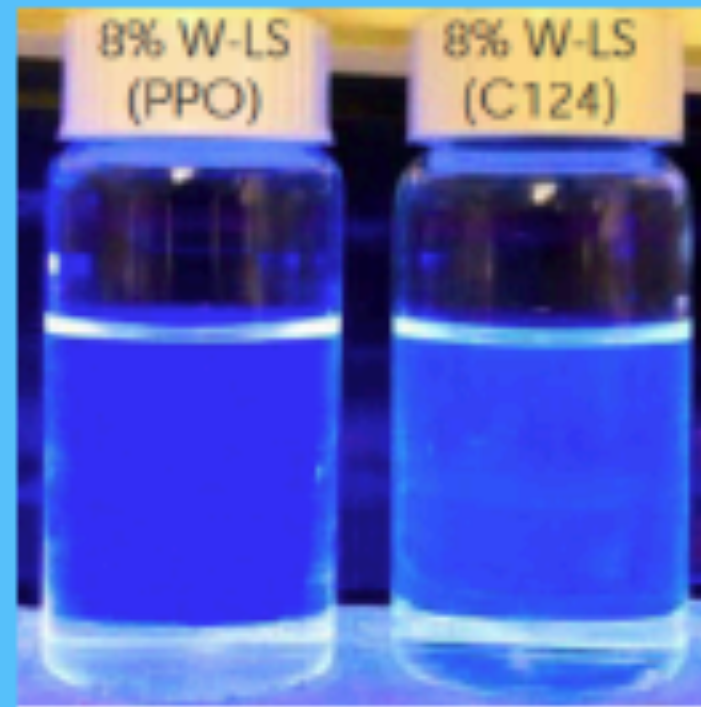
OVERVIEW OF R&D PATHS

A. MASTBAUM

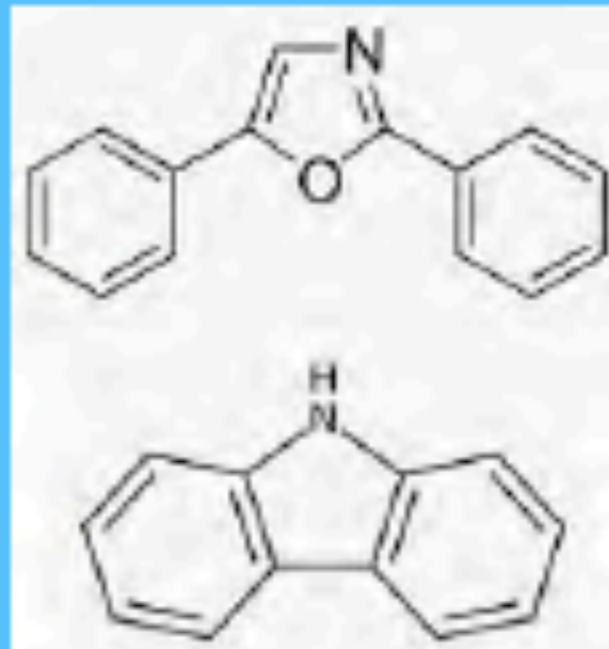


(Wb) SCINTILLATOR

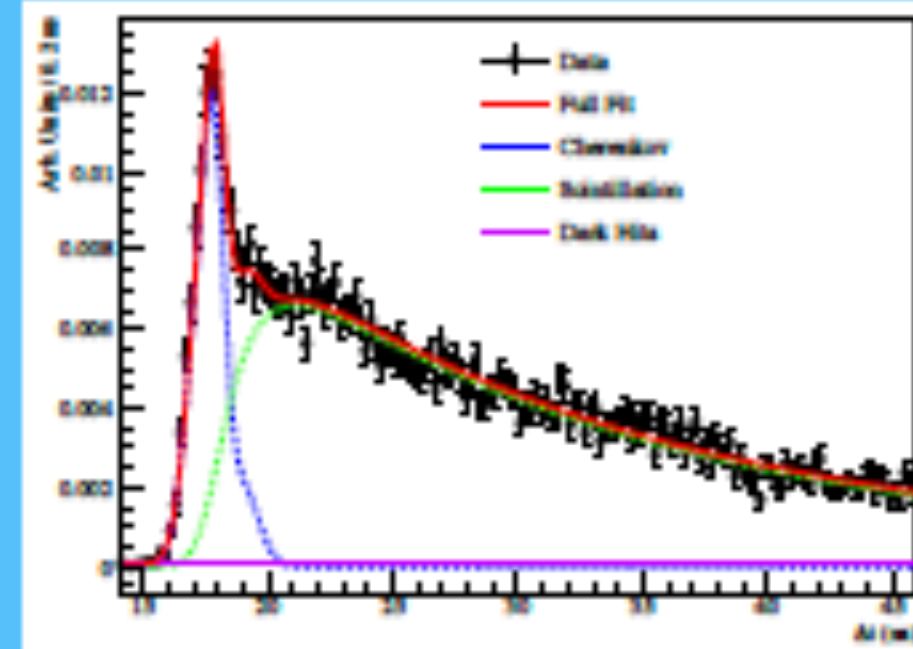
WbLS R&D
(BNL, Mainz)



WbLS tuning
(LBNL)



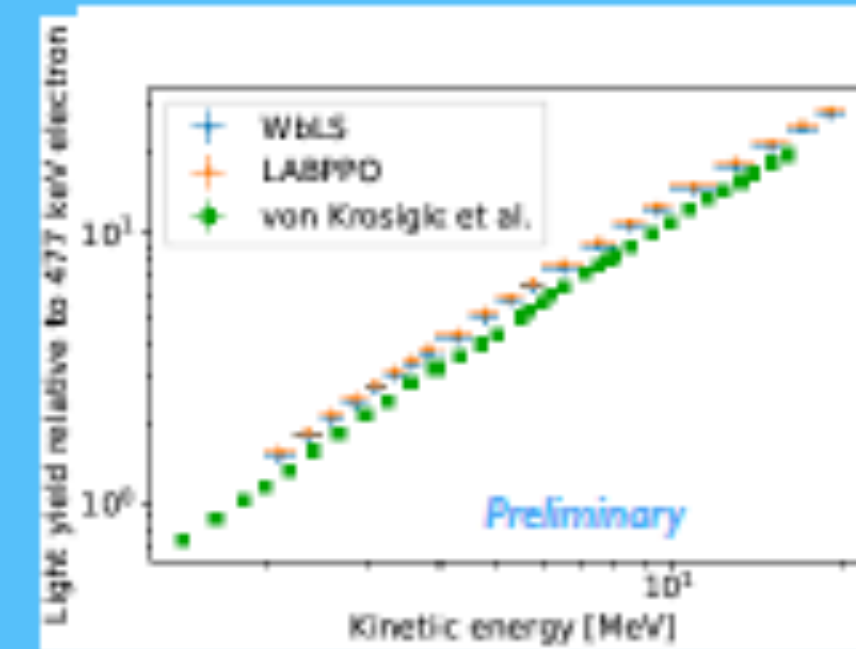
Slow LS
(Oxford, Mainz)



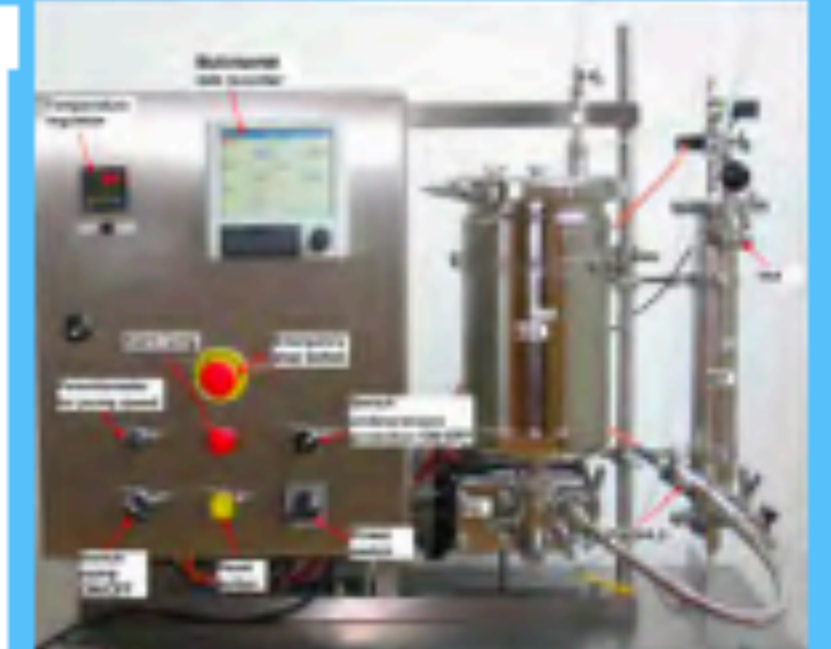
Attenuation
(UC.B, LLNL, Davis)



Hadron LY
(LBNL)

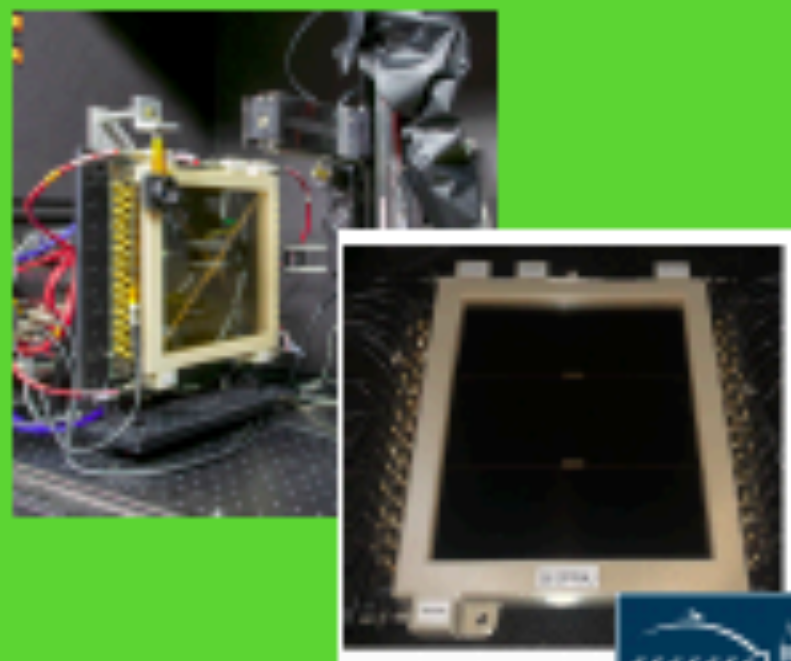


Filtration
(Davis)

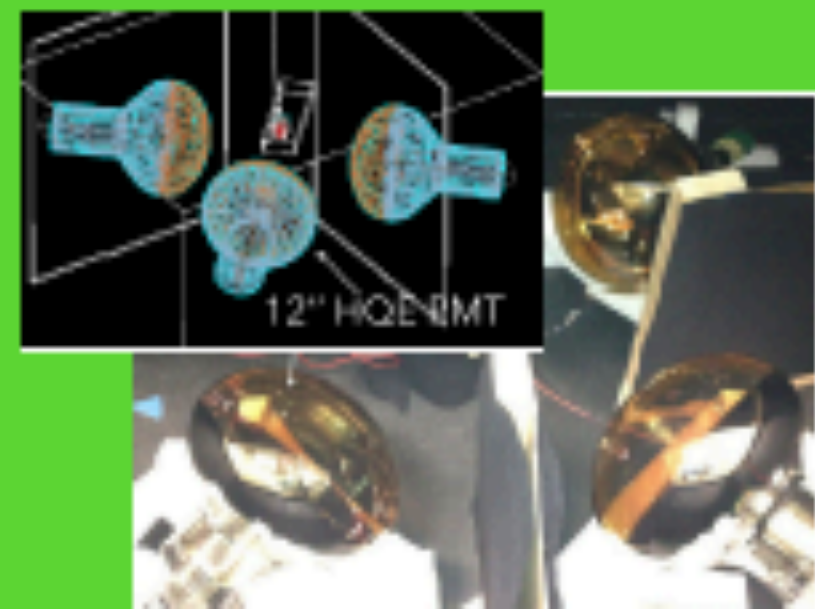


FAST DETECTORS

LAPPD R&D
(Iowa State, LBNL)

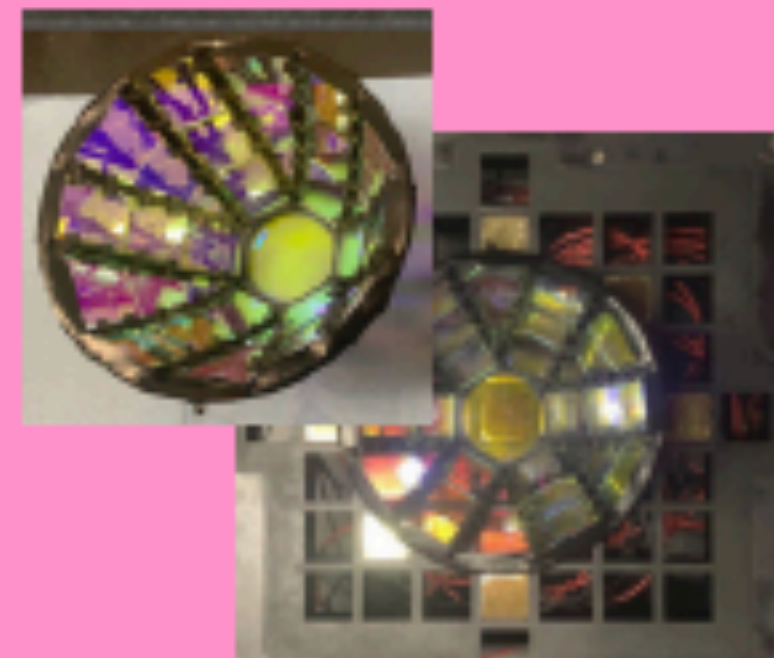


Fast PMTS
(Penn, LBNL)



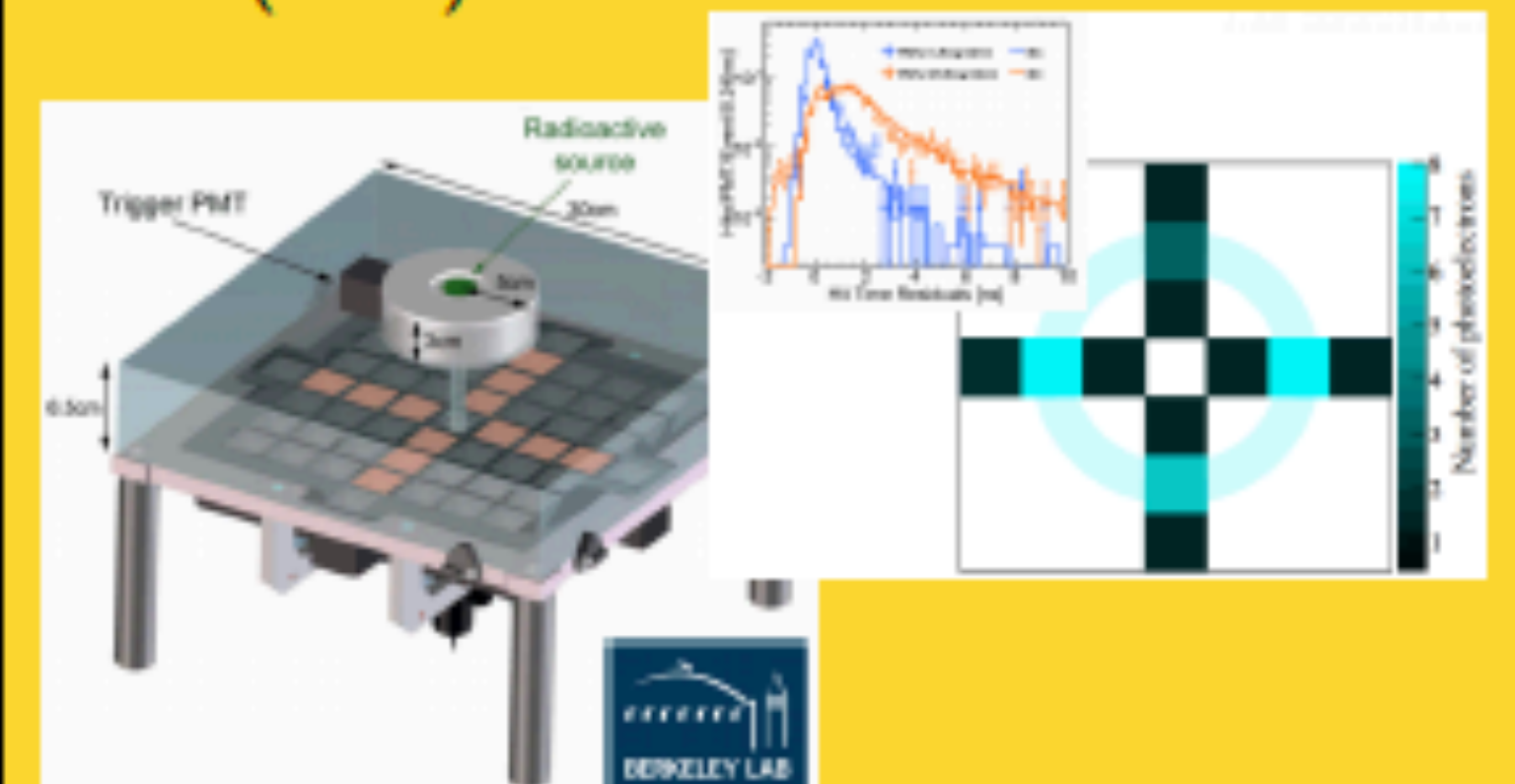
SPECTRAL

Dichroicons
(Penn, LBNL)



INTEGRATED

CHESS
(LBNL)



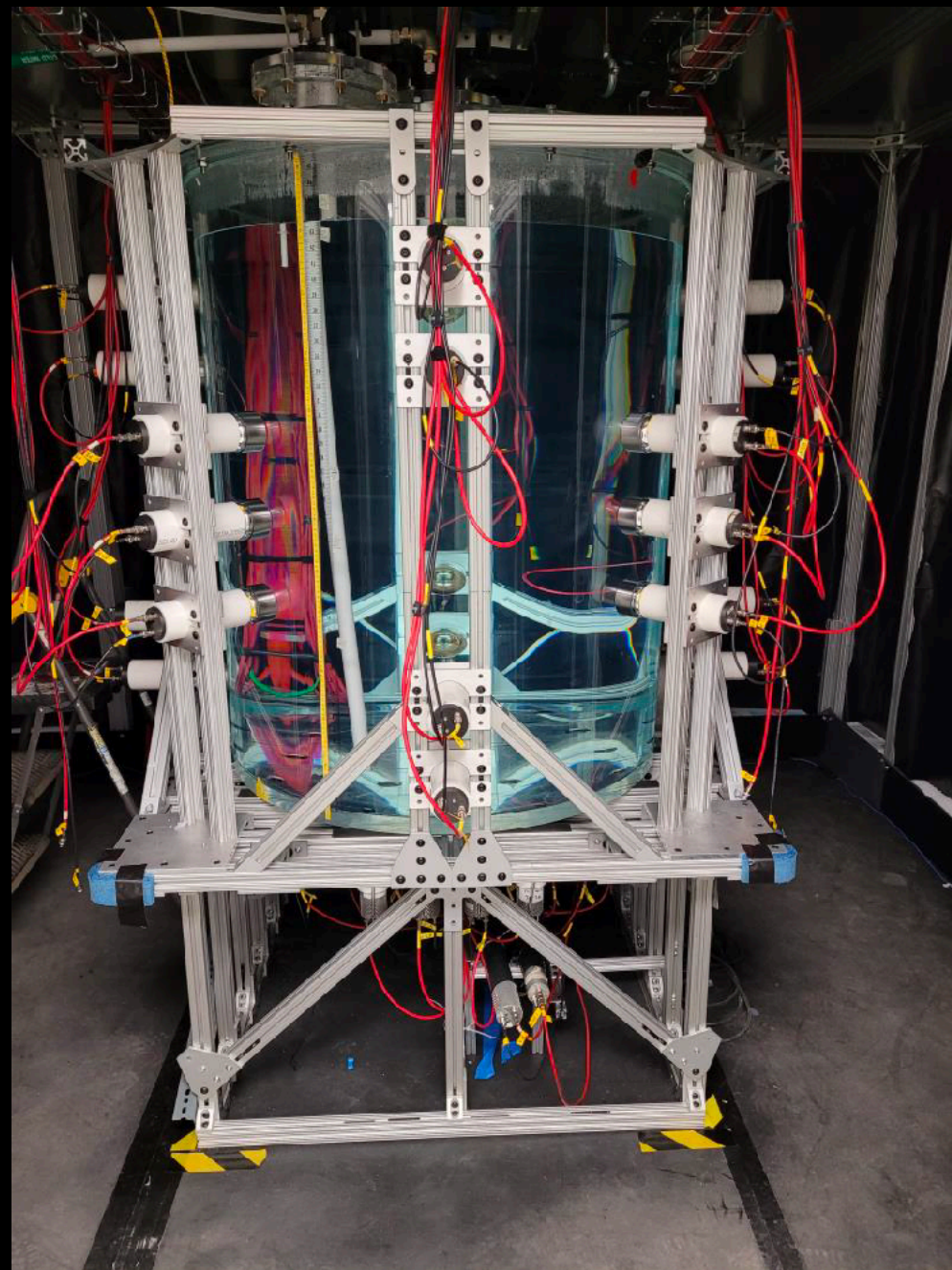
TECHNOLOGY TESTBEDS

BNL 1 TON, 30 TON

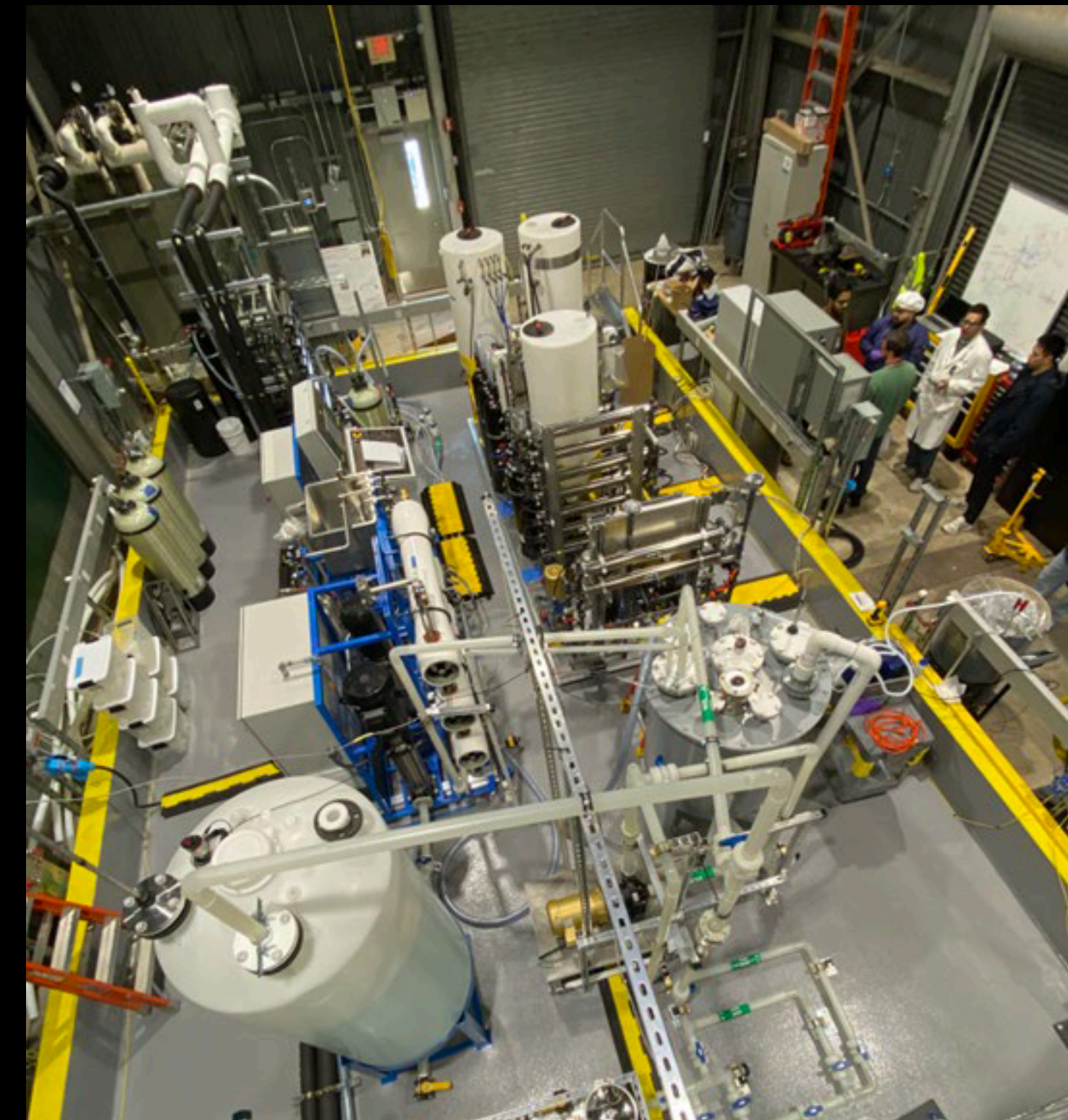
M. YEH, A. BALDONI, R. WANG



- BNL 1 T detector
 - Acrylic tank 1.3m tall, 1m diameter
 - 58 PMTs
 - 30 2" diameter tubes on bottom
 - 28 3" diameter tubes on side
 - 1% WbLS (DIN+PPO)

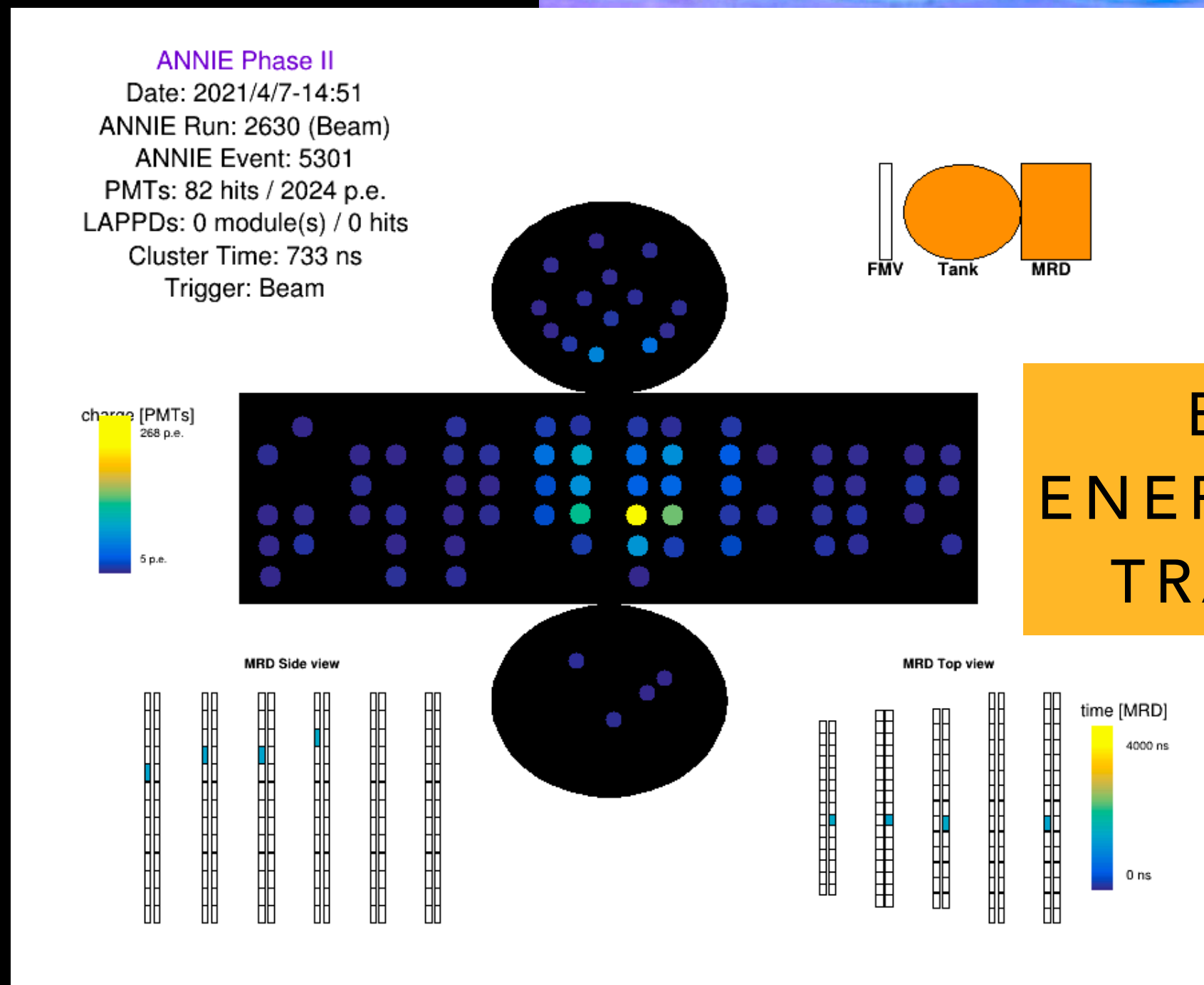
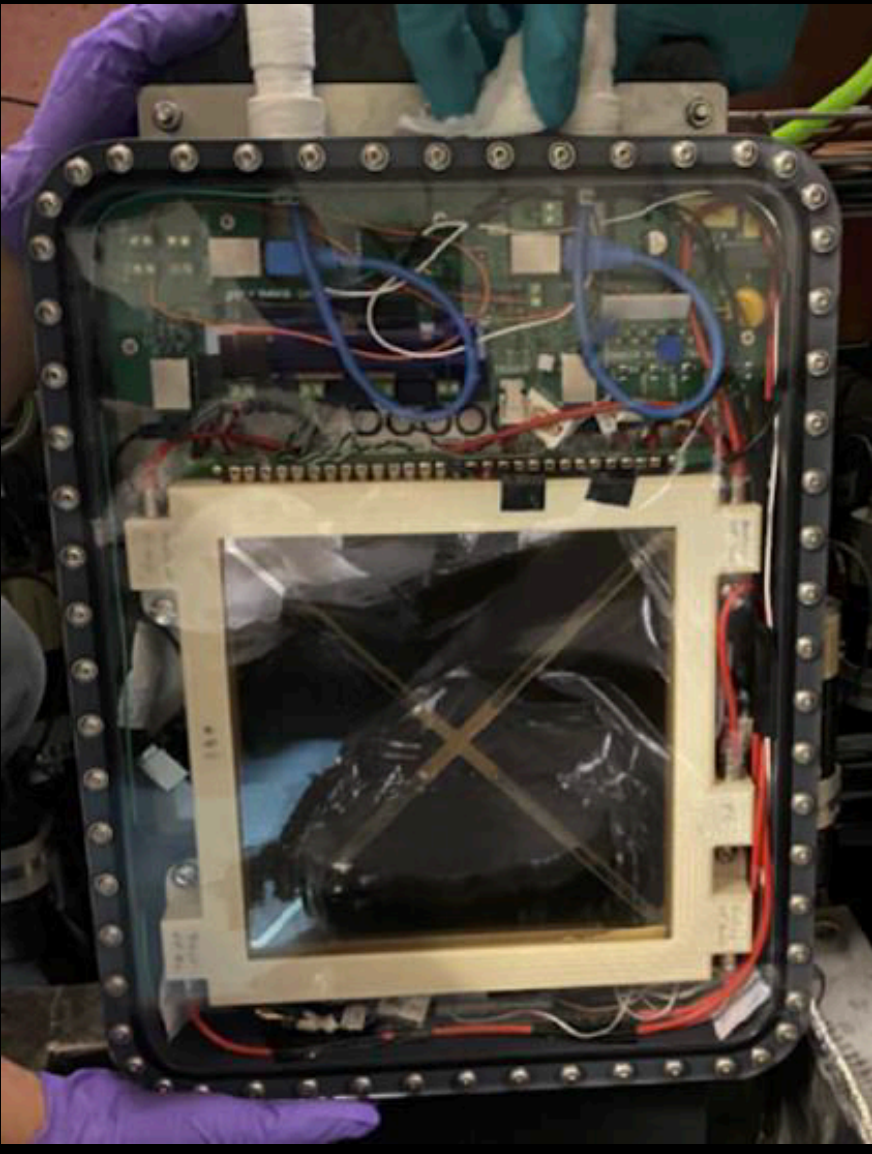
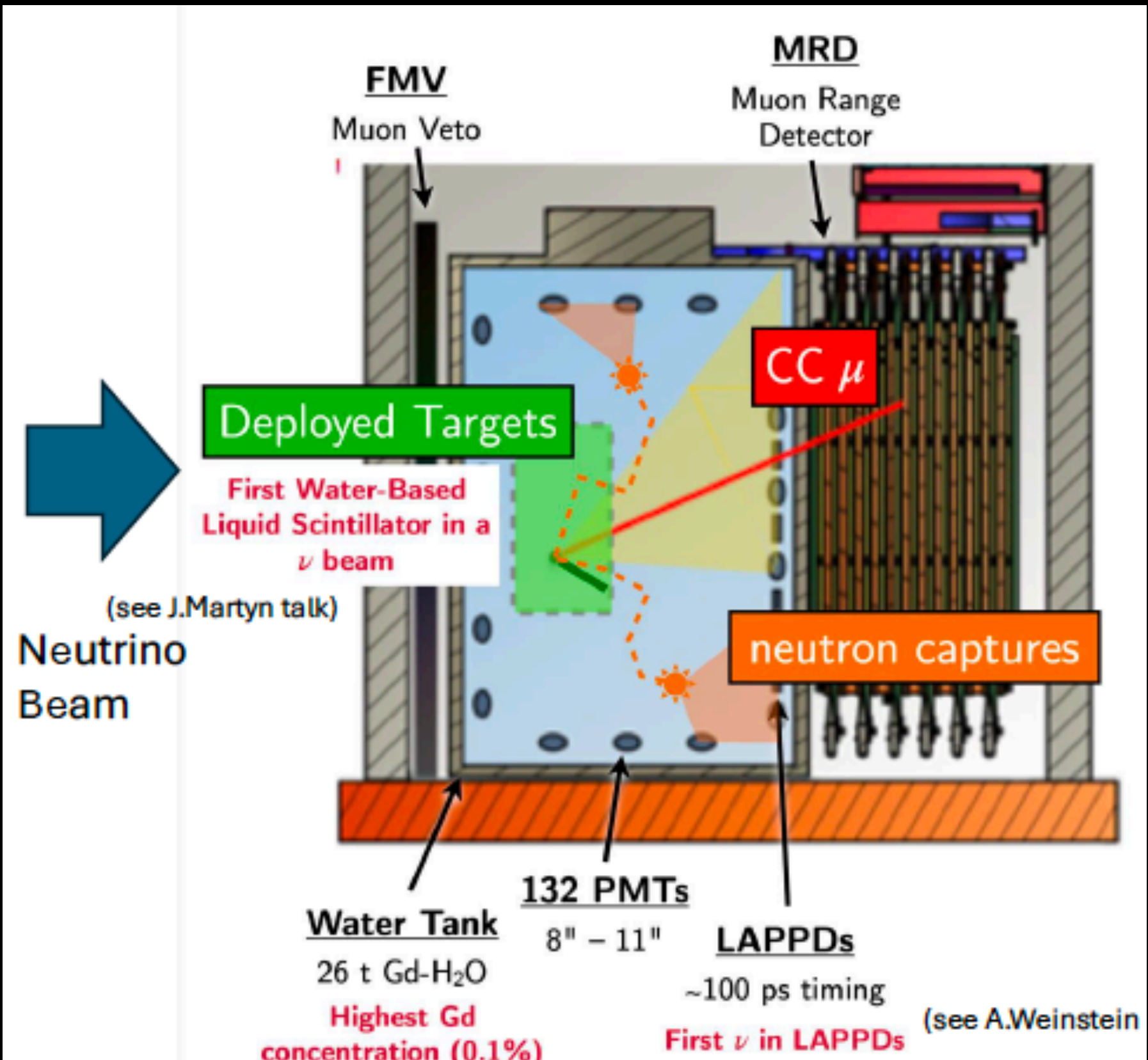


- BNL 30 T detector
 - Steel tank, 36 PMTs
 - Muon taggers
 - WbLS increasing from 0.35% to 1%

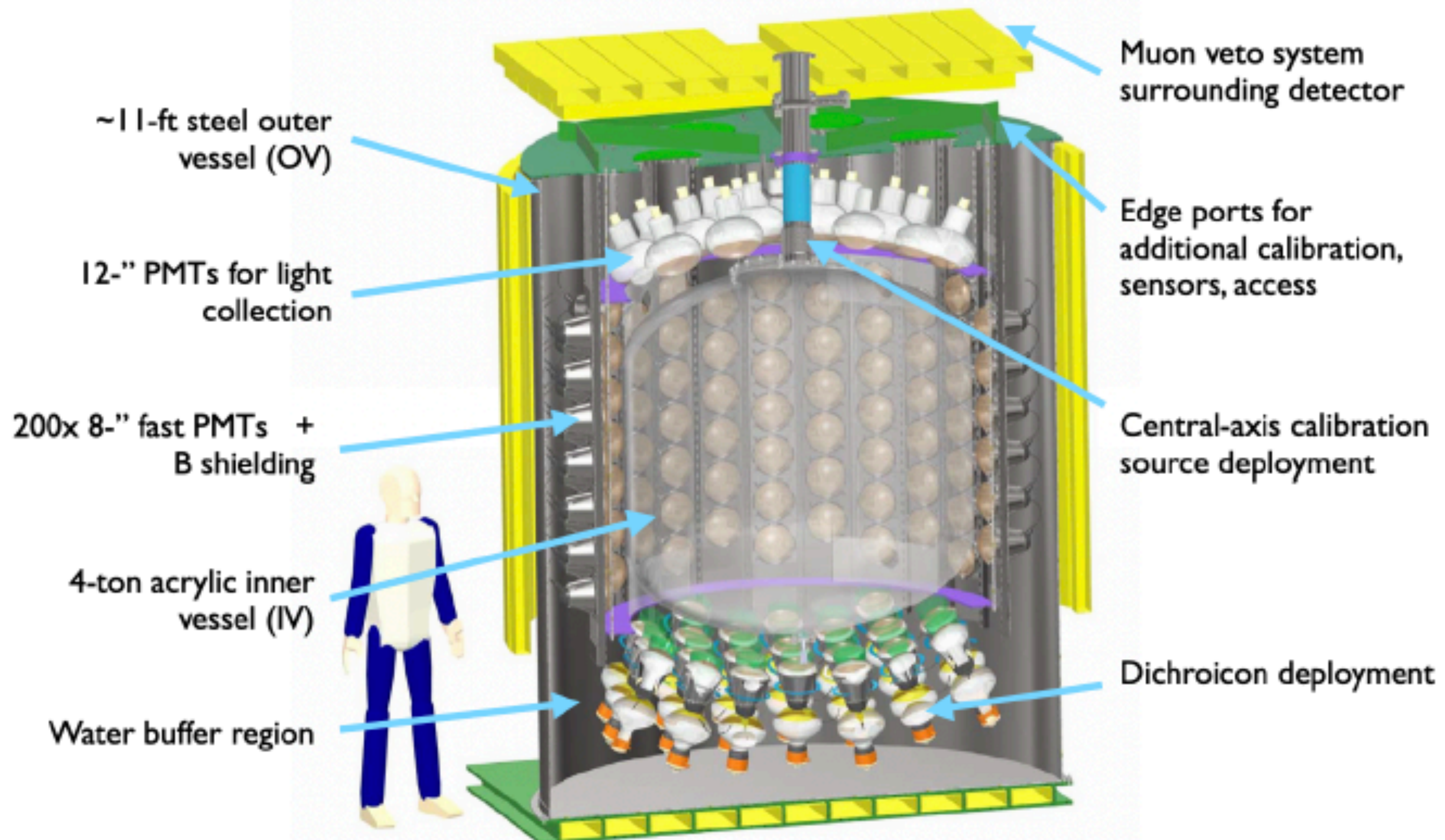




- Broad physics program with beam ν_μ in water
- Testbed for hybrid detector technologies
 - WbLS
 - LAPPDs

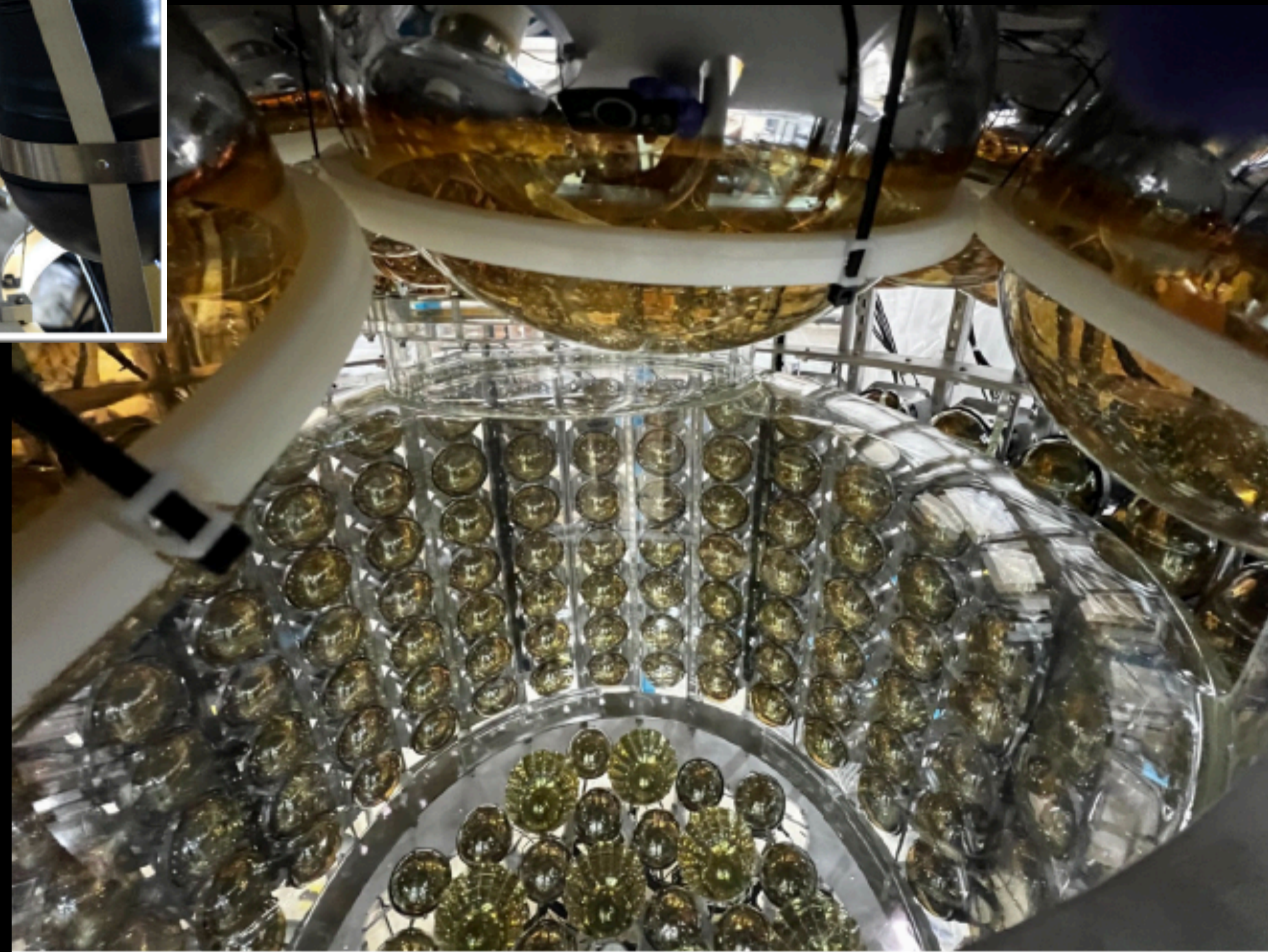


BASELINE PERFORMANCE
ENERGY RESOLUTION ON SINGLE
TRACK MUONS IS ABOUT 12%



EOS: LOTS OF NICE PHOTOS!

L. PICKARD



17

EOS CALIBRATIONS



L. PICKARD

THE EOS CALIBRATION SOURCE ARRAY

Laserball

- Isotropic light source
- Picosecond lasers
- Four wavelengths (374, 408, 442 and 515 nm)

AmBe

- 4.4 MeV gamma coincident with neutron

Cosmics

- Michel electron and neutron followers

Cherenkov

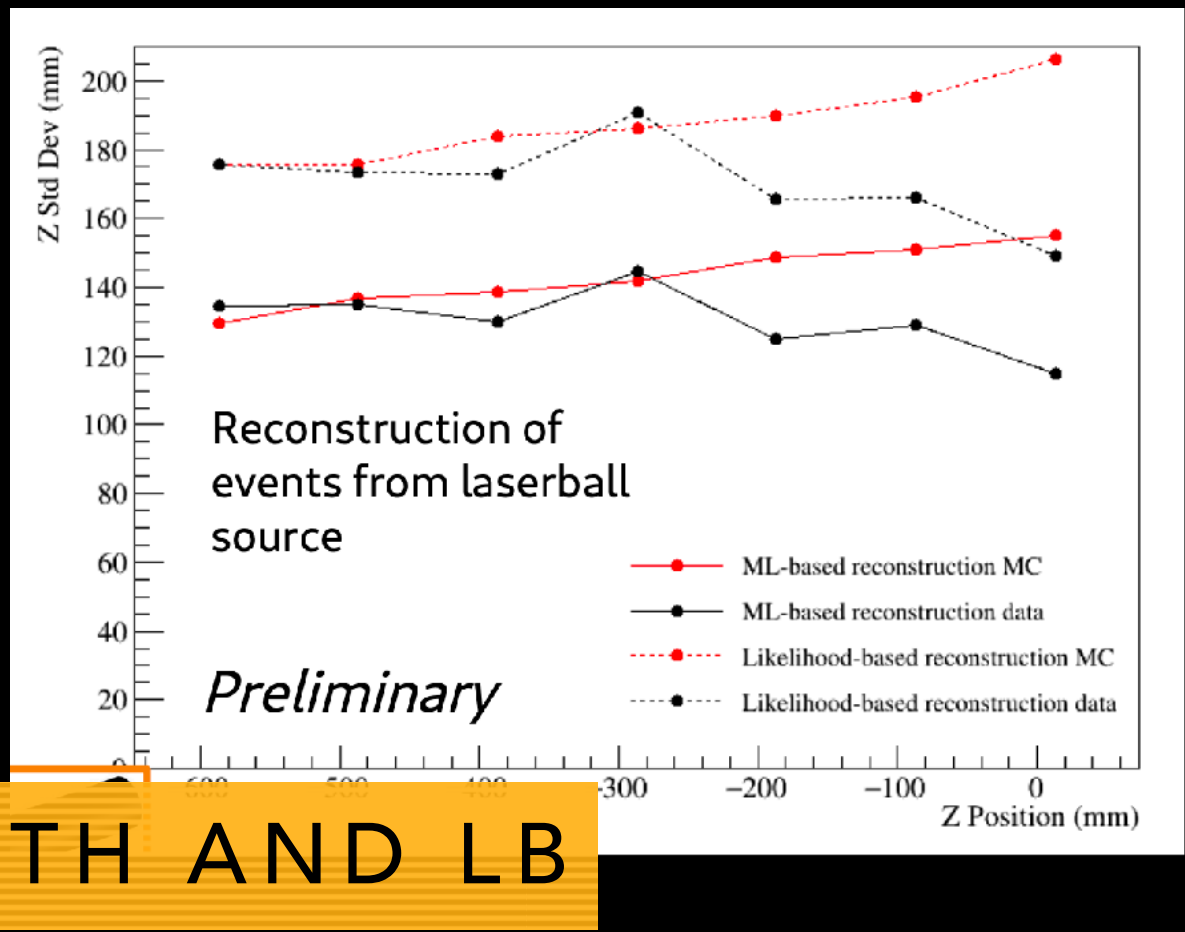
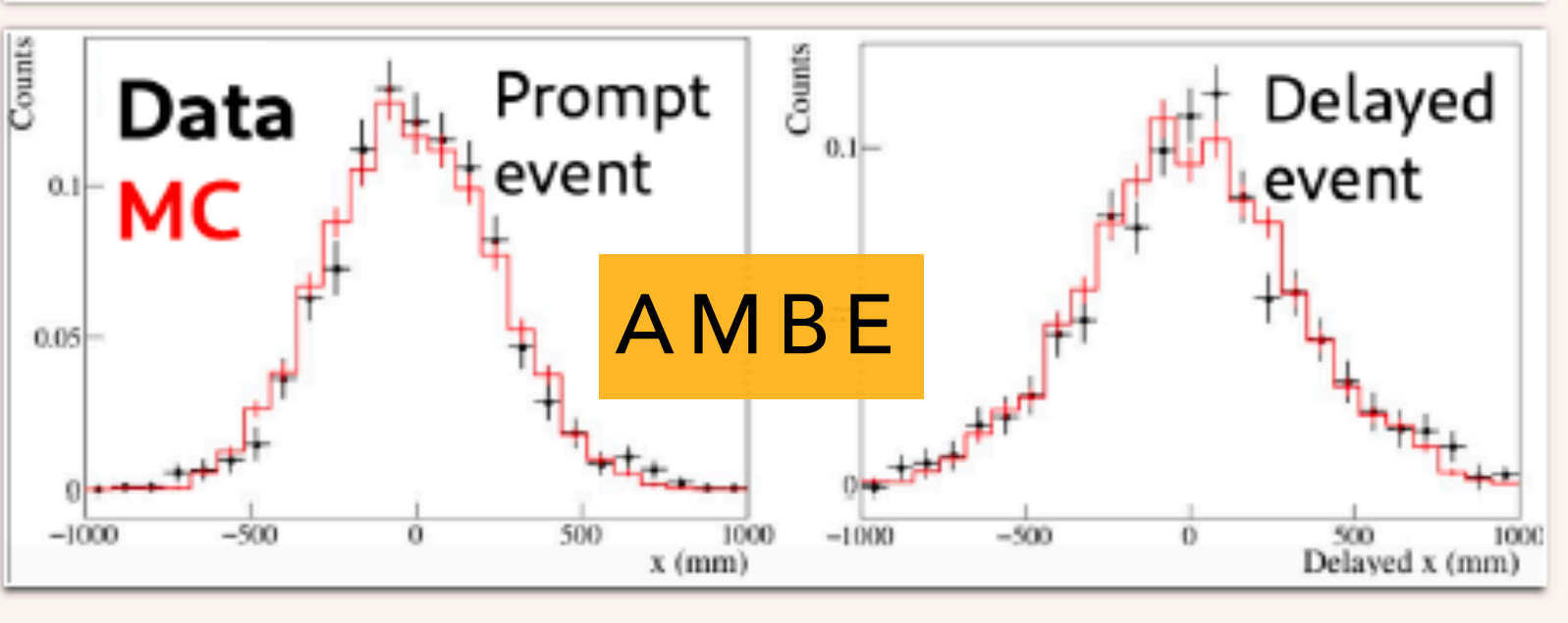
- ⁹⁰Sr source in UVT acrylic housing
- Cherenkov only light production

Directional

- Directional e⁻ from ⁹⁰Sr or ¹⁰⁶Ru

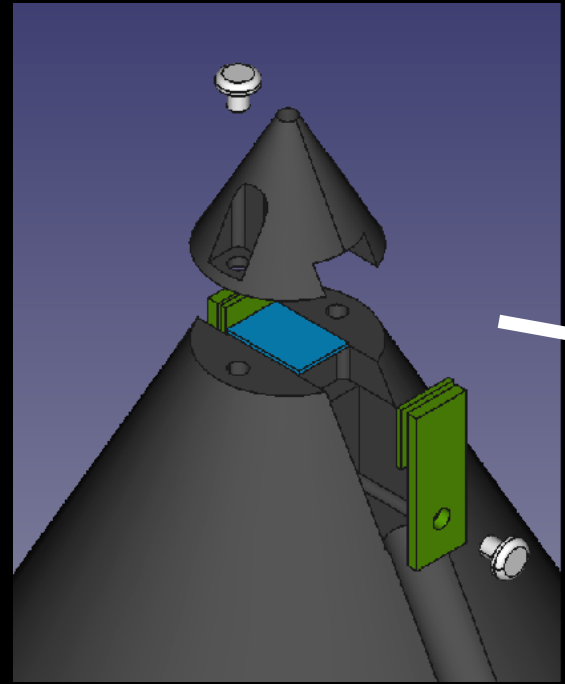
Thorium

- Primarily 2.6 MeV gammas from ²⁰⁸Tl



EOS DIRECTIONAL SOURCE

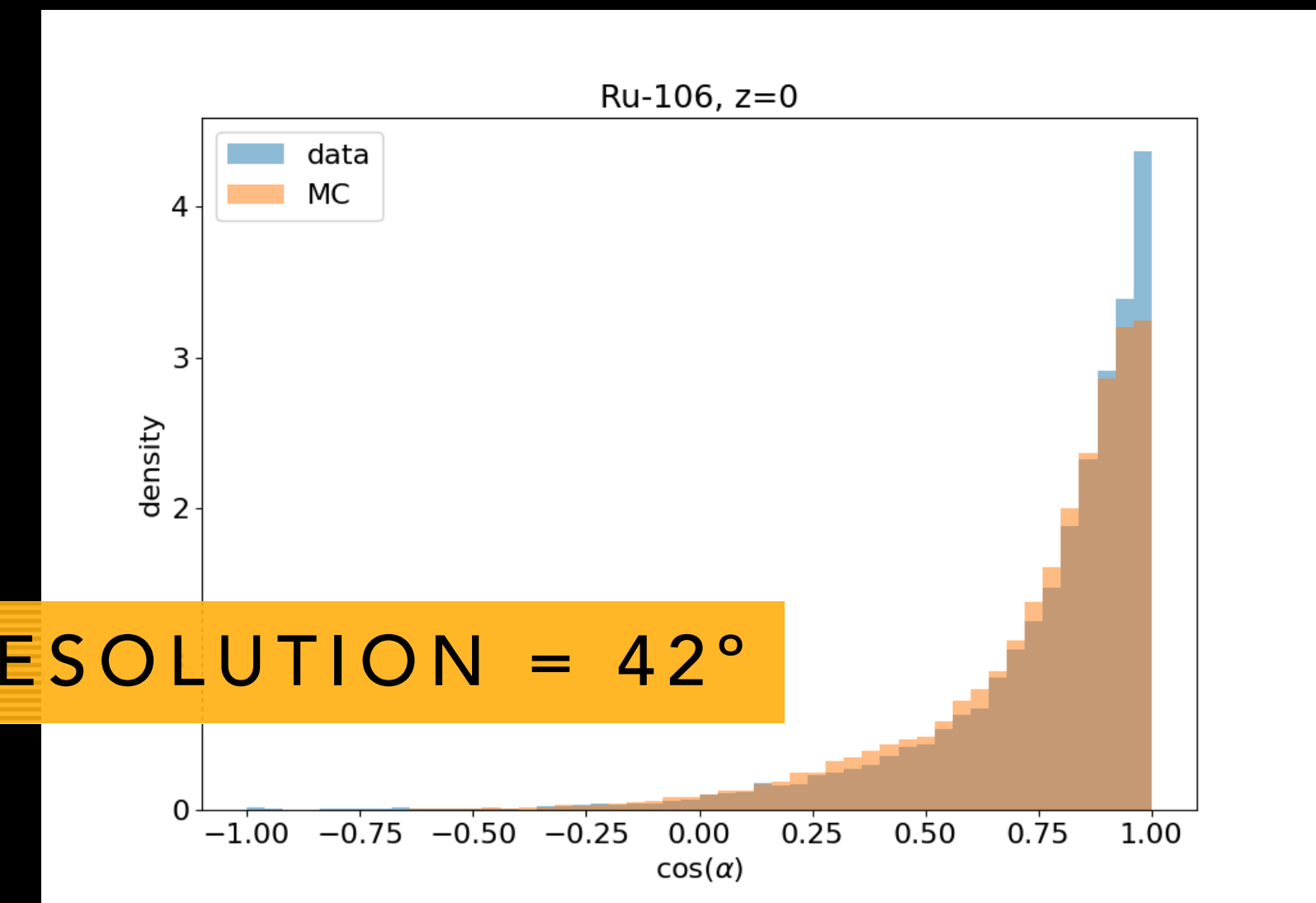
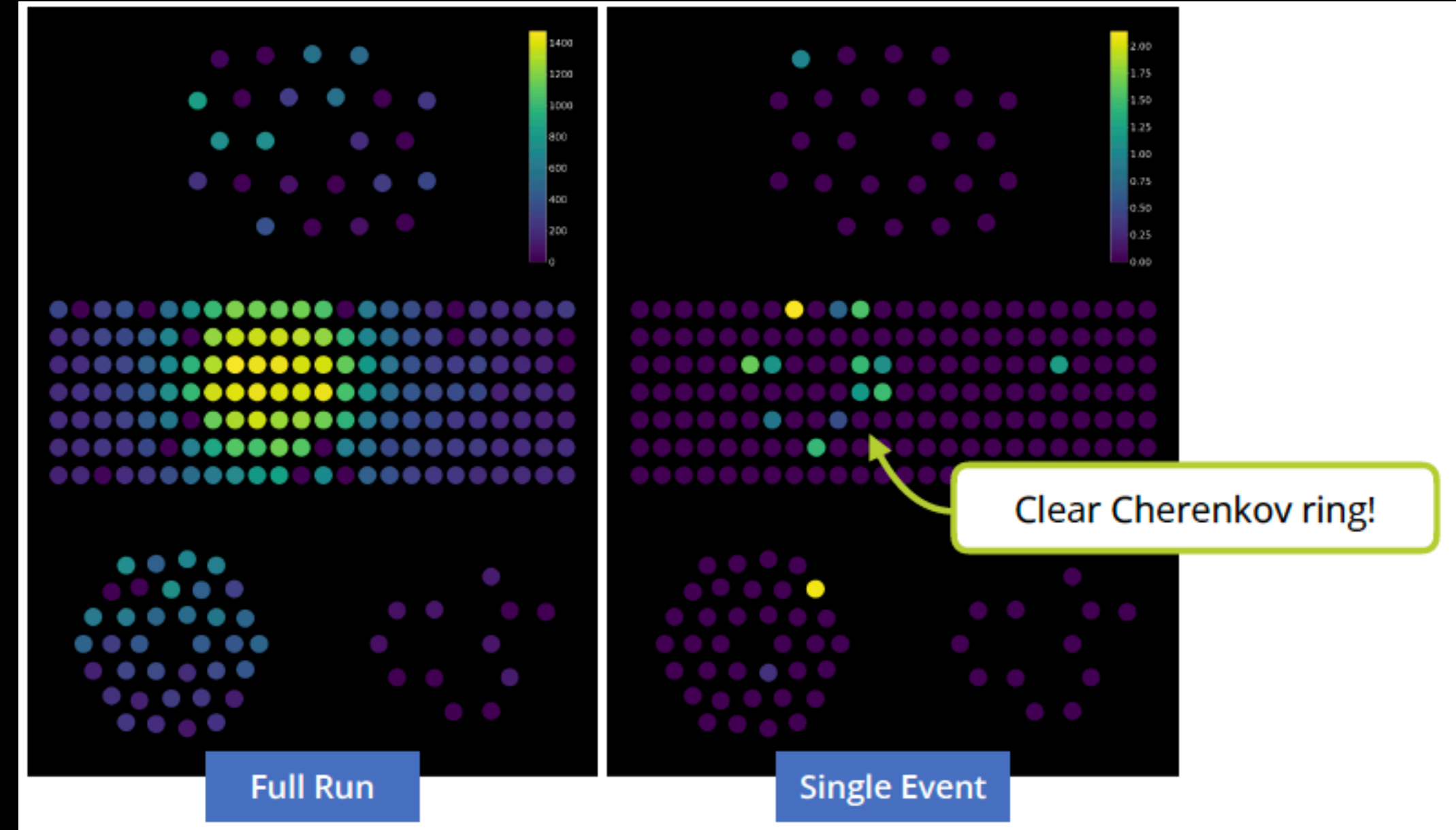
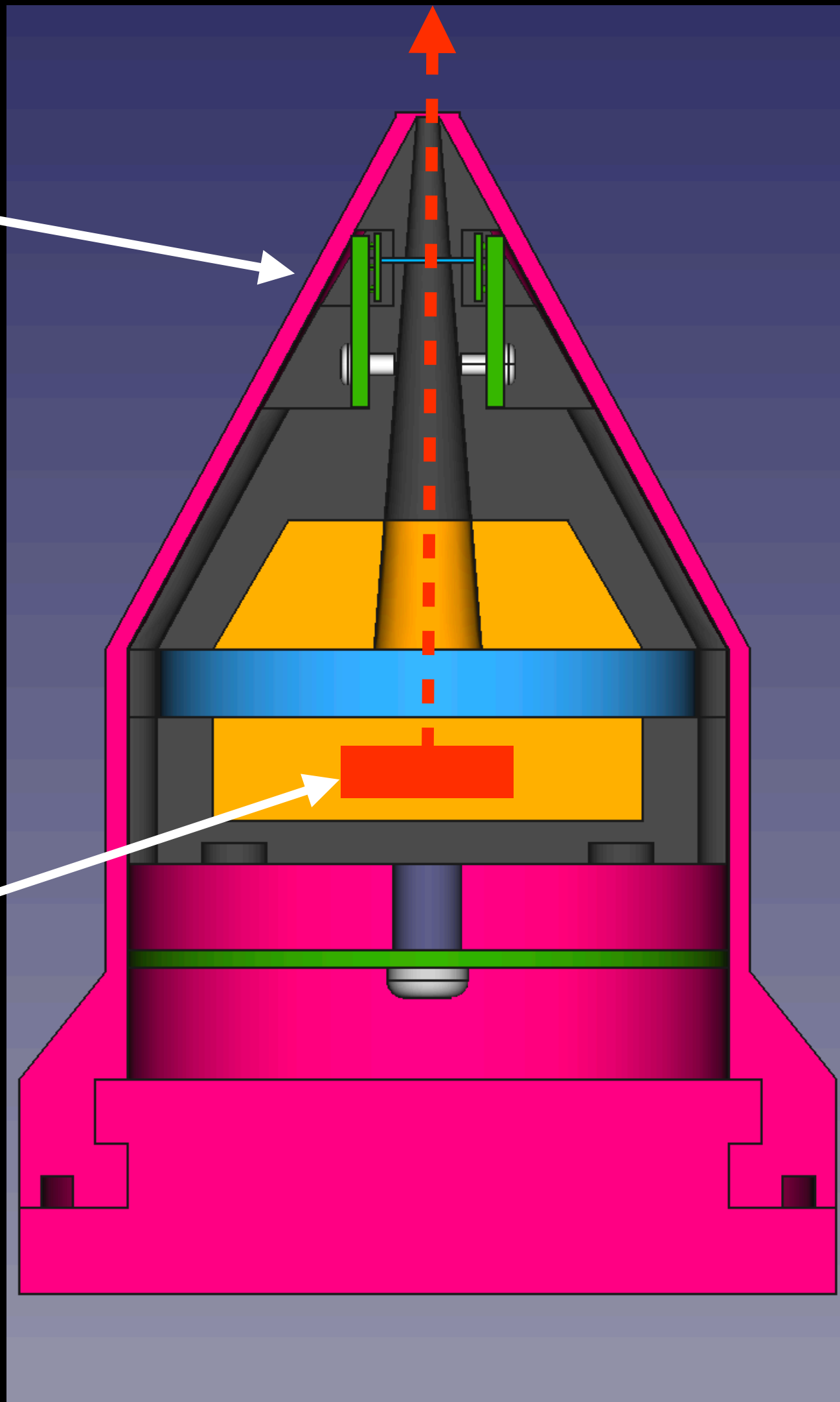
S.Y. JEON



fiber + SiPM
trigger



beta source

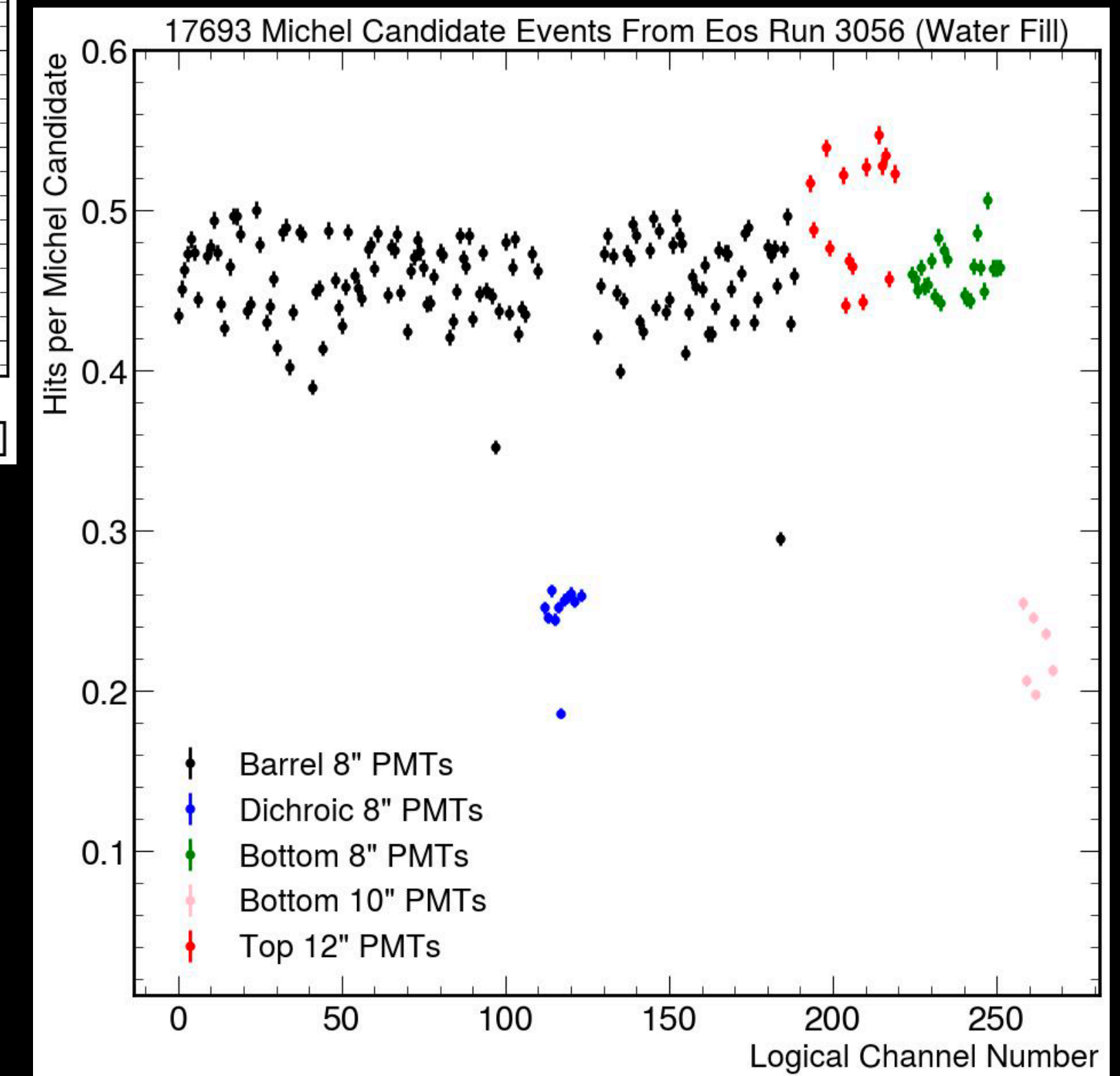
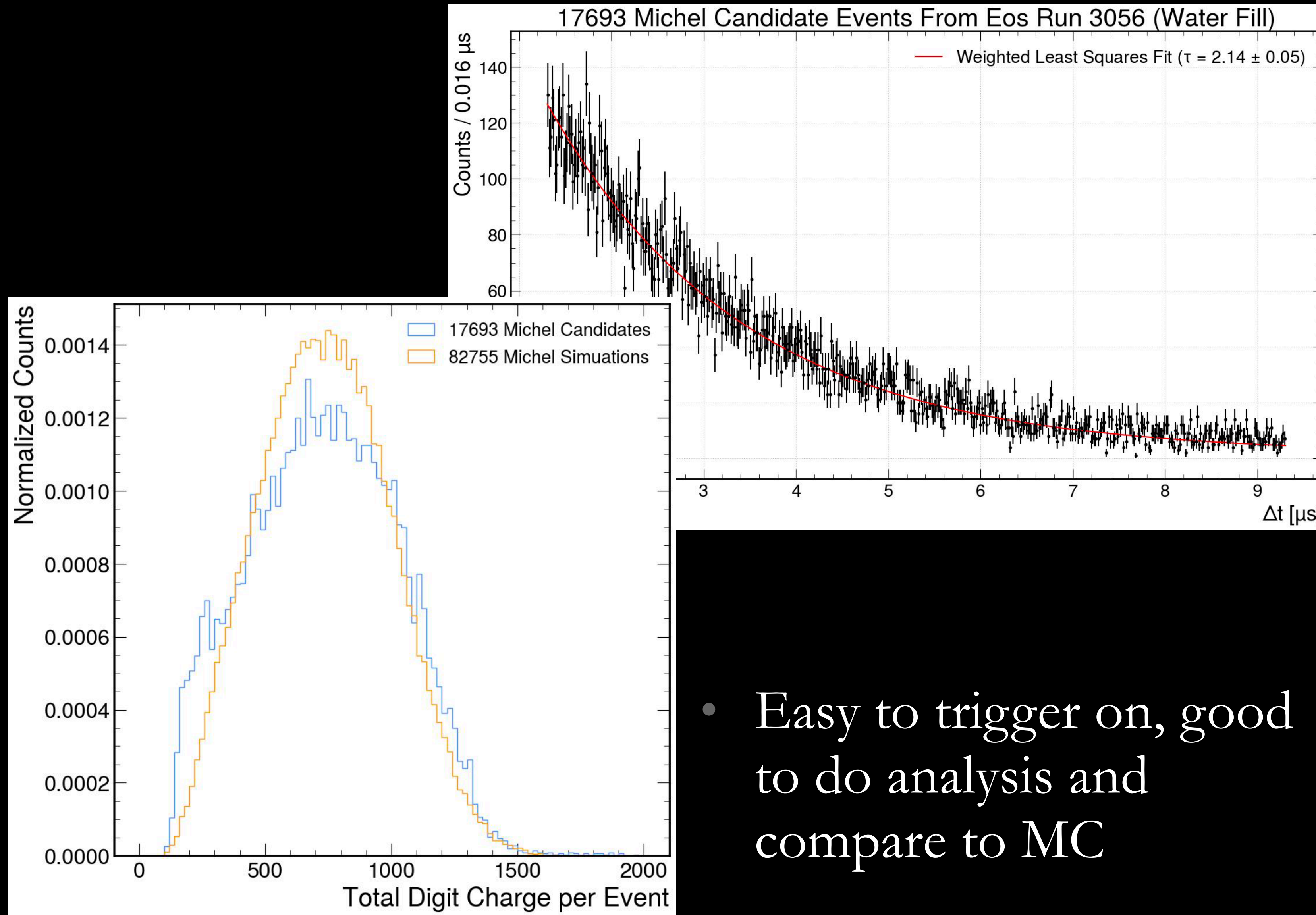


RESOLUTION = 42°

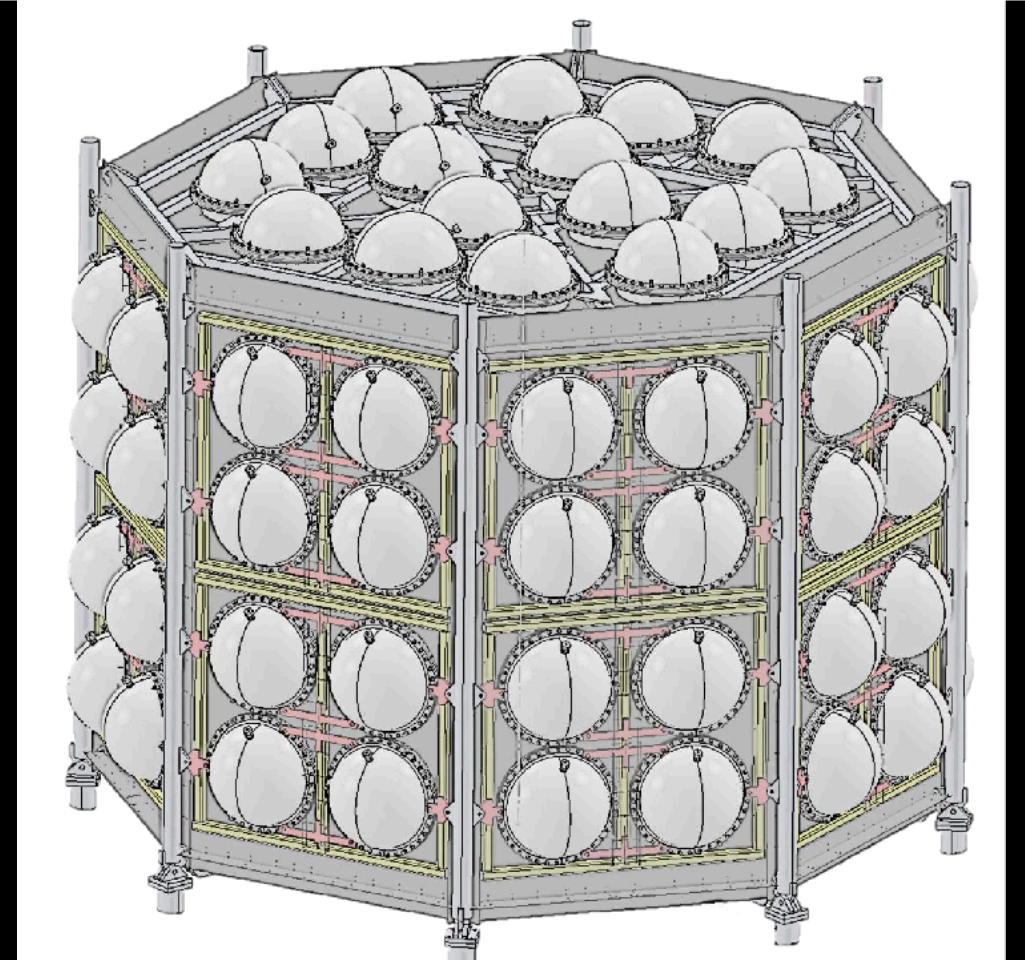
MICHELS ON EOS



B. HARRIS

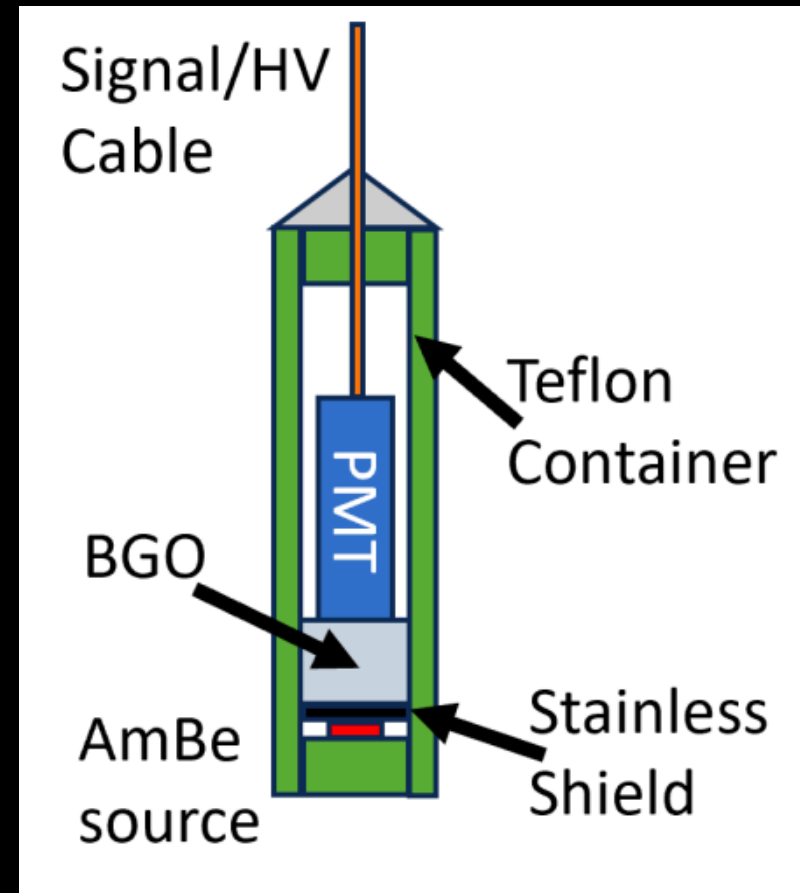
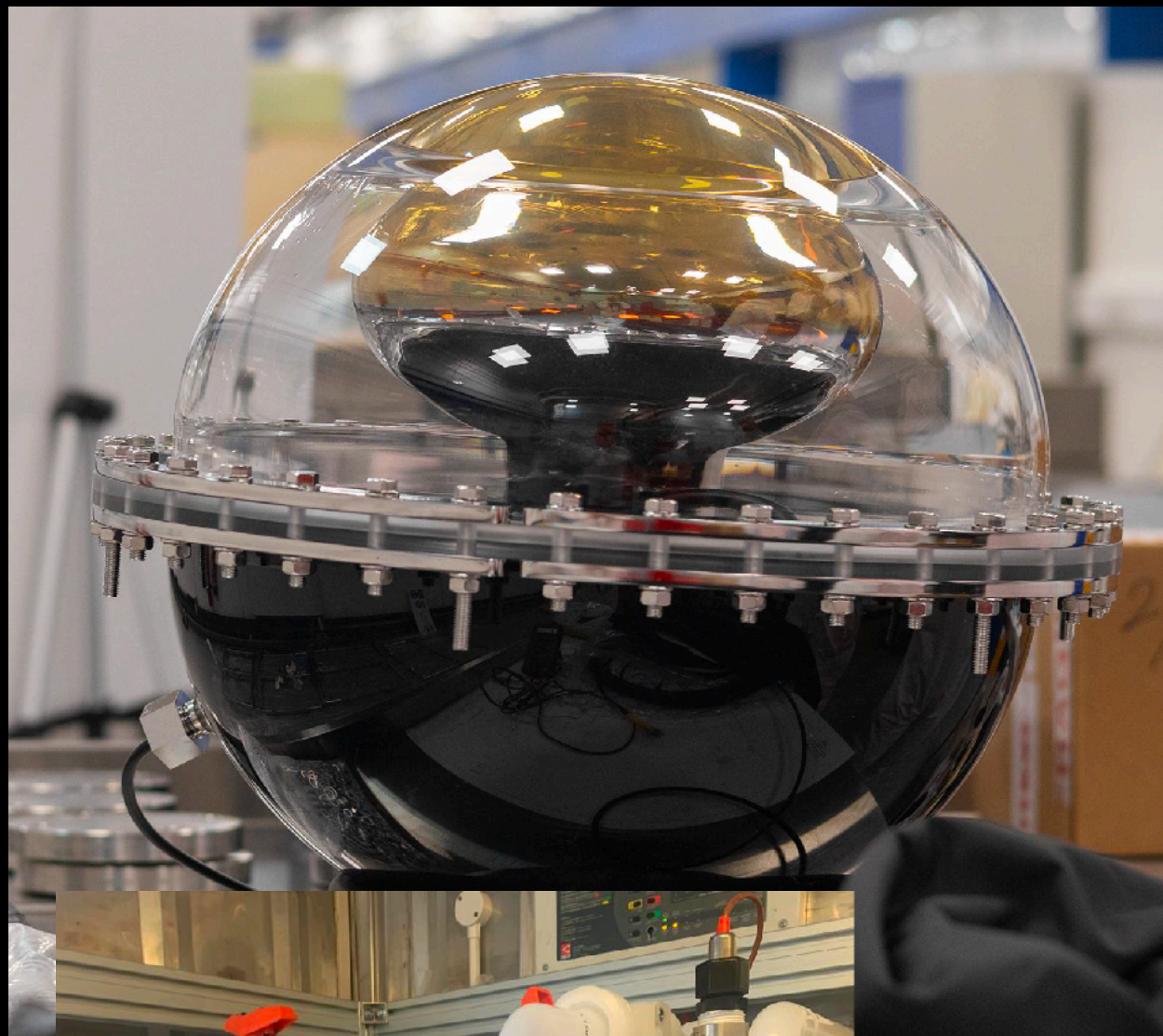


- New detector / test facility just/almost complete
- @Boulby mine, UK. 1.1 km deep, low background rock salt
- Flexibility to test different photosensors and media
 - $\text{H}_2\text{O} \rightarrow \text{Gd-H}_2\text{O} \rightarrow \text{WbLS} \rightarrow \text{Gd-WbLS} \rightarrow \text{future fills (LS?)}$

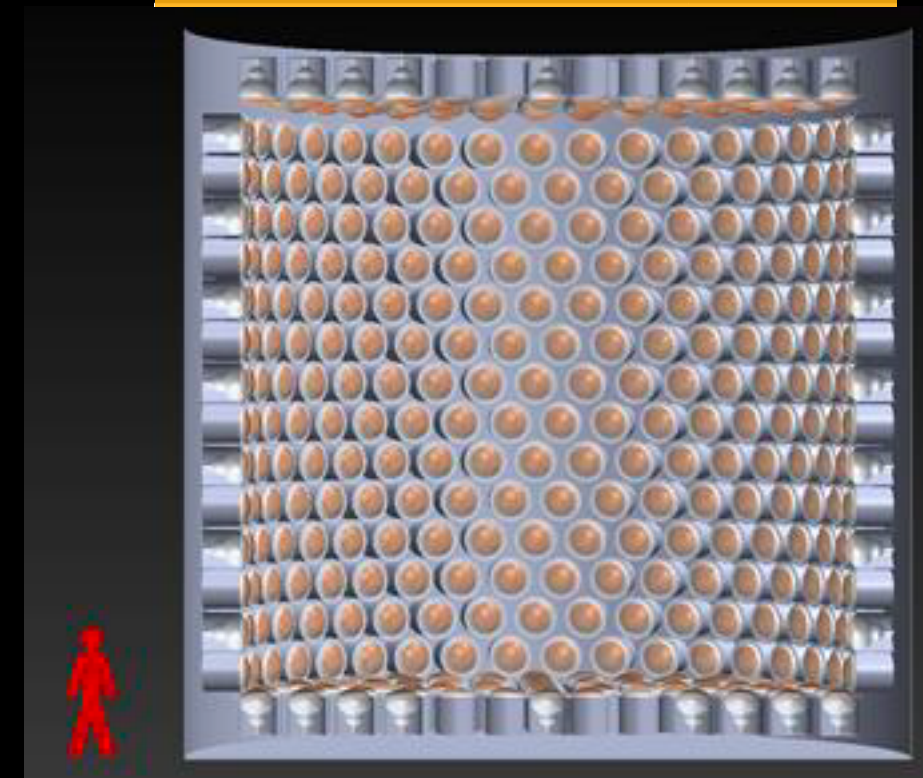


NOW: PMTS
POWERED ON!

FUTURE: 1 KT



AMBE AND
LIGHT SOURCES



NUDOT

S. AXANI

- New detector @ Univ. of Delaware, testing Ch/Sc separation in LAB/PPO through fast timing (small and big PMTs)

0.9m diameter Acrylic Sphere

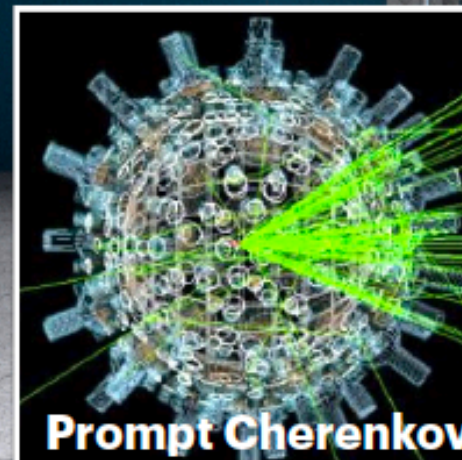
- 800L of Linear Alkyl Benzene (LAB) + PPO
- 6-inch diameter neck for calibration to insert calibration devices
- Suspended in 7500L of mineral oil

2" Hamamatsu R13089

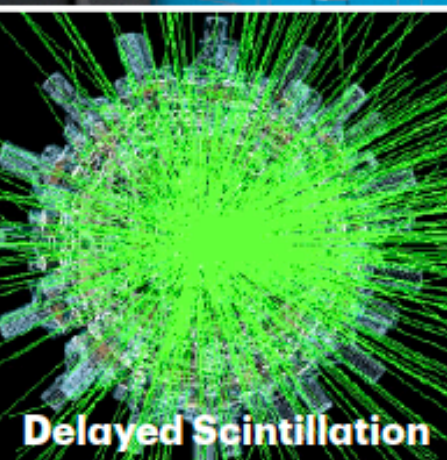
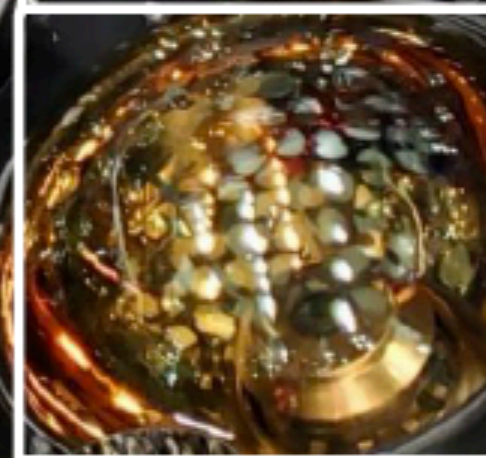
- x151 of them
- 6% photocathode coverage
- TTS = 200ps (precision timing)
- Winston cones
- Mu-metal shielding

8" PMTs

- x59 PMTs, assorted
- 34% photocathode coverage
- Large light collect area



Prompt Cherenkov

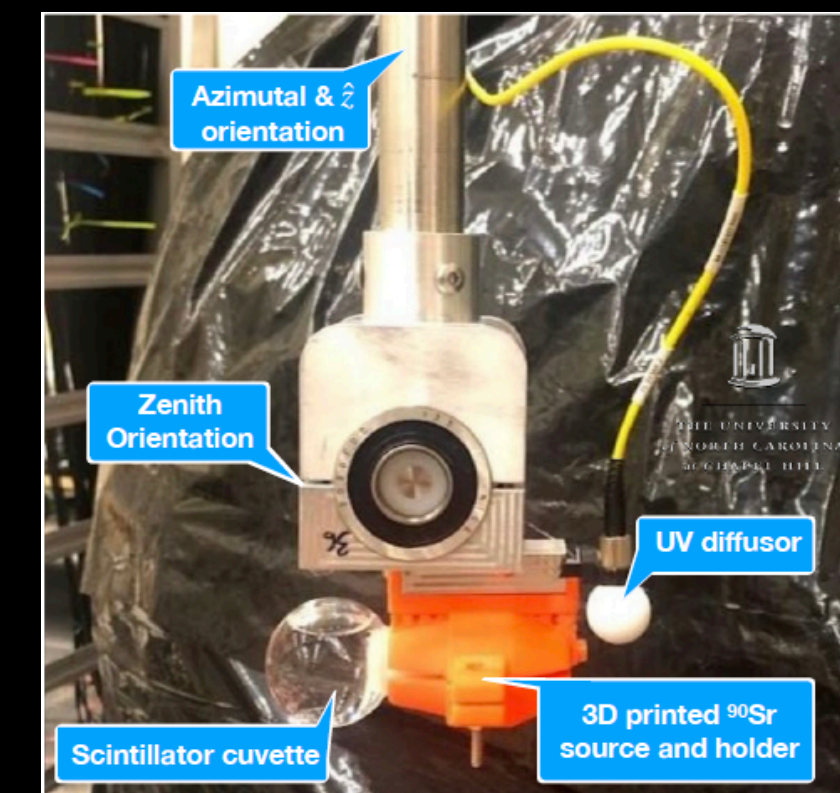


Delayed Scintillation

First goal: demonstrate Cherenkov/scintillation separation at the ton-scale, through **directionality** and precision **timing**.



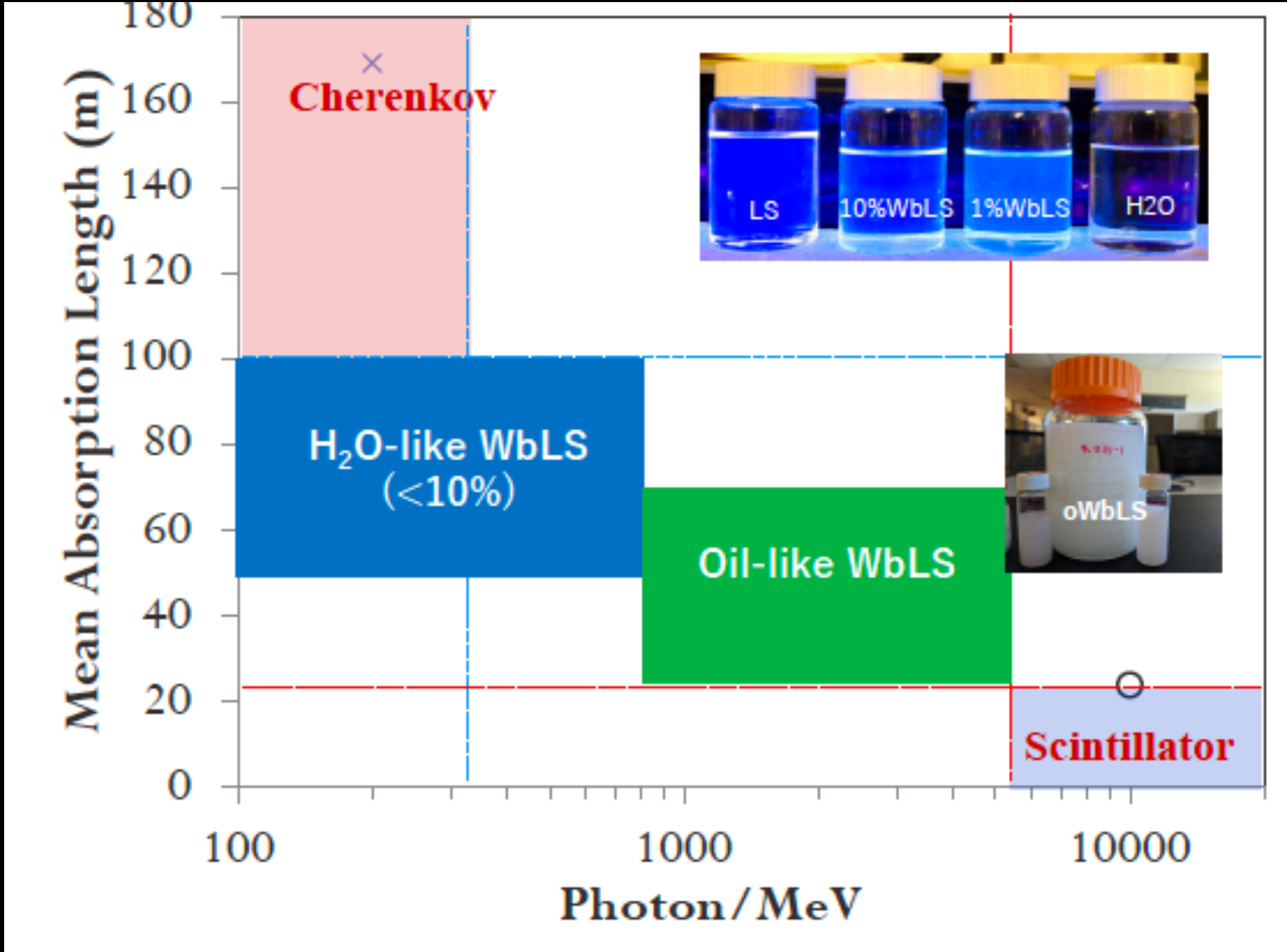
Being commissioned now,
with cosmic muons,
directional source



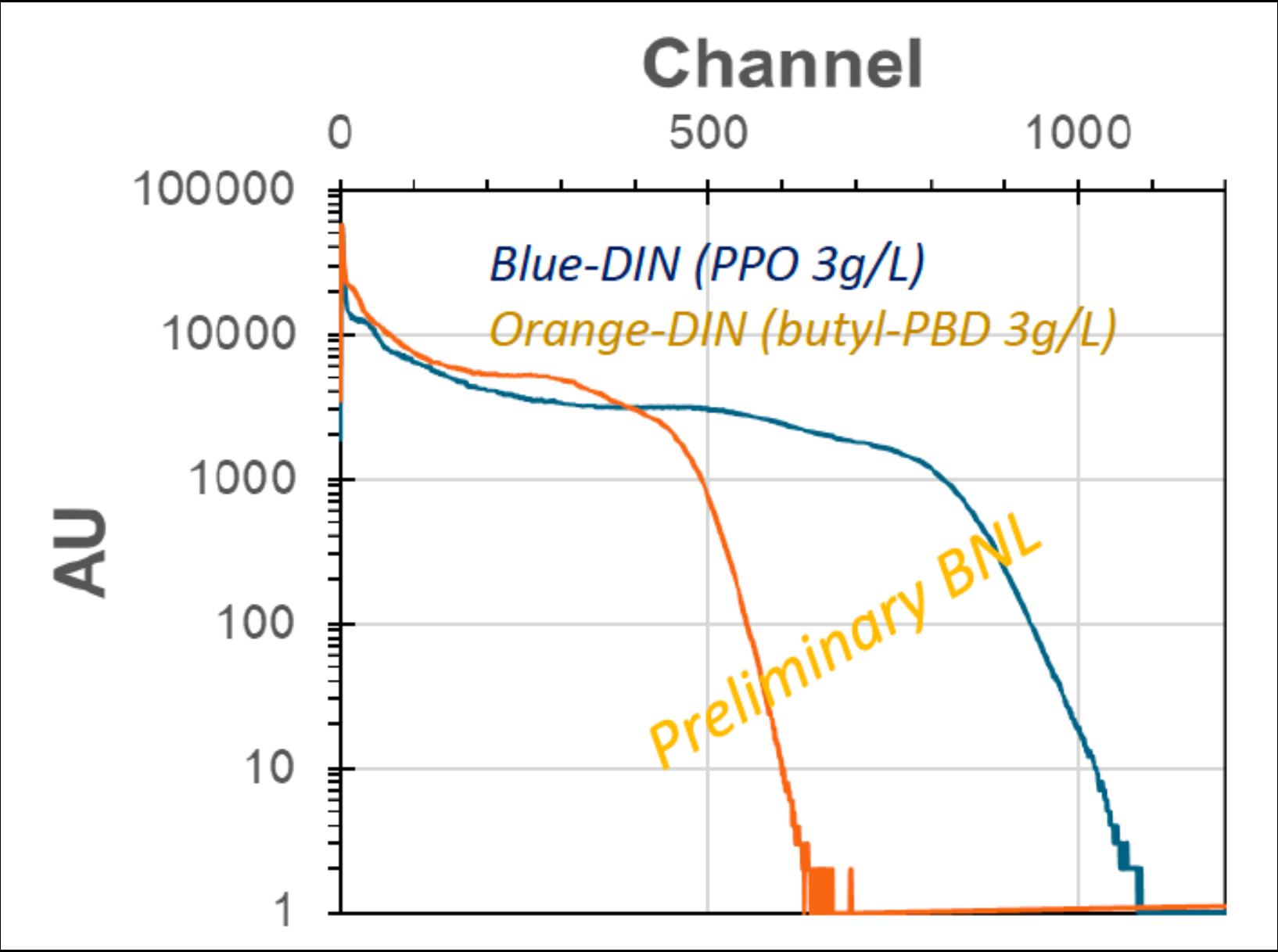
WATER BASED LIQUID SCINTILLATOR

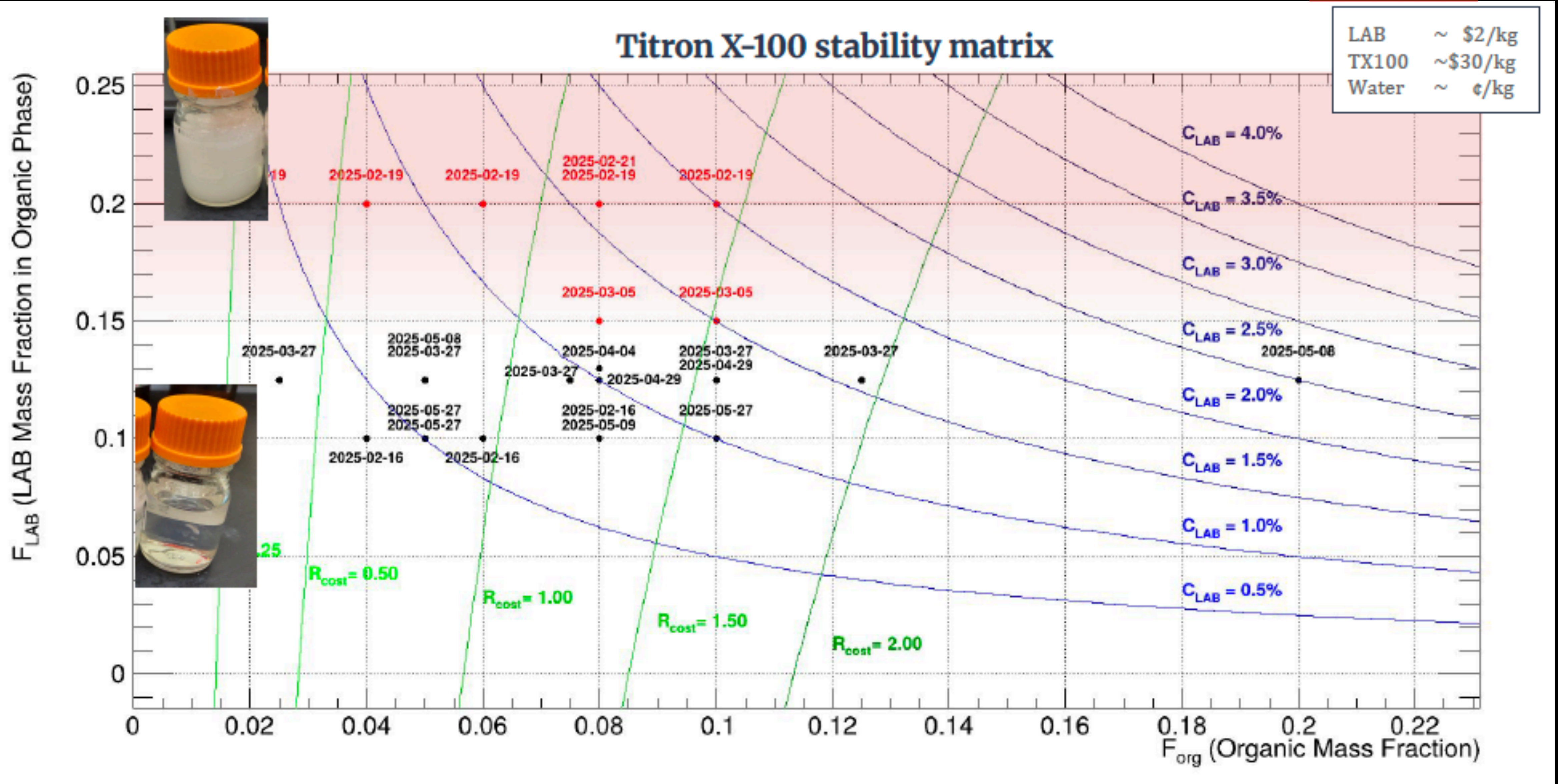
- Advantages w/r LS
 - Cost, attenuation length, scalability, safety, possible metal-loading (Gd, Te, Li)
- Advantages w/r water
 - Calorimetry from scintillation light

Molecule	chemical formula	abs. max.	em. max.
PPO	C ₁₅ H ₁₁ NO	303 nm	358 nm
PBD	C ₂₀ H ₁₄ N ₂ O	302 nm	358 nm
butyl-PBD	C ₂₄ H ₂₂ N ₂ O	302 nm	361 nm
BPO	C ₂₁ H ₁₅ NO	320 nm	384 nm
p-TP	C ₁₈ H ₁₄	276 nm	338 nm
TBP	C ₂₈ H ₂₂	347 nm	455 nm
bis-MSB	C ₂₄ H ₂₂	345 nm	418 nm
POPOP	C ₂₄ H ₁₆ N ₂ O ₂	360 nm	411 nm
PMP	C ₁₈ H ₂₀ N ₂	295 nm	425 nm



- Trying several combinations of solvent, fluor





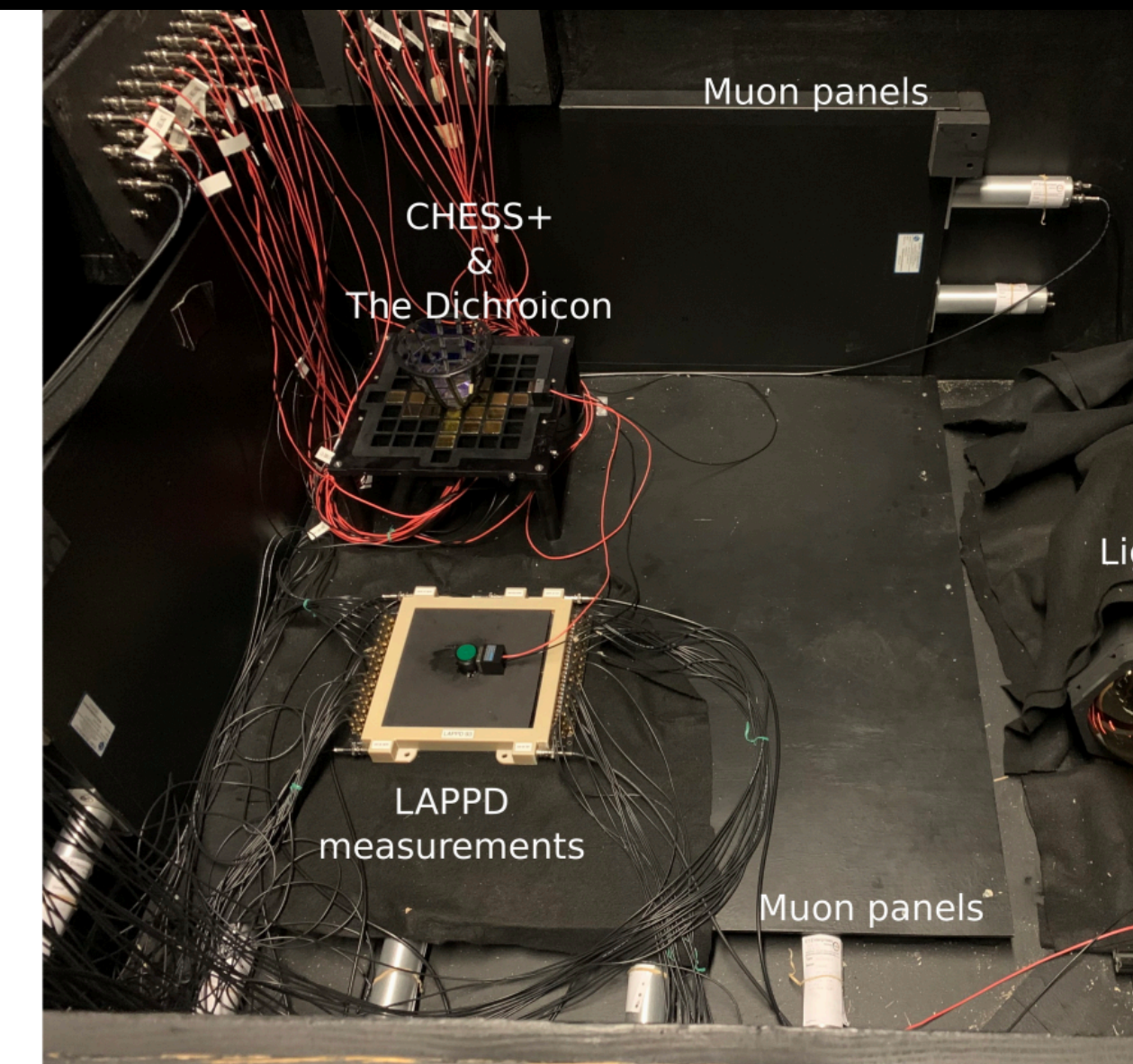
SCINTILLATOR TESTS @CHESS



E. CALLAGHAN

- Extensive characterization of several mixtures
- LAPPD for fast, PMT for slow, components
- Good MC agreement

LIGHT YIELD



Material	S_β [photons/MeV]	$\langle N \rangle_\alpha$ [photons]
1% WbLS	$257 \pm 4^{+25}_{-24}$	$58 \pm 2 \pm 6$
5% WbLS	$754 \pm 10^{+73}_{-70}$	$281 \pm 3 \pm 28$
10% WbLS	$1380 \pm 14^{+134}_{-128}$	$516 \pm 8 \pm 153$
LAB + 2 g/L PPO	~ 12200	

^{90}Sr source



AV

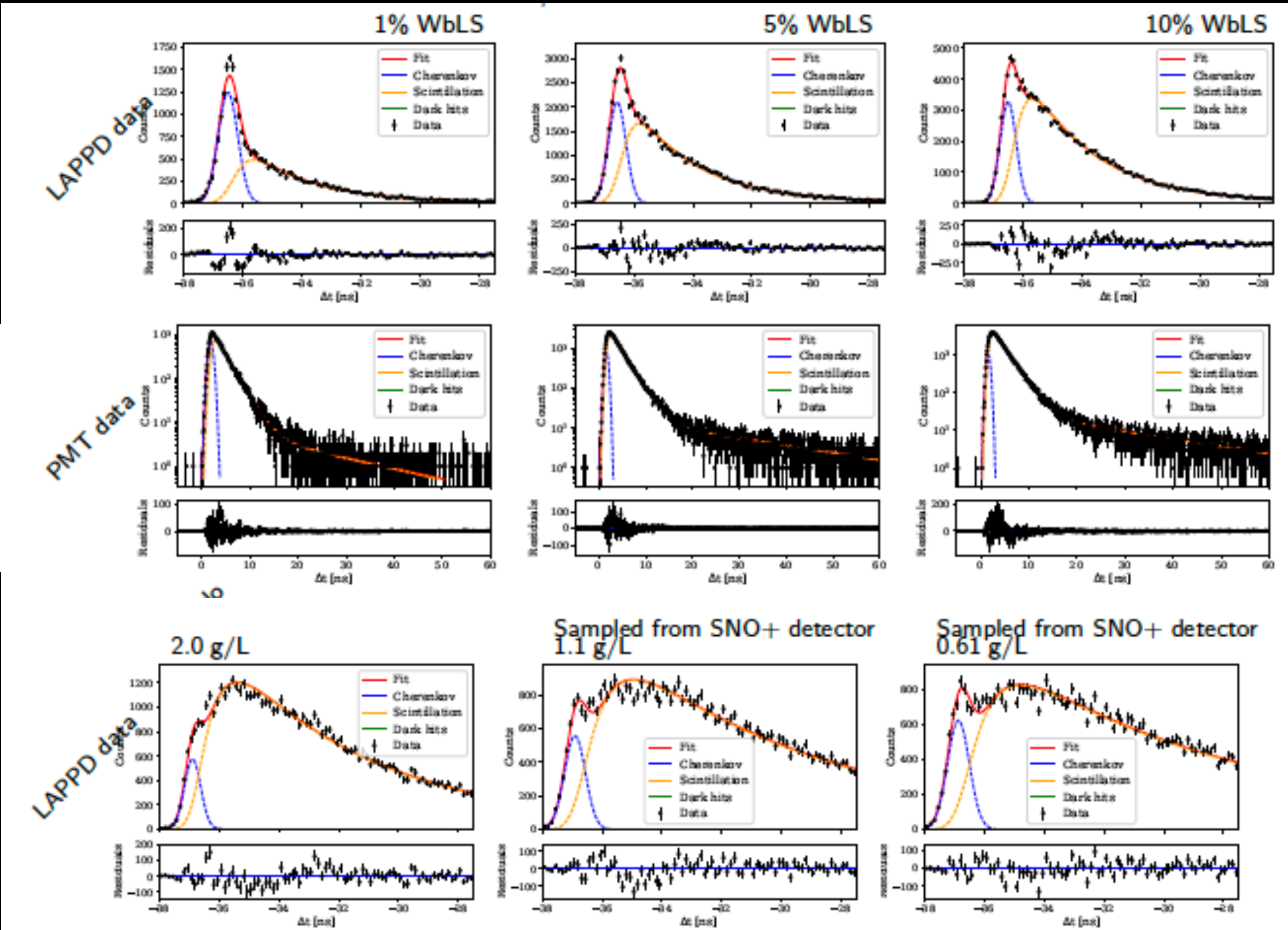
Trigger PMT

BETA TIMING

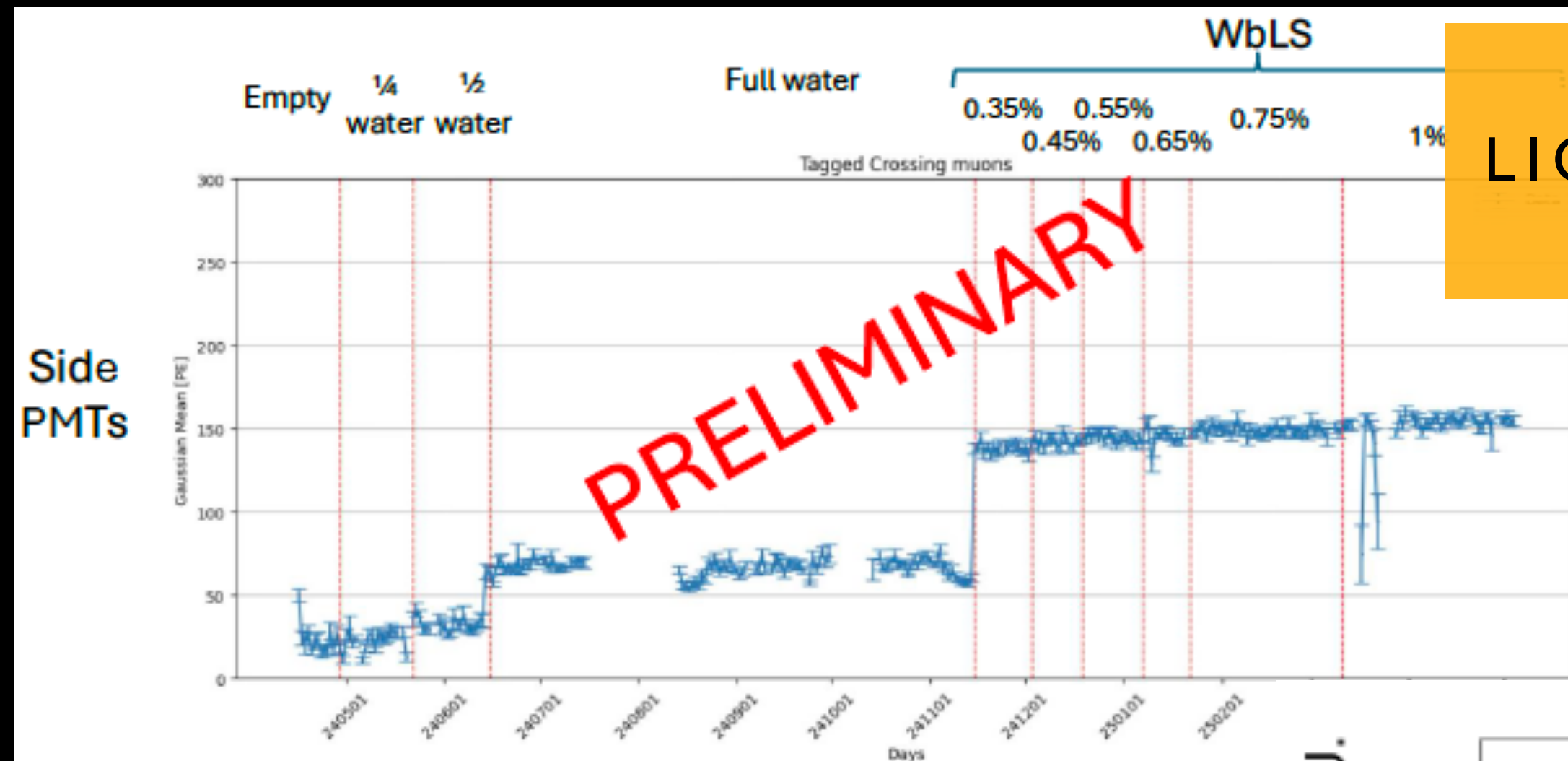
Increasing scintillator fraction →

	1% WbLS	5% WbLS	10% WbLS	2 g/L LS
τ_R [ps]	270^{+26}_{-20}	209^{+10}_{-11}	276^{+7}_{-7}	594^{+22}_{-15}
τ_1 [ns]	$2.22^{+0.02}_{-0.02}$	$2.25^{+0.01}_{-0.01}$	$2.36^{+0.01}_{-0.01}$	$4.64^{+0.06}_{-0.06}$
τ_2 [ns]	$17.7^{+1.3}_{-1.1}$	$23.5^{+1.0}_{-0.9}$	$22.8^{+0.7}_{-0.7}$	$18.1^{+0.6}_{-0.6}$
A_1 [%]	$95.6^{+0.3}_{-0.3}$	$94.8^{+0.1}_{-0.1}$	$94.9^{+0.1}_{-0.1}$	$78.9^{+0.8}_{-0.9}$
χ^2/ndf	2967.6/2388	3031.1/2388	3373.2/2388	2706.0/2388
Purity in MC [%]	80.4	68.6	64.3	-

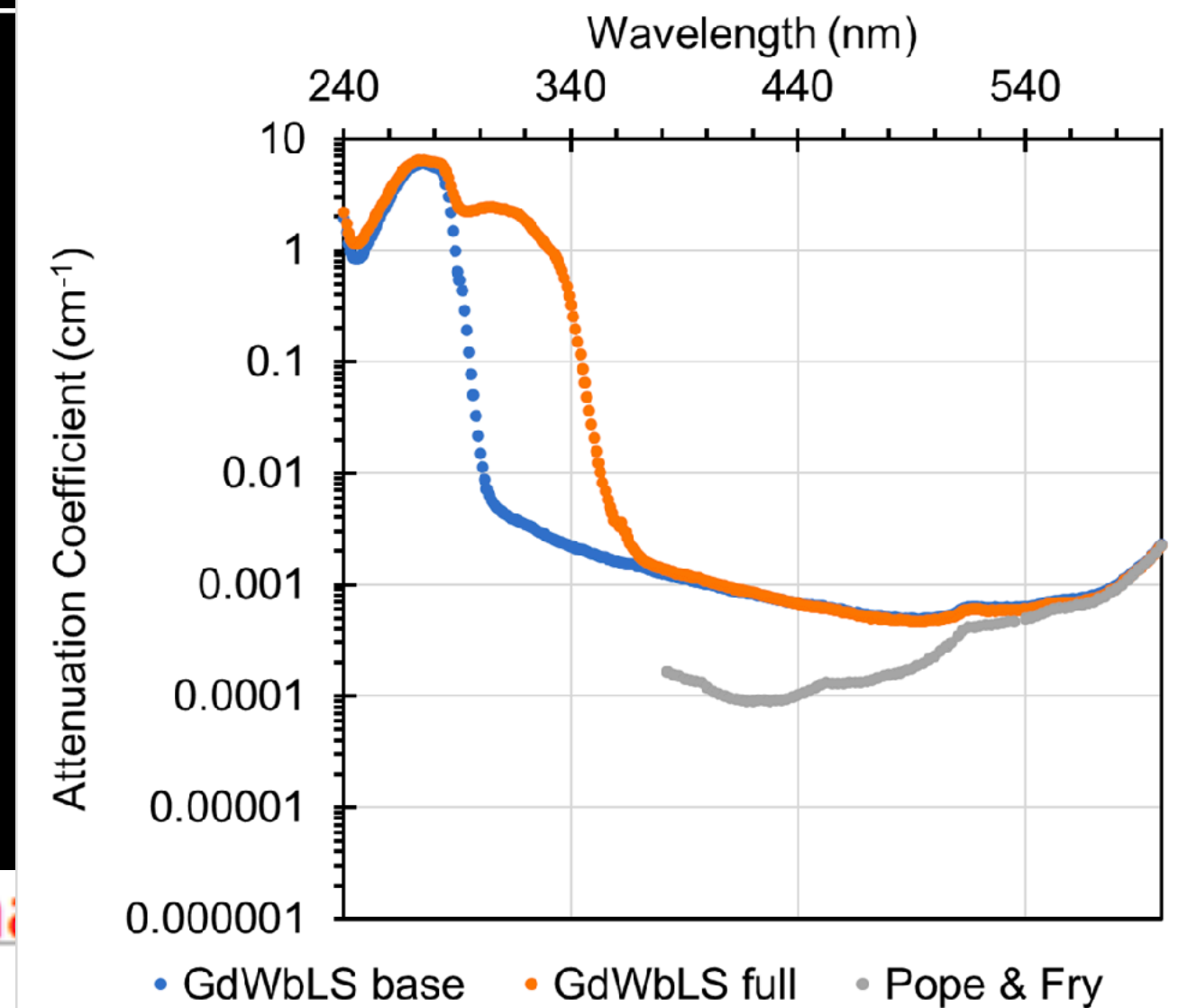
	Slower German	Slow German	0.1% GdWbLS
Light yield [ph./MeV]	6679 ± 268	9345 ± 375	$\lesssim 100$
τ_R [ps]	140 ± 40	120 ± 43	0.5 ± 19
τ_1 [ns]	11.7 ± 3.2	13.0 ± 3.4	1.74 ± 0.03
τ_2 [ns]	29.1 ± 3.5	26.3 ± 4.6	11.1 ± 0.8
A_1 [%]	21.0 ± 6	44.0 ± 7	91.6 ± 1.6
χ^2/ndf			2618.3/2388
Purity in MC [%]	90.1	80.3	-



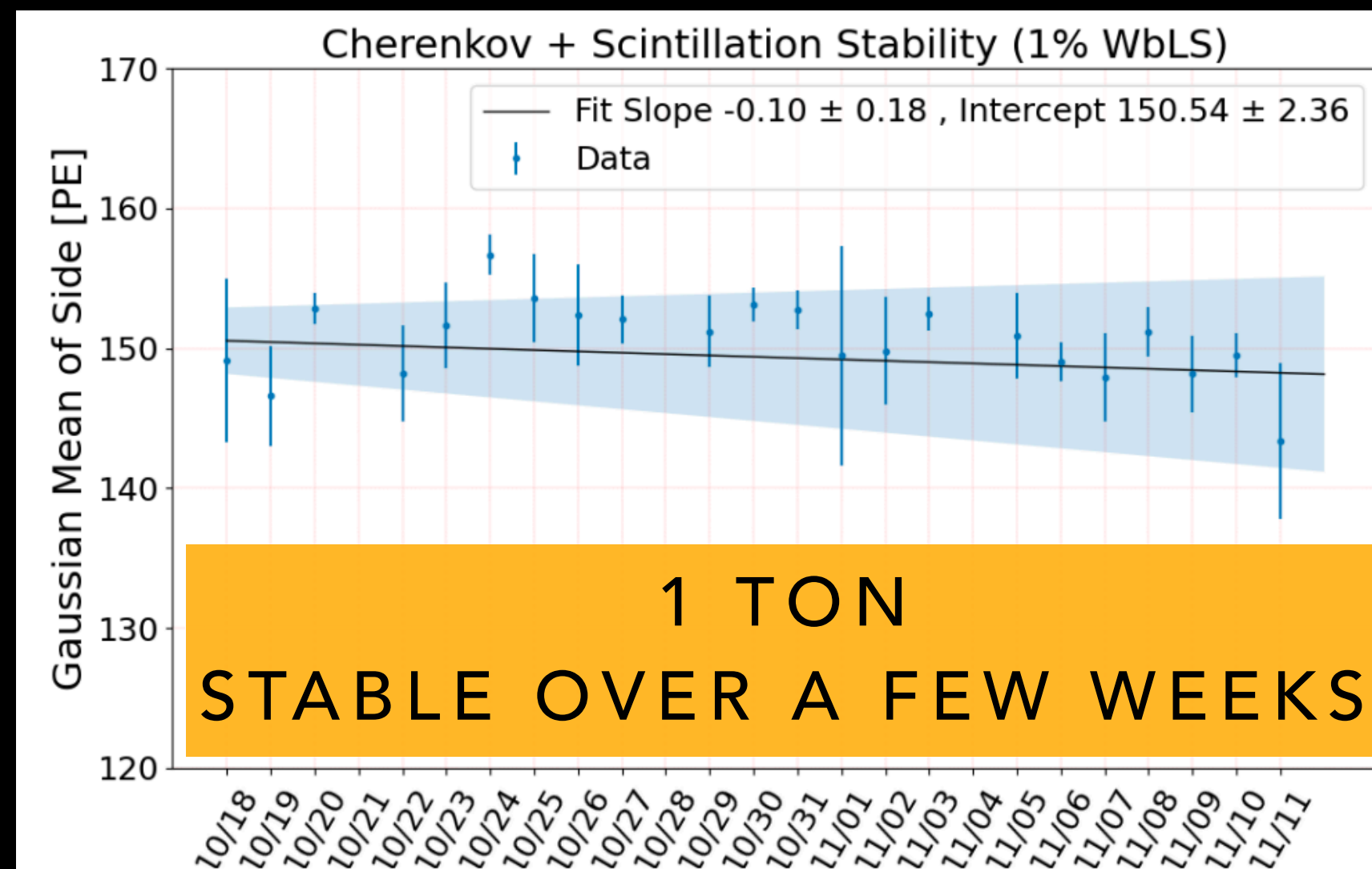
ALFA/BETA PSD
SEEMS HARD



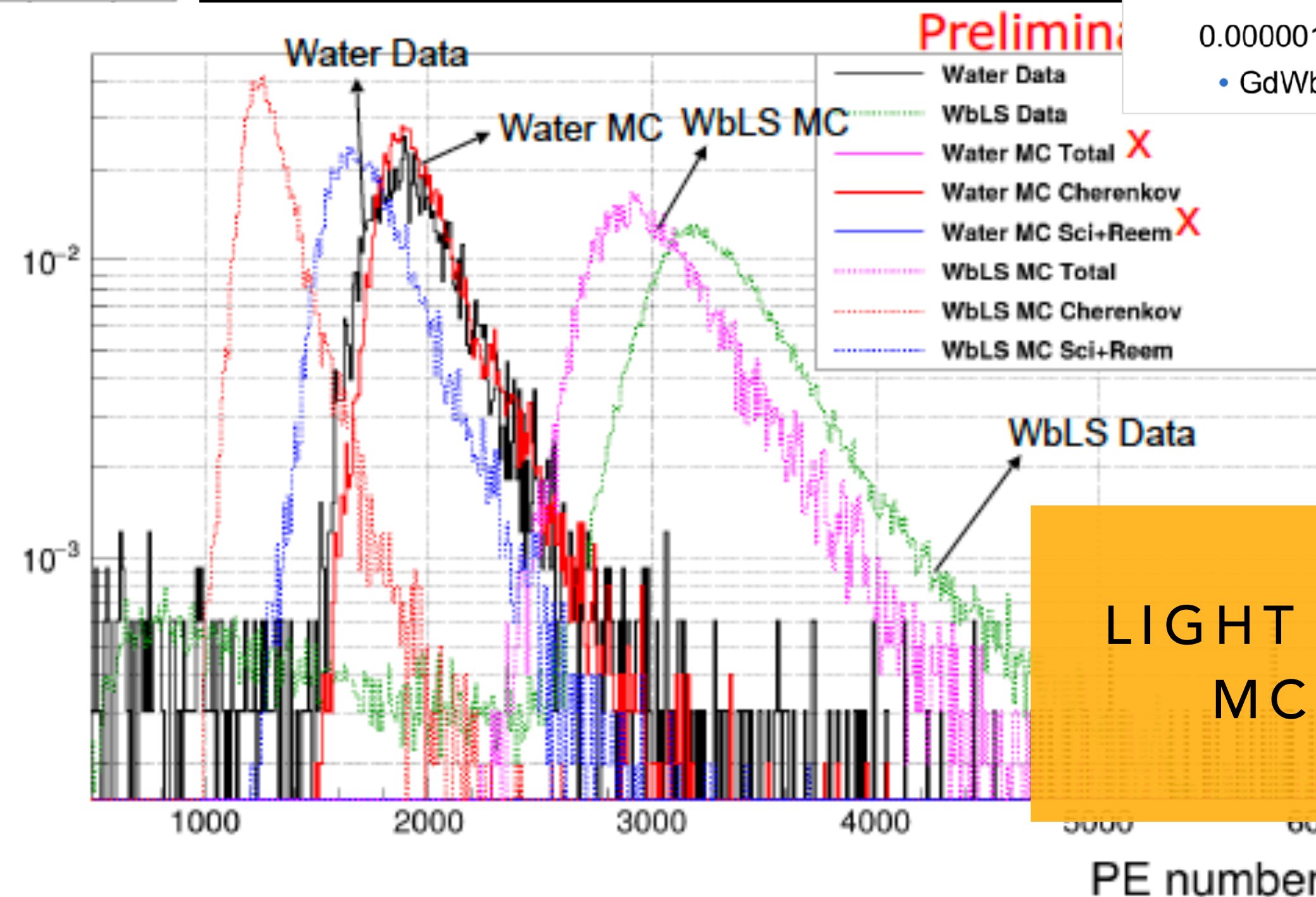
1 TON
LIGHT INCREASE AS WATER
REPLACED BY WBLS



30 TON
GD-LOADED WBLS



1 TON
STABLE OVER A FEW WEEKS



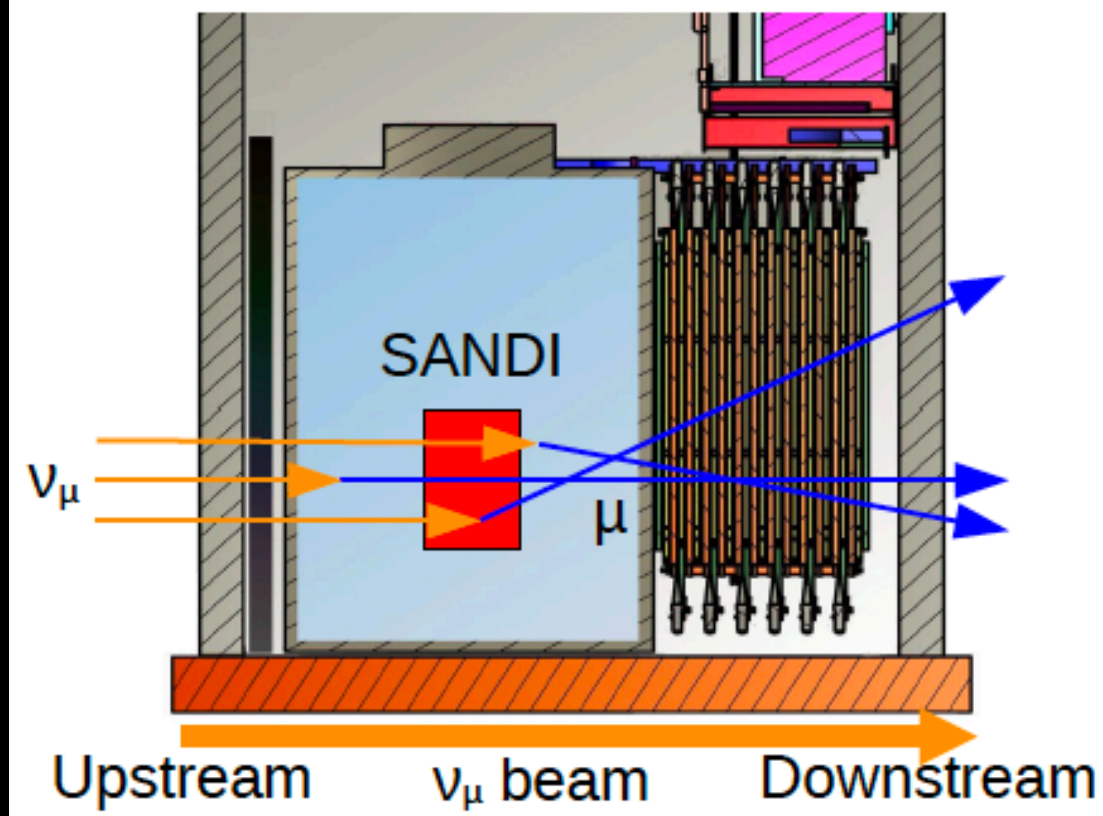
30 TON
LIGHT DOUBLES IN WBLS
MC COMPARISONS
ONGOING

WBLS AT ANNIE, EOS

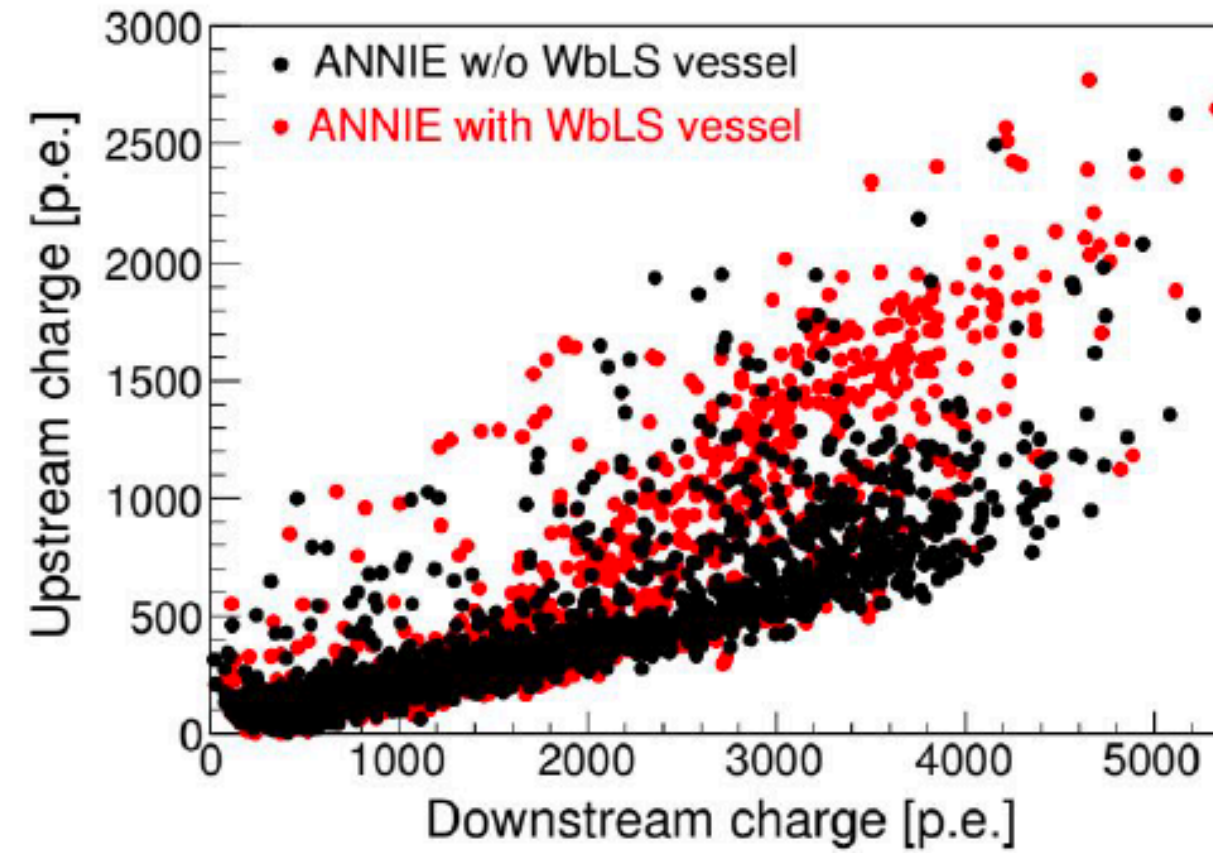
J. MARTYN, R. SVOBODA,
L. PICKARD



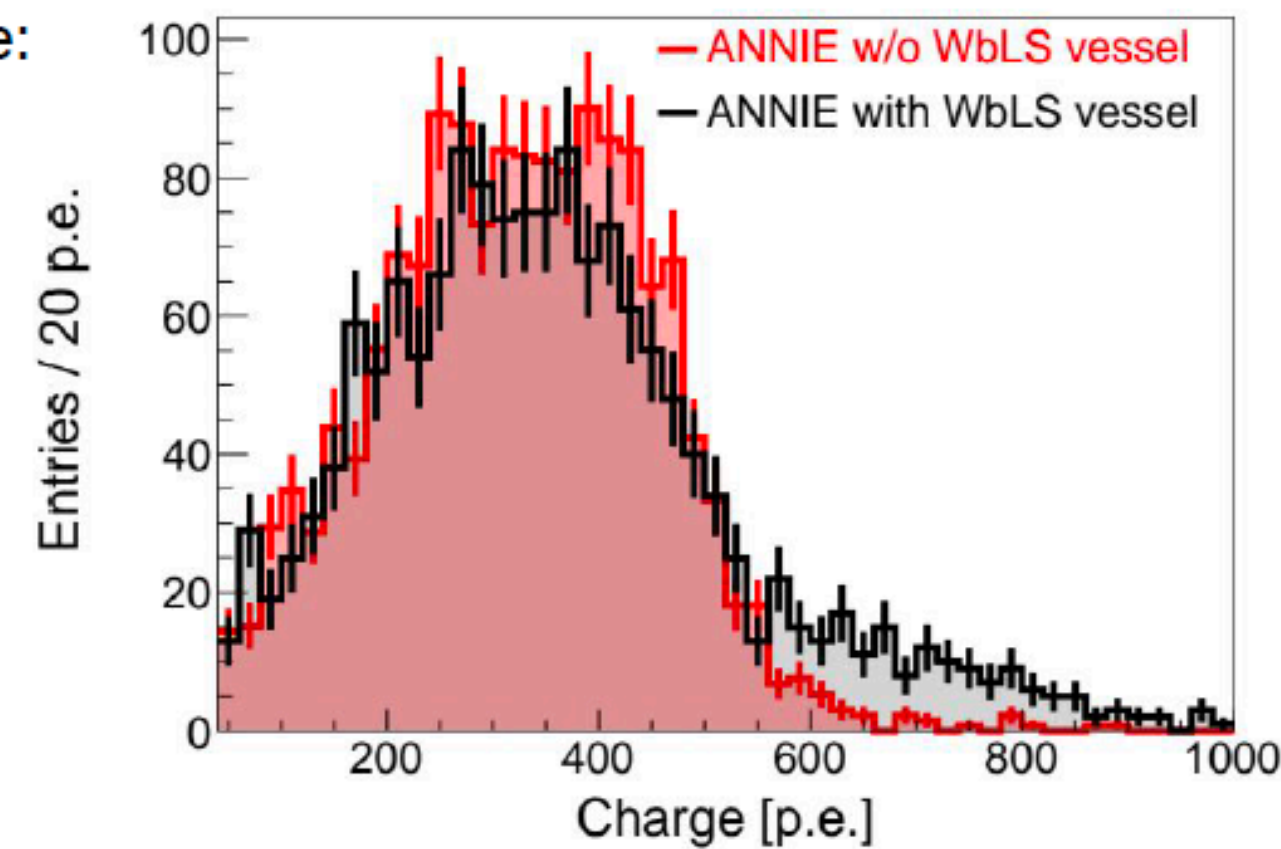
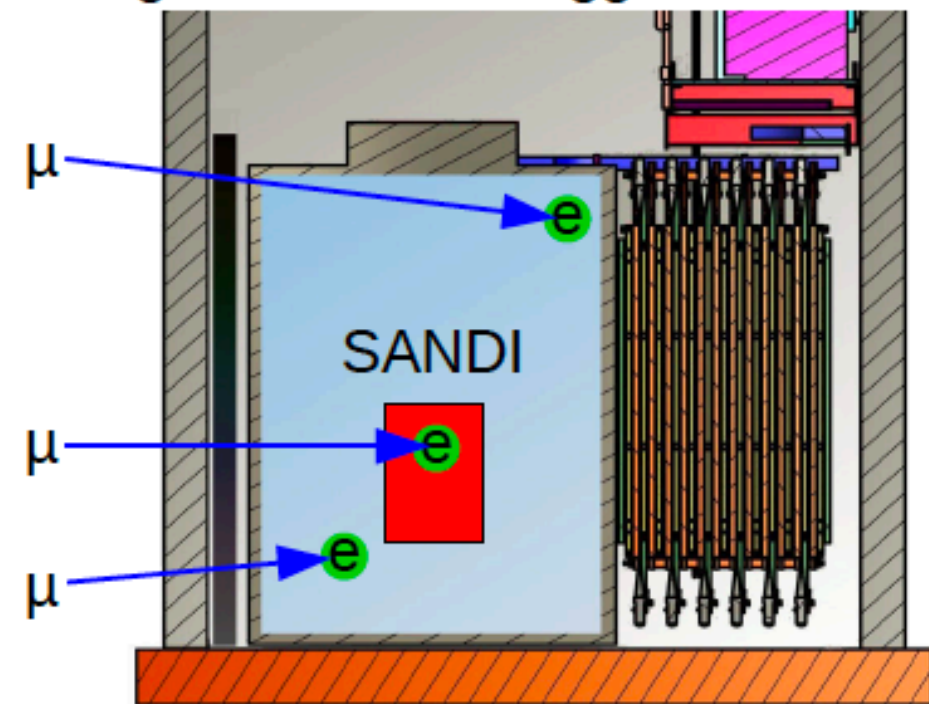
No FMV trigger: neutrino candidates



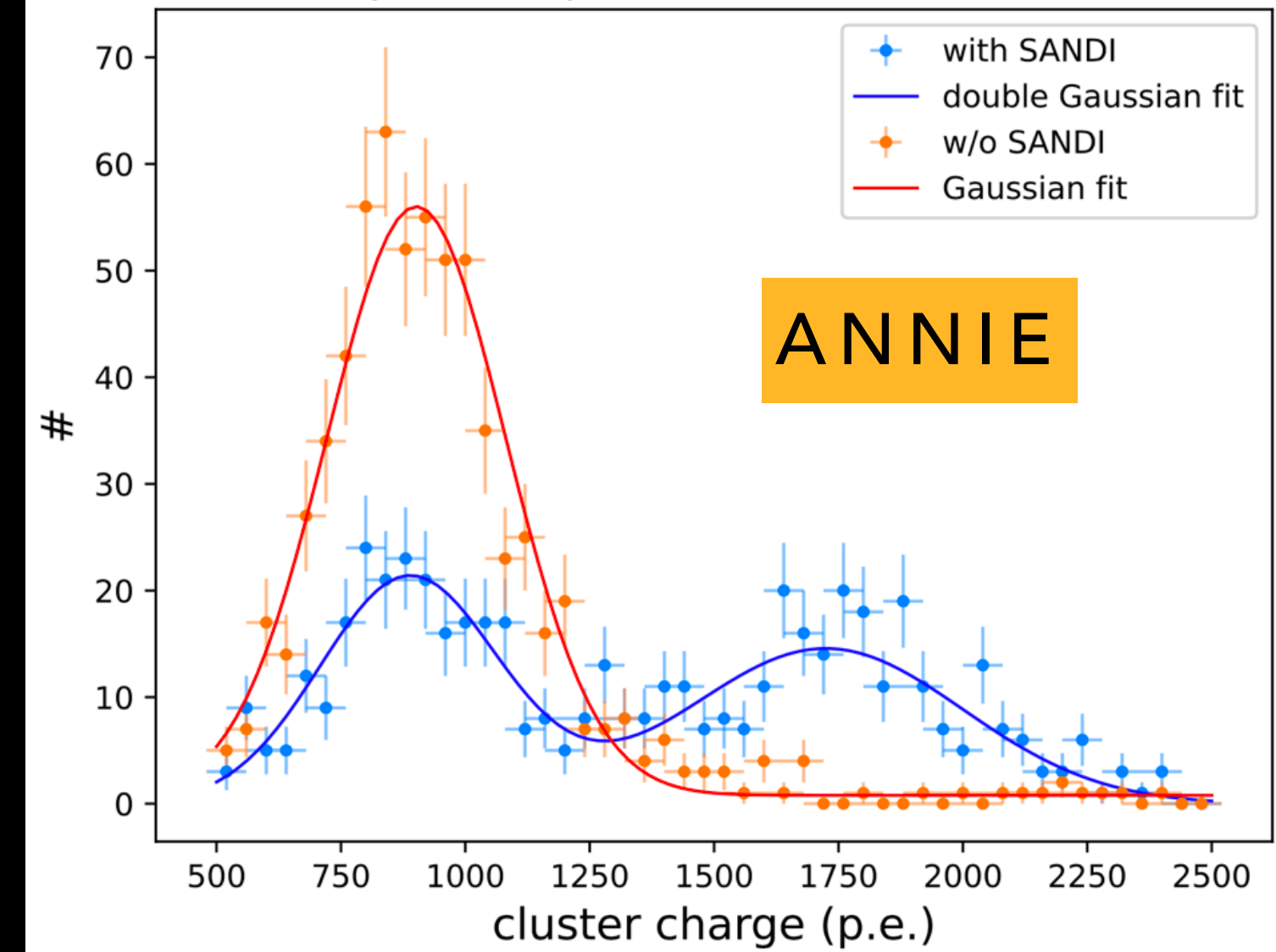
Neutrino candidate events



FMV signal, no MRD trigger, event coincidence:

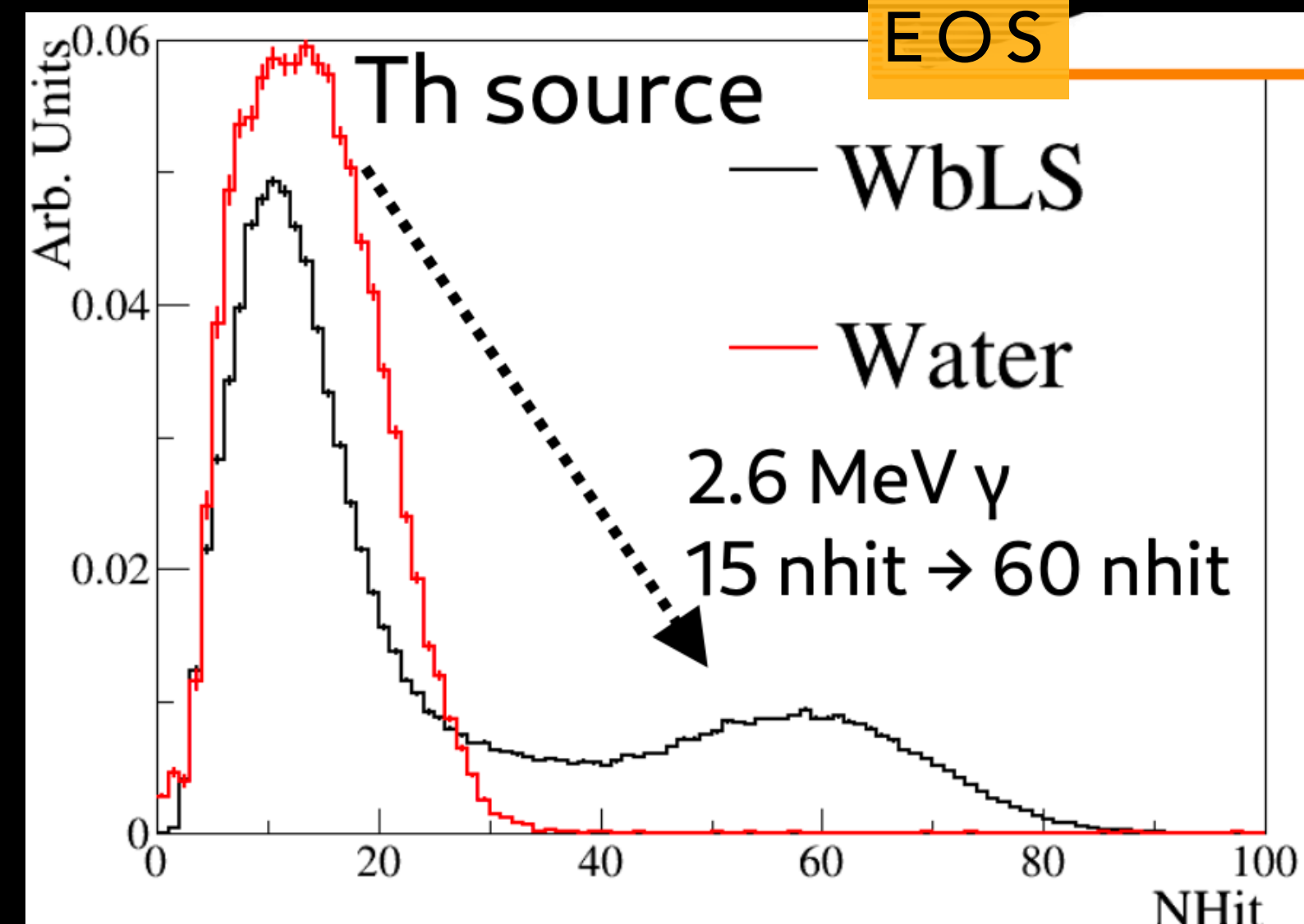


upstream peaks, SANDI at -0.75m

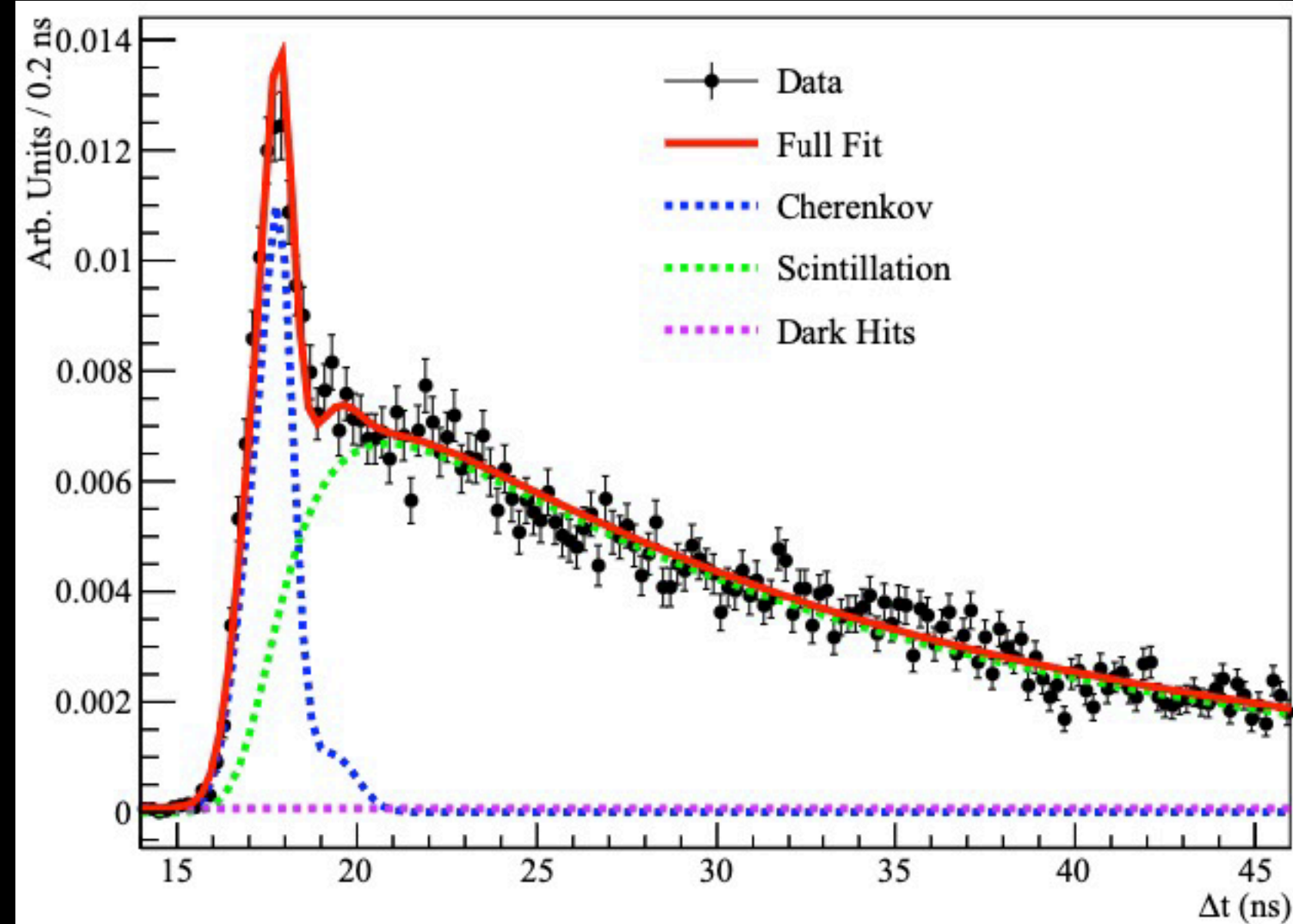


ANNIE

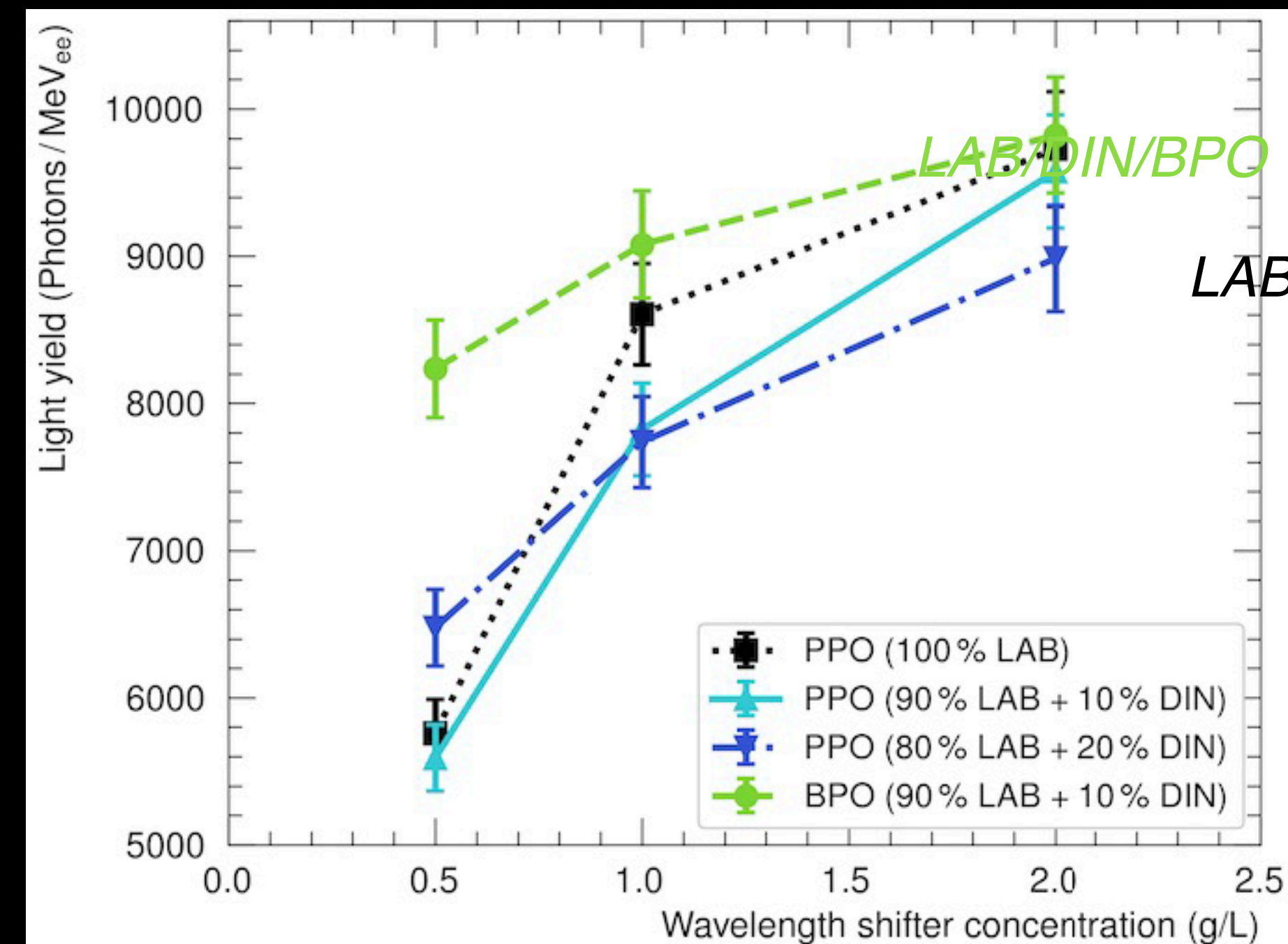
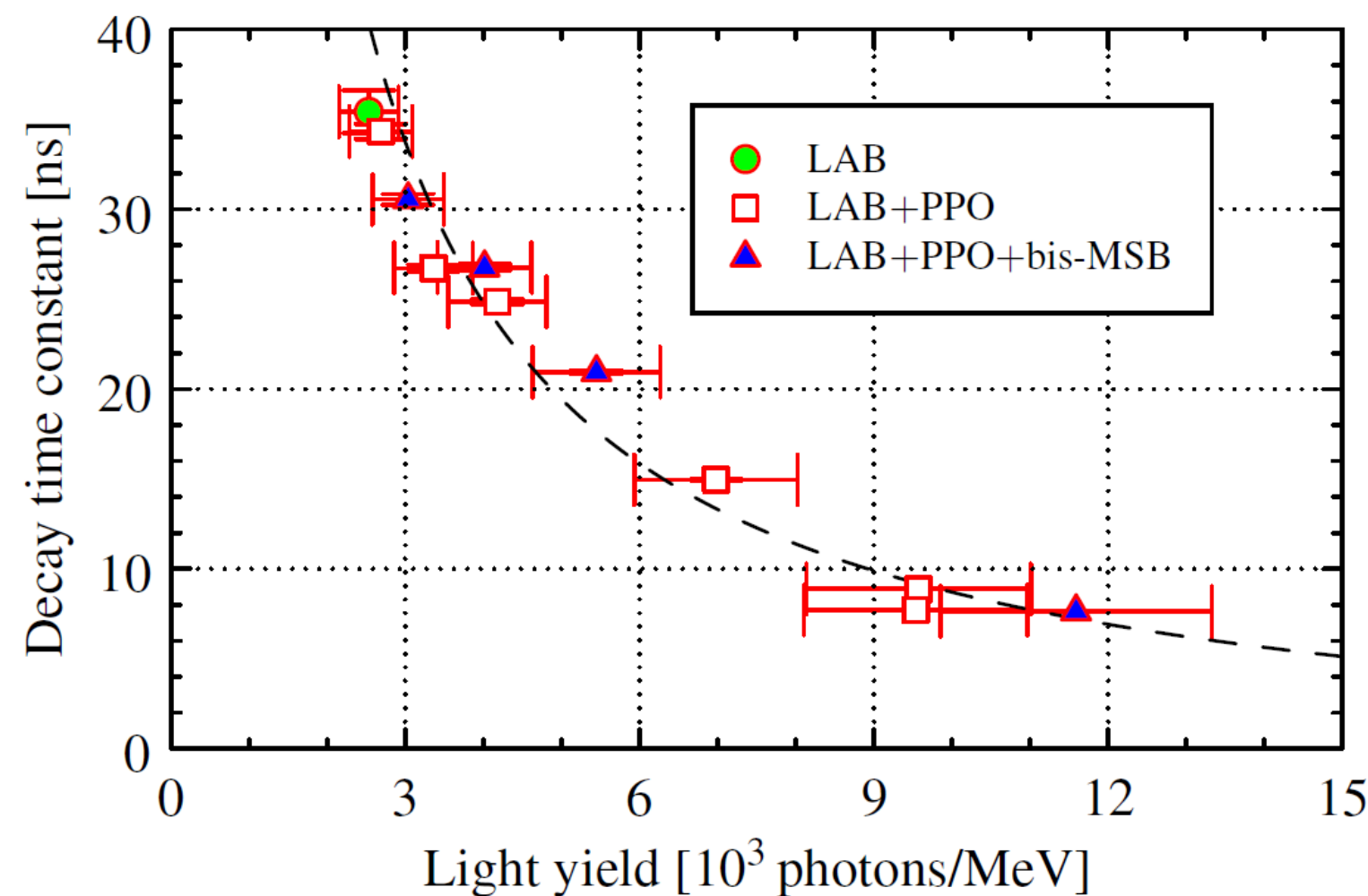
EOS



MORE
SCINTILLATOR
DEVELOPMENT

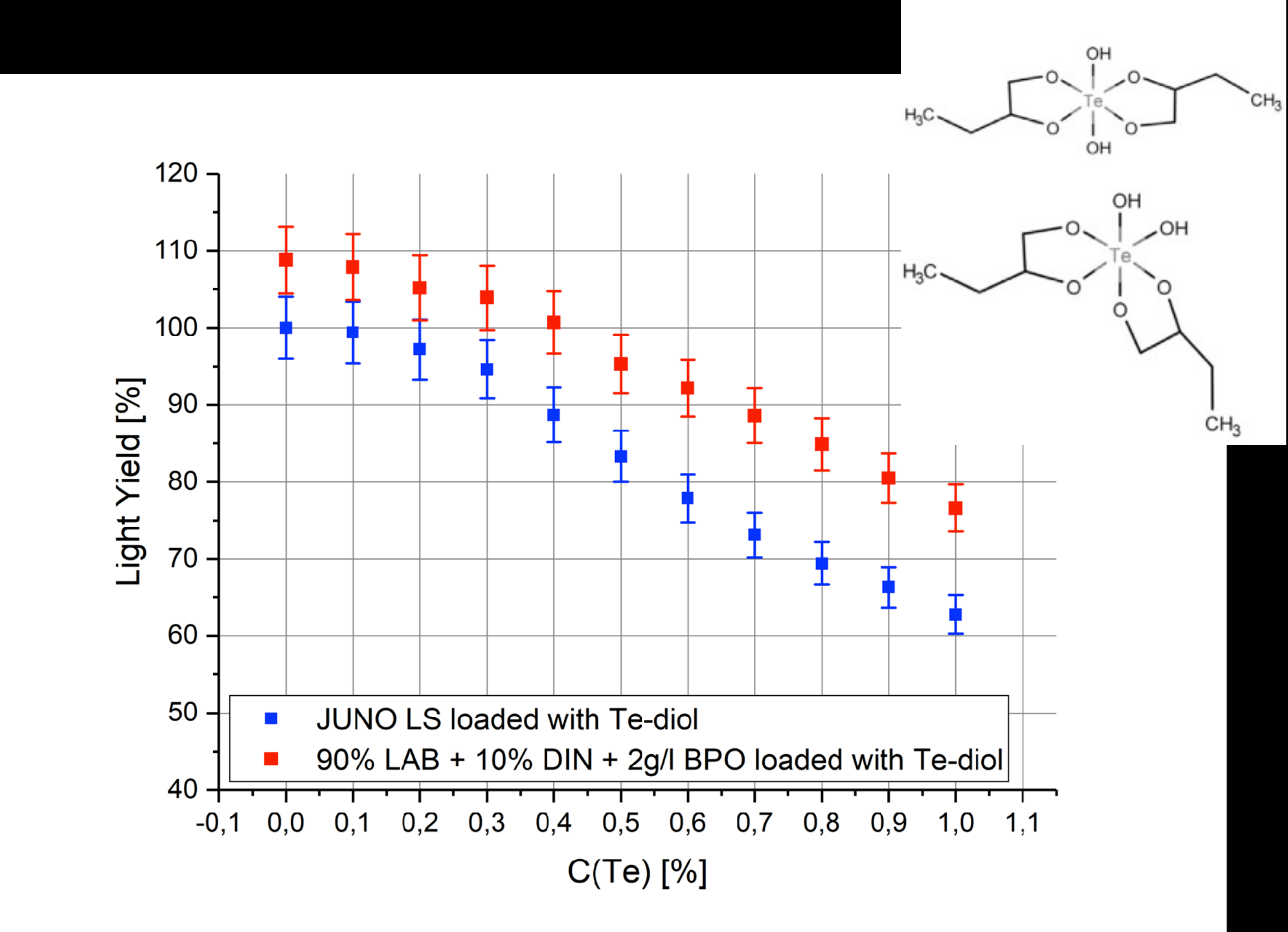
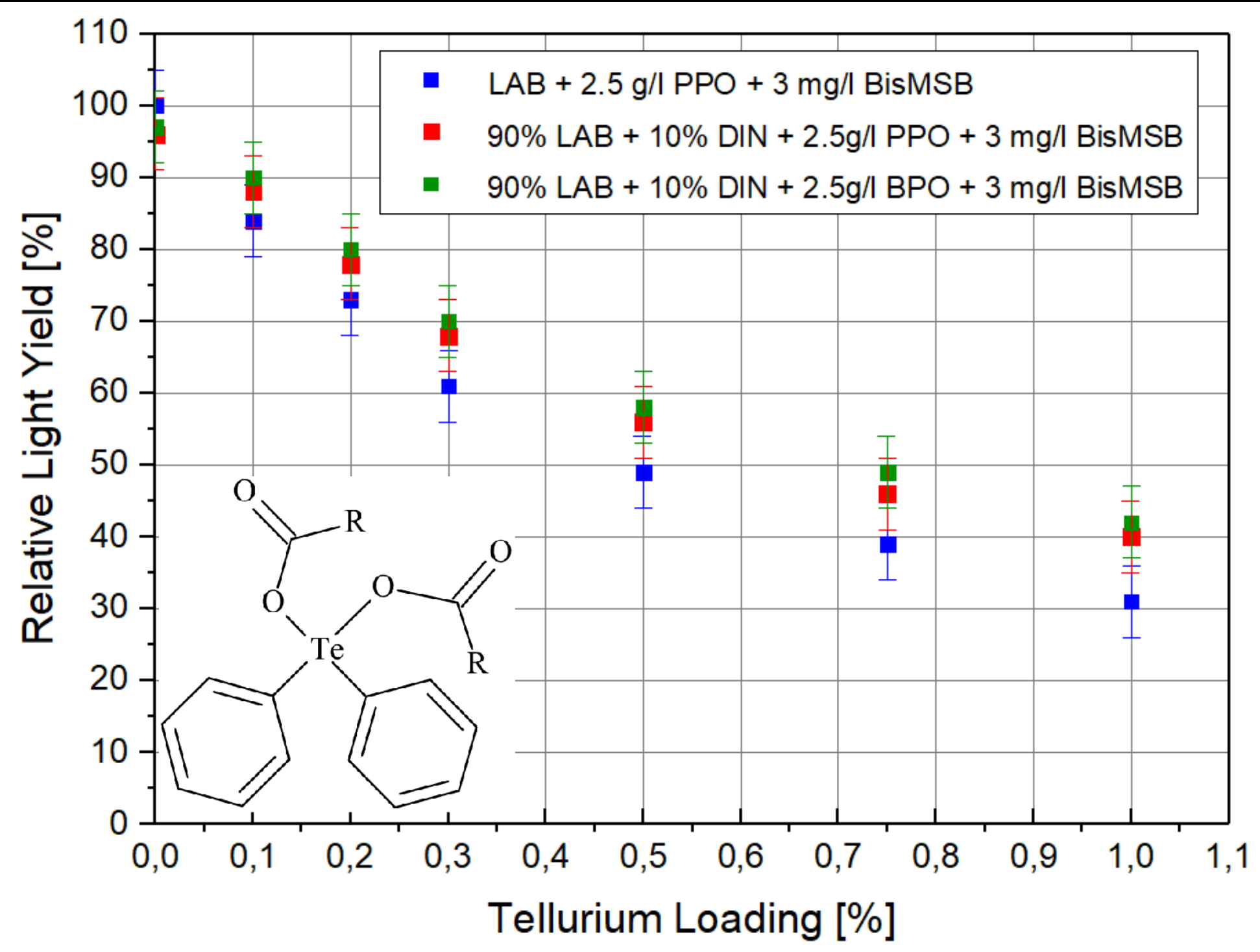


- Slow scintillators: improve Cherenkov separation
- 1. Lower the fluor concentration. Low light yields, excellent transparency
- 2. Slow fluors. Several problems: expensive, toxic, emission deep in the UV, some loss in LY
- 3. Multi-solvent cocktails (e.g. LAB/DIN)



LOADING VIA THE METHOD OF I.A. SUSLOV ET AL., DIPHENYLTELLURIUM DICARBOXYLATES

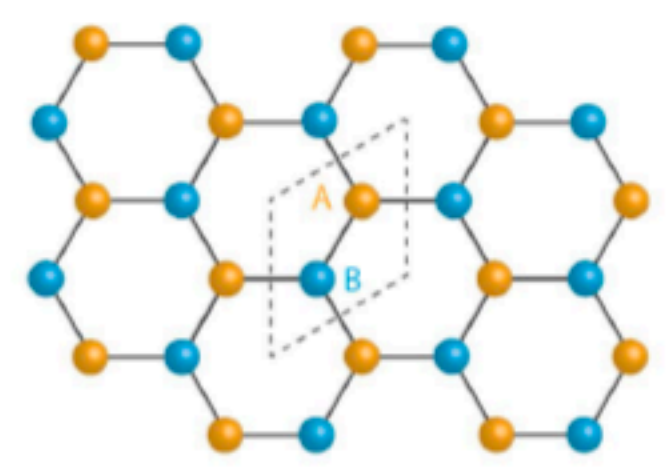
LOADING WITH DIOLS (SNO+ TECHNIQUE) BETTER LY



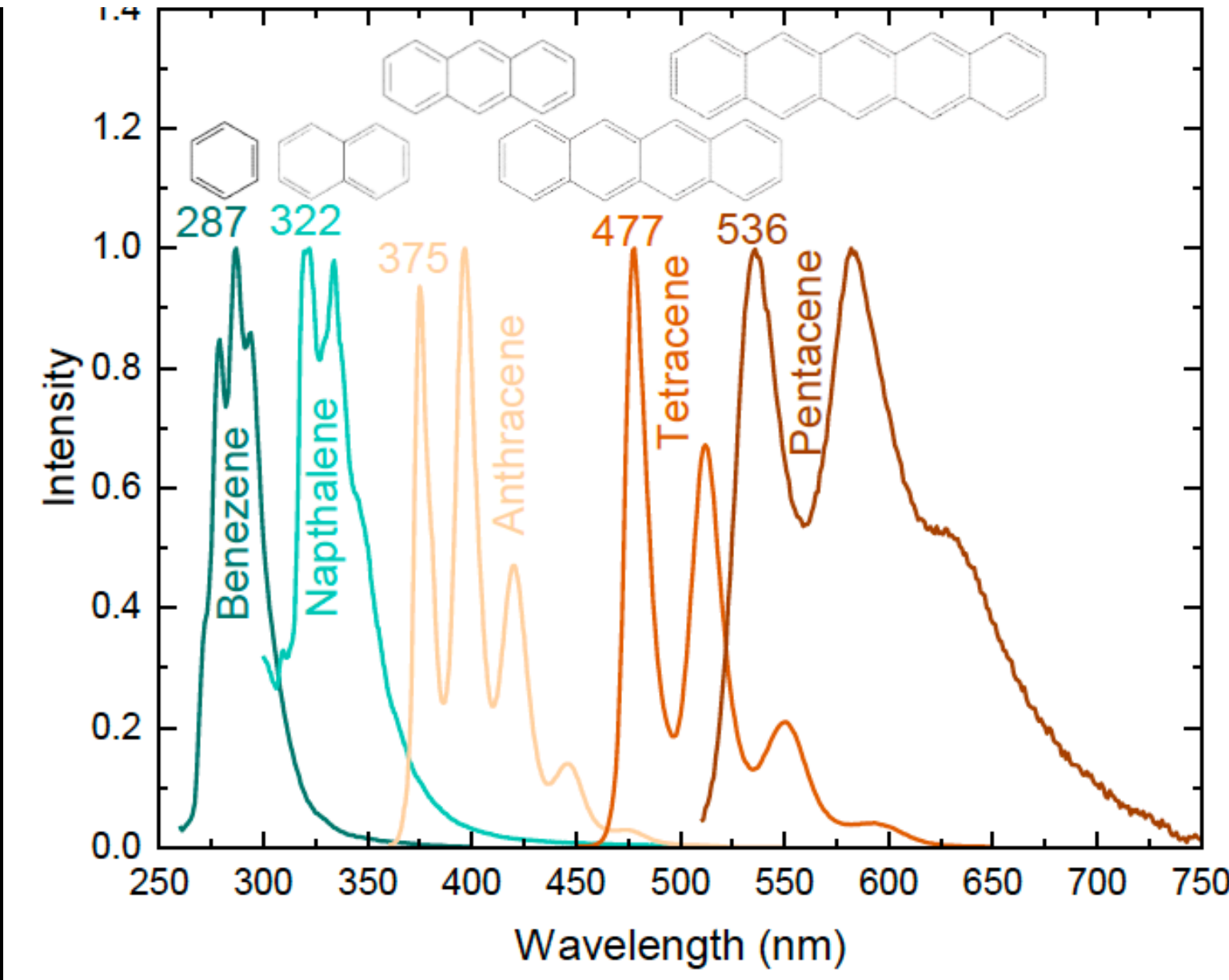
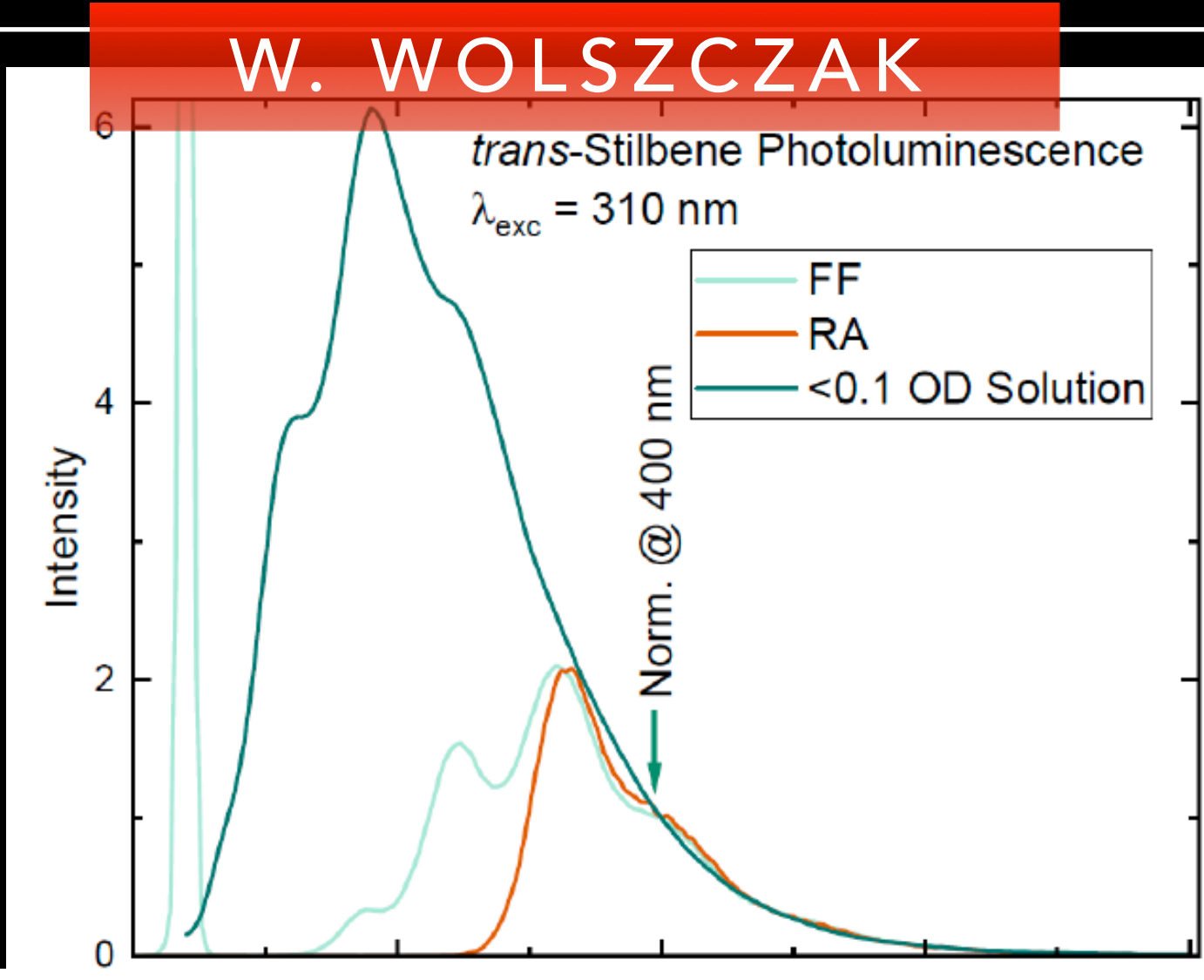
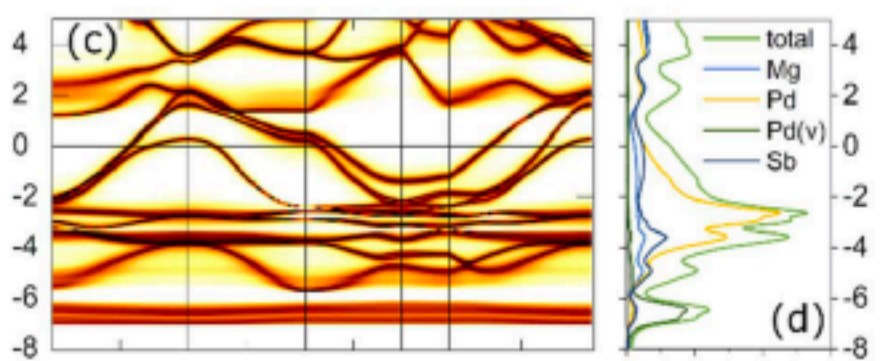
MODEL SCINTILLATOR PROPERTIES



The Periodic Table of the Elements																																																					
1	2																	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18																				
1	H																	3	Li	4	Be											19	K	20	Ca																		
5	B	6	C	7	N	8	O	9	F	10	Ne											21	Sc	22	Ti	23	V	24	Cr	25	Mn	26	Fe	27	Co	28	Ni	29	Cu	30	Zn	31	Ga	32	Ge	33	As	34	Se	35	Br	36	Kr
9	F	10	Ne																	35	Br	36	Kr											51	Sb	52	Te	53	I	54	Xe									85	At	86	Rn

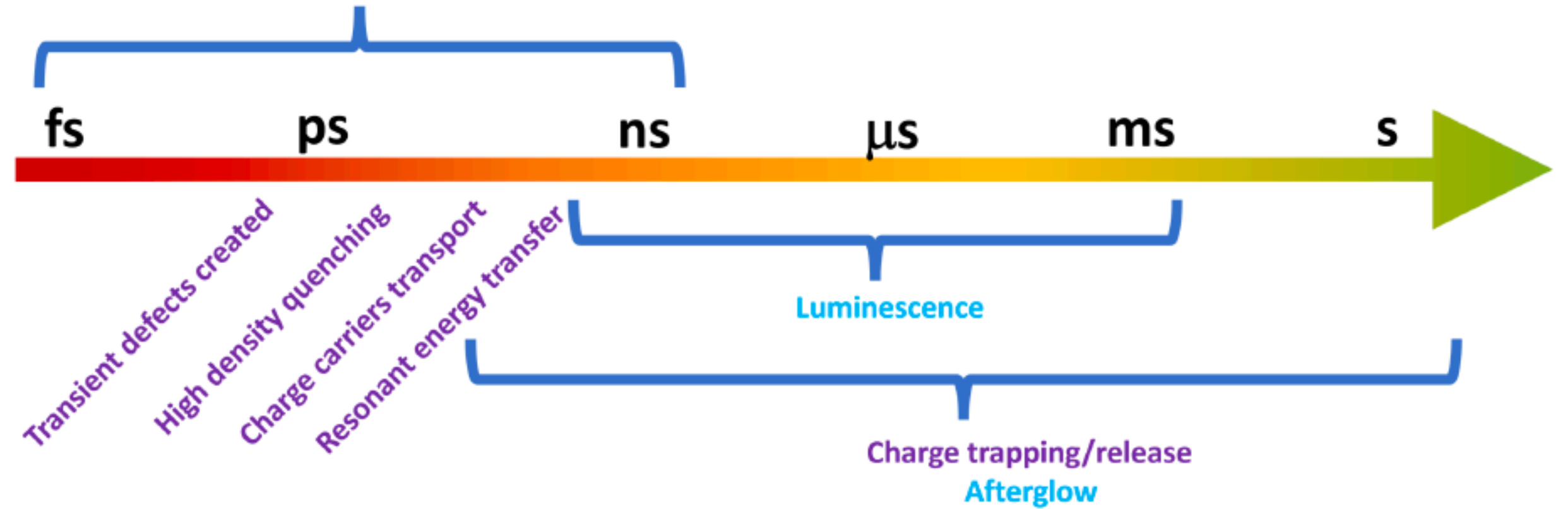


Properties = Composition + Structure

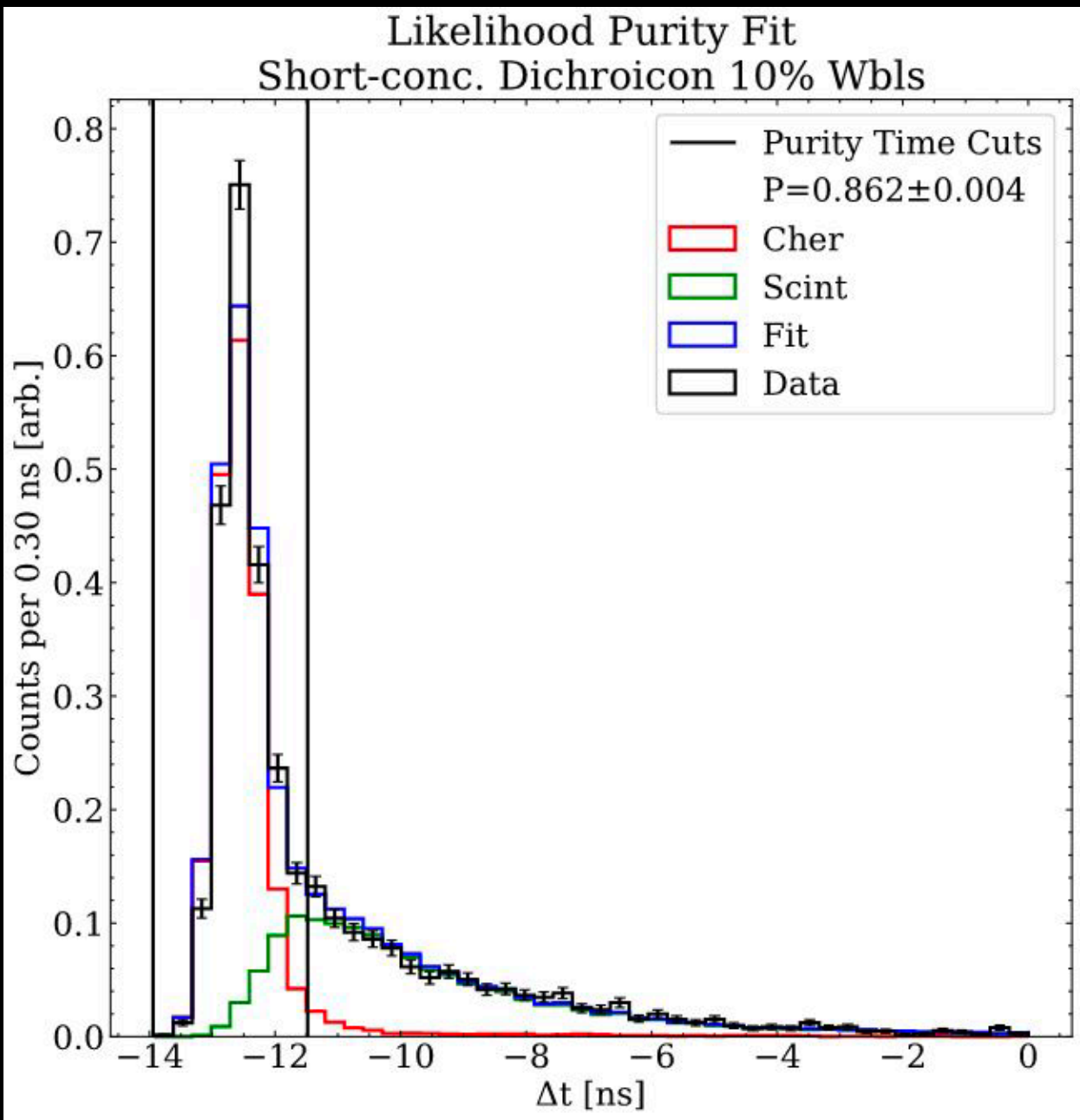
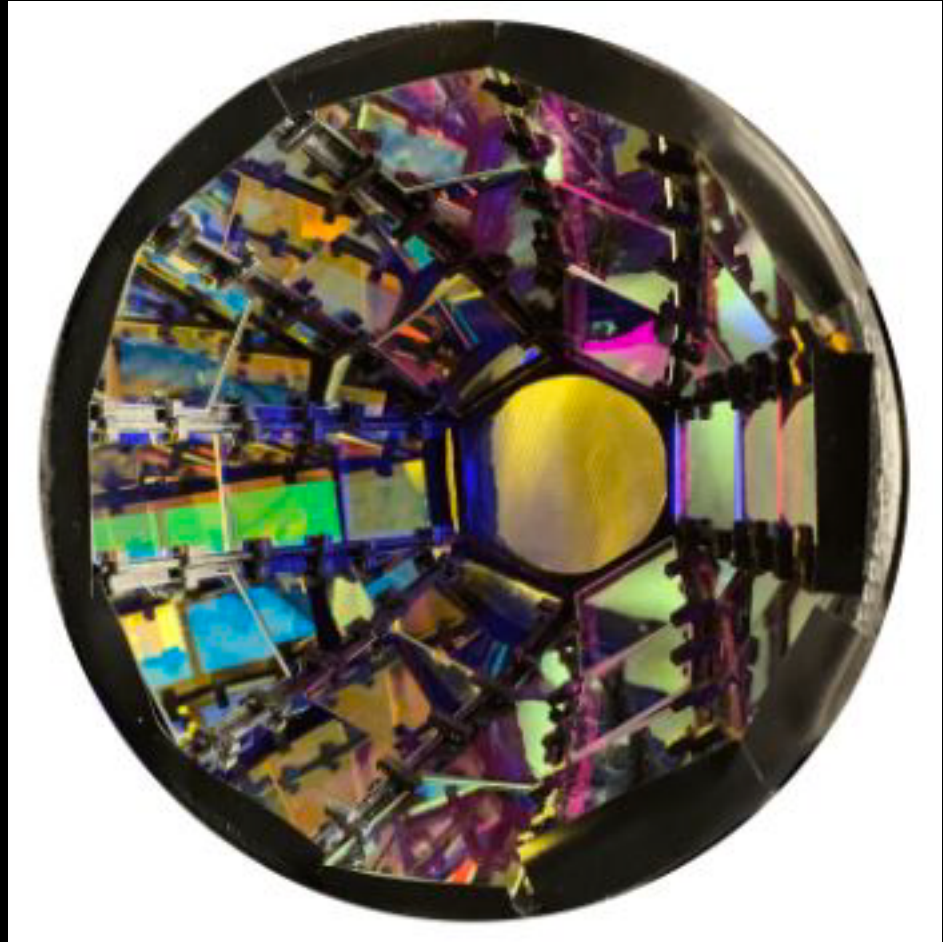
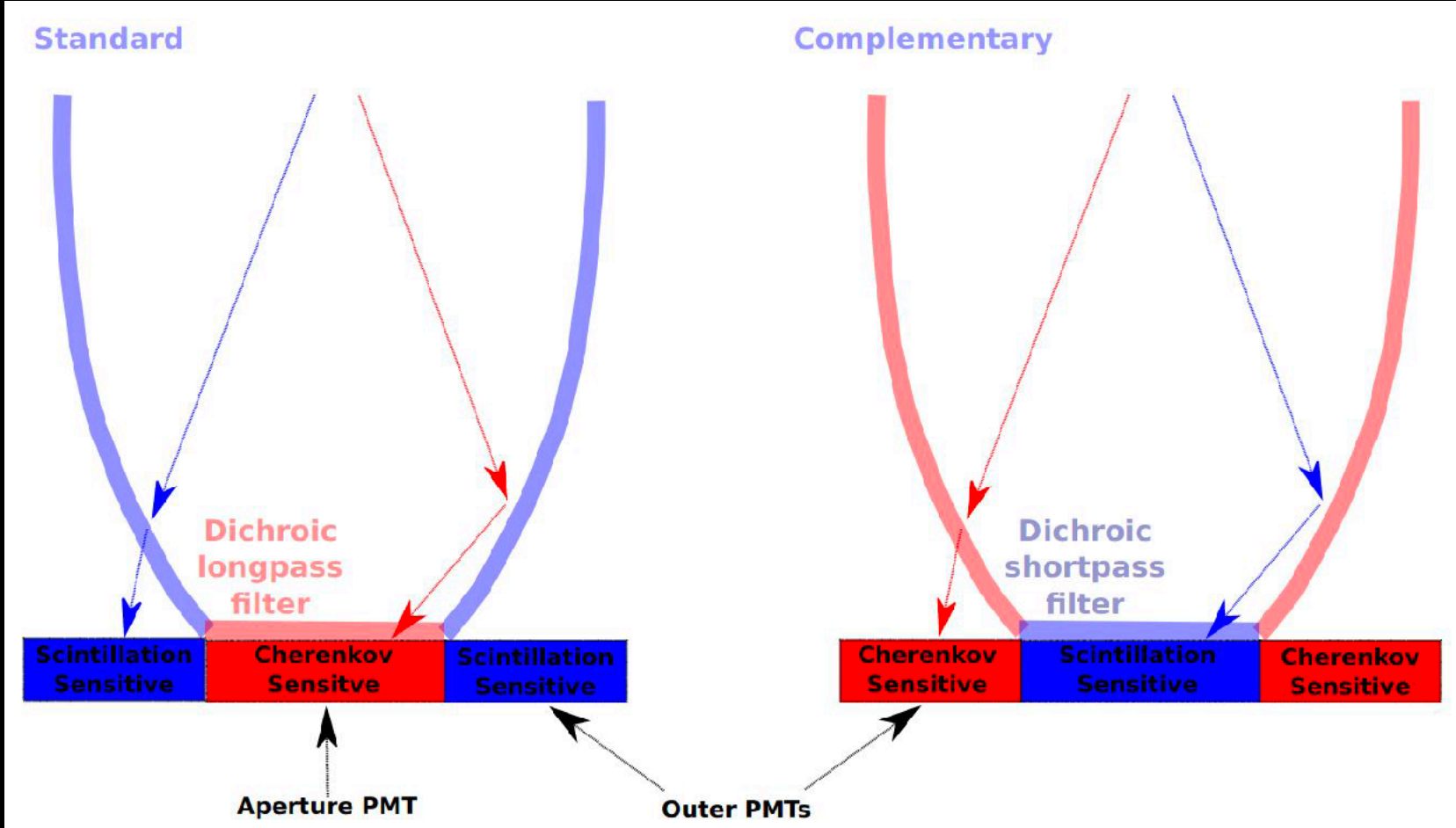
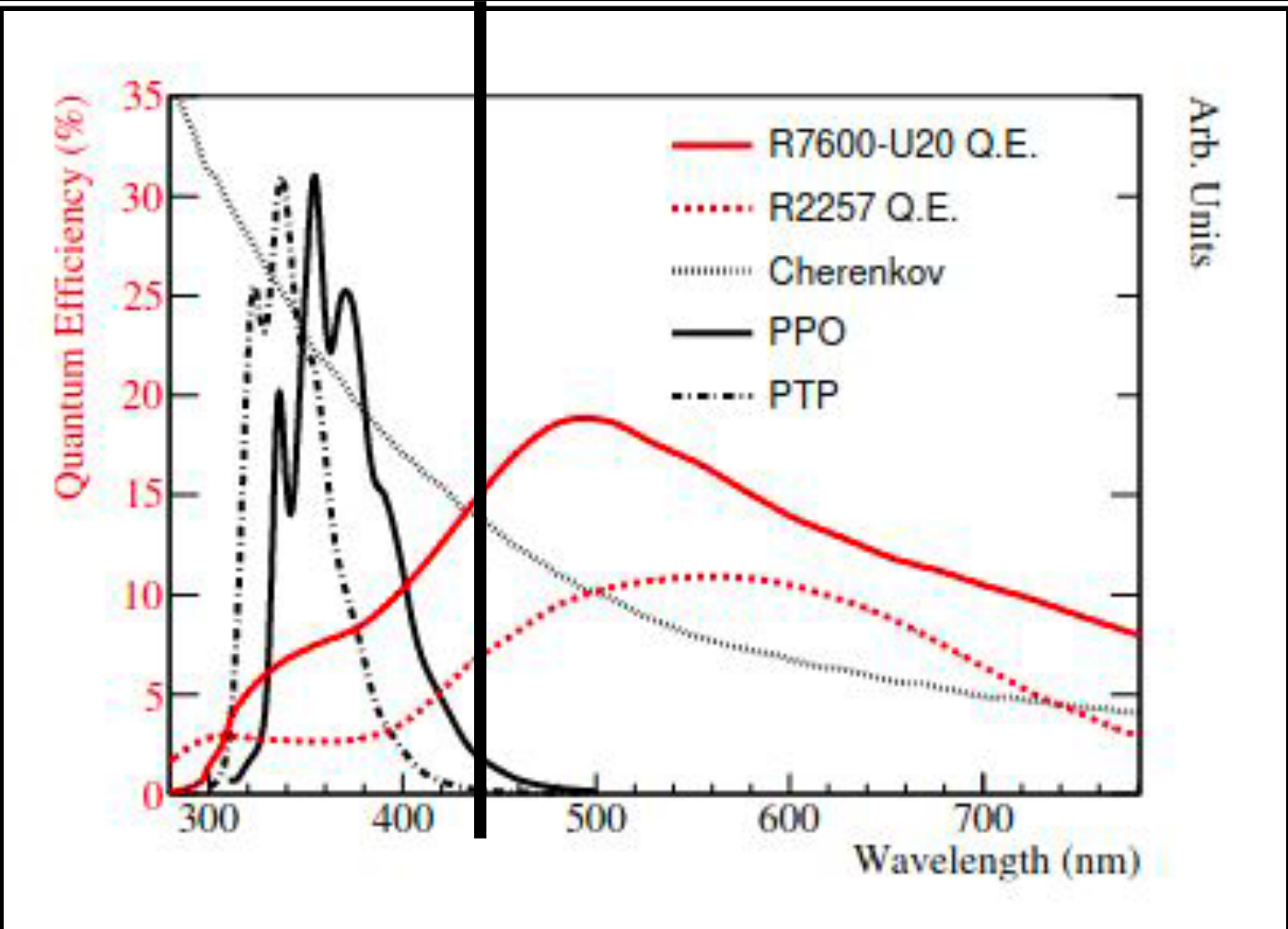


Why ultrafast spectroscopy?

- Accessible only through ultrafast techniques:
- Transient absorption (pump & probe experiments)
 - Ultrafast luminescence (time & wavelength resolved)

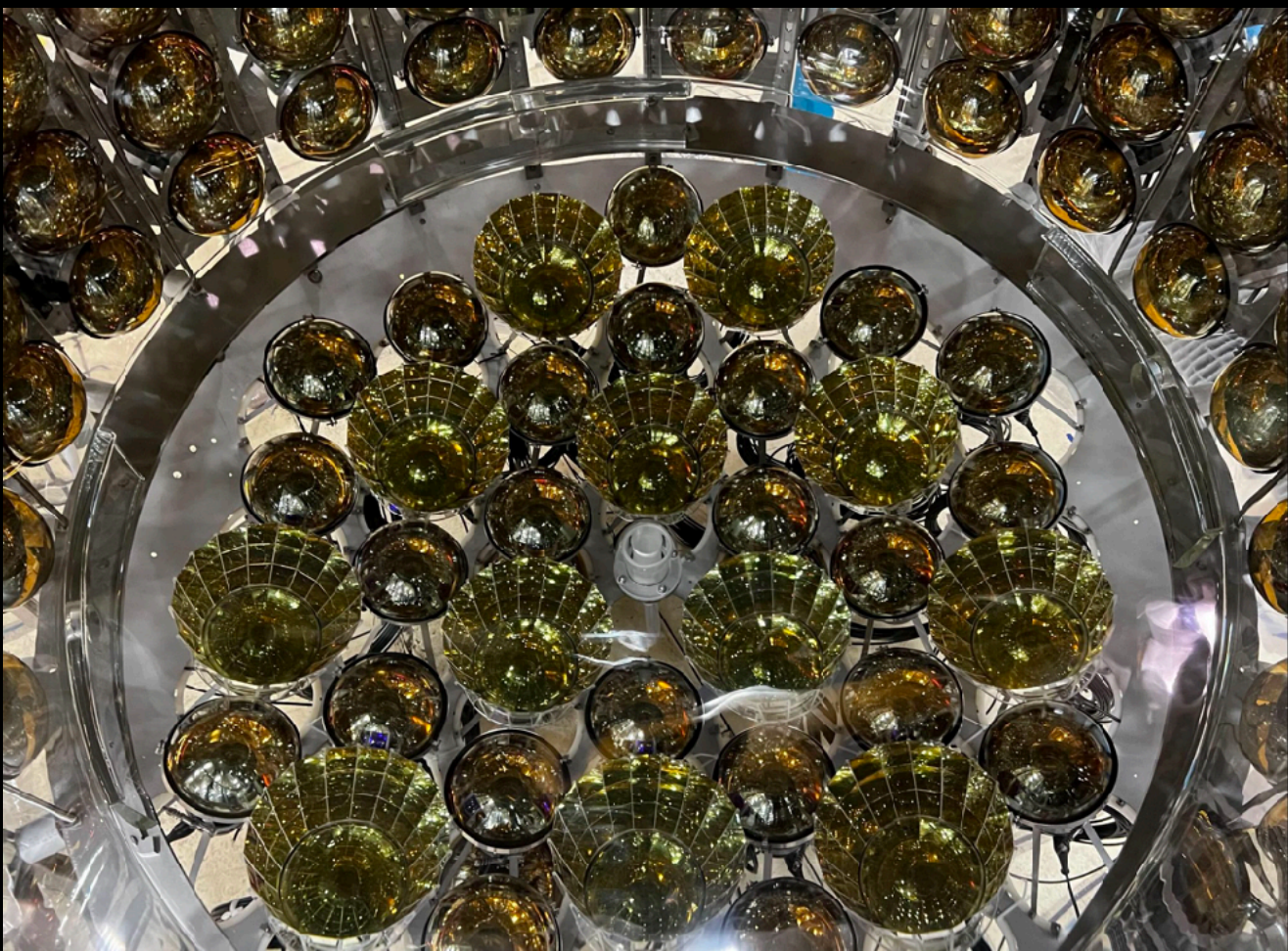


PHOTON SENSORS

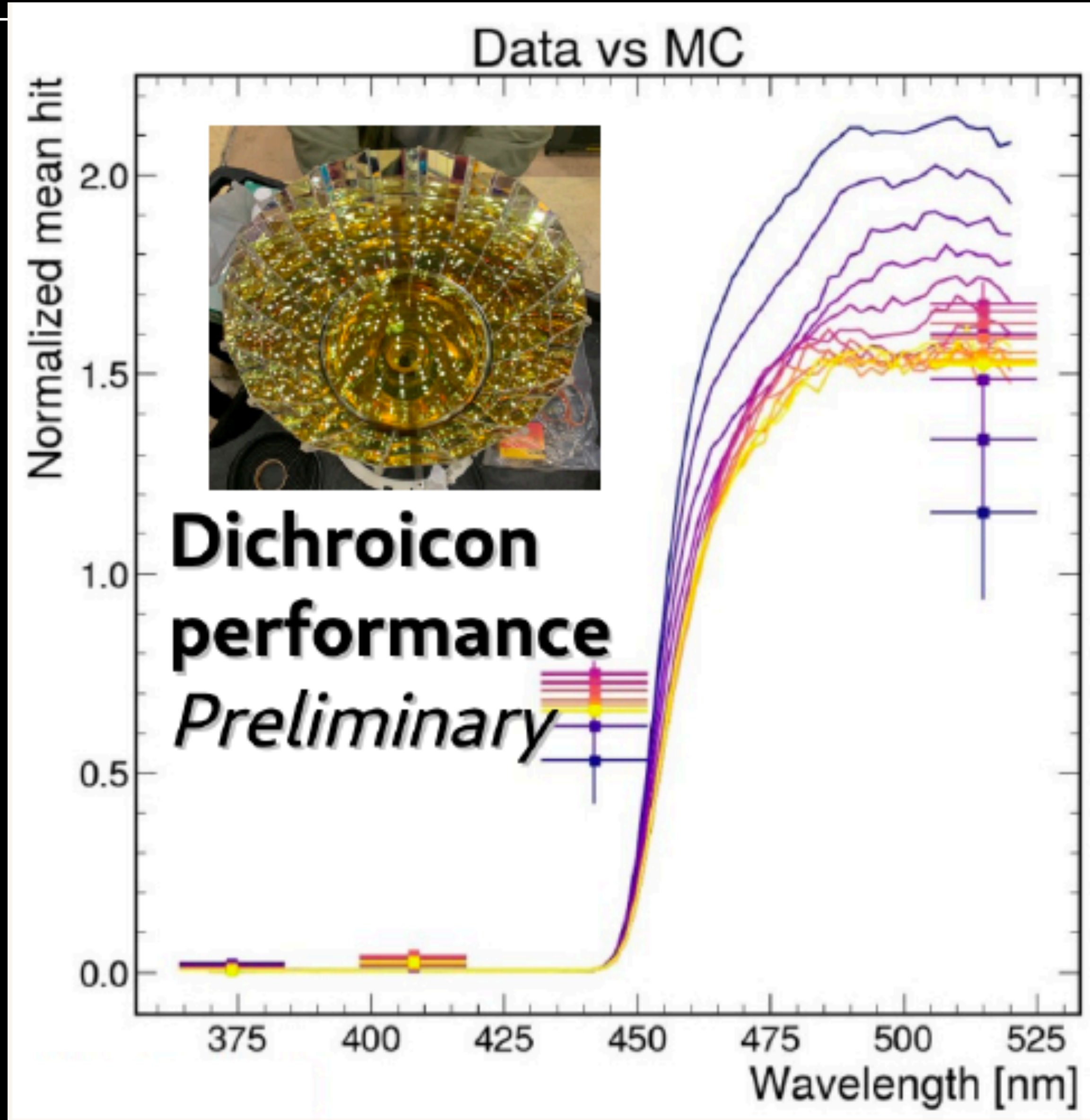


Purities		
	Long-conc.	Short-conc.
10% WbLS	0.978 ± 0.004	0.862 ± 0.004
LABPPO	0.990 ± 0.001	0.832 ± 0.002

- Several promising results coming out of tests at Penn
- Now several of these are in Eos, more results soon



- Optical calibration using laserball

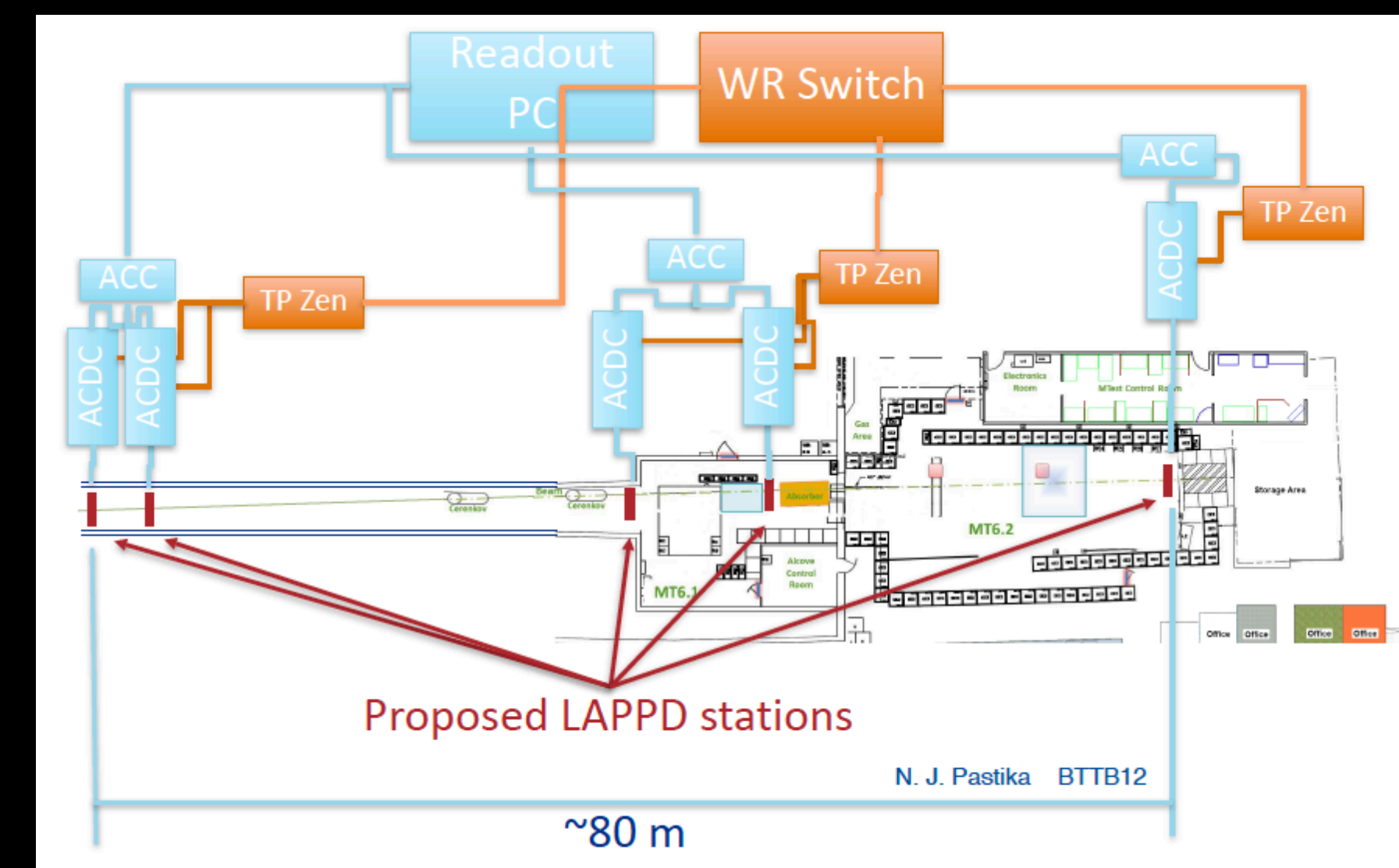
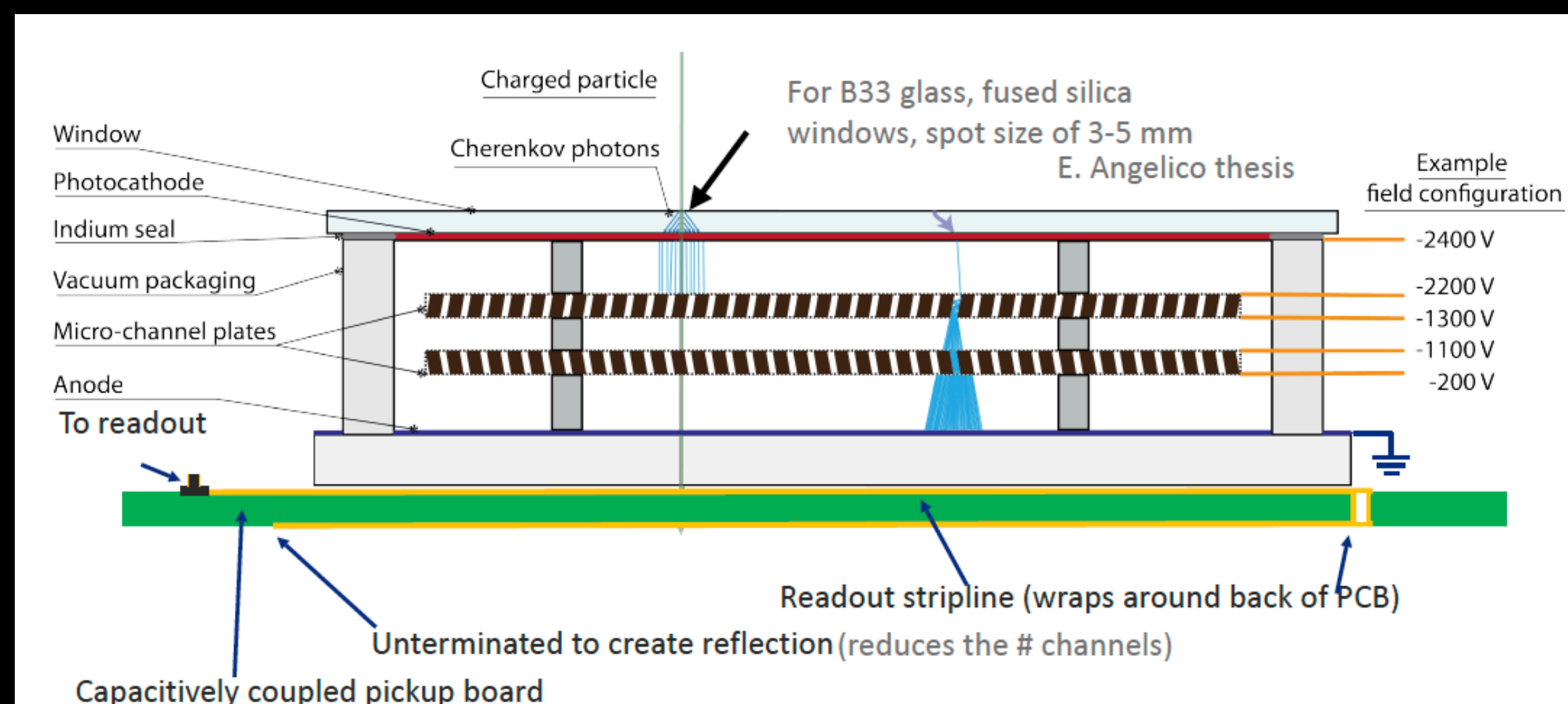
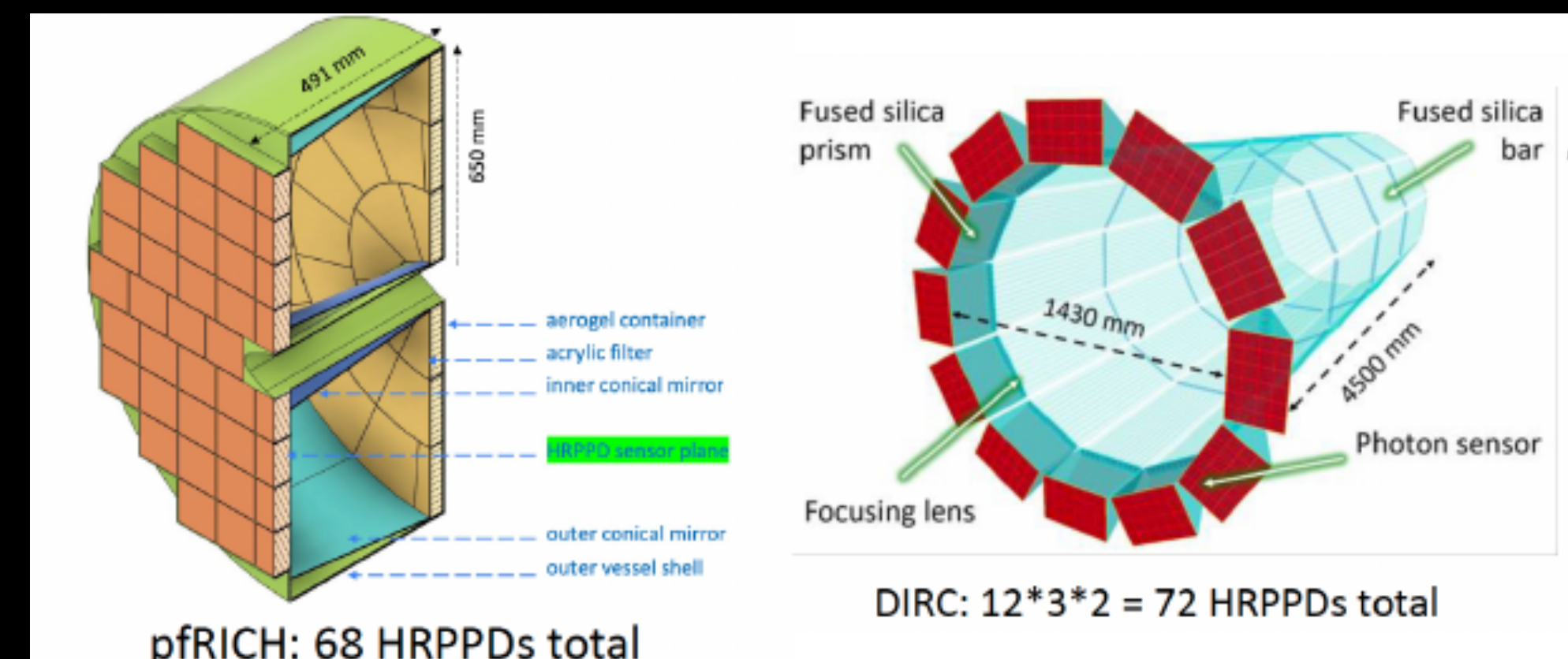


LAPPD CONCEPT, DEVELOPMENT



A. WEINSTEIN

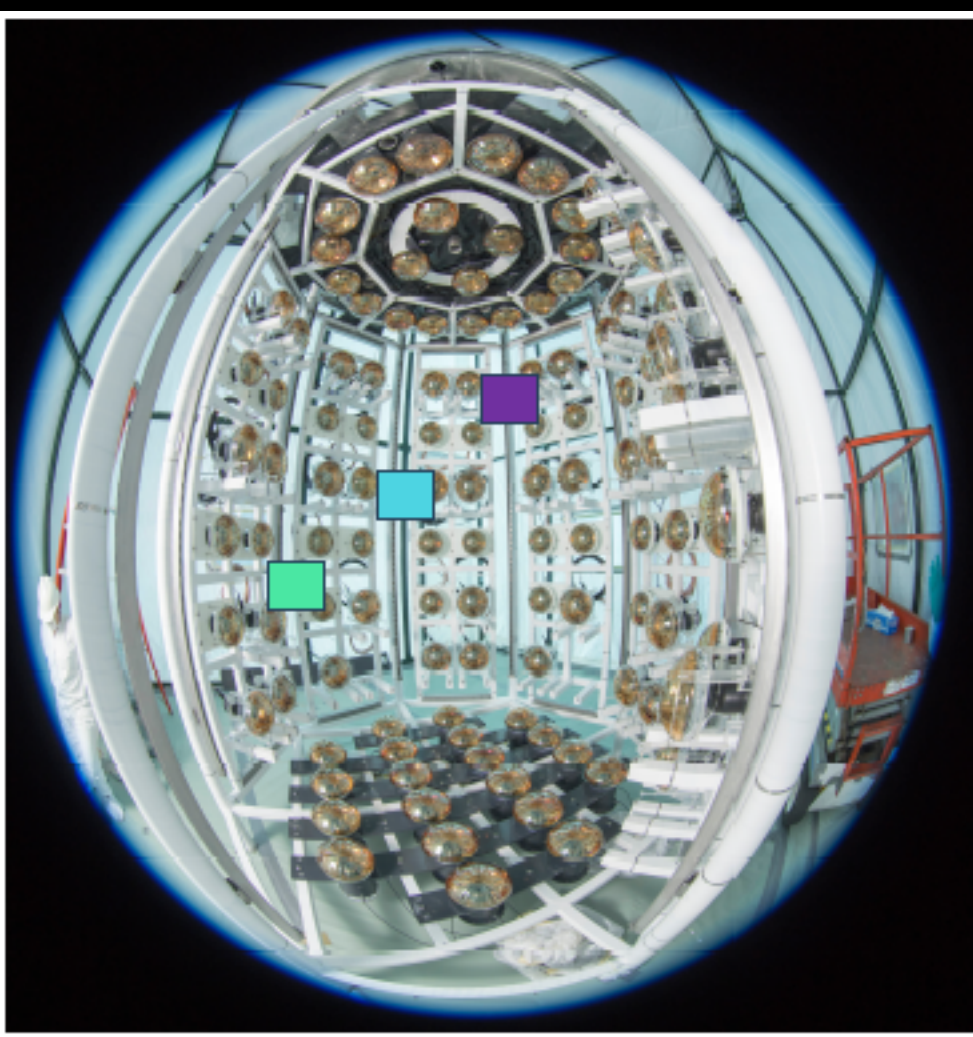
- Large Area Picosecond Photo-Detectors
 - Photocathode + microchannel plate amplification + strips readout
 - Excellent timing (~ 50 ps), high QE ($\sim 30\%$), position sensitive, large area (e.g. 20×20 cm)
- Starting to be used in several HEP applications
 - pfRICH and DIRC (subdetectors of EIC gp det.)
 - Fermilab test beam facility



LAPPD PERFORMANCE @ANNIE

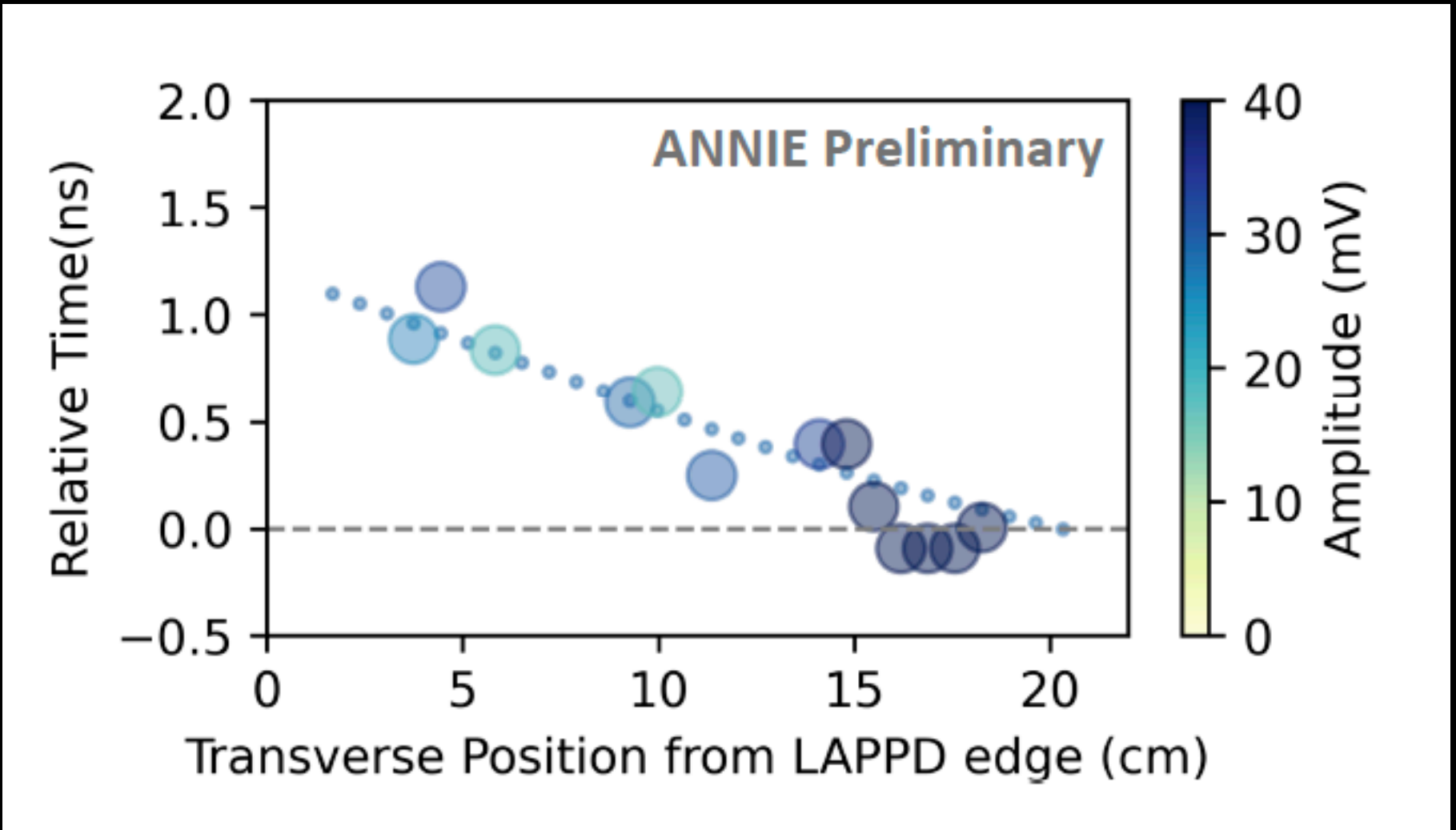
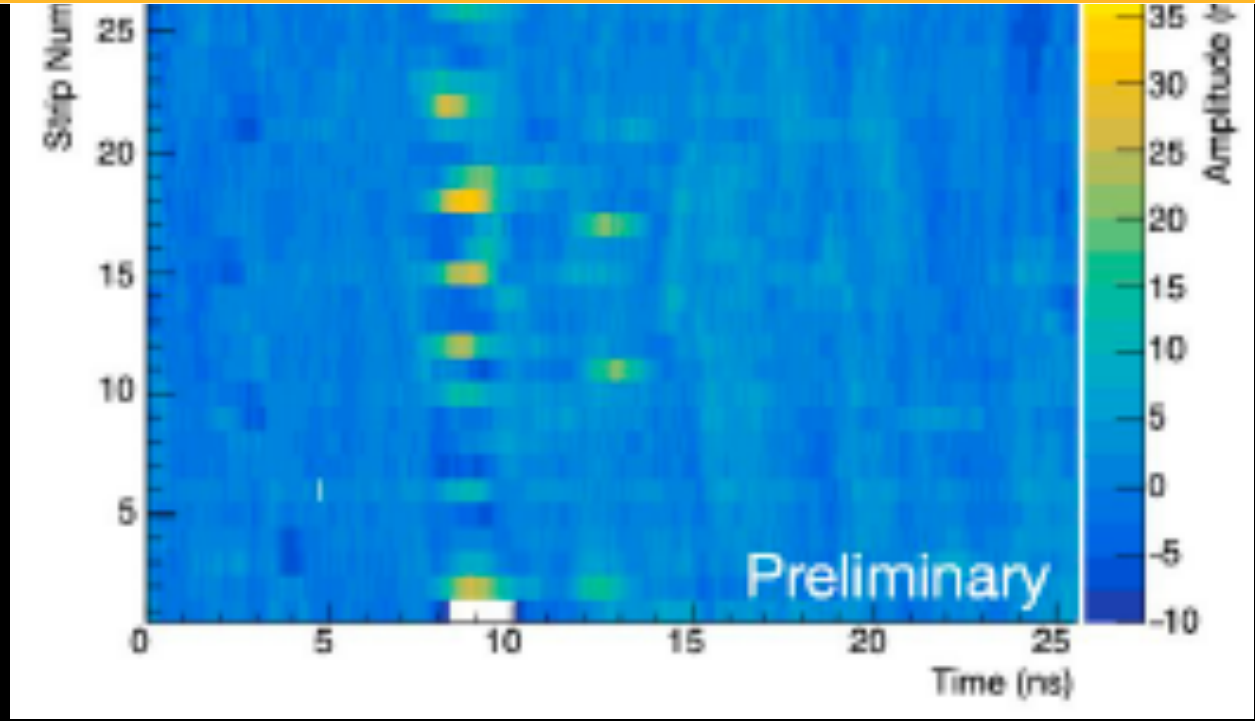


A. WEINSTEIN,
R. SVOBODA

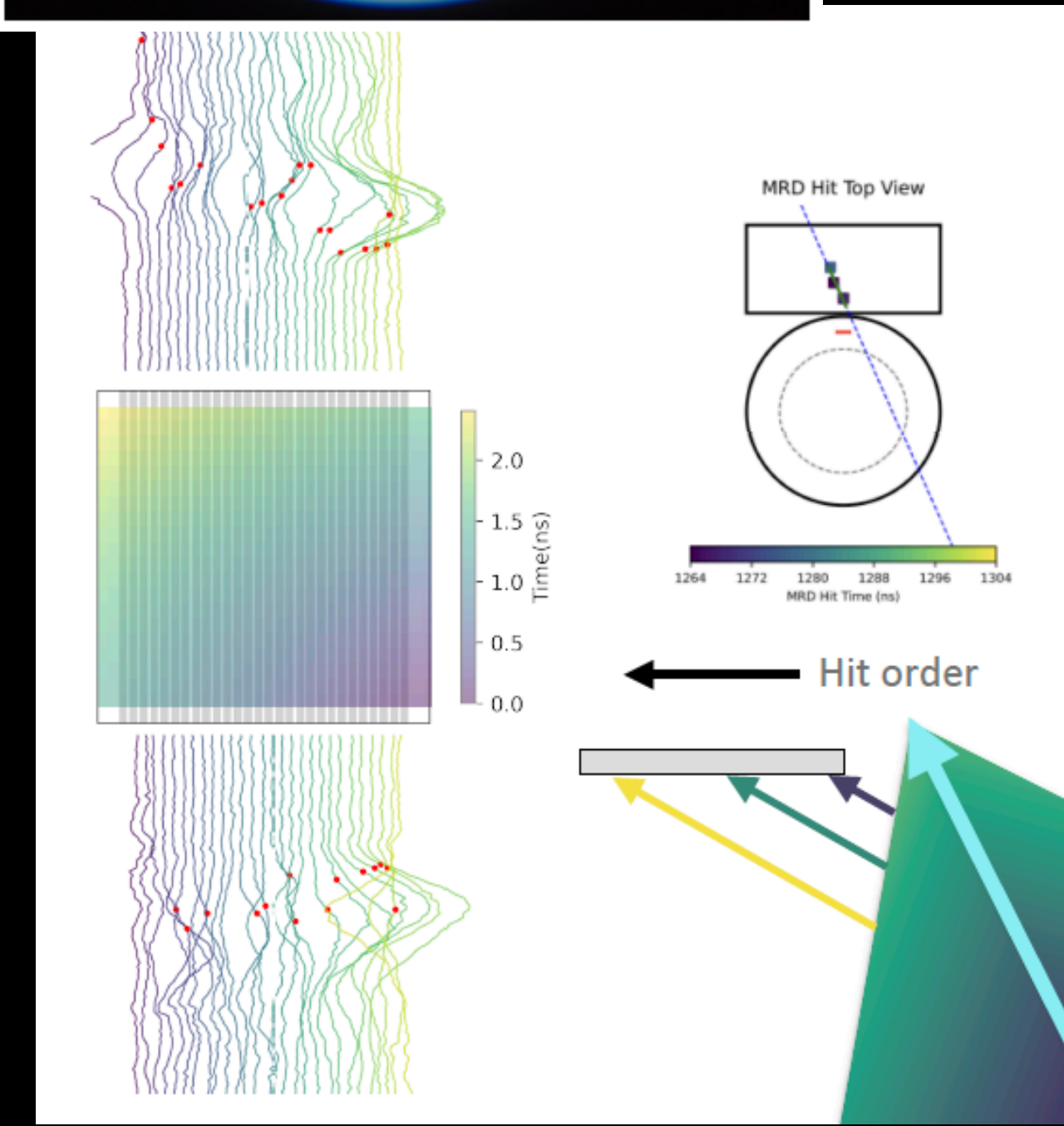
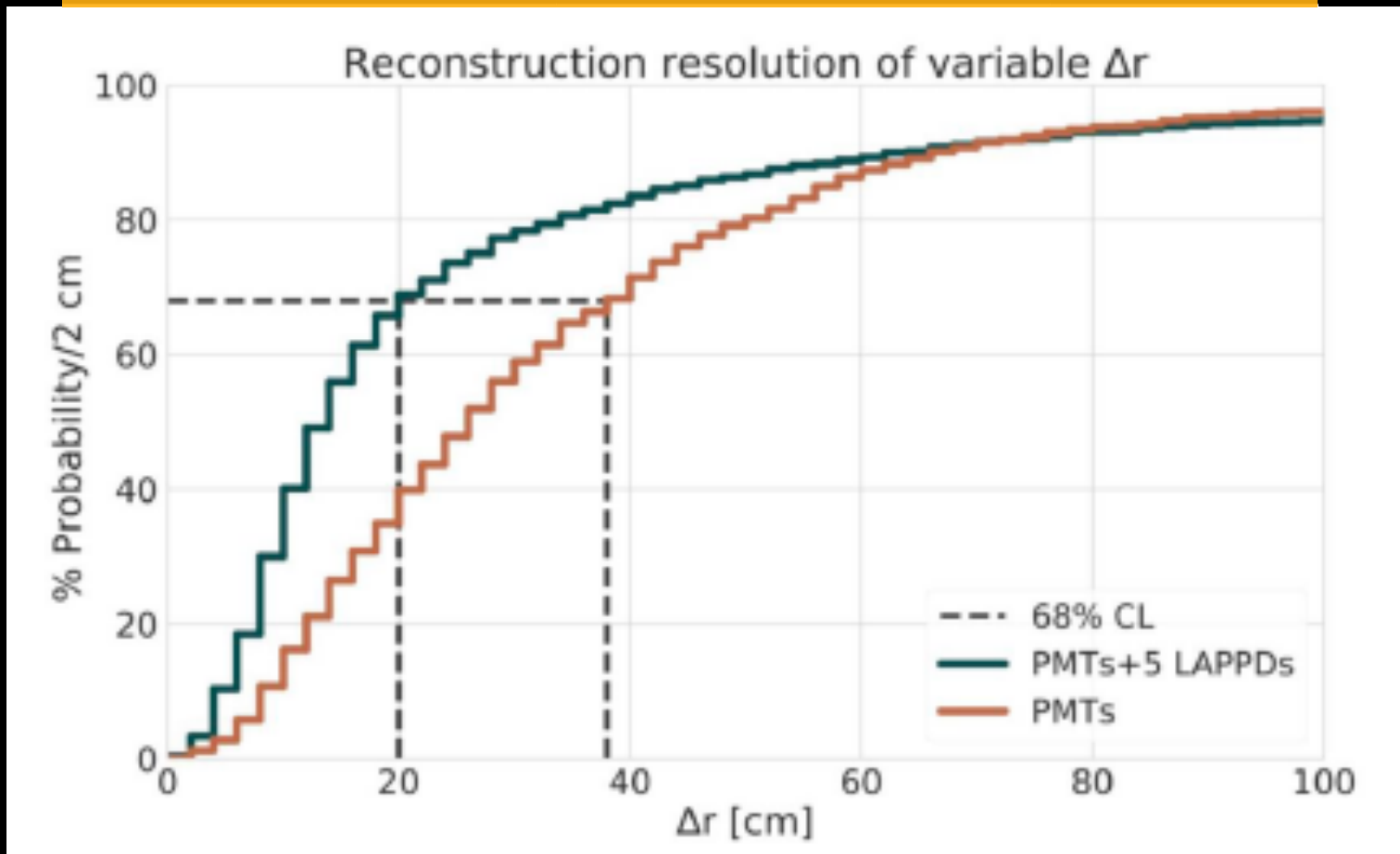


- LAPPDs packaged together with electronics in underwater housing
- 3 deployed in ANNIE at the same time

NEUTRINO BEAM TIMING!



IMPROVING RESOLUTION



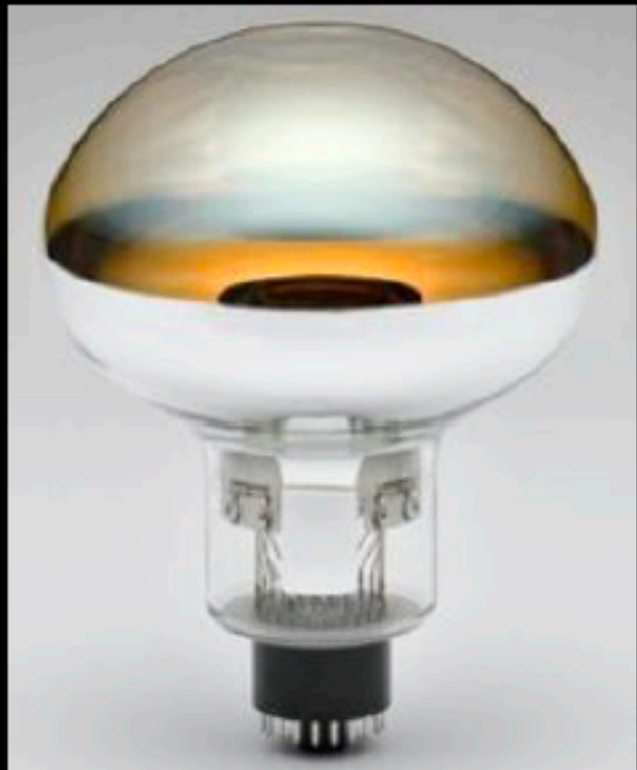
- Timing in each strip correlated to angle of muon relative to wall
- They work !

HAMMAMATSU R14688 PMTS



T. KAPTANOGLU,
L. PICKARD

Eos
TTS ~ 1.0 ns



8-inch PMT
R14688 (R5912)
T. Kaptanoglu et al, NIM A 19 02 (2024)

IceCube
TTS ~ 3.0 - 3.5 ns



10-inch PMT
R7081
IceCube Collaboration, NIM A 618 (2010)

LBNE
TTS ~ 3.0 ns

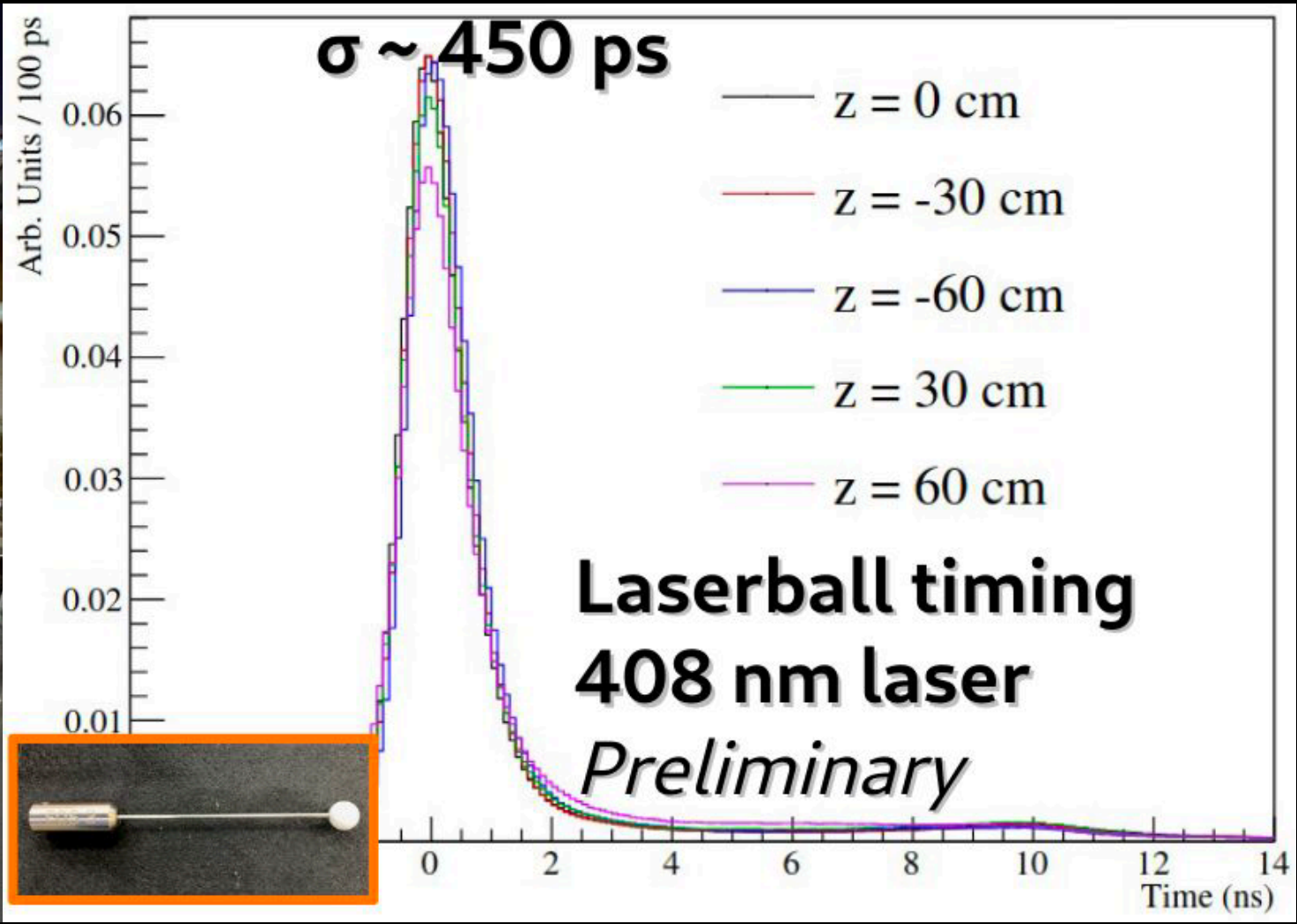
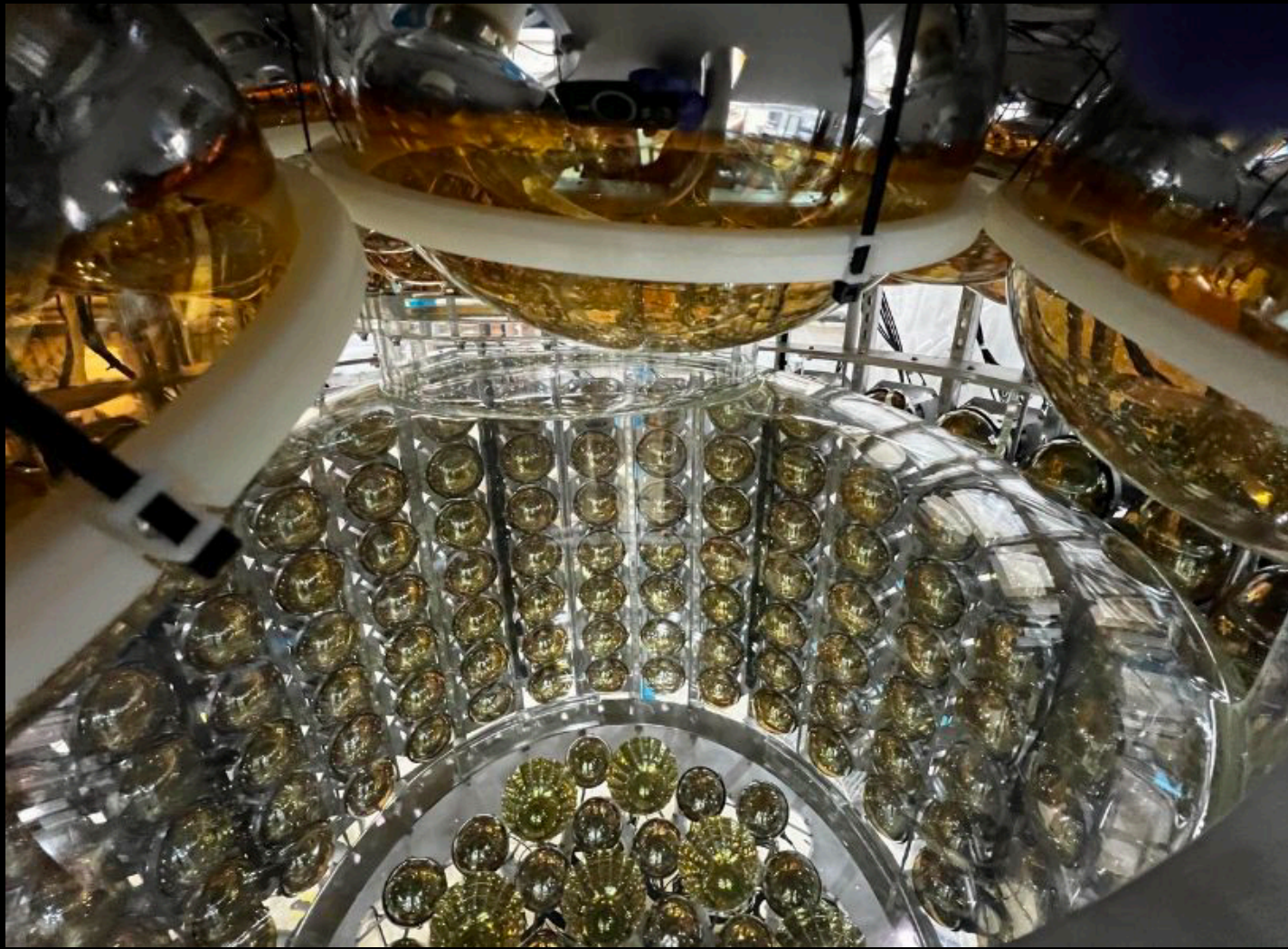
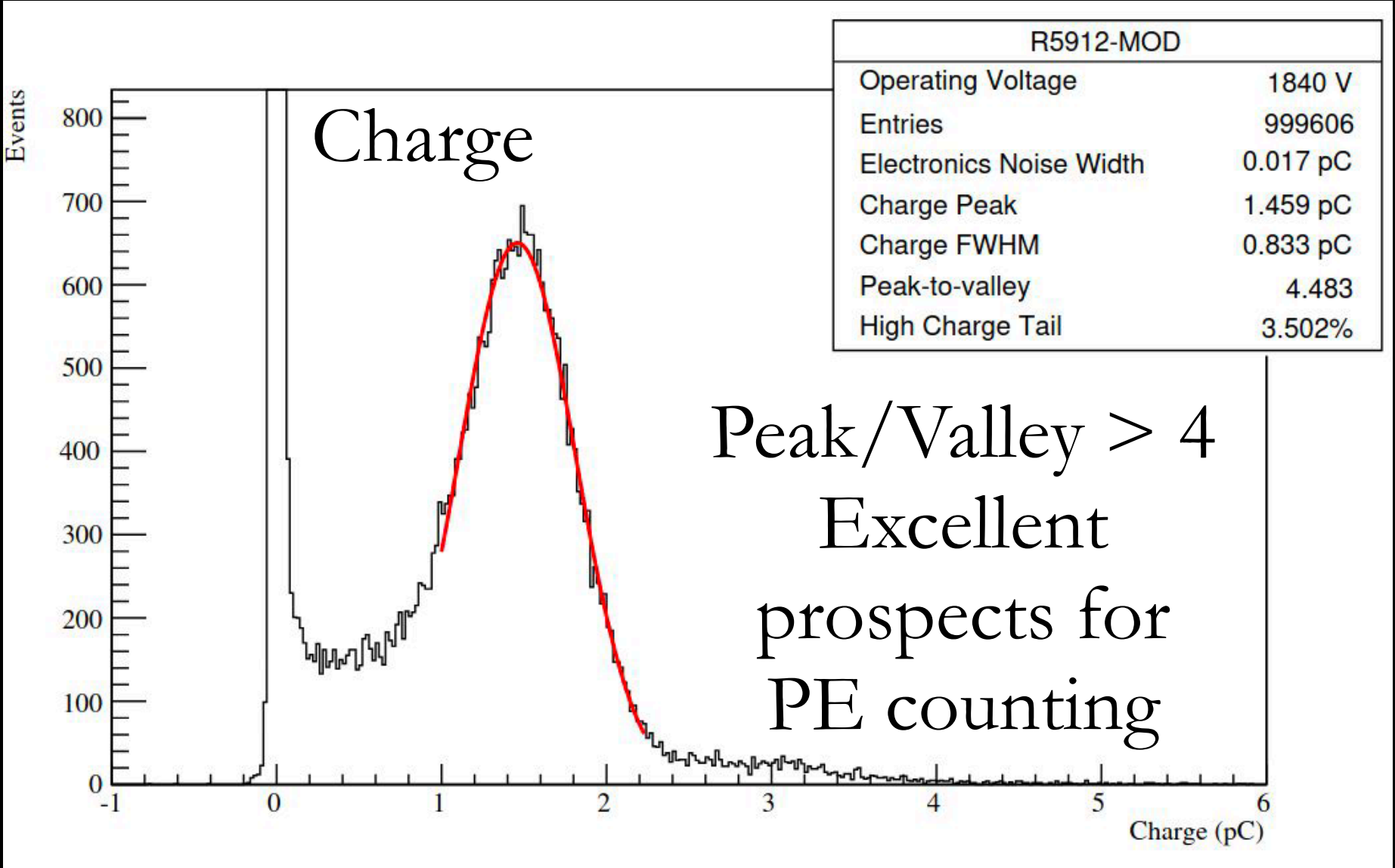


12-inch PMT
R11780
J. Brack et al., NIM A 712 (2013)

Hyper-K & JUNO
TTS ~ 3.0 ns

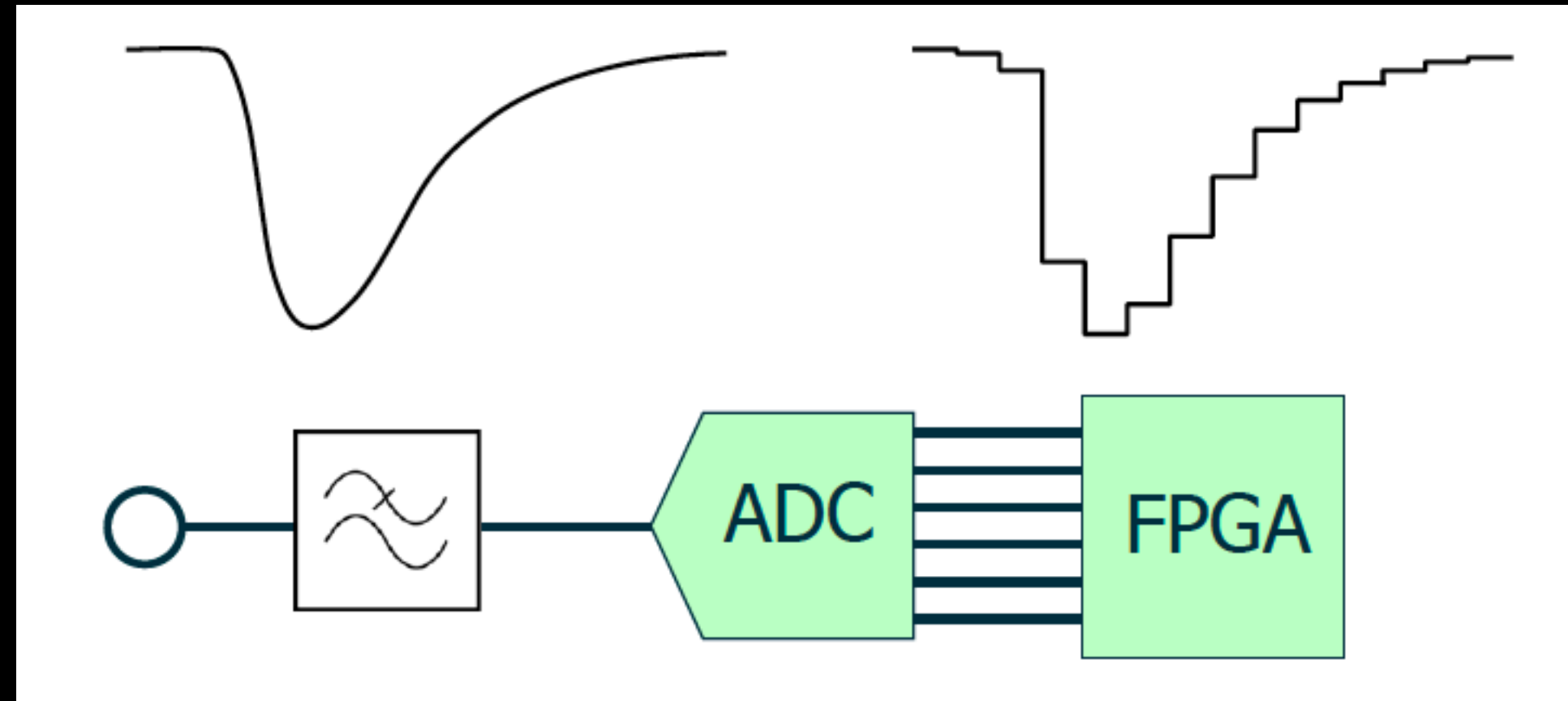


20-inch PMT
R12860
C Bronner et al., J. Phys.: Conf. Ser. 1468 (2020)



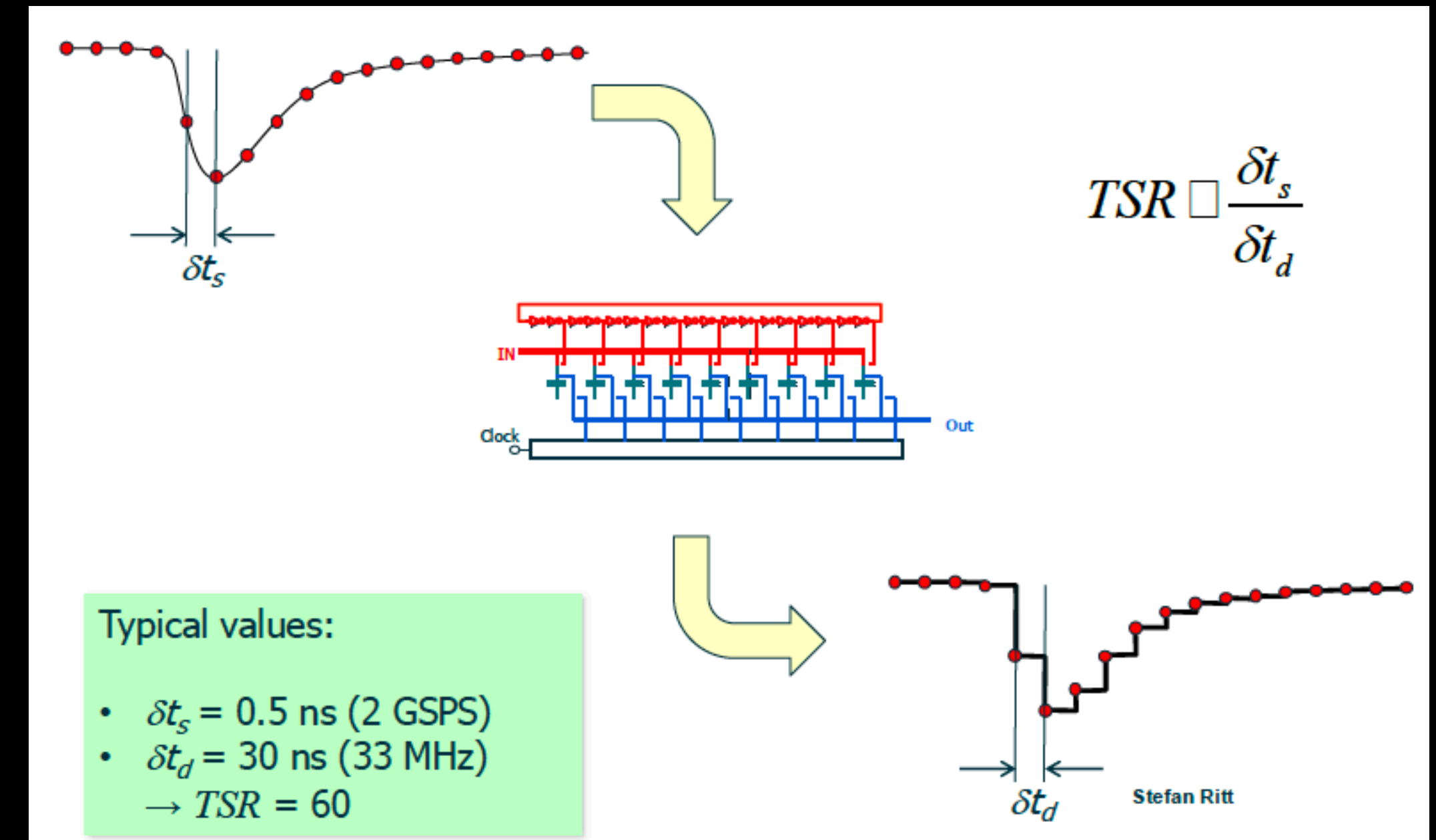
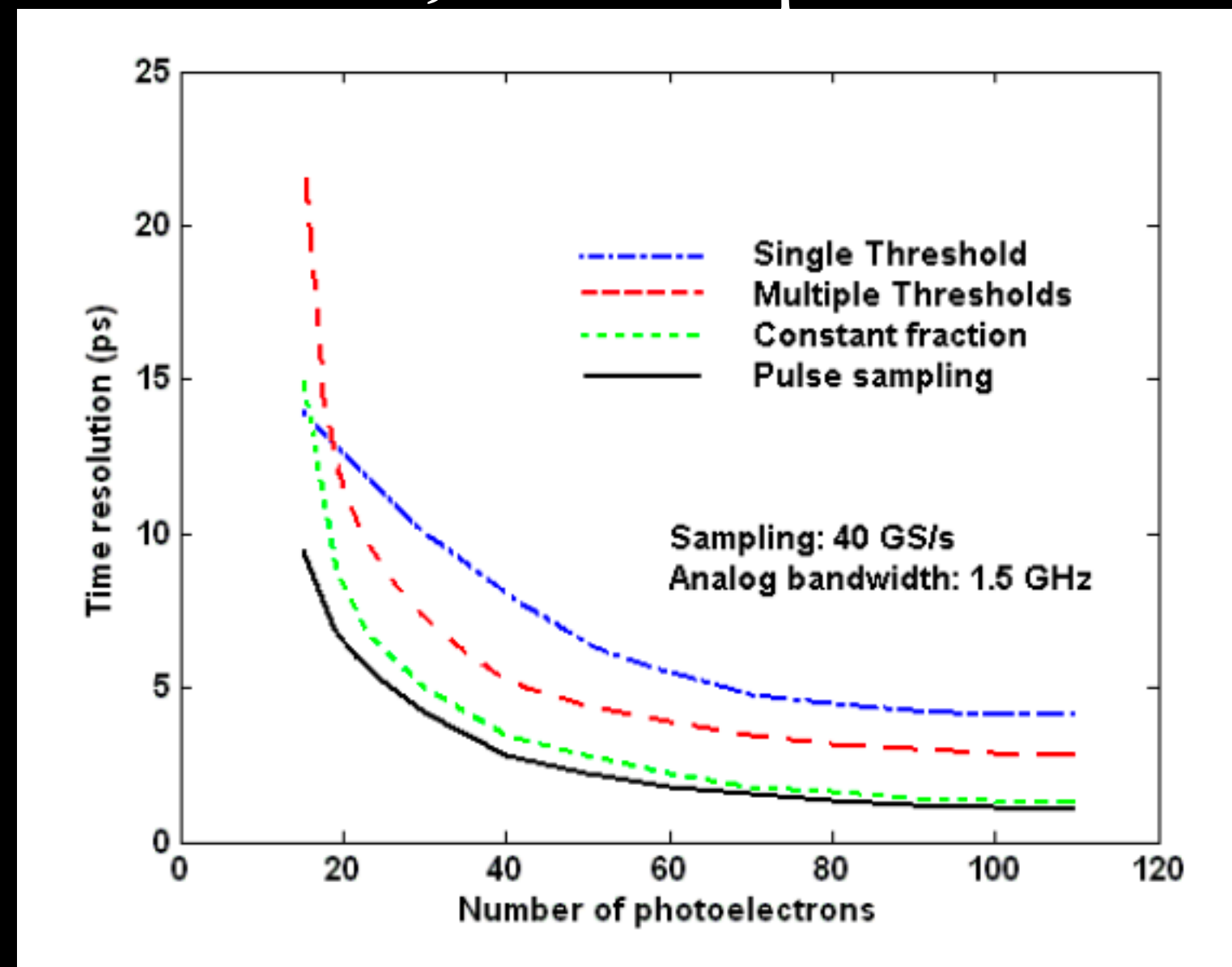
Excellent candidate for a
future hybrid detector !

ELECTRONICS



Switched Capacitor Array decouples fast sampling (into an “analog memory”) from slow readout

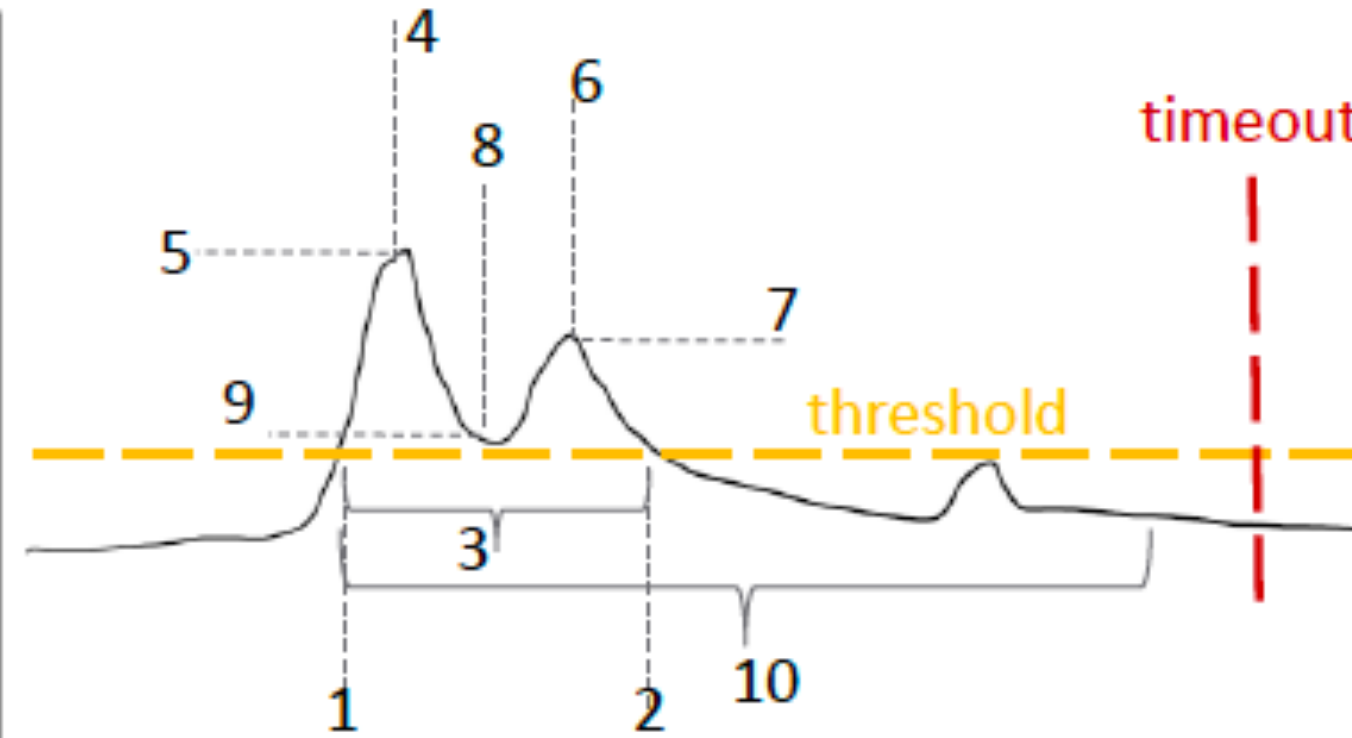
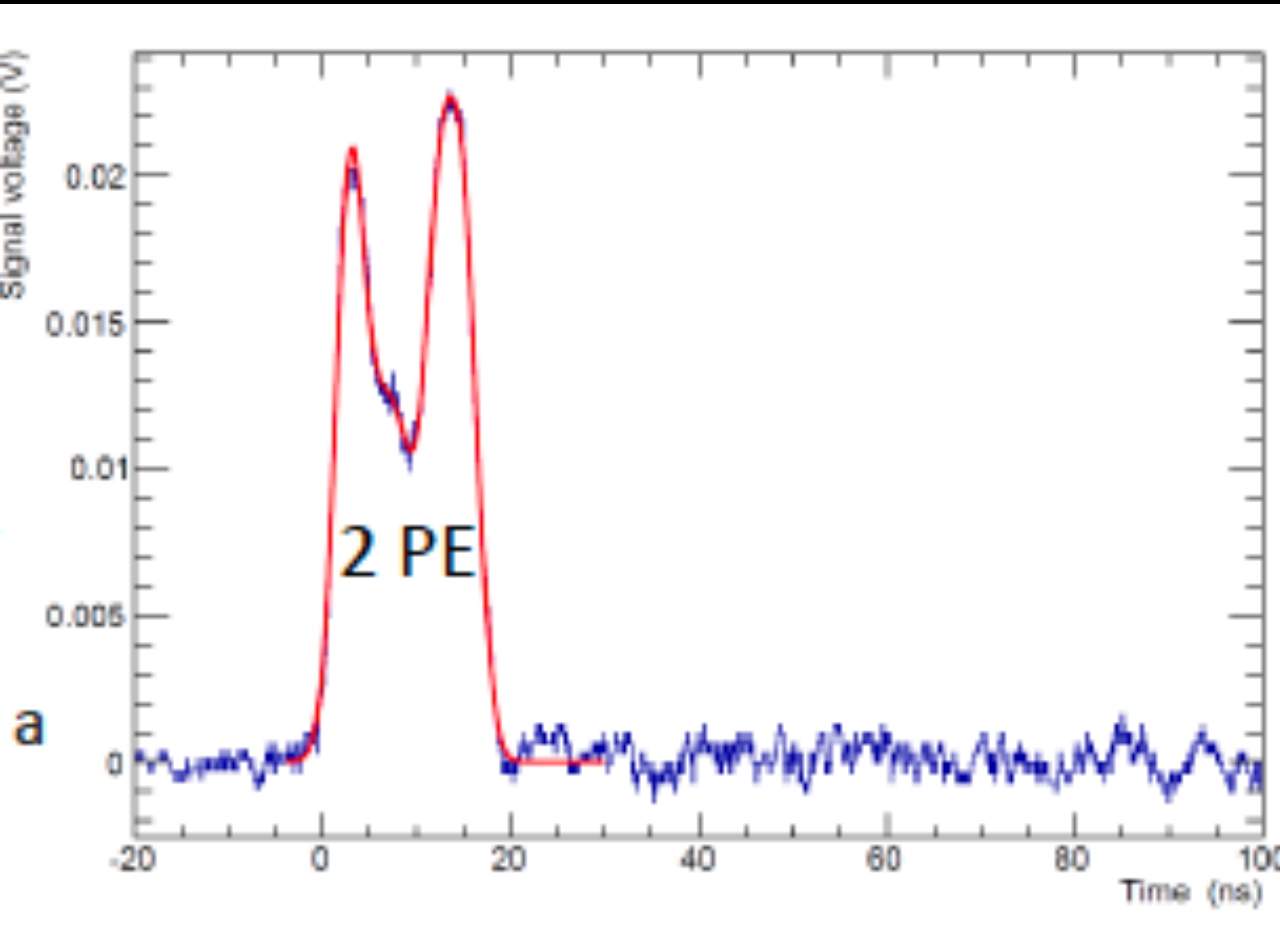
Pulse sampling always better, but expensive



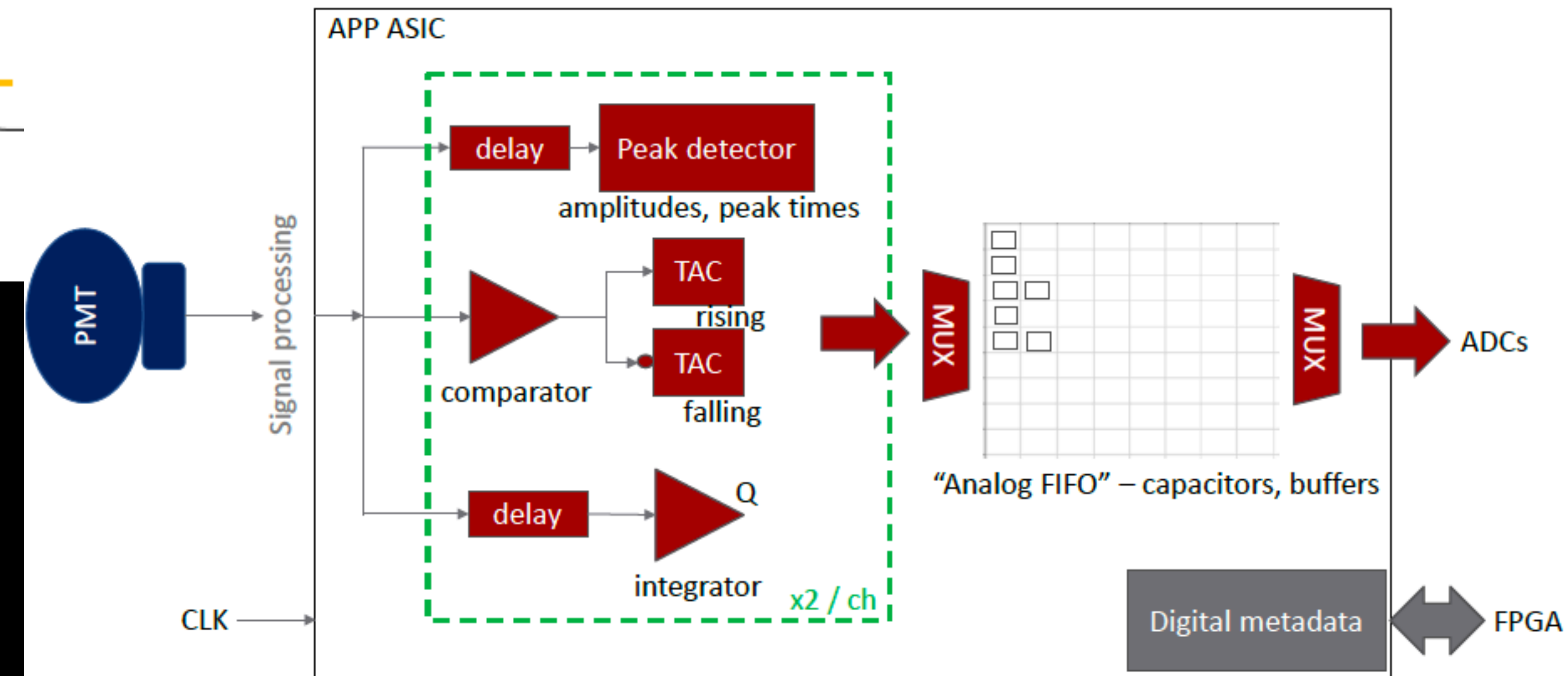
- Other approaches
 - NeuPix for custom pulse-shape discrimination
 - TDC with FPGA can be an alternative for high number of channels

NOT DIGITIZATION

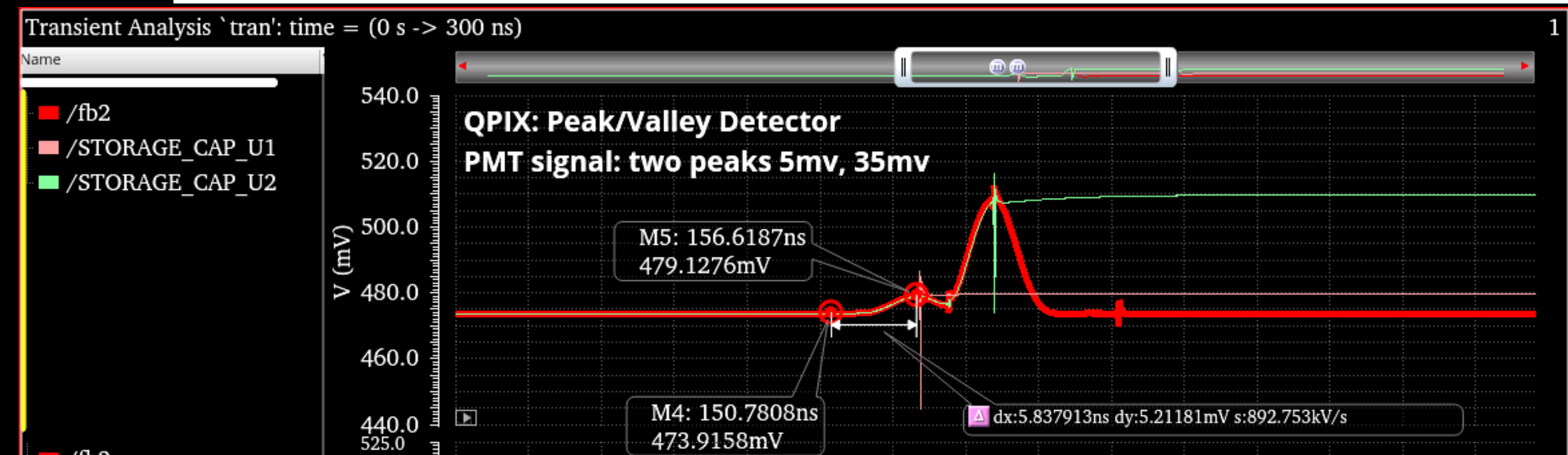
A. NIKOLICA



Block diagram (very simplified)

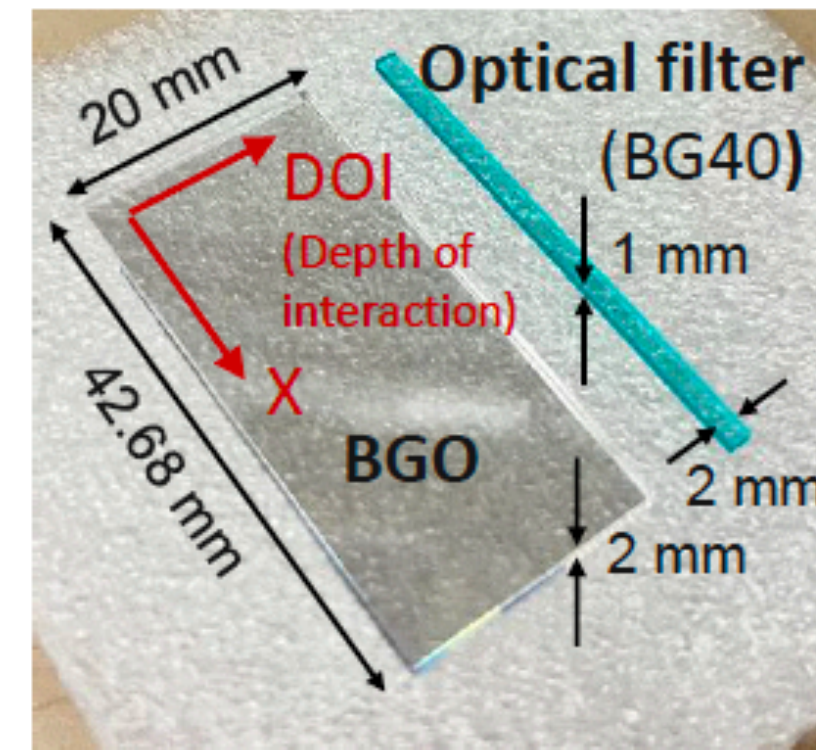


Can we do peak measurement and photoelectron counting without expensive full digitization?
Exploring Analog Photon Processor



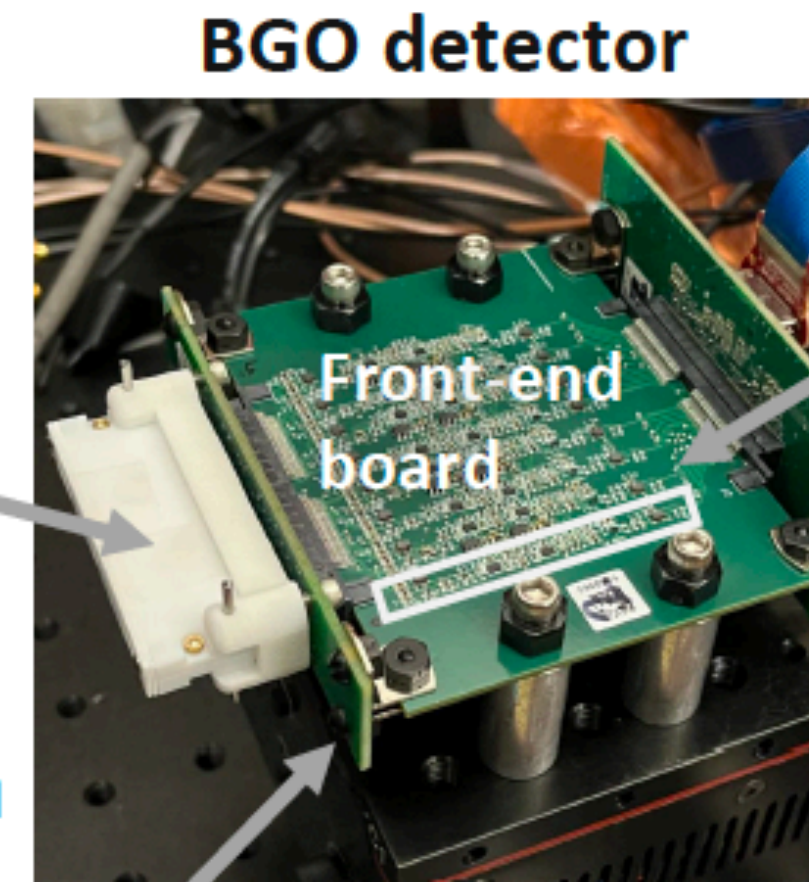
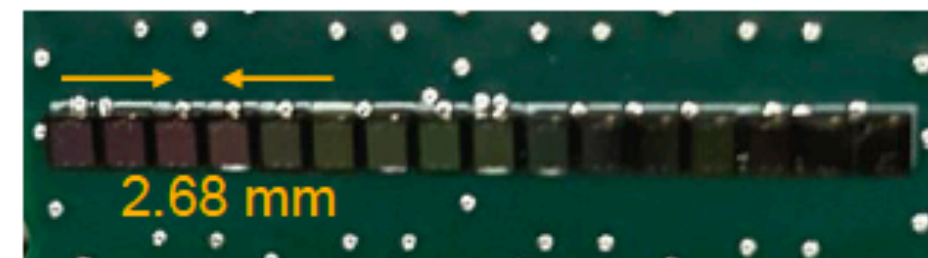
J. CATES

- BGO + SiPM detector used in TOF-PET
- Readout electronics and signal processing chain

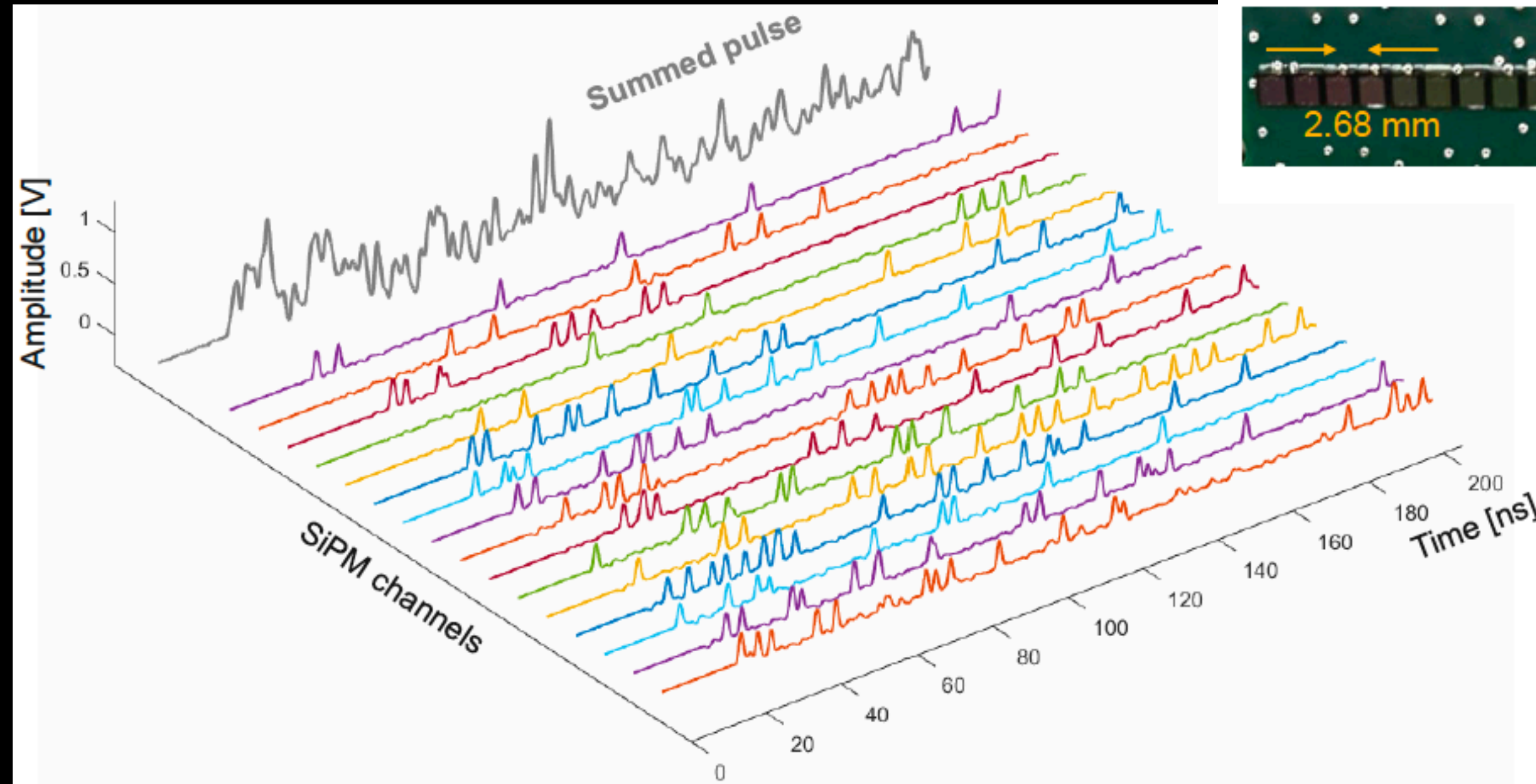
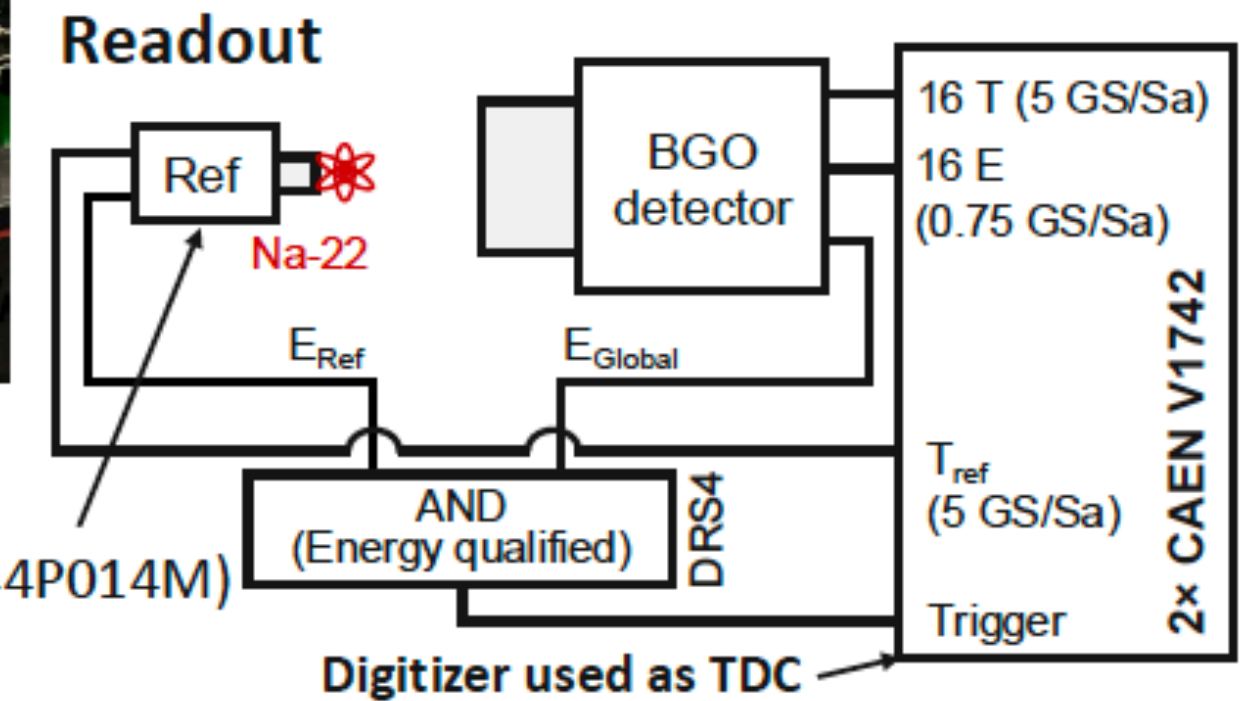
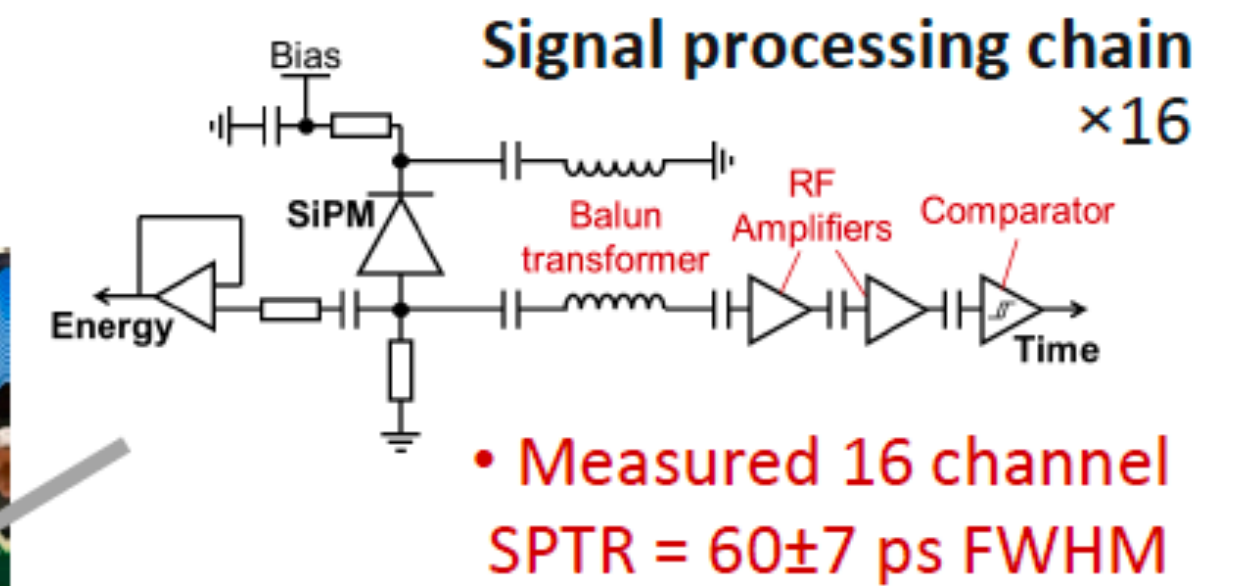


16×1 2-mm SiPMs

- Broadcom AFBR-S4N22P014M
- Overvoltage = 16 V

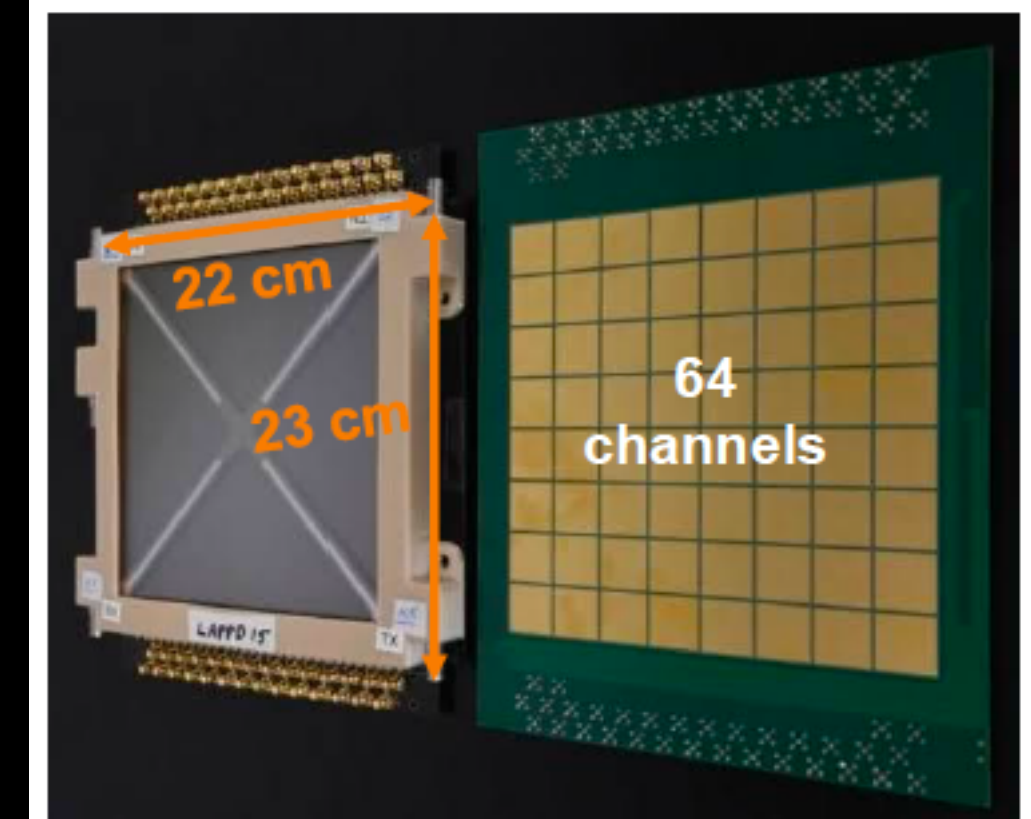


2×2×3 mm³ LYSO:Ca,Ce
+ 4-mm SiPM (AFBR-S4N44P014M)



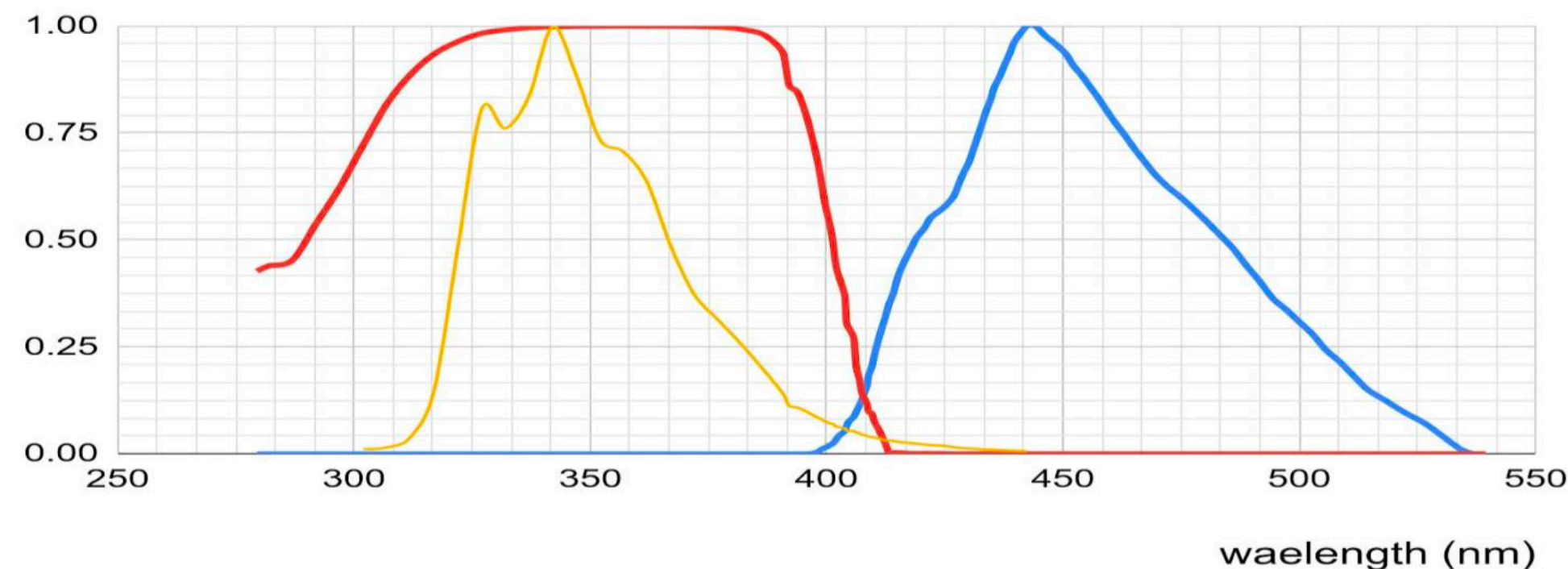
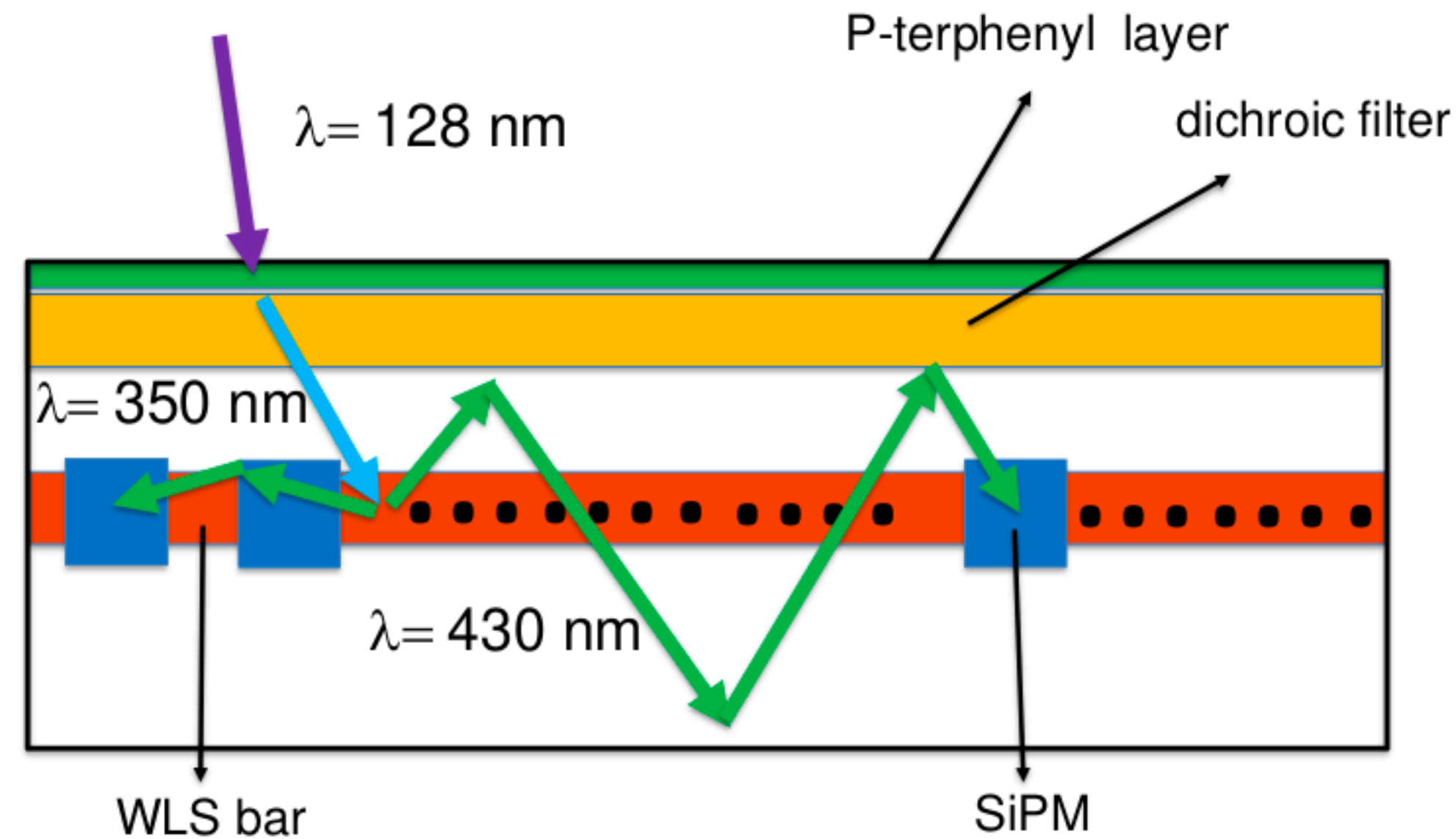
Could be applied to EOS and segmented LAPPDs

LAPPD with Segmented Readout



ARAPUCAS

- Large Area Photon Detectors developed for LAr scintillation (128 nm)
- First use of dichroic filters (?), coupled to WLS and SiPM

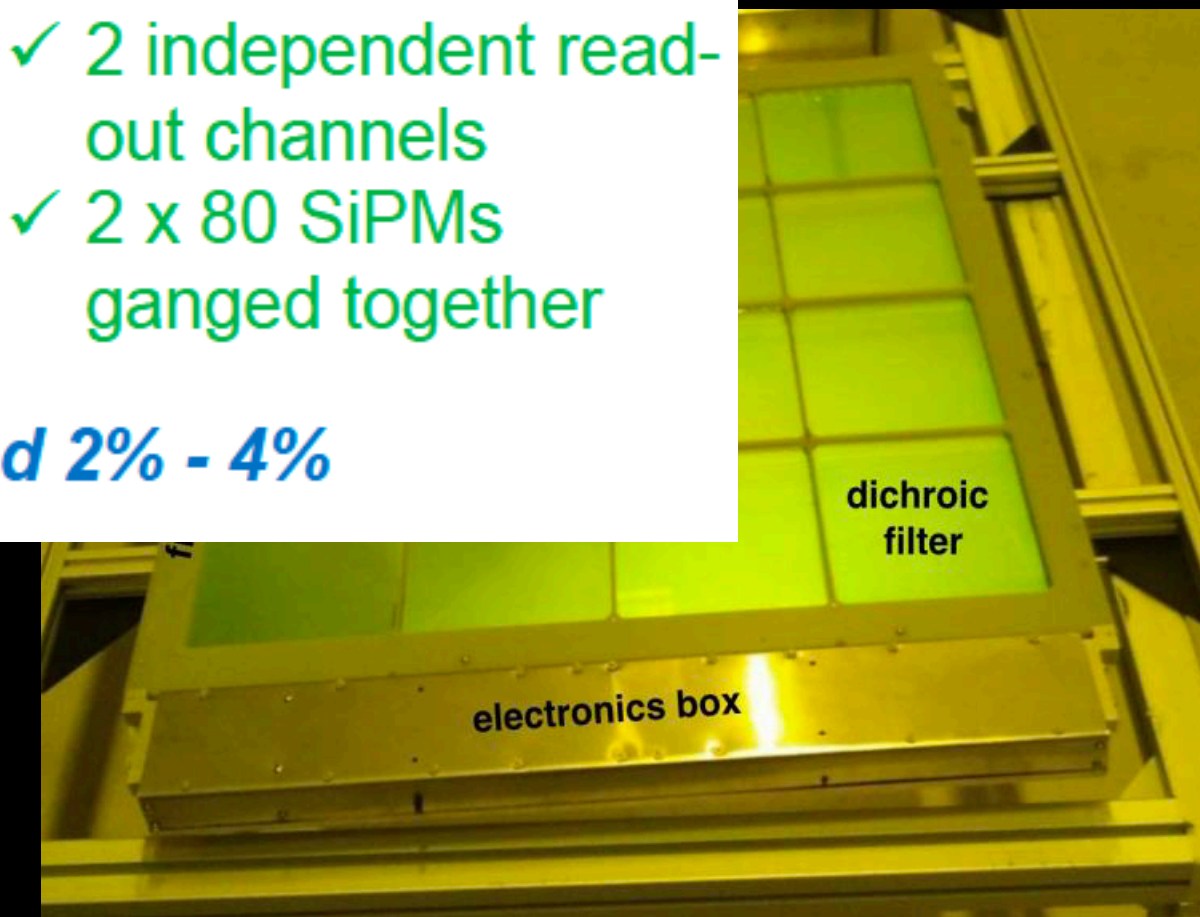
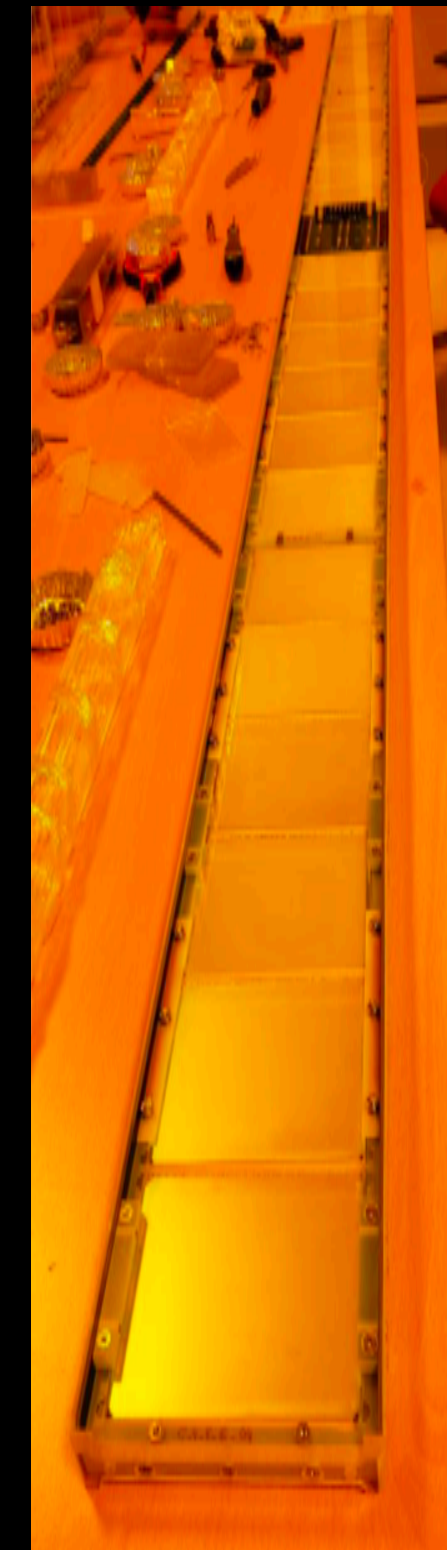


X-ARAPUCAS IN DUNE

- ✓ Bar shaped modules
- ✓ 200 x 10 cm²
- ✓ 4 independent read-out channels
- ✓ 4 x 48 SiPMs ganged together

- ✓ Square modules
- ✓ 60 x 60 cm²
- ✓ 2 independent read-out channels
- ✓ 2 x 80 SiPMs ganged together

Efficiencies around 2% - 4%



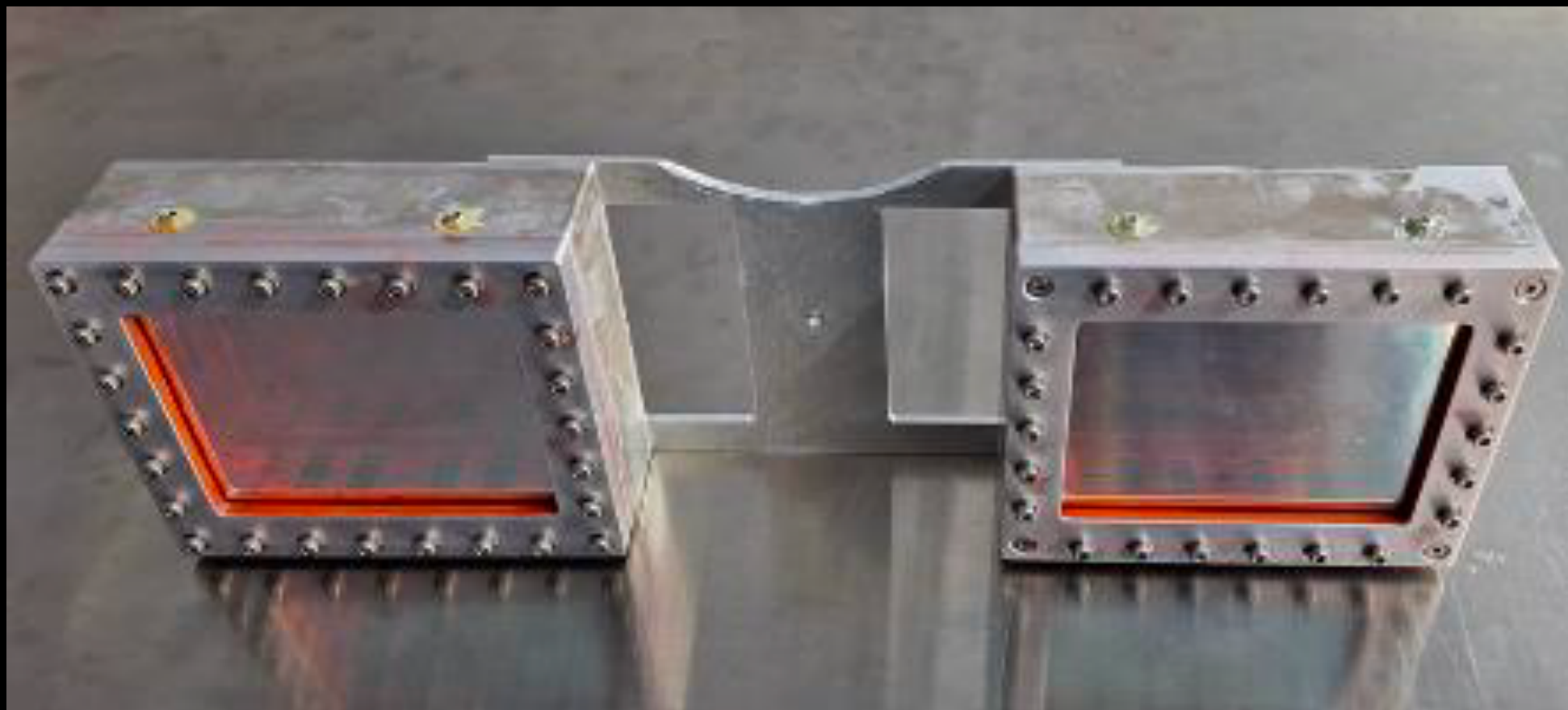
E. SEGRETO NNN24

A.A. MACHADO ET AL 2018 JINST 13 C04026

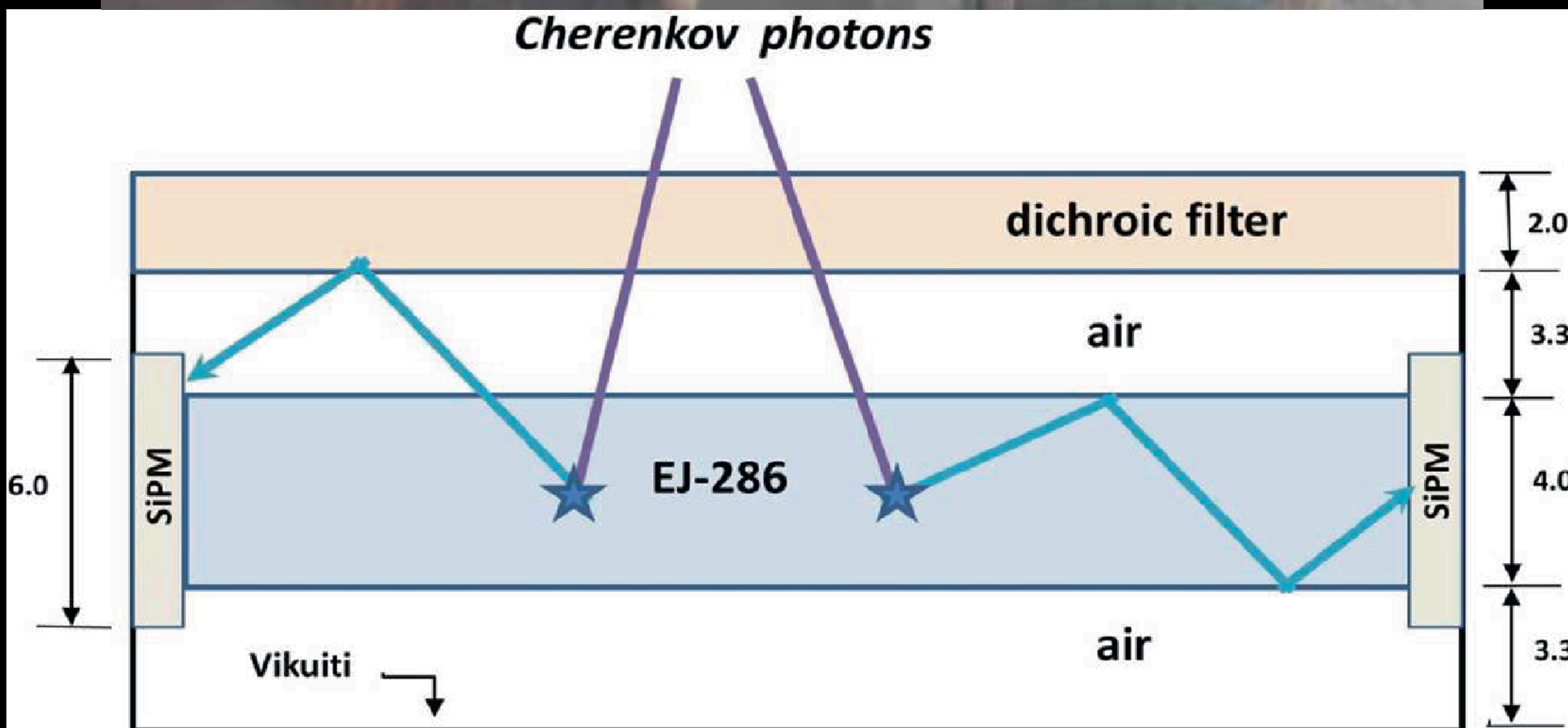
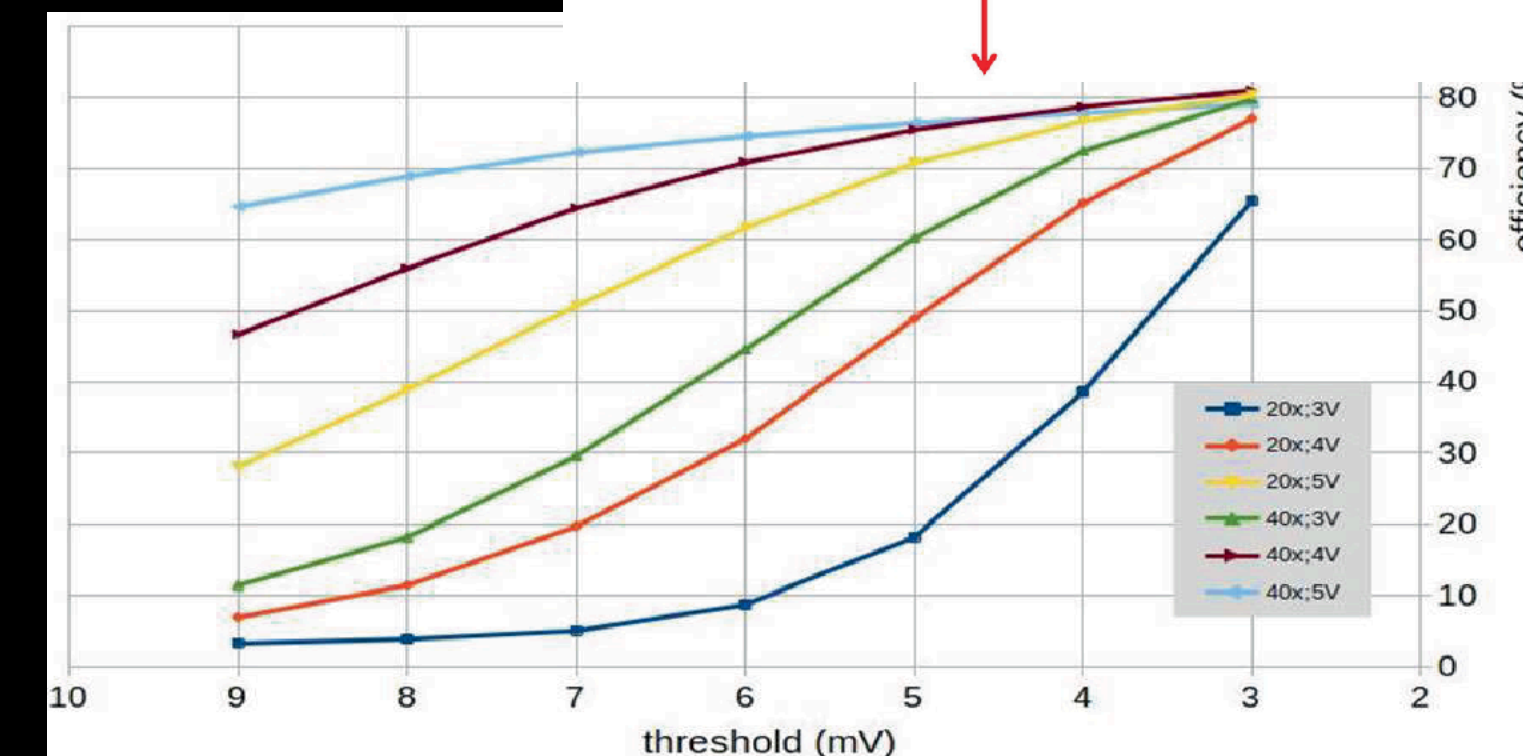
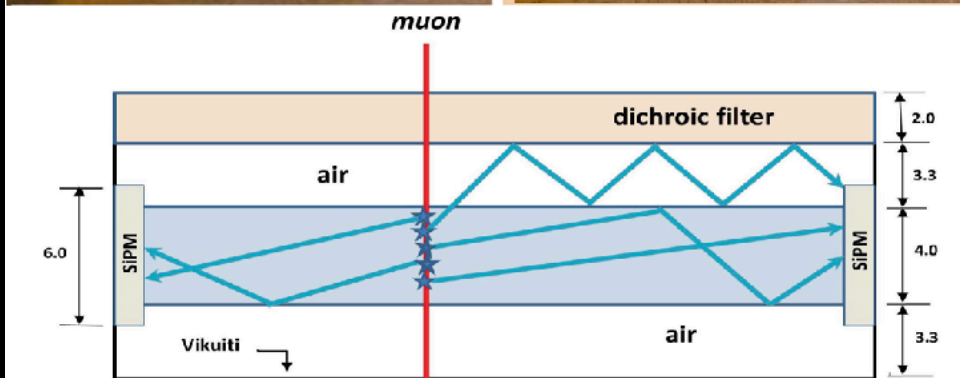
C-ARAPUCA

A. FAUTH, A. MACHADO ET AL.
[HTTPS://DOI.ORG/10.1002/ASNA.20240123](https://doi.org/10.1002/asna.20240123)

- Developed for water Cherenkov
- Simpler design (no PTB), low pass filters



Preliminary tests with muons
and water tank at Campinas



COULD THIS BE USED FOR HYBRID
DETECTORS? PHOTON DETECTION
EFFICIENCY IS MAIN CHALLENGE,
BUT GEOMETRY IS SIMPLE

ANALYSIS AND SIMULATION FOR A HYBRID DETECTOR

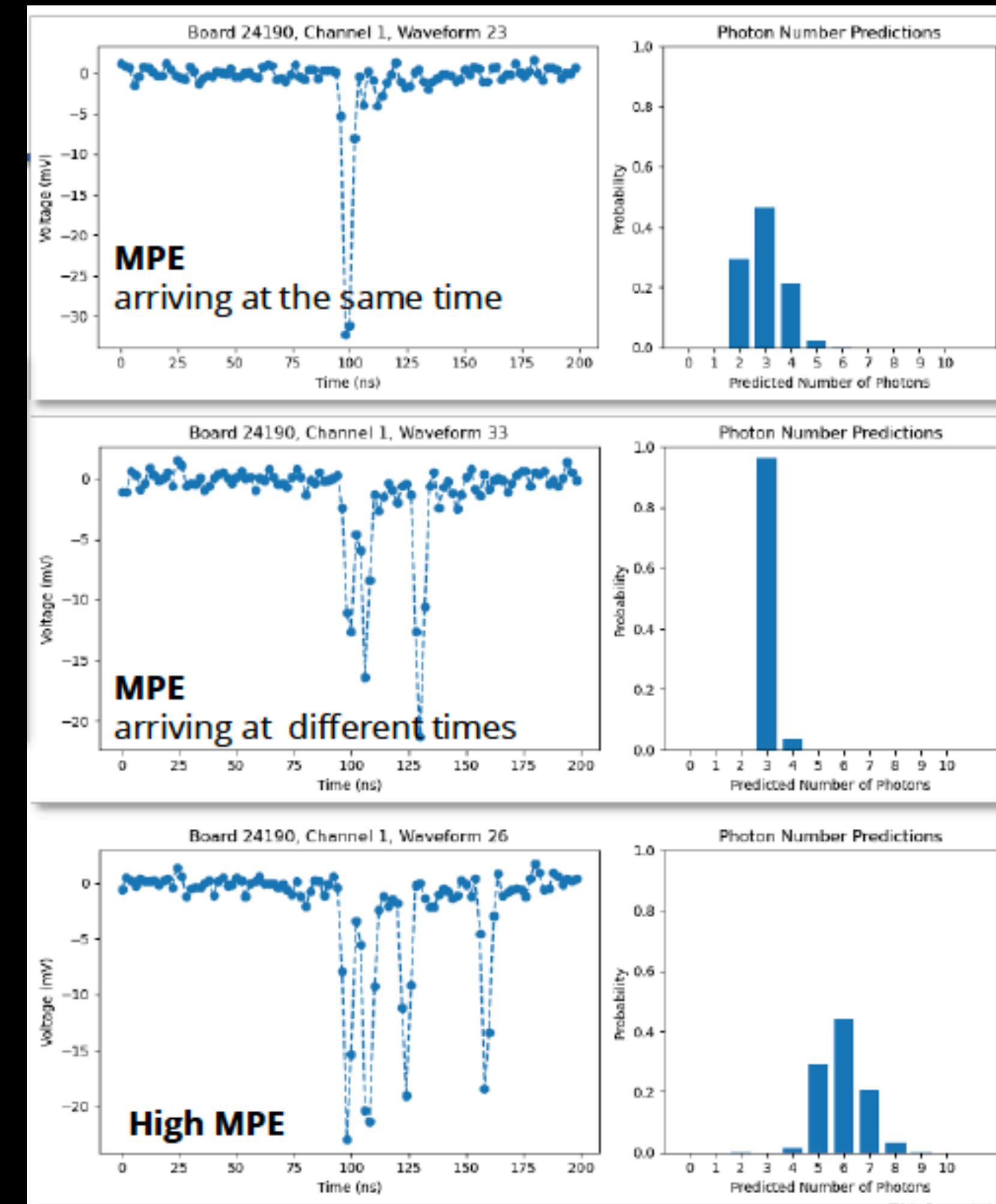
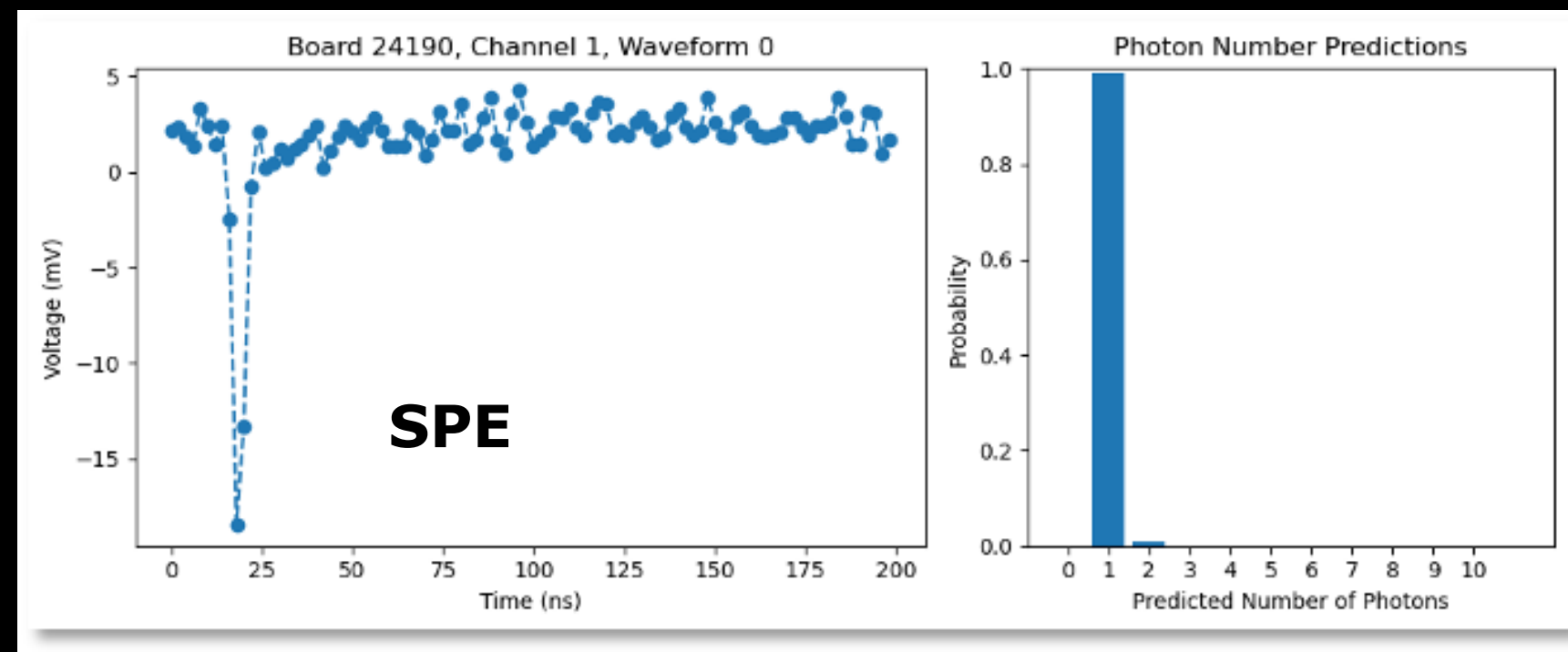
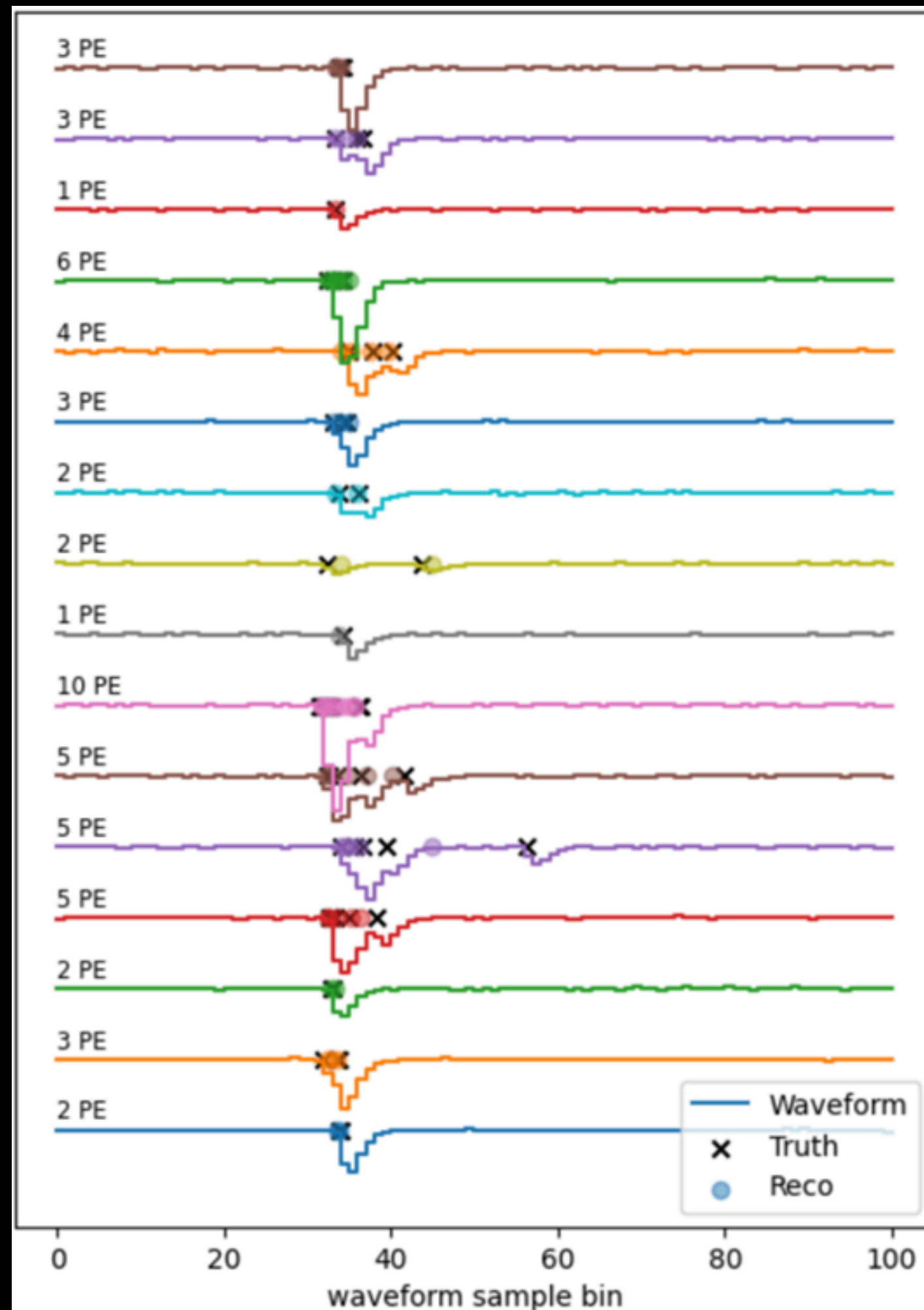
WAVEFORM ANALYSIS TECHNIQUES



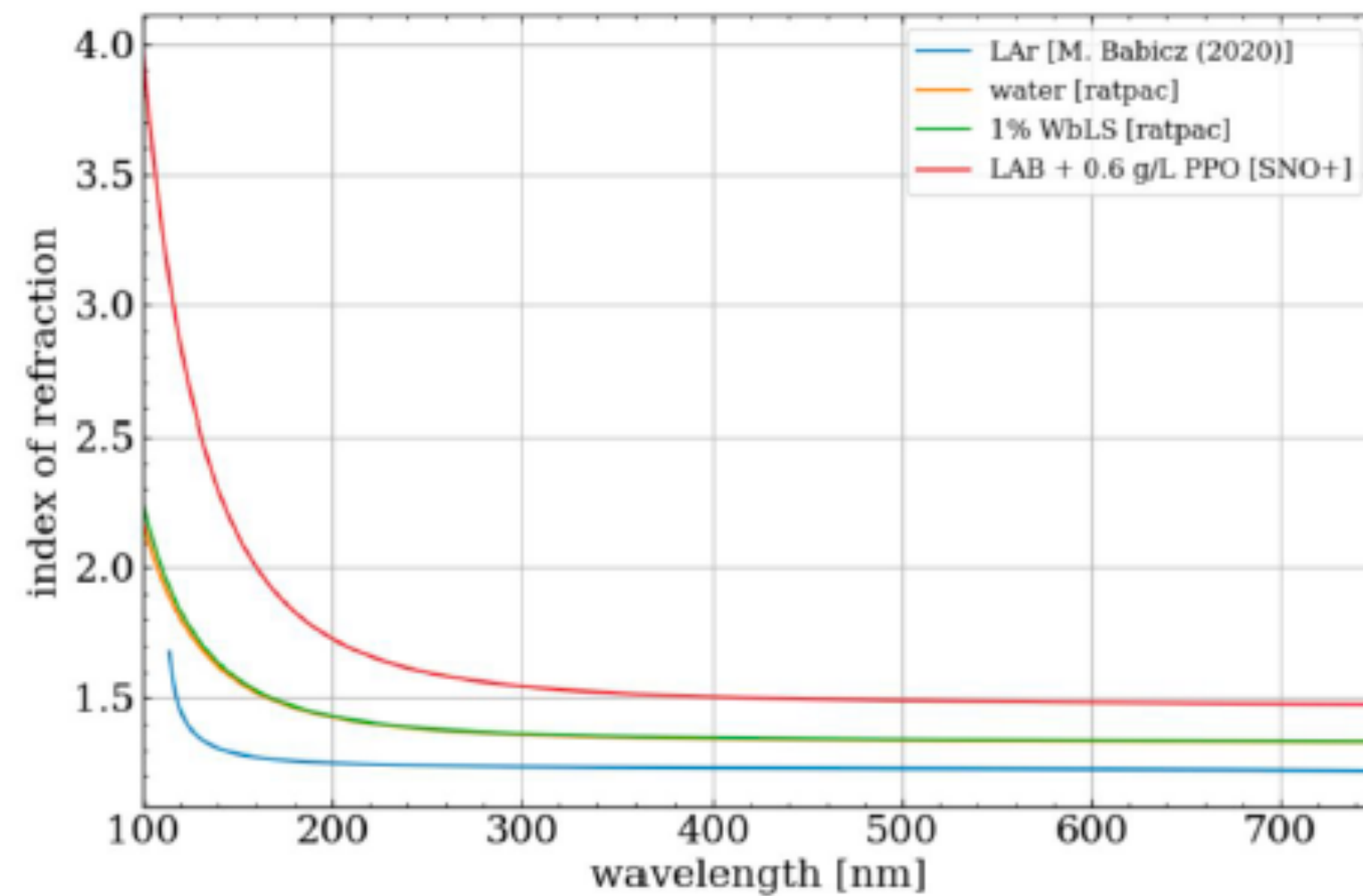
K. DE HOLTON

- EOS readout through waveform digitization 0.5 GHz
- Several methods being explored to estimate number of photoelectrons and timing

Convolutional Neural Network shows promise

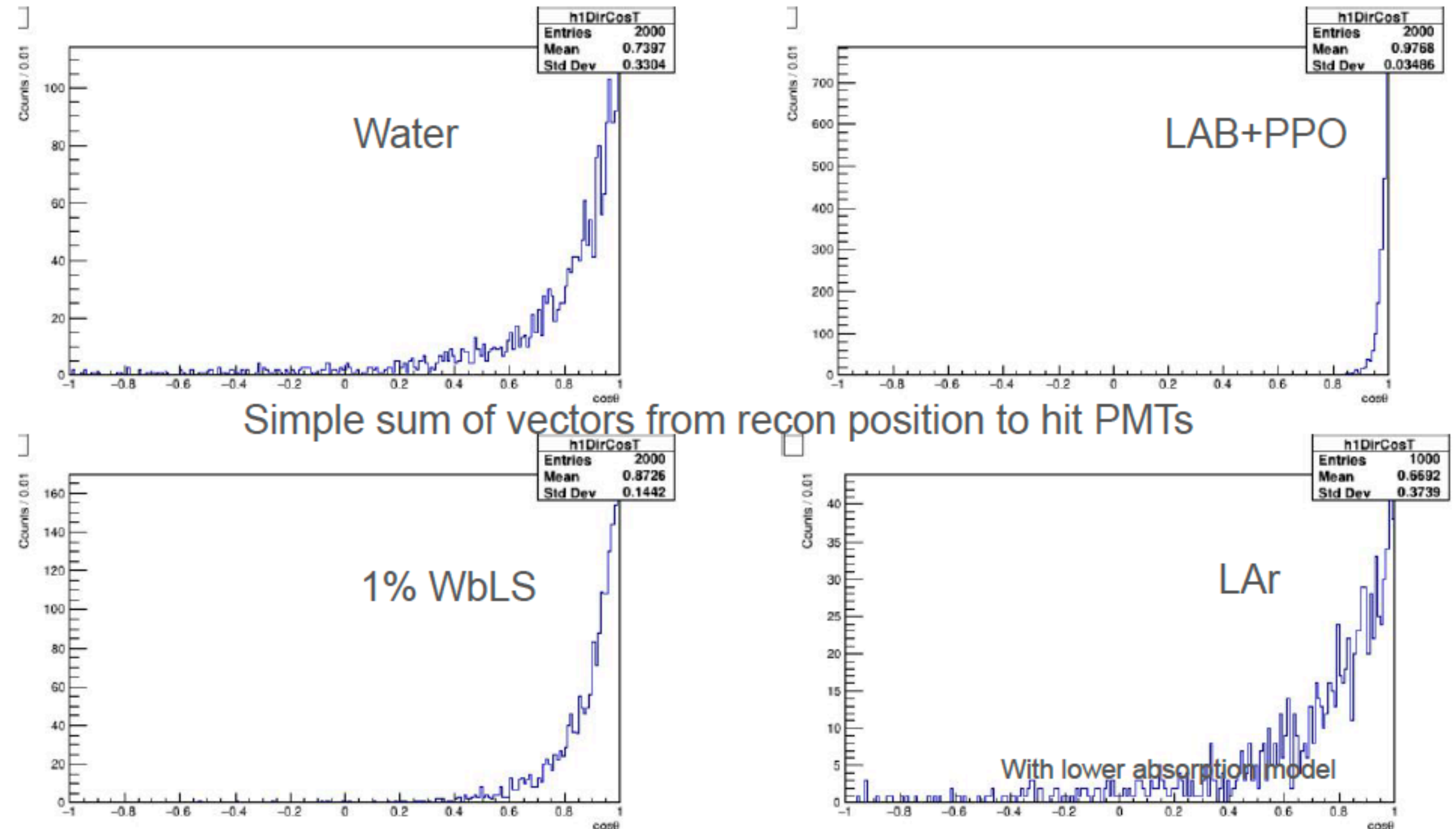


Cherenkov



Directionality performance, with scintillation light off

- Interesting insight:
LAB+PPO is the best.
Likely due to highest
refractive index

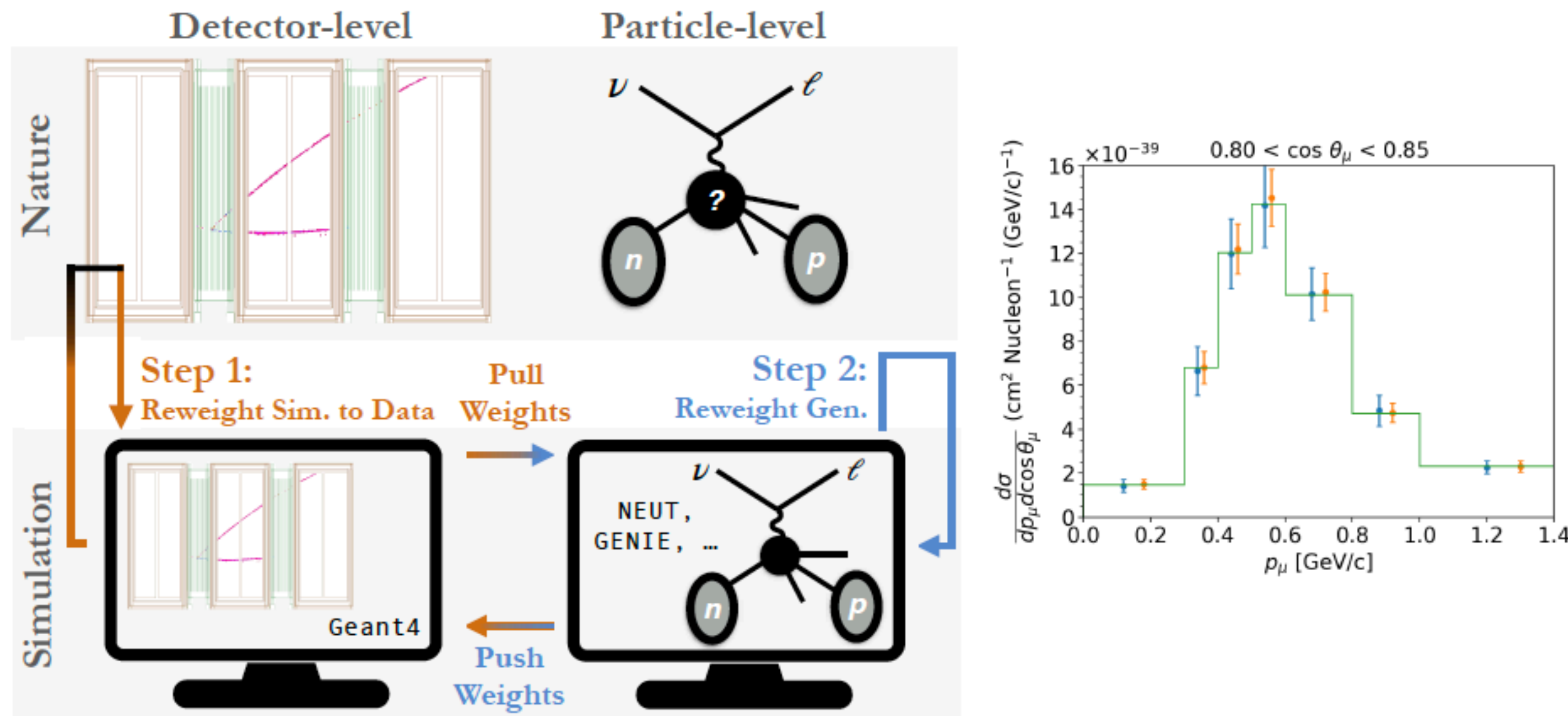


- A world of opportunities in simulation, reconstruction, inference
- Many developments in HEP. Neutrino Physics example:

Inference - differential cross-sections

12

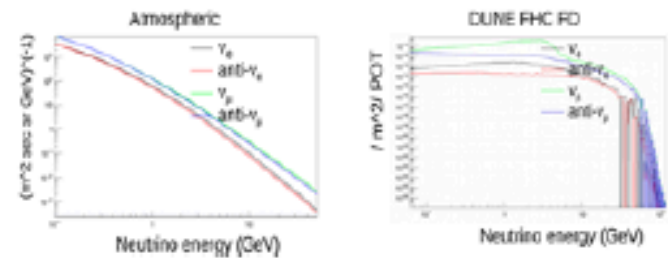
for neutrino example, see T2K study in 2504.06857



Long-baseline Analysis Workflow

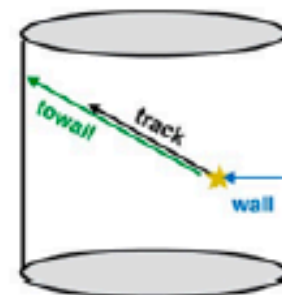
Flux weight

Atmospheric neutrino flux weighted to the DUNE flux



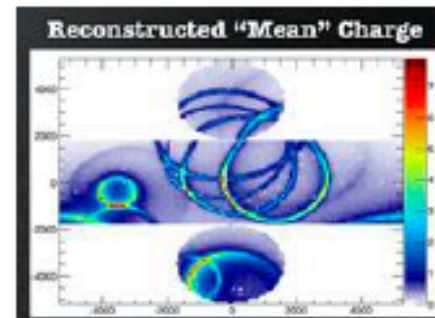
Pre-cut selection

Fully contained Fiducial volume events selected



Ring reconstruction

Estimate each ring's PID and kinematics



Energy reconstruction

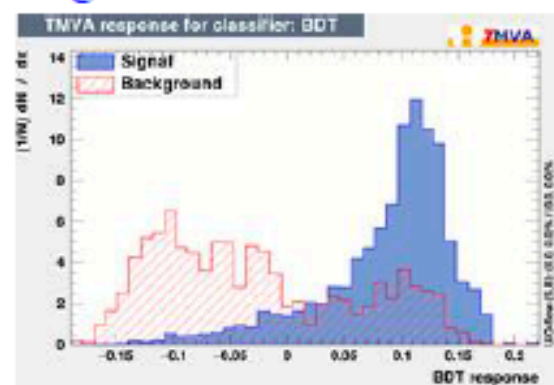
Energy estimated based on the ring number and decay number of the event

$$E_\nu \approx \frac{2M_n E_\ell - m_\ell^2}{2(M_n - E_\ell + p_\ell \cos \theta_\ell)}$$

$$(p_\nu + p_n - p_\ell - p_p)^2 = m_p^2$$

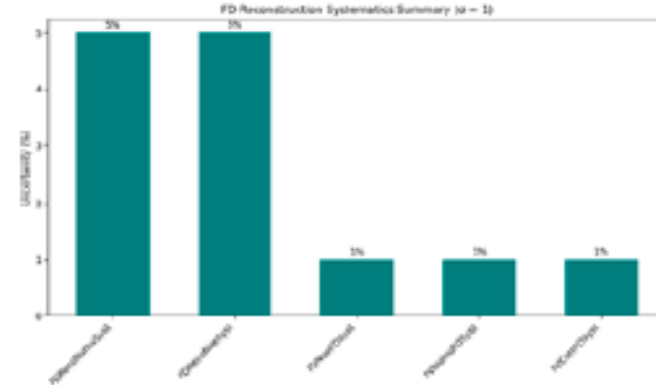
π^0 background reduction

BDT used to reduce the NC background



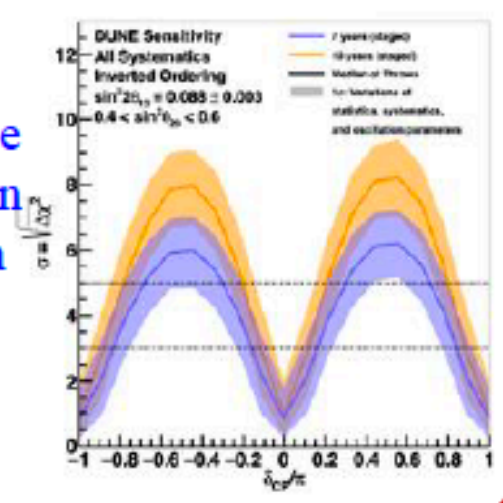
Systematic Model

TDR flux systematics applied
TDR LAr detector systematics applied

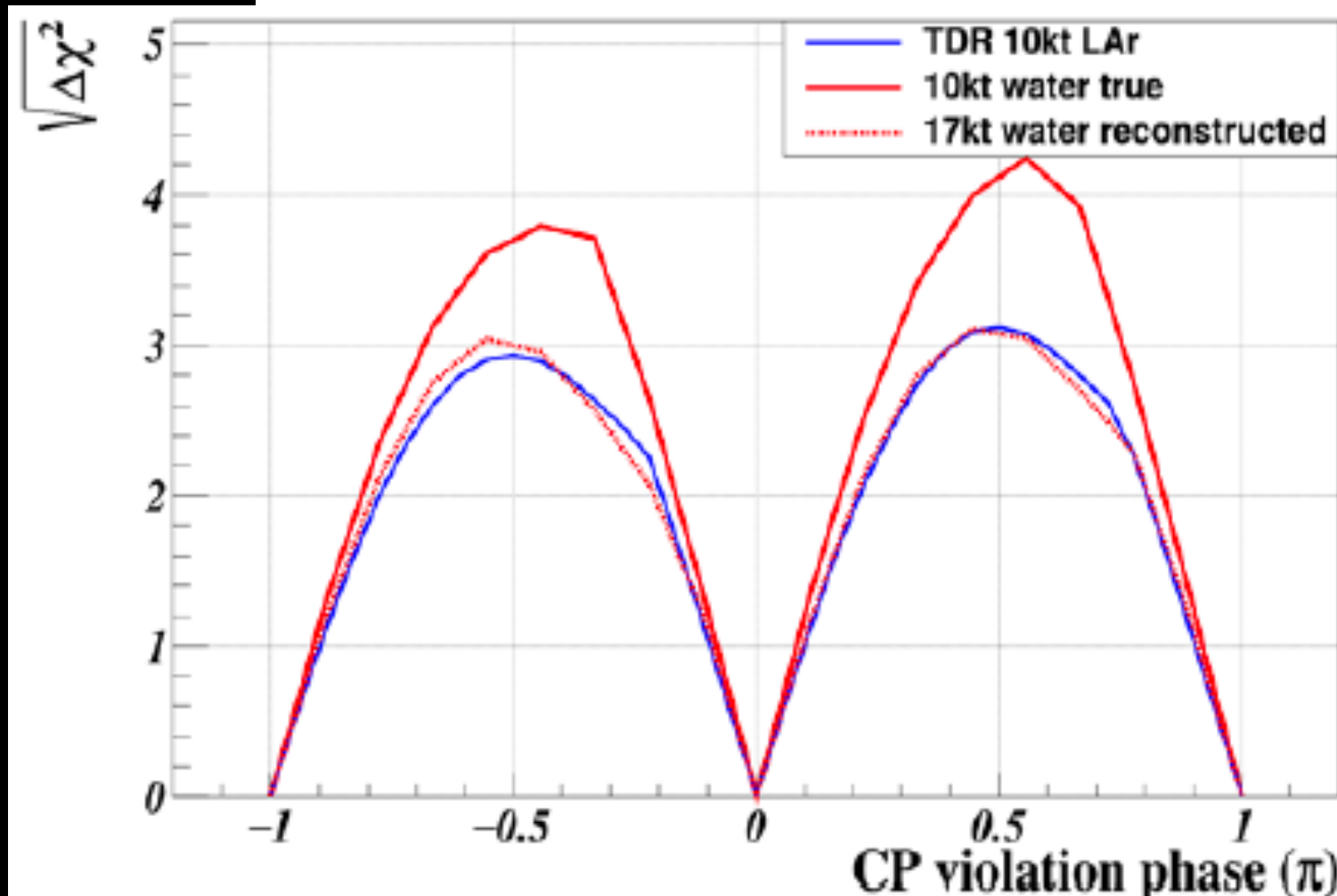
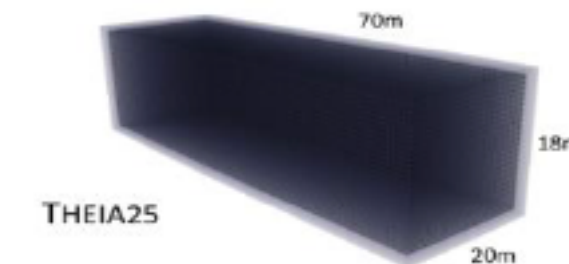


Oscillation Analysis

TDR Cafana is used to estimate the CP violation sensitivity with a pure water detector

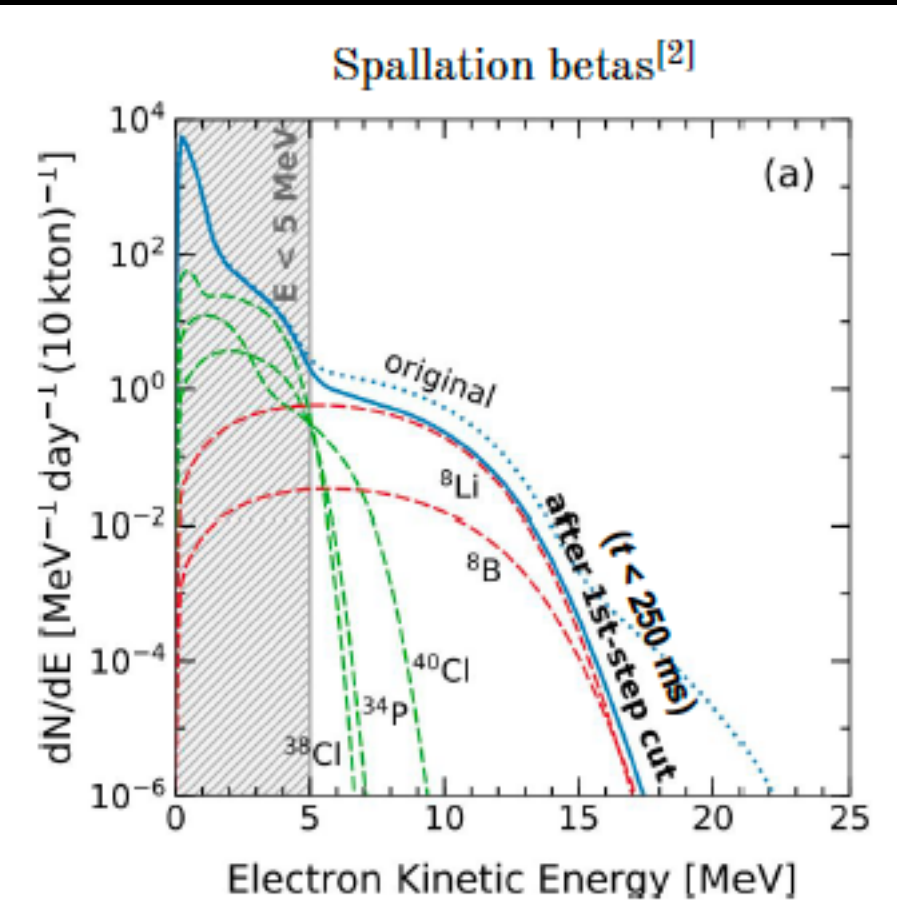
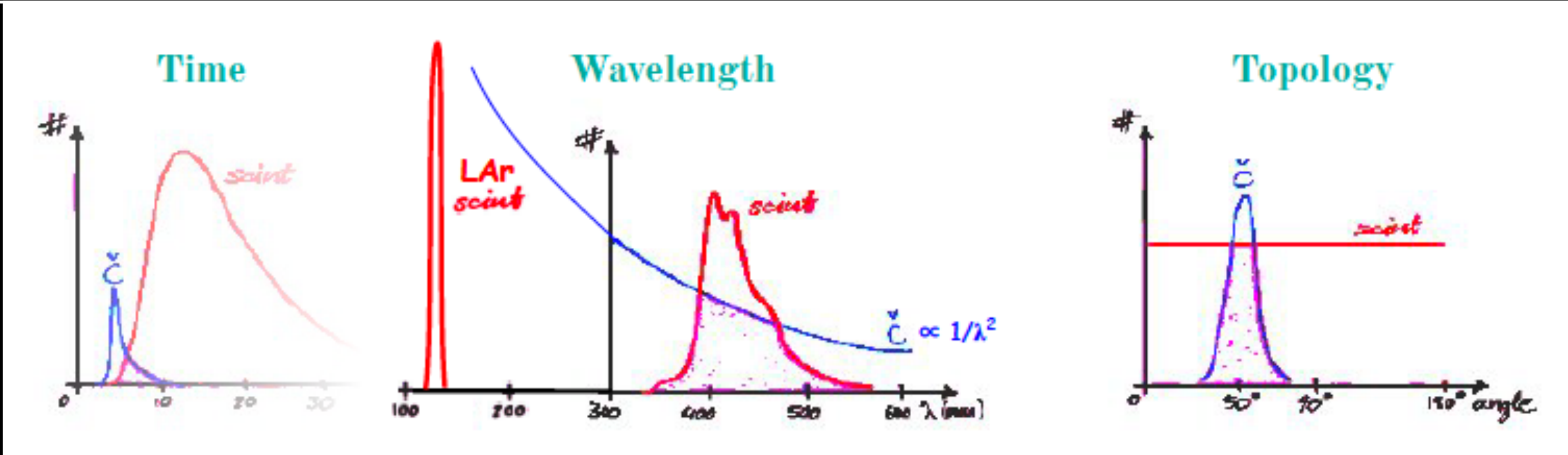


- Theia25 geometry
- 5% Water-based Liquid Scintillator
- 40% photo-coverage with $\sim 46,000$ 10-inch PMTs or $\sim 12,000$ 20-inch PMTs
- Ratpac-two is used to simulate the PMT charge and time.
- Cherenkov + scintillation light

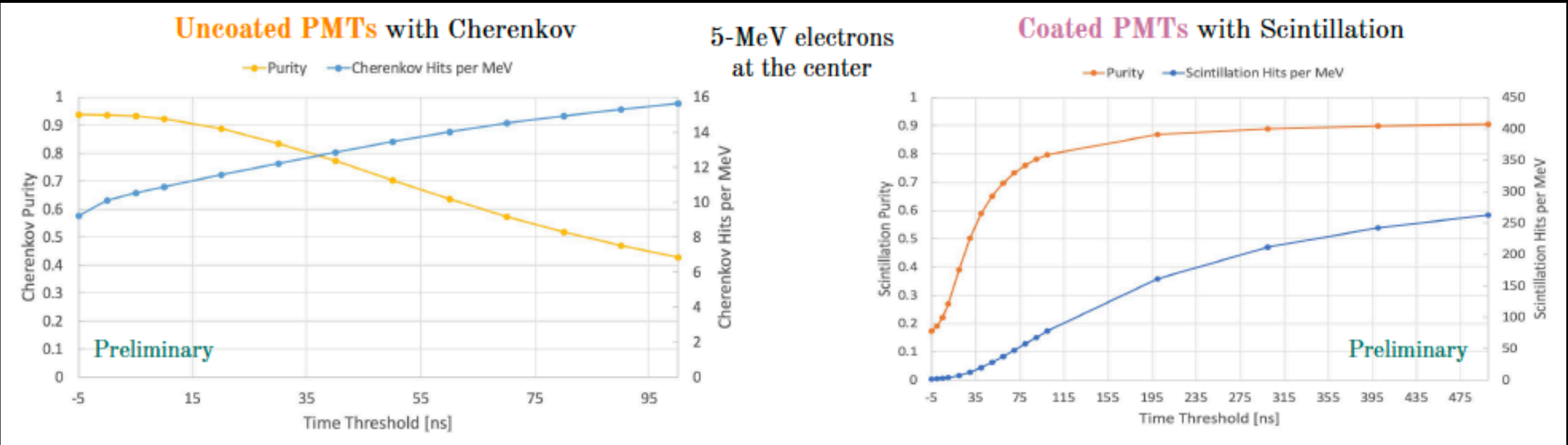


- Even without scintillation light, the LBL CP sensitivity for 17kt water detector is similar to 10kt LAr detector
- Next: add scintillation light to fiTQun reconstruction software

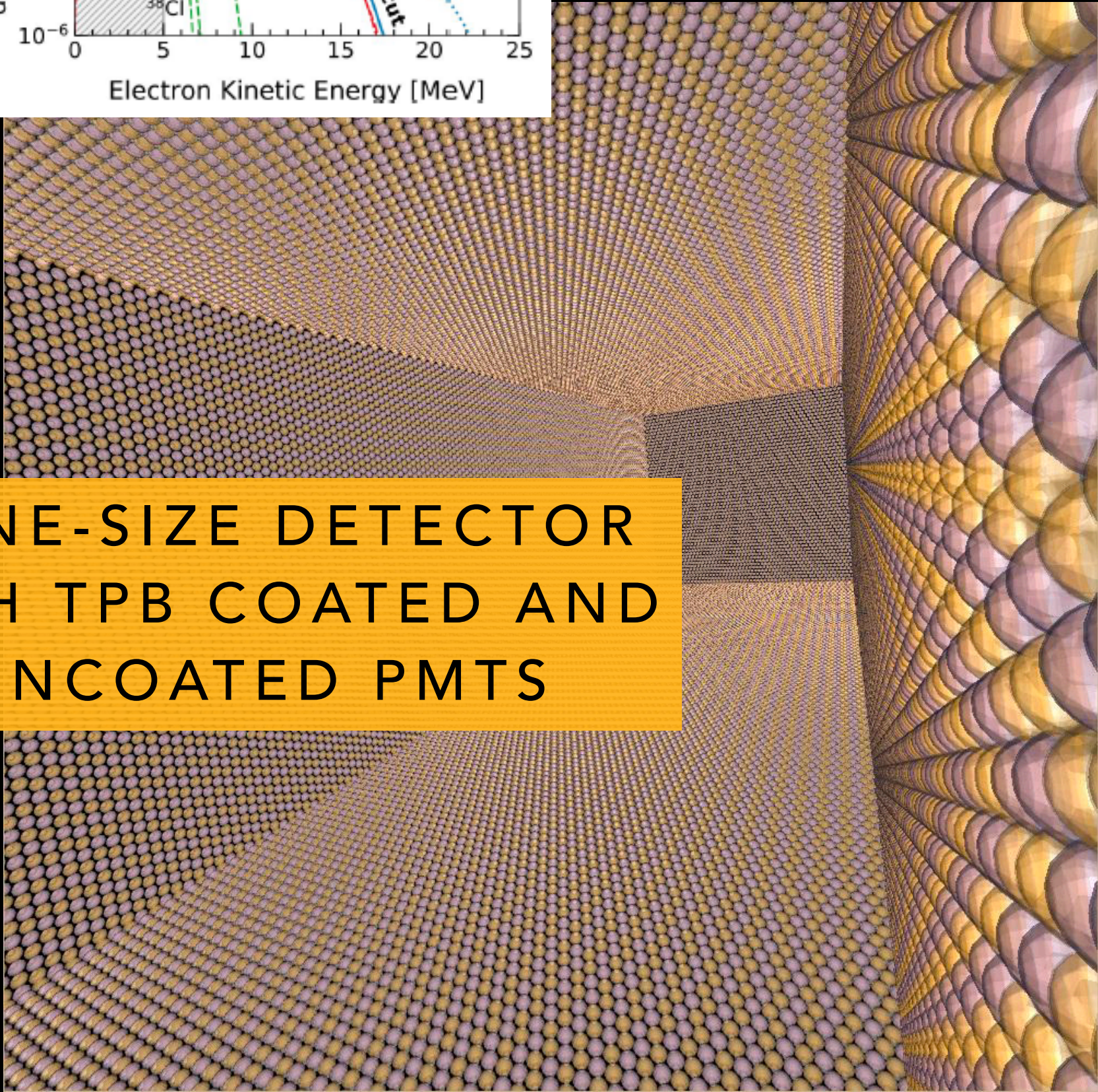
NEW IDEAS



- Liquid Argon Hybrid detector:
 - Backgrounds are very high below 5 MeVm but...
 - Cherenkov/Scintillation identification benefits from a very good spectral separation (scintillation is 128 nm).

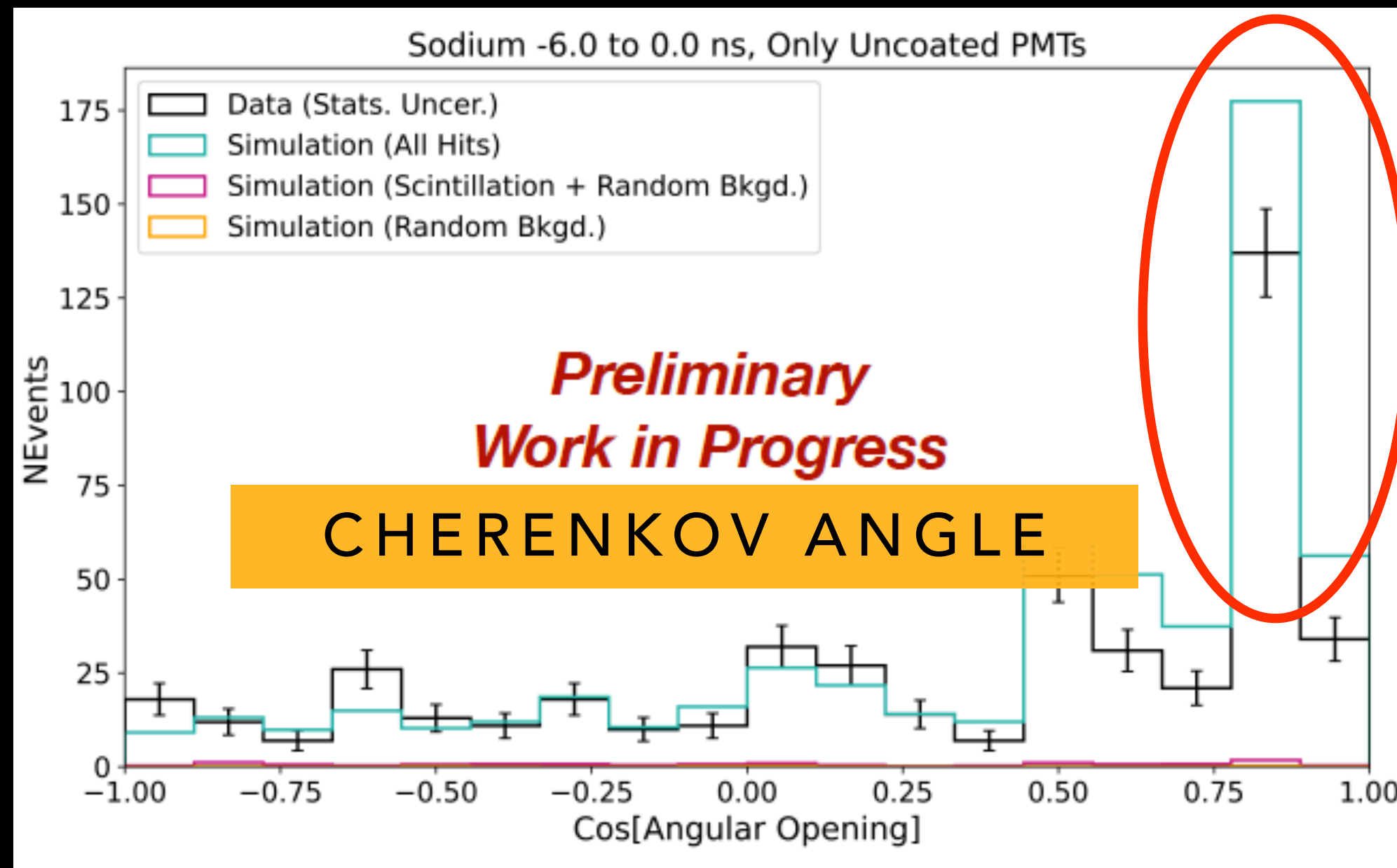
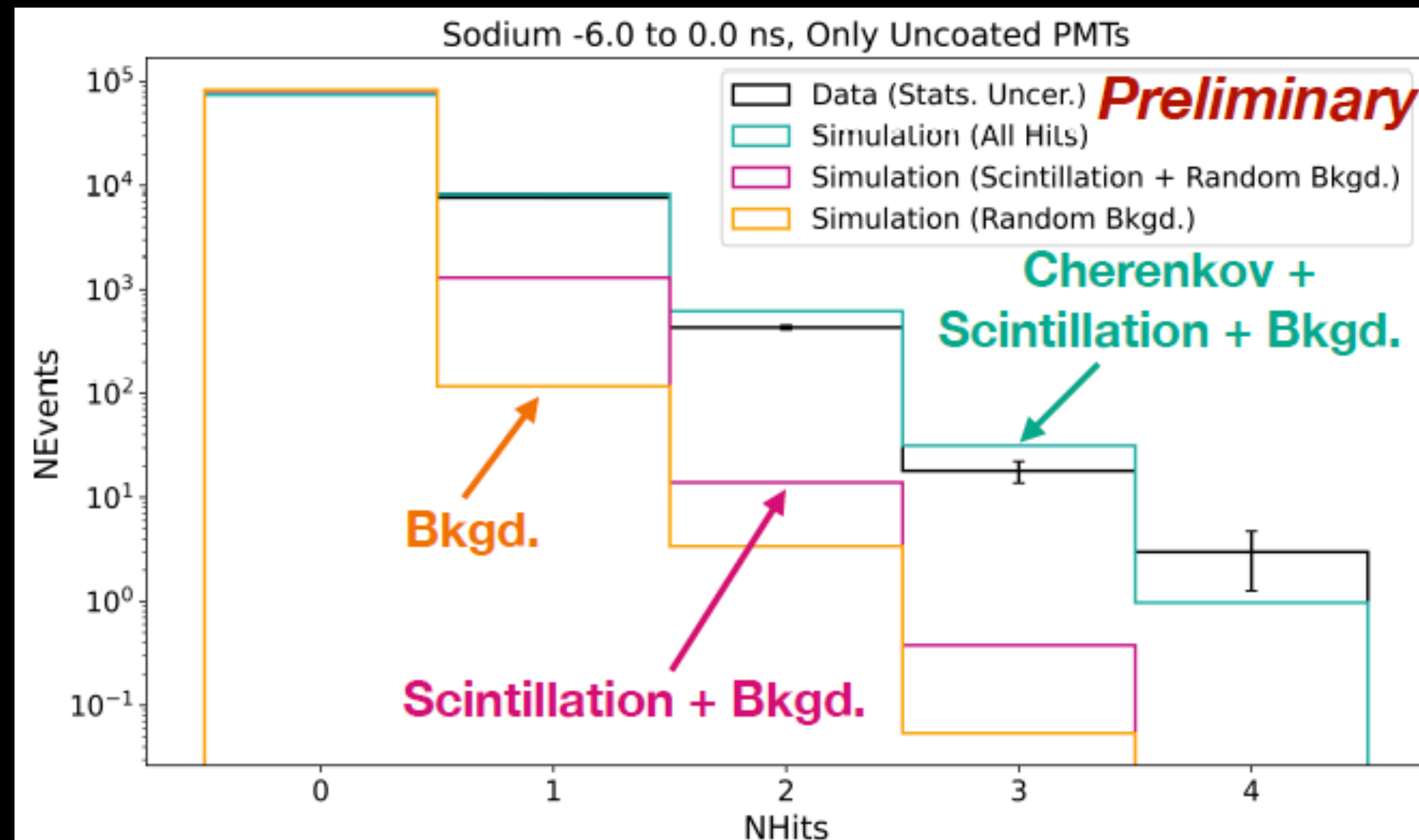


DUNE-SIZE DETECTOR
WITH TPB COATED AND
UNCOATED PMTS





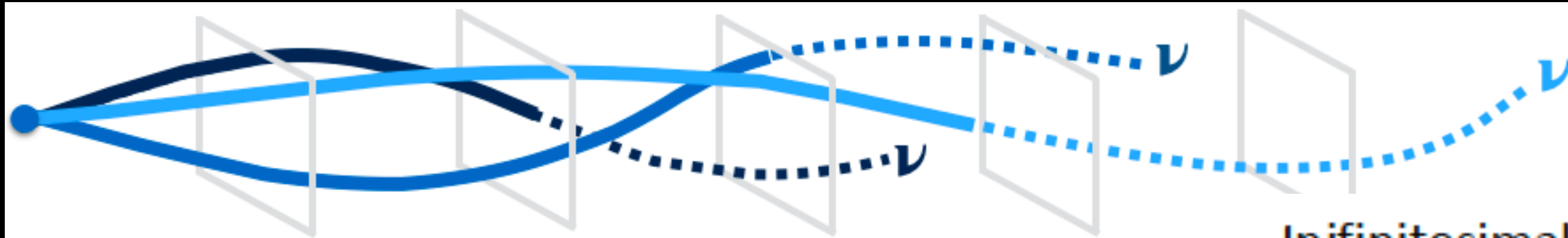
- 7 ton active LAr volume, 200 8" PMTs, 50% photocoverage, 2 ns, Los Alamos
- 160 PMTs coated w/ TPB, 40 uncoated
- Calibration with Na22 source
- Cherenkov: early hits in uncoated PMTs



TIME SORTING BEAM NEUTRINOS

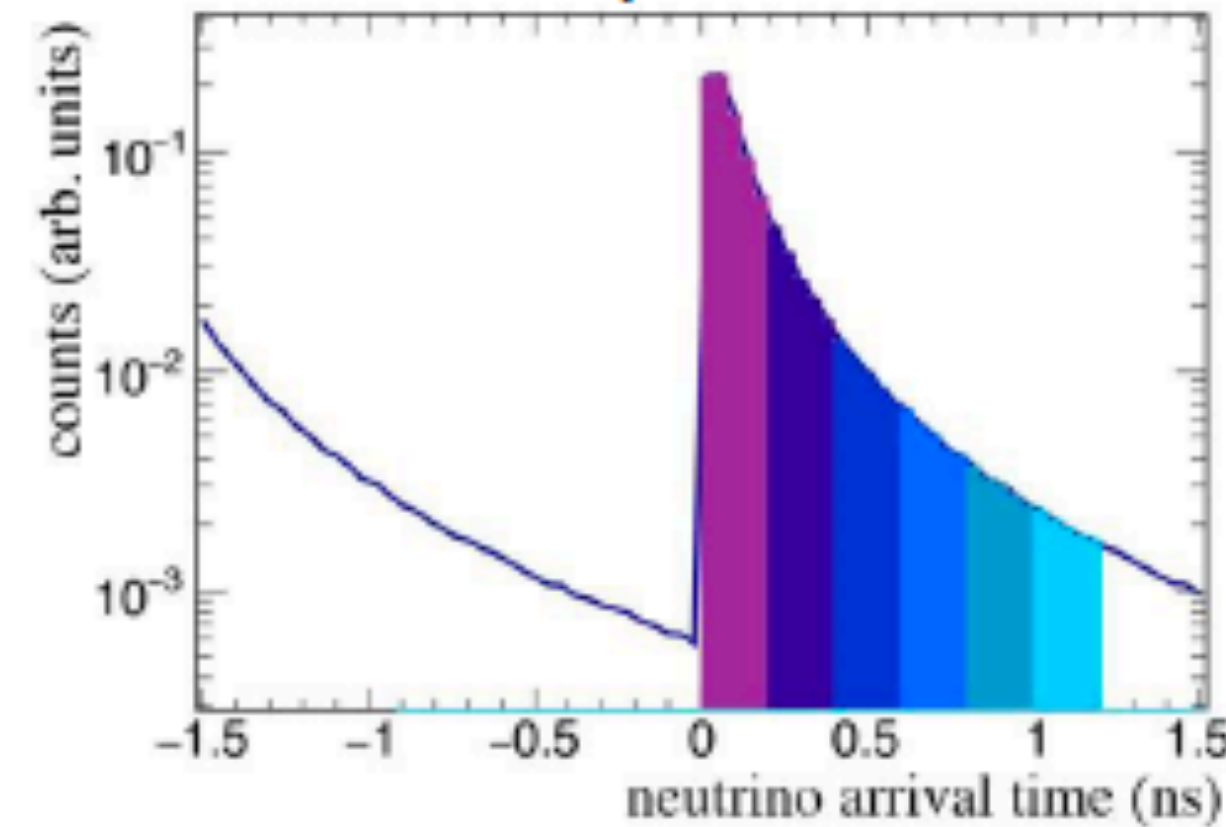


M. WETSTEIN

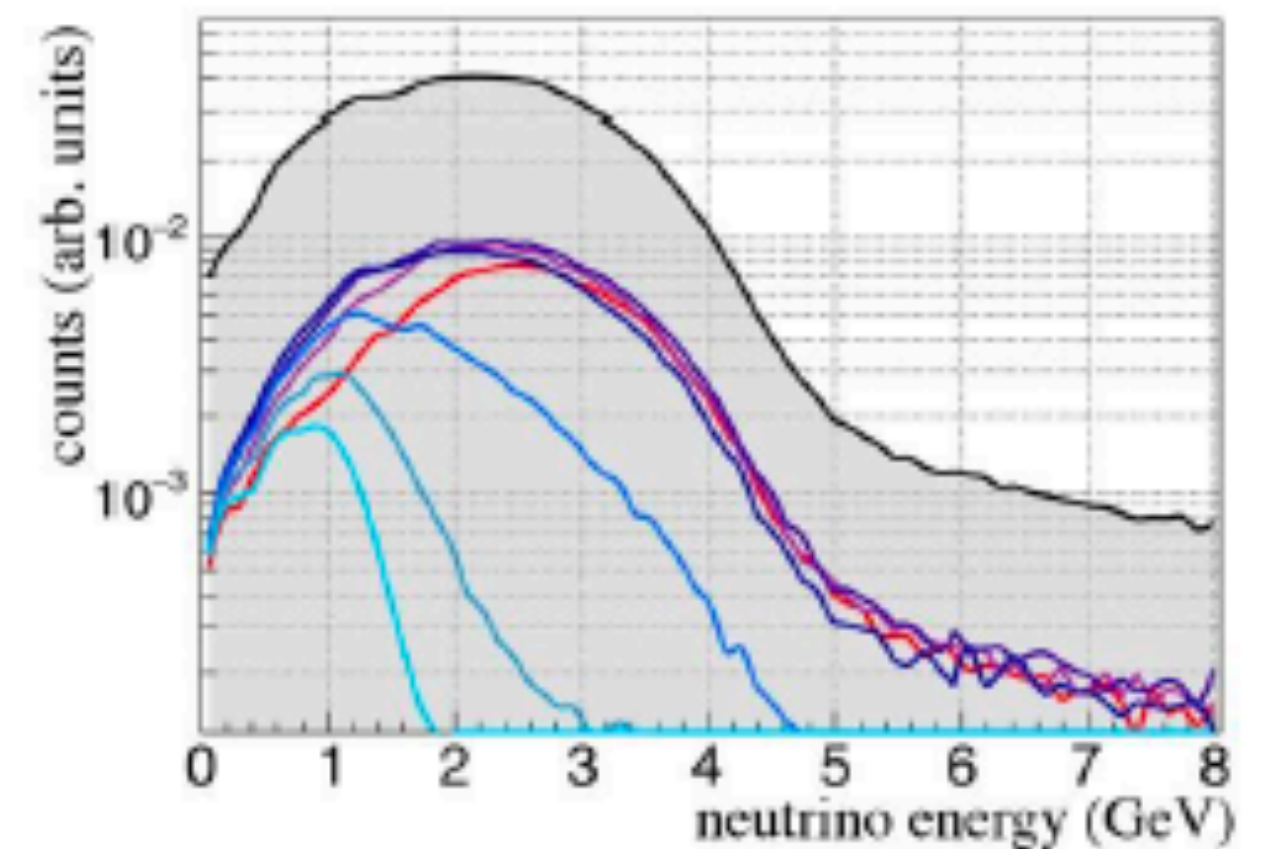
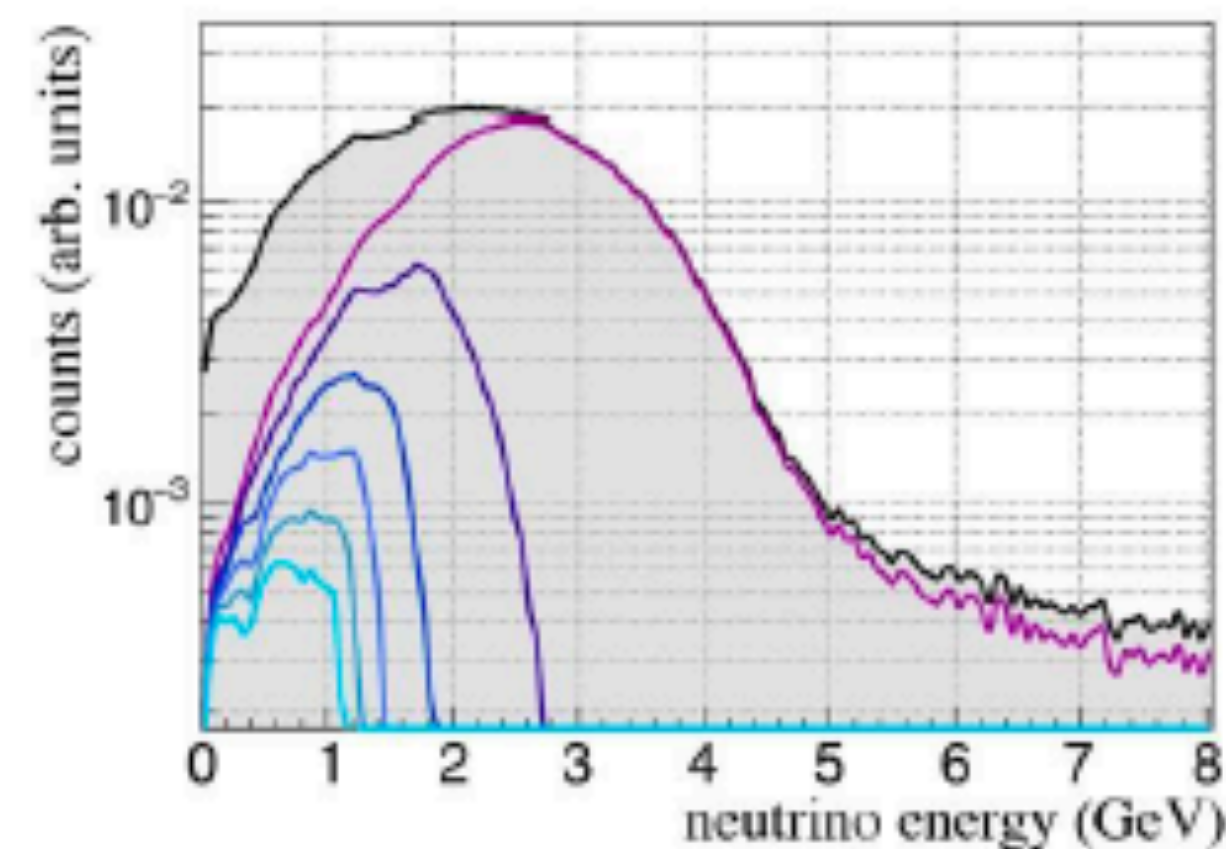
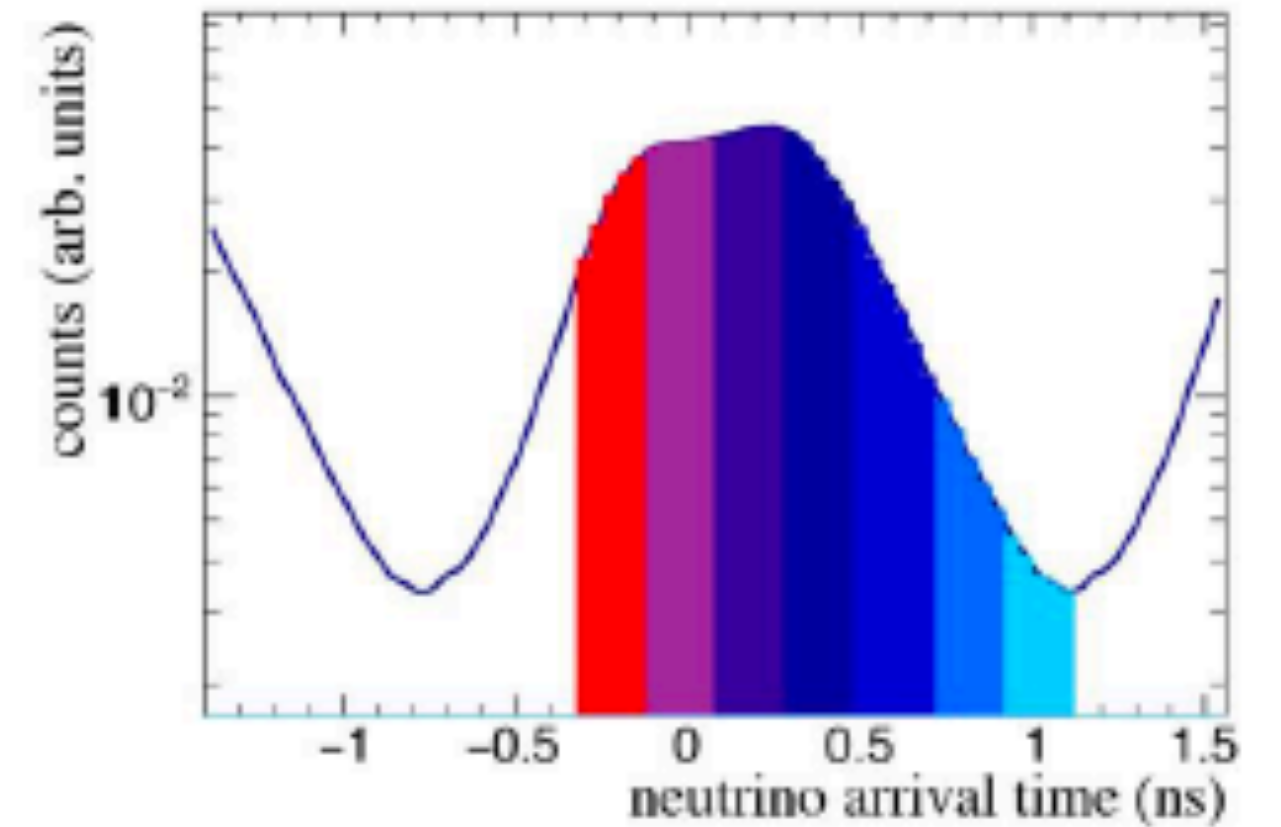


- Low energy pions are slower
- Low energy neutrinos arrive later
- Split the events in time slices, each has a different energy spectrum
- Possibly powerful tool to constrain systematics, combine with PRISM
- Requires sub-ns timing

Infinitesimal proton bunches



"realistic scenario"



3. PATH FORWARD

BACK TO PHYSICS

WHAT PHYSICS CAN WE EXPECT?



- Precision pep and low energy 8B: MSW transition region
- Precision CNO: solar model metallicity
- Double beta decay:
 - lower solar neutrino background a “slam dunk”
 - more than that will be hard. Even if you identify 2 rings, some backgrounds have them
- Supernova neutrinos: directionality
- High energy: Beam, atmospheric, proton decay
 - should improve over water Cherenkov
 - similar performance as LAr, with a simpler detector

Future solar neutrinos

T. KAPTANOGLU

The Jinping detector in China is planning on building a roughly SNO+-size detector and fill with slow LS (potential for Li loading) (CNO and ^8B upturn).

HOW LIKELY IS THIS?

JUNO claims sensitivity to CNO flux similar to BX (10-15% in 5 years).

(JUNO collaboration <https://arxiv.org/pdf/2303.03910>)

CARBON COSMOGENICS?

DUNE plans to measure the hep neutrinos and the day-night asymmetry.

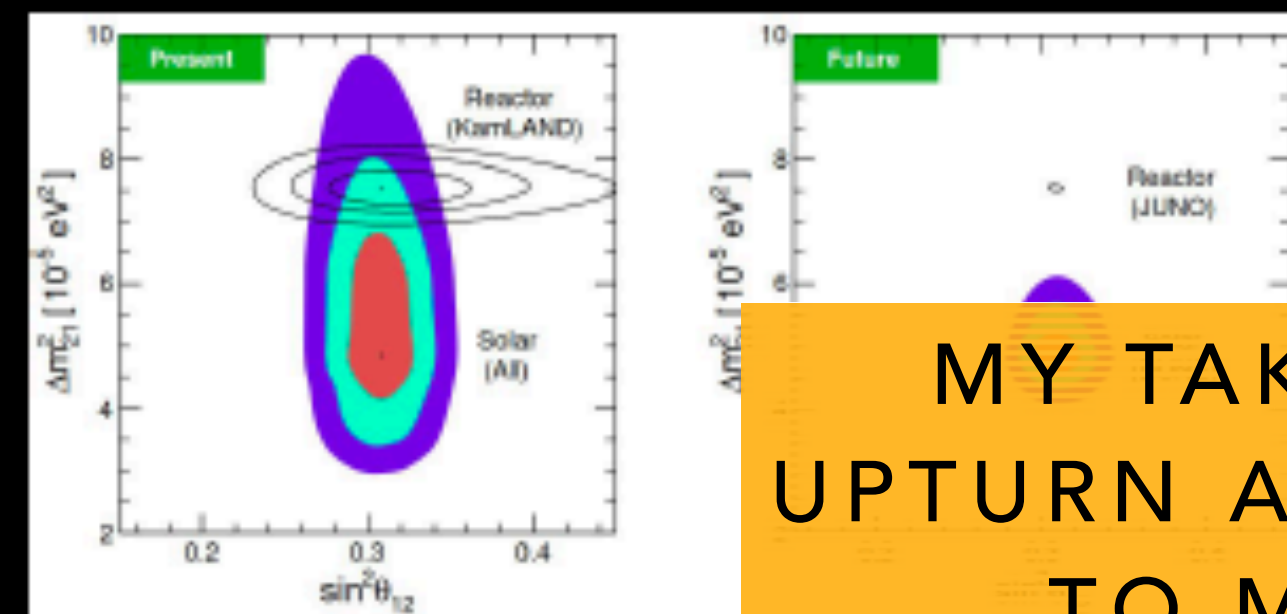
(Beacom et al., <https://arxiv.org/abs/1808.08232>)

SLAM DUNK

Precision measurements of the Δm^2_{21} from SNO+, JUNO, and DUNE may resolve current Solar/KamLAND tension.

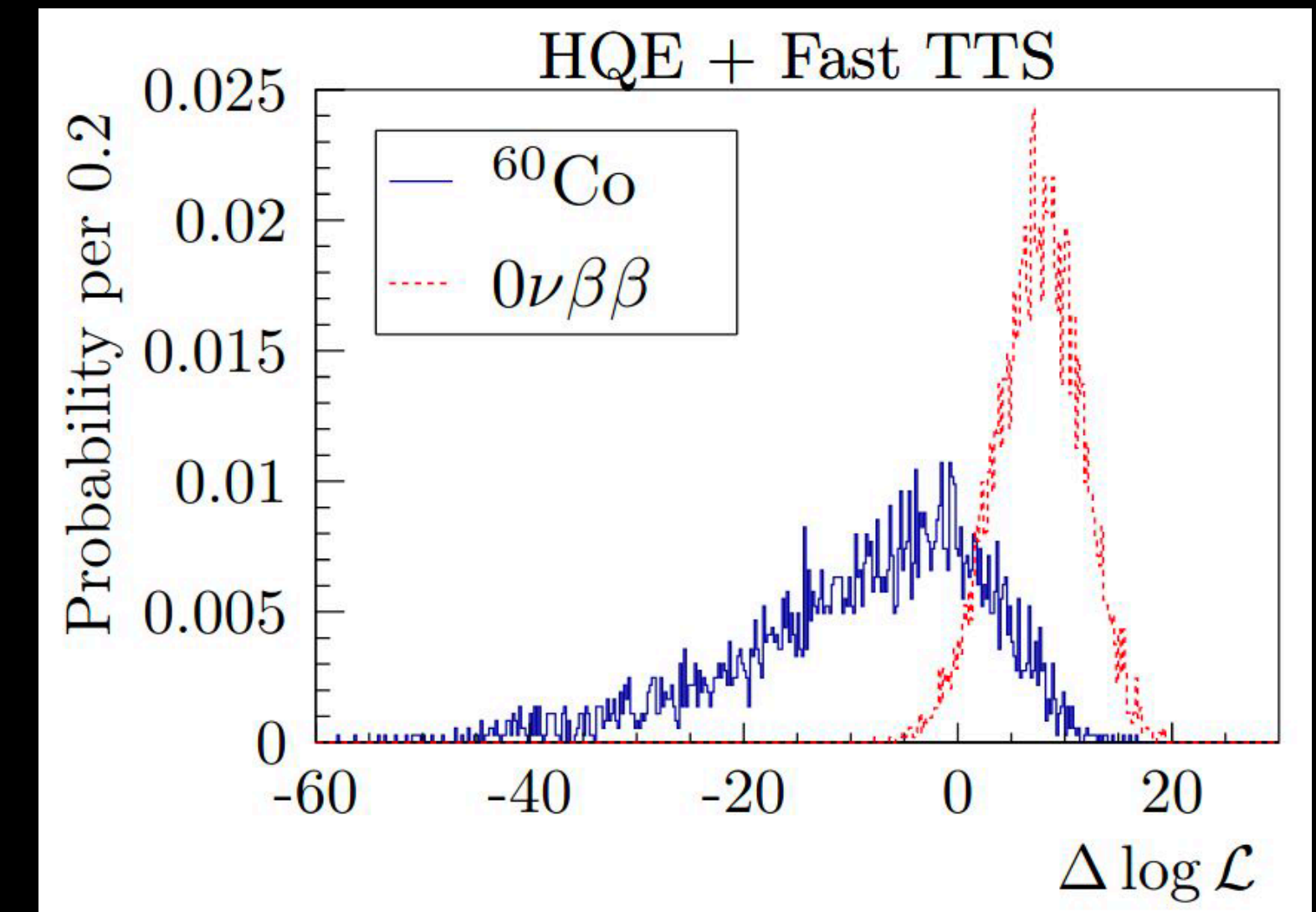
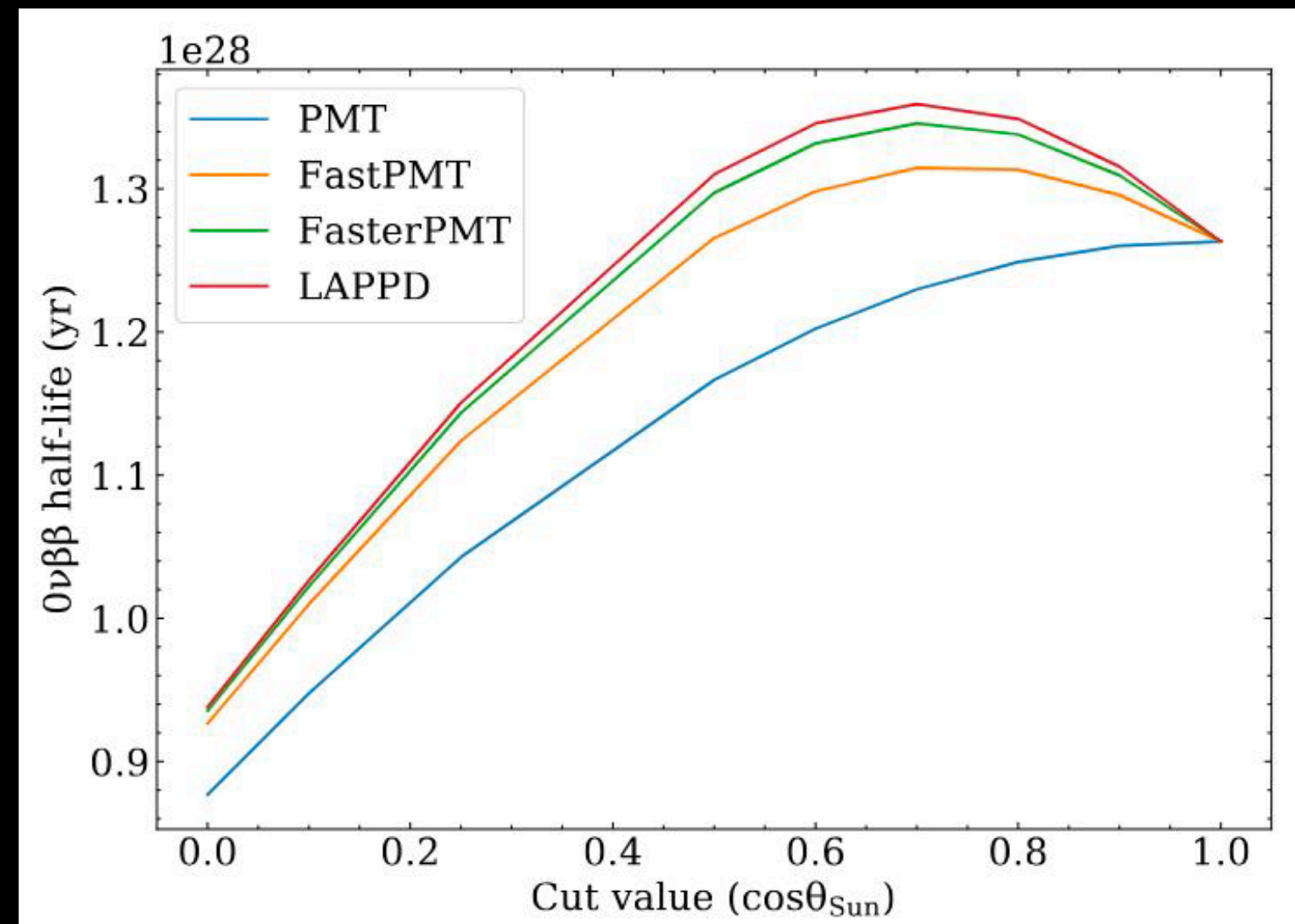
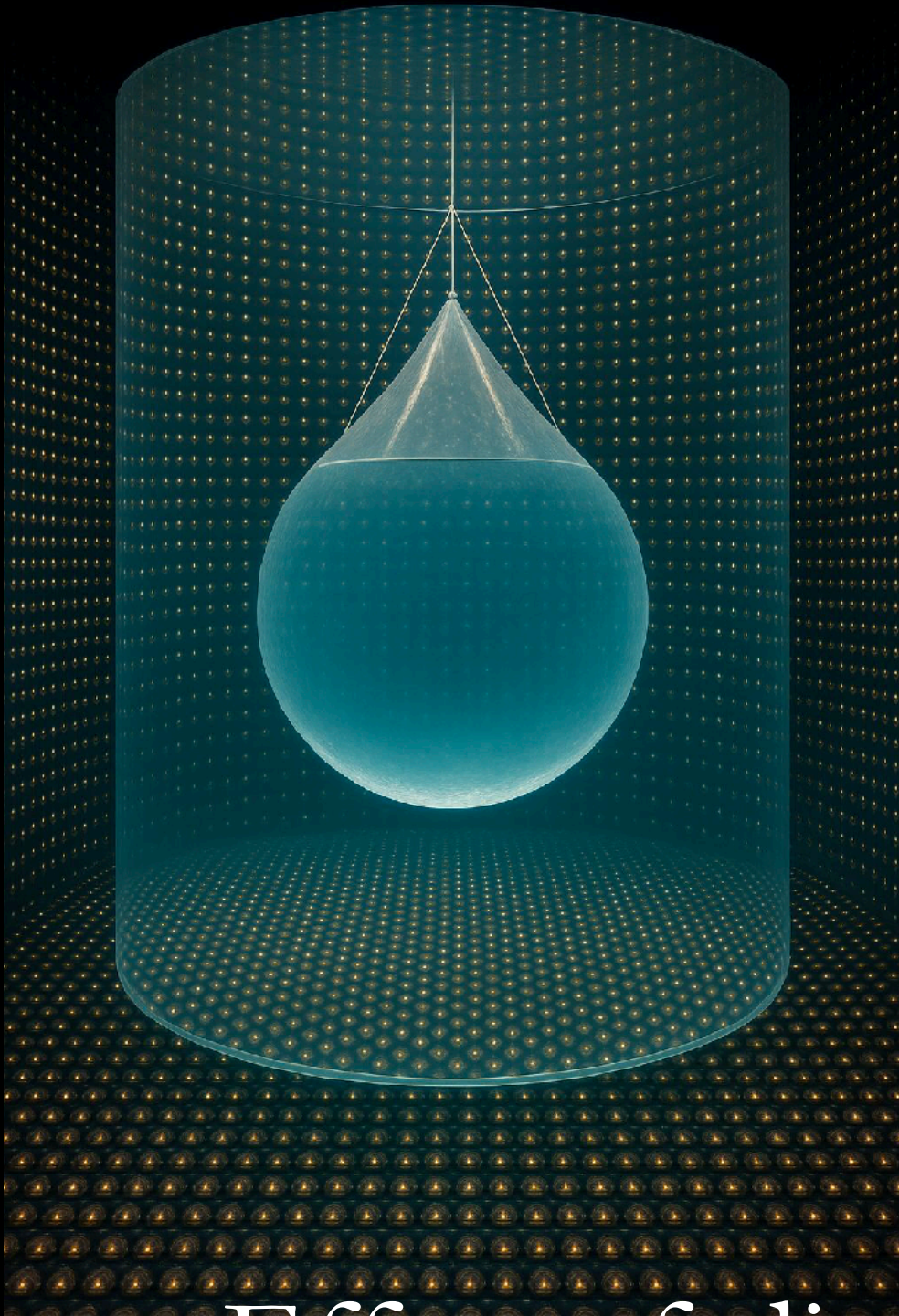
SLAM DUNK

THEIA should be creative and ambitious for what solar neutrino measurements can be made with a future hybrid detector.



MY TAKE: ONLY CNO AND ^8B UPTURN ARE REAL OPPORTUNITIES TO MAKE A DIFFERENCE

- 5% natTe in LAB+PPO with a PMT coverage of 90% (light level of 1200 ph/MeV)
- 90% CL 10-year limit: $T_{1/2} > 10^{28}$ yrs ($m_{\beta\beta} < 6.3$ meV)



- Effect of directionality cut not game-changing. Need to explore other advantages of hybrid detectors, such as multi-site gamma rejection.

$0\nu\beta\beta$ STRETCH GOAL

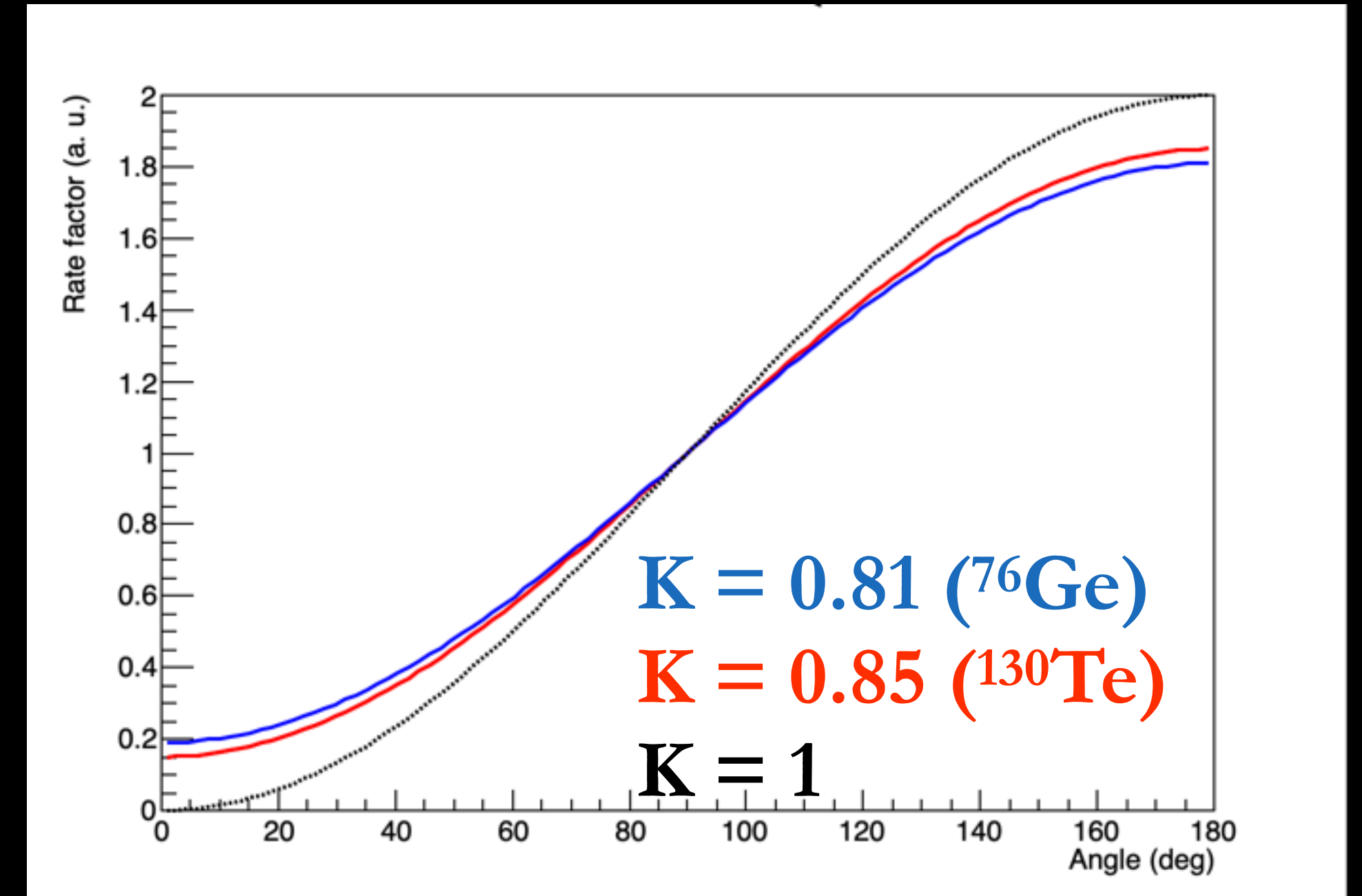


- Angular correlations in double-beta decay?

$$\frac{d\Gamma}{d\theta} = 1 - K \cos \theta$$

	^{76}Ge	^{82}Se	^{100}Mo	^{130}Te	^{136}Xe
K	0.81	0.88	0.88	0.85	0.84

- With light Majorana neutrinos, $K_{0\nu}$ varies little, has $\sim 10\%$ uncertainty
- $K_{2\nu}$ depends on energy. @ $Q_{\beta\beta}$, $K_{2\nu} \gtrsim K_{0\nu} \dots$
- Full range $-1 < K_{0\nu} < +1$ for models such as R-parity violating SUSY or Left-Right Symmetric



- Possible smoking gun for DBD
- Probe underlying physics
- Can Hybrid detectors do it?

A. ALI ET AL., ARXIV:0706.4165

NOW ADD ALL THIS INTO
A COHERENT DETECTOR!

- Scintillator and photon sensors panel discussion
 - Emphasis on safety and regulations issues. it's a big deal...
 - Pure LS: Better cleanliness, LY. WbLS: Better cost, Ch rings.
 - Can photon sensors compensate?
 - Discussion on dynamic range
- Wrap-up panel discussion
 - A lot of progress in recent years. Technologies are essentially ready
 - Define a few realistic scenarios based on location
 - SNOLAB: prioritize DBD. What do you need for solar?
 - SURF: prioritize LBL. What do you need for DBD, solar?

COMPROMISES, COMPROMISES



- Different physics push in different directions.
 - HE needs bigger detectors and ring identification, LE needs more light, better purity
- So where's the advantage in putting it all together?
 - Biggest synergy is in the photon detectors. They give advantages at both scales
 - The compromise lies essentially in the choice of target material

Table adapted from G. Orebi Gann

Physics	Size	Priorities		
		Ring Imaging	Light Yield	Cleanliness
NLDBD	~ few kt	Medium	Very high	Very high
Low-E solar ν (<1 MeV)	~ 10 kt	High	Very high	Very high
High-E solar ν (>1 MeV)	> 50 kt	High	Low	High
Geo/reactor $\bar{\nu}$	~ 10 kt	Low	High	Medium
DSNB	> 50 kt	Low	High	Medium
Long-baseline ν	> 50 kt	Very high	Low	Low
Nucleon decay	> 100 kt	High	High	Low

MANY THANKS!



- To Gabriel and Josh for the invitation, for such a great, focused, workshop and the warm welcome to Philadelphia!
- To all of you who provided material for this talk!
- Last but not least, to my funding agency in Portugal, FCT - Fundação para a Ciência e a Tecnologia, via the project PTDC/FIS-PAR/2679/2021

