جامعة نيويورك ابوظبي
NYU | ABU DHABI

CENTER
FOR ASTRO, PARTICLE,
AND PLANETARY PHYSICS

The DARWIN observatory: the ultimate detector for direct dark matter search

DARWIN

Light collection in DARWIN

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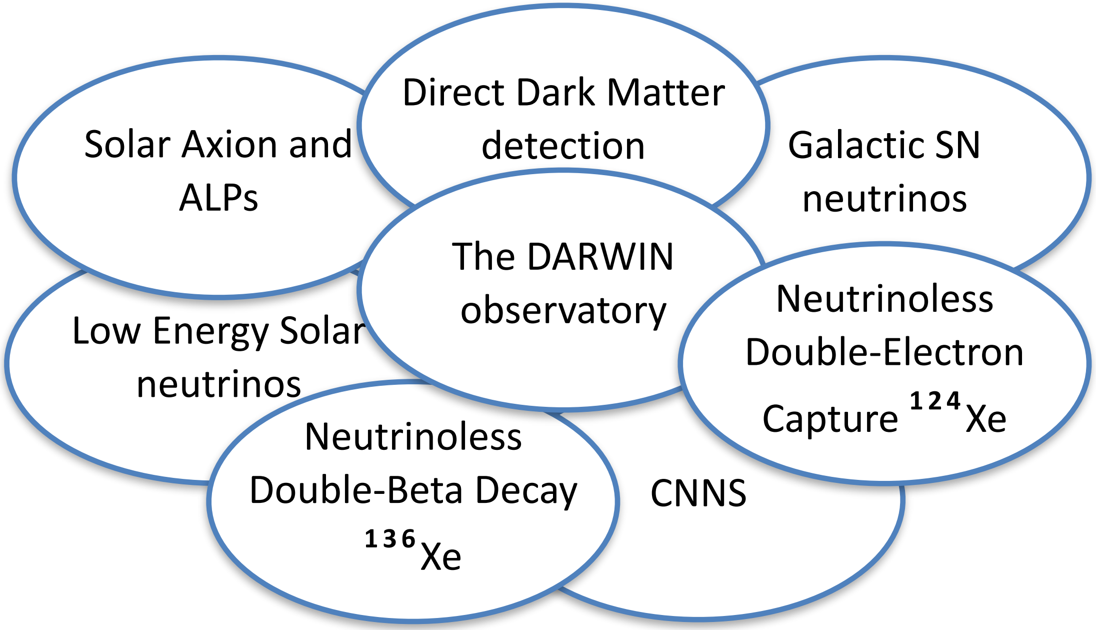
NYUAD and WIS Collaboration - December 22, 2020

Much more than a DM detector



Major challenges:

- **Build and Operate the largest LXe target ever**
- **Unprecedented level of cleanliness**
- **Highest light collection efficiency**
- **The largest storing capability of xenon on Earth**
- **Xenon procurement (~ yearly worldwide production)**

DM direct detection: exploiting the effects

SIMPLE
PICO
…

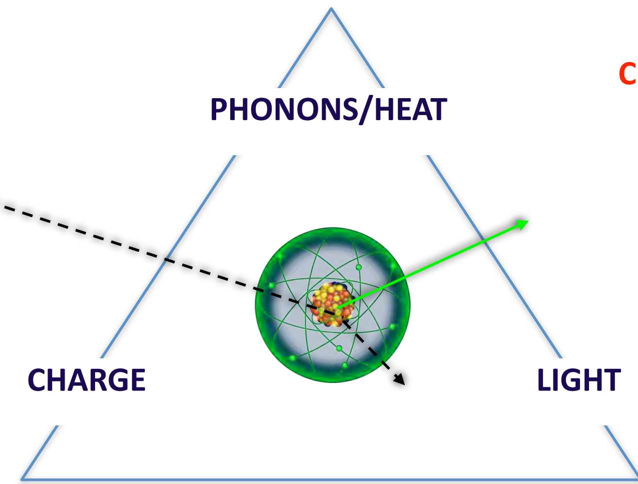
(cryogenic bolometers/ superheated liquids)

(cryogenic bolometers+charge collection)

SuperCDMS
EDELWEISS
…

CRESST
…

(scintillating cryogenic bolometers)



(Ge detectors/ directional detectors)

COGENT
TEXONO
CDEX
DMTPC
DRIFT
MIMAC
Newage
…

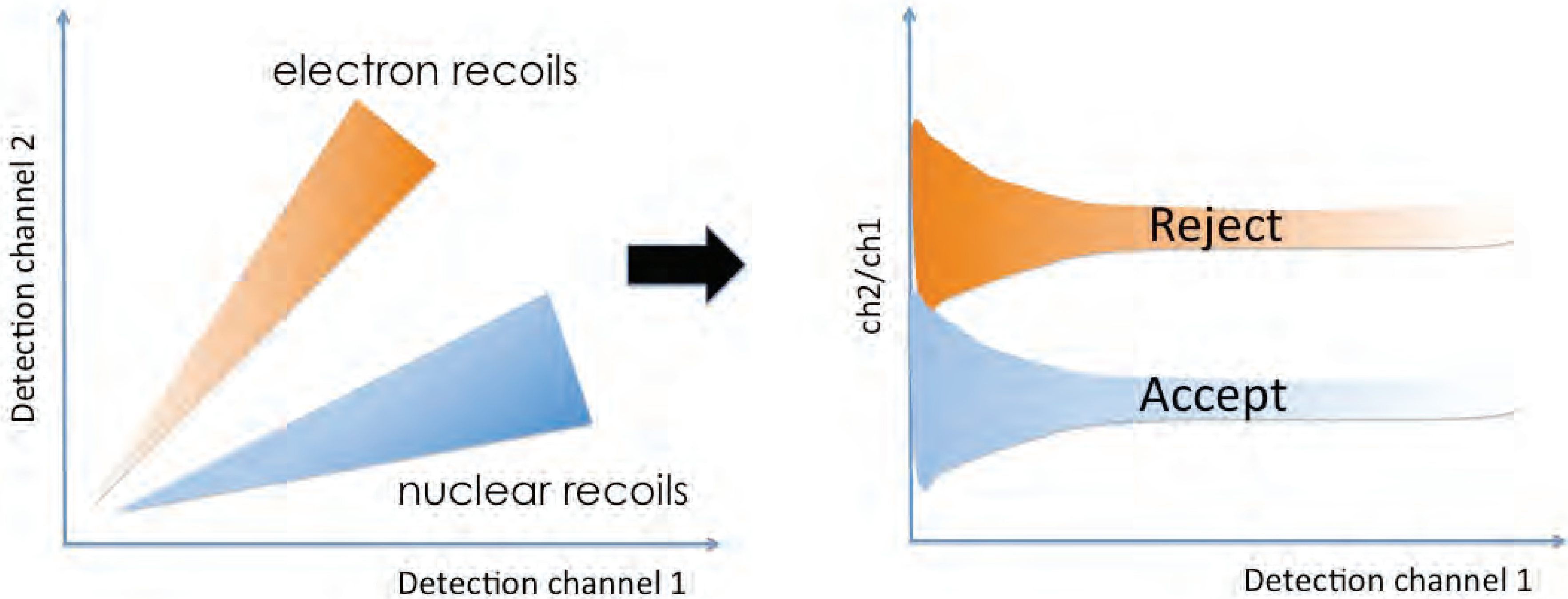
LZ
XENON
DARKSIDE
PANDA-X
DARWIN
…

DEAP
CLEAN
DAMA/LIBRA
XMASS
COSINE
SABRE
…

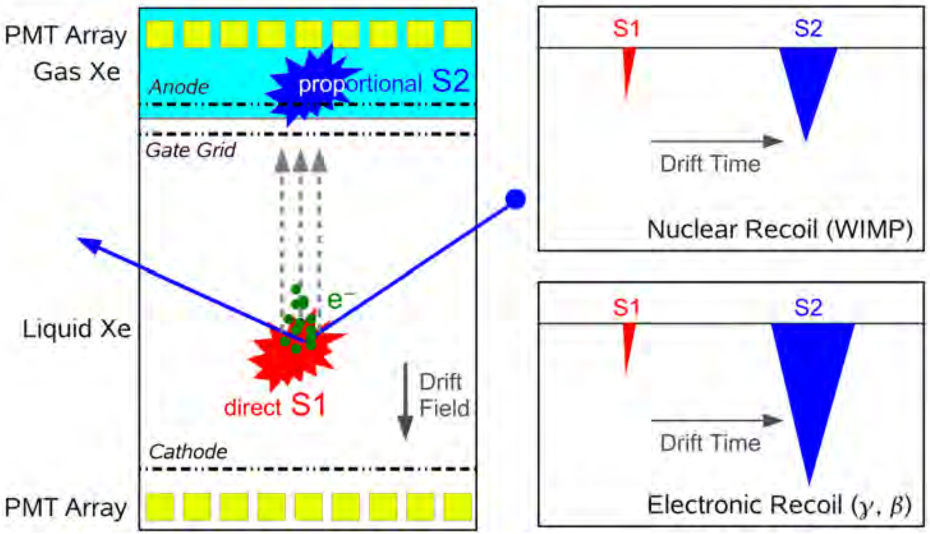
(scintillating crystals/ liquid noble gas detector

(dual-phase liquid noble gas detectors + TPCs)

(A possible) Detection strategy



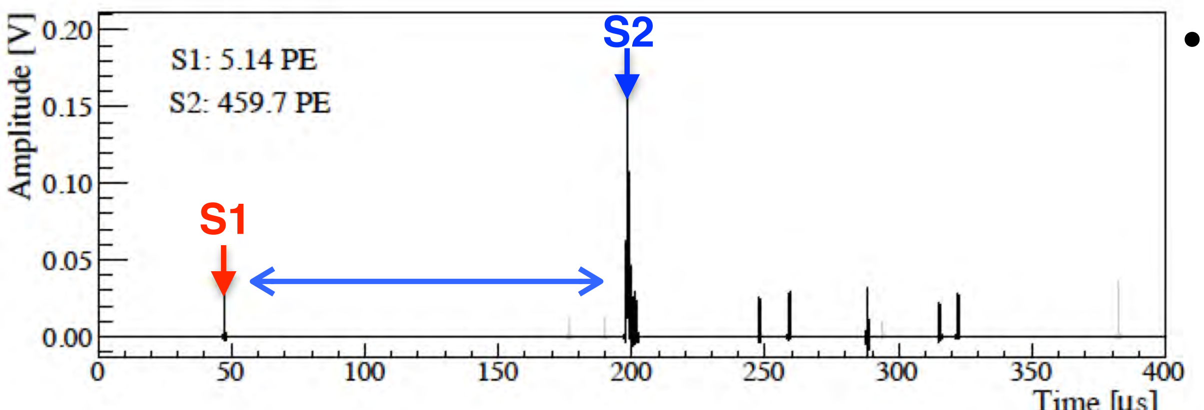
The detection strategy: ER vs NR



- **Two channels recorded:** **S1** from prompt scintillation **(Light)** and **S2** from delayed scintillation ($\propto$ **Charge**)

$$\frac{S2}{S1}_{ER} > \frac{S2}{S1}_{NR}$$

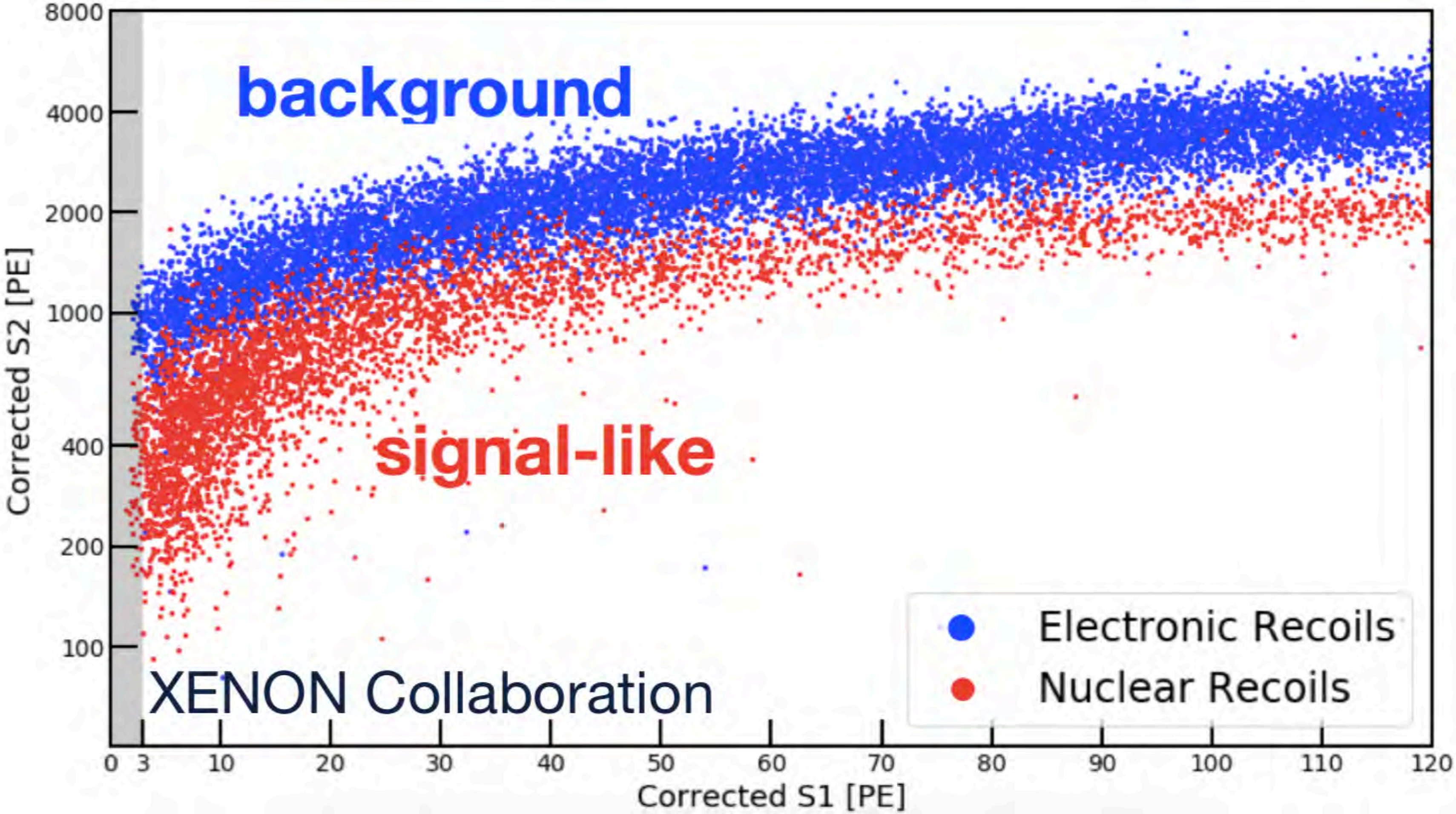
- **Pulse shape discrimination**
- **XY event positioning**



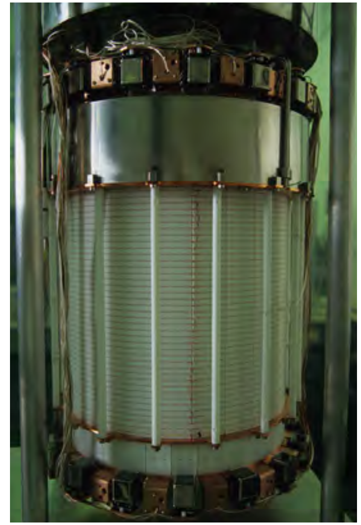
- **Z positioning from the drift time** *(knowing the operating parameters)*

Position resolution ~ mm

The detection strategy: ER vs NR

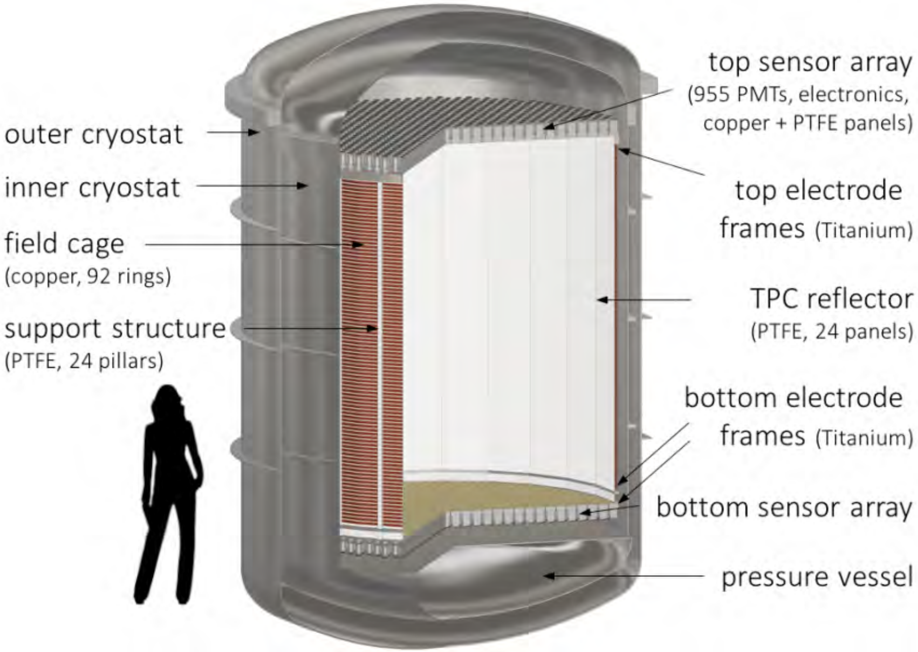


The benchmark: the XENON legacy at LNGS



	XENON10	XENON100	XENON1T	XENONnT
Livetime [yyyy]	2005-2007	2008-2016	2015-2018	2020-202x
Xe mass [kg]	25	161	2300	8400
Target m [kg]	15	62	2000	5900
Drift [cm]	15	30	96	150
VETO	NO	NO	Muons	Muons+Neutrons
σ_{SI} [cm^2]	8.8 X 10^{-44} @ 100 GeV/c^2	1.1 X 10^{-45} @ 55 GeV/c^2	4.1 X 10^{-47} @ 30 GeV/c^2	**1.4 X 10^{-48} @ 50 GeV/c^2**

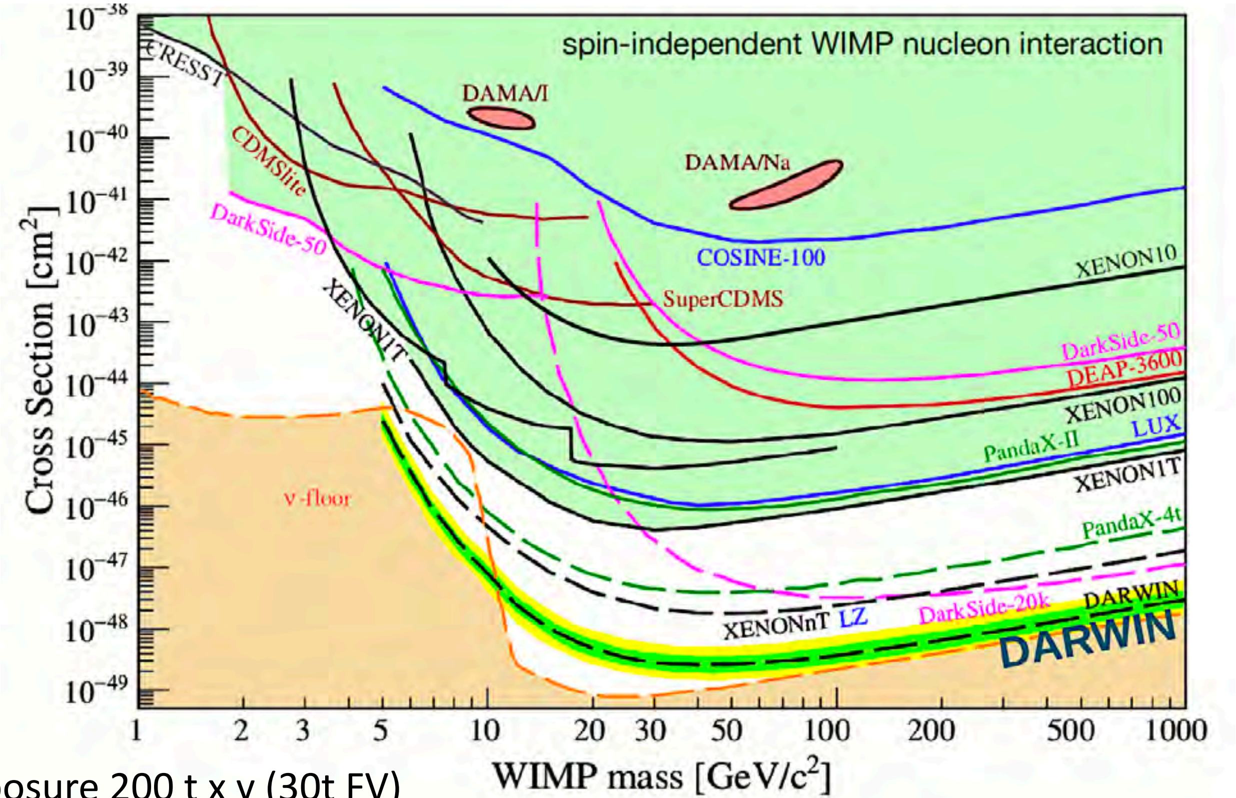
The DARWIN observatory



VETO	Muons+Neutrons
Livetime [yyyy]	2026-203x
Xe mass [kg]	50000
Target m [kg]	40000
Fiducial m [kg]	Up to 30000
Drift [cm]	260
σ_{SI} [cm^2]	Few X 10^{-49} @ 50 GeV/c^2

- **Dual-phase Time Projection Chamber (TPC), 2.6 m diameter, 2.6 m height**
- **Two photo/charge sensor arrays (top and bottom)**
- **Low-background double-wall cryostat**
- **Outer shield filled with water (12 m diameter)**
- **Neutron/Muon Veto**

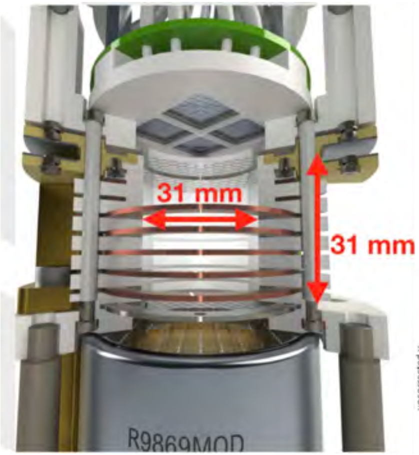
Sensitivity to Spin Independent models

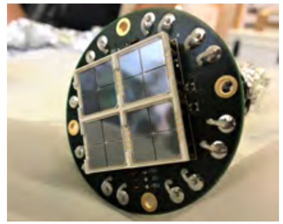


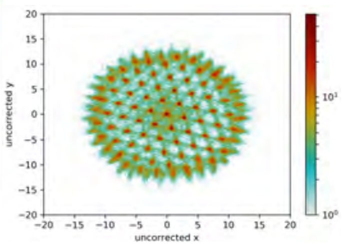
Assumed an exposure 200 t x y (30t FV)
99.98% ER rejection (30% NR acceptance)
Combined (S1+S2) energy scale
Energy window 5-35 keVNR
Light yield 8 p.e. / keV

Light and charge sensors & readout

Extensive SiPM/MPPC characterization in dedicated LXe test facilities

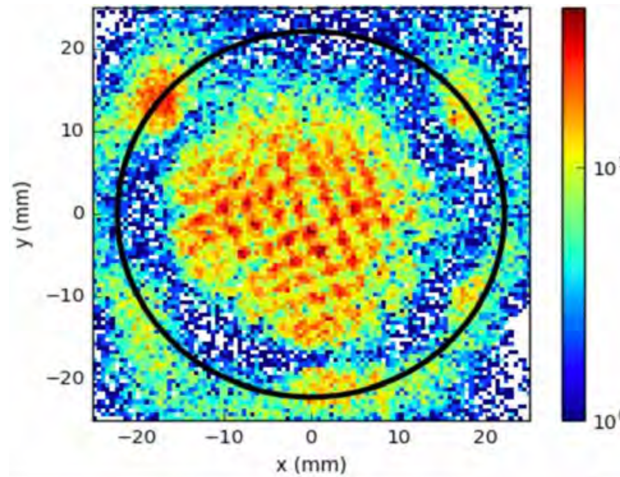


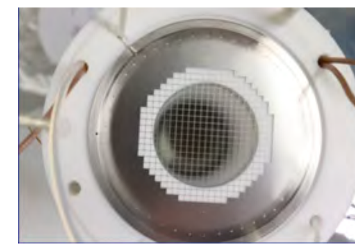




- *Small-scale R&D TPC*
- *Top array with 4×4 S13371 VUV-4 Hamamatsu*

Eur. Phys. J C 80 (2020) 477
JINST 13 (2018) P10022



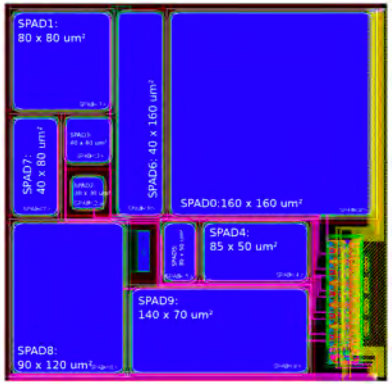


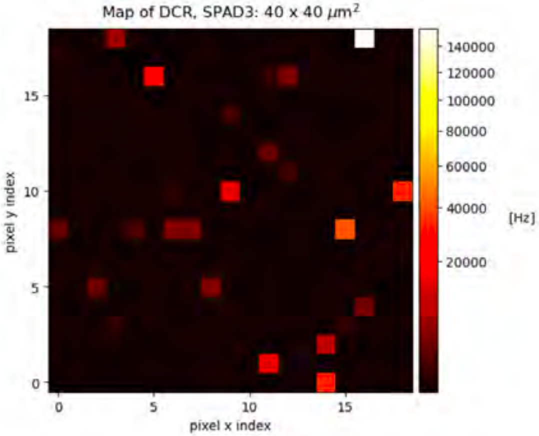
- *SiPMs for position reconstruction*
- *Field dependence of electronic recoils*
- *Pulse shape discrimination*

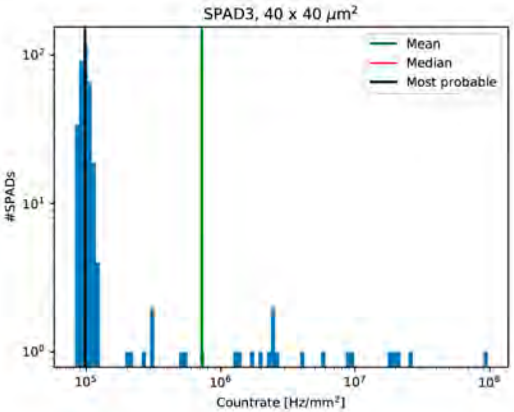
https://doi.org/10.1088/1748-0221/13/05/P05016
https://doi.org/10.1088/1748-0221/13/10/P10031

Light and charge sensors & readout

Digital SiPM







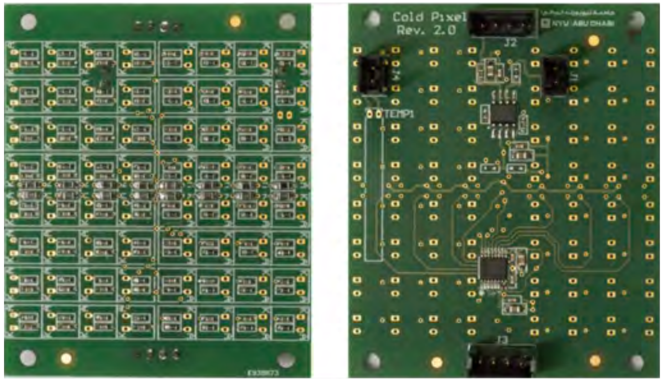
(Preliminary)

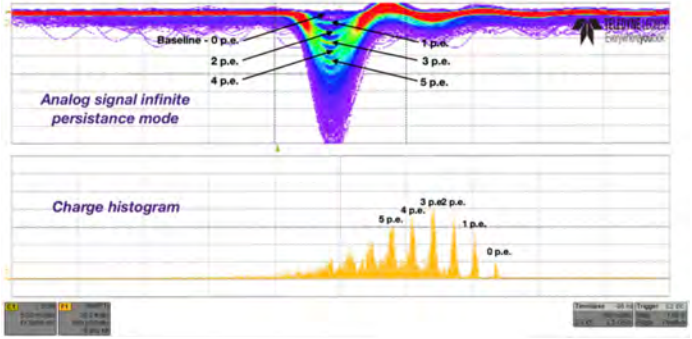
Single SPAD switching ON-OFF capability embedded.

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Schaltungstechnik und Simulation

Cryogenic Preamplifiers for VUV4 MPPC





Multiple MPPCs operated as single channel

NIM A (2018) Vol. 893, 117-123

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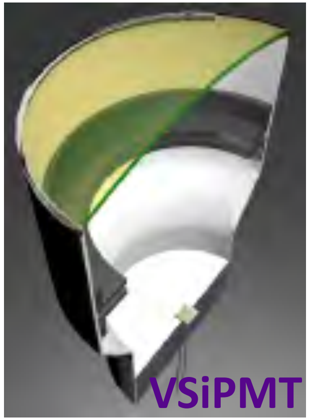
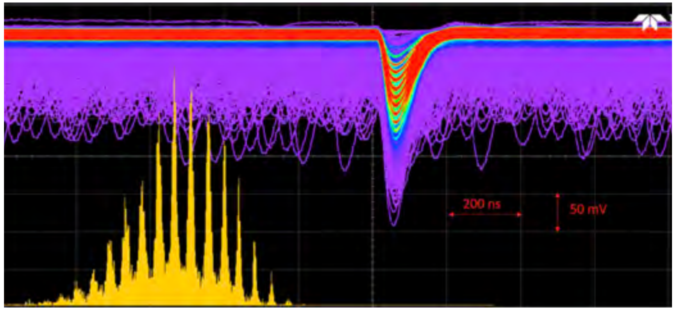
Light and charge sensors & readout

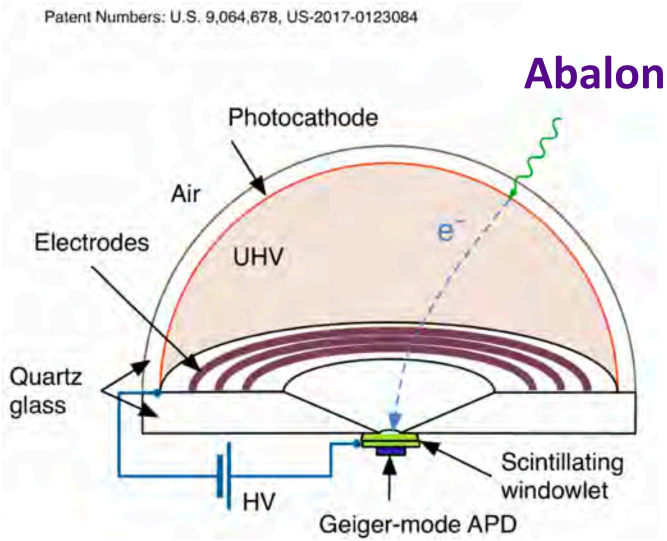




- "PMT-Like" coverage
- HiRes Single Photon Detection Capability
- DCR typical of SiPM

https://doi.org/10.1016/j.astropartphys.2015.01.003

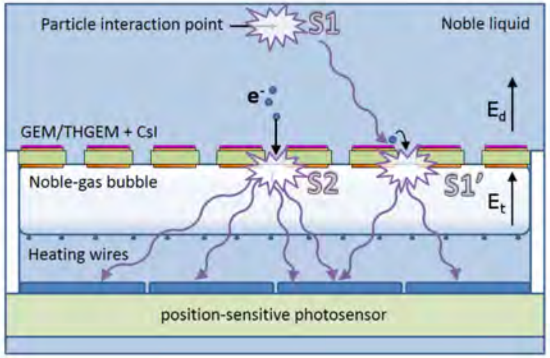
Università degli Studi di Napoli Federico II
INFN



- Huge area coverage
- Low DCR (similar/better than PMT)
- MidRes Single Photon Detection Capability

https://doi.org/10.1016/j.nima.2018.10.176

Liquid Hole Multipliers in LXe



- Very long term stability
- HiRes Position reconstruction

https://doi.org/10.1088/1748-0221/13/12/P12008

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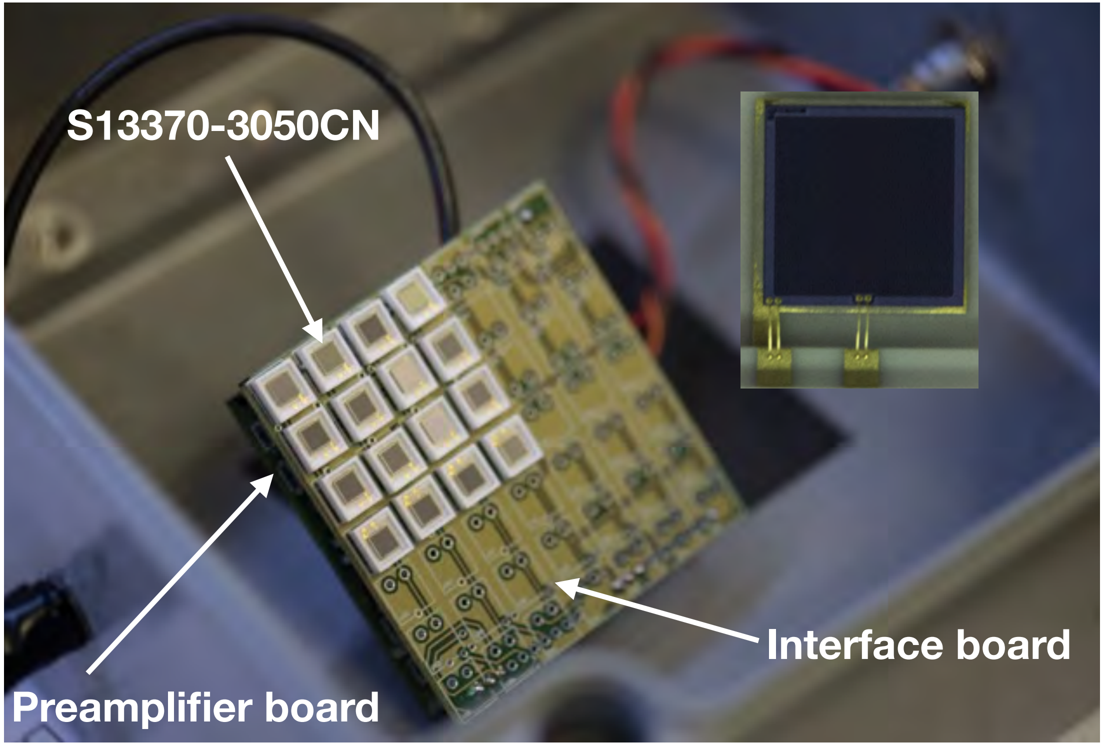
Light collection in DARWIN @ NYUAD

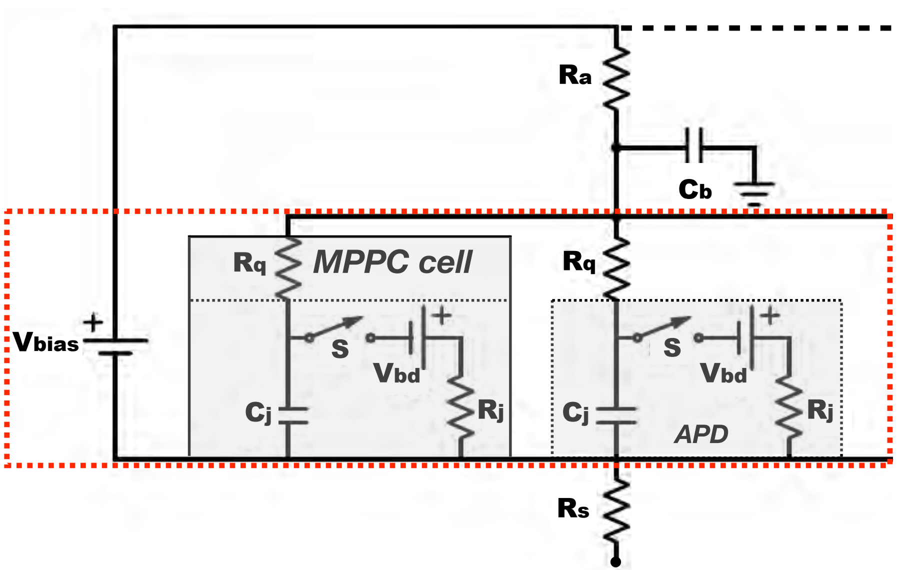
- **VUV4 MPPC:** Vacuum Ultraviolet sensitive Multi-Pixel Photon Counters - 4th Generation
- Cryogenic Readout for a VUV4 detector array based on commercial operational amplifier (AD8011)
- Array of “many” MPPCs readout as a single channel
- Single photon detection capability

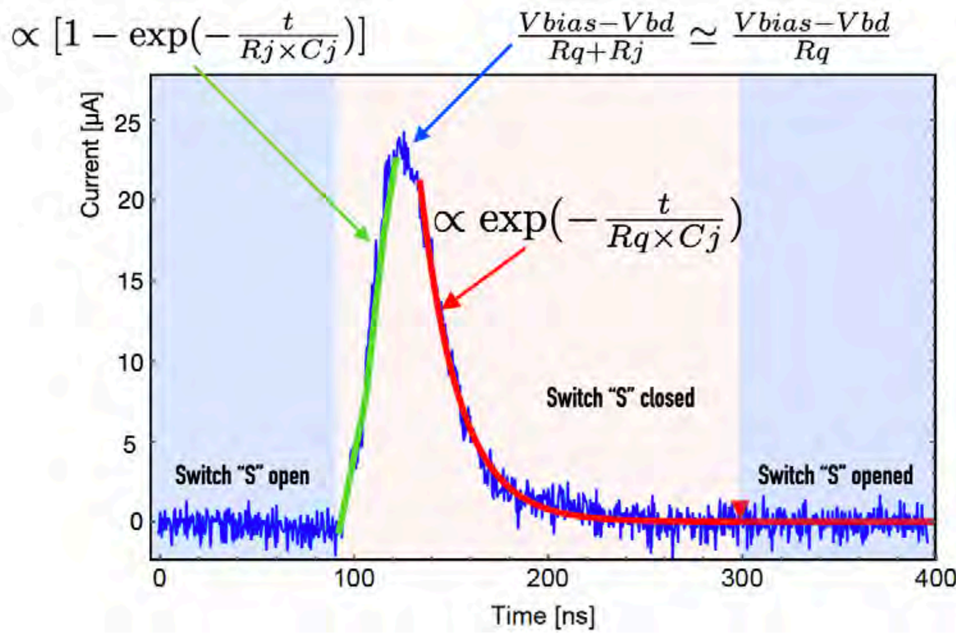


PROS:
- Sensitive to LXe-LAr scintillation light
- P.D.E. (@ 178 nm) ~ 24%
- Intrinsic Single Photon Detection capability
- “Cold proof”
- Low Voltage operation (~56 V @ 298 K)
- Gain ~ standard PMT

CONS:
- Dark Counting Rate, Cross Talk, Afterpulses
- Characteristics = f(Temperature)
- Size (usually < cm^2)
- “Large” Pixel Capacitance: fraction of pF
- ~ Naked: handle with care
- Grouping of many MPPCs is challenging

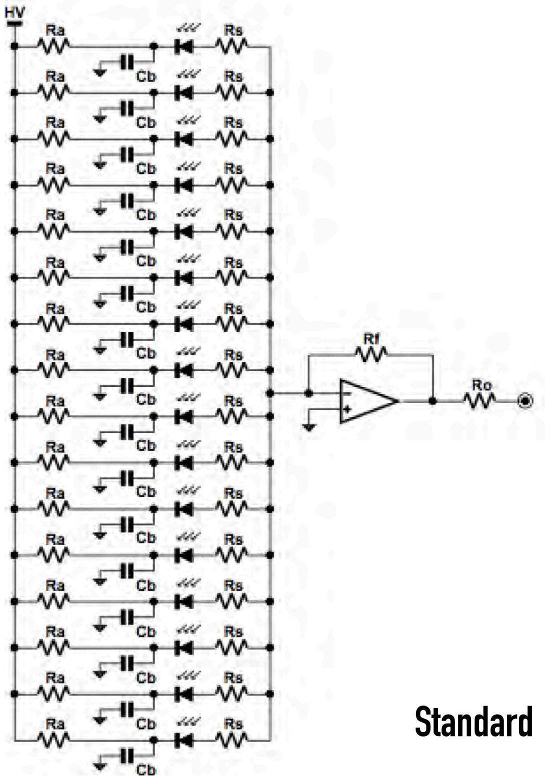
MPPC working principle



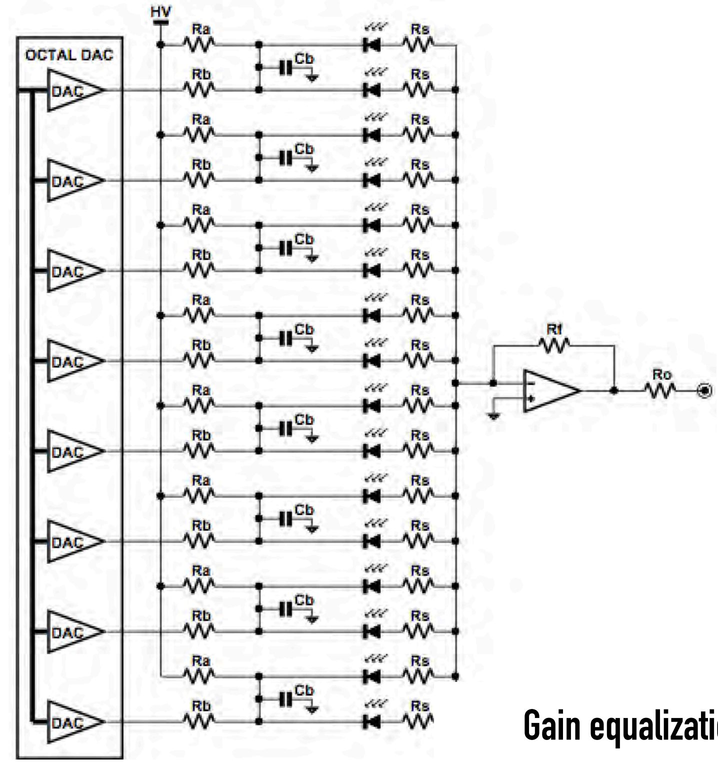


- **APD "ingredients"**: junction resistance (Rj), junction capacitance (Cj), voltage source (Vbd), light switch (S)
- **MPPC cell "ingredients"**: APD + quenching resistor (Rq)
- Current limiting resistor (Ra), Bypass capacitor (Cb) and **decoupling resistor (Rs)** are all external components
- **A MPPC is usually made of thousands of cells connected in parallel**

Schematics of 16-channels-electronics: a possible approach



Standard

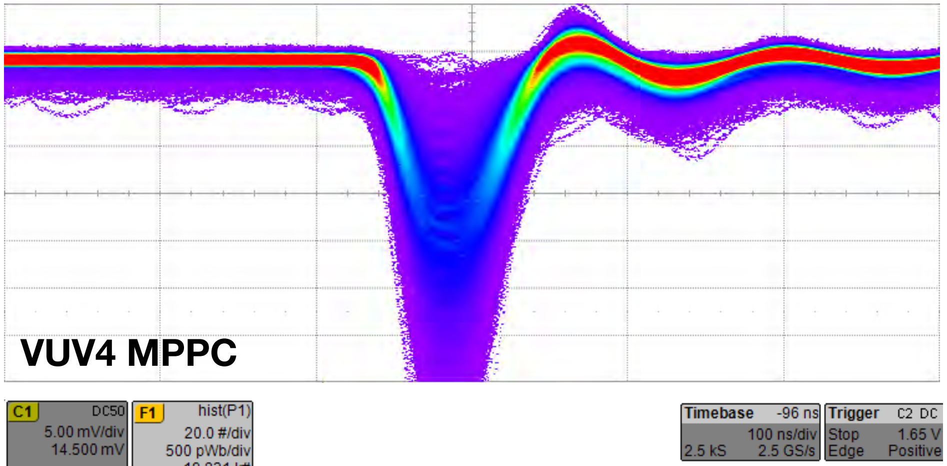


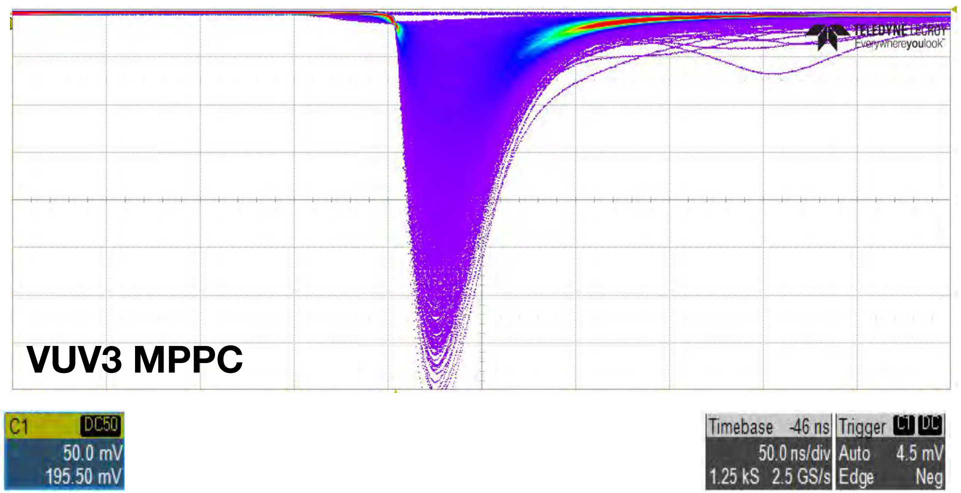
Gain equalization

- This technique is effective if **Dark Counting Rate (DCR), Cross Talk (CT) and Afterpulse (AP)** contributions are "small enough"(see slide "VUV3 vs VUV4")
- Noise contribution must be evaluated
- A similar "Standard" circuit was proposed by DarkSide collaboration: JINST 10 (2015) P08013

VUV3 vs VUV4: in the manufacturer hands

Parameter	VUV 4	VUV 3
DCR (@ 3V OV, 173 K, 178 nm)	~24 % *	~10 %
DCR (@ 3V OV, 173 K, 0.5 pe)	~0.1 Hz/mm²	few Hz/mm²
CT (@ 3V OV, 173 K)	~5 %	~30 %
AP (@ 3V OV, 173 K))	few %	> 70 %
Price (3 mm x 3 mm)	~90 USD	~90 USD
Quenching R value	~ constant	f(T)

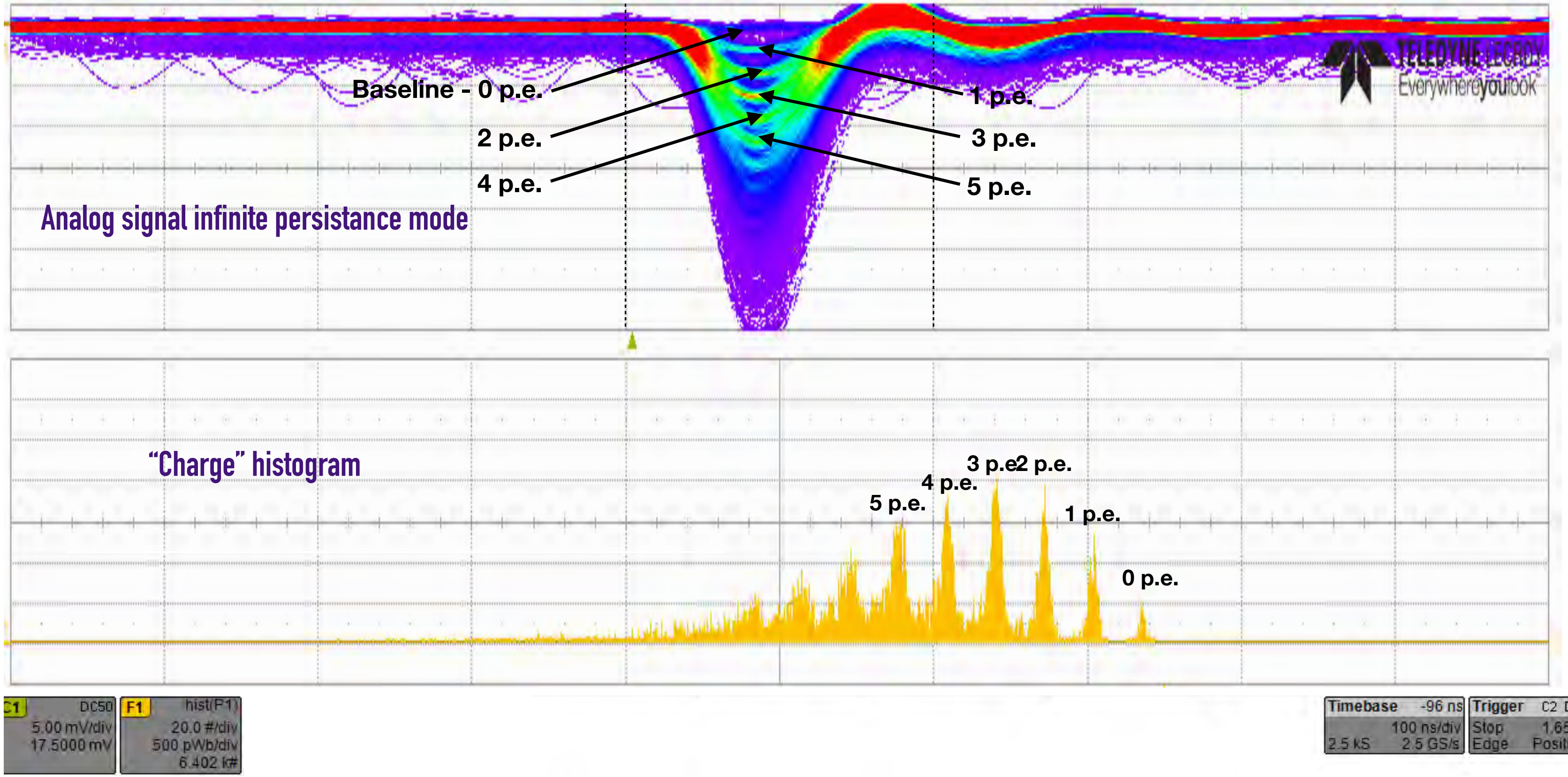




Δt = 3 years

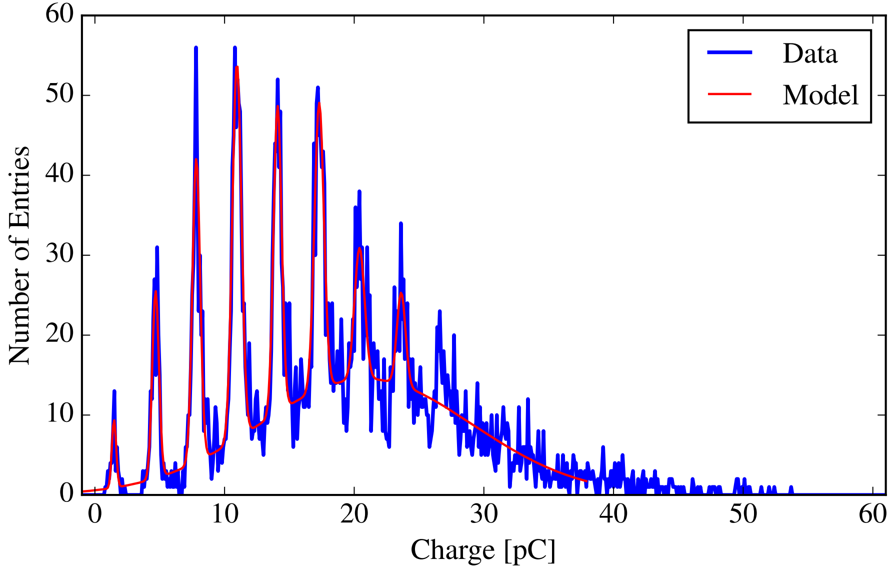
*** = claimed value, NEXO measured (11-18) %**

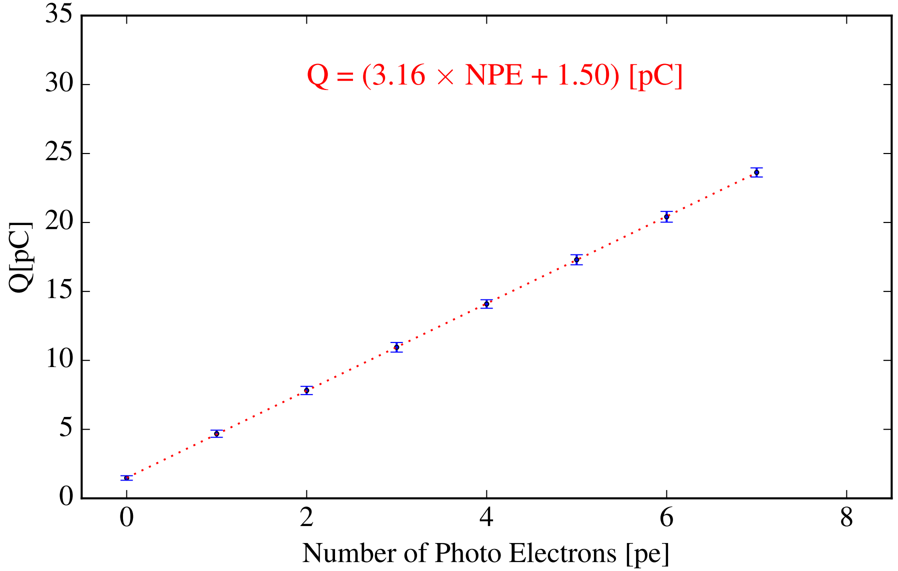
Single photon counting capability (@ 3 V of over voltage, 175 K)



- The DAC control for the biasing fine tuning unactivated here.
- NO Hardware FILTER (hardware). NO offline FILTER (Optimum, Matched, …).
- No Y-axis increased resolution.

Single photon counting capability (@ 3 V of over voltage, 175 K)





- 8 gaussian functions used to fit the charge distribution
- The gain of the array operating @ 3 V of over voltage, 175 K is ~ 2 x 10^7
- The charge of the 1 p.e. is (3.21 ± 0.26) pC
- The overall charge noise (pedestal) is (1.47 ± **0.16**) pC

$$\sigma^2_{p.e.} = \sigma^2_{ELE} + \sigma^2_{DC}{}^{*} + \sigma^2_{AP}{}^{*} + \sigma^2_{CT}{}^{*} + \sigma^2_{GF}$$

*= discrete contribution, but still a game changer

Light collection in DARWIN @ NYUAD

- We developed a cryogenic electronics based on the commercial current feedback operational amplifier AD8011 to operate a “large” number of MPPCs as single detector (1.44 cm^2).

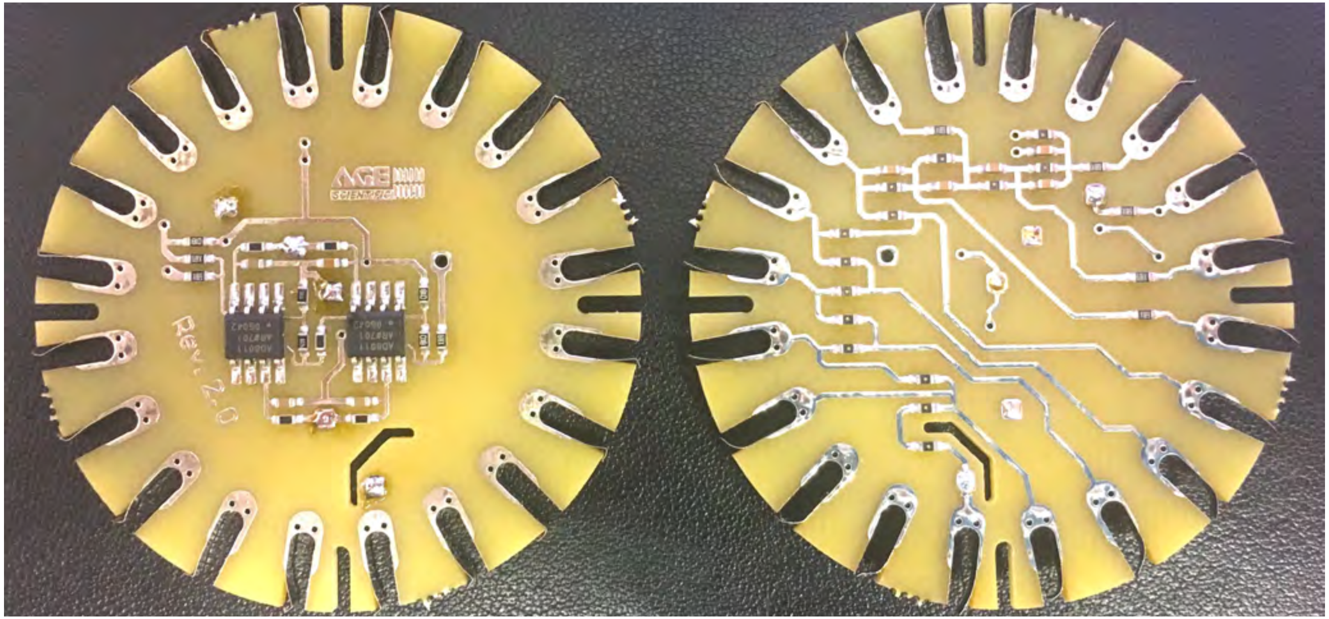
- We will test the device in Liquid Xenon at NYUAD cryogenic facility CRISTALX (see GM talk).

- We will increase the sensitive surface (2X to 4X).

- Signal to noise ratio assessment and its optimization by exploiting Optimum/ matched filters (software anytime, hardware to be implemented).

BACKUP

An amplifier for VUV Hamamatsu R11410 PMT operating in cryogenic environment



- ~ 80 MHz Bandwidth (Rise time: Input signal <4 ns, Output signal ~12 ns)
- IN/OUT impedance 50 Ohm
- 2X **AD8011** operational amplifiers (**± 5V, can be "unbalanced" to match the dynamics**)
- Low Noise (< **200 µV RMS @ 5X amplification**)
- Designed for **0.5 X & (5 X to 15 X)** dedicated outputs
- Power consumption: Min 6 mW, Max 20 mW (amplification unaffected, only dynamic range)

Radioactivity screening of AD8011

Radio Nuclide	Activity [mBq/kg]	Concentration [10^{-9}g/g]	Activity [µBq/pc]	Activity SMD* [mBq/kg]
Ra-228	<39	<9.6	< 2.9	280 ± 40
Th-228	(60 ± 20)	(15 ± 4)	(5 ± 1)	290 ± 30
Ra-226	(50 ± 20)	(4 ± 2)	(4 ± 1)	810 ± 40
Th-234	$(1.0 \pm 0.5)X10^3$	(80 ± 40)	(70 ± 40)	$(4.9 \pm 0.7)X10^3$
Pa-234m	<1,400	<110	< 100	$(4.1 \pm 1.1)X10^4$
U-235	<50	<88	< 3.7	240 ± 80
K-40	<700	$<2.3 X 10^4$	< 51	$(1.2 \pm 0.2)X10^3$
Cs-137	<3.3	-	< 0.24	<7.4
Co-60	<3.4	-	< 2.5	<5.8

*SMD RESISTOR RMCF0805JT15M0