Imperial College London

R&D ON PHOTODETECTORS FOR NOBLE LIQUID APPLICATIONS

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PPTAP Detectors Workshop, 2—4 June 2021

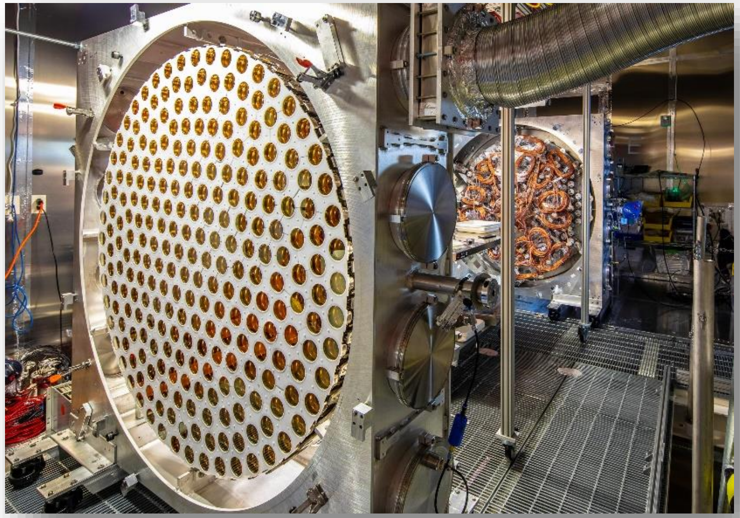
https://indico.stfc.ac.uk/event/316/

OUTLINE

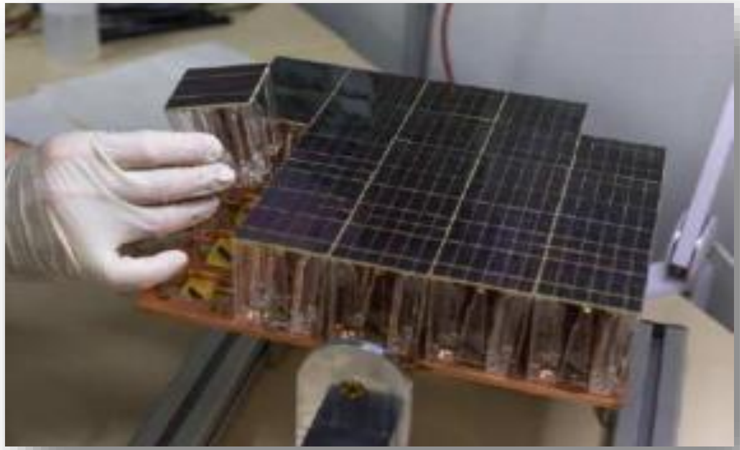
- **Requirements** for LXe (DM, $0\nu\beta\beta$) and LAr experiments (DM, ν)
- **VUV photon detection** strategies
- **VUV devices**: vacuum and silicon photomultipliers (PMTs, SiPMs)
- **VUV materials**
- **Integration**
- **Radiogenic backgrounds**

Focus on PMT and SiPM readout in LXe experiments –
see A. Szelc's talk on SiPM R&D for LAr

See also ECFA Detector R&d Roadmap Symposium
- Giuliana Fiorillo – TF2 Liquid Detectors
- Samo Korpar – TF4 Photon Detectors



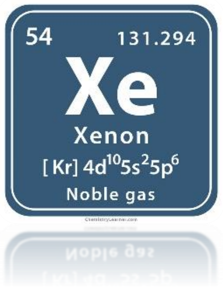
LUX-ZEPLIN (LZ) photomultiplier arrays



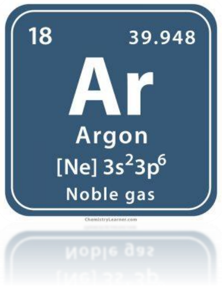
DarkSide-20k photo-detector modules

SCINTILLATION PROPERTIES

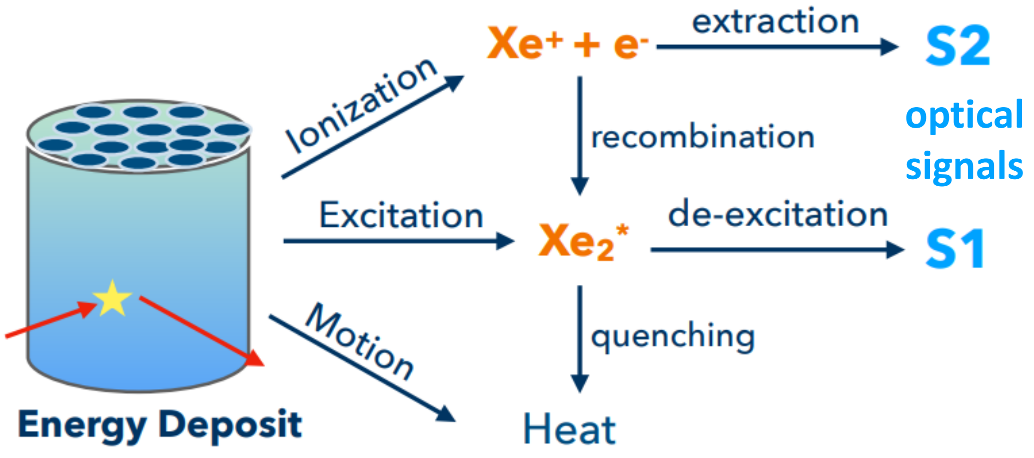
Dual-phase LXe/LAr-TPCs

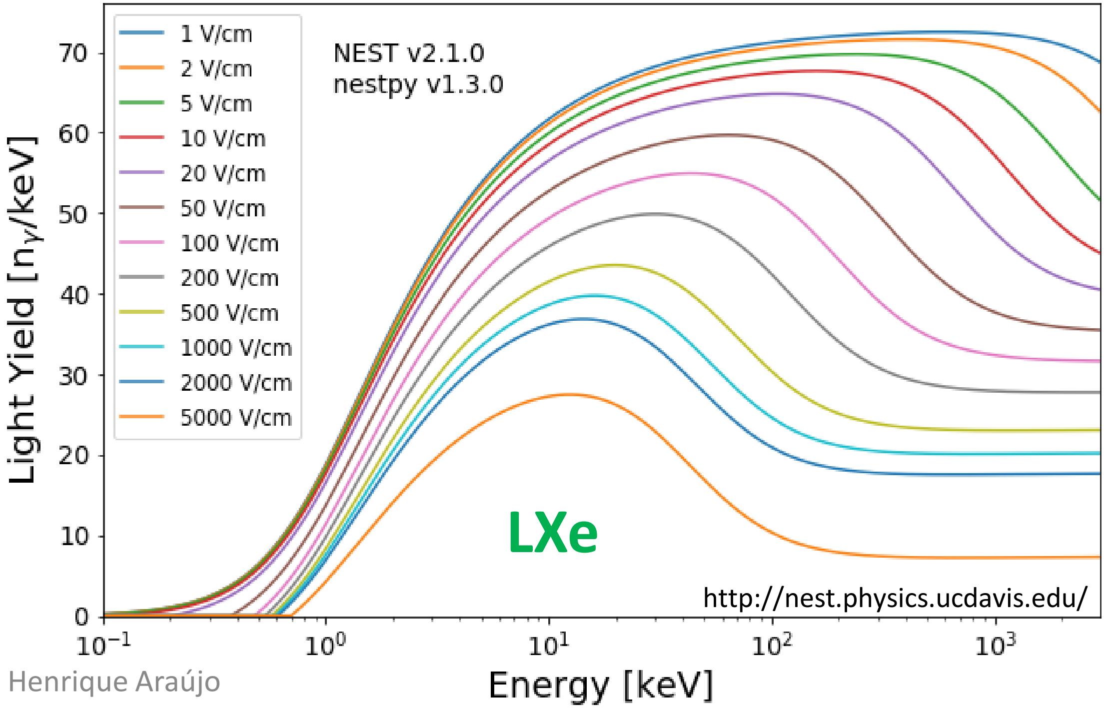


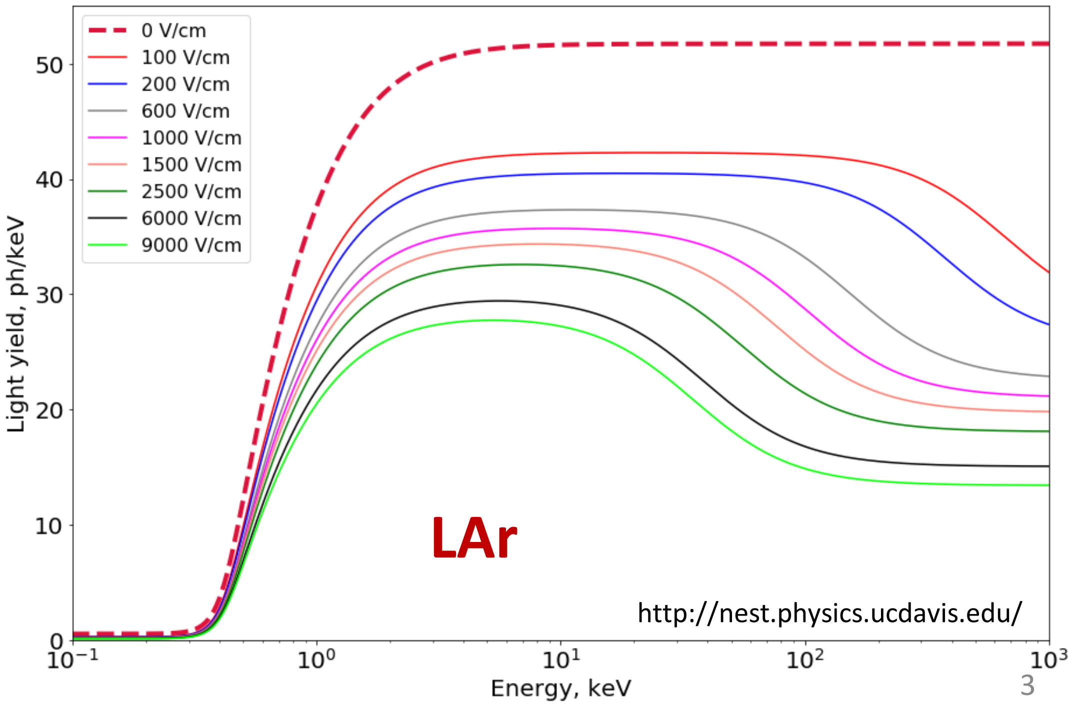
Liquid xenon
BP = 165 K
ρ = 2.9 g/cm^3
λ = 175 nm
n = 1.69
L_R = 29/36 cm
τ_1 = 3 ns, τ_3=27 ns, τ_r~45 ns



Liquid argon
87 K
1.4 g/cm^3
128 nm
1.45
55/90 cm
6 ns, τ_r~?, 1600 ns







NOBLE LIQUIDS: PHOTON DETECTION REQUIREMENTS

DM searches with dual-phase detectors (LAr, LXe)

Light collection
Photon detection efficiency
Photon counting capability
Dark count rate, correlated noise
Backgrounds
Cryogenic operation, resilience, power dissipation
Liquid poisoning
Cost

$0\nu\beta\beta$ searches with single-/dual-phase detectors (LXe)

Backgrounds, backgrounds, backgrounds…
Photon detection efficiency
Dark count rate, correlated noise
Cryogenic operation, resilience, power dissipation
Liquid poisoning
Cost

Giant LAr-TPCs

Light collection
Photon detection efficiency
Cryogenic operation, resilience
Cost

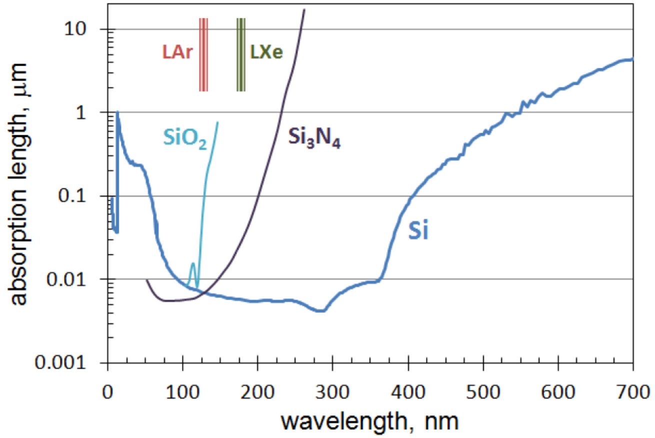
Other applications: TOF-PET, Cherenkov, …

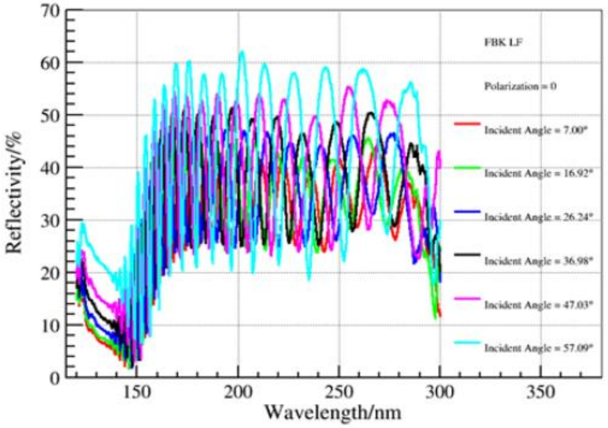
More diverse requirements
Timing performance
Size
etc.

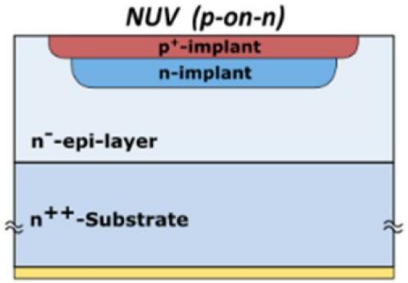
SCINTILLATION DETECTION STRATEGIES

Hamamatsu R11410

- Detect VUV photon detection
  - LXe: quartz-window PMTs or VUV SiPMs (optimised p-on-n)
  - LAr: MgF_2-window PMTs, VUV SiPMs – but low PDE
  - Hybrid devices: QUPID, ABALONE, SIGHT, …
- Wavelength shifting (LAr)
  - LAr: SiPMs a better choice
  - WLS (TPB, PEN): SiPM (RGB, NUV)
  - Xe-doping: SiPM (VUV), PMTs
- Light collection/shifting/concentrators/…
  - LXe: PTFE
  - LAr: WLS, reflectors, dichroics, light traps, …







VUV optimisation of "p-on-n" doping profile

- Reduce p^+ contact layer
- Optimise ARC/passivation

VUV devices and WLS

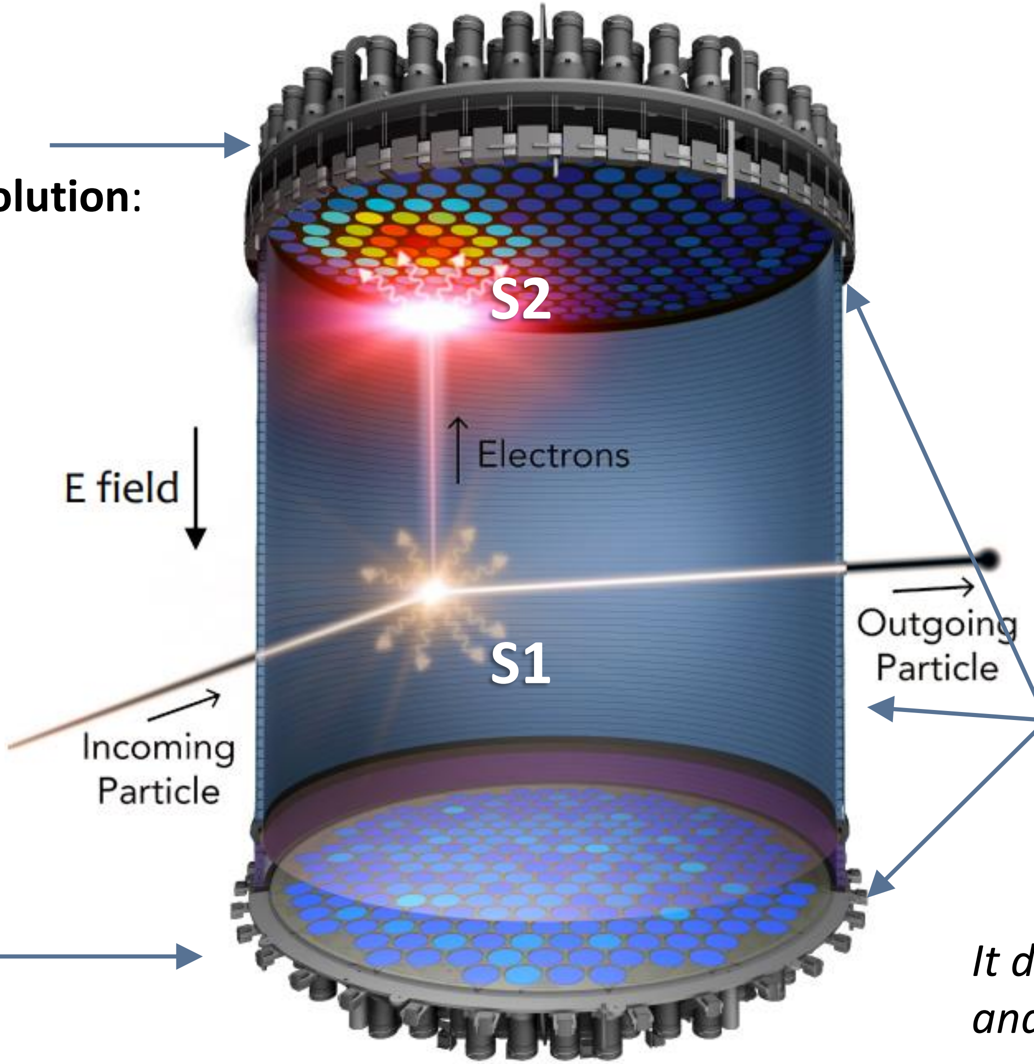
UK not major producer of VUV devices
but has capabilities (e.g. testing, WLS, integration,…)

SO – IN LXE, PMTs OR SiPM? YES.

Comparison for liquid xenon readout

Parameter	PMT	SiPM
QE/PDE (175 nm)	25%-40%	25%
Gain	5-10M	1-5M
Dark rate, Hz/mm^2	0.006	0.1-1
SPE resolution	35%	3-5%
Afterpulse rate	1%	10%
Crosstalk	-	4%-20%
Single photon timing, ns	0.2-10	0.1-5
Size	+	+++
Cabling	+++	+/+++
Magnetic fields	+	+++
Electric fields	++	+++
Bias voltage	+++	+
Backgrounds	++	++/+++
Cost	++	++/+++

Top array driven mostly by **backgrounds** and **spatial resolution**: Could be PMTs or SiPMs



"Skin" region readout requires **compact** and **low background**, operating near high **electric fields**: SiPMs more natural here

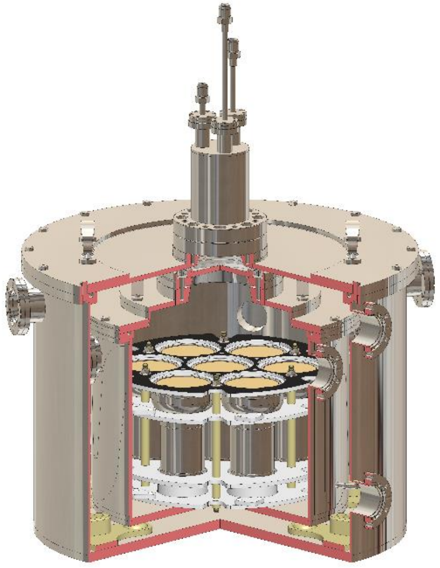
Bottom array driven mostly by **light collection**: Probably PMTs here

It depends on the science (DM and/or $0\nu\beta\beta$), and the answer may be "both" – need to engage with both technologies

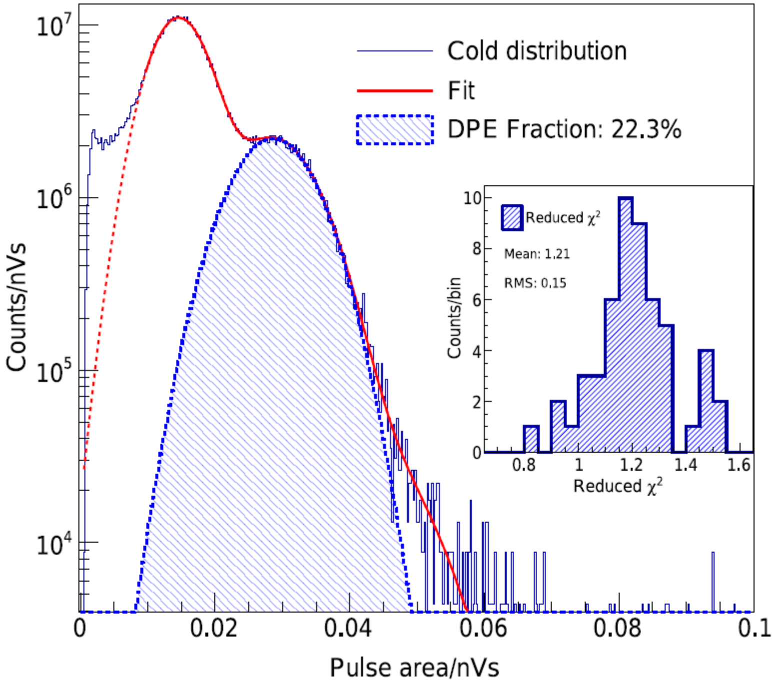
DEVICE CHARACTERISATION

VUV PMTs

- Cryogenic performance
  - Response and resilience in detector conditions
- PMT QE for pulsed operation in the VUV
  - New photocathodes show substantial dual-photoelectron (DPE) emission
  - Not taken into account by manufacturers…



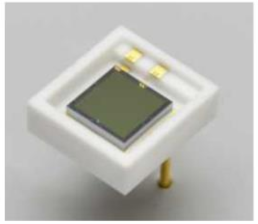
Lopez-Paredes 2018



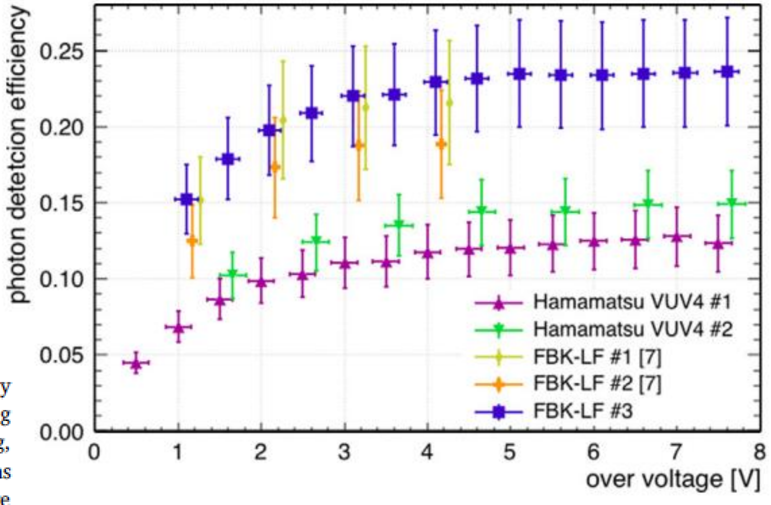
VUV SiPMs

- Discrepancy for pulsed PDE also for SiPMs!
- Calibration against PMTs at 175 nm must also take their DPE into account…
- ARCs: performance in vacuum vs in liquid

Hamamatsu S13370 –
Stated 37% PDE at 175 nm (maybe…)



Gallina 2019



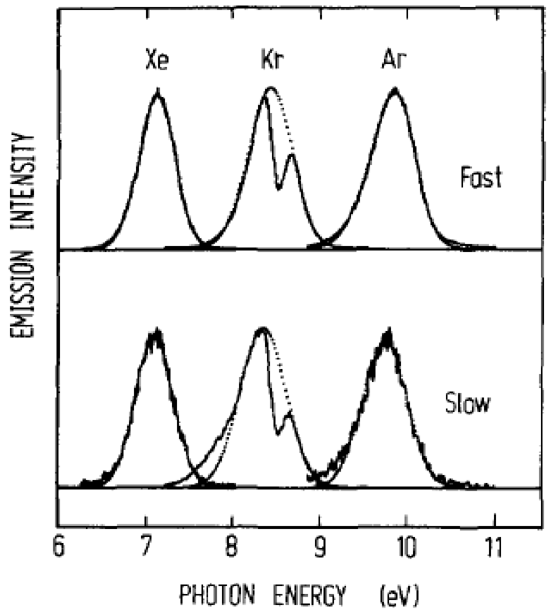
[7] This discrepancy could be related to the different technique used by Hamamatsu to evaluate the VUV4 PDE. Accordingly to an internal meeting with Hamamatsu the PDE reported in [33] was not assessed by pulse counting, but reading out instead the MPPC current under illumination. However, as shown in [38], the MPPC current is affected by CA noise and it is therefore easier to overestimate the PDE if the CA noise contribution is not accounted properly.

Cryogenic VUV calibration
R&D ongoing, UK has capability

VUV MATERIAL CHARACTERISATION

- Scarcity of high-quality data for key materials in the VUV range
- Detailed data needed for design and simulation models (analysis)
- Reflectors
  - VUV reflectivity <-> sensor coverage
  - Different reflectivity of liquid-X and vacuum-X interfaces
  - Surface quality, contamination, temperature, …
  - The role of fluorescence
  - Metals: e.g. electrode grids can dominate photon extinction
- Absorbers
  - Need VUV-black materials to tune spatial resolution
  - Very little data for these (PEEK, Kapton, etc.)
  - The role of fluorescence

Morikawa 1989



These energies destroy chemistry…
Impact on stability of optical surfaces, detachment of volatile species, …

Neves 2017

PTFE/LXe hemispherical reflectivity

	Diffuse model (D)		Diffuse + Specular model (DS)			
	A	λ (mm)	A	n_{PTFE}	λ (mm)	BHR
807NX	0.972 (> 0.97)	4800	0.961 (> 0.955)	1.73	4600	0.961 (> 0.955)
NXT85	0.986 (> 0.984)	3600	0.975 (> 0.973)	1.8	4600	0.975 (> 0.973)
LUX	0.987 (> 0.985)	4200	0.978 (> 0.975)	1.79	3000	0.978 (> 0.975)

VUV optical properties

Some opportunities here – ECRs?

INTEGRATION

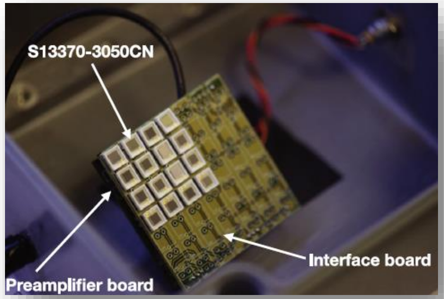
- SiPM arrays
- Lenses / collimators / concentrators
- Low-bk interconnects
- Ganging (passive, active)
- Cold electronics
- Feedthroughs

Integration at low-background

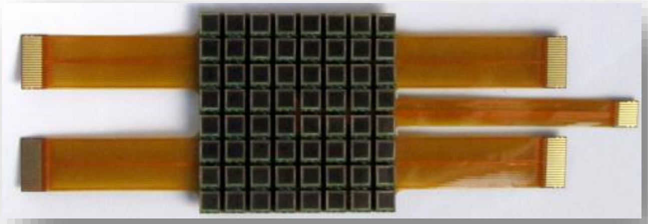
- Xenon Futures R&D project
- DarkSide-20k project

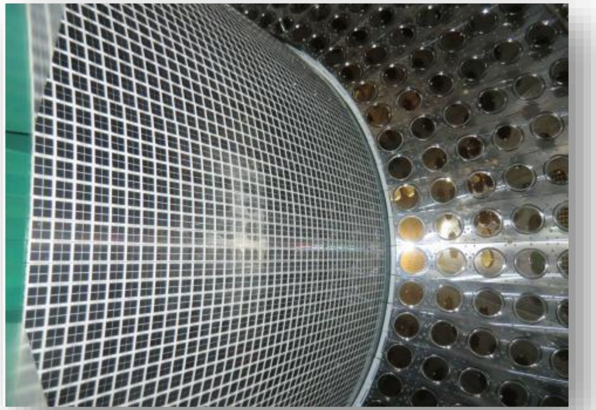
Low-background integration
UK is developing capability

Arneodo 2019

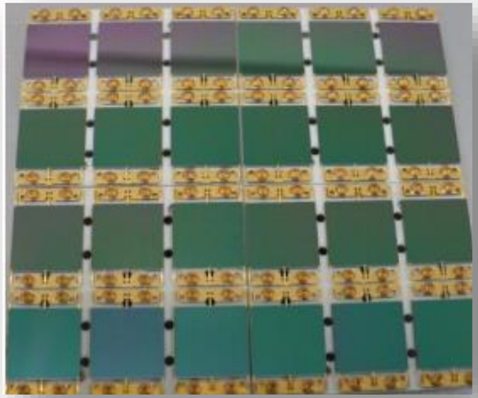


Tahirovich 2019

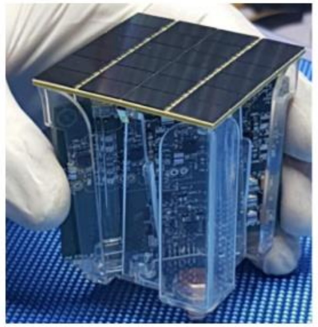




MEG-II calorimeter

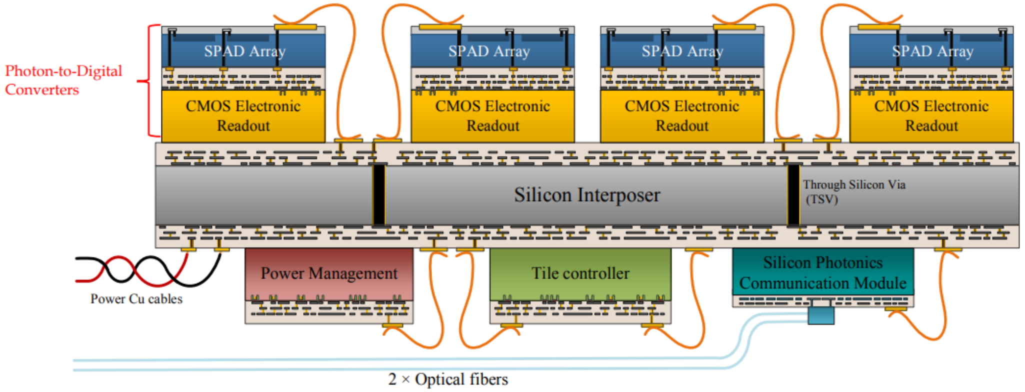


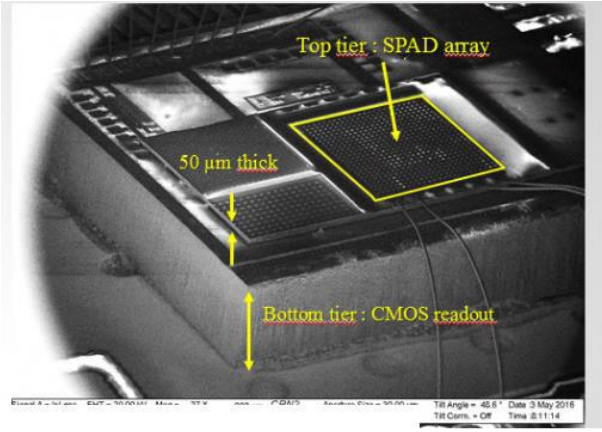
nEXO prototype staves



DS-20k PDM

FULL INTEGRATION: “PHOTON-TO-DIGITAL CONVERSION”



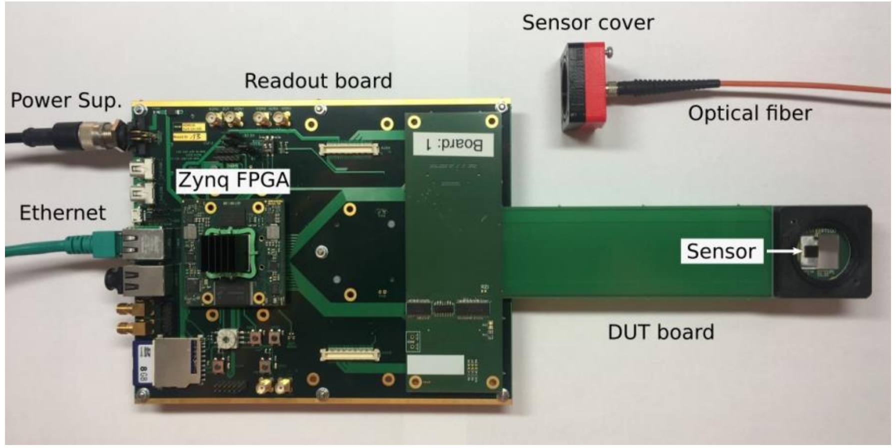


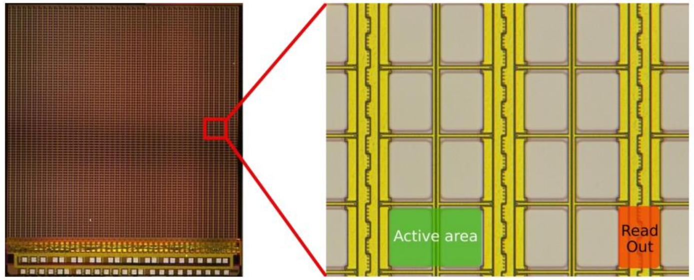
3D-dSiPM

- Tier1: SPAD
- Tier2: Electronics
- Tier3: Data aggregator & trigger

CMOS SPAD arrays

- SPADs + RO on single chip
- No readout ASIC
- Ultra low power
- Proof of principle



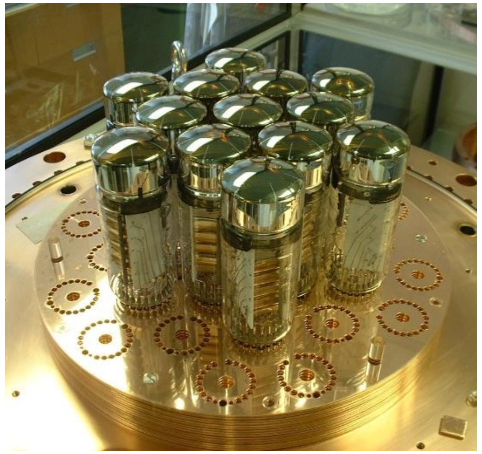


Integrated digital readout

Why is the UK not here…

PHOTOMULTIPLIERS: THE RADIOACTIVITY JOURNEY

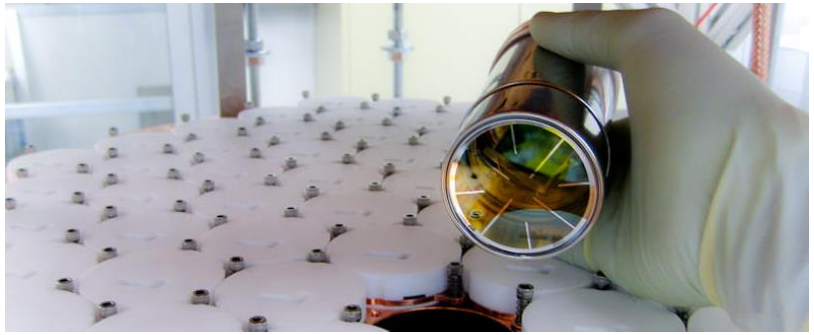
2005



ZEPLIN-III FSR
ETEL D730Q
1.4 γ/s/PMT
Araujo 2012

2010

ZEPLIN-III SSR / ETEL D766Q
0.044 γ/s/PMT
Araujo 2012



LUX / Hamamatsu R8778
0.040 γ/s/PMT
Akerib 2015

2015

LZ
Hamamatsu R11410
0.007 γ/s/PMT
Akerib 2020

NEXT-GEN

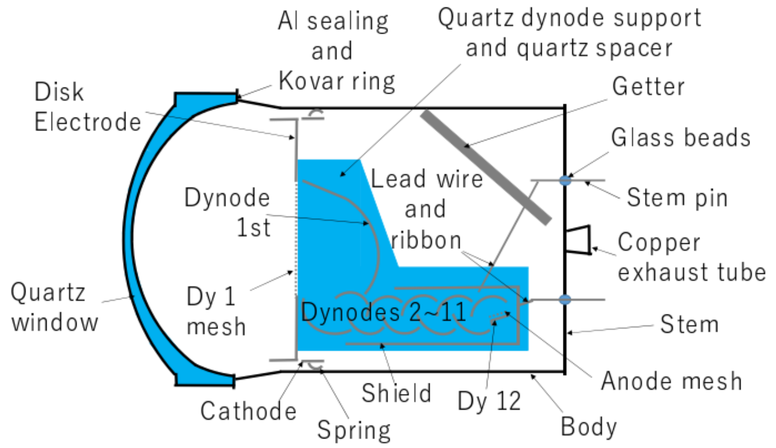
Goal
~0.001 γ/s/PMT

~1000-fold reduction

THE PMT RADIOACTIVITY JOURNEY

- Radioactivity of existing PMTs already good enough for LXe-G3 dark matter experiment
  - Neutrons from LZ PMT-systems: 40% of NR background from materials, <3% of total NR background
- Need further x3-x5-fold reduction for $0\nu\beta\beta$ decay search in Xe-136 at G3 (natural Xe)
  - Bi-214 (U-238 chain) and Tl-208 (Th-232 chain) close to $Q_{\beta\beta}$ = 2,458 keV
  - Some improvements already achieved by Hamamatsu/XMASS
- Commensurate decrease in radioactivity from PMT bases

0NBB background	*Bi-214*	*Tl-208*			
Measured	Ra-226	Ra-228			
Contaminant	**U-238_l**	**Th-232_l**	**K-40**	**Co-60**	**[mBq/PMT]**
R11410-22 LZ	0.6	0.3	12	1.9	Akerib 2020
R11410-21 X1T	0.5	0.4	12	0.7	Aprile 2015
R13111 XMASS	0.41	0.25	2	0.2	Abe 2020
G3 0NBB (R11410/5)	0.11	0.07	2	0.2	
LZ PMT BASES	0.39	0.17	0.26	0.01	Akerib 2020
G3 0NBB (LZ/5)	0.08	0.03	0.26	0.01	



R13111 Abe 2020

SiPM RADIOACTIVITY

- SiPM materials are intrinsically clean: comparable to or better than PMT activities
- However, this does not include interconnects or cold electronics – that is the critical part

Table 2. SiPM radioassay results from gamma-ray spectroscopy for the uranium and thorium decay chains, as well as for the ^{40}K single isotopes in mBq/cm^2. Results are given at 90% confidence level for upper limits of the silicon and quartz samples. Upper limits for the resin samples are given at 68% confidence level. The ICP-MS results (indicated by *) were obtained with a 90% recovery efficiency. Detections for both SiPM samples and PMTs [22] are given with uncertainties of $\pm 1\sigma$.

Sample type	^{238}U	^{226}Ra	^{228}Ra (^{232}Th*)	^{228}Th	^{40}K
Silicon chips	< 0.002*	< 0.0003	< 0.00007*	0.0004(1)	< 0.0014
Bonding resin, type C	< 0.299	0.0043(9)	< 0.003	< 0.003	0.02(1)
Bonding resin, type D	< 0.588	< 0.0027	< 0.006	0.003(1)	< 0.00004
Quartz window	< 0.013	0.00009(3)	< 0.00001	0.0001(3)	0.004(2)
Quartz packaging	< 0.006	0.00011(1)	0.00011(2)	0.0001(2)	< 0.0001
Total SiPM	< 0.908	< 0.0075	< 0.0092	< 0.0066	< 0.026
Total R11410 PMT	< 0.4	0.016(3)	0.016(4)	0.012(3)	0.37(6)

Baudis 2018

PMT & SiPM radioassay
UK has experience and world-class capability (Boulby, UCL, RAL)

CONCLUSION

The UK is well engaged in this area, not so much by developing new devices but by working closely with manufacturers – on requirements, backgrounds, device testing, etc.

- A lot of R&D comes under the radar, mostly unfunded – low “entry cost”
- My view: this (un)funding model has ensured the UK is not truly leading/innovating here

Key synergy areas

- Low-background development/radioassay: both PMTs and SiPMs can meet requirements for rare-event searches, but further development needed; long-standing UK involvement; exploit UK assets (Boulby, etc.)
- Device characterisation: more work is needed esp. in VUV – collaborate with industry and each other
- More work needed to characterise VUV materials in detector conditions
- Major synergies on integration/interconnects at low background / high cleanliness

Future

- More ambitious programmes where the UK gains IP – requires well-funded and sustained R&D