TRIUMF

Light detection in liquid Xenon for nEXO and beyond

Fabrice Retiere for the nEXO collaboration

NSERC CRSNG

CANADA FIRST RESEARCH EXCELLENCE FUND | APOGÉE CANADA FONDS D'EXCELLENCE EN RECHERCHE

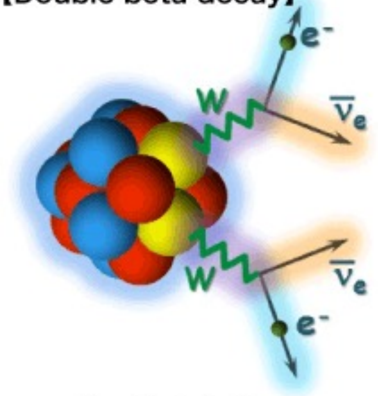
Arthur B. McDonald Canadian Astroparticle Physics Research Institute

INNOVATION.CA CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION

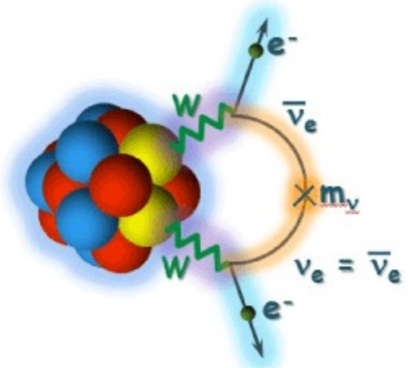
Discovery, accelerated

nEXO for 0νββ

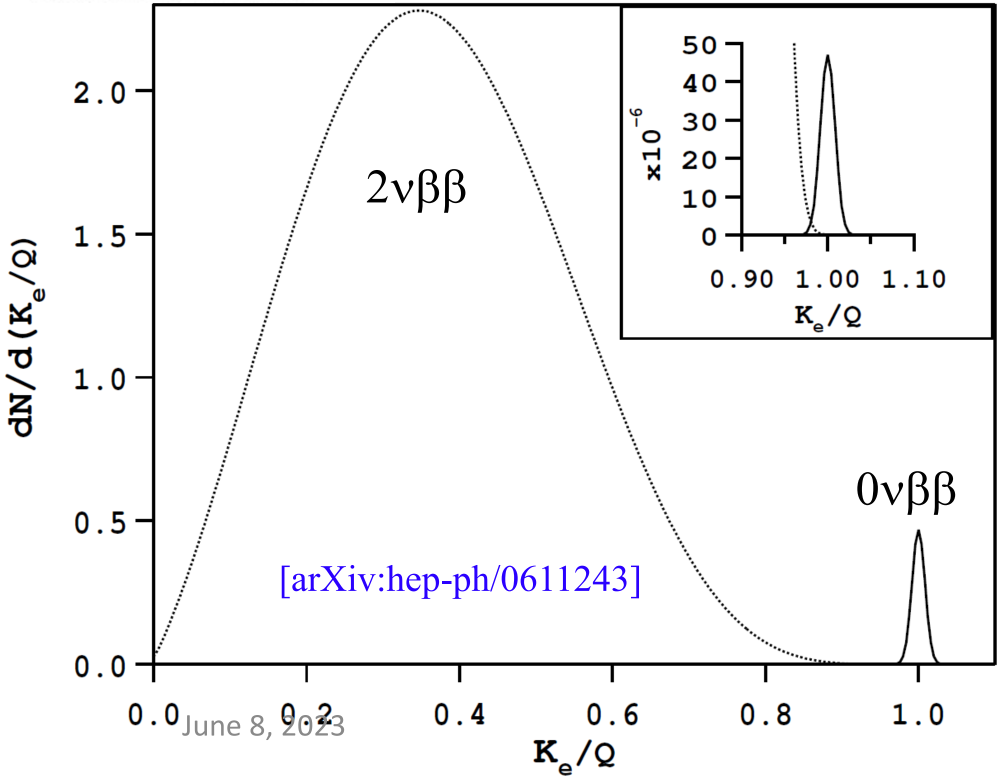
【Double beta decay】

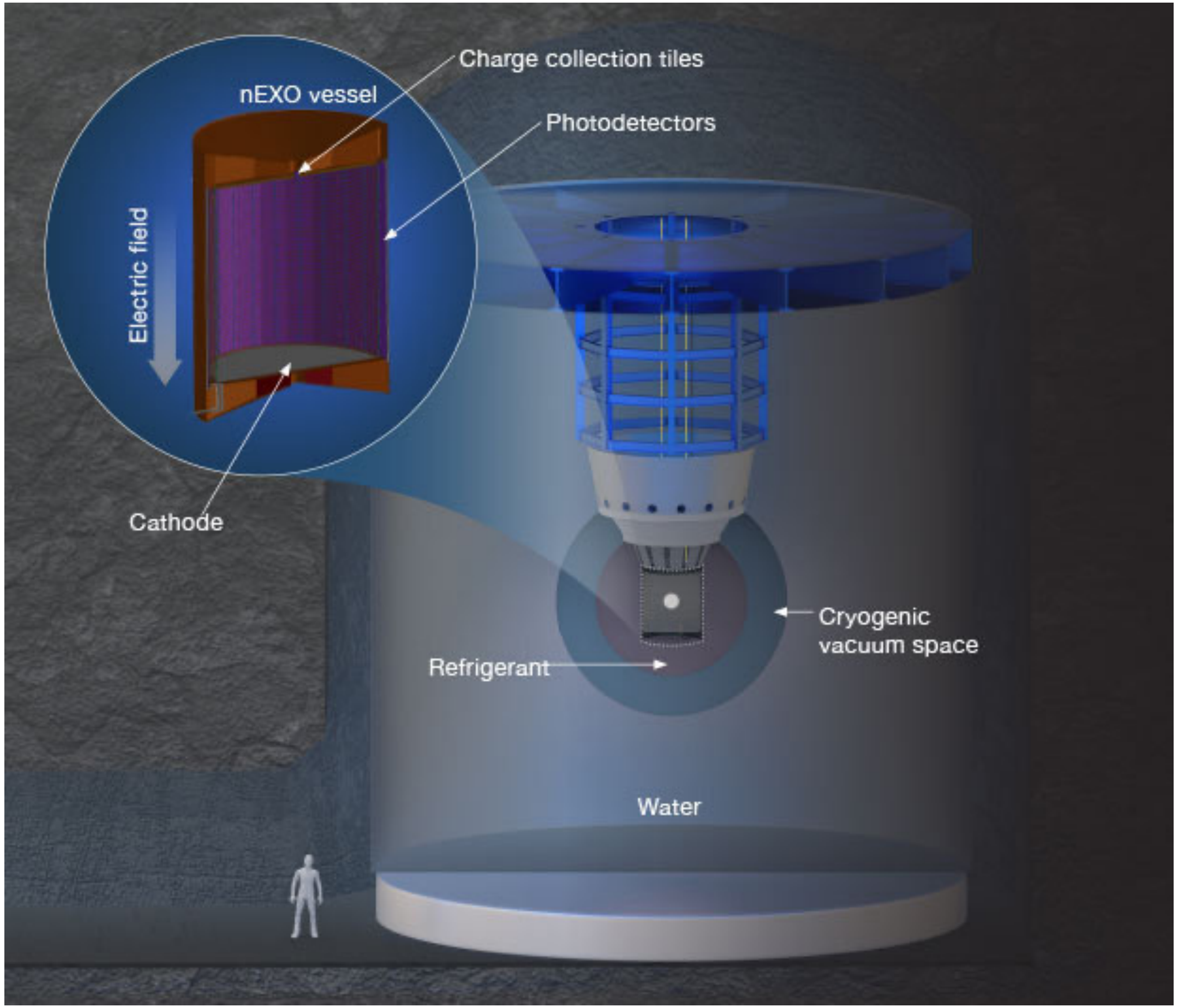


Double beta decay
which emits anti-neutrinos



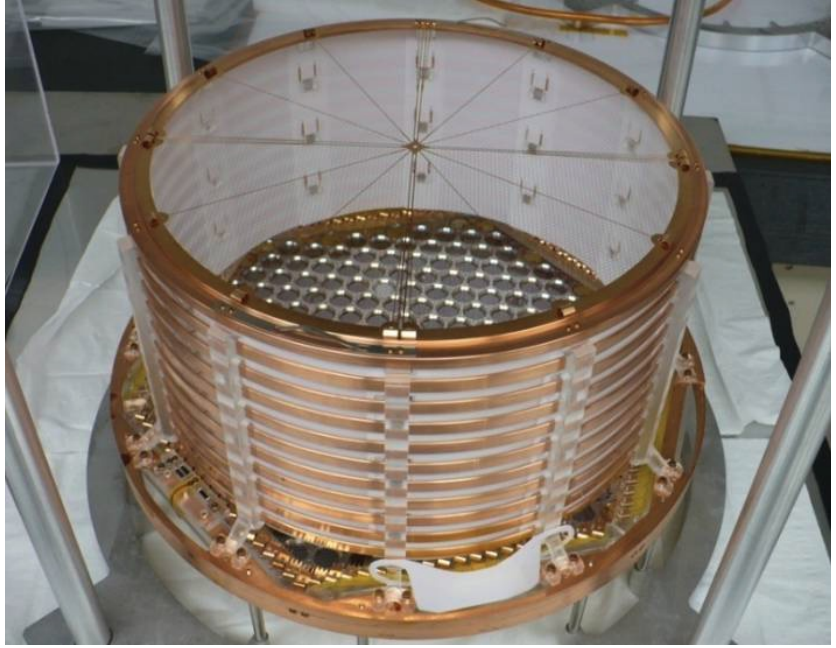
Neutrinoless
double beta decay

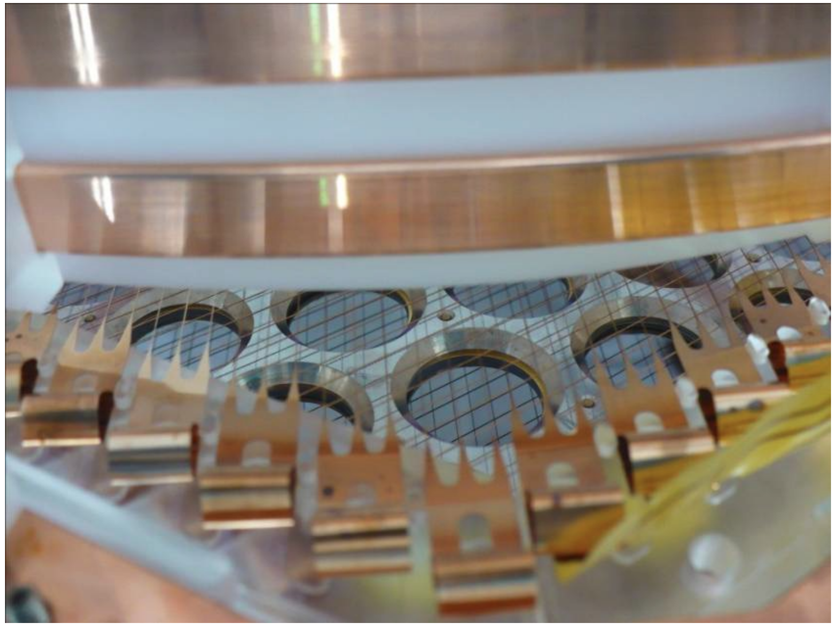




EXO-200

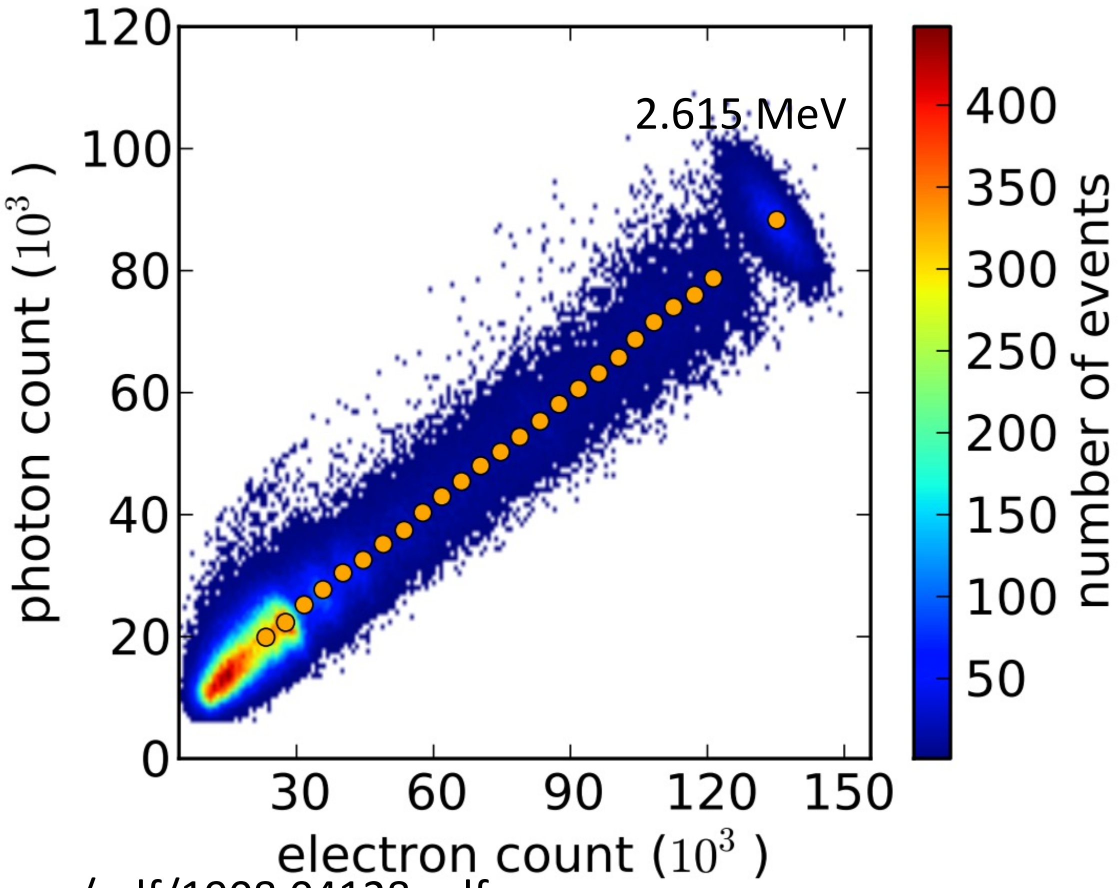
- Double sided Time Projection chamber
  - Optically transparent cathode in the center
  - 15 cm drift length
- Charge detection by crossed-wires
- Light detection by Avalanche photo-diodes
  - And teflon “light guide”

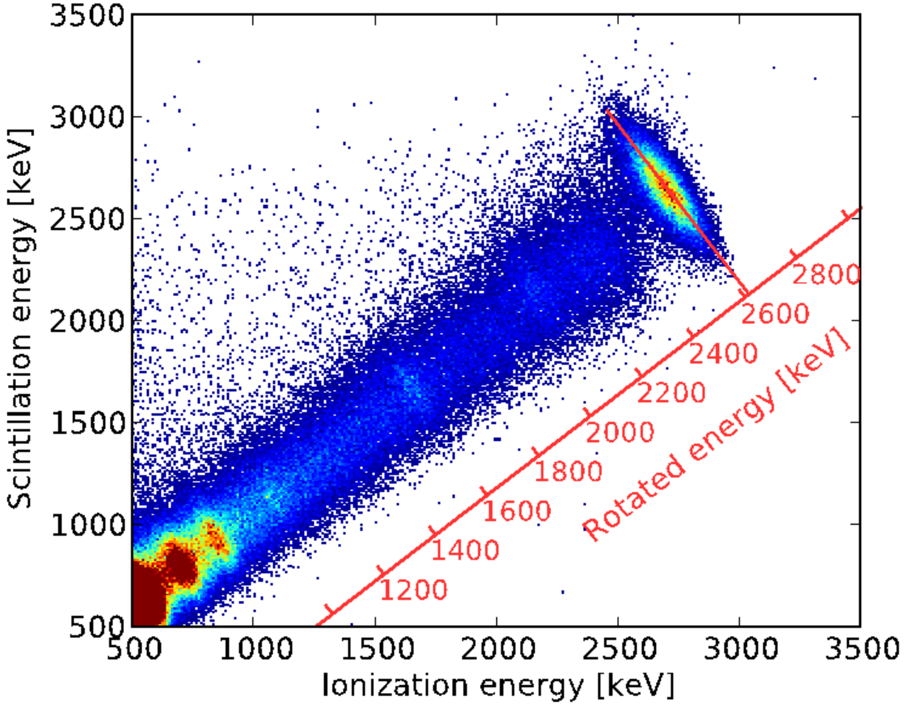


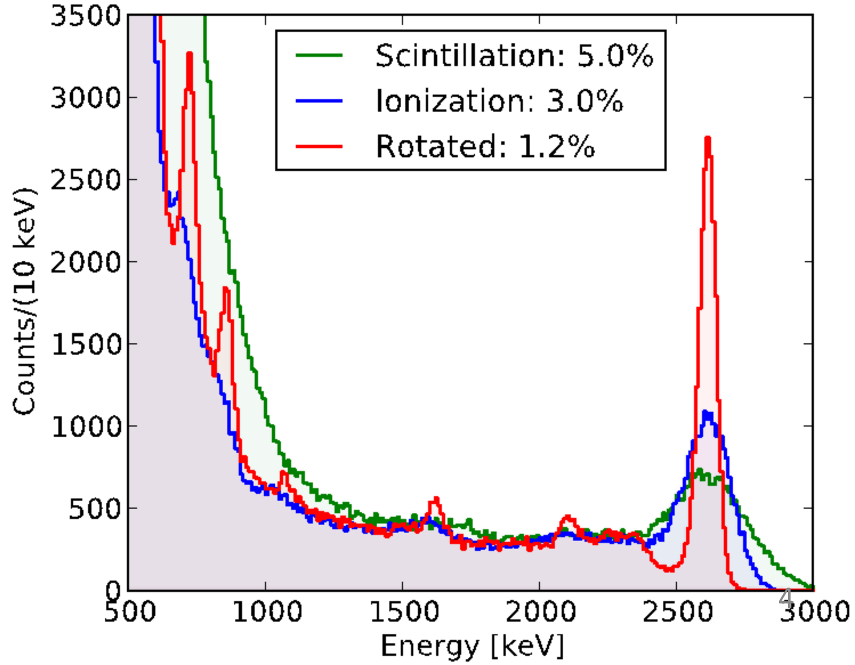


Optimum energy estimator

Optimum estimator is linear combination of ionization + scintillation quanta
Cancels fluctuation in relative quanta production







https://arxiv.org/pdf/1908.04128.pdf

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EXO-200 final

- Operation ended in 2018
- Decommissioning essentially completed
- Full analysis paper out

Search for Neutrinoless Double-Beta Decay with the Complete EXO-200 Dataset

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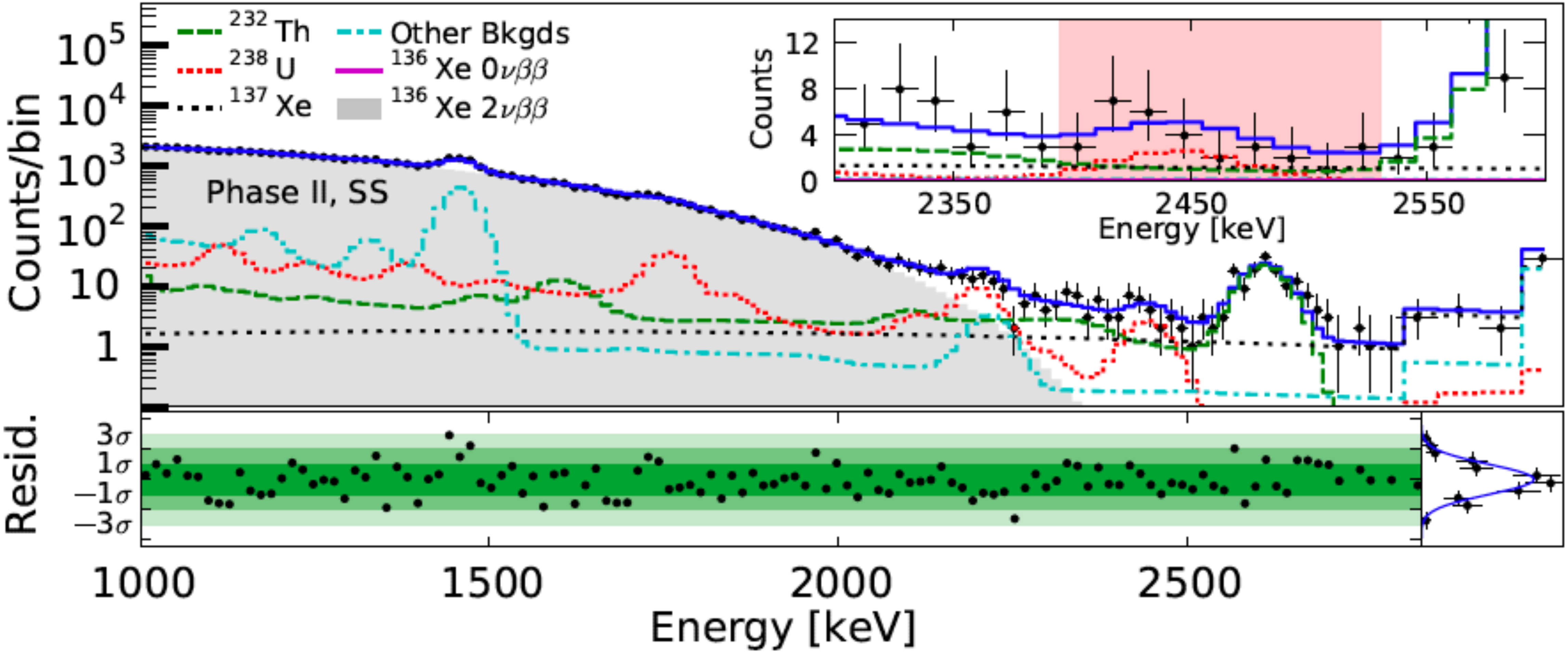
(Dated: October 21, 2019)

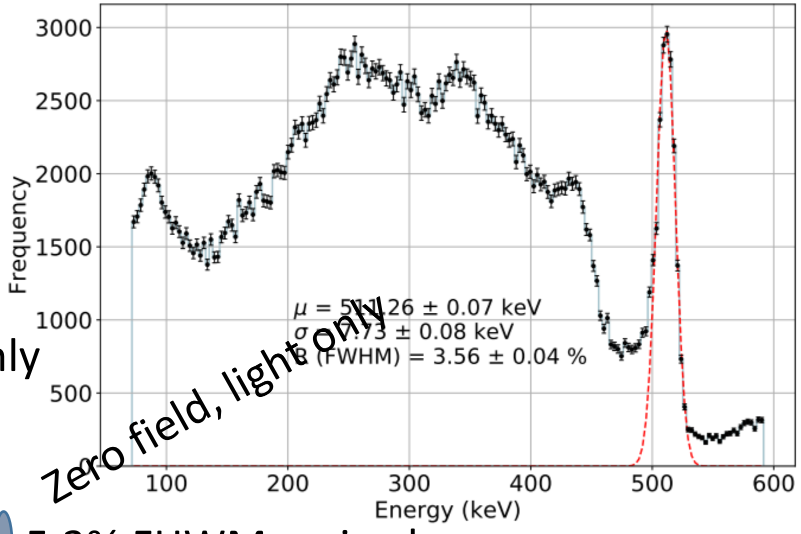
Phys. Rev. Lett. 123, 161802 (2019)

EXO-200 final limit $T_{1/2}$>3.5 10^{25} years



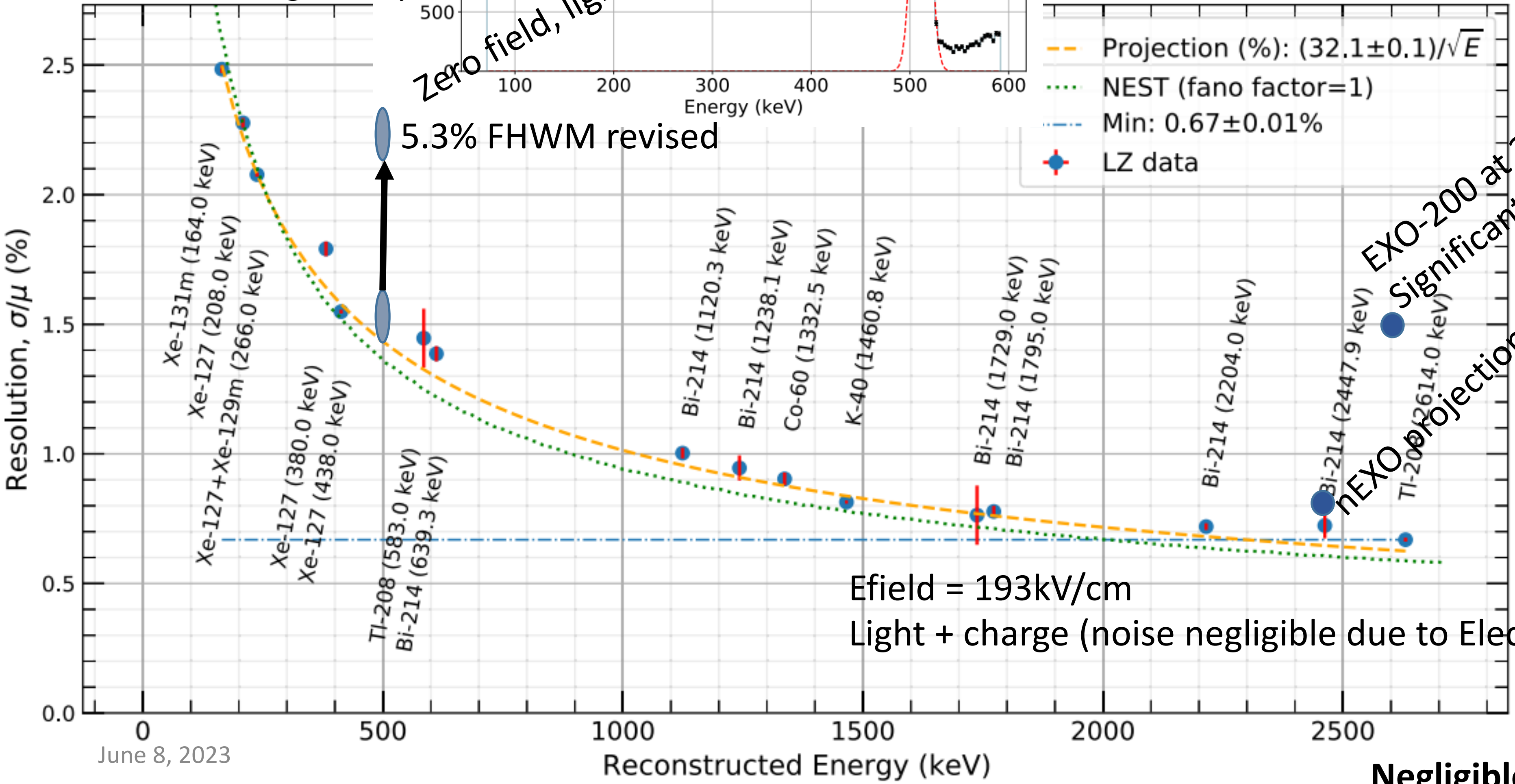
Latest

Xmass
4% at 122keV
Zero field, light only



Zero field, light only

5.3% FHWM revised



Efield = 193kV/cm
Light + charge (noise negligible due to Elec. Lum.)

EXO-200 at 200 kV/cm
Significant noise for both light and charge

nEXO projection

Measurement of the scintillation resolution in liquid xenon and its impact for future segmented calorimeters

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(Dated: January 27, 2023)

Energy resolution of the LZ detector for high-energy electronic recoils

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G. Pereira et al 2023 JINST 18 C04007

Negligible intrinsic fluctuations…

Gallina, G., Guan, Y., Retiere, F. et al. *Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO.* Eur. Phys. J. C 82, 1125 (2022), https://arxiv.org/pdf/2209.07765.pdf

Modeling energy resolution: nEXO projection

$$\frac{\sigma_n}{\langle n\rangle} = \frac{\sqrt{\left(\frac{(1-\varepsilon_p)n_p}{\varepsilon_p} + \frac{n_p}{\varepsilon_p}\cdot\frac{\sigma_\Lambda^2}{(1+\langle\Lambda\rangle)^2} + n_p^2\sigma_{lm}^2\right) + \left(\frac{n_q t}{\tau} + \frac{\sigma_{q,noise}^2}{\varepsilon_q^2}\right)}}{\langle n\rangle}$$

Efficiency contribution

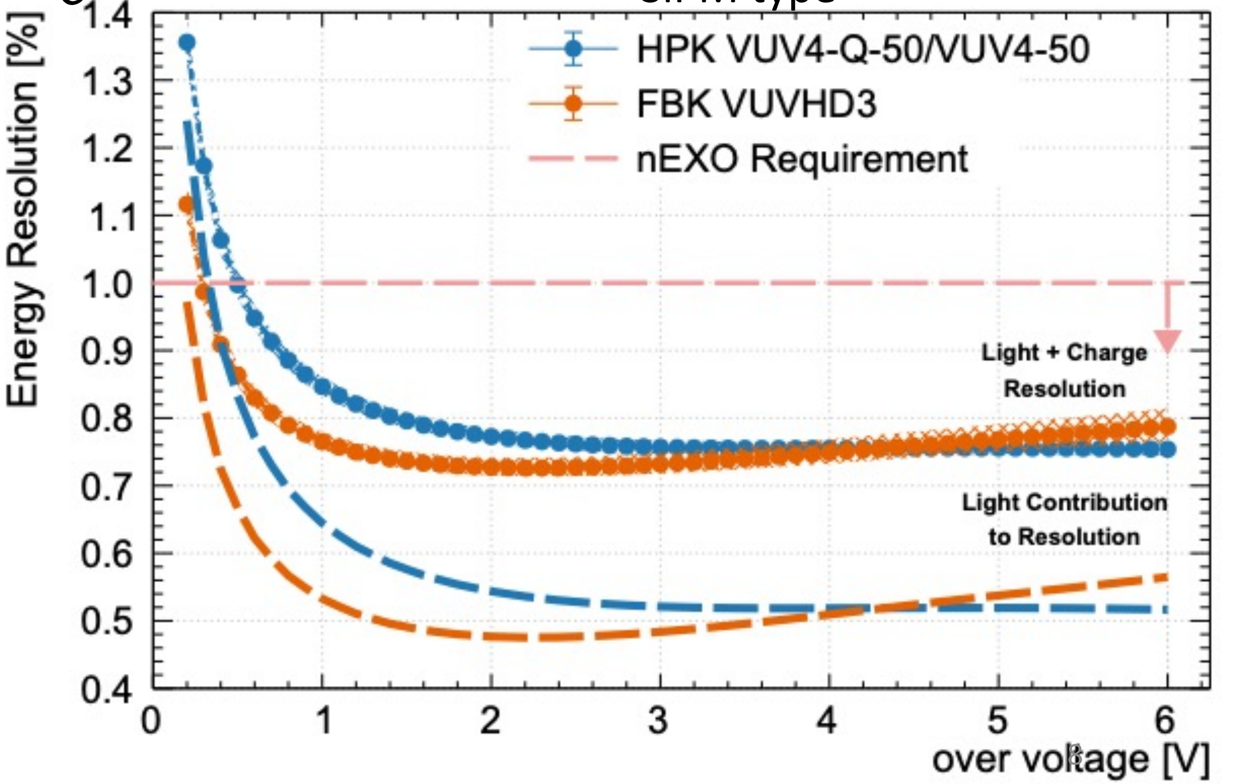
Photo-detector correlated avalanche (excess noise factor)

Light map calibration

Charge attenuation

Charge noise

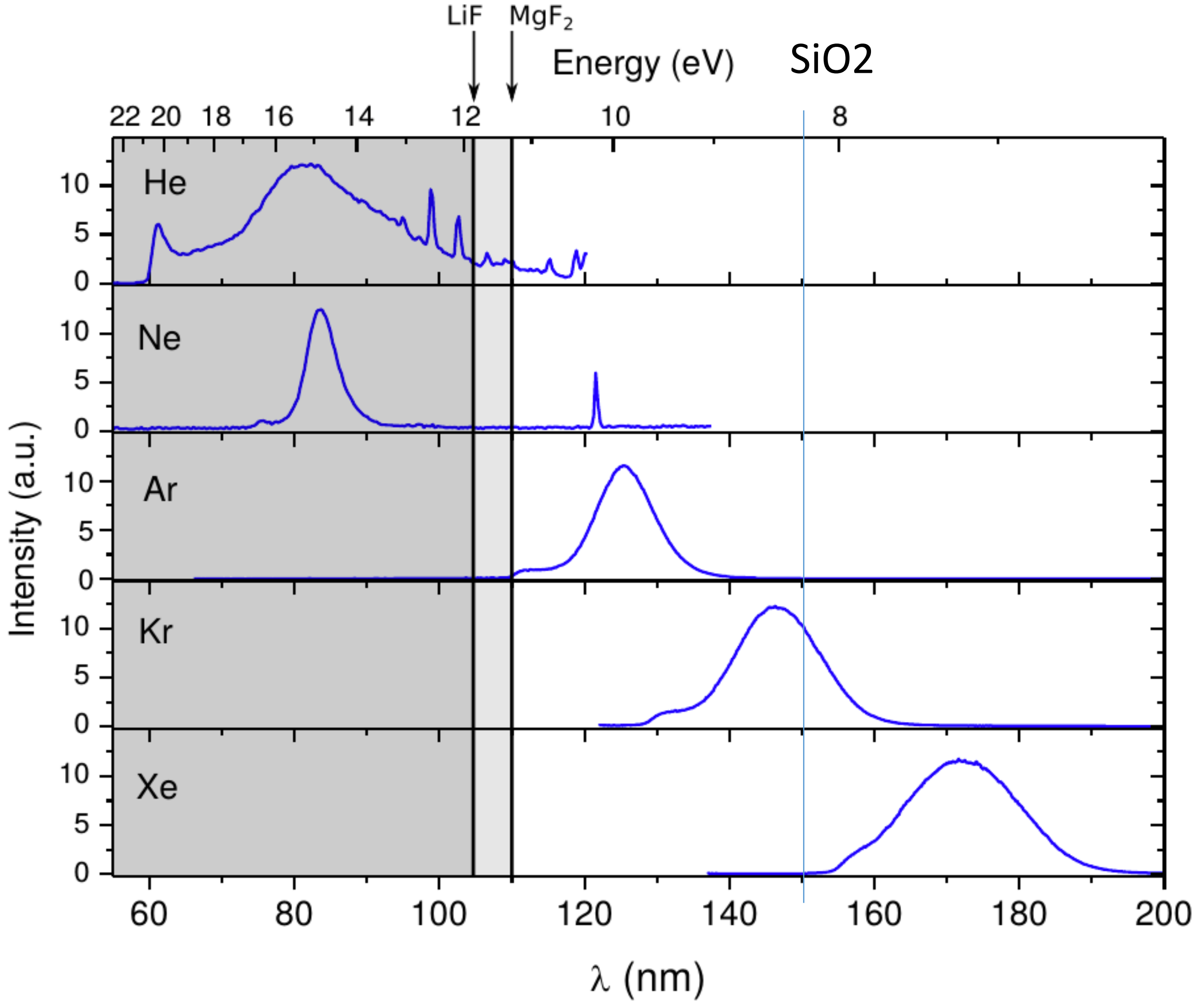
SiPM type



Parameter related to photo-detector bias

- Assumptions
  - Negligible intrinsic light+charge fluctuations
  - Photo-detector noise negligible
    - High gain
  - No external cross-talk considered

Liquid Xenon scintillation at ~175nm

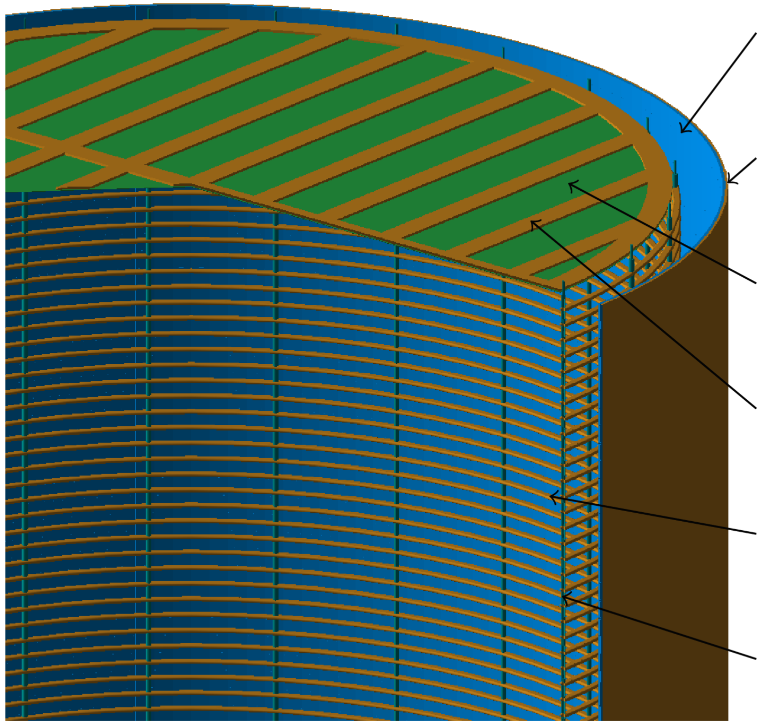


- Easiest Noble-gas liquid scintillation to detect
- Above SiO2 cut-off
  - Can still use standard silicon technology
- Bright and short flash
  - Number of photons produced ~91,000 at 2.458 MeV
  - All photons emitted within 100ns

Alexander Neumeier: Optical Properties of Liquid Noble Gas Scintillators
TUM PhD thesis

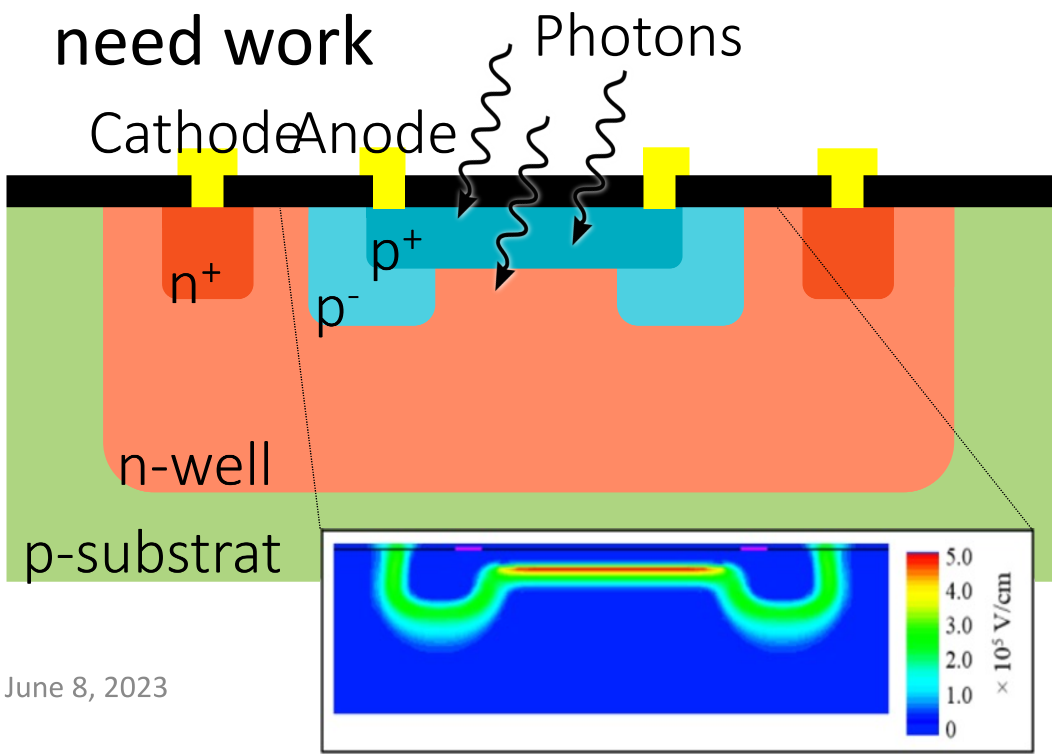
Photon detection in nEXO

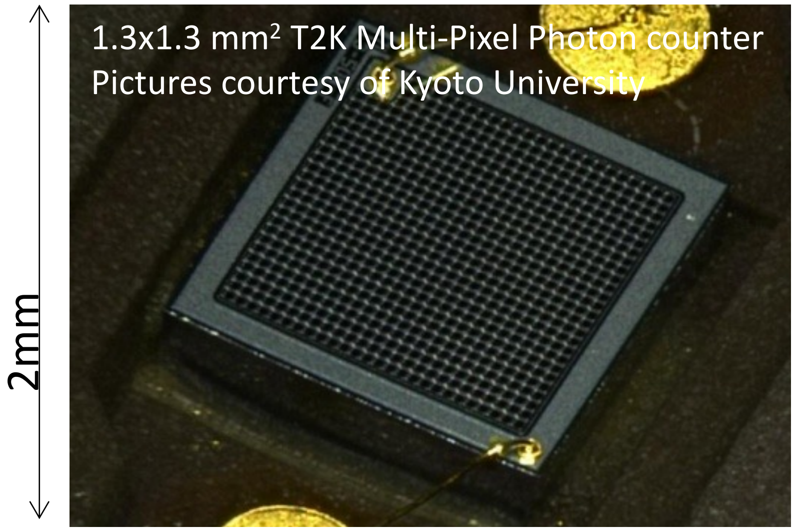
- Energy resolution dominated by light
  - Need 3% efficiency of detecting scintillation photons for 1 % energy resolution
  - With negligible noise for light detection
- Need at least 4 m^2 of detection area
- Need reflective electrodes

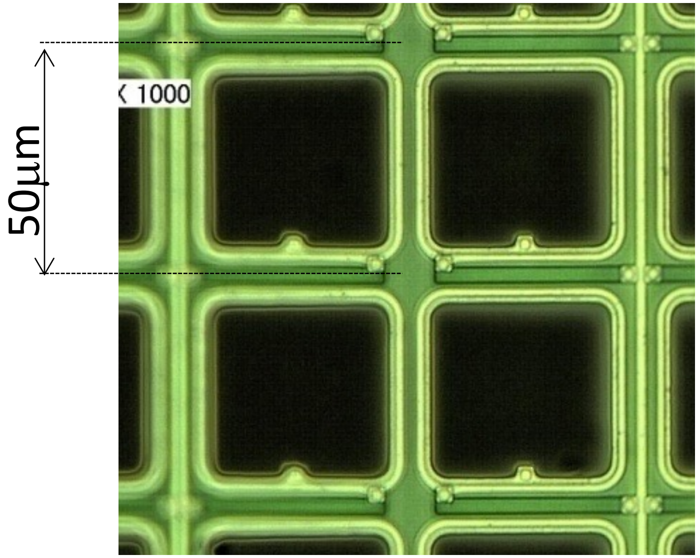


SiPMs, baseline photo-detector solution for nEXO

- High gain (low noise)
- Large manufacturing capabilities
- But efficiency and radioactivity need work







Two SiPM options for nEXO (baseline)

- Fondazione Bruno Kessler
  - Development chain driven by nEXO:
    - VUV-HD1
    - VUV-HD2, $1x1cm^2$, did not work
    - VUV-HD3, $6x6mm^2$, good performances
    - VUV-HD4, 2022-2023, $1x1cm^2$, does not seem to work well
- Hamamatsu
  - VUV4 Multi-Pixel Photon Counter
  - Single $6x6mm^2$. Appears to have worse performance
  - Quad 2x2 $6x6mm^2$
  - $1x1cm^2$ integrated on nEXO tile

Technology decision in 2024

SiPM for lowest radioactivity content

	^{238}U	^{232}Th	^{40}K
Prelim. nEXO requirements for 4m^2	< 0.1 nBq/cm^2	<1 nBq/cm^2	< 10 nBq/cm^2
FBK SiPM (bare wafers) [A]	<0.4 nBq/cm^2	~0.6 nBq/cm^2	~3 nBq/cm^2
SensL SiPM (packaged) [B]	<1.1 mBq/cm^2	<33 μBq/cm^2	<69 μBq/cm^2
Hamamatsu PMT R11410-21 [c]	<0.4 mBq/cm^2	0.016 mBq/cm^2	0.37 mBq/cm^2

[A] Counting at U.Alabama after nuclear activation at MIT

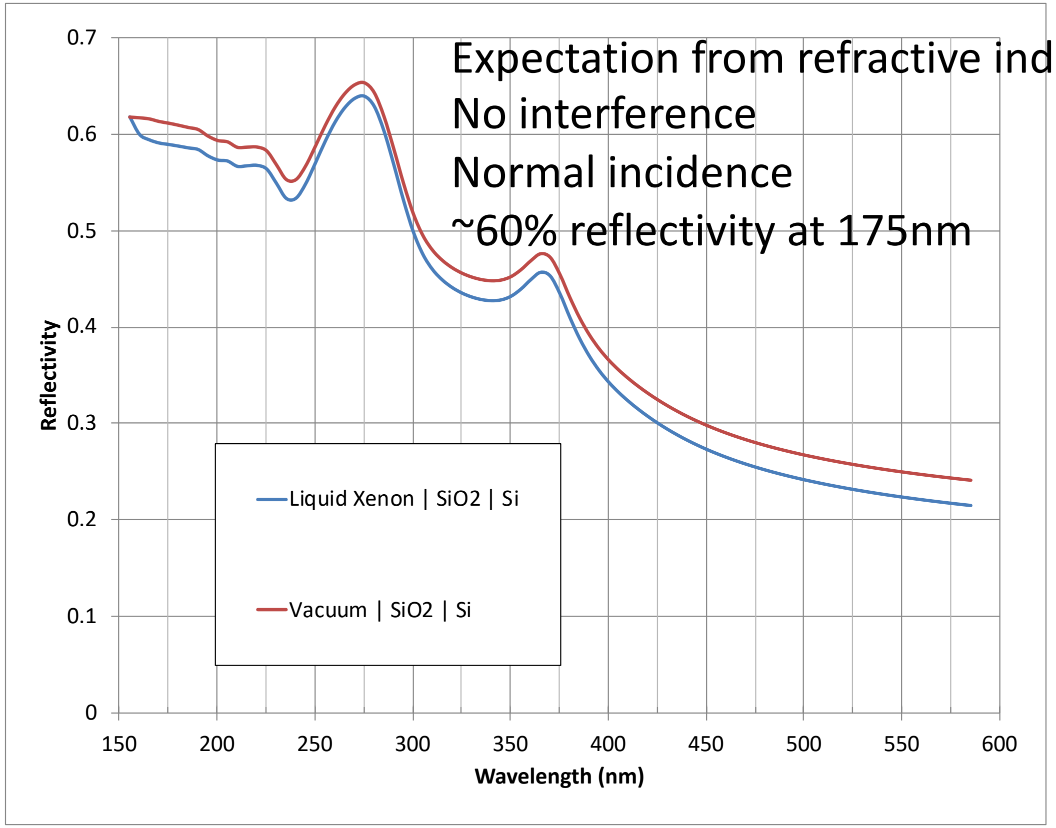
[b] NEXT Ge counting. http://arxiv.org/abs/1411.1433

[C] E. Aprile et al. Material radioassay and selection for the XENON1T dark matter experiment. Eur. Phys. J., C77(12):890, 2017, https://arxiv.org/pdf/1705.01828.pdf

PMT type	Normalized activity [mBq/cm^2]						Ref.
	^{238}U	^{226}Ra	^{228}Th	^{235}U	^{40}K	^{60}Co	
R11410-21	< 0.4	0.016(3)	0.012(3)	0.011(3)	0.37(6)	0.023(3)	this work
R11410-20	< 0.56	< 0.03	0.028(6)	< 0.025	0.37(6)	0.040(6)	this work
R11410-10	< 3.0	< 0.075	< 0.08	< 0.13	0.4(1)	0.11(2)	[20]
R11410-10 (PandaX)	–	< 0.02	< 0.02	0.04(4)	0.5(3)	0.11(1)	[12]
R11410-10 (LUX)	< 0.19	< 0.013	< 0.009	–	< 0.26	0.063(6)	[21]
R11410	1.6(6)	0.19(2)	0.09(2)	0.10(2)	1.6(3)	0.26(2)	[20]
R8778 (LUX)	< 1.4	0.59(4)	0.17(2)	–	4.1(1)	0.160(6)	[21]
R8520	< 0.33	0.029(2)	0.026(2)	0.009(2)	1.8(2)	0.13(1)	[20]

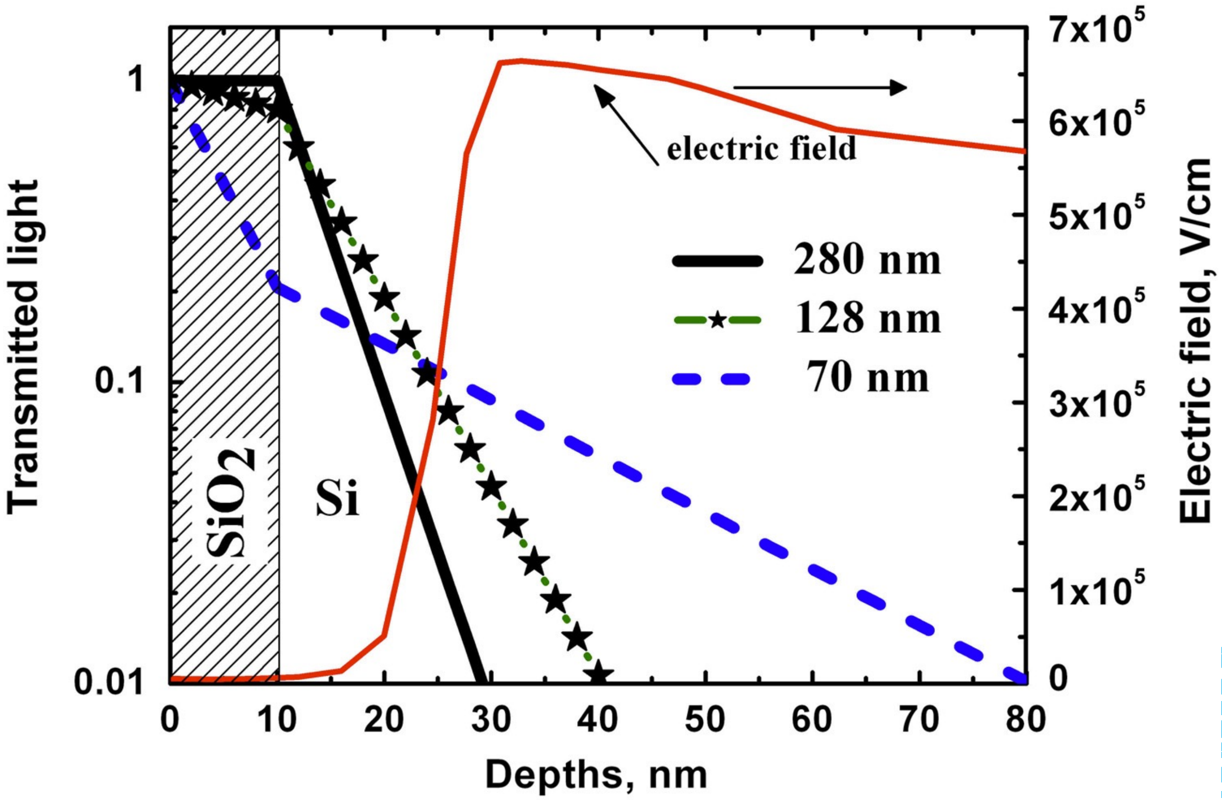
VUV light detection challenges

- Reflections



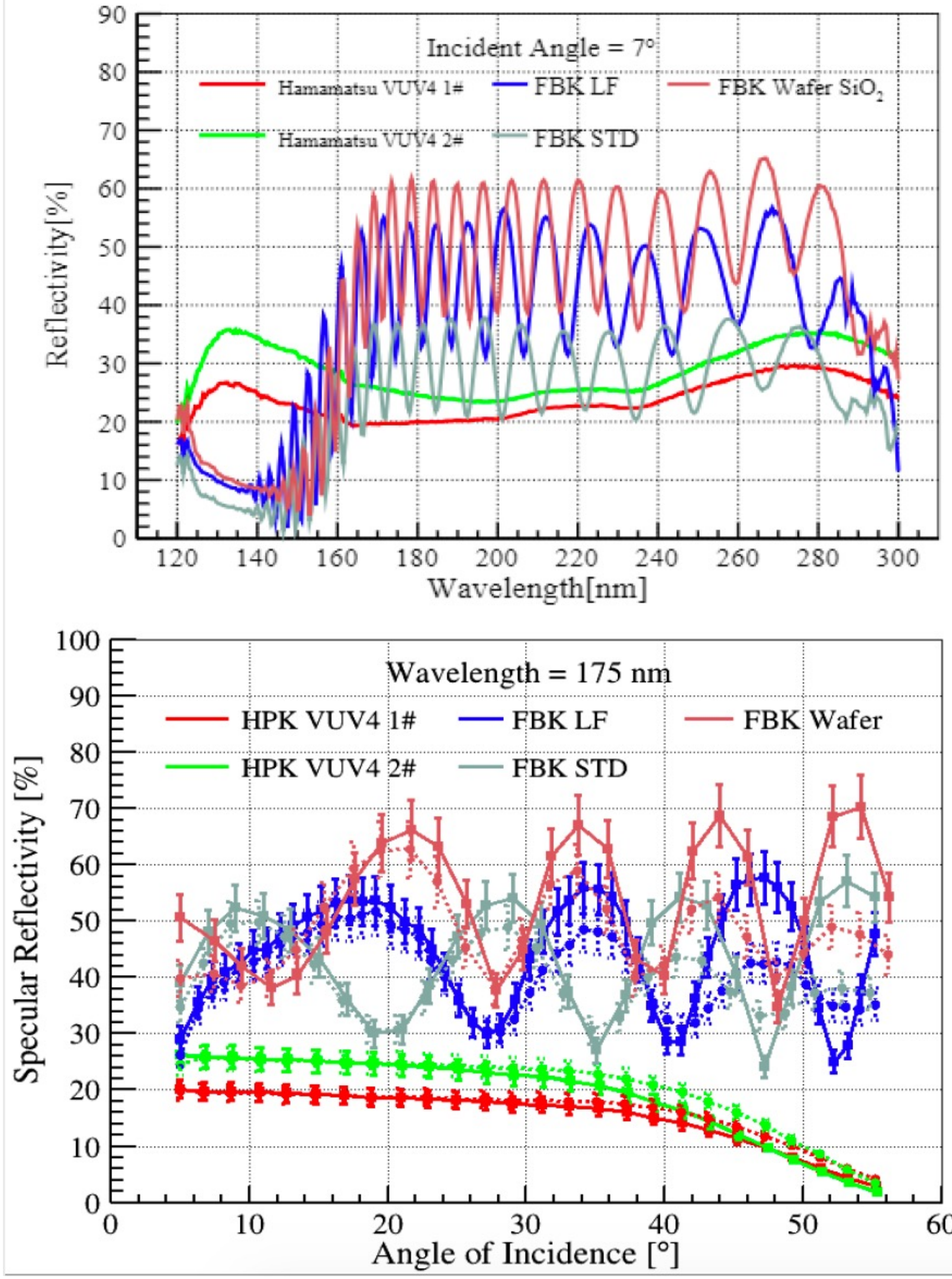
Expectation from refractive indexes
No interference
Normal incidence
~60% reflectivity at 175nm

- Shallow absorption depth



Measuring reflections

- In vacuum, oscillation due to the SiO2 layer (~1.5um for FBK)
  - Expected to disappear in Lxe as SiO2 and LXe have roughly the same n
- FBK matches expectation
- Hamamatsu does not
  - Is the SiO2 less transparent that expected?
  - May be batch specific

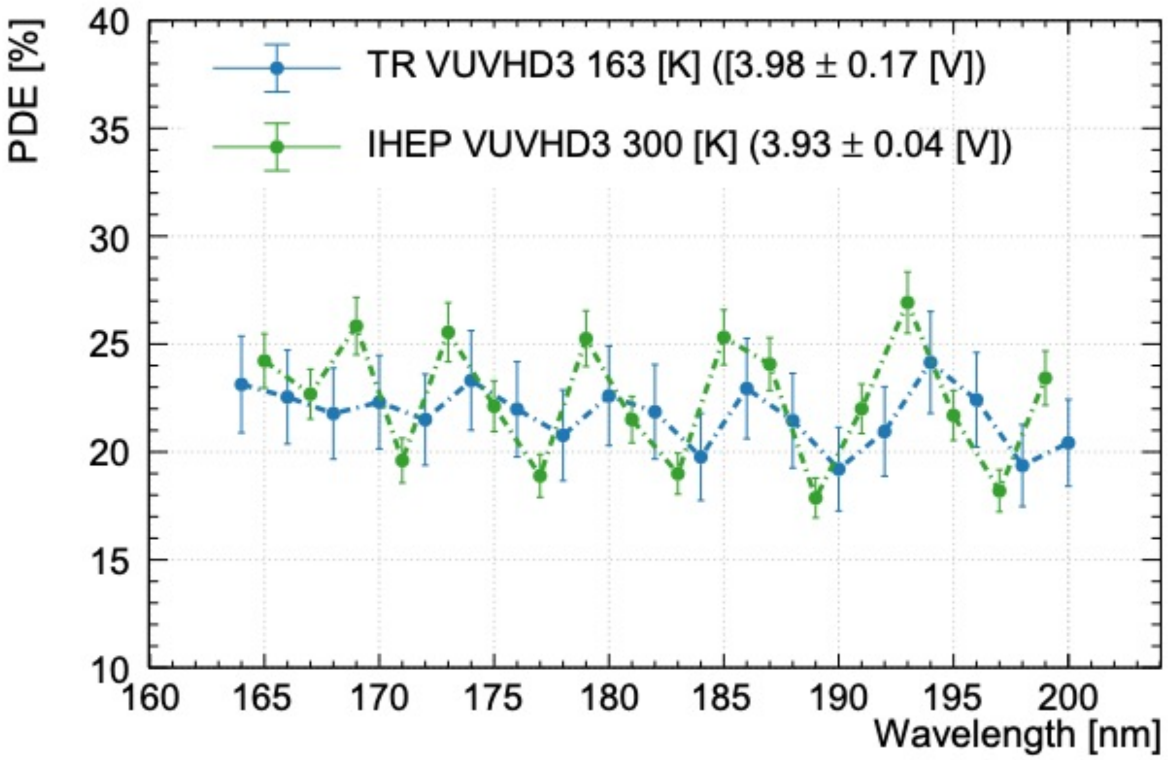


arXiv preprint arXiv:1912.01841

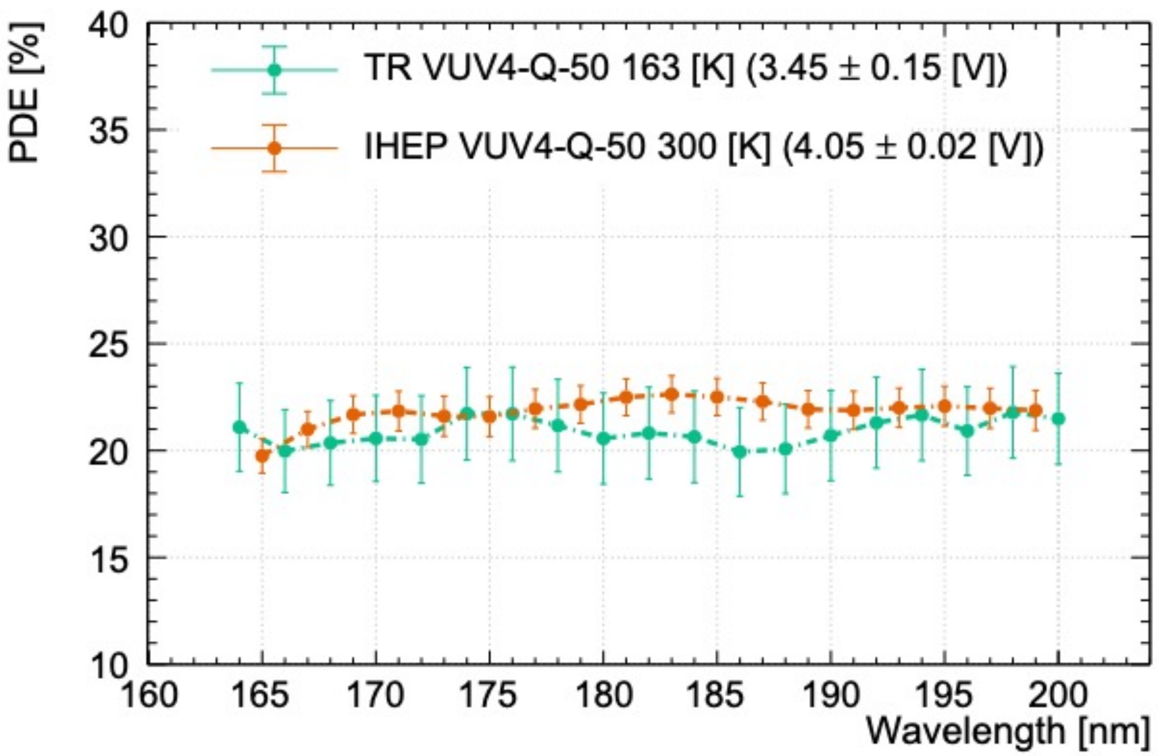
Gallina, G., Guan, Y., Retiere, F. et al. *Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO.* Eur. Phys. J. C 82, 1125 (2022), https://arxiv.org/pdf/2209.07765.pdf

Corresponding oscillation in efficiency

FBK SiPM

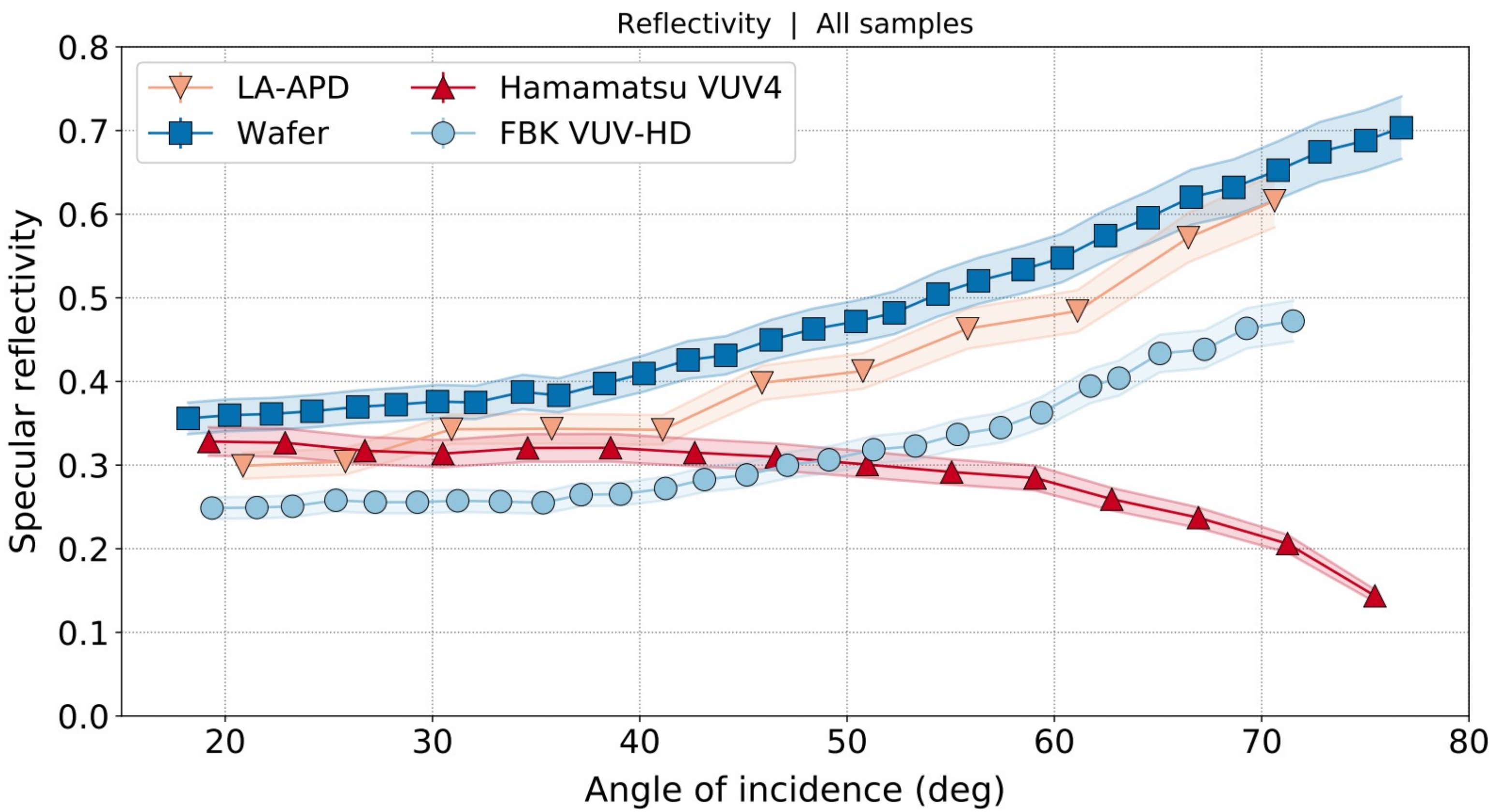


Hamamatsu MPPC



Systematic matching of reflectivity and efficiency still to be done

Reflectivity in LXe



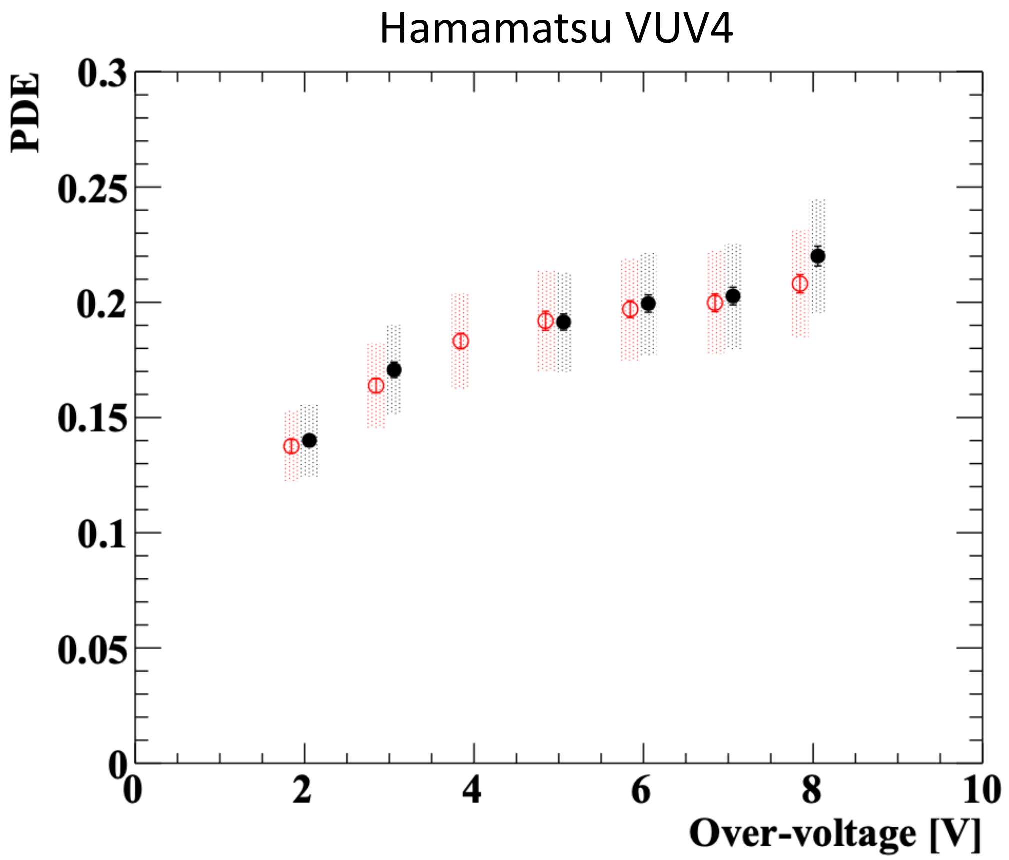
Done using U.Muenster setup

Extrapolation from vacuum to Lxe not so easy

*M. Wagenpfeil et al 2021 JINST **16** P08002*

https://arxiv.org/pdf/2104.07997.pdf

Corresponding efficiency in liquid Xenon



- Some difficulty in measuring efficiency in liquid Xenon
- Any issues?
  - MEG-II lower efficiency + degradation?

K. Ieki et al., Large-area MPPC with enhanced VUV sensitivity for liquid xenon scintillation detector, NIM A, https://arxiv.org/abs/1809.08701

SiPM nuisances

- Dark noise
  - Thermal. At room temperature ~100kHz/mm^2
- Carrier trap and release => after-pulsing
- Light emission during avalanche
  - Direct cross-talk
  - Delayed cross-talk
  - External cross-talk, aka hit another SiPM
- Large capacitance ~50pF/mm^2

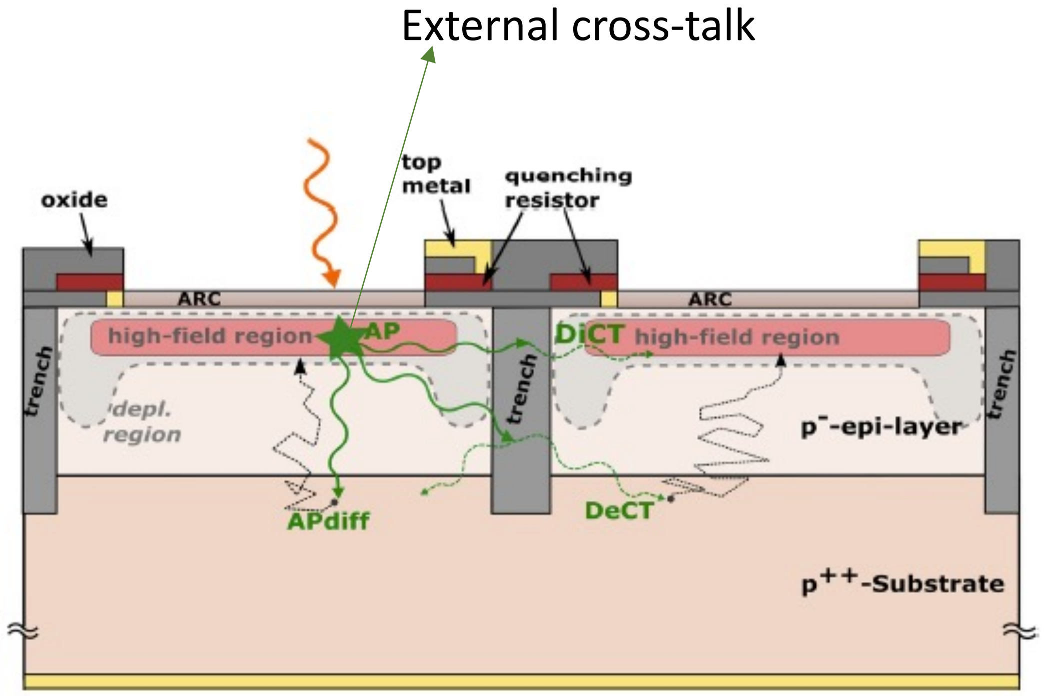


Fig. 1. Schematic representation of the internal structure of FBK Silicon photomultiplier, made in RGB-HD or RGB-UHD technology, with deep trenches between cells (SPADs).

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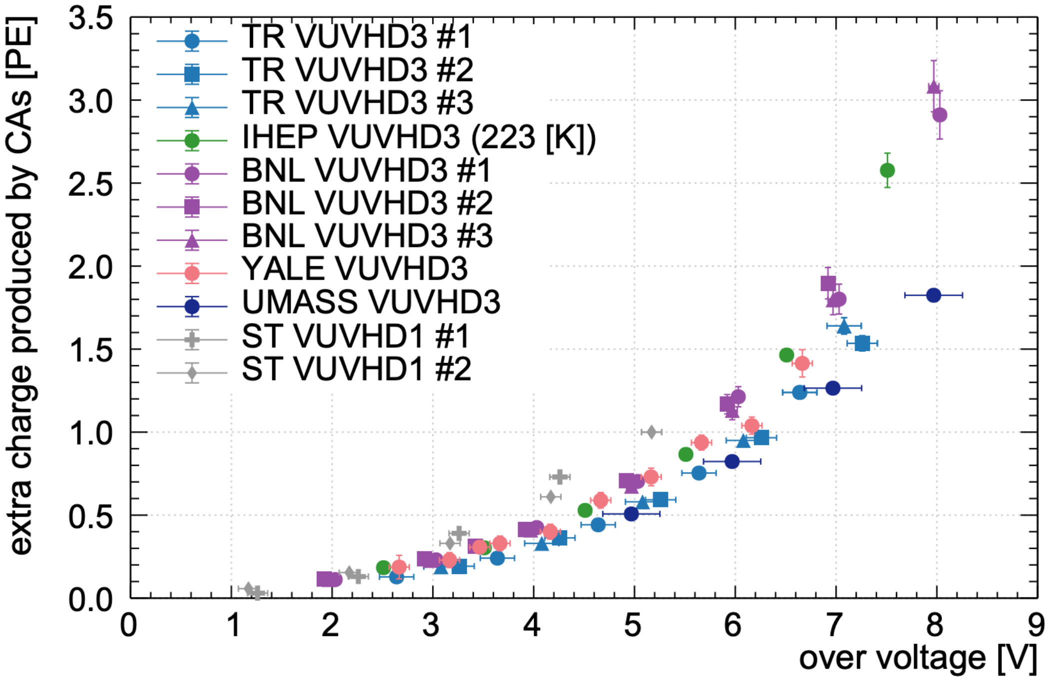
Gallina, G., Guan, Y., Retiere, F. et al. *Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO.* Eur. Phys. J. C 82, 1125 (2022), https://arxiv.org/pdf/2209.07765.pdf

Correlated avalanches

FBK

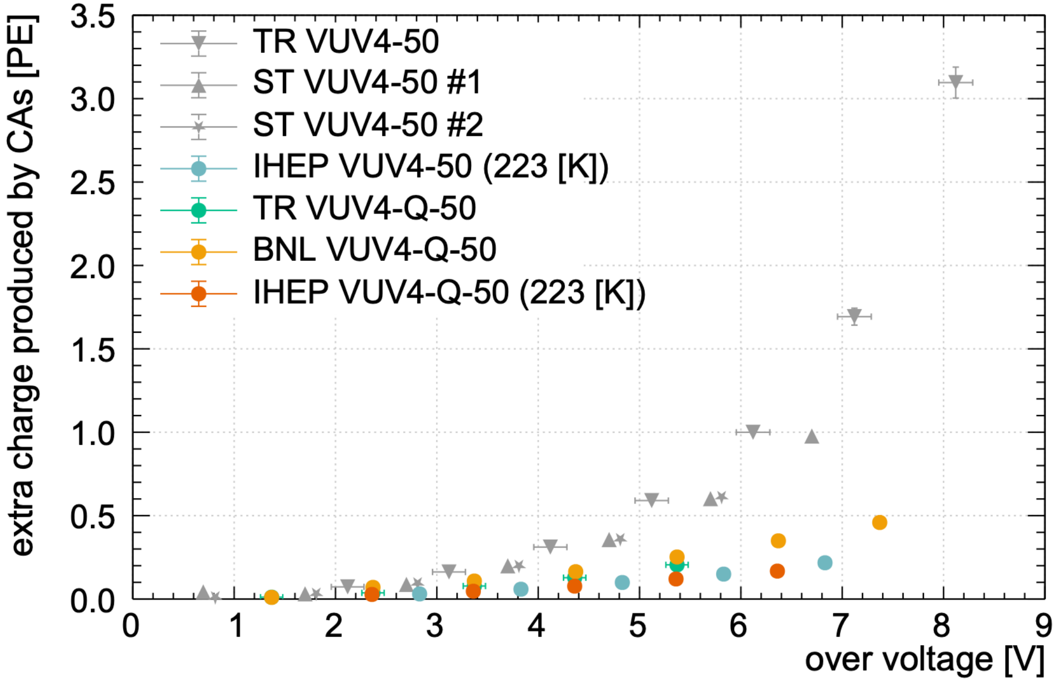
Dominated by cross-talk (prompt additional avalanche)



Hamamatsu

Dominated by after-pulsing

Significant batch to batch variation



Discovery, accelerated

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Photo-detector performance comparison

Parameters at LXe temperature for cm^2 scale channel size	PMT R11410-21[a]	FBK VUV-HD3 @ 3V [b]	HPK VUV4 MPPC @ 3V [b]
Single channel active area	128 cm^2	25 cm^2 [c]	6 cm^2 [d]
Efficiency at 175nm	34%	24.4 ± 1.4%	20.5 ± 1.1%
Single avalanche charge resolution	25%	5%[c]	5%[d]
Dark noise rate (Hz/cm^2)	1.3 ± 0.4	19 ± 1	35 ± 1
# correlated avalanche in 1 μs	0.02 ± 0.005	0.23 ± 0.06	0.06 ± 0.02
# Photons emitted per avalanche	N/A	1 ± 0.5	1 ± 0.5
Single photon timing resolution, σ	3.9 ± 0.6ns	~10 ns[c]	~100 ns[d]
Radiopurity per active area	**~mBq/cm^2**	Medium [c]	< 10 nBq/cm^2 [d]
Power consumption in LXe	0.75 mW/cm^2	2 mW/cm^2 [c]	2 mW/cm^2 [d]

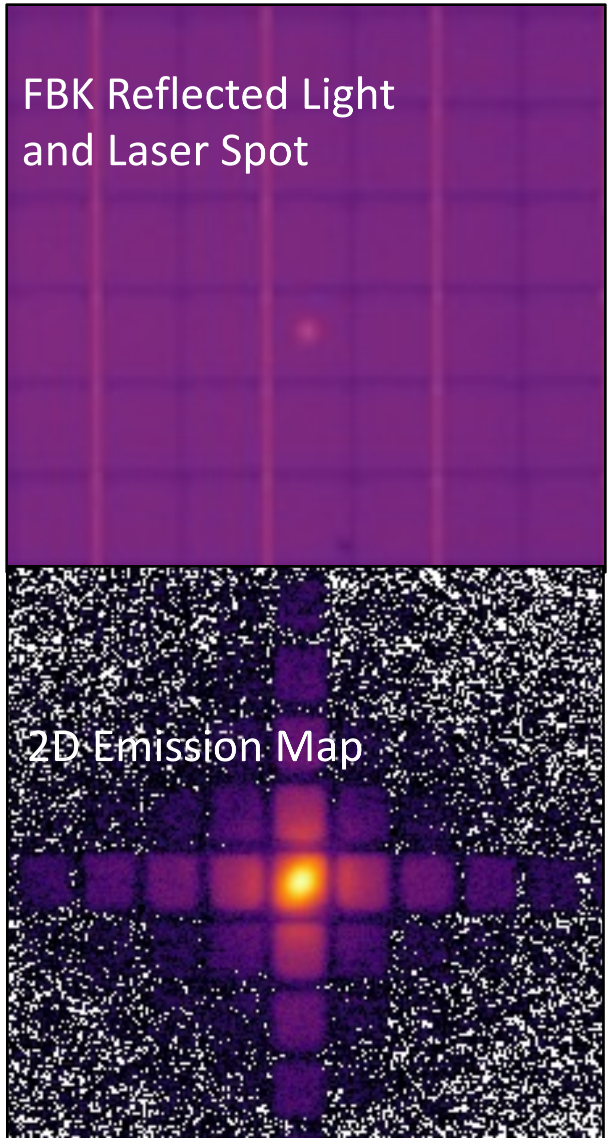
[a] Massaged from P. Barrow et al., https://arxiv.org/pdf/1609.01654.pdf
[b] G.Gallina et al., https://arxiv.org/pdf/2209.07765.pdf
[c] DarkSide-20k readout scheme for 25 cm^2 channel size
[d] nEXO readout scheme for 6 cm^2 channel size (can be applied to FBK)

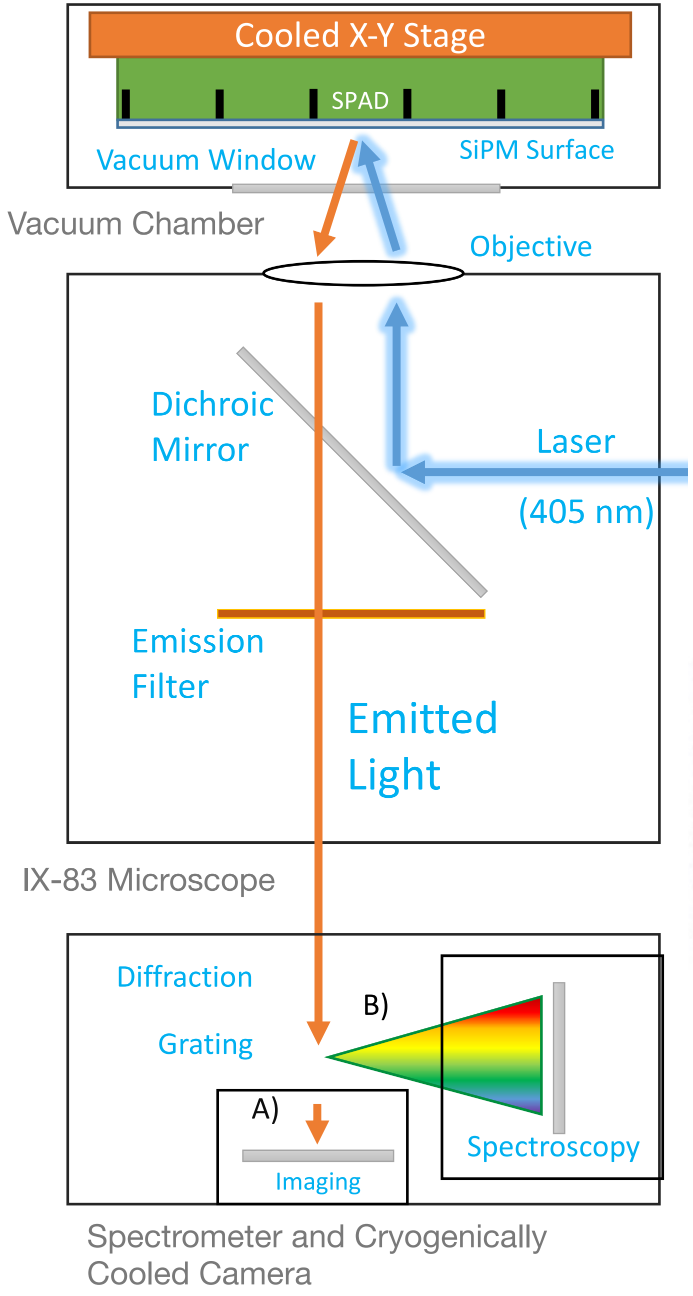
Open questions with light detection

- Light production
  - Intrinsic fluctuations really negligible?
  - Can Cerenkov light be used for anything?
  - Any other wavelengths?
- Issues
  - **Is external cross-talk a problem?**
  - Do we really understand the optics in LXe? May be material dependent
- Improving performances
  - Reducing dark noise. Not important for nEXO but can be for DM experiments
  - Improving efficiency
  - Transition for analog to digital SiPM

TRIUMF Microscope for the Injection and Emission of Light

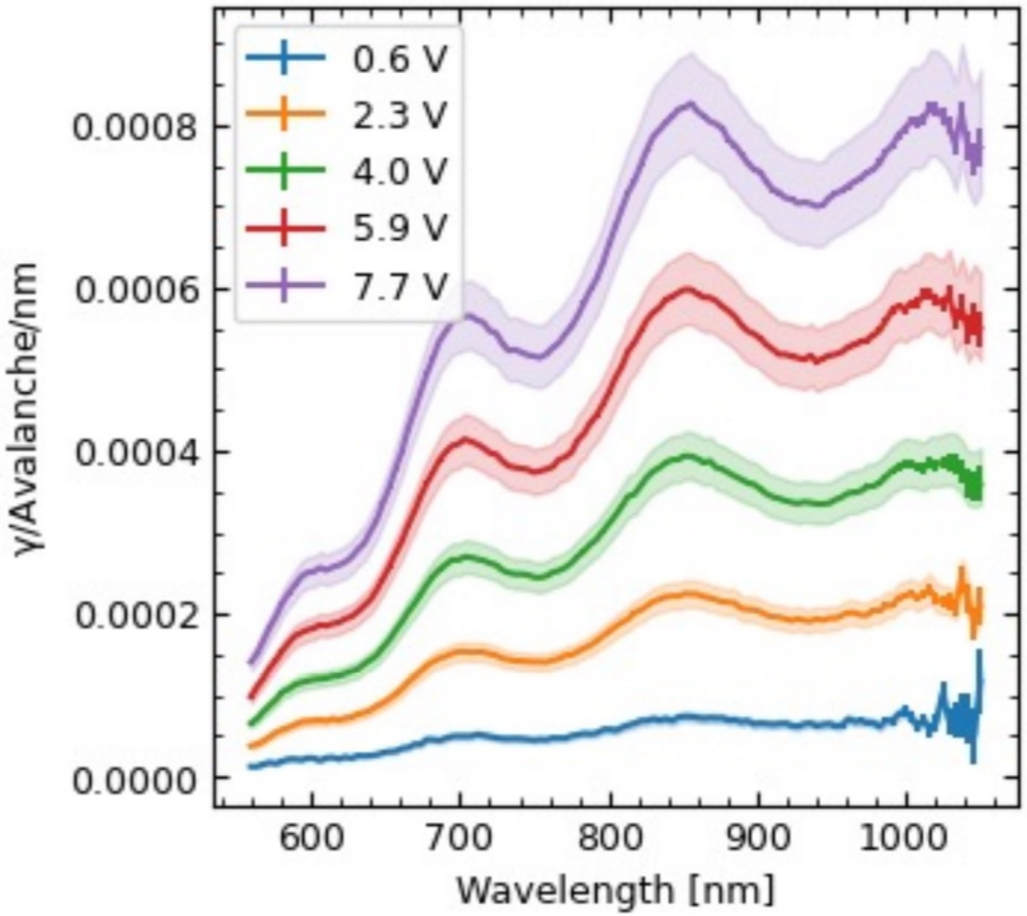
Imaging mode





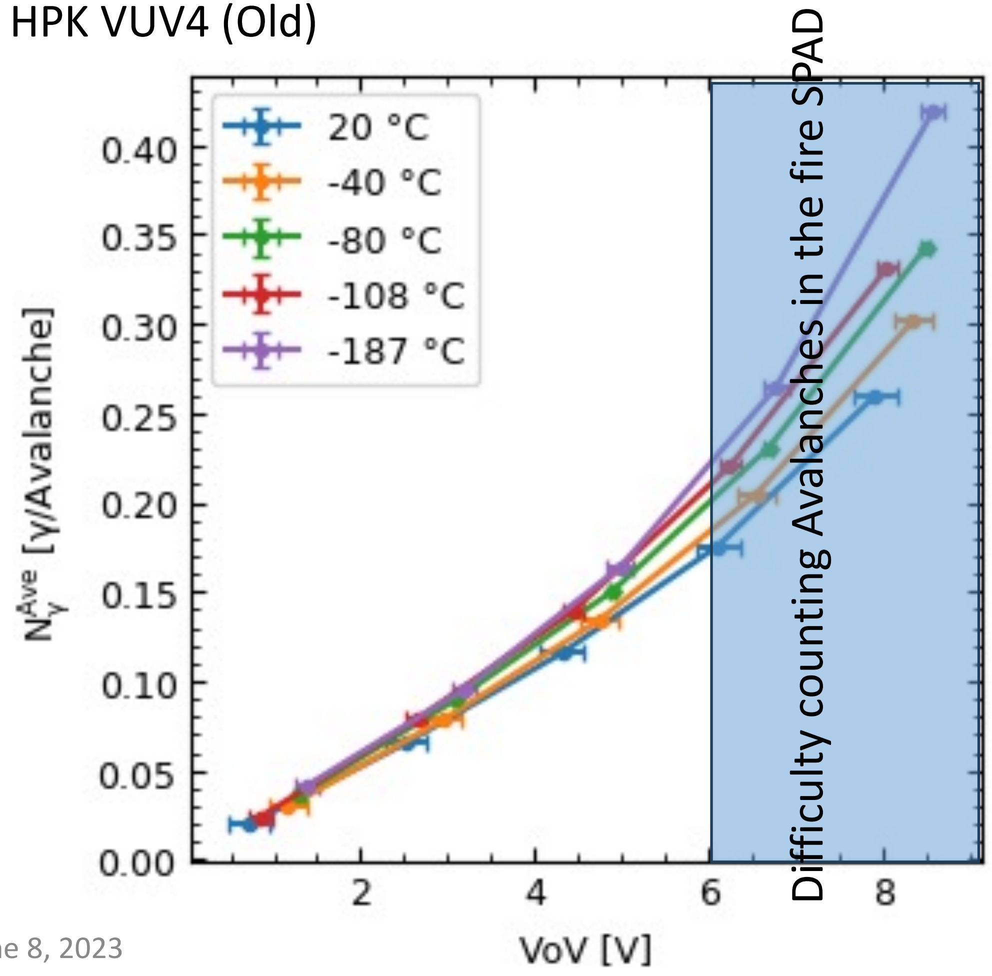
Spectroscopy mode

FBK VUV-HD3 emission spectrum
In NA < 0.45

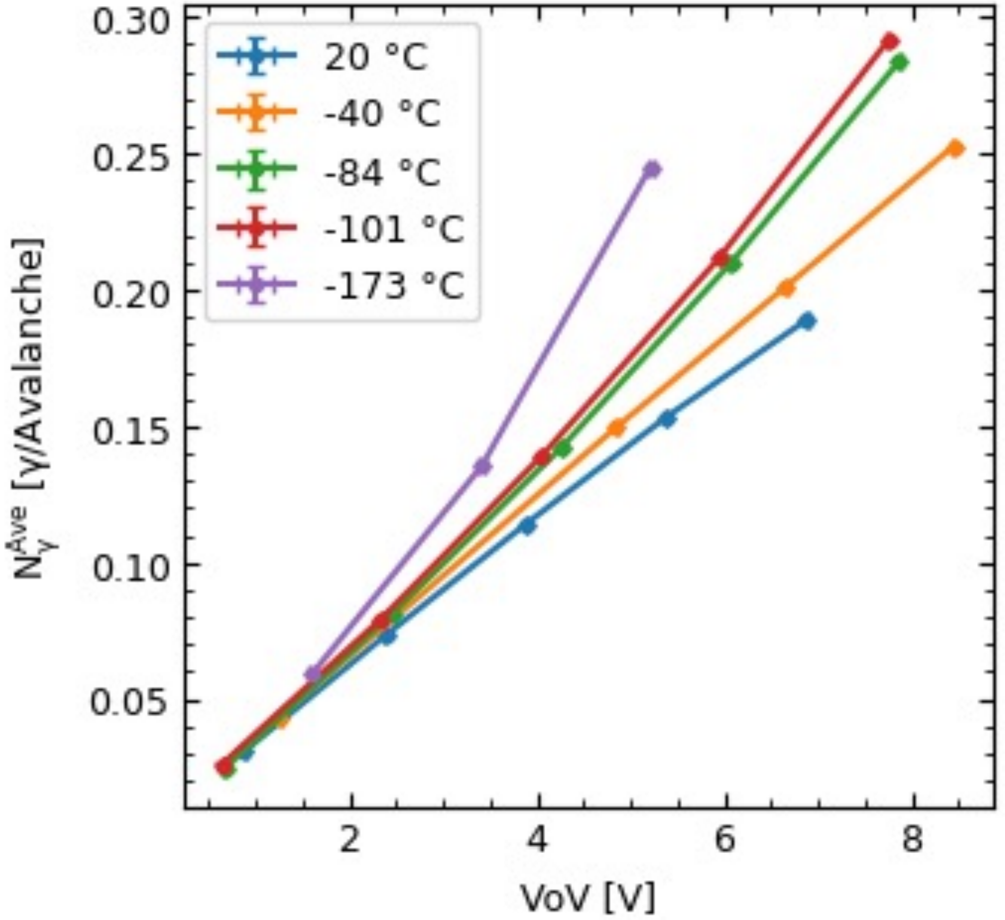


Yield Photons into a 0.45NA Objective vs V_{oV}

HPK VUV4 (Old)

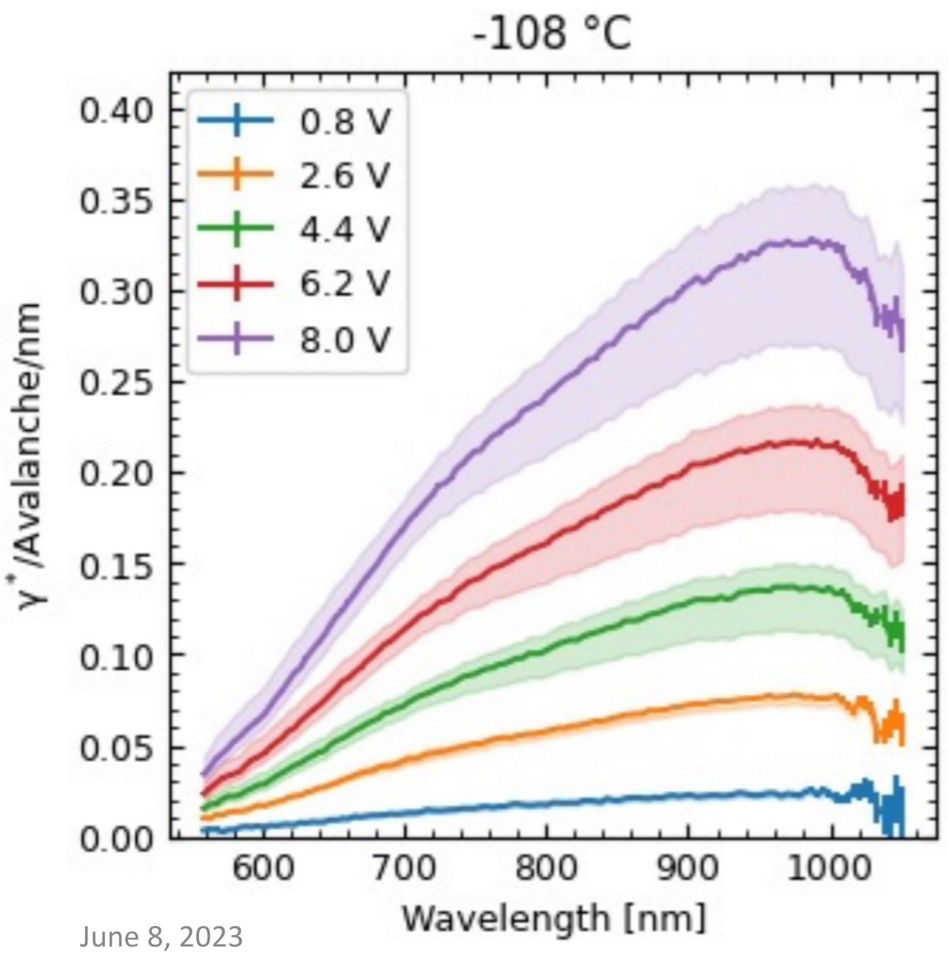


FBK VUVHD3

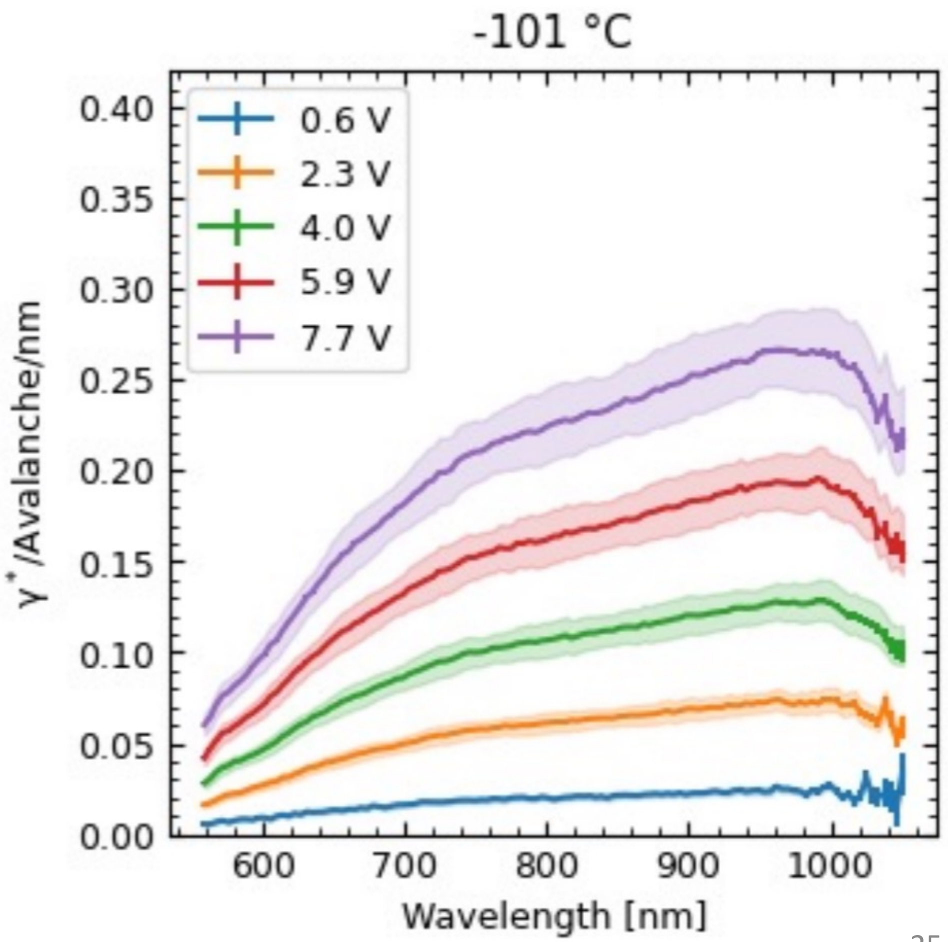


Spectrum at source assuming isotropic emission

HPK VUV4 (Old)

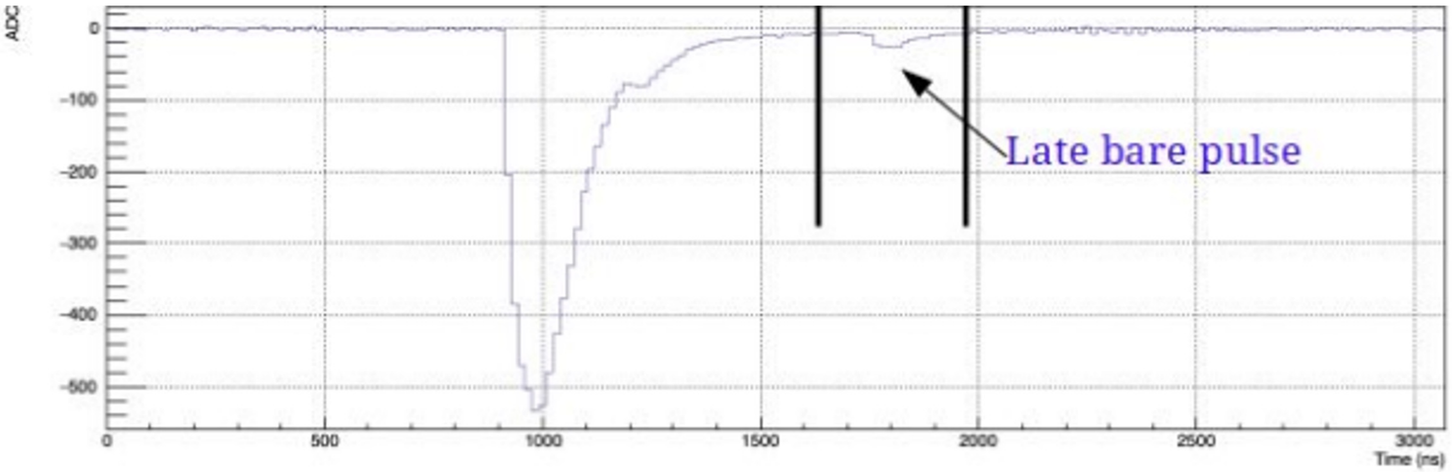


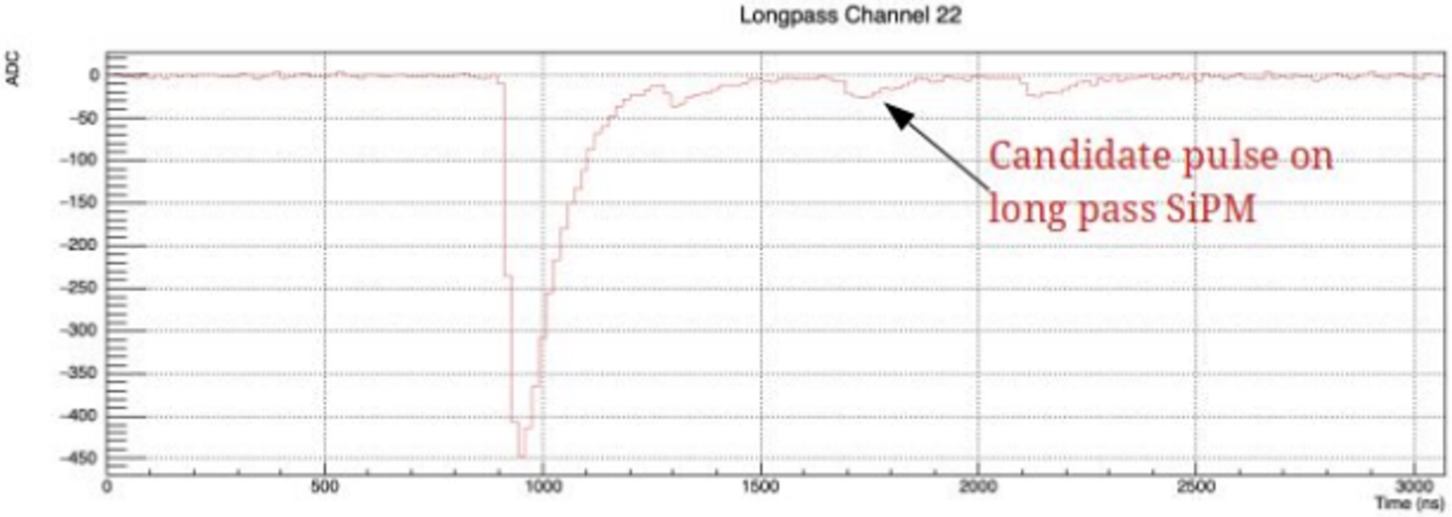
FBK VUVHD3

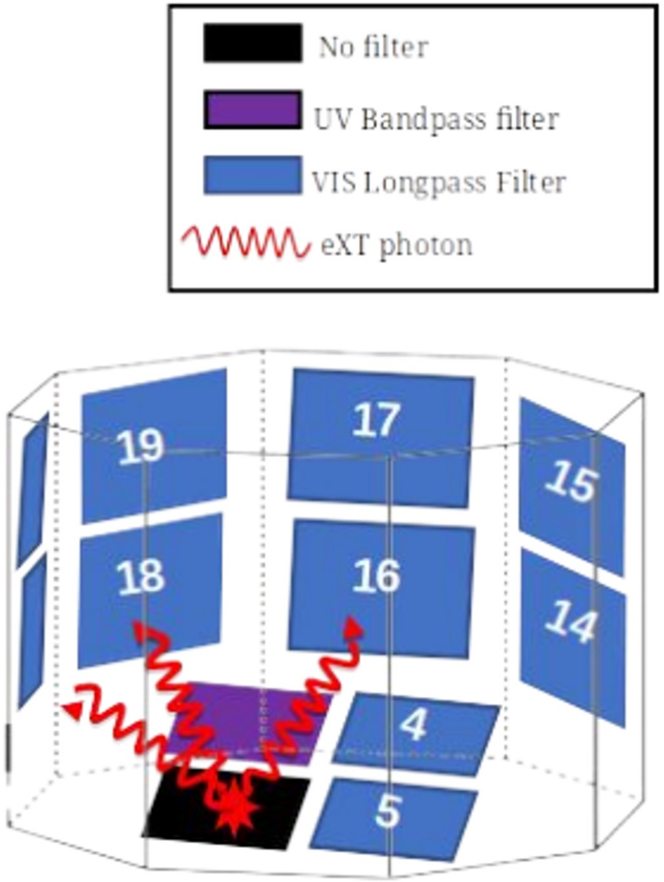


Externa cross-talk seen by LoLX phase 1

Probability of 1 avalanche producing another one
Preliminary result: 3 ± 1% @ 4V and 5 ± 1 % @ 5V
Working on investigating match with simulations
Should not be a major worry for nEXO







Open questions with light detection

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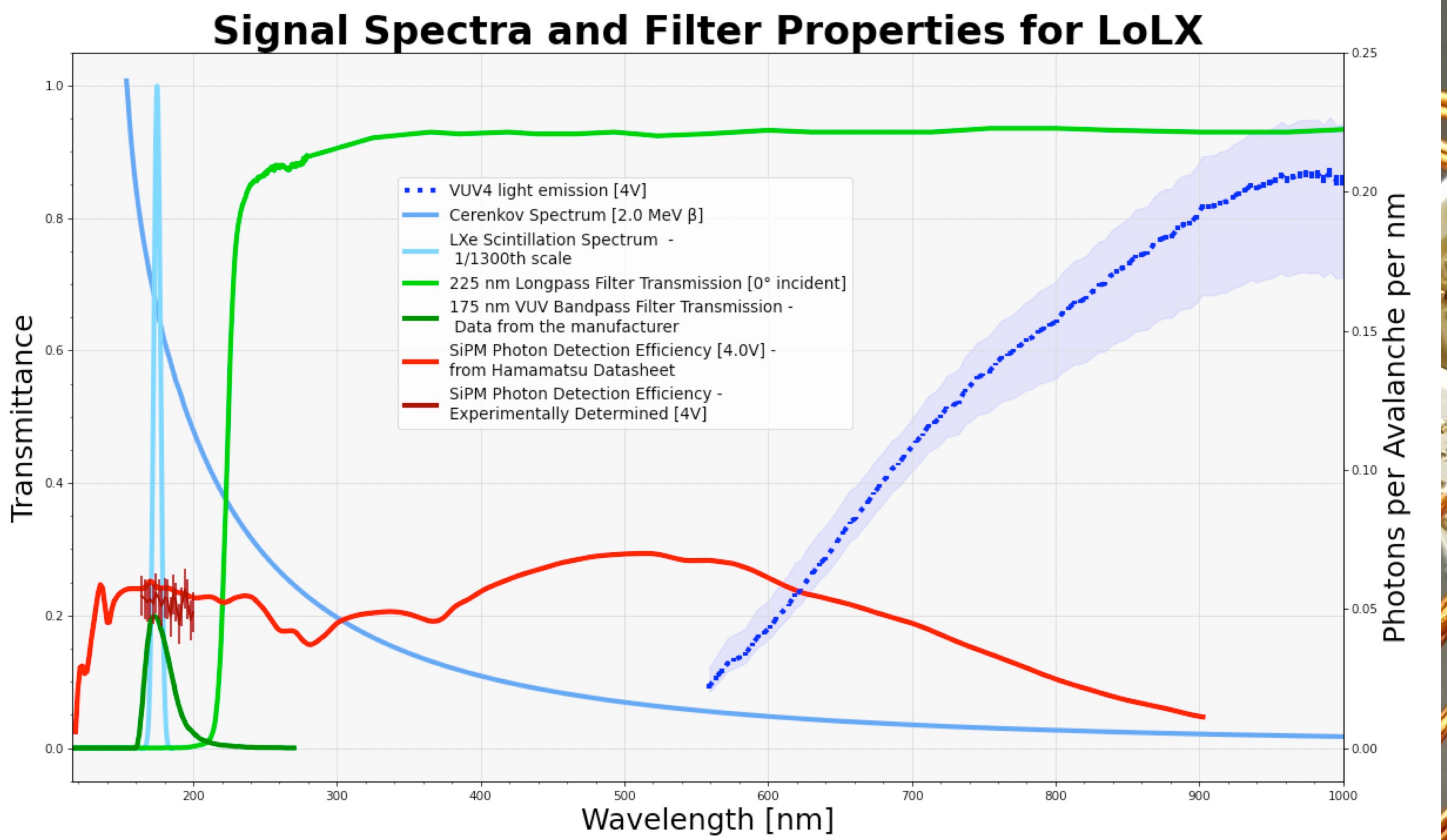
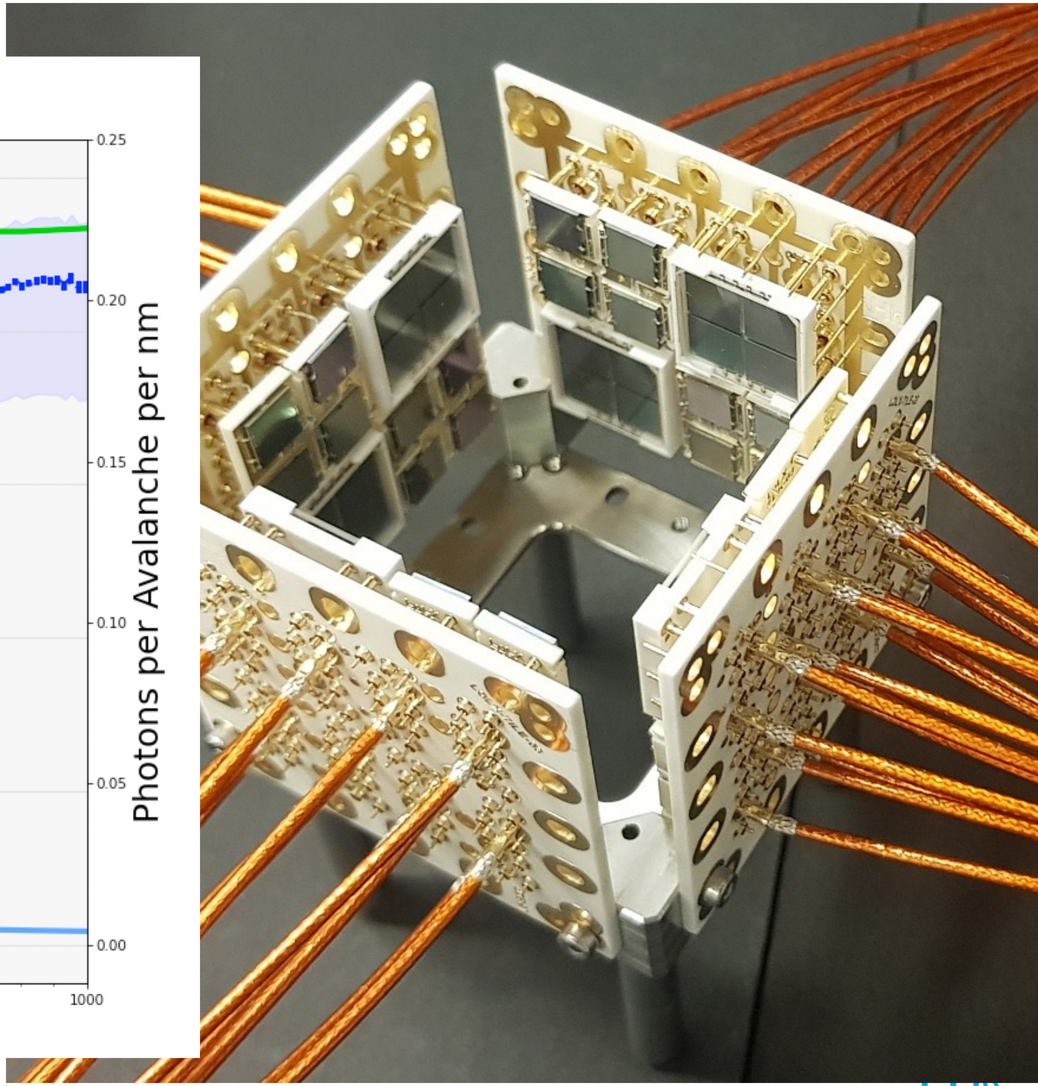
  - Reducing dark noise. Not important for nEXO but can be for DM experiments
  - Improving efficiency
  - Transition for analog to digital SiPM

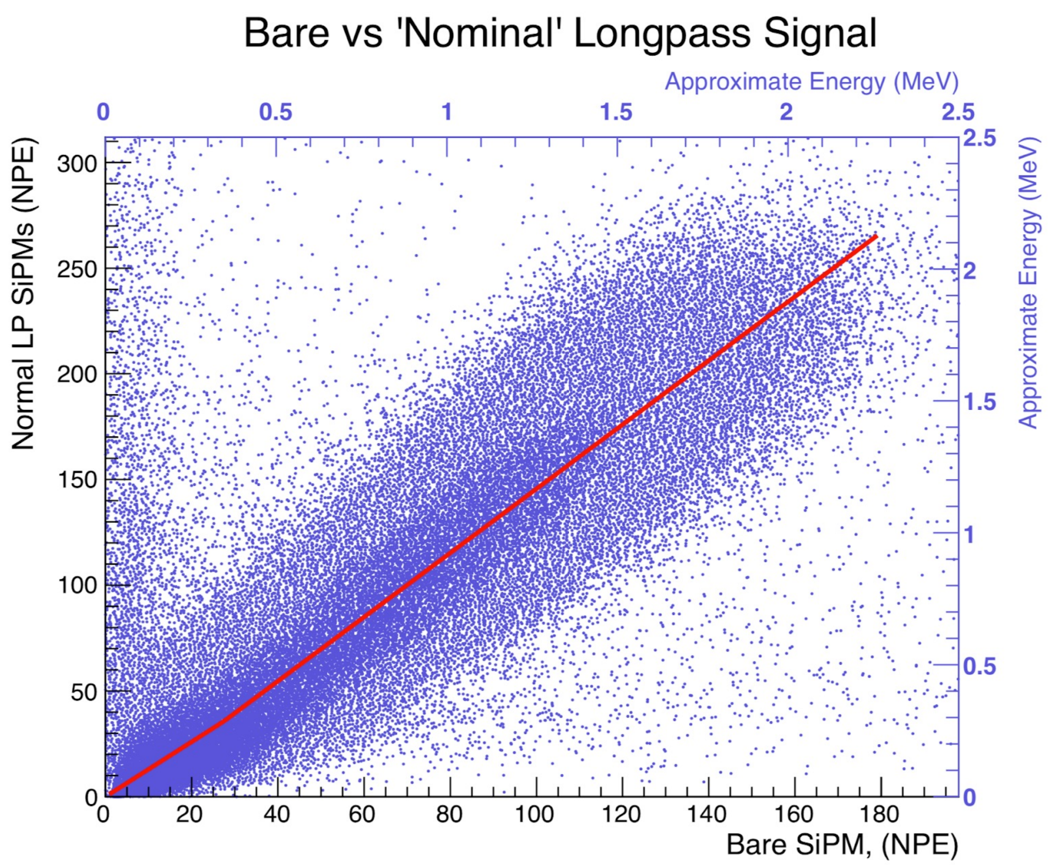
All processes in Lxe probed by the light only liquid Xenon experiment





LoLX phase 1 to phase 2

Filtered SiPMs. Was expecting 1/10 less light



Unfiltered SiPMs. Was expecting twice as much light

- LoLX phase 1
  - data with ^{90}Sr
  - Too much light > 225nm: fluorescence established
  - Not enough scintillation: bad xenon or low SiPM efficiency?
  - External crosstalk paper first publication
- LoLX phase 2
  - Address efficiency question first: HPK SiPM + FBK SiPM + PMT
  - Then back to Cerenkov
  - Light only energy resolution
  - <1ns scintillation characterization

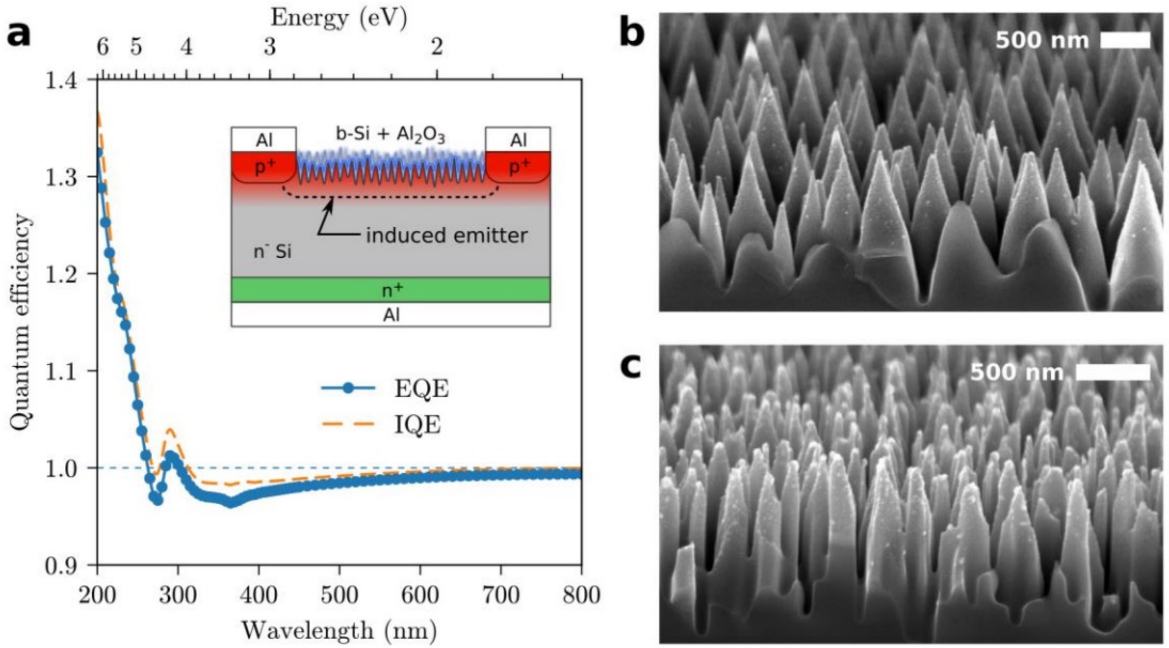
Open questions with light detection

- Light production
  - Intrinsic fluctuations really negligible?
  - Can Cerenkov light be used for anything?
  - Any other wavelengths?
- Issues
  - Is external cross-talk a problem?
  - Do we really understand the optics in LXe? May be material dependent
- Improving performances
  - Reducing dark noise. Not important for nEXO but can be for DM experiments
  - **Improving efficiency**
  - Transition for analog to digital SiPM

Improving efficiency

Published in *Physical Review Letters* 8.9.2020. Please cite: Phys. Rev. Lett. 125(11), 117702 (2020), doi: 10.1103/PhysRevLett.125.117702
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.125.117702

- Ultra-shallow surface contact
  - nm scale
  - Epitaxial growth
  - Pure-Boron
  - …
- Anti-reflective coating
  - 1D conventional thin film is tricky due to lack of materials
  - Go 3D – Black silicon. Long term stability is question mark
- Do all that while reducing dark noise!

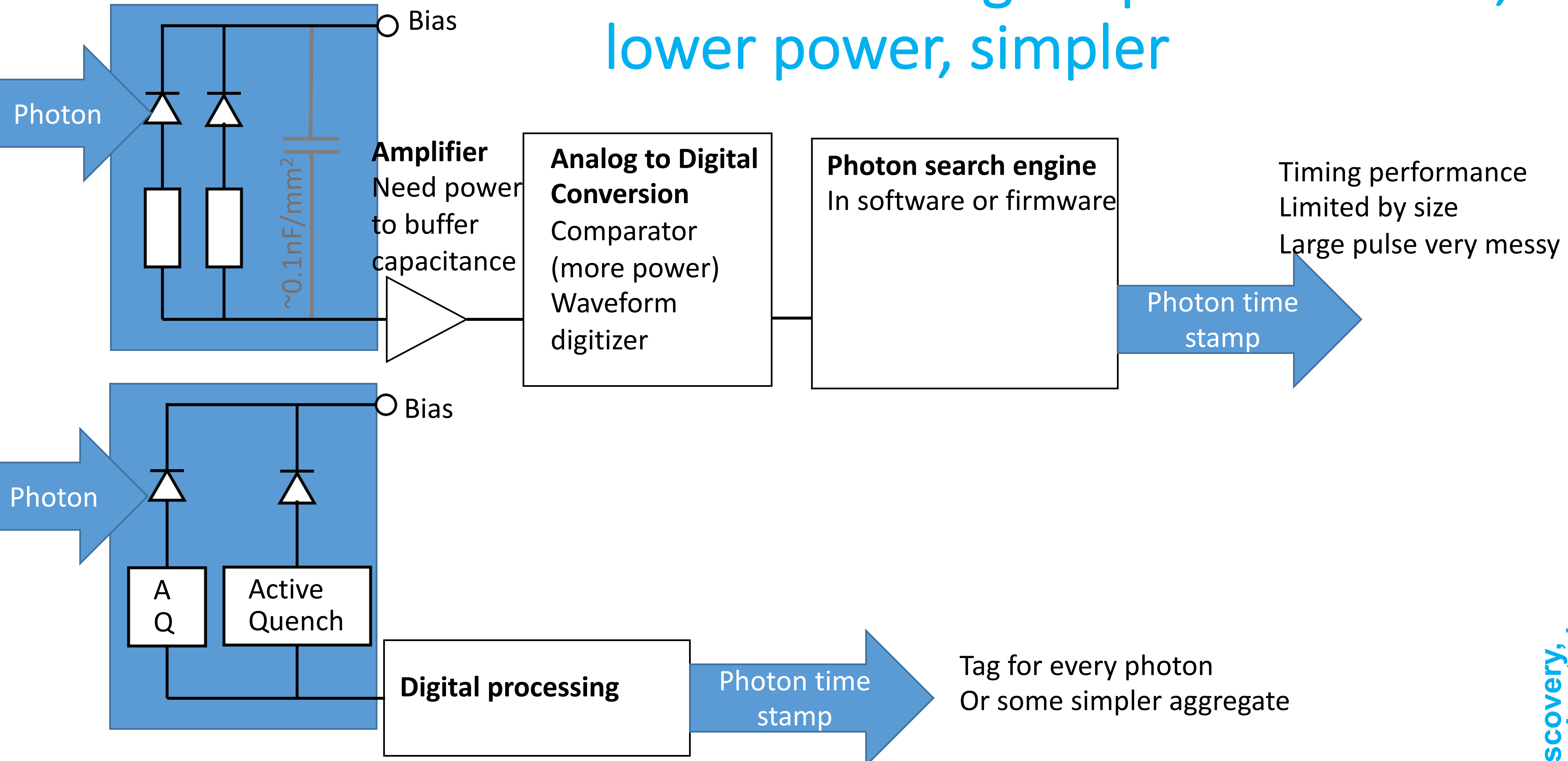


Discovery, acceleratec

Open questions with light detection

- Light production
  - Intrinsic fluctuations really negligible?
  - Can Cerenkov light be used for anything?
  - Any other wavelengths?
- Issues
  - Is external cross-talk a problem?
  - Do we really understand the optics in LXe? May be material dependent
- Improving performances
  - Reducing dark noise. Not important for nEXO but can be for DM experiments
  - Improving efficiency
  - **Transition for analog to digital SiPM (non nEXO baseline)**

Motivation: higher performances, lower power, simpler



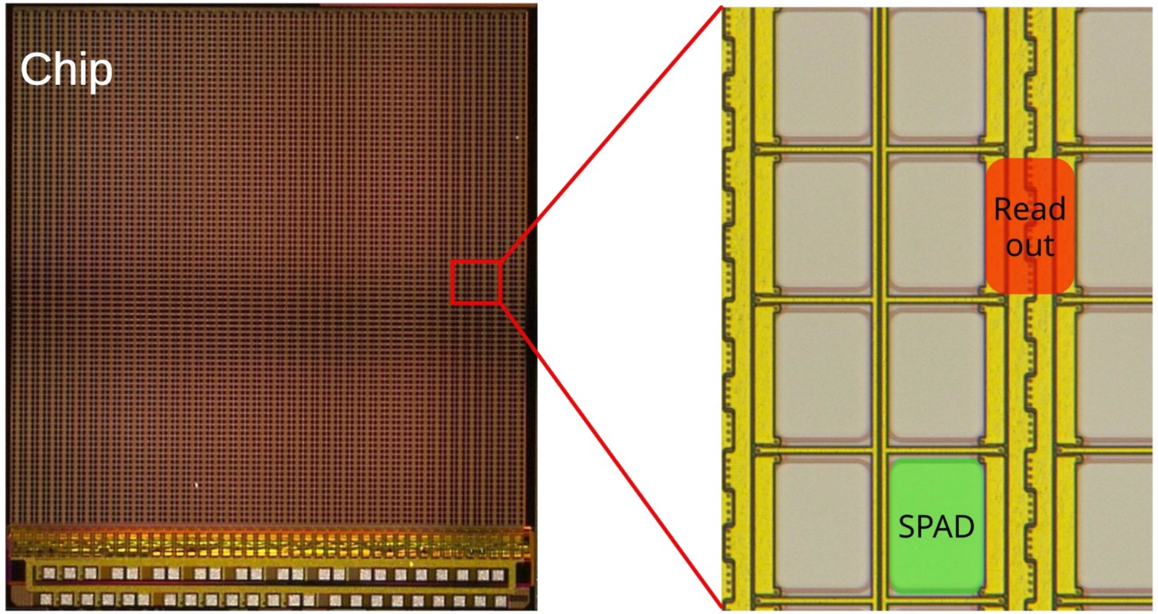
2D SPAD @ Heidelberg

- 2D SPAD array designed by Heidelberg built by Fraunhofer IMS
- The good
  - Single chip doing everything
  - Dark noise rate of 0.02 Hz/mm^2
- The bad
  - Some loss of active area
  - No VUV sensitivity… yet

Digital SiPMs for DARWIN

Michael Keller, Peter Fischer, Robert Zimmermann, Michael Ritzert – University of Heidelberg

DARWIN Collaboration Meeting 2023 at University of Heidelberg

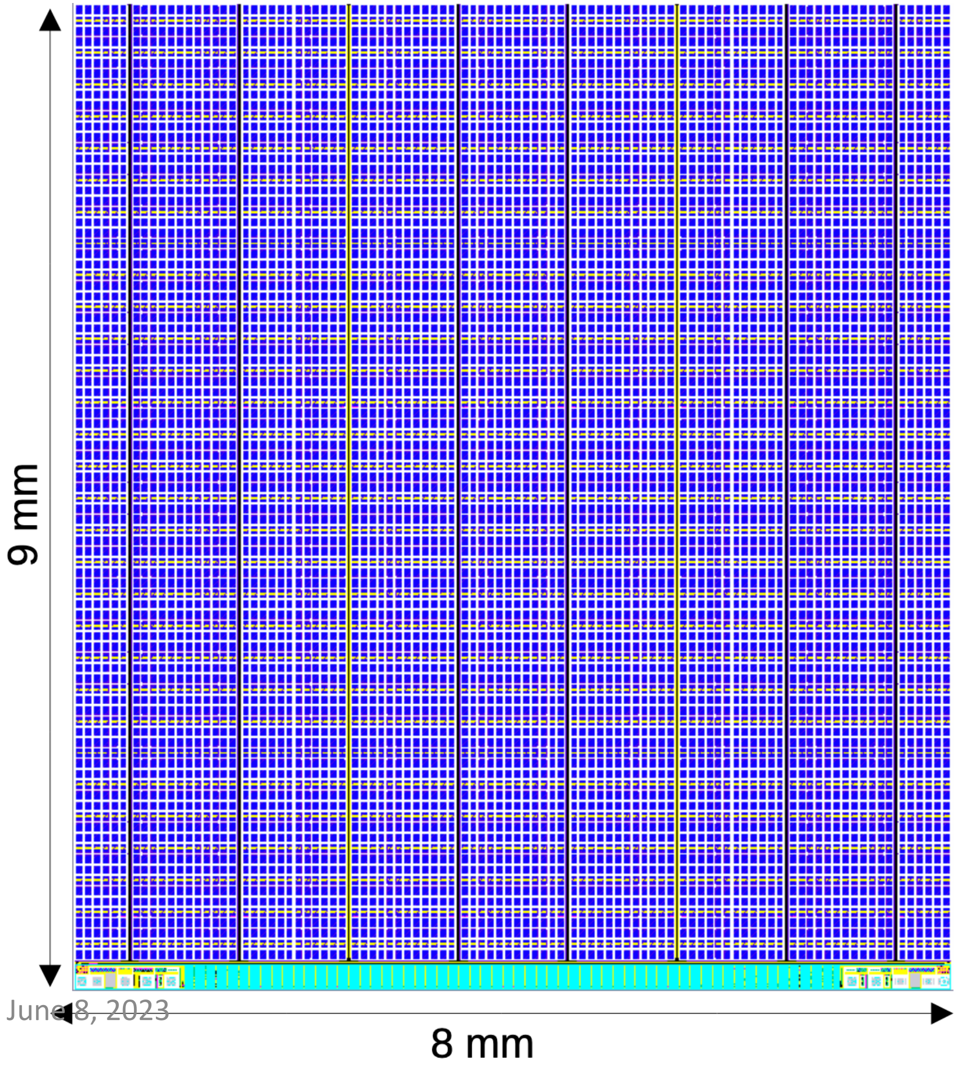


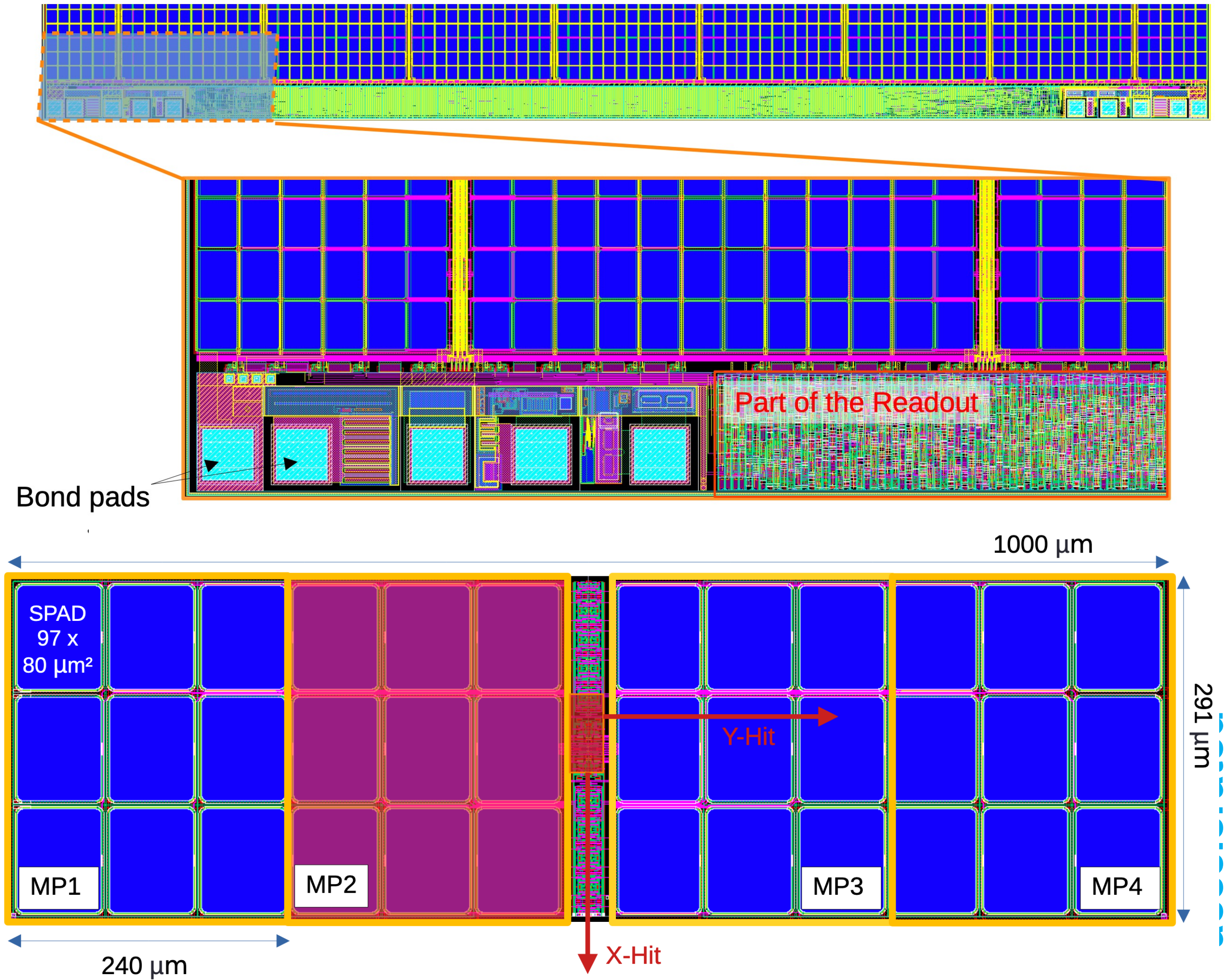
2D SPAD array for DARWIN

Digital SiPMs for DARWIN

Michael Keller, Peter Fischer, Robert Zimmermann, Michael Ritzert – University of Heidelberg

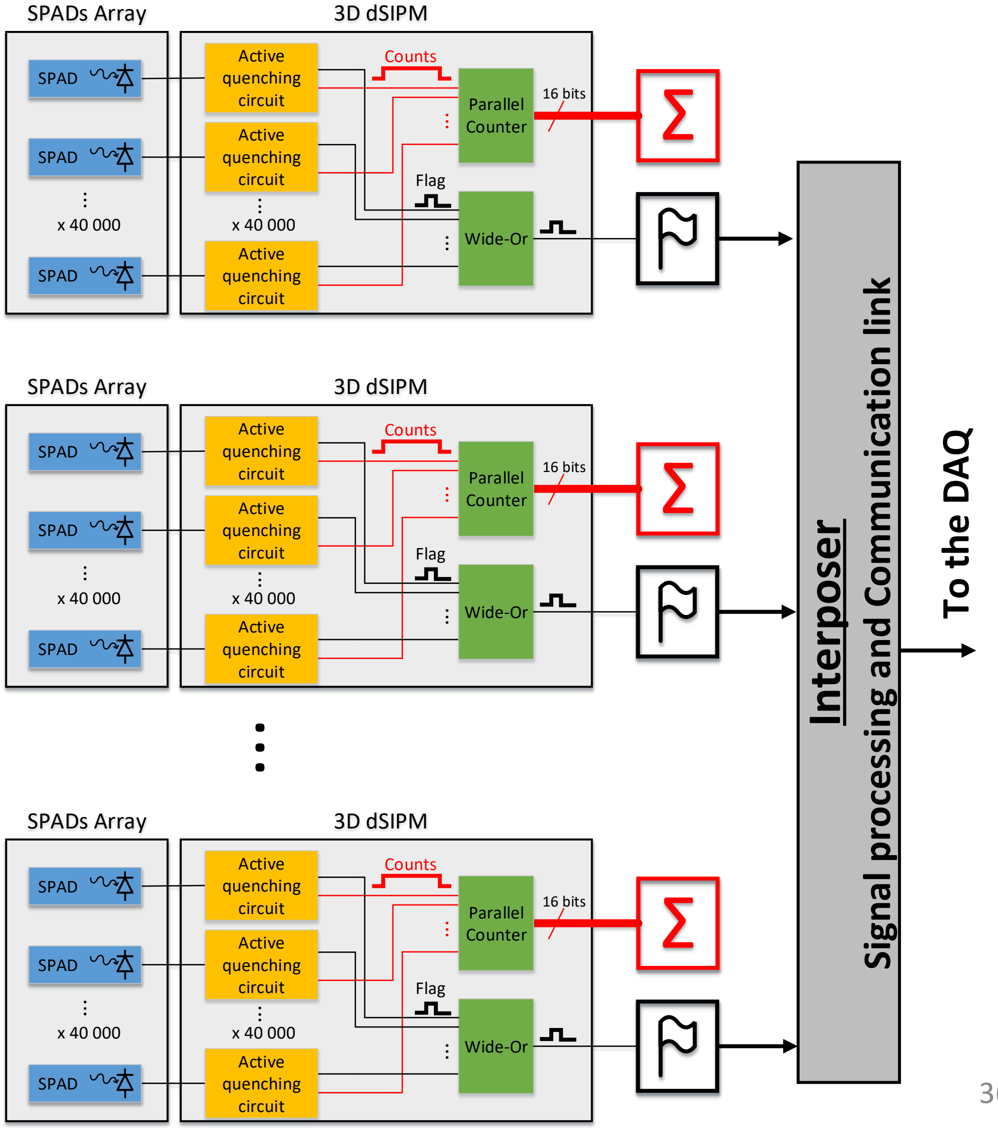
DARWIN Collaboration Meeting 2023 at University of Heidelberg



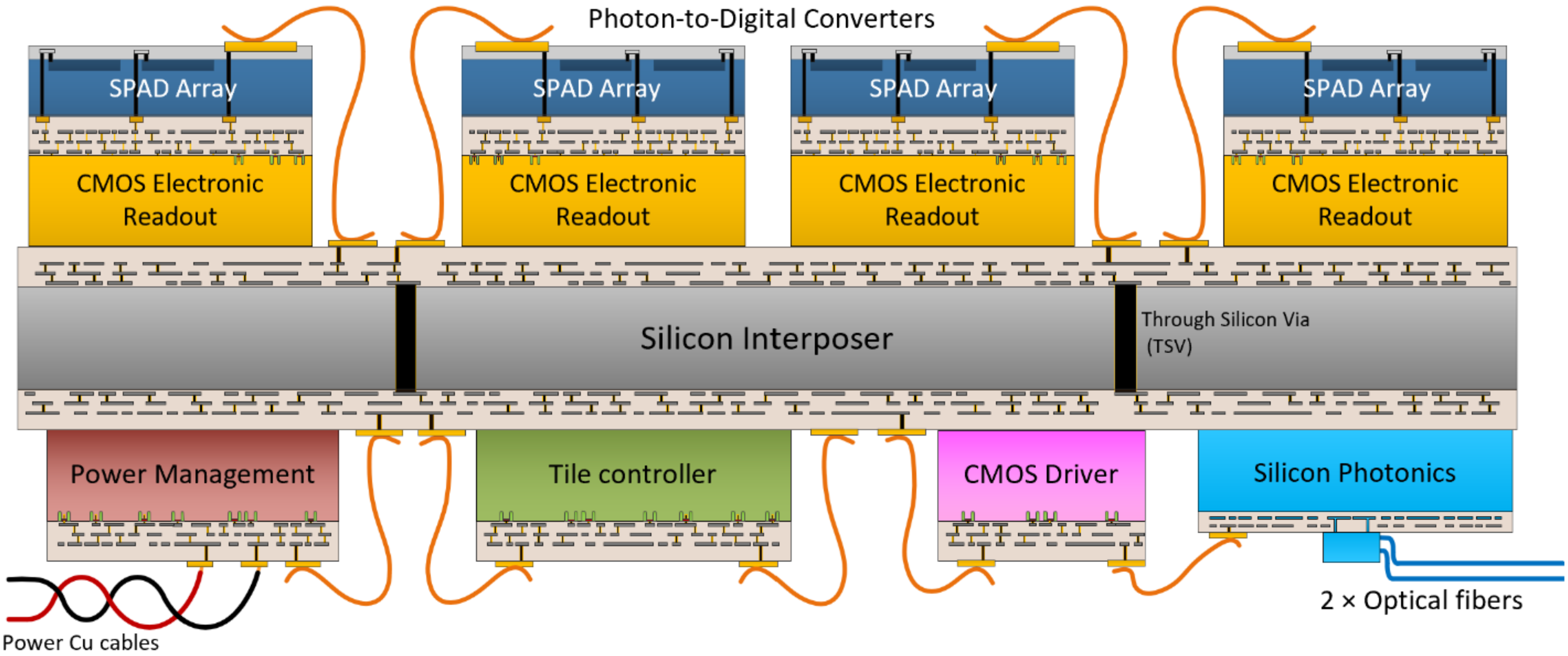


Photon to Digital Converter

- Designed by Sherbrooke (Canada) and built at Teledyne-DALSA (Canada)
- The good
  - Can optimize sensor and readout separately
  - Excellent fill factor – possibly 100% in back-side configuration
- The bad
  - Tricky to build

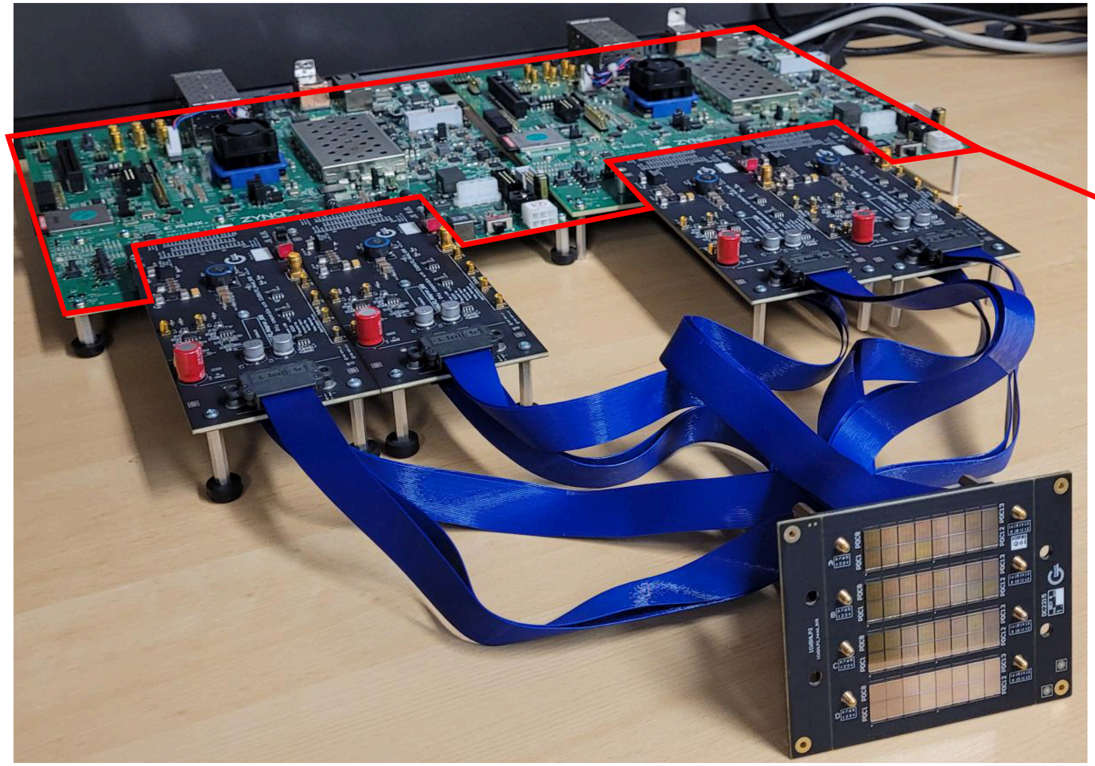


Photon to Digital Converter – complete system

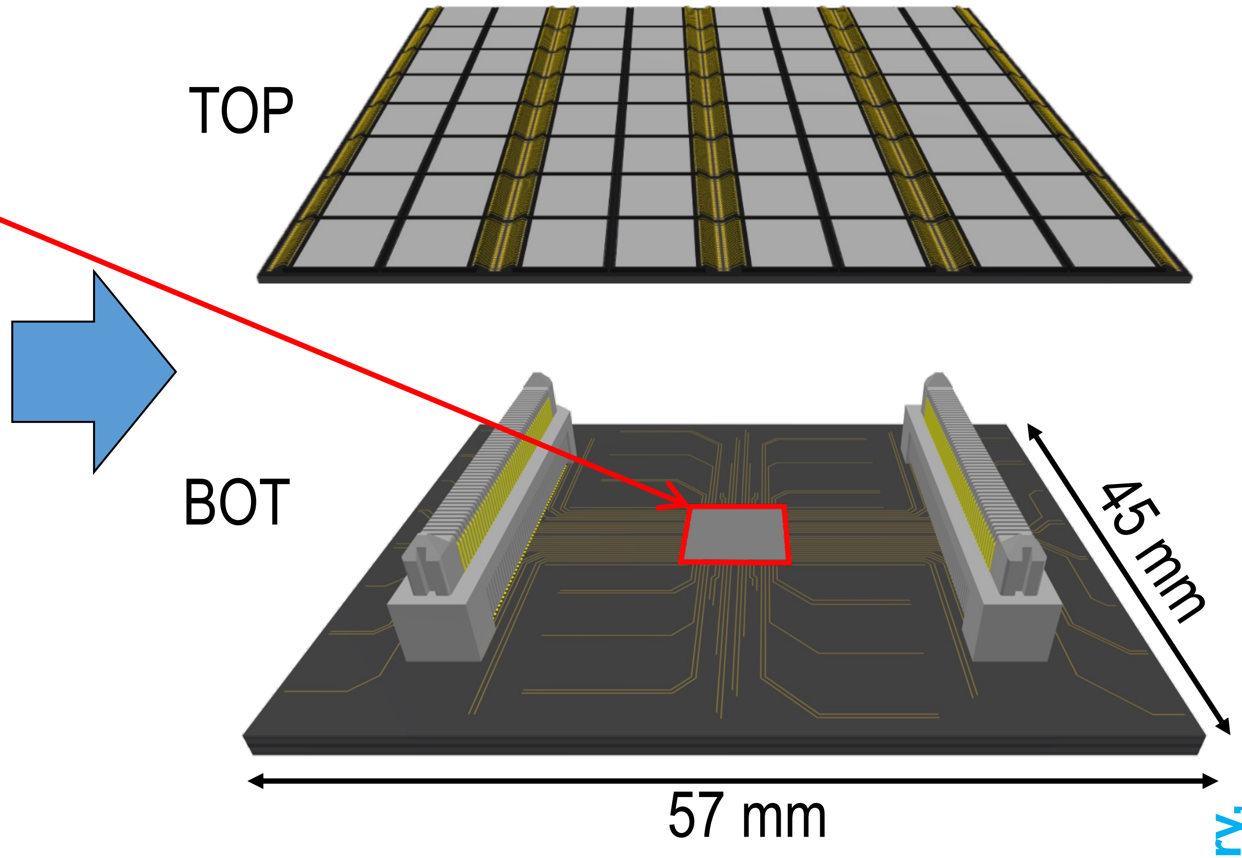


Current development state

FPGA-based Controller



ASIC-based Controller



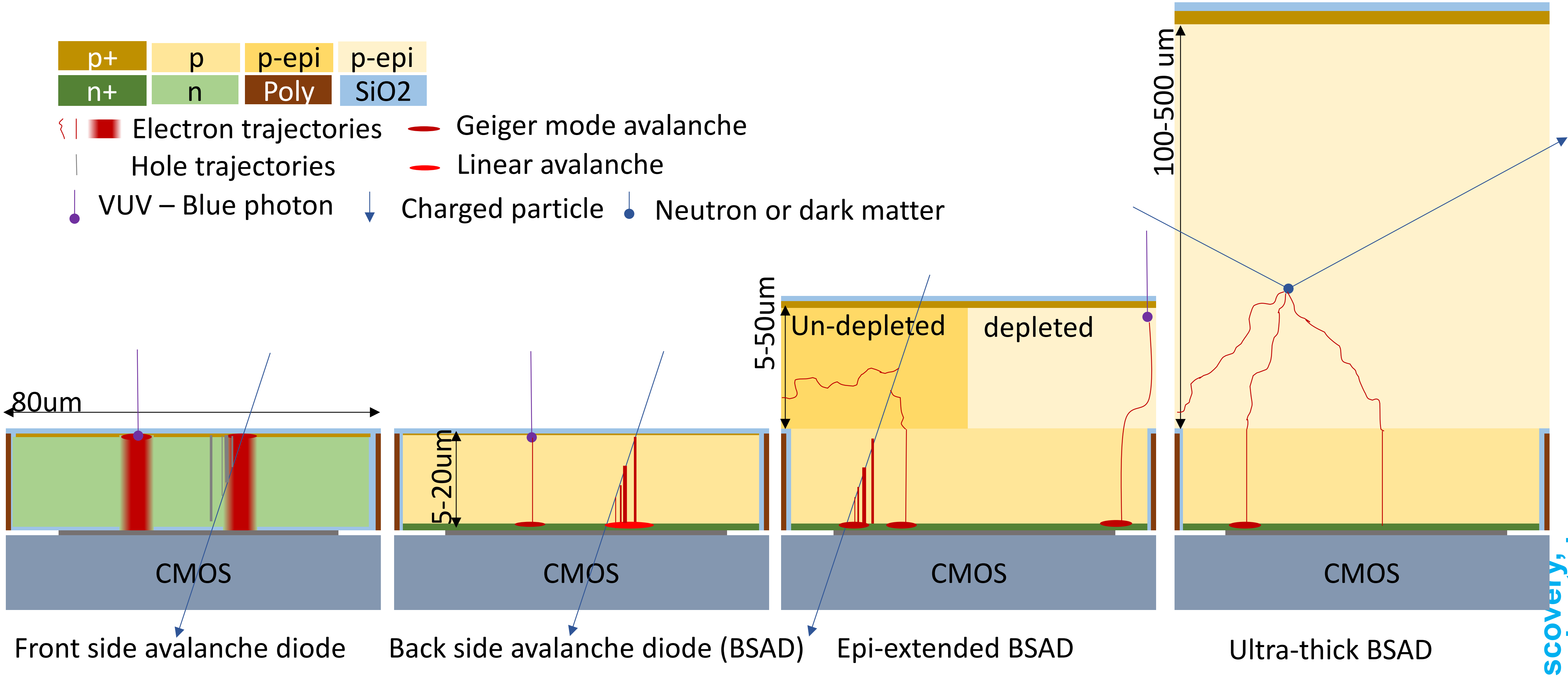
Summary: photo-detector performance comparison

2 possible solutions for nEXO

Parameters at LXe temperature for cm^2 scale channel size	PMT R11410-21[a]	FBK VUV-HD3 @ 3V [b]	HPK VUV4 MPPC @ 3V [b]	Heidelberg 2D SPAD array	Sherbrooke 3D SPAD array
Efficiency at 175nm	34%	24.4±1.4%→?	20.5±1.1%→?	0→25%→?	0→25%→?
Single avalanche charge resolution	25%	5%[c]	5%[d]	N/A	N/A
Dark noise rate (Hz/cm^2)	0.23 ± 0.07	19 ± 1	35 ± 1	2	1000
# correlated avalanche in 1 μs	0.02 ± 0.005	0.23 ± 0.06	0.06 ± 0.02	AP=0, XT=?	AP=0, XT=?
# Photons emitted per avalanche	N/A	1 ± 0.5	1 ± 0.5	?	?
Single photon timing resolution	3.9 ± 0.6ns	~10 ns[c]	~100 ns[d]	100ps	100ps
Radiopurity per active area	**~mBq/cm^2**	Medium [c]	< 10 nBq/cm^2 [d]	~nBq/cm^2	~nBq/cm^2
Power consumption in LXe	0.13 mW/cm^2	2 mW/cm^2 [c]	2 mW/cm^2 [d]	< 1mW/cm^2	< 1mW/cm^2

[a] Massaged from P. Barrow et al., https://arxiv.org/pdf/1609.01654.pdf
[b] G.Gallina et al., https://arxiv.org/pdf/2209.07765.pdf
[c] DarkSide-20k readout scheme for 25cm^2 channel size
[d] nEXO readout scheme for 6cm^2 channel size (can be applied to FBK)

Outlook – 3D integration for other things



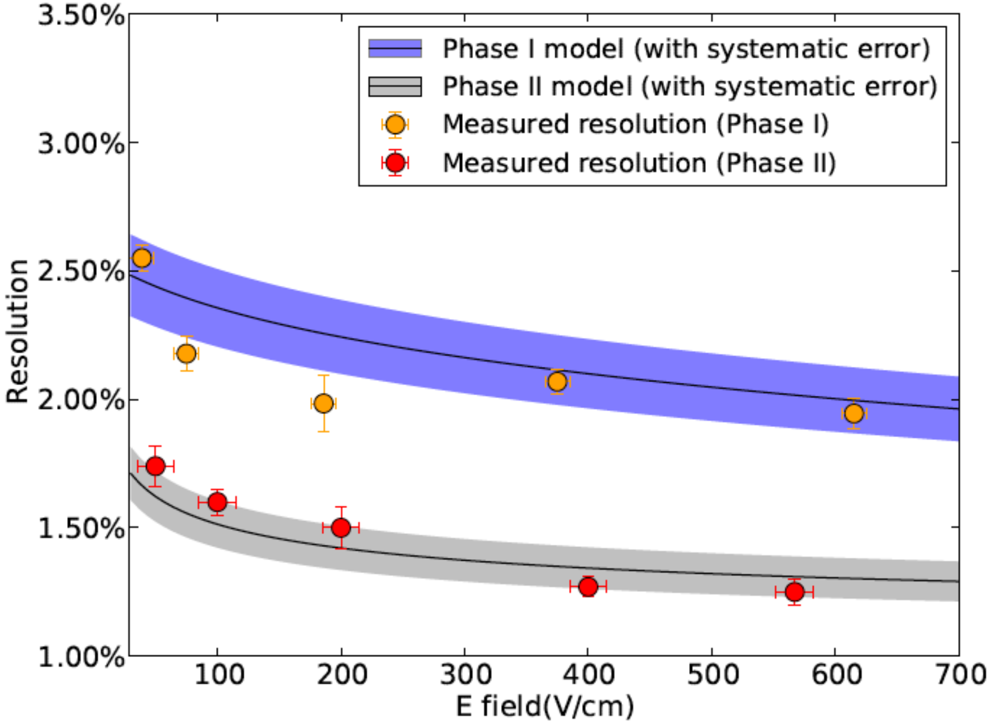
Join us, we are recruiting

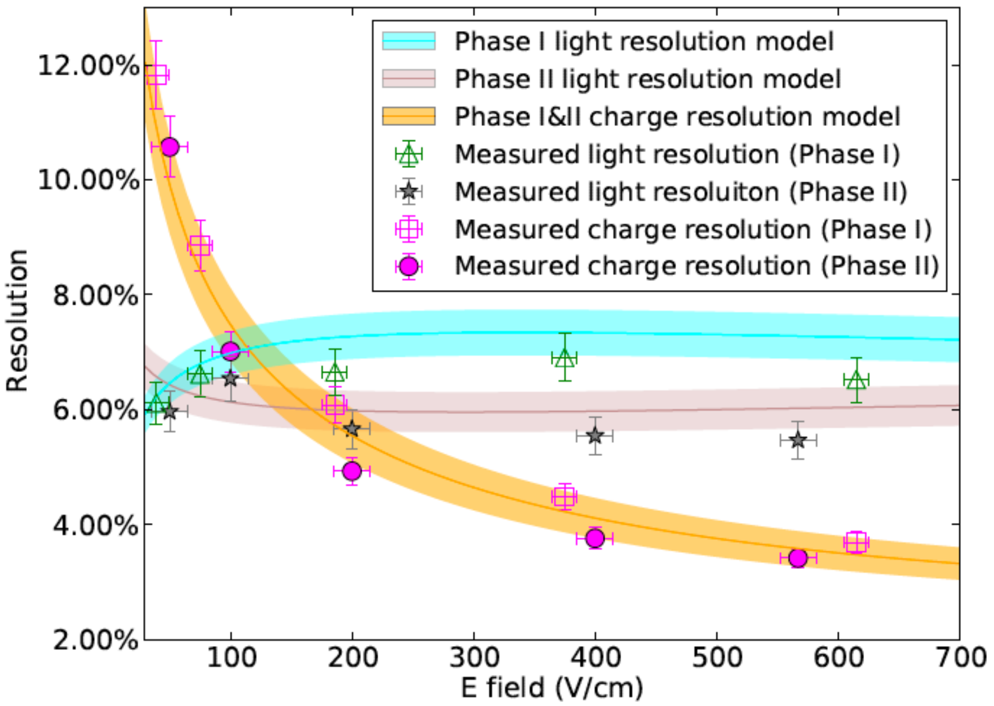
Postdoc - light detection in nEXO

Postdoc - DarkSide Data acquisition

EXO-200. Modeling energy resolution

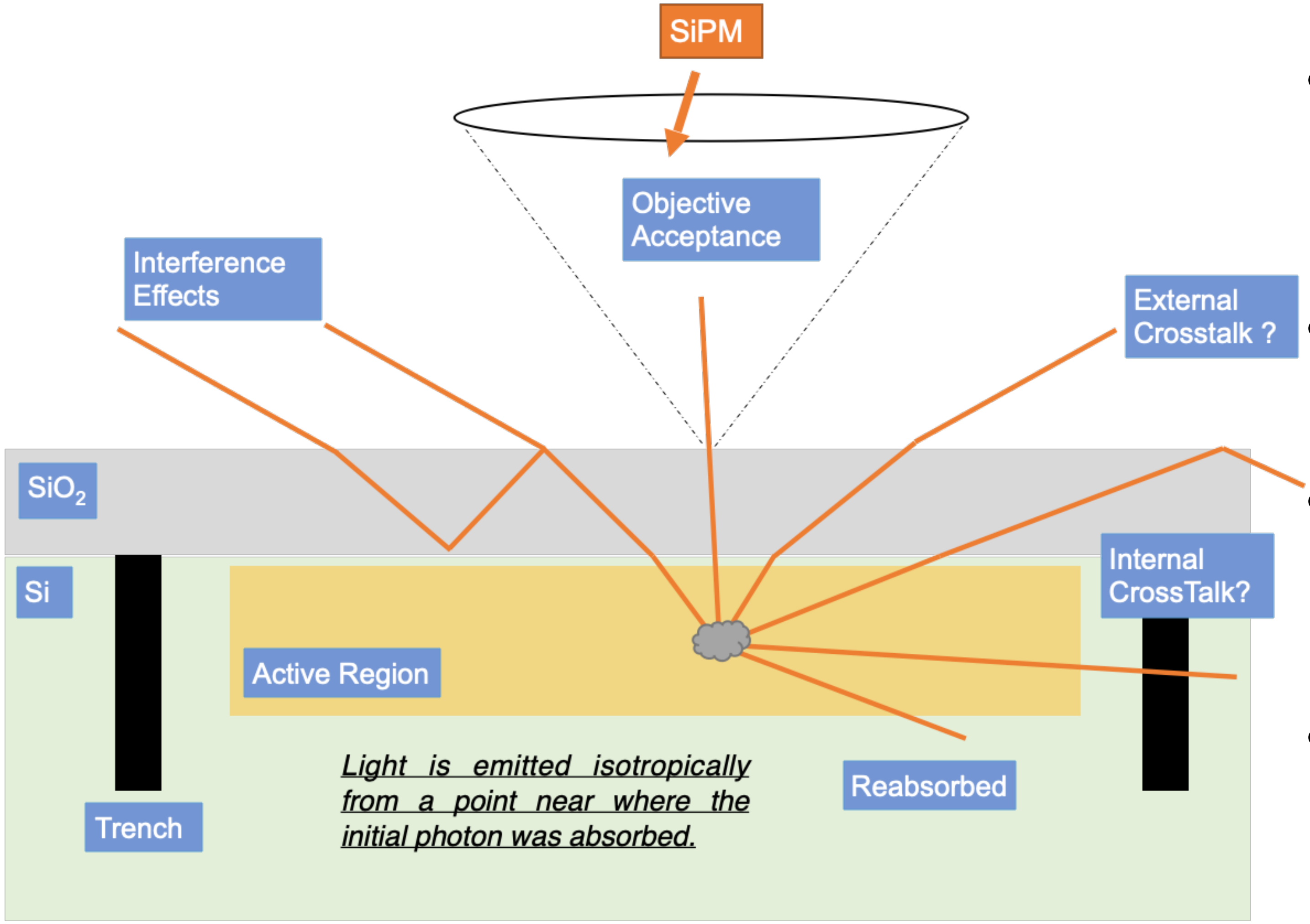
- EXO-200 data shows very strong (98% correlation) between recombination (e- loss) and increase scintillation
- EXO-200 energy resolution dominated by APD electronics noise





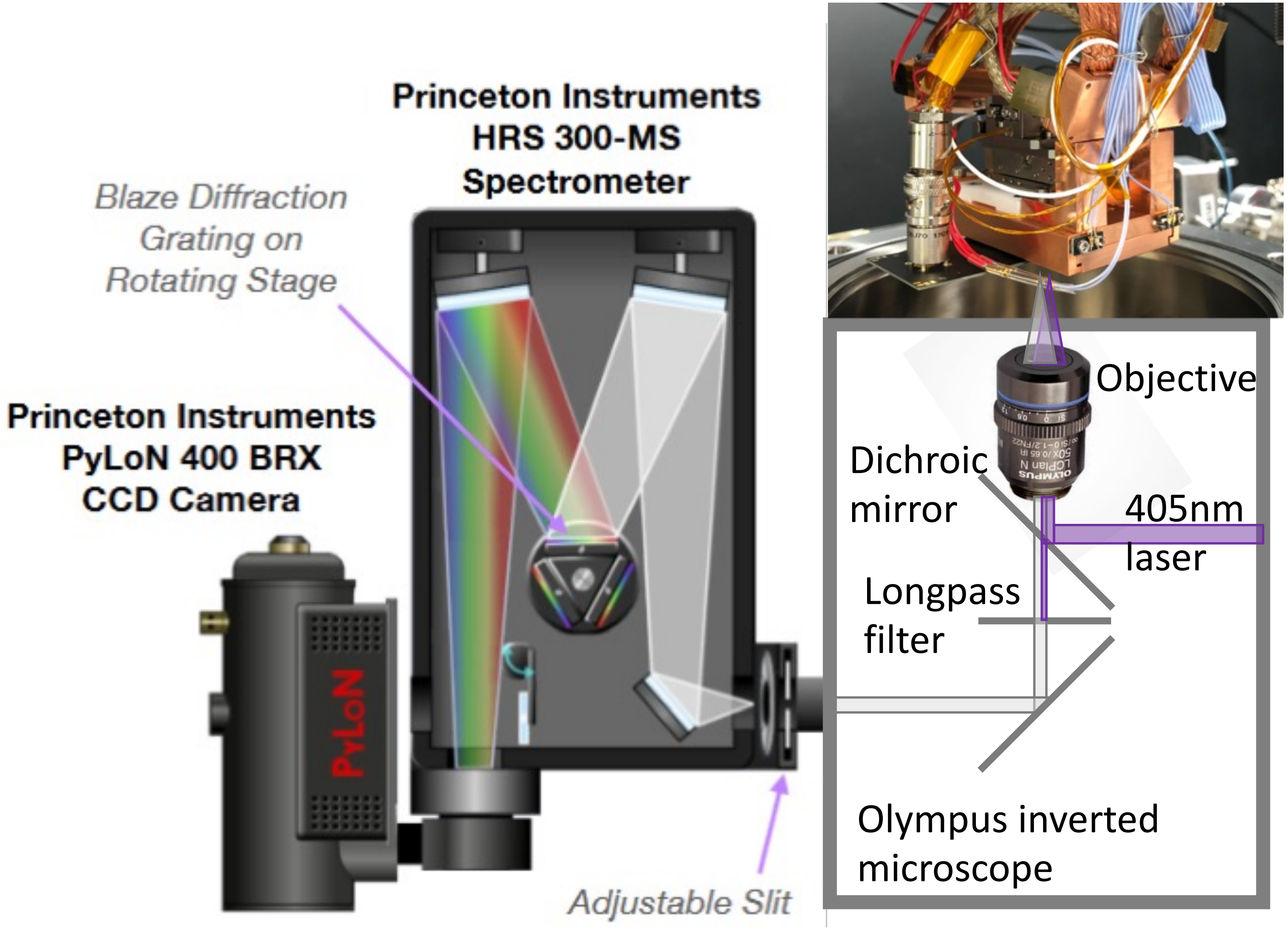
https://arxiv.org/abs/1908.04128 accepted by Phys. Rev. C

Or are they? What about light emission into the detector?



- Light emission assumptions:
  - At p-n junction – maximum field
  - Isotropic
- External cross-talk
  - Photon escaping the SiPM surface
- Internal cross-talk
  - Photons being absorbed in a neighboring SPAD
- We measure photons escaping with objective acceptance

Microscope for the Injection and Emission of Light

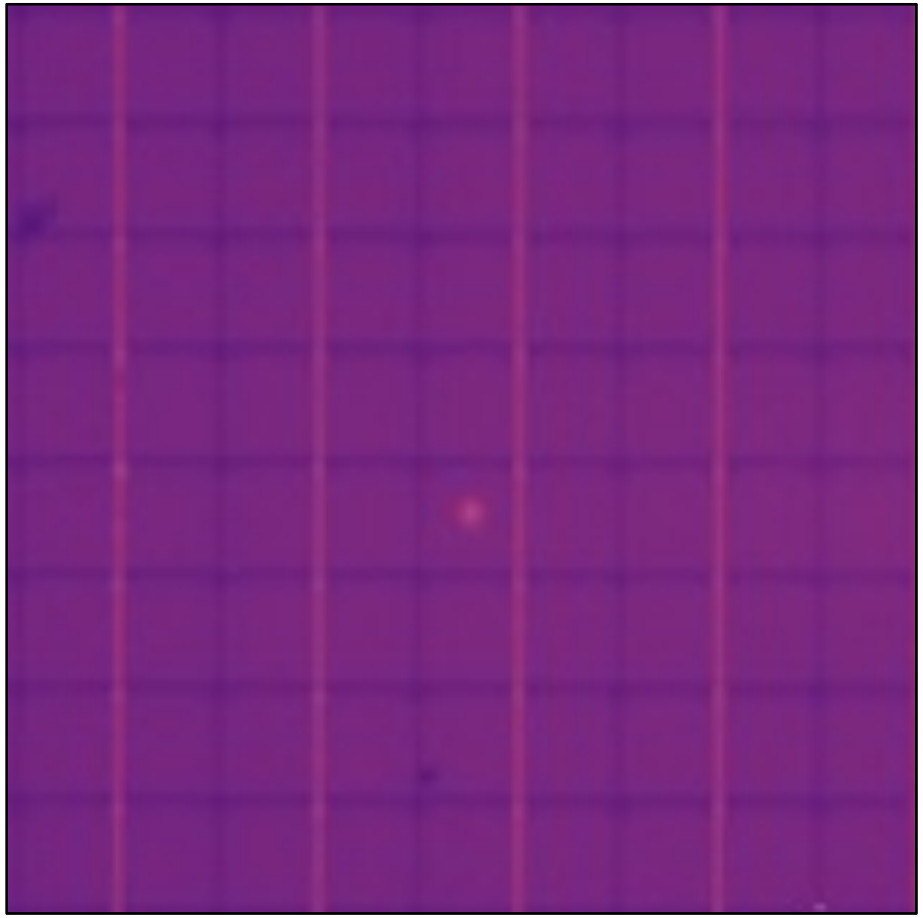


- Cryogenic stage: 80-290K
- Laser injection at 405nm
- Record SiPM signal with waveform digitizer
  - Assess the probability that the laser trigger an avalanche

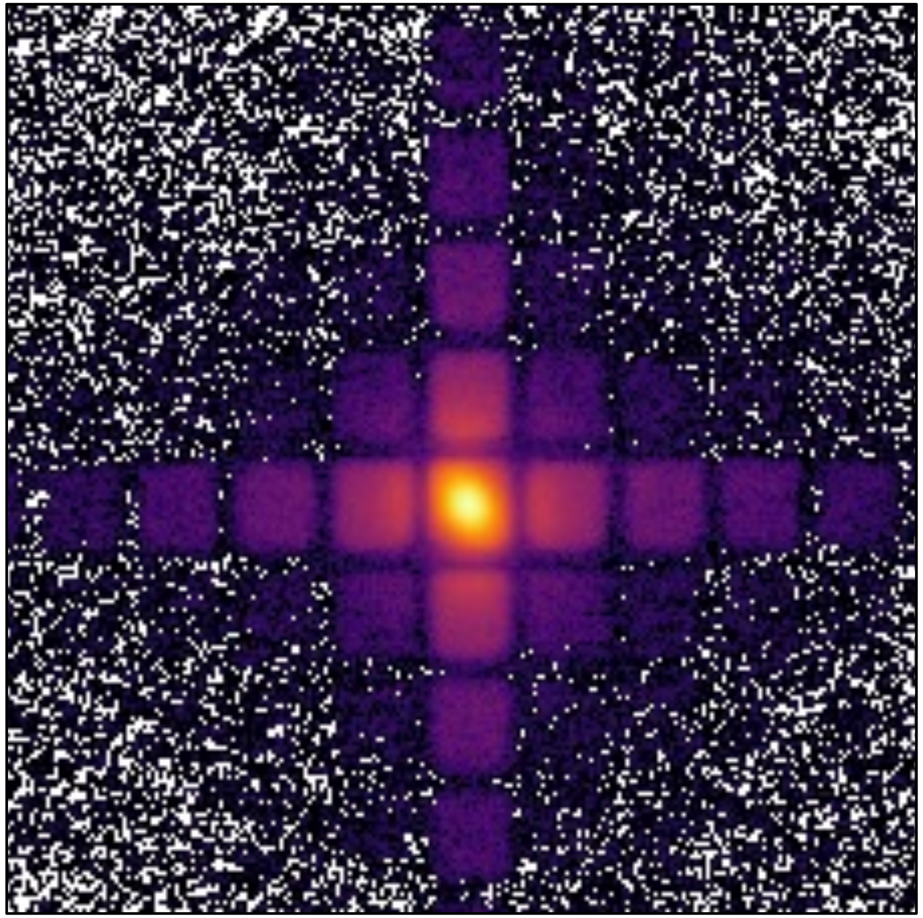
Imaging re-emitted light

FBK VUV-HD3

Reflected light



Re-emitted light



Spectra

Acceptance:
Objective NA=0.45, i.e. $\theta < 26.7°$
Simulation shows that acceptance is about 10% of total