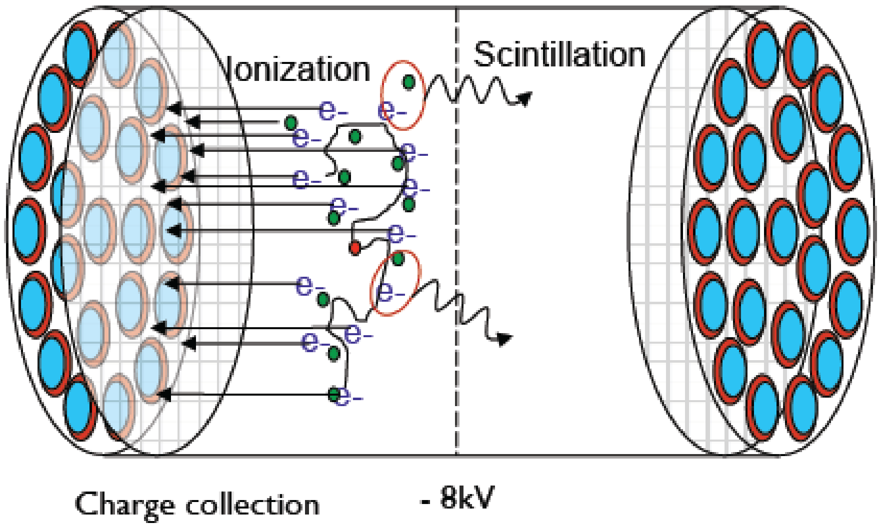
TRIUMF

MPPCs for nEXO

Fabrice Retière for EXO photo-detector group

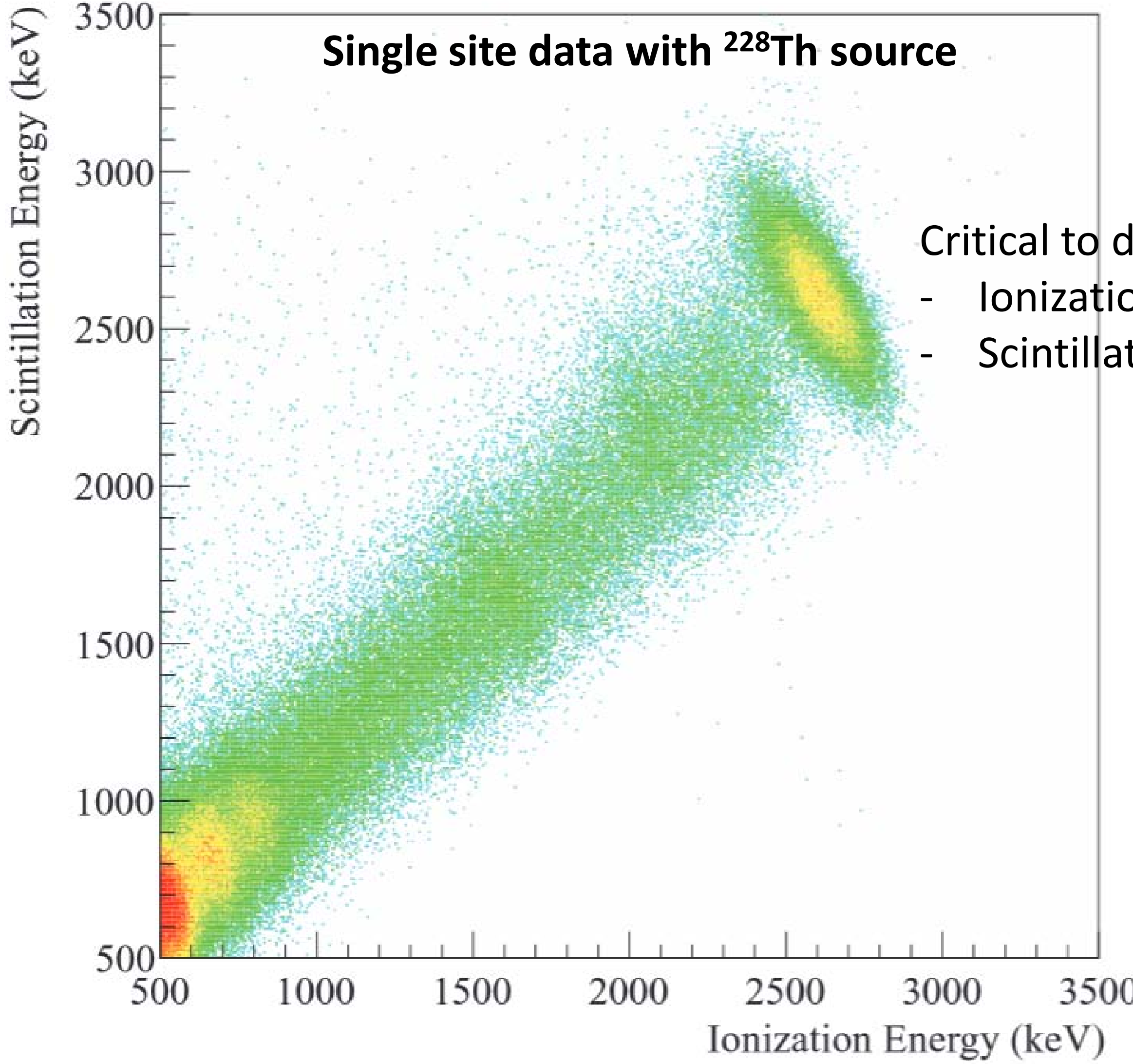
Enriched Xenon Observatory for double beta decay

The EXO concept



- Charge readout
  - 2D position
  - Charge arrival time
  - Energy
- Light readout
  - Timing resolution
  - Event start time
    - No need for good energy resolution
  - Energy

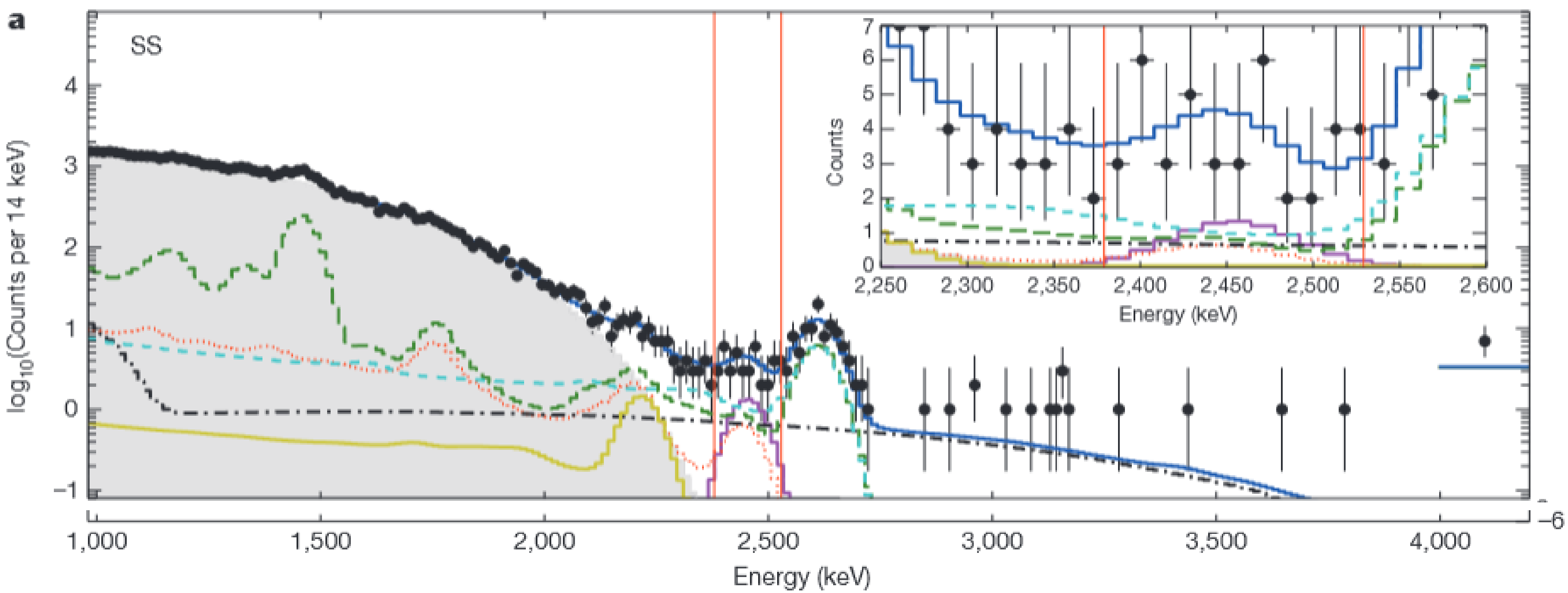
Light/charge fluctuations



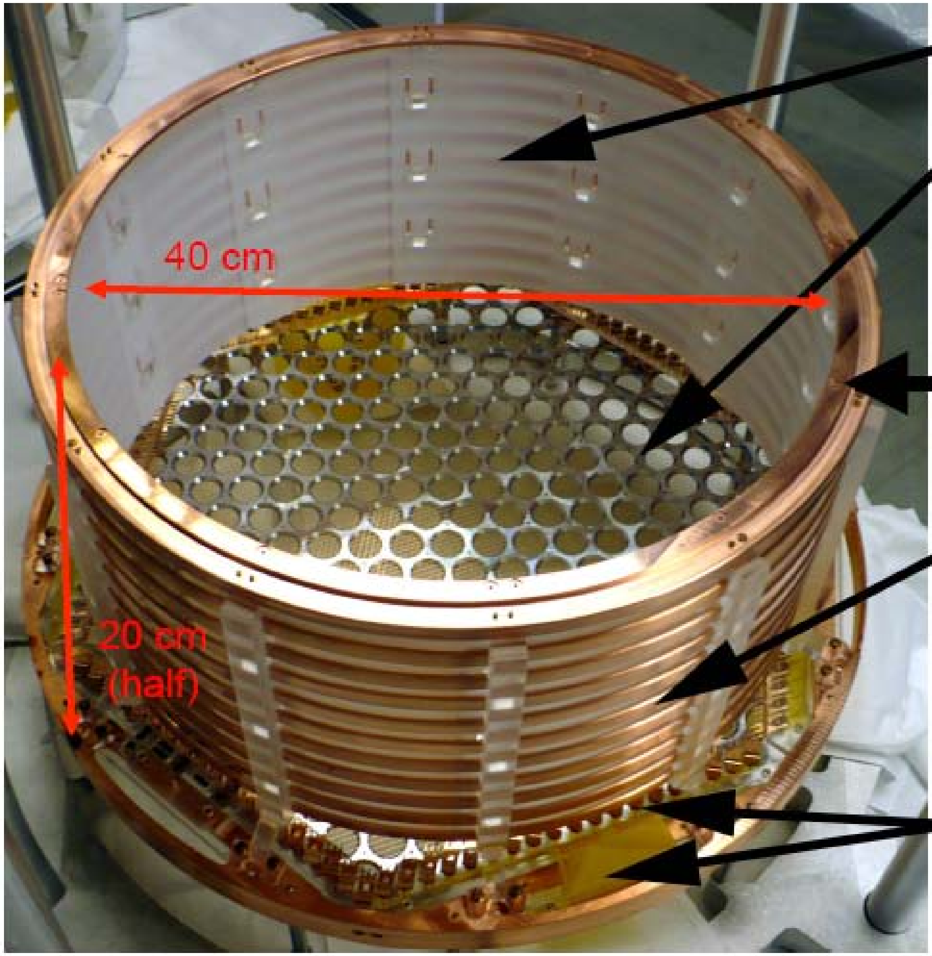
Critical to detect simultaneously
- Ionization electrons
- Scintillation photons at 175nm

EXO-200 looking for 0νββ

- Nature 510, 229–234 (12 June 2014)
- Background reduction:
  - Energy resolution
  - Low radioactivity
  - LXe self shielding an dMulti-site / single-site (does not affect light)



EXO-200



Teflon Reflectors
(increase light collection)

APD plane and wire planes
(wires are photo-etched)

Central HV plane
(photo-etched phosphor bronze)

Acrylic supports
and field
shaping rings

Kapton flex cables
(spring connections
eliminate solder joints
and glue)

Light detection in EXO-200

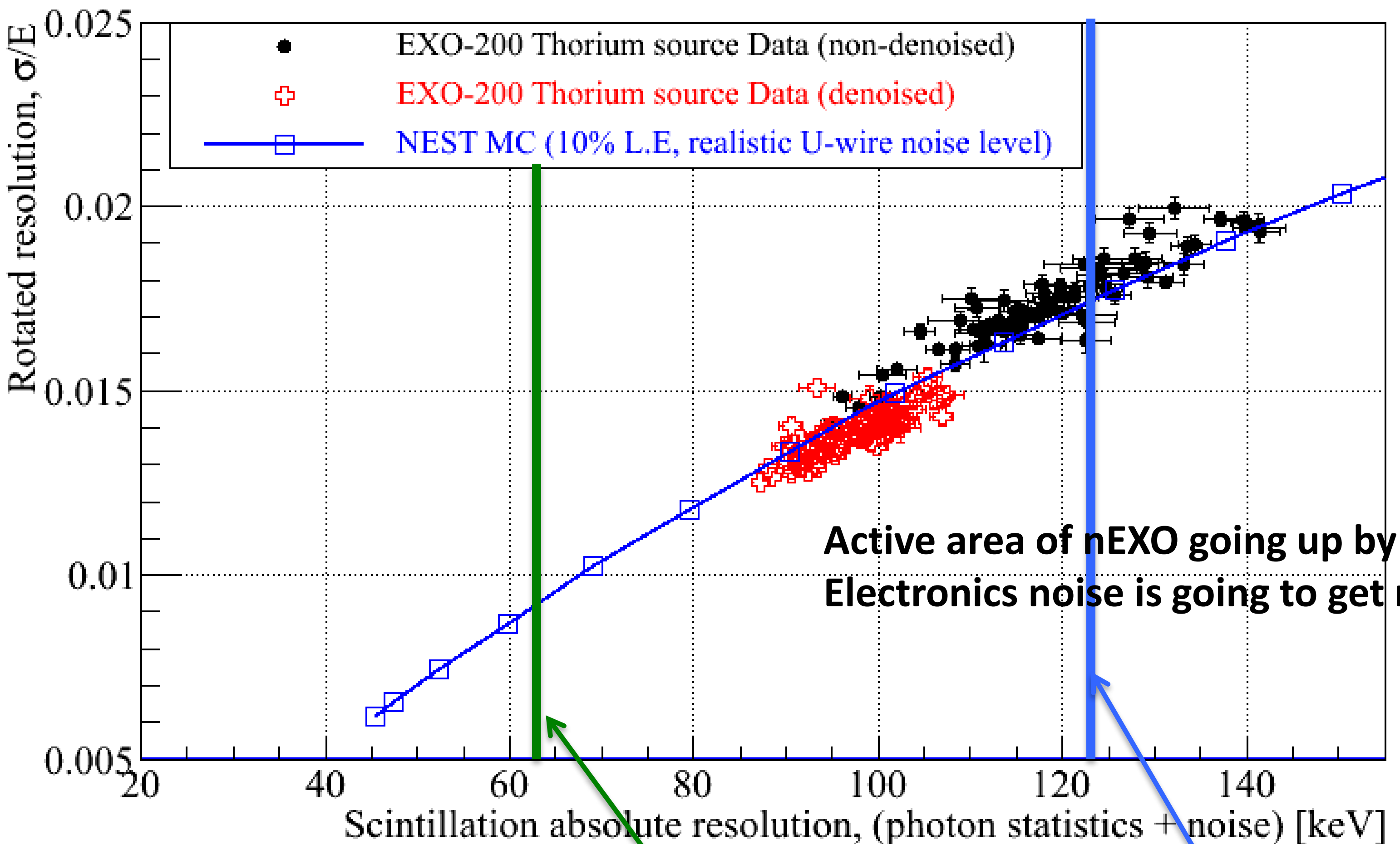
R. Neilson, et al. NIM A 608 (2009) 6875

- very clean & light-weight,
- very sensitive to VUV

QE > 1 at 175nm

Gain set at ~200
V~1500V, ΔV < ±0.5V
ΔT < ±0.1K APD is the driver
for temperature stability
Small Leakage current at LXe Temp.

EXO-200 resolution limited by APD noise



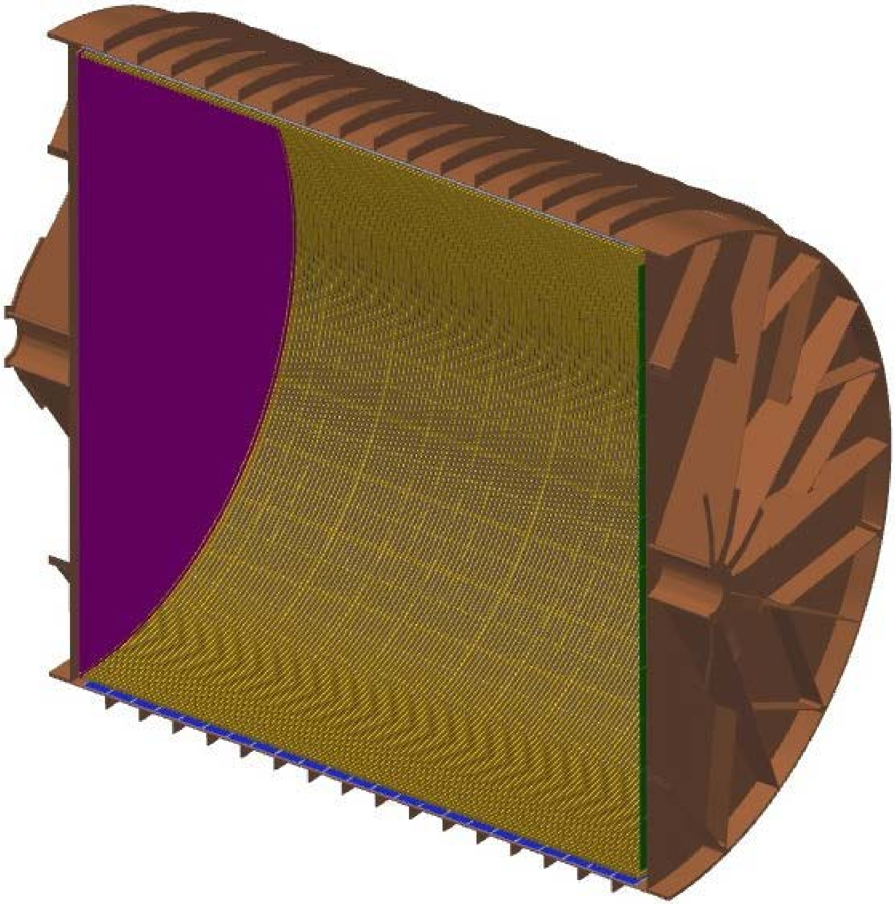
Active area of nEXO going up by more than x10
Electronics noise is going to get much worse...

Expected APD noise after electronics upgrade

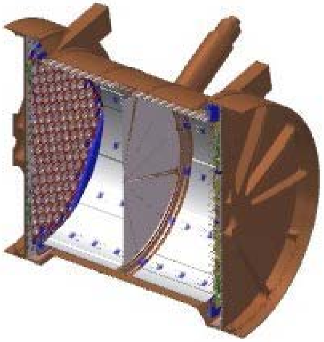
Average APD Noise at WIPP

EXO-200 to nEXO

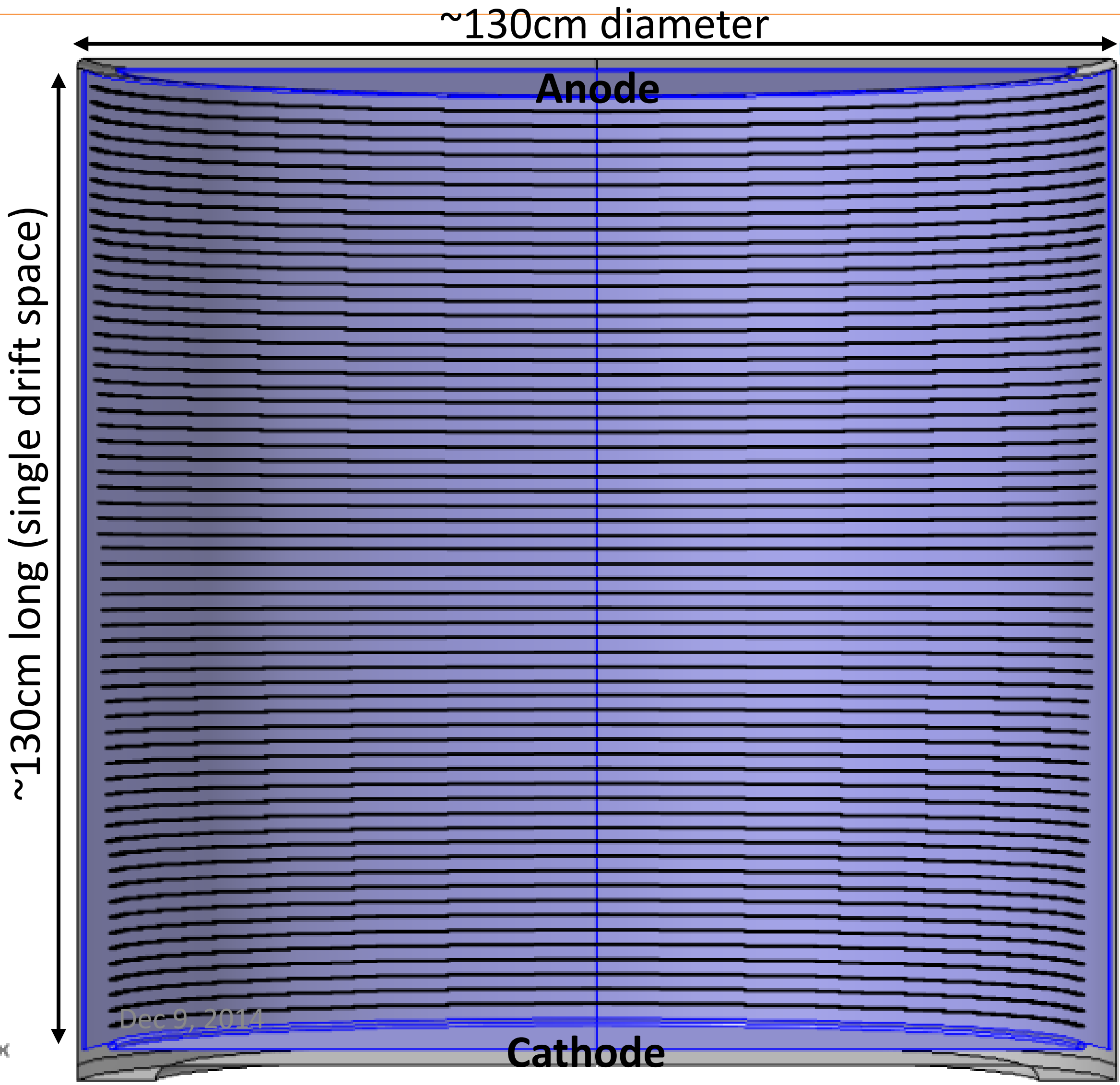
nEXO: at the conceptual stage

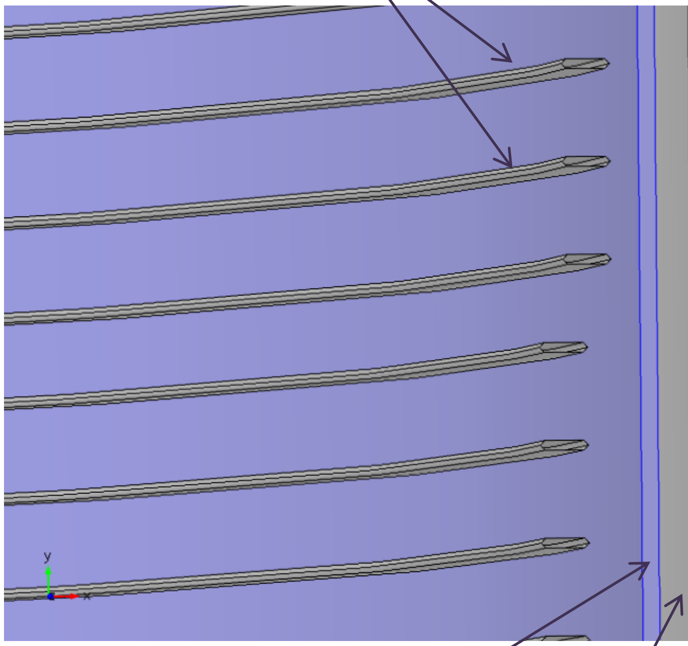


EXO-200 “operating” detector
Two drift regions (central cathode)
Charge collection on anode wires
Light readout by ~500 APDs



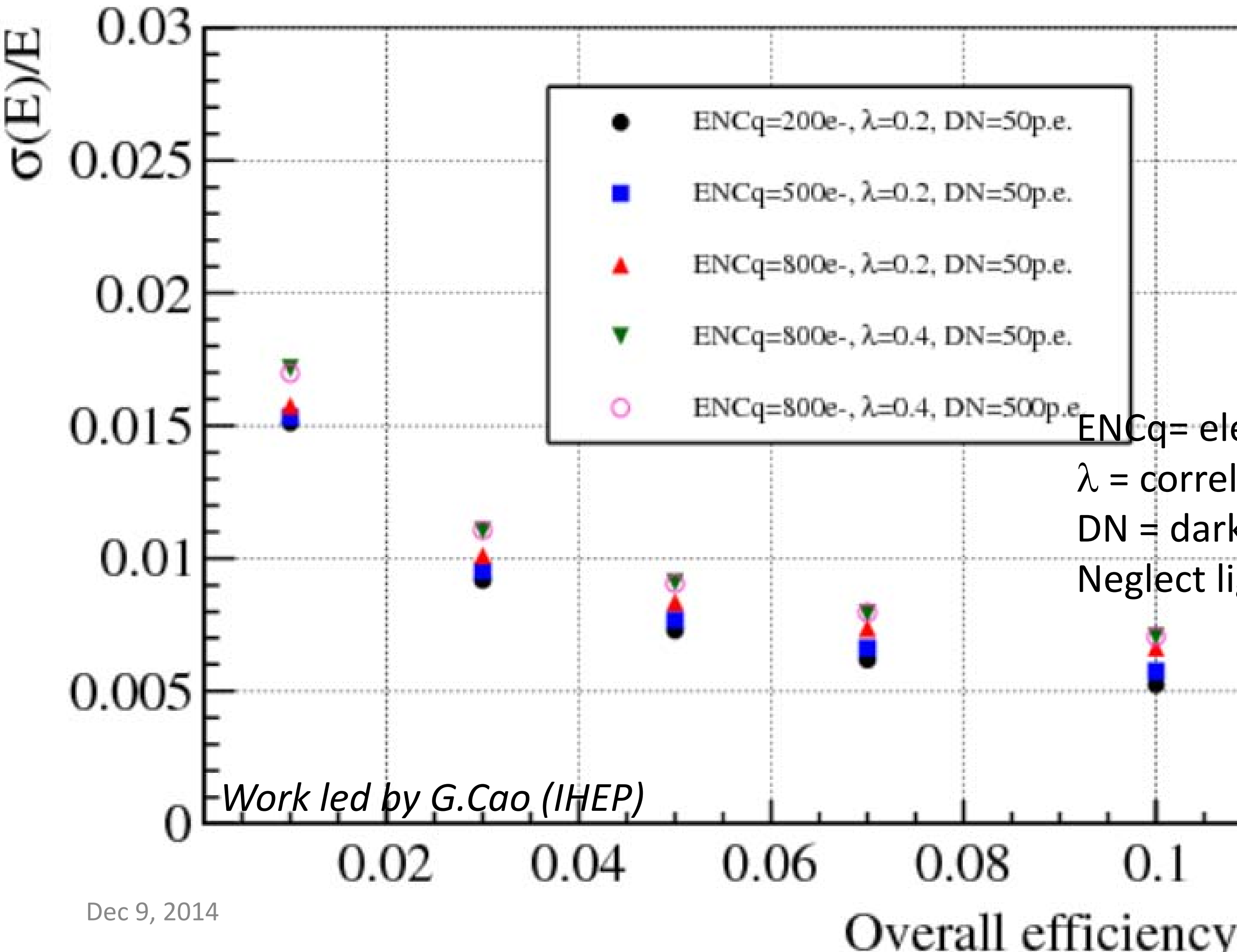
nEXO baseline configuration
Up to 4 m^2 of photo-detectors





Drawing by T.Tolba (Bern)

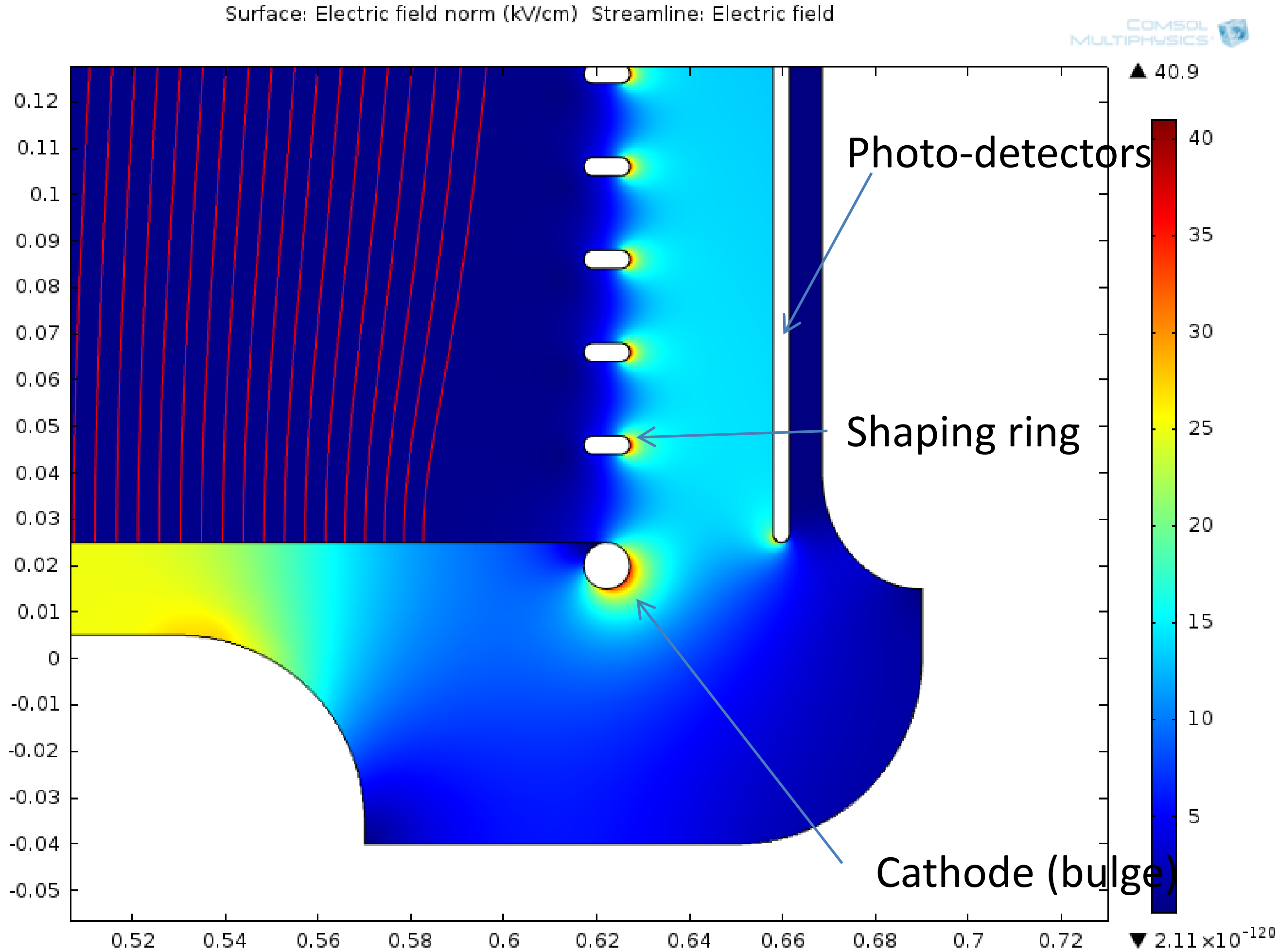
Scintillation photon detection requirements for nEXO



Work led by G.Cao (IHEP)

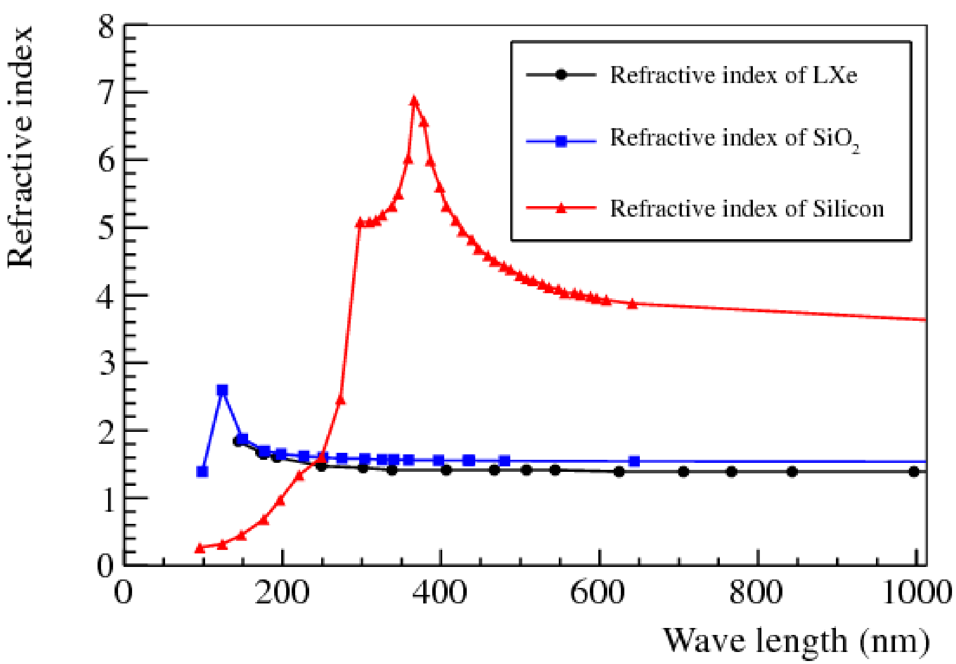
ENCq= electronics noise on charge
λ = correlated avalanche (AP+CT)
DN = dark noise rate
Neglect light electronics noise

Side issues about E-Field
Charge may land on MPPCs



Aside about index of refraction

- $n_{LXe} \sim n_{SiO2} \sim 1.7$
- $Re(n_{Si}) \sim 0.7\text{-}0.8$
  - Surprisingly large uncertainty
- Very significant reflections at Lxe/SiO2-Si
  - Anti-reflective coating with MgF2?
- Reflected photons have a fair chance of being detected later on
  - Account for reflectivity in simulations
- Need careful scaling from measurements in gas/vacuum



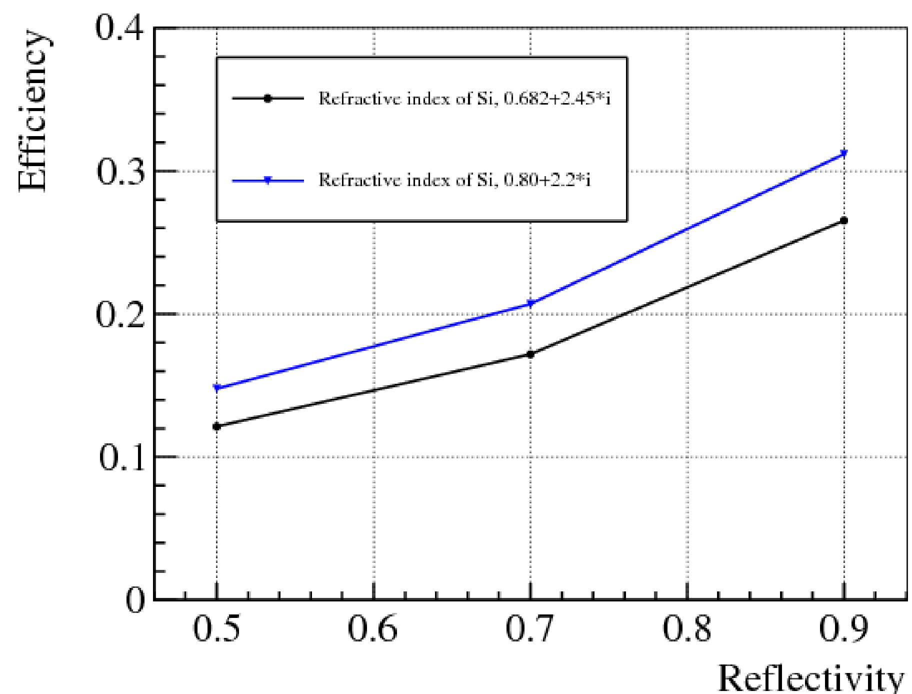
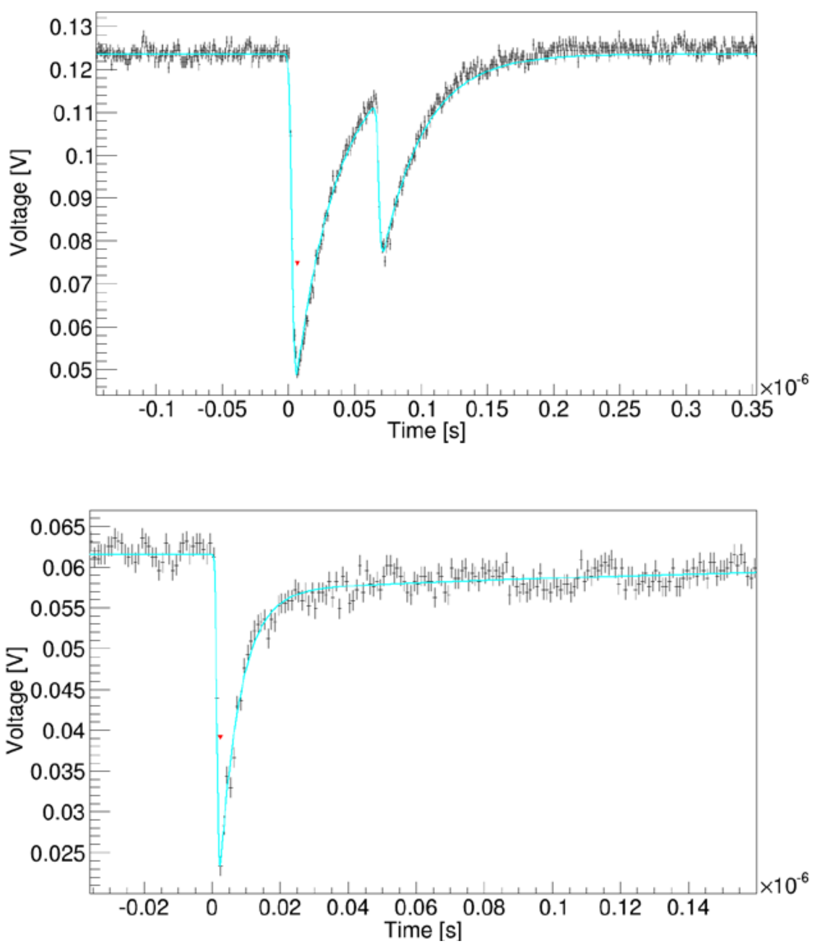


Photo-detector specifications for nEXO

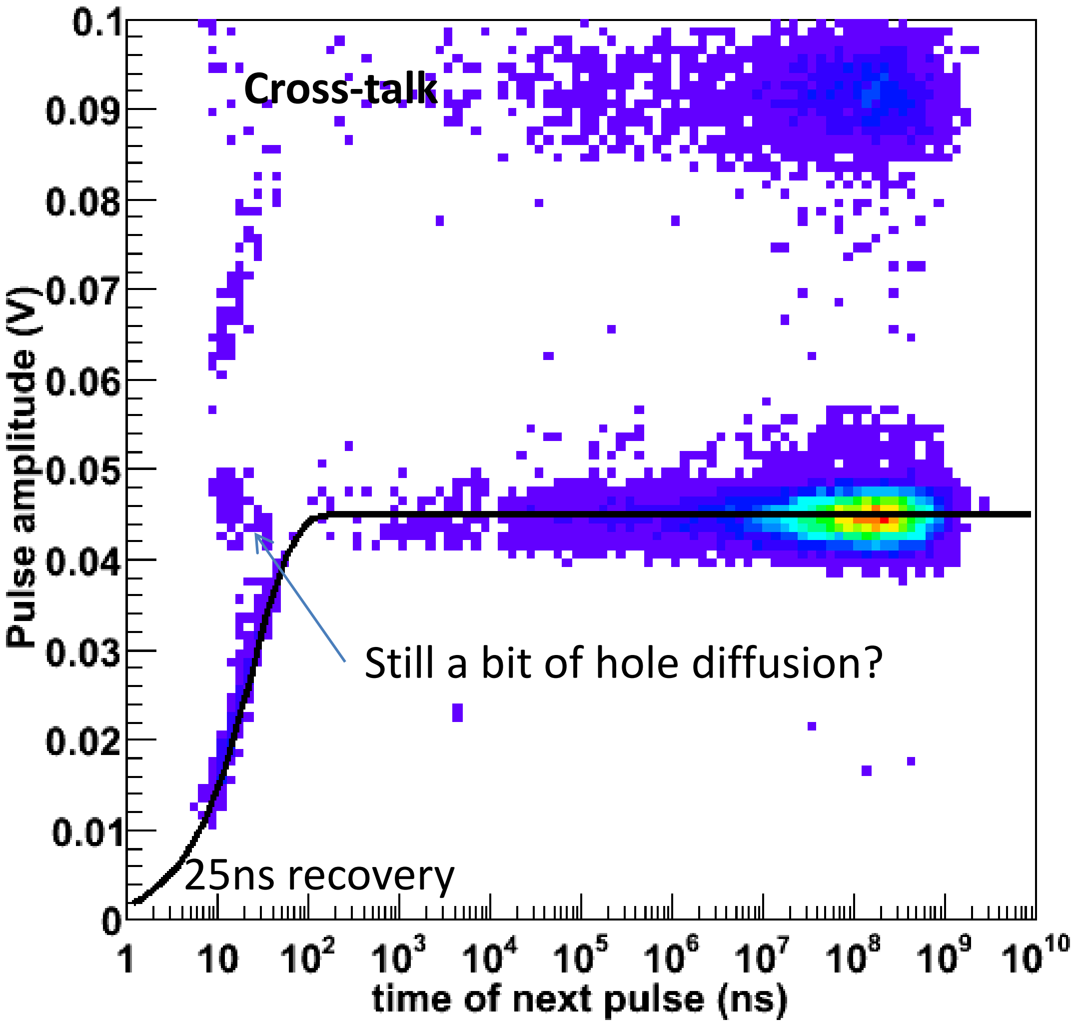
Parameters	Value
Photo-detection efficiency at 175-178nm (without AR coating measured in gas/vacuum)	≥15%
Radiopurity: contribution of photo-detectors to the overall background	<1%
Dark noise rate at -100°C	≤50Hz/mm^2
Average number of correlated avalanches per parent avalanche at -100°C	≤0.2
Single photo-detector active area	≥1cm^2
Capacitance	<50pF/mm^2

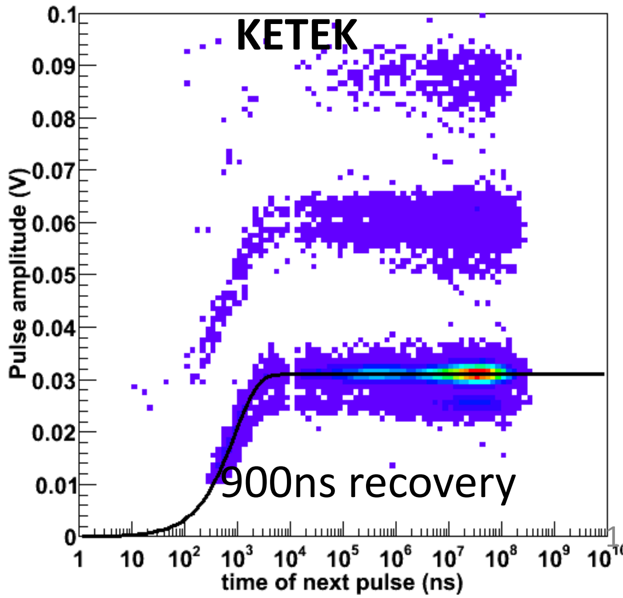
Assessing nuisance parameters TRIUMF test setup



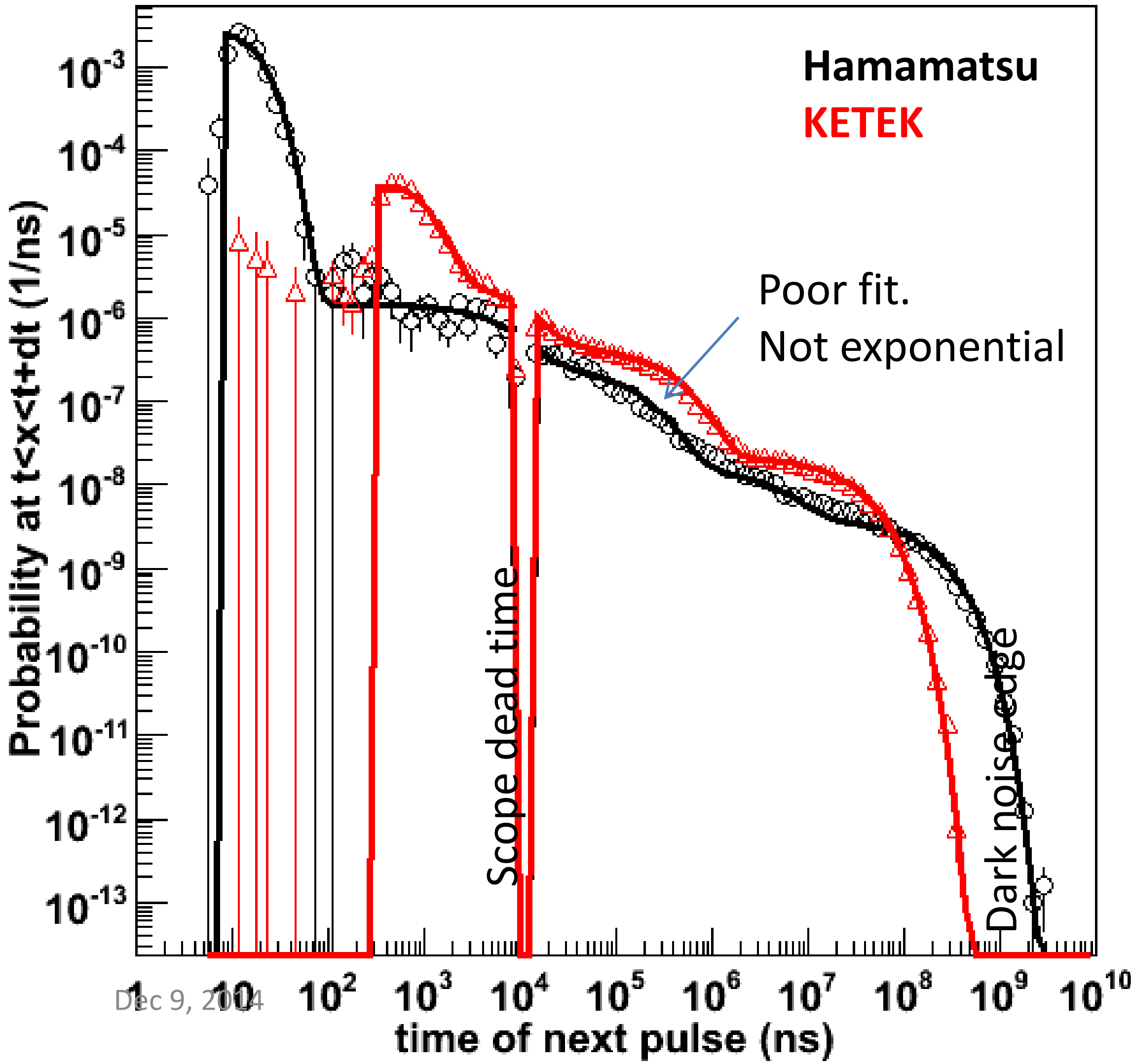
- Control temperature down to -110C
- Trigger on dark noise pulses with threshold ~0.5PE
  - Measure cross-talk as
    - P1 = 1-N1/Ntrig
    - N1 = number of single PE
- Measure all pulses following trigger
  - Fit when pulses are close to each others
  - Use scope time for late pules
  - Built time difference distribution between trigger and next pulse

Amplitude and time after an avalanche





Timing analysis at -100°C



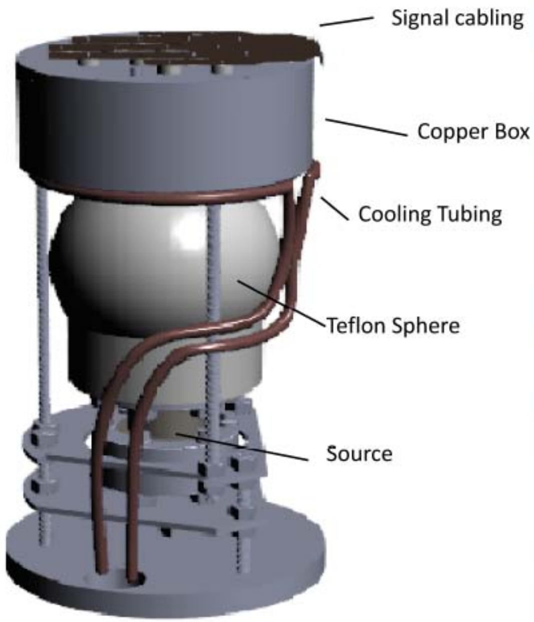
$$P_{AP+ND}(t) = \left(1 - \int_0^t P_{AP}(t')dt'\right) P_{DN}(t) + \left(1 - \int_0^t P_{DN}(t')dt'\right) P_{AP}(t)$$

$$P_{DN}(t) = \frac{1}{\tau} \cdot e^{\frac{-t}{\tau}}$$

$$P_{AP}(t) = \sum_{i=1}^{n} \frac{P_{ap}}{\tau_i} \cdot e^{\frac{-t}{\tau_i}} \cdot (1 - e^{\frac{-t}{\tau_{Rec}}})$$

Dark noise edge yields ~0.5Hz/mm2
But some not so clear issue with long time constants
Short AP time constant ~2% probability

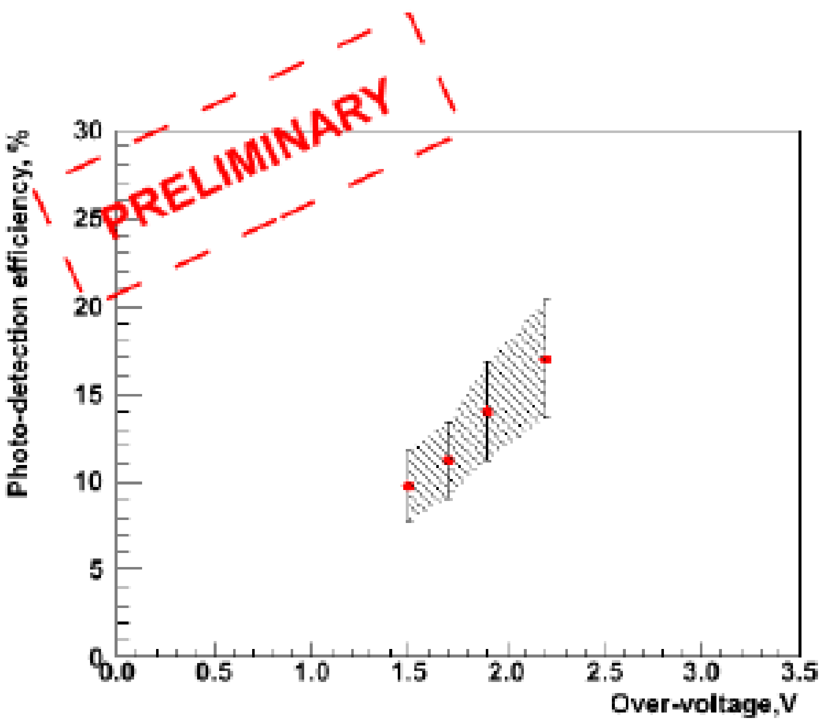
Efficiency measurement at Stanford



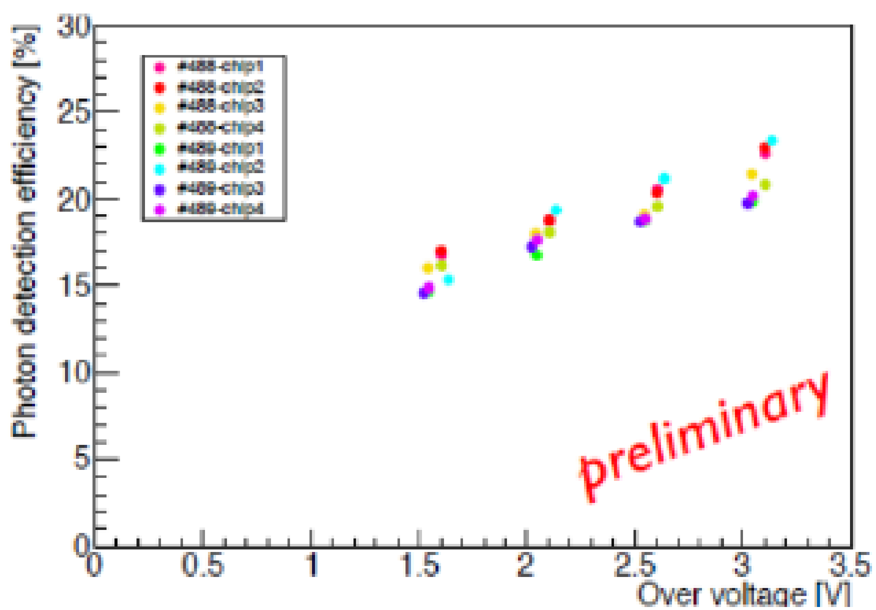
- In vaccum
- Light source: Xe gas scintillation
- Liquid nitrogen cooler
- Use reference Rxxx PMT for light yield calibration

Efficiency measurement at Stanford

This measurement



From the W.Ootani's talk at NDIP-2014



Low radioactivity issue

- Hoping to have the photo-detectors contribute less than 1% of total background
  - ^{238}U and ^{232}Th are <9mBq/kg (<0.73pg/g) and <43mBq/kg (<10pg/g)
  - Impossible to measure by counting: 1kg of material yield 1 count in 30h.
- Assaying either by neutron activation in a reactor or Inductively Coupled Plasma Mass spectrometry
  - Measure content of stable isotopes and assume equilibrium
  - Assaying must happen in parallel with device characterization
- Low radioactivity packaging: looking at bounding Silicon chip on quartz plates

Low radioactivity packaging

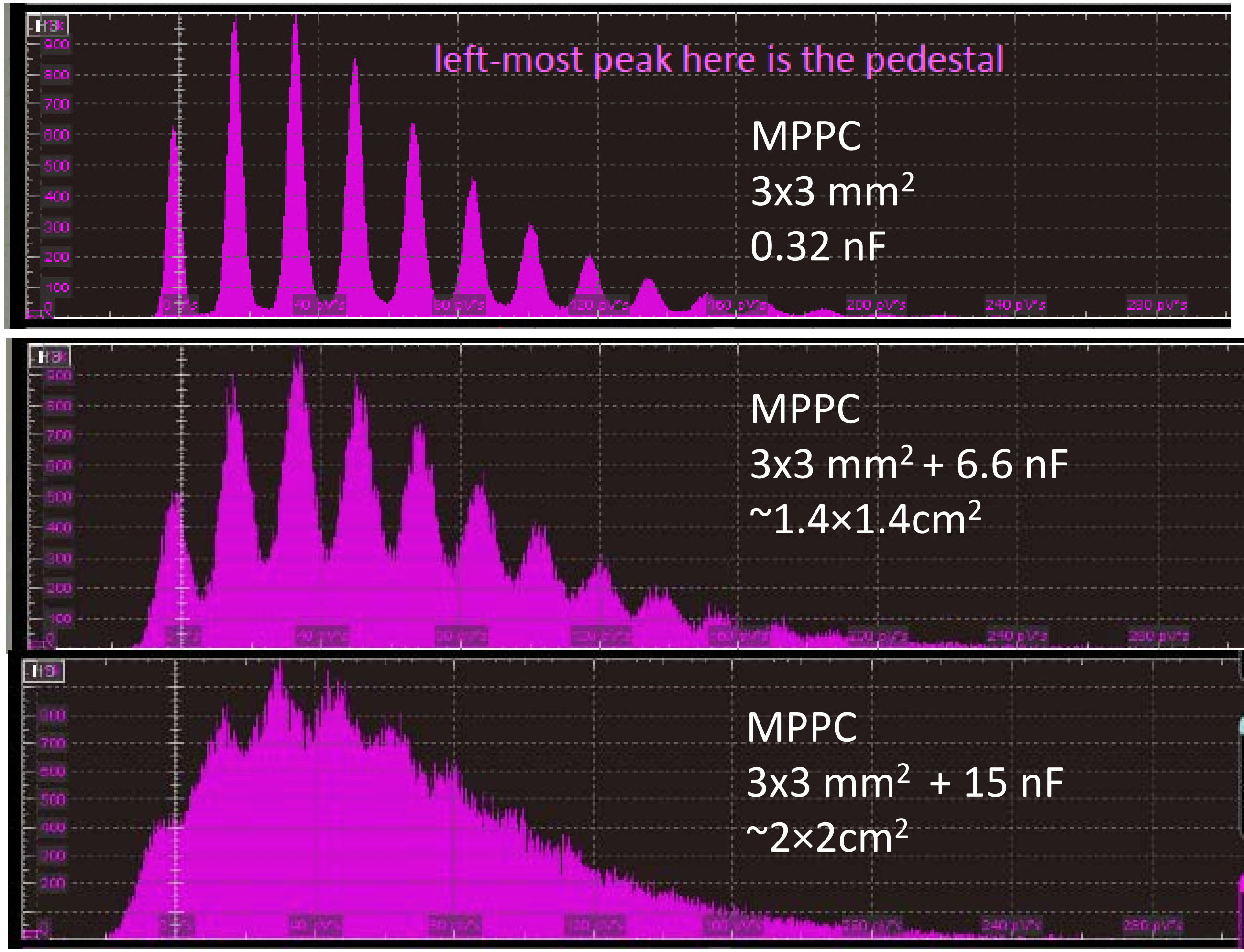
- nEXO requirements are extremely low
  - Much lower than dark matter experiments
- Strategy:
  - Use as little material as possible
    - E.g. Mount MPPCs directly on Photo-detector Readout Board. I.e. Without carrier board. Make testing very cumbersome however
  - Assay every single pieces of material
    - EXO would like to assay raw materials (e.g wire bound, epoxy) before they get used in the final product
      - Assay a sample of silicon before packaging
  - Use Nuclear Activation for Enhanced sensitivity

Low radioactivity material

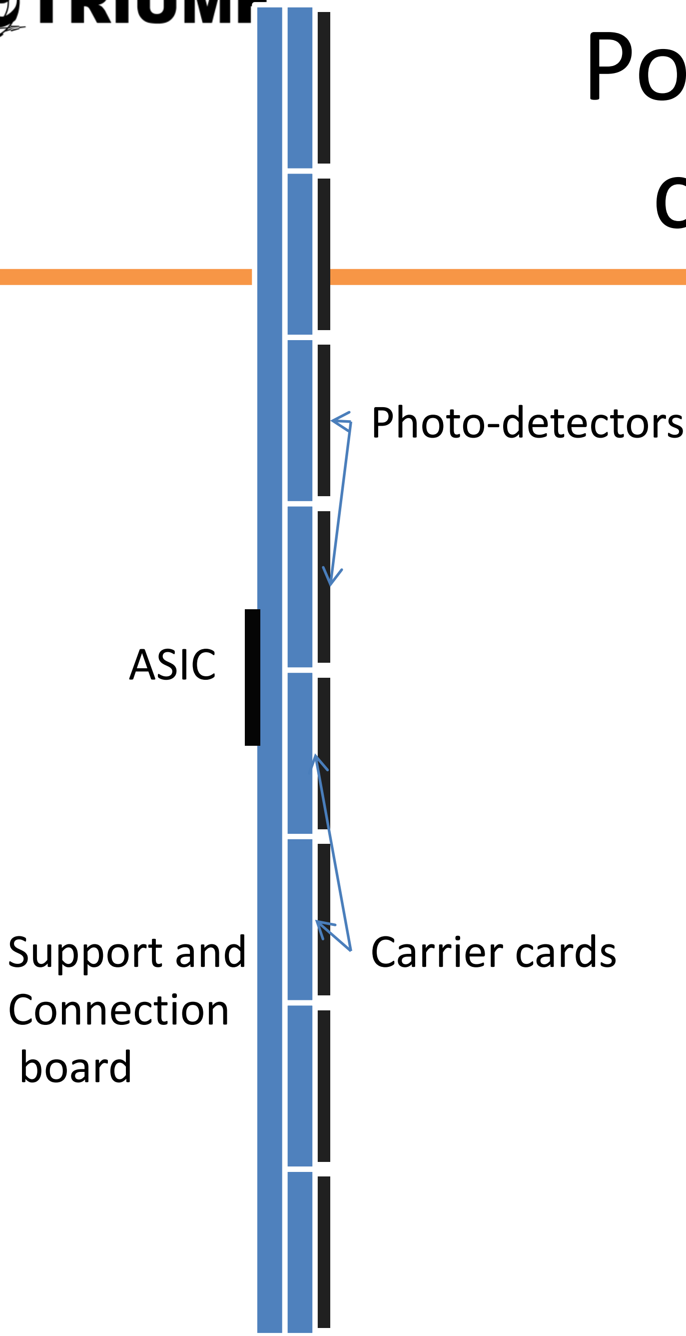
- Silicon is expected to be fine
  - Though, may depend on details...
- Wire bound. Little material. Probably ok
- Epoxy. Little material. Probably ok
  - Some Epoxies were found to be acceptable in EXO-200
    - Electrically conductive epoxies have not be tested though
  - Also possible issue with contamination of the liquid Xenon
- Carrier board material. Significant amount of material (more than Silicon) so risky
  - EXO currently investigating using quark or Saphire
- Metal for electrical connection
  - Some copper has very low radioactivity. Can be provided by nEXO
- Solder for board to board connections
  - Can be very radioactive and should be avoided as much as possible
- Other possible materials: optical thin films, window in front of the MPPC will have to be assayed

Large area readout issues

- PD area~4m2
- # channel~ 100-10,000
- Channel area up to 20×20cm^2
- Common base option may work
  - Single photon identification compromise with >10nF
- Total power < 50W

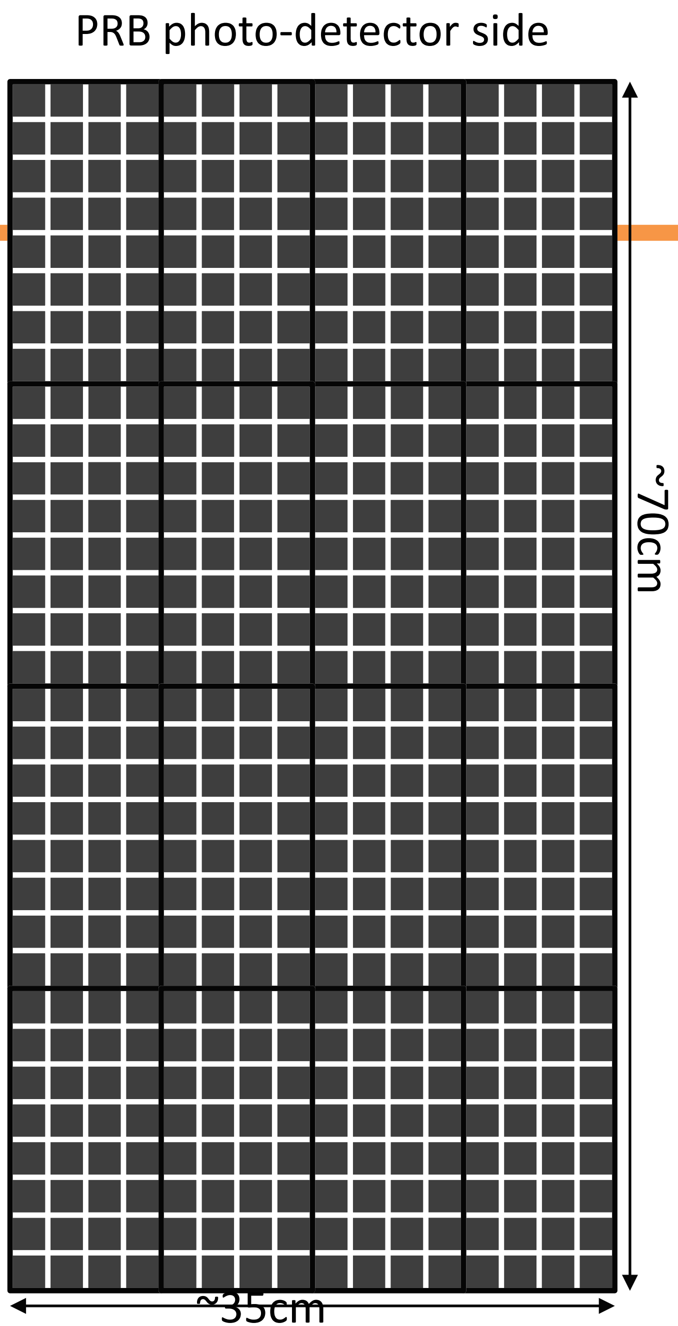


Possible readout configuration



- Photo-detectors
  - $2 \times 2 cm^2$
- Carrier card
  - Holding photo-detector
    - May not be needed
  - $2.2 \times 2.2 cm^2$
- Support and connection board
  - 16 readout ASICs on the back side
  - All connections on the back side

Possible configuration 2



- 16 ASICs per photo-detector readout boards (PRB)
- 1 coincidence unit per PRB and possibly ADC and timing capabilities
- Would require ~24 PRBs
  - x2 segmentation in z
  - x12 in azimuth
- Total number of photo-detectors

Note that the numbers don't fully add-up accounting for nEXO's current baseline geometry. But it does not matter right now.

MPPC configuration

- Area requirement 4 to 5 cm^2
  - Based on 3x3 mm2 devices
    - 8x8 matrix = 2.4x2.4 = 5.76 cm^2 (need ~10,000 in that case)
    - 7x7 matrix = 2.1x2.1 = 4.41 cm^2
    - 6x6 matrix = 1.8x1.8 = 3.24 cm^2
  - Or possibly on different sizes
- Desirable to connect all the MPPCs on the silicon to minimize connections
  - The question is whether or not to have some MPPCs in series vs parallel
    - One option: 4x4 matrix of 6x6mm2 (or 8x8 of 3x3mm2) making 4 groups of MPPCs connected in parallel (either 4 6x6mm2 or 16 3x3mm2) and then connect the 4 groups in series
    - Or for better uniformity connect first in series 4 6x6 mm2 (or 16 3x3mm2) and then connect in parallel.

Using MEG MPPC for development

- Investigate series vs parallel solution using MEG MPPCs at TRIUMF
  - PCB holding the MPPC must fit on the cold chuck

Cold board
1 MEG MPPC

Analog board
Schematics: L. Fabris, ORNL
Layout: M. Constalbles, TRIUMF?

Test performances with
-1 6x6mm2
- 4 6x6mm2 in series
- 4 6x6mm2 in parallel

Cold board
4 MEG MPPCs

Analog board
Schematics: L. Fabris, ORNL
Layout: M. Constalbles, TRIUMF

Test performances with
-16 6x6mm2 in parallel
- 4 6x6mm2 in series then parallel
- 4 6x6mm2 in parallel then series

The current landscape

Parameters	Spec.	FBK-2010	HPK	KETEK	SensL
Over-voltage	N/A	5V	2.5V	2.5V	
PDE at 175nm (%)	>15%	10^{S}	17^{S} , 19^{M}	0	0
Dark noise rate at -100C (Hz/mm^2)	<50	$10^{3\ S}$	0.5^{T}	4^{T}	?
Cross-talk probability		0.06^{S}	0.34^{T}	0.1^{T}	?
Total after-pulsing rate at -100C		?	0.16^{T}	0.25^{T}	?
Xt+AP within 10 μs at -100C	<0.2	?	0.38^{T}	0.15^{T}	?
Recovery time		?	25ns^{T}	900ns^{T}	?
Pulse rise time (Gaussian σ)		?	1.6ns^{T}	0.5ns^{T}	?
Pulse fall time(s) (exp. constant)		?	30ns^{T}	6/300ns^{T}	?
Capacitance (pF/mm^2)	<50	330	35	100	80 / 3.2
Thorium content (μBq/kg)	< 43	<13 ^{A}	?	?	<2 $10^{6\ N}$
Uranium content (μBq/kg)	< 9	<2.5 $10^{2\ A}$	?	?	<94 $10^{6\ N}$
Potassium content (μBq/kg)	?	<1.4 $10^{2\ A}$	?	?	<4.7 $10^{6\ N}$

^{S} Measured at Stanford, ^{T} Measured at TRIUMF, ^{A} measured at U.Alabama with neutron activation
^{M} Measured by the MEG collaboration, ^{N} measured by the NEXT collaboration by Ge counting

Summary

- Hamamatsu MPPCs are very well suited for nEXO if 2 issues can be addressed
  - Lower cross-talk with trenches. Easy?
  - Find a way to achieve the required extremely low radioactivity... Hard?
- Would be nice add-ons:
  - Increase efficiency using anti-reflective coating. Possible?
  - Lower capacitance per unit area. Possible?

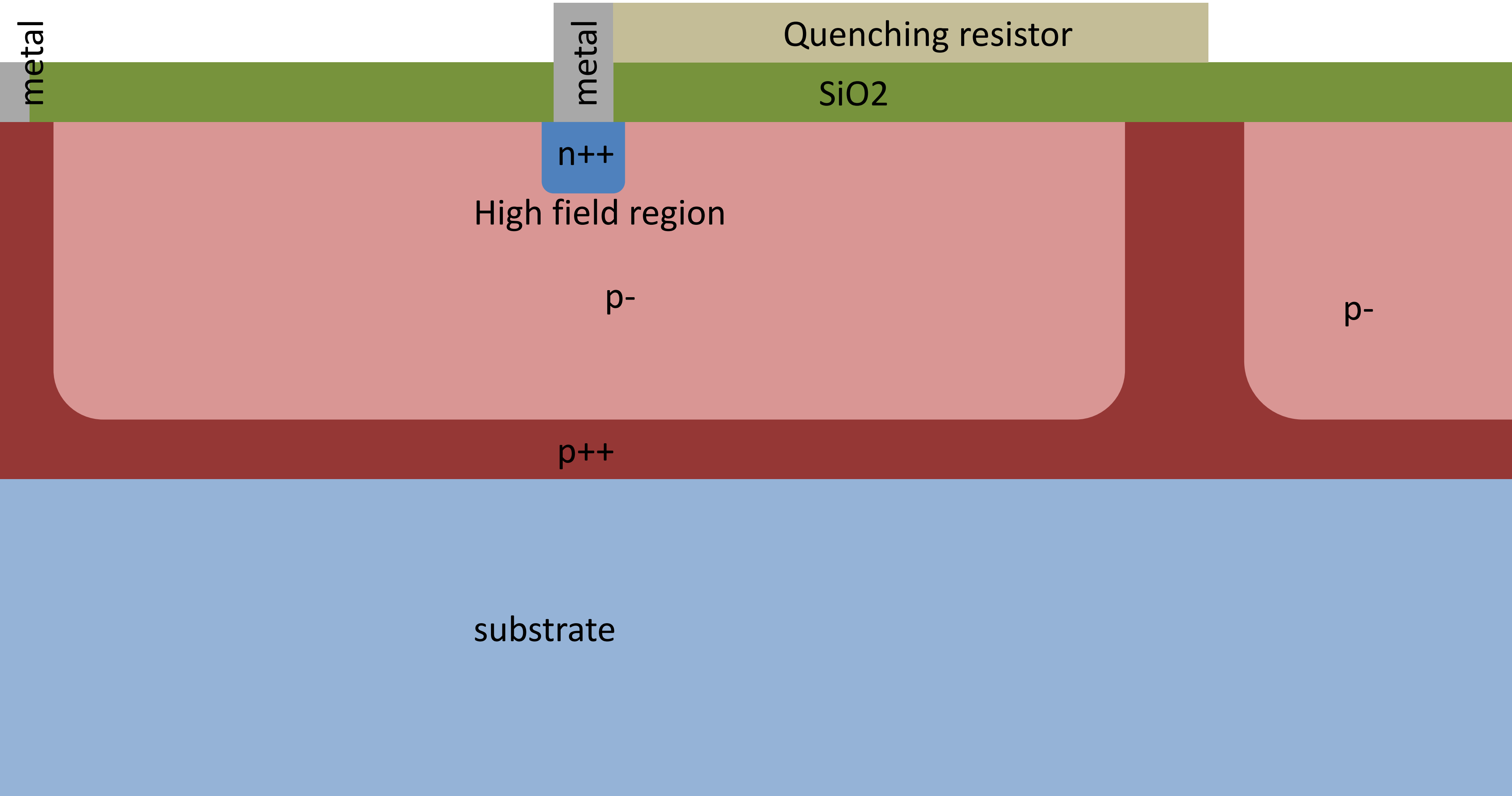
Time scale

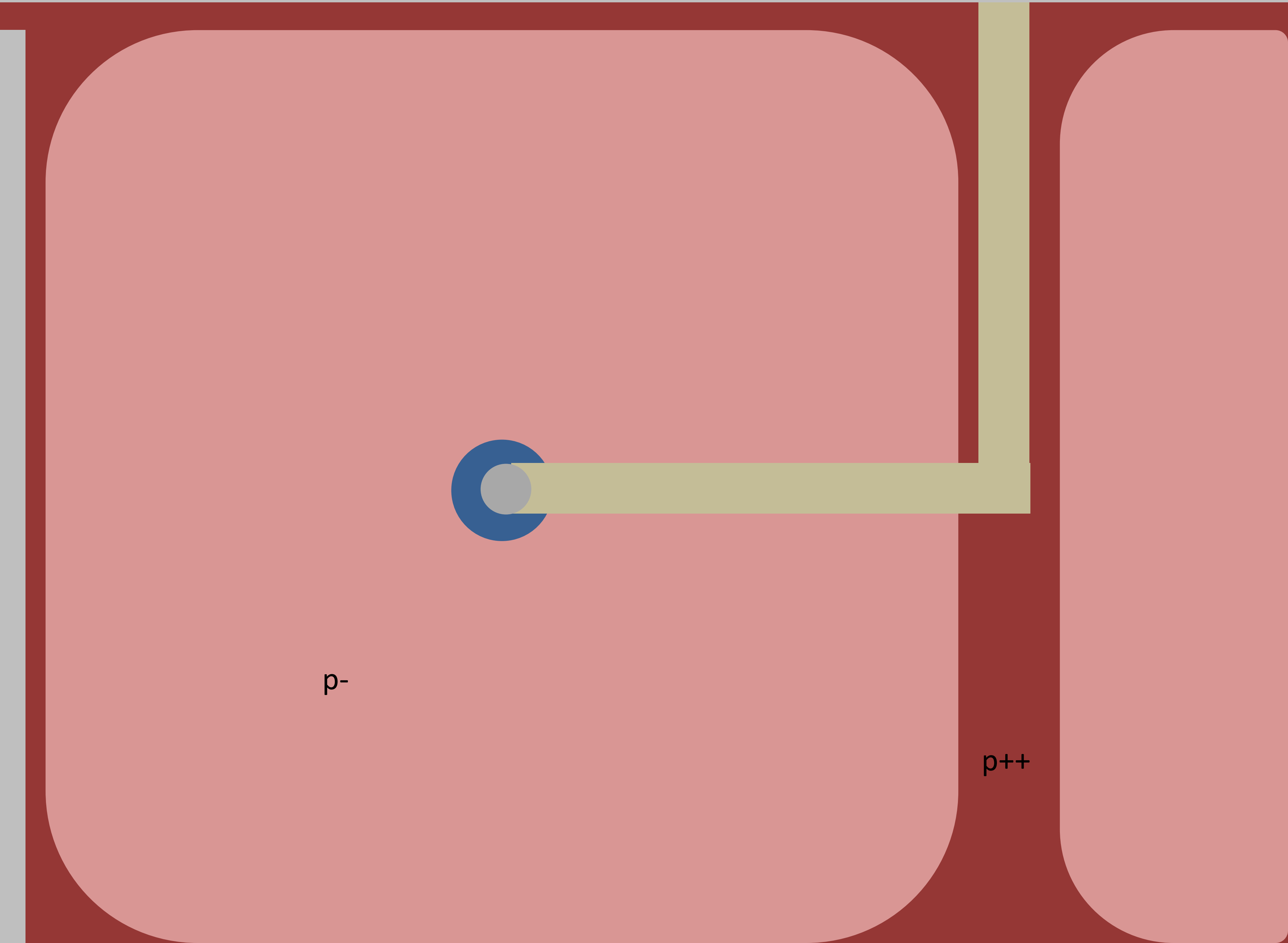
- Identify compelling photo-detector(s) by the end of 2016
- Build a small scale (10x10x10cm3) demonstrator by early 2017
- Down-select by DOE in 2016 or 2017
  - Chose technology, i.e. Germanium or Xenon
- Construction starting in 2017 or 2018

Add-on

Low capacitance SiPM concept

- Motivations
  - Lower electronics noise. Can live with lower gain
  - Less gain: reduce correlated avalanche rate
    - Maintain same peak current which to first order is defined by $\Delta V/R_{quench}$. Peak current is critical for good timing
  - Narrow pulse. Fall time ~ R_{quench} x Cpix
- Idea
  - "Point" contact diode
  - Need electric field to drift carrier to point contact
  - Impact ionization only occurs close to point contact
  - Single carrier detection (e- prefered)
  - Block carriers from substrate from reaching the drift field region


metal
metal
Quenching resistor
SiO2
n++
High field region
p-
p-
p++
substrate


p-
p++