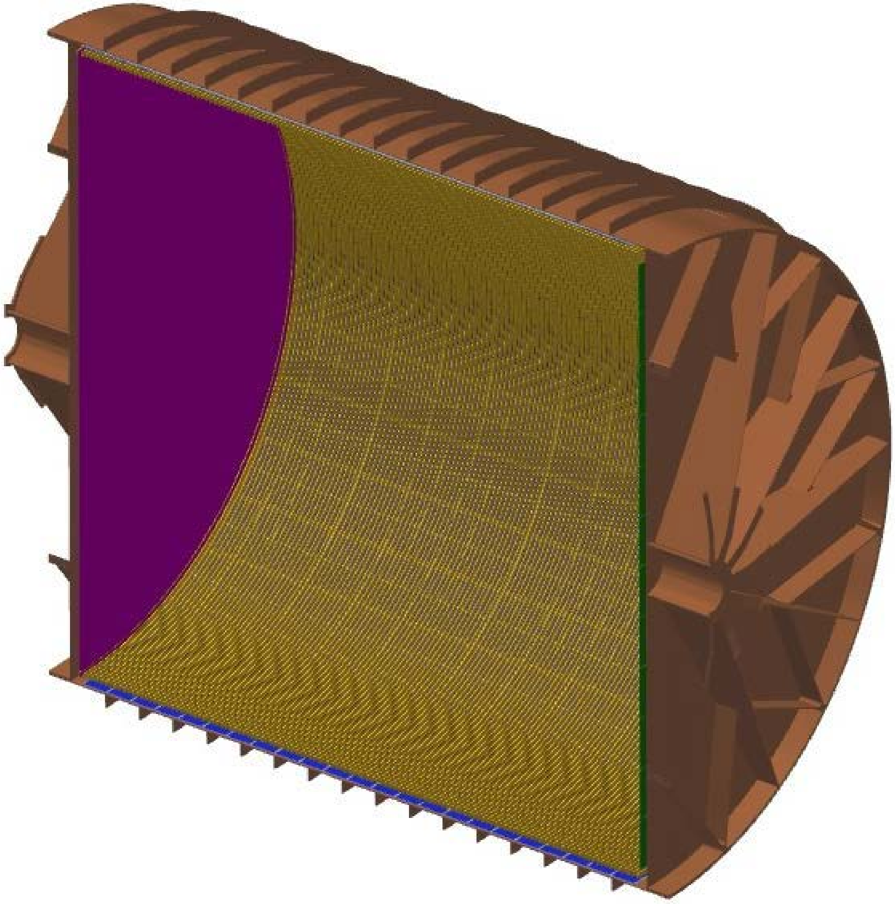
Photo-detector development for nEXO

Achieving optimum energy resolution with PPDs (SiPMs)

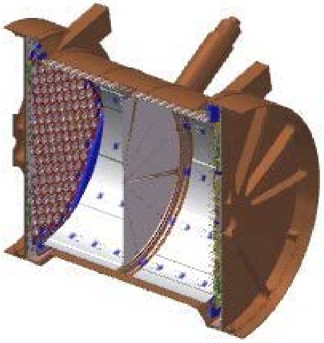
Fabrice Retière for EXO photo-detector group

nEXO: a 5 ton liquid Xenon TPC

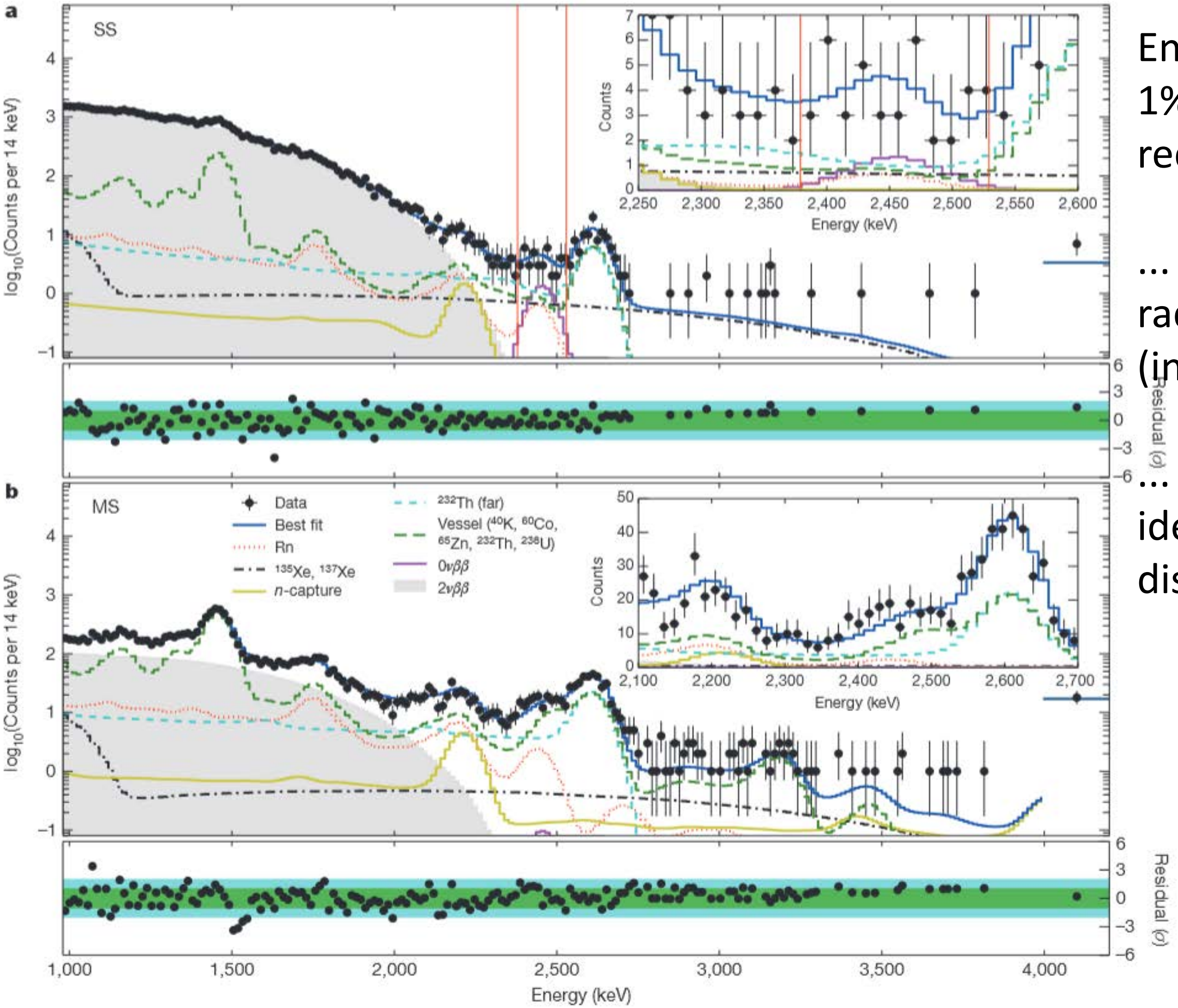
nEXO: at the conceptual stage



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



EXO-200 looking for 0νββ



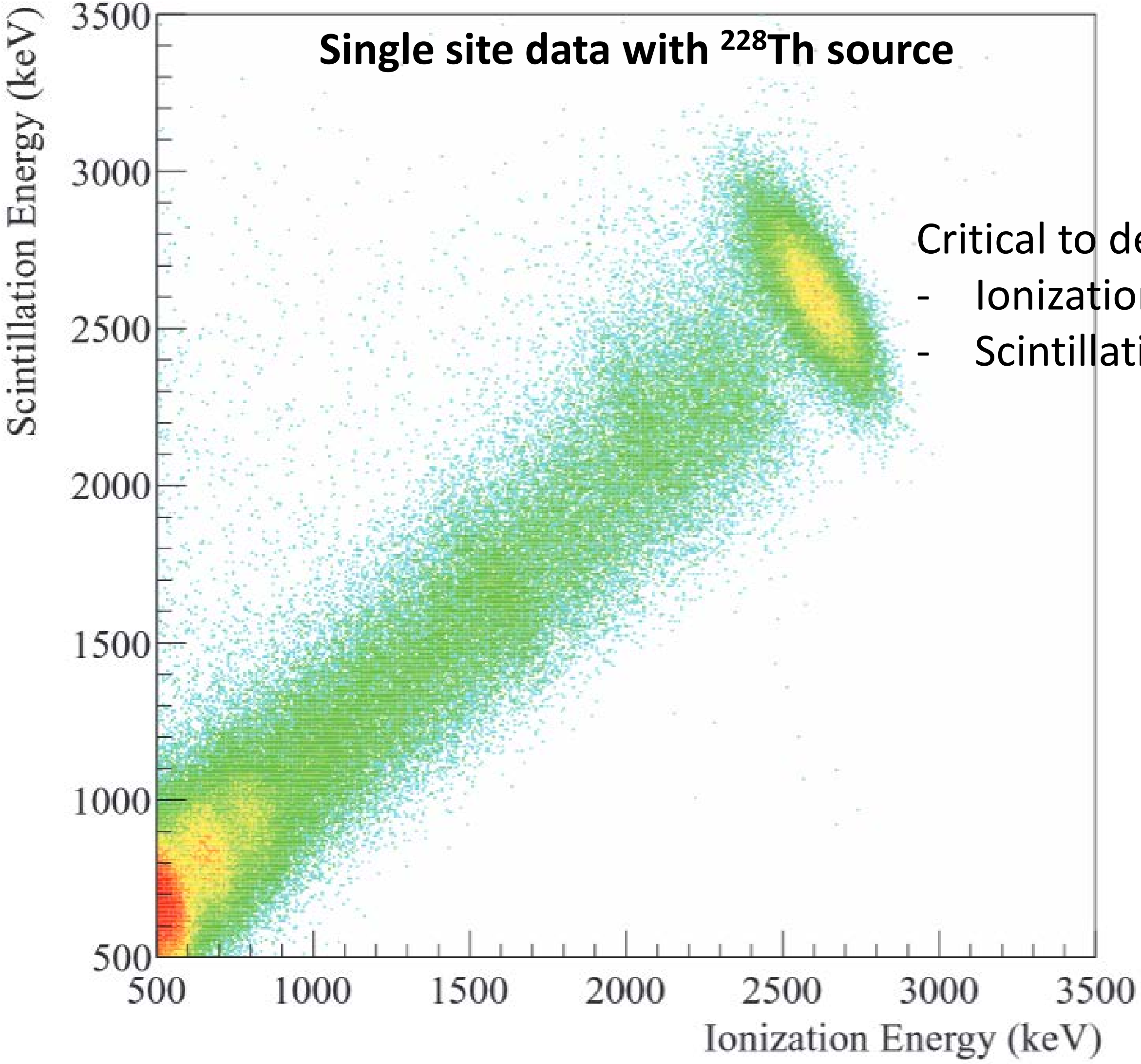
Energy resolution is key 1% at 2.5MeV or less is required

... and very low radioactivity material (including photo-detectors)

... and multi-site (Compton) identification that I will not discuss

Nature 510, 229–234 (12 June 2014)

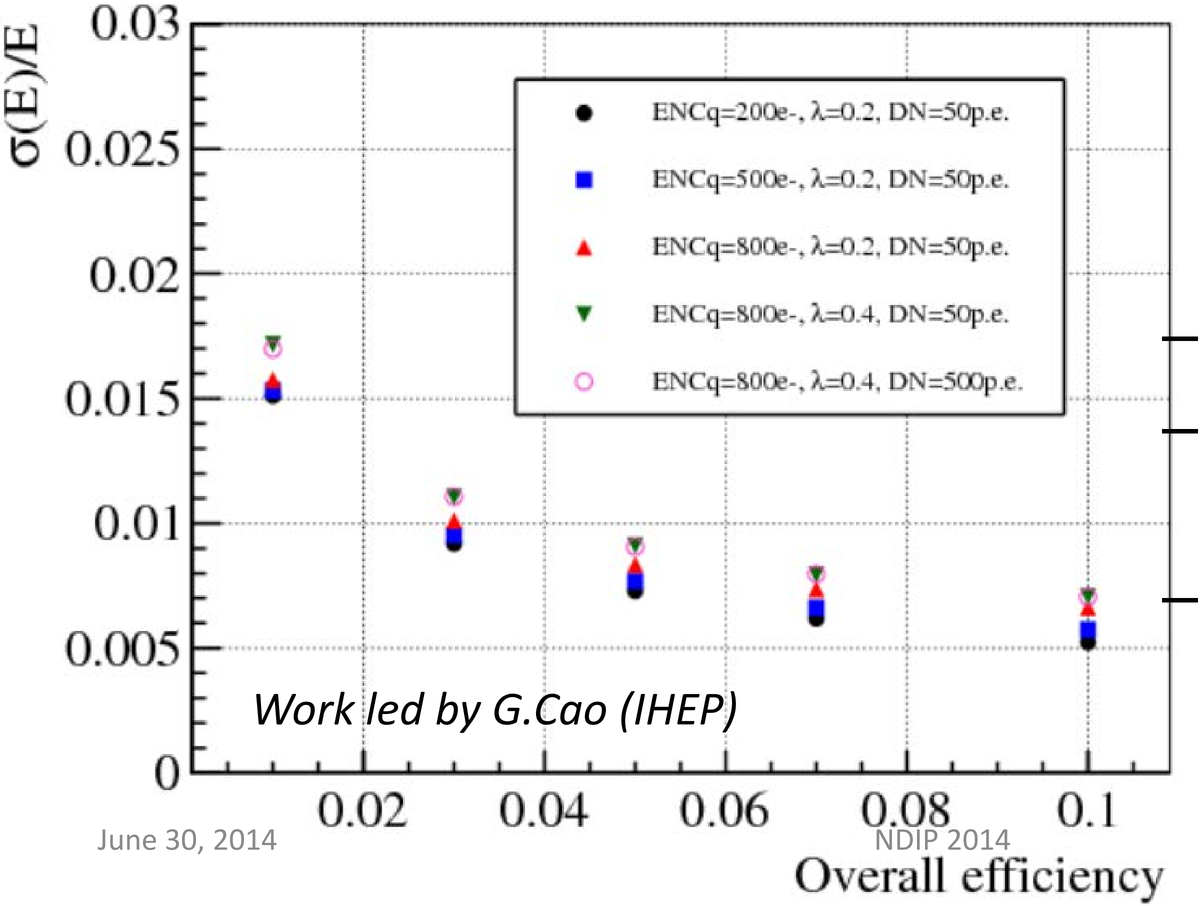
Light/charge fluctuations



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

Scintillation photon detection requirements

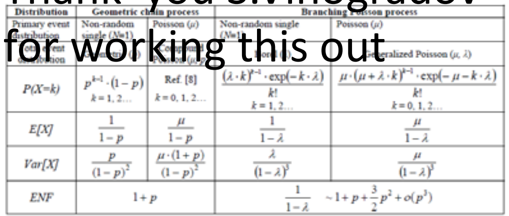
- Excellent energy resolution mostly driven by light detection



Work led by G.Cao (IHEP)

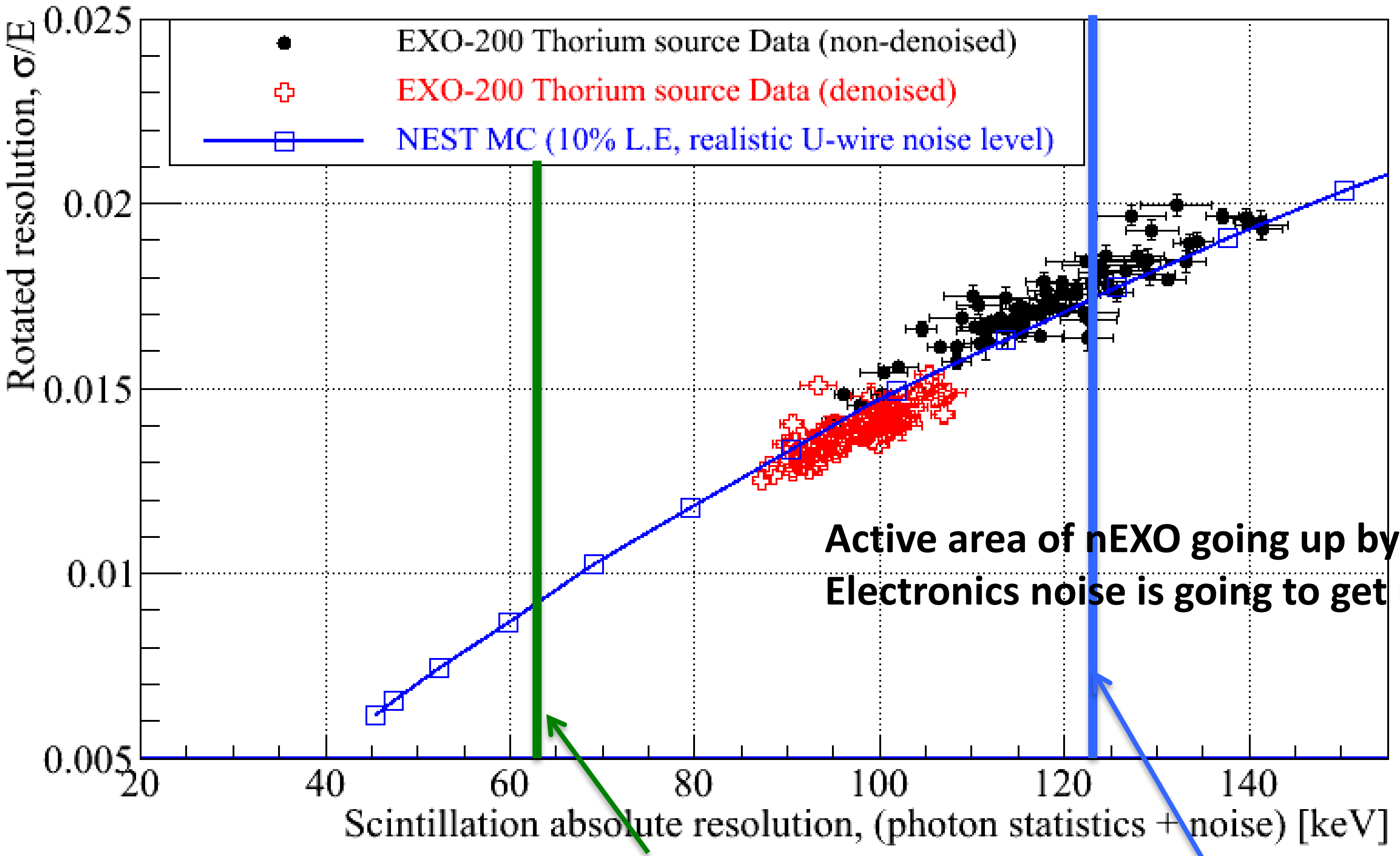
- Parameters that matter
  - Efficiency
    - Collection: detector configuration
    - Detection: photo-detector performance
  - Dark noise
  - Gain fluctuation / correlated avalanche
  - Electronics noise

Thank you S.Vinogradov for working this out



Distribution	Geometric chain process		Branching Poisson process	
Primary event distribution	Non-random single (N=1)	Poisson (μ)	Non-random single (N=1)	Poisson (μ)
Total event distribution	Geometric (p)	Compound Poisson (μ, p)	Borel (λ)	Generalized Poisson (μ, λ)
$P(X=k)$	$p^{k-1}\cdot(1-p)$ $k=1, 2\ldots$	Ref. [8] $k=0, 1, 2\ldots$	$\frac{(\lambda\cdot k)^{k-1}\cdot\exp(-k\cdot\lambda)}{k!}$ $k=1, 2\ldots$	$\frac{\mu\cdot(\mu+\lambda\cdot k)^{k-1}\cdot\exp(-\mu-k\cdot\lambda)}{k!}$ $k=0, 1, 2\ldots$
$E[X]$	$\frac{1}{1-p}$	$\frac{\mu}{1-p}$	$\frac{1}{1-\lambda}$	$\frac{\mu}{1-\lambda}$
$Var[X]$	$\frac{p}{(1-p)^2}$	$\frac{\mu\cdot(1+p)}{(1-p)^2}$	$\frac{\lambda}{(1-\lambda)^3}$	$\frac{\mu}{(1-\lambda)^3}$
ENF	$1+p$		$\frac{1}{1-\lambda}\quad\sim 1+p+\frac{3}{2}p^2+o(p^3)$	

EXO-200 resolution limited by APD noise

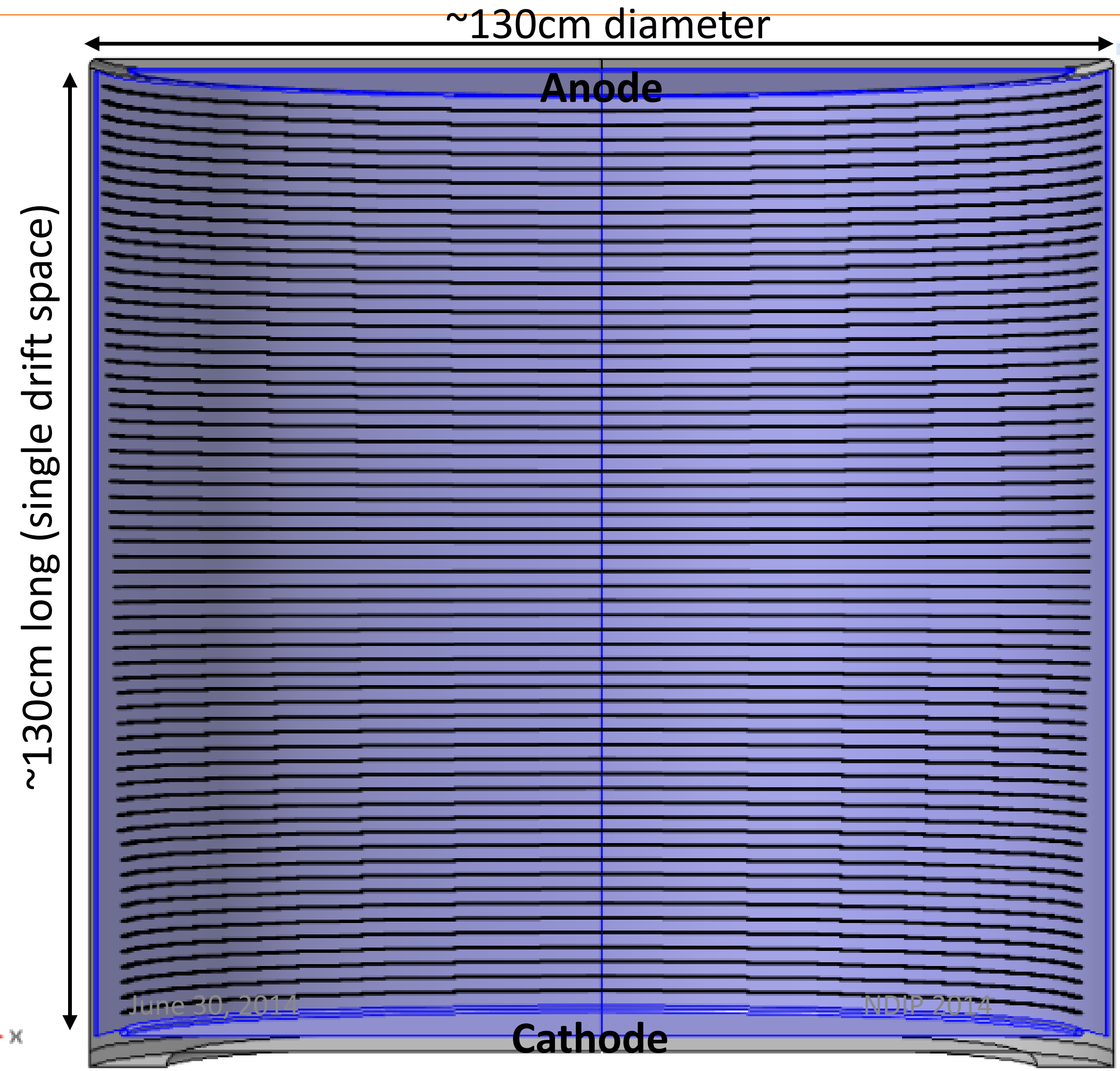


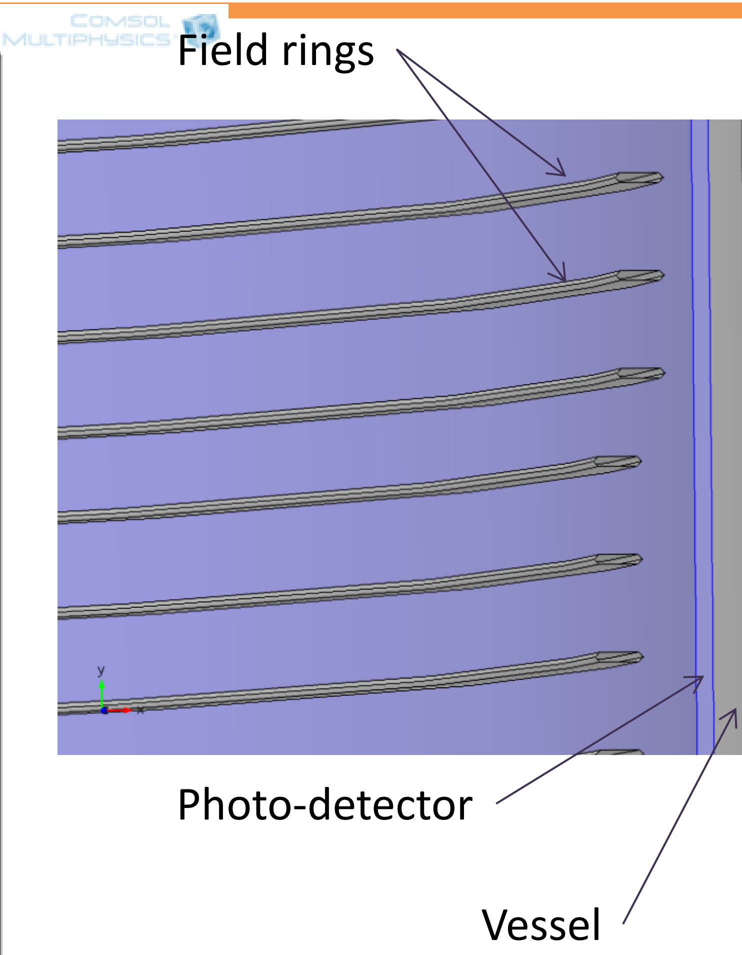
Active area of nEXO going up by more than x10
Electronics noise is going to get much worse...

Expected APD noise after electronics upgrade

Average APD Noise at WIPP

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





Drawing by T.Tolba (Bern)

Trade-off between electric field uniformity and light collection

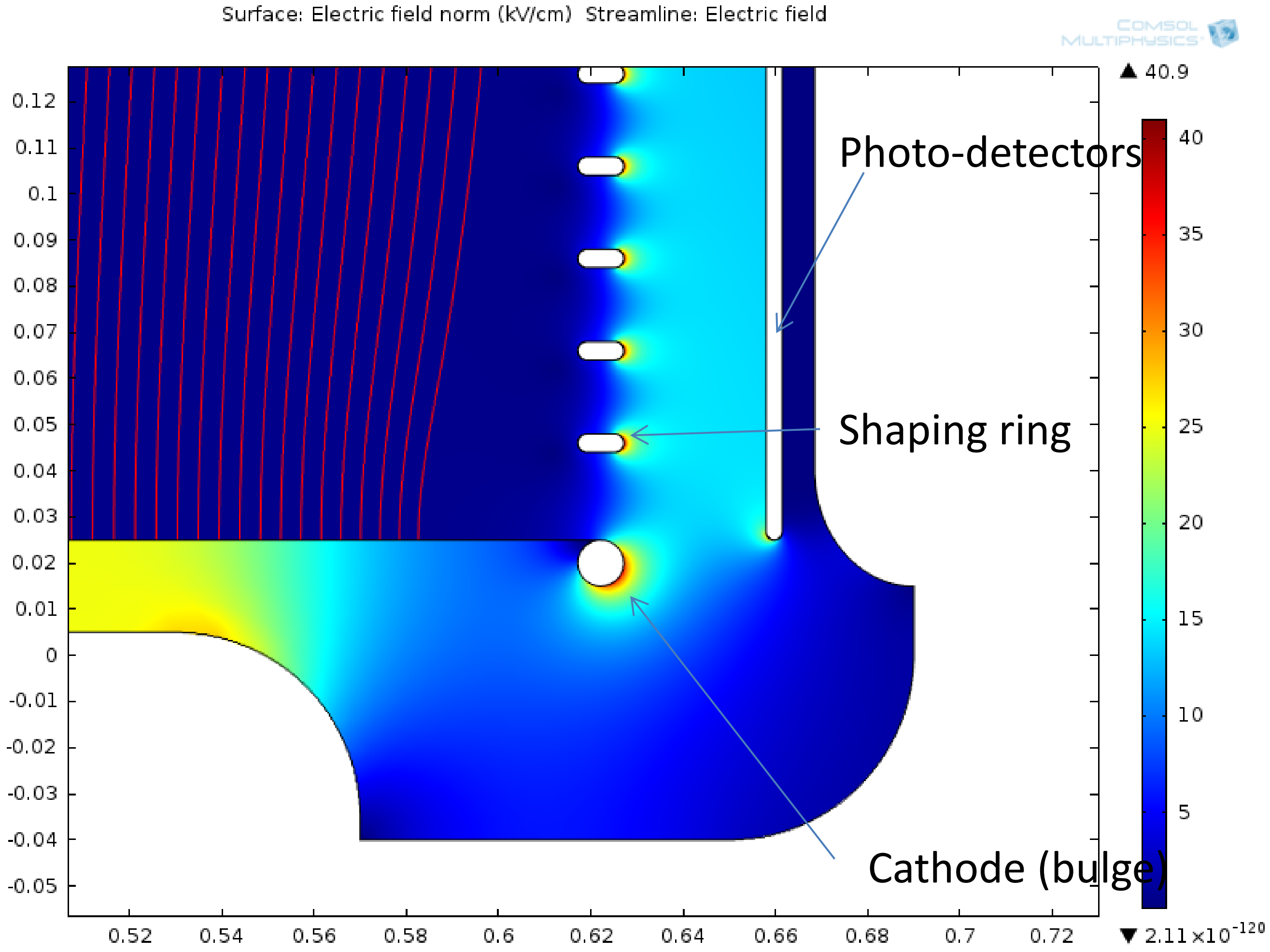


Photo-detectors

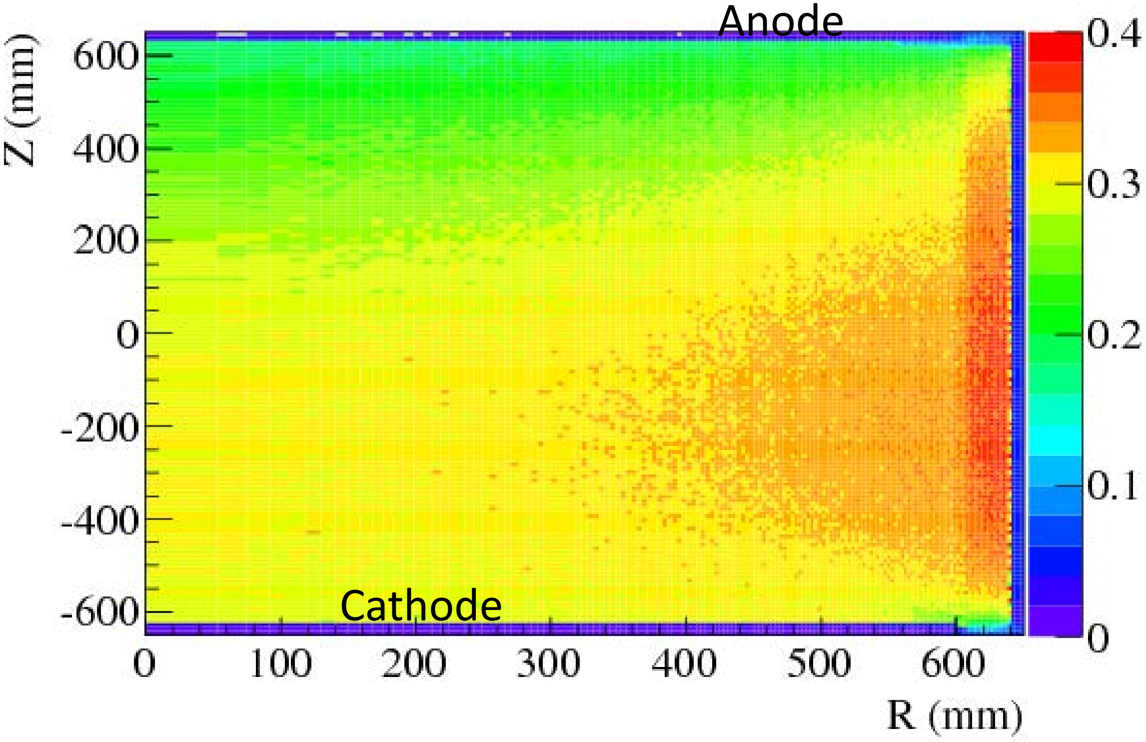
Shaping ring

Cathode (bulge)

Light collection for silicon photo-detectors

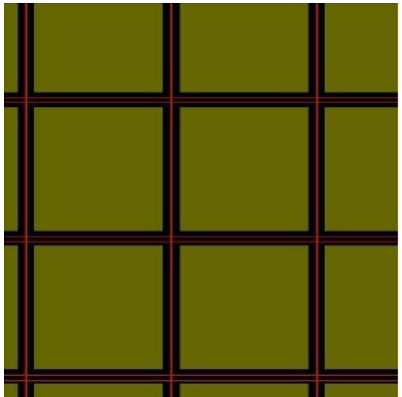
Light collection efficiency map

Probability that a photon gets absorbed in Silicon



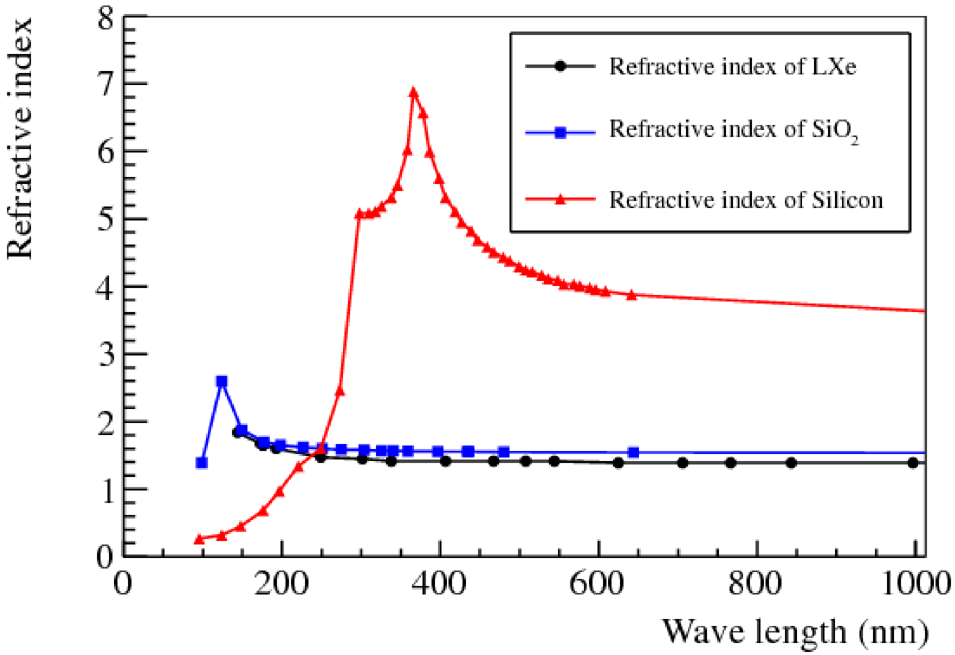
Work led by G.Cao (IHEP)

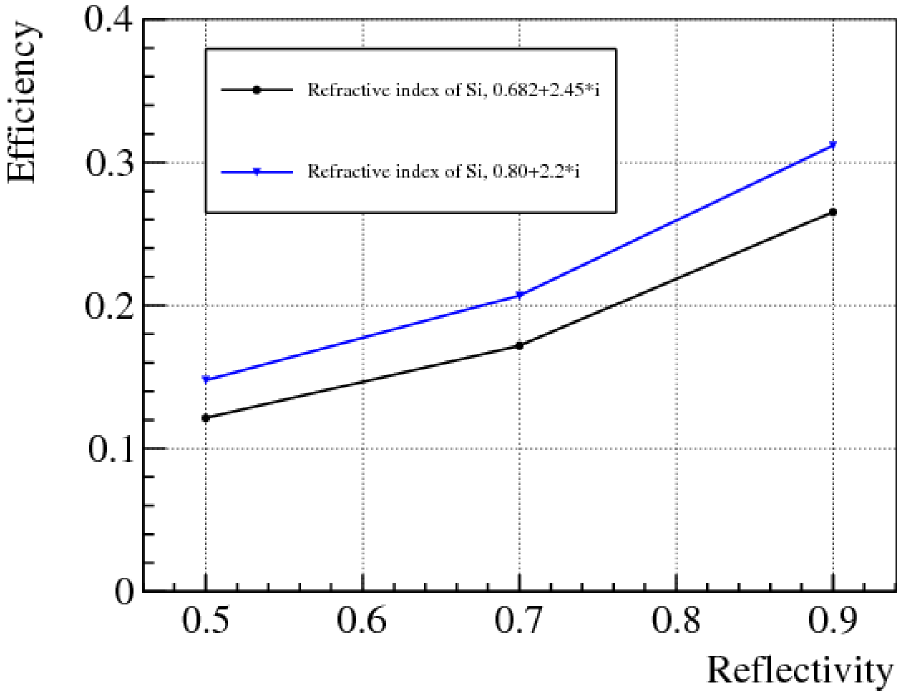
- Configuration
  - Field rings: 2cm pitch, 4mm thick, 10mm long
  - Reflectivity: field rings=0.9, cathode =0.9, anode=0.5
  - 4m^2 photo-detector
    - Silicon on quartz



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



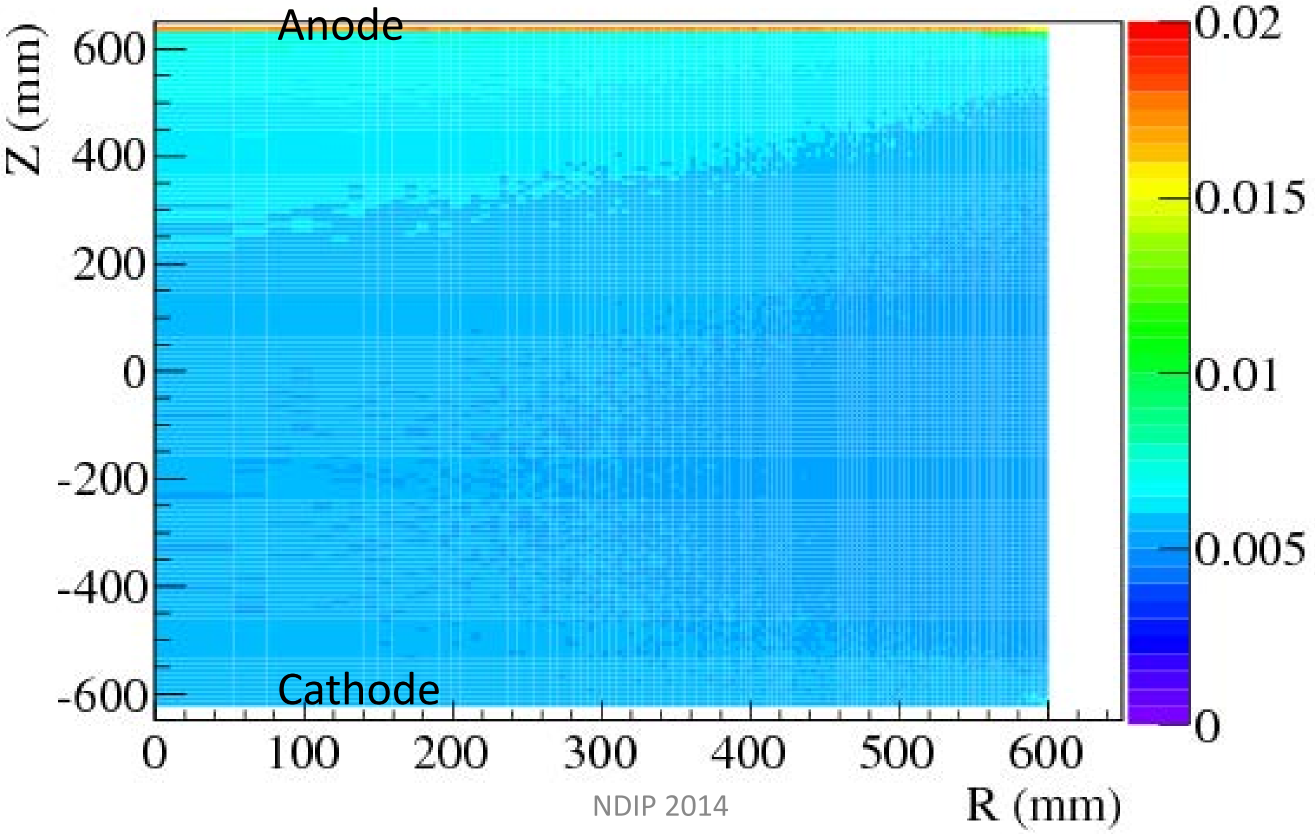


APD, SiPMs, SiPMs+wavelength shifter or something else?

- PMTs no go because too radioactive
- APDs: high efficiency but limited production facilities (API phasing out production) and probably overwhelming electronics noise
- SiPMs
  - Pros: low electronics noise and gain fluctuation, large production facilities
  - Cons: low(?) efficiency at 175nm, large dark noise, large capacitance per unit area
- SiPMs + wavelength shifters: overcome issue of low efficiency at 175nm but more cumbersome
- Something else? Probably too short time scale

Energy resolution with SiPMs <1% throughout

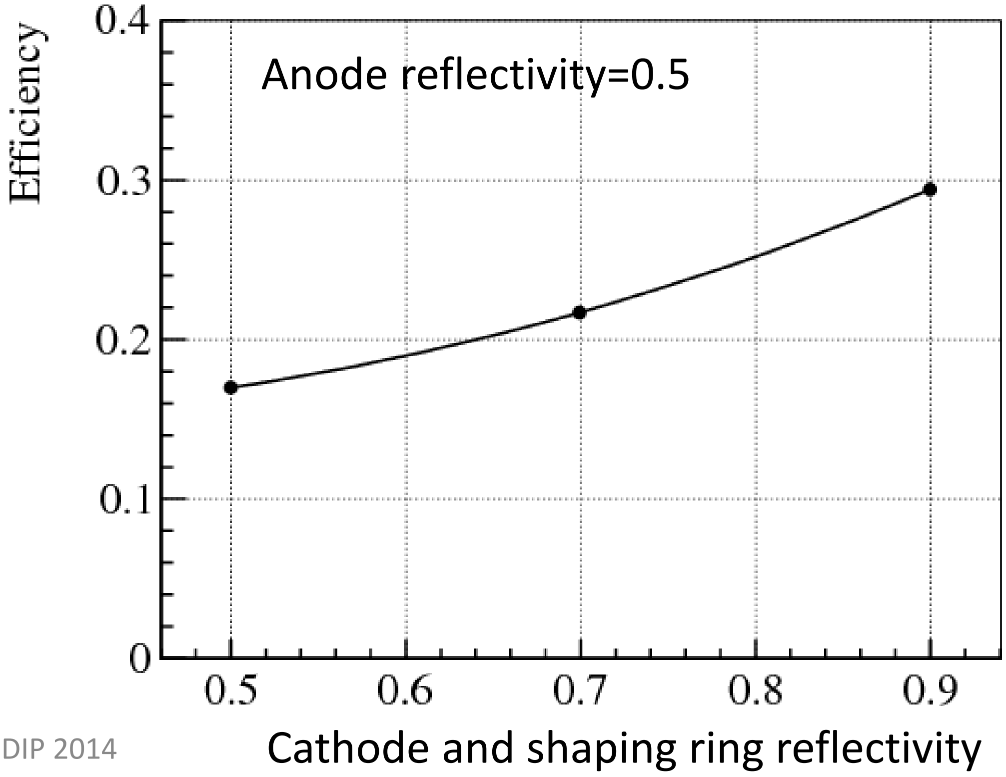
- Internal SiPM efficiency (excluding reflections) = 33%
  - Dark noise=500PE, Electronics noise=25PE, correlated noise=0.2



Work led by G.Cao (IHEP)

Critical items for achieving the required energy resolution

- High efficiency, low noise photo-detector
  - Target light collection * PD efficiency = 10%
    - Yield ~10,000 photo-electron (PE)
  - Dark noise and electronics noise must be <1,000 PE
  - Effective gain fluctuations <20%
- Highly reflective surfaces
  - Anode, Cathode and shaping rings



Work led by G.Cao (IHEP)

Passive optics development

- Best mirror solution: Aluminum covered by AlF_3 or MgF_2 can reach 90% reflectivity
  - Proven solution for in-space astronomy
- Open questions for nEXO
  - Material radiopurity
  - Conductivity of MgF_2/AlF_3 if deposited on cathode
  - Fabrication over large area? Find manufacturer or develop deposition solution
- Need to measure reflectivity vs angle at 175nm: VUV ellipsometry
  - Characterize small mirrors at 175nm
  - Measure index of refraction of silicon at 175nm

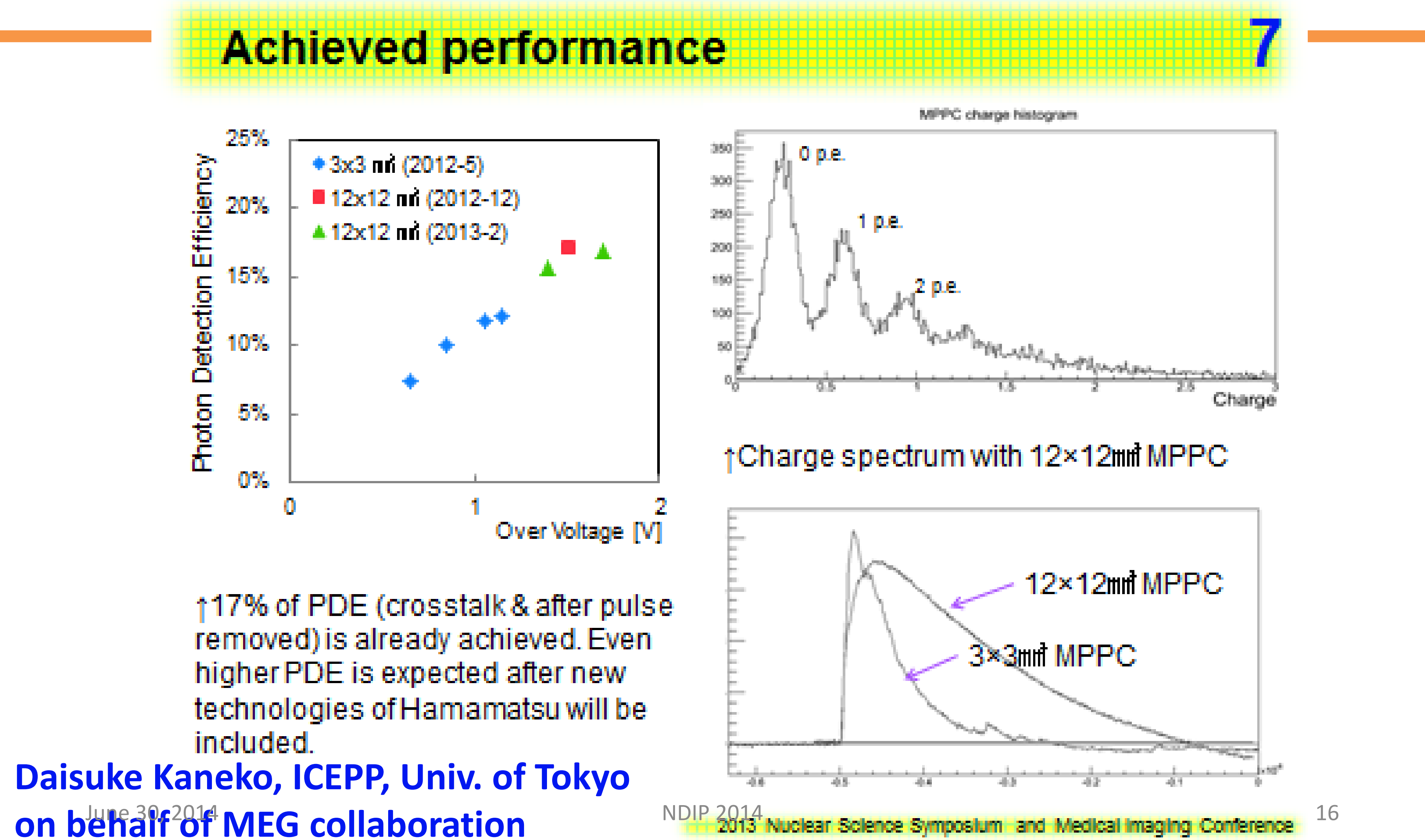
Work led by A.Pocar (Umass)

Photo-detector specification guidelines for the vendors

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
Gain fluctuations + electronics noise	<0.1PE
Pulse width (after possible electronics shaping)	<100ns
Single photon timing resolution (σ)	<1ns

Aggressive specifications that may need to be relaxed
Goal is to find one or more suitable photo-detector candidate by 2016

Already a solution? Required performances achieved by Hamamatsu but radio-purity is a question



Achieved performance

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↑Charge spectrum with 12×12㎟ MPPC

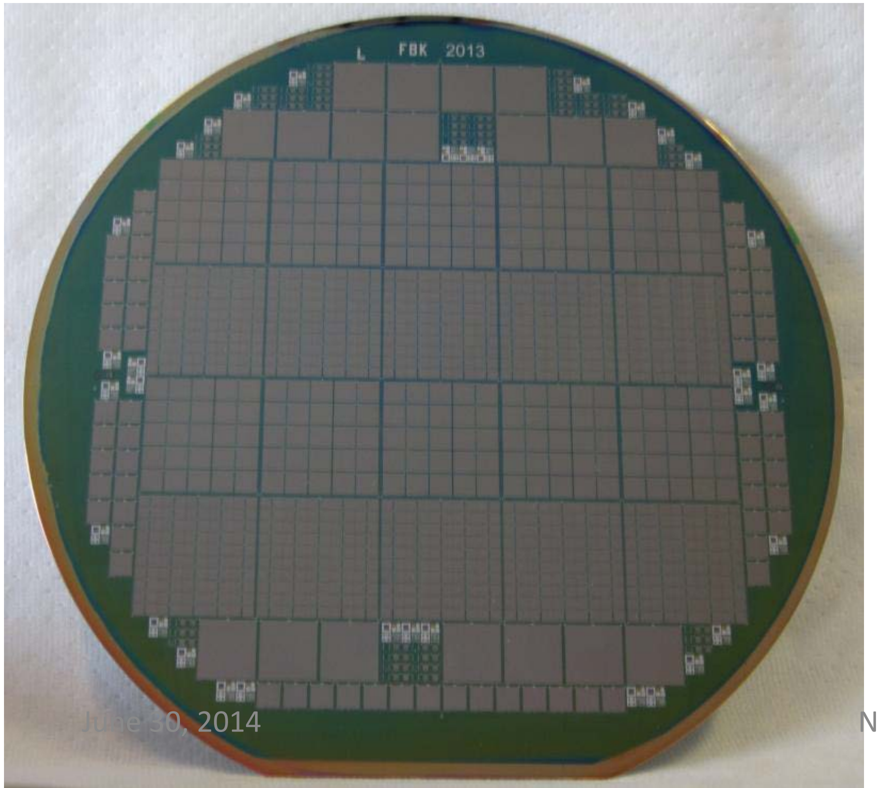
↑17% of PDE (crosstalk & after pulse removed) is already achieved. Even higher PDE is expected after new technologies of Hamamatsu will be included.

2013 Nuclear Science Symposium and Medical Imaging Conference

Daisuke Kaneko, ICEPP, Univ. of Tokyo on behalf of MEG collaboration

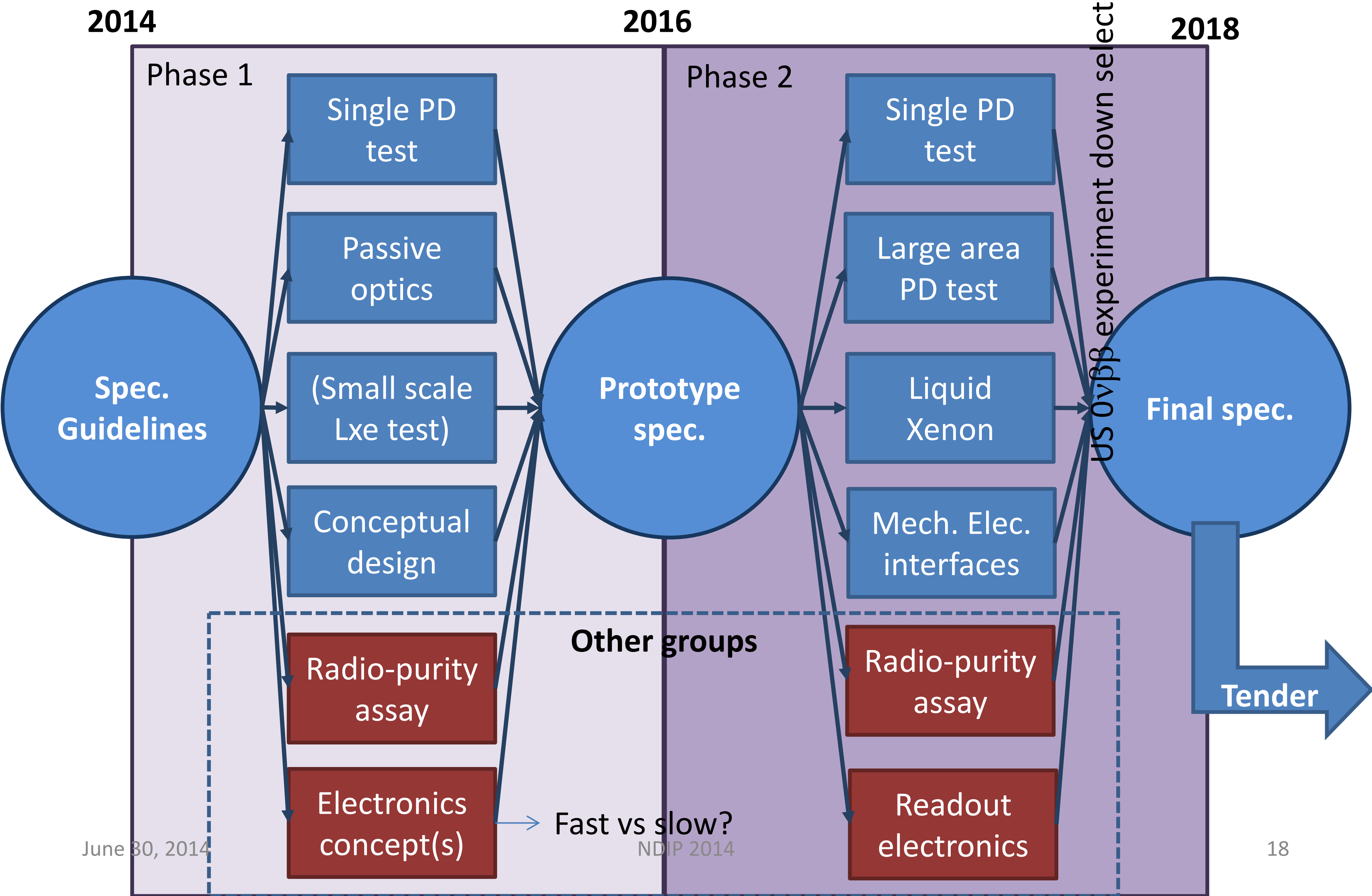
Photo-detector solutions

- FBK primary partner
  - Collaboration with Stanford for the development of SiPM for nEXO



- Other options
  - Hamamatsu
    - Need a way to assess radiopurity
  - RMD
    - SiPMs and APDs
    - SBIR being considered
  - Zecotek MRS-APD (SiPM)
    - Canada collaborative development
  - KETEK (Germany)
  - (Excelitas)

nEXO photo-detector R&D plan



2014

2016

2018

Phase 1

Spec. Guidelines

Single PD test

Passive optics

(Small scale Lxe test)

Conceptual design

Radio-purity assay

Electronics concept(s)

Fast vs slow?

Prototype spec.

Phase 2

Single PD test

Large area PD test

Liquid Xenon

Mech. Elec. interfaces

Radio-purity assay

Readout electronics

Other groups

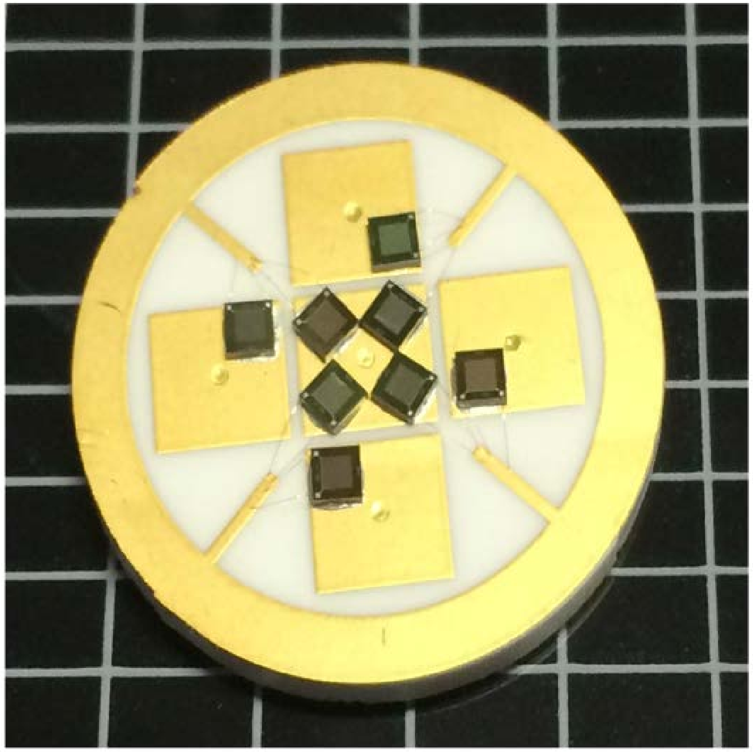
US 0νββ experiment down select

Final spec.

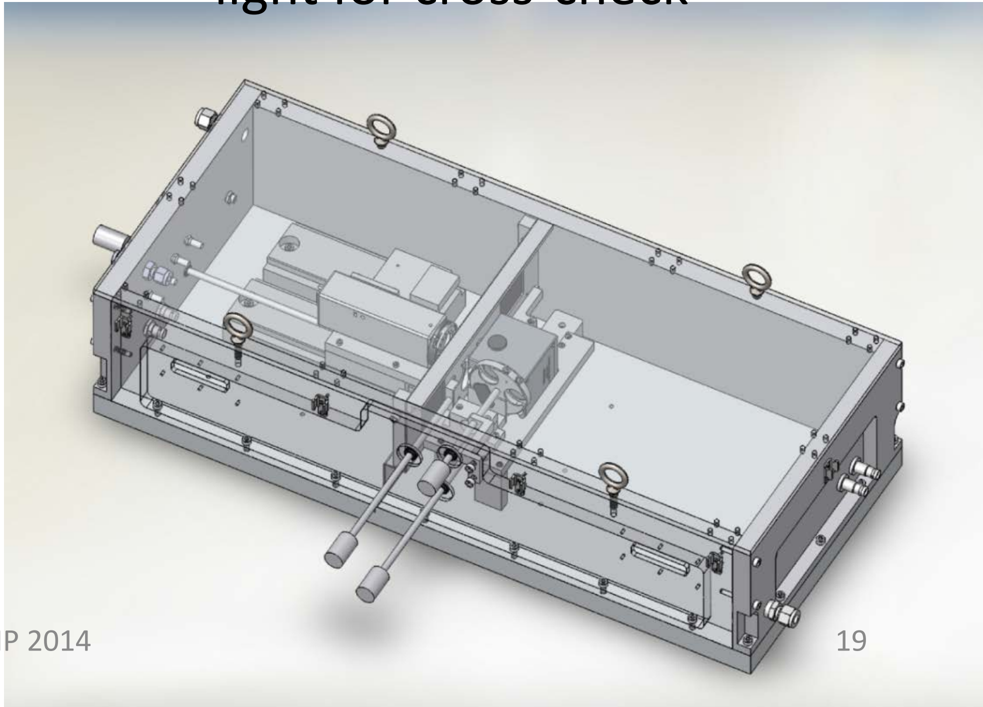
Tender

Single photo-detector test setups

- Stanford setup
  - Being upgraded
  - Vacuum field
  - Gas Xe scintillation cell

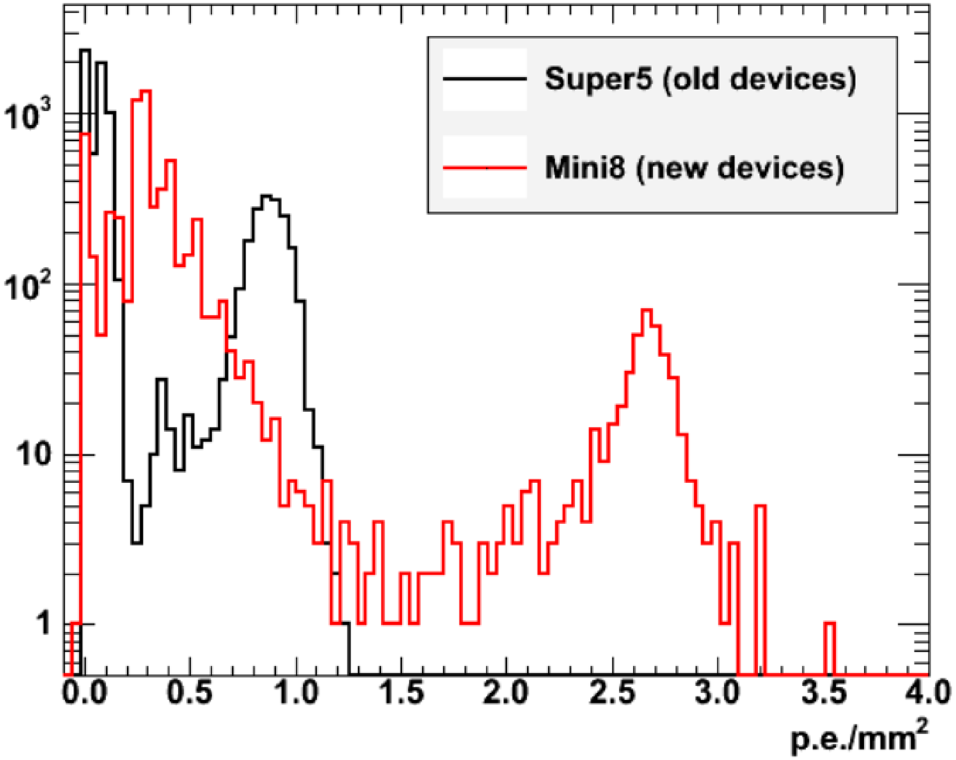


- TRIUMF setup
  - Being constructed
  - N2 gas field
  - Xenon flash lamp & visible light for cross-check

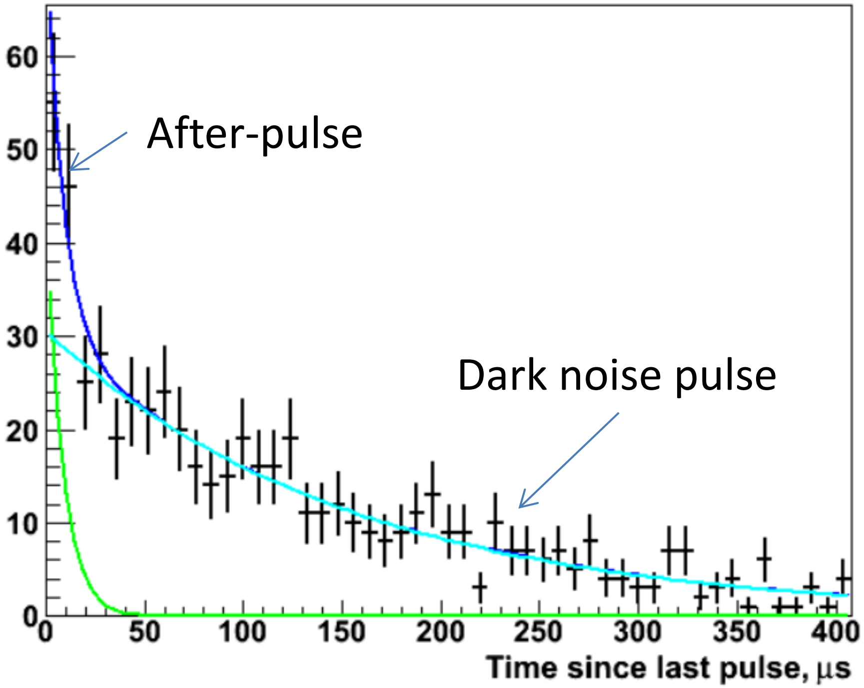


FBK SiPM test results using Stanford setup

Photo-detection with ^{252}Cf source



Distribution of the time between dark pulses (i.e. no source)


After-pulse

Dark noise pulse

Inferred efficiency of new FBK devices~5%

Inferred dark noise rate = 800Hz/mm2 at -104C

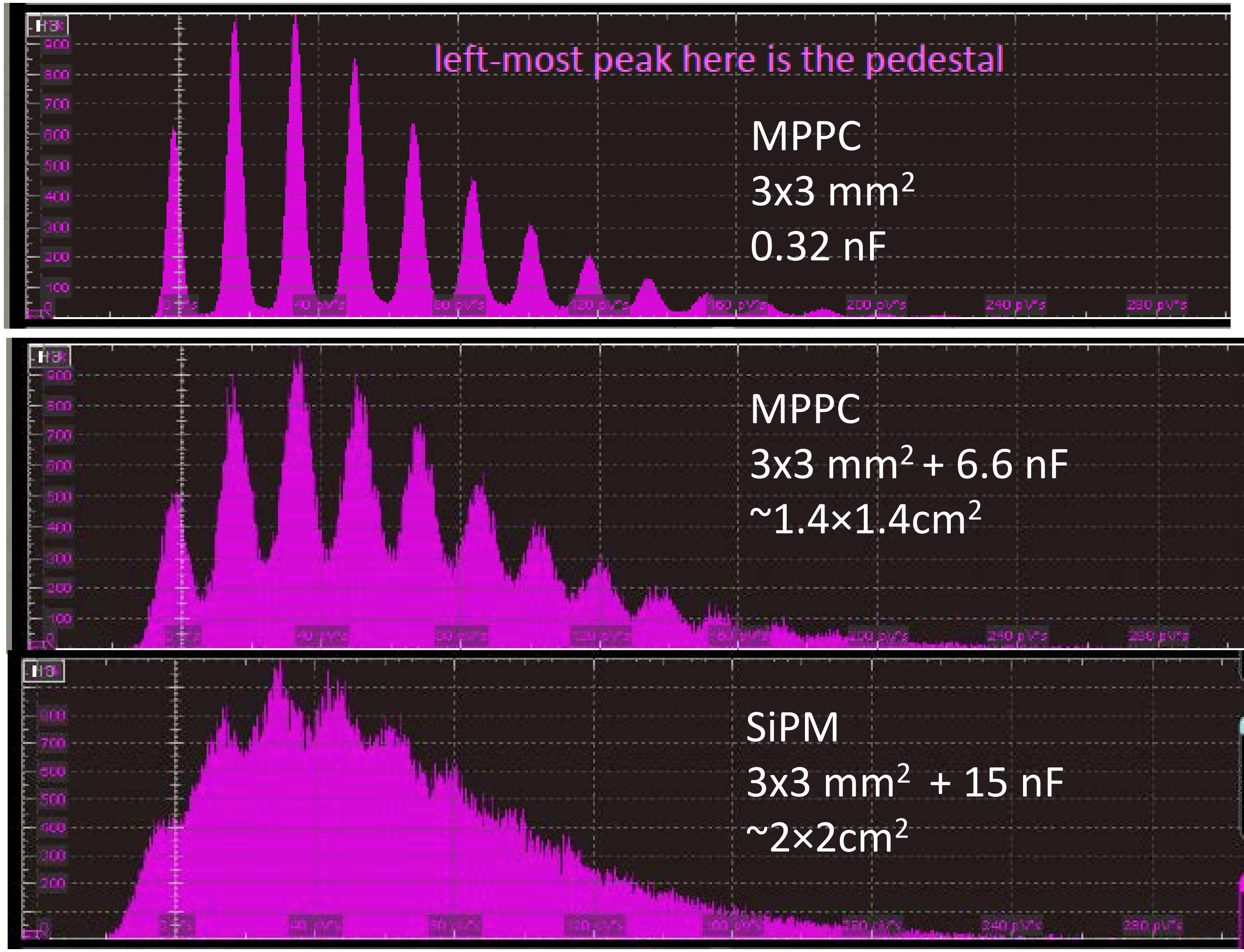
Work led by I.Ostrovskiy (Stanford)

TRIUMF

G. Visser

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


left-most peak here is the pedestal

MPPC
3x3 mm^2
0.32 nF

MPPC
3x3 mm^2 + 6.6 nF
~1.4×1.4cm^2

SiPM
3x3 mm^2 + 15 nF
~2×2cm^2

Low radioactivity issue

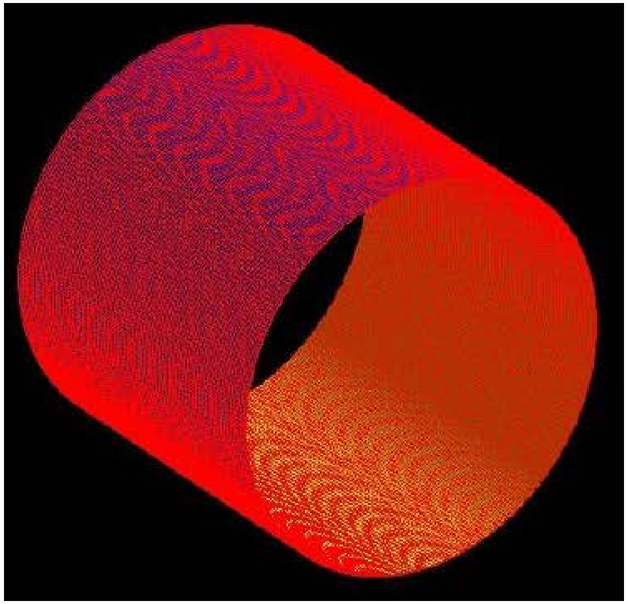
- Hoping to have the photo-detectors contribute less than 1% of total background
  - ^{238}U and ^{232}Th are <9mBq/kg (<0.73pg/g) and <43mBq/kg (<10pg/g)
  - Impossible to measure by counting: 1kg of material yield 1 count in 30h.
- Assaying either by neutron activation in a reactor or Inductively Coupled 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

A lot to do!

- nEXO must identify a viable photo-detector in the next 2 years and develop high reflectivity mirrors
  - Critical to make a compelling case for 0nbb down select
- nEXO must also solve integration issues
  - Large area readout: 10×10cm^2 planes to be built in 2016
  - Low radioactivity packaging
- Fortunately, lots of work towards the development of SiPMs for use in LXe and LAr
  - Looking forward to several interesting talks this week!
  - And to possible collaborations within nEXO or between collaborations
  - And to organizing a dedicated workshop?

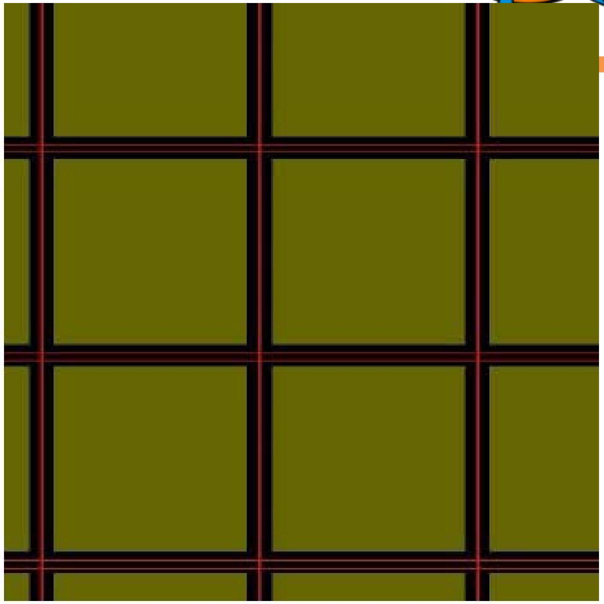
The end

Simulation details

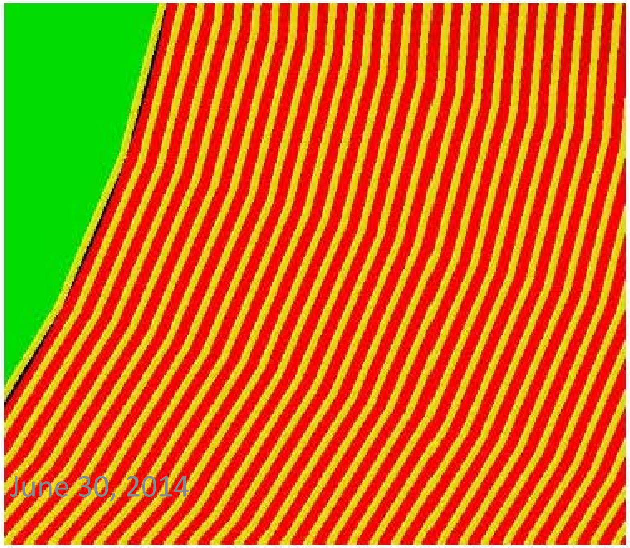


SiPM

Zoom in



Size of each pixel:
1.34 × 1.34 (cm)
Size of active area:
1.2 × 1.2 (cm)
Total active area: ~4m^2



Field shaping plates:

- Thickness → 0.5mm ~ 3mm
- Length → 5mm ~ 20mm
- Distance → 5mm ~ 30mm
- Reflectivity (same with cathode) → 0.5, 0.7, 0.9

To study light collection efficiency in above parameter space.