SiPMs for XAMS: A dual-phase liquid xenon TPC for dark matter direct detection R&D

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OUTLINE

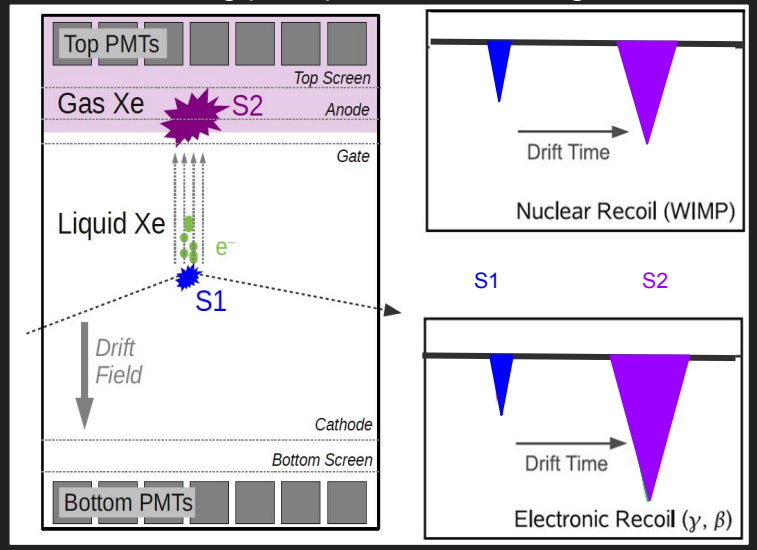
- XAMS & SiPMs
- SiPM characterization setup
- Field measurements with XAMS & future TPCs

Dual-Phase TPC

Application:
- dark matter direct detection

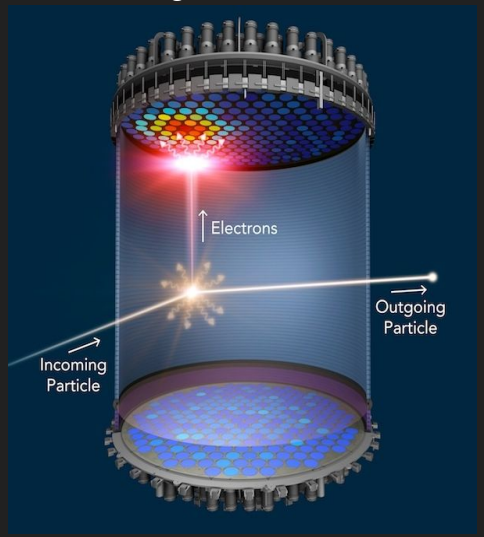
Working principle:
- ER & NR
- S1 & S2 signals
- S2/S1 discrimination
- position reconstruction
  - z ⟶ drift time
  - x,y ⟶ light distribution

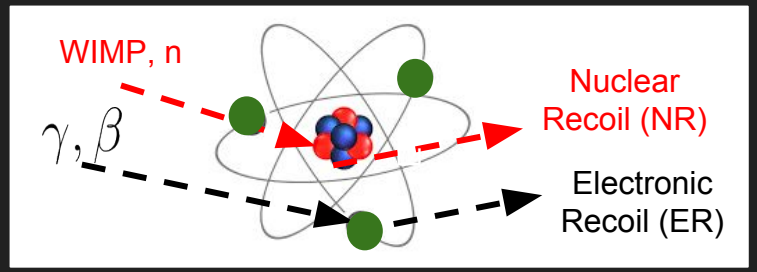
TPC working principle

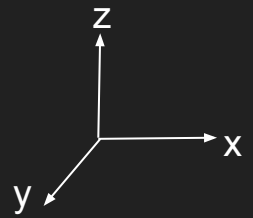


signals

S2 light distribution







XAMS

What is XAMS?

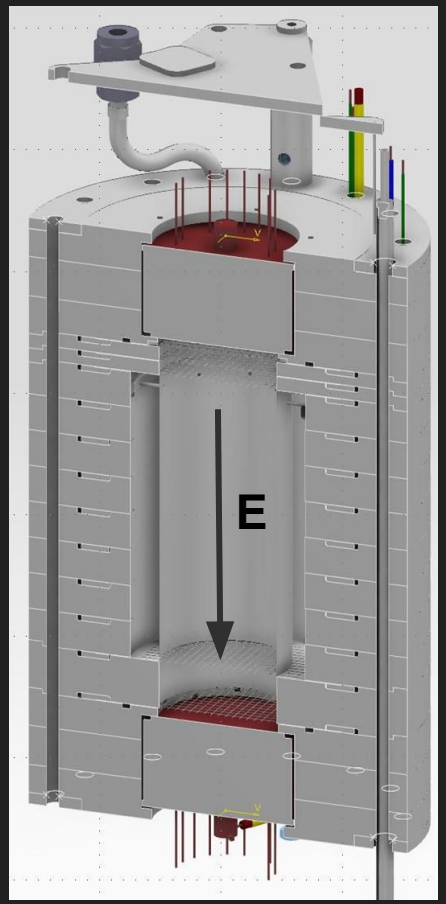
- dual-phase Xe TPC R&D

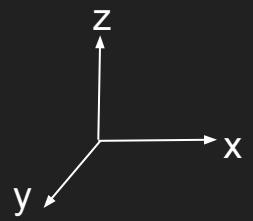
Why XAMS?

- properties of Xe TPCs
  - scintillation and ionization signals
  - charge transport dynamics
  - xenon purity & backgrounds
  - field dependencies (this talk)

Limitation:

- single PMTs
  - lateral position reconstruction (x,y)





SiPMs

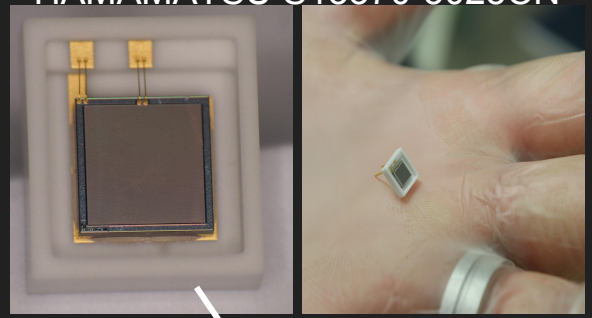
SiPMs for XAMS:

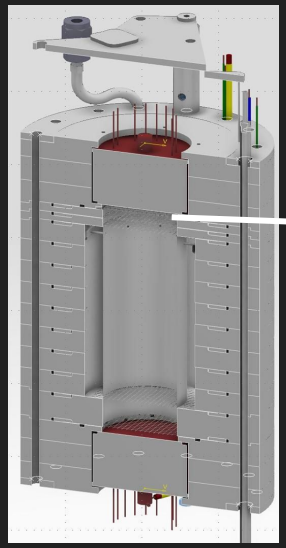
- lateral position reconstruction
  - SiPM ring in GXe
  - relative response
  - compare with simulation

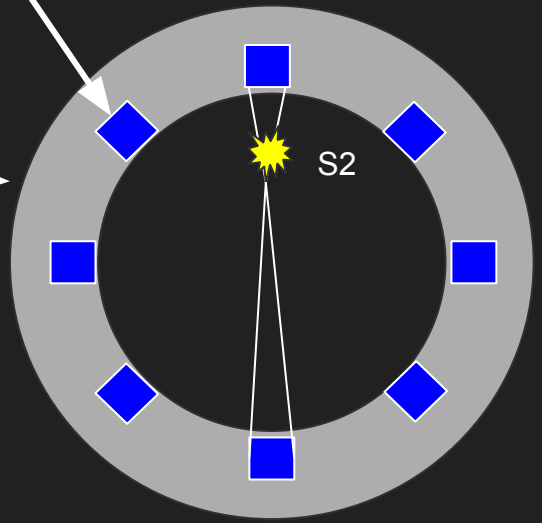
What is a SiPM?

- solid state photodetector
  - single photon sensitivity
  - ~24% photon detection efficiency for LXe (178 nm)
  - cryogenic stability with reduced noise
  - low voltage + high gain

HAMAMATSU S13370-3025CN







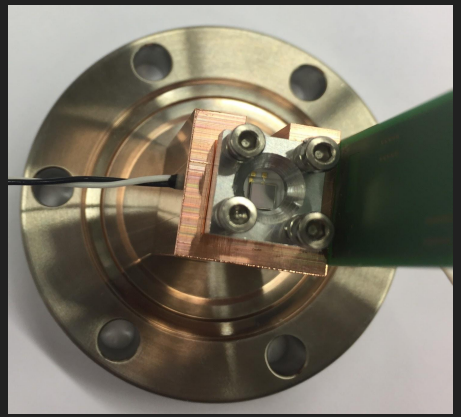
SiPM Characterization

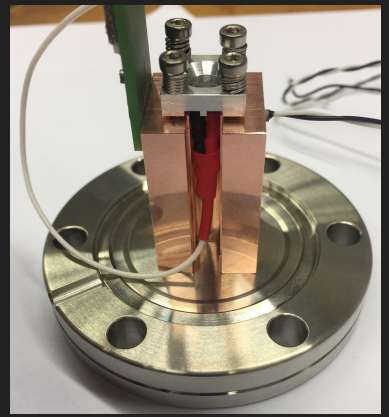
What is the Cold Finger?

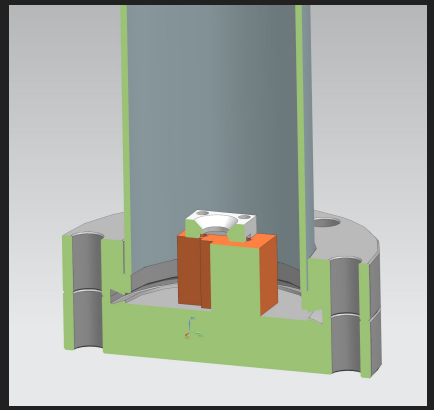
- SiPM characterization setup

Characterization:

- SiPMs' temperature dependence (gain, noise, bias, etc.)

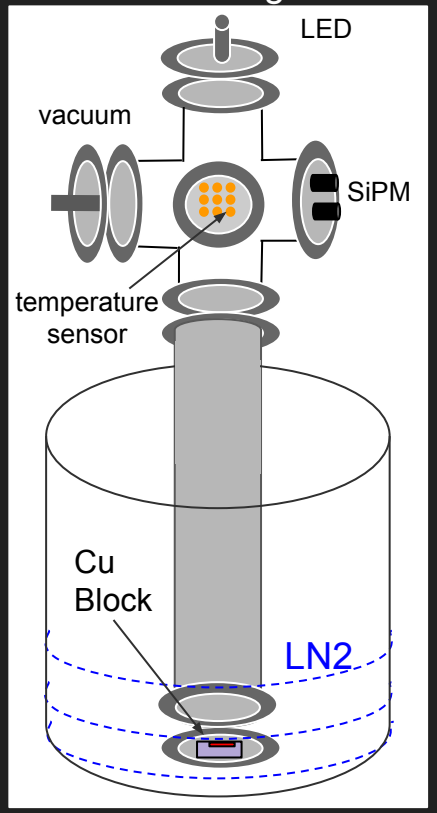






Drawing by Martin Doets

"Cold Finger"



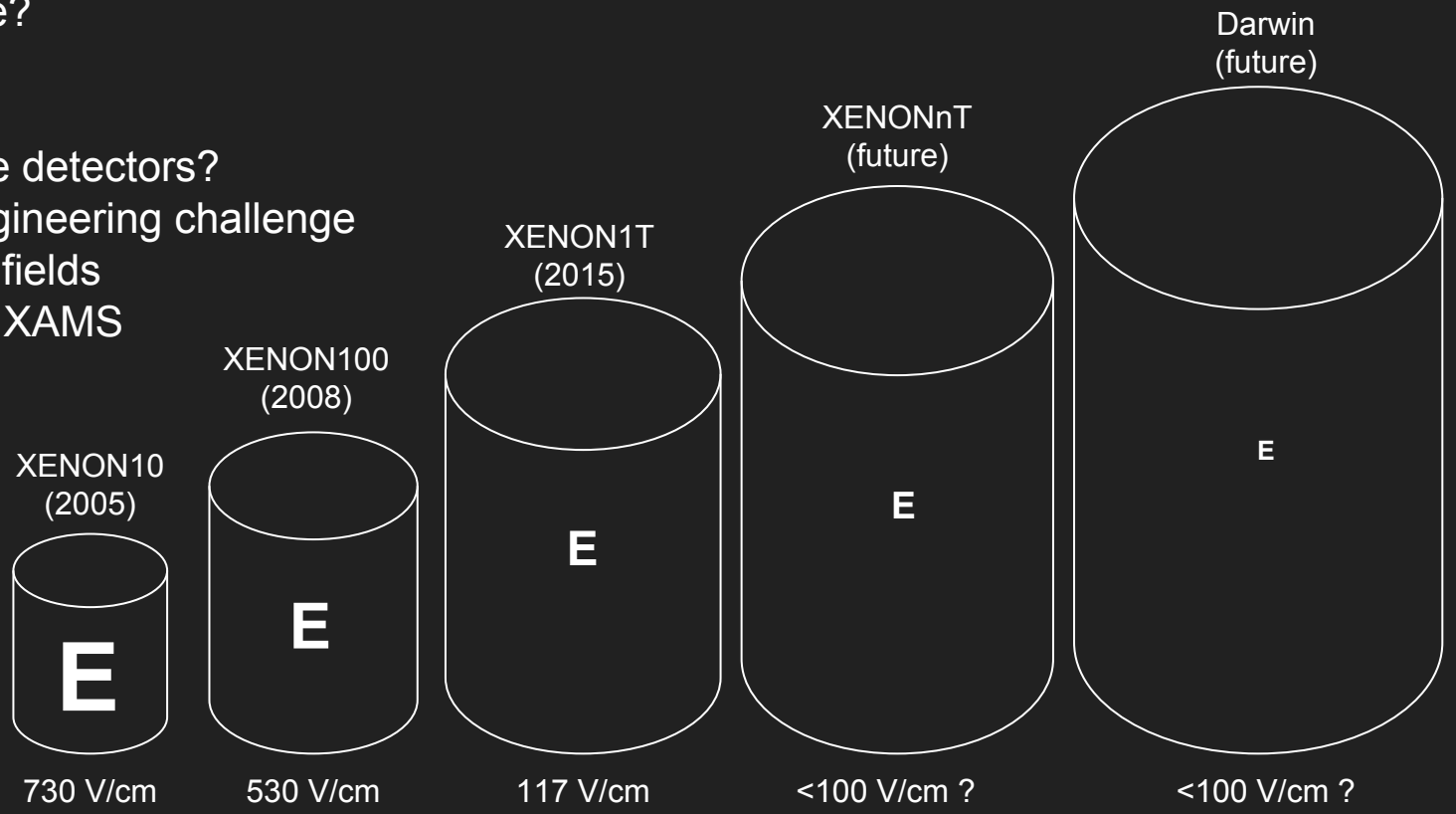
TPCs for DM Direct Detection

Why the growing size?

- exposure

Implications for future detectors?

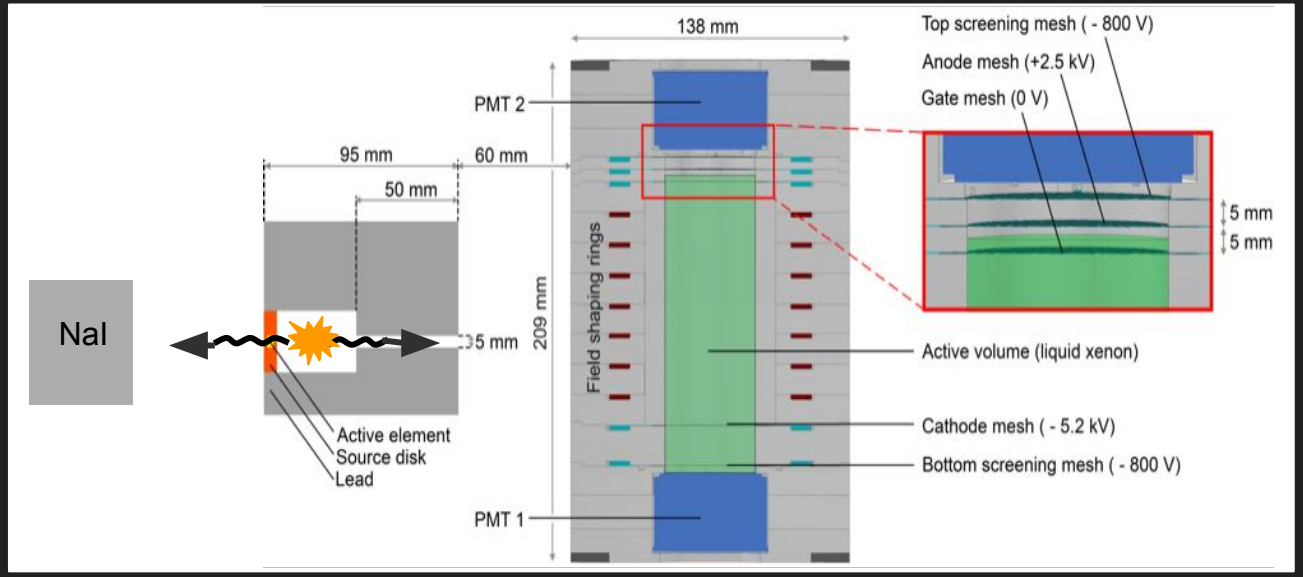
- high voltage engineering challenge
- decreasing drift fields
  - probe with XAMS



XAMS ER Studies

22Na source:

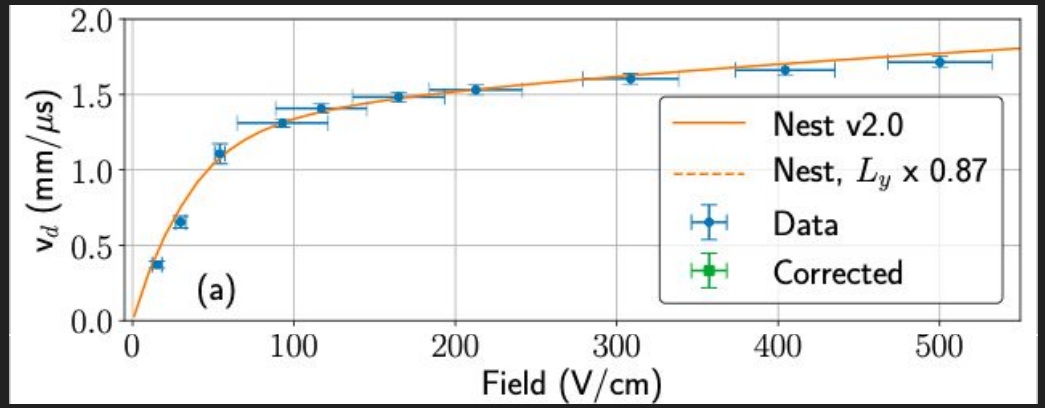
- beta decay
- 511 keV back-to-back photons
- triple coincidence (PMT1 + PMT2 + NaI)

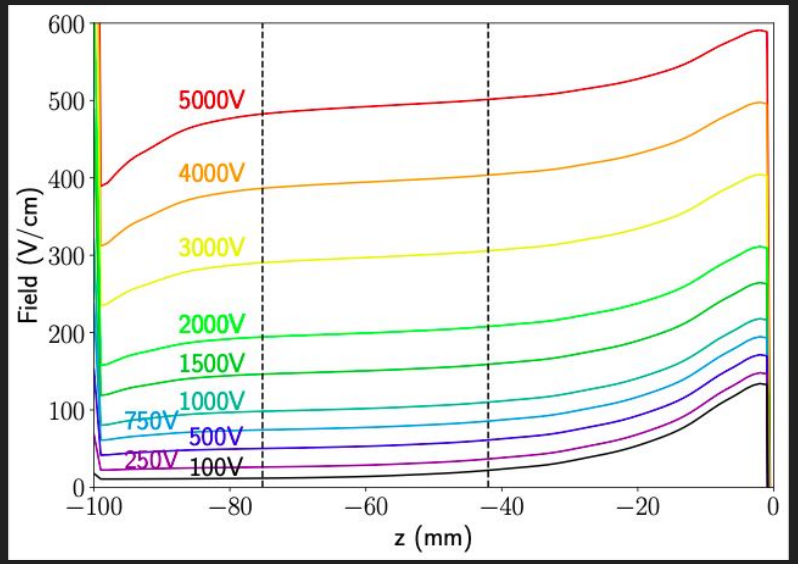


Drift Velocity vs Field

Uncertainties:

- field distortion (near anode + cathode)
- z-position (cathode location + travel time)





TPC bottom

TPC top

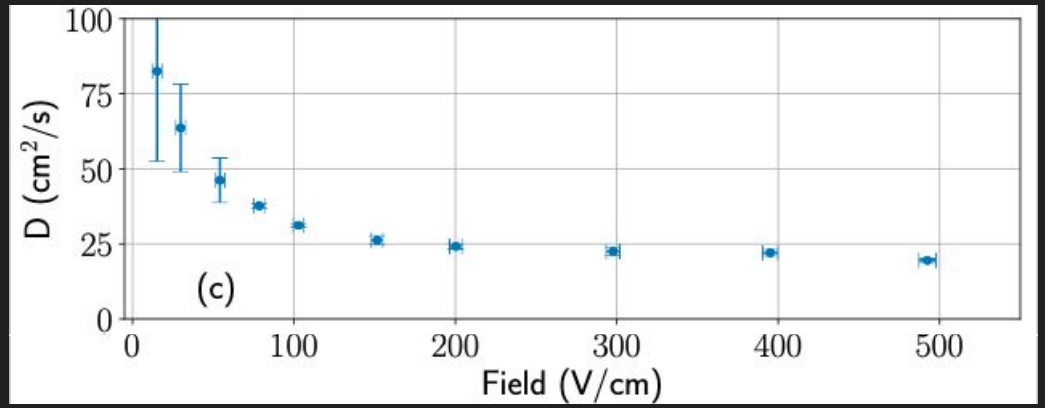
*NEST: Noble Element Simulation Technique

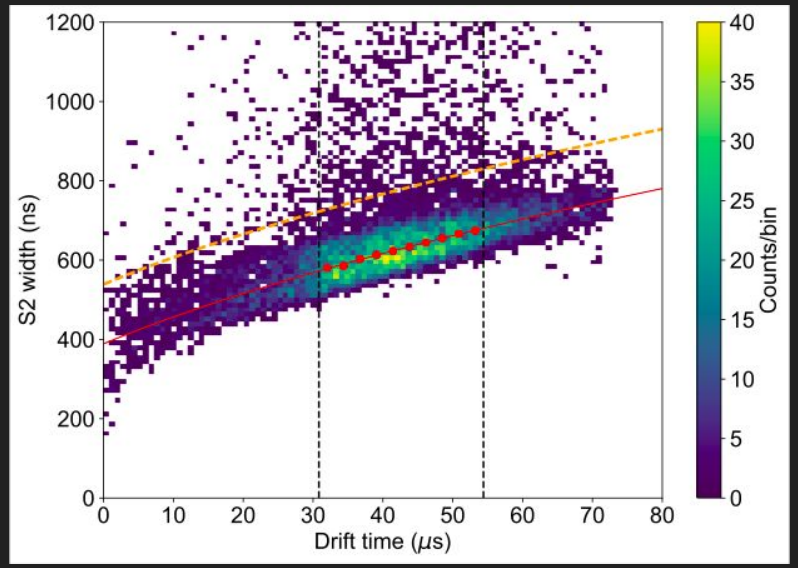
- excitation, ionization and scintillation of liquid noble elements

Diffusion vs Field

S2 width:

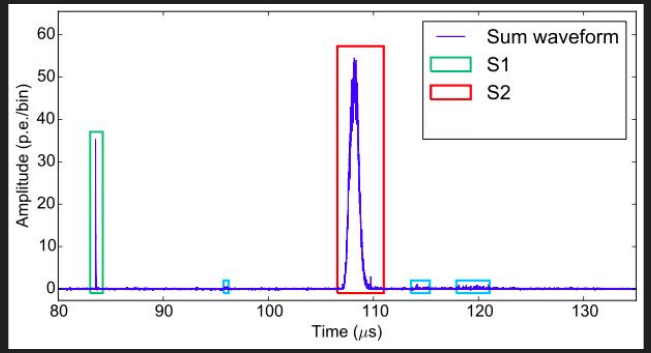
- electron diffusion
- higher fields ⟶ fit
- lowest 3 fields ⟶ drift time slice





$$\sigma_{S2} = \sqrt{\frac{2Dt_d(z)}{v_d^2} + \sigma_0^2}$$

$$\frac{d\sigma_{S2}^2}{dt_d} = \frac{2D(z(E))}{v_d^2}$$



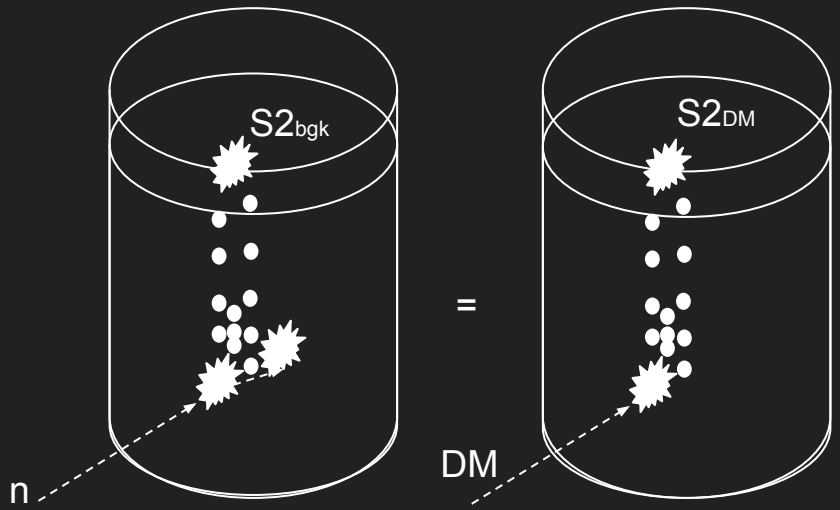
TPC bottom

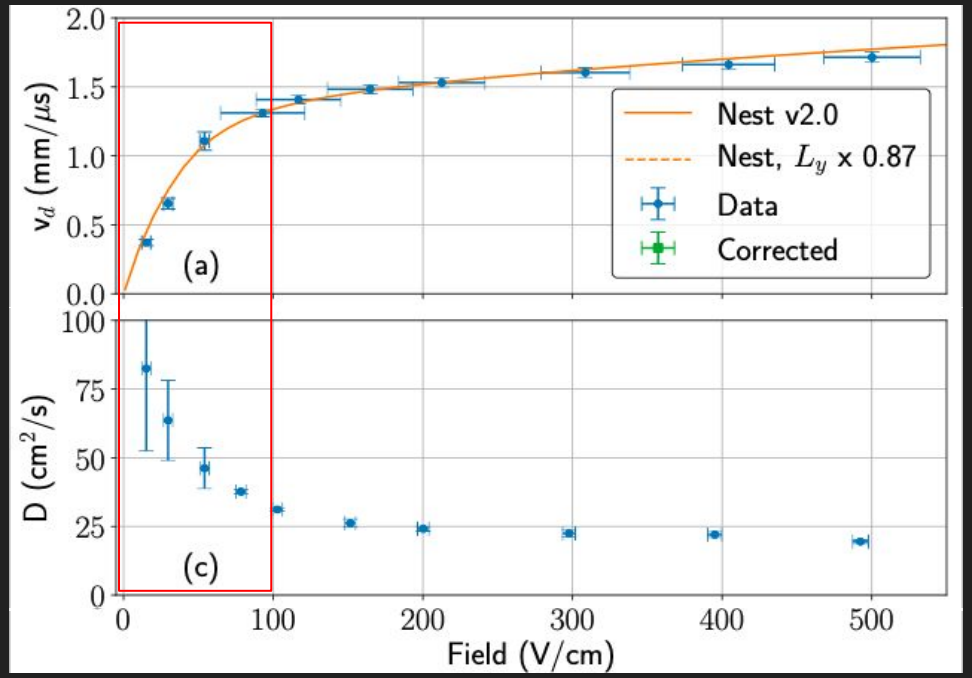
TPC top

Future TPCs

Implication for dark matter (DM) search:

- low V_d + high D
  - wide S2
  - multiple scatter background
    - z-position resolution





LIMITING SENSITIVITY TO DM SEARCH!

Conclusion

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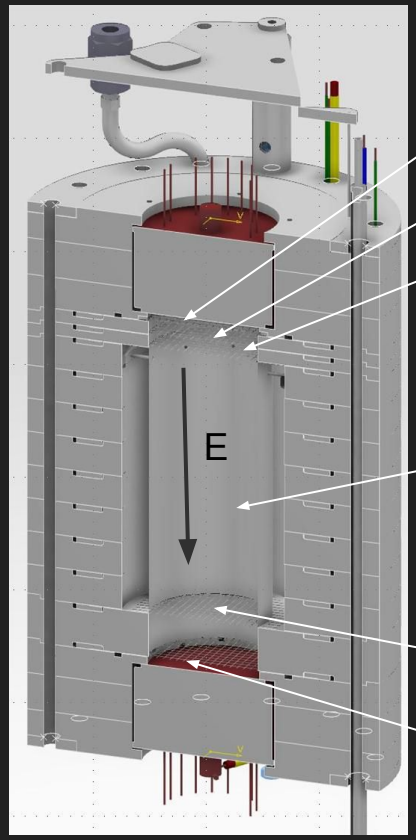
- XAMS - TPC R&D for dark matter direct detection
- SiPM characterization for lateral position reconstruction in XAMS
- XAMS field measurements for multiple scatter backgrounds in future (larger) TPCs

BACKUP

XAMS Description

- “Xenon Amsterdam”
- dual-phase TPC
  - PTFE
  - 154cm^3 active volume (Ø45 x 100 mm)
  - ~430g LXe at -90°C
  - PMT1 & PMT2 (UV sensitive - 178 nm)
  - 7 field shaping rings (resistor chain)
  - 5 meshes



top screen (~ -800 V)

anode (~ +2.5 kV)

gate (0 V)

active volume (LXe)

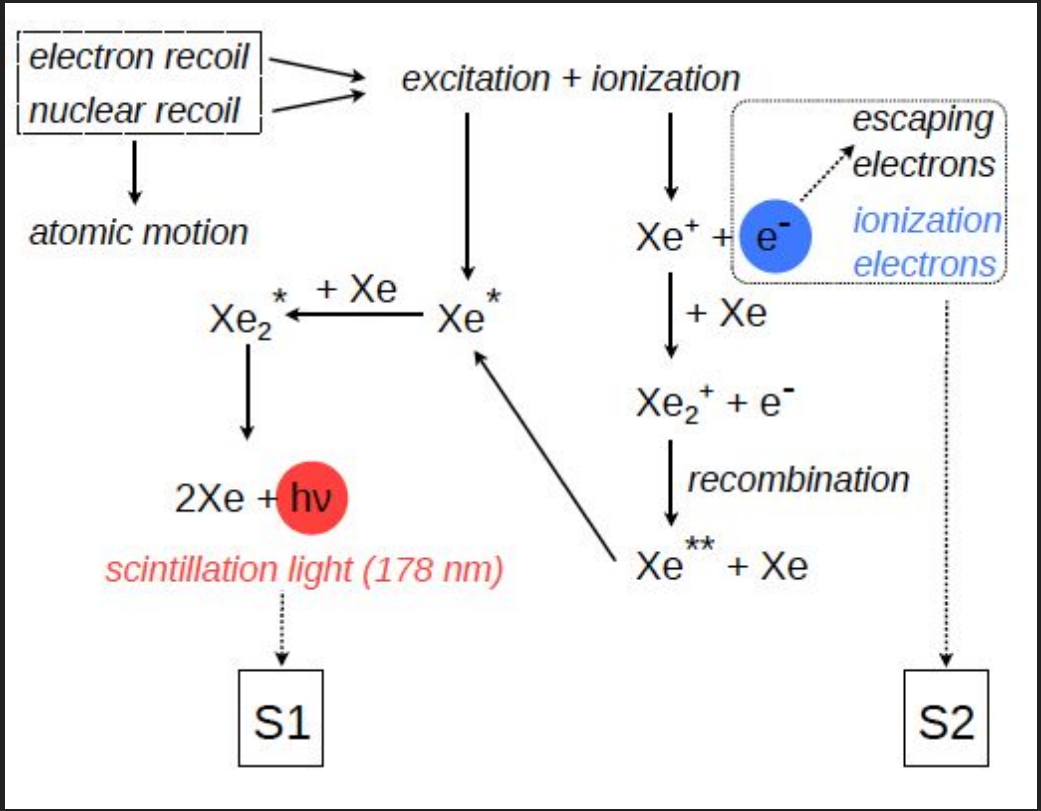
cathode (~ -5 kV)

bottom screen (~ -800 V)

Scintillation in Xe

Xe* = exciton

Xe2* = excimer



XAMS Signal Corrections

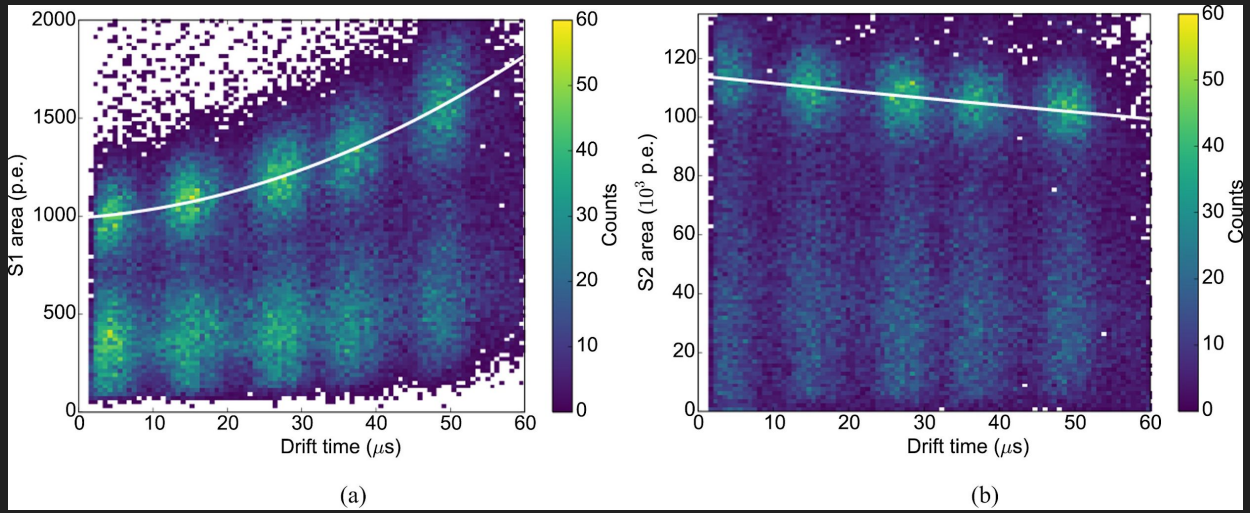
cS1:

- z-position dependence
  - opening angle
  - PTFE reflection
  - absorption by meshes and impurities

cS2:

- electron lifetime
  - xenon purity

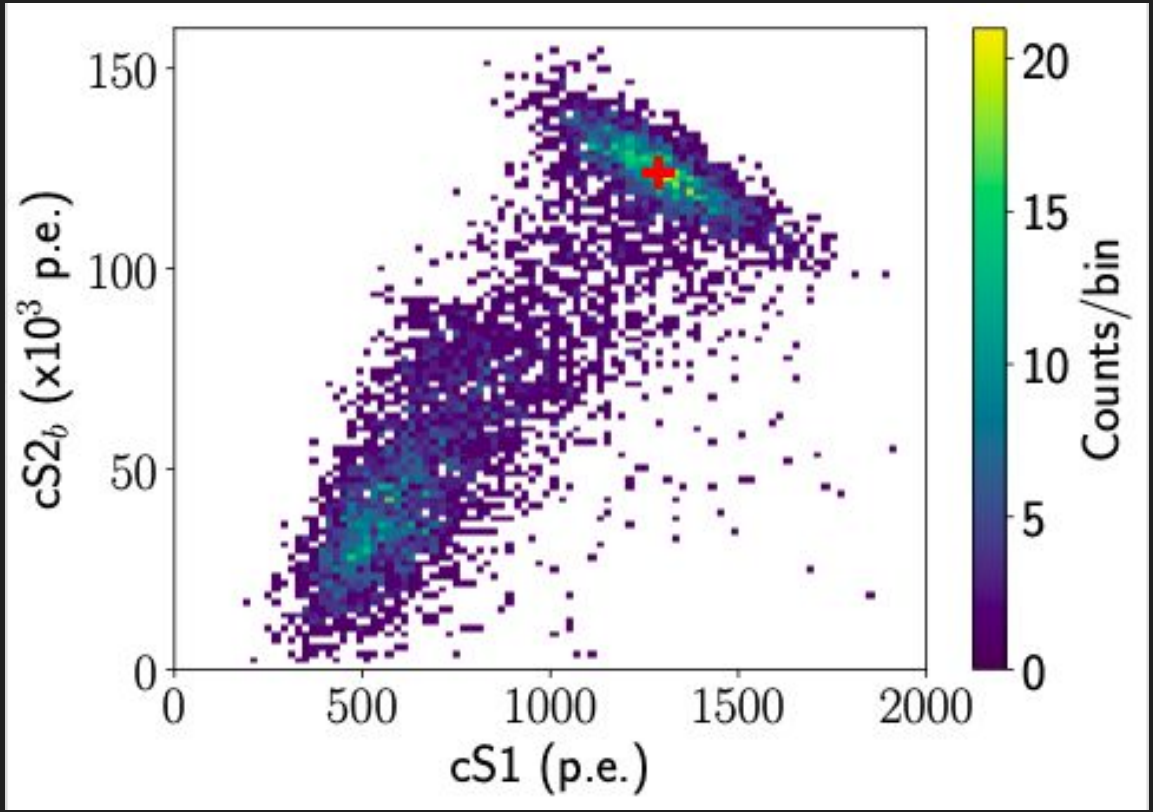
arXiv:1602.01974



low drift time ⟶ TPC top

high drift time ⟶ TPC bottom

XAMS cS2 vs cS1



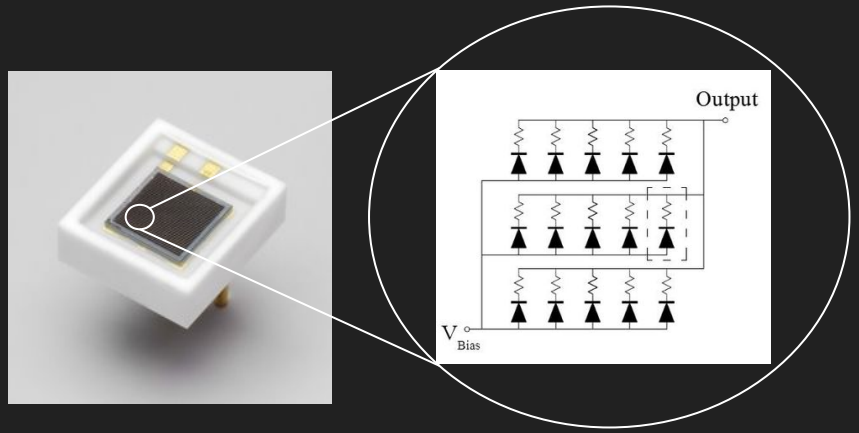
SiPMs

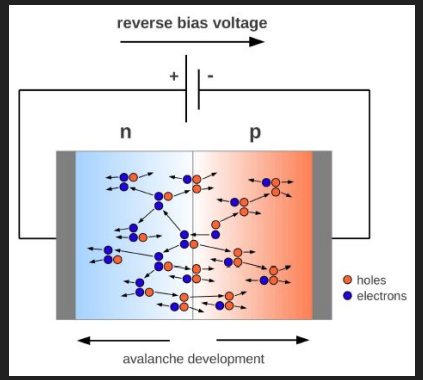
What is an SiPM?

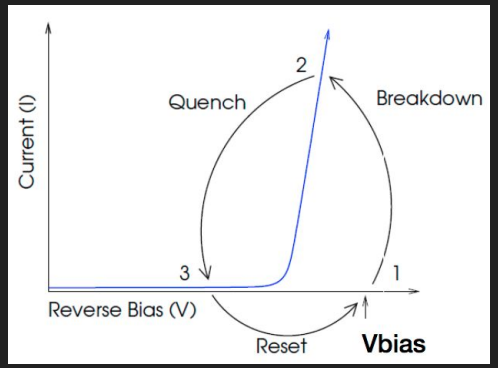
- solid state photodetector
- cells in parallel: G-APD + quenching

How does it work?

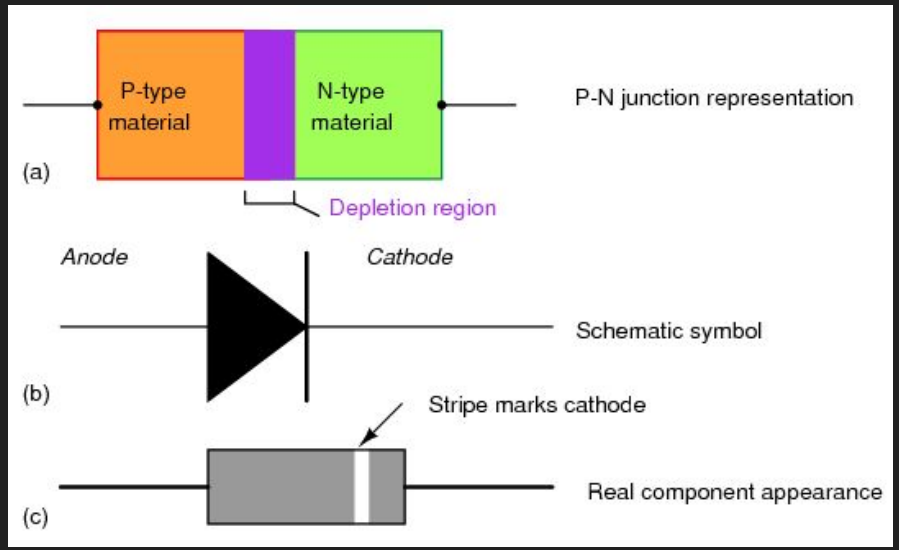
- SiPM in “Geiger mode” ($V_{bias} > V_{br}$)
- photon creates e^-/h^+ pair
- charge carriers impact ionize, creating an avalanche (current)
- current is quenched and G-mode is restored

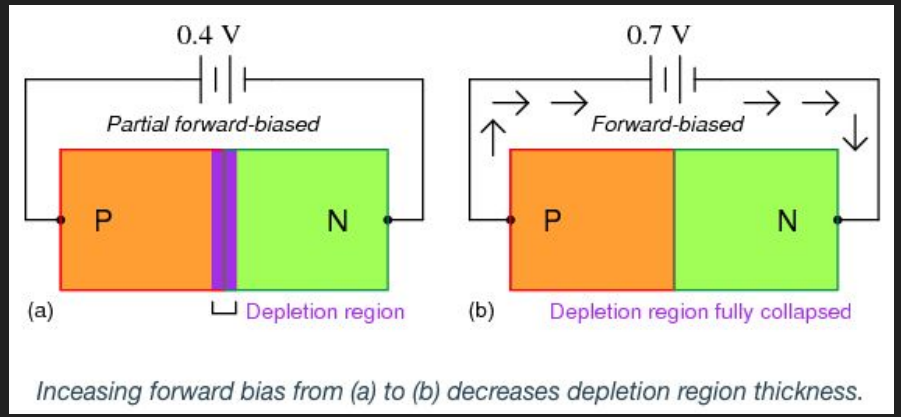


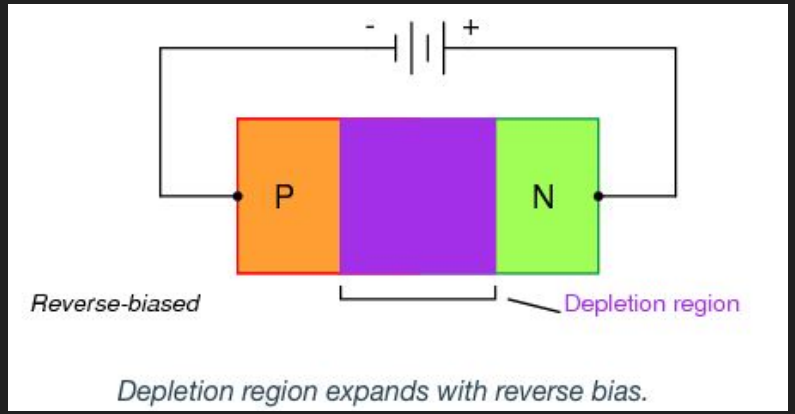




Diodes


P-type material
N-type material
P-N junction representation
(a)
Depletion region
Anode
Cathode
Schematic symbol
(b)
Stripe marks cathode
Real component appearance
(c)


0.4 V
0.7 V
Partial forward-biased
Forward-biased
P
N
P
N
(a)
Depletion region
(b)
Depletion region fully collapsed
Inceasing forward bias from (a) to (b) decreases depletion region thickness.


-
+
P
N
Reverse-biased
Depletion region
Depletion region expands with reverse bias.

Noise in SiPMs

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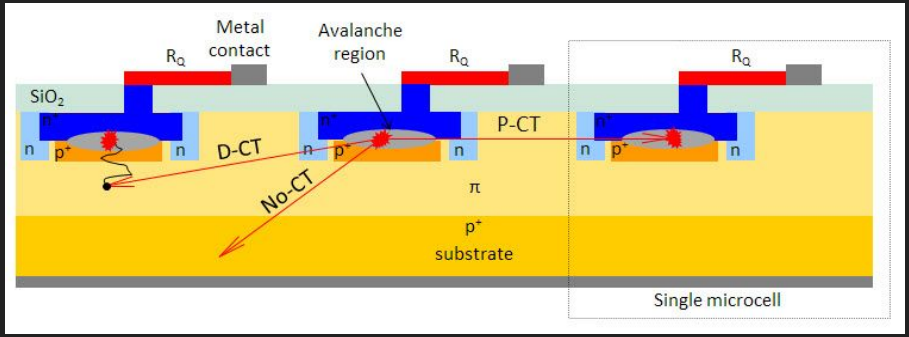
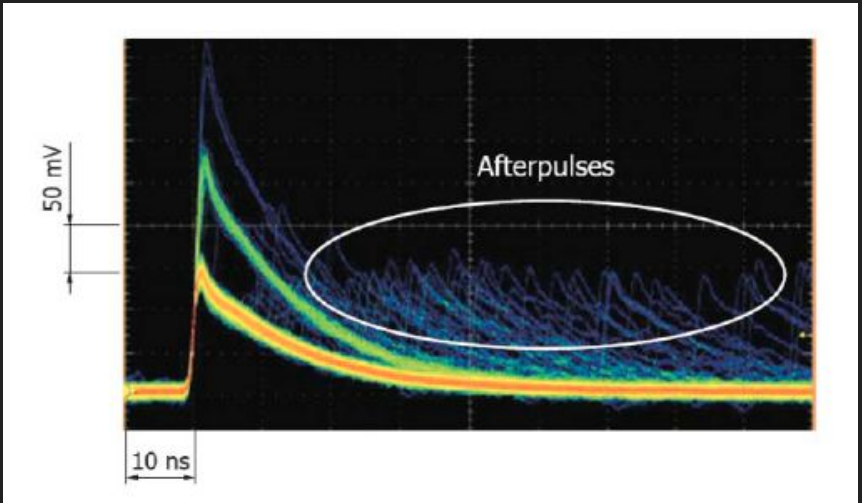
Noise sources in SiPM?

- Dark Count Rate
  - thermally generated
- Afterpulses
  - charge de-trapping
- Optical Crosstalk
  - charge carrier photon emission



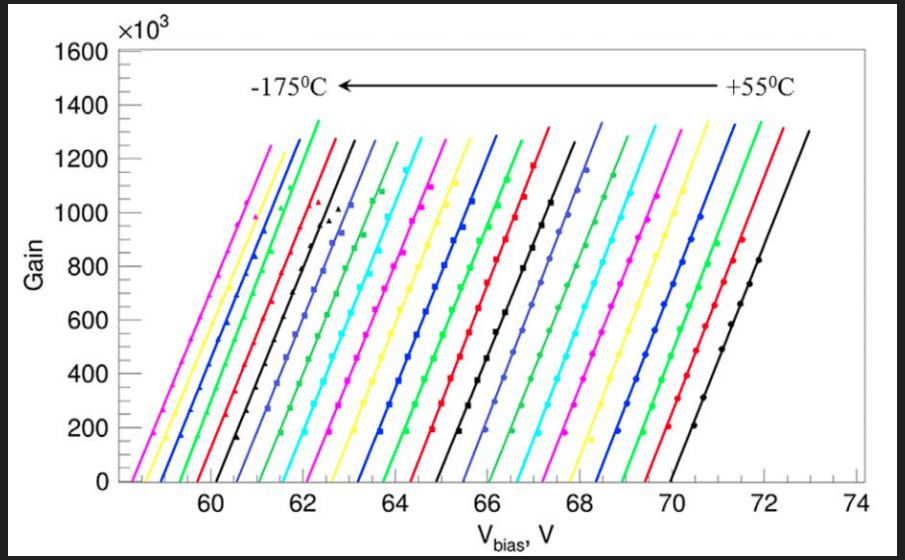
How to identify noise?

- Dark Count Rate
  - measurements in dark condition
- Afterfulses
  - pulse height + time delay
- Optical Crosstalk
  - time delay



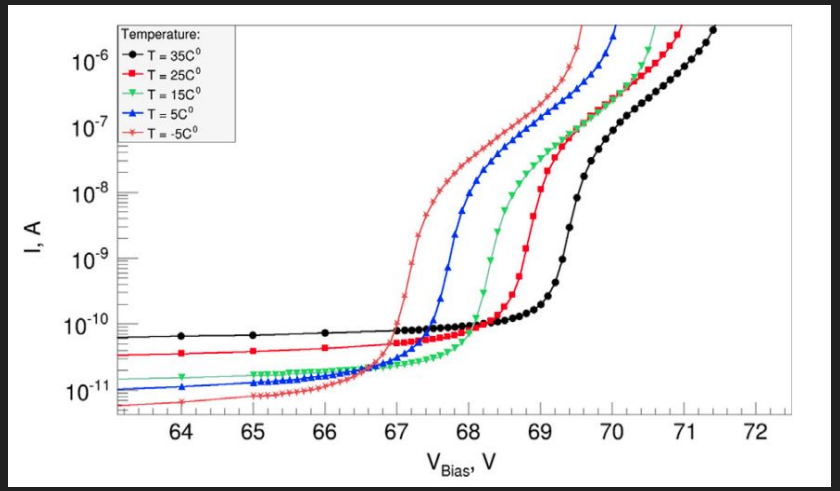
SiPM Gain Measurements

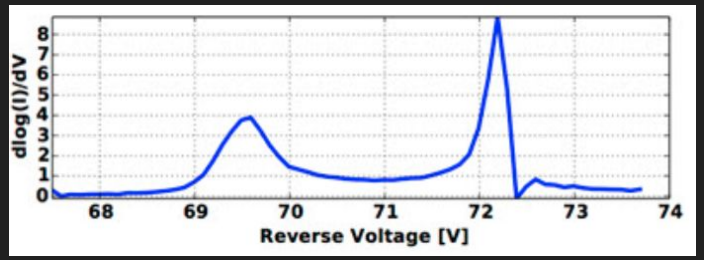
Example Result
(N. Dinu et al. 2014)



$$G_{mc} = \frac{Q}{e} = \frac{\int I(t)dt}{e} = \frac{\int V_{out}(t)dt}{R_{load}G_{amp}e} = \frac{C_J \Delta V}{e}$$

Example Result
(N. Dinu et al. 2014)

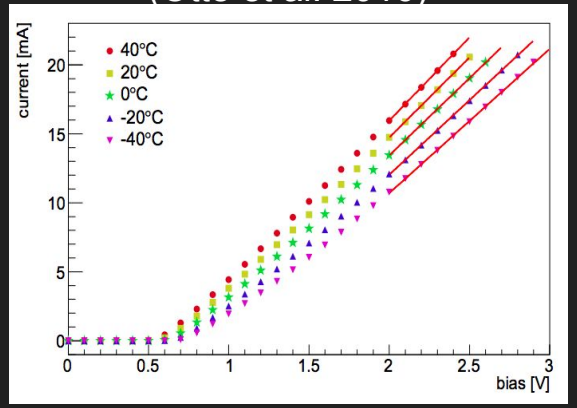


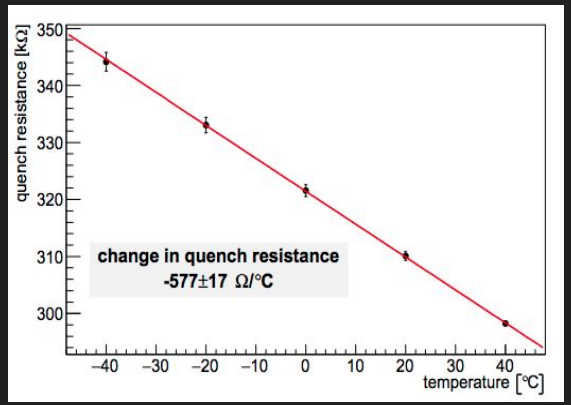


SiPM R_Q Measurements

Example Result
(Otte et al. 2016)

$$\frac{1}{R_{Q_{tot}}} = \sum_{i=1}^{N} \frac{1}{R_i} = \frac{N}{R_i} \rightarrow R_i = \frac{N}{R_{Q_{tot}}}$$





SiPM DCR Measurements

Example Result
(N. Dinu et al. 2014)