SIPM WORKSHOP
FROM FUNDAMENTAL RESEARCH TO INDUSTRIAL APPLICATIONS

CRYOGENIC SIPM-BASED PHOTO-DETECTORS FOR DARKSIDE

Bari 4/10/2019

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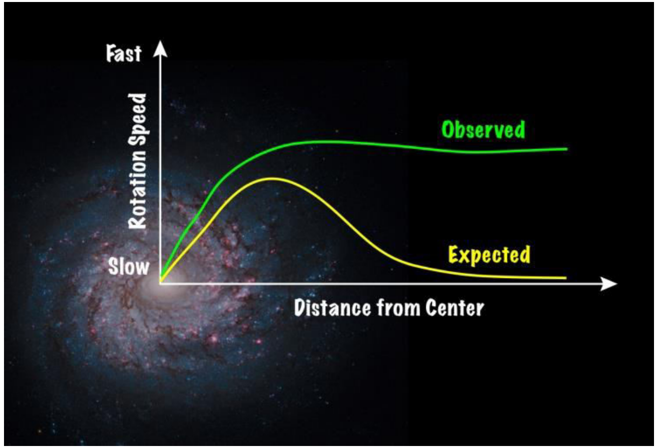
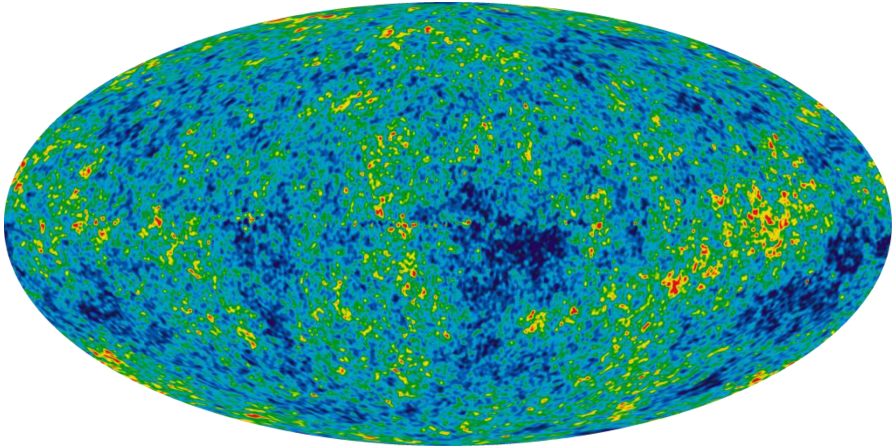
DarkMatter

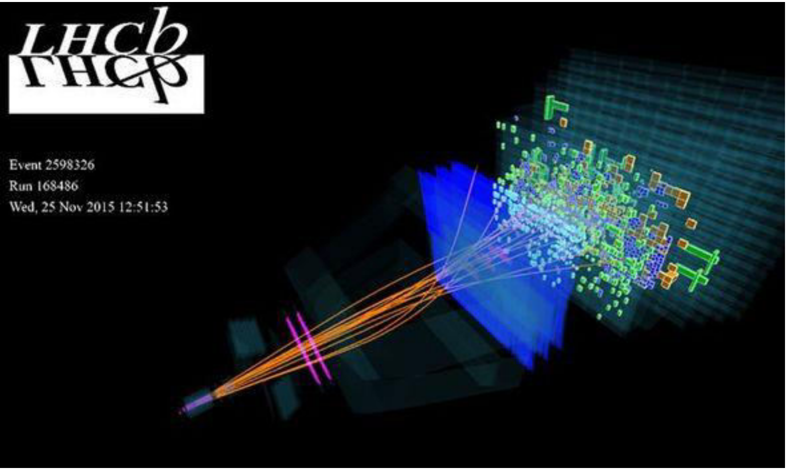
- Many evidences hint that ordinary matter accounts only for 15% of the total matter in the universe
  - The rotation curve of galaxies
  - Weak lenses
  - Cosmic microwave backgroung
- Dark matter is invisible to our telescopes
  - The primary candidate for dark matter is some new kind of elementary particle not yet discovered

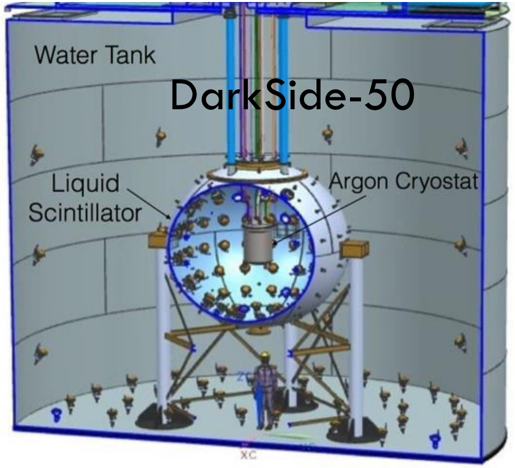




DM Detection techniques

- Dark matter can be probed with
  - Accelerators looking for missing energy in high energy interactions
  - Indirect searches looking for product of decay of DM particles
  - Direct detection experiments looking for interactions of DM particles in large instrumented detectors

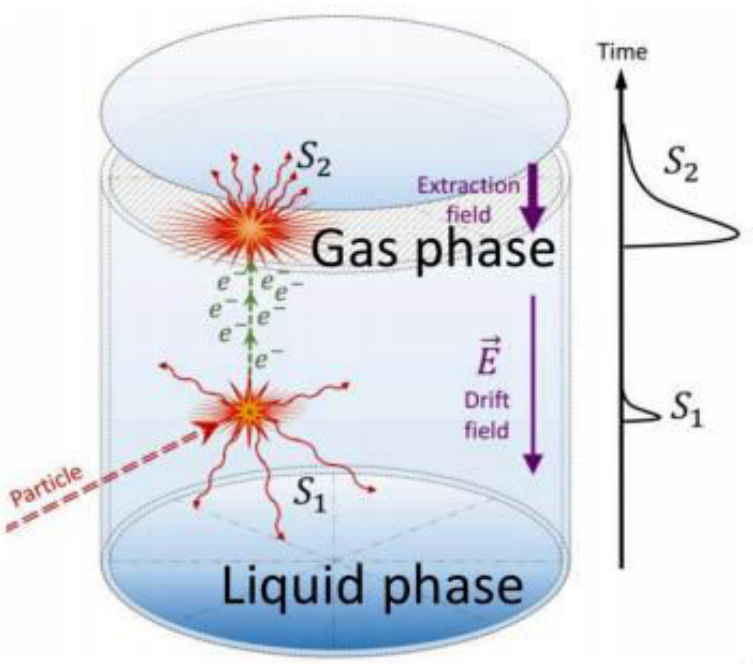




Direct detection challenges

- Assuming that the DM is constituted by weekly interacting particles (WIMPs)
  - The interaction rate with a 100 ton experiment is below few per year
  - While the natural radioactivity produce a background larger than 10^{15} interactions per year
- The challenge of dark matter detectors is to reduce the background to 0.1 counts/year
  - By installing the detectors in underground laboratories
  - By using selected low radioactivity materials to build the detector themselves
  - By designing experiments capable of tagging the background with high efficiency

Double phase TPCs



- In a dual phase time projection chamber a nobile gas is liquified (Ar, Ne, Xe)
- The interaction of a particle emits a primary light pulse (S1) ~ 100-1000 fotons in few µs
  - In the interactions electrons are generated as well
- The electrons are drifted toward a gas pocket on the top of the detector
  - Where they produce a second light pulse (S2)
    - ~ 1000-10000 photons in 20 µs
- The light is detected by a set of photo-detectors
- This configuration allows to reconstruct the position of the interaction
  - With a further suppression of external background

Pulse Shape Discrimination

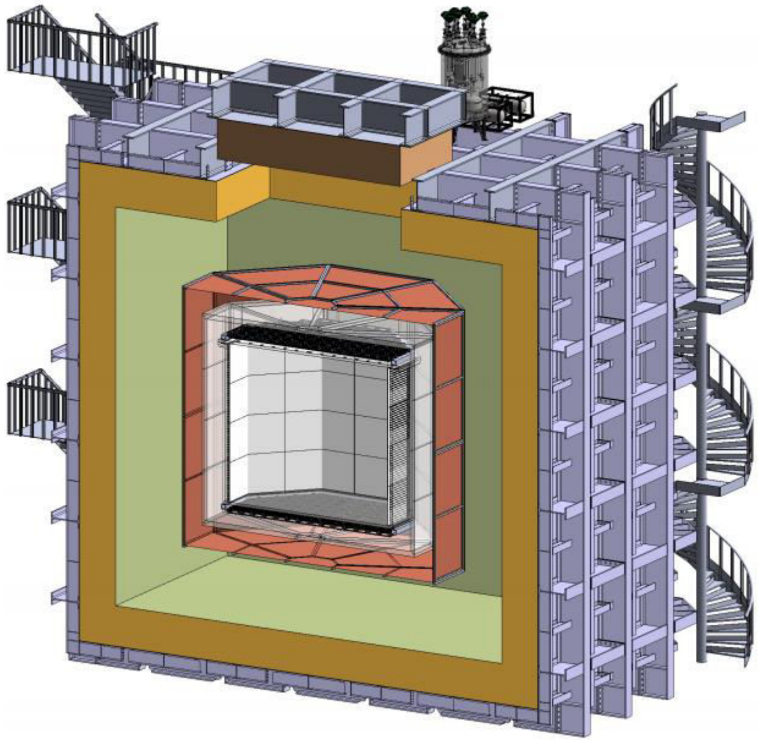
- For argon the light temporal profile of the S1 light strongly depends on the incoming particle
  - For nuclear recoils 70% of the light is emitted in the first 100 ns
  - For e^-/γ interaction only 30% is emitted in the first 100 ns
- It is then possible to develop an algorithm for discriminating nuclear recoils from electromagnetic interation
  - This technique has proven capable of a discrimination power of ~1 part over 10^9
- This is important because most natural background is e^-/γ
  - And we are looking for WIMPs-induced nuclear recoil
    - Thanks to the pulse shape discrimination (PSD) Ar-based detectors can reject most of the natural backgroung
- <u>Optimal light detection is of primary importance for LAr detector</u>

DARKSIDE-20K

DarkSide program

- The DarkSide collaboration aims to discover dark matter with a series of stepped size LAr-based detector
  - From 10 kg to 300 ton
- The collaboration includes about 300 scientist from Europe, Russia, USA, Canada, China, Brazil
  - And unites all the effort for argon-based dark matter experiments
- The DarkSide collaboration has a strong R&D program to improve the detector technologies
  - Light detection based on SiPM in collaboration with FBK
  - Extraction of underground argon to get rid of ^{39}Ar
    - Naturally present isotope in atmospheric argon with a 1 Bq/kg activity

DarkSide-20k



- DarkSide-20k is a dual phase TPC filled with about 50 ton of LAr
- The detector is installed in a cryogenic vessel designed for Proto-Dune
  - Containing about 700 ton of LAr
- The photo-detectors are SiPM-based
  - With a total instrumented surface of ~ 28 m^2
- On the other hand ^{39}Ar is a naturally recurring isotope in atmospheric argon
  - To suppress the background

DarkSide-20k facts

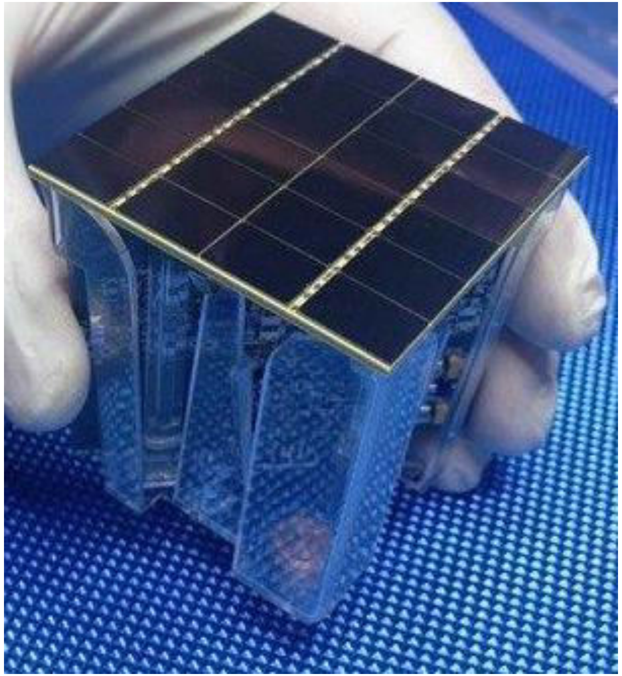
DS-20k TPC Dimensions	
TPC Drift Length	350 cm
Octagonal Inscribed Circle Diameter	355 cm
Total LAr Mass	51.1 t
Active LAr Mass	49.7 t
Fiducial Cut Distance (vertical)	70 cm
Fiducial Cut Distance (radial)	30 cm
Fiducial LAr Mass	20.2 t
Nominal TPC Fields and Settings	
Drift Field	200 V/cm
Extraction Field	2.8 kV/cm
Luminescence Field	4.2 kV/cm
Cathode Voltage	−73.8 kV
Extraction Grid Voltage	−3.8 kV
Anode Voltage	ground
Gas Pocket Thickness	7 mm
Grid Wire Spacing	3 mm
Grid Optical Transparency	97 %
SiPM PDM	
Number of PDM on TPC Top	4140
Number of PDM on TPC Bottom	4140
PDM Effective Area	$50 \times 50\,mm^2$

+ VETO ~ 3000

Parameter	Value
ProtoDUNE Cryostat parameters for AAr	
ProtoDUNE Cryostat inner width	8548 mm
ProtoDUNE Cryostat inner height	7900 mm
LAr height in ProtoDUNE Cryostat	7500 mm
Total AAr in ProtoDUNE Cryostat	700 t
ProtoDUNE Cryostat insulation per unit area	$6.5\,W/m^2$
Thermal Heat Load of ProtoDUNE Cryostat	2.7 kW
TPC PDM Cold Electronics Power	1.5 kW
Veto PDM Cold Electronics Power	0.5 kW
AAr System Design Mass Circulation Speed	10 000 std L/min
Minimum heat recovery efficiency of AAr heat exchanger	>95 %
AAr Turn Over Time	30 d
Total Cooling Power Required	10 kW
LAr boiling threshold at 3 m depth	$60\,mW/cm^2$
Minimum AAr condenser cooling power to hold LAr inventory	2.7 kW
ProtoDUNE AAr top pressure	1.075 bar

Photo Detector Module

- The Photo Detector Module (PDM) is the light sensitive unit of DarkSide-20k
  - 24x SiPM 12x8 mm^2 mounted on a tile
  - A front-end cryogenic pre-amplifier with differential output
- PDMs are sensitive to the single photons
  - Up to a total of few thousands photons
- Each PDM is connected to a 120 MS/s digitizer
  - the acquired waveform is digitally processed
    - To extract only the photon arrival time & charge
- Offline the collected times & charges are summed
  - To reconstruct the original shape of light emission
    - Extracting the physical data of the interaction



total energy, asymmetry, pulse shape, event position, ...

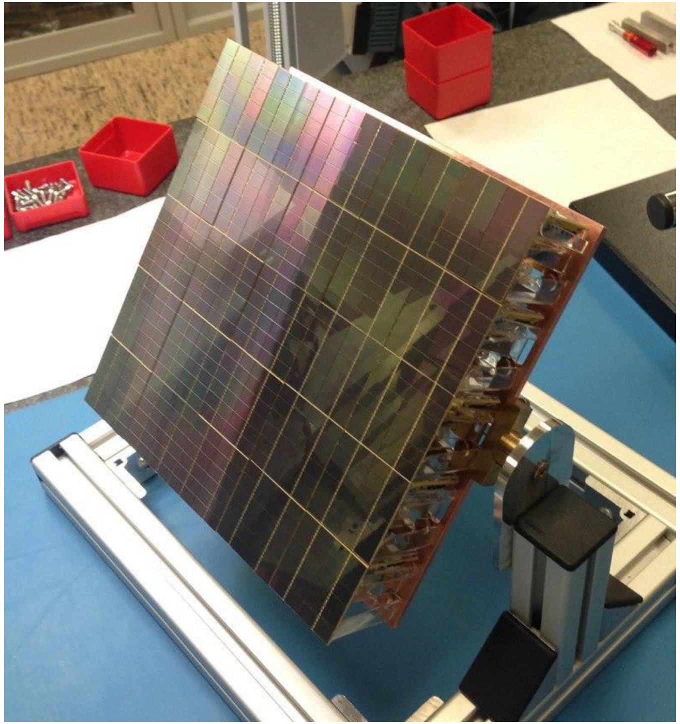
PDM specifications

- The specifications for the PDMs of DS20k require
  - 5x5 cm^2 surface
  - PDE @ 420 nm > 40%
  - DCR < 0.08 cps/mm^2
  - Baseline hit rate $\leq$ DCR $\leftrightarrow$ SNR > 8
  - Timing resolution ~ 10 ns

Baseline hit happens when the baseline noise (gaussian) goes above threshold emulating a real photo-electron.
Can be reduced with low noise front-end

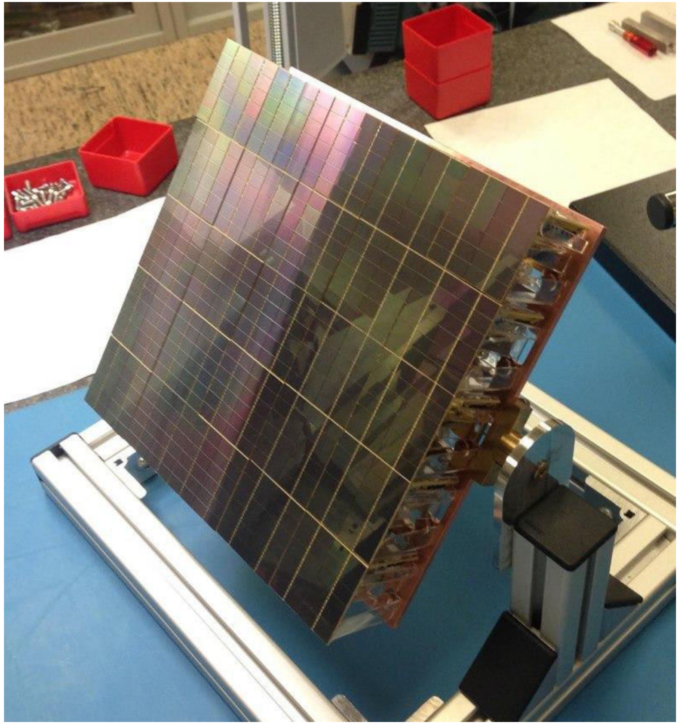
- These parameters directly impact the PSD
  - In the integration window of 6 μs
    - $20.7\ m^2 \circ 6\ \mu s \circ DCR = 10$ pe
  - Larger random hits could spoil the PSD at low energy

Motherboards



- PDMs are mounted on motherboards
  - 25 PDM per motherboard
- Each motherboard has
  - A power distribution hub capable of disabling individually each PDM
    - Called steering module
  - A differential to optical linear transmitter
    - Signals are extracted over high purity optical fibers
      - No faraday cage penetration, no ground loop → less noise
- The PDMs are installed on a high purity copper frame

Motherboards



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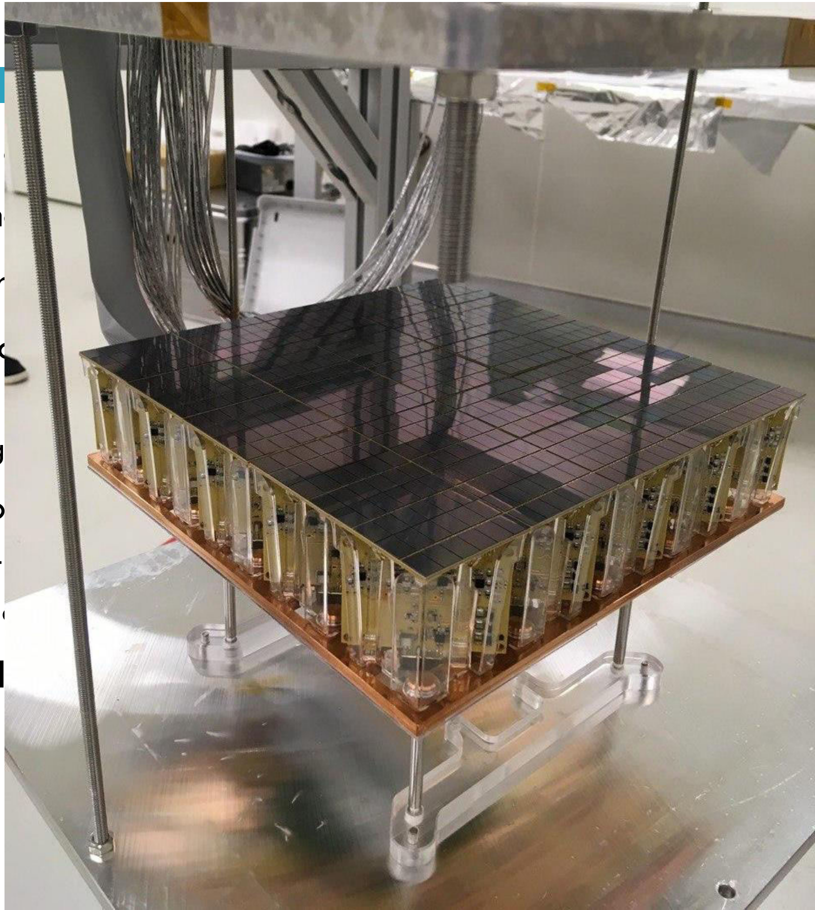


CRYOGENIC SIPMS

Collaboration with FBK

Collaboration with FBK started in 2014

- A shared R&D path started to improve the performances of SiPMs at cryogenic temperature

NUV-HD → Stable at 77 K only with High R_q; DCR too high

↓

NUV-HD-LF → Stable at 77 K up to 5 VoV; DCR ~ 5 mcps/mm^2

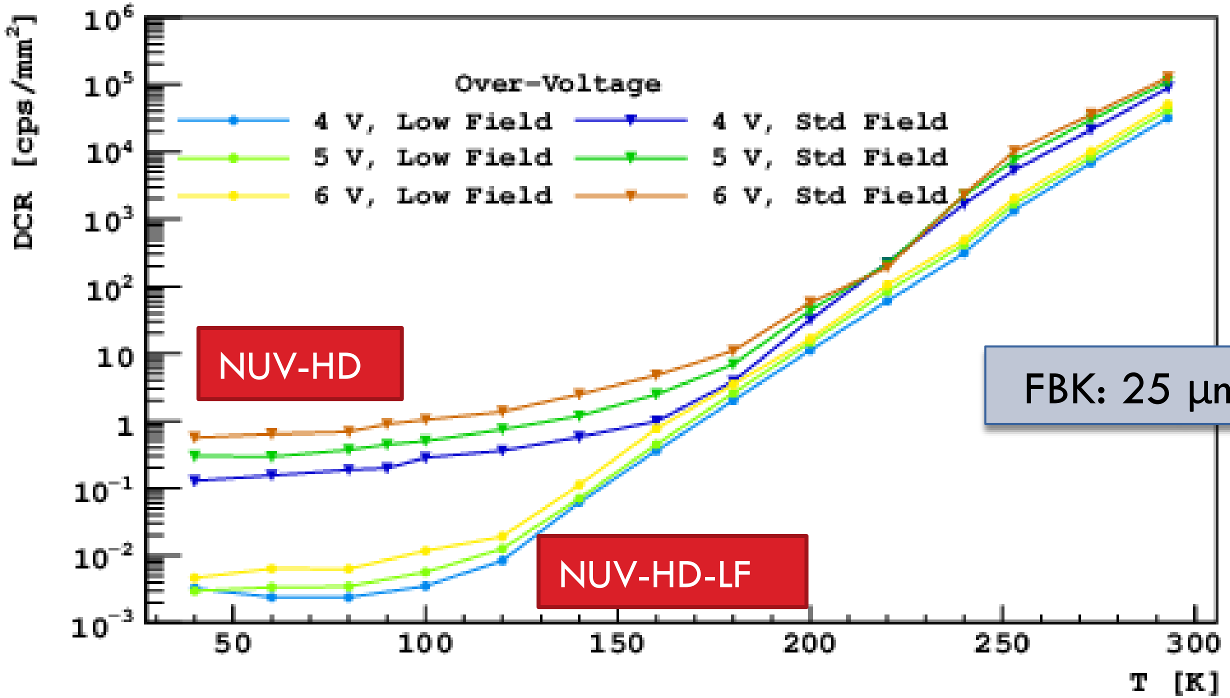
↓

NUV-HD-Cryo → Stable at 77 K beyond 9 VoV; DCR ~ 5 mcps/mm^2

RGB-HD → Stable at 77 K; DCR too high; PDE not matched

NUV-HD vs NUV-HD-LF

DOI 10.1109/TED.2016.2641586



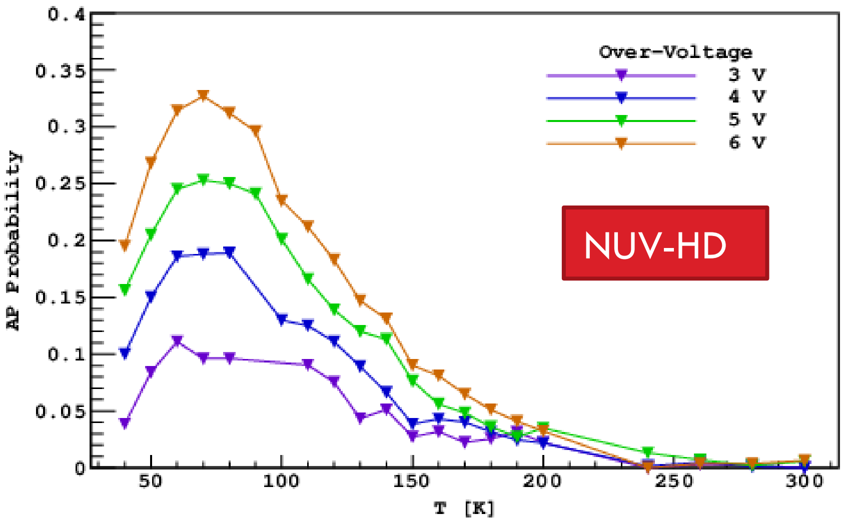
FBK: 25 µm ~15 MΩ

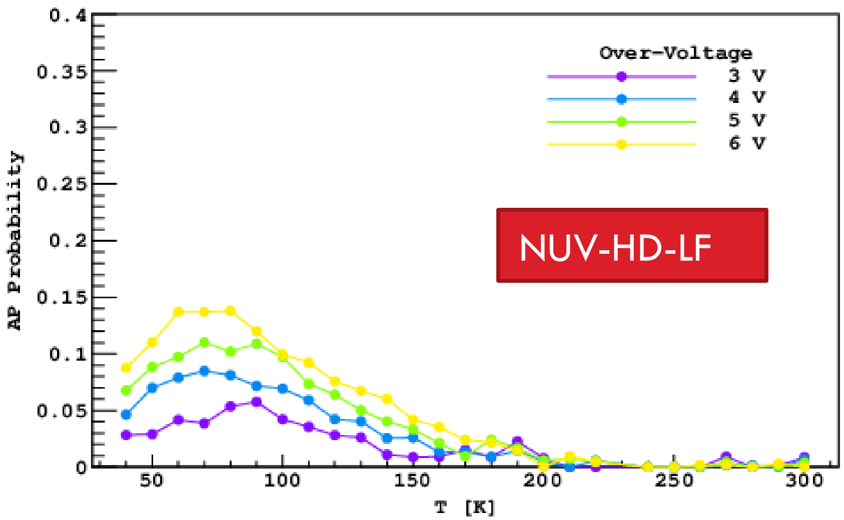
Below 150 K the tunneling is the main contribution to DCR

Lower field ↔ lower DCR

NUV-HD vs NUV-HD-LF

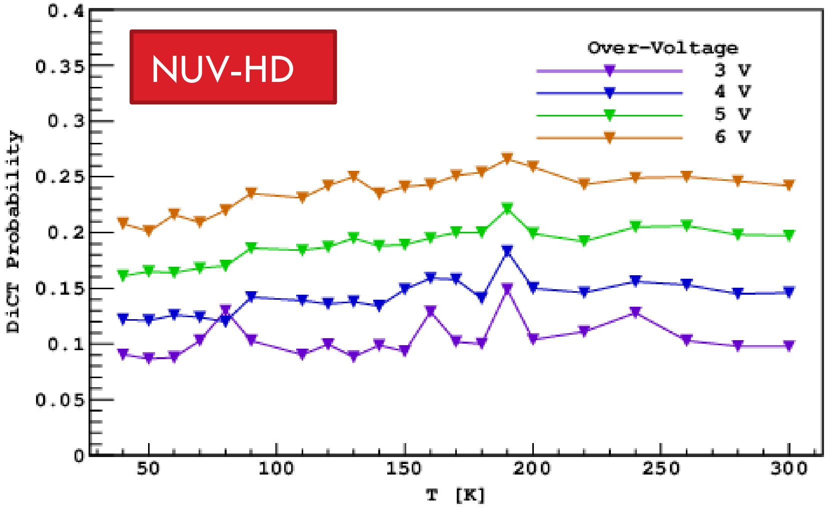
After-pulse probability

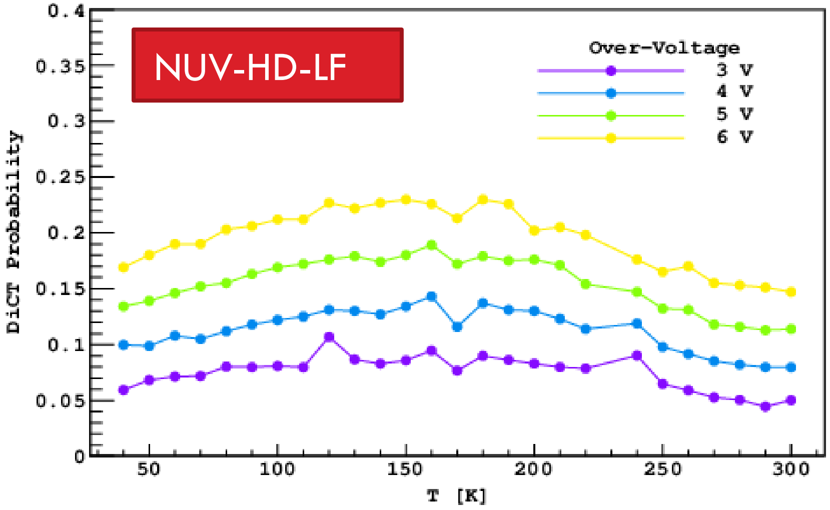




NUV-HD vs NUV-HD-LF

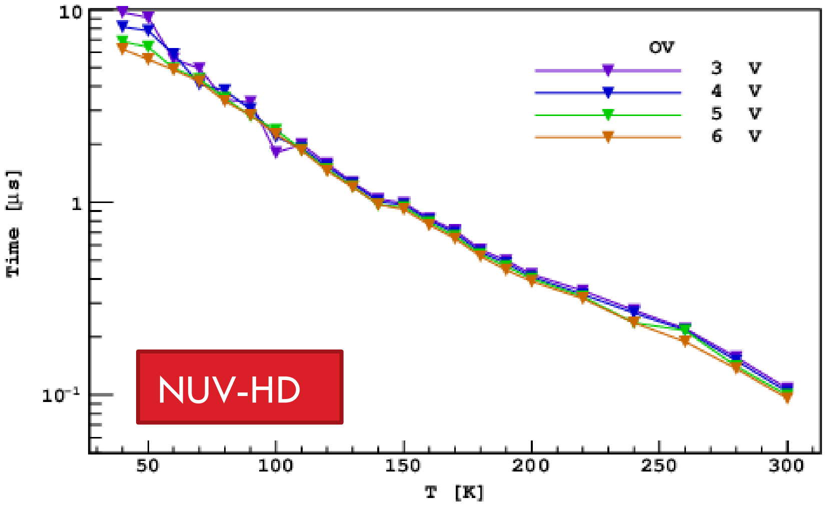
Direct Cross-Talk probability

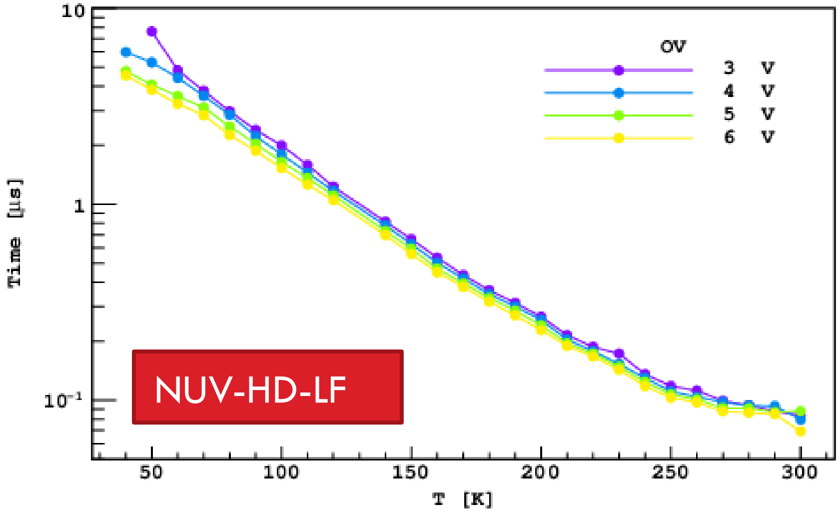




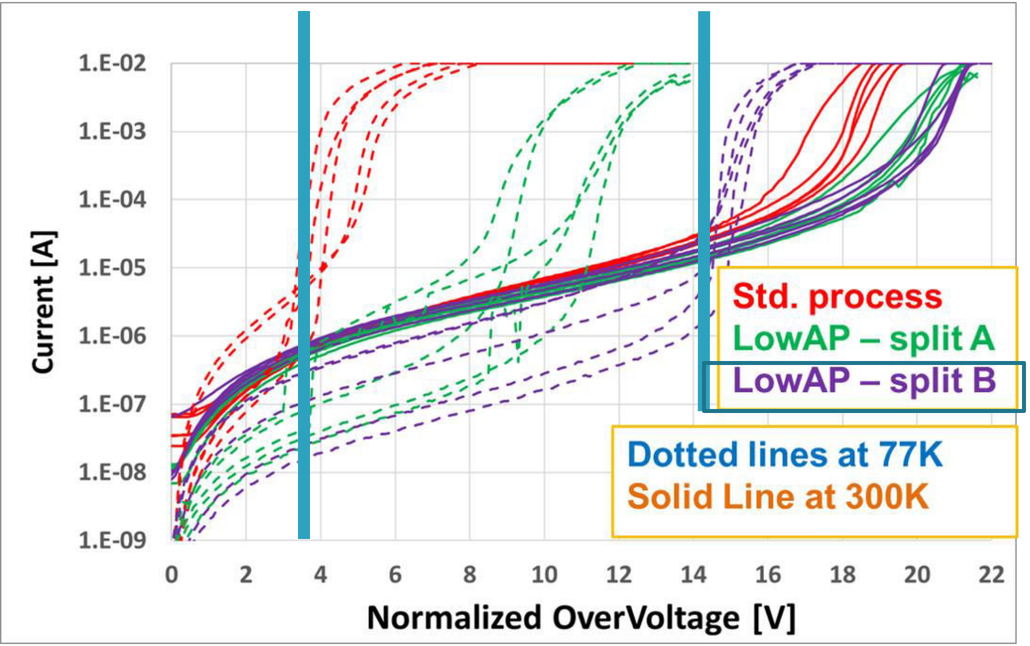
NUV-HD vs NUV-HD-LF

Recharge time



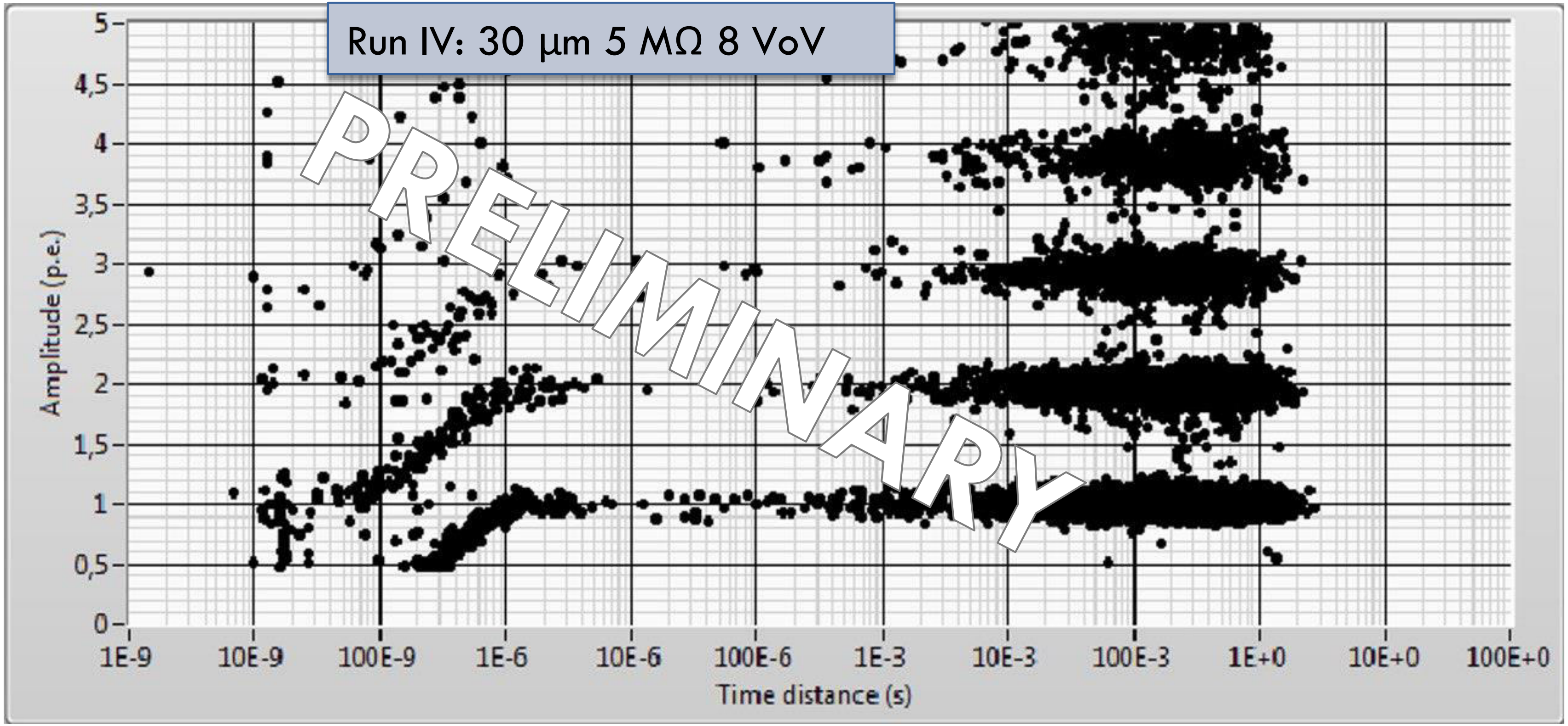


NUV-HD-Cryo



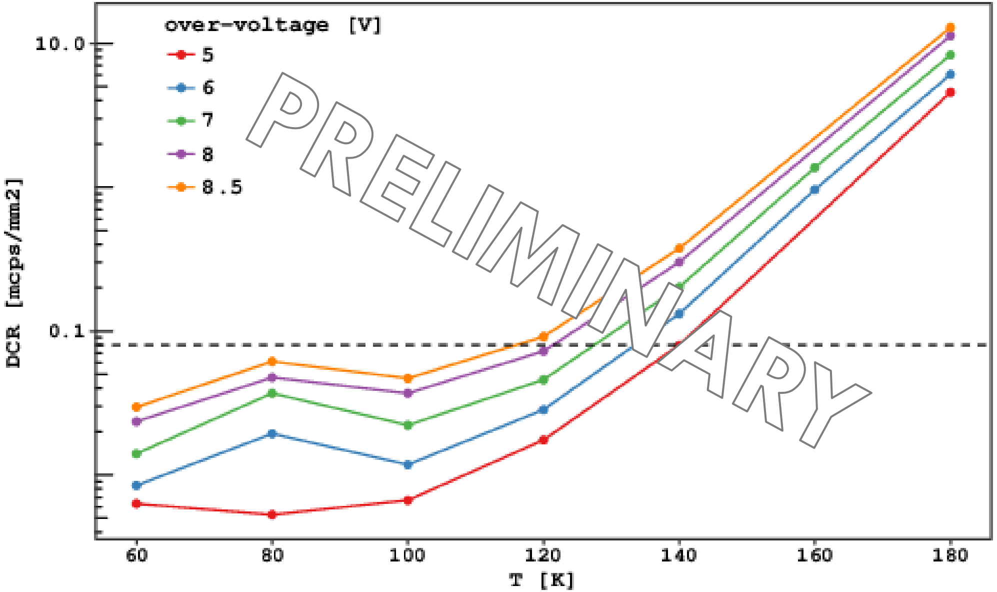
- The main limitation of NUV-HD-LF is the narrow overvoltage for stable operation at 80 K with short recharge time (small R_q)
  - 5 VoV with recharge time ~ 300 ns
- NUV-HD-Cryo were developed to overcome this limitation
  - Up to 14 VoV

NUV-HD-Cryo

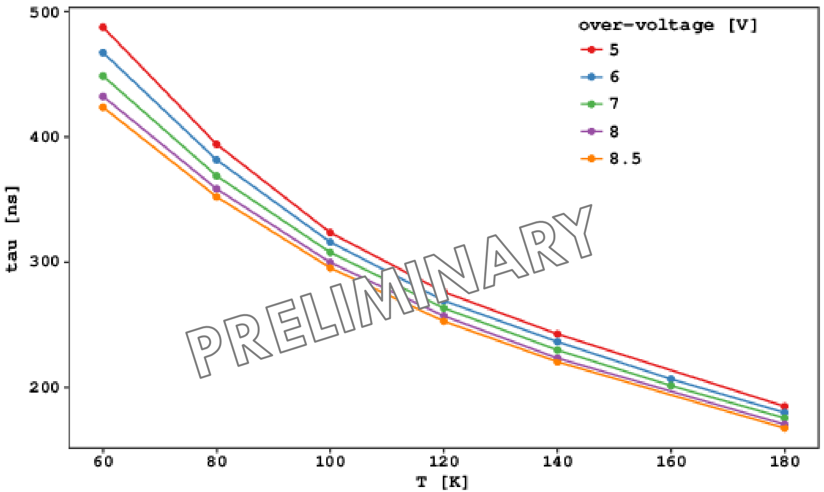

Run IV: 30 µm 5 MΩ 8 VoV
PRELIMINARY
Amplitude (p.e.)
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
5
1E-9
10E-9
100E-9
1E-6
10E-6
100E-6
1E-3
10E-3
100E-3
1E+0
10E+0
100E+0
Time distance (s)

NUV-HD-Cryo

Run IV: 30 μm 5 MΩ



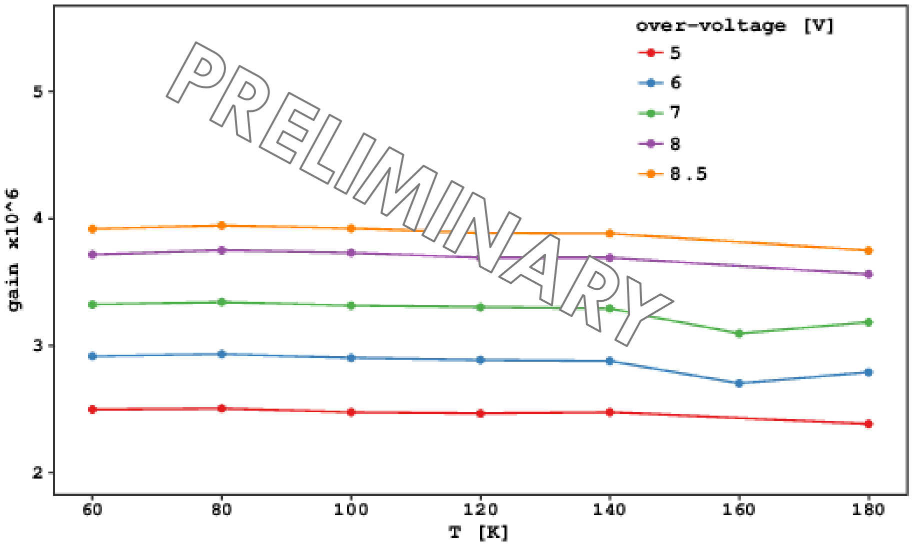
Data analysis ongoing

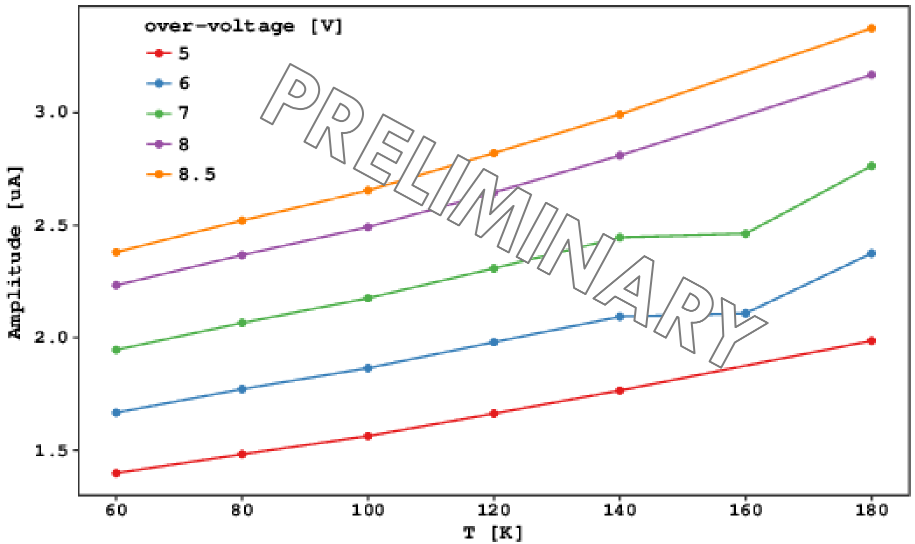


@ 9 VoV the DCR is ~60 mcps/mm^2

With a recharge time ~ 350 ns

NUV-HD-Cryo


over-voltage [V]
5
6
7
8
8.5
PRELIMINARY
gain x10^6
T [K]
60
80
100
120
140
160
180
2
3
4
5


over-voltage [V]
5
6
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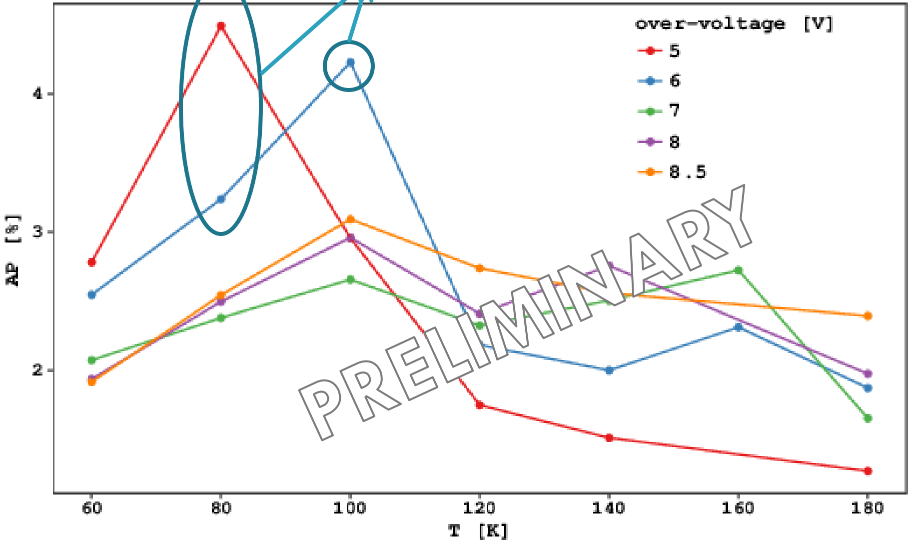
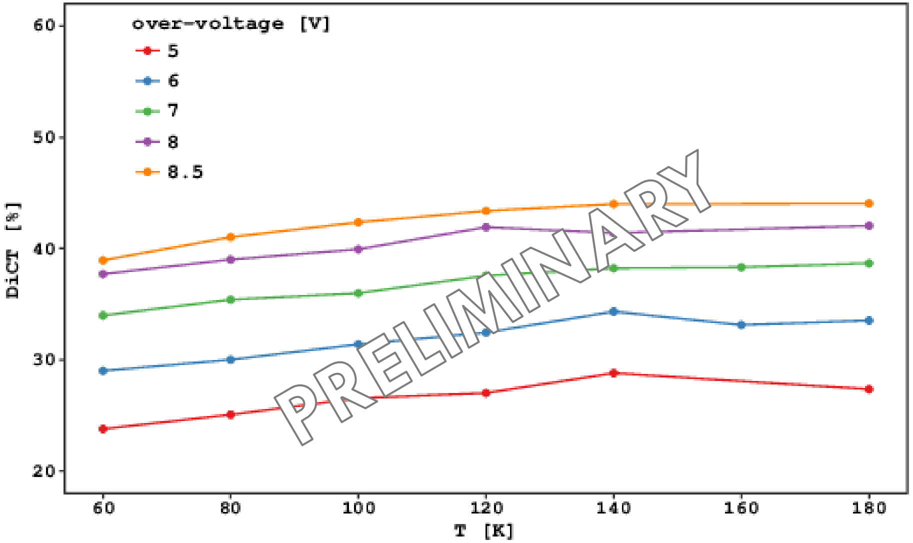
8
8.5
PRELIMINARY
Amplitude [uA]
T [K]
60
80
100
120
140
160
180
1.5
2.0
2.5
3.0

NUV-HD-Cryo

baseline noise ⟷ data analysis ongoing



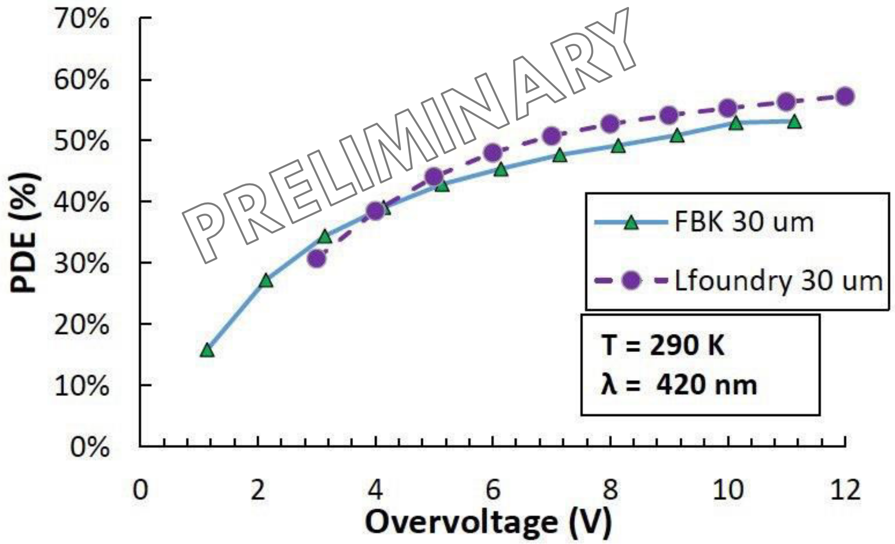


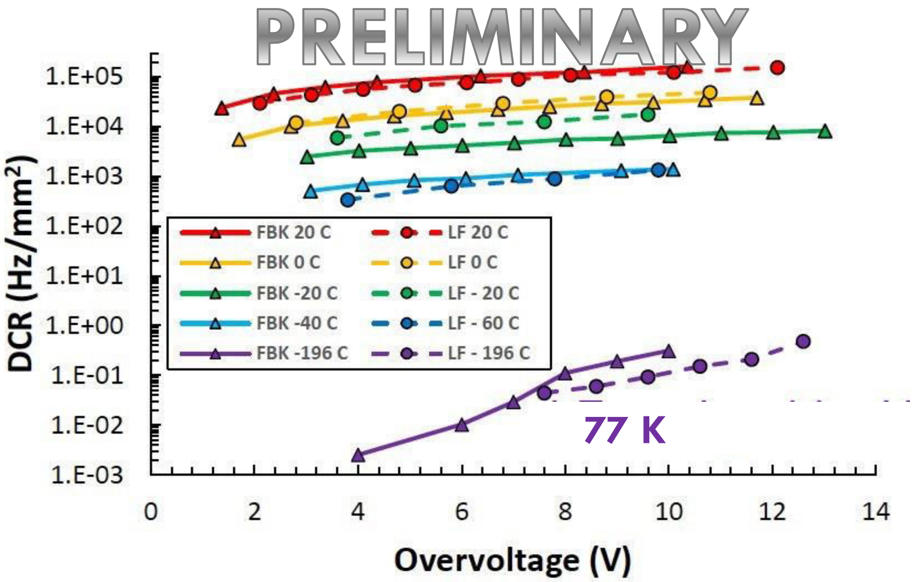
The Afterpulse is always lower than few %

LFoundry

- For DarkSide-20k around 28 m^2 of SiPMs are required
  - The collaboration opted to produce them in an industrial grade foundry
  - LFoundry won the INFN tender for silicon production
- FBK started transfering the NUV-HD-Cryo technology to LFoundry in 2018
  - A first test run was produced and verified in FBK
    - 1x1 mm^2 with several variants to qualify the processes
    - The results are very positive
      - Smaller issues were found with the backside metallization
- 3 runs 8x12 mm^2 are going to be delivered within mid October
    - 25 8" wafers each corresponding to ~ 250 * 75 SiPMs
    - These SiPMs will be used to instrument a 1 ton prototype
- LFoundry & DarkSide are collaborating to have deep TSV for the forth test run

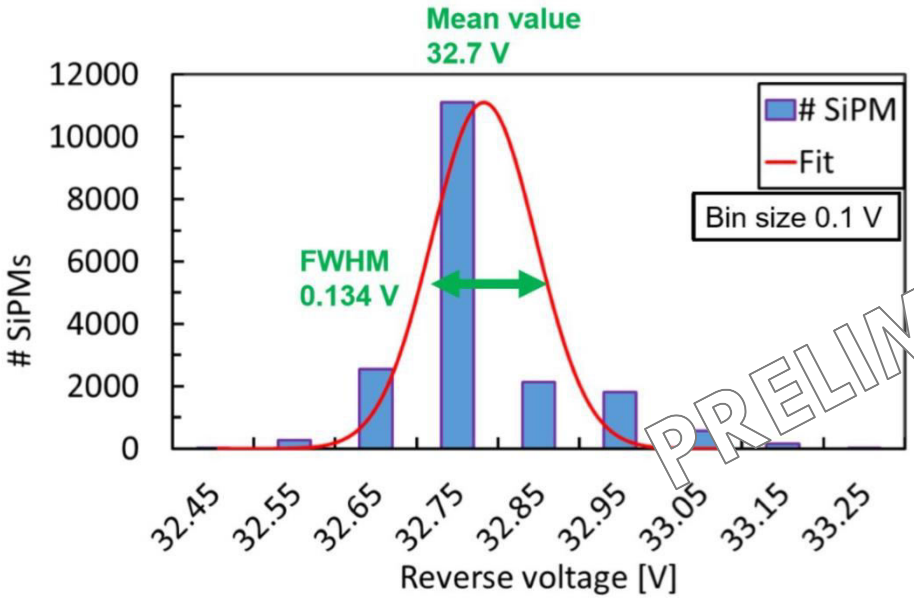
LFoundry NUV-HD-Cryo

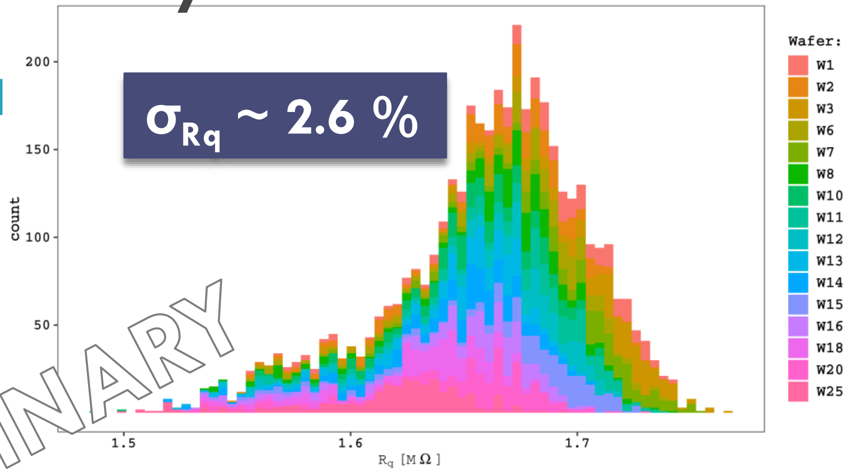


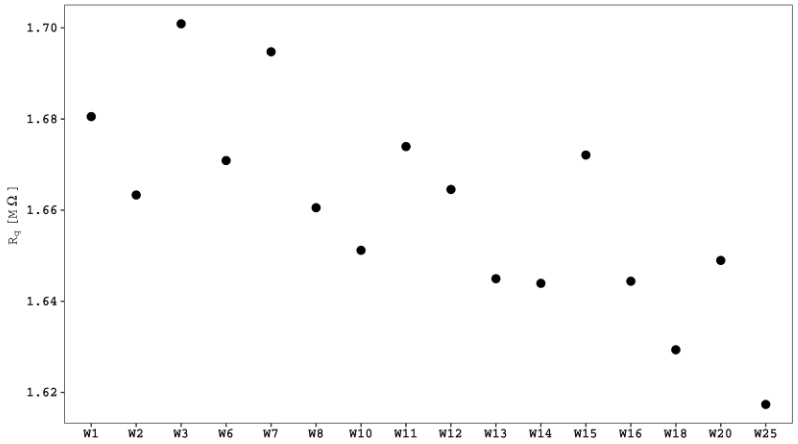


Direct FBK vs LFoundry production

LFoundry NUV-HD-Cryo





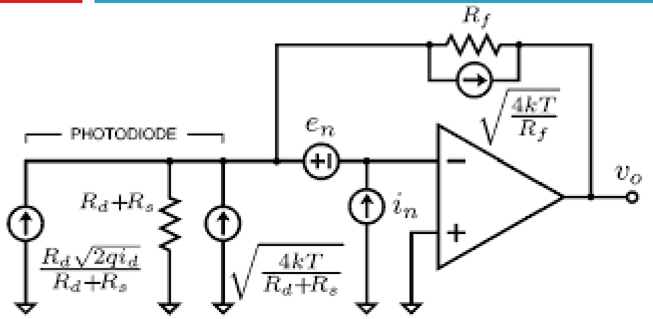


CRYOGENIC FRONT-END

Cryogenic front-end board

- A PDM includes 24 SiPMs 12x8 mm^2
- An analog aggregated output is desired
  - Equivalent to a 2”-3” PMT
- A cryogenic front-end board is required
  - Capable of managing the ~ 24 x 5 nF capacitance of the SiPMs
  - To locally amplify the signal to few mV/pe scale
  - With good SNR (>8), bandwidth (>30 MHz) & dynamic range (>50 pe) to fulfill the PDM requirements
    - A trans-impedance amplifier topology is needed
  - With low power dissipation to avoid bubbling
  - Using low radioactivity components

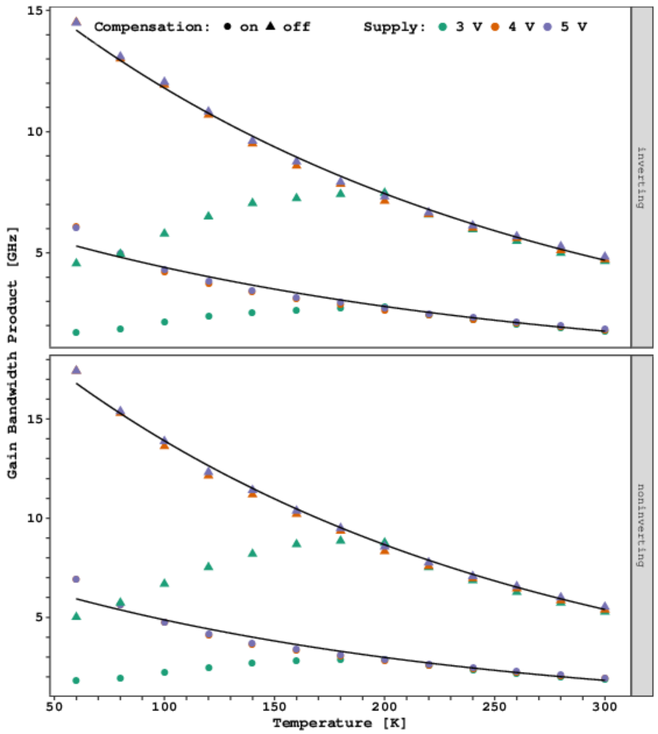
Heterojunction electronics



- Standard BJT detectors are not working < 150 K
- FET are working down to 10-40 K
- FET technology typically: $e_n \sim 4$ nV/√Hz & $i_n \sim 10$ fA/√Hz
- For fast TIA amplifiers e_n is more important than i_n
- FET technology may not be the best choice

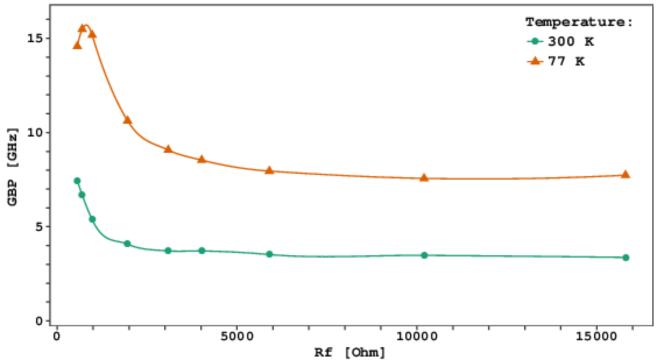
- Most producers are distributing heterojunction BJT based amplifiers
  - For high bandwidth applications (GHz) or for very low noise applications (sub-nV/√Hz)
- HBTs are great signal amplifiers at cryogenic temperature
  - They are BJT -> very low en
  - Low 1/f noise
  - Noise and bandwidth improve at cryogenic temperature

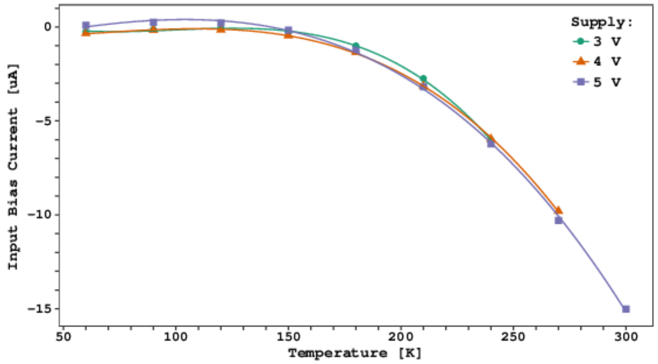
LMH6629 characterization



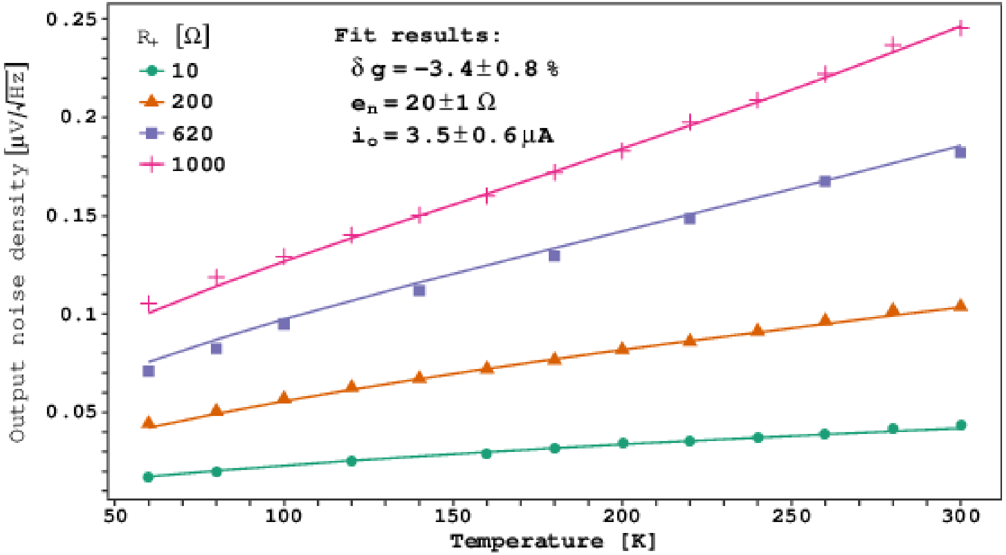
LMH6629 from TI:

- Works down to 40 K
- Stable for |Av| > 10
- Very high bandwidth
  - 4 GHz
    - Up to 15 GHz @ 77K
- Very low noise
  - 0.6 nV/√Hz
    - 0.3 nV/√Hz
- Max bias 5 V
  - 60 mW @ 77 K
- P_{out}(1dB) = 16 dBm
  - 3.8 Vpp





LMH6629 Noise Model



$$N_o = \frac{G}{2}\sqrt{4k_B T R_{eq}^J + e_n^2(T) + i_n^2(T) R_i^2}$$

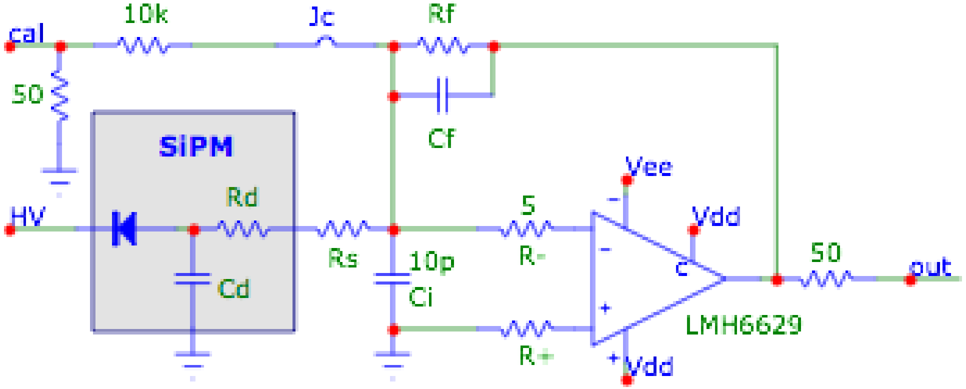
Where:

- R_{eq} accounts for all resistors
- e_n is modeled as a Johnson source
- i_n is the Shotky noise of $|i_b| + |i_o|$
- N_o is the output noise density @ 1MHz
- The fit reproduces the data at better than 2.5 %

<u>The voltage noise density of the LMH6629 is equivalent to a 20 Ω resistor</u>

M D'Incecco et al., IEEE TNS 65,4,18

TIA design & results on SiPM



- Standard trans-impedance design
  - Based on operational amplifier
- Few tweaks for stabilization
  - R_+ , R_-, C_i
- C_f is due to parasitic effects (~0.2 pF)
- The series resistor R_s reduce the noise gain

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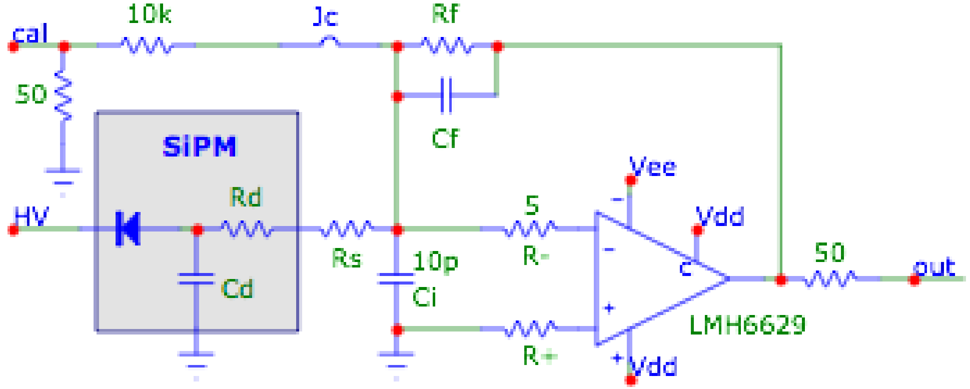
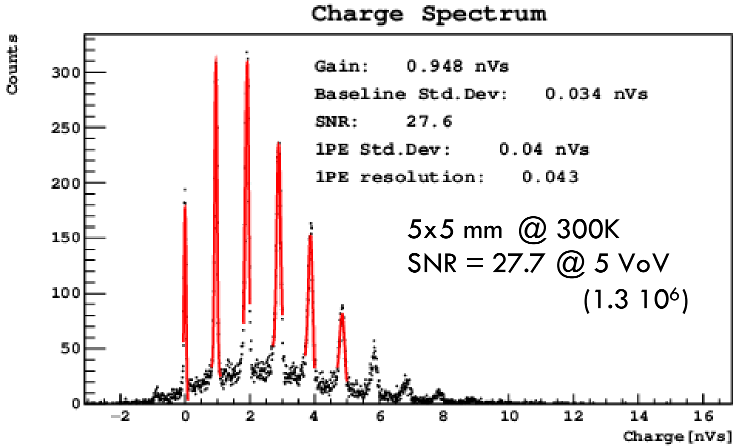
TIA design & results on SiPM

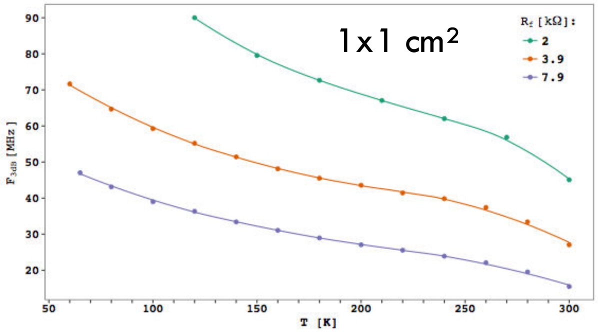


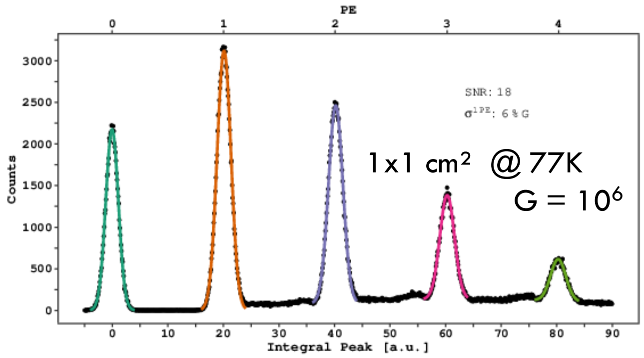


5x5 mm @ 300K

SNR = 27.7 @ 5 VoV

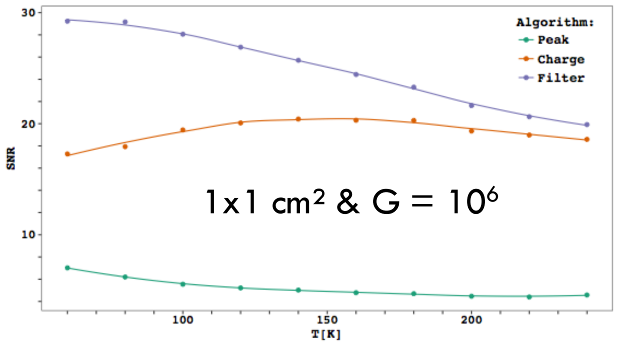
($1.3\ 10^6$)





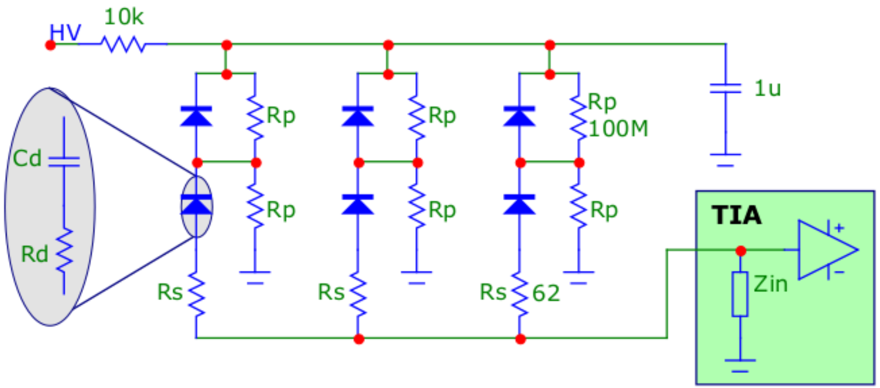
1x1 cm² @ 77K

$G = 10^6$



1x1 cm² & $G = 10^6$

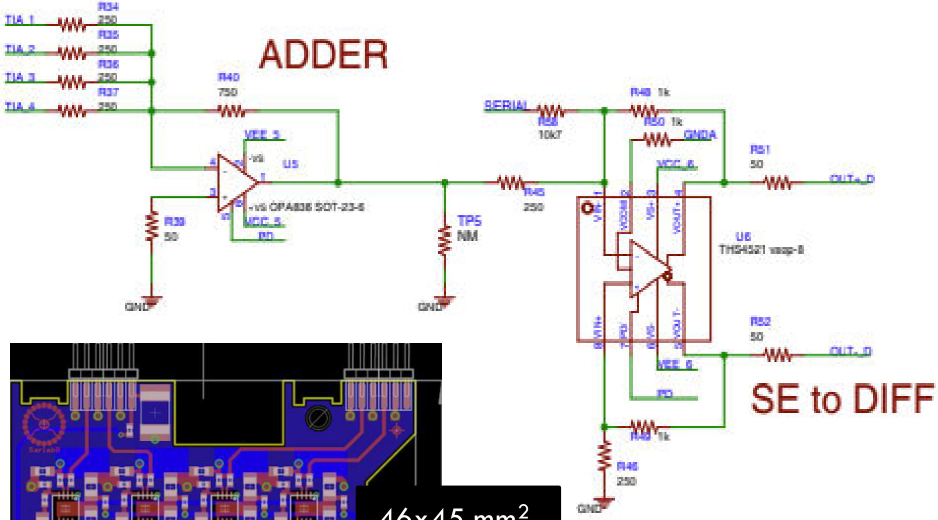
From 1 cm^2 to 6 cm^2

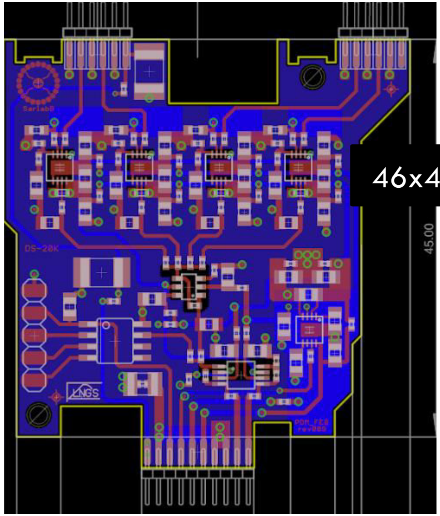


TIA bandwidth ~ 30 MHz @ 77 K
→ 9 nF input capacitance & $R_s/3$ (+Rd)
30 MHz = 7 ns rise time

- To read 6 cm^2 with the same amplifier a hybrid ganging solution is used
  - Virtual ground summing does not change the shape of the signal
- This design increases the capacitance seen by the TIA only by 50%
  - Respect to a single 1 cm^2 SiPM
- For cryogenic use a precision voltage divider is required
  - Otherwise the voltage division will be defined by the leakage current

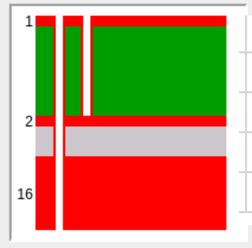
From 6 cm^2 to 24 cm^2





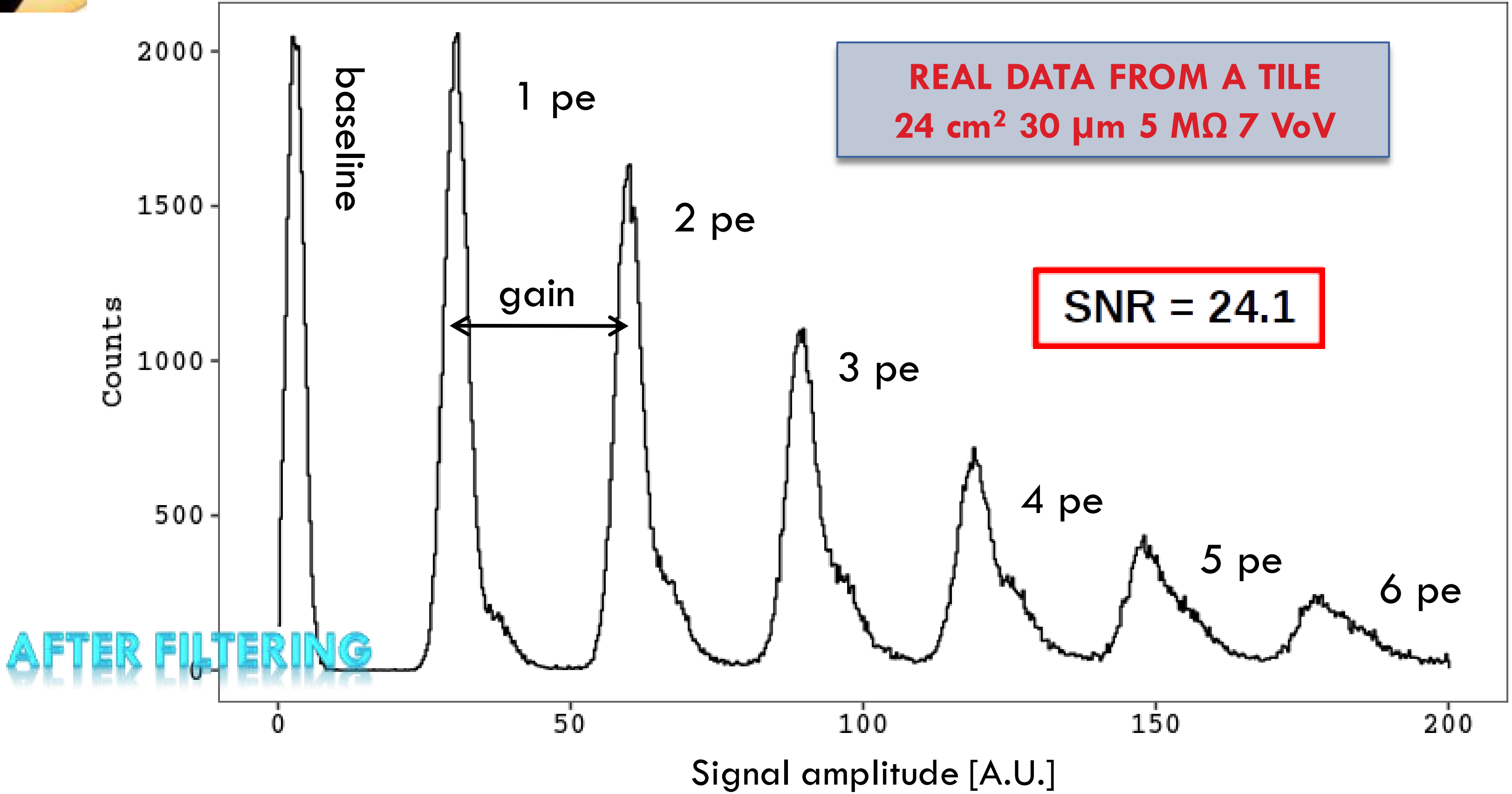
46x45 mm^2

- 4 independent TIA pre-amplifiers
  - each connected to 6 SiPM
- An active adder sums the 4 signals
  - A single-ended to differential
  - Total gain 26 kV/A
- Plus a voltage regulator & a uC for ID
- Total power ~ 250 mW
- PCB based on Pyralux
  - Custom stackup for high radiopurity

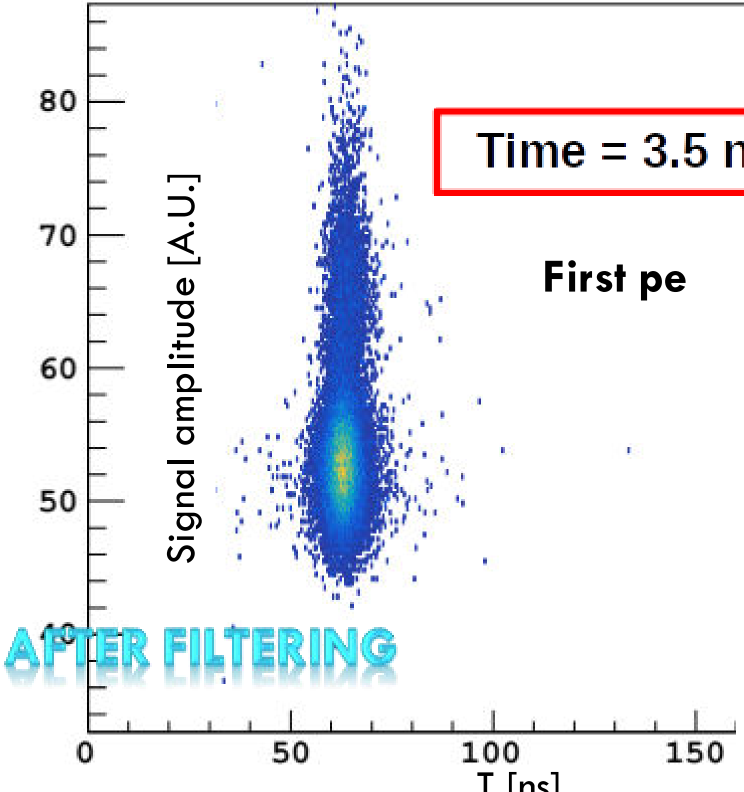


Copper	0.035mm
Core	0.3mm
Copper	0.035mm
Prepreg	0.1mm
Copper	0.25mm

SiPM signal: SPE spectrum

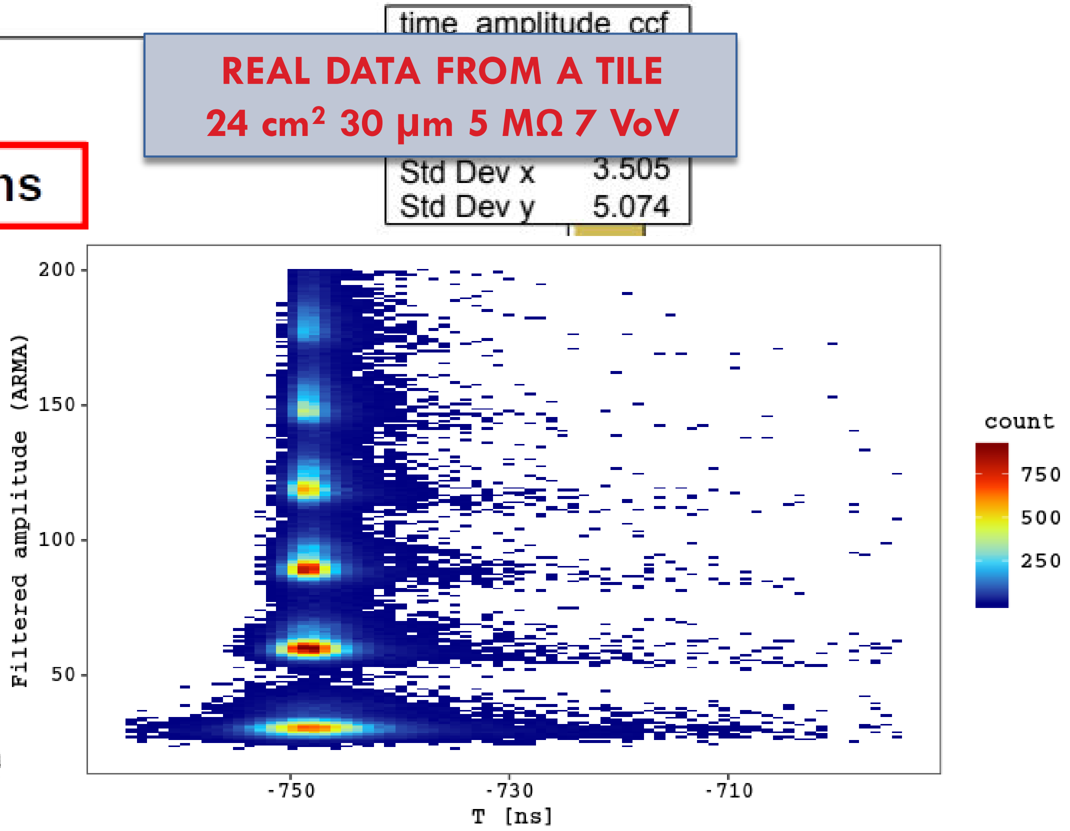


SiPM signal: timing



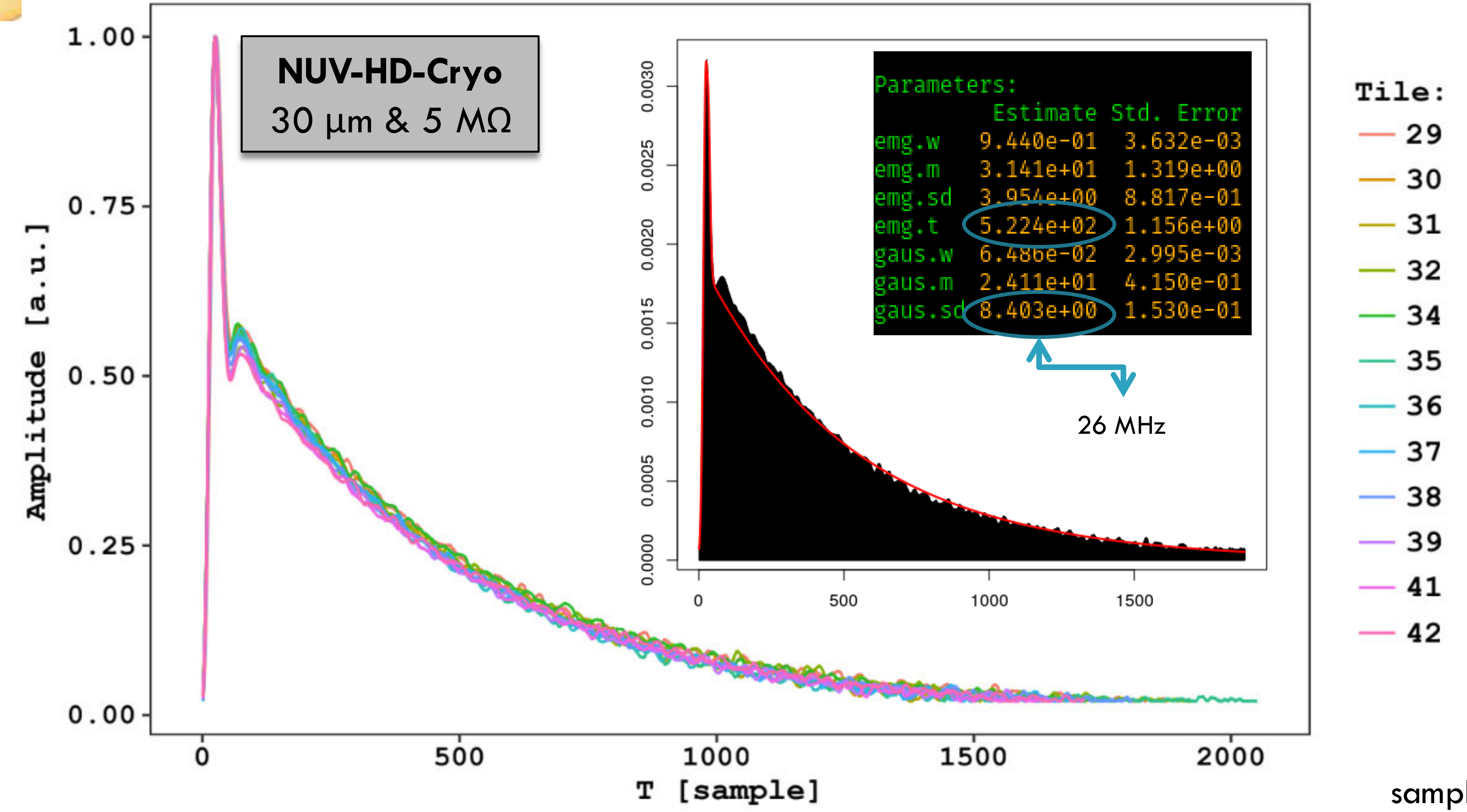
REAL DATA FROM A TILE

24 cm^2 30 μm 5 MΩ 7 VoV



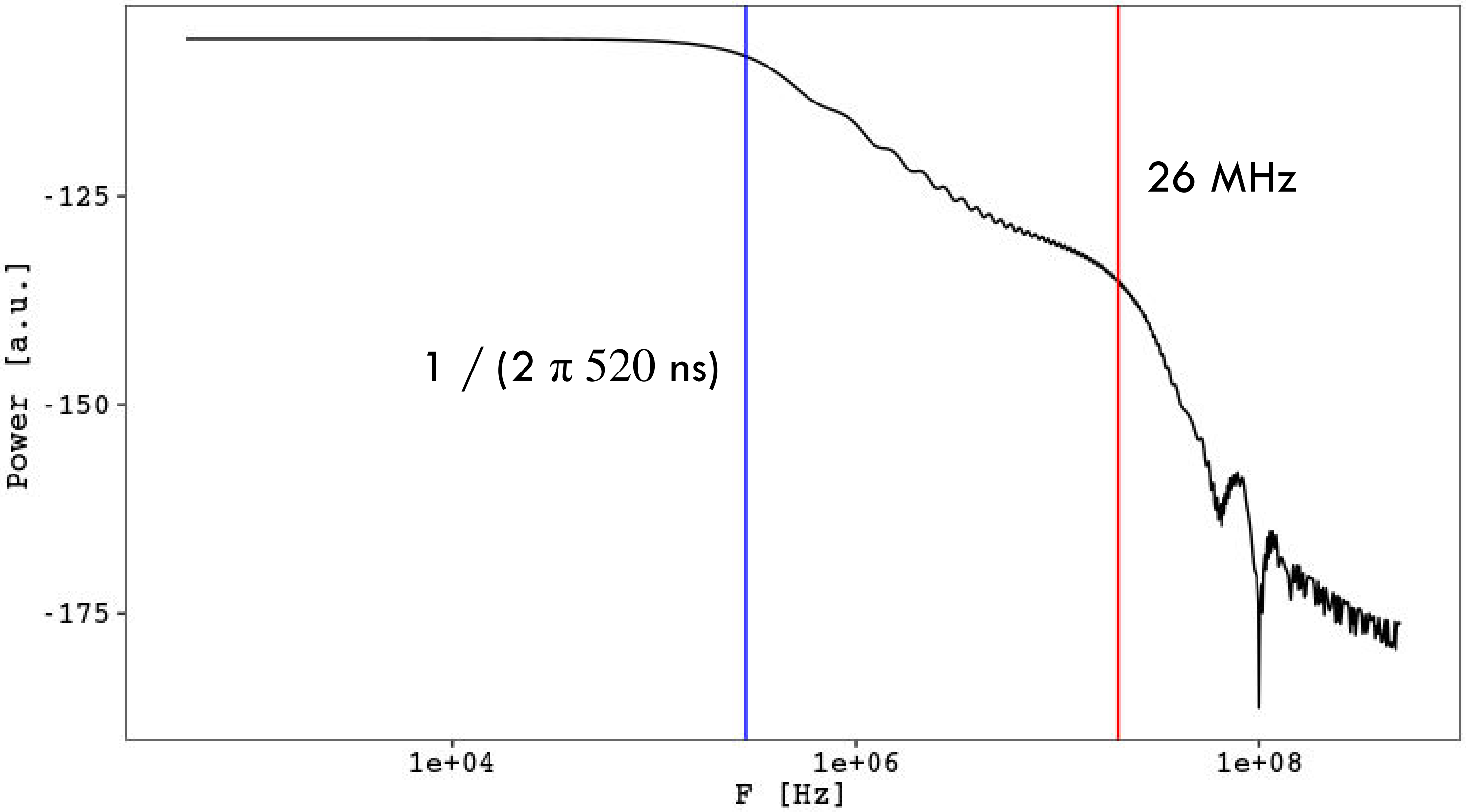
SIGNAL & BASELINE

Signal Shape

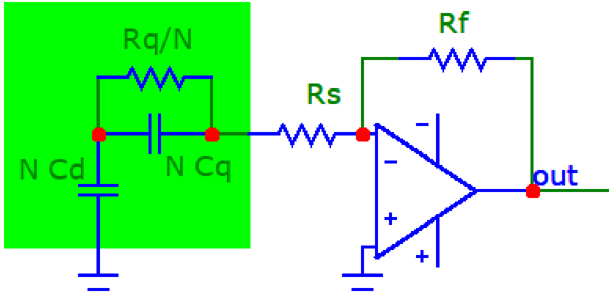


sampling = 1 ns

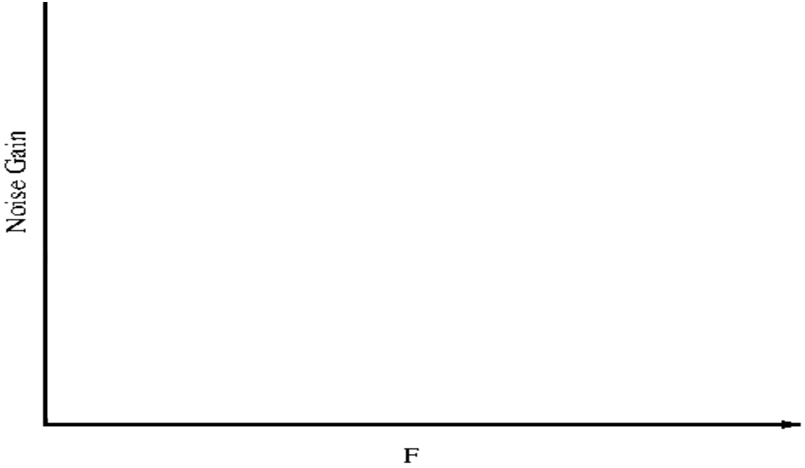
Signal power spectum



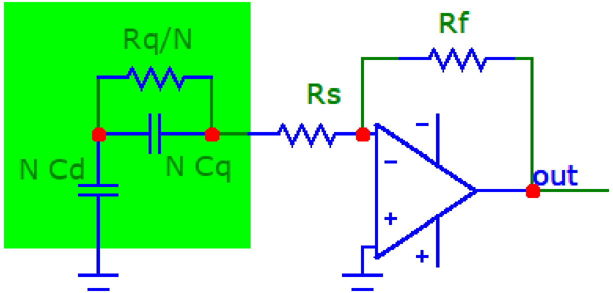
Baseline noise: noise gain



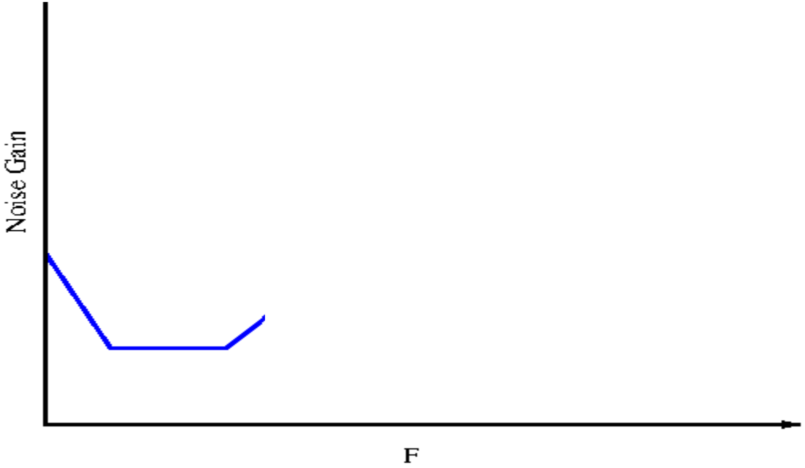
- BW & output noise spectrum depends on the SiPM static model
- 4 regions can be identified



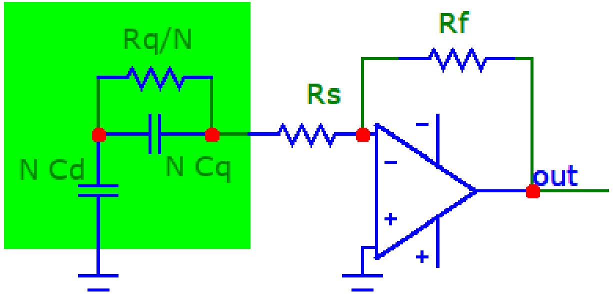
Baseline noise: noise gain

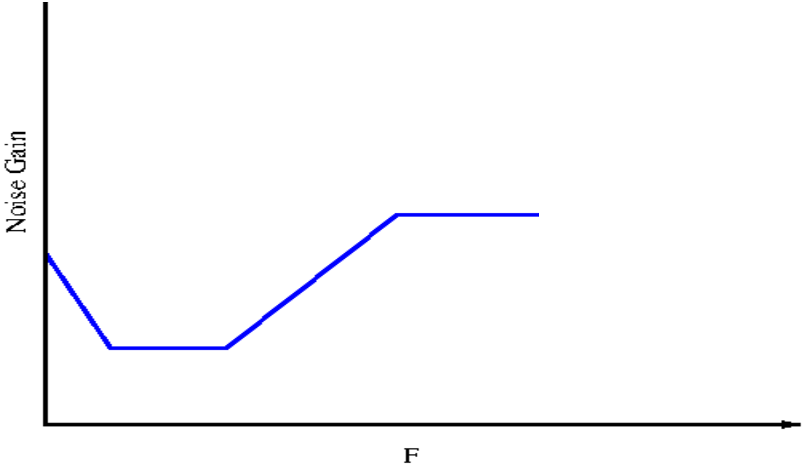


- BW & output noise spectrum depends on the SiPM static model
- 4 regions can be identified
  - F << $\frac{1}{2\pi(NR_s + R_q)C_q}$: intrinsic unamplified e_n



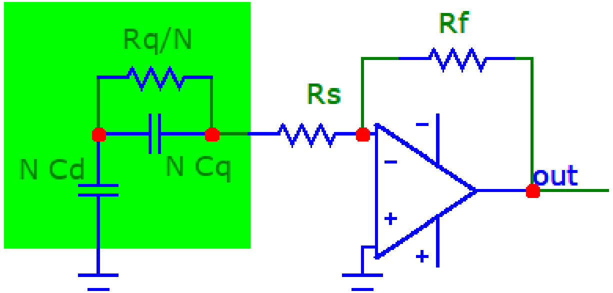
Baseline noise: noise gain

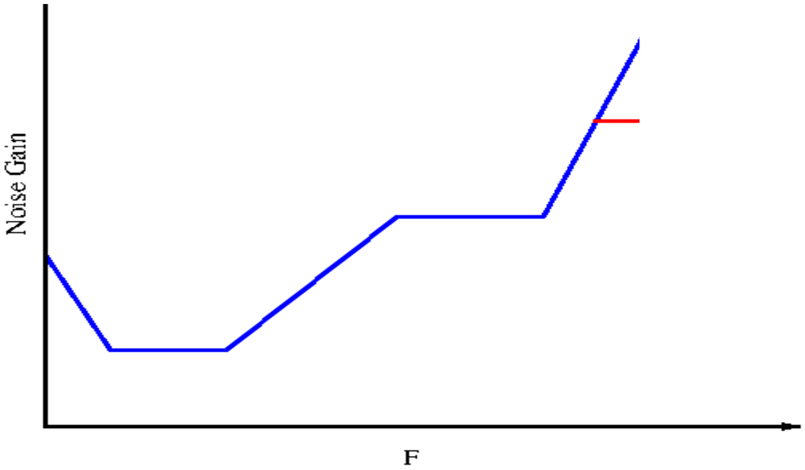




- BW & output noise spectrum depends on the SiPM static model
- 4 regions can be identified
  - F << $\frac{1}{2\pi(NR_s + R_q)C_q}$: intrinsic unamplified e_n
  - F << $\frac{1}{2\pi R_q C_q}$: e_n + e_T amplified by $\frac{R_f}{R_q/N + R_s}$

Baseline noise: noise gain





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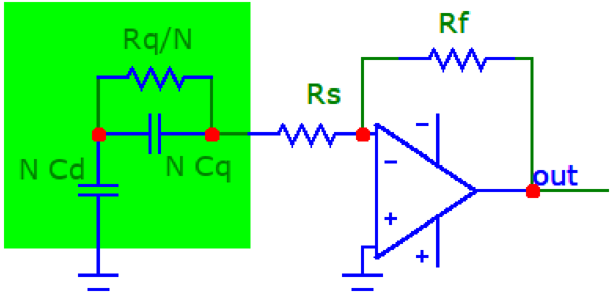
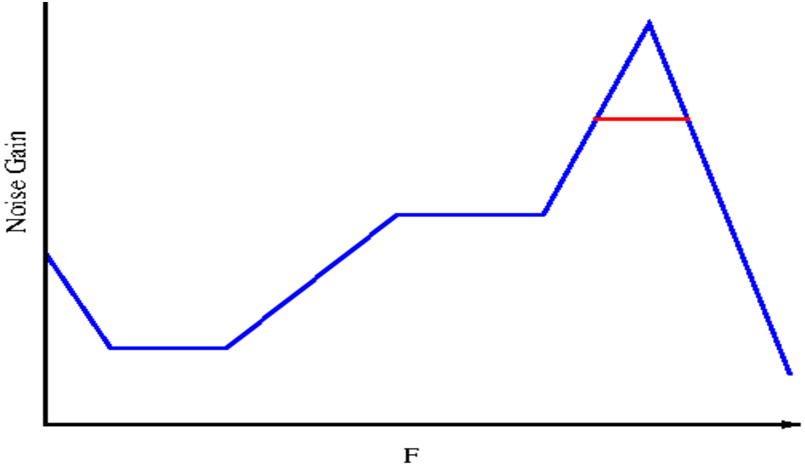
  - F << $\frac{1}{2\pi R_q C_q}$: $e_n + e_T$ amplified by $\frac{R_f}{R_q/N + R_s}$
  - F > $\frac{1}{2\pi R_q C_q}$: $e_n + e_T$ amplified by $\frac{R_f}{R_s}$ (if present)

Baseline noise: noise gain





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  - F << $\frac{1}{2\pi R_q C_q}$: $e_n + e_T$ amplified by $\frac{R_f}{R_q/N + R_s}$
  - F > $\frac{1}{2\pi R_q C_q}$: $e_n + e_T$ amplified by $\frac{R_f}{R_s}$ (if present)
  - Natural cut-off of the amplifier

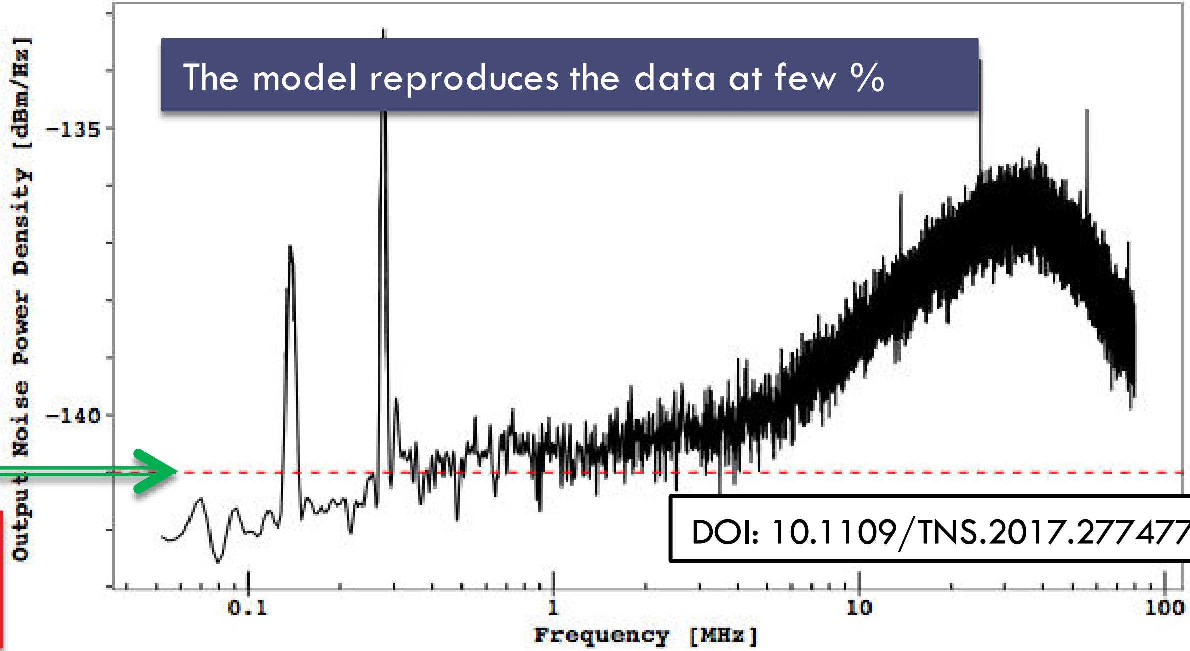
Baseline noise: power spectrum

$$S_I^{\max} = \frac{G}{\tau} \propto \frac{G}{R_{eq} + R_s} \qquad n_I = \frac{\sqrt{4K_BT(R_{eq}+R_s+R_n)}}{R_{eq}+R_s} \qquad S/N \propto \frac{G}{\sqrt{4K_BT(R_{eq}+R_s+R_n)}}$$

1 cm^2 @ 77 K:

- $R_n = 20\ \Omega$
- $R_s = 20\ \Omega$
- $R_{eq} = 60\ \Omega$
- $Rf = 3.9\ k\Omega$

$n_o = -141$ dBm



The model reproduces the data at few %

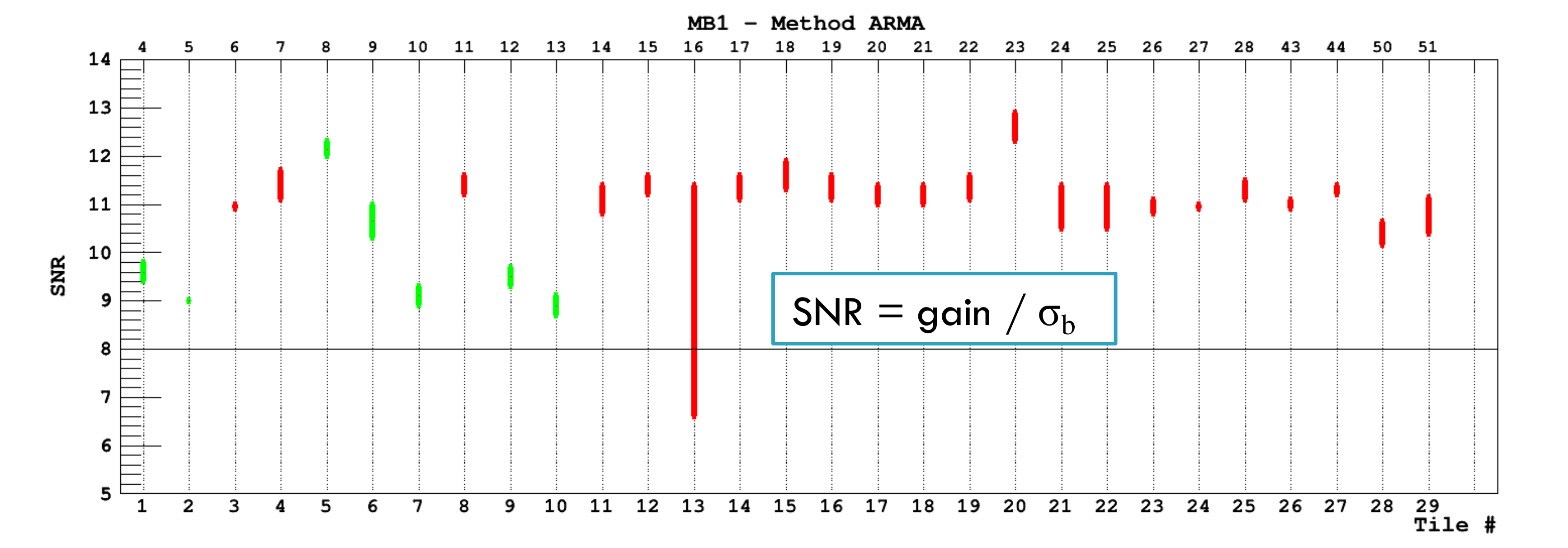
DOI: 10.1109/TNS.2017.2774779

To maximise the SNR optimal filtering is needed

MB PERFORMANCES

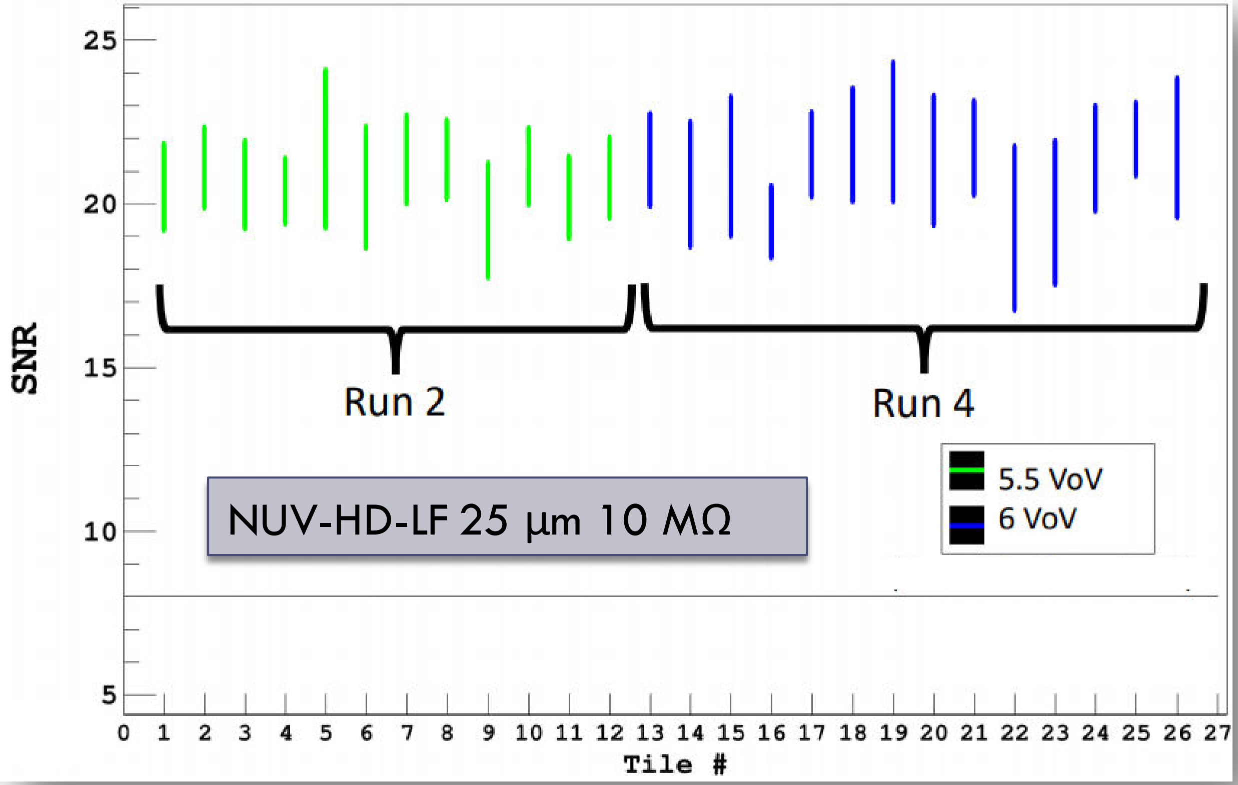
MB1 performances

NUV-HD-LF 25 μm 10 MΩ



$SNR = gain / \sigma_b$

MB2 perfomances



- MB2 built from 2 FBK runs
  - The break-down voltage of the 2 runs is 0.5 V different
- Darkside-20k MBs have a common bias
  - Run 2 SiPM are slightly underbiased
- The performances are well beyond expectation
  - SNR ~ 20
  - Timing ~ 3 ns
  - 600 SiPMs @ 77 K

Conclusion

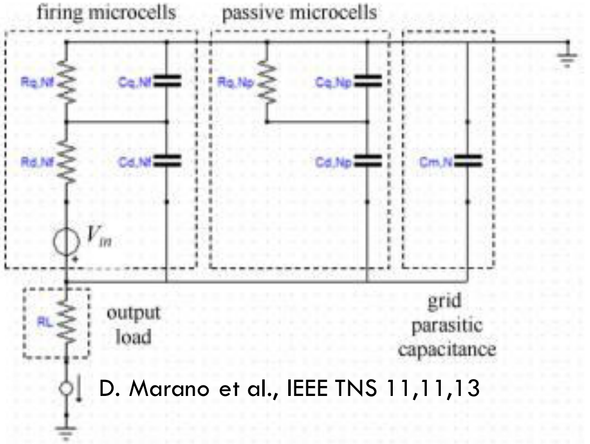
- The DarkSide collaboration undertook an ambitious R&D program on SiPM in 2014
- The R&D is now concluded
  - We can read 20 m^2 of SiPM instrumented surface
    - 200.000x 1cm^2 SiPMs
  - With about 8200 channels
  - With a SPE resolution better than 5% and 3 ns timing
- Within October we will receive the first LFoundry SiPM batches
  - 75x 8" wafers
  - Qualifications & MB processing will require 6 months
- Within end of 2020 we will start the mass production at NOA
  - 2.5 years to produce & test all the PDMs + 6 months for the detector commissioning
  - Then we will hunt dark matter

Thank you

Backup slides

Signal shape

- The signal out from a SiPM includes different components
- Initial peak: total charge ~10% of total
  - Rise time: limited by electronics
  - Duration: ~ 10 ns
- Recharge: 90% of total
  - 2 exponential components
    - $\tau_1 \approx \tau_q + \tau_L$ & $\tau_2 \approx$ 5-10 $\tau_q \,||\, \tau_L$ where $\tau_q \approx R_q C_d$ & $\tau_L \approx R_L C_{SIPM}$
    - R_L can be tuned to keep them equal
  - In DS we have Cd = 50 fF, R_q = 5 M Ω, C_{SIPM} = 6 nF, R_L = 60 Ω
    - $\tau \approx$ 500-600 ns in LN_2/LAr
- The intrinsic spread of the amplitude is due to fluctuation of gain (V_{bd}) within the SPADS (few %)



D. Marano et al., IEEE TNS 11,11,13

SPE identification

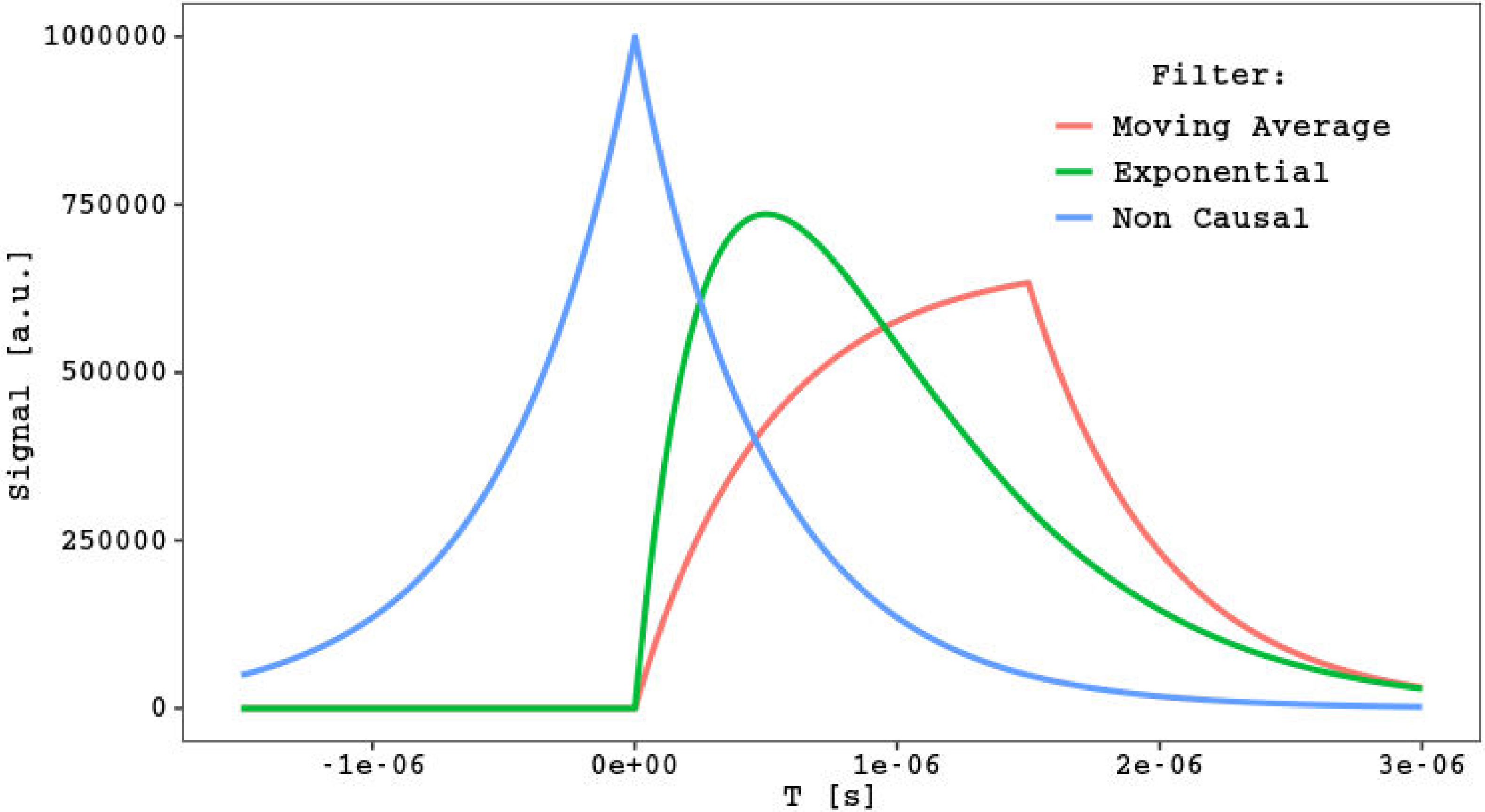
- We want to be able to extract spe from the waveform
  - Limiting the rate of fake hits (R_{BS}) to < 180 cps
  - With low losses ε_{TH} < 1-2 %
  - Defining the timing of the hit with ns accuracy
- Considering a simple threshold η,
  - the rate of fake hits is $R_{BS} = F_{TIA}/\sqrt{3}\, \exp(-SNR^2 / 2 * \eta^2)$ with F_{TIA} = 30 MHz
  - The hit detection efficiency is $\varepsilon_{TH} = 1 - \mathrm{erf}(\eta, \mu=1, \sigma=1/SNR)$
  - SNR > 8
- Our raw waveform do not reach the SNR of 8
  - Data filtering is needed

Filtering

- The noise is peaked at high frequency 1-30 MHz
- Most of the signal is at low frequencies < 0.5 MHz
- A low pass filter would already increase significantly the SNR
  - This aproach is used in the TO/Veto electronics
  - However by cutting high frequencies most the timing information are lost.
- 2 low pass filters are naturally implemented:
  - Exponential with $\tau = \tau_{ref}$ ~500 ns (as from data)
    - 1 order filter with 3dB cut $F_{3dB} = 1/(2\pi\ \tau_{ref}) = 320$ kHz, brick wall $= \pi/2\ F_{3dB}$
  - Moving average with lenght = $3 * \tau_{ref}$
    - Corresponds to the integral of the signal with ballistic deficit of 5%
    - Sync response with 3dB cut $F_{3dB} = 2.78/(2\pi\ 3\tau_{ref}) = 300$ kHz, brick wall $= 1.14\ F_{3dB}$
  - In first approssimation the SNR are similar:
    - $G_{exp} \propto 1/e\tau_{ref}$ & $N_{exp} \propto \sqrt{\pi/2\ F_{3dB}}$
    - $G_{ma} \propto (1-e^{-3})/3\tau_{ref}$ & $N_{ma} \propto \sqrt{1.14\ F_{3dB}}$

Ignoring the fast peak in the waveform

Filtered waveforms



Smarter filtering

- In digital signal processing smarter filtering is possible
  - Non causal filters have H(t) != 0 for $t < 0$
- We can for example use the time inverted exponential as $H(t) = e^{t/\tau_{ref}}\,\Theta(-t)$
  - $G_{exp} \propto 1/2\tau_{ref}$ & $N_{exp} \propto \sqrt{\pi}\,/2\,F_{3dB}$
  - SNR increased by e/2 -> 36 %
- Matematically we are doing a correlation with the standard exponential
  - The output is symmetric $O(t) = e^{-|t/\tau_{ref}|} / 2\,\tau_{ref}$
  - The peak can easily been identified
    - For normal low pass filter output is $O(t) = t\,e^{-|t/\tau_{ref}|} / \tau_{ref}^2$ the peak is not so clear
- Is it the best we can do?

Θ(-t) Heaviside Step Function

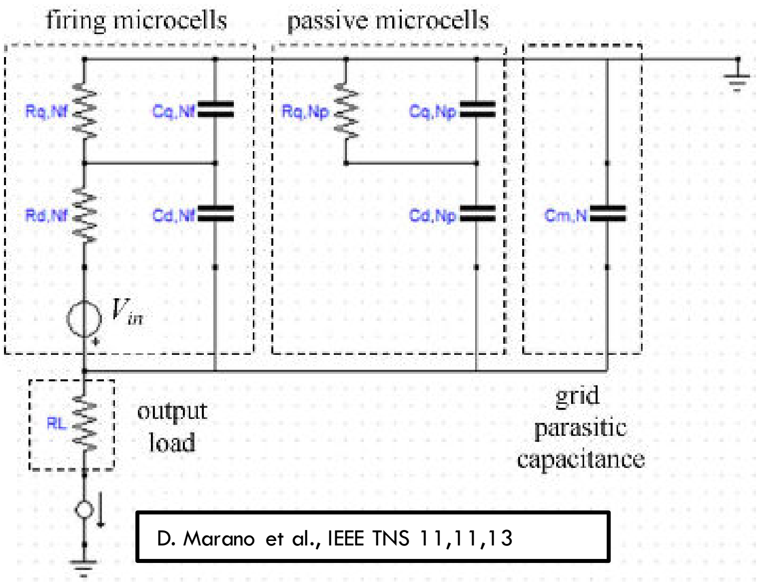
Ignoring the fast peak in the waveform

Matched filtering

- Matched filters were developed in 1950-1960
  - To detect radar pulses in the receiver noise
- Matched filters assumes that the signal contains a known signal plus a stochastic noise
  - $s(t|t_0,c) = c\ f(t - t_0) + n(t)$
- Under this hypothesis it can be shown that the SNR is optimized by convoluting s(t) with f(-t)
  - $s^*(t|t_0,c) = s(t|t_0,c) \circ f(-t)$
  - Matched filter are the solution of least square problem

- <u>Within linear filtering, matched filters are the best to detect the SPE</u>

SiPM detailed electrical model

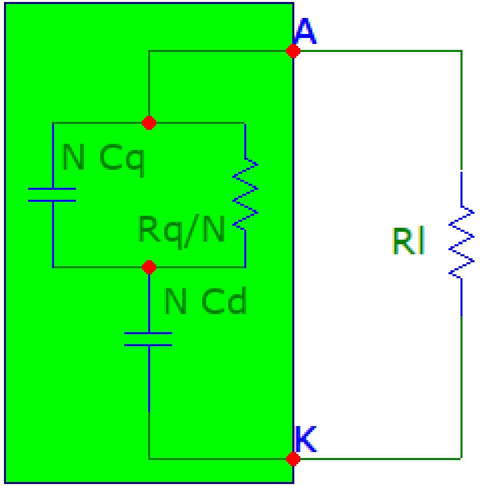


D. Marano et al., IEEE TNS 11,11,13

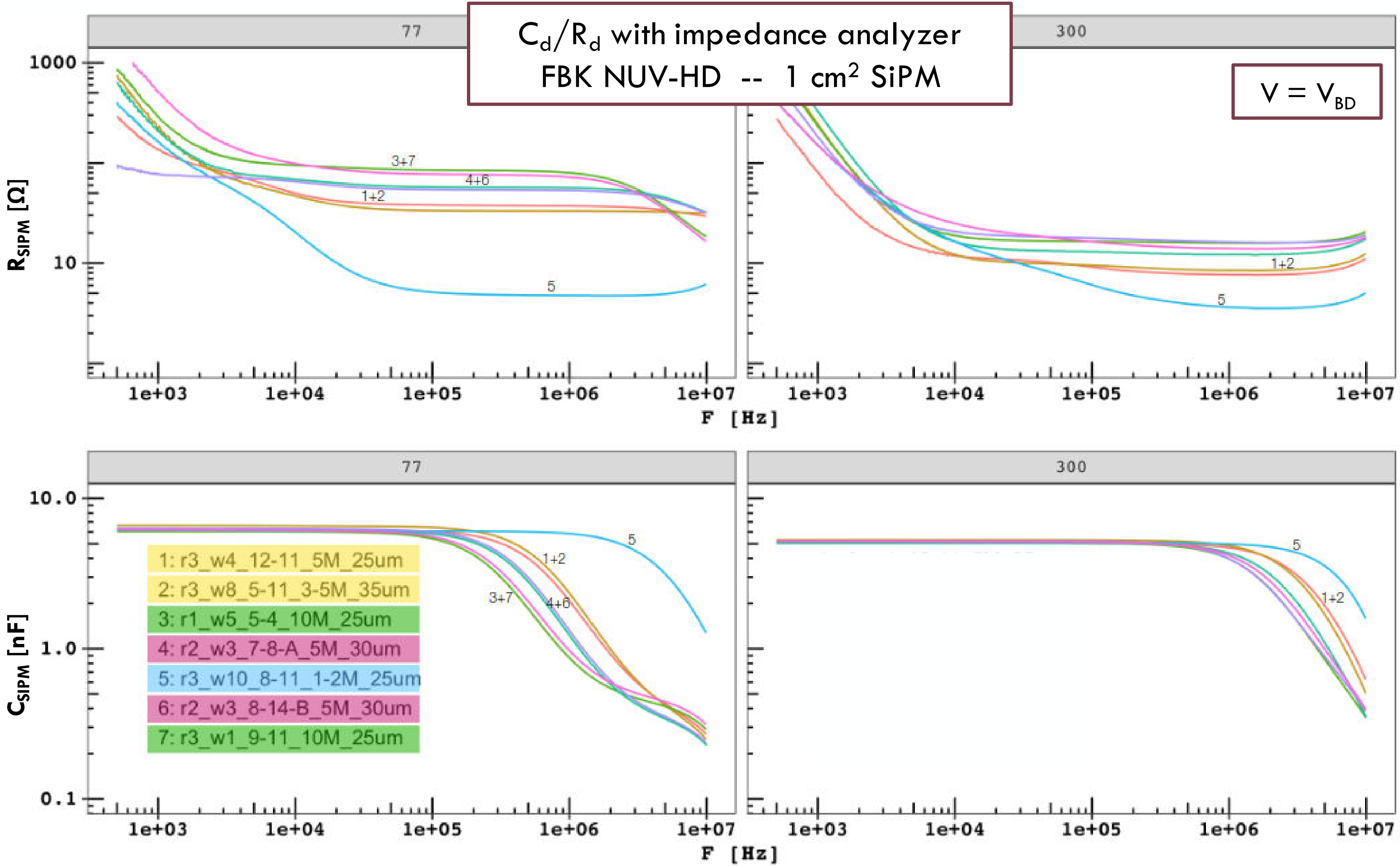
Static SiPM model

For FBK at 77 K:
- C_d ~ 20 – 100 fF
- Rq ~ 2 – 10 MΩ

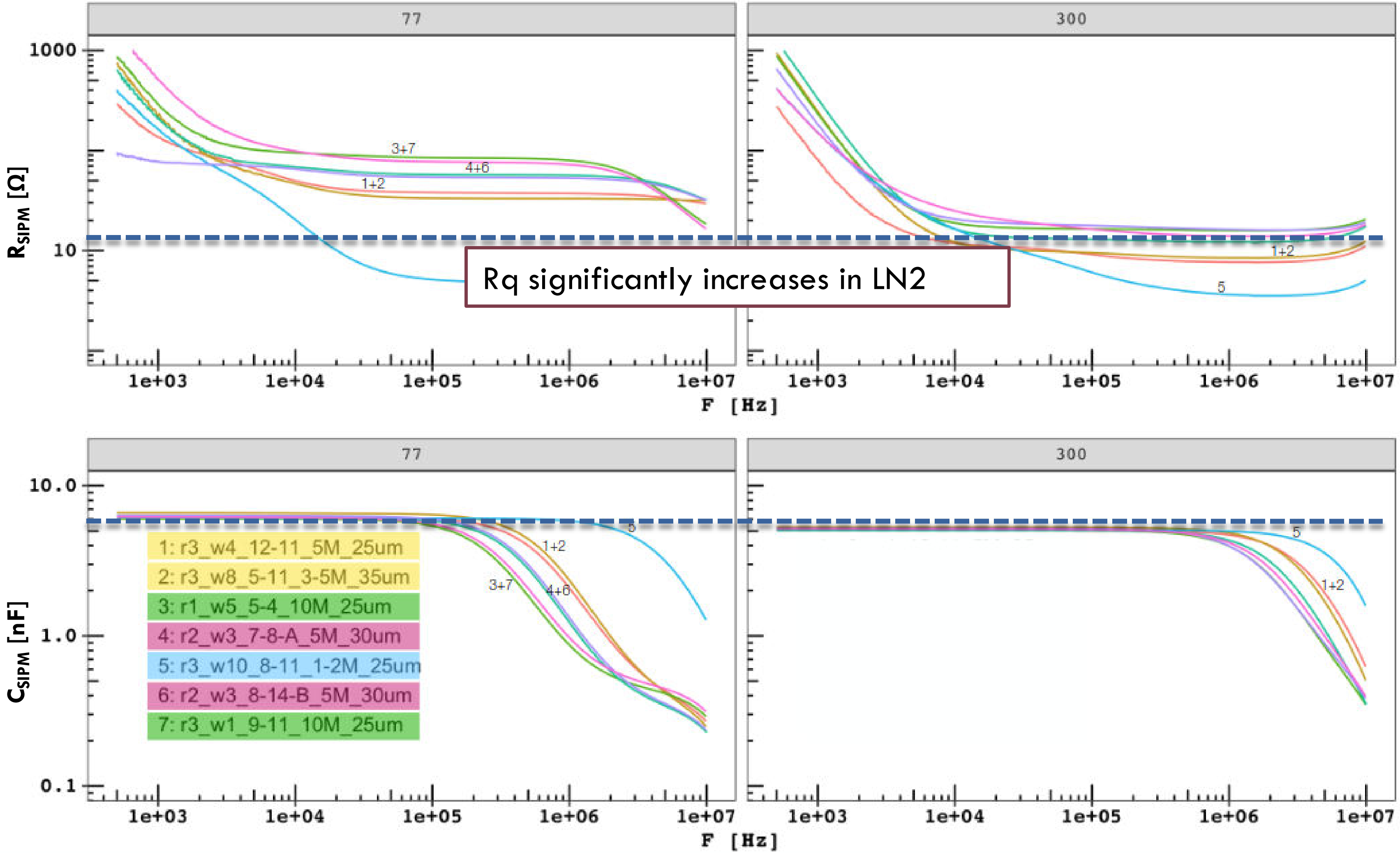
Transition frequencies are size independent



The static model defines the noise gain of the connected amplifier



Cd/Rd with impedance analyzer
FBK NUV-HD -- 1 cm2 SiPM
V = VBD
77
300
RSIPM [Ω]
CSIPM [nF]
F [Hz]
3+7
4+6
1+2
5
1: r3_w4_12-11_5M_25um
2: r3_w8_5-11_3-5M_35um
3: r1_w5_5-4_10M_25um
4: r2_w3_7-8-A_5M_30um
5: r3_w10_8-11_1-2M_25um
6: r2_w3_8-14-B_5M_30um
7: r3_w1_9-11_10M_25um


77
300
1000
10
R_{SIPM} [Ω]
3+7
4+6
1+2
5
Rq significantly increases in LN2
1e+03
1e+04
1e+05
1e+06
1e+07
F [Hz]
10.0
1.0
0.1
C_{SIPM} [nF]
1: r3_w4_12-11_5M_25um
2: r3_w8_5-11_3-5M_35um
3: r1_w5_5-4_10M_25um
4: r2_w3_7-8-A_5M_30um
5: r3_w10_8-11_1-2M_25um
6: r2_w3_8-14-B_5M_30um
7: r3_w1_9-11_10M_25um