SiPMs for future Dark Matter Experiments

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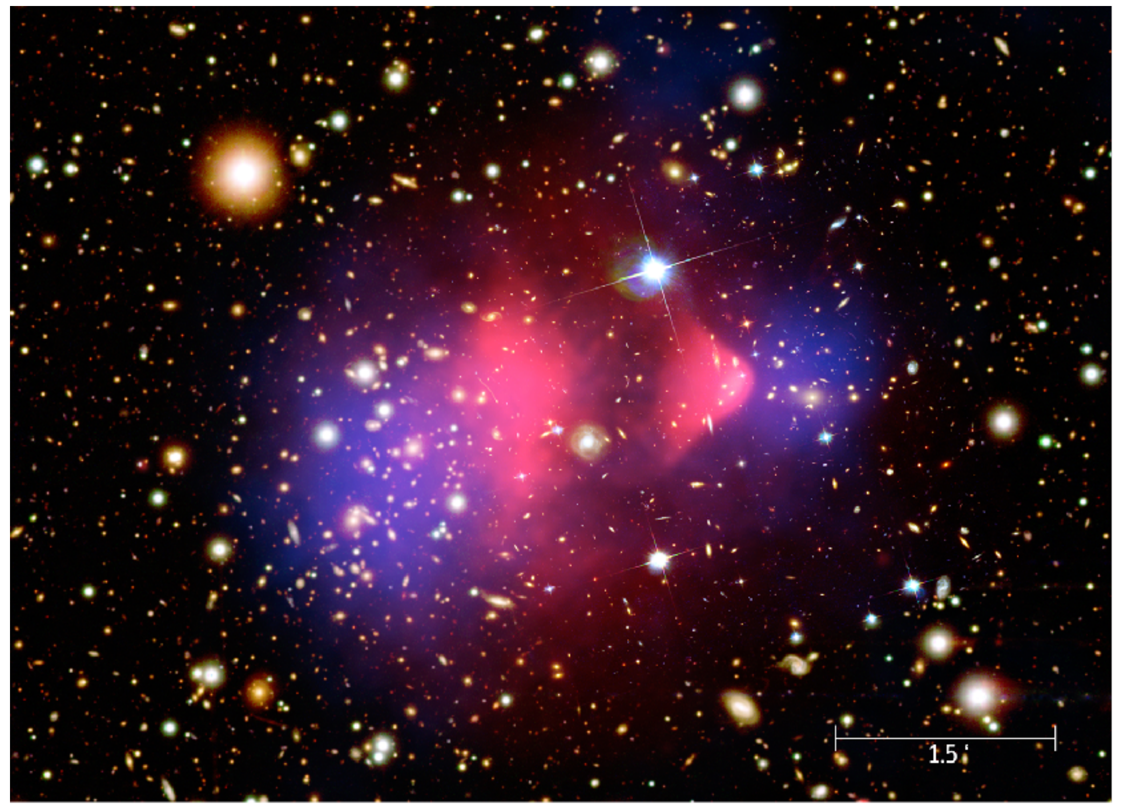
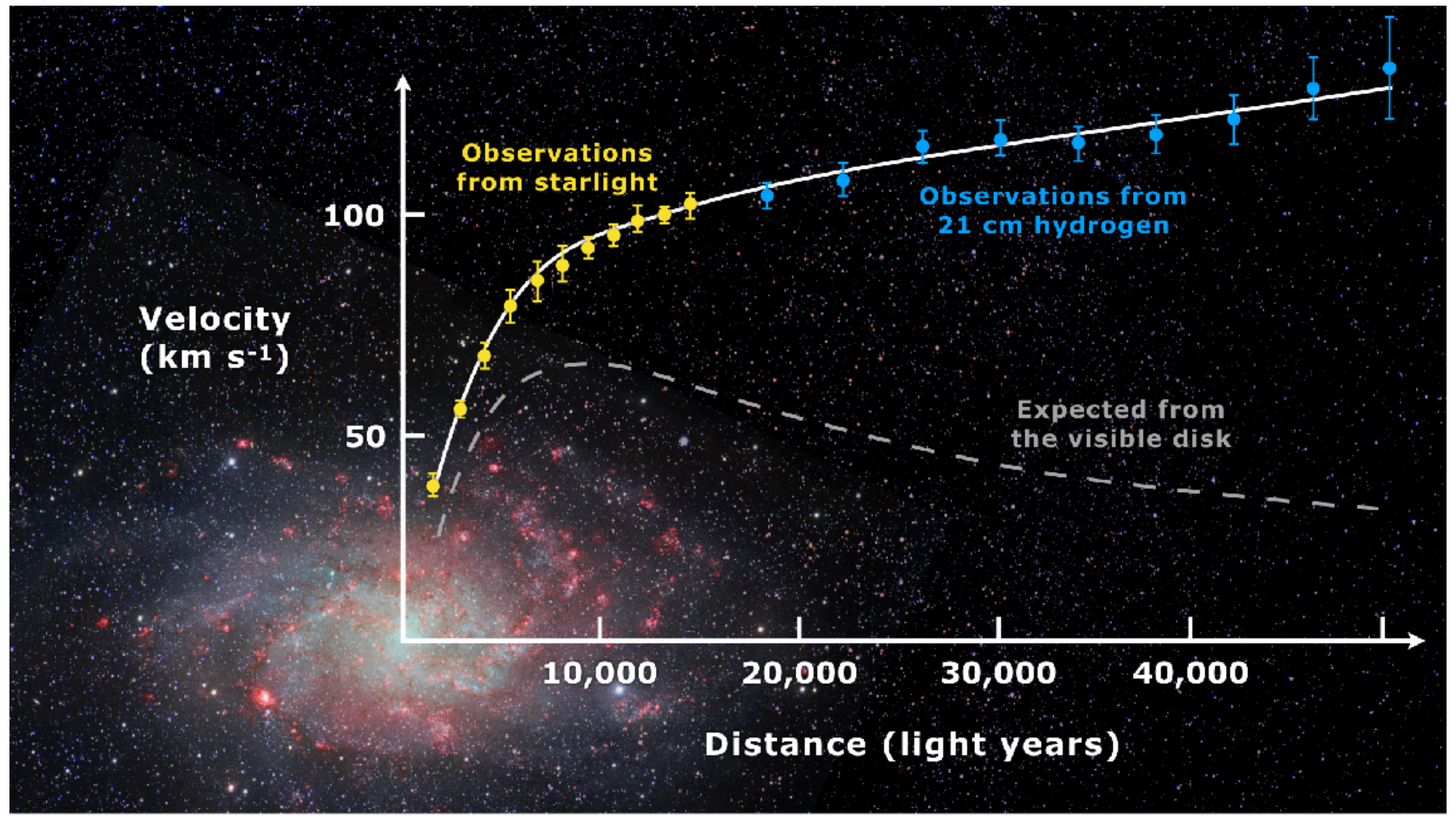
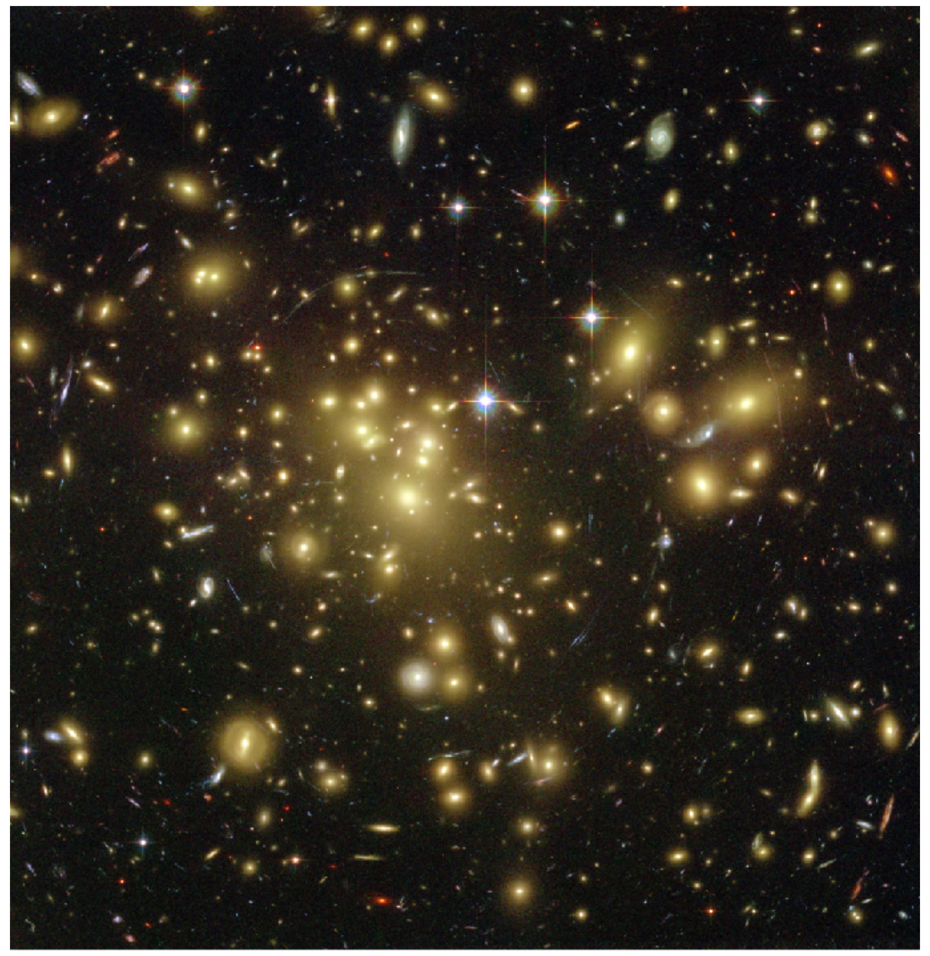
Astronomical Evidences



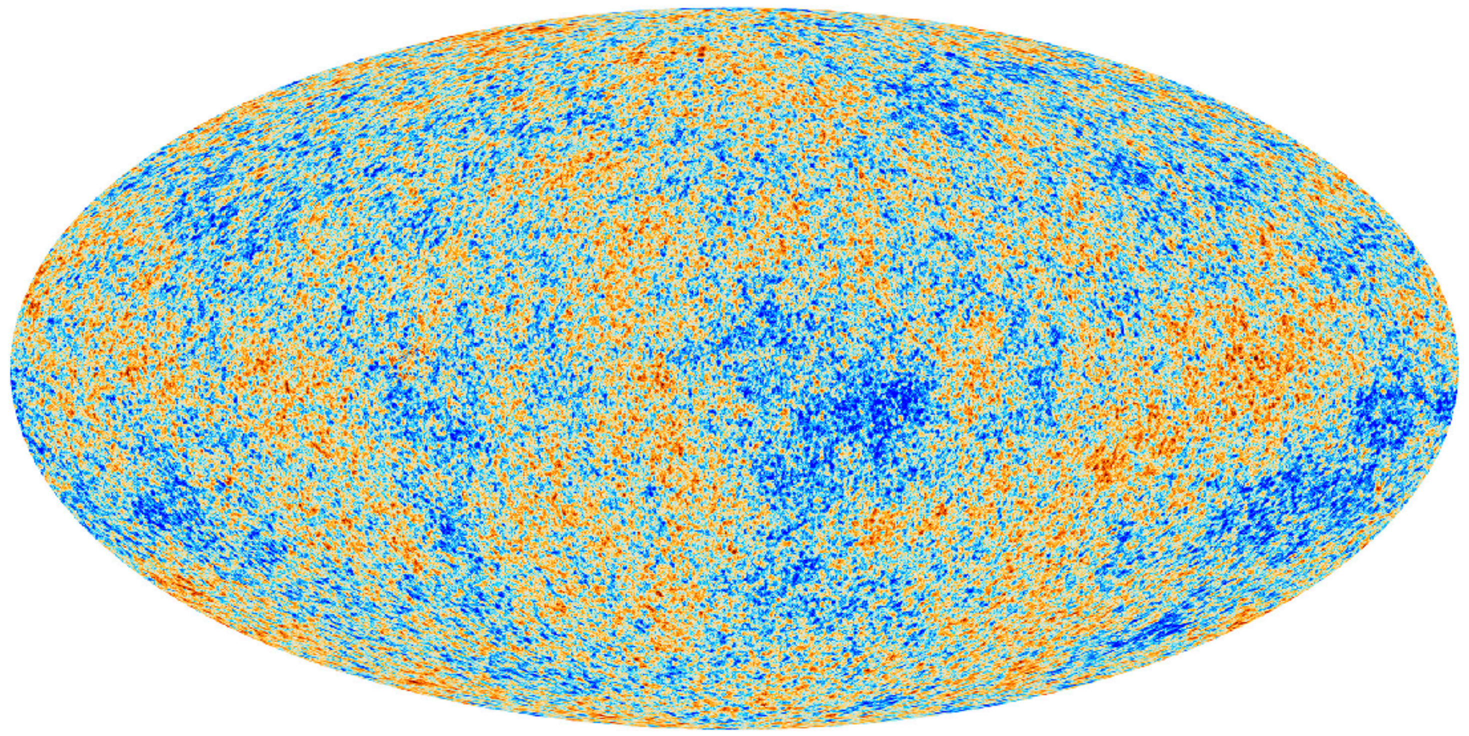
Colliding galaxies



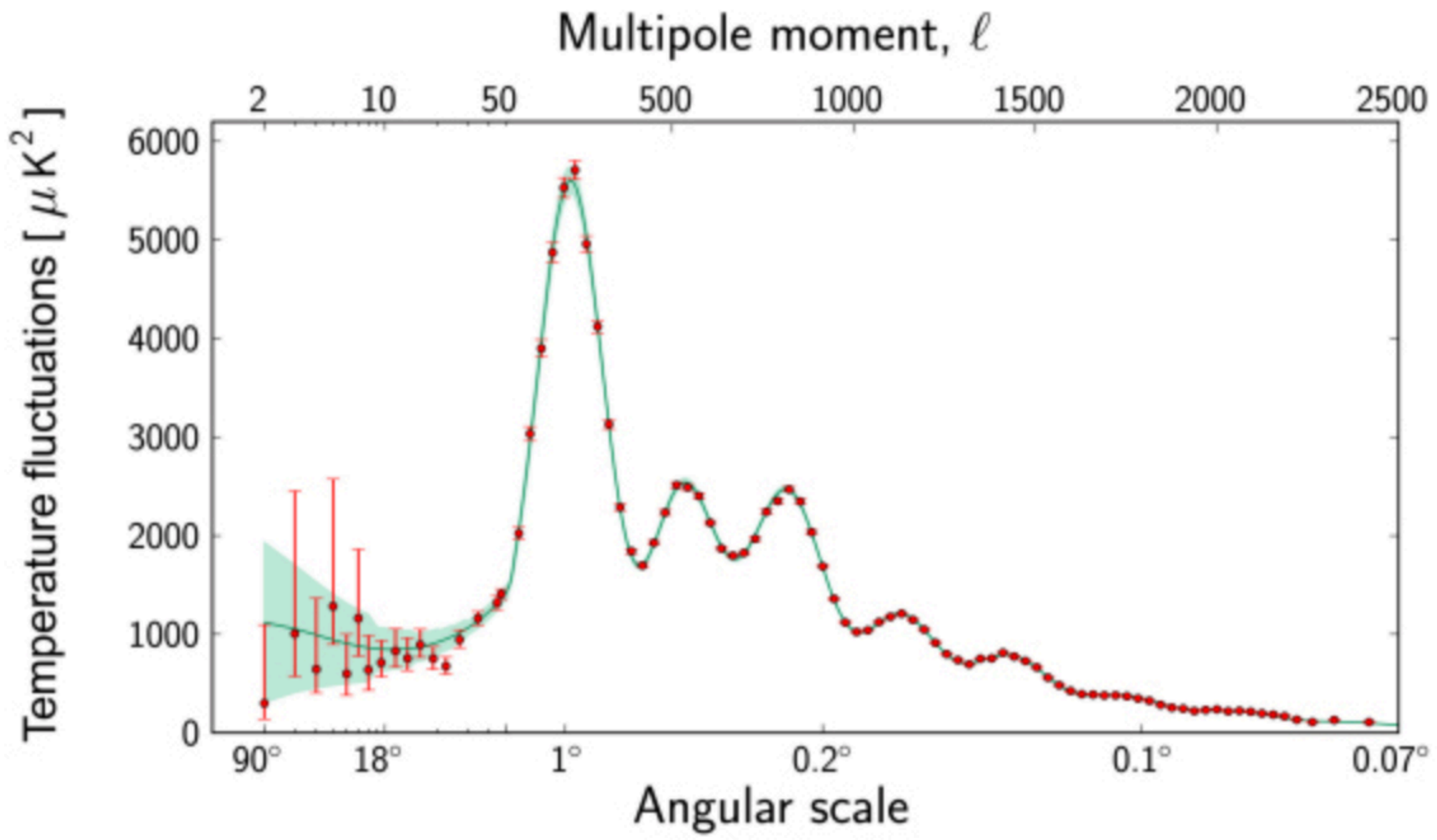
rotation curves of the galaxies



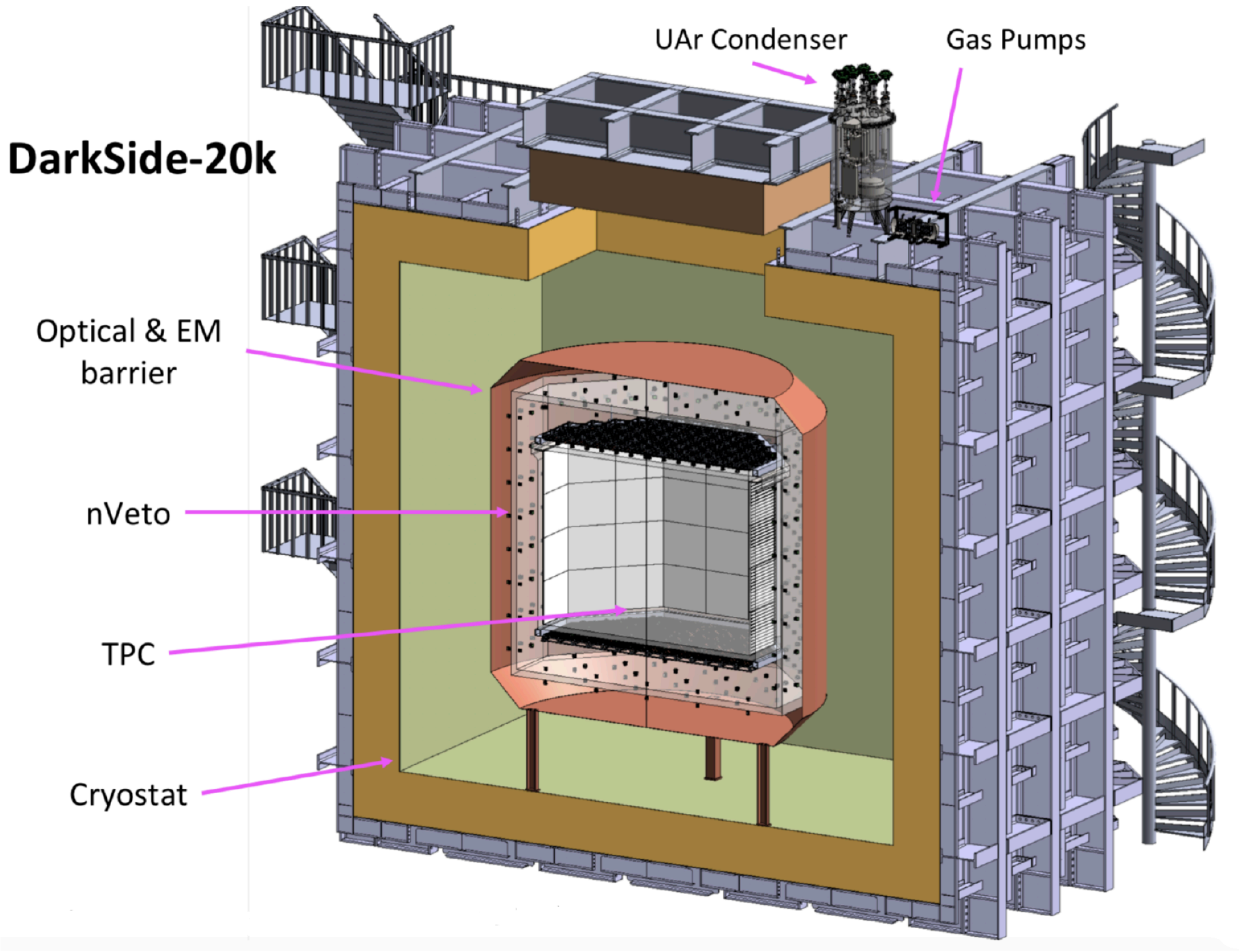
Strong Gravitational lensing



Cosmic Microwave Background



DarkSide-20k and Beyond

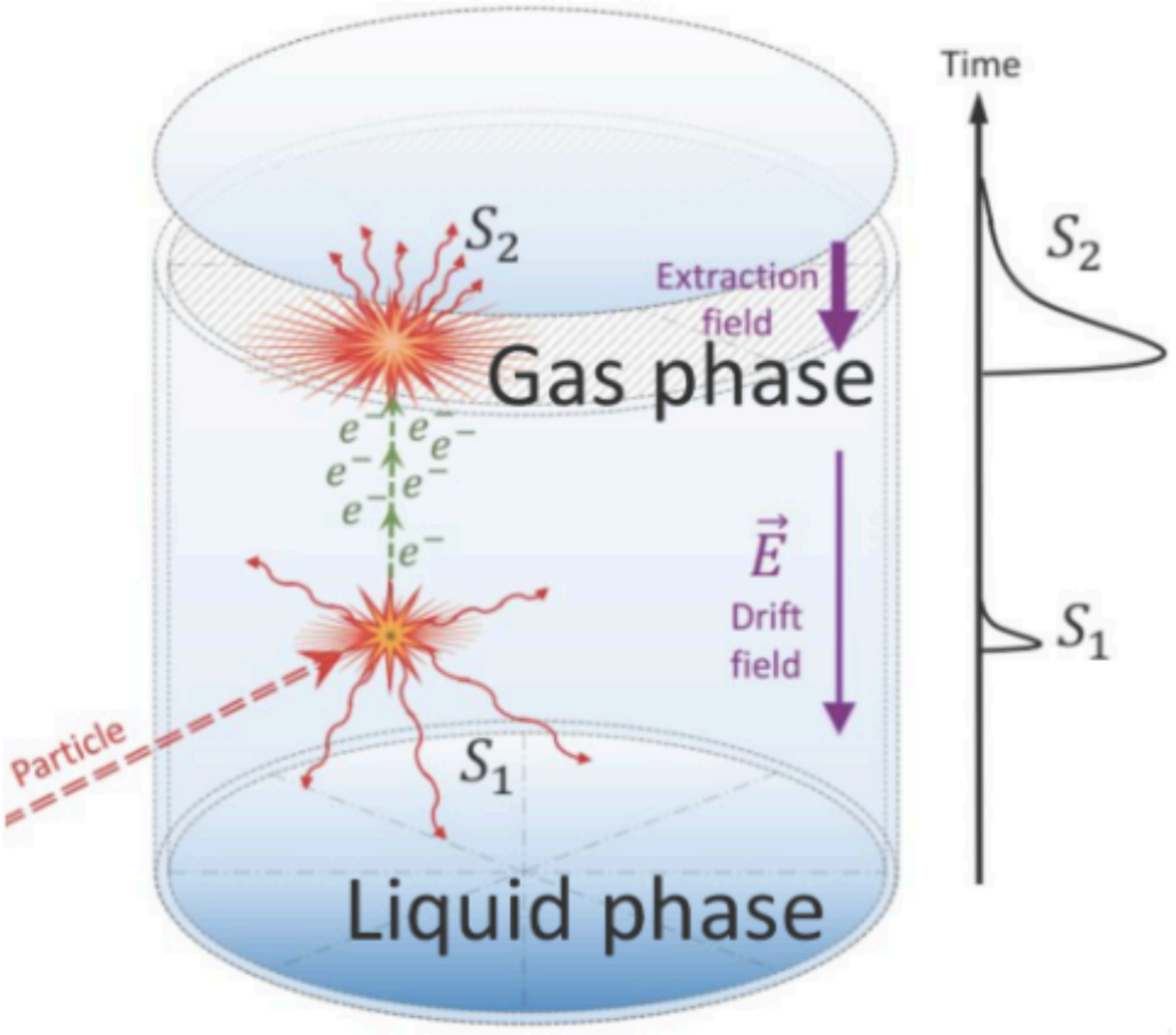


- With the 100 t yr exposure, 1.6 NR events are expected from coherent scattering of atmospheric neutrinos making DarkSide-20k first ever dark matter detector to achieve that milestone

- After DS-20k, GADMC is planning build Argo detector with 300 ton fiducial volume for ultimate Dark Matter search with exposure of 3000 t yr over 10 years — neutrino floor reach

- Due to the increased detector active volume, it will undergo huge pileup (due to the background events) — limitation of the size of dual TPC gives poor position reconstruction

Dual Phase Time Projection Chamber



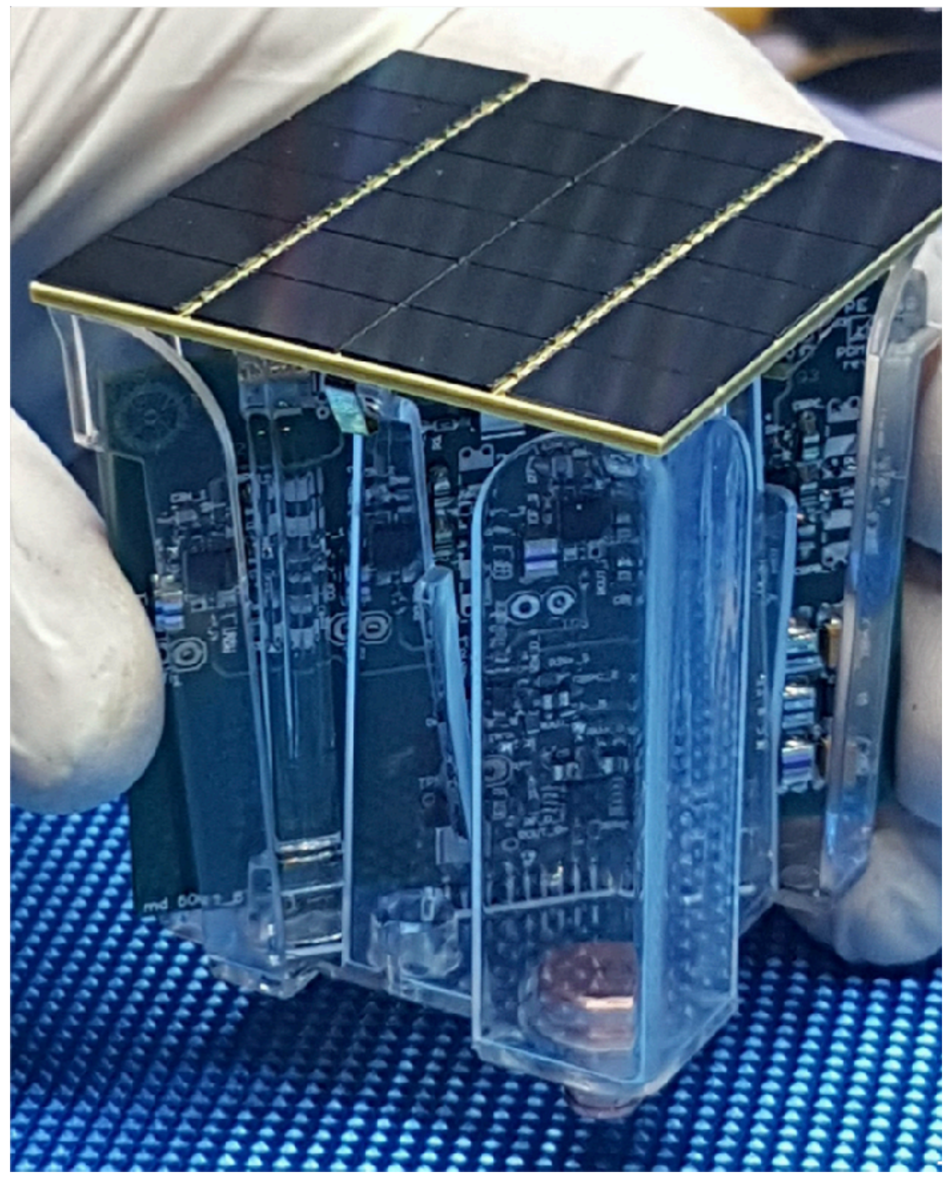
- XY position reconstruction can be studied with the spatial distribution in the top array by S2 signal
- The position reconstruction starts to diminish when pileup becomes dominant in large volume detector
- Precise timing resolution becomes an important feature for position reconstruction in future large volume detectors
- DarkSide-20k will be become the first dark matter detector to mass employ SiPM detector arrays as photodetector modules.

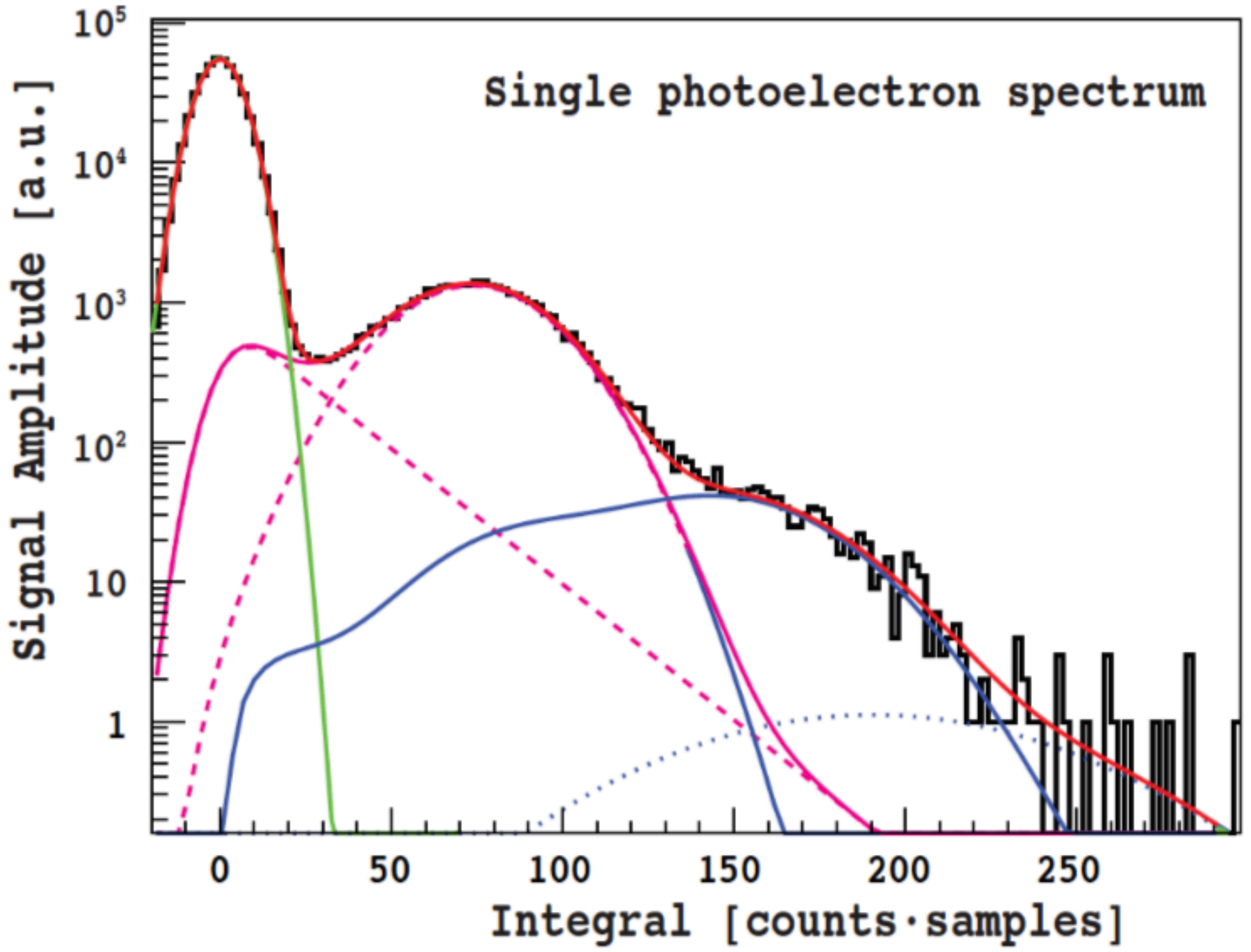
Why SiPMs over PMTs?

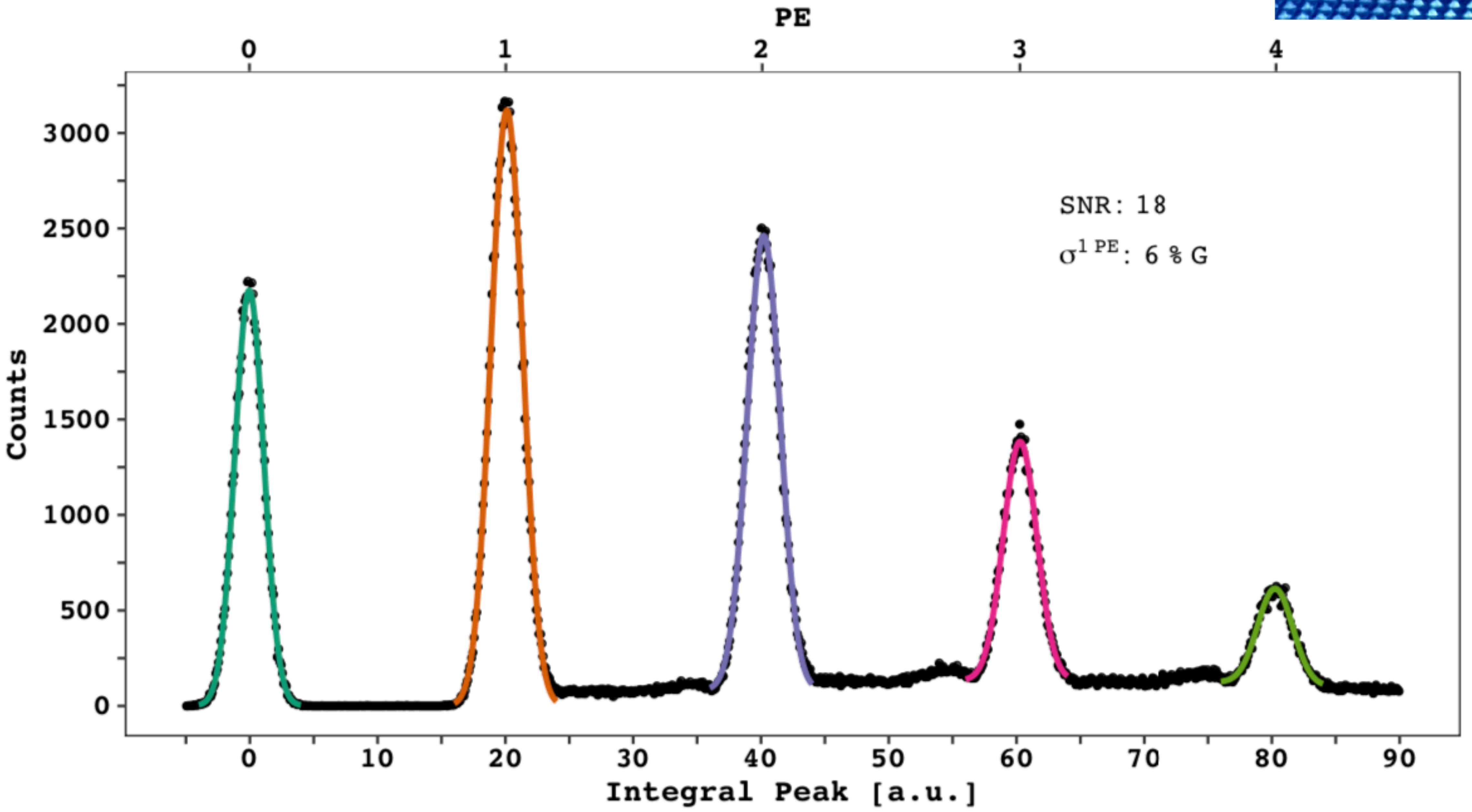
- SiPMs can exhibit Photon Detection Efficiency upto 50%

- High geometrical fill factor and low power consumption

- As per DarkSide-20k requirements, a 20% more light yield than DarkSide-50
    1. SiPM Photo-Detection Modules (PDM) will have 25 cm^2 area.
    2. Each module should produce total noise < 250 Hz
    3. The single photon resolution for SiPMs is 2% whereas PMTs is 20%

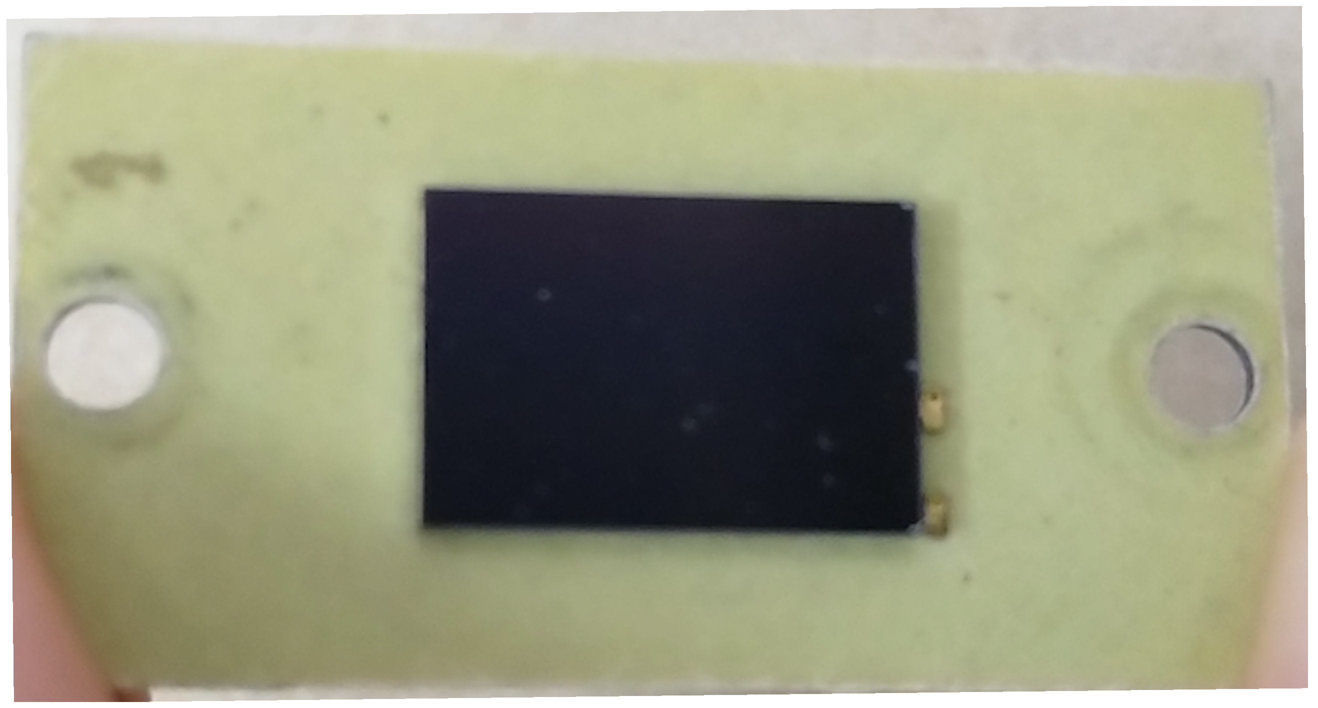


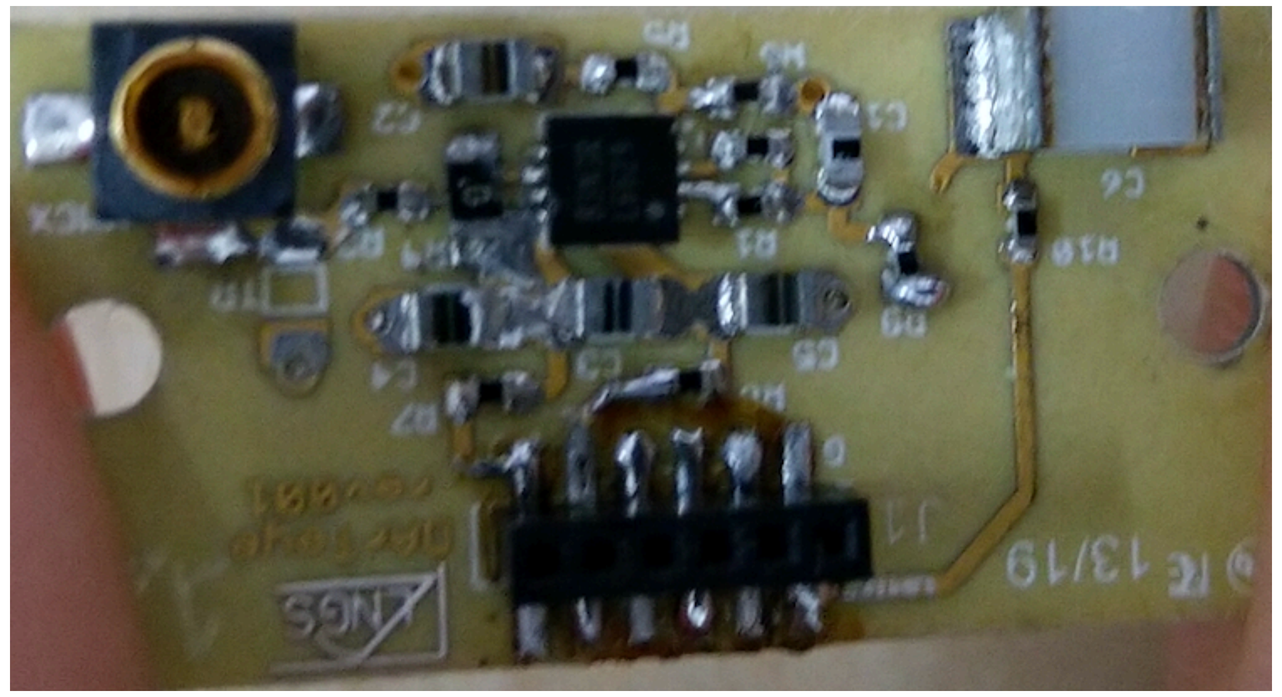




Challenges with the SiPMs

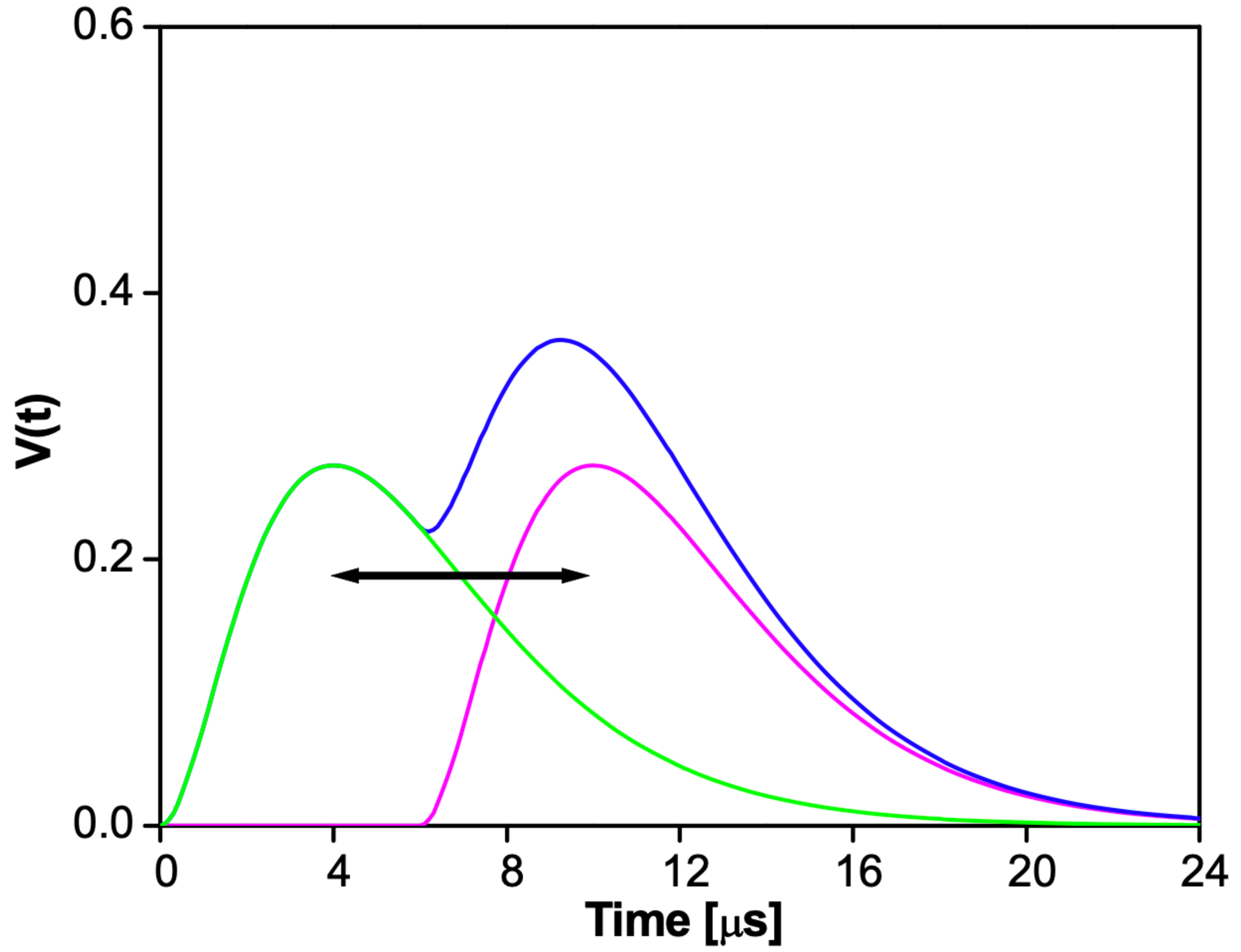
- As the size of TPC can not be increased beyond 100 tons due to the intense pileup of signals — accuracy in timing resolution can provide stringent time-of-flight measurements
- This will facilitate Particle Identification through pulse shape discrimination to estimate cuts for background event rejection
- To gain enhanced timing results for the applications in future experiments, SiPMs under study at LNGS are 1 cm^2 in area which are sensitive to NUV wavelengths.



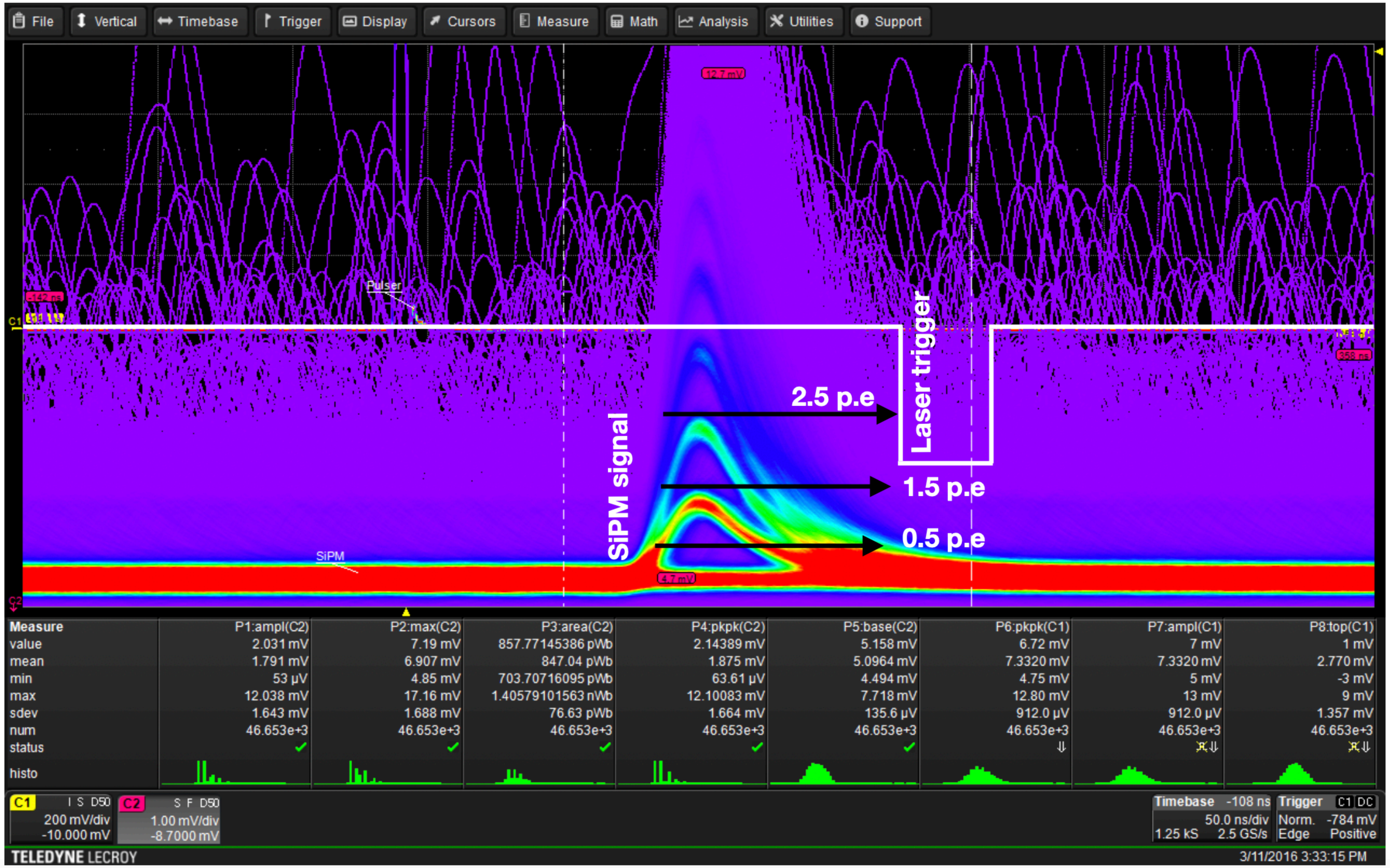


Importance of Timing Resolution and PDE

- In low energy particle physics and medical applications, to determine time-of-flight and position reconstruction, timing resolution is a key factor
- Alongwith timing resolution, precise PDE of the detector will provide energy reconstruction to give strong pulse shape discrimination
- The goal is to study these properties of SiPMs (at room and cryogenic temperatures) to establish best results for the future detector performances
- With large active area for detection, SiPM produce bad timing and energy resolution
- To mitigate this challenge, zero-pole cancellation filter is implemented in the form of digital signal processing.



Zero-Pole Cancellation technique

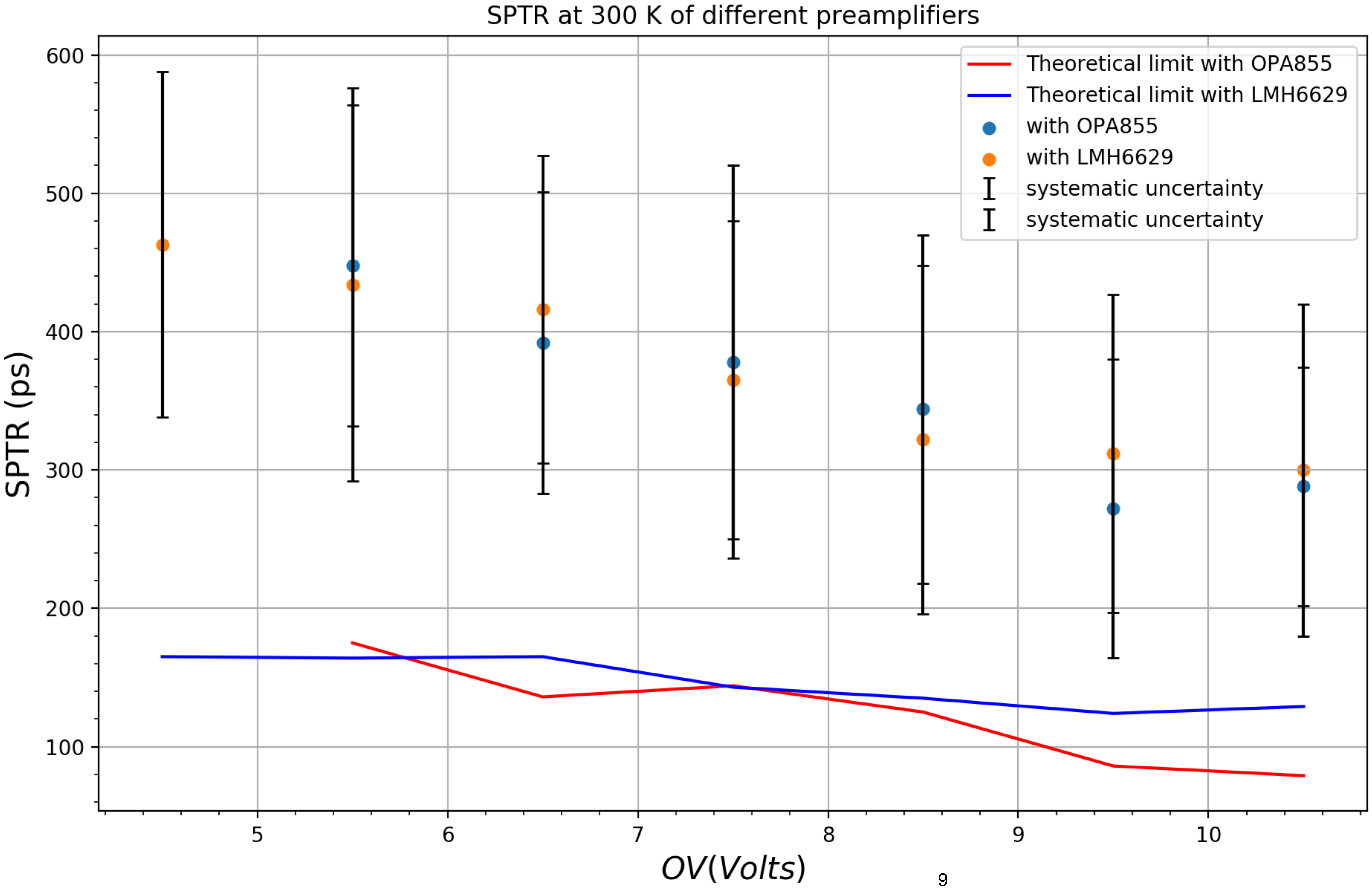


Under constant low intensity light and temperature, threshold

Time Jitter distribution =

$$Time_{lasertrigger} - Time_{SiPMsignal}$$

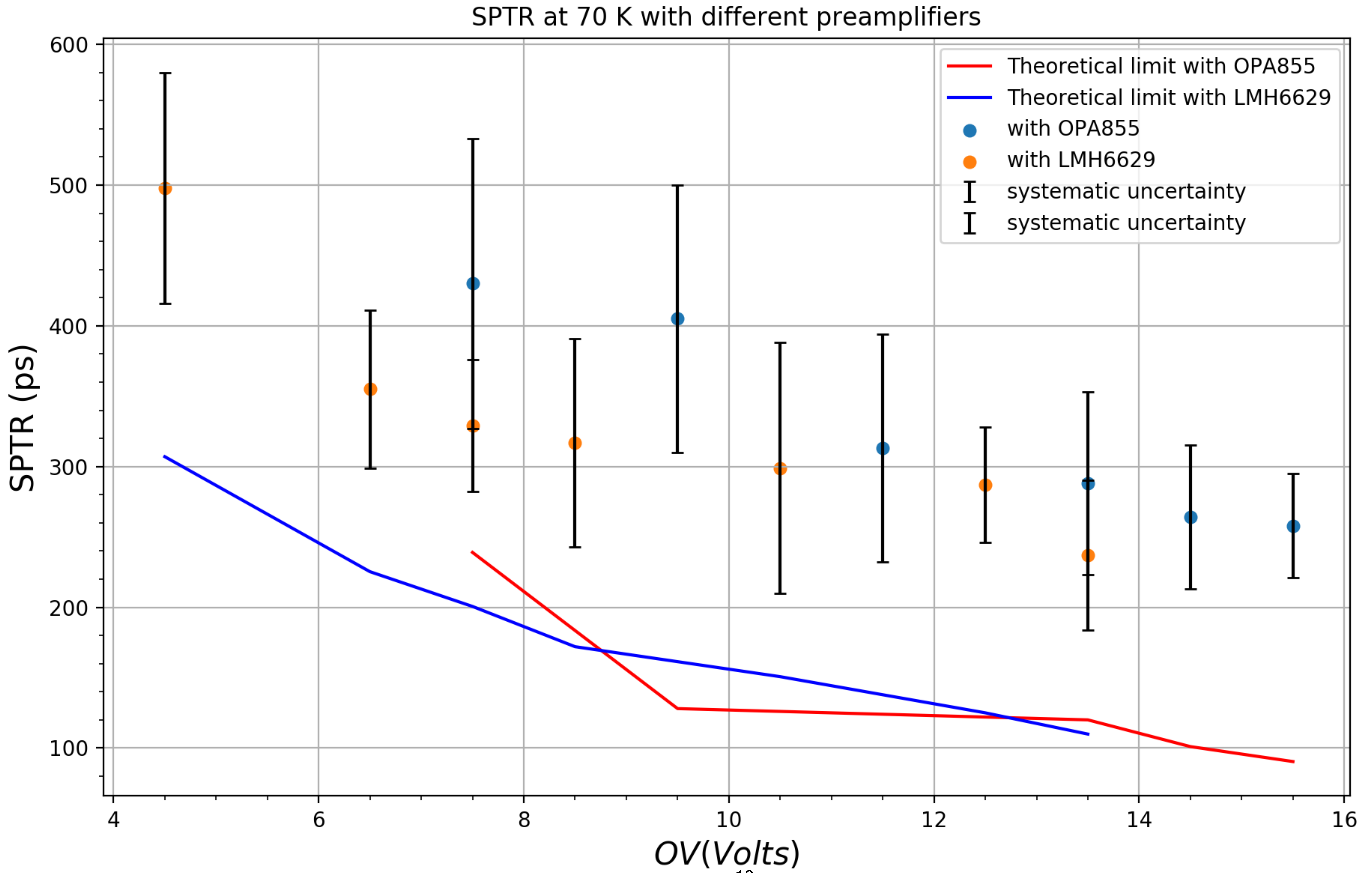
Results



$$Risetime = \frac{0.35}{bandwidth}$$

$$Th_{jitter} = \frac{Risetime}{SNR}$$

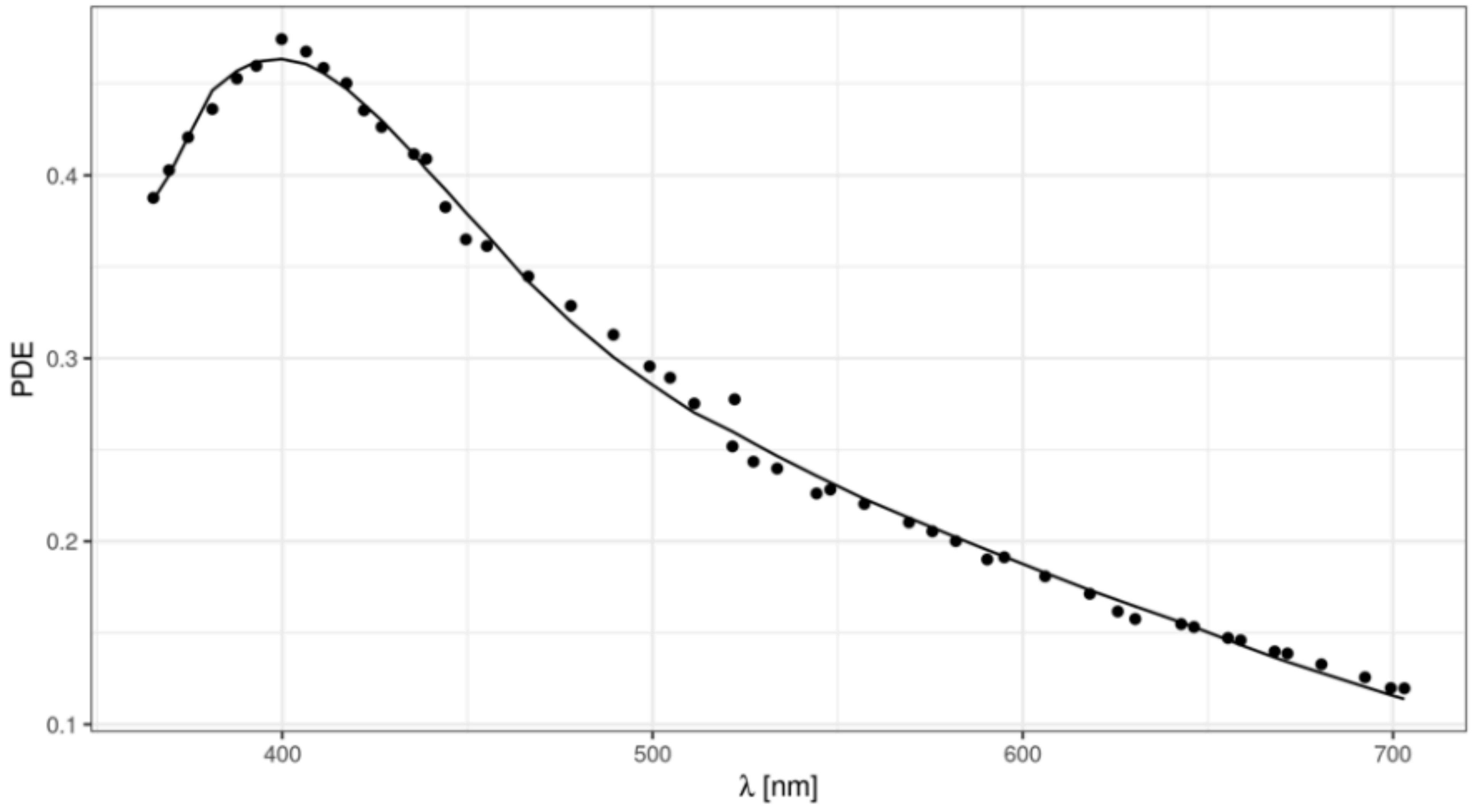
Results

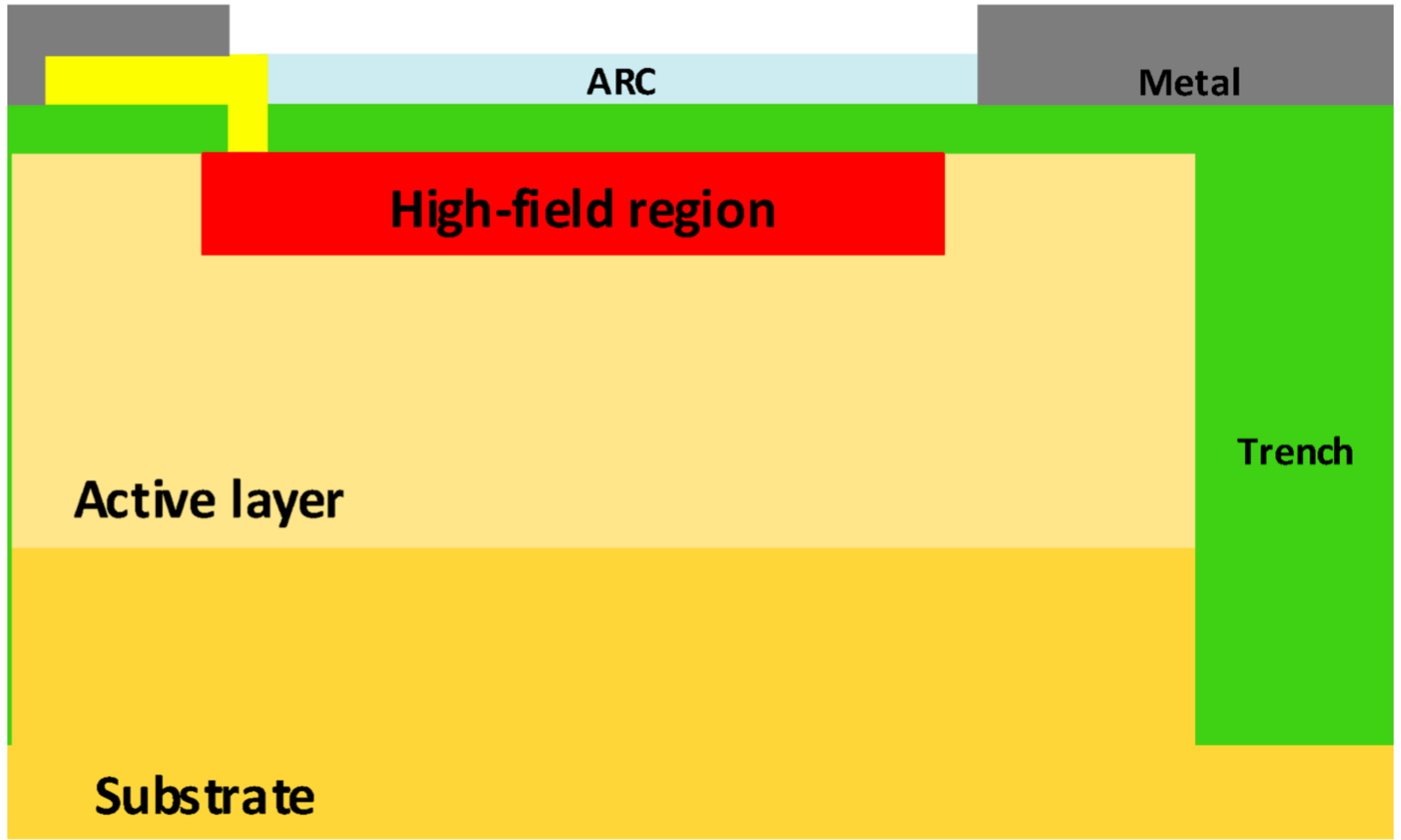

SPTR at 70 K with different preamplifiers
Theoretical limit with OPA855
Theoretical limit with LMH6629
with OPA855
with LMH6629
systematic uncertainty
systematic uncertainty
SPTR (ps)
600
500
400
300
200
100
4
6
8
10
12
14
16
OV(Volts)

Future Prospects

Optimising PDE at cryogenic temperatures

- Continuing the characterisation of SiPMs, PDE measurements at cryogenic temperatures need to be carried out to have conclusive estimates for the performance of future experiments.
- The current SiPMs are suitable for light detection at room temperature and loose their performance at cryogenic temperatures
- Studying PDE at cryogenic temperatures will create a profile of SiPMs customised for low-energy event reconstruction
- This can be done by studying the absorption length and thickness of the depletion region over different wavelengths.
- With optimum profiling, we aim to achieve PDE upto 60%





Future Prospects

Back illuminated SiPMs for low mass Dark Matter detection

- An optimised electronics and PDE, may lead to innovative low mass Dark Matter detector for masses < 1 GeV
- Low ionisation potential of Silicon makes it ideal target for low mass Dark Matter search
- The possibility to design a SiPM-based detector with 1 kg Silicon having sensitivity of $10^{-42} cm^2$ at mass of 1 GeV
- This will push the low energy threshold to 100 eV
- Back illuminated SiPMs will make bulk region of the SiPM as target and setup will have Liquid Nitrogen to act as a veto

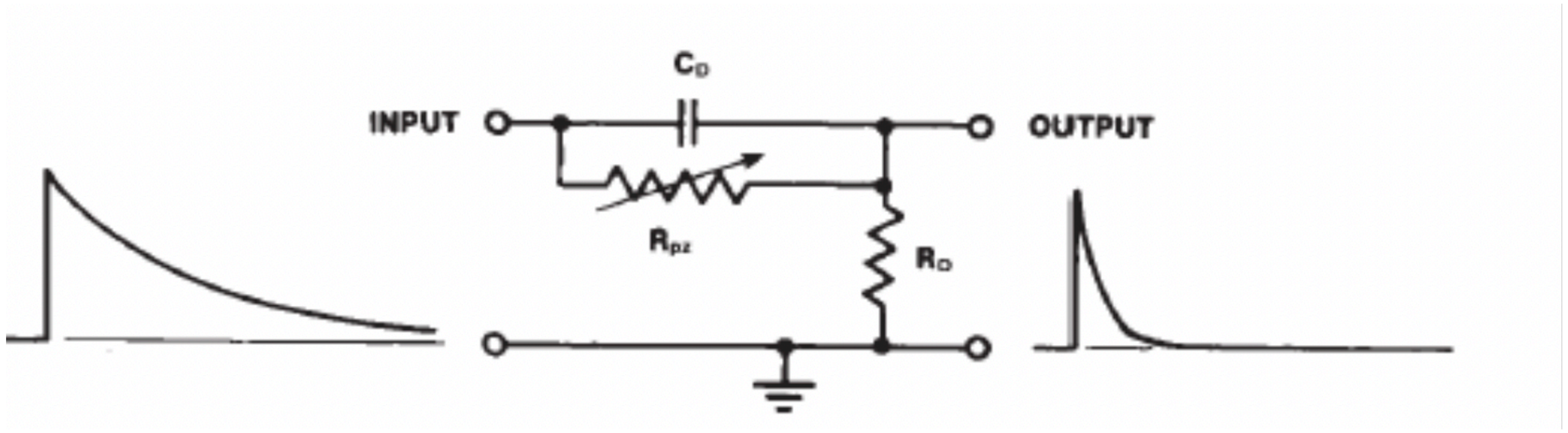
Thank you

DarkSide-50 delivered a zero-background and the best limit with the Argon target.
A low analysis threshold of DarkSide-50 enabled to study very low energy events at 100 eV_{ee}.
With powerful pulse shape discrimination to have high electron recoil background rejection factor 10^7,
With the 100 t yrexposure, 1.6 NR events are expected from coherent scattering of atmospheric neutrinos making DarkSide-20k first ever dark matter detector to achieve that milestone.
After DS-20k, GADMC is planning build Argo detector for ultimate Dark Matter search with exposure of 3000 t yr over 10 yr

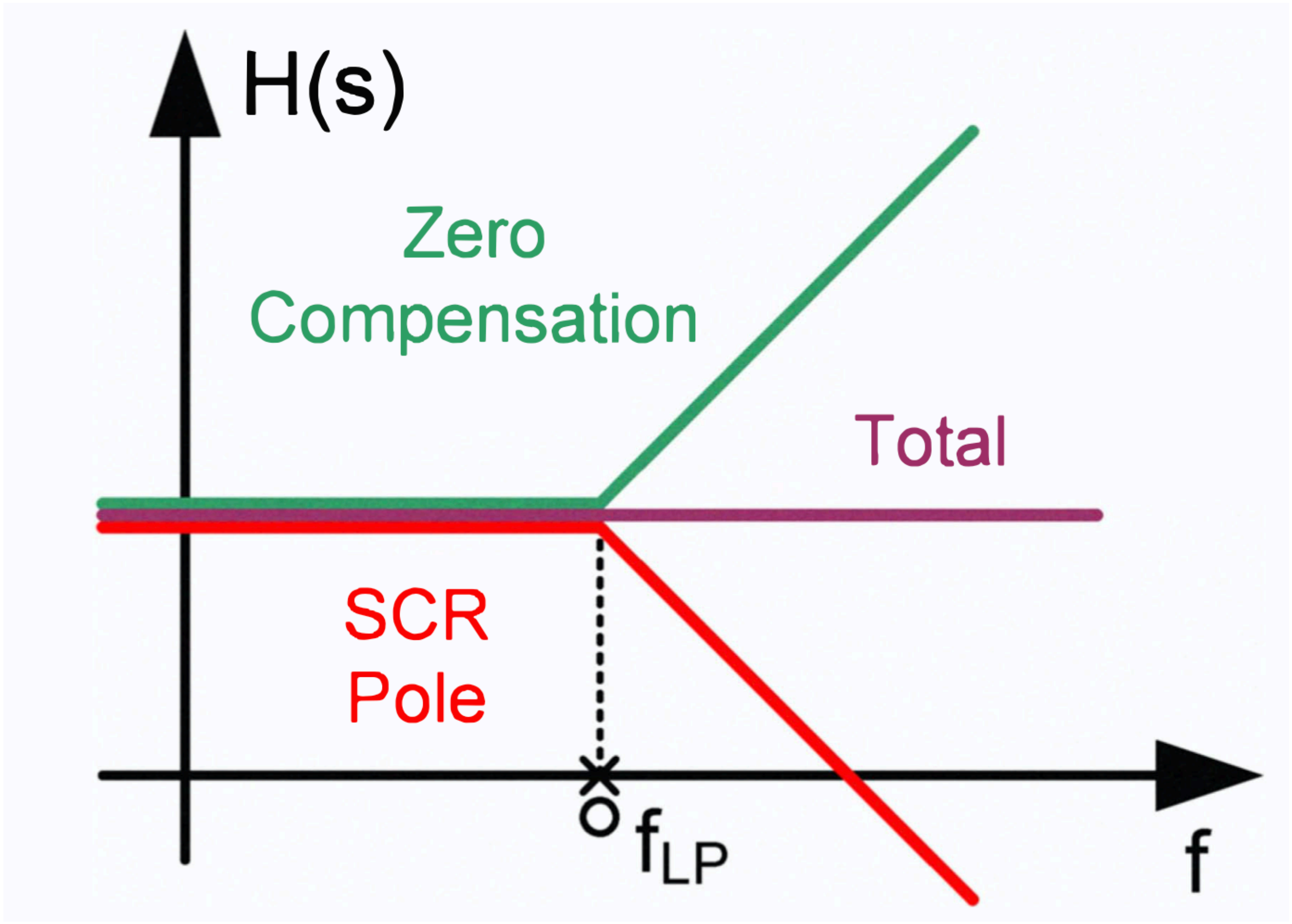
The goal of Argo design is to combine the precise position / energy reconstruction of events from the dual phase TPC principle and detection of only primary scinitillation signal to measure the time-of-flight for position reconstruction.

Both these techniques will be combined to mitigate backgrounds in the Argo design phase to increase the sensitivity by factor 1000.

Zero-Pole Cancellation technique



Equivalent analog circuit to the digital filter



- This technique produces a high pass filter that eliminates the long exponential tail of the signal in order to limit accumulation of pulses.
- As a result, it produces sharper pulses with improved Signal-to-Noise Ratio at room temperature.

Output waveform (LT)

$$O(\omega) = F(\omega) * \left(1 + \frac{j\omega}{\omega_0})\right)$$

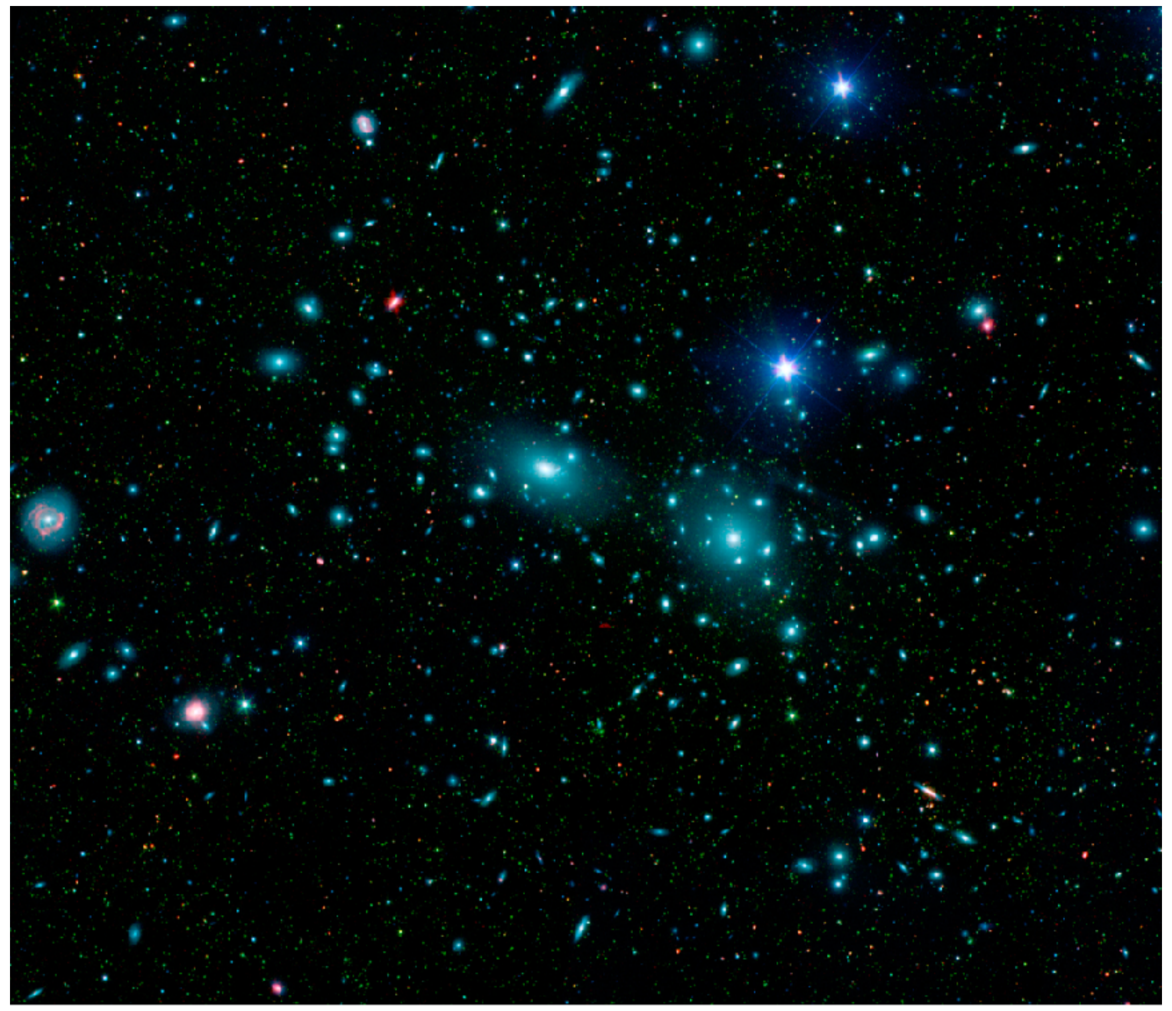
Output waveform (Inverse FT)

$$O(t) = f(t) + \frac{f'(t)}{\omega_0}$$

Astronomical Evidences

- Fritz Zwicky in 1930’s studied Coma Cluster which was 350 million light years away from Earth.
- Performed two types of measurements: estimation of total mass of galaxies from total luminosity, measurement of Doppler shift of the light emitted to determine radial velocities.
- Surprisingly!!! Fast radial velocities were observed for the galaxies which implied that cluster should have “EVAPORATED”.
- Conclusion: Presence of invisible mass called “DARK MATTER” which has a gravitational pull but does not contribute to galaxy luminosity.

DARK MATTER = 500 * (Visible Mass)



Source: Coma Cluster, NASA/JPL-Caltech/SDSS

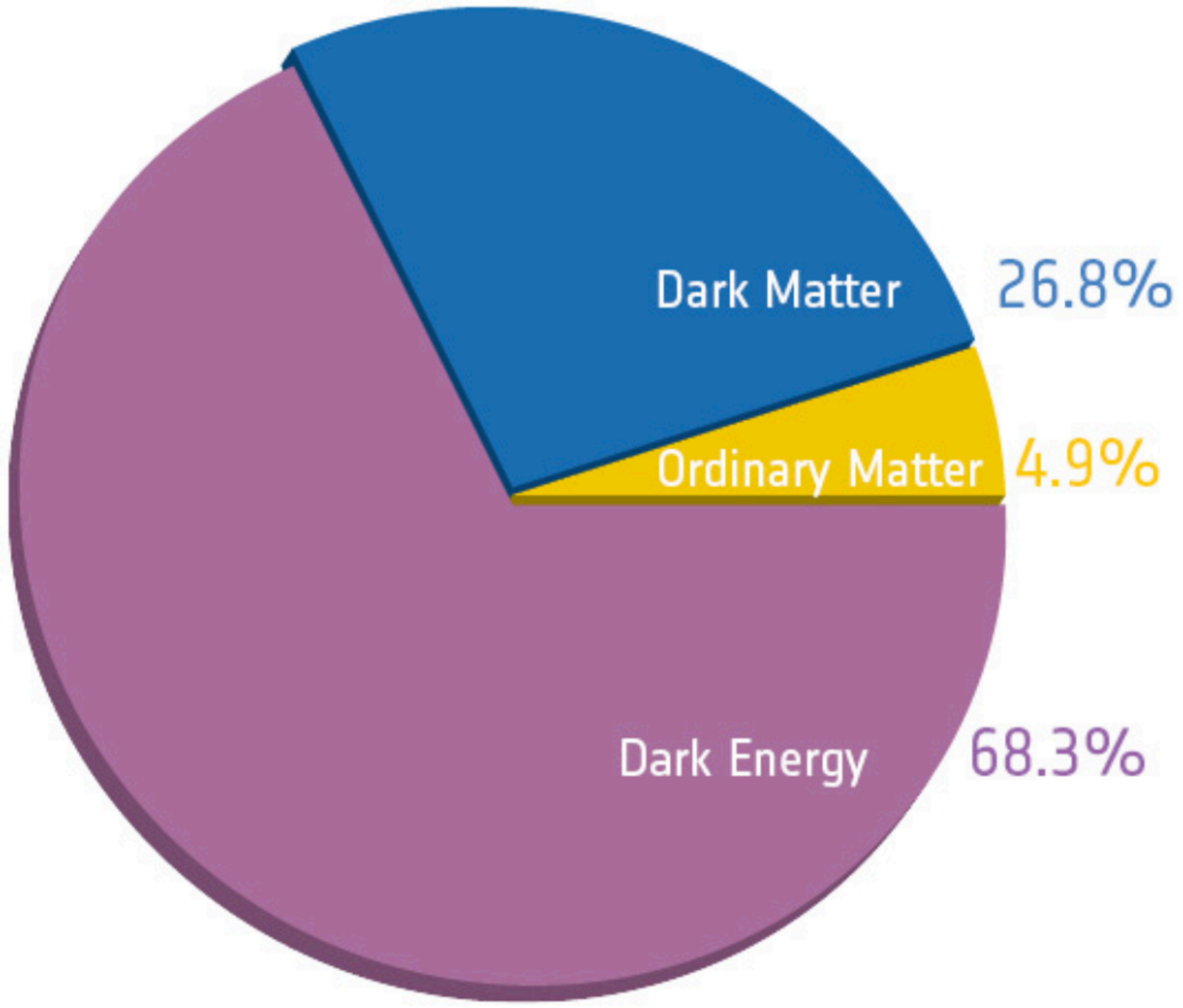
- The single photon timing resolution of the detector is an important parameter that influences the detector response
- In low energy particle physics and medical applications, to determine time-of-flight and position reconstruction, timing resolution is a key factor
- It can be described as the precision on the arrival time of the single photon initiated signal.
- Alongwith timing resolution, precise PDE of the detector will provide energy reconstruction to give strong pulse shape discrimination
- The goal is to study these properties of SiPMs to establish best results for the future detector performances
- At room temperature, SiPM suffers issue of pile up resulting in bad SNR and energy resolution
- To mitigate this challenge, zero-pole cancellation filter is implemented in the form of digital signal processing.

- An optimised electronics and PDE, may lead to innovative Dark Matter detector for masses < 1 GeV
- Low ionisation potential of Silicon makes it ideal target for low mass Dark Matter search
- The possibility to design a SiPM-based detector with 1 kg Silicon having sensitivity of $10^{-42} cm^2$ at mass of 1 GeV
- Back illuminated SiPMs will make bulk region of the SiPM as target and setup will have Liquid Nitrogen to act as a veto

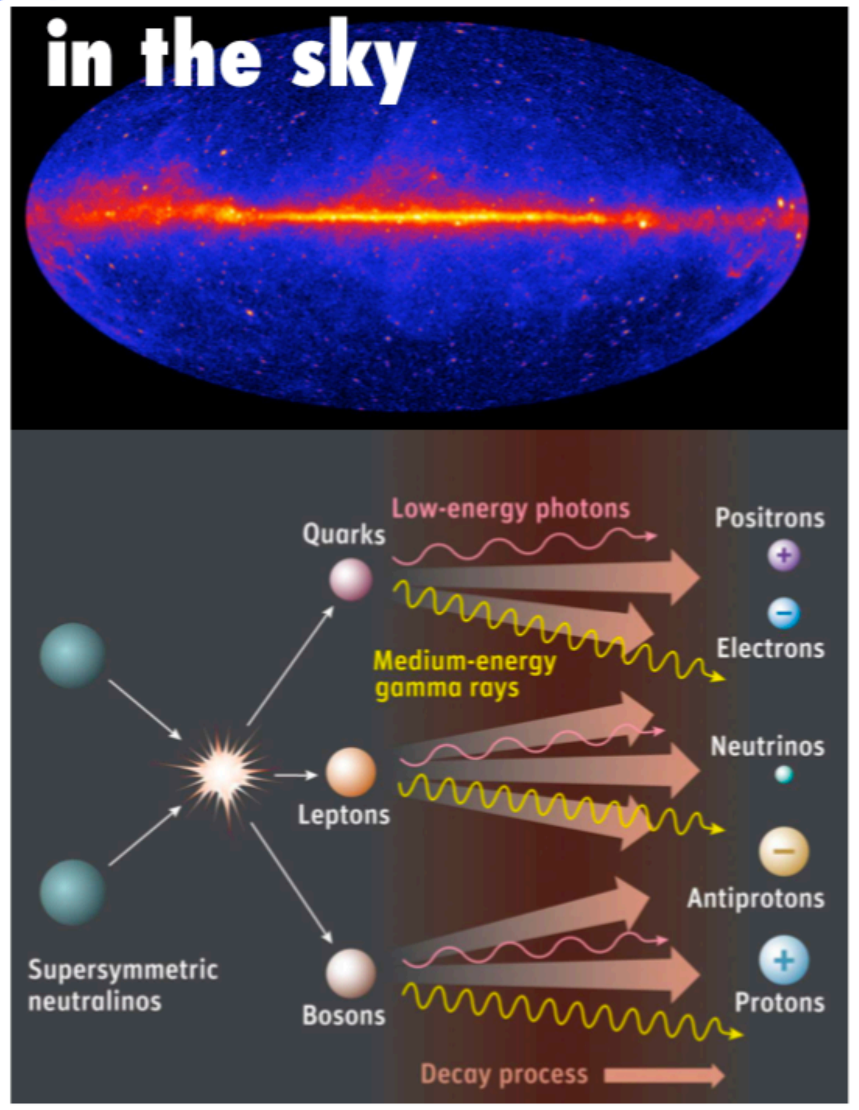
- From the recent GADMC results, the possibility of developing SiPM array with 25 cm^2 large area photo-detection in Liquid Argon seems promising with extremely low noise characteristics
- Silicon has proven to be optimal target for low mass dark matter searches at low recoil energies
- With this idea, the design for an SiPM based Silicon target detector is proposed which will be capable of achieving very low threshold of 100 eV
- In this setup the SiPMs will be illuminated from the the back side (close to the bulk region that will behave as the target) and submerged in Liquid nitrogen acting as a veto
- The setup with 1 kg of Silicon target will be sensitive to WIMP masses <1 GeV and will be able to achieve sensitivity upto $10^{-42} cm^2$

What is Dark Matter?

- Dominant matter in the universe is Non-Baryonic in nature.
- When ordinary visible matter in vicinity of it, clumps it together — Weak Lensing Effect on ordinary matter.
- Neutral and Non-luminous
- Interact weakly (new kind of weak force) or gravitationally with Baryonic Matter

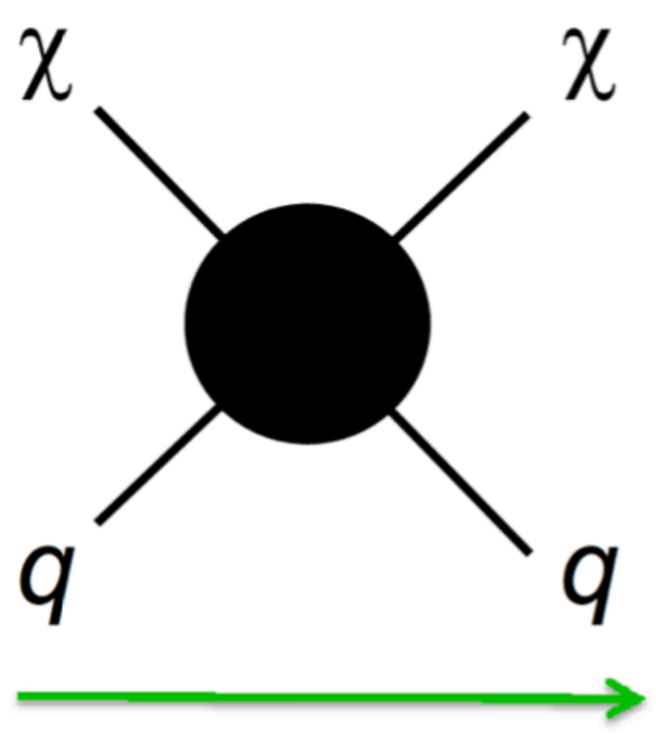


How to detect Dark Matter?



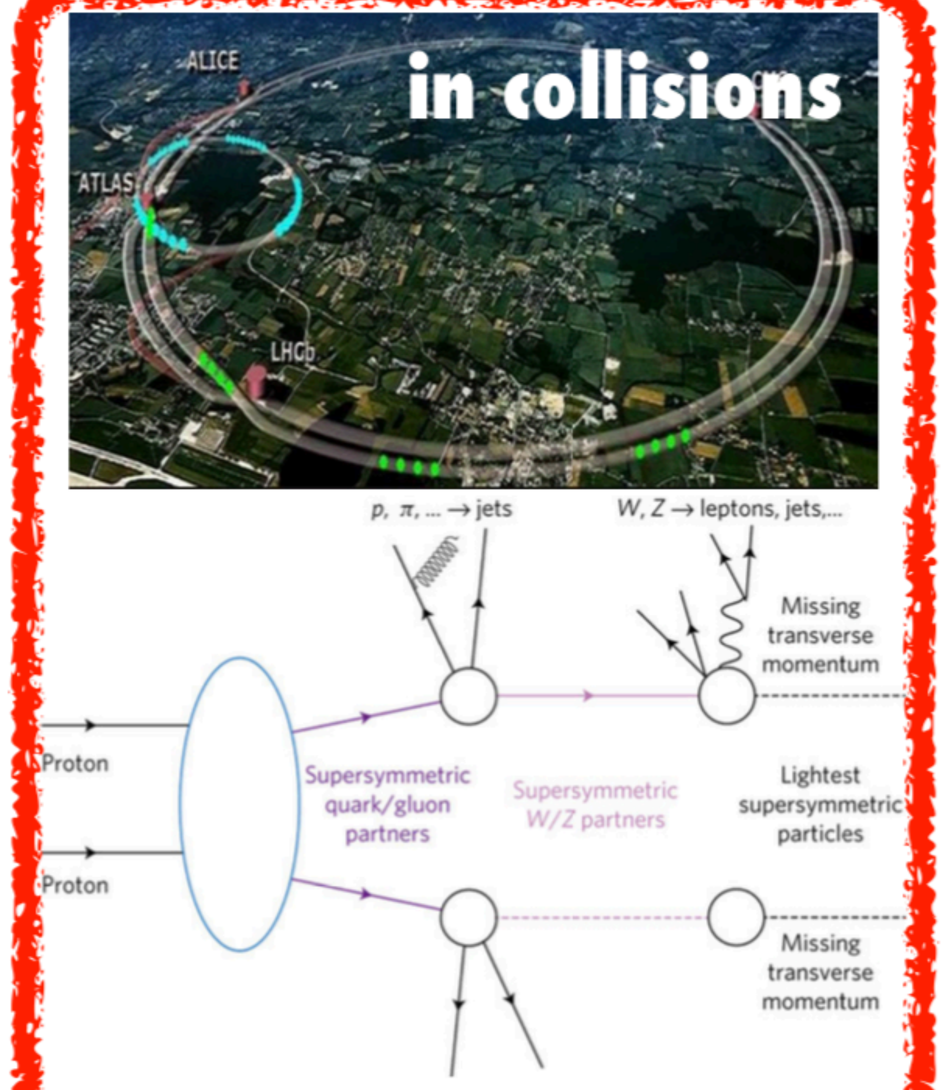
$\chi\chi \to e^+e^-, p\bar{p}$

Efficient annihilation now
(Indirect detection)

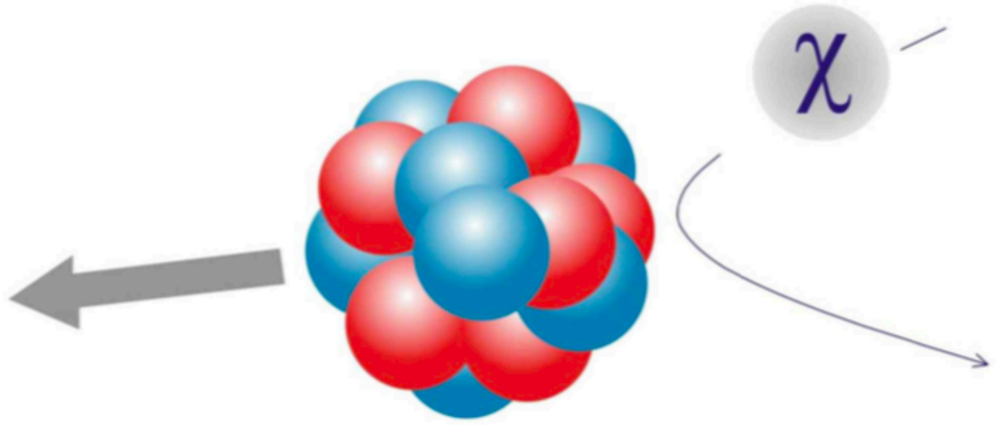


Efficient scattering now
(Direct detection)

Efficient production now
(Particle colliders)

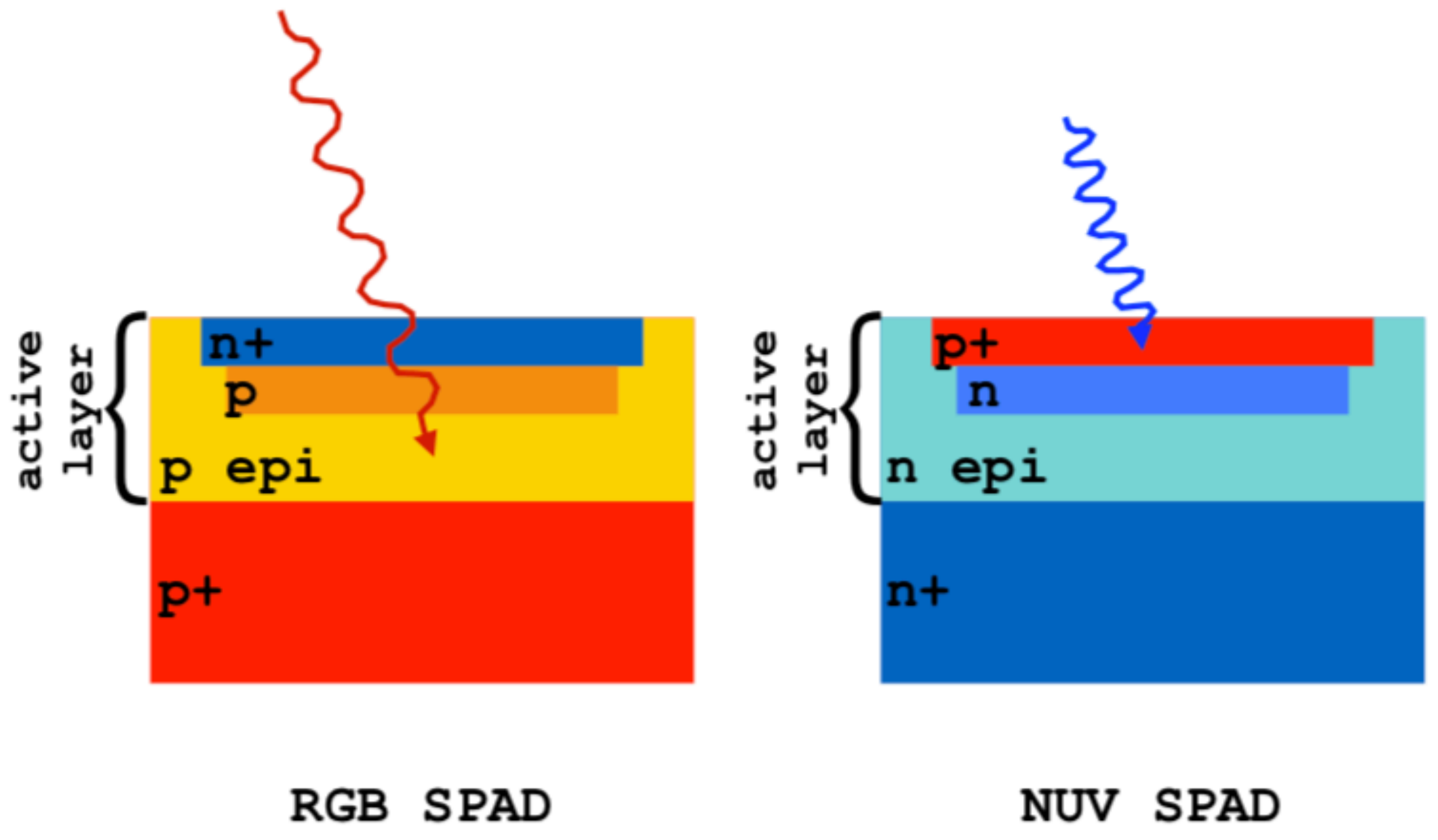


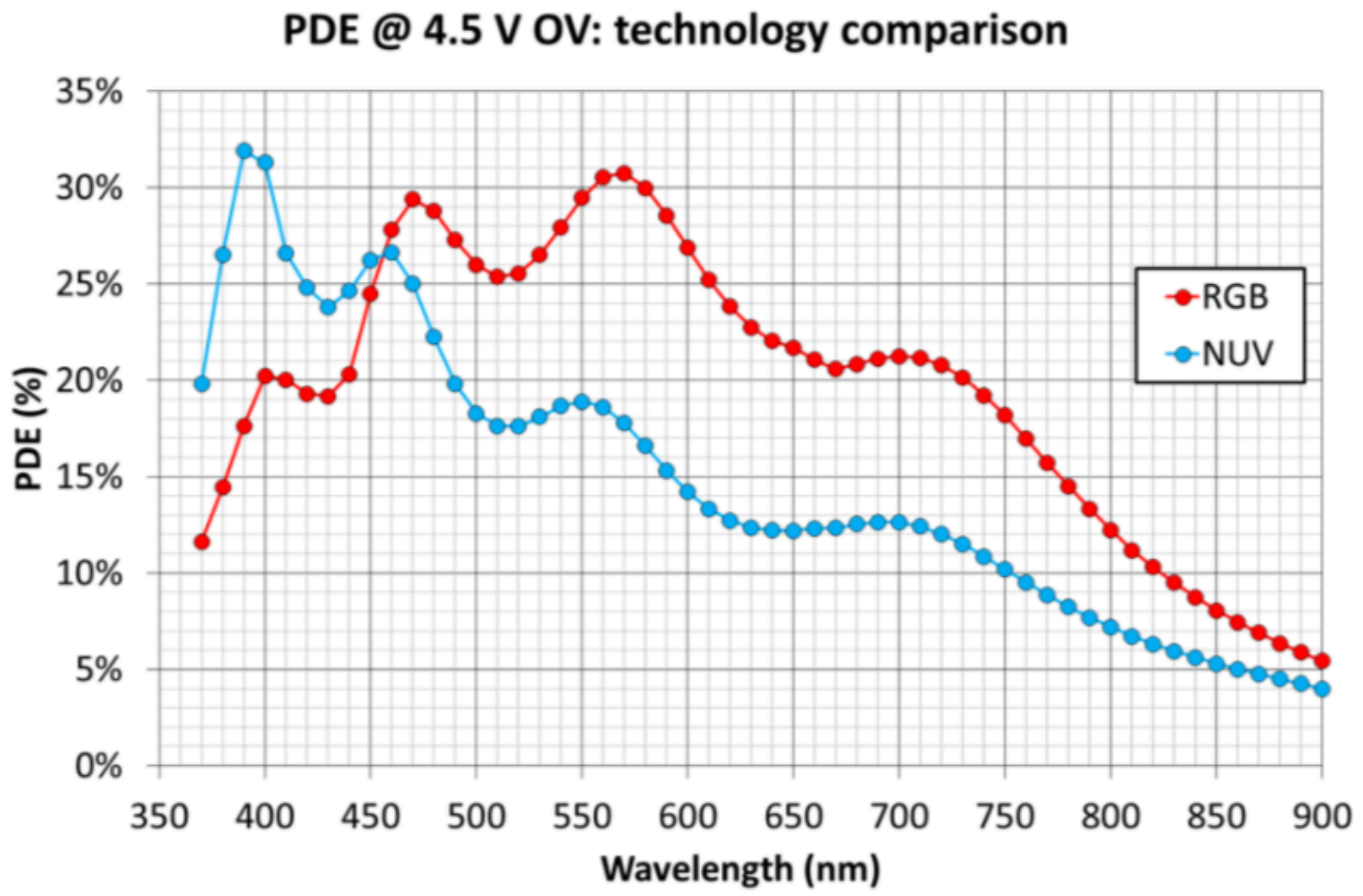
$p + p \to \chi + \text{a lot}$



$\chi N \to \chi N$

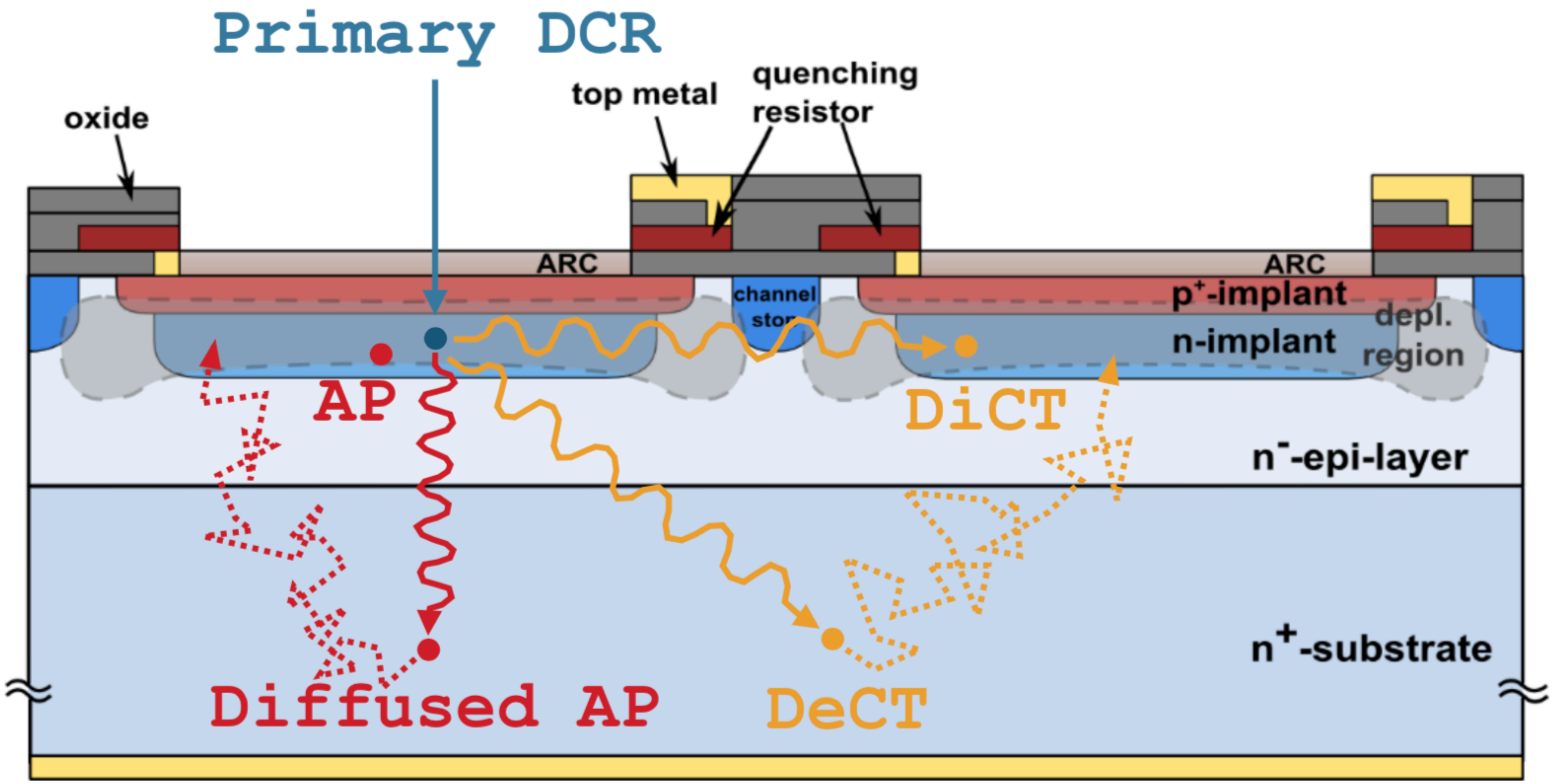
SiPM working





For DarkSide requirement: NUV SiPMs are the best choice due to the PDE performance at 420 nm

SiPM working and properties



Terminology :

DiCT - Direct Crosstalk Talk

DeCT- Delayed Cross talk

AP- AfterPulses

DCR - Dark Count Rate

Temperature dependent factors

For the NUV SiPMs used in DarkSide

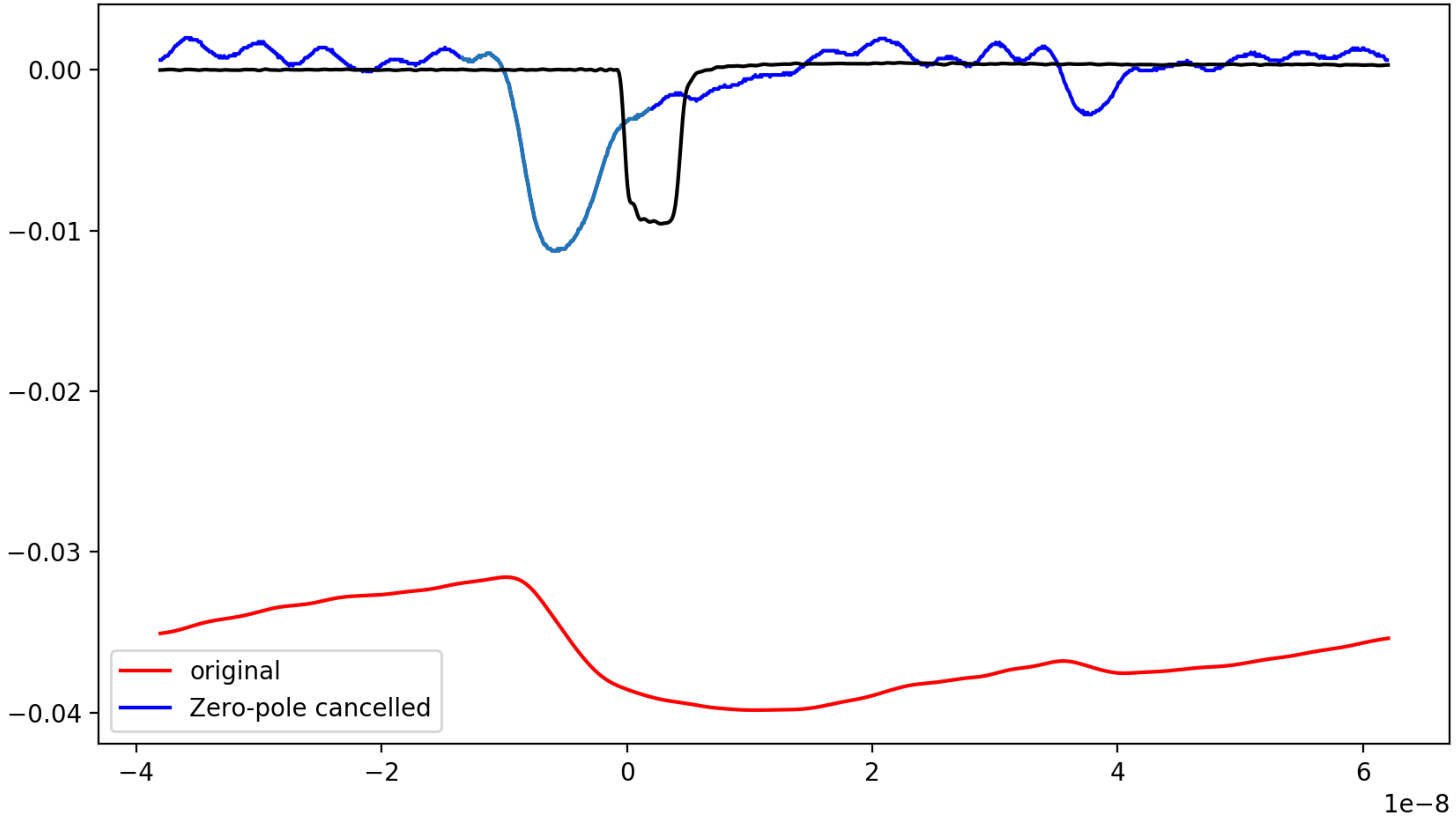
DCR @ 300K = 1 MHz/mm^2 at 5 OV

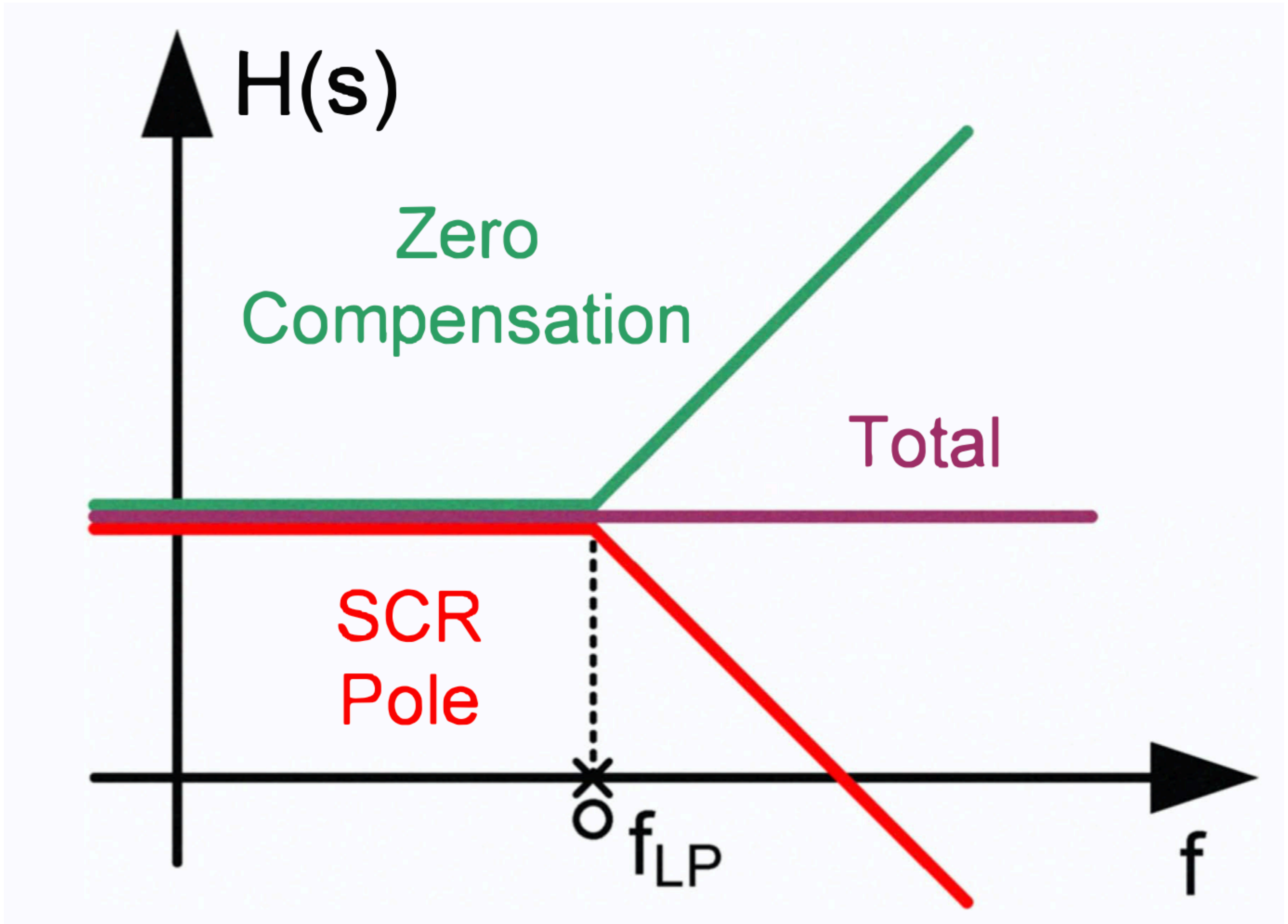
DCR @ 70K = 0.1 Hz/mm^2 at 5 OV

DCR introduces huge pile up signals —> understanding the limit of NUV SiPMs for applications at room and cryogenic temperature

- SiPMs can exhibit Photon Detection Efficiency upto 50%
- High geometrical fill factor and low power consumption
- As per DarkSide requirements, a 20% more light yield than DarkSide-50
    1. SiPM Photo-Detection Modules (PDM) will have 25 cm^2 area.
    2. PDE of a module > 40 %
    3. Timing resolution needs to be of the order of 10 ns
    4. Each module should produce total noise < 250 Hz
    5. Dynamic range from each module should be > 50 p.e

Zero-Pole Cancellation technique





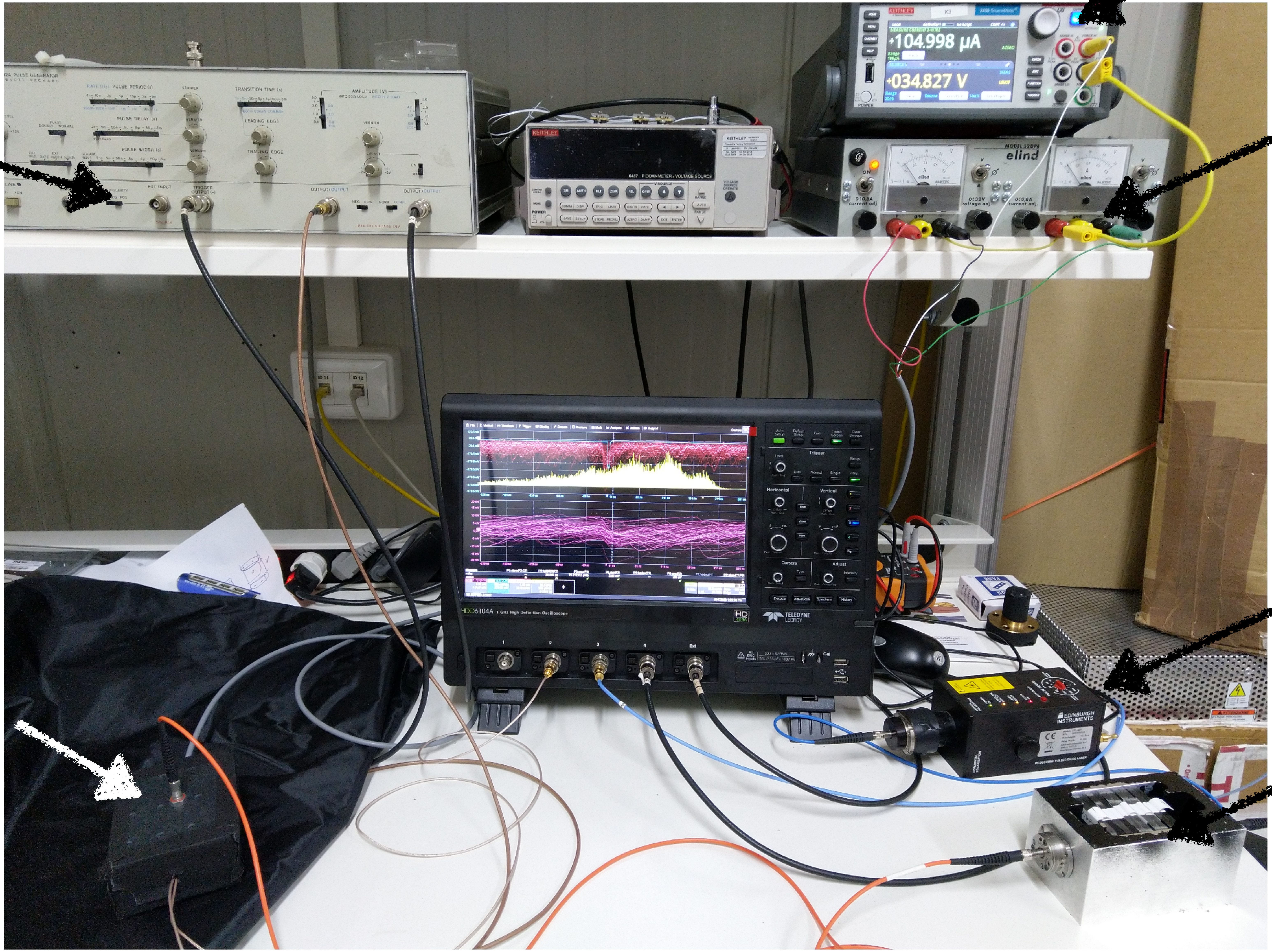
- This technique produces a high pass filter that eliminates the long exponential tail of the signal in order to limit accumulation of pulses.
- As a result, it produces sharper pulses with improved Signal-to-Noise Ratio at room temperature.

Measurement Setup

Sourcemeter (to bias the SiPM)

Pulse generator

Power supply to power up the amplifier



Laser source (408 nm)

Box containing 1 cm2 SiPM + preamplifier board

Filter box (to vary the light intensity)