darkside
two-phase argon TPC for Dark Matter Direct Detection

The DarkSide-20k detector: a closer look to SiPMs

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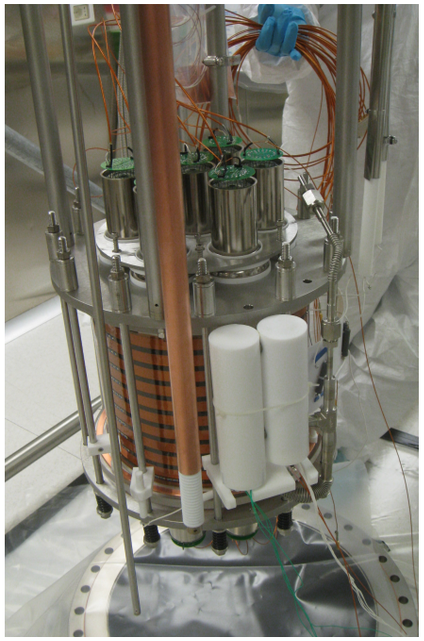
13th Rencontres du Vietnam
Exploring the Dark Universe

The DarkSide program: an overview

- **Scientific target**: probe SI WIMP-nucleon interaction cross sections up to ~10^{-47}cm^2@1TeV/c^2.
- **Type of detectors**: double-phase Argon Time Projection Chambers.
- **Appealing feature**: background free search.

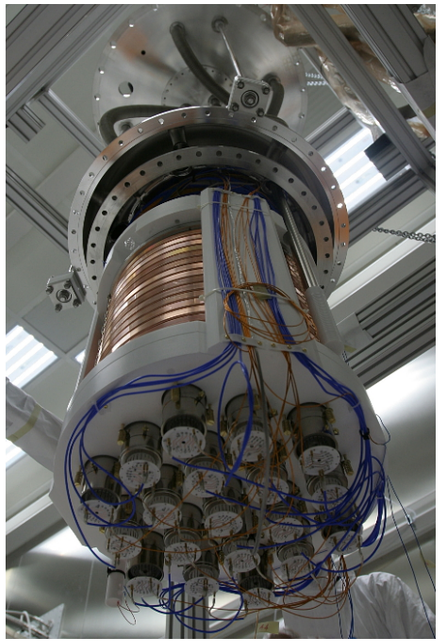
DarkSide-10



Operation: 8 months since 2011.

Demonstrated LAr ER/NR discrimination power.

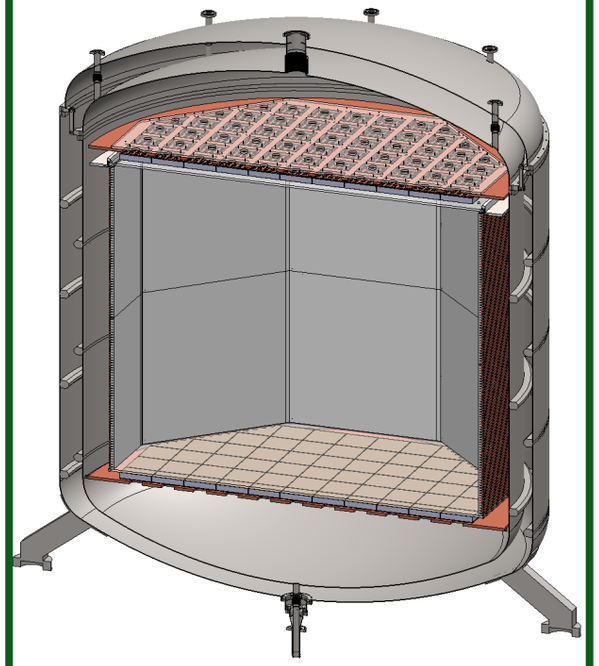
DarkSide-50



Operation: 2013-ongoing.

Used UAr successfully reducing the β background.

DarkSide-20k



Operation: 2021 - >2026.

Use of 23t(20t) of UAr.

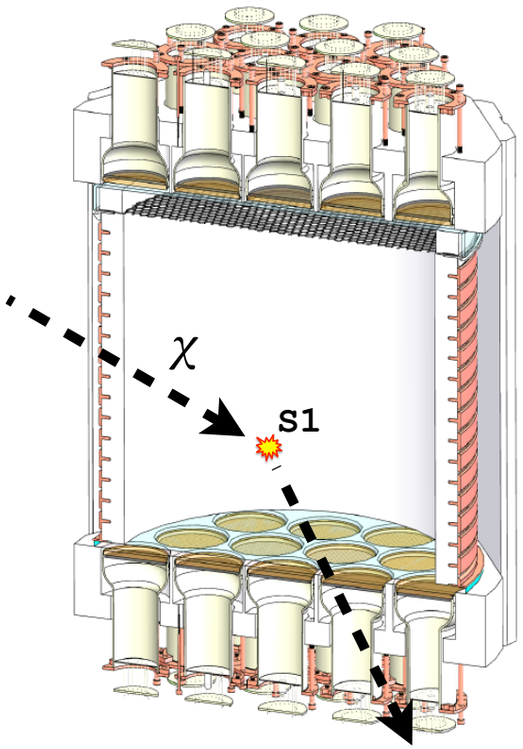
Upgrade from PMT to SiPM technology.

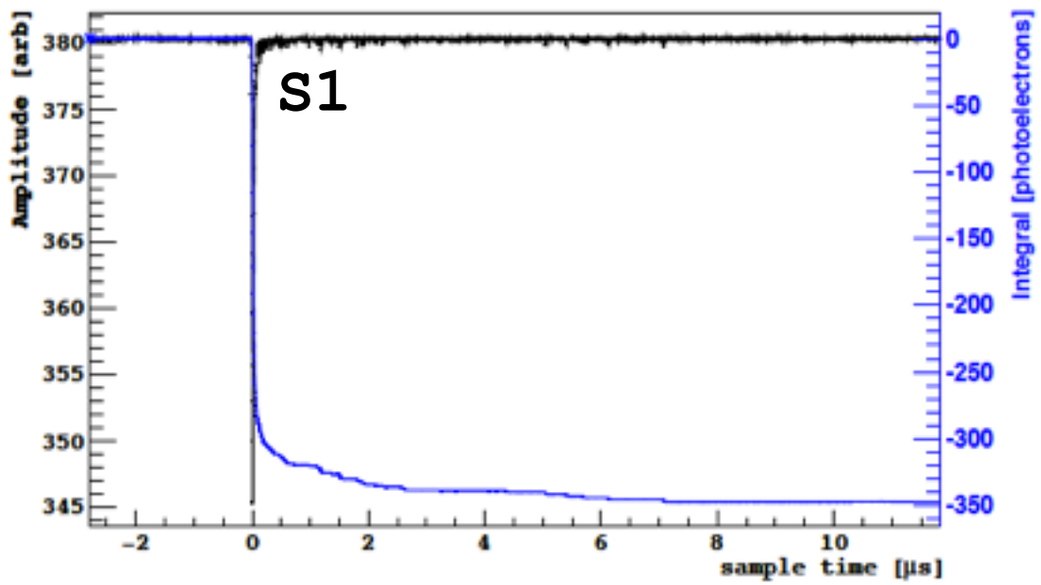
Location: LNGS, Italy

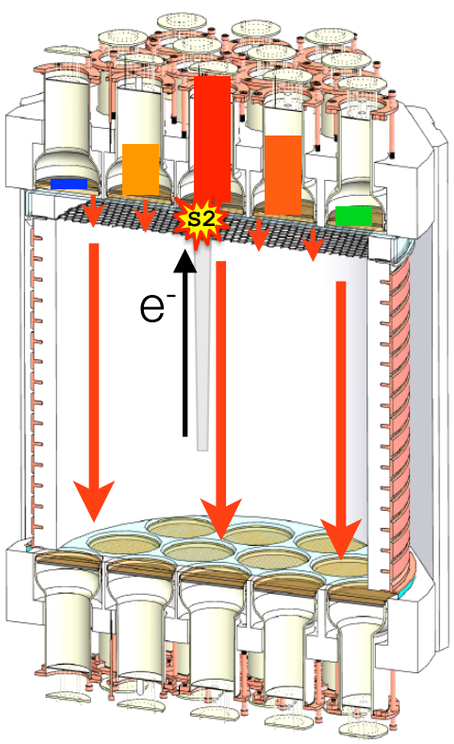
- Natural shield of 1400m of rock (3800 m.w.e.) from cosmic rays. *Muon flux suppression factor: 10^6.*
- *~10^3 reduction in neutron flux* with respect to surface due to low U and Th content in dolomite rock.
- Direct access to the labs from the highway.

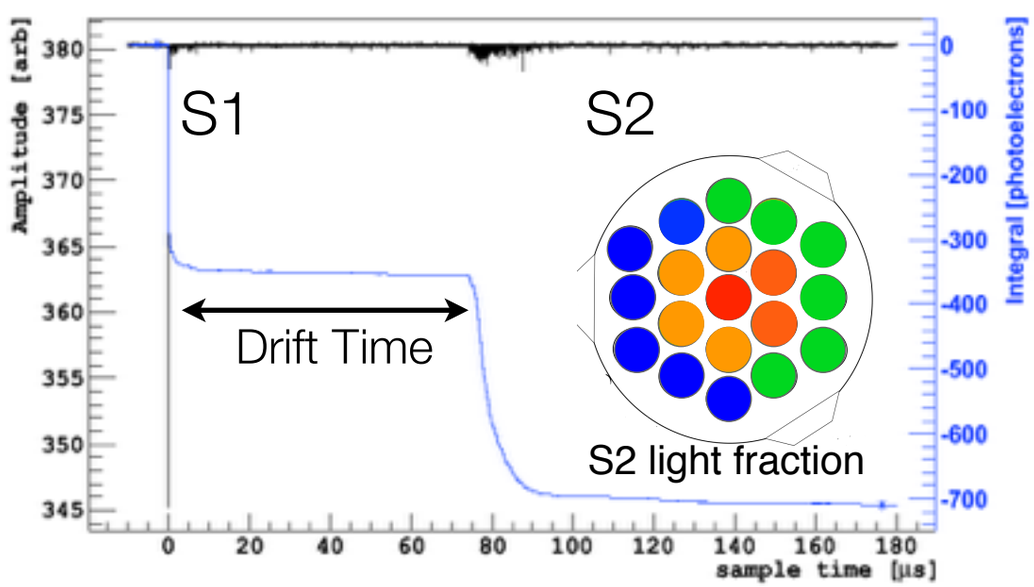
3800m.w.e. ⇕ 1400m of rock

Dual phase TPC: concept









- A NR induces a first scintillation pulse (S1) and ionizes Ar.
- Electrons are drifted by the E field to the LAr surface.
- A further field extracts the e^-, causing a second and brighter light pulse S2 (electroluminescence).
- Δt among S1 and S2 gives the Z coordinate.
- XY position is reconstructed looking at the distribution of S2 photons on the PMTs.

Fighting Background

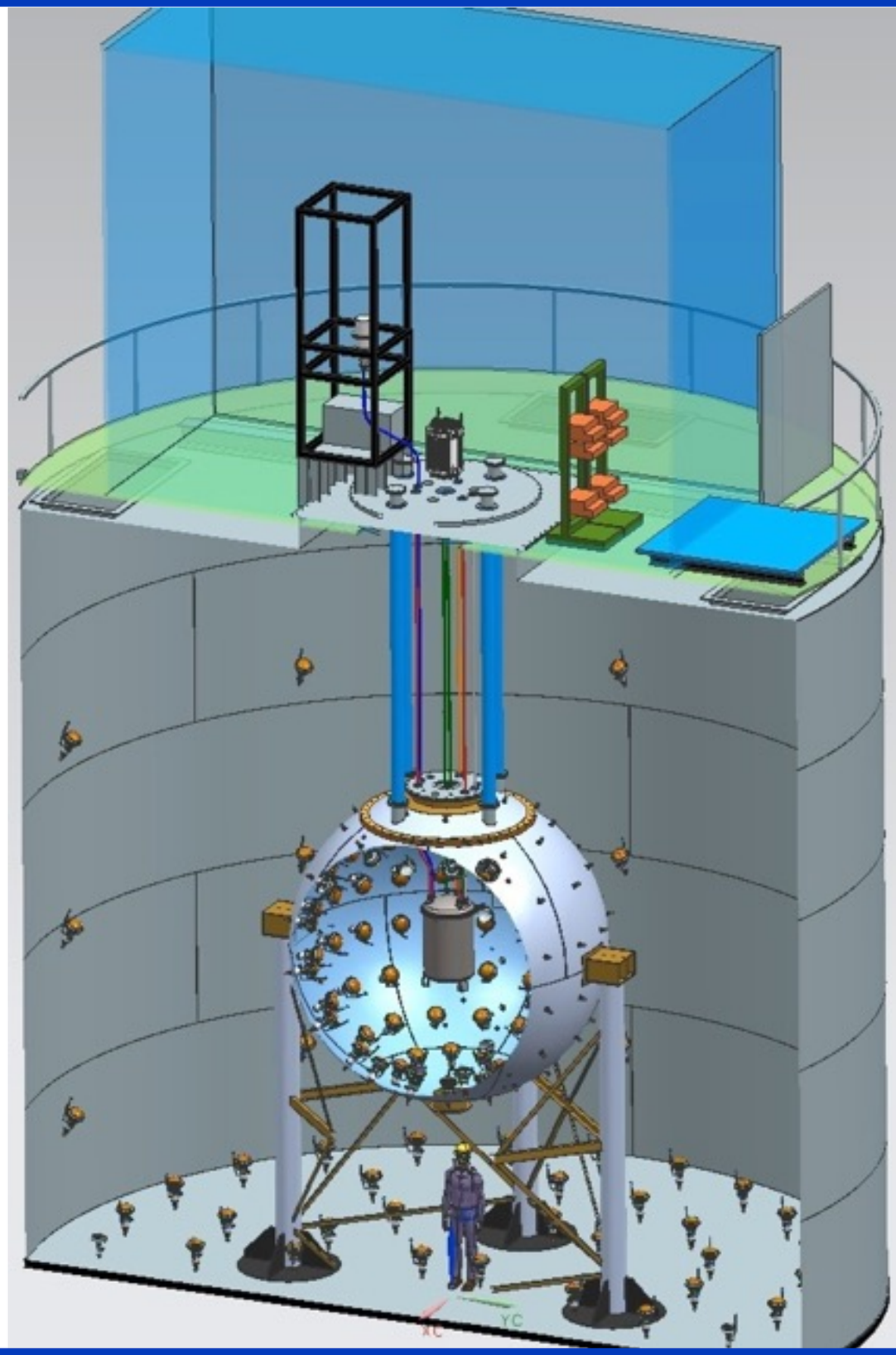
Observables in LAr

- ER: β and γ → Backgrounds
- NR: neutrons, neutrinos, WIMPs

1. <u>Active shielding</u>:
   - Muon Veto (Water Cherenkov Detector)
   - Neutron Veto (Liquid Scintillator)

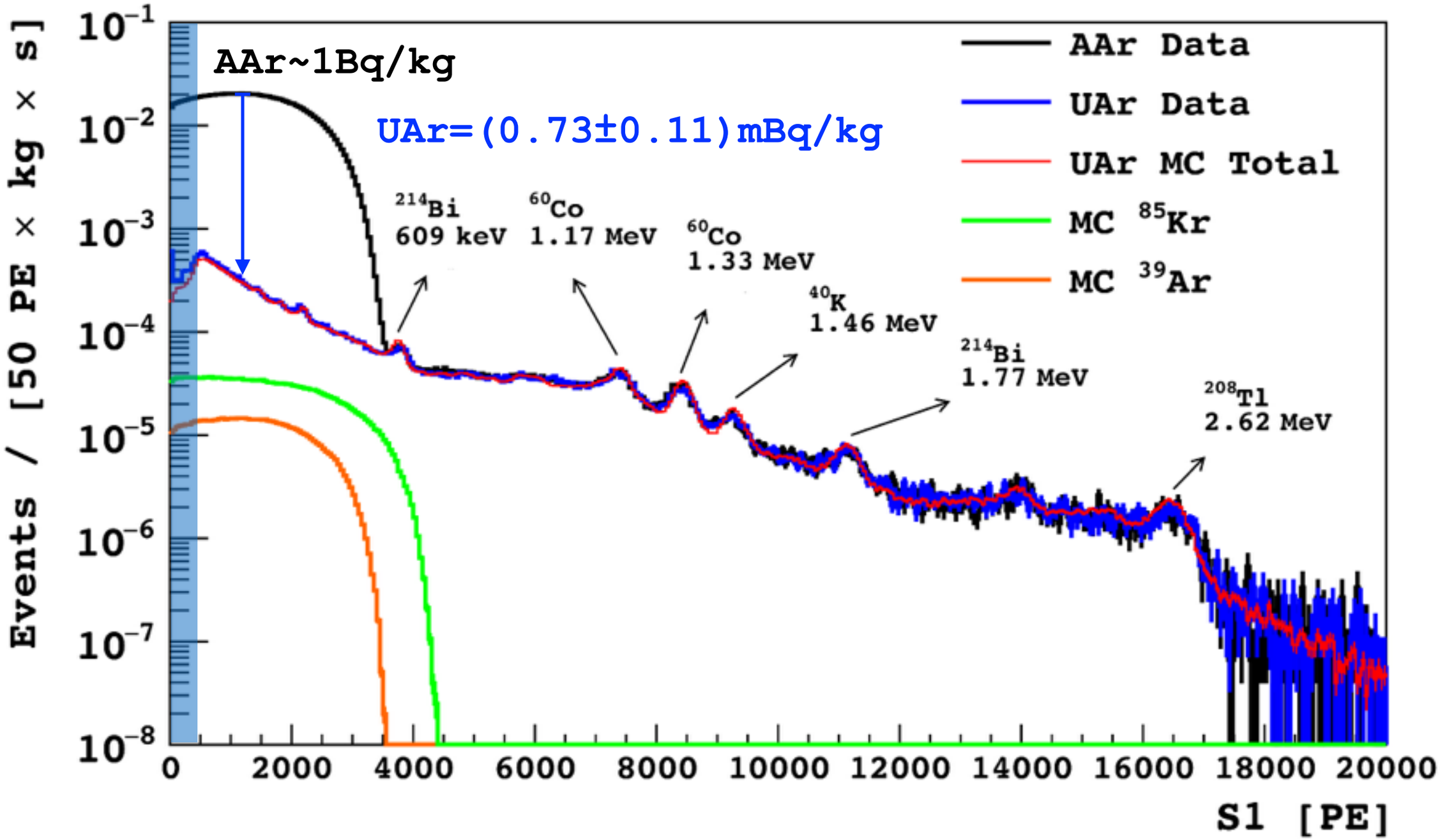
2. <u>Passive suppression</u>:
   - Low radioactive materials
   - Isotopically depleted Argon
   - Low radioactive light-detectors

3. <u>Identification</u>:
   - Multiple scattering within TPC
   - Surface events (position reconstruction)
   - ER/NR discrimination via S2/S1
   - ER/NR discrimination using PSD



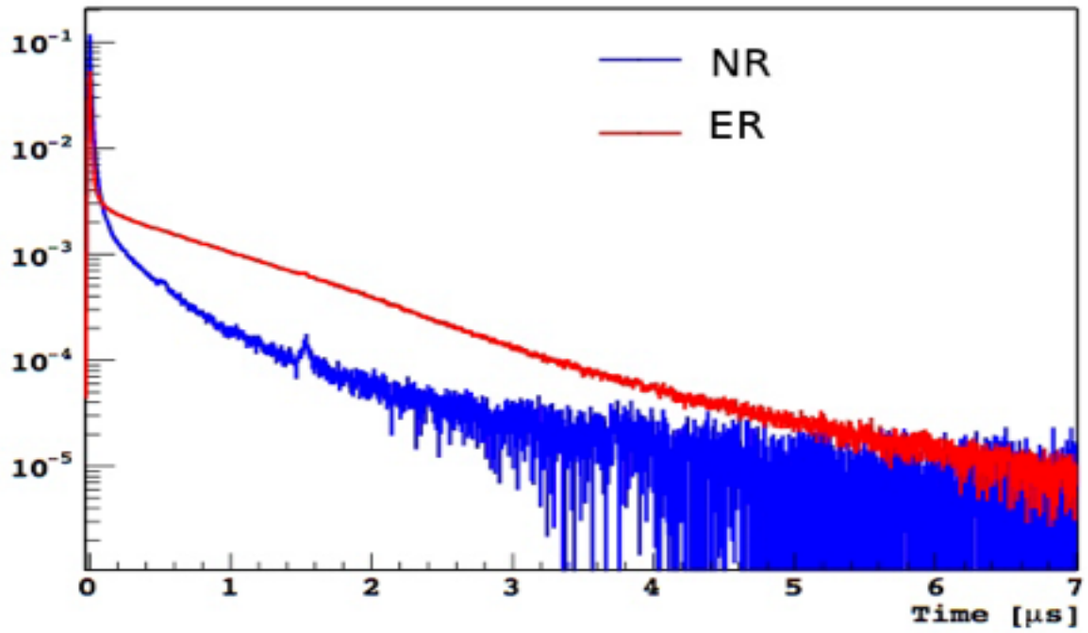
Suppression: AAr Vs UAr

Strongest background for Ar based experiments is ^{39}Ar induced ER.



Argon extracted from an underground gas mine in Colorado has an ^{39}Ar activity 1400 times lower than Atmospheric Ar.

ER/NR Discrimination

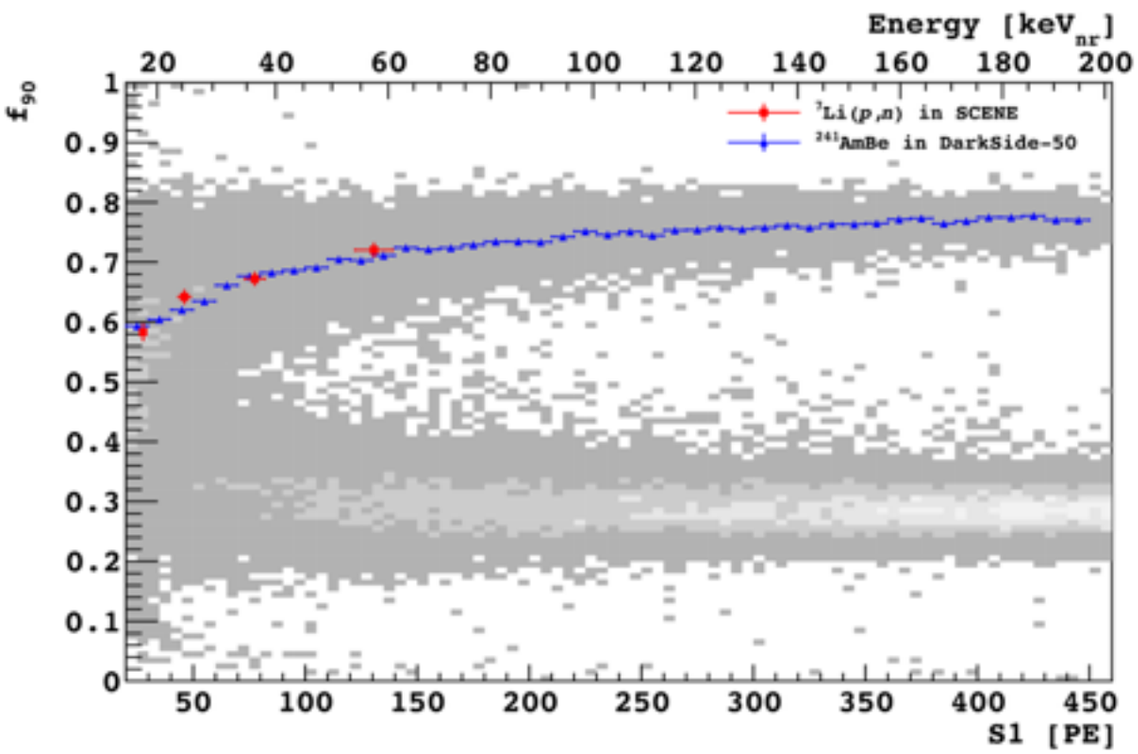


LAr scintillation light has 2 decay times: τ_{fast}=7ns, τ_{slow}=1600ns

Discriminating variable:

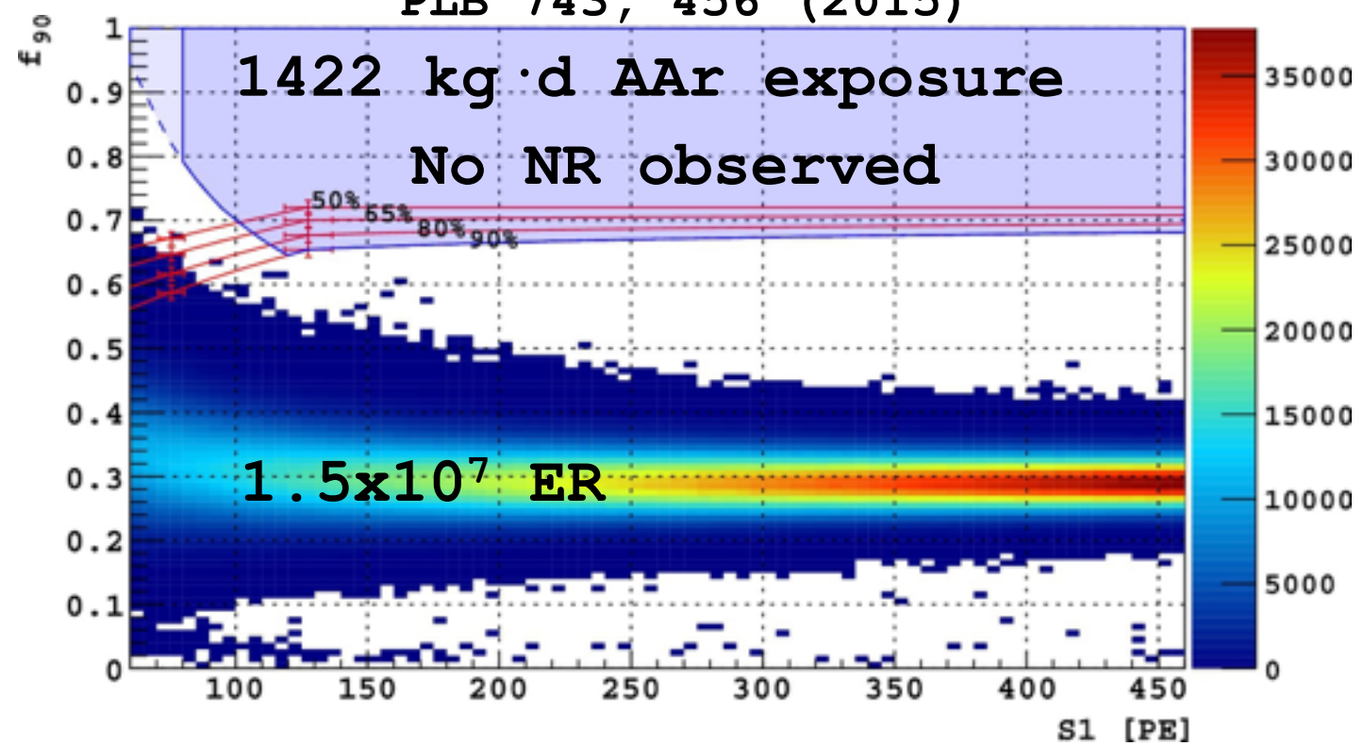
$$f_{prompt} = \frac{\#\ \text{prompt photons}}{\#\ \text{total photons}}$$

In DS-50 90ns is the optimal time window to optimize PSD.



ER and NR produce light with different τ_{fast}/τ_{slow} fractions.

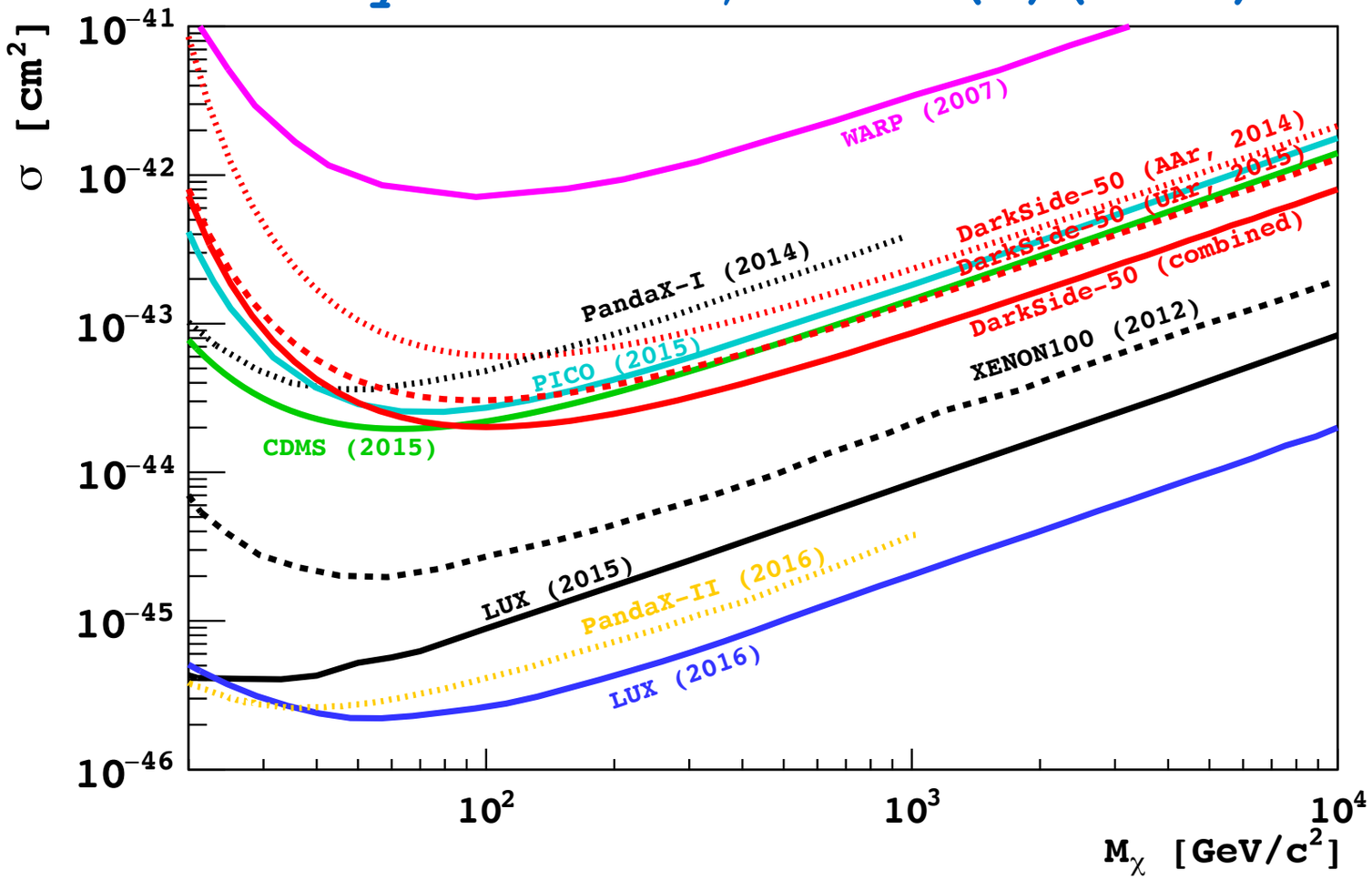
PLB 743, 456 (2015)



Discrimination Power > 1.5 x 10^7
Background-free UAr exposure: 5.5ton·yr

Latest limits with DS-50

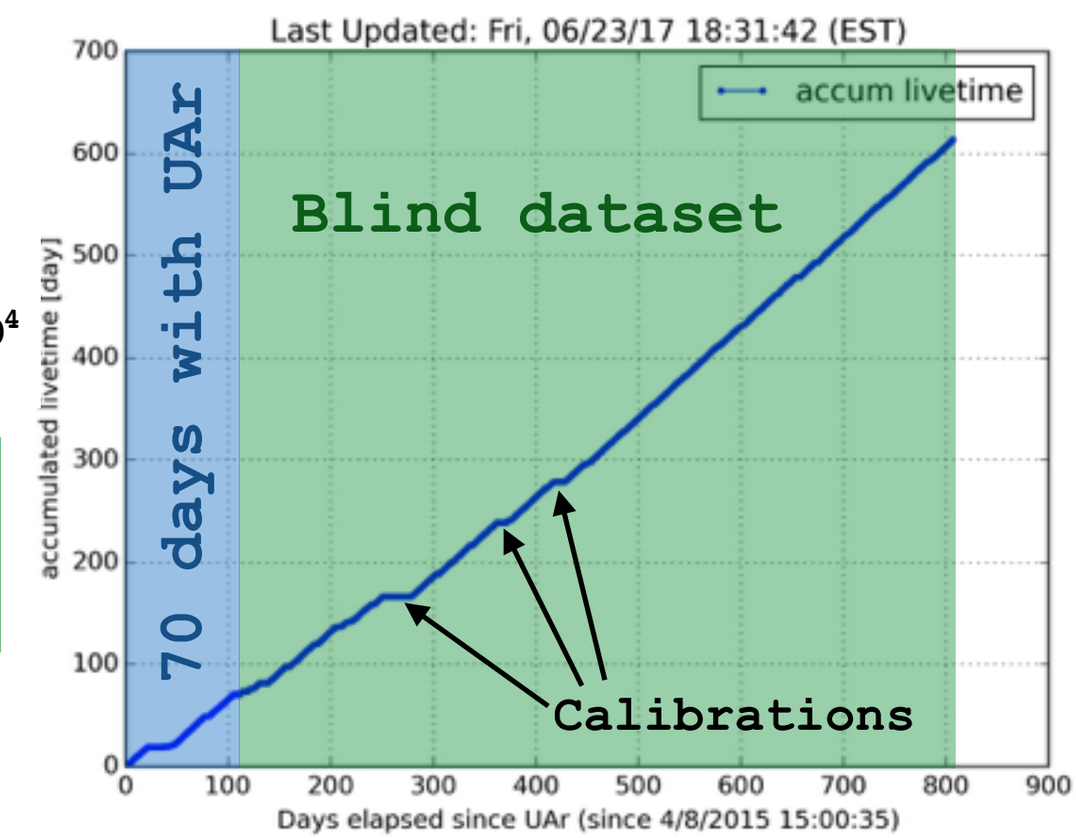
Phys.Rev.D93,081101(R)(2016)



Since then >500 days of data in WIMP search mode acquired.

Blind analysis approach for current dataset.

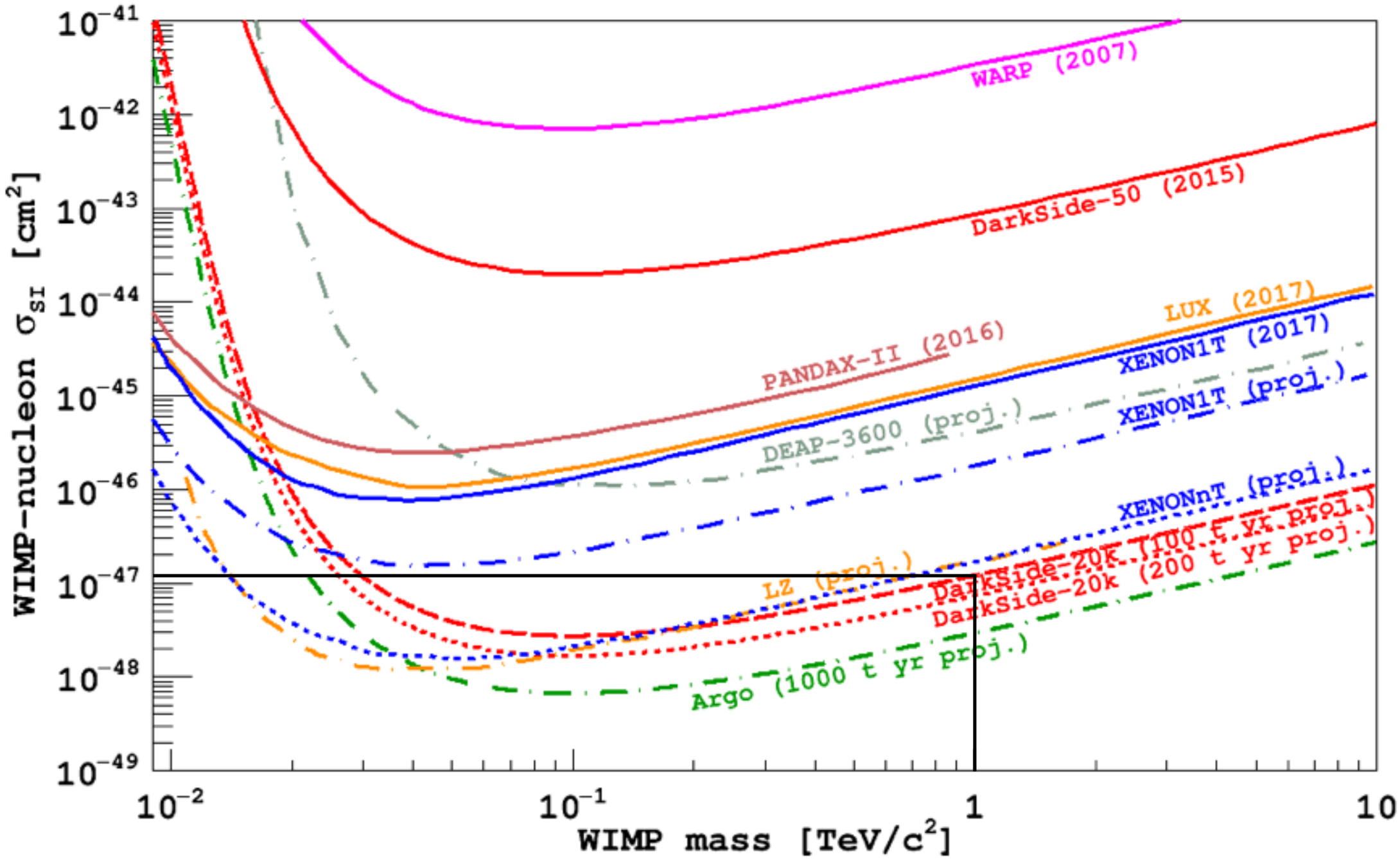
Unblinding hopefully by end of summer.



Combined Dataset (2015):
50 days with AAr + 70 days with UAr

DS-20k sensitivity projections

DS-20k Letter of Intent on arXiv:1707:08145

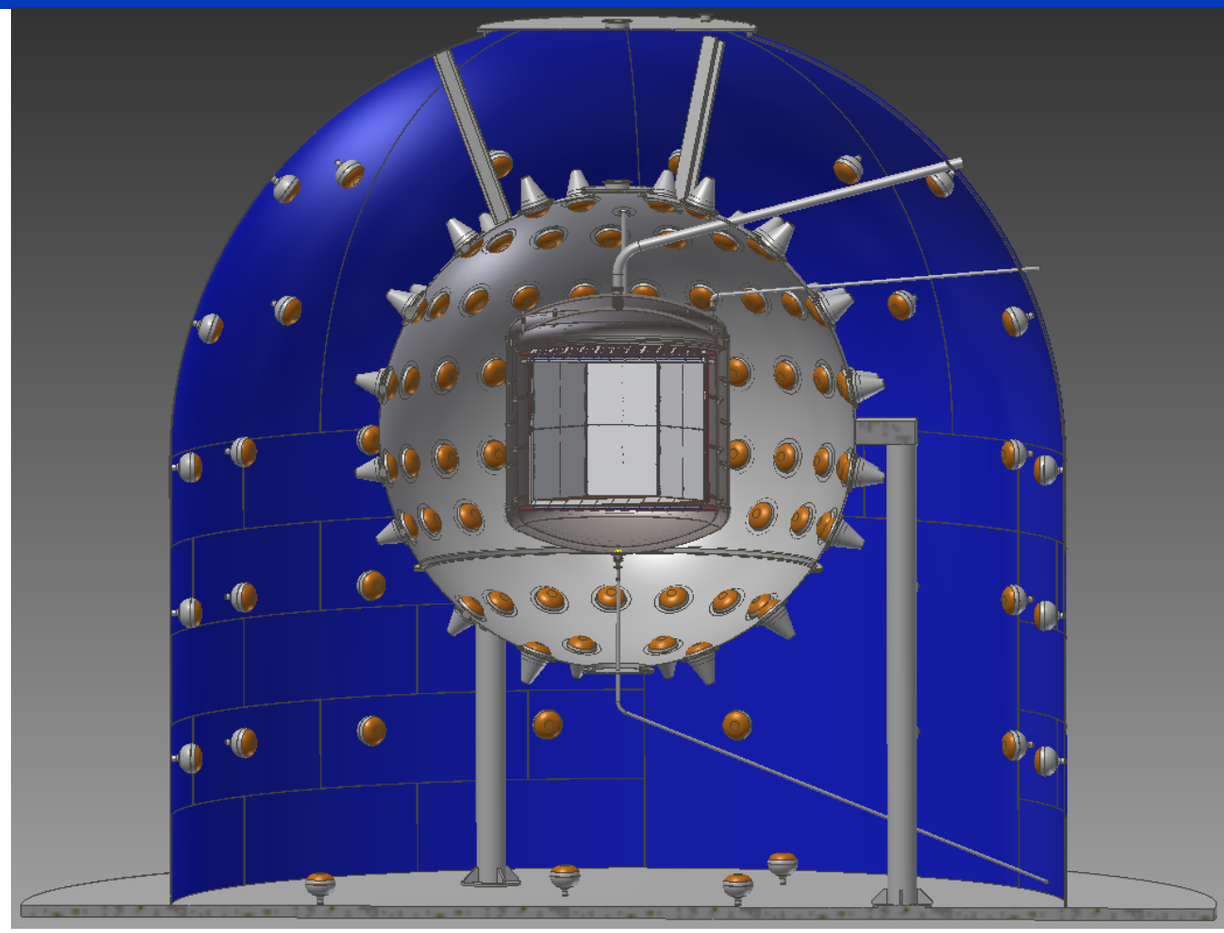


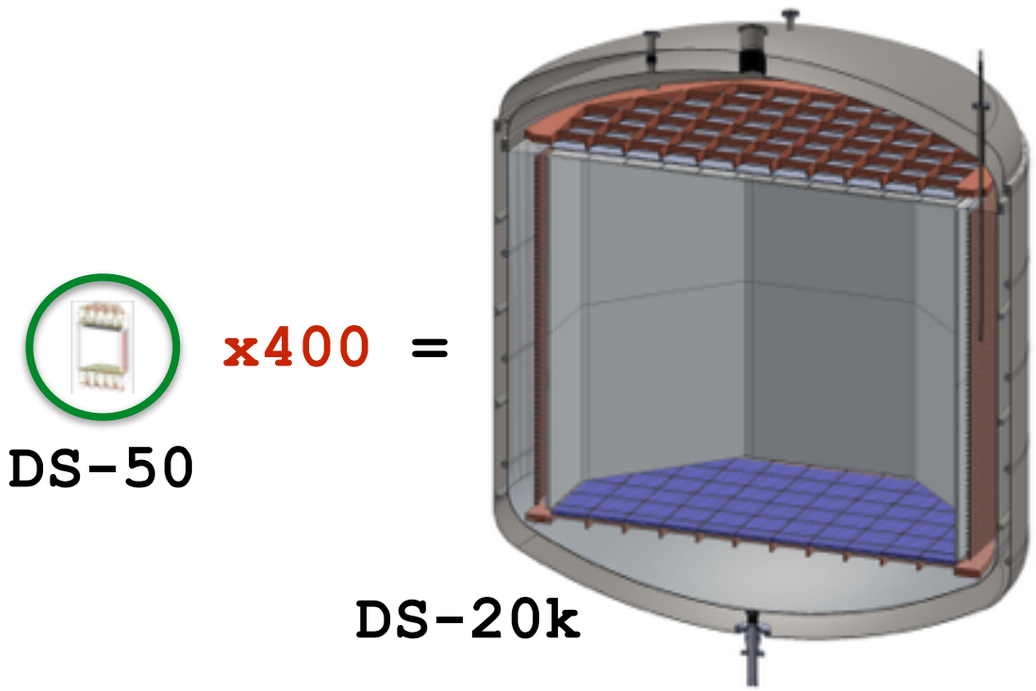
Scaling up: DarkSide-20k

- Next generation detector aims to reach a sensitivity $10^{47}cm^2$@1TeV/c^2 with 100 ton·yr of exposure.

- A target of 23ton (*20ton of fiducial volume*) is foreseen.

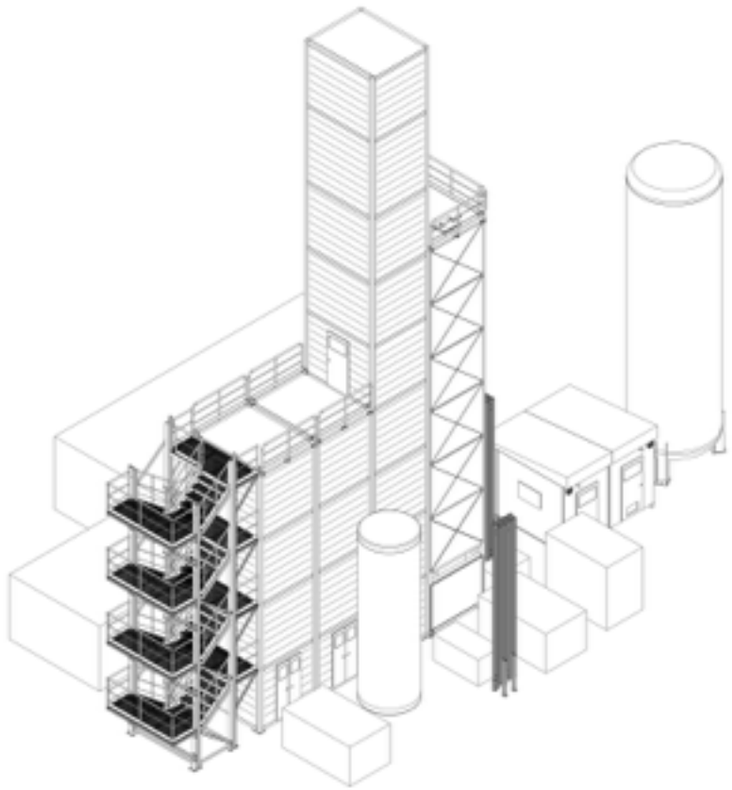
- A radical upgrade of all the systems is needed to achieve the <u>(reducible) background free condition</u> for such an exposure:
  1. New and bigger veto systems (WCD and LVD).
  2. Ultra-clean stain-less steel/ titanium for cryostat.
  3. Underground Argon, possibly further depleted.
  4. New, radio-pure light detectors: Silicon PhotoMultipliers (~13m^2).





Argon purification

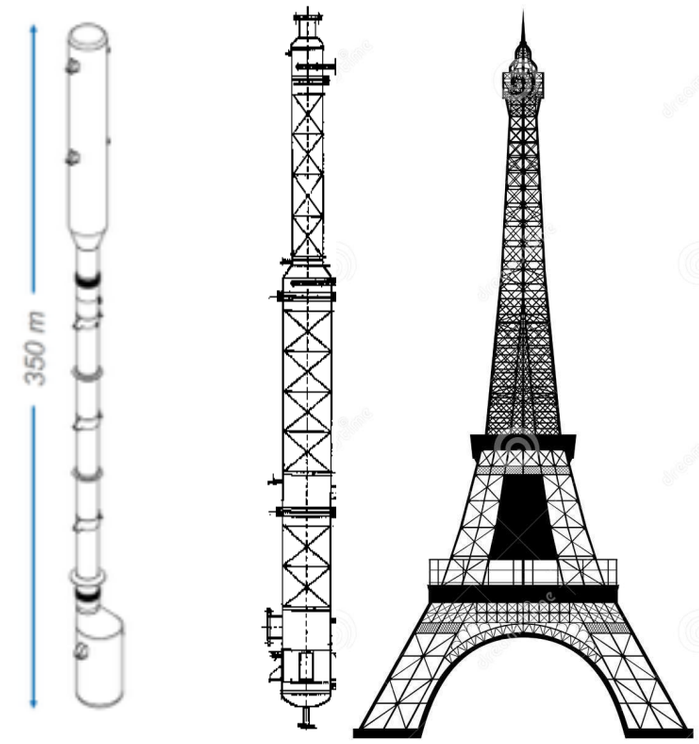
Urania



- New bigger plant to extract UAr from the Colorado mine.
- Foreseen operation capacity for DS-20k: 100kg/day.

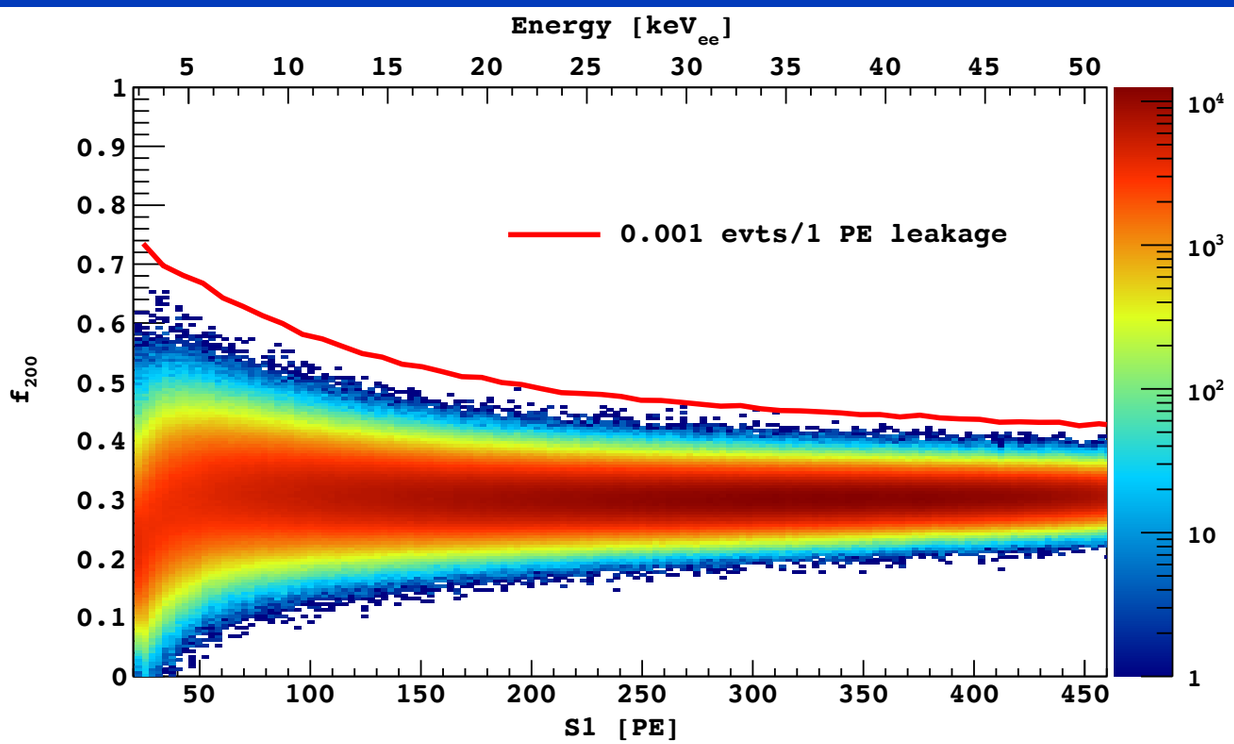
Aria

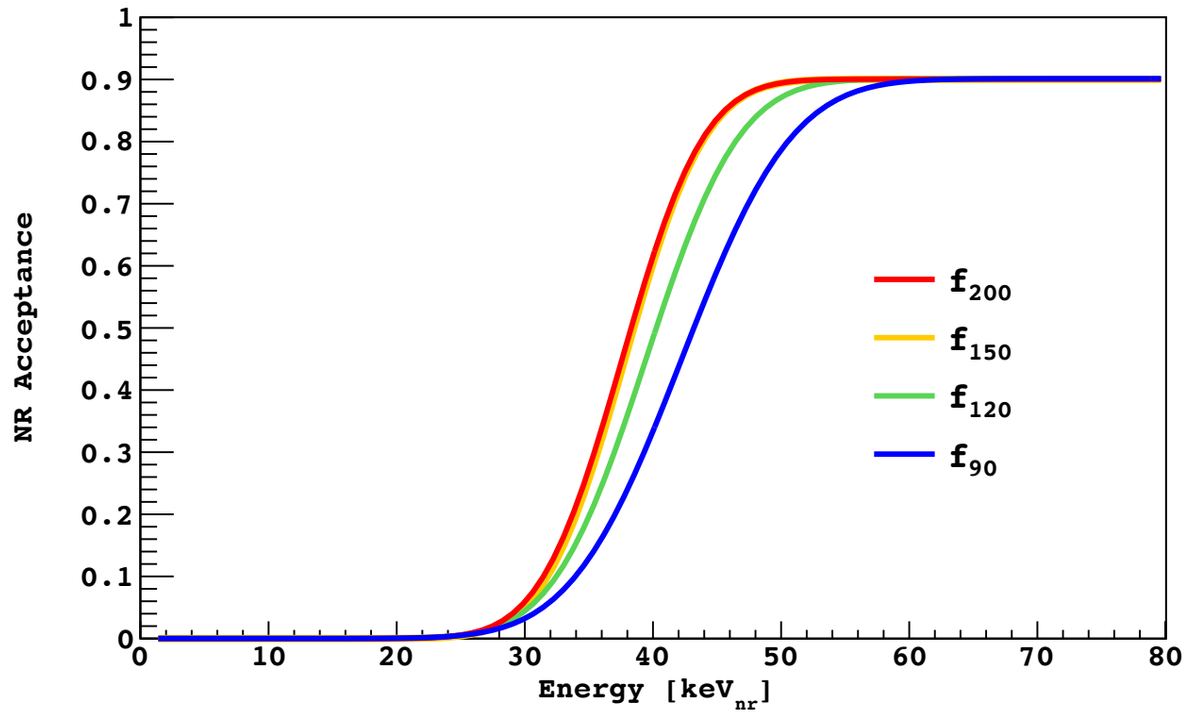
Seruci-I Seruci-II

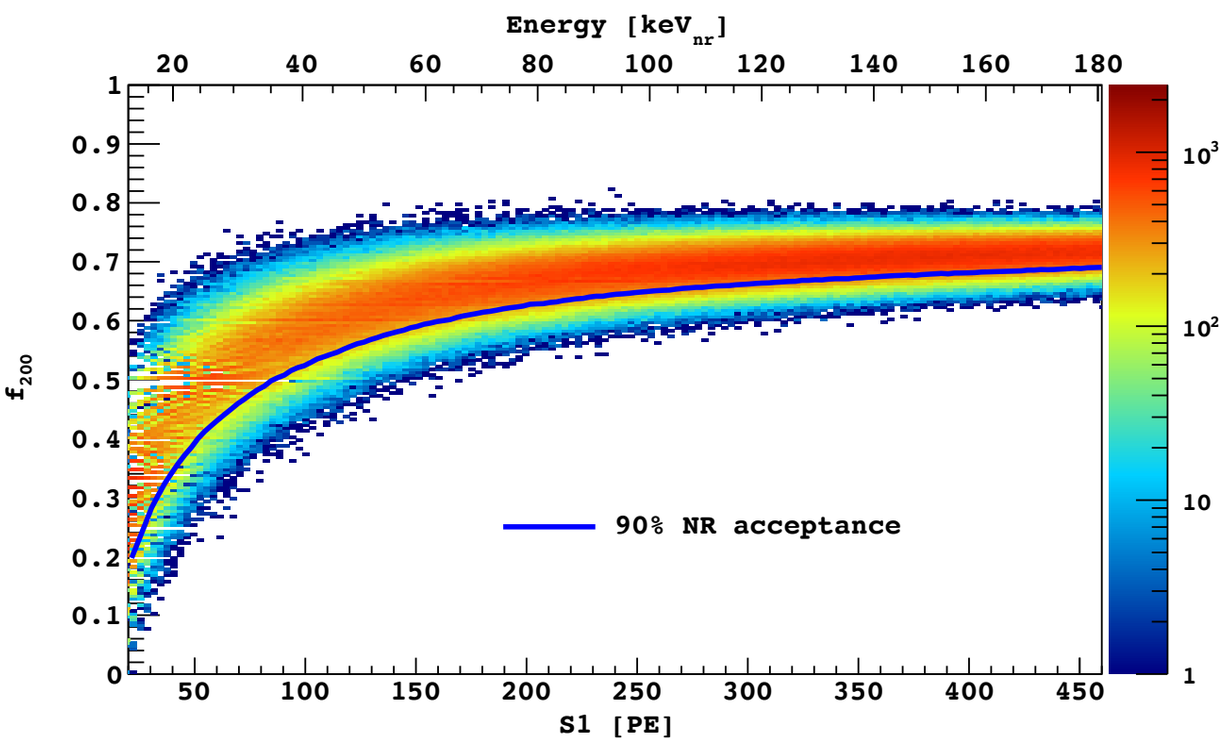


- <u>Seruci-I</u> will remove chemical impurities in UAr to 0.25-1ppm level at the rate of 1 ton/day.
- <u>Seruci-II</u> (yet to be funded) could perform a step of *isotopic purification* for UAr further suppressing the ^{39}Ar content of a factor 10 per pass.

PSD in DS-20k

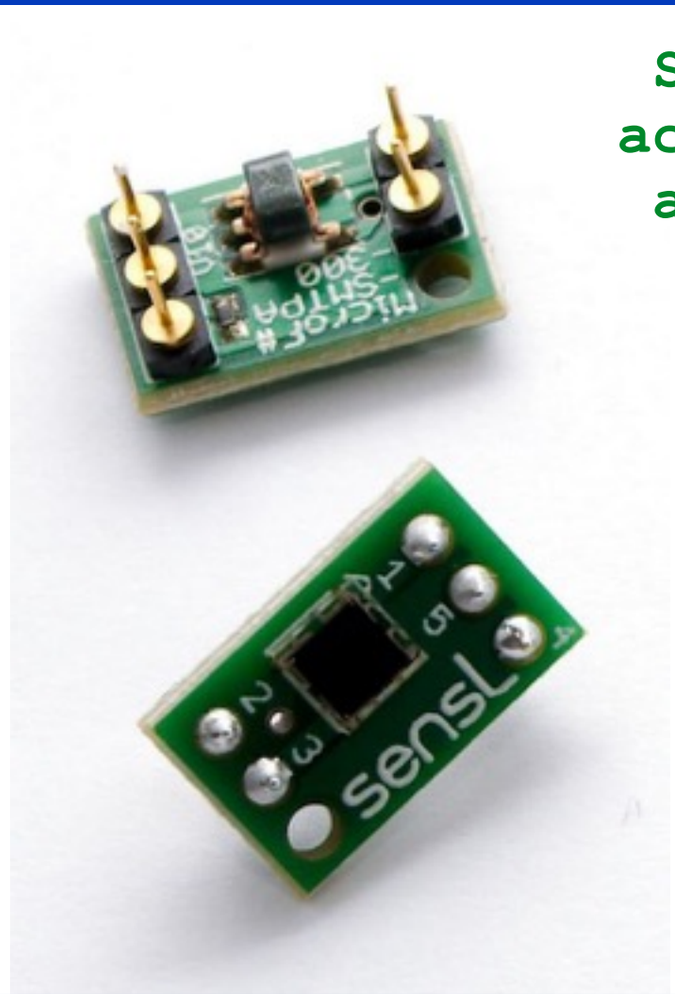






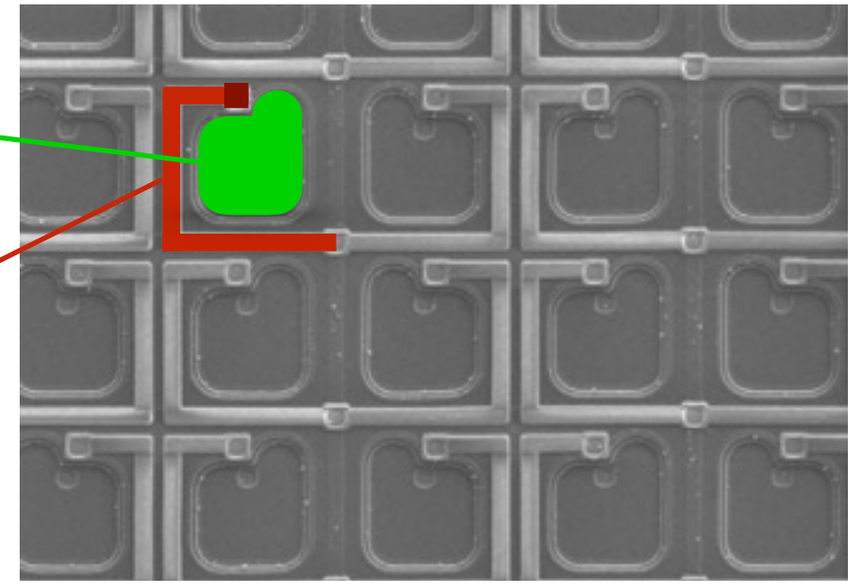
- Light Yield ~10PE/keV (20% higher than DS-50) thanks to SiPMs PDE.
- MC simulations predict a ER/NR discrimination power >3x10^9 for f_{200}.
- f_{200} provides a higher sensitivity with respect to f_{90}.

SiPM technology



SPAD active area

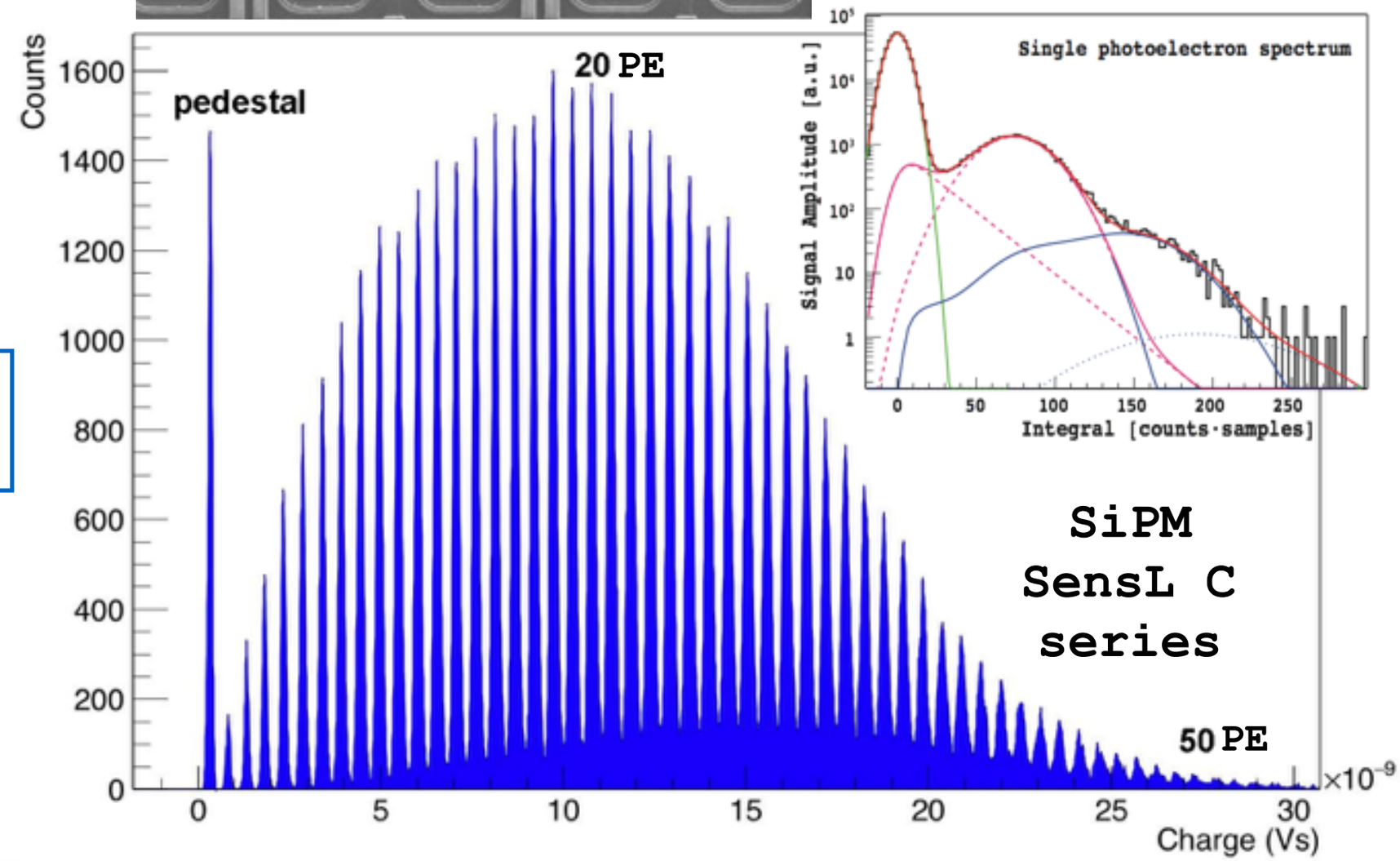
R_q



SPAD gain uniformity is essential

Photon Spectra comparison at 77K

PMT



SiPM SensL C series

SiPM: matrix of SPADs mounted in parallel

↓

SPAD: APD operated in geiger mode

↓

Avalanche quenched with R_q~MΩ resistor

PMT Vs SiPM: the starting point

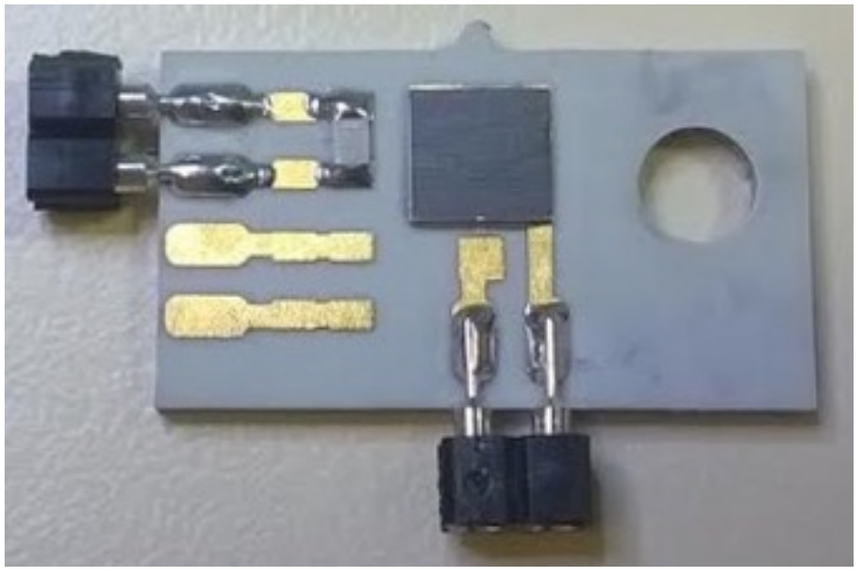
Good motivations to upgrade to SiPMs,

but…

a strong R&D was needed to compete with PMTs.

3″ diameter

4x4mm^2



Comparison among commercial devices at CRYOGENIC temperature (87K)

	PMT	SiPM
Bias Voltage	~(1000-2000)V	~(30-40)V
Sensitivity to B fields	Yes	No
QE/PDE@420nm@300K	25%	(40-50)%
Packing efficiency	60%	(80-90)%
SPE resolution	25%	~(2-5)%
Dynamic Range	>> 10^3	O(10^3)
Gain	10^6-10^7 nominal ($3 \cdot 10^5$ real)	O(10^6)
DCR	O(1cps/PMT)	(10-1000)cps/mm^2

From SiPMs to PDMs: DS-20k requirements

Surface: 50x50 mm²

In order to contain the number of channels. Foreseen number: 5210

PDE: ≥ 40%

Higher PDE wrt Hamamatsu PMTs together with higher active area coverage will boost the light yield.

Overall Noise Rate: <0.1Hz/mm²

DCR+TCN+BN <250Hz/PDM ⇒ SNR_{PDM} > 8

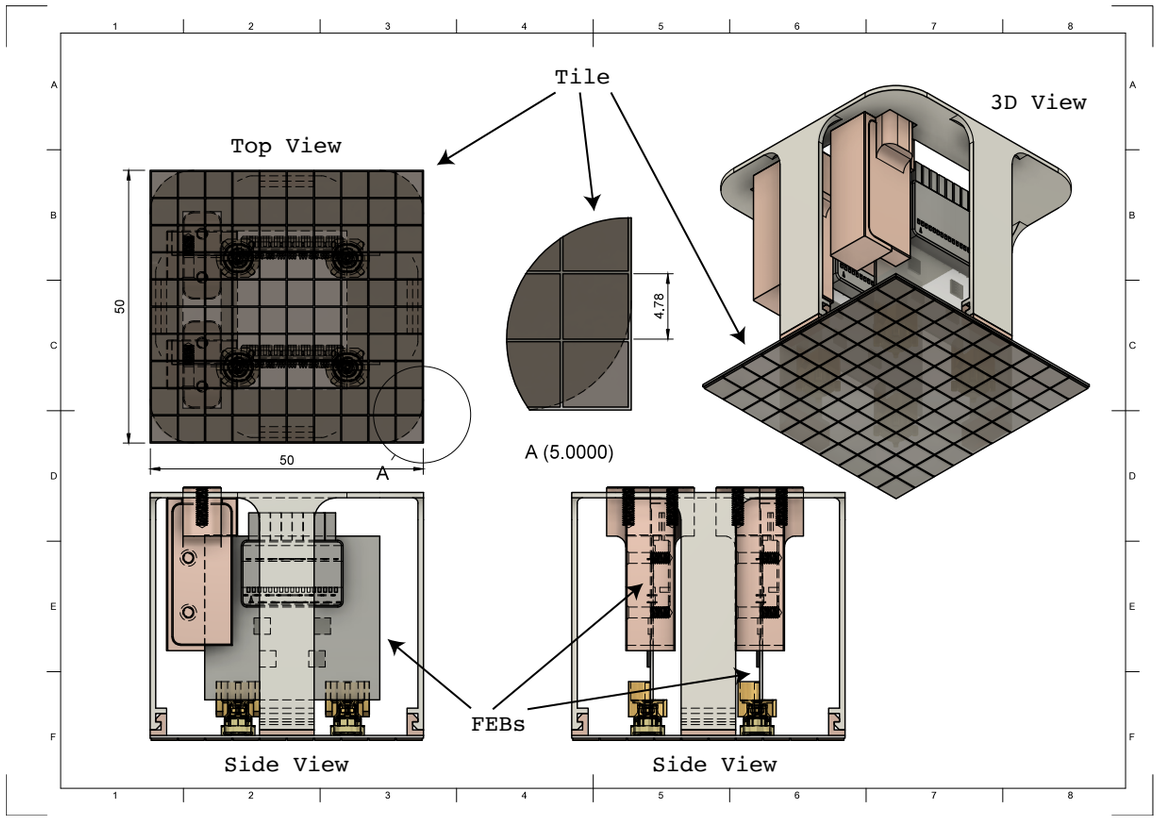
Higher rates would impact on trigger efficiency and PSD power.

Time resolution: O(10ns)

Necessary to keep the ER/NR discrimination power with f_{prompt}.

Dynamic Range: ≥ 50PE

Precise S2 reconstruction.



Power dissipation density: ≤ 100μW/mm²

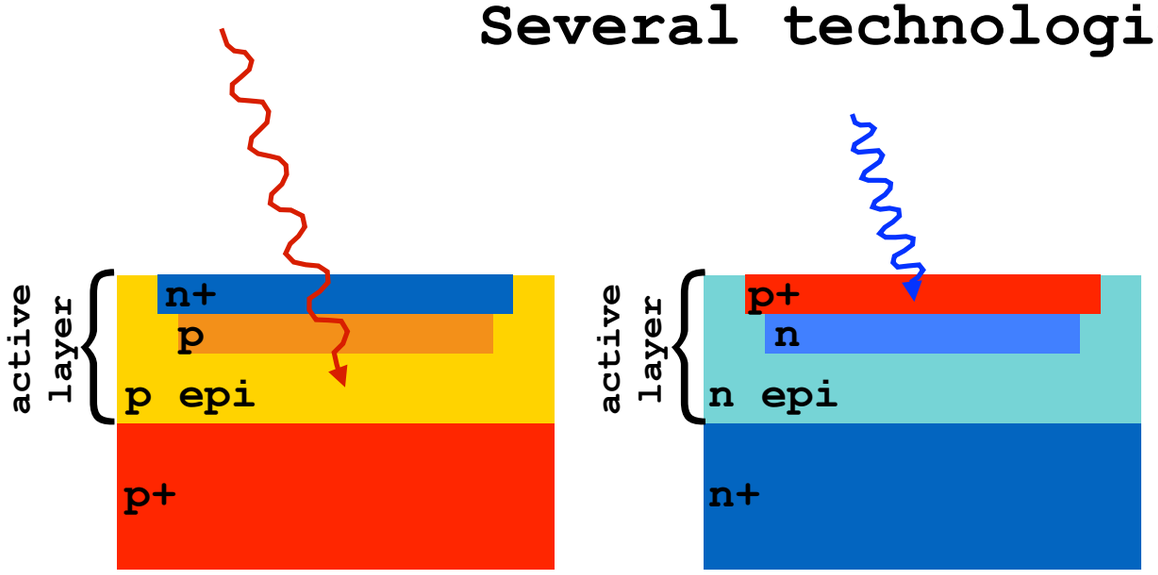
Total Power dissipation per PDM: ≤ 250mW

Avoid bubbling in LAr and excessive thermal load on the cryogenic system.

Strong constraints to SiPMs, electronics and readout performances.

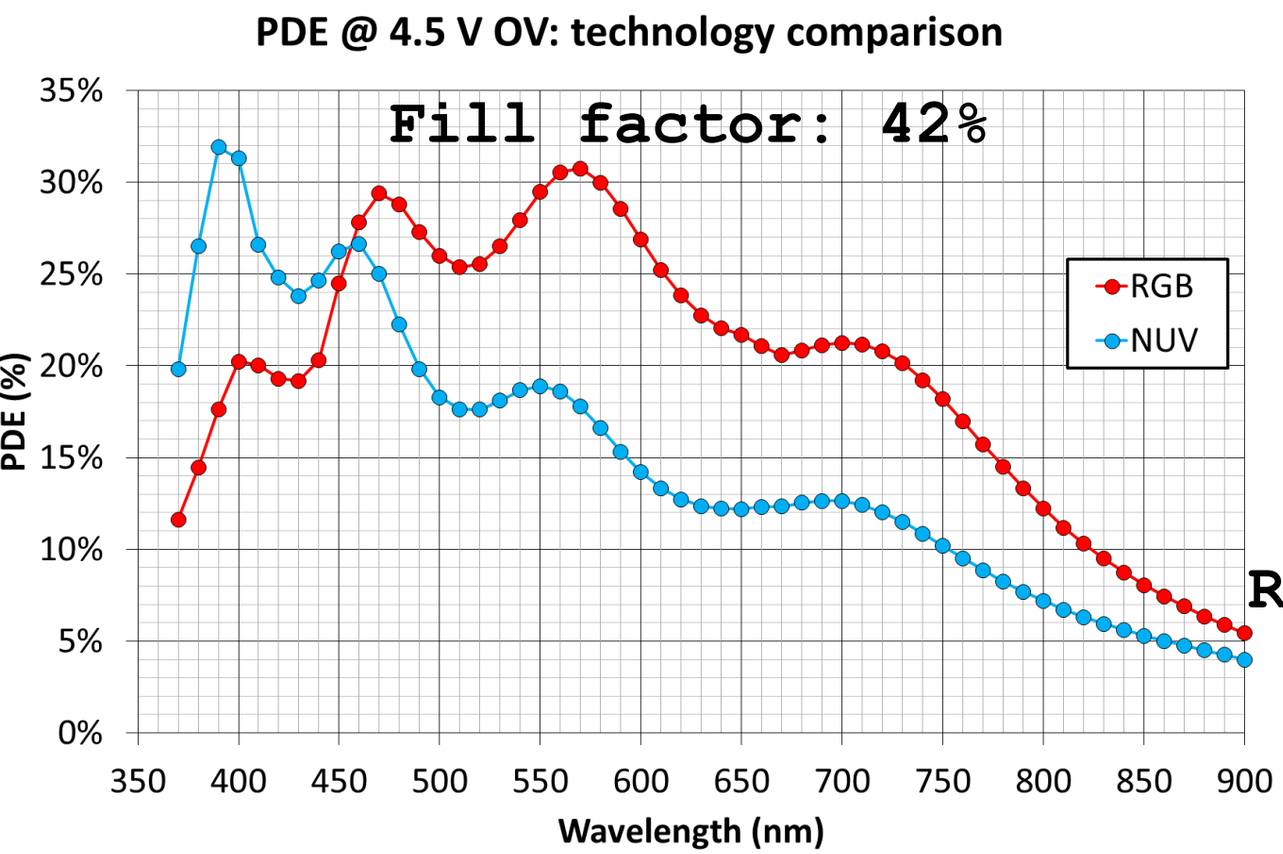
SiPM R&D at FBK/LNGS

Several technologies customized and tested



RGB SPAD

NUV SPAD



RGB

NUV

Lower dead border region

RGB-HD

-SF

-LRq
Fast Recharge time

-HRq
Low TCN

NUV-HD

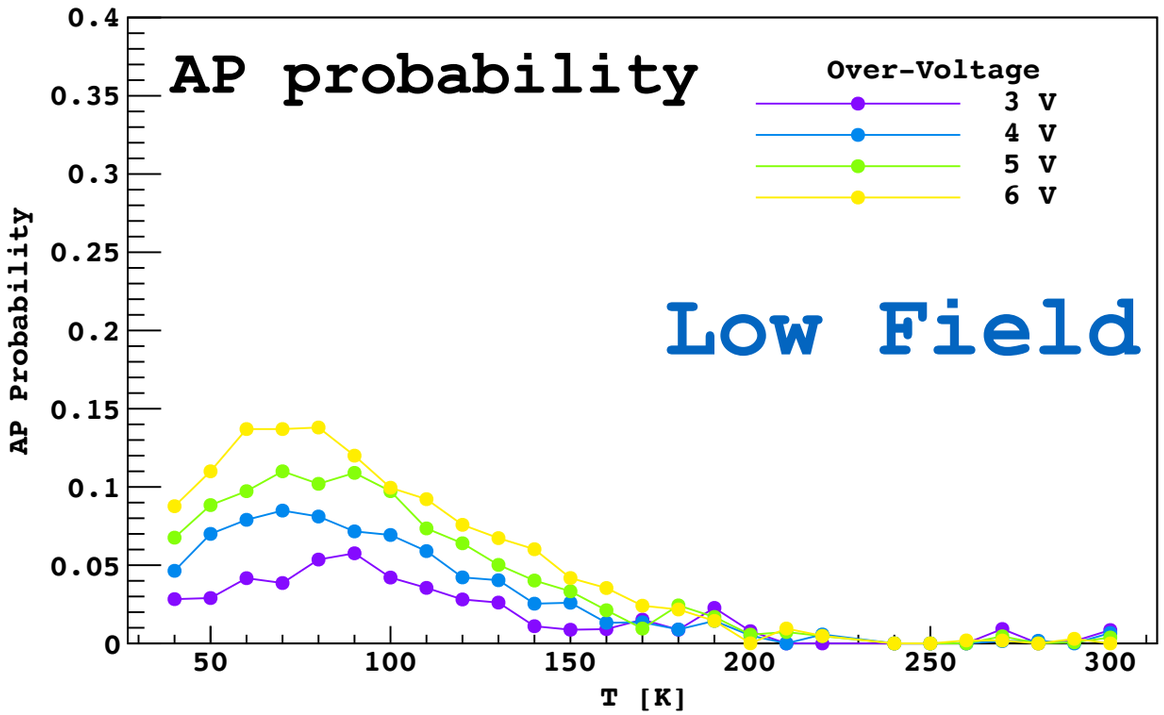
-SF

-LF
Low DCR
Low TCN

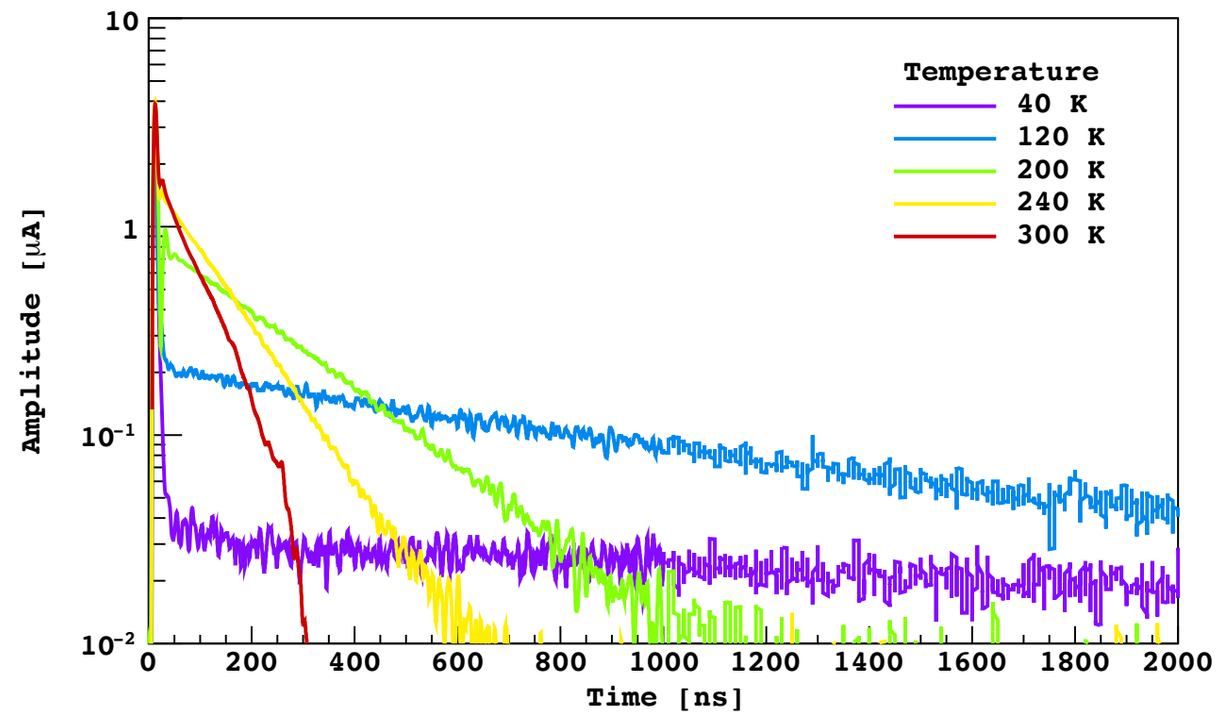
All these technologies were tested with different cell sizes.

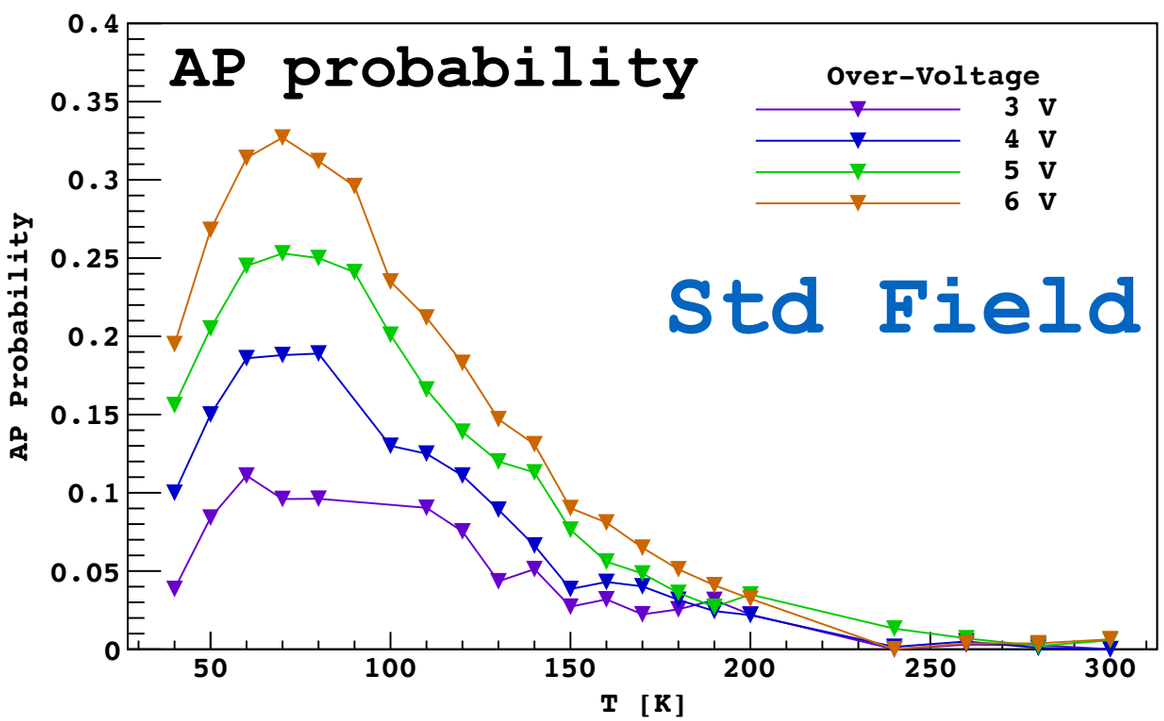
Std/Low Field High/Low Rq

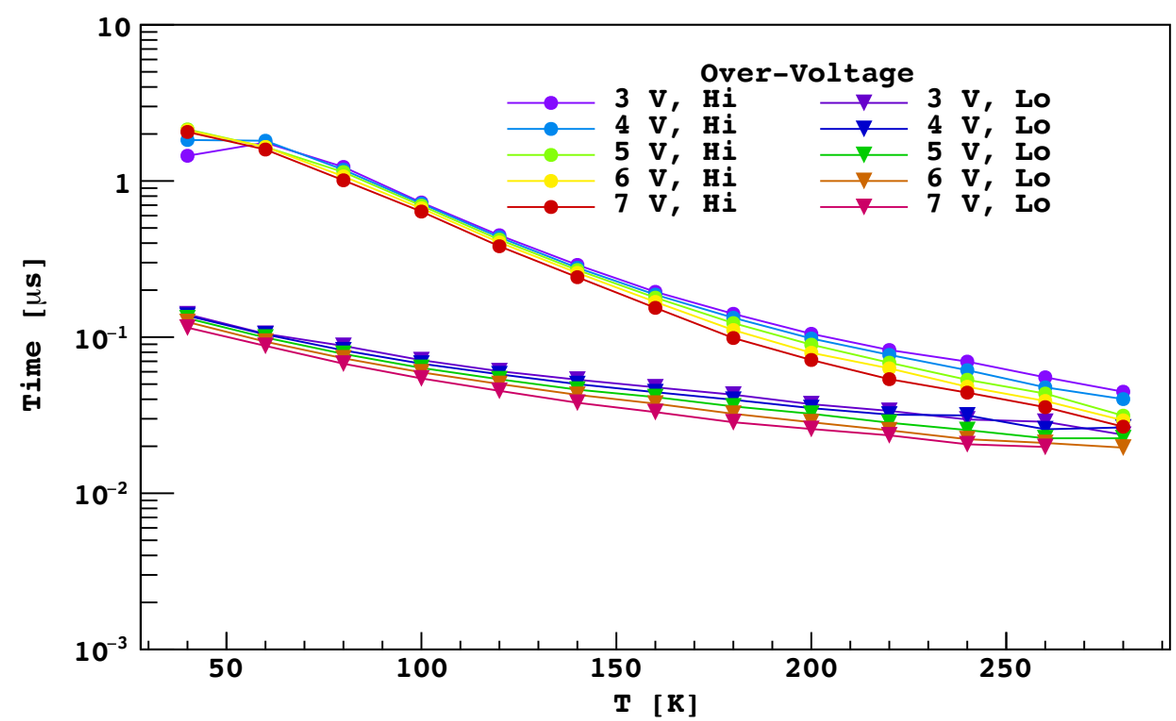
Low Field reduces noises



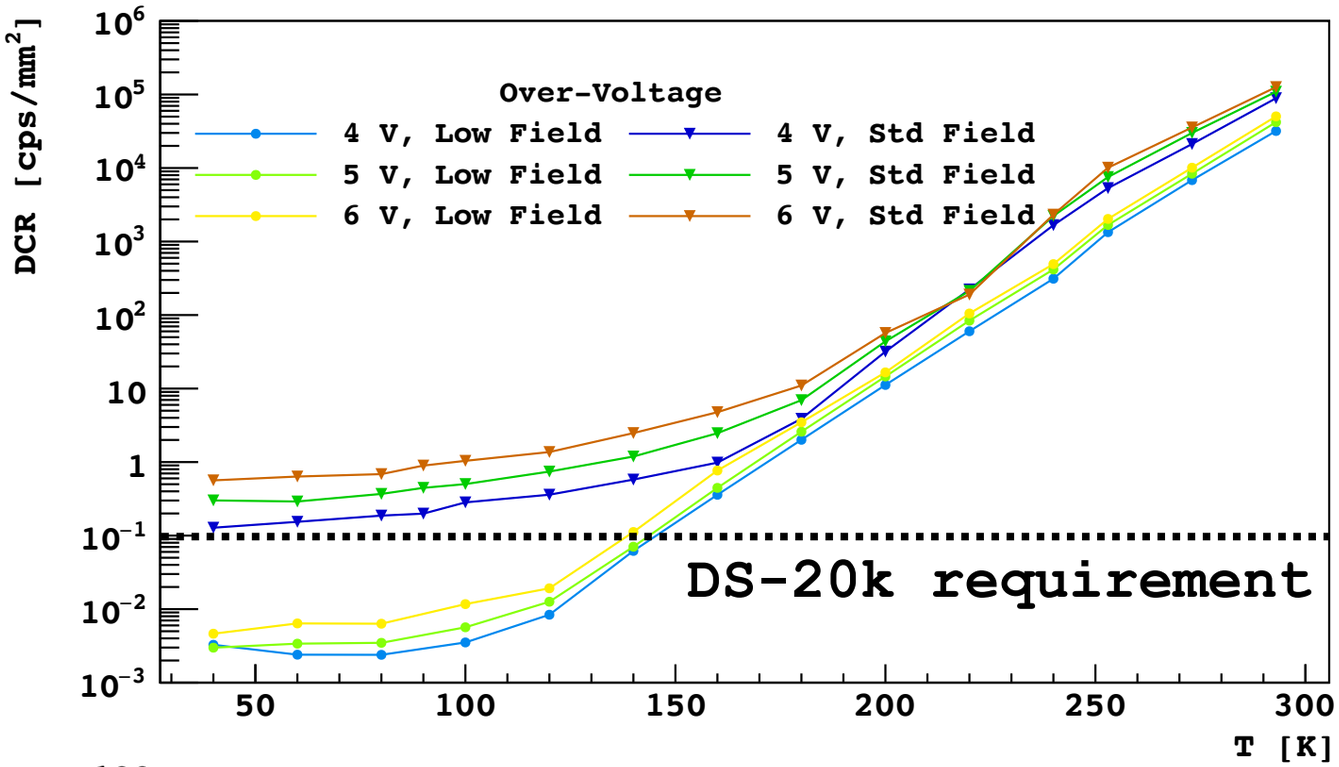
$\tau_{recharge} \propto R_q$ which depends on T

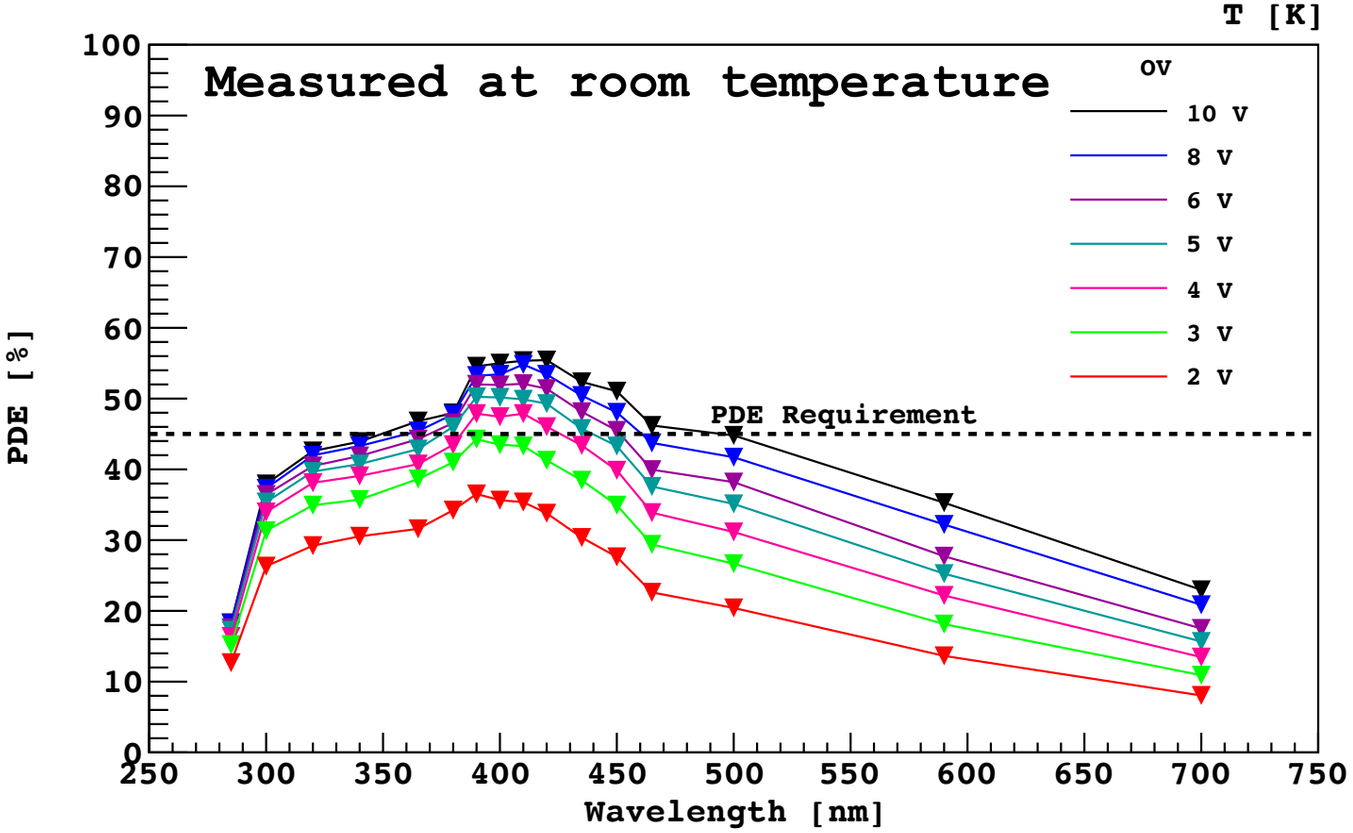






The Choice: NUV-HD-LF





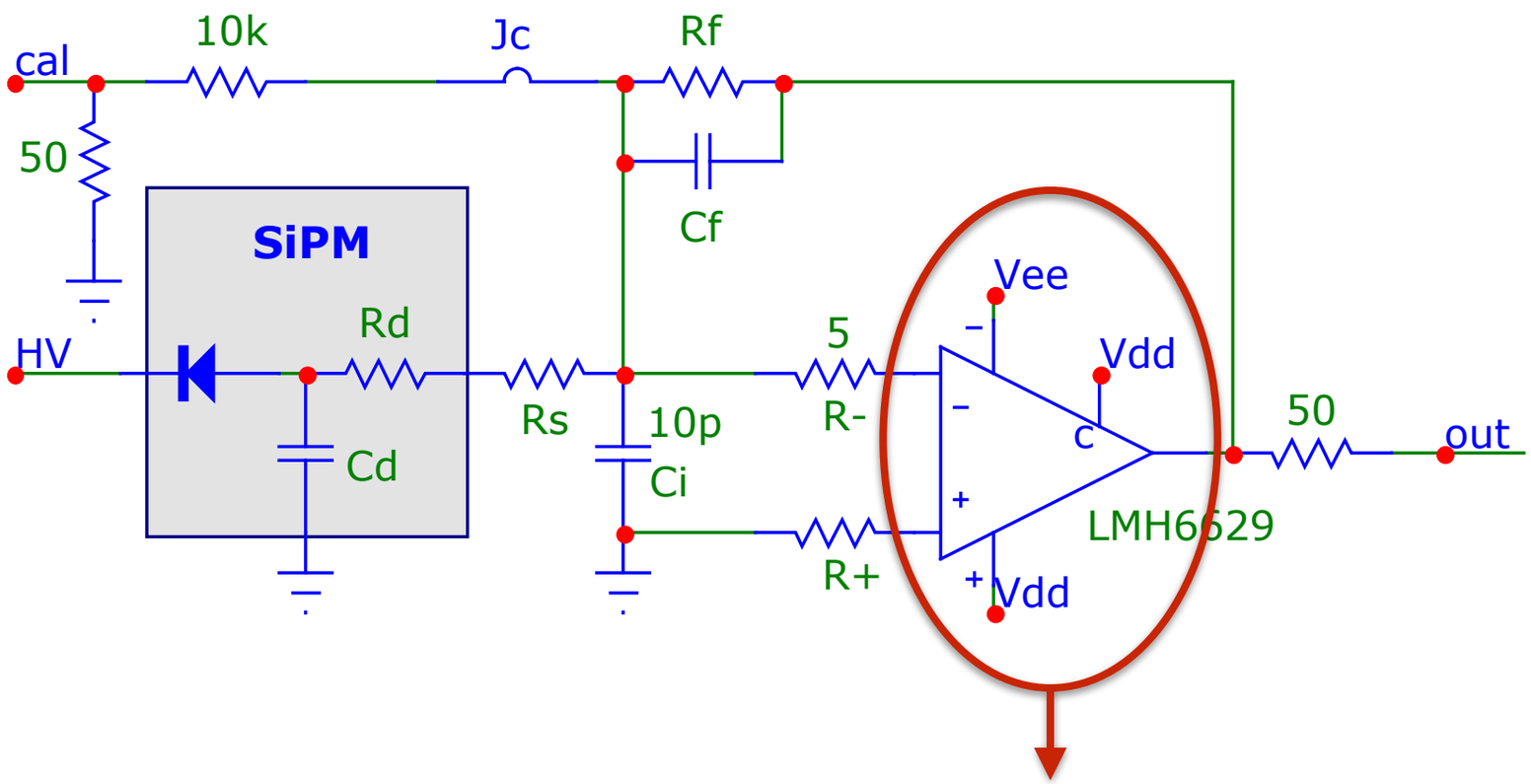
Low Field technology proved to fulfill the strict requirements.

- DCR ~ 4×10^{-3}cps/mm^2 at 5VOV, LAr temperature.
- AP+DiCT probability <60% at LAr temperature.
- PDE 50% at 5VOV at 420nm.
- Cell Recharge Time at LN ~500ns.
- Surface: 1cm^2

IEEE Trans. Electron Dev. 64 2, 2017

Electronics: a fast cryogenic pre-amp

- Some pre-amplification is needed in LAr before sending signals out of the cryostat.
- SiPMs present a huge output capacitance (~50pF/mm^2).
- A Transimpedance amplifier is the most suitable choice: High Bandwidth and Low Noise at cryogenic temperatures.

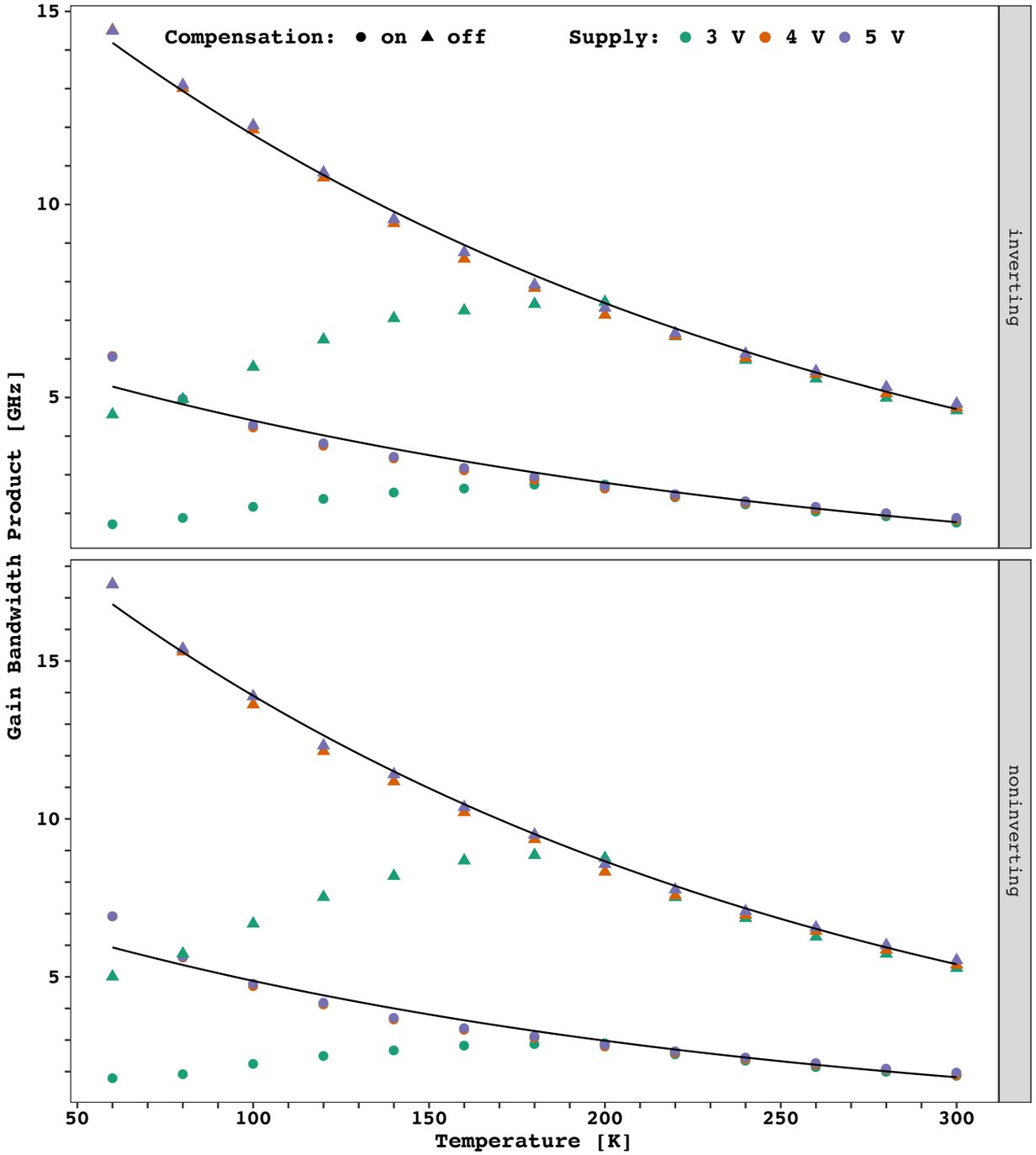


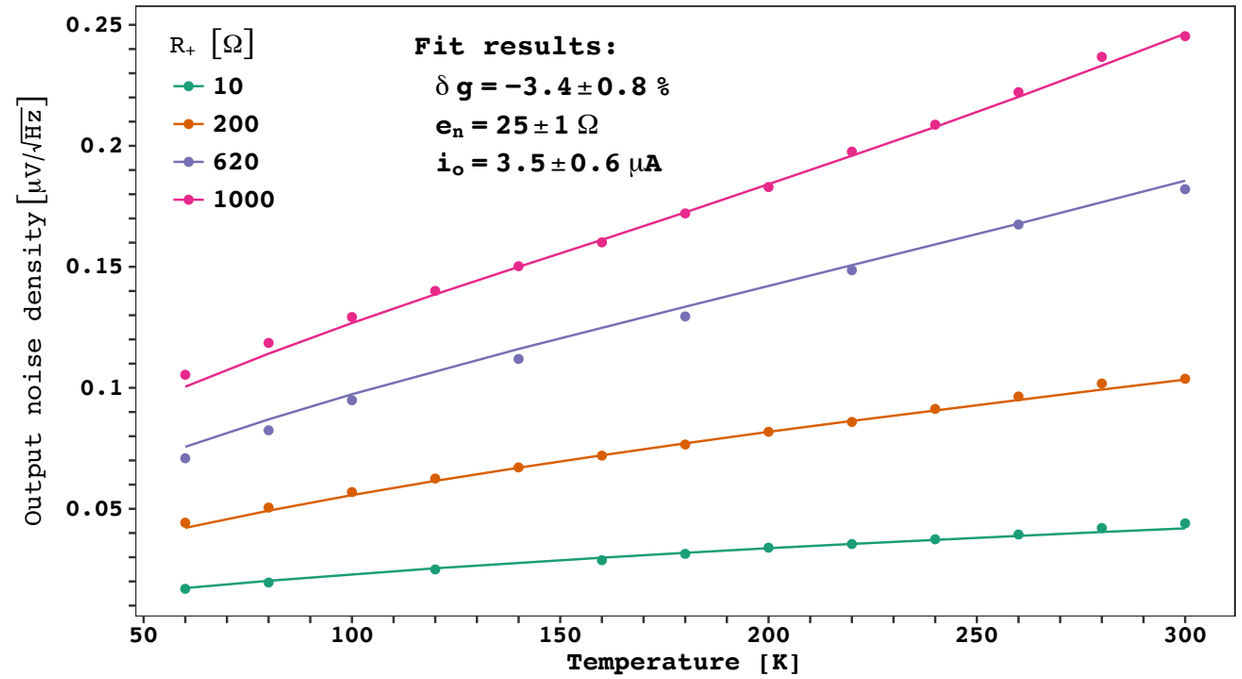
But a high BW, Low-Noise Op.Amp. is needed!
(and should be stable at 87K)

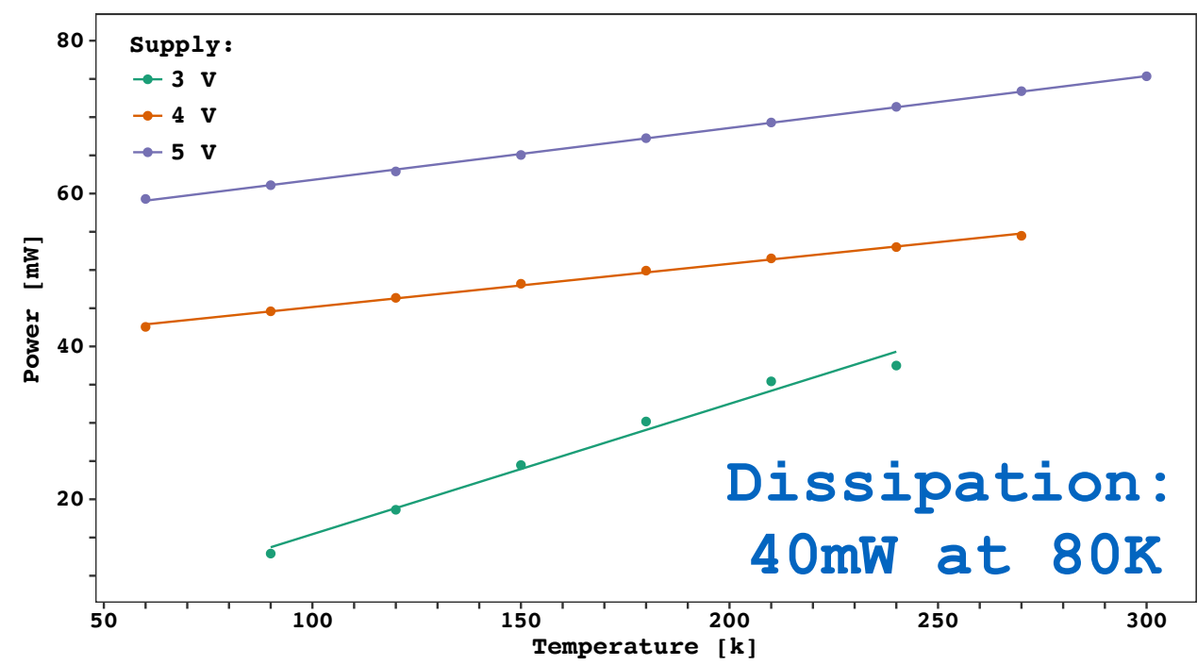
Texas Instruments SiGe LMH6629

GBP = 13GHz at 80K

Input Noise at 80K: e_n=0.3nV√Hz
i_n=1.1pA√Hz



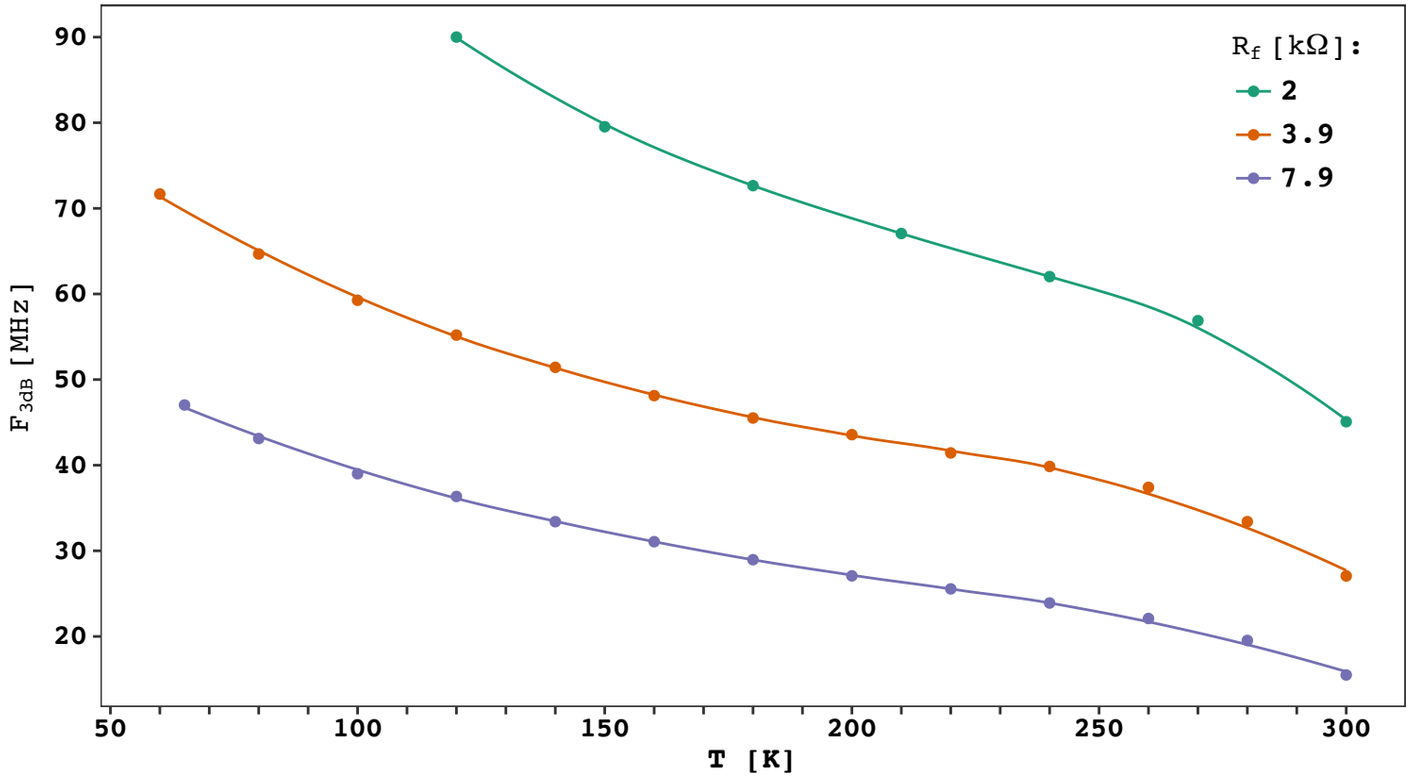


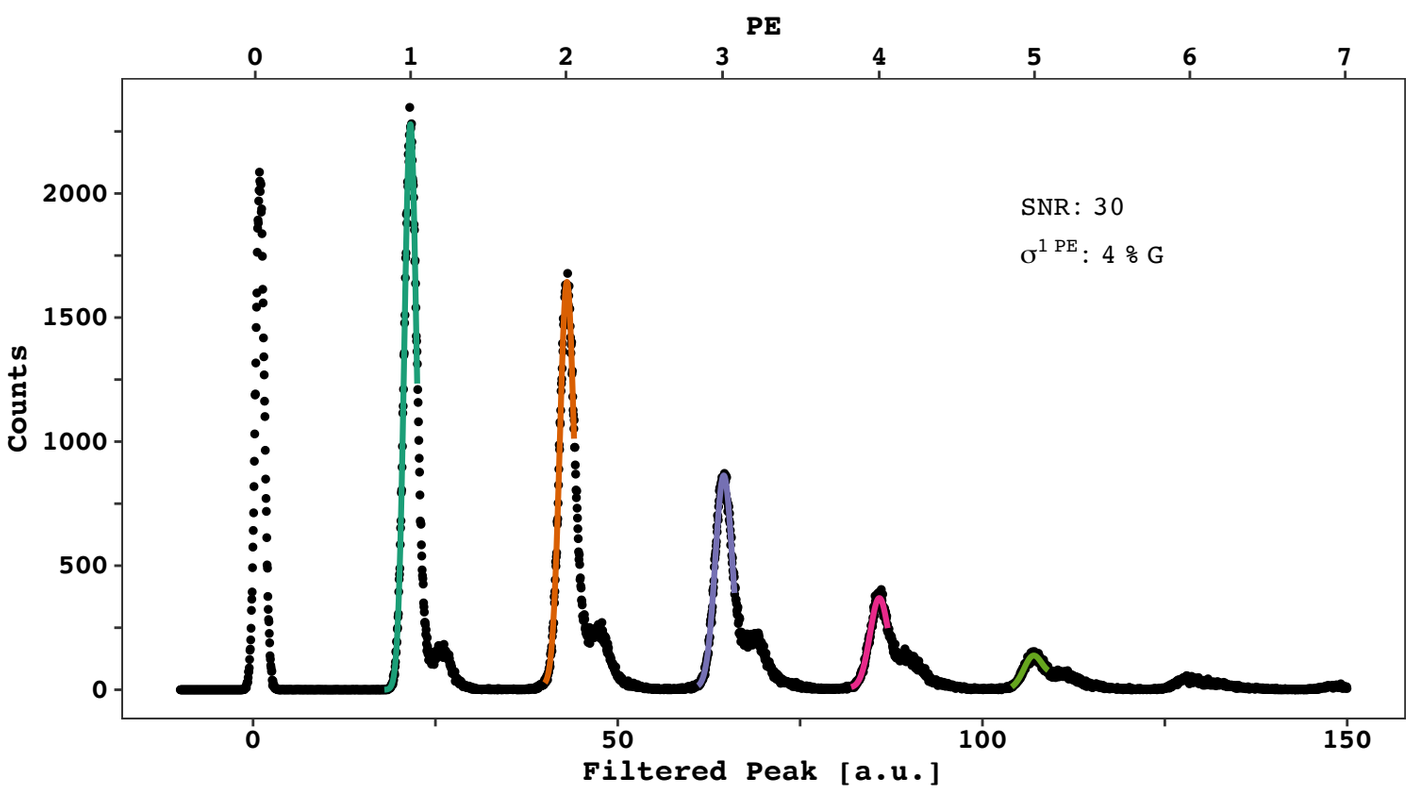


Dissipation:
40mW at 80K

arXiv:1706:04213

TIA performances





- The Bandwidth of the amplifier rises at cryogenic temperatures.
- F_{-3dB} = 65MHz at 80K with 3.9kΩ of gain and C_{in}~5nF.

Test with a 10x10mm^2 NUV-HD-LF at 80K:

- σ_{1PE} = 4% μ_{1PE}
- SNR ≡ μ_{1PE}/σ_b = 30

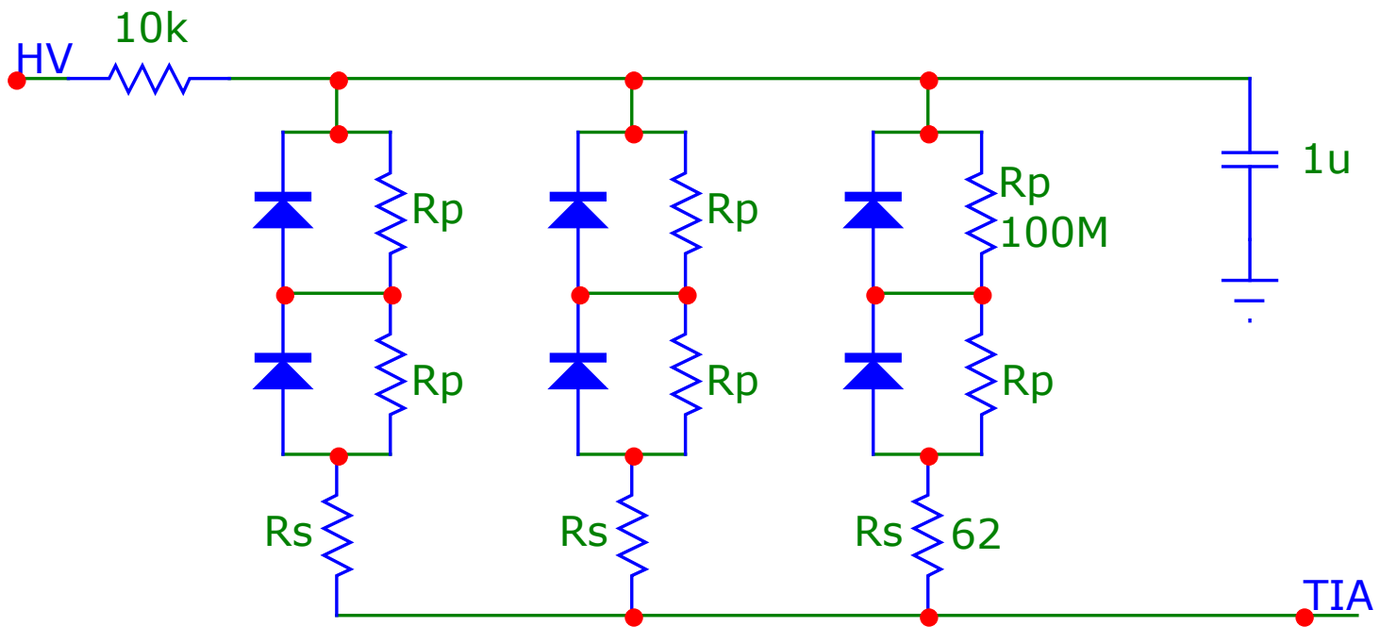
A matched filtering technique is applied to boost SNR and timing resolution (~1ns).

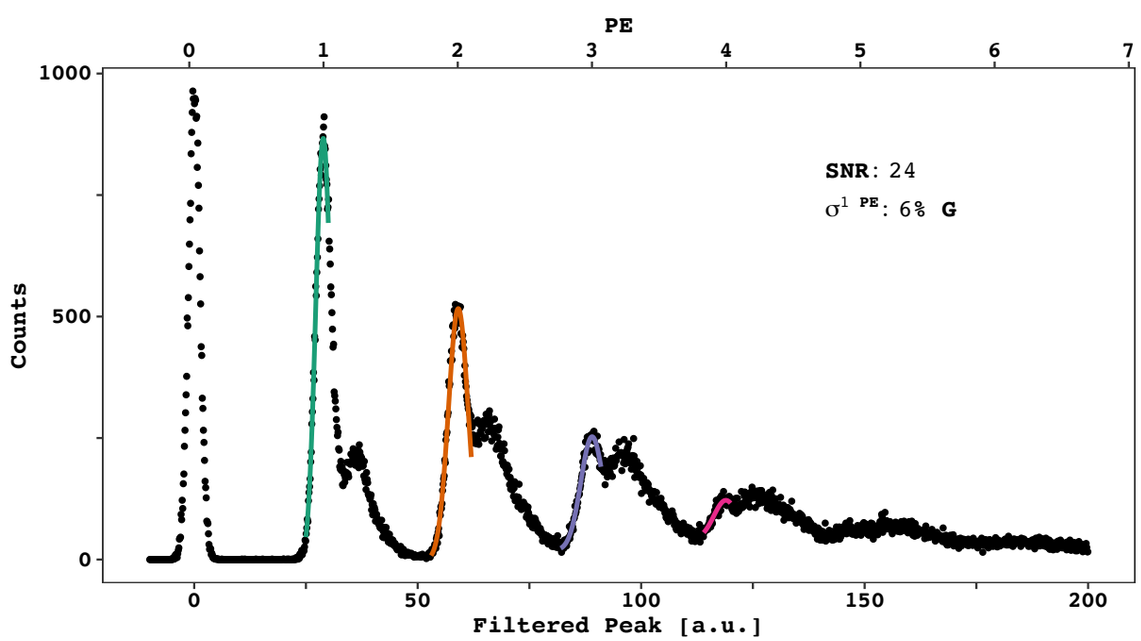
arXiv:1706:04213

SiPM ReadOut: from 1cm² to 6cm²

Not a trivial task:
- The signal comes from only 1 SiPM but noise is readout from 24.
- The bigger input capacitance reduces the BW of the system.

2s3p configuration (6cm²):
- C_{in} equivalent to 1.5cm².
- R_p stabilizes the bias/gain of each SiPM.
- R_s further reduces the effective C_{in} by decoupling SiPMs and TIA.



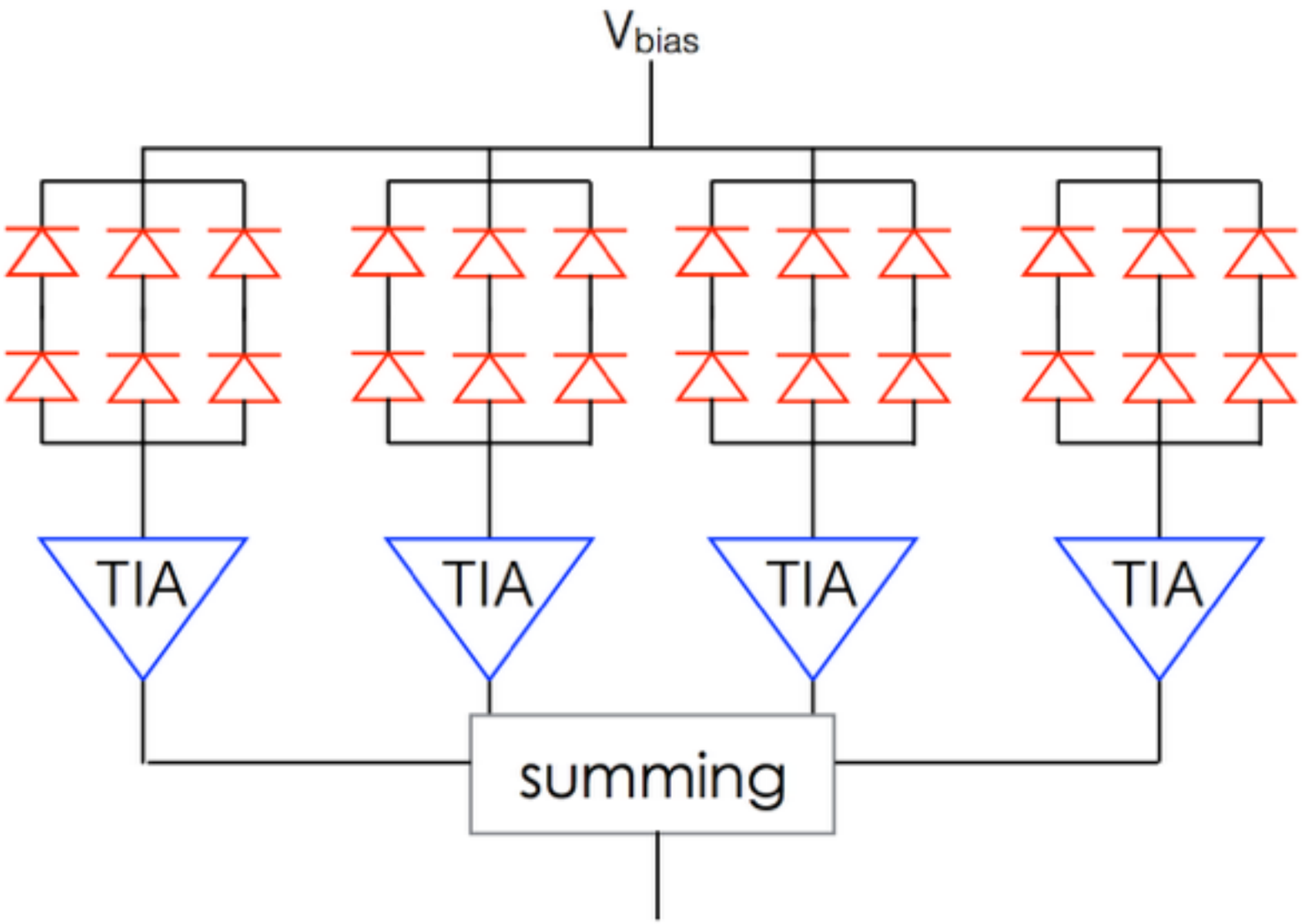


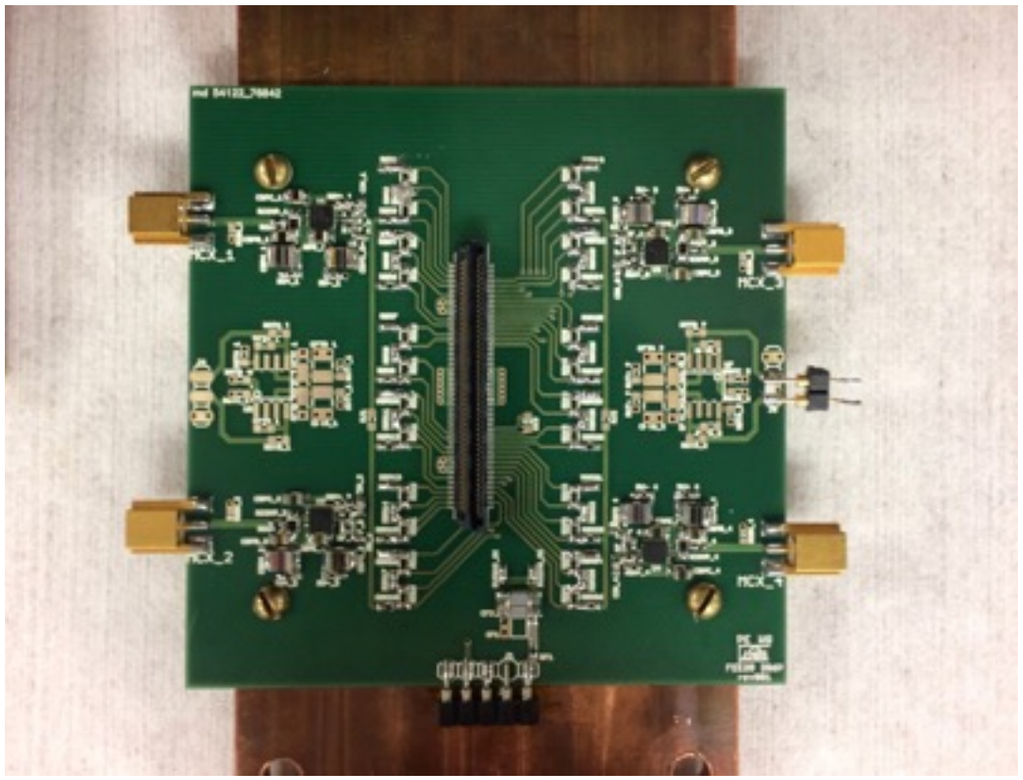
Test results with 6 NUV-HD-LF at 80K:
- $\sigma_{1PE} = 6\% \ \mu_{1PE}$
- SNR = 24

The bumps to the right of the peaks are due to AfterPulses.

arXiv:1706:04220

Summing: from 6cm^2 to 24cm^2



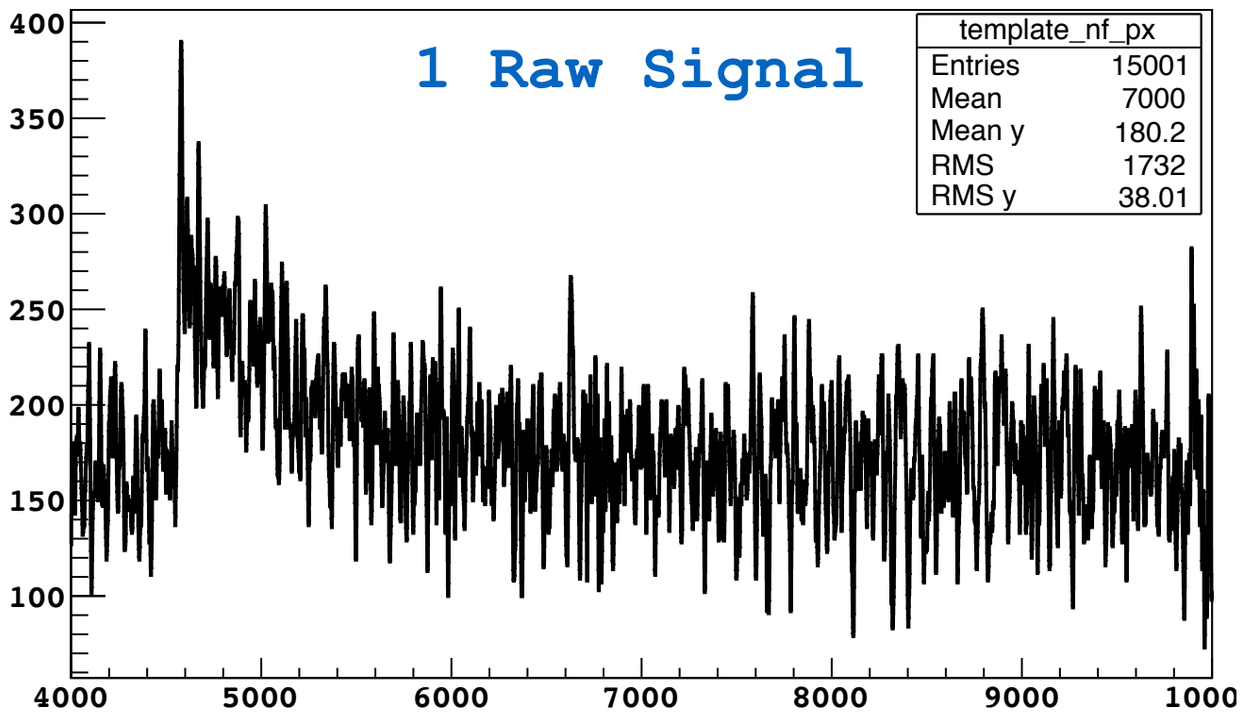


arXiv:1706:04220

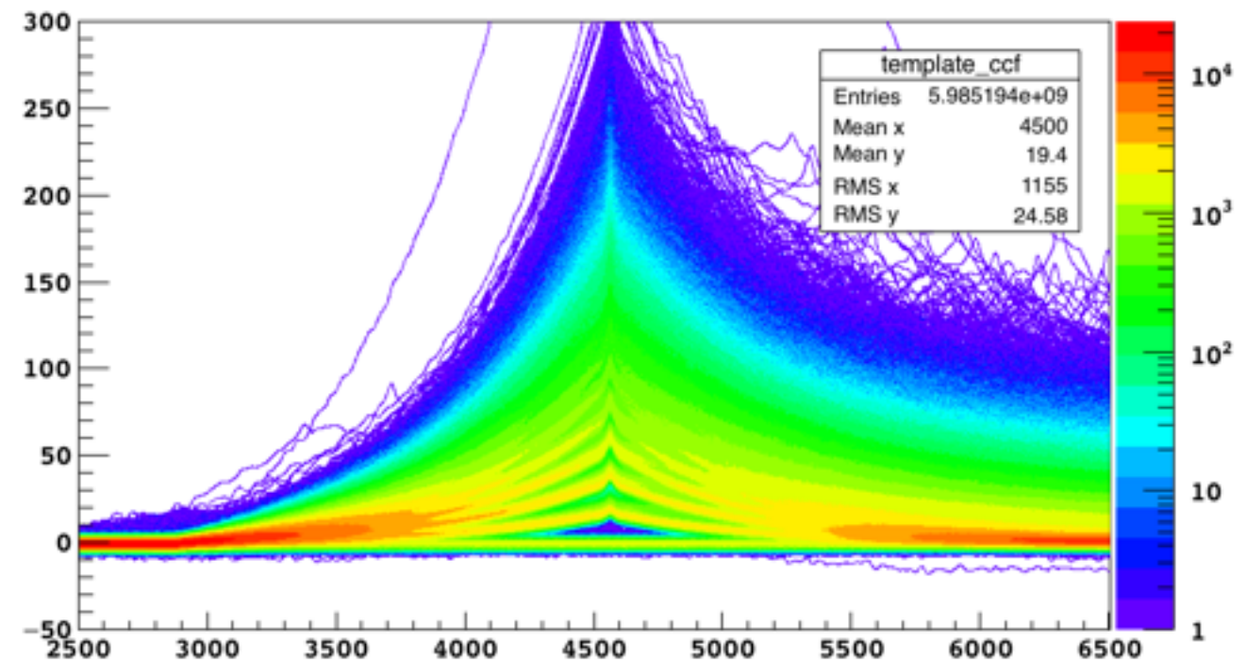
- The noise injected by the summing stage is negligible.
- The summing chip introduces a further x8 amplification.
- Final Dynamic Range: 80-100 PE

<u>Power budget</u>: 40mW x 4TIAs + 8mW x 1diff. transmitter
= 168mW per 24cm^2 PDM (max allowed is 250mW/PDM)

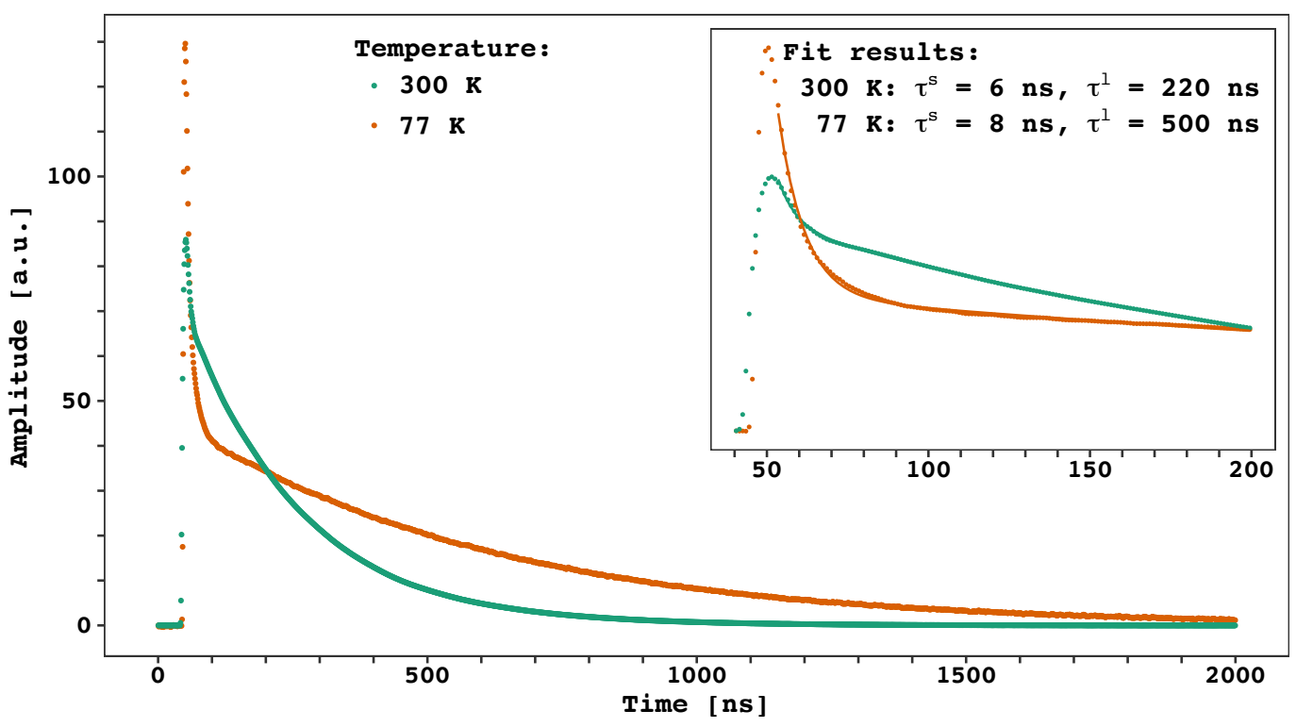
Matched Filtering

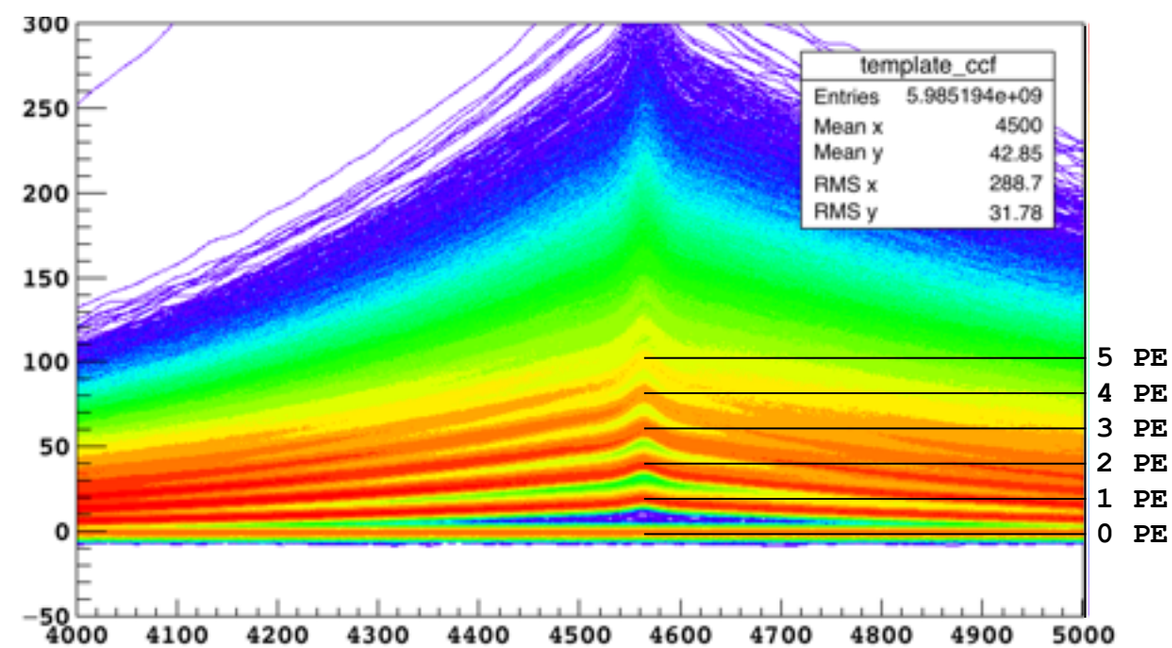


Filtering result



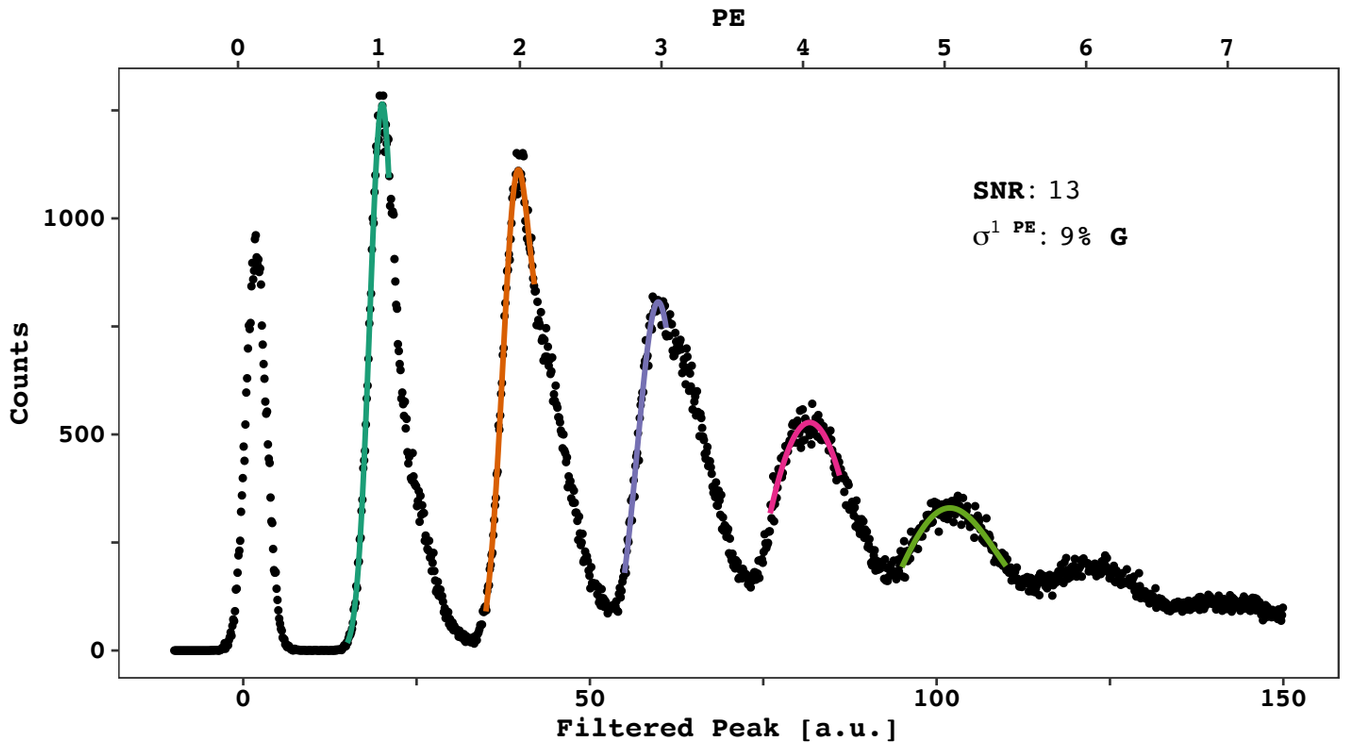
1PE Template





Clean waveform symmetrical with respect to its max.

Prototype Tile performances



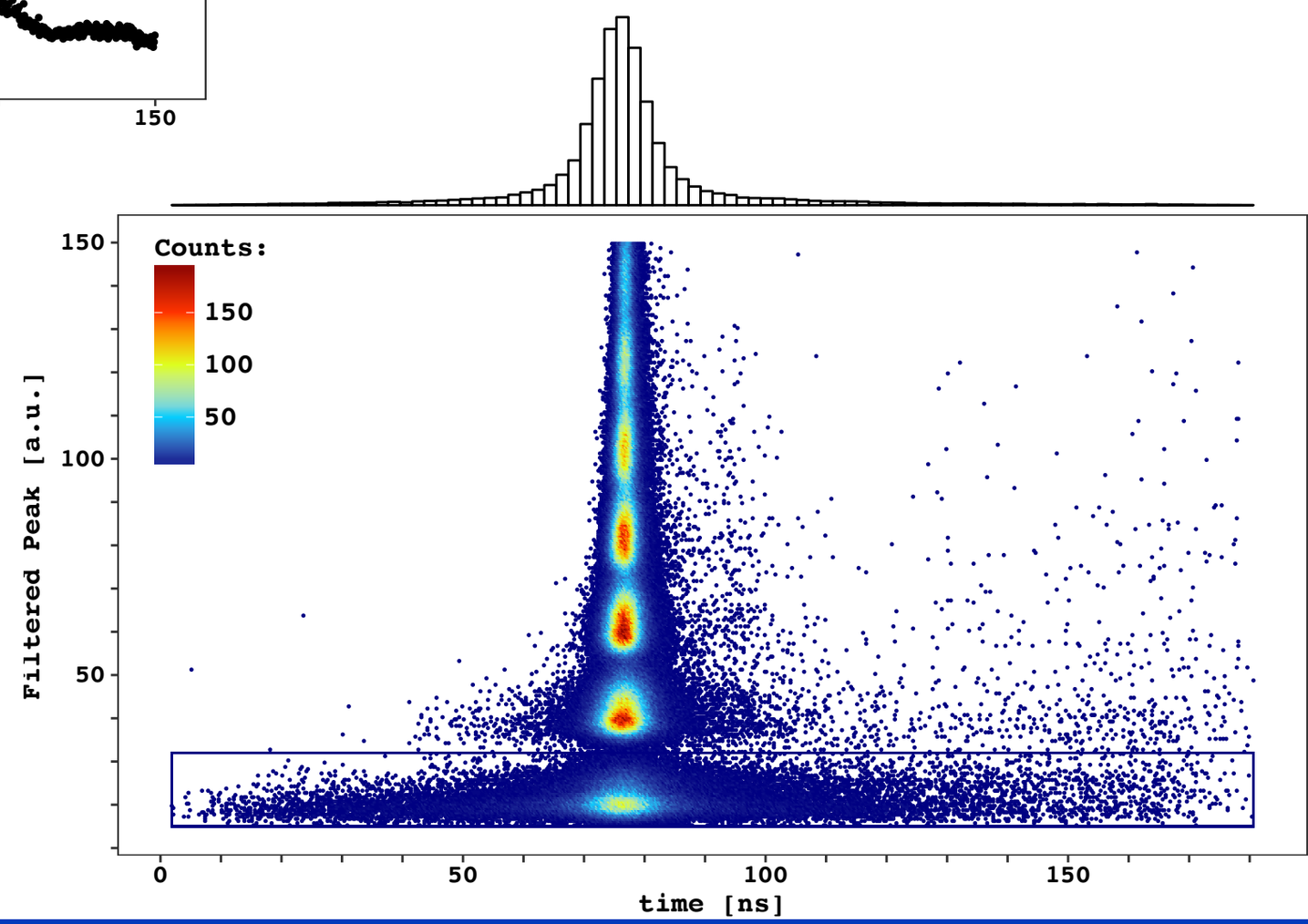
1PE Time resolution: 16ns

Sufficiently good to use PSD. In DS-20k the discrimination variable is f_{200}.

Full 24cm² tile with NUV-HD-LF at 80K 5VOV:

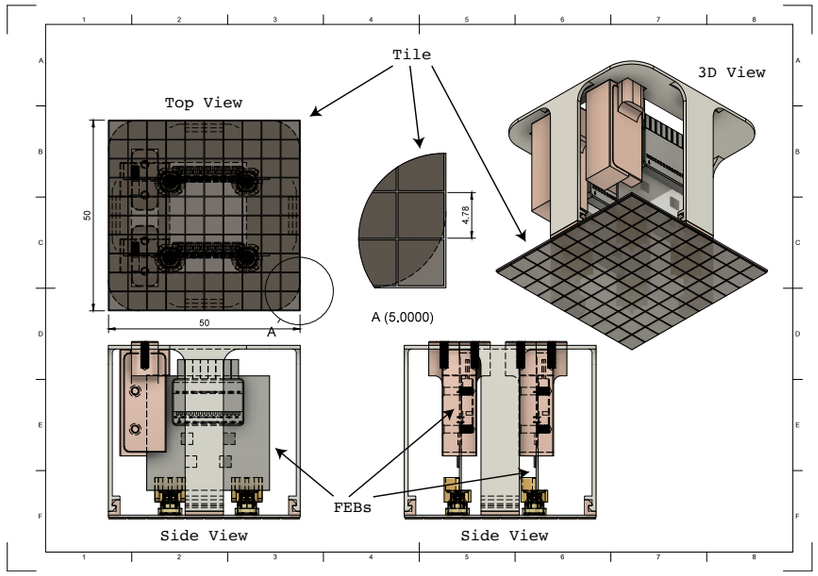
- σ_{1PE} = 9% μ_{1PE}
- SNR = 13

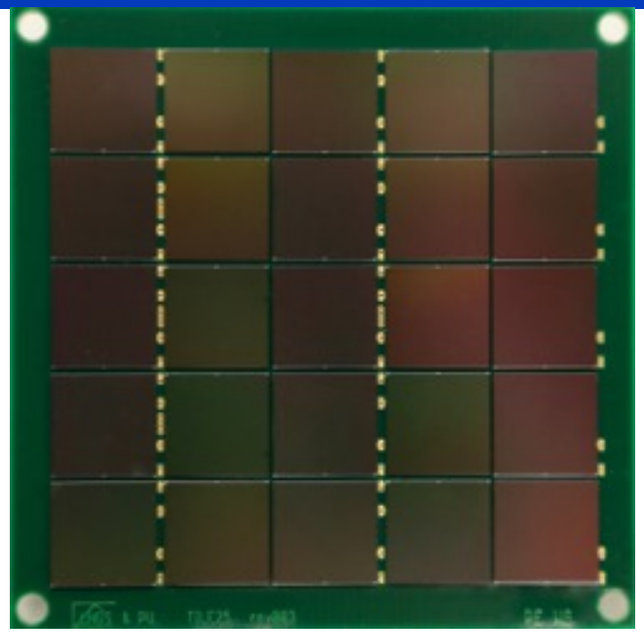
With such an SNR we don't expect any baseline noise induced hit.



arXiv:1706:04220

A fast recap





	DS-20k requirement	SiPM tile (PDM)	
Surface	$5x5cm^2$	$24cm^2$ prototype $25cm^2$ final PDM	✓
Power dissipation	<250mW	~170mW	✓
PDE	>40%	$50\% \cdot \varepsilon_{geom} = 45\%$	✓
Noise Rate	$<0.1cps/mm^2$	$0.004cps/mm^2$	✓
Time Resolution	O(10ns)	16ns	✓
Dynamic Range	>50	~100	✓

R&D phase can be considered concluded, with some minor steps to be finalized to pass from the prototype to mass production.

Conclusions

- DS-20k aims to probe the spin-independent WIMP-nucleon cross section up to $10^{-47}cm^2$@1TeV/c^2.
- The background-free mode will allow to claim a hypothetical discovery of DM with a low number of NR events.
- Many technological challenges.
- SiPMs have come to represent a viable alternative with respect to PMTs.
- SiPM-based light detectors as the one presented can be used in a variety of other experiments (DM,ν,cosmic rays…).