The Darkside Program for Dark Matter Searches

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Colloquium
IFAE
Universidad Autonoma de Barcelona
Barcelona
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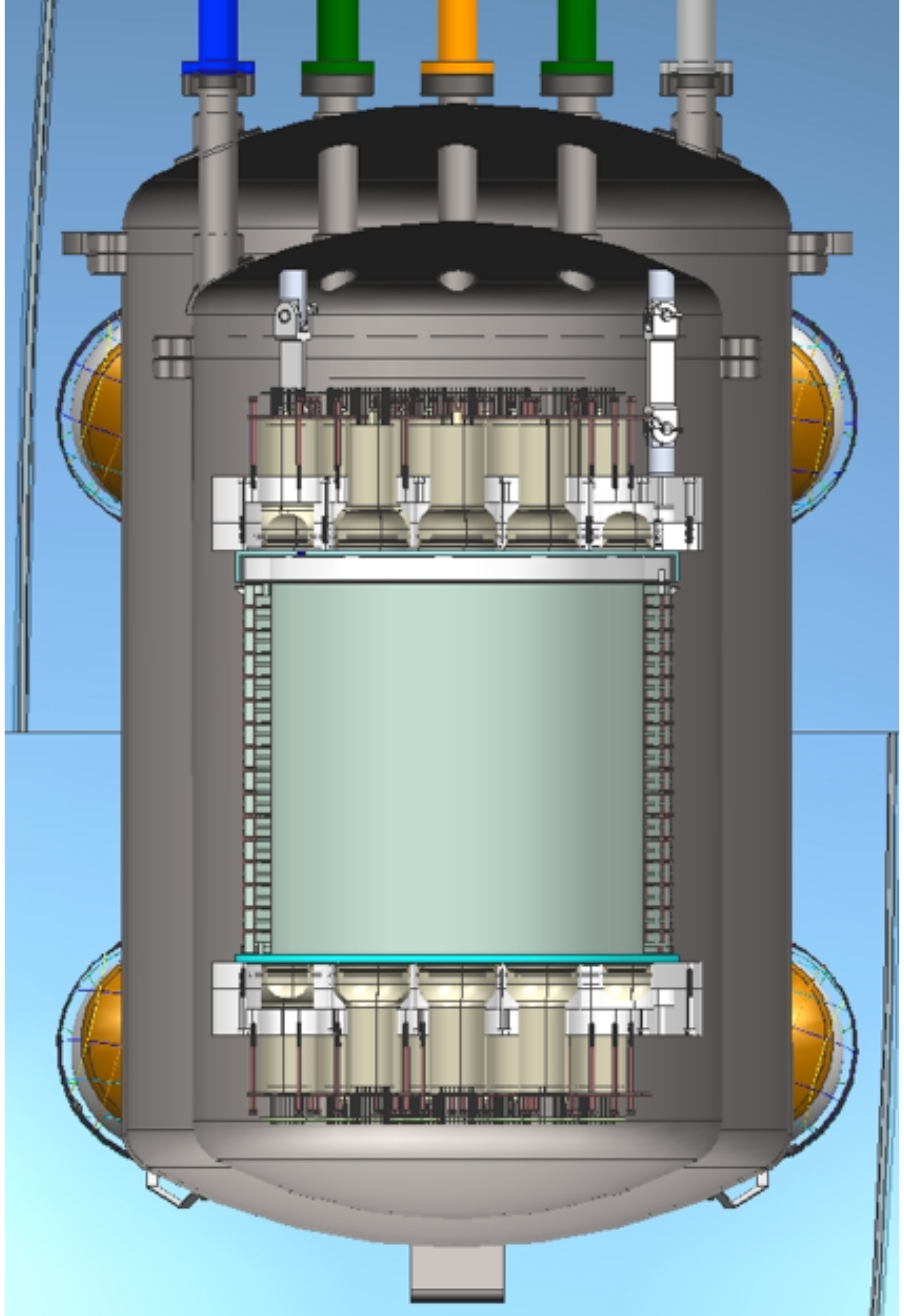
The DarkSide Program

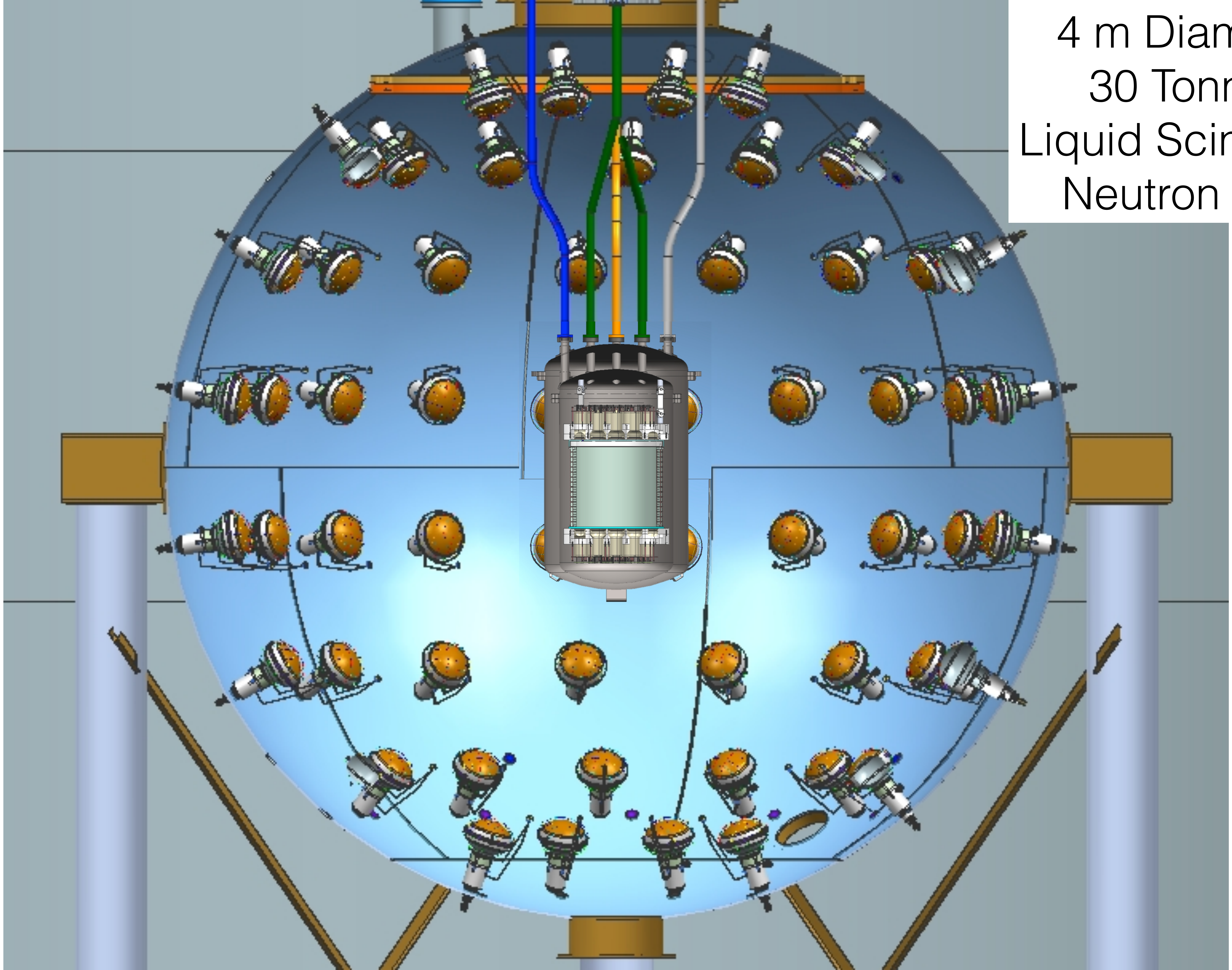
- The DarkSide-50 direct dark matter search:
  - A liquid argon TPC in stable operation having matched or surpassed all basic requirements
  - Thanks to Fermilab, first dark matter detector operating with isotopically enhanced target
  - Dark matter search operating in background-free mode

An Ambitious Discovery Program

- Ambitious program for discovery of heavy dark matter
- Raising the bar: 0.1 ton×yr ⇒ 1000 ton×yr
- Complementary to LHC and raising its energy scale:
  - 500 GeV ⇒ 1 TeV ⇒ 10 TeV ⇒ …
- “Zero Background” absolutely necessary
- Strong investment in ^{40}Ar by INFN, NSF, and Fermilab

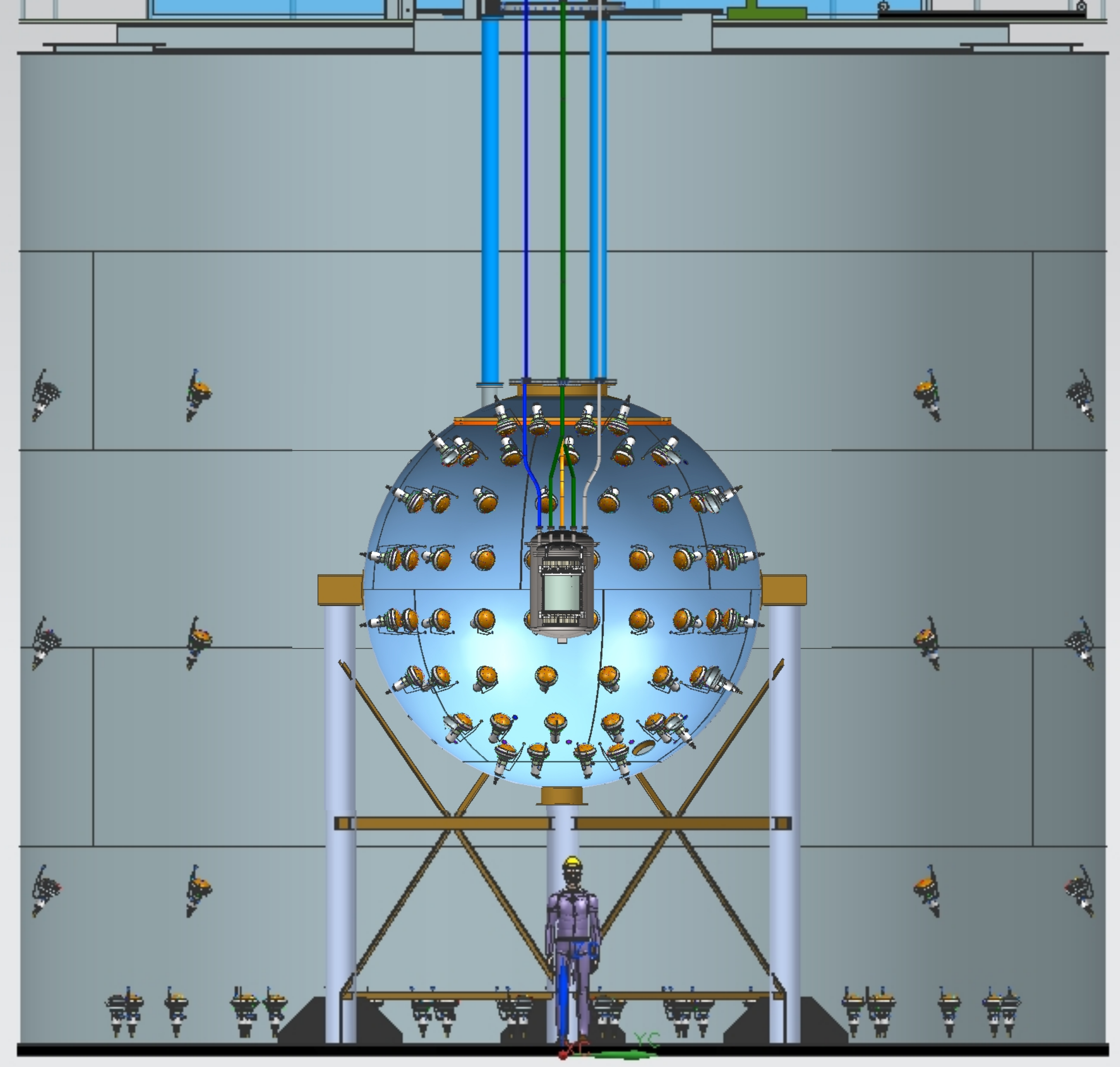
Liquid Argon TPC
153 kg ^{39}Ar-Depleted
Underground Argon
Target

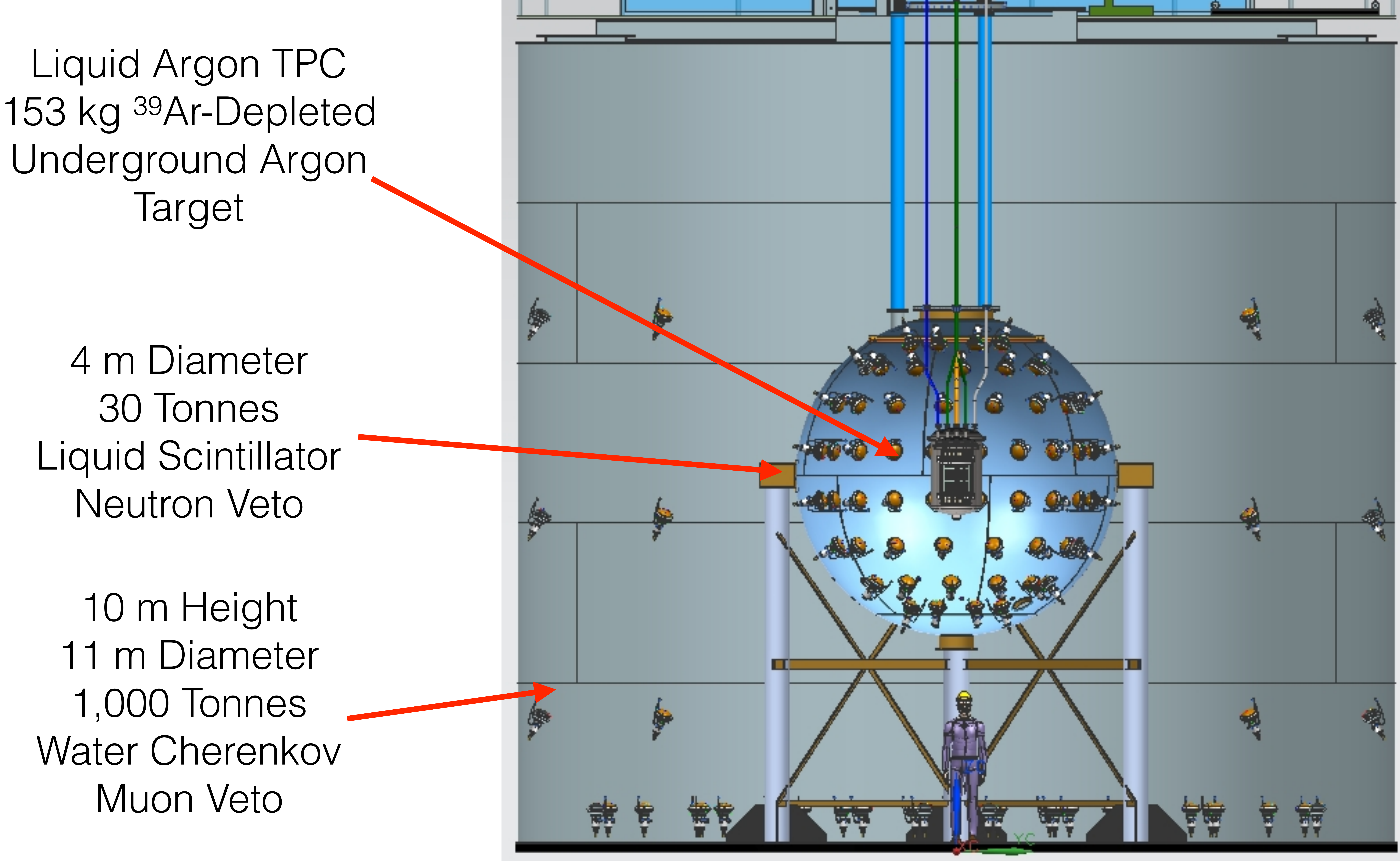




4 m Diameter
30 Tonnes
Liquid Scintillator
Neutron Veto

10 m Height
11 m Diameter
1,000 Tonnes
Water Cherenkov
Muon Veto

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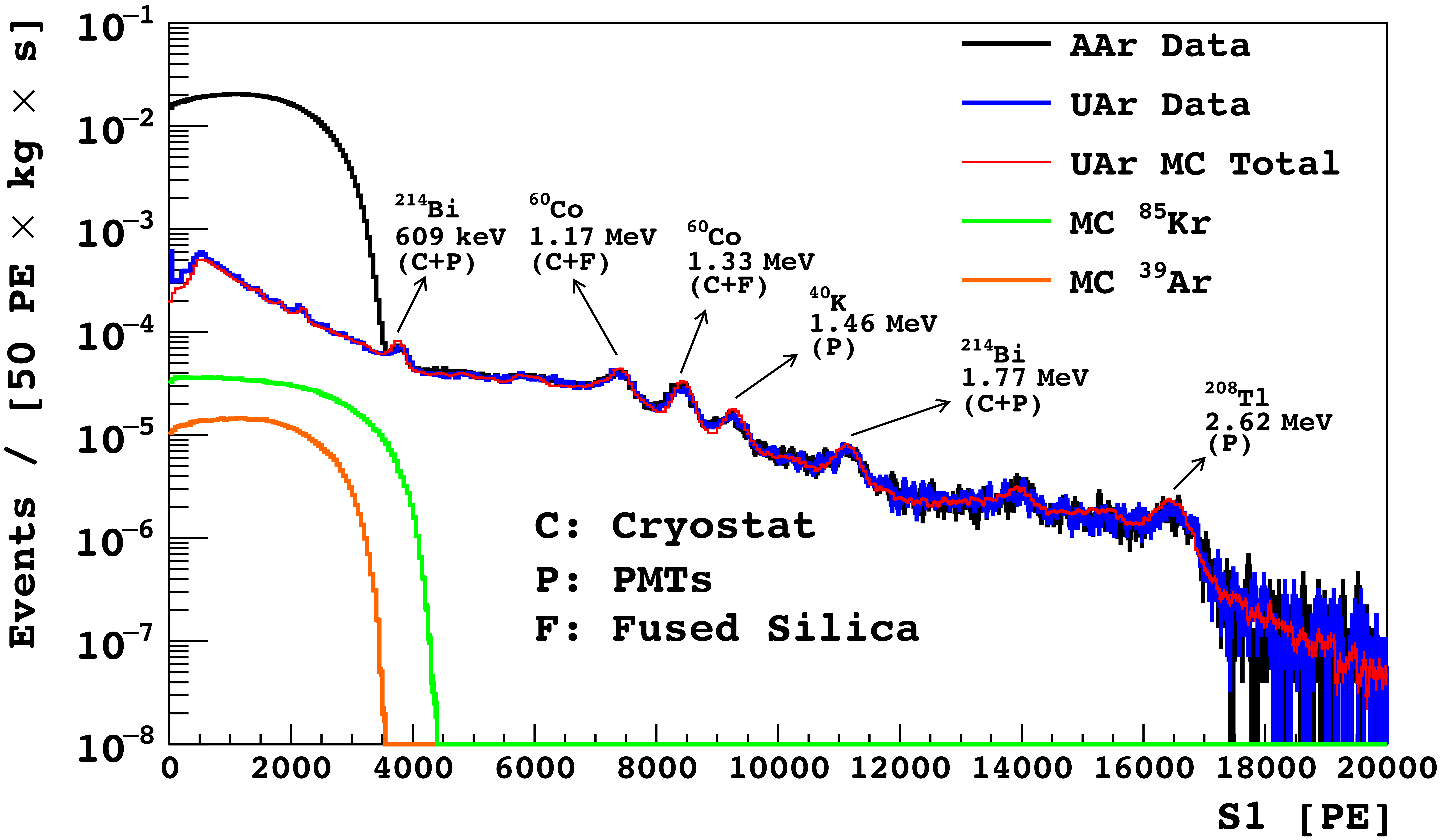
DarkSide-50 Milestones

- Oct 2013: three detectors commissioned, cryostat filled with AAr
- Oct 2014: WIMP search results with 1422 kg d AAr exposure
- Fall 2014: Calibration campaign
- Winter 2014: Refurbishment of LSV, ^{14}C rate from 150 kHz to 0.3 kHz
- Apr 2015: cryostat drained and filled with 153 kg of UAr
- Oct 2015: WIMP search results with 2616 kg d UAr exposure

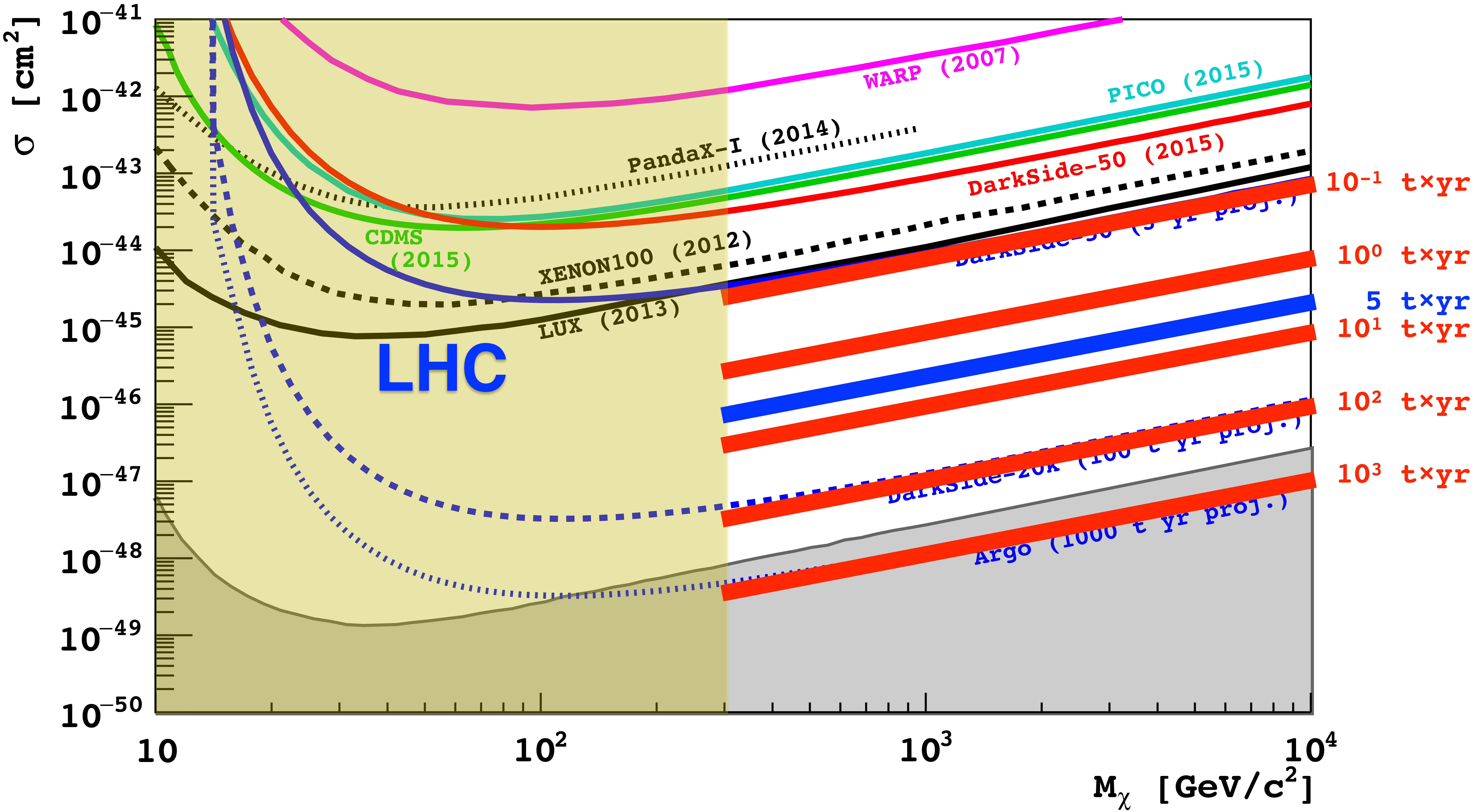


Events / [50 PE × kg × s]
S1 [PE]
AAr Data
UAr Data
UAr MC Total
MC 85Kr
MC 39Ar
214Bi 609 keV (C+P)
60Co 1.17 MeV (C+F)
60Co 1.33 MeV (C+F)
40K 1.46 MeV (P)
214Bi 1.77 MeV (C+P)
208Tl 2.62 MeV (P)
C: Cryostat
P: PMTs
F: Fused Silica

Energy [keV$_{nr}$]
20 40 60 80 100 120 140 160 180 200
f_{90}
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
50 100 150 200 250 300 350 400 450
S1 [PE]
50% 65% 80% 90% 95% 99%
0 5000 10000 15000 20000 25000
1,422 kg d AAr - PLB 743, 456 (2015)

Energy [keV$_{nr}$]
20 40 60 80 100 120 140 160 180 200
f_{90}
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
50% 65% 80% 90% 95% 99%
50 100 150 200 250 300 350 400 450
S1 [PE]
0 50 100 150 200 250
2,616 kg d UAr - arXiv:1510.12345 (2015)

Energy [keV$_{nr}$]
20 40 60 80 100 120 140 160 180 200
f_{90}
1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0
50% 65% 80% 90% 95% 99%
50 100 150 200 250 300 350 400 450
S1 [PE]
0 10 20 30 40 50
2,616 kg d UAr - arXiv:1510.12345 (2015)



σ [cm^2]
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10
10^2
10^3
10^4
M_χ [GeV/c^2]
WARP (2007)
PICO (2015)
PandaX-I (2014)
DarkSide-50 (2015)
CDMS (2015)
XENON100 (2012)
LUX (2013)
LHC
Argo (1000 t yr proj.)
10^{-1} t×yr
10^0 t×yr
5 t×yr
10^1 t×yr
10^2 t×yr
10^3 t×yr

“Zero Background” condition (<0.1 background events) necessary to conduct discovery program

What are the backgrounds for large scale, high mass dark matter searches?

Scatters of *pp* solar neutrinos
on electrons

Radioactive noble gases (^{39}Ar)

Elastic Scatters of *pp* Solar Neutrinos on Electrons

- 200 events/tonne×yr in ROI
- 200,000 background events @neutrino floor
- Defeated in argon thanks to β/γ rejection better than $1 \div 1.6 \times 10^7$

^{39}Ar Rejection

1,422 kg×day (@AAr)

↓ x1400
(^{39}Ar AAr/^{39}Ar UAr)

5.5 tonne×yr (UAr)

↓ additional active
isotopic depletion
and higher light yield

1,000 tonne×yr (UAr/DAr)

Based on what we know today, can a depleted argon experiment be background free at the scale of 1000 tonnes$\times$yr?

Yes

Based on what we know today, can a xenon experiment be background free at the scale of 1000 tonnes$\times$yr?

10.2 keVee
9.0
7.8
6.6
5.4
4.2
2.9
1.7
33 keVnr
3
9
15
21
27
log10[S2(phd)]
S1 (phd)
4
3.5
3
2.5
2
0
5
10
15
20
25
30
35
40
45
50

2,616 kg d UAr - arXiv:1510.12345 (2015)
Energy [keV$_{nr}$]
20
40
60
80
100
120
140
160
180
200
f_{90}
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
50%
65%
80%
90%
95%
99%
50
100
150
200
250
300
350
400
450
S1 [PE]
0
10
20
30
40
50

Meeting Basic Requirements Pays Off

- Light Yield: > 8 p.e./keV
- Electron meanlife: >>5 ms
- ^{39}Ar contamination: 0.7 mBq/kg, factor 1,400 reduction res to atmosphere
- ^{222}Rn contamination: <2 μBq/kg

Impact of Basic Research on Industry

Air Products and Helium: A Success Story

- Based on research for underground argon funded by US NSF, the discovery of a sustained fraction of helium in the Kinder Morgan CO_2 stream

- An investment by Air Products resulted in the most modern helium extraction plant

- Production started in June 2015 accounts for 15% of the total production by the US govt at the National Helium Reservoir

Cryogenic Distillation Column at Fermilab

Goals of Future Program

- Procurement of 30 tonnes by 2020 in support of DarkSide-20k
  - 100 tonne$\times$yr background free exposure for dark matter
- Procurement of 300 tonnes by 2030 in support of Argo
  - 1000 tonne$\times$yr background free exposure for dark matter
  - Precision solar neutrino measurements
- Possible procurement of larger quantities … maybe to enable solar and supernova relic neutrino physics in DUNE?

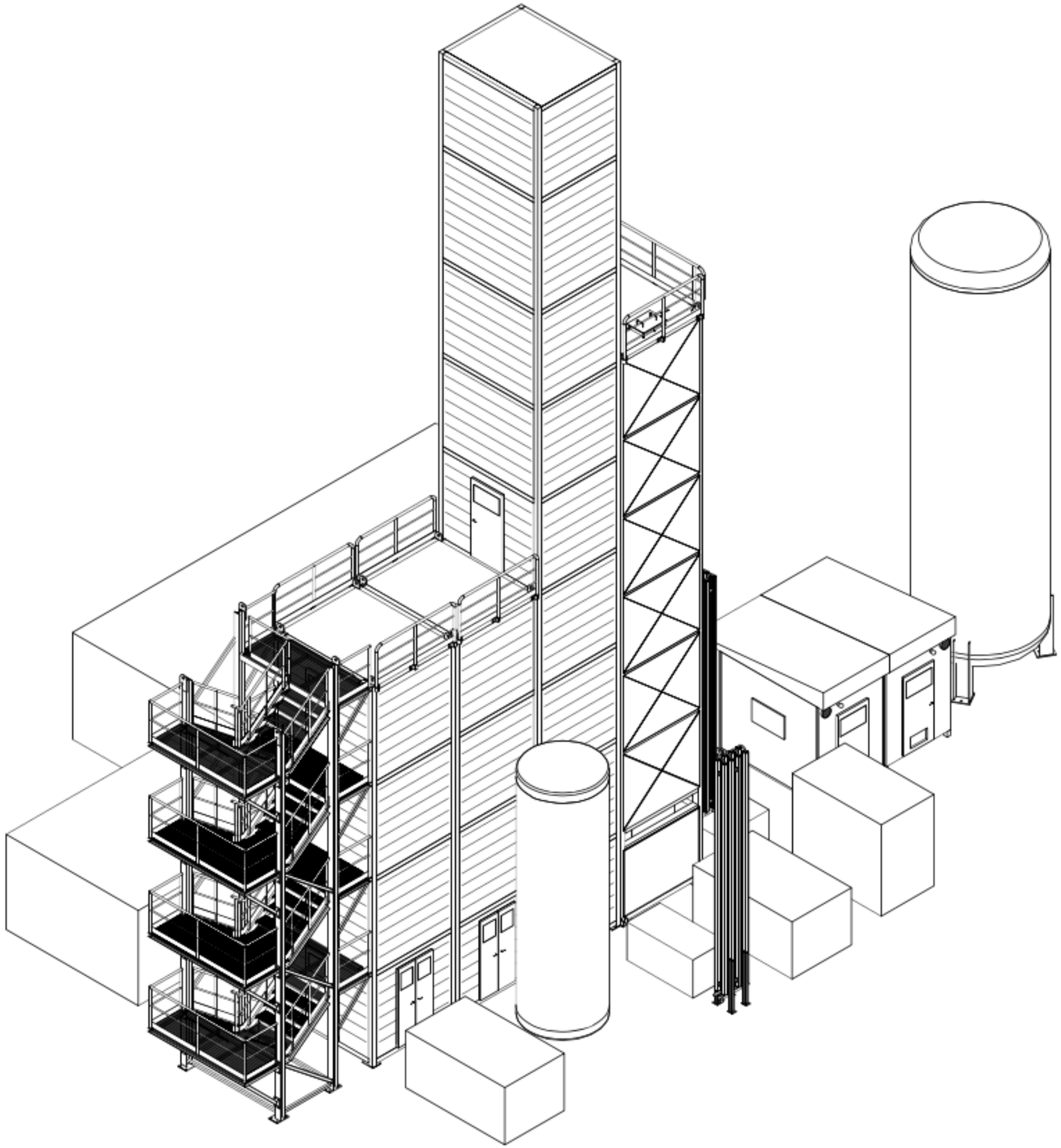
Urania

- The goal is to build a plant capable of extracting UAr at a rate of about 100 kg/d from the Cortez, CO source

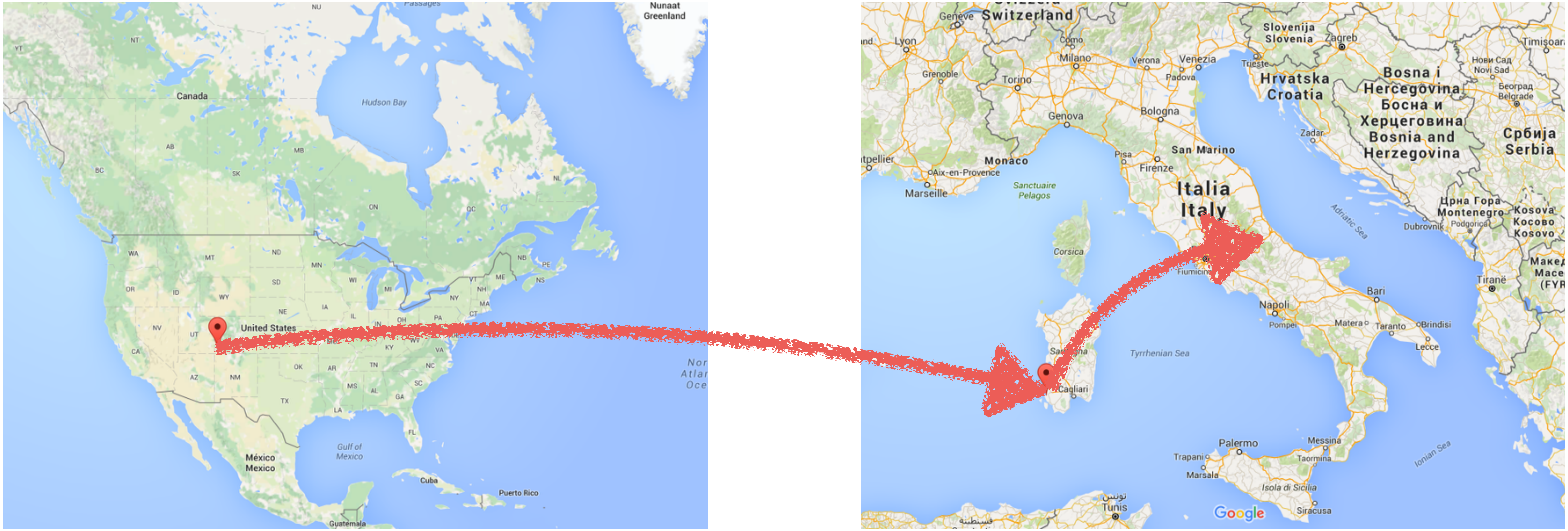
- Cooperation with Air Products and utilization of a premium stream from their He extraction plant may result in a significant boost of production with the same plant

Argon Purification Unit

- A set of elemental process units:
  - The first cryogenic column removes the bulk of CO2 and CH_4
  - The Pressure Swing Adsorption columns removes the traces of CO2 and CH_4
  - The second cryogenic column removes N_2 and He
  - The third cryogenic column refines the argon-rich stream detector-grade argon



Urania to Aria to LNGS



Aria

- The purpose of Aria is the reduction of ^{39}Ar in the target of the DarkSide detectors
- The method of isotopic separation is cryogenic distillation
- The project is supported by INFN, US NSF, and Regione Autonoma della Sardegna

Isotope Vapor Pressure

- First measurements of relative volatility of argon isotopes by Boato and Scoles in the 1960's
- Detailed measurements of the $p(^{36}Ar)/p(^{40}Ar)$ relative volatility
- General model to calculate the vapor pressure ratio of argon isotope developed by Fieschi and Terzi
- Small difference in ratio of volatilities $O(10^{-3})$ requires thousands of equilibrium stages

Seruci Wells

Seruci in Sardinia an excellent location

DarkSide-20k

20-tonnes fiducial dark matter detector
start of operations at LNGS within 2020
100 tonne×year background-free search for dark matter

Argo

300-tonnes depleted argon detector
start of operations at LNGS within 2025
1,000 tonne×year background-free search for dark matter
precision measurement of solar neutrinos

DarkSide-20k Institutions

APC

LNGS

GSSI

AU AUGUSTANA UNIVERSITY

БелГУ 1876

Black Hills State University

STVDIORVM VNIVERSITAS CARALITANA

UNICAMP UNIVERSIDADE ESTADUAL DE CAMPINAS

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

THE UNIVERSITY OF CALIFORNIA DAVIS

JOINT INSTITUTE FOR NUCLEAR RESEARCH JINR

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

FONDAZIONE BRUNO KESSLER

UNIVERSITY OF HAWAI'I MANOA 1907

UNIVERSITY OF HOUSTON Founded 1927

Institute of High Energy Physics
Chinese Academy of Sciences

INFN

IPHC Institut Pluridisciplinaire Hubert CURIEN STRASBOURG

LPNHE PARIS

NATIONAL RESEARCH NUCLEAR UNIVERSITY MEPhI MOSCOW ENGINEERING PHYSICS INSTITUTE

POLITECNICO MILANO

НГУ

STUDIUM GENERALE CIVITATIS PERUSII A.D. MCCCVIII

IN SUPREMÆ DIGNITATIS 1343

Pacific Northwest NATIONAL LABORATORY

STVDIVM VRBIS

ROMA TRE UNIVERSITÀ DEGLI STUDI

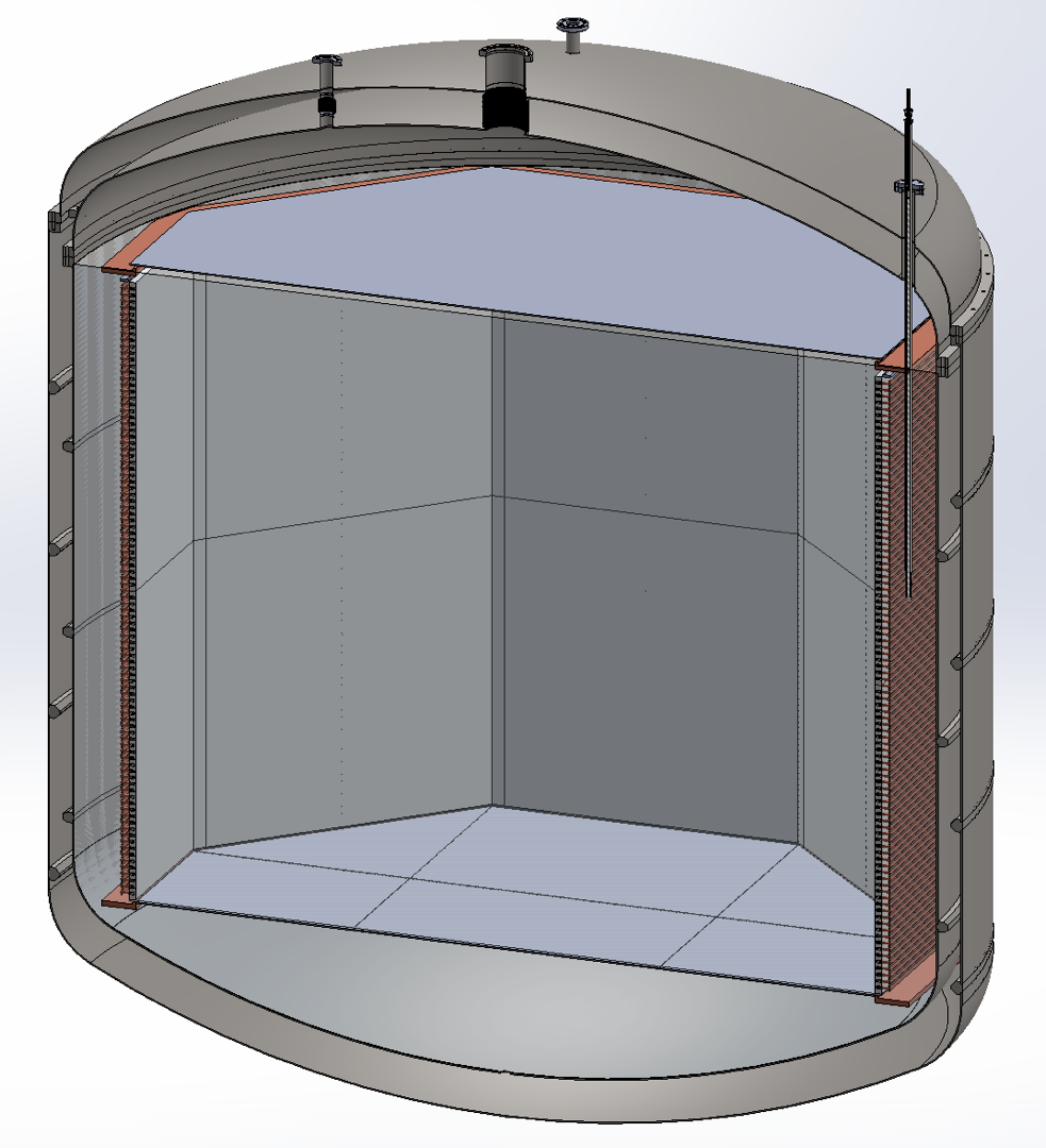
TEMPLE UNIVERSITY

TIFPA Trento Institute for Fundamental Physics and Applications

THE UNIVERSITY OF CALIFORNIA UCLA

UNIVERSITY OF MASSACHUSETTS AMHERST 1863

SCIENTIA VINCES



Photosensors for LAr Detectors

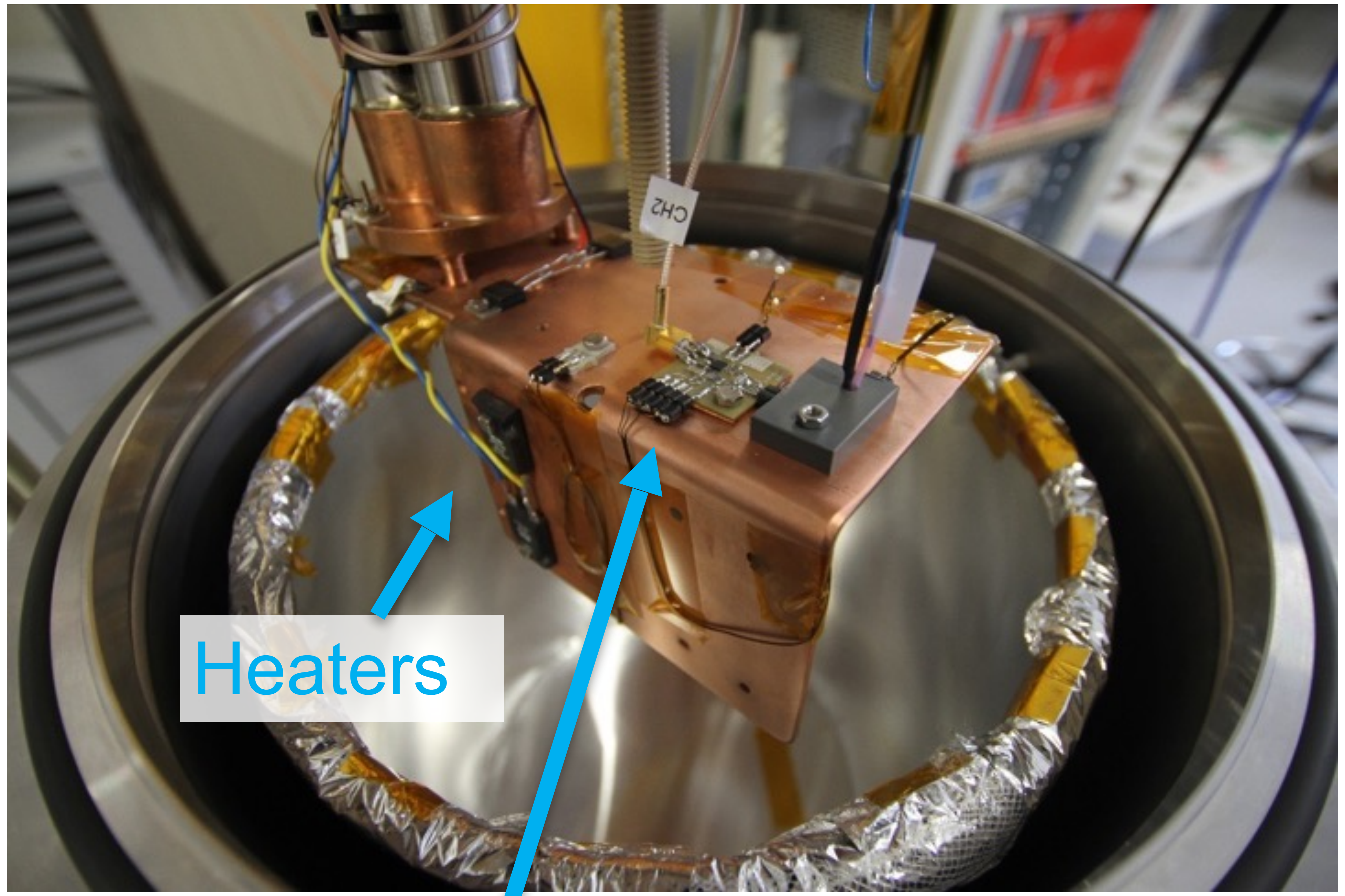
Trento Institute for Fundamental Physics and Applications

- A new program of FBK/TIFPA and LFoundry under the guidance of INFN and Princeton: complete replacement of Hamamatsu cryogenic PMTs
  - Much lower radioactivity
  - Light yield increase by 50%
  - Greater stability
  - Ten-fold reduction of costs per unit area vs. R11065-xx
  - Capability of large-scale production at LFoundry

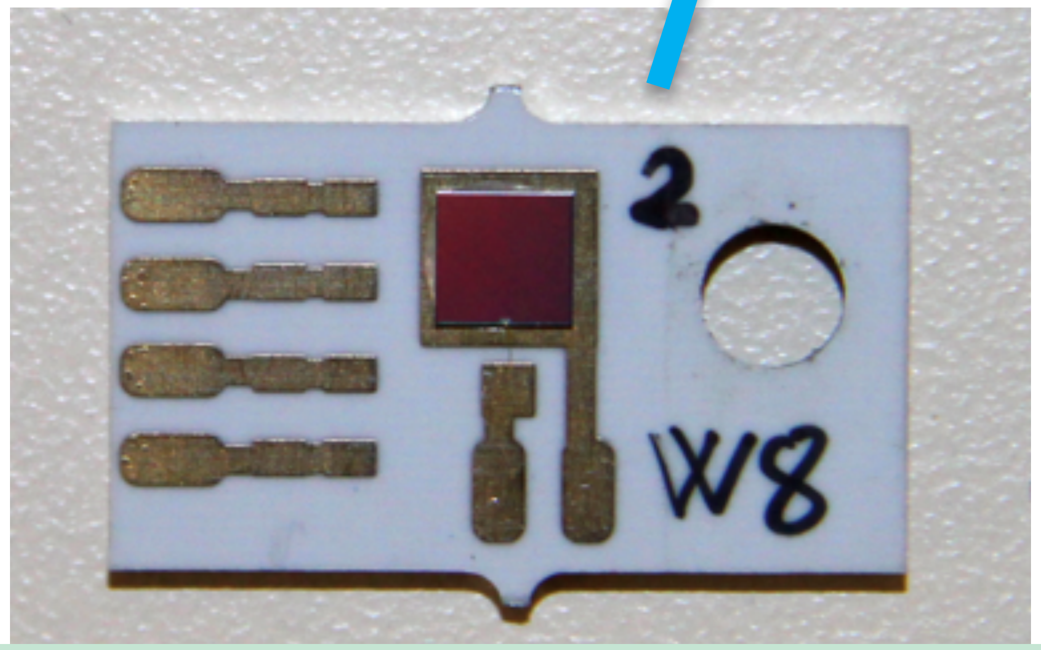
Requirements for DarkSide

1. PDE larger than 40% at 420 nm, signicant improvement over the 34% QE of the photocathode of the Hamamatsu R11065 PMTs used in DarkSide-50;
2. Dark count rate (DCR) lower than 1 Hz/mm^2, as higher rates would impact both the trigger efficiency and the pulse shape discrimination power;
3. Total correlated noise probability (TCNP) (crosstalk + afterpulsing) lower than 40%;
4. Inactive gap between devices smaller than 200 µm to maximize the tiling efficiency;
5. Photo-electron gain larger than 1M and a signal duration of less than 300 ns; and
6. Overall surface 14 m^2.

Measurement Setup @ LNGS



Cables and optical fiber feedthrough



4x4 mm^2 SiPMs

Measured quantities:

- Noise: primary and correlated
- Photo Detection Efficiency

from 40 K to 300 K!

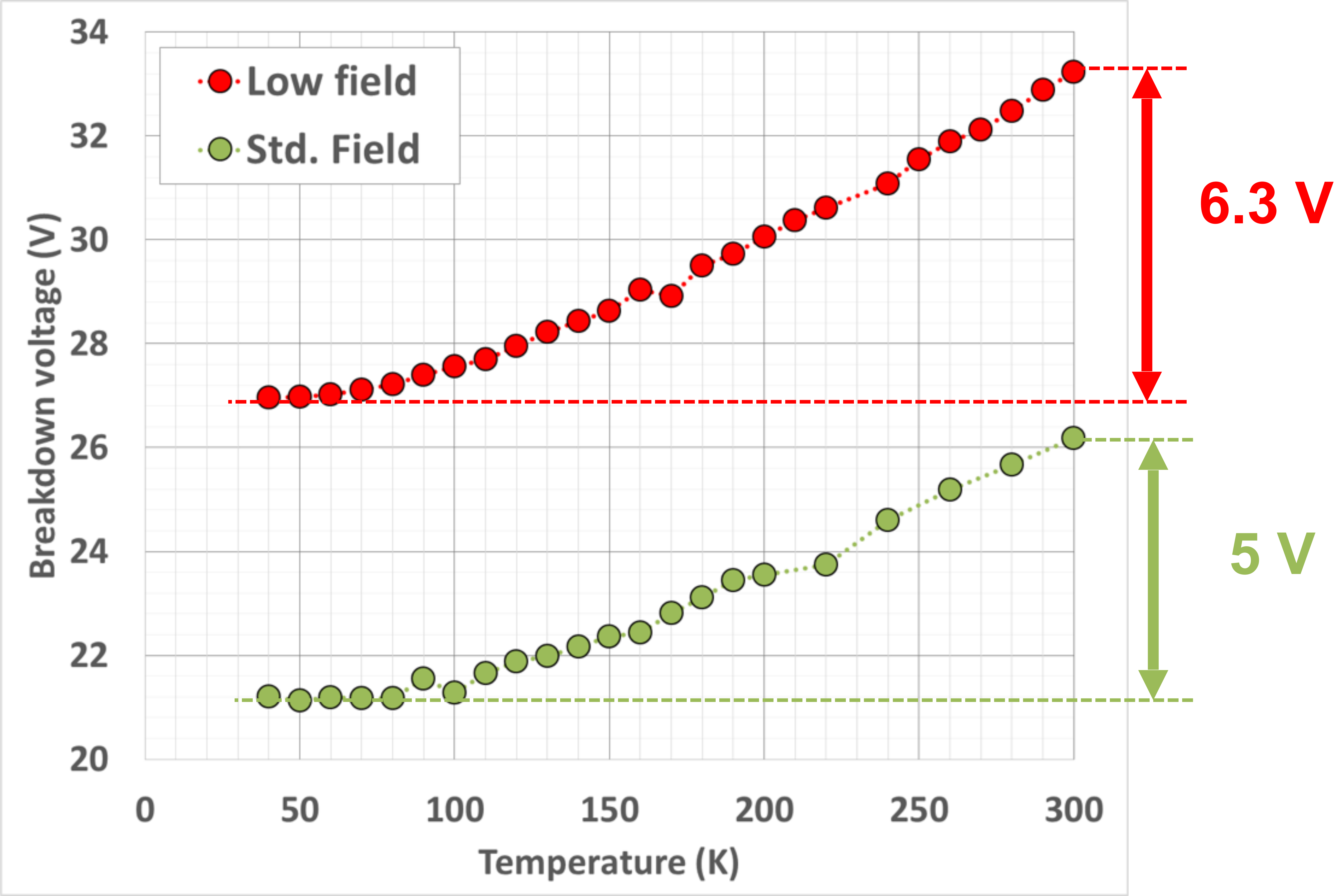
Devices Under Test

Parameters (@ room T)	NUV-HD Std. field	NUV-HD Low-field
Cell Size	25 µm	25 µm
Fill Factor	73%	73%
Breakdown Voltage	26.5 V	32 V
Max PDE	50%	50%
Peak PDE λ	410 nm	410 nm
DCR (20°C)	< 150 kHz/mm^2	< 150 kHz/mm^2
Direct CT (~ps)	25%	25%
Del. CT + AP (~ns)	2%	2%

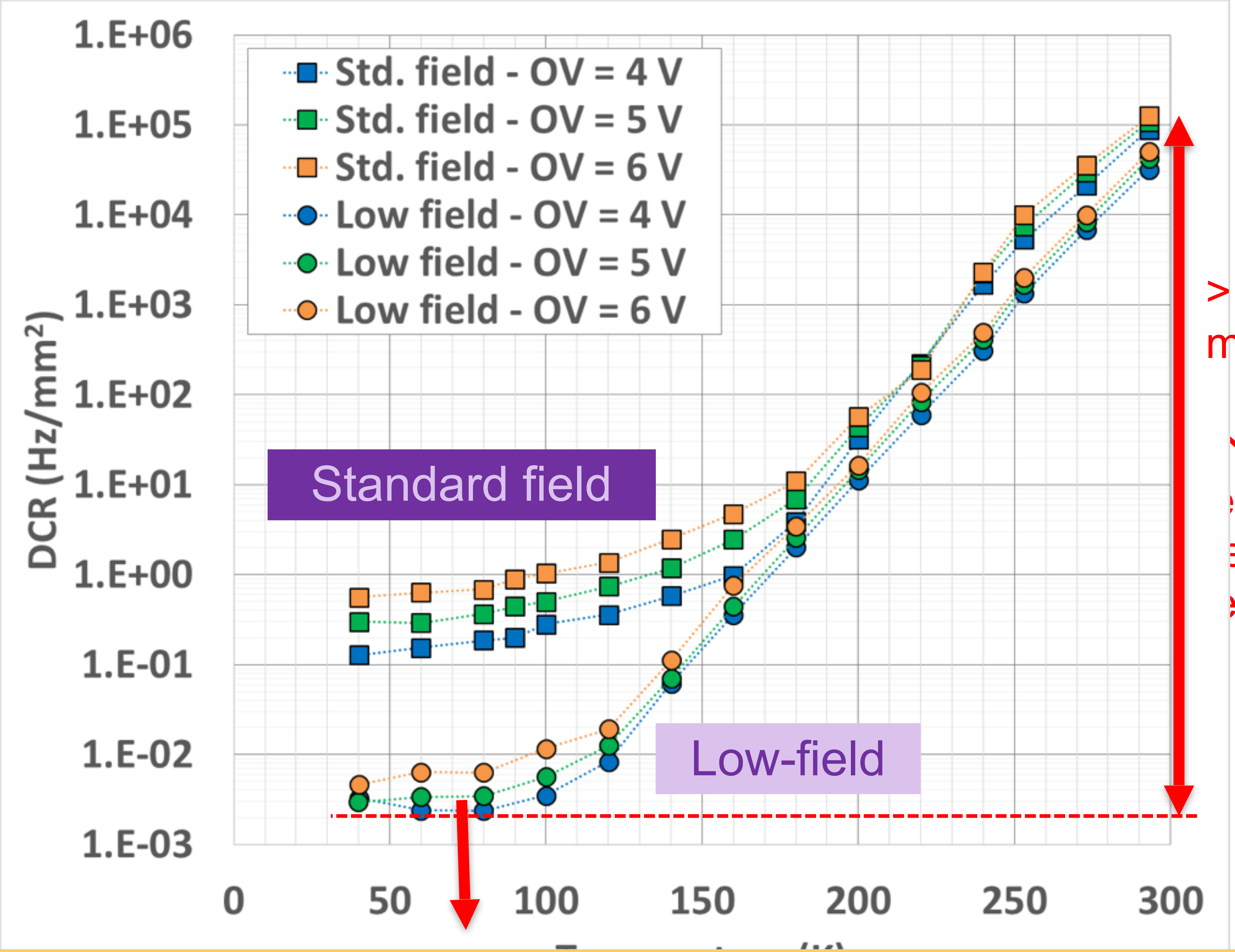
Optimized for low temperature operation

Breakdown Voltage vs. Temperature

The mean free path of the carriers in the high-field region increases with decreasing temperature.



DCR / mm² vs. Temperature



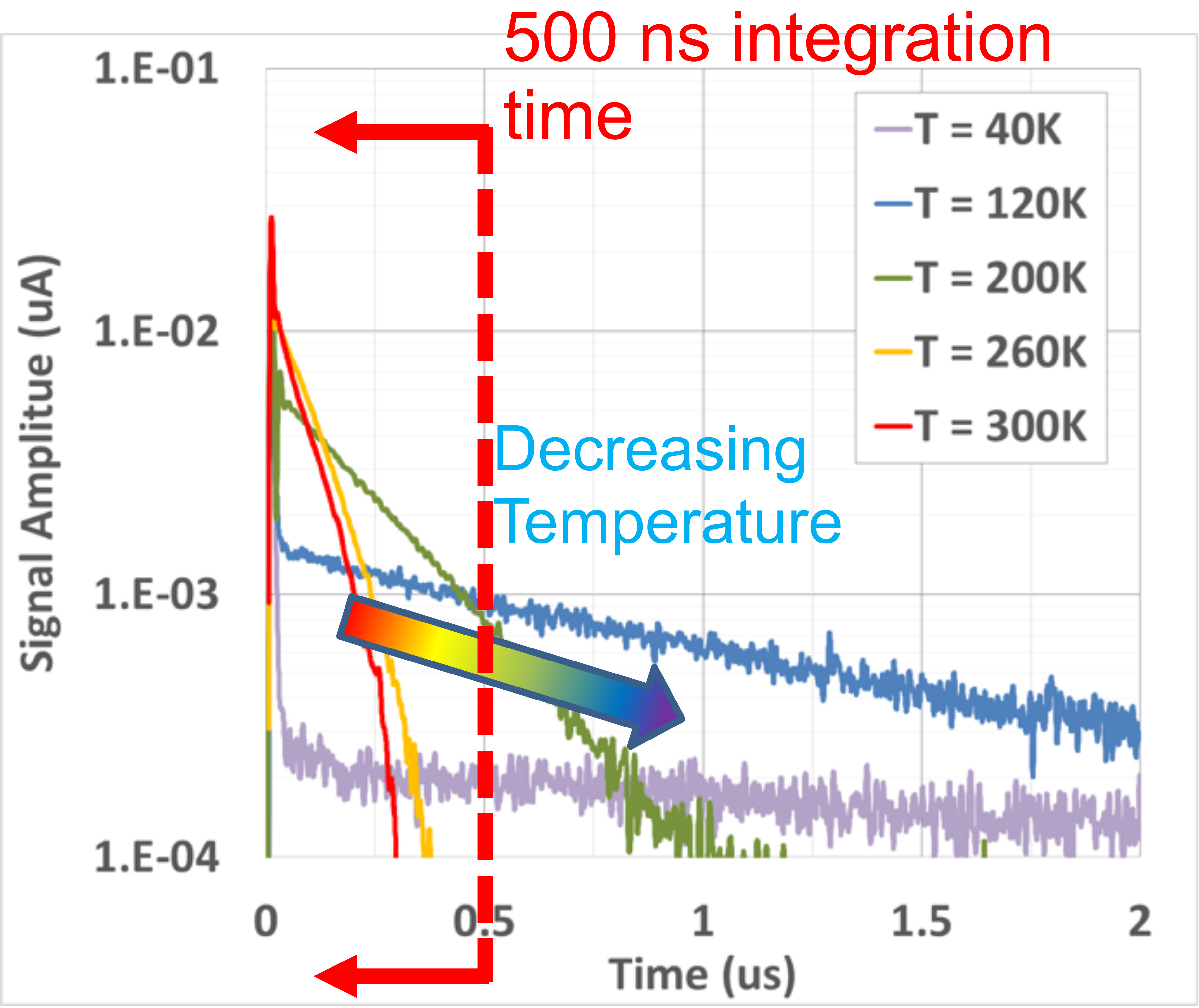
> 7 orders of magnitude !

xponential
espect to
erature.

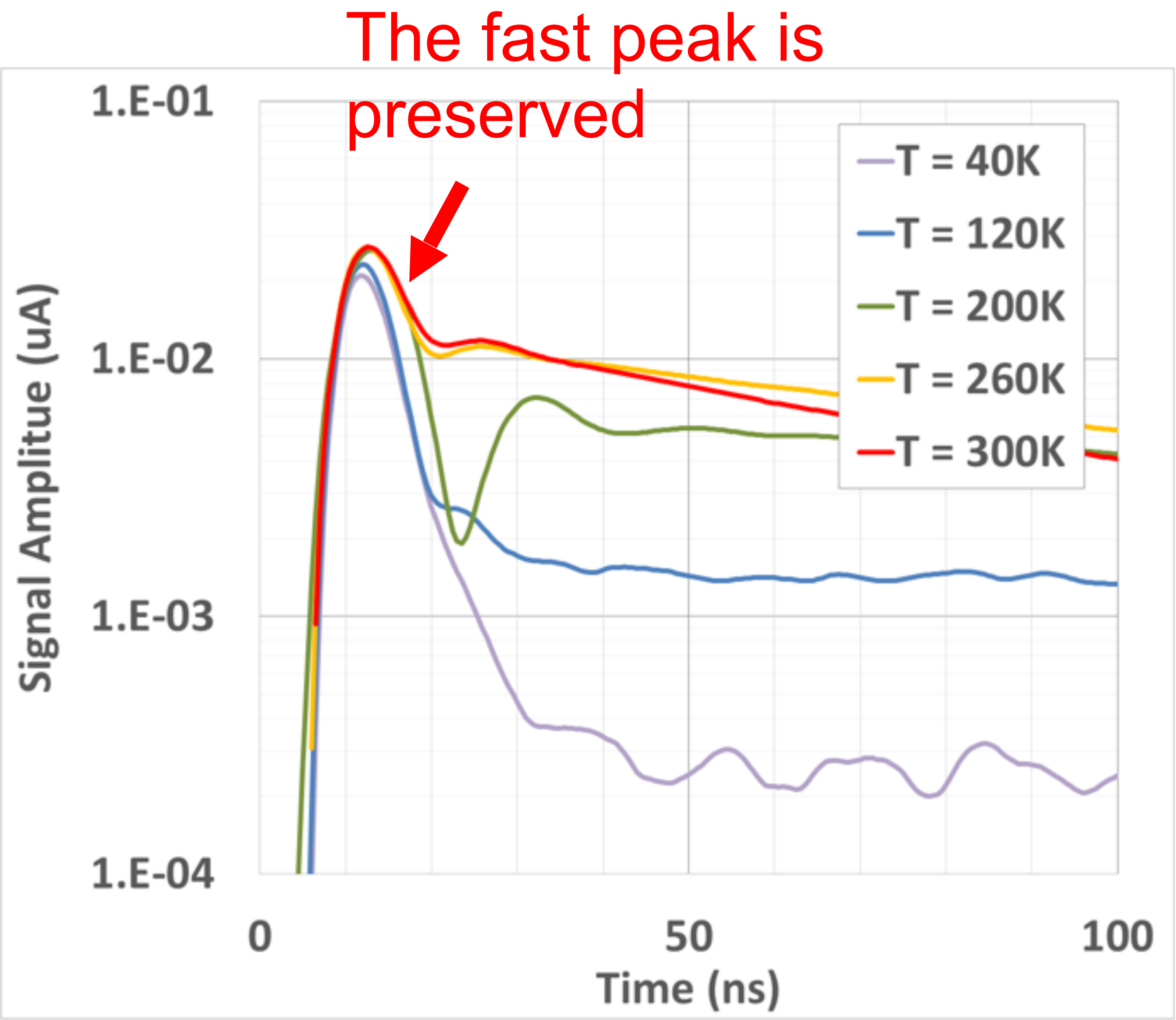
A 10x10 cm² SiPM array has a total DCR < 100 Hz!

Signal Shape

The exponential tail of the single cell response (SCR) becomes almost negligible at cryogenic temperature.



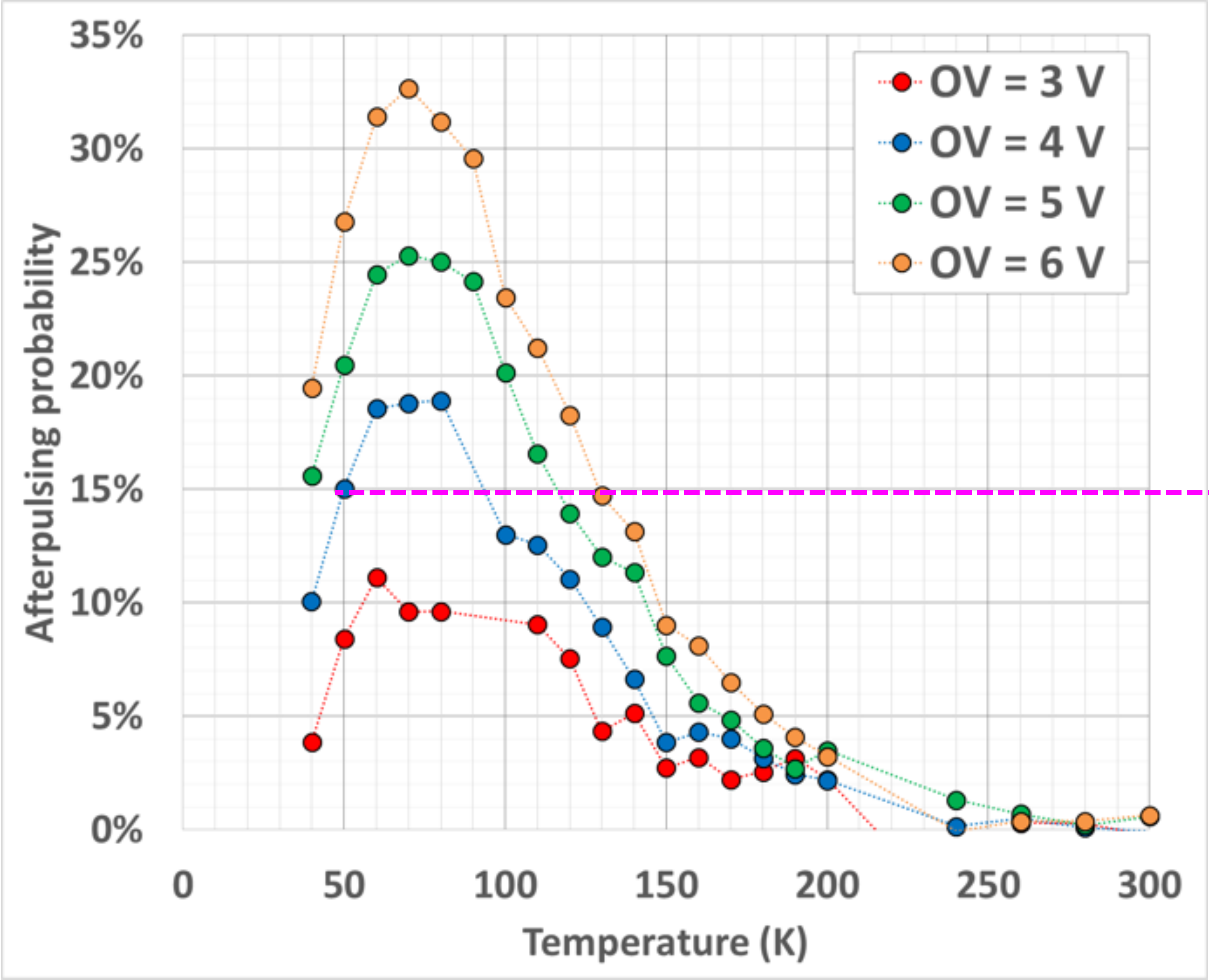
Average SCR

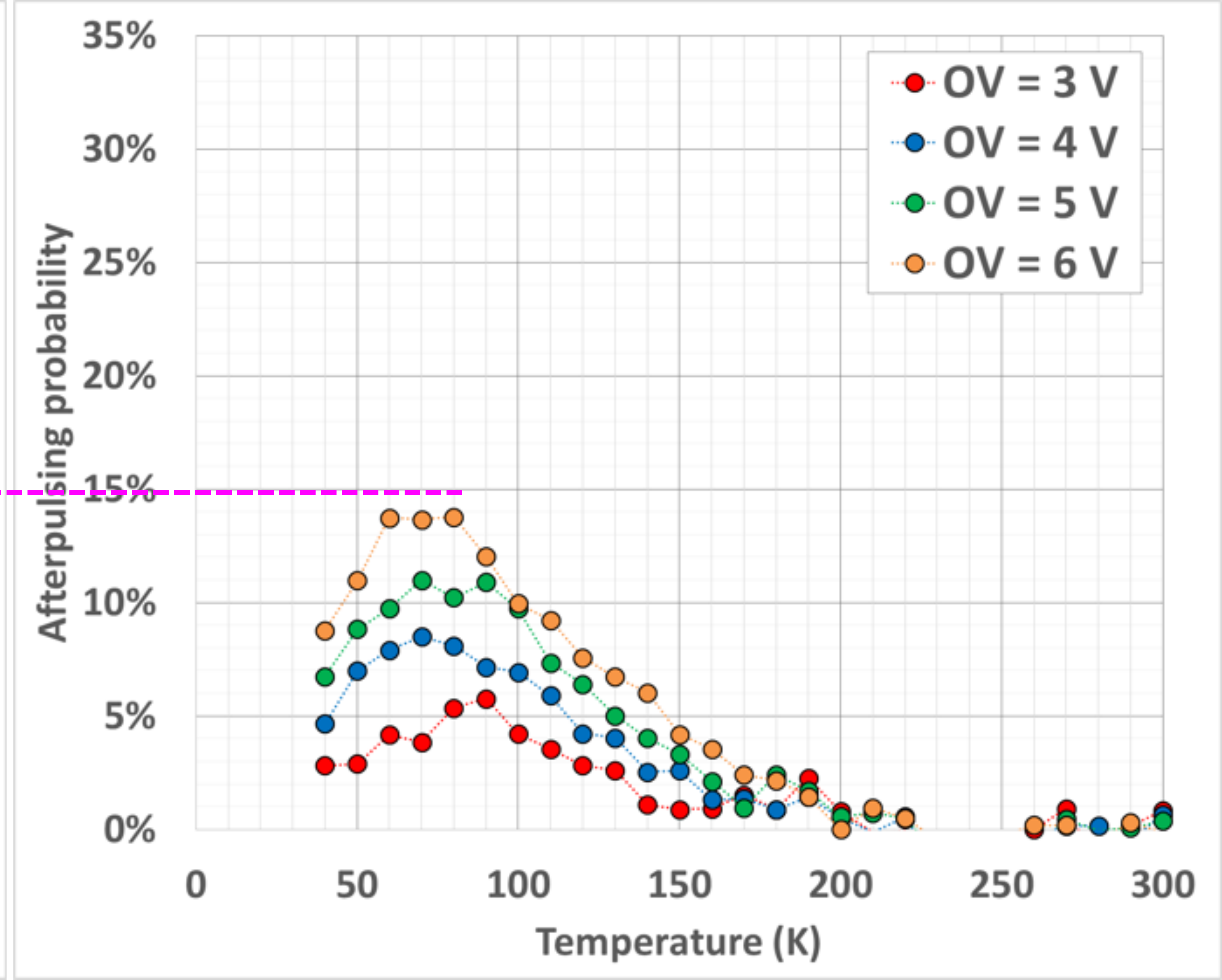


Zoom of the first part of the SCR

Afterpulsing Probability vs. Temp

The growth of the microcell recharge time constant helps reducing the afterpulsing at low temperature.





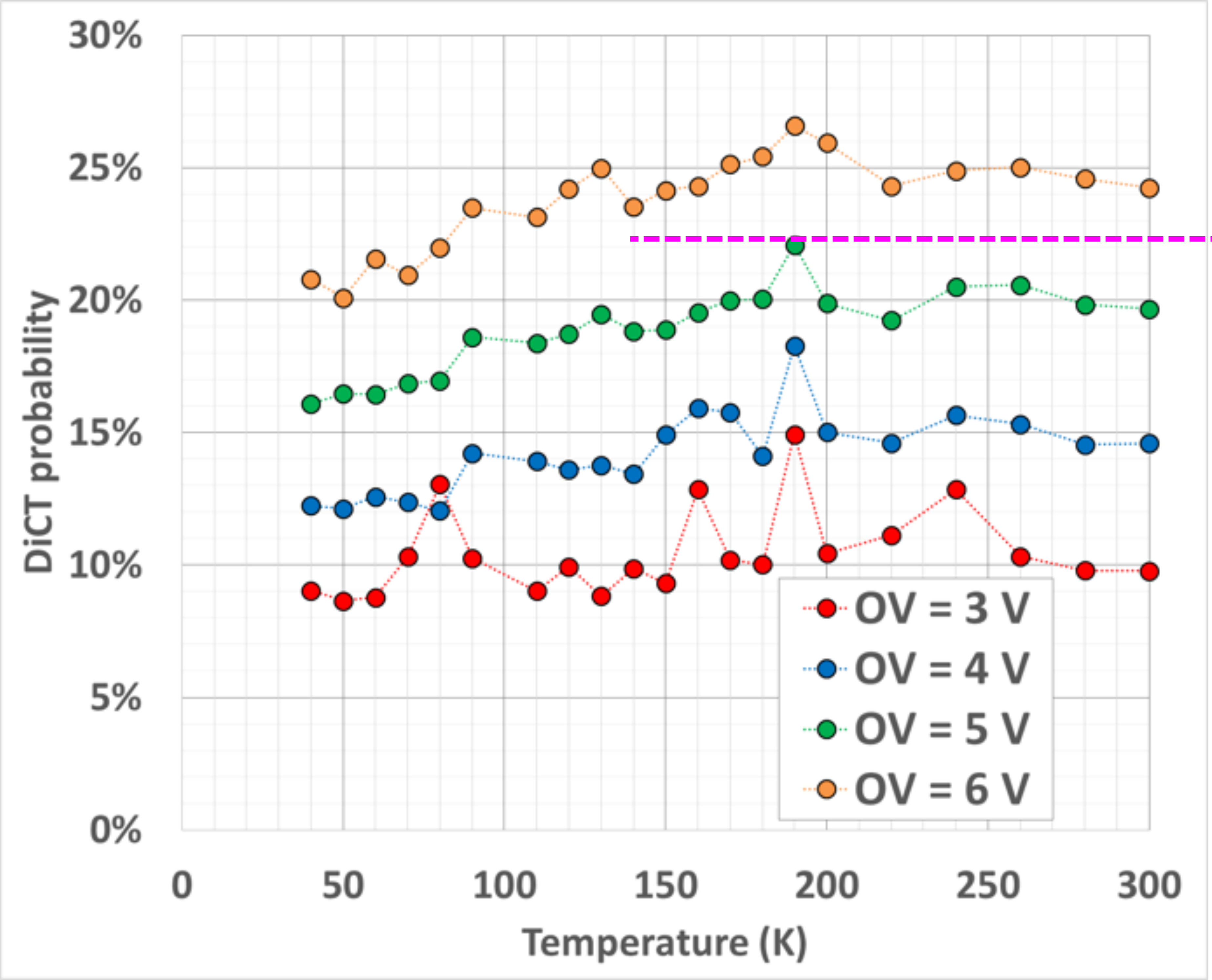
Standard field

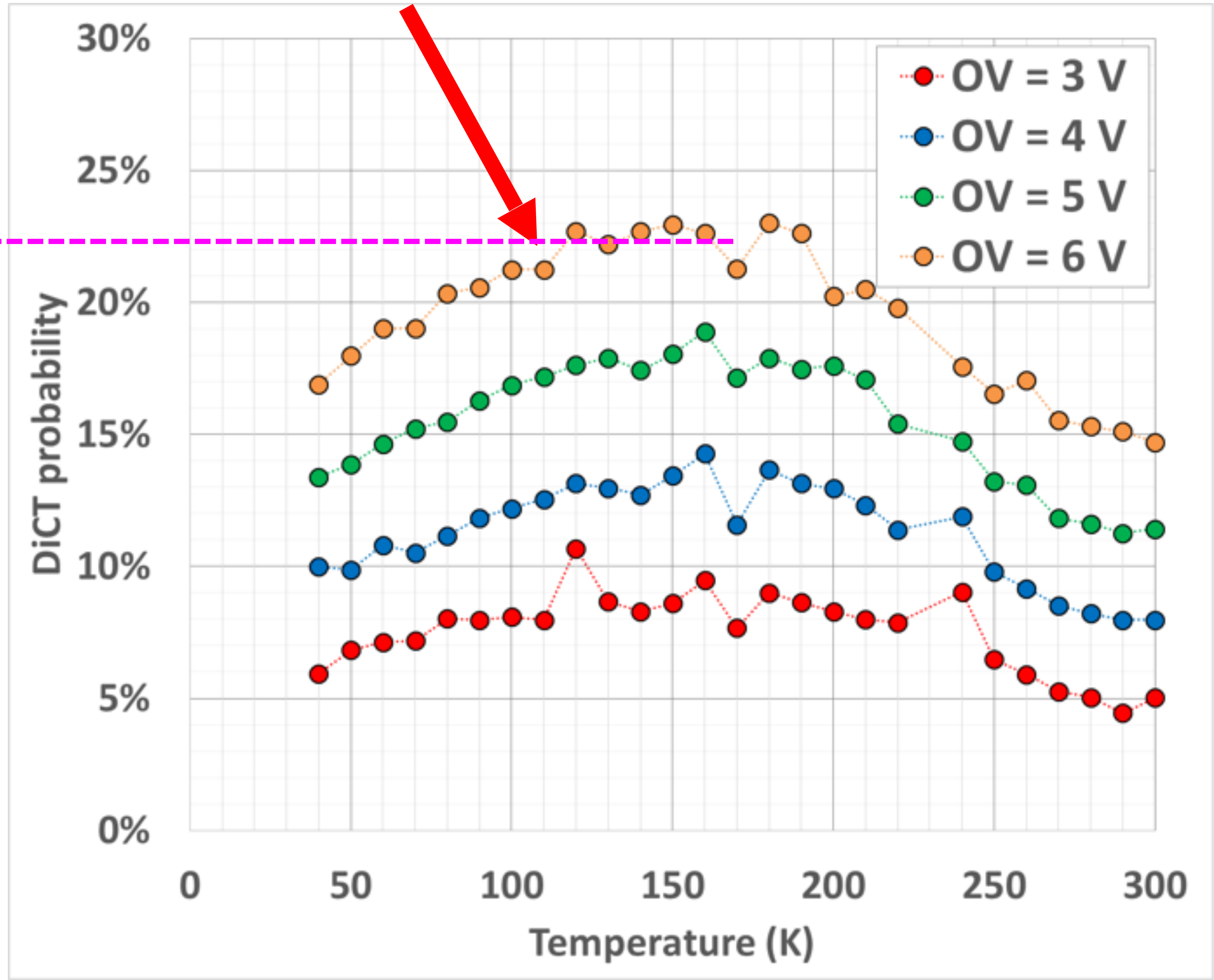
Low-field

Direct CT vs. Temp

The direct crosstalk probability has only minor variations with respect to temperature.

Slightly lower gain and triggering probability at the same overvoltage.





Standard field

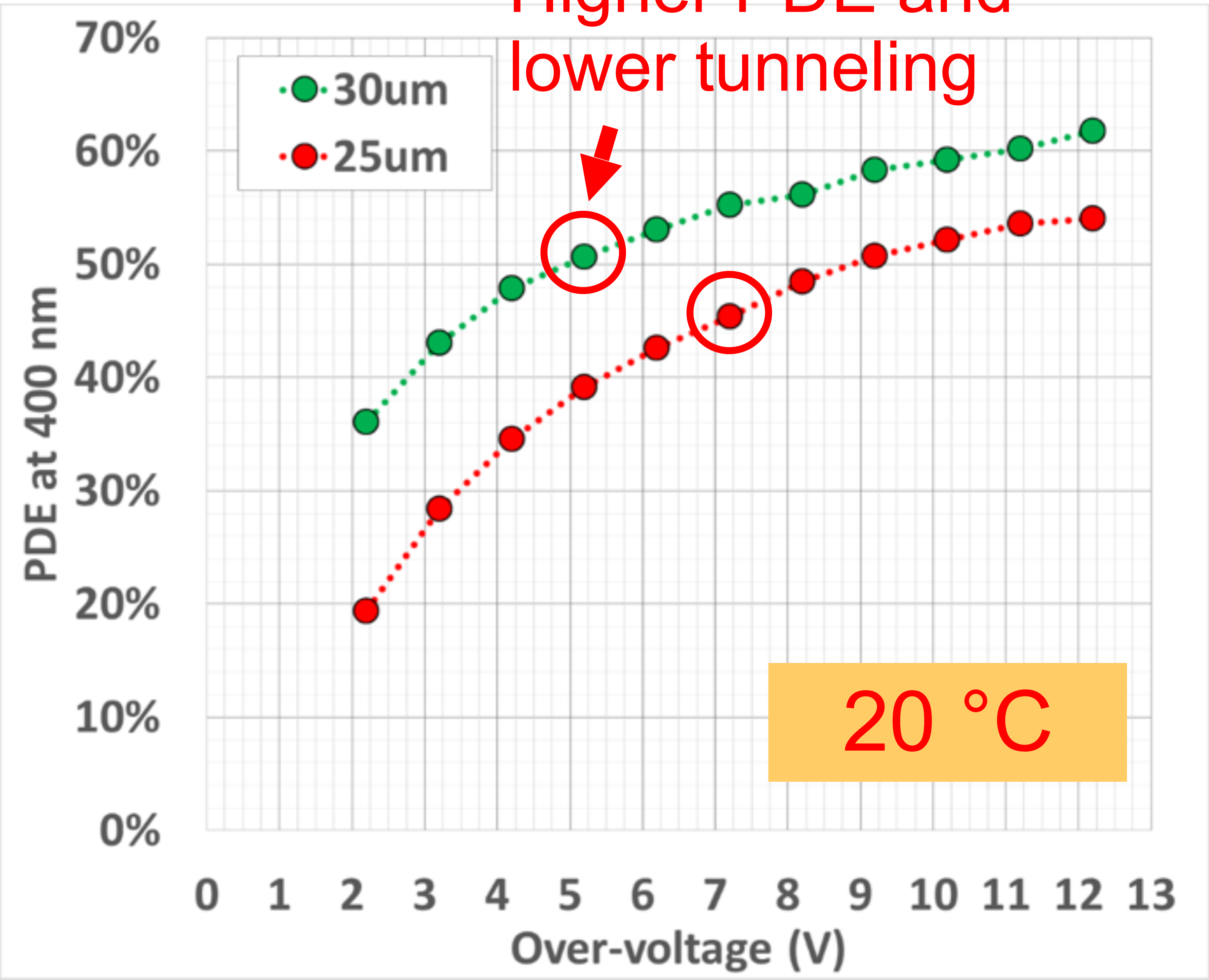
Low-field

PDE @ 400 nm – NUV-HD Low field

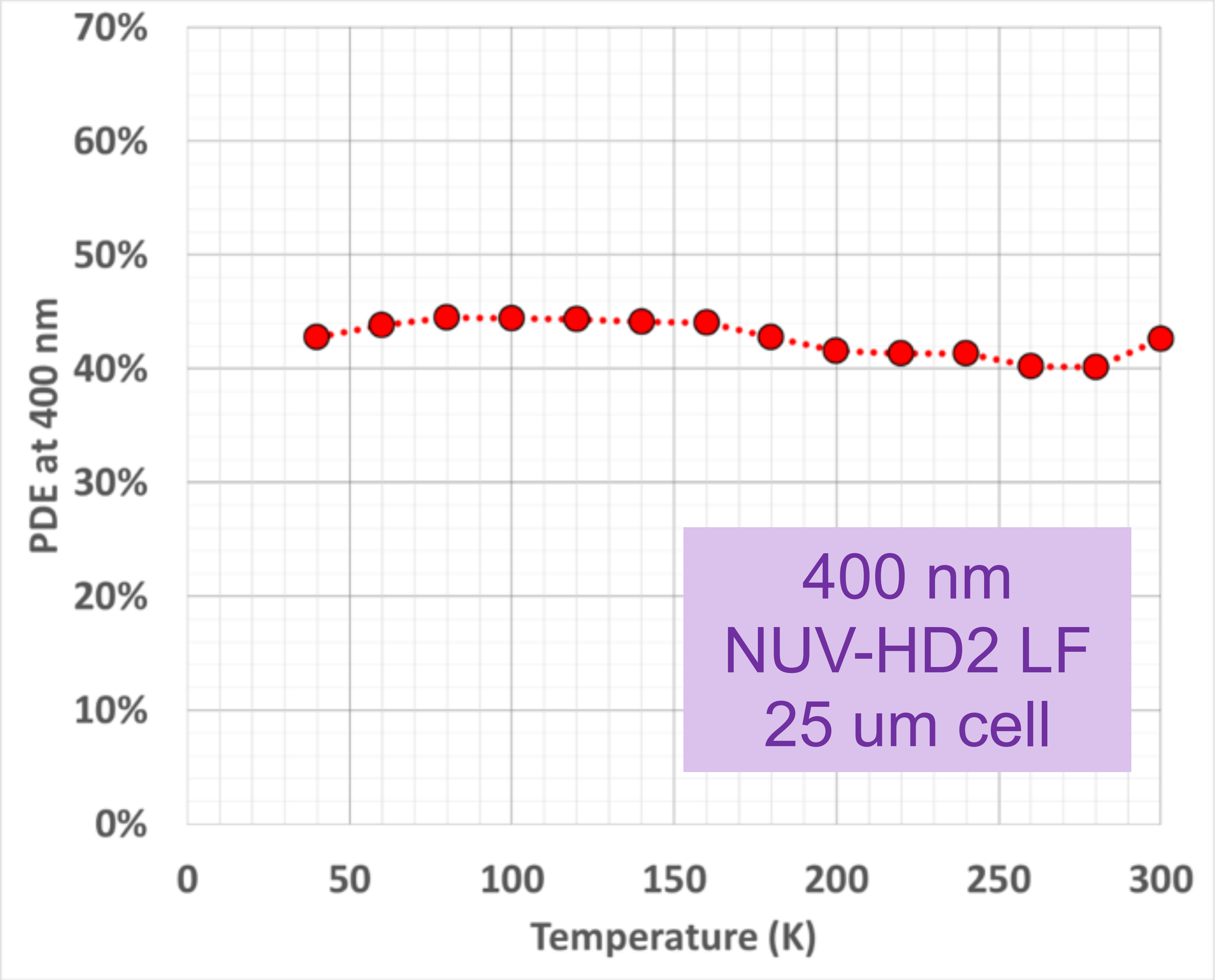
We used a pulsed, low-level light source and the p(0) method to calculate the PDE.

TPB emission between 400 and 450 nm

Higher PDE and lower tunneling

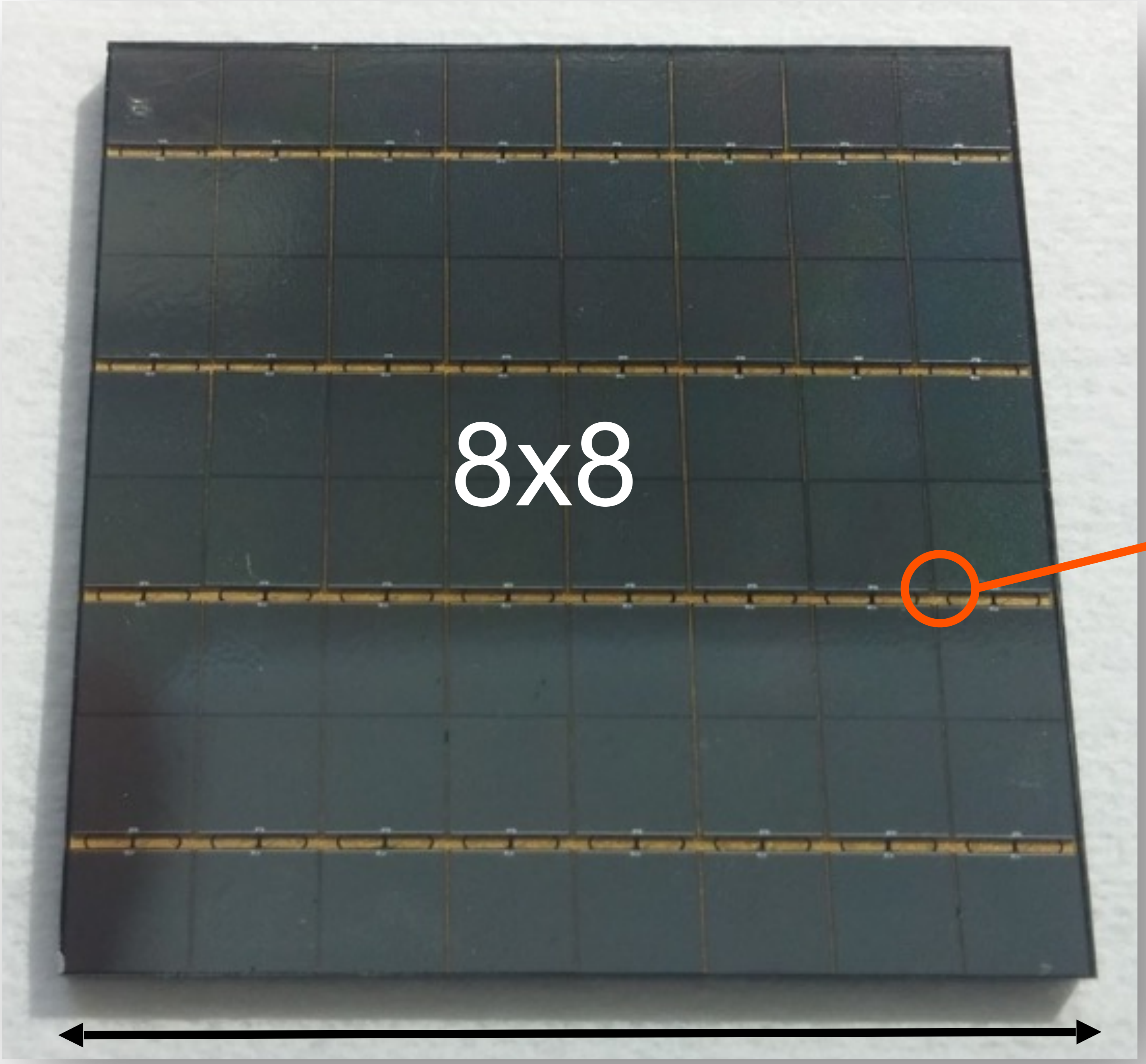


PDE for different NUV-HD LF cell sizes.

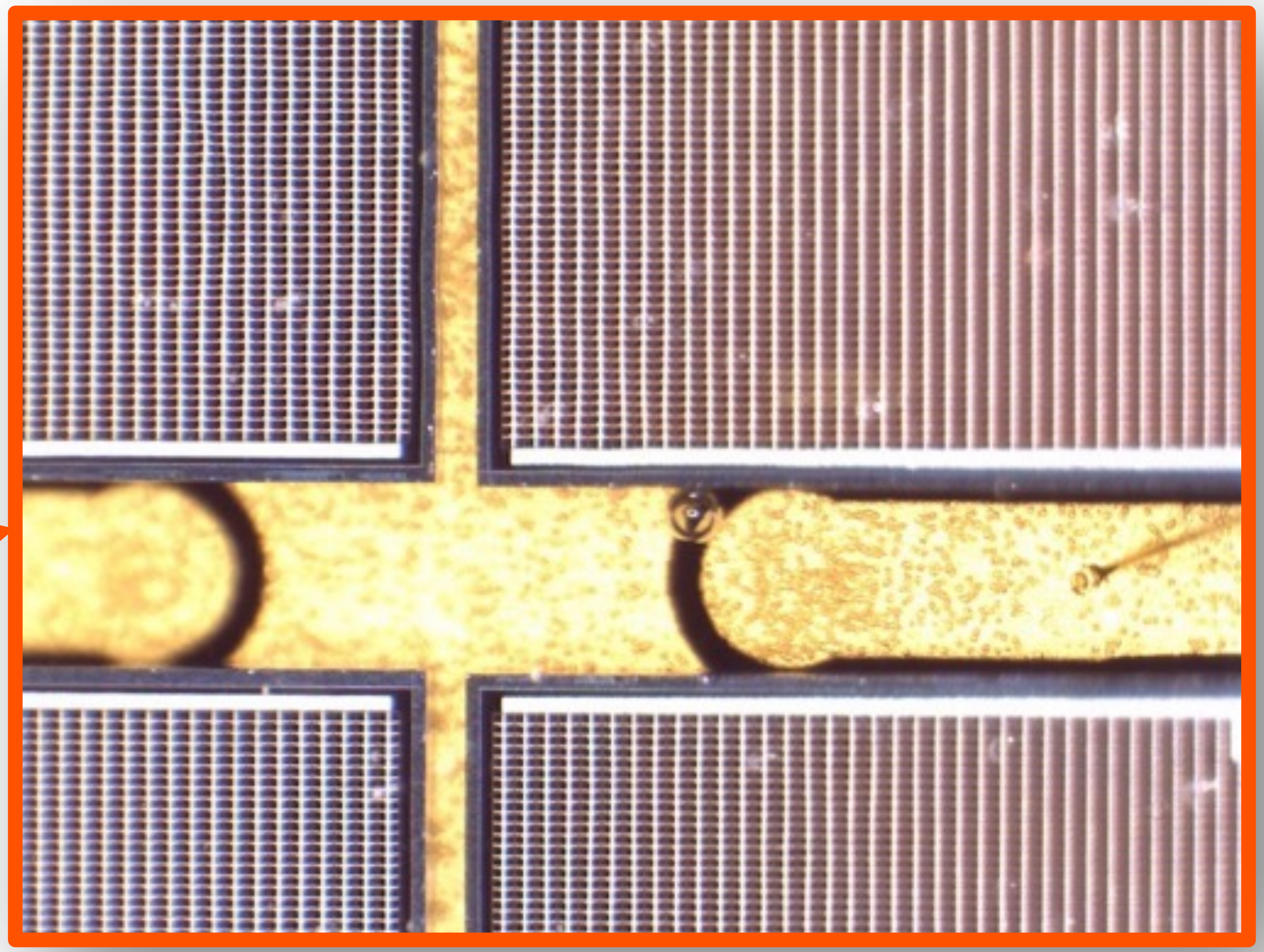


PDE variations with temperature

Tile concepts (1)

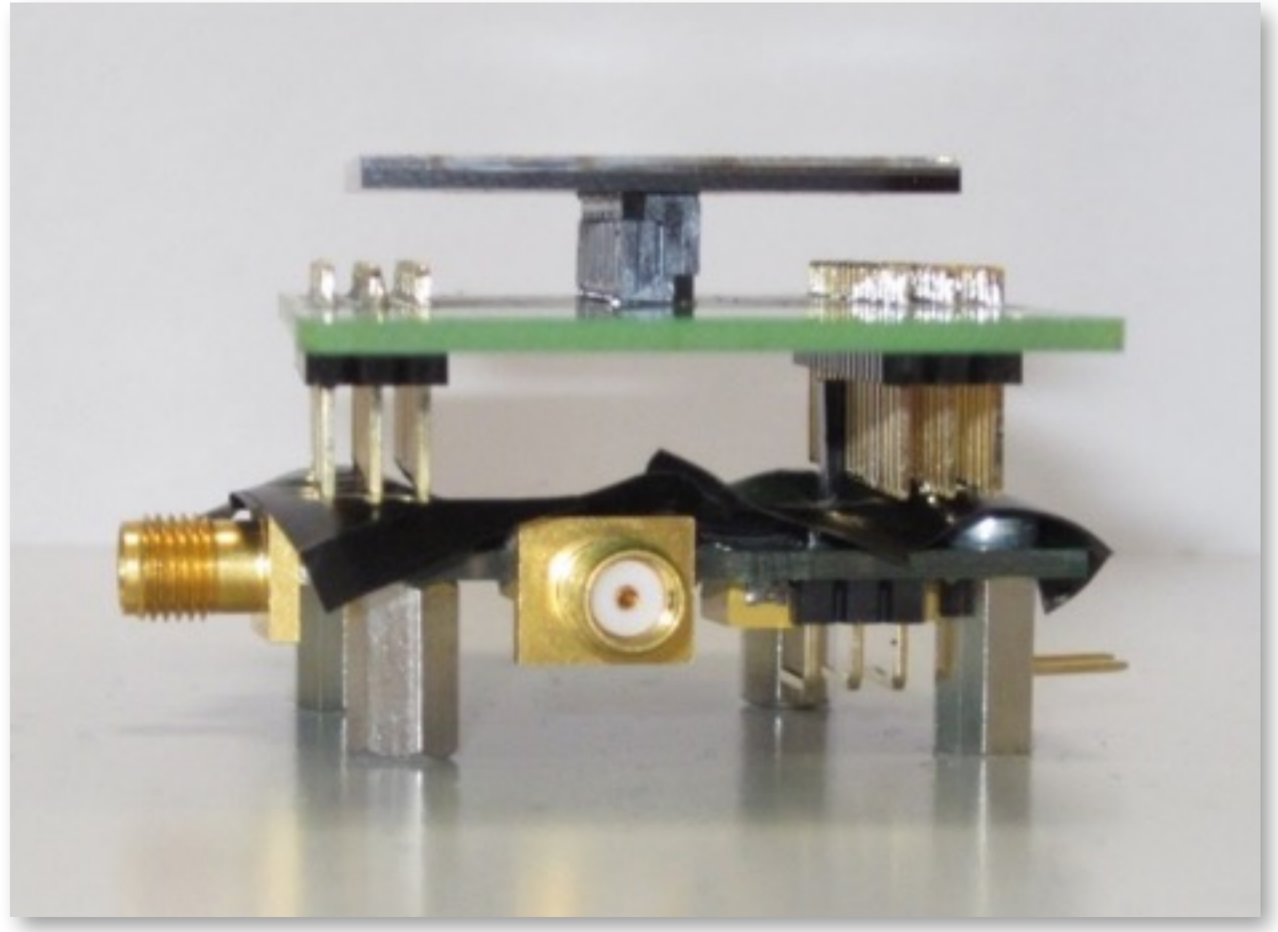


3.23 cm

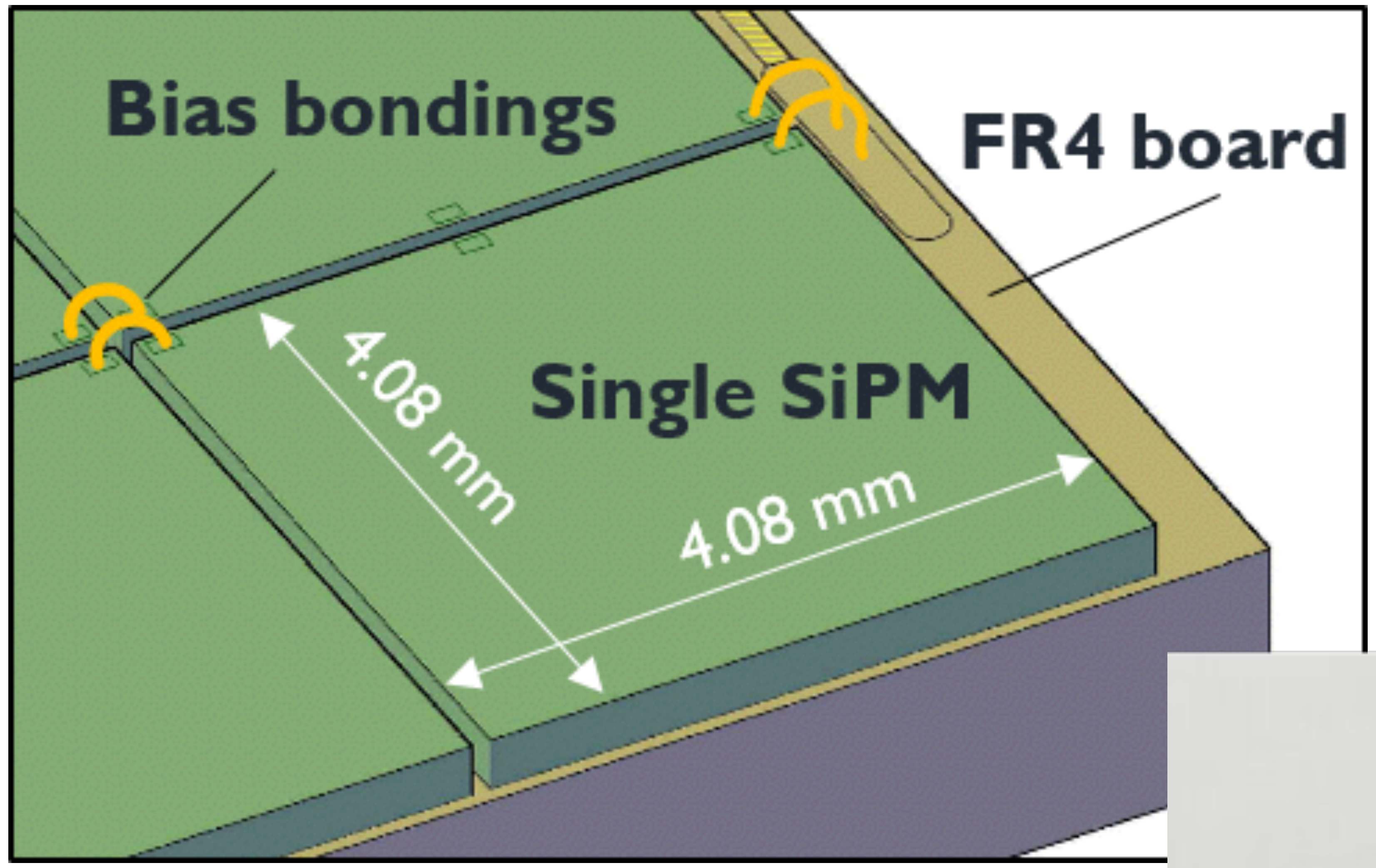


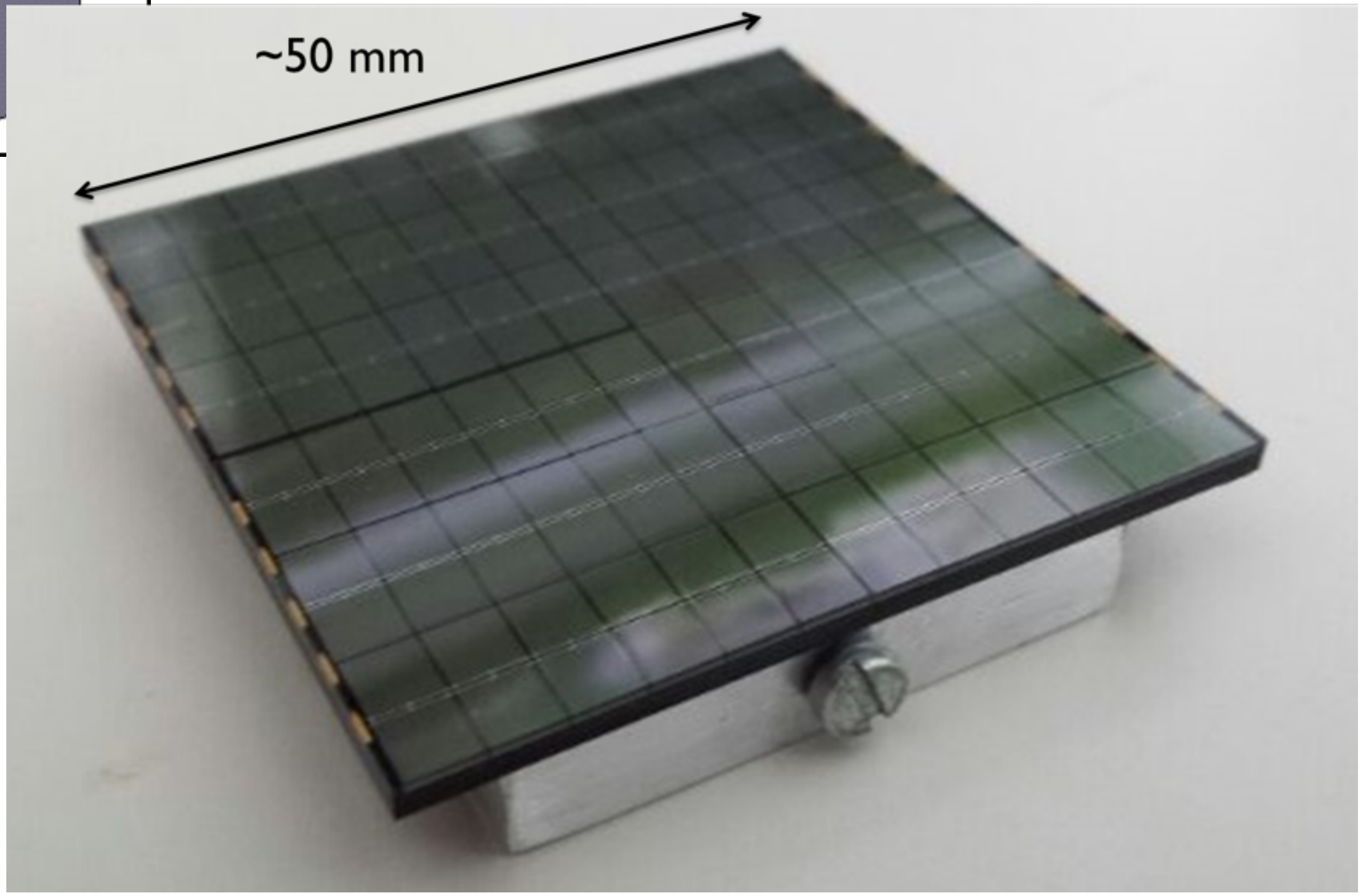
~ 200µm active-to-active distance

- 4mm pitch in x and y
- **85% (packaging) fill factor**



Tile concepts (2)

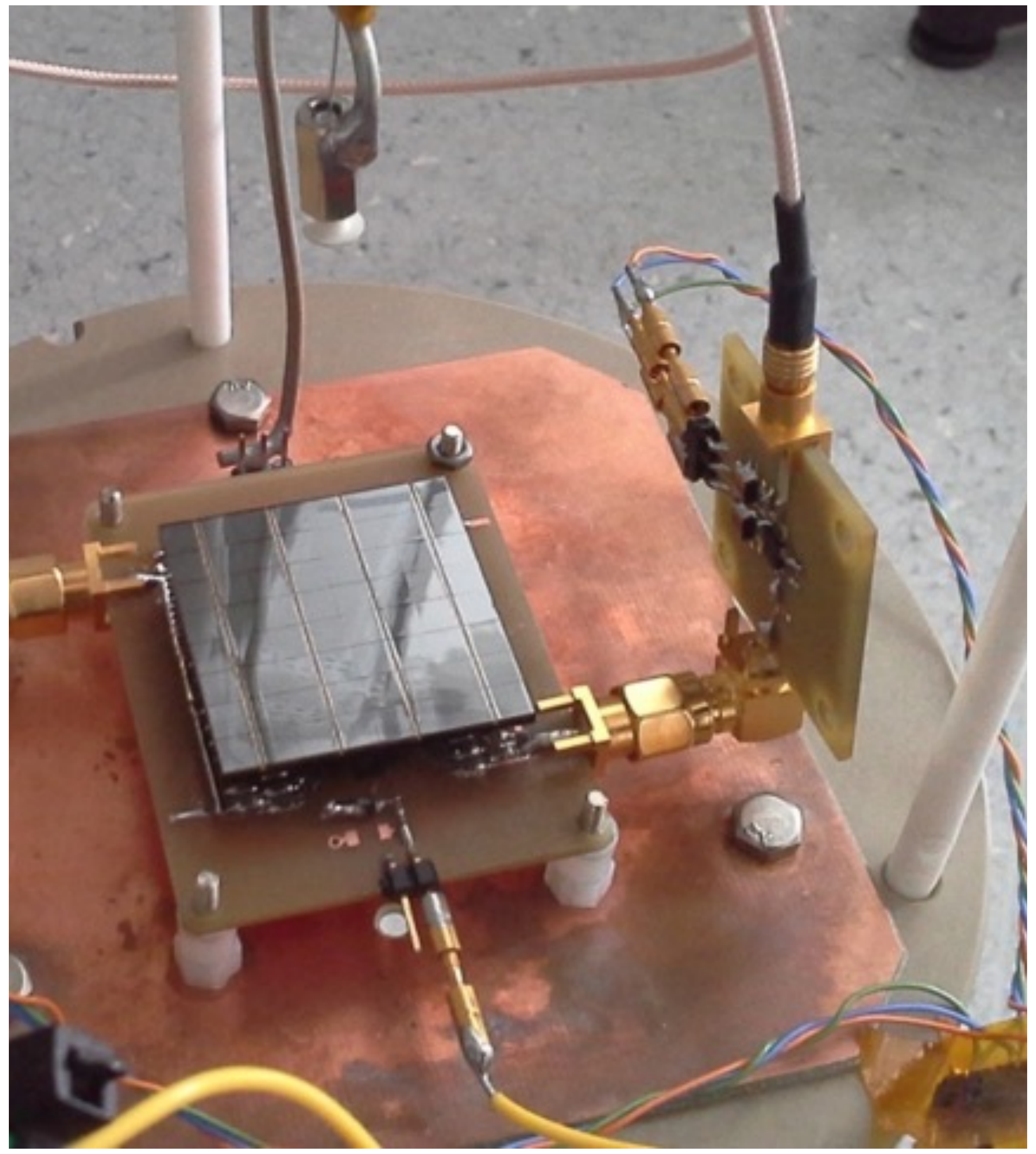


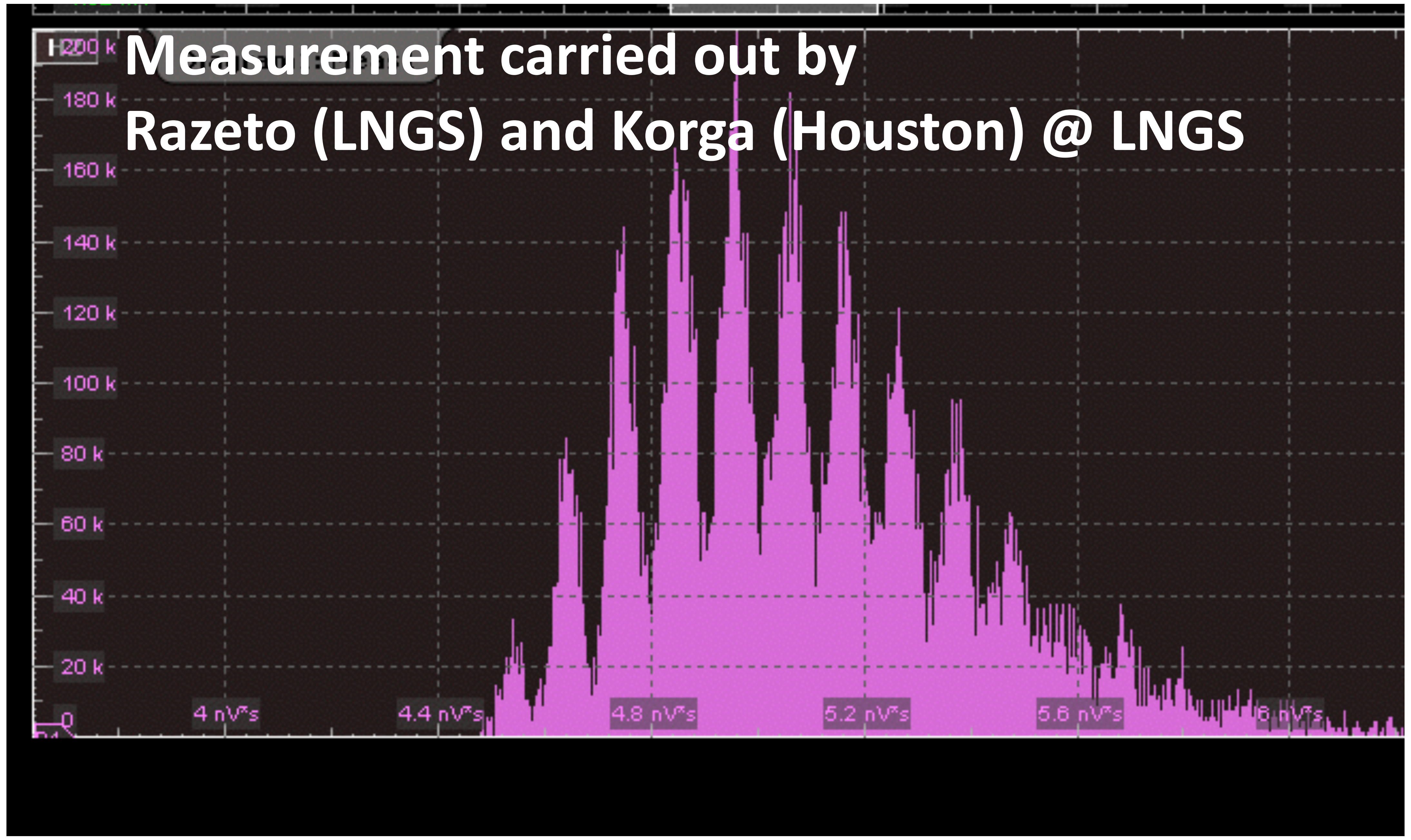


- Fill factor: 89%

First Test on 10cm^2 tile at 80K

All channels connected together on one front-end.
Tile illuminated with laser. Integration time = 6us.





Single-photon spectrum visible!!

- low noise
- very uniform behavior of the SiPMs!!

The End