Direct Detection with Argon

Presentation at UCLA DM 2023

Cristiano Galbiati | Princeton University and Gran Sasso Science Institute | March 29, 2023

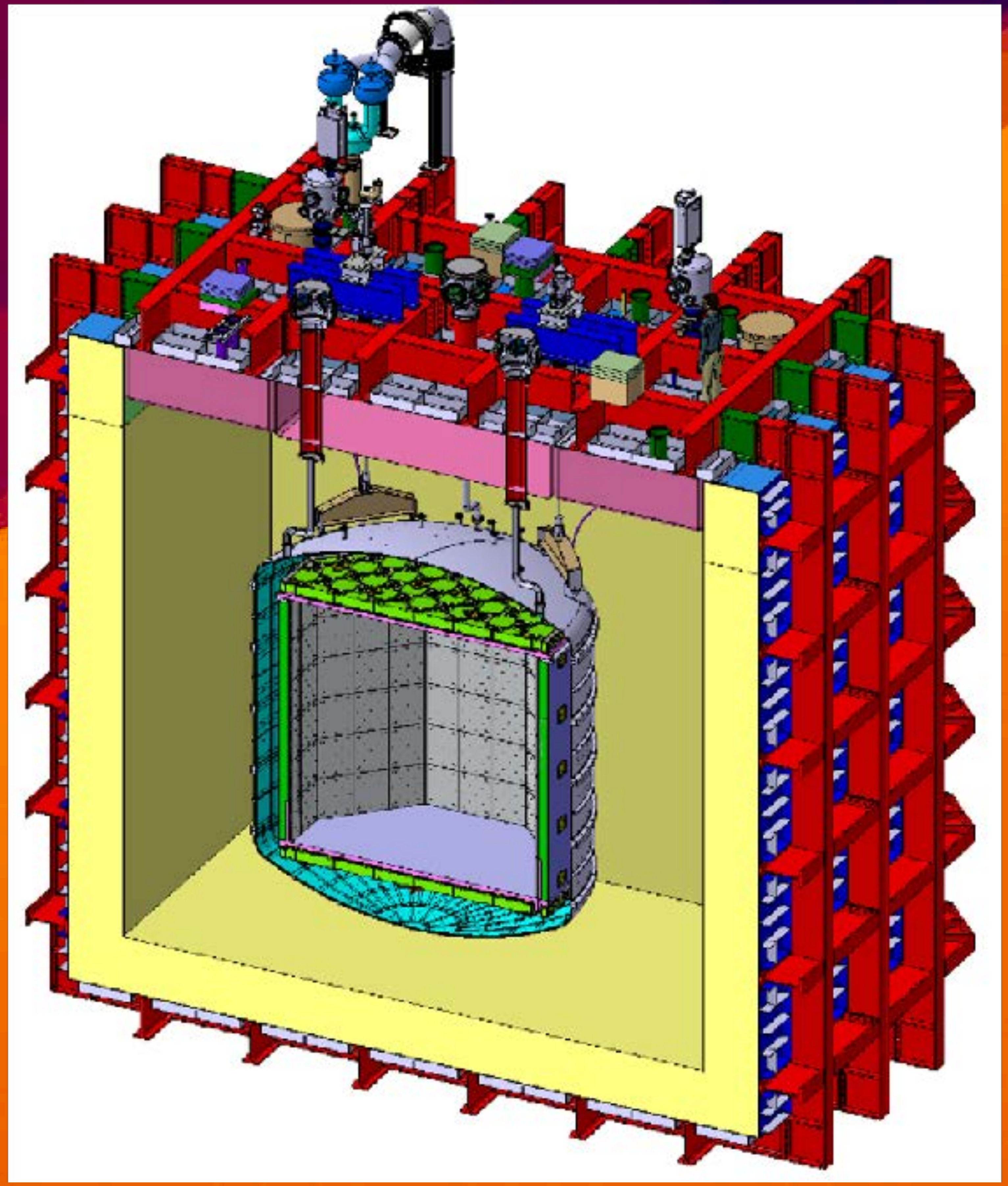
Since 2017

The Global Argon Dark Matter Collaboration (GADMC)

GADMC unified in a single Collaboration more than 400 scientists interested in DM searches with argon to explore heavy (and light) dark matter to the neutrino floor and beyond

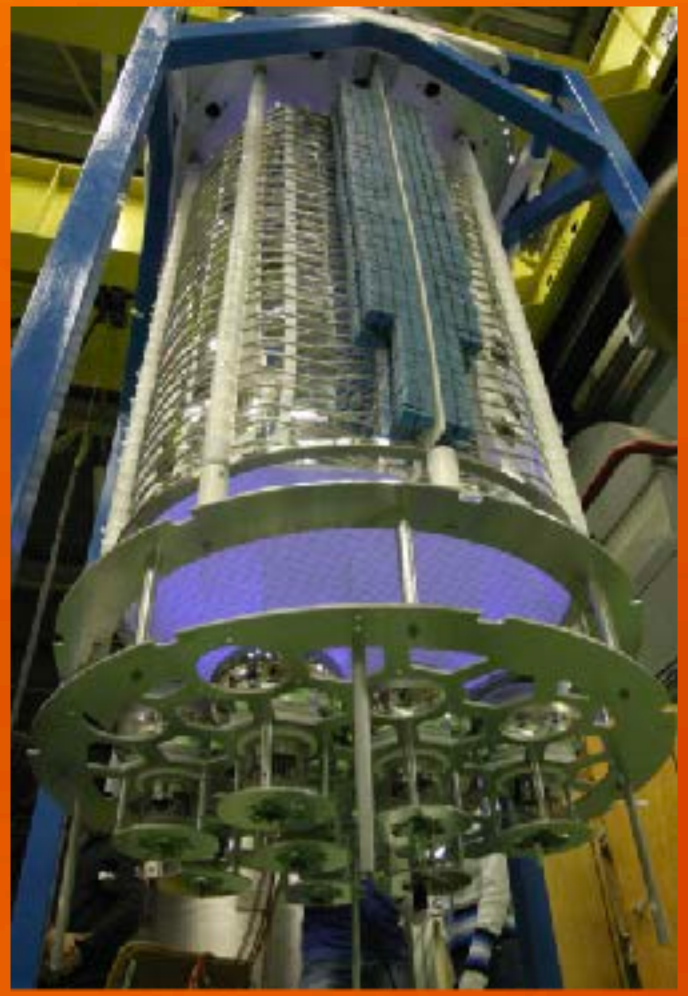
DEAP-3600

DarkSide-50



MiniCLEAN

ARDM



Other GADMC Talks at This Conference

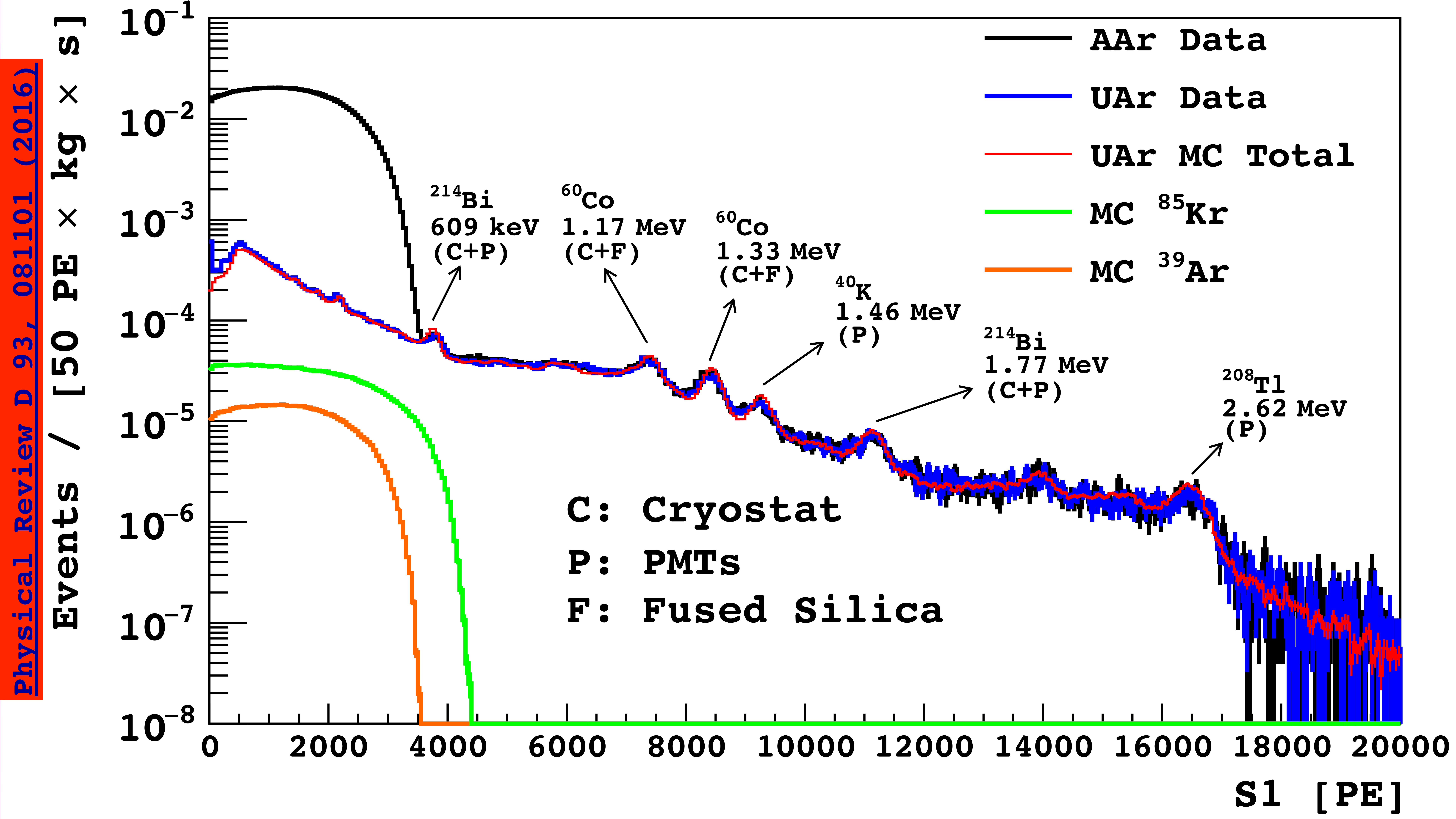
Thomas Thorpe, Mar 31 at 8:00 AM:
DarkSide-20k: The Next Stage in the Direct Dark Matter Search Using Liquid Argon

Michela Lai, Mar 31 at 8:30 AM:
Dark matter search in DEAP-3600: results and prospects

Andrea Capra, Mar 31 at 3:45 PM:
From Photoelectrons to Bytes in DarkSide-20k

Federico Gabriele, Mar 31 at 6:00 PM:
The innovative Underground Argon Project: the path from procurement to purification for search of Dark Matter

Roberto Tartaglia, Apr 1 at 8:00 AM:
The NOA Facility @ LNGS



Physical Review D 93, 081101 (2016)
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

European Physics Journal C 81, 823 (2021)

8–10 orders of magnitude suppression of ER backgrounds

no deviation from statistical expectations

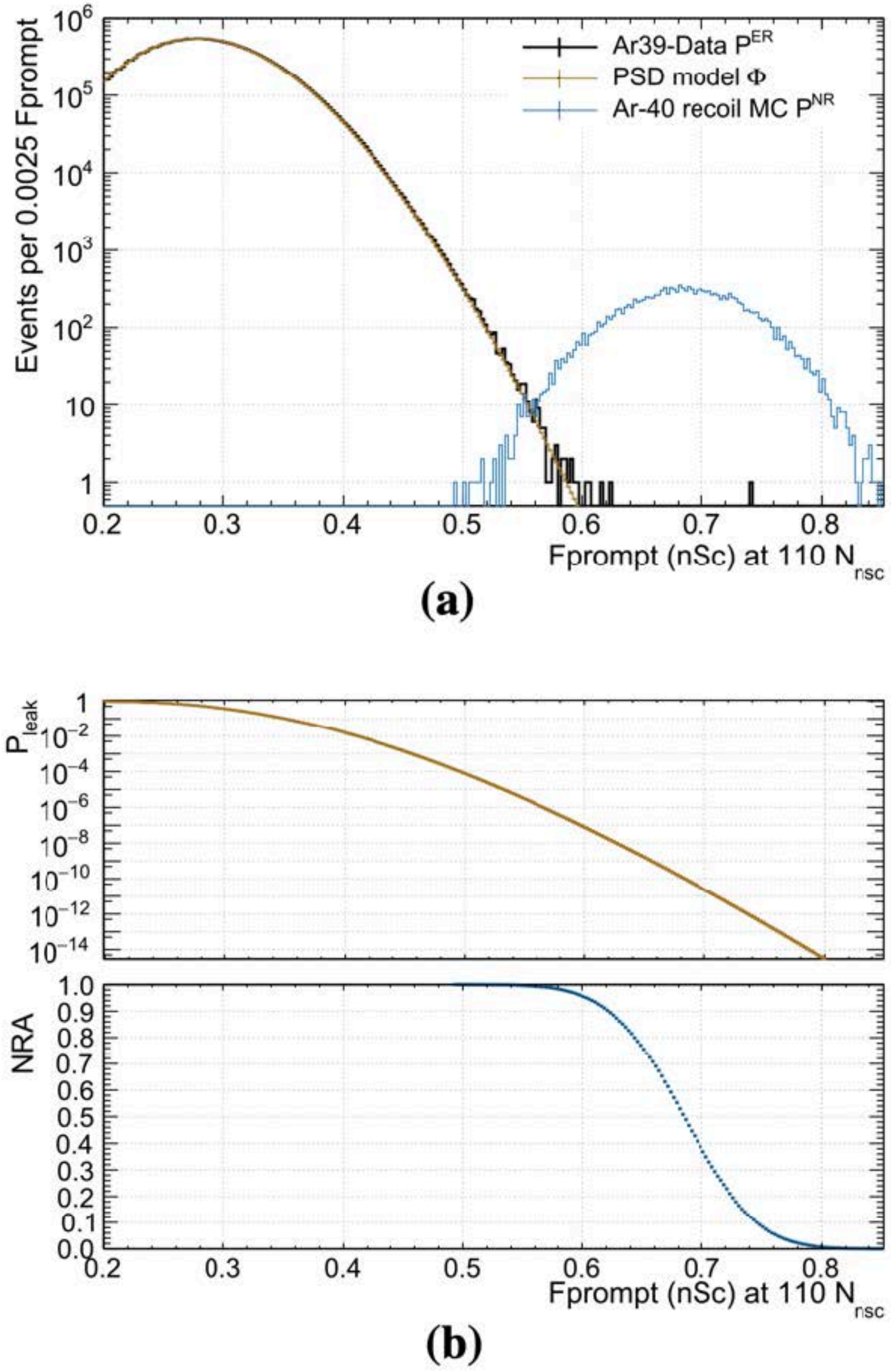
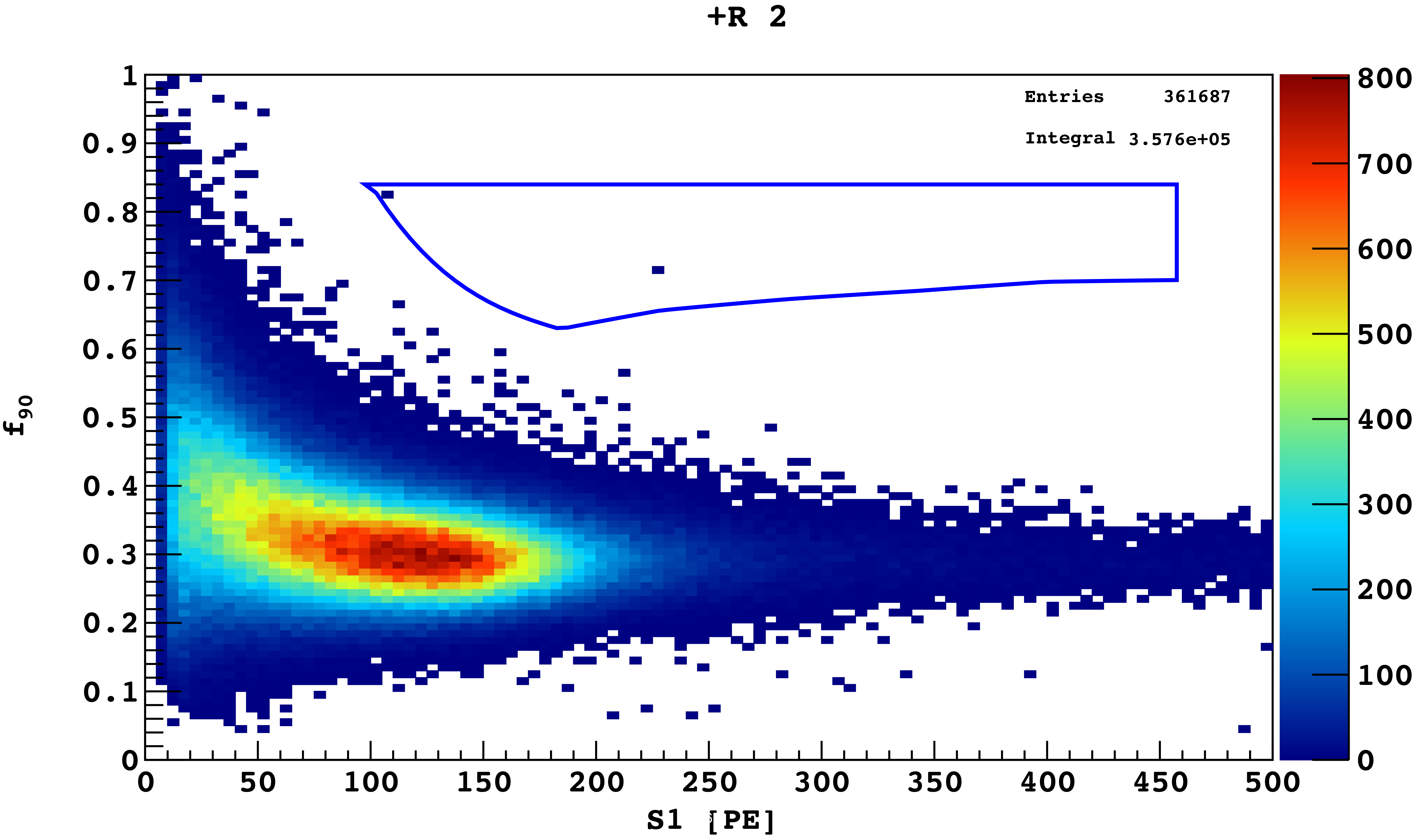


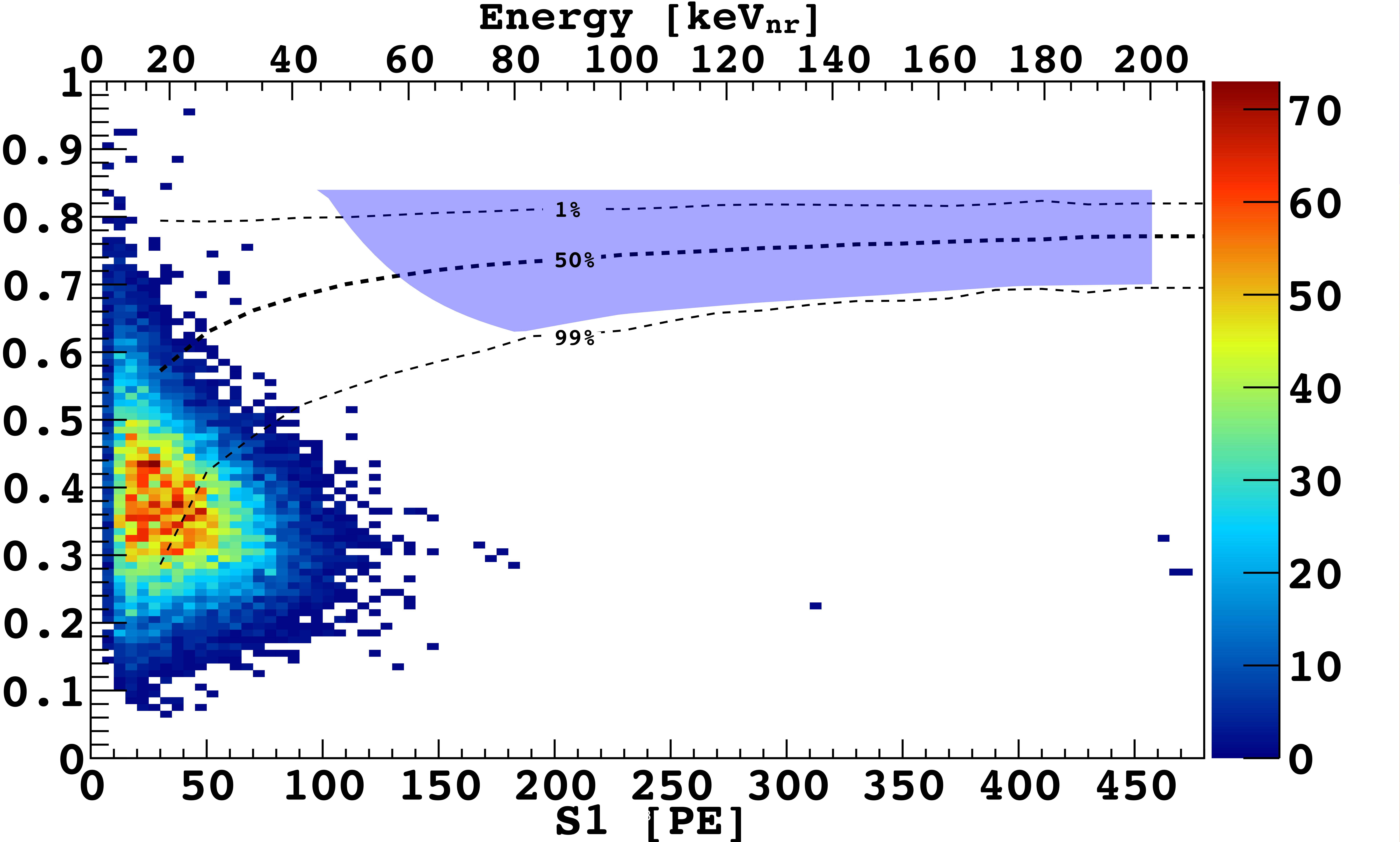
Fig. 4 **a** The $F_{\mathrm{prompt}}^{\mathrm{nsc}}$ distributions at 110 N_{nsc} are shown for ^{39}Ar β events (background), together with the model fit, and for simulated ^{40}Ar recoil events (signal). **b** The background leakage probability (based on the fit model to ^{39}Ar data) and signal acceptance (based on signal MC) as a function of the PSD parameter is shown

both DEAP-3600 and DarkSide-50 have rejected more MIP's than we will encounter in DarkSide-20k



Physical Review D 98, 102006 (2018)

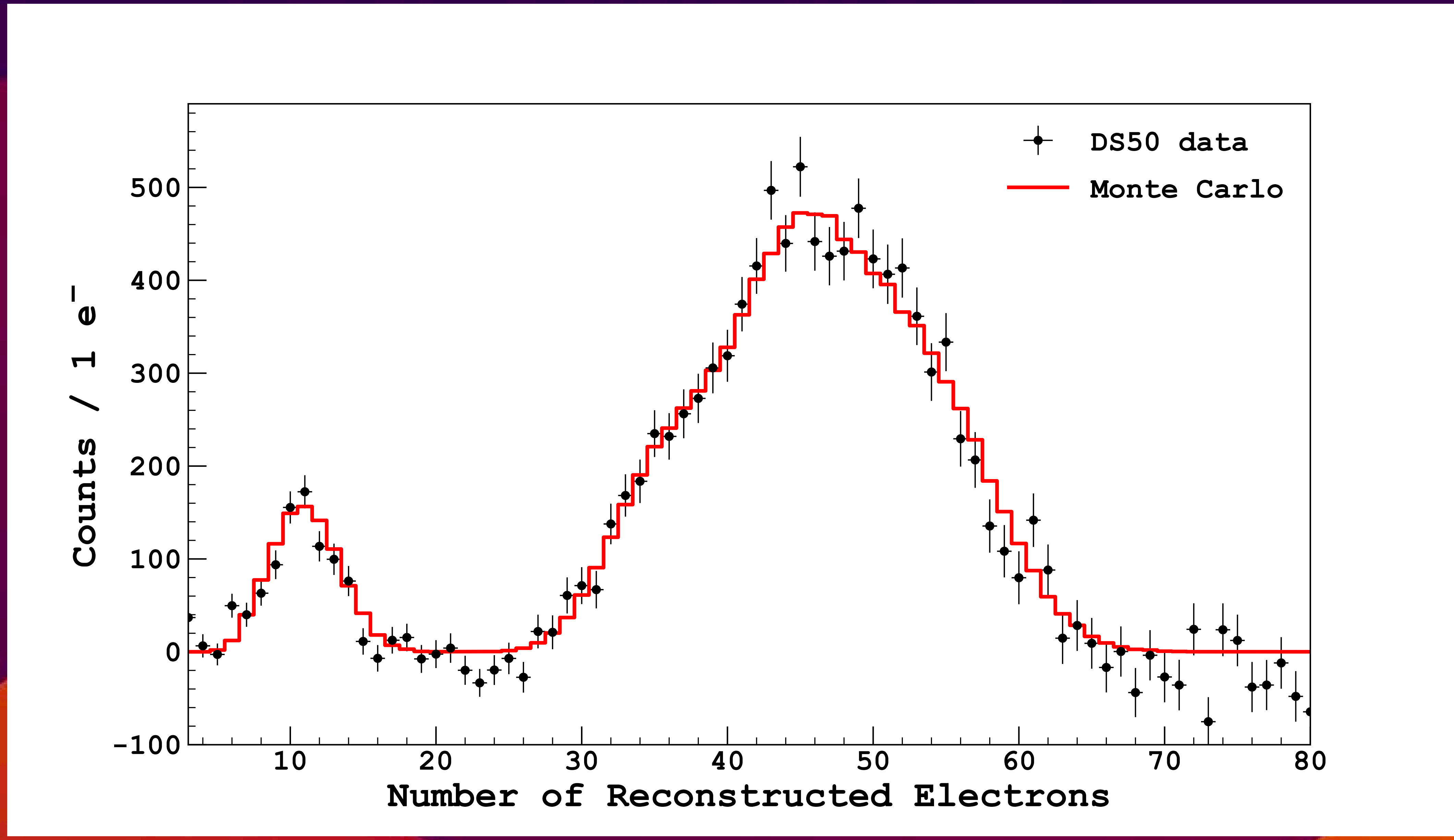
Energy [keVnr]
0 20 40 60 80 100 120 140 160 180 200
1 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0
f90
1%
50%
99%
500 400 300 200 100 0
0 50 100 150 200 250 300 350 400 450
S1 [PE]
Physical Review D 98, 102006 (2018)

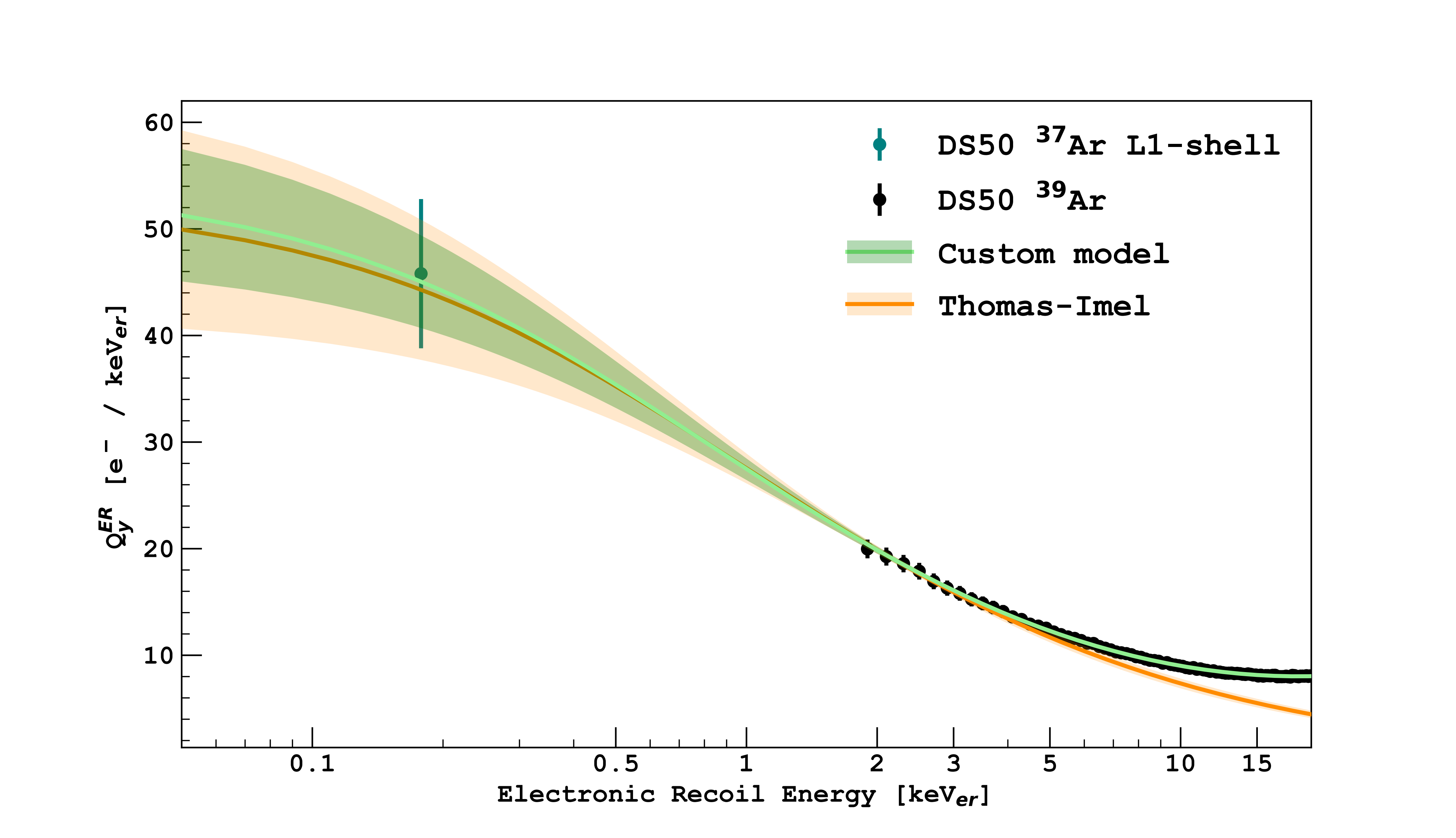


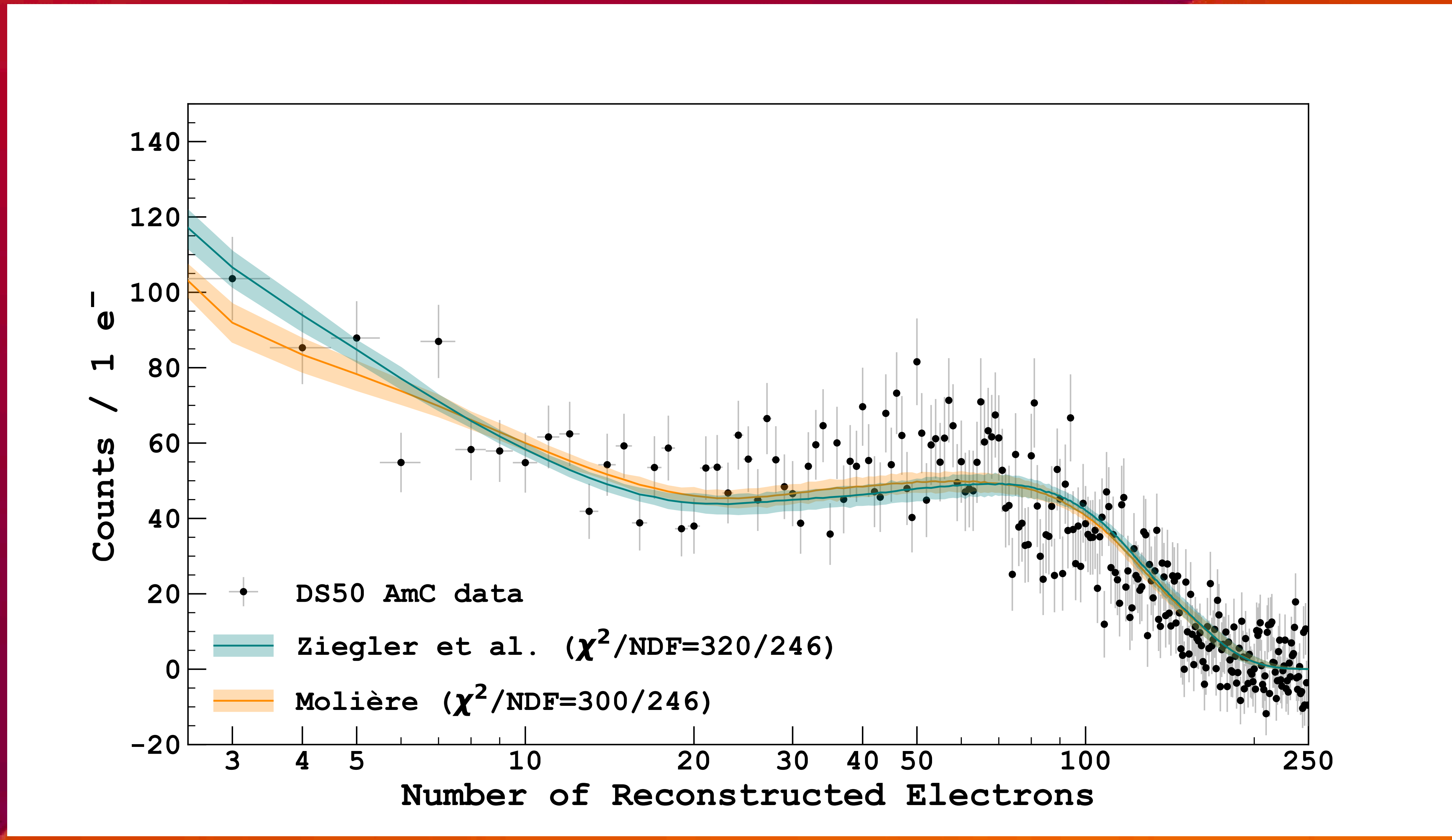
Energy [keV$_{nr}$]
0
20
40
60
80
100
120
140
160
180
200
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
f_{90}
1%
50%
99%
70
60
50
40
30
20
10
0
0
50
100
150
200
250
300
350
400
450
S1 [PE]

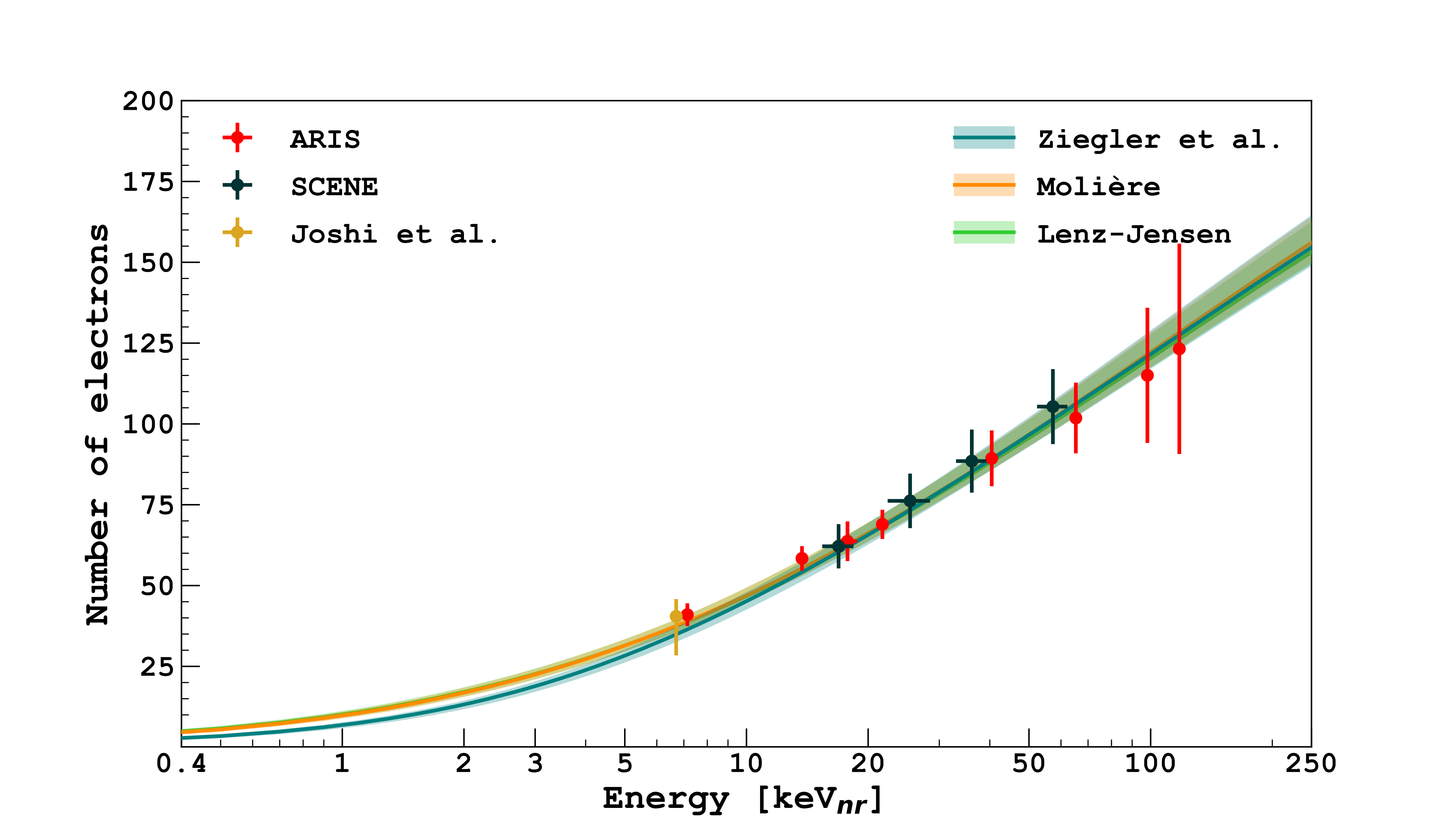
Energy [keVnr]
0
20
40
60
80
100
120
140
160
180
200
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1%
50%
99%
This is what a WIMP signal
would have looked like!
0
50
100
150
200
250
300
350
400
450
S1 [PE]
70
60
50
40
30
20
10
0
Physical Review D 98, 102006 (2018)

Physical Review D 104, 082005 (2021)

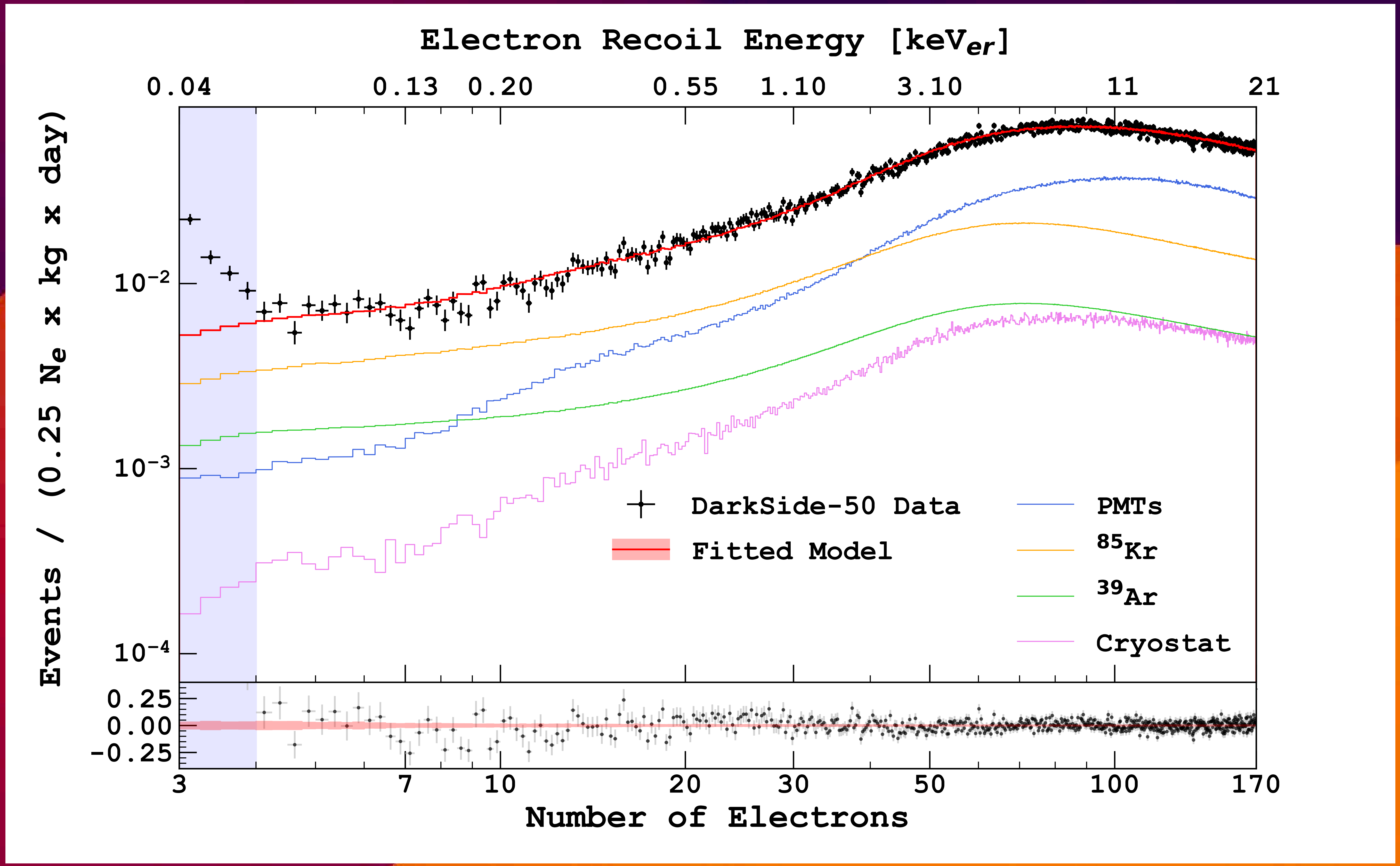


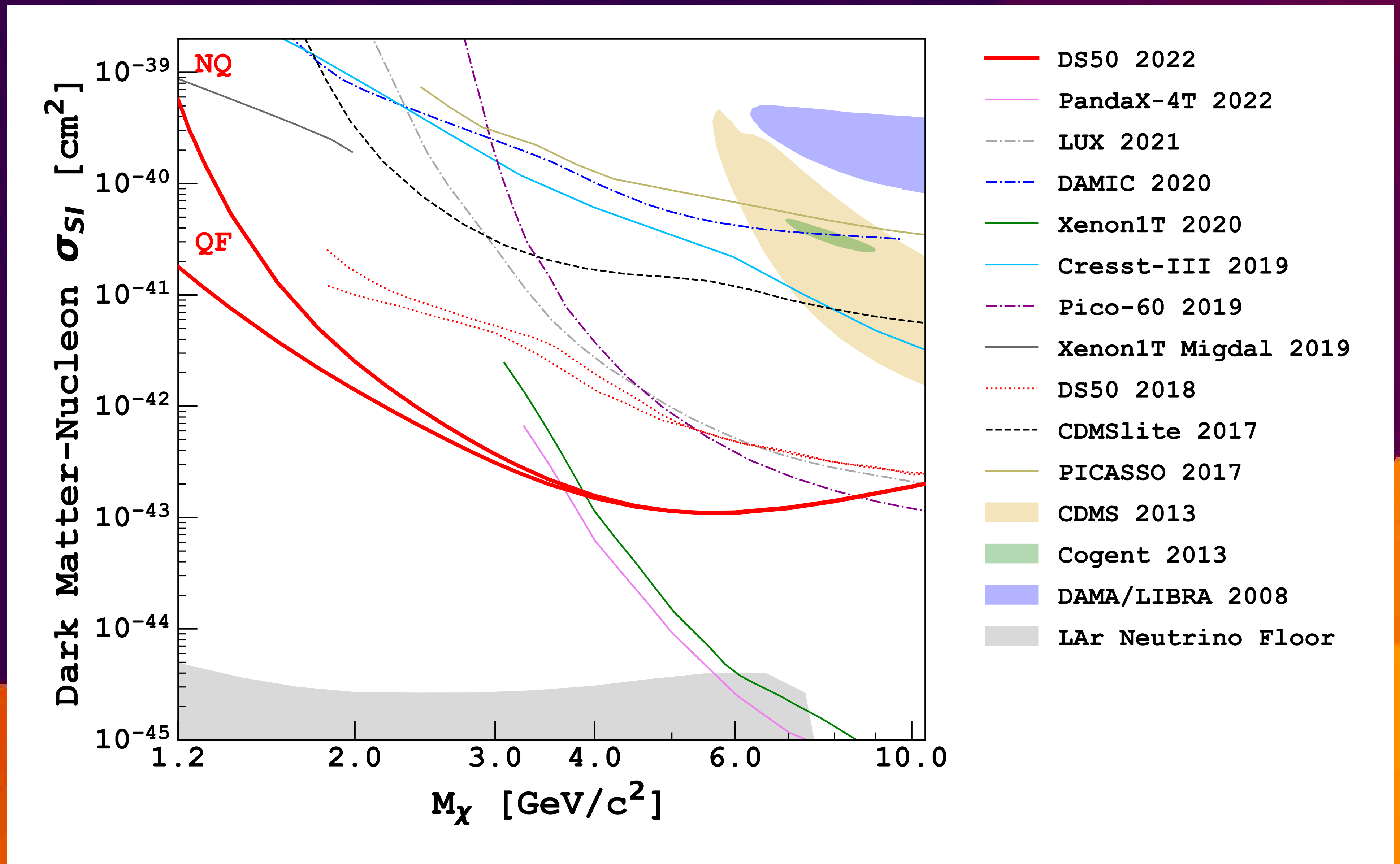


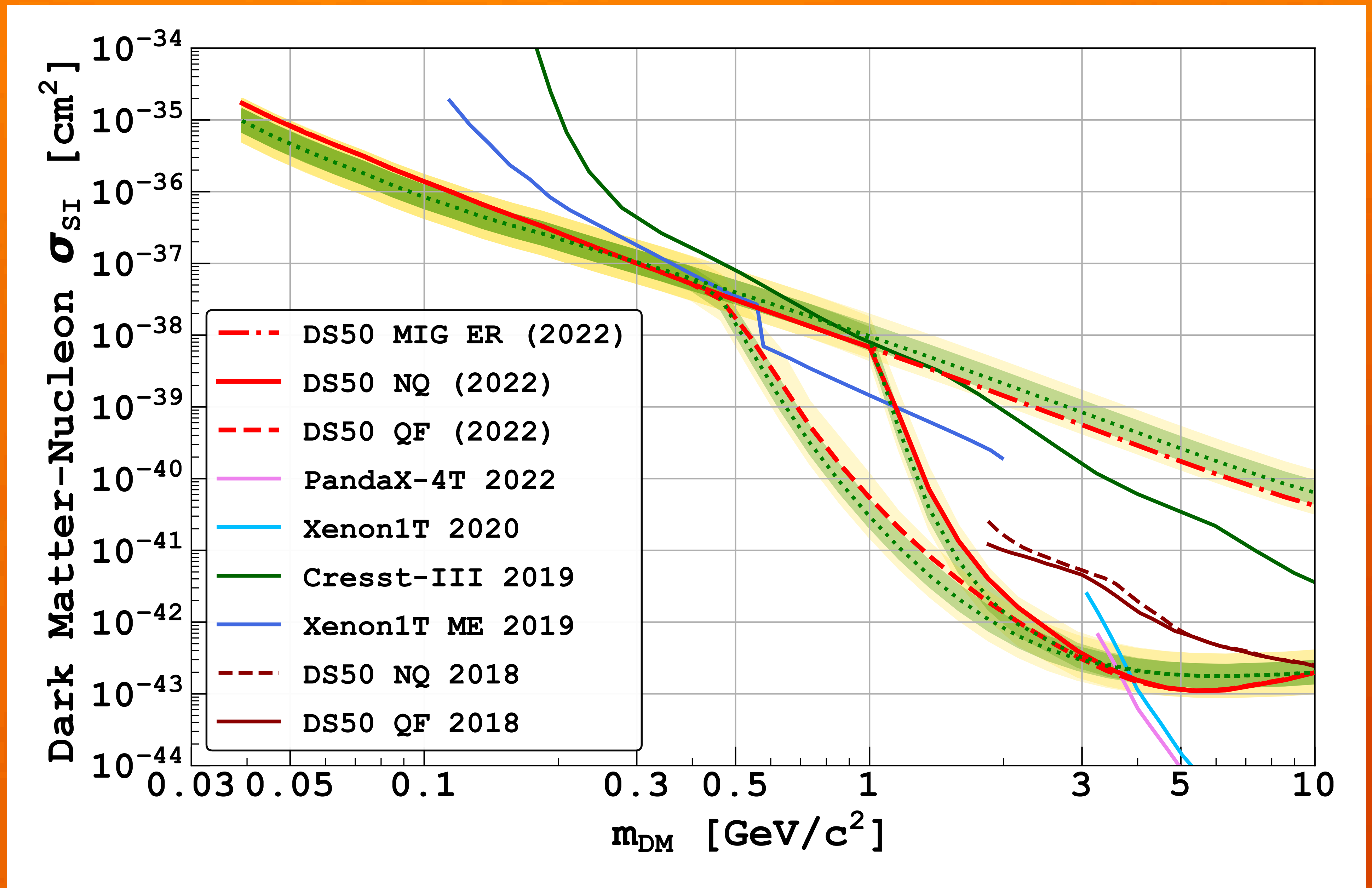




Physical Review D 107, 063001 (2023)

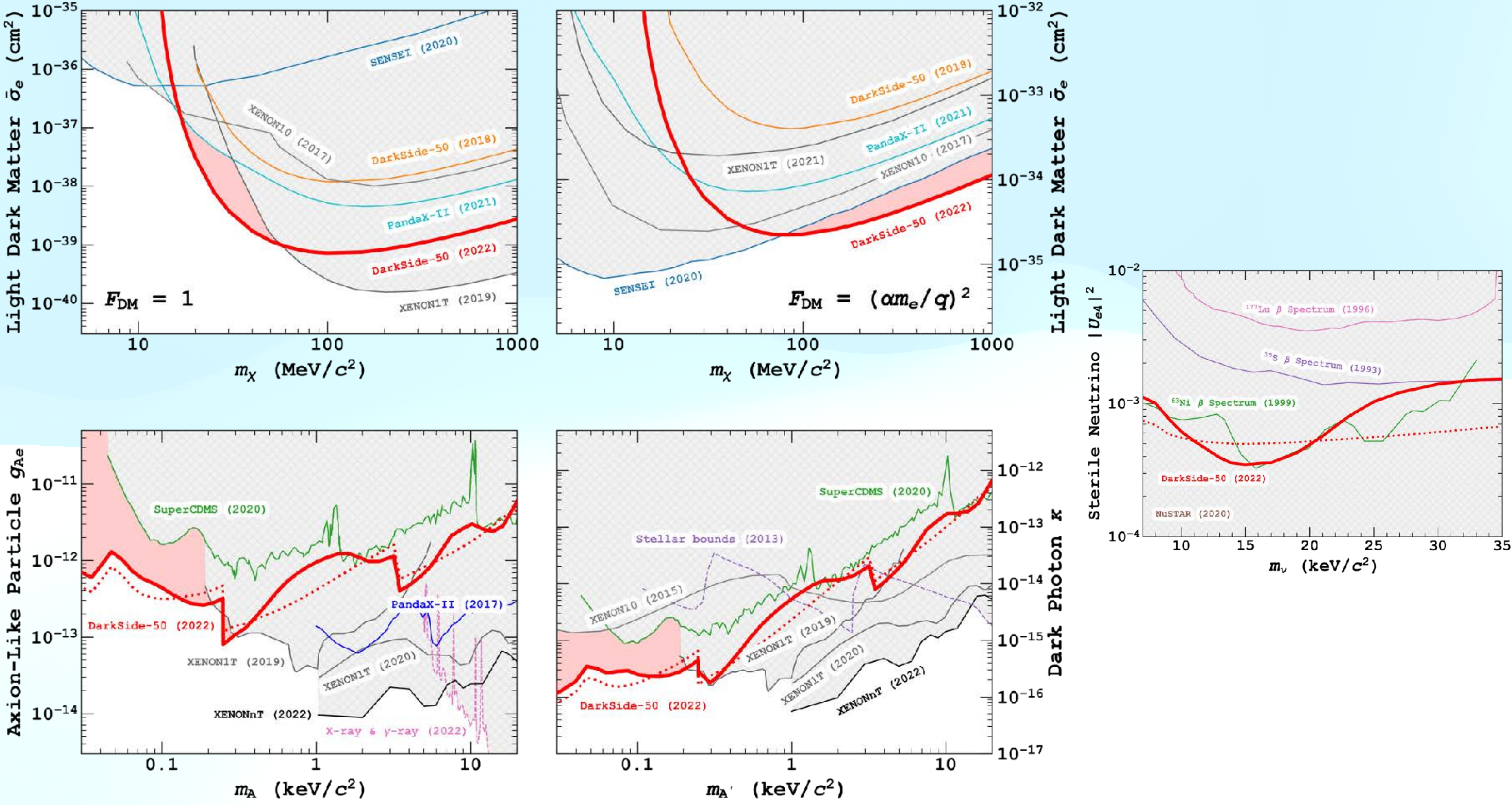






Physical Review Letters 130, 101001 (2023)

Physical Review Letters 130, 101002 (2023)



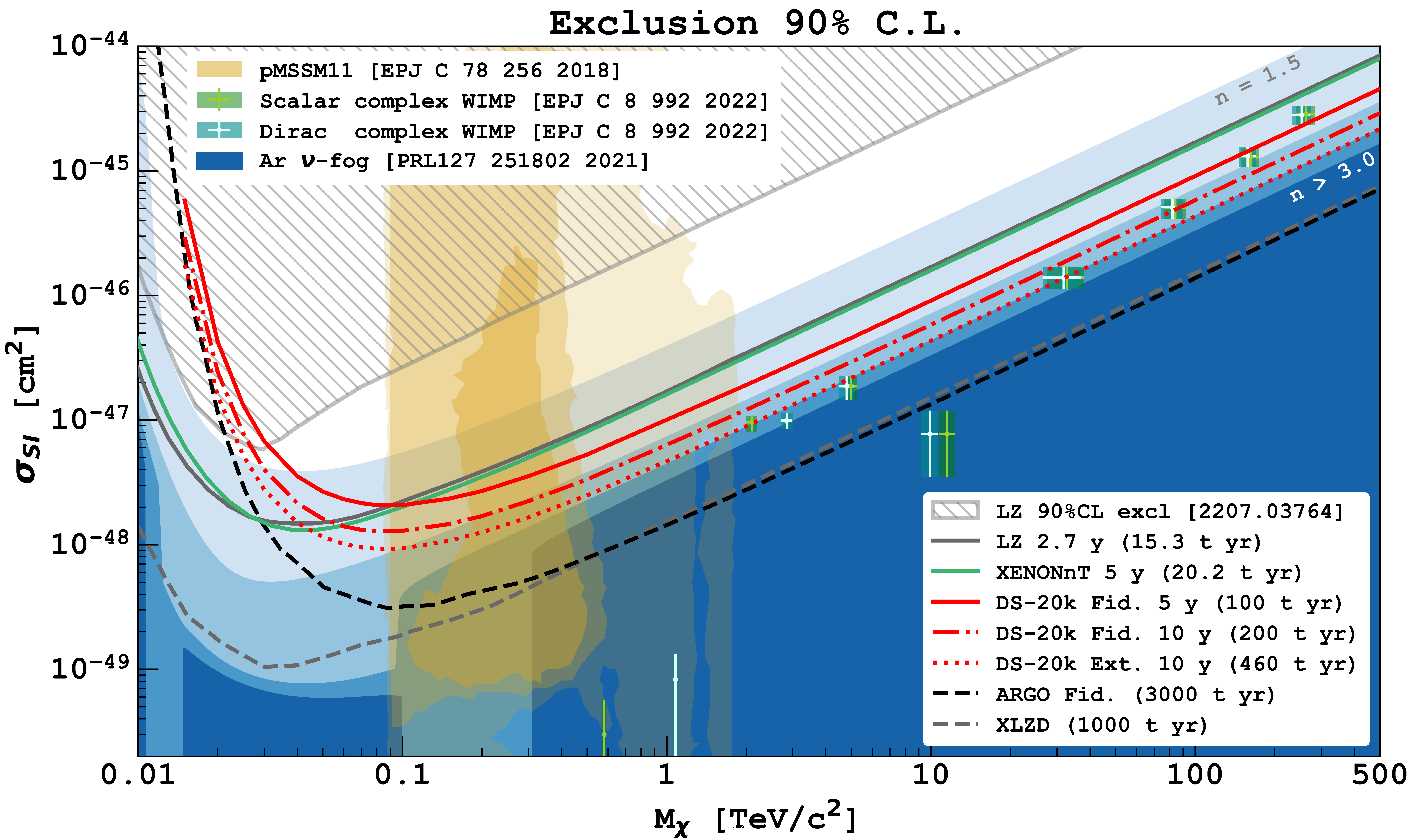
ArDM
DarkSide-50
DEAP
MiniCLEAN

The Global Argon Dark Matter Collaboration

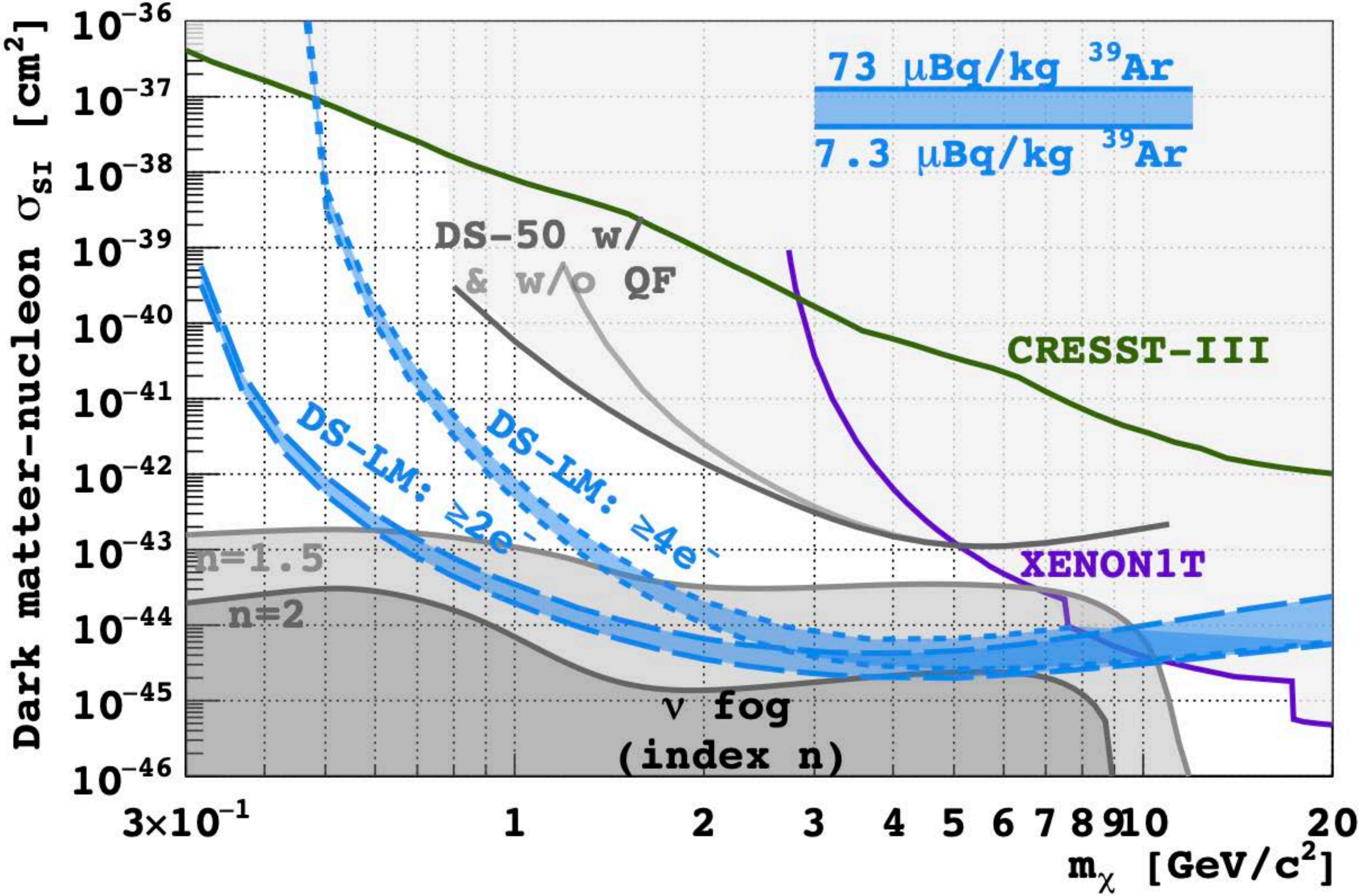
DS-20k [20 t]

Argo [300 t]

DS-LM [1 t]



Exclusion 90% C.L.
pMSSM11 [EPJ C 78 256 2018]
Scalar complex WIMP [EPJ C 8 992 2022]
Dirac complex WIMP [EPJ C 8 992 2022]
Ar ν-fog [PRL127 251802 2021]
n = 1.5
n > 3.0
LZ 90%CL excl [2207.03764]
LZ 2.7 y (15.3 t yr)
XENONnT 5 y (20.2 t yr)
DS-20k Fid. 5 y (100 t yr)
DS-20k Fid. 10 y (200 t yr)
DS-20k Ext. 10 y (460 t yr)
ARGO Fid. (3000 t yr)
XLZD (1000 t yr)
σSI [cm2]
Mχ [TeV/c2]
10−44
10−45
10−46
10−47
10−48
10−49
0.01
0.1
1
10
100
500



73 μBq/kg 39Ar
7.3 μBq/kg 39Ar
DS-50 w/
& w/o QF
CRESST-III
DS-LM: ≥2e⁻
DS-LM: ≥4e⁻
XENON1T
n=1.5
n=2
ν fog
(index n)
Dark matter-nucleon σSI [cm2]
mχ [GeV/c2]
10−36
10−37
10−38
10−39
10−40
10−41
10−42
10−43
10−44
10−45
10−46
3×10−1
1
2
3
4
5
6
7
8
9
10
20

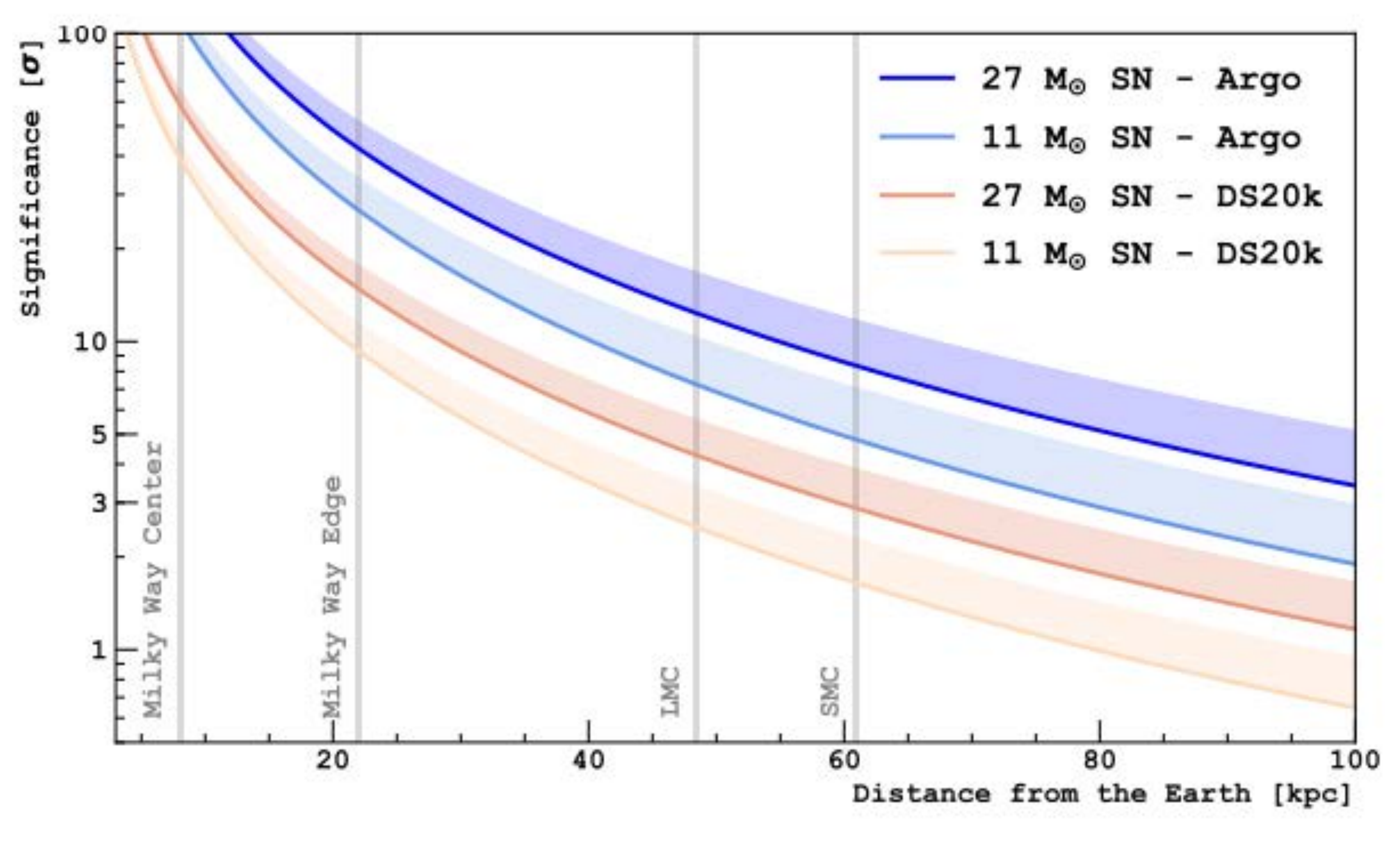
Solar and supernova neutrinos: DS-20k and Argo as neutrino observatories

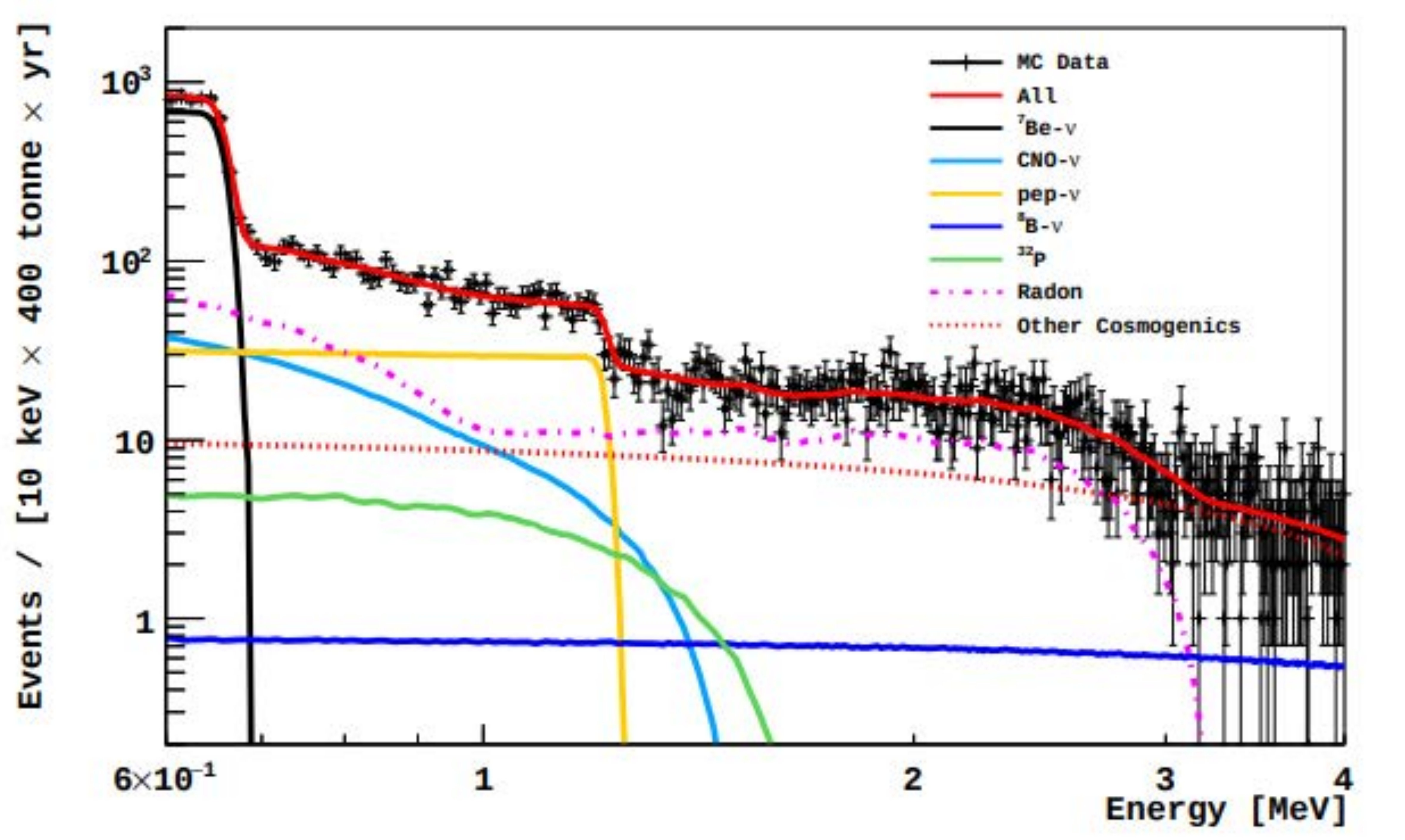
Core-collapse supernova neutrinos

Sensitivity to core-collapse supernova burst neutrinos beyond the Milky Way, with >3σ sensitivity to the neutronization burst

Solar neutrino measurements

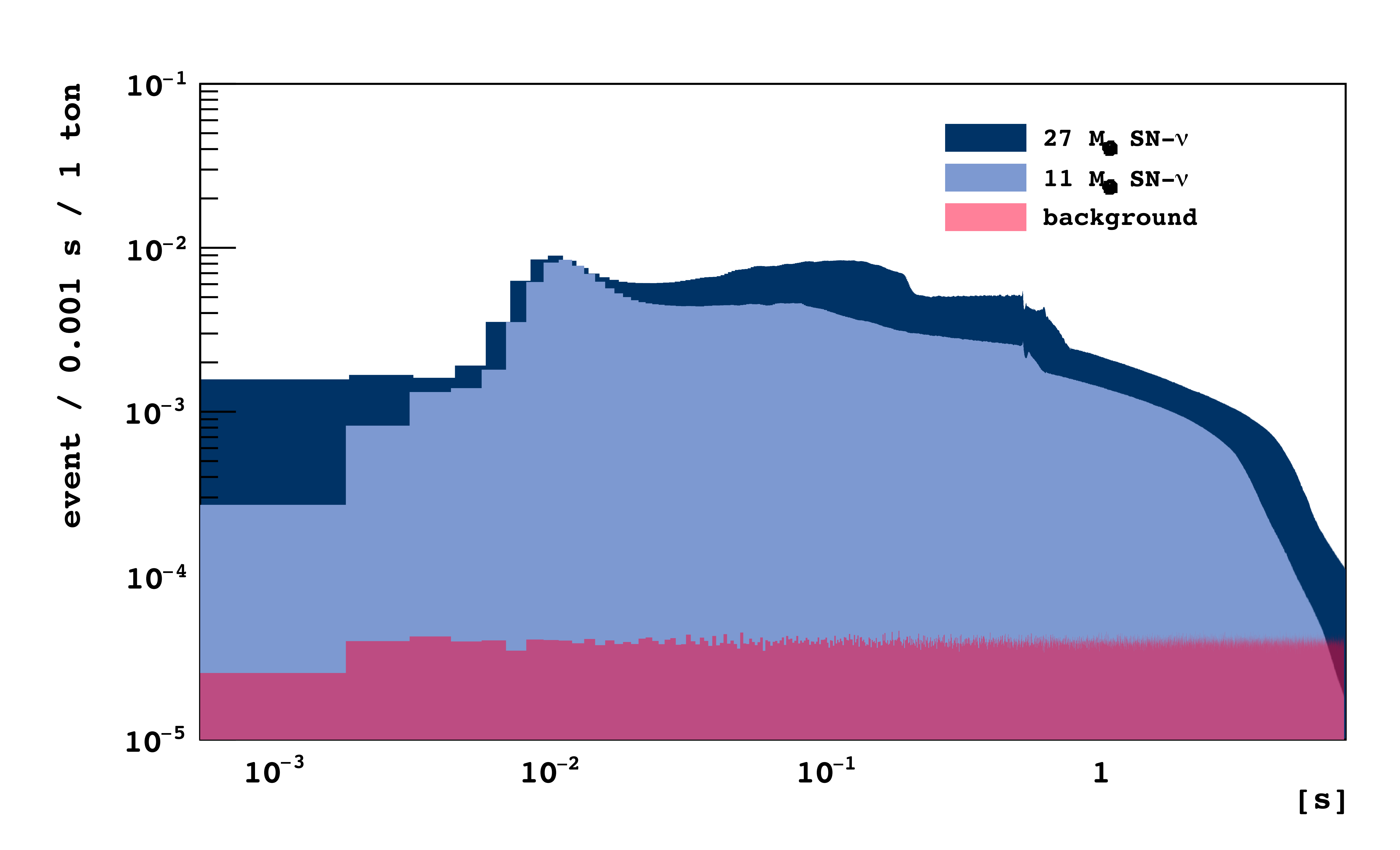
High-precision solar neutrino measurements via electron-scattering and other channels; potential to resolve solar metallicity models

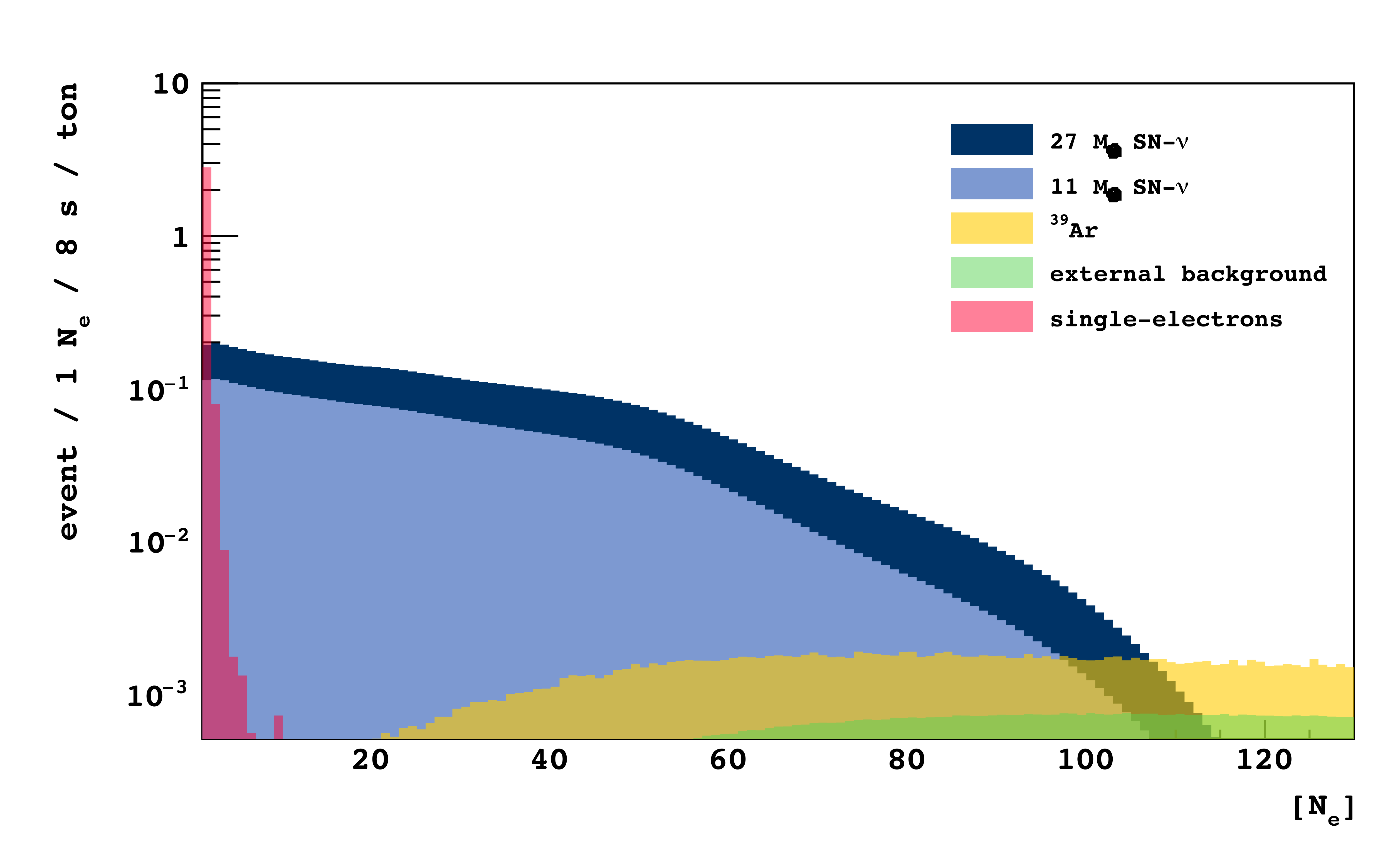




SN Neutrinos via CEvNS S2-only in DS-20k

- 180 (350) neutrino events from 11 (27) $M_\odot$ SNs at 10 kpc against 7 bg events
- Flavour insensitive, measurement of the entire SN-ν flux
- Detection of the neutronization burst, sensitive to neutrino mass ordering
- Measurement of SN mean and integrated neutrino energies





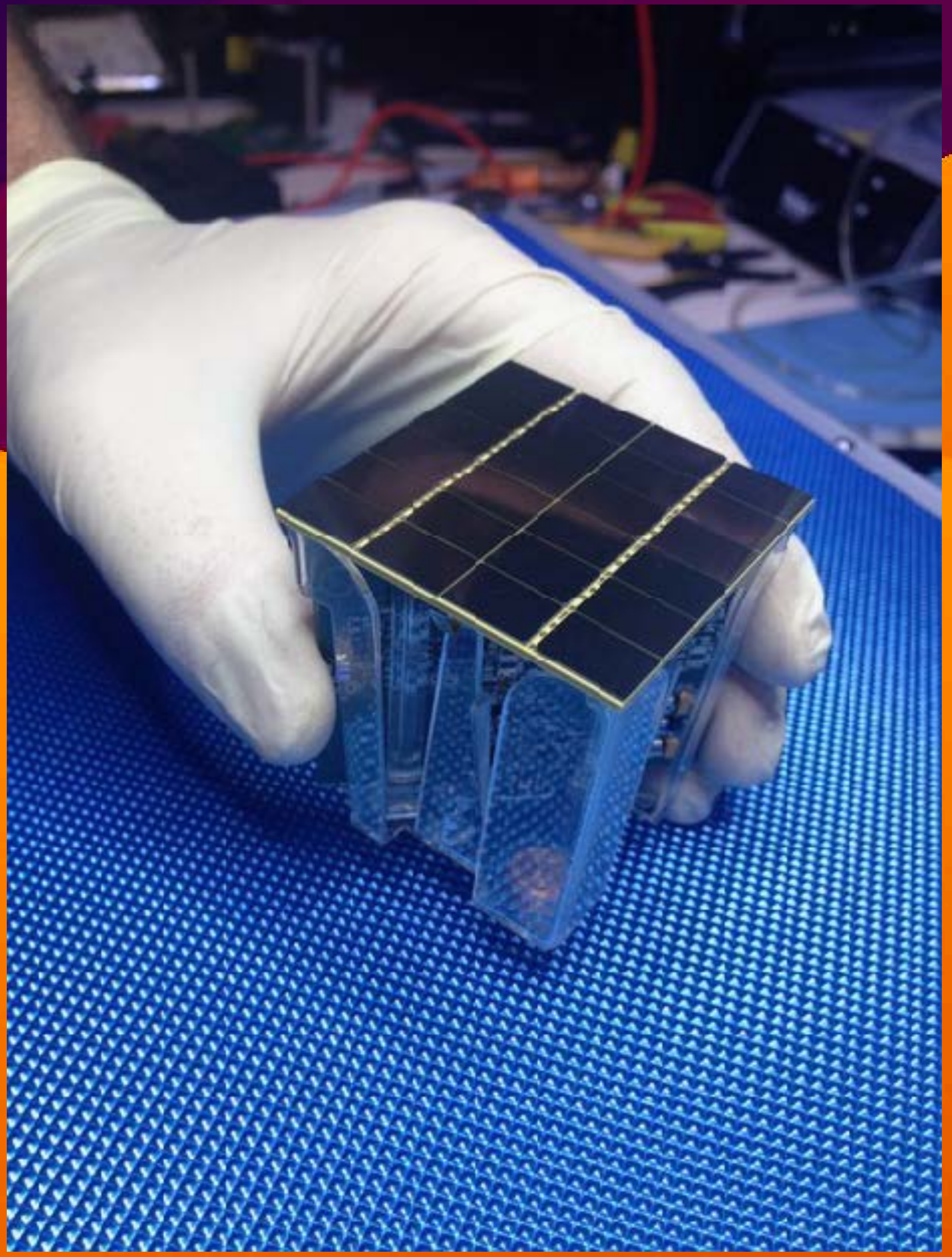
The Cornerstones of the GADMC Program

- Pulse shape discrimination for complete electron recoil rejection
- Underground argon for pile-up avoidance
- DUNE-like cryostat for shielding and cryogenic buffer protection of isotopic-enhanced target
- Use of PMMA vessel for containment of active volume coupled - ultrapure PMMA for anode and cathode window and Gd-PMMA barrel for enhancement of neutron vetoing
- Custom SiPM-based photosensors for maximal photon collection

Transitioning to a new technology

Why?

- Lower radioactivity
- Higher Photon Detection Efficiency
- Higher active area
- Operated with low bias
- Lower cost



But…there's no such thing as a free meal!

- Higher dark rate and correlated noises (after-pulse, cross-talk)
- Small area (many channels)
- High output capacitance (high electronic noise, low bandwidth)

Low-radioactivity, High Efficiency SiPMs

- Developed with Fondazione Bruno Kessler (FBK)
  - Photon detection efficiency: **>40%** at 77 K
  - Dark count rate: **<0.01 Hz/mm²** at 77 K
  - SNR: **>8** (TPC PDU)
- ***A new tool for particle physics:*** low-radioactivity, low-noise, high-efficiency SiPM arrays can cover large areas in a cost-effective manner

PDU packaging and assembly at Nuova Officina Assergi (NOA) at LNGS

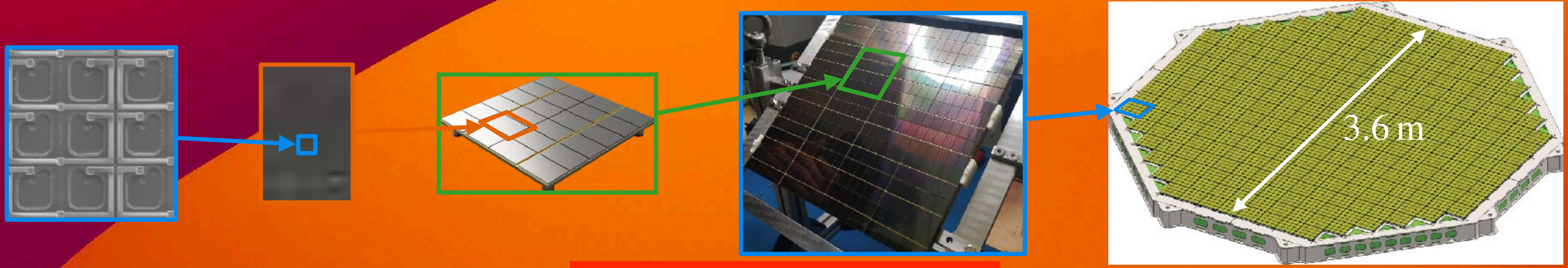
SPAD $30 \times 30\,\mu m^2$

SiPM $8 \times 12\,mm^2$

Tile (24 SiPM) $5 \times 5\,cm^2$

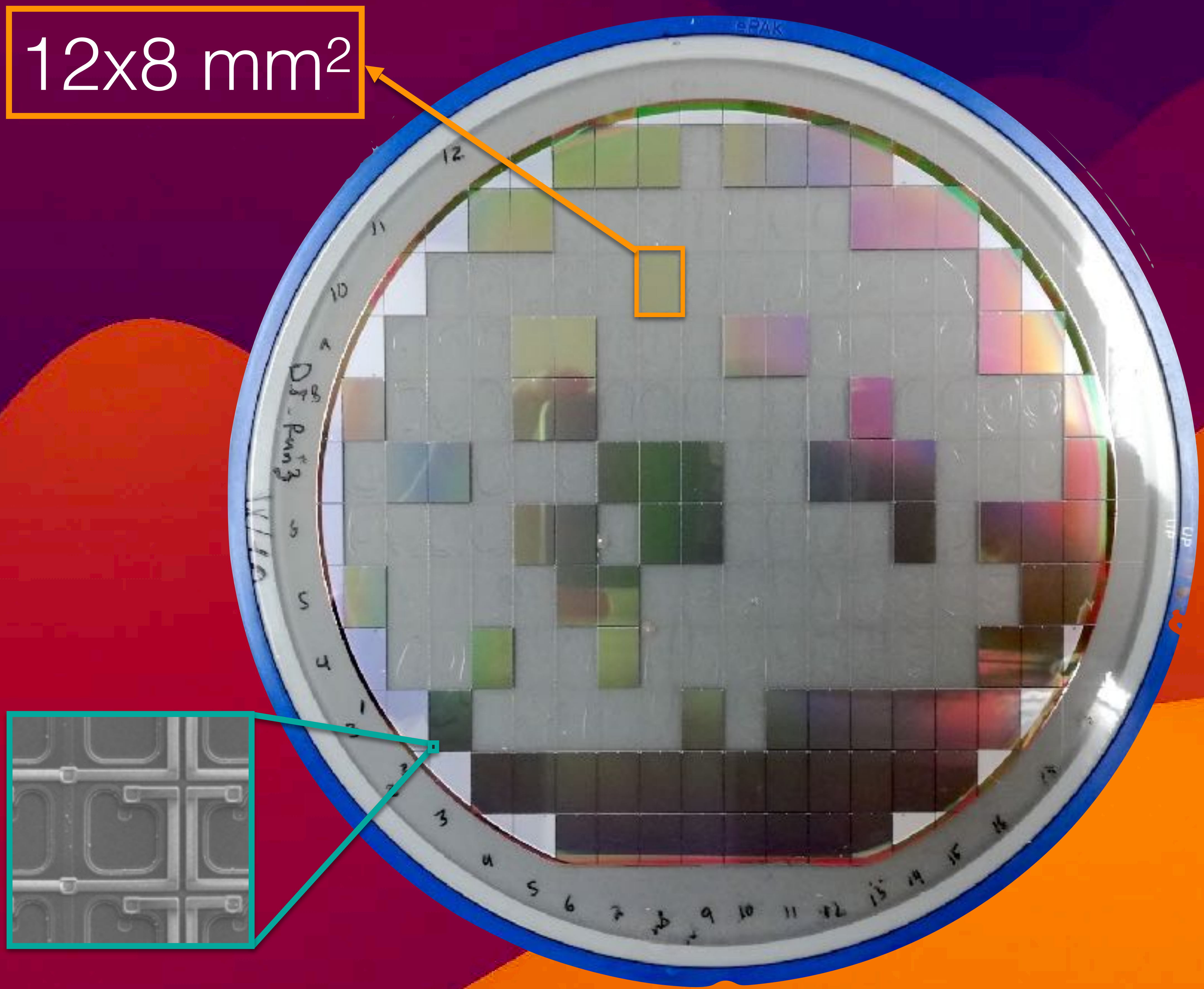
PDU (16 Tiles) $20 \times 20\,cm^2$

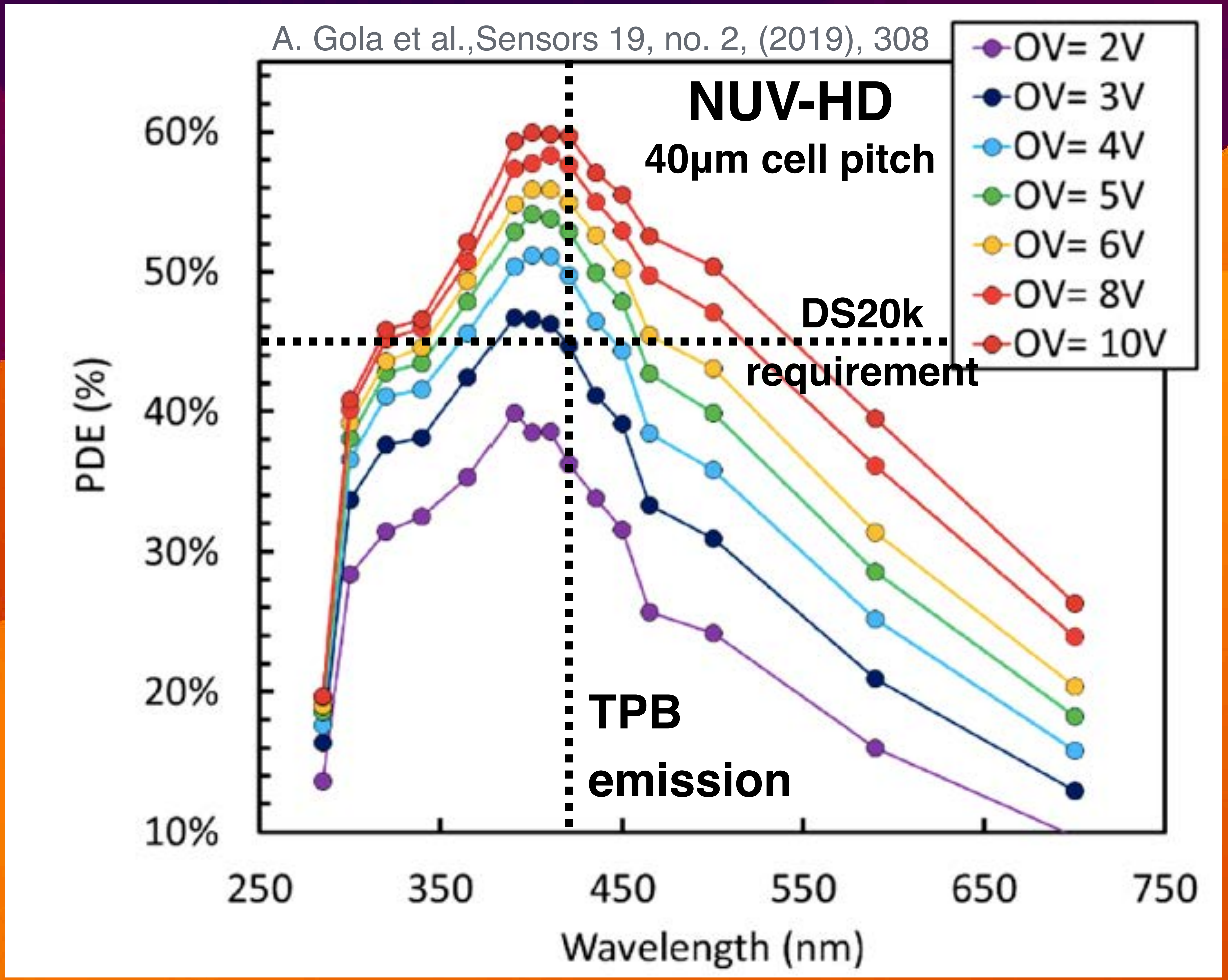
Optical Plane (264 PDUs) $21\,m^2$ in TPC, $5\,m^2$ in Veto



JINST 12, P09030 (2070)

Step 1: SiPMs development



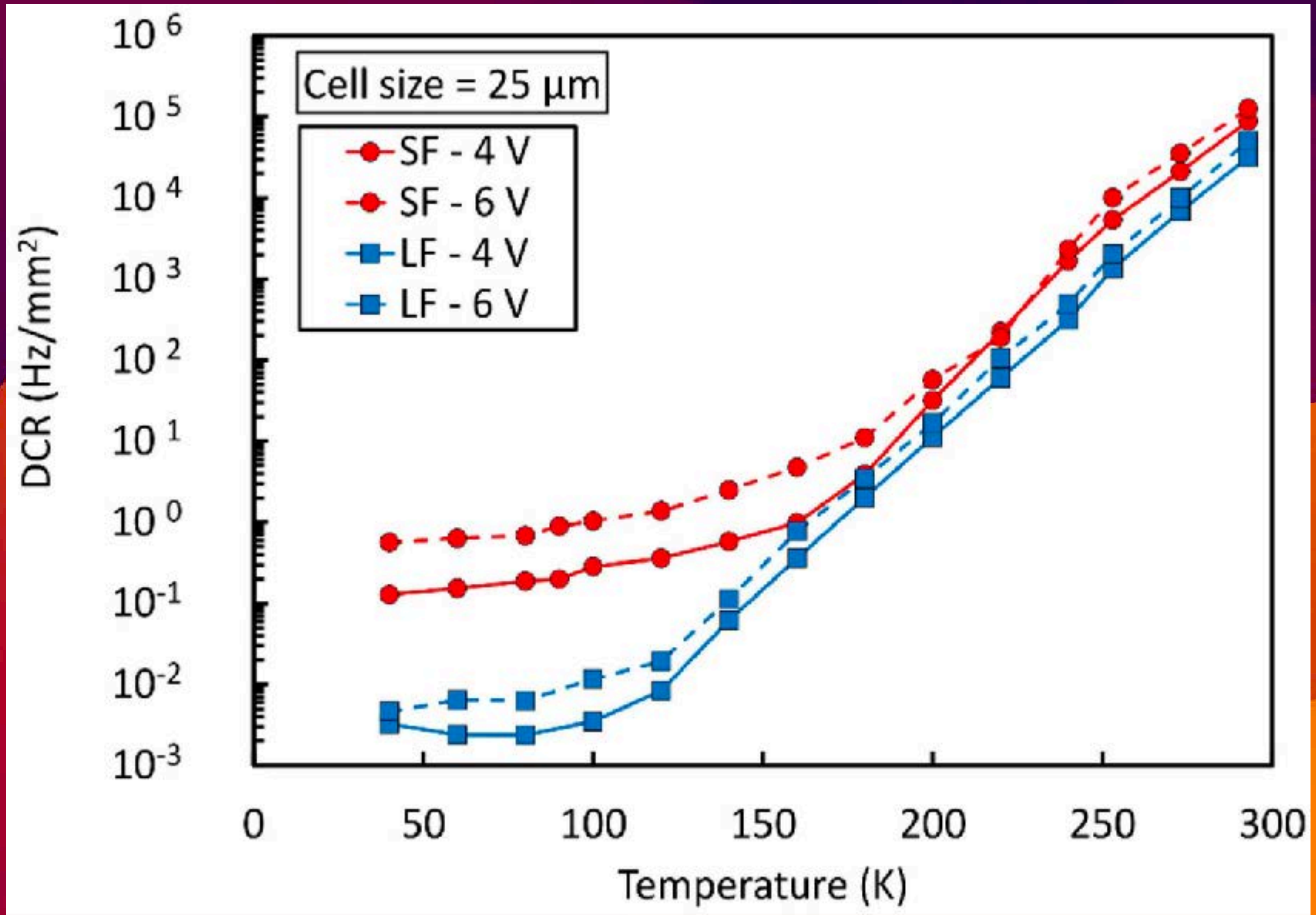


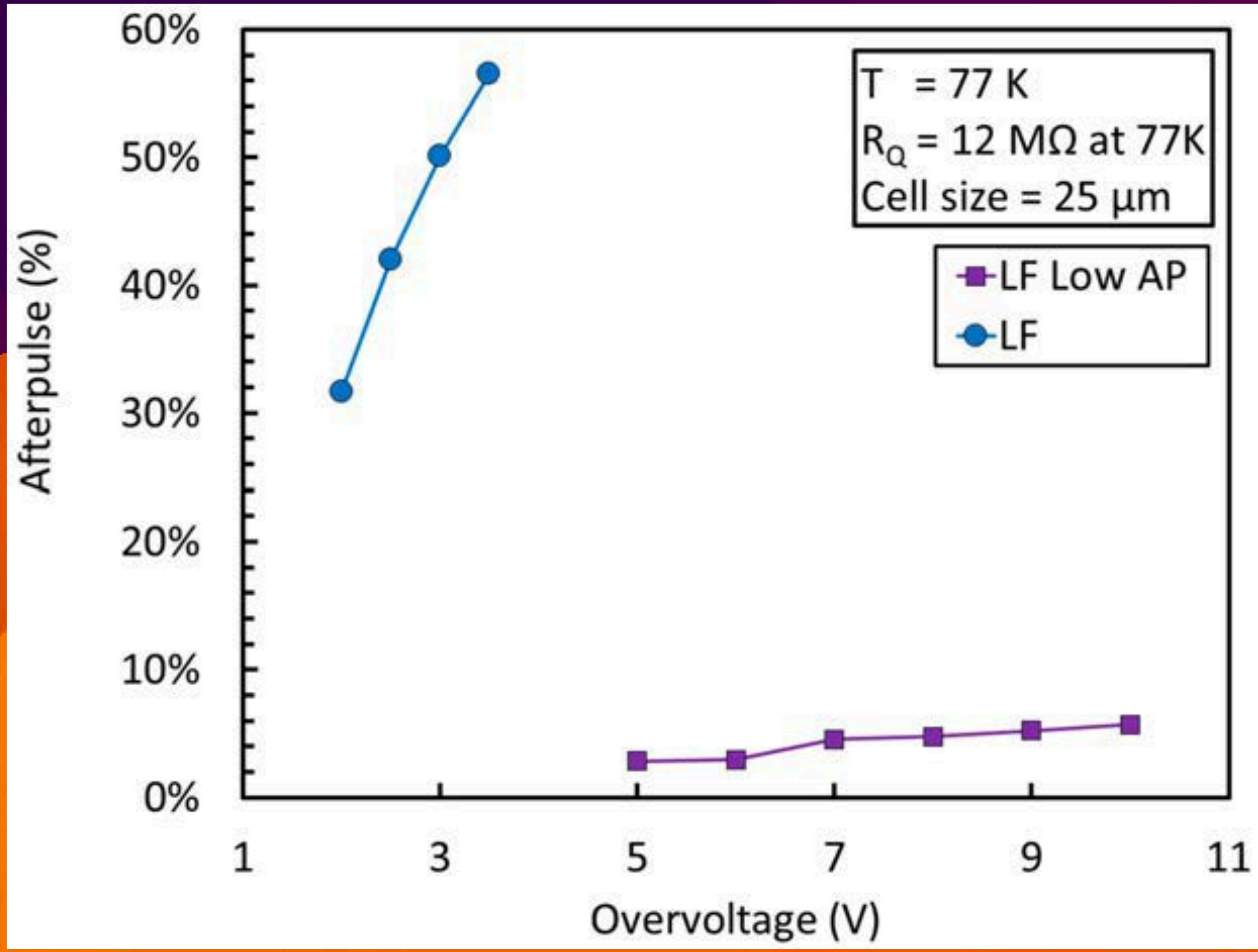
- NUV vs RGB choice (P01)
- Cell pitch and fill factor (FF) optimization
- **E field profile ⇒ DCR+CN reduction**

$PDE = QE \times P_{01} \times FF$

PDE > 55% @ 290K

Step 1: SiPMs development

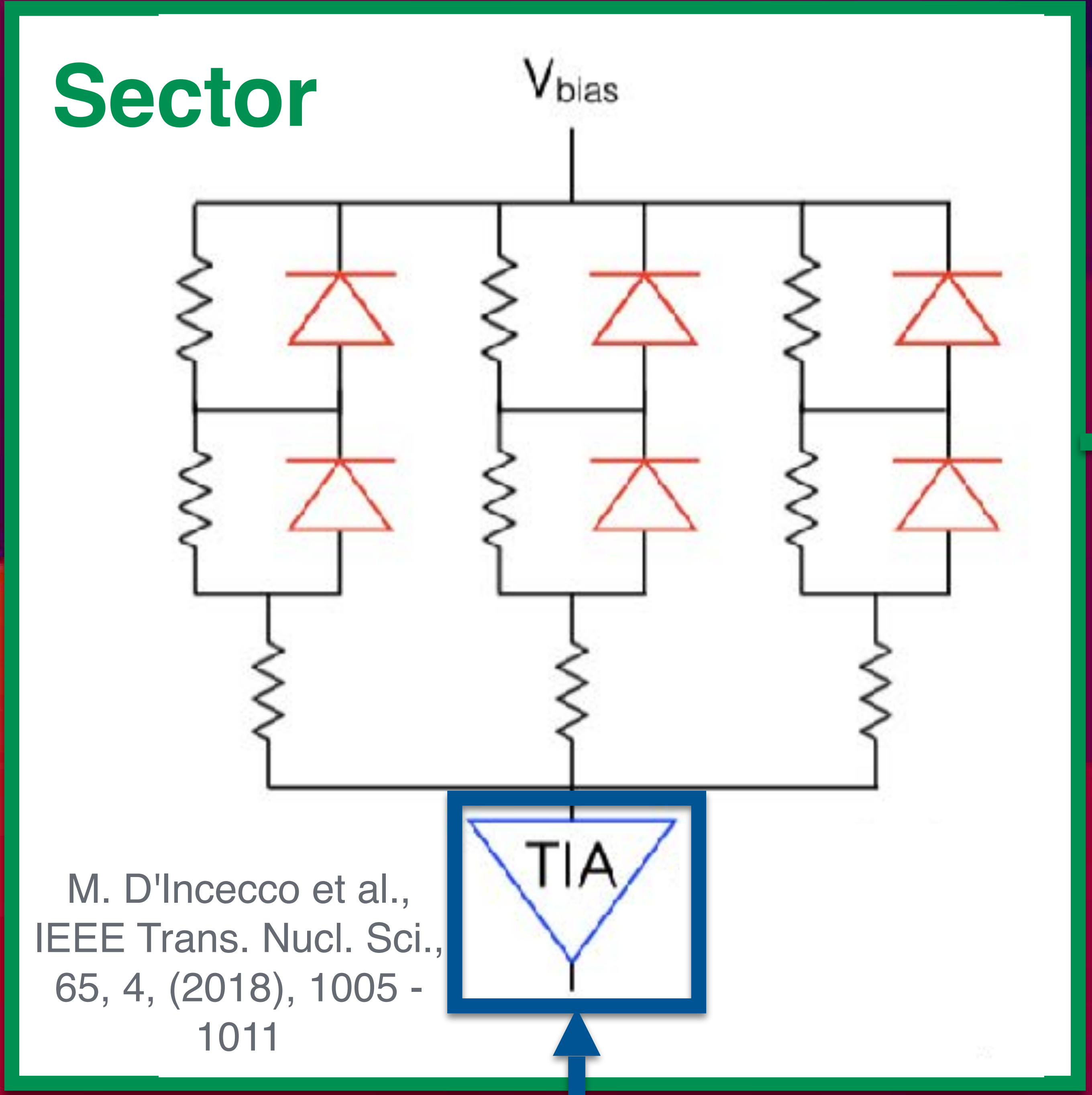




- DCR has 2 generation mechanisms
- Thermal agitation dominant @T>100K
- Field-assisted tunneling @T<100K
- **E** field profile engineered to suppress tunneling.

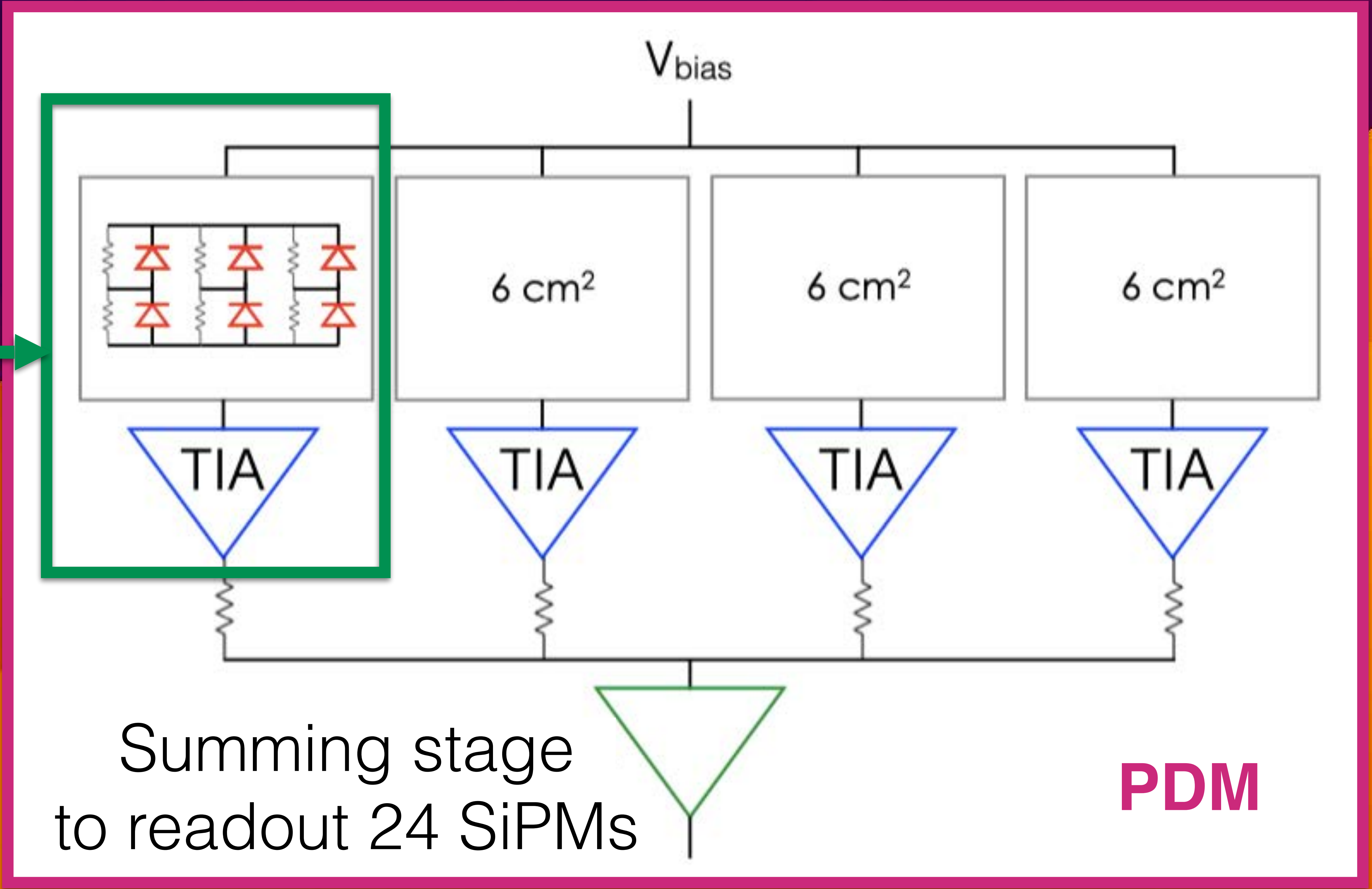
- AP dangerous to PSD
- Suppressed by introducing a dopant into the SPAD junctions.
- DiCT suppressed by the low **E** field

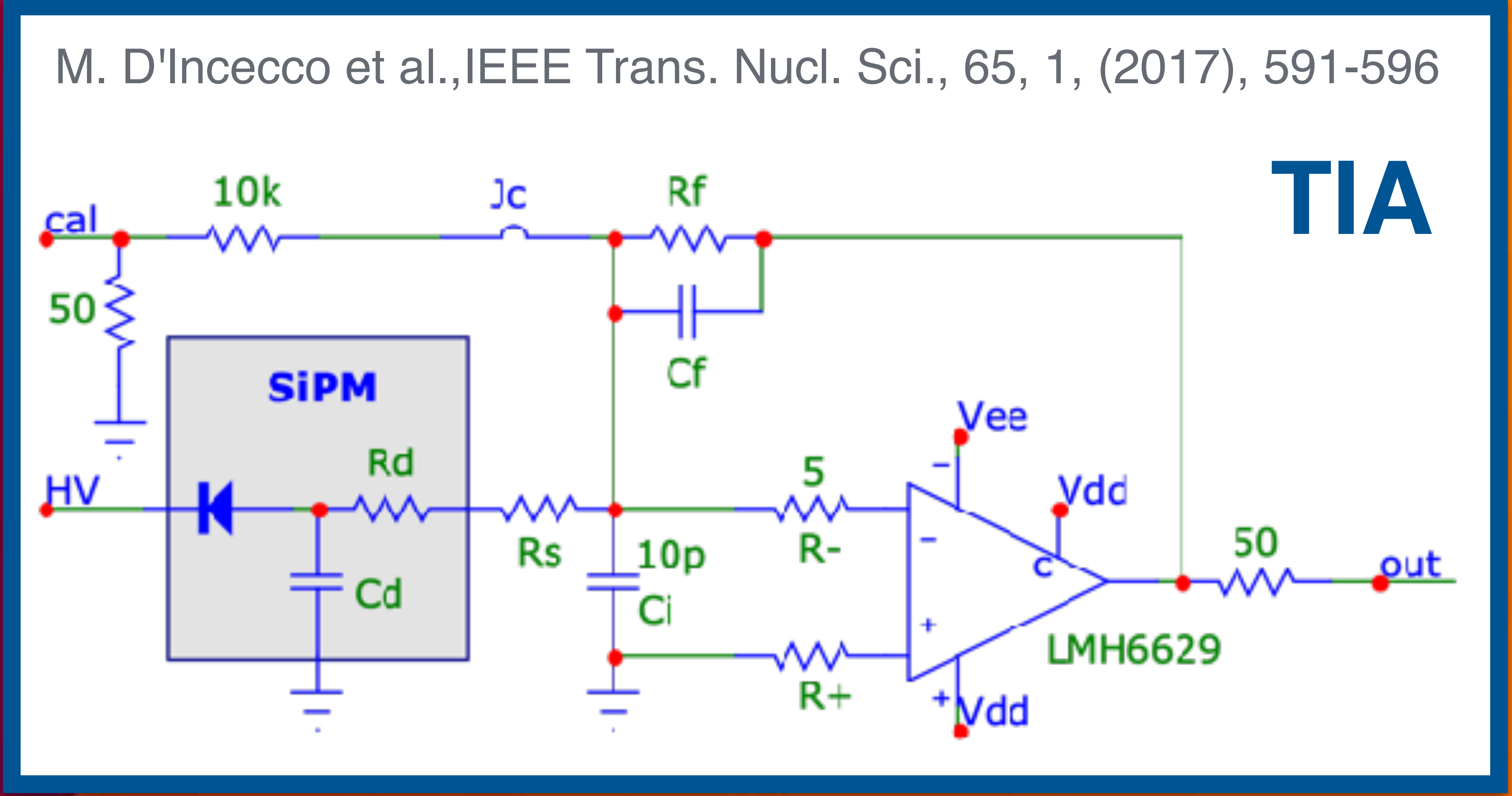
Step 2: readout electronics design…



Mixed series/parallel configuration

Reduce Cin@TIA
Preserve BW





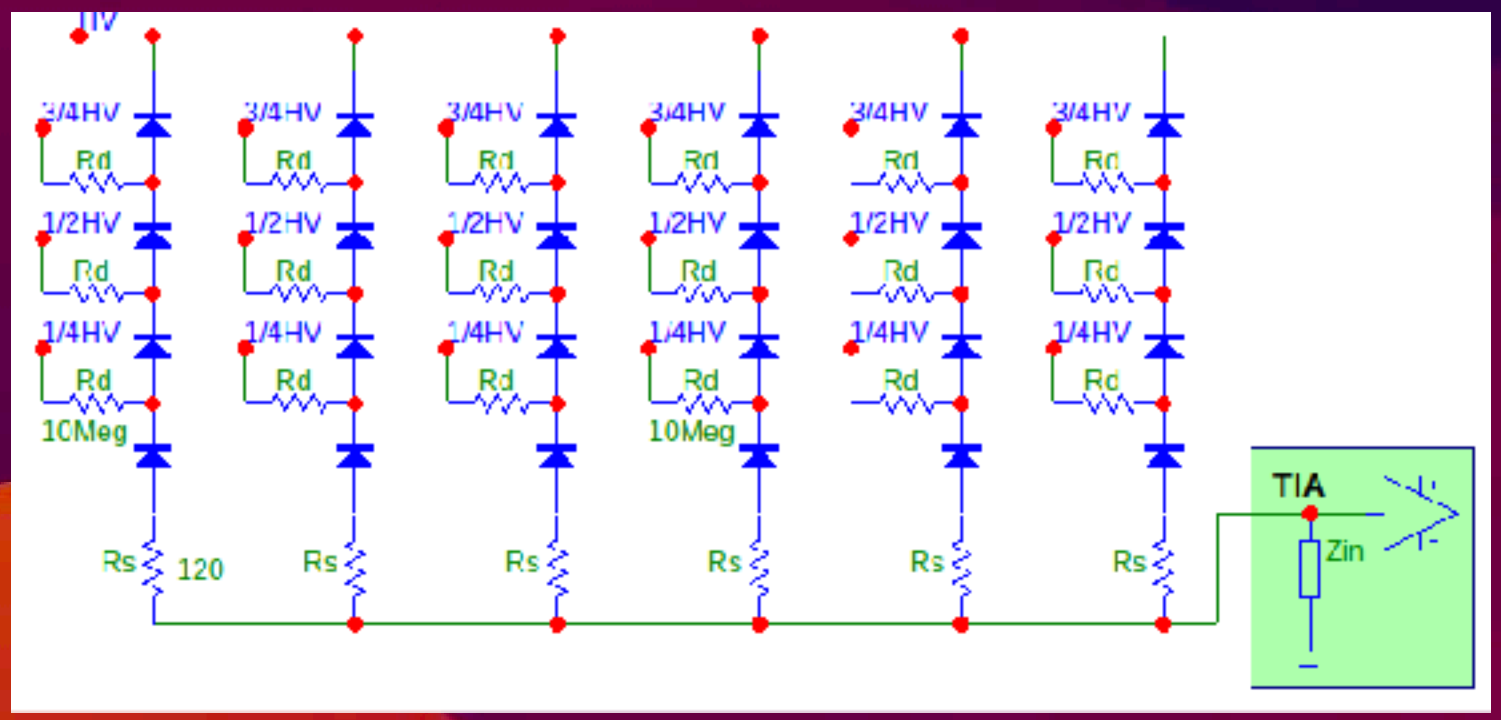
SiPM = current generators + huge output capacitance (~50pF/mm2)

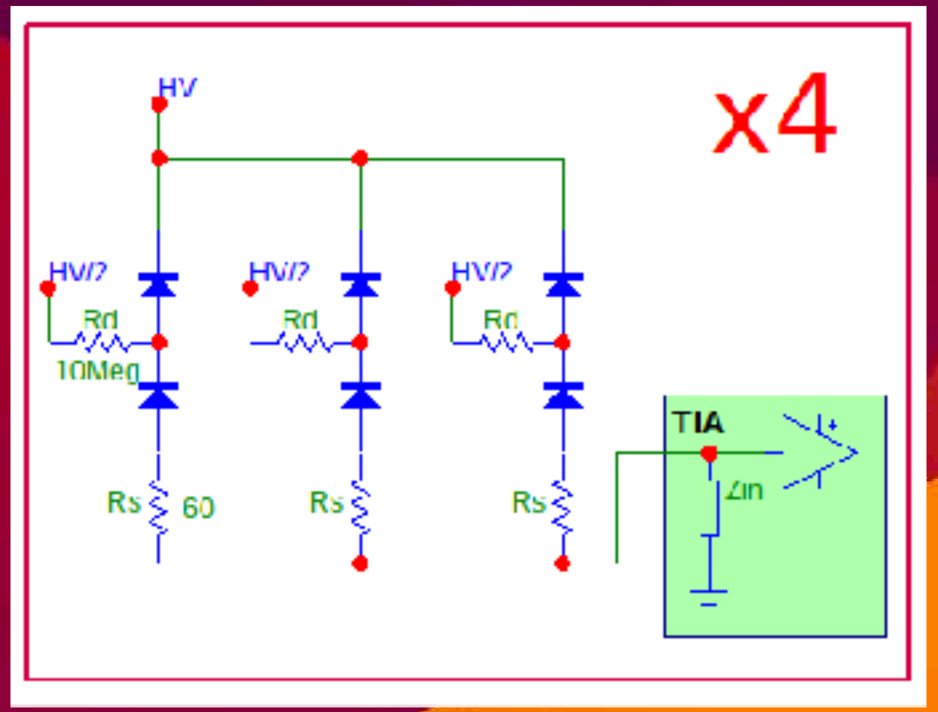
Transimpedance amplifier (TIA) **High Bandwidth** and **Low Noise**

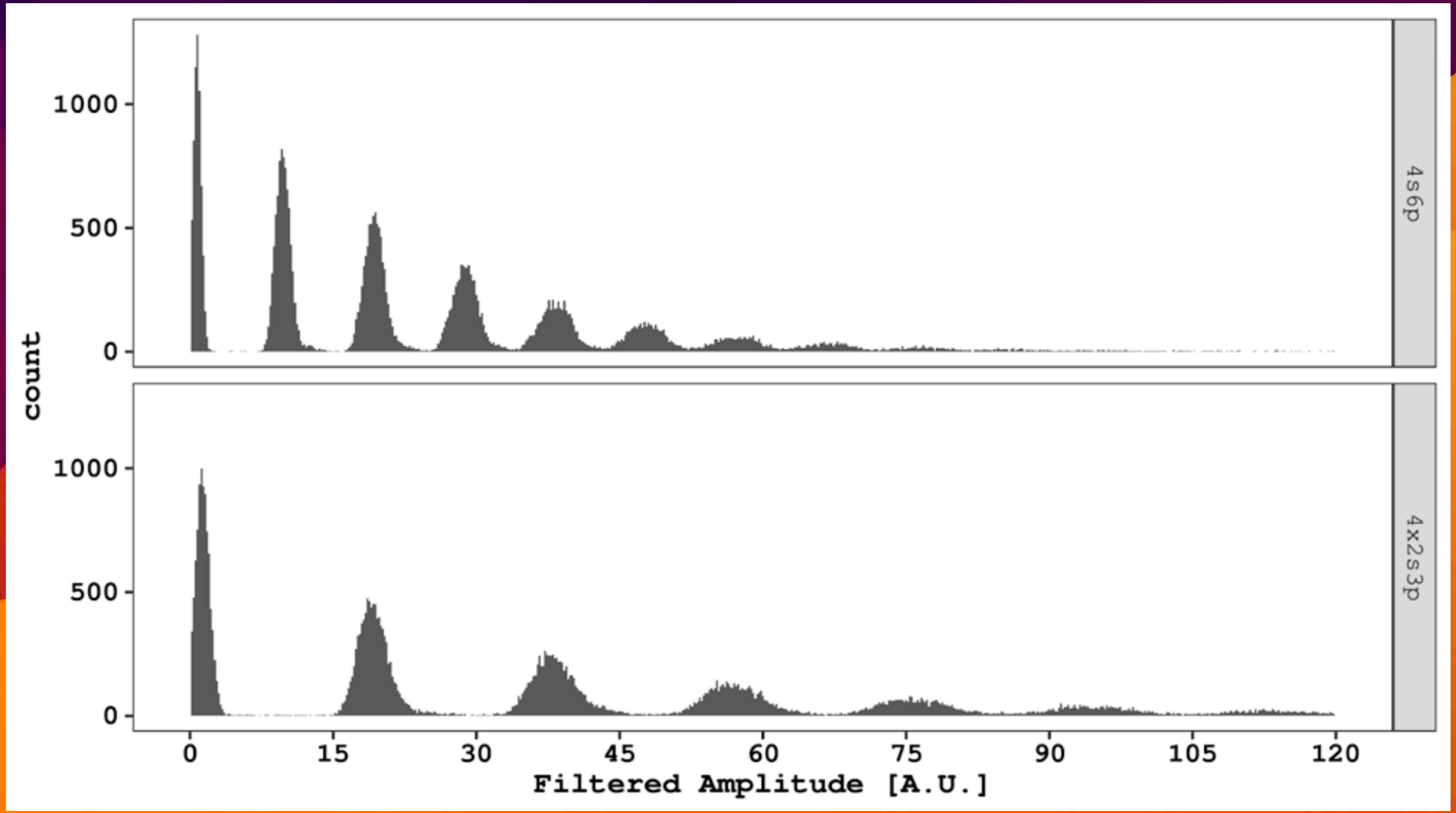
SNR is reduced wrt a single SiPM, but still very high

Power dissipation is < 250mW per PDM

Step 2: …and upgrades



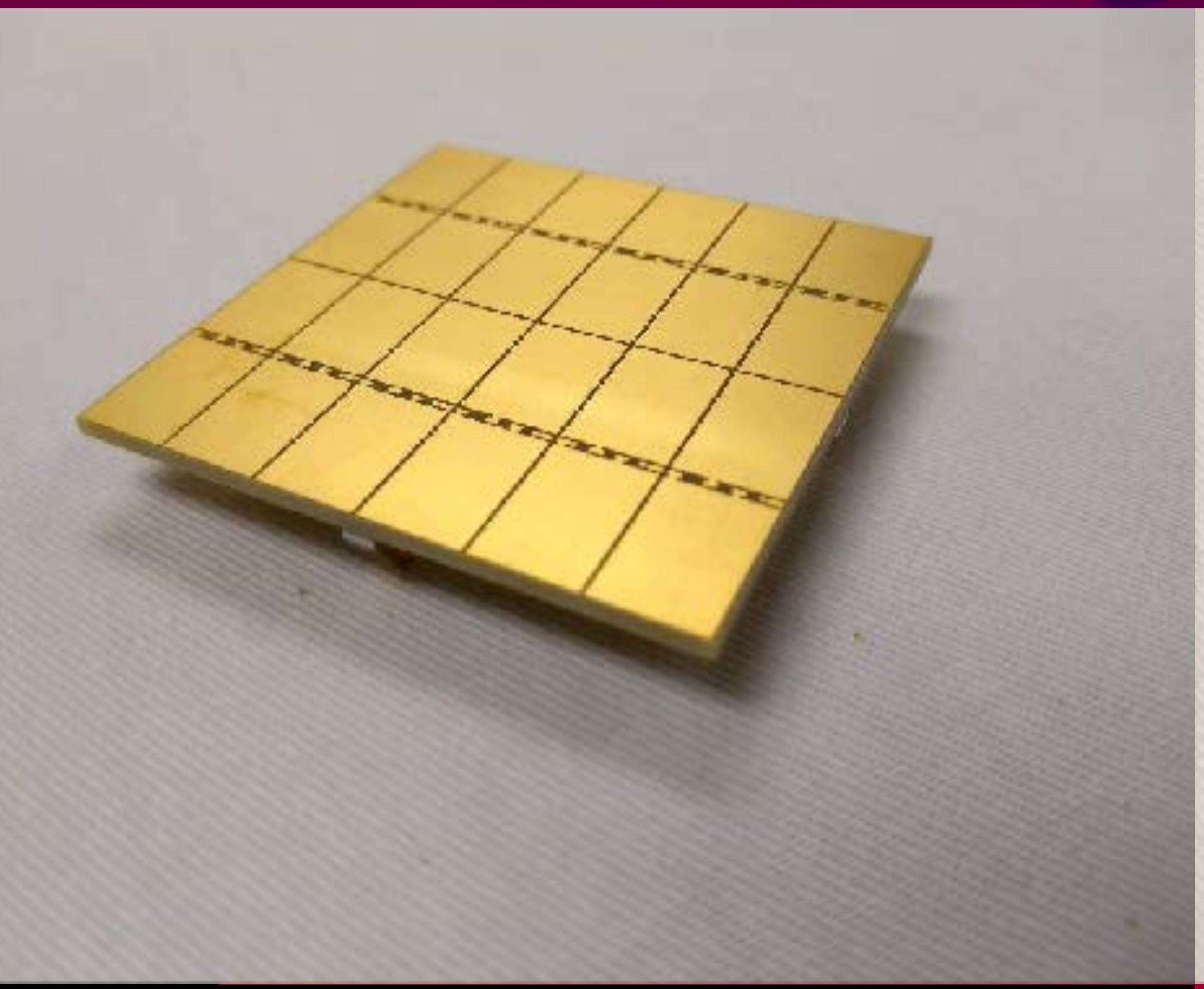


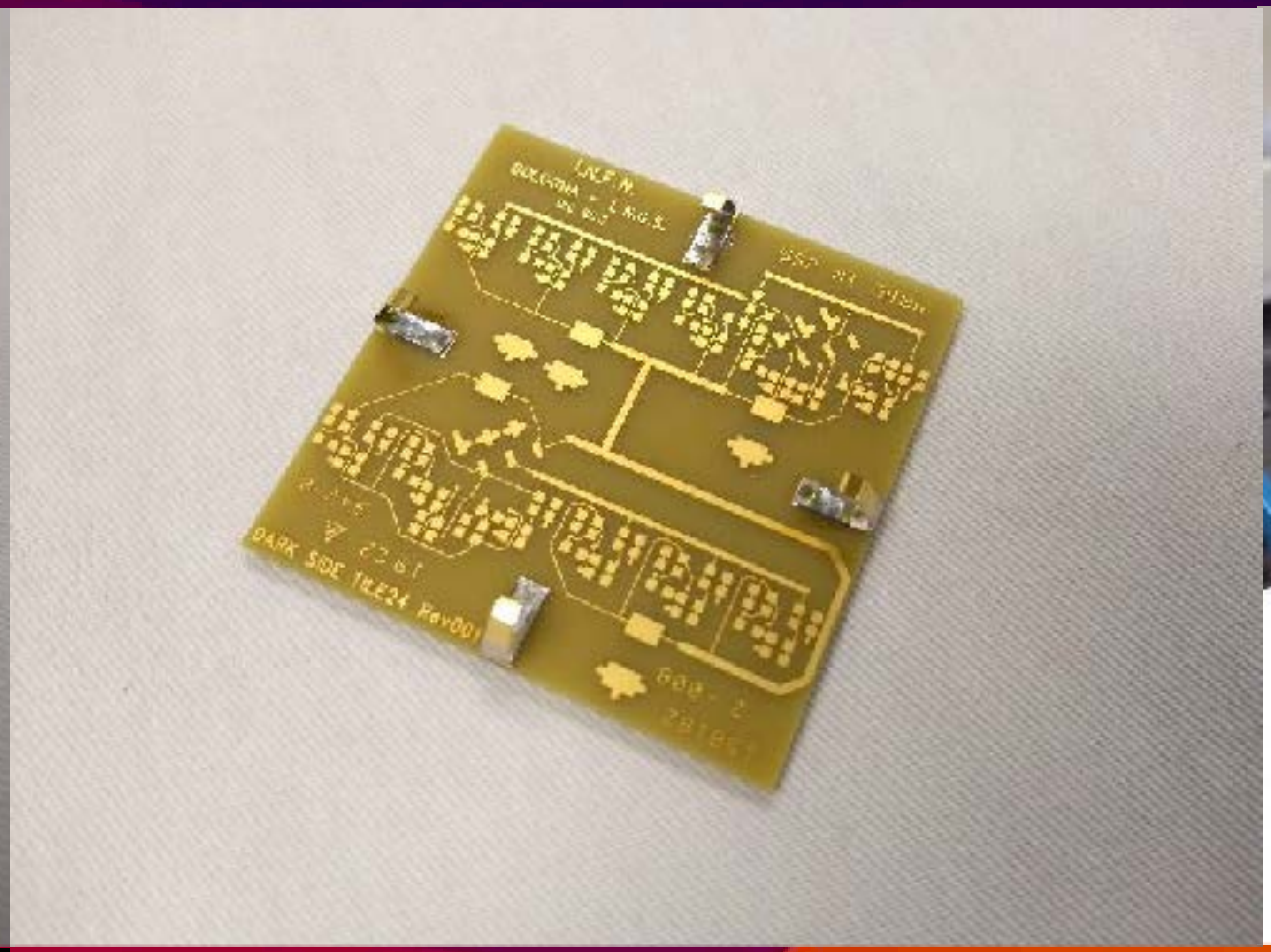


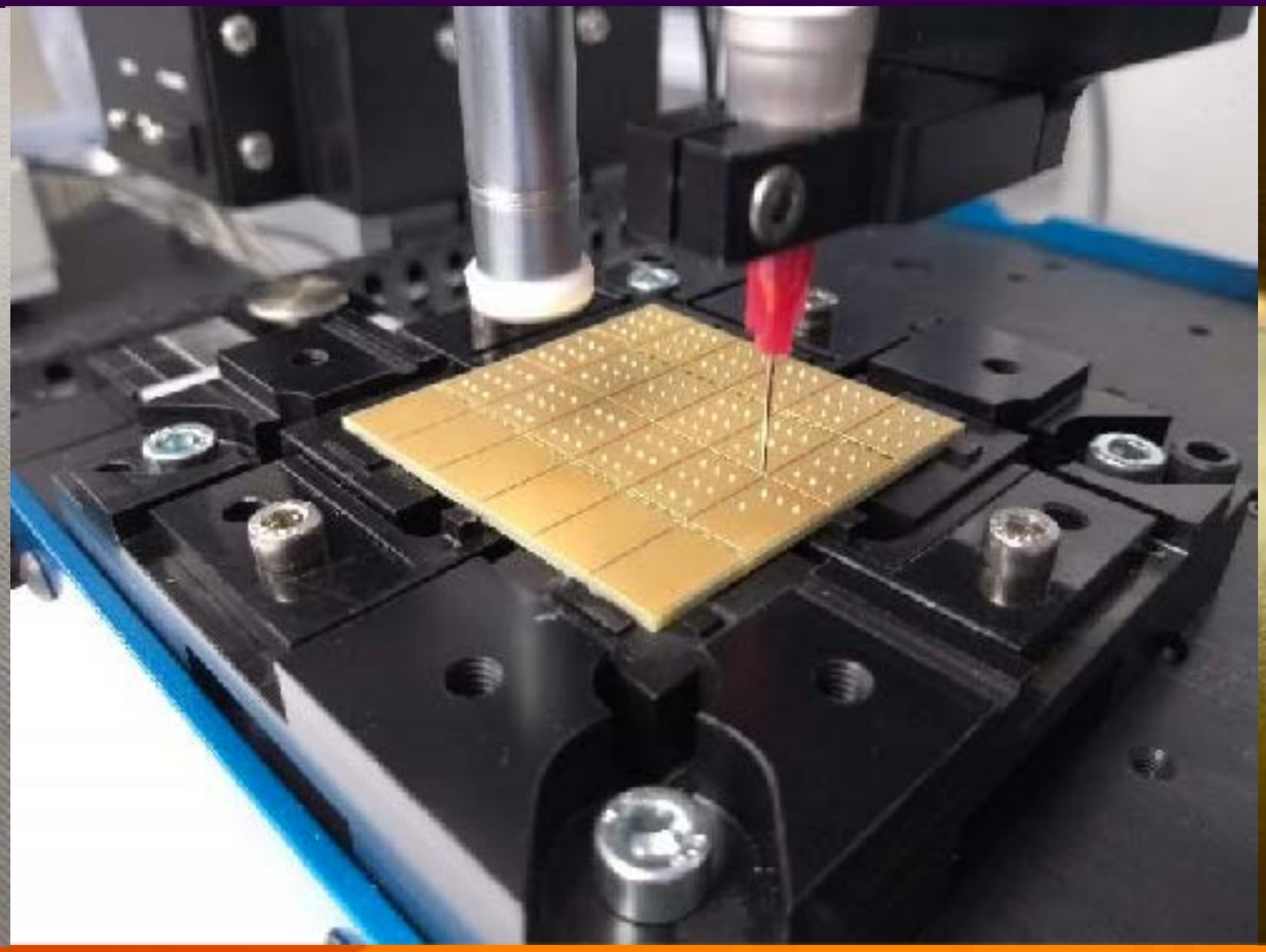
Switch from 4 sectors ($6cm^2$) to 1 single $24cm^2$ unit

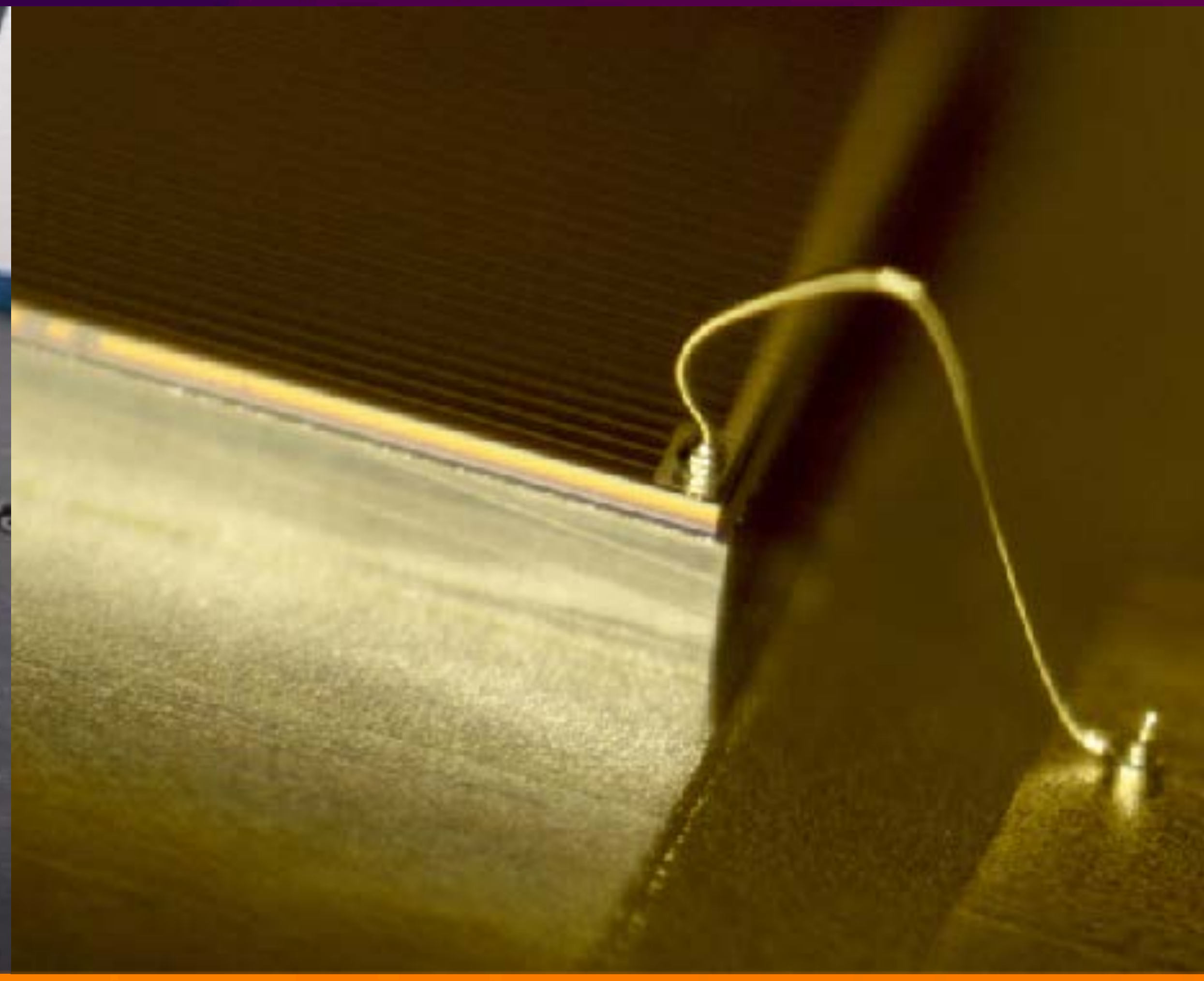
Power dissipation < 50mW per tile

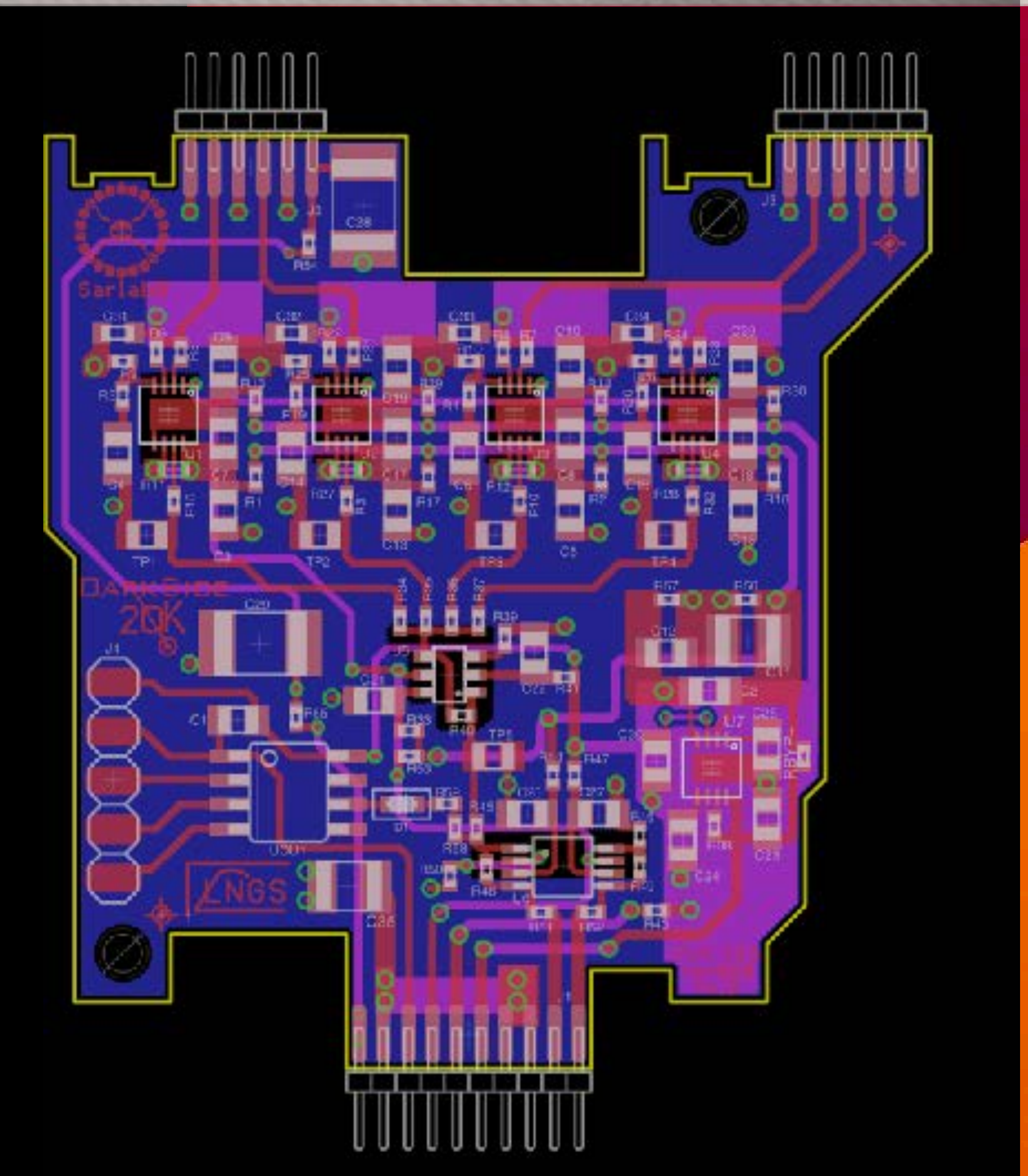
Step 3: packaging and production









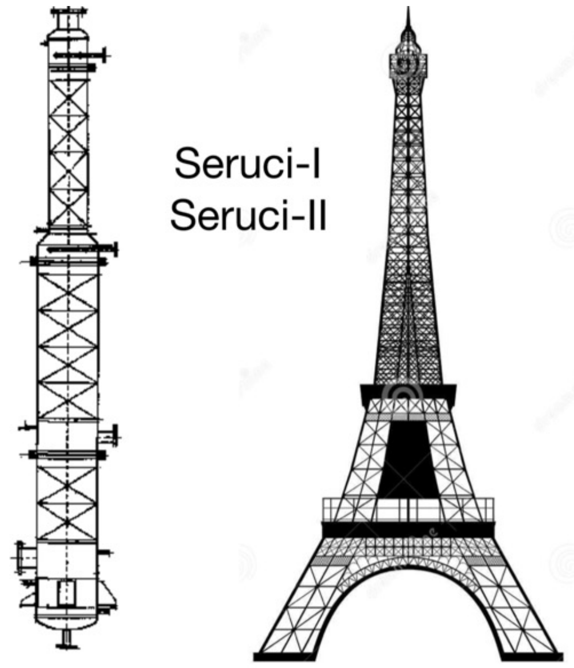


- SiPM development and readout electronics design are only the beginning!
- Wire-bonding and die-bonding procedures finalized.
- Materials and components are selected to ensure the fulfillment of radio-purity requirements.
- Final assembly to happen at the NOA packaging facility (in LNGS, Italy) - see dedicated presentation by Roberto Tartaglia on Apr 1 at 8:00 AM - and UK facilities LSDC and STFC interconnect.
- Final testing in dedicated facility at Università di Napoli Federico II.

Industrial Scale Underground Argon (UAr)

Production – URANIA – Cortez, CO, US

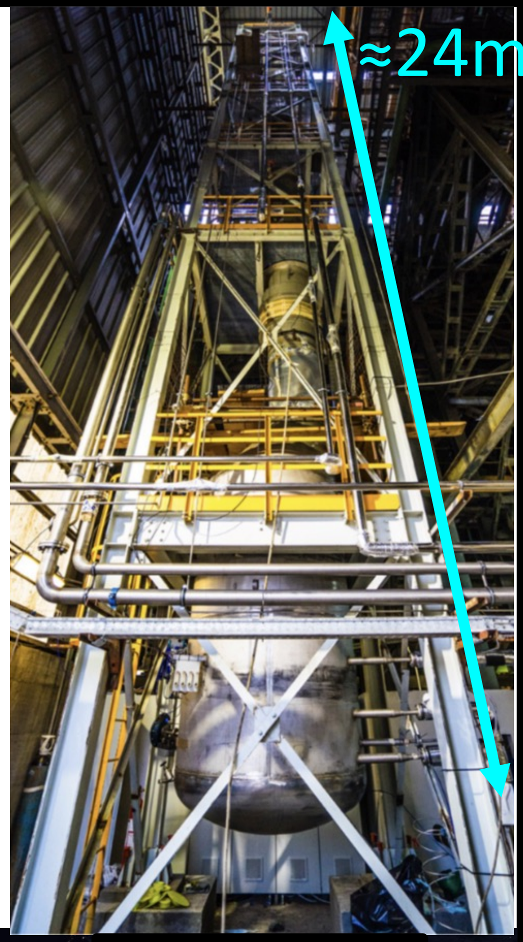
- Industrial scale extraction plant
- Extraction rate: 250-330 kg/day
- Production capability ≈ 120 t over two years for DS-20k
- UAr purity: 99.99%



Purification – Aria – Sardinia, IT

Eur. Phys. J. C (2021) 81:359

- Seruci-0 (demonstrator) tested
- 350 m cryogenic distillation column
- O(1 tonne)/day capability
- Resulting UAr purity: 99.999%



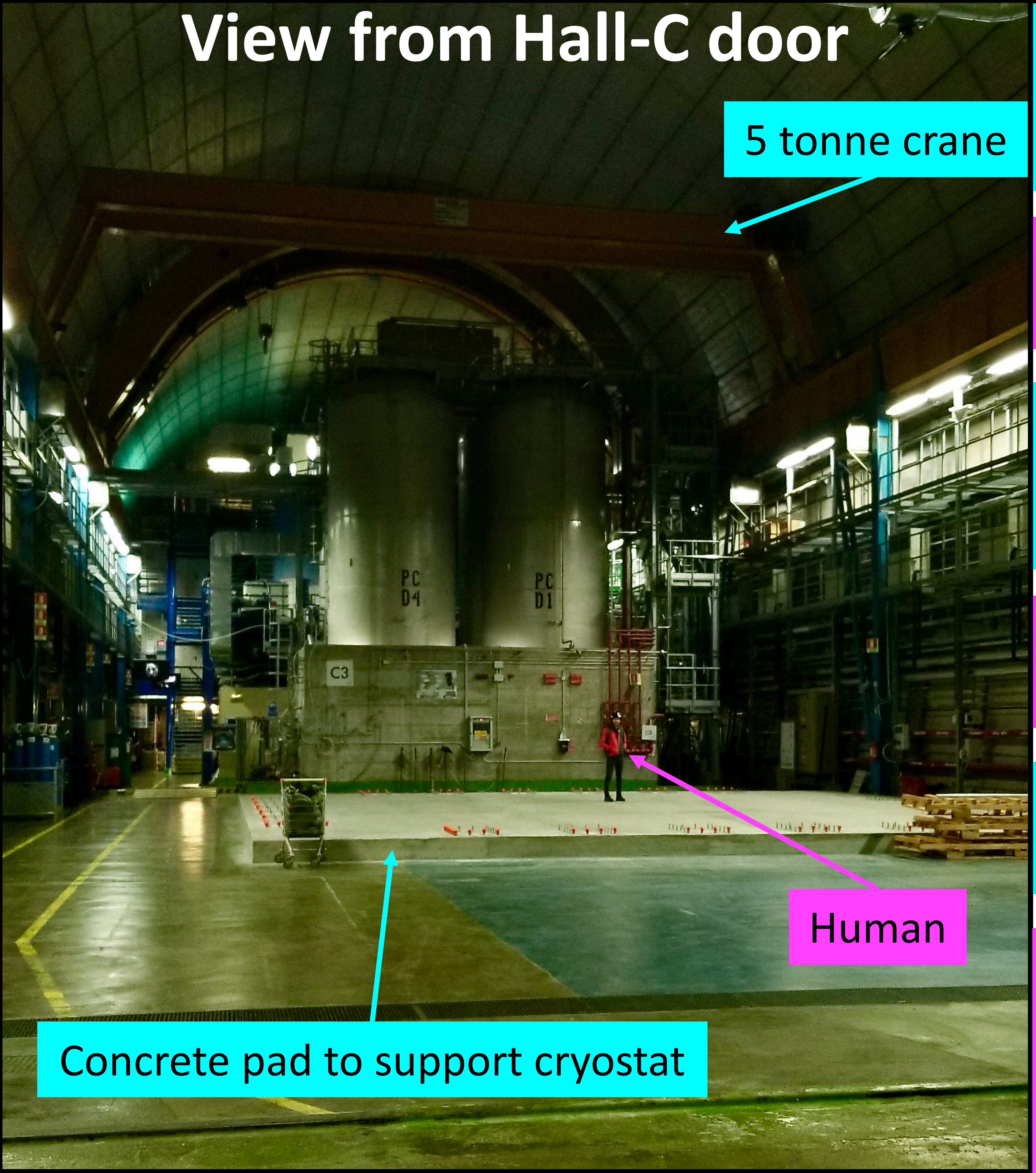
Seruci-0

DArtInArDM: LSC-supported facility of qualification of UAr in ^{39}Ar and ^{42}Ar

Keep the UAr production going!

- Once tuned at max production of 90 tonne/yr, the Urania and Aria plant in their current form can produce all the UAr for:
  - DarkSide-20k
  - LEGEND
  - COHERENT
  - Argo
  - Other small efforts part of DUNE R&D

DS-20k Cross Section Within Membrane Cryostat



Membrane "ProtoDUNE-like" cryostat

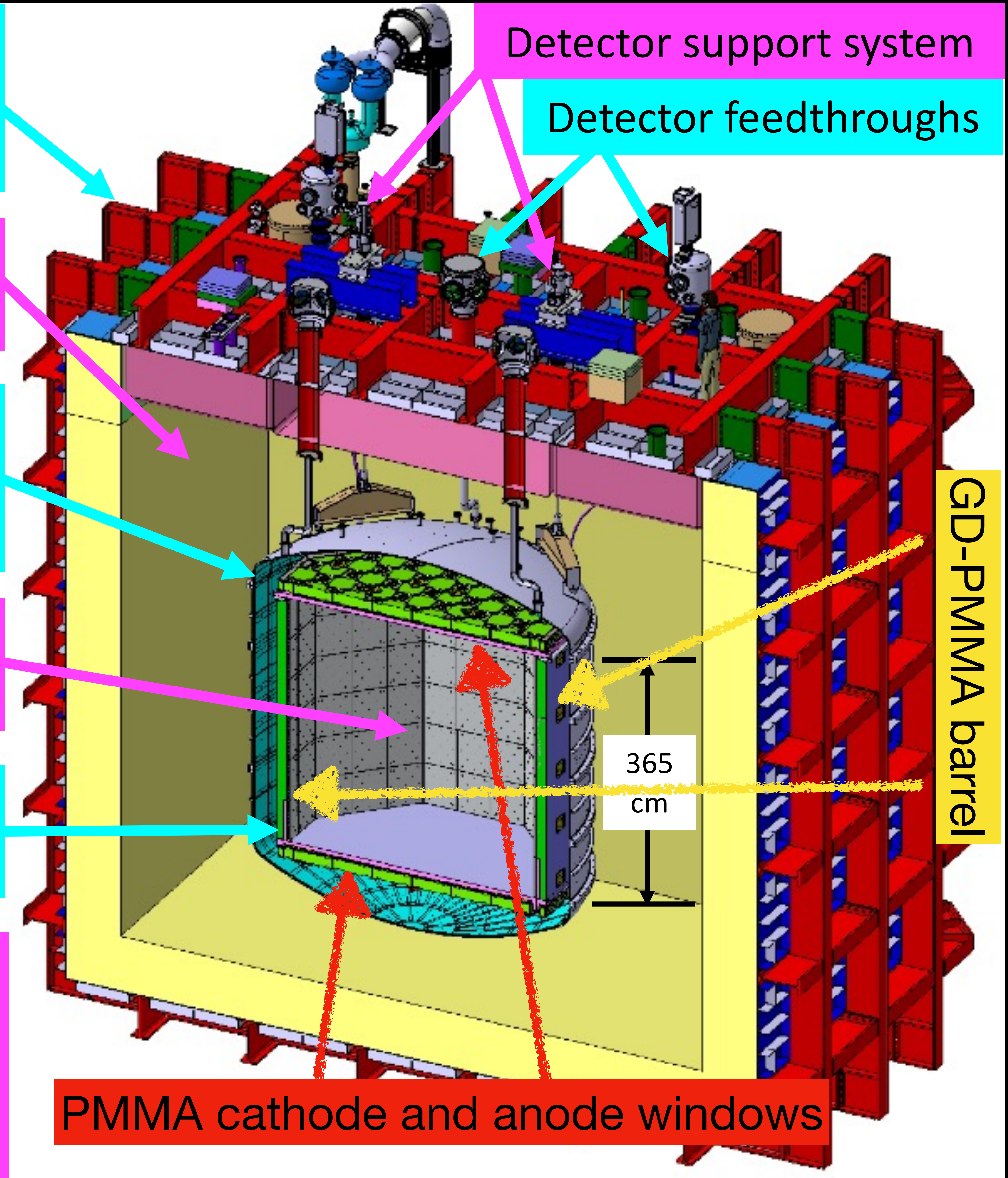
Atmospheric argon (AAr) volume (≈700 t)

Vacuum vessel containing UAr and TPC/veto

Underground argon (UAr) volume (≈100 t)

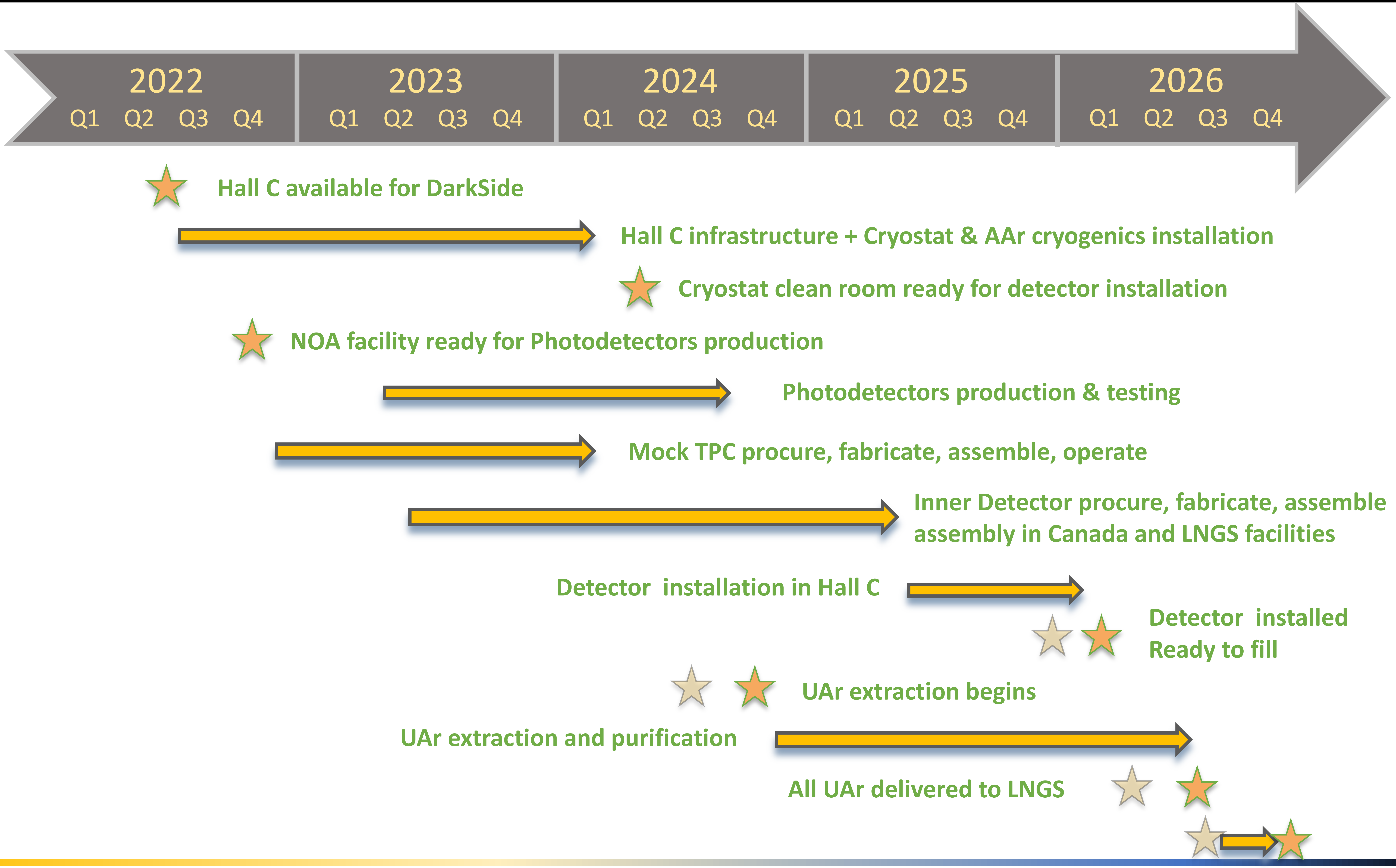
"Inner detectors", TPC and neutron veto

Outer veto will consist of SiPM arrays near the cryostat walls looking inward



DS-20k Experimental Project Summary Timeline

Slide Credit: Tom Thorpe (UCLA/LANL)



ARGO: Key Elements of Conceptual Design

Front-side SiPMs with wavelength shifter and backside-illuminated VUV-sensitive SiPMs, arranged as photon-to-digital converters (PDCs).

Data rates:

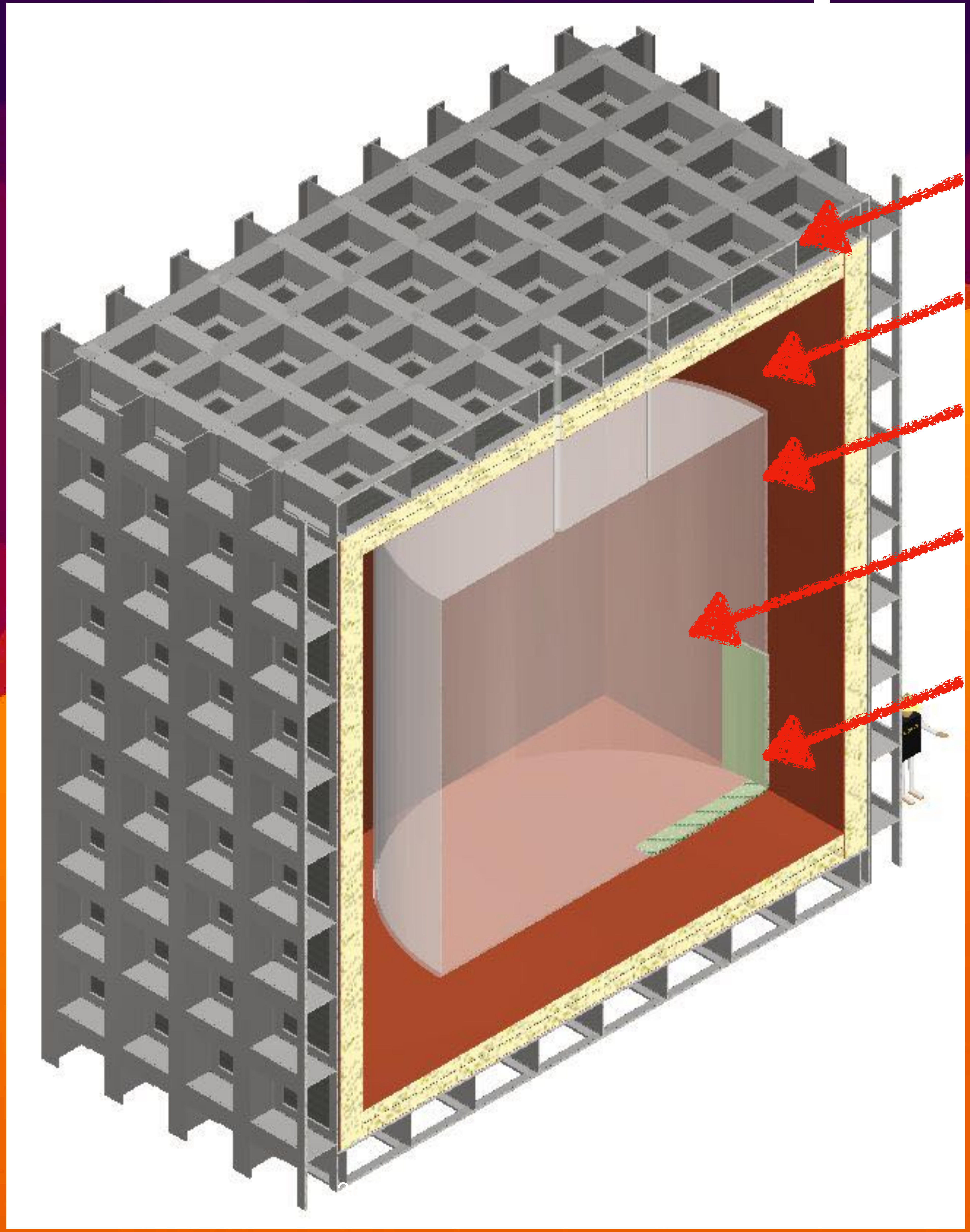
- operation 5k p.e./($m^2 \times s$);
- calibration 100k p.e./($m^2 \times s$).

Both single- and double-phase under active consideration.

Event vertex reconstruction and particle ID using spatial and temporal photon hit pattern.

UAr Mass:

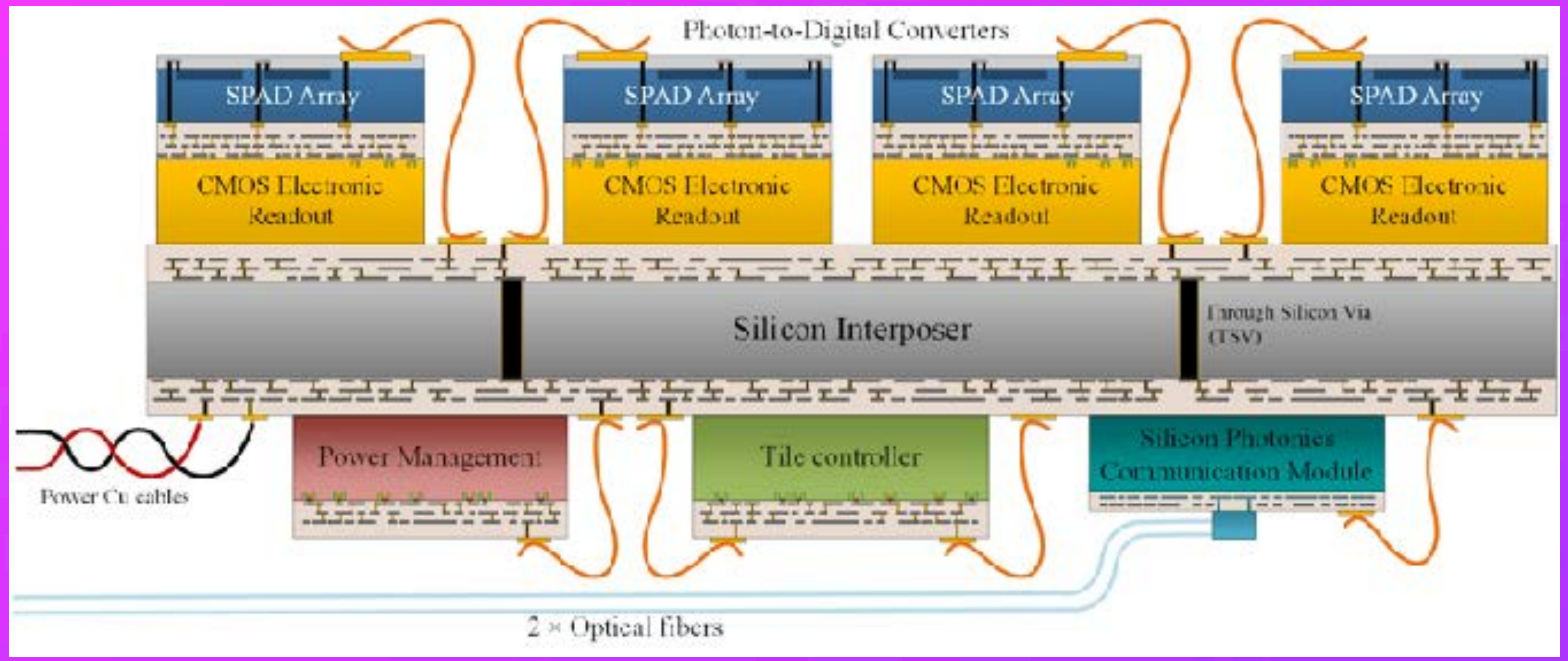
- total 400 tonnes;
- fiducial 300 tonnes.



Development of photon-to-digital converters:

- Signal processing at sensor level allows much simpler implementation;
- All-digital system not affected by electronic noise encountered in analog;
- Ability to disable noisy Single Photon Analog Diodes (SPAD);
- Active quenching suppresses essentially all after-pulsing;
- Lower power consumption: no event no power for digitizing;
- Excellent potential for time resolution: ~100ps.

Going further to enable large scale detectors: **A fully digital photodetector module**

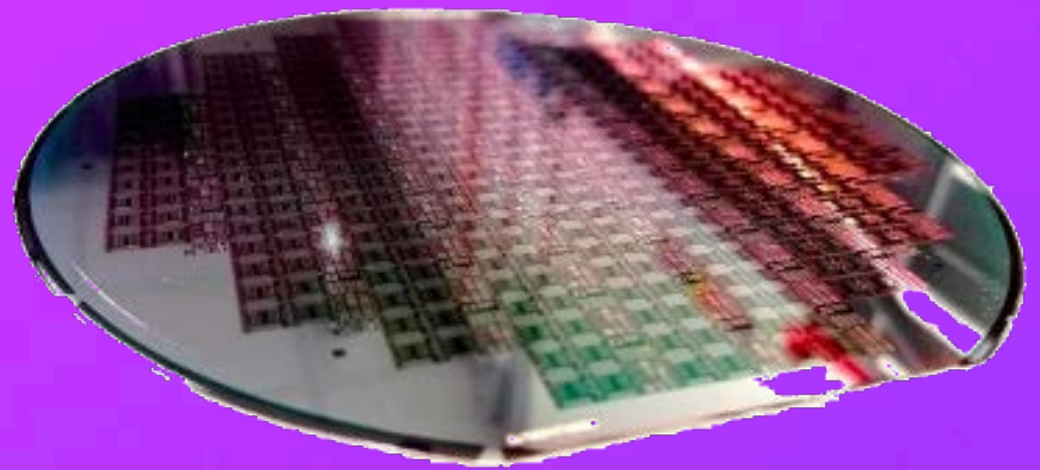


To reduce wire count and mass:
- On tile power management
- Bidirectional digital optical communication

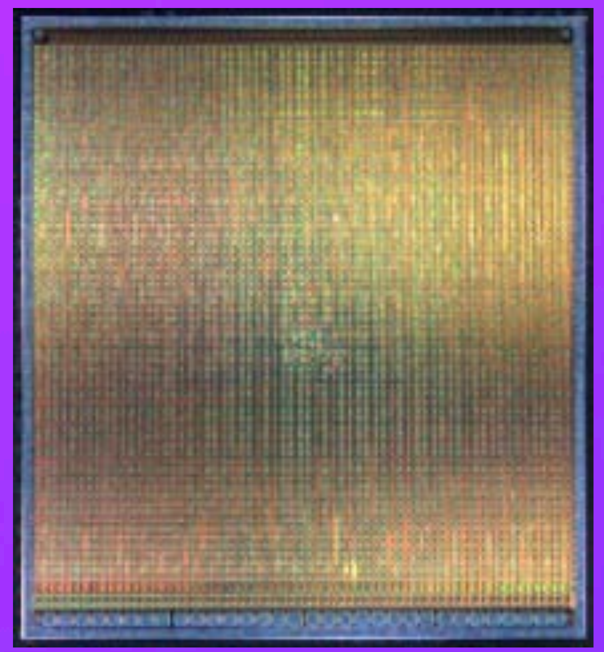
Low background and cryogenic operation:
- Silicon based tile substrate - low background
- CTE matched to silicon - PDCs and ASICs

Leverages past CFI and NSERC funding:

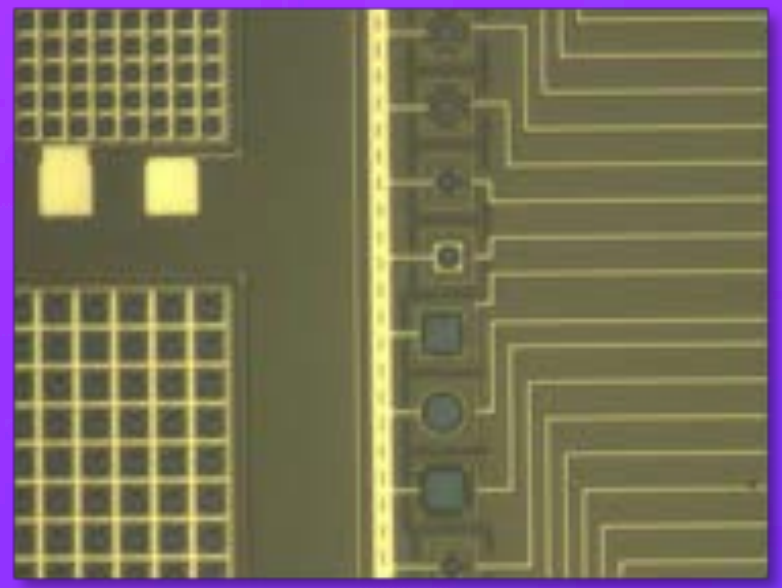
Wafer level development (SPAD)



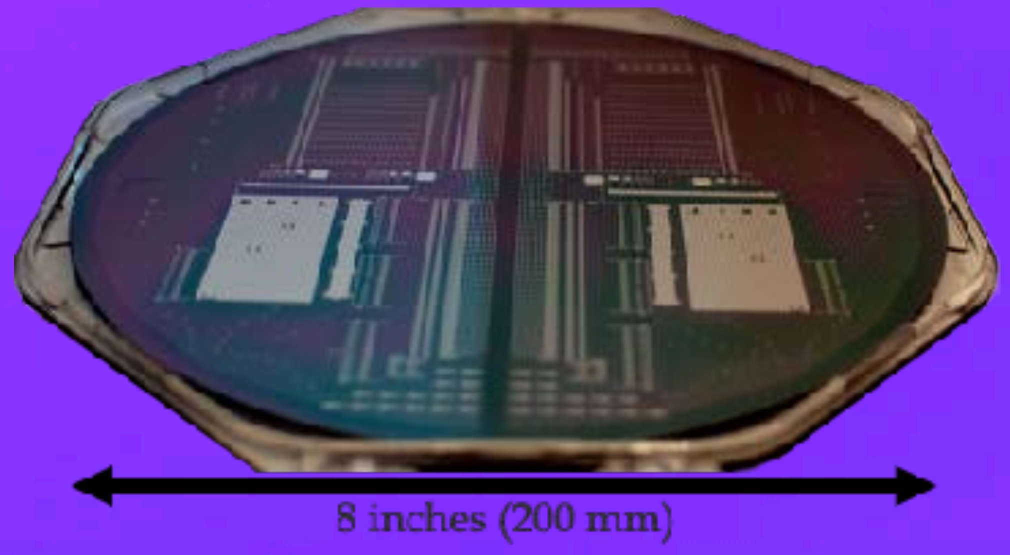
CMOS readout (2 revisions)



Sensitivity enhancement for direct detection



Silicon interposer development



The GADMC

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Conclusion

- DarkSide-20k in construction, operation expected by 2026:
  - Exciting prospect for first direct DM search at tens of tonnes scale, free from instrumental background
- Argo on the longer term horizon:
  - Compelling program to extend argon direct searches to 300 tonnes fiducial detector, exploiting infrastructure for argon collection and purification and SiPMs photosensors built for DarkSide-20k
- 1 tonne DarkSide-LowMass detector under consideration to extend leading low-mass results in 0.3-6 GeV/c^2 region

The End