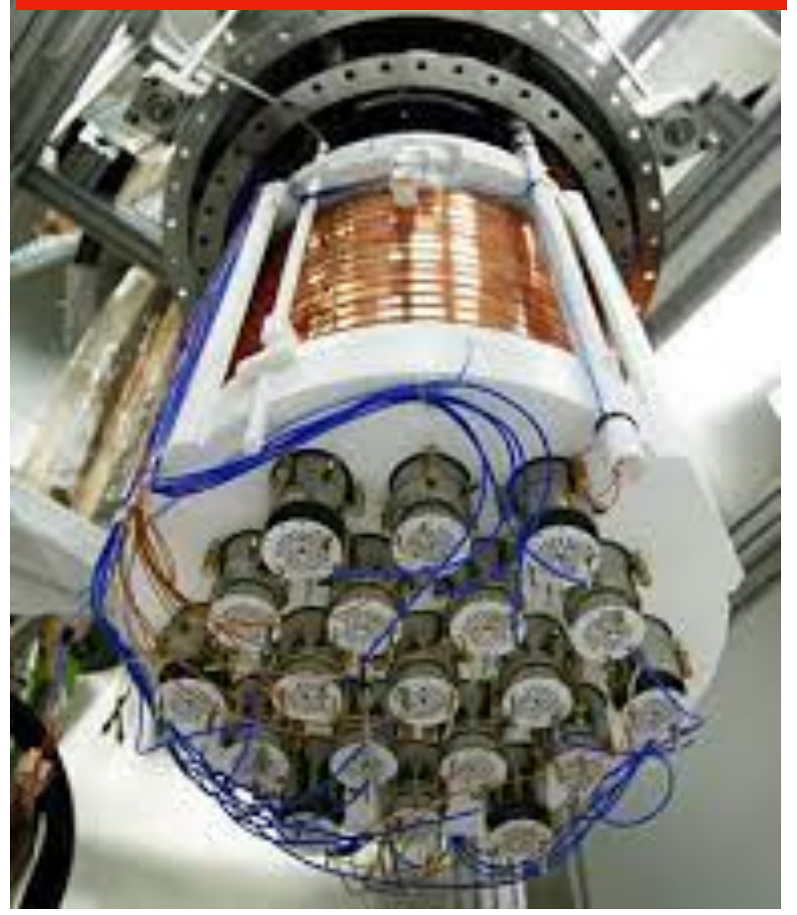
DarkSide-20k:
A global direct dark matter search experiment

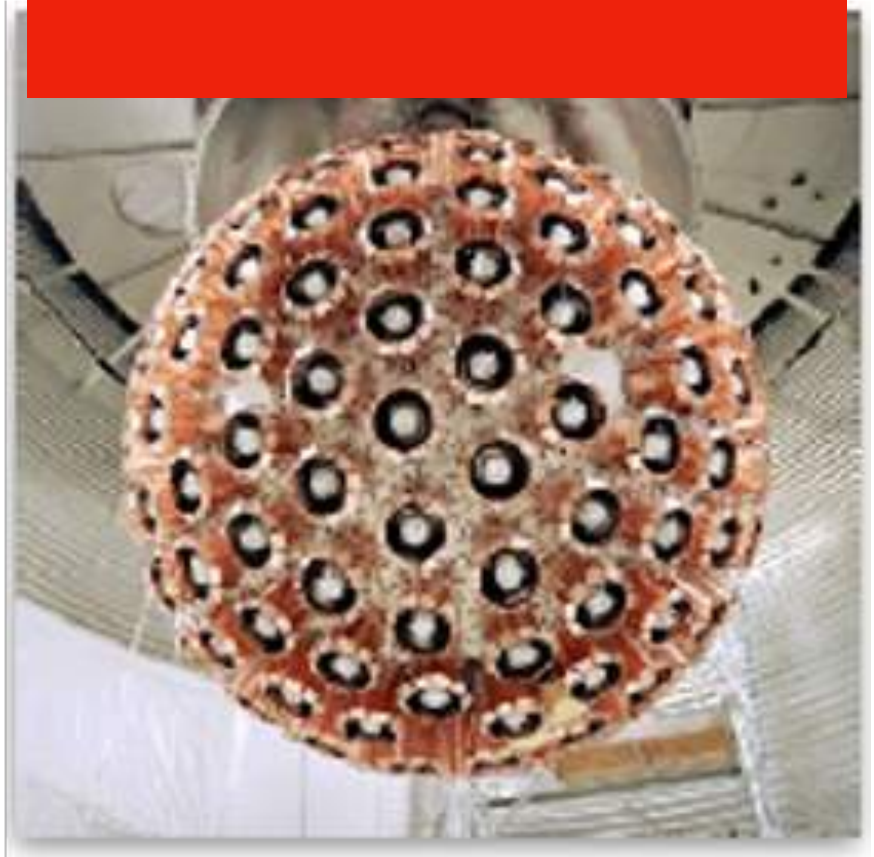
Daria Santone, University of Oxford
RAL PPD seminar, 06/03/2024

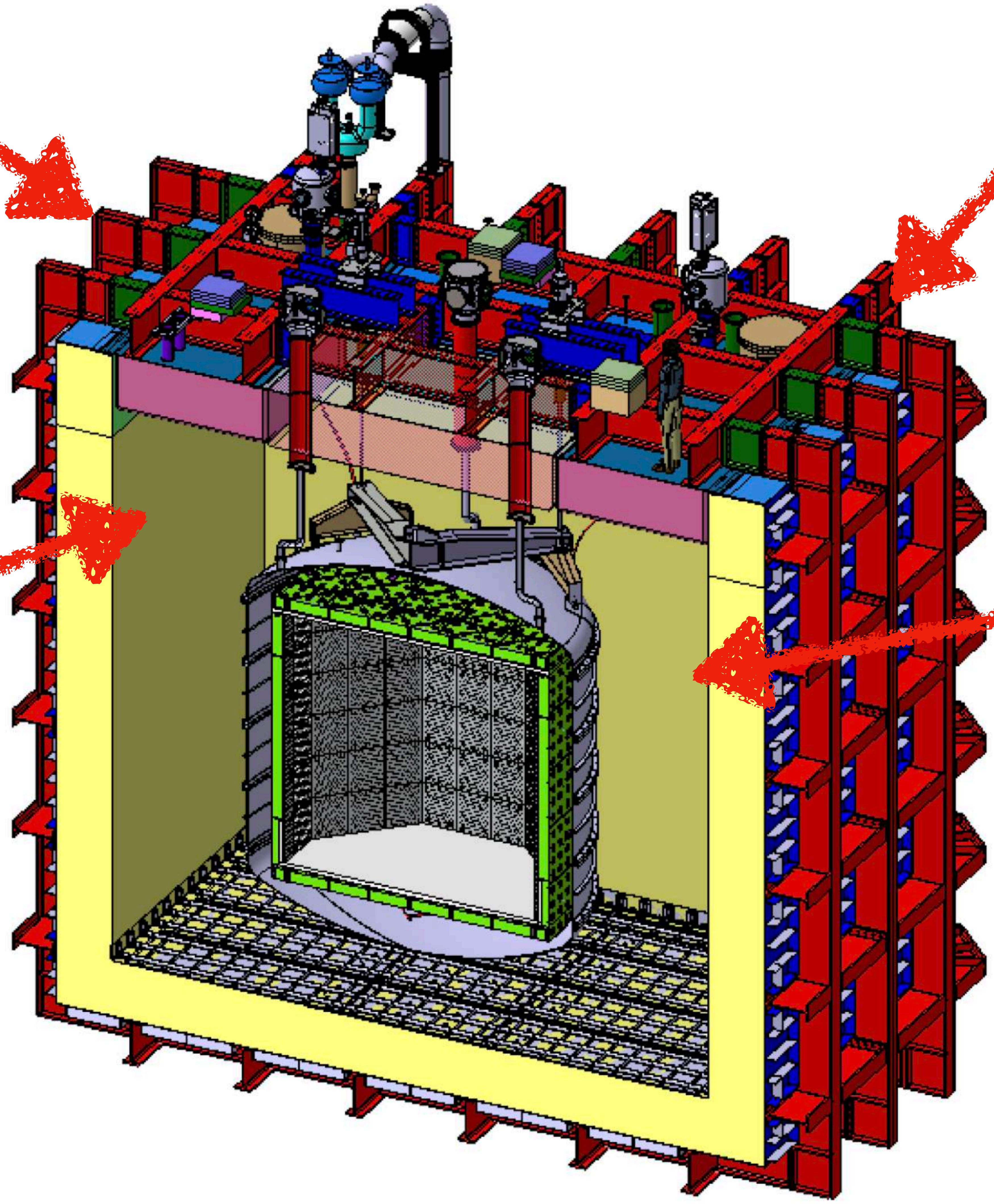
DARKSIDE-20k

DS-50 @LNGS



DEAP @SNOLAB





Miniclean @SNOLAB

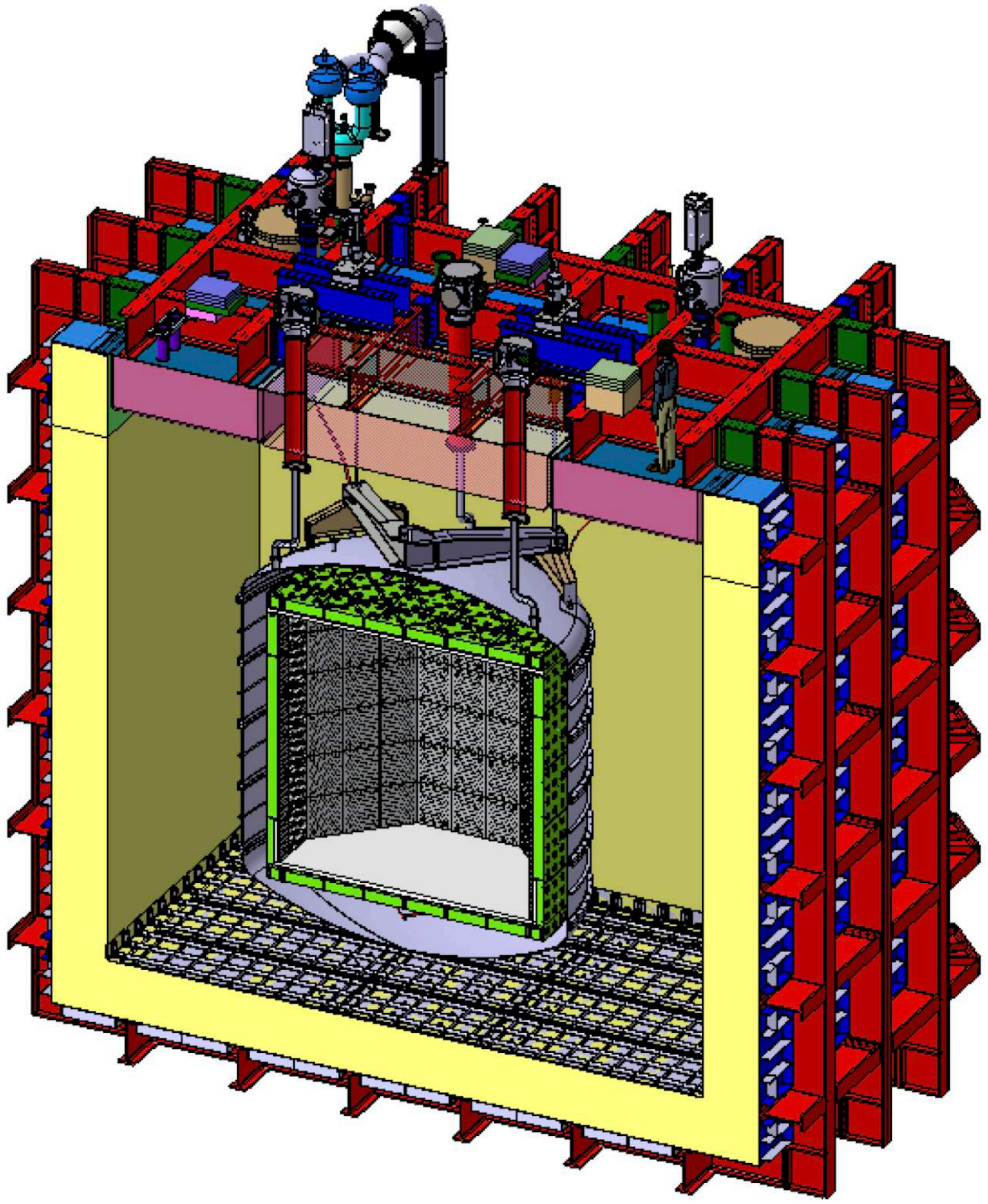
ArDM @CANFRANC

DARKSIDE-20k collaboration

Global Argon Dark Matter Collaboration (GADMC) is a joint effort among all dark matter experiments with Ar target: >400 collaborators from ~15 countries towards DarkSide-20k

OUTLINE

- Dark matter evidence
- Dark matter candidates and their detection
- New low mass results from DarkSide-50
- Darkside-20k:
    - Detector overview
    - Silicon photomultiplier (SiPMs) light detection system
    - Neutron veto design optimisation

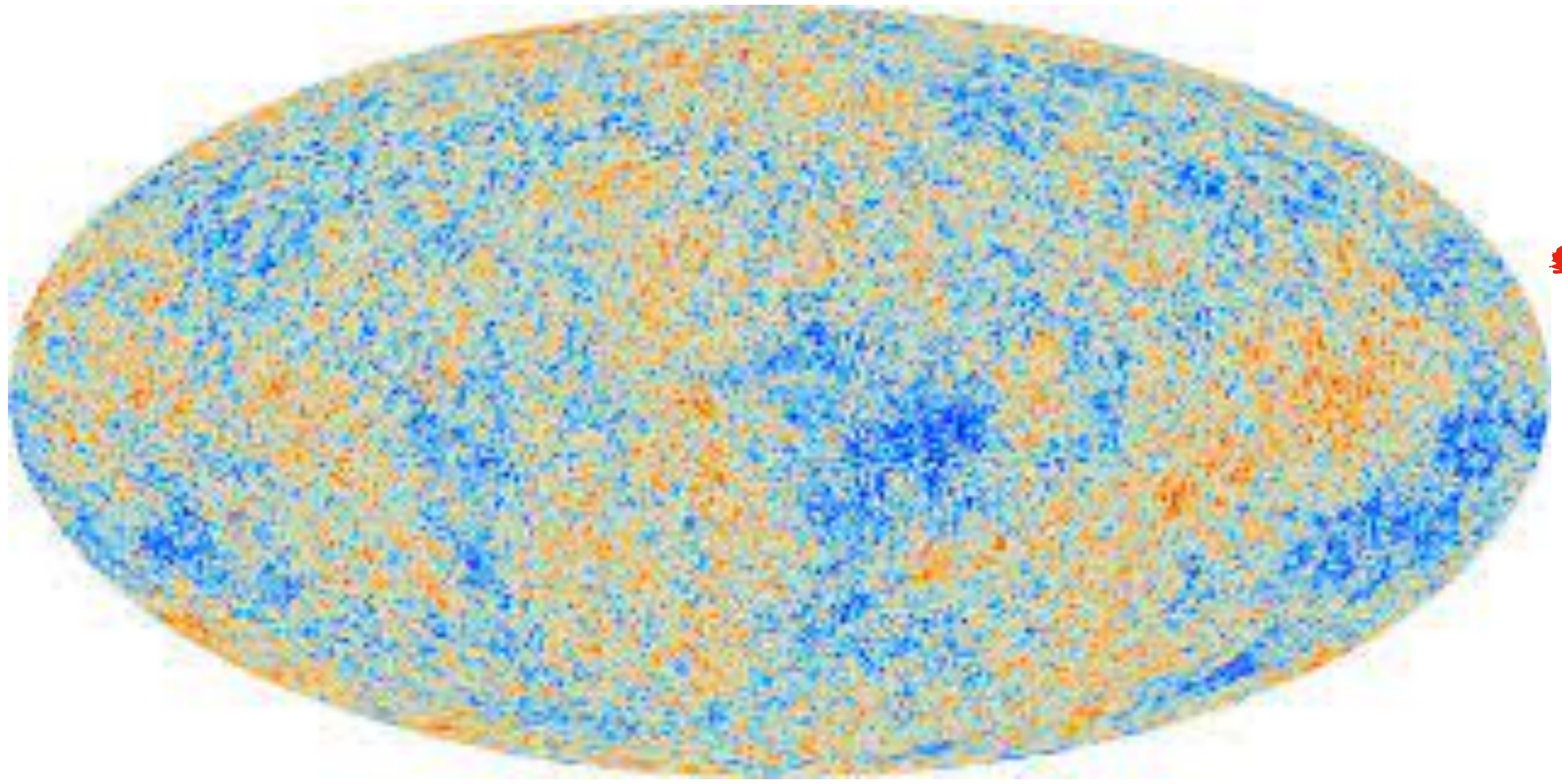


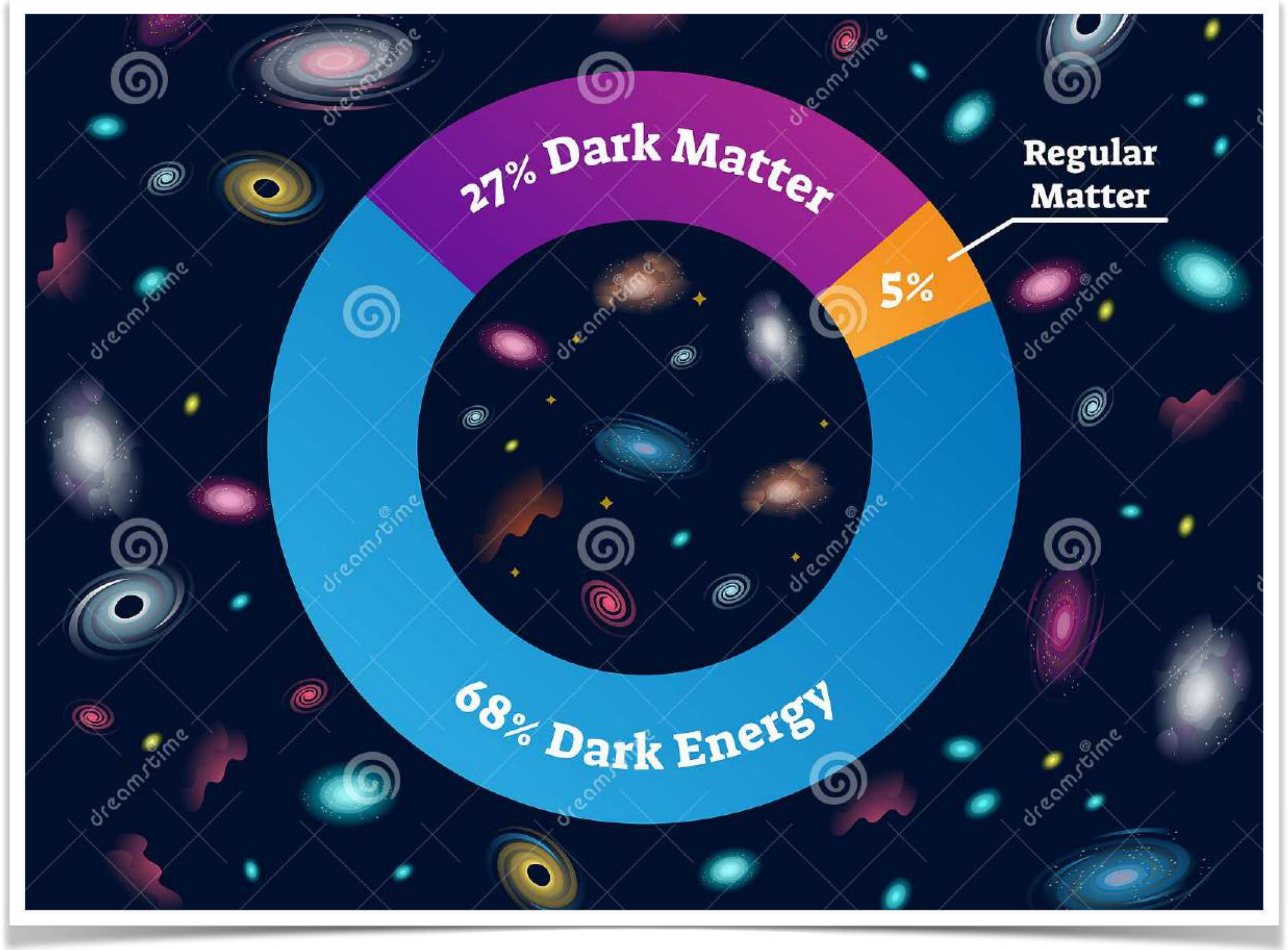
DARK MATTER EVIDENCE

Cluster galaxies

Gravitation lensing

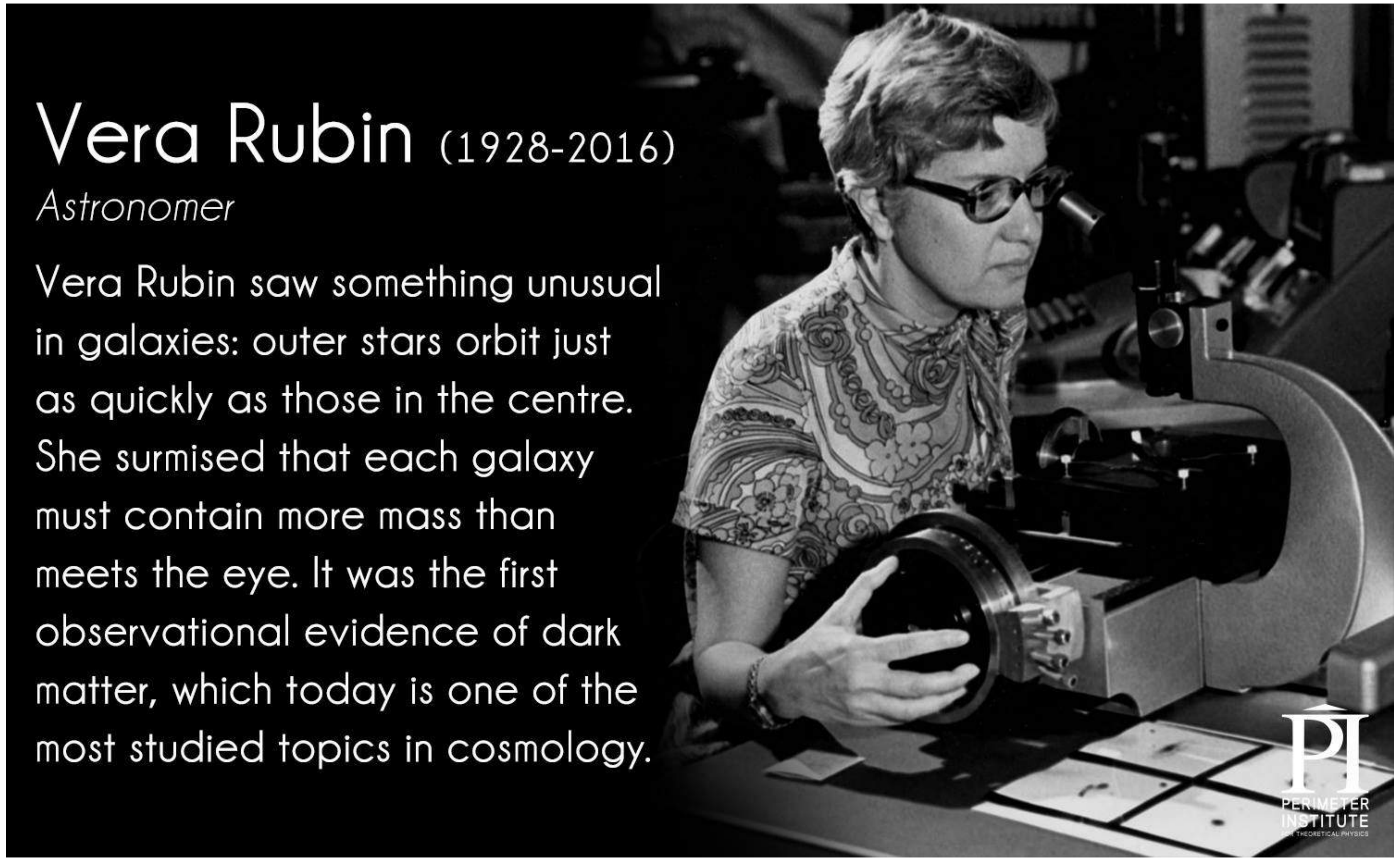
CMB observation

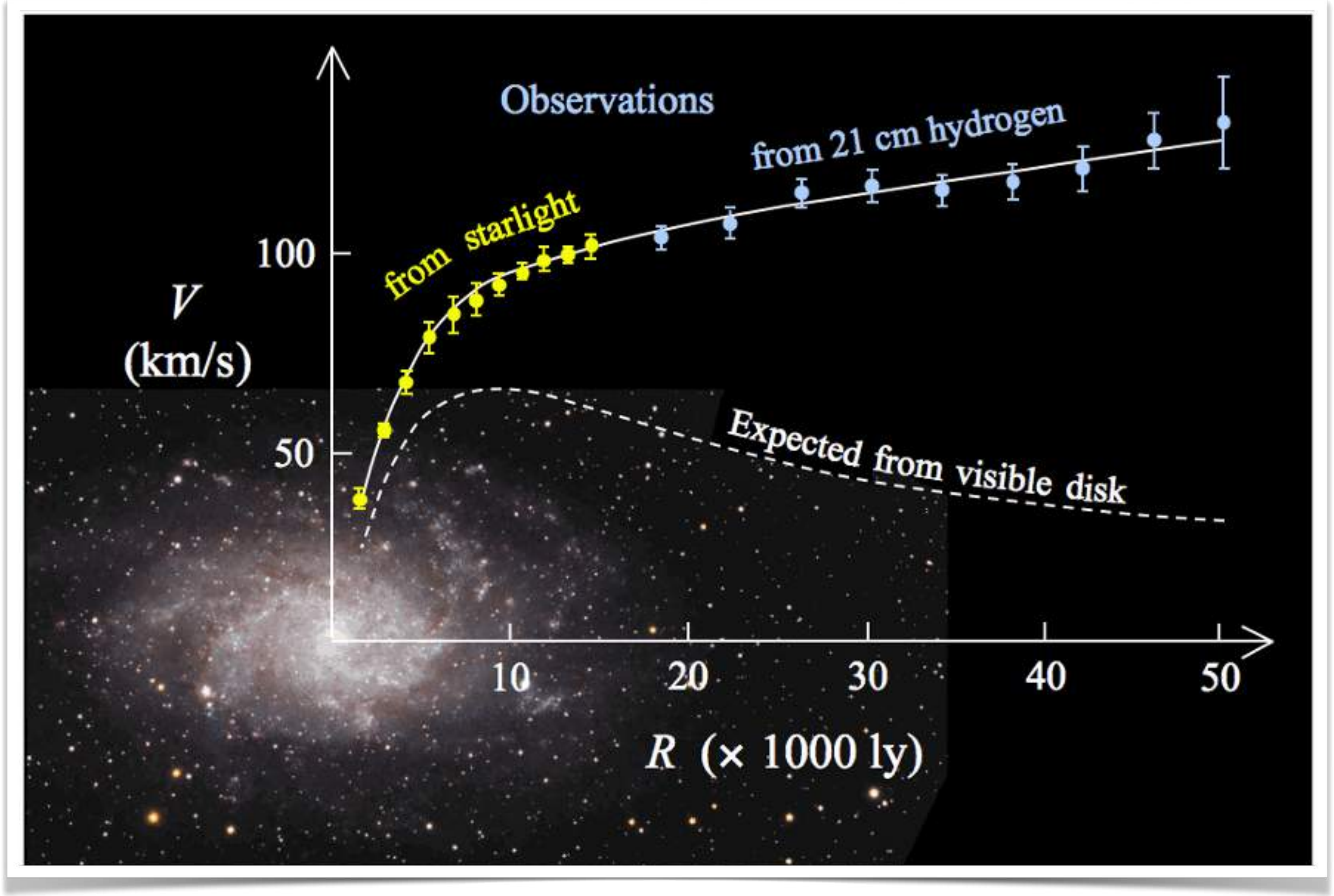




DARK MATTER EVIDENCE (2)

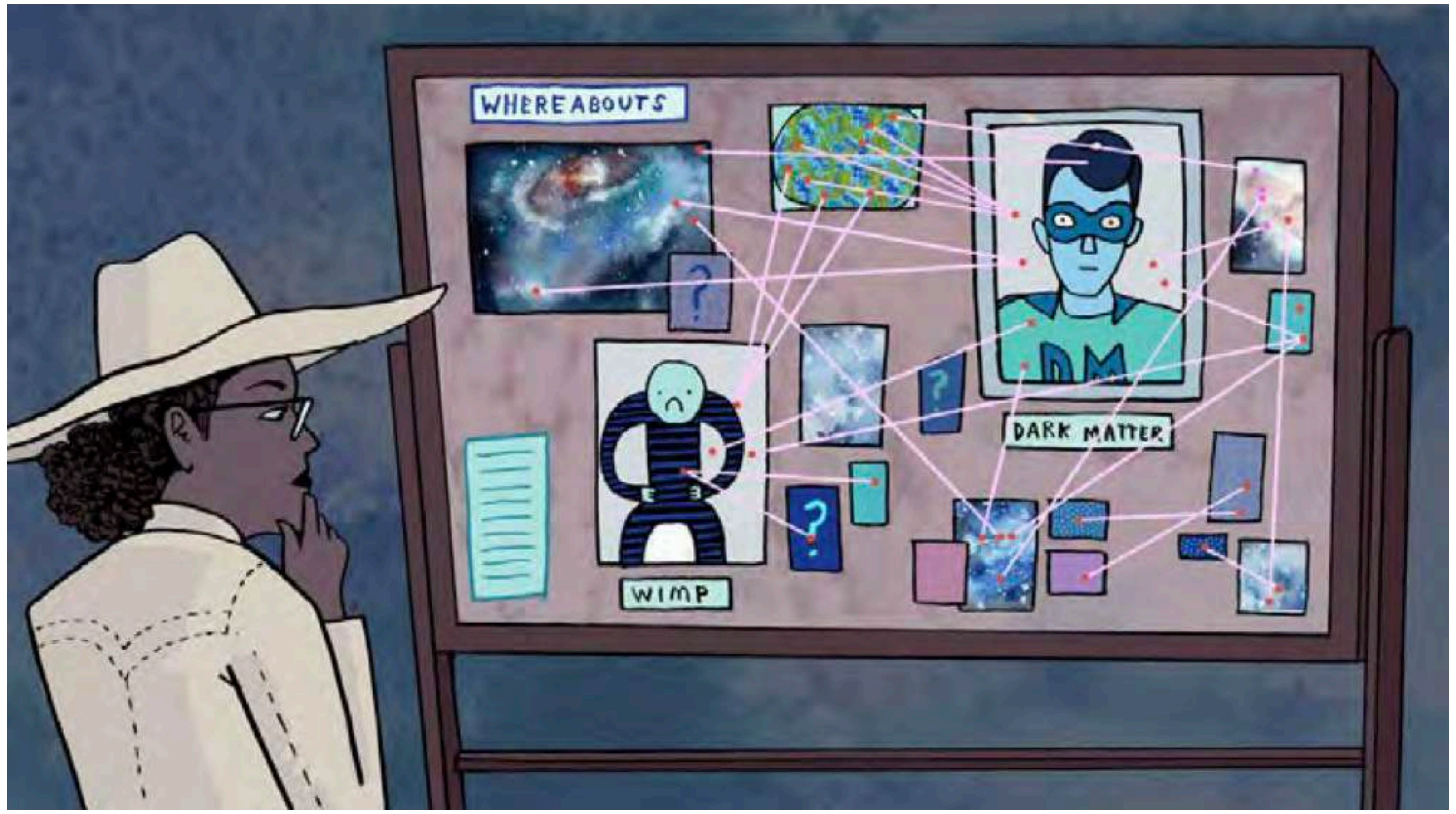
1960 - 1970: Dark matter observation in spiral galaxies





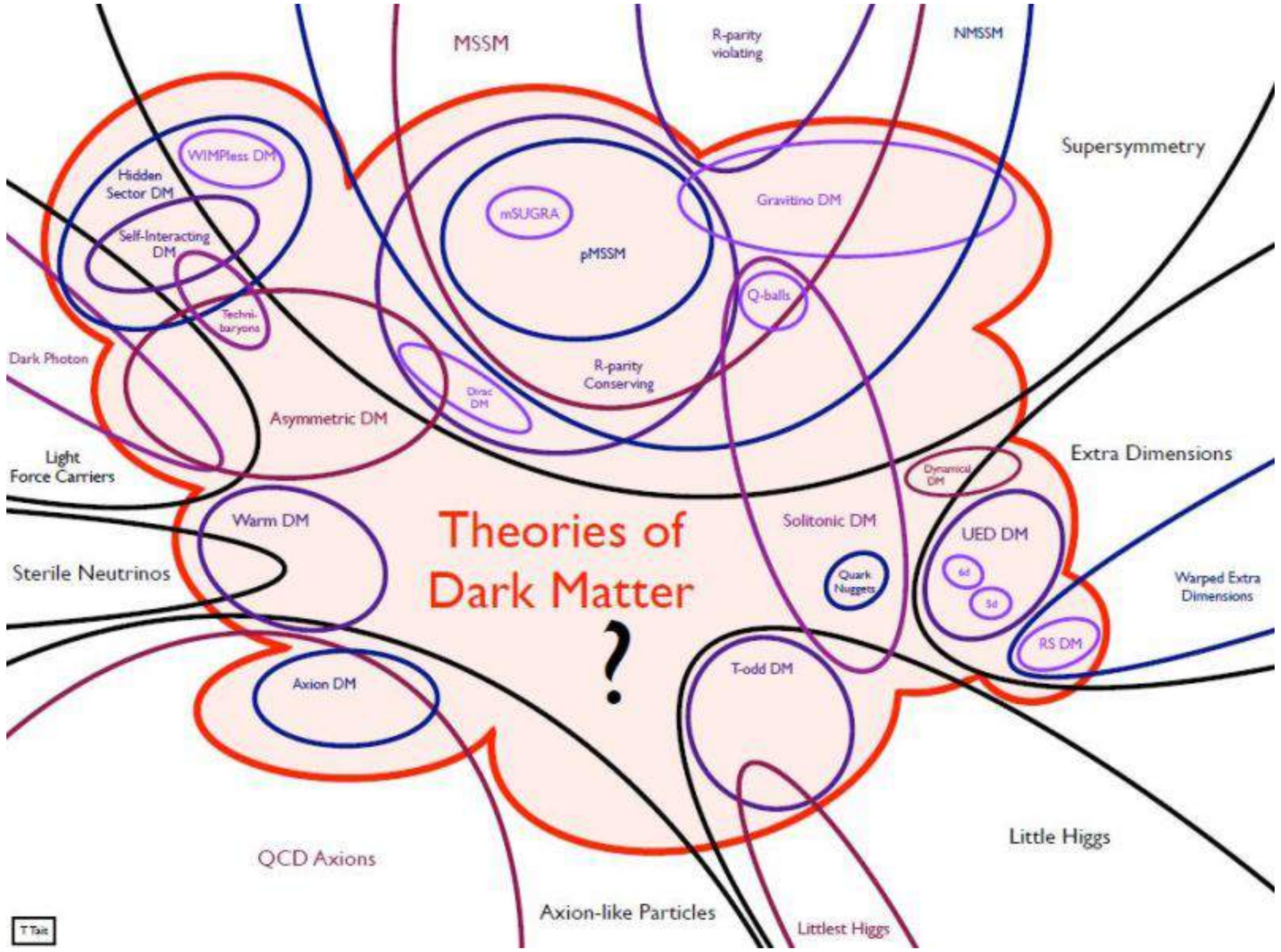
DARK MATTER PROPERTIES

- *Dark*: does not interact electromagnetically
- *Stable*: very long lived
- *Cold*: not relativistic at freeze-out
- Only gravitationally, or, very weakly interacting
- Local density around 0.3 GeV/cm^3



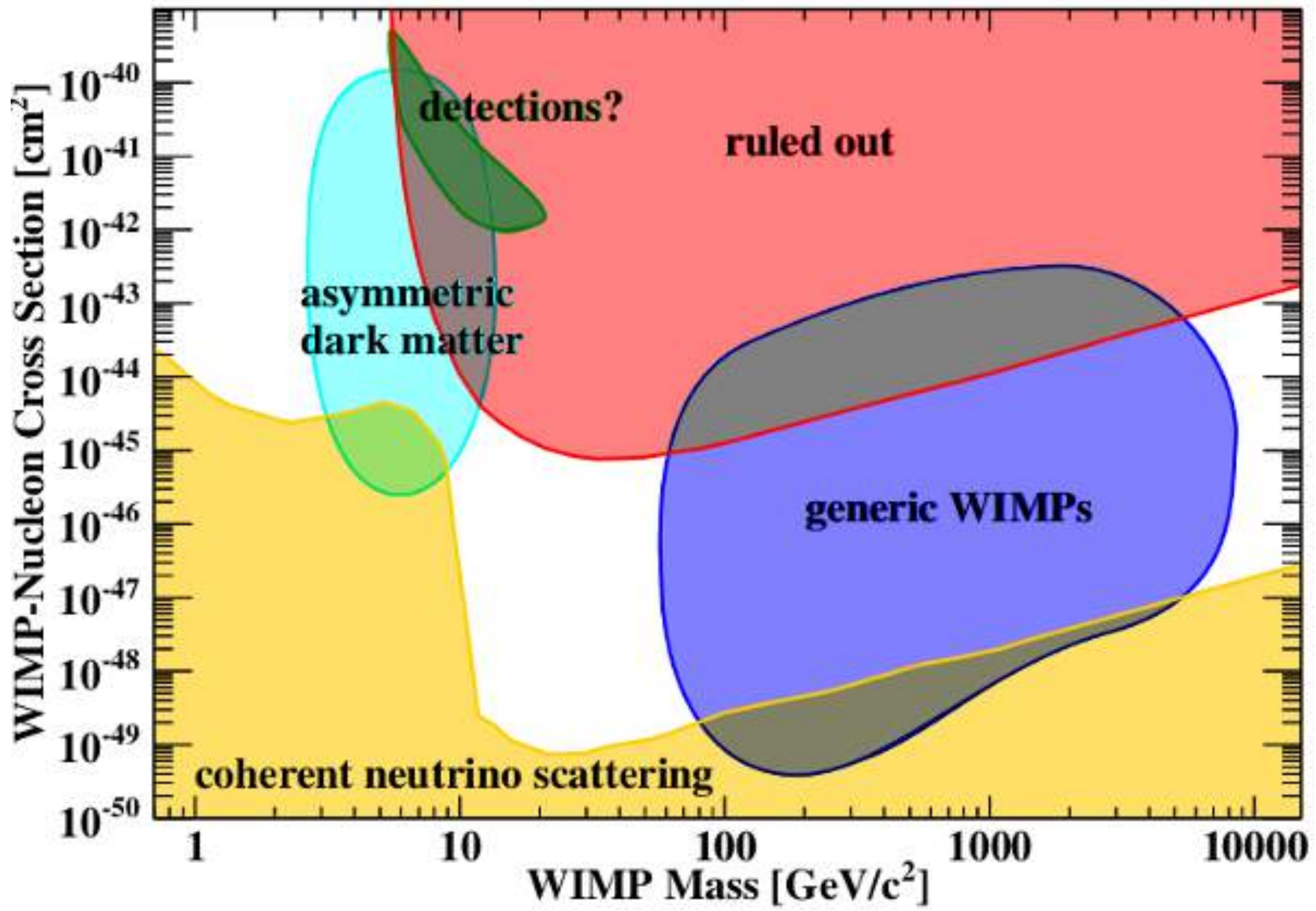
Beyond the Standard Model
of Particle Physics

DARK MATTER CANDIDATES

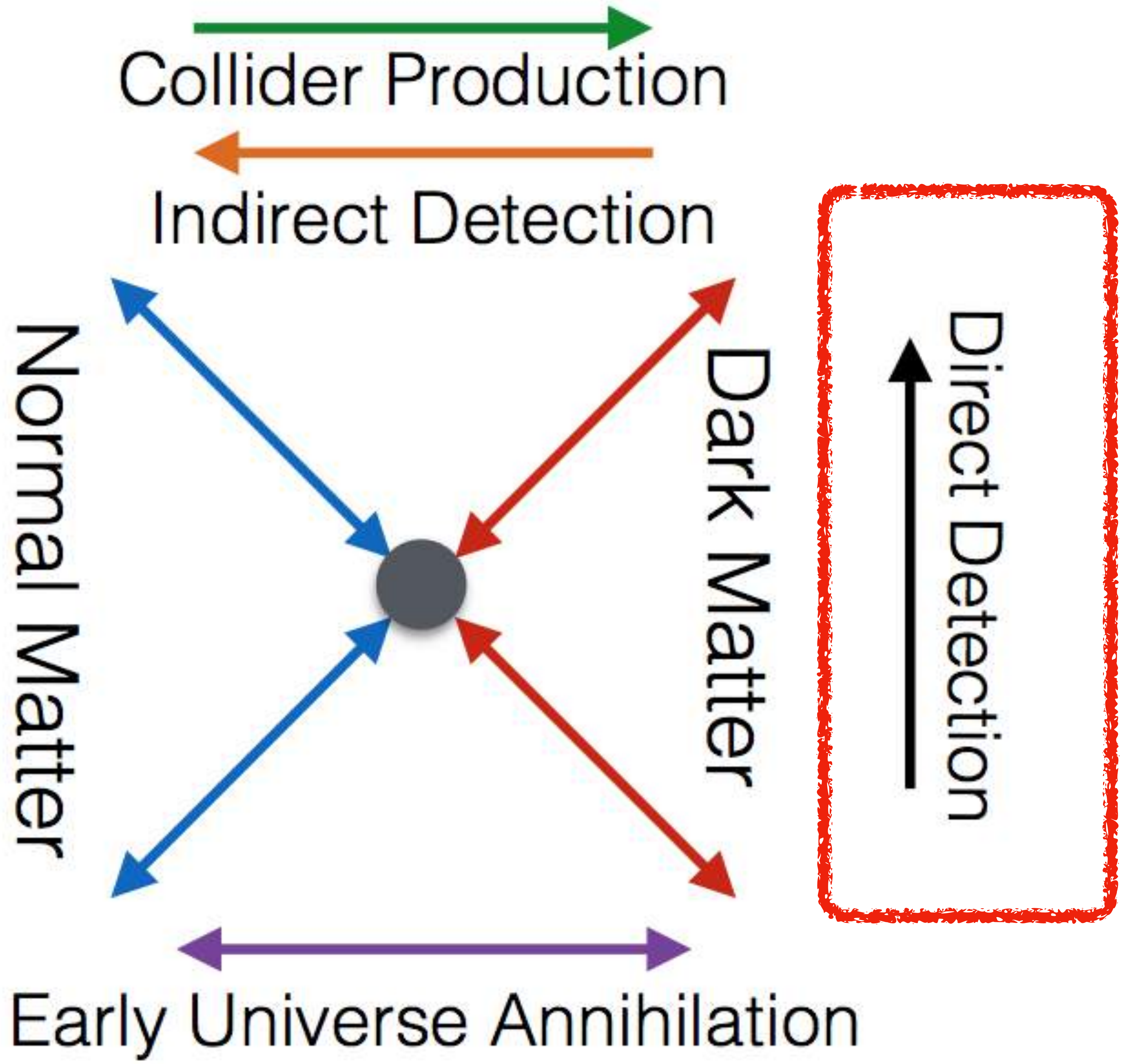


WIMP “Miracle"

- Weak scale interaction lead to correct density in the universe
- Mass scale: MeV - 100 TeV
- Motivated by many theories



DARK MATTER DETECTION

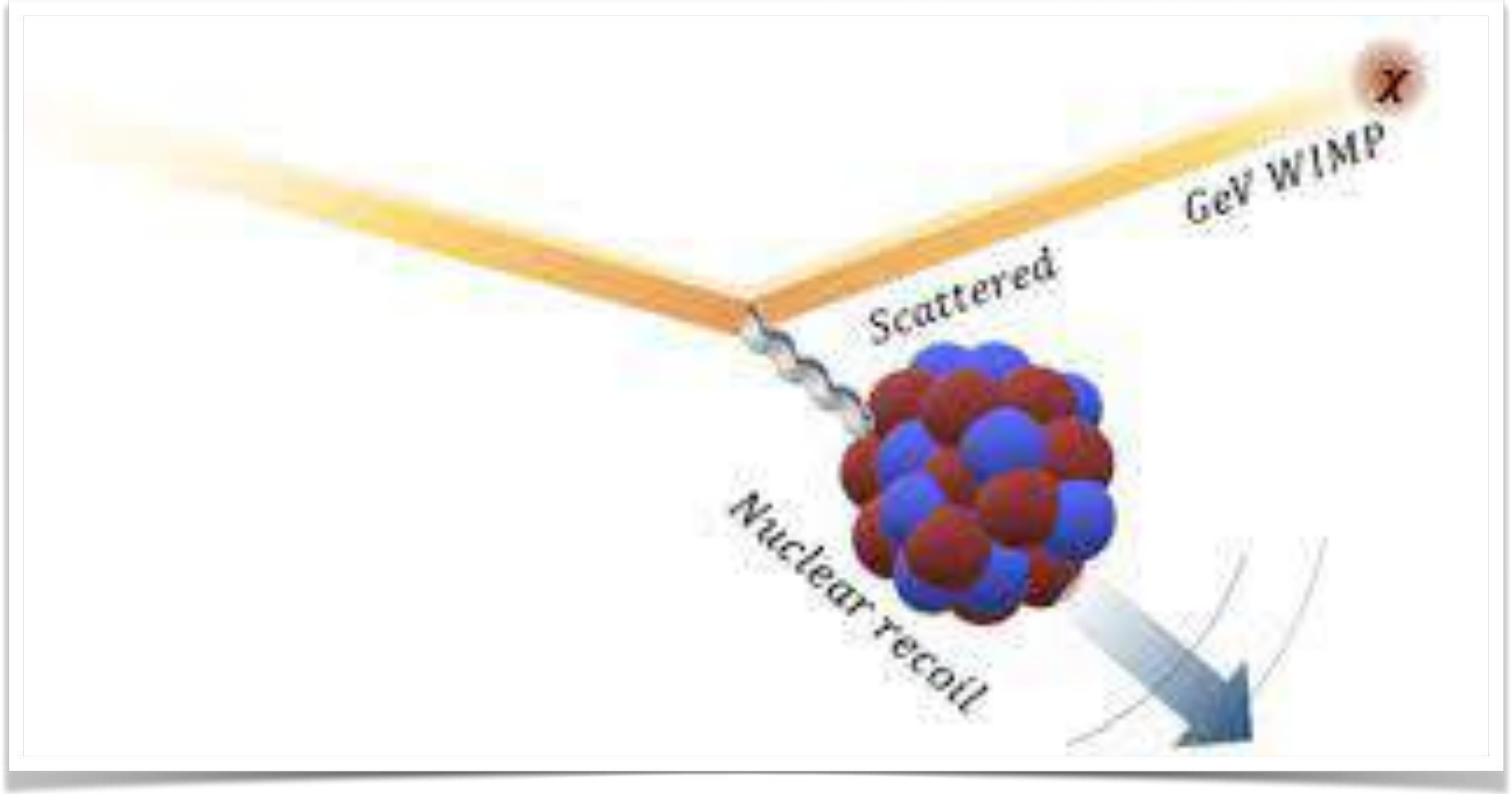


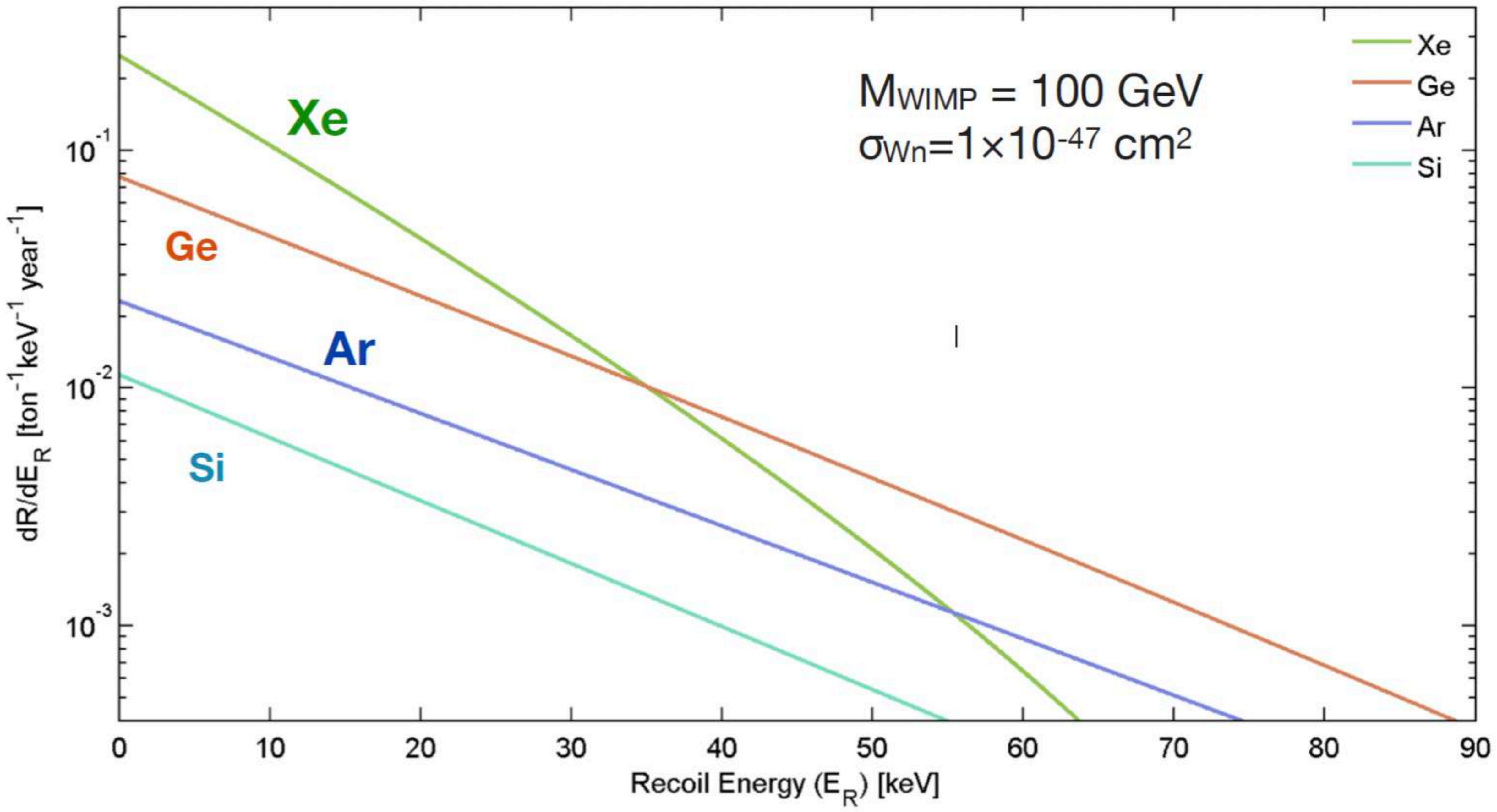
DIRECT DETECTION

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

Interaction rates depend on:

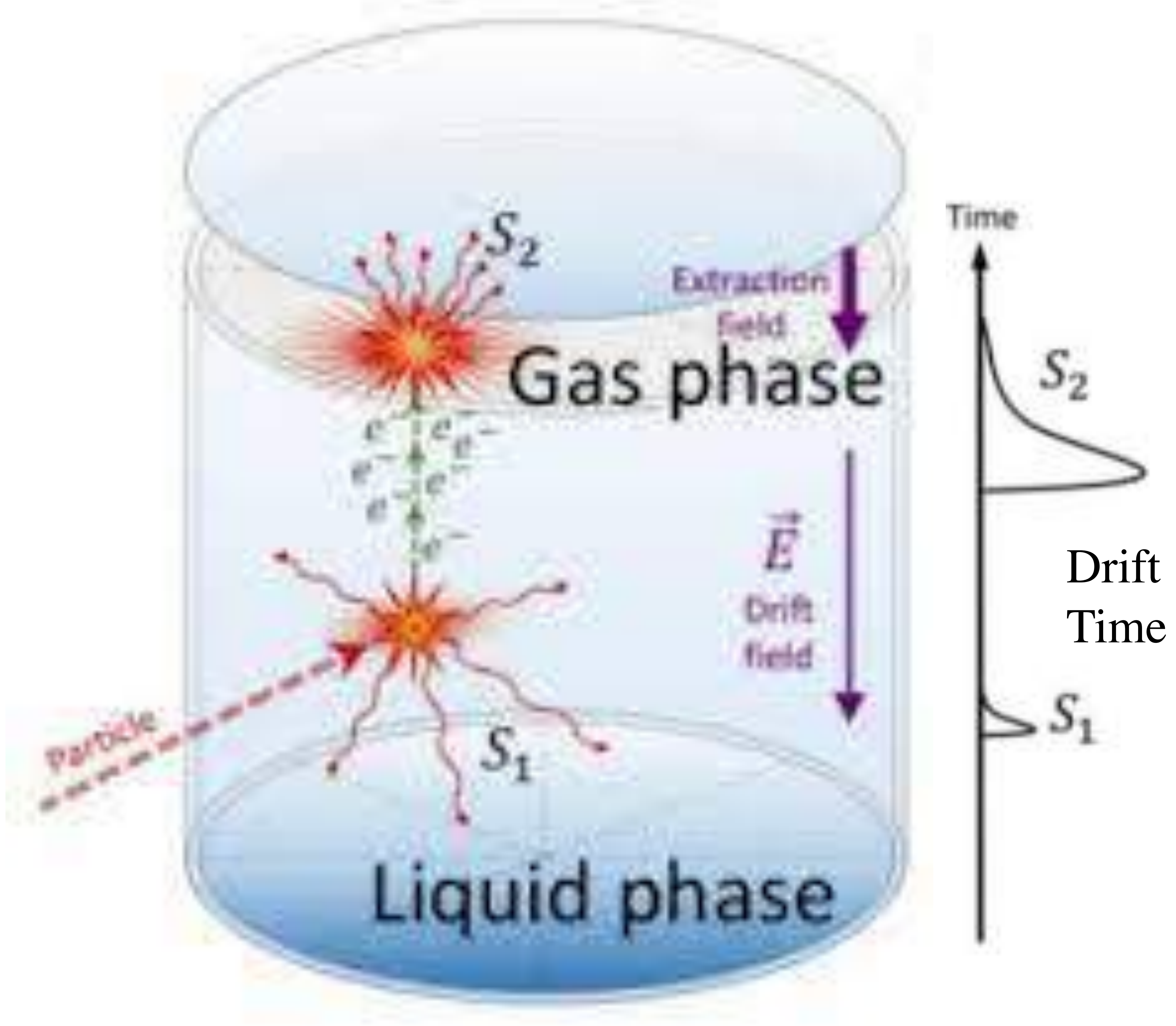
- Our model of how the sun and heart move through the galaxy
- How fast earth travel relative to WIMPs





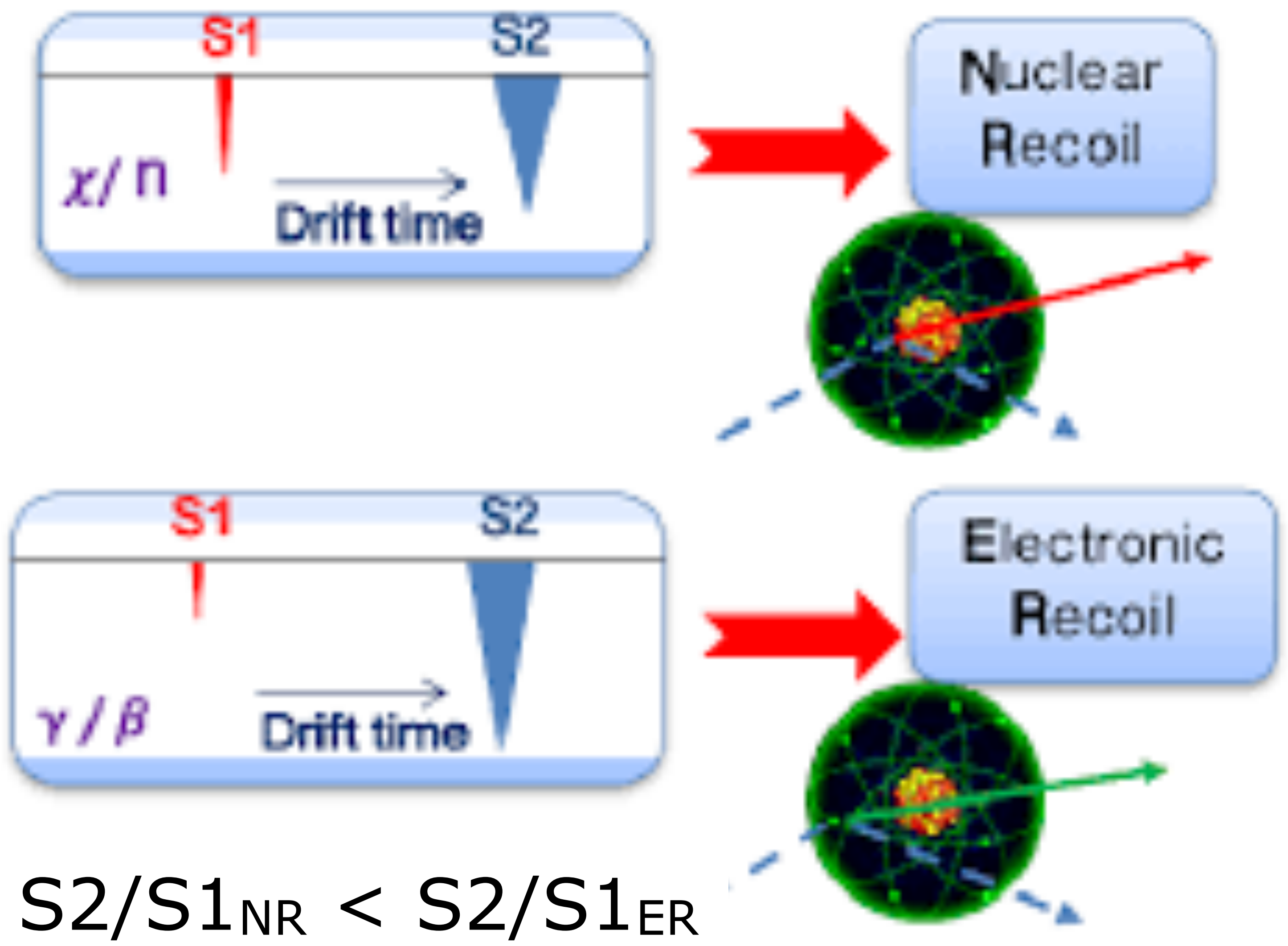
DARK MATTER SEARCH IN DARKSIDE

Dual phase Time projector Chamber (TPC)



DarkSide Target material: liquid Ar from underground (UAr)

- Signal: S1 (primary scintillation) + S2 (charge signal)
- S2 light pattern gives x-y position
- Drift time give z position
- S1-S2 relative size give particle information

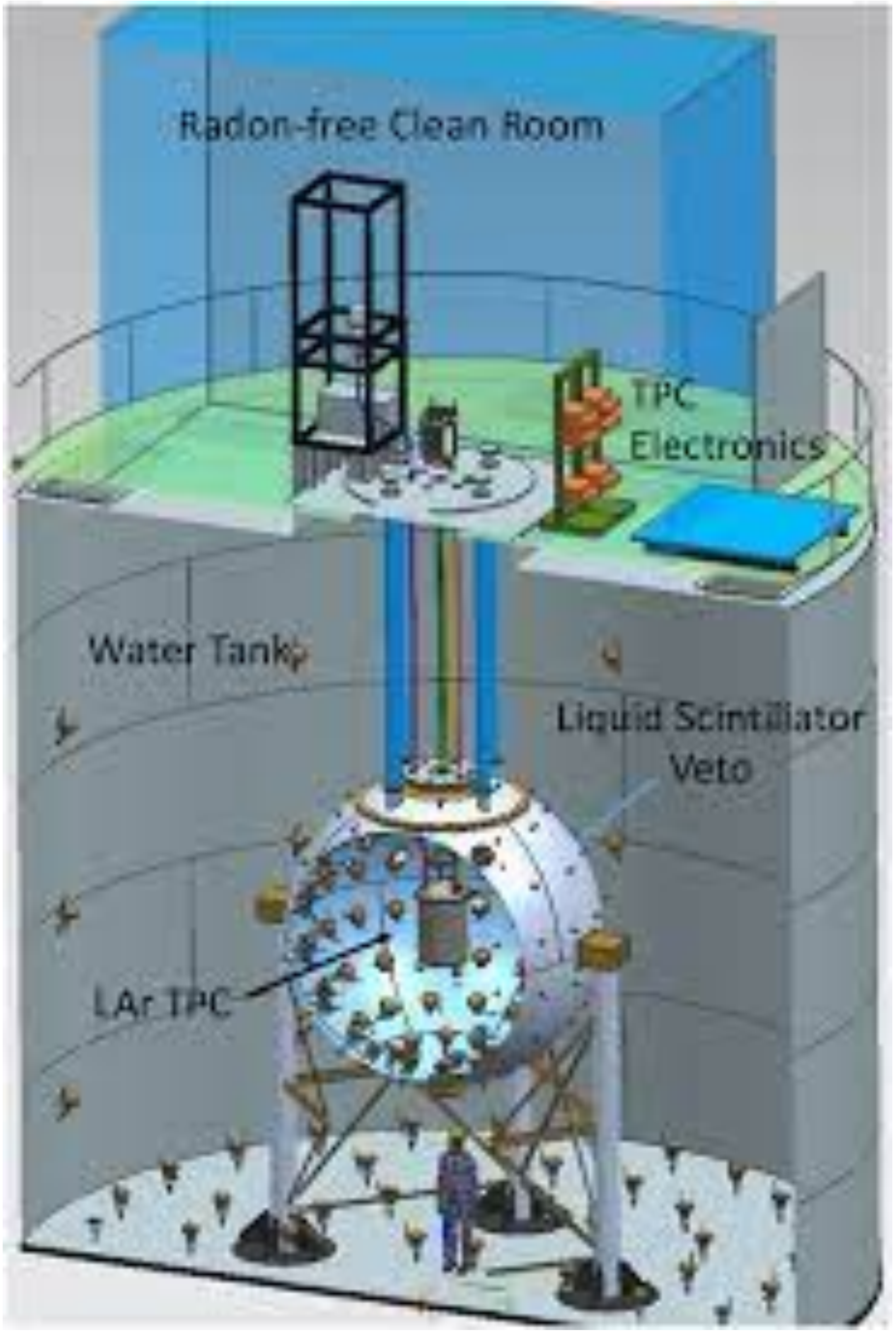


$S2/S1_{NR} < S2/S1_{ER}$

LOW MASS DARK MATTER SEARCH

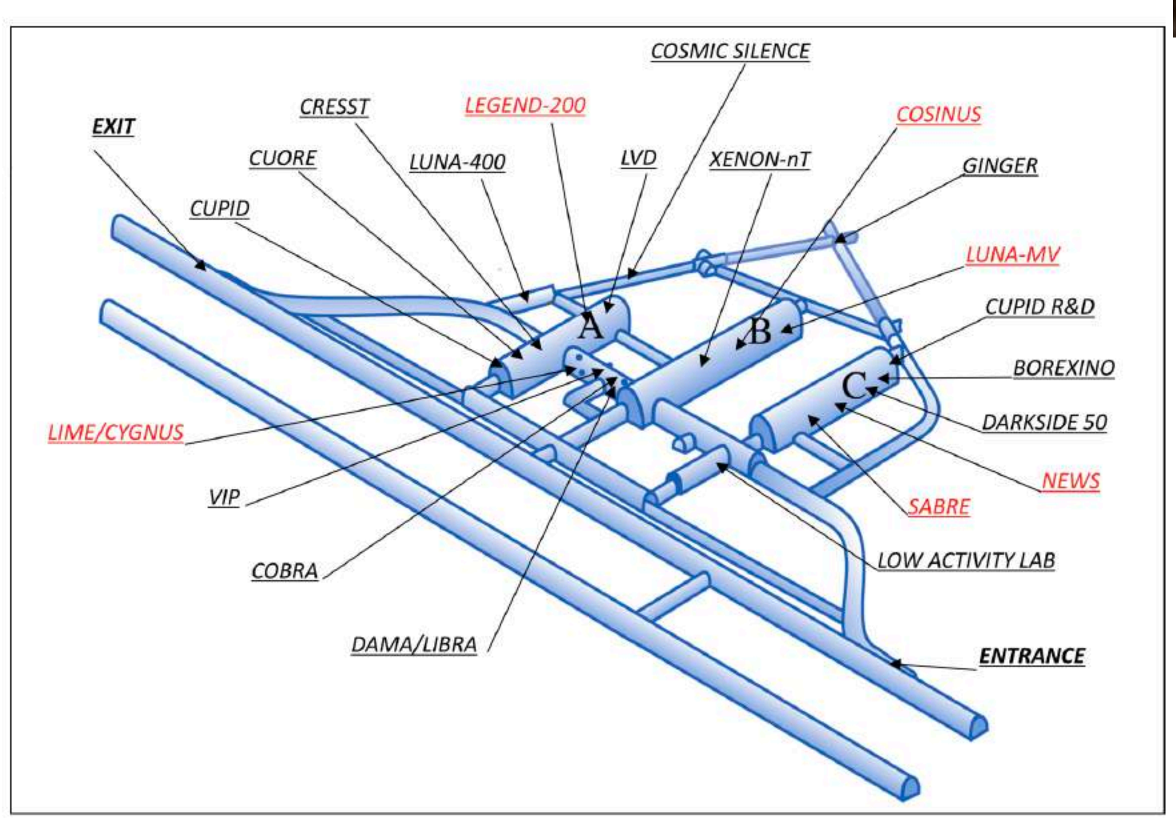
DARKSIDE-50

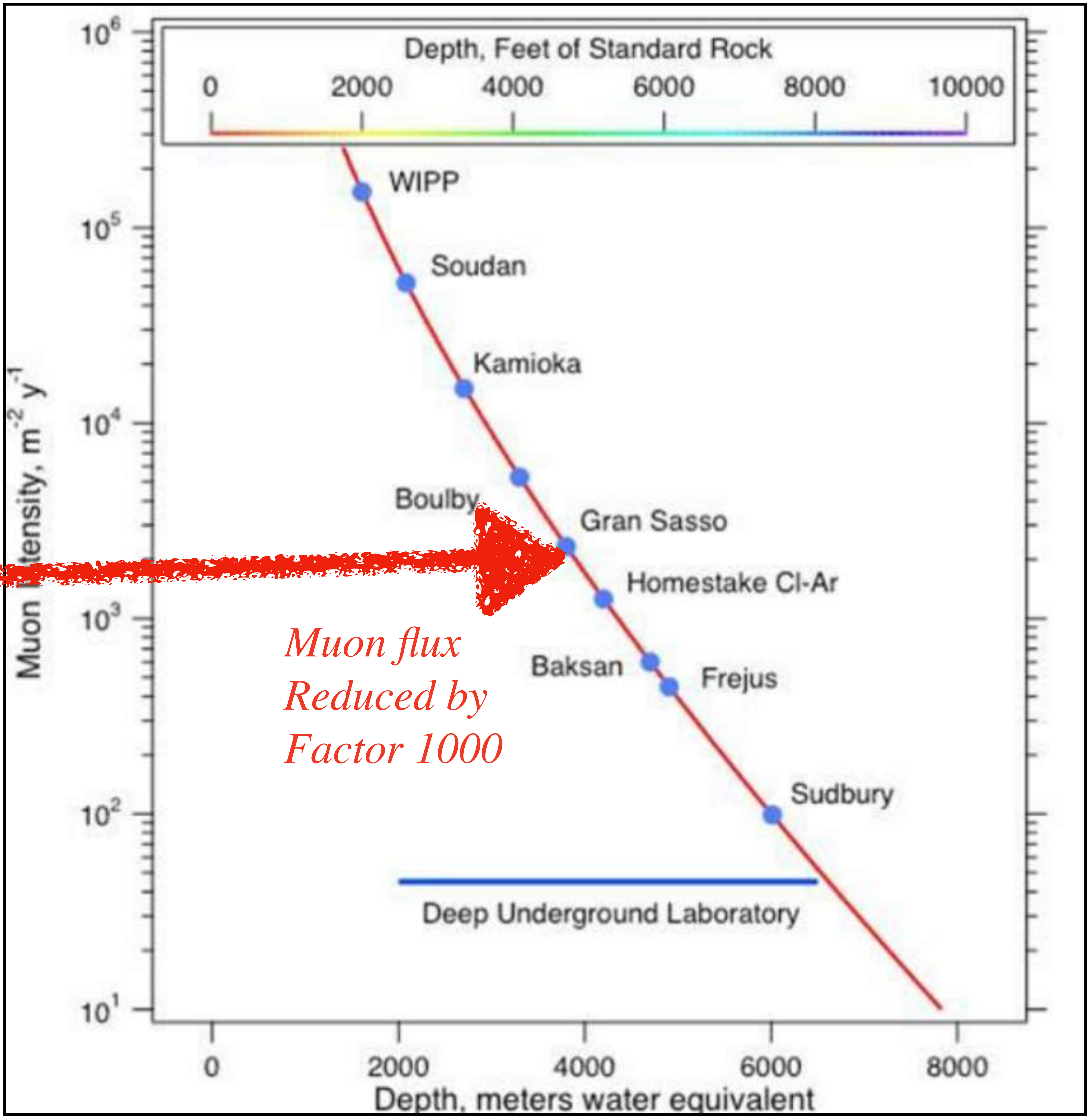
- Dual phase liquid argon filled with 50 kg of Underground Argon (UAr)
- Light detector: PhotoMultiplier (PMTs)
- Veto:
    - Liquid scintillator as neutron moderator
    - Water Cherenkov as cosmogenic veto
- Data taking: 2013 - 2018, total exposure of 0.03 tons x years
- **Low mass search: [1.2, 3.6] GeV/c^2 WIMP mass range**



LABORATORI NAZIONALI DEL GRAN SASSO (LNGS)

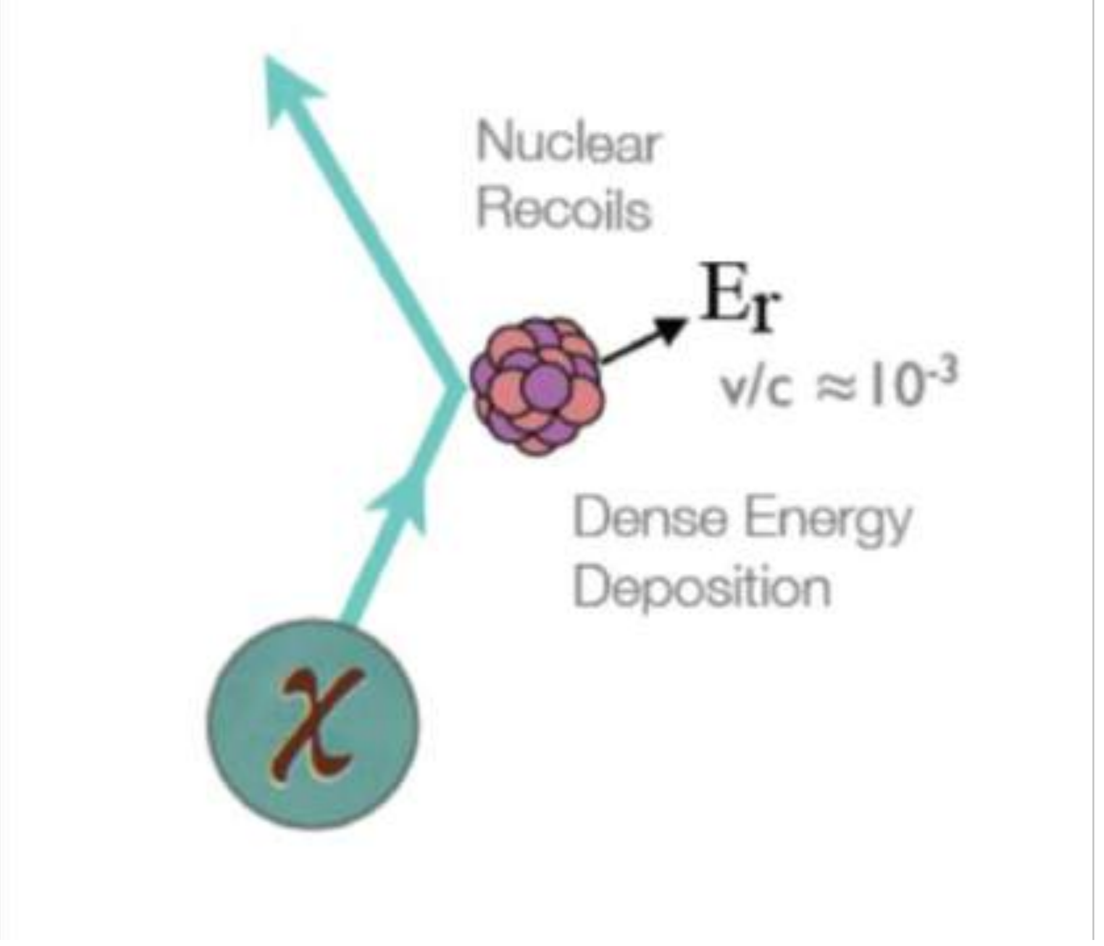
DarkSide is located in HALL C at LNGS, Italy
At 3400 m of water equivalent





WIMP SIGNAL & BACKGROUNDs

WIMP SIGNAL



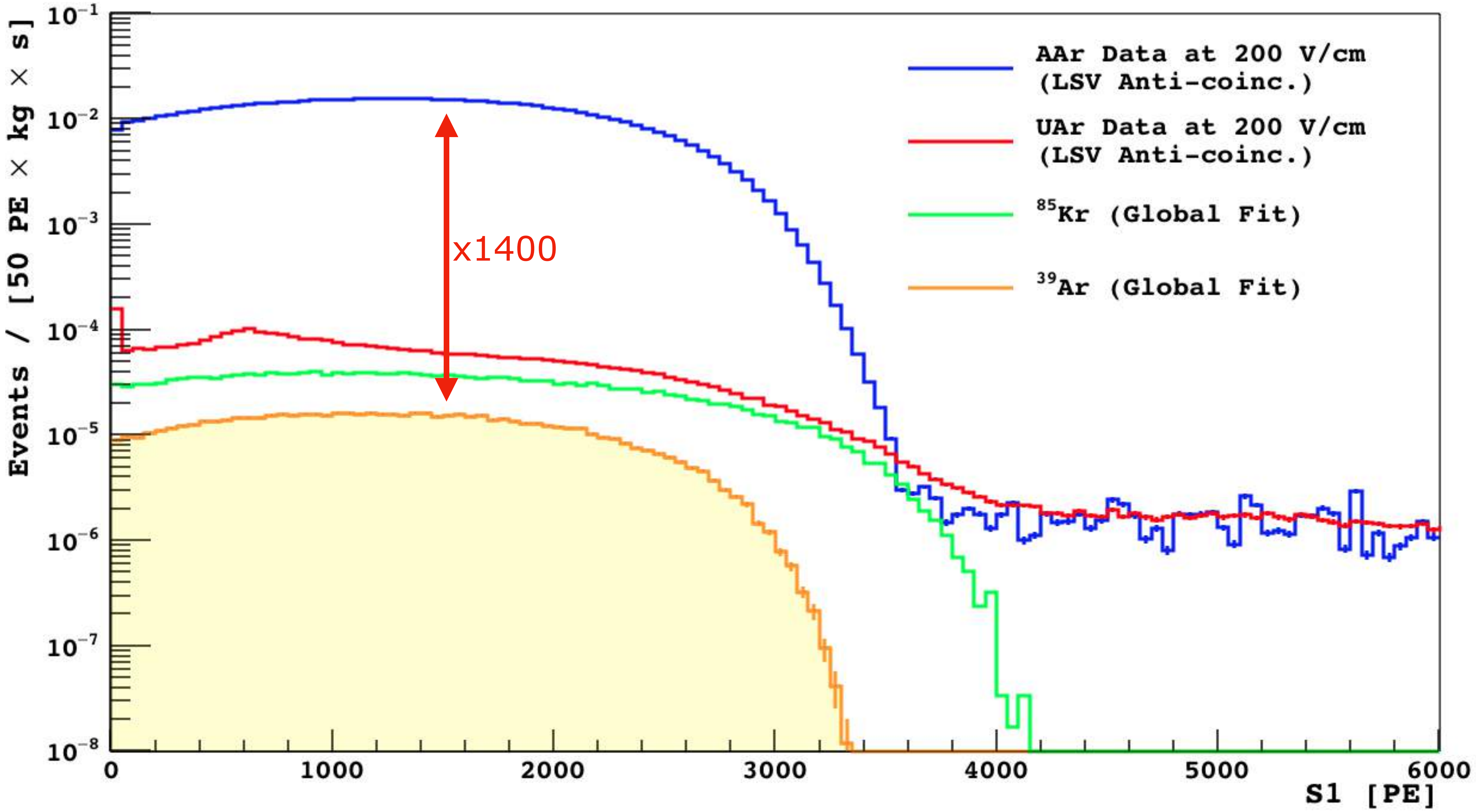
- Single nuclear recoil
- Energy recoil between 1 and 100 keV

BACKGROUND

Background source	Mitigation strategy
39Ar β decay	Use Underground Argon + pulse shape discrimination
γ from rock and γ,e from material	Pulse shape discrimination Selection material
Radiogenic neutron (α,n) reaction in detector material	Material screening & selection Definition of Fiducial volume in the TPC **Veto to reject neutron signal**
Surface contamination due Rn progeny	Surface cleaning Reduce the number of surfaces Installation of Rn abated system
Muon induced background	Cosmogenic veto
Neutrino coherent scatter	Irreducible

UNDERGROUND ARGON(UAr)

TPC and veto are filled with UAr in order to reduce Ar-39, which is produced in Atmospheric Argon by **cosmogenic activation** with activity ~ 1 Bq/kg.It is a beta emitter with **endpoint to 565 keV** and **half life of 269 years**.

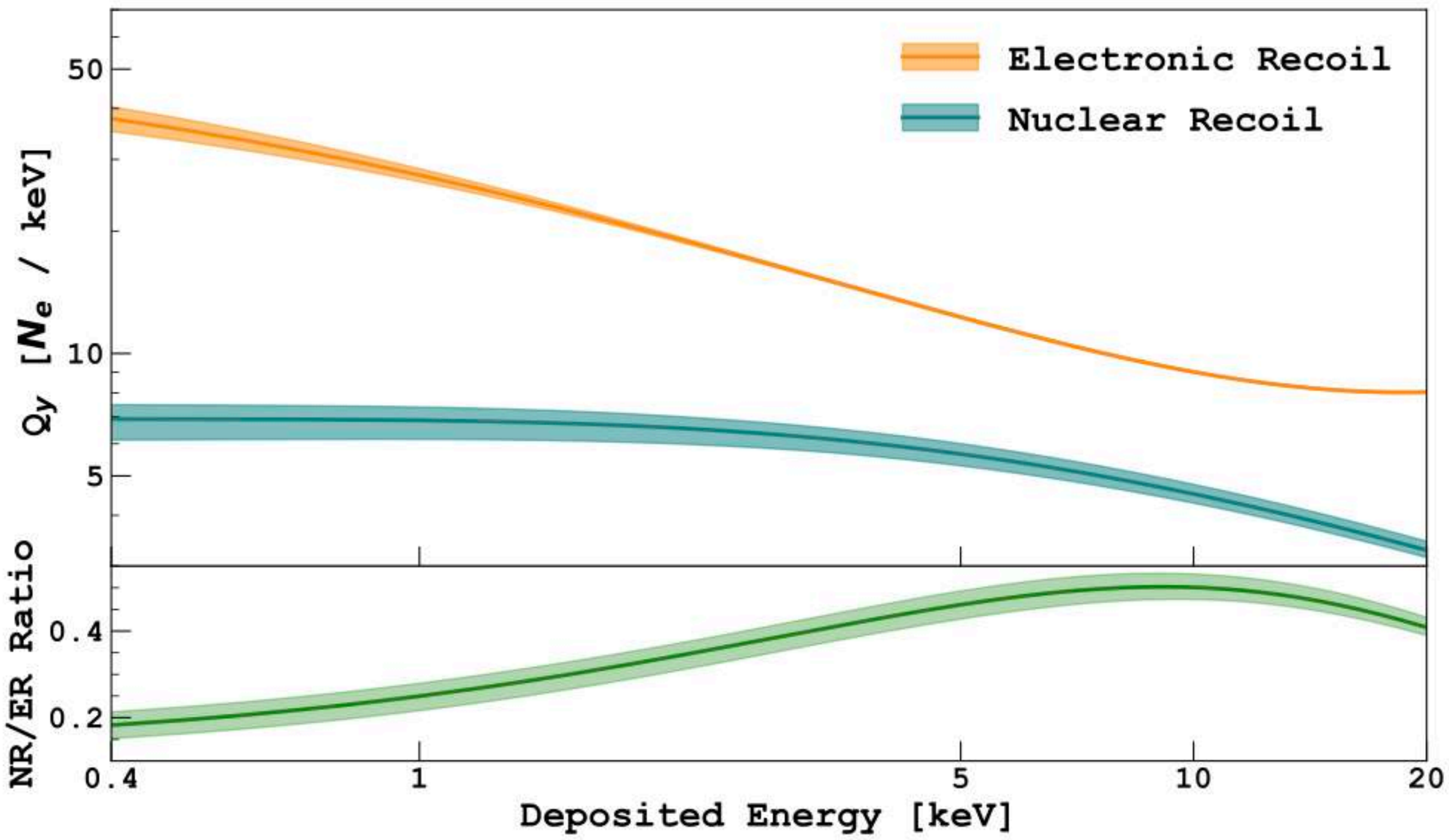


DS-50 results: Phys. Rev. D 93, 081101(R) (2016)

WIMP NUCLEON INTERACTION

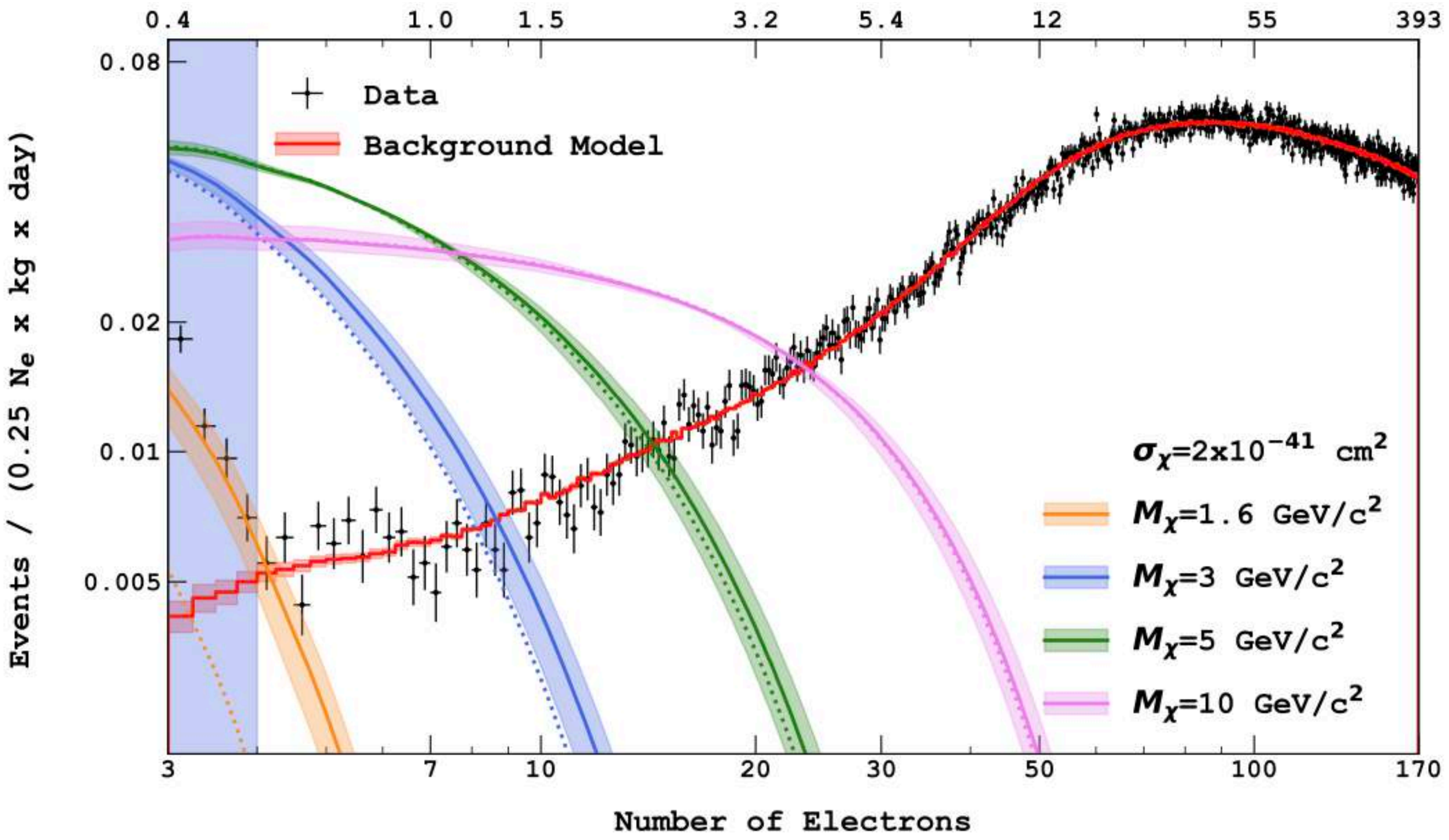
Re-analyse the full DS50 dataset with a more detailed calibration model

Phys. Rev. Lett. 130, 101001



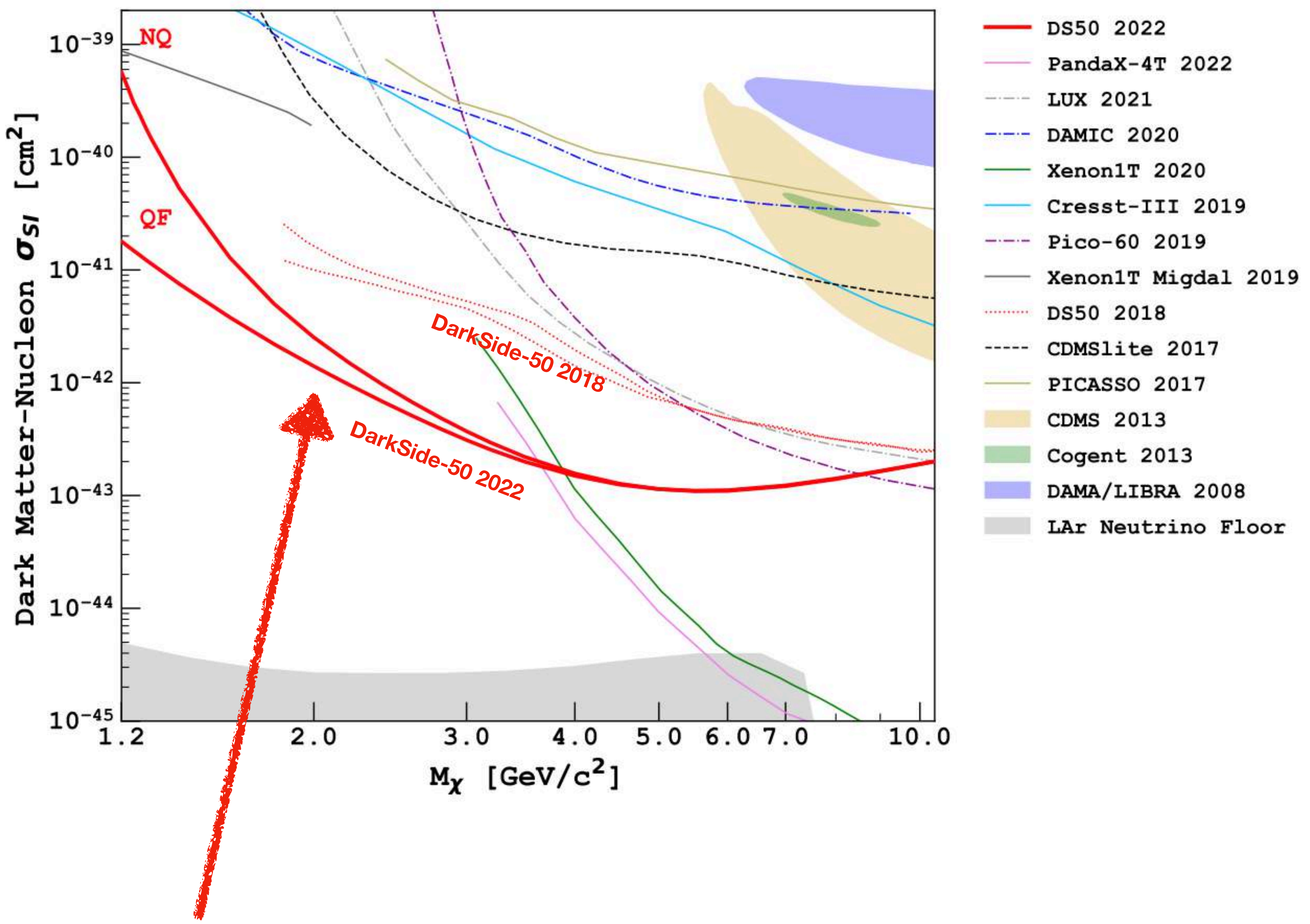
- Electron recoil modelling using ^{37}Ar, ^{39}Ar decay naturally in the early LAr dataset, focus on ionisation signal below 180 eV_{er}
- Nuclear recoil from in-situ neutron calibration (AmC), energy down to 500 eV_{nr}

LOW MASS RESULTS



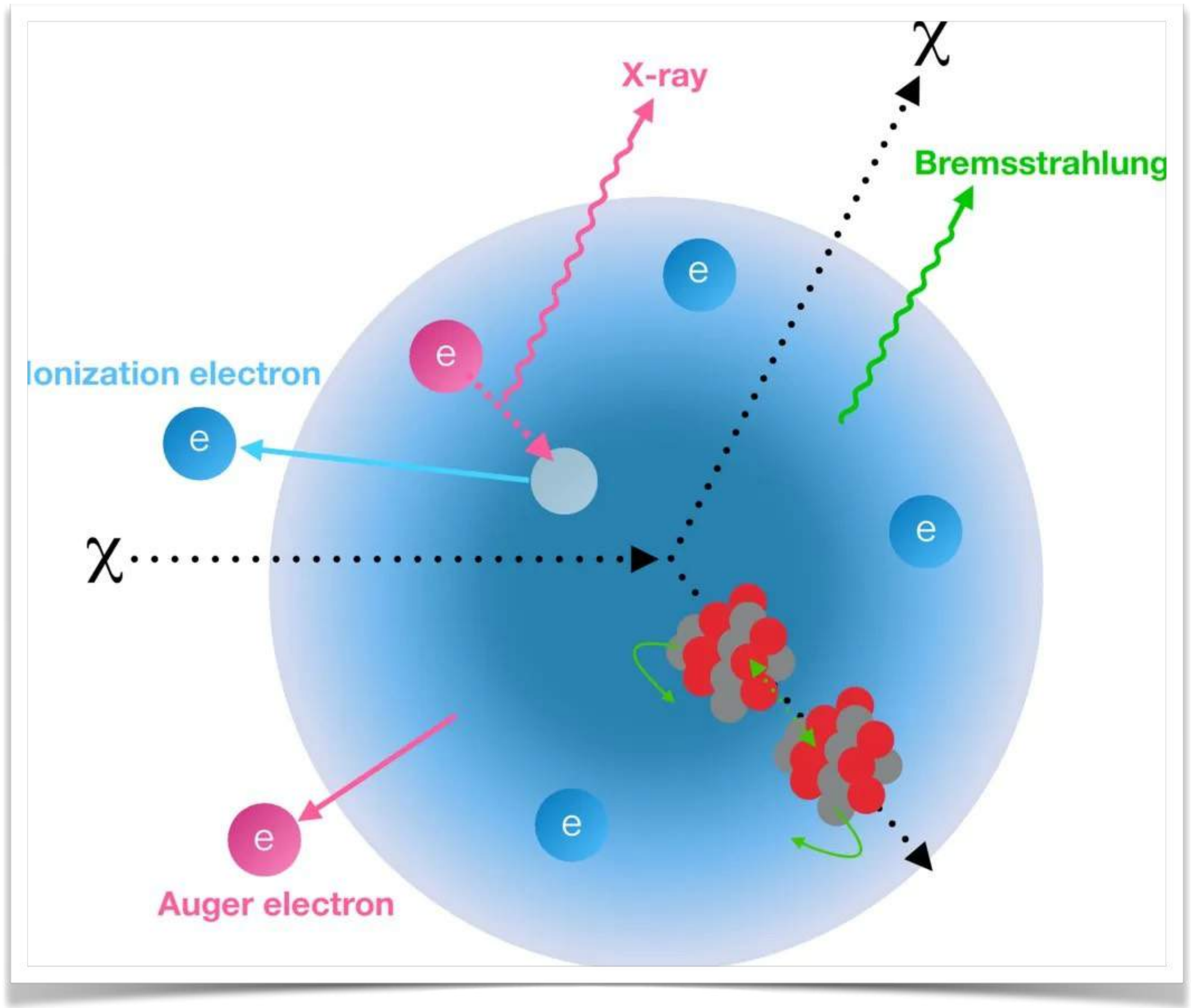
Background spectra compared with expected WIMP spectra below 10 GeV/c²
The dominant background comes from ^{85}Kr,^{39}Ar

Phys. Rev. Lett. 130, 101001



Best limit in the region between 1.2 and 3.6 GeV/c²

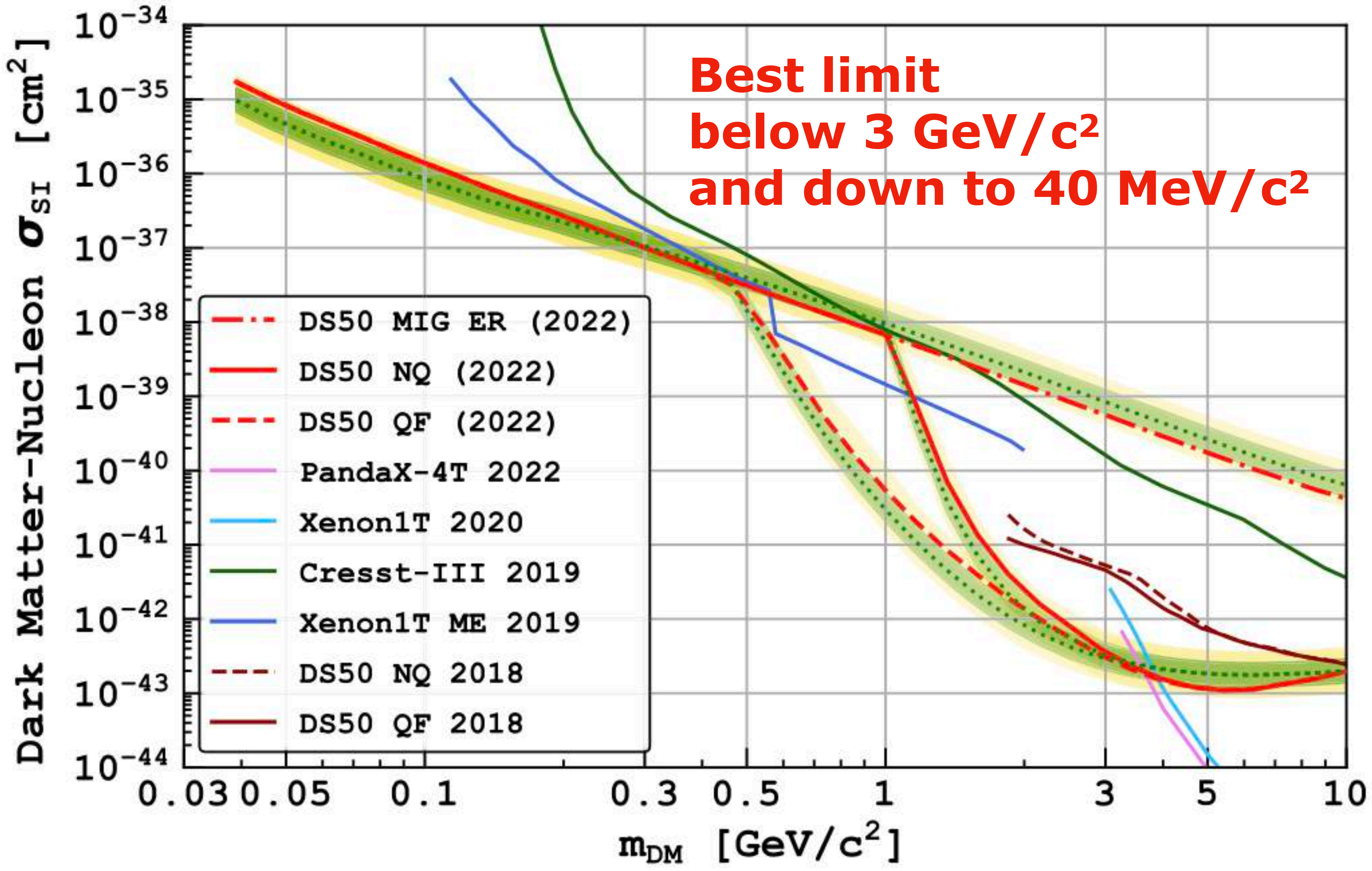
MIGDAL EFFECT



- Reinterpretation of published Ar and Xe resulting including Migdal effects benchmarked again published results

- New constrain on sub-GeV WIMP mass trough Migdal effect

Phys. Rev. Lett. 130, 101002



Kings + Manchester + RHUL main contributors!

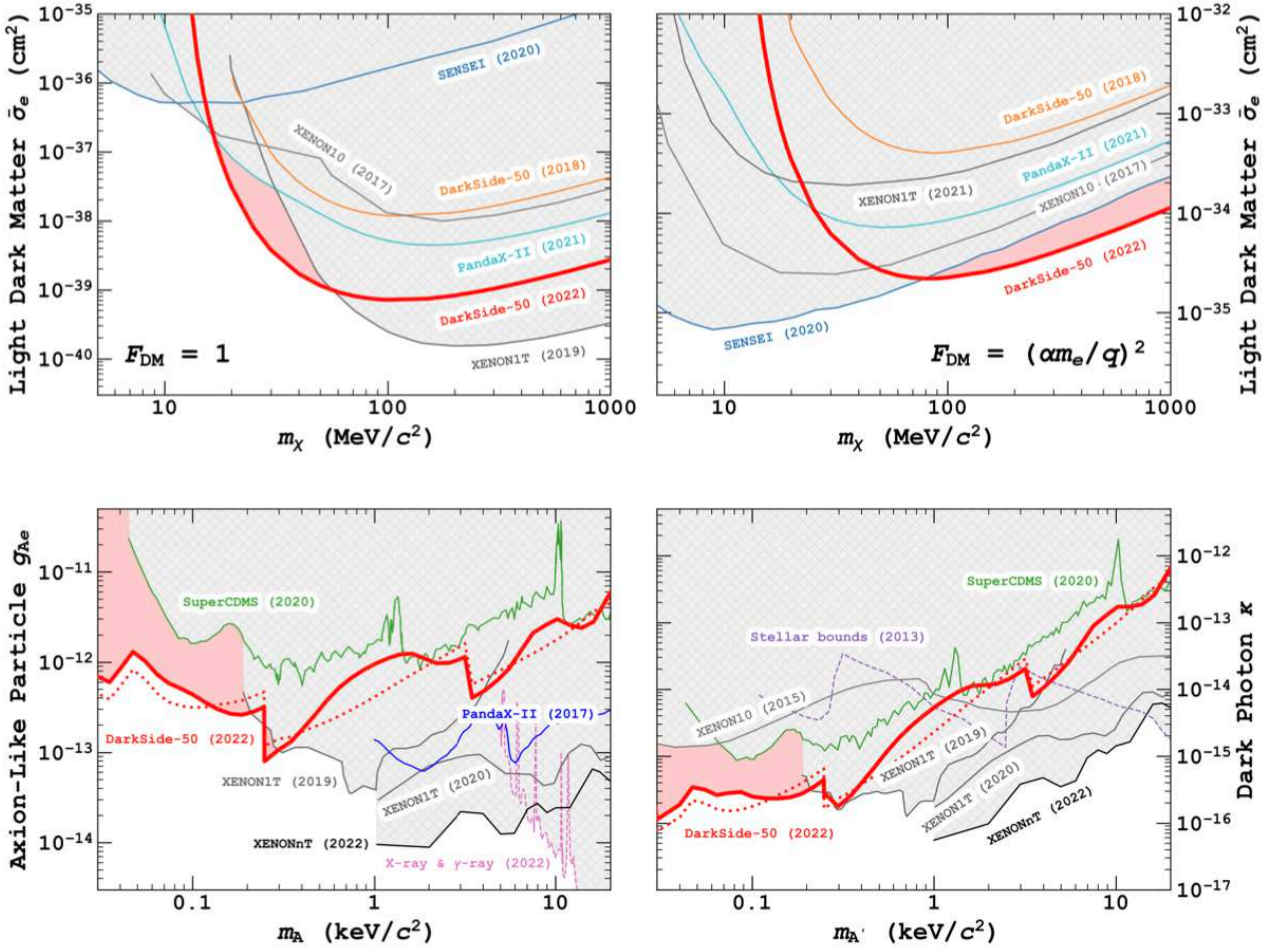
DM-e- SCATTERING RESULTS

Phys. Rev. Lett. 130, 101002 (2023)

- Exclusion limits at 90% C.L. on DM particle

  interactions with electron final states
- Limits on dark matter-electron scattering in the [16, 56] MeV/c2 mass range for a heavy mediator and

  above 80 MeV/c2 for a light mediator

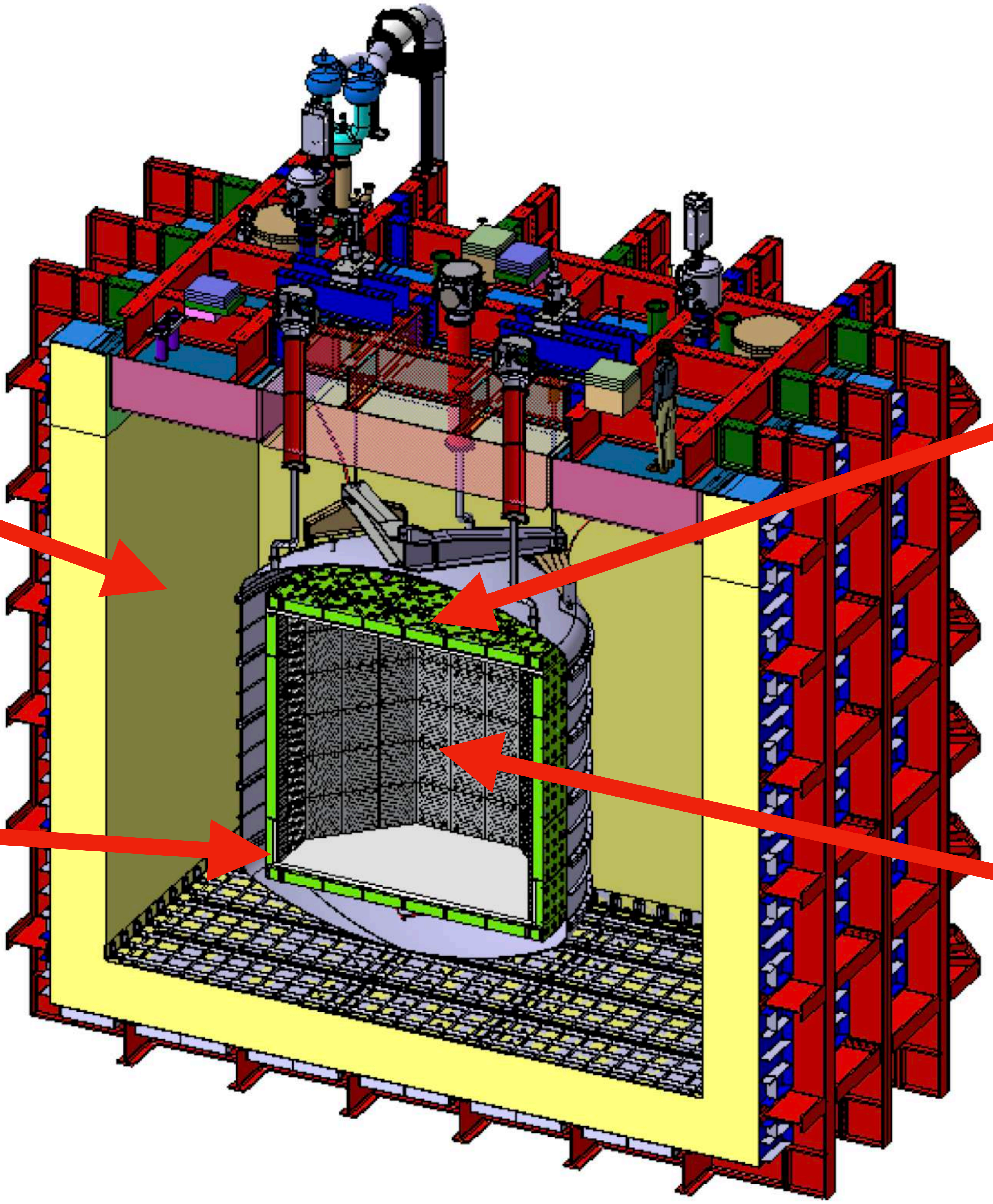


DARKSIDE-20k DETECTOR

DARKSIDE-20k

Outer cryostat filled with 600 tonnes of Atmospheric Argon (AAr) acts as cosmogenic veto

SS vessel



Gd-PMMA acts as neutron Veto surrounded by 35 tonnes of UAr

Dual phase time projection Chamber (TPC) filled with 50 tonnes of UAr

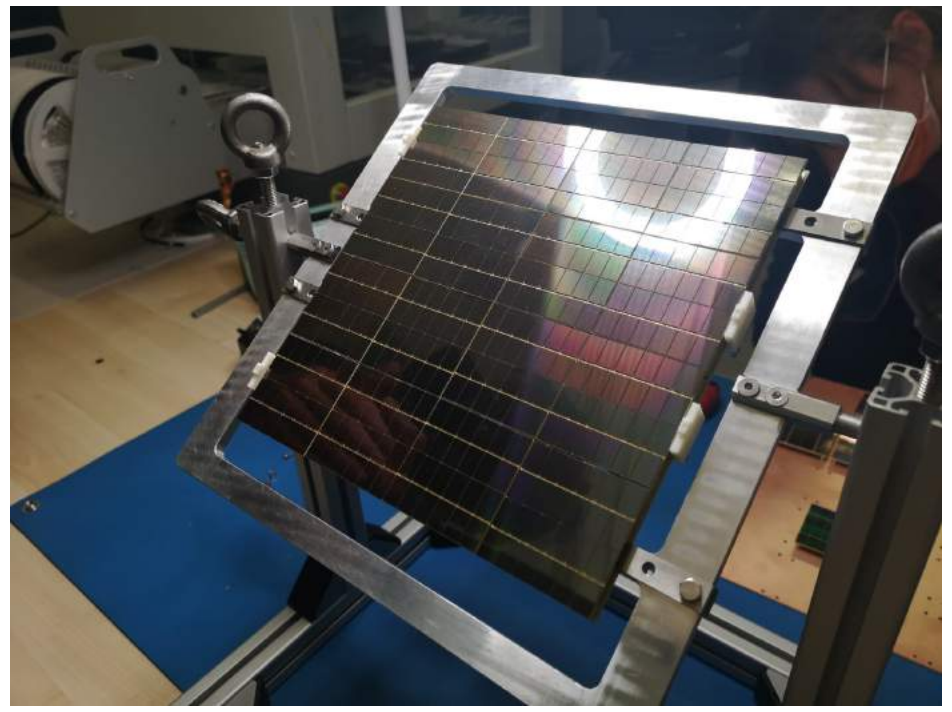
INNER DETECTOR

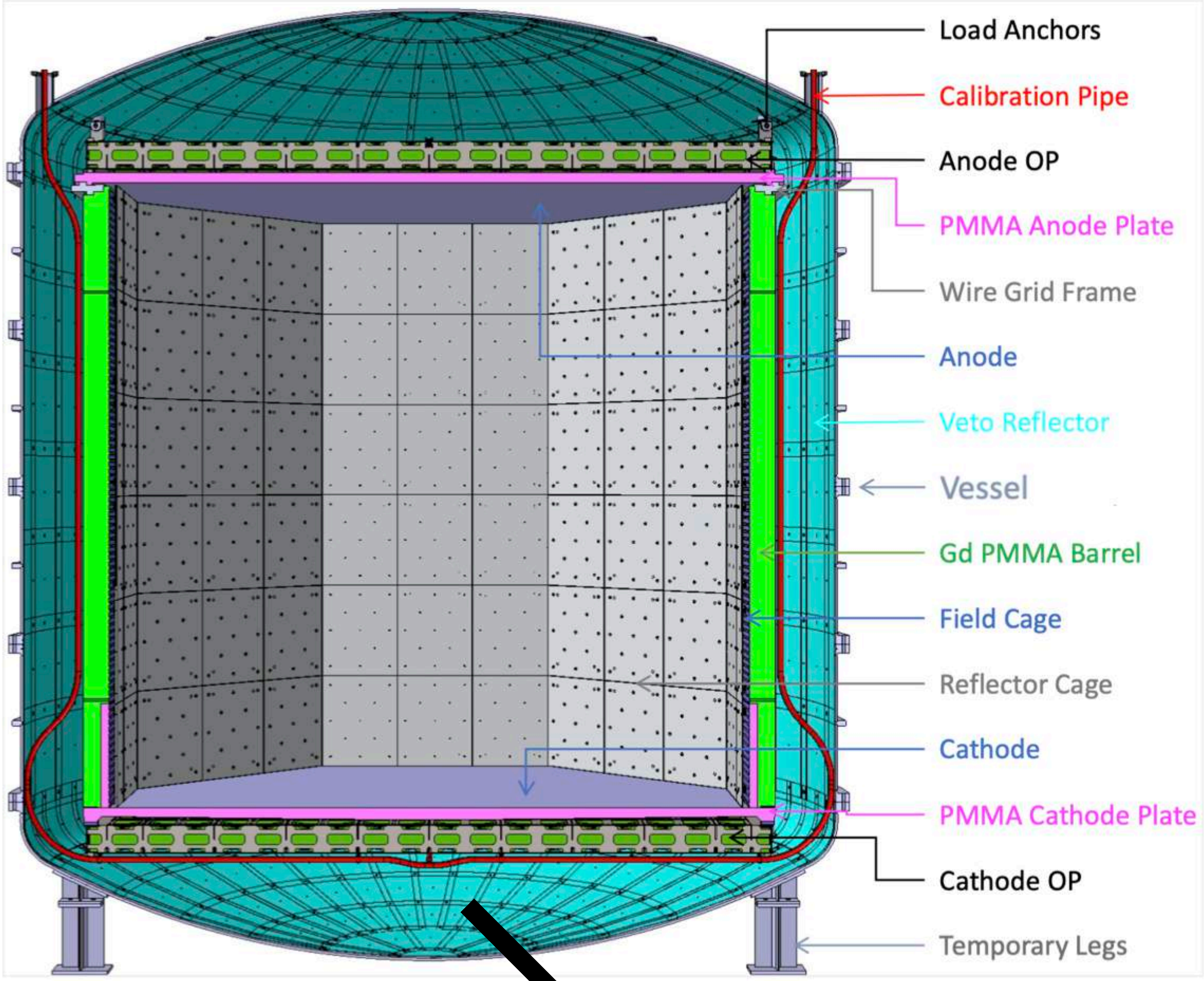
1. **Dual phase time Projection chamber (TPC)** filled with 50 tonnes of Underground Argon -> 20 tons of fiducial volume

2. **Neutron veto**: Gd-PMMA immersed in a 35 tonnes of underground liquid argon

TPC and veto are equipped with large area silicon photomultiplier (SiPMs) arranged in a photo detection unit (PDU)

- 518 PDU in the TPC
- 120 PDU in the veto

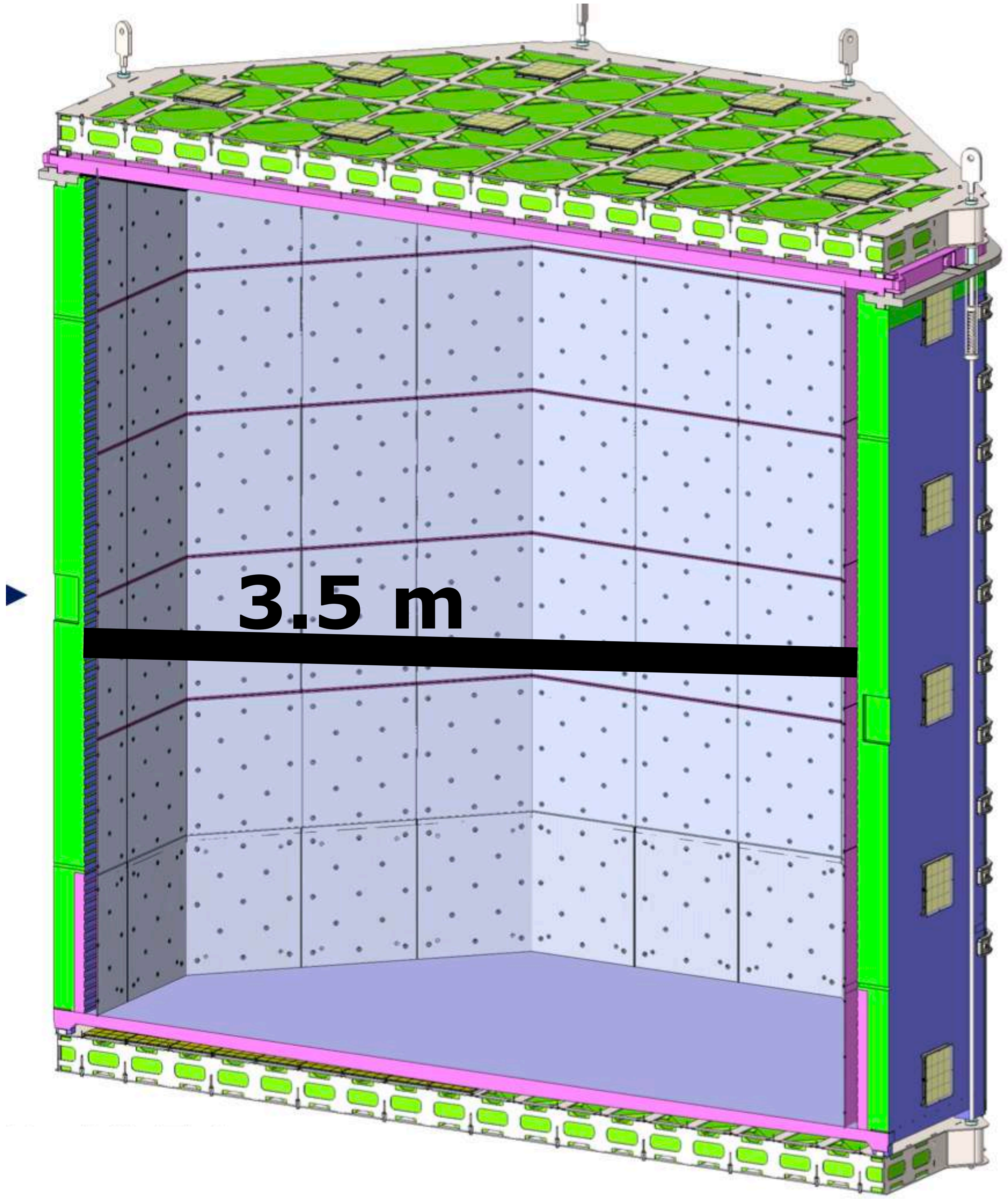




The inner detector is enclosed in a SS vessel, total mass of 13 tons

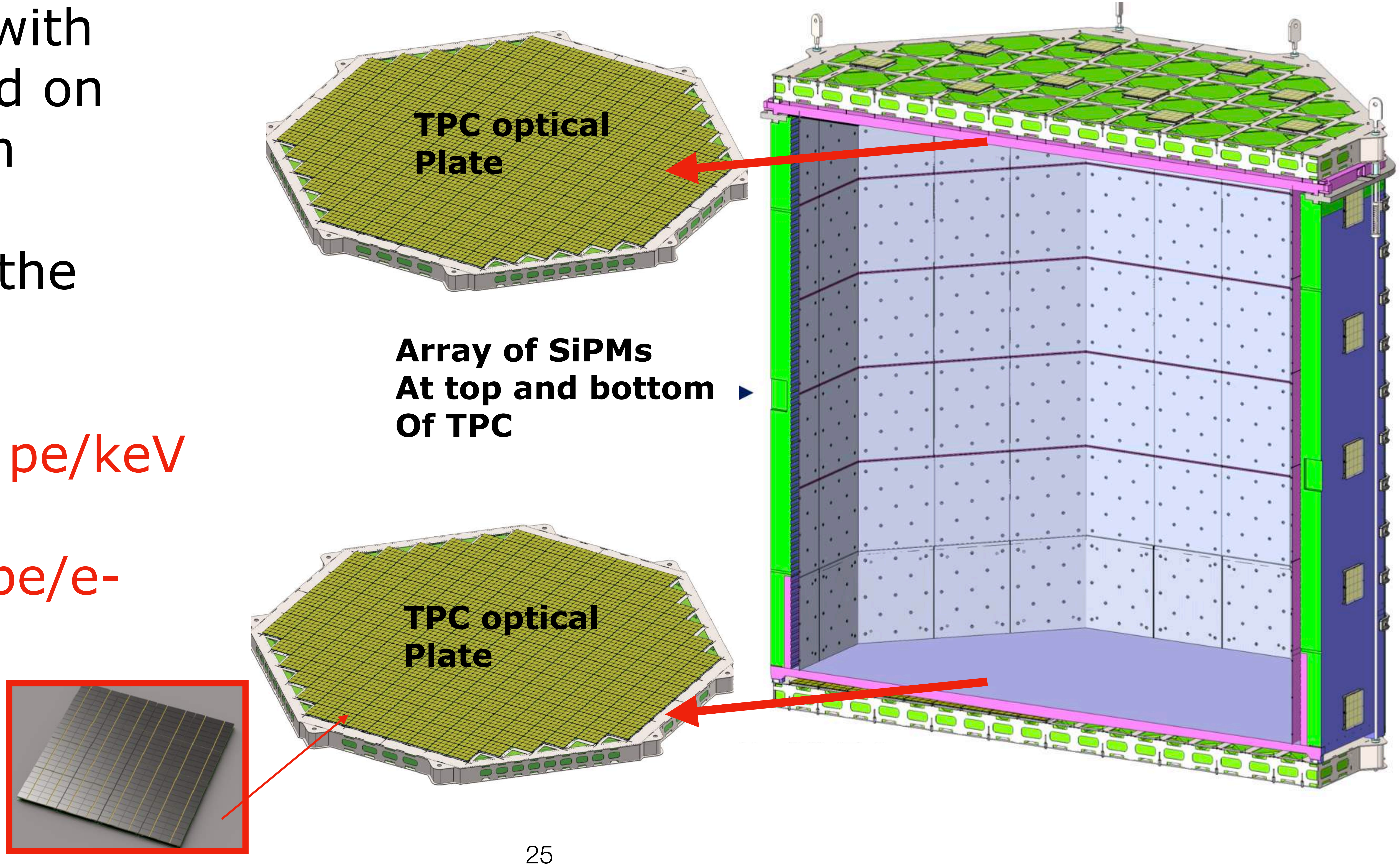
INNER DETECTOR: TPC

- Octagonal shape
- Drift field: 200V/cm
- Extraction field: 2.8 kV/cm
- Cathode voltage: -73.38 kV
- ESR as reflector, TPB as wavelength shifter
- SS wire grid



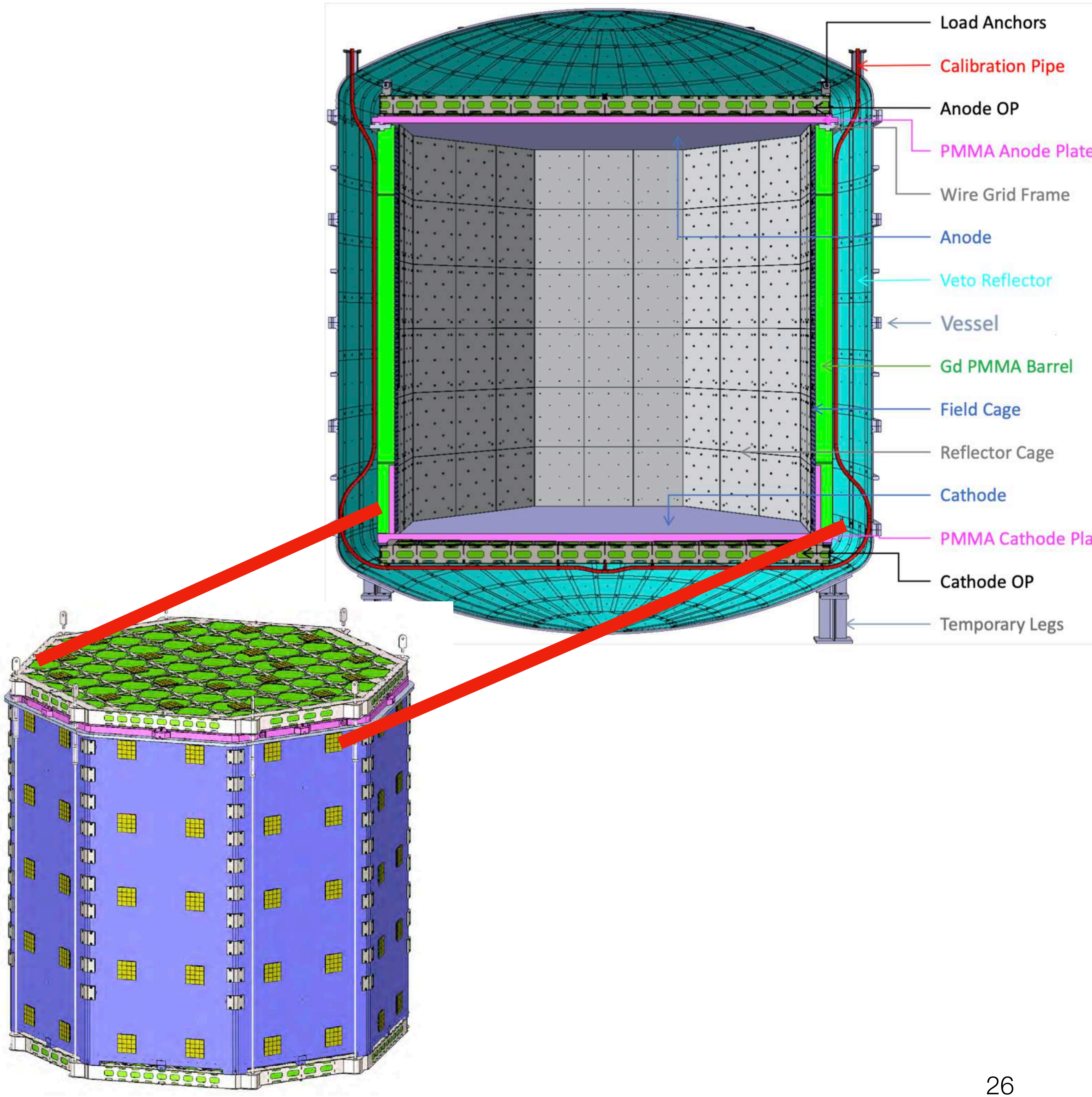
INNER DETECTOR: TPC

- TPC equipped with 518 PDU placed on top and bottom
- Total SiPMs in the TPC: 198912
- Light yield: 10 pe/keV
- S2 yield > 20 pe/e-

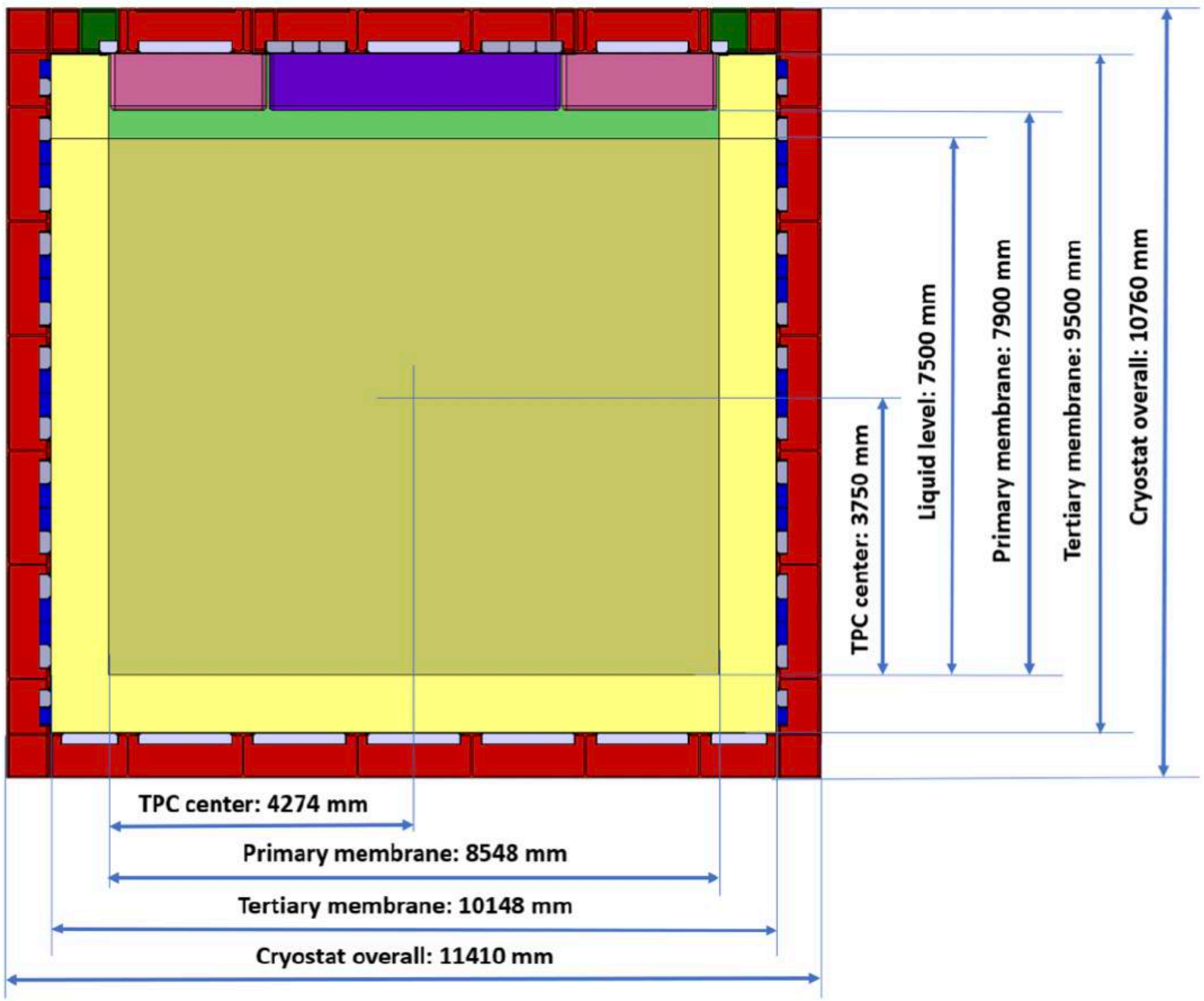


INNER DETECTOR: neutron veto

- Novel technology: TPC+veto integrated system -> Gd-PMMA (11.2 tons) around TPC wall to capture neutrons (4π coverage)
- SiPMs matrix (assembled in veto photodetector unit-> vPDU) around TPC wall for light detection -> 7 m^2 of SiPM array detector readout vPDU (Light yield: 2.0 pe/keV)
- Reflector+ PEN for light collection optimisation
- Enclosed in a SS vessel filled with around 35 tonnes of underground Argon



OUTER VETO

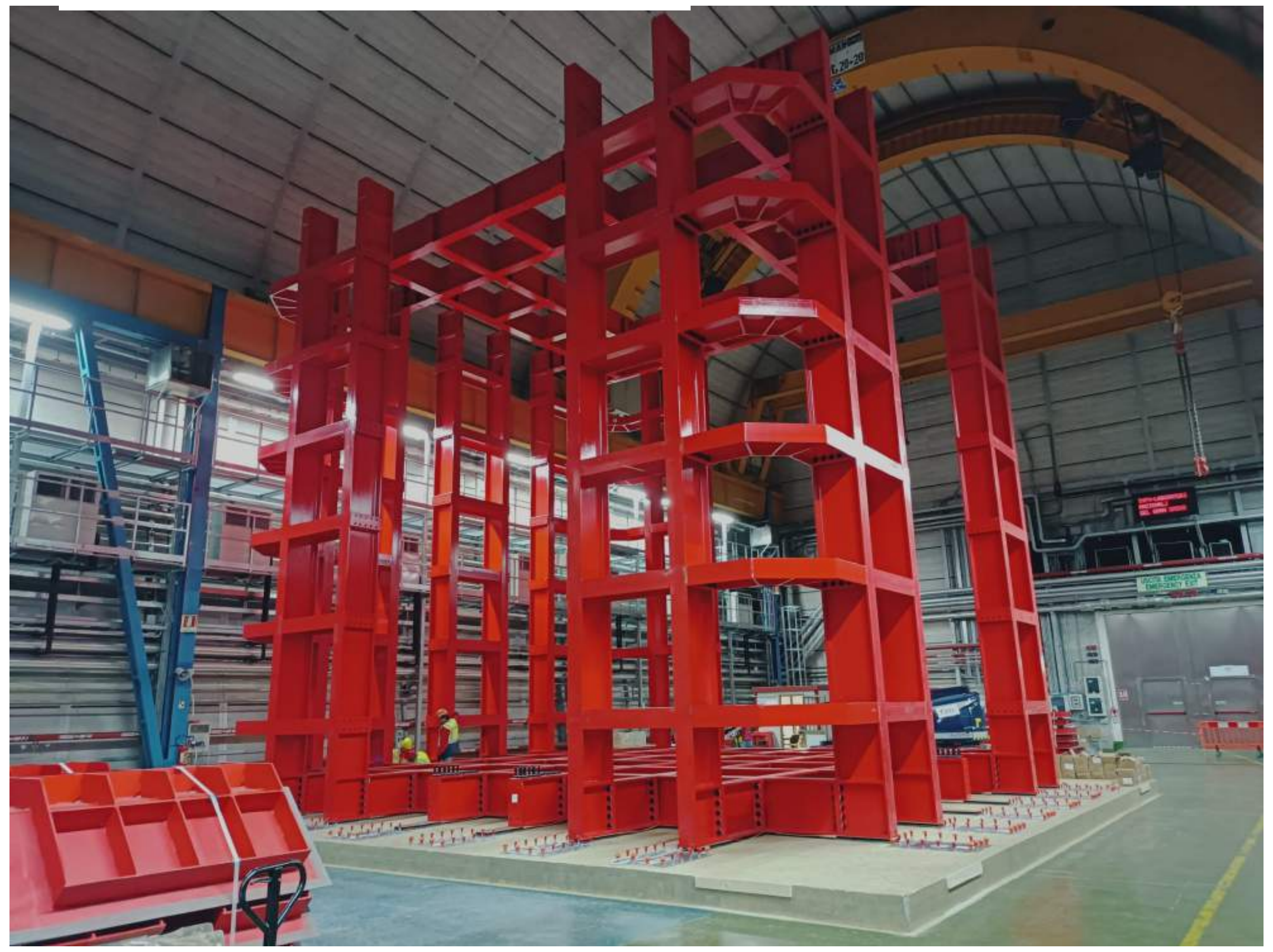


- Proto-dune like outer cryostat filled with 600 tons of Atmospheric Liquid Argon
- Equipped with 32 PDUs placed on SS vessel
- Tyvek + PEN for light optimisation
- Light yield: 1 pe/MeV
- Acts as cosmogenic veto

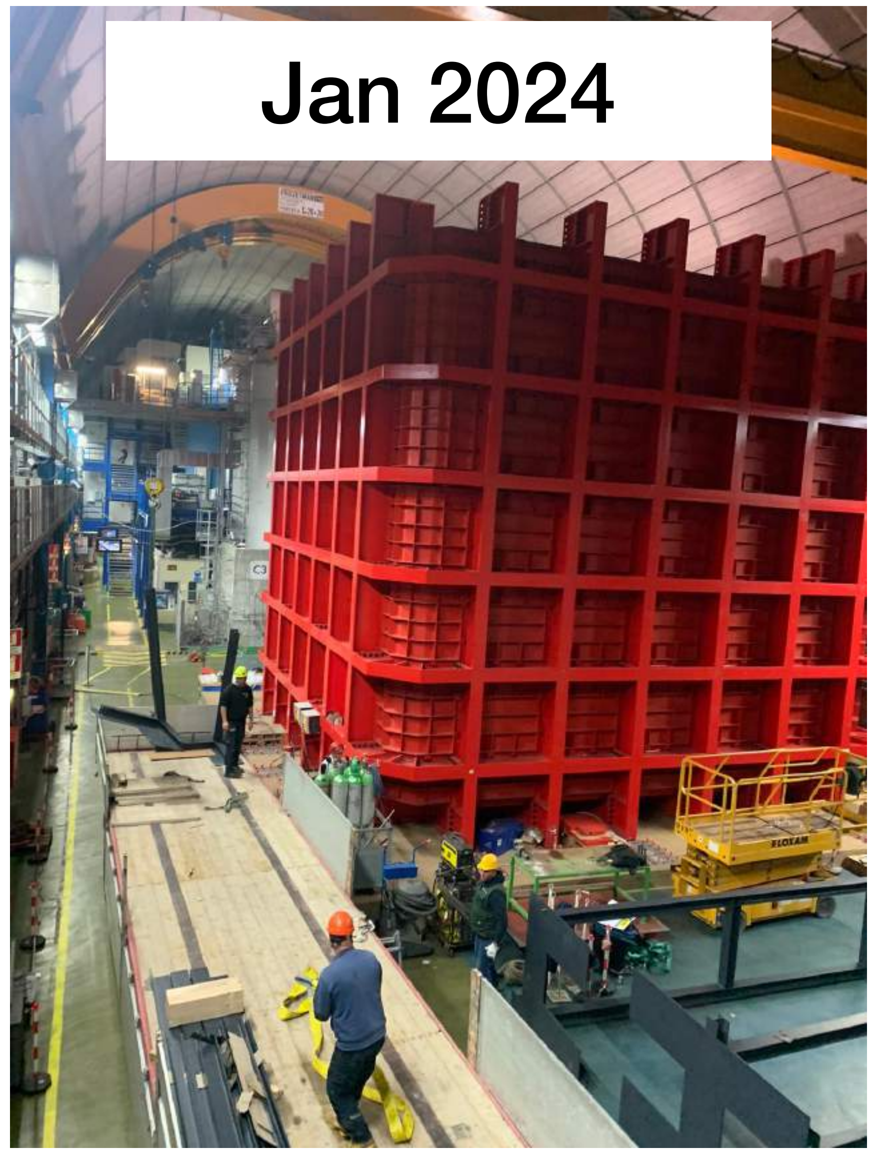
DARKSIDE-20k: Installation

DarkSide-20k installation has started
Data taking will start in 2026

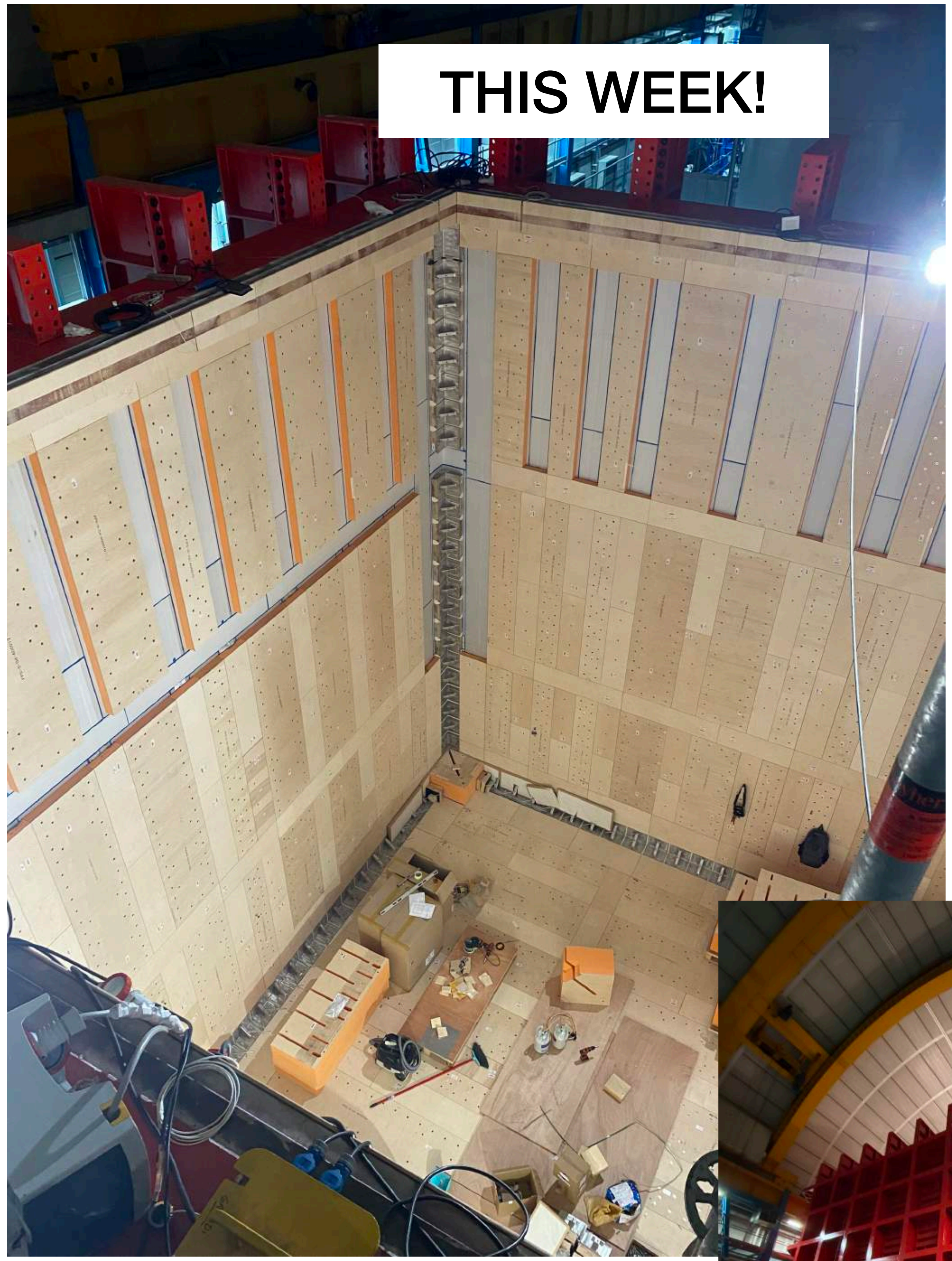
June 2023



Nov 2023



Jan 2024



THIS WEEK!

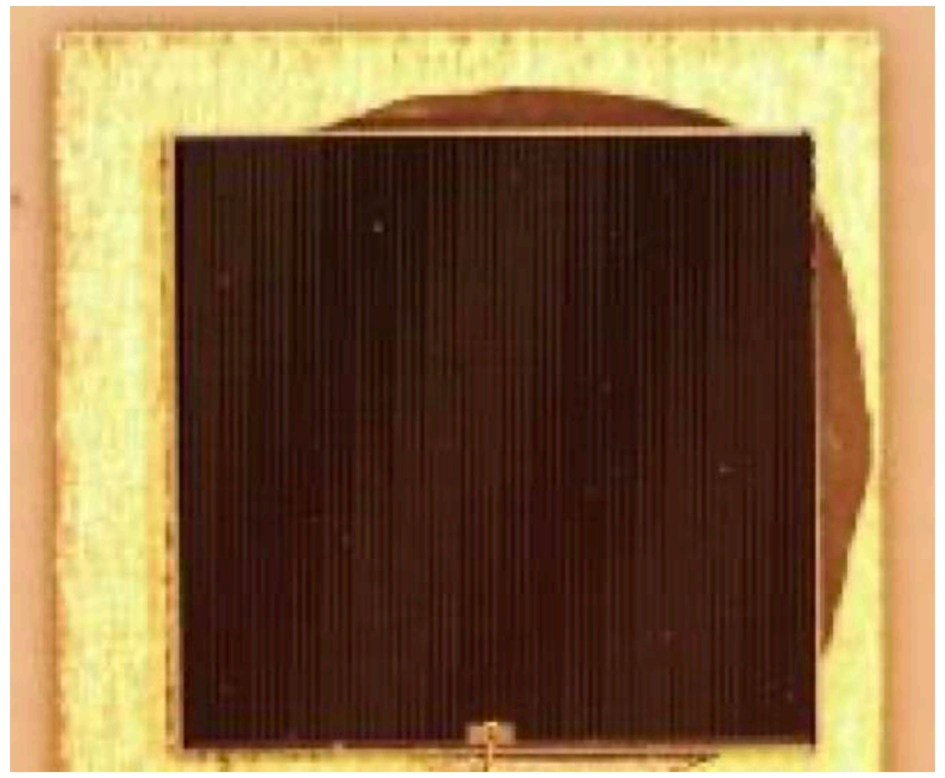
LIGHT DETECTION SYSTEM: Large area Silicon Photomultipliers (SiPM)

DARKSIDE SIPM REQUIREMENTS

From PhotoMultiplier (PMT)

To

Silicon PhotoMultiplier (SiPM)

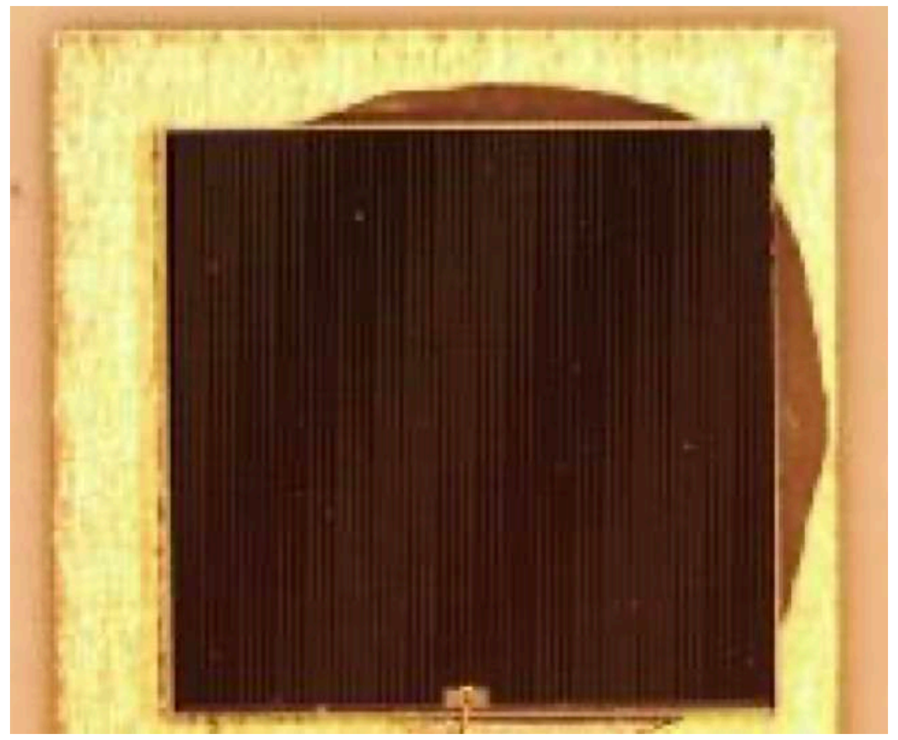


Quantity	Requirement
Breakdown voltage	26.8 +/- 0.2 V
SiPM response - recharge time	300 - 600 ns
Single Photoelectron (SPE) spectra	distinct PE
Gain	stable gain
Signal to noise ratio (SNR)	> 8
Dark count rate (DCR)	< 0.01 Hz/mm^2 (7 Vov) < 0.1 Hz/mm^2 (9 Vov)
Internal cross talk (CT) probability	< 33 % (7 Vov) < 50 % (9 Vov)
Afterpulsing (AP) probability	< 10 %

SILICON PHOTOMULTIPLIERs (SiPMs)

SPADs

SiPMs: 1mm²



SPAD - Single Photon Avalanche Diodes: semiconductor devices based on a p-n junction, reverse biased well above breakdown voltage (operating in Gieger mode).

SiPM - Silicon PhotoMultiplier: A single SiPM consists of around 94,900 SPADs.

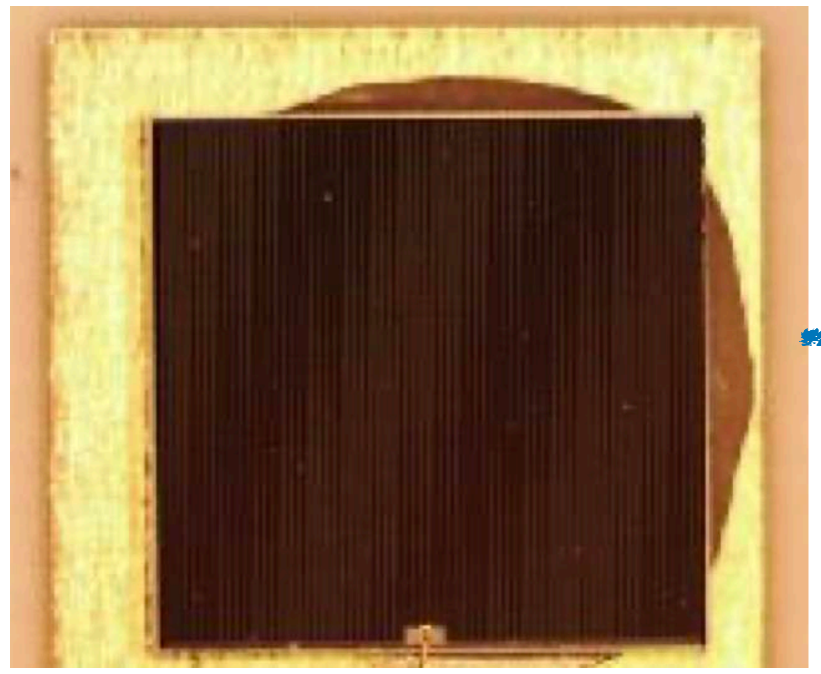
Why SiPMs

- Cryogenic temperature stability
- Better single photon resolution
- **Higher detection photo-detection efficiency**
- Low voltage operation
- **Radio-purity an order of magnitude lower than PMTs**
- Lower cost

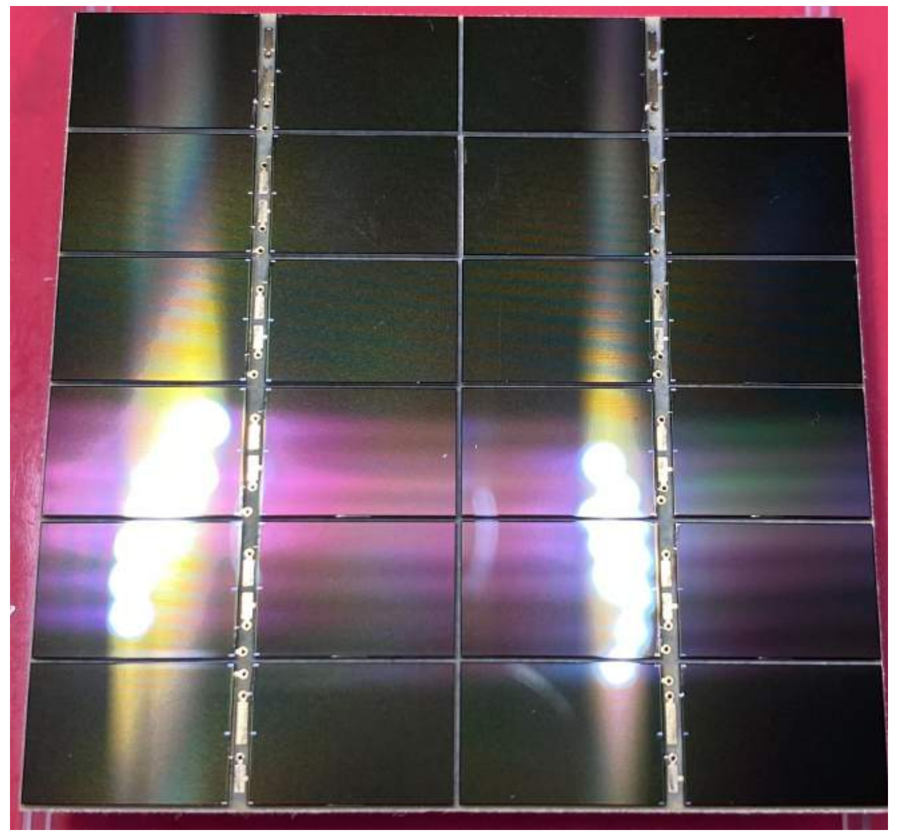
SILICON PHOTOMULPLIER: tile

SPADs

SiPMs: 1mm²



Side 1: 24 SIPMs



Tile: single printed circuit (PCB)
For SiPMs & eletroncis

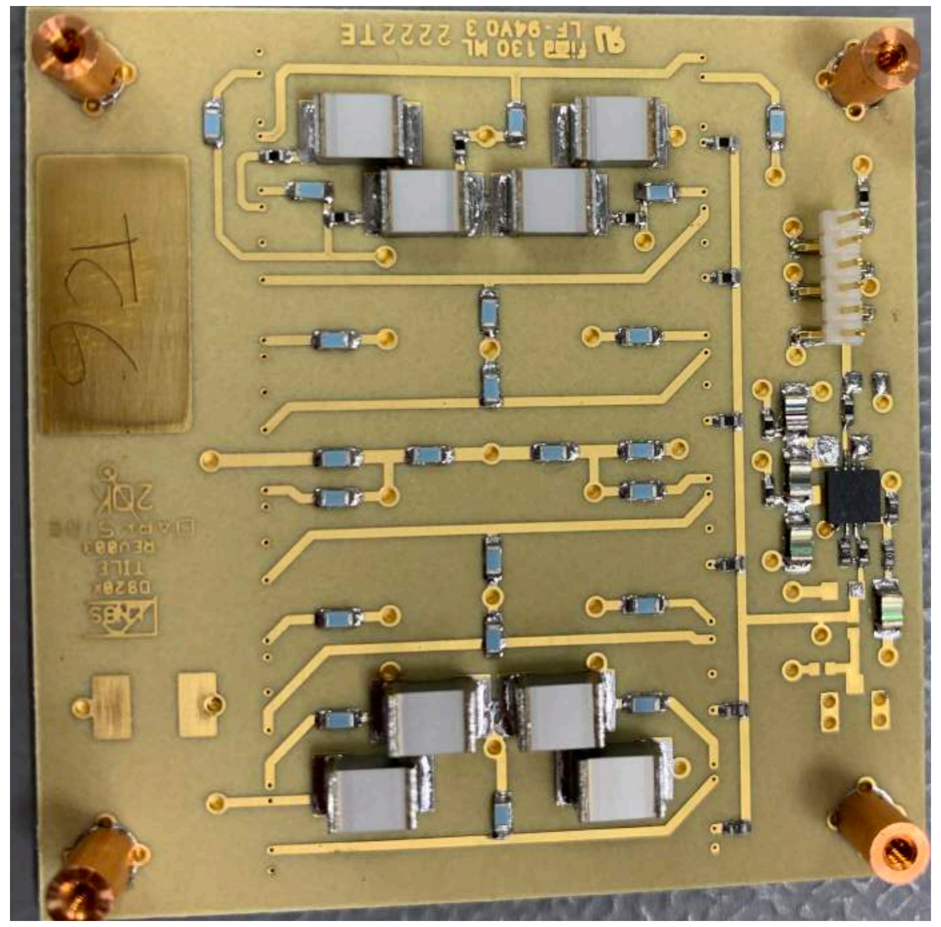
- Side 1: array of 24 SiPMs
  For a total size of 24 cm2,
  The signals of all SiPMs are
  Summed
- Side 2: front-end electronics for
  Signal amplifier -> ASIC for veto
  And discrete element for TPC

SPADs - Single Photon Avalanche Diodes: semiconductor devices based on a p-n junction, reverse biased well above breakdown voltage (operating in Gieger mode).

SiPMs - Silicon PhotoMultiplier: A single SiPM consists of around 94,900 SPADs.

Side 2: front-end electronics

TPC Tile



Veto Tile (vTile)

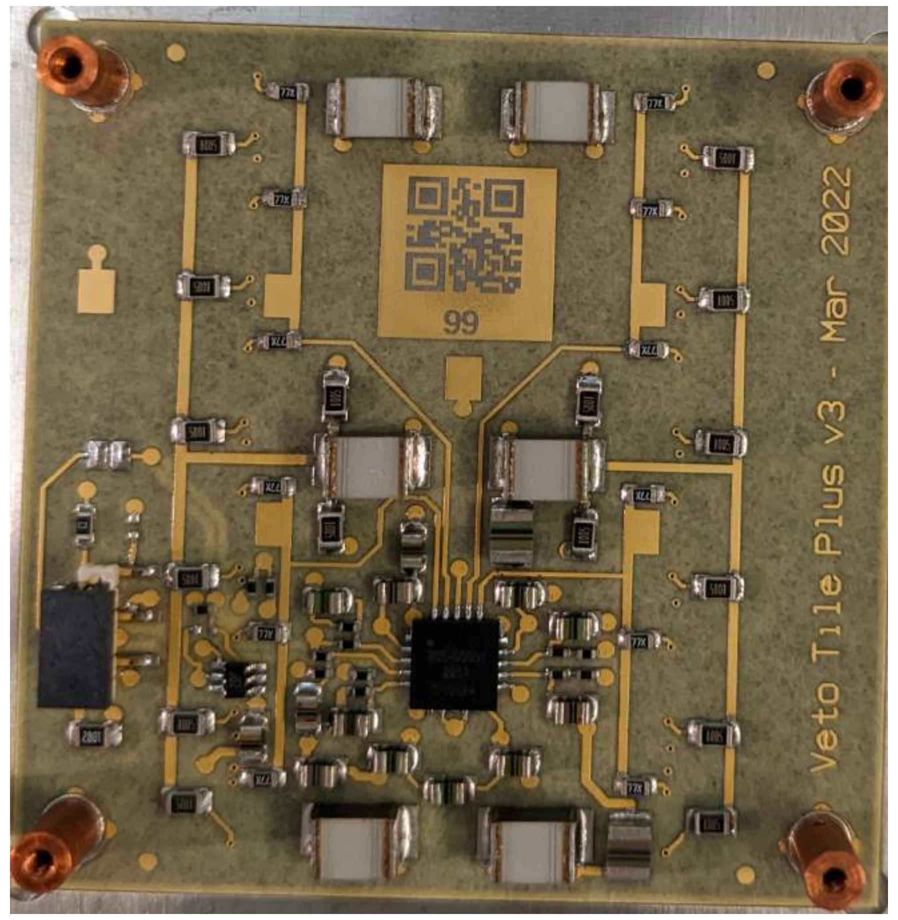
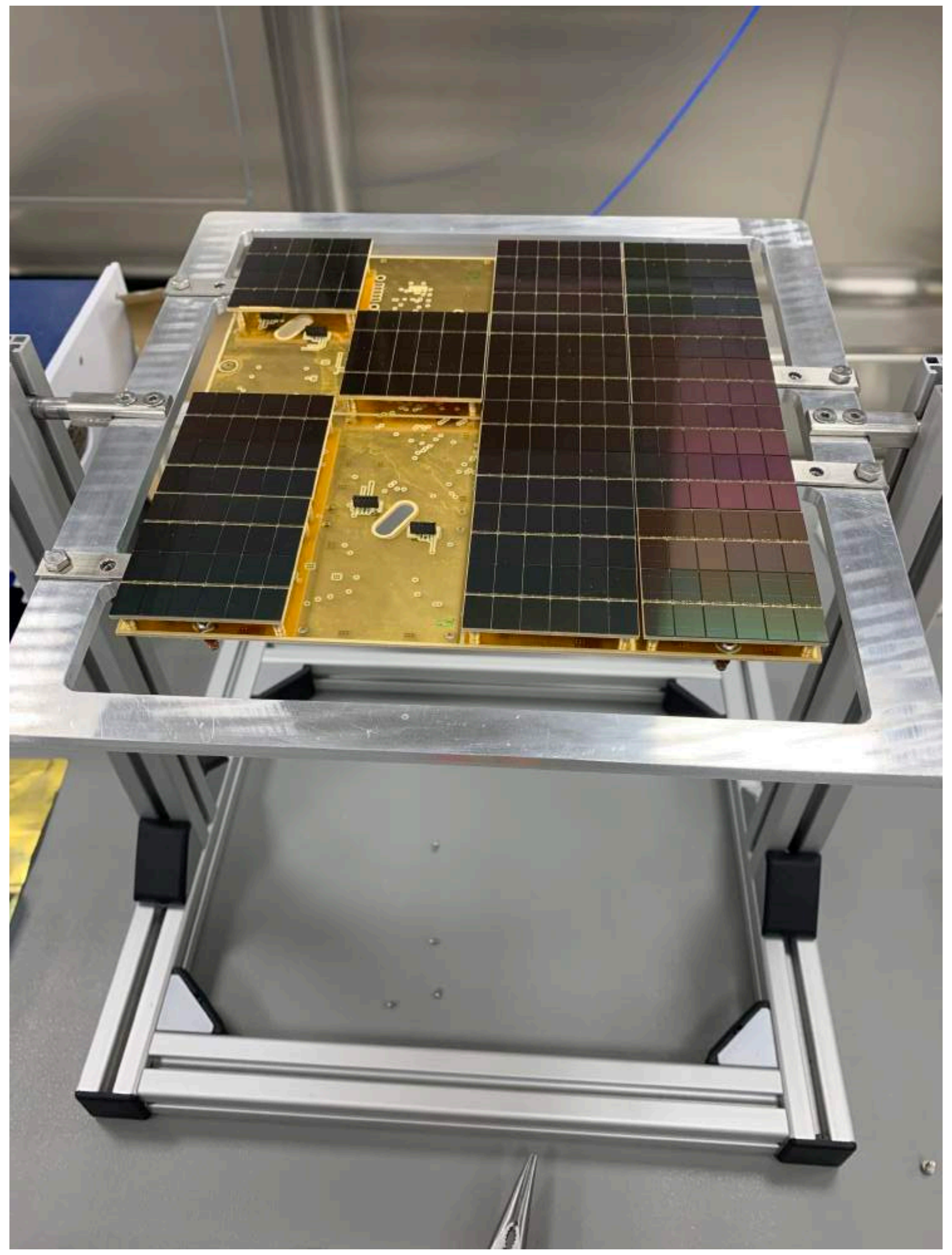
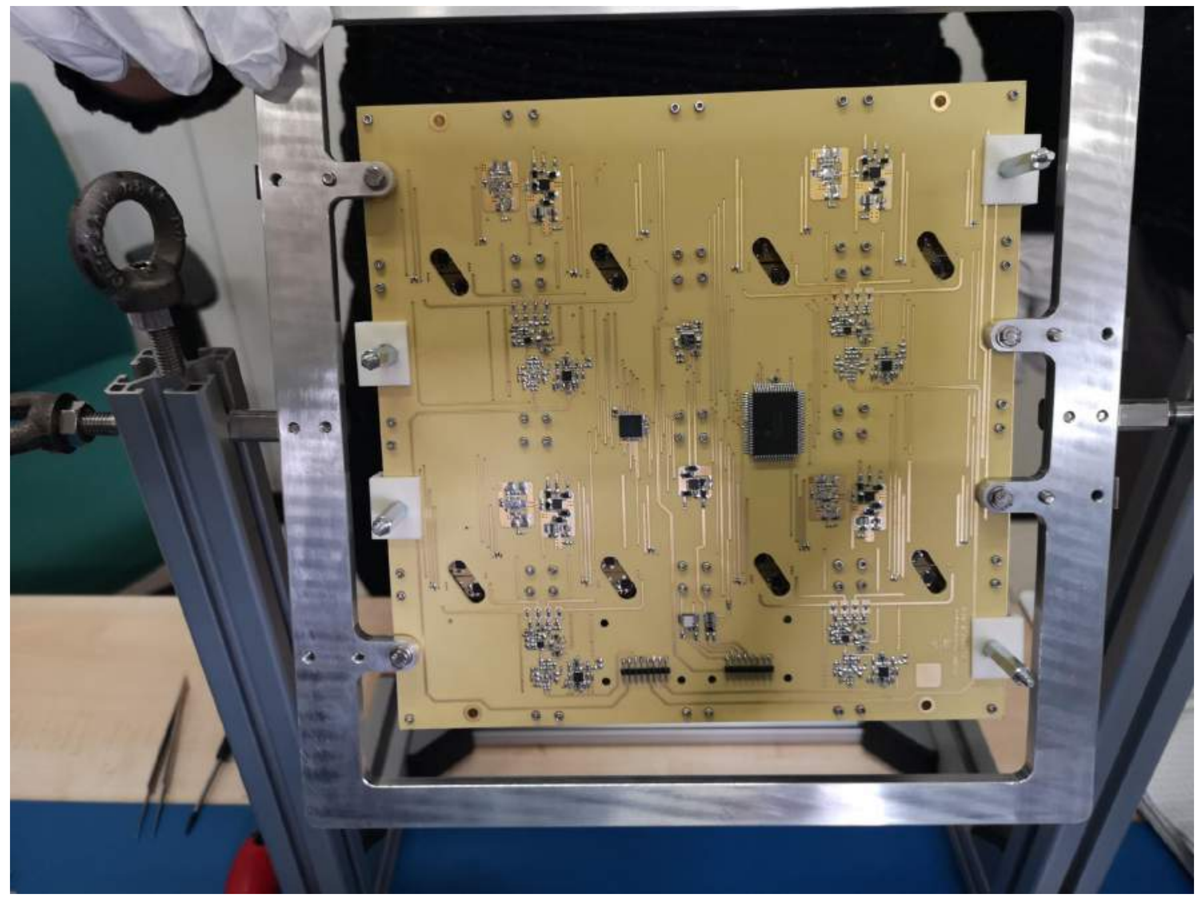
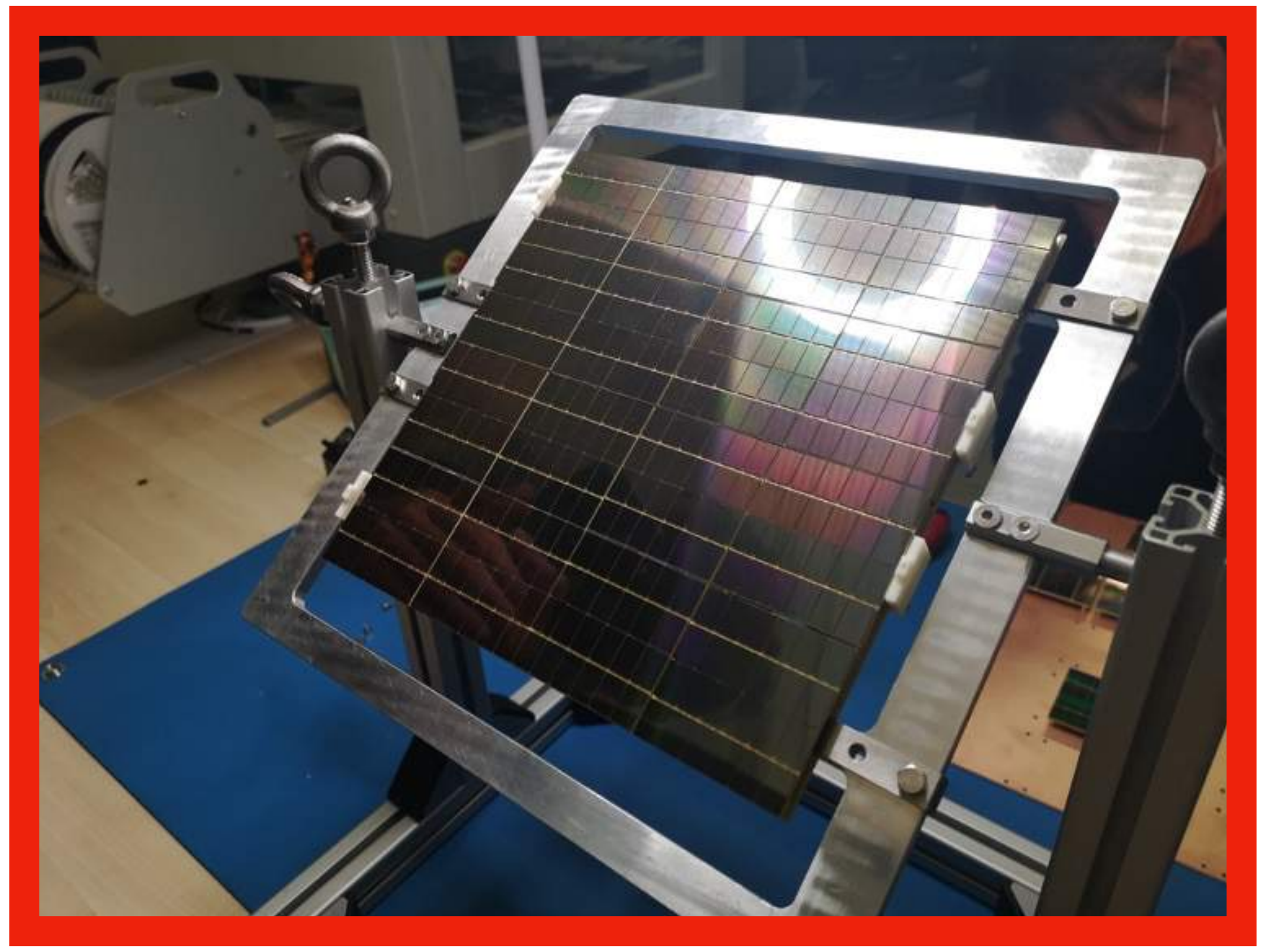


PHOTO DETECTION MODULE (PDU)



- 16 tile are assembled together in a **P**hoton **D**etection **U**nit (**PDU**): 20 x 20 cm^2
- 1 large PCB for control signal, bias each tile and summed the signal of the tile
- 4 tile are summed together, i.e. 4 tile correspond to 1 DAQ channel
- 4 outputs: 1/4 DAQ channel-> 1/4 cables-> lower radioactivity



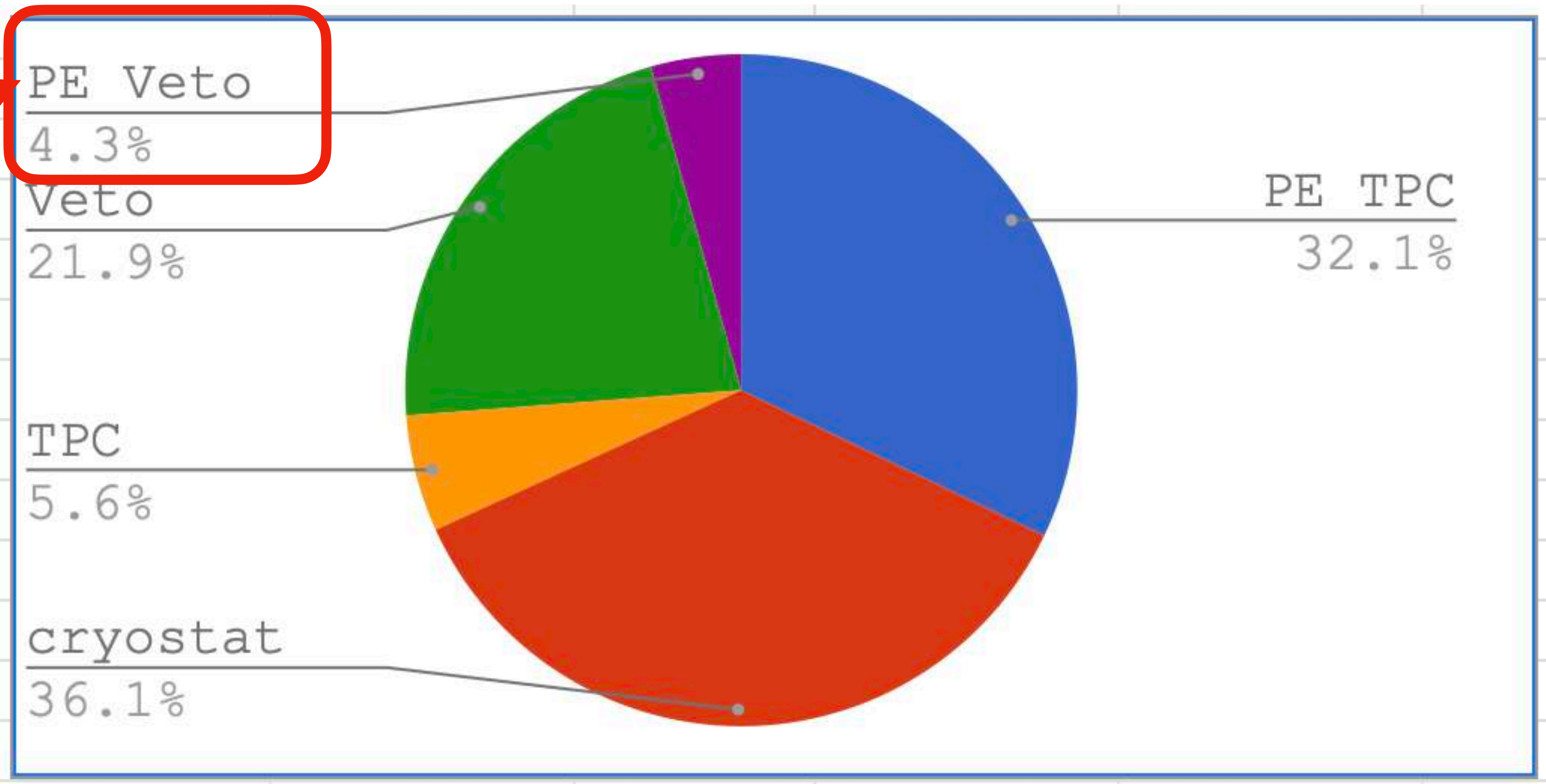


vPDU: radio-purity control

- Stringent radio-purity control and material selection
- Each component for vPDU has been assayed through ICPMS/ BeGe
- Assay of final populated board at STFC's Boulby Underground Laboratory to qualify assembly process -> *no additional contamination introduced*
- **vPDU contributes to the 4.3% of the total neutron background budget**

Comparison between sum of each components vs final populated board

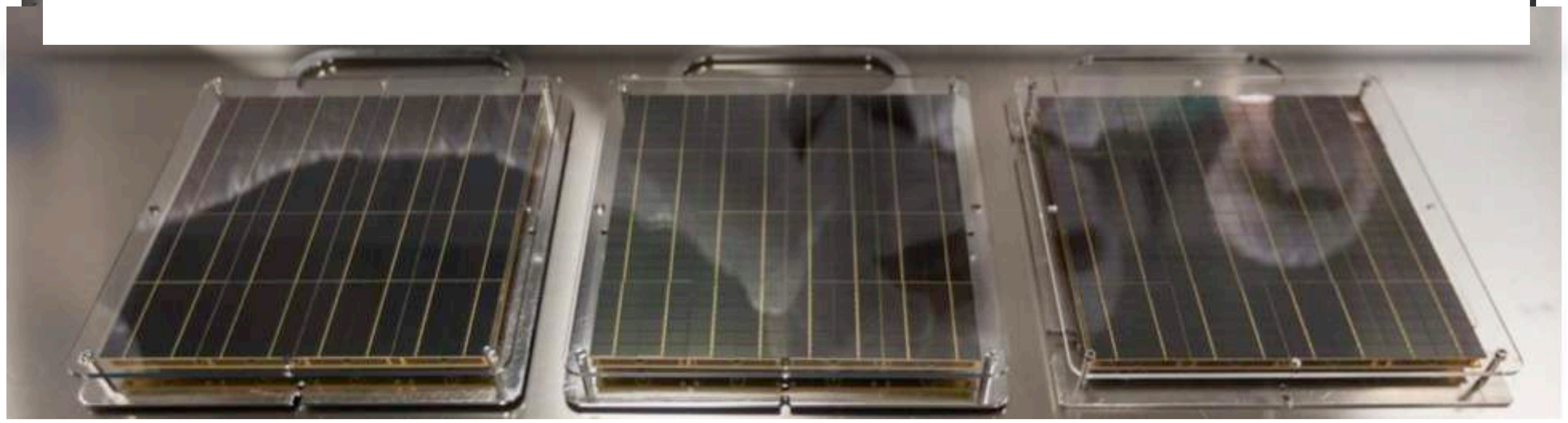
	From summing [Bq]	From assay [Bq]
Uup	2.2E+00	2.3E+00
Umid	1.2E+00	1.3E+00
Ulow	5.8E+01	**8.4E+01**
Th232	1.3E+00	1.1E+00
Ur-235	1.6E-01	1.1E-01
K40	1.4E+01	1.3E+01



ITALIAN FACILITIES

NOA at LNGS:
TPC PDU production and tileTesting

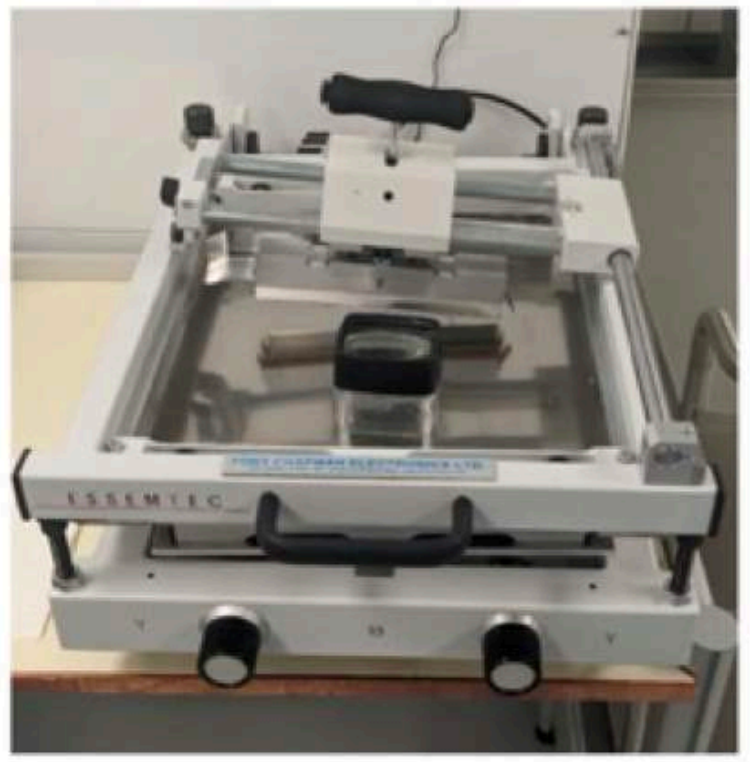
Successfully assembled 3 pre-production TPC PDU
Production will be start in May



Naples: PDU testing facilities

UK FACILITIES: PCB production @Birmigham

Application of Solder paste using stencil printer



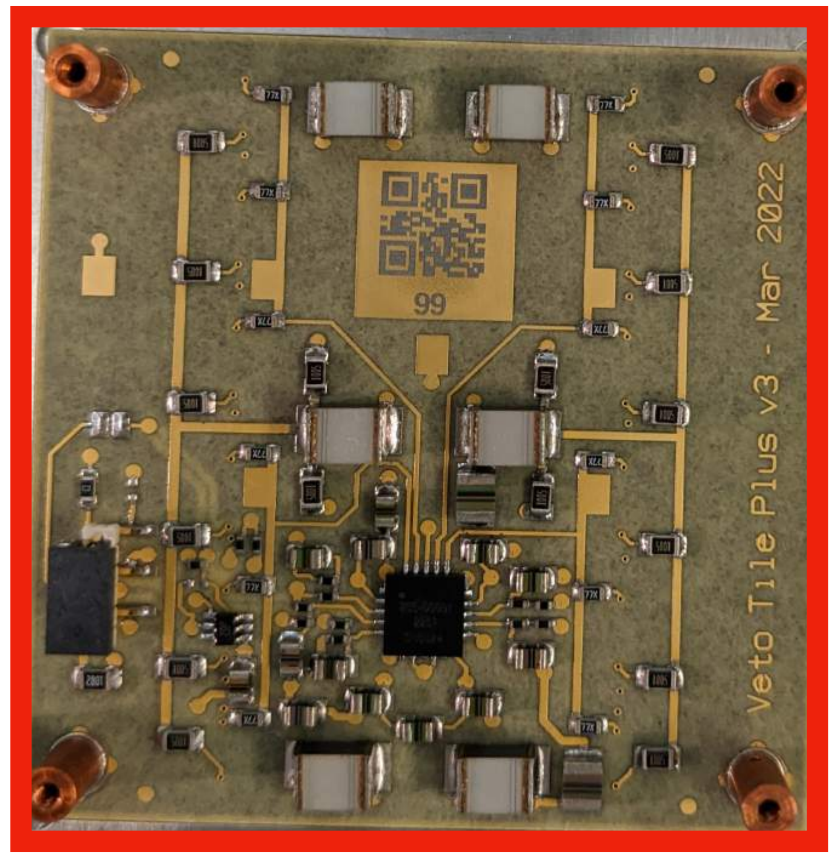
ESSEMTEC SP-002 Manual Stencil printer
Solder paste: CHIPQUIK

Pick and Place machine – PCBs to come as 4x3 sheet

MECHATRONICA M60 pick and place

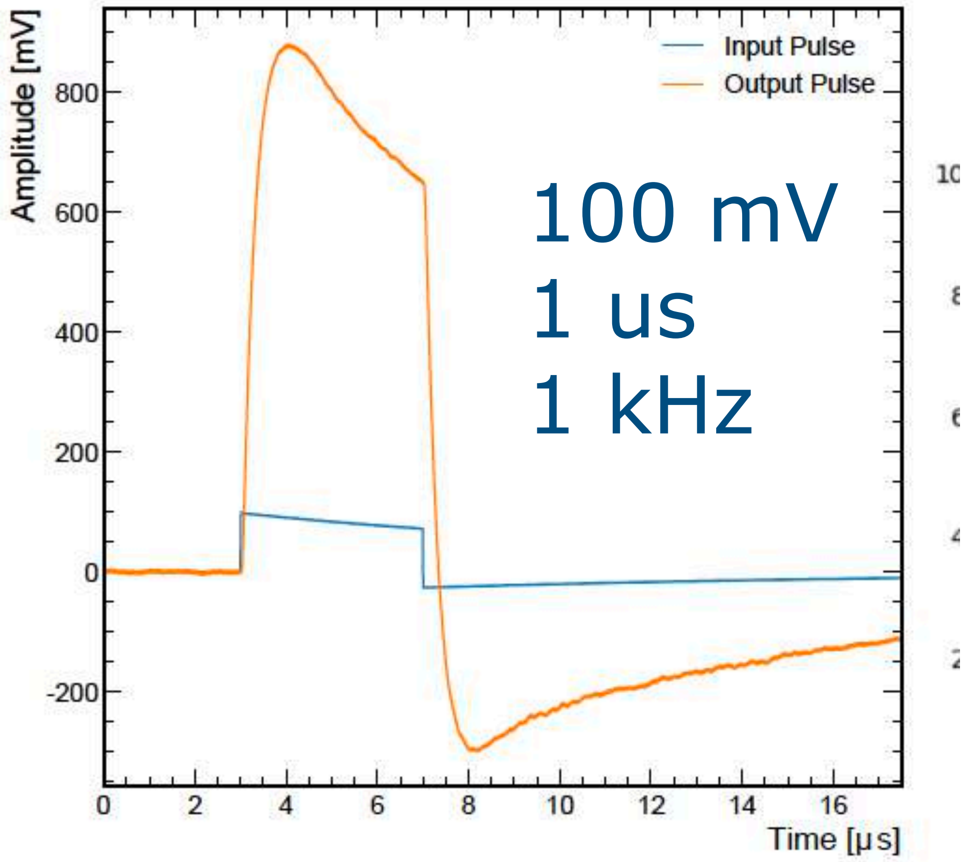
New Reflow oven:
3 temperature probes
5 minutes at 150°C
1 minute at 200 °C

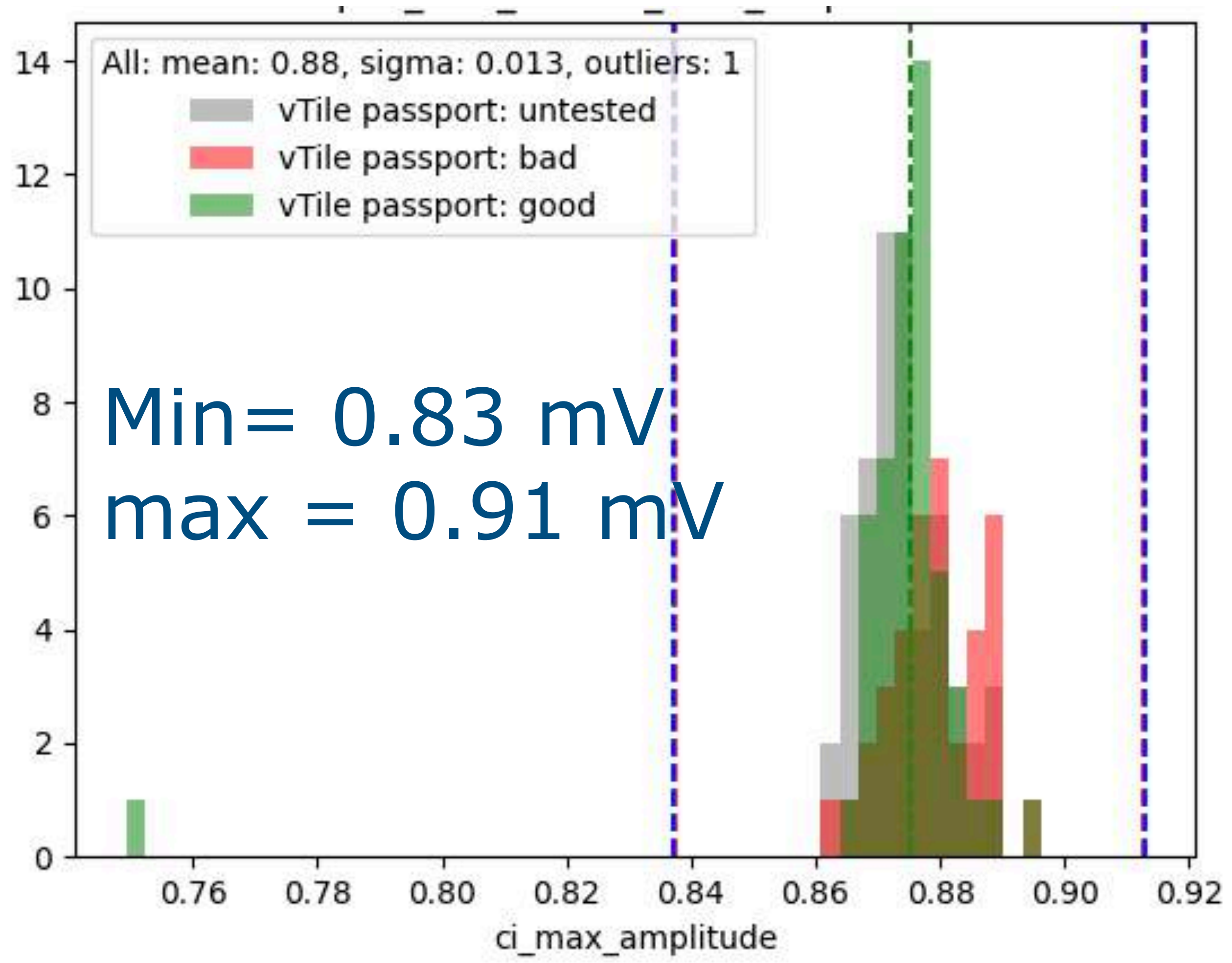
C.I.F FT05 advanced forced convection oven

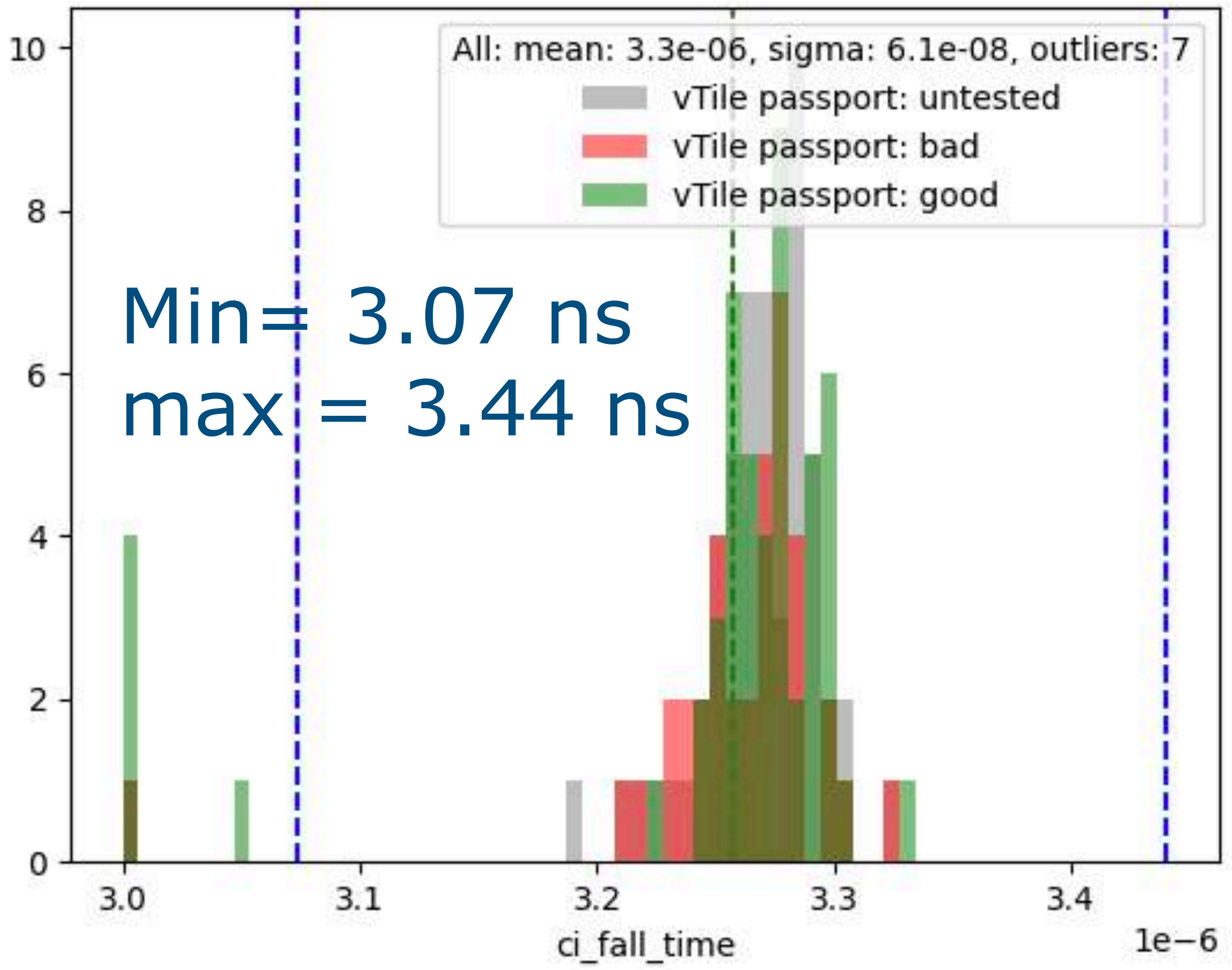


ISO-6 Clean room
Radon controlled system
(<5 Bq/mm²)

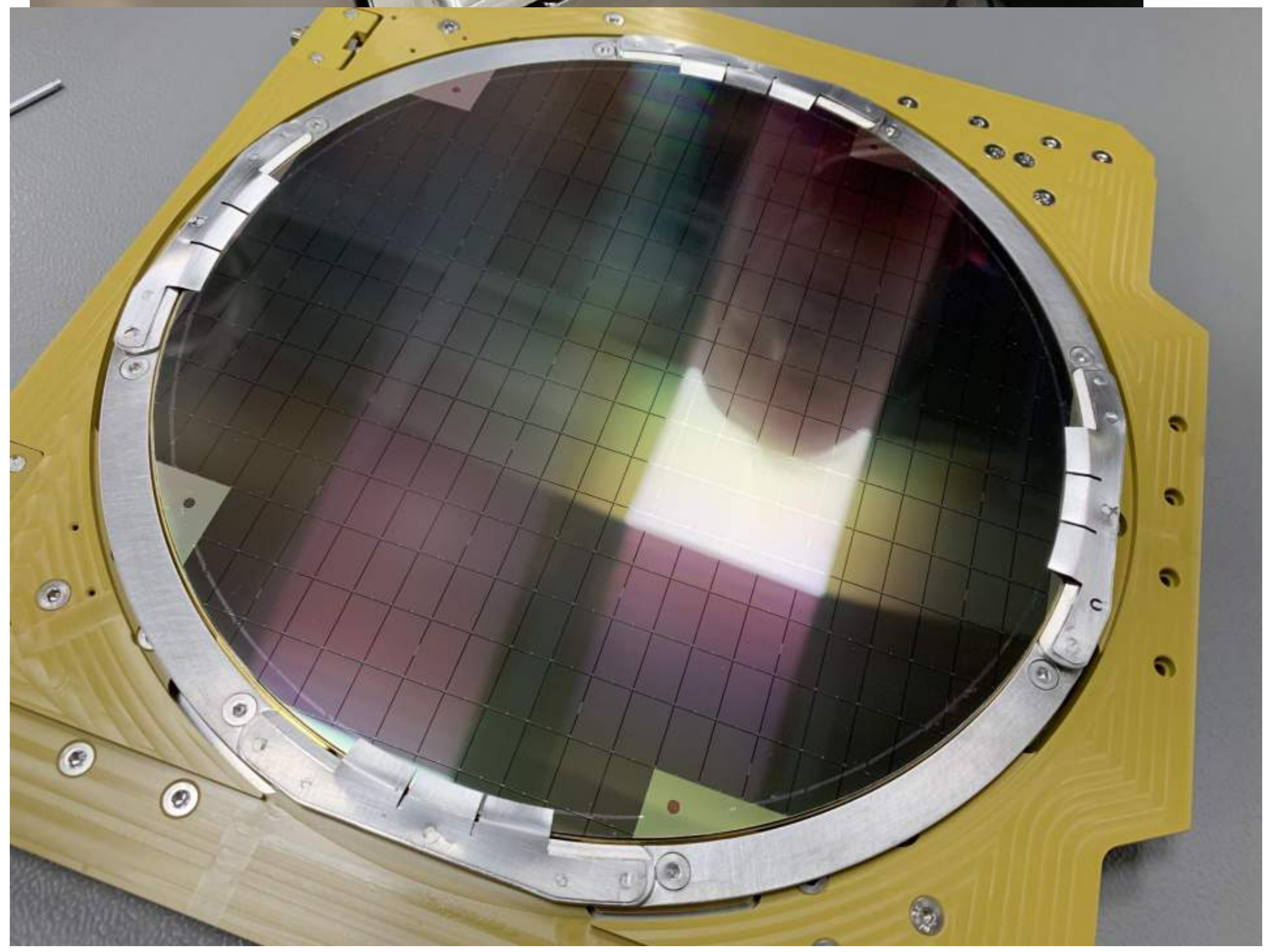
QA/QC criteria from charge injection test



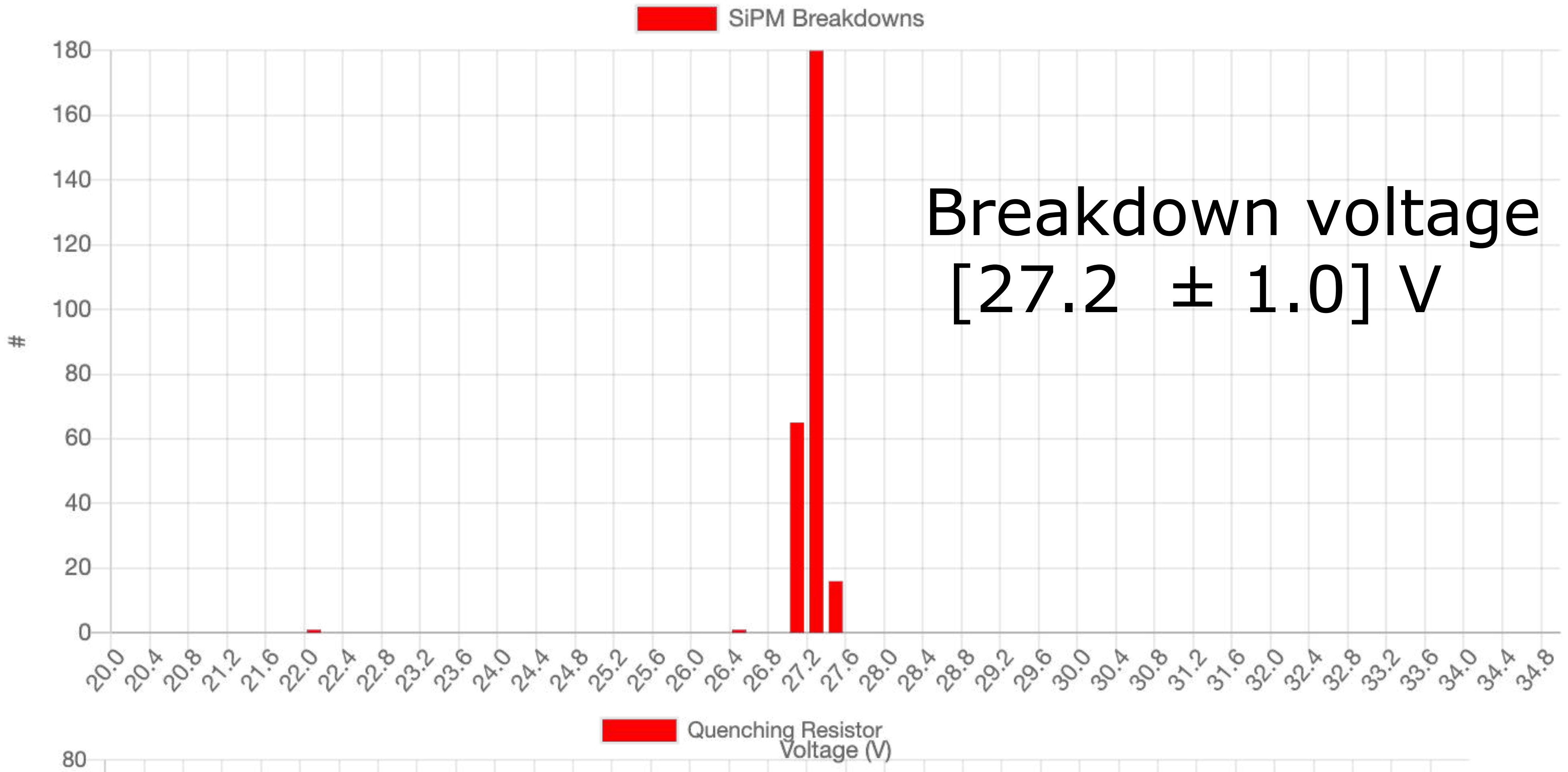


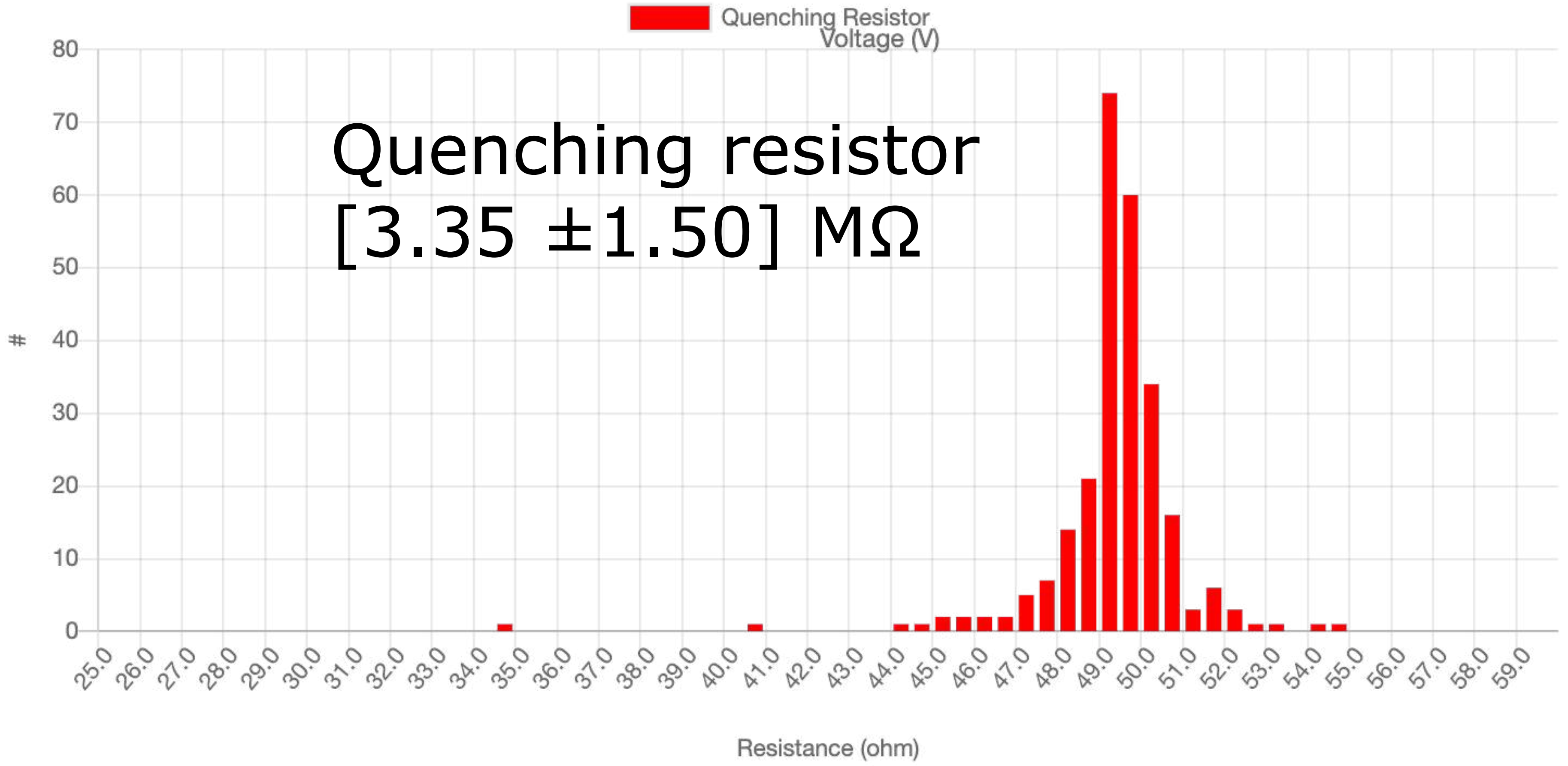


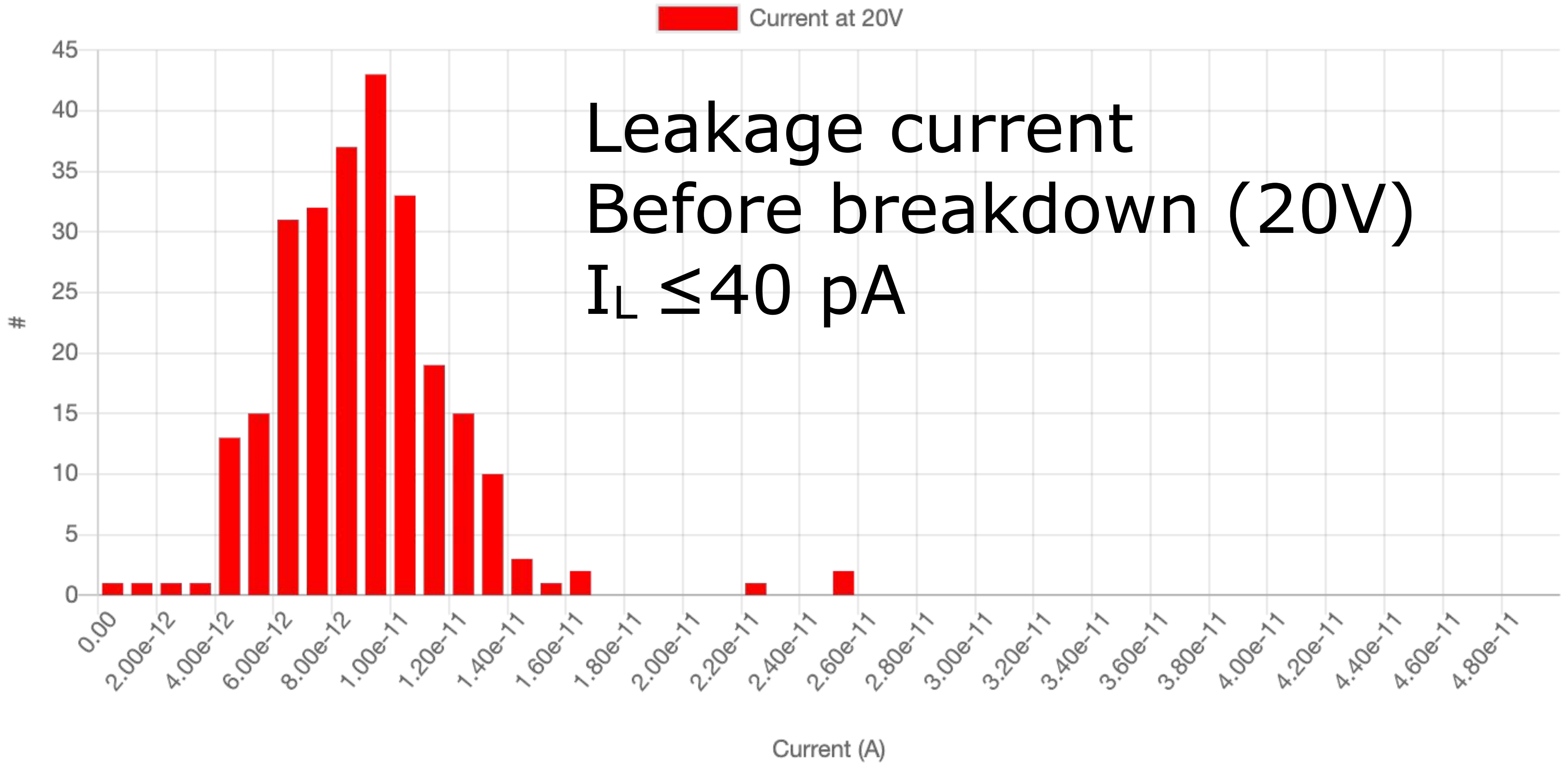
SiPM wafer characterisation



major contributions from Lancs, RHUL



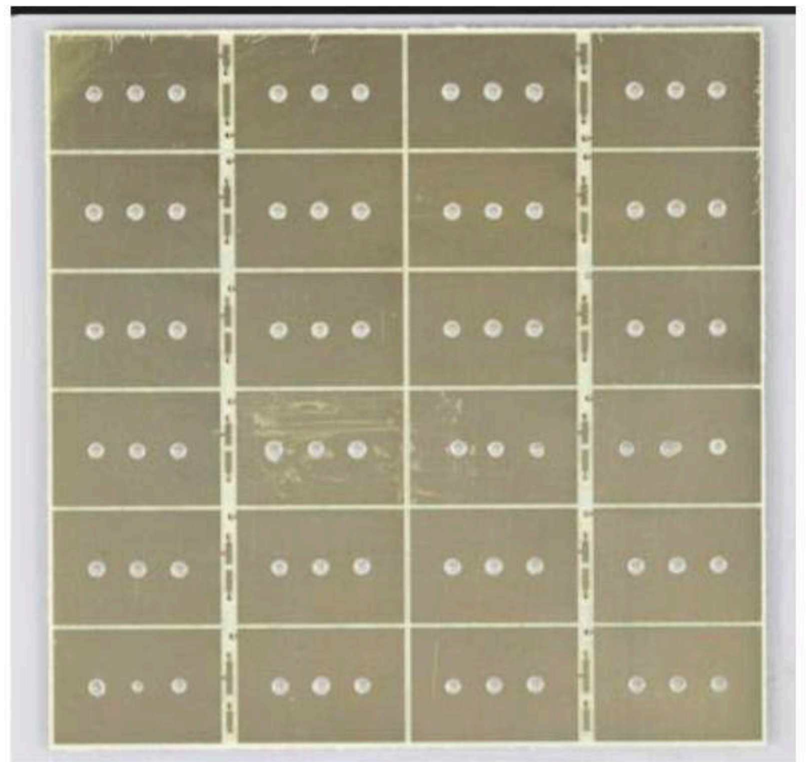




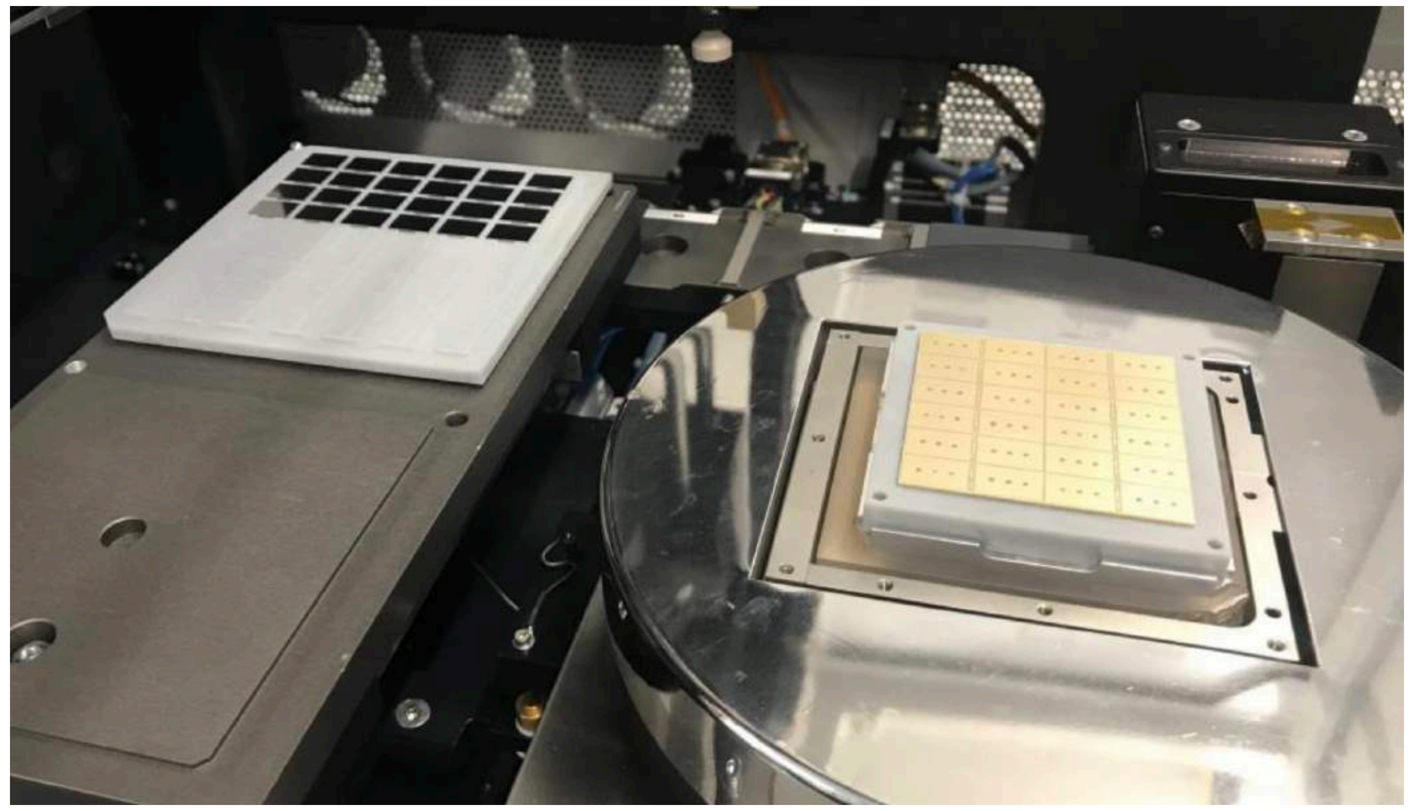
UK FACILITIES: Tile assembly @STFC interconnect

ISO5
Clean room

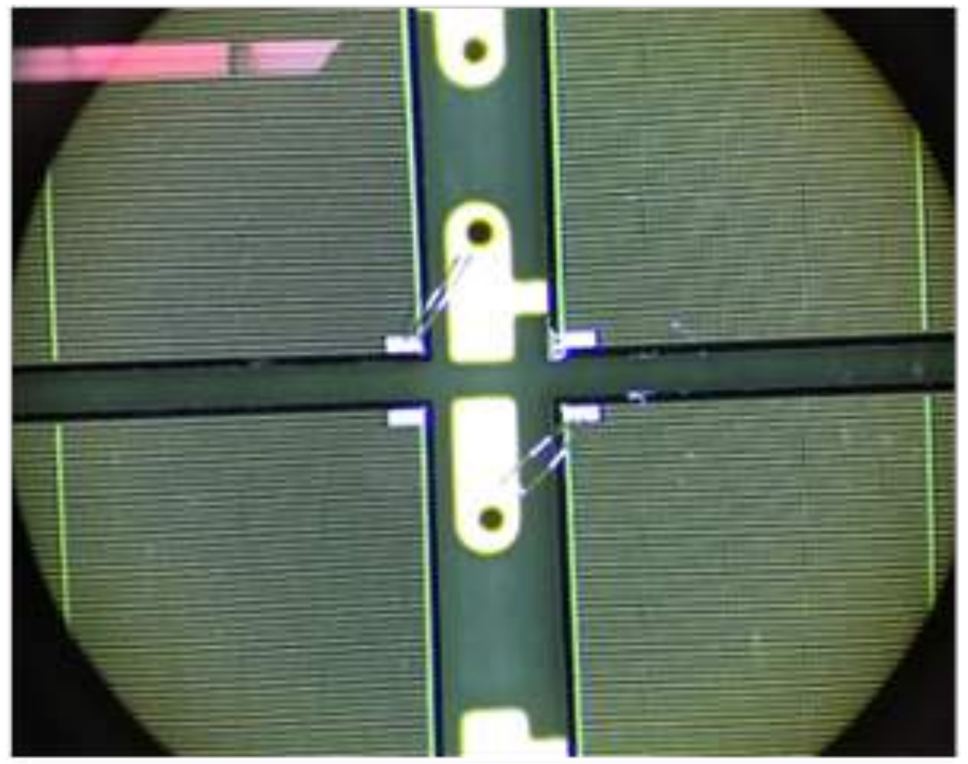
Glue dispense



Die attach



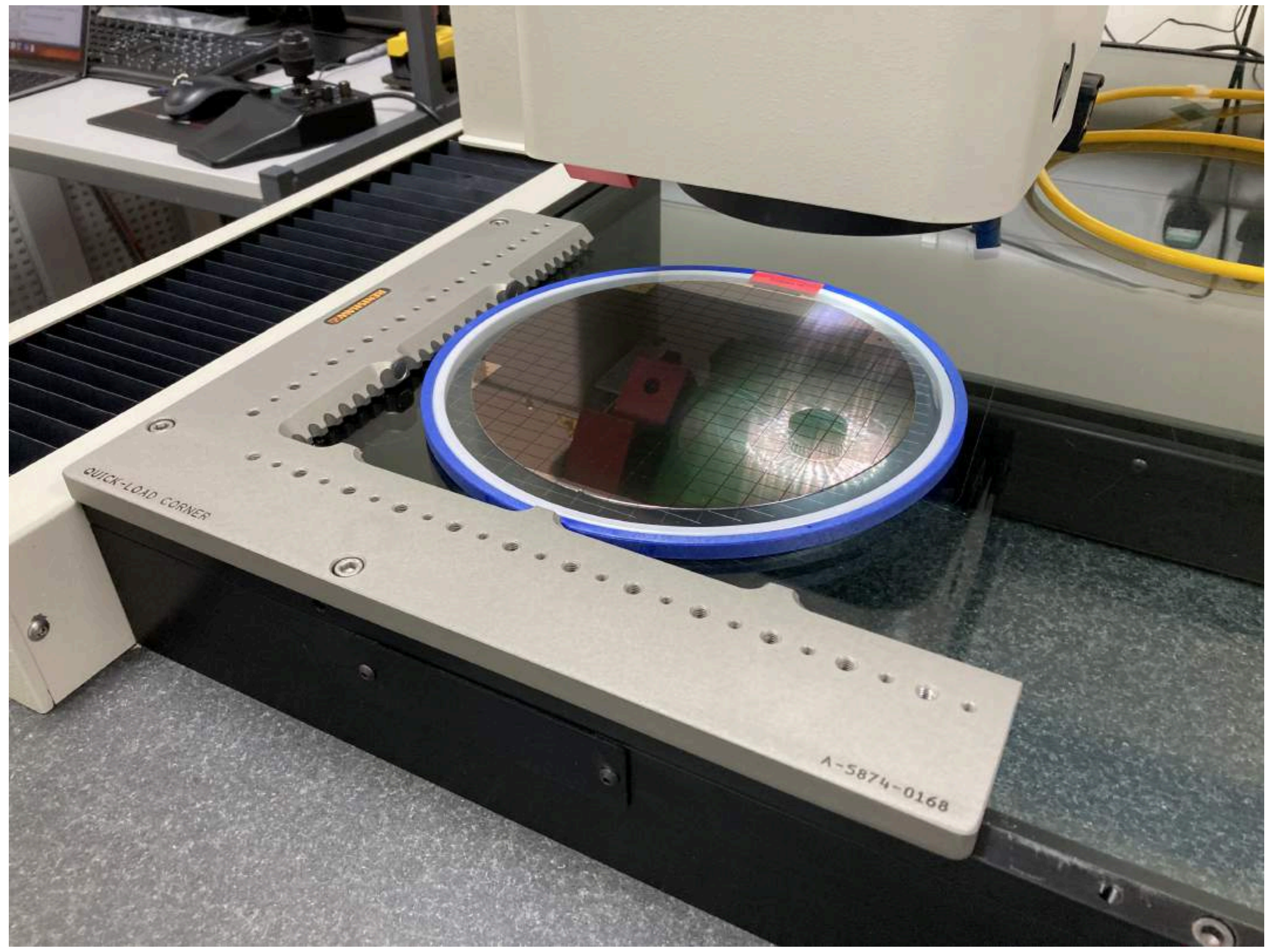
Wire Bonding



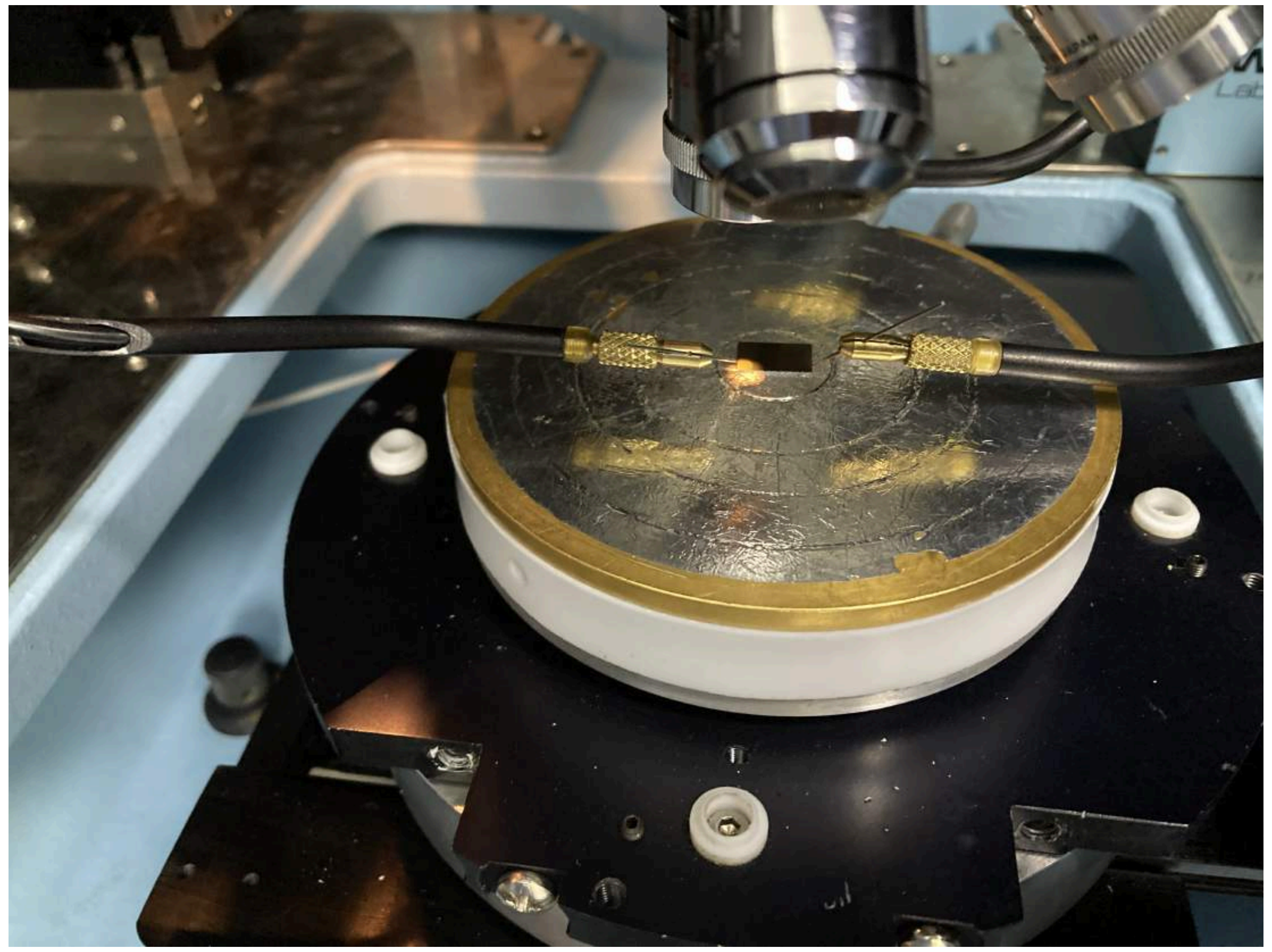
UK FACILITIES: Tile assembly @Liverpool

ISO5
Clean room

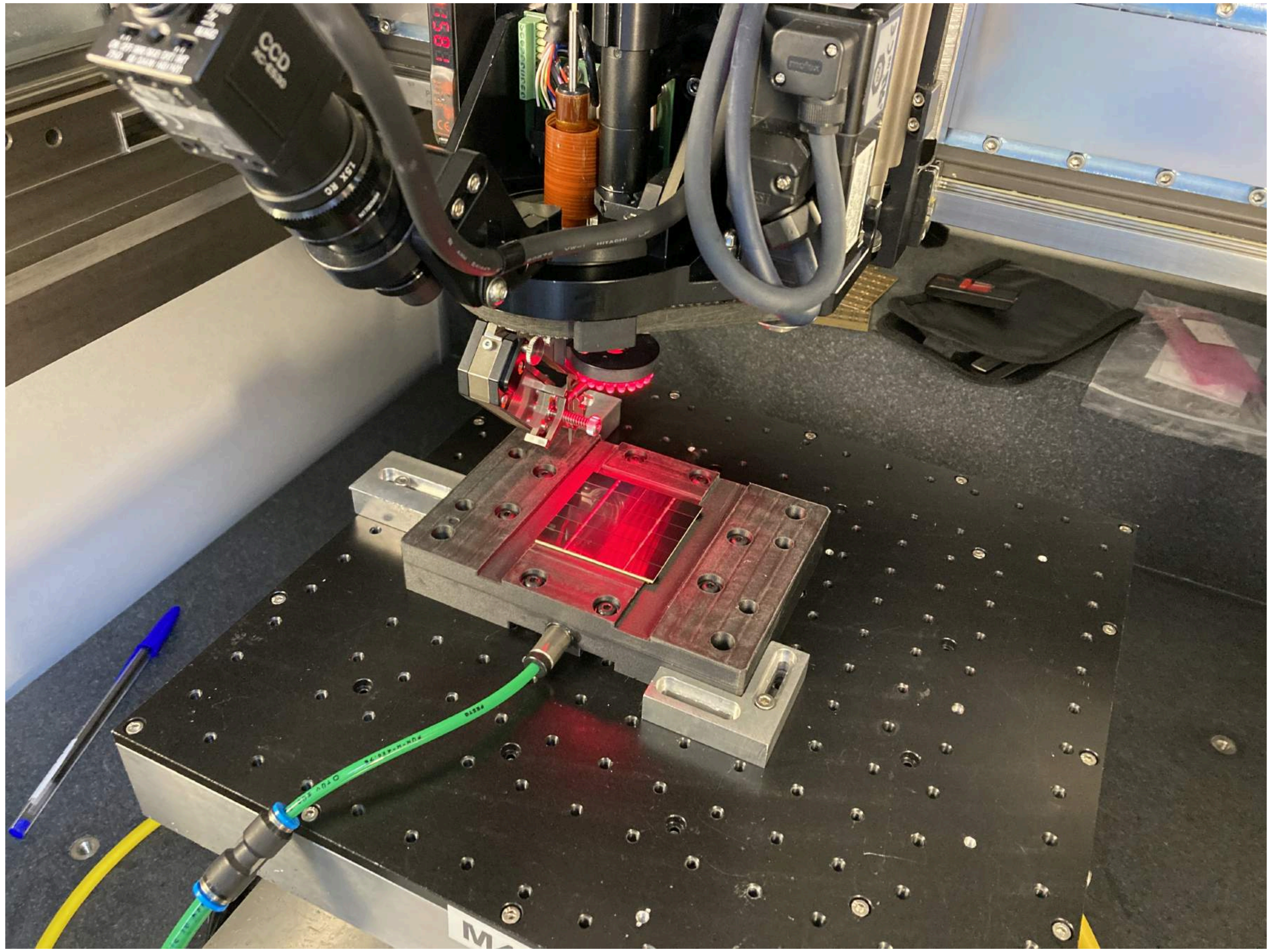
SiPMs Wafers inspection



SiPMs testing before put on the tile



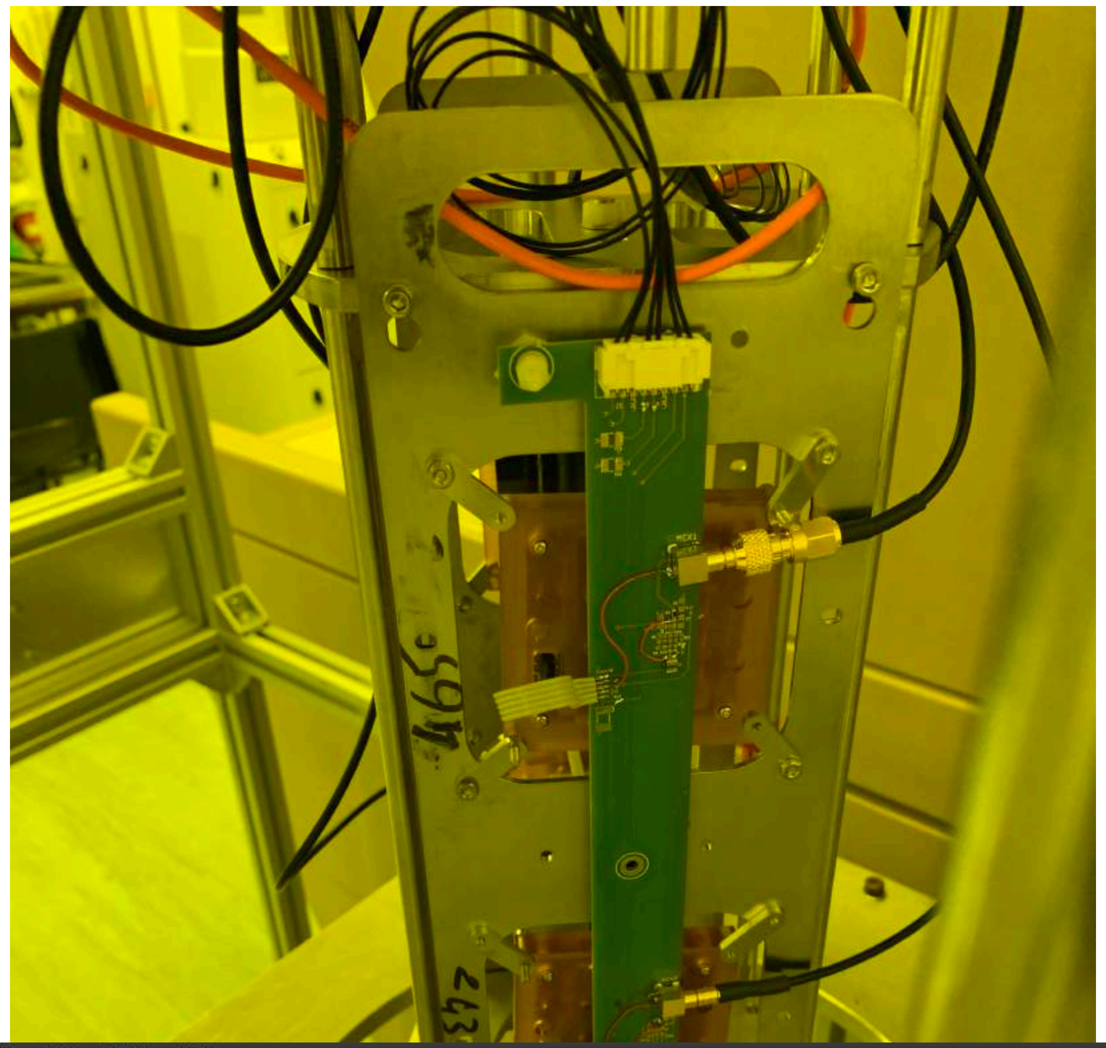
Wire Bonding a vTile

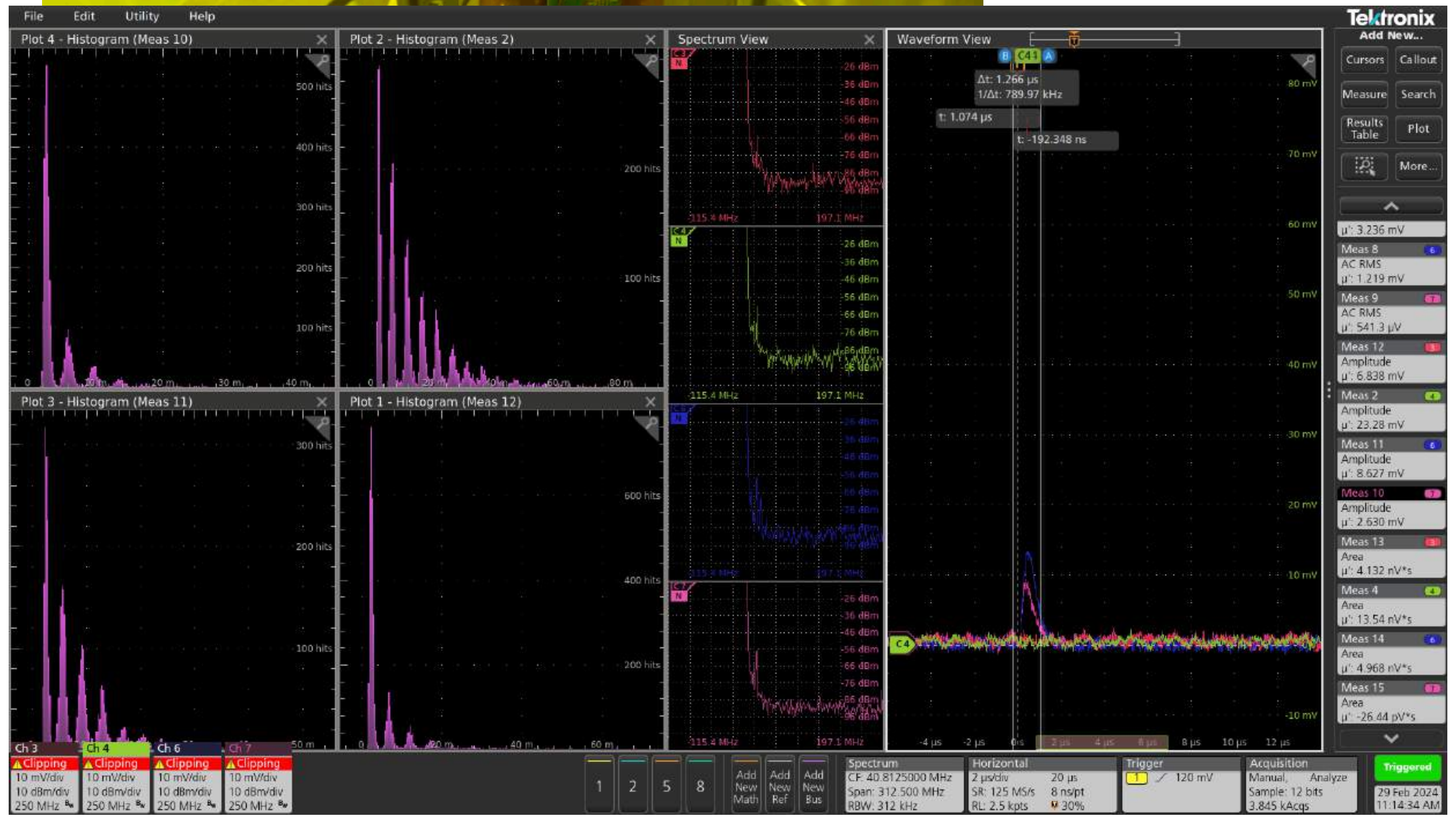


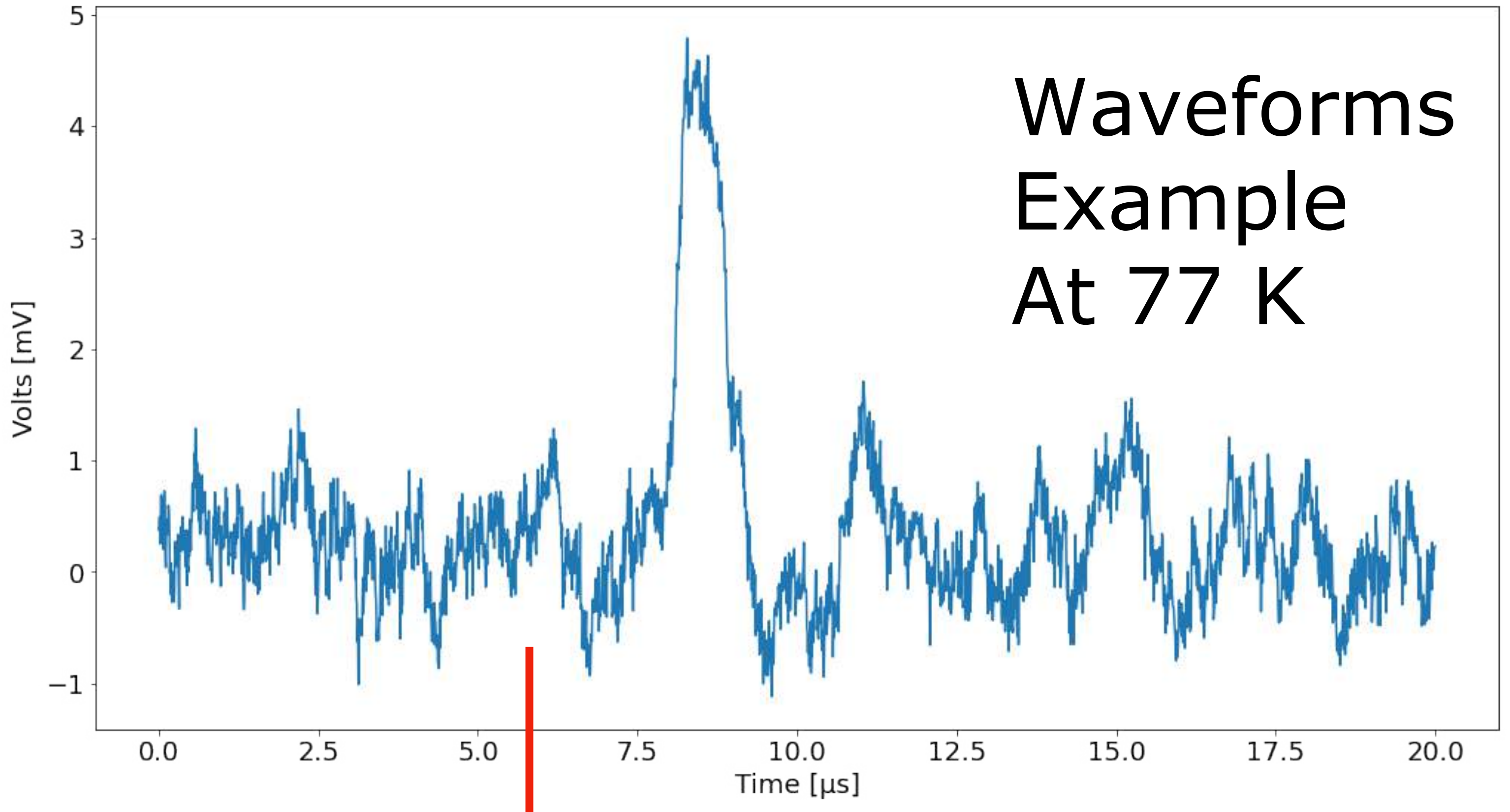
vTILE TESTING

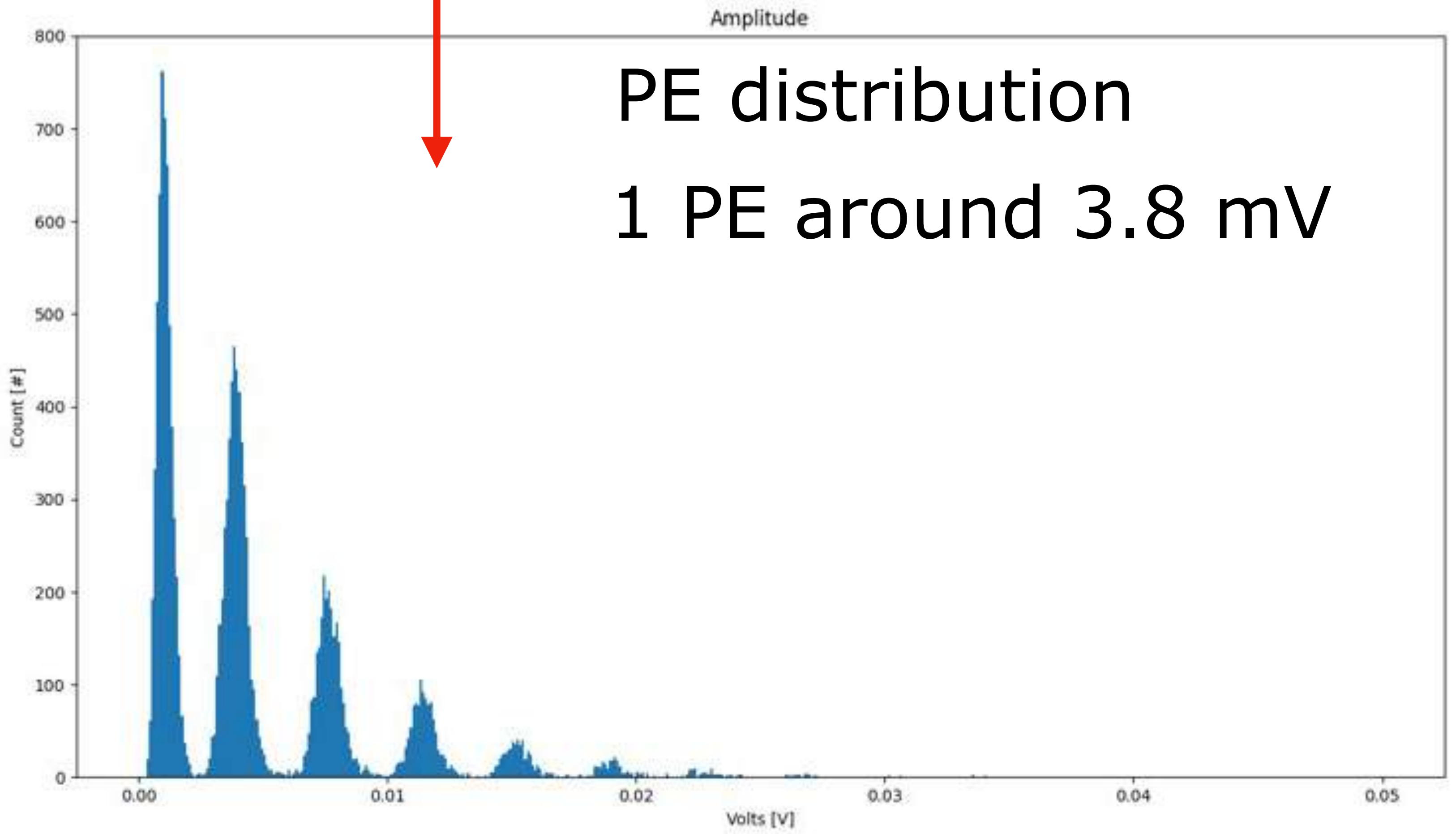
Tile testing @Oxford in liquid nitrogen

4 tiles tested simultaneously





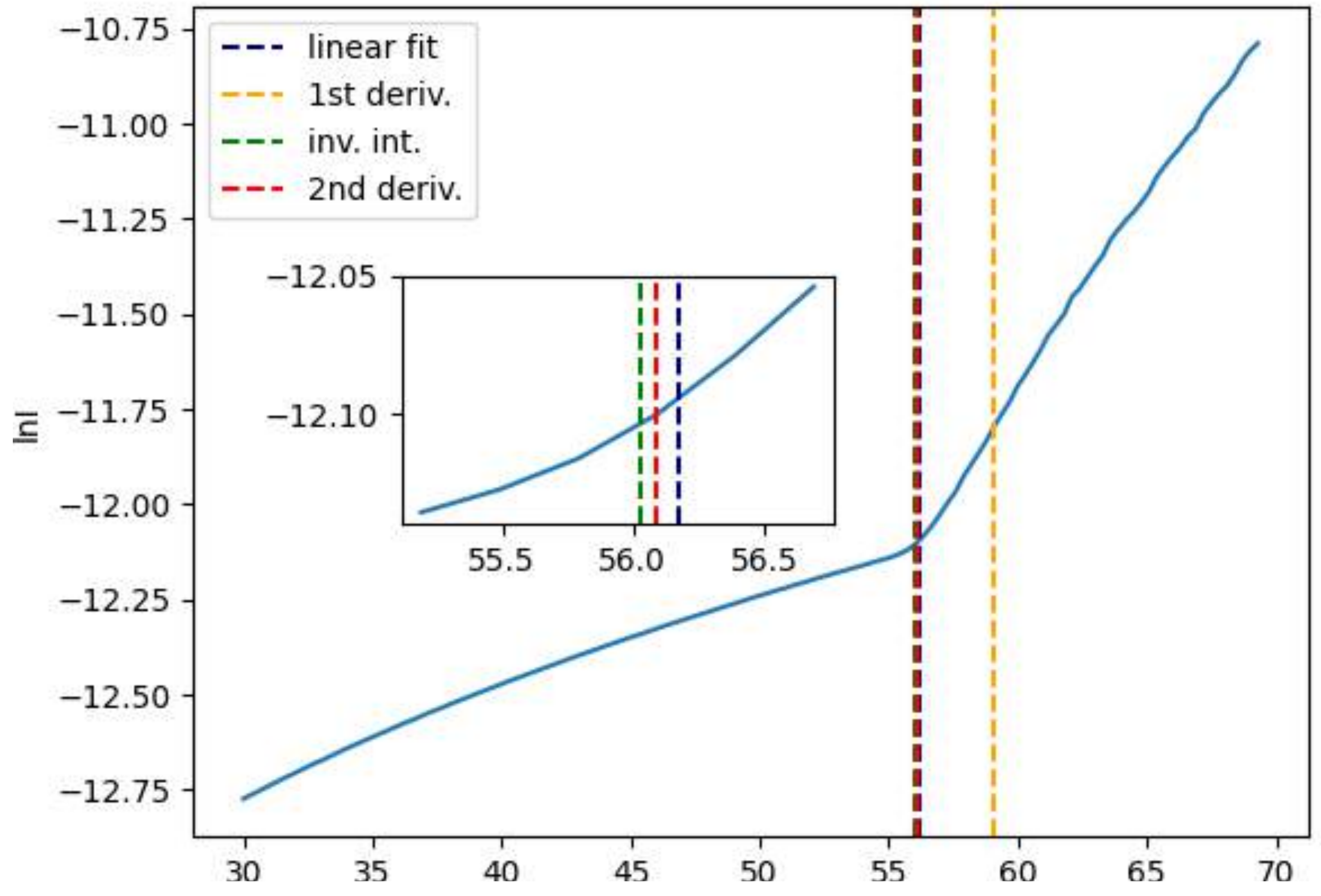


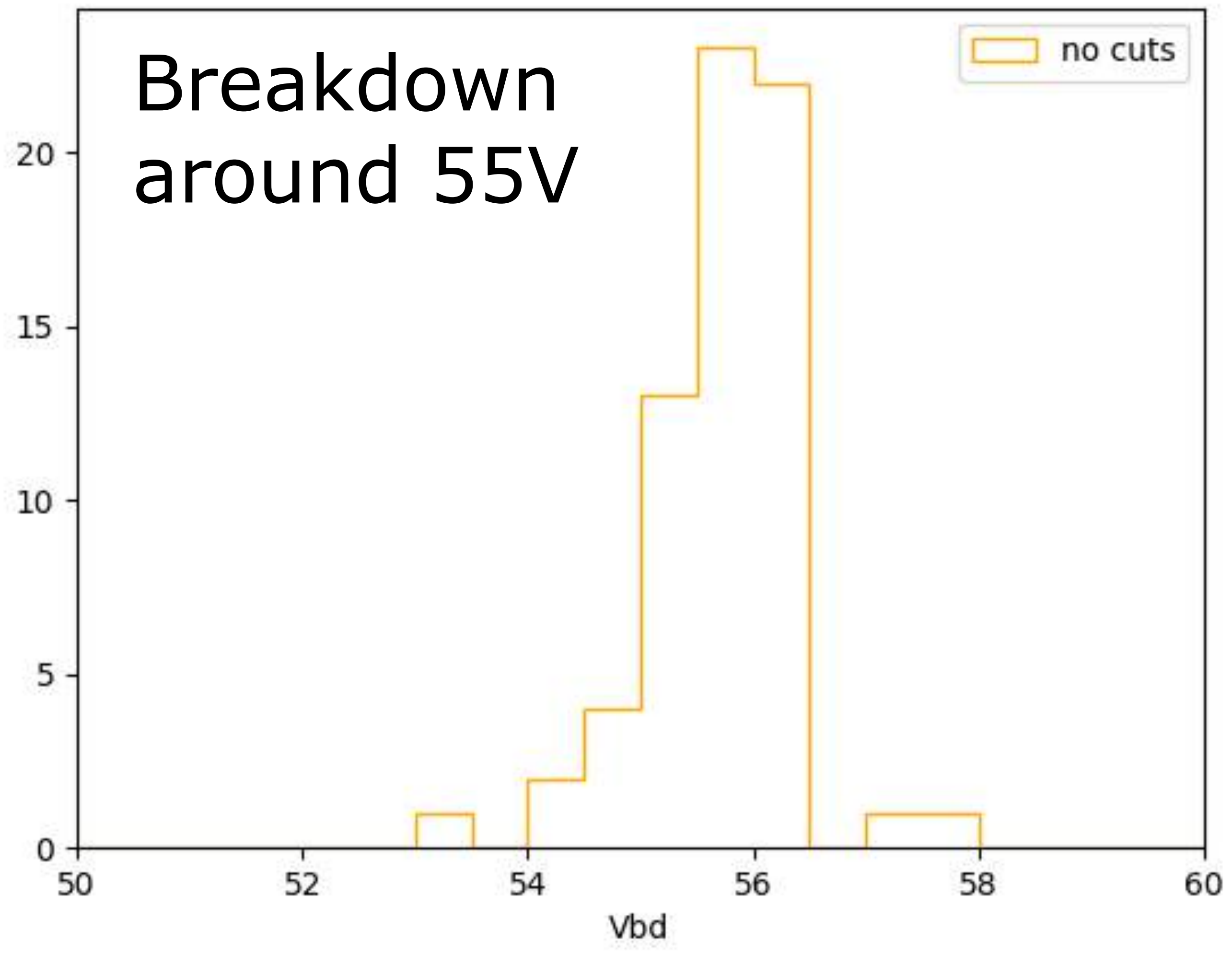


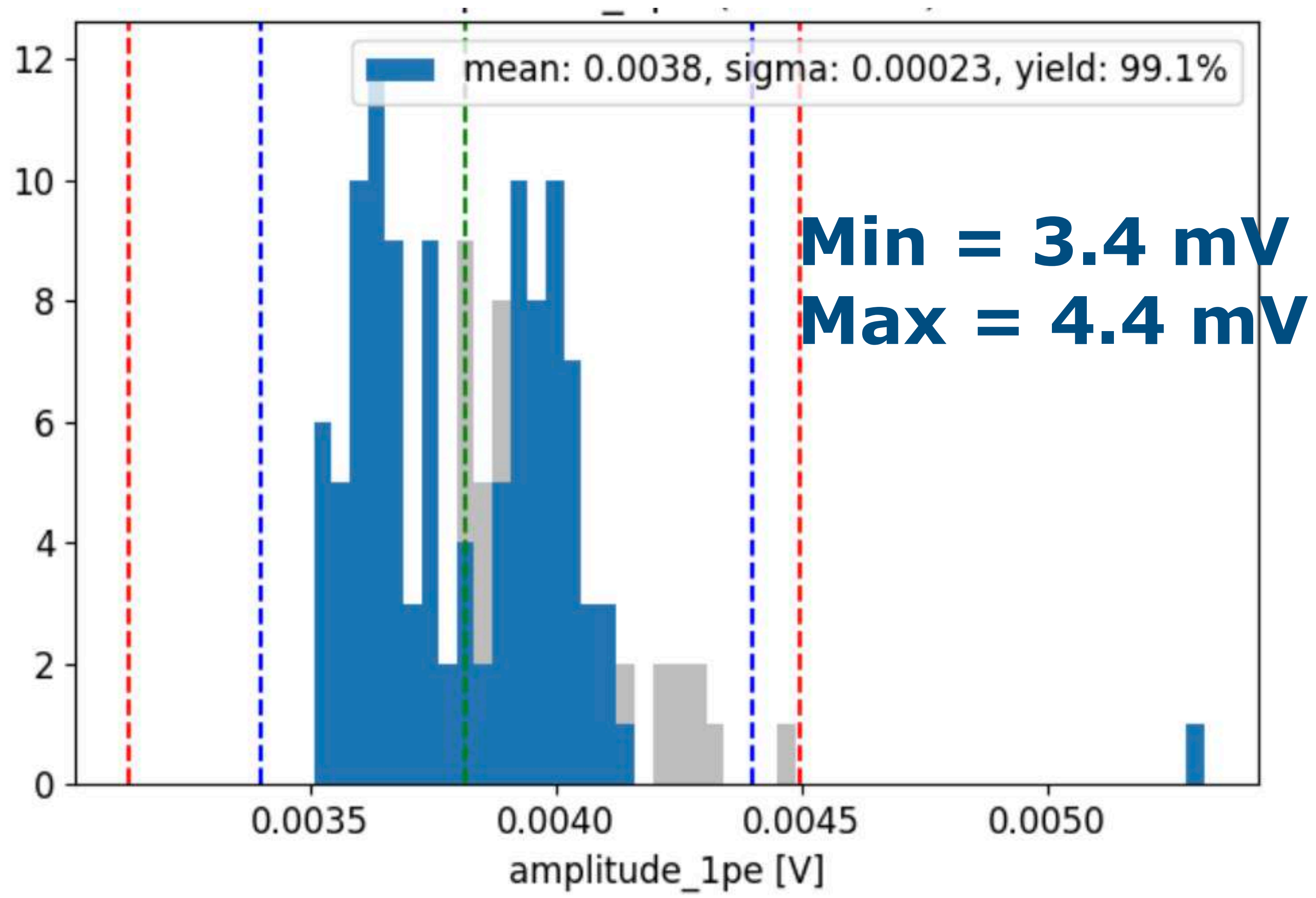
A replica of tile test stand will installed at STFC Interconnect today!!!

vTILE TESTING: QA/QC criteria

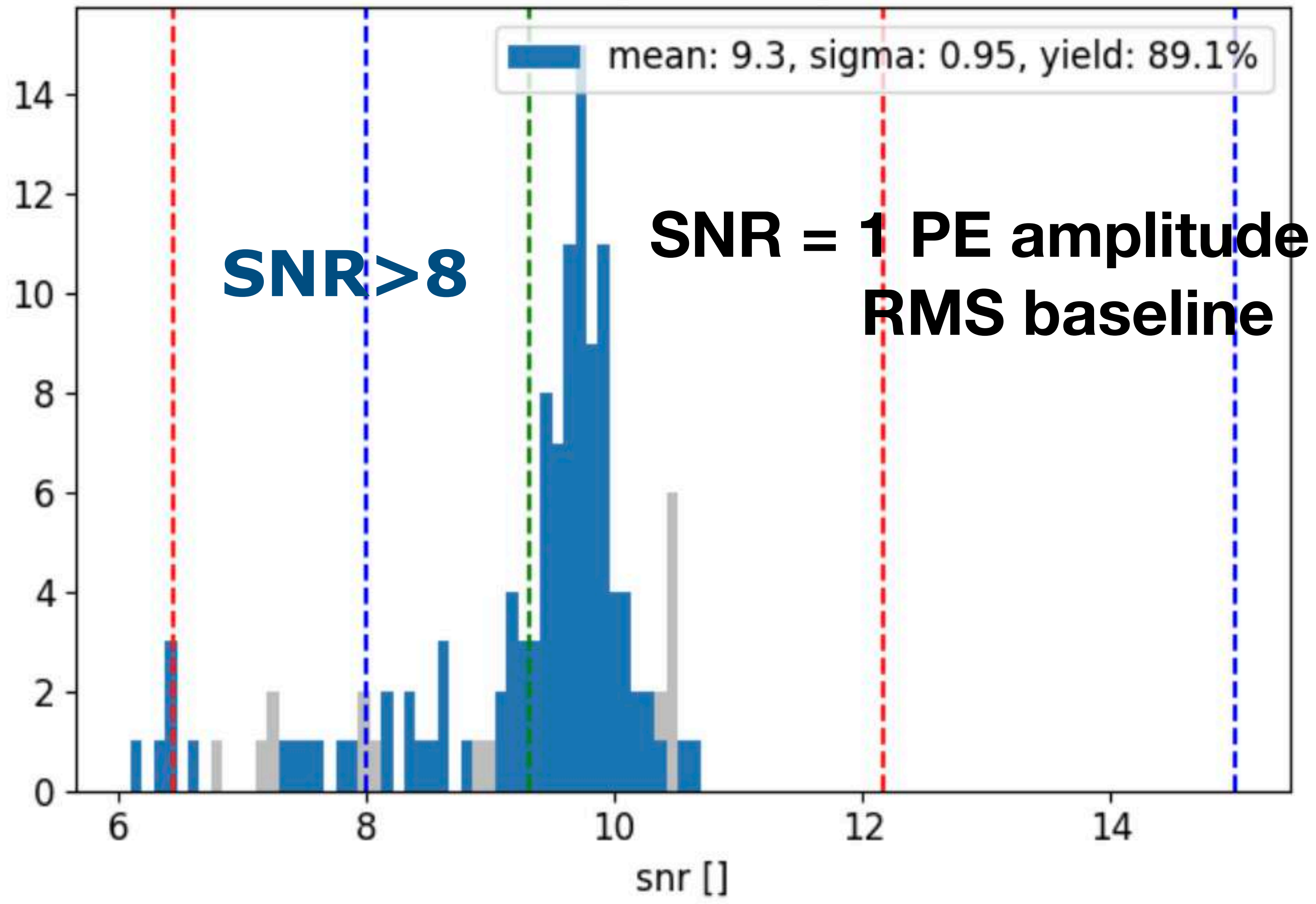
Second derivate fitting procedure
To determinate the breakdown voltage







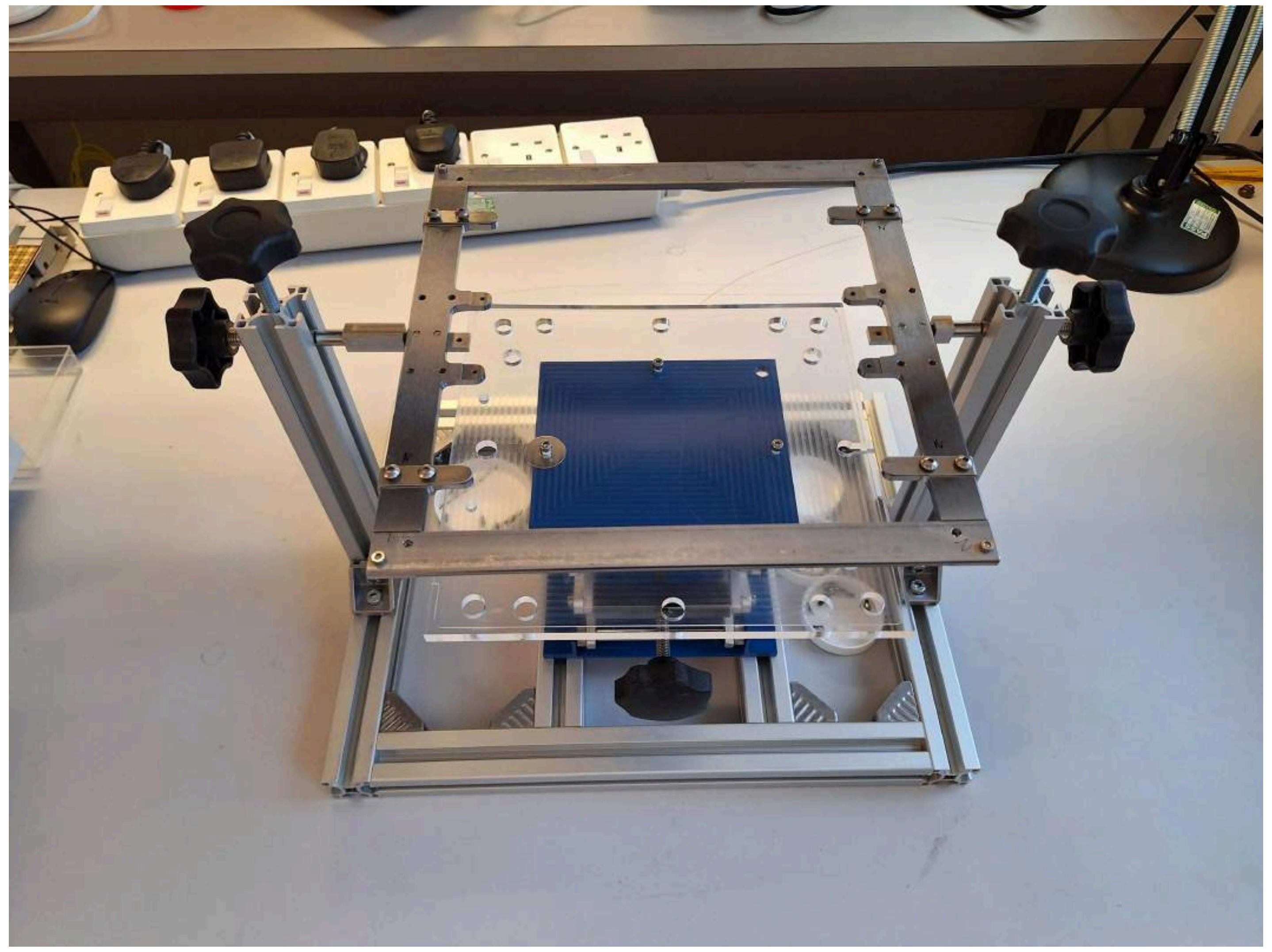
Cryo-probed production SiPM
Pre-production SiPM

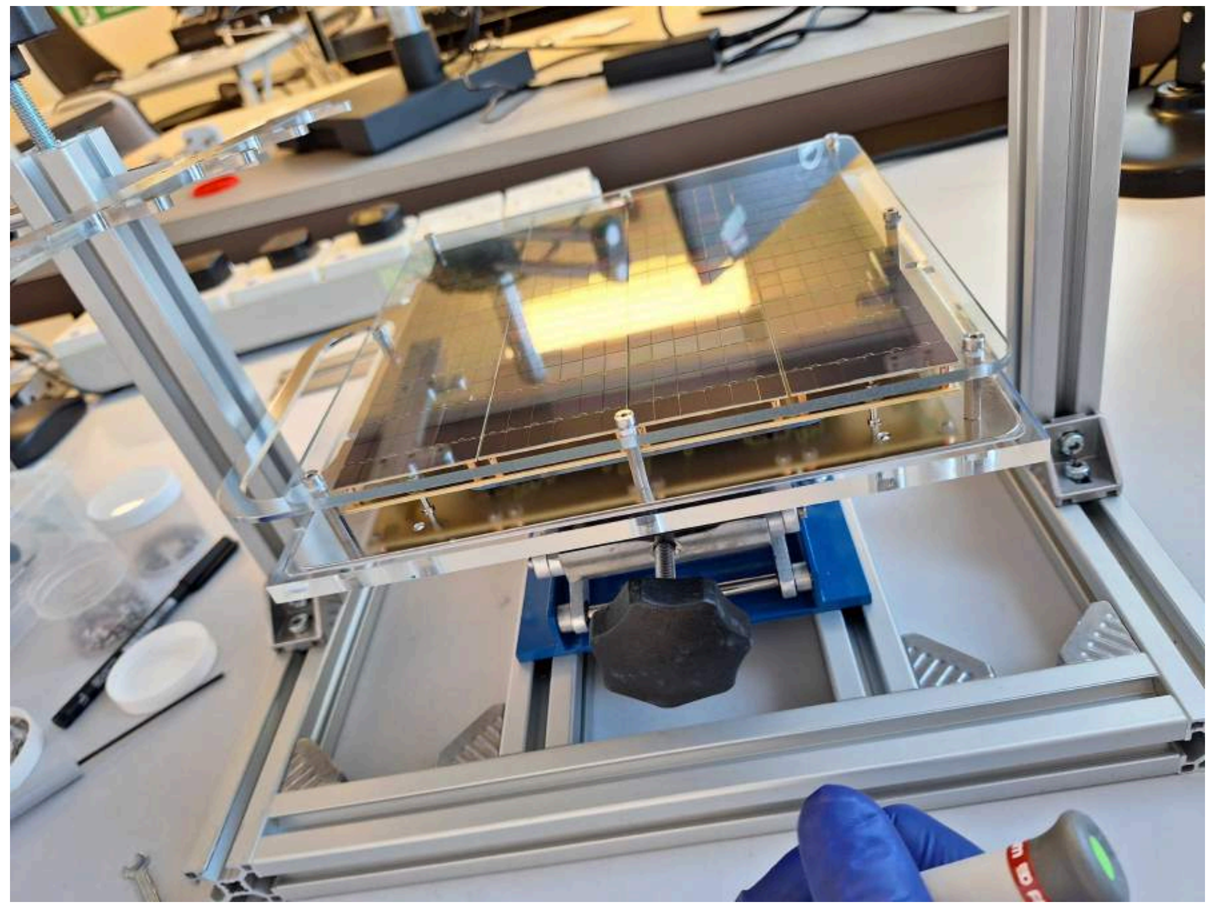


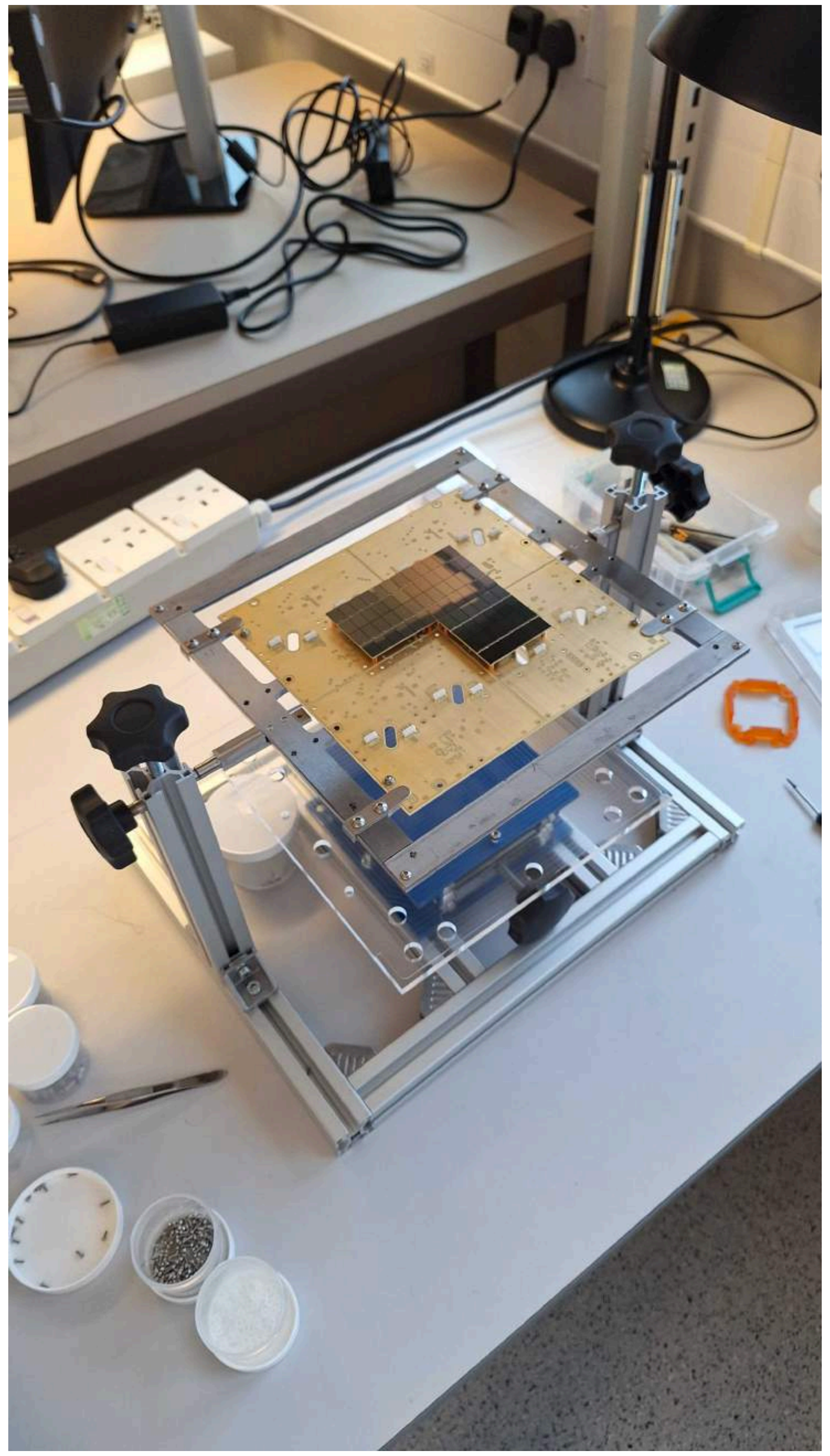
Define a set of QA/QC criteria to determine whether a tile has single PE performance good enough to be integrated into a vPDU

UK FACILITIES: PDU assembly & testing @Manchester

Successfully assembled six vPDU!





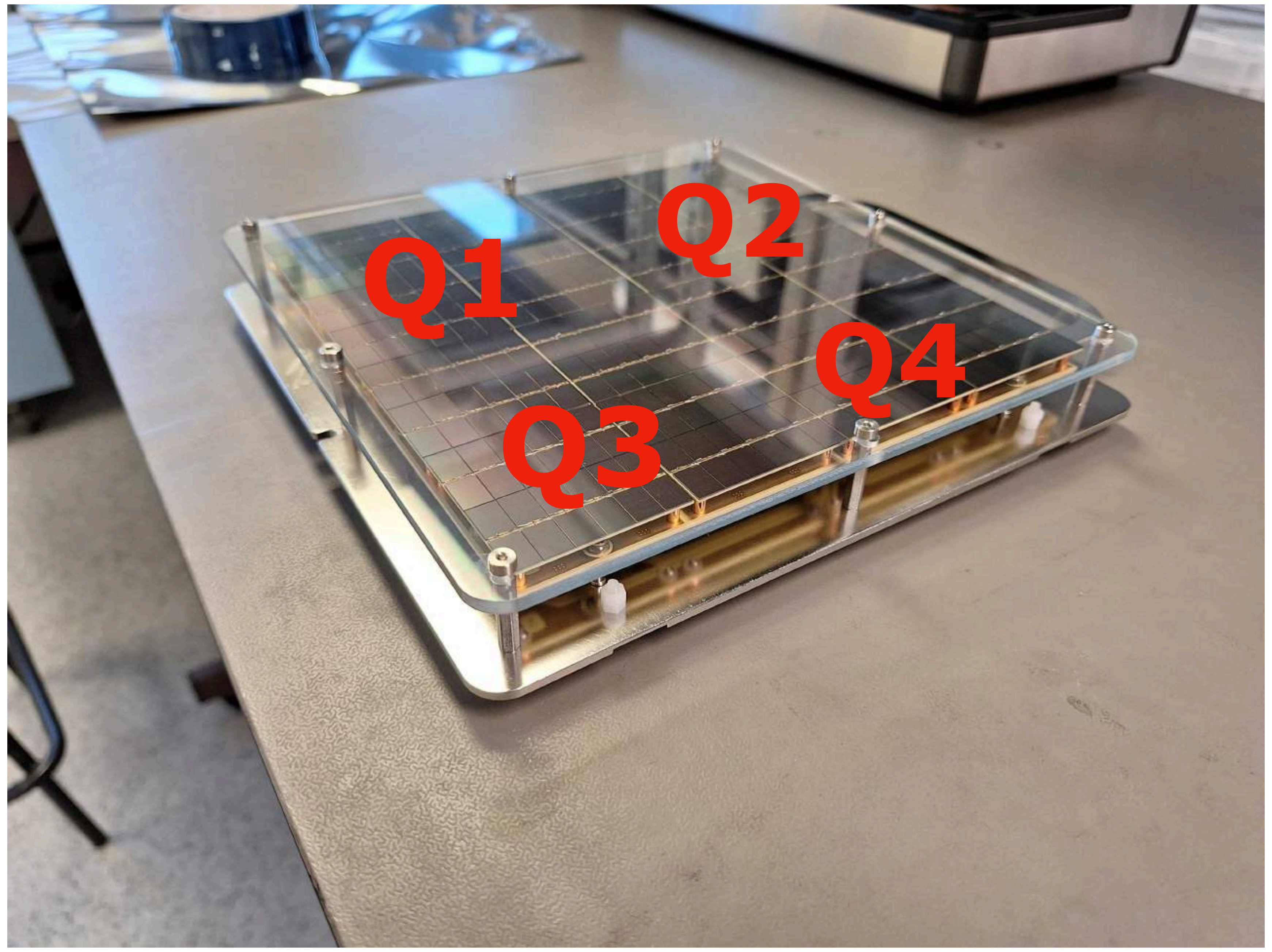


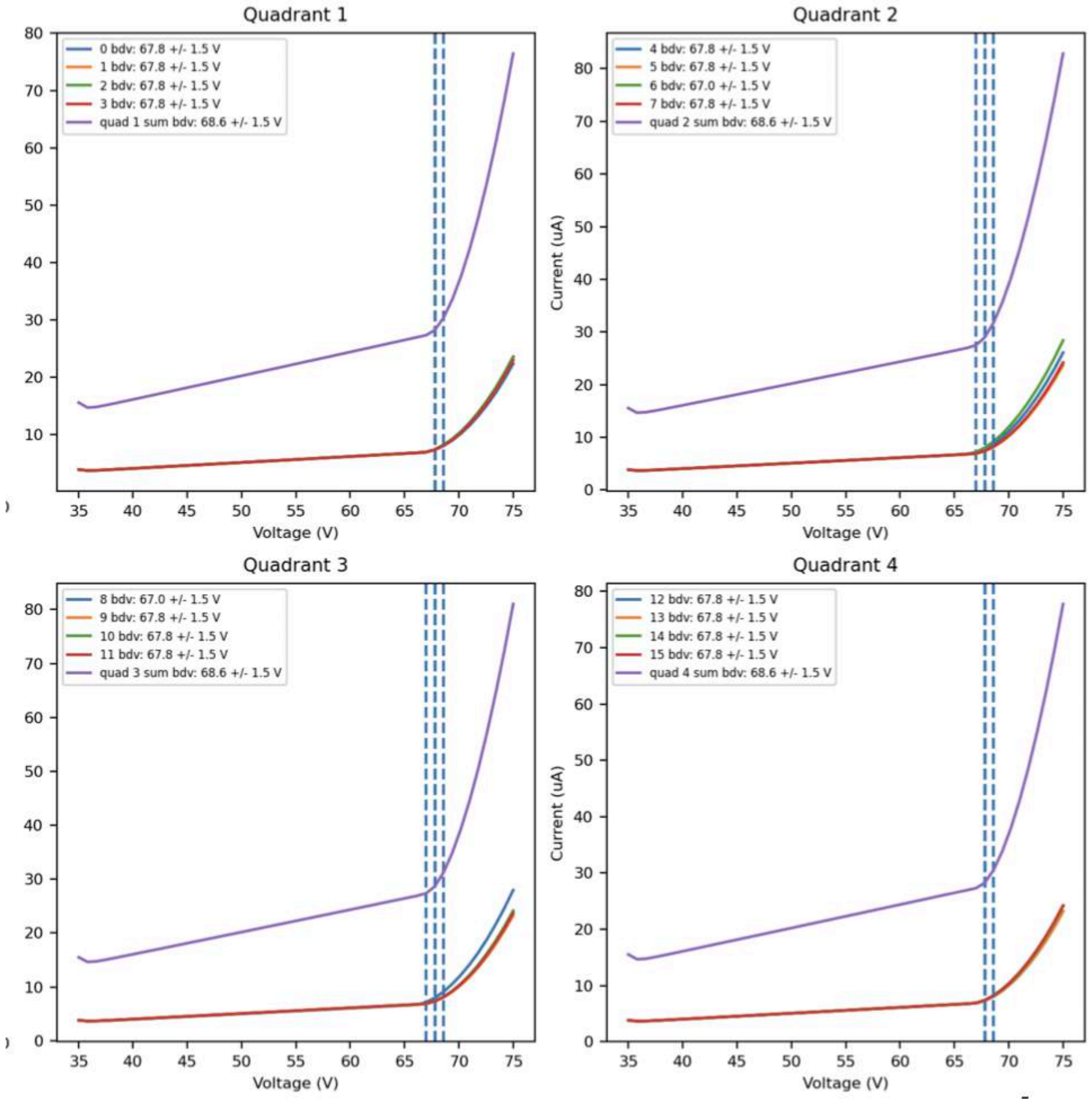
vPDU Production
have started in July 2023

Warwick WARM testing setup @Manchester

vPDU: warm test

Preliminary check to check that all tile and all 4 quadrant are
Working properly. IV curve -> expected breakdown around 67V



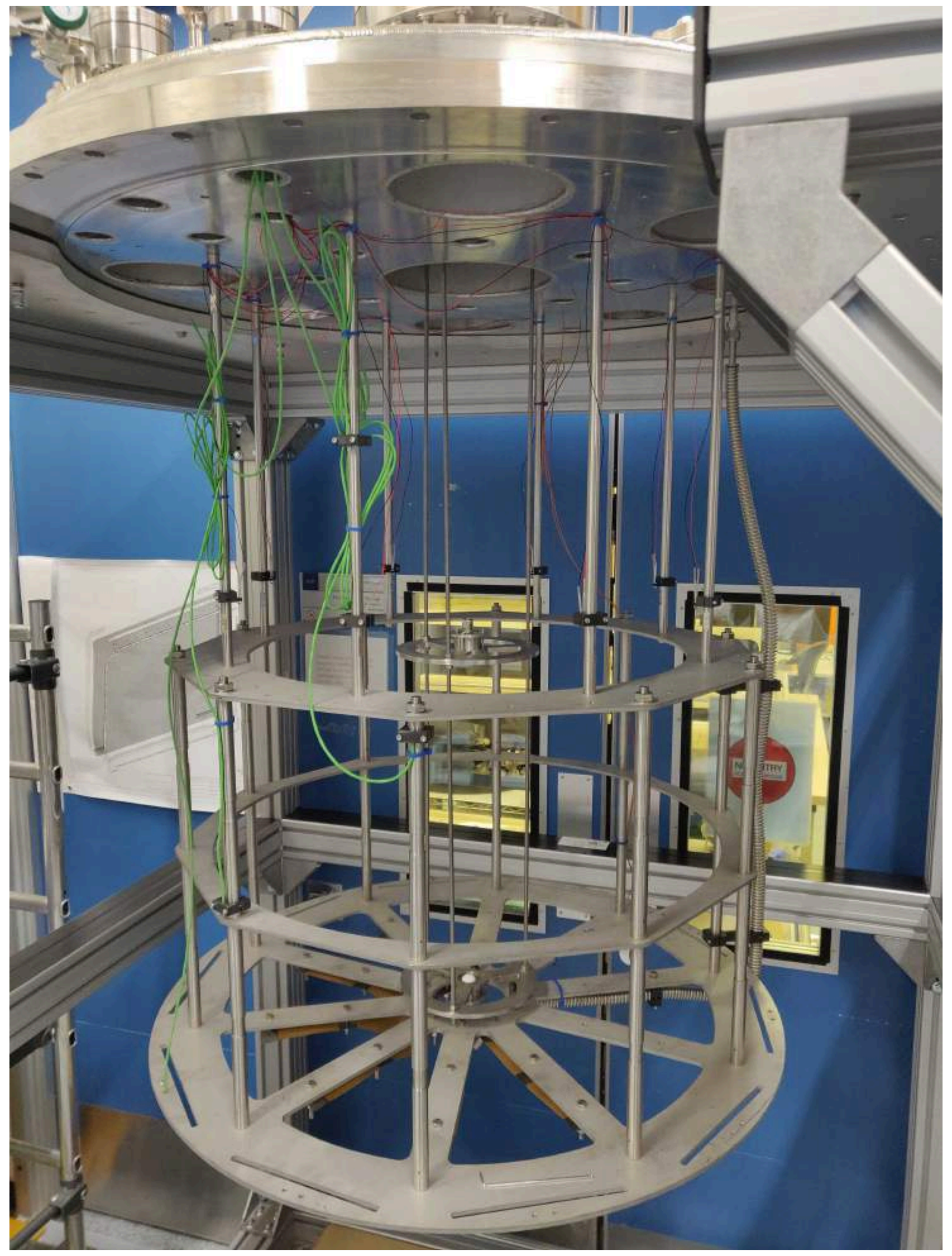


major contributions from Manchester, Warwick groups

vPDU TEST FACILITIES

Cold testing setup @Liverpool

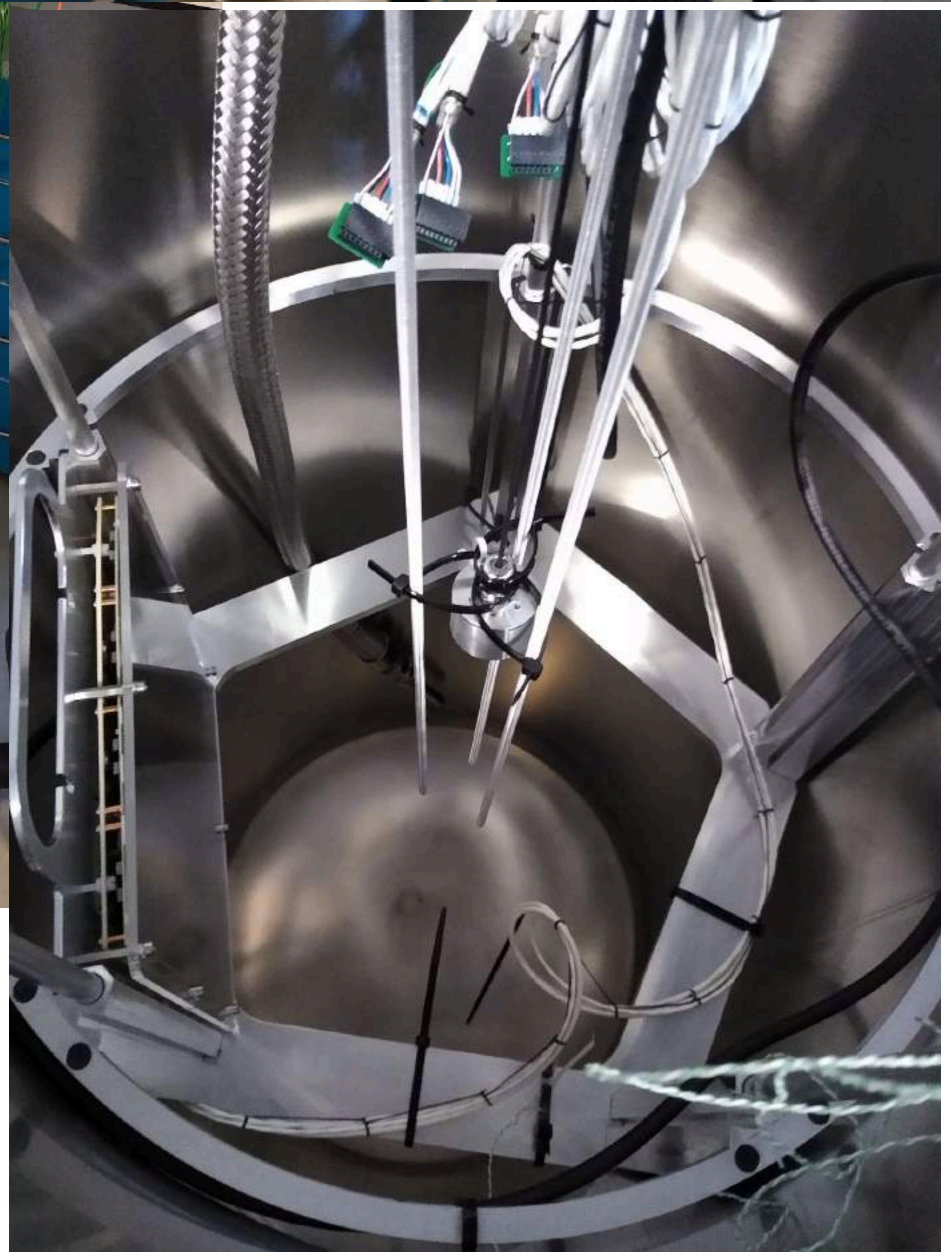
PHAIDRA



Main test facilities: 20 vPDU per time

Ready to go!

Cold testing setup @Edinburgh



4 vPDU per time

Fully operational from Summer 2023!

vPDU TEST FACILITIES

Cold testing setup @ASTROCENT (Poland)

10 vPDUs per time
Fully operational
from September 2023!

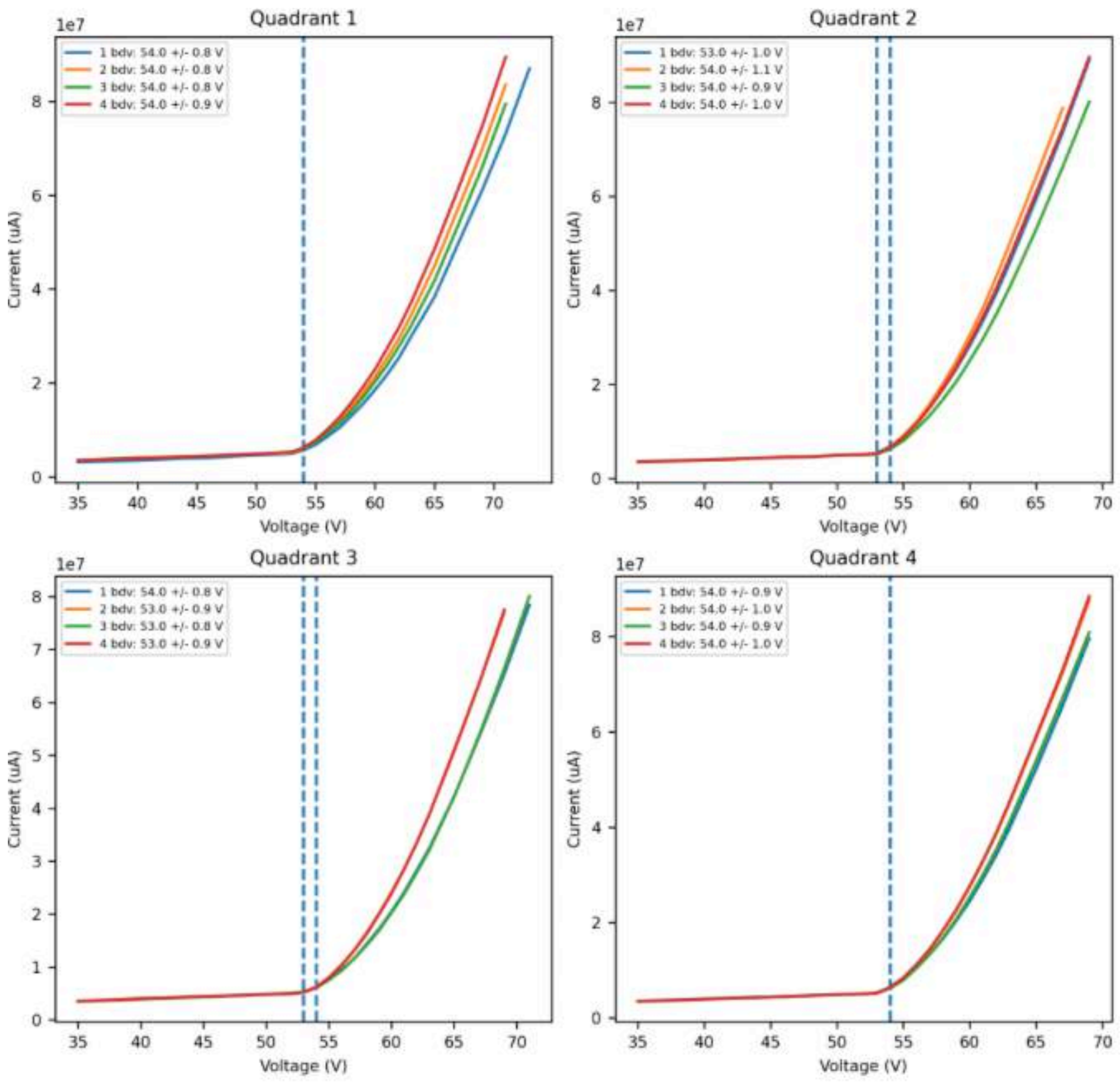
Cold testing setup @Lancaster

4 vPDUs per time
vDPU hospital!
Finalising data acquisition system

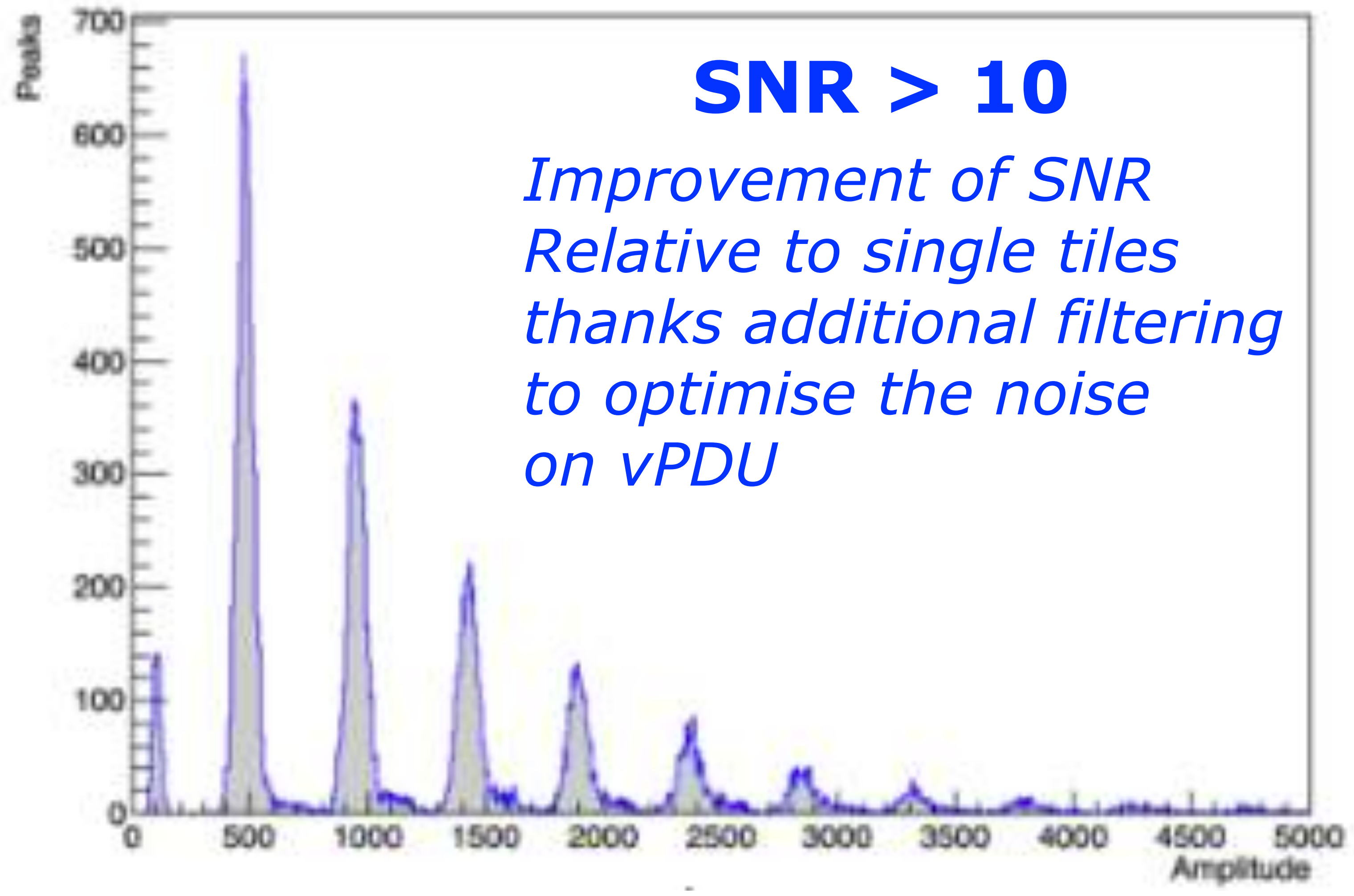
vPDU: cold test

Preliminary results
Shows that the vPDU
Meet the design
requirement

Breakdown around 55 V



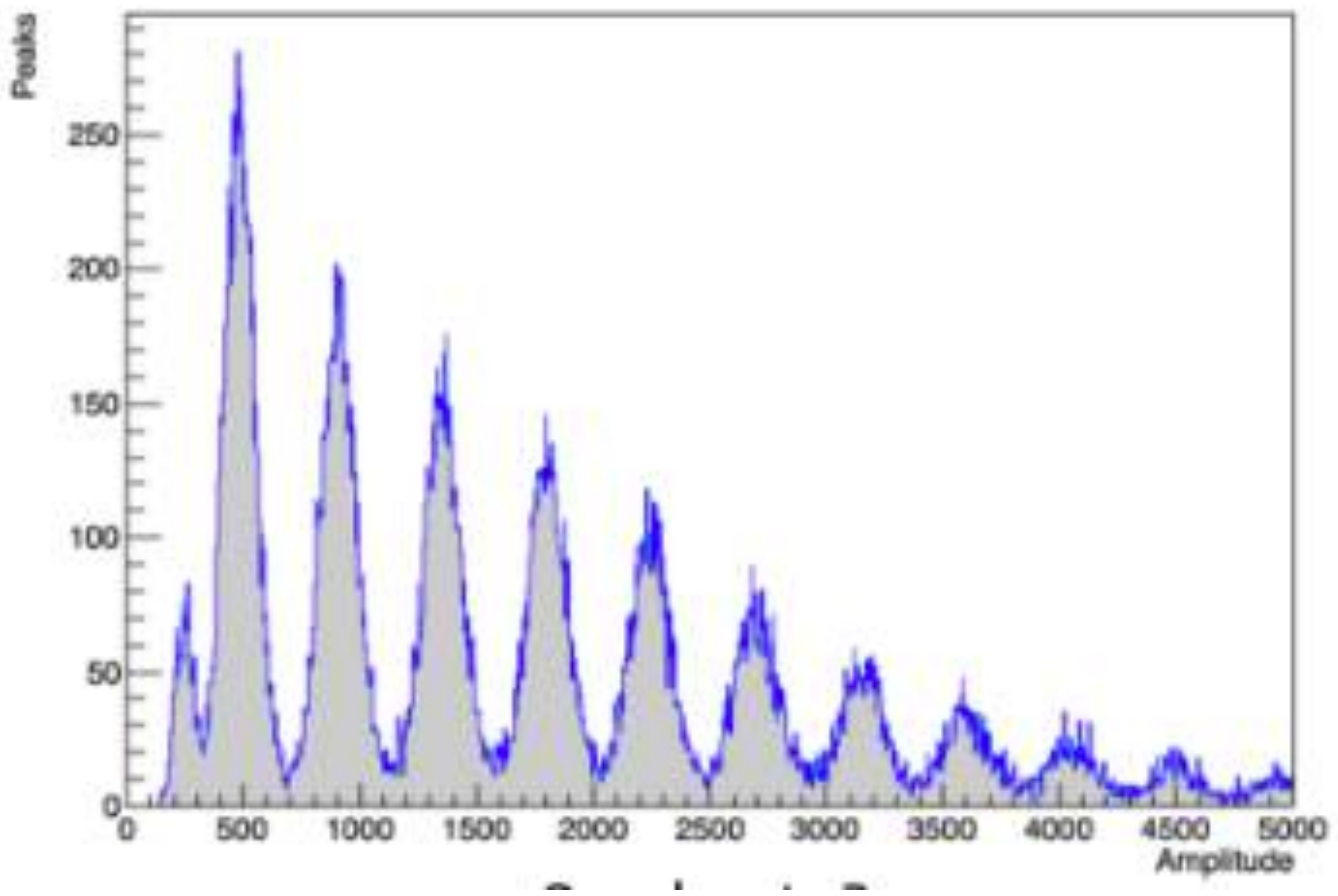
Single tile PE distribution



SNR > 10

Improvement of SNR
Relative to single tiles
thanks additional filtering
to optimise the noise
on vPDU

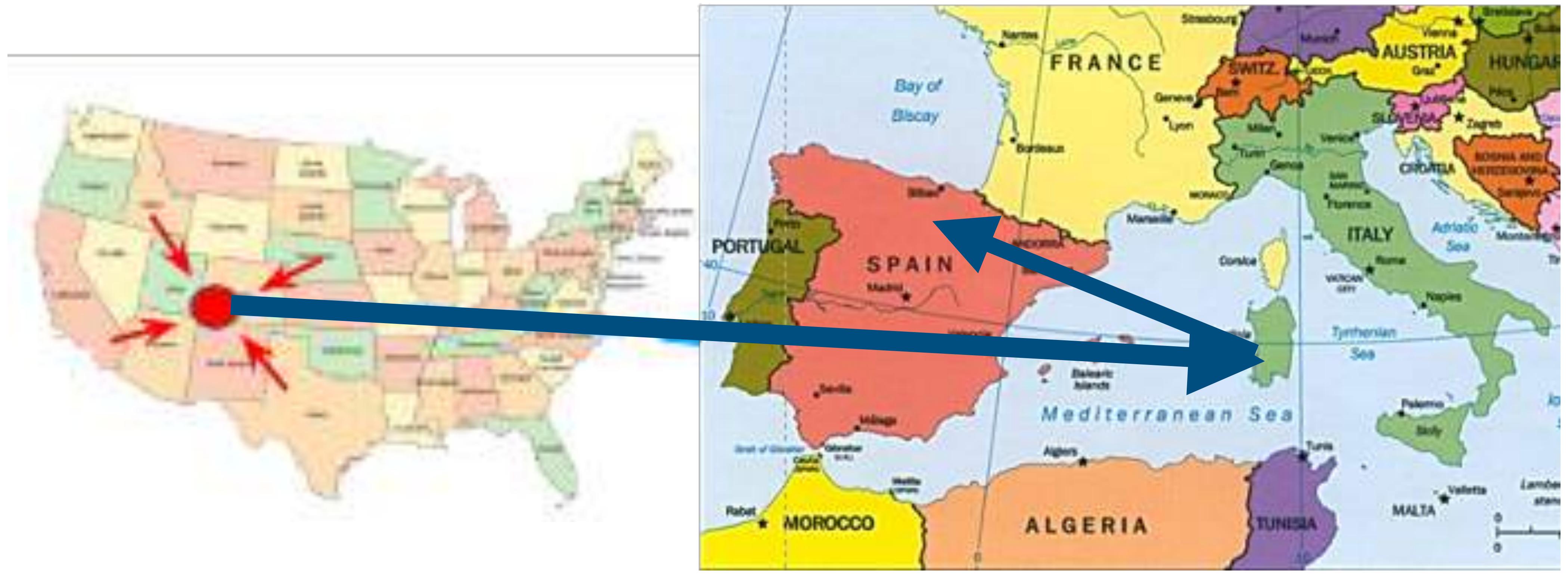
Quadrant PE distribution: summing of 4 tile -> 10 x 10 cm2 area!



- **1 PE of 16 mV** ✓
- **SNR of 5** ✓

BACKGROUNDs in DARKSIDE-20k

THE PATH TOWARS PURE UAr: Urania->Aria->DArT



1. Urania: UAr extraction

- CO_2 well in Cortez, CO, USA;
- Industrial scale extraction plant;
- UAr extraction rate: 250-330 kg/day;
- Purity 99.99%
- Plant complete, construction onsite underway

2. ARIA: UAr purification

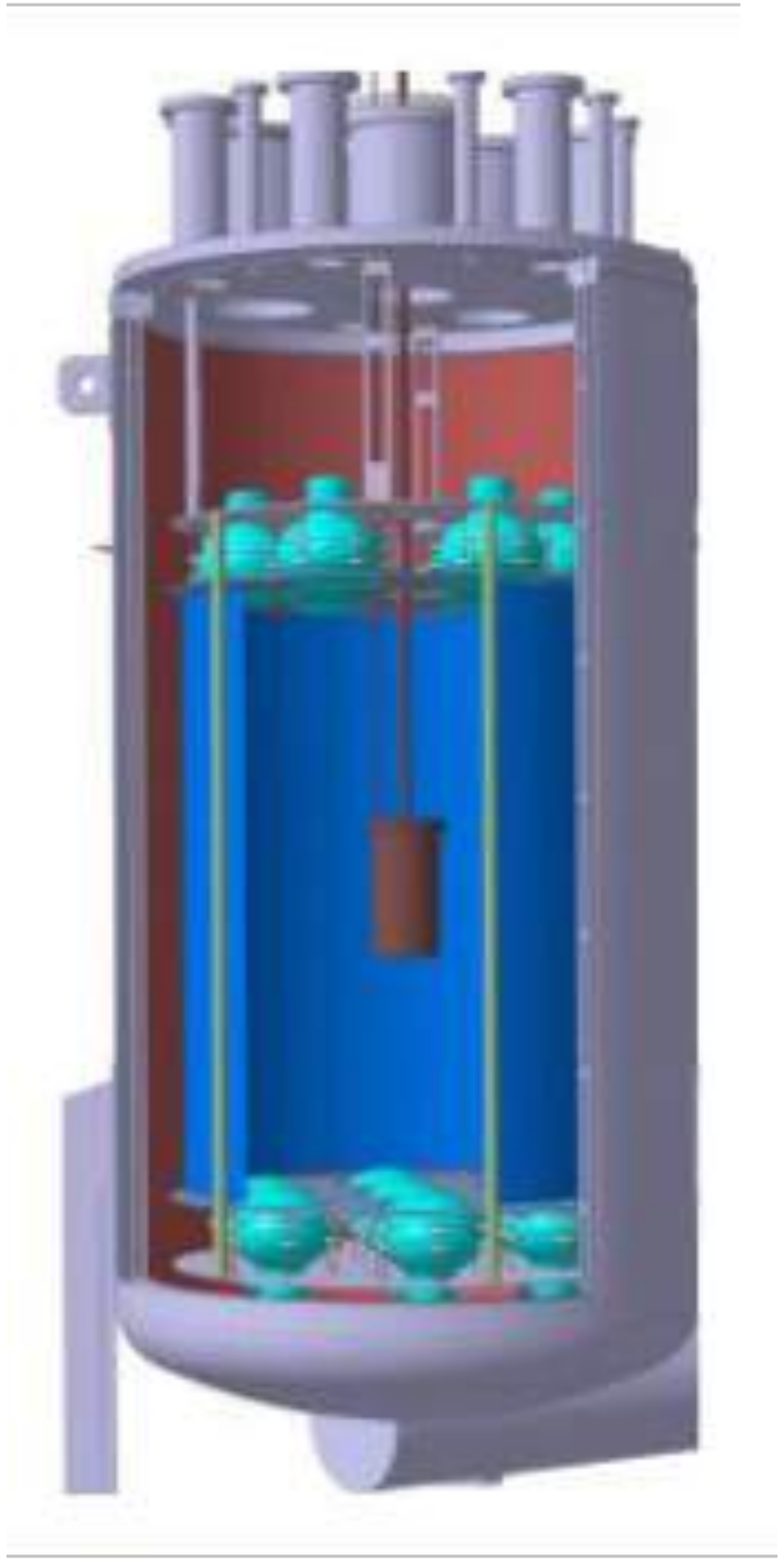
- Cryogenic distillation column in Sardinia (Italy)
- Chemical purification rate: 1 t/day
- Ar-39 separation power > 1000
- First module operated according to specs with Nitrogen in 2019
- Run completed with Ar at the end of 2020

Eur.Phys.J.C 81 (2021) 4, 359

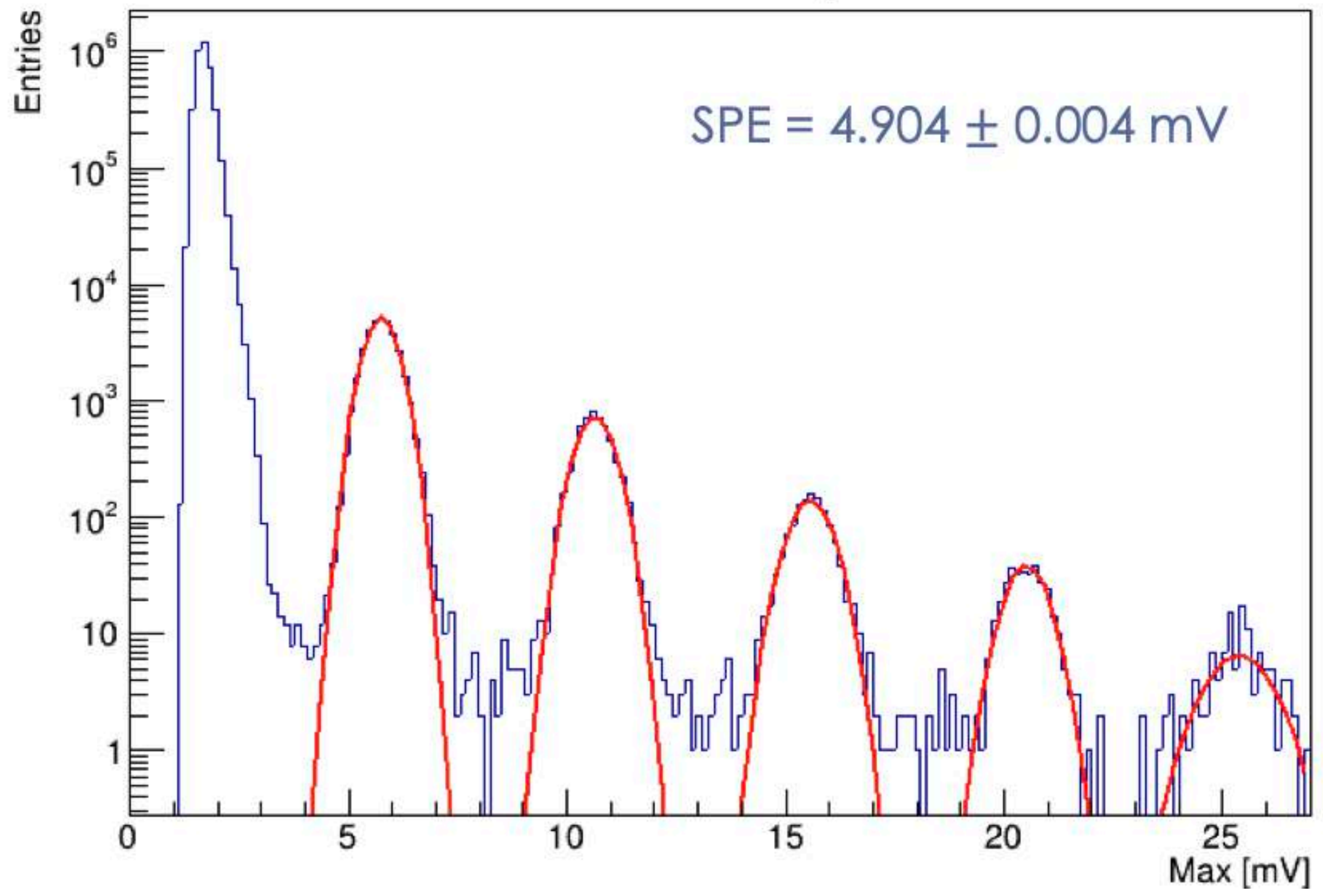
DArT:
Ar purity measurement

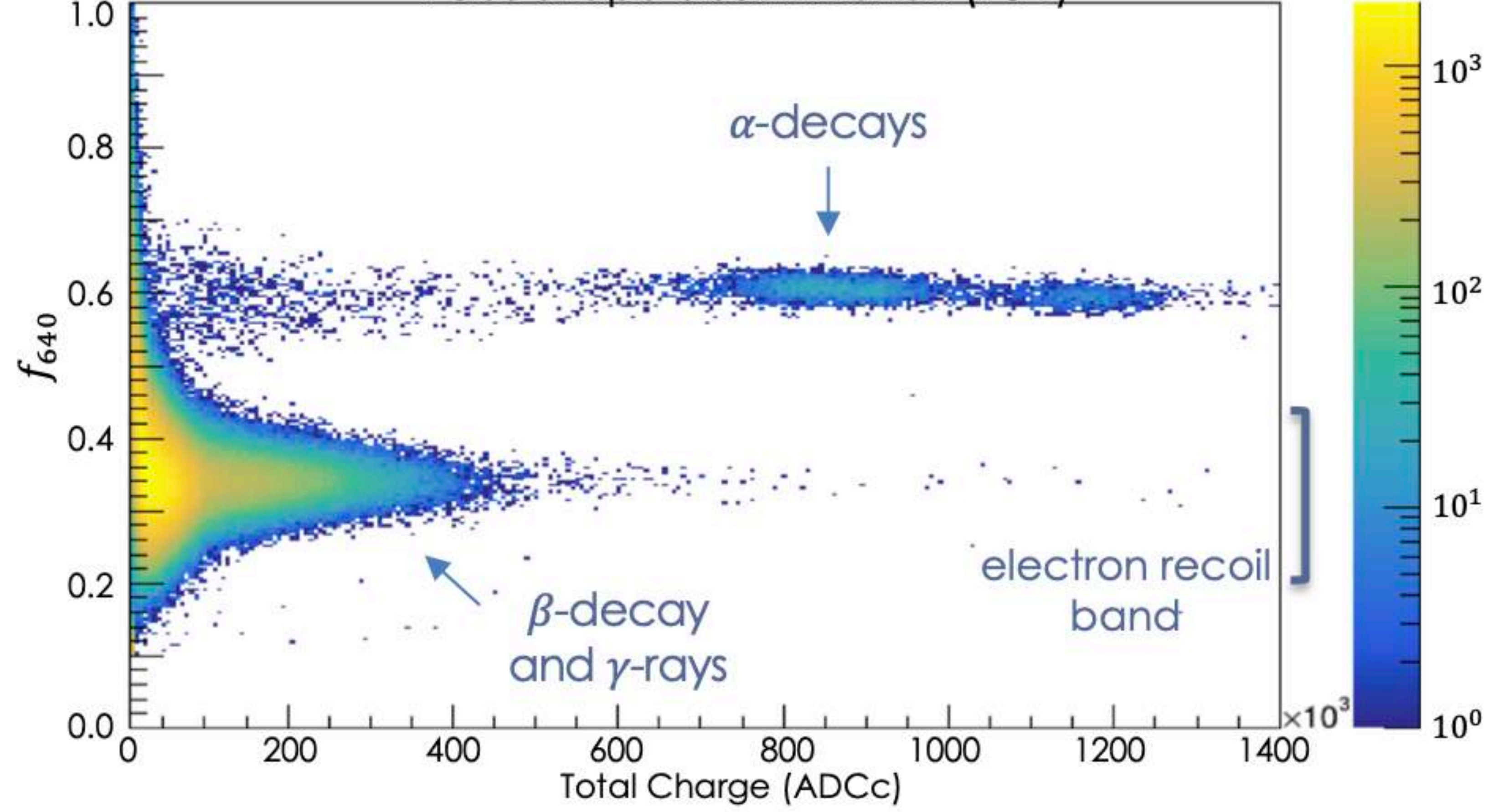
Located at LCS, Canfranc

- Double phase TPC with active volume of 1.4 kg of liquid UAr
- Two 1 cm^2 SiPMs at the top & bottom
- External acrylic support
- Internal acrylic covered with TPB (WLS)
- Ar-39 depletion factor sensitivity: 6 x 10^4 90% C.L



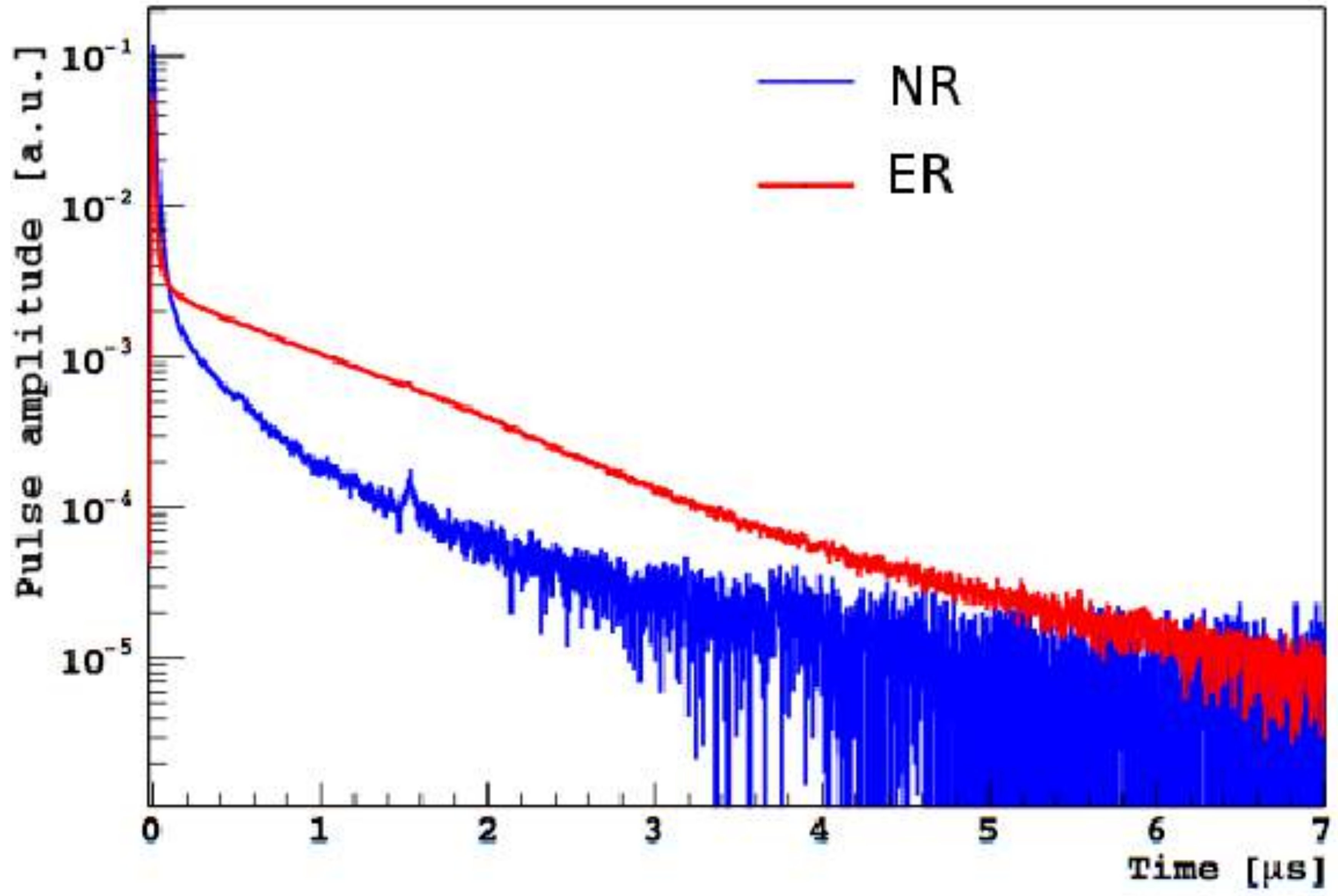
SiPMs calibration





ELECTRON RECOIL

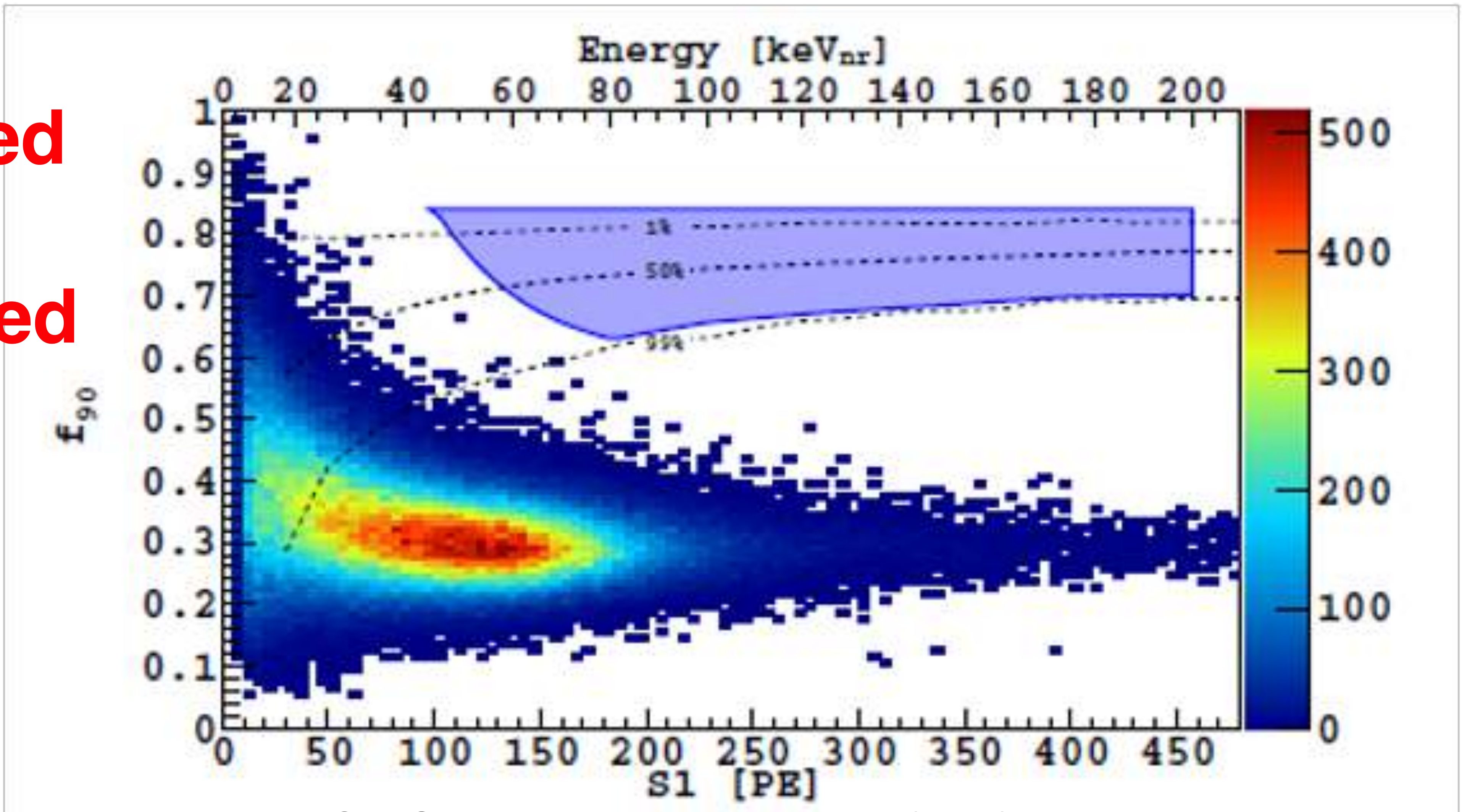
S1 pulse shape in LAr



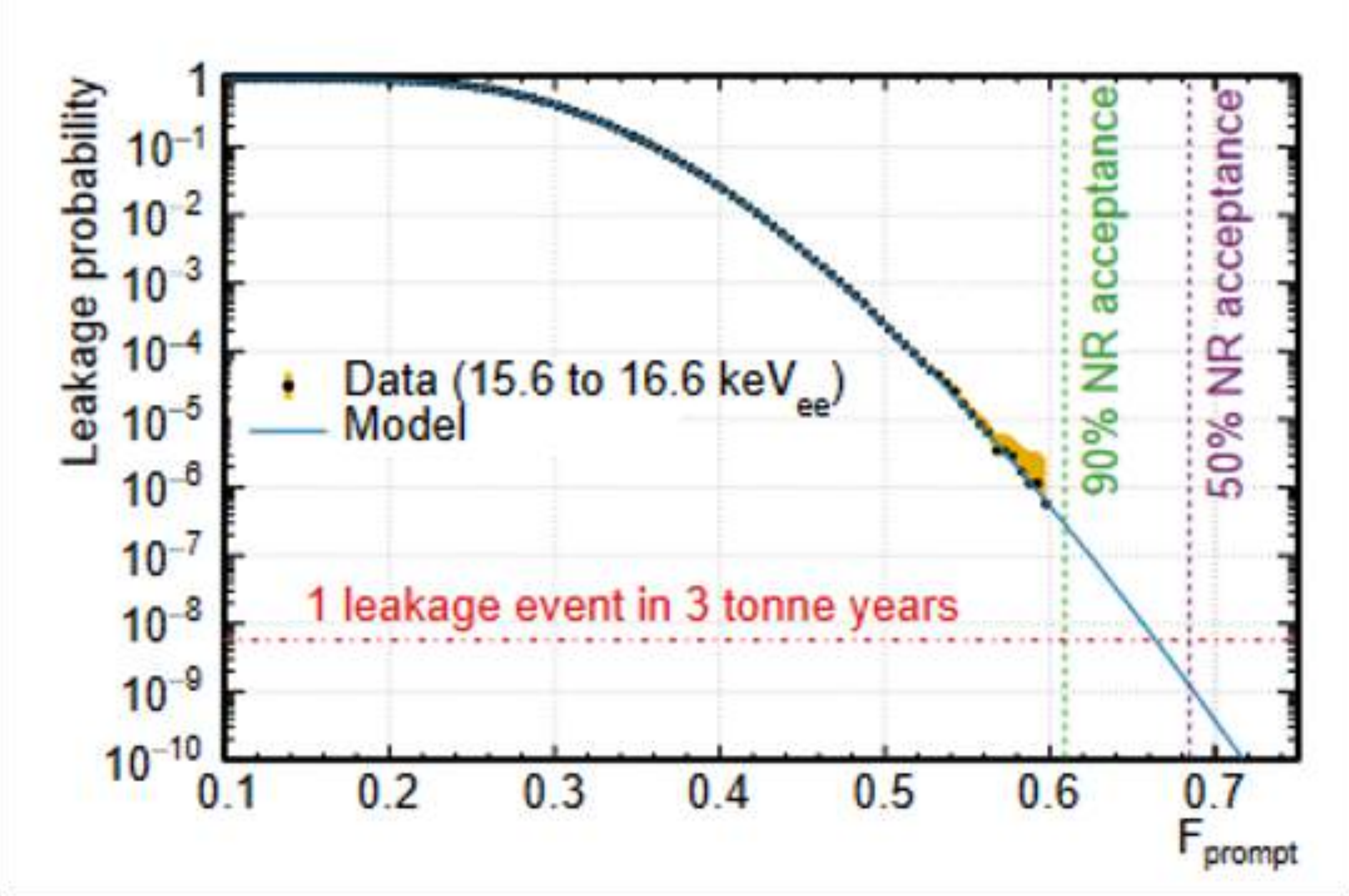
electronic recoils are rejected by Pulse shape discrimination, demonstrated by DS-50 & DEAP

Pulse shape parameter

$$PSD = \frac{PROMPT\ LIGHT}{PROMPT + LATE\ LIGHT}$$



DS50 Collaboration., *Phys.Rev.D* 98 (2018) 102006



DEAP Collaboration, *Phys.Rev.D* 100 (2019) 2, 022004

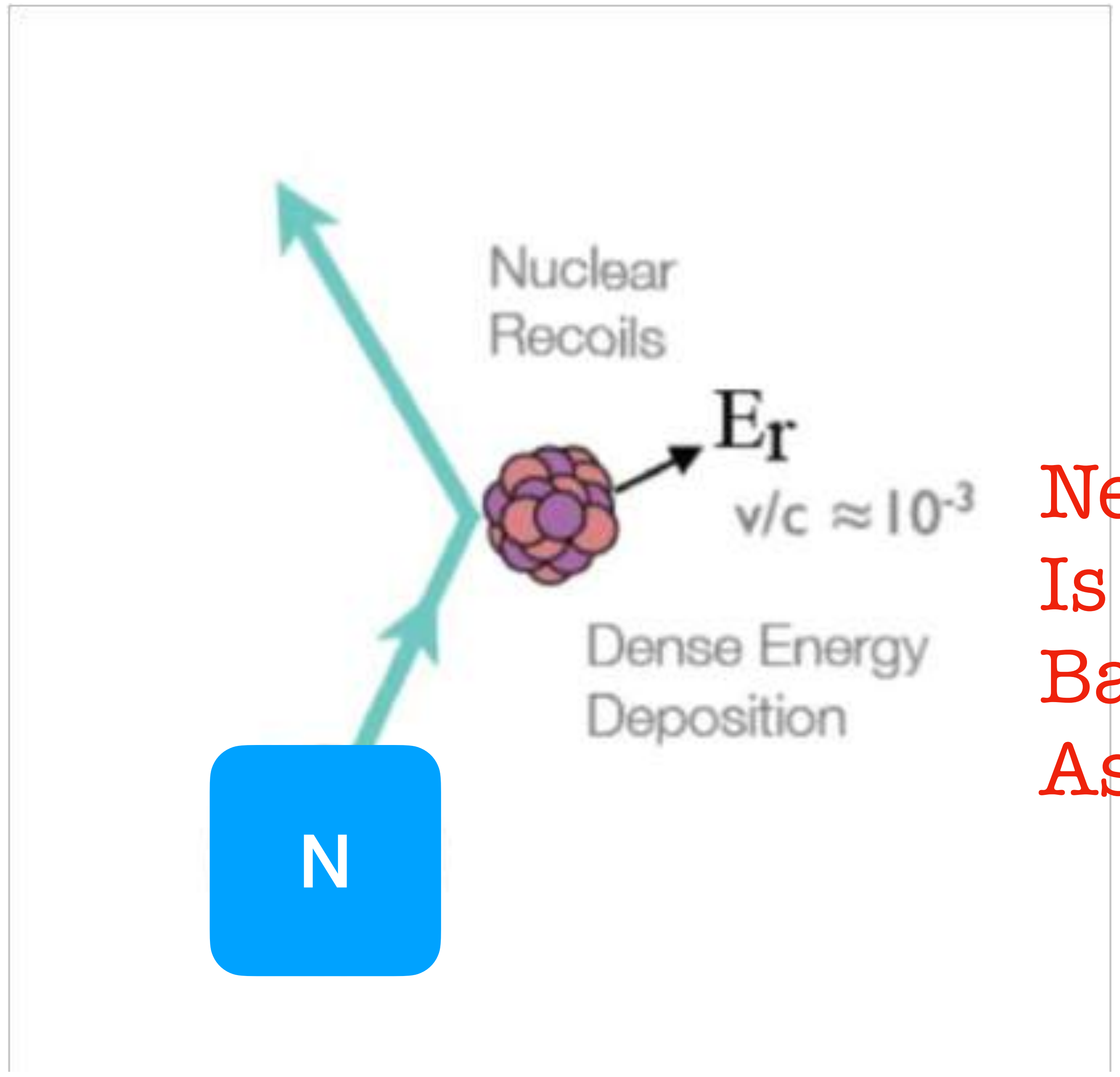
Ar-39 deplaction factor in UAr: around 1400

- **TPC= 50 tons -> 36 Hz of Ar-39**
- **Veto = 35 tons -> 26 Hz of Ar-39**

Mitigated with pulse shape discrimination:

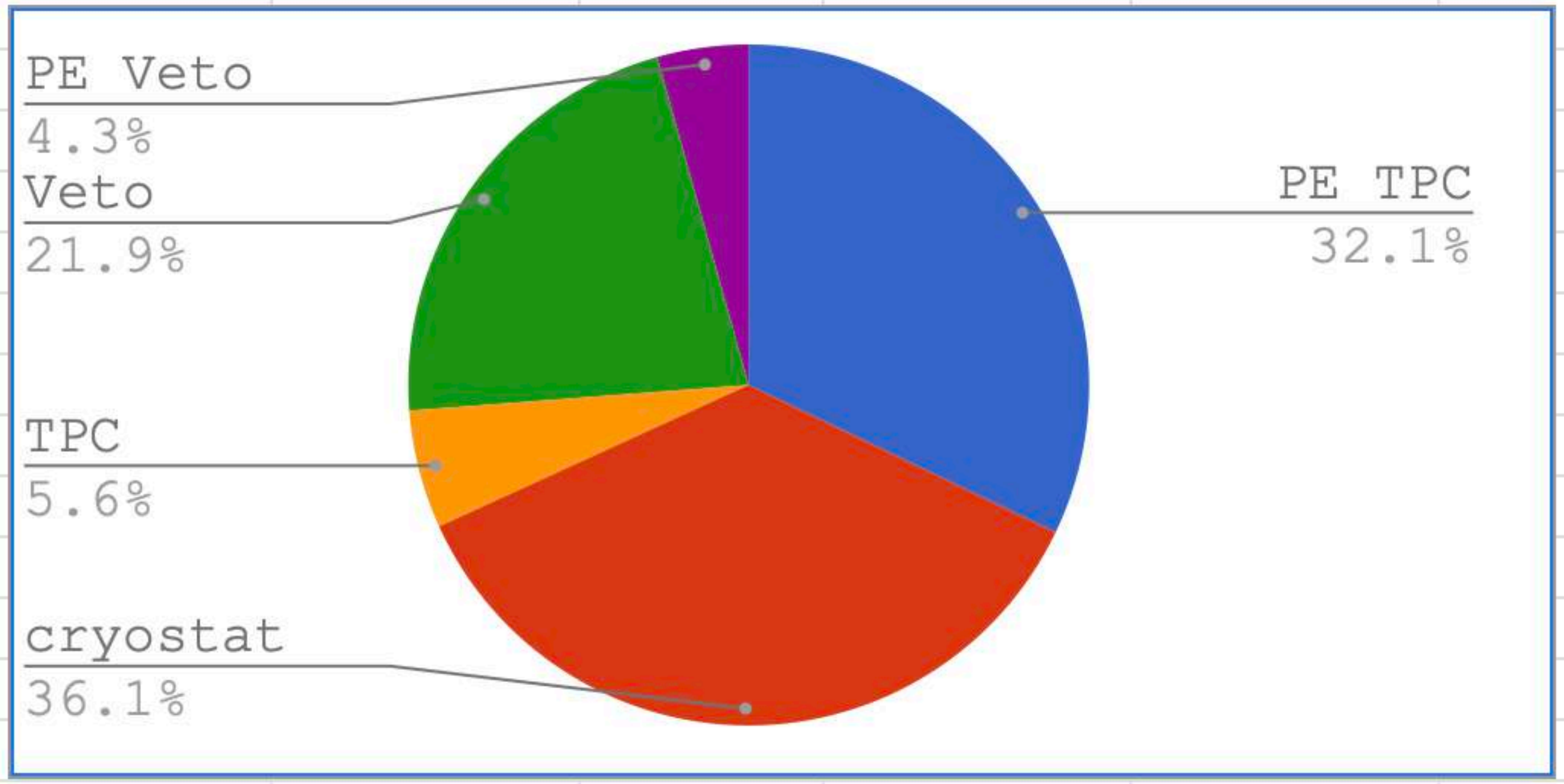
- Residual background is < 0.01 events / 200 tonne x year
- Dead time negligible

NUCLEAR RECOIL



Neutron background
Is the most dangerous
Background -> same recoil
As WIMP

Neutron background budget for radio assay and Simulation of all detector components



Neutron sources:

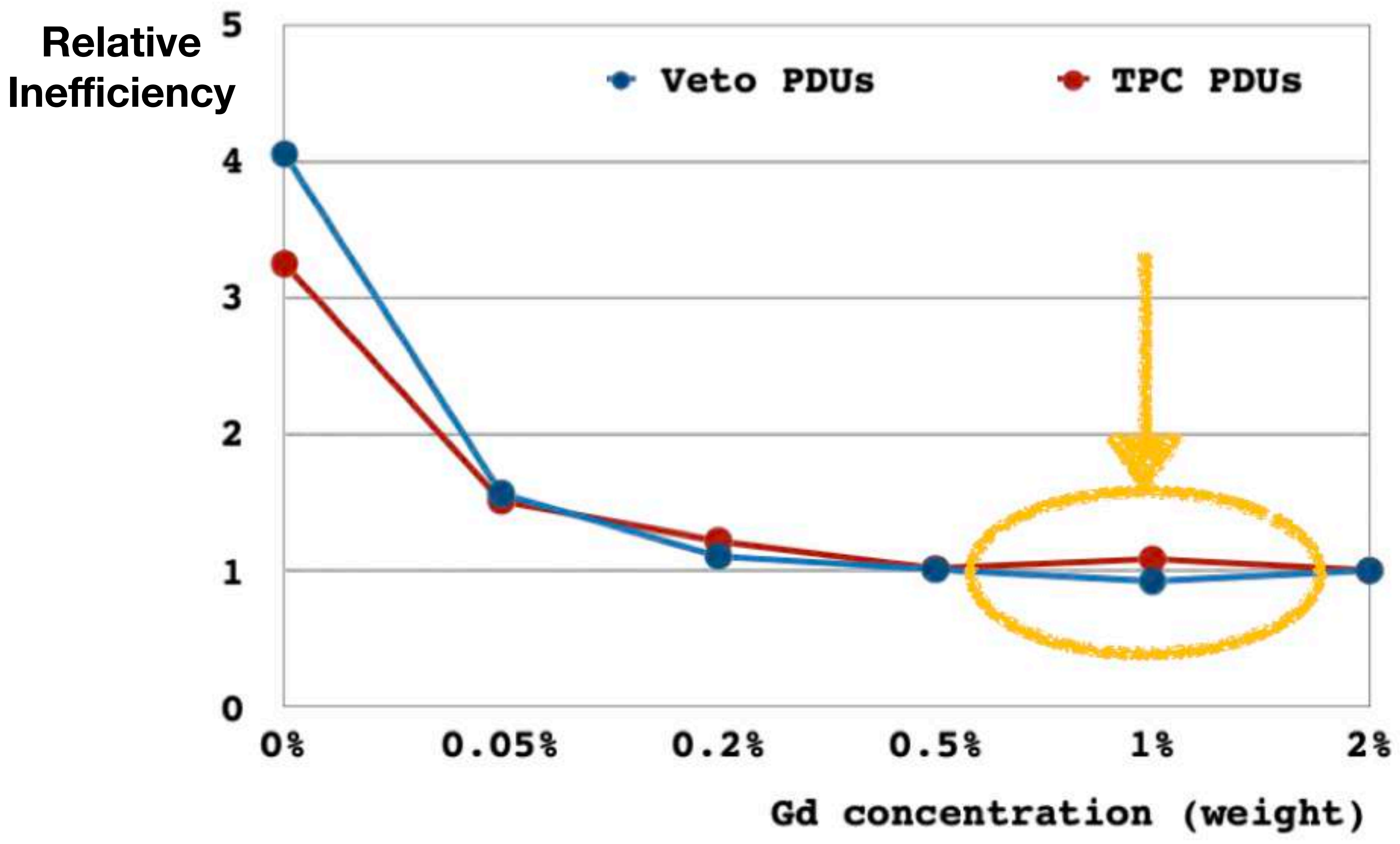
- ^{238}U and ^{232}Th contaminations of the detector material
- Cosmogenic interaction due the cosmic ray
- (α,n) reaction in the detector material
- Spontaneous fission decays

major contributions to radio-assay campaign from STFC's Boulby Underground Laboratory

NEUTRON IDENTIFICATION

- DarkSide-20k has developed a novel Gd-PMMA material for use surrounding the TPC to capture neutrons, and optimised thickness is 15 cm thick
- Gd concentration chosen to have neutron capture on Gd dominates w.r.t capture on H
- Neutron capture on Gd produces a gammas cascade with a energy of 8 MeV
- Gd-PMMA is highly efficient at moderating and then capturing neutrons

Neutron detection inefficiency vs Gd concentration



Gd concentration chosen to 1%

—> maximise neutron detection and mimimize background from Gd-PMMA

Gd-PMMA RECIPE

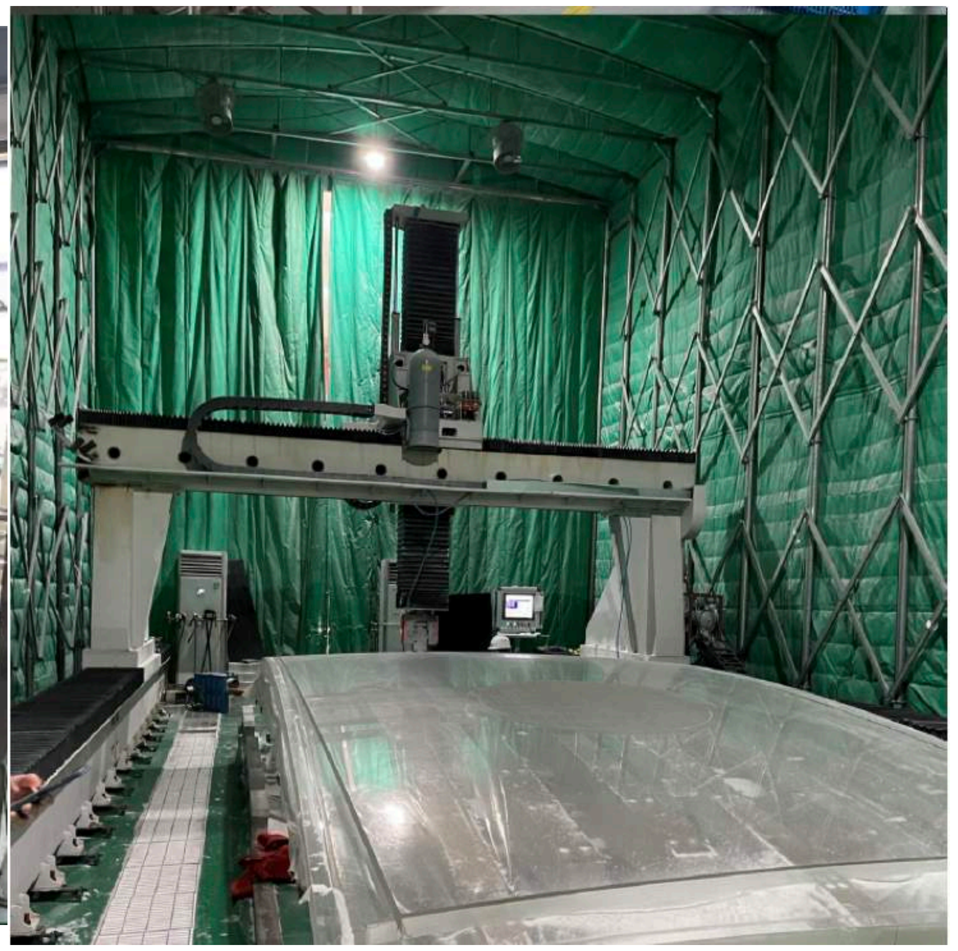
- Gd$(MMA)_3$ doped acrylics with 1wt% of Gd concentration successfully developed by Yangzhou University
- Technology transferred to DonChamp company: produced 5 cm thick for qualification> **full production ongoing**
- DonChamp: low background environment -> already used for JUNO PMMA production
- **Gd-PMMA radio-purity satisfies DarkSide-20k requirement**

Gd-PMMA acrylics sheet

Assay results (Preliminary)

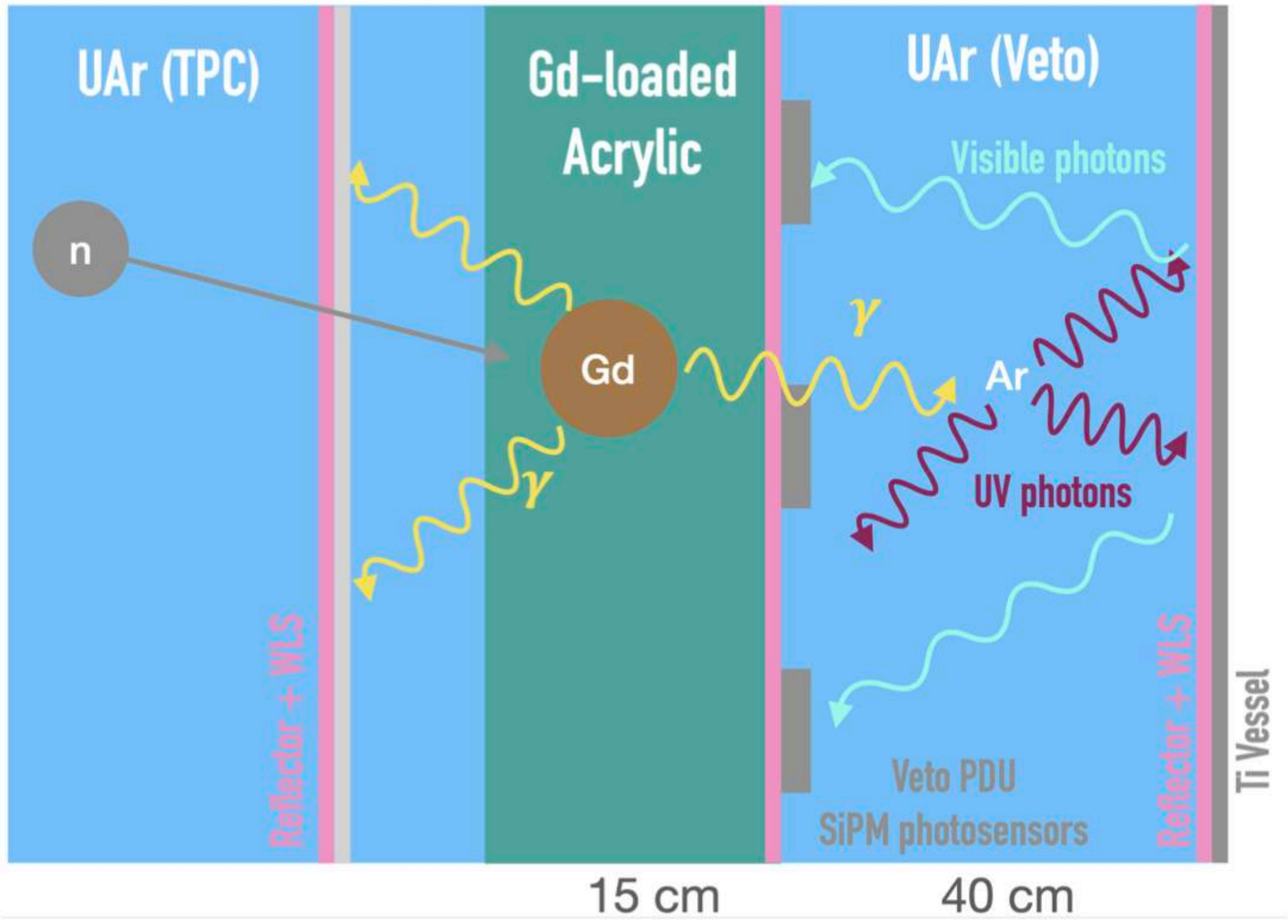
- Ra-226 (U): 1.0 ± 0.4 mBq/kg
- Ra-228 (Th): < 0.33 mBq/kg
- K-40: < 9 mBq/kg.

DompChamp facilities



NEUTRON DETECTION

Neutron capture on Gd detected in TPC and veto



- **Neutron identification**:
  - Single NR
  - Energy in ER: 7.5< E_{ER}< 50 keVee
  - R-z position cuts —> FV = 20 tons
  - Energy deposit in ER in the TPC > **50 keV OR** energy deposit in UAr veto > **200 keV**
  - TPC-veto window of 800 μs

Monte-Carlo simulation to define neutron detection inefficiency looking energy deposit in TPC and veto

Neutron source	Fraction inducing at least 1 NR in the TPC	Fraction surviving TPC and WIMP ROI	Fraction surviving TPC and Veto cuts
TPC PDMs	1.80e-01	3.6E-5	2.2E-6
Veto Gd-Acrylic	8.55e-02	1.5E-4	5.8E-6
Veto PDMs	1.43E-02	5.4E-7	8.7E-7
Vessel	3.40e-03	6.8E-6	6.8E-6
Cryostat	4.0E-4	4.9E-9	2.2E-10

TABLE 51. Neutron Veto inefficiency from topical positions in the detector.

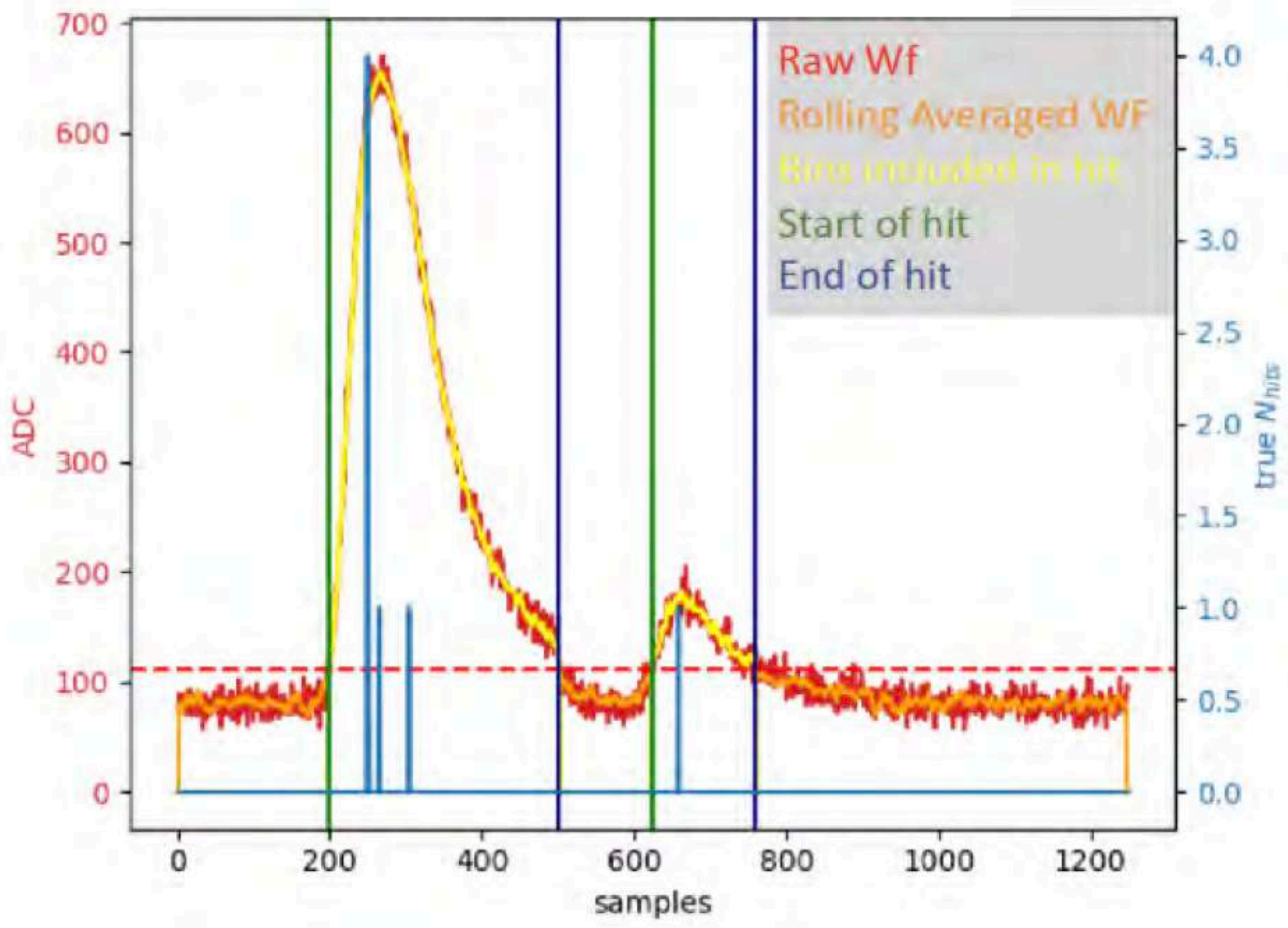
Total neutron Detection Inefficiency is 1.6E-5

NEUTRON DETECTION (2)

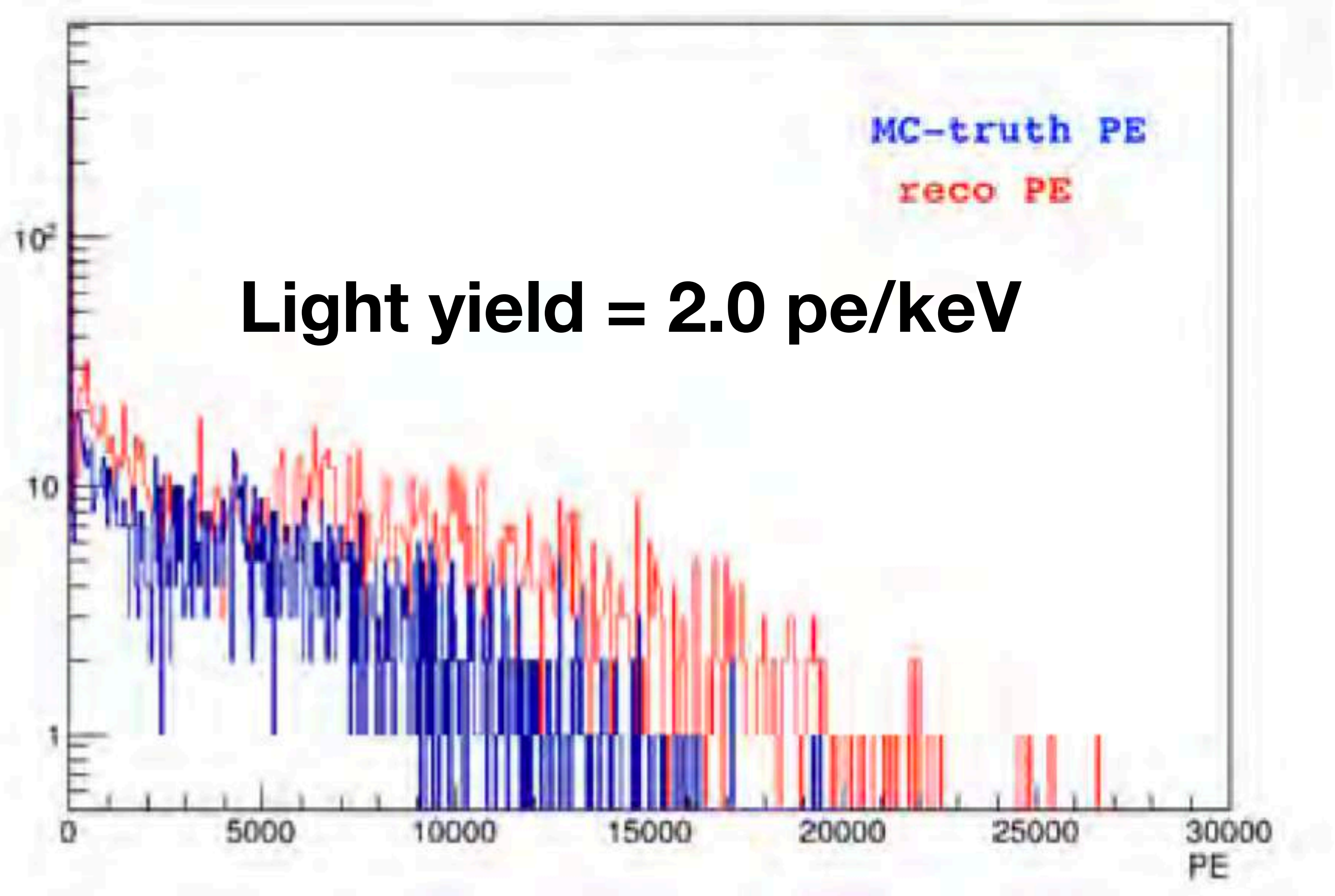
More realistic MonteCarlo Simulation introducing:

- Electronics response
- SIPMs noise
- Pile up effects

Waveform example



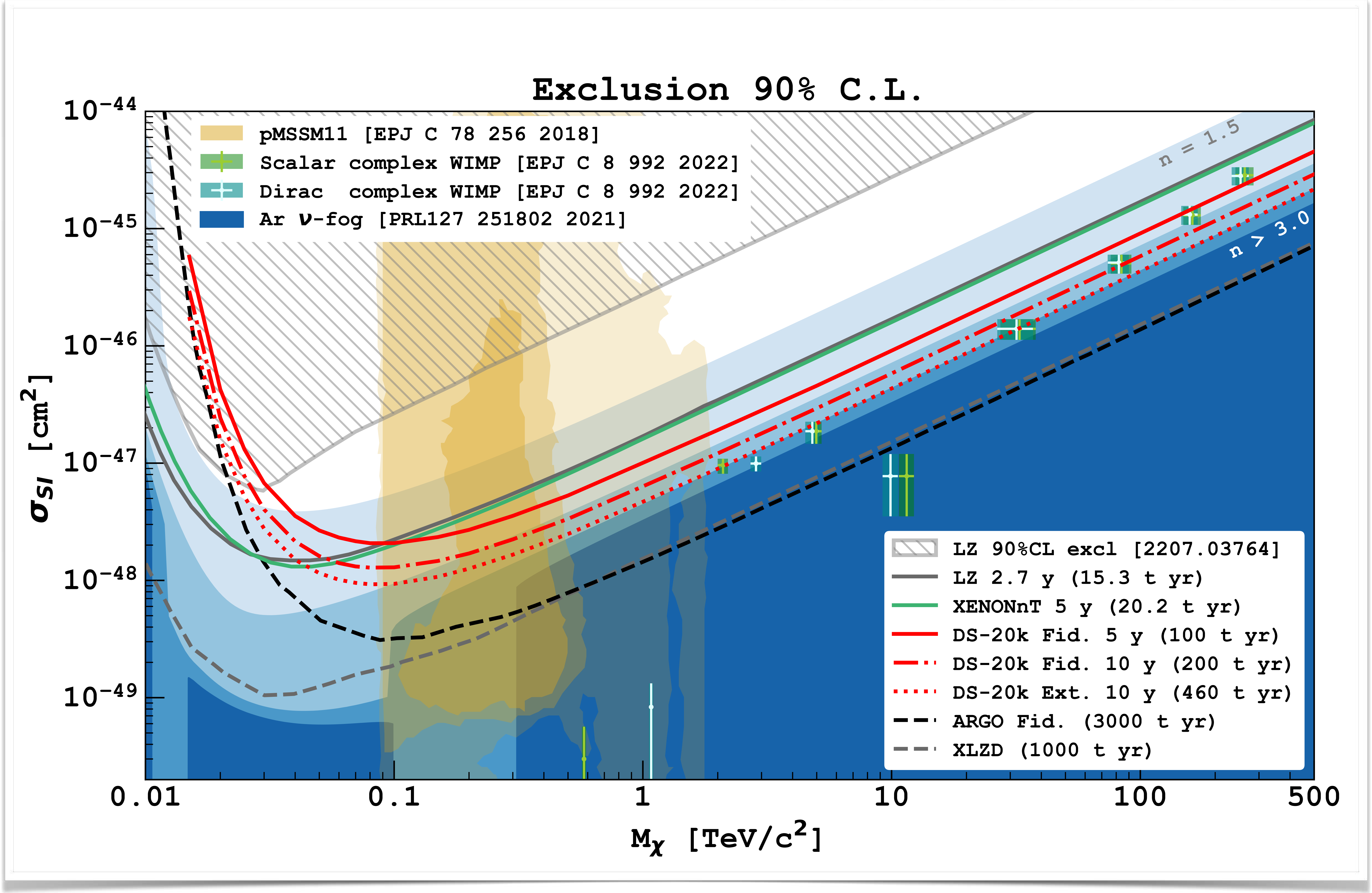
PhotoElectrons (PE) distribution



- Neutron detection inefficiency increased by **20%** including electronics response, SIPMs noise and pile-up effects
- **Neutron background after veto cuts: < 0.1 event in the full exposure of 200 tons x years -> satisfies DarkSide-20k requirement**

Major contribution from RHUL/Oxford

HIGH MASS DARK MATTER SENSITIVITY



- Sensitivity to high mass WIMP-nucleon scatter cross section of 7.4 x 10^{-48} cm^2 for a 1 TeV/c^2 WIMP for a total exposure of 200 tons x years
- Total background events after all cuts: < 0.1 neutron wimp like events in a total exposure of 200 tons x years
- S2-only analysis sensitivity projection coming soon...

SUMMARY AND OUTLOOK

- The Global Argon Dark Matter Collaboration (GADMC) is a joint effort among all dark matter experiments with Ar target: >400 collaborators from ~15 countries, collaborating to build DarkSide-20k
- **DarkSide-20k is pushing the state-of-the-art in several directions**: SiPM technology, underground argon extraction & purification, Gd-PMMA, background assay campaign
- **DarkSide-20k is in position to lead the search for WIMPs**, with complimentary reach above the LHC center of mass energy
- **Fundamental role played by UK groups in producing 25% of the SiPM readout modules (7 m^2!), to instrument the veto detector** which is key to achieving the <0.1 instrumental backgrounds to the dark matter search! And expanding the reach beyond heavy WIMPs…
- **Darkside-20k construction has started, data taking will start in 2026**

Thank you for attention