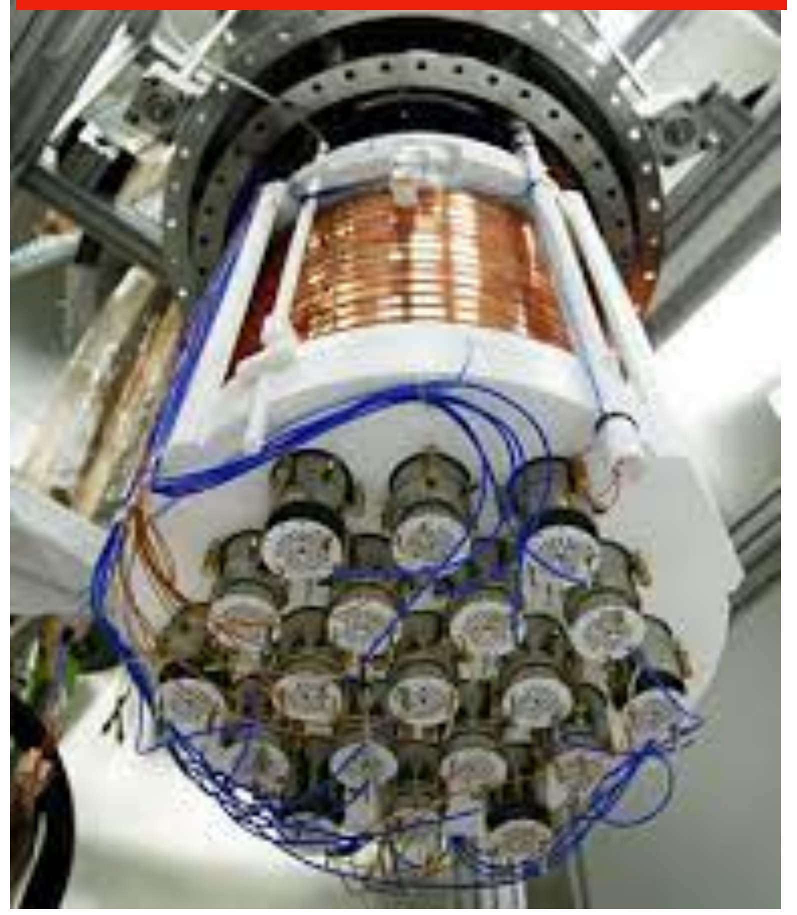
Darkside-20k: A global direct dark matter search experiment

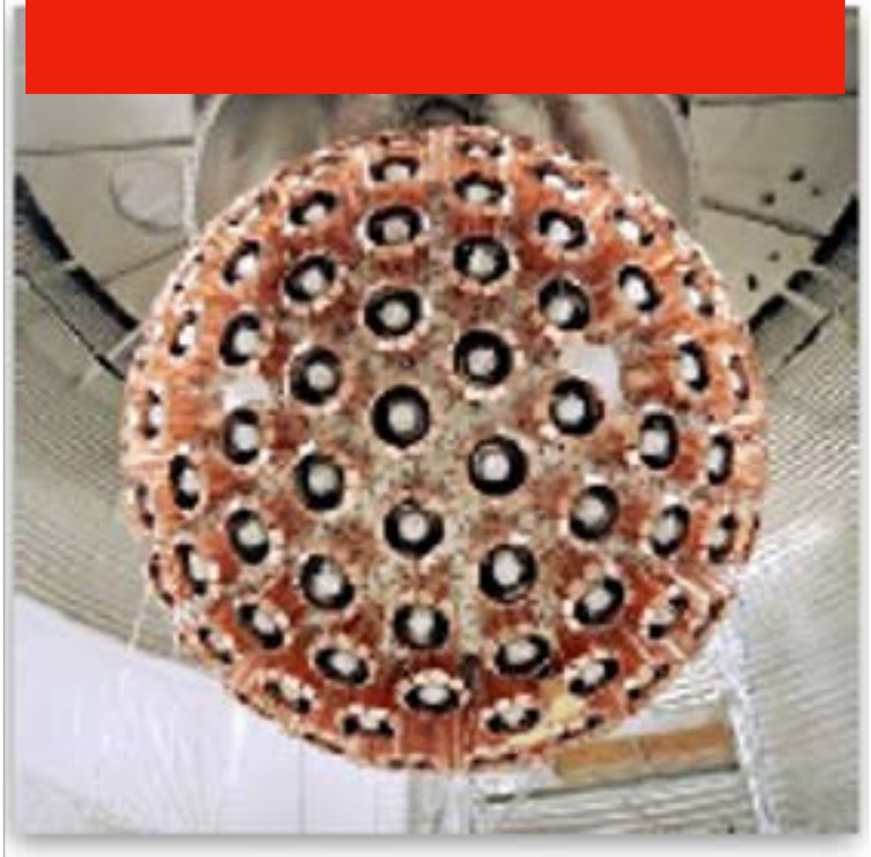
Daria Santone, University of Oxford
Warwick seminar, 12/10/2023

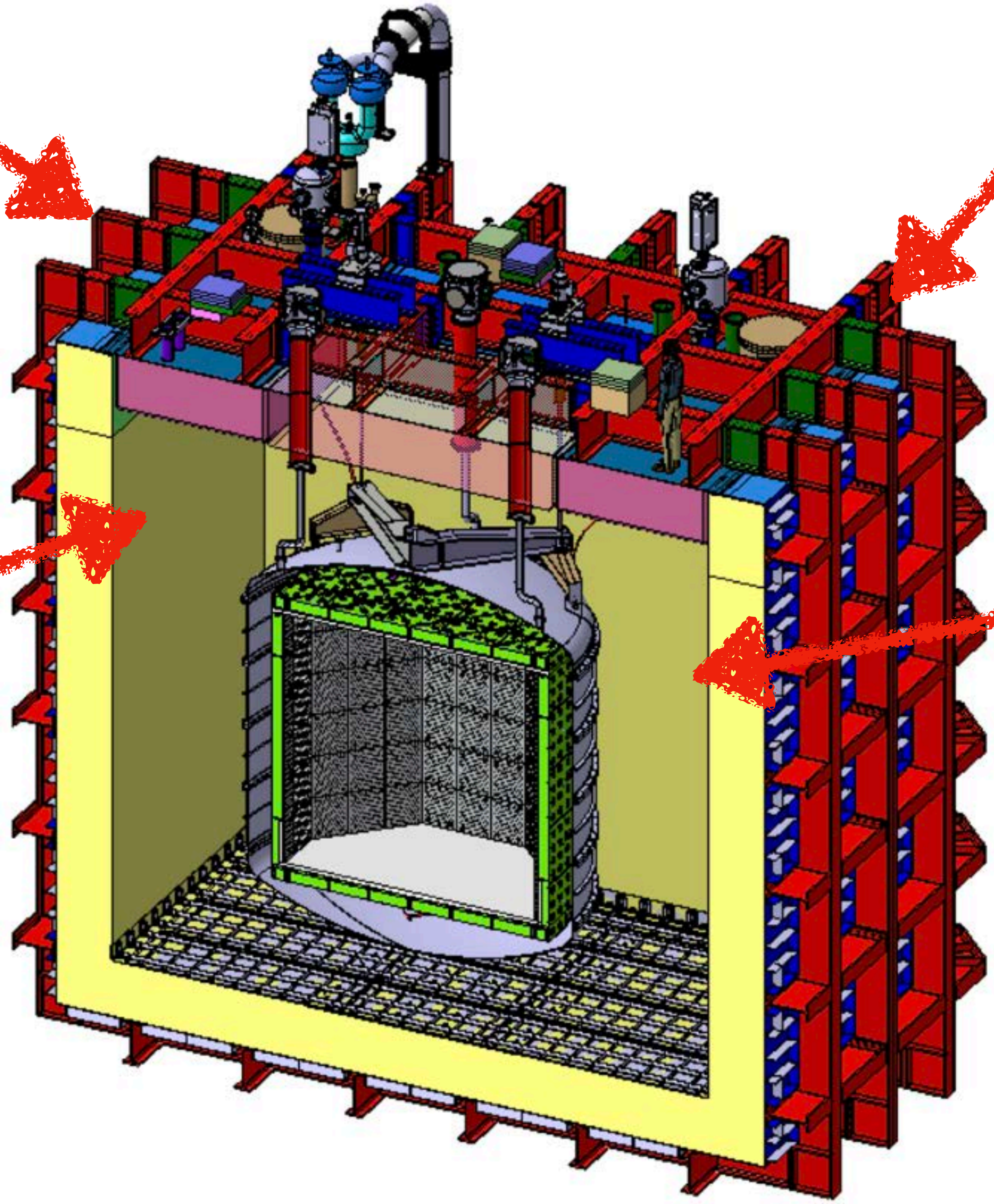
DARKSIDE-20k

DS-50 @LNGS



DEAP @SNOLAB





Miniclean @SNOLAB

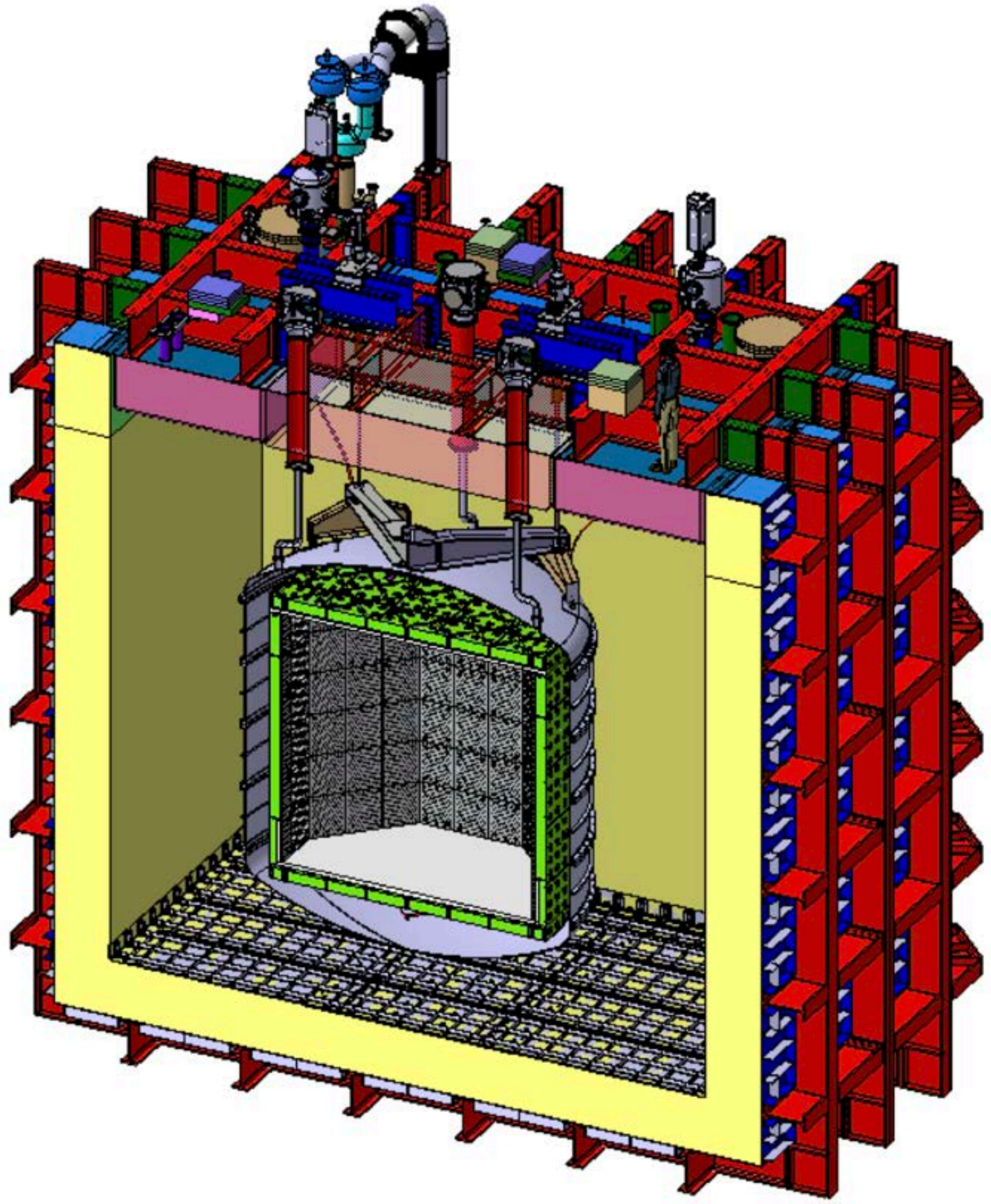
ArDM @CANFRANC

DARKSIDE-20k collaboration

Global Argon Dark Matter Collaboration (GADMC) is a joint effort among all dark matter experiments with Ar target: >400 collaborators from ~100 institutions 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 photomulplier (SiPMs) light detection system
  - Neutron veto design optimisation

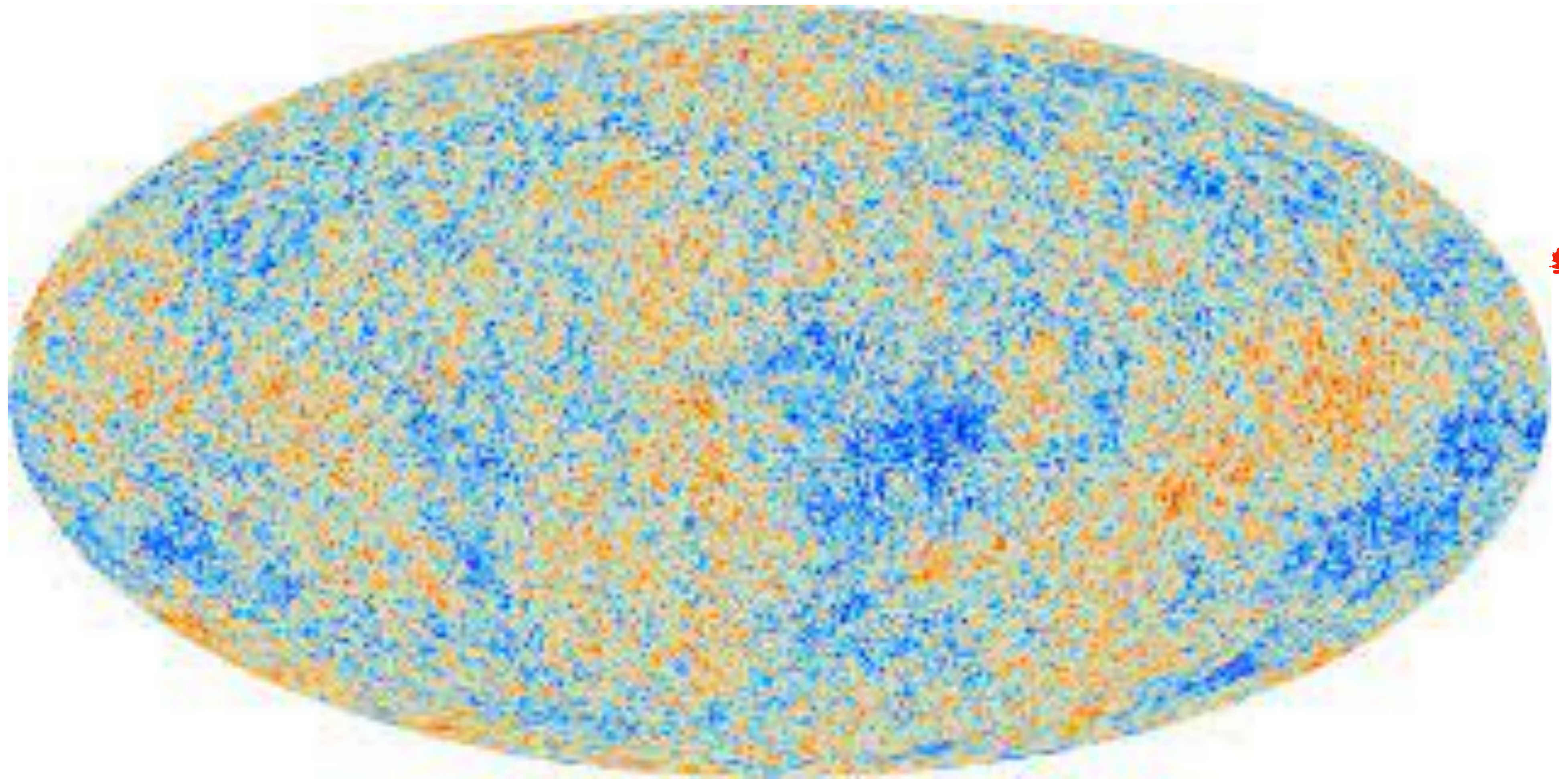


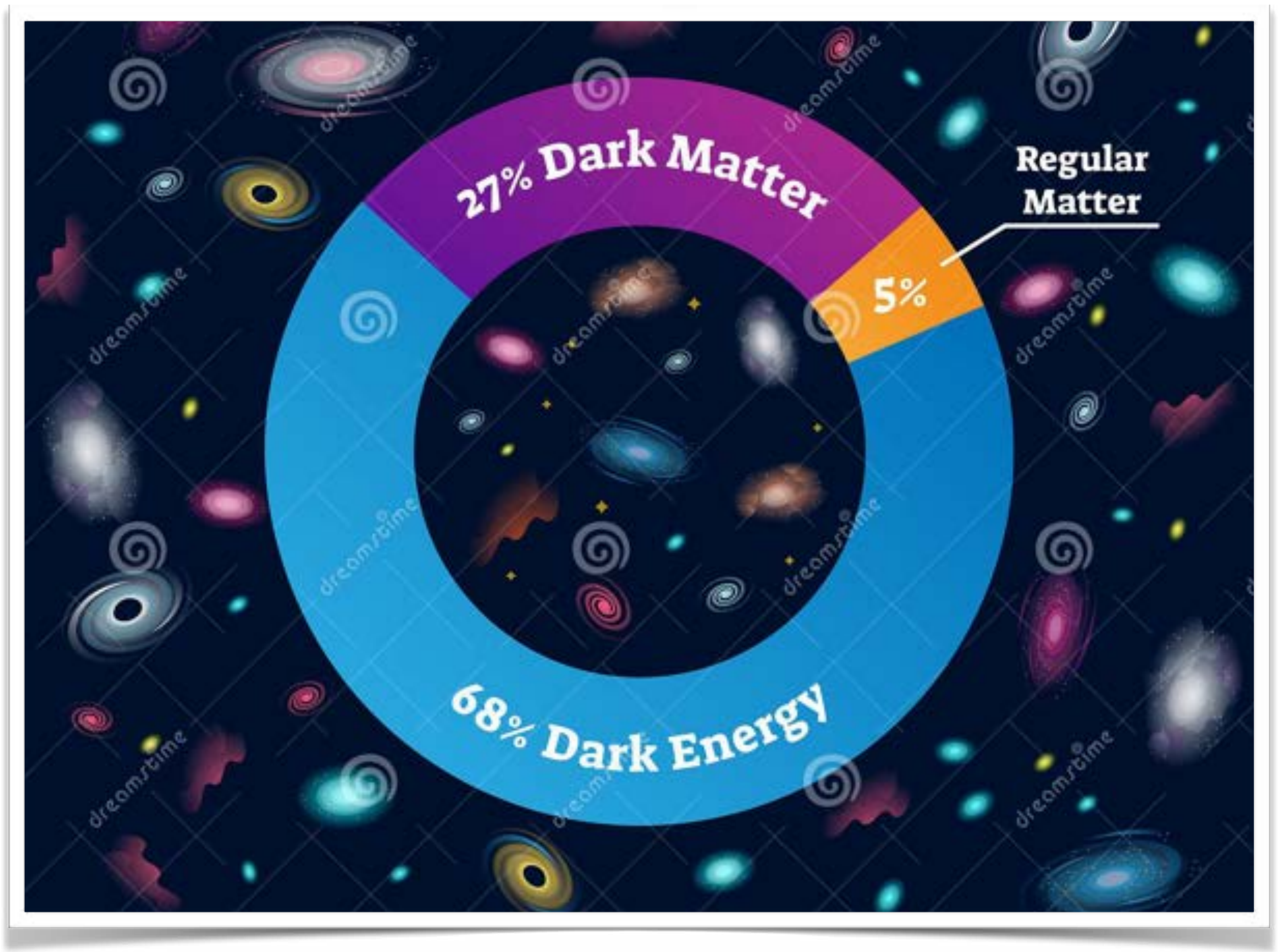
DARK MATTER EVIDENCE

Cluster galaxies

Gravitation lensing

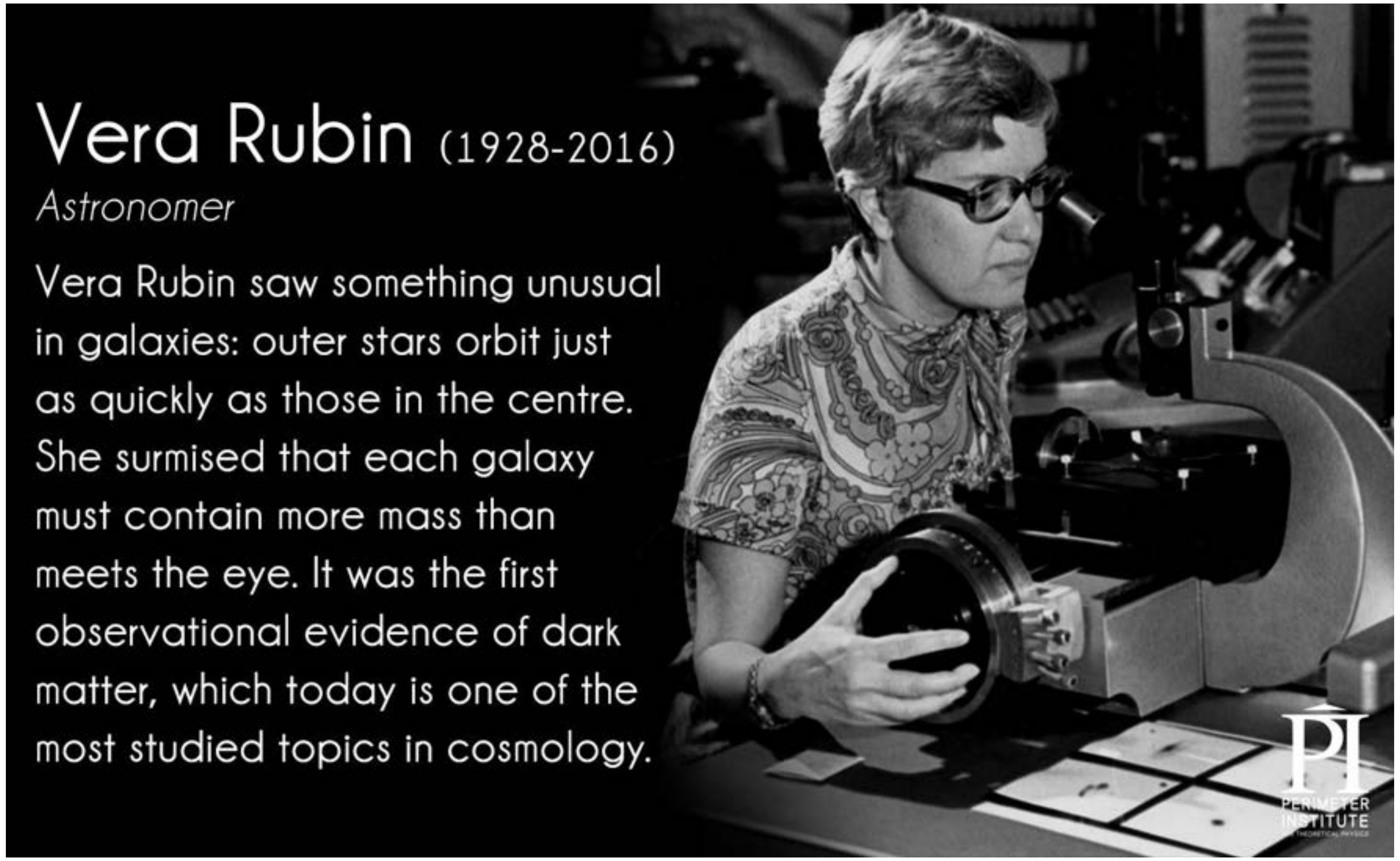
CMB observation

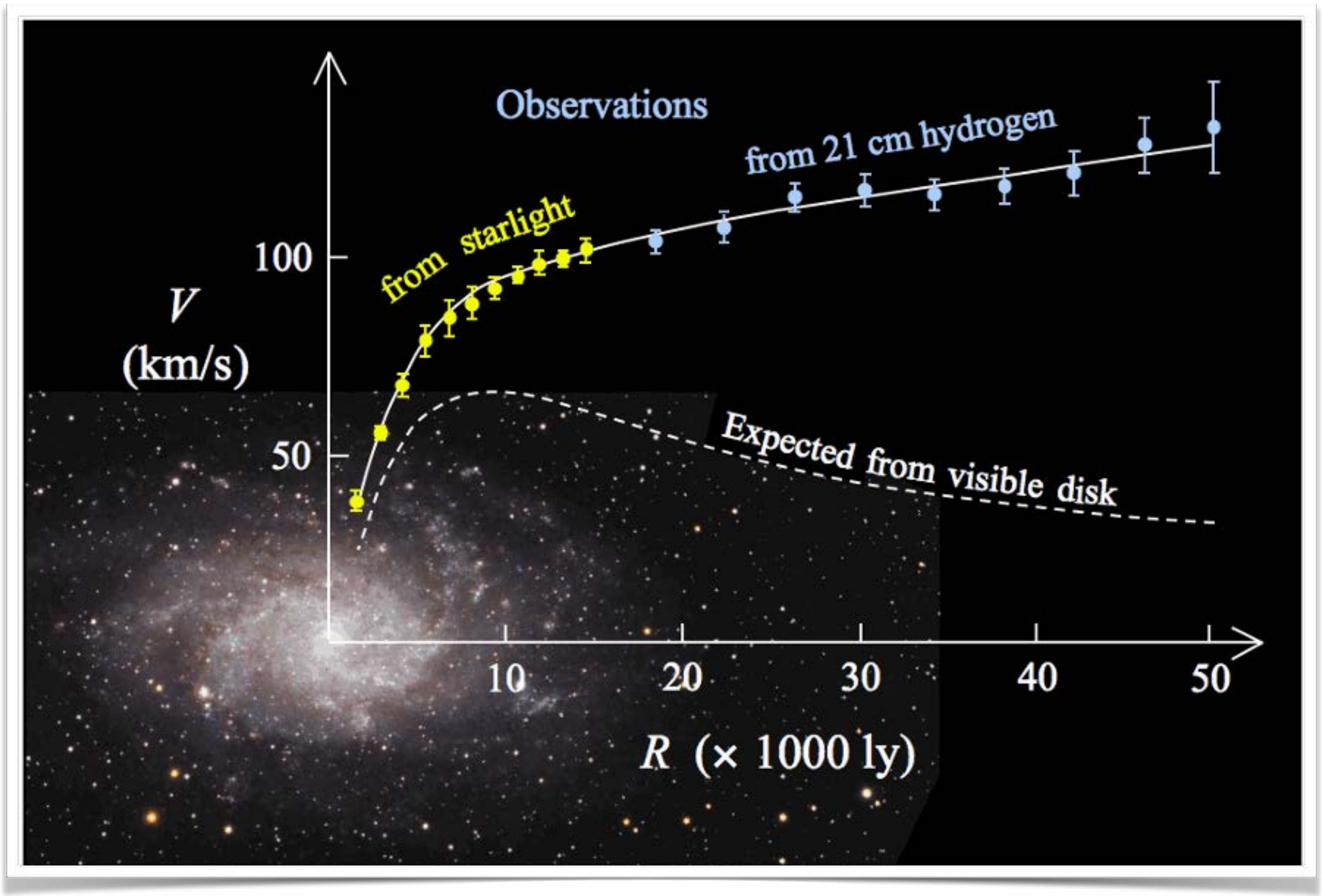




DARK MATTER EVIDENCE (2)

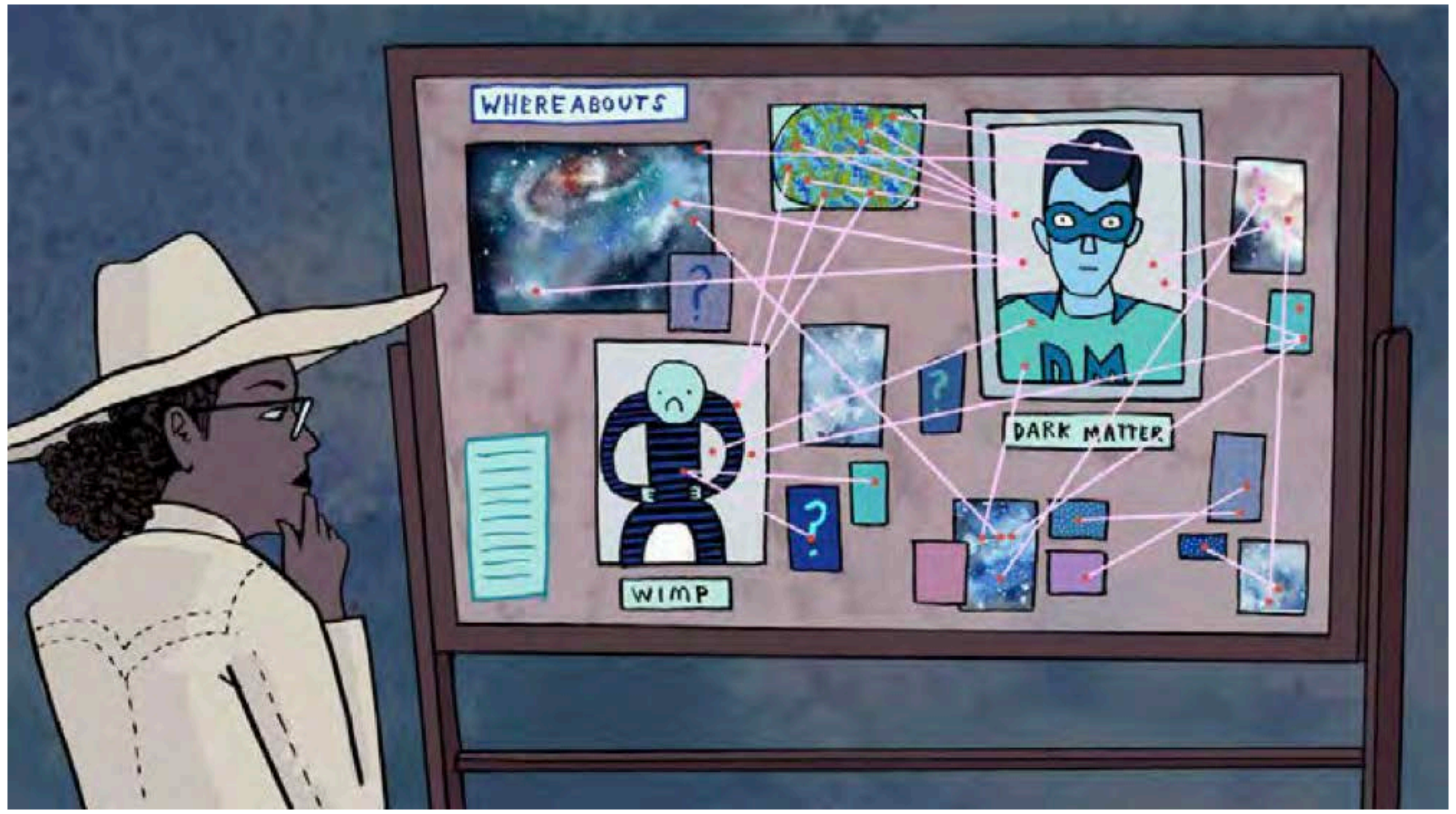
1960 - 1970: Dark matter observation in spiral galaxies





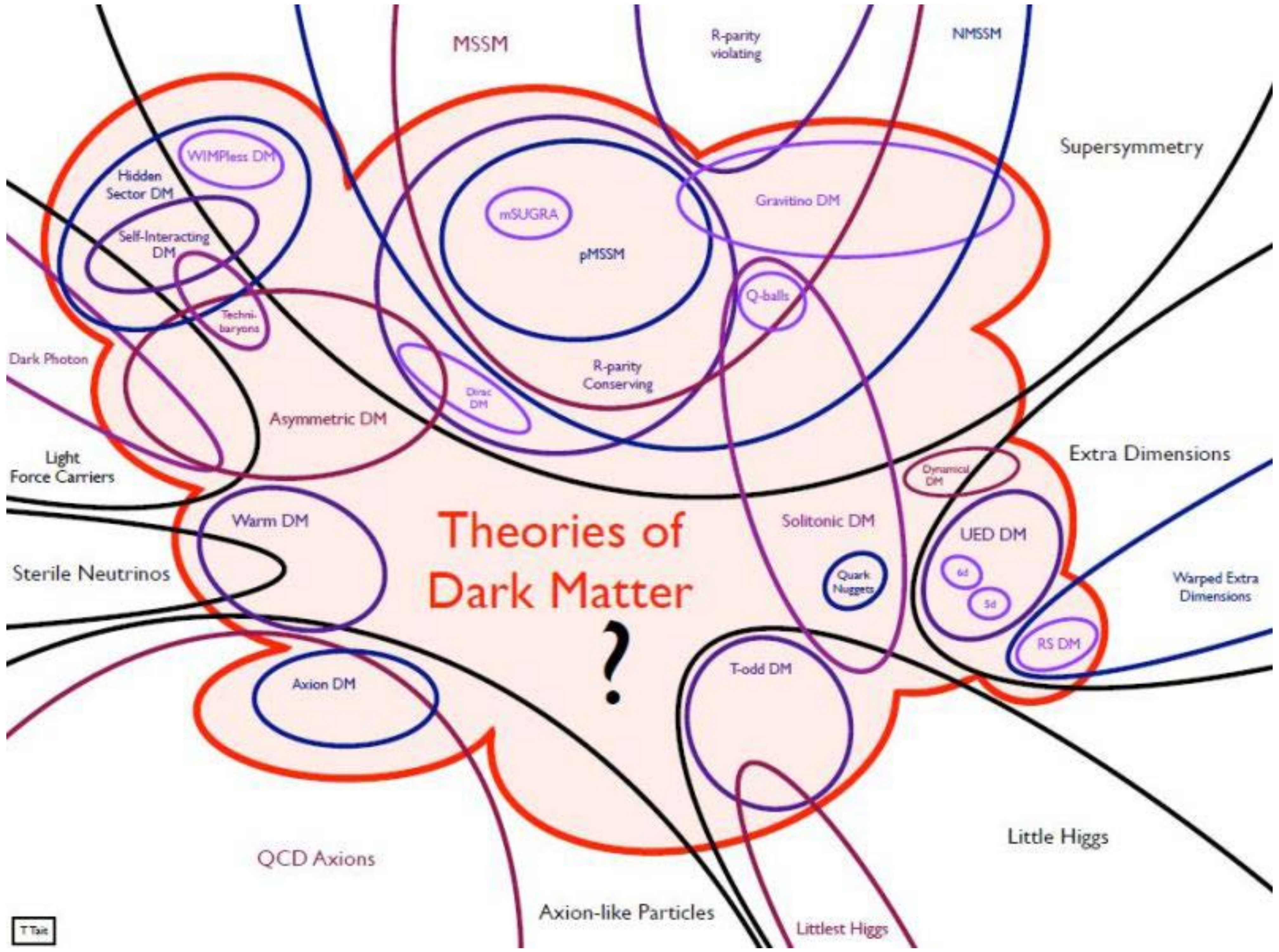
DARK MATTER PROPERTIES

- *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



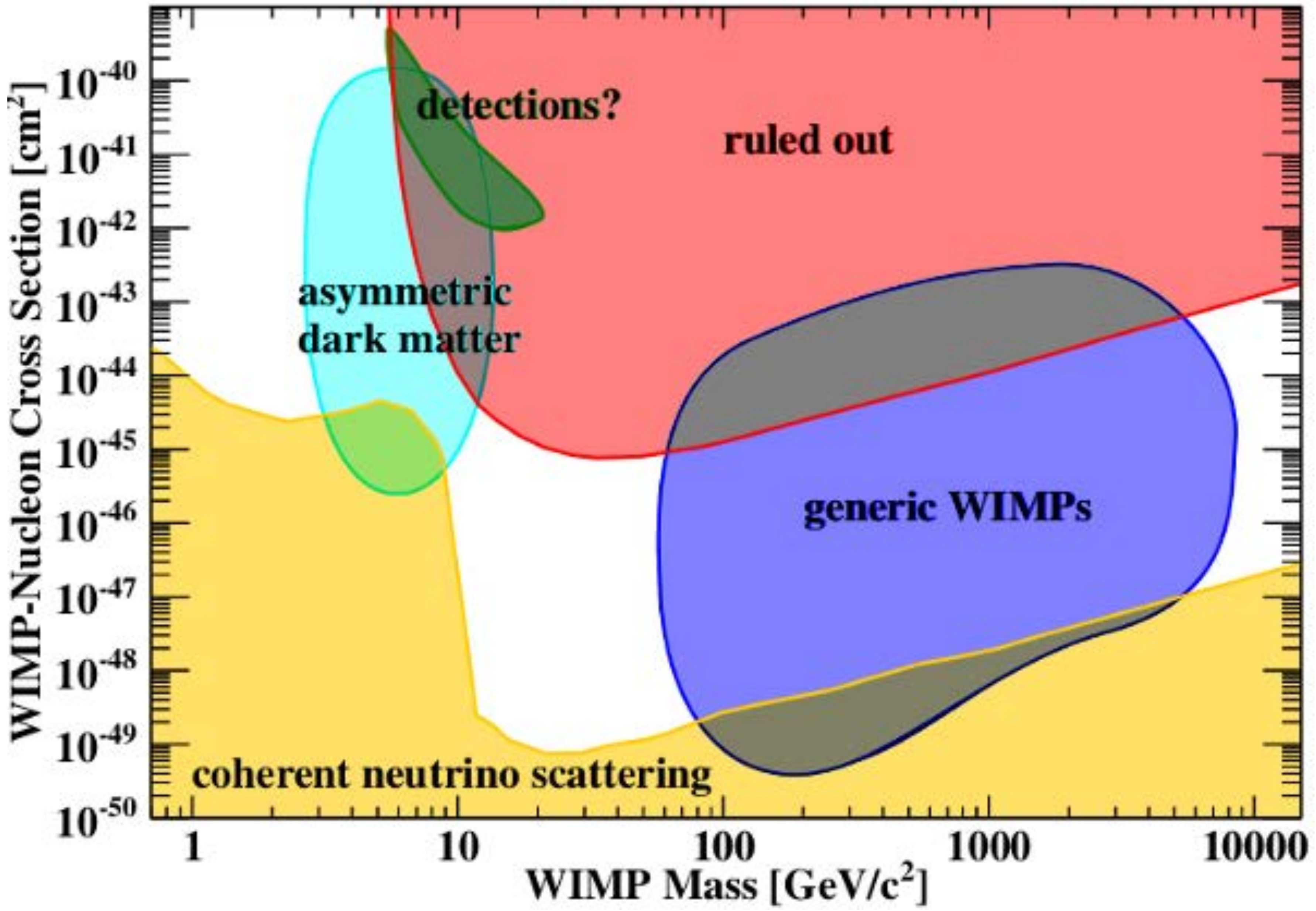
Beyond the Standard Model of Particle Physics

DARK MATTER CANDIDATES

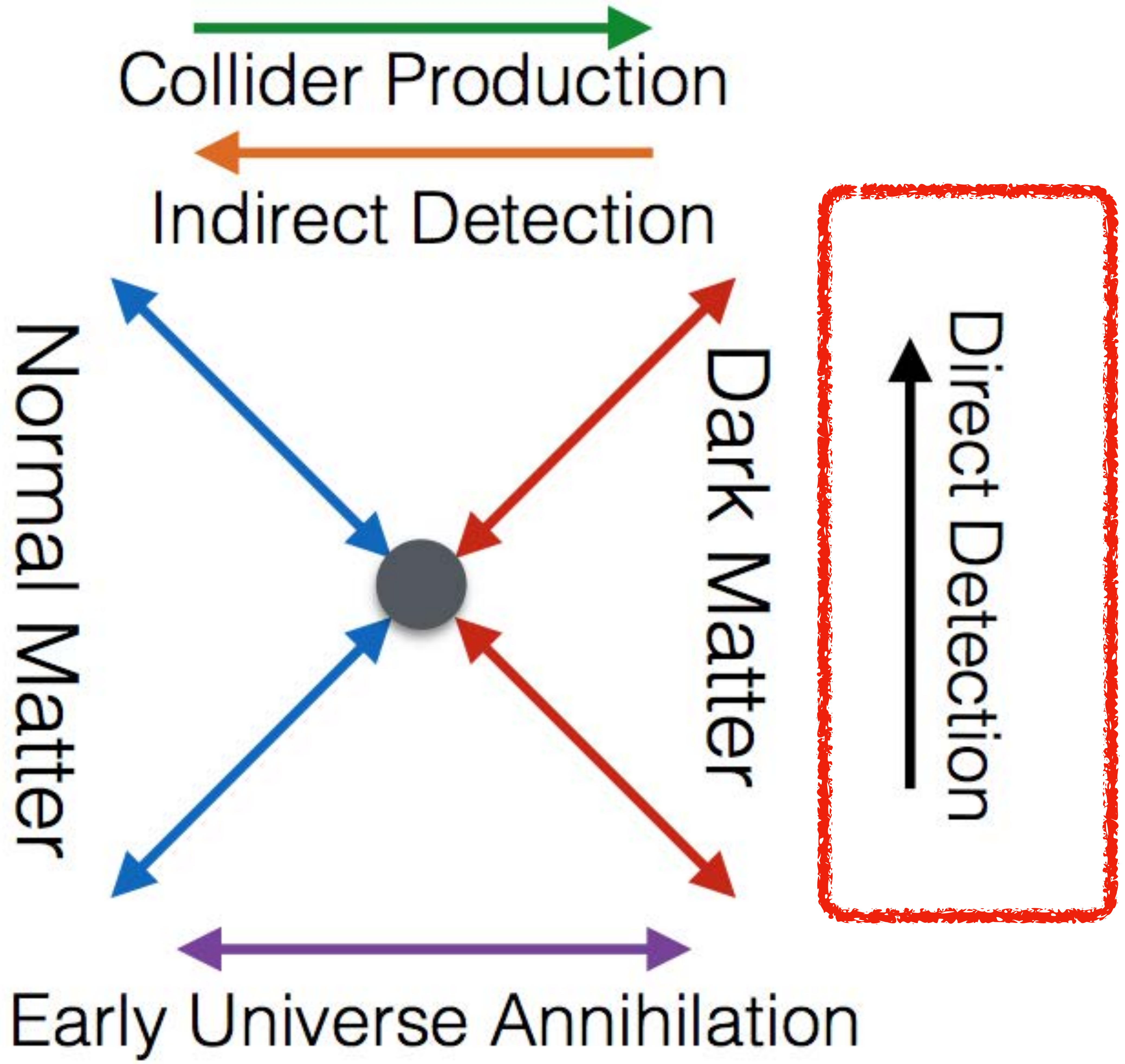


WIMP "Miracle"

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



DARK MATTER DETECTION

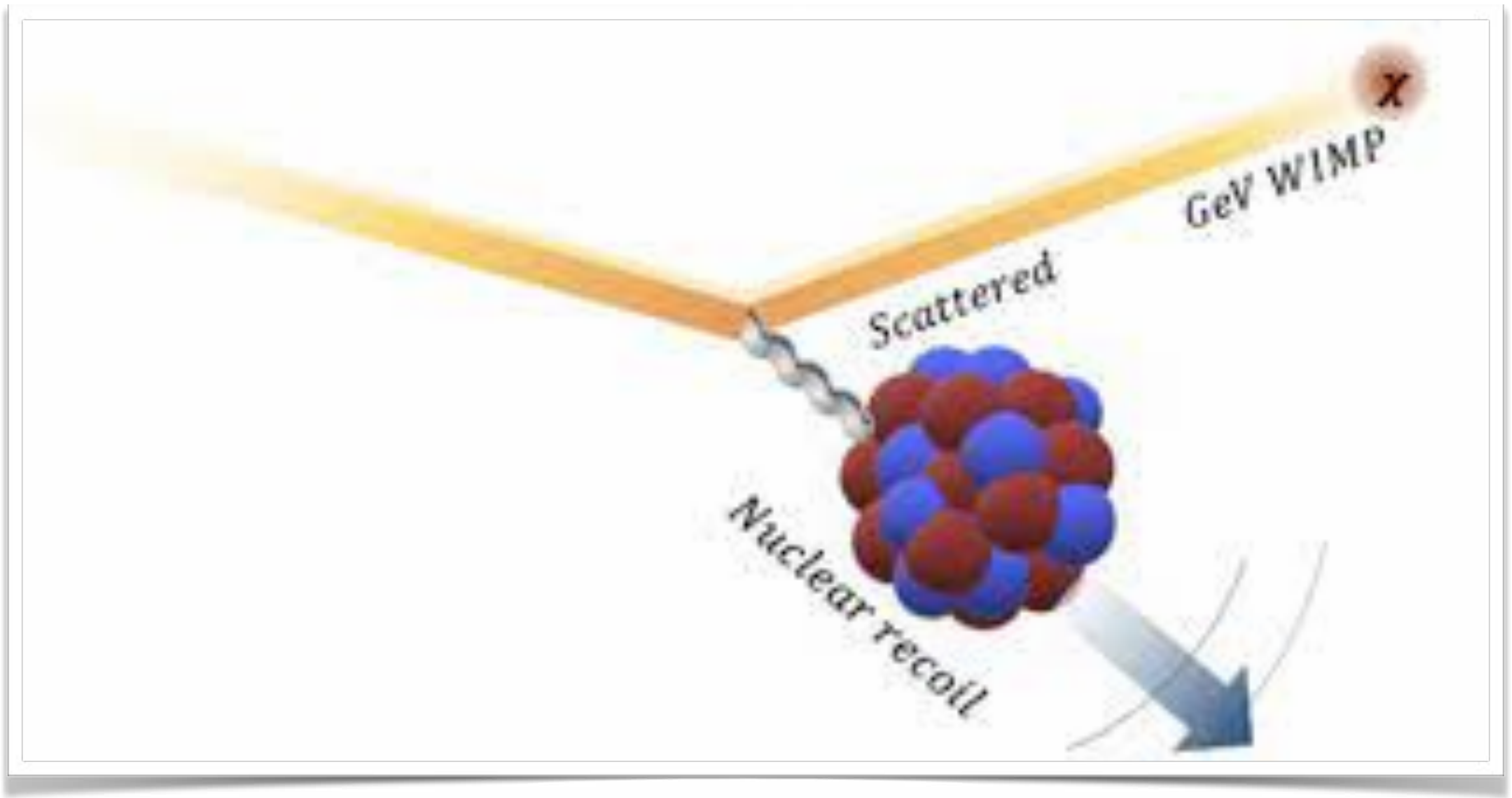


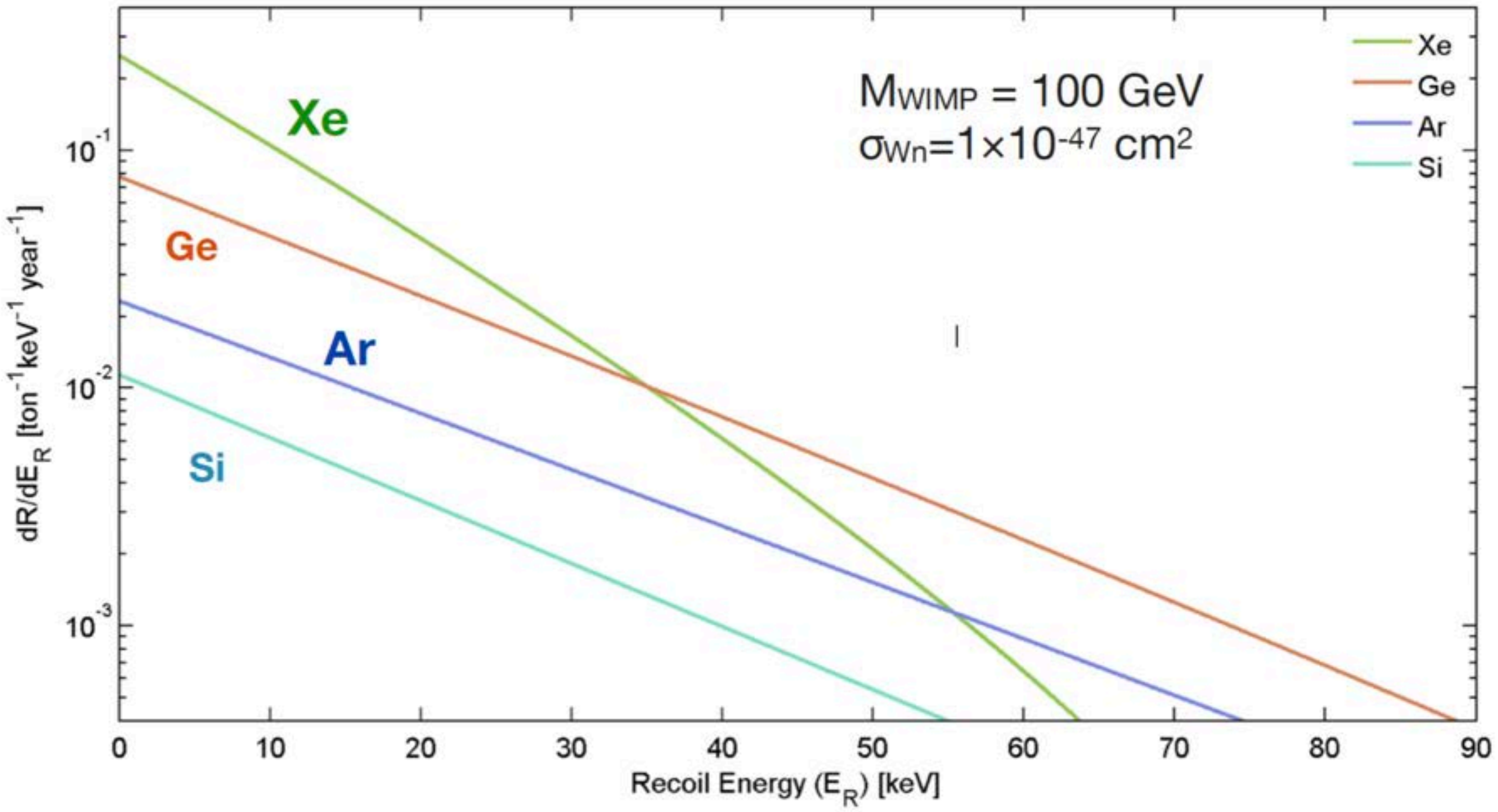
DIRECT DETECTION

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

Interaction rates depend on:

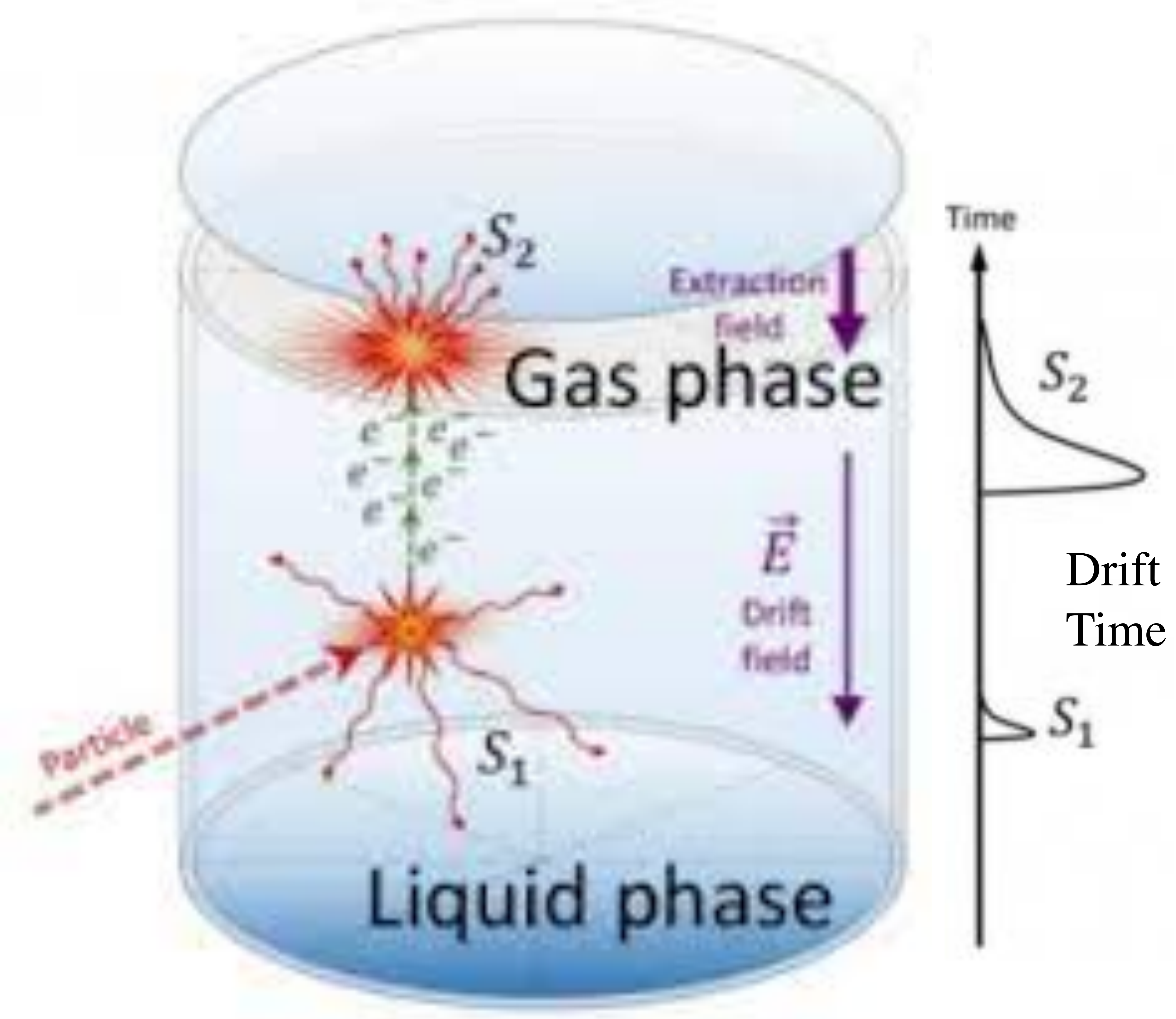
- Our model of how the sun and heart move through the galaxy
- How fast earth travel relative to WIMPs





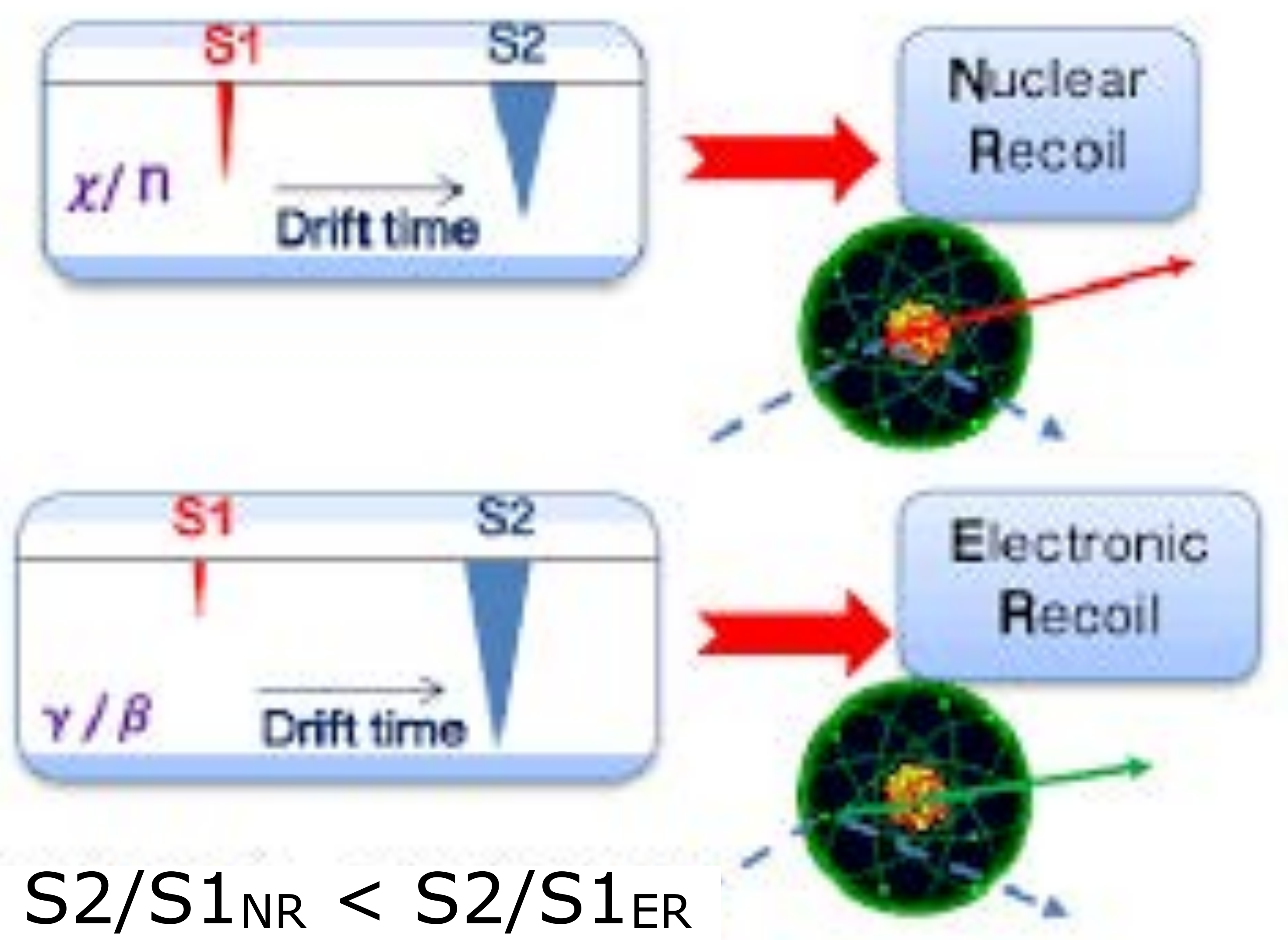
DARK MATTER SEARCH IN DARKSIDE

Dual phase Time projector Chamber (TPC)



Drift Time

- 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



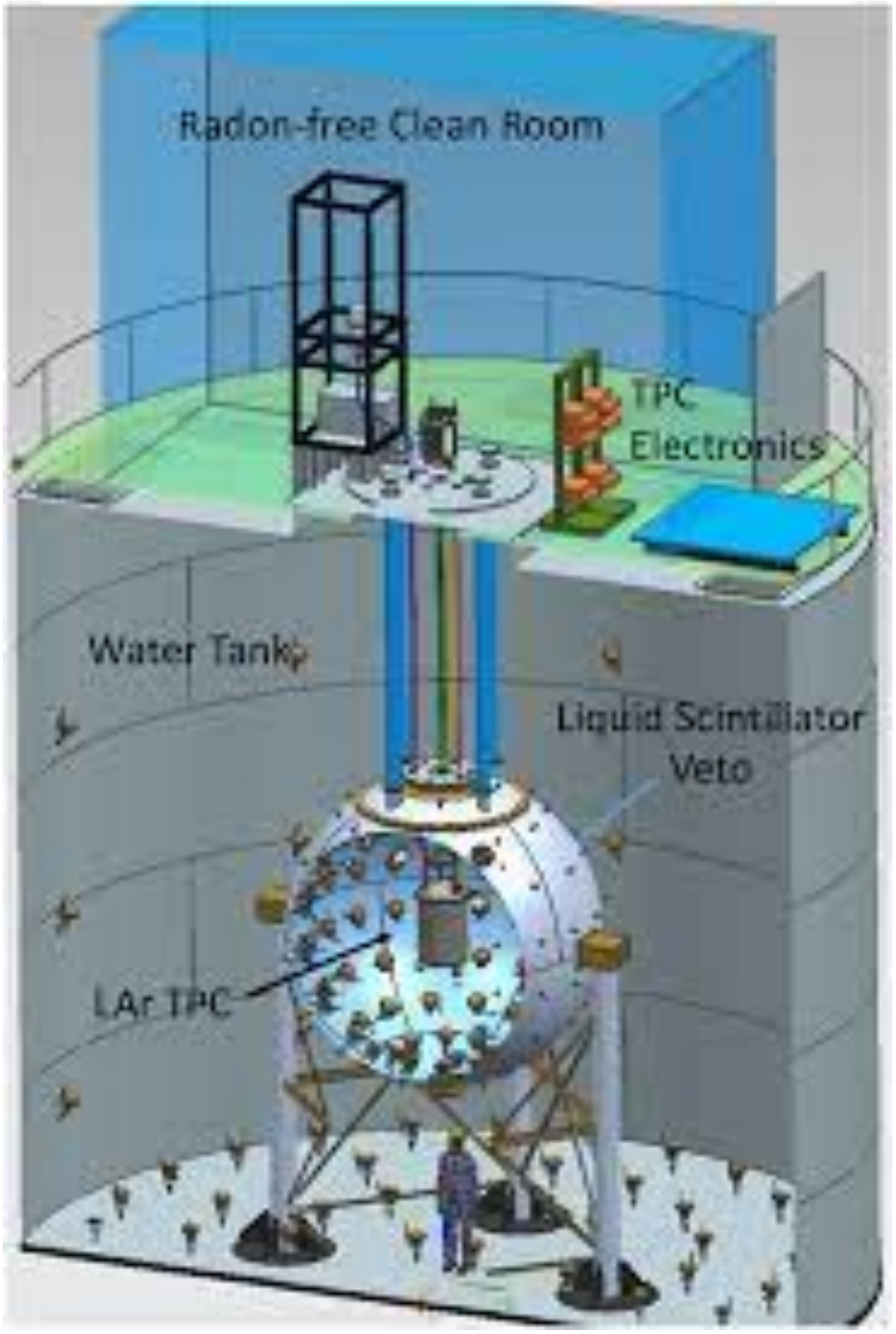
$S2/S1_{NR} < S2/S1_{ER}$

DarkSide Target material: liquid Ar from underground (UAr)

LOW MASS DARK MATTER SEARCH

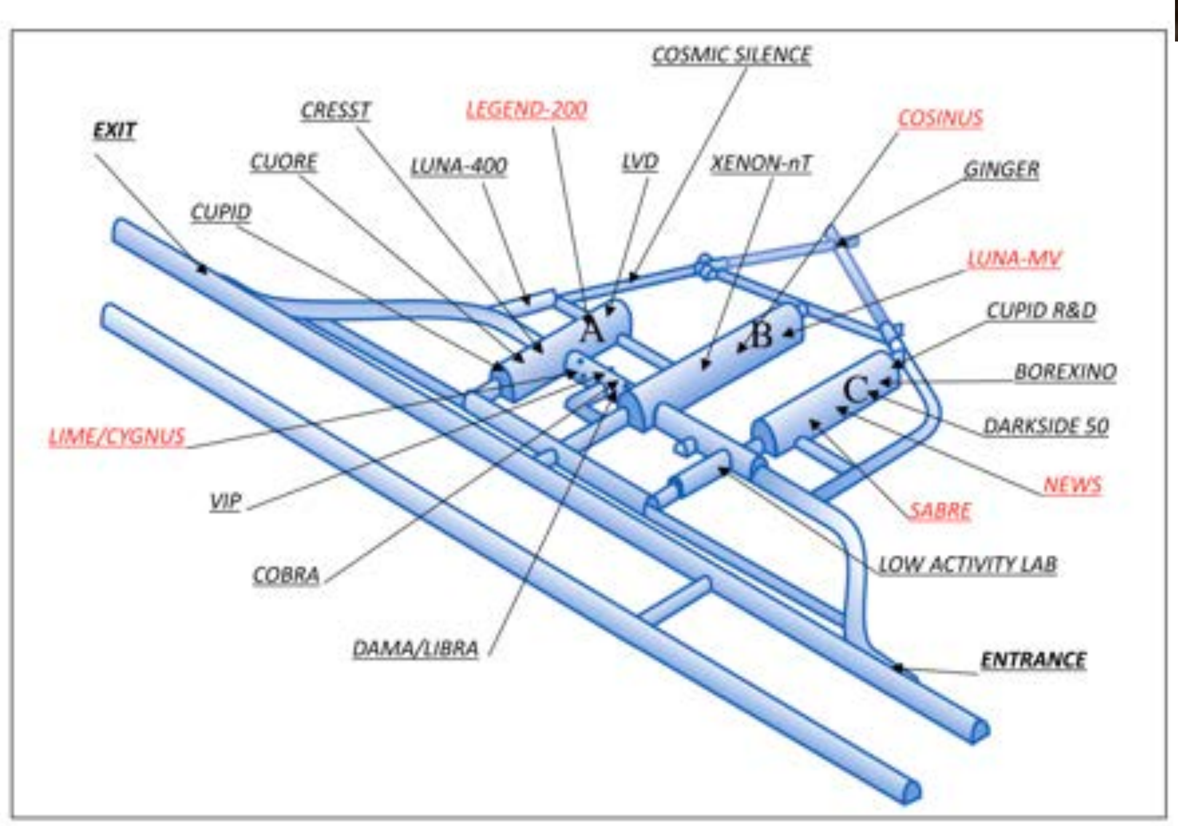
DARKSIDE-50

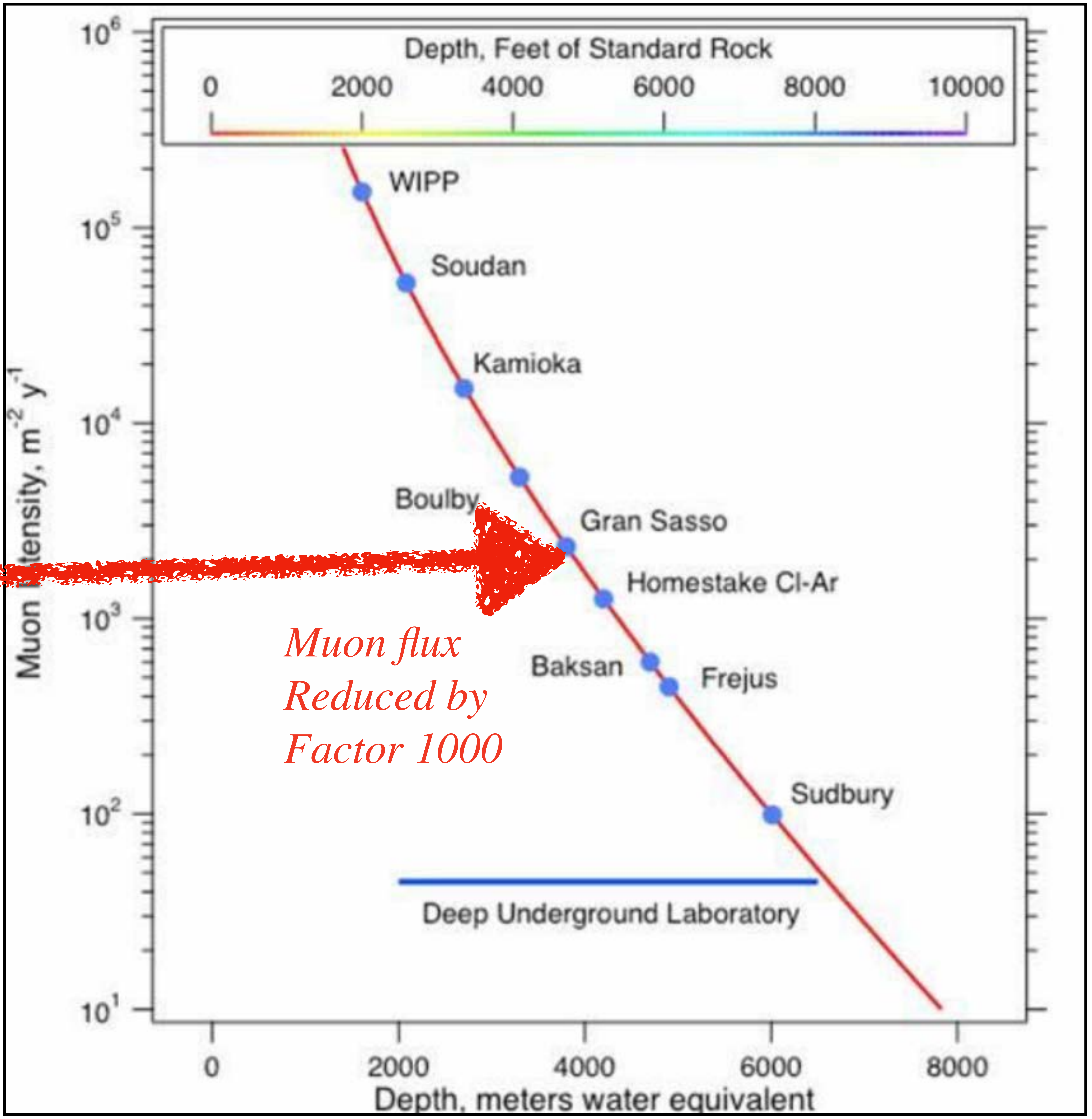
- Dual phase liquid argon filled with 50 kg of Underground Argon (UAr)
- Light detector: PhotoMultiplier (PMTs)
- Veto:
  - Liquid scintillator as neutron moderator
  - Water Cerenkow as cosmogenic veto
- Data taking: 2013 - 2018, total exposure of 0.03 tons x years
- **Low mass search: [1.2, 3.6] GeV/c^2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



LABORATORI NAZIONALI DEL GRAN SASSO (LNGS)

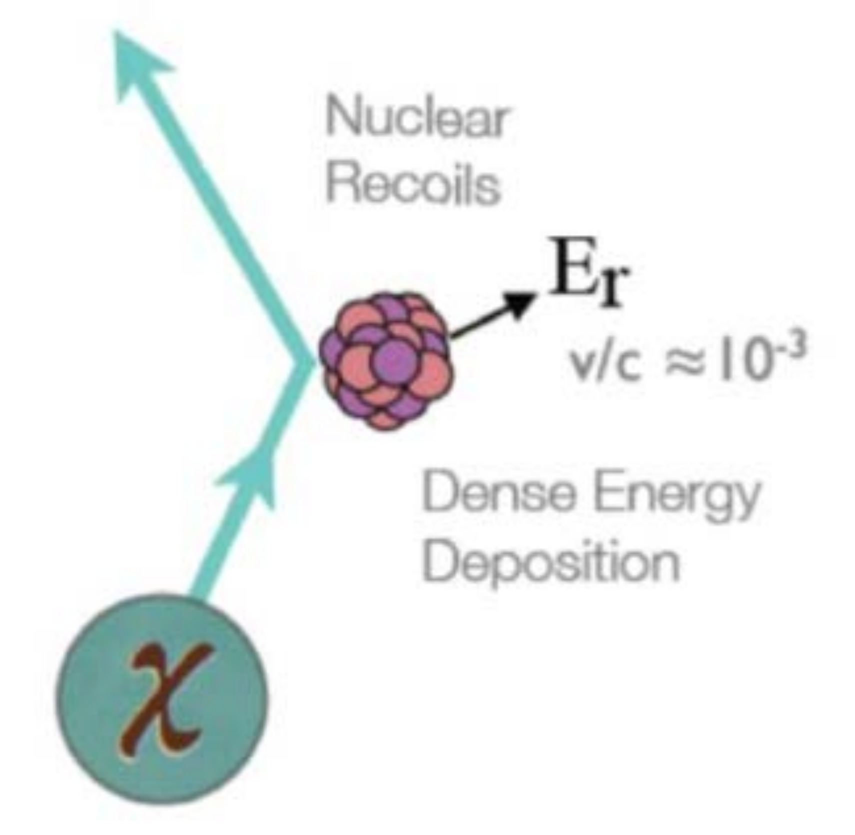
DARKSIDE is located in HALL C at LNGS, Italy
At 3400 m of water equivalent





WIMP SIGNAL & BACKGROUNDs

WIMP SIGNAL



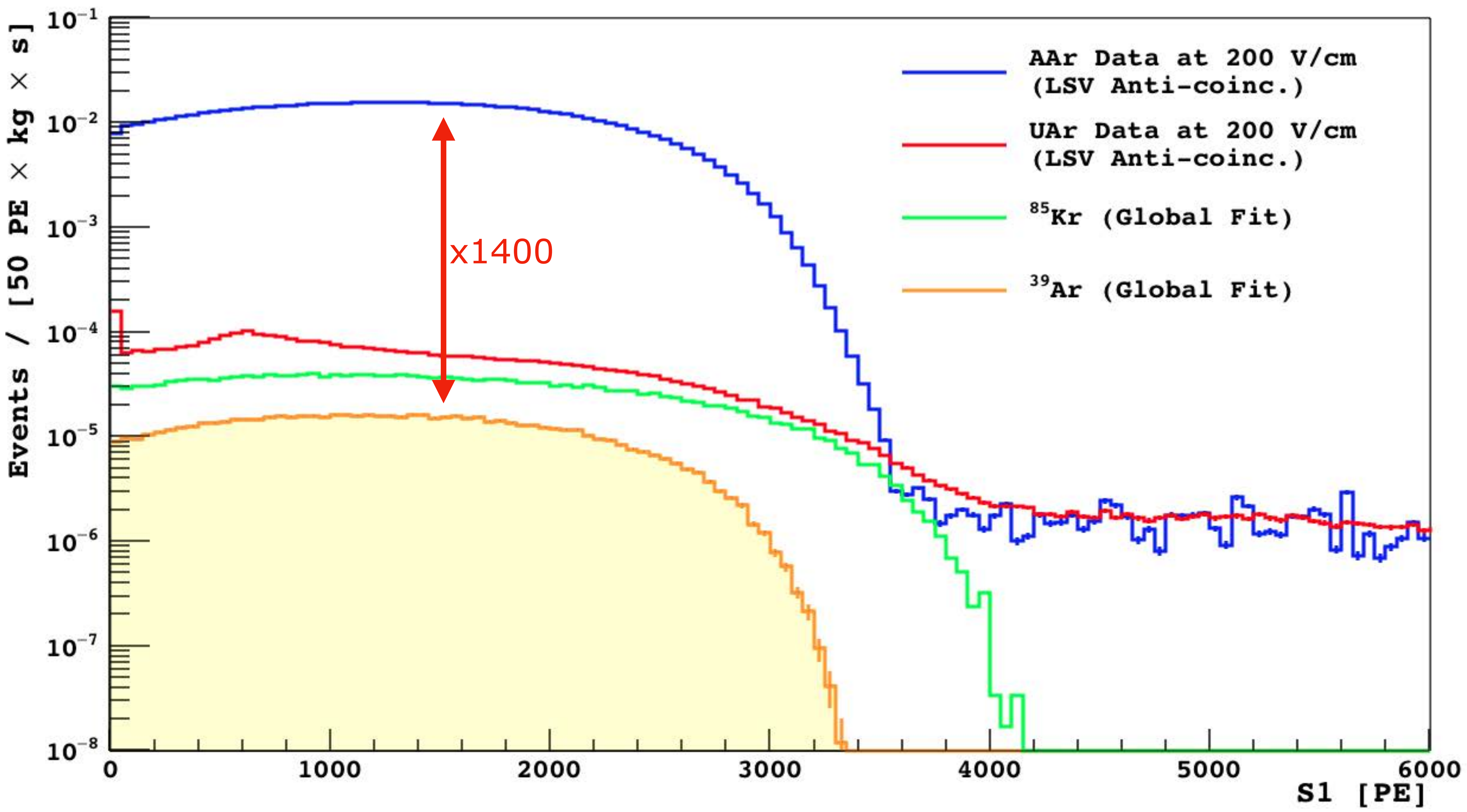
- Single nuclear recoil
- Energy recoil between 1 and 100 keV

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**.

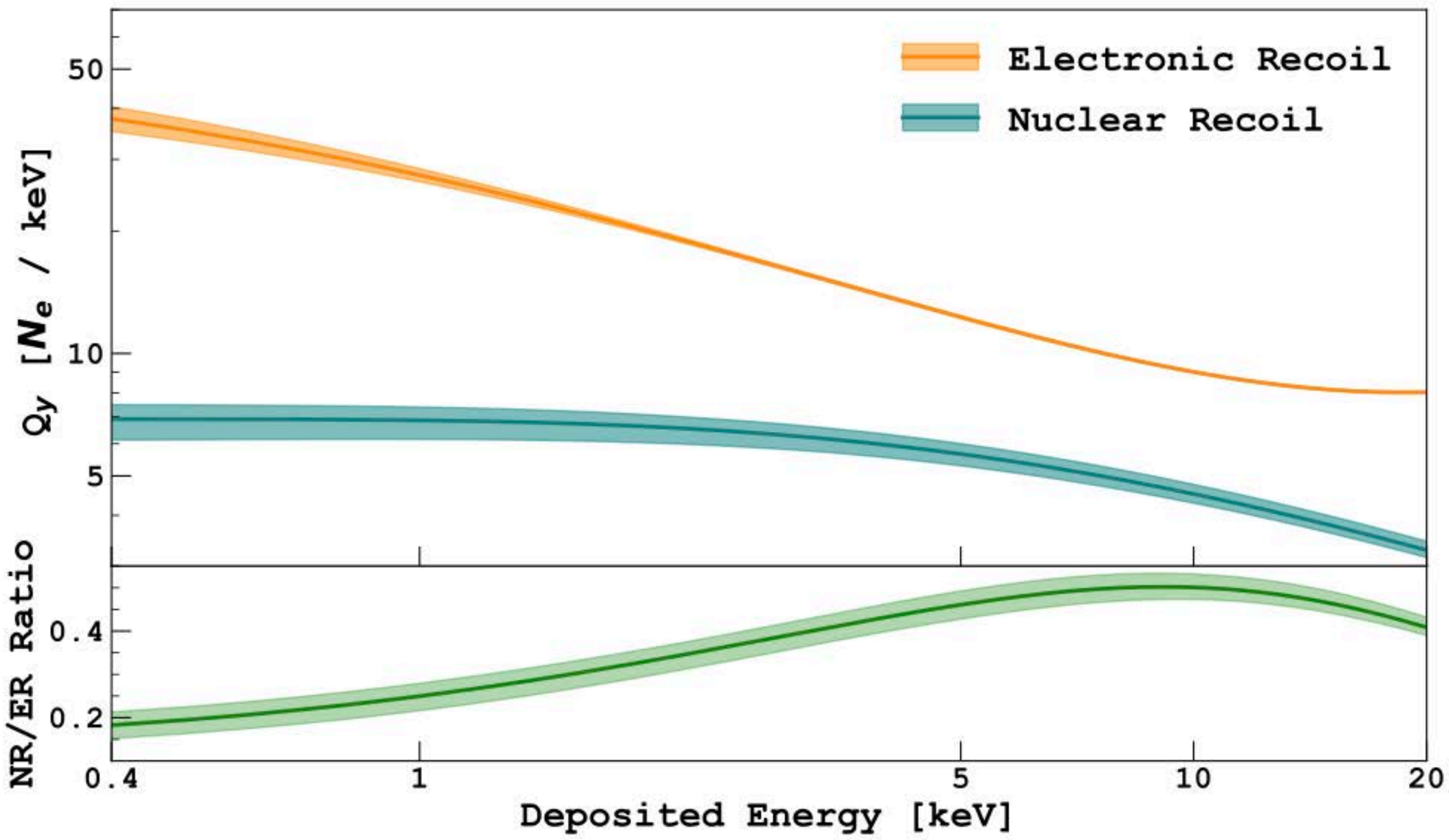


DS-50 results: Phys. Rev. D 93, 081101(R) (2016)

WIMP NUCLEON INTERACTION

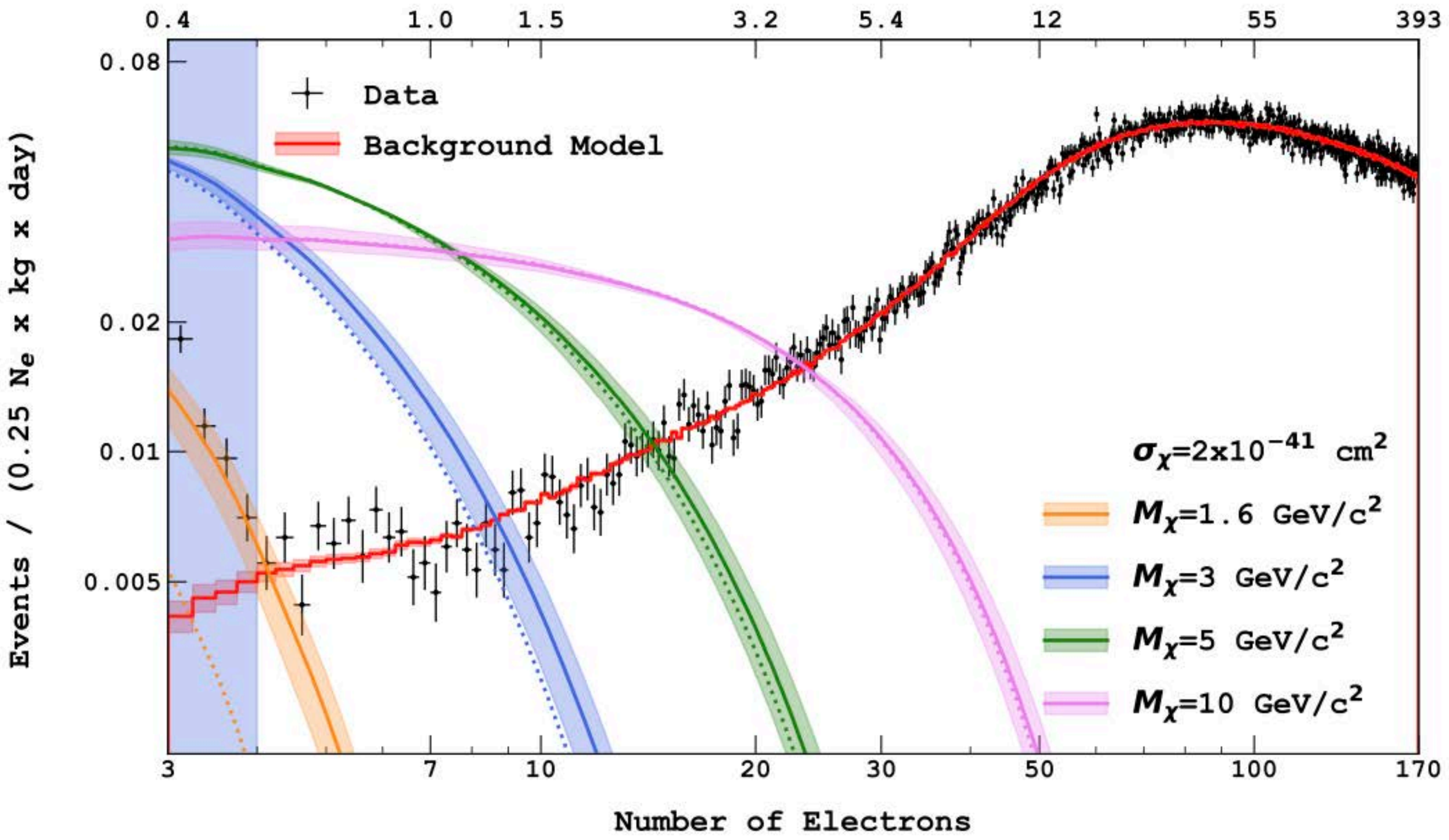
Re-analyse the full DS50 dataset with a more detailed calibration model

Phys. Rev. Lett. 130, 101001



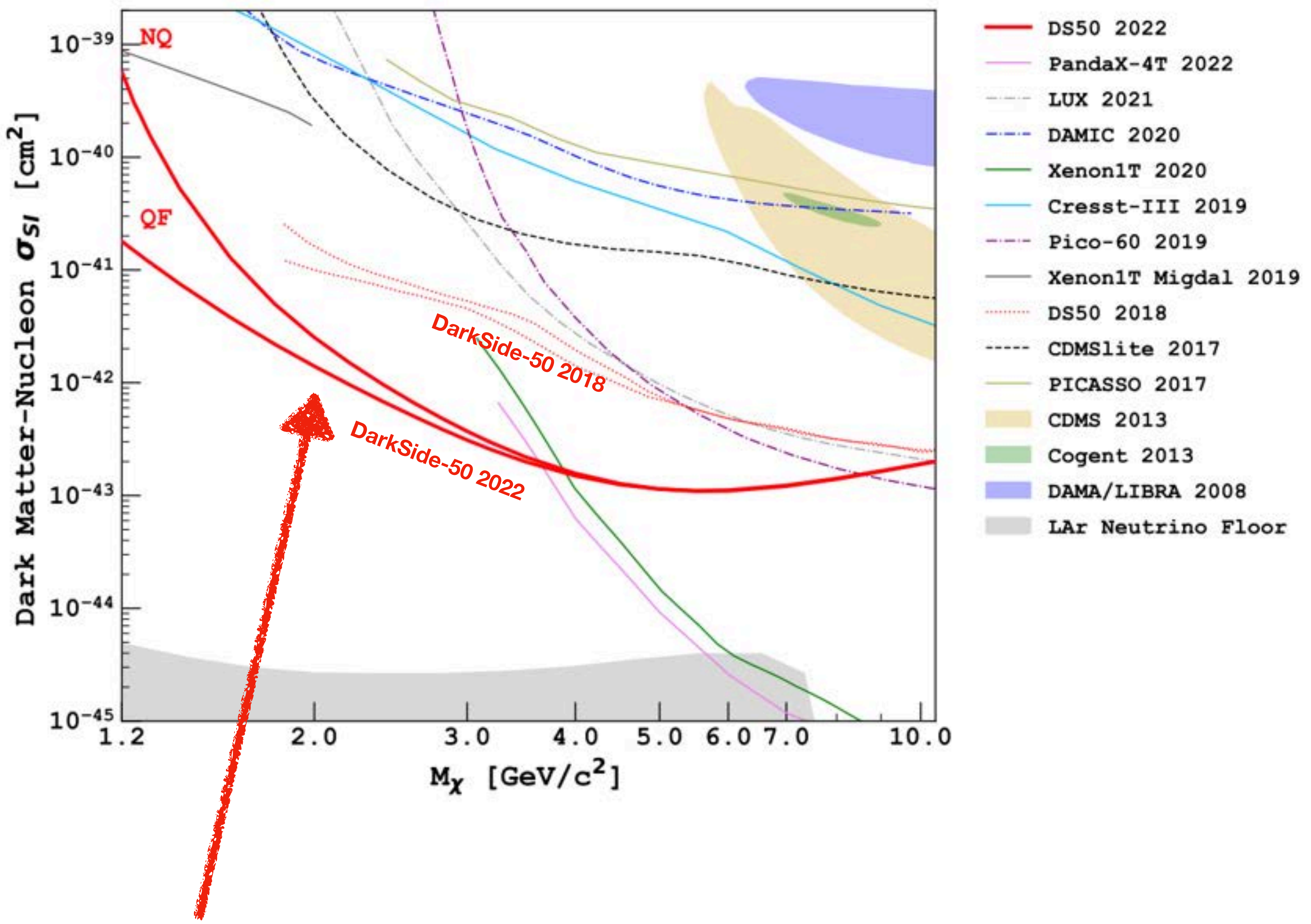
- Electron recoil modelling using ^{37}Ar, ^{39}Ar decay naturally in the early LAr dataset, focus on ionisation signal below 180 eV_{er}
- Nuclear recoil from in-situ neutron calibration (AmC), energy down to 500 eV_{nr}

LOW MASS SENSITIVITY



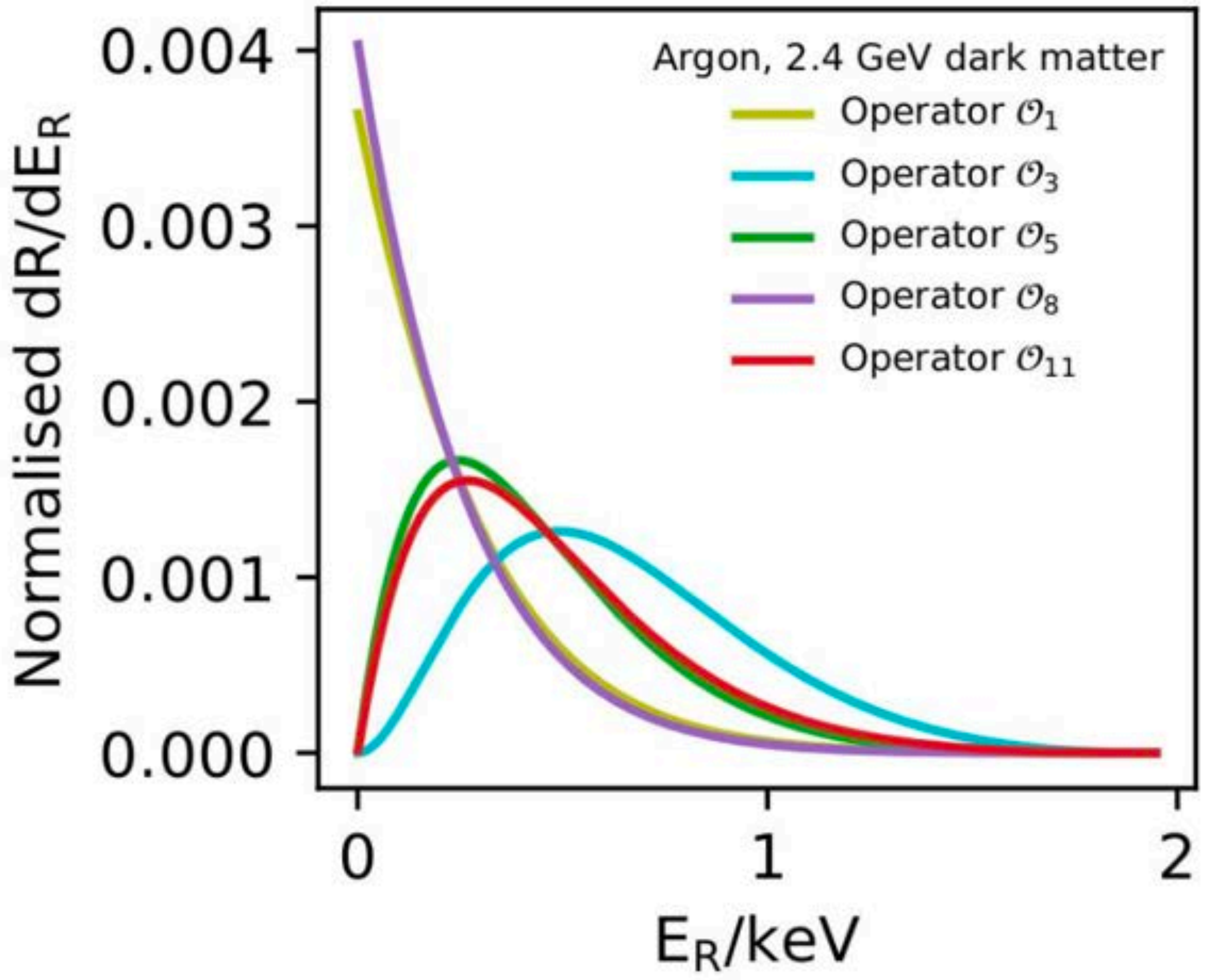
Background spectra compared with expected WIMP spectra below 10 GeV/c^2
The dominant background comes from ^{85}Kr,^{39}Ar

Phys. Rev. Lett. 130, 101001

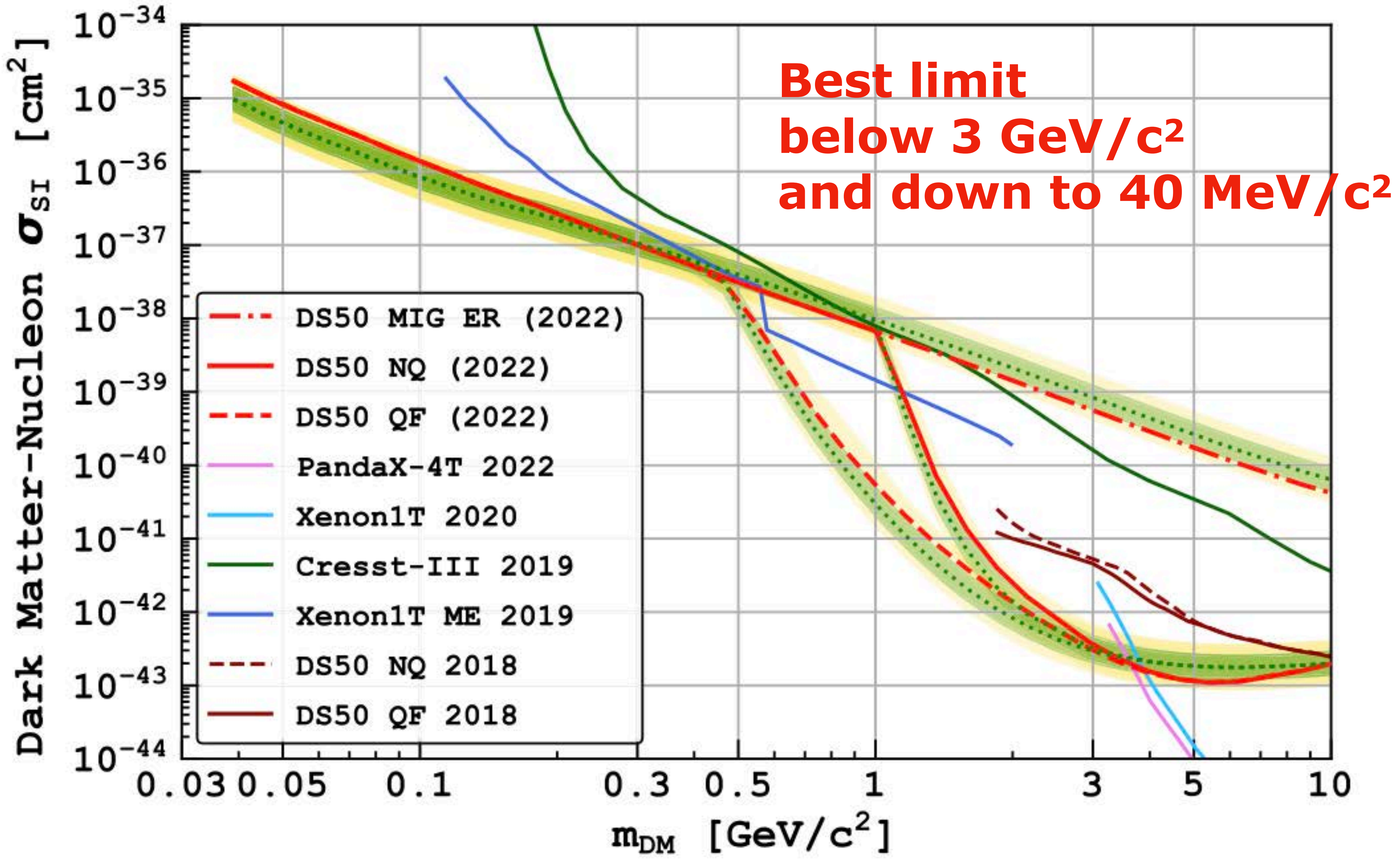


Best limit in the region between 1.2 and 3.6 GeV/c²

MIGDAL EFFECT



Phys. Rev. Lett. 130, 101002

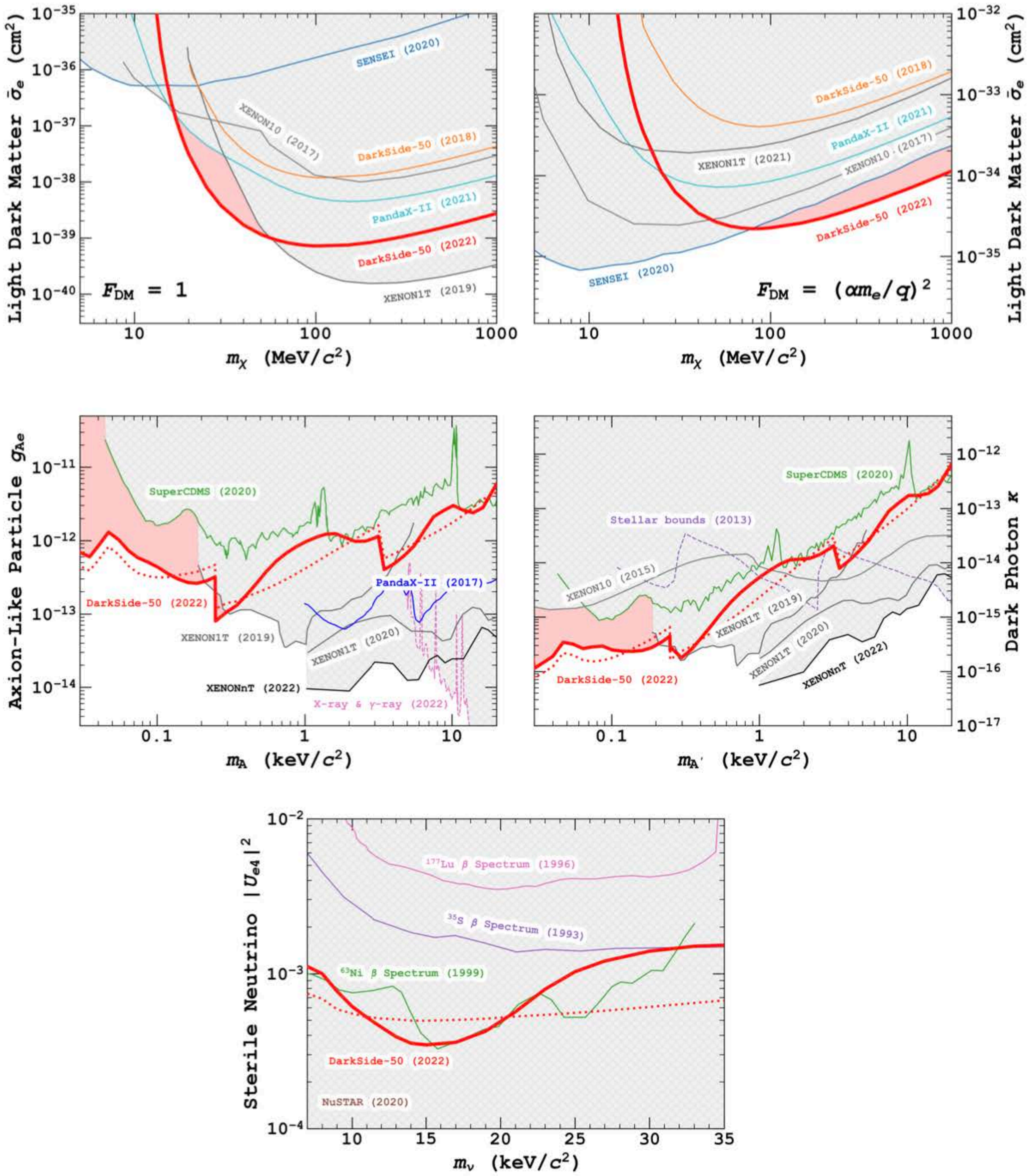


- Reinterpretation of published Ar and Xe resulting including Midgal effects benmarked again published results
- New constrain on sub-GeV WIMP mass trough Migdal effect

Kings + Manchester + RHUL main contributors!

DM-e-SCATTERING RESULTS

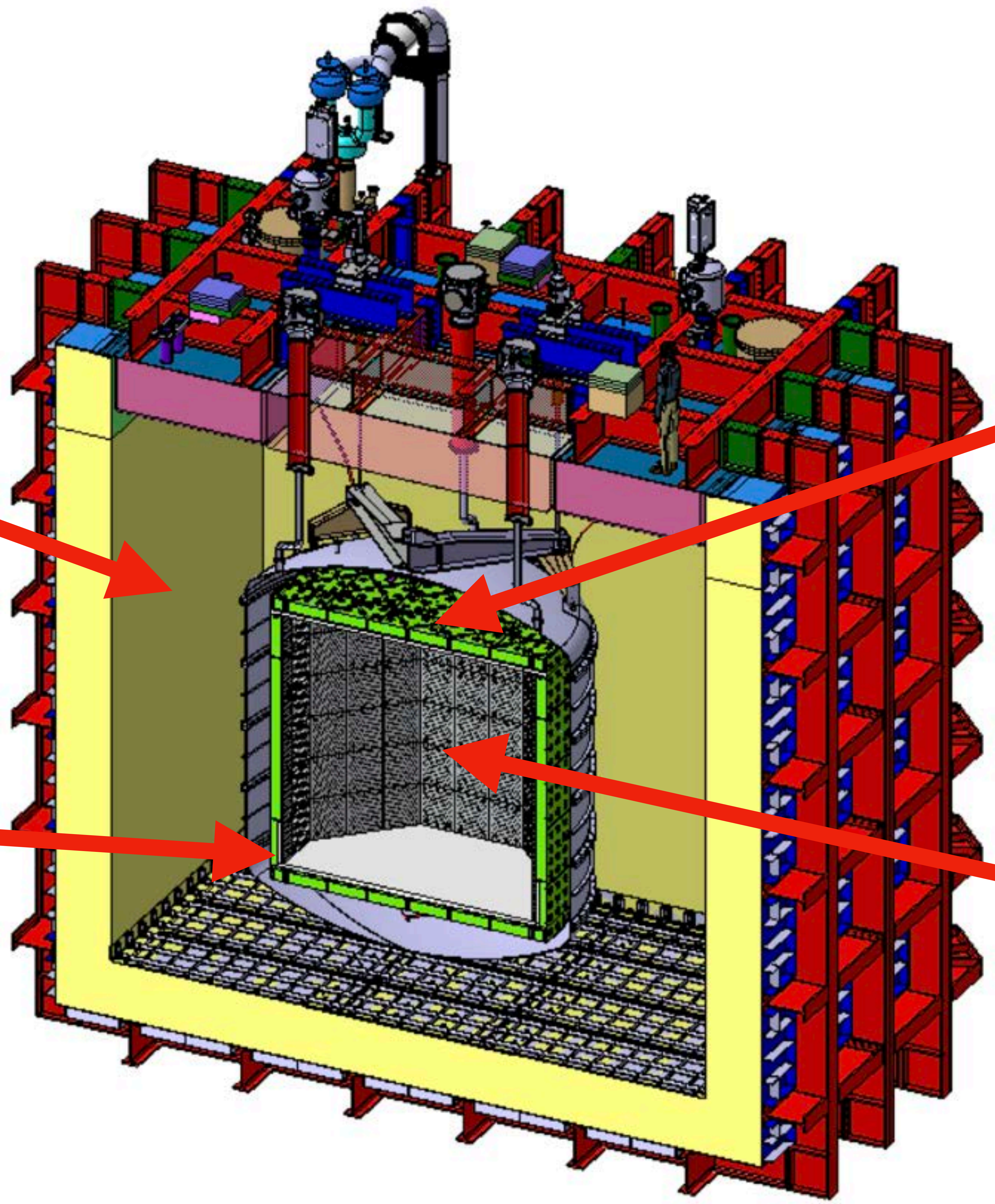
Phys. Rev. Lett. 130, 101002 (2023)



- 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

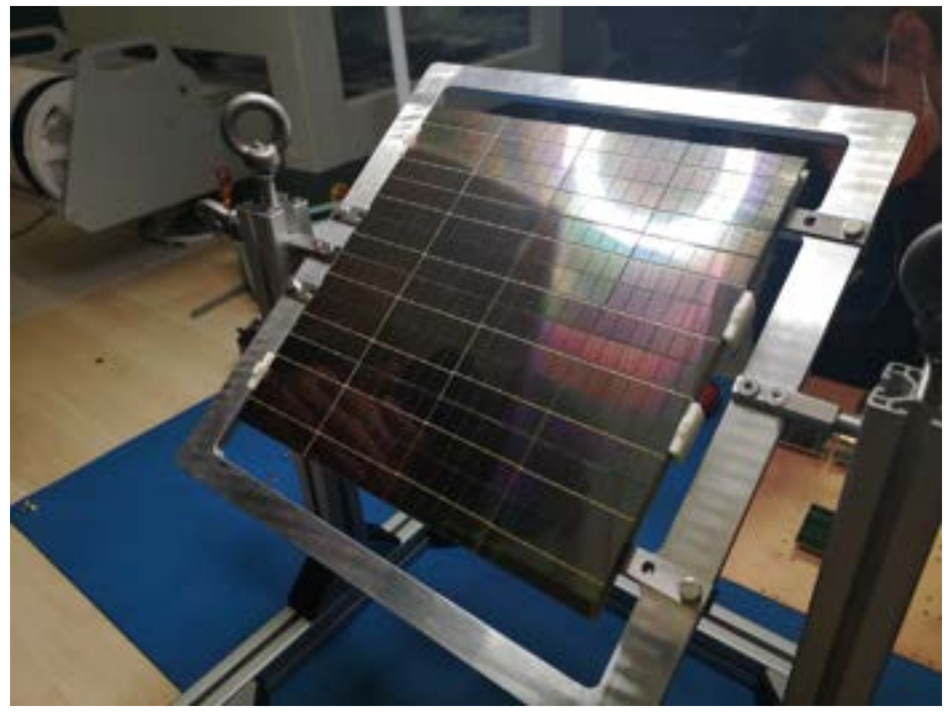
INNER DETECTOR

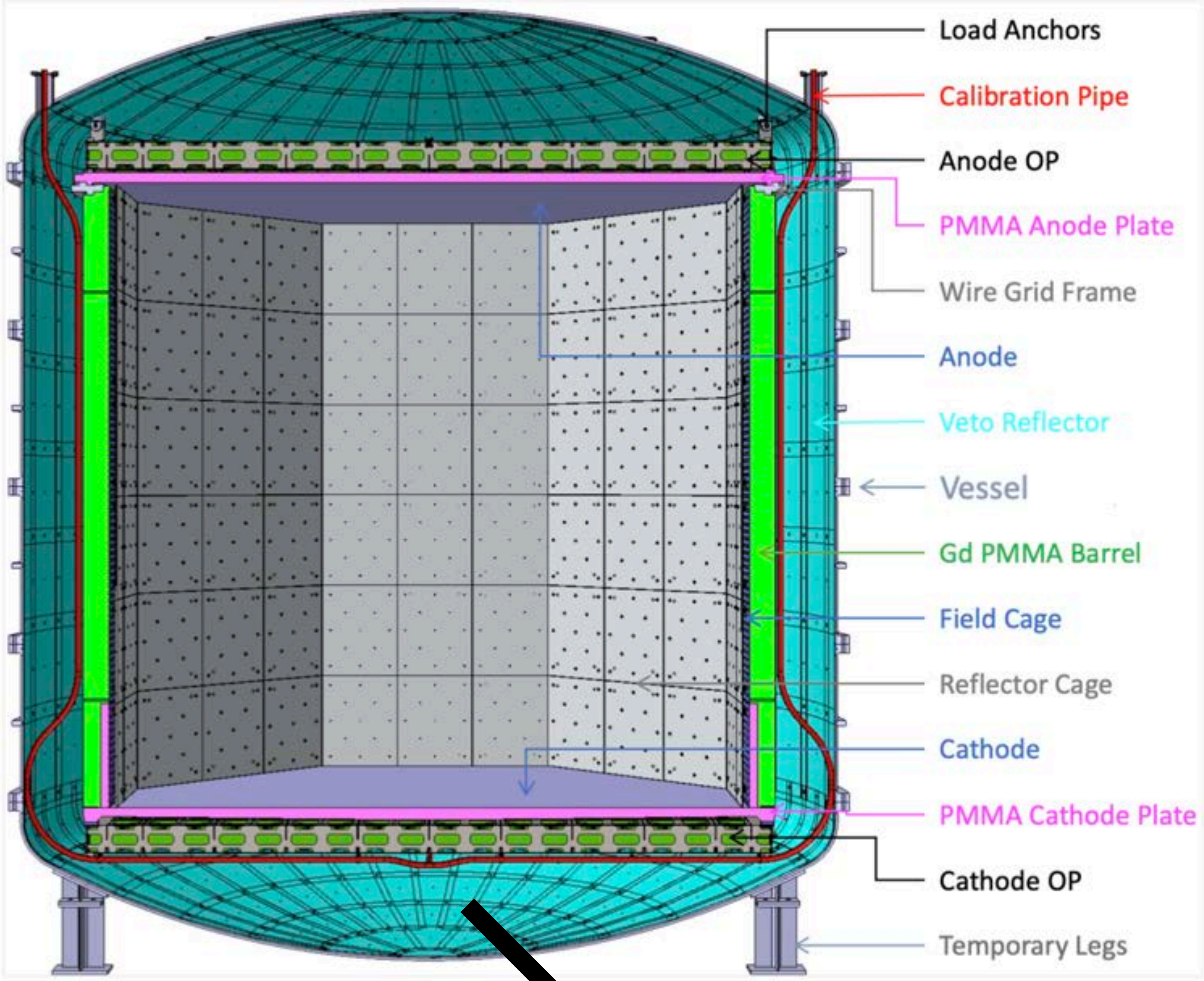
1. **Dual phase time Projected chamber (TPC)** filled with 50 tonnes of Underground Argon -> 20 tons of fiducial volume

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

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

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

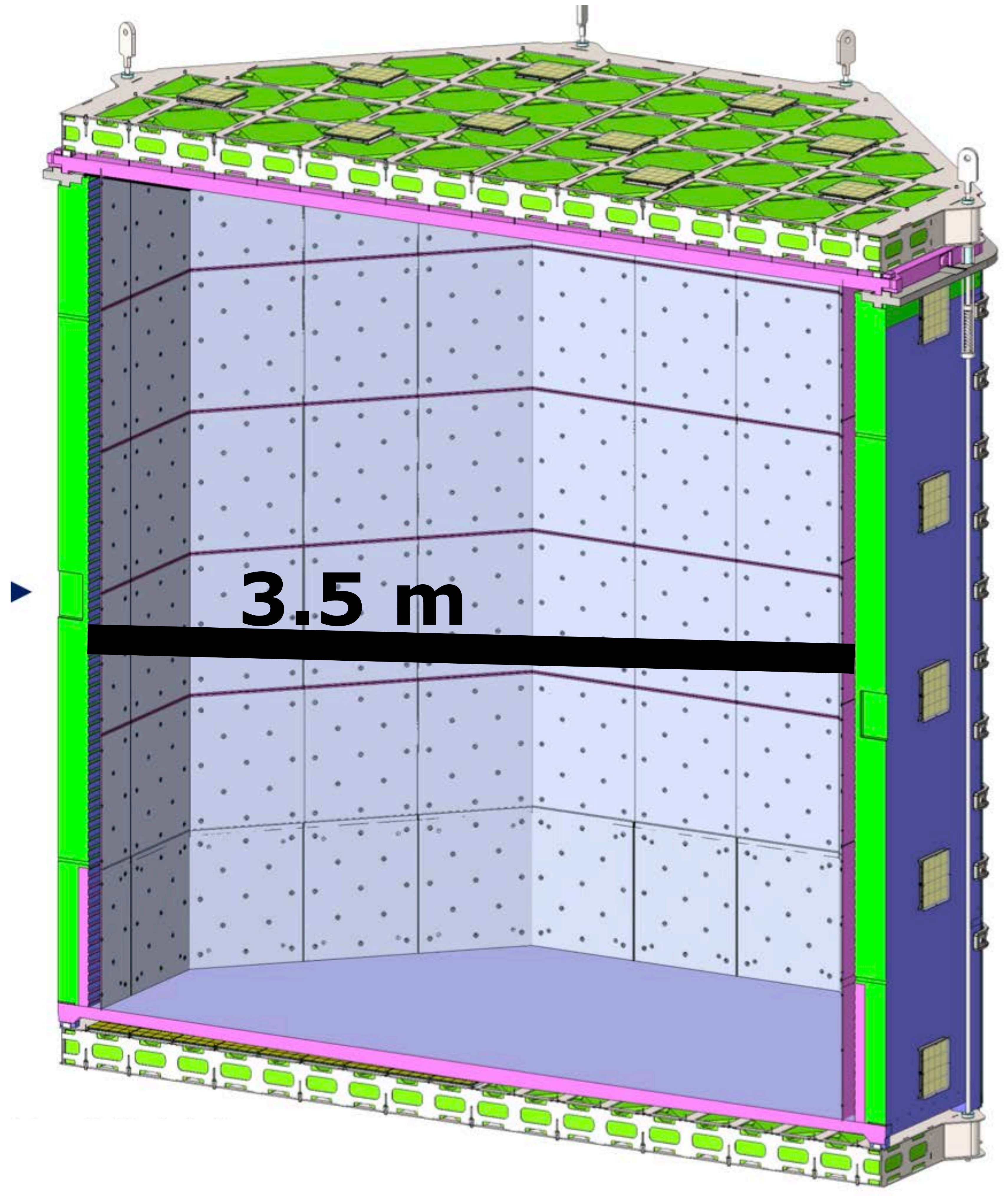




The inner detector is enclosed in a SS vessel, total mass of 12 tons

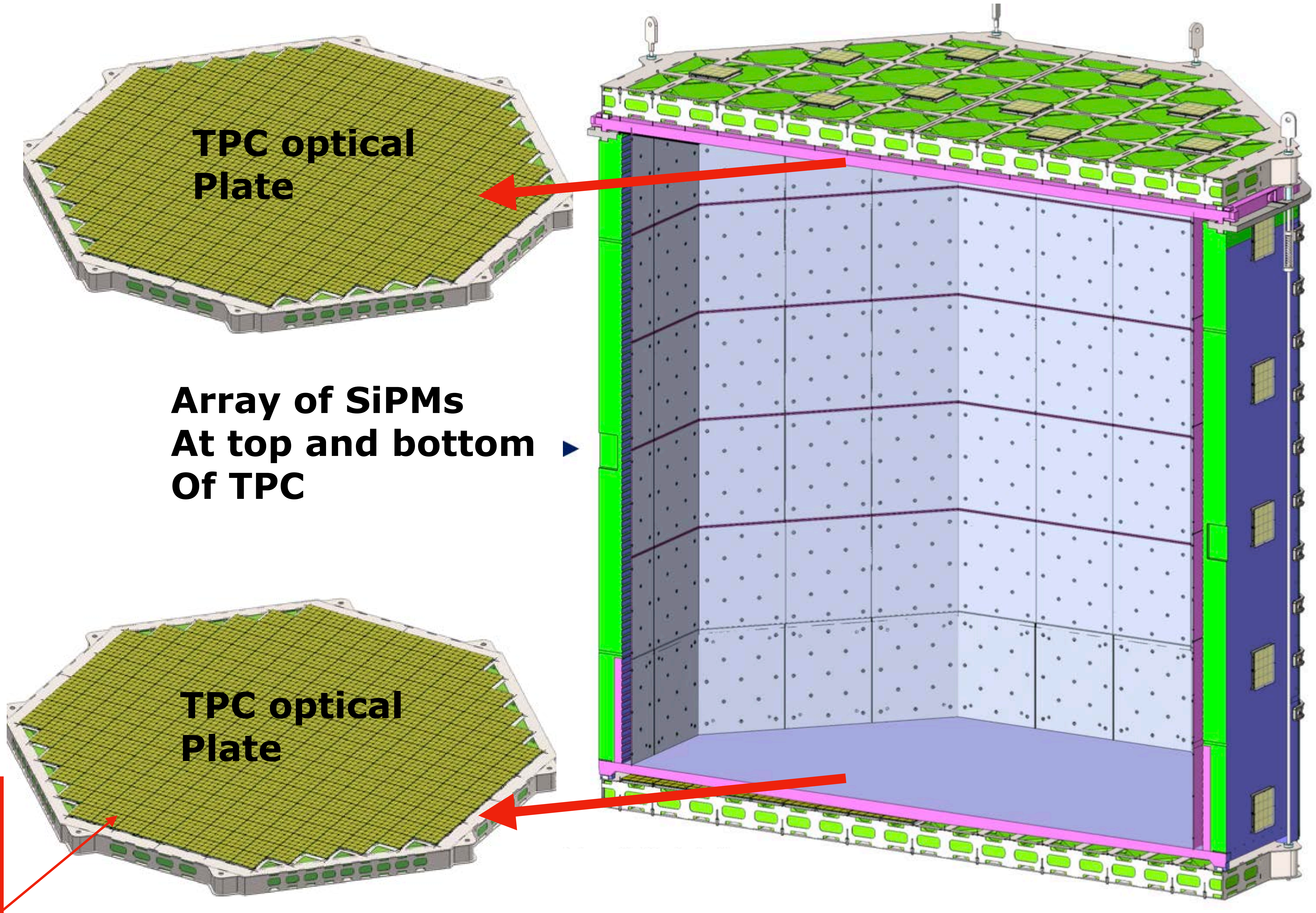
INNER DETECTOR: TPC

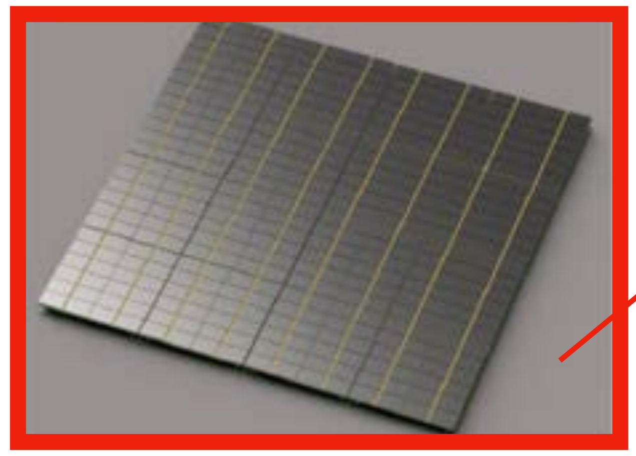
- Octagonal shape
- Drift field: 200V/cm
- Extraction field: 2.8 kV/cm
- Cathode voltage: -73.38 kV
- ESR as reflector, TPB as wavelength shifter
- SS wire grid



INNER DETECTOR: TPC

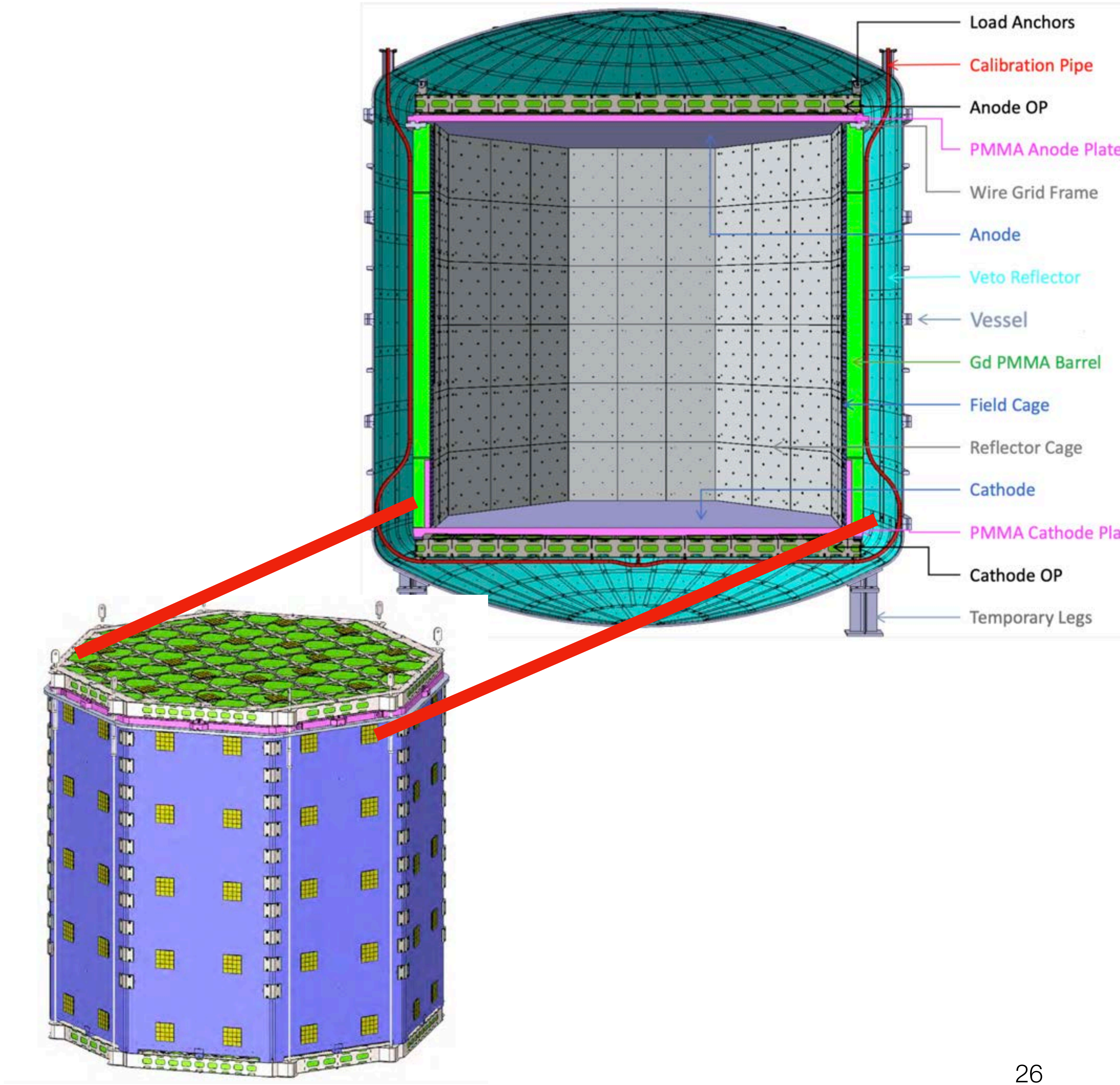
- TPC equipped with 518 PDU placed on top and bottom
- Total SiPMs in the TPC: 198912
- Light yield: 10 pe/keV
- S2 yield > 20 pe/e-



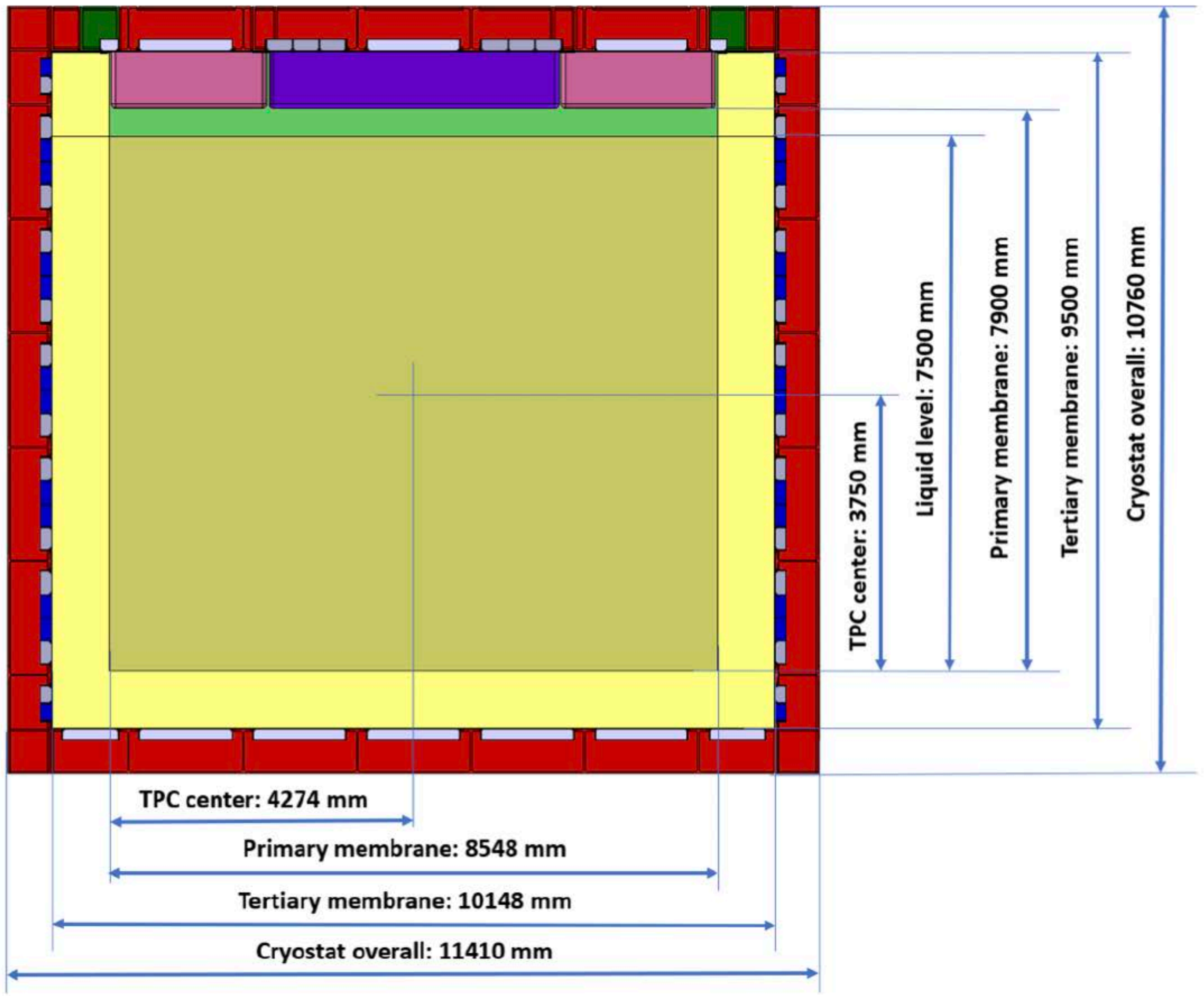


INNER DETECTOR: neutron veto

- Novel technology: TPC+veto integrated system -> Gd-PMMA (11.2 tons needed) around TPC wall to capture neutrons (4π coverage)
- SiPMs matrix (assembled in veto photodetector unit-> vPDU) around TPC wall for light detection -> 120 vPDU in total (Light yield: 2.0 pe/keV)
- Reflector+ PEN for light collection optimisation
- Enclose in a SS vessel filled with around 35 tonnes of underground Argon



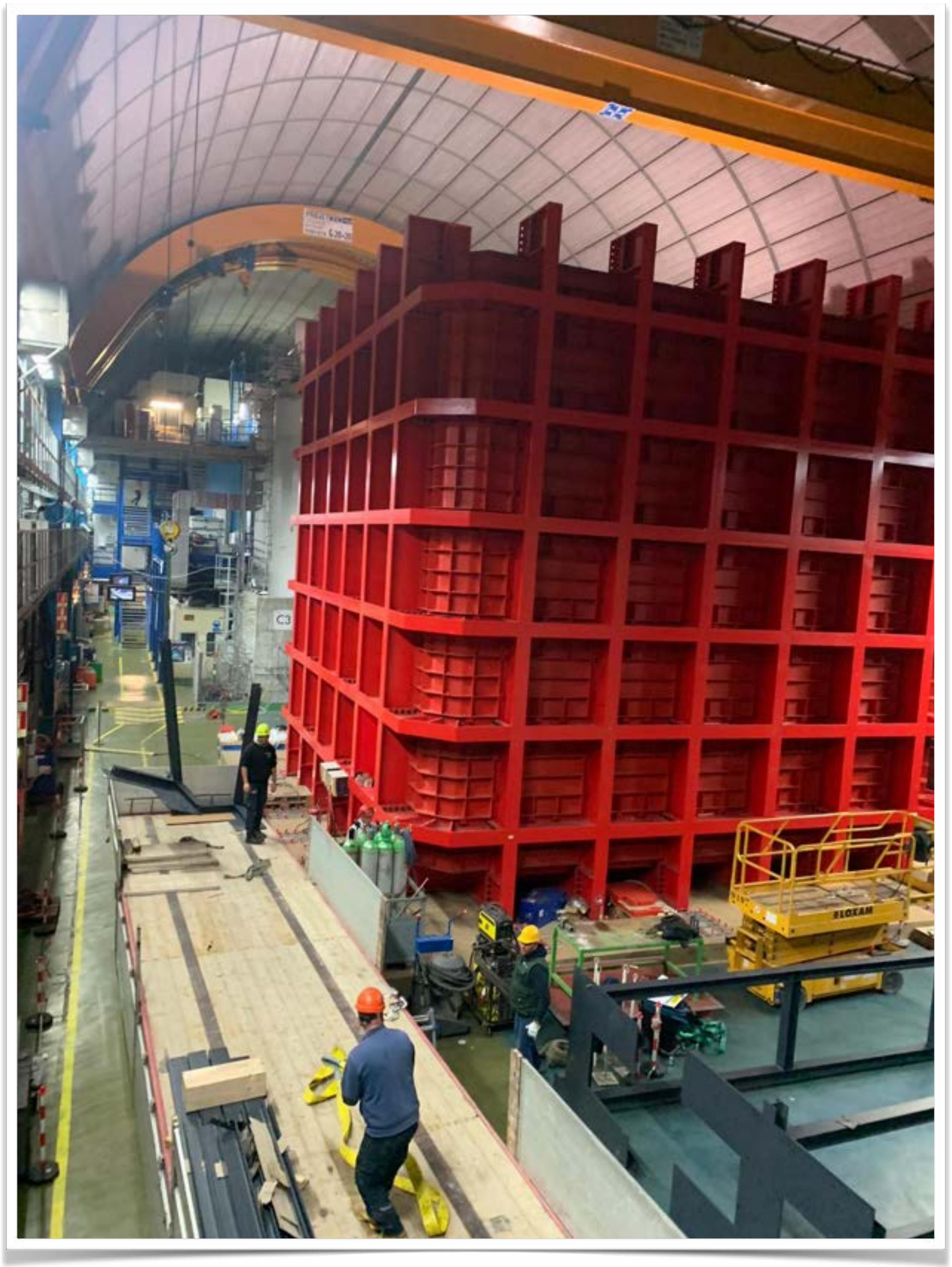
OUTER VETO



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

DARKSIDE-20k: this week!

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



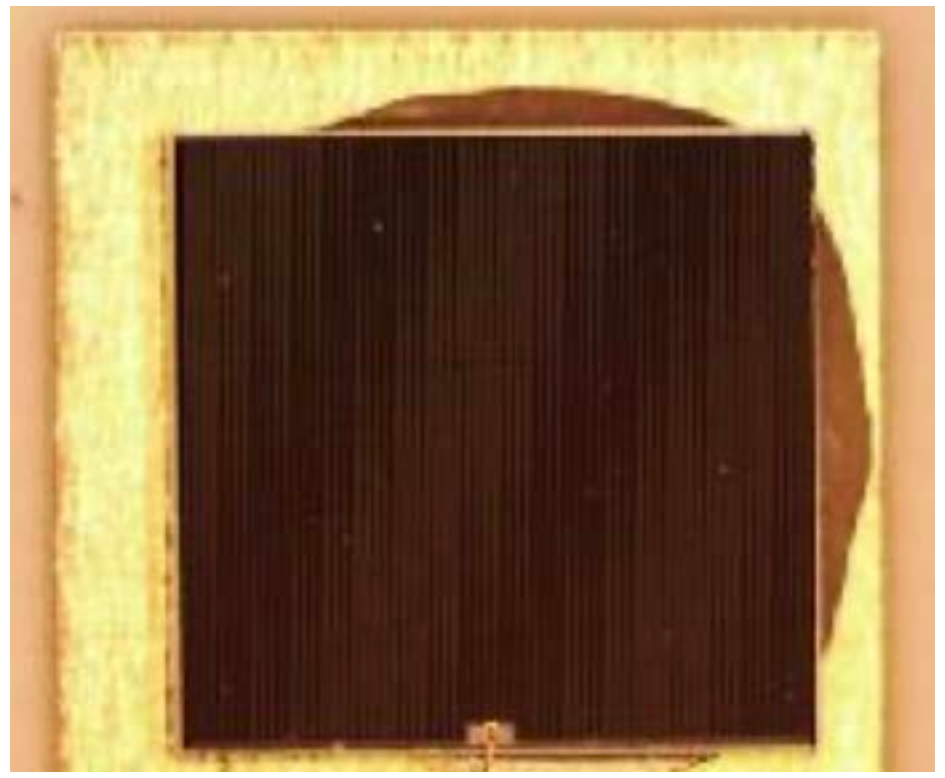
LIGHT DETECTION SYSTEM:
Large area Silicon Photomultipliers (SiPM)

DARKSIDE SIPM REQUIREMENTS

From PhotoMulplier (PMT)

To

Silicon Photomulplier (SiPM)

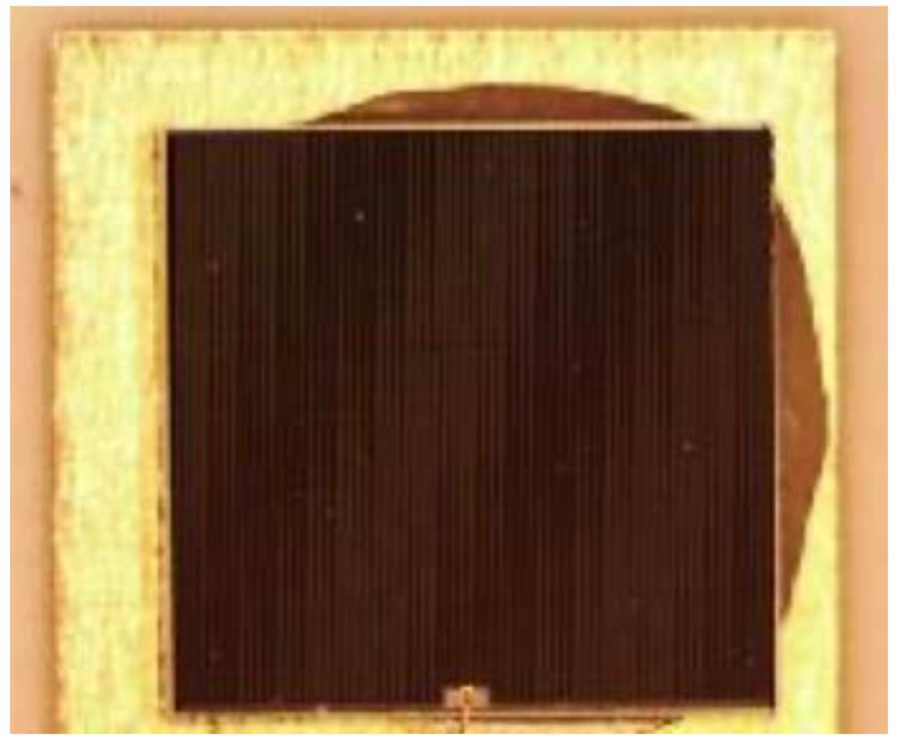


Quantity	Requirement
Breakdown voltage	26.8 +/- 0.2 V
SiPM response - recharge time	300 - 600 ns
Single Photoelectron (SPE) spectra	distinct PE
Gain	stable gain
Signal to noise ratio (SNR)	> 8
Dark count rate (DCR)	< 0.01 Hz/mm^2 (7 Vov) < 0.1 Hz/mm^2 (9 Vov)
Internal cross talk (CT) probability	< 33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

SILICON PHOTOMULTIPLIERs (SiPMs)

SPADs

SiPMs: 1mm²



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 Photomulplier: A single SiPM consists of around 94,900 SPADs.

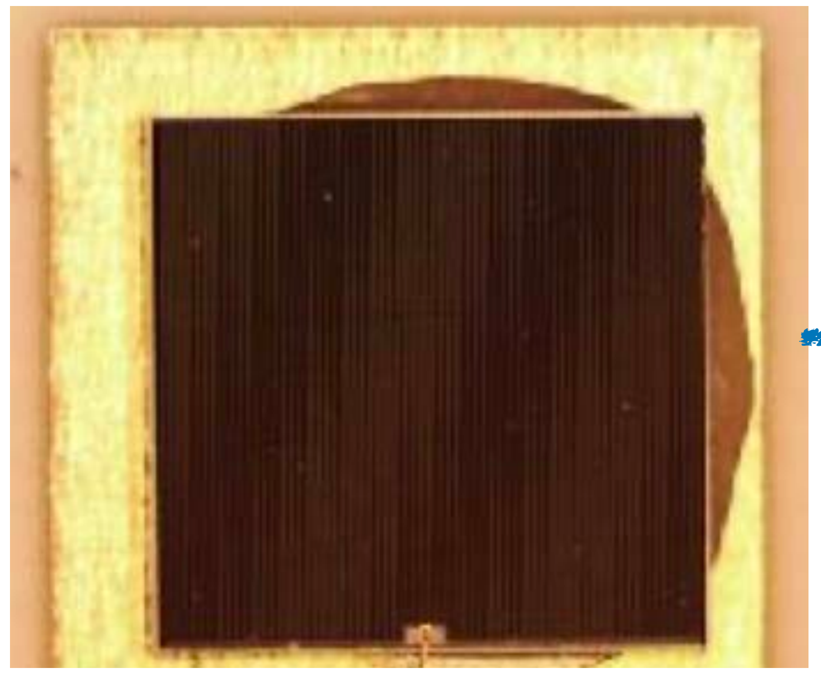
Why SiPMs

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

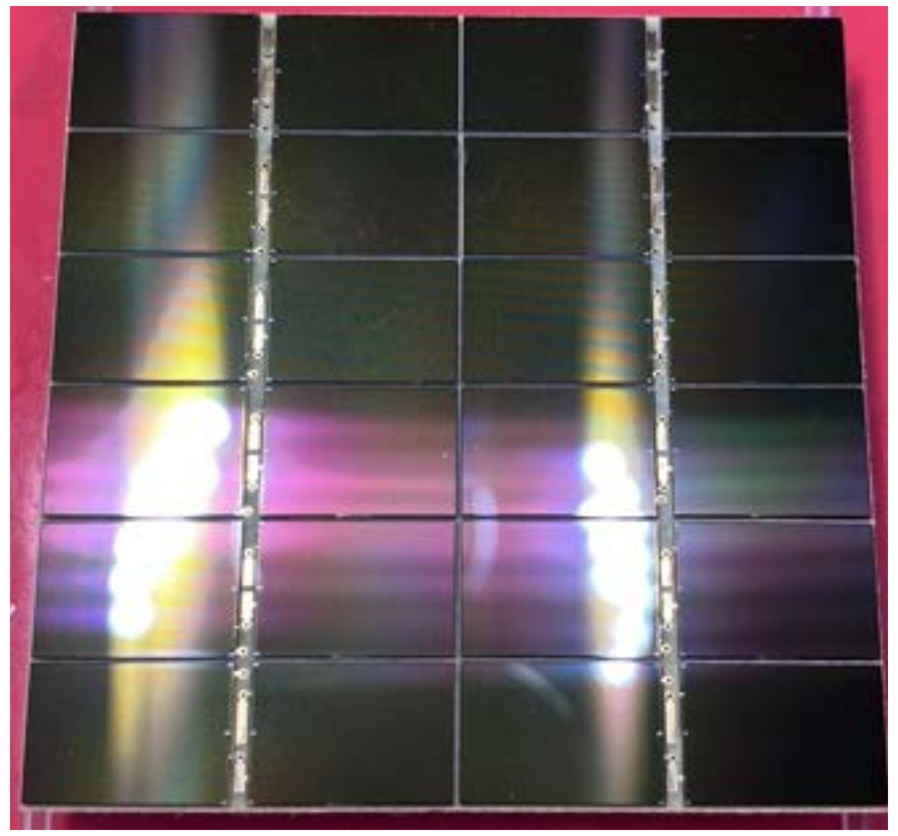
SILICON PHOTOMULPLIER: tile

SPADs

SiPMs: 1mm²



Side 1: 24 SIPMs



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

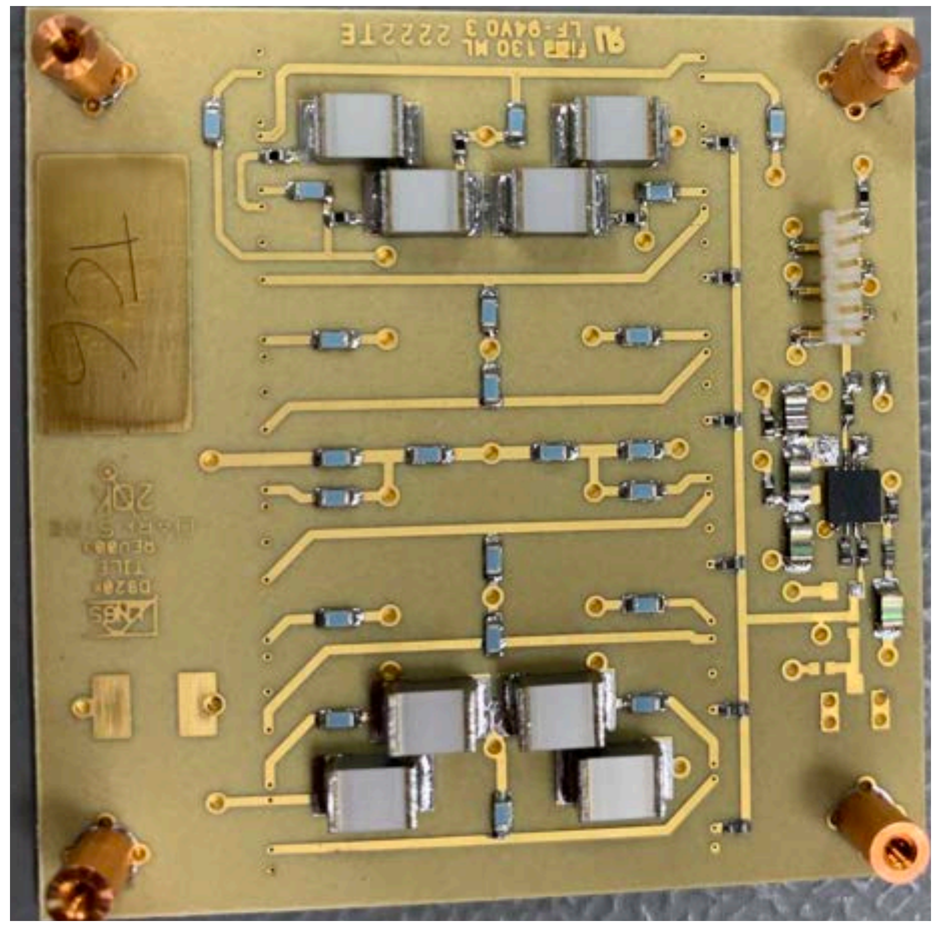
- Side 1: array of 24 SiPMs For a total size of 24 cm2, The signals of all SiPMs are Summed
- Side 2: front-end electronics for Signal amplifier -> ASIC for veto And discrete element for TPC

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 Photomulplier: A single SiPM consists of around 94,900 SPADs.

Side 2: front-end electronics

TPC Tile



Veto Tile (vTile)

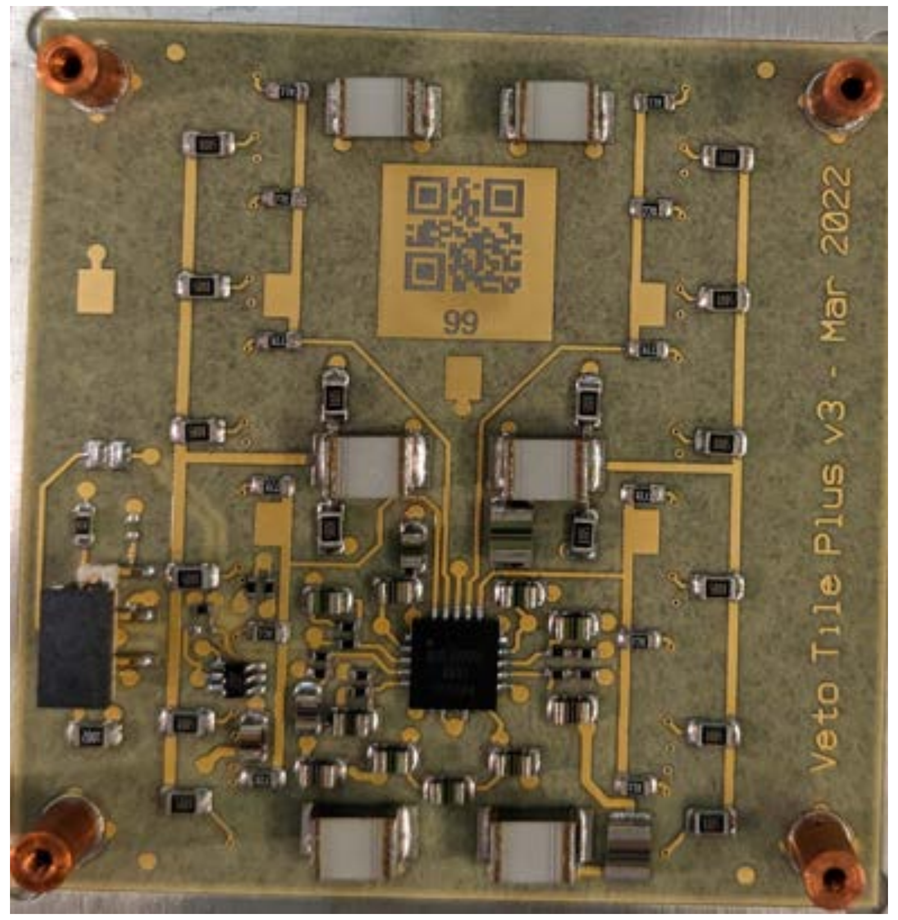
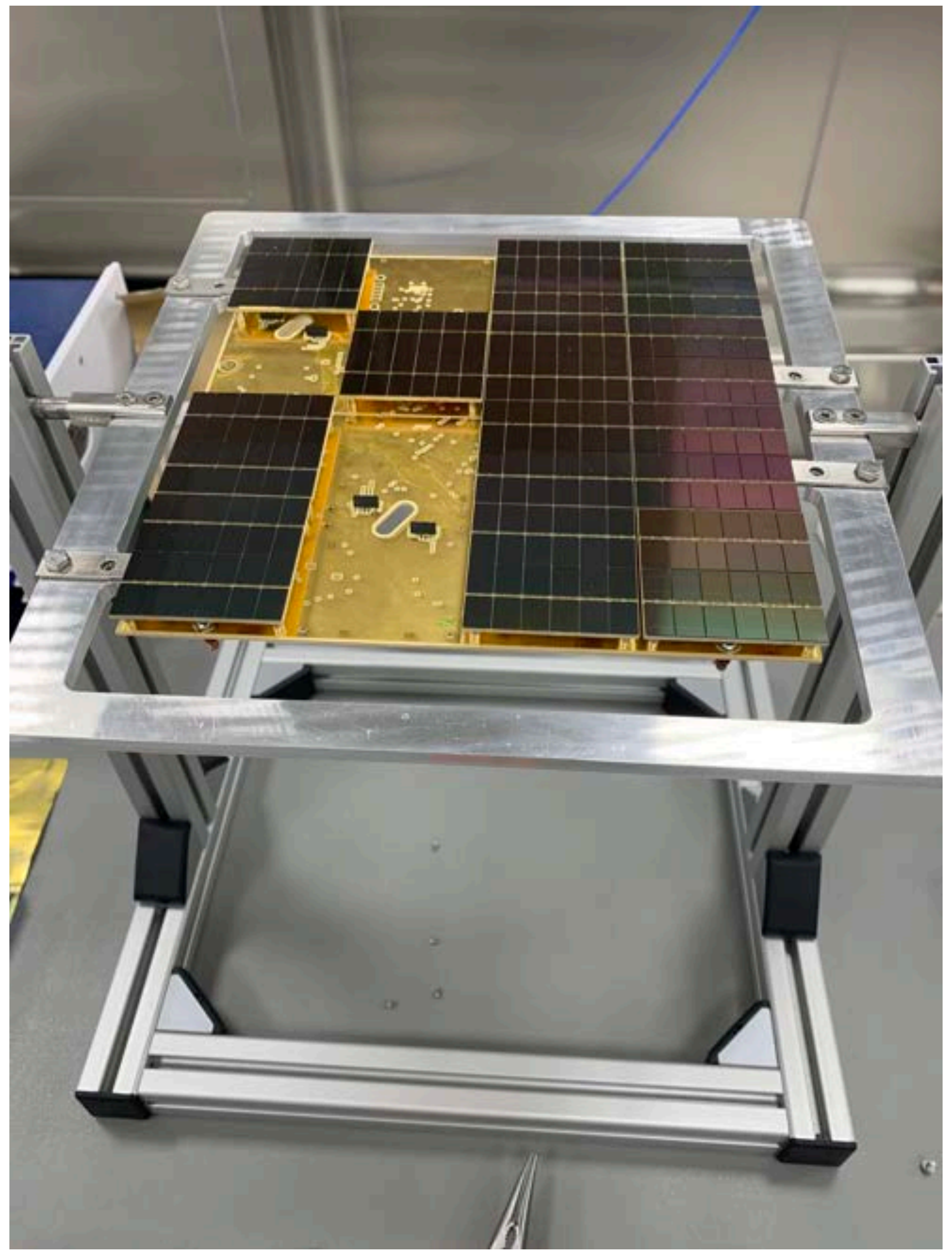
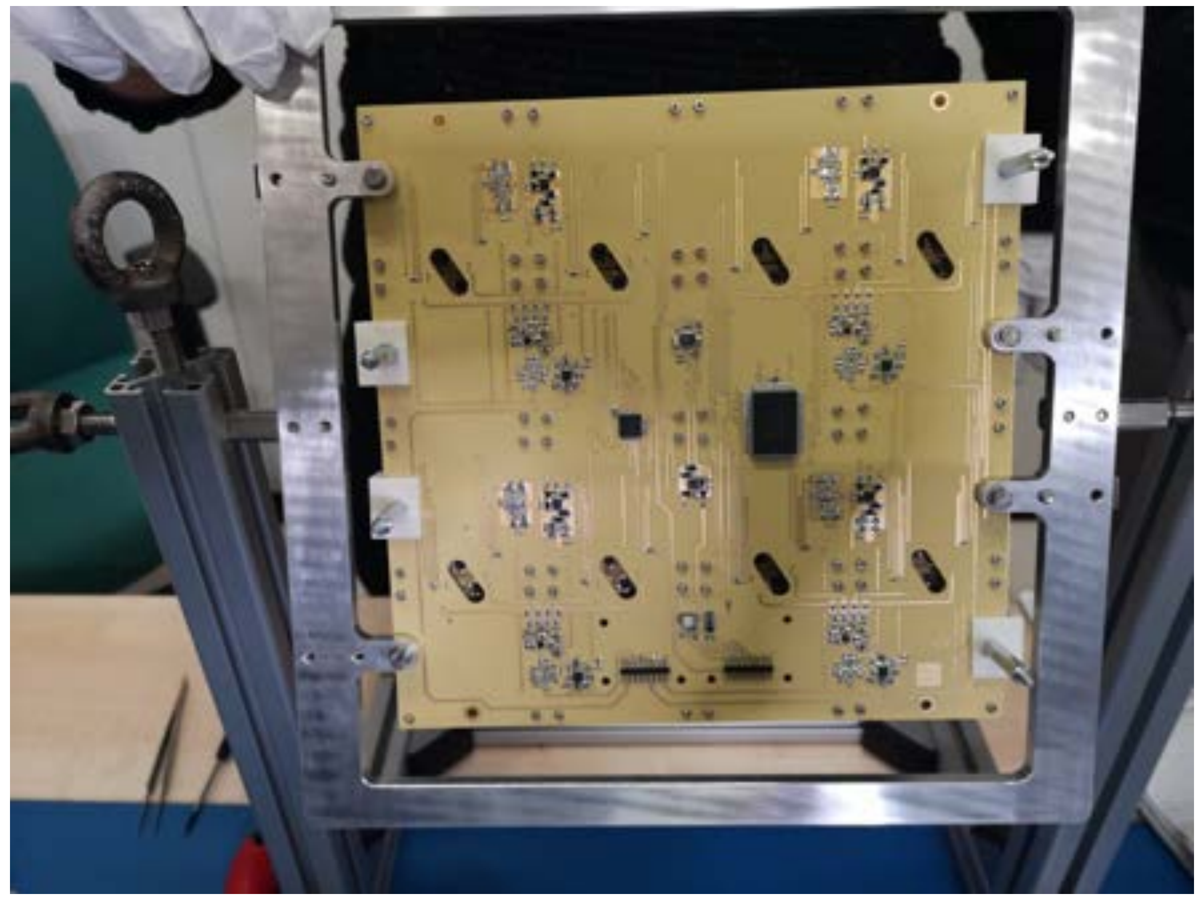
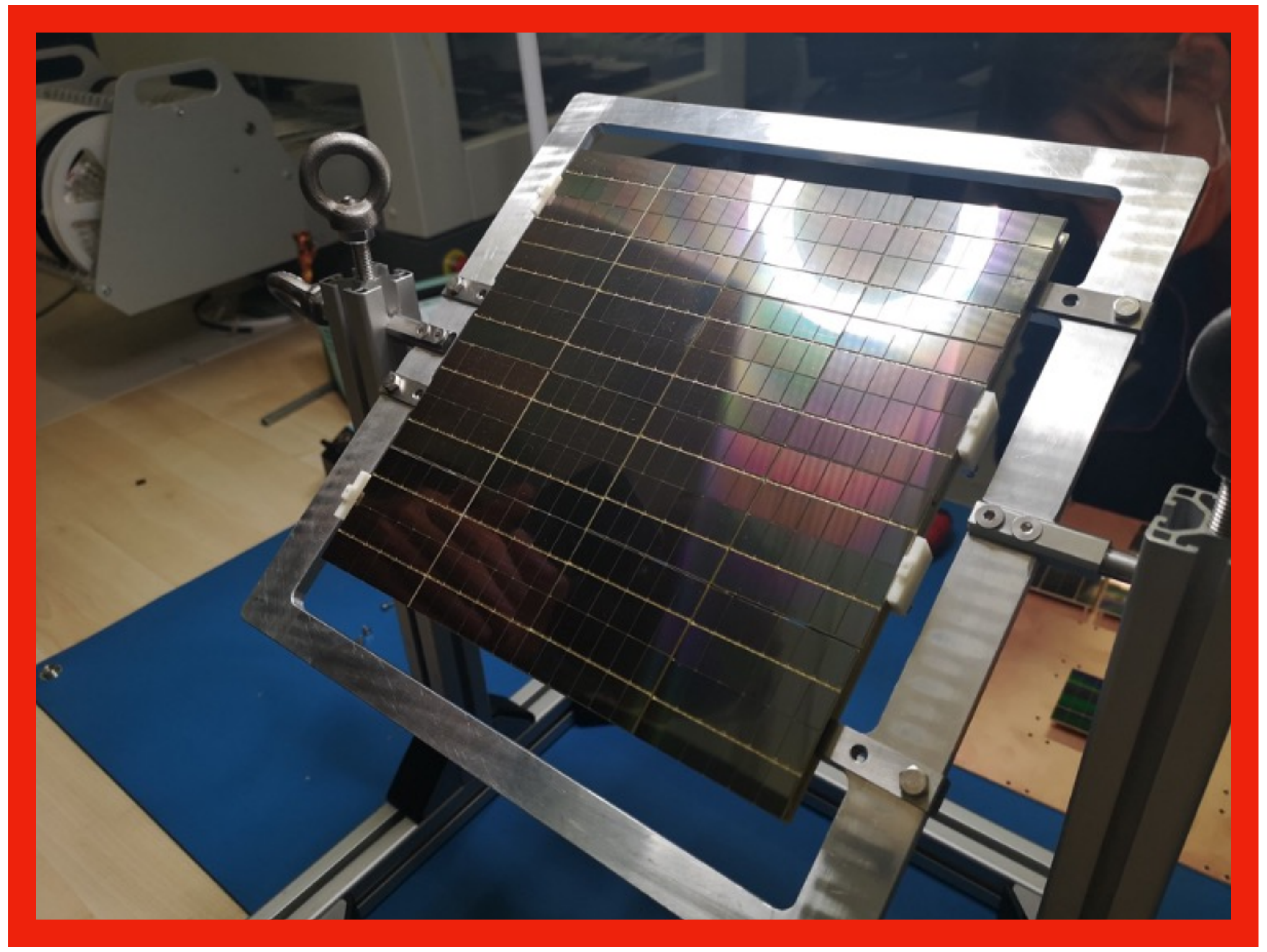


PHOTO DETECTION MODULE (PDU)



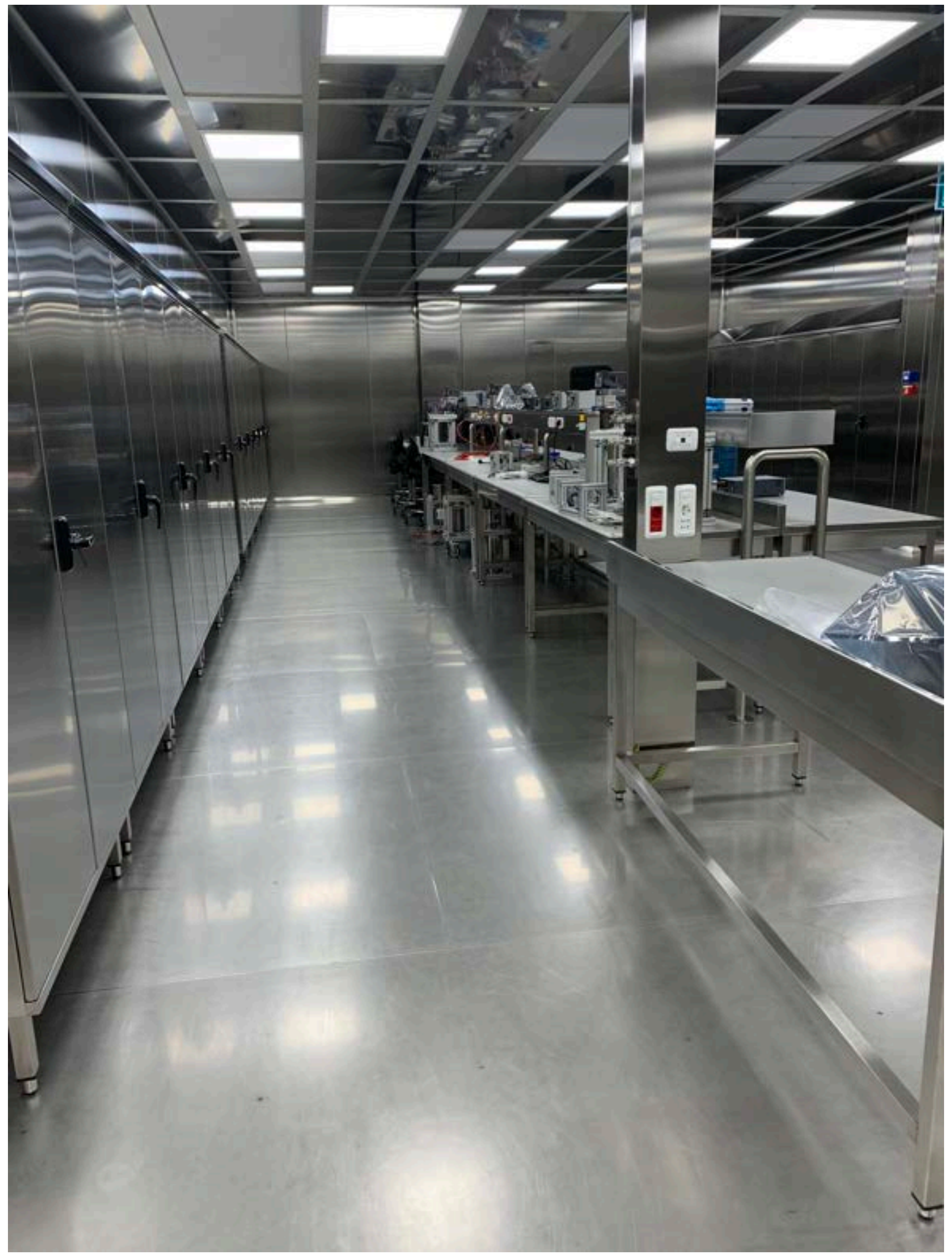


- 16 tile are assembled togheter in a **P**hoton **D**etection **U**nit (**PDU**)
- 1 large PCB for control signal, bias each tile and summed the signal of the tile
- 4 tile are summed together, i.e. 4 tile correspond to 1 DAQ channel
- 4 outputs



PDU FACILITIES

NOA at LNGS:
TPC PDU production and tileTesting

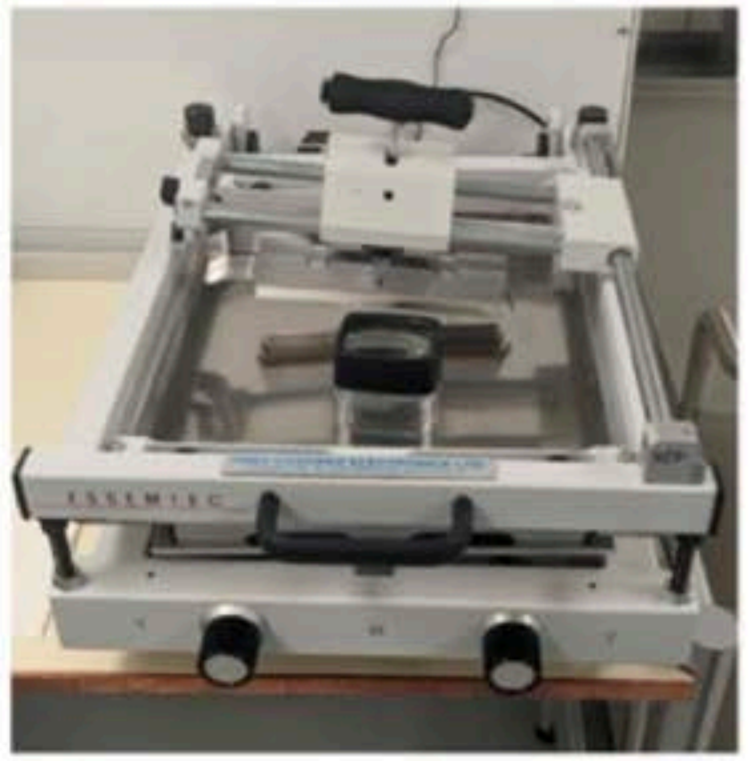


Naples: PDU testing facilities

UK FACILITIES: PCB production

PCB production @Birmigham

Application of Solder paste using stencil printer



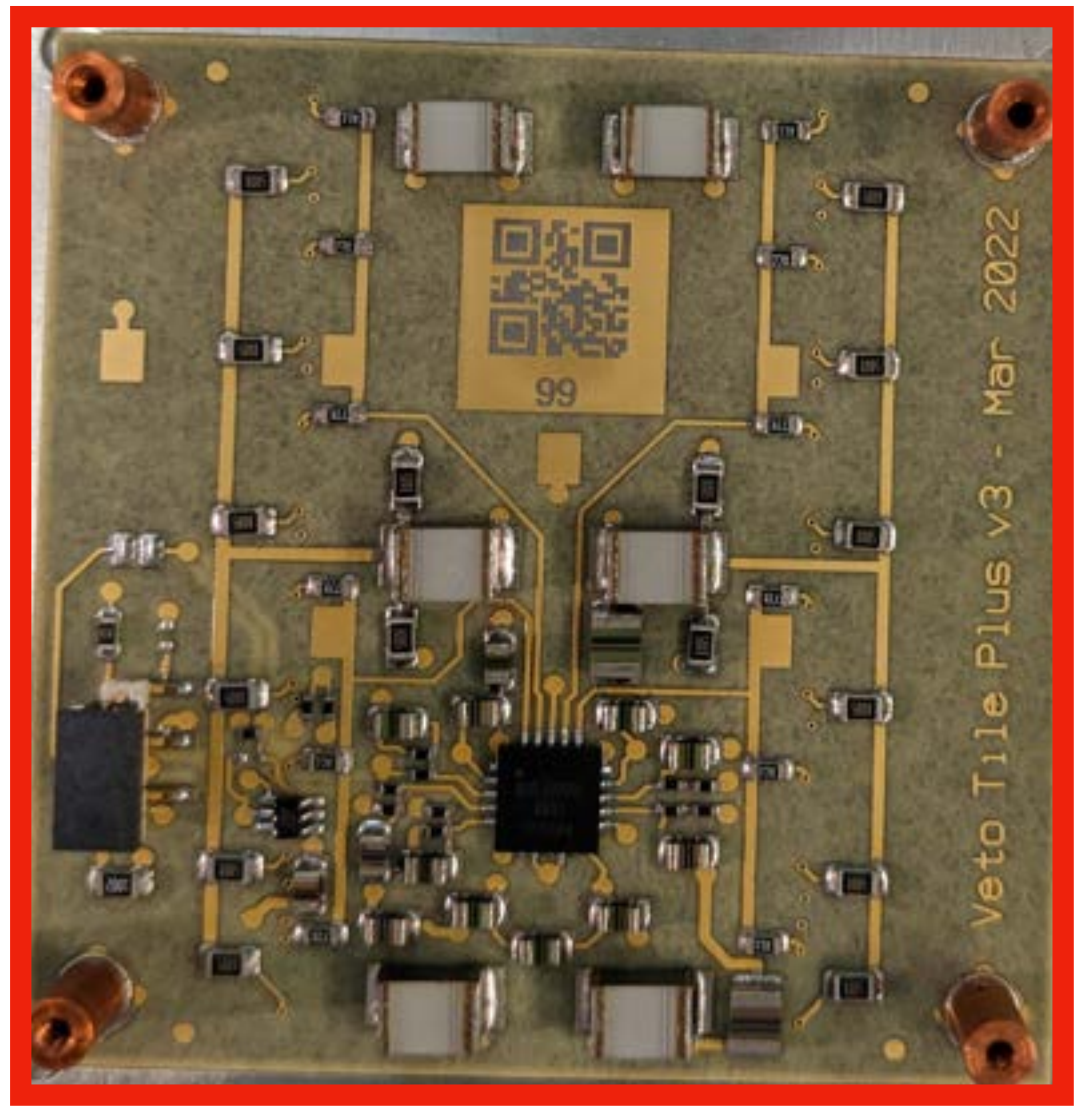
ESSEMTEC SP-002 Manual
Stencil printer
Solder paste: CHIPQUIK

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

MECHATRONICA M60 pick and place

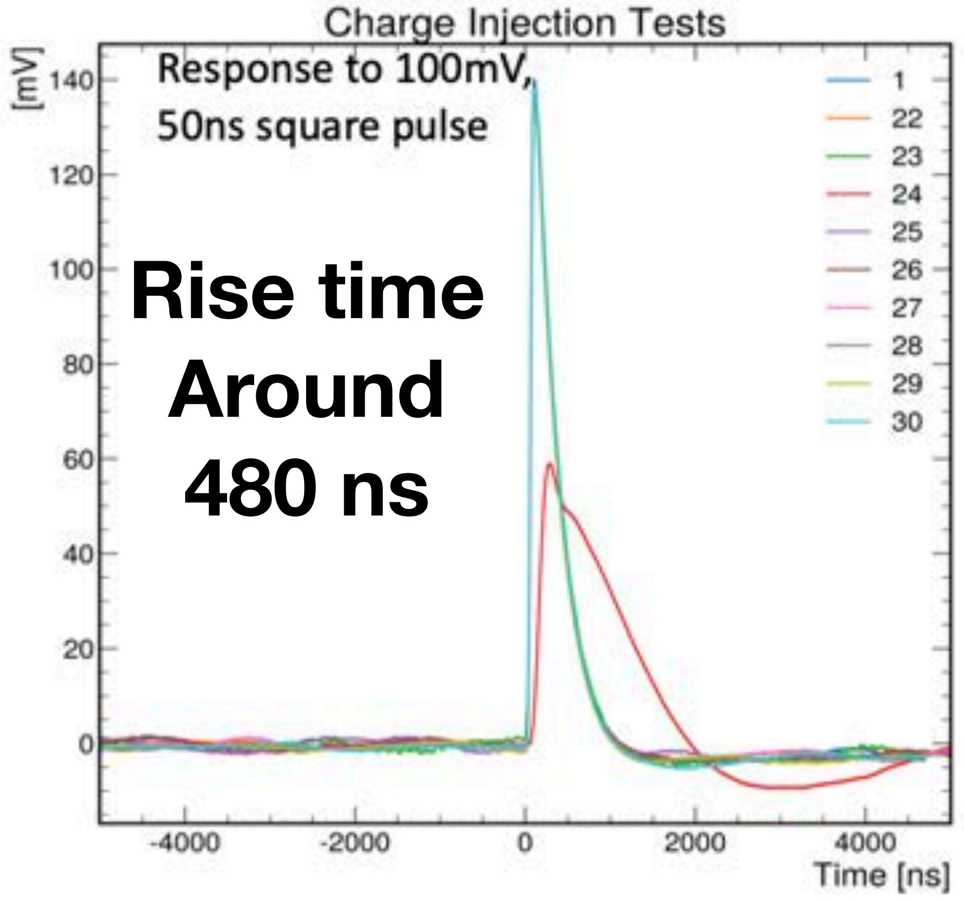
New Reflow oven:
3 temperature probes
5 minutes at 150°C
1 minute at 200 °C

C.I.F FT05 advanced forced convection oven

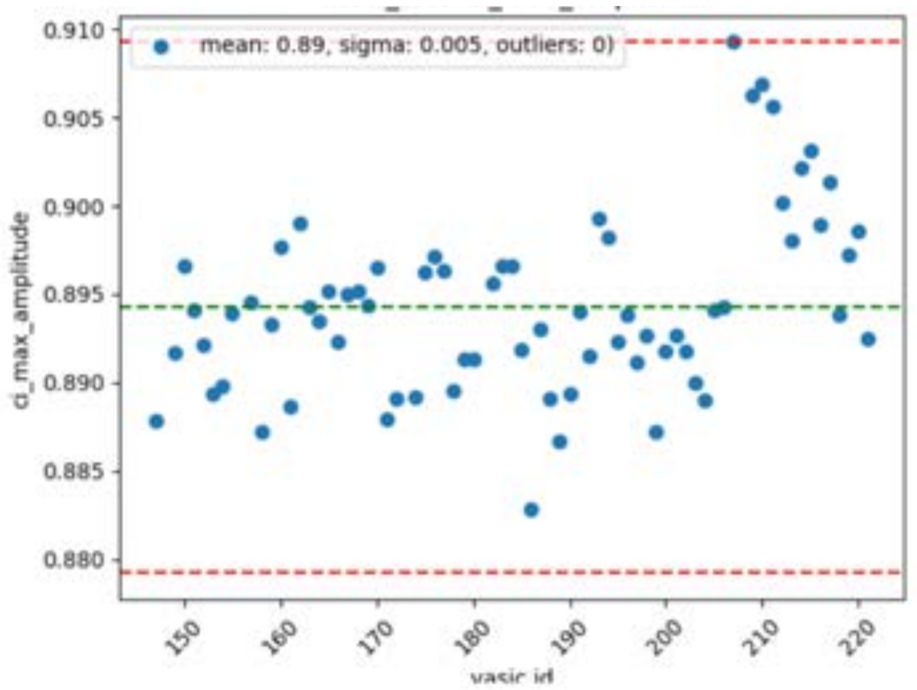


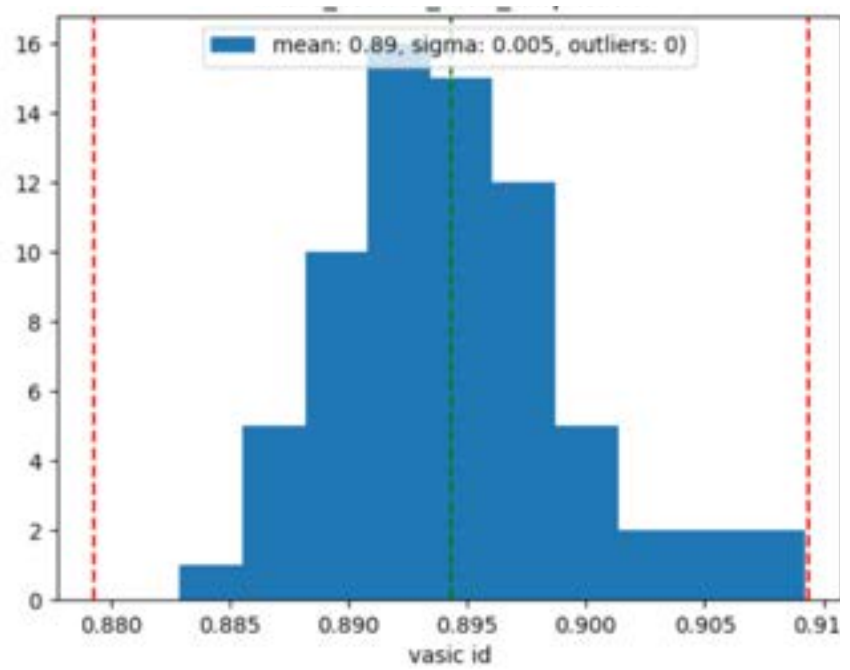
ISO-7 Clean room
Radon controlled system
(<5 Bq/mm^2)

Accumulating Statistics to define QA/QC acceptance criteria



Amplitude distribution



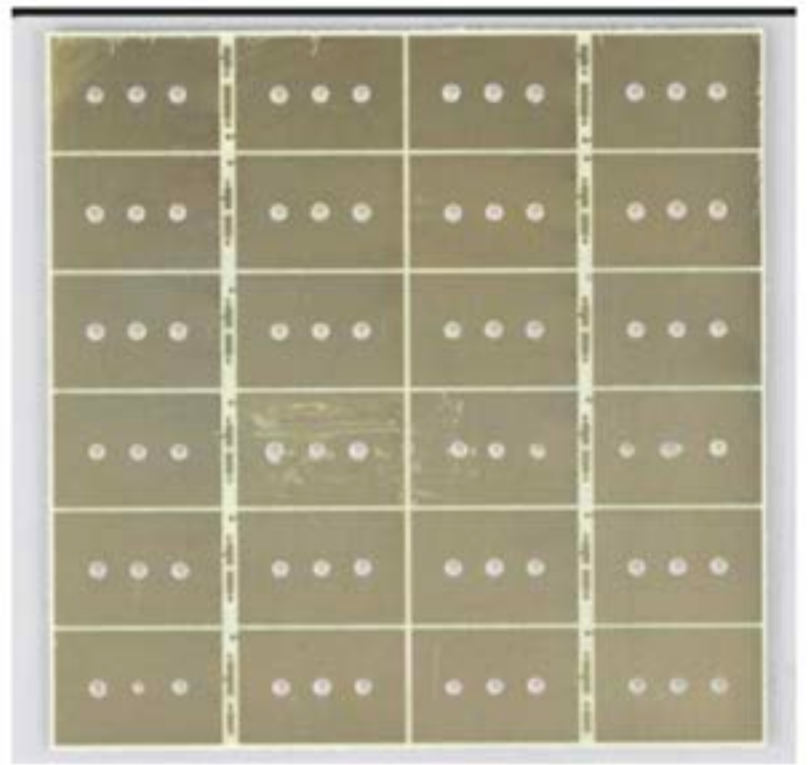


Amplitude around 880 mV

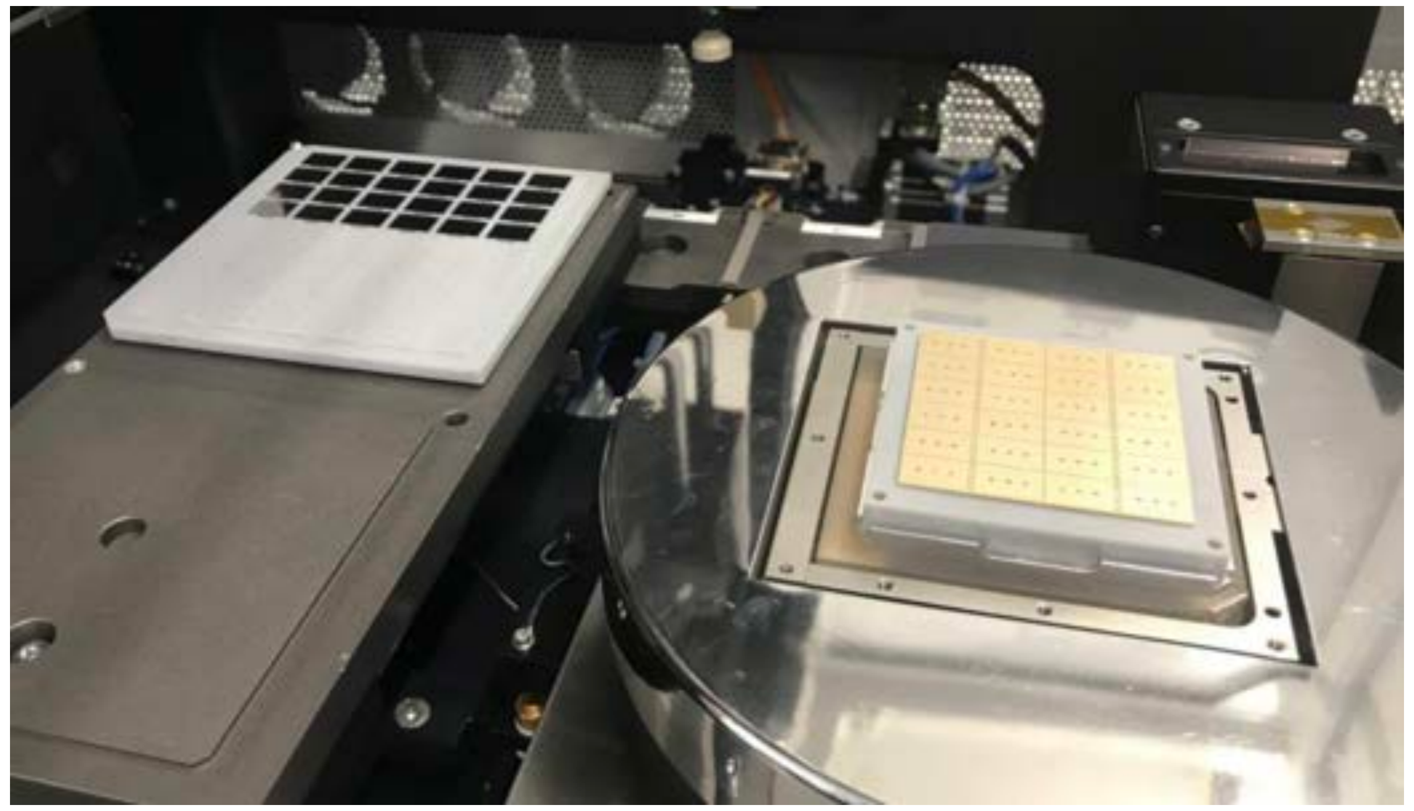
UK FACILITIES: Tile assembly @STFC interconnect

ISO7 Clean room

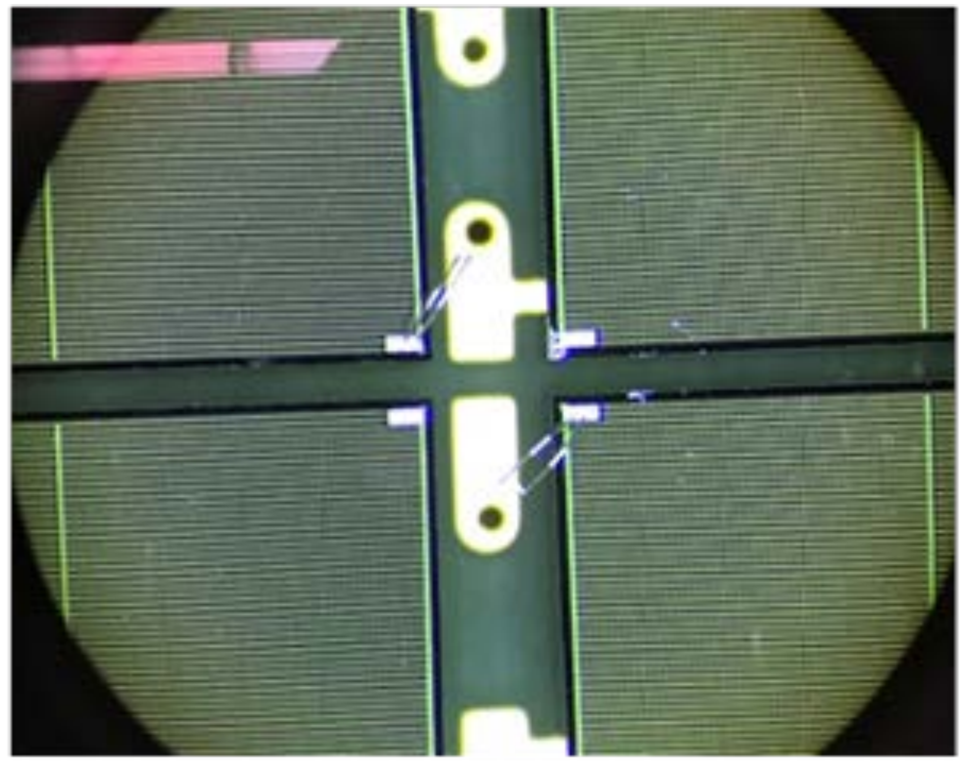
Glue dispense



Die attach



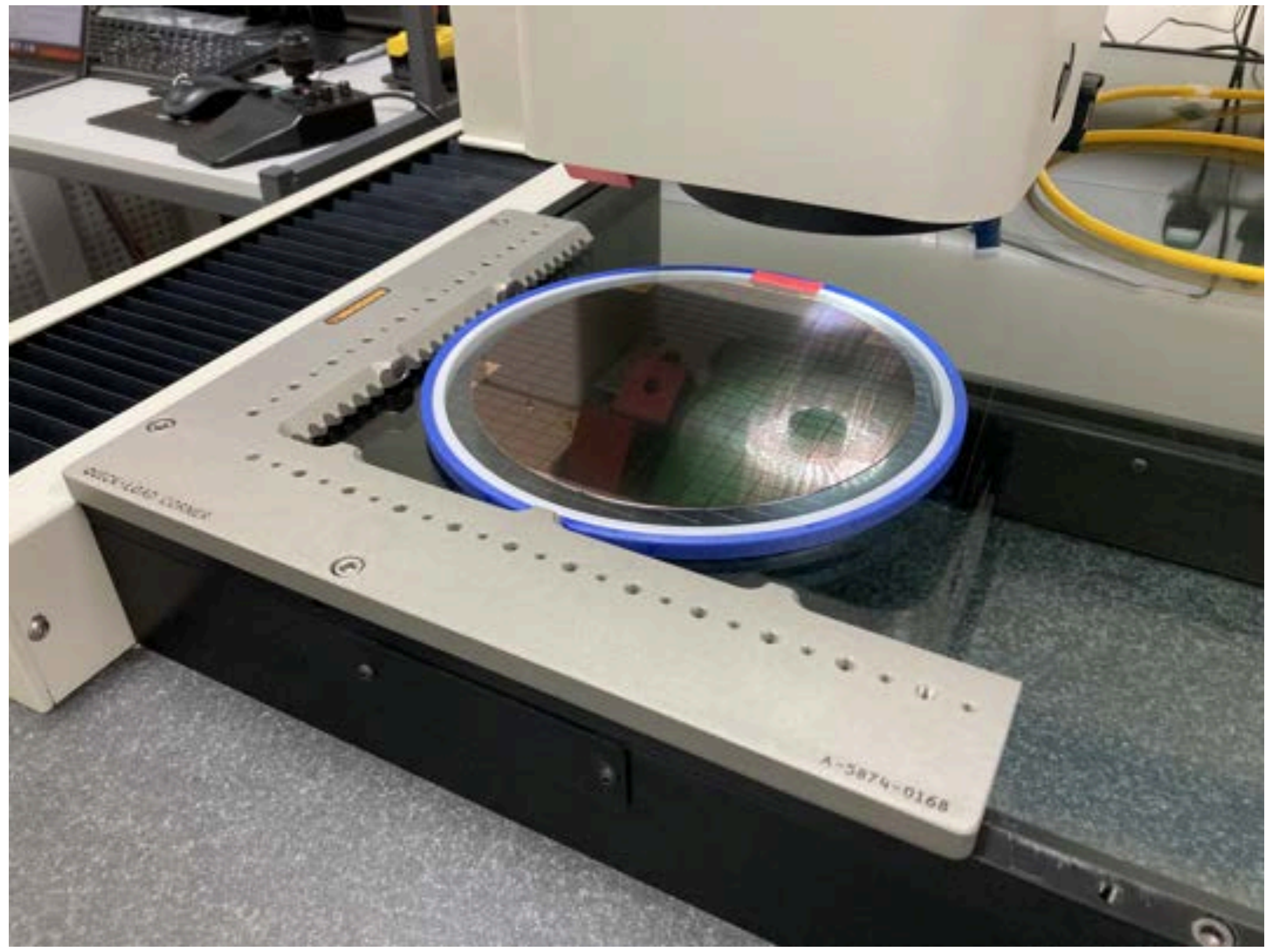
Wire Bonding



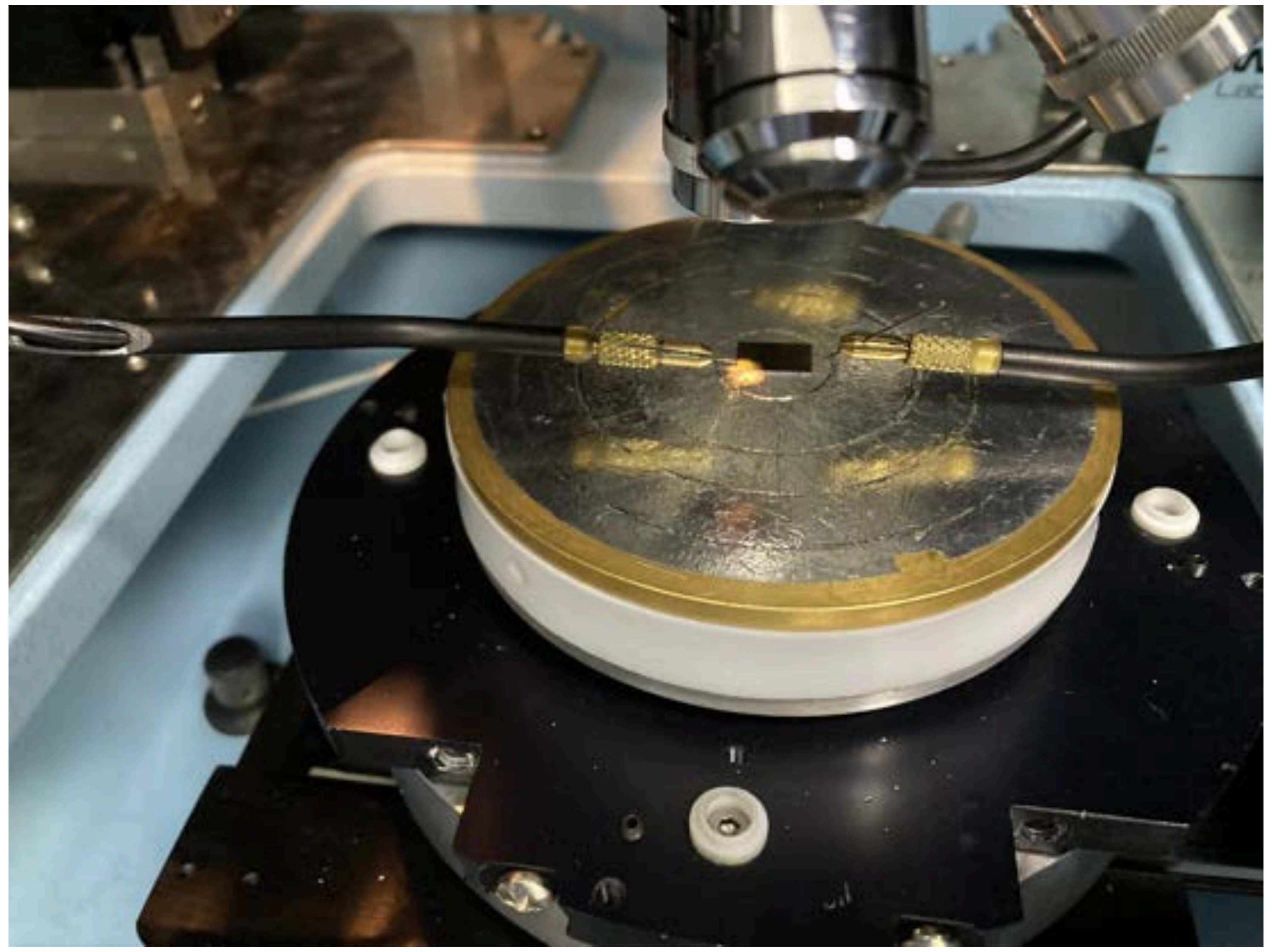
UK FACILITIES: Tile assembly @Liverpool

ISO7
Clean room

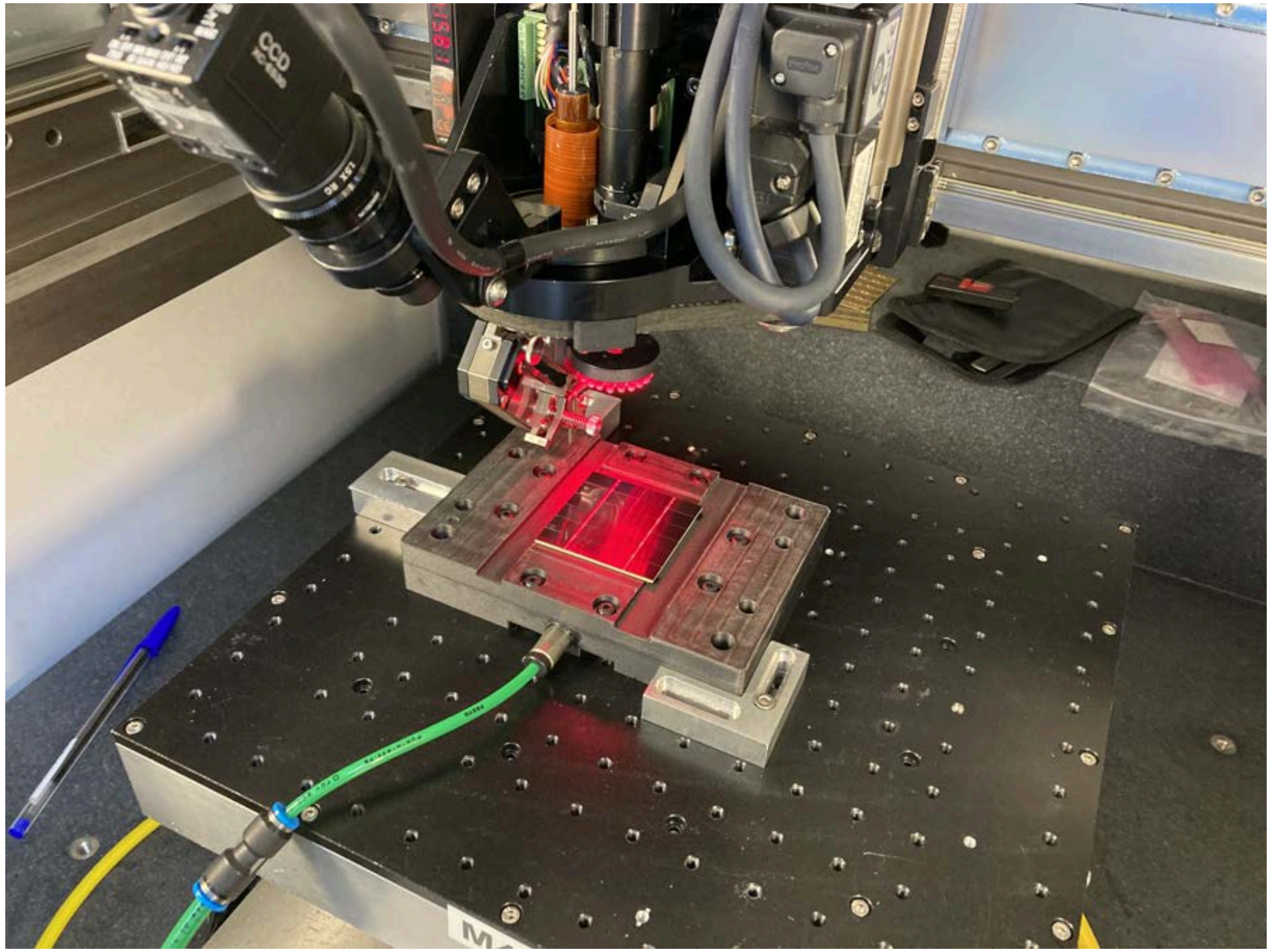
SiPMs Wafers inspection



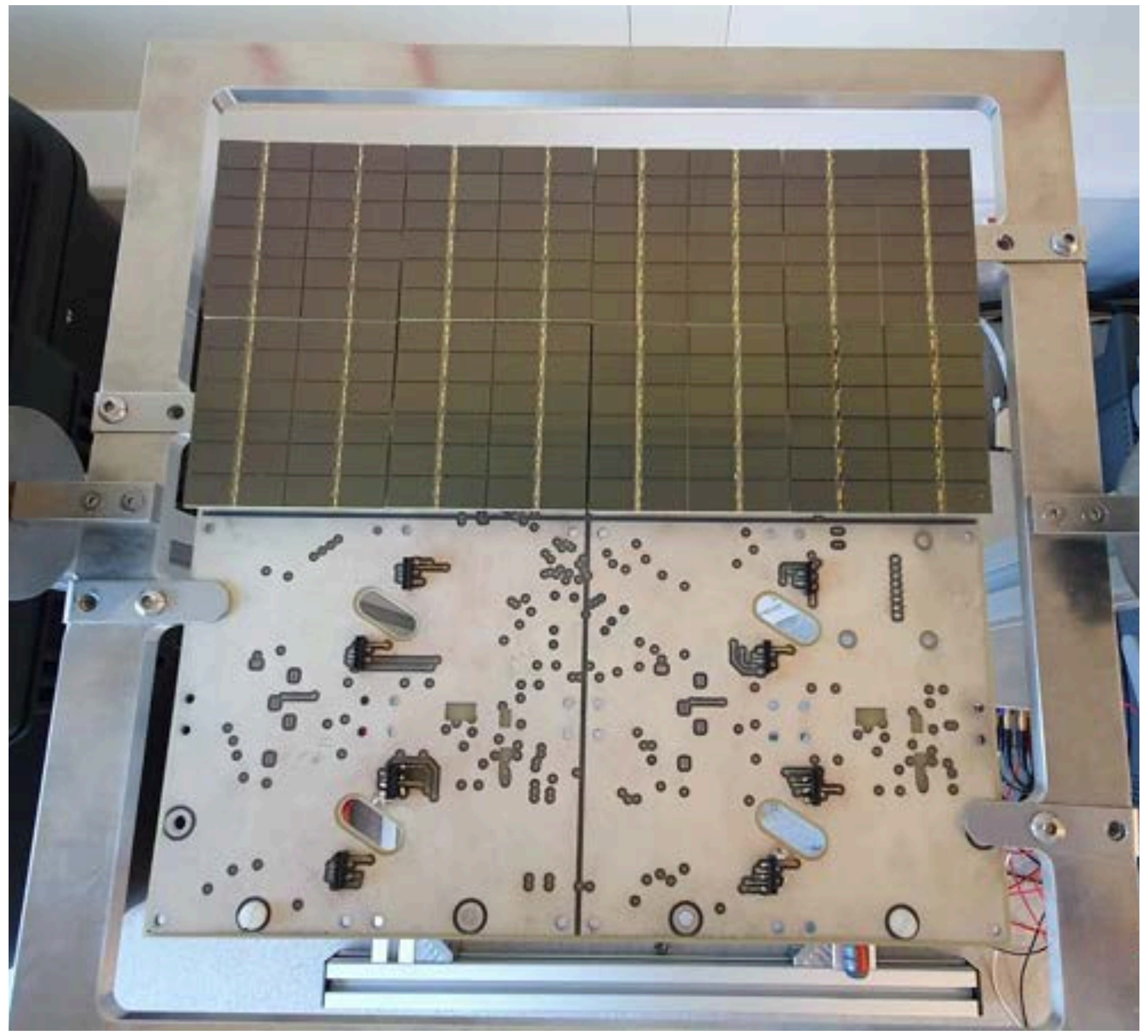
SiPMs testing before put on the tile

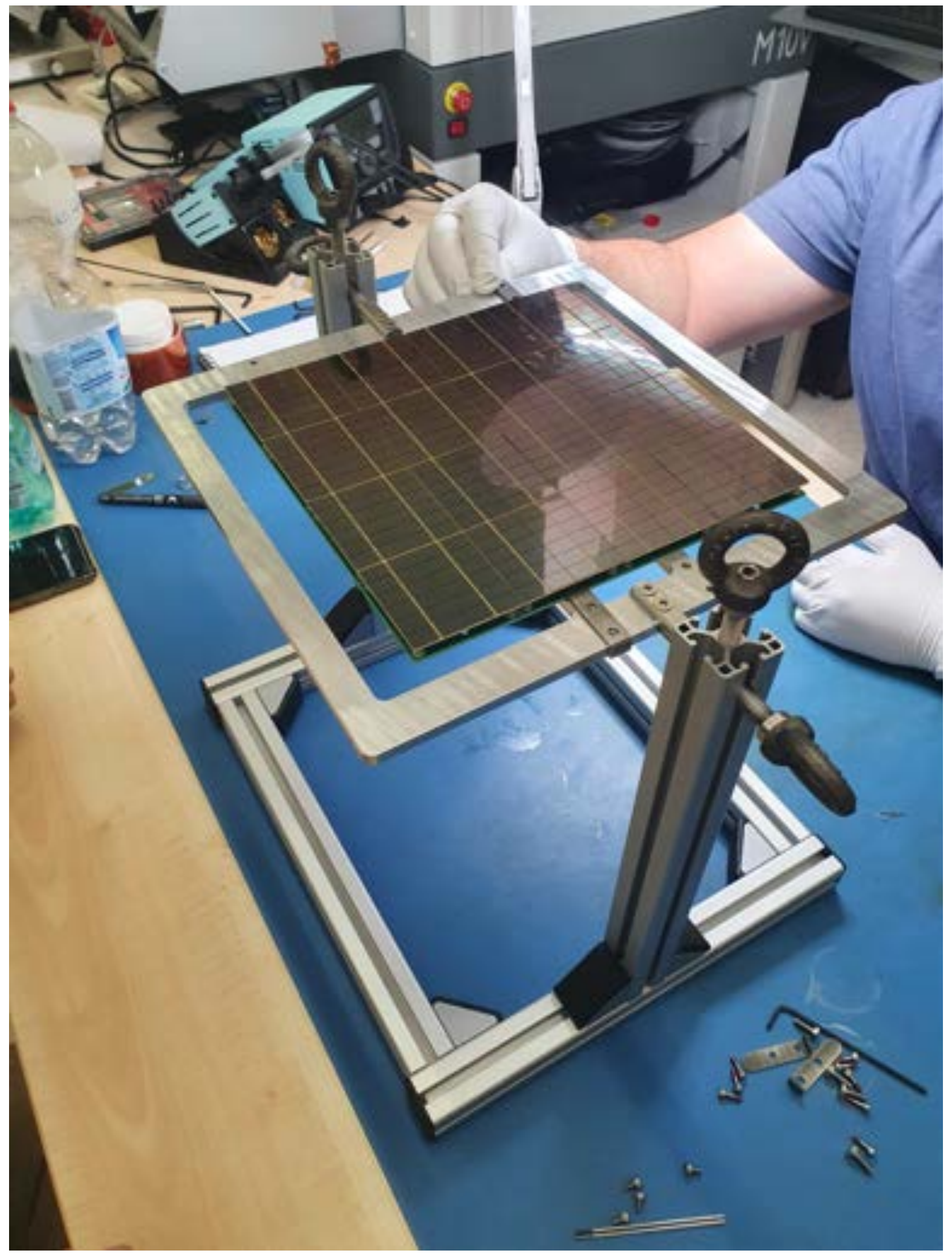


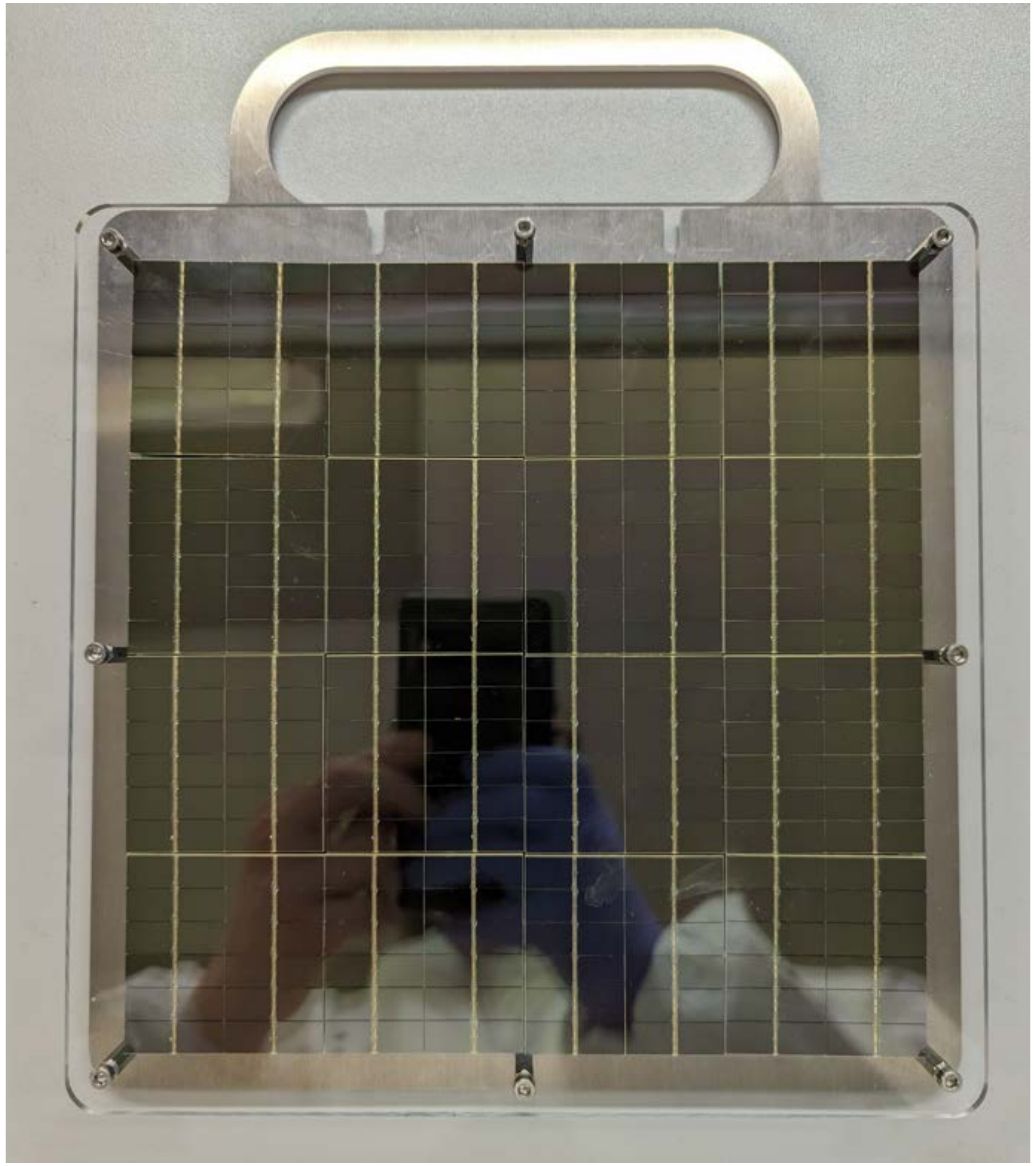
Wire Bonding a vTile

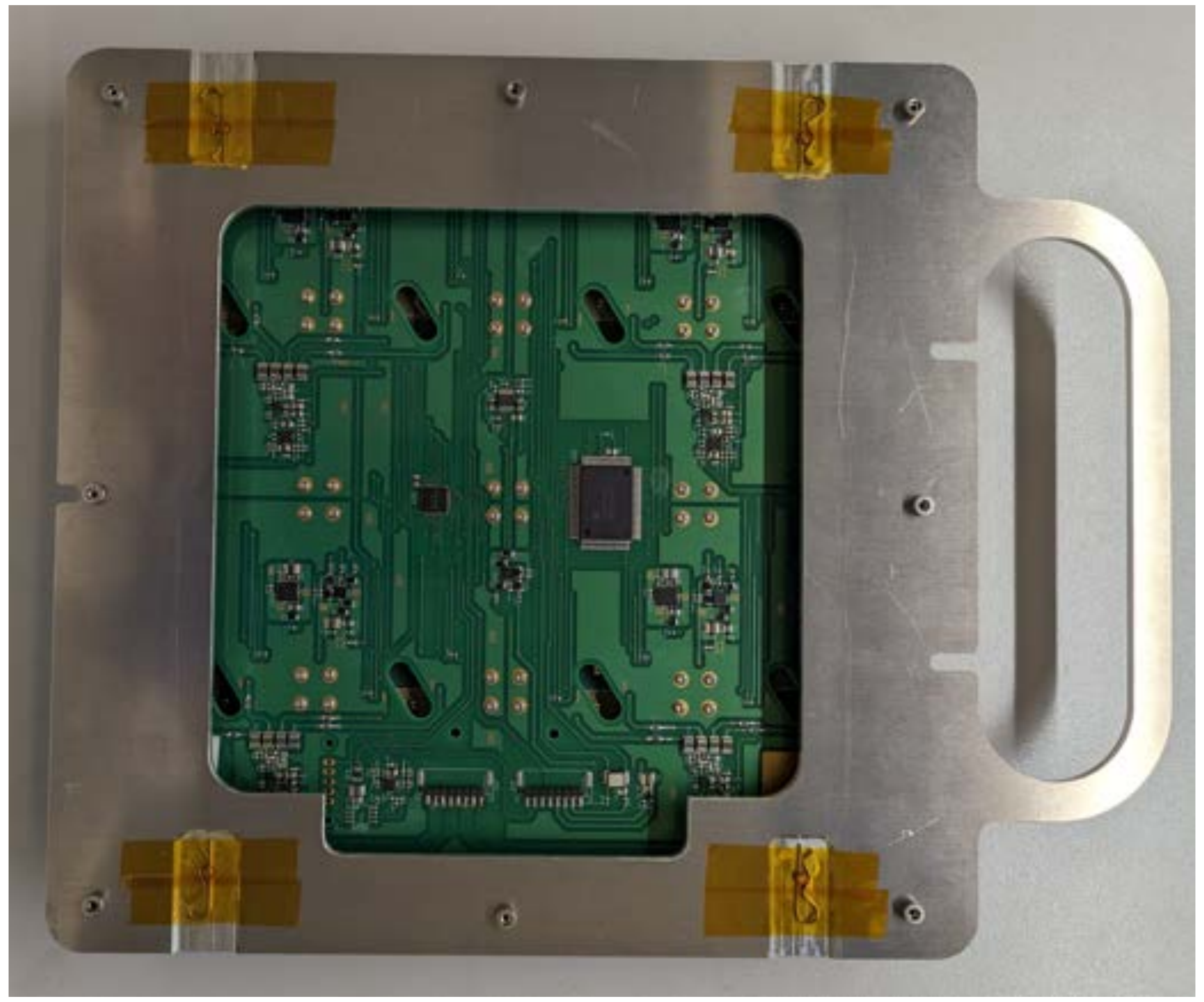


UK FACILITIES: PDU assembly @Manchester





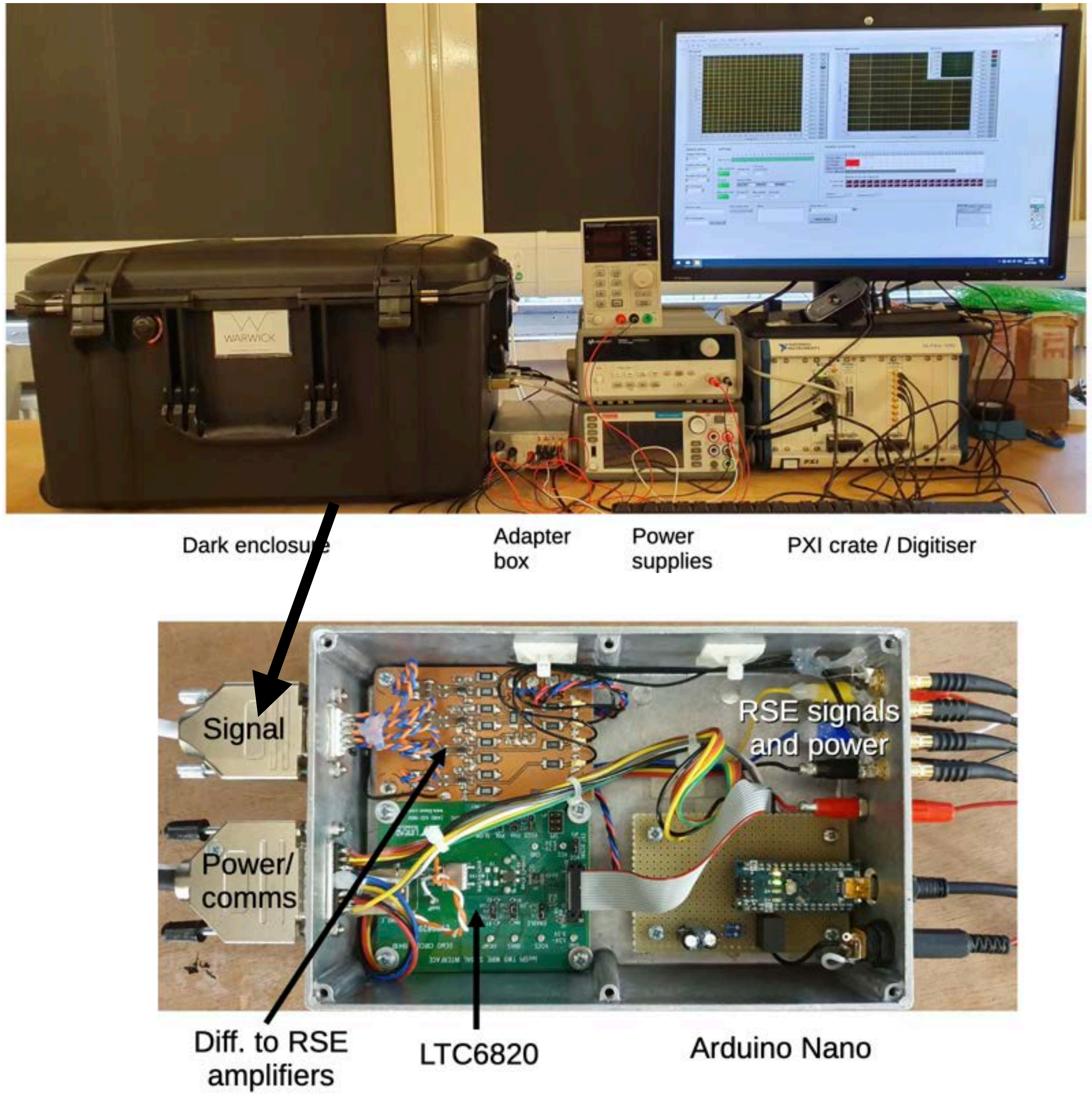


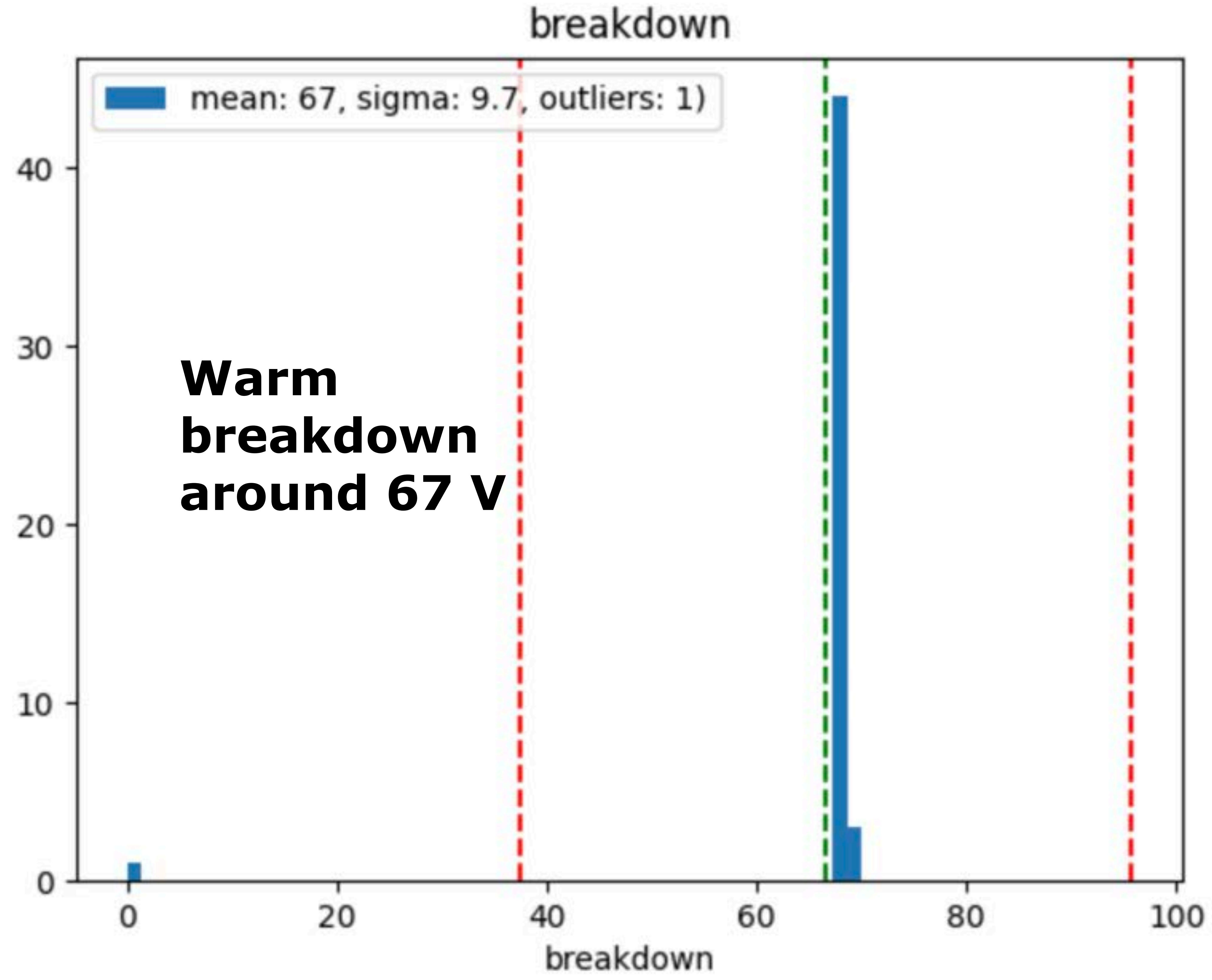


first three vPDUs
assembled,
4th vPDU ongoing

vPDU TEST FACILITIES

WARM testing setup @Manchester/@Warmick



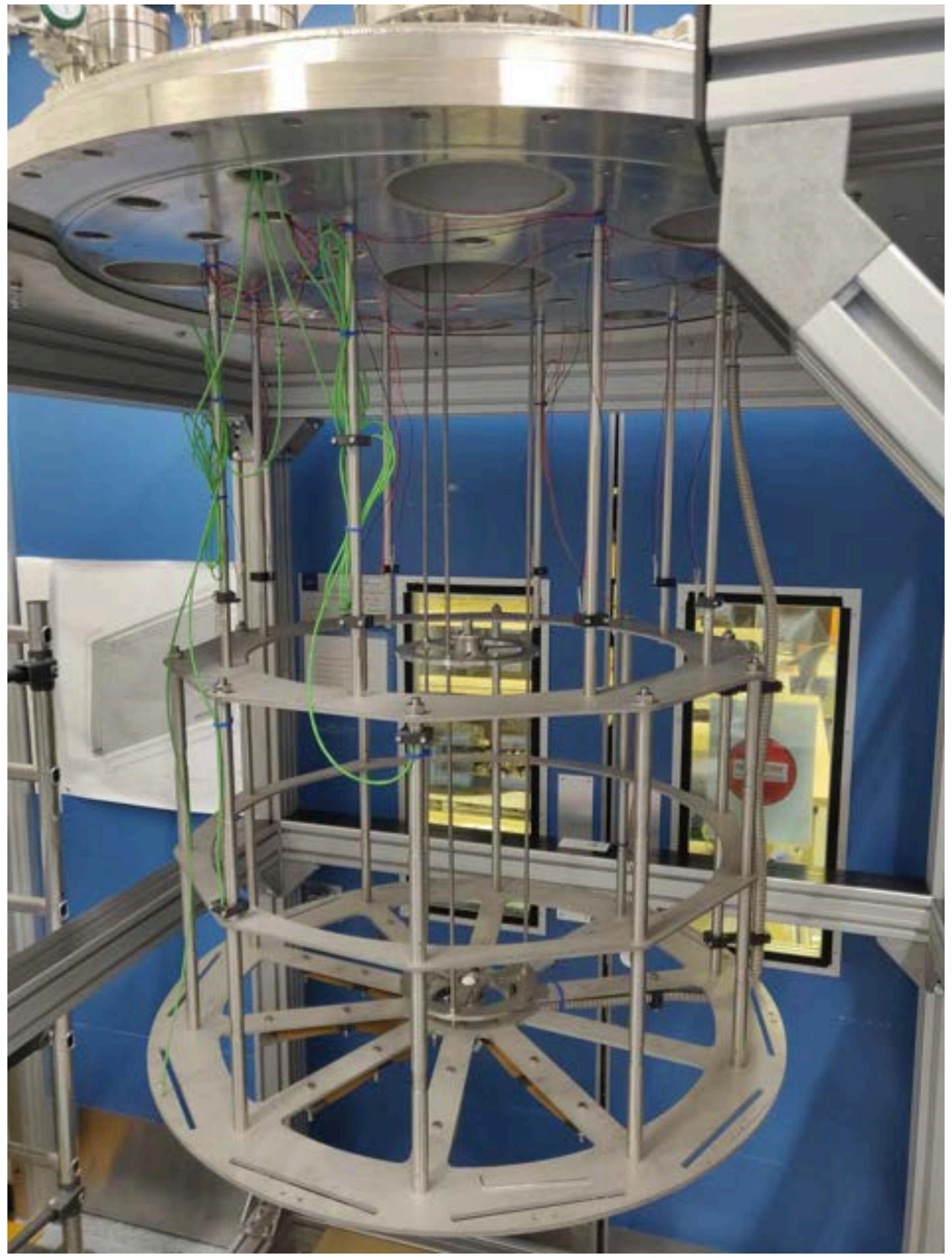


Warm breakdown around 67 V

vPDU TEST FACILITIES (2)

Cold testing setup @Liverpool

PHAIDRA



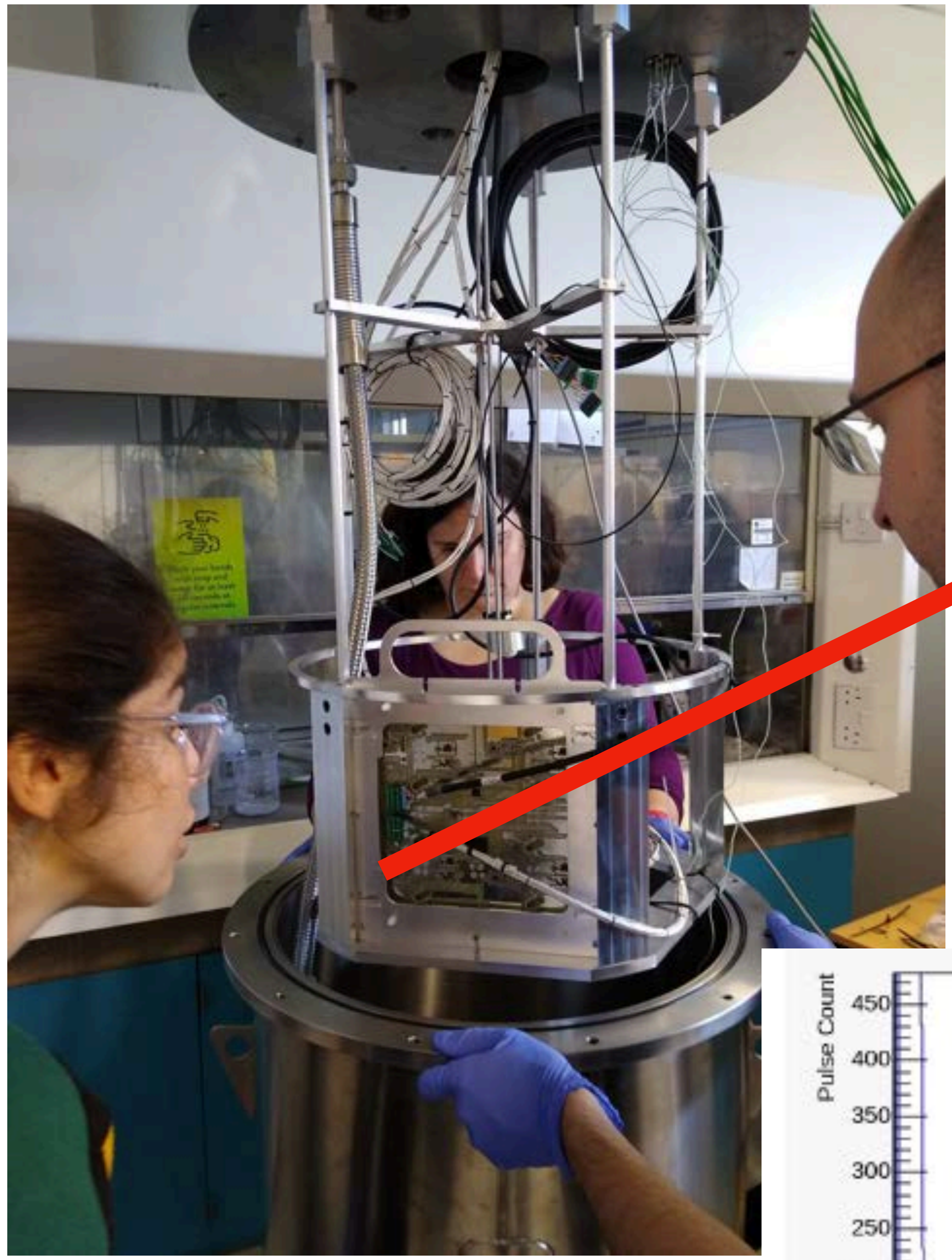
- Main cold test facility
- Test capability: 10 vPDU/day
- Ready for vPDU testing

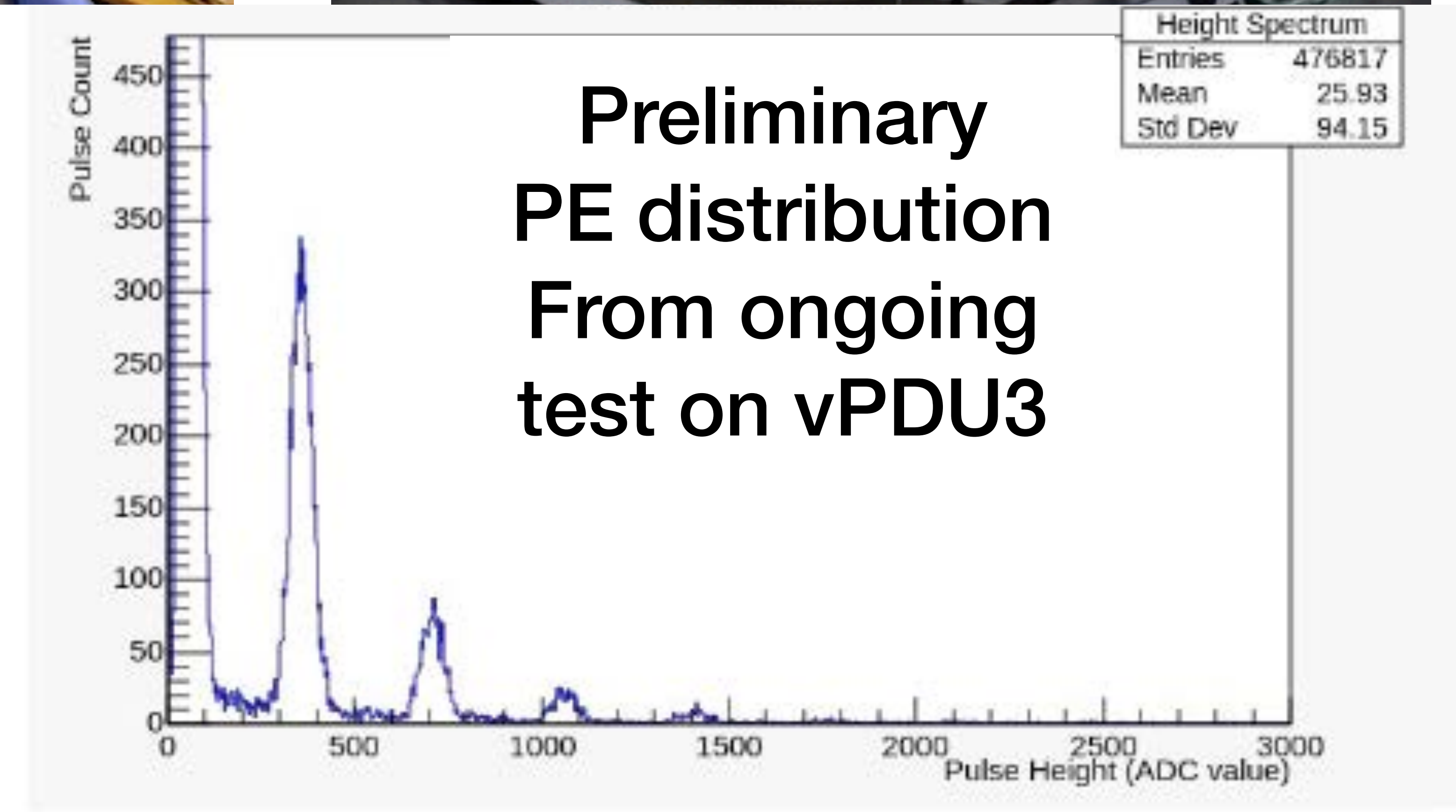
vPDU TEST FACILITIES (3)

smaller cold test setups @Edinburgh

Test capability: 4 vPDU/time

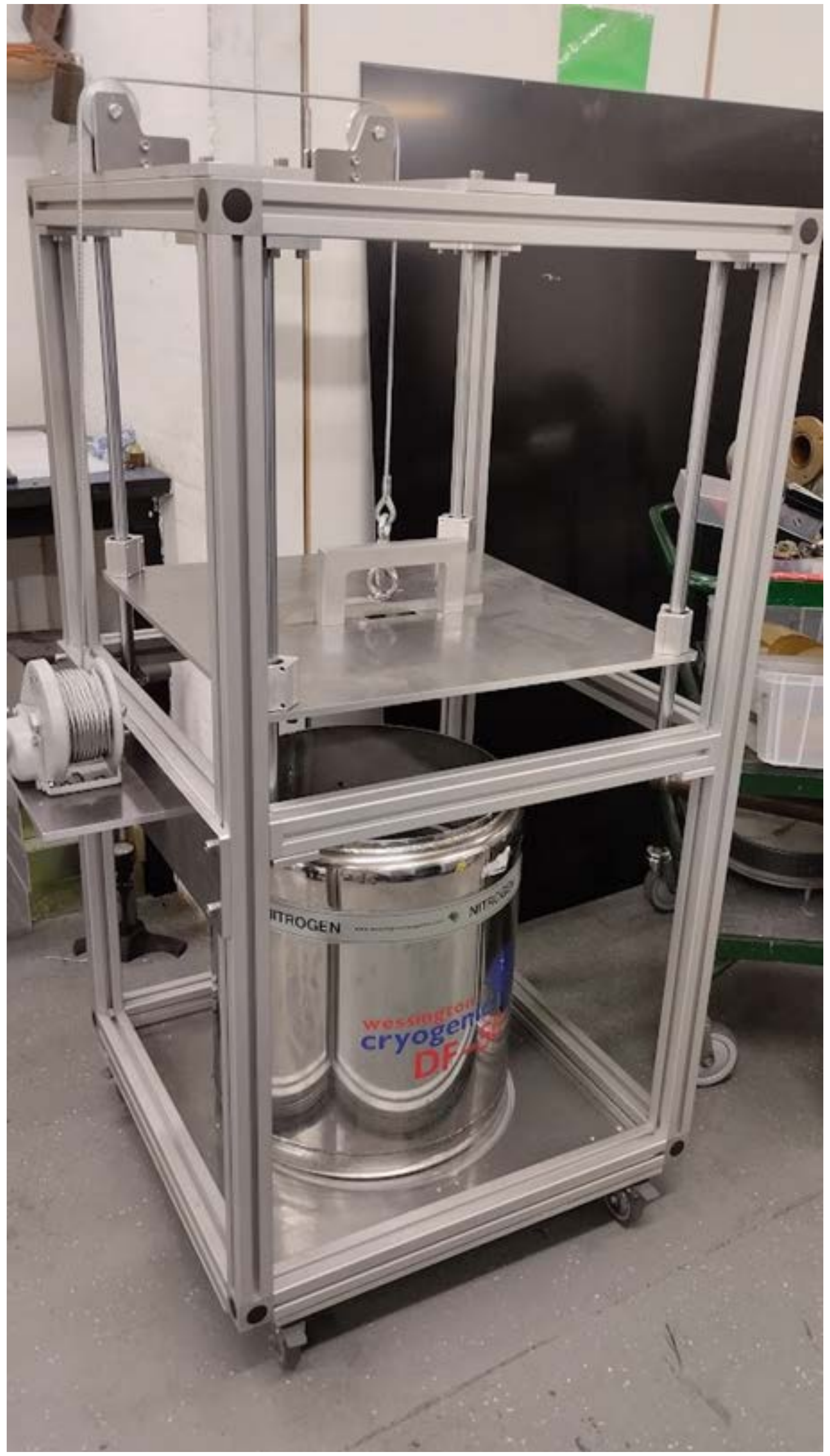
Host 4 tile/time





vPDU TEST FACILITIES (4)

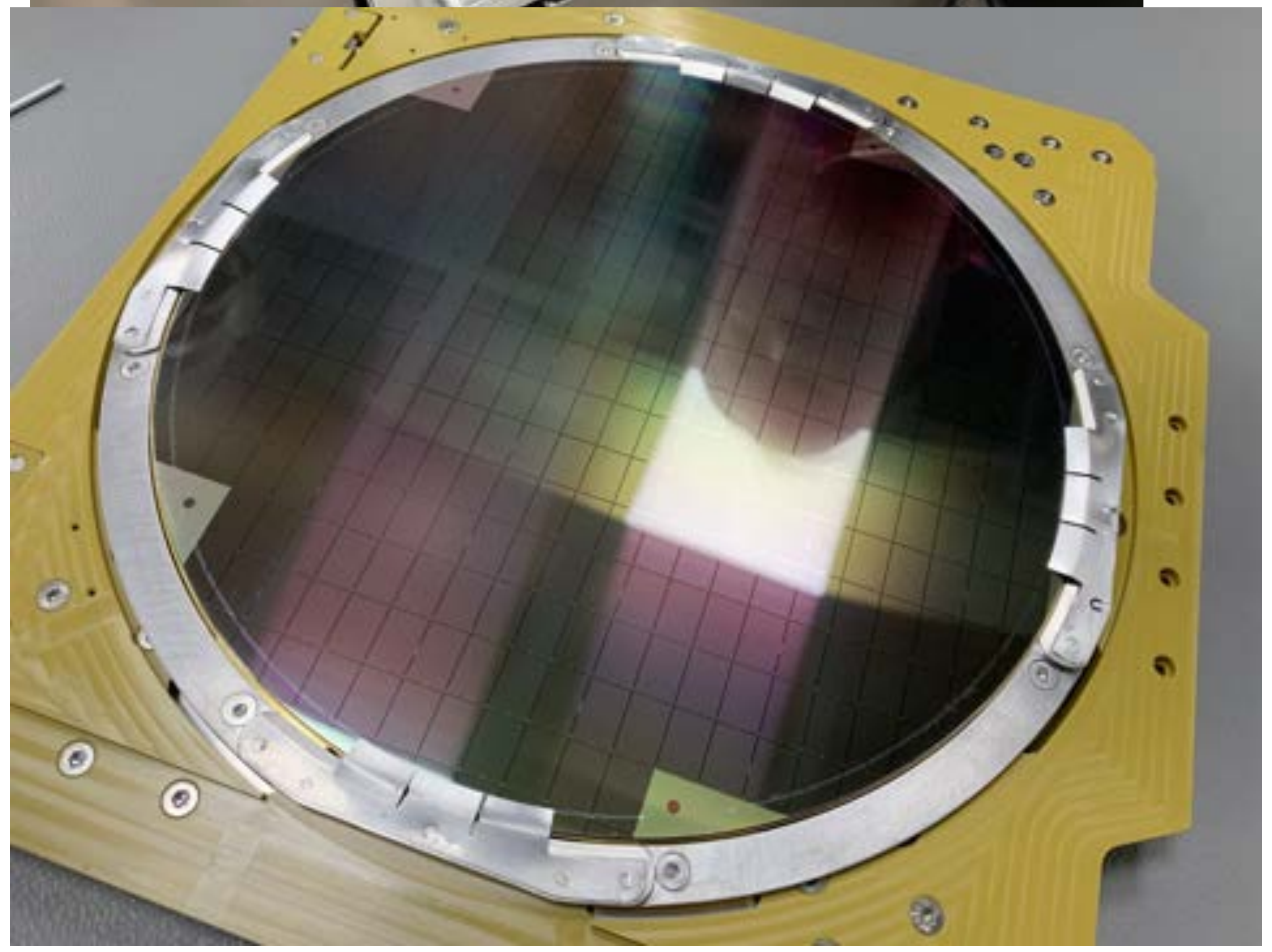
@Lancaster

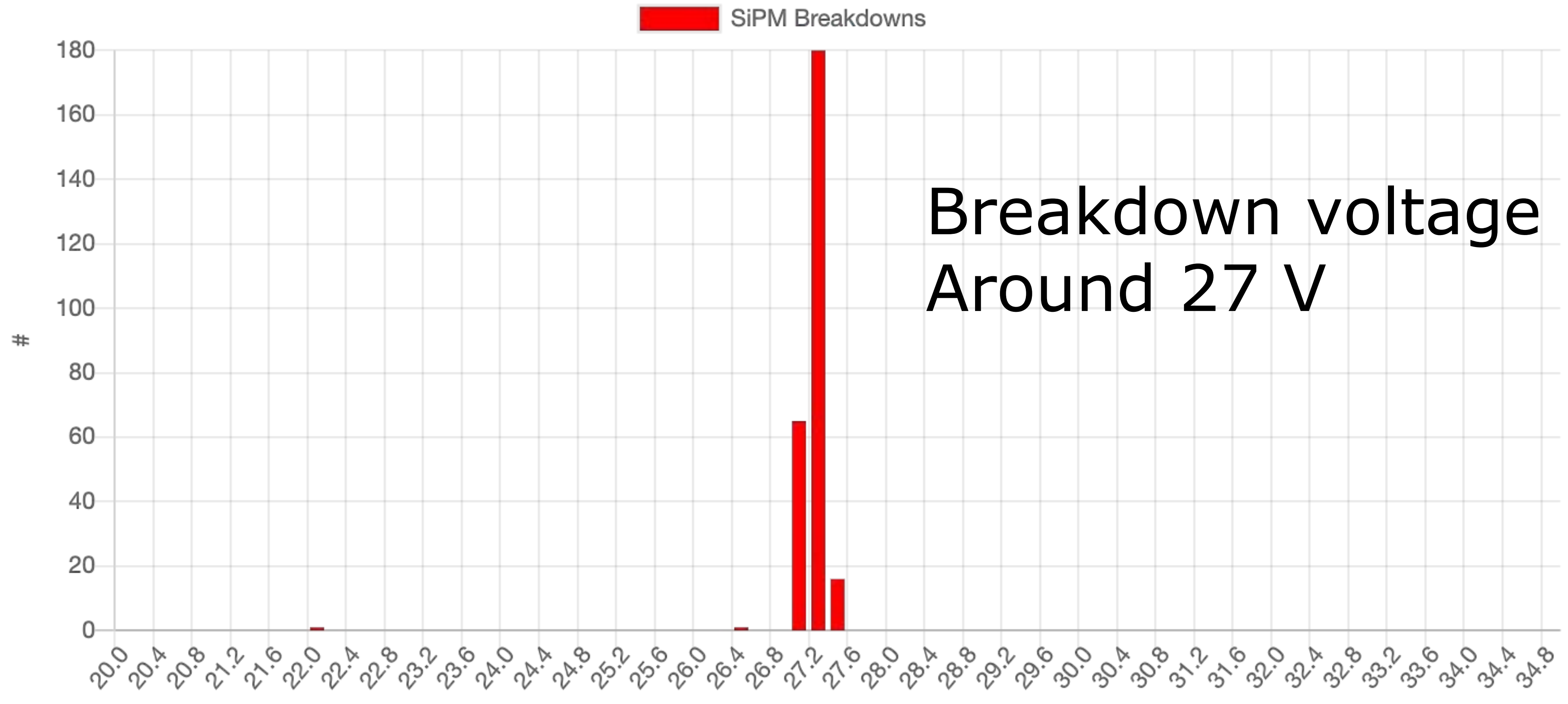


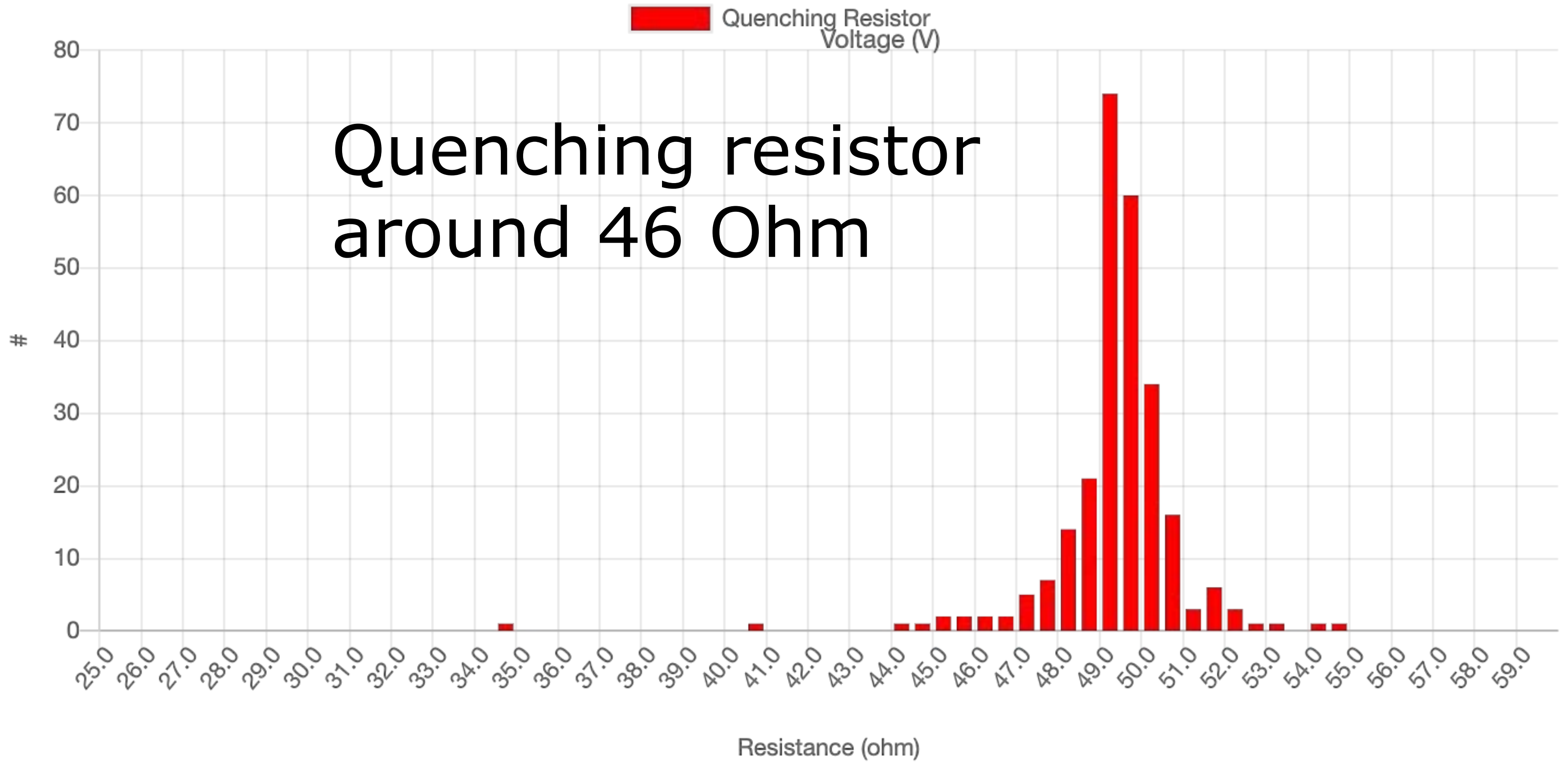
@ASTROCENT

Test capability: 4 vPDU/time

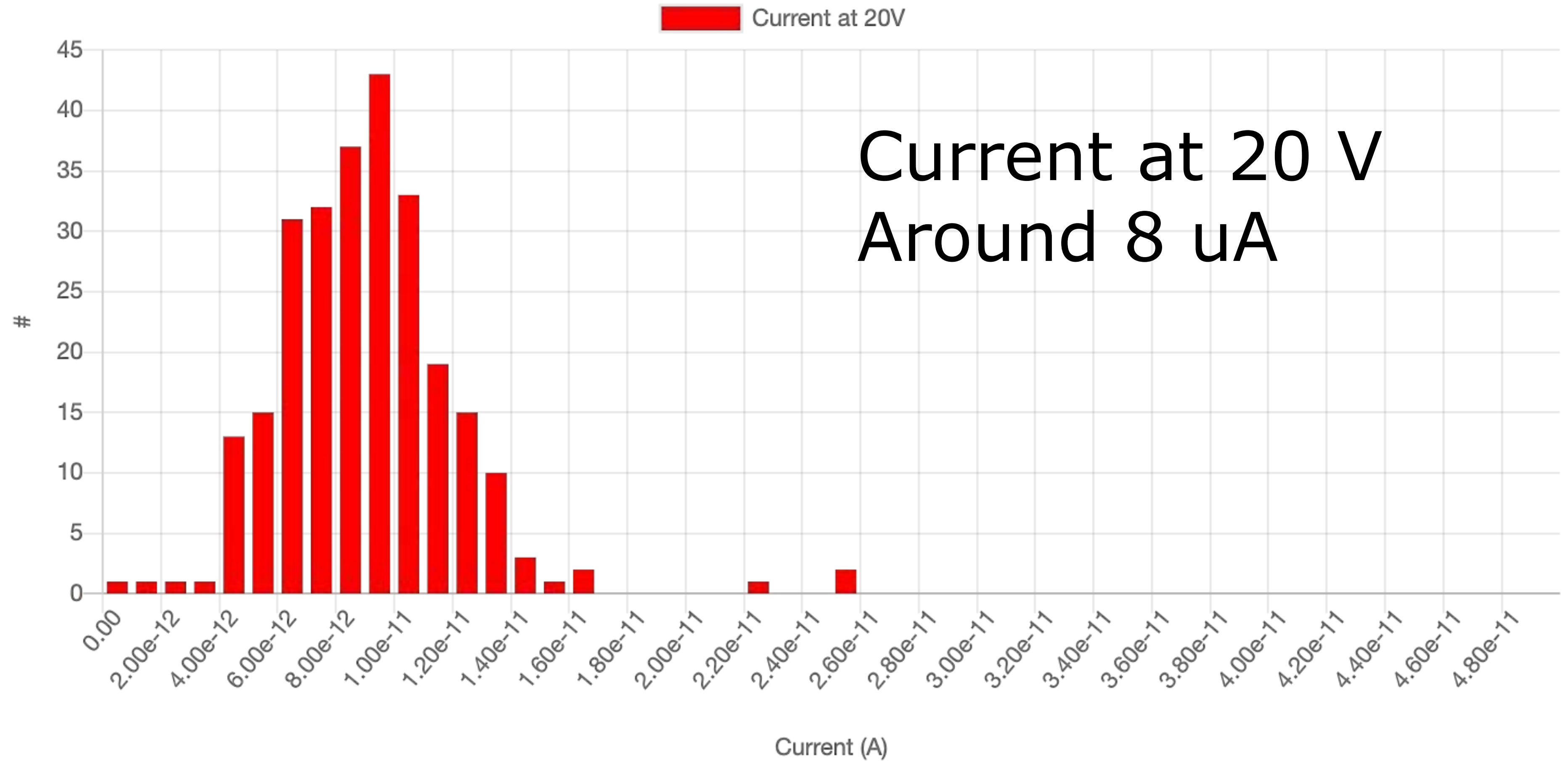
SiPM wafer characterization





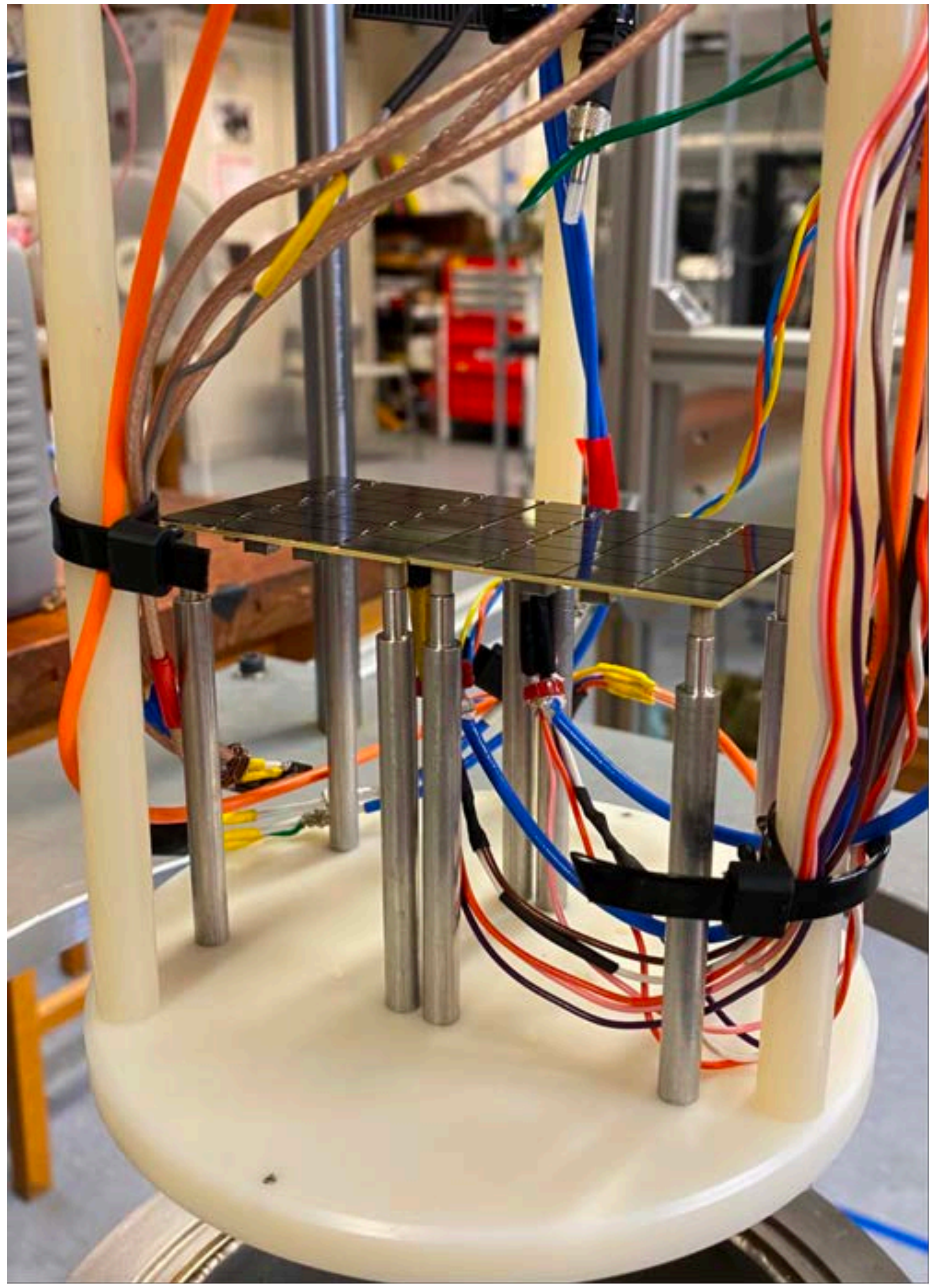


major contributions from Lancs, RHUL

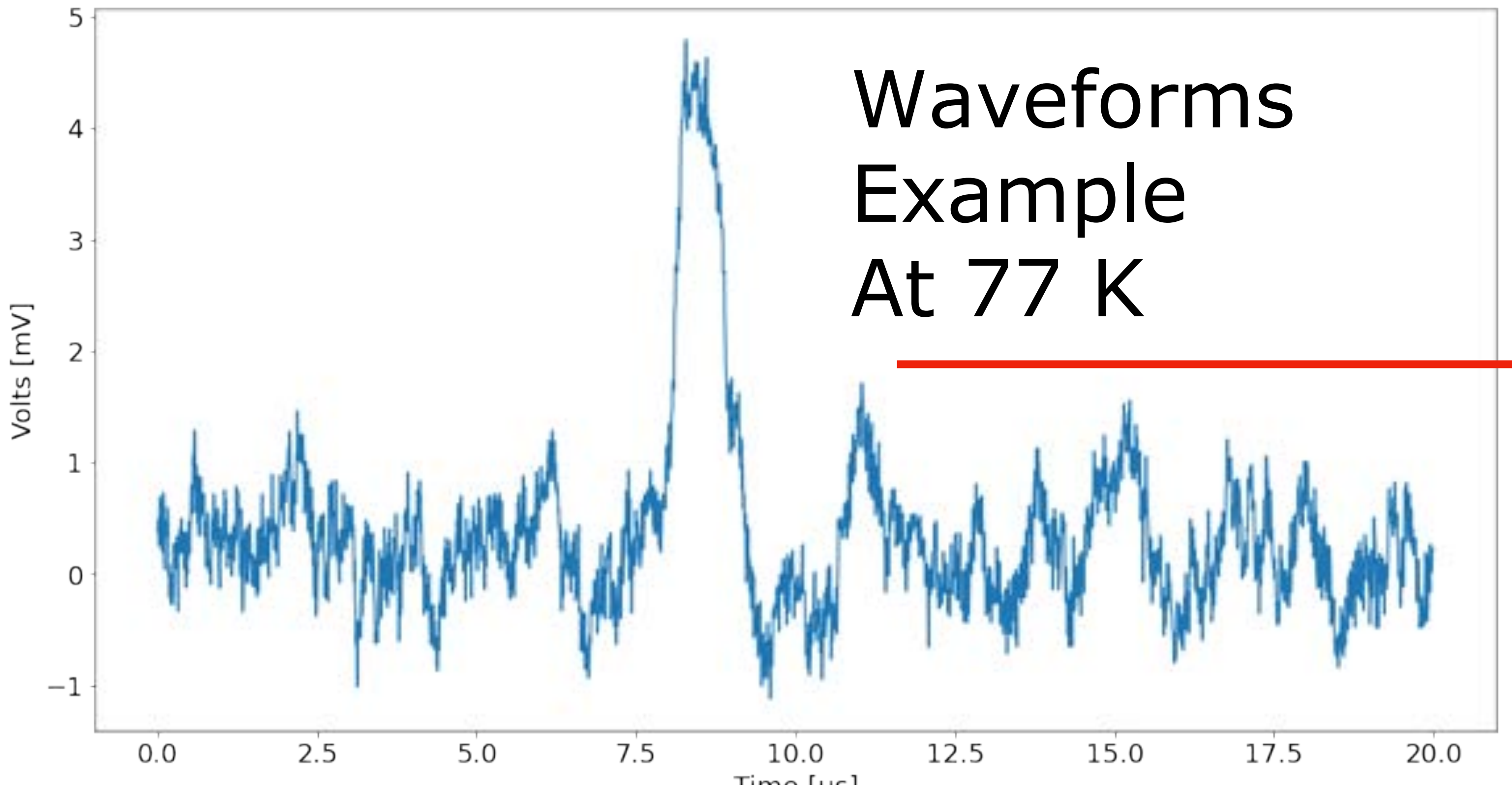


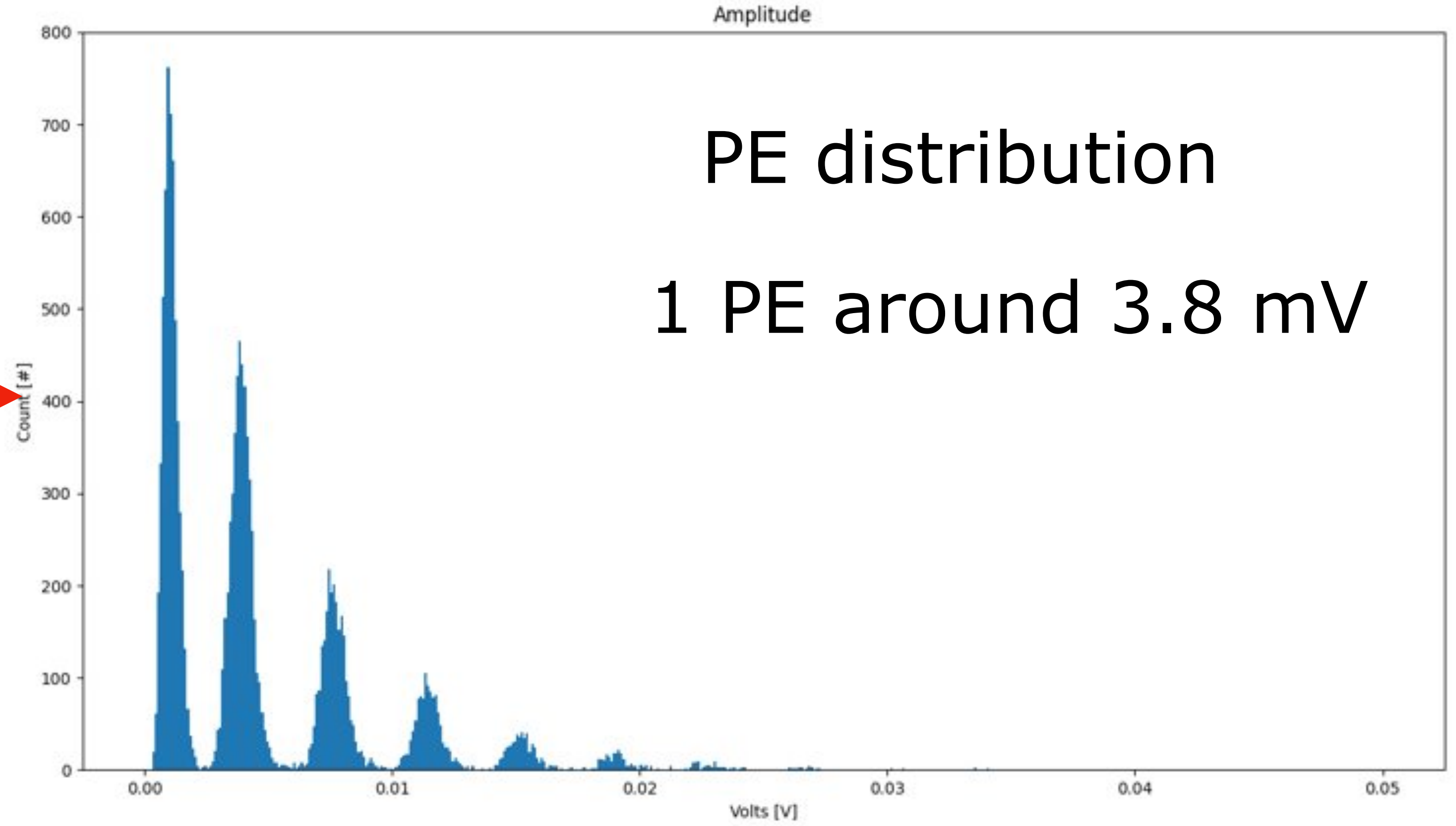
vTILE TESTING

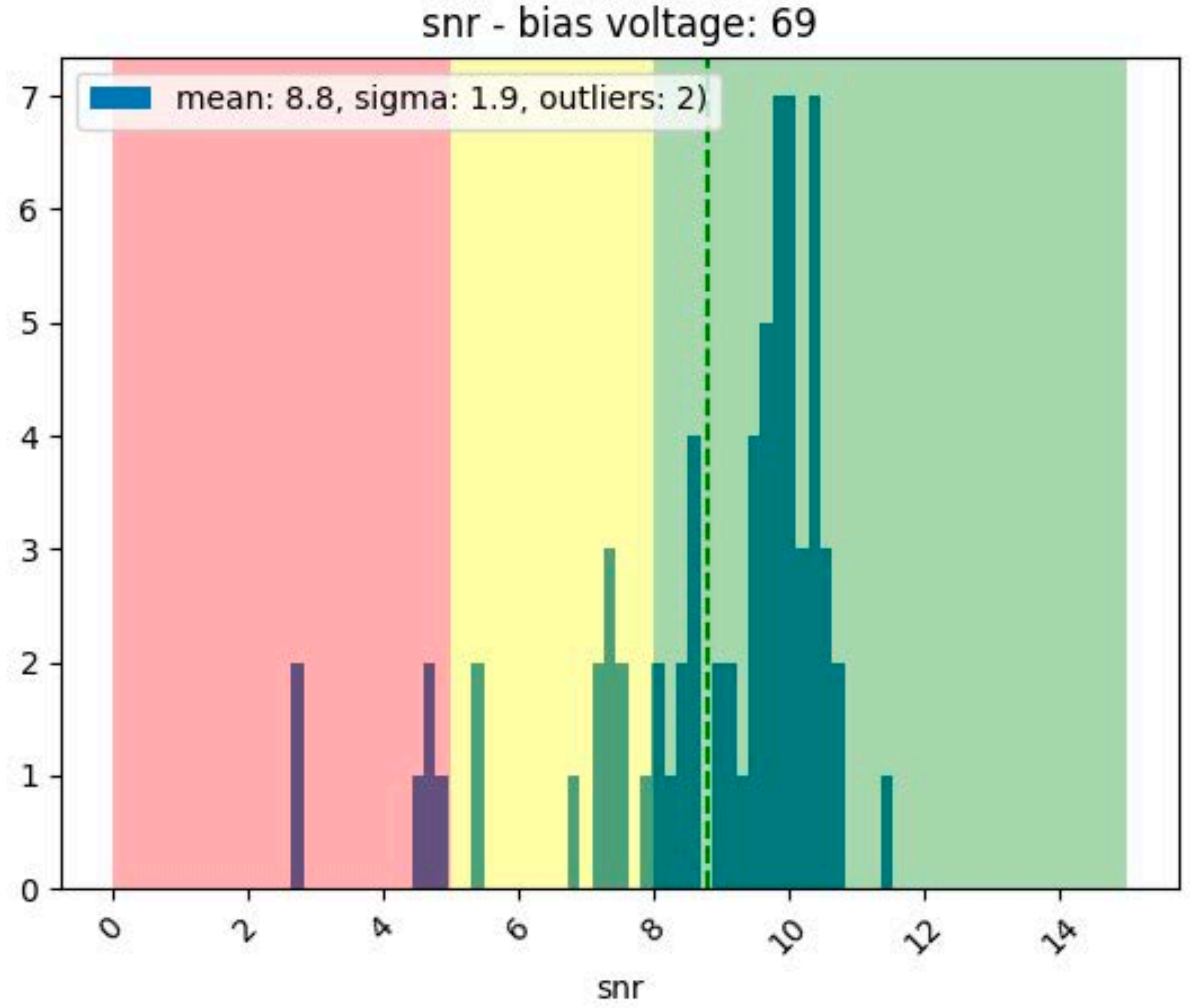
Tile testing @RHUL
In liquid nitrogen



Two new test stand @Oxford/STFC interconnect







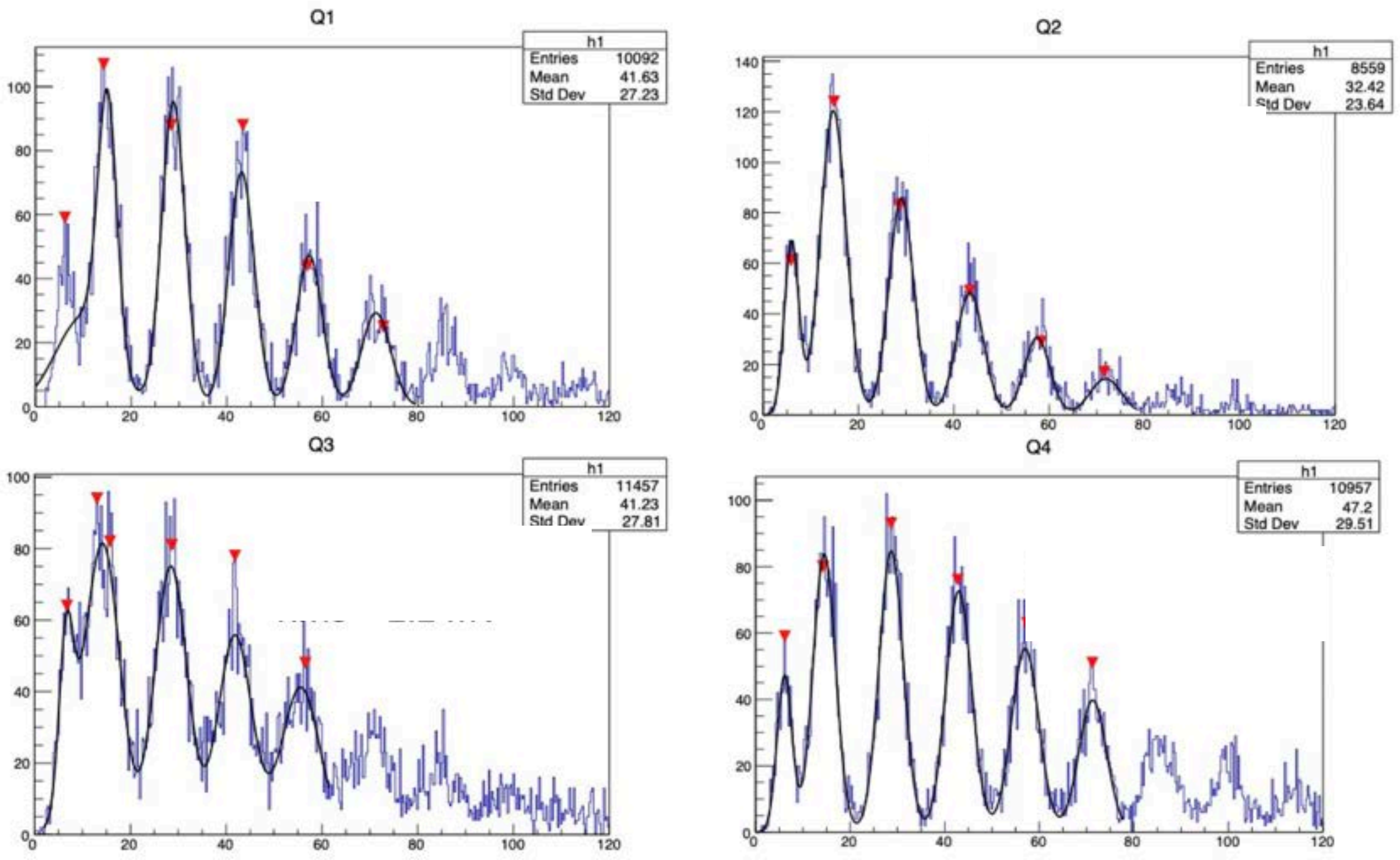
$$\text{SNR} = \frac{\text{1 PE amplitude}}{\text{RMS baseline}}$$

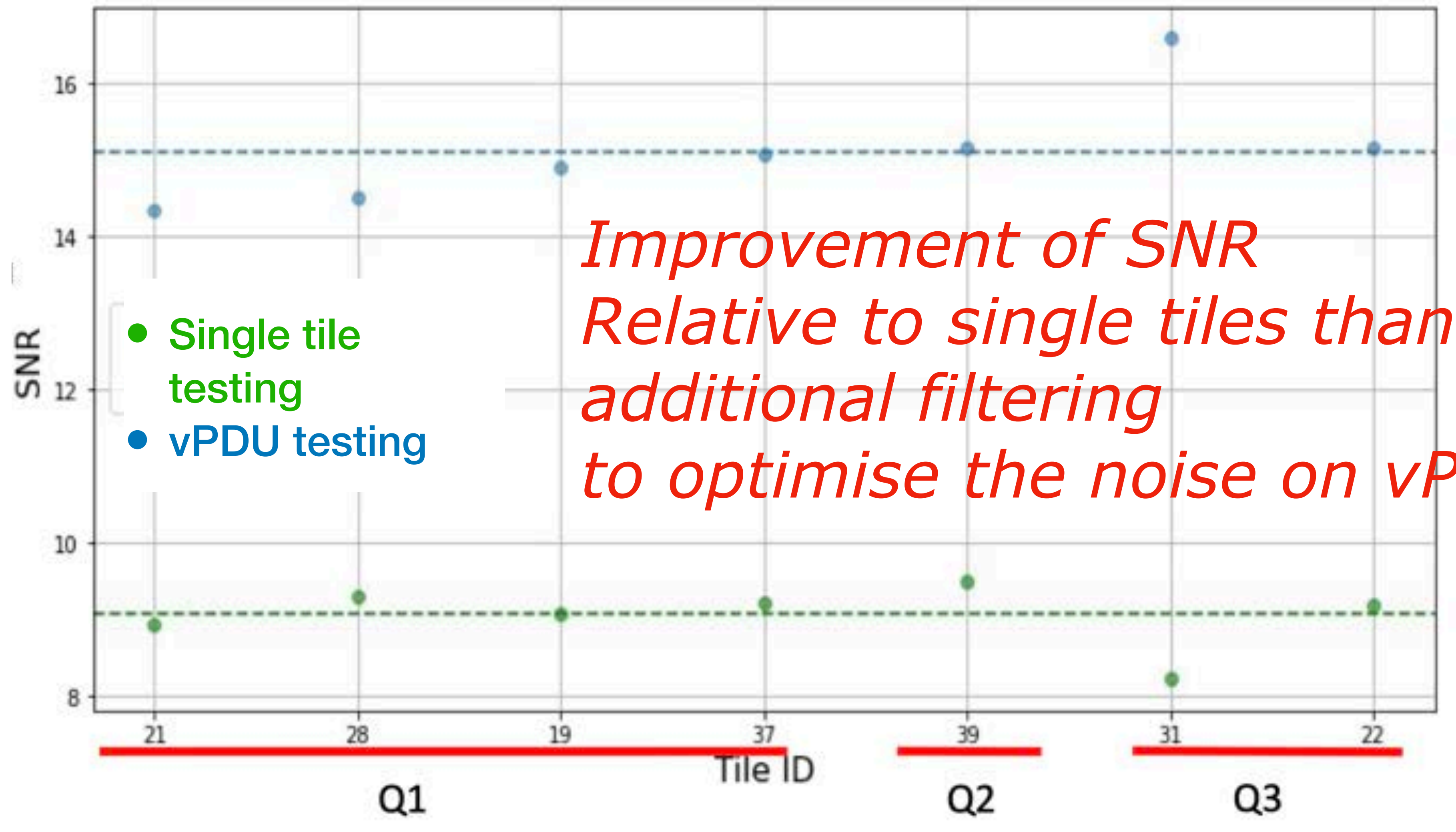
- *Improvement on test stand to optimise throughput*
- *Accumulating statistics to define QA/QC acceptance:* ***SNR > 8***

vPDU testing

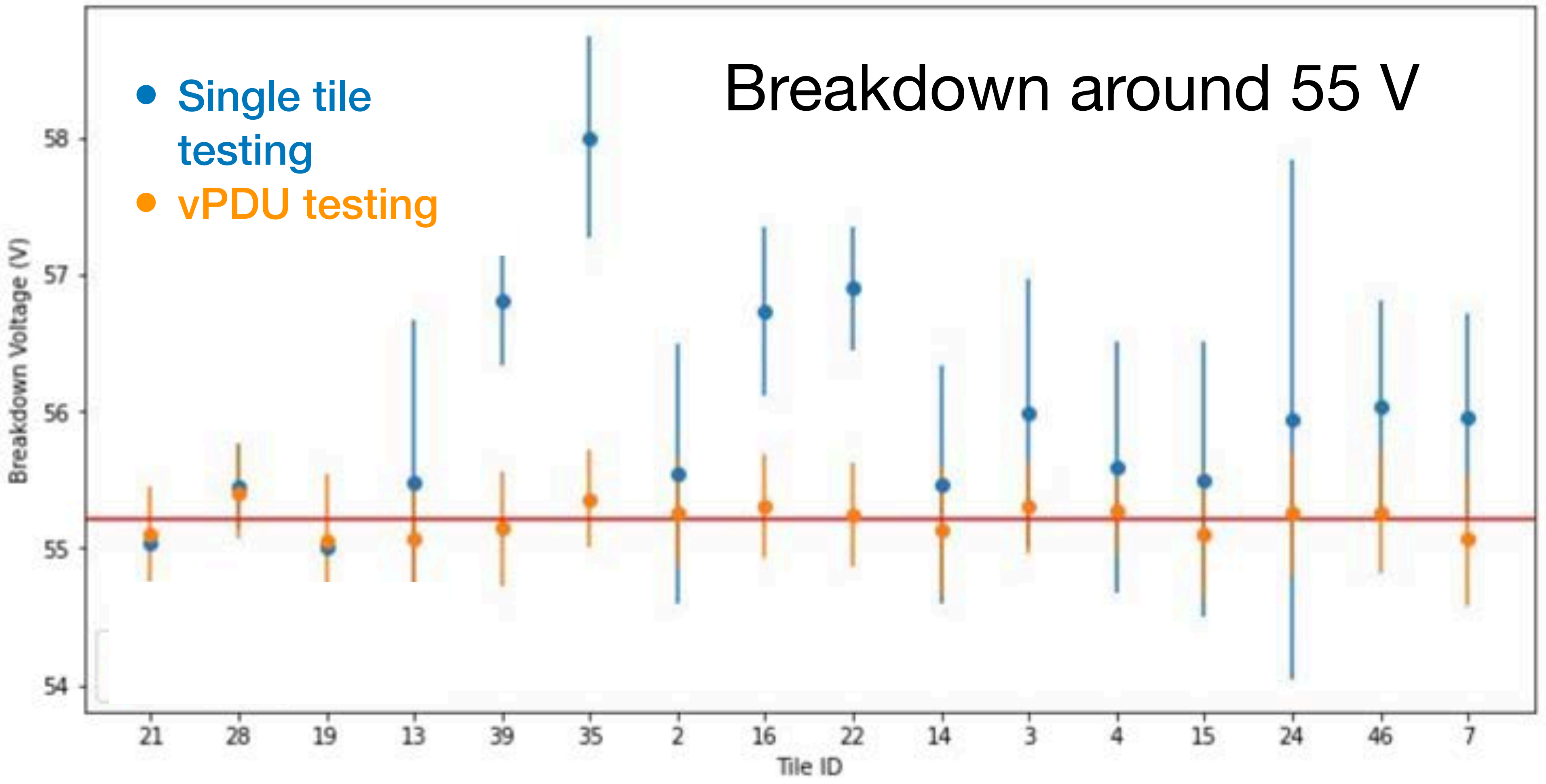
Preliminary

PE distribution per quadrant = sum of 4 tiles = 10 cm x 10 cm area!
1 PE around 14 mV





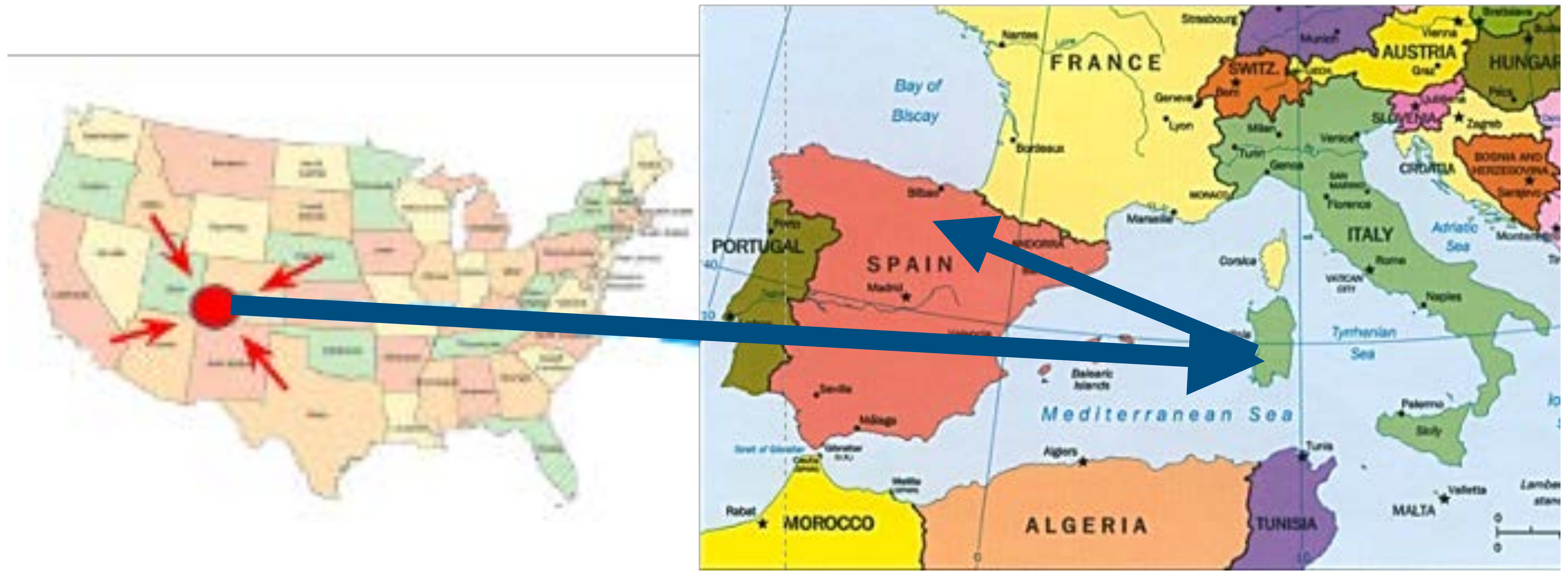
Improvement of SNR Relative to single tiles thanks additional filtering to optimise the noise on vPDU



Breakdown around 55 V

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 ready to be shipped

2. ARIA: UAr purification

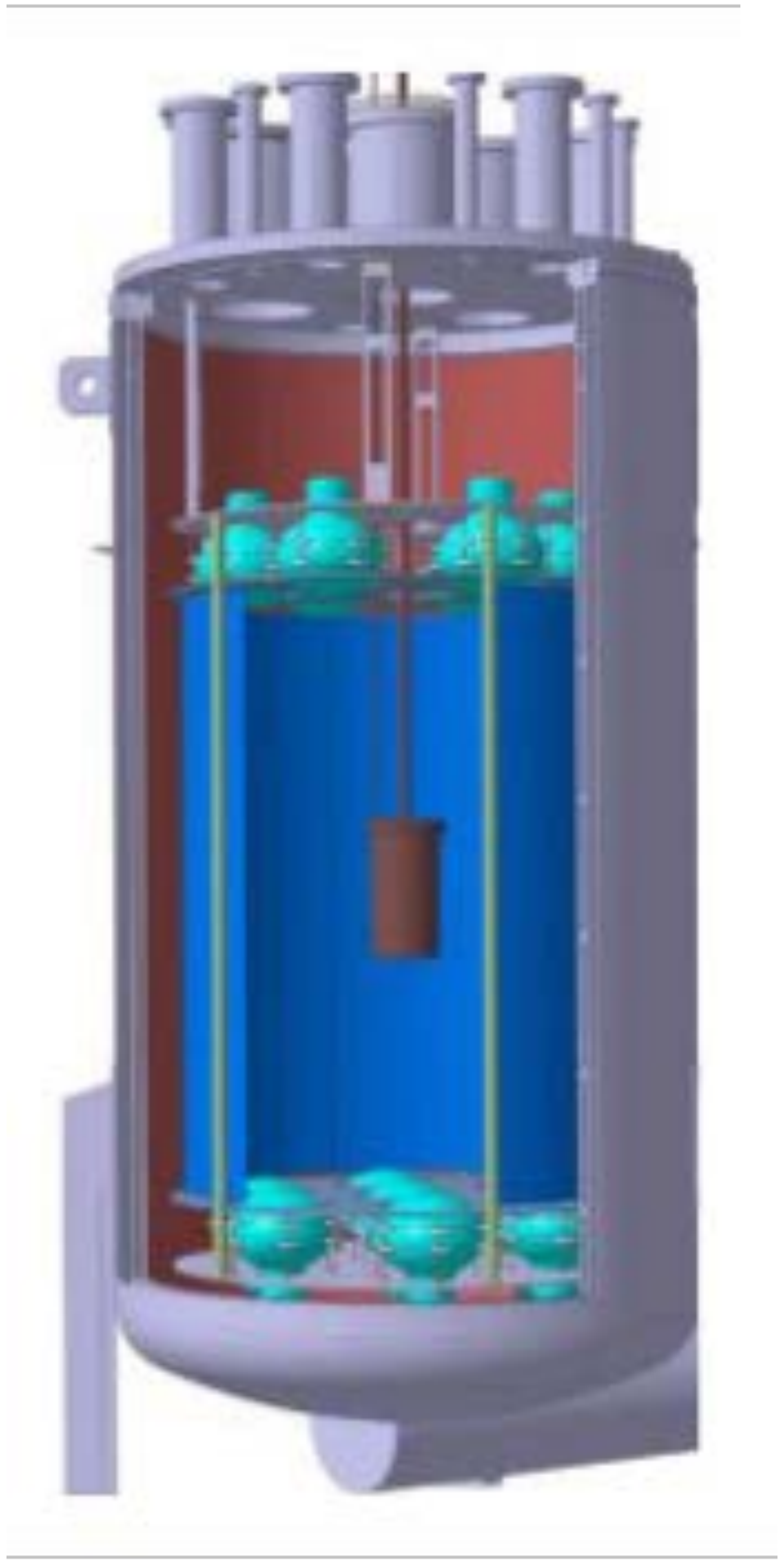
- Cryogenic distillation column in Sardinia (Italy)
- Chemical purification rate: 1 t/day
- Ar-39 separation power > 1000
- First module operated according to specs with Nitrogen in 2019
- Run completed with Ar at the end of 2020

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

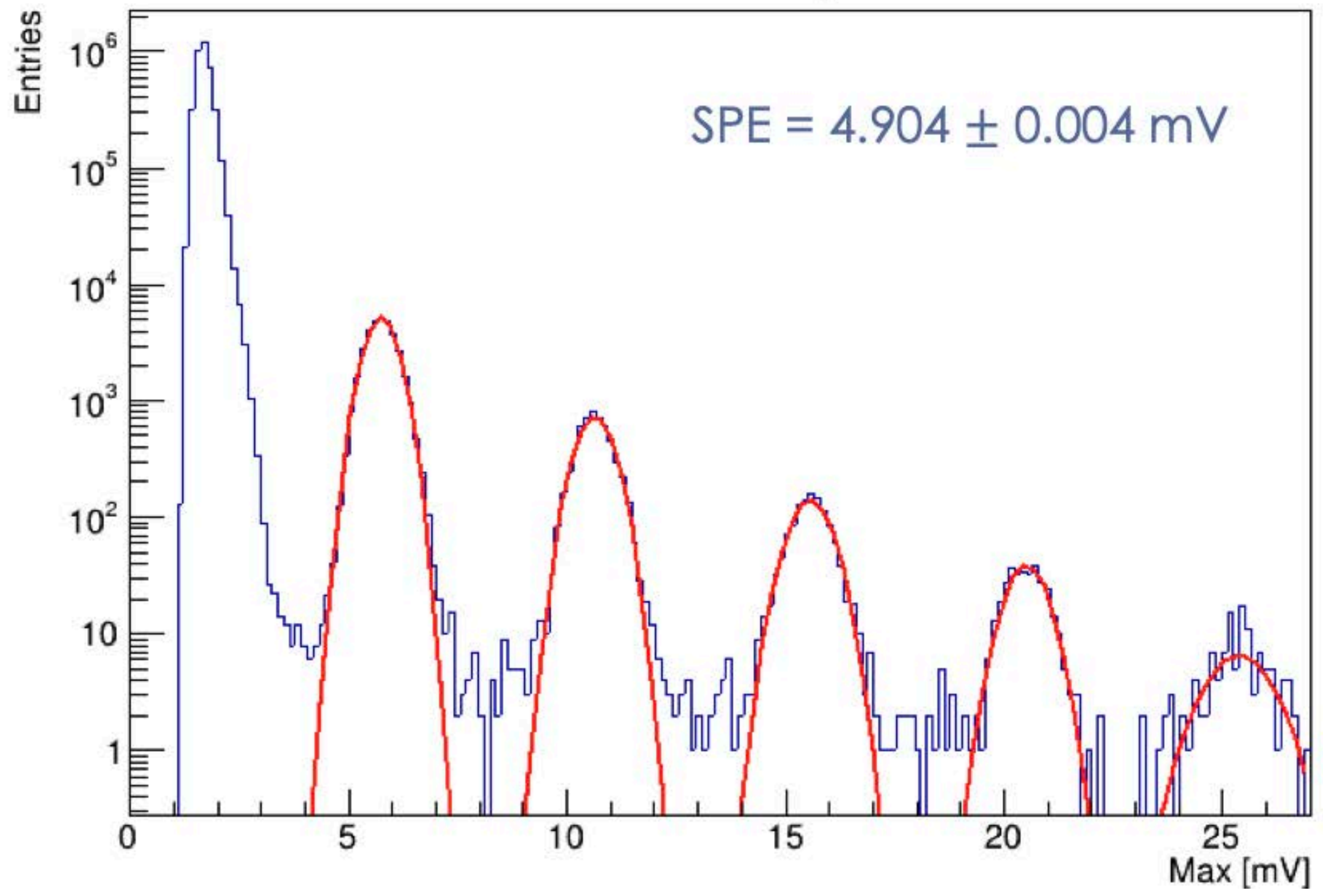
DArT:
Ar purity measurement

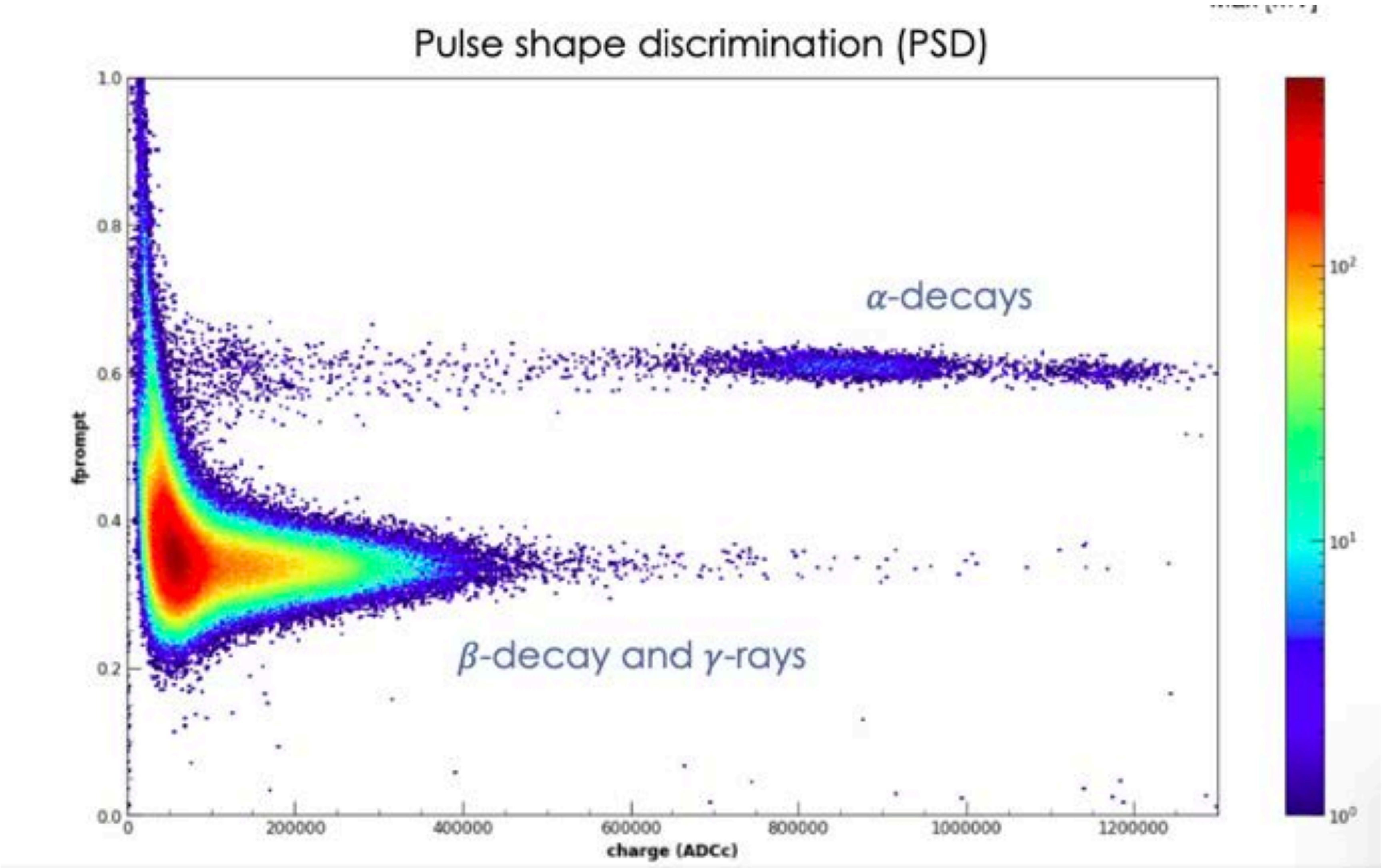
Located at LCS, Canfranc

- 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: 6×10^4 90% C.L



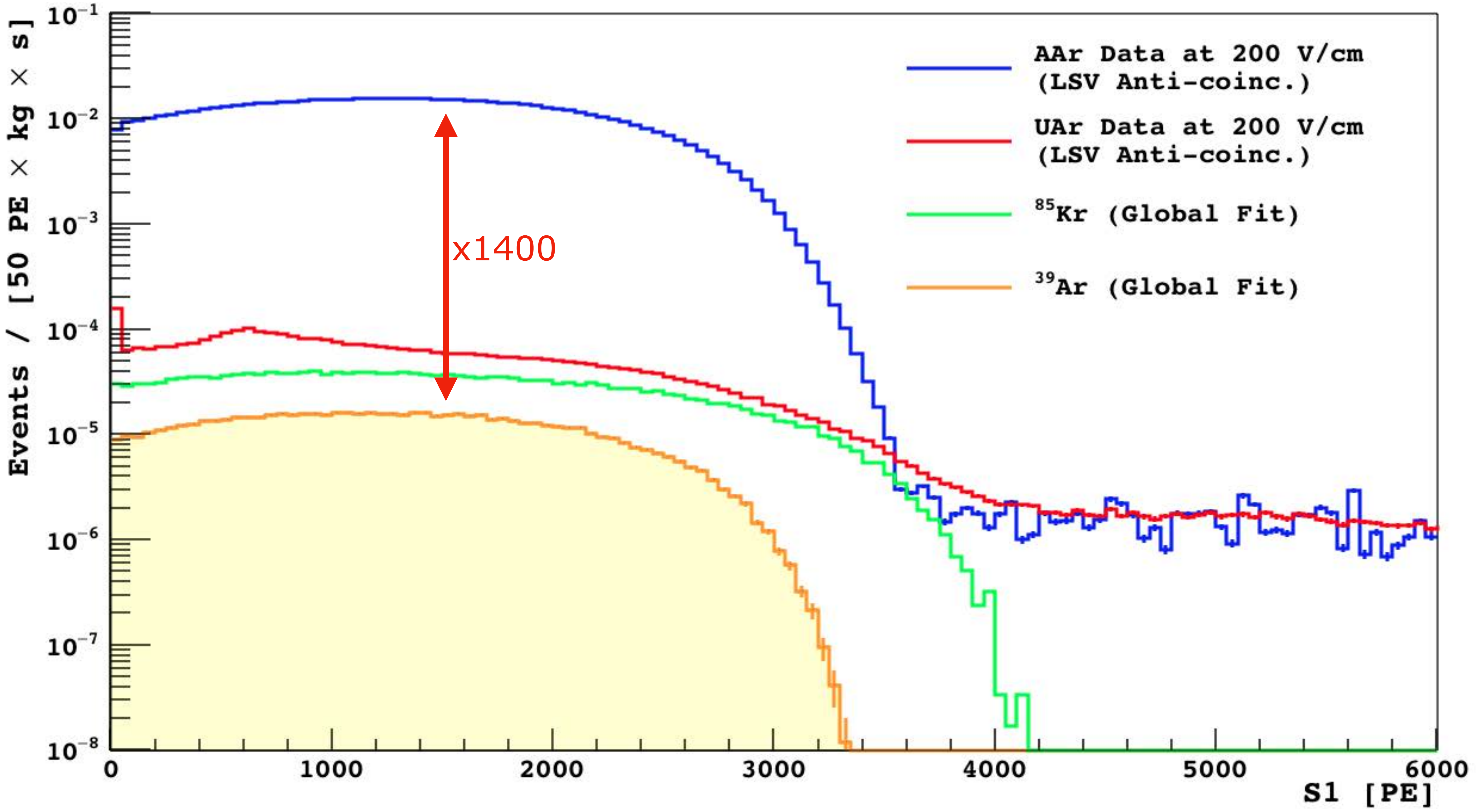
SiPMs calibration





UNDERGROUND ARGON (UAr)

Reduction of Ar-39 thanks UAr successfully demonstrated by Darkside-50k



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

Ar-39 deplaction factor: around 1400

Total UAr:

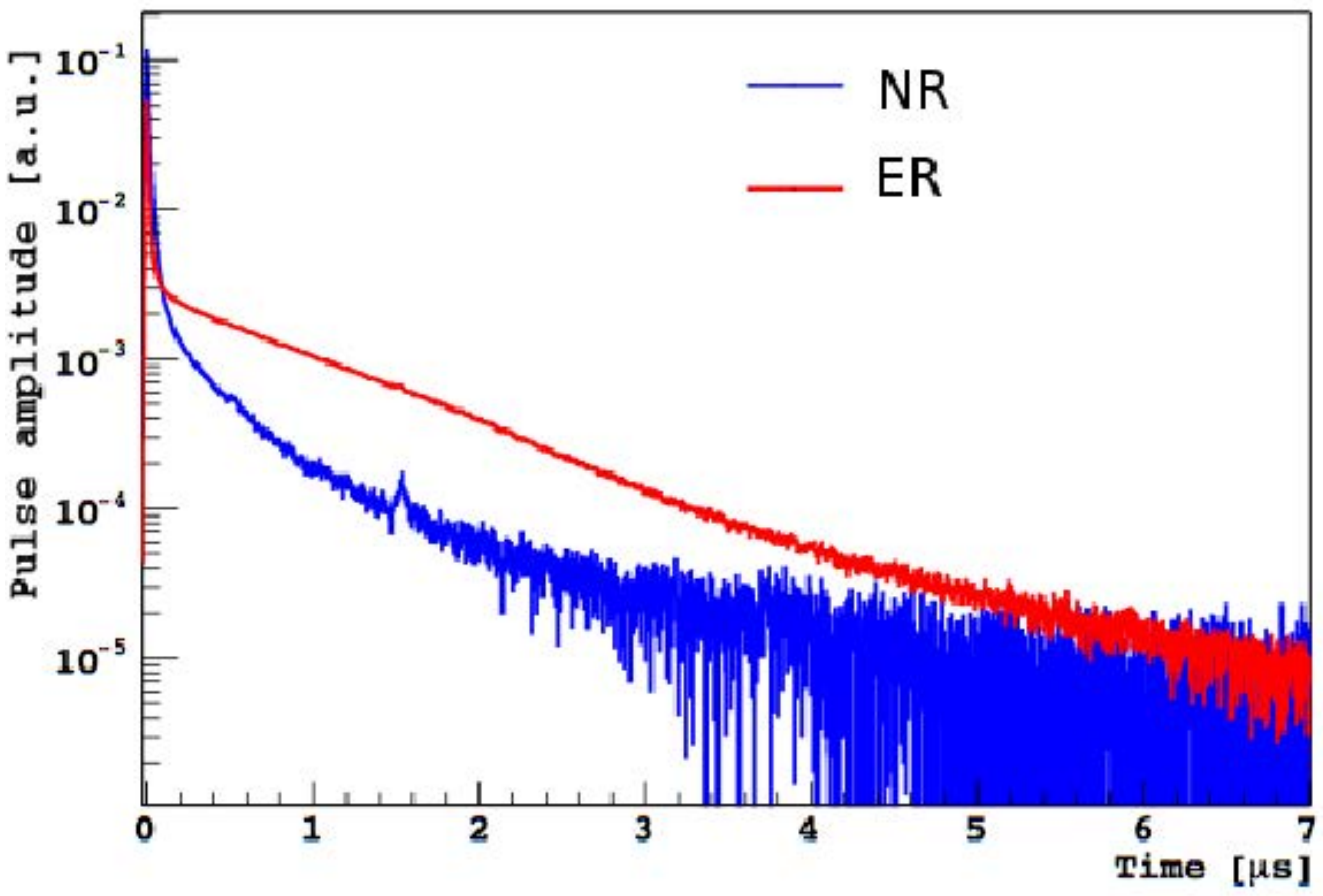
- **TPC= 50 tons -> 36 Hz of Ar-39**
- **Veto = 35 tons -> 26 Hz of Ar-39**

Mitigated with pulse shape discrimination:

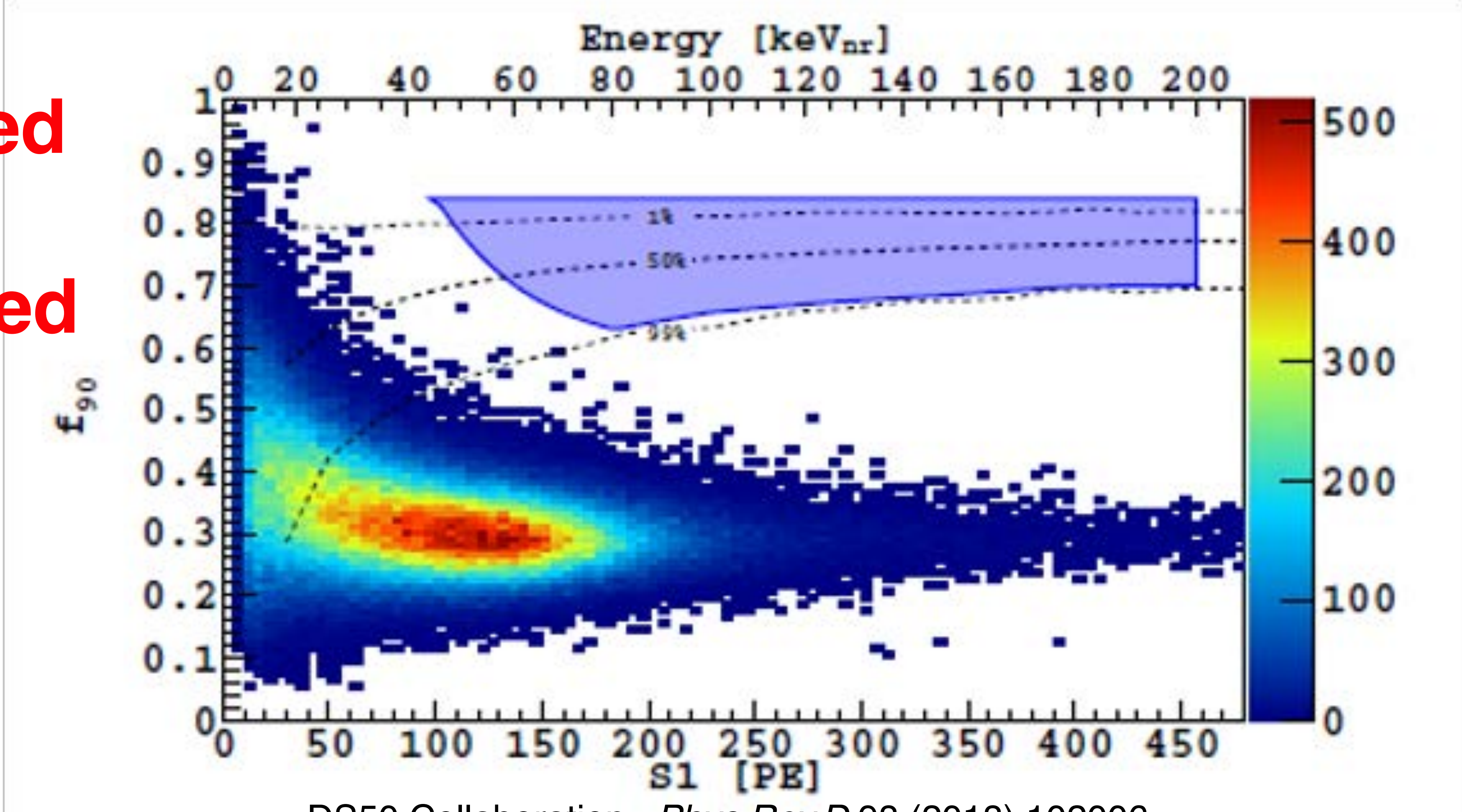
- Residual background is < 0.01 events / 200 tonne x year
- Dead time negligible

ELECTRON RECOIL

S1 pulse shape in LAr



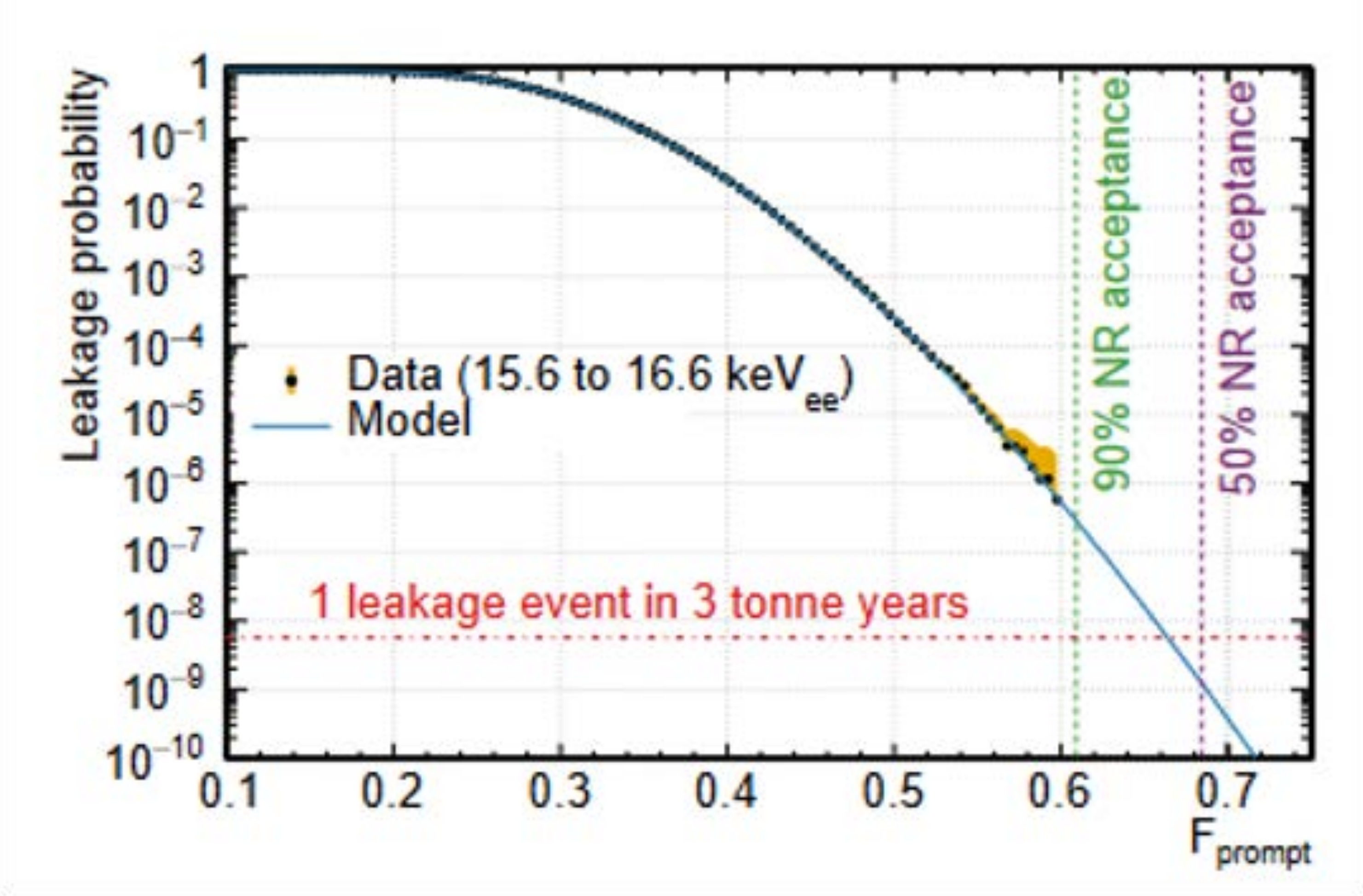
electronic recoils are rejected by Pulse shape discrimination, demonstrated by DS-50 & DEAP



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

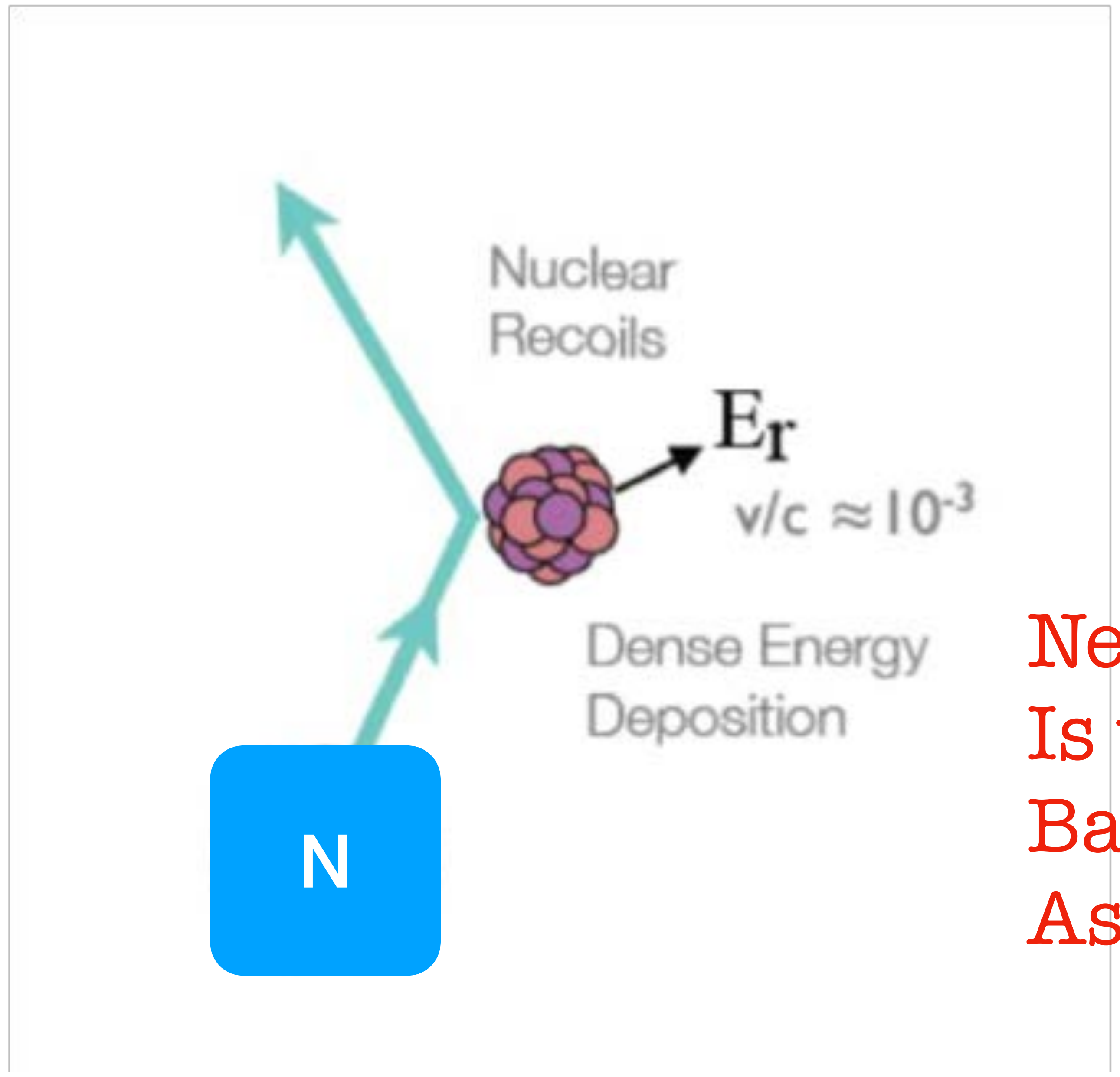
Pulse shape parameter

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



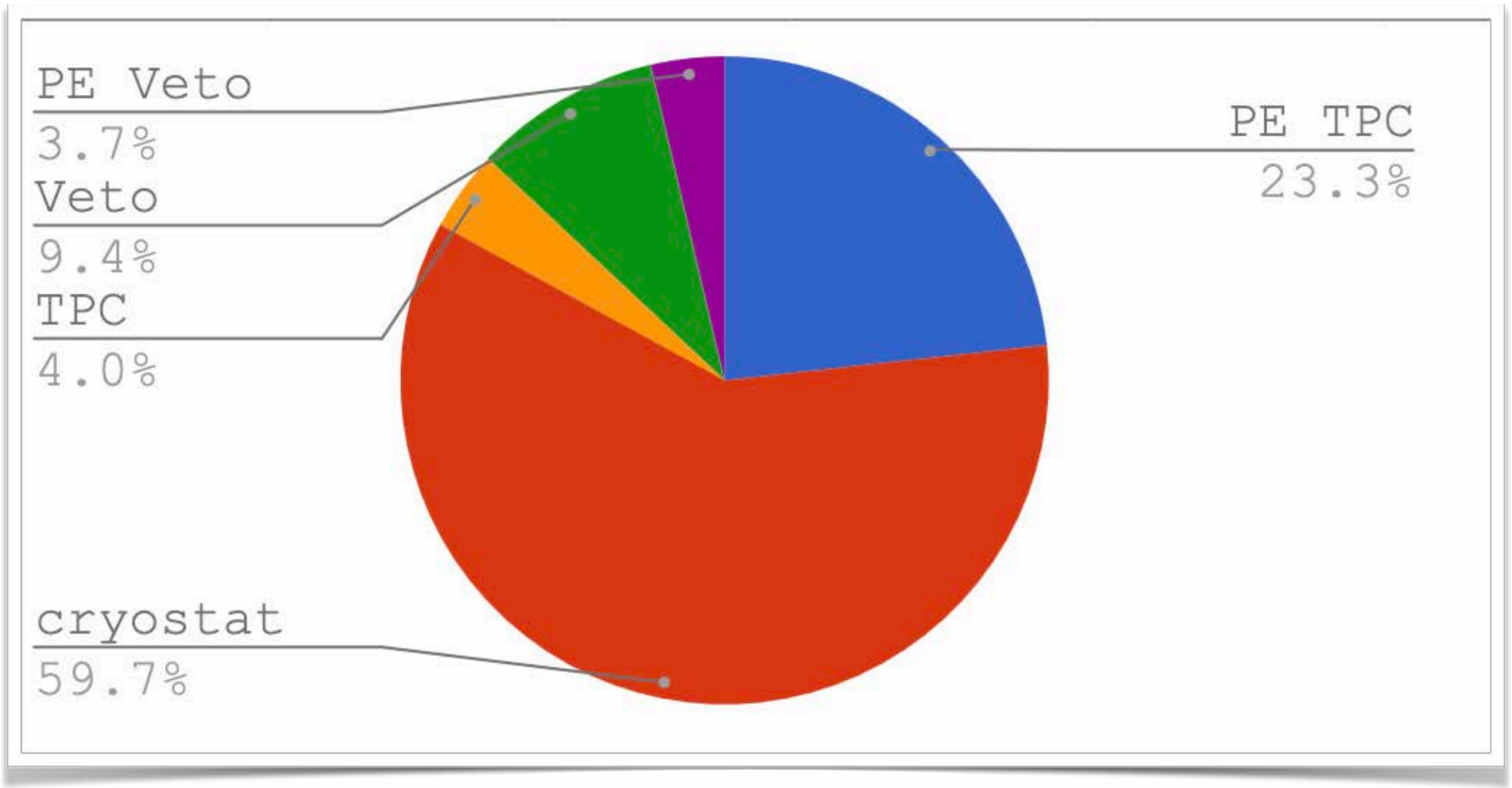
DEAP Collaboration, *Phys.Rev.D* 100 (2019) 2, 022004

NUCLEAR RECOIL



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

Neutron background budget for different Detector components



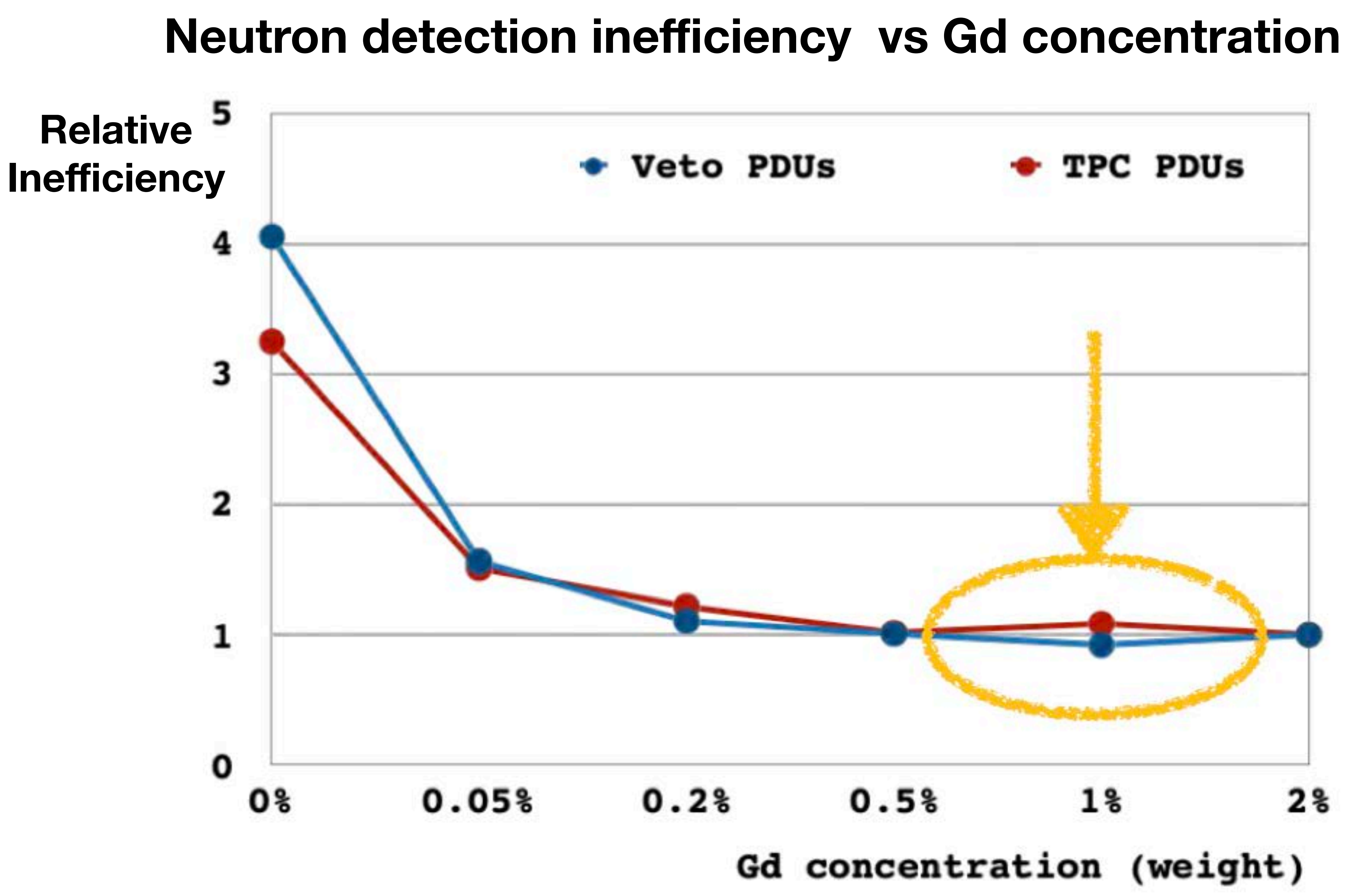
major contributions to radio-assay campaign from Boulby

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

NEUTRON IDENTIFICATION

- Gd-PMMA is highly efficient at moderating and then capturing neutrons
- Gd-PMMA 15 cm thick
- Gd concentration chosen to have neutron capture on Gd dominates w.r.t capture on H
- Neutron capture on Gd produced a gammas cascade with a energy of 8 MeV



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 samples and finalise the production -> **ready for full production**

- DonChamp: low background environment -> already used for JUNO PMMA production

- **Pure-PMMA radio-purity satisfies DarkSide-20k requirement**

Gd-PMMA acrylics sheet

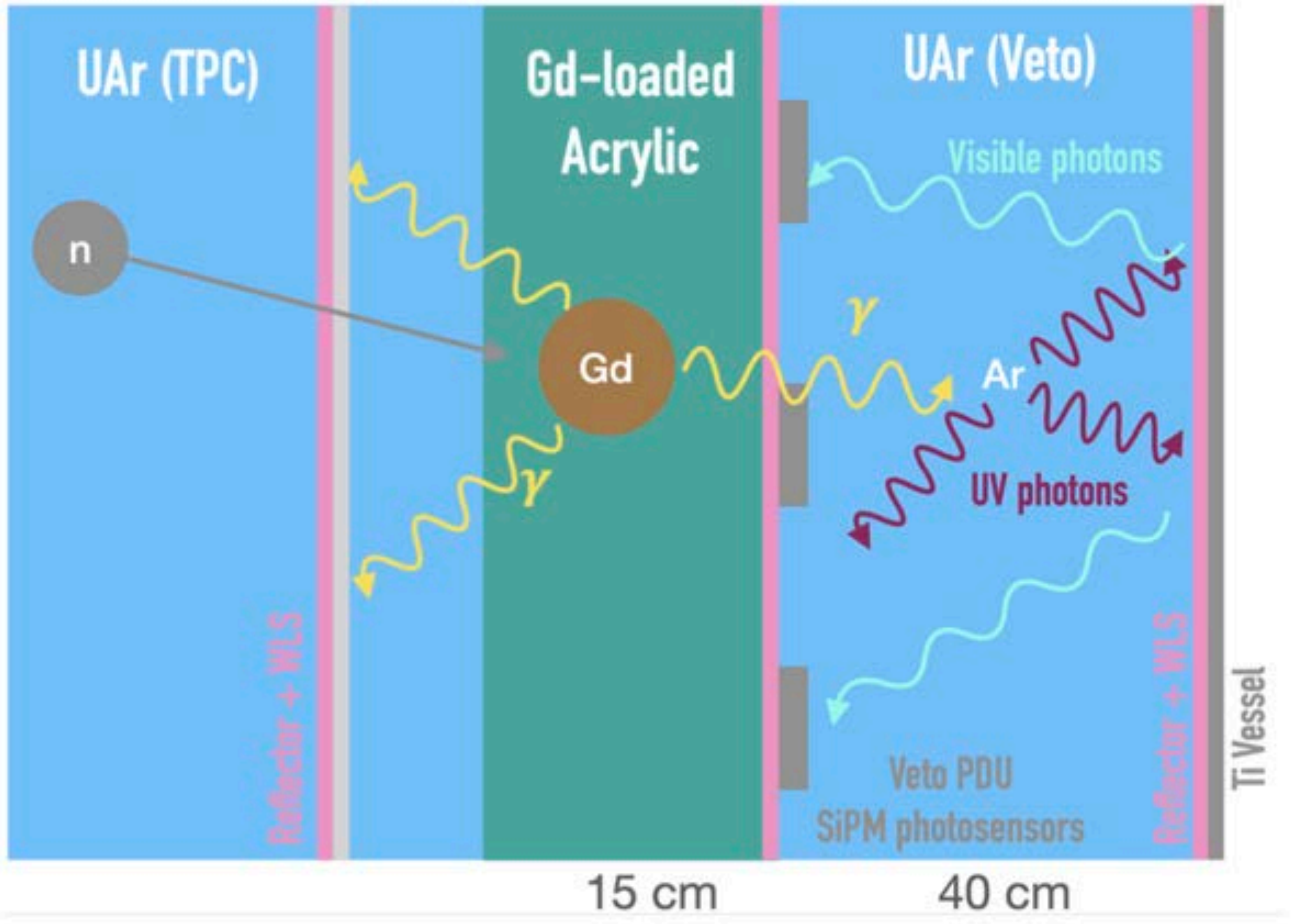
Pure PMMA measured at LGNS

Isotope	mBq/kg
137Cs	<0.025
40K	<0.41
232Th_228Ac	<0.14
232Th_228Th	<0.08
235U	<0.07
238U_226Ra	0.05
238U_234mPa	<1.8

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.

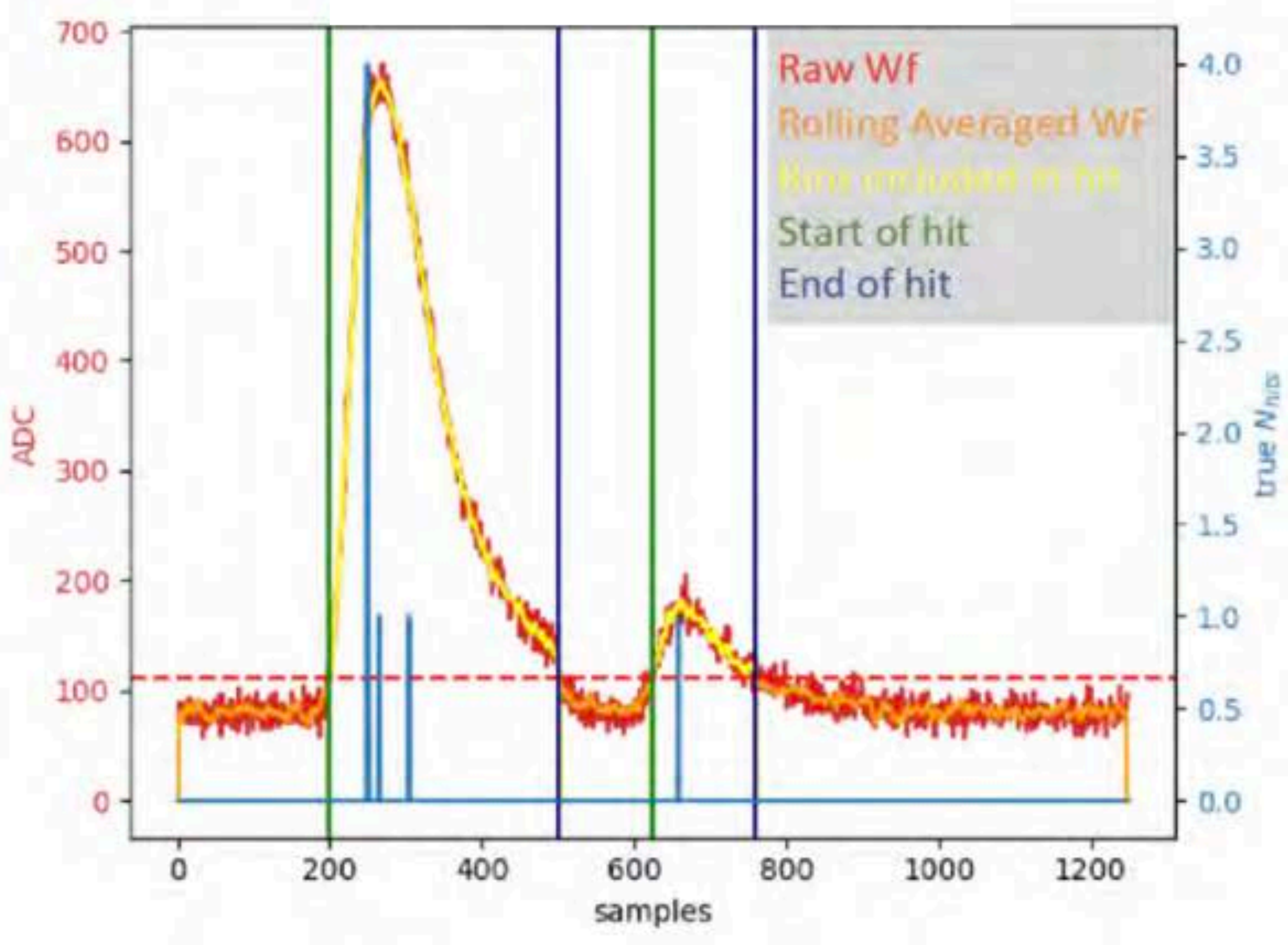
Total neutron Detection Inefficiency is 1.6E-5

NEUTRON DETECTION (2)

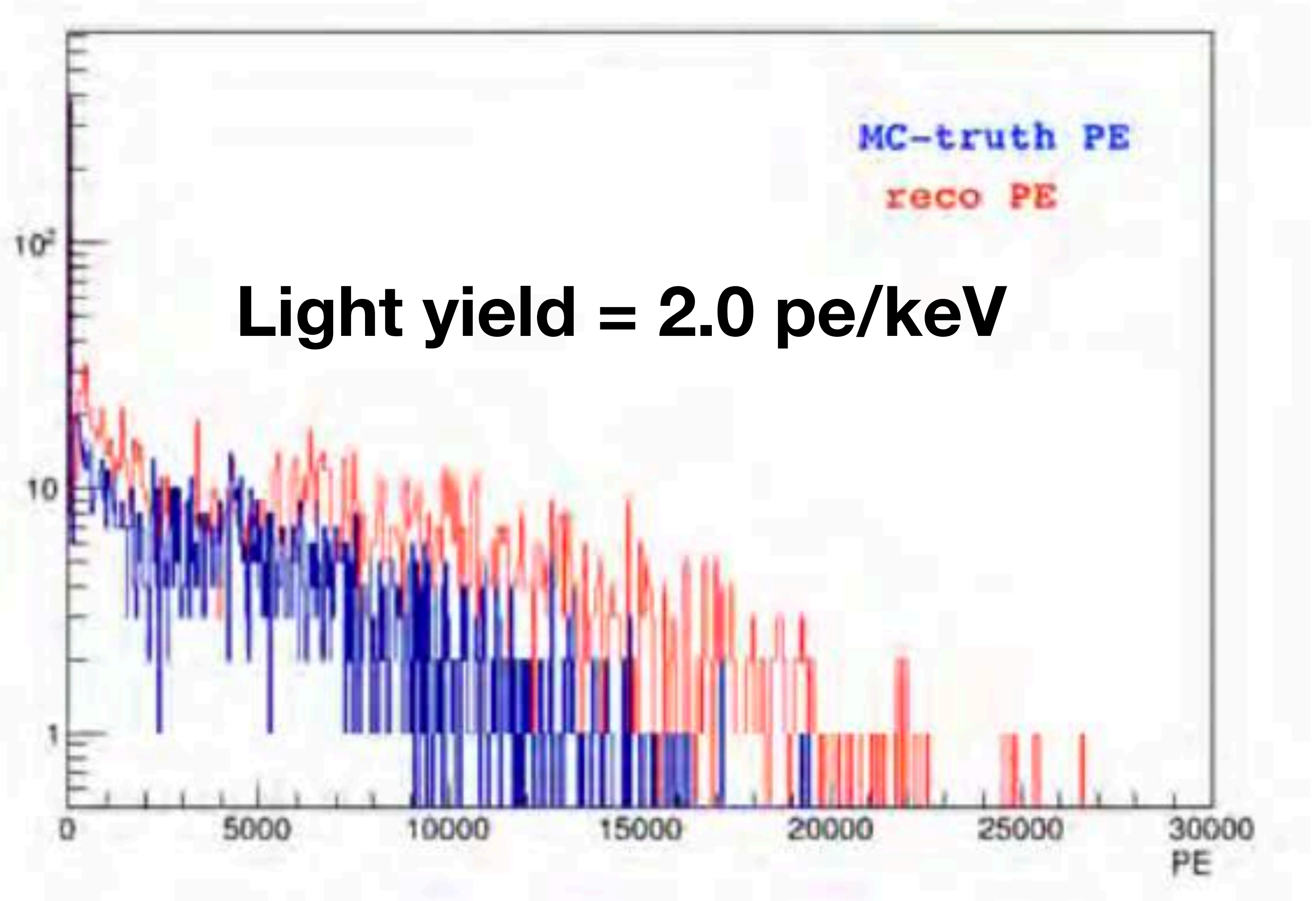
More realistic MonteCarlo Simulation introducing:

- Electronics response
- SIPMs noise
- Pile up effects

Waveform example



PhotoElectrons (PE) distribution

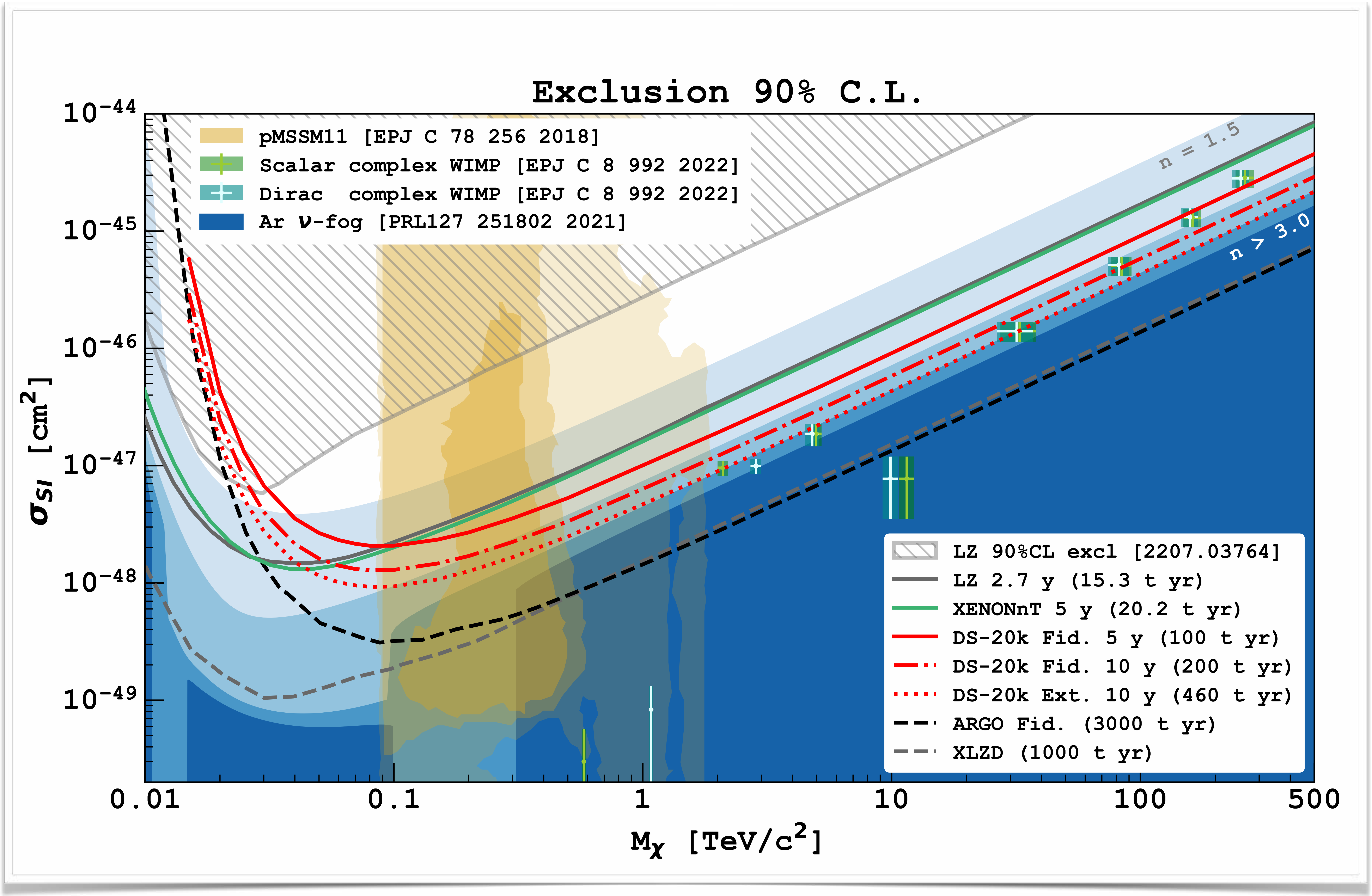


- Neutron detection inefficiency increased by **20%** including electronics response, SIPMs noise and pile-up effects

- **Neutron background after veto cuts: < 0.1 event in the full exposure of 200 tons x years -> satisfies DarkSide-20k requirement**

major contributions from RHUL

HIGH MASS DARK MATTER SENSITIVITY



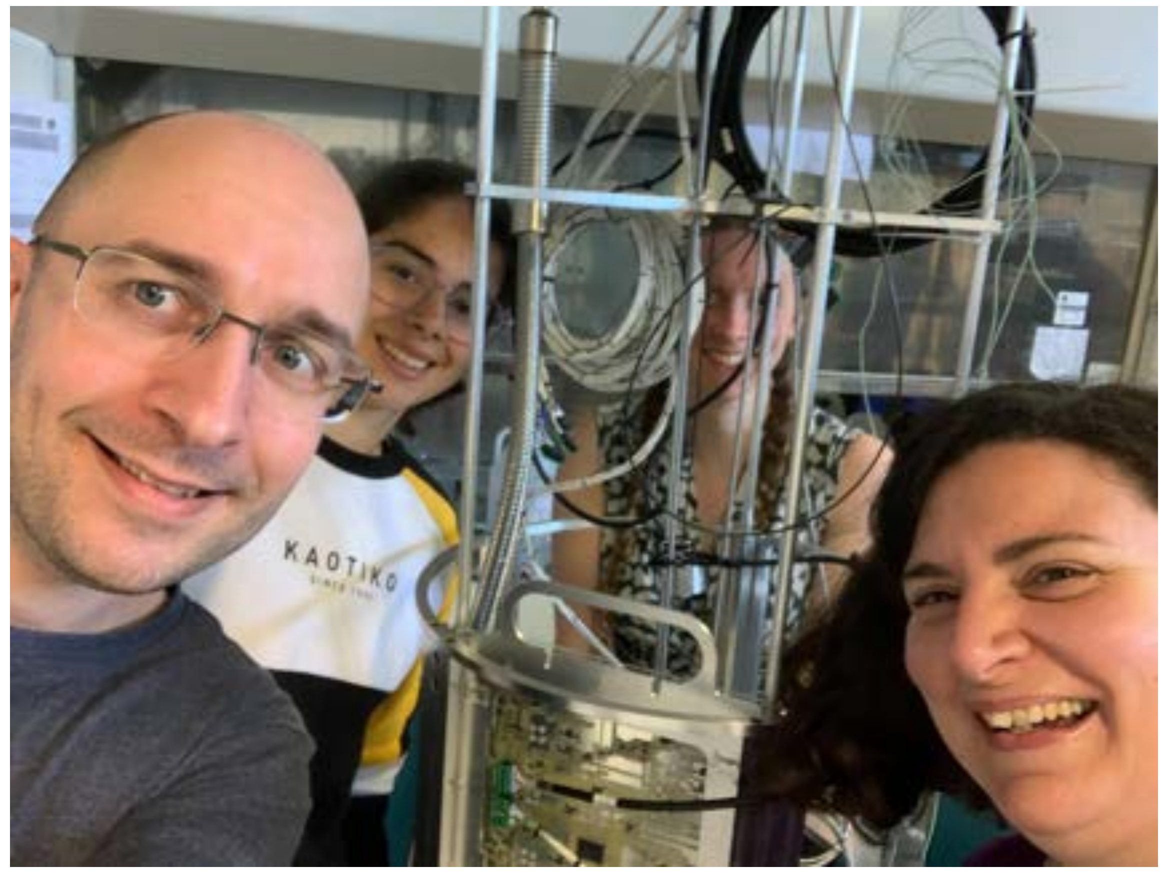
- Sensitivity to high mass WIMP-nucleon scatter cross section of 7.4 x 10^{-48} cm^2 for a 1 TeV/c^2 WIMP for a total exposure of 200 tons x years
- Total background events after all cuts: < 0.1 neutron wimp like events in a total exposure of 200 tons x years
- S2-only analysis sensitivity projection 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 ~100 institutions, 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 your
Attention


PHYSICS WEST
DS-UK CM-Birmigham


KAOTIKO