Quality Assurance and Quality Control of the $26\ m^2$ SiPM production for the DarkSide-20k dark matter experiment

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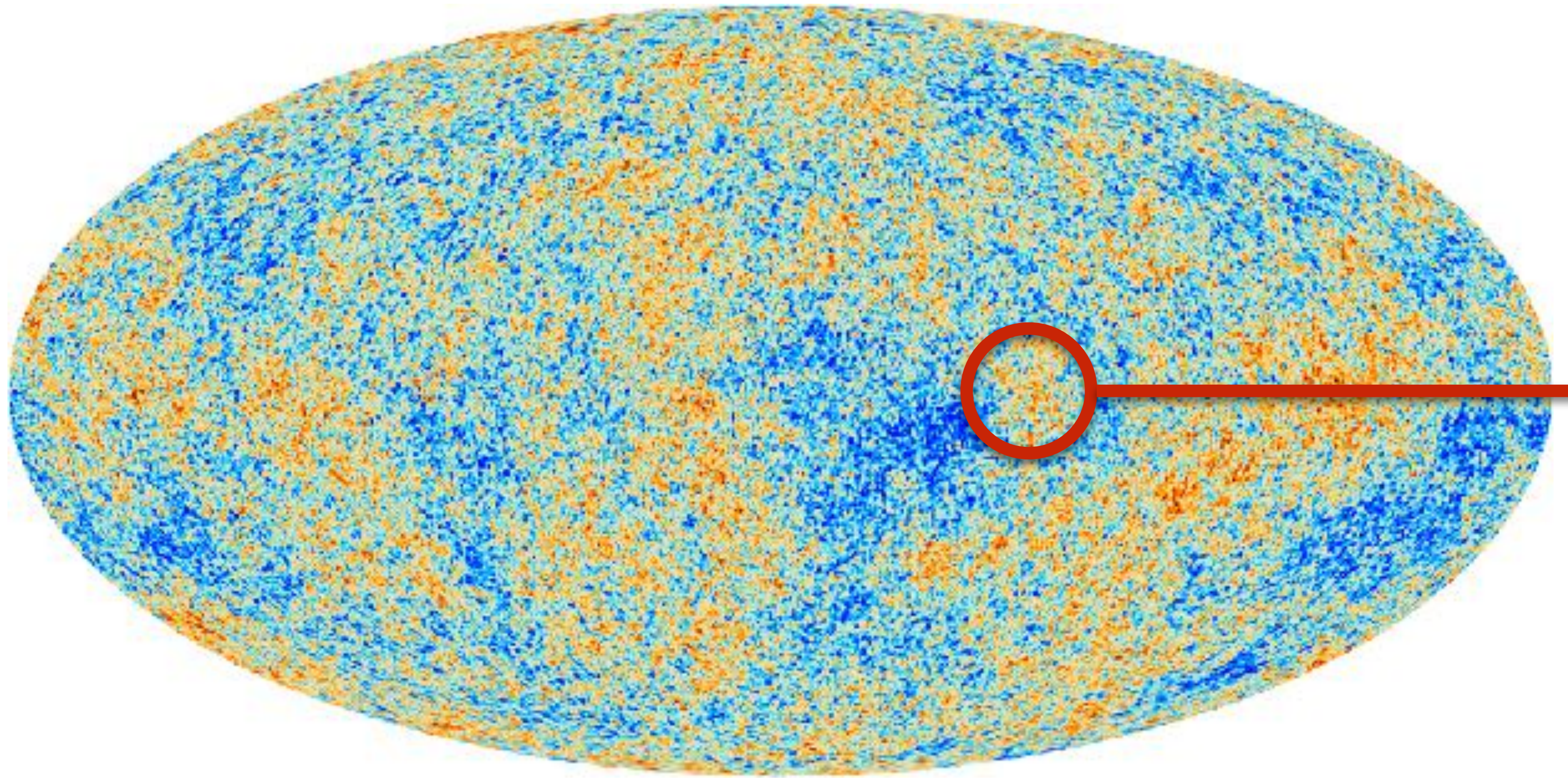
on behalf of the GADMC

2/15/2024

The physics case

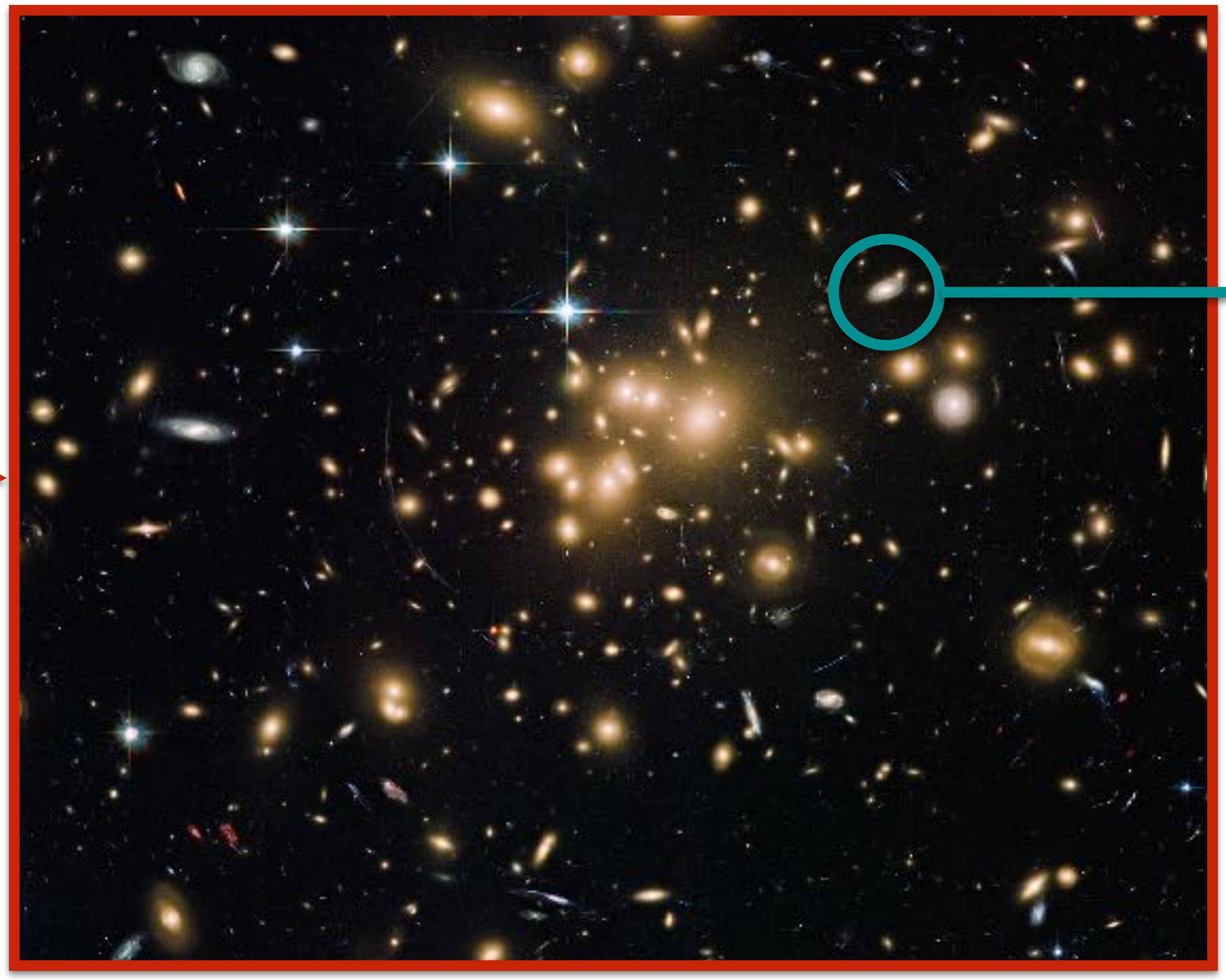
CMB



Thermal anisotropies

multipole expansion

Galactic clusters



Galaxy velocities

Gravitational lensing (Bullet)

Galaxies

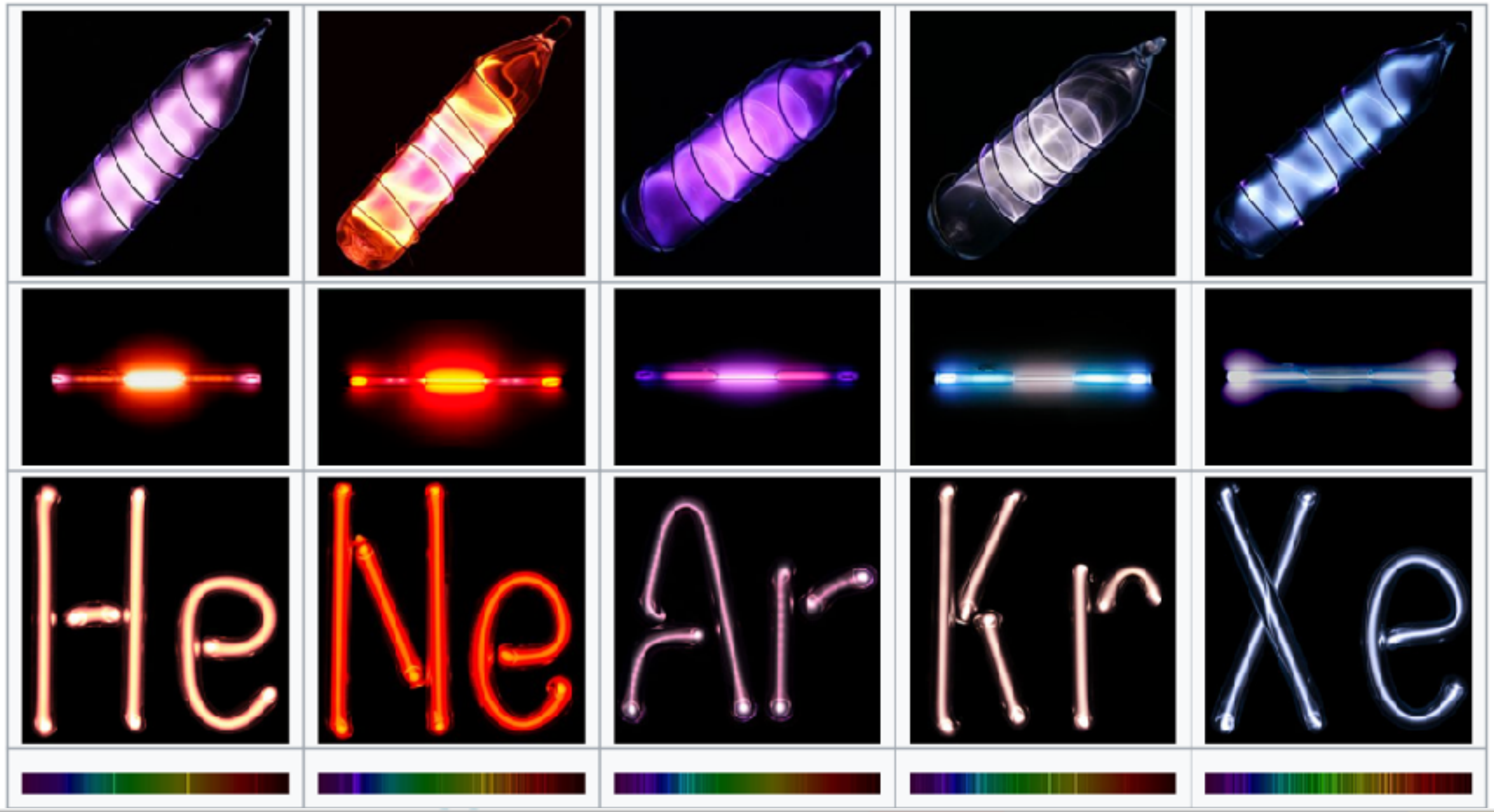
Rotation curves

Gravitational lensing

Convincing evidence at all scales

Search with liquified noble elements

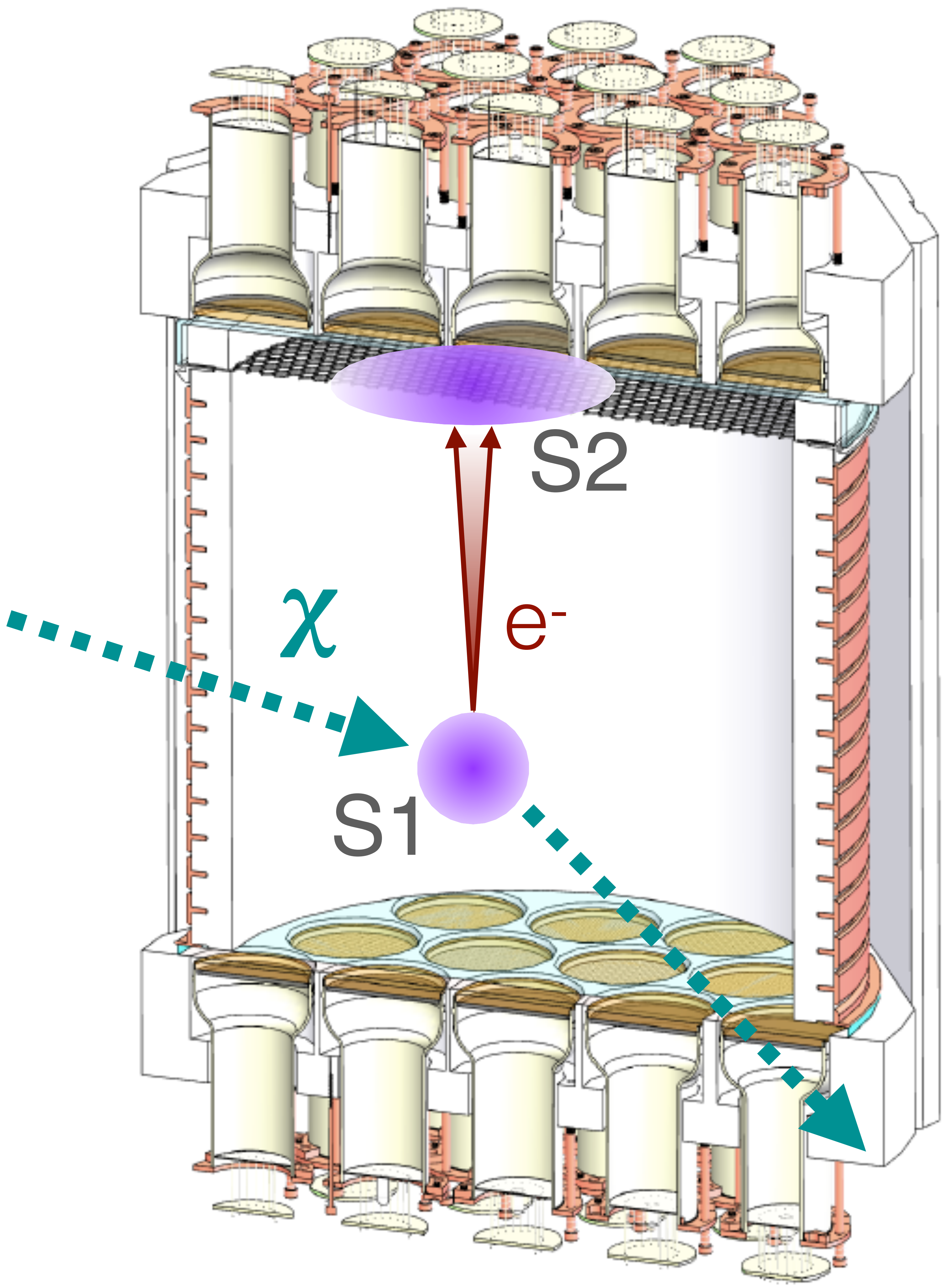
- High density ✔
  - Self screening
  - Good scalability
- Easy(-ish) purification, also online ✔
- Scintillation: good light yield ✔
- Ionisation ✔
- ER rejection ✔
- NR quenching at low energies ✘



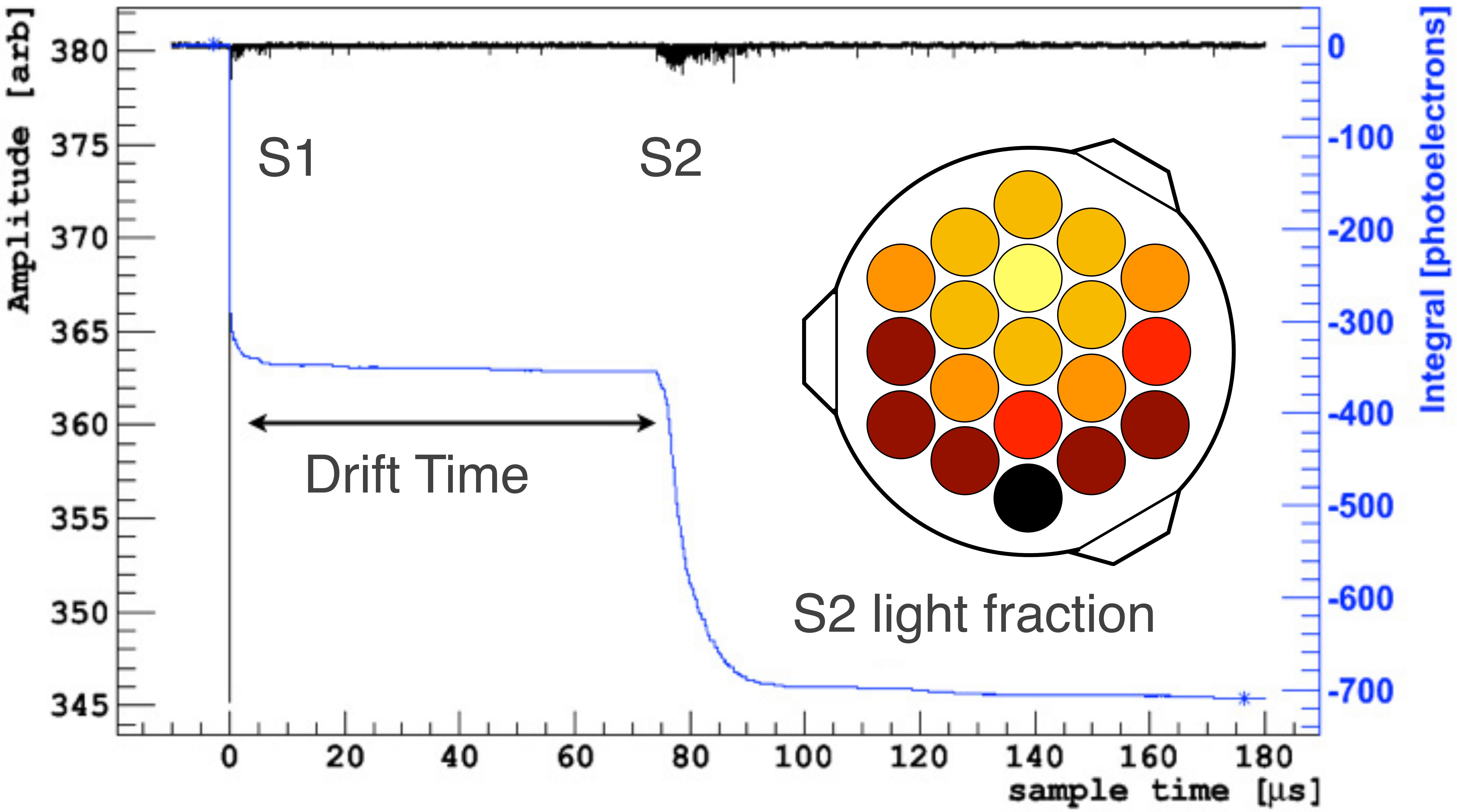
		LAr	*LKr*	*LXe*
Physical properties	Atomic number	18	36	54
	Boiling point at 1 bar, T_b (K)	87.3	119.8	165.0
	Density at T_b (g/cm^3)	1.40	2.41	2.94
Ionisation	W (eV)[1]	23.6	20.5	15.6
	Fano factor	0.11	~0.06	0.041
	Drift velocity (cm/μs) at 3 kV/cm	0.30	0.33	0.26
	Transversal diffusion coefficient at 1 kV/cm (cm^2/s)	~20		~80
Scintillation	Decay time[2], fast (ns)	5	2.1	2.2
	slow (ns)	1000	80	27/45
	Emission peak (nm)	127	150	175
	Light yield[2] (phot./Mev)	40000	25000	42000
	Radiation length (cm)	14	4.7	2.8
	Moliere radius (cm)	10.0	6.6	5.7

Excellent discrimination power!

Dual-phase TPCs



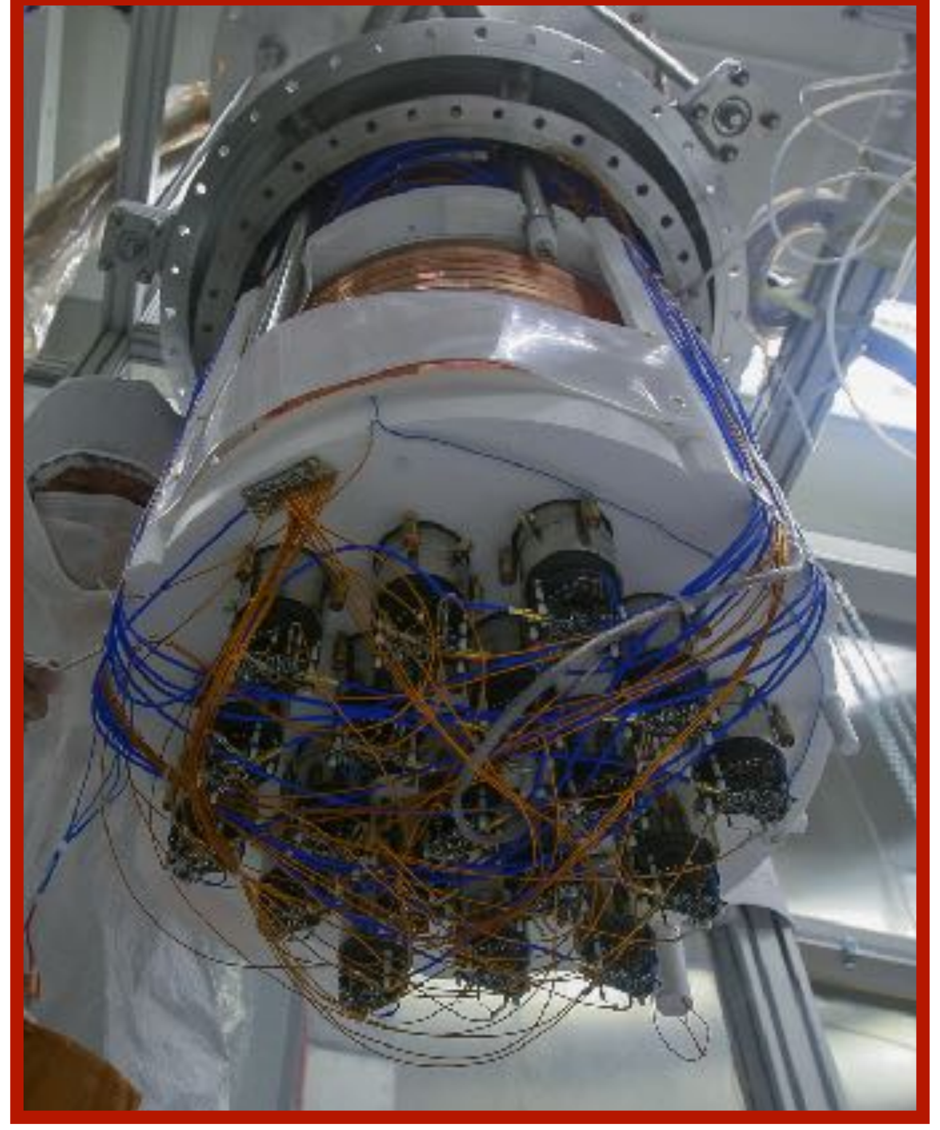
3D position reconstruction



- Z from S1-S2 time difference
- XY from S2 light distribution
- Reliable fiducialization
- Multiple scattering rejection

The GADMC

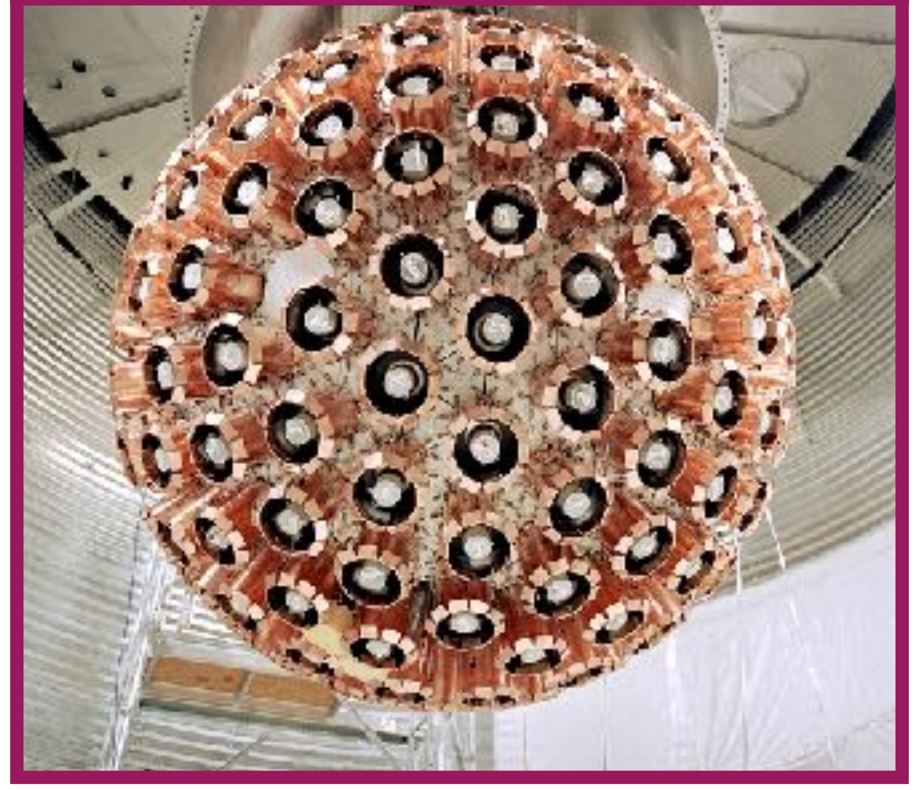
DarkSide-50 @ LNGS



ArDM @ Canfranc

MiniClean @ Snolab

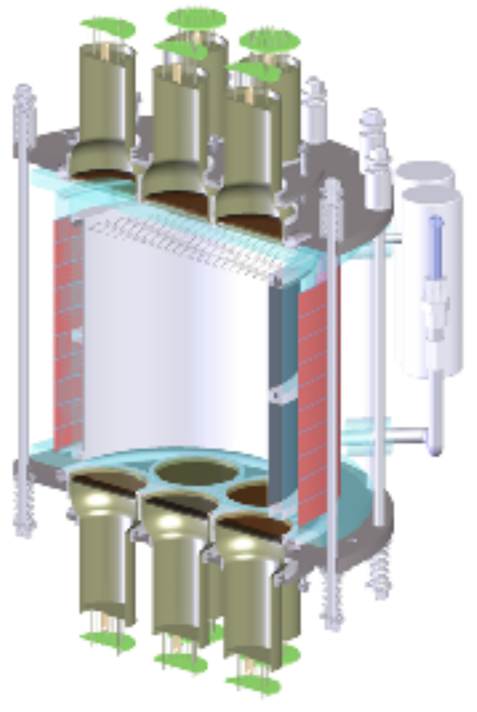
DEAP @ Snolab



>400 scientists, >100 institutions distributed across 13 countries

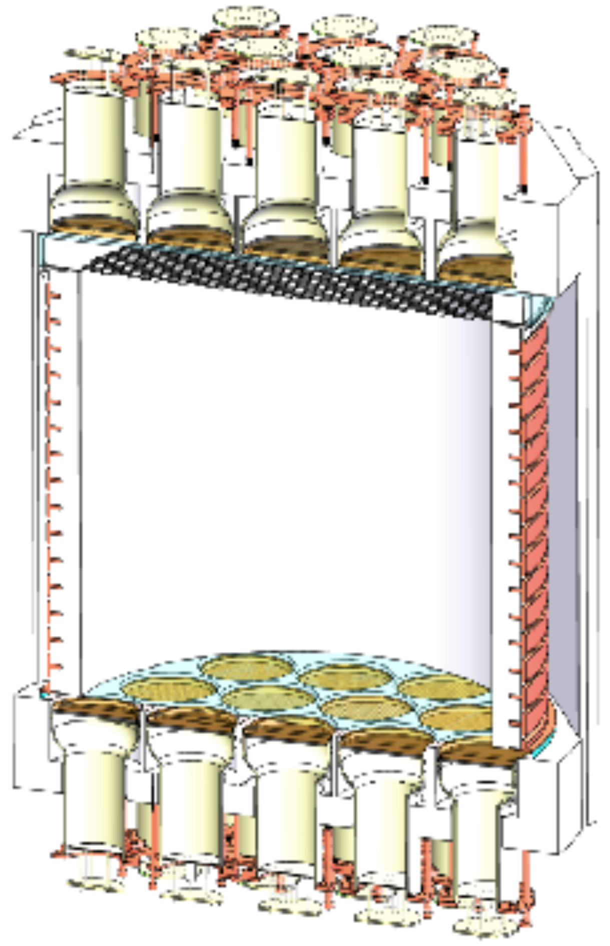
A multi-stage approach

2012 | **2013 - 2018** | **2025 - 2035** | **2030s - ...**



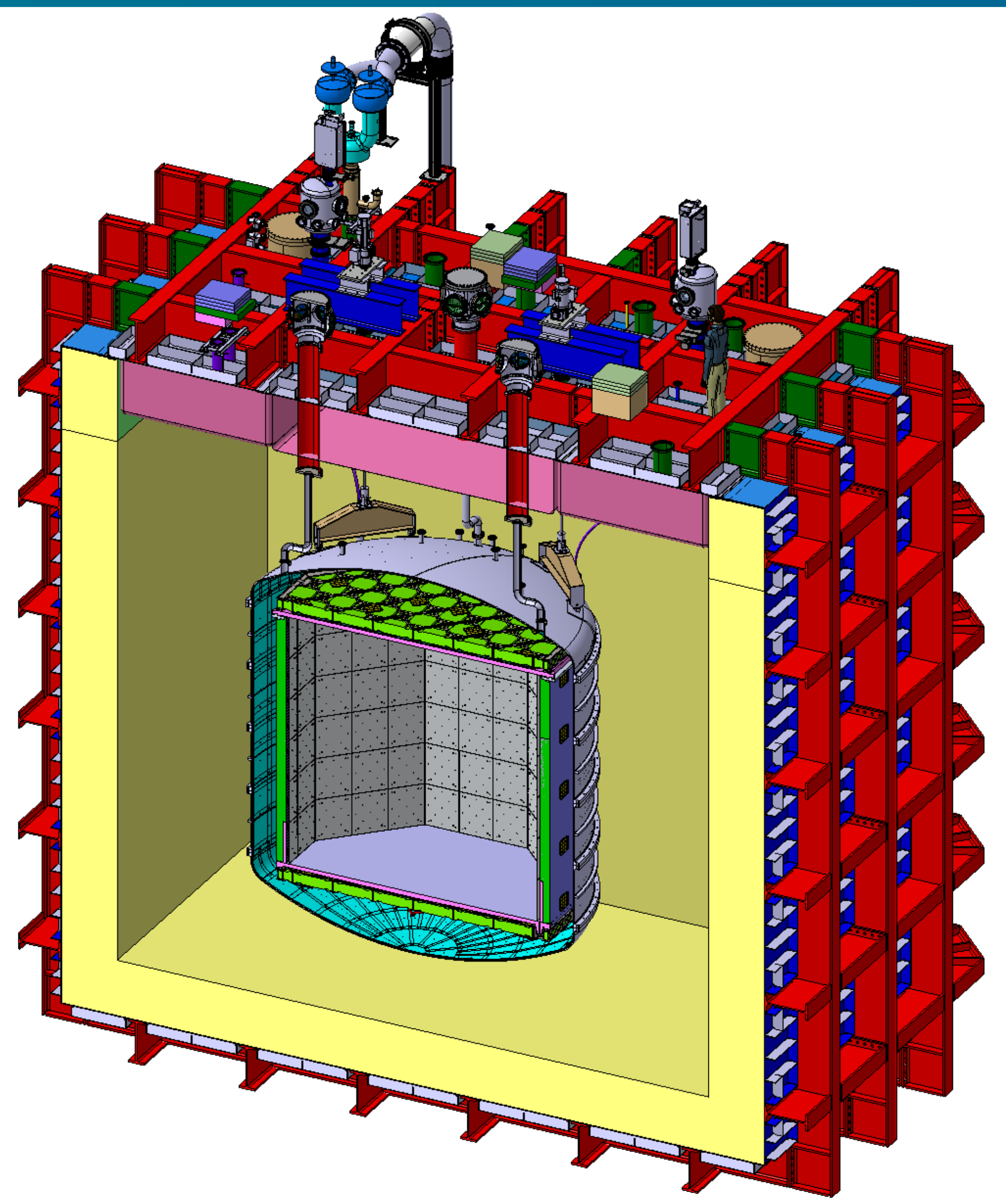
DarkSide-10

- First prototype
- Helped to refine TPC design
- Demonstrated a light yield >9PE/keV$_{ee}$



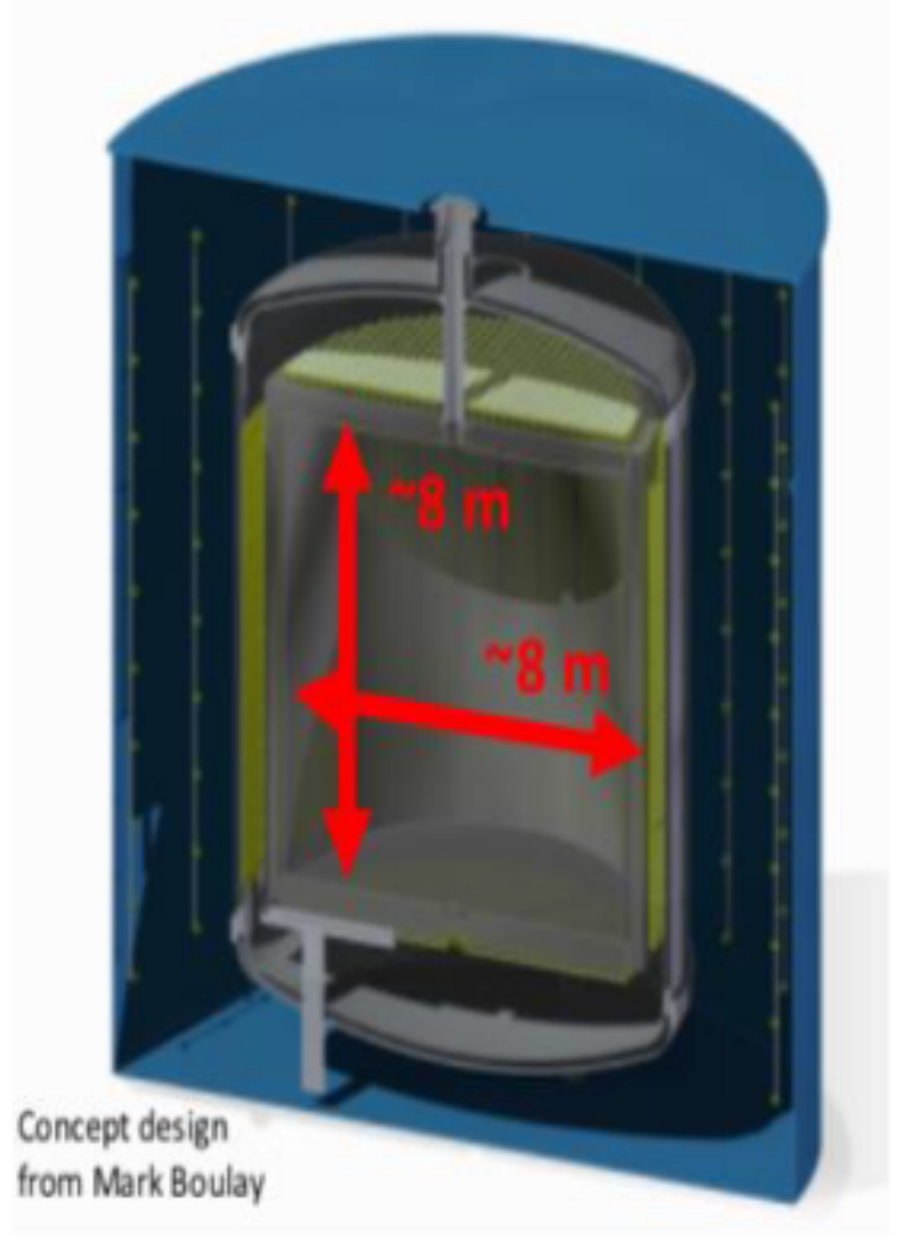
DarkSide-50

- Science detector
- Demonstrated the use of UAr
- First background-free results
- Best limits for low mass WIMP searches



DarkSide-20k @ LNGS

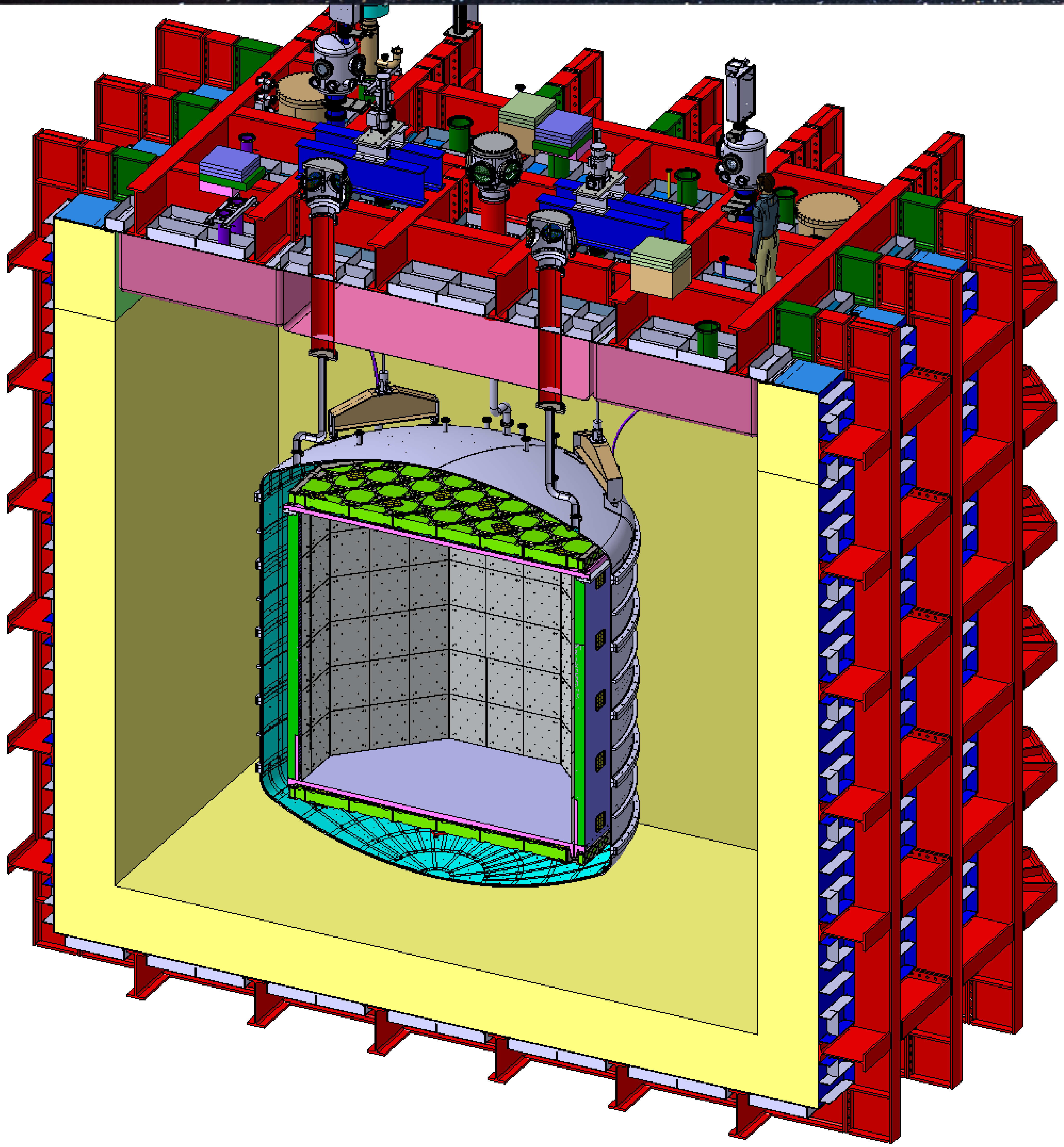
- Novel technologies
- First peek into the neutrino fog
- Nominal exposure: 200 t y



Argo @ SNOLAB

- Ultimate LAr DM detector
- Push well into the neutrino fog
- Nominal exposure: 3000 t y

DarkSide-20k overview



Nested detectors structure:

ProtoDUNE-like cryostat ($8x8x8m^3$) - Muon veto

Ti vessel separating AAr from underground UAr.

Neutrons and γ veto

WIMP detector: dual-phase TPC hosting 50t of LAr

Fiducial mass: 20 tonnes

Multiple detection channels for bkg supression:

Neutron after cuts: < 0.1 in 10 y

β and γ after cuts: < 0.1 in 10 y

Position reconstruction resolution:

~ 1 cm in XY

~ 1 mm in Z

The DS-20k PDU

- 24 FBK NUV-HD-Cryo SiPMs are aggregated in objects called tiles
- Tile have 4s6p topology
- SiPMs are read by a low noise transimpedance amplifier (TIA) or by a custom designed ASIC
- Tiles, in groups of four, are further aggregated in quadrants each of them read as 1 analog readout channel

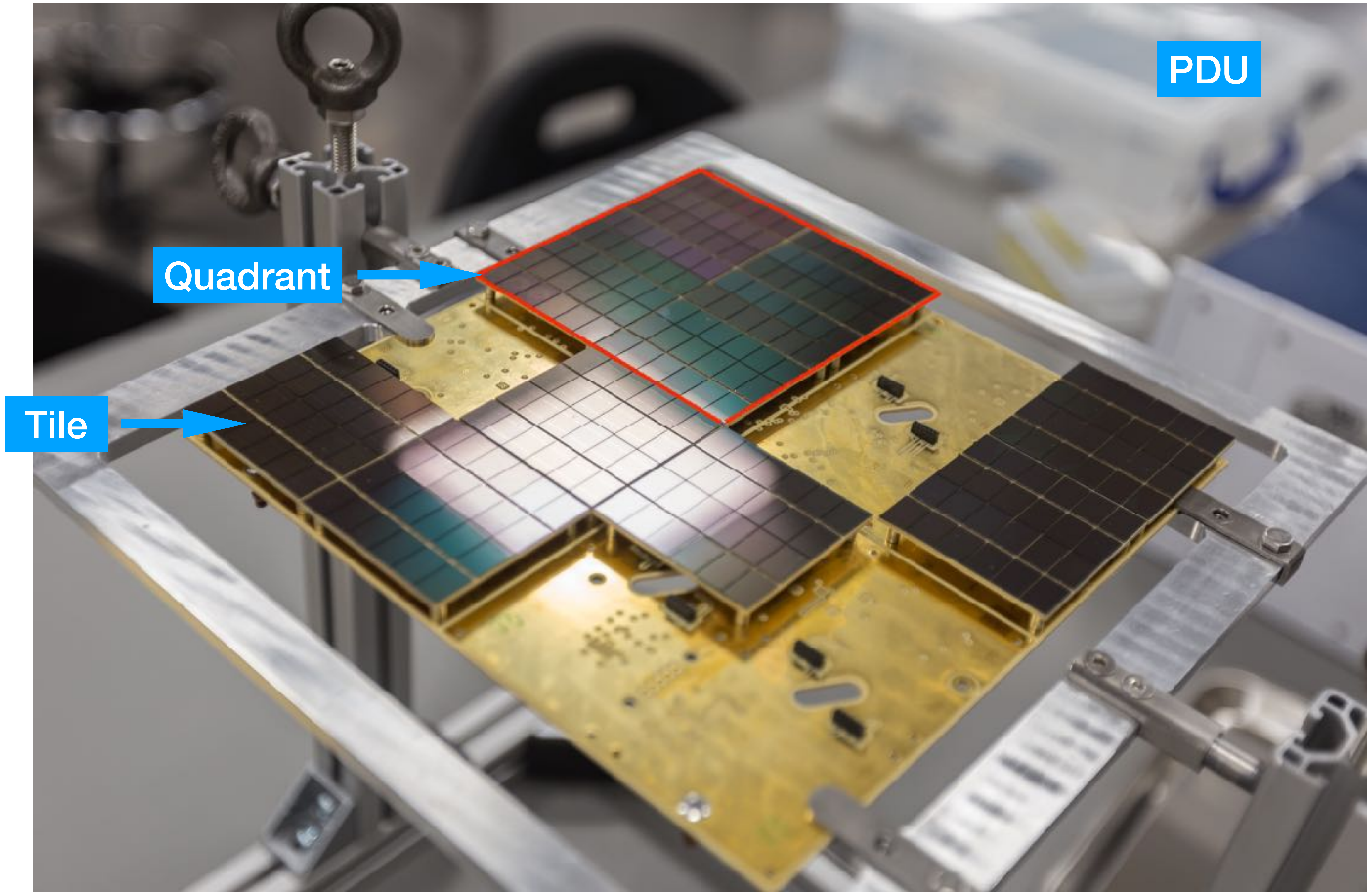
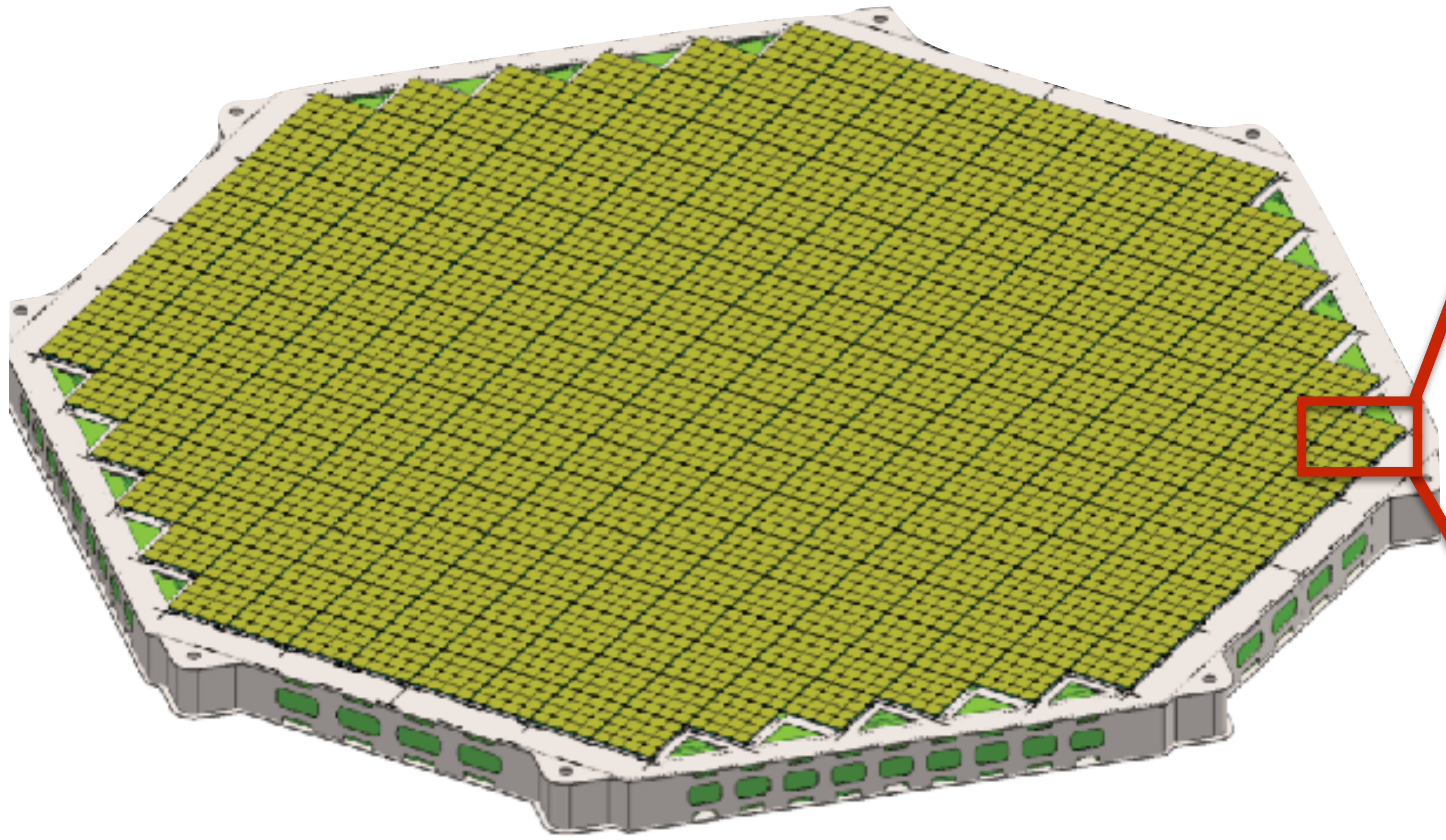


Photo-detection system

TPC optical plane

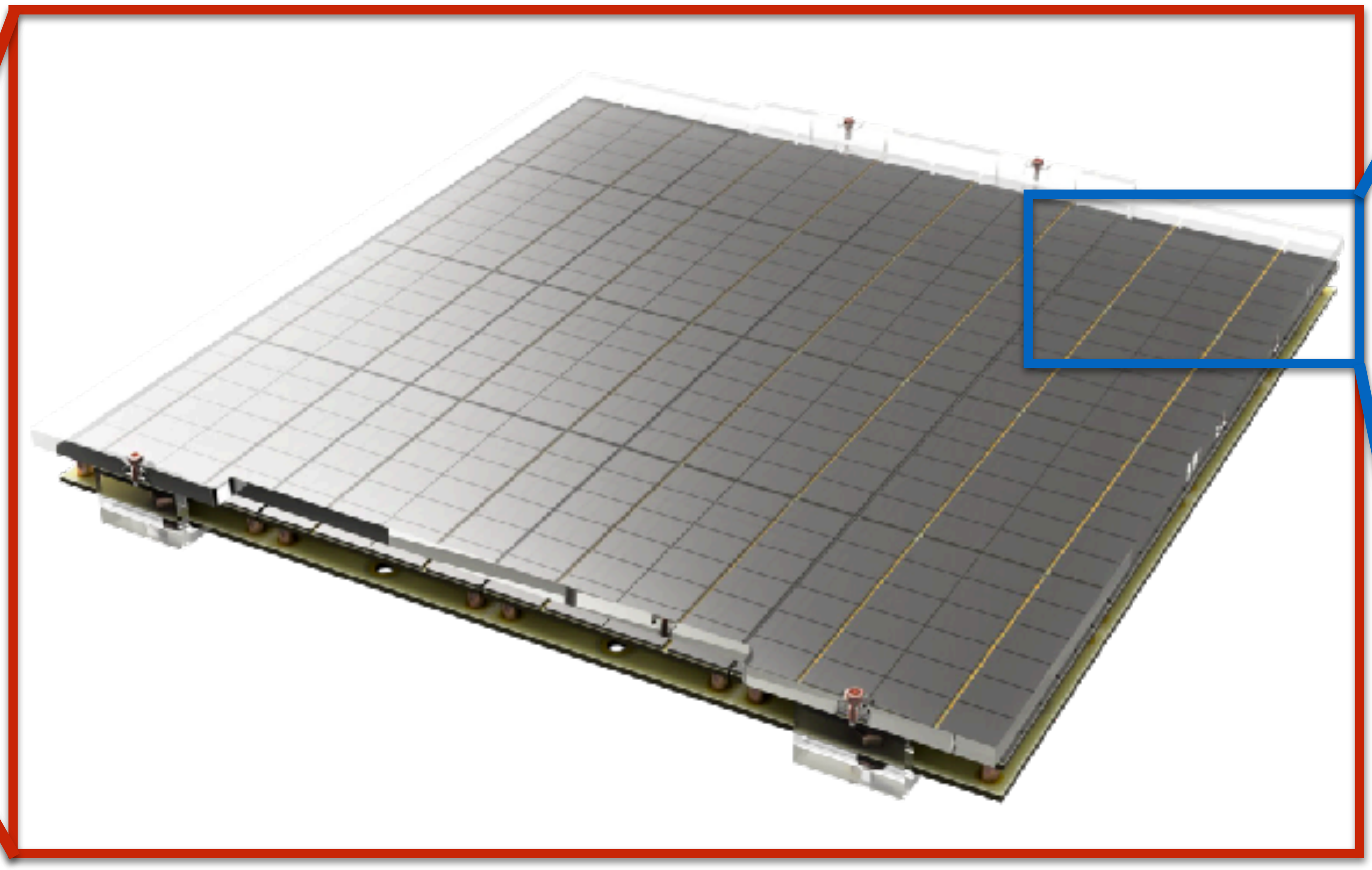


TPC planes area: ~21m^2

Organized in 525 PDUs

100% coverage of TPC top and bottom

Photo-Detection Unit



16 tiles arranged in 4 readout channels

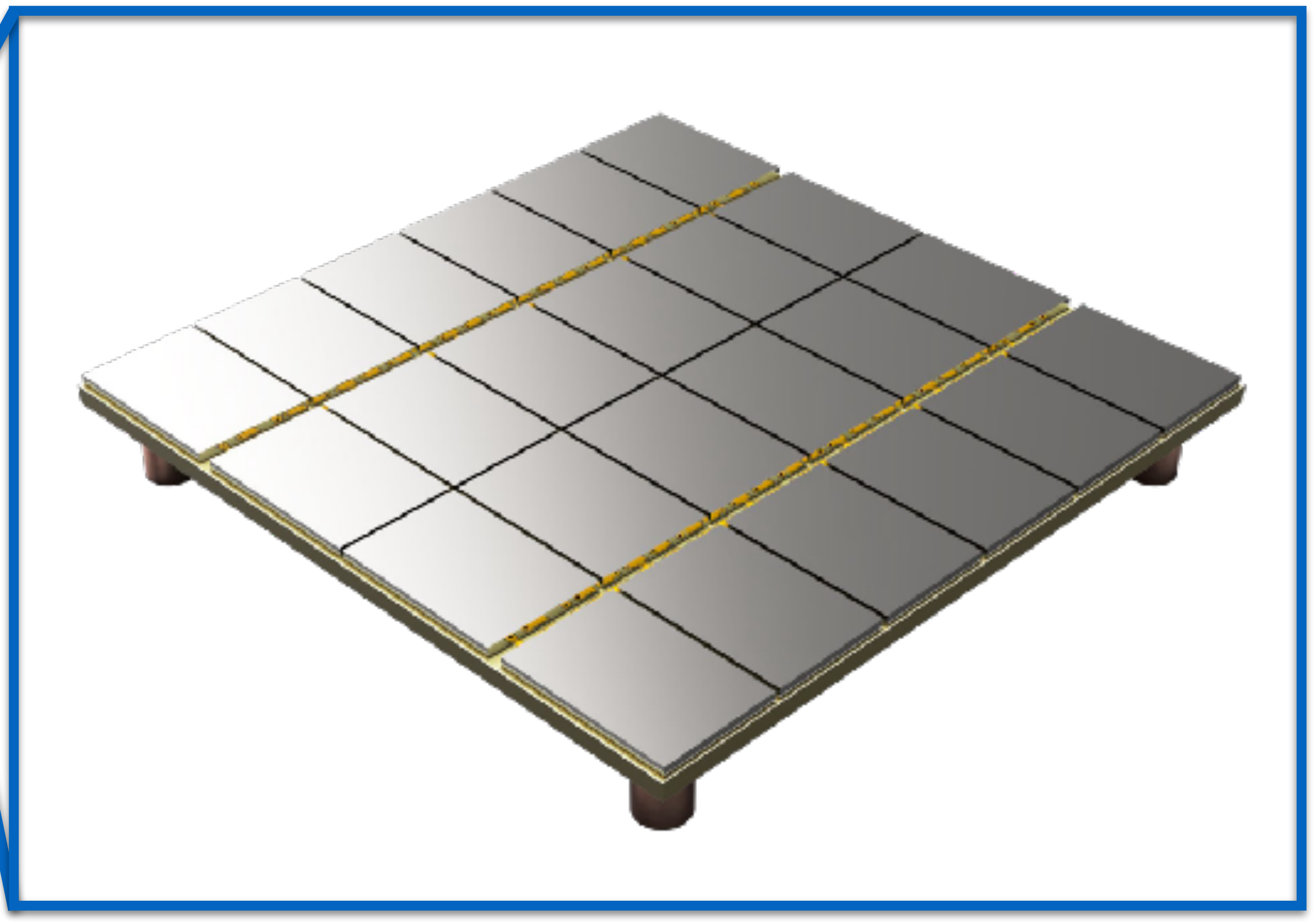
SiPM bias distribution

cryogenic pre-amplifiers bias

Signal transmission

Channels switch-on/off

Tile

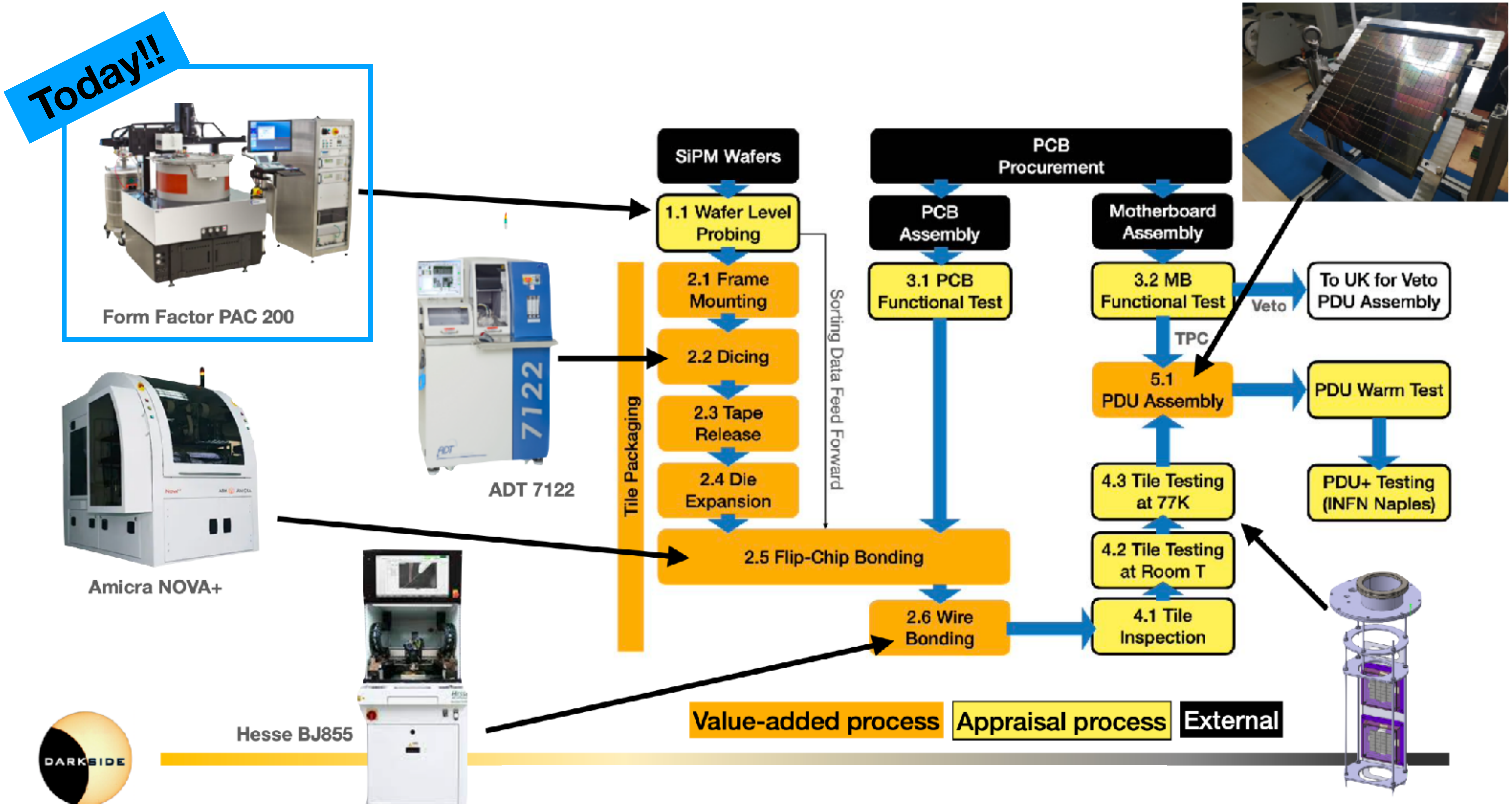


Photosensor

Array of 24 SiPMs

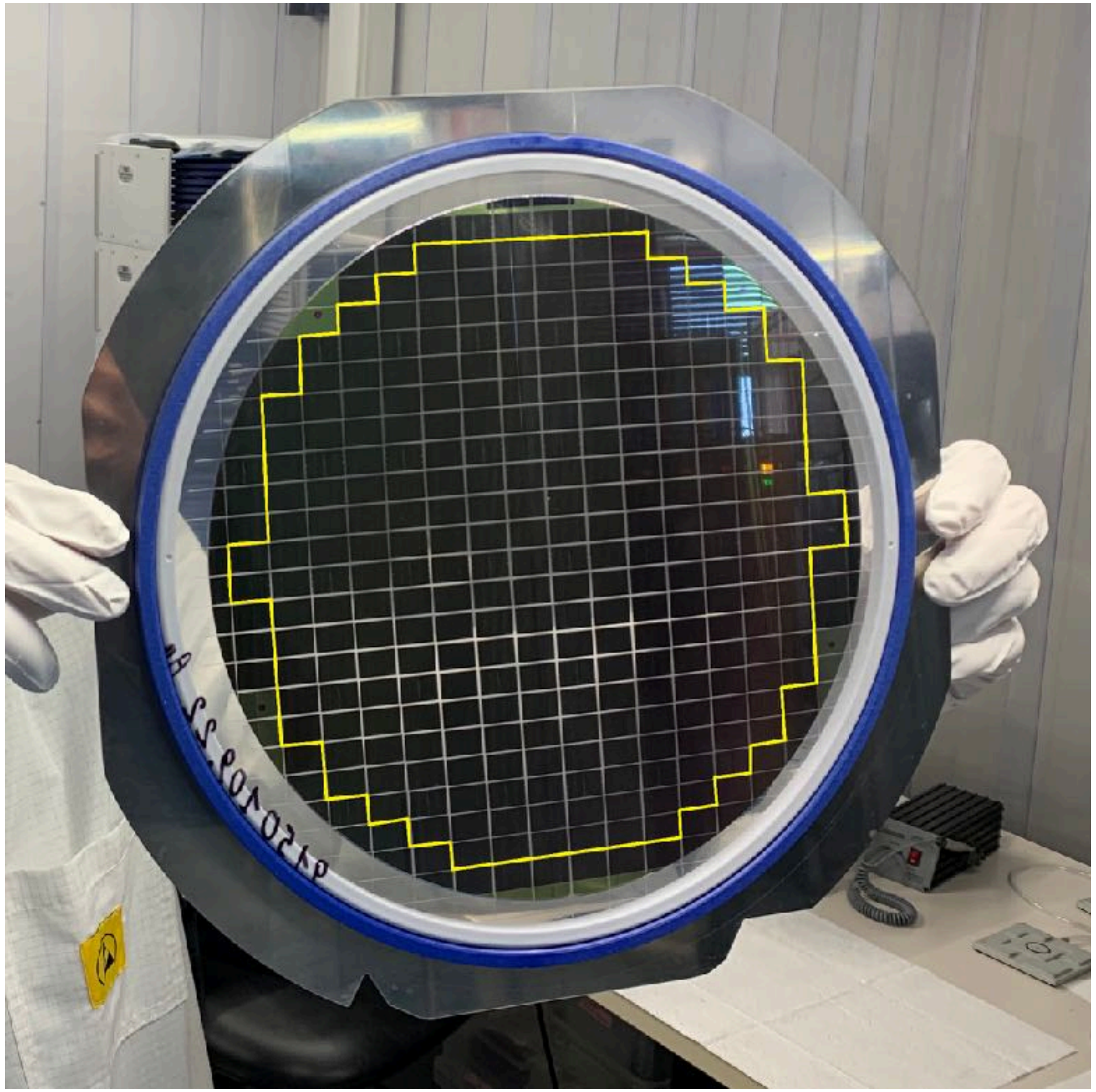
Signal pre-amplification

The DS-20k Silicon Packaging



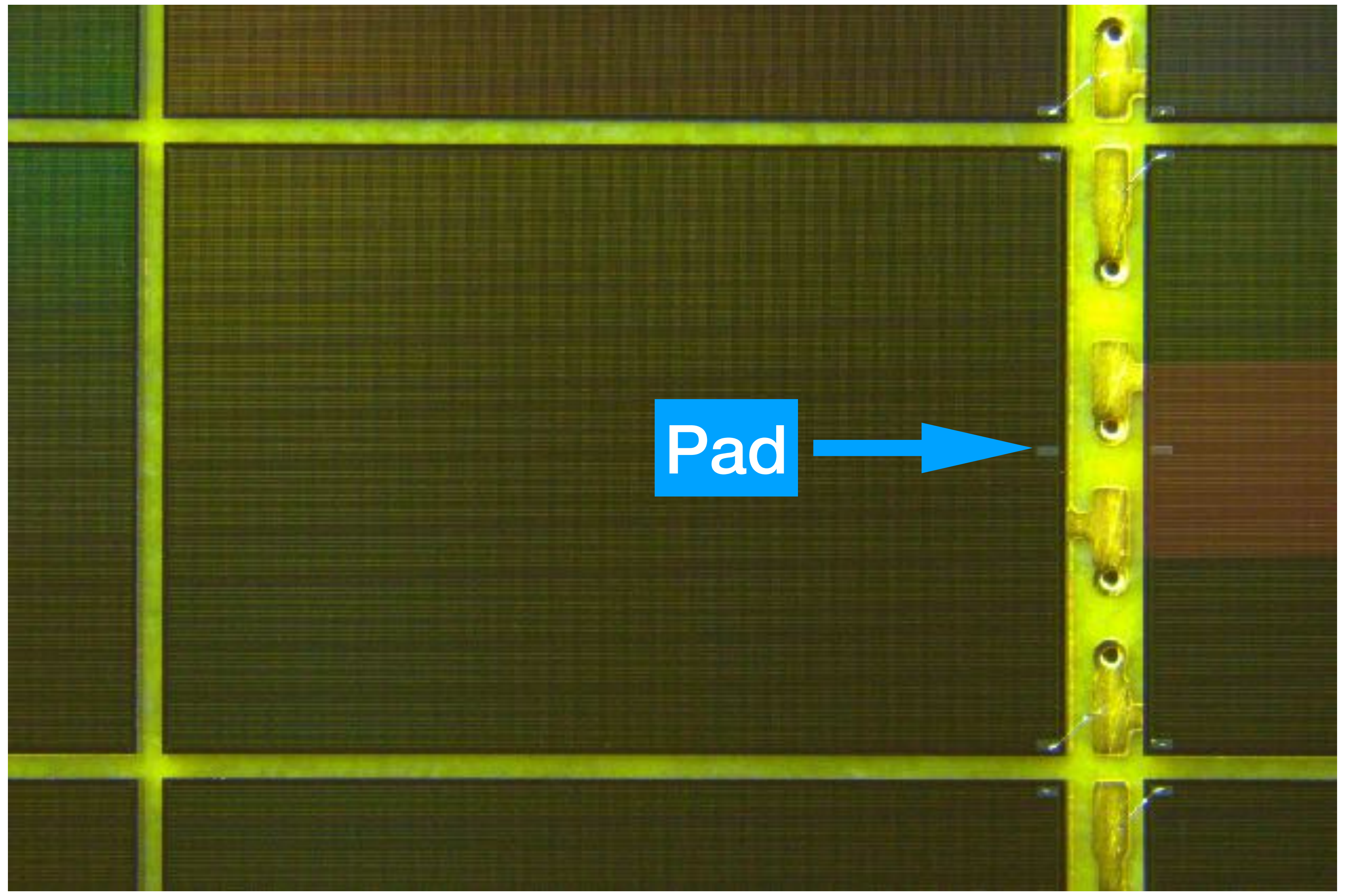
Wafers

- Wafers are produced by LFoundry (1400 in total) s.r.l. (Avezzano, AQ, Italy).
- 268 potentially working dice x wafer (264 testable).
- Wafer are produced by LFoundry in Lots (~25 wafers), 57 in total.
- Each of the ~25 wafers in a Lot travels together through the foundry process steps.
- The largest variation in the wafer performance is expected when comparing different lots.



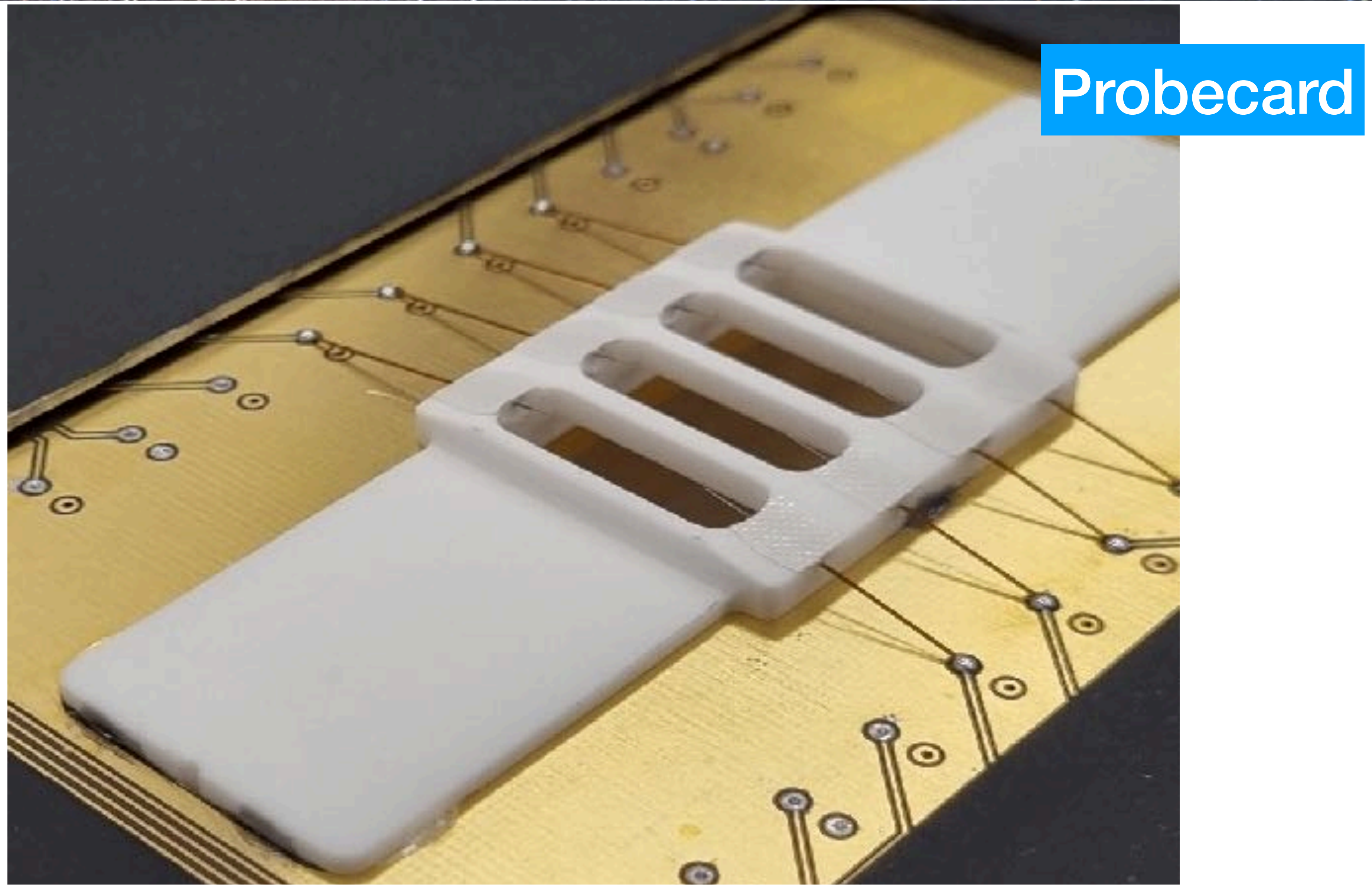
FBK NUV-HD Cryo SiPMs

- SiPM used in Darkside are FBK NUV-HD Cryo SiPM
- Each wafer in the Lot has a gold-coated backside that acts as the SiPM cathode.
- The SiPM anode contact is composed by three short-circuited aluminum pads.
- One pad is used for cryoprobing, the other two for wire bonding.
- SiPMs are soldered on an Arlon-based PCB (tile) and then wire bonded.



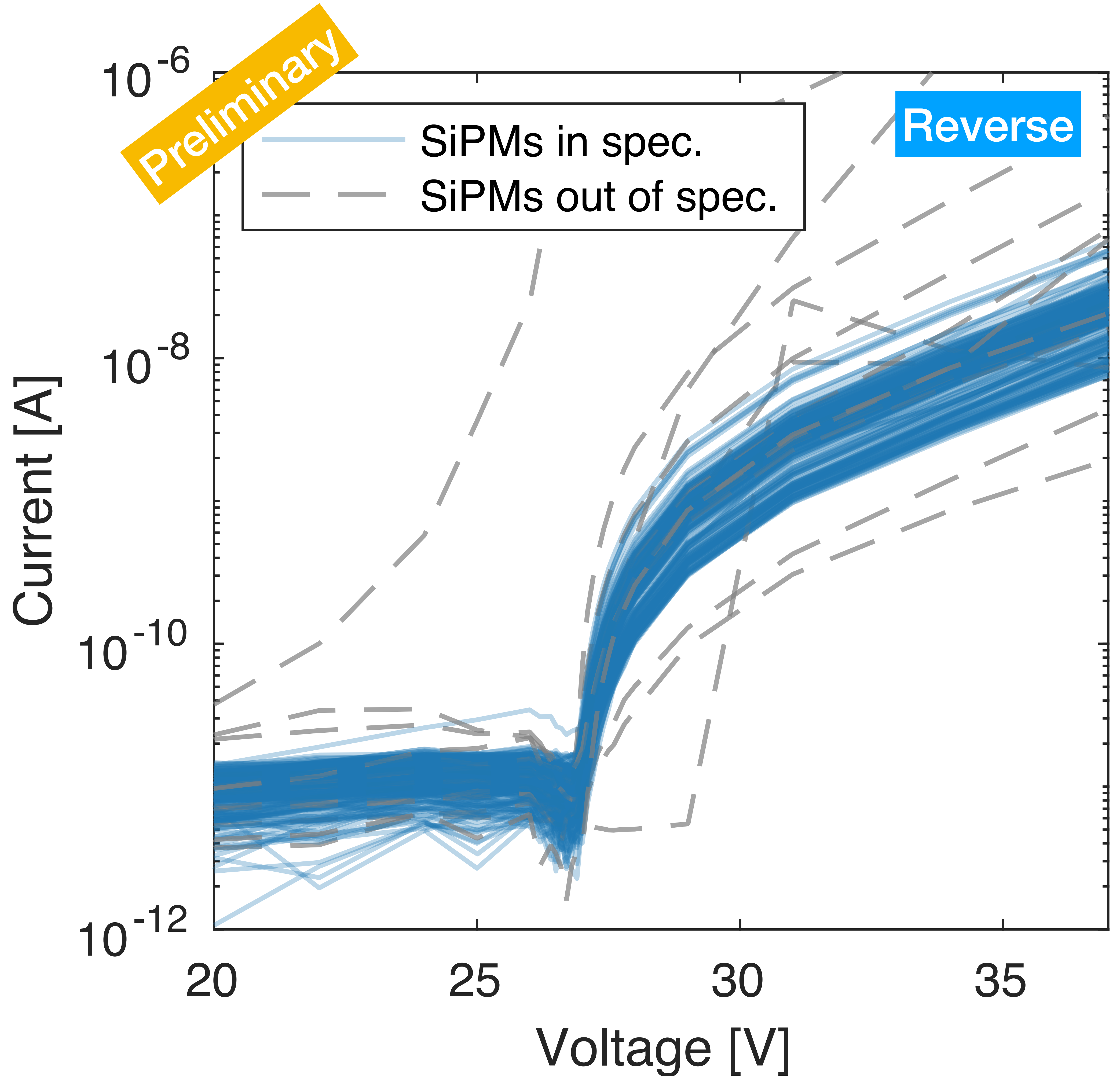
Hardware Setup

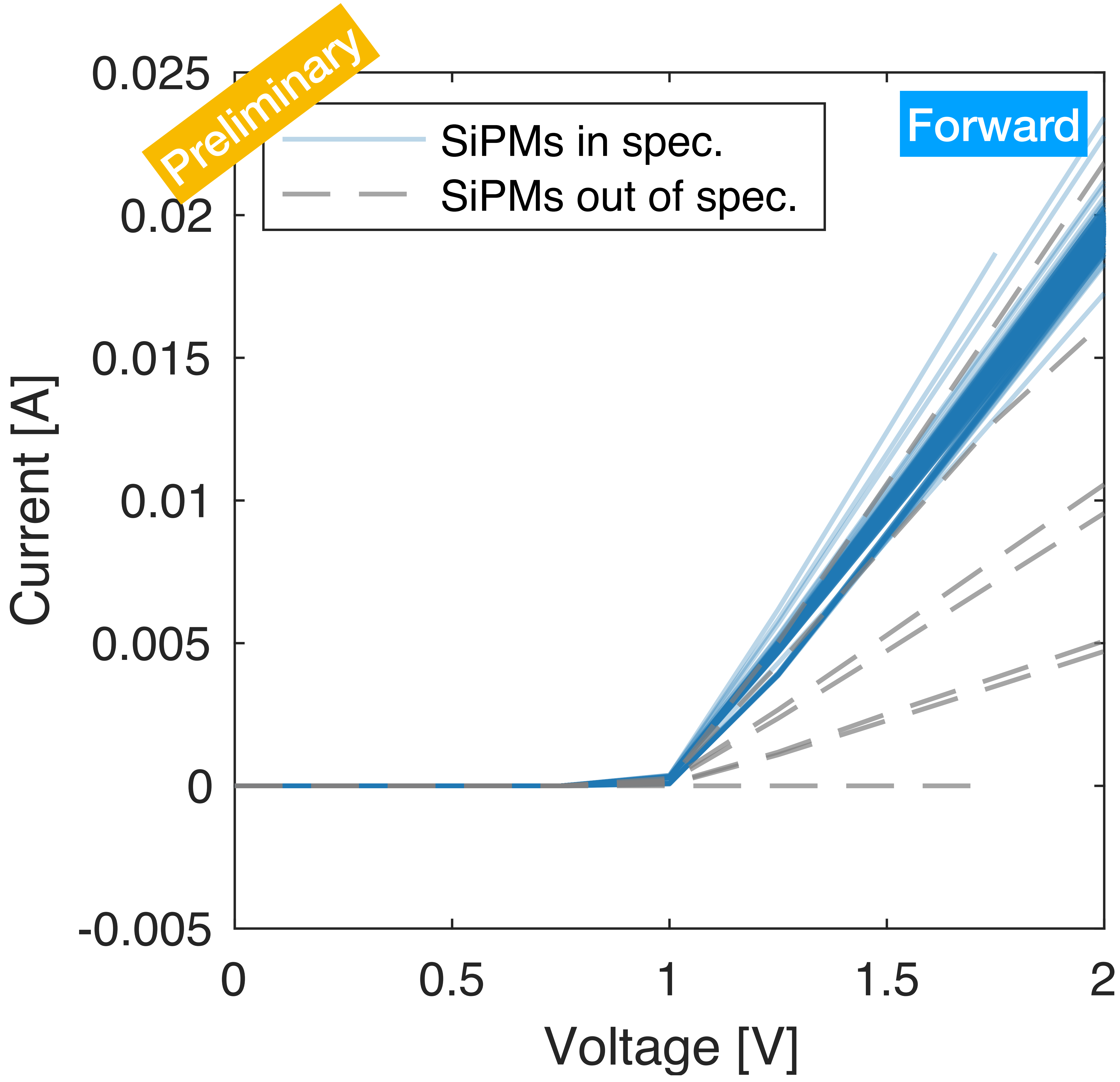
- Wafer are tested with a PAC-200 cryoprobe with a needle-based probecard (common cathode)



Experimental Details

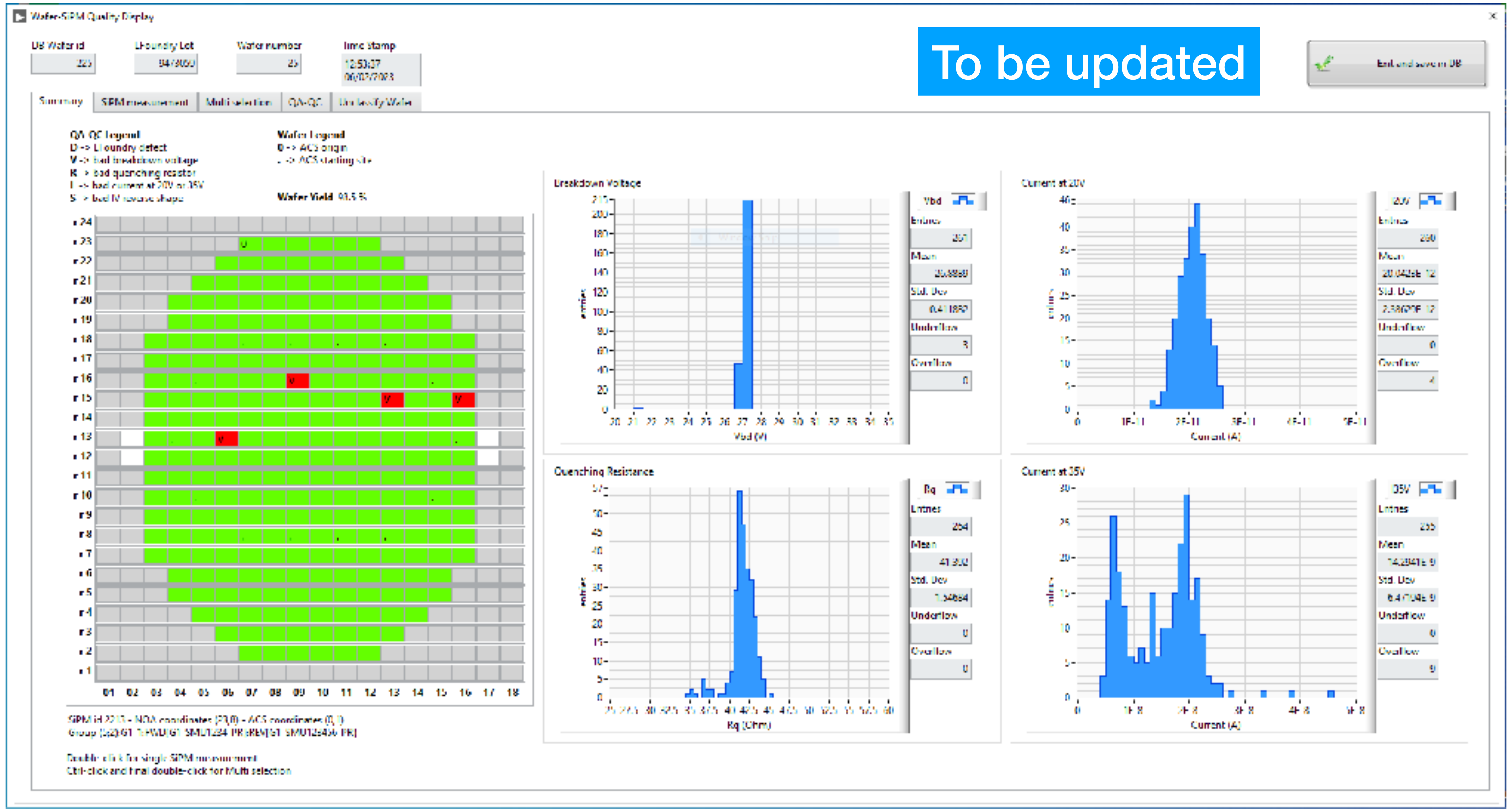
- 1 **Reverse** and 1 **Forward** bias IV curves are measured on each wafer SiPM dice at 77 K





Software Details

- Custom Labview based application
- Used for QA/QC enforcement
- Used for shifter operation (wafer alignment)
- Work in conjunction with Keithley ACS software and Form Factor Velox software
- Push the data to the database.
- It handles all probecard configuration (2x12 and 2x4) automatically



Acceptance Parameters

The reverse and forward bias IV curves of every SiPM dice from every production wafer are analyzed to ensure compliance with the following DS-20k wafer-level requirements:

1. Breakdown voltage $V_{\mathrm{bd}} \in [27.2 \pm 1.0]$ ← Reverse bias IV
2. Quenching resistor $R_{\mathrm{q}} \in [3.35 \pm 1.50]$ MΩ ← Forward bias IV
3. Leakage current before breakdown (at 20 V) ← Reverse bias IV

   $I_L \leq 40$ pA
4. Goodness of Fit GOF ≤ 25 ← Reverse bias IV

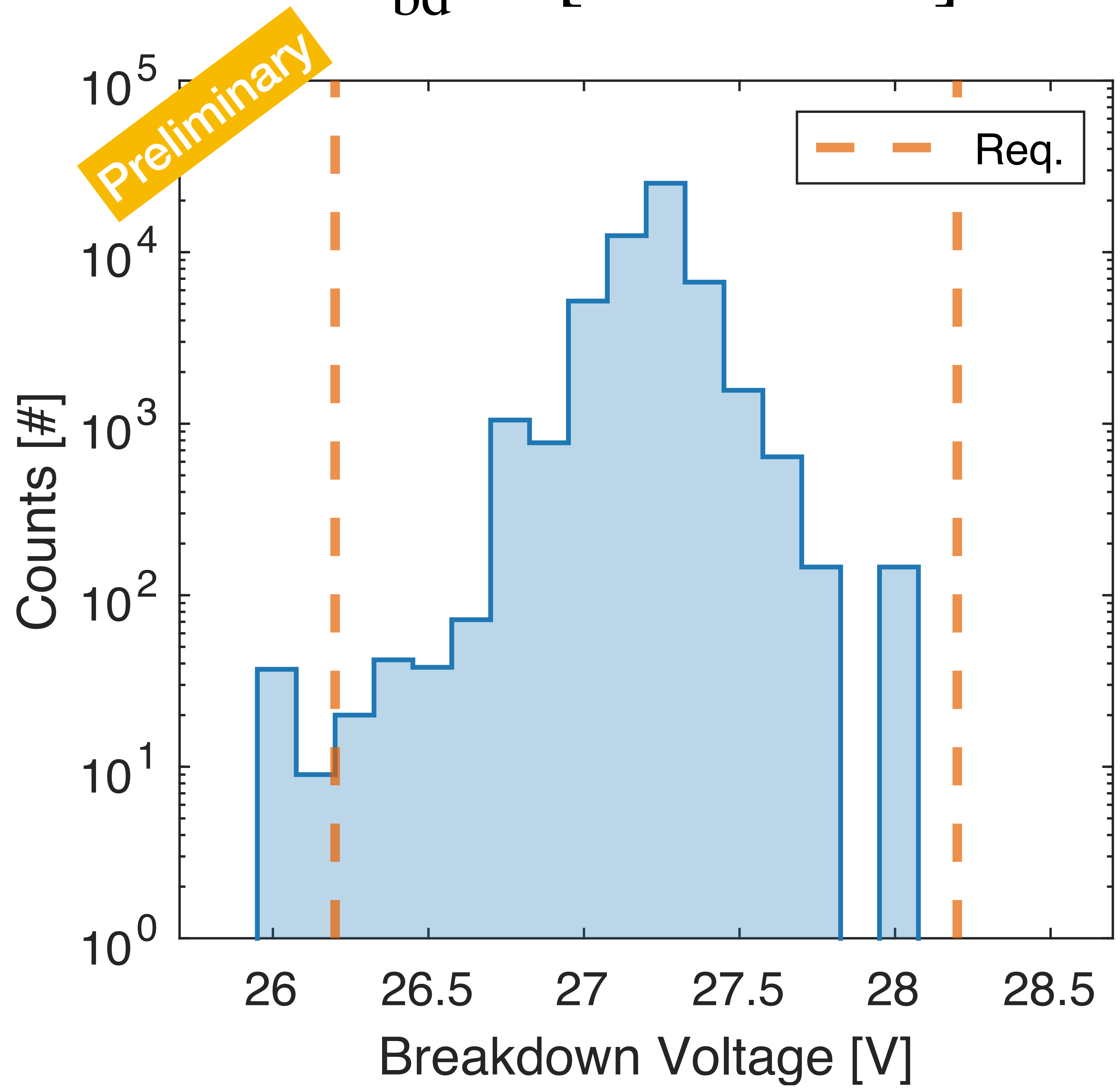
1),2) based on measurements on pre-production FBK wafers

* Shown today

Breakdown Voltage Distribution

Computed from the 1st derivative of IV curve

$$V_{\mathrm{bd}} \in [27.2 \pm 1.0]$$



<u>Variance Component Analysis</u>

$$\sigma^2_{V^P_{\mathrm{bd}}} = \sigma^2_{V^P_{\mathrm{bd}}/\textbf{Lot}} + \sigma^2_{V^P_{\mathrm{bd}}/\textbf{Wafer}} + \sigma^2_{V^P_{\mathrm{bd}}/\textbf{SiPM}} \sim 0.025\,\mathbf{V}$$

$\sigma^2_{V^P_{\mathrm{bd}}/\textbf{Lot}} \sim 0.010\ \mathbf{V}$ Lot-to-Lot variability

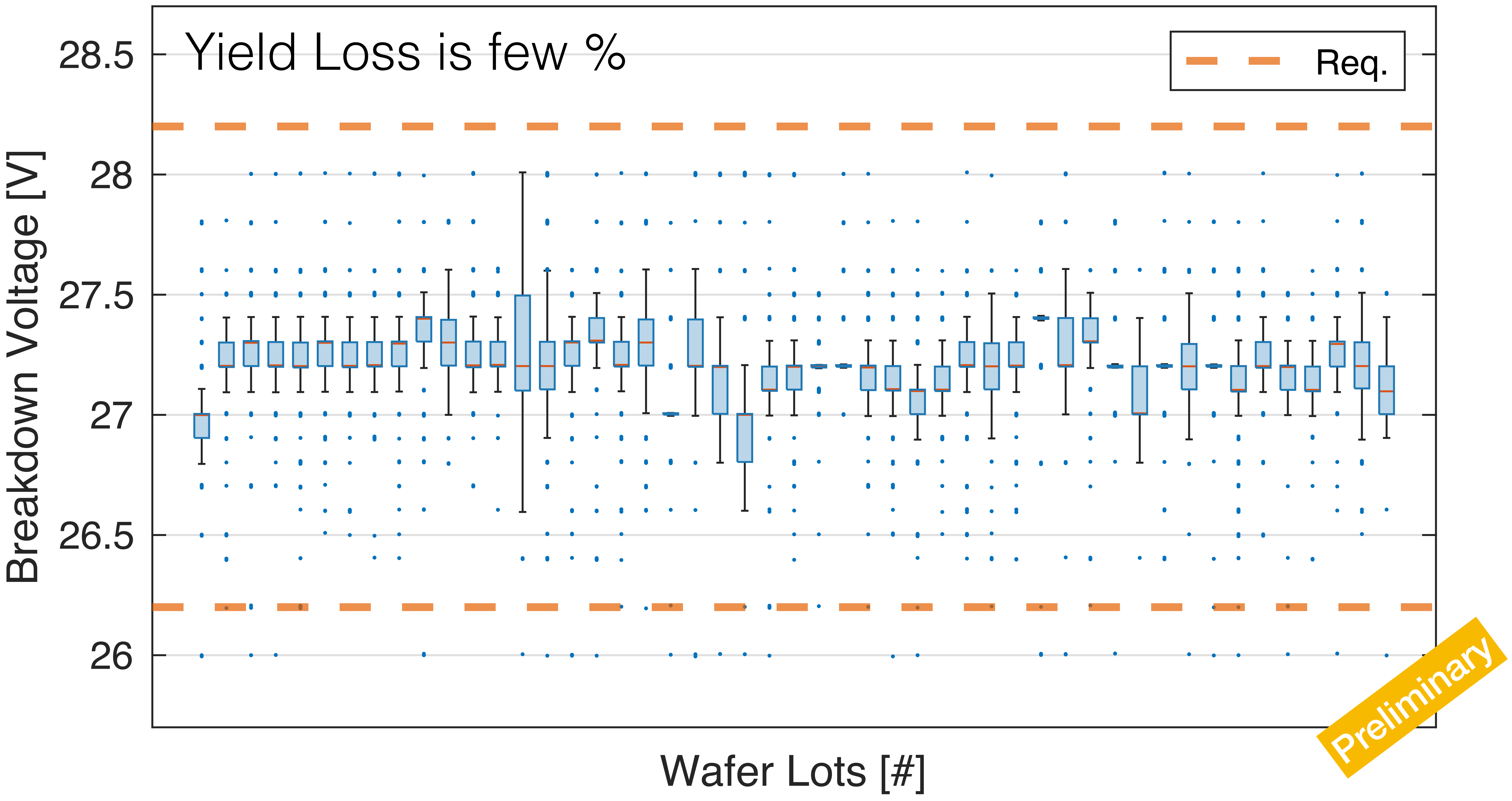
$\sigma^2_{V^P_{\mathrm{bd}}/\textbf{Wafer}} \sim 0.001\ \mathbf{V}$ Wafer-to-Wafer variability in single Lot

$\sigma^2_{V^P_{\mathrm{bd}}/\textbf{SiPM}} \sim 0.015\ \mathbf{V}$ SiPM to SiPM variability

- 54648 SiPMs tested up to now
- Lot-to-Lot variability dominates
- W-to-W variability is negligible

Breakdown Voltage Distribution

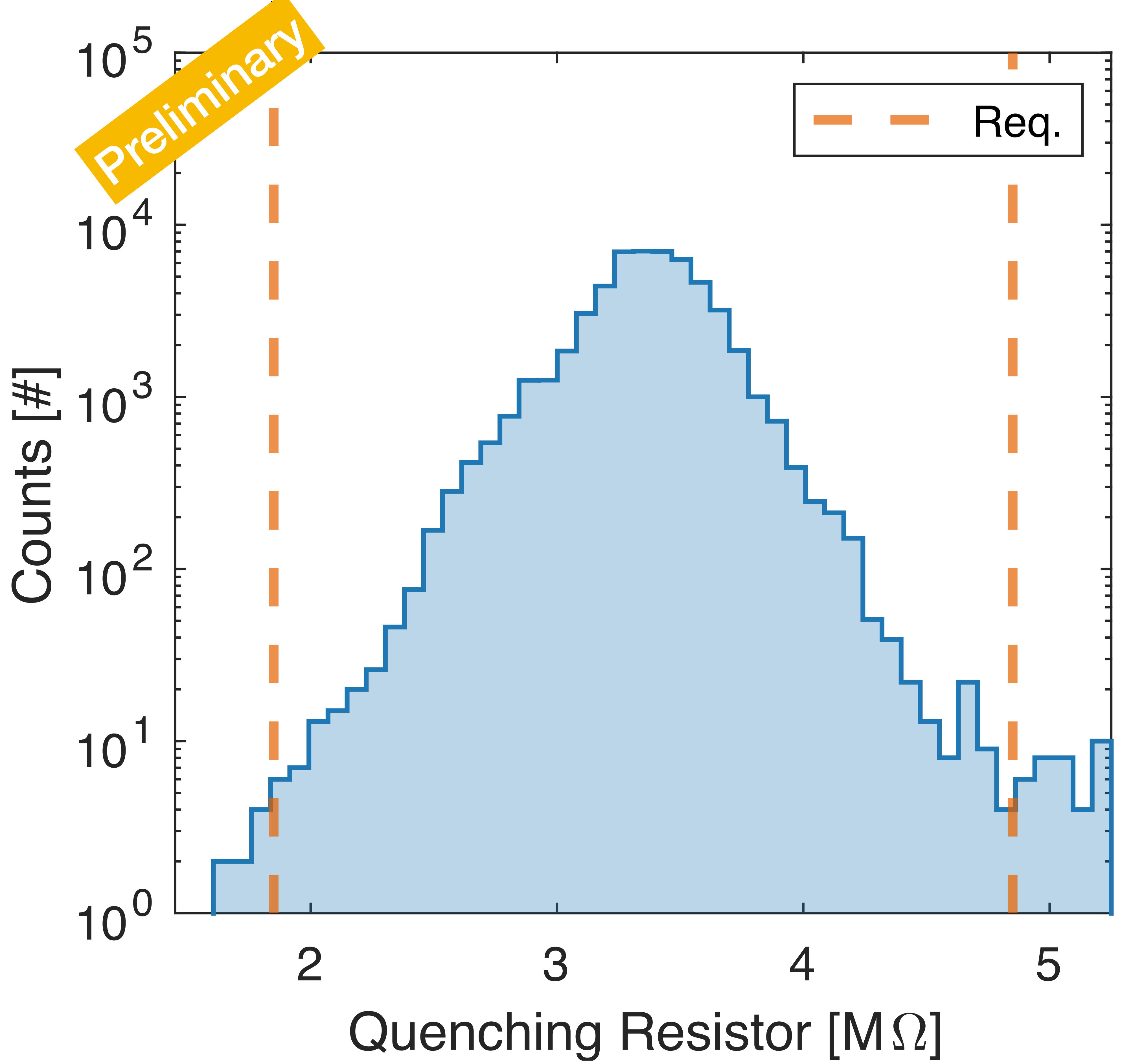
The largest variability (Lot-to-Lot) is clearly visible when doing a box plot of the entire prod.



Quenching Resistor Distribution

Computed from the linear fit of FWD bias IV

$R_q \in [3.35 \pm 1.50]\ \mathrm{M\Omega}$



<u>Variance Component Analysis</u>

$$\sigma^2_{R^P_q} = \sigma^2_{R^P_q/\mathbf{Lot}} + \sigma^2_{R^P_q/\mathbf{Wafer}} + \sigma^2_{R^P_q/\mathbf{SiPM}} = 0.077\ \mathbf{M\Omega}$$

$\sigma^2_{R^P_q/\mathbf{Lot}} \sim 0.046\ \mathbf{M\Omega}$ Lot-to-Lot variability

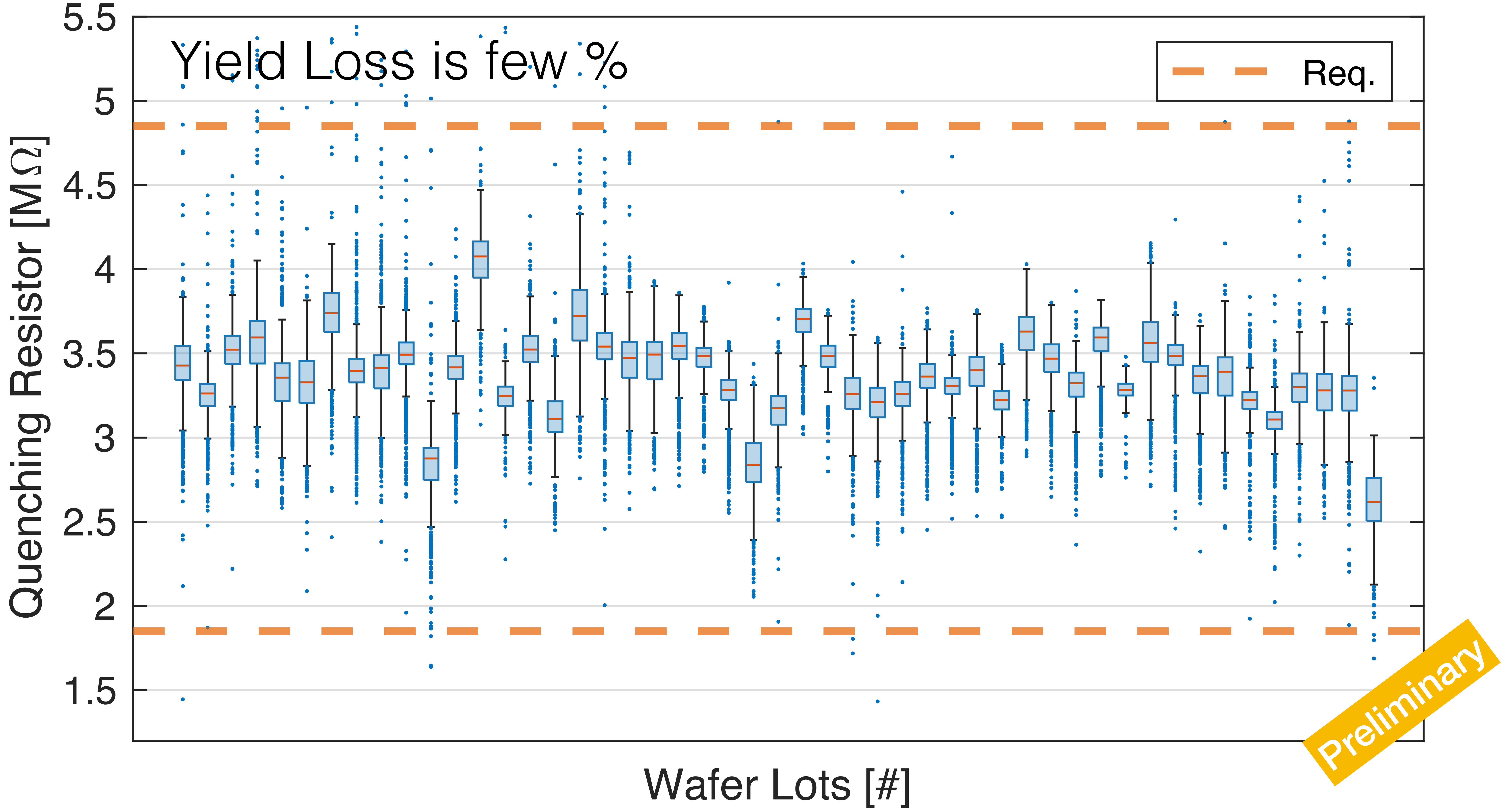
$\sigma^2_{R^P_q/\mathbf{Wafer}} \sim 0.008\ \mathbf{M\Omega}$ Wafer-to-Wafer variability in single Lot

$\sigma^2_{R^P_q/\mathbf{SiPM}} \sim 0.023\ \mathbf{M\Omega}$ SiPM to SiPM variability

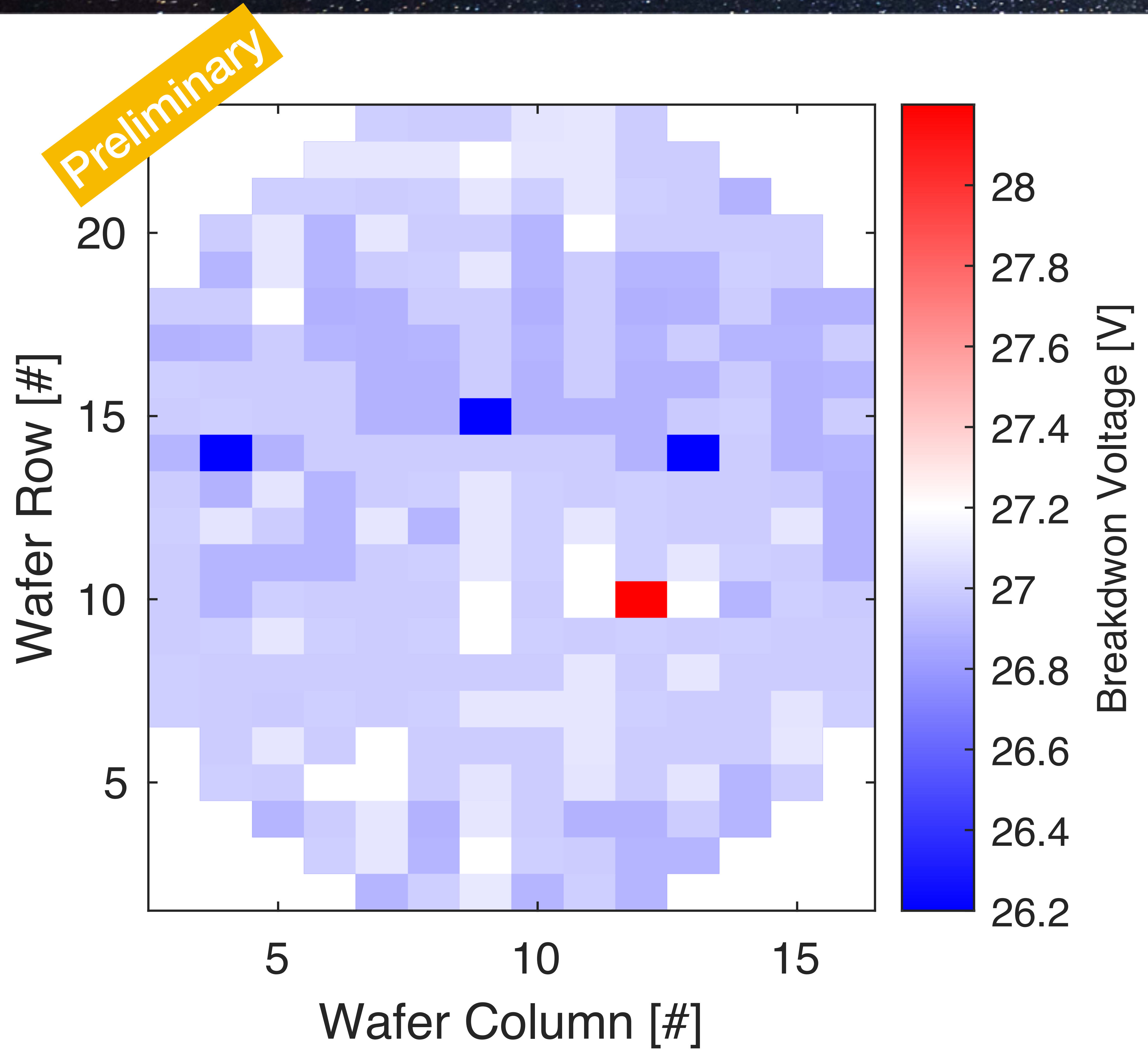
- 54648 SiPMs tested up to now
- Lot-to-Lot variability dominates
- W-to-W variability is negligible

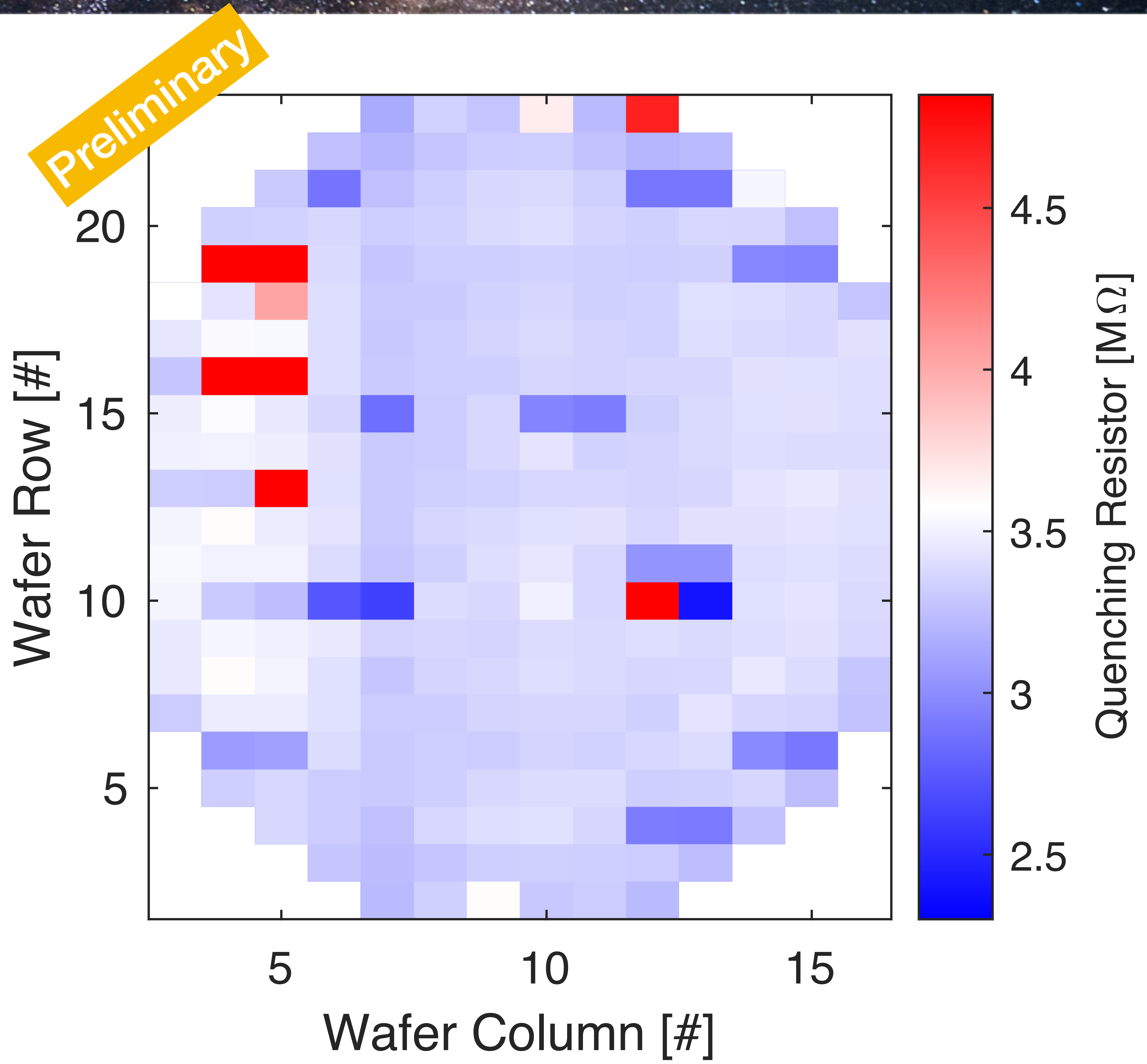
Quenching Resistor Distribution

The largest variability (Lot-to-Lot) is clearly visible when doing a box plot of the entire prod.



Spatial Distribution





Excellent uniformity <u>within the same wafer</u>! Plan is to use “Lots” as the main production quantity to control at the tile assembly stage. No sorting is planned.

Goodness of Fit (GOF)

In general, the SiPM current under illumination can be written as

$$I(V,\lambda) = f(V) \times \left[\mathbf{PDE}_\lambda(V) \times \Phi(\lambda) + \mathbf{R}^{\mathbf{DCR}}_{\mathbf{SiPM}} \right] \quad \text{~Hz}$$

$$f(V) \sim q_e \times \left(1 + \overline{\Lambda}\right) \times \overline{\mathbf{G}}_{1\ \mathbf{PE}},$$

Correlated noise

If we assume that all the SiPMs have identical characteristics

$$\frac{I_1(V,\lambda)}{I_2(V,\lambda)} = \frac{\Phi_1(\lambda)}{\Phi_2(\lambda)} \equiv k\,.$$

In order to ensure compliance of the wafer level IV curves we introduce a parameter

called Goodness of Fit (GOF) defined as $\text{GOF} = \sum_i \frac{(I_i - k\overline{I}_i)^2}{\overline{\sigma_i^2}}$

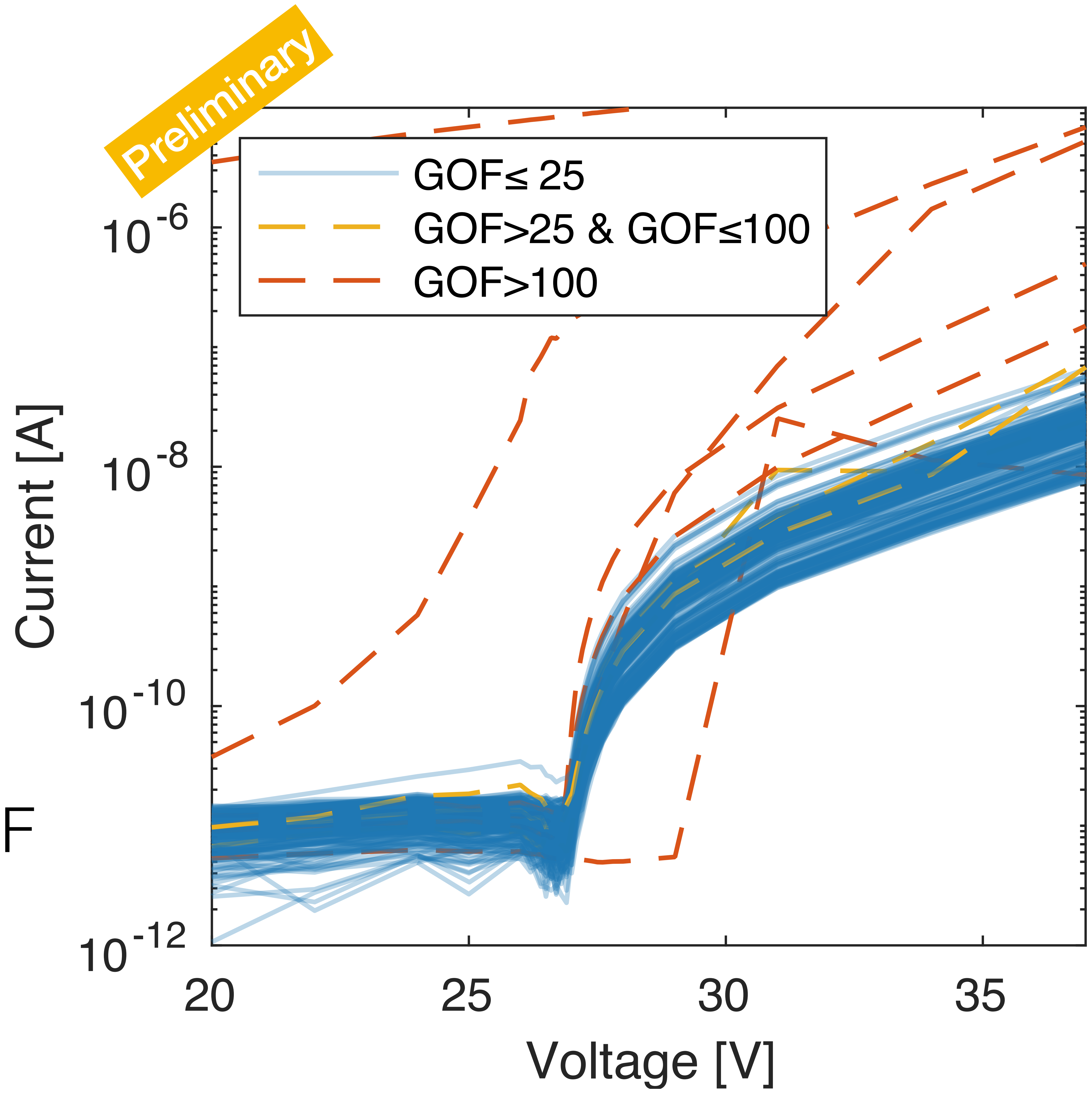
Goodness of Fit (GOF)

$$\text{GOF} = \sum_i \frac{(I_i - k\overline{I_i})^2}{\overline{\sigma_i^2}} \qquad k = \frac{\sum_i (\overline{I_i} \times I_i)/\overline{\sigma_i^2}}{\sum_i \overline{I_i^2}/\overline{\sigma_i^2}}$$

Scaling Factor

Measured IV Reference IV

- SiPM are categorised accordingly to their GOF parameter
- Really effective to screen SiPMs



Goodness of Fit (GOF)

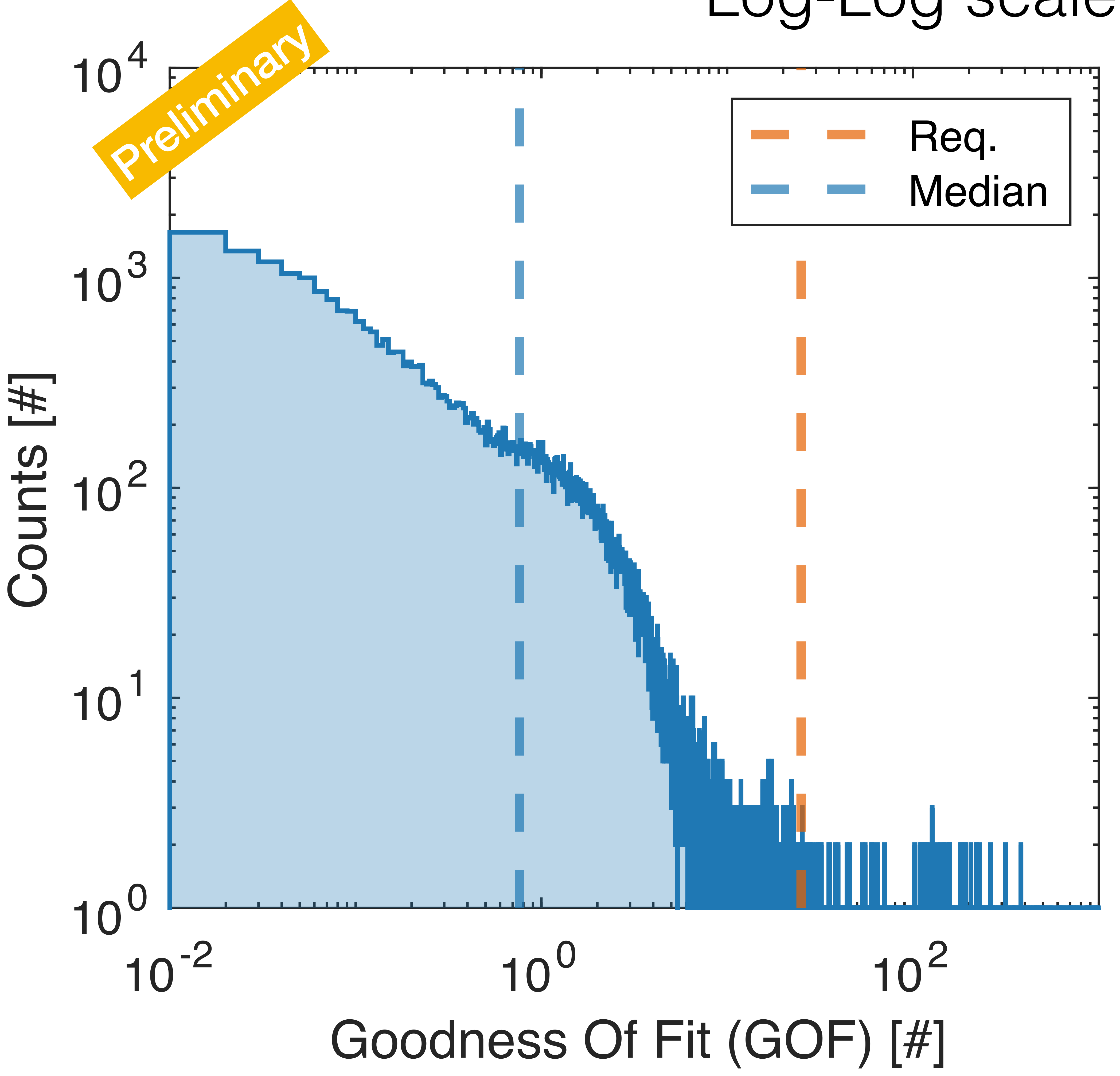
$$GOF = \sum_i \frac{(I_i - k\overline{I}_i)^2}{\overline{\sigma_i^2}} \qquad k = \frac{\sum_i (\overline{I}_i \times I_i)/\overline{\sigma_i^2}}{\sum_i \overline{I_i^2}/\overline{\sigma_i^2}}$$

Scaling Factor

Measured IV Reference IV

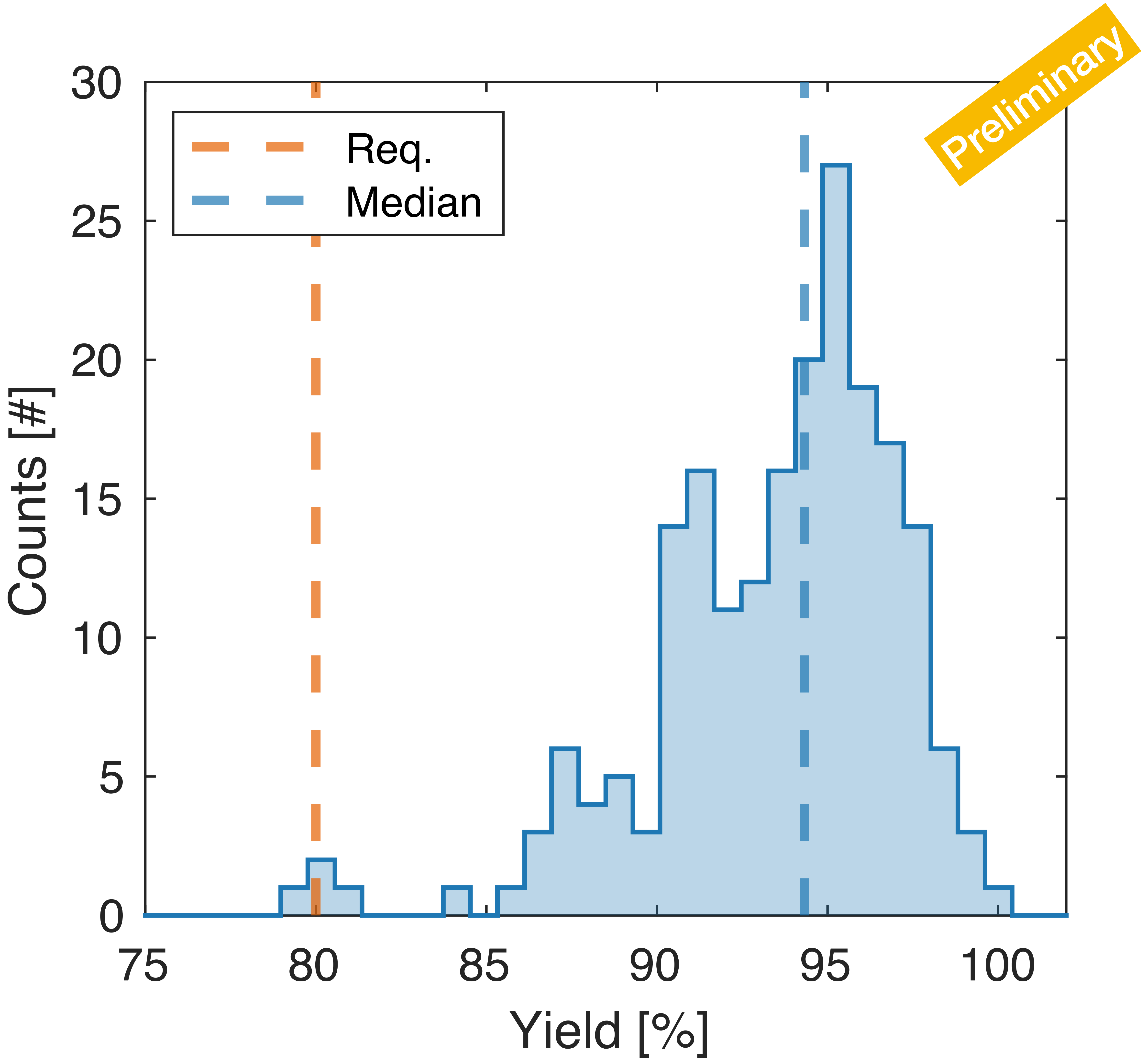
The distribution has a tail that ends at a GOF~25 that was assumed as the requirement based also on the results of a **simulation** of the GOF parameter

Log-Log scale



Production Yield

- The Yield is computed assuming 264 testable dice (not the total 268)
- Average yield is 92.9 ± 0.4 %
- Significantly exceeds the required 80%



Conclusion

- The results presented today are based on the first 200 wafers (15% of the entire production).
- Cryoprobe operation restarted 2 weeks ago after a couple of months of stop for maintenance
- **A paper on the wafer level QA/QC** is in preparation!
- A bit more than 1 year to screen the entire DS-20k production
- Production of the first detector PDU scheduled to start in 2024!

Thanks!

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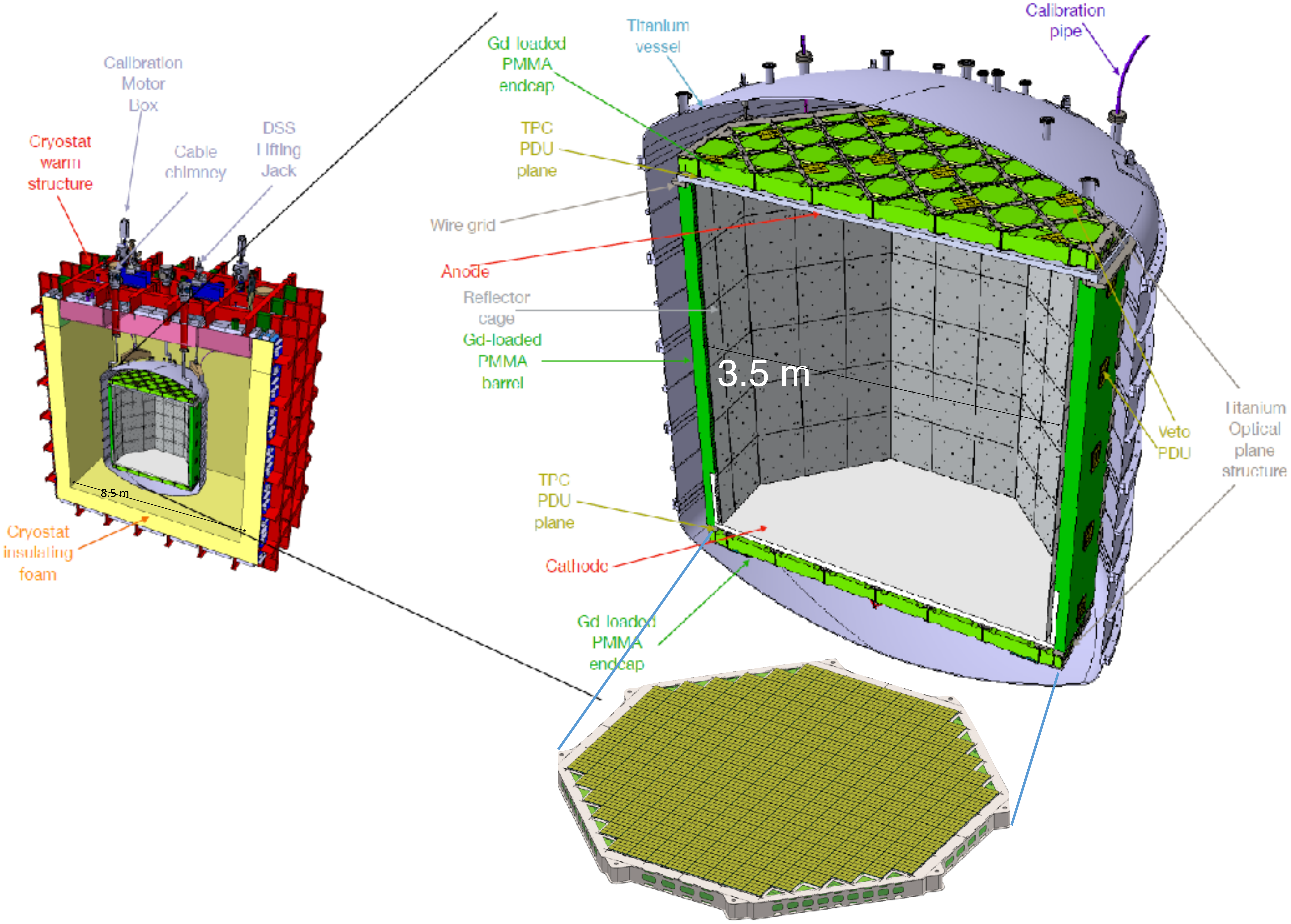
Inner detector

- Integration of **TPC** and **VETO** in a single object
- **TPC Vessel:**
  - top and bottom: transparent pure acrylic
  - lateral walls: Gd-loaded acrylic + reflector + WLS
  - anode, cathode and field cage made with conductive paint (Clevios)
- **TPC readout:** 21m^2 cryogenic SiPMs
- **Veto:**
- TPC surrounded by a single phase (S1 only) detector in UAr
- TPC lateral walls + additional top&bottom planes in Gd loaded acrylic (PMMA)
  - to thermalize n (acrylic is rich in Hydrogen)
  - neutron capture releases high energy γ
- **Veto readout:** 5 m^2 cryogenic SiPMs

99 t UAr held in Ti vessel



TPC photo-detection system