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

G. Gallina

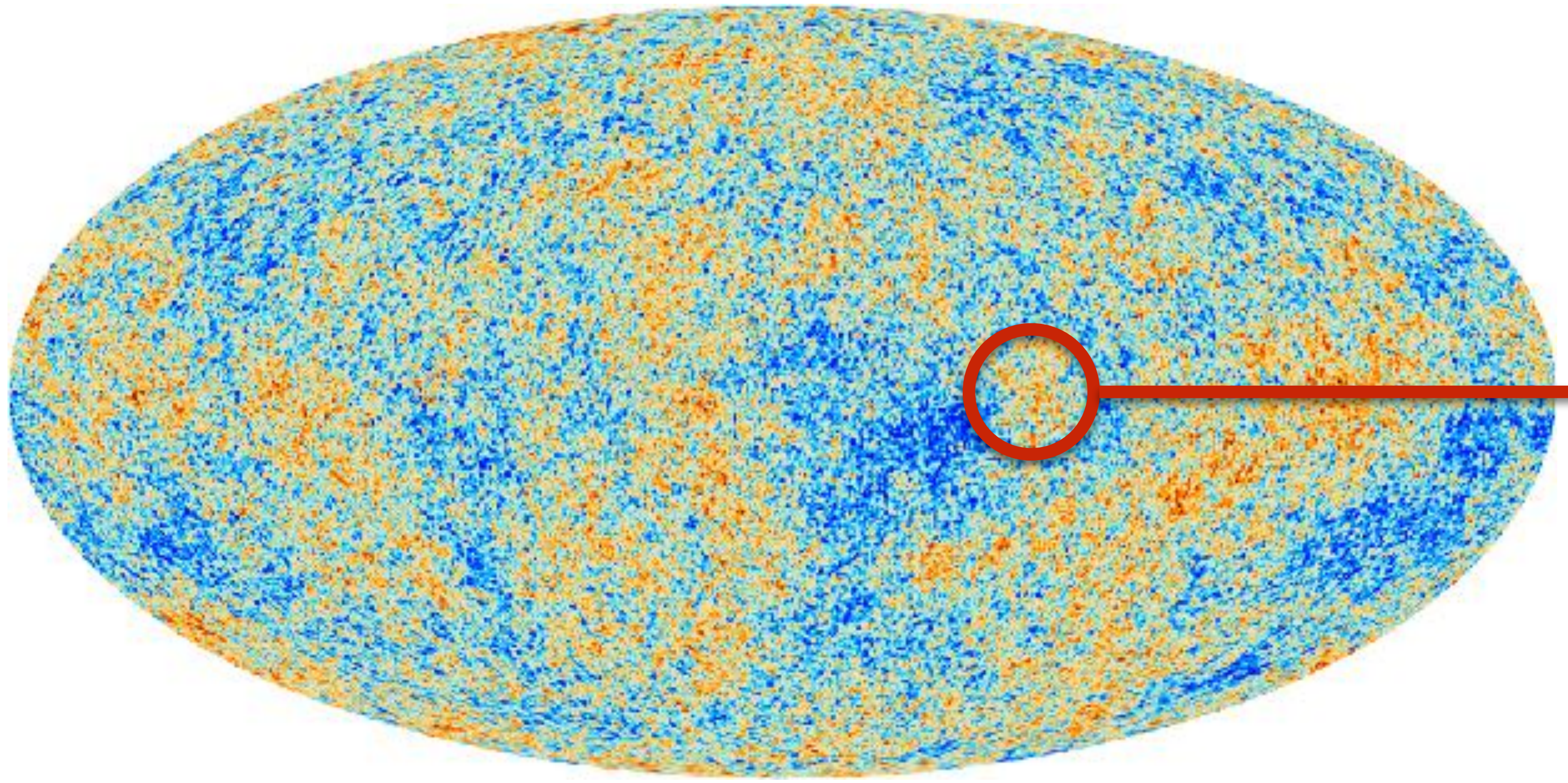
*Princeton University, INFN*

*on behalf of the GADMC*

11/8/2023

# The physics case

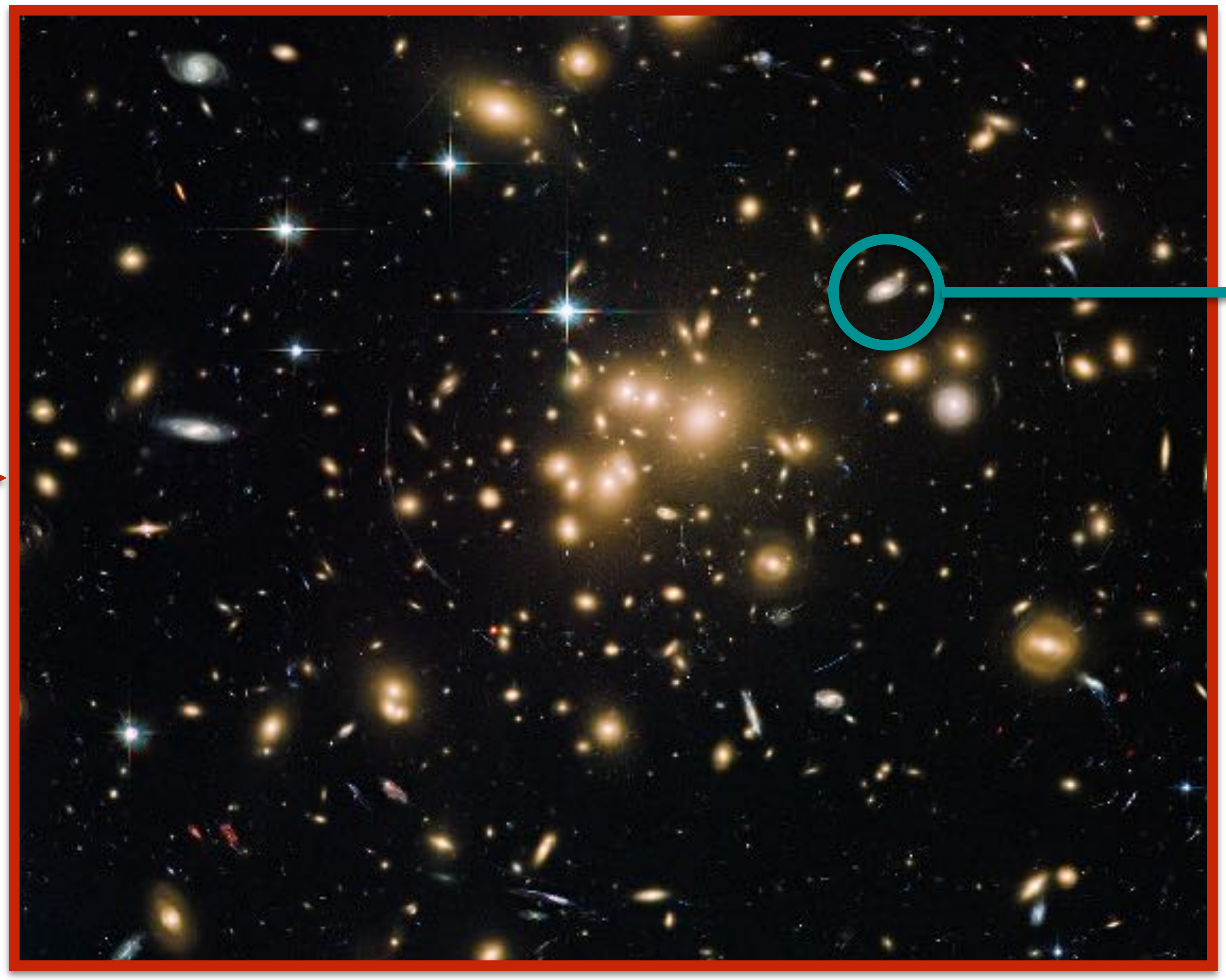
## CMB



Thermal anisotropies

multipole expansion

## Galactic clusters



Galaxy velocities

Gravitational lensing (Bullet)

## Galaxies

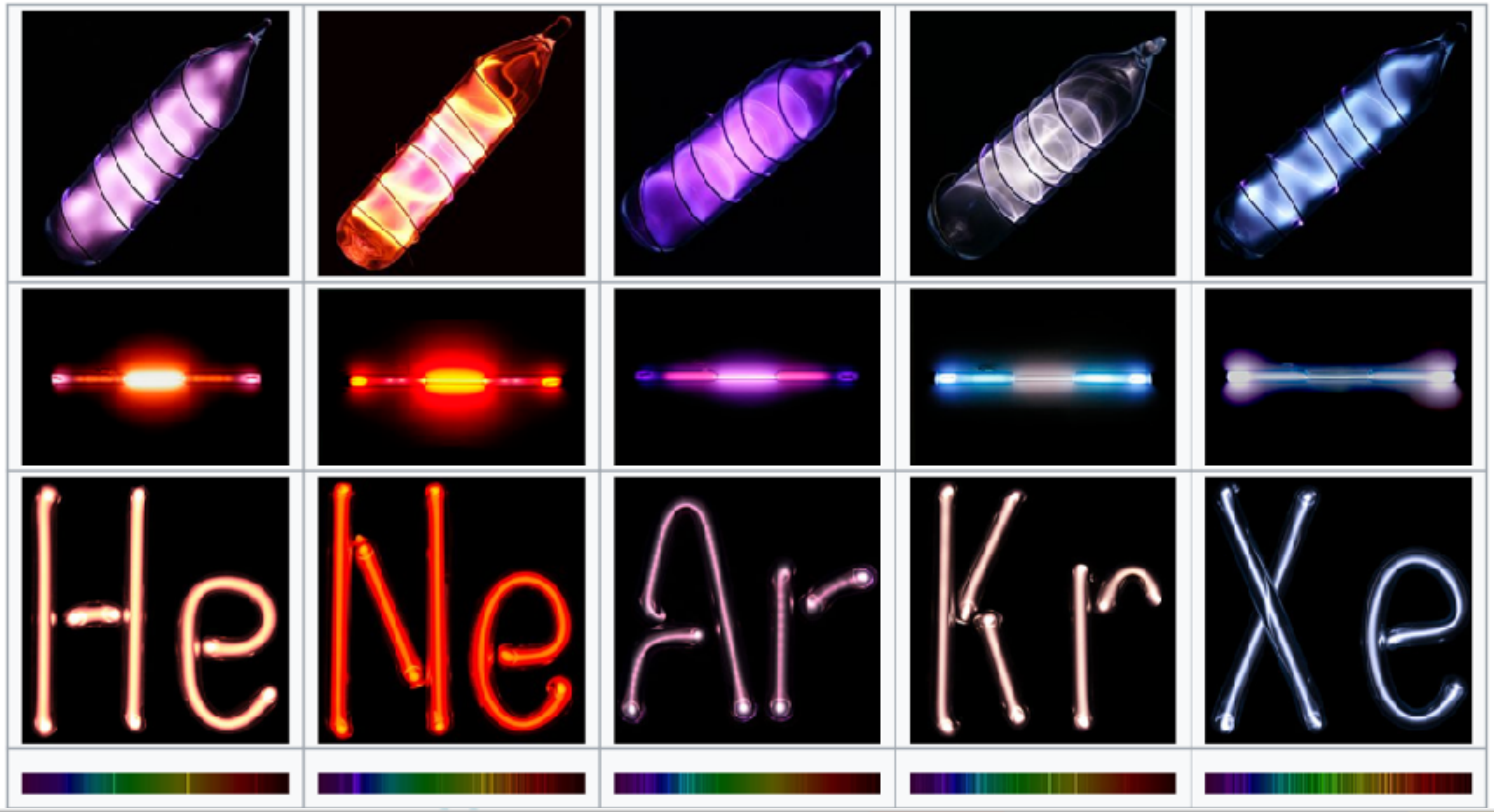
Rotation curves

Gravitational lensing

**Convincing evidence at all scales**

# Search with liquified noble elements

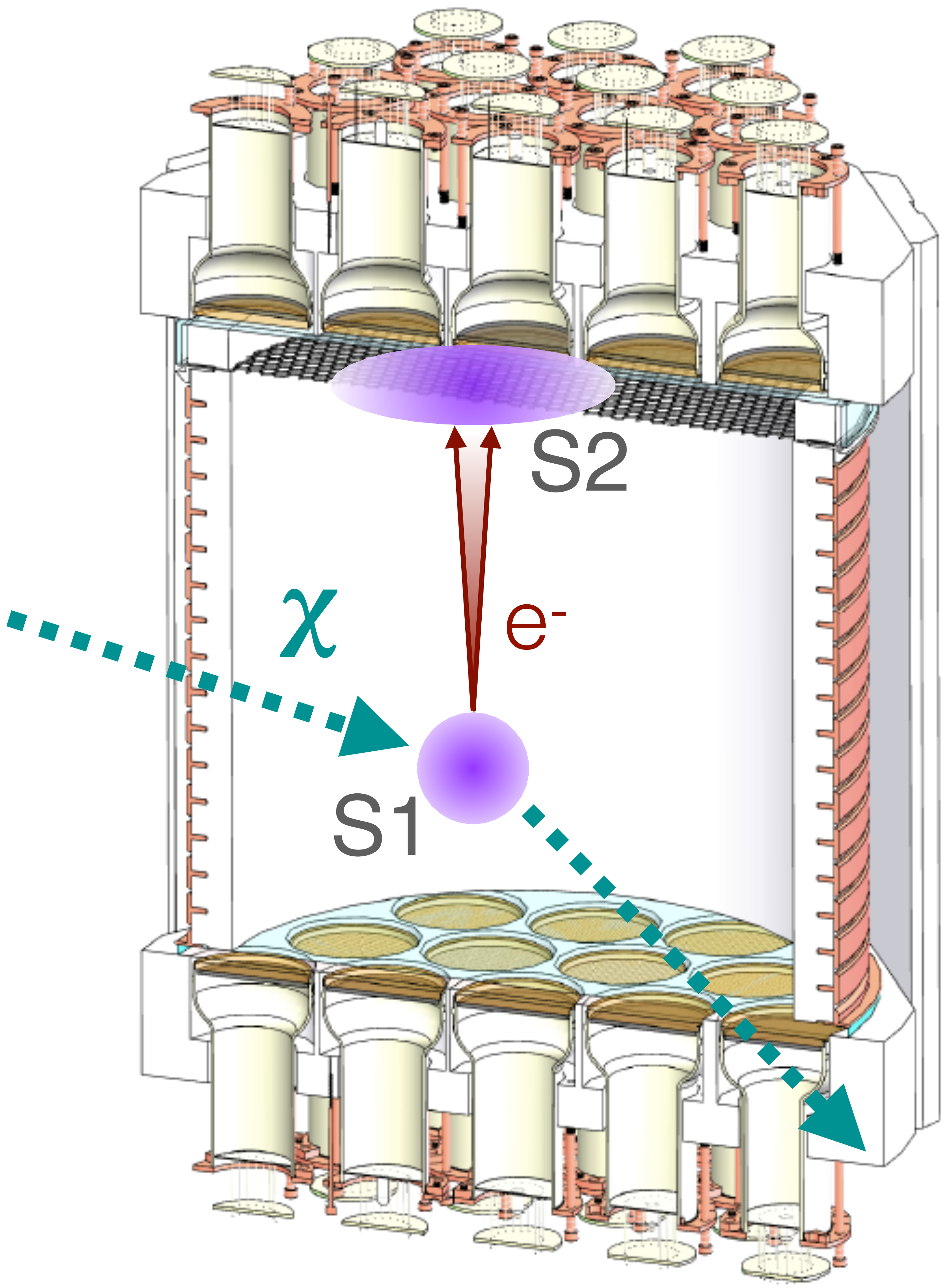
- High density ✔
  - Self screening
  - Good scalability
- Easy(-ish) purification, also online ✔
- Scintillation: good light yield ✔
- Ionisation ✔
- ER rejection ✔
- NR quenching at low energies ✘



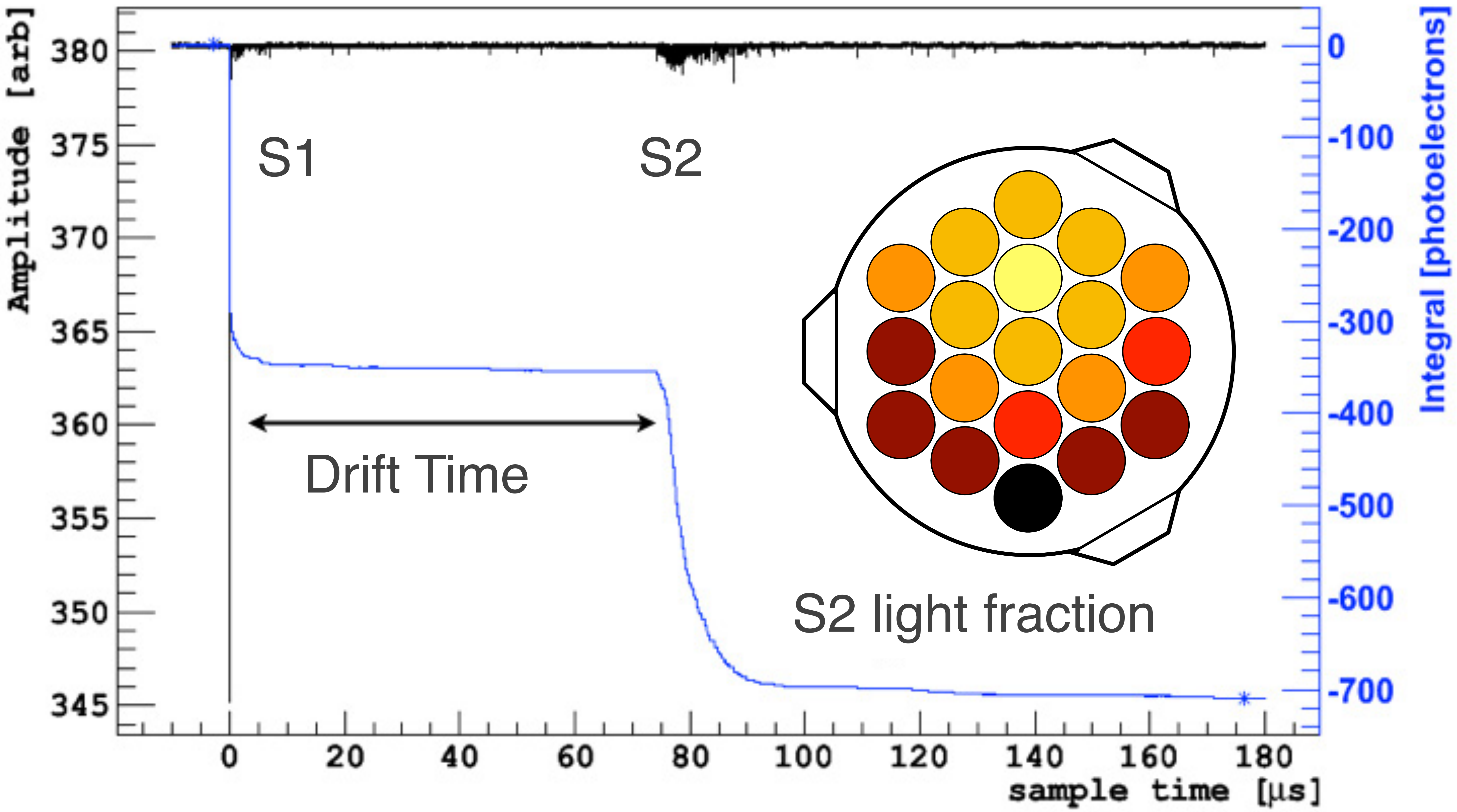

| | | LAr | LKr | LXe |
|---|---|---|---|---|
| Physical properties | Atomic number | 18 | 36 | 54 |
| | Boiling point at 1 bar, $T_b$ (K) | 87.3 | 119.8 | 165.0 |
| | Density at $T_b$ (g/cm$^3$) | 1.40 | 2.41 | 2.94 |
| Ionisation | W (eV)[1] | 23.6 | 20.5 | 15.6 |
| | Fano factor | 0.11 | ~0.06 | 0.041 |
| | Drift velocity (cm/$\mu$s) 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



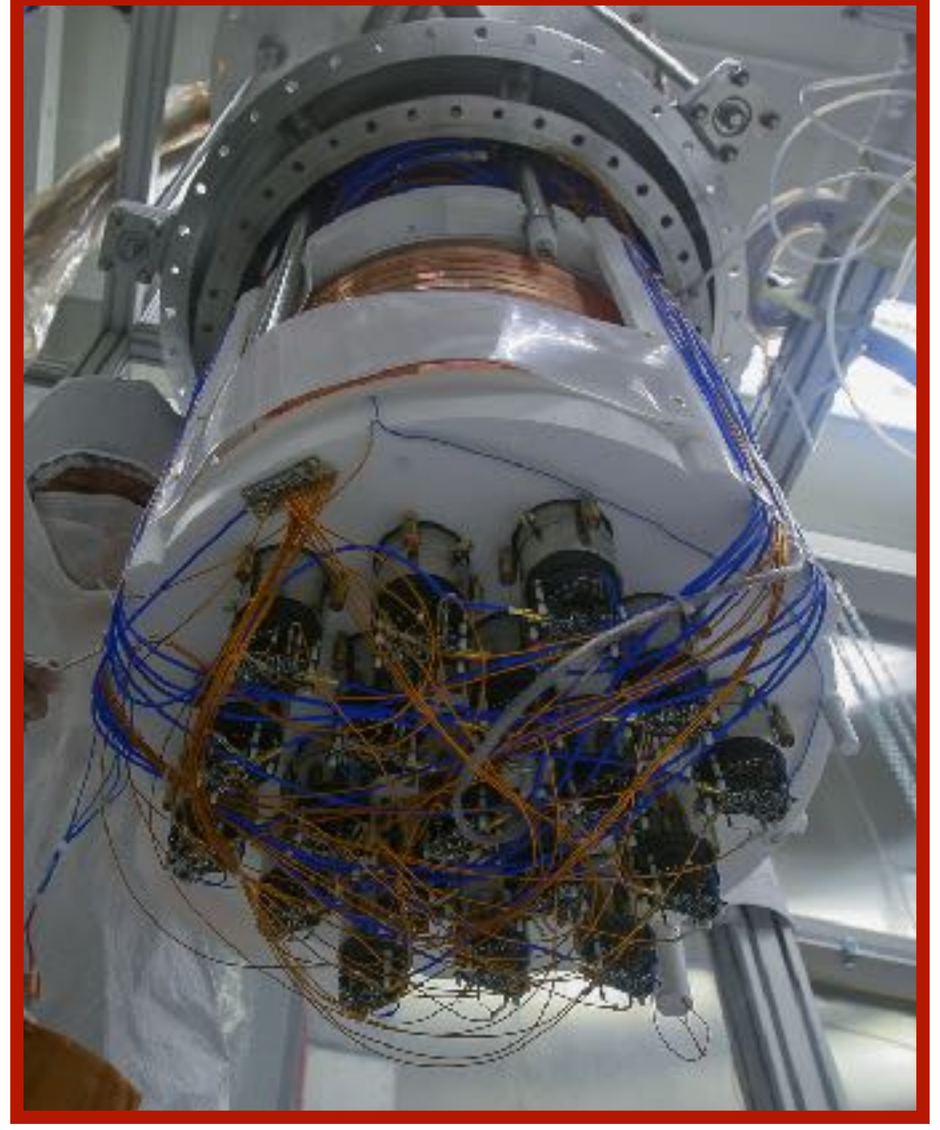

## 3D position reconstruction




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

# The GADMC

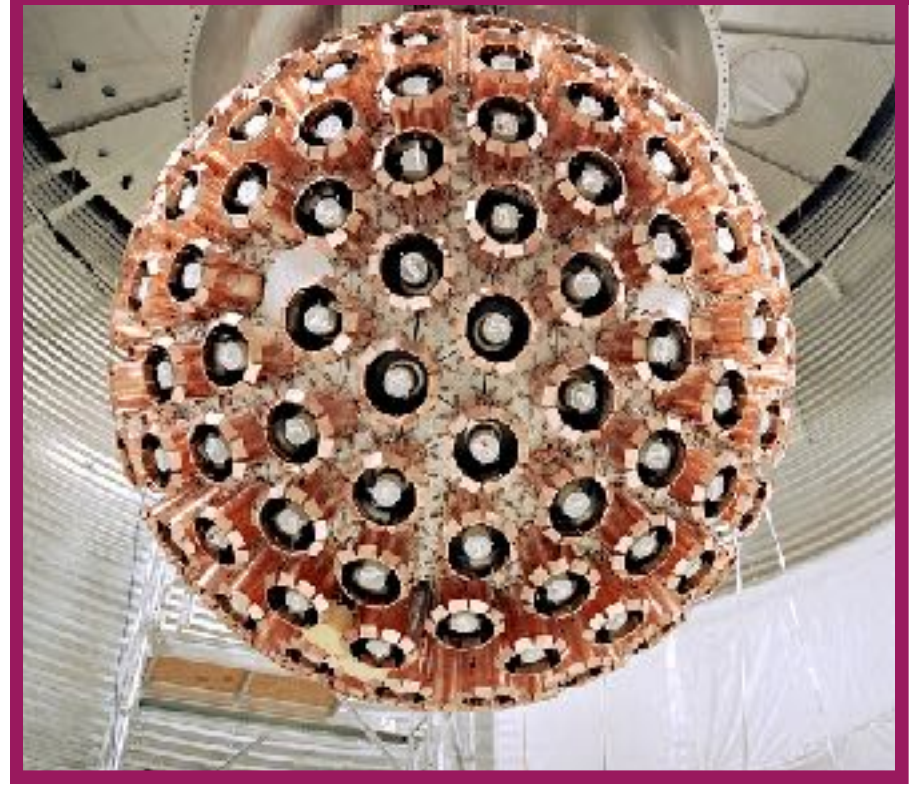
**DarkSide-50 @ LNGS**



**ArDM @ Canfranc**

**MiniClean @ Snolab**

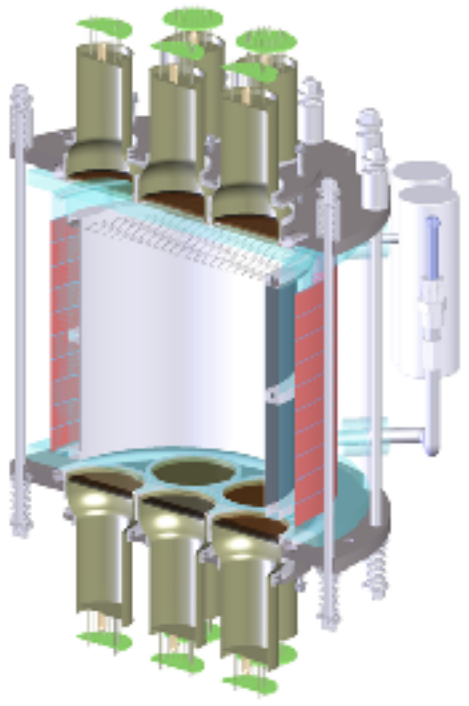
**DEAP @ Snolab**



>400 scientists, >100 institutions distributed across 13 countries

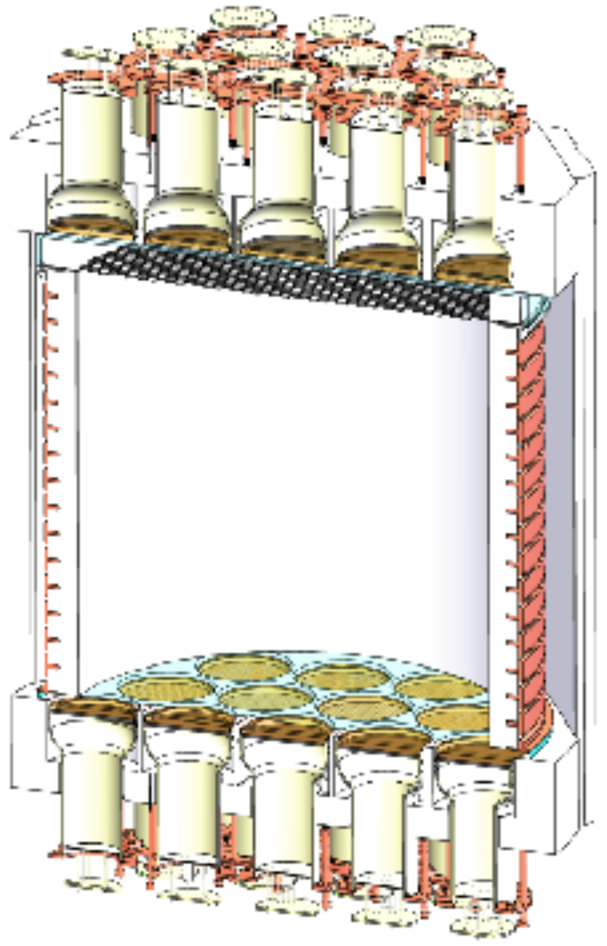
# A multi-stage approach

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



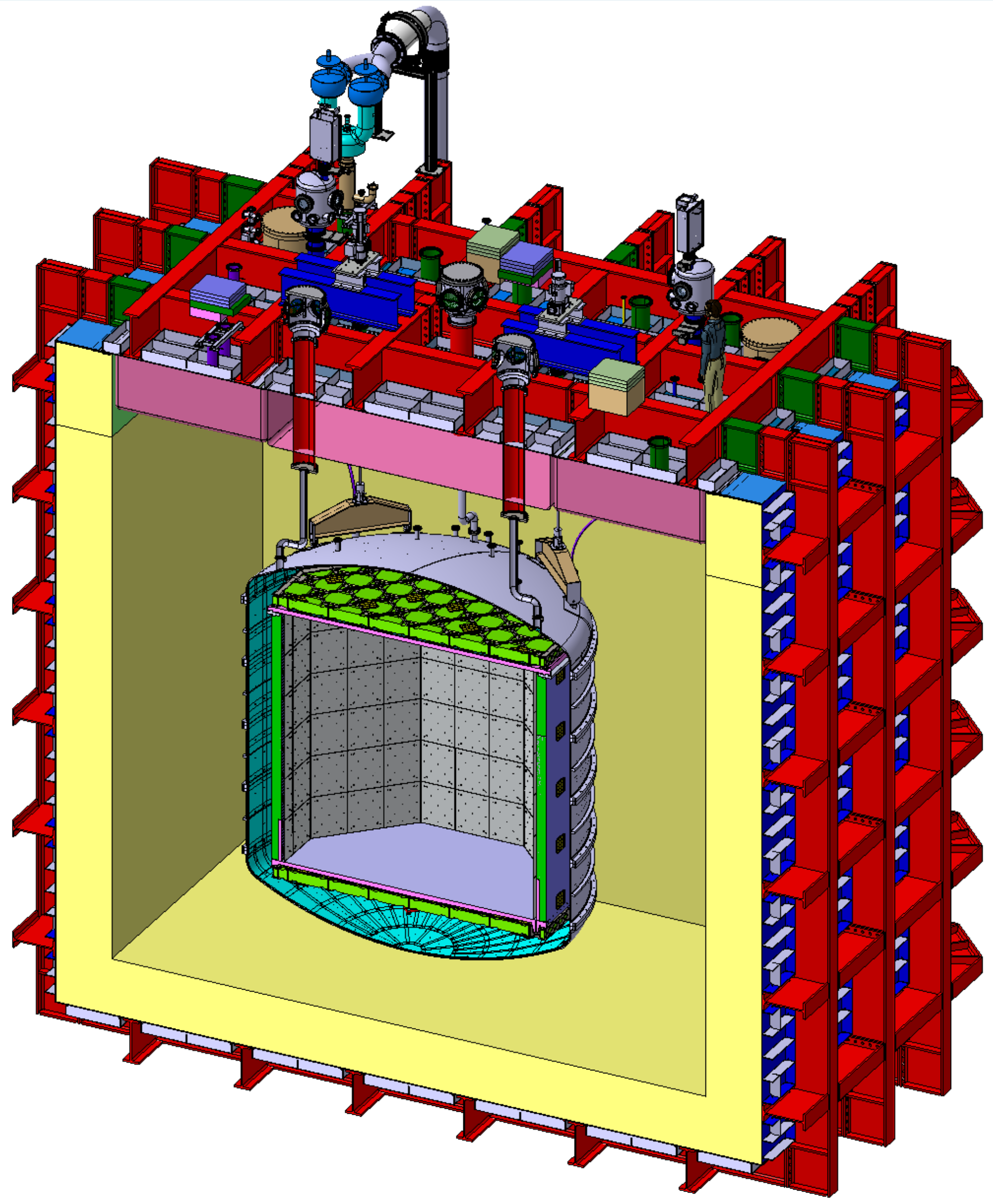
**DarkSide-10**

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



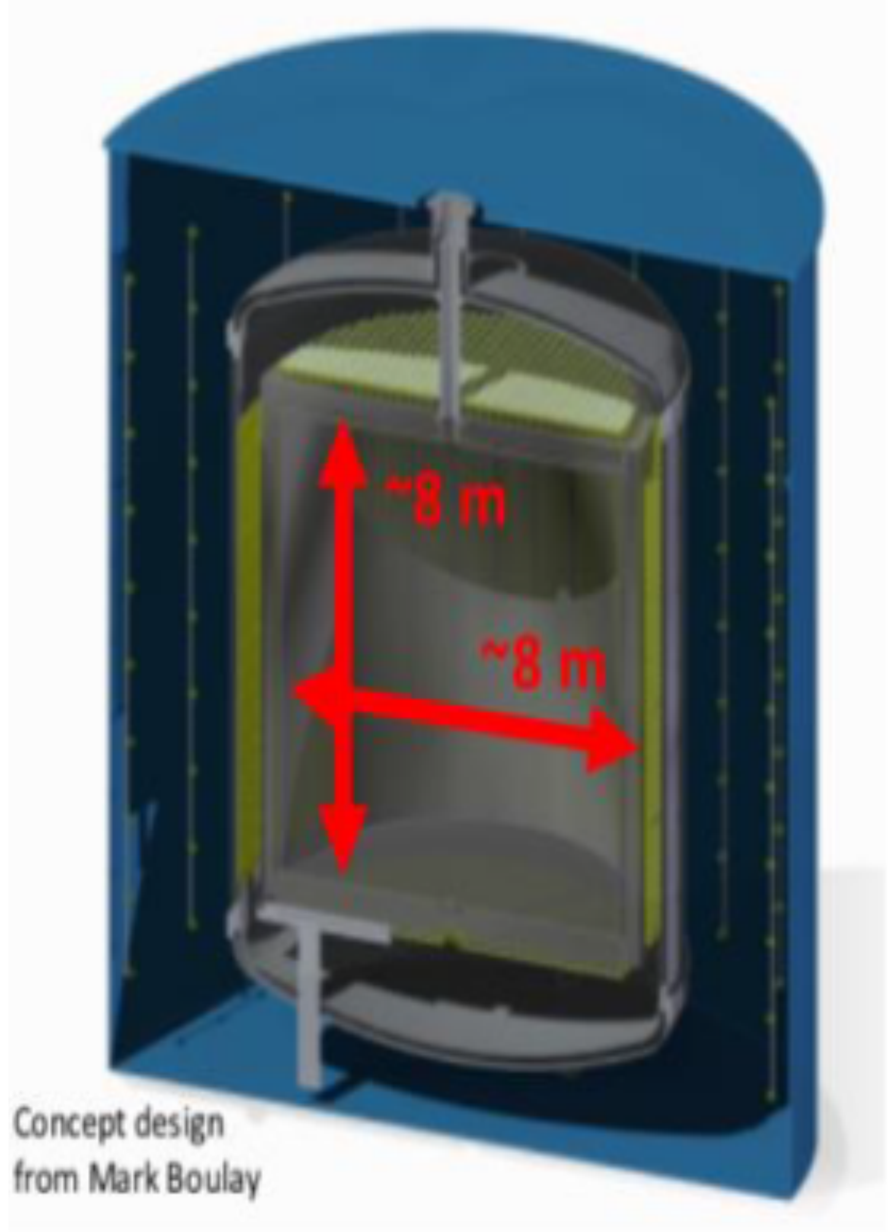
**DarkSide-50**

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



**DarkSide-20k @ LNGS**

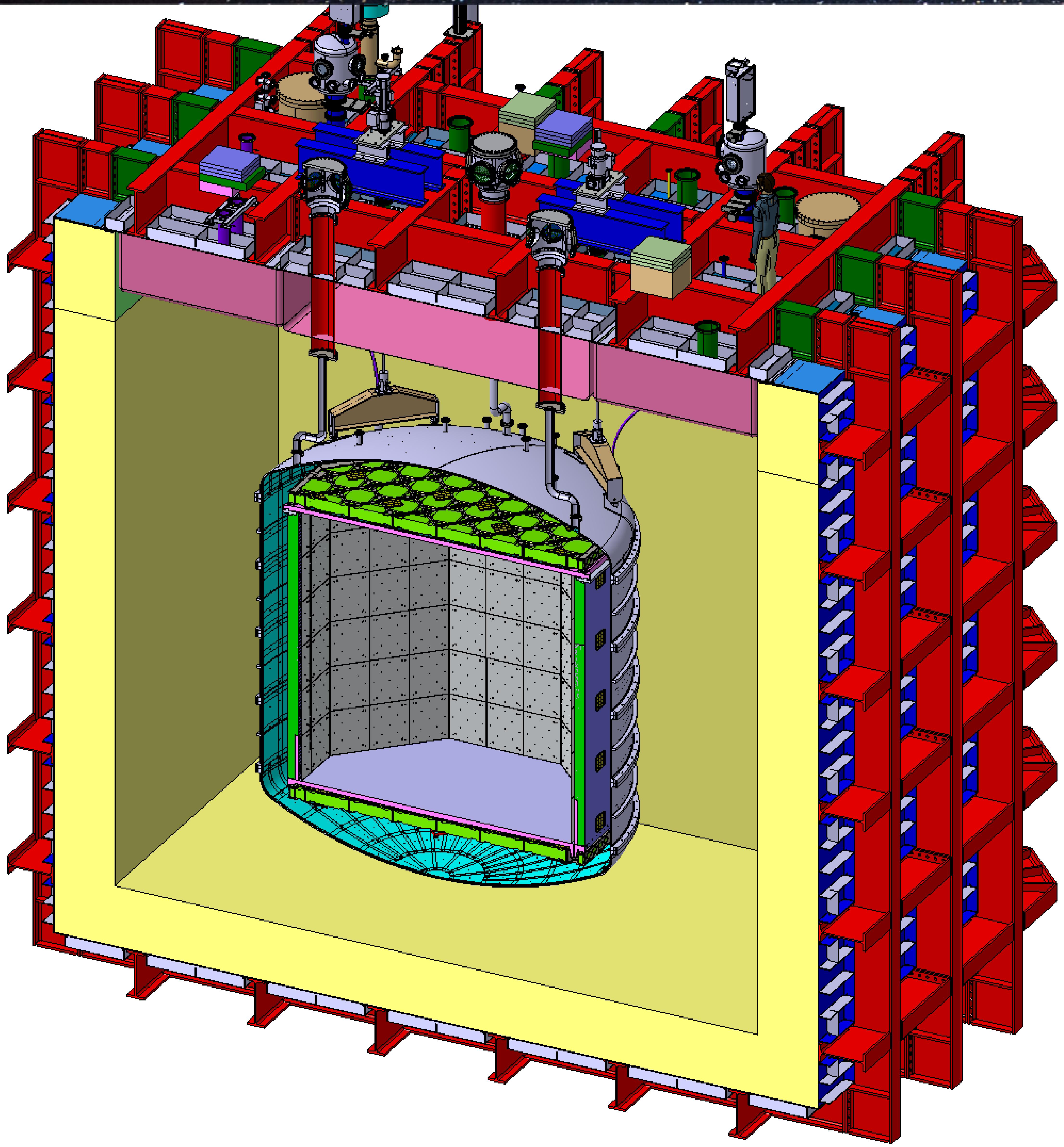
- Novel technologies
- First peek into the neutrino fog
- Nominal exposure: 200 t y




**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

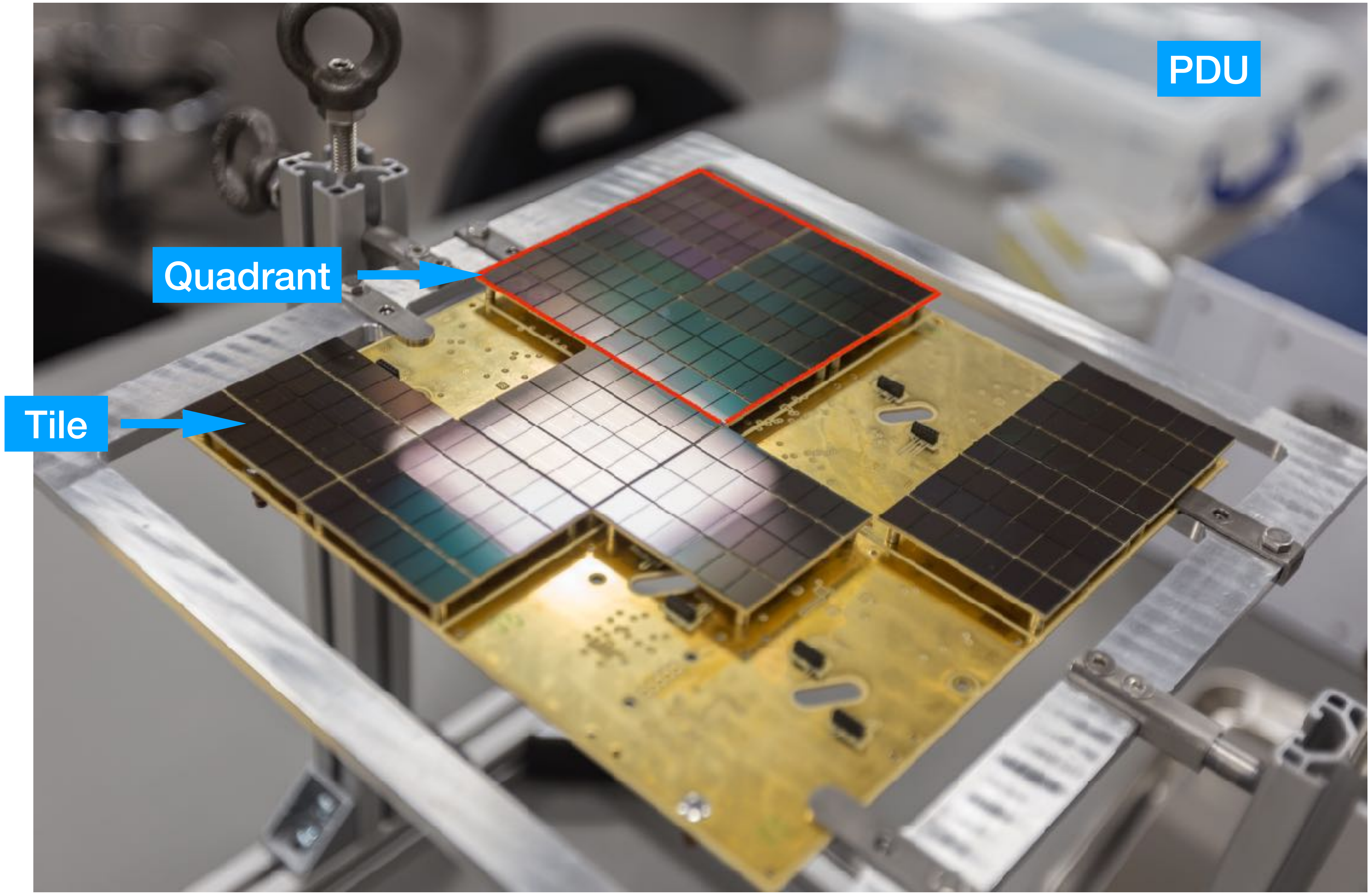
**Position reconstruction resolution:**

~ 1 cm in XY

~ 1 mm in Z

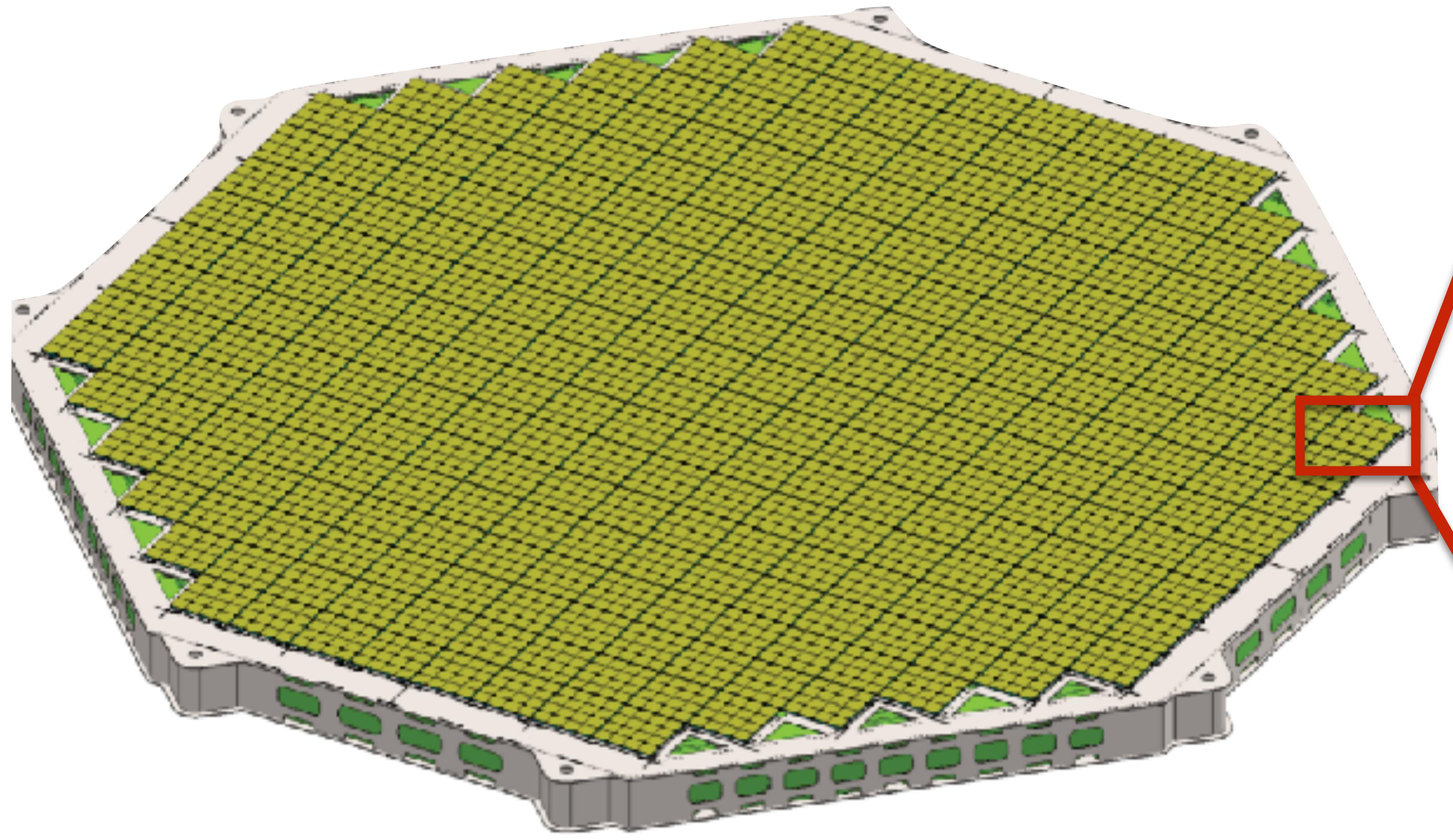
# The DS-20k PDU

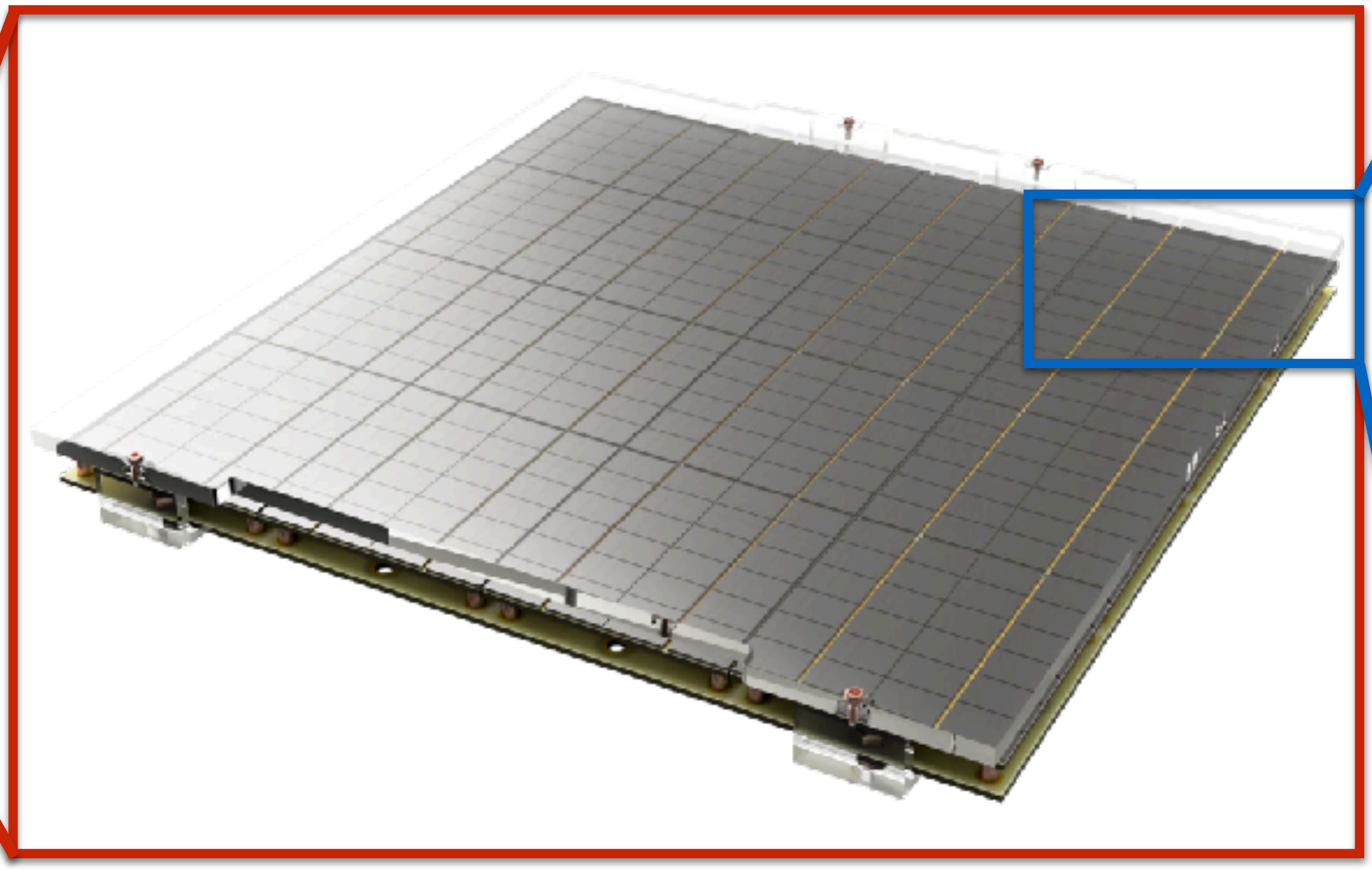
- 24 FBK NUV-HD-Cryo SiPMs are aggregated in objects called tiles
- Tile have 4s6p topology
- SiPMs are read by a low noise transimpedance amplifier (TIA) or by a custom designed ASIC
- Tiles, in groups of four, are further aggregated in quadrants each of them read as 1 analog readout channel

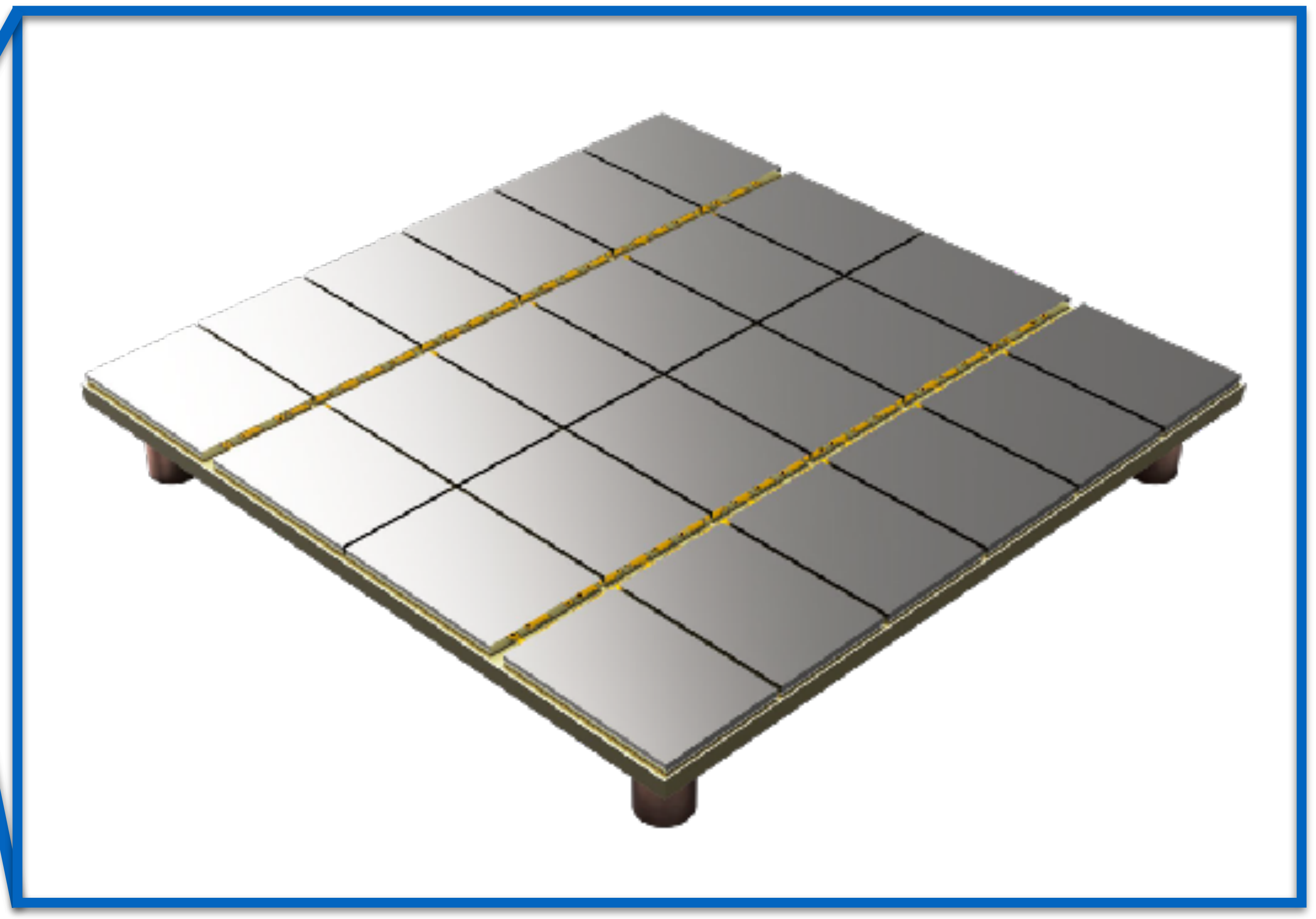


# Photo-detection system

**TPC optical plane** | **Photo-Detection Unit** | **Tile**







16 tiles arranged in 4 readout channels

TPC planes area: ~21m$^2$

Organized in 525 PDUs

100% coverage of TPC top and bottom

SiPM bias distribution

cryogenic pre-amplifiers bias

Signal transmission

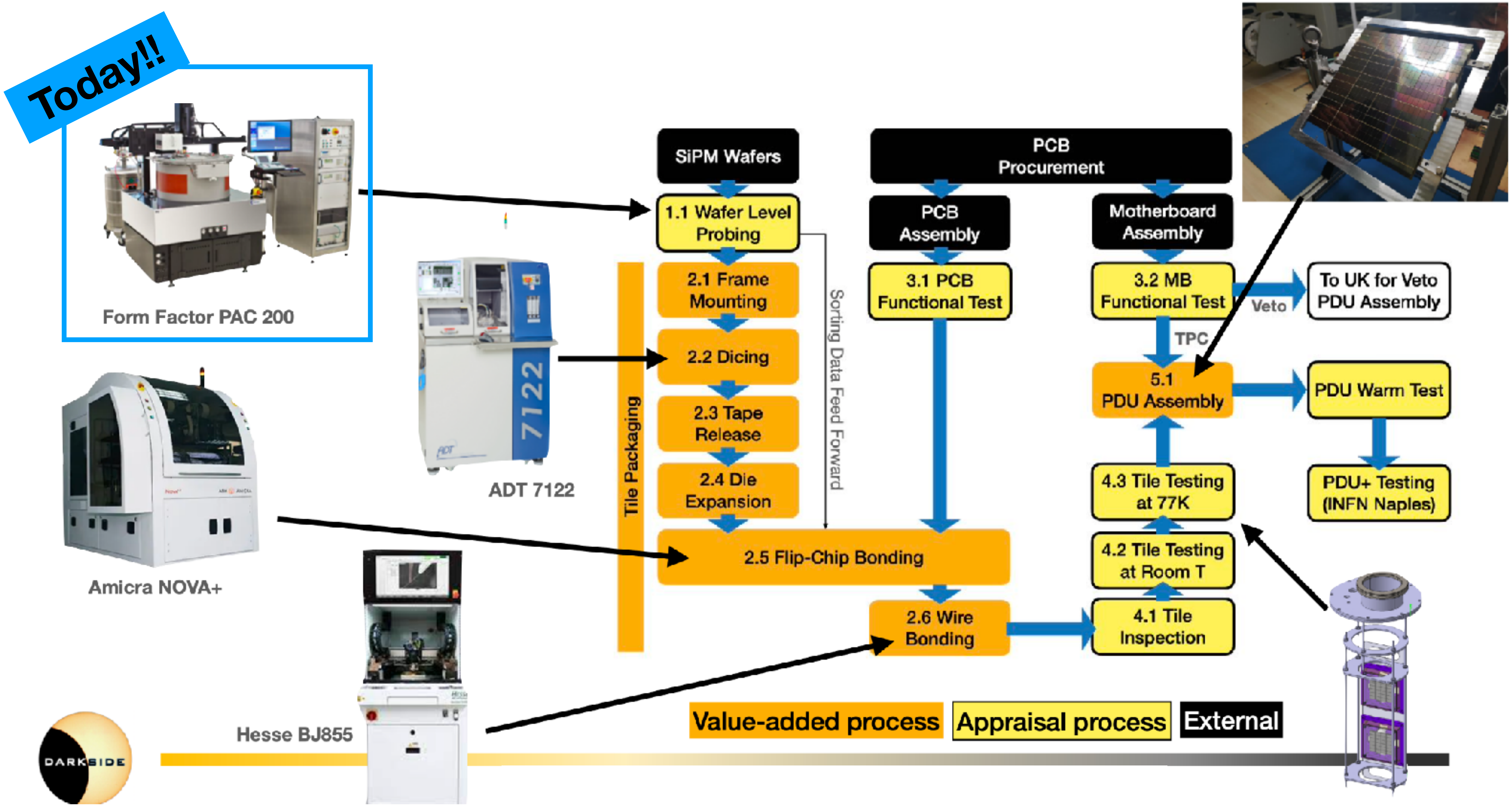
Channels switch-on/off

Photosensor

Array of 24 SiPMs

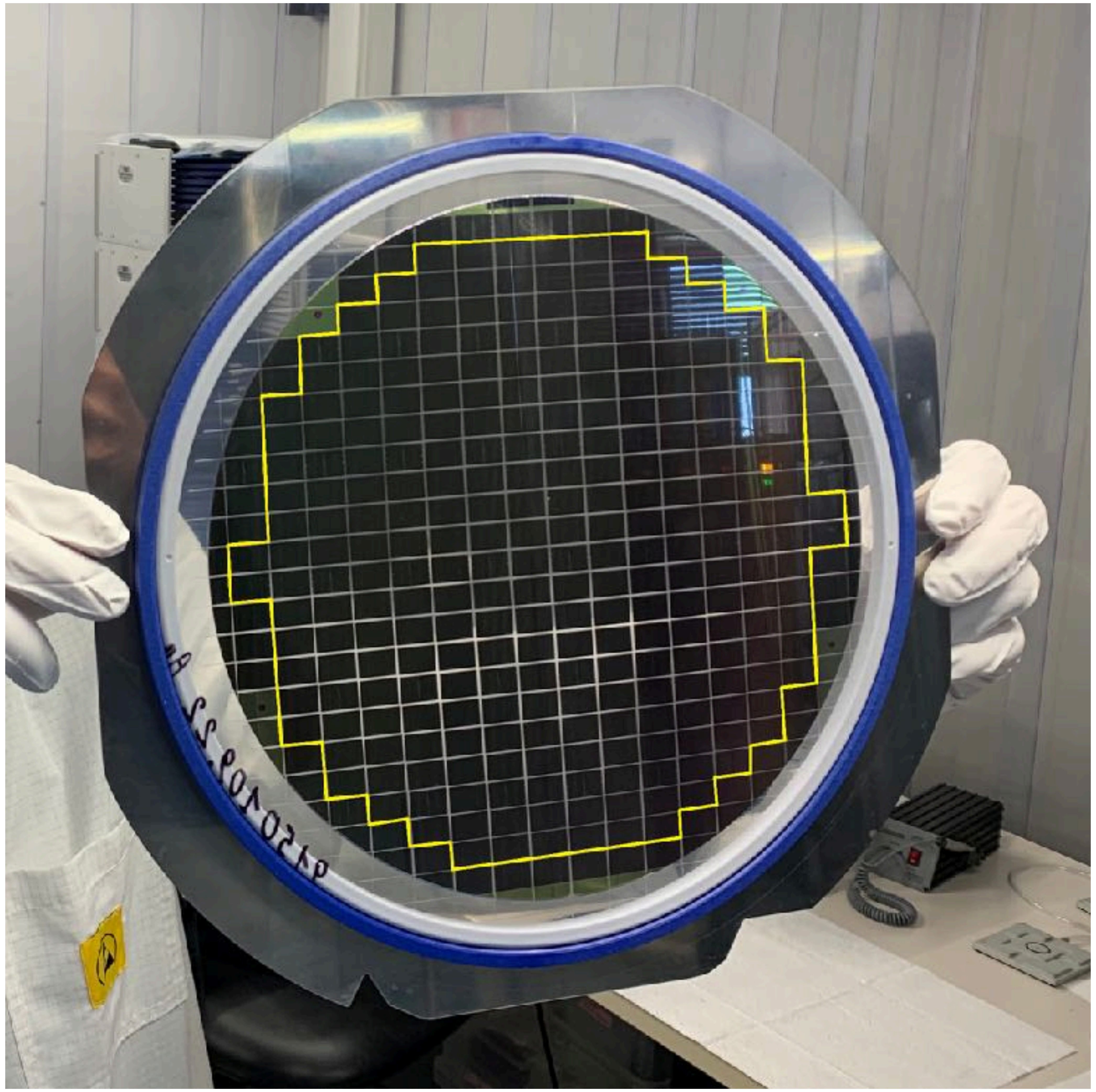
Signal pre-amplification

# The DS-20k Silicon Packaging



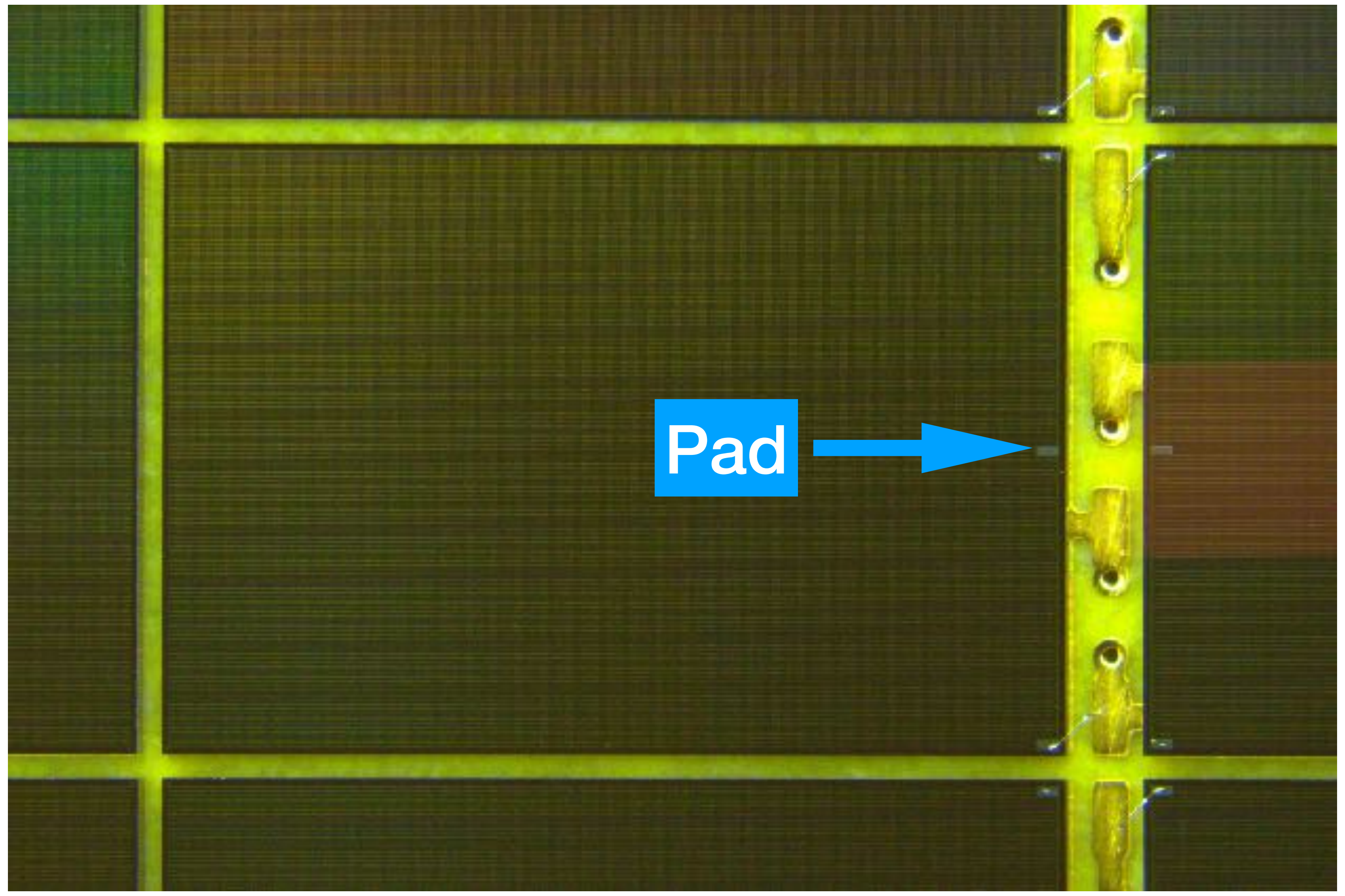
# Wafers

- 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.



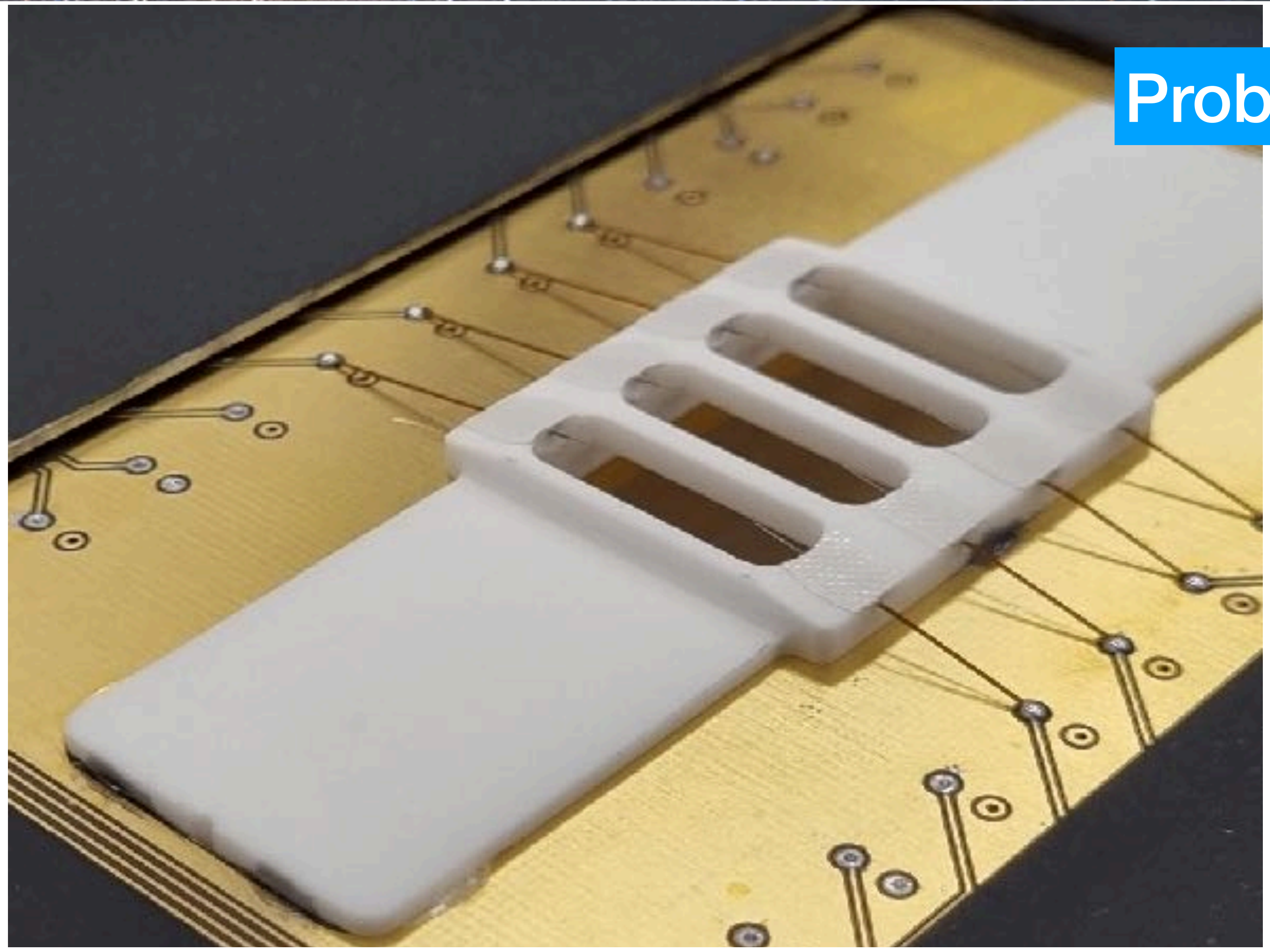
# FBK NUV-HD Cryo SiPMs

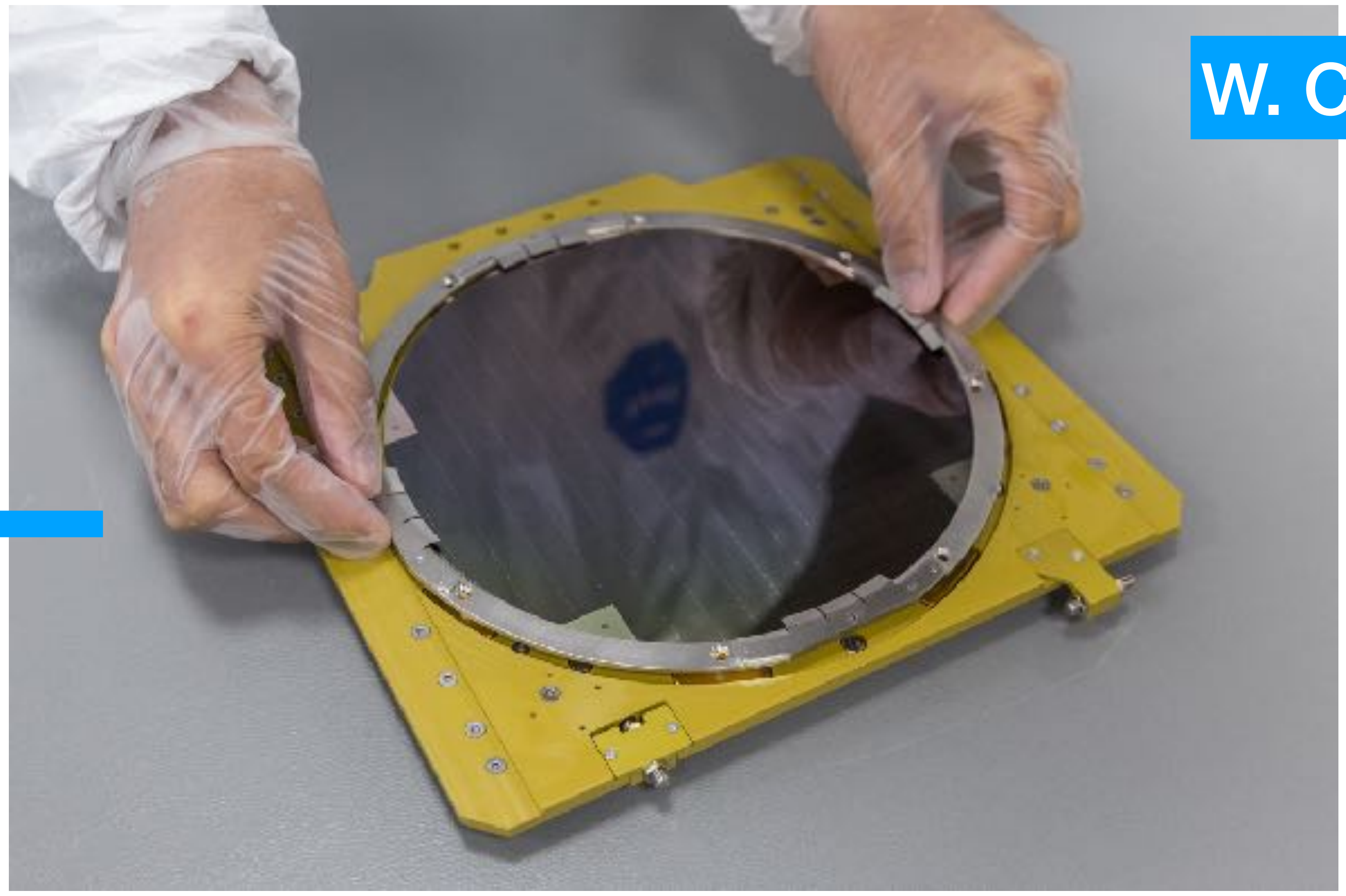
- SiPM used in Darkside are FBK NUV-HD Cryo SiPM
- Each wafer in the Lot has a gold-coated backside that acts as the SiPM cathode.
- The SiPM anode contact is composed by three short-circuited aluminum pads.
- One pad is used for cryoprobing, the other two for wire bonding.
- SiPMs are soldered on an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

# Hardware Setup

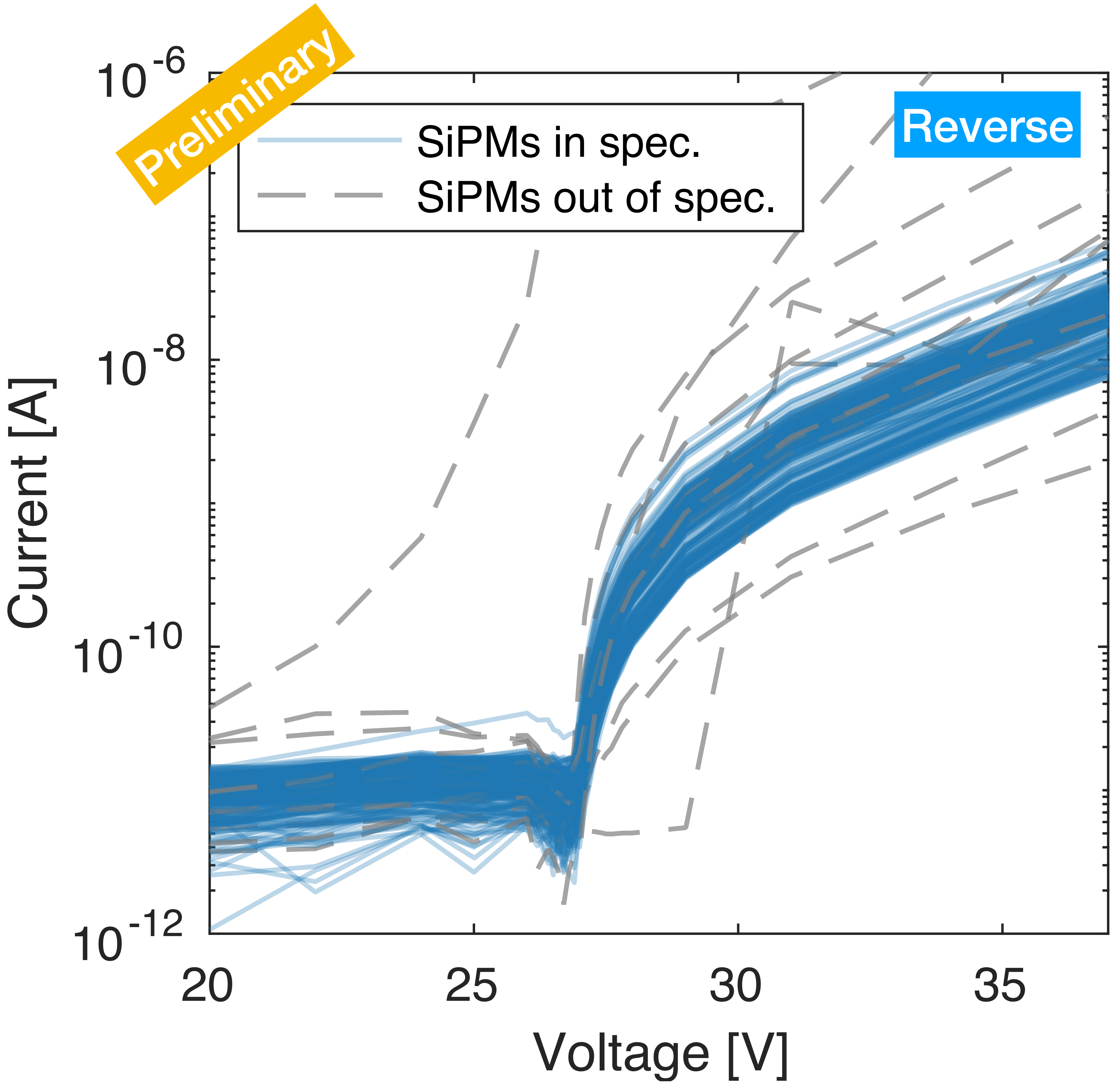
- Wafer are tested with a PAC-200 cryoprobe with a needle-based probecard (common cathode)

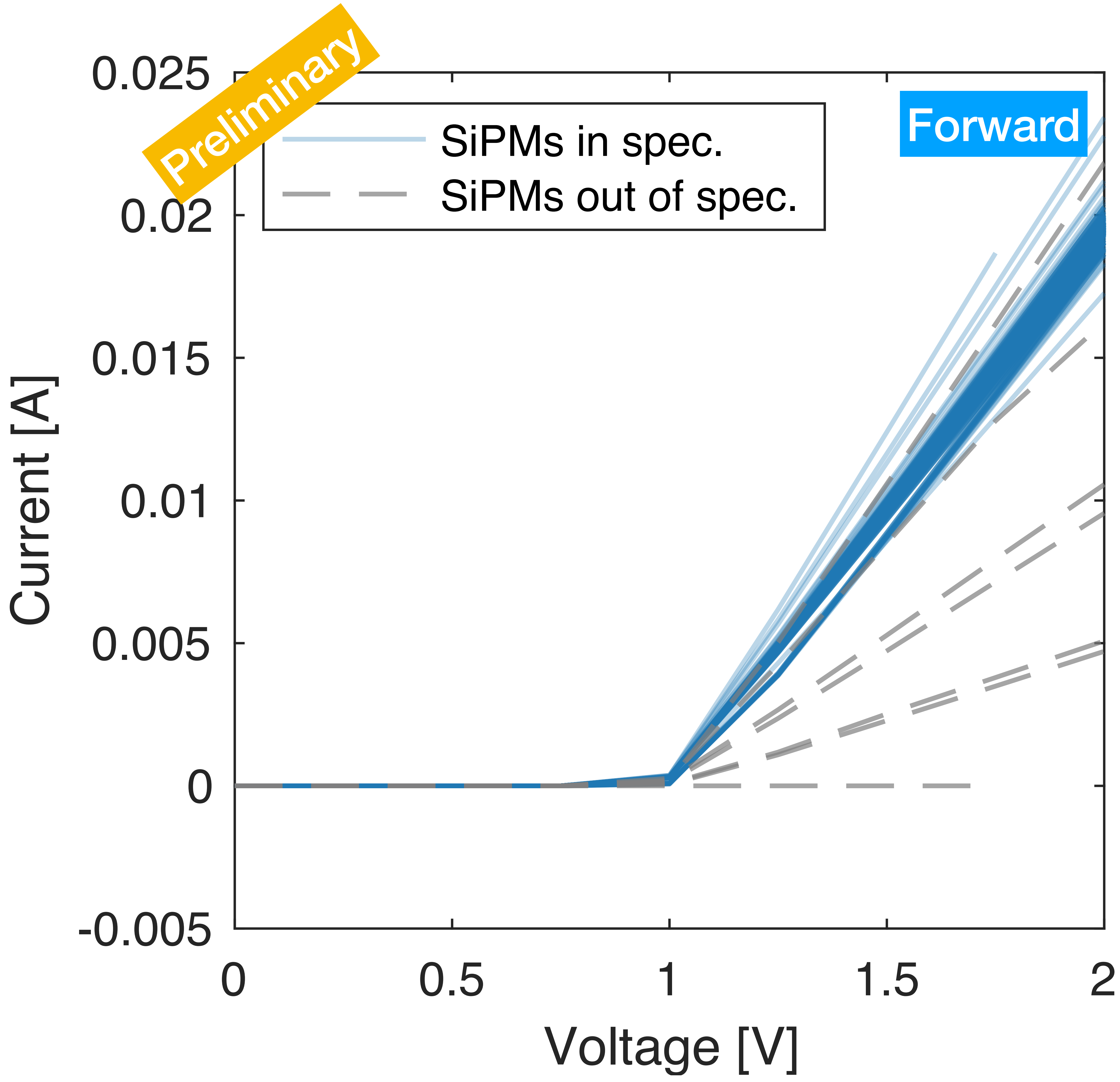



# Experimental Details

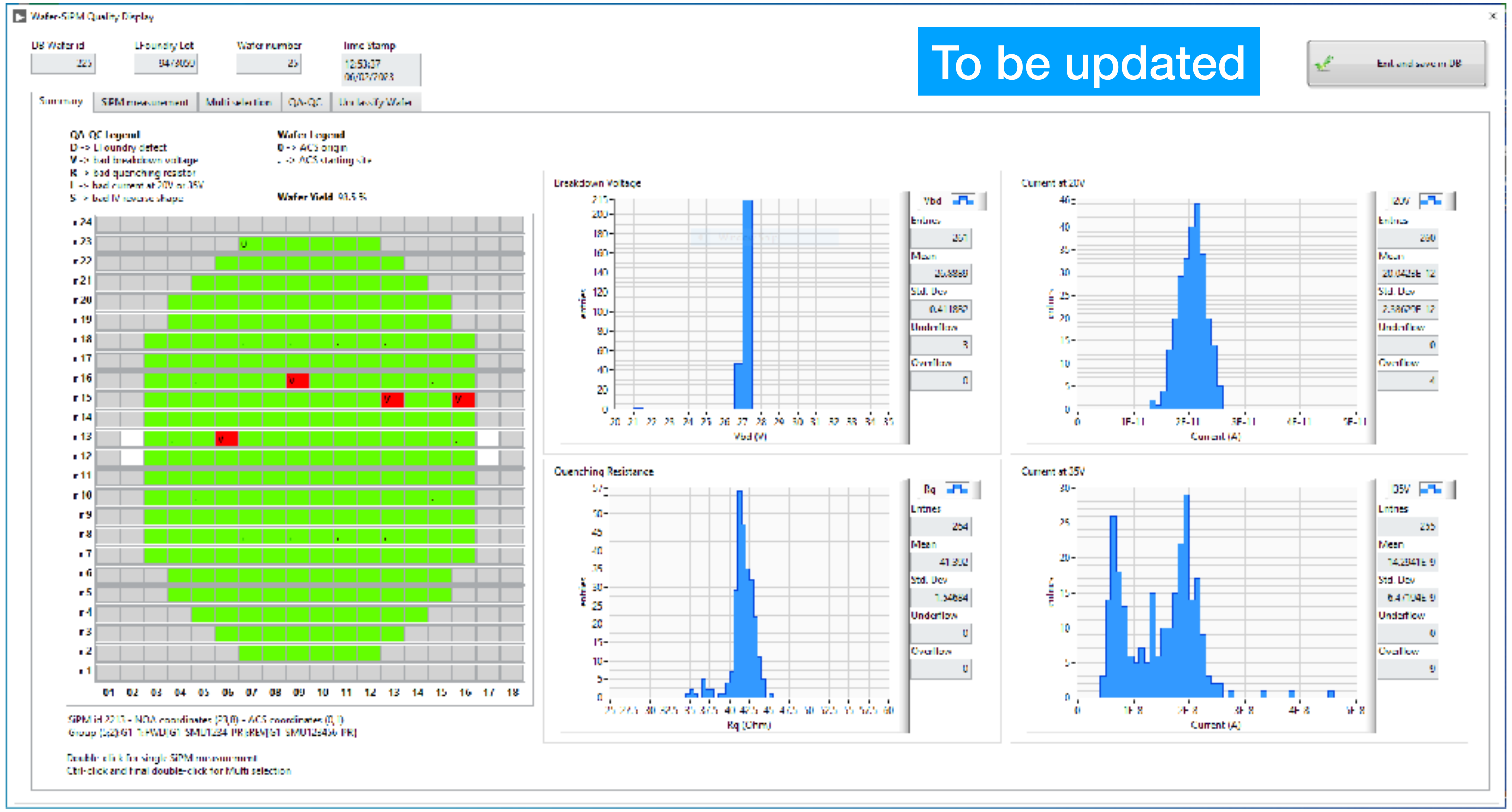
- 1 **Reverse** and 1 **Forward** bias IV curves are measured on each wafer SiPM dice at 77 K



# 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 $\leq 25$ ← Reverse bias IV

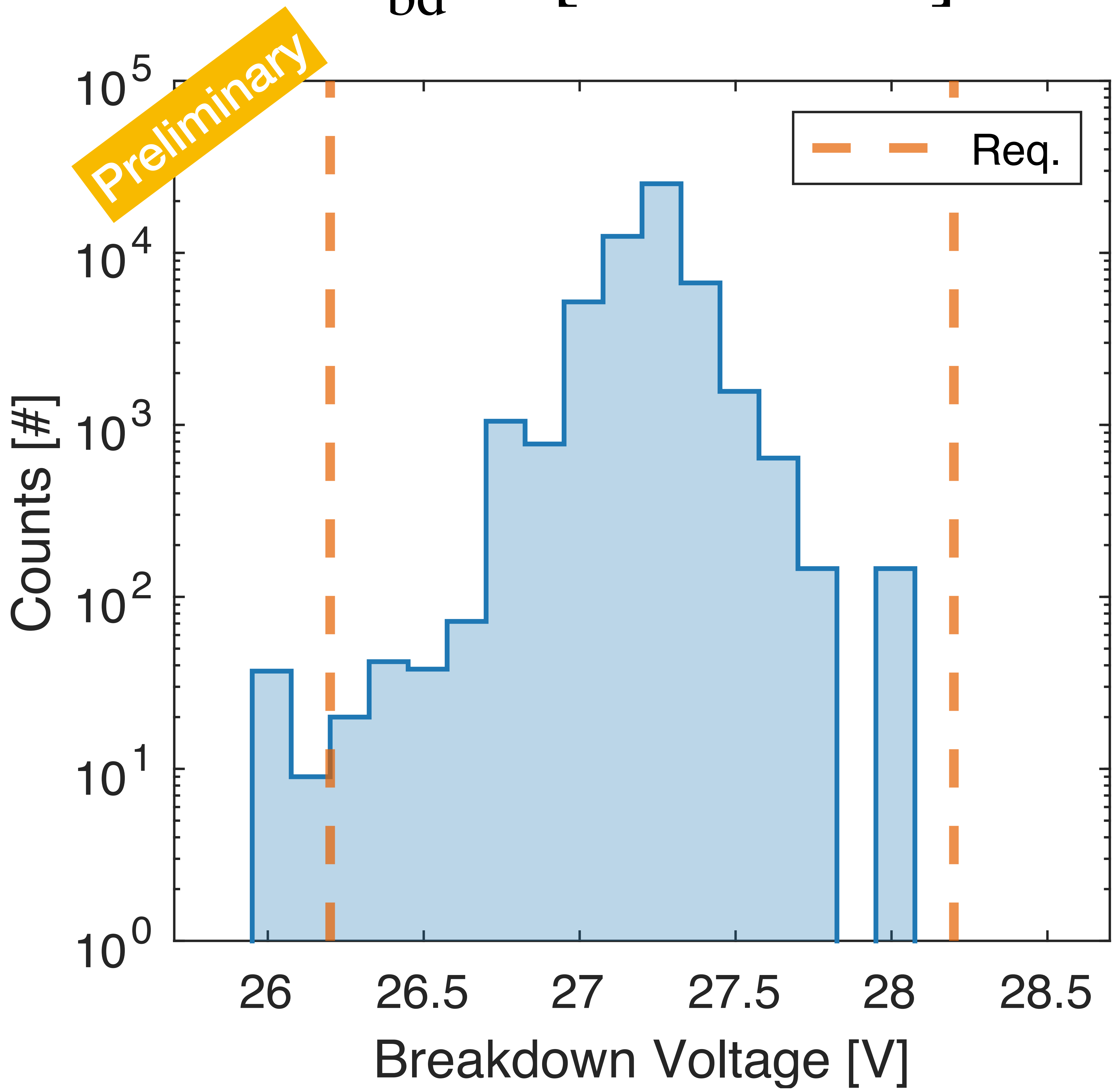
1),2) based on measurements on pre-production FBK wafers

* Shown today

# Breakdown Voltage Distribution

Computed from the 1st derivative of IV curve

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




## Variance Component Analysis

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

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

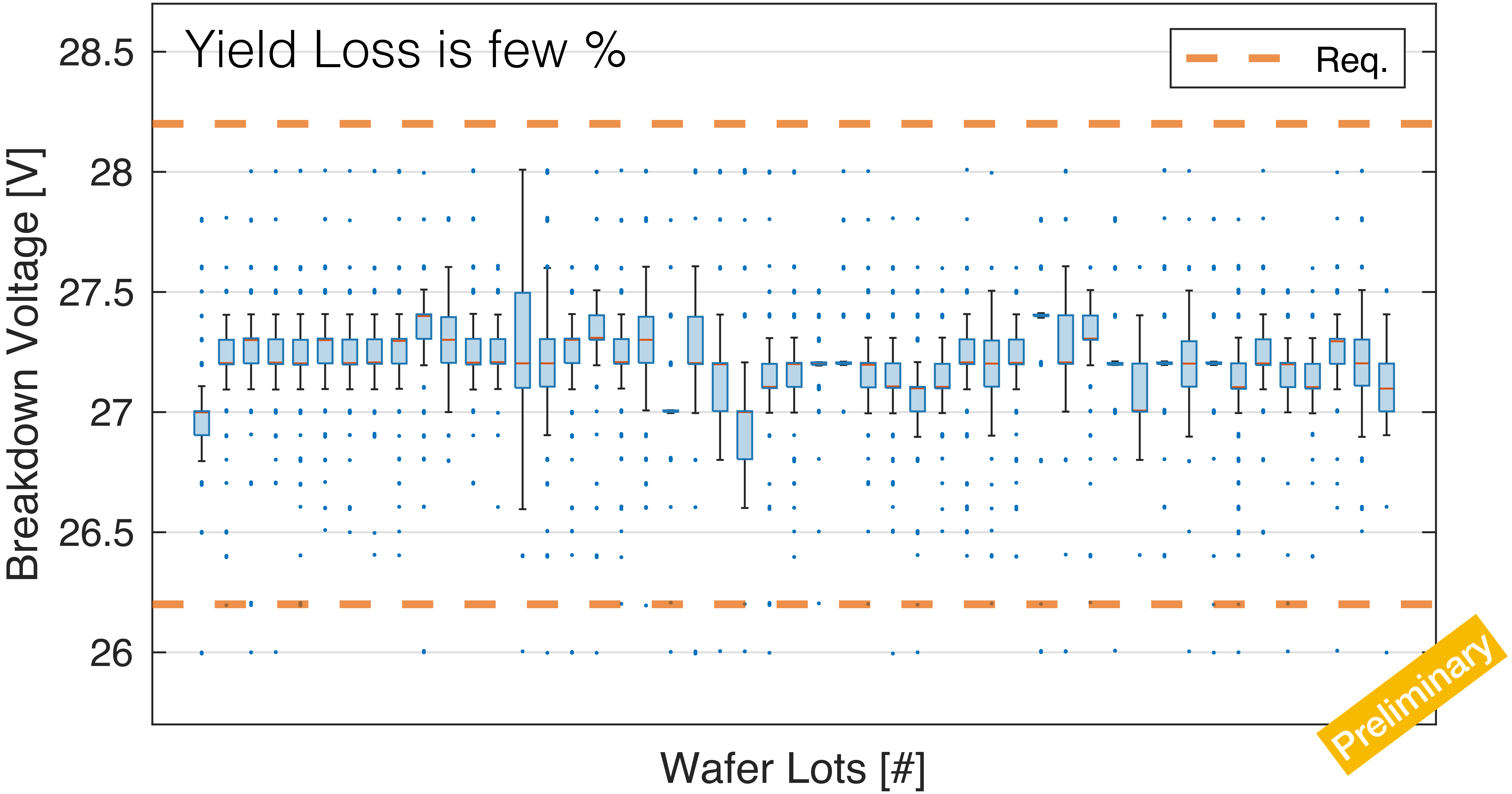
$\sigma^2_{V^P_{\rm bd}/\textbf{Wafer}} \sim 0.001$ **V** Wafer-to-Wafer variability in single Lot

$\sigma^2_{V^P_{\rm bd}/\textbf{SiPM}} \sim 0.015$ **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

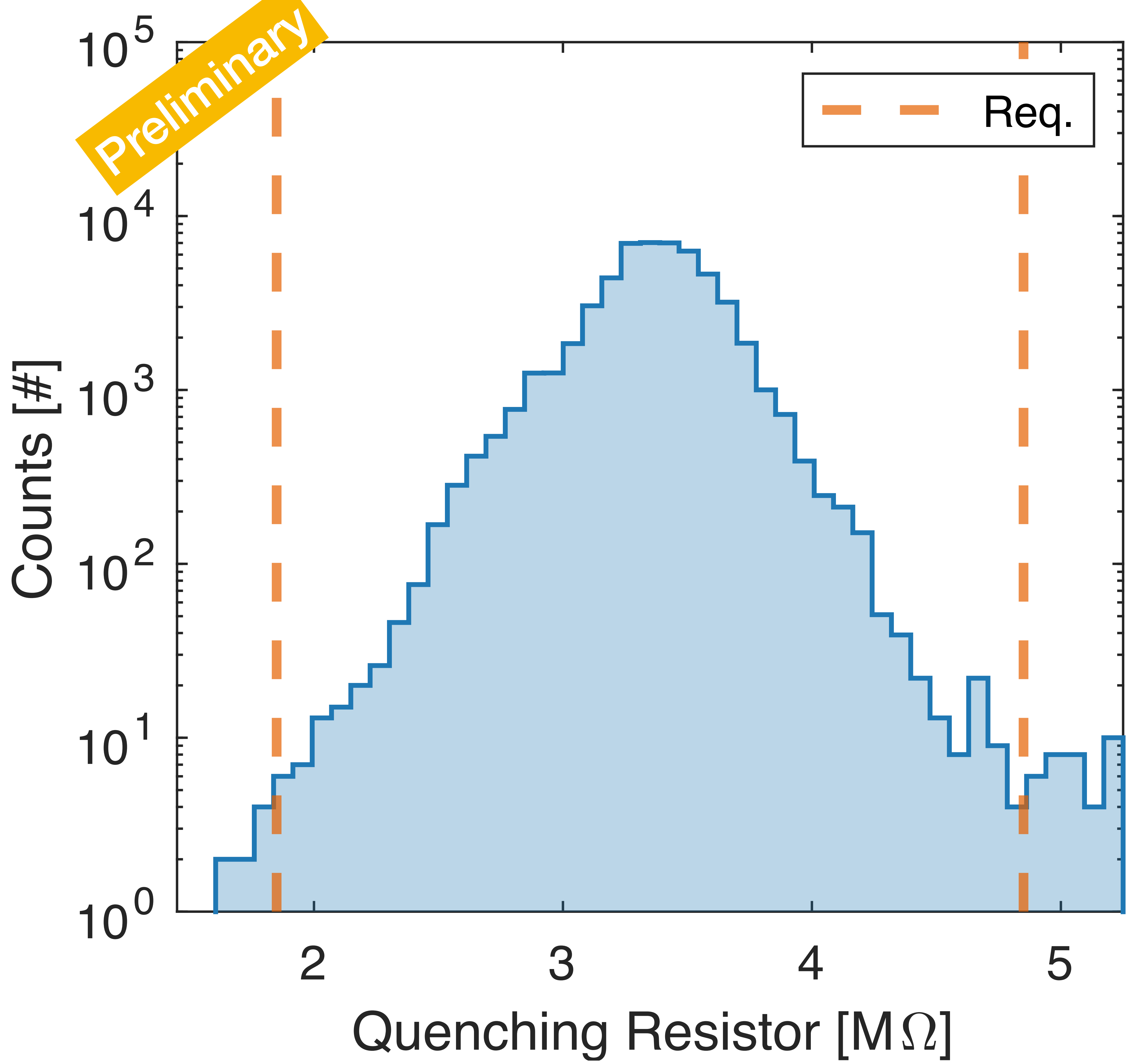
The largest variability (Lot-to-Lot) is clearly visible when doing a box plot of the entire prod.



# 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>

$$\sigma^2_{R_q^P} = \sigma^2_{R_q^P/\textbf{Lot}} + \sigma^2_{R_q^P/\textbf{Wafer}} + \sigma^2_{R_q^P/\textbf{SiPM}} = 0.077\ \mathbf{M\Omega}$$

$\sigma^2_{R_q^P/\textbf{Lot}} \sim 0.046\ \mathbf{M\Omega}$ Lot-to-Lot variability

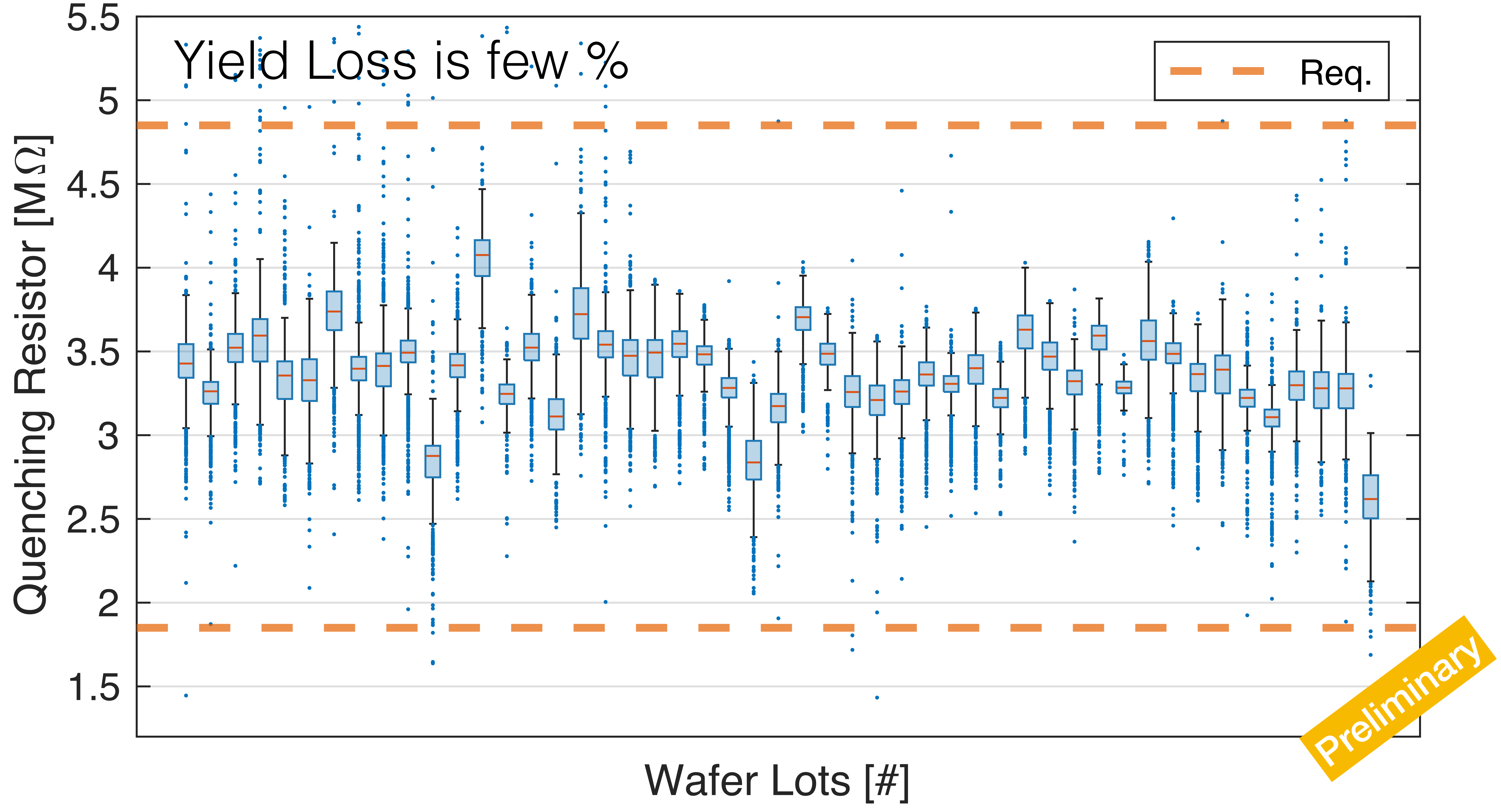
$\sigma^2_{R_q^P/\textbf{Wafer}} \sim 0.008\ \mathbf{M\Omega}$ Wafer-to-Wafer variability in single Lot

$\sigma^2_{R_q^P/\textbf{SiPM}} \sim 0.023\ \mathbf{M\Omega}$ SiPM to SiPM variability

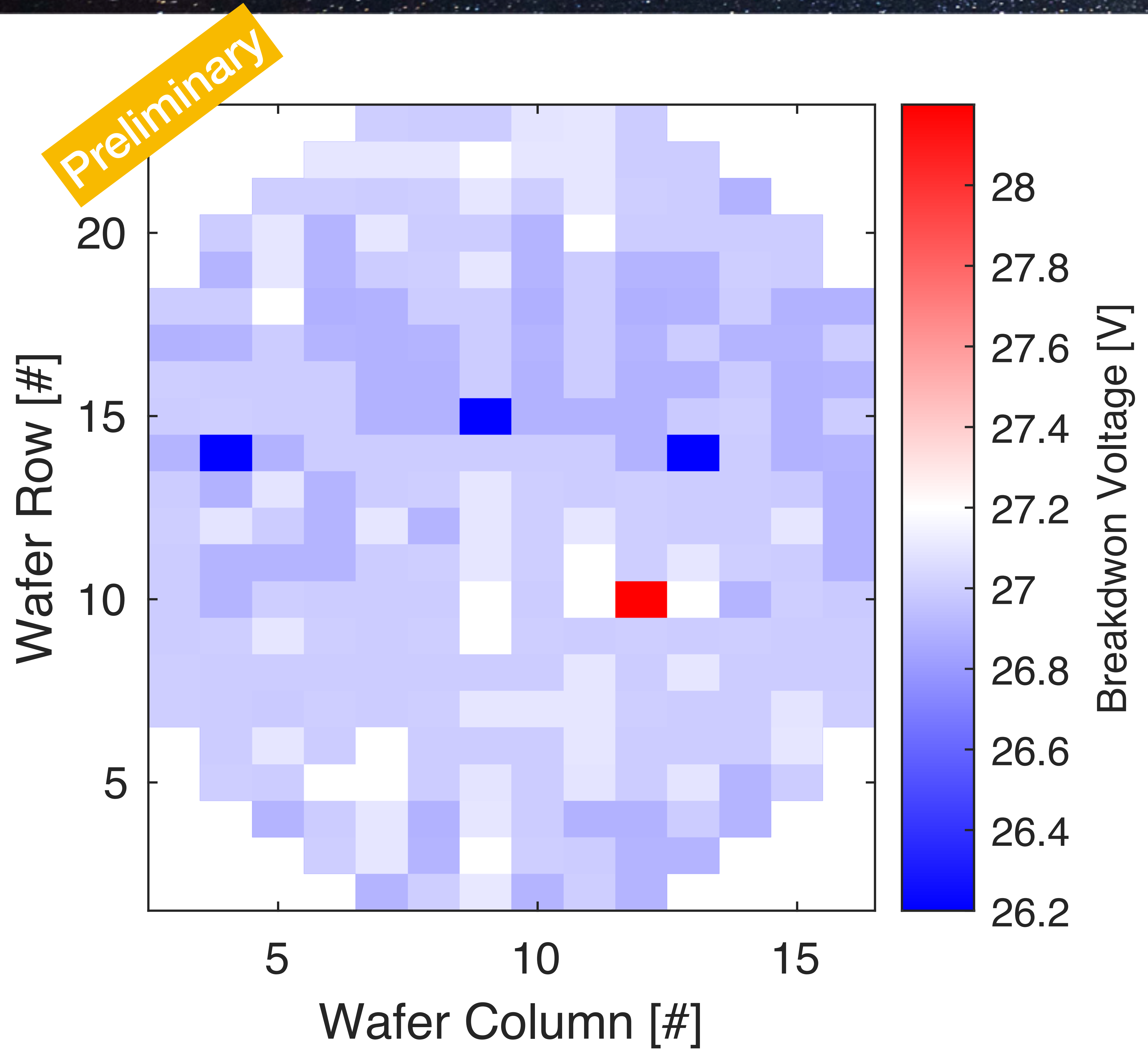
- 54648 SiPMs tested up to now
- Lot-to-Lot variability dominates
- W-to-W variability is negligible

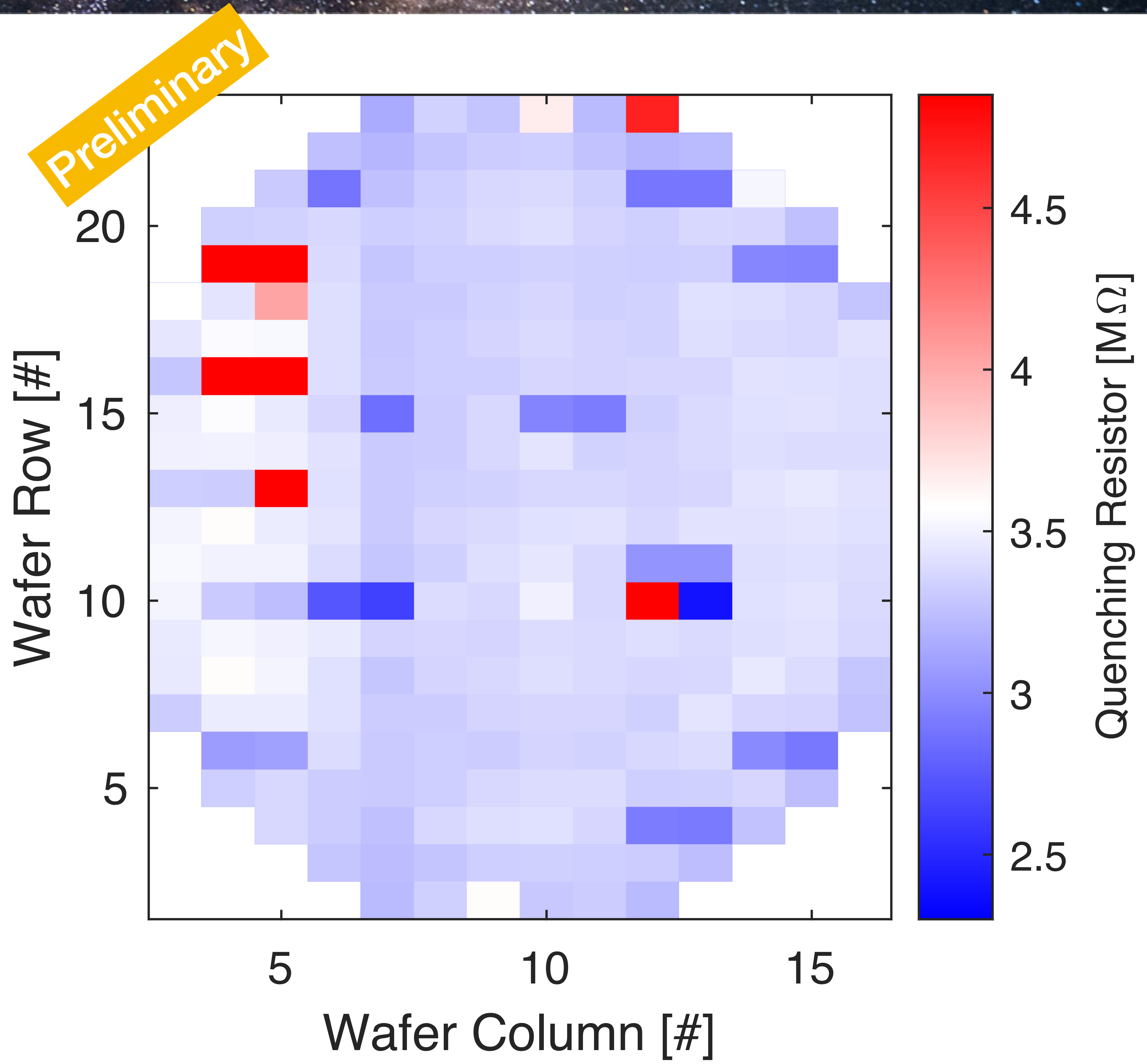
# Quenching Resistor Distribution

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

~Hz

$$I(V,\lambda) = f(V) \times \left[\mathbf{PDE}_{\lambda}(V) \times \Phi(\lambda) + \mathbf{R}^{\mathbf{DCR}}_{\mathbf{SiPM}}\right] \qquad f(V) \sim q_e \times \left(1 + \overline{\Lambda}\right) \times \overline{\mathbf{G}}_{1\ \mathbf{PE}},$$

If we assume that all the SiPMs have identical characteristics

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

Correlated noise

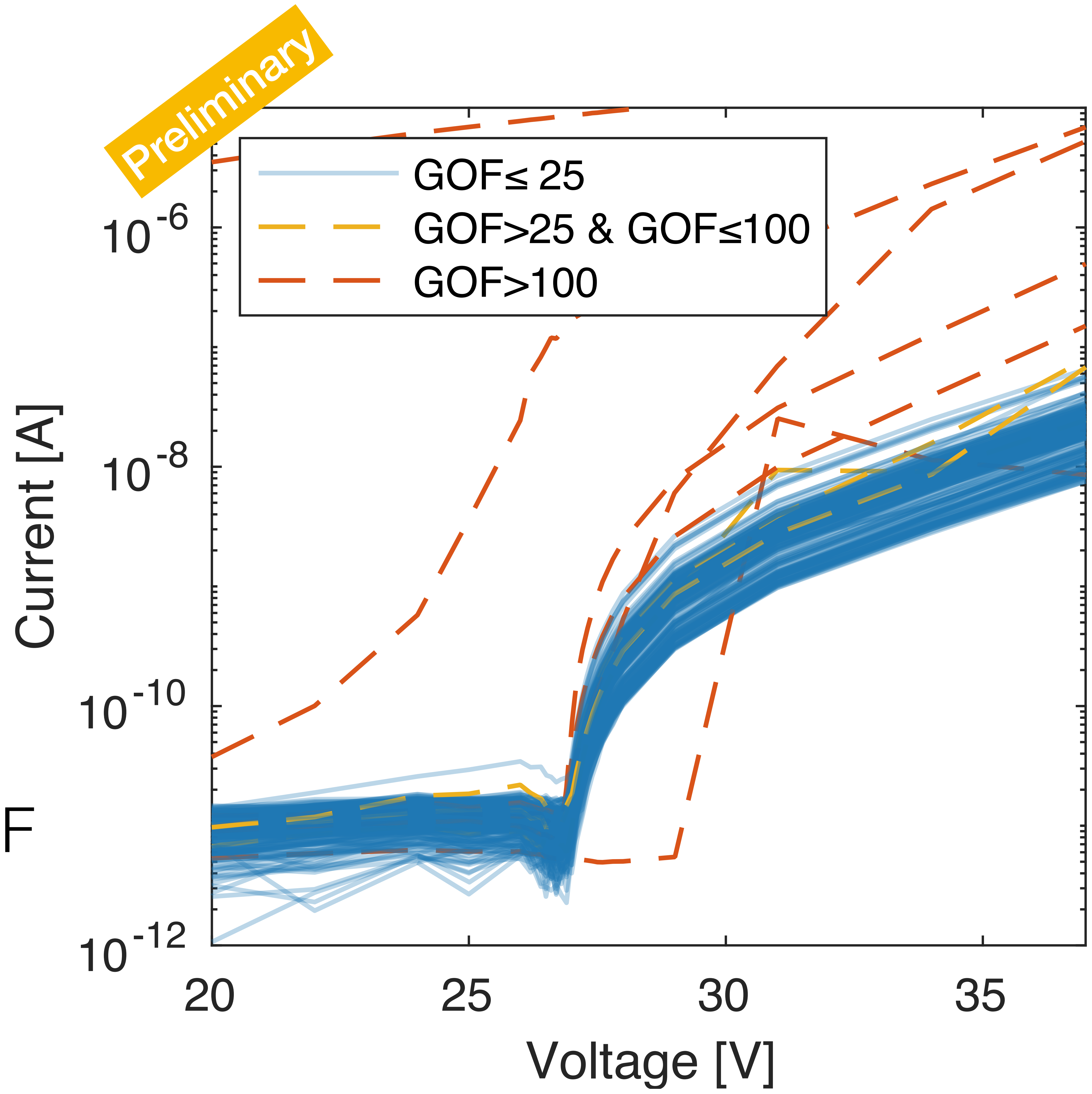
In order to ensure compliance of the wafer level IV curves we introduce a parameter called Goodness of Fit (GOF) defined as $\mathrm{GOF} = \sum_i \frac{(I_i - k\overline{I_i})^2}{\overline{\sigma_i^2}}$

# Goodness of Fit (GOF)

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

Measured IV Reference IV

Scaling Factor




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

# Goodness of Fit (GOF)

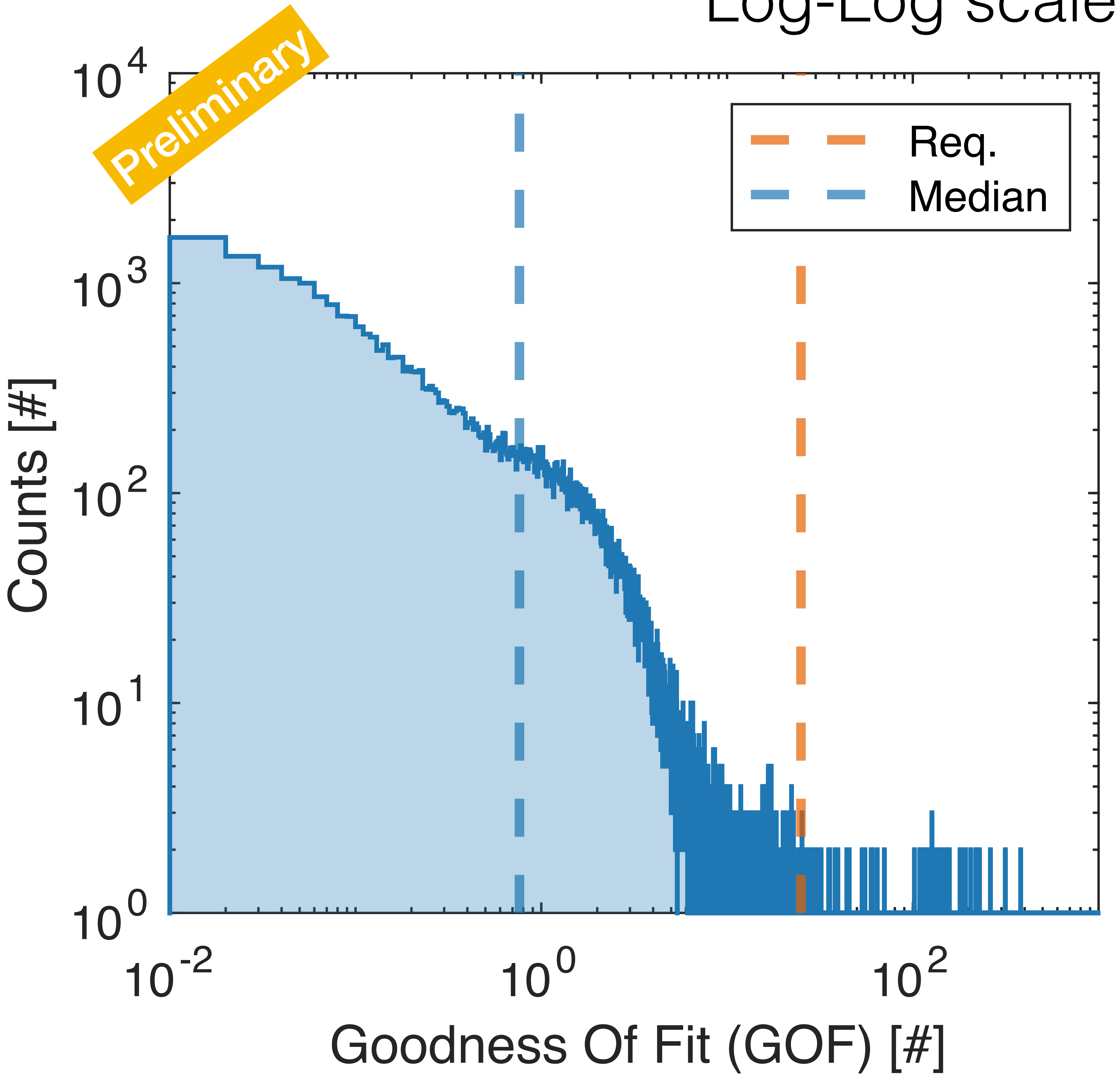
$$GOF = \sum_i \frac{(I_i - k\overline{I_i})^2}{\overline{\sigma_i^2}} \qquad k = \frac{\sum_i (\overline{I_i} \times I_i)/\overline{\sigma_i^2}}{\sum_i \overline{I_i^2}/\overline{\sigma_i^2}}$$

Scaling Factor

Measured IV Reference IV

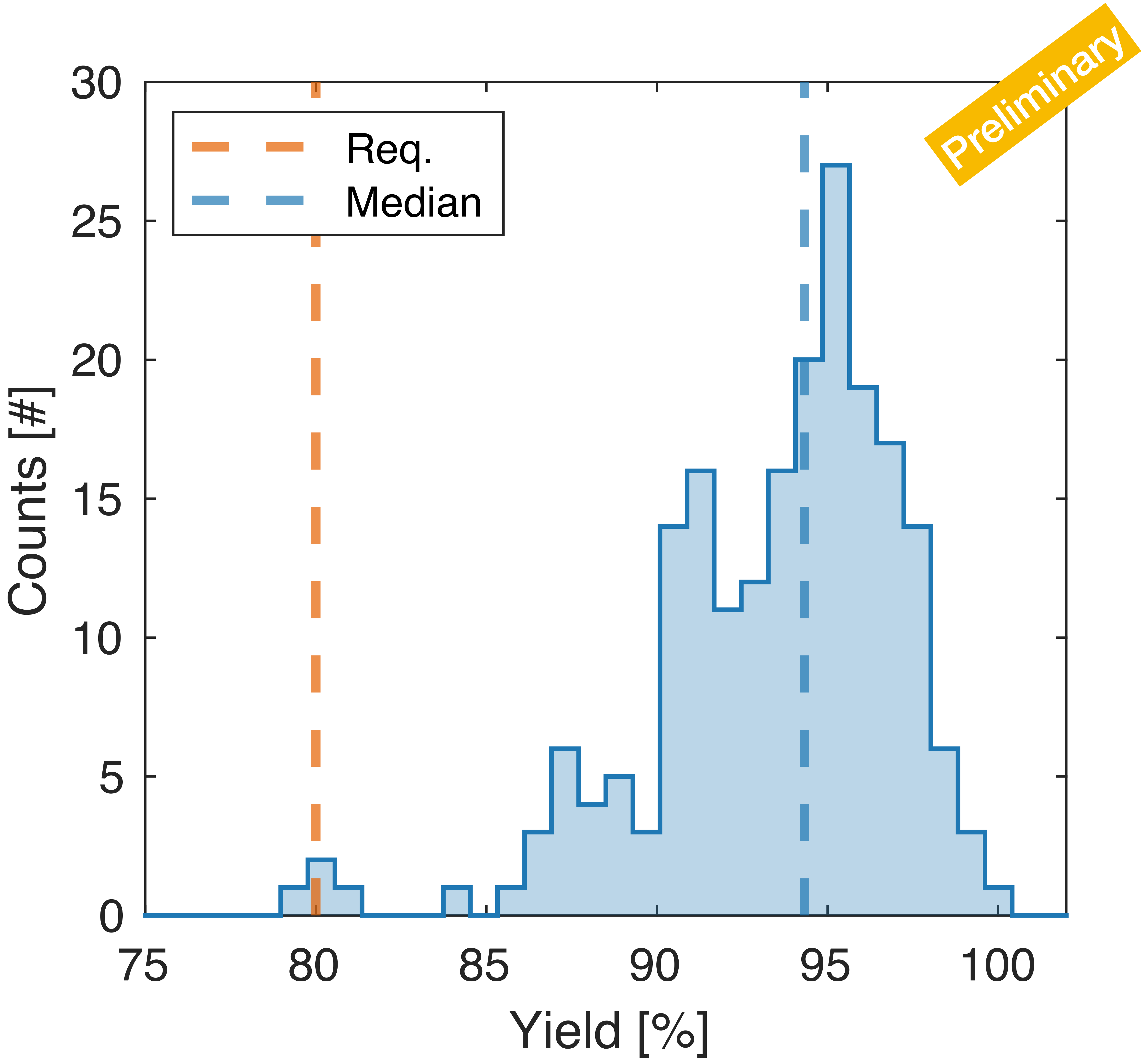
The distribution has a tail that ends at a GOF~25 that was assumed as the requirement based also on the results of a **simulation** of the GOF parameter

Log-Log scale



# Production Yield

- The Yield is computed assuming 264 testable dice (not the total 268)
- Average yield is $92.9 \pm 0.4$ %
- 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!

**Contacts:**
gallina@princeton.edu

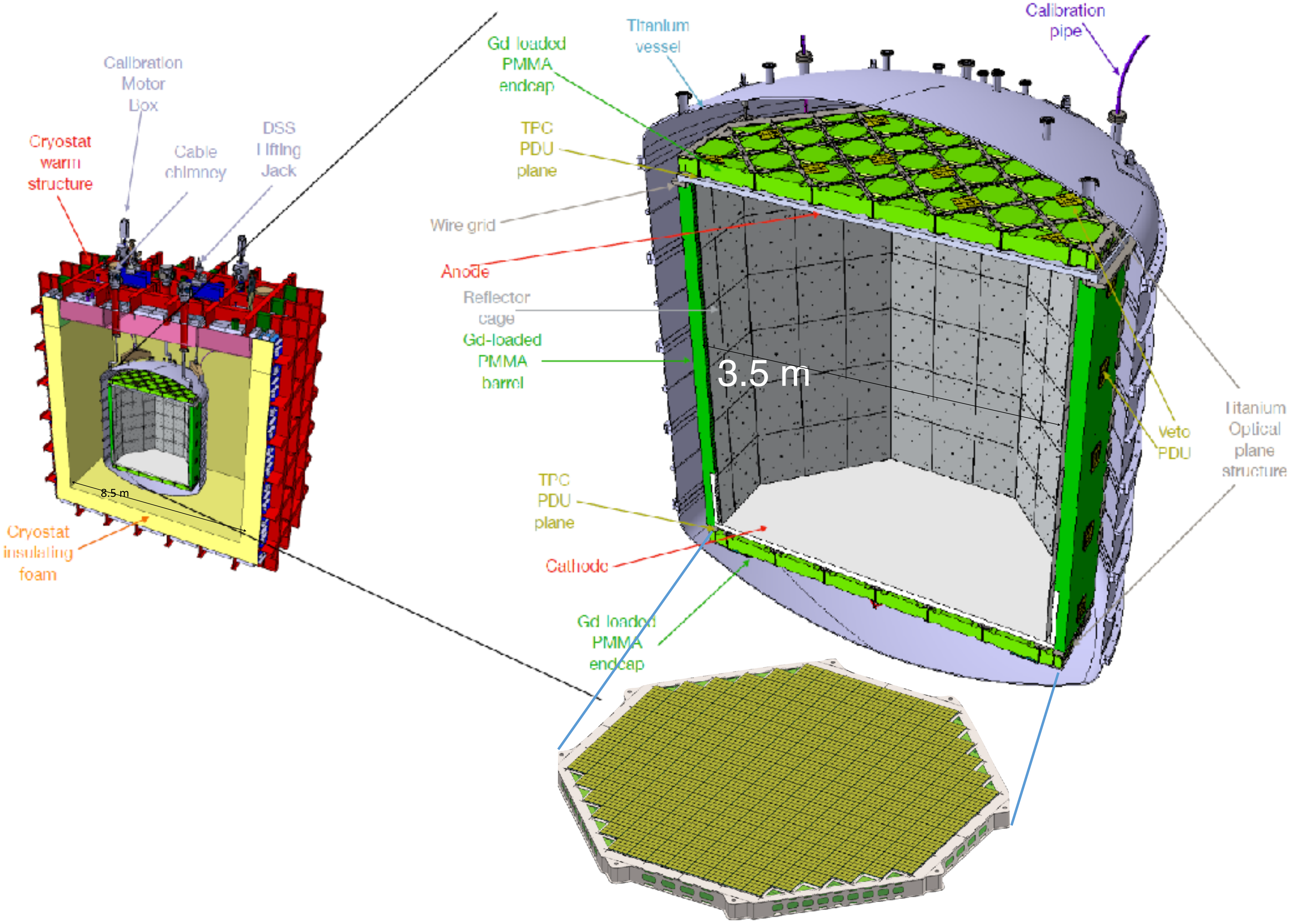
# Inner detector

- 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**