Status and perspectives of the DarkSide experimental program

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on behalf of the Global Argon Dark Matter Collaboration

Princeton University

CPAD Workshop 2022

Stony Brook University, November 29th

Overview

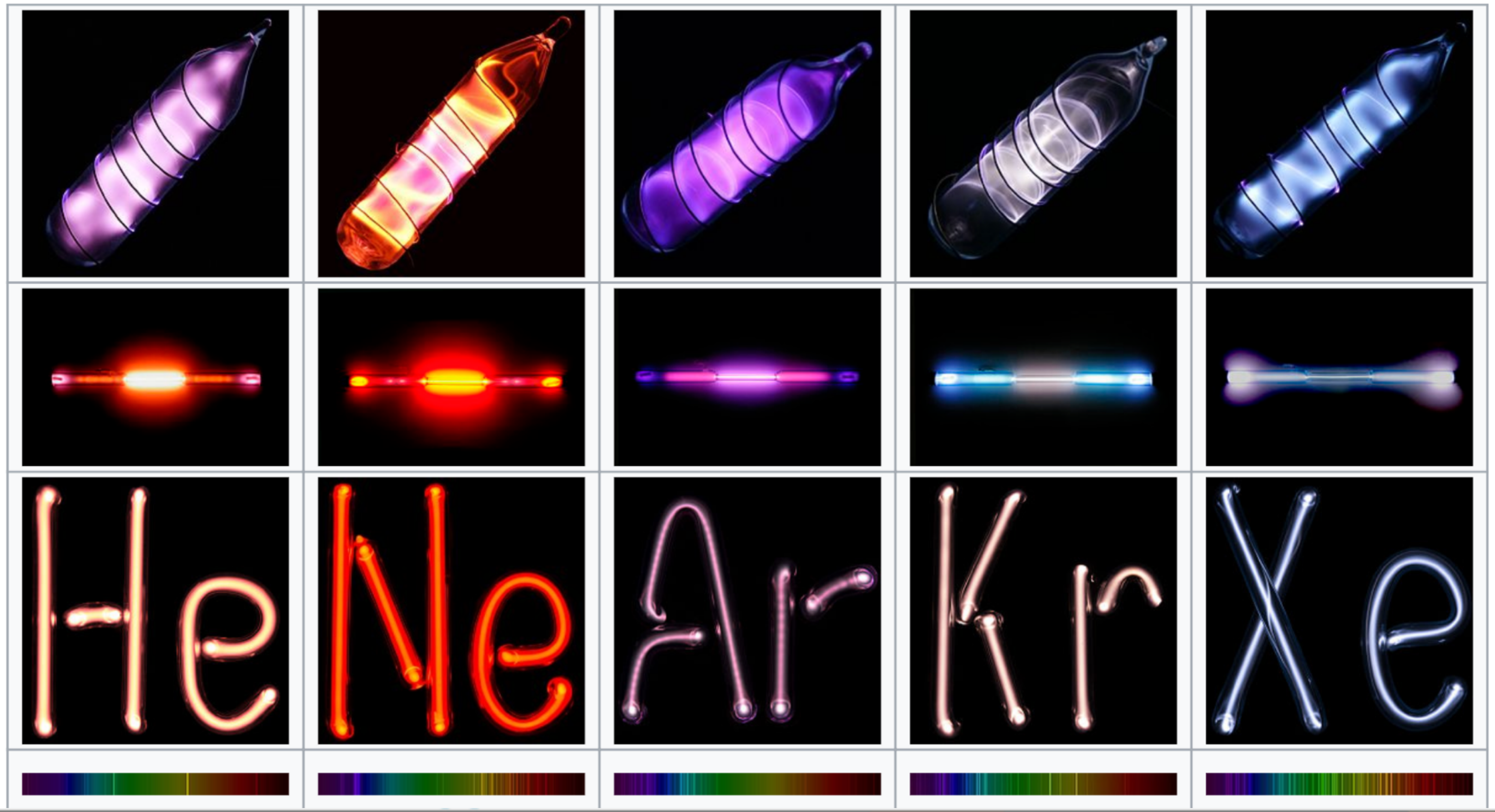
1. **Argon targets for direct detection**
2. **DarkSide status and perspectives**
    - The experimental program
    - DarkSide-20k overview
    - Detector design
    - Argon target procurement

Dark Matter and direct detection trivia

Search with liquefied noble elements

- WIMP DM signal: nuclear recoils (NR)
- Electron Recoils (ER) are background

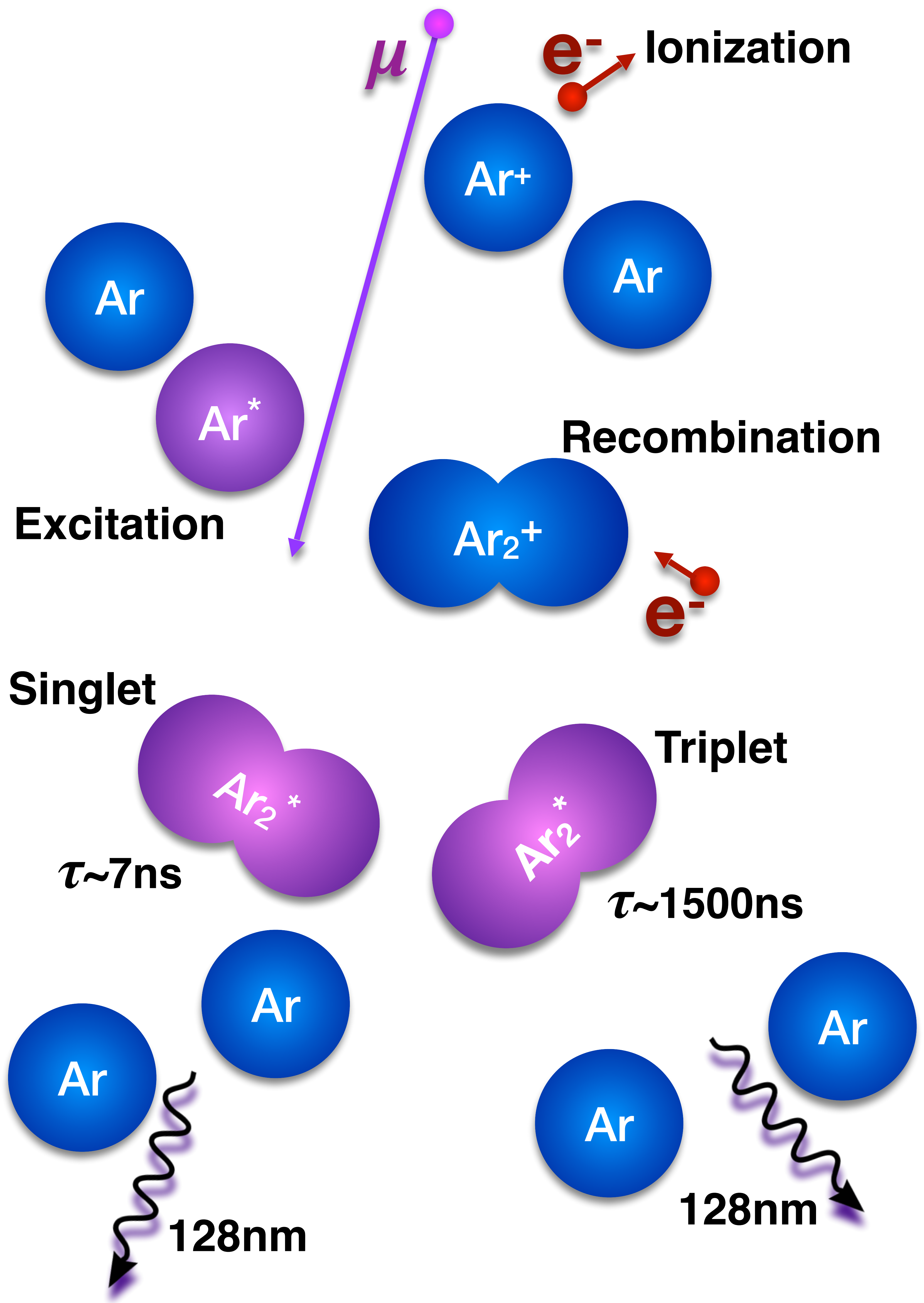
- High density ✔
  Self screening
  Good scalability
- Easy(-ish) purification, also online ✔
- Scintillation: good light yield ✔
- Ionisation ✔
- ER rejection ✔
- NR quenching at low energies ✘

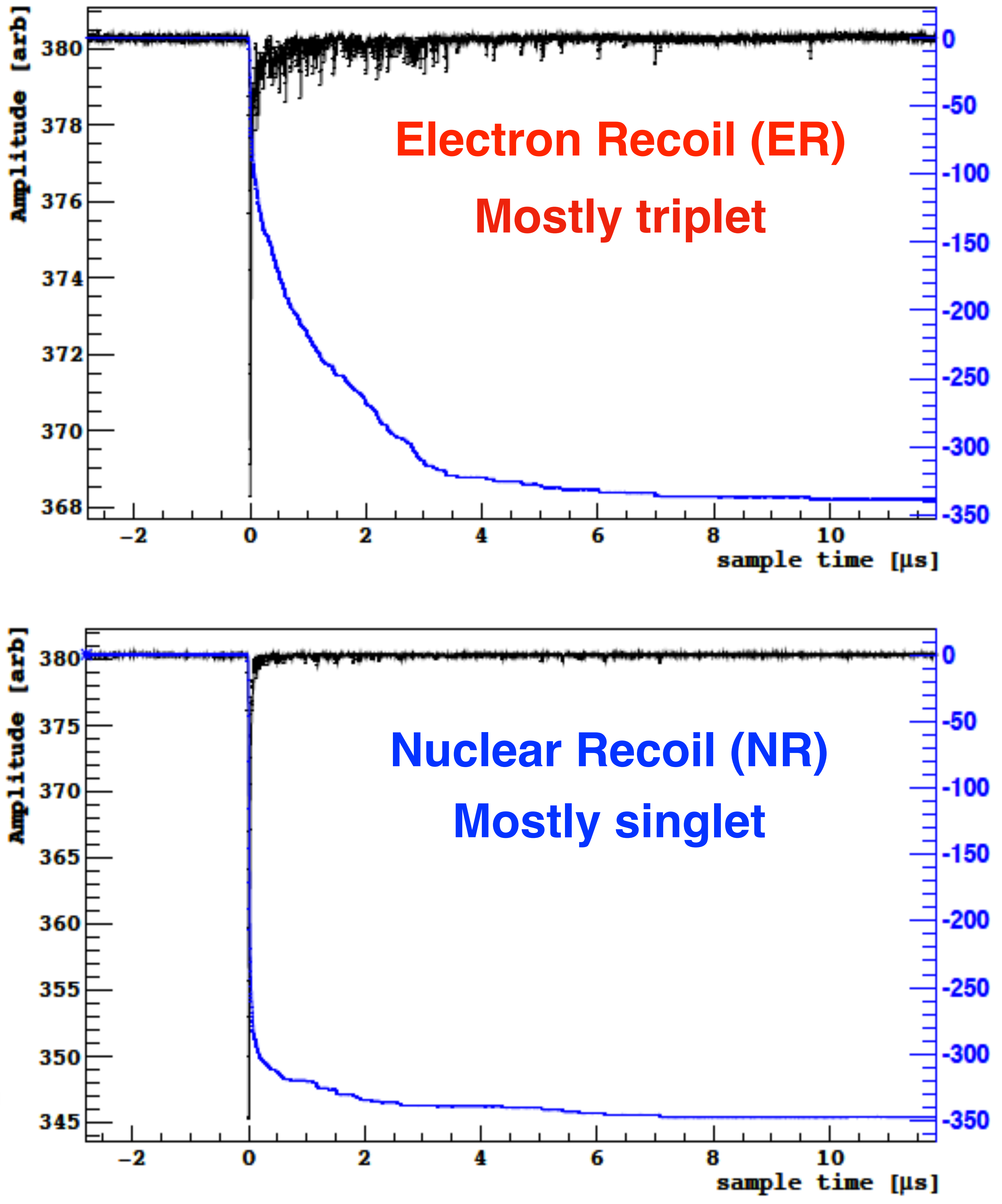


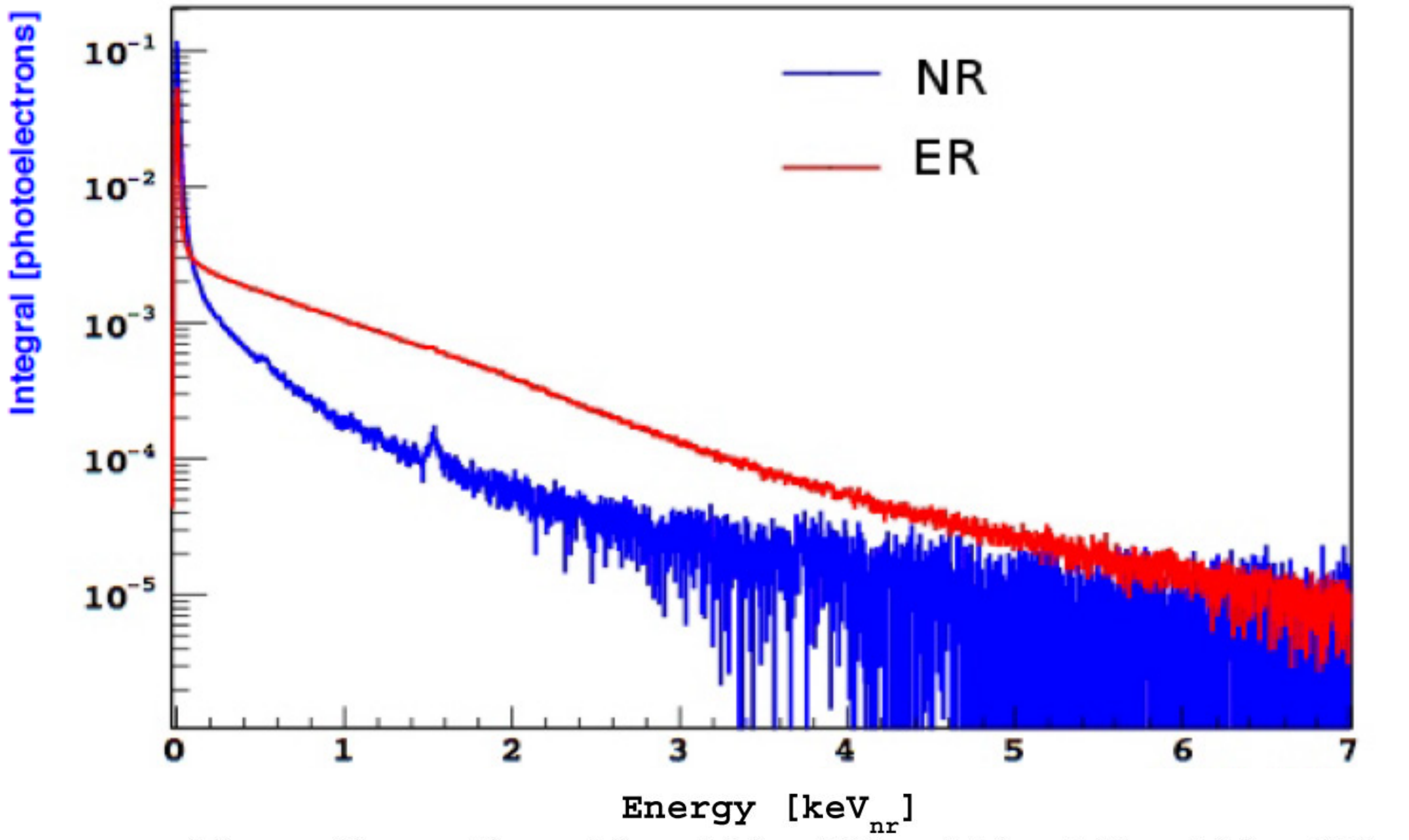
		LAr	LKr	LXe
Physical properties	Atomic number	18	36	54
	Boiling point at 1 bar, T_b (K)	87.3	119.8	165.0
	Density at T_b (g/cm^3)	1.40	2.41	2.94
Ionisation	W (eV)[1]	23.6	20.5	15.6
	Fano factor	0.11	~0.06	0.041
	Drift velocity (cm/μs) at 3 kV/cm	0.30	0.33	0.26
	Transversal diffusion coefficient at 1 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

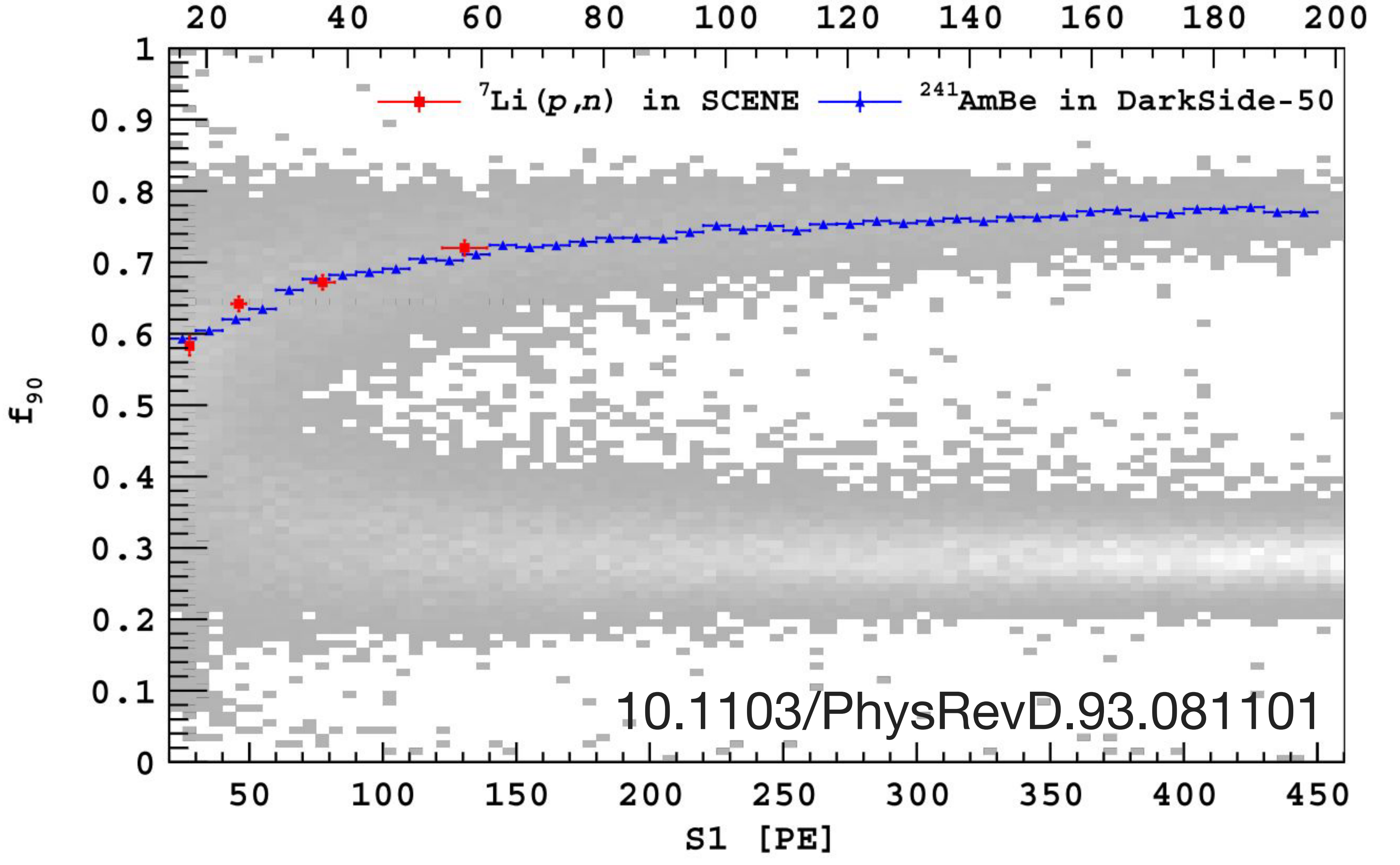
Excellent discrimination power!

ER rejection in LAr









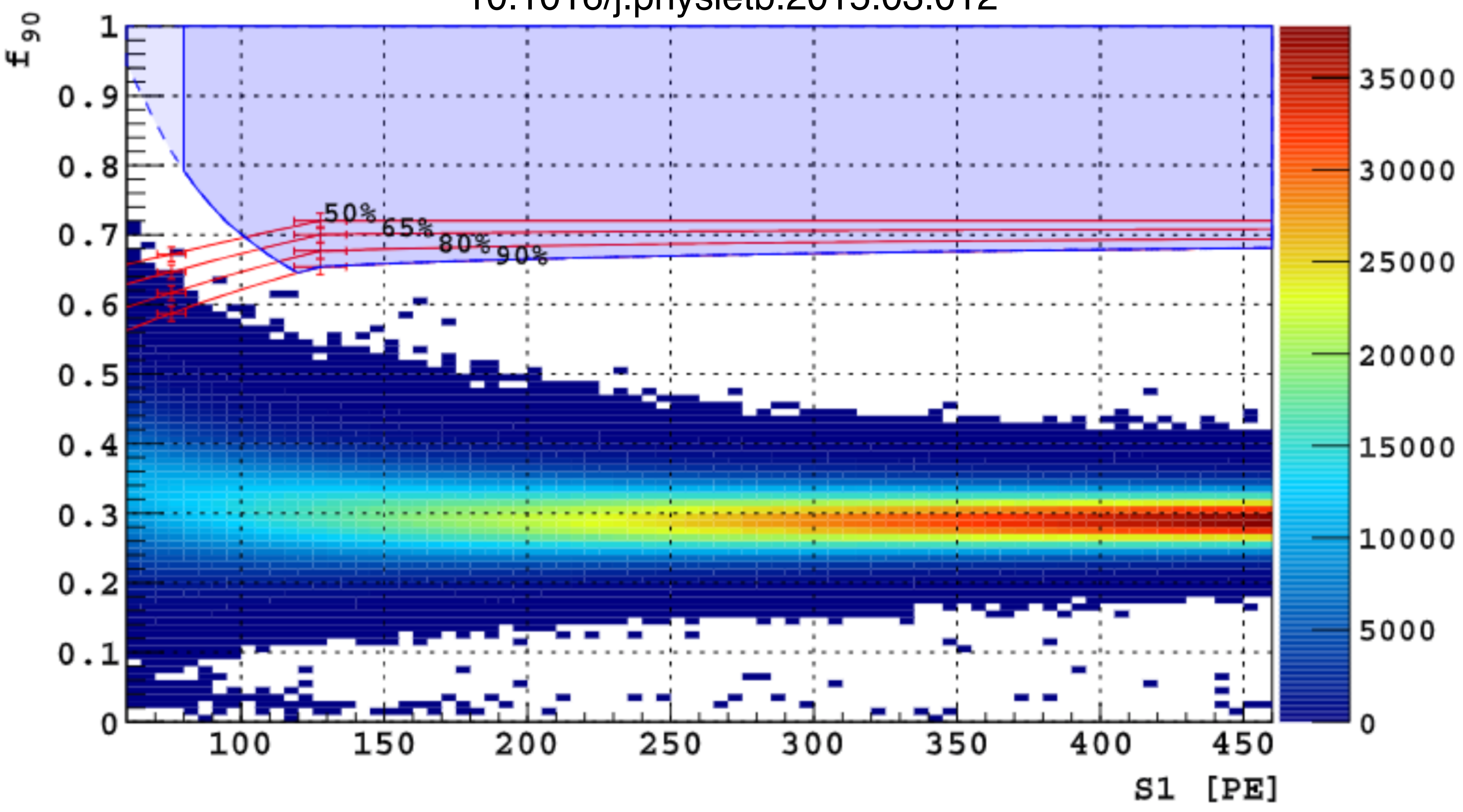
$\beta,\gamma \rightarrow$ ER $\quad \nu$, n, WIMPs $\rightarrow$ NR

$$f_{prompt} = \frac{\text{prompt light}}{\text{total light}}$$

ER rejection in LAr

DarkSide-50

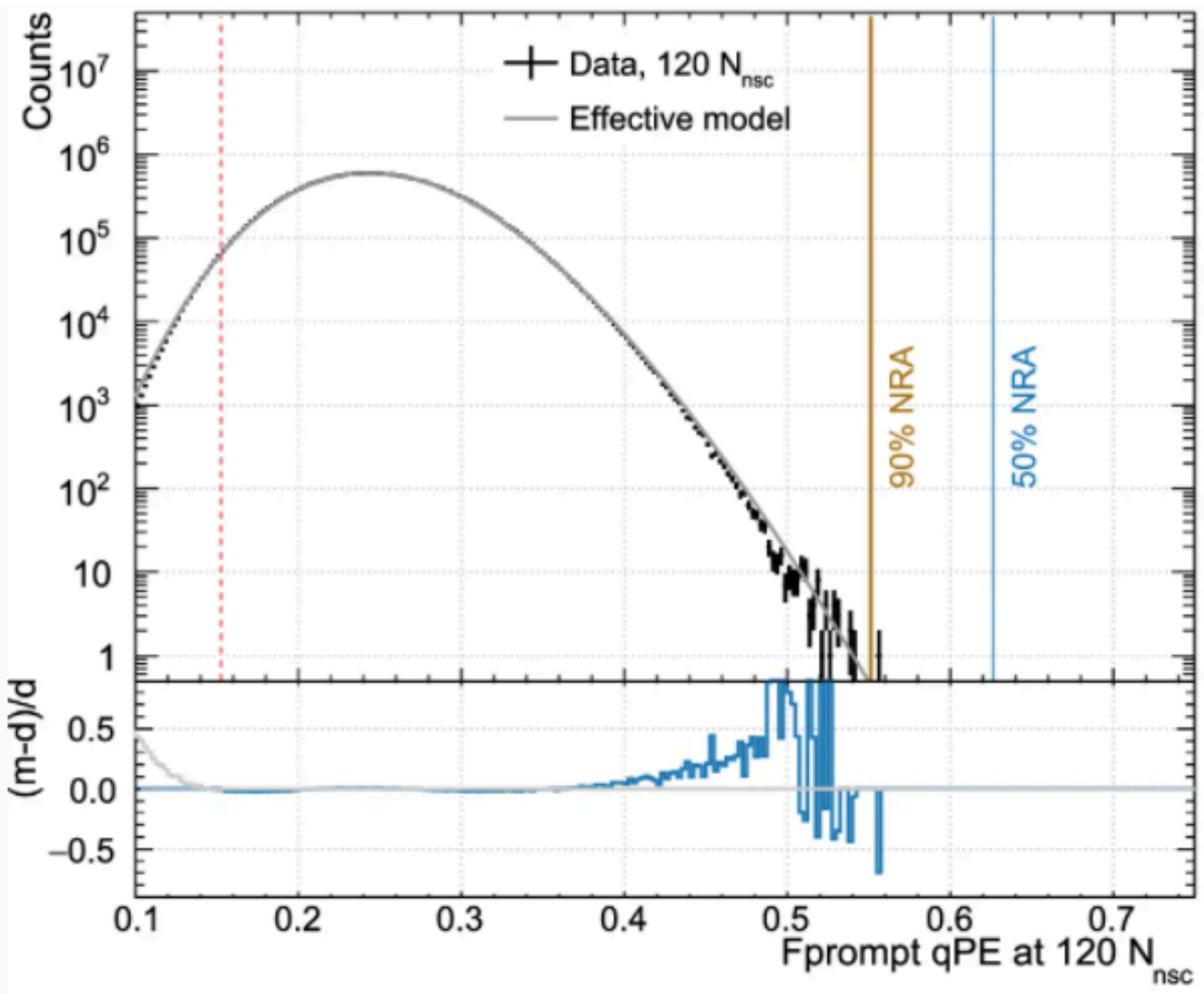
10.1016/j.physletb.2015.03.012



β,γ rejection better than 1.5x10[7]

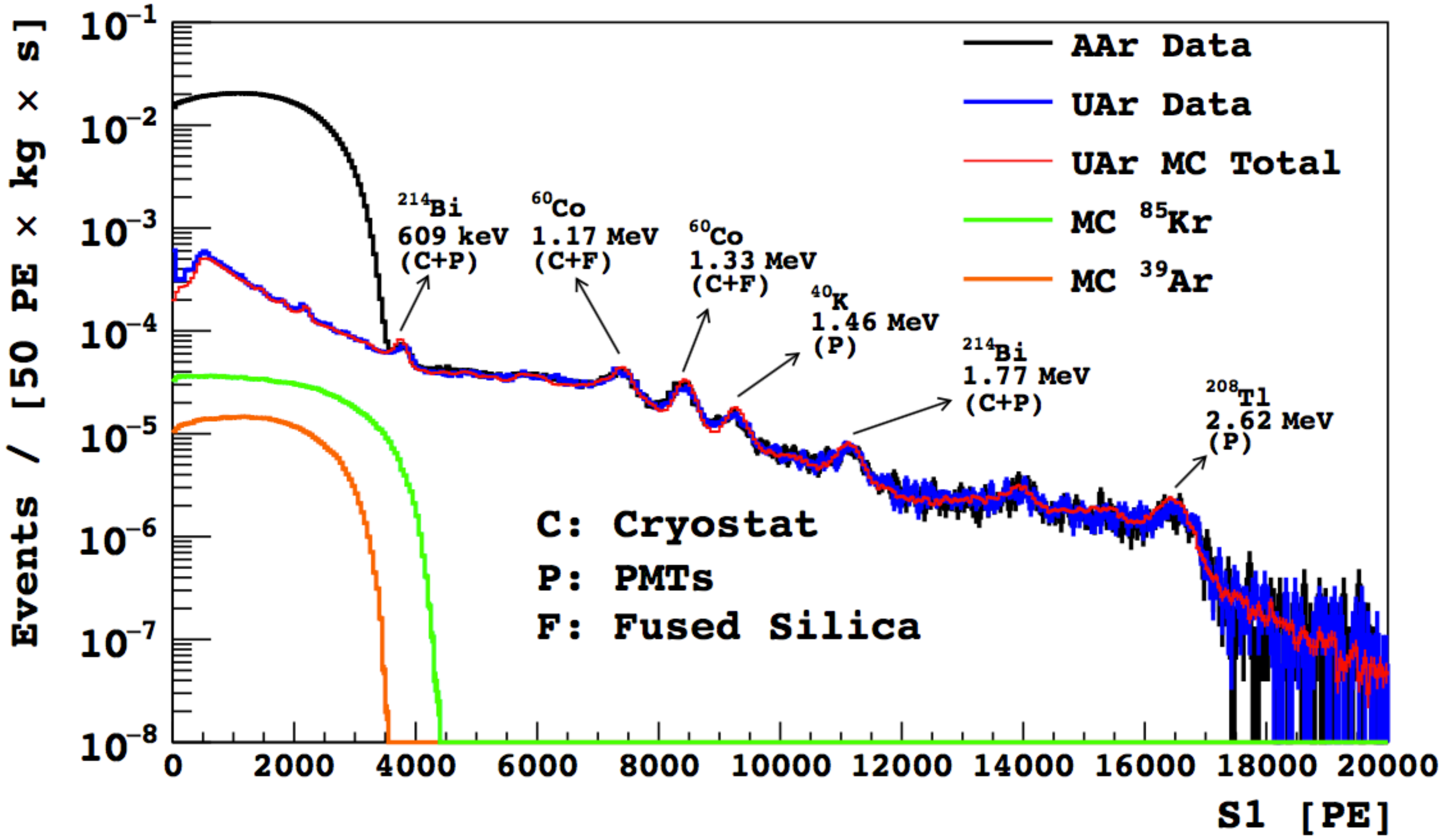
DEAP-3600

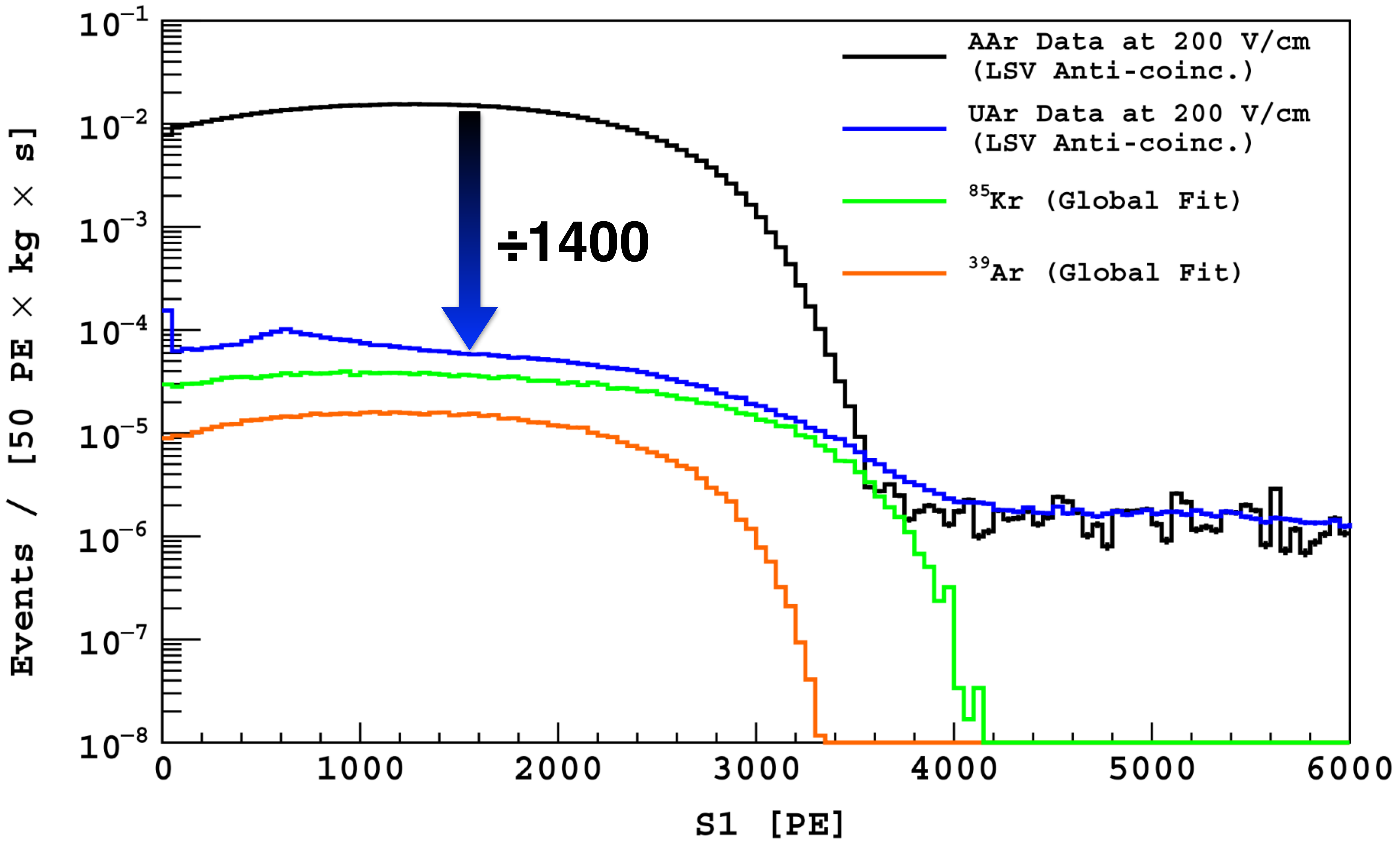
Eur. Phys. J. C 81,823 (2021)



β,γ rejection better than 10[8]

LAr challenges: ^{39}Ar

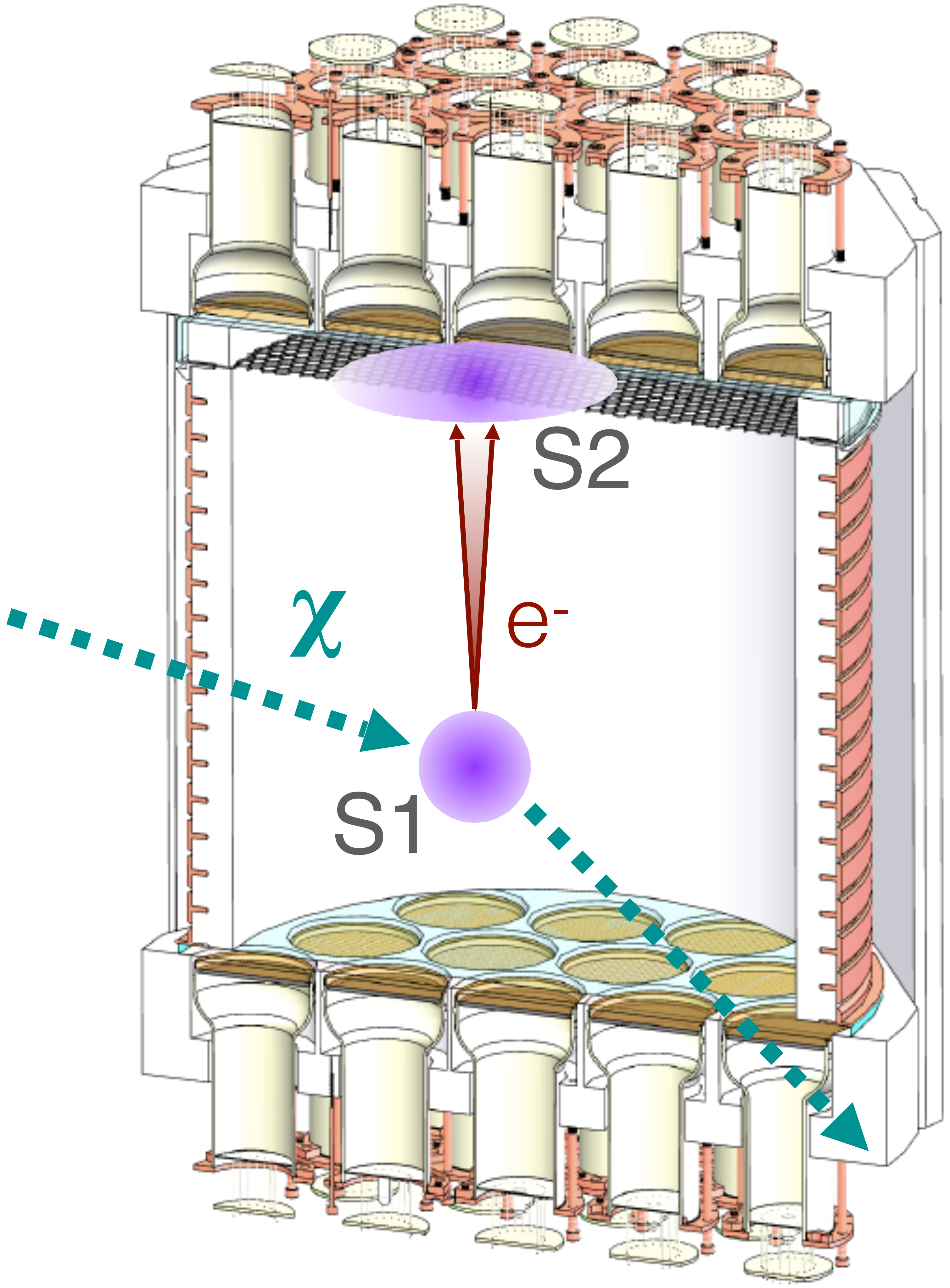




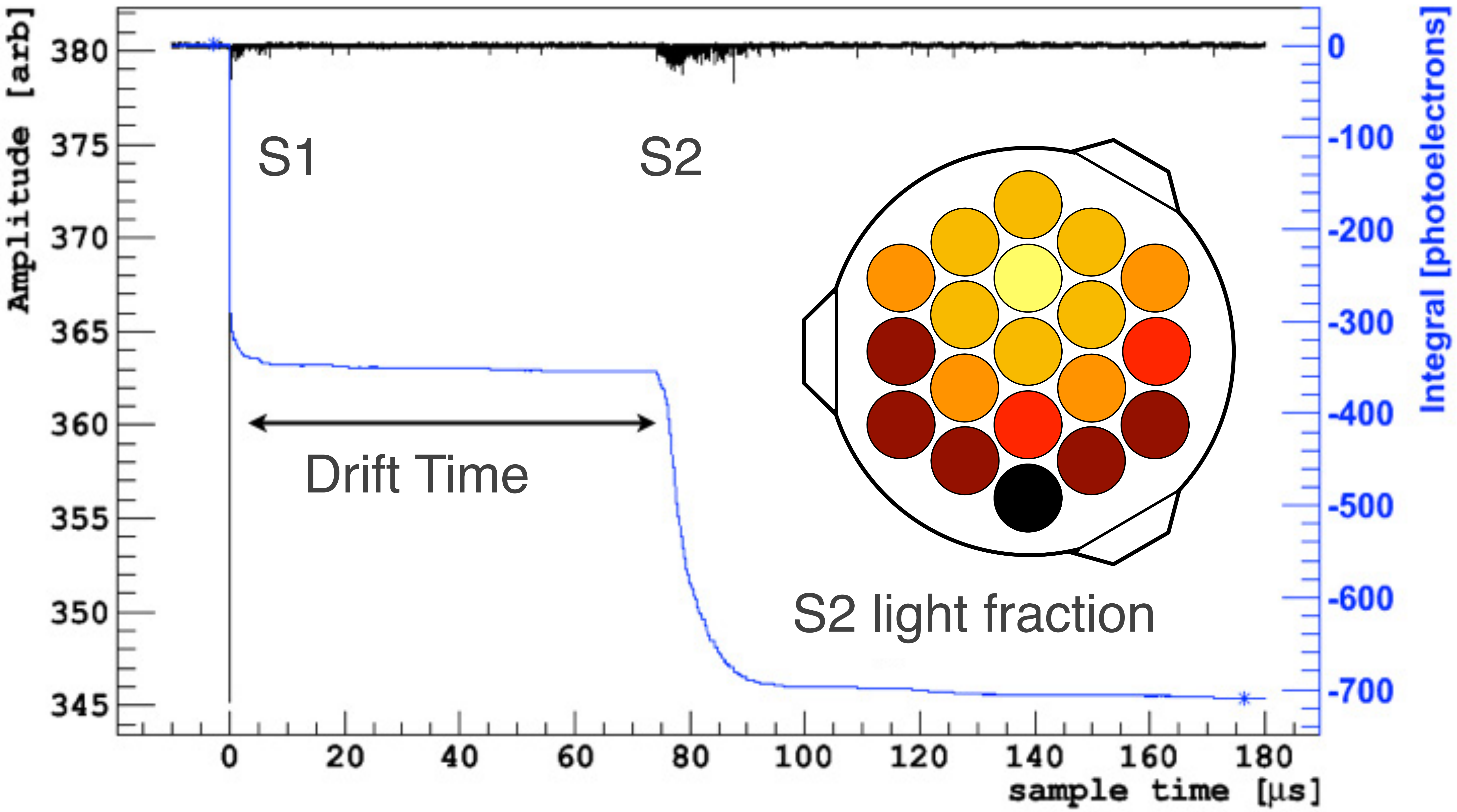
- ^{39}Ar is a cosmogenic isotope
- β-decay with 565 keV endpoint and ~269y of half life
- ~1Bq/kg in atmospheric Ar
- Rejection possible with f_{prompt}, but there's pile-up!

- No activation in Ar from deep gas reservoirs (UAr)
- Suppression factor ~1400 demonstrated in DS-50
- Possibly higher depletion factor

Dual-phase TPCs



3D position reconstruction

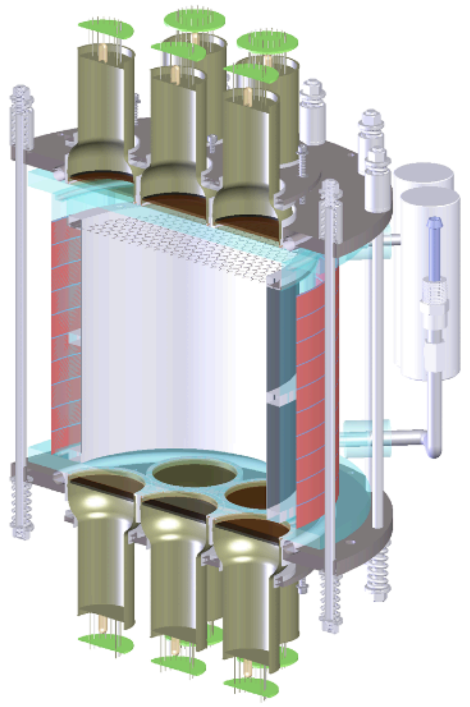


- Z from S1-S2 time difference
- XY from S2 light distribution
- Reliable fiducialization
- Multiple scattering rejection

The DarkSide program

A multi-stage approach

2012

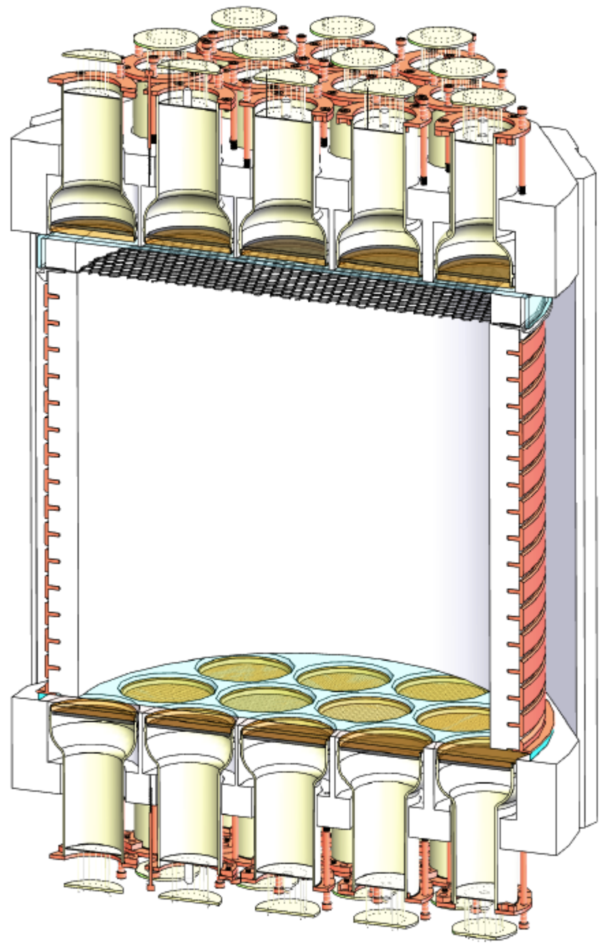


DarkSide-10

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

2013 - 2018

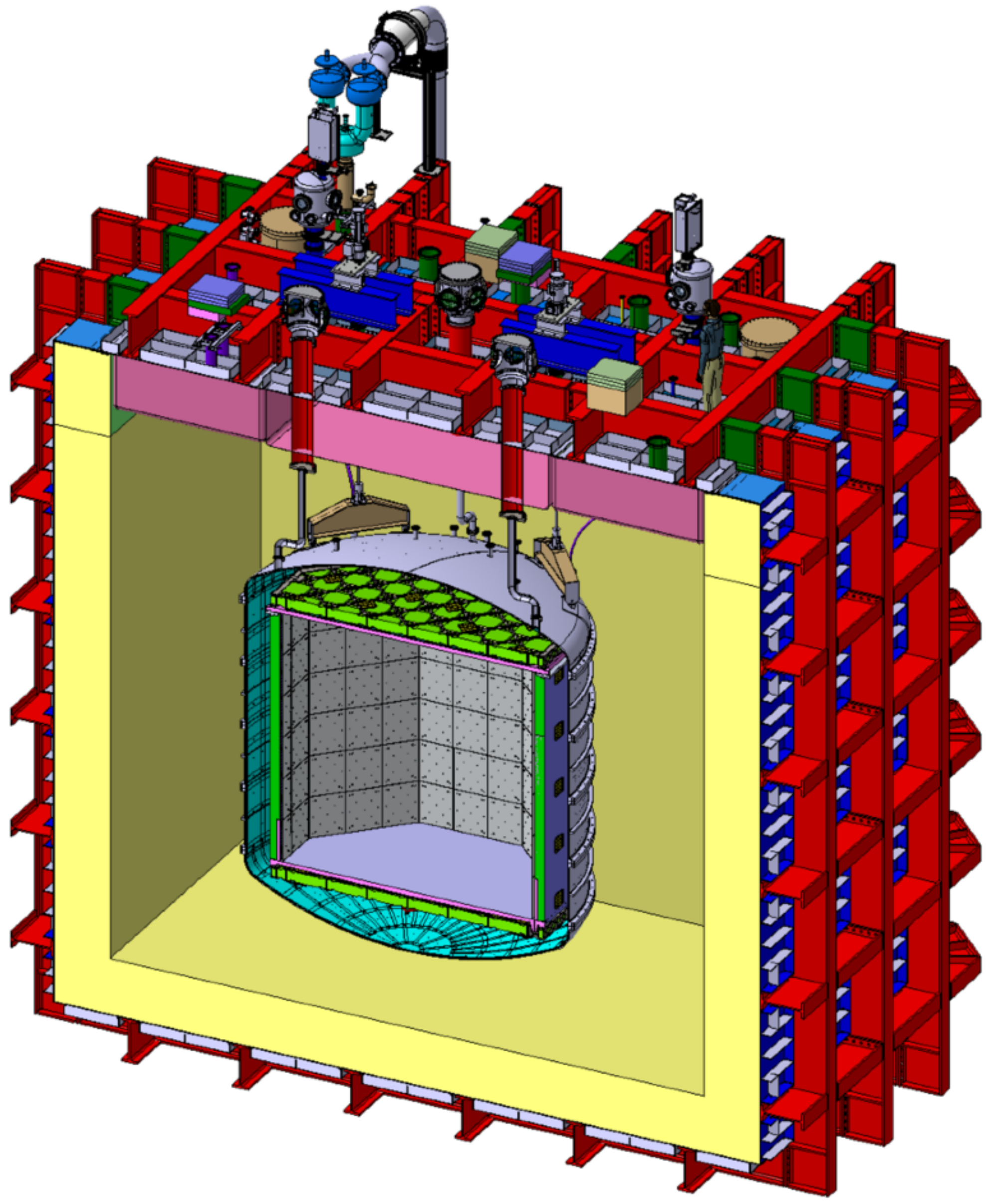
For more info on DS50 results attend E. Berzin talk on Thursday at 8:50am!



DarkSide-50

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

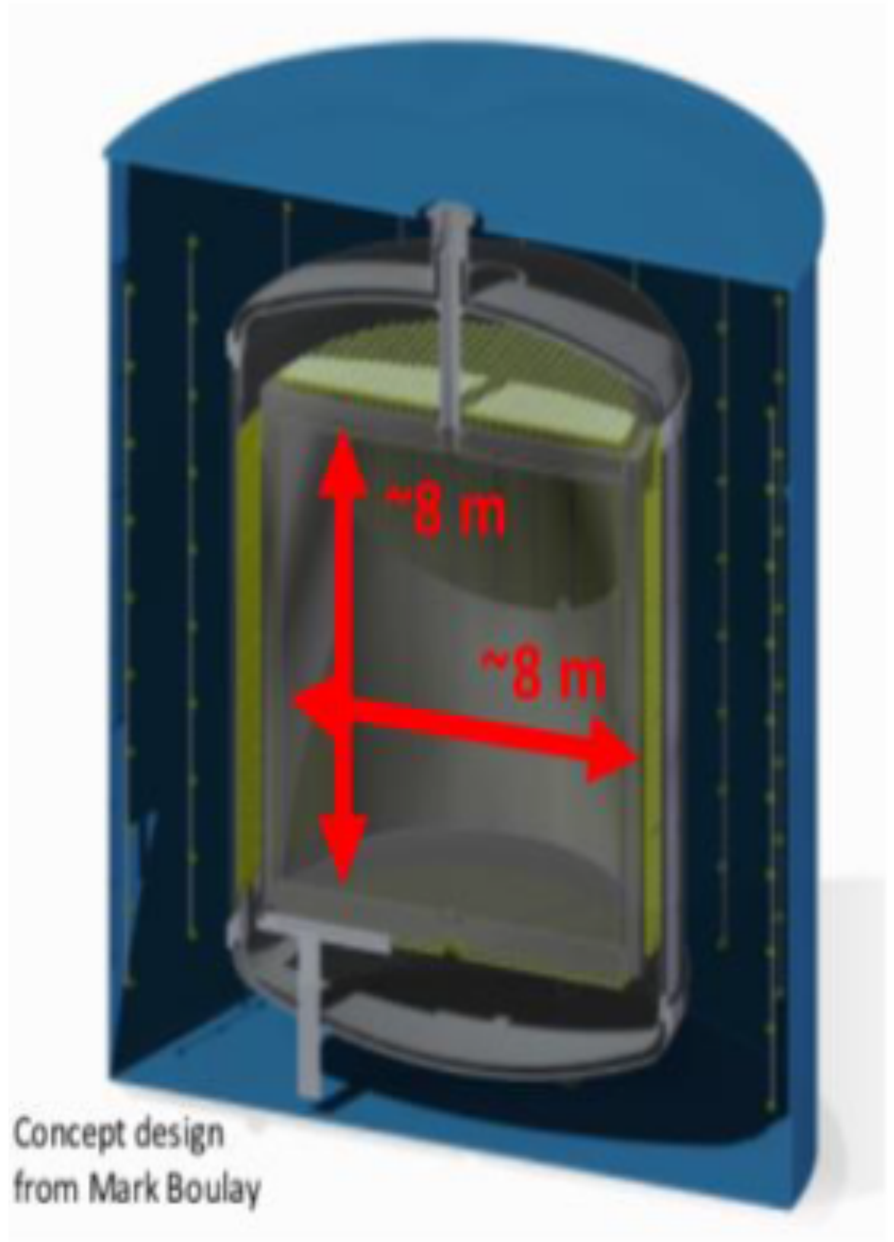
2025 - 2035



DarkSide-20k @ LNGS

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

2030s - ...

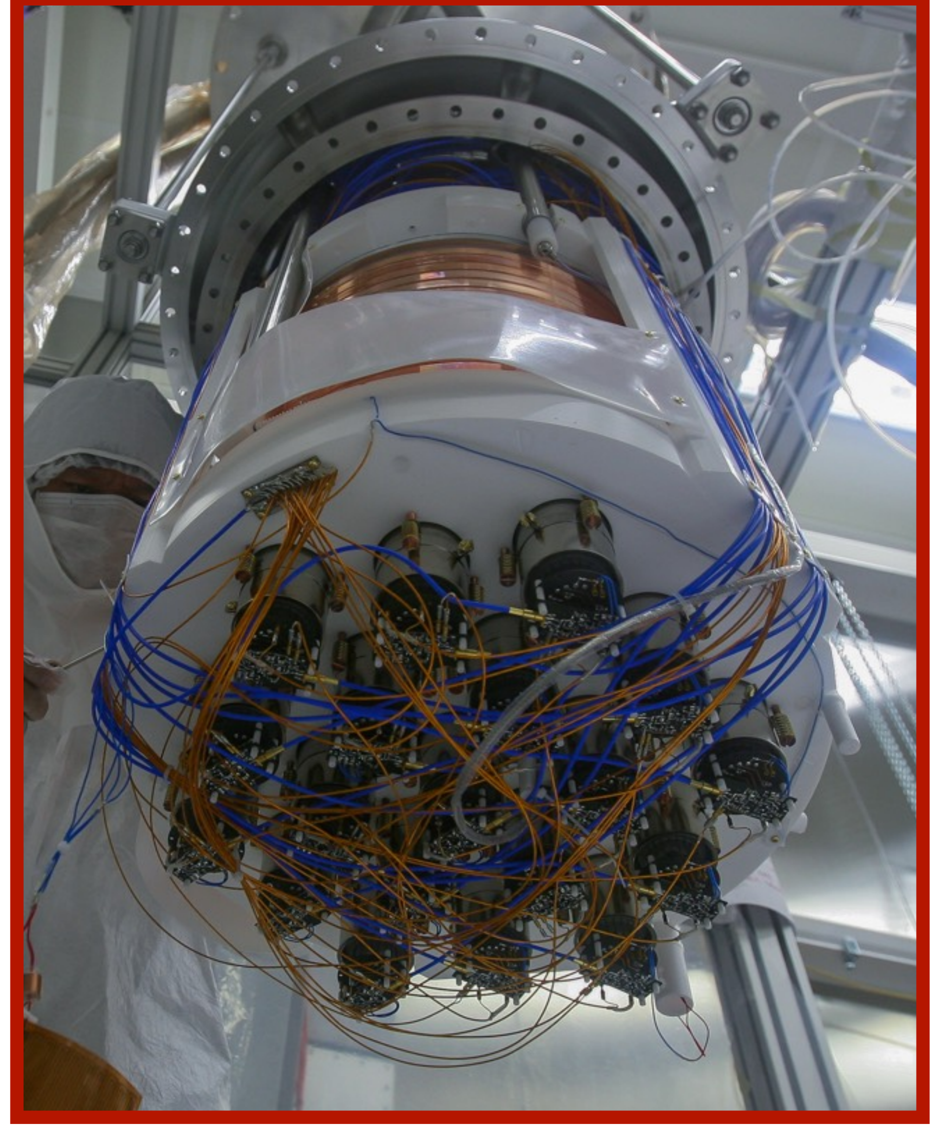


Argo @ SNOLAB

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

The GADMC

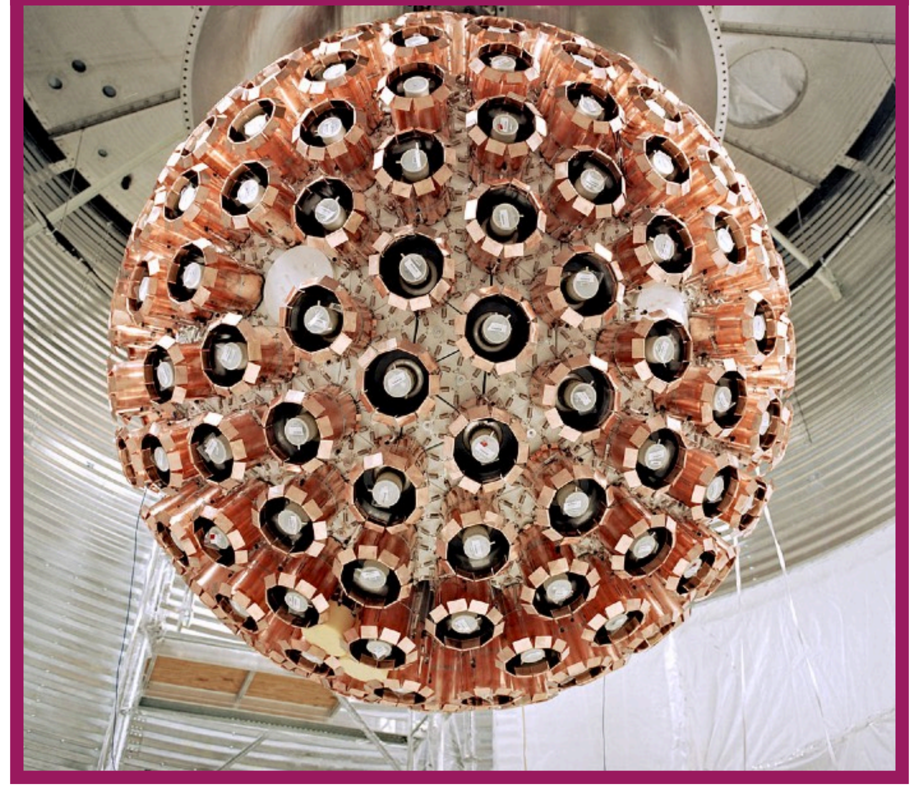
DarkSide-50 @ LNGS



ArDM @ Canfranc

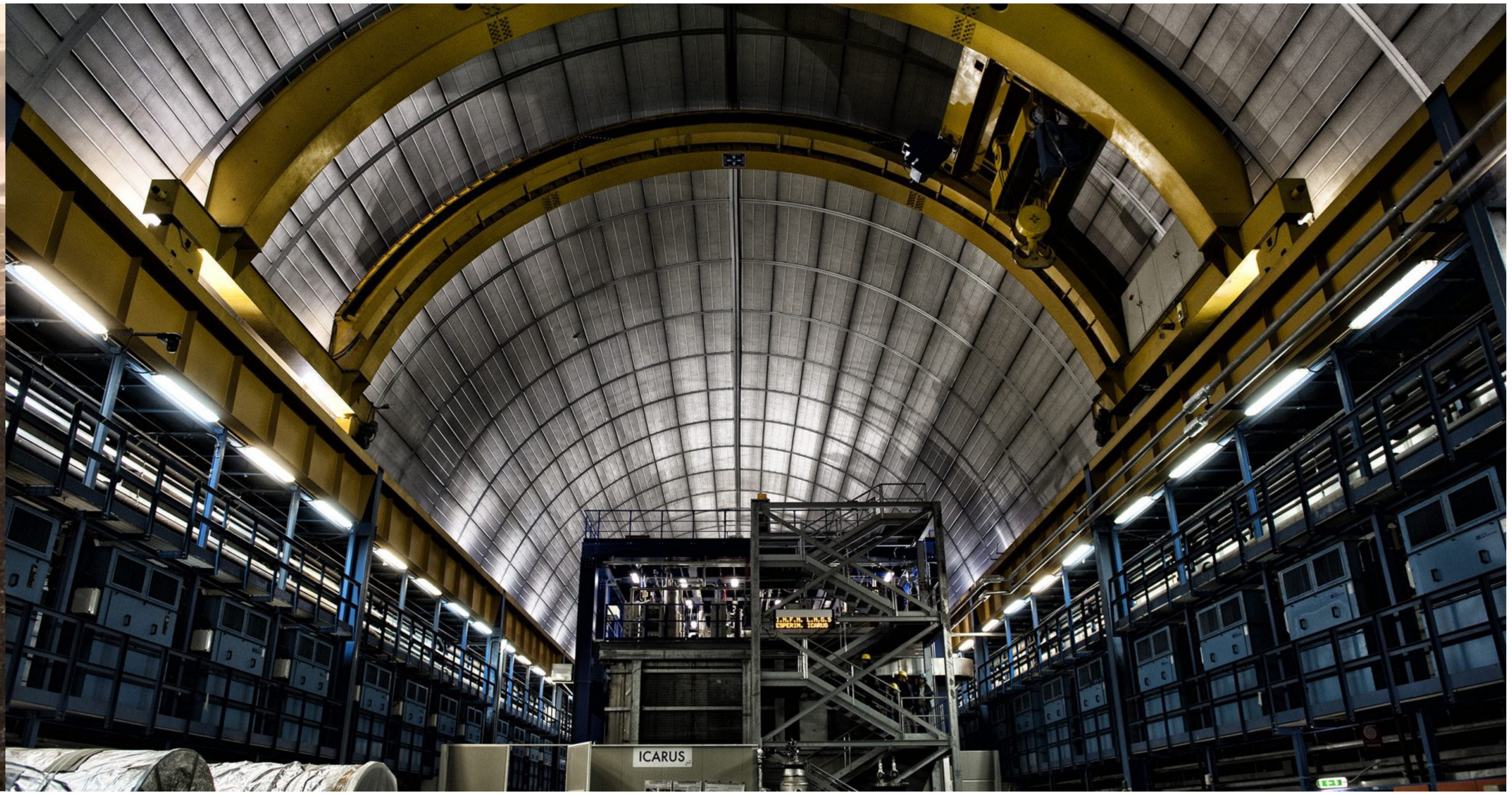
MiniClean @ Snolab

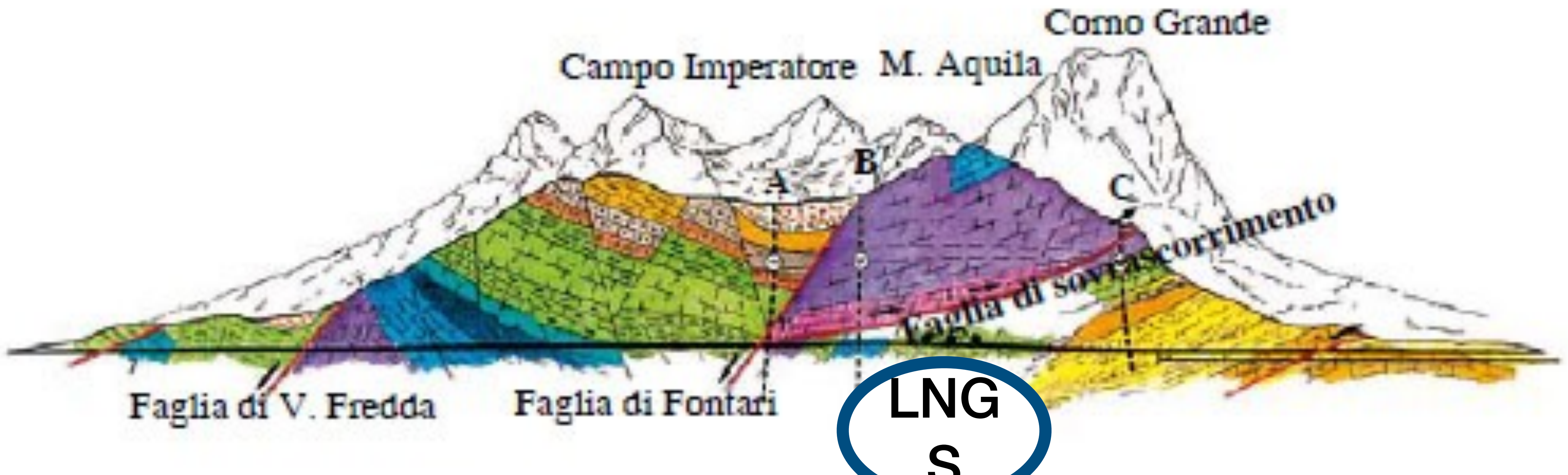
DEAP @ Snolab



>400 scientists, >100 institutions distributed across 13 countries

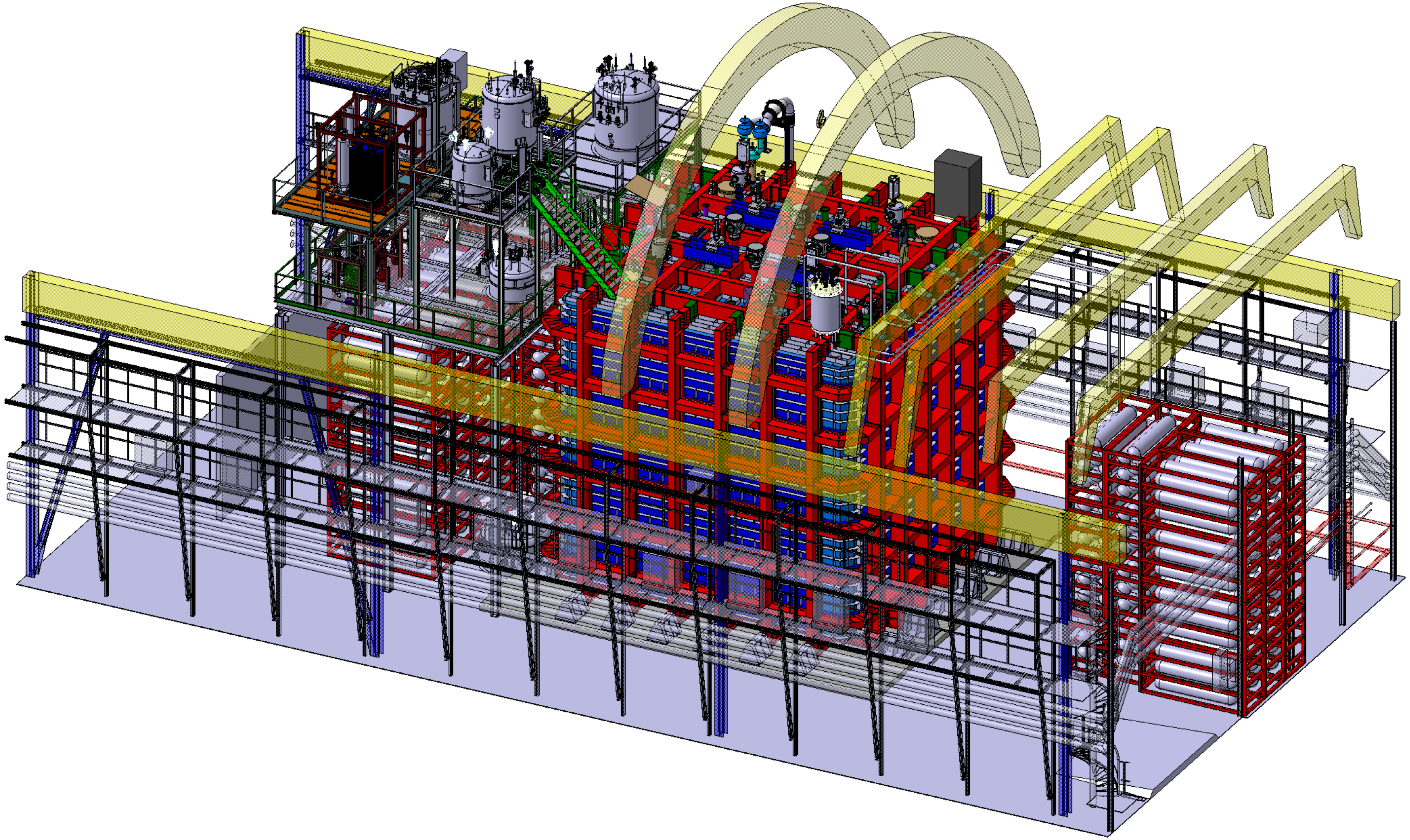
Host laboratory: LNGS



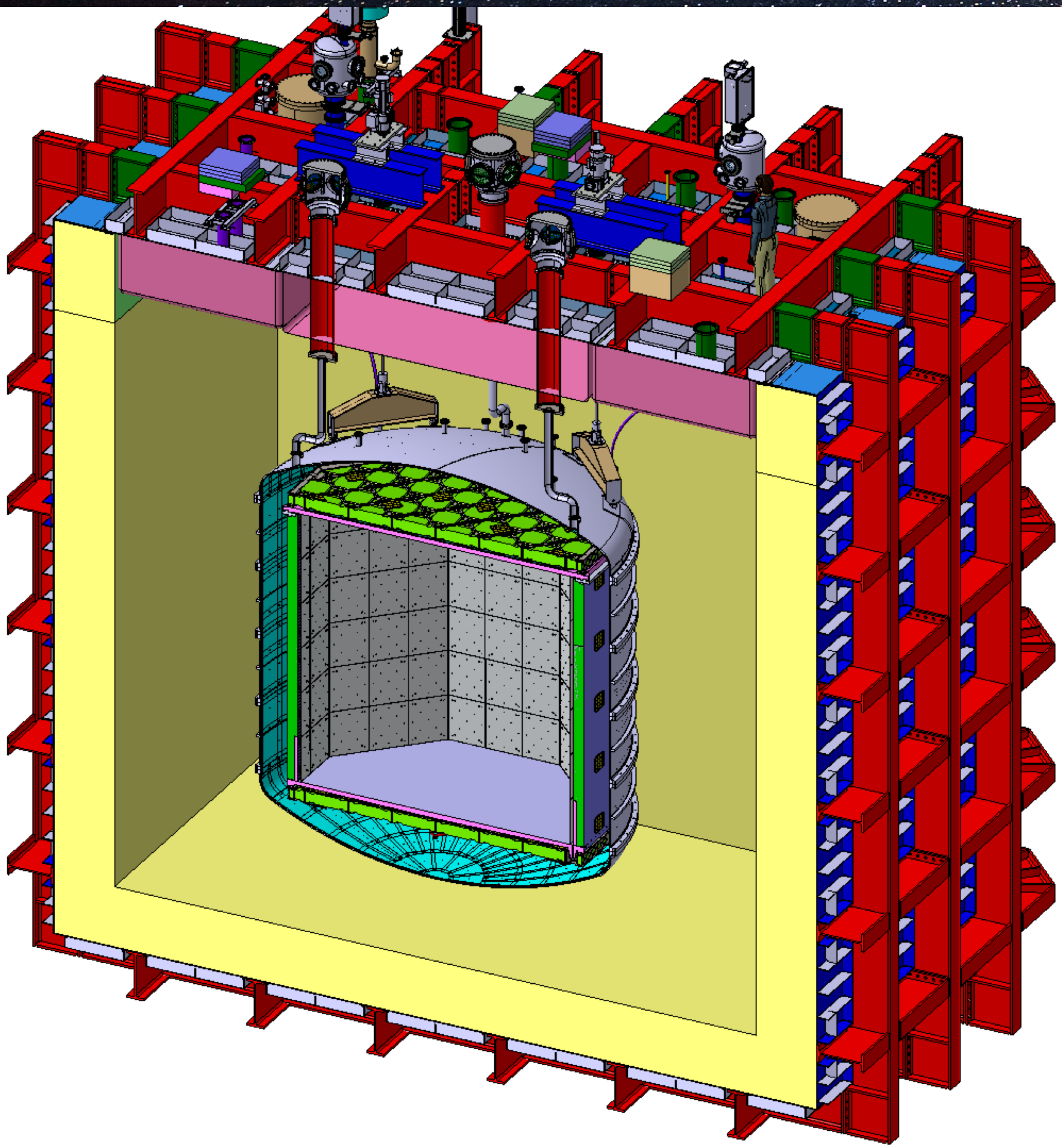


- Below ~1400m of rock (3400 m.w.e)
- Muon flux reduction factor ~10^6
- 3 main experimental halls (20x100x18 m^3)

DarkSide-20k in Hall C @ LNGS



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

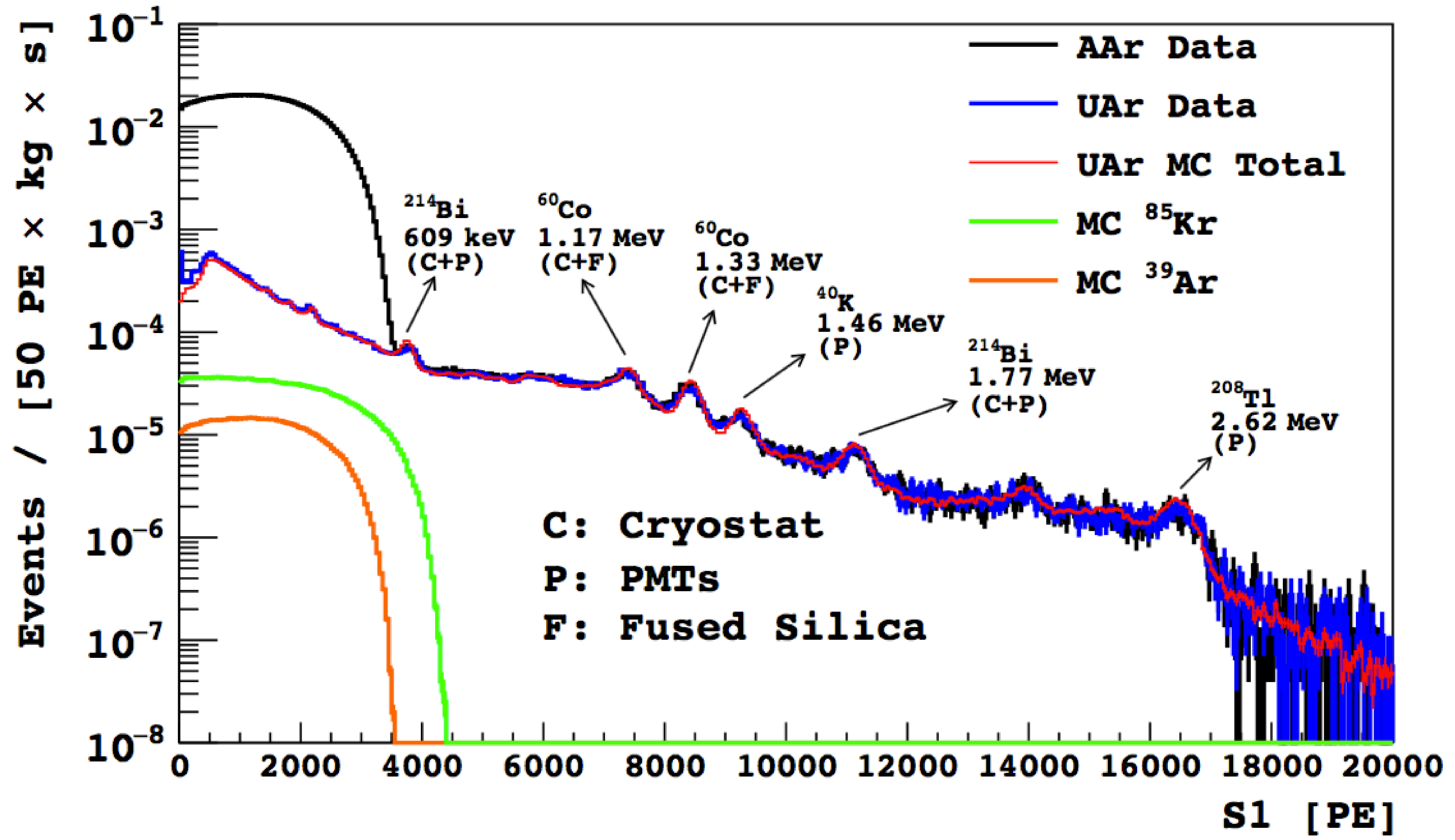
β and γ after cuts: < 0.1 in 10 y

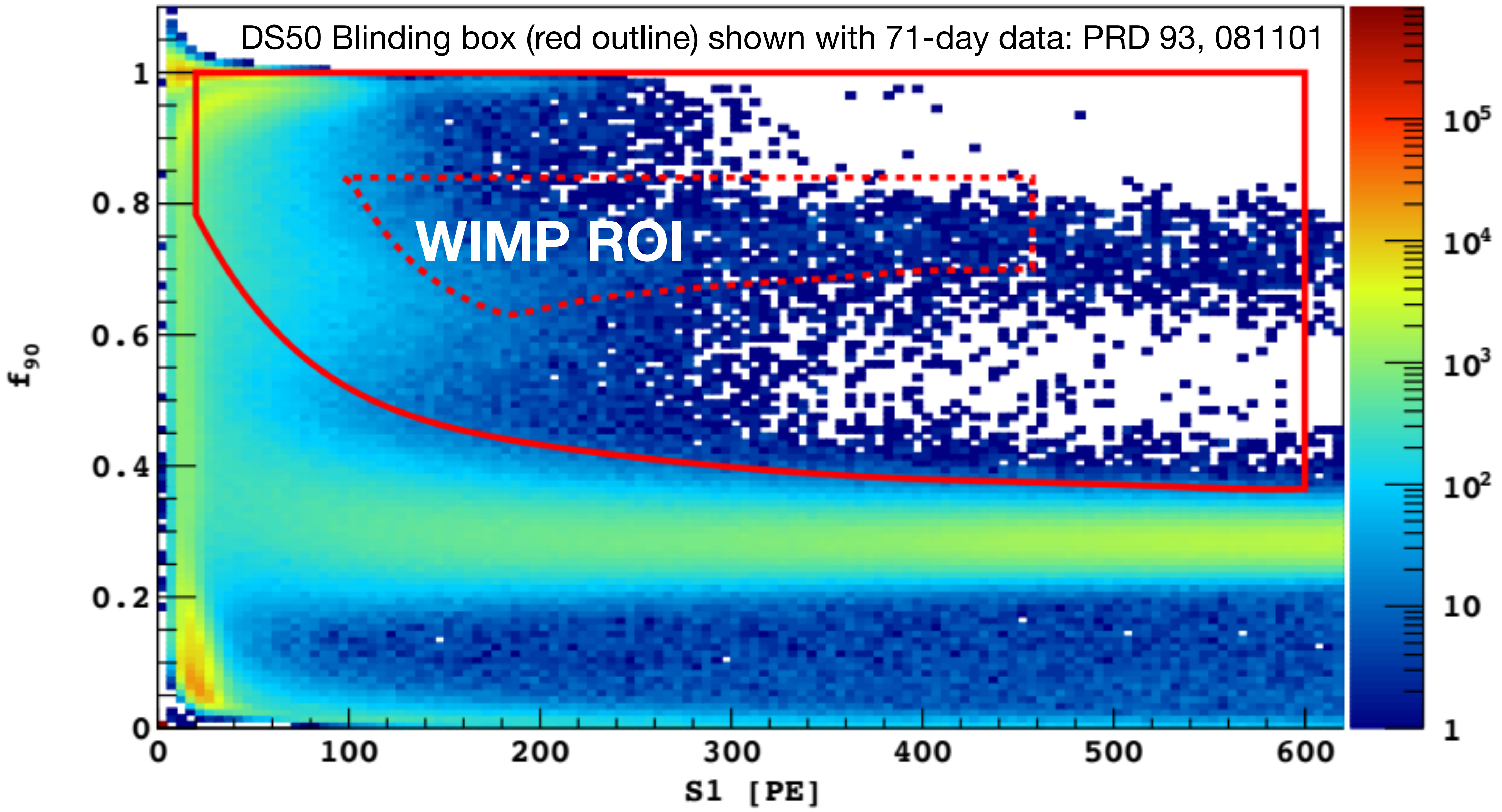
Position reconstruction resolution:

~ 1 cm in XY

~ 1 mm in Z

Backgrounds and Mitigation Strategies





Electron Recoils (ER)

^{39}Ar β decays → Use of UAr, PSD

γ decays from U,Th chains + non actinides (^{40}K, ^{60}Co, ^{137}Cs) → Material selection, PSD

Surface events Position reconstruction

Radon progeny → Surface cleaning, Rn abatement

Nuclear Recoils (NR)

Radiogenic neutrons, mainly from (α,n) reactions.
→ Material selection, Neutron Veto

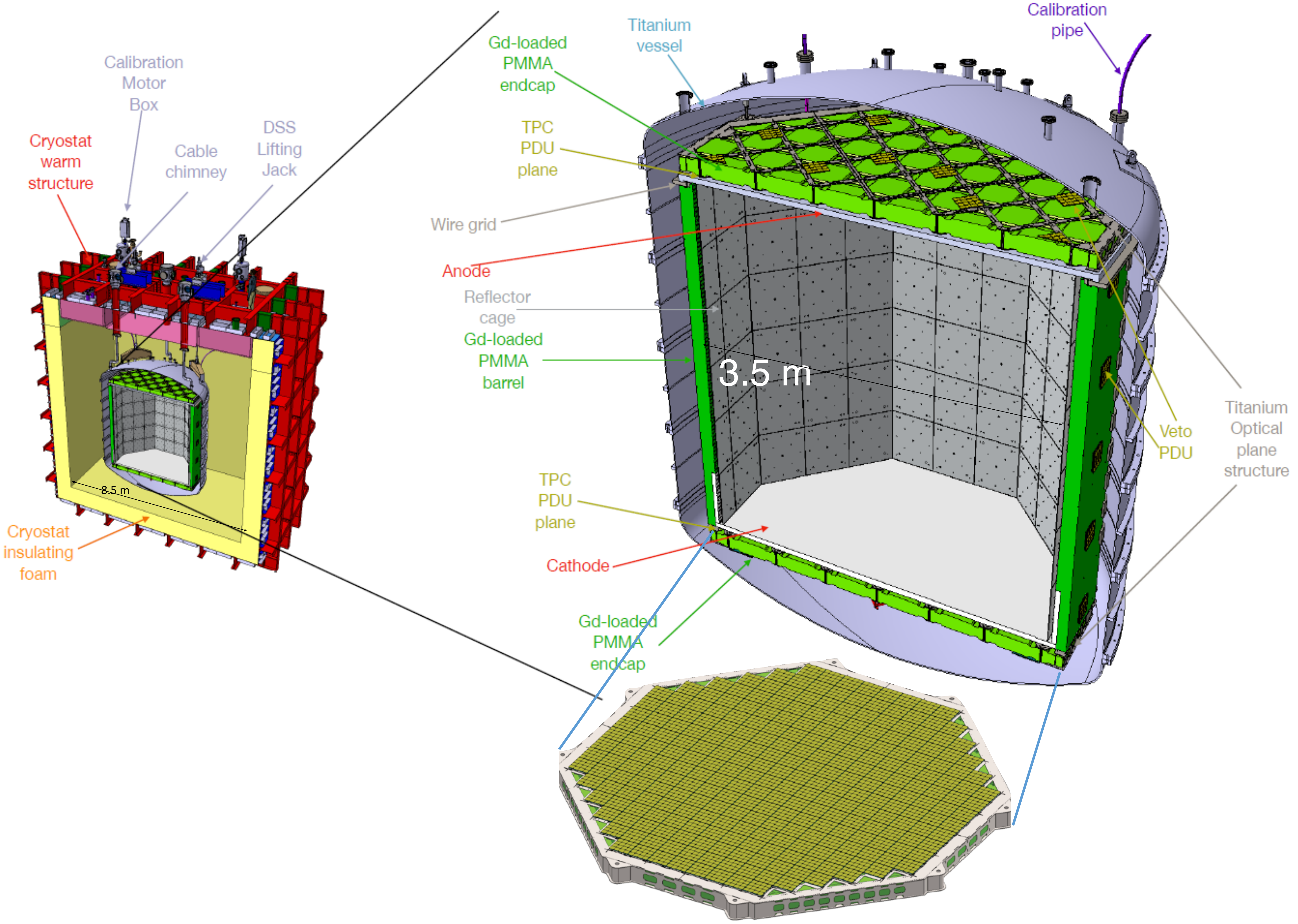
Cosmogenic neutrons, from materials activation due to residual muon flux → Muon Veto

Atmospheric neutrinos → Irreducible

Inner detector

- Integration of **TPC** and **VETO** in a single object
- **TPC Vessel:**
  - top and bottom: transparent pure acrylic + wavelength shifter (TPB)
  - lateral walls: Gd-loaded acrylic + reflector + wavelength shifter (TPB)
  - 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

Photo-detection system

TPC optical plane

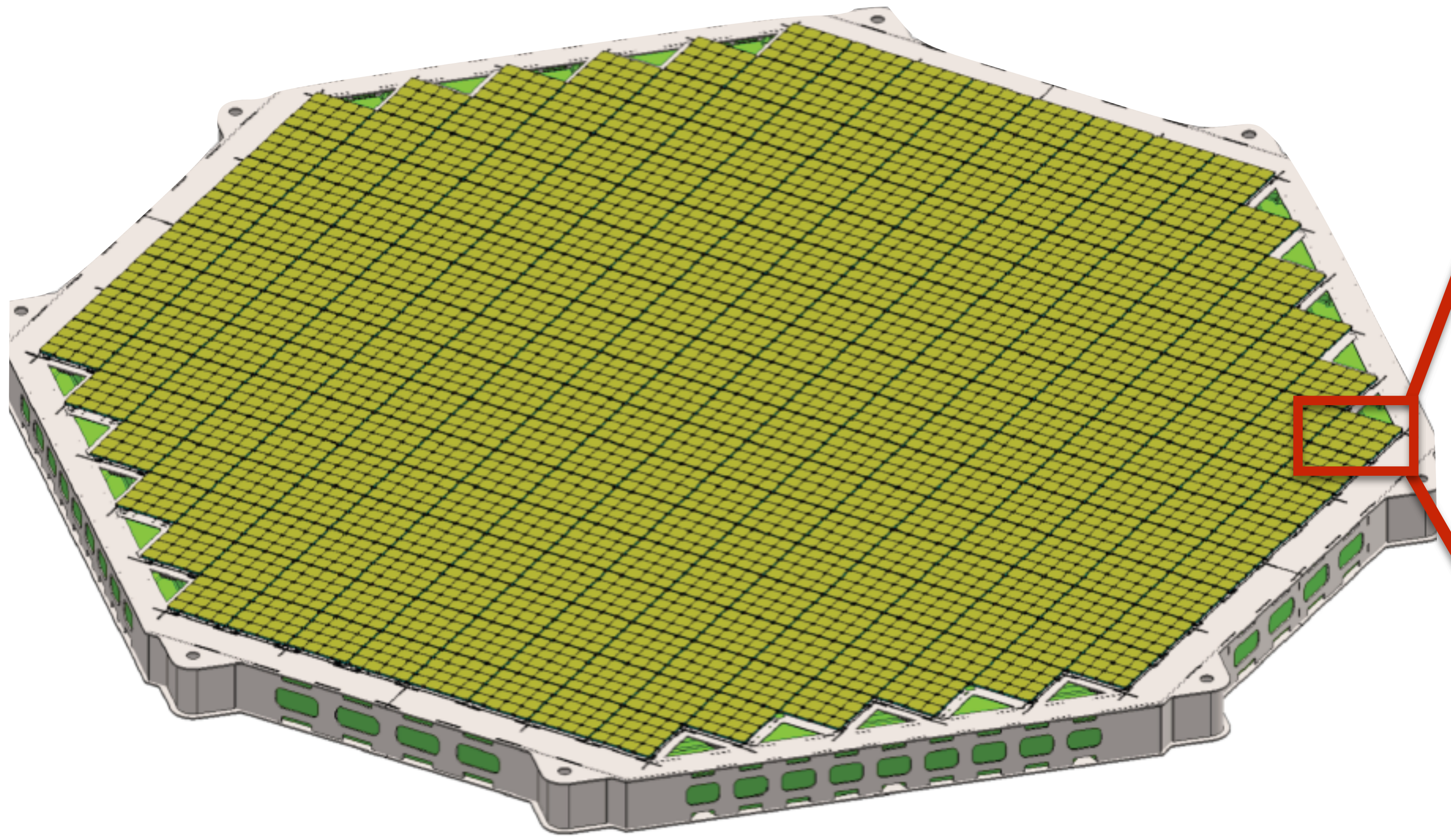
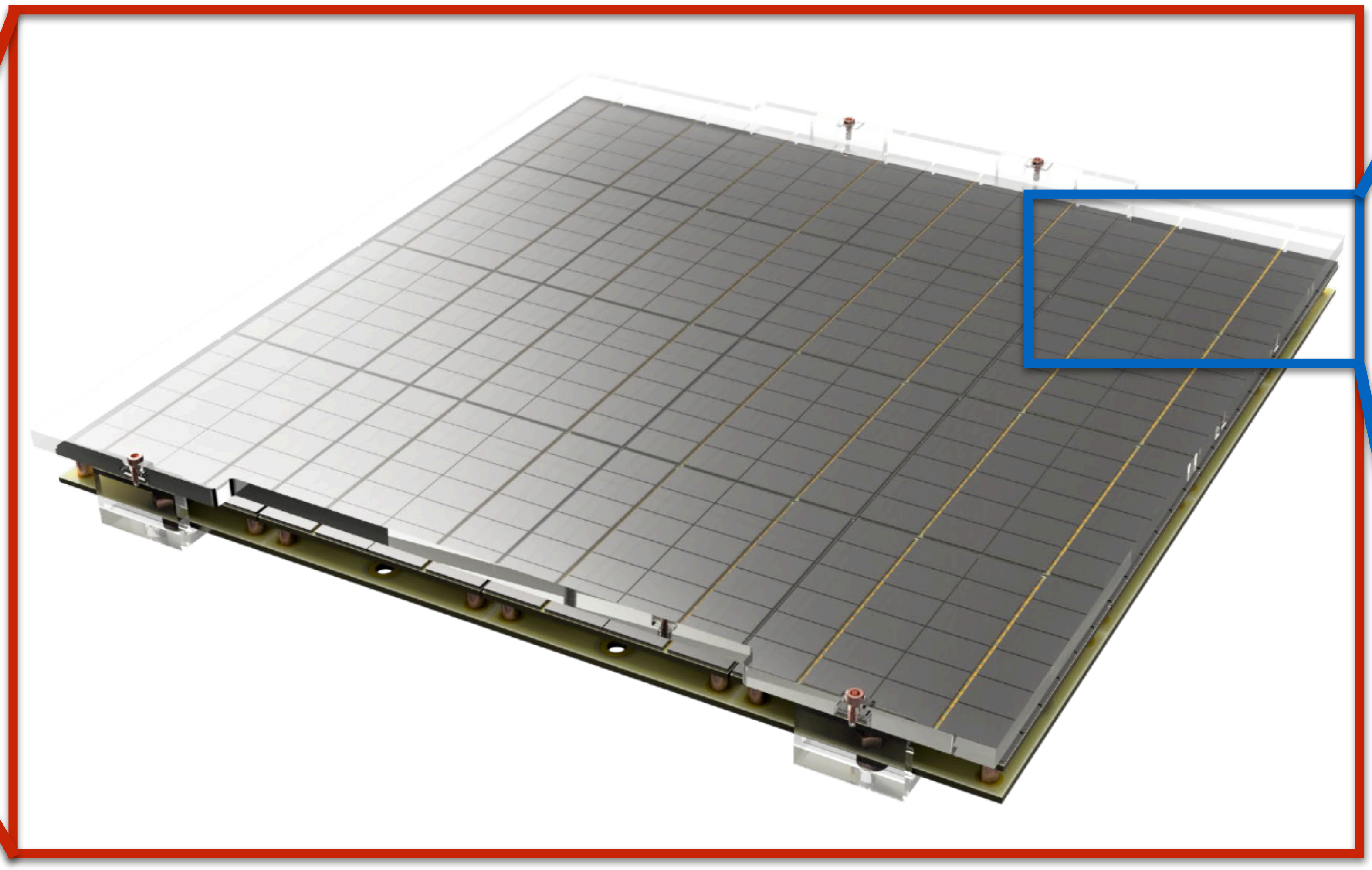
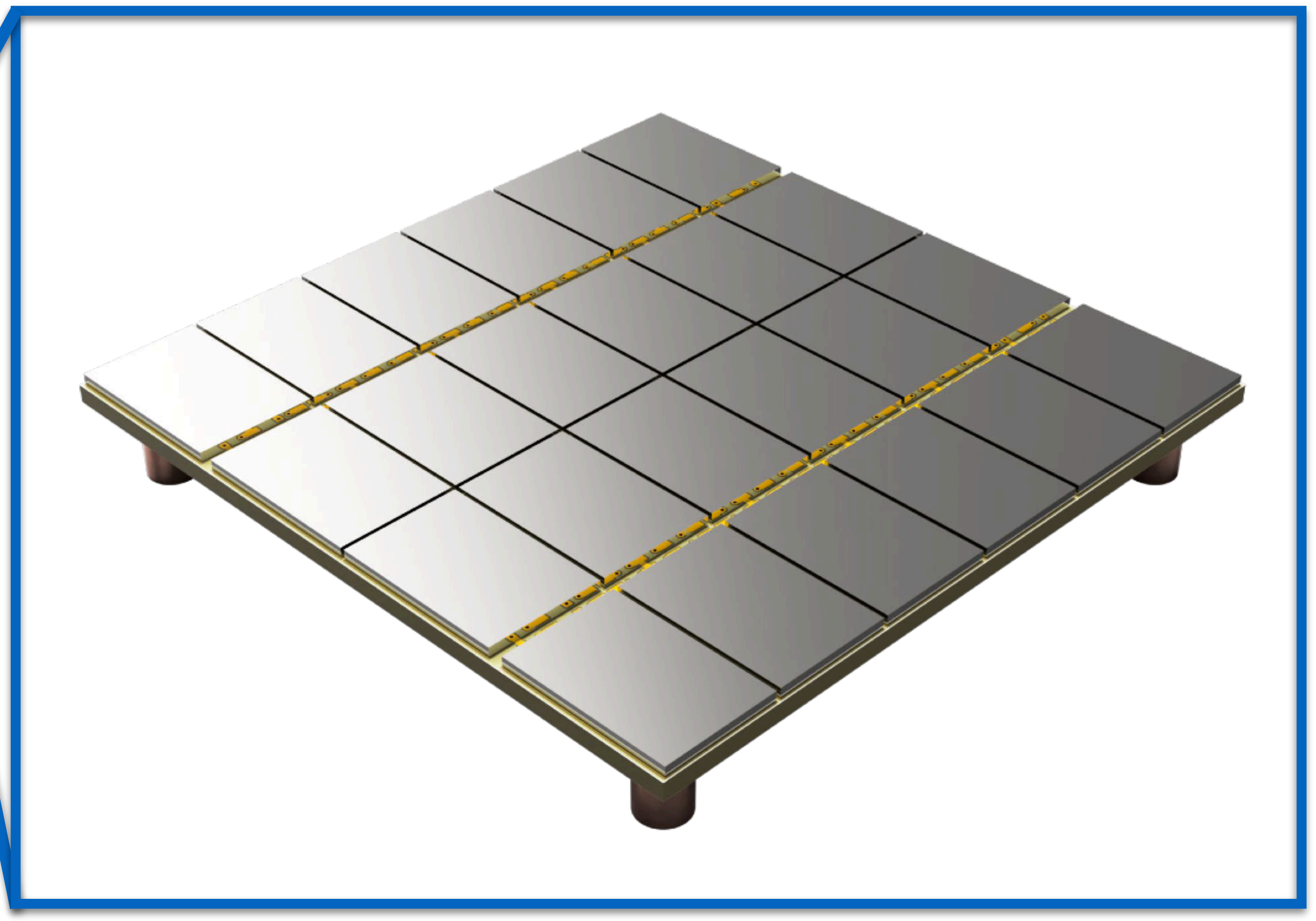


Photo-Detection Unit



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

For more info on DS20k SiPMs, I'll give a dedicated talk later today (5pm)

The journey of UAr: extraction

Picture of the extraction plant used to procure DS50 UAr target (<0.5kg/d)

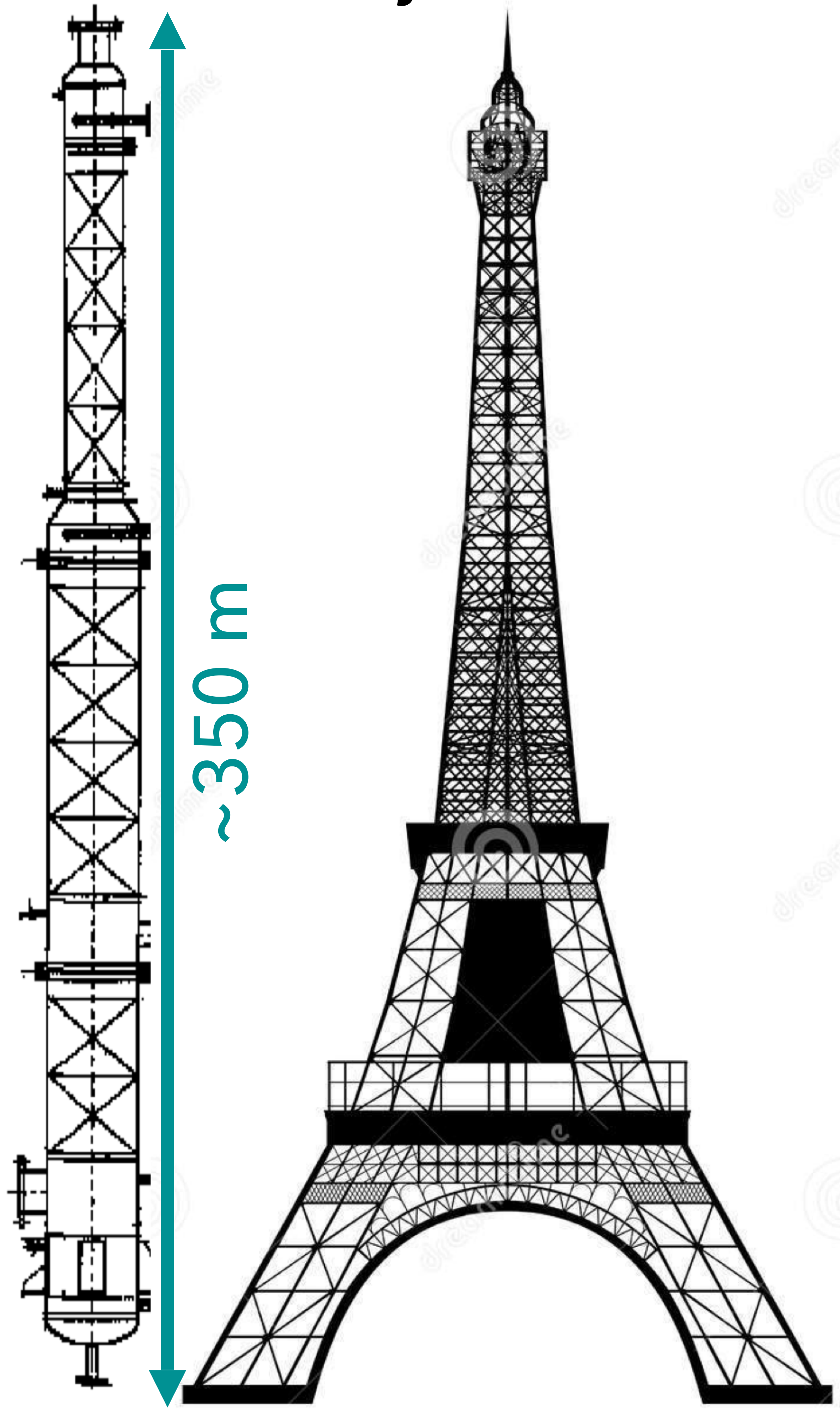
- CO_2 well in Cortez, CO, USA;
- Industrial scale extraction plant;
- Plant ready to be shipped;
- Civil work ongoing;
- Expected argon purity at outlet: 99.99%;
- UAr extraction rate: 250-330 kg/day;

The journey of UAr: purification

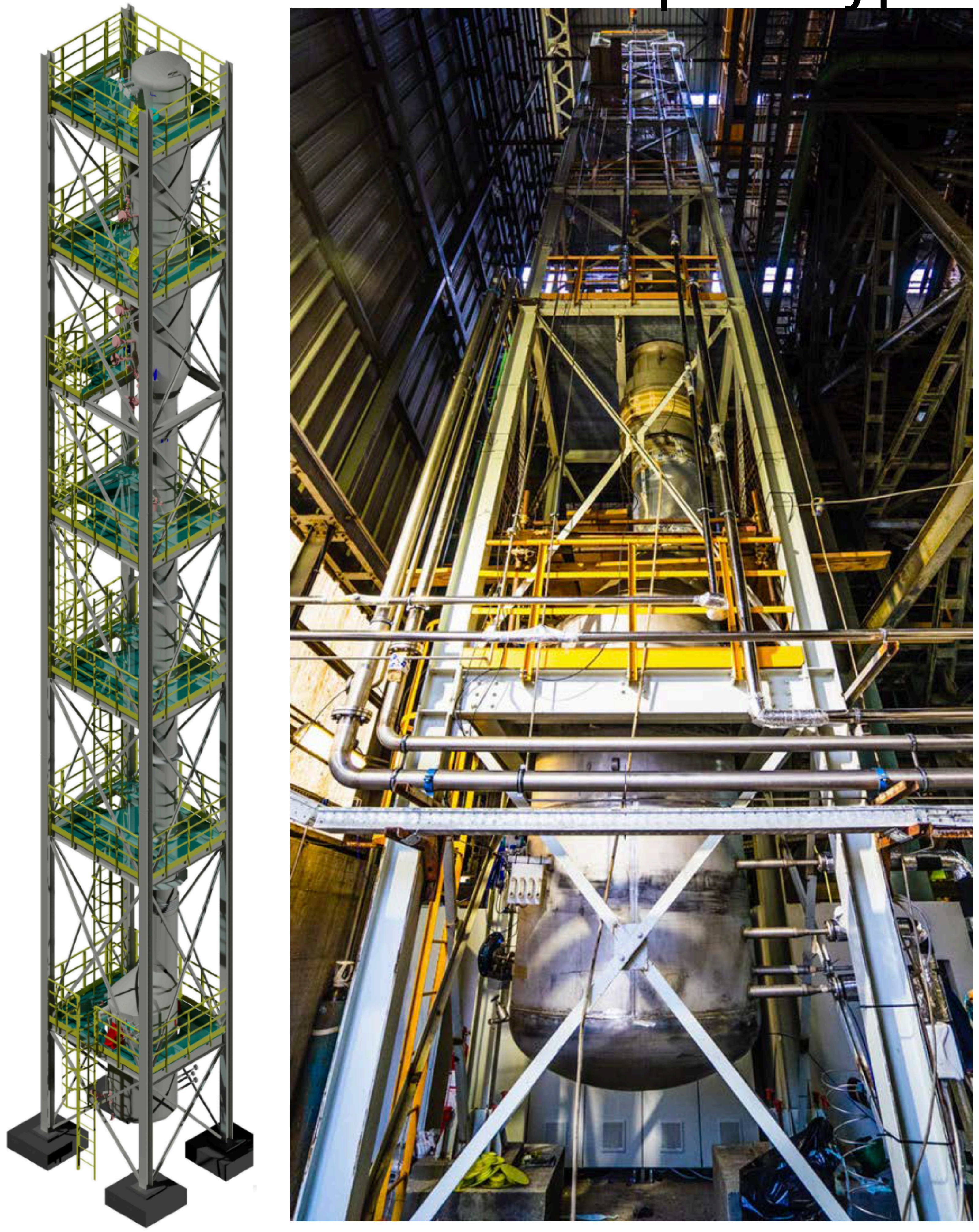
ARIA: UAr distillation plant

- Cryogenic distillation column in Sardinia (Italy).
- Installed in the shaft of a coal mine
- Three sections: bottom reboiler, 28 central modules (12 m each), top condenser
- Chemical purification rate: 1 t/day
- First module operated according to specs with nitrogen in 2019 (Eur. Phys. J. C (2021) 81:359)
- Run completed with Ar at the end of 2021: results to be published soon.
- Full assembly to start in 2023

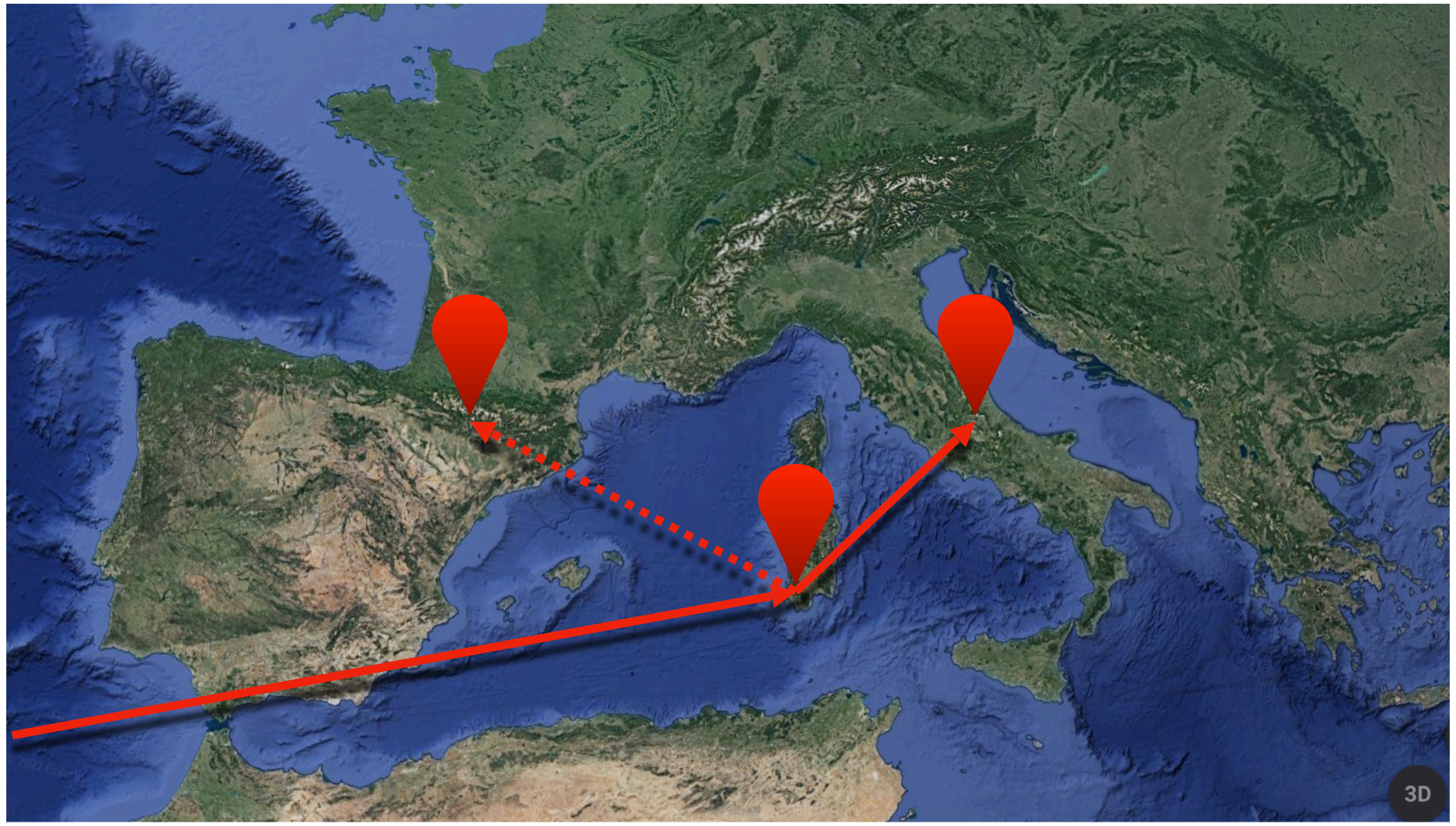
Sketch of ARIA when fully assembled

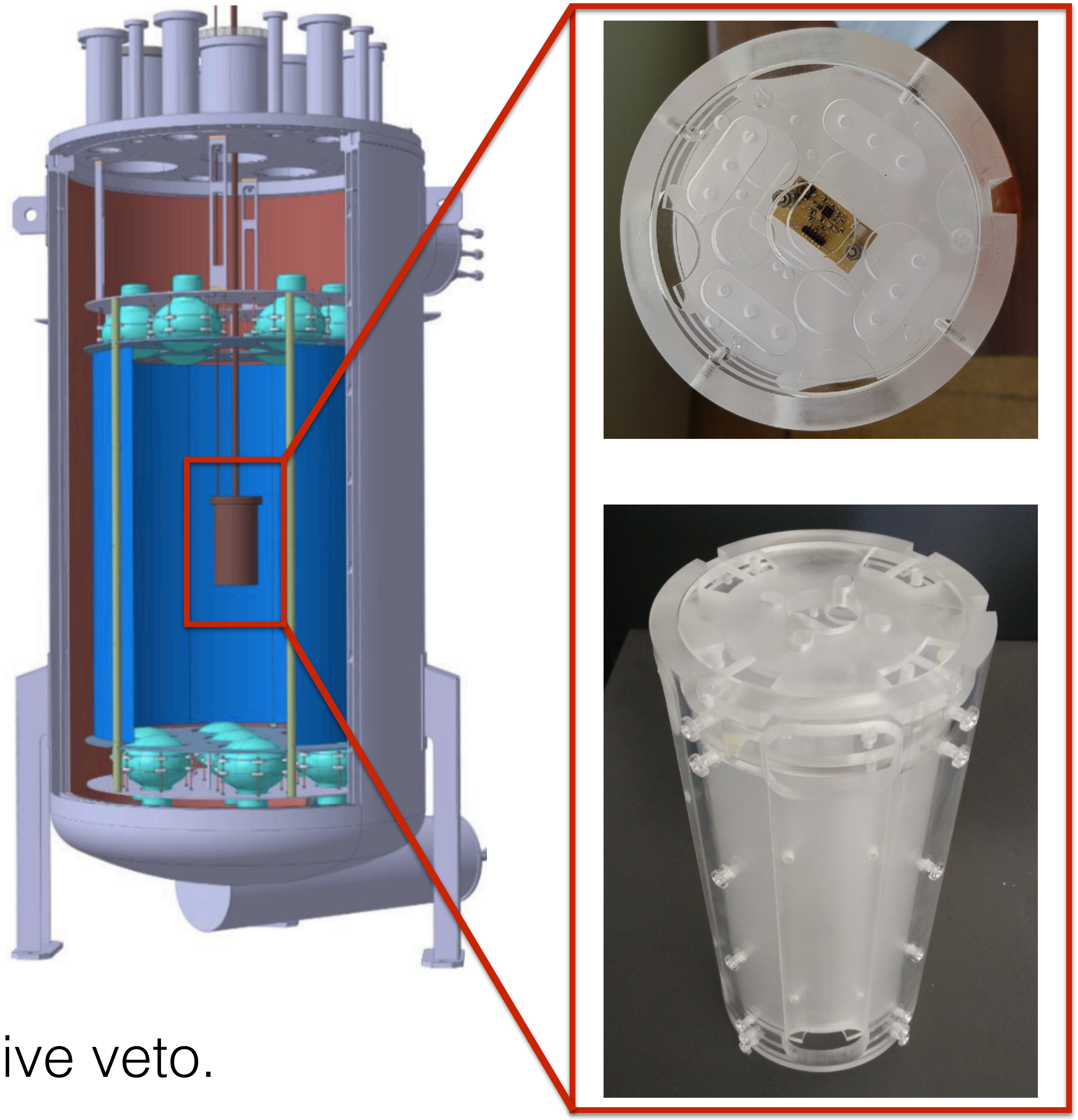


Drawing and picture of ARIA distillation column prototype



The journey of UAr: ^{39}Ar assaying



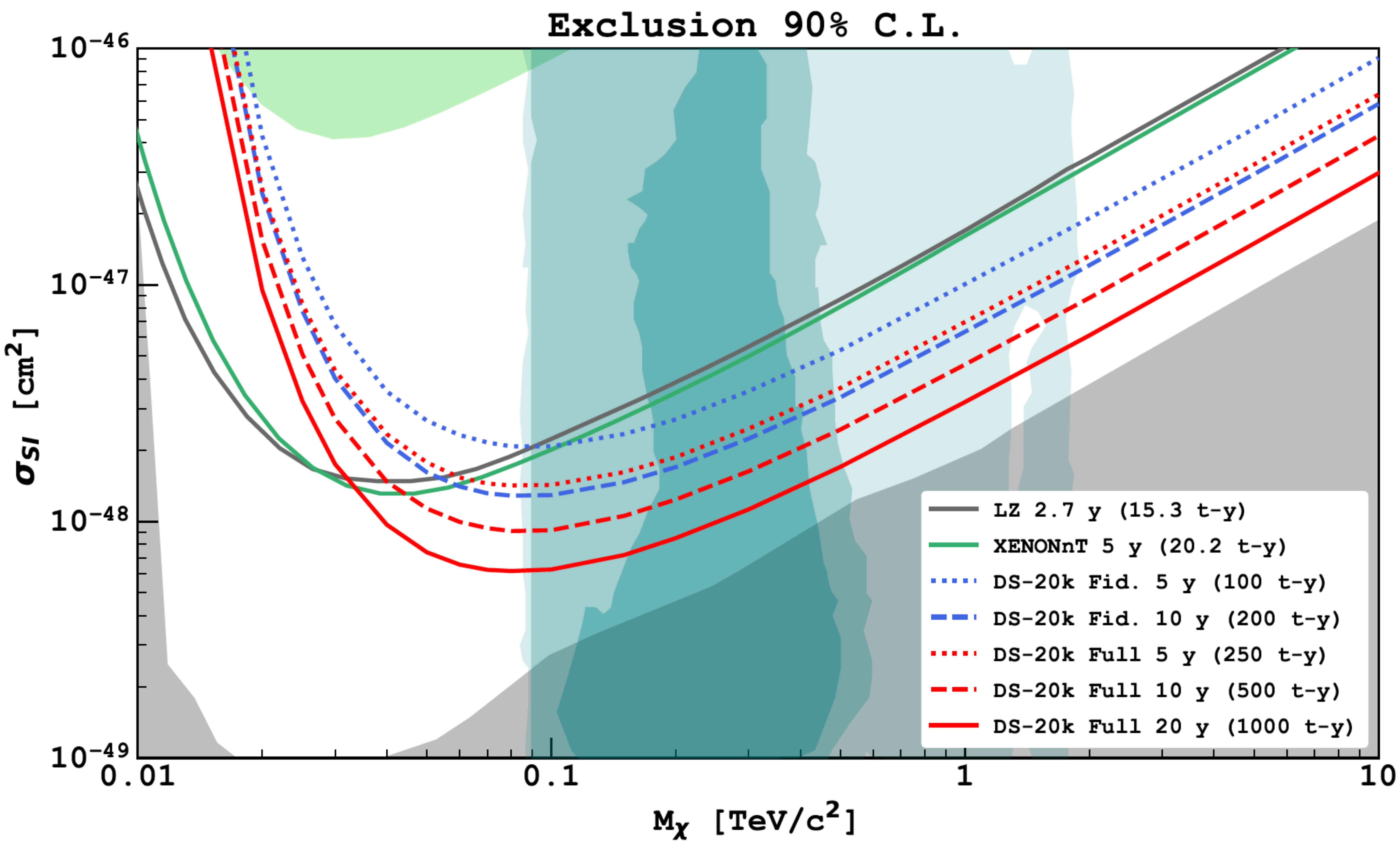


DArT : Measurement of the activity of the ^{39}Ar

- LSC, Canfranc, Spain
- Single-phase inner detector for 1.42 kg of liquid UAr
- Will be installed inside ArDM detector, acting as an active veto.
- ^{39}Ar depletion factor sensitivity: U.L. 90% CL. 6×10^4 (2020 JINST 15 P02024).

DarkSide-20k physics reach

- Sensitivity: 6.3×10^{-48} cm^2 for a 1 TeV/c^2 WIMP (90% C.L.)
- (5σ) discovery: 2.1×10^{-47} cm^2
- Nominal exposure: (20×10) t yr
- Instrumental Background: 0.1 events in 200 t yr
- Expected neutrinos: 3.2 events in 200 t yr



Thanks!

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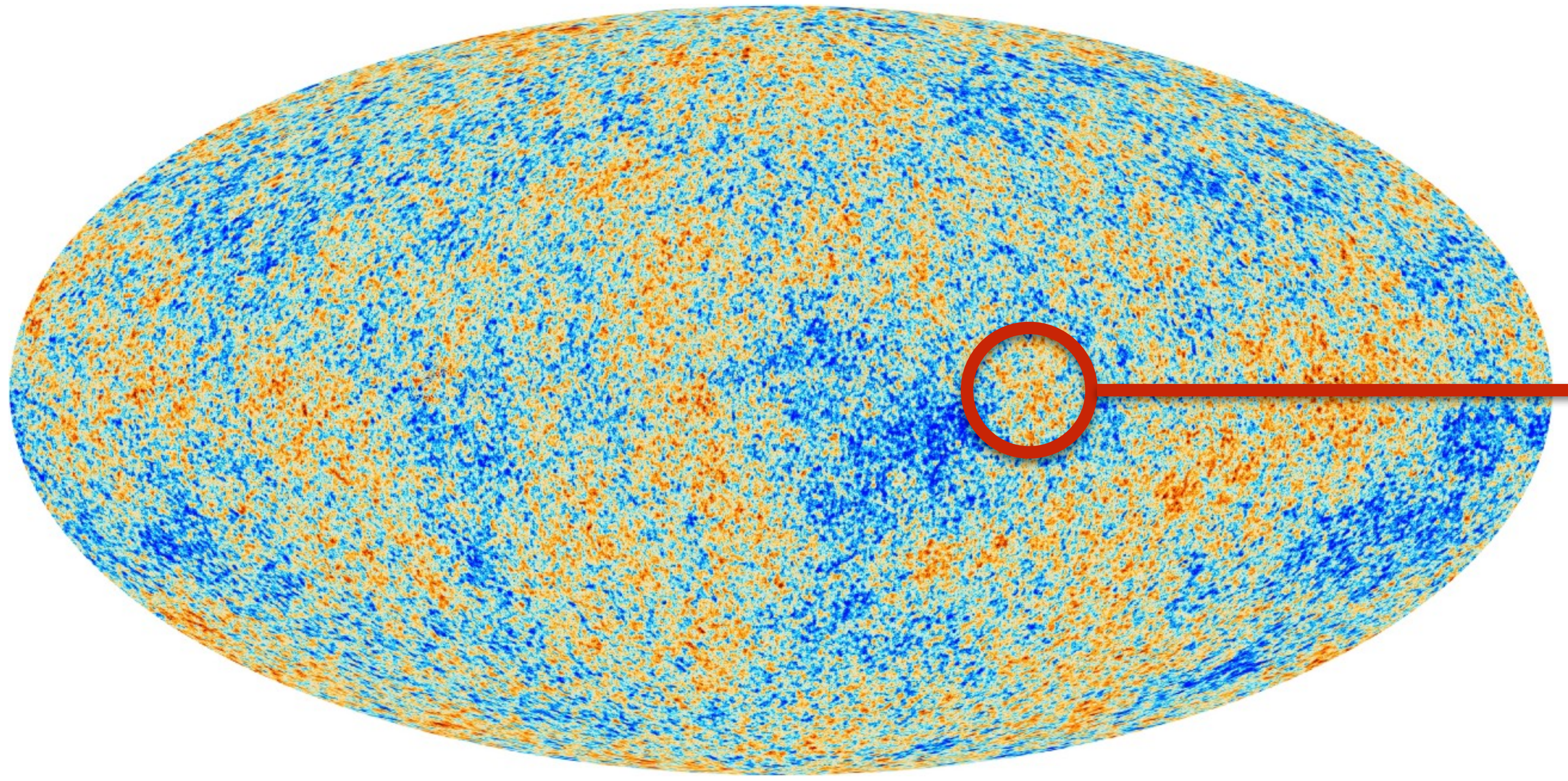
Princeton University
(609) 933-8160

Backup slides

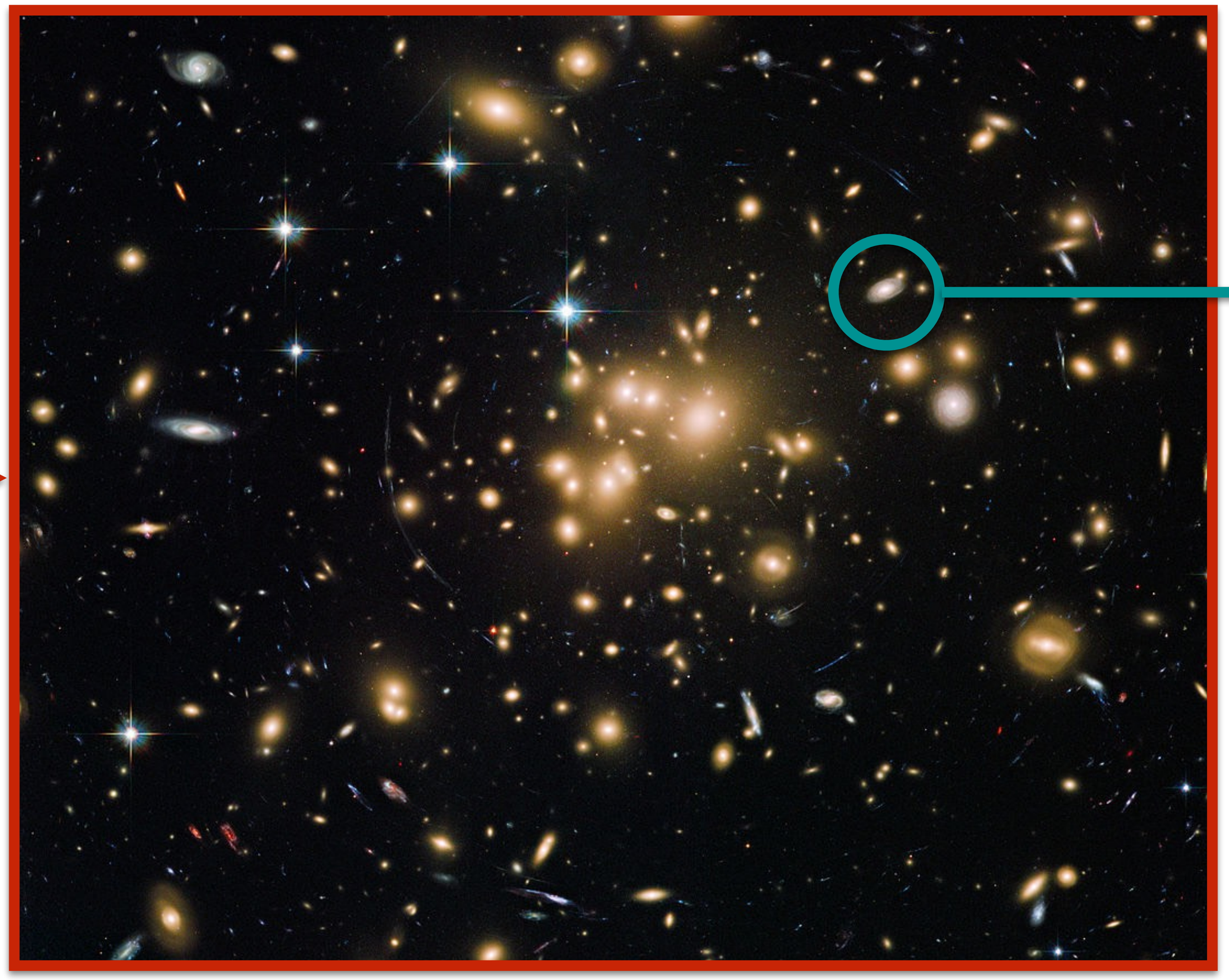
The physics case

CMB



Thermal anisotropies
multipole expansion

Galactic clusters



Galaxy velocities
Gravitational lensing (Bullet)

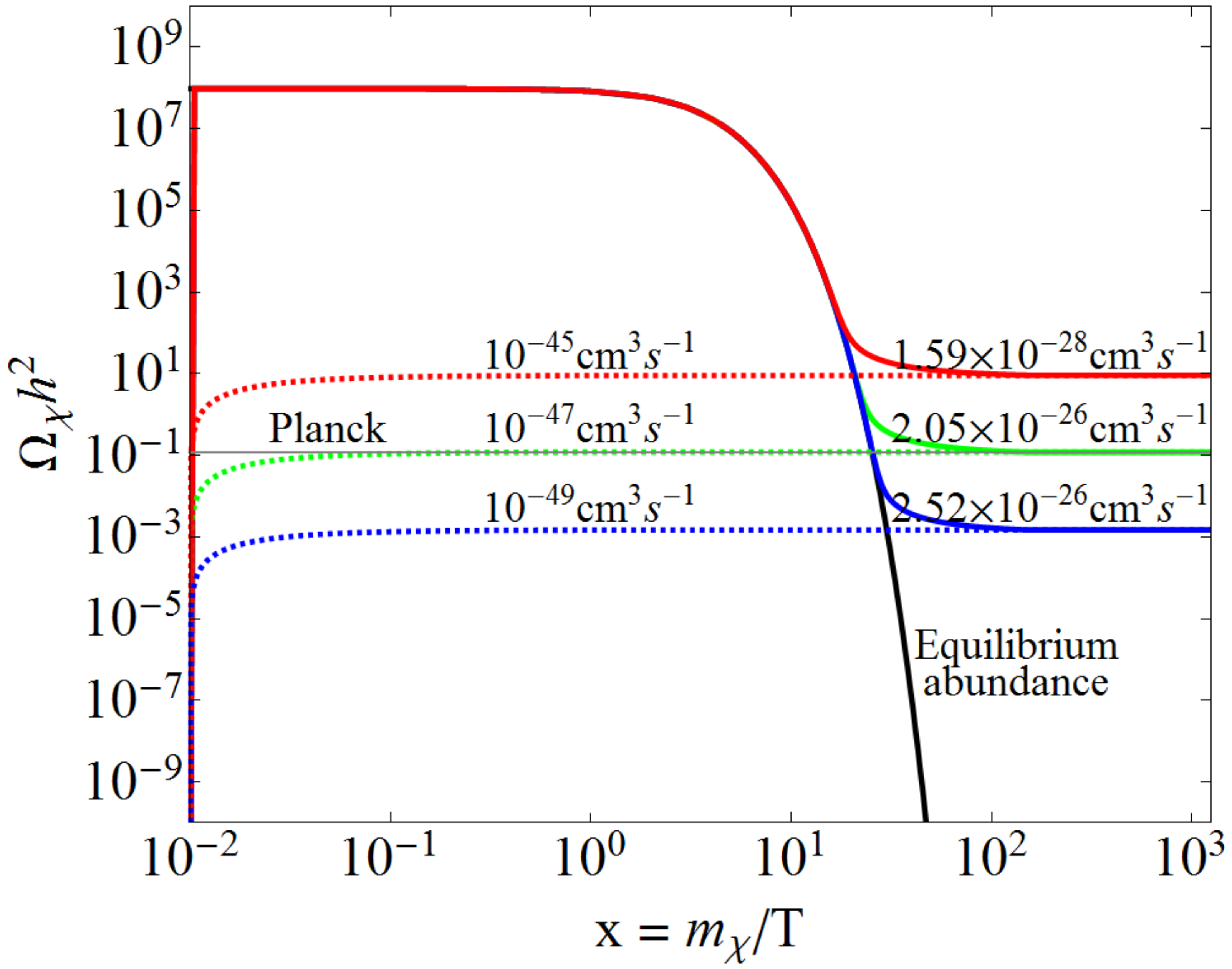
Galaxies

Rotation curves
Gravitational lensing

Convincing evidence at all scales

The WIMP realm

The WIMP miracle

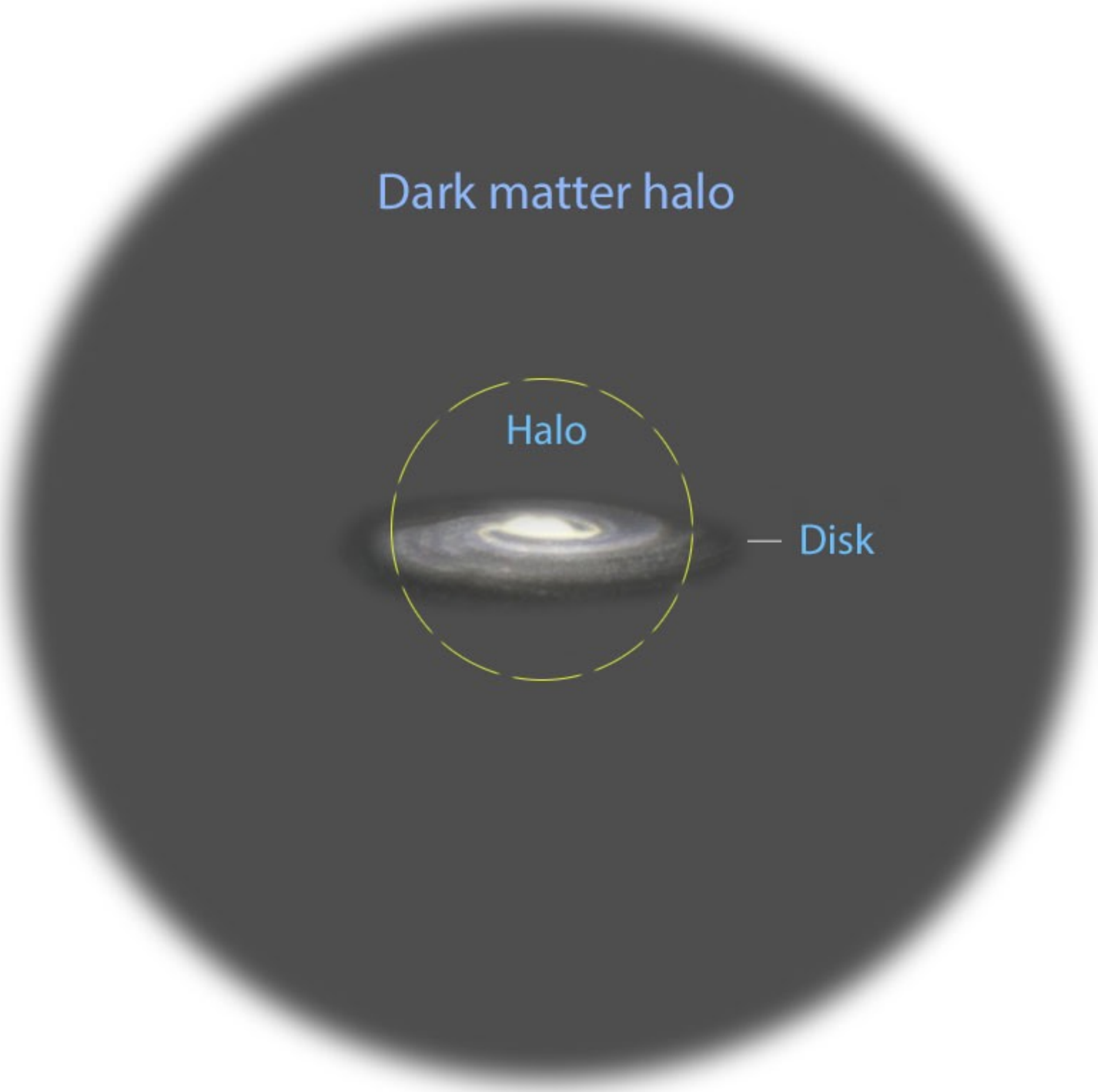


Weak X-section

Mass at EW scale

Observed DM abundance

CDM

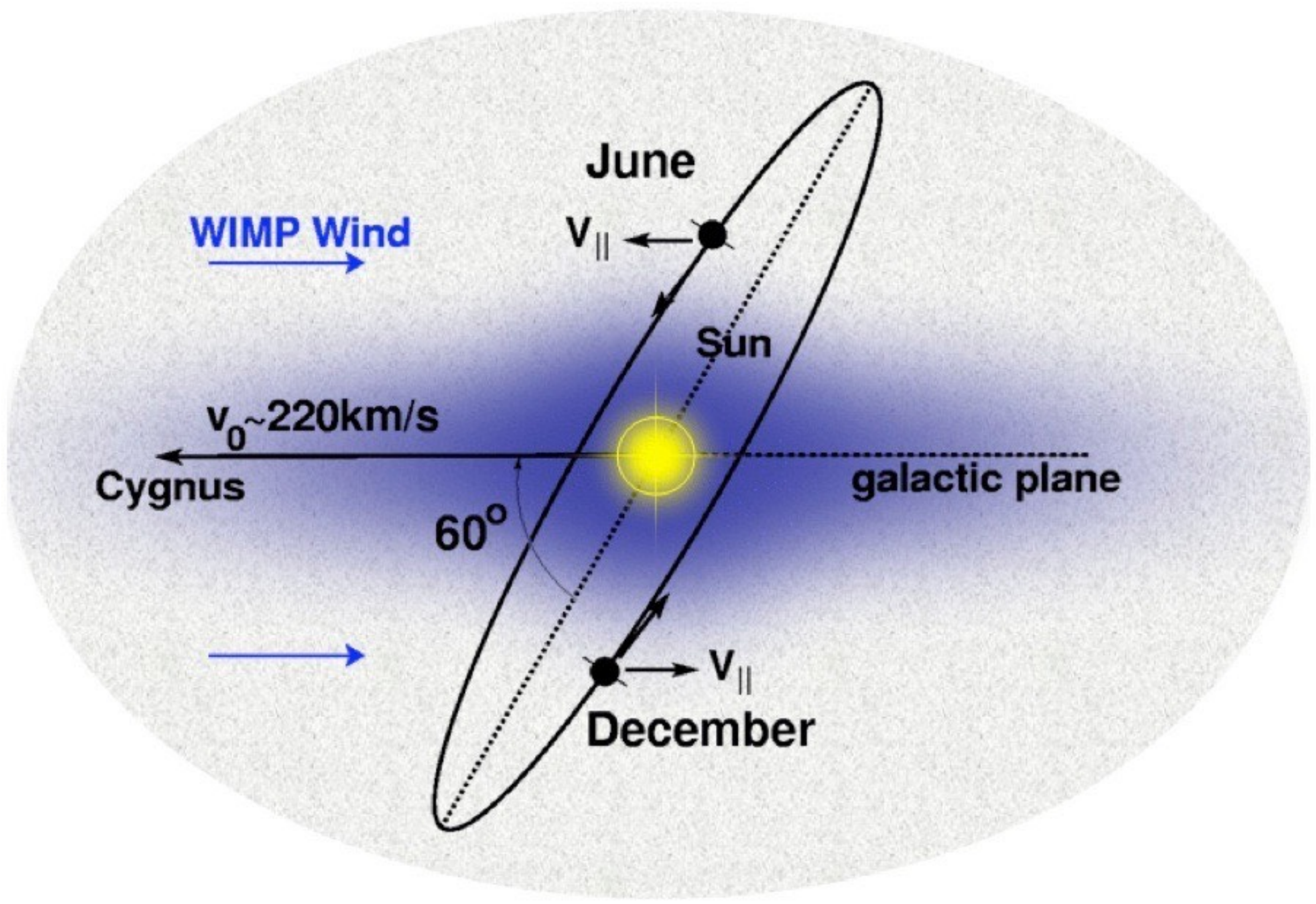


Milky Way model

CDM preferred by halo simulations

Maxwell velocity distribution

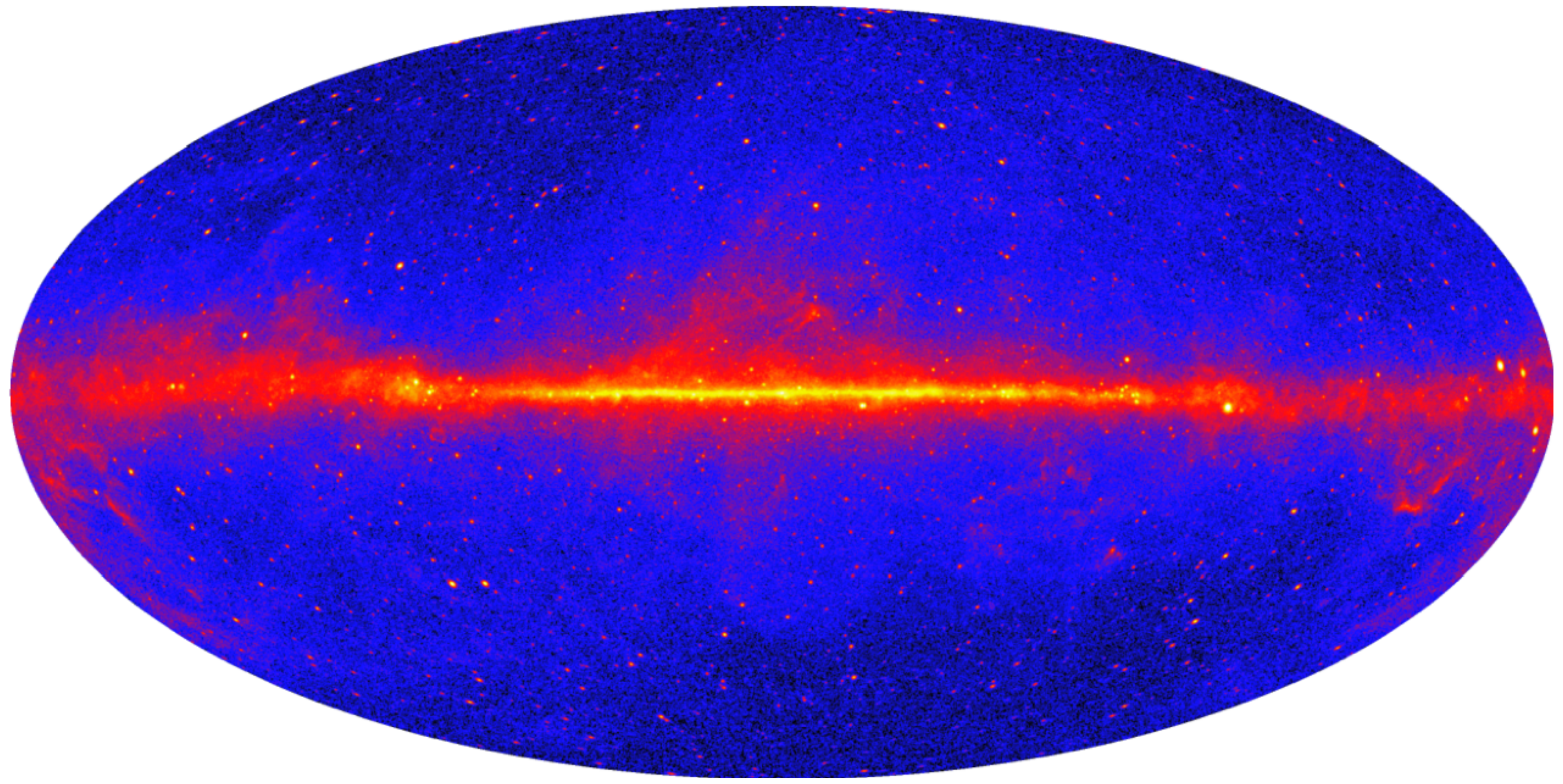
WIMP Wind

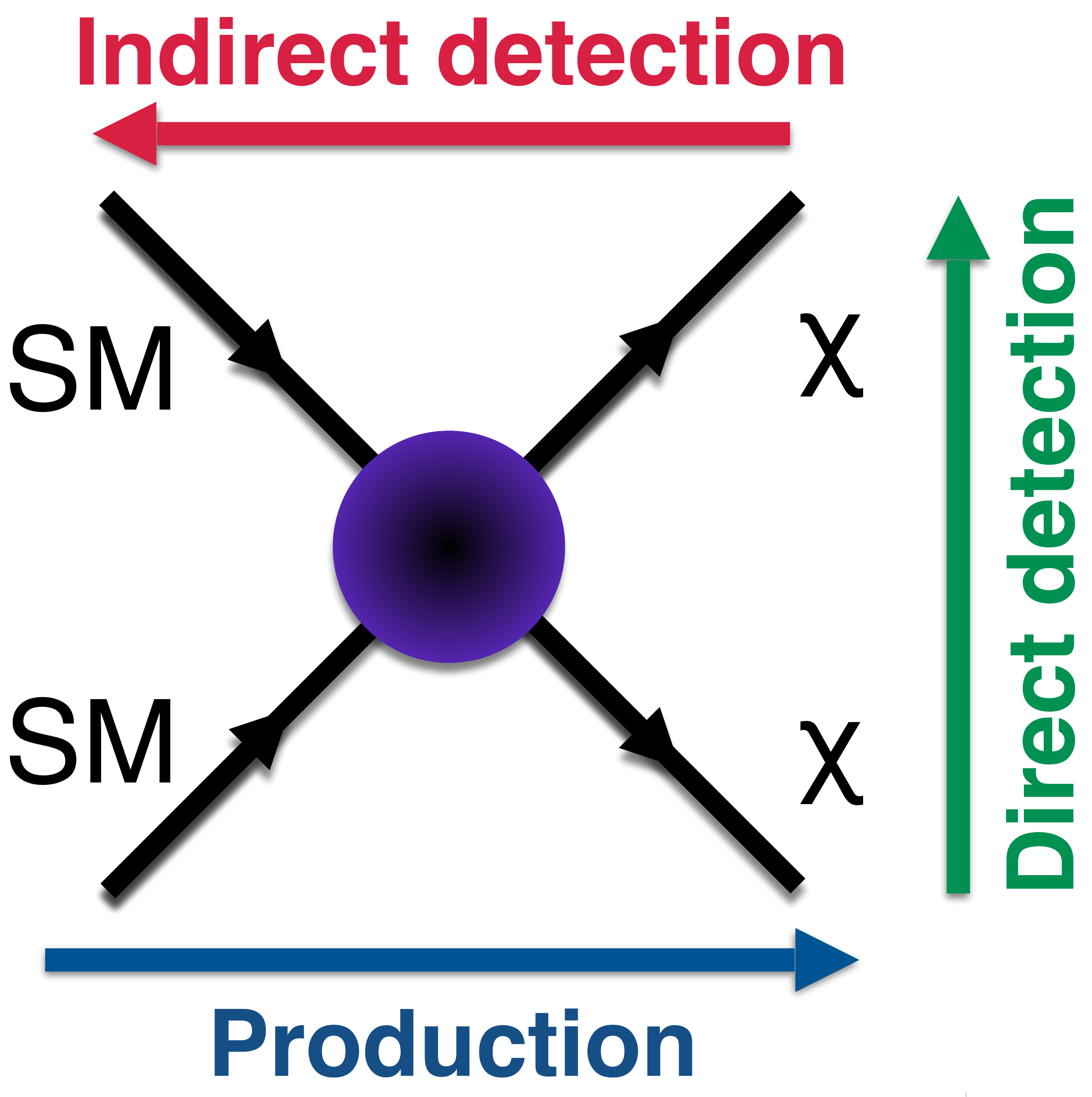


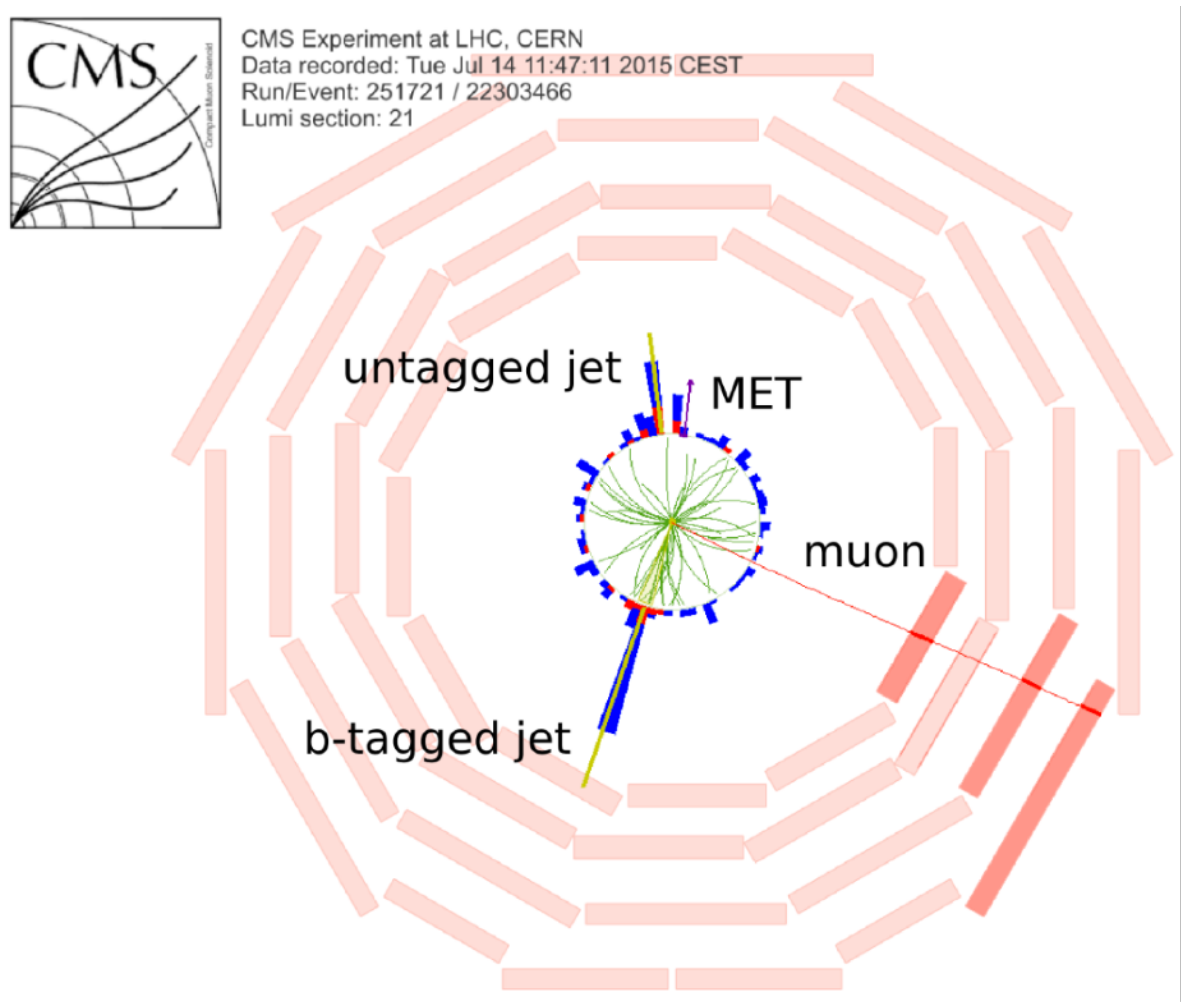
Sun motion ⇒ directional signature

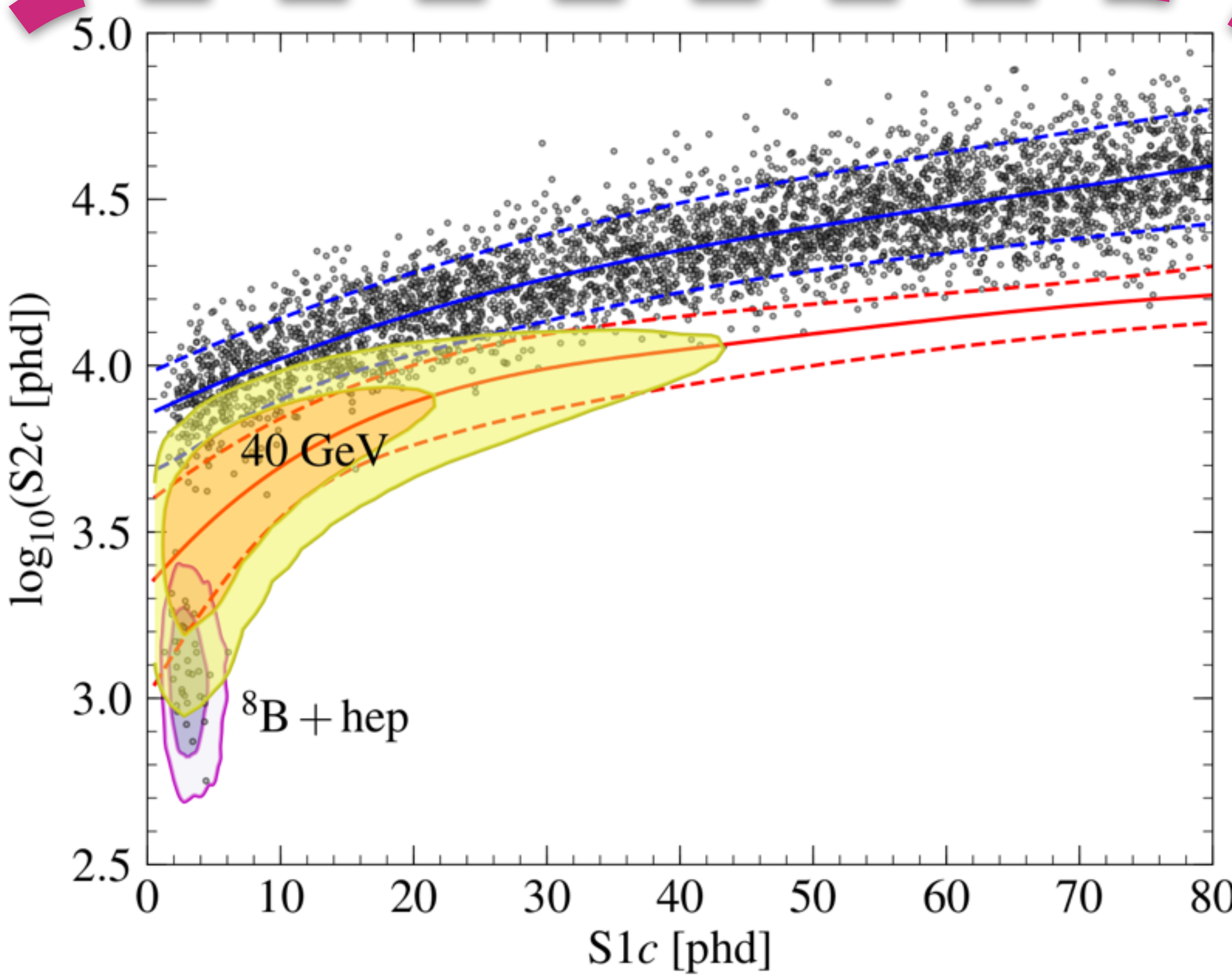
Earth orbit ⇒ annual modulation

Hunt it down!





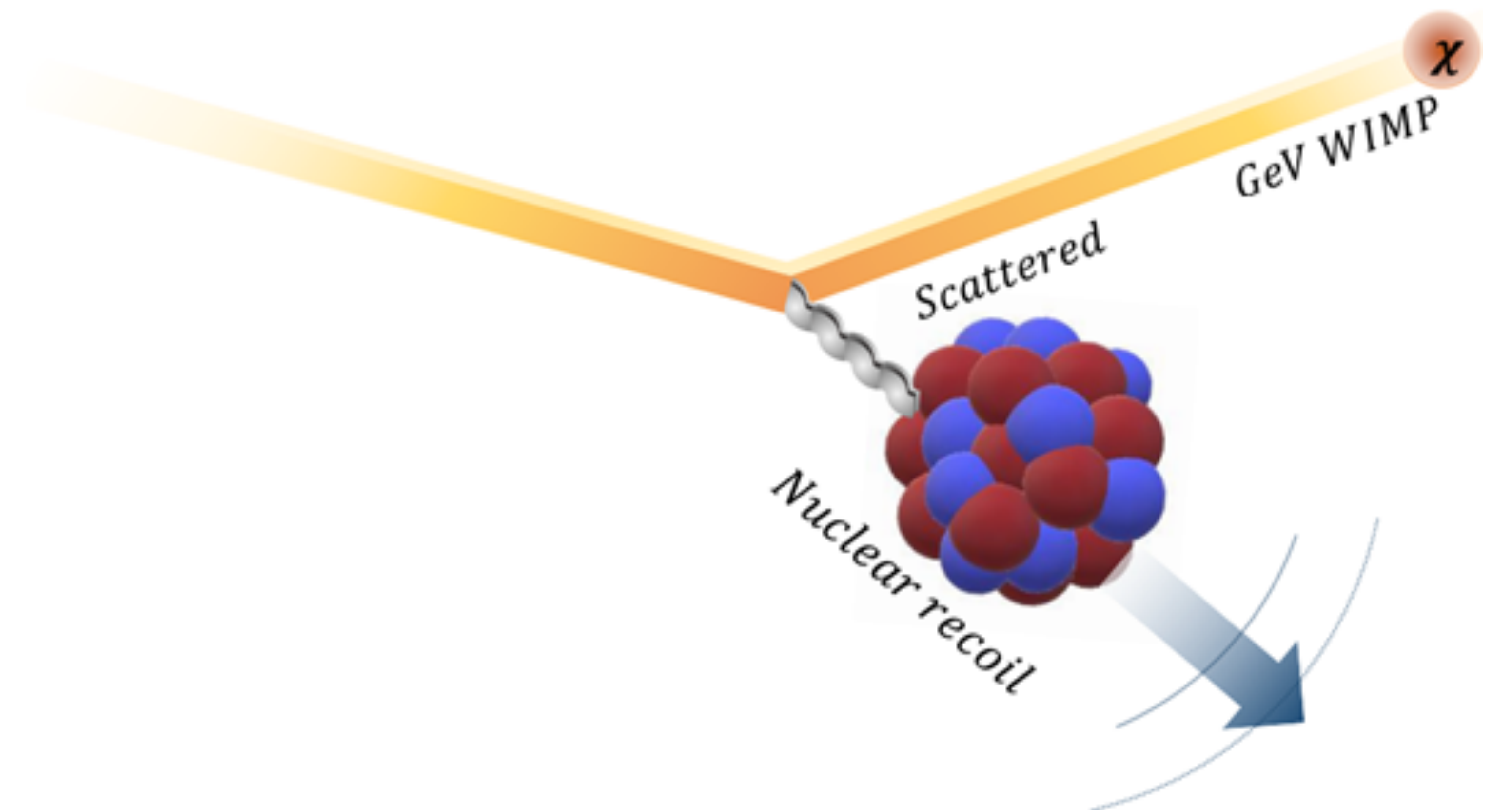




- Annihilation in SM particles
- Universe is our lab! ✔
- Mostly space-based detectors ✘
- Background fluxes difficult to predict ✘

- Scattering with SM particles
- Spans over many orders of magnitude in mass ✔
- Depends on local ρ_{DM} ✘
- Rare events and huge bkg ✘

WIMP spectra

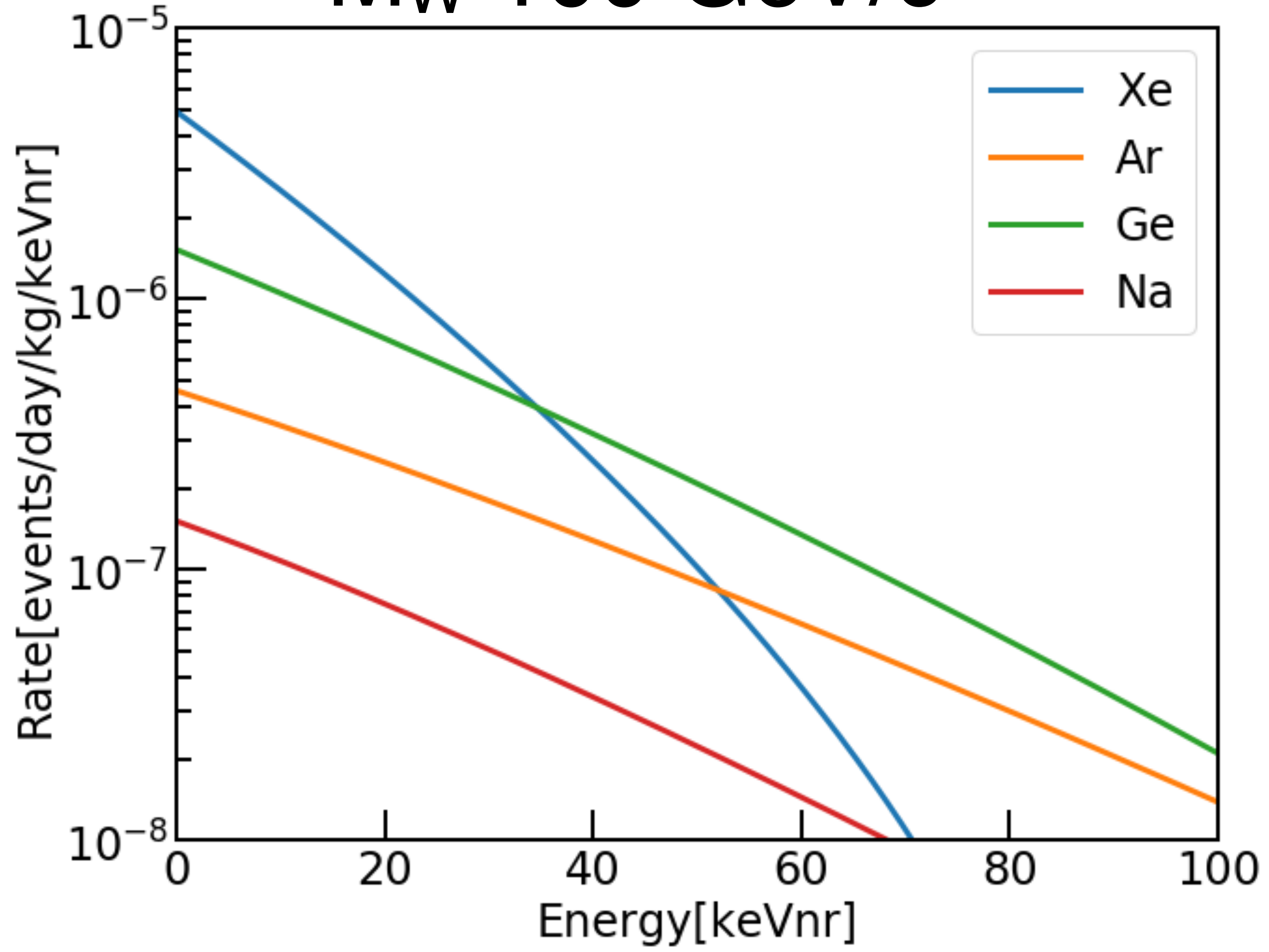


- Non relativistic regime (v << c)
- **Signal: nuclear recoils (NR)**
- Coherent scattering enhancement (A^2)
- High energy suppression (F^2)
- Rate exponential in obs. energy
- σ_{WN} and ρ_{DM} degenerate

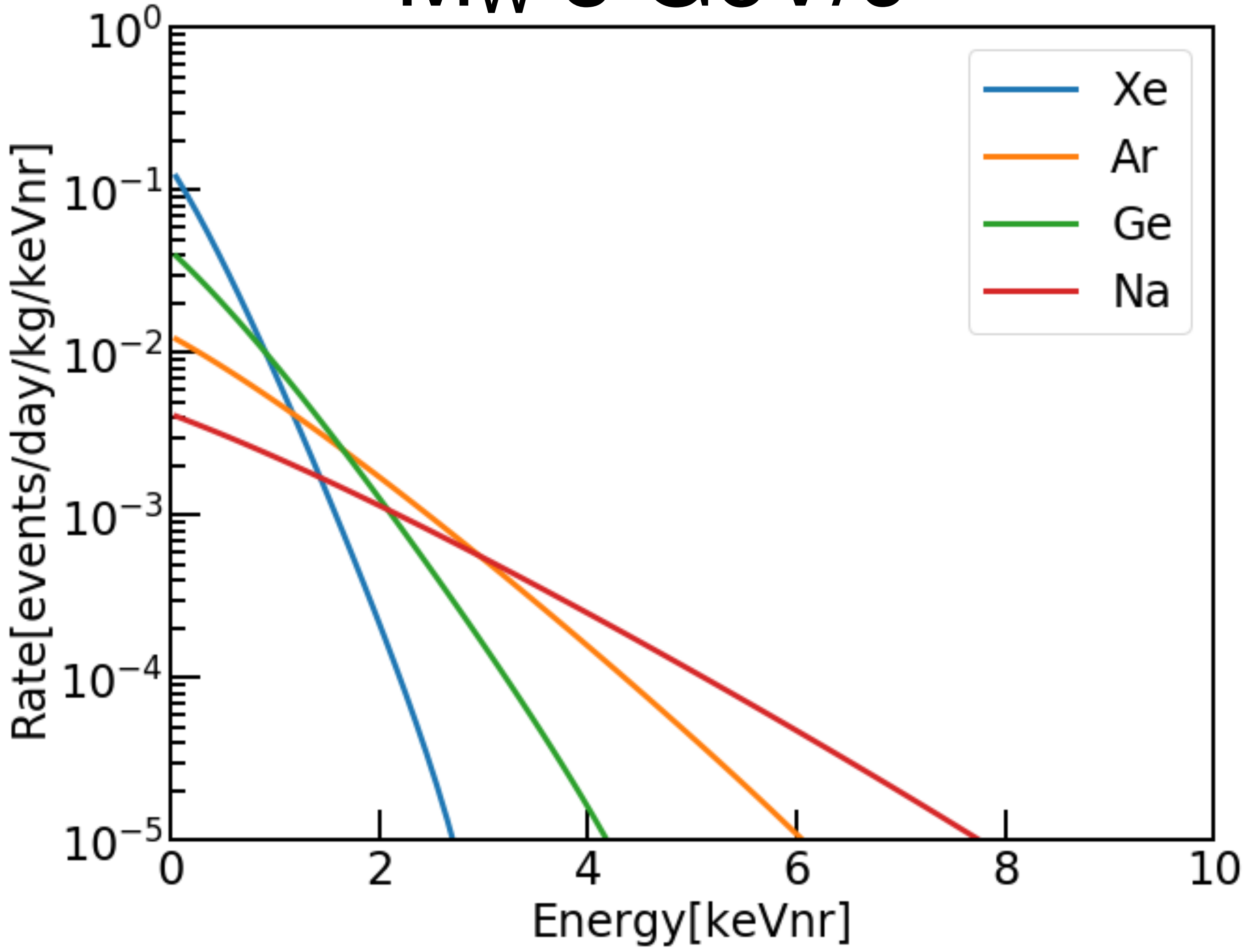
$$\frac{dR}{dE_r} = \frac{MT}{2m_W\mu_N^2} \times \sigma_{Wn} \times \frac{\mu_N^2}{\mu_p} A^2 \times F^2(E_r) \times \rho_0 \times \int_{v_{min}}^{v_{max}} \frac{f(\vec{v})}{v} d^3v$$

Particle physics (σ_{Wn}) — Nuclear physics ($F^2(E_r)$) — Astrophysics ($\rho_0 \times \int_{v_{min}}^{v_{max}} \frac{f(\vec{v})}{v} d^3v$)

M_W 100 GeV/c^2



M_W 5 GeV/c^2

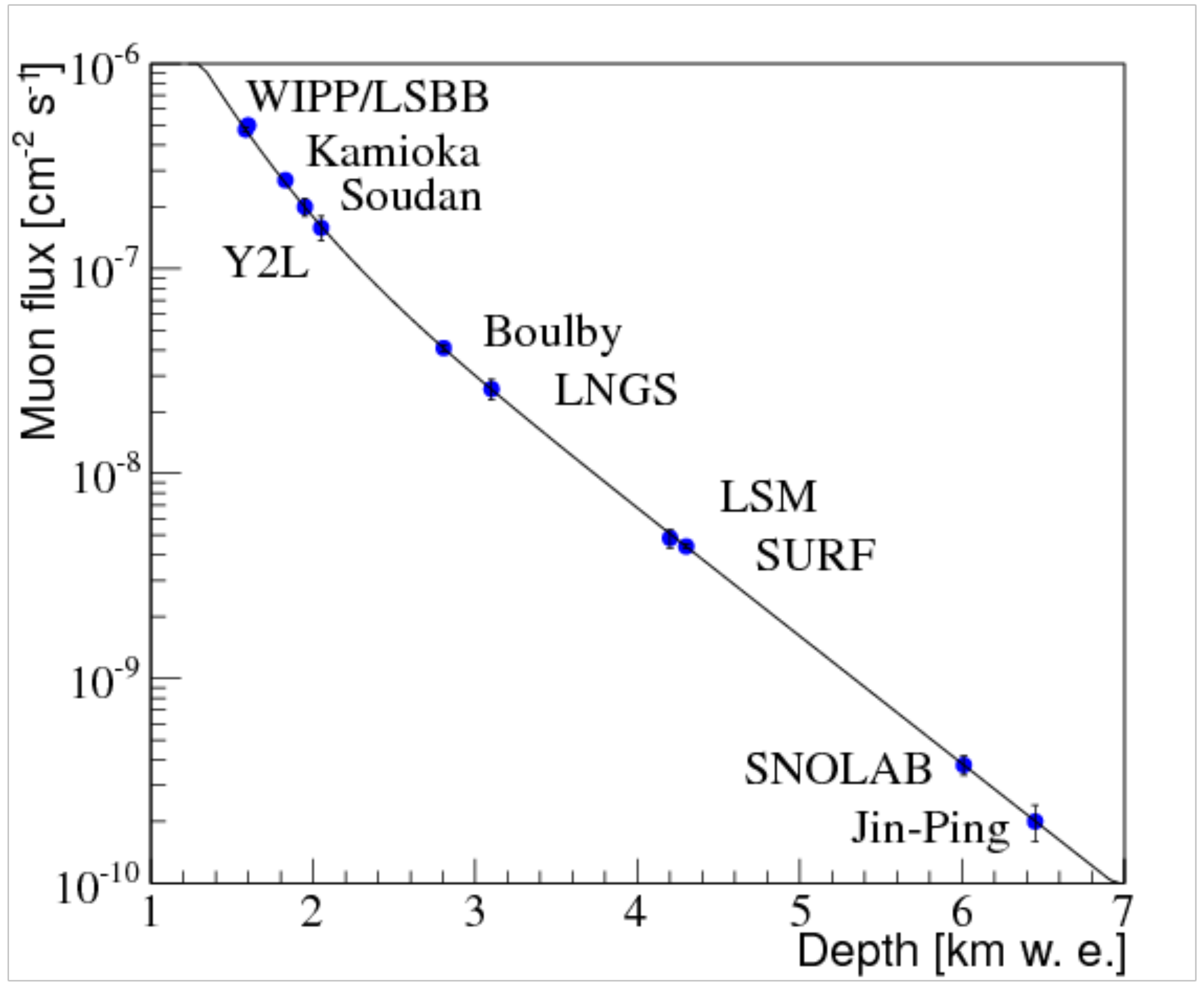


High M_W →
- Low number density ✘
- High recoil energies ✔
- High A target ✔

Low M_W →
- High number density ✔
- Low recoil energies ✘
- Low A target ✘

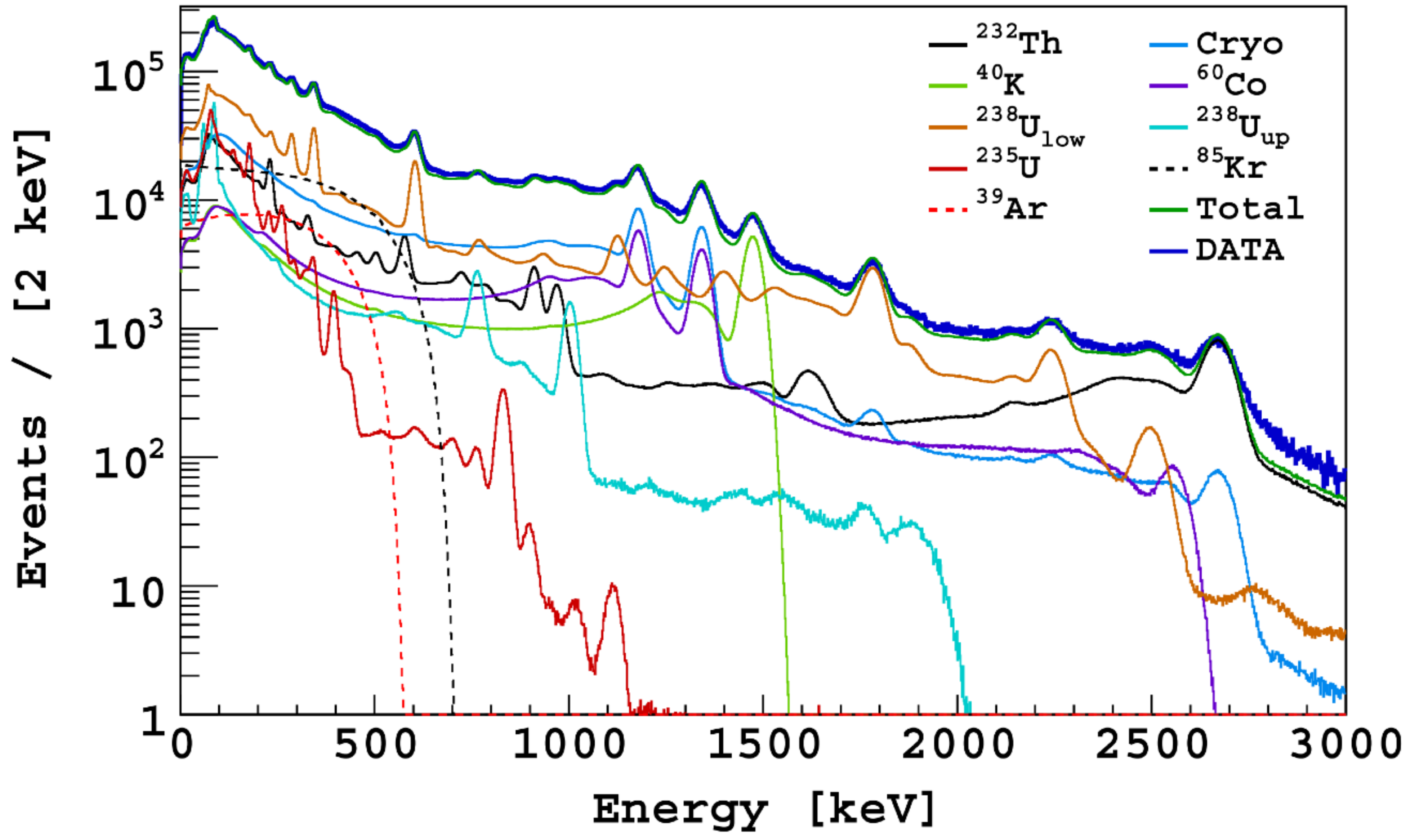
Radiogenic and cosmogenic backgrounds

From above



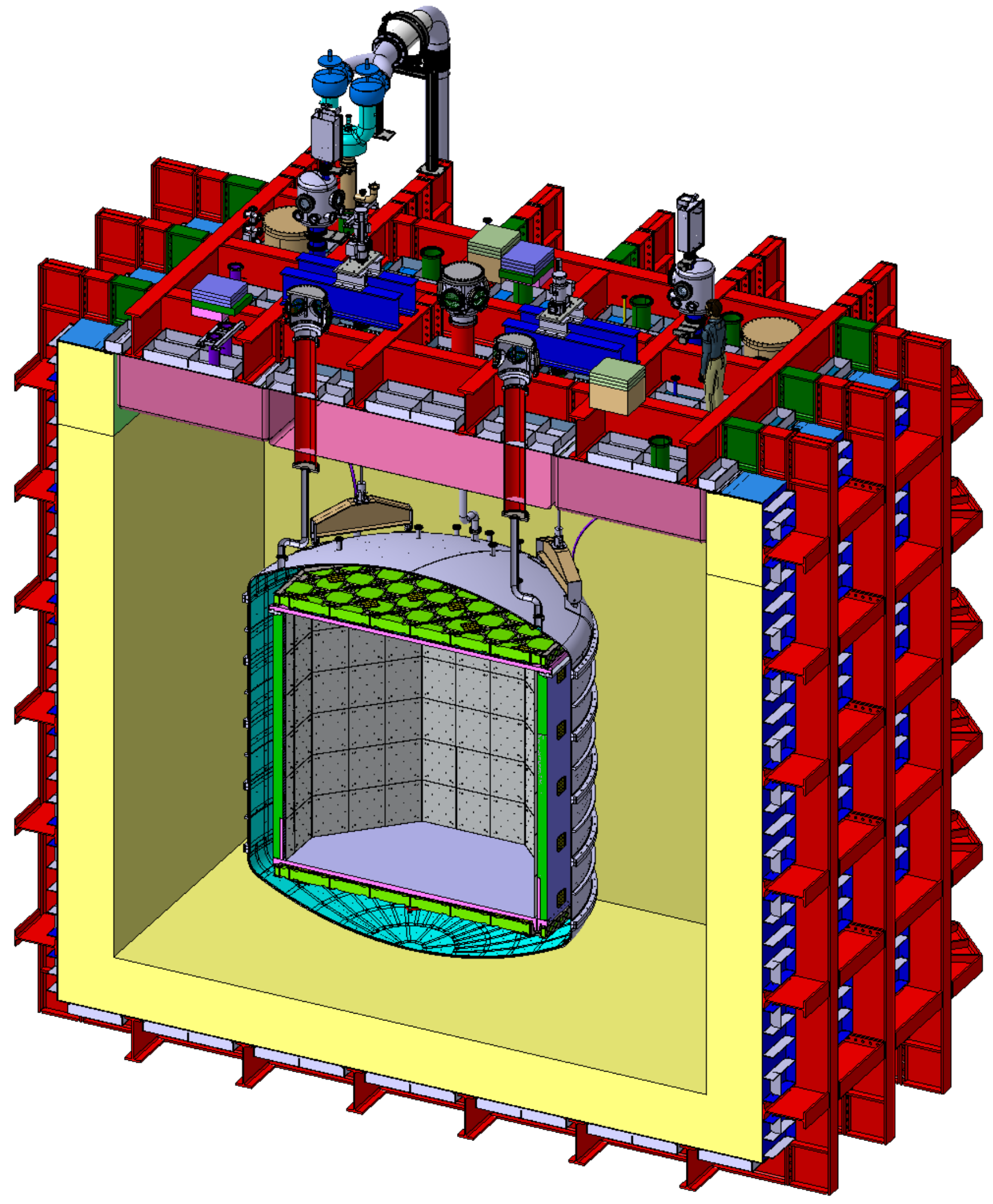
- Excessive muon rate at surface
- Radioactive isotopes activated
- Neutron generation
- Go underground!

From below



- Natural radioactive isotopes: U and Th chains, non-actinides
- Material assay and selection
- Particle identification: ER/NR
- Fiducialization: surface events

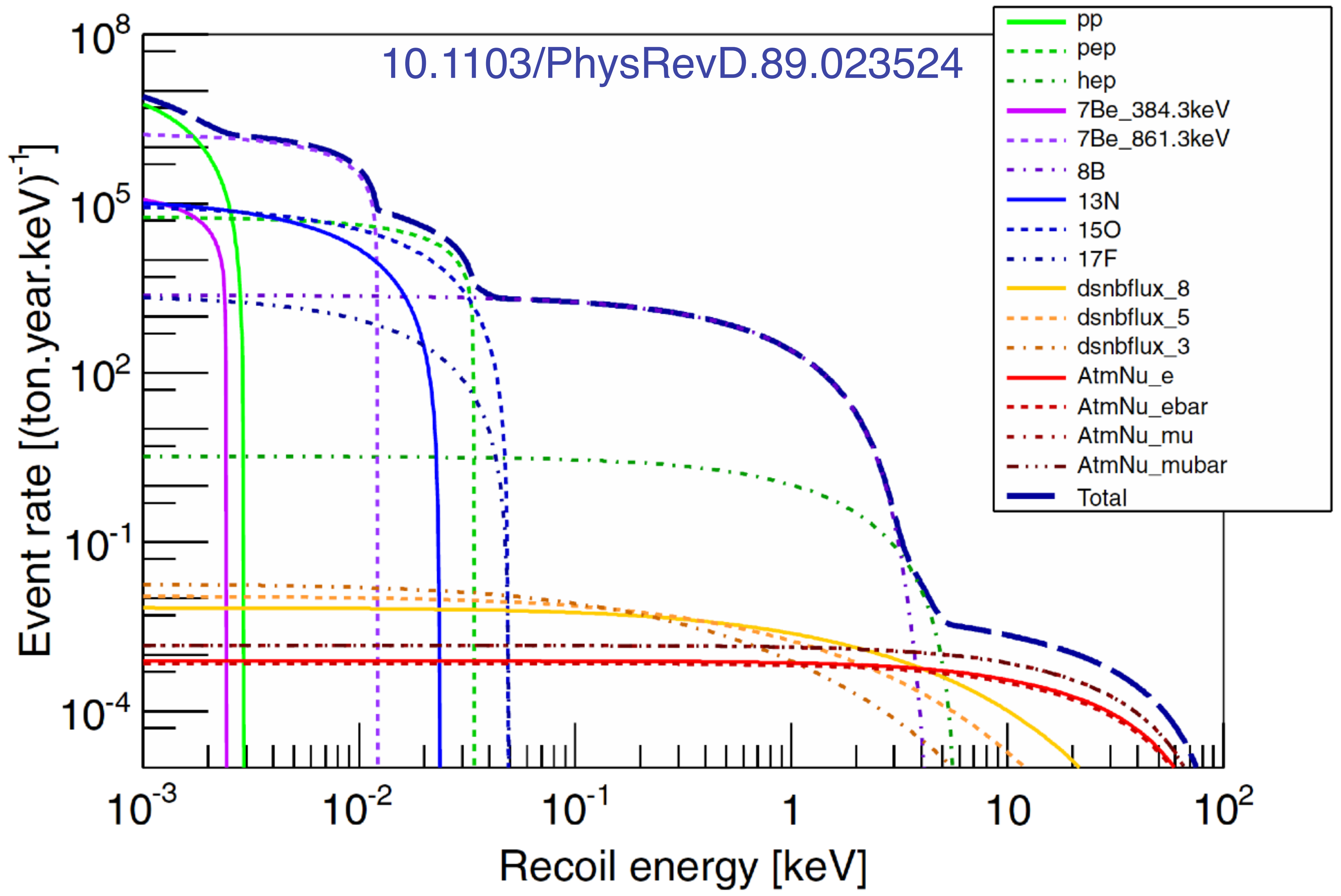
Solution



- Onion-like structure:
  1. Muon veto
  2. Neutron veto
  3. WIMP detector

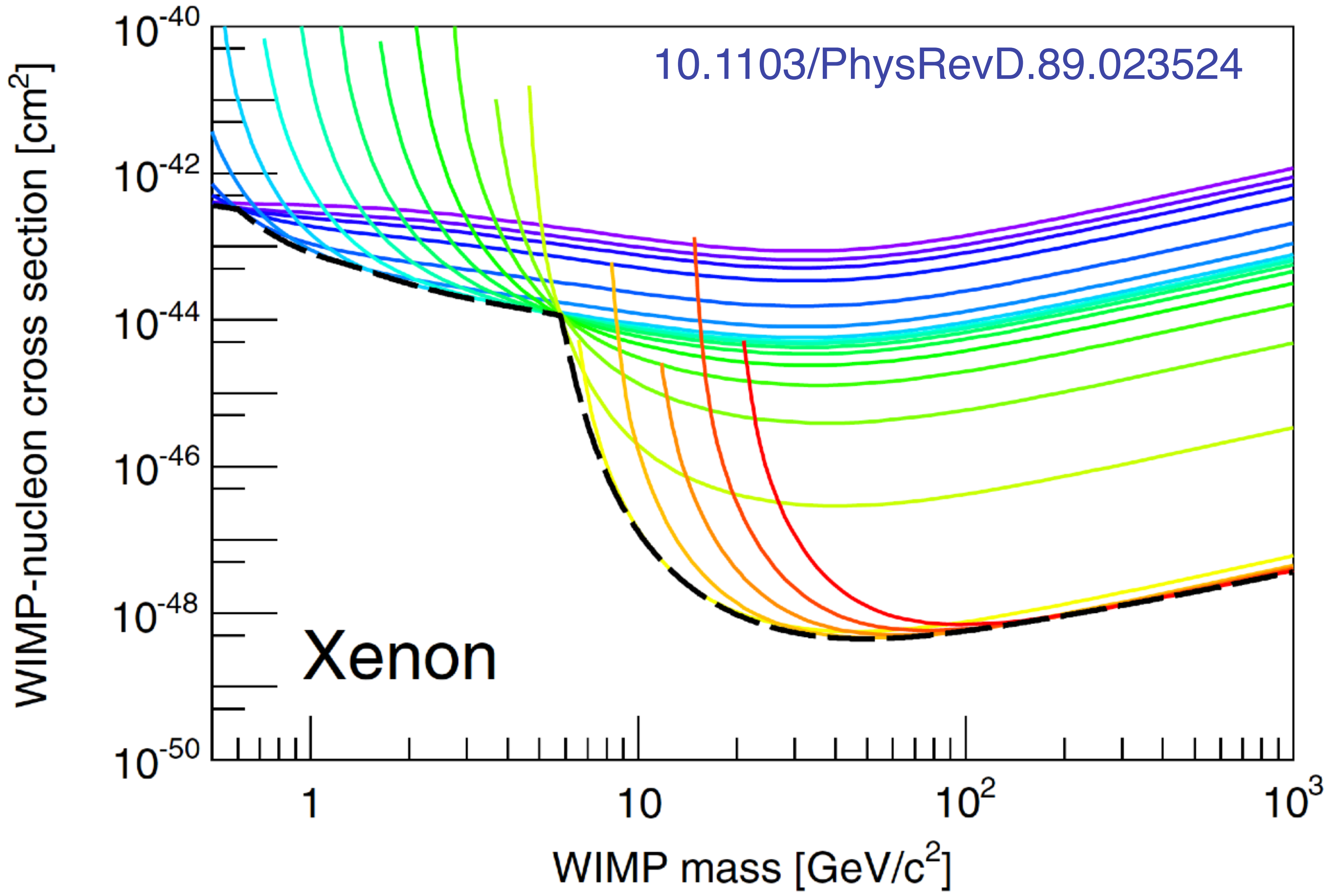
Neutrinos

Solar and atmospheric



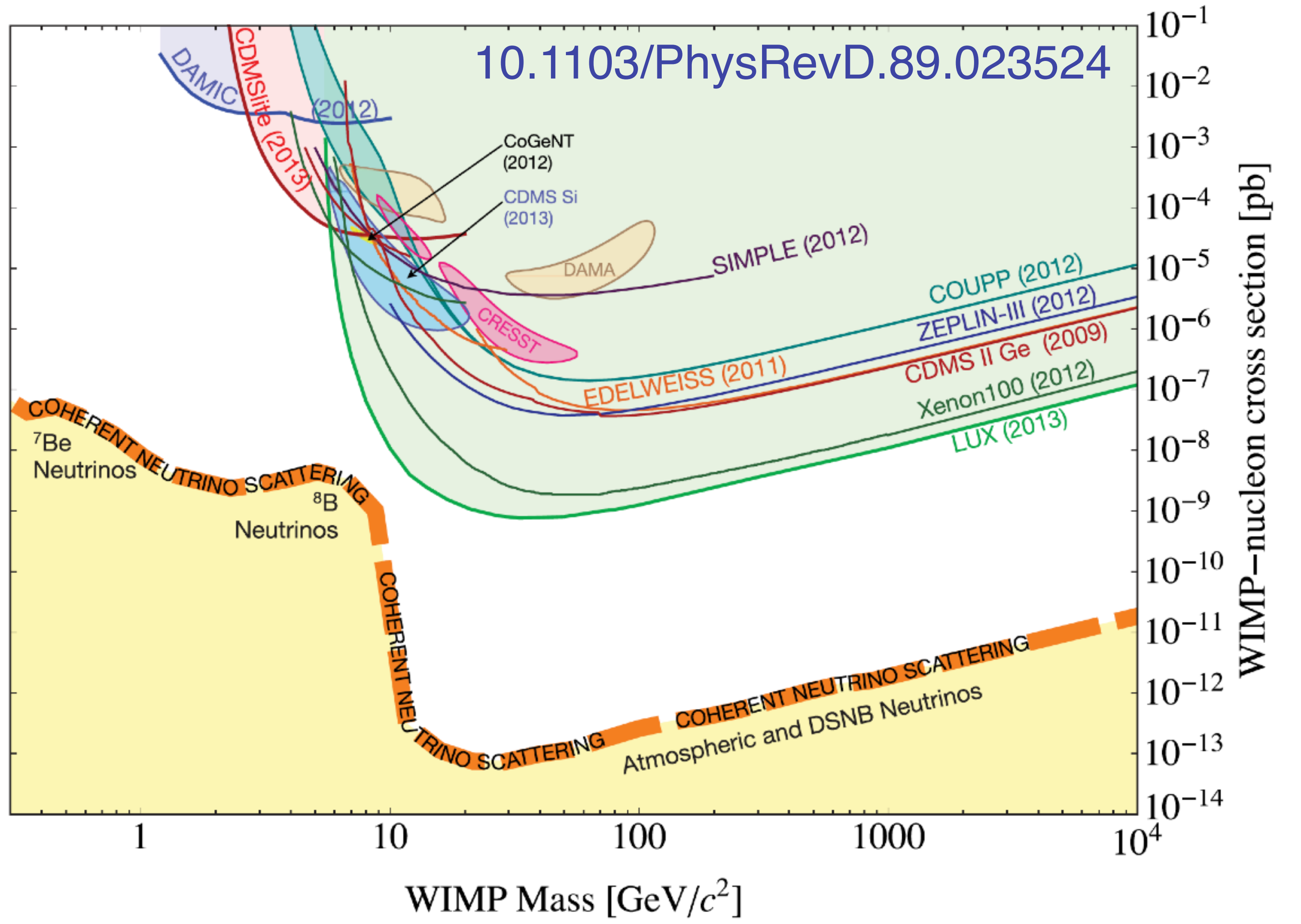
- Solar ^{8}B at low energies
- Coherent scattering on nuclei
- Atmospheric ν at high energies
- CC interactions with ^{40}Ar

Sensitivity vs E_{th}



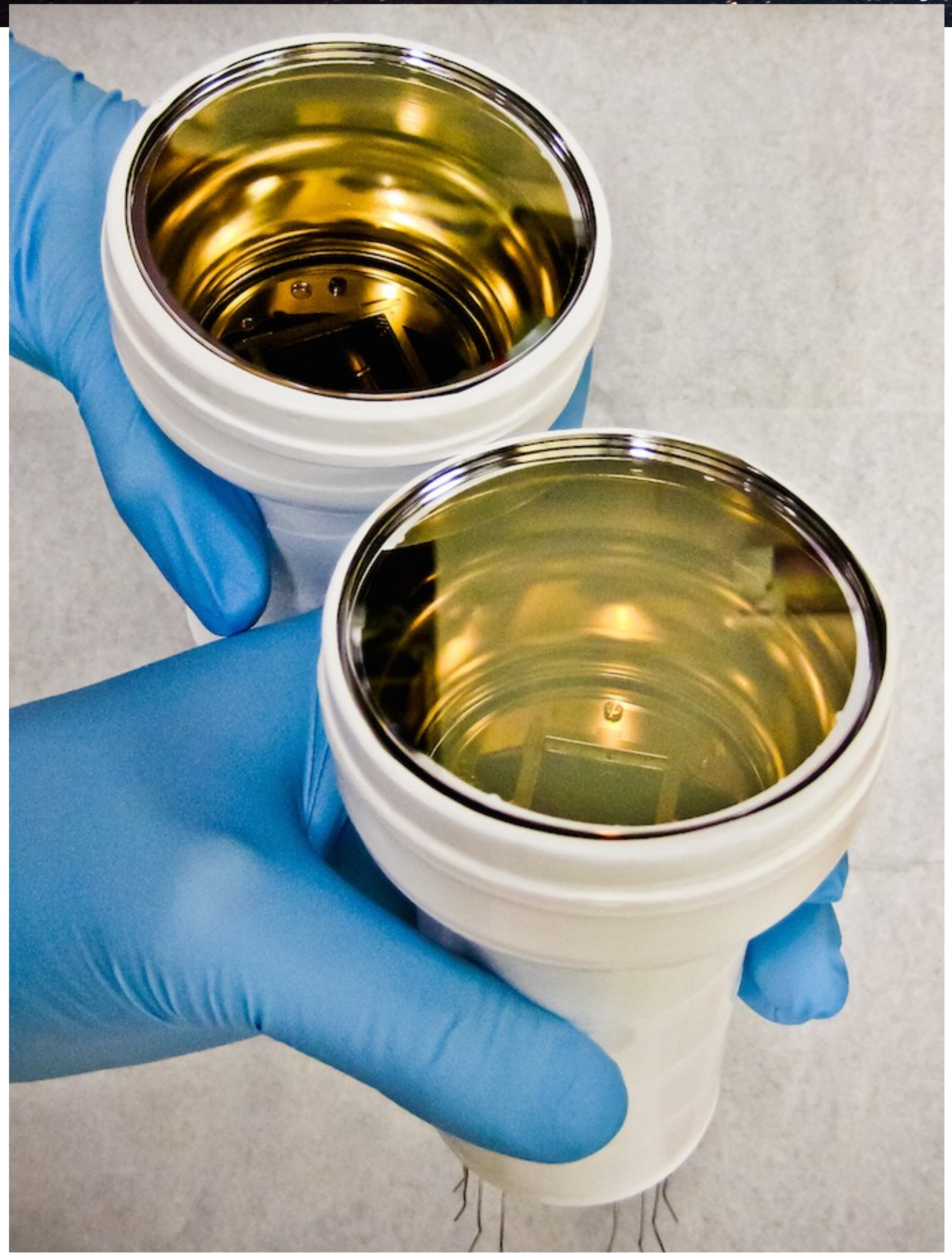
- Background-free sensitivity for exposures reaching 1 event
- Different energy thresholds
- Envelope forms the neutrino floor

Neutrino floor/fog



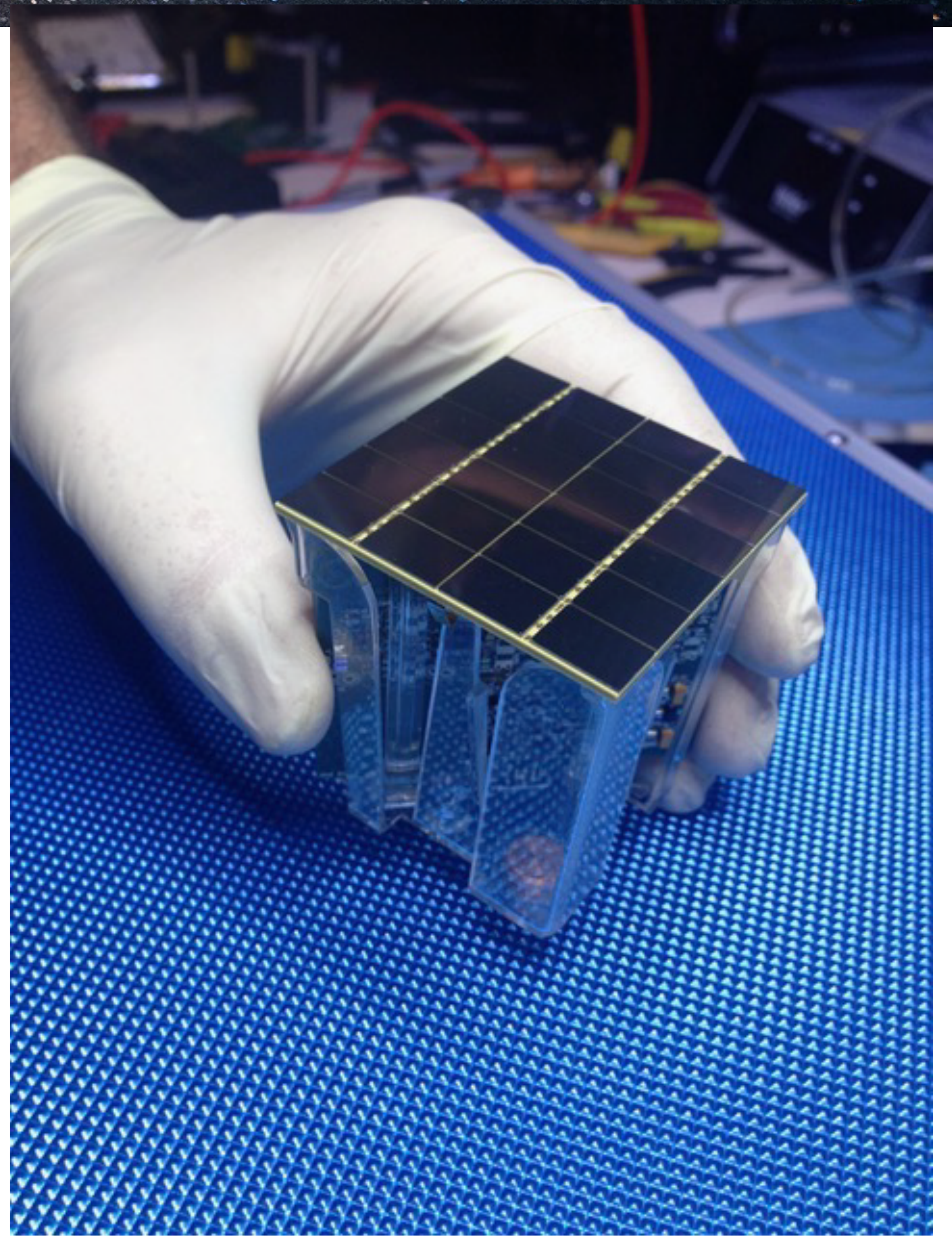
- Limit on experimental sensitivity for any detector
- How to go beyond?
  - Modulation
  - Directionality

Transitioning to a new technology



Why?

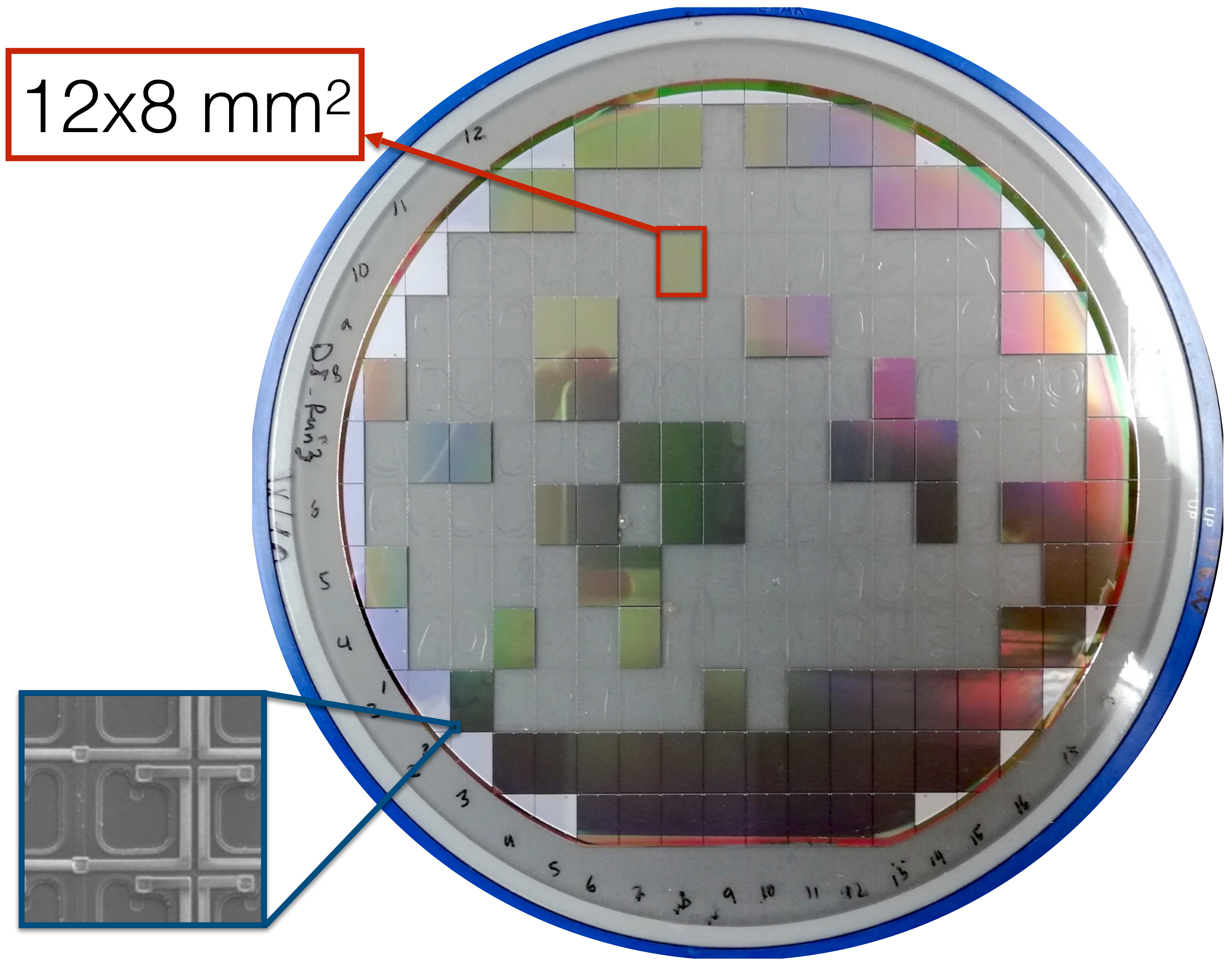
- Lower radioactivity
- Higher Photon Detection Efficiency
- Higher active area
- Operated with low bias
- Lower cost



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

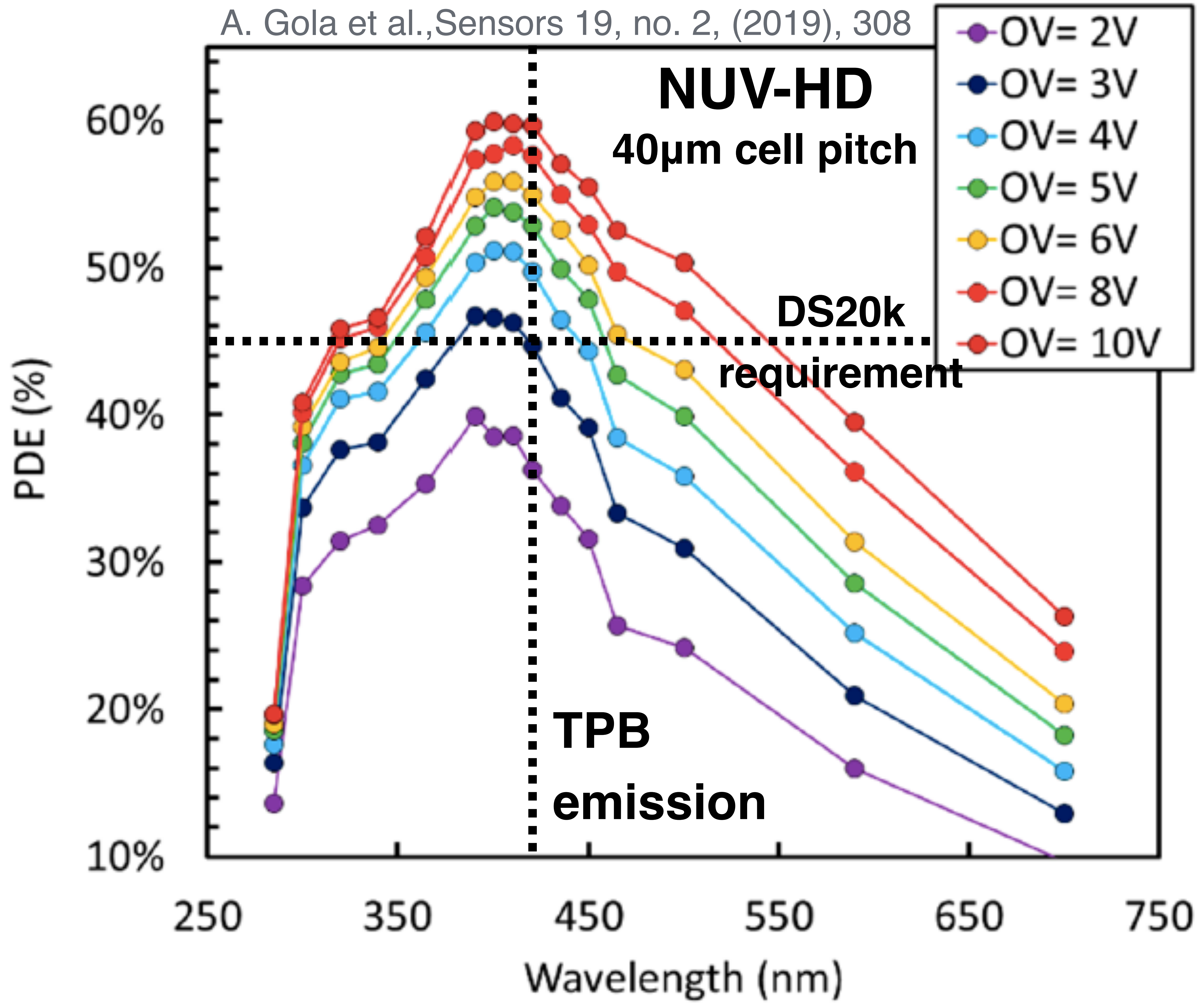
- Higher dark rate and correlated noises (after-pulse, cross-talk)
- Small area (many channels)
- High output capacitance (high electronic noise, low bandwidth)

Step 1: SiPMs development



- NUV vs RGB choice (P_{01})
- Cell pitch and fill factor (FF) optimization
- **E** field profile ⇒ DCR+CN reduction

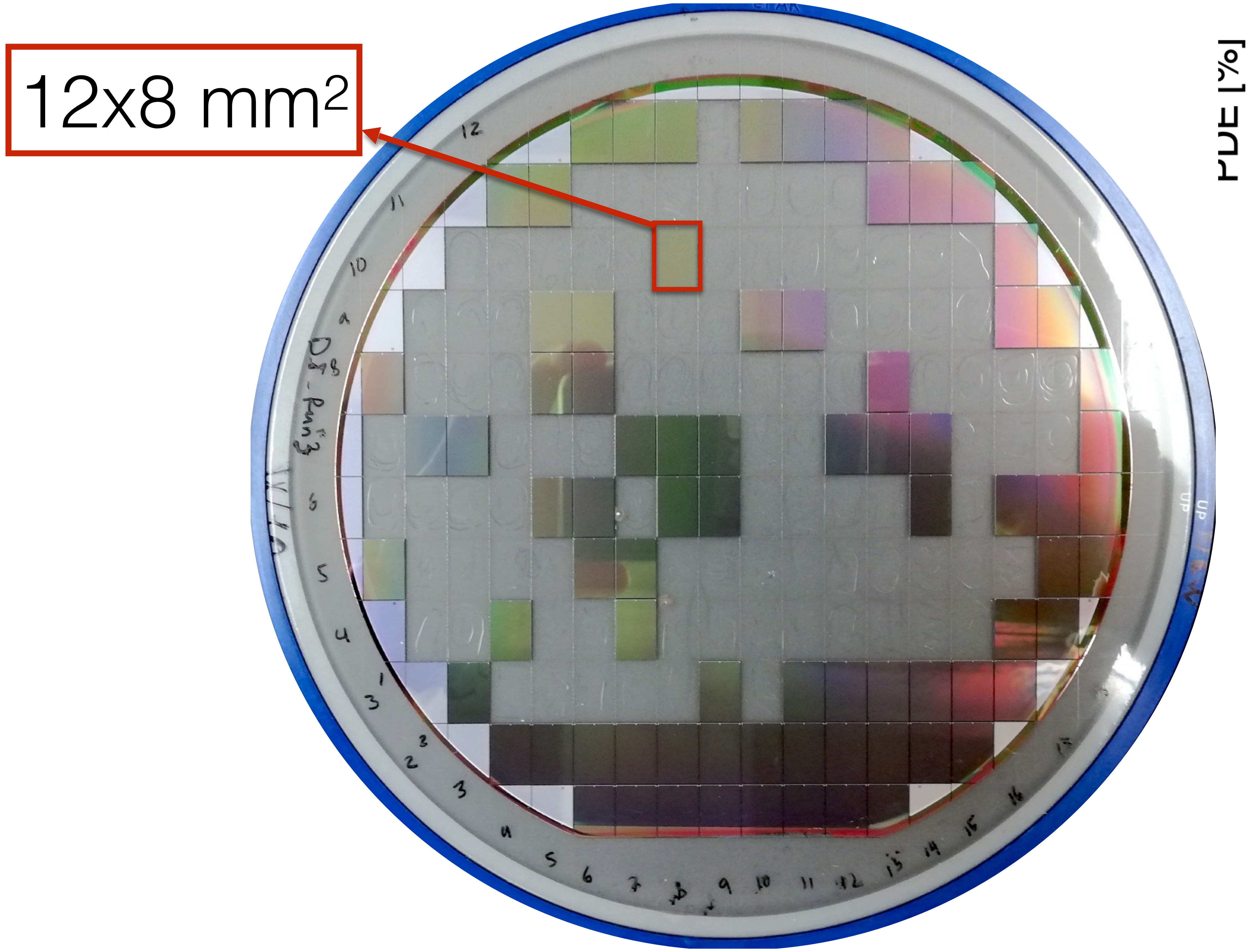
A. Gola et al.,Sensors 19, no. 2, (2019), 308

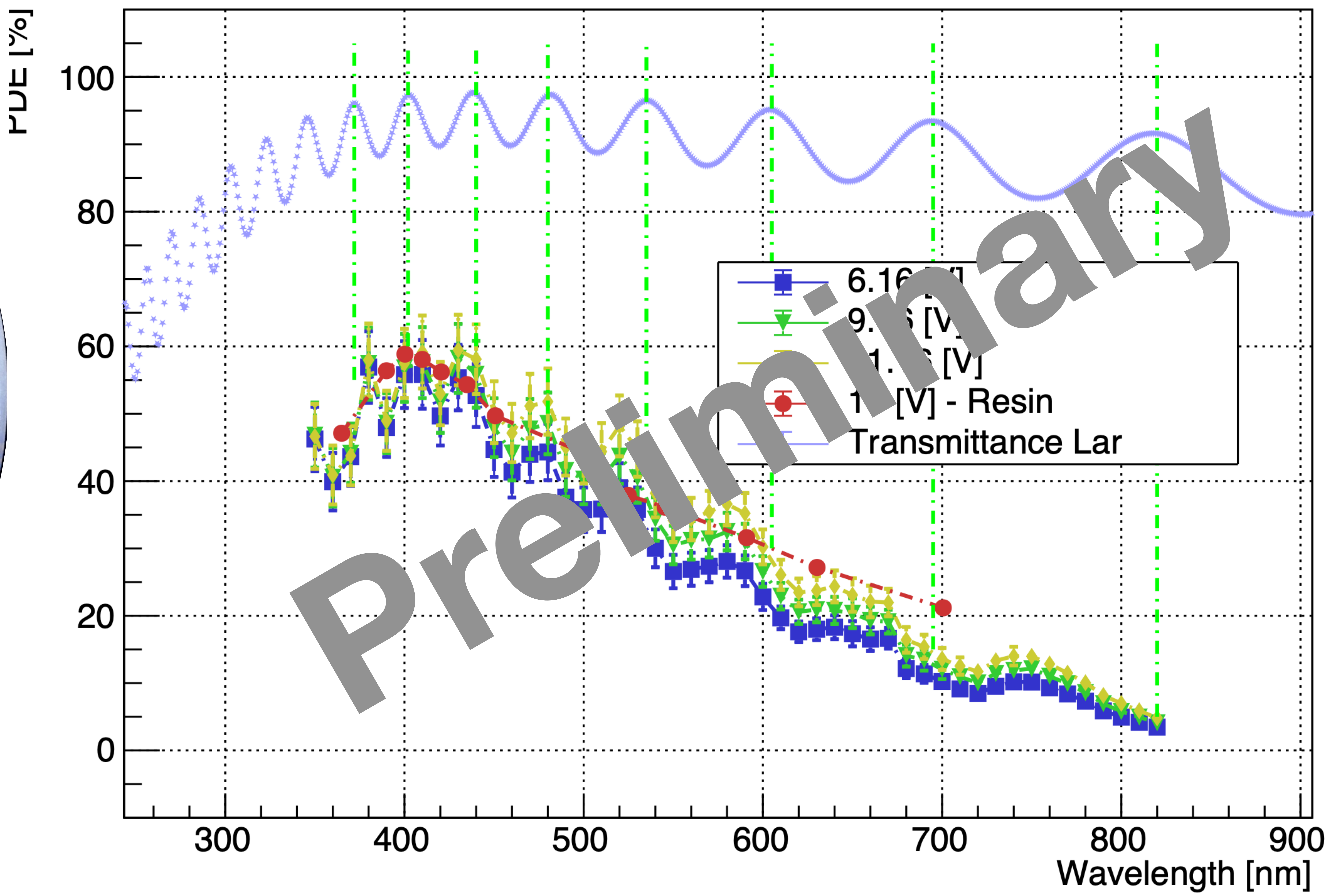


$PDE = QE \times P_{01} \times FF$

PDE > 55% @ 290K

Step 1: SiPMs development



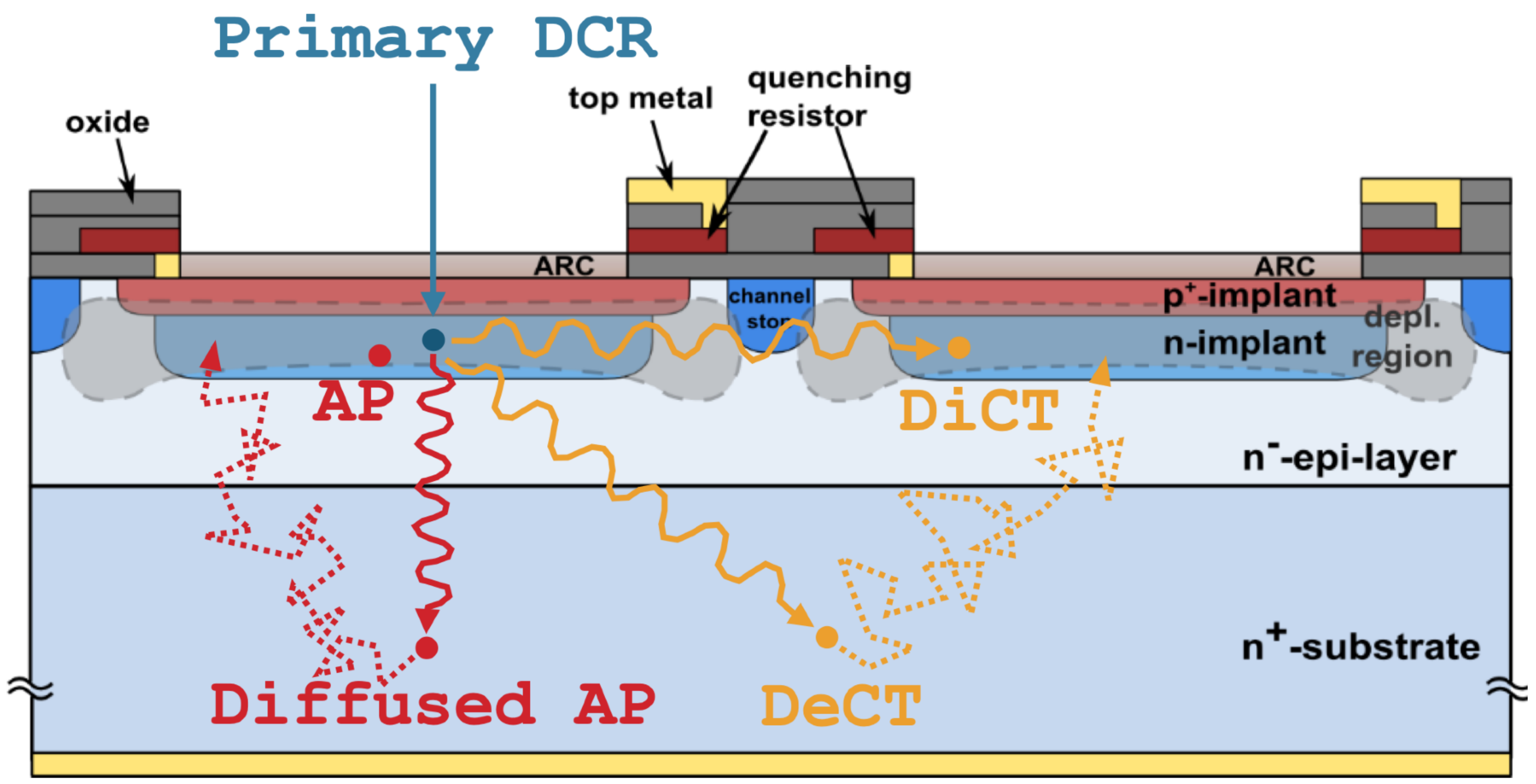


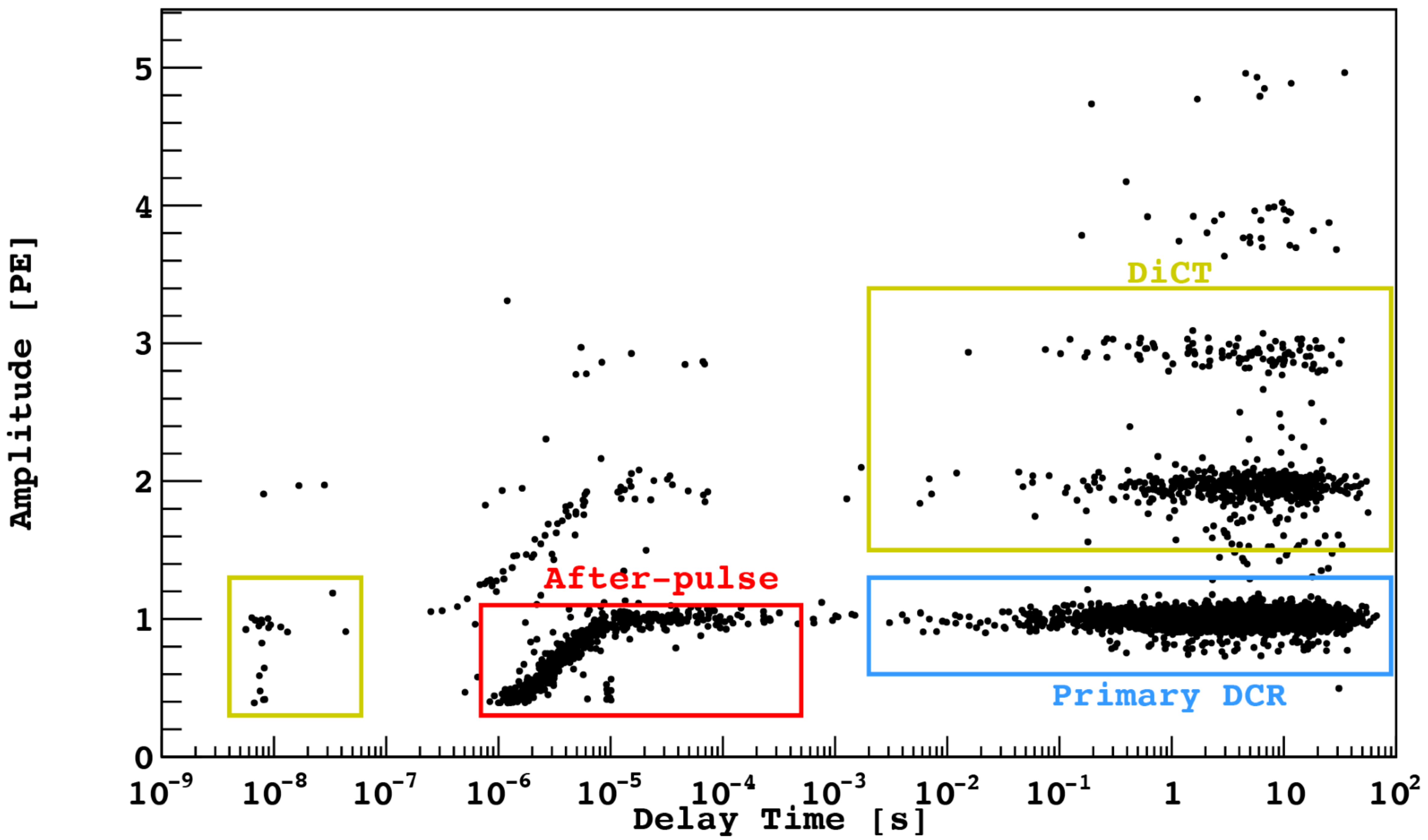
- NUV vs RGB choice (P_{01})
- Cell pitch and fill factor (FF) optimization
- **E** field profile ⇒ DCR+CN reduction

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

PDE ~50% in LAr

Step 1: SiPMs development



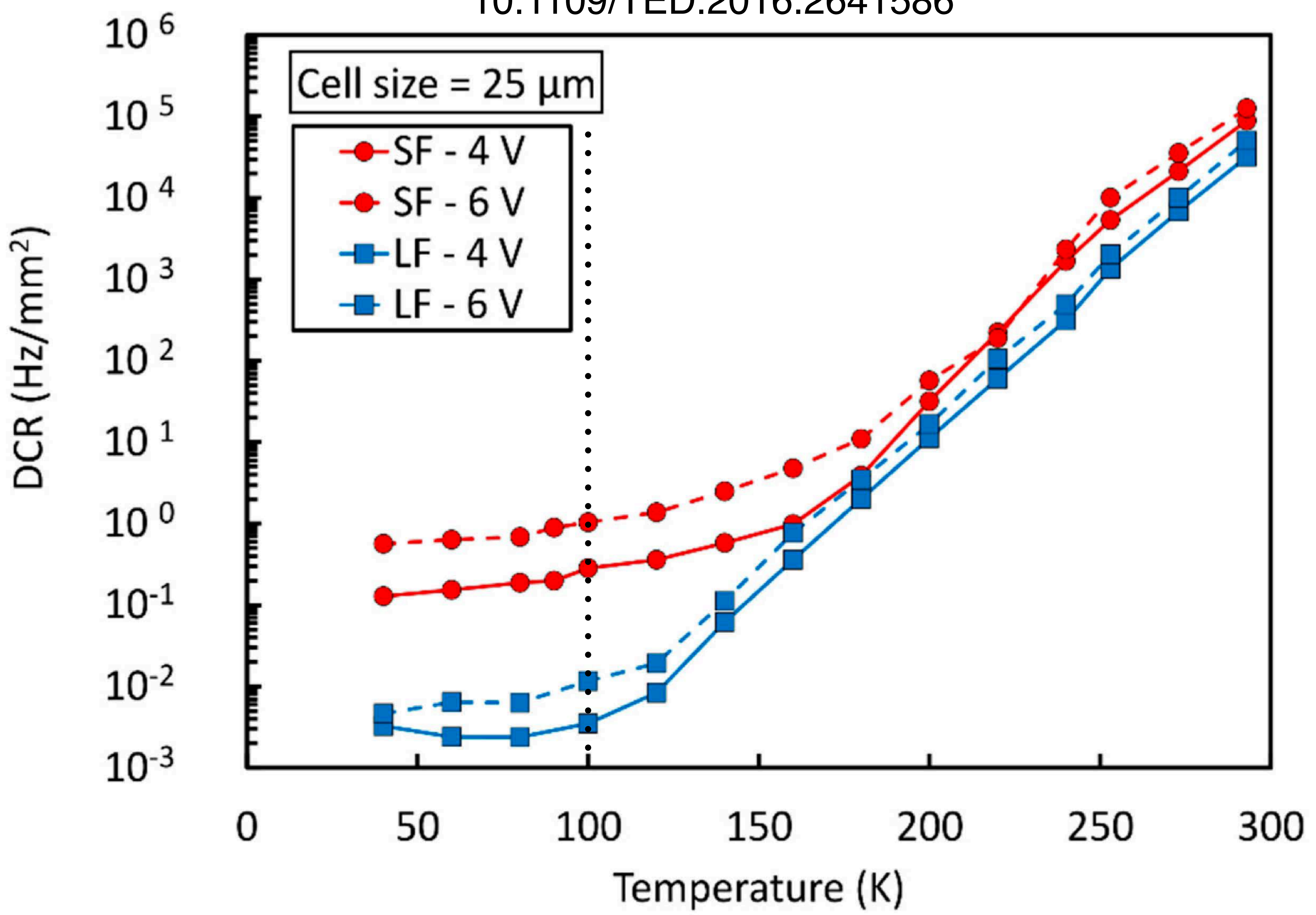


- Noises can be primary or correlated
- Primary: DCR
- Correlated: AP, DiCT, DeCT

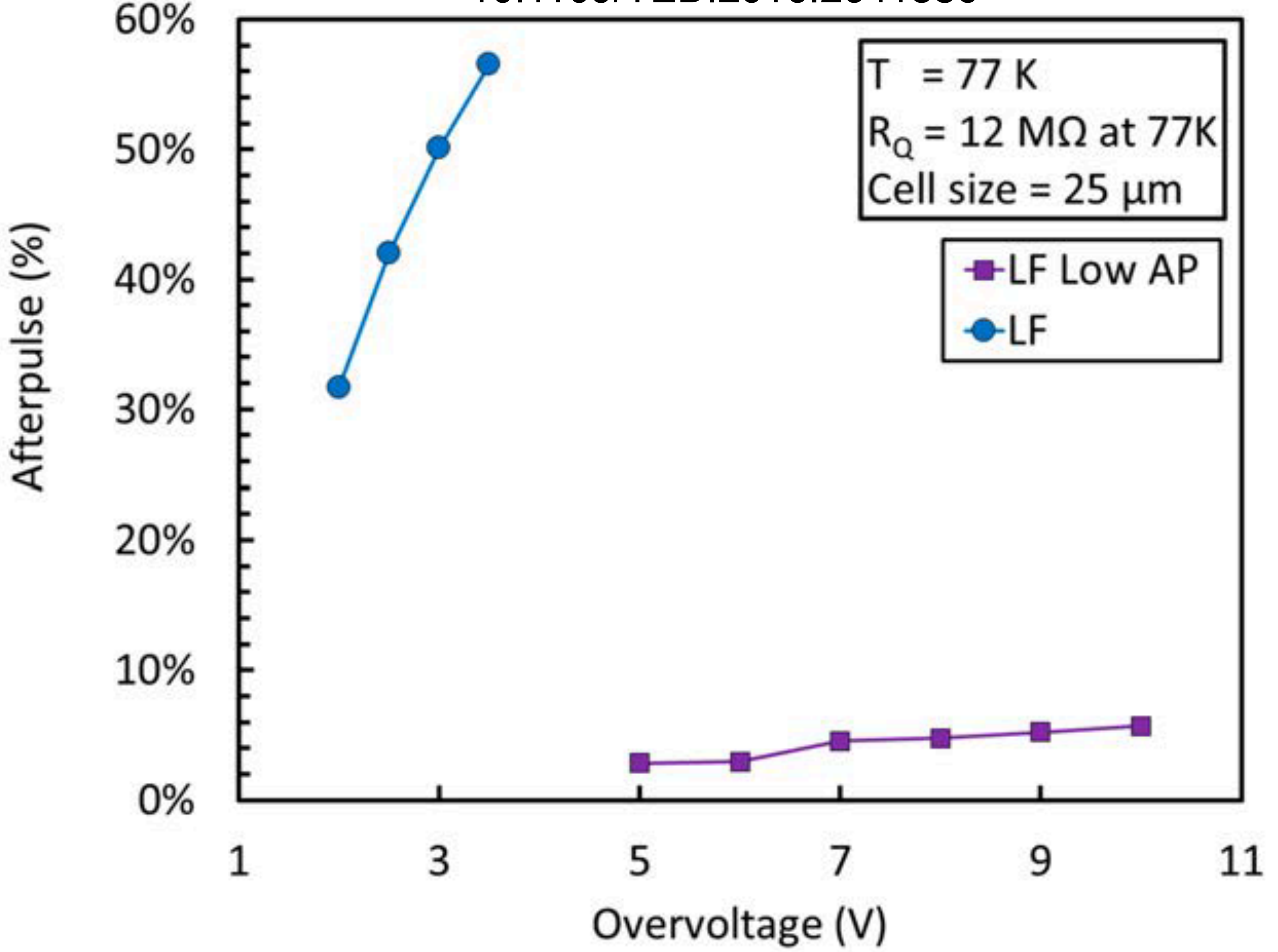
- Different generation mechanism
- Different behavior

Step 1: SiPMs development

10.1109/TED.2016.2641586



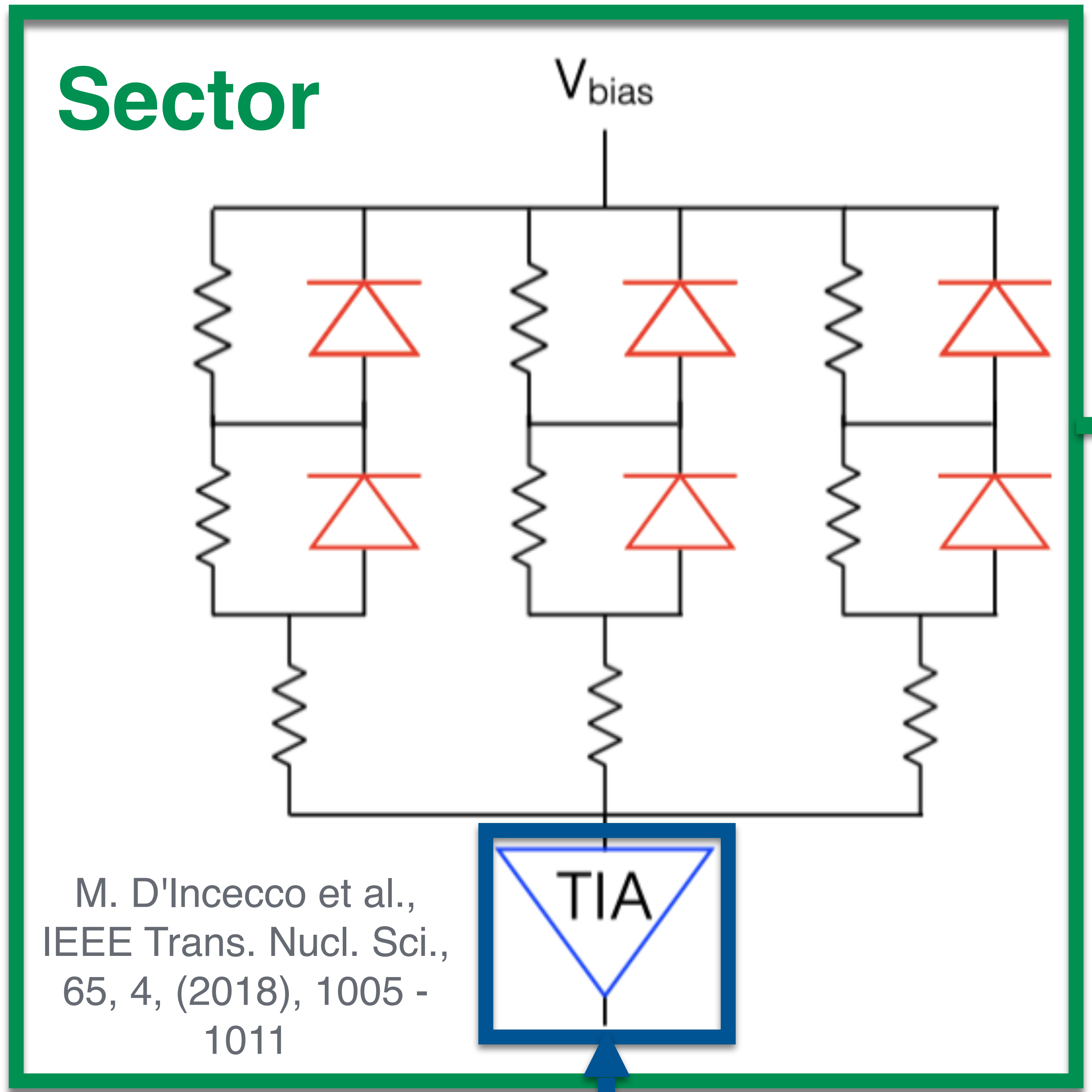
10.1109/TED.2016.2641586



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

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

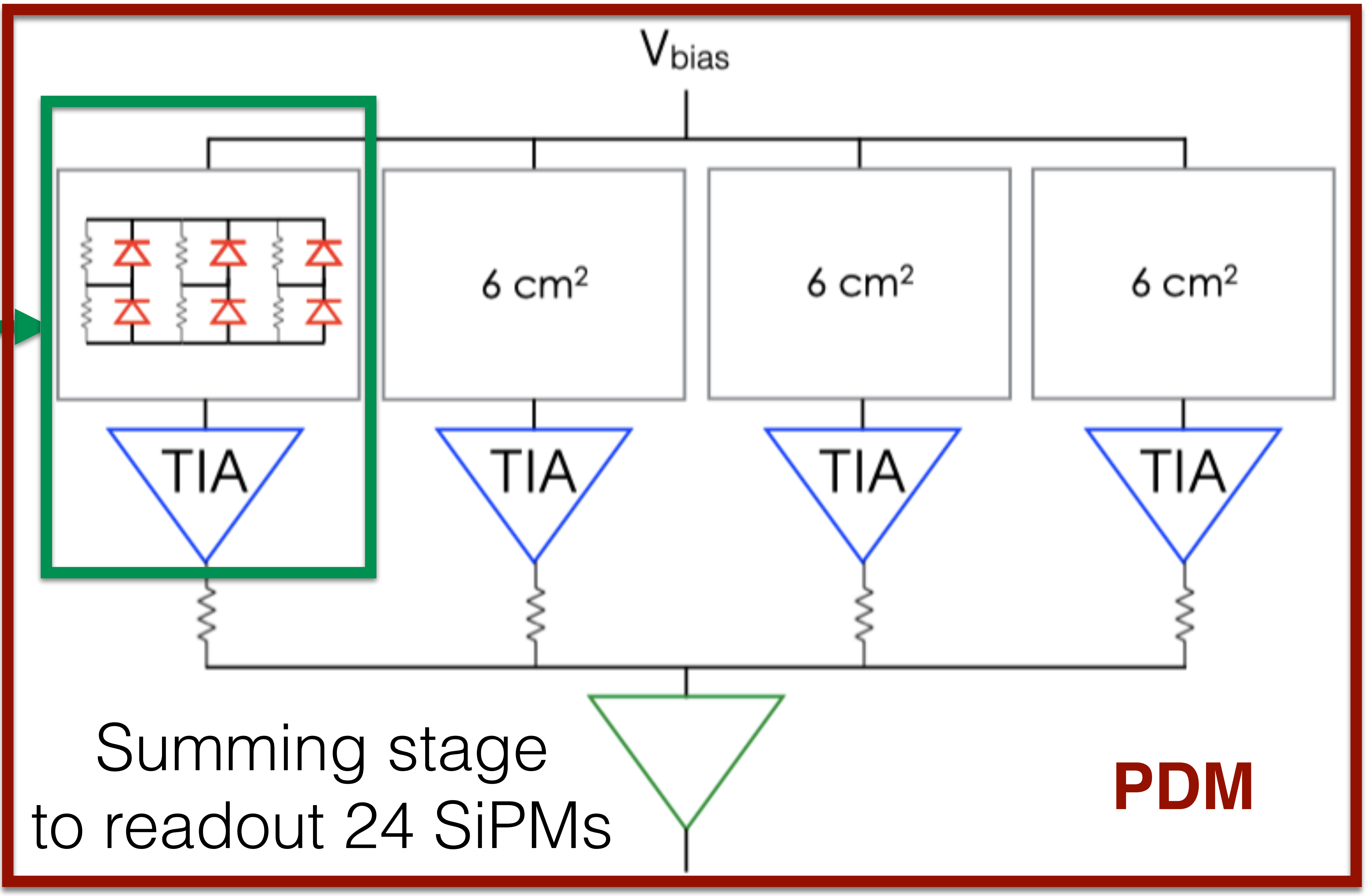
Step 2: readout electronics design…

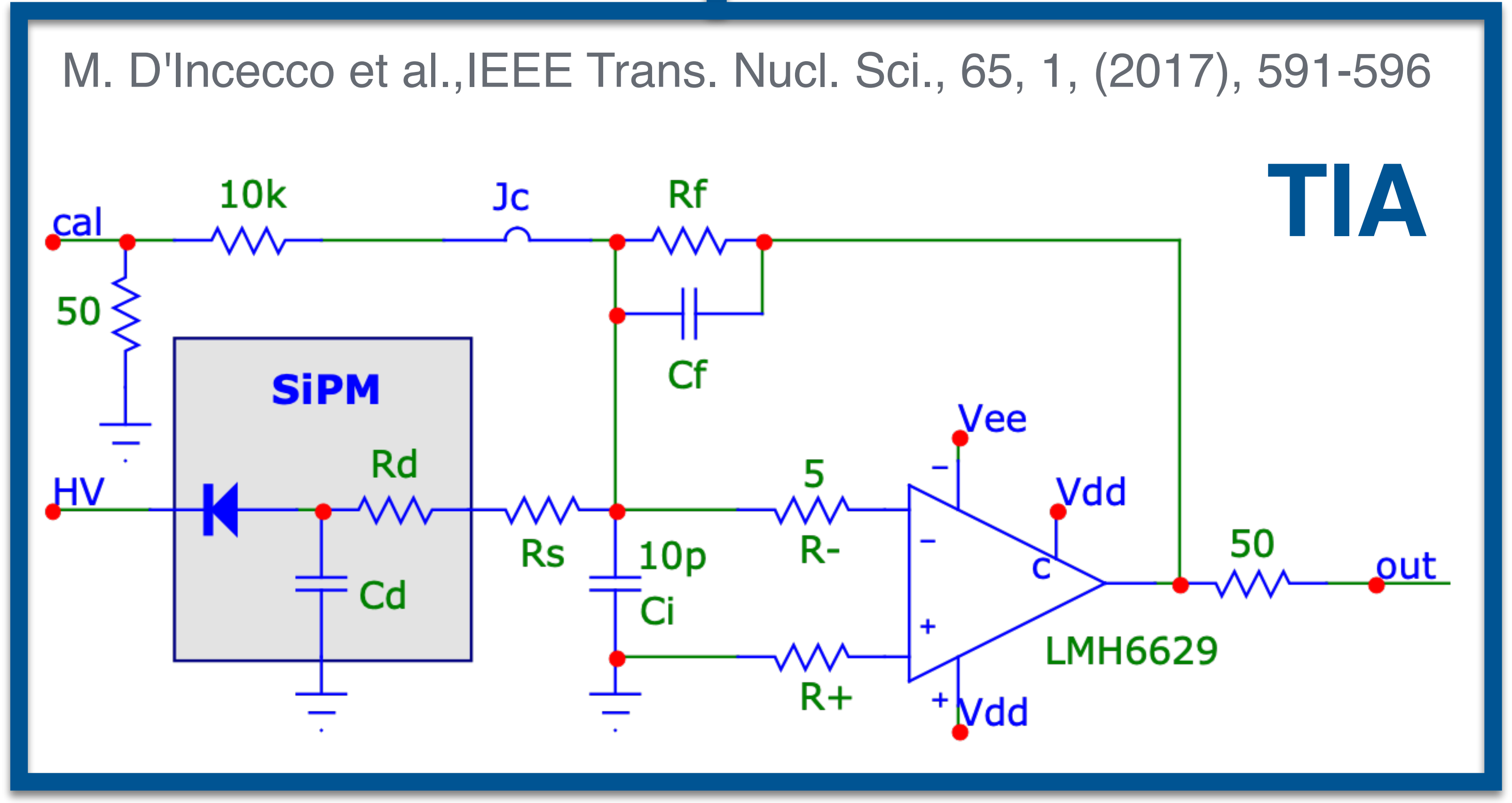


Mixed series/parallel configuration

Reduce C_{in}@TIA

Preserve BW





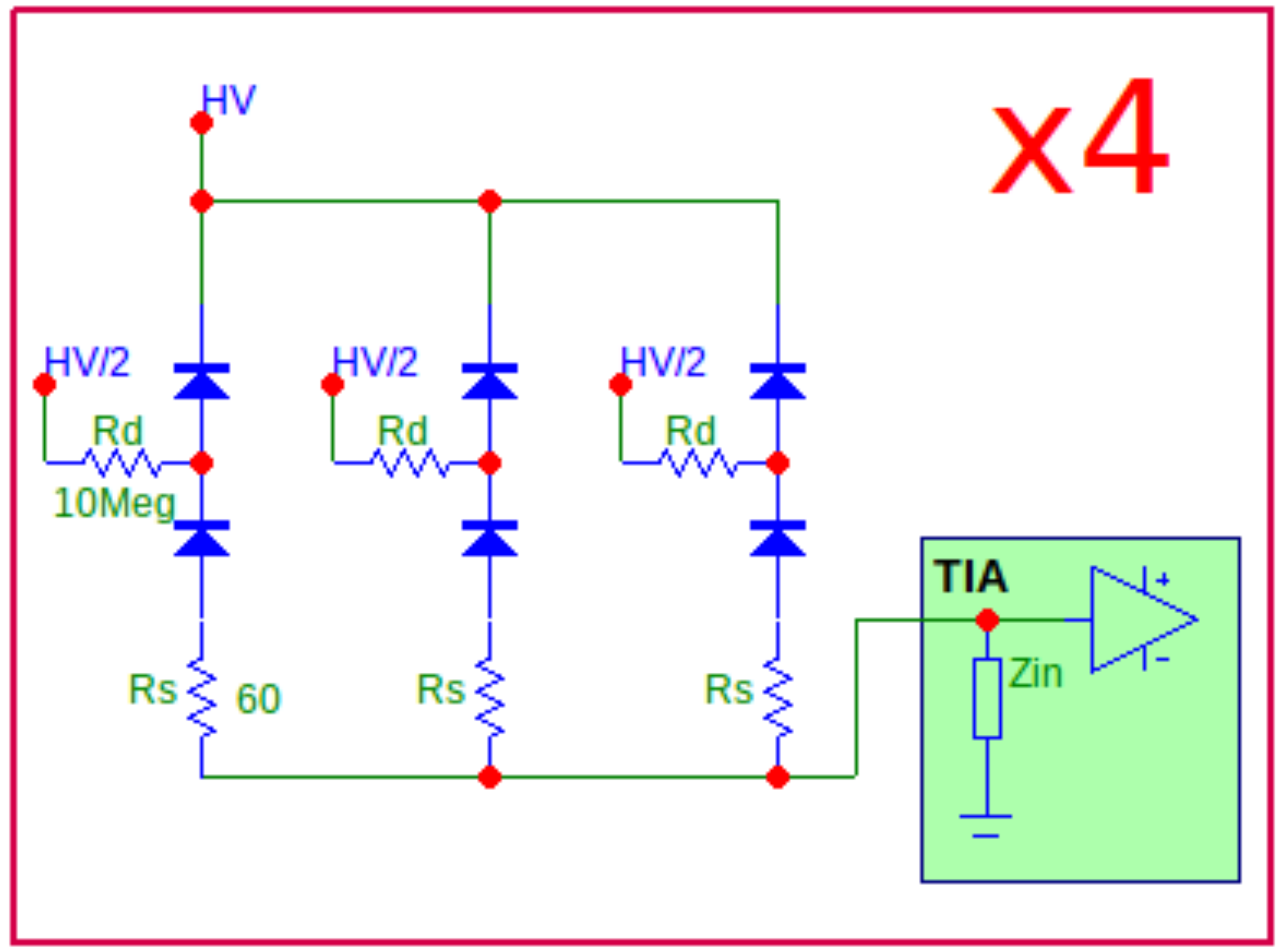
SiPM = current generators + huge output capacitance (~50pF/mm²)

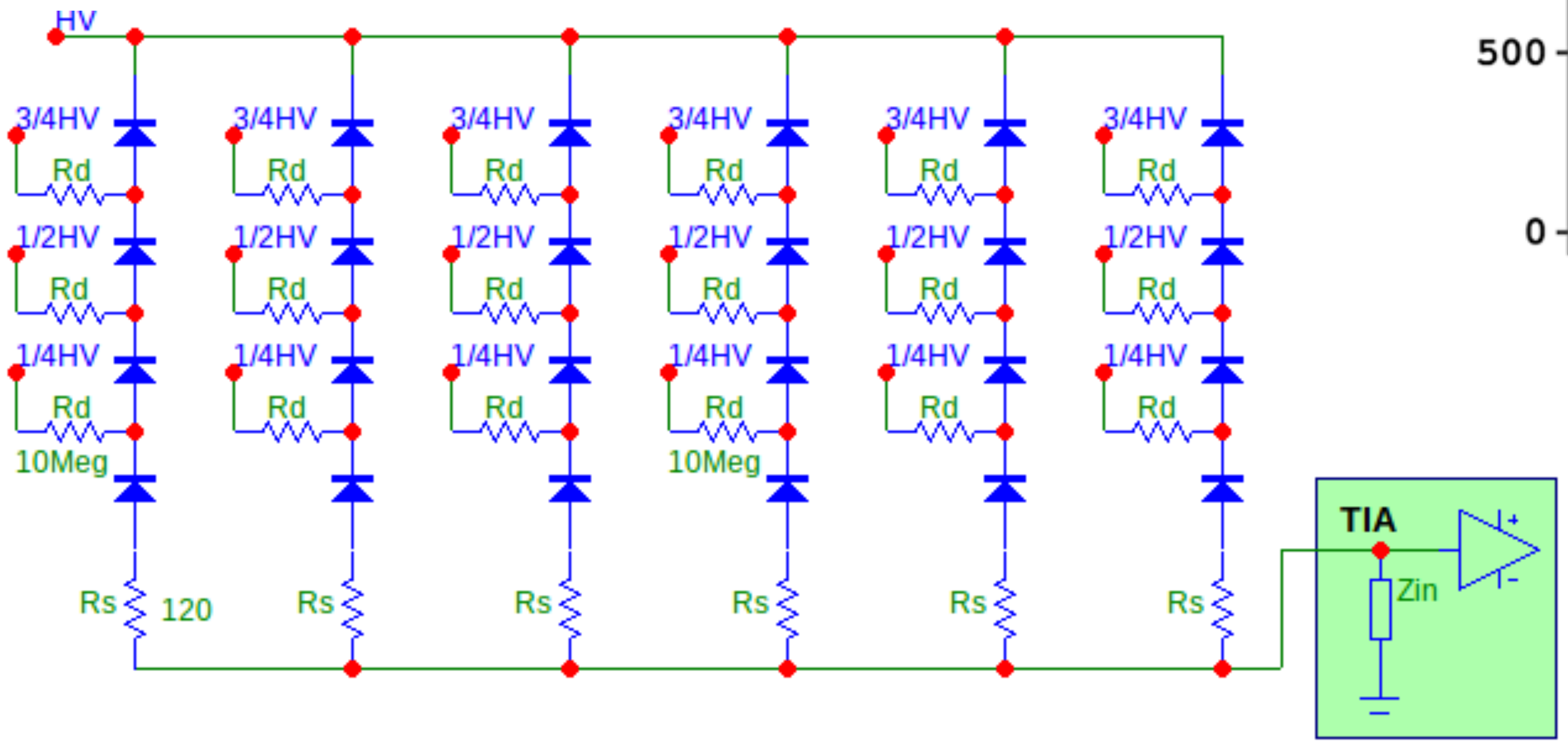
Transimpedance amplifier (TIA) High Bandwidth and Low Noise

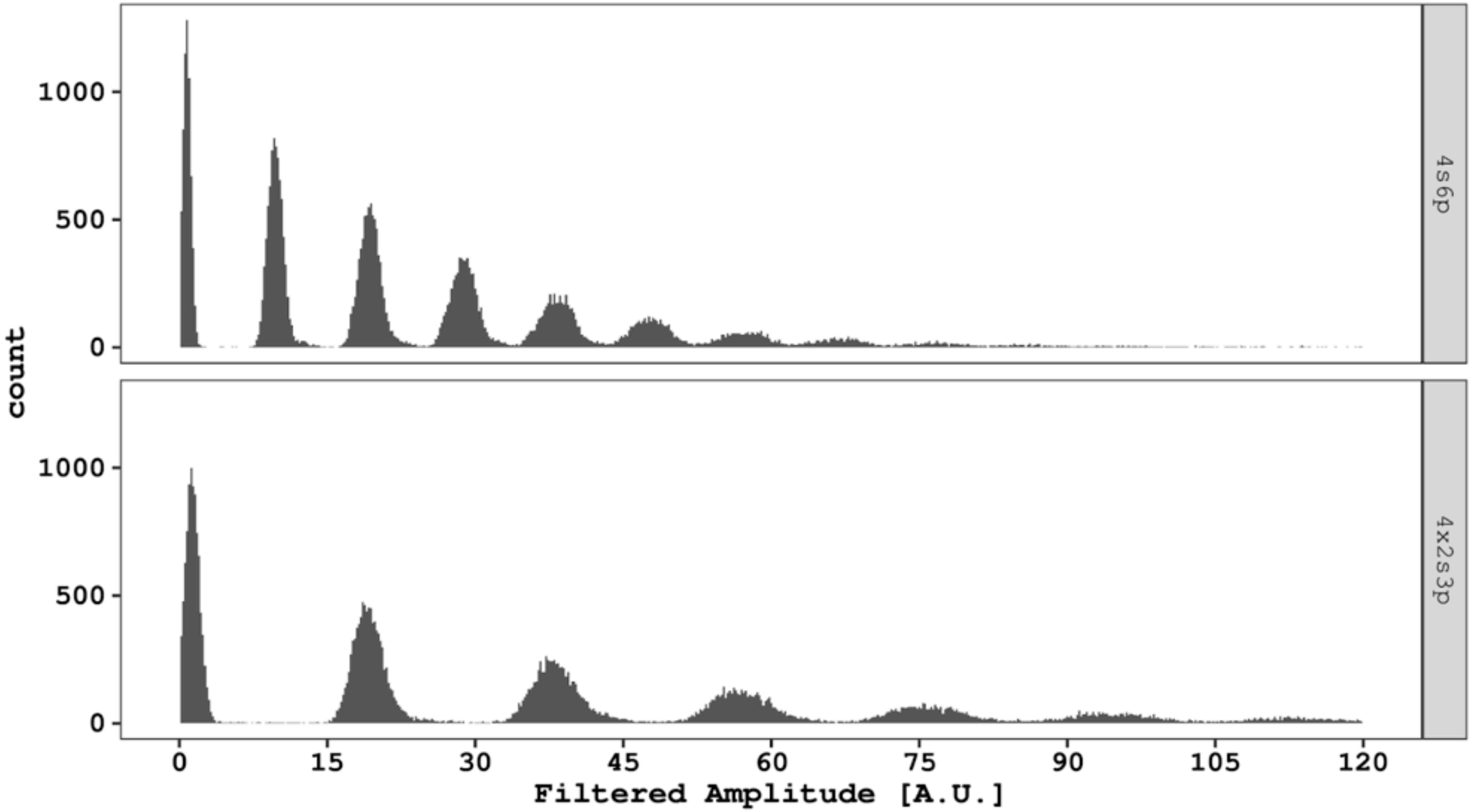
SNR is reduced wrt a single SiPM, but still very high

Power dissipation is < 250mW per PDM

Step 2: ...and upgrades



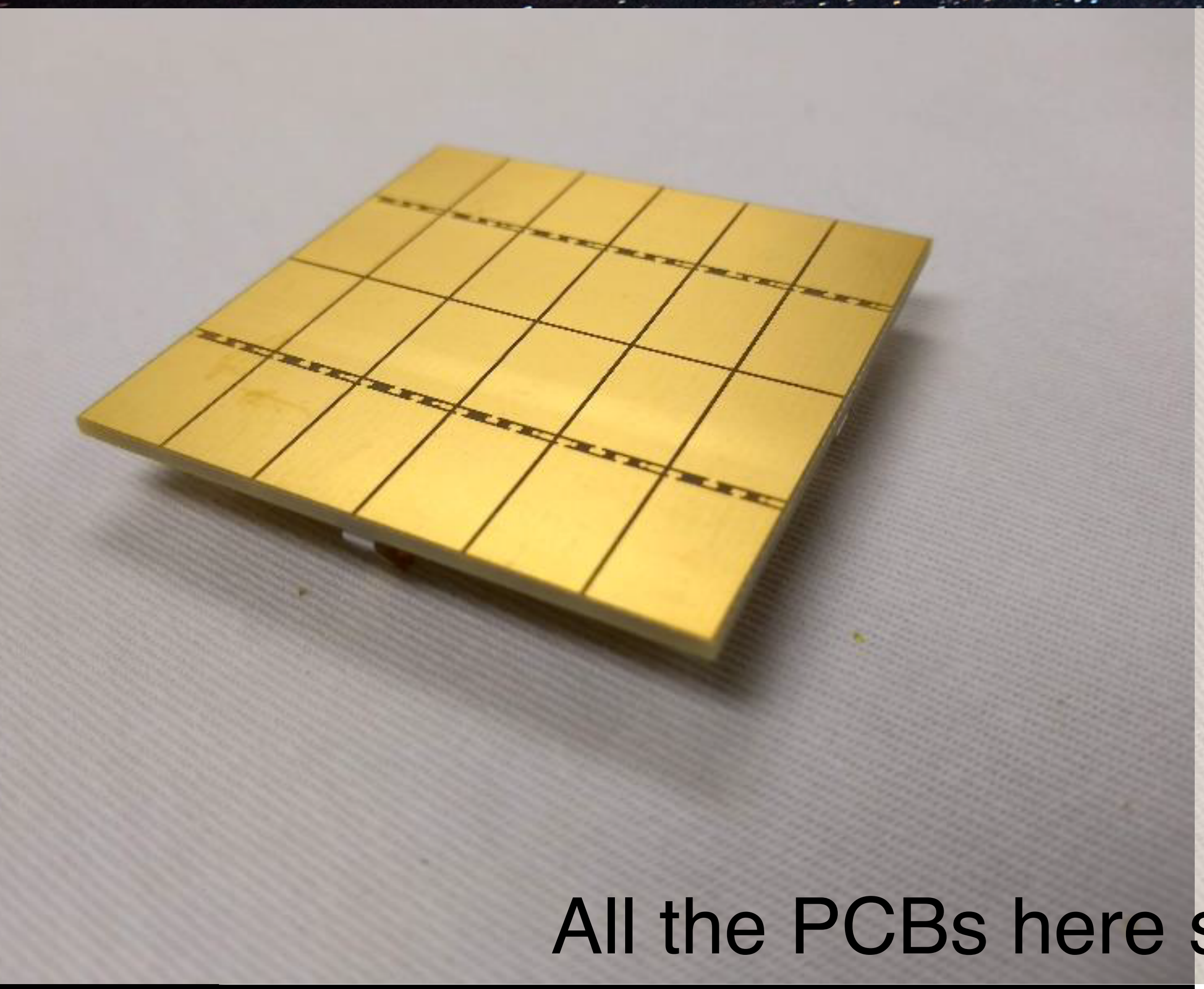
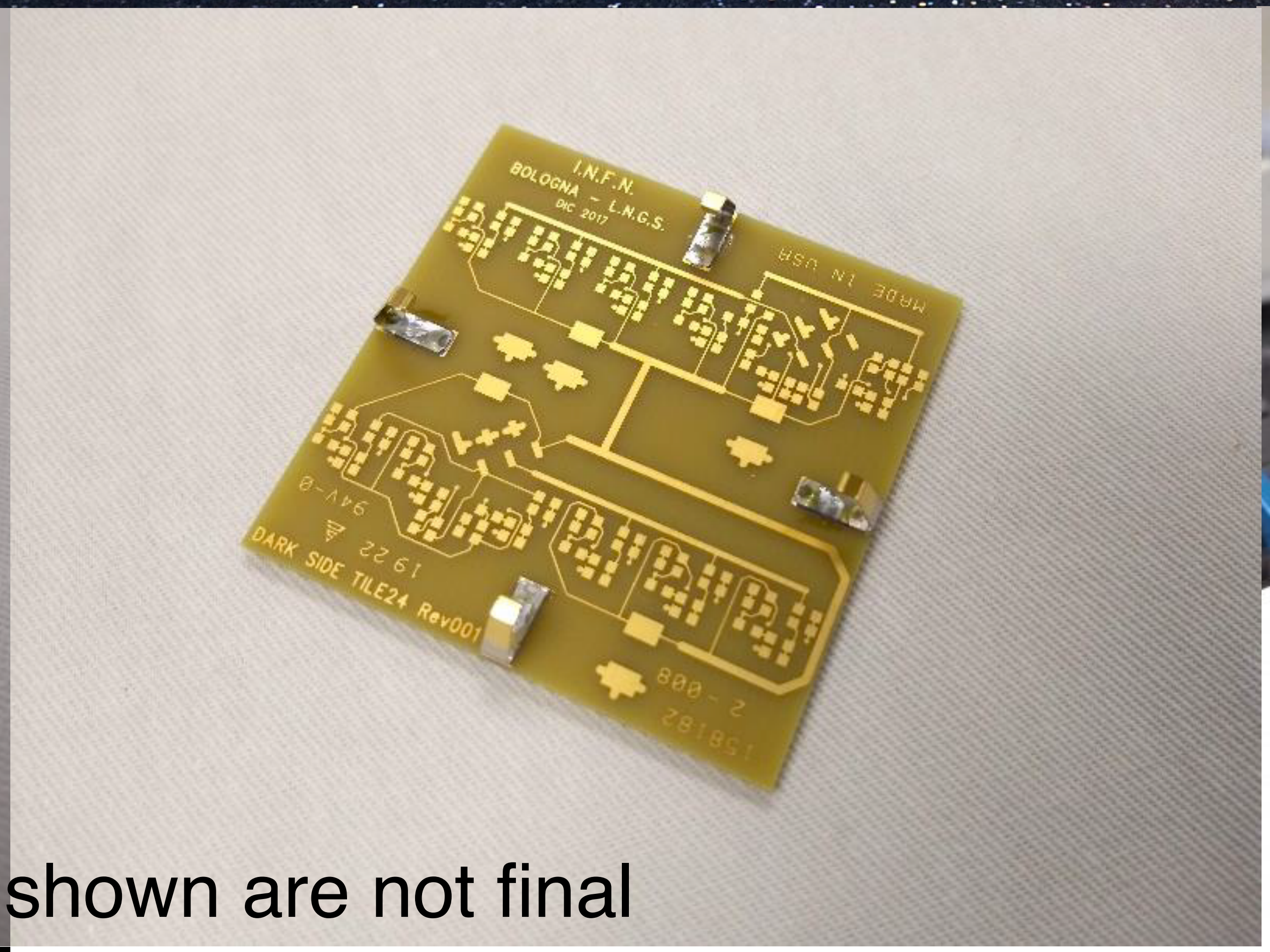
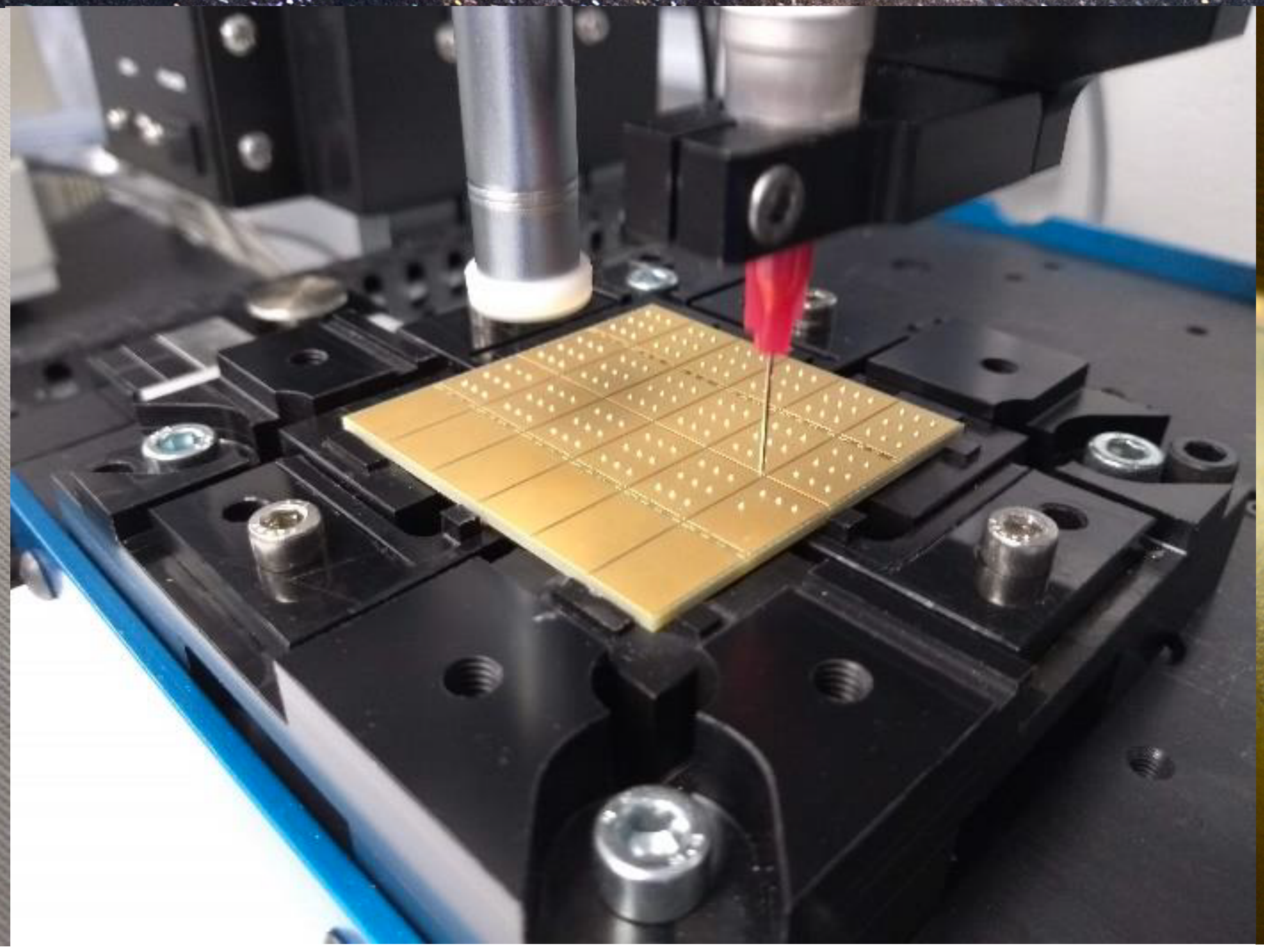
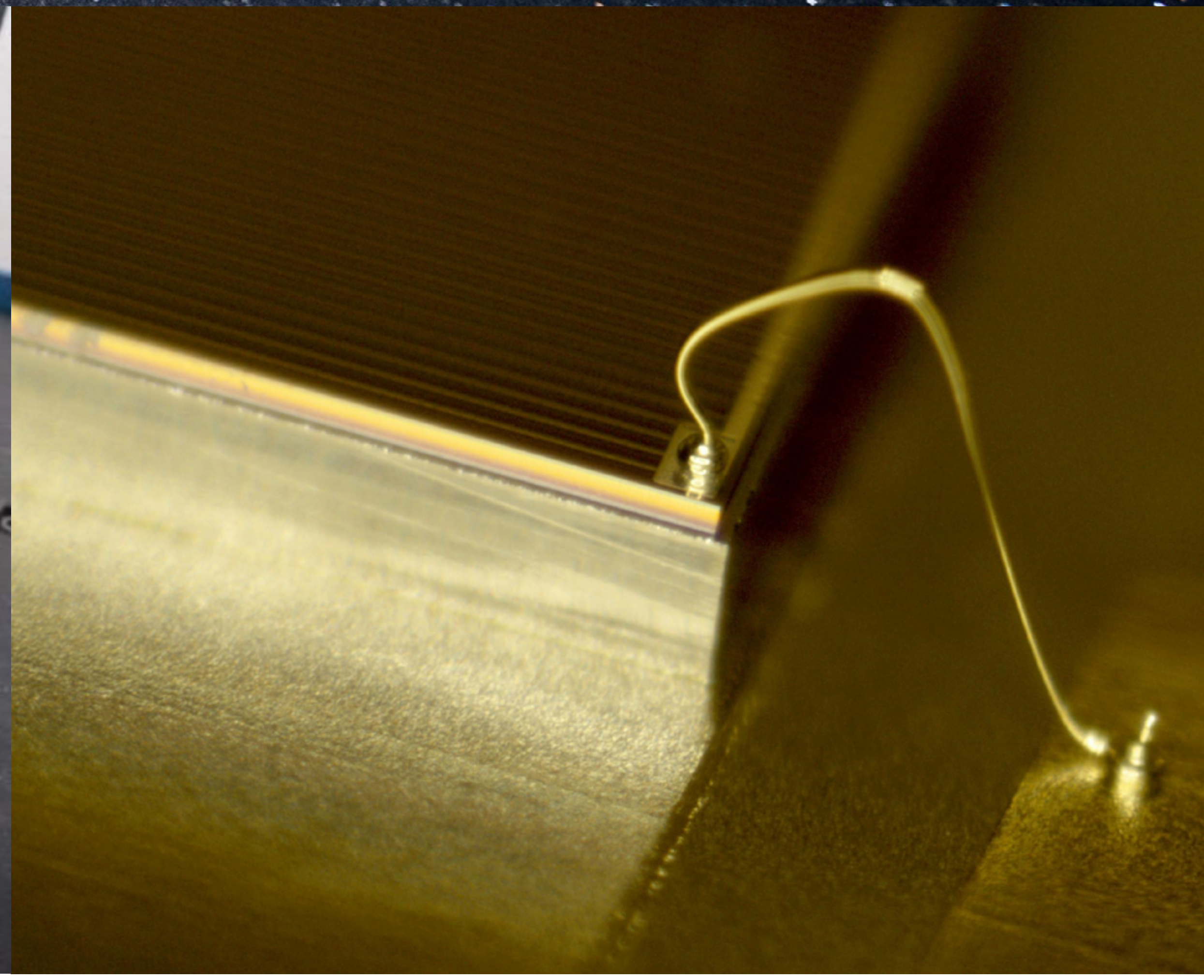




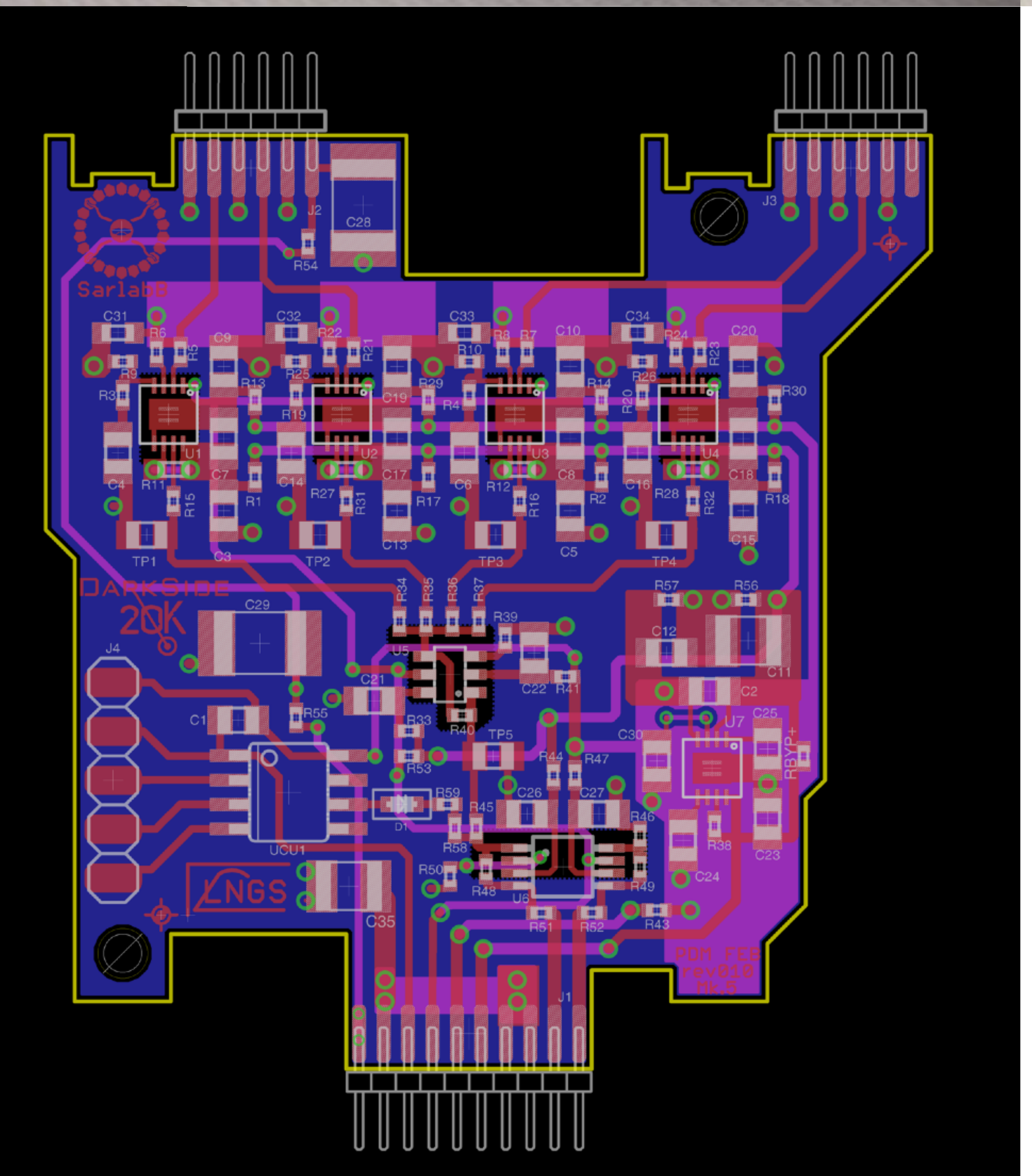
Switch from 4 sectors (6cm²) to 1 single 24cm² unit

Power dissipation < 50mW per tile

Step 3: packaging and production

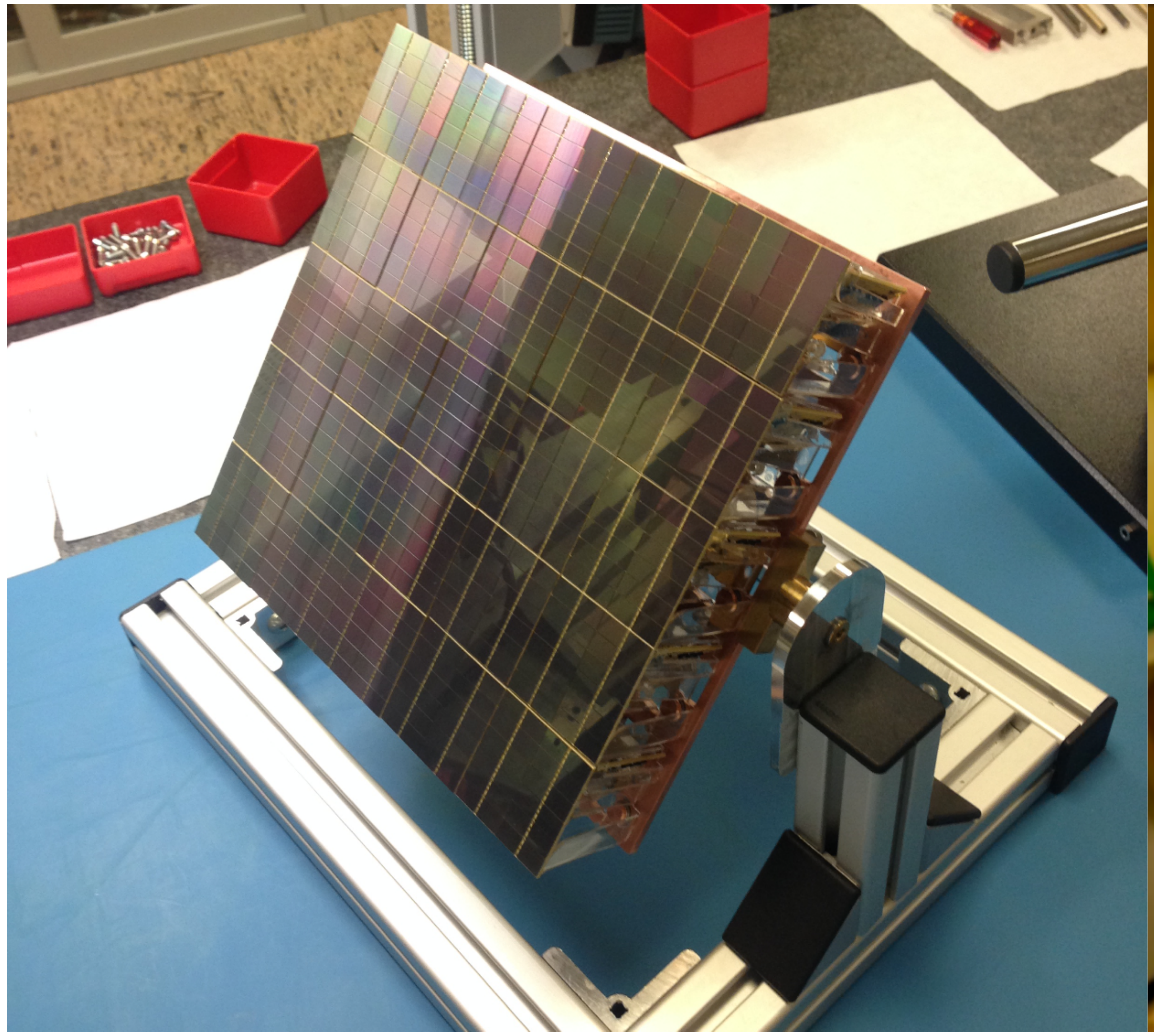





All the PCBs here shown are not final

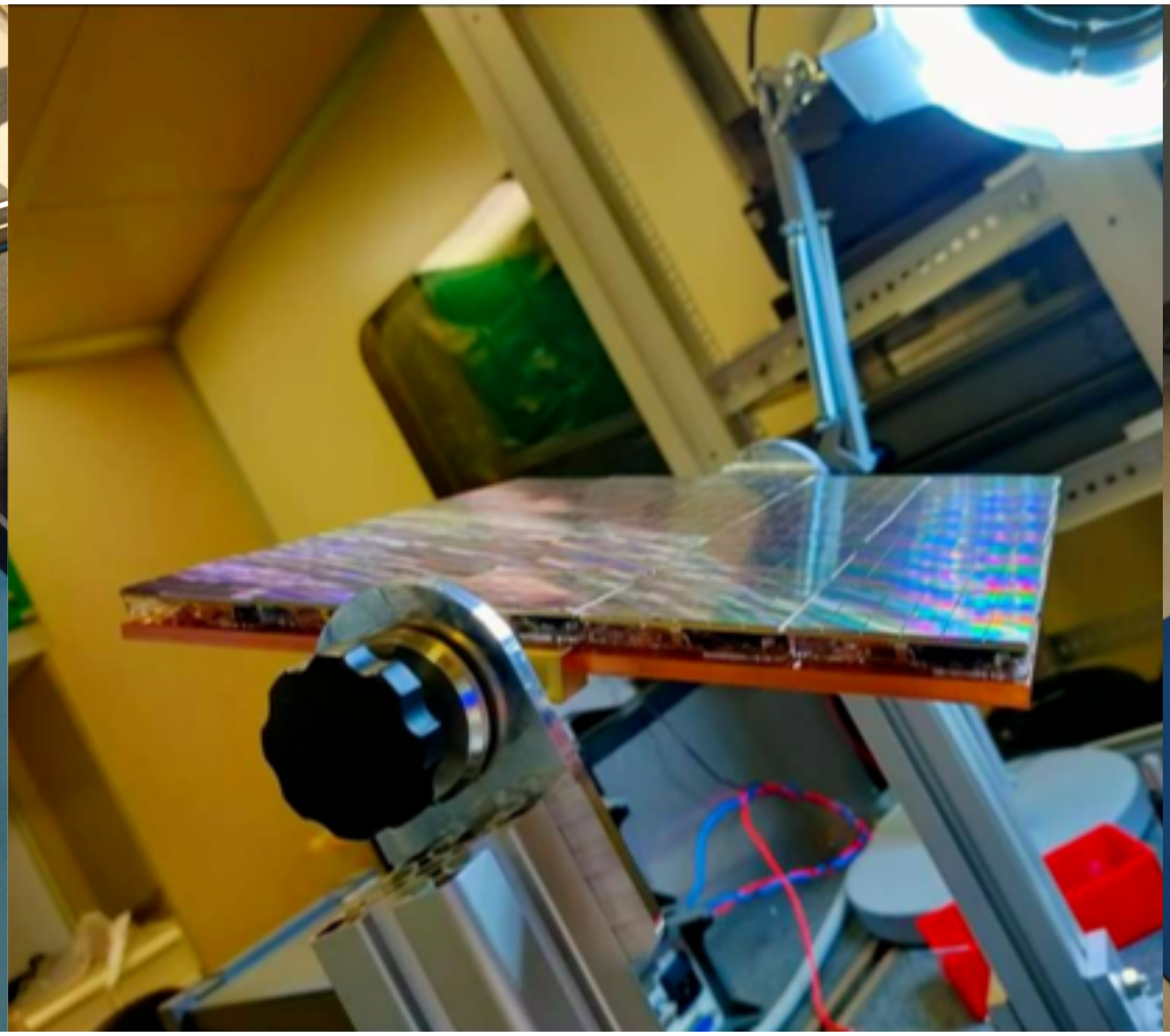


- SiPM development and readout electronics design are only the beginning of the journey!
- Wire-bonding and die-bonding procedures finalized.
- Materials and components are continuously being assayed and selected to ensure the fulfillment of radio-purity requirements.
- Final assembly to happen at the NOA packaging facility (in LNGS, Italy).

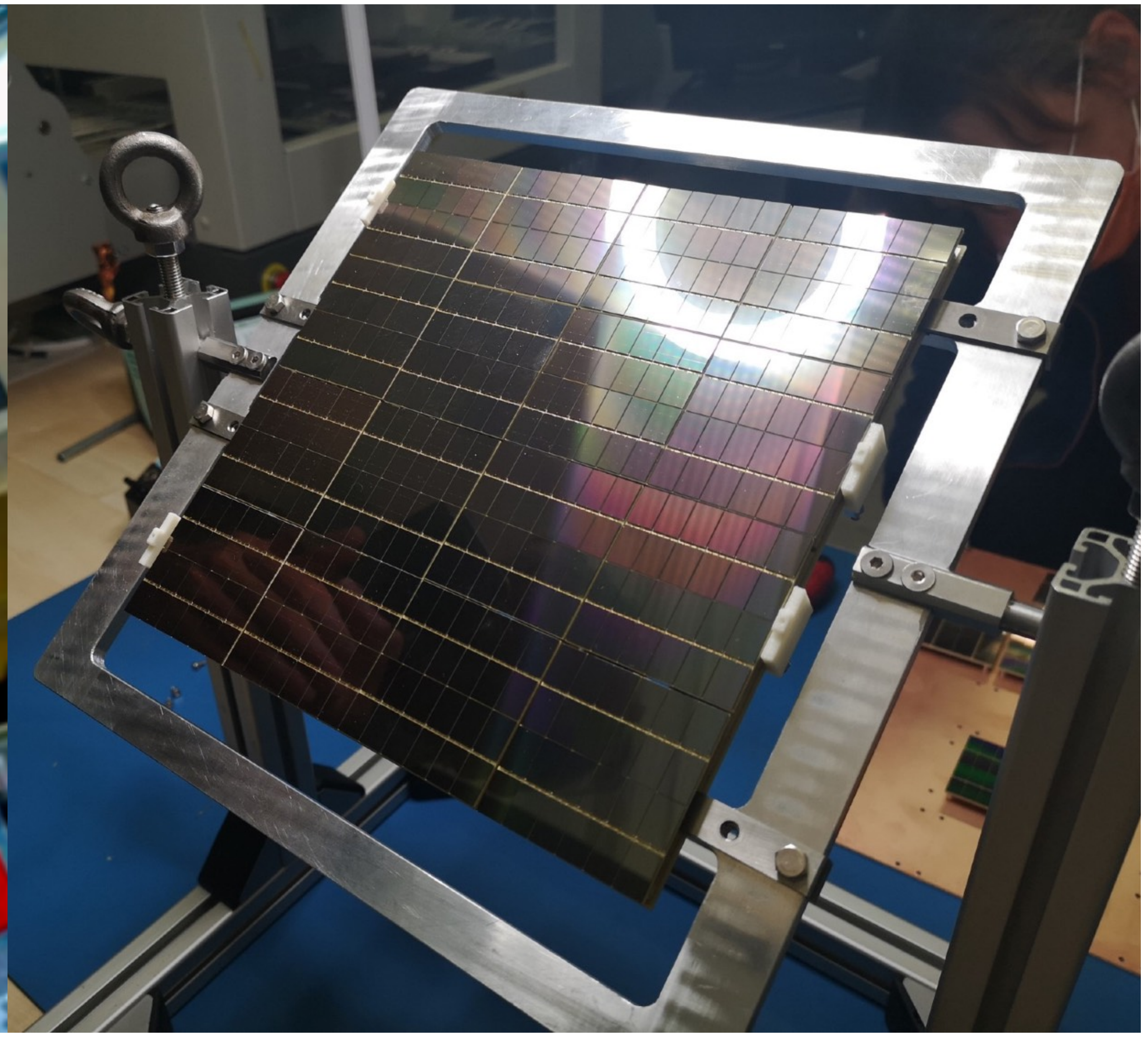
Status of photo-detection systems



First PDU prototype with 25 channels



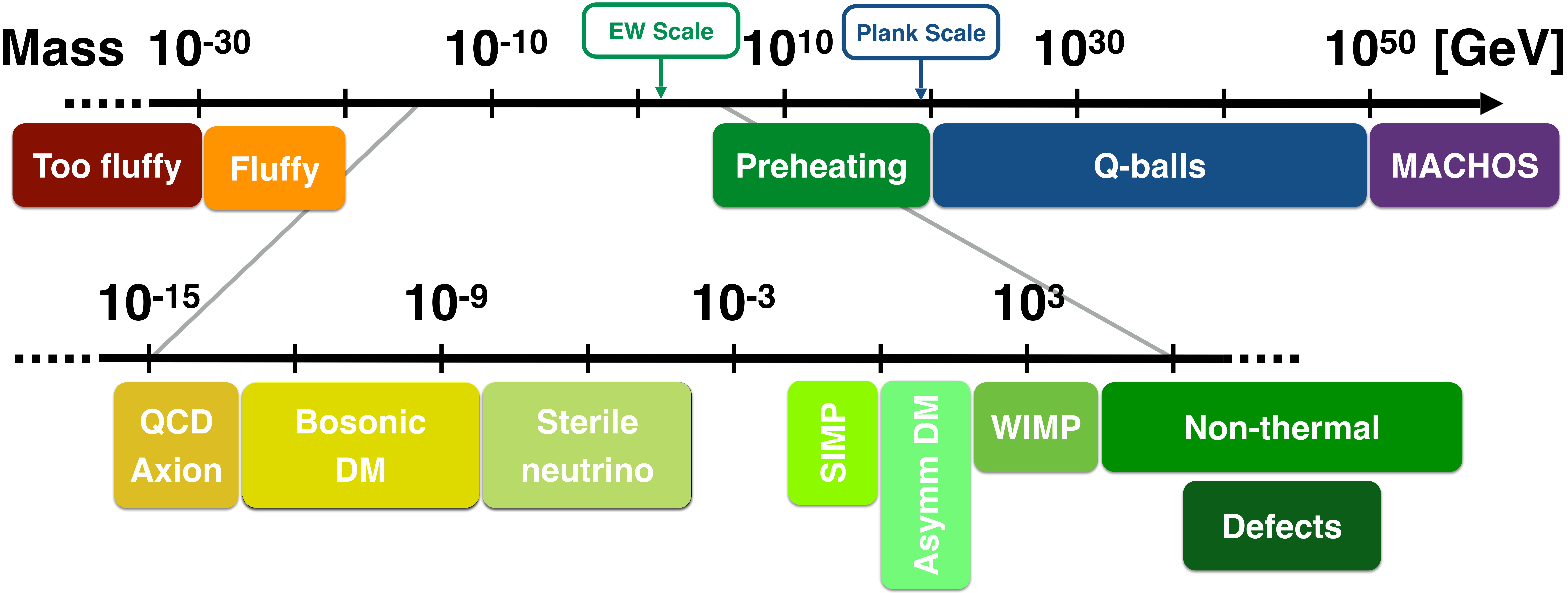
PDU with 25 channels, less material



Final PDU: 16 tiles grouped
in 4 or 8 readout channels

- Several prototypes of Photo-Detection Units (PDU) have been produced and tested in LN and LAr.
- All the requirements on gain, SiPM noises, SNR and timing resolution are met or exceeded.
- Mass production soon to start in a dedicated facility (NOA).

Where should we look?



~70 orders of magnitude and a zoo of theoretical models!