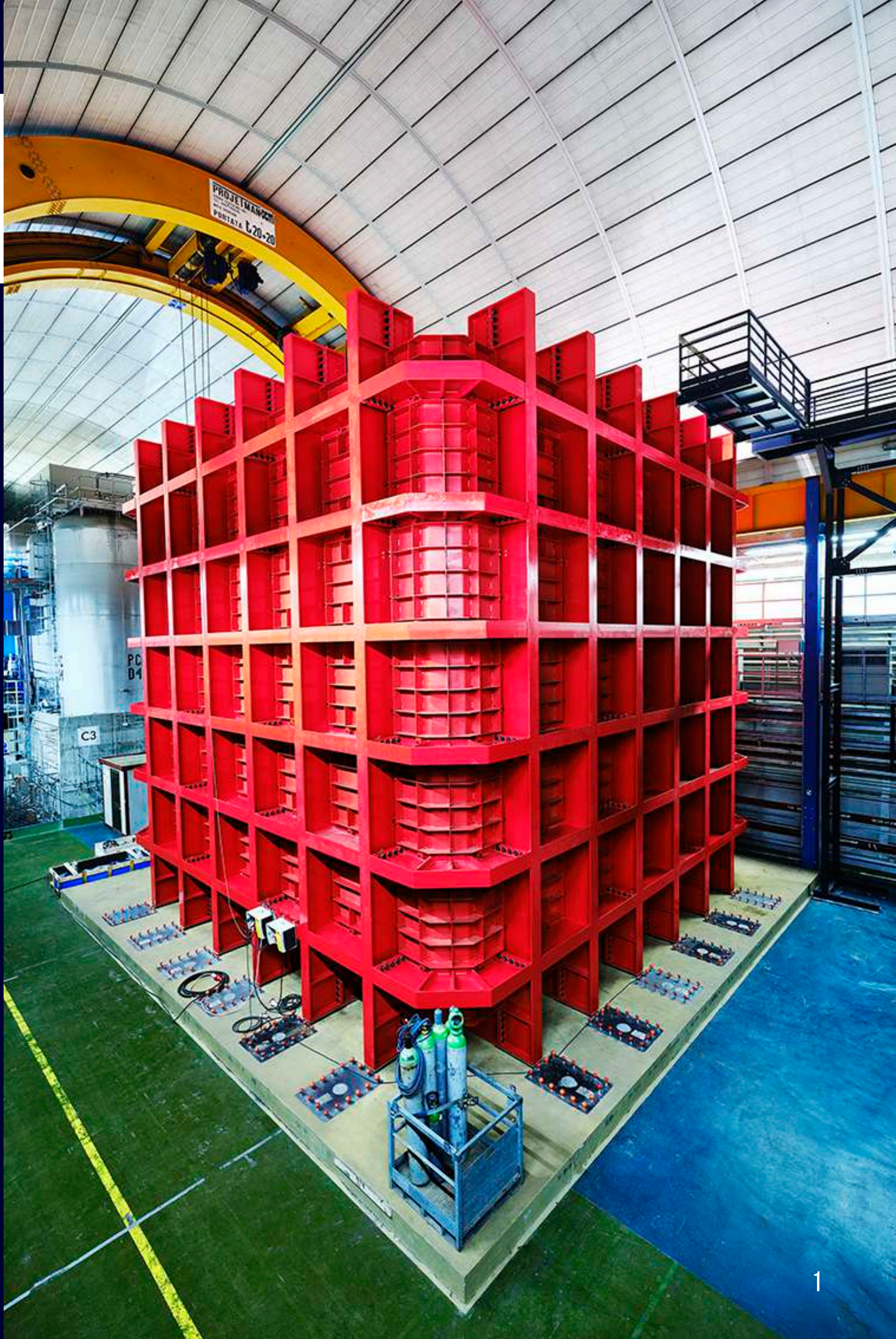
Bianca Bottino
on behalf of the DarkSide Collaboration
Genoa University and INFN Genoa

DarkSide-20k
a zoom on the cryogenic system

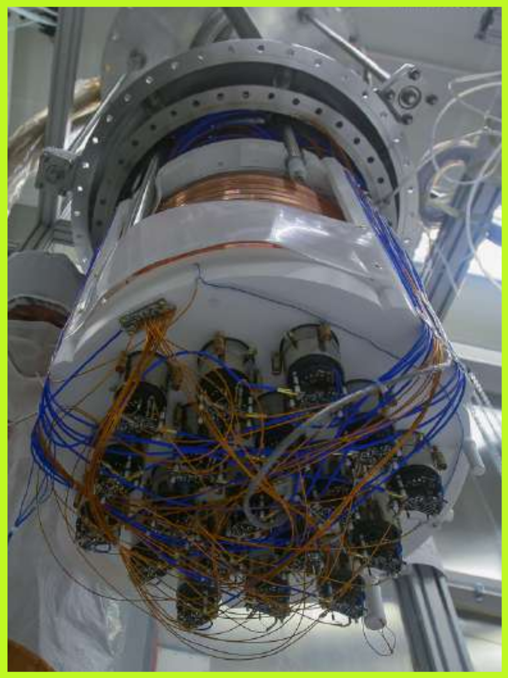
APPEC TECH FORUM VACUUM AND CRYOGENICS 2025



The DarkSide Program

DarkSide-10

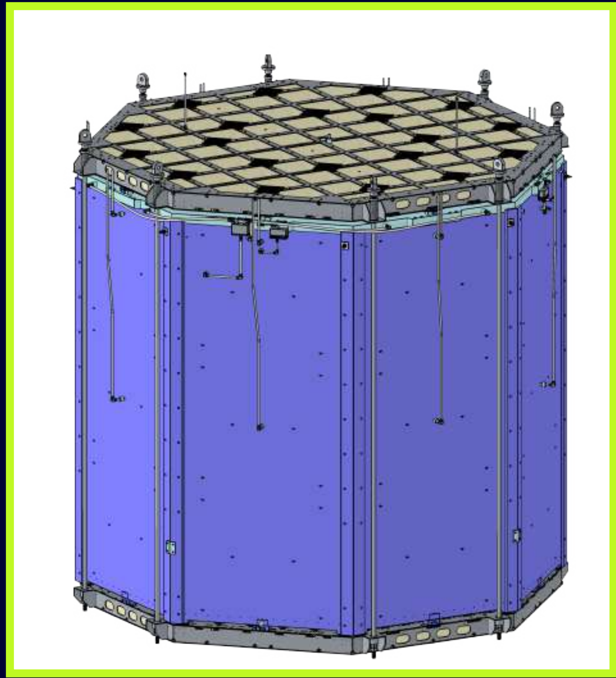
DarkSide-50



Proto-0

1 ton mockup

DarkSide-20k

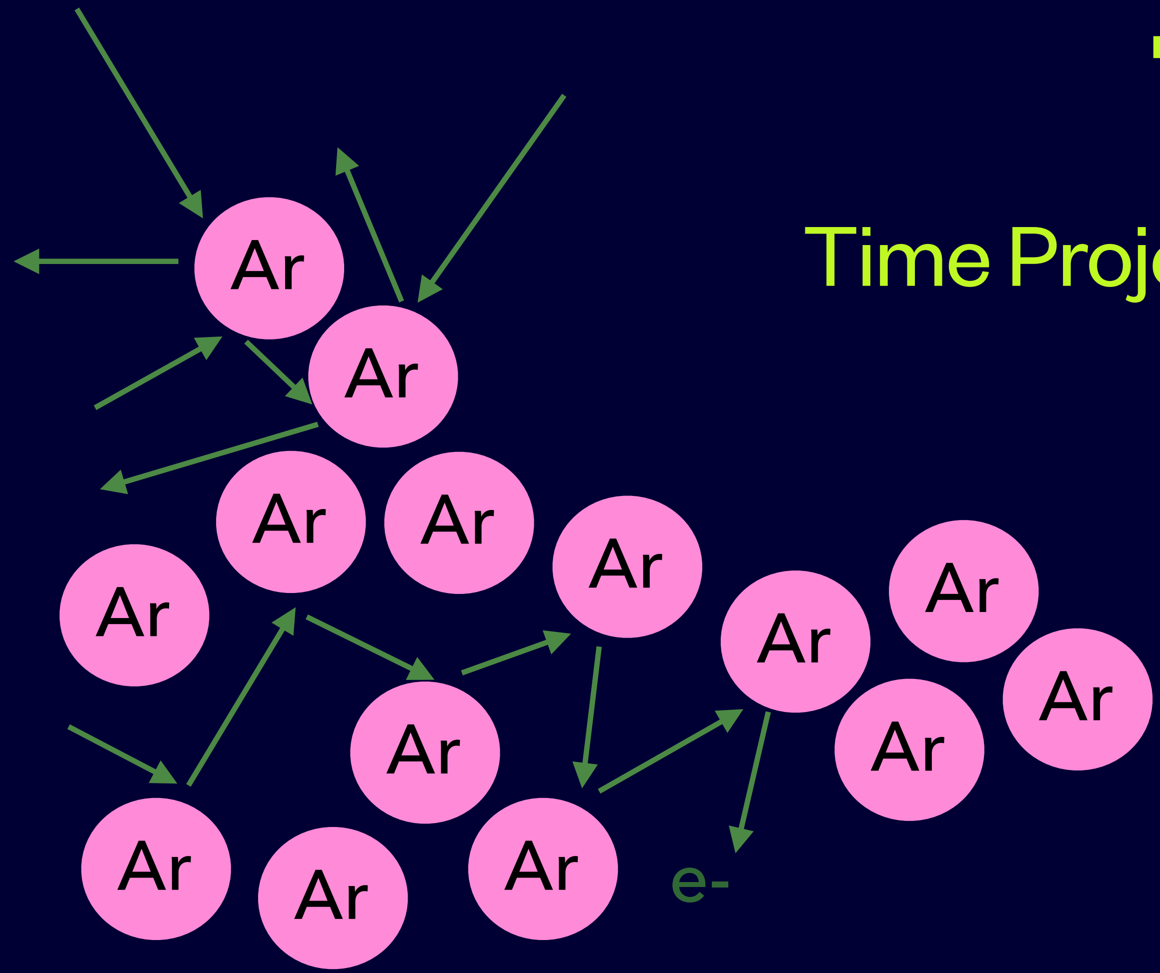


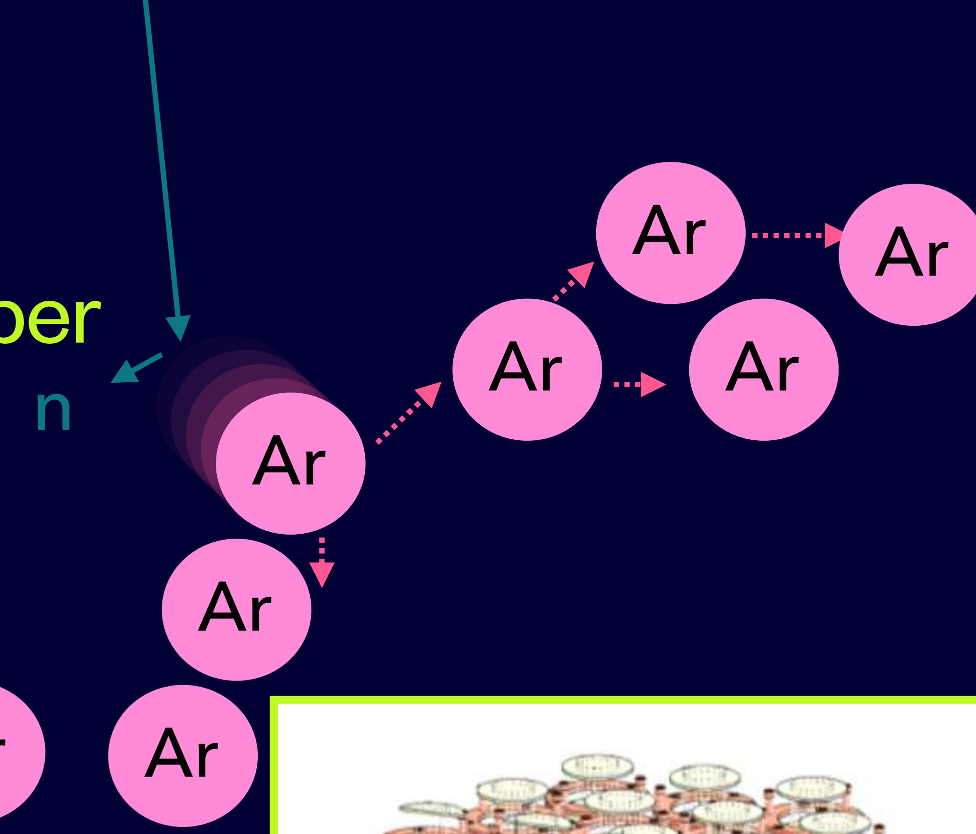
Direct detection search for **dark matter**, based on a **dual-phase argon time projection chamber** (TPC).

Design philosophy: very low background levels that can be further reduced through active suppression, for background-free operation from both neutrons and β/γ's.

TPC

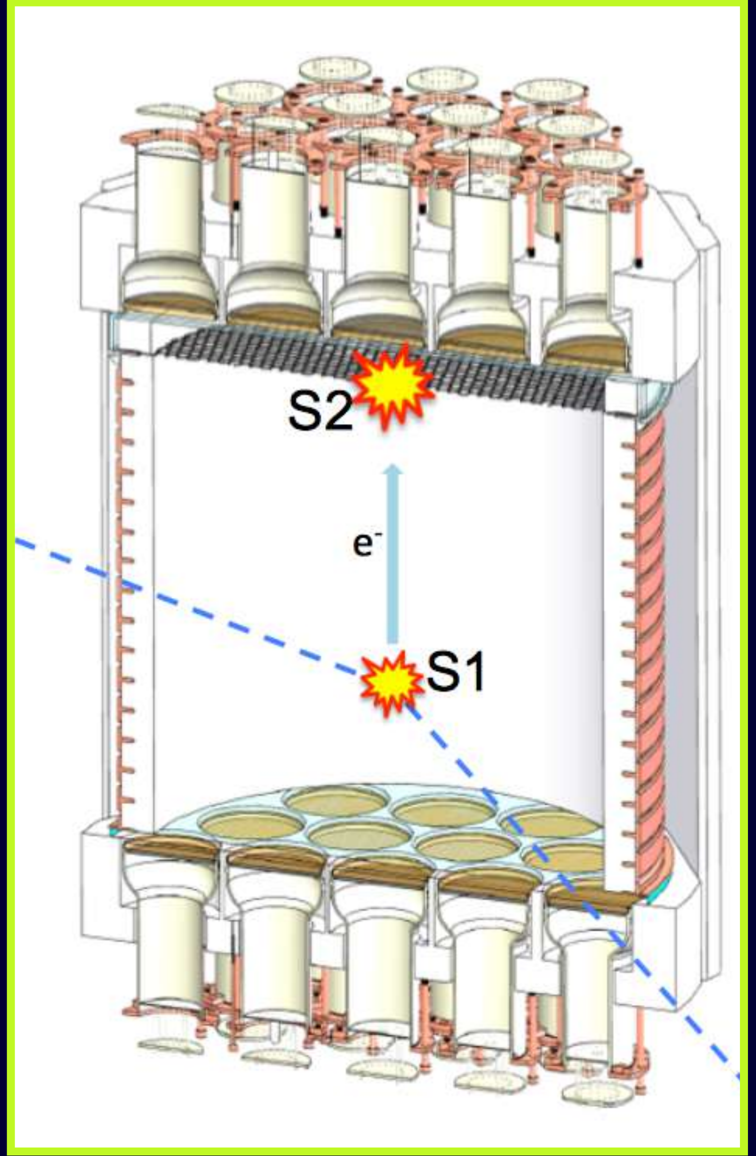
Time Projection Chamber





Detection of two signals:

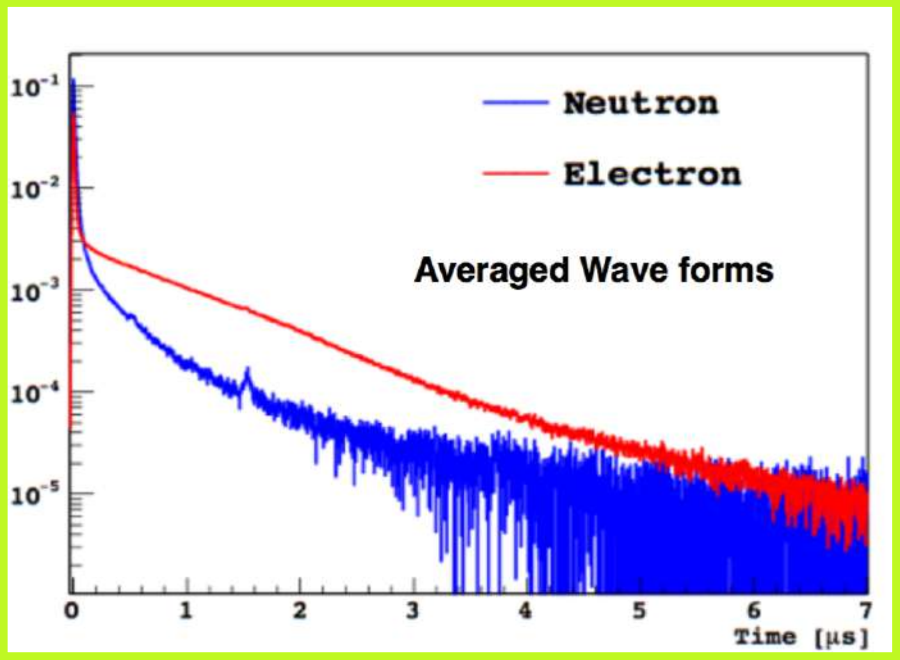
- **S1**: produced in the liquid by the **scintillation light** due to both the excited Ar atoms, and the recombined fraction of ionized atoms.
- **S2**: produced in the gas layer by the **free electrons** escaped from recombination and drifted up to the liquid surface.



Why Argon?

Argon has an exceptional **discrimination power** that opens the possibility to distinguish between nuclear and electron recoil.

PSD: Pulse Shape Discrimination



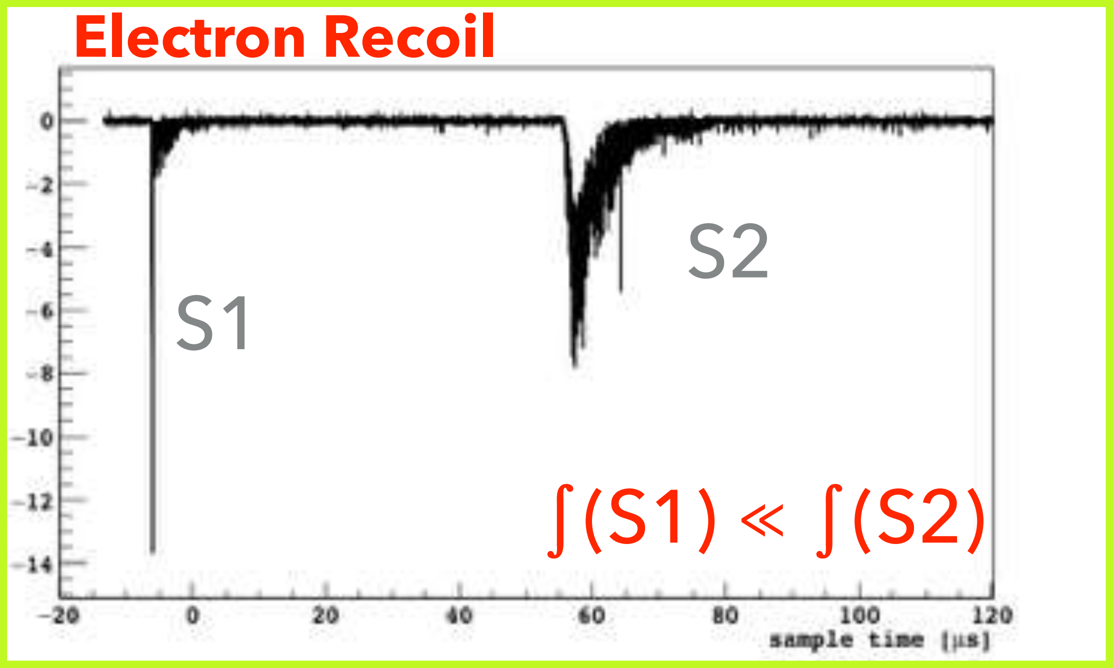
Two scintillation time constants in liquid argon: singlet (~ 6 ns) and triplet (~ 1.6 μs)

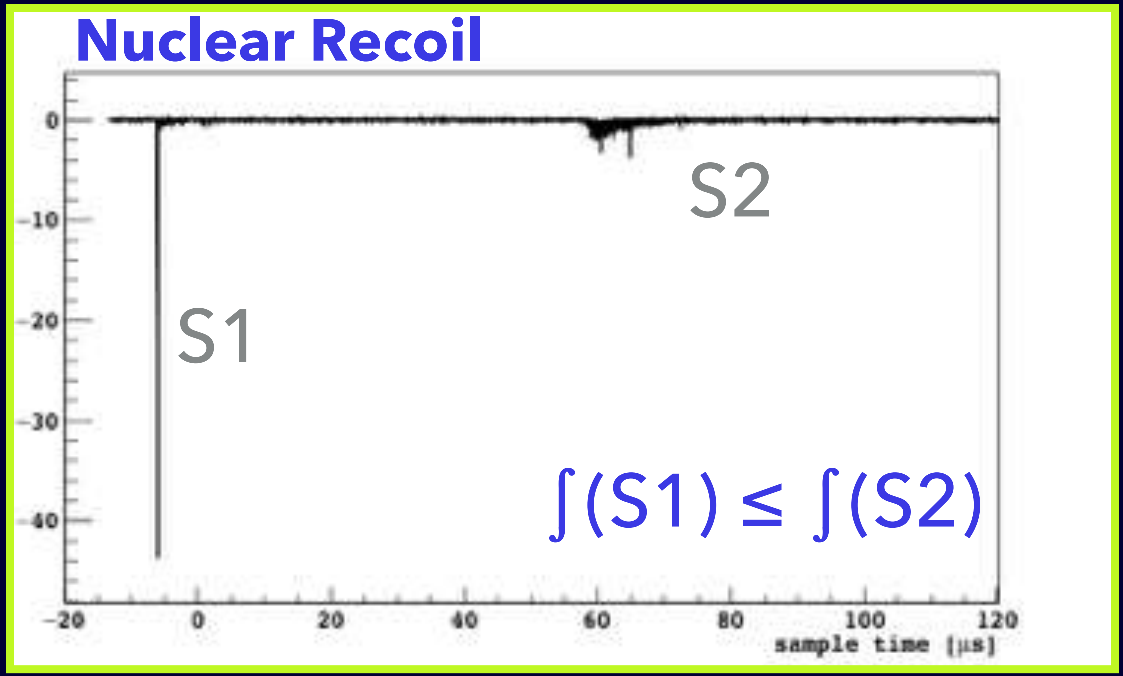
Nuclear and electron recoils have different ratios of singlet and triplet states, so their signals have a different shape in time.

$$f_{prompt} = \frac{\text{Light in the first tens of ns}}{\text{Total light}}$$

DEAP 3600 showed a suppression of ER backgrounds between 8 and 10 orders of magnitude.
Eur. Phys. J. C 81, 823 (2021)

Light (S1)/Charge (S2)





Underground Argon

PROBLEM

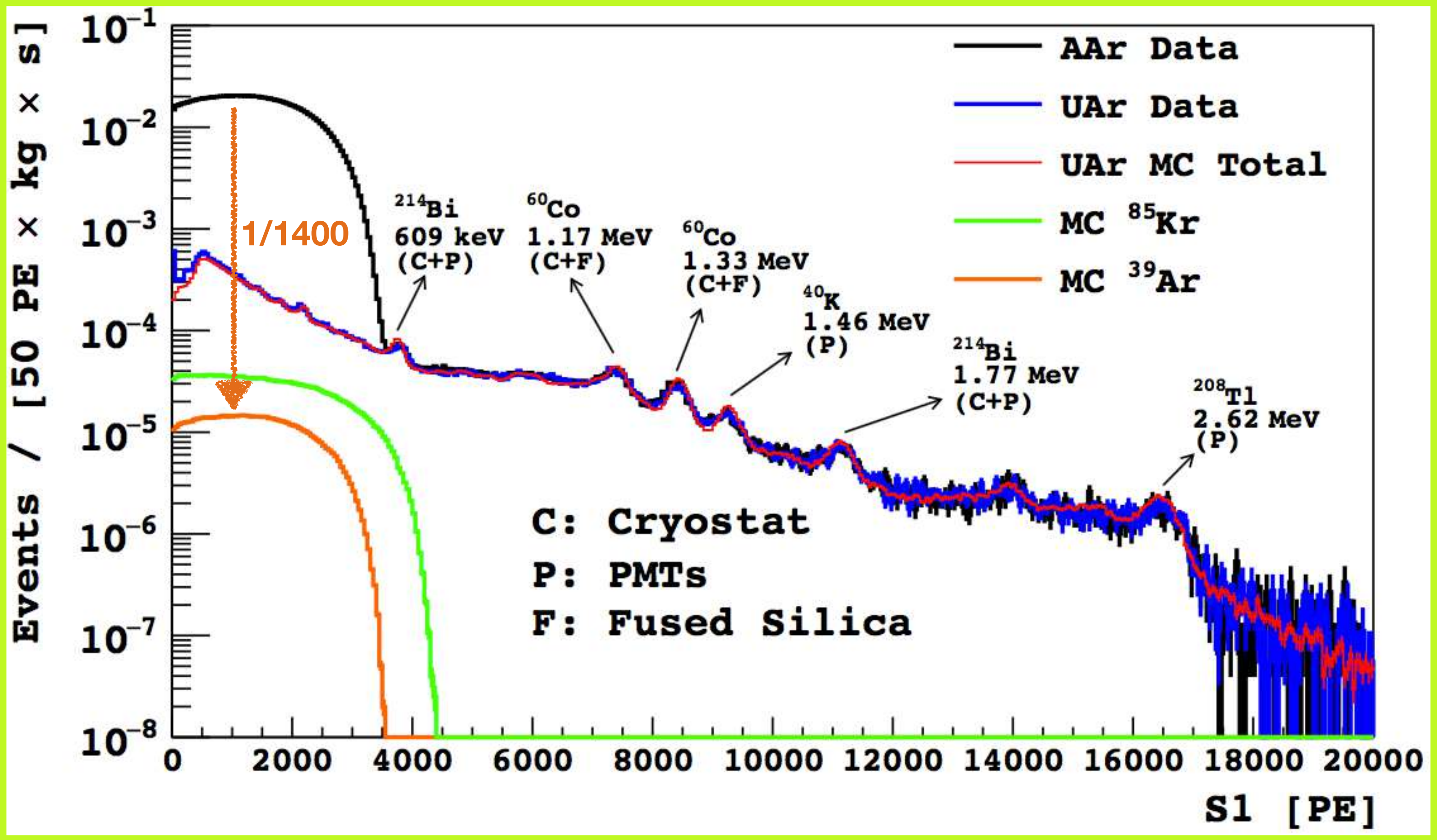
- Intrinsic ^{39}Ar radioactivity in atmospheric argon is a source of background for argon-based detectors and in particular limits the possibility of scaling up the mass of dual-phase TPCs;
- ^{39}Ar, produced by cosmogenic activation emits β with τ=269 years and Q-value=565 keV;
- ^{39}Ar activity sets the dark matter detection threshold at low energies (where pulse shape discrimination is less effective).

SOLUTION

Use underground Argon (UAr), extracted from deep sources.

The ^{39}Ar content is **1400 times less than in atmospheric argon**, as proved by DarkSide-50.

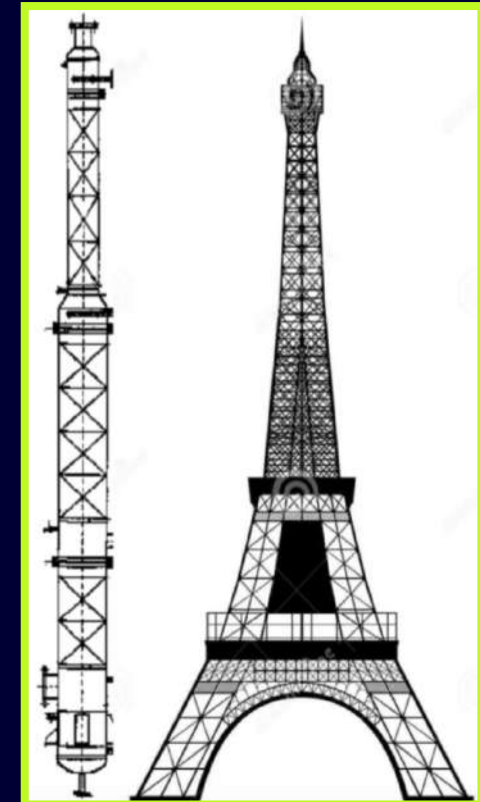
Physical Review D 93 (8), 081101 (2016)

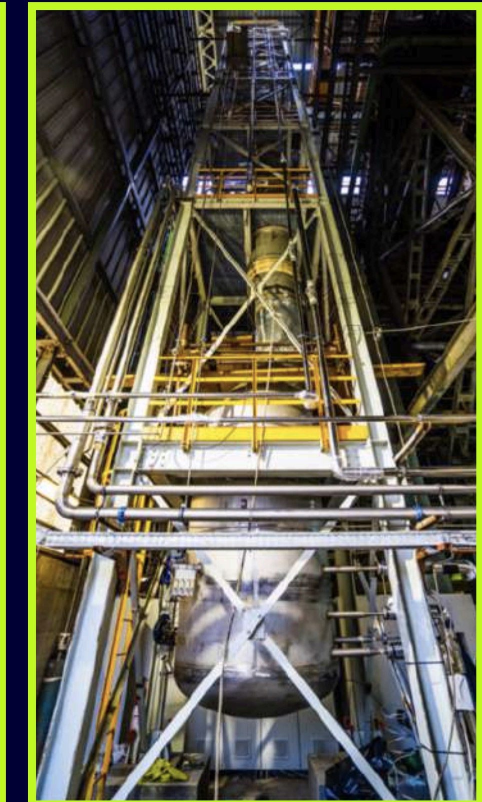


How to get UAr?

Urania - Argon extraction and purification plant in Cortez, Colorado. Capable to provide 250 kg/d of UAr with a 99.99% purity.

DArT - Characterized @ Canfranc with a dedicated detector to measure the ^{39}Ar depletion factor

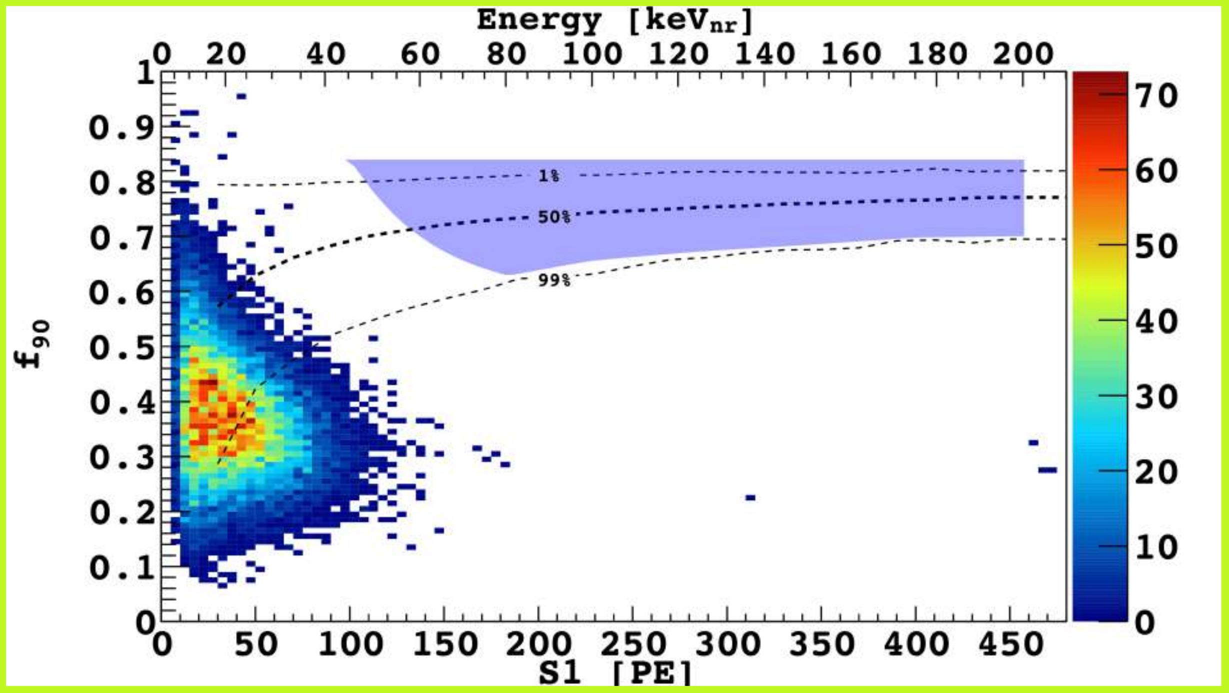




Aria - Further purification in Seruci, Sardinia, Italy. Capable of chemical purification using a 350 m cryogenic distillation column. Target purity 99.999%

Expected sensitivity

DarkSide-50 results - obtained combining the use of UAr, the pulse shape discrimination and the cuts based on S2/S1 - show the separation between backgrounds and the dark matter search region.



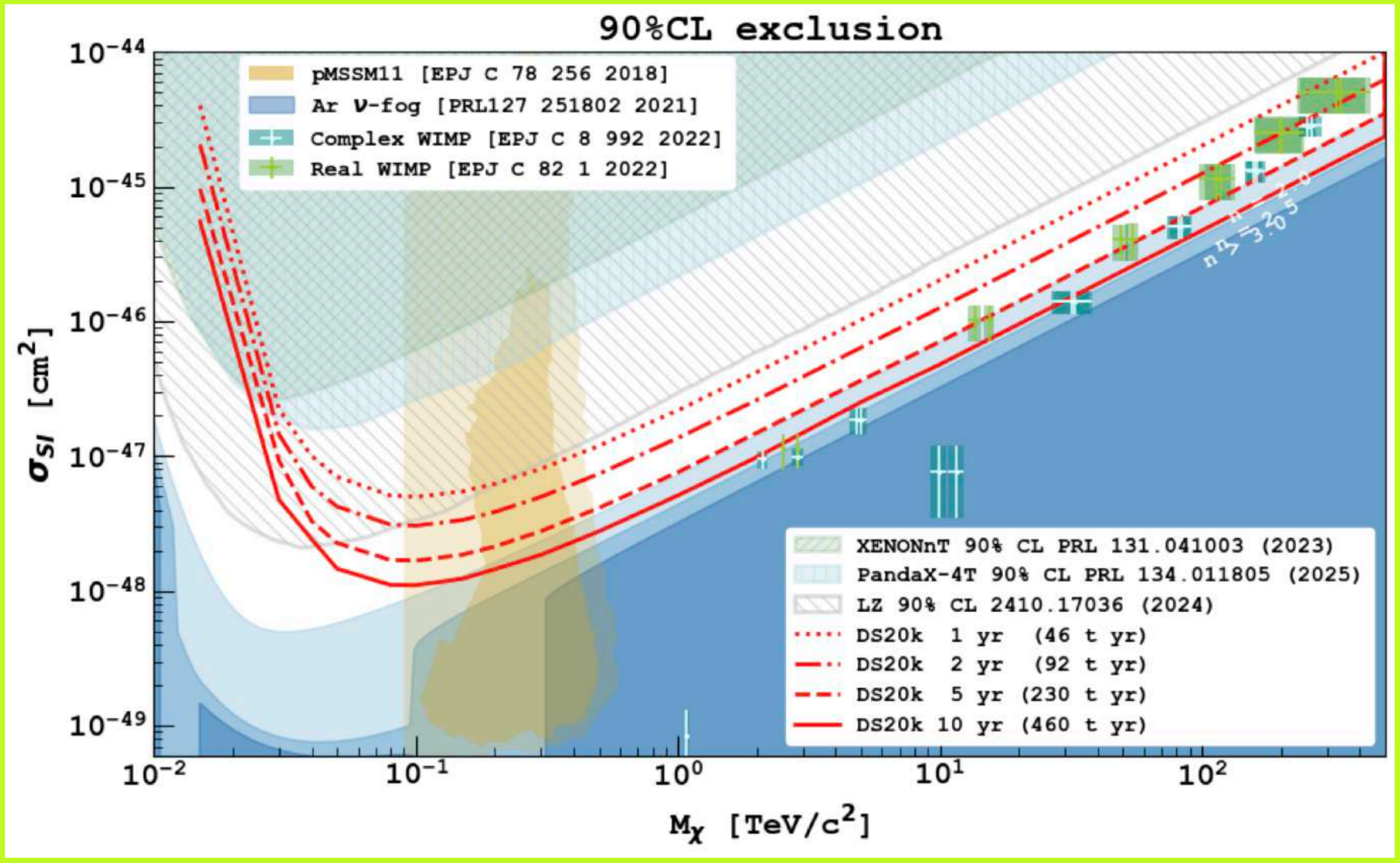
Physical Review D 98 (10), 102006 (2018)

DarkSide-20k sensitivity to Spin-Independent interactions

With the nominal exposure of 200 ton y):

- 90% C.L. exclusion: 6.3×10^{-48} cm^2 @1 TeV/c^2 ;
- 3 σ evidence: 2.1×10^{-47} cm^2 @1 TeV/c^2 ;
- ~3.5 CEvNS events expected.

Aimed instrumental background: < 0.1 neutrons in Region of Interest (E ~ 30 –200 keV$_{nr}$)

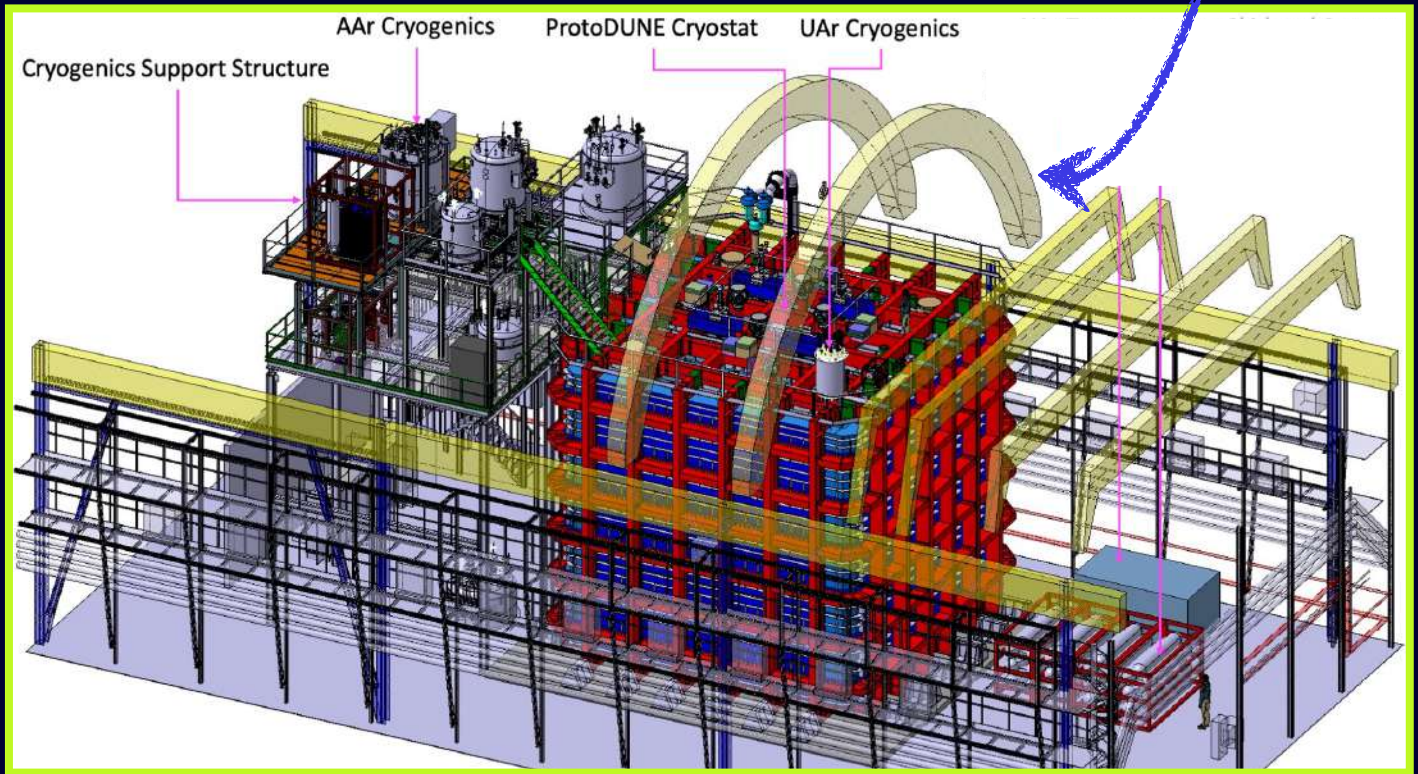


DarkSide-20k

Abruzzo, Italy

Gran Sasso Underground
National Laboratories

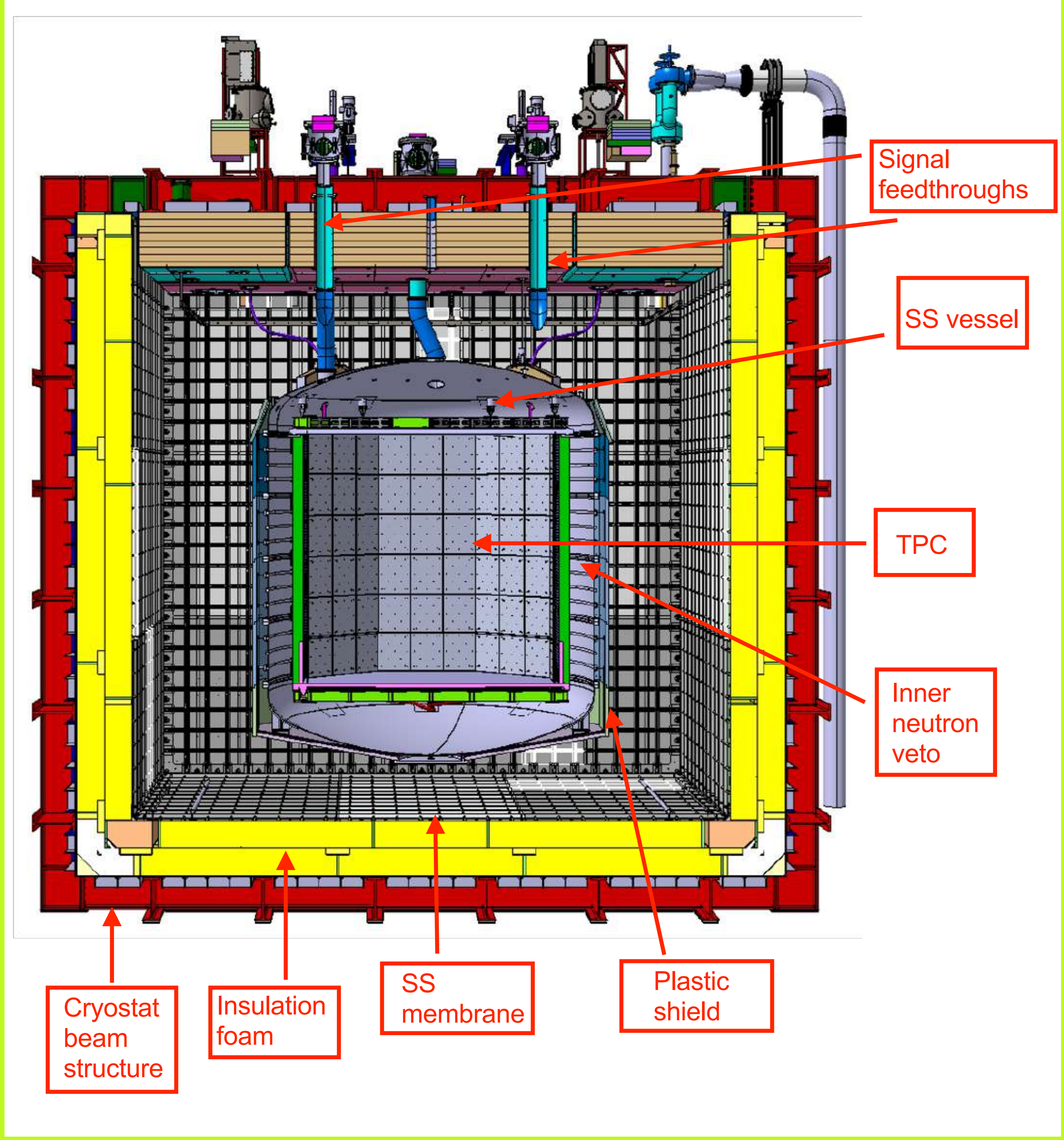
Hall C



DarkSide-20k detector

The detector has a nested structure:

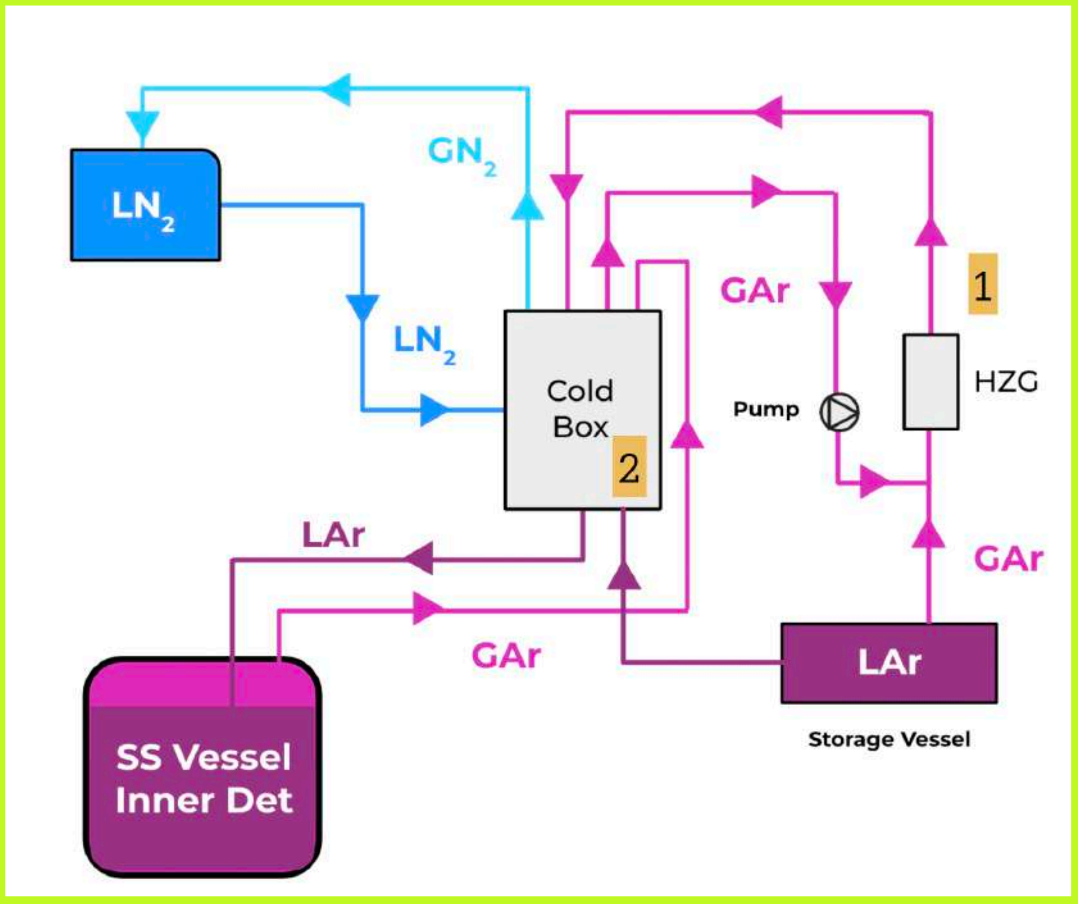
- The innermost part is an octagonal **ultra pure acrylic TPC** integrated with the **inner neutron veto**;
- TPC and neutron veto are enclosed in a **SS vessel**, filled with ~100 t of UAr;
- TPC and veto signals are read with low-background, cryogenic photosensors based on silicon photomultipliers (SiPMs).
- The SS vessel is surrounded by ~5 cm of plastic shielding needed to moderate n from the membrane cryostat and the Hall C walls;
- A **membrane cryostat** like the ProtoDune one will be filled with AAr and will contain the outer muon veto.



Two cryogenic systems for two Ar flavours

Underground Argon (UAr)

Argon Liquefaction: 8kW of cooling power required and satisfied with a high-efficiency custom-made heat exchange mechanism with liquid nitrogen.
Gas recirculation: equipped with purification and Radon trap



Atmospheric Argon (AAr)

Proximity cryogenics system includes eight cryogenic valve boxes and one warm valve box, each equipped for a specific function (argon purification, argon condensing, argon phase separation, radon trap, and argon/nitrogen distribution).

Overview AAr

- The system is basically an industrial plant, derived from the ProtoDUNE one, that will recirculate and purify continuously commercial 6.0 Argon.
- Cryogenic fluid handling system is composed of 9 valve boxes, 16 cold + 18 warm transfer lines, and two warm skids.
- It’s a complex engineering system stemming from broad functional analysis and previous experience (ProtoDUNE), based on:
    - Requirements (purity, thermodynamic, safety)
    - Constraints (operational modes, mechanical performance, compliance with standards, etc.)

AAr system requirements

Purity requirements

- Contamination levels: ^{222}Rn < 0.01 Bq/kg; N_2 < 1 ppm; O_2 < 0.1 ppm; H_2O < 0.1 ppm
- Recirculation rate : 600 ton / 4 days
- Purification system with liquid filter VB, 2 gas filters VB, each with 3 internal filters

Thermodynamic stability

- Minimal heat load into cryostat
- Stable pressure and temperature inside the cryostat
- Uniform temperature across cryostat (< 1 K)

Operational modes

- Piston purge (gas Argon)
- Cool-down and filling (liquid Argon)
- Steady-state (cooling, recirculation, filtering, etc.)
- Emptying

Elements of the system

Pumps

Mechanical filter

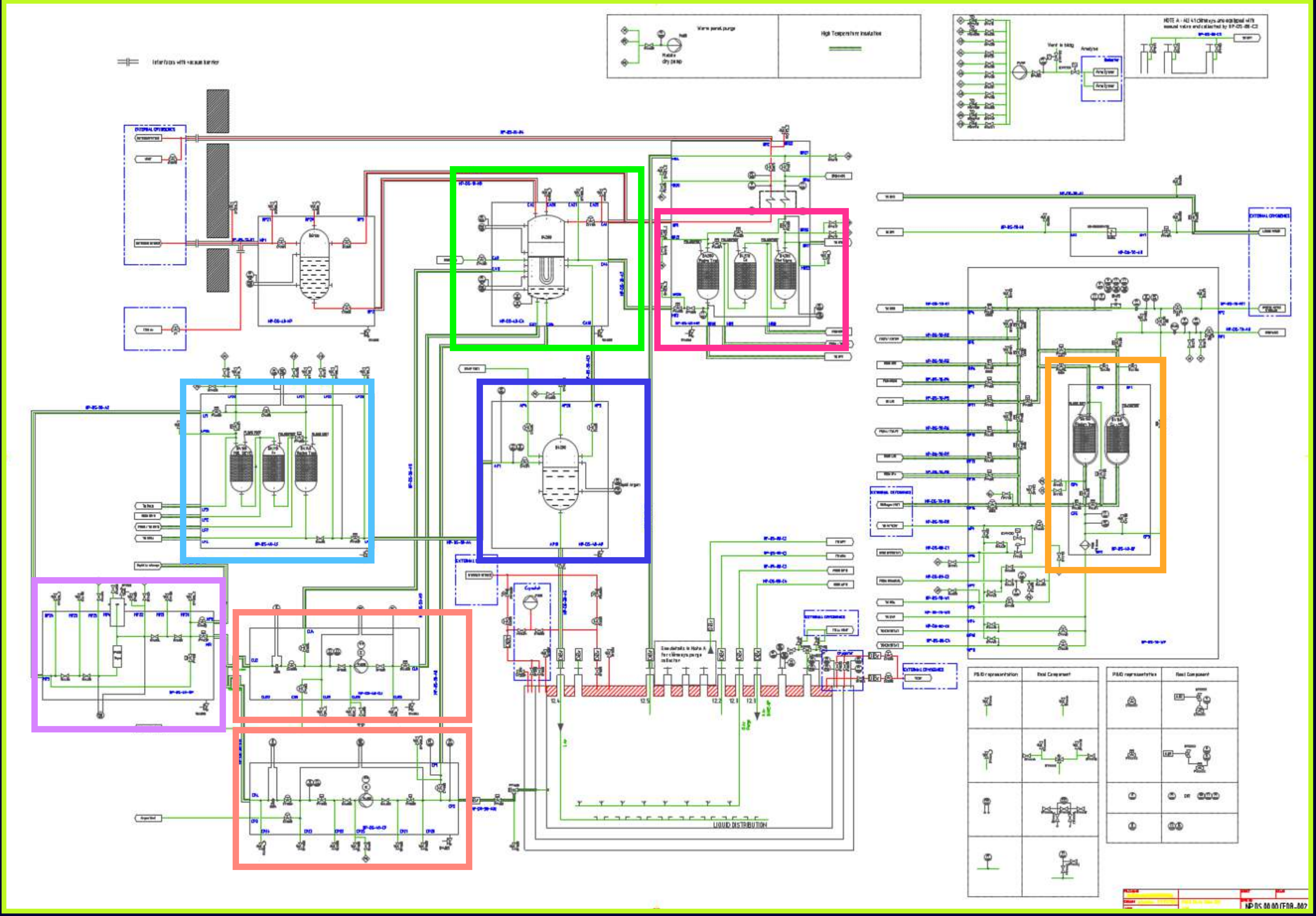
Liquid filter

Ar phase separator

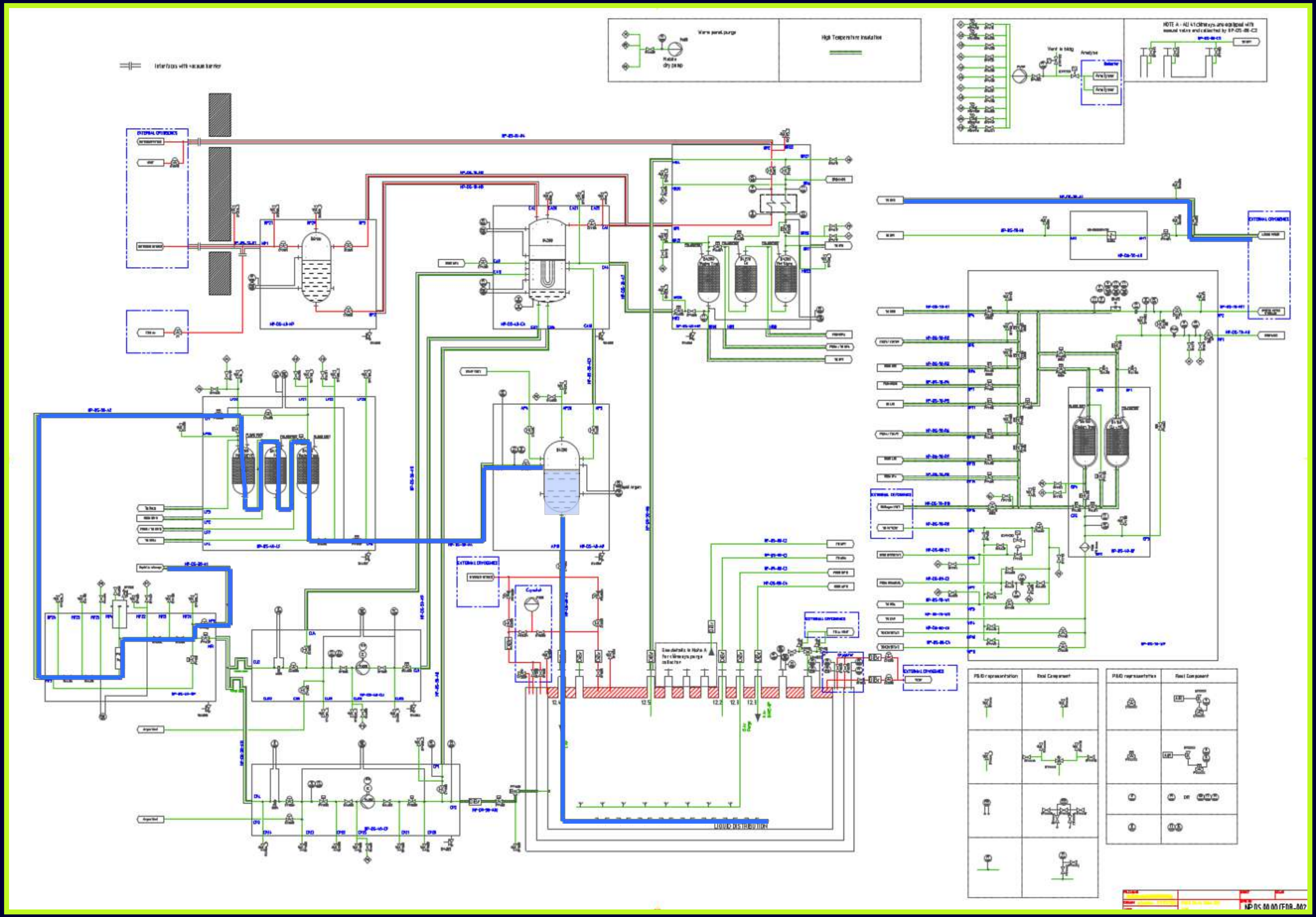
Condenser

Cold gas filter

Warm gas filter



Working modes - cool down and filling

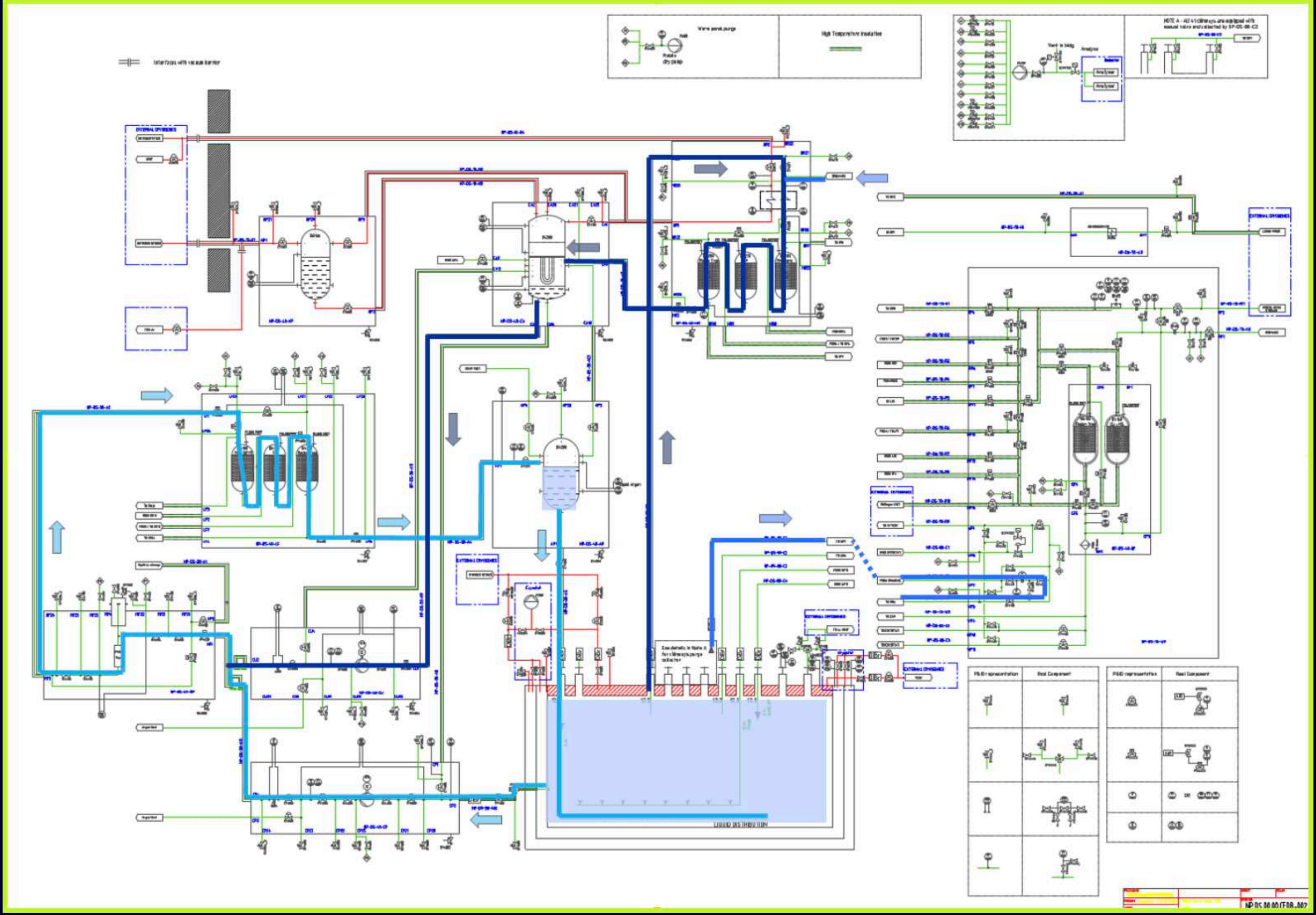


Working modes - normal mode

Liquid recirculation

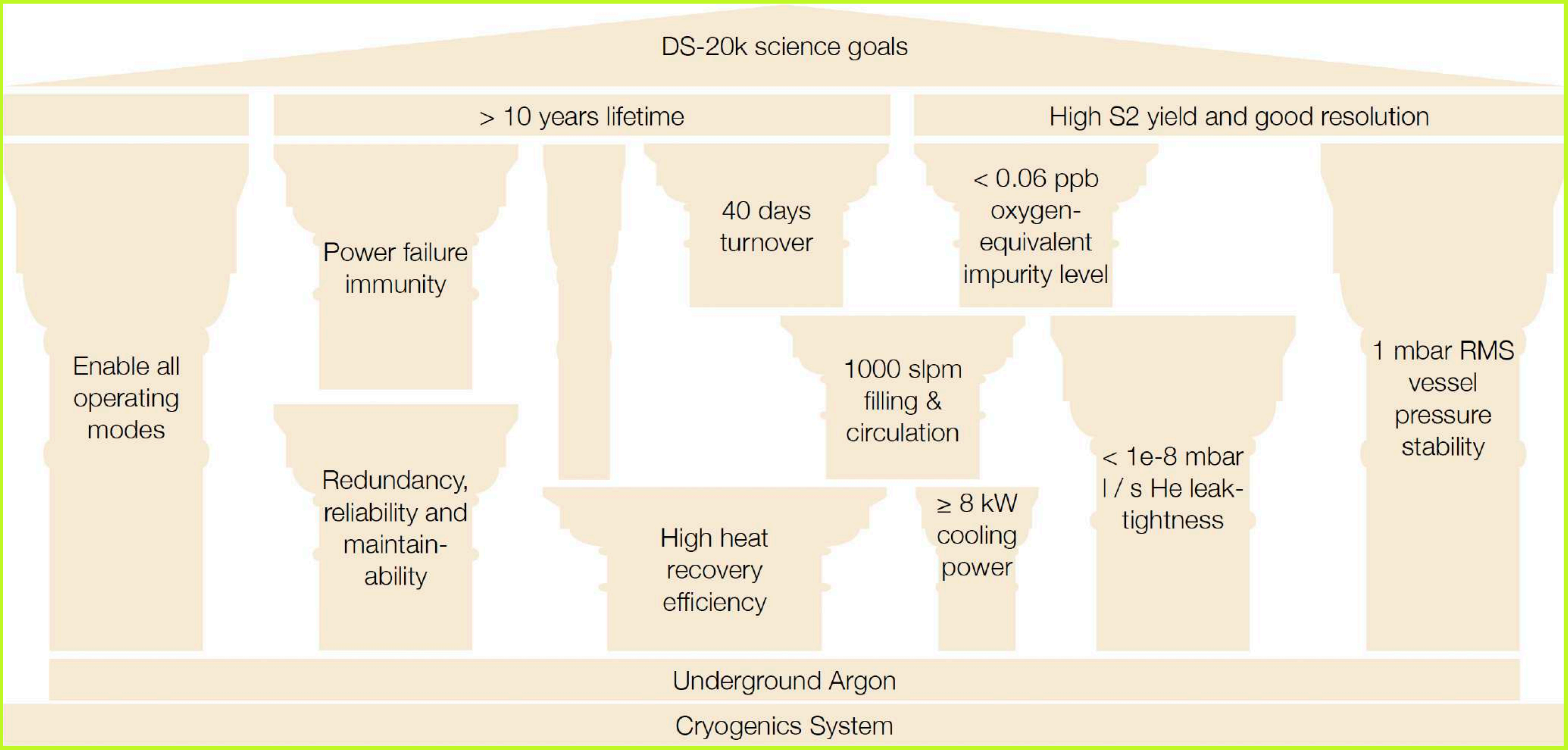
Chimney gas recirculation

Boil off recovery and recondensation



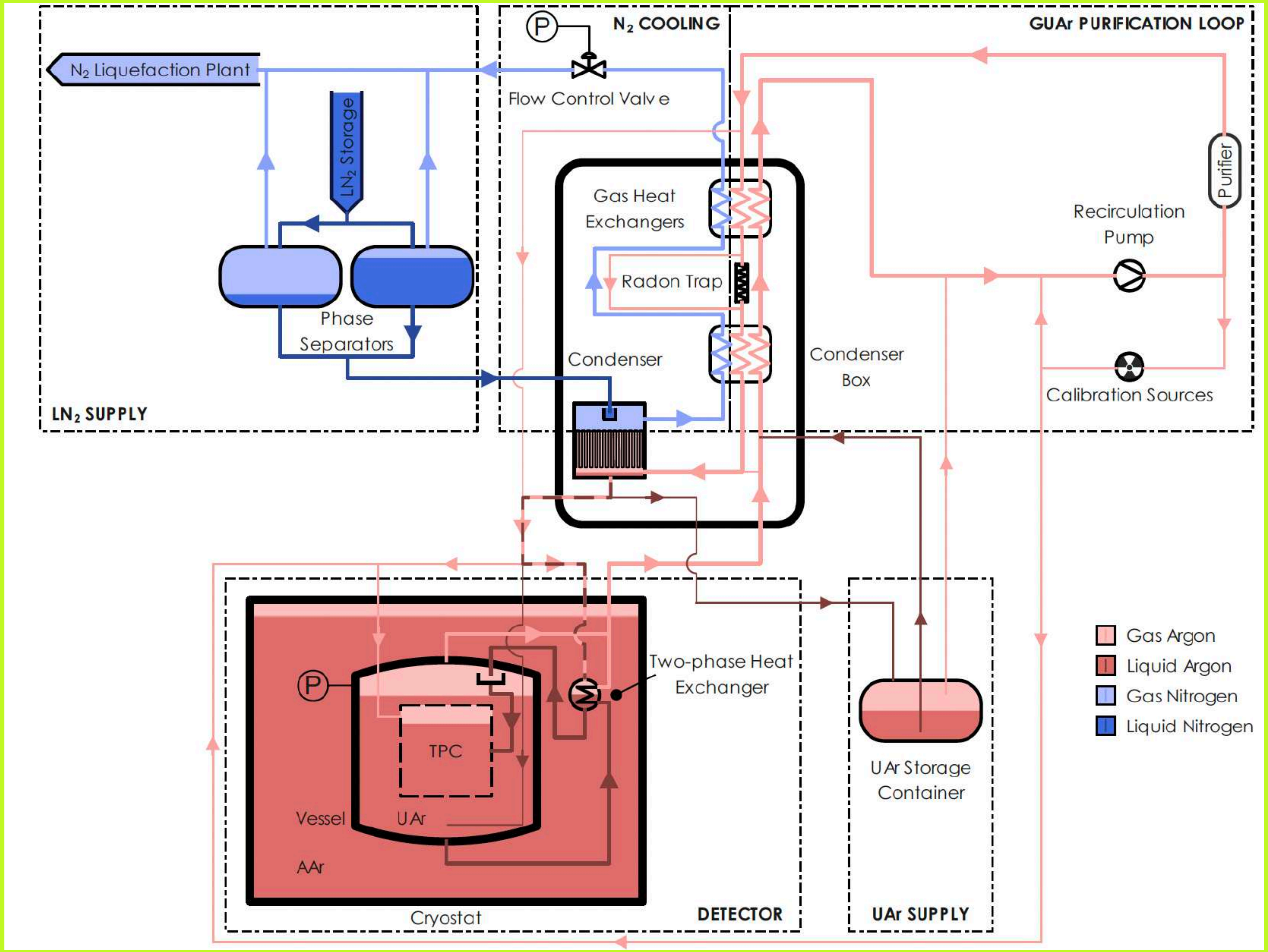
Status of the construction

UAr system requirements



Credits to Kevin Thieme

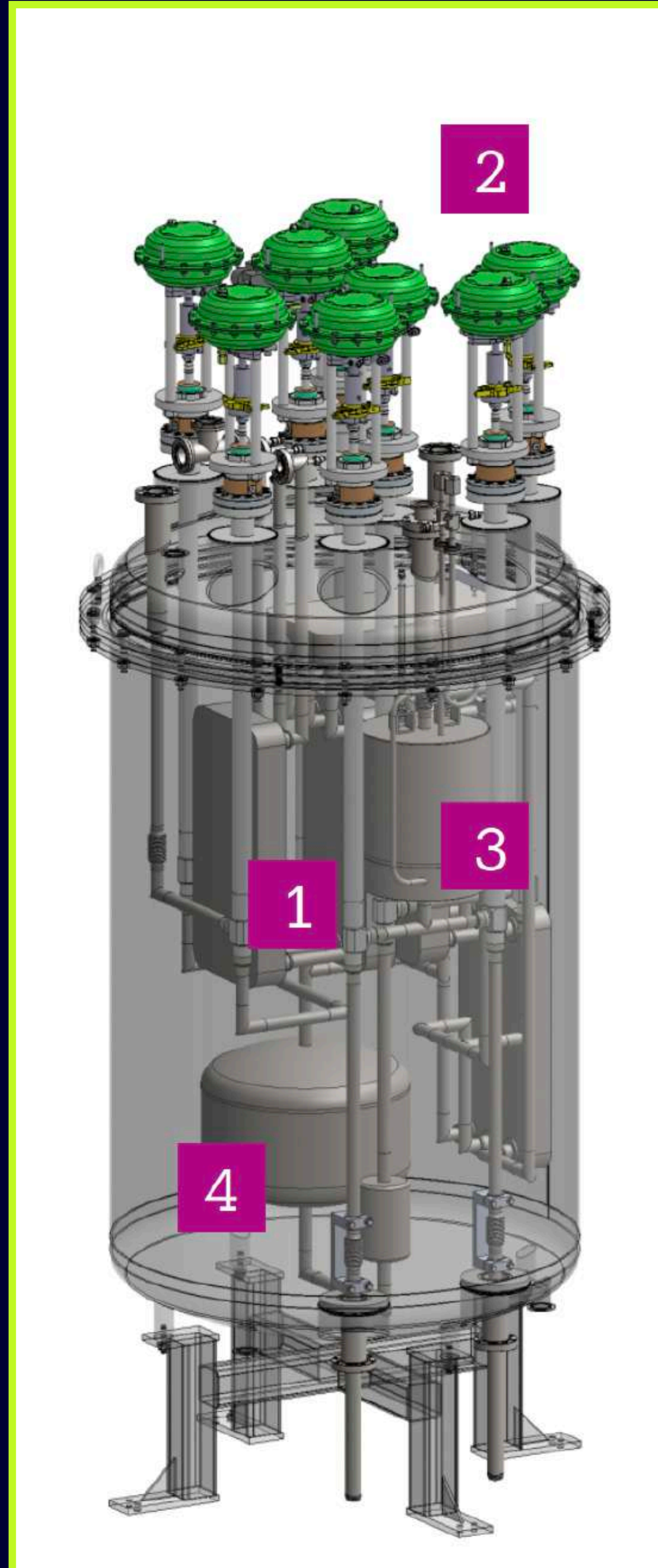
Conceptual design

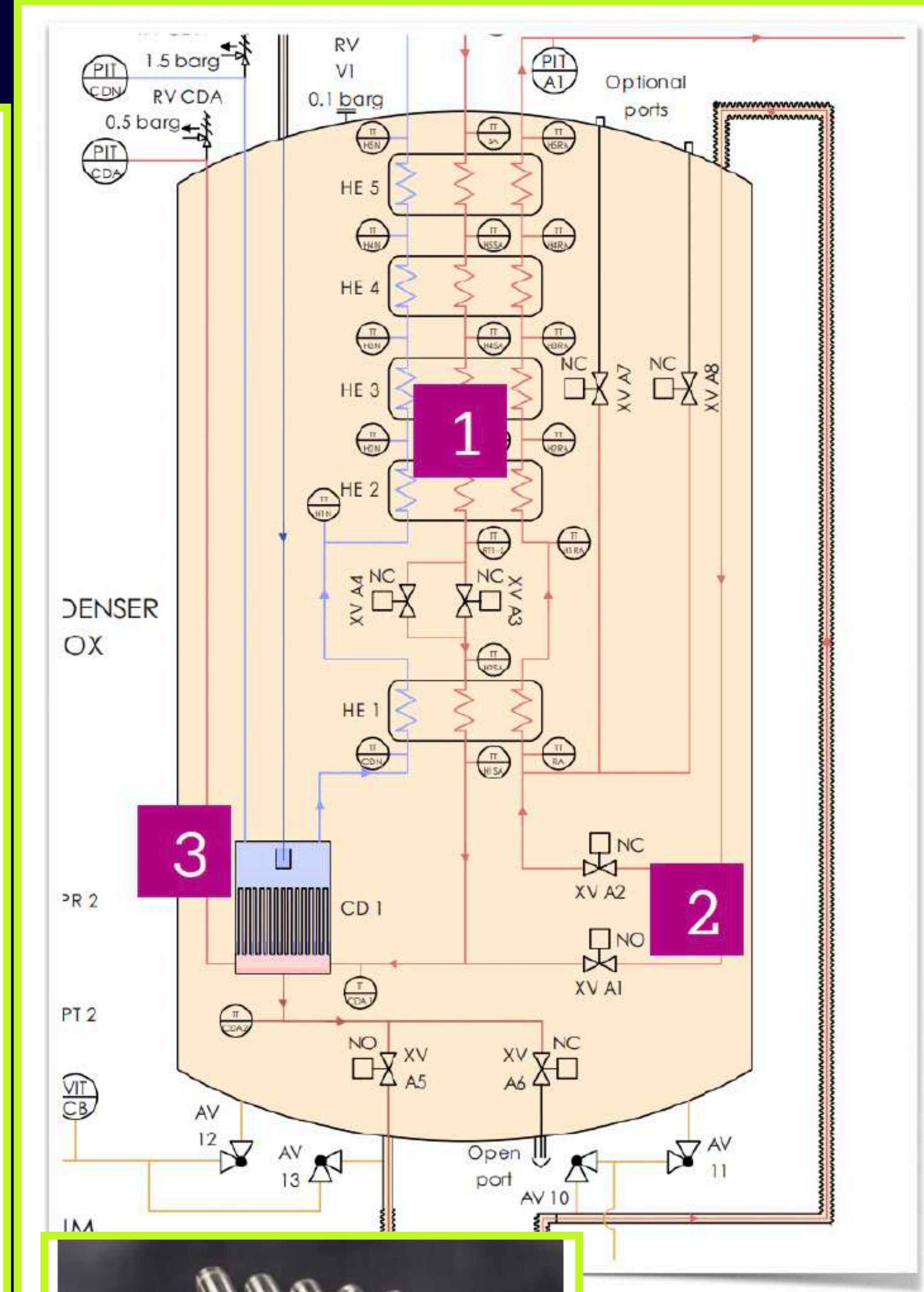


Many of the system's core components have already been built and assembled in a 1-ton mockup at the Gran Sasso National Laboratories. Since 2023, the system has been tested under various conditions, and the results are presented in [F. Acerbi et al 2025 JINST 20 P02016].

Condenser box

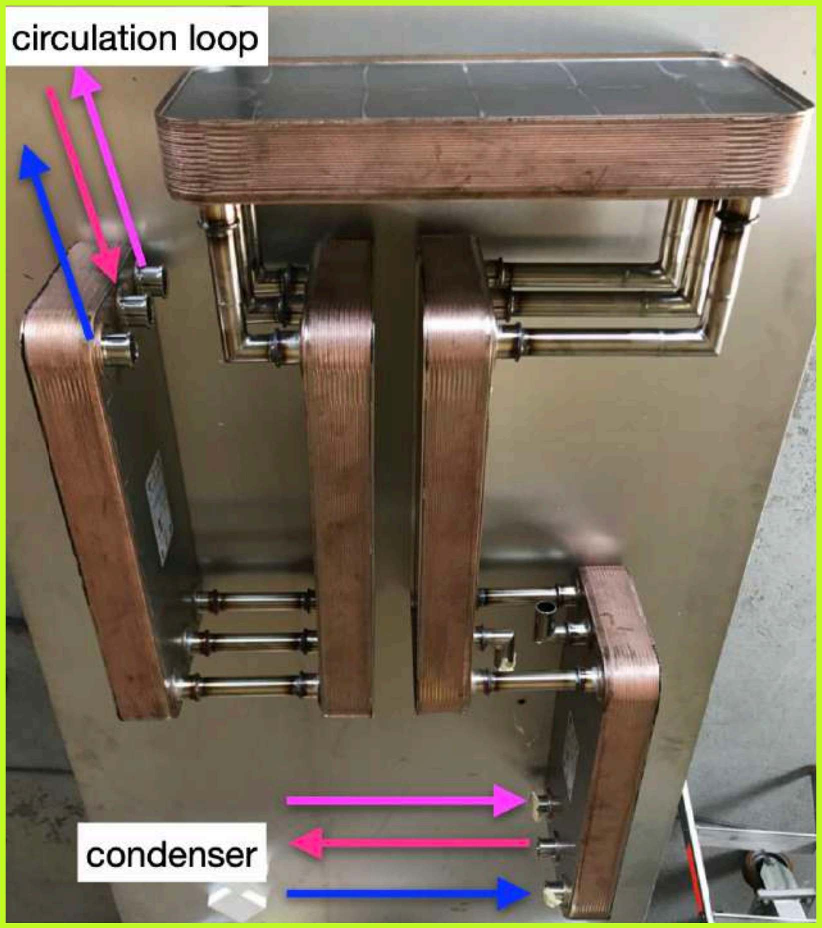
- 5 dual-circuit plate heat exchangers
- 8 pneumatically-actuated cryogenic valves
- Tube condenser with “chicken feeder” mechanism
- Radon trap (not installed for tests, in construction phase at Columbia University)
- 8 kW total* cooling power at 1000 slpm of GN2 flow, considering latent heat in the condenser and gas enthalpy in gas-gas heat exchangers.



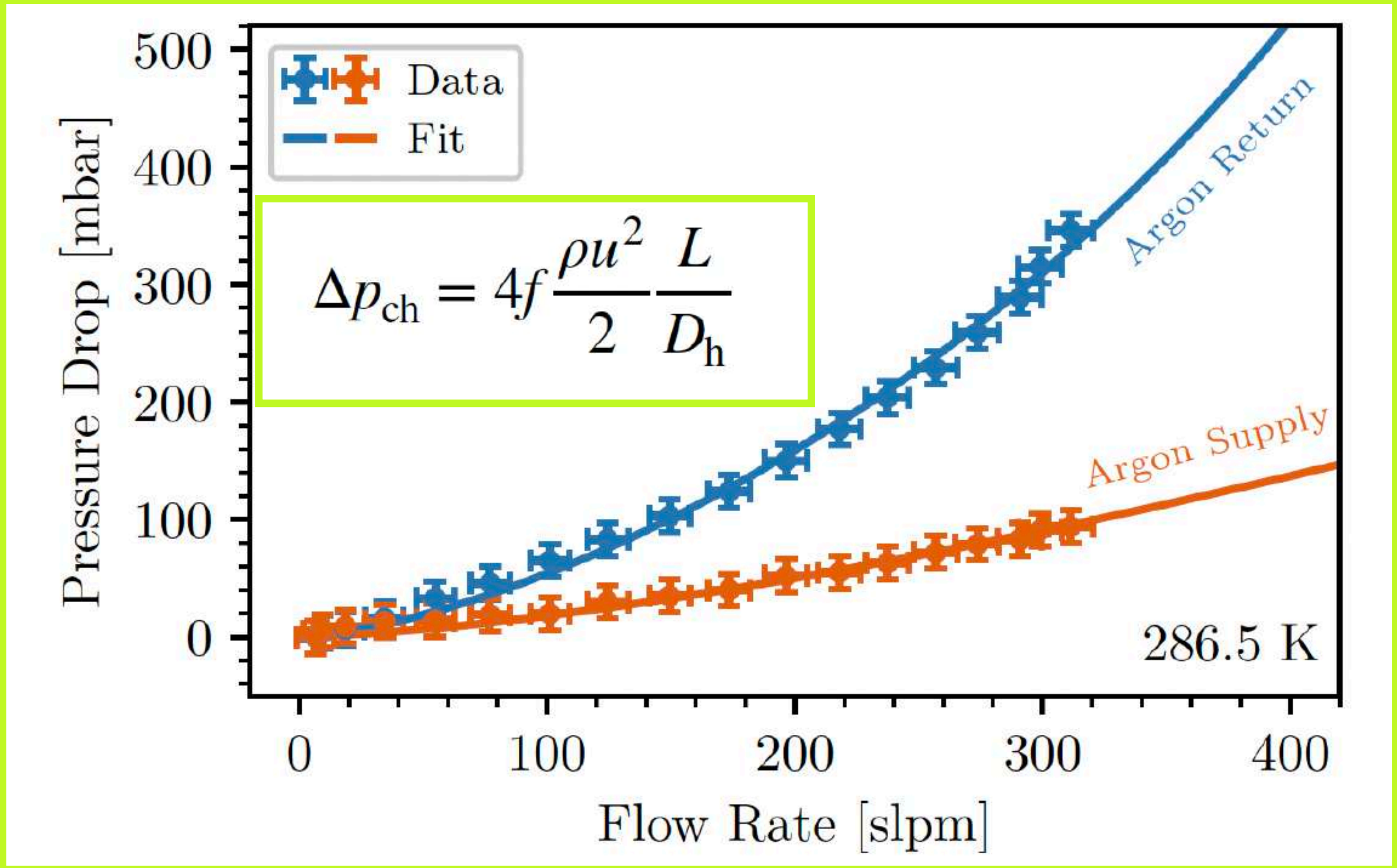


Circuit resistance

- The circuit resistance is dominated by pressure drop over heat exchanger cascade (dual-circuit type with twice as many channels on the supply side)
- Measured pressure drop over the heat exchanger cascade in the centre channel (supply) and an outer channel (return) with argon gas at 286.5K in short circuit mode.

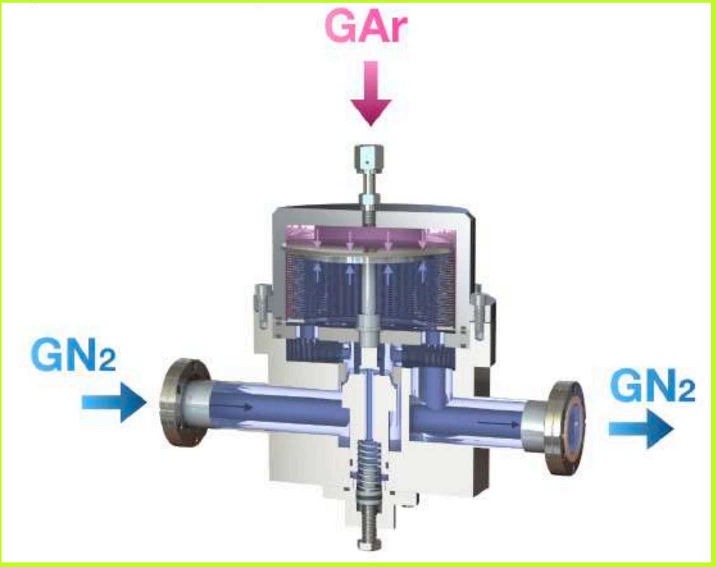


- The pressure on the argon side of the condenser was maintained at a stable 1065 mbar, facilitated by its coupling to the cryostat buffer.
- Acquired pressure data in flow range [5,311] slpm.
- Modelled with the Darcy-Weisbach equation.
- The effective inner-plate distance is reduced compared to the results from the manufacturer's data.

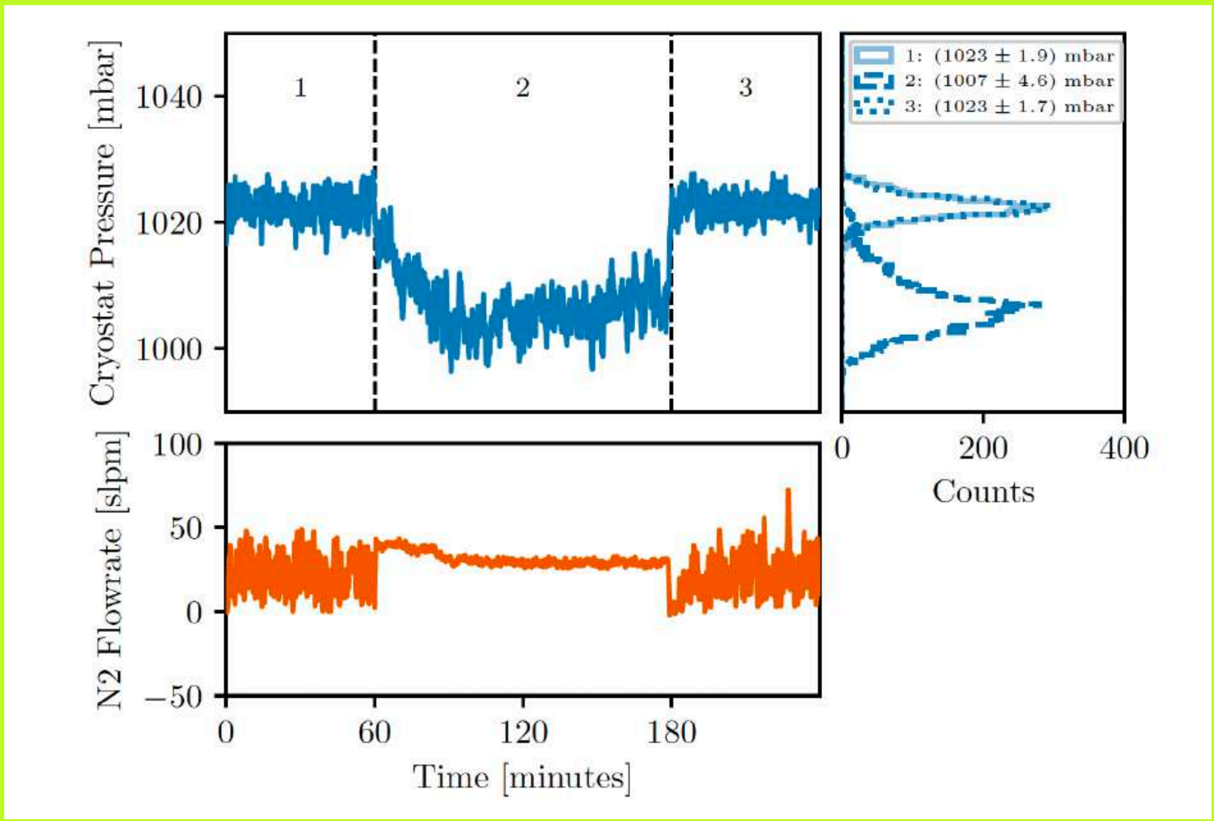


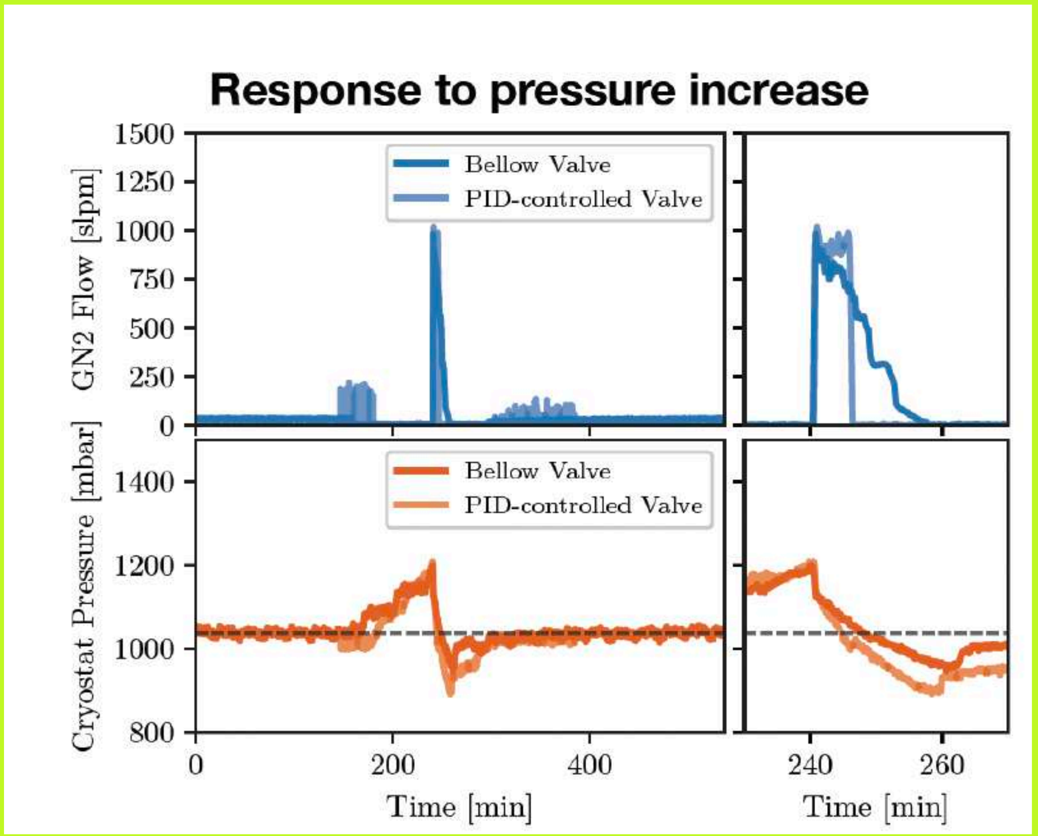
Cooling control

- The **cooling power**, given by the nitrogen flow, is based on the **feedback given by the argon pressure** inside the cryostat.
- There are two independent flow control valves for the nitrogen: a pneumatically actuated PID-controlled proportional valve and a passive bellow valve, which requires no power.



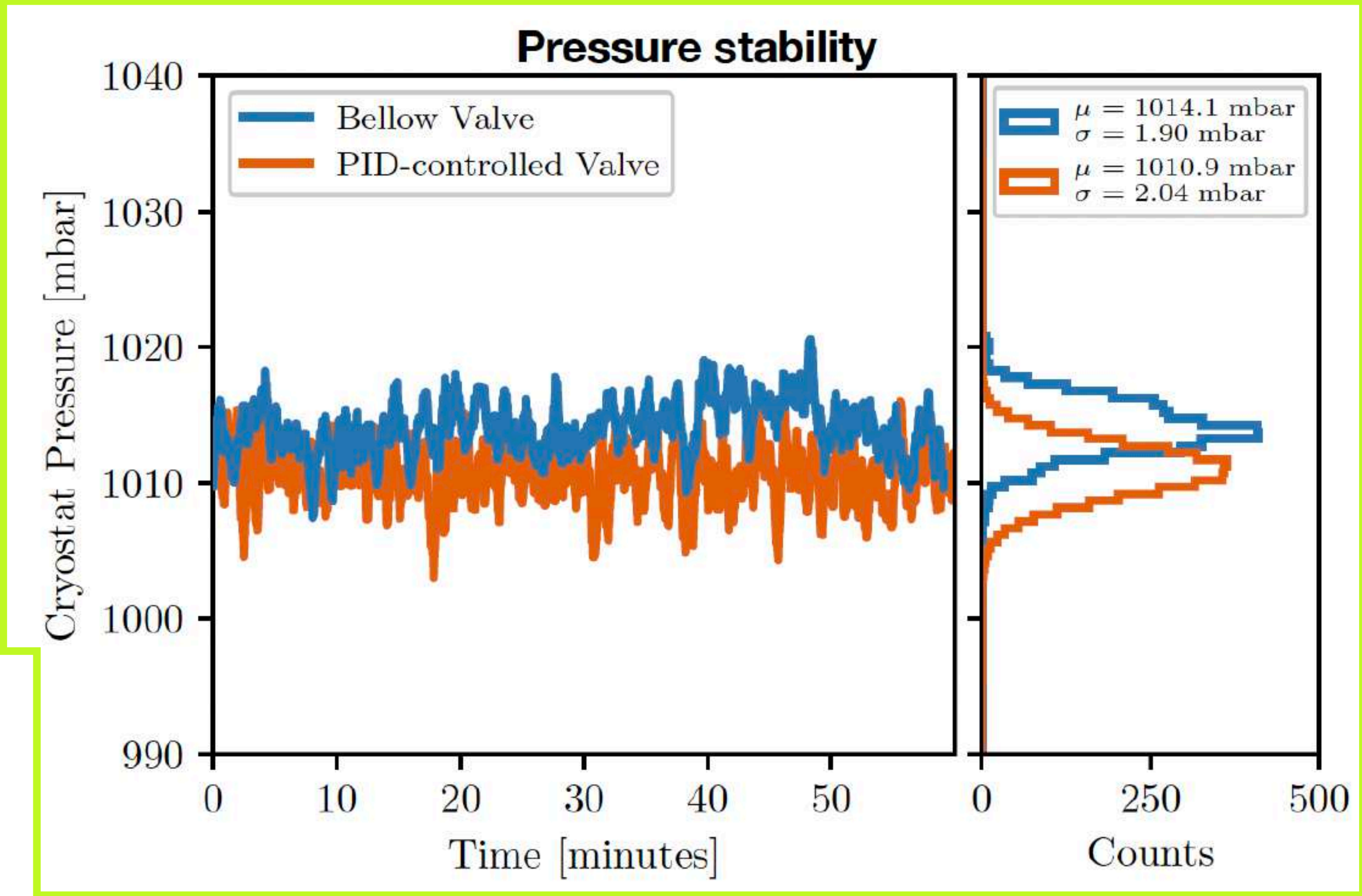
- Operated at various N_2 pressures in the range 1.2–2.0 bara
  - **Cooling control and cryostat pressure with both valves stable at all N_2 pressures**
  - LAr temperature from the condenser showed variations of the order of 0.1 K, around the nominal 84.4 K at 1.5 bara N_2
  - Expect percent-level changes of required GN_2 flow (cannot be observed at O(10 slpm) flows with deployed flow meter)
- Tested switching between bellow and PID valve and response to sudden pressure increases

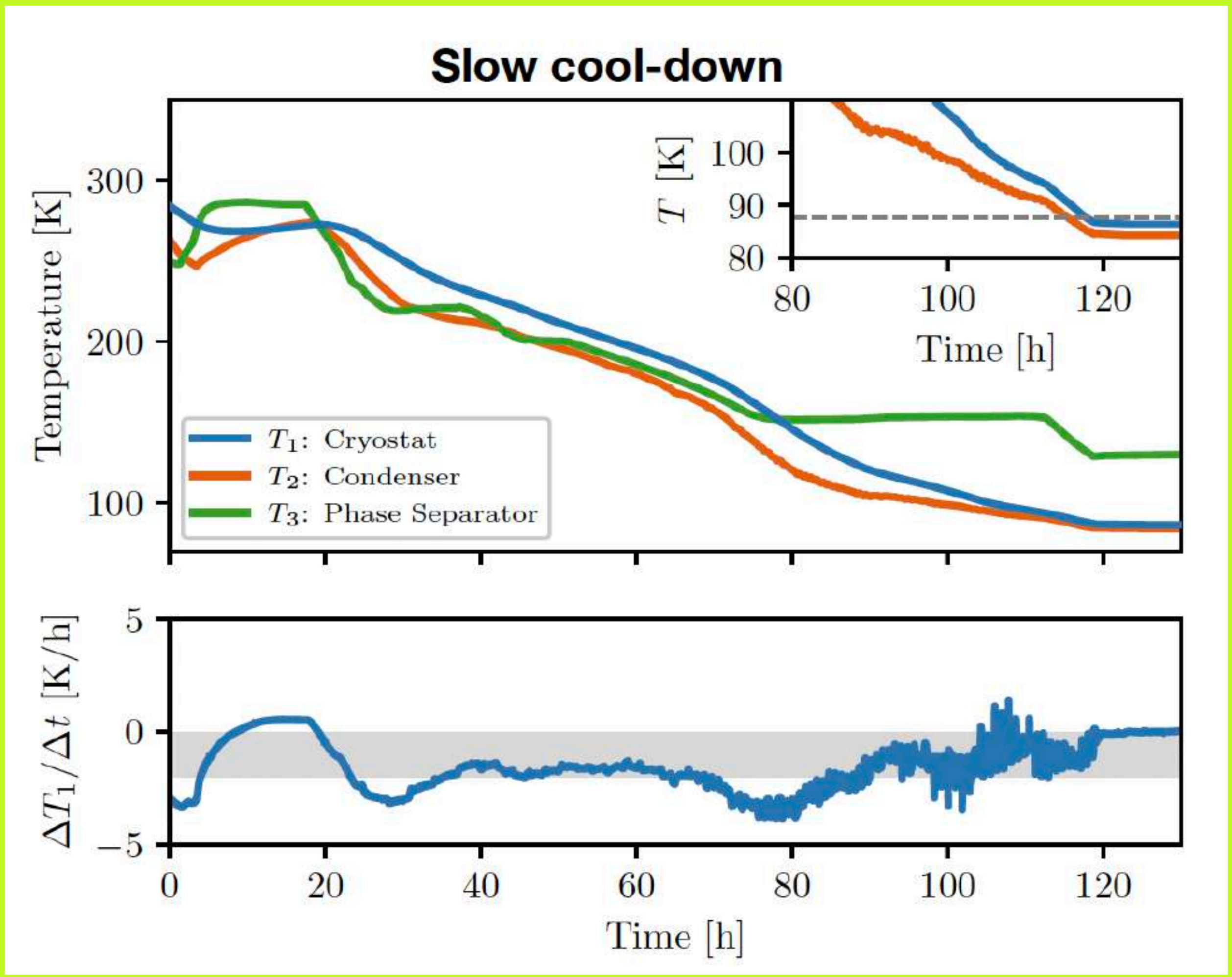




Cooling performance and pressure stability

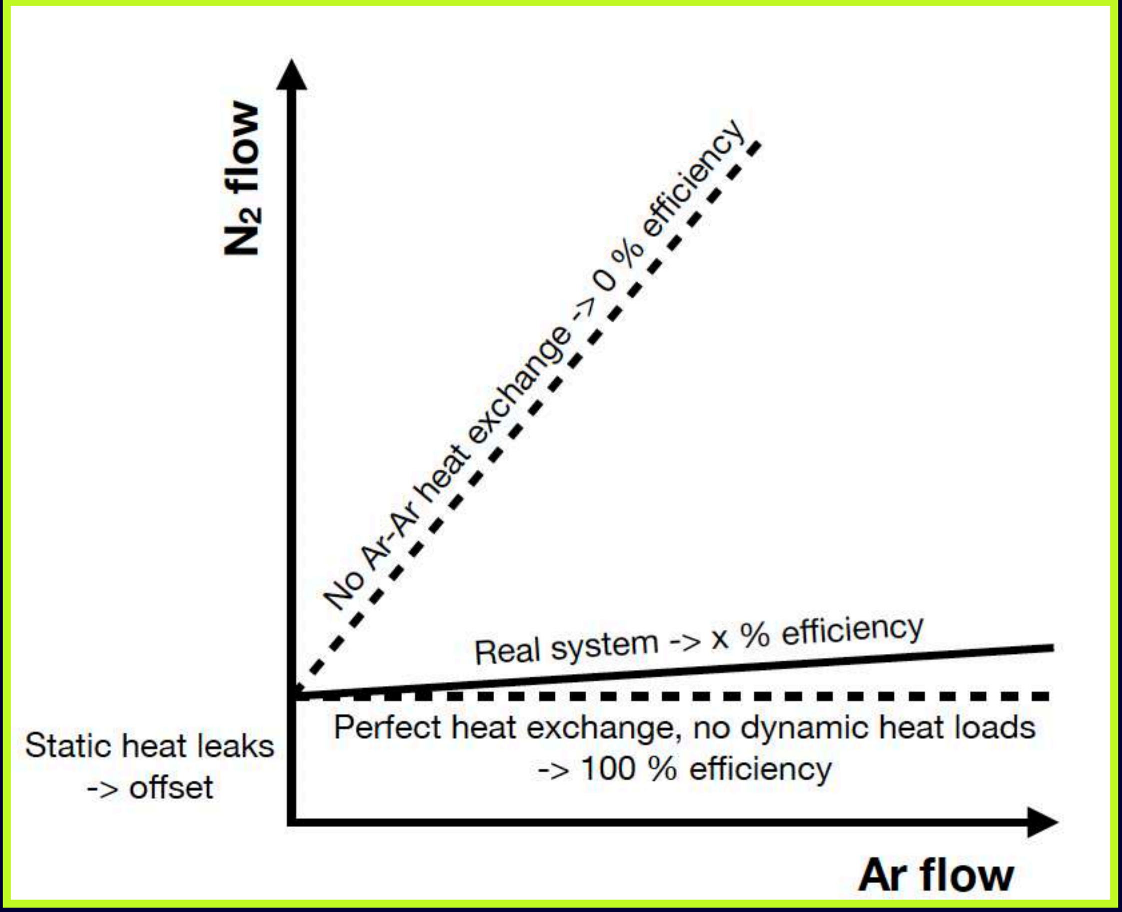
- Slow cool-down to keep a small temperature gradient, in time and space, to minimise the material stresses.
- Done empty cryostat (low heat capacity): stayed **within -2 K/h for most of the time**
- Using GAr in the cryostat almost until the end -> no temperature step

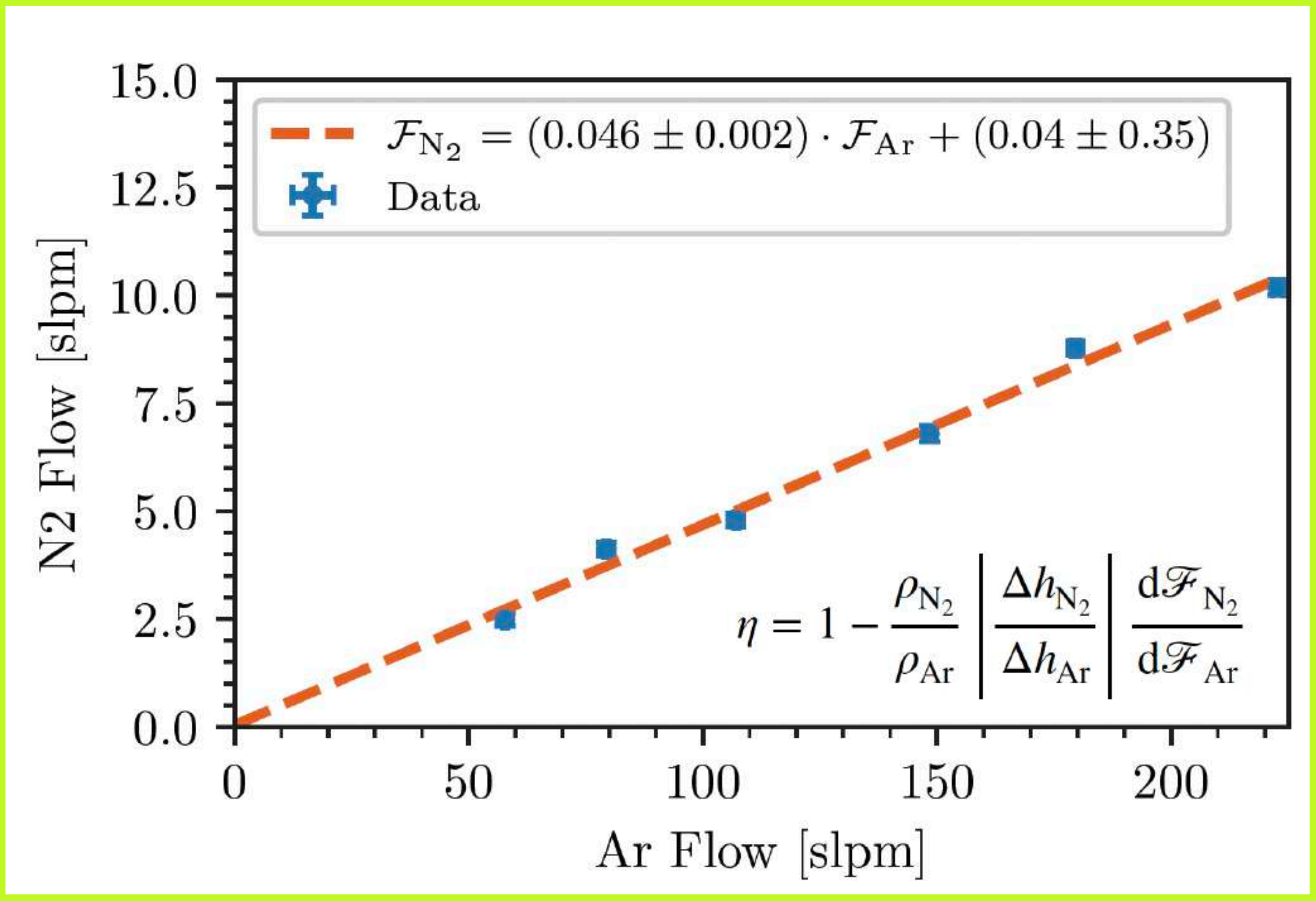




- Pressure stability of the system is of great importance for a stable operation of the gas pocket and the uniformity of S2 gain as a function of time.
- **Pressure stability within 2 mbar RMS** (with low-pass filter).
- Pressure stability within 0.1 mbar (bellow valve) and 0.2 mbar (PID valve) RMS after subtraction of electronic noise.

System efficiency





- Evaluation of the efficiency of the system by measuring the increment in nitrogen flow in response to the argon one, attributed to the introduction of heat into the system.
- Measurement of nitrogen flow as function of the argon flow, at various pump speeds in equilibrium conditions.
- After the subtraction of the static heat load the efficiency obtained is $\eta = 94.9\%$, which means we will need less than 50 slpm GN_2 @ 1000 slpm GAr if linearity is preserved.

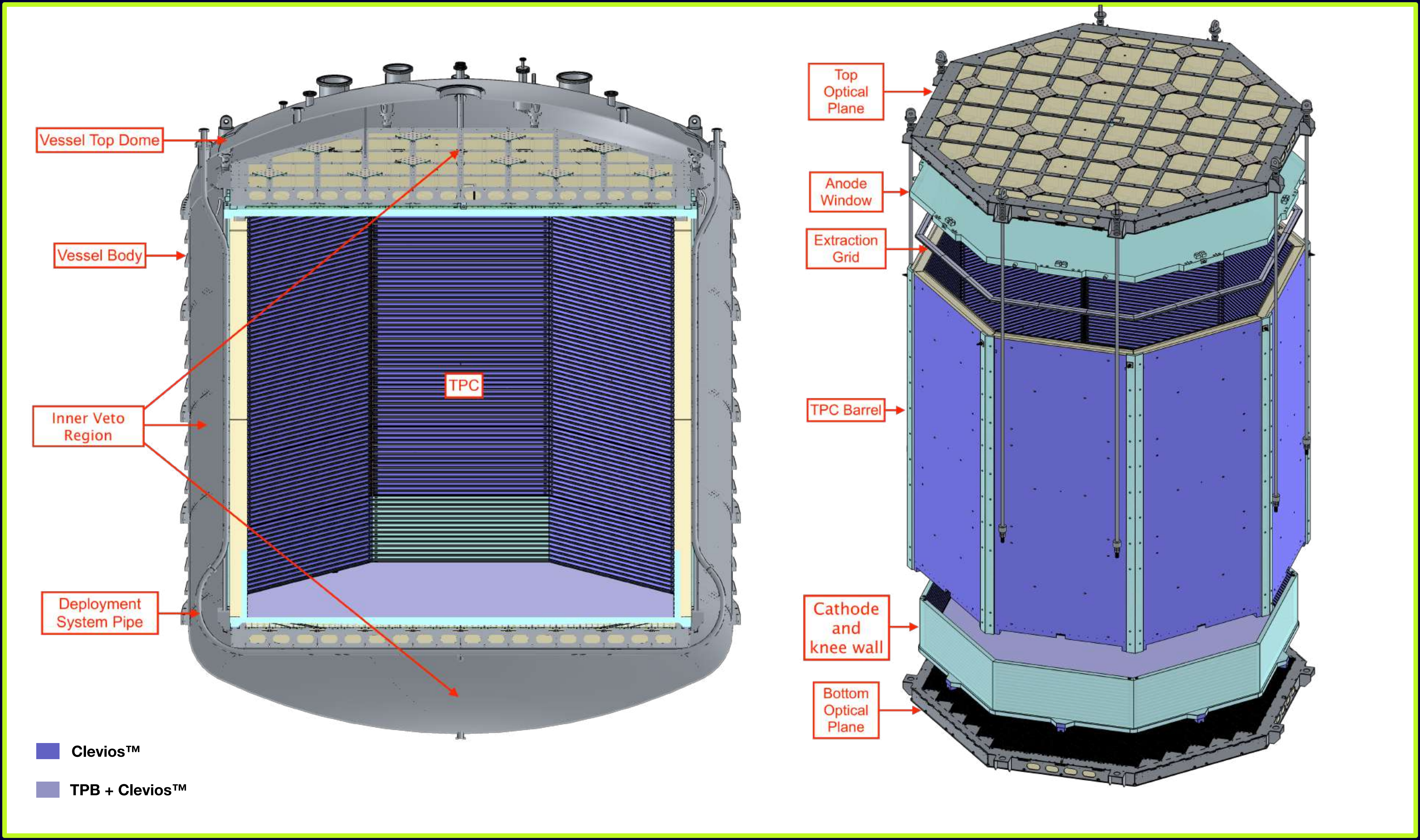
Conclusions

- The DarkSide-20k experiment, dedicated to the direct search for dark matter, is currently under construction at LNGS.
- The detector will use two types of argon: atmospheric argon as a thermal bath and as the target for the muon veto, and ultra-pure underground argon as the target for dark matter particles and for the neutron veto.
- There are two distinct cryogenic systems to liquefy, purify, and recirculate the two types of argon independently.
- The cryogenic system for atmospheric argon, which must handle approximately 600 t of argon, has been built and installed underground in Hall C at LNGS.
- The cryogenic system for underground argon is nearly complete; all of its core components were tested in the mockup setup at LNGS between 2023 and 2025.
- Test results provided useful inputs for the finalisation and optimisation of the DS-20k UAr cryogenics. Technical details and findings are published **F. Acerbi et al 2025 JINST 20 P02016**

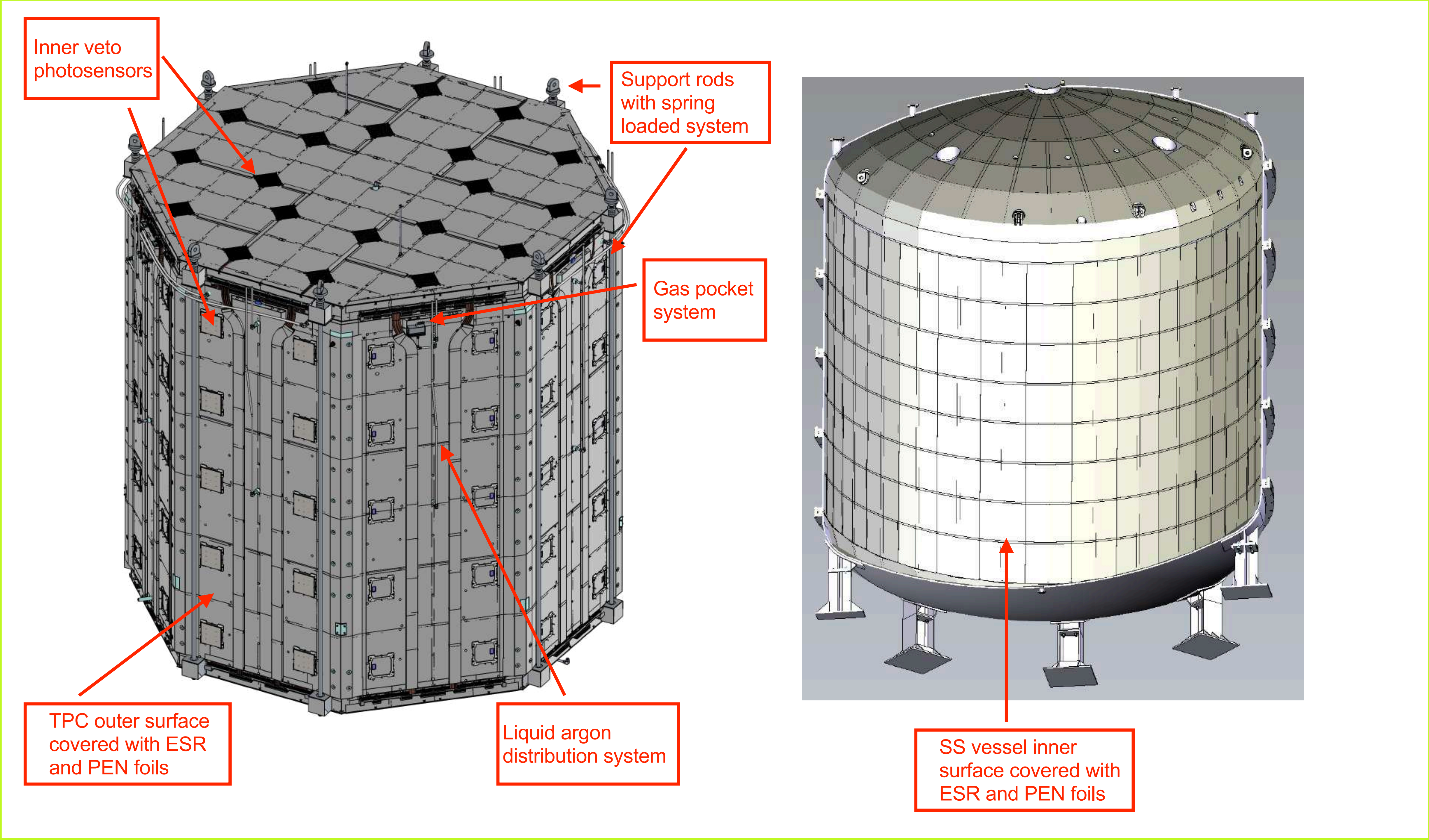
Thank you for your attention!

Backup slides

Inner detector: TPC + neutron veto



Inner detector: TPC + neutron veto



Photodetectors

- Custom cryogenic SiPMs developed in collaboration with Fondazione Bruno Kessler (FBK), in Italy.

- Key features:
  - Photon detection efficiency (PDE) ~45%
  - Low dark-count rate < 0.01 Hz/mm^2 at 77K (7 Volts overVoltage)
  - Timing resolution ~ 10 ns

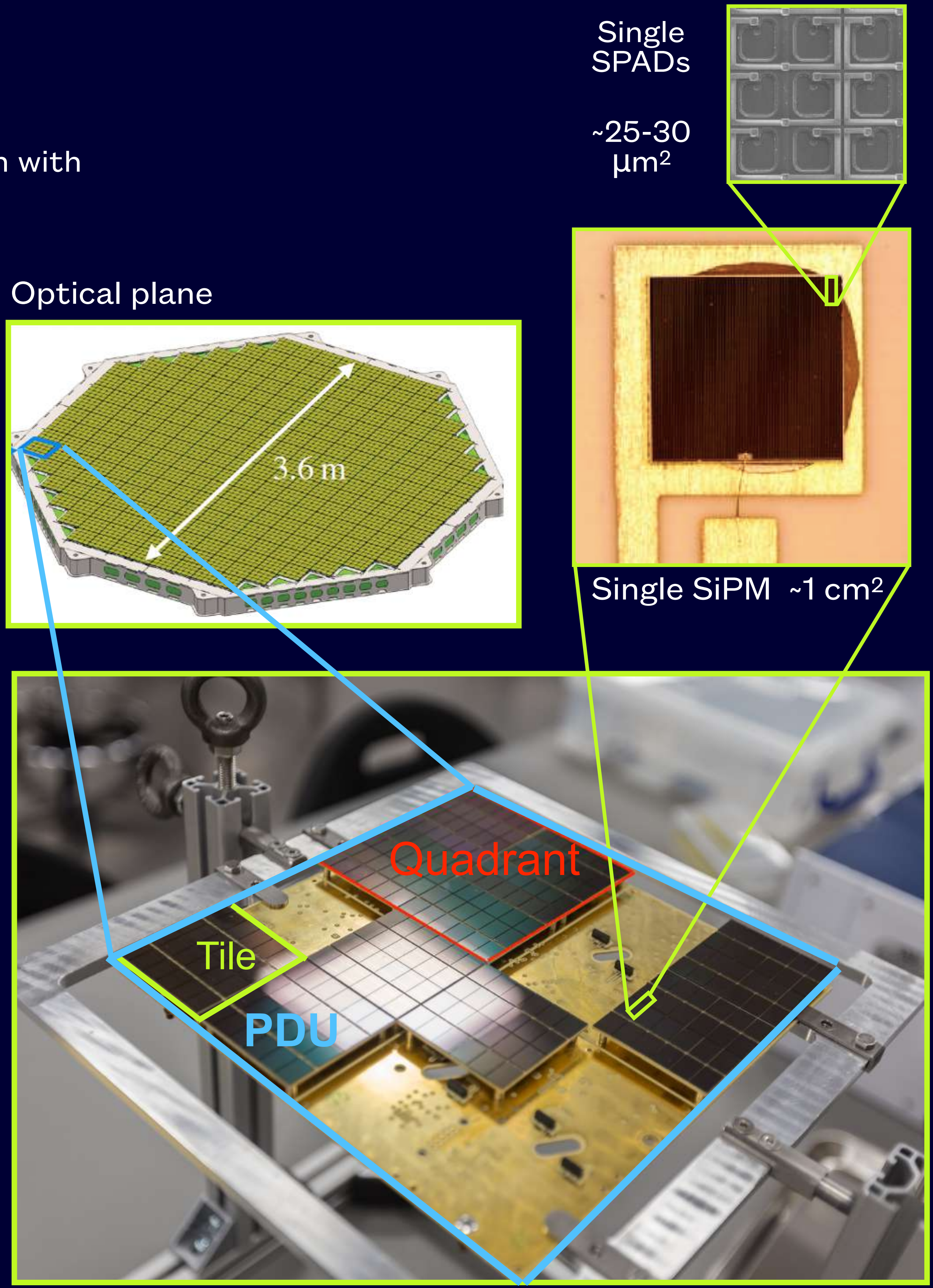
- 24 FBK NUV-HD-Cryo SiPMs are aggregated in 5 x 5 cm^2 objects called **tiles;**

- SiPMs are read by a low noise trans-impedance 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;

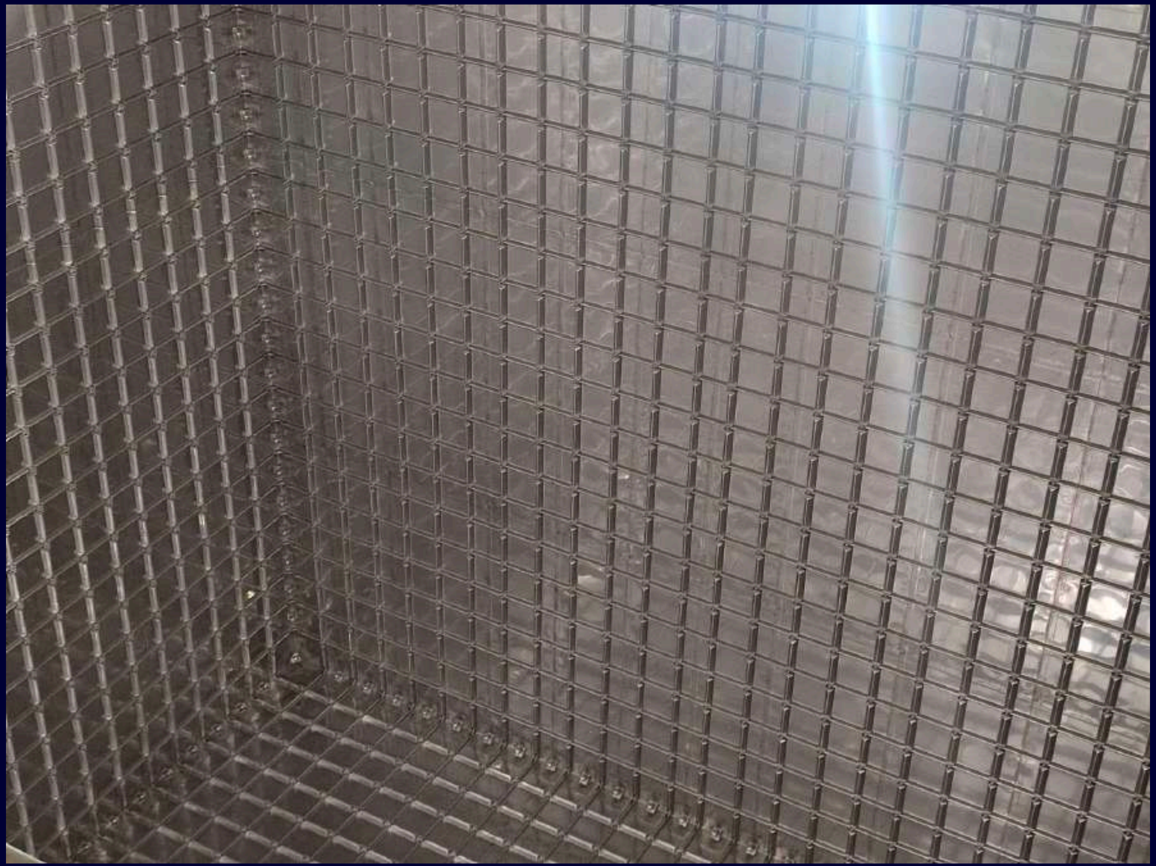
- A **PDU** - PhotoDetector Unit is made of 4 quadrants, which means 16 tiles

- PDUs are aggregated in the Optical Planes for the TPC and left sparse for the neutron veto readout.



Membrane cryostat

Membrane cryostat



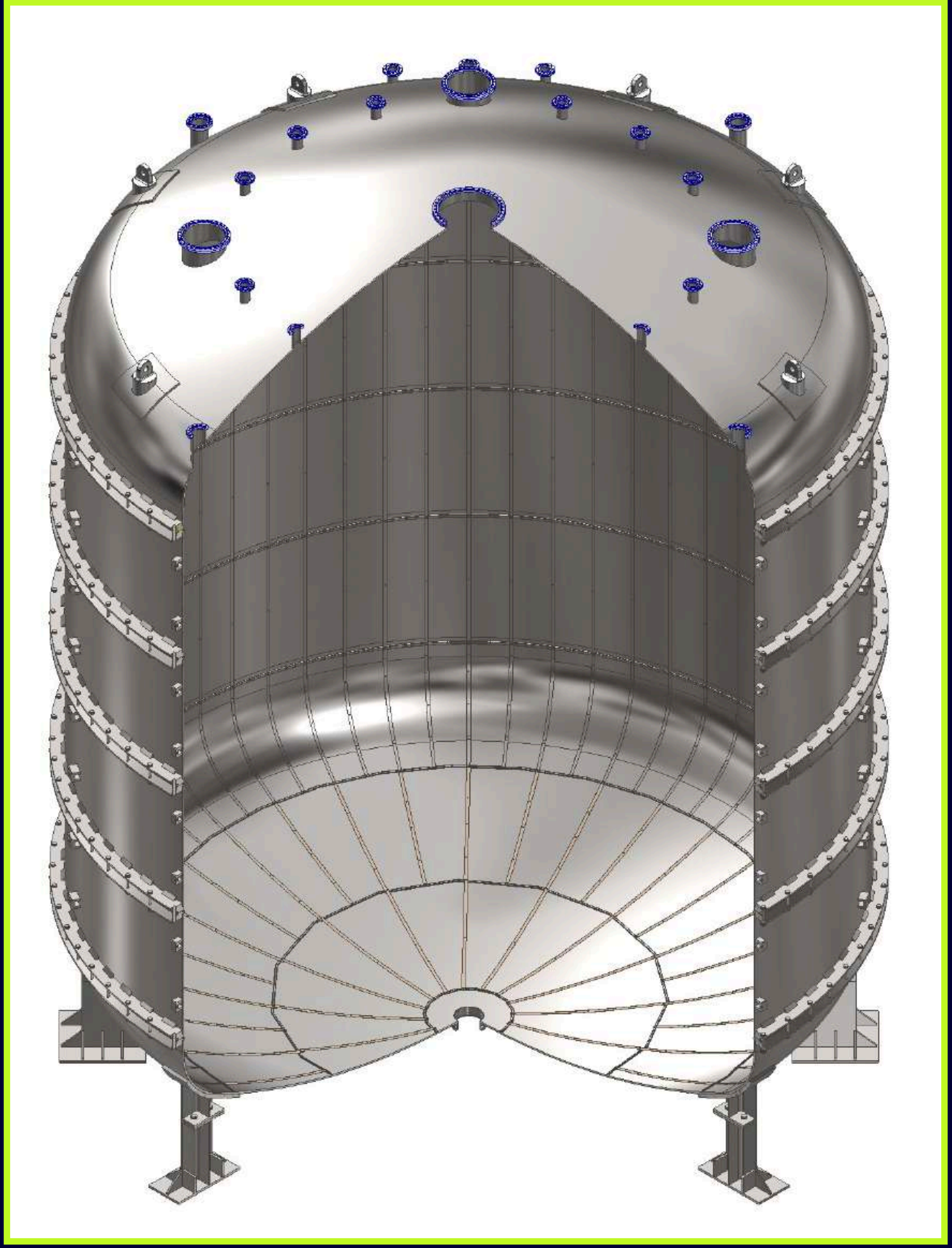
SS vessel

Main dimensions and parameters

- number of modules: 6
- int/ext diameter: 4650/4850 mm
- overall height: 5880 mm
- thickness: 12 mm
- overall mass: 15 ton

Internal light structure to support reflector

foils



Purification

•Three filter VB (HR, LF, GF), each equipped with three dedicated filters:

- Molecular sieve for moisture (H_2O) – “Mol. Sieve”
- Copper filter for oxygen (O_2) – “Cu filter”
- Activated charcoal filter for Radon (Rn) – “Rn trap”

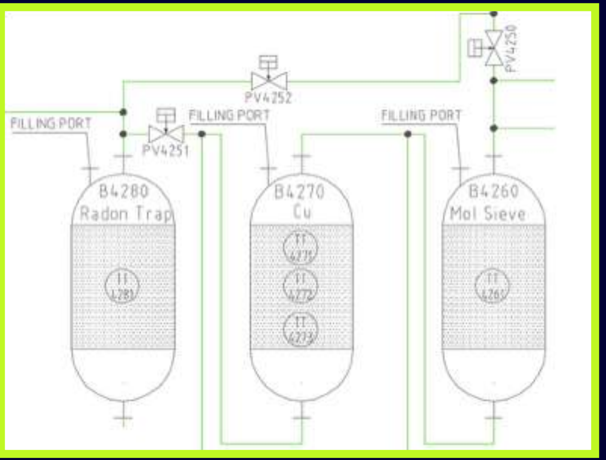
•Continuous purification and analysis of LAr and GAr (boil-off + chimneys) circuits

•Individual filters are “activated” at temperatures of [420 – 500] K

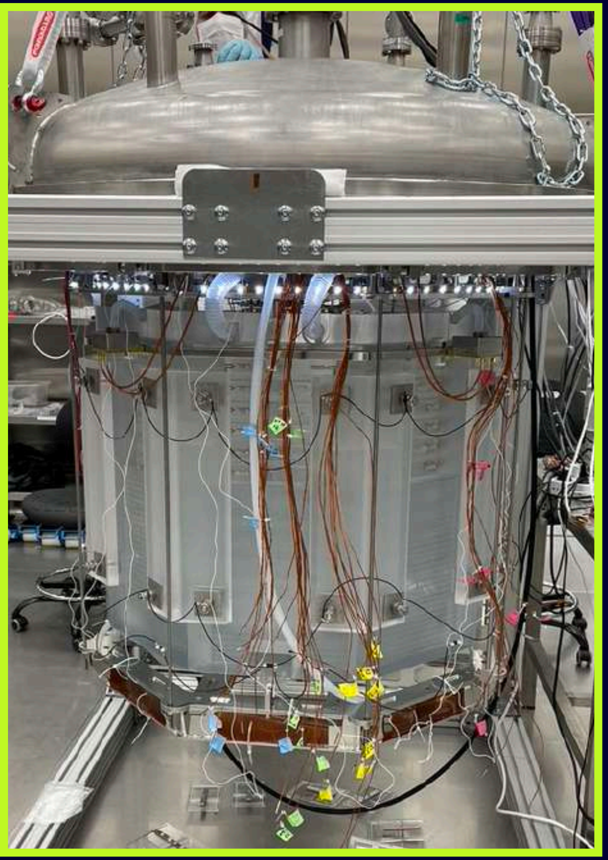
•Cu filter activation: heating (GAr) + copper reduction (eqn. 1)

$$CuO + H_2 \rightarrow Cu + H_2O \quad (1)$$

$$O_2 + 2Cu \rightarrow 2CuO \quad (2)$$

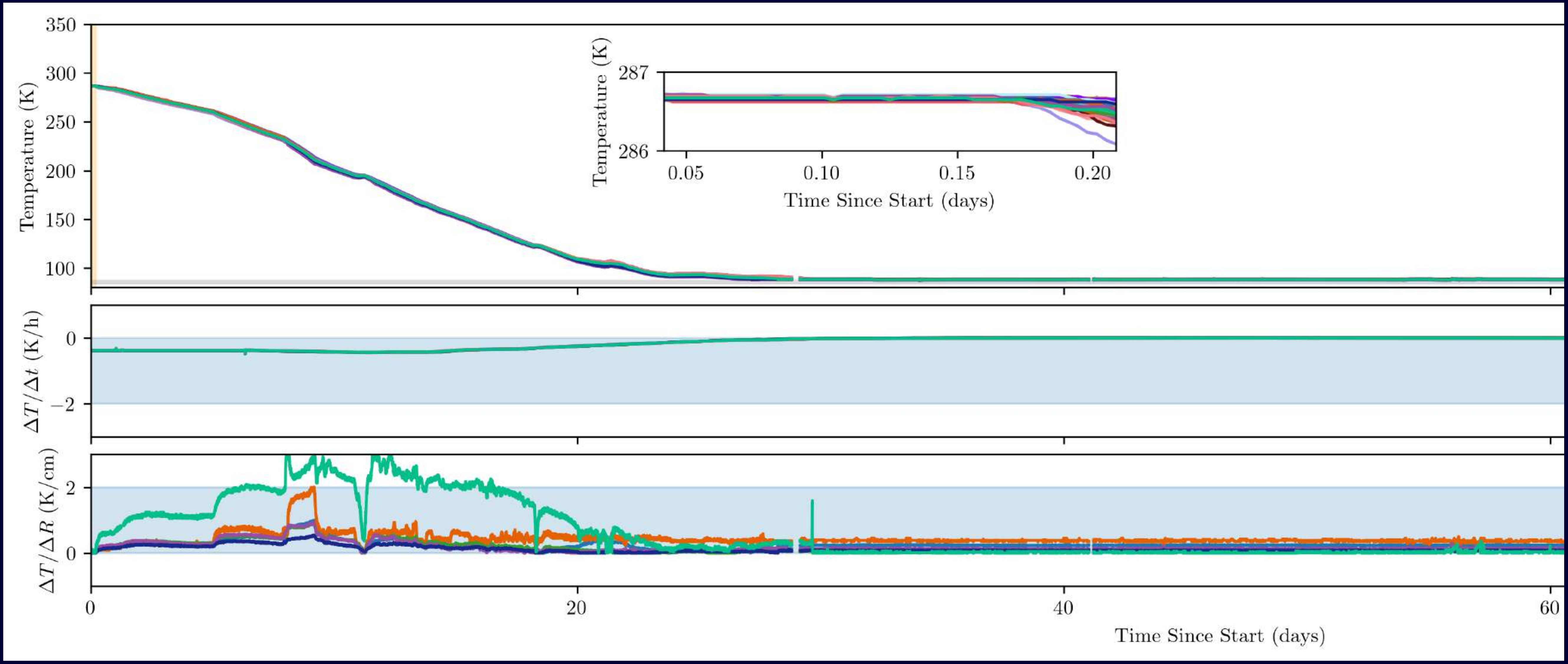


1 ton scale mockup

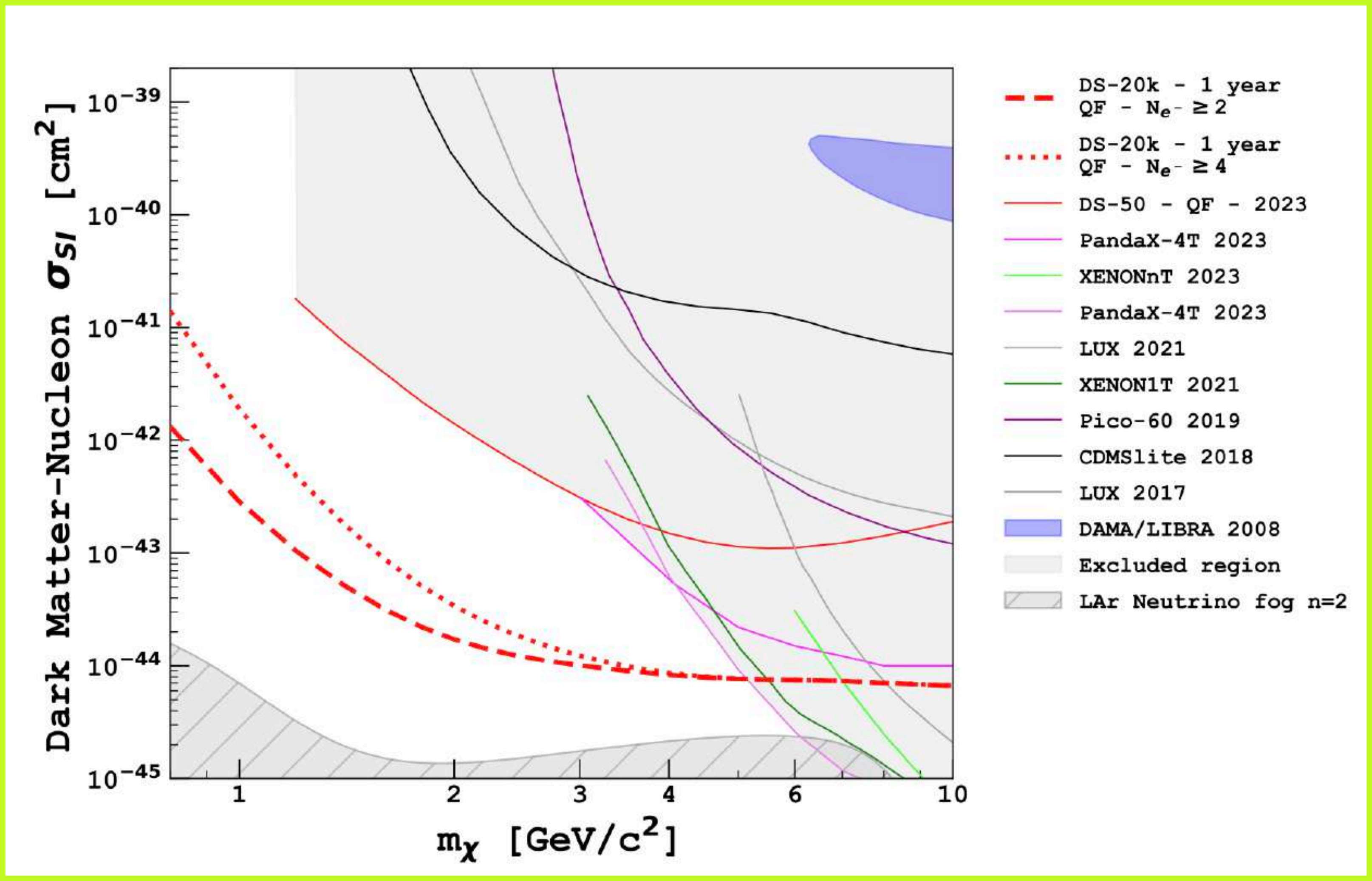


- The mockup is a testing facility for the UAr cryogenic system and some aspects of the TPC.

Mockup TPC cooling



Low mass sensitivity



Commun Phys 7, 422 (2024)

DarkSide-50 has already demonstrated the technology's capability and obtained the world's best sensitivities to light DM particles using only the S2 signal.

The study, for DarkSide-20k, includes a **detailed background** study, and prediction for many **light DM** candidates.

The first assessment of DarkSide-20k sensitivity to low-mass dark matter particles highlights the physics potential: with one year of data, a sensitivity improvement to DM–matter interaction cross-sections by at least one order of magnitude with respect to DS-50 is expected for a wide range of DM models.
This result further strengthens the physics reach of DarkSide-20k with a leading role below 5 GeV/c².