XENON1T:

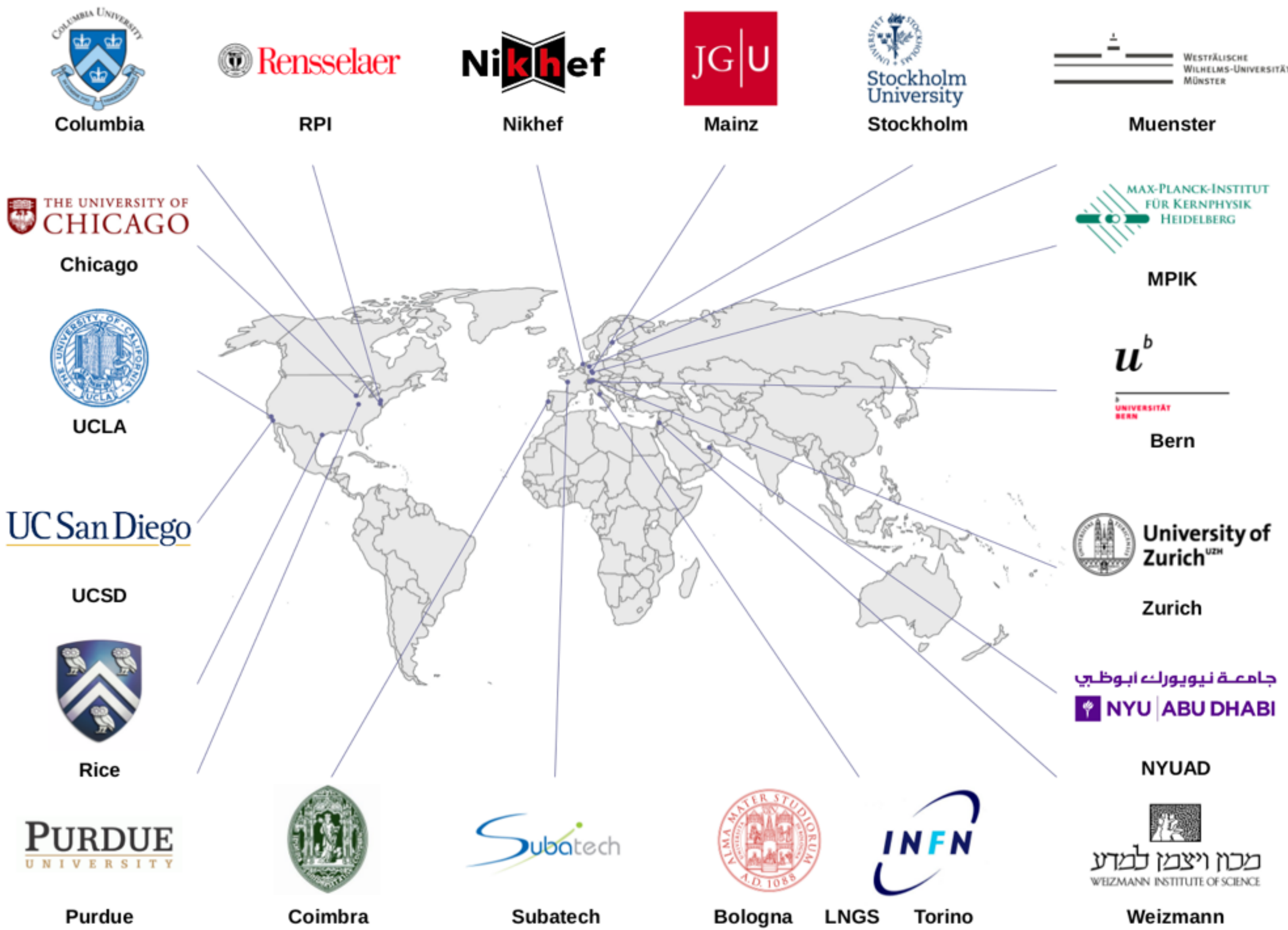
we are ready to turn on the light on Dark Matter

Marcello Messina, Columbia University

on behalf of the Collaboration, LNGS SC, November 12, 2015

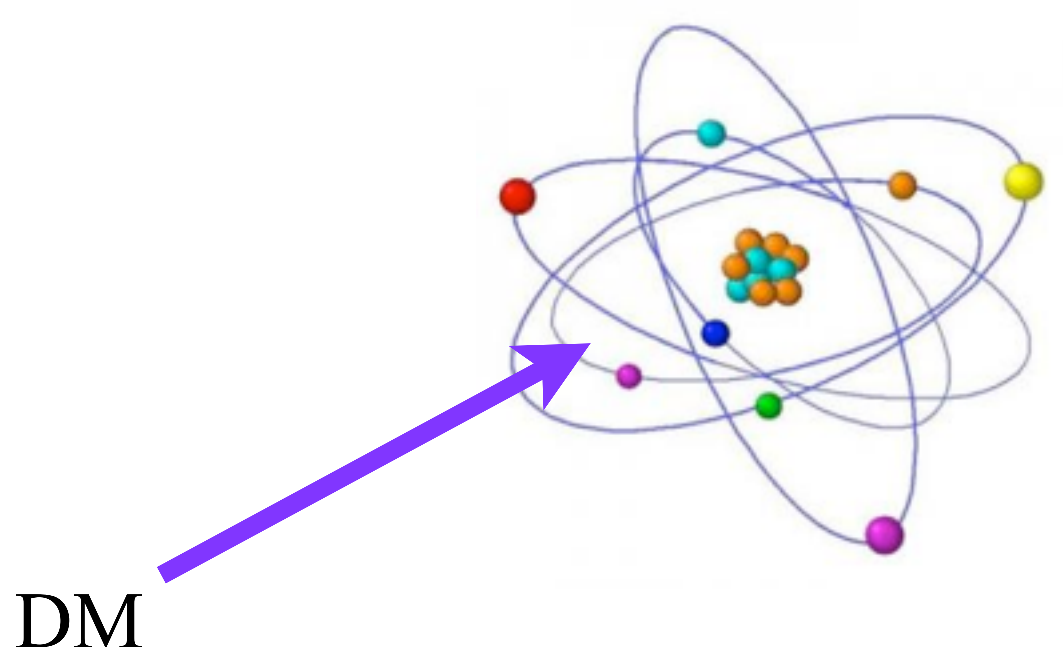
The XENON Collaboration

currently 126 scientists from 21 institutions


Columbia
RPI
Nikhef
Mainz
Stockholm
Muenster
Chicago
MPIK
UCLA
Bern
UCSD
Zurich
Rice
NYUAD
Purdue
Coimbra
Subatech
Bologna
LNGS
Torino
Weizmann

Our Goal

Discover Dark Matter with the most sensitive liquid xenon imaging detector located in the best underground laboratory worldwide



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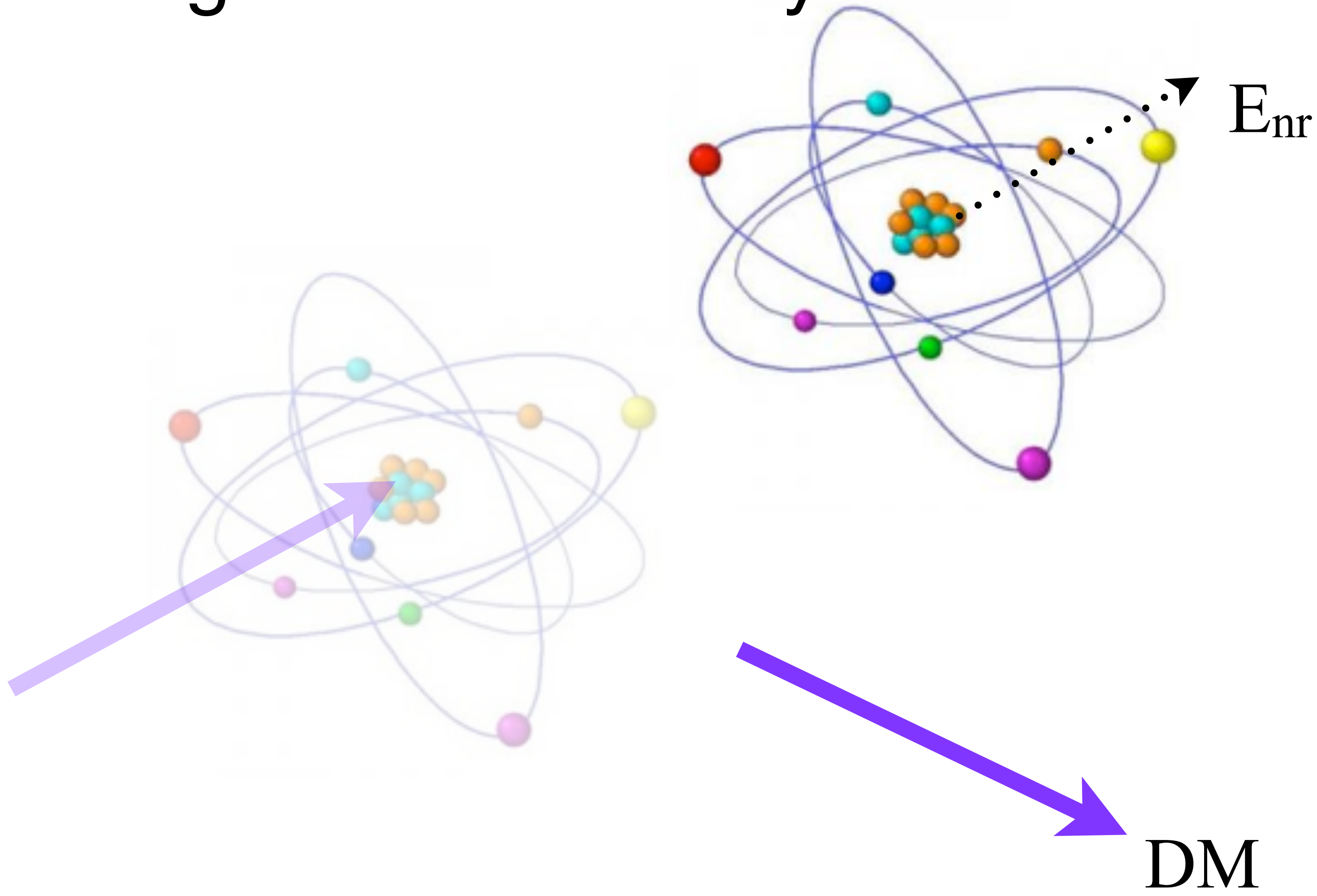
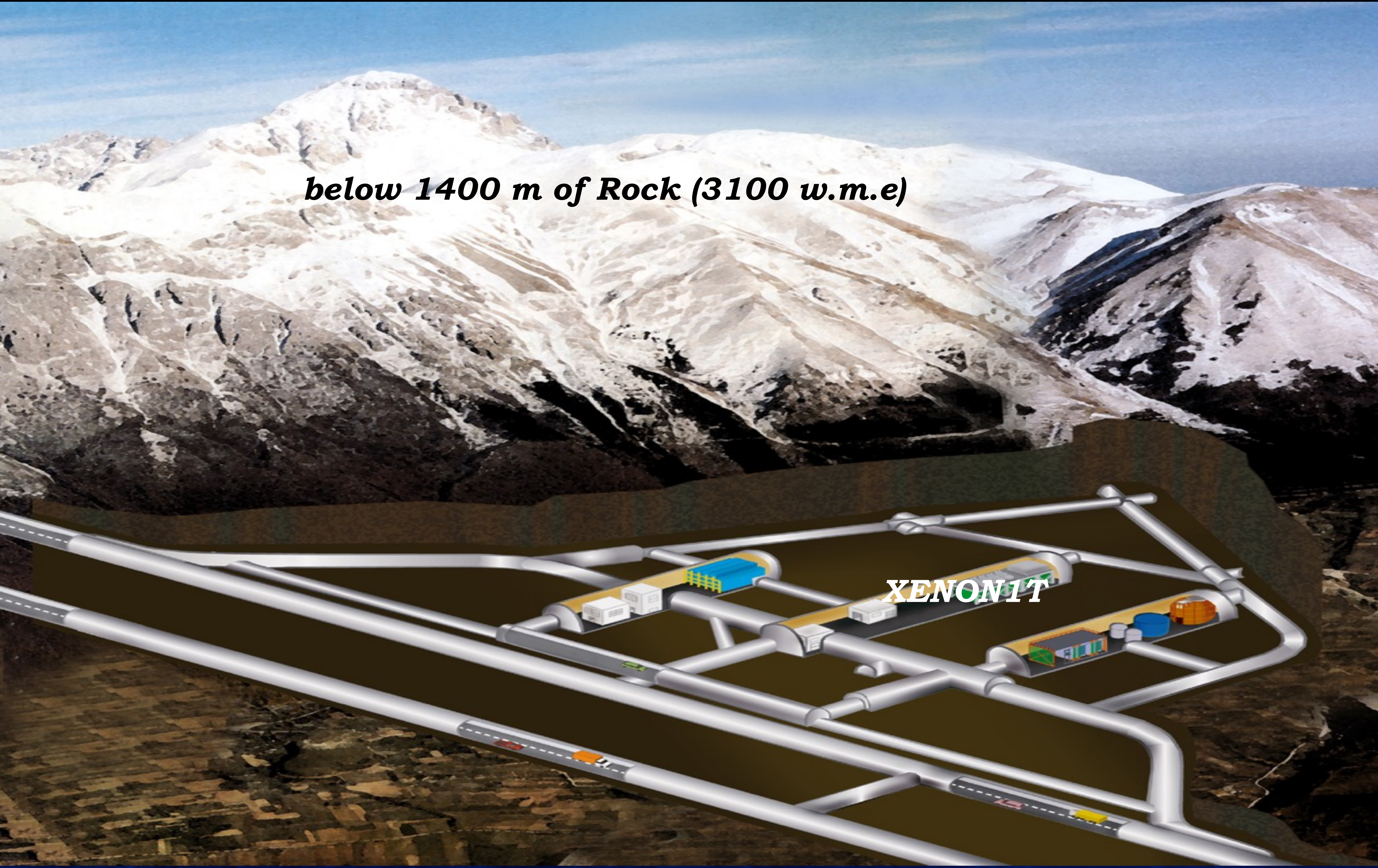
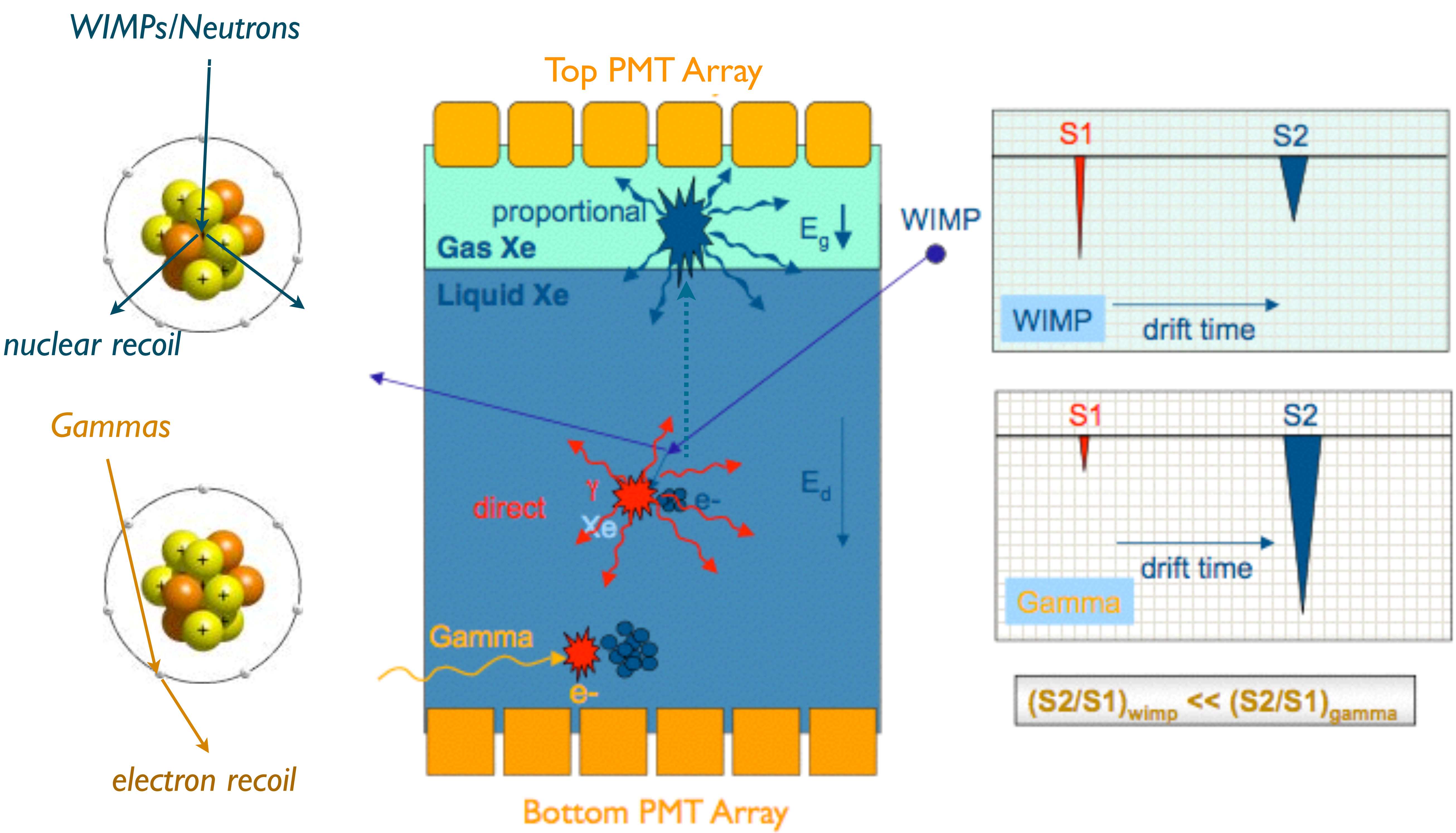


Gran Sasso Underground Laboratory

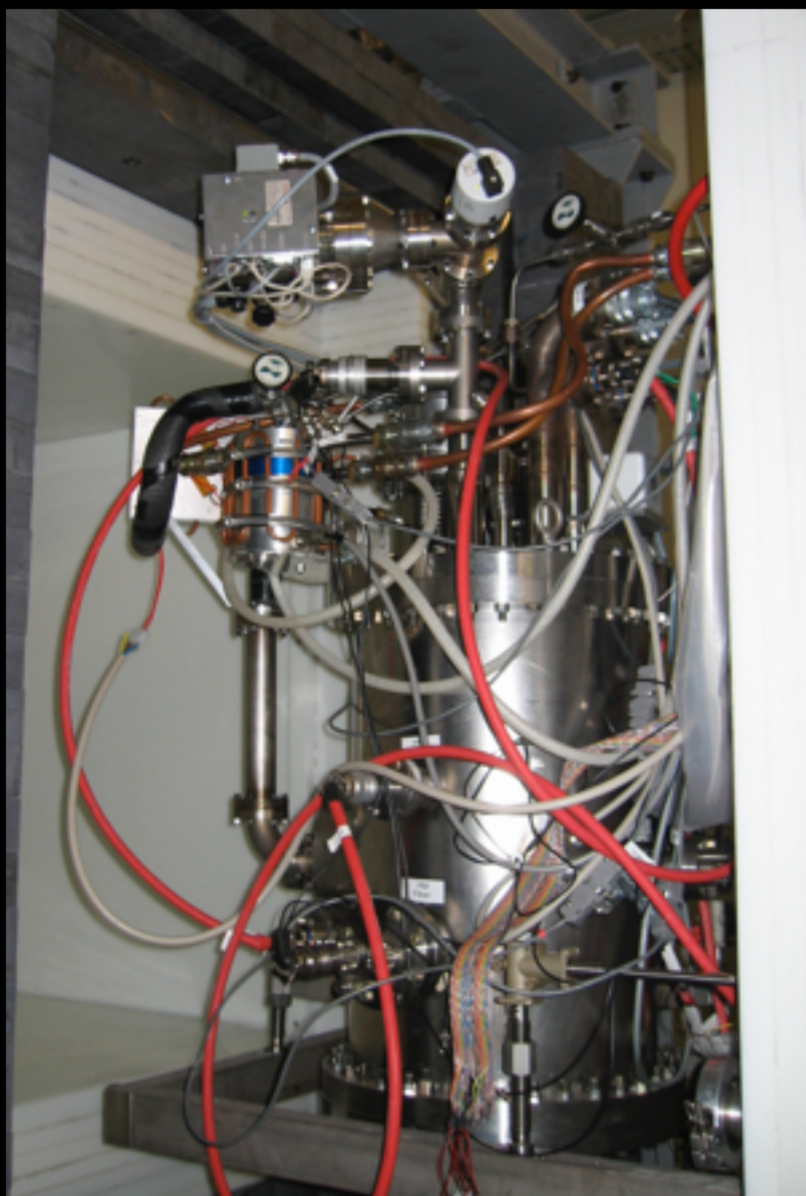


to detect these signals we use a two-phase Xe
Time Projection Chamber



The XENON Dark Matter Program

2005-2007



XENON10

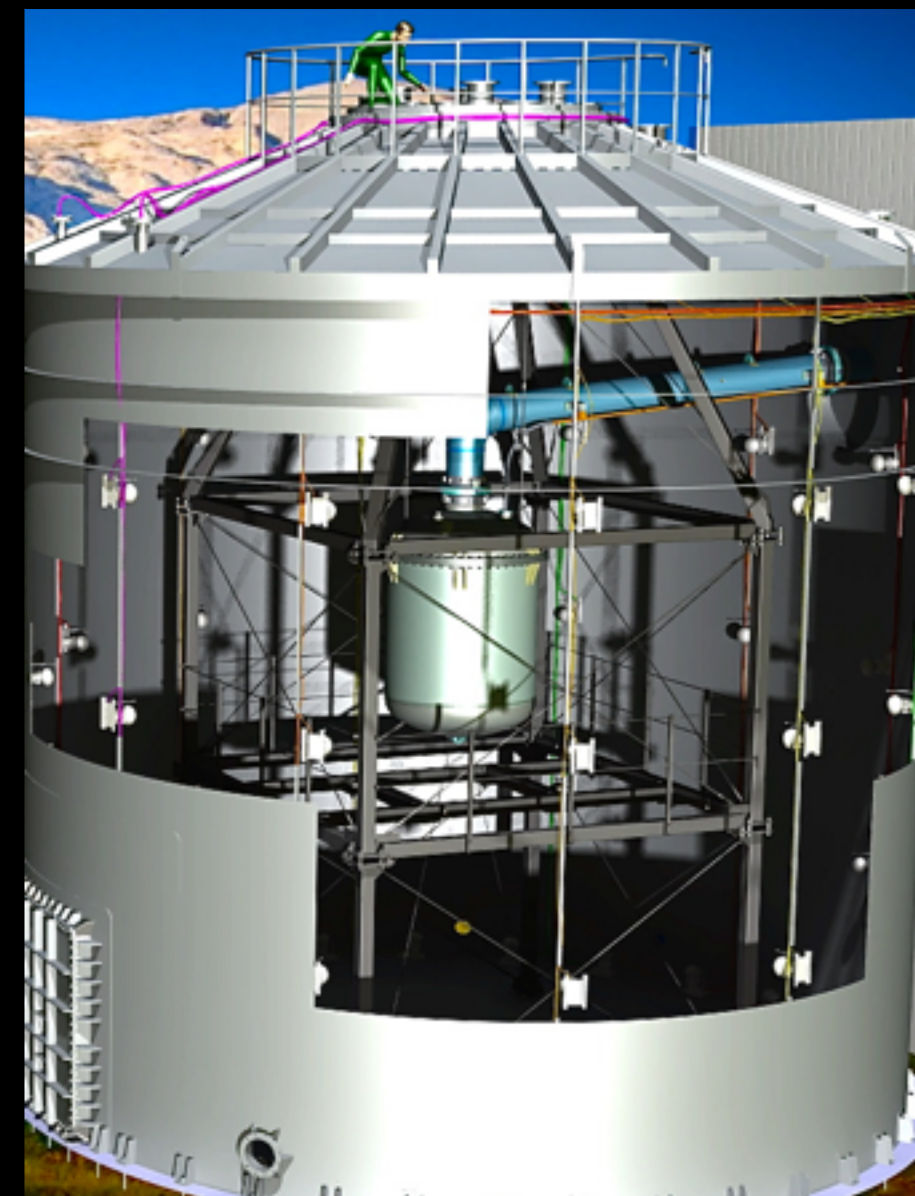
15 cm drift TPC - 25 kg

2007-2015

XENON100

30 cm drift TPC - 161 kg

2012-2022



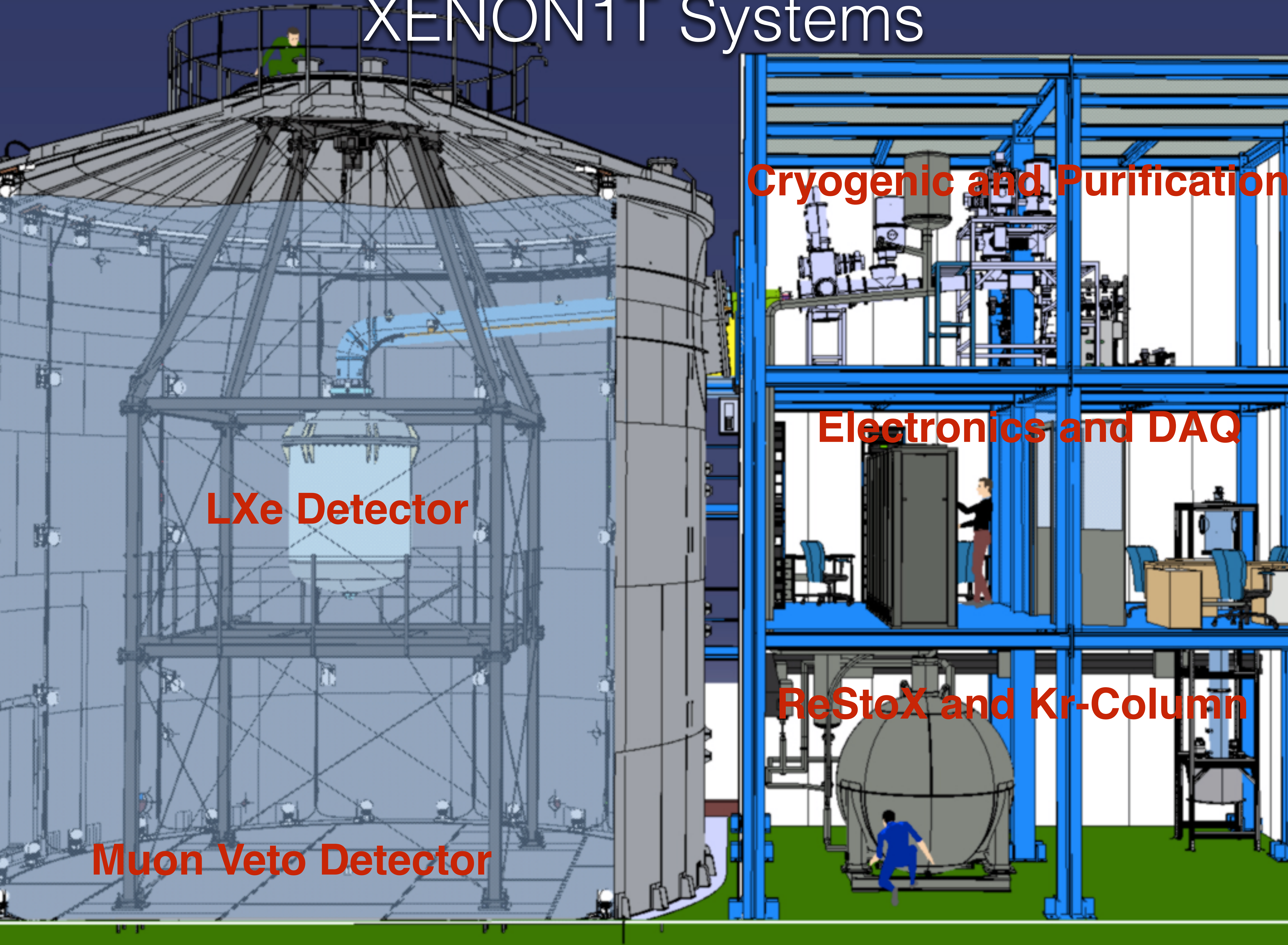
XENON1T/XENONnT

100 cm drift TPC - 3500 kg/7000 kg

The XENON1T Experiment

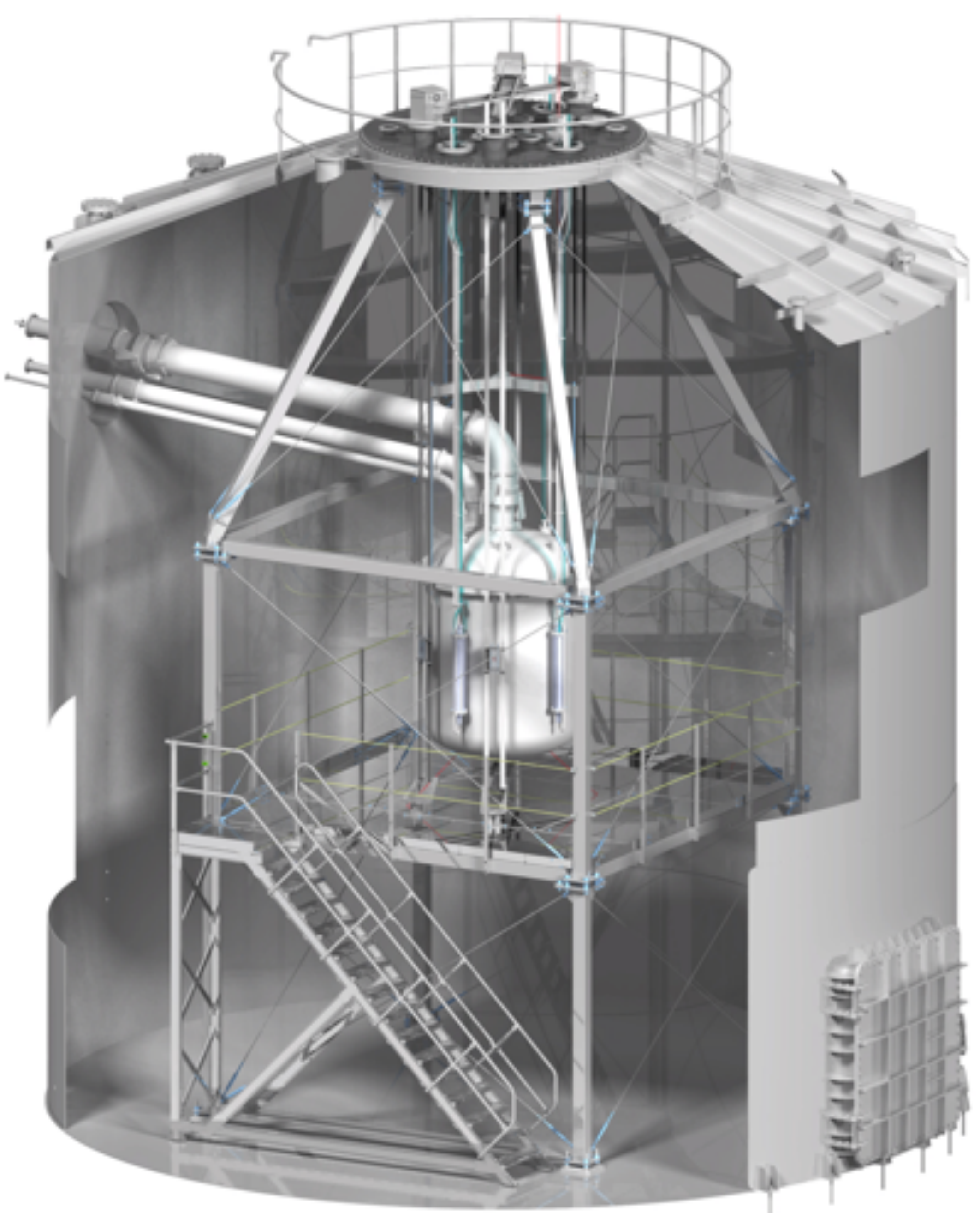

Xe
XENON
Matter Project
enlightening the

XENON1T Systems



Water Systems: WIS/ INFN-LNGS/NYU-Abu Dhabi

Goal: provide a “house” and clean water for an active shield around the LXe detector. Provide access points and breakthroughs for water purification, calibration sources and detector leveling



Water Tank Design:

- 10.5 m high and 9.6 m in diameter stainless steel tank filled with 700 m^3 of demineralized water
- 30 tons of AISI 304 Stainless steel
- Built by DiZio Company (Pescara)

Water Plant Design:

- capable to provide 2 m^3 /hr de-mineralized water.
- Maximum filling time (24 hr/day) ~ 2 weeks
- Built by Osmoplanet Company (Como)

Water Circulation Loop:

- normal loop rate: 2 - 4 m^3 /hr
- Full tank water exchange in ~10 days
- Water quality sampling

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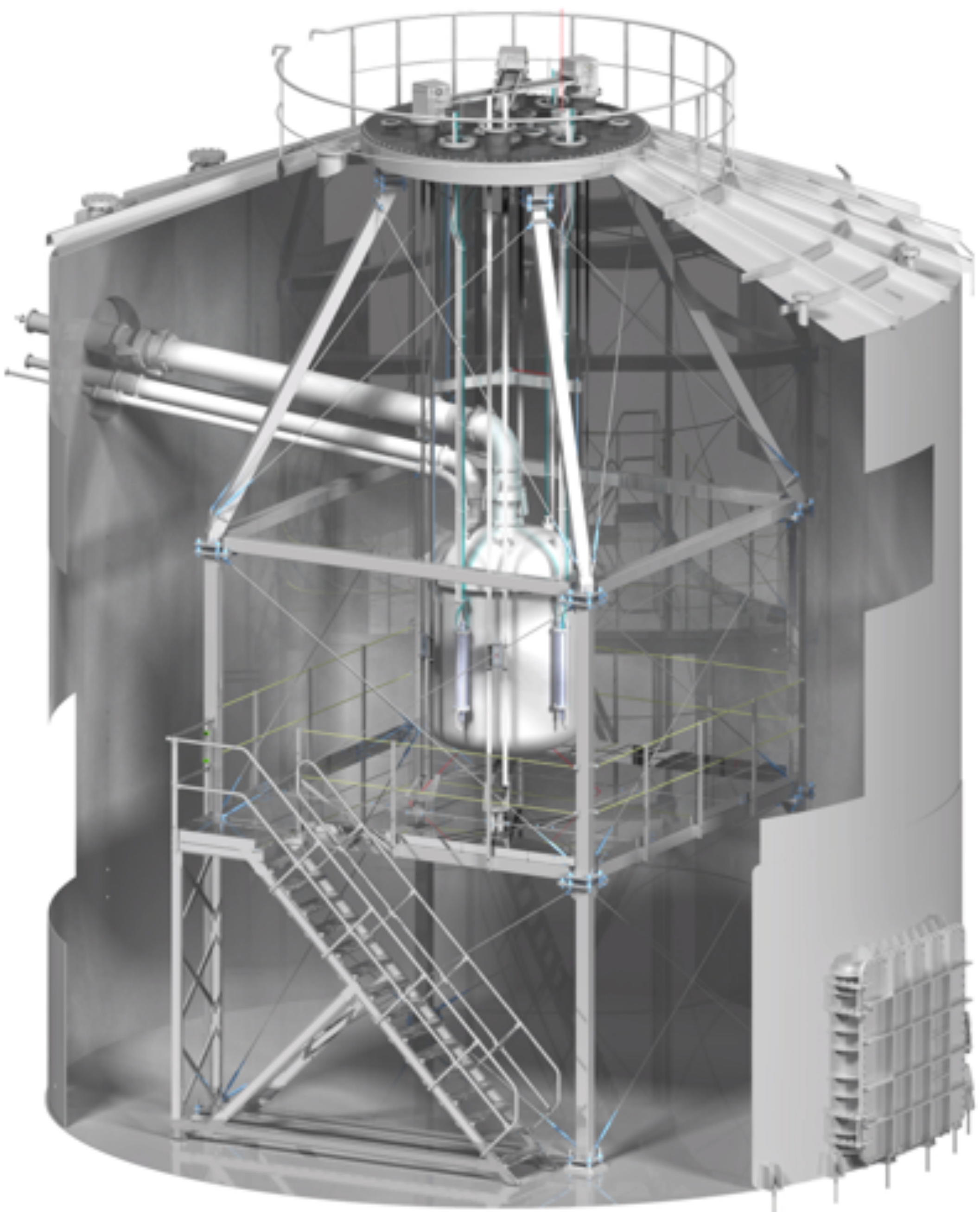

Water Tan
- 10.5 m ... eel tank filled wit
- 30 tons
- Built by

Water Pla
- capable ... er.
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- Built by (

Water Circ
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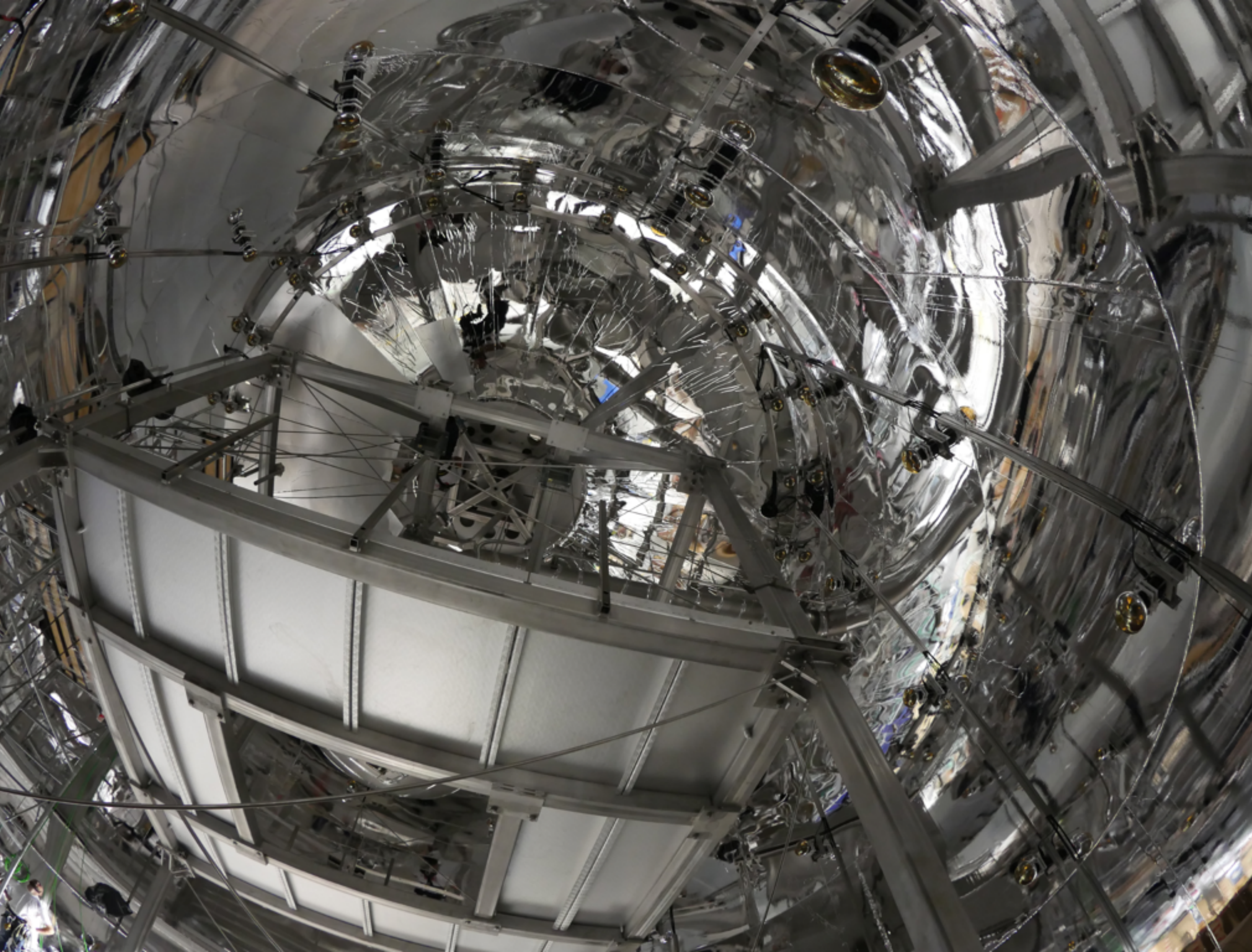
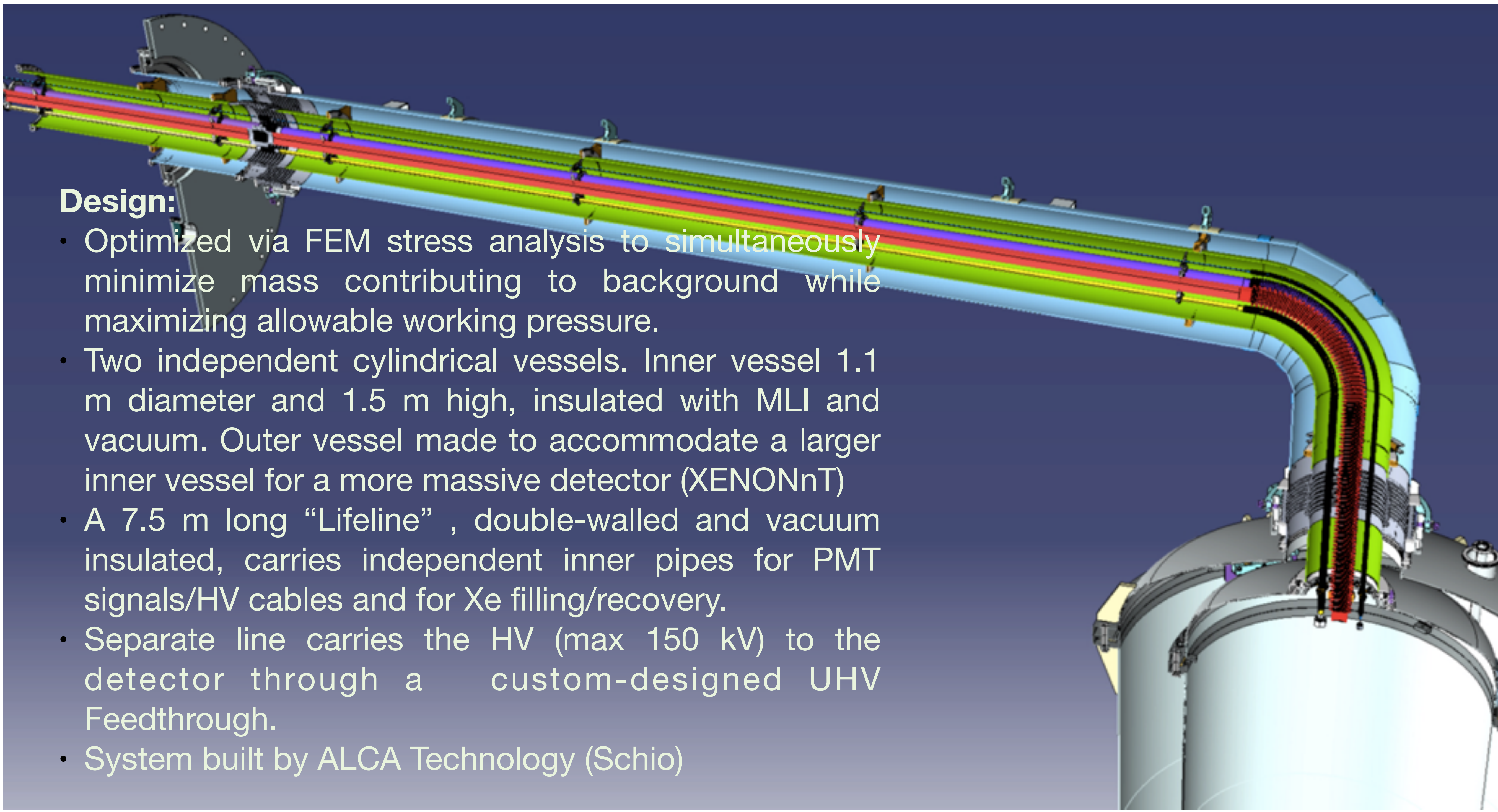
- Full tank
- Water quality


جامعة نيويورك أبوظبي
NYU ABU DHABI



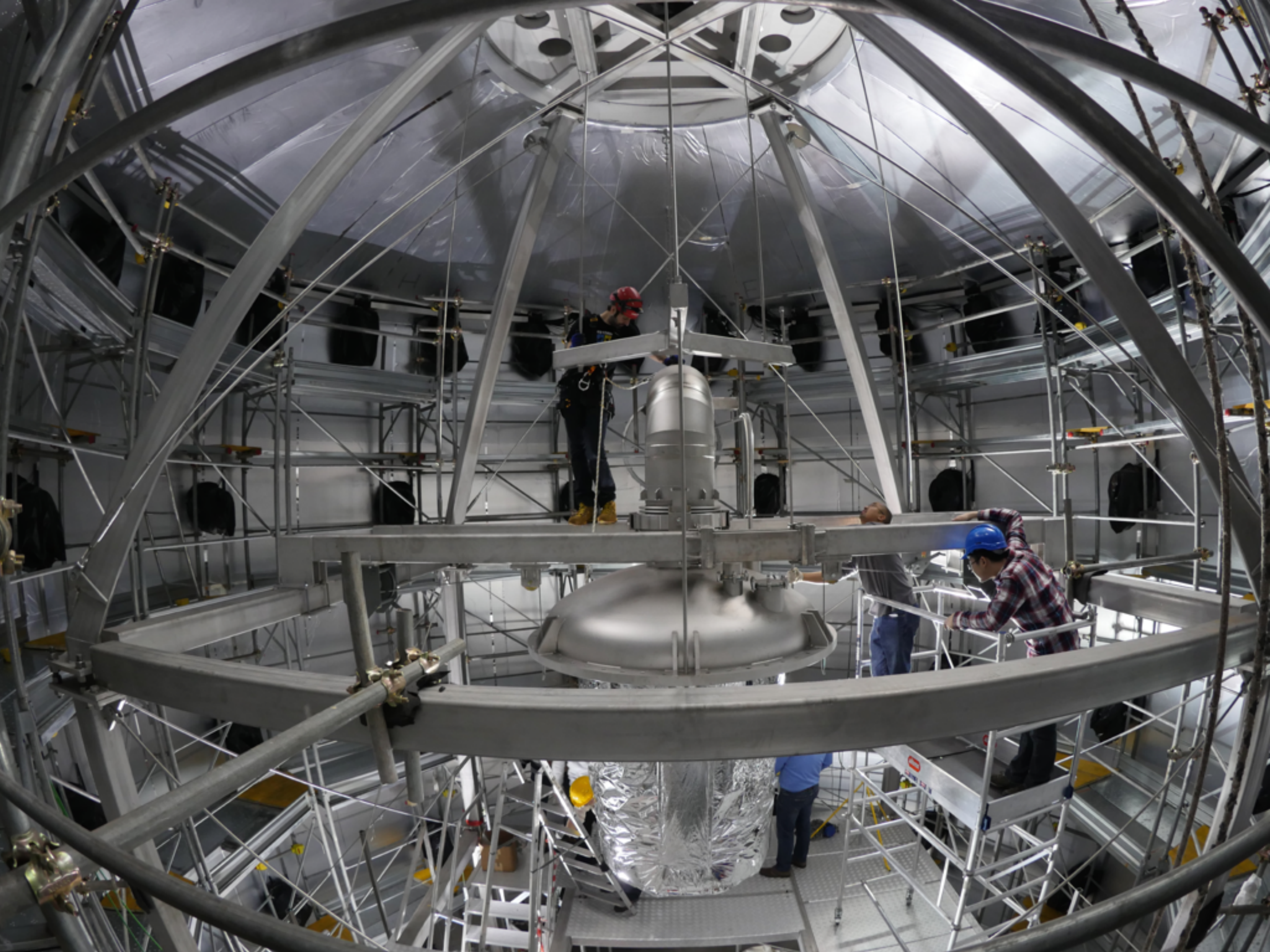
Cryostat: Columbia

Goal: a ultra-high-vacuum, thermally insulated system made of low-radioactivity material, to contain the detector with 3.5 tons of LXe at -95 C and 2 bar pressure and to couple it to the cryogenics system outside the water shield. Electropolished and with minimum welds, without thorium or cerium.



Design:

- Optimized via FEM stress analysis to simultaneously minimize mass contributing to background while maximizing allowable working pressure.
- Two independent cylindrical vessels. Inner vessel 1.1 m diameter and 1.5 m high, insulated with MLI and vacuum. Outer vessel made to accommodate a larger inner vessel for a more massive detector (XENONnT)
- A 7.5 m long “Lifeline” , double-walled and vacuum insulated, carries independent inner pipes for PMT signals/HV cables and for Xe filling/recovery.
- Separate line carries the HV (max 150 kV) to the detector through a custom-designed UHV Feedthrough.
- System built by ALCA Technology (Schio)





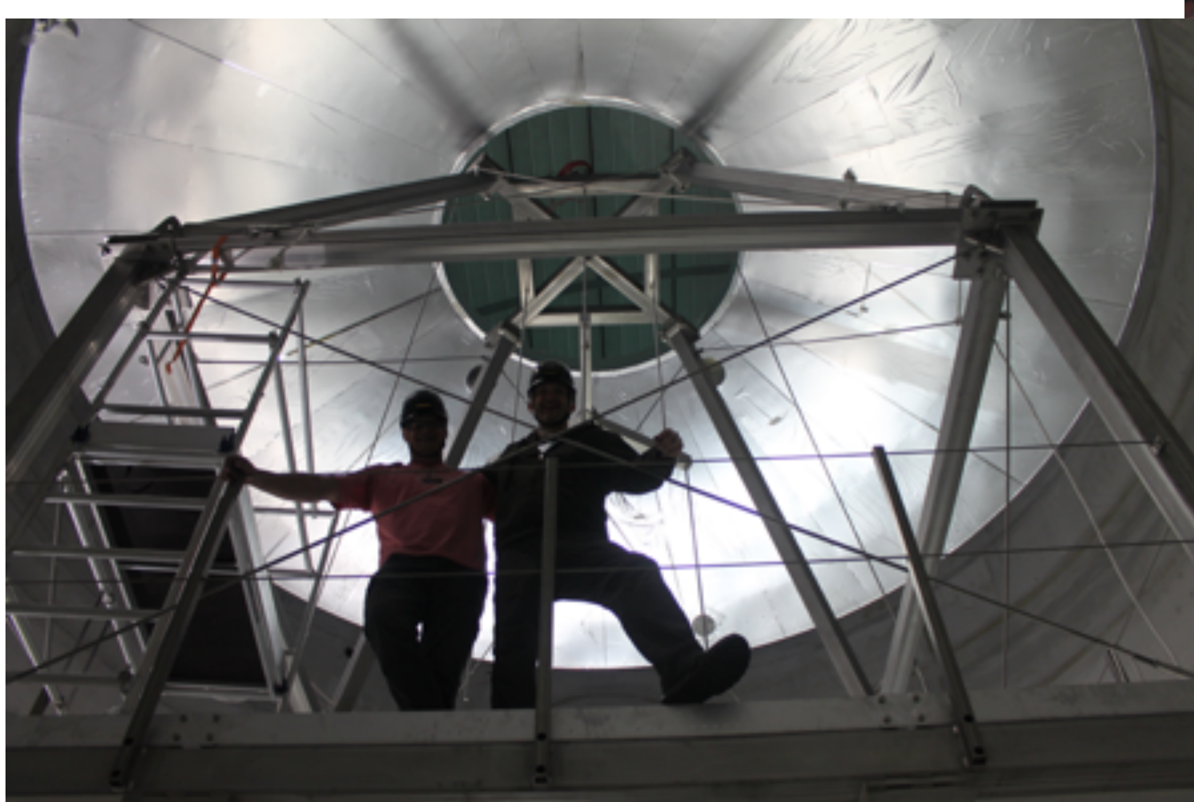
The Cryostat Support: Nikhef

Goals:

- suspension for the cryostat
- provide working platform under cryostat
- provide system to change level of cryostat/TPC

Features:

- designed by Nikhef in 2011- 13
- built by DVL in the Netherlands
- installed at LNGS in 2014



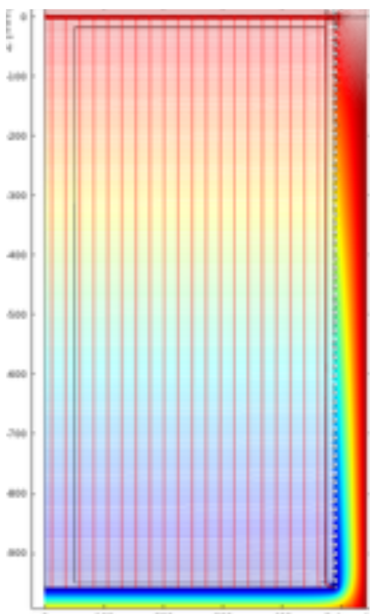
Time Projection Chamber

Goal: build a ultra-low-background two-phase XeTPC with the best performance for WIMP detection.

The XENON1T TPC has the longest drift (~1 m) and largest active mass of LXe (~2000 kg) of any TPC built to-date

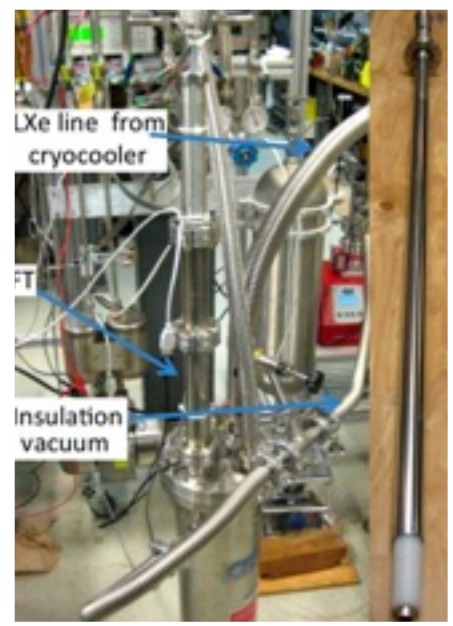
Team: Bern, Columbia, Zürich, Rice, UCLA, Mainz, Chicago, Abu Dhabi, Coimbra, Münster.

XENON Demonstrator
@ Columbia



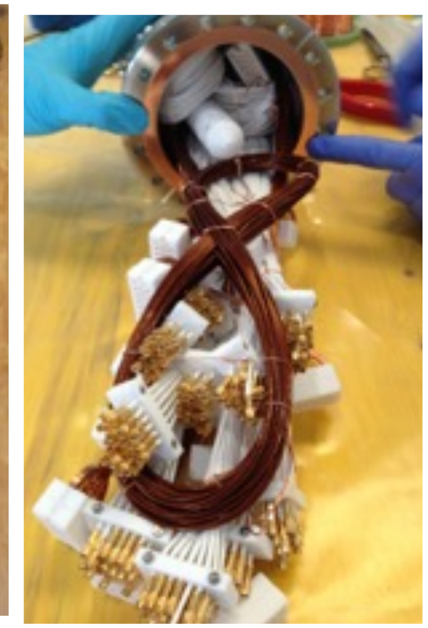
Electric Field Simulations
@ Rice, UCLA, Zürich, Coimbra

PTFE Reflectivity:
@ Münster, Bern, Columbia

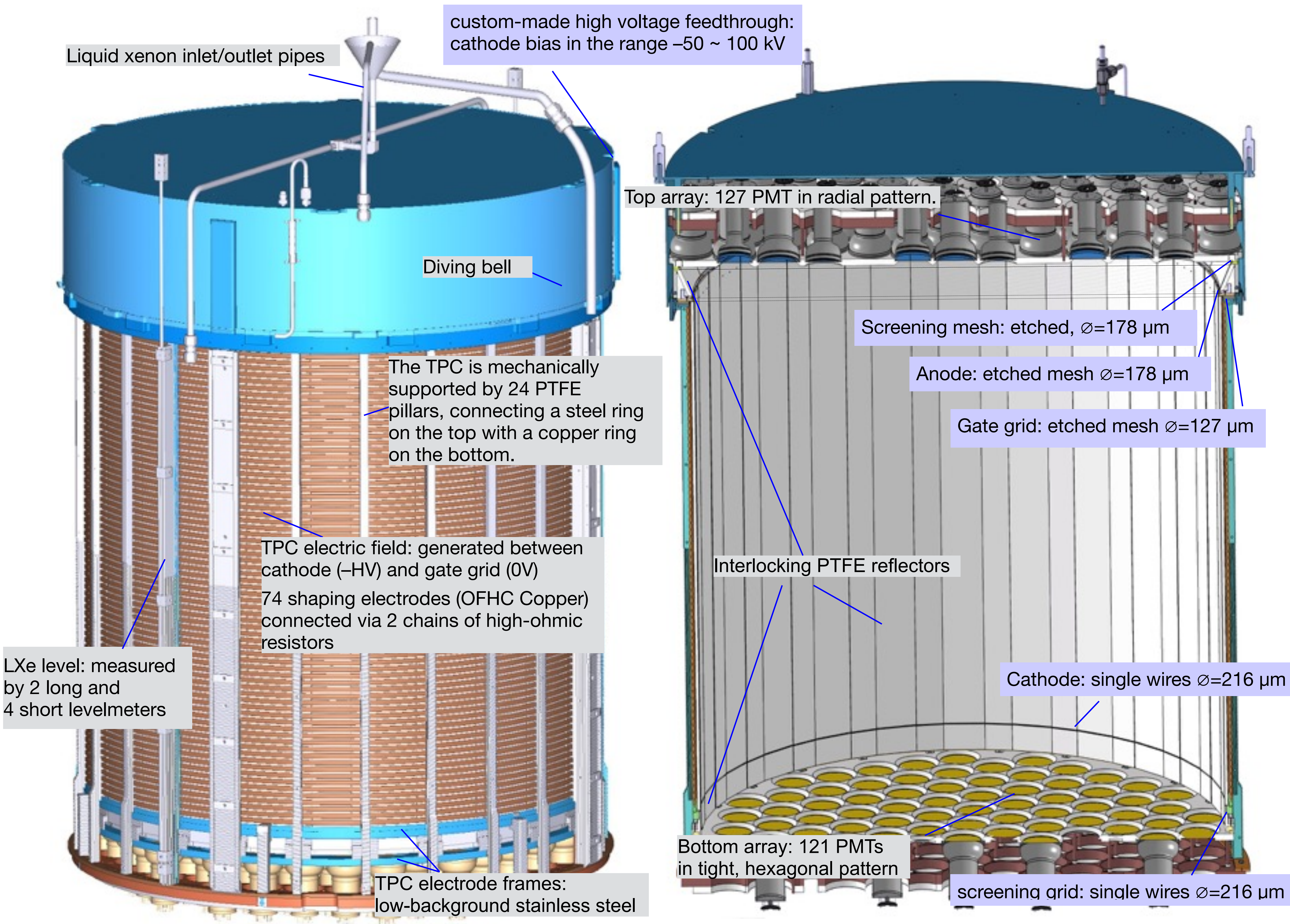


High voltage feedthough @ UCLA

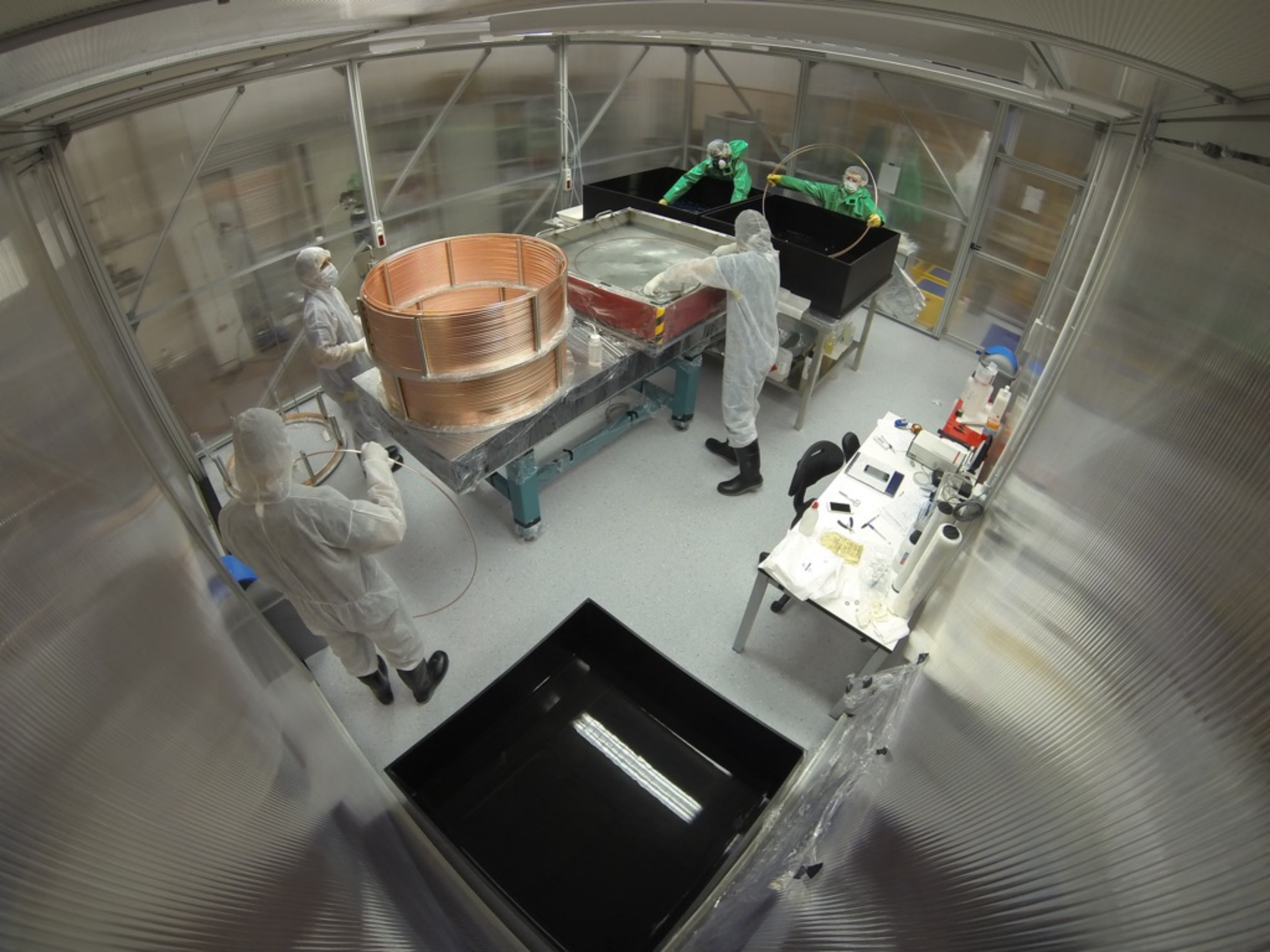
Cables and Connectors:
@ Zürich, Bern

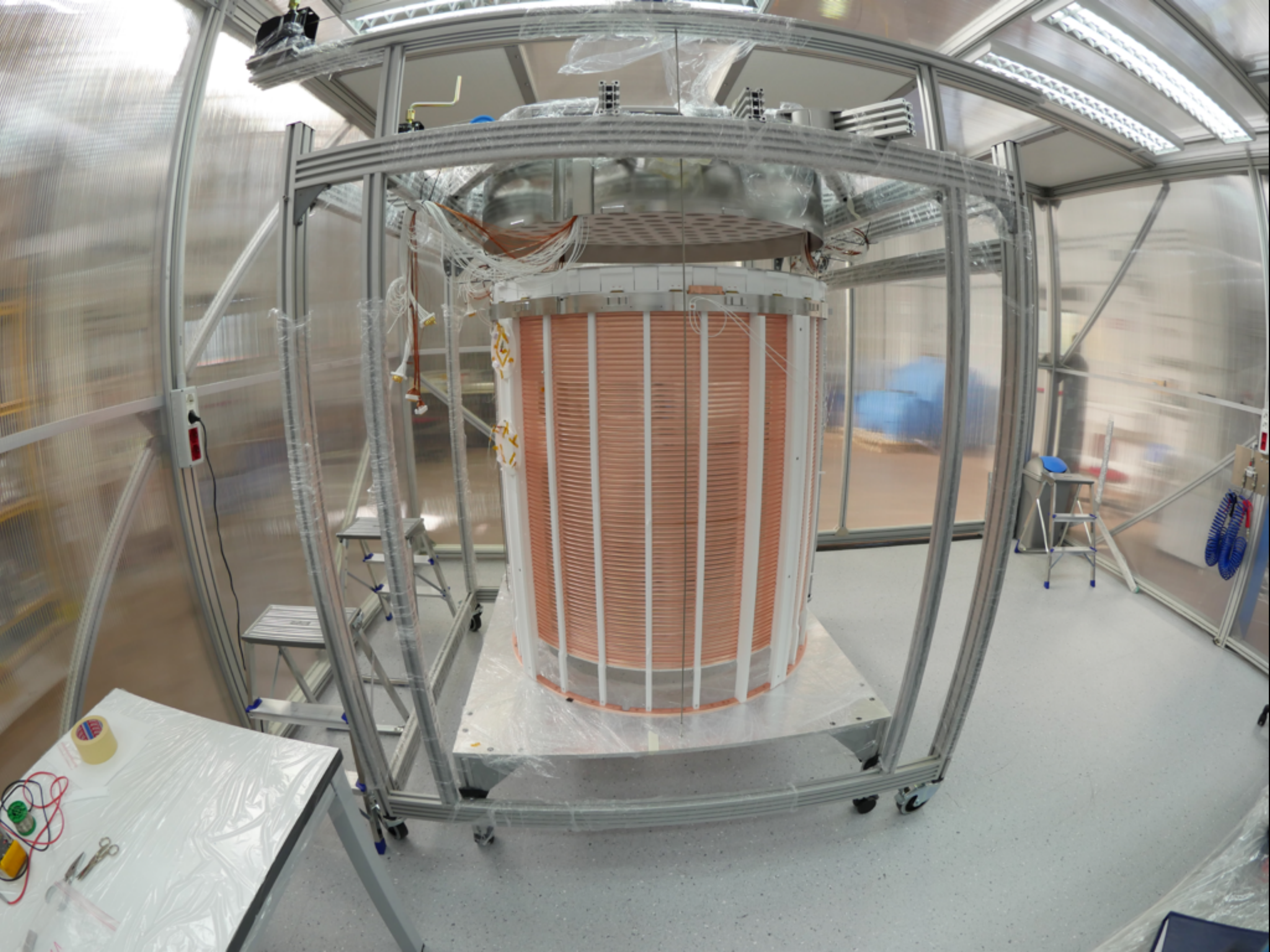


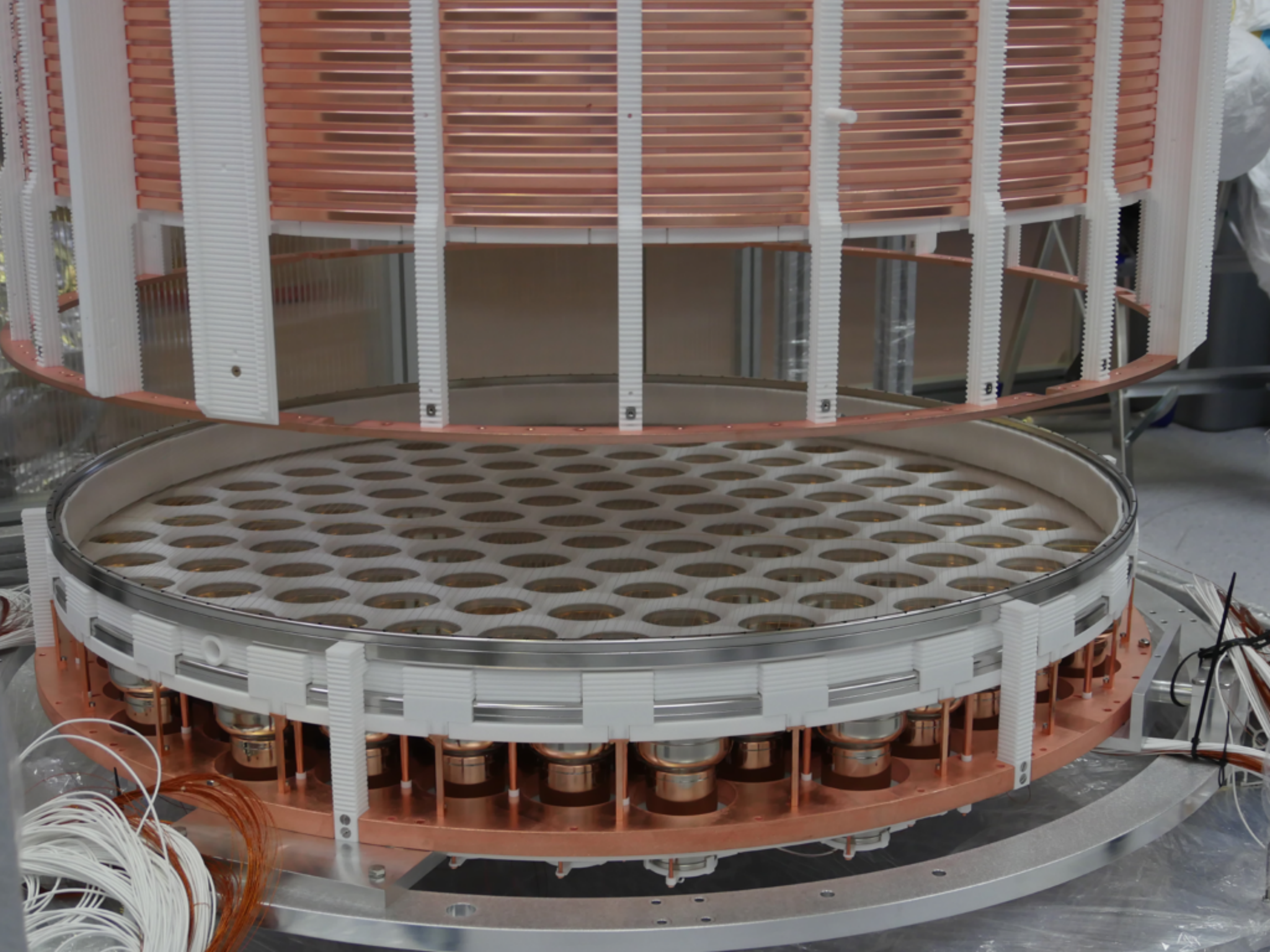
Status:
Installed in CR above ground and moved inside cryostat last week. Filling with 3500 kg of LXe will start before end of 2015.



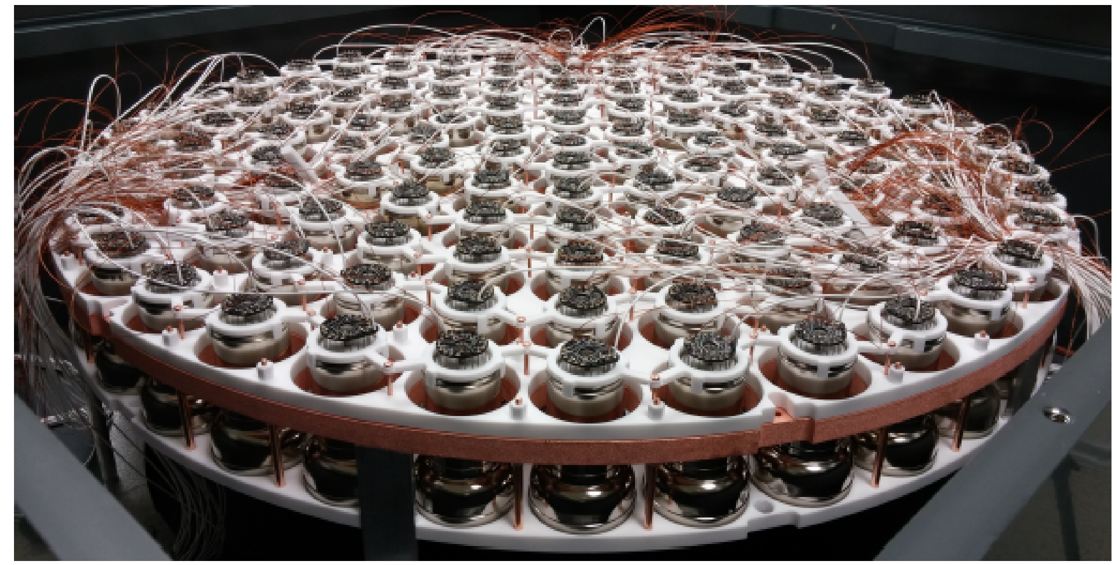
Liquid xenon inlet/outlet pipes
custom-made high voltage feedthrough: cathode bias in the range –50 ~ 100 kV
Top array: 127 PMT in radial pattern.
Diving bell
Screening mesh: etched, ∅=178 µm
Anode: etched mesh ∅=178 µm
The TPC is mechanically supported by 24 PTFE pillars, connecting a steel ring on the top with a copper ring on the bottom.
Gate grid: etched mesh ∅=127 µm
TPC electric field: generated between cathode (–HV) and gate grid (0V)
74 shaping electrodes (OFHC Copper) connected via 2 chains of high-ohmic resistors
Interlocking PTFE reflectors
LXe level: measured by 2 long and 4 short levelmeters
Cathode: single wires ∅=216 µm
Bottom array: 121 PMTs in tight, hexagonal pattern
TPC electrode frames: low-background stainless steel
screening grid: single wires ∅=216 µm

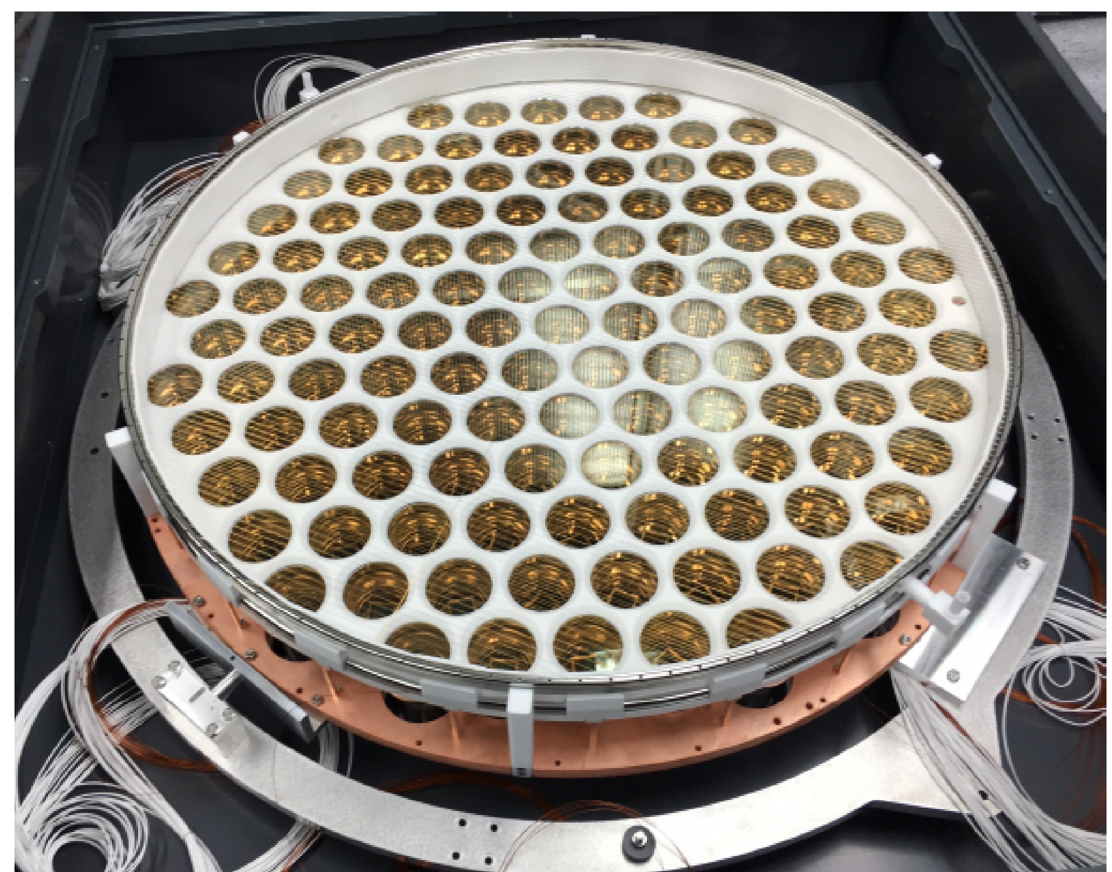






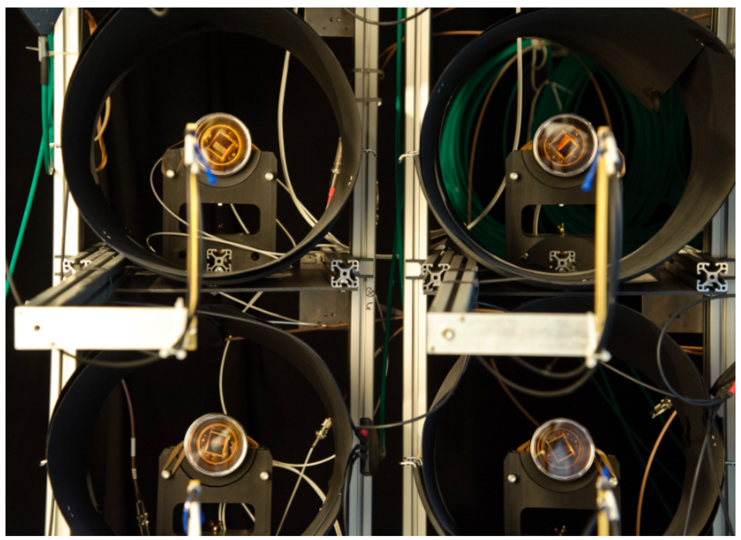
The PMTs: MPIK and Zurich

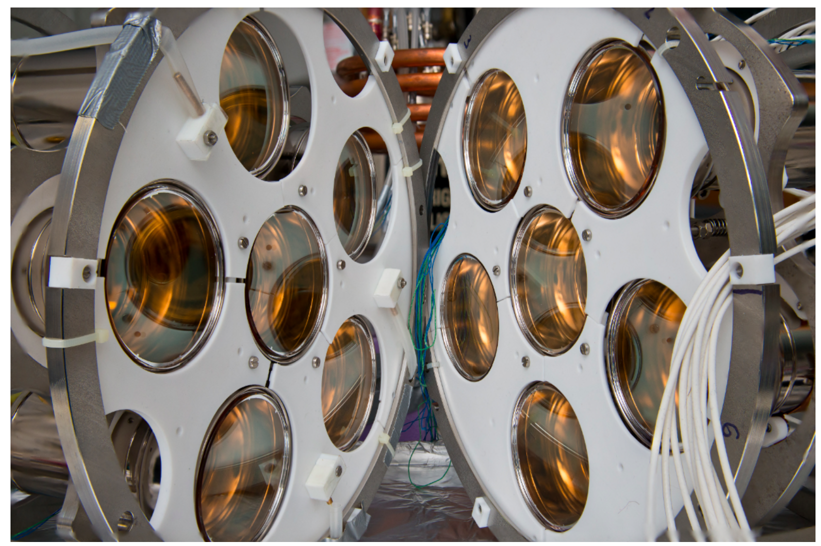


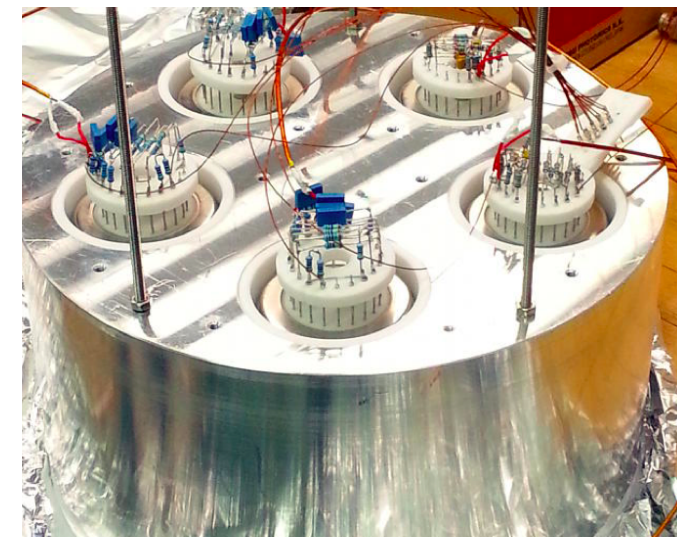


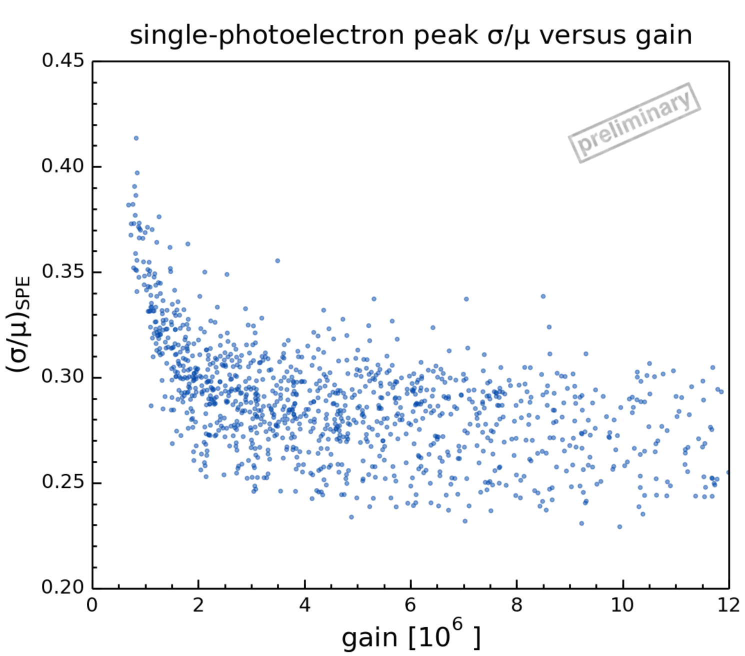
Characterization of PMTs

- Setups at MPIK and Zurich to test all delivered PMTs

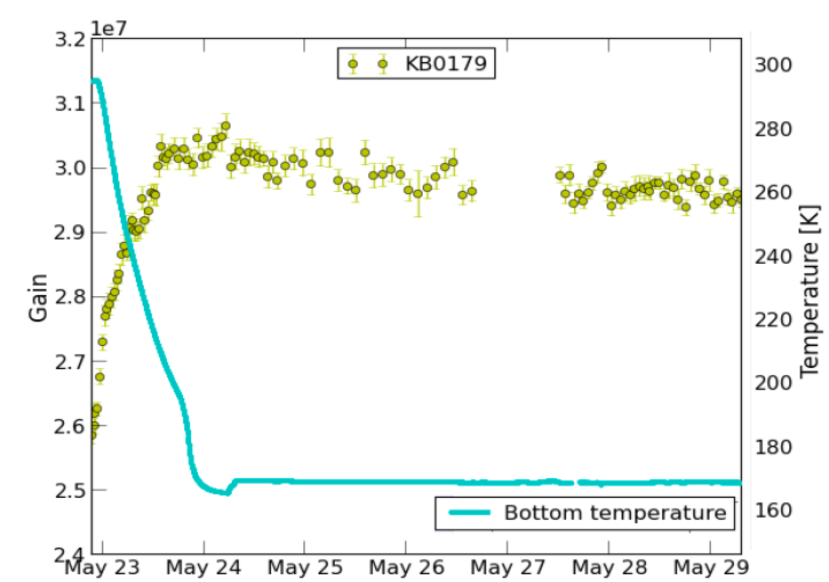

Dark room setup for room T tests


Setup to cool down 250 PMTs


Setup for testing part of the PMTs in LXe



- Average QE at 34%
- Gain average @1500 V: 5×10^6
- Single photoelectron resolution: 30%
- Dark count rate at $-100°$: ~ 40 Hz



PMT stability in LXe

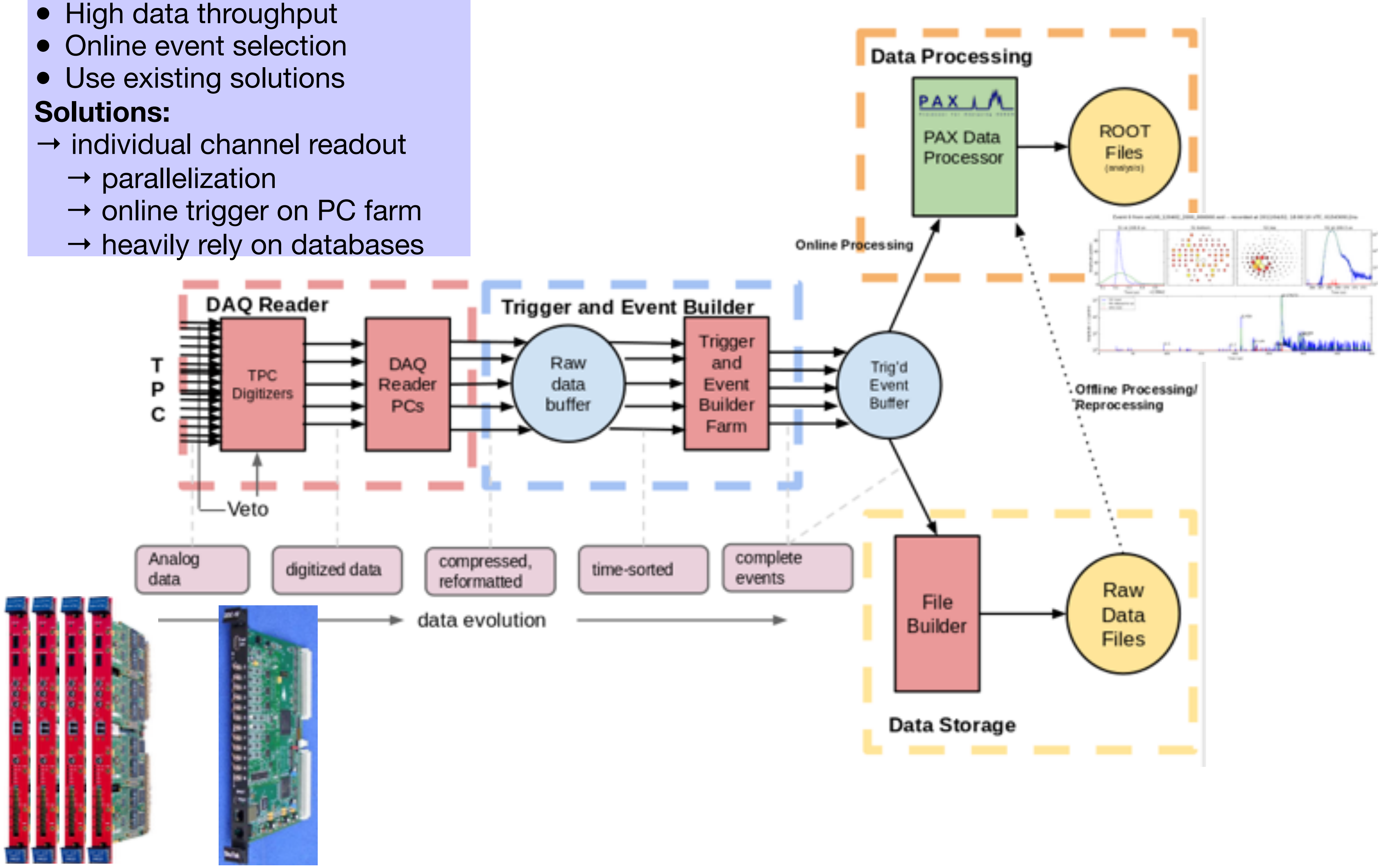
Data Acquisition (DAQ): Bern/Nikhef

Goal: Read the data from PMTs at high speed, select interesting events (online veto and event selection), store data to file, process raw data to get to physical quantities.

Design goals:
- Lowest possible threshold
- High data throughput
- Online event selection
- Use existing solutions

Solutions:

→ individual channel readout
  → parallelization
  → online trigger on PC farm
  → heavily rely on databases



Status:
- Successfully tested on 80ch end-to-end prototype and on XENON100. Installed underground. Ready for first XENON1T data, which is required to fine-tune the system.

Xenon 1T Slow Control System:
Coimbra, Weizmann, ROI, Columbia, Muenster

Goal: The Slow Control system operates and monitors the experiment.

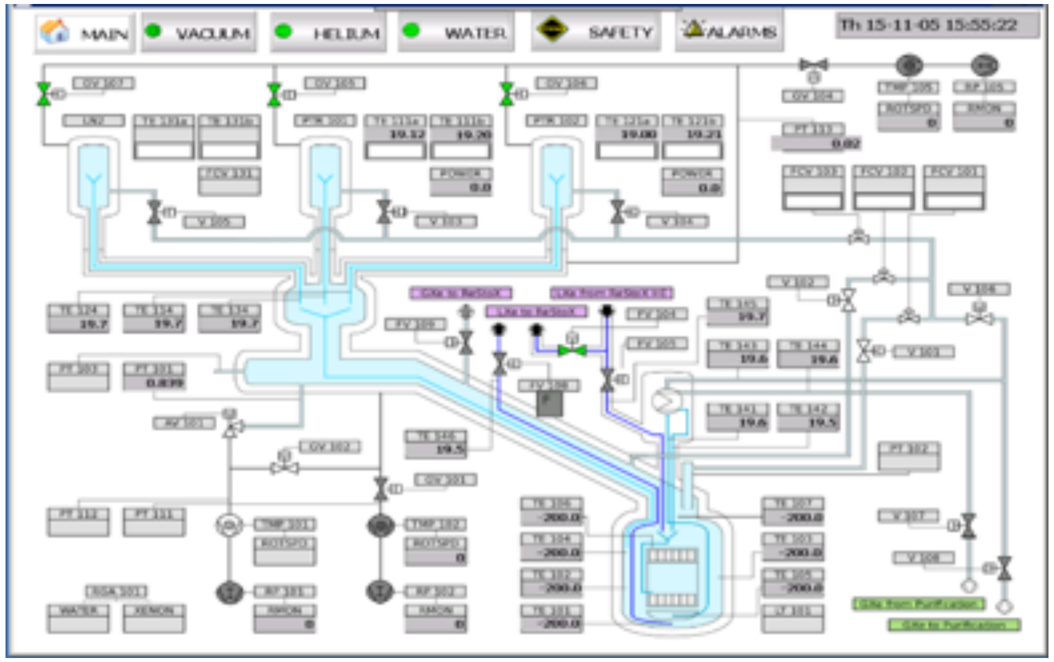
- Display and secure storage of the history of all operating parameters
- Extreme care of the instrumentation and 3.5T of LXe by means of alarms, guarded operations and redundant systems

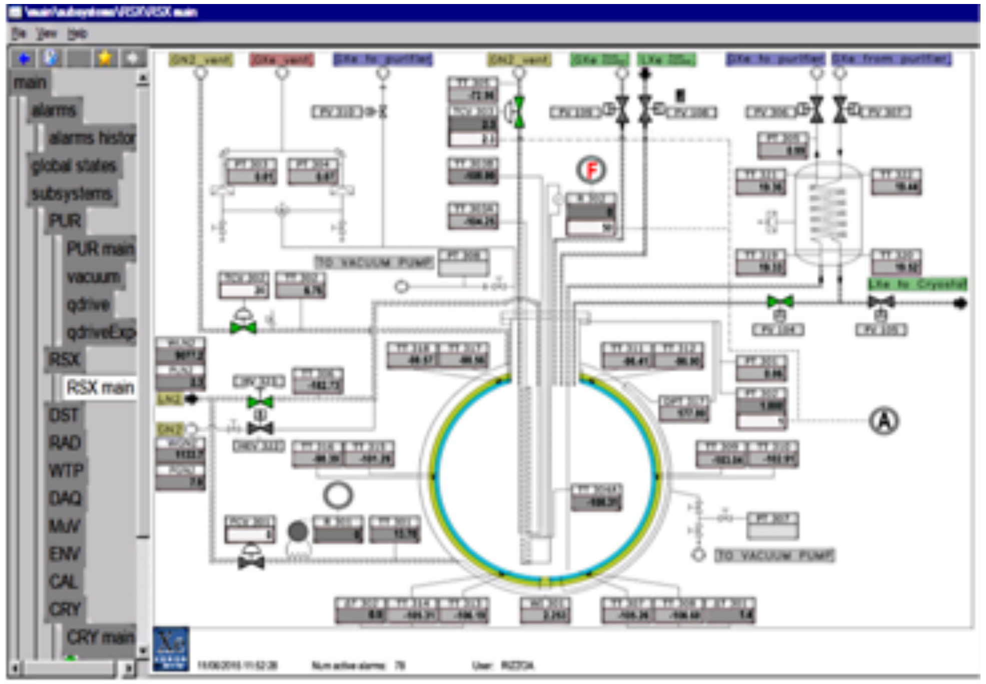
Status: The Slow Control system operates and monitors the experiment.

Local Control Station comprising an industrial Programmable Automation Controller (PAC) and its IO modules

Photographs gallery

The Cryogenic system touch panel





Central system user interface showing the ReStoX control panel

Display of historical values

To arrive at this beautiful detector it took years of design optimization with the strength of the experience and knowledge acquired with past XENON detectors but also with a long campaign to select materials with highest radio purity, through systematic screening and measurements to control and minimize Rn emanation

Material Screening and Selection: MPIK and UZH

Goal: Improve radio purity of all materials used in XENON1 detector by screening and selection: PMTs, Cryostat Stainless Steel, PTFE etc.

Method: multiple facilities available to Collaboration (at LNGS and MPIK). 200 samples measured with gamma spectroscopy and ~40 samples with mass spectroscopy.

GeMPI-1

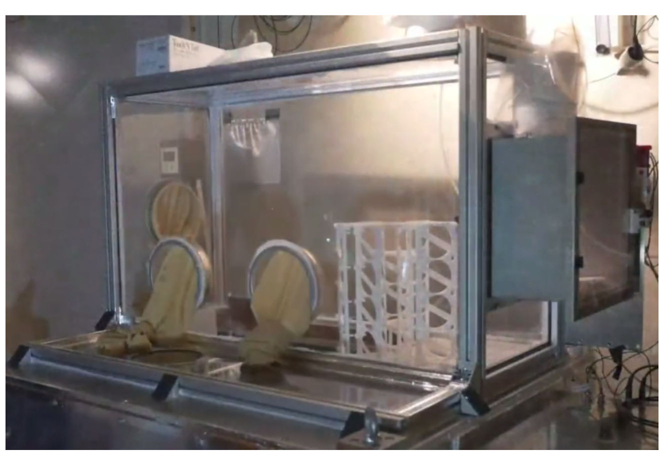
GeMPI-4

GeMPI facility at LNGS

GIOVE at MPIK

Screening Facilities:

- 3 GeMPIs (MPIK, located at LNGS)
- Gator (UZH, located at LNGS)
- 3 HPGe (MPIK, located at Heidelberg)
- Further detectors (LNGS, located at LNGS
- ICPMS (LNGS, located at LNGS)
- GDMS (UC, EAG company)



GATOR at LNGS

LNGS screening facility

Screening: PMTs

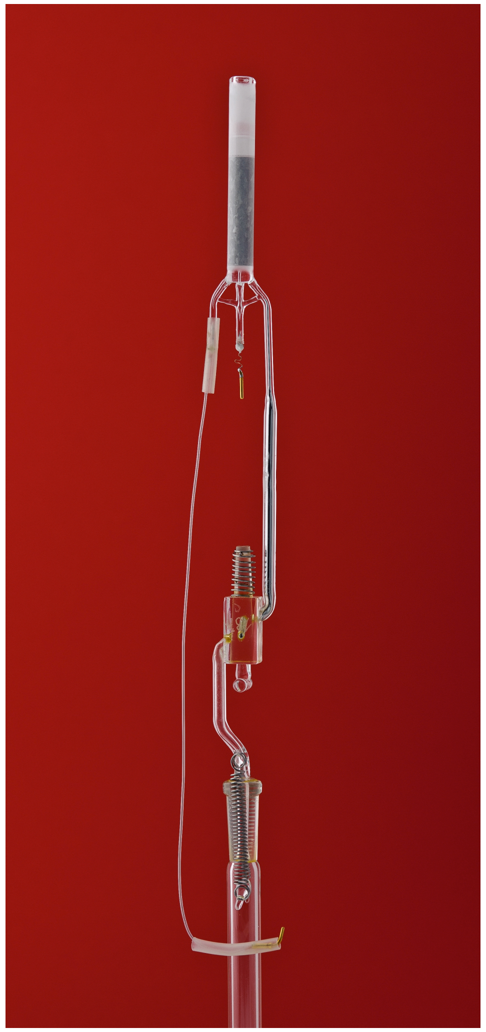
Radon Control and Measurement: MPIK

Goals:

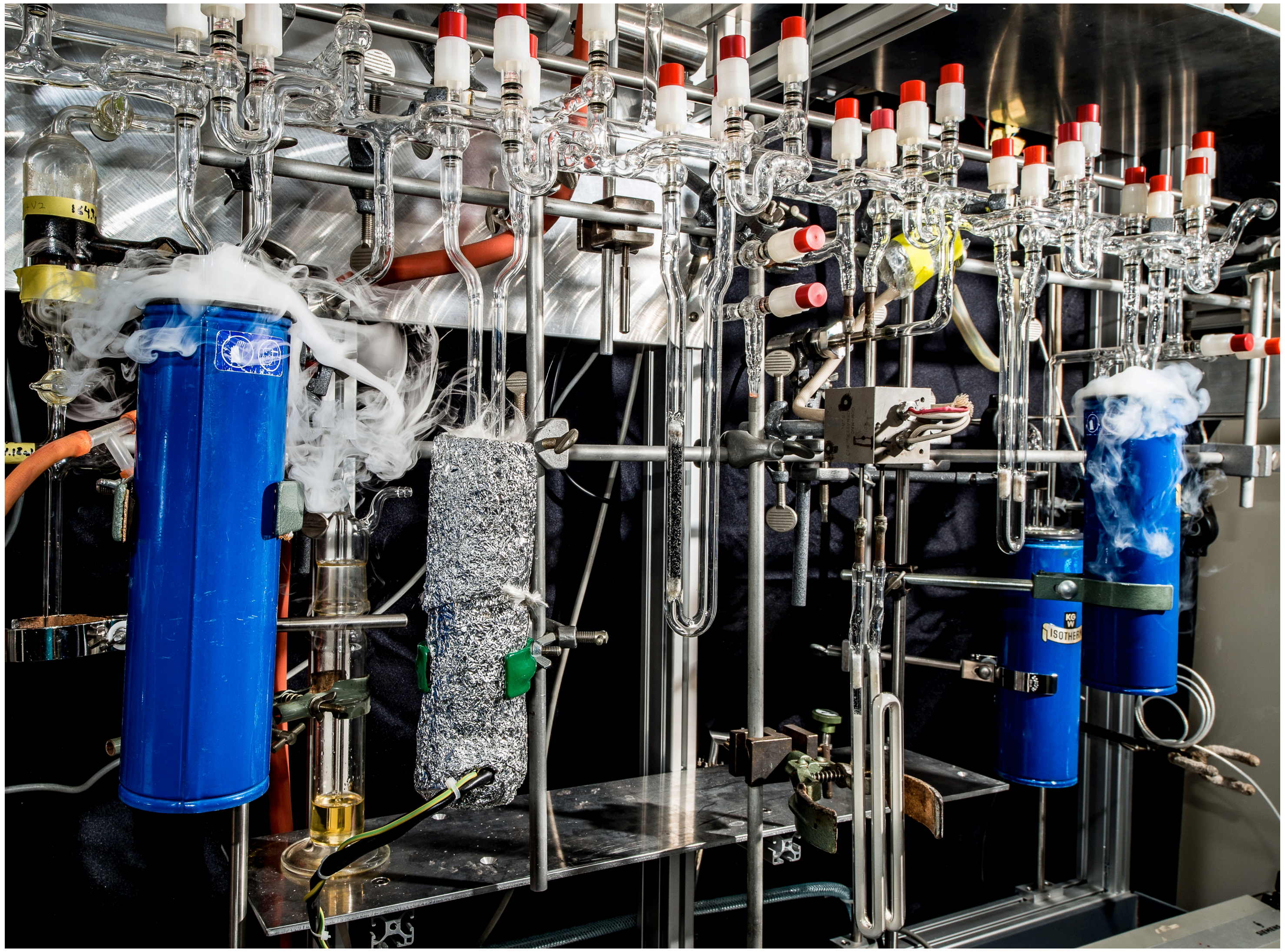
- Select construction materials with low radon (^{222}Rn) emanation rate.
- Implement measures to further reduce ^{222}Rn (alternative materials, surface cleaning procedures, etc.)
- Quantify and locate remaining ^{222}Rn sources

Method:

- ^{222}Rn detectors: Ultra-low background proportional counters. Sensitivity: 10 ^{222}Rn atoms (!).
- Screening of ~100 samples (2010 — 2015). Usually 2-3 measurements for each sample.
- Measurement of fully assembled sub-systems (cryostat, purification system, cryogenic system).
- Development of surface cleaning procedures optimized for ^{222}Rn in cooperation with TPC group.



Ultra-low background proportional counter.



Dedicated ultra-low background gas handling system for samples testing

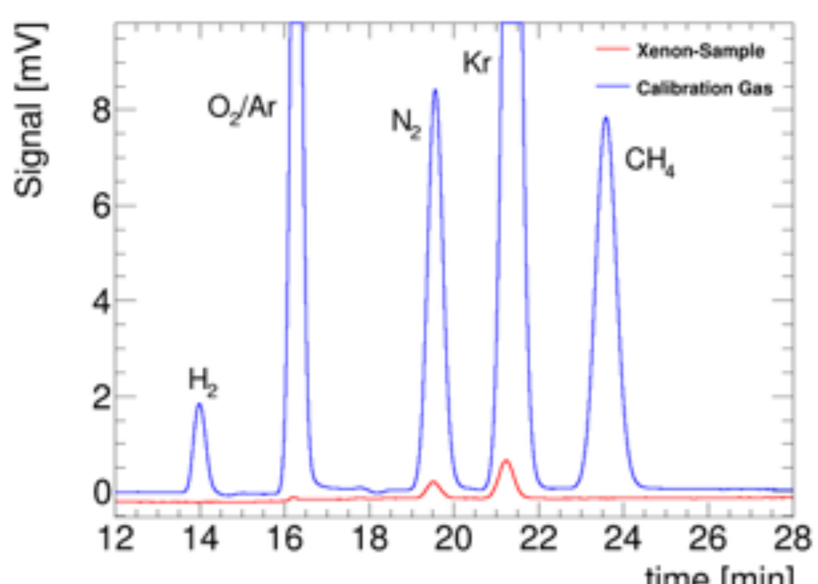
It takes ~600,000 liters of Xe gas to fill XENON1T with 3500 kg of LXe

Gas handling and impurity control: MPIK

Goal: measure impurities level of each cylinder of Xe gas prior to transferring into storage vessel (ReStoX) using a dedicated Gas Chromatograph.

- Connect and analyze up to four gas cylinders
- Sensitivities: 20 ppb (Kr), 50 ppb (N2, O2, Ar)

- Recuperate gas residuals during detector filling
- Interface for xenon transfer (detector to bottles, distillation column to bottles, bottles to bottles)



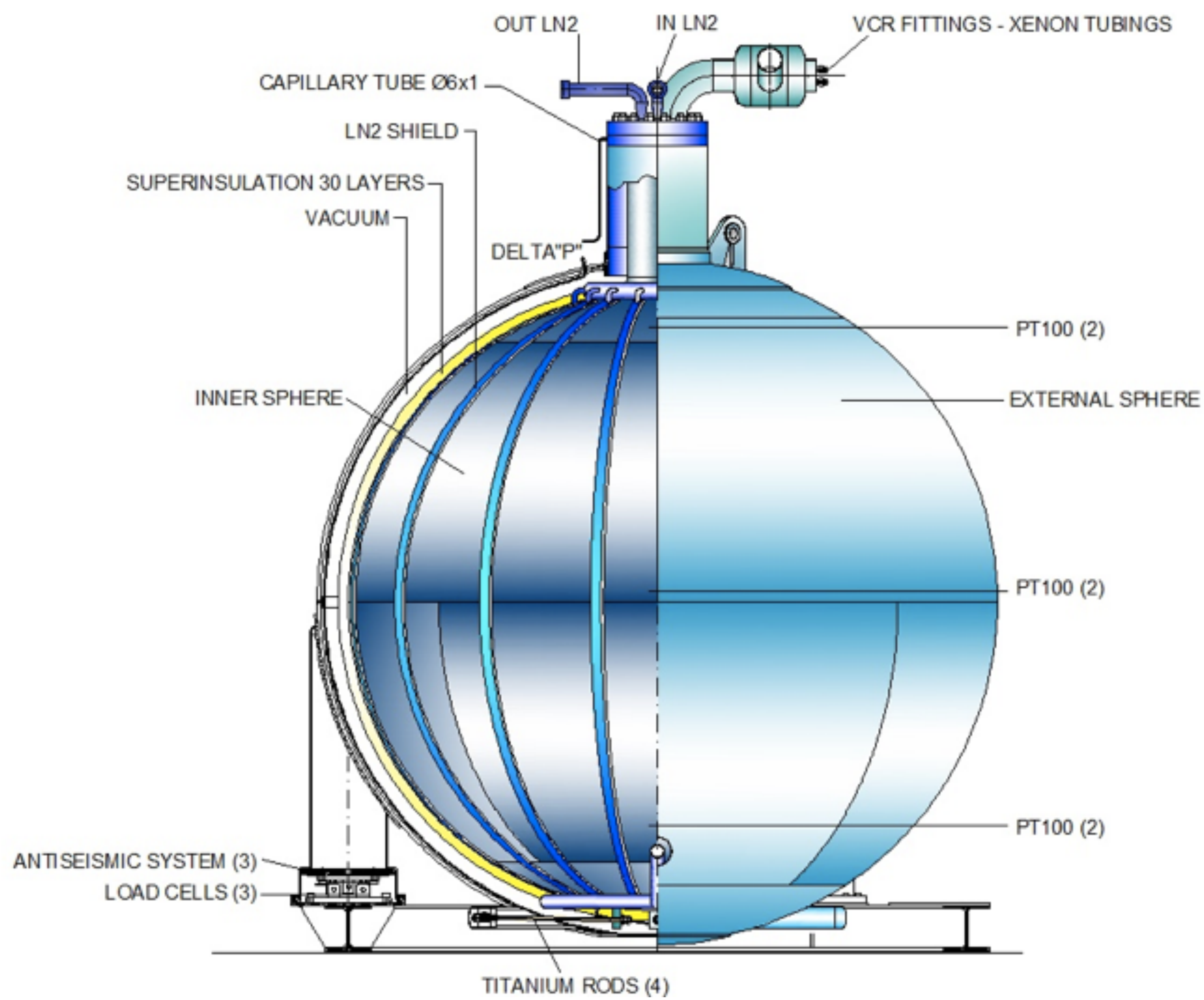
Recovery and Storage of Xe (ReStoX): Columbia/Subatech/Mainz

Goals:

- store up to 7600 kg of Xe in gaseous or liquid/solid phase under high purity conditions
- fill Xe in ultra-high-purity conditions into detector vessel
- recover all the Xe from the detector. In case of emergency all Xe can be safely recovered in a few hours

Method:

- Double walled, high pressure (72 bar) vacuum insulated sphere of 2.1 meter diameter, cooled by LN2 and by an internal LN-based condenser.
- Sphere built by Costruzioni Generali (Milano)
- Condenser built by DATE (France)
- Cryogenic Valves by Thermosess (Milano)
- Heat Exchanger by Ravanat (France)



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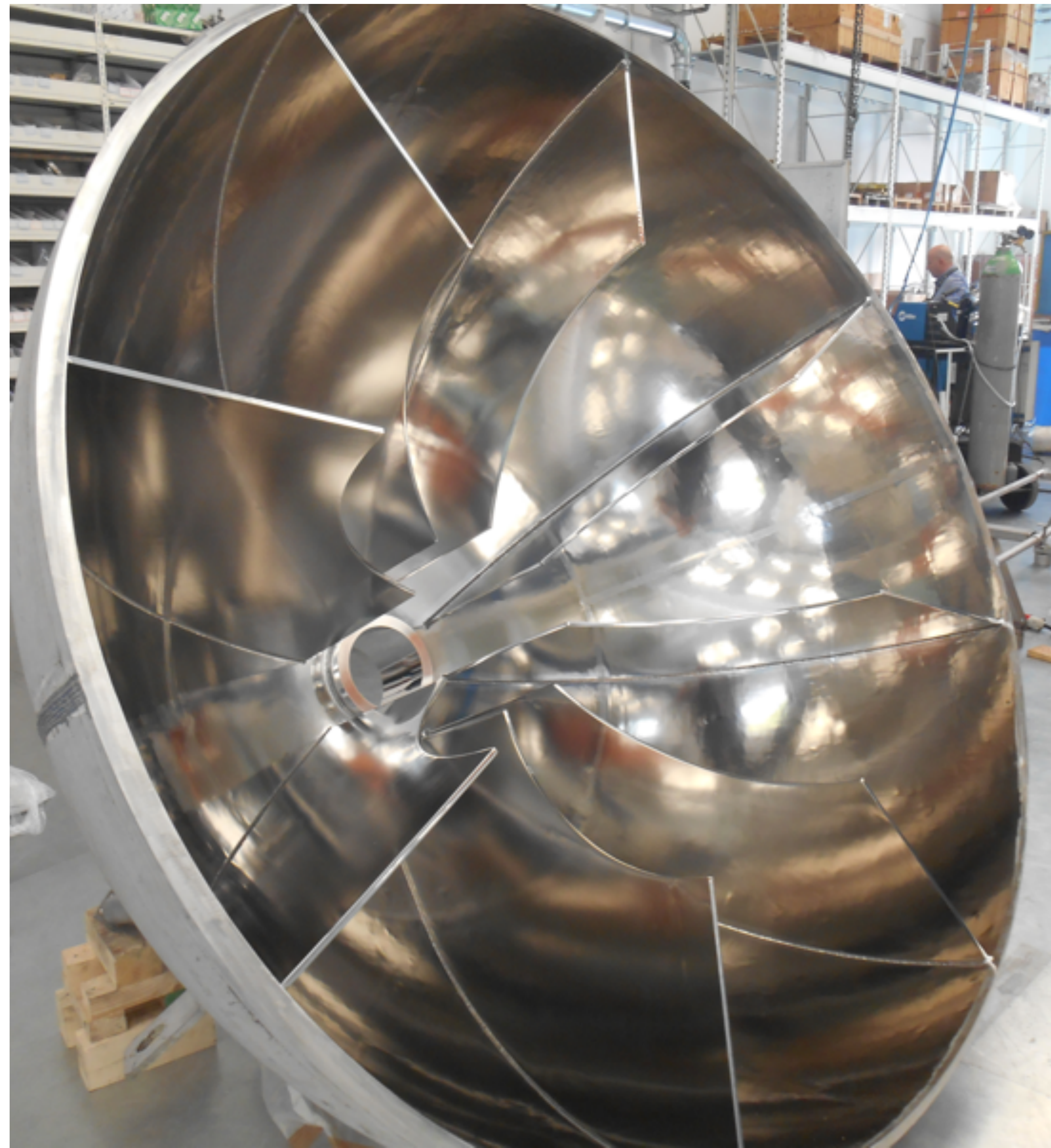
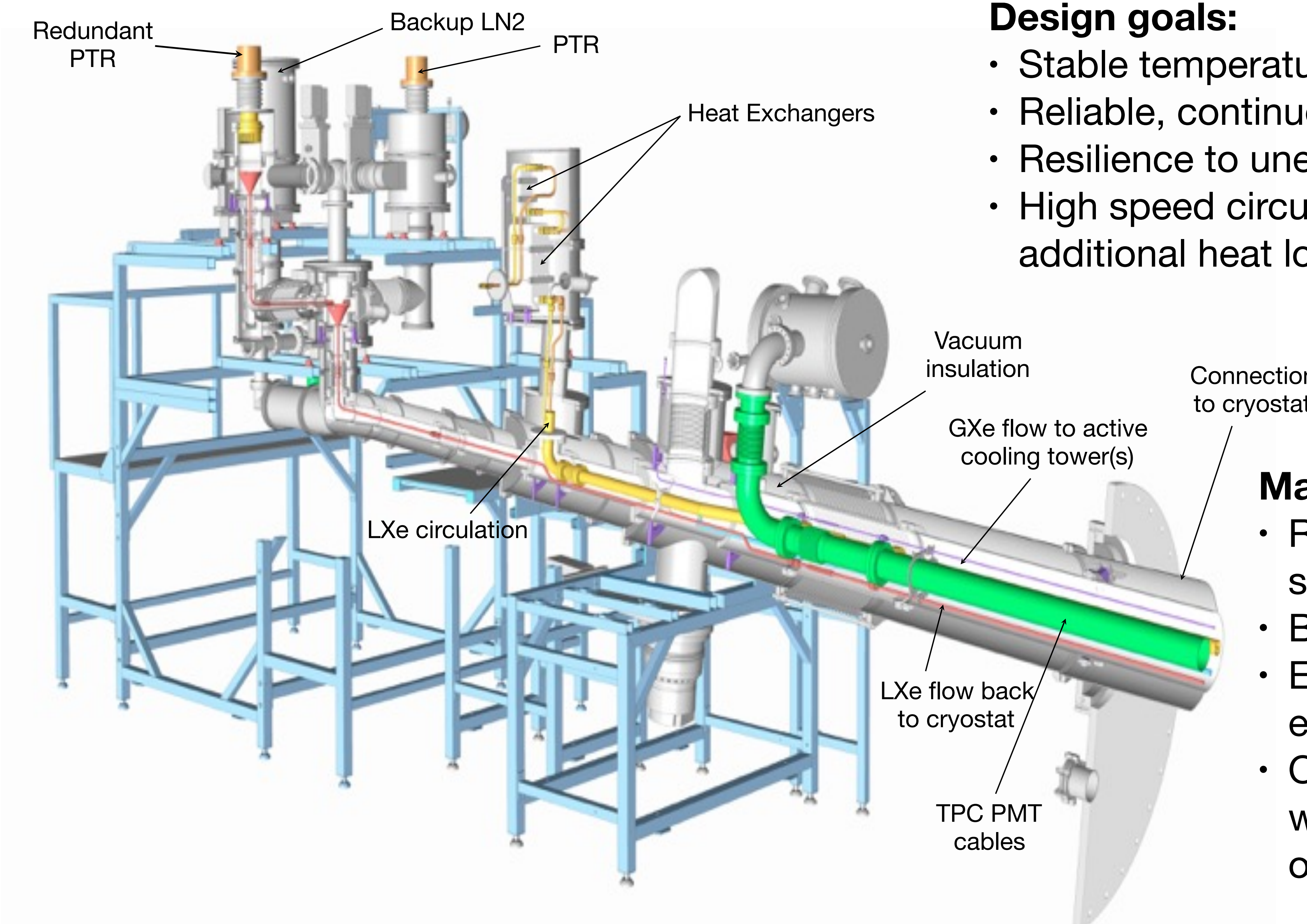


Cryogenic System: Columbia University

Goal: liquefy 3500 Kg of Xe and maintain the xenon in the cryostat in liquid form, at a constant temperature and pressure, and so for years without interruption.



Design goals:

- Stable temperature and pressure control
- Reliable, continuous, long term operation
- Resilience to unexpected failures
- High speed circulation with low additional heat load

Main features:

- Redundant PTR cooling systems
- Backup LN2 cooling tower
- Efficient two-phase heat exchangers
- One PTR can be serviced while the other is in operation


PFEIFFER VACUUM
PrismaPlus

Purification System: Columbia/Muenster/Rensselaer

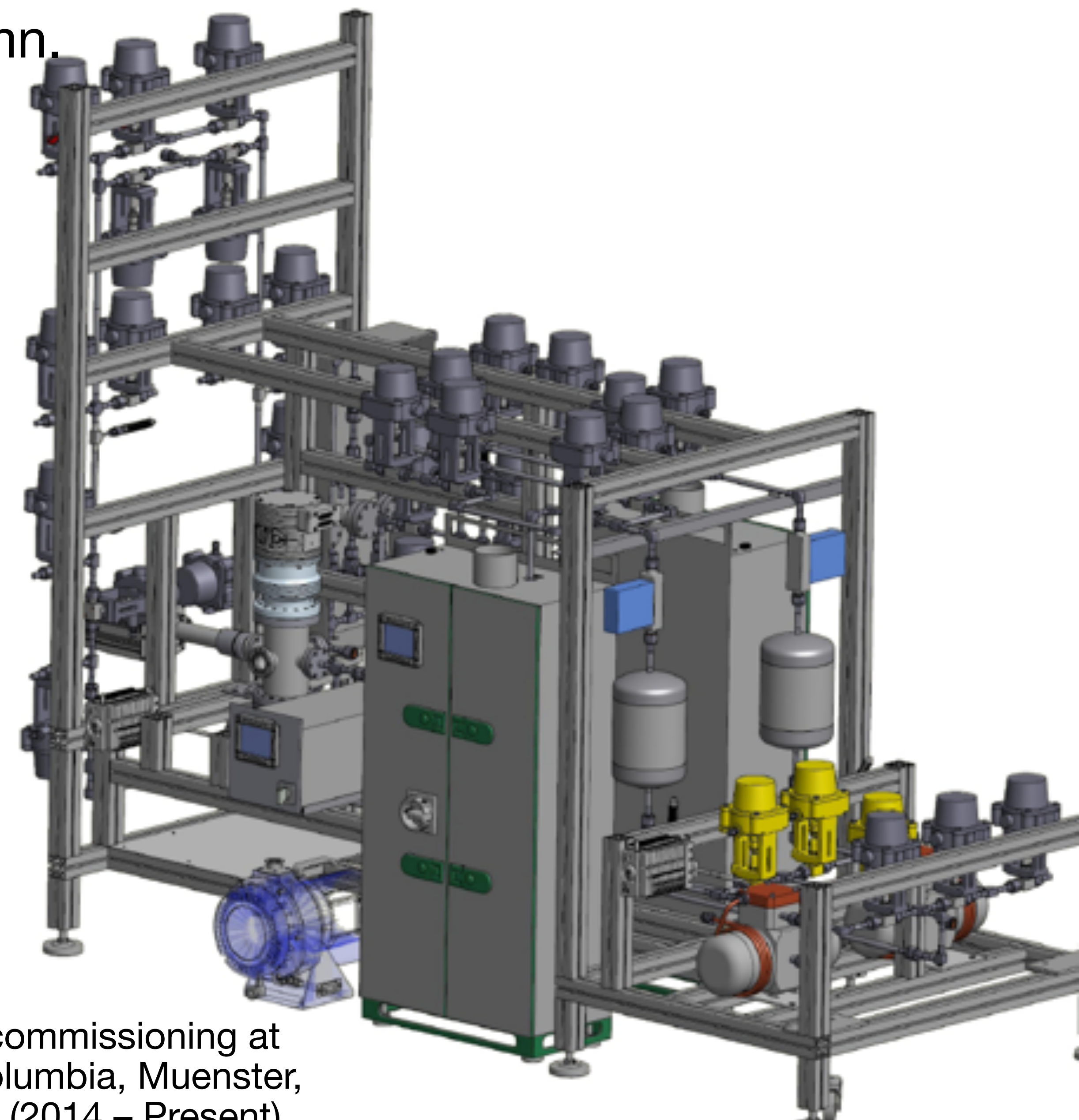
Goal: clean Xe from electronegative impurities via continuos circulation of gas through heated getters.

Method: implement a high flow rate purification system (100 SLPM) with two parallel custom-developed pumps (QDrive by Chart Industries) and two high capacity purifiers (Zirconium getter by SAES). Ultra clean components. Fully-automated remote operation. Successfully integrated and tested with the cryogenics/ReStoX and Kr-column.

Pump selection and characterization in Muenster and Columbia (2011 - 2013)

Assembly and commissioning in Muenster (2013 - 2014)

Installation and commissioning at LNGS, by the Columbia, Muenster, Rensselaer team (2014 – Present)



Cryogenic Distillation Column: Muenster

Goal: Active removal of Kr contamination in Xe. Natural Xe has Kr/Xe ~ $10^{-9} - 10^{-6}$ with trace amounts of ^{85}Kr of $^{85}\mathrm{Kr}/^{\mathrm{Nat}}\mathrm{Kr} \sim 10^{-11}$

Principle: cryogenic distillation exploits the 10 times higher vapor pressure of Kr w.r.t. Xe at -95°C to reach $^{\mathrm{Nat}}$Kr/Xe < 0.2 ppt for XENON1T.

Diagnostics: Atom Trap Trace Analysis **(**Columbia) and Rare Gas Mass Spectroscopy (MPIK)

5m

Design parameters:

- Separation factor: $10^4 - 10^5$
- Flow rate of 3kg/h -> whole XENON1T inventory can be purified within 6 weeks
- 99% Xenon recovery

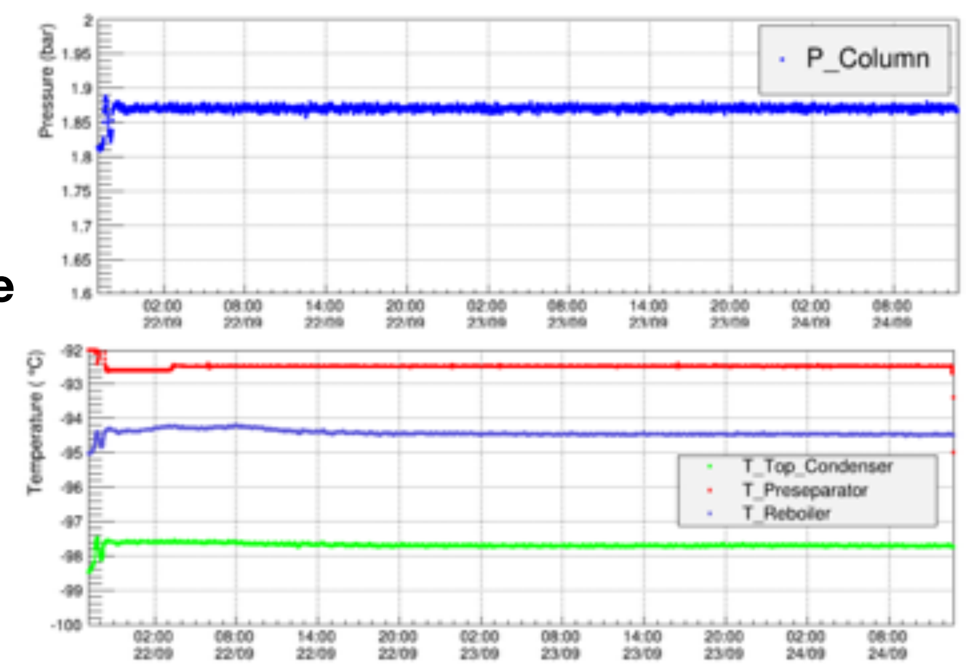
First results with distillation test facility (phase 1: 1m package material):

- Purified liquid out: $^{\mathrm{Nat}}$Kr/Xe < 0.026 ppt (90% c.l.)
- A factor ~10 better than required for XENON1T !
- Measured with GC-RGMS system at MPIK (S. Lindemann & H. Simgen, Eur. Phys. C 74 (2014) 2746): only a limit could be set!
- Alternative measurements by ATTA (E. Aprile et al., Rev. Sci. Instr. 84 (2013) 093105)

Reference:

- S. Rosendahl et al., JINST 9 (2014) P10010
- S. Rosendahl et al., Rev. Sci. Instr. 86 (2014) 115104
- E. Brown et al., JINST 8 (2013) P02011

Commissioning of the distillation column at XENON1T



- 70 hours of continuous distillation, 210 kg processed!
- Thermodynamic stability under design parameters demonstrated!
- Separation factor >100.000 demonstrated by GC-RGMS (MPIK)

Cryogenic Distillation Column: Muenster

Goal: Active removal of Kr contamination in Xe. Natural Xe has Kr/Xe ~ 10^{-9} – 10^{-6} with trace amounts of ^{85}Kr of ^{85}Kr/^{Nat}Kr ~ 10^{-11}

Principle: cryogenic distillation exploits the 10 times higher vapor pressure of Kr w.r.t. Xe at -95°C to reach ^{Nat}Kr/Xe < 0.2 ppt for XENON1T.

Diagnostics: Atom Trap Trace Analysis **(**Columbia) and Rare Gas Mass Spectroscopy (MPIK)

Design parameters:

- Separation factor: 10^4 – 10^5
- Flow rate of 3kg/h -> whole XENON1T inventory can be purified within 6 weeks
- 99% Xenon recovery

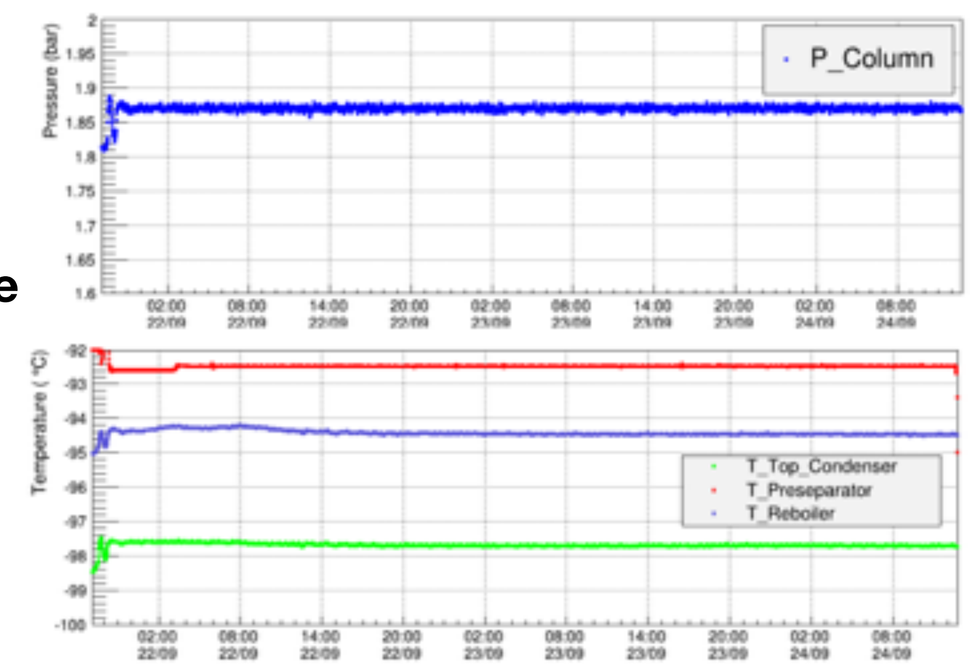
First results with distillation test facility (phase 1: 1m package material):

- Purified liquid out: ^{Nat}Kr/Xe < 0.026 ppt (90% c.l.)
- A factor ~10 better than required for XENON1T !
- Measured with GC-RGMS system at MPIK (S. Lindemann & H. Simgen, Eur. Phys. C 74 (2014) 2746): only a limit could be set!
- Alternative measurements by ATTA (E. Aprile et al., Rev. Sci. Instr. 84 (2013) 093105)

Reference:

- S. Rosendahl et al., JINST 9 (2014) P10010
- S. Rosendahl et al., Rev. Sci. Instr. 86 (2014) 115104
- E. Brown et al., JINST 8 (2013) P02011

Commissioning of the distillation column at XENON1T



- 70 hours of continuous distillation, 210 kg processed!
- Thermodynamic stability under design parameters demonstrated!
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Diagnostics: Atom Trap Trace Analysis **(**Columbia) and Rare Gas Mass Spectroscopy (MPIK)

Package material, type EX Sulzer

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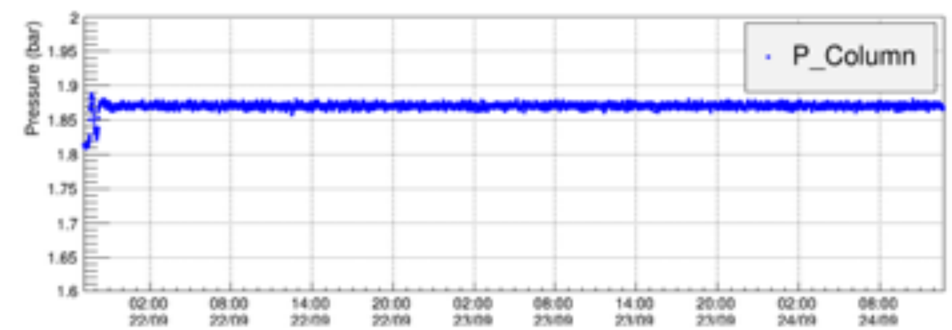
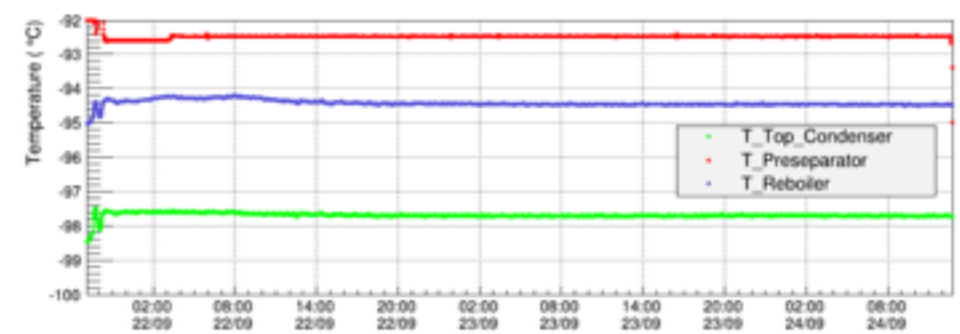
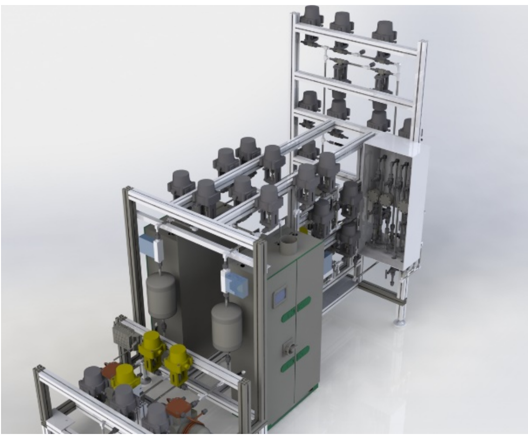


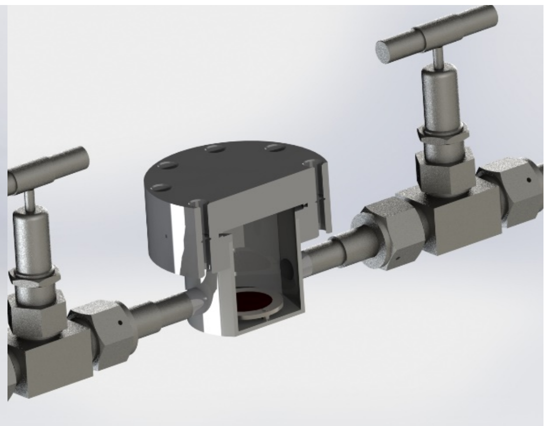


- 70 hours of continuous distillation, 210 kg processed!
- Thermodynamic stability under design parameters demonstrated!
- Separation factor >100.000 demonstrated by GC-RGMS (MPIK)

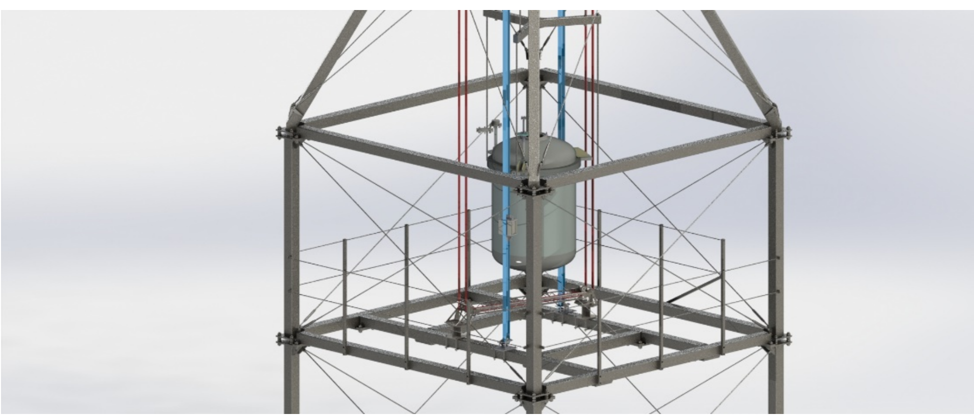
Detector Calibration: Purdue/WIS/Nikhef/UZH/UCSD

Goal: Accurately calibrate the detector response to electron and nuclear recoils

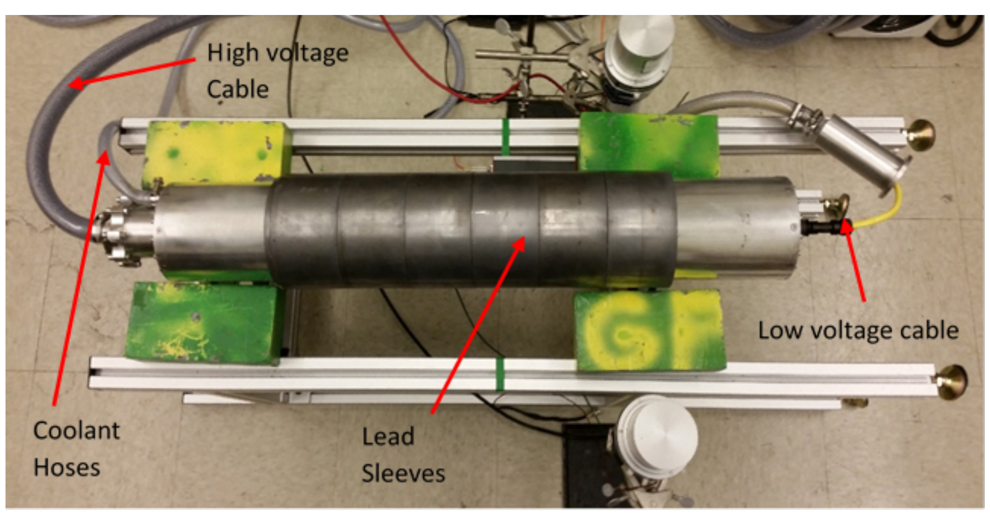




Internal Calibration Systems:
- Introduce radioactive sources directly into the gaseous xenon for uniform illumination.
- Use 220Rn, 83mKr and tritiated methane



Calibration Belts:
- Allow for transport of external sources into position around the cryostat
- Two belts for vertical displacement of sources
- One belt below cryostat



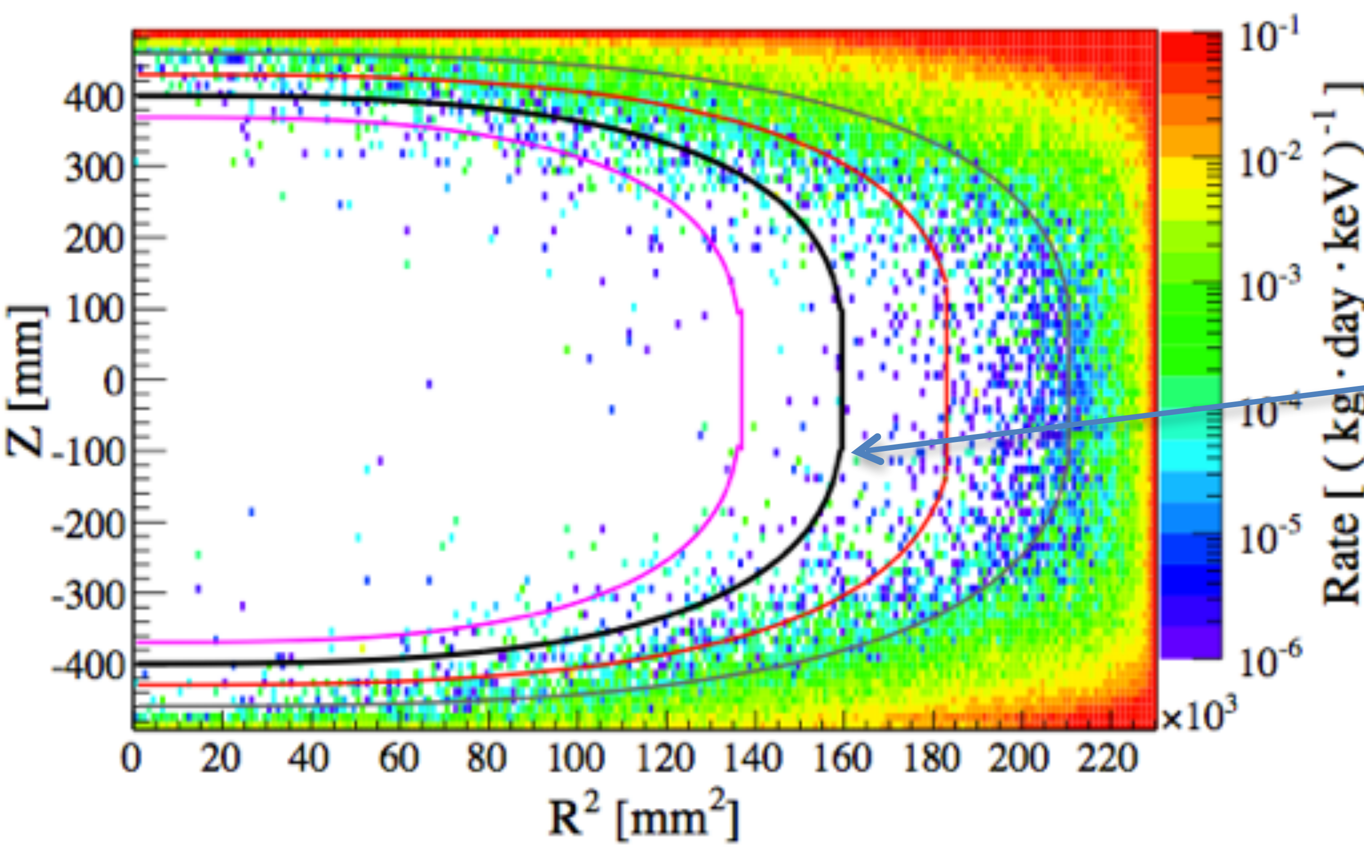
Neutron Generator:
- Use mono-energetic (2.5MeV) neutrons from deuterium-deuterium fusion generator
- Double scatter of neutrons will allow for in-situ calibration of nuclear recoil response

LED Calibration:
- Fiber optics guide light from external LED light sources into TPC
- Used to monitor performance of PMTs

Monte Carlo: Simulation of the experiment and estimation of the sensitivity

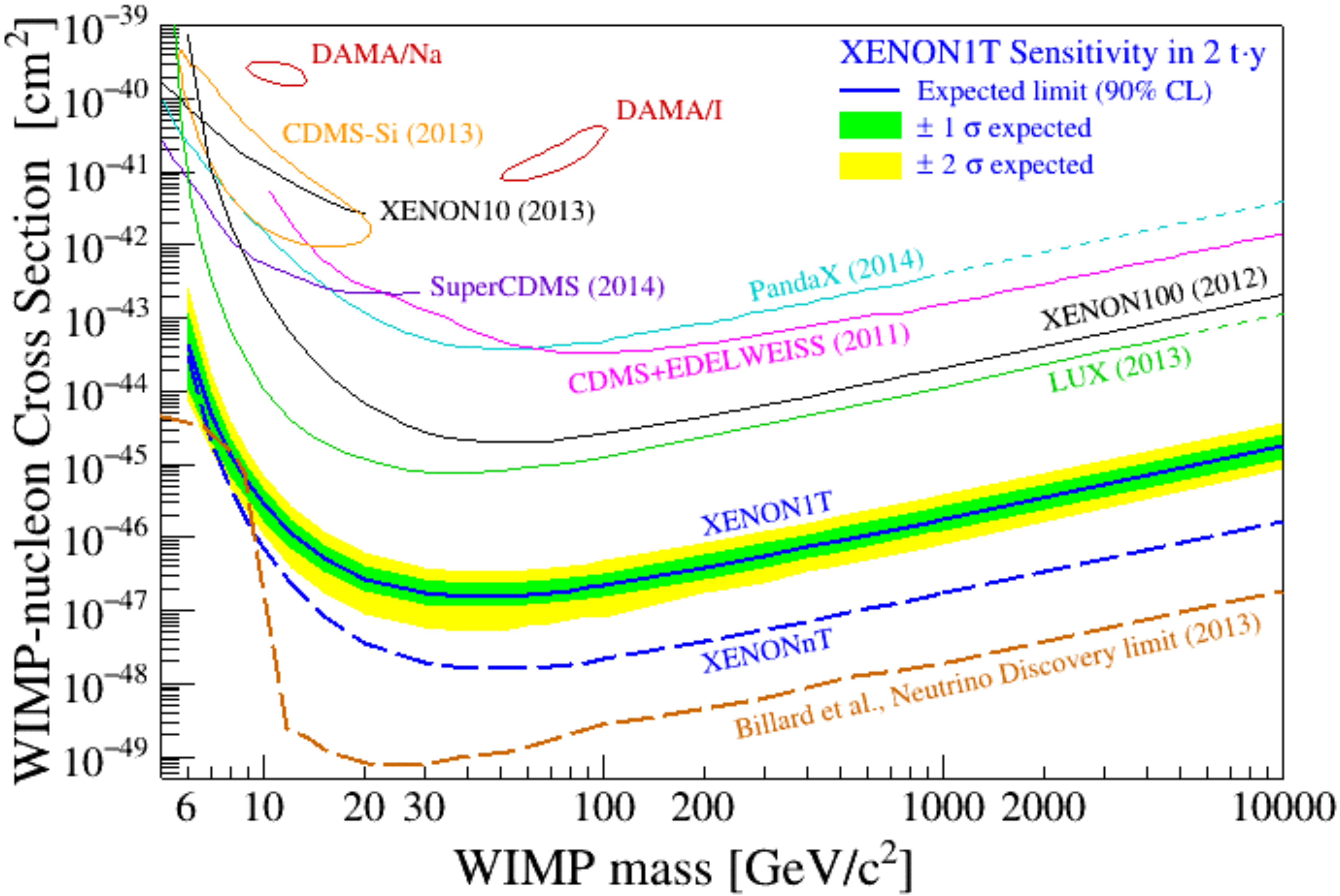
Goal: Reproduce via software the performance of the XENON1T detector, and predict the sensitivity of the experiment.

Team: Bologna University & INFN; Columbia University; Nikhef; Purdue University; Stockholm University; Universität Mainz; University of California San Diego; Universität Zurich; Weizmann Institute of Science.



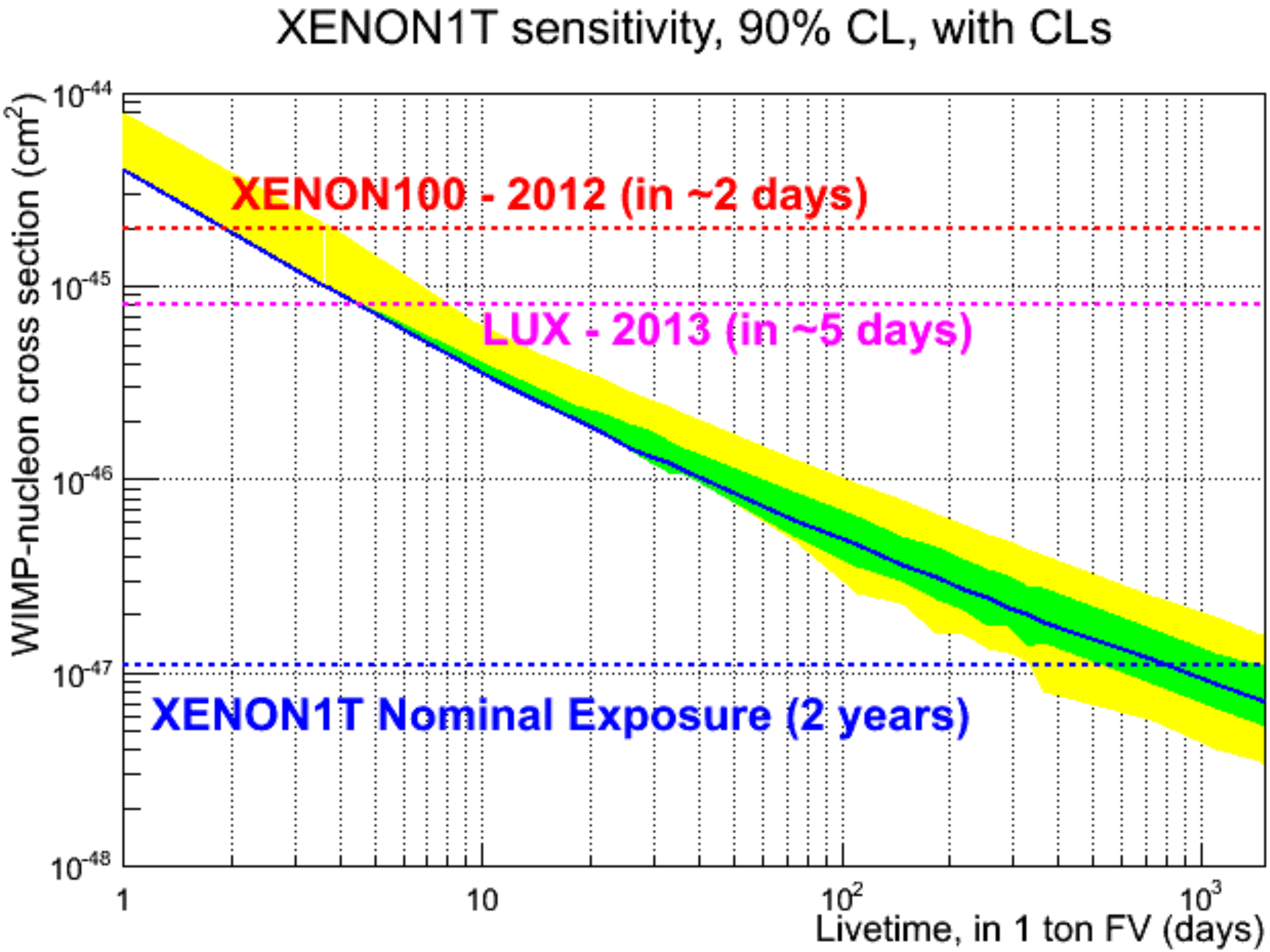
Position of the ER background from the materials: they are negligible inside the 1 ton fiducial volume.

XENON1T sensitivity



With XENON1T, 2 t*y, minimum cross section: $\sigma = 1.6 \times 10^{-47}$ cm^2 @ m = 50 GeV/c^2
Improvement by an order of magnitude with XENONnT, 20 t*y.

XENON1T Sensitivity vs Exposure



Summary and outlook

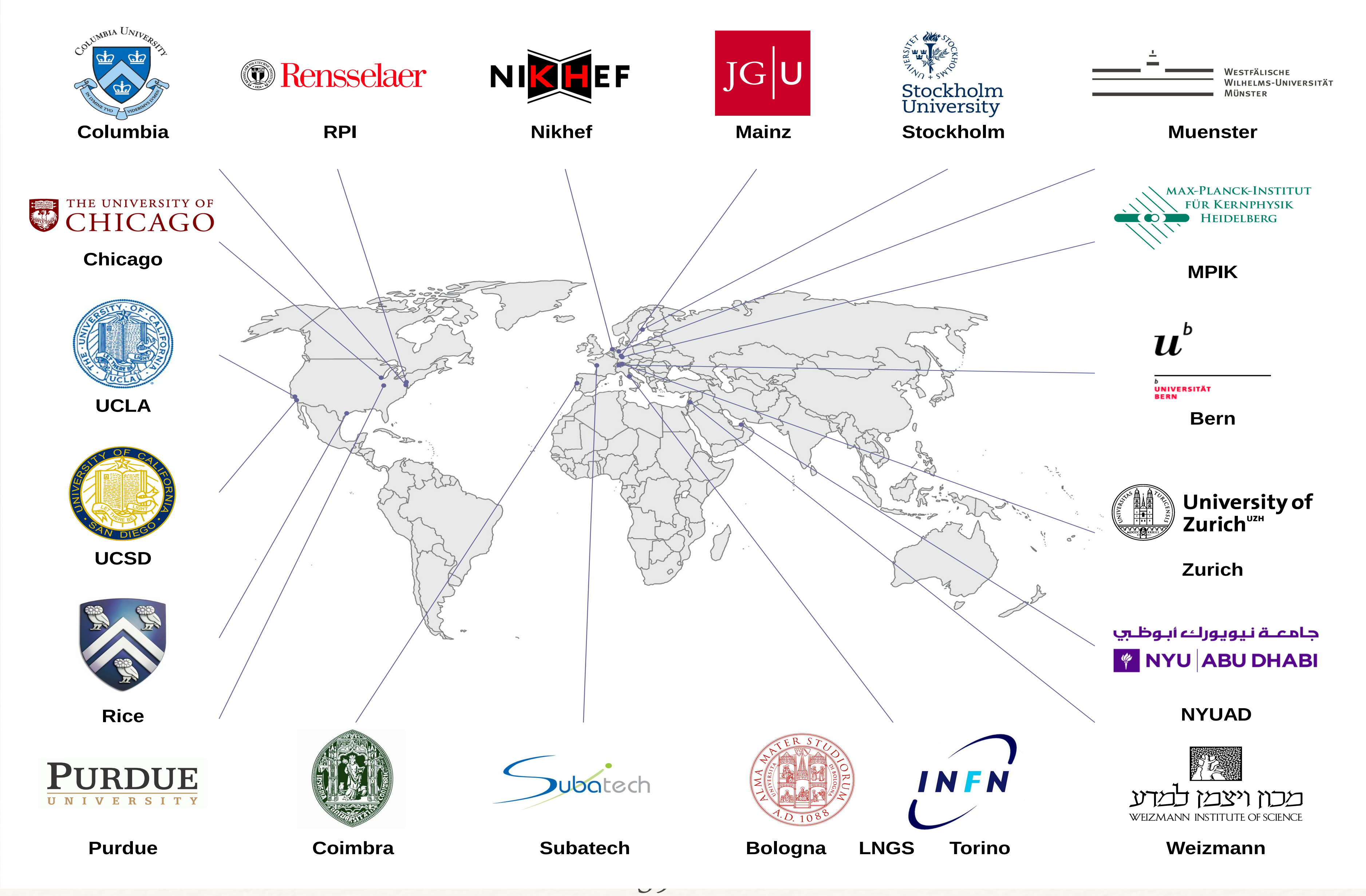
- Liquid Xenon detectors with multiple tons of Xe will soon start a new chapter in the search for WIMPs with unprecedented sensitivity.
- If WIMPs are out there XENON1T will be the first in line to discover them.

- Next steps:

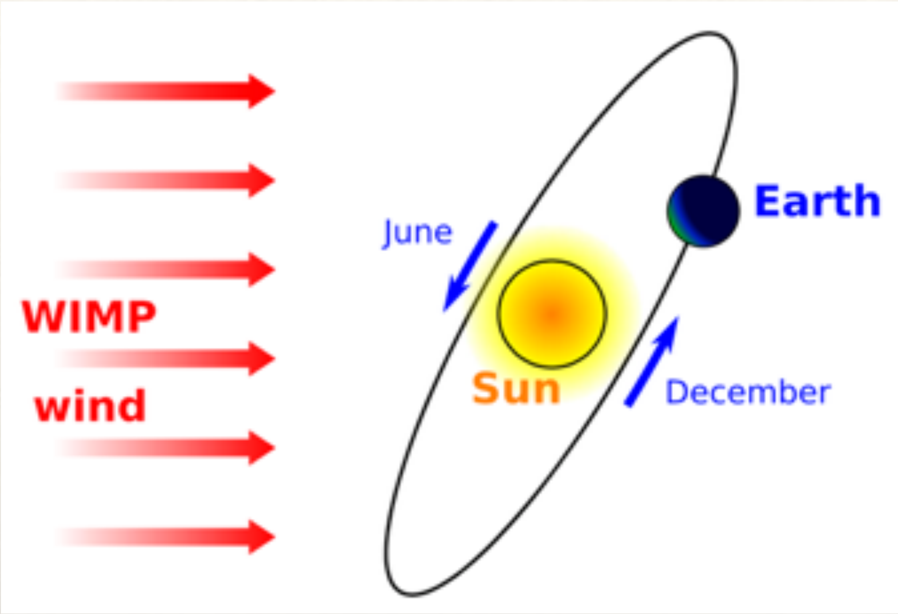
- Complete the commissioning
- The first data by the spring or so.

XENON100 expriment

XENON100 so far not only provided great physics results but has been also a fundamental test bench for the XENON1T experiment



Annual modulation and DAMA/LIBRA



Freese *et al*., Rev. Mod. Phys. 85, 1561 (2013)

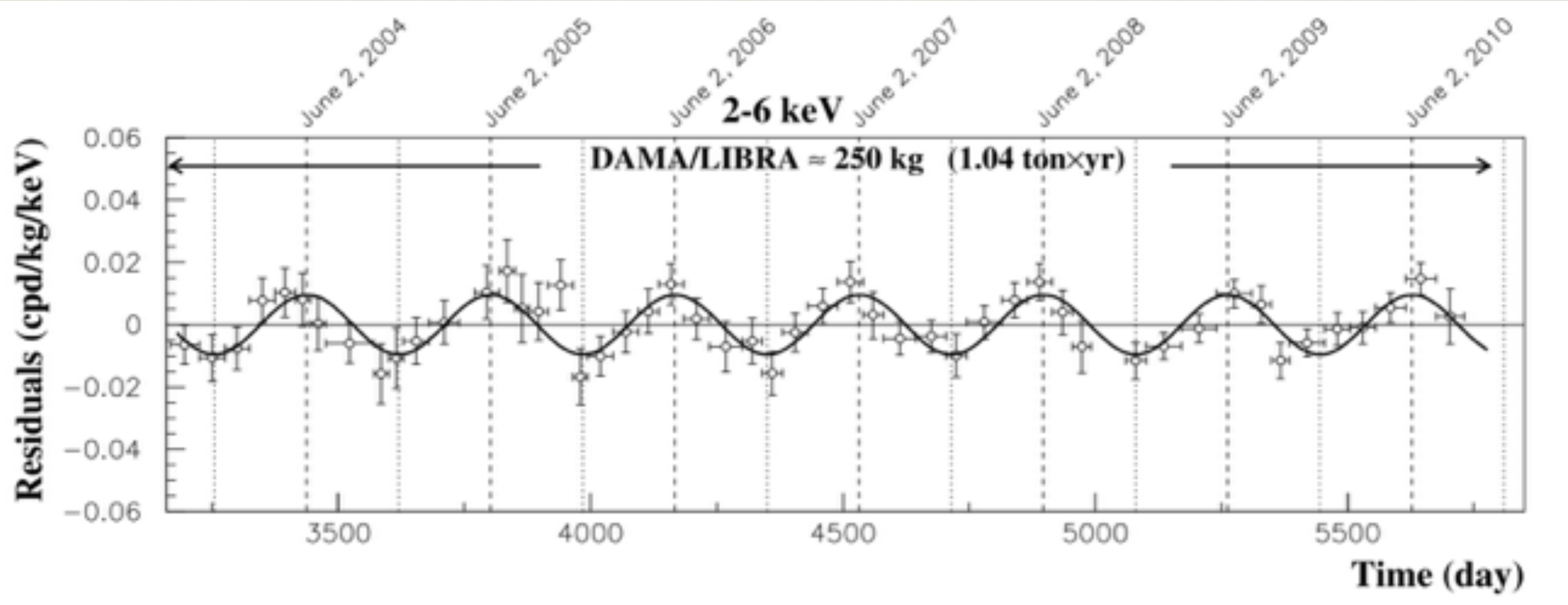
Dark matter (DM) signal rate is expected to be annually modulating

peak phase 152 days (June 1)

A key feature to distinguish signals from overwhelming backgrounds

DAMA/LIBRA:

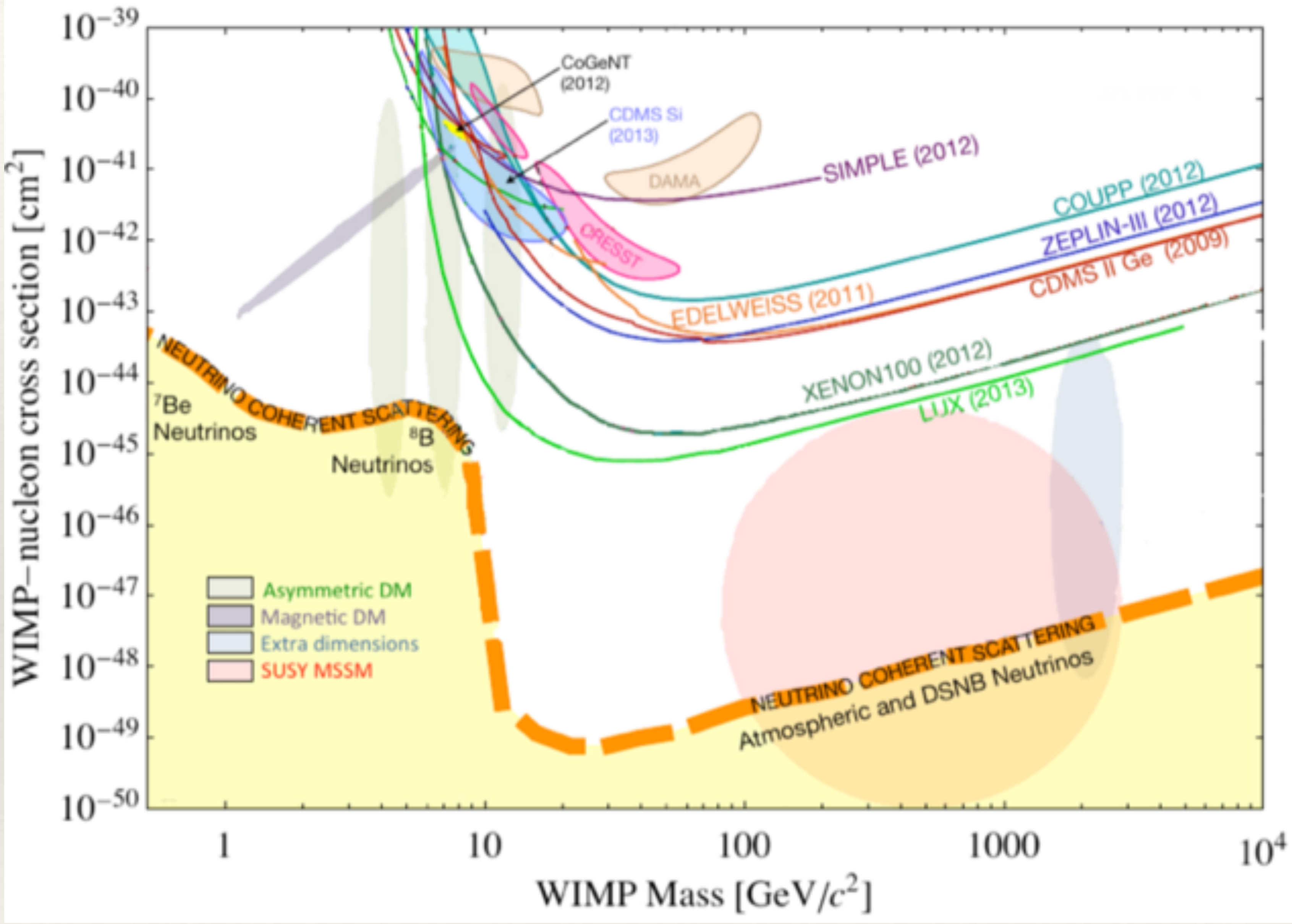
- 9.3 sigma significance
- only for single hit
- Phase (144 +- 7) days
- No signal above 6 keV



Bernabei *et al*., Eur. Phys. J. C 73, 12 (2013)

Seems to be a convincing evidence, HOWEVER…

Nuclear Recoil Interpretation



Nuclear recoil interpretations of DAMA/LIBRA modulation have been challenged by several more sensitive experiments with background rejection power

How about Leptophilic DM?

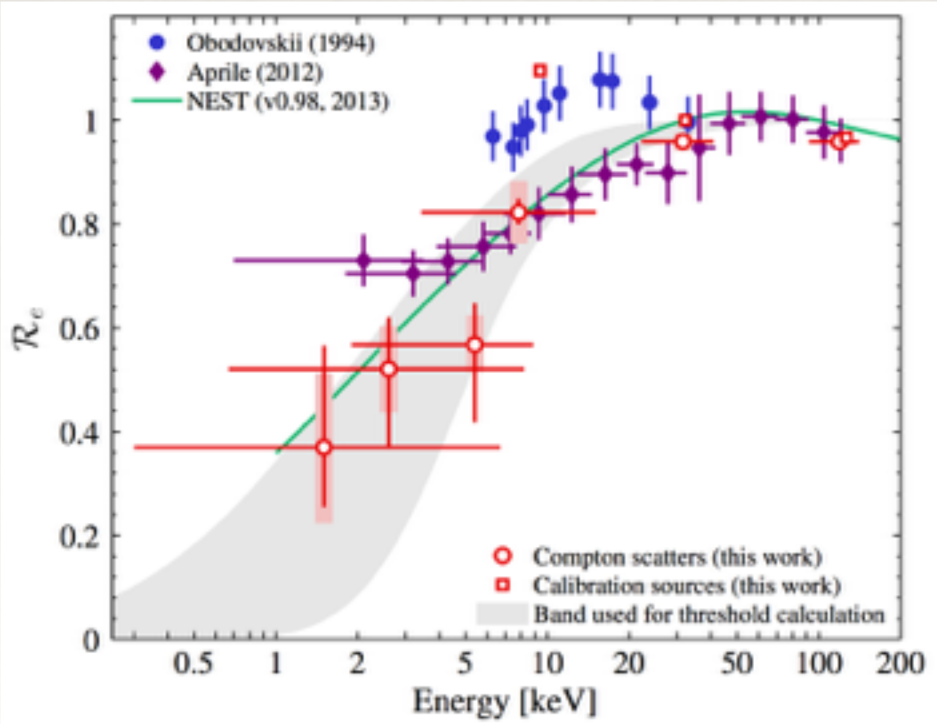
- DAMA/LIBRA annual modulation can be interpreted as signals from Leptophilic DM models
- We tested three representative models in XENON100 using the electronic recoil data:
- 1, DM-electron scattering through axial-vector coupling
- 2, Mirror DM model
- 3, Luminous DM model

Light Response in XENON100

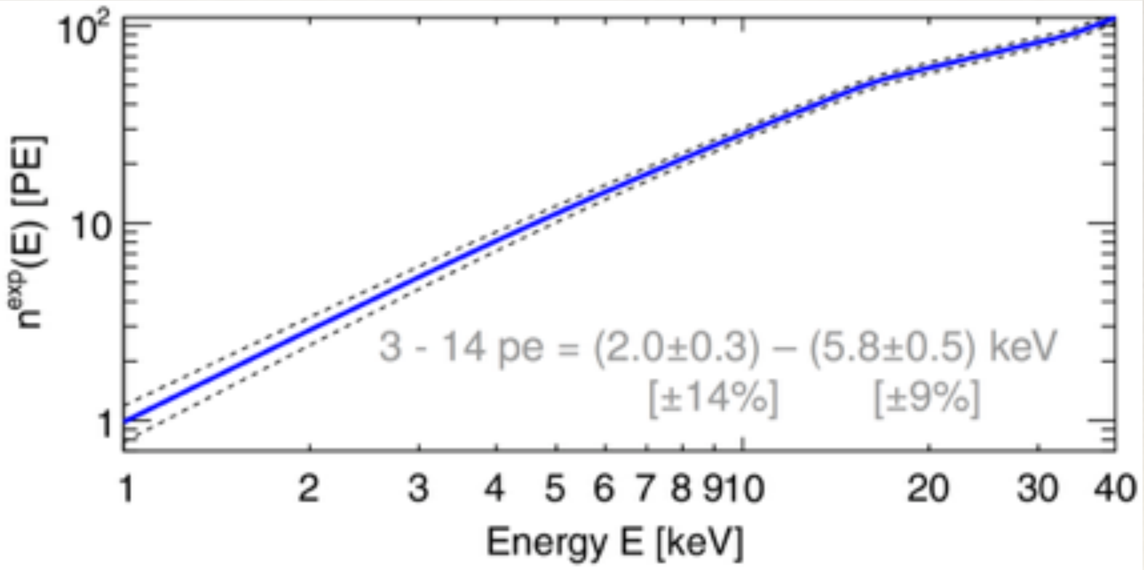
light response is determined with low energy measurements interpolated by NEST v0.98, uncertainties are from NEST and spread of measurements

Szydagis et al., J. Instrum. 6, P10002 (2011)

DAMA/LIBRA 2-6 keV Electronic recoil (ER) corresponds to 3-14 PE in XENON100



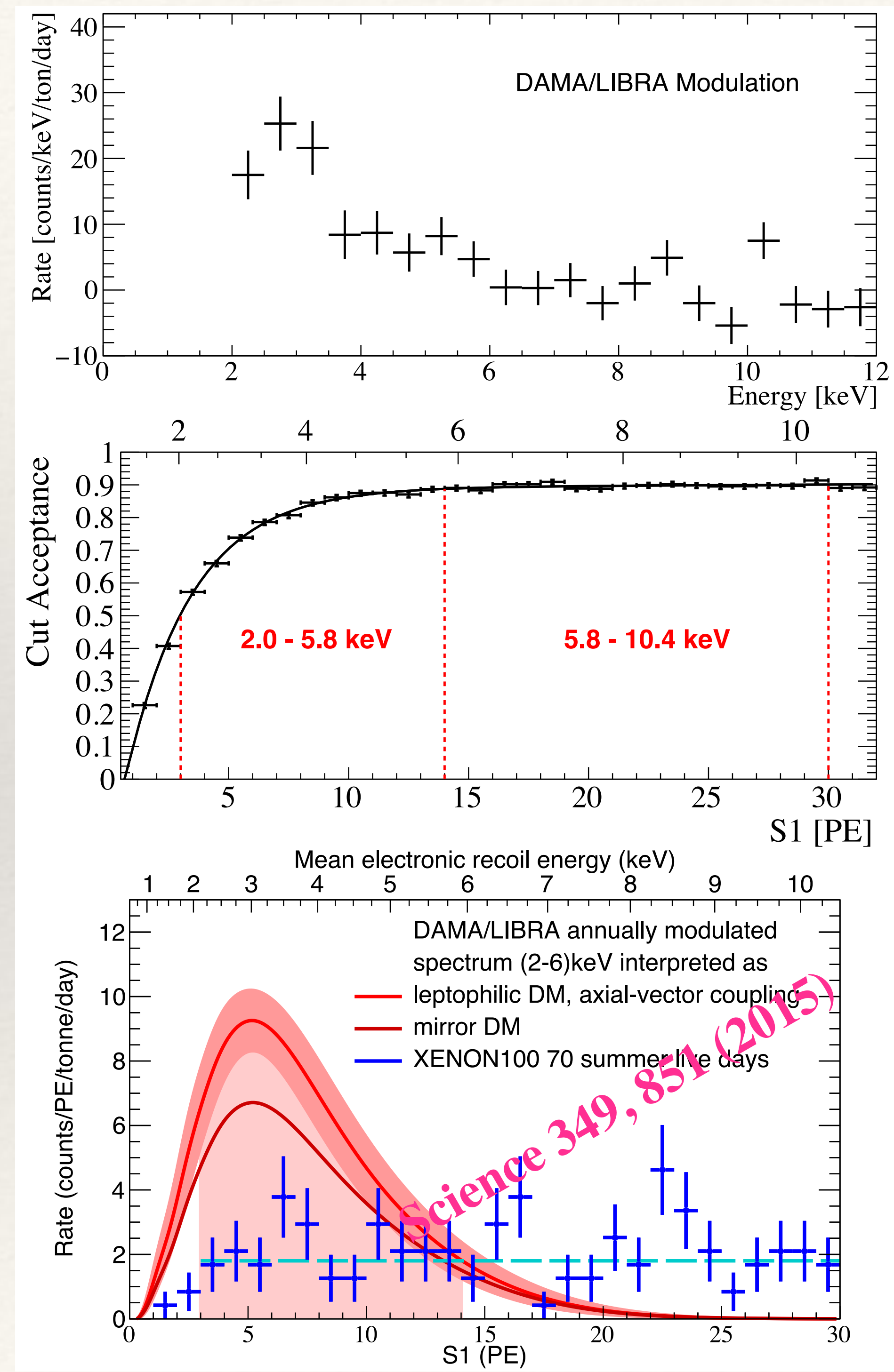
Baudis *et al*., Phys. Rev. D 87, 115015 (2013)



Aprile *et al*., Phys. Rev. D 90, 062009 (2014)

DAMA/LIBRA Comparison

- DAMA/LIBRA rate converted to XENON100 spectrum assuming leptophilic DM model, axial vector coupling
- Energy response, resolution and cut acceptance applied
- Compare XENON100 average rate with DAMA/LIBRA modulation amplitude
- Constraints on DM interpretation of DAMA/LIBRA (assuming 100% modulation):
  - WIMPs-electron scattering 4.4-sigma
  - Mirror dark matter model 3.6-sigma
  - Luminous dark matter model 4.6-sigma

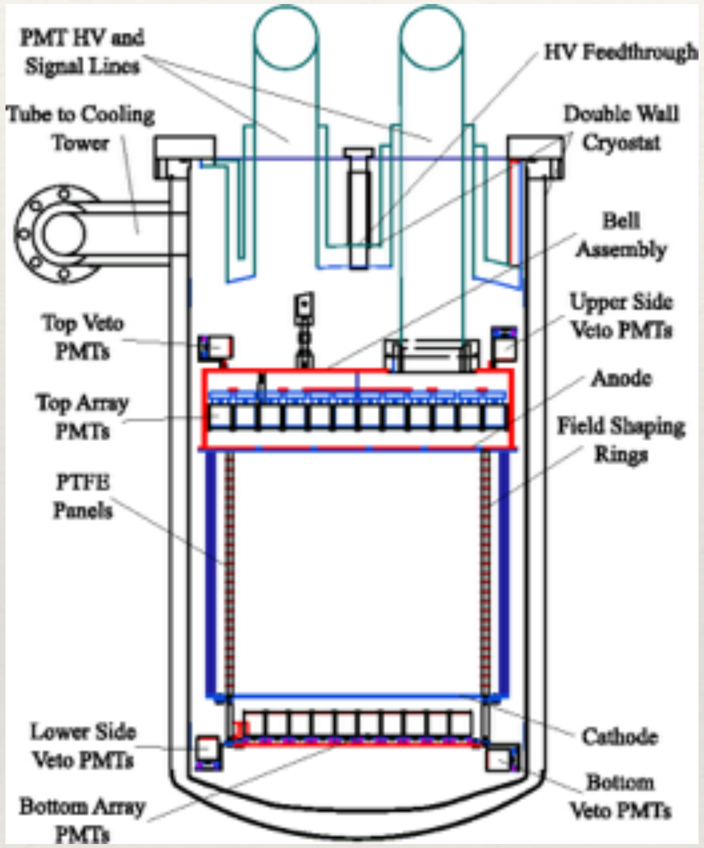


Search for Modulations

- The first LXe TPC with more than one year of stable running conditions
- The first modulation search for DM at Gran Sasso Lab after DAMA/LIBRA
- Demonstration for future XENON modulation searches
- Search for leptophilic DM signals
- Require good understand of the stability of detector and backgrounds

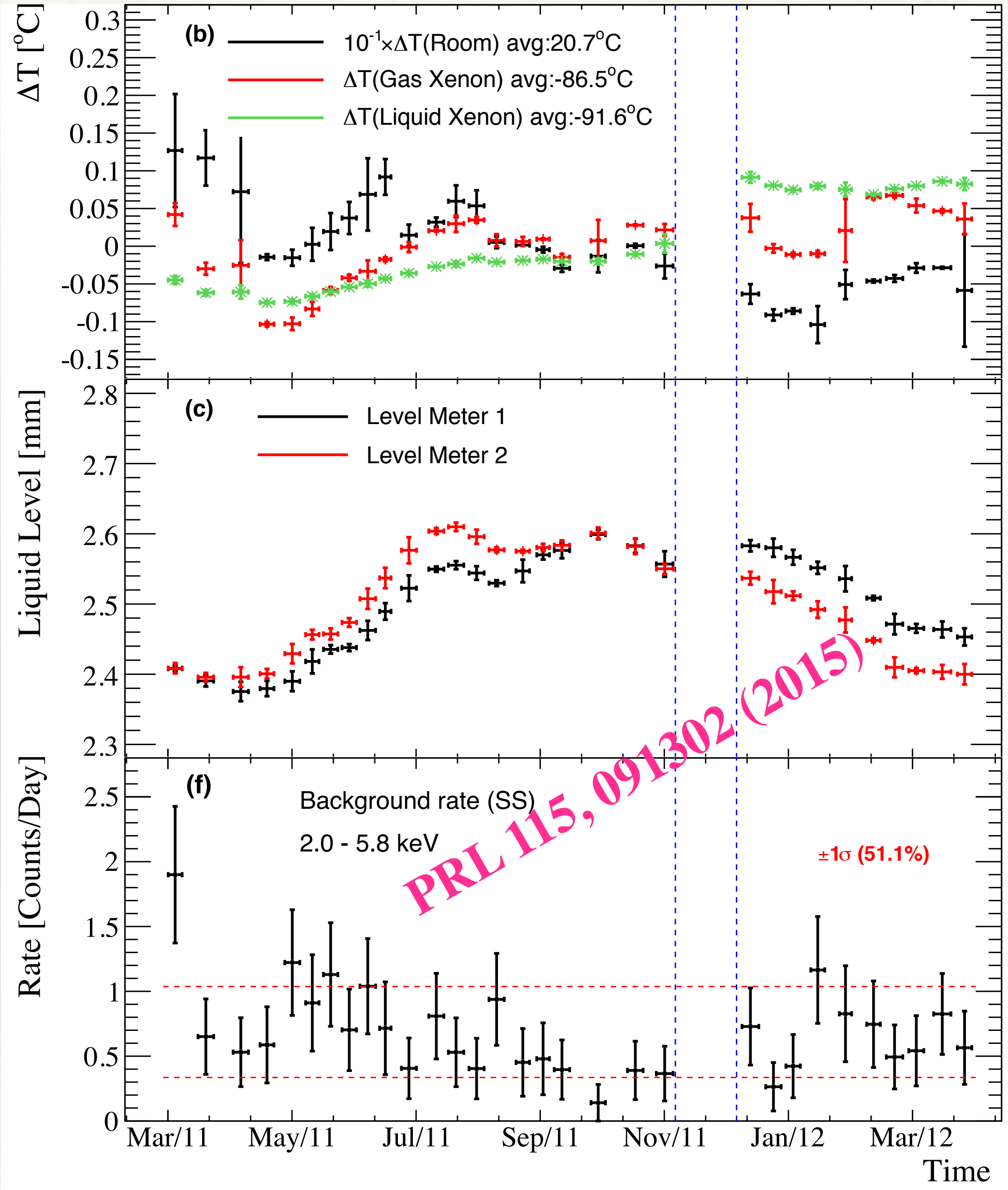
Stability of the Detector

Aprile *et al.*, Astropart. Phys., 35, 573-590 (2012)



- Detector pressor (2)
- Room pressor
- LXe temperature (4)
- PTR temperature
- Room temperature
- Purification flow rate
- LXe levels (2)
- PMT gain
- Radon level (2)
- Stability of cut acceptance

checked with weekly ER calibration



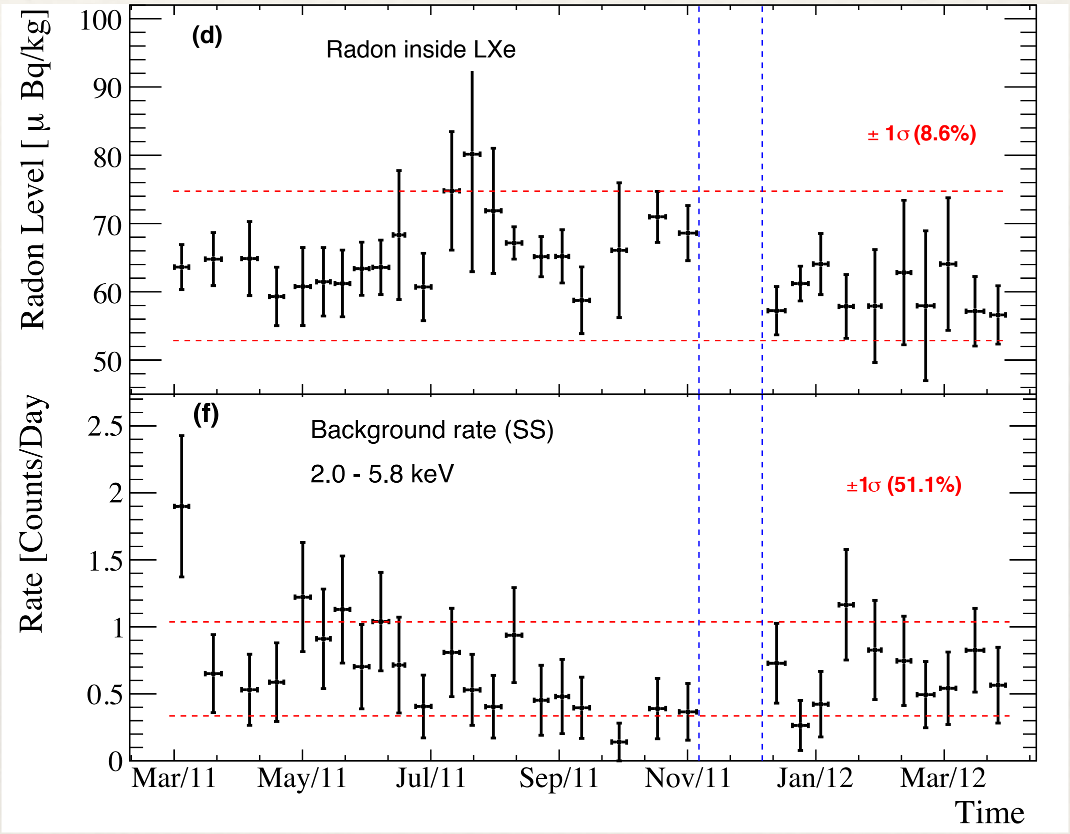
Very tiny absolute variations

No correlations with ER rate

No significant impact on ER rate!

Stability of Backgrounds

- Co60 ($T_{1/2}$ = 5.3 year) gamma background is time dependent, but the absolute contribution is negligible.
- Radon and krypton background concentration are time dependent due to tiny air leak
  - Radon contributes by less than 20%. Hence the absolute contribution to fluctuation is negligible.
  - Krypton concentration variation is taken into account.
- No correlation between radon and ER rate.



Profile Likelihood Analysis

Cut acceptance

constant background

Event Rate:

$$f(t) = \epsilon(t)\left(C + Kt + A\cos\left(2\pi\frac{(t-\phi)}{P}\right)\right)$$

krypton variation due to air leak

modulation

$$\mathcal{L} = \left(\prod_{i=1}^{n} \tilde{f}(t_i)\right) \mathrm{Poiss}\left(n|N_{\mathrm{exp}}(E)\right) \mathcal{L}_{\epsilon}\mathcal{L}_{K}\mathcal{L}_{E}$$

energy response

observed number of events

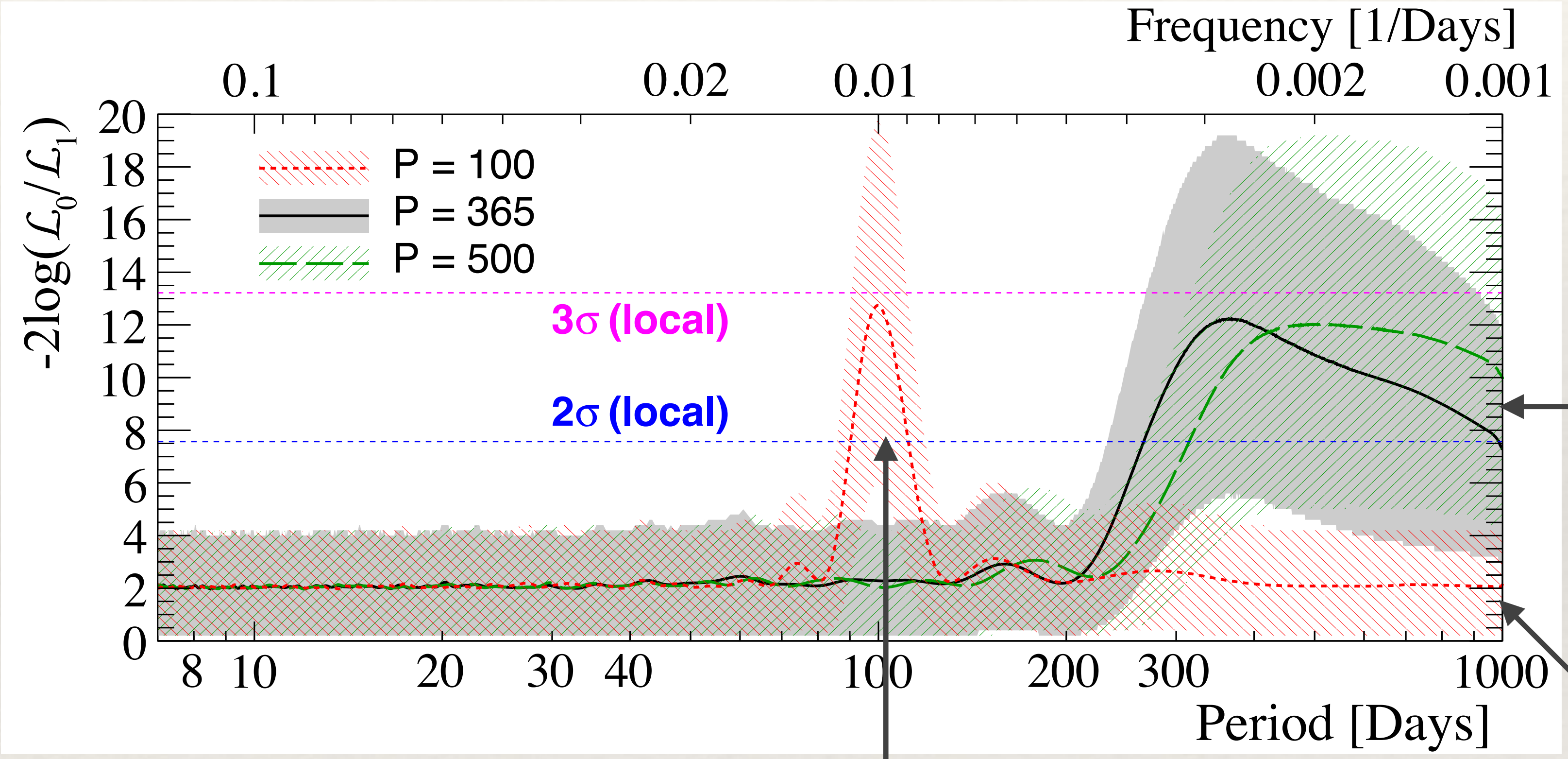
Constraints

We performed an unbinned **profile likelihood** analysis to search for modulation signal

Discovery Potential

Simulated modulation signals

A=2.7 events/(keV · tonne · day) ~ best fit value for P=365.25 days



PRL 115, 091302 (2015)

Characteristic plateau

no resolution on period

no rise at large period

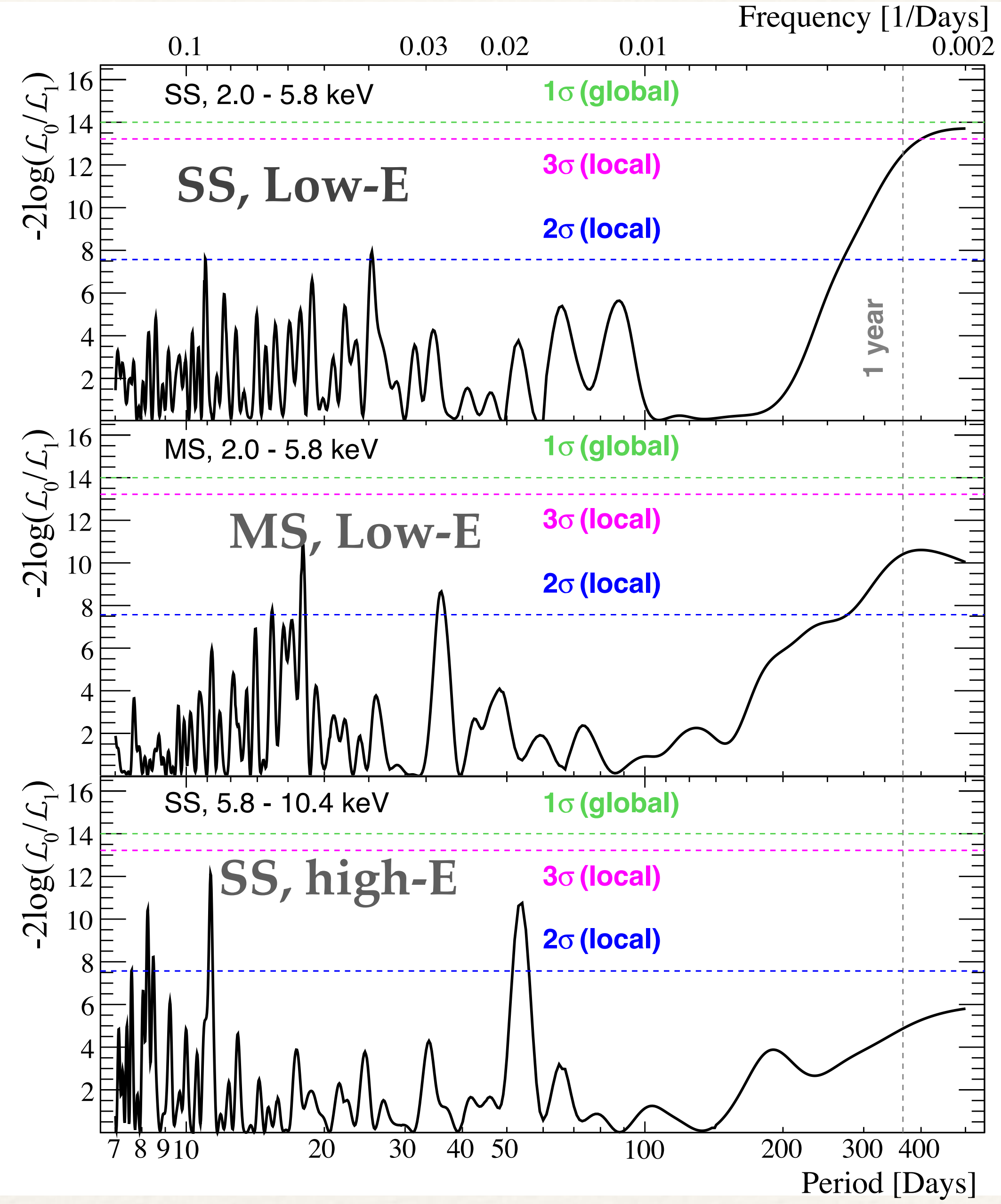
good resolution on period

Average significance of 3 sigma assuming ~25% DAMA/LIBRA modulation

The data is only sensitive to modulation with period < 500 days

Modulation Search Results

- No evident peak crossing the 1-sigma global significance threshold!
- SS in the Low-E (2.0-5.8 keV) range shows increasing significance at long period region. 2.8-sigma local significance at one year period
- MS background only control sample in Low-E range shows similar power spectrum as SS. This disfavors a WIMPs interpretation of the SS spectrum
- SS in high-E (5.8-10.4 keV) does not show high significance at long period region



PRL 115, 091302 (2015)

Summary and outlook

- The first stable LXe TPC sufficient for modulation searches.
- No significant modulation is found in the XENON100 electronic recoil data.
- The increasing significances at long period in both SS and MS samples does not favor a dark matter interpretation
- Leptophilic DM models to interpret DAMA/LIBRA modulation have been challenged by XENON100
- WIMPs-electron scattering 4.4-sigma
- Mirror dark matter model 3.6-sigma
- Luminous dark matter model 4.6-sigma
- **More data are ready for modulation searches.**

Science 349, 851 (2015)

PRL 115, 091302 (2015)

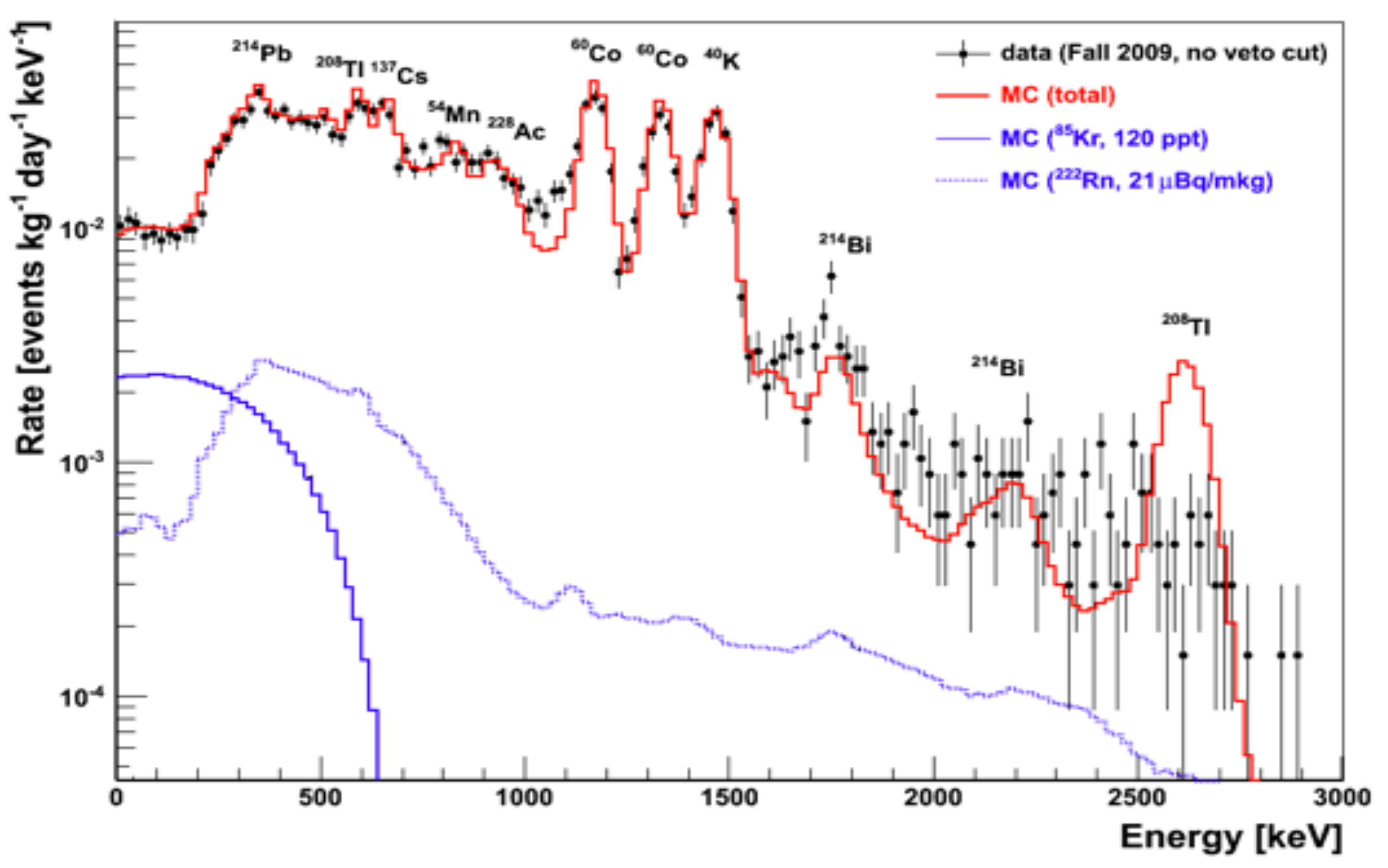
Furthermore it has been a great test bench for XENON1T.
Many calibration system has been and will be tested: among all the tritiated methane.
The distillation column and the DAQ were tested

XENON100 ER background

Very good data/MC absolute matching inside fiducial volume!!!

Radioactivity from screening values, no turning!

E. Aprile et al. (XENON100), Phys. Rev. D83, 082001 (2011)

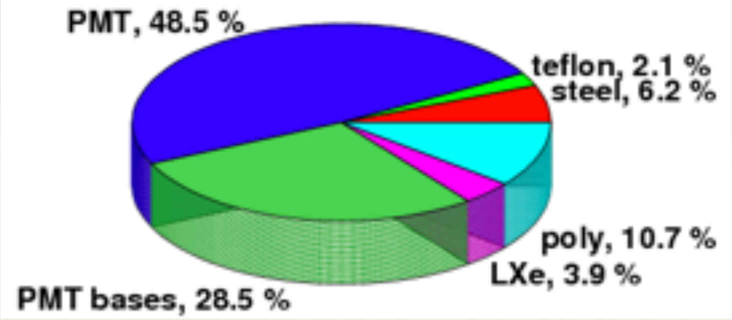


ER background:

Beta decay from krypton

Beta decay from radon

Gammas from materials



Need XENON1T to suppress PMT background

Mirror electron scattering

- Multi-component mirror models
- DM halos are composed of a multi-component plasma of mirror particles (same mass as their partners)
- Mirror electron scatters on electron through kinematically mixed coupling
- Scatter rate proportional to number of loosely bound electrons (binding energy < 1 eV)
- Constant scaling of 0.89 between XENON100 and DAMA/LIBRA

. R. Foot, Int.J.Mod.Phys. A29, 1430013 (2014)

Luminous Dark Matter

- Upper scattering inelastic dark matter scattering, the interaction rate is determined by dipole moment
- ~keV mass splitting produce X-rays
- Interaction in the earth besides the detector, and produce X-rays inside the detector
- 3.0 keV mass splitting fits well with the DAMA/LIBRA modulation

. B. Feldstein et.al, Phys.Rev. D82, 075019 (2010)