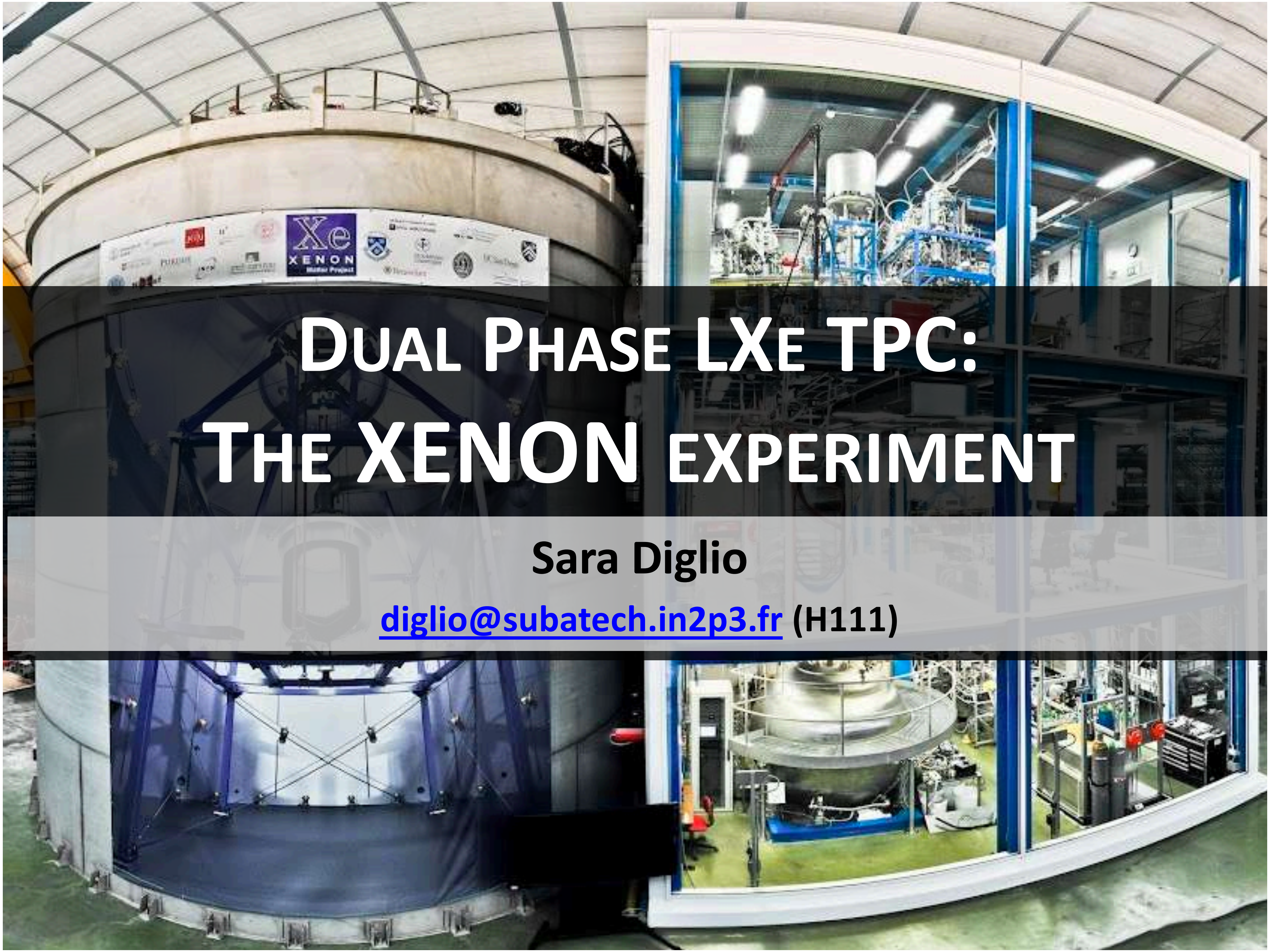


Dual Phase LXe TPC: The XENON experiment

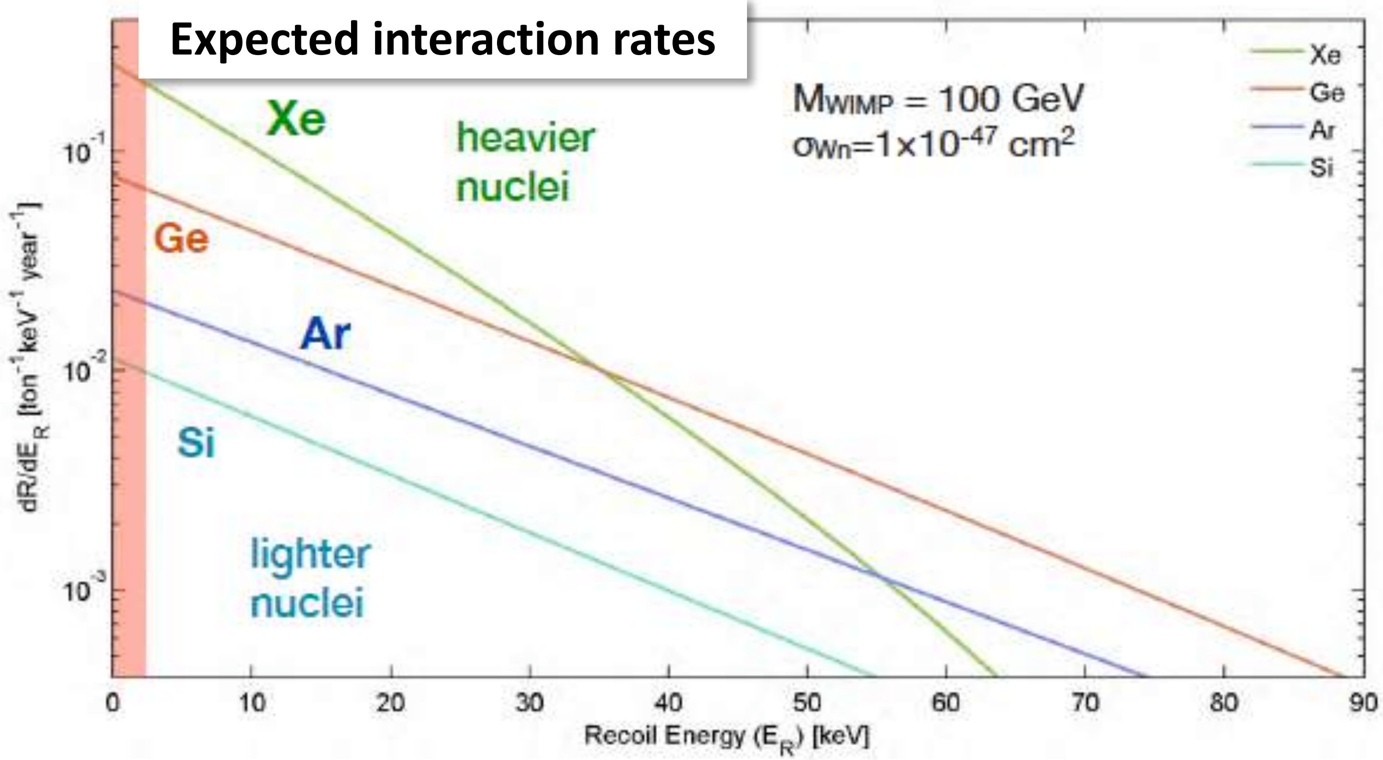
Sara Diglio

diglio@subatech.in2p3.fr (H111)

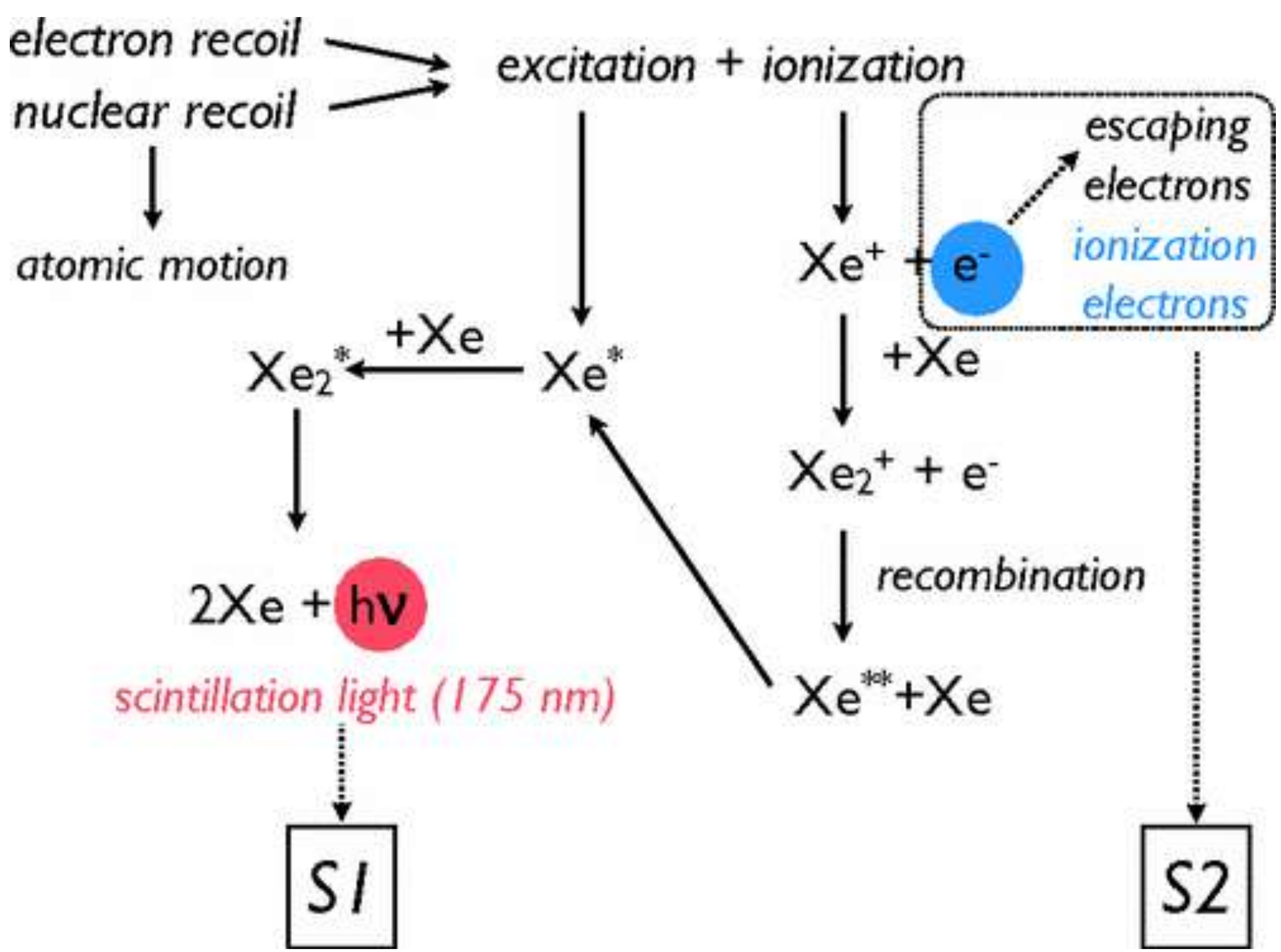
Why Xenon as a Detector Medium?

- **High mass number :** high rate for Spin Independent interactions ($\sigma \sim A^2$)
- **Odd-nucleon isotopes :** ^{129}Xe, ^{131}Xe for Spin Dependent Interactions
- **Self shielding :** high Z=54, high density $\rho \sim$ 3 kg/l
- **Intrinsically pure:** no long-lived radioactive isotopes (^{85}Kr that can be reduced to < ppt)
- **Charge & Light :** highest among the noble liquids
- **Scalability :** compact detectors, scalable to larger dimension

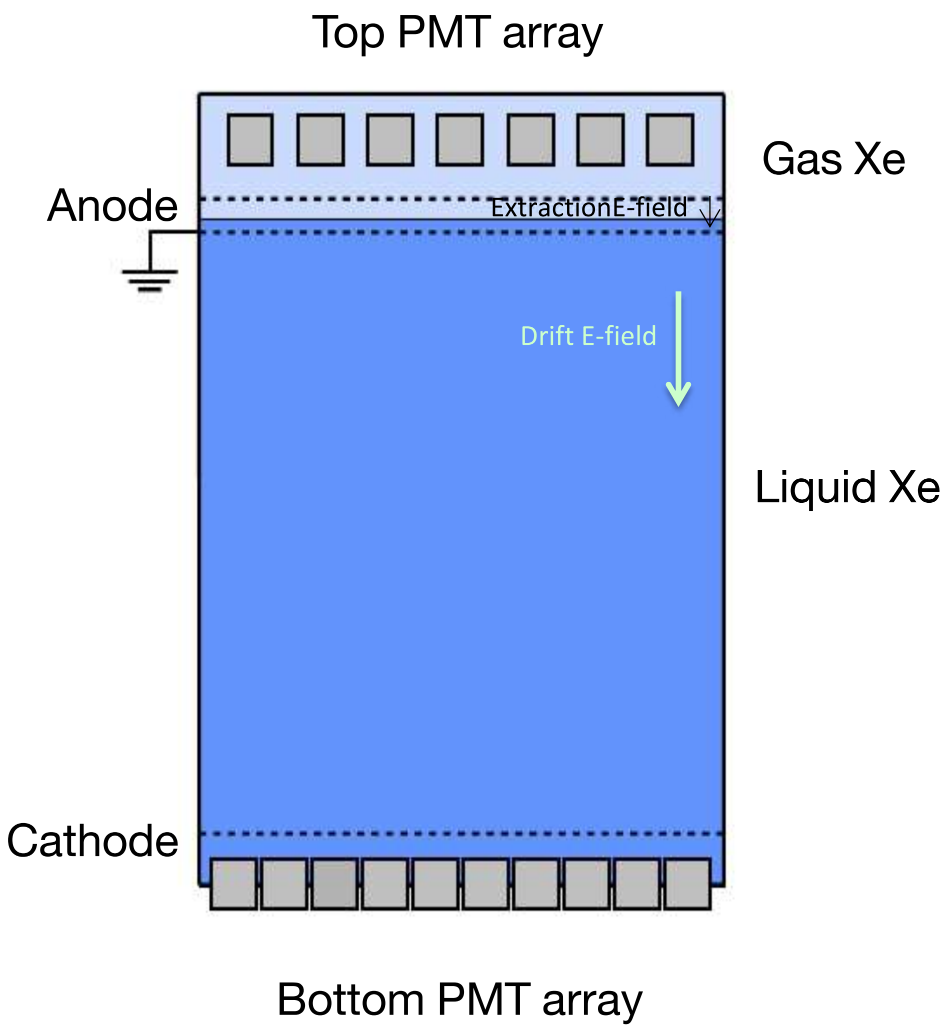
Expected interaction rates



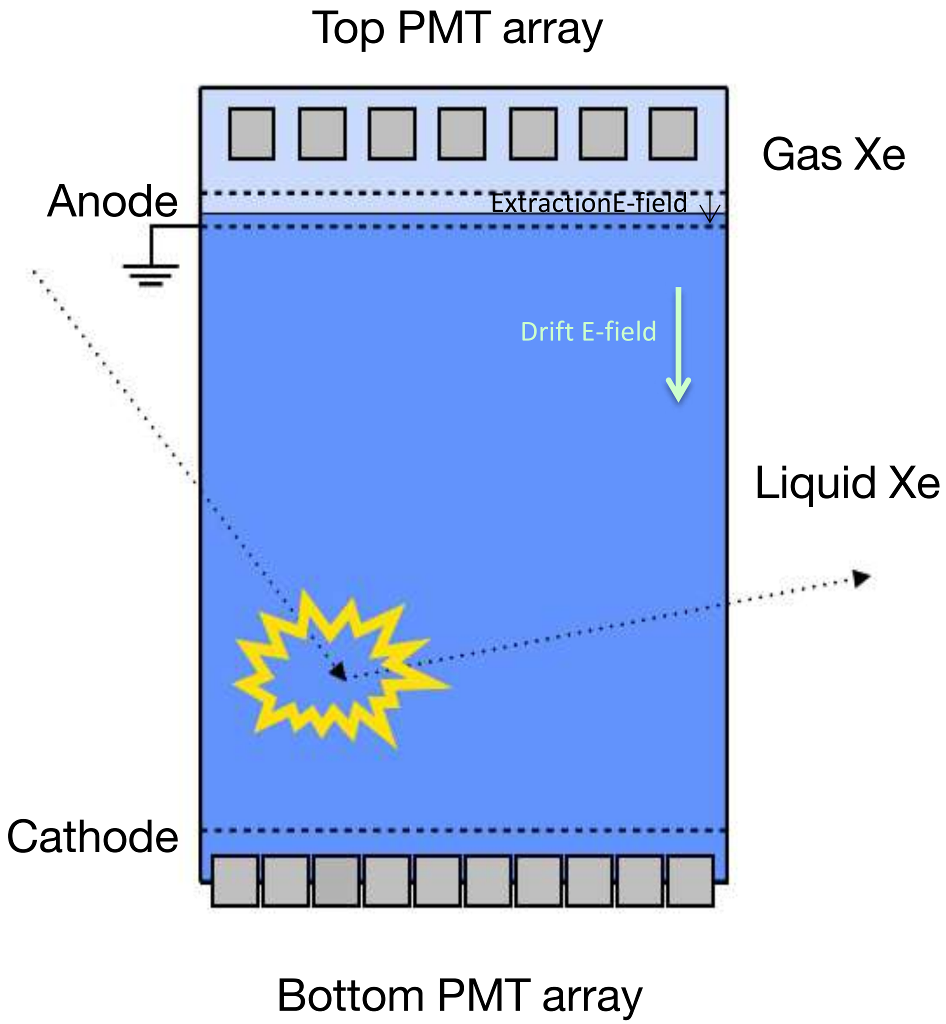
SCINTILLATION AND IONIZATION SIGNALS



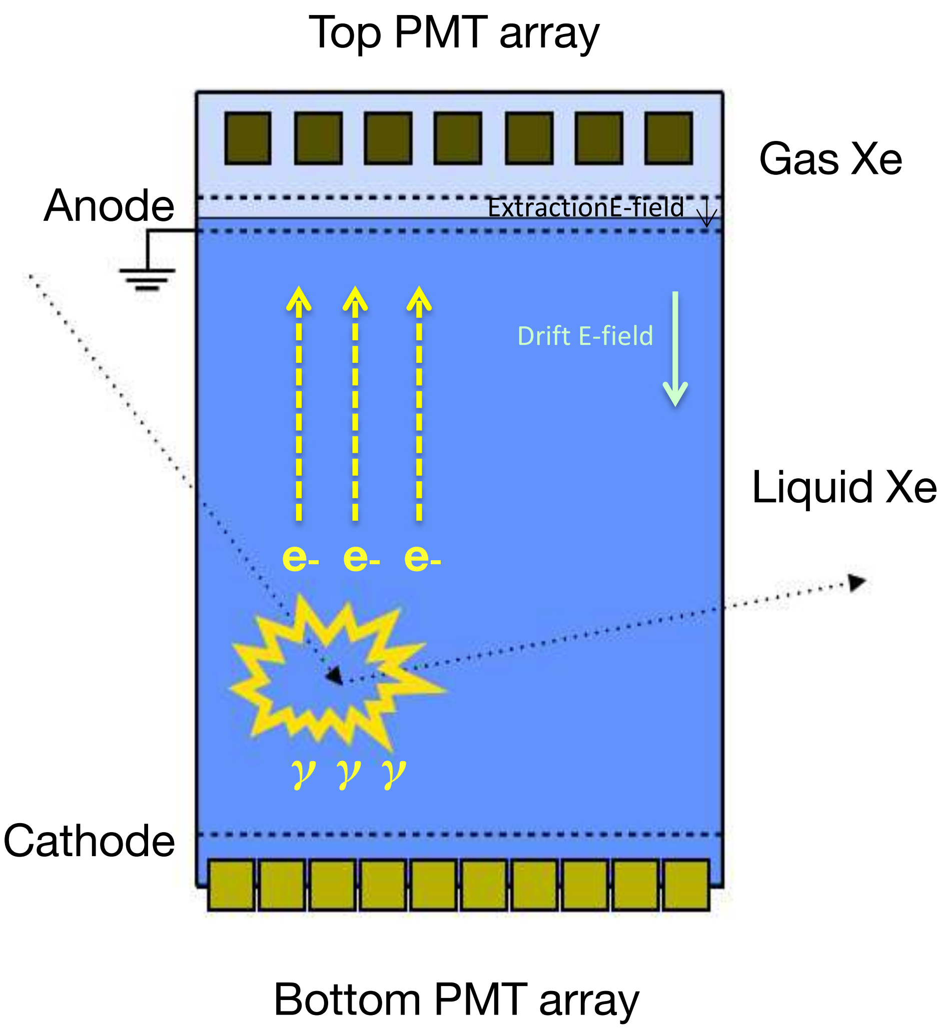
DUAL PHASE LXE TIME PROJECTION CHAMBER



Dual Phase LXe Time Projection Chamber



Dual Phase LXe Time Projection Chamber



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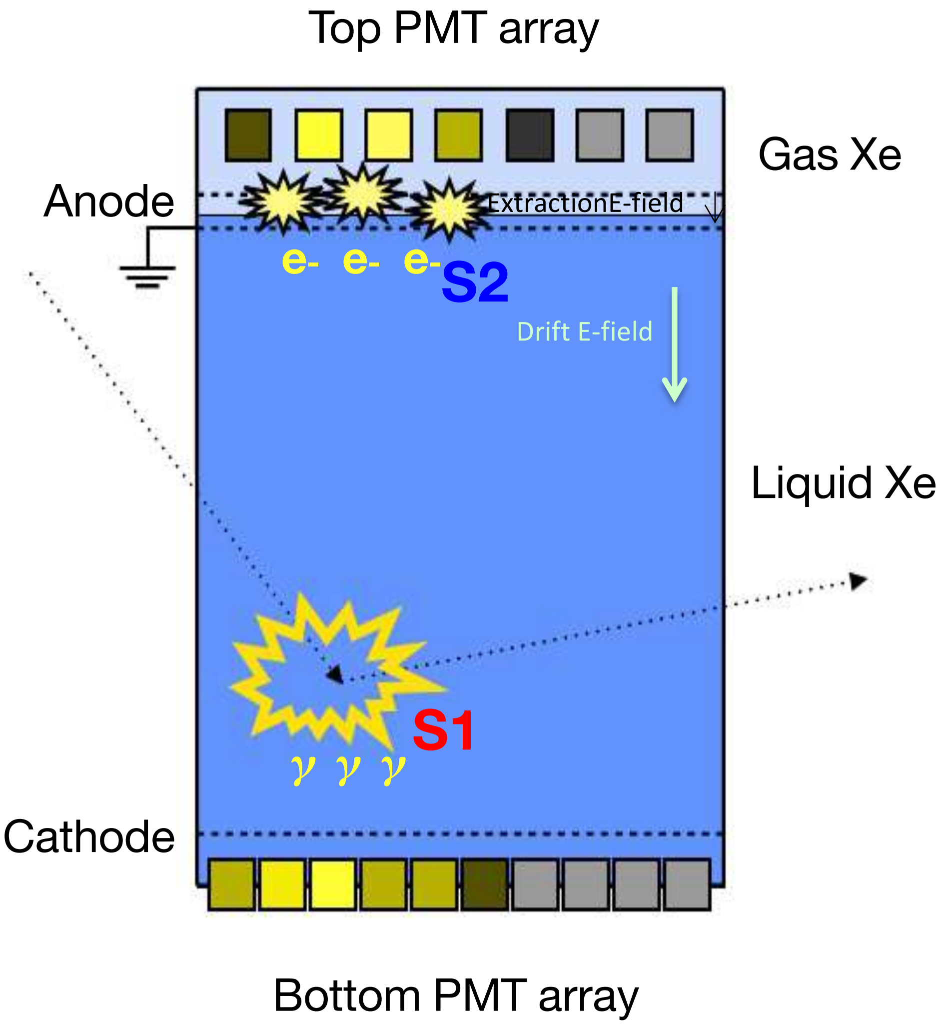
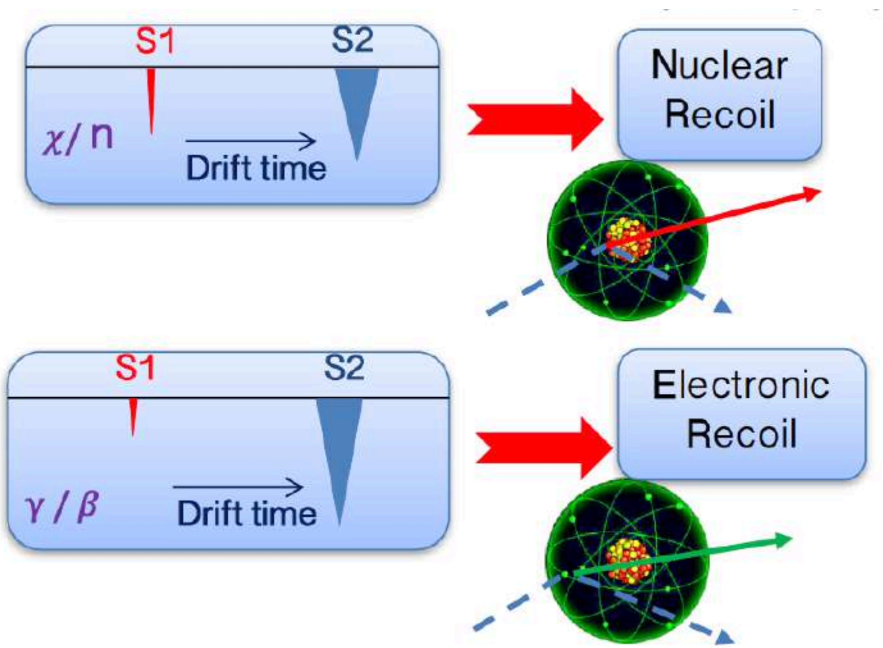


S1 → light

Prompt Scintillation

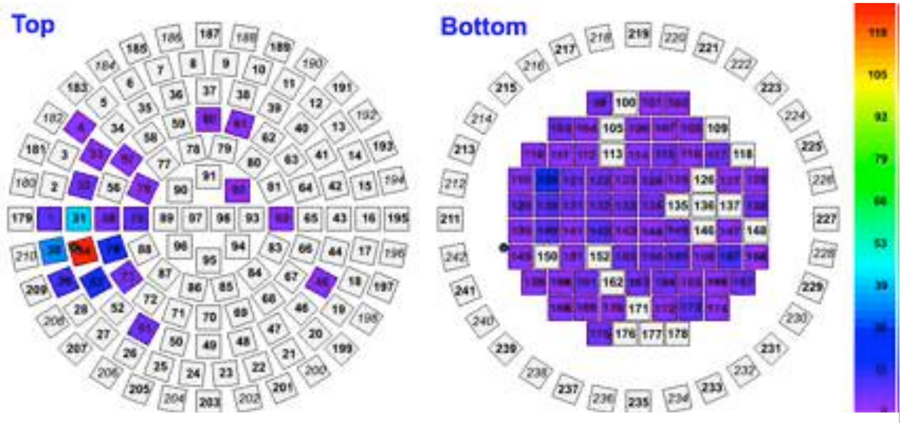
S2 → charge

Proportional scintillation following e⁻ drift and extraction into gas

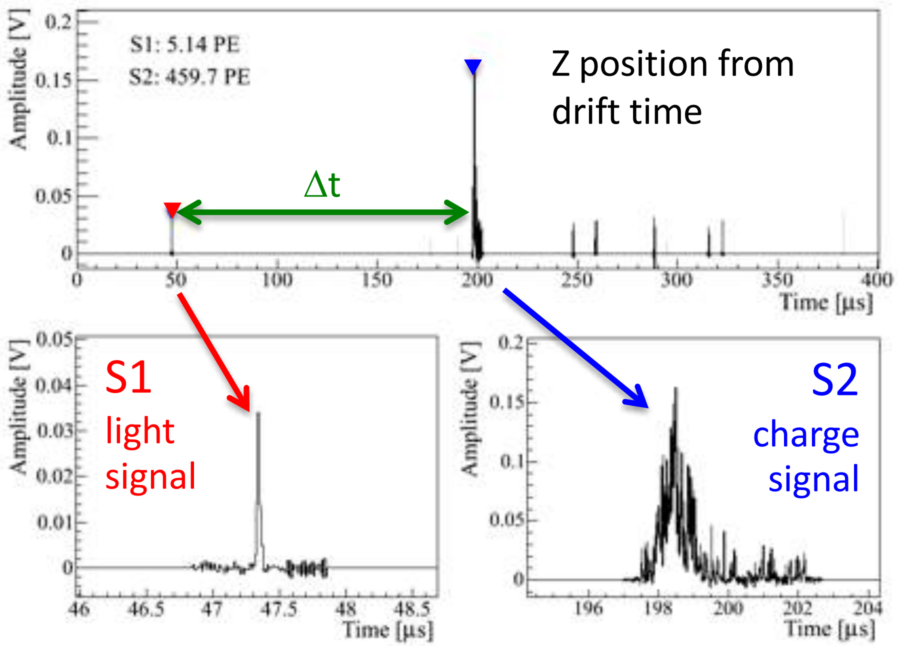


Dual Phase LXe Time Projection Chamber

3D Interaction vertex reconstruction



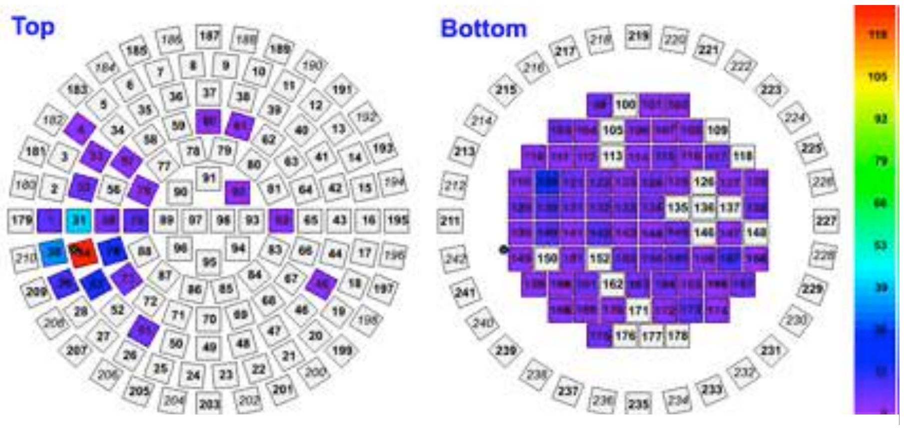
X and Y position from S2 hit pattern on top PMTs



Figures from XENON100

DUAL PHASE LXE TIME PROJECTION CHAMBER

3D Interaction vertex reconstruction



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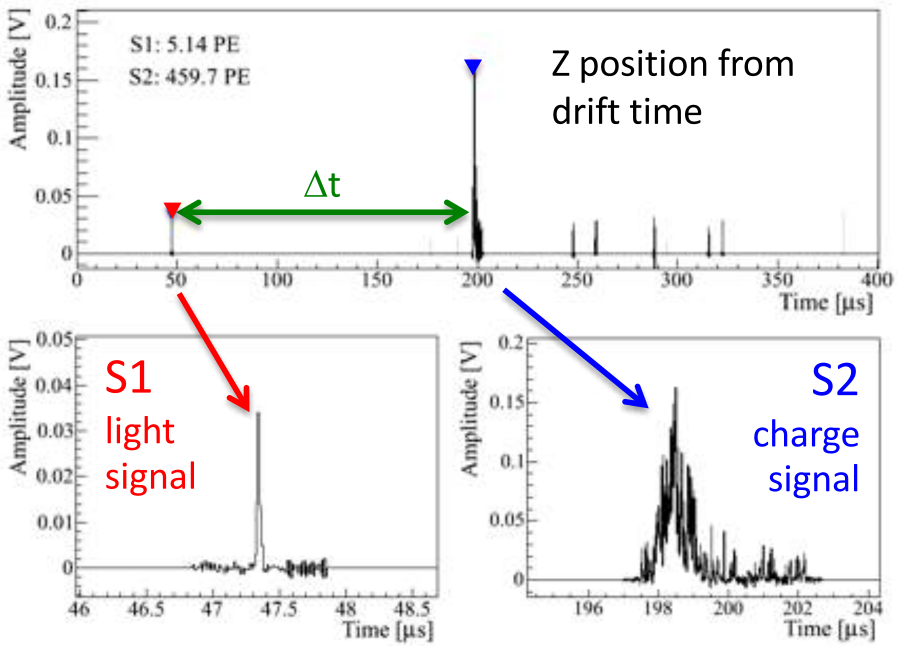
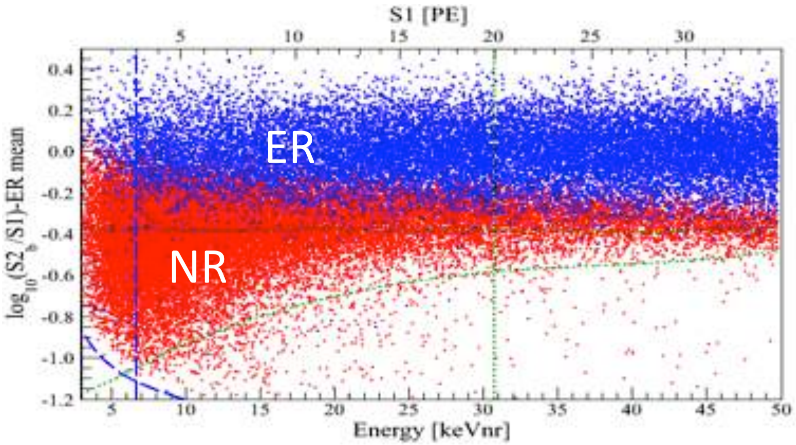
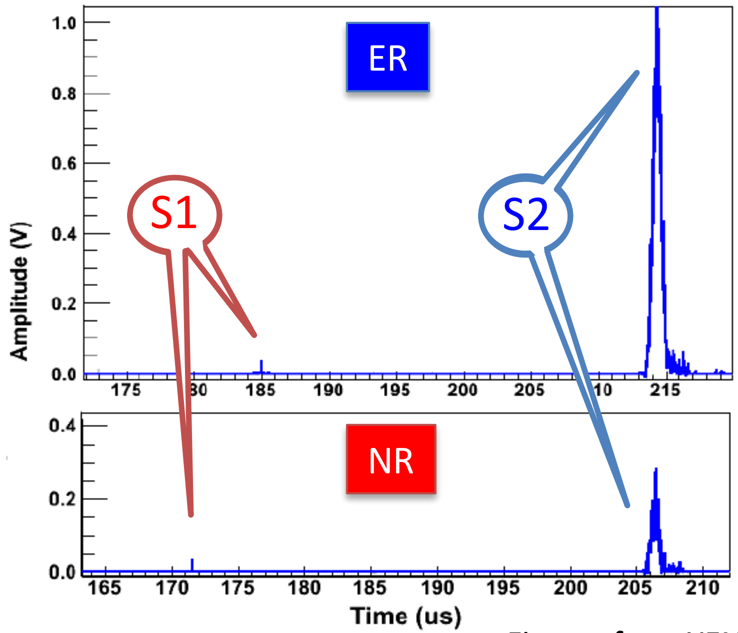


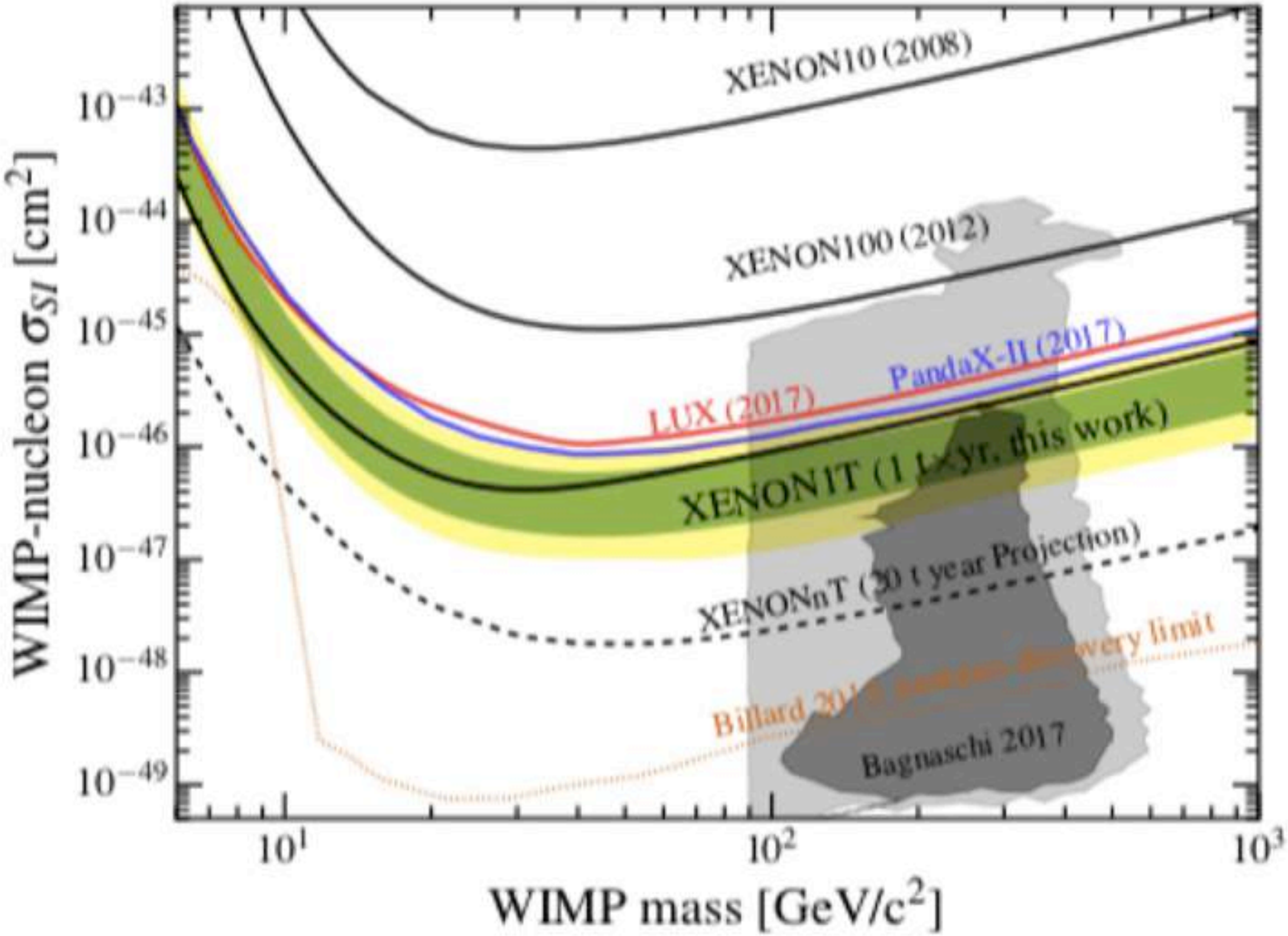
ER vs NR discrimination





Figures from XENON100

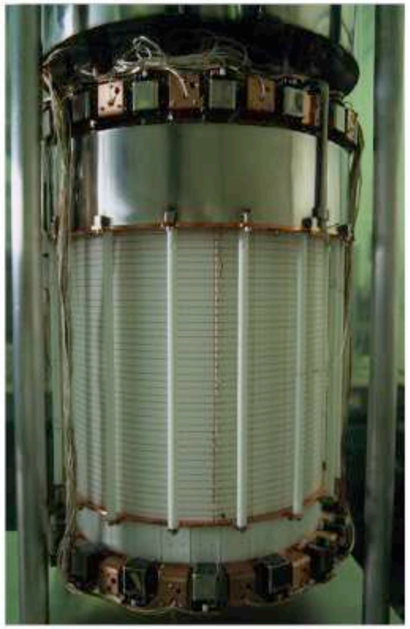
THE STATE-OF-THE-ART: DRIVEN BY LXeTPC EXPERIMENTS

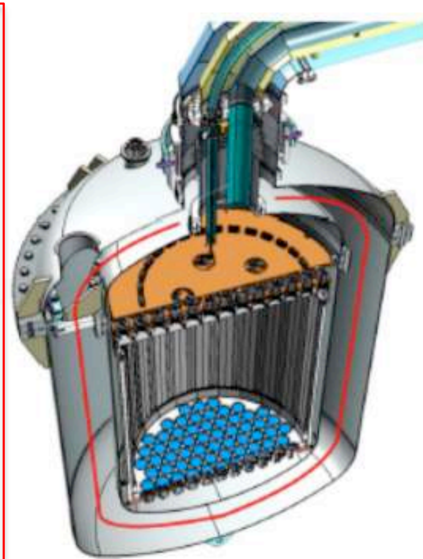


Minimum at $\sigma_{SI} = 4.1 \times 10^{-47}$ cm^2 for a WIMP of 30 GeV/c^2

The XENON Project

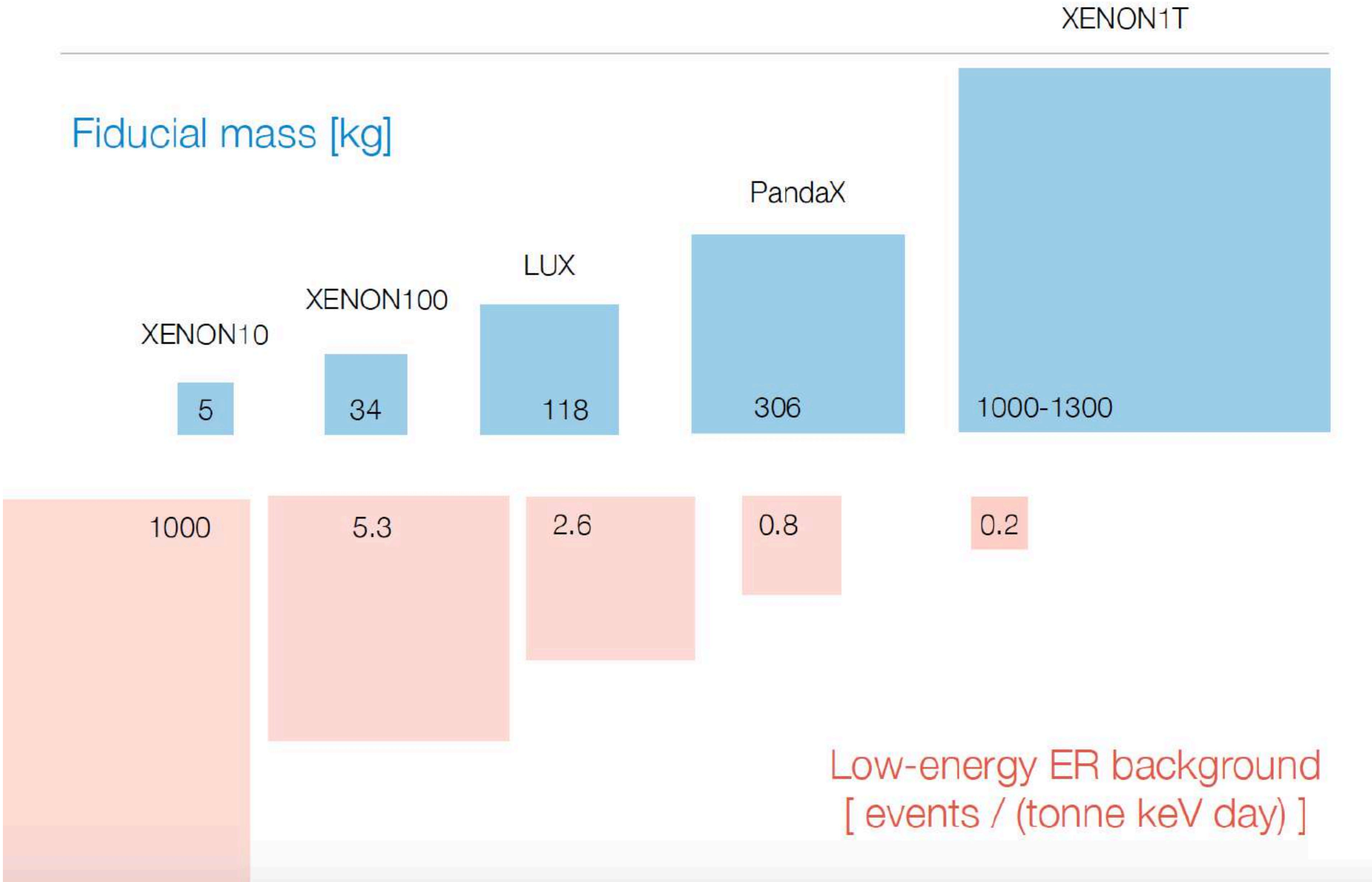
Time



XENON10	XENON100	XENON1T	XENONnT
2005-2007	2008-2016	2012-2018	2019-2023
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8 ton - 1.5 m drift
$\sim 10^{-43}$ cm^2	$\sim 10^{-45}$ cm^2	$\sim 10^{-47}$ cm^2	$\sim 10^{-48}$ cm^2

THE IMPRESSIVE LXETPCS AS WIMP DETECTORS



SCALING CONSIDERATIONS

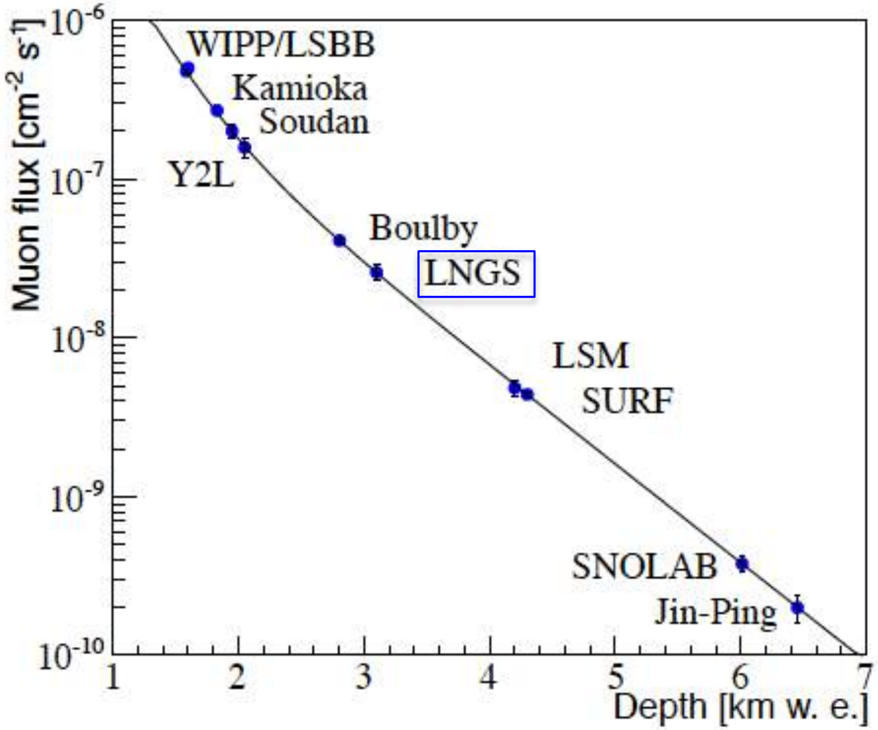
Technological challenges

- Longer drift length → HV
- Increased mass → cryogenics, LXe purification, safe storage
- Detector response → calibration & required corrections
- More or bigger photo-sensors → LY, QE, long term stability
- Diameter → TPC electrodes

Ultra low backgrounds

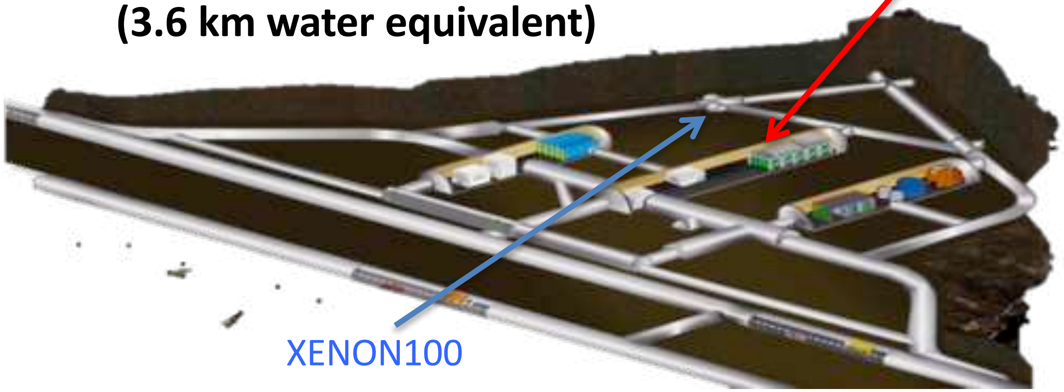
- Cosmogenic backgrounds → underground laboratory, μ-veto, n-veto
- Fiducialization
- Detector materials
  - Radio-pure detector components, surfaces, γ's, neutrons from (α,n)
  - very clean cryo-liquid → e-drift length, avoid ^{222}Rn, ^{85}Kr, ...
  - techniques to select clean materials (g and Rn screening)
  - techniques to monitor LXe purity at required level
- Active background suppression → distillation

Laboratori Nazionali del Gran Sasso



Below 1400 m of rock

(3.6 km water equivalent)

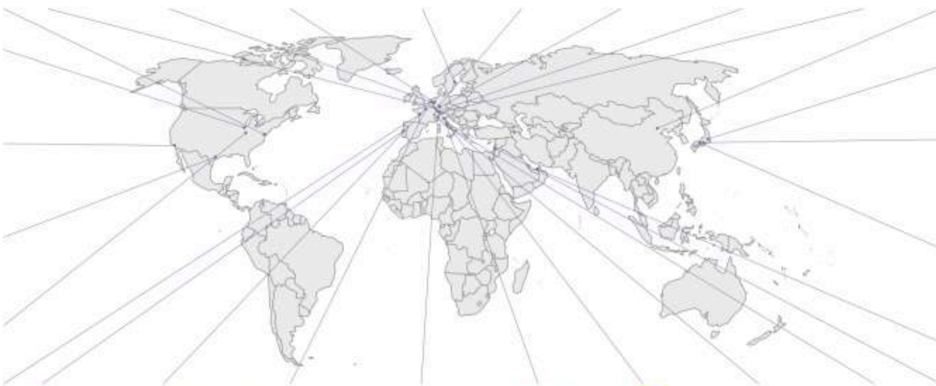


The XENON Collaboration

~ 170 scientists

31 institutions

11 countries



THE XENON1T DETECTOR

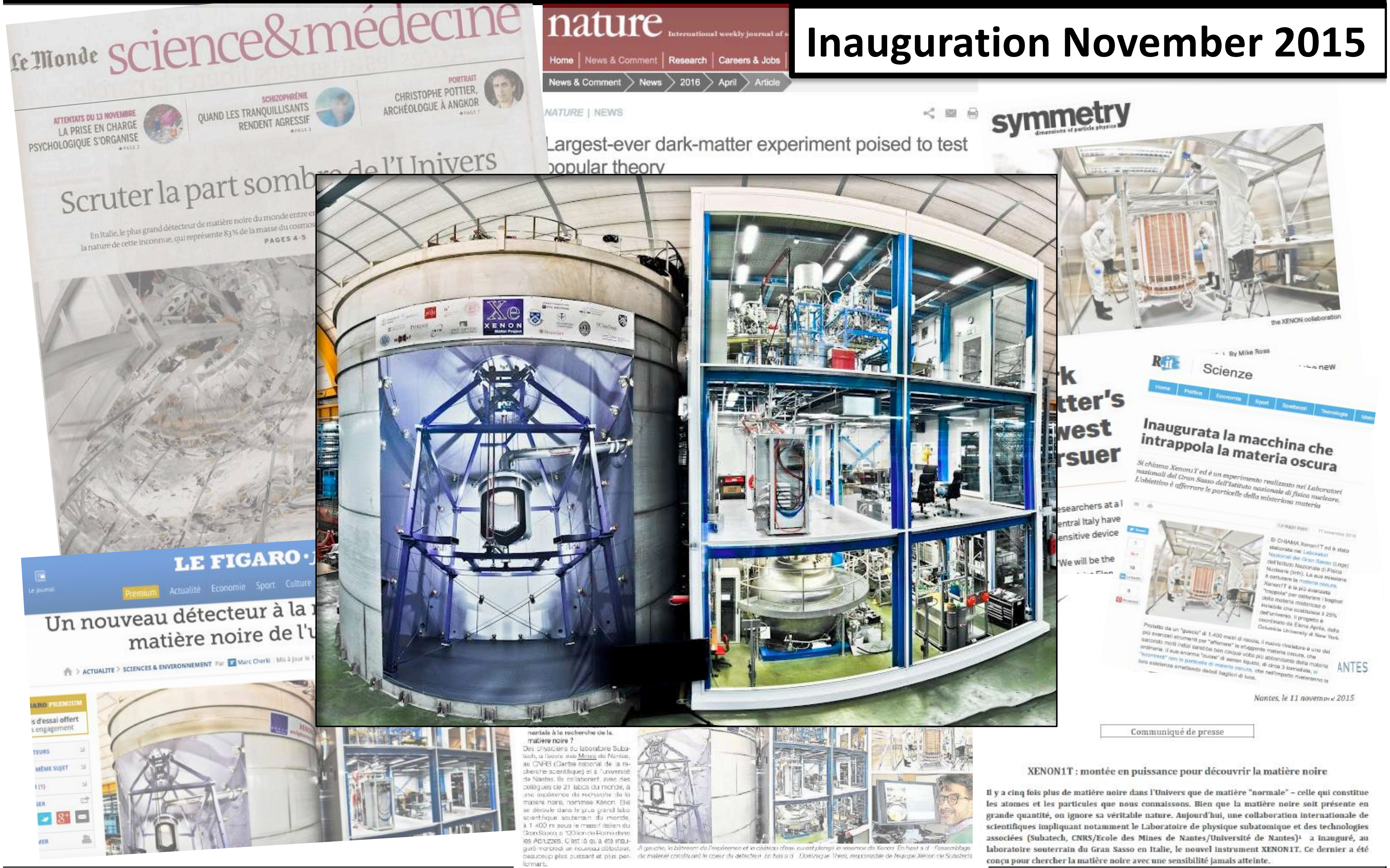
THE XENON1T EXPERIMENT

The XENON1T Experiment

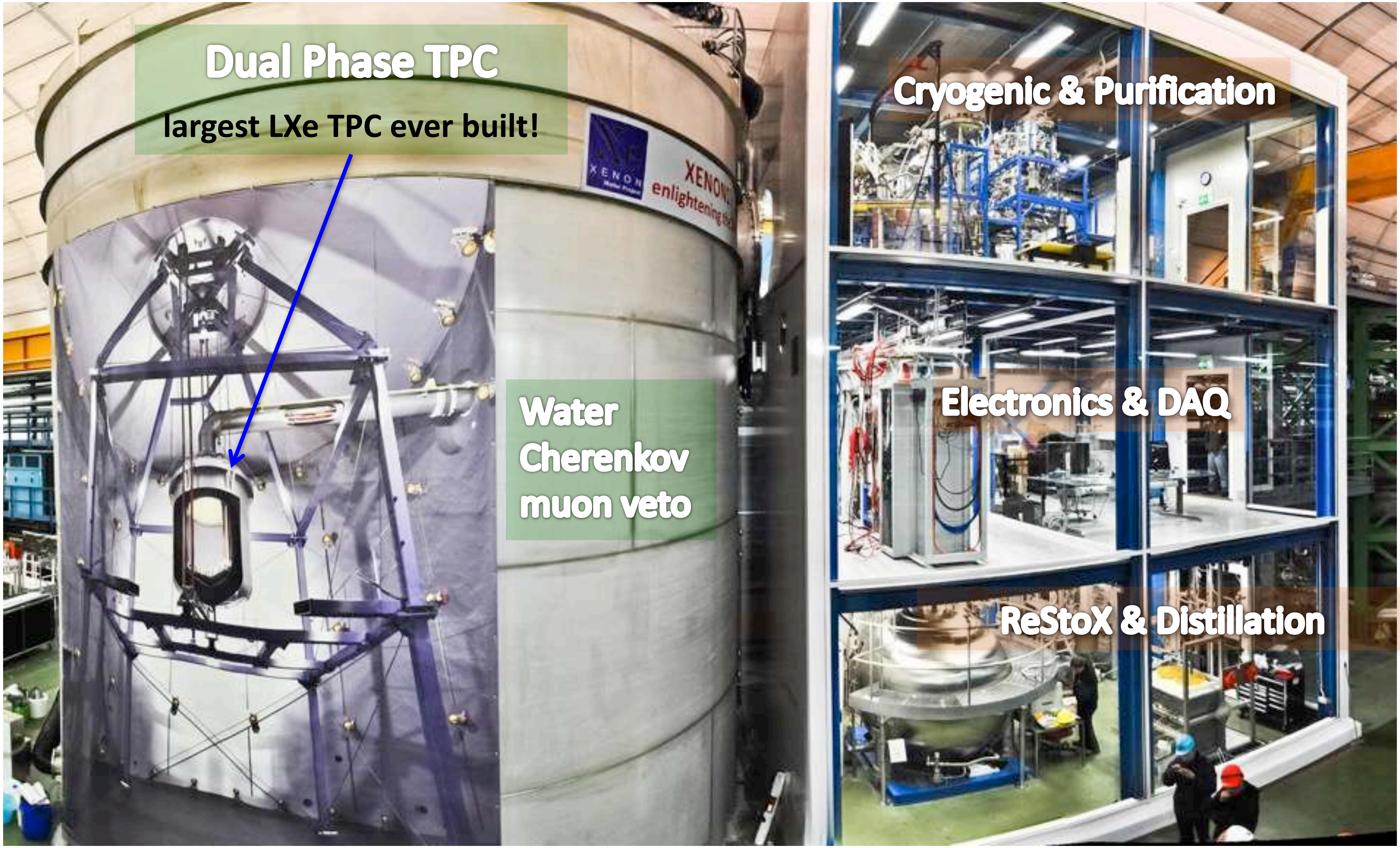
The XENON1T Experiment

THE XENON1T EXPERIMENT

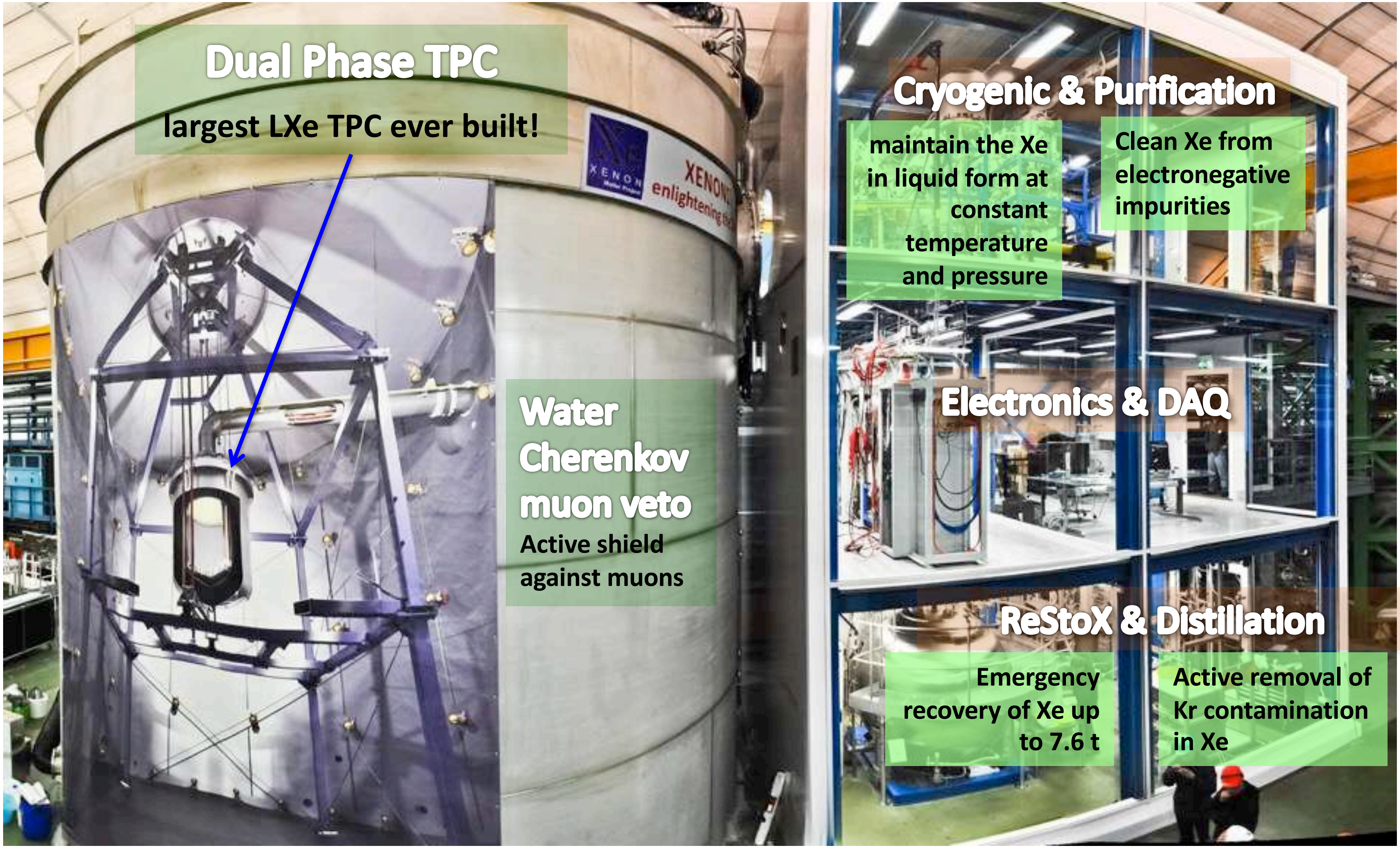
Inauguration November 2015



THE XENON1T EXPERIMENT



The XENON1T Experiment



WATER SYSTEM AND CHERENKOV MUON VETO

Water System

Water Cherenkov Muon Veto

Goals

- 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

Goal

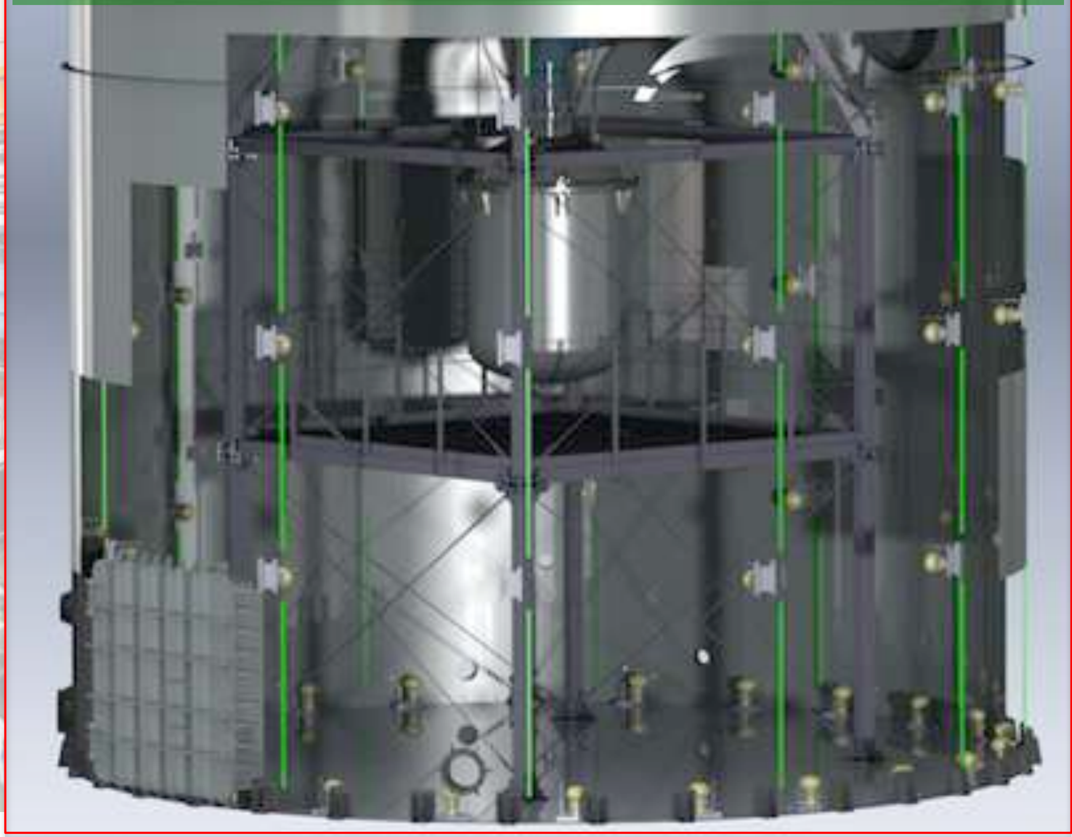
Identify cosmic ray muons reaching the detector and their induced neutrons that are a source of background for XENON1T

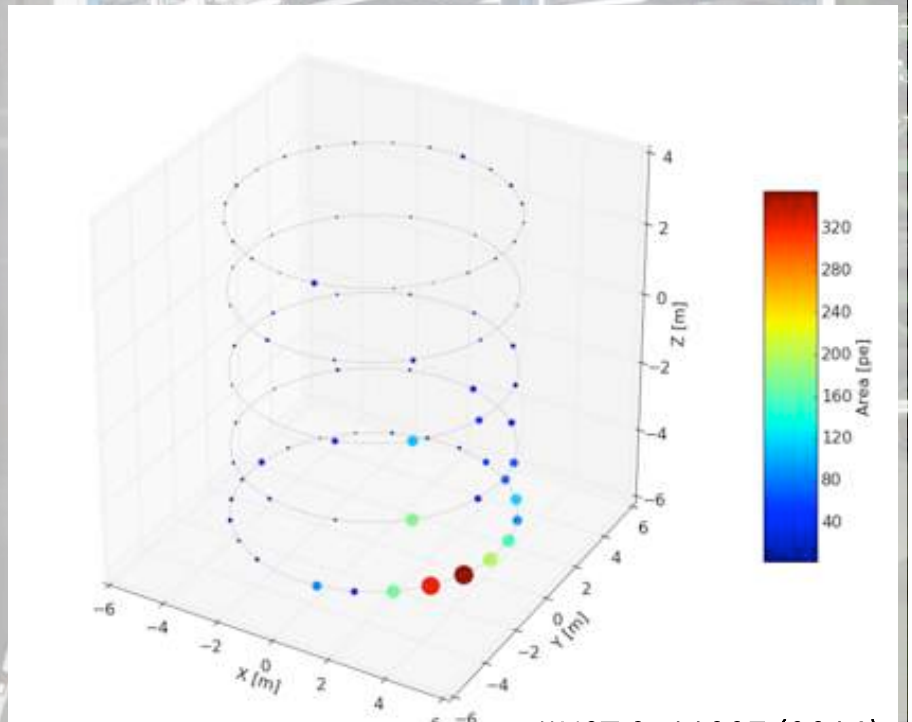
Principle: detection of the passage of the muon or its secondary charged particles through the Cherenkov light they produce in a mass of pure water surrounding the cryostat

E. Aprile et al. (XENON Collaboration), JINST 9, P11006 (2014)

WATER CHERENKOV MUON VETO

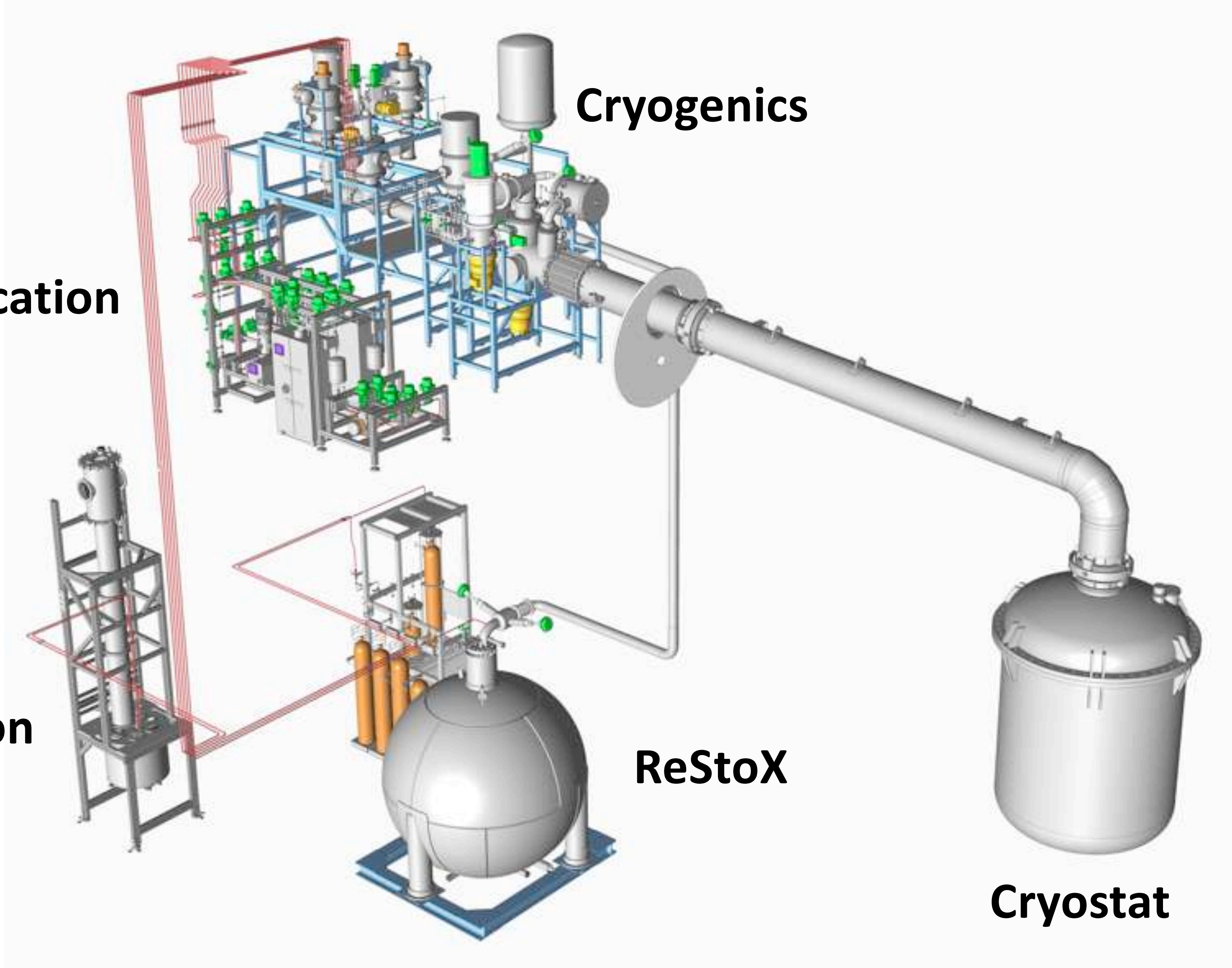
- Active shield against muons
- 700 m^3 of demineralized water
- 84 x 8” PMTs
- Muon tagging efficiency > 99.5%
- Can suppress cosmogenic background to < 0.01 ev/tonne/yr



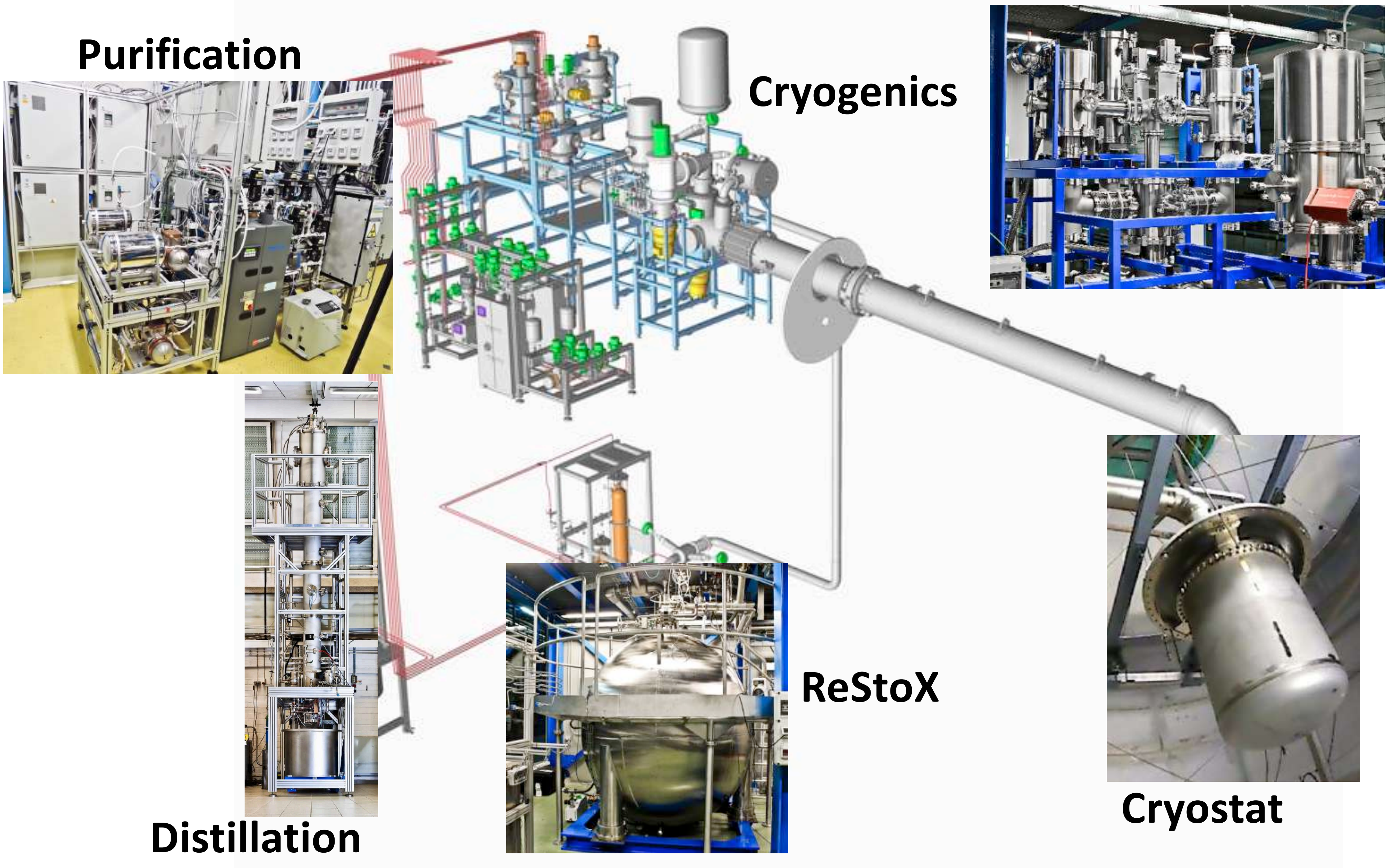


JINST 9, 11007 (2014)

CRYOGENIC AND GAS SYSTEMS



CRYOGENIC AND GAS SYSTEMS



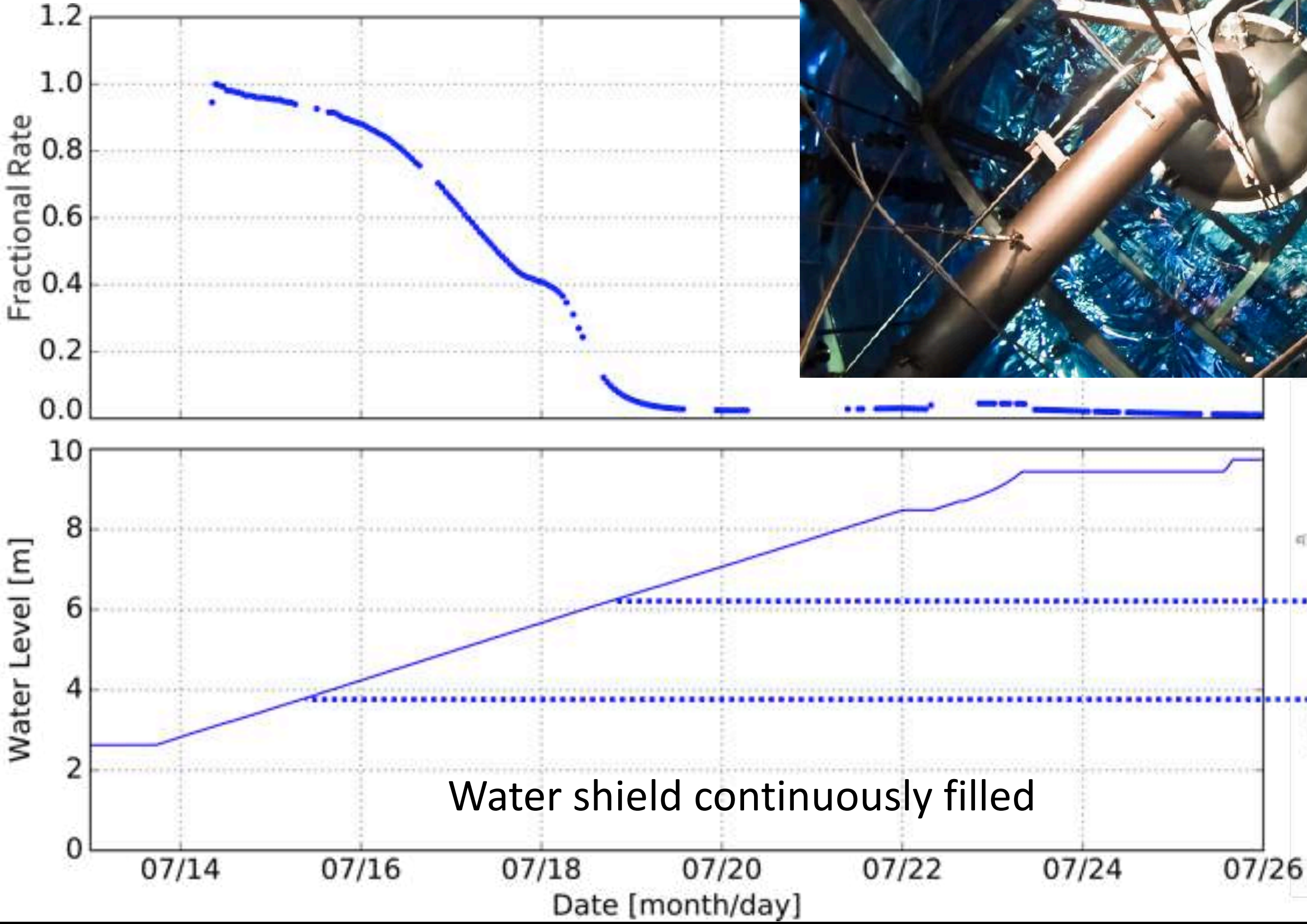
THE CRYOSTAT

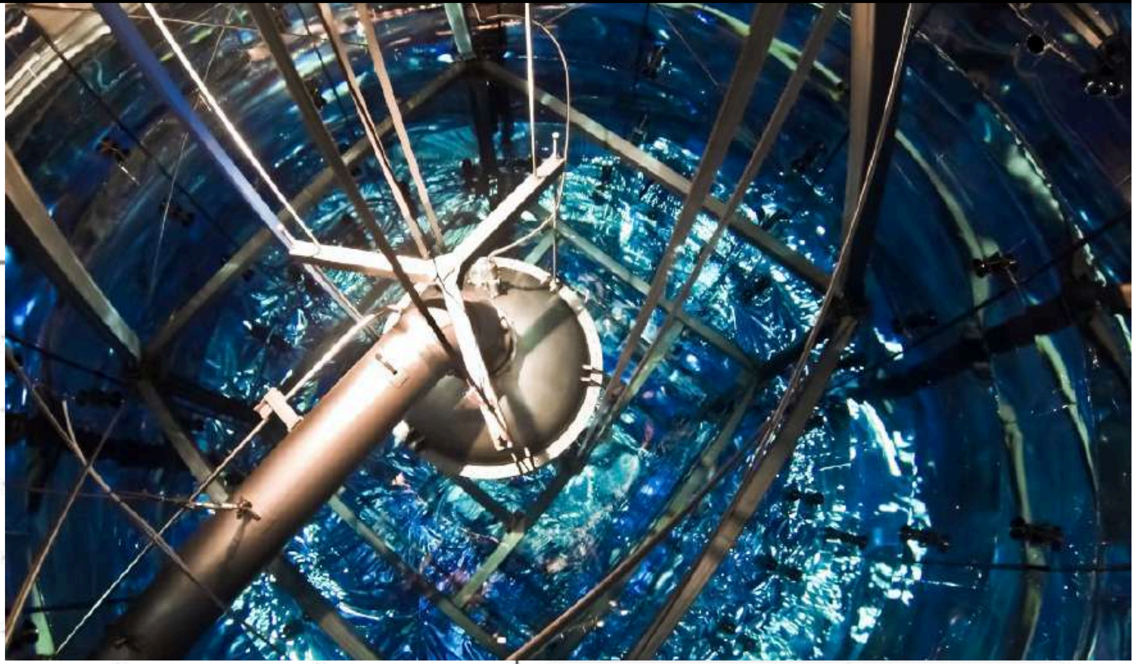
Goal

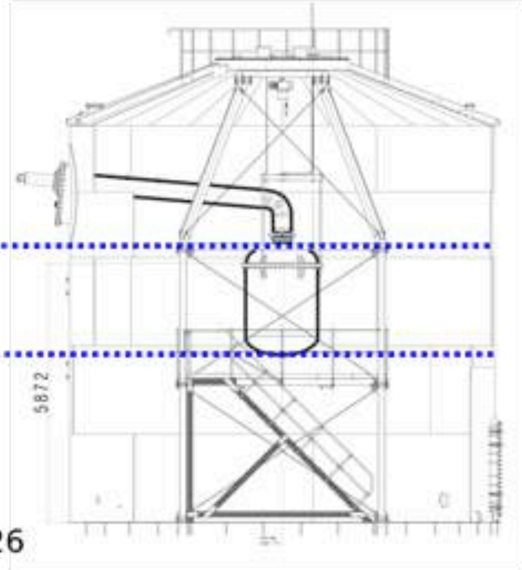
a ultra-high-vacuum, thermally insulated system made of low-radioactivity material, to contain the detector with 3.5 tons of LXe at -95 °C and 2 bar pressure and to couple it to the cryogenics system outside the water shield

Cryostat in the Water Tank

TPC filled with 3.2 t of Xe







Water shield continuously filled

TIME PROJECTION CHAMBER

Goal

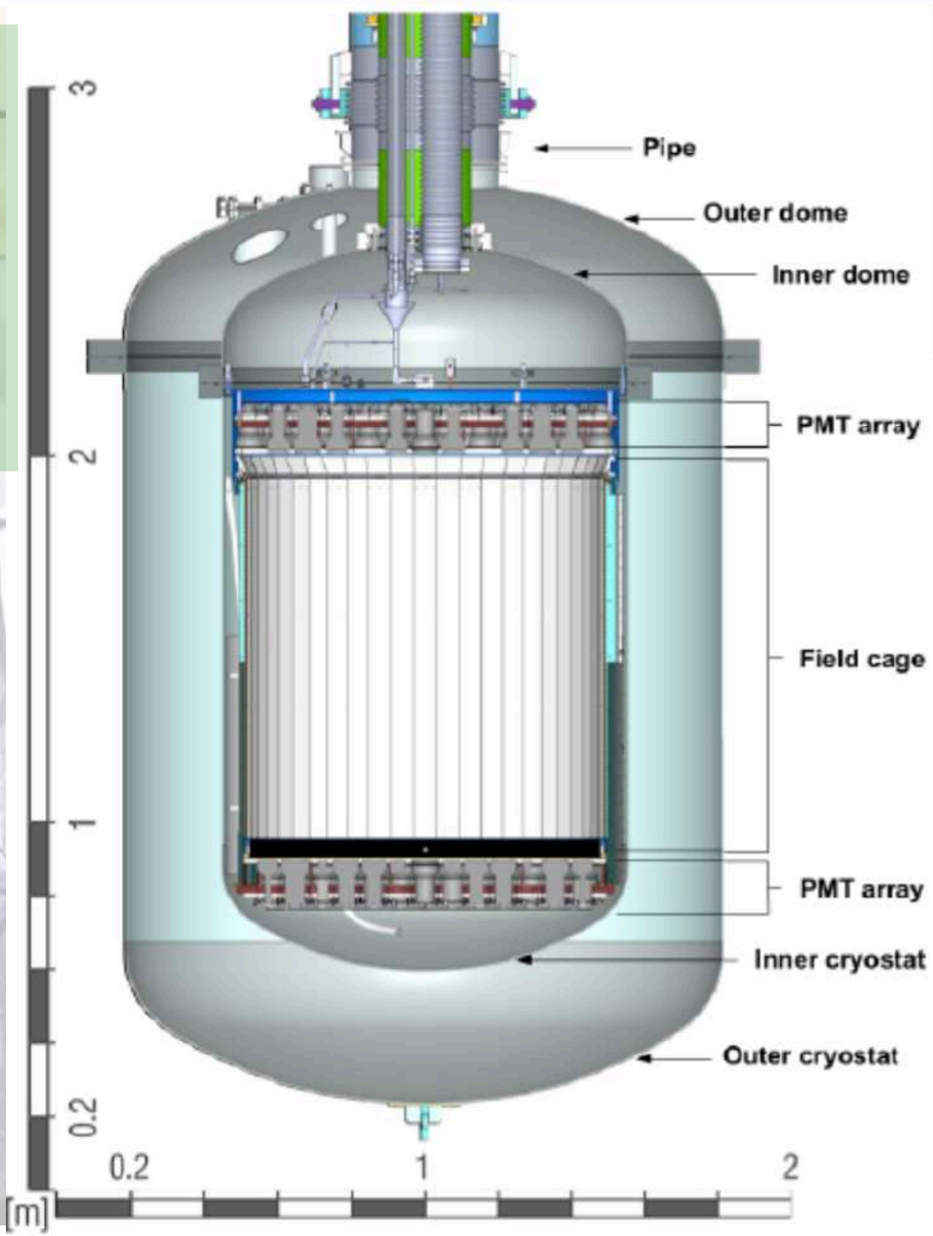
build a ultra-low-background two-phase XeTPC with the best performance for WIMP detection

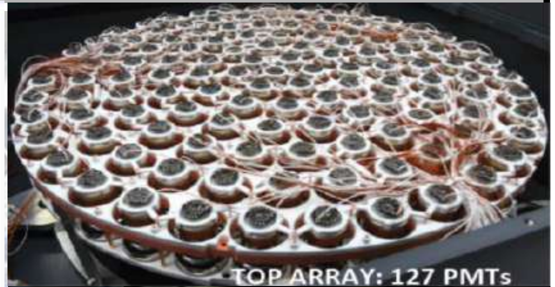
TIME PROJECTION CHAMBER

TIME PROJECTION CHAMBER

- Total Xe: 3.2 t
- Active Xe: 2t
- Diameter ~ 1m
- Height ~1m

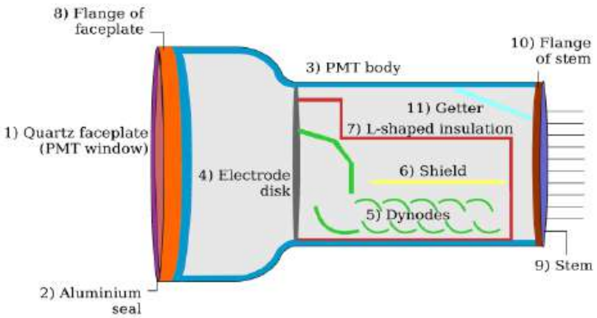
Eur. Phys. J. C75, 11, 546 (2015)
JINST 8, P04026 (2013)
JINST 12, P01024 (2017)
arXiv:1509.04055

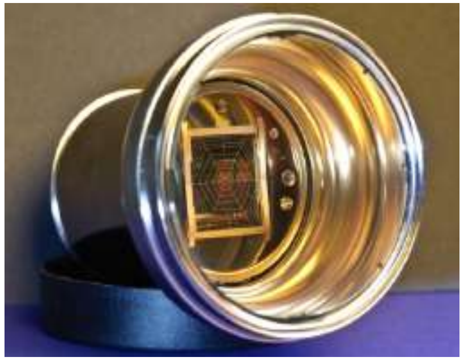


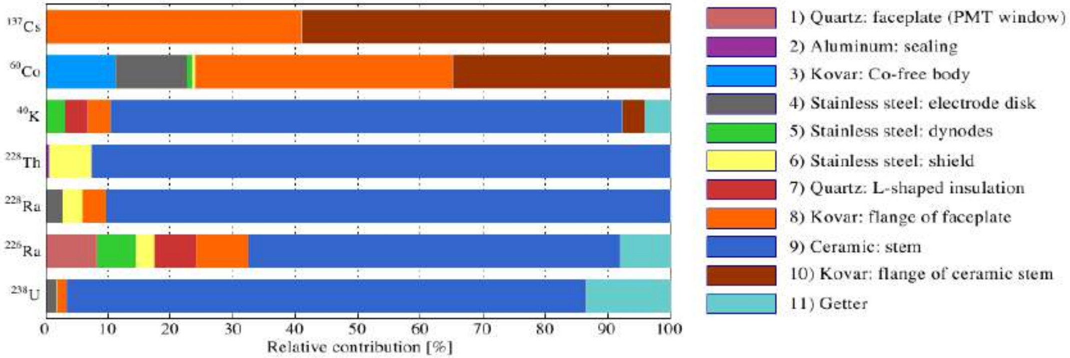


PHOTOMULTIPLIERS (PMTS)

- 248 Hamamatsu R11410, 3” PMTs
- Low radioactive background
- 35% QE @ 178 nm
- operating gain $5x10^6$ @ 1.5kV stable within 1-2%
- Extensive pre-testing/characterization campaign







E. Aprile et al. (XENON), Eur. Phys. J. C75 (2015) 11, 546
arXiv:1503.07698

MATERIAL SCREENING AND SELECTION

Goal

Improve radio purity of all materials used in XENON1T detector by screening and selection: all relevant components of the cryostat and the TPC have been measured

GeMPI-1, LNGS

GeMPI-4, LNGS

GIOVE, MPIK

GATOR at LNGS

LNGS screening facility

Method

- multiple facilities available to the Collaboration
- 200 samples measured with gamma spectroscopy and ~40 samples with mass spectroscopy

Radon Control and Measurement

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
- 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

Dedicated ultra-low background gas handling system for samples testing

GAS HANDLING AND IMPURITY CONTROL

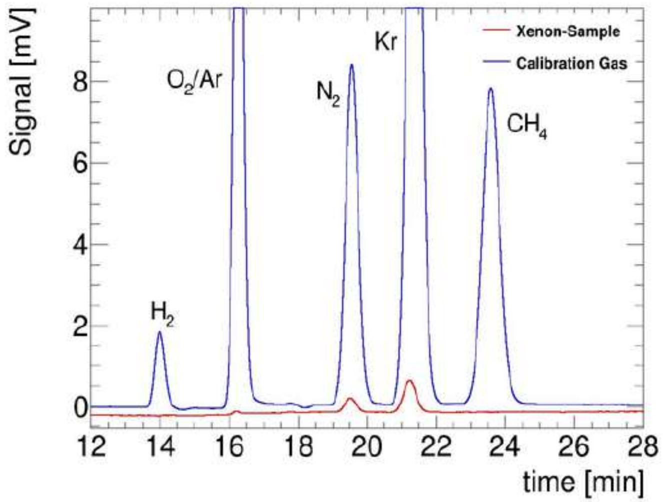
It takes ~600.000 liters of Xe gas to fill XENON1T with 3500 kg of LXe

GAS HANDLING AND IMPURITY CONTROL

It takes ~600.000 liters of Xe gas to fill XENON1T with 3500 kg of LXe

Goal

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



Method

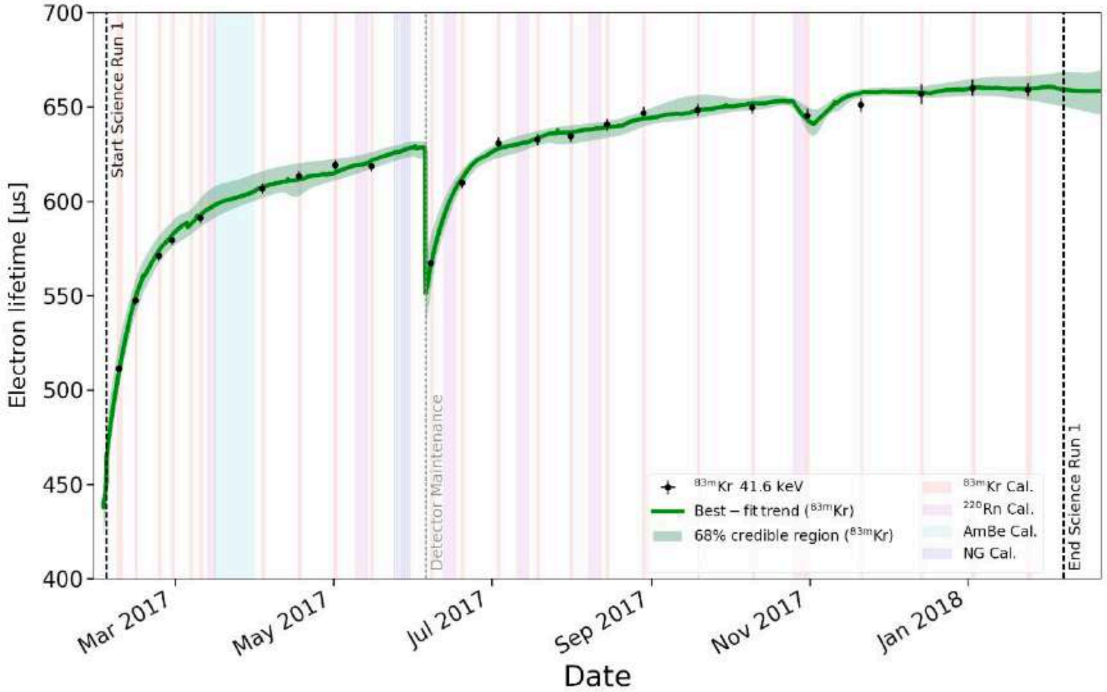
- Connect and analyze up to four gas cylinders
- Recuperate gas residuals during detector filling
- Interface for xenon transfer (detector to bottles, distillation column to bottles, bottles to bottles)

PURIFICATION SYSTEM

- Electronegative impurities in the Xe gas and from materials outgassing reduce charge (and light) signal
- To drift electrons over 1 m requires < 1ppb (O_2 equivalent)

Goal

clean Xe from electronegative impurities via continuous gas purification through heated getters



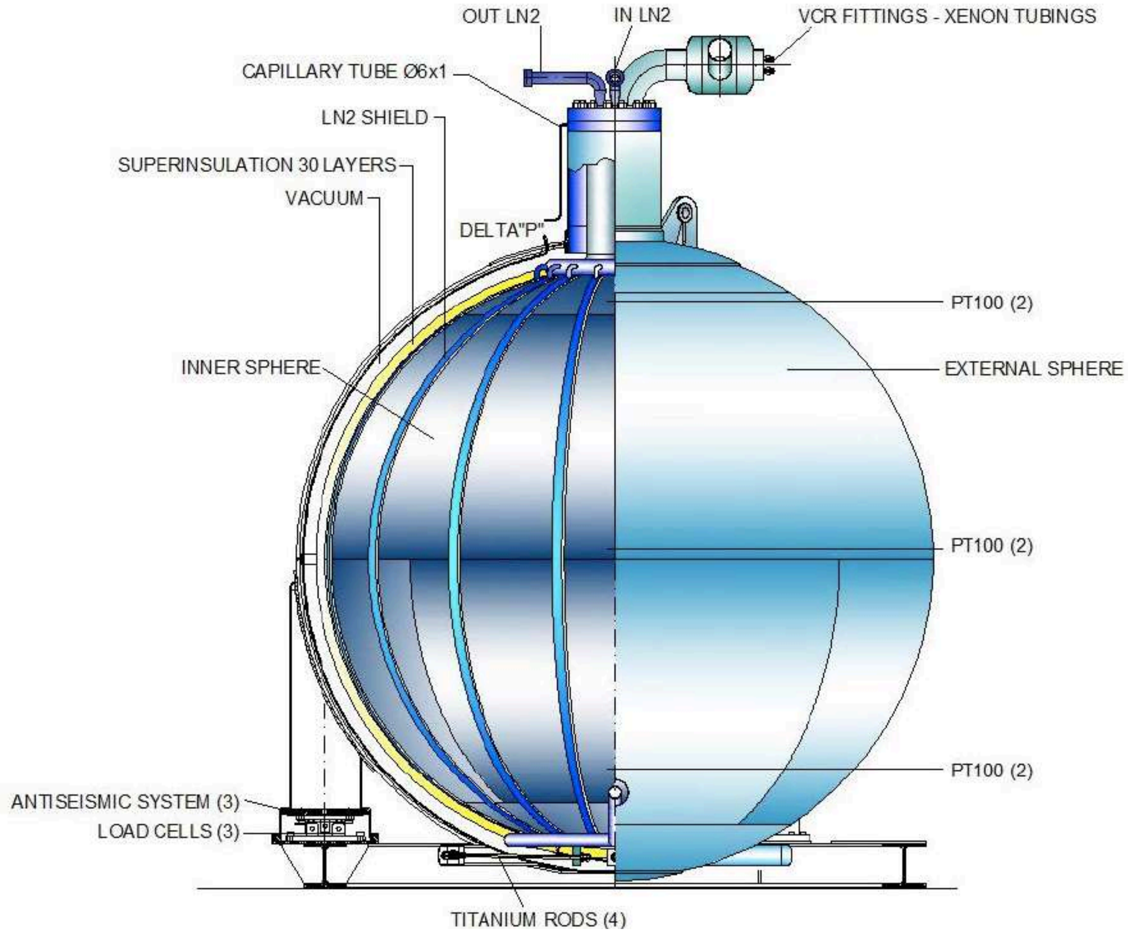
Charge loss by impurities corrected with e-lifetime measured from ^{83m}Kr calibration

Recovery and Storage System

Fast Recovery and Storage of Xenon: **ReStoX**

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



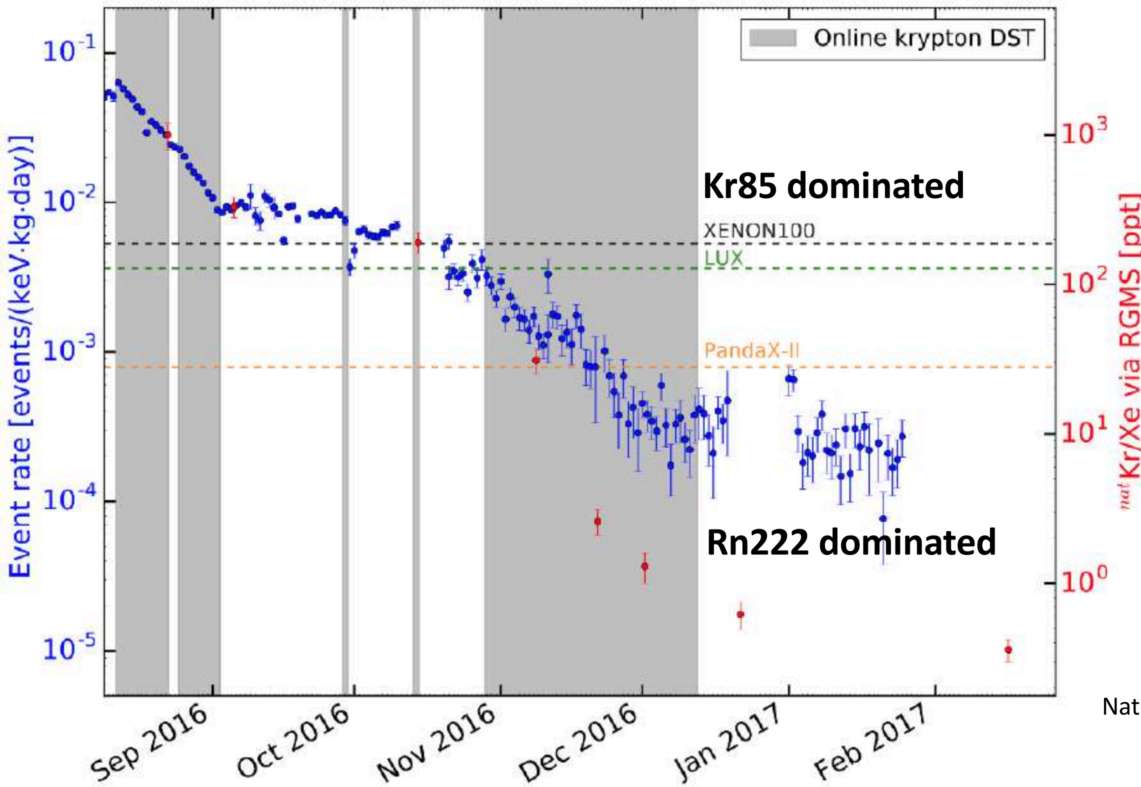
System conceived by AirLiquide and Subatech

ReStoX Construction Phases

CRYOGENIC DISTILLATION COLUMN

Goal

Active removal of ^{85}Kr contamination in Xe



^{nat}Kr/Xe

(2.60 ± 0.05) ppt beginning 1st science run

(0.36 ± 0.06) ppt 1 month after the end of the 1st science run

First results:

Purified liquid out:
^{Nat}Kr/Xe < 0.026 ppt (90% c.l.)
A factor ~10 better than required for XENON1T!

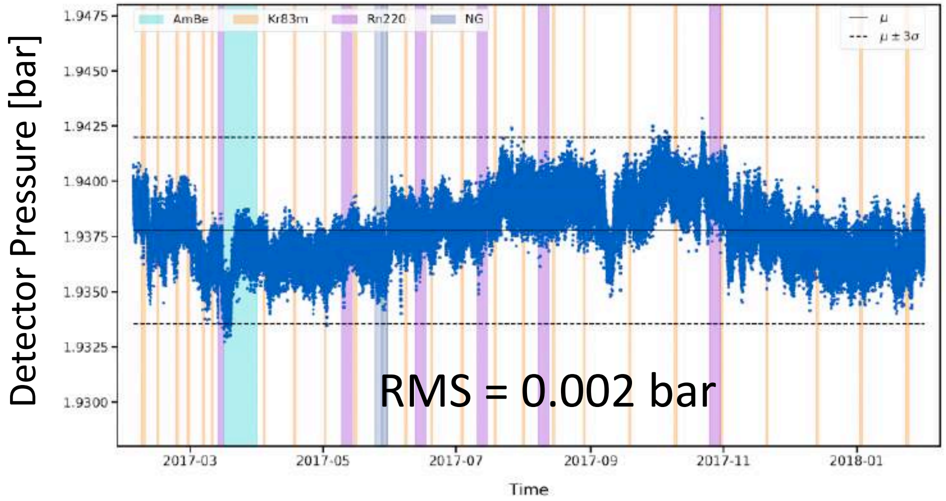
Eur. Phys. J. C77 (2017)

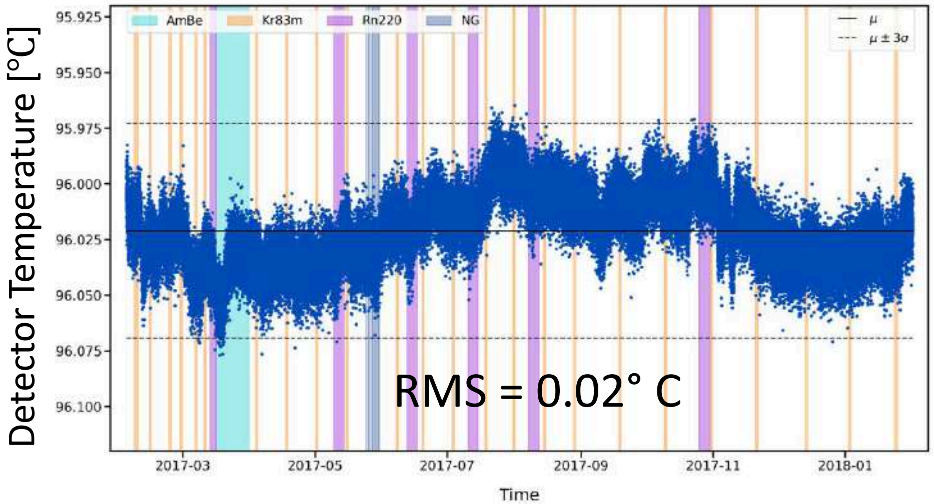
- Commercial Xe: 1 ppm - 10 ppb of Kr
- XENON1T sensitivity requires: ~0.2 ppt
- on-line distillation used to reduce Kr/Xe while taking data

CRYOGENIC SYSTEM

Goals

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





All critical detector parameters are stable throughout science runs

DETECTOR CALIBRATION

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 ^{220}Rn, ^{83m}Kr and tritiated methane

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  - Allow for transport of external sources around the cryostat
  - Two belts for vertical displacement of sources
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- **Neutron generator**
  - Mono-energetic (2.5MeV) neutrons from deuterium-deuterium fusion
  - Double scatter of neutrons, calibration of nuclear recoil response

Detector Calibration

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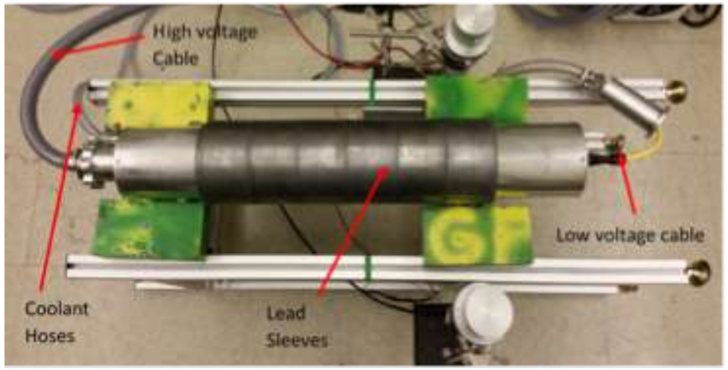

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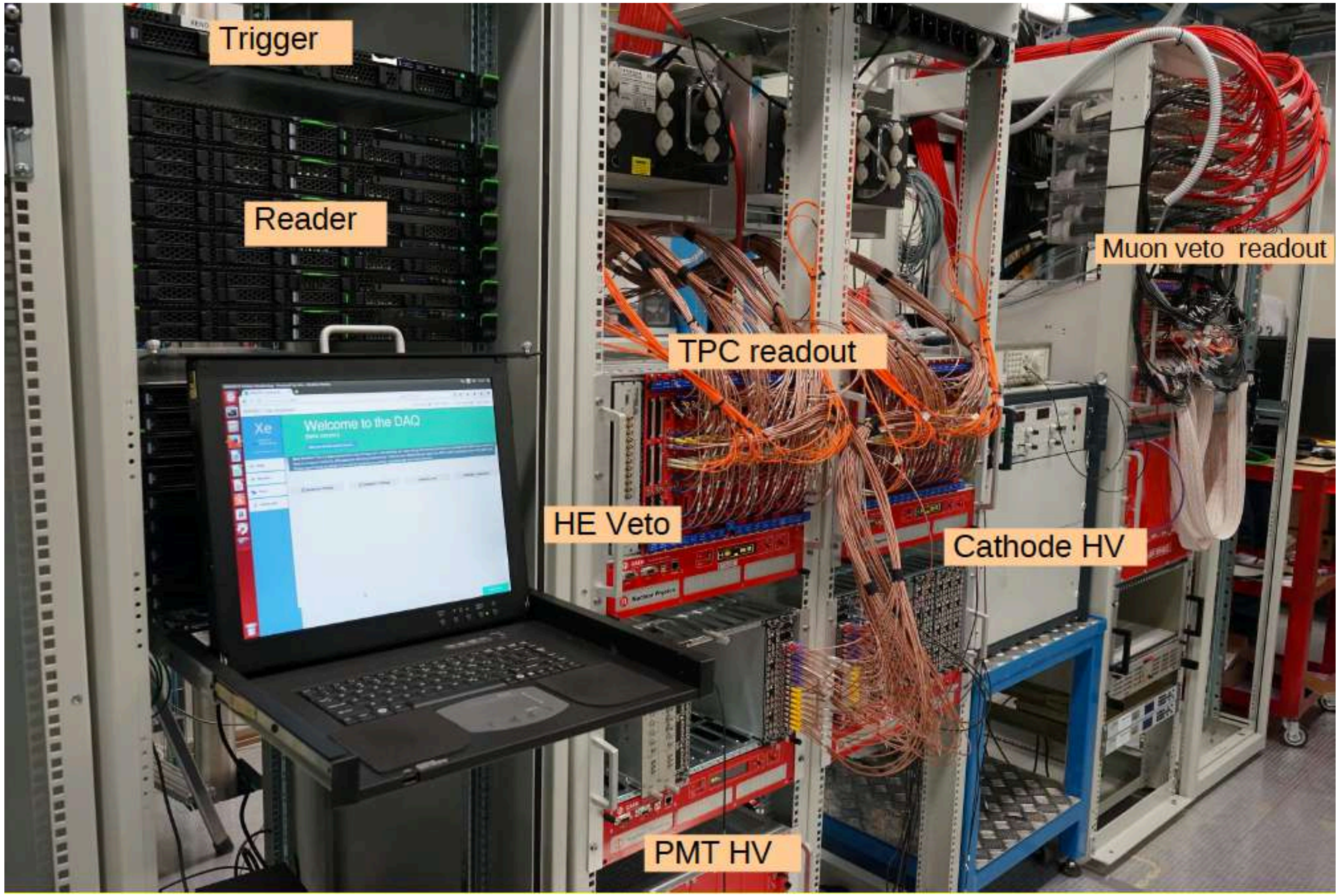
- **LED Calibrations**
  - Fiber optics guide light from external LED light sources into TPC
  - Used to monitor performance of PMTs

DATA ACQUISITION (DAQ) & COMPUTING SYSTEM

Data Acquisition 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.



Computing System Goals

- Providing enough computing facilities to process raw data and to allow data analysis by all Collaboration members
- Development and use of sharing resources

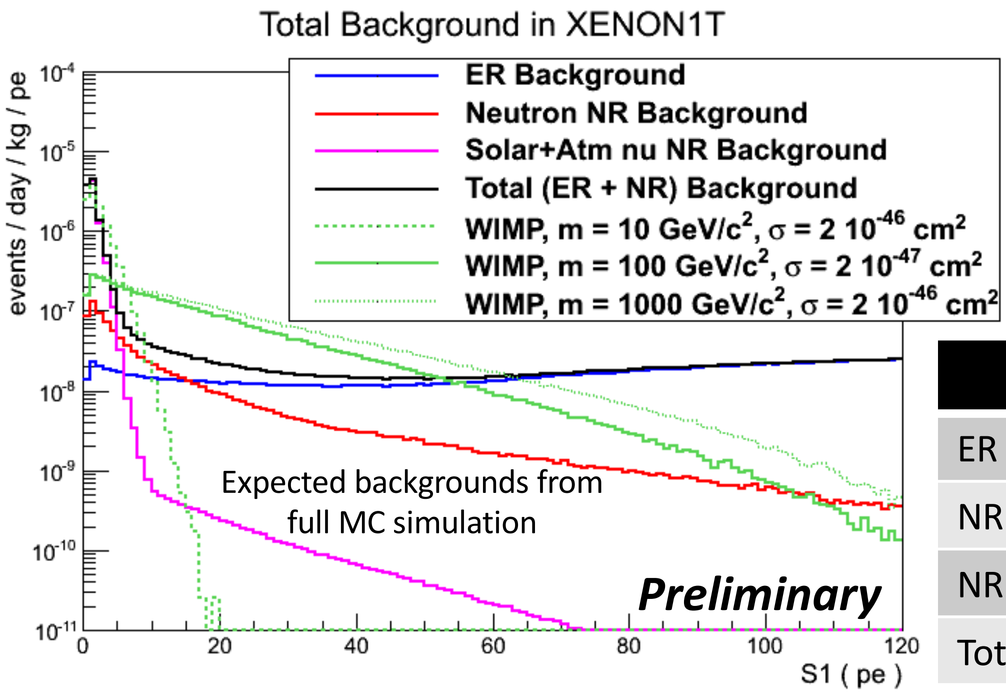
MONTE CARLO SIMULATION

Goal

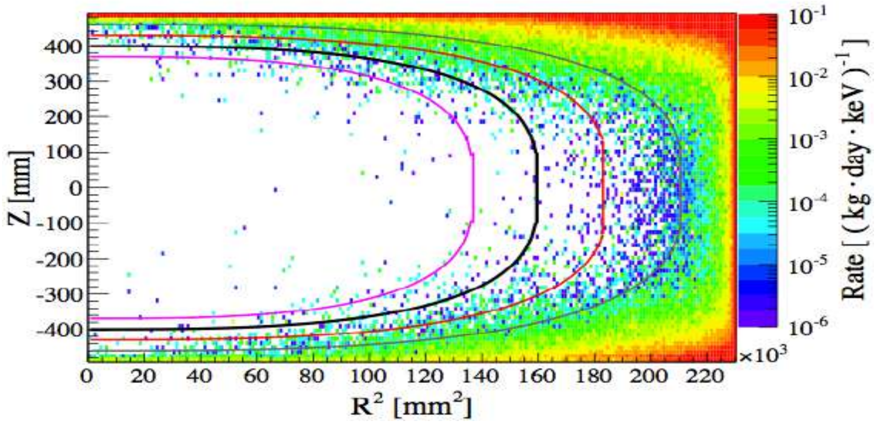
Reproduce via software the performance of the XENON1T detector, and predict the sensitivity of the experiment

Method:

- Input from screening campaign by all detector components
- Monte Carlo simulation with GEANT4
- Statistical treatment

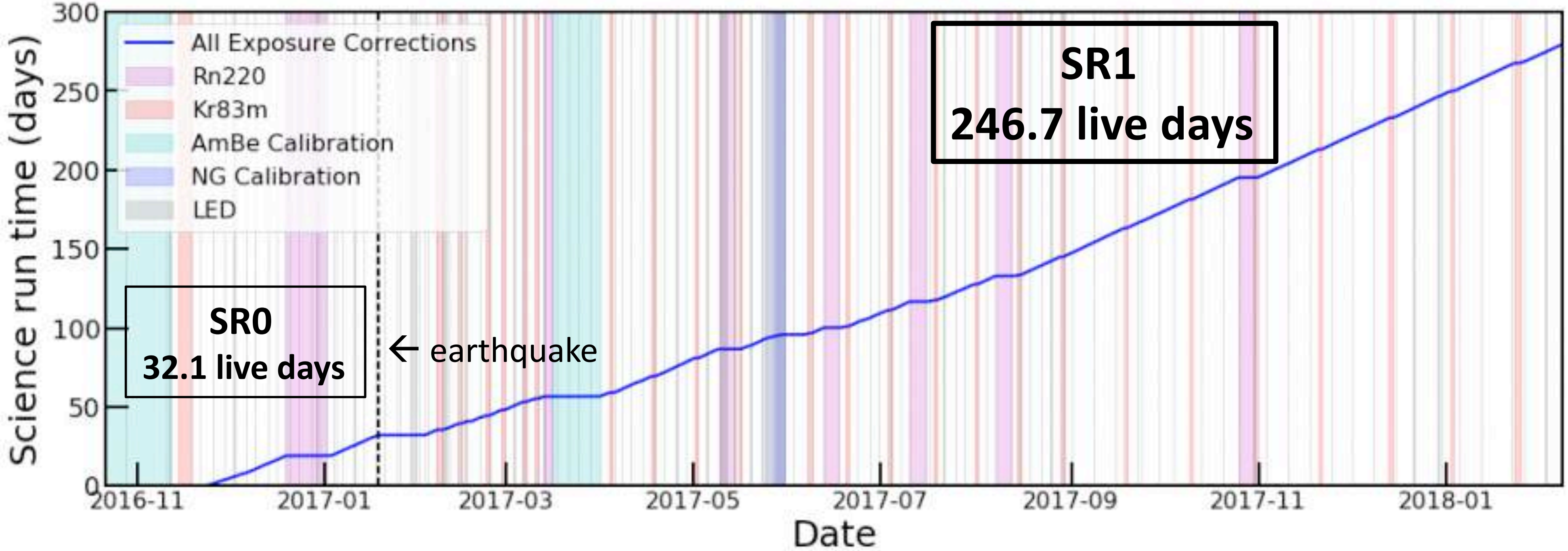


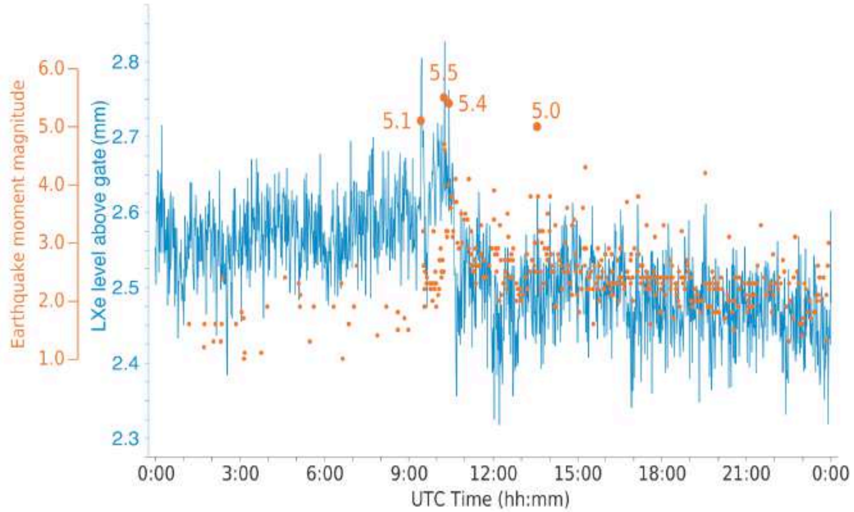
Position of the ER background from the materials← they are negligible inside the 1 ton fiducial volume



Source	Bkg (evts/ton/year)
ER (materials + intrinsic + solar ν)	0.32
NR from radiogenic neutrons	0.22
NR from ν coherent scattering	0.21
Total	0.75

XENON1T DATA TAKING & RESULTS

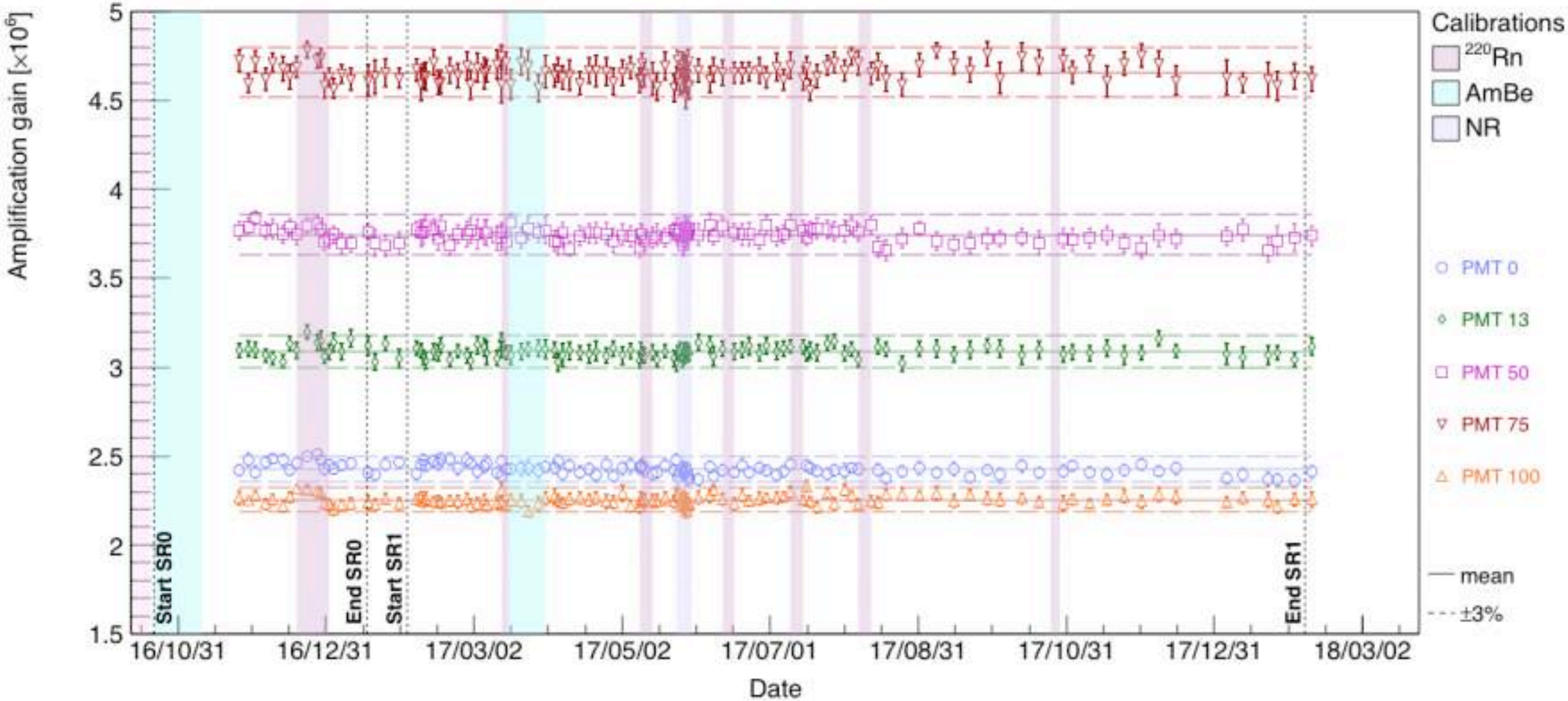




- DM total exposure SR0+SR1: 278.8 Live days
- Calibration:
  - LED → PMT gain monitoring
  - ^{83m}Kr →Stability monitoring, Signals corrections
  - ^{220}Rn →Low energy electronic recoils: **ER-bands**
  - ^{241}AmBe and NG →Signal response: **NR-bands**

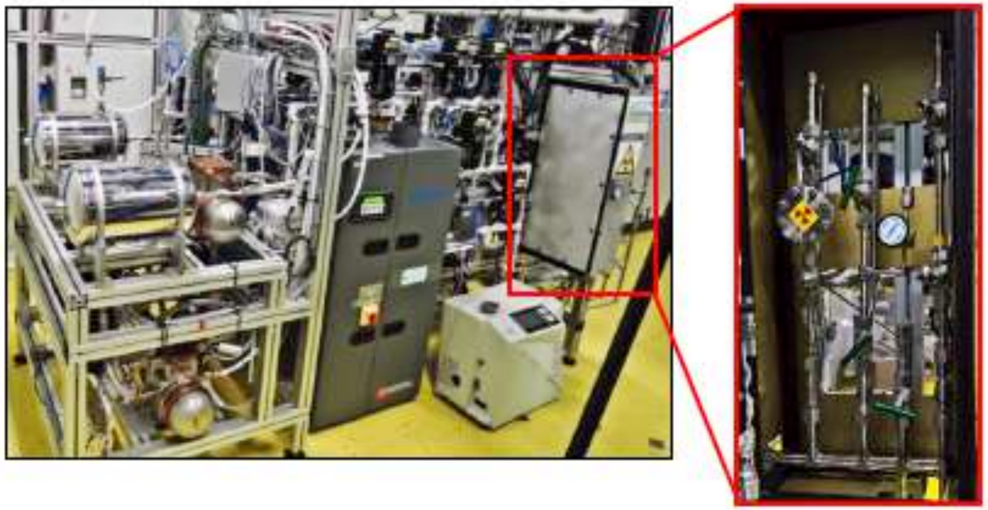
LED CALIBRATION

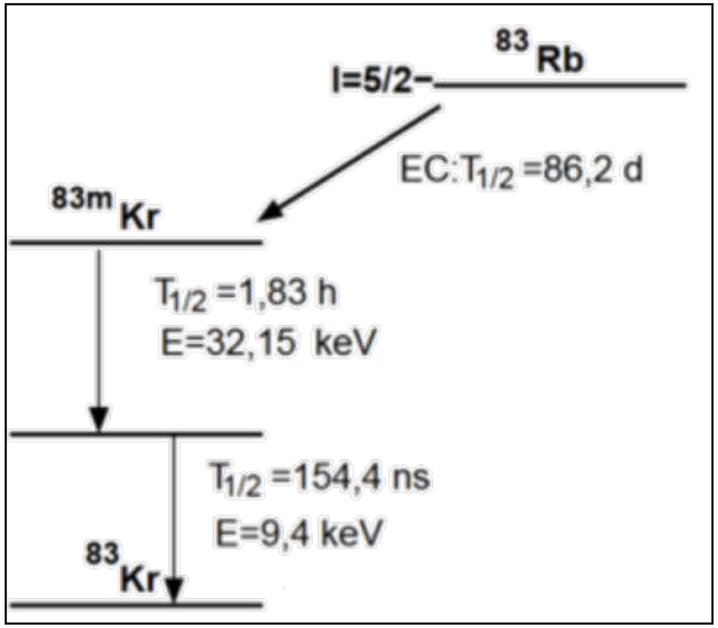
PMT gain evolution during science data taking

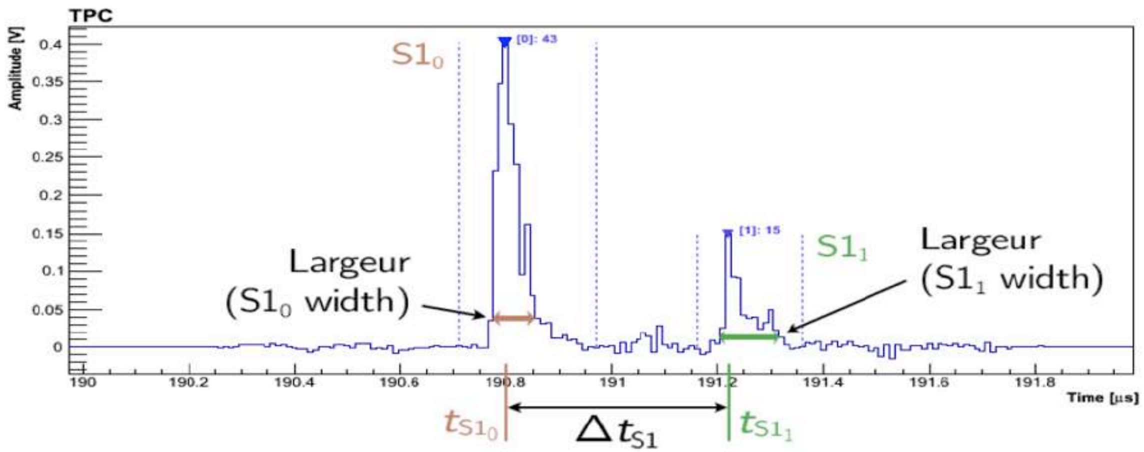


^{83M}Kr Calibration

- Internal ^{83}Rb (^{83m}Kr) source
- Uniformly distributed within the LXe
- 2 γ rays : 32 keV & 9 keV
- Energy region of interest for DM
- Short decay lifetime → allow for a fast restart of DM data taking



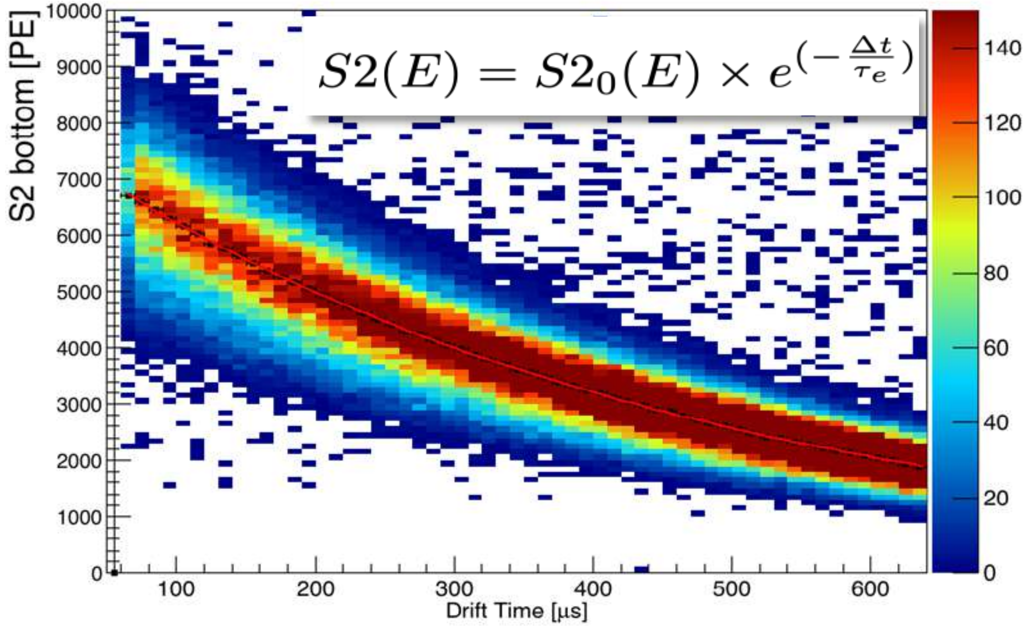




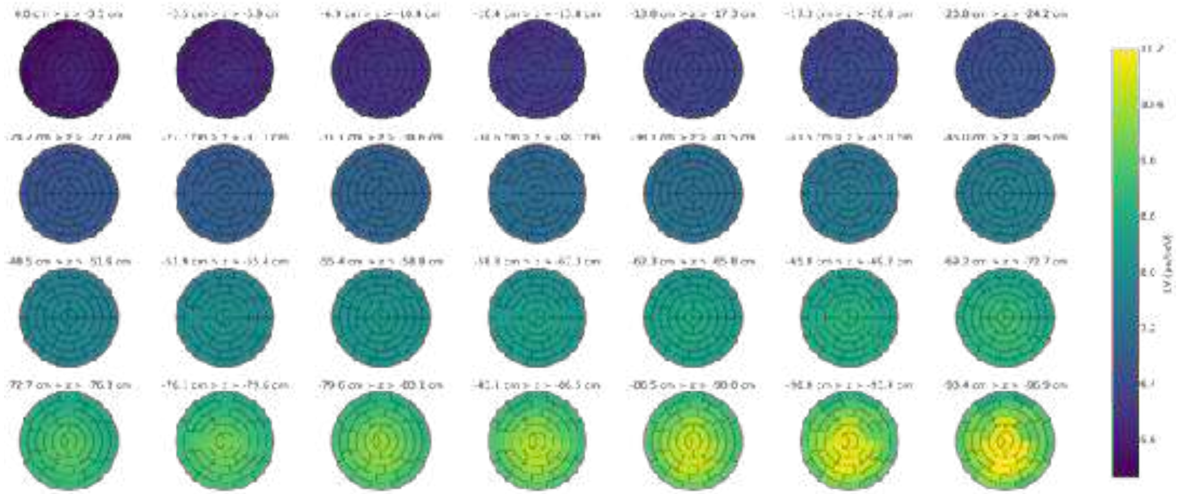
$$\Delta t_{S1} = t_{S1_1} - t_{S1_0}$$

^{83M}Kr Calibration

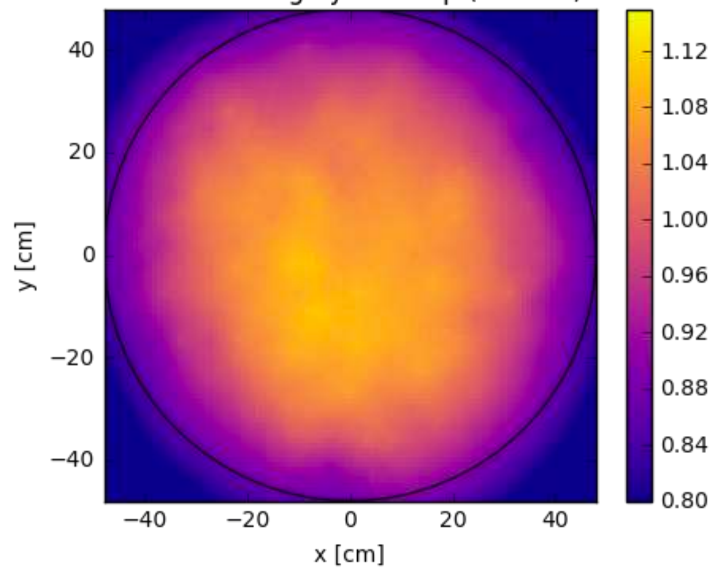
- **Signal corrections**
  - position-dependent light collection efficiency
  - position-dependent S2 amplification
  - electric field non-uniformity
- electron lifetime cross-check
- light/charge yield stability



Light collection efficiency maps

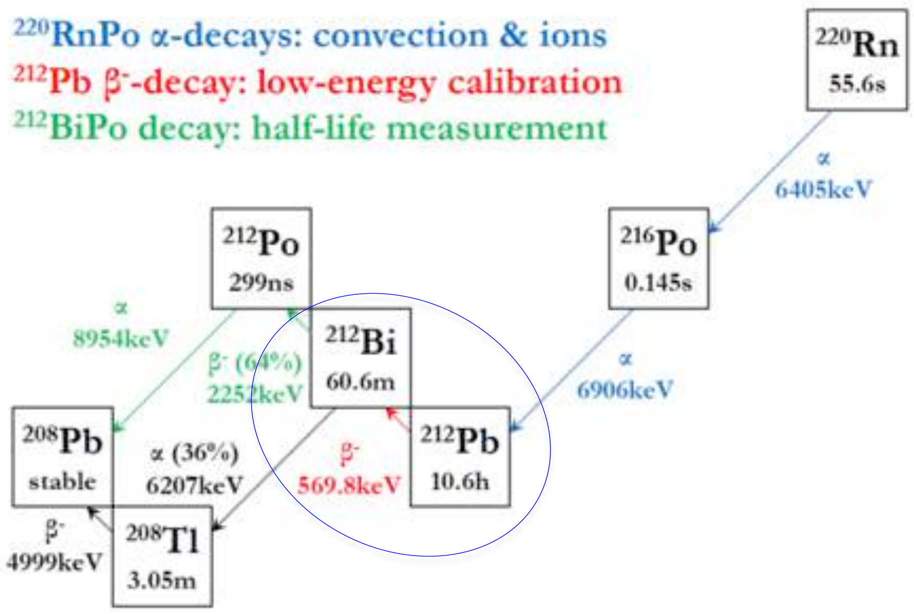


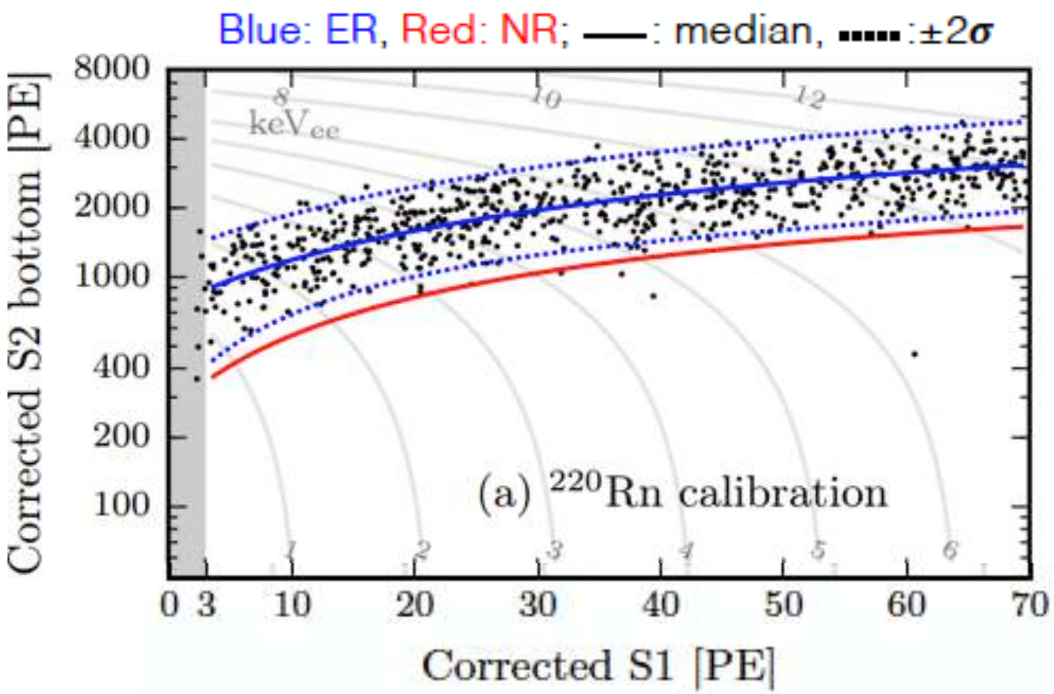
Final S2 charge yield map (bottom)



^{220}Rn Calibrations

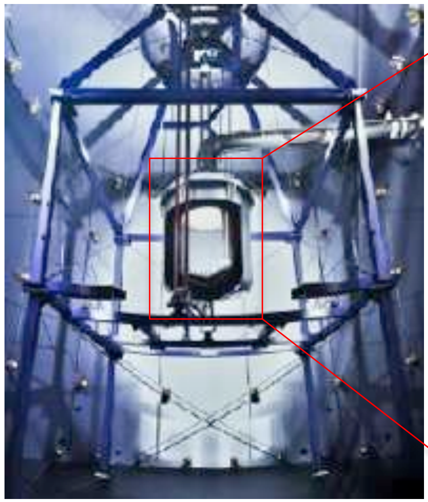
- Internal ^{228}Th source emanates **^{220}Rn** directly into LXe
- **β-decay** of ^{212}Pb to ^{212}Bi → **low energy** events (2-20 keV) to calibrate **ER band**
- Decay of activity dominated by ^{212}Pb half-life (10.6 h)
  - No long lived isotopes
  - No purification requirement on LXe
- Bkg and signal predictions from tuned models → Fitting model to data

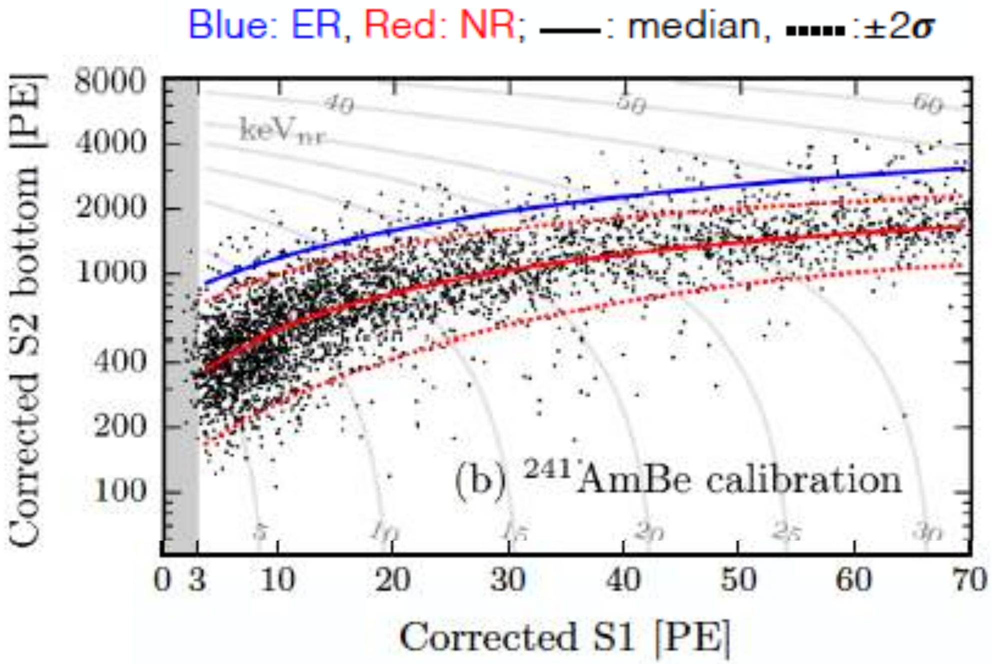




^{241}AmBe & neutrons Calibrations

- External ^{241}**AmBe** source mounted on a belt
- The α particles emitted by the decay of the Am collide with the light Be nuclei producing fast neutrons → used to calibrate **NR-band**
- Upgrade to neutron generator
  - Commissioned May 2017
  - Calibration time: weeks→ days
- Bkg and signal predictions from tuned models → Fitting model to data

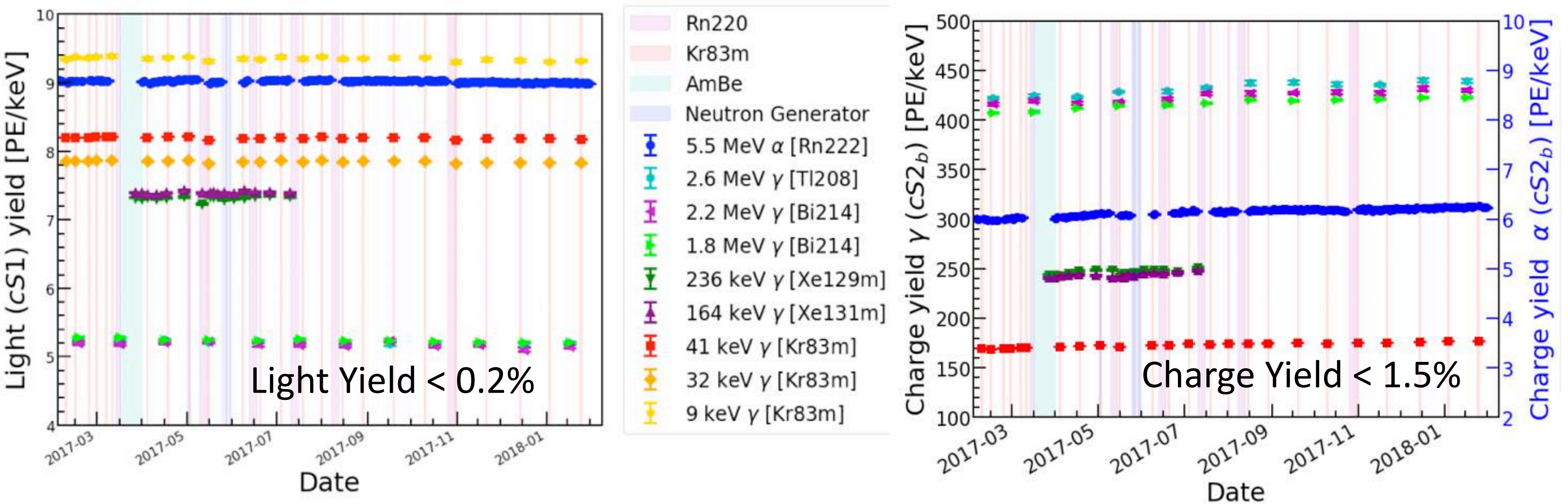




DETECTOR STABILITY MONITORING

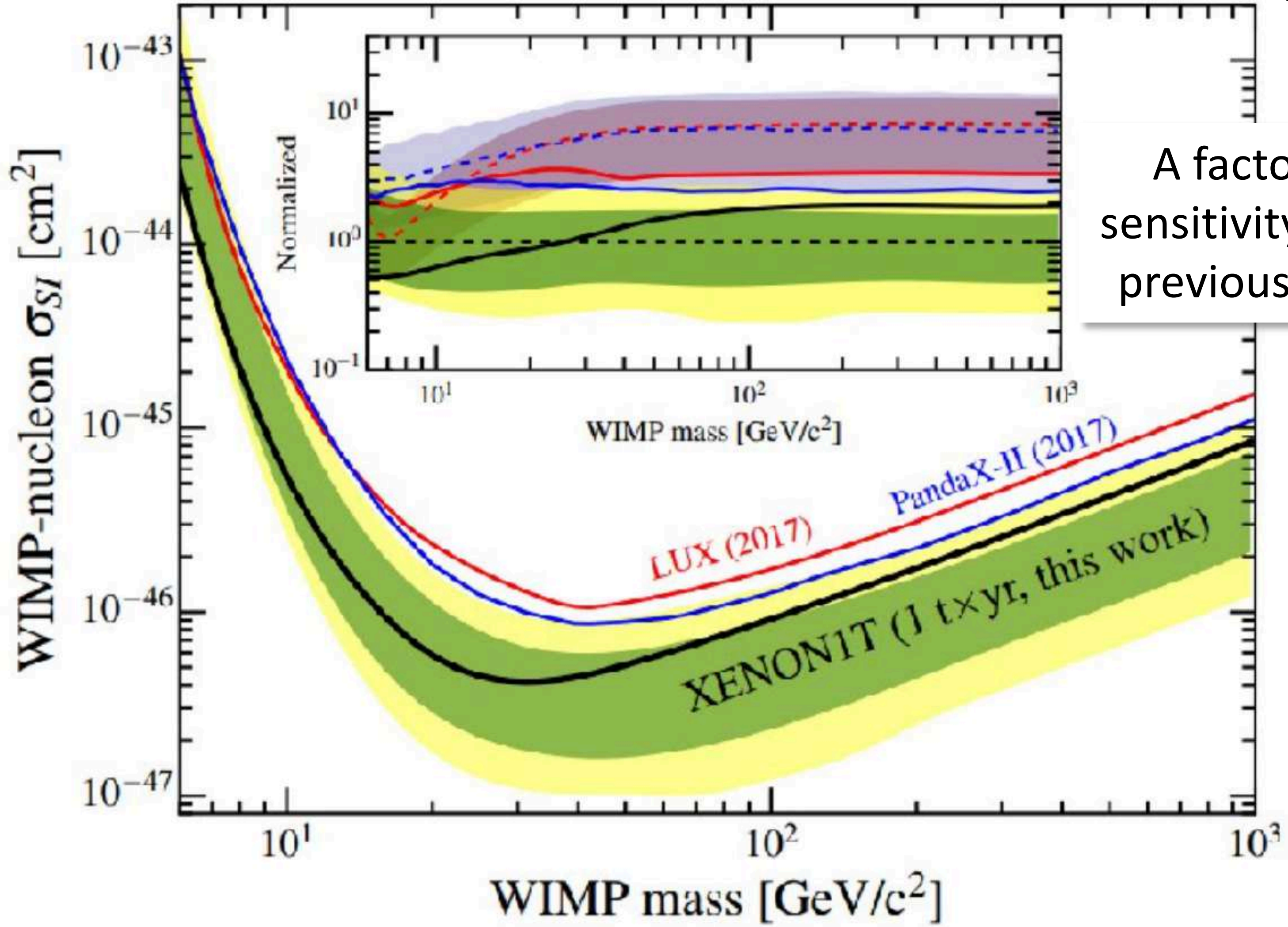
The quality of the data strongly depends on detector conditions during the experiment operation

→ It is important to check the stability of the detector during data-taking



SI WIMP-nucleon 1 T x Year Results

Phys.Rev.Lett. 121, 11130



A factor of 7 more sensitivity compared to previous experiments

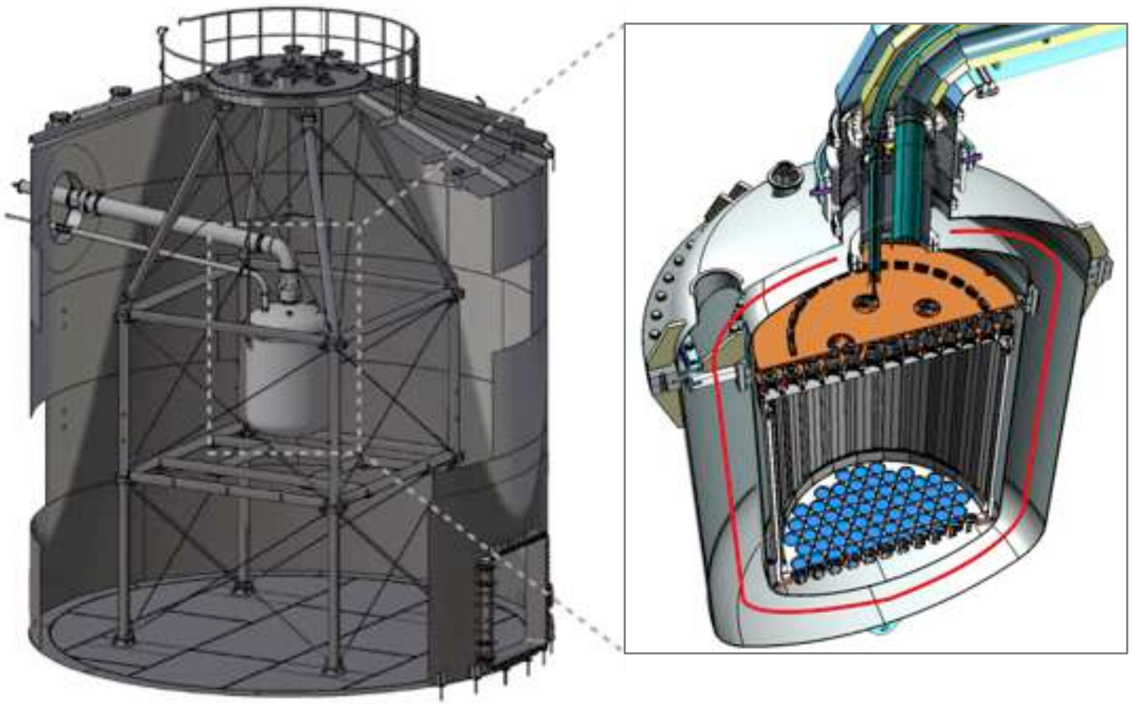
Minimum at σ_{SI} = 4.1 x 10^{-47} cm^2 for a WIMP of 30 GeV/c^2

XENON1T → XENONnT

XENON1T infrastructure already designed to host XENONnT

Fast upgrade of XENON1T

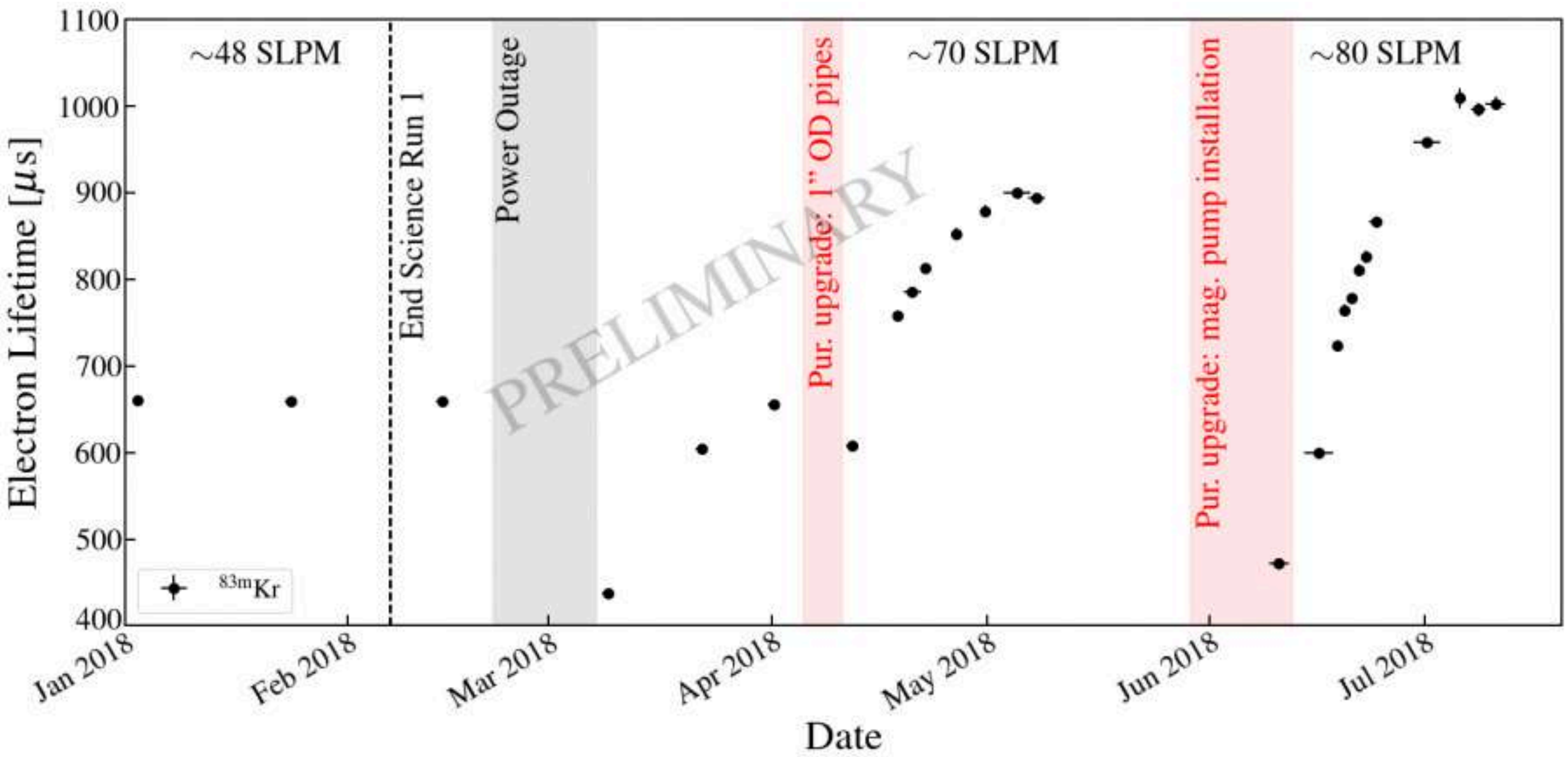
- **Total LXe mass ~8 t**
- **Active LXe mass** increases x3: 2.0 t → **6.0 t**
- **Additional PMTs** (and electronics): 248 → **476**
- **New TPC and Inner Cryostat**
- **Additional recovery system**



All the other systems already sized to host and run XENONnT:
Outer Cryostat, Cryogenics, DAQ, Purification, Support structure, Muon veto, DAQ, Calibration system, screening facilities

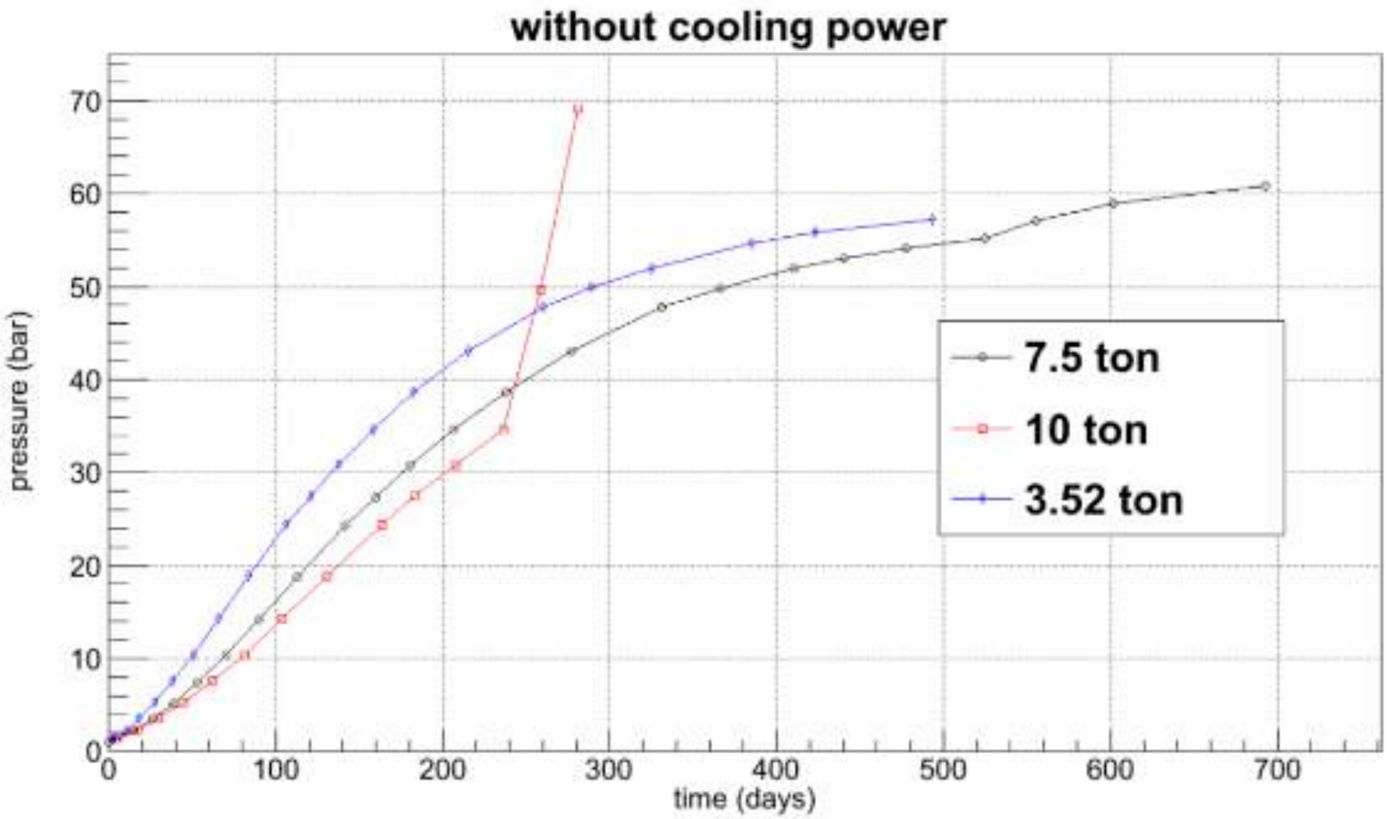
XENON1T POST SR1 TESTS TOWARDS XENONnT

- Increased purification gas flow
  - increased by 39% wrt Q-drive
  - electron lifetime of 1 ms reached



ReStoX2: SXe /GXe Storage System

- ReStoX capacity is not sufficient for XENONnT
- XENONnT needs to increase the recovering capacity in case of emergency



XENONnT : TPC Electrodes

- Work started in summer 2017
- design, relationship with companies, mechanical simulation, mechanical realization and assembly …
- Prototype tested at LNGS in summer 2018

Conception, Design and Construction of the 5 electrodes

DARWIN

Ultimate liquid xenon TPC

- 2.6 m drift length
- 2.6 m diameter TPC
- Active target ~40 t
- Aim at **sensitivity of a few 10^{-49} cm^2** limited by irreducible ν-bkg :
- **Projected to start after XENONnT**