The challenges of the direct dark matter search with liquid xenon

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CNRS

October 22nd, 2018, HDR defense, LPNHE

Xe
XENON
Dark Matter Project

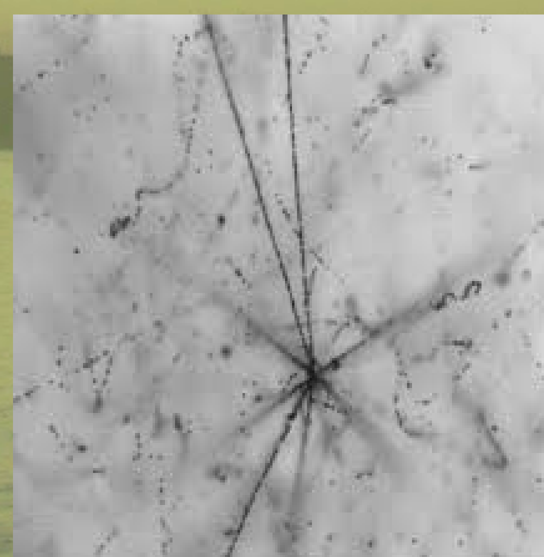
My background

Università di Napoli "Federico II"

+ 5 month in Nagoya, Japan

CHORUS experiment

(WANF, CERN)



(the neutrino, at that time candidate to explain all the dark matter)

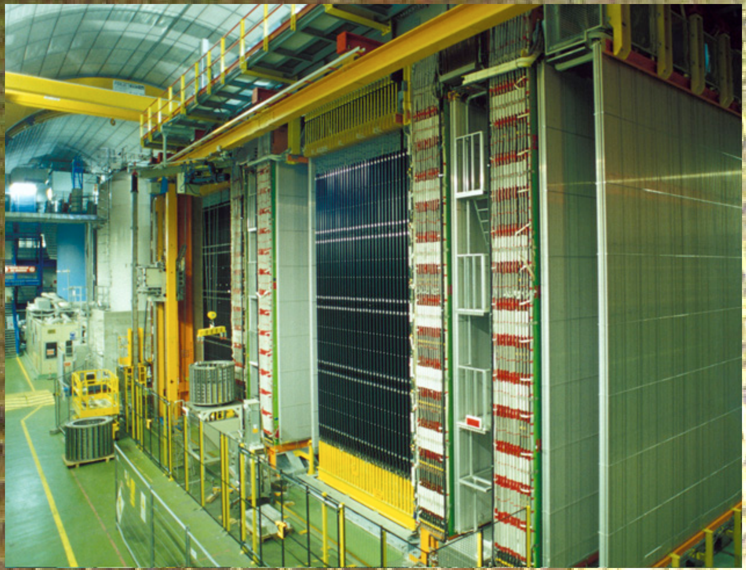
Università di Napoli "Federico II"

+7+7 months at Berne, Switzerland

OPERA experiment

(CERN → LNGS)

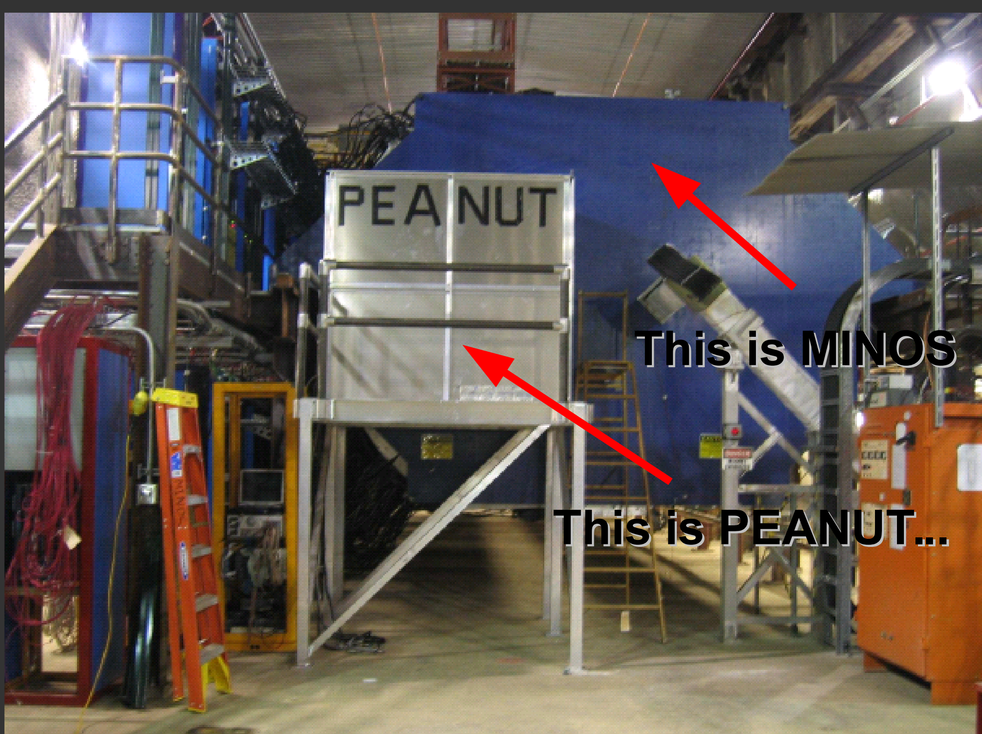
OPERA



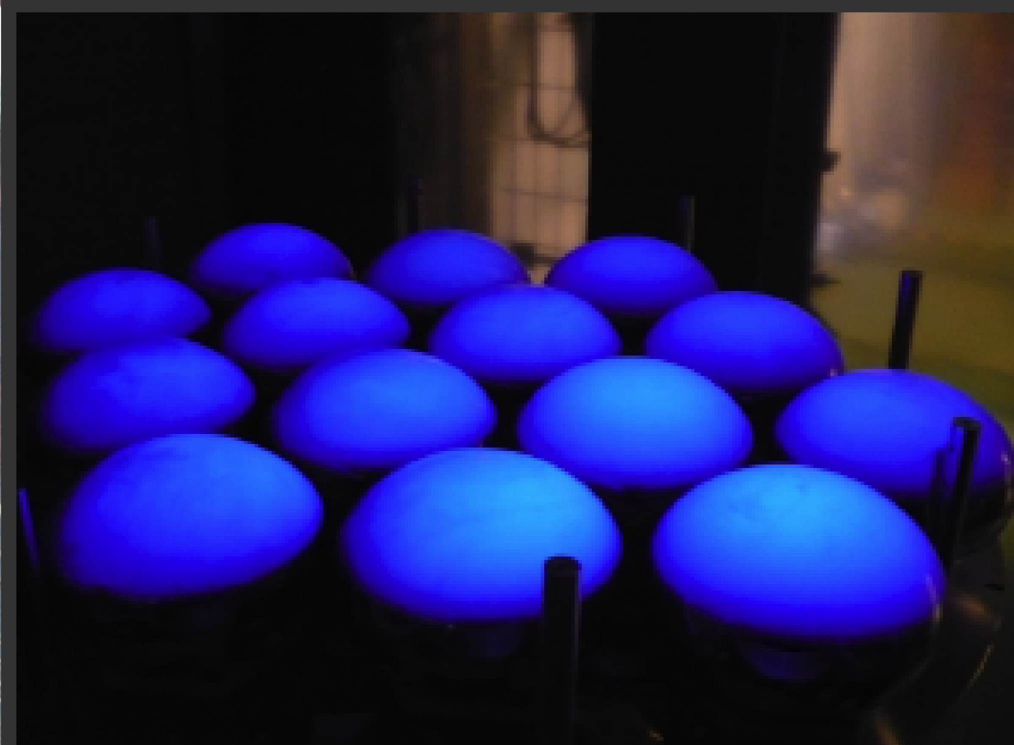
(validation pf $\nu_\mu \rightarrow \nu_\tau$ oscillation through the direct observation of ν_τ)

Switzerland...

PEANUT (LHEP, Berne) :
construction of a ν_e detector at Fermilab with the NuMi beam for MINOS



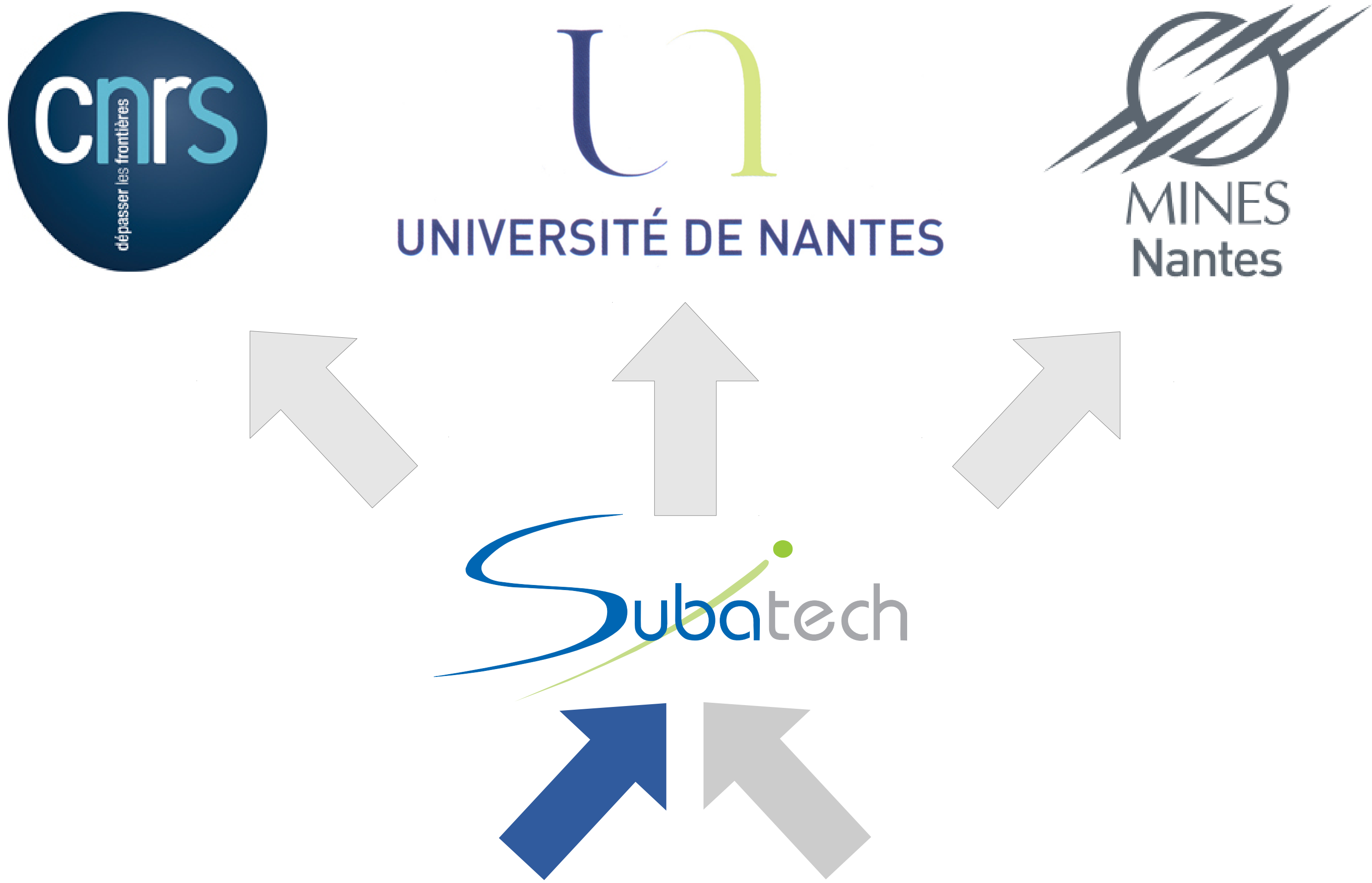
ArDM (UZH/CERN) :
Direct dark matter search with 1ton of liquid Argon



Then in France . . .

(arrived in France in 2010)

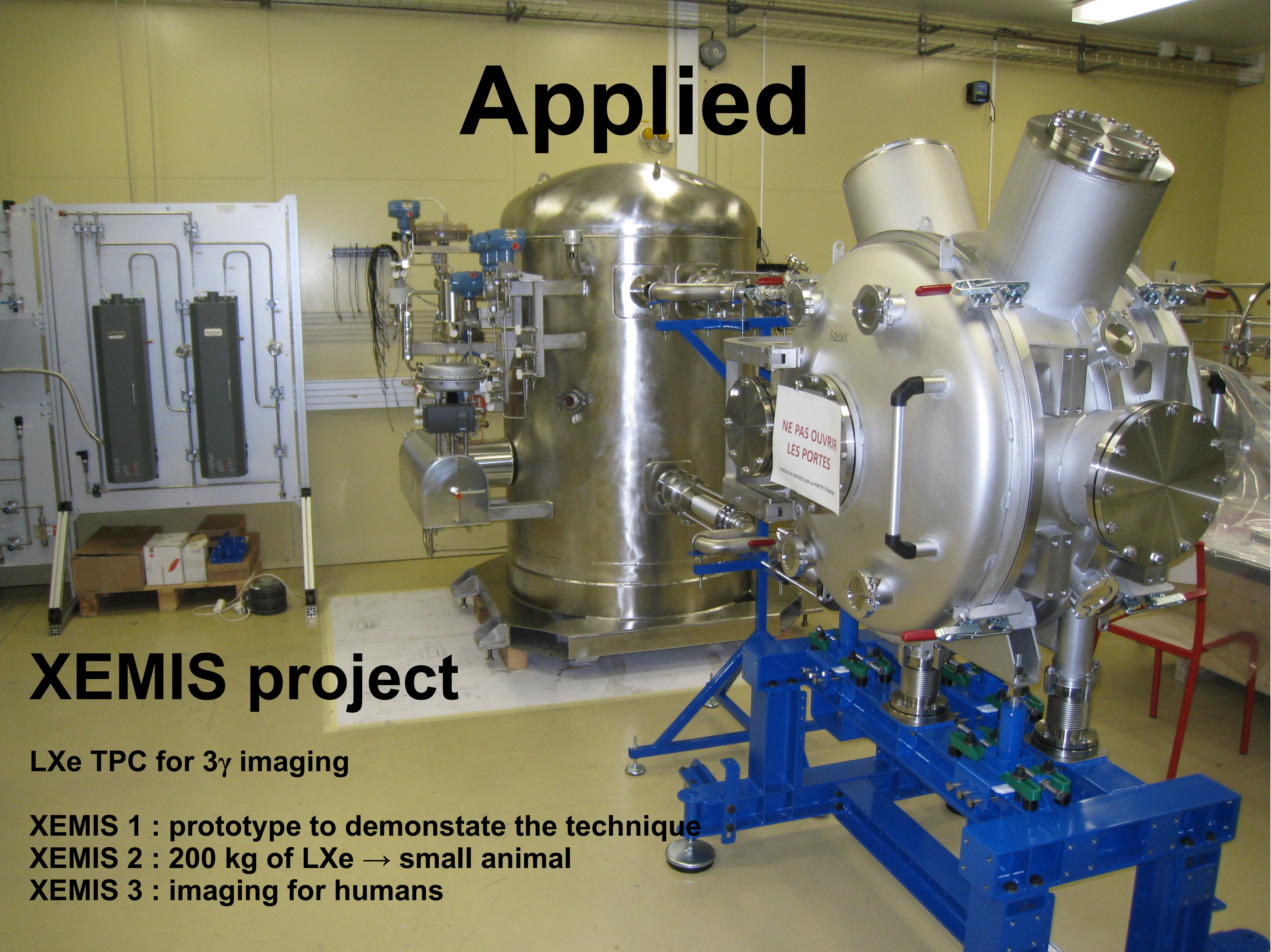
CNRS researcher, CR2, Laboratoire Subatech, groupe Xénon



Fundamental and applied

Applied

XEMIS project



LXe TPC for 3γ imaging

XEMIS 1 : prototype to demonstate the technique
XEMIS 2 : 200 kg of LXe → small animal
XEMIS 3 : imaging for humans

...and fundamental

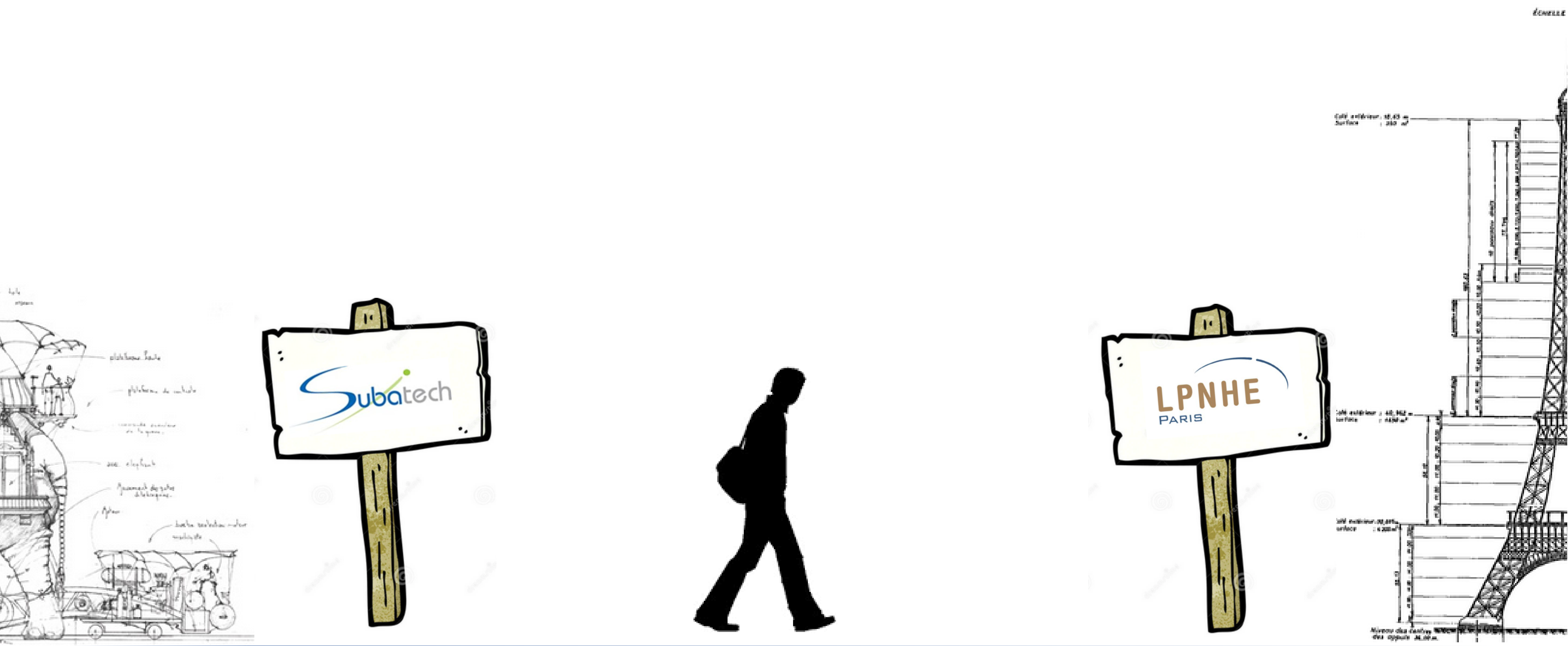
XENON project

LXe TPC for the direct dark matter search

Computing and data analysis . . .

. . . and hardware

XENON @ LPNHE



Direct dark matter search

WIMP Dark Matter wind

WIMP is required to be:

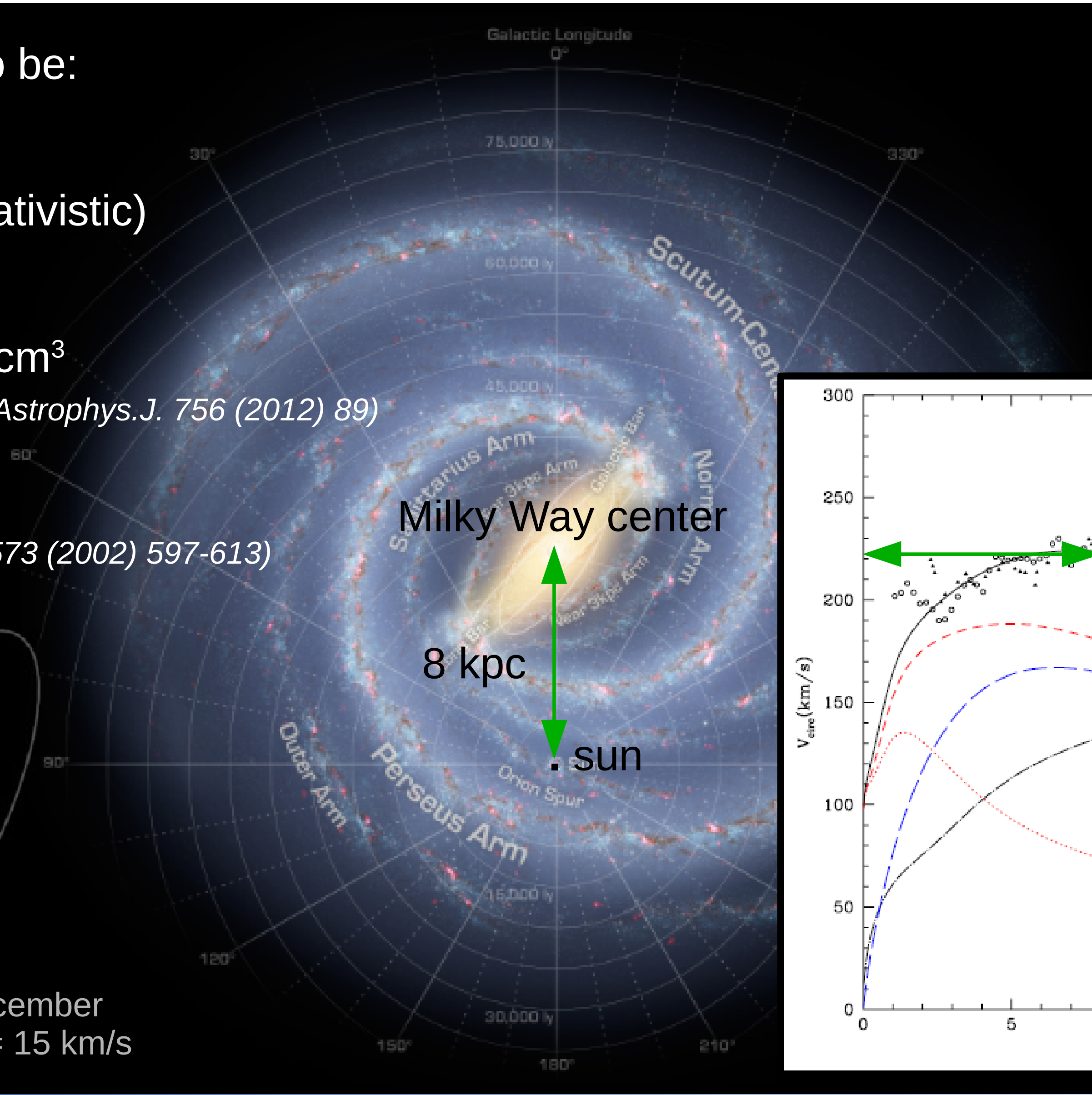
- Neutral
- Non-baryonic
- Cold (non-relativistic)
- New Particle

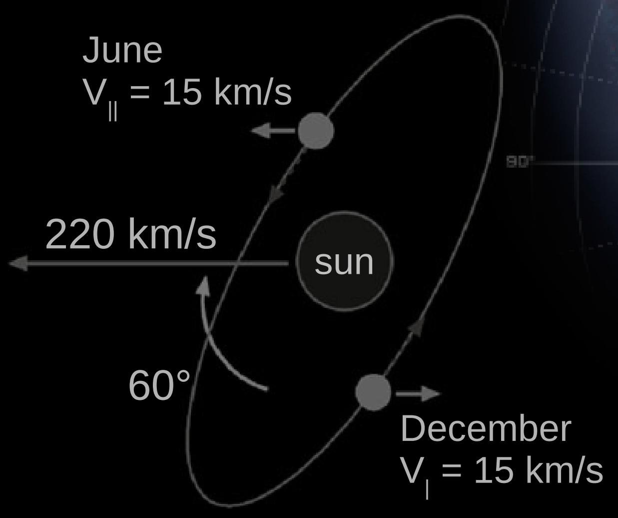
$\rho_\chi = 0.3 \pm 0.1$ GeV/cm^3

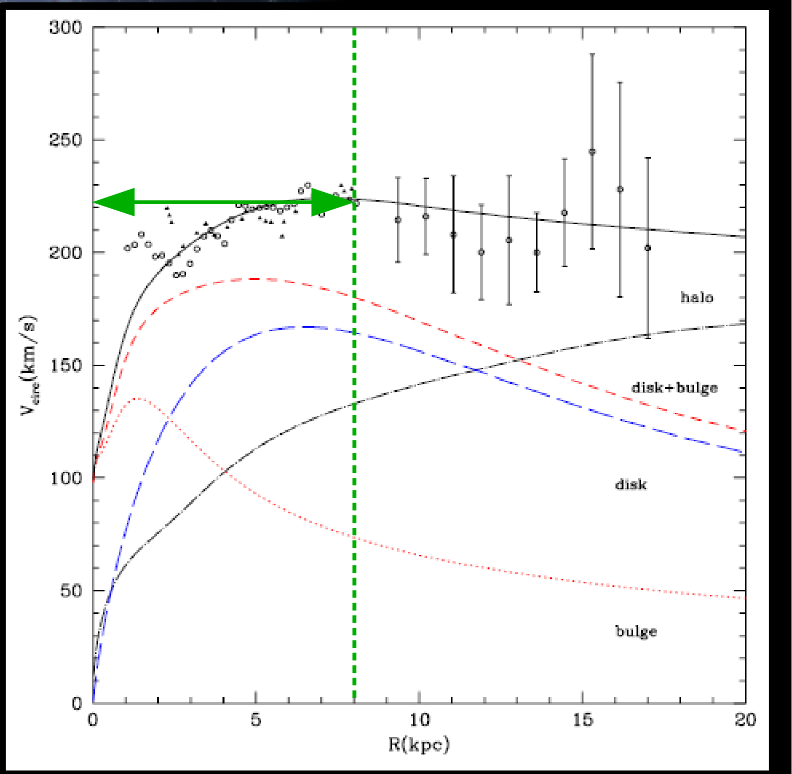
(J. Bovy and S. Tramaine, Astrophys.J. 756 (2012) 89)

$V_{sun} \sim 220$ km/s

(Klypin et al. Astrophys.J. 573 (2002) 597-613)

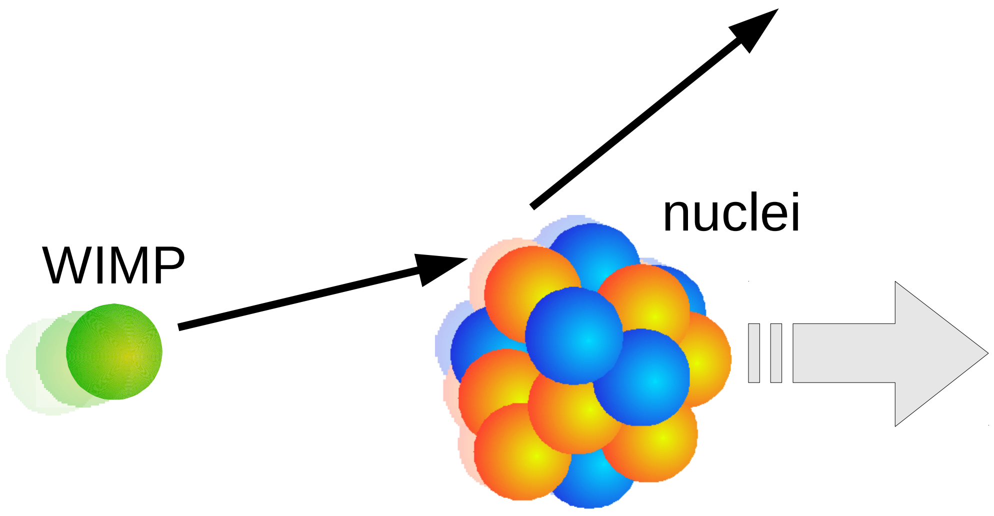






The direct detection principle

WIMP elastically scatters off nuclei → nuclear recoils



χ + N → χ + N

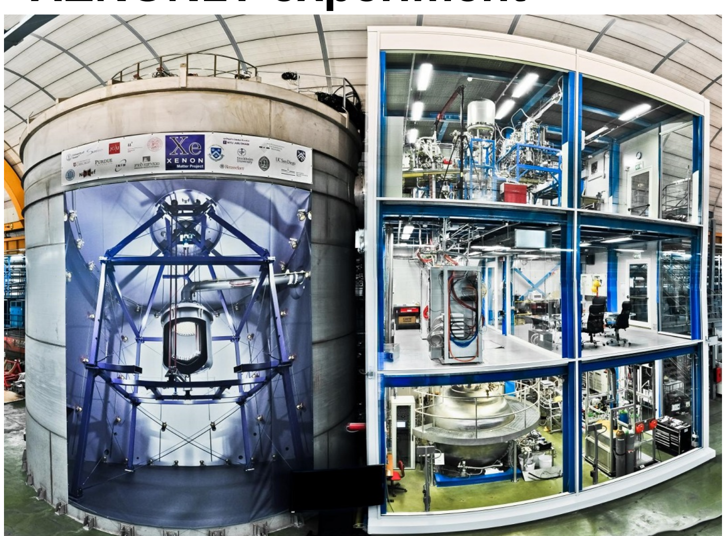
$$v \sim 230\ km/s$$
$$m_\chi = 10 - 10^4\ GeV/c^2$$
$$\rho_\chi \sim 0.3\ GeV/c^2/cm^3$$

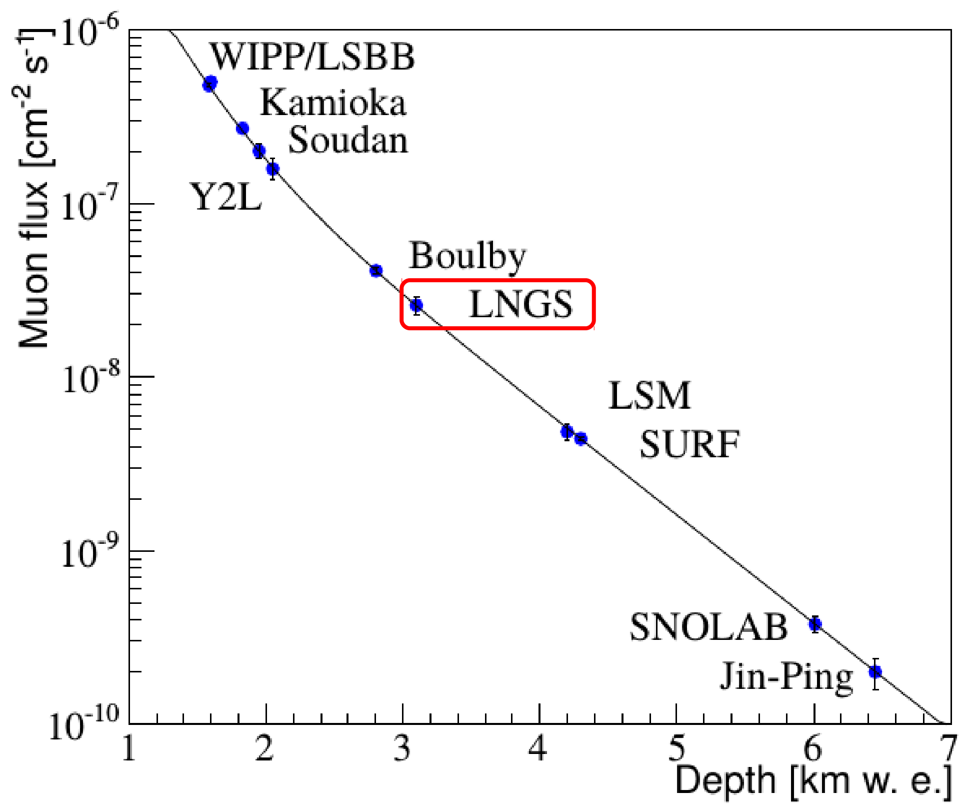
Small recoil energy $$E = \frac{\mu^2 v^2}{m_N}(1 - cos\theta) \lesssim 100keV$$

Small event rate $$\frac{dR}{dE} = \frac{\rho_\chi}{m_\chi}\frac{\sigma|F(E)|^2}{2\mu_p^2}\int_{v_{min(E)}}^{v_{esc}} d^3v \frac{f_\oplus(\vec{v},t)}{v}$$

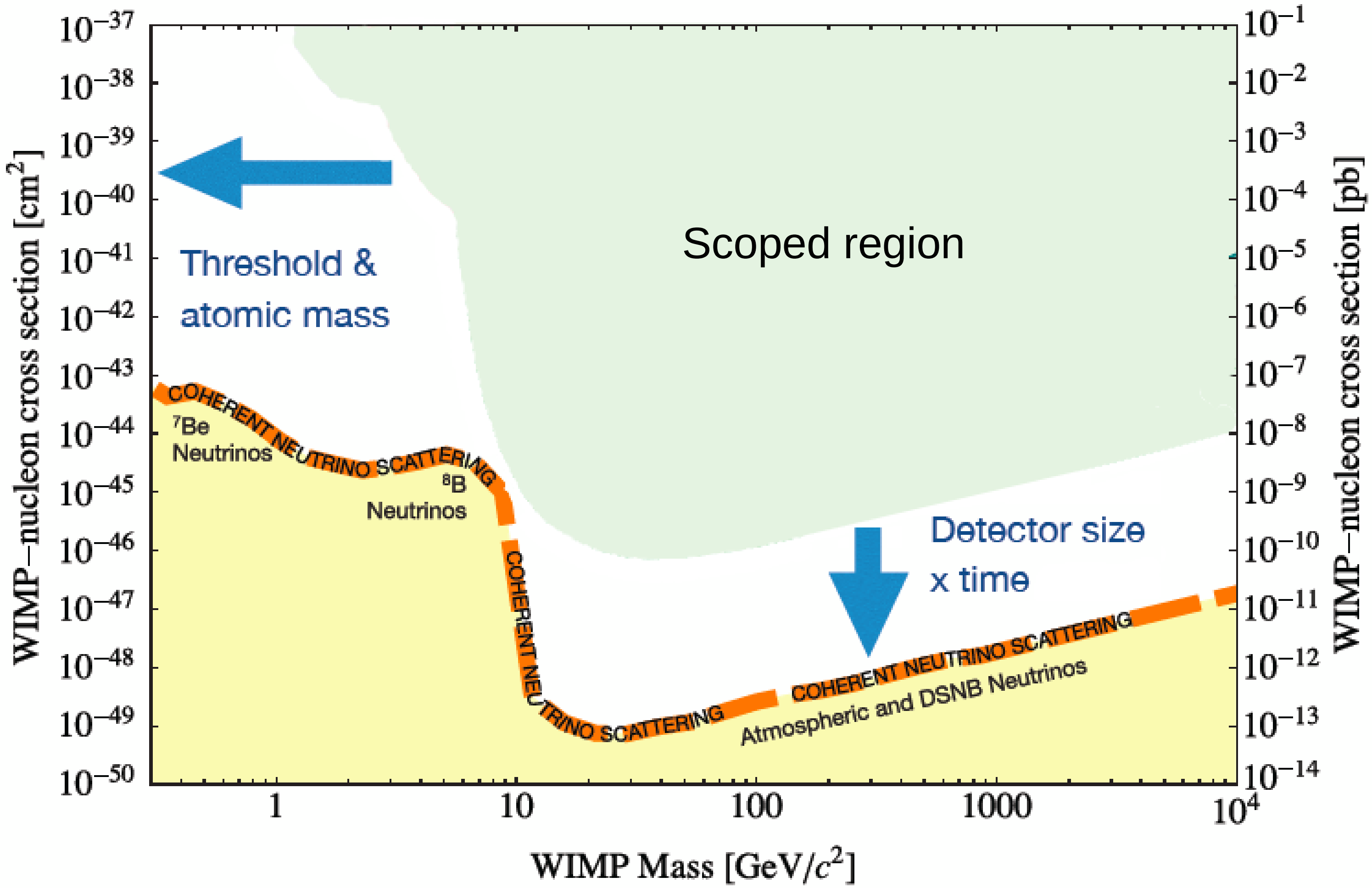
Gran Sasso mountain, Italy

XENON1T experiment



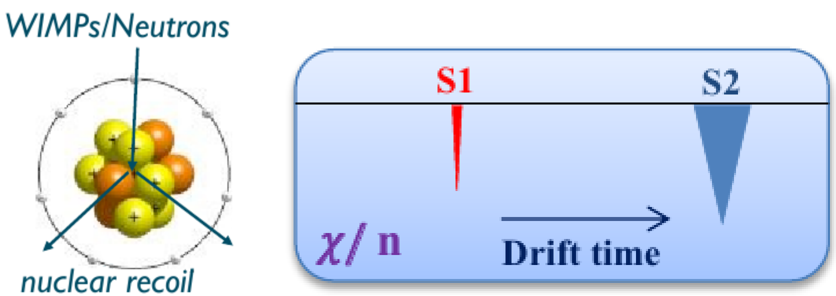


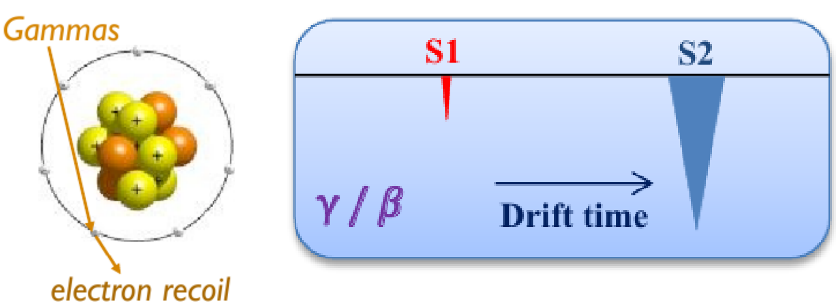
Where is the field of direct detection today?



Advantages of two-phase xenon TPC principle

Background rejection: charge-to-light ratio



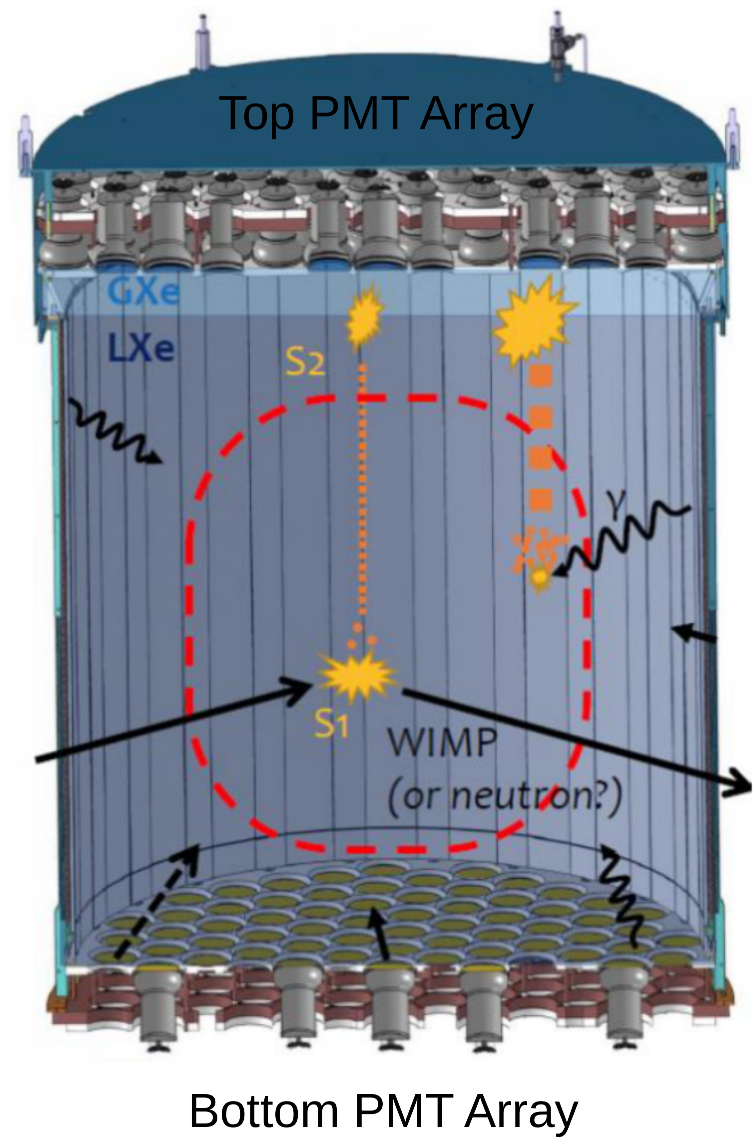


$(S2/S1)_{WIMP} << (S2/S1)_{gamma}$

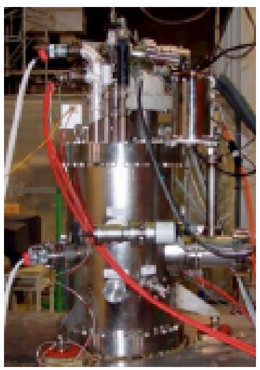
Scalability: massive target at modest cost

Intrinsically pure: no long-lived radioactive isotopes

3D reconstruction: strong reduction of neutron interactions



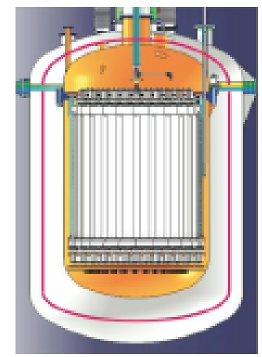
The XENON roadmap



XENON10
Total Xe: 25 kg
Target: 14 kg
Fiducial: 5.4 kg
Limit: ~10^{-43}

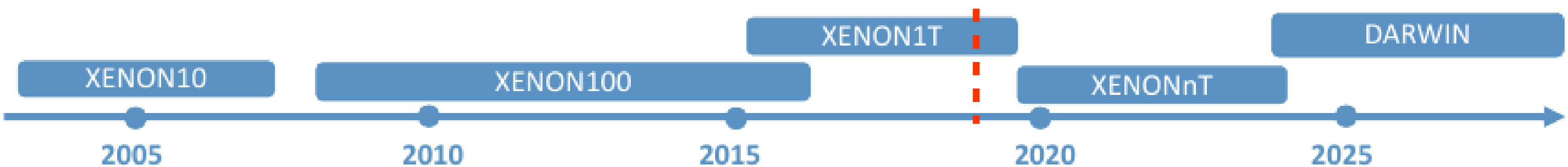
XENON100
Total Xe: 162 kg
Target: 62 kg
Fiducial: 34/48 kg
Limit: ~10^{-45}

XENON1T
Total Xe: 3.2 ton
Target: 2 ton
Fiducial: 1 ton
Limit: ~10^{-47}



XENONnT
Total Xe: ~8 ton
Target: ~6.5 ton
Fiducial: ~5 ton
Limit: ~10^{-48}

DARWIN
Total Xe: 50 ton
Target: 40 ton
Fiducial: 30 ton
Limit: ~10^{-49}



Background sources

Neutrons :

(Th,U chains assumed in secular equilibrium)

- (α,n) reactions through Th, U chains

Source → site (surrounding rock), detector components
Estimations → More complex: material-dependent cross-section of (α,n) reactions and branching ratios for transitions to excited states. To be calculated for each relevant material in the detector

- Spontaneous U fission (mostly ^{238}U)

- Induced by cosmic rays muons

Gamma and beta :

- ^{238}U, ^{235}U, ^{232}Th chains and ^{40}K, ^{60}Co

- "intrinsic bg" (i.e. diluted in the target): ^{85}Kr, Rn

Physical backgrounds :

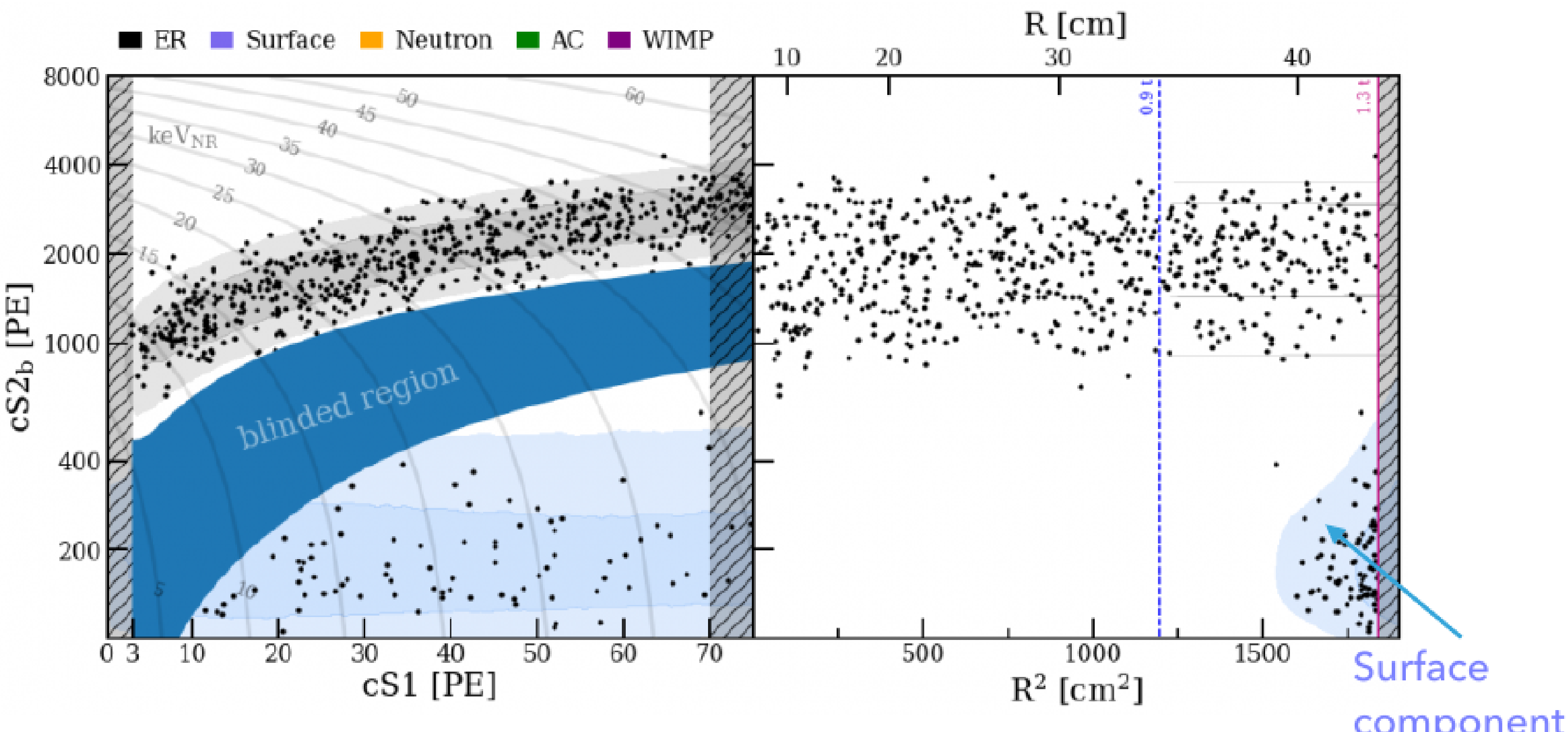
- Solar neutrinos

- ^{136}Xe $2\nu\beta\beta$ decay

- Blinded: avoid bias in event selection and S/B modelling
- Salted: protect against post-unblinding tuning of cuts and background models

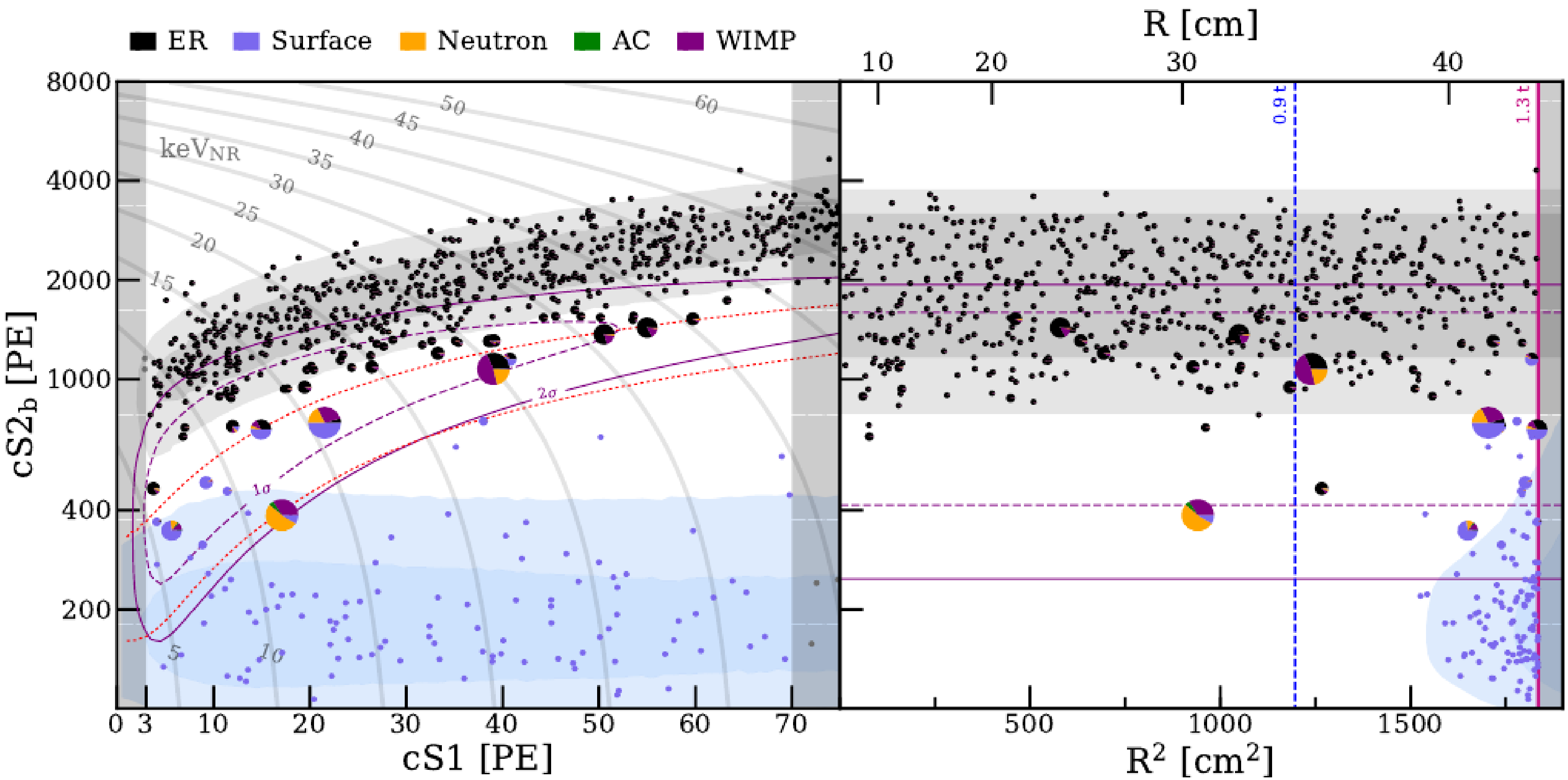
Blinded region:

- S2 > 200 PE
- below the ER -2σ quantile in $S2_b$ versus S1 space

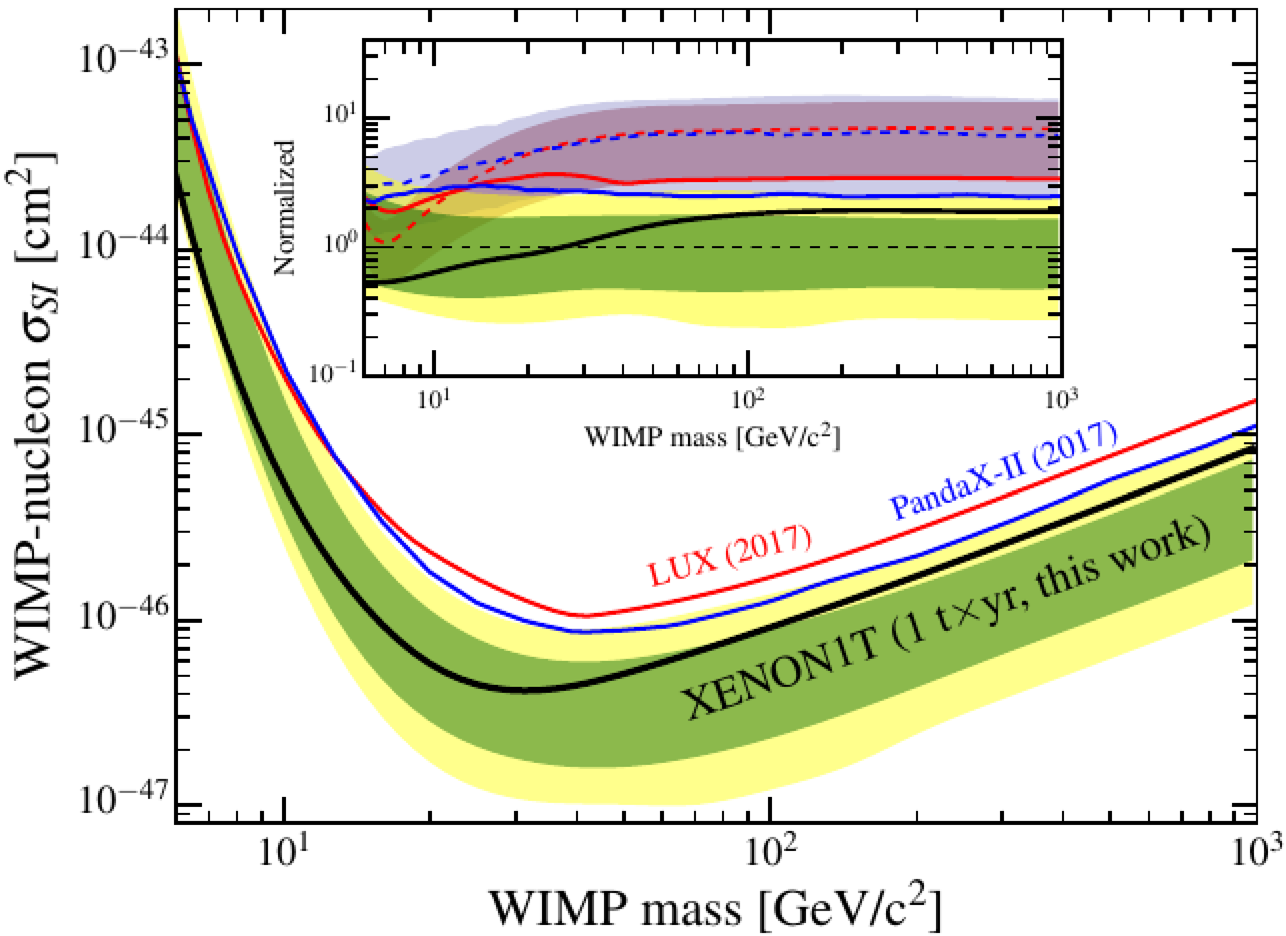


After unblinding and unsalting

- Results interpreted with unbinned profile likelihood analysis (all model uncertainties included in the likelihood as nuisance parameters)
- Piecharts: relative PDF from the best fit of 200 GeV WIMPs with 4.7×10^{-47} cm^2



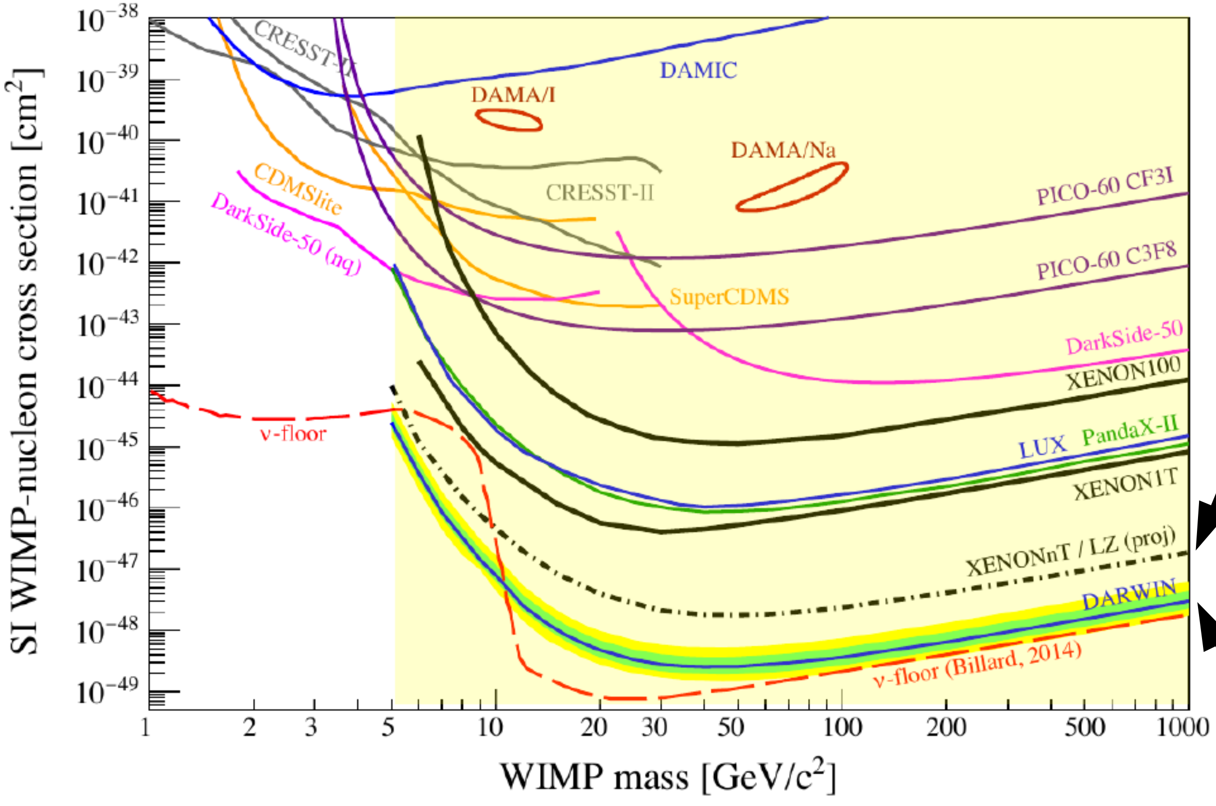
Exclusion limit



Minimum at 4.1×10^{-47} cm^2 for a WIMP of 30 GeV/c^2

- Most stringent 90% CL upper limit on WIMP-nucleon cross section at all masses above 6 GeV
- Factor of 7 more sensitivity compared to previous experiments (LUX, PandaX-II)
- ~ 1sigma upper fluctuation at high WIMP masses, could be due to background or signal

Near (XENONnT) and far (DARWIN) future . . .



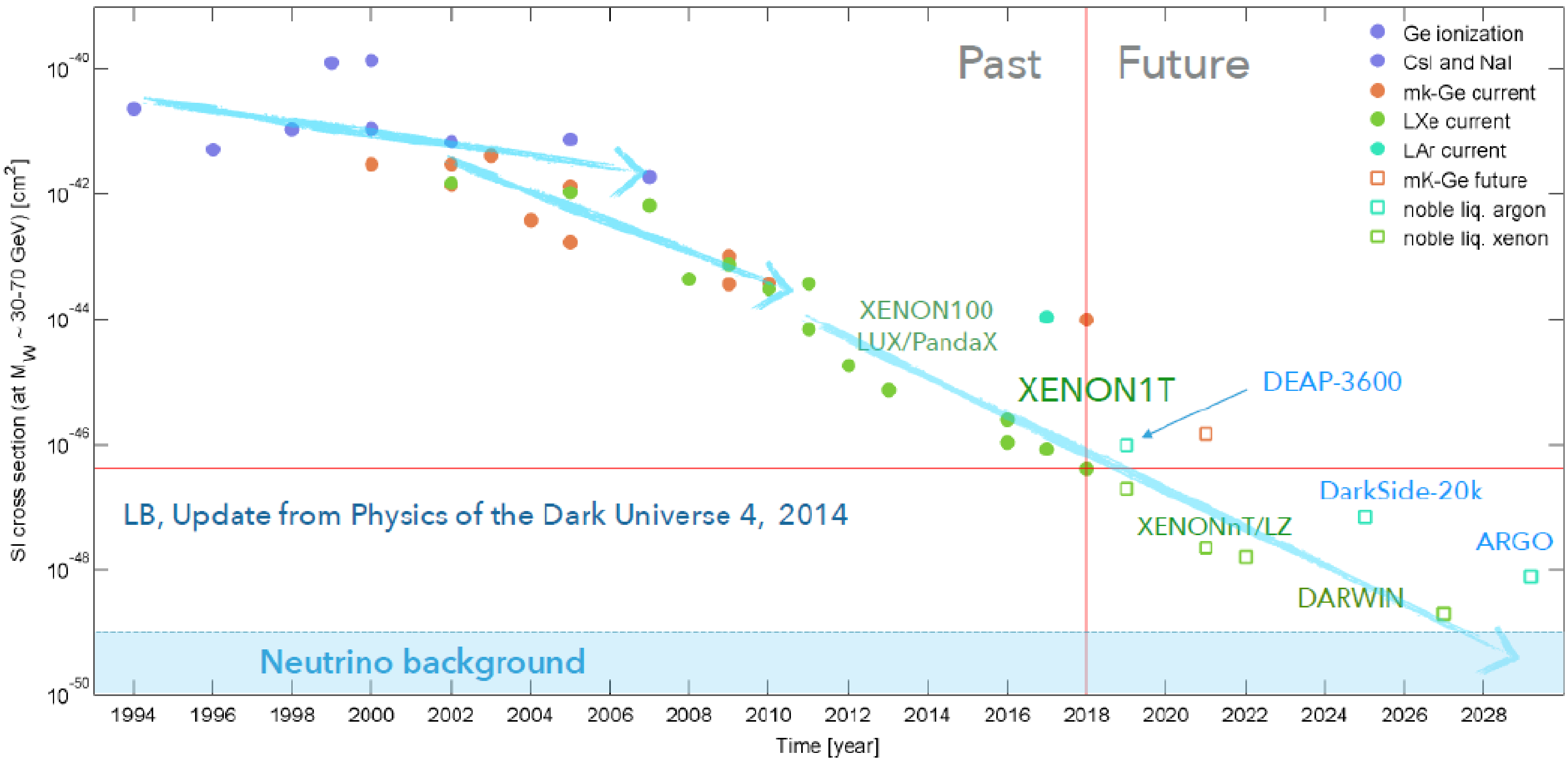
XENONnT

It's a XENON1T upgrade (8tons)
Construction started
Starts data taking in **Fall 2019**

DARWIN

New, ultimate, detector (50 tons)
Reaches "neutrino floor"
Data taking foreseen in **2023**

Direct detection versus time



Some challenges for next generation experiments

Scaling the detector target size is technically feasible for liquid xenon
But it still requires new solutions and a dedicated R&D

Handling bigger xenon quantities — *Hardware: new Storage and Recovery system*

- Bigger storages
- Faster operations
- Improved redundancies and safety

Improving data treatment — *Software, data monitoring and calibration*

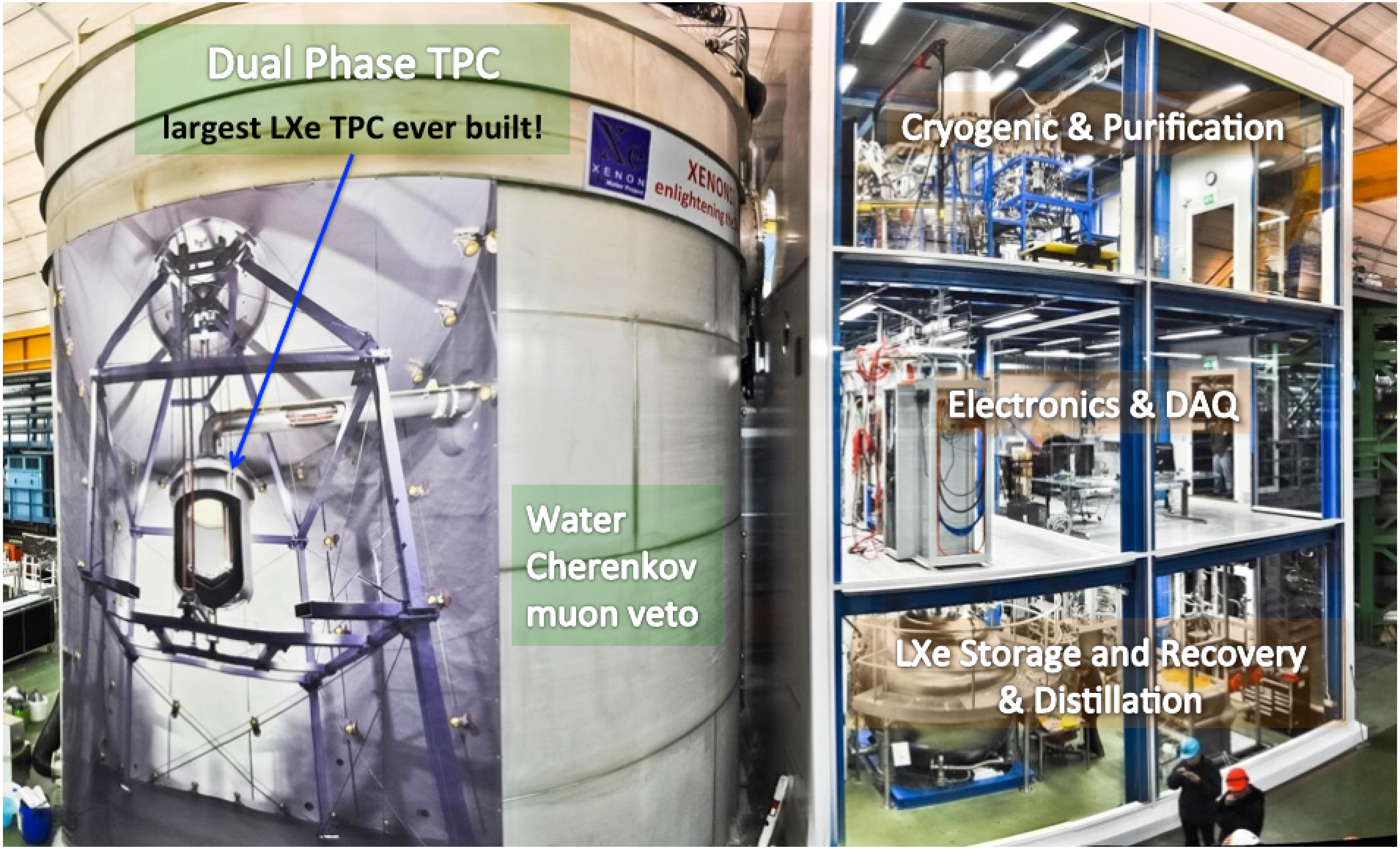
- Monitoring stability of light yield and gain from ionization signal
- Correction of ionization signal from the losses due to electronegative impurities
- Detecting and correcting live time losses due to unexpected issues in the detector

Improved knowledge about atypical background sources — *Data analysis*

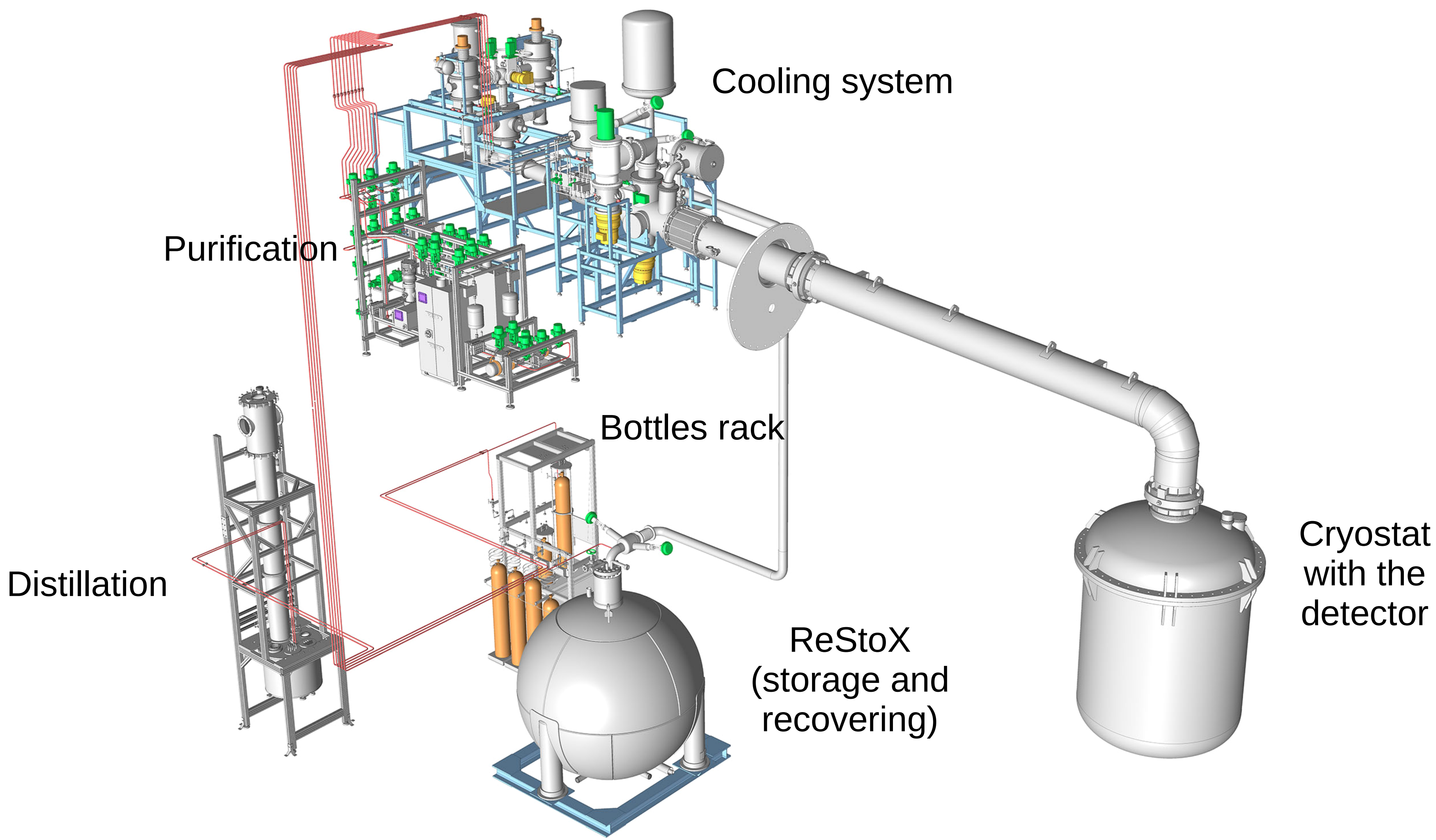
- Bias from previously triggered events
- Random coincidences
- Signal from isolated electrons in the TPC

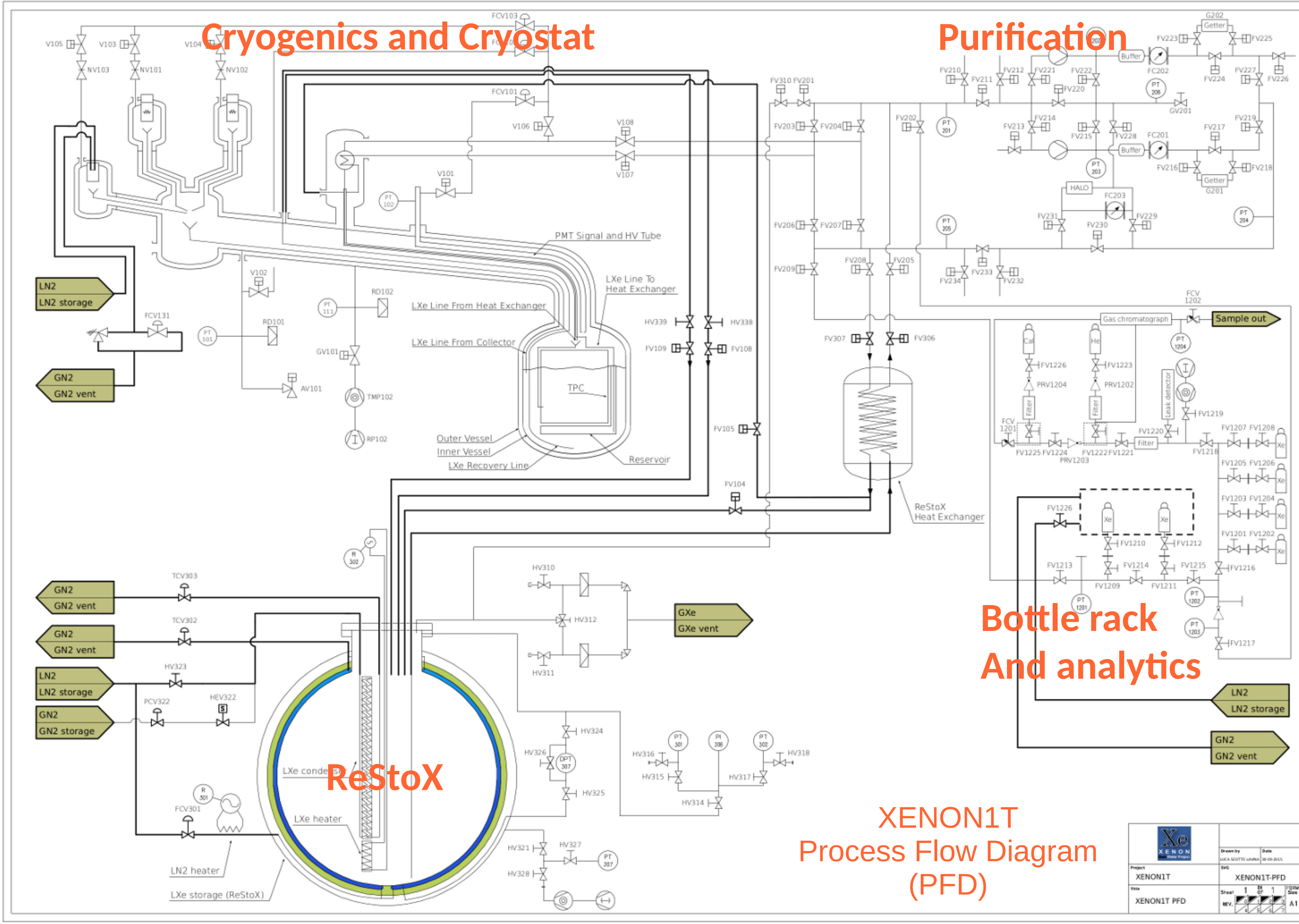
Hardware: new Storage and Recovery system

XENON1T with all subsystems

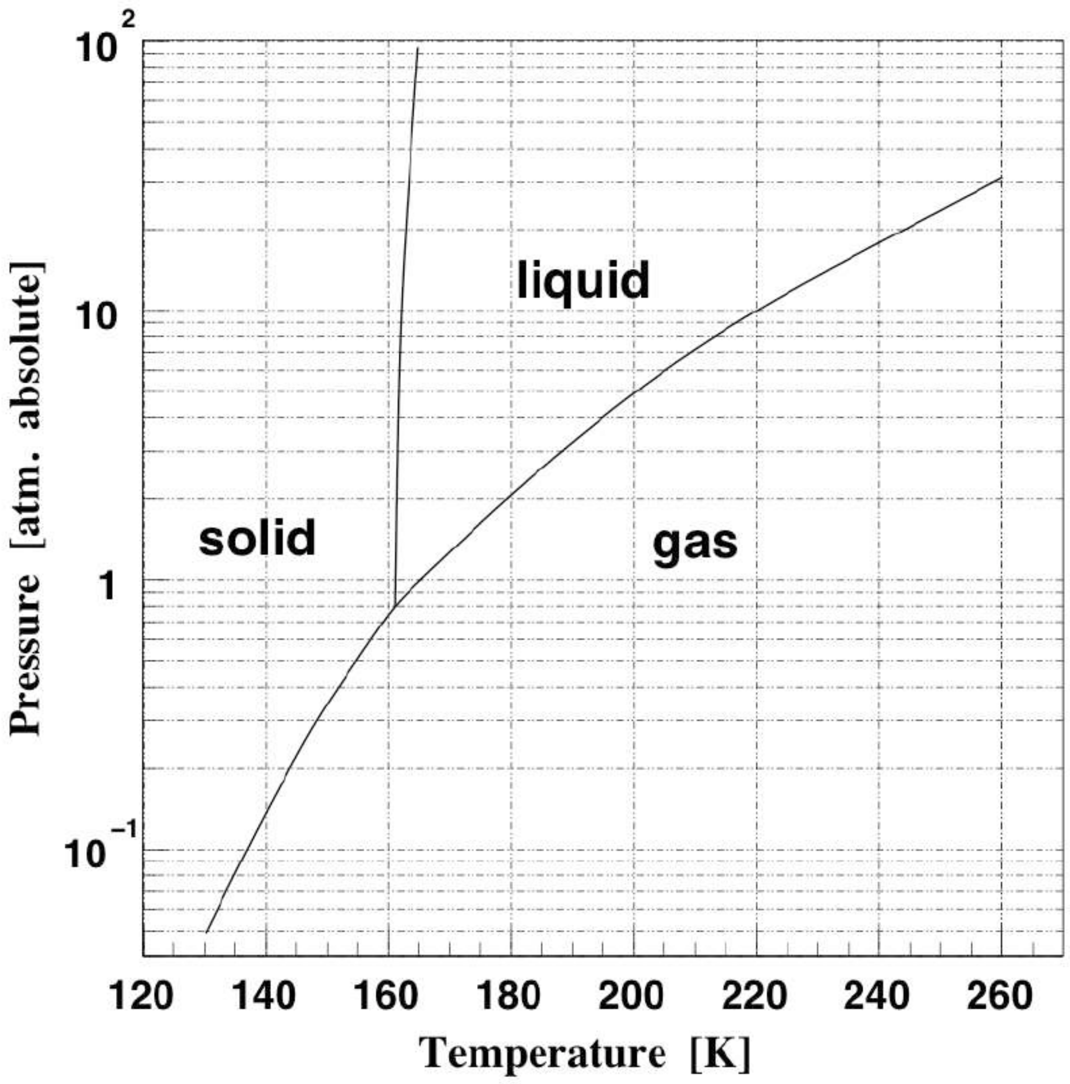


XENON plants




Cryogenics and Cryostat
Purification
ReStoX
Bottle rack
And analytics
XENON1T
Process Flow Diagram
(PFD)
PMT Signal and HV Tube
LXe Line To Heat Exchanger
LXe Line From Heat Exchanger
LXe Line From Collector
TPC
Outer Vessel
Inner Vessel
LXe Recovery Line
Reservoir
ReStoX Heat Exchanger
Gas chromatograph
Sample out
LN2 storage
GN2 vent
GN2 storage
GXe vent
LN2 heater
LXe storage (ReStoX)
LXe heater
XENON1T PFD

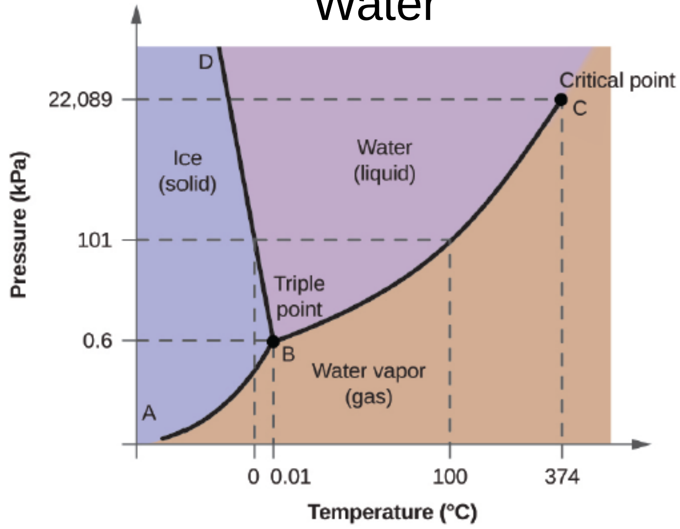
Phase diagram of xenon



At atmospheric pressure, the liquid phase of xenon extends over a narrow T range:

~ 162K – 165K

Water



XENON procurement

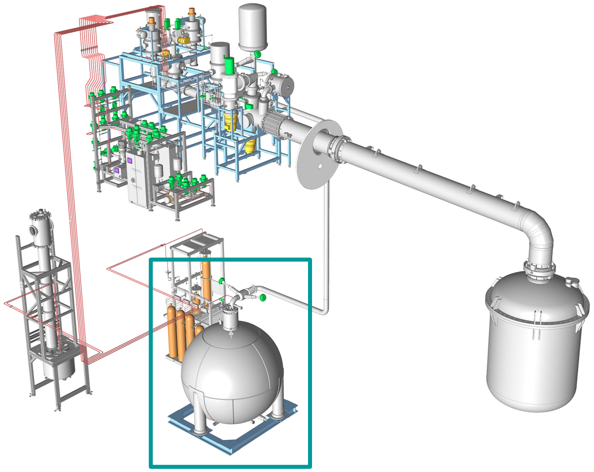
Xenon production is linked to the krypton production that is, in turn, linked to the oxygen extraction from air

Worldwide production is 10000 m^3 → ~60 tons

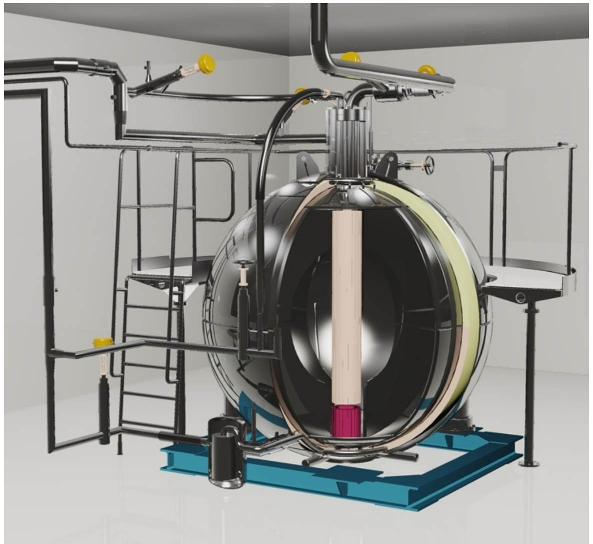
Separation between krypton and xenon is done via a series of distillation processes

Element	Boling Point [K] (at 101.325 kPa)
Nitrogen	77.3
Air	80.9
Argon	87.3
Oxygen	90.2
Krypton	119.8
Xenon	164.9

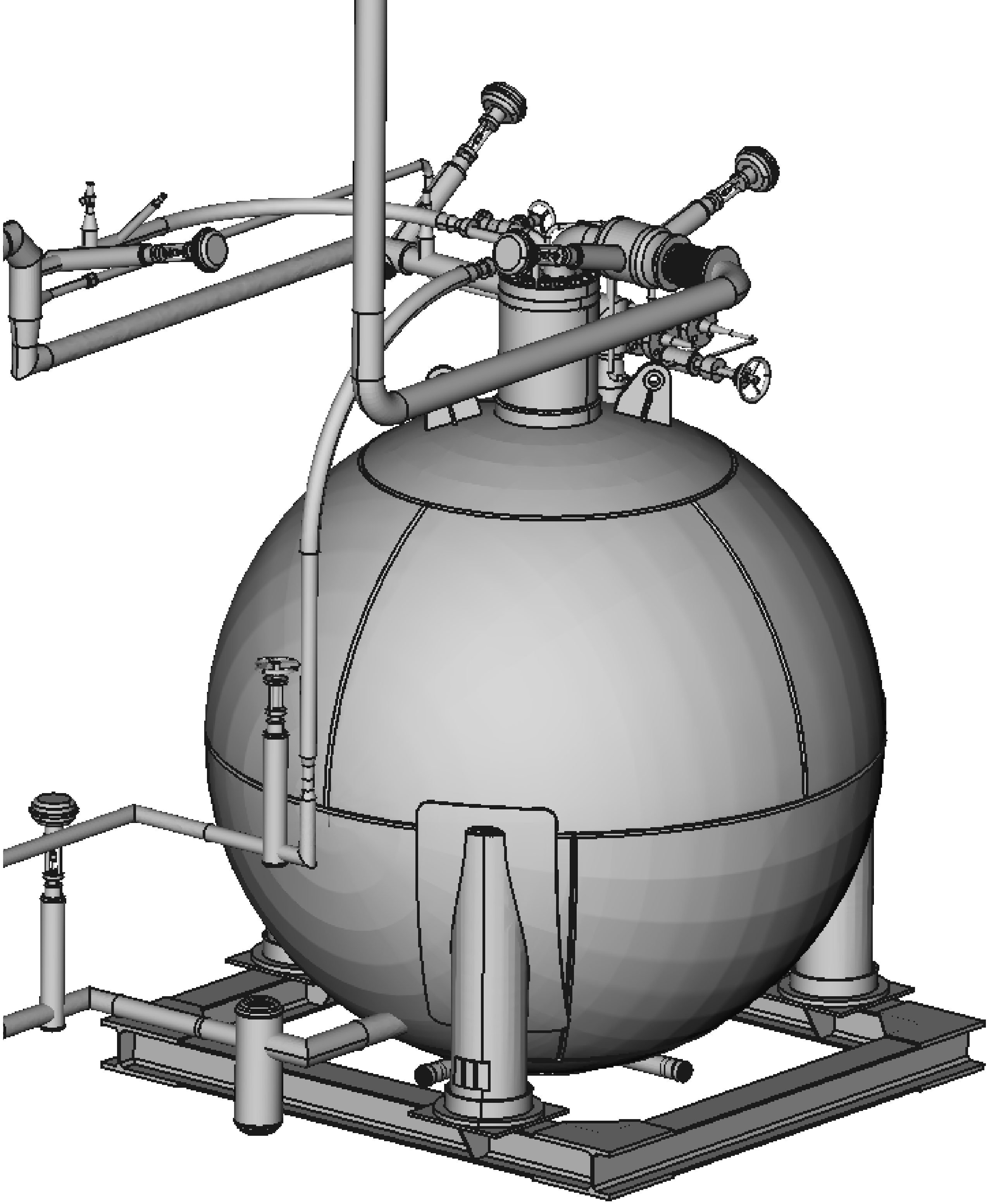
Liquid xenon storage and recovery : ReStoX



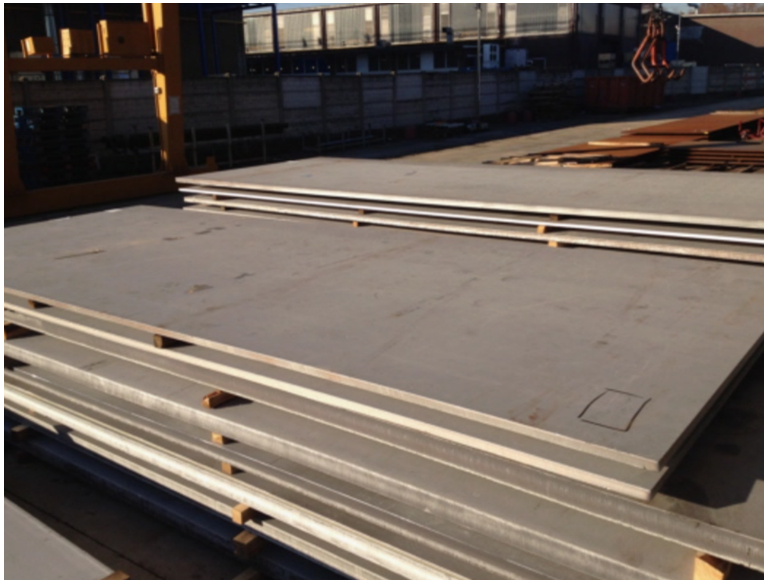
Capacity: 7.6 tons of liquid, solid or gazeous xenon
Max pressure : 75 bar
Insulation : double sphere with vacuum and 30 layers of mylar
Two N_2 cooling systems : inner (heat exchanger) and outer
Heater to regulate pressure at high precision



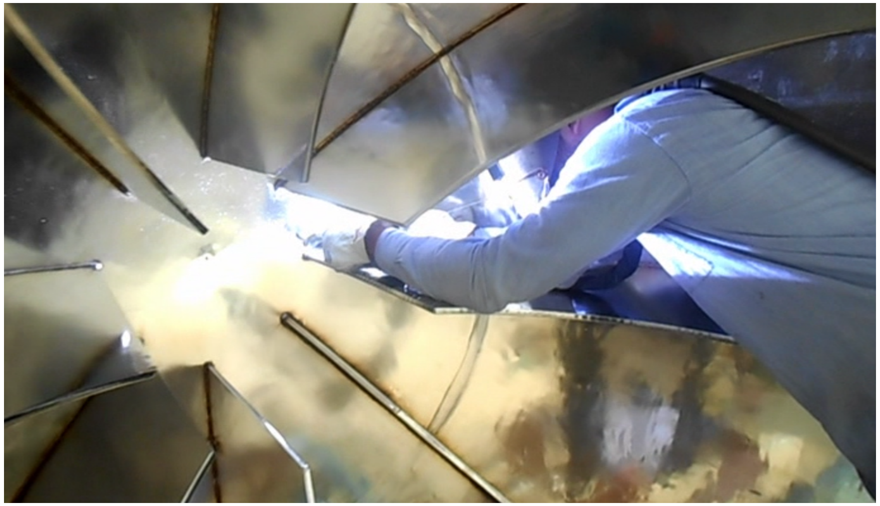
The sphere...

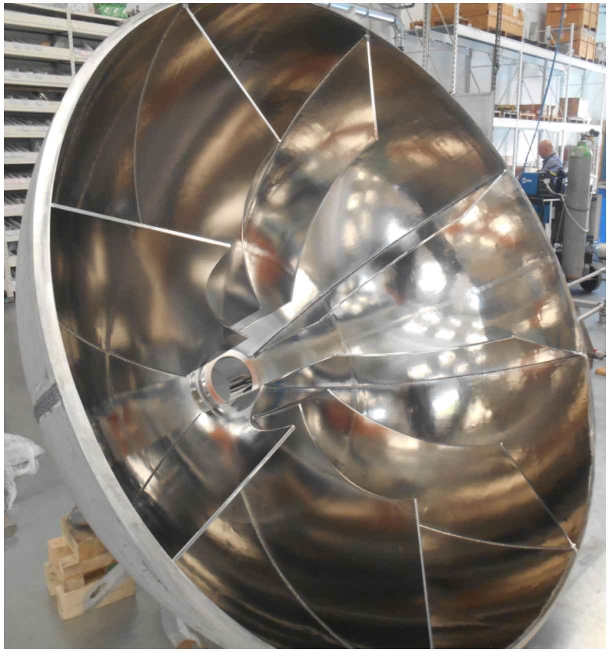


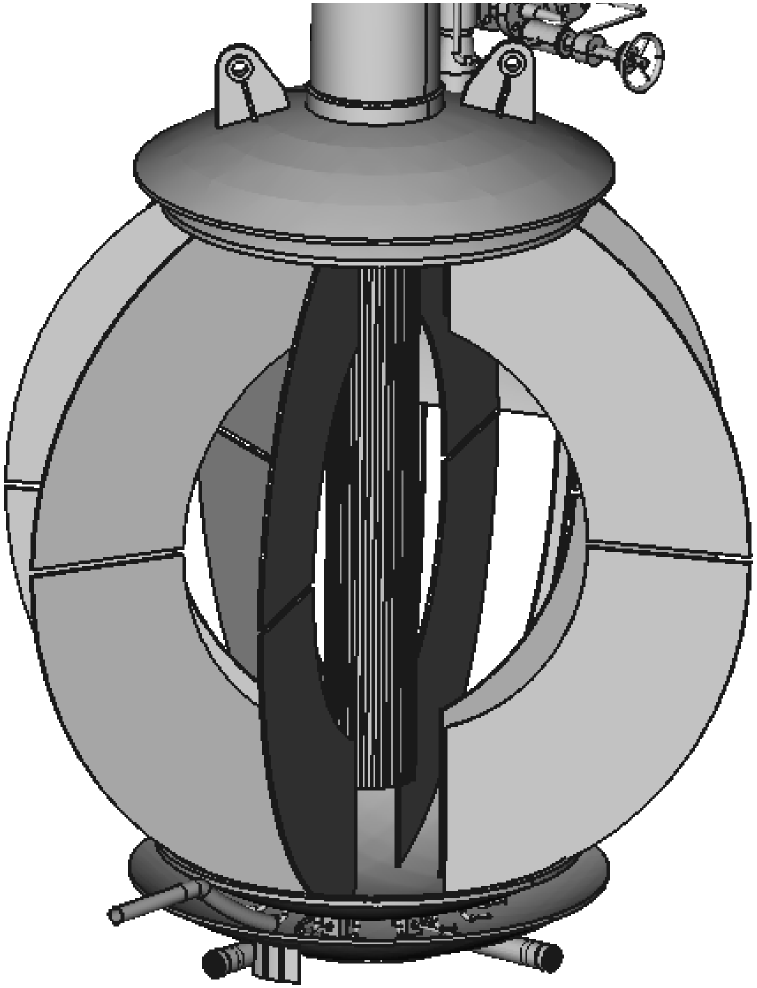
… before being a sphere



Fins inside the inner sphere

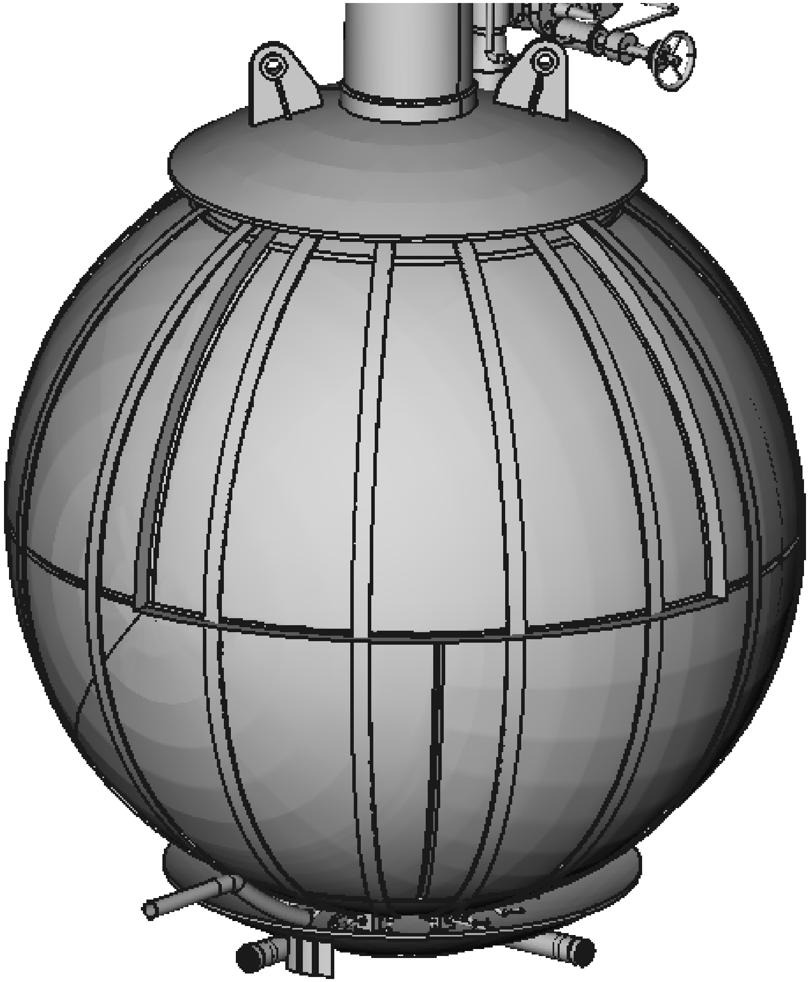






XENON Dark Matter Project

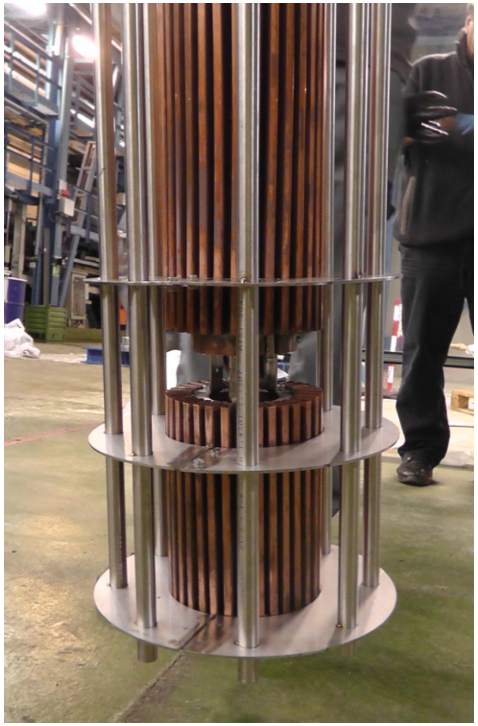
Nitrogen circuit around the inner sphere

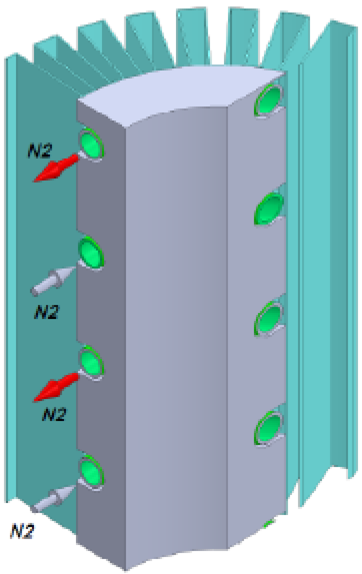


Heat exchanger

Condenser

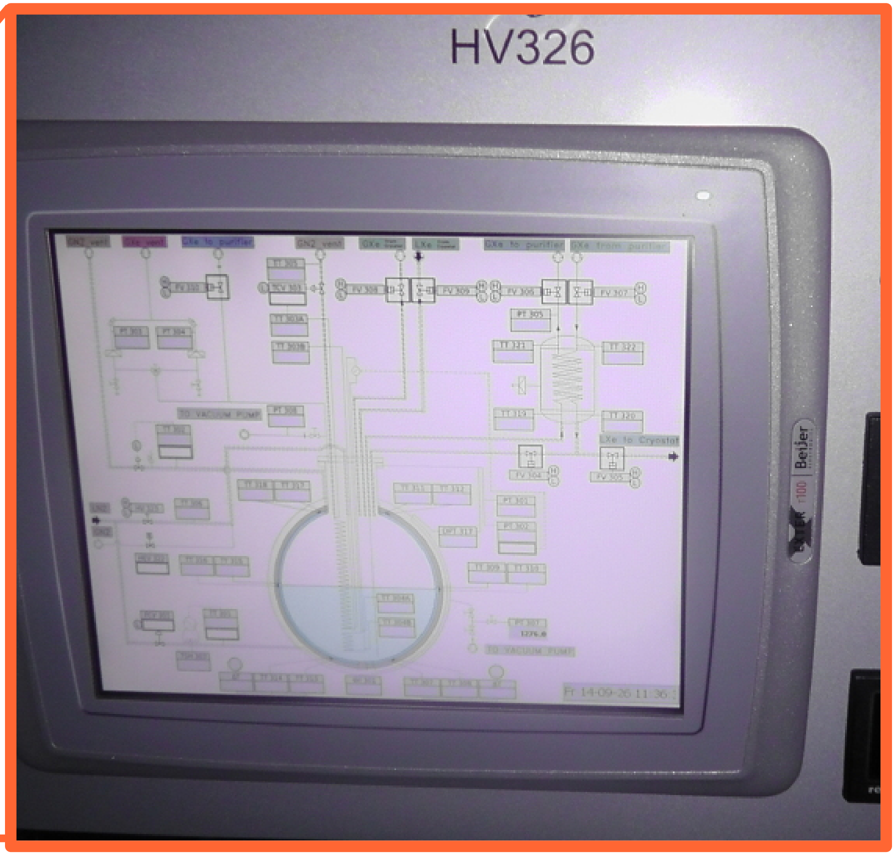
Produced : DATE
Exchange surface : copper
Max. cooling power > 2 kW
Thermal calculations in SolidWorks





	Xe Circuit	N2 Circuit
Mass flow	30 g/s	20 g/s
Inlet Temperature	165 K	77 K
Outlet Temperature	165 K	77 K
Nominal pressure	1 à 3 bars	1 bar
Maximum pressure	65 bars	1 bar

Slow control



Cryogenic valves

Valves

Company : Thermomess

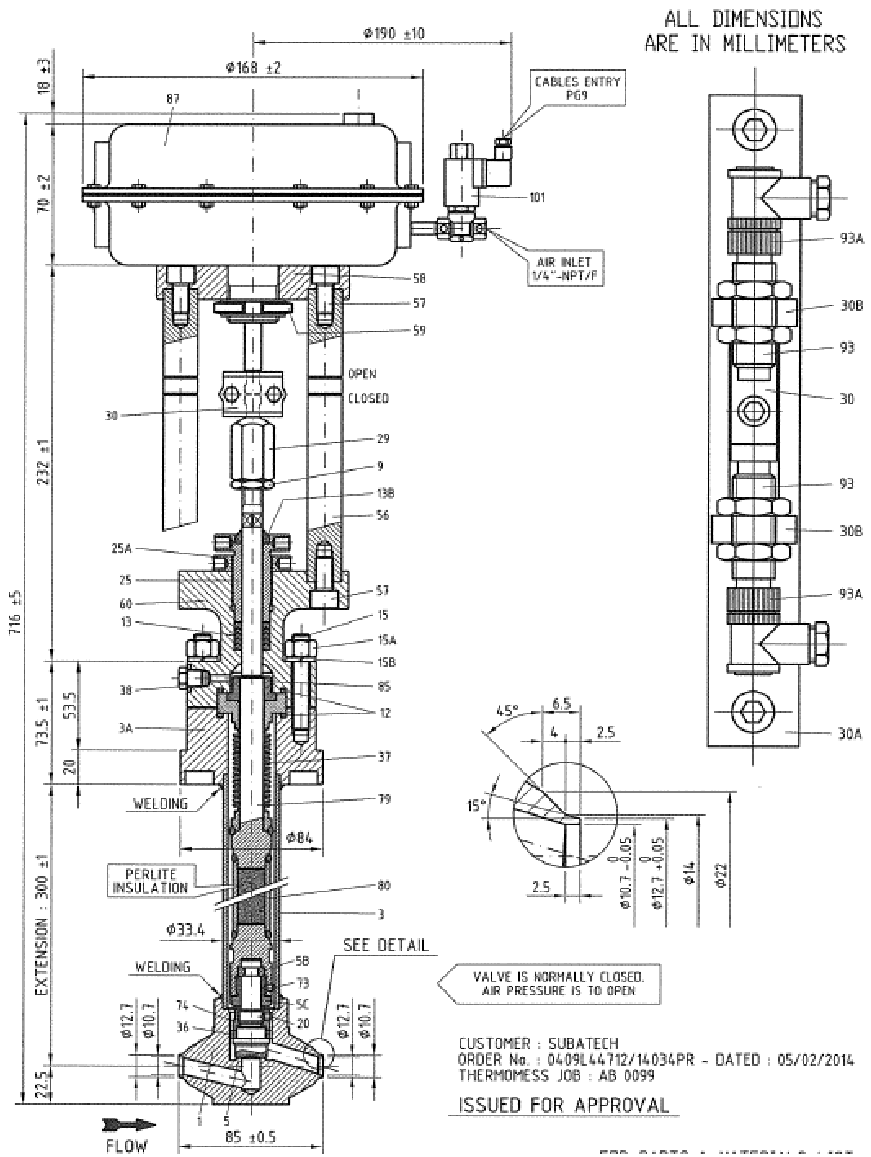
Different models whether if they are warm/cryogenic, two/three-ways, with manual/pneumatic actuator.

Common properties:

- Withstand high pressures (75 bar)
- Metal to metal seal
- Spheric disc
- Electro-polished
- Set to be normally closed
- Aimed internal tightness : $1 \cdot 10^{-8}$ mbar l/s
- Aimed external tightness : $1 \cdot 10^{-9}$ mbar l/s

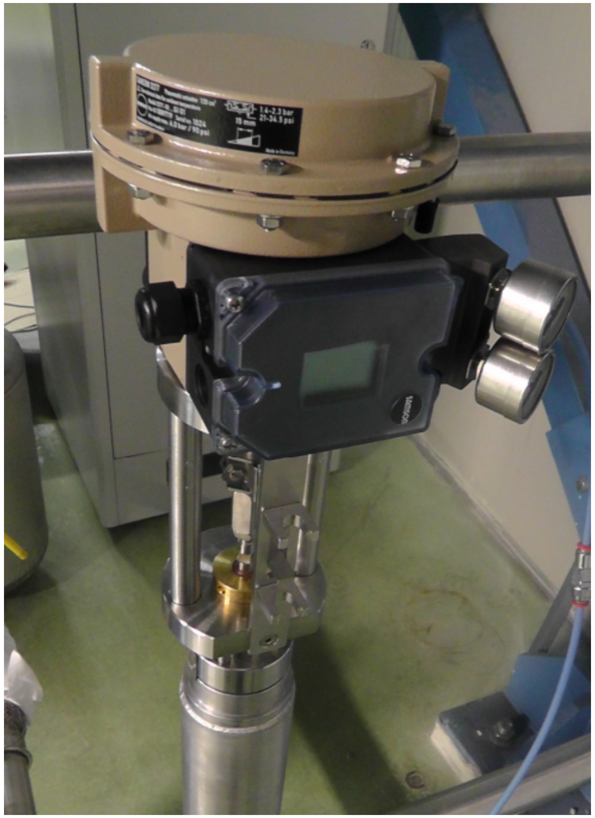
The automatic ones have:

- Pneumatic actuator
- 2 inductive switches
- A solenoid valve

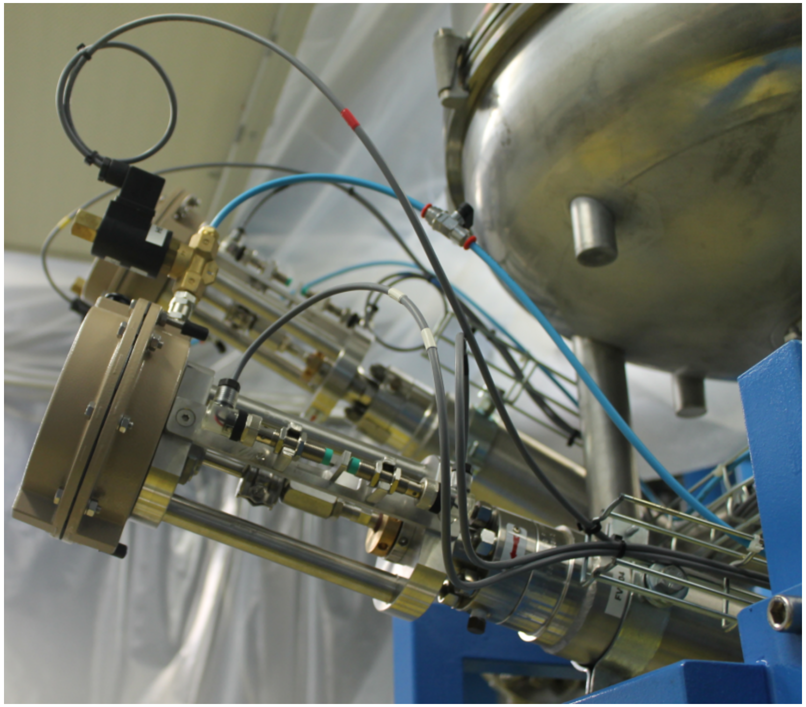


Cryogenic valves

Valve for nitrogen circuit

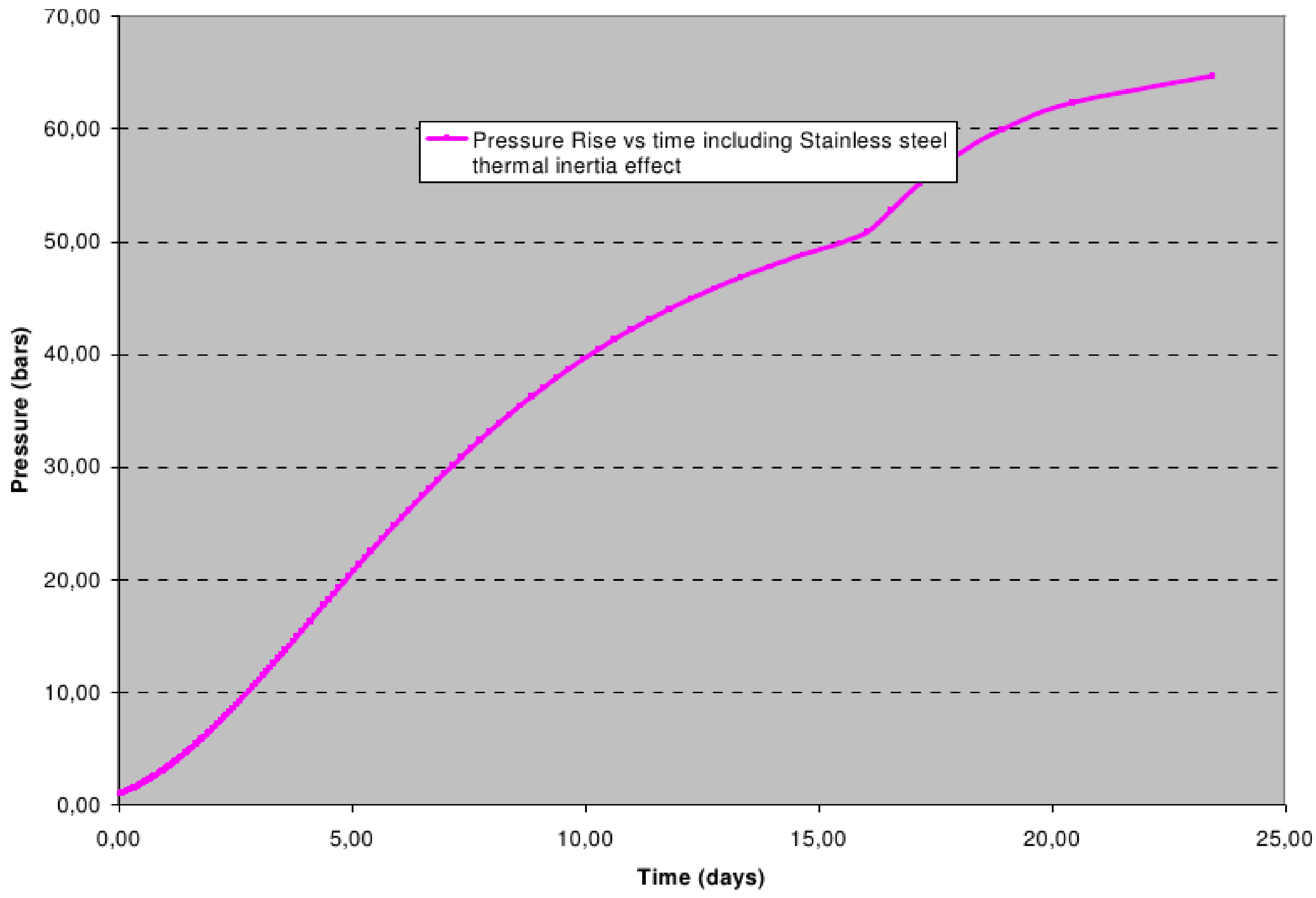


Valve under the heat exchanger
for LXe transfer

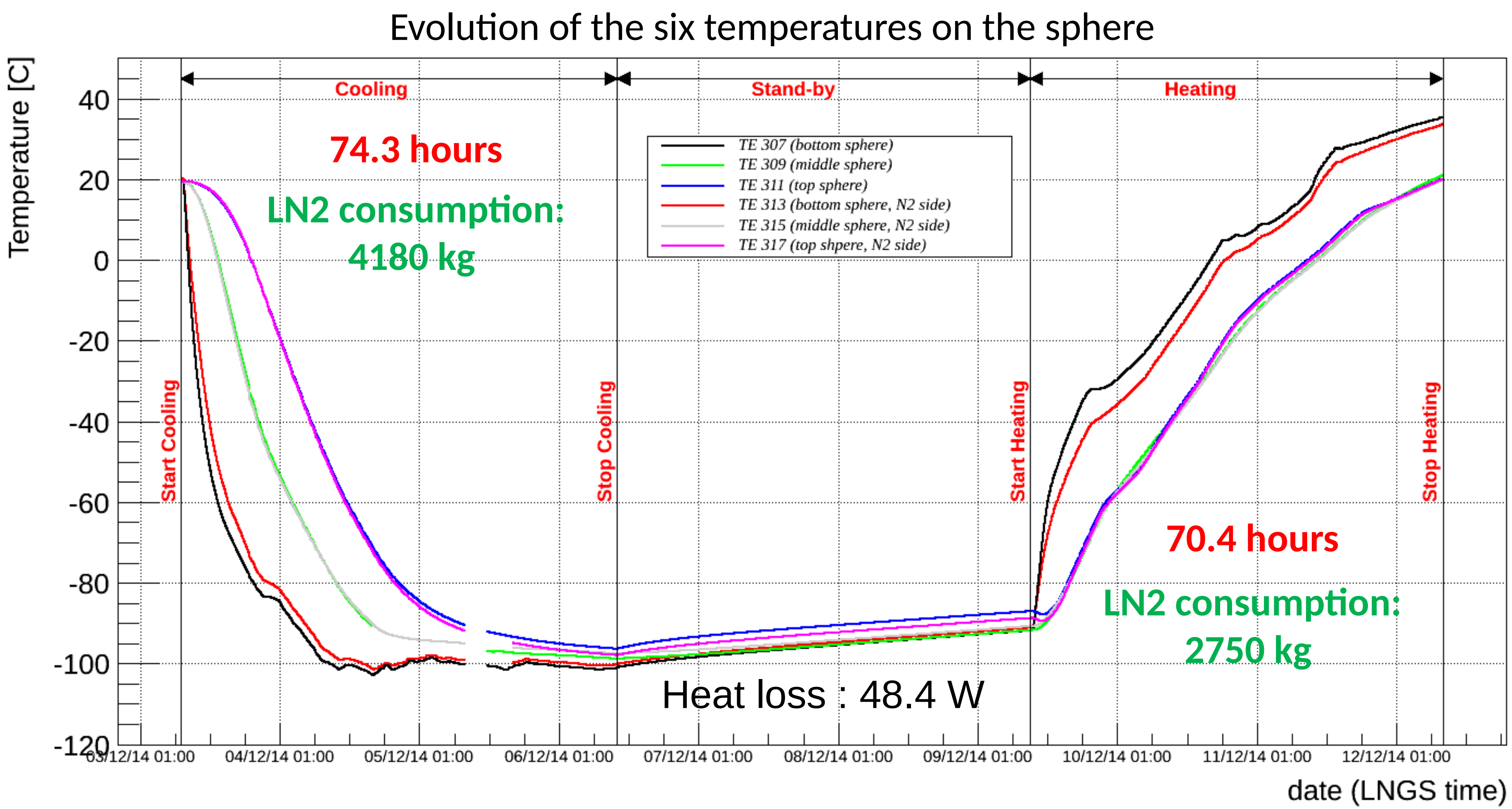


August 13th 2014
ReStoX installed
in LNGS

Thermal simulation : from liquid to supercritical fluid

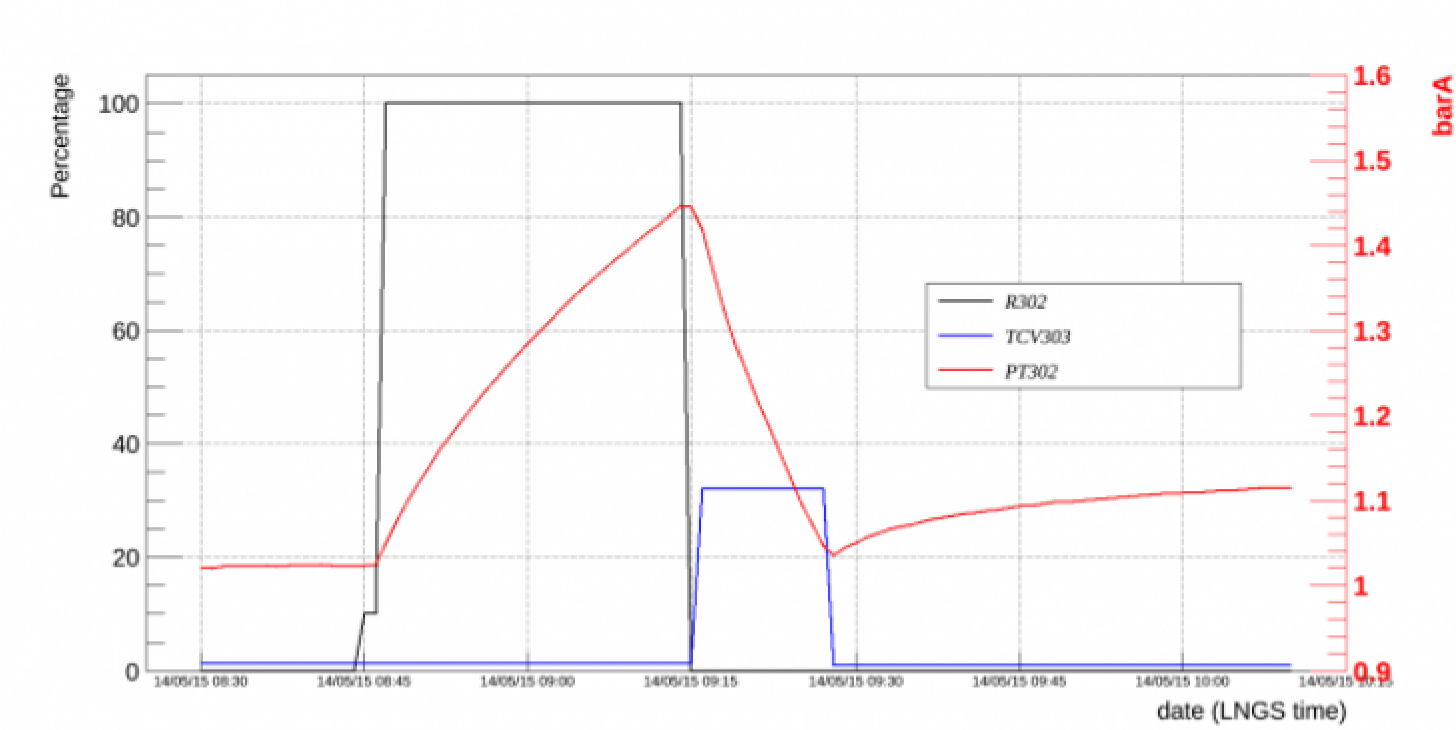


Cooling test #1 : cooling with the sphere cooling system

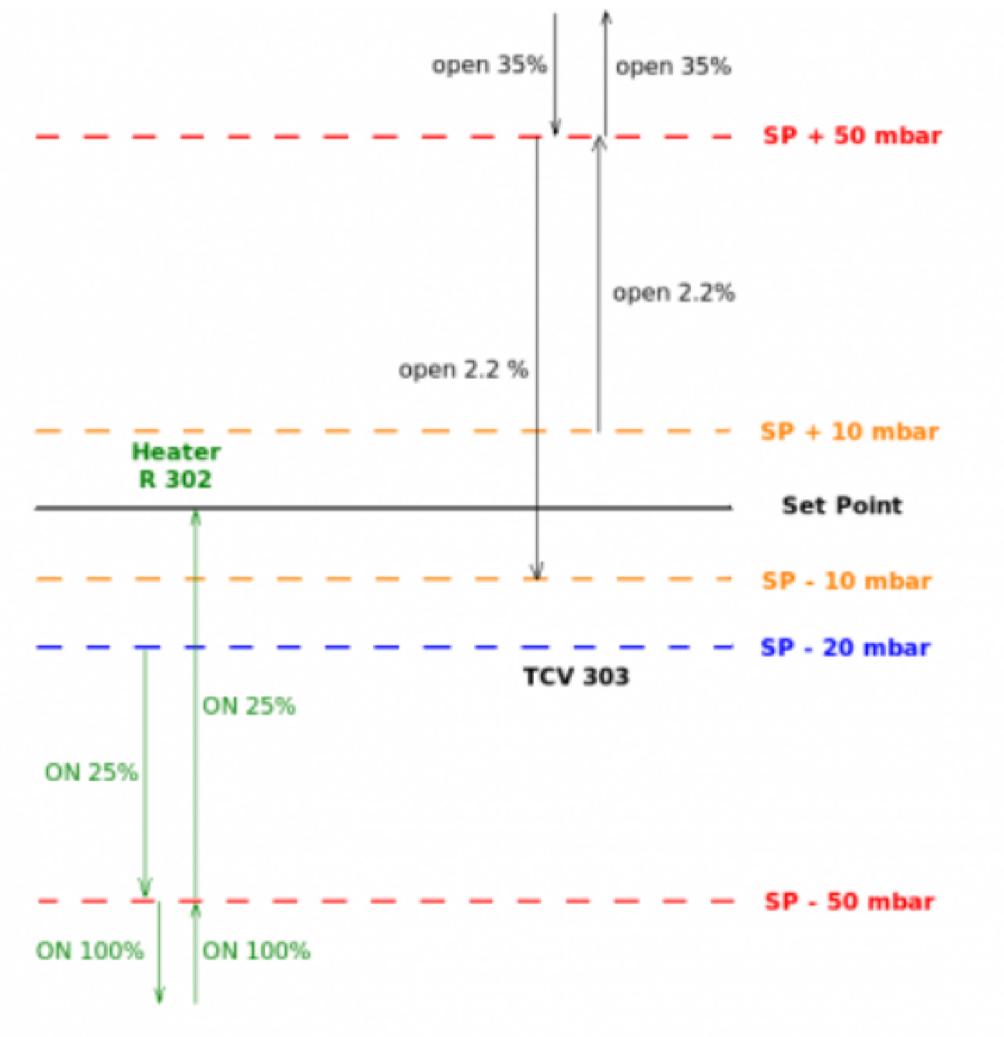


Cooling test #2 : cooling with the condenser

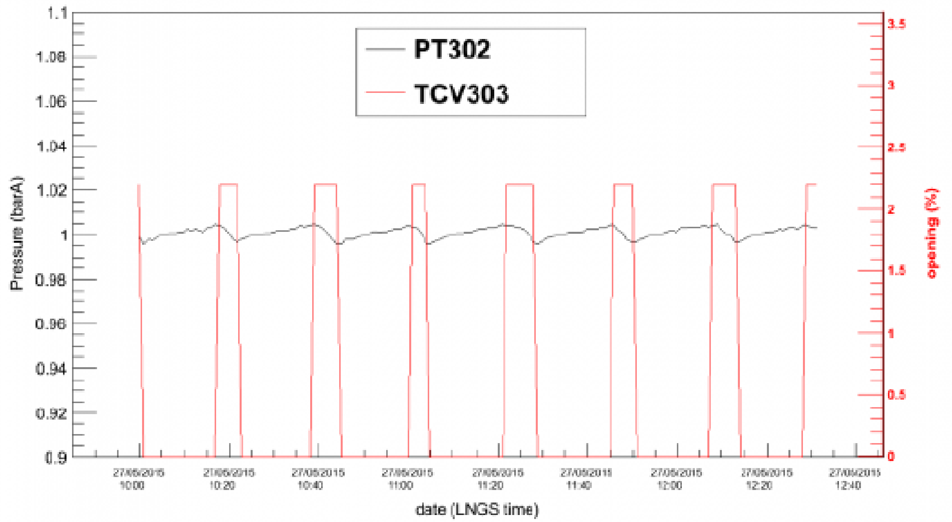
P[bar]	T[K]	t[s]	U[kK/kg]	ΔU[kJ/kg]	W[kW]
1.45	171.56	0	6282.6		
1.25	168.8	300	5343.8	938.8	3.13
1.05	165.67	720	4266.3	1077.5	2.56



Pressure stability



Managed to keep the pressure fluctuations down to 5 mbar



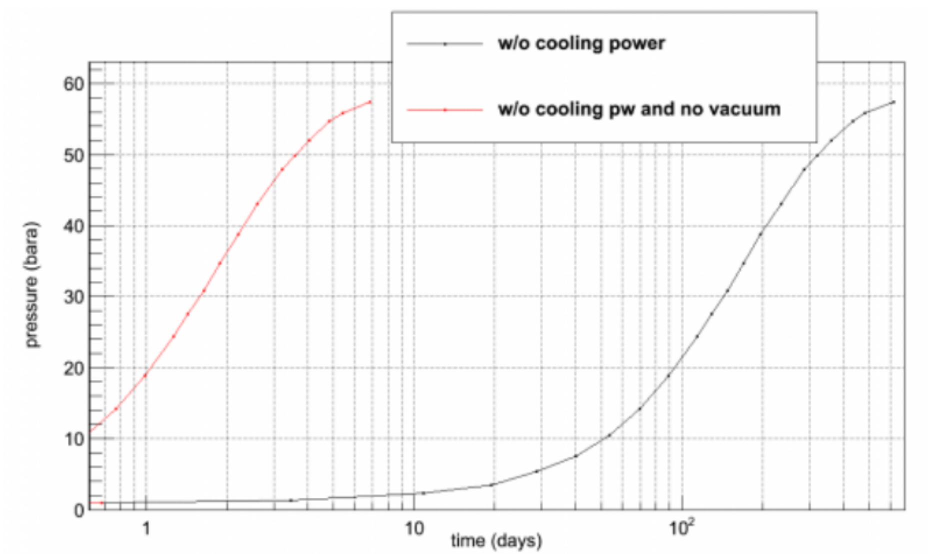
. . . and so on

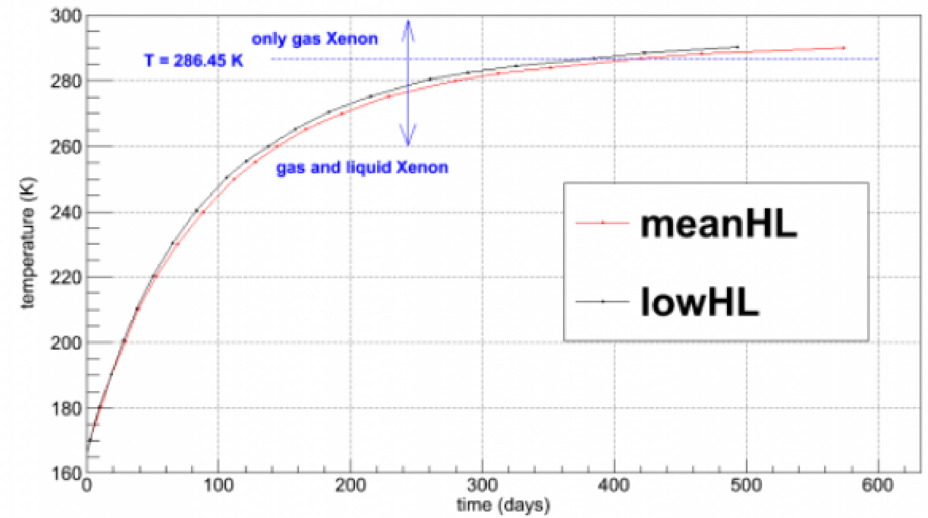
- Filling and recovery test
- Pressure rise test on cryostat
- Measurement of heat load in ReStoX

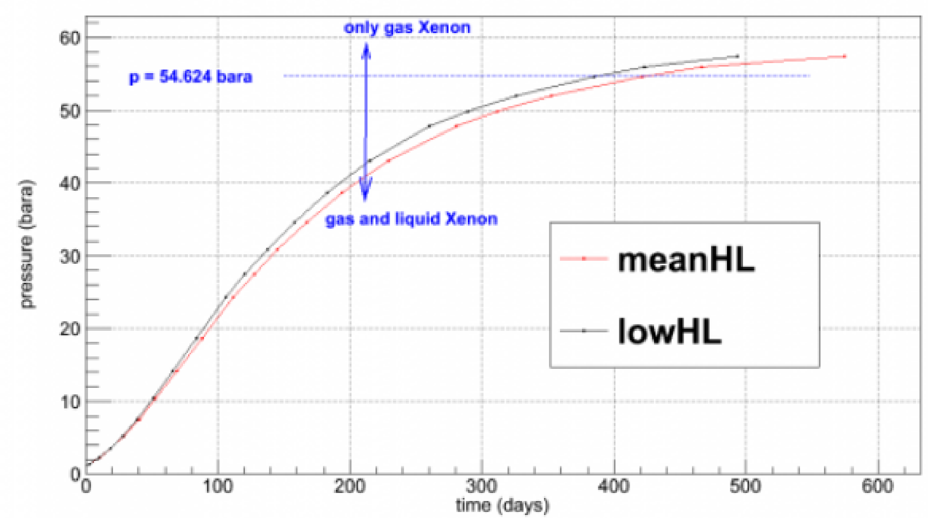
Increase of pressure and temperature:

- **in absence of cooling system** and,

- in addition, with a **vacuum insulation loss**







From XENON1T to XENONnT

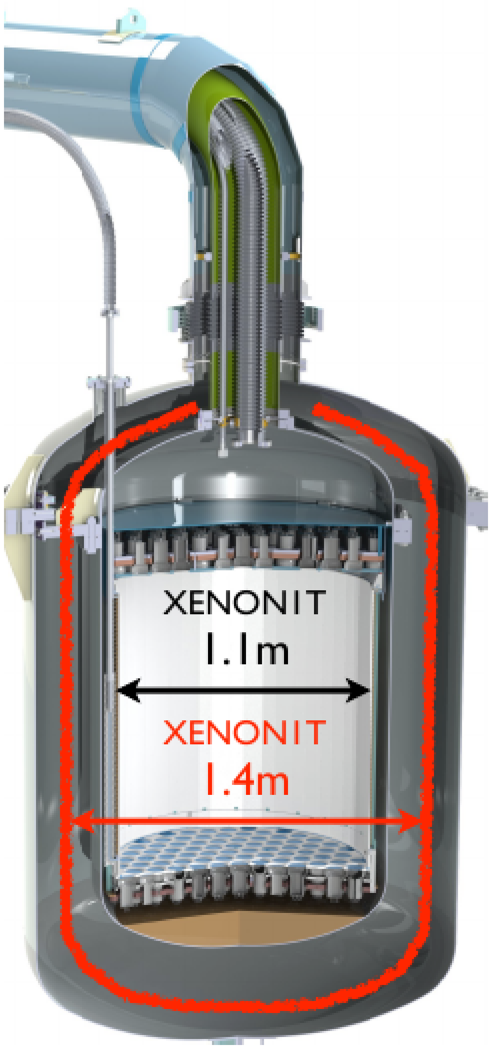
XENONnT is a rapid upgrade of the XENON1T detector:

• New inner cryostat vessel inside the same outer vessel
• Total LXe mass will be ~8t with 6t active (x3 more than XENON1T)
• New TPC structure with increased diameter and height (x1.4), additional PMTs (and electronics): 248 -> 476

All other systems can handle a larger detector with a target mass of up to 10t: Cryogenics, Purification, Recovery, Support structure, DAQ, Slow Control. Their established performance will enable the operation of XENONnT on a fast timescale.

However, **new storage and recovery system** for improved recovery performances

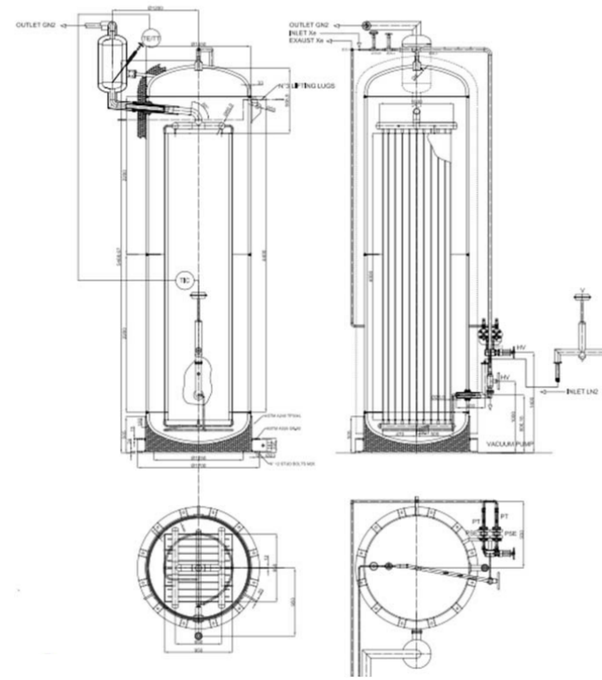
Current schedule: **start XENONnT in 2019**

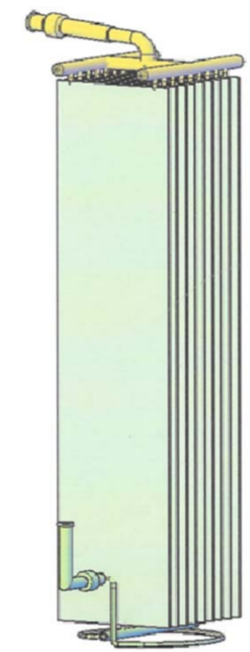


XENONnT : new storage and recovery system

ReStoX

ReStoX2





Built with financial contribution from:
- Columbia
- Subatech
- Mainz

Financial contribution exclusively from **XENON-France** consortium:

- Subatech (cryostat)
- LPNHE (heat exchanger and slow control)
- LAL (cryo valves and piping)

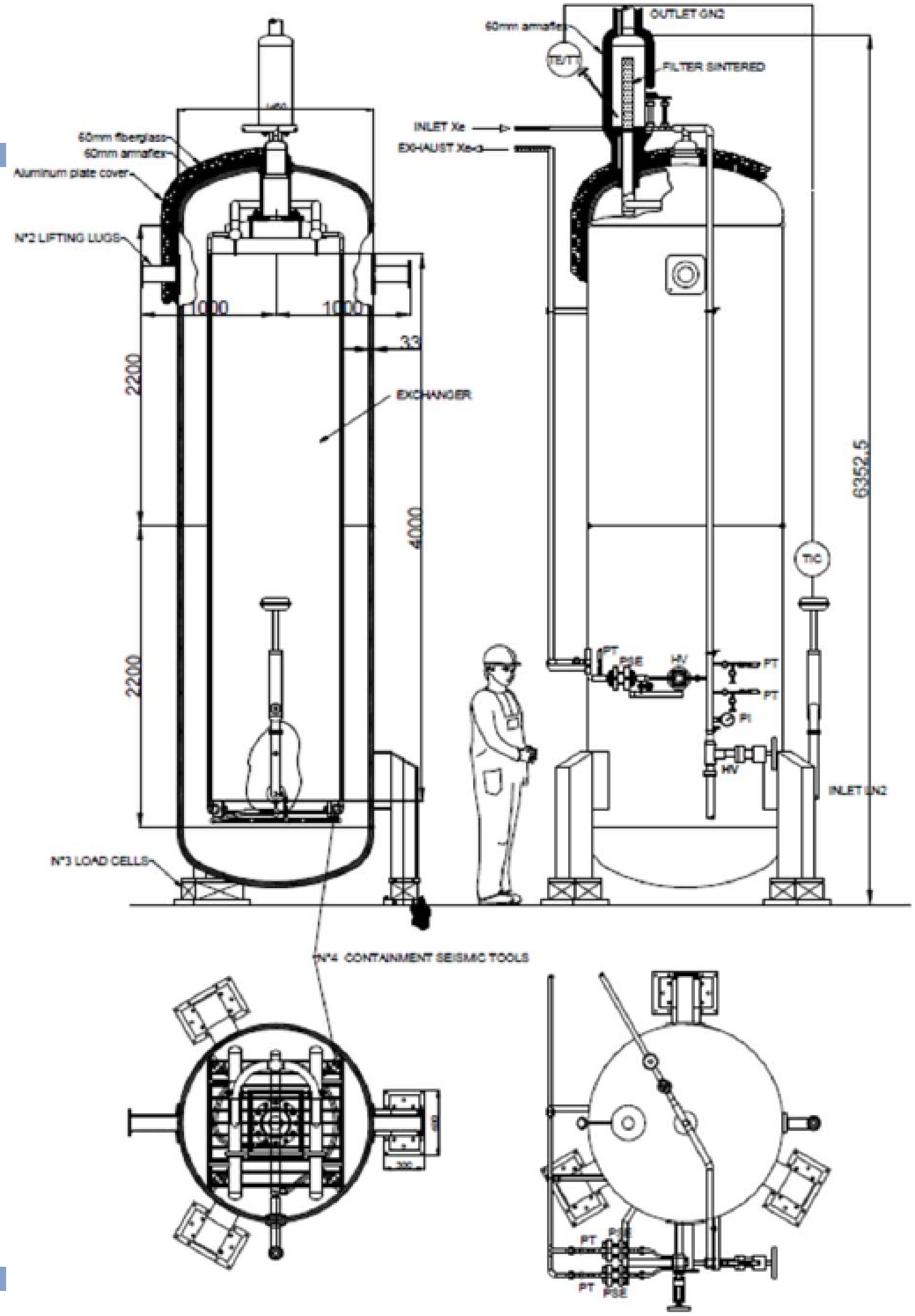
ReStoX2

Main characteristics :

- Connected to both ReStoX1 and the TPC
- Maximum xenon charge 10 tons
- Cooled by LN2
- High pressure storage vessel
- Fast recovering with xenon crystallization (1 ton/hour expected)

Fabrication:

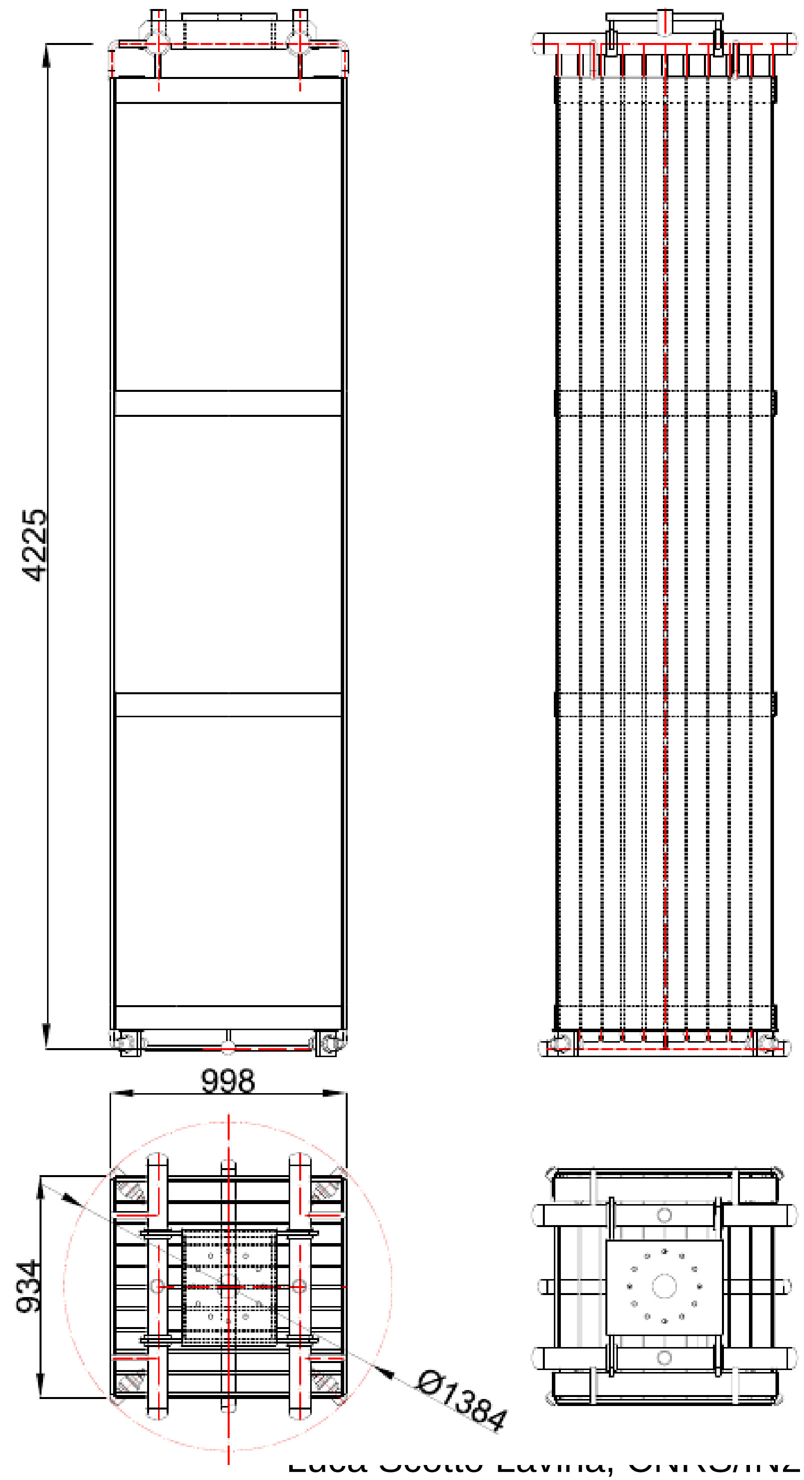
- Main vessel by Costruzioni Generali
- Heat exchanger by DATE
- Cryo valves by Thermomess



The ReStoX2 cooling system

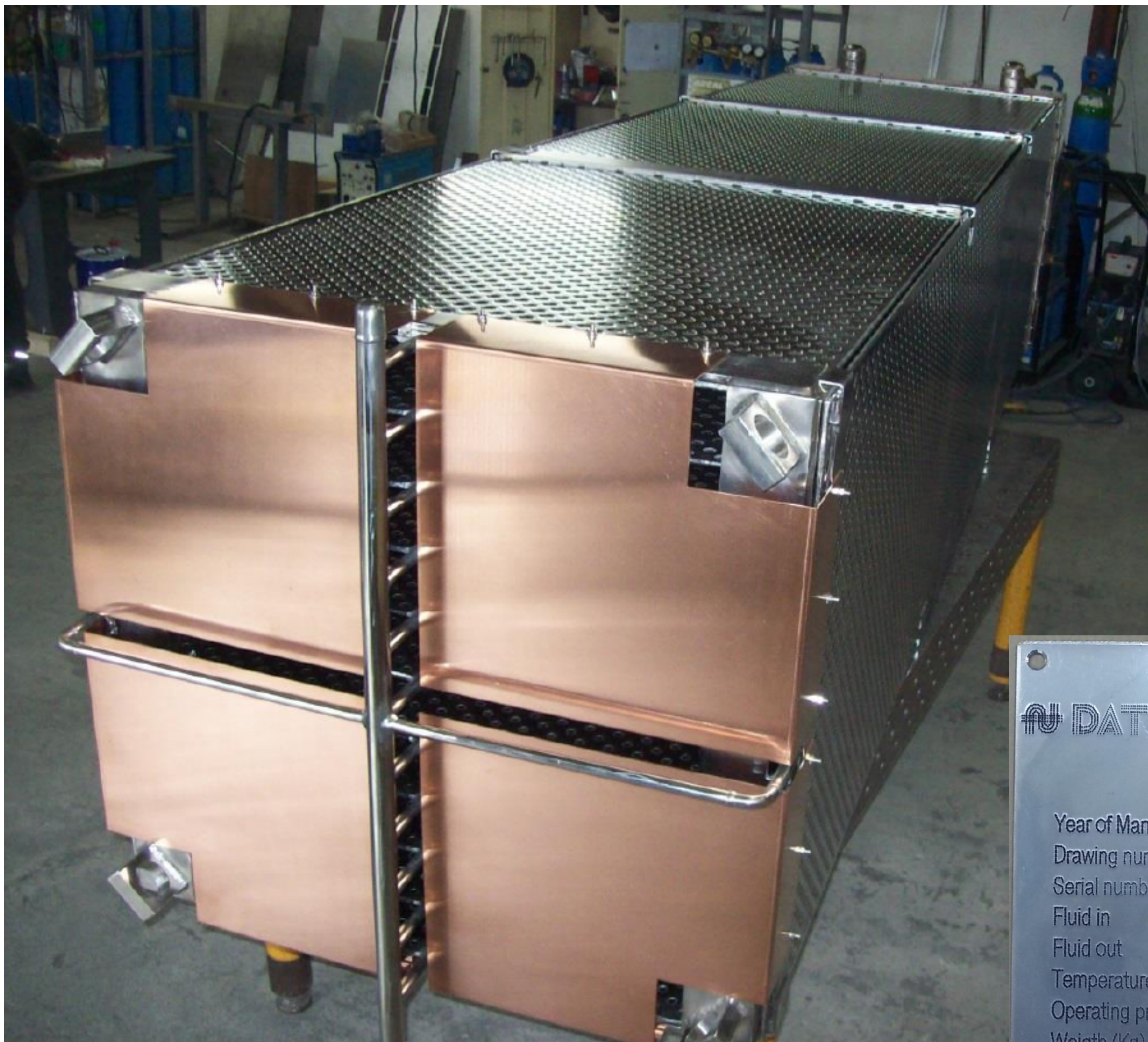
Main specifications:

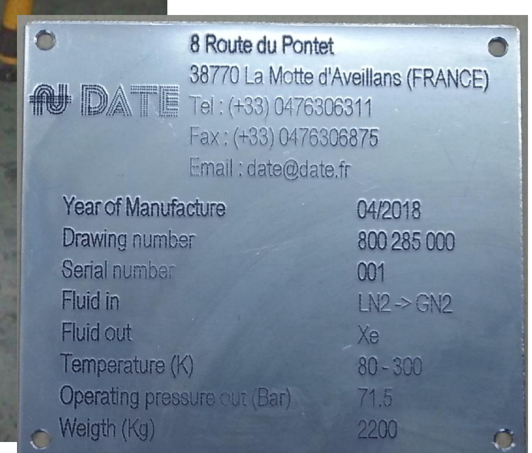
- Built by DATE
- Material: stainless steel
- 11+2 rectangular plates cooled by N_2
- Dimensions: 0.95m x 0.95m x 4m
- Exchange surface: ~100 m^2
- Max pressure: 71.5 bar
- T of service: from -196° to +50° C

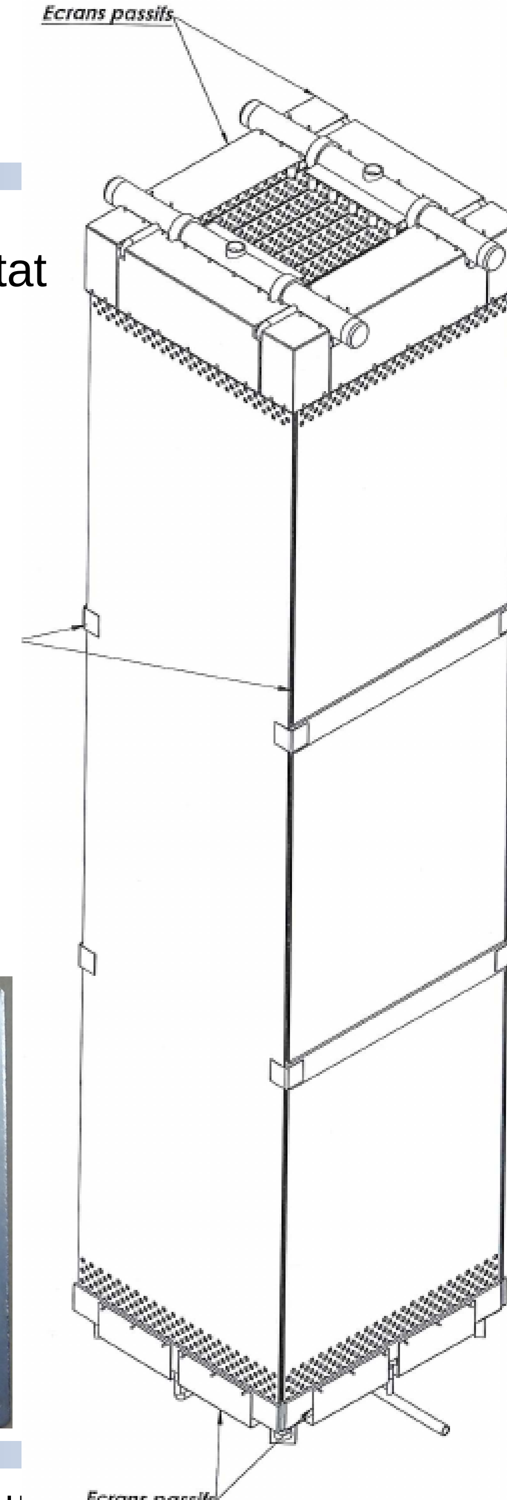


The ReStoX2 cooling system

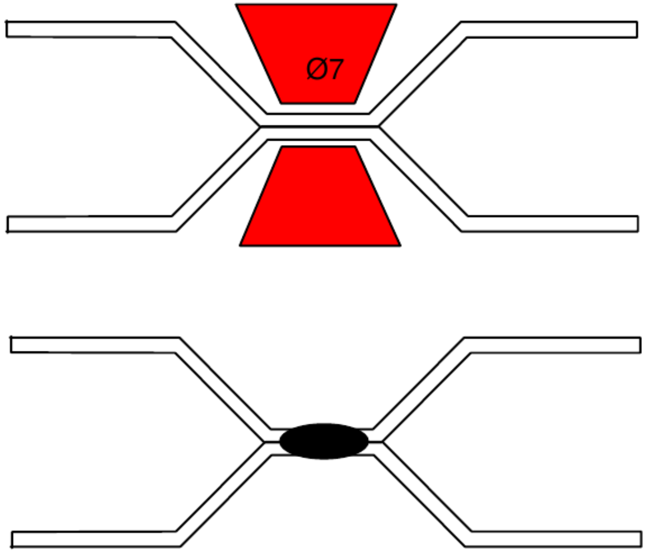
Completed in April 2018 and sent in Italy to be integrated with the cryostat



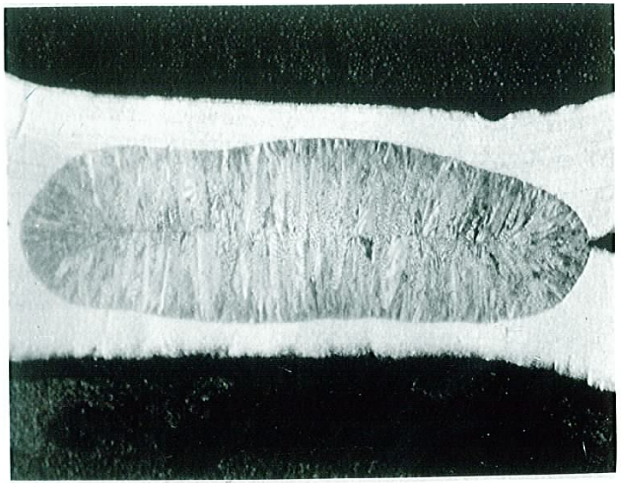




The heat exchanger parallel plates



Macrographic test



Software, data monitoring and calibration

Scintillation signal

$$\mathrm{cs1} \approx n_\gamma(E_{\mathrm{nr}}, \mathcal{E})\langle\mu\rangle$$

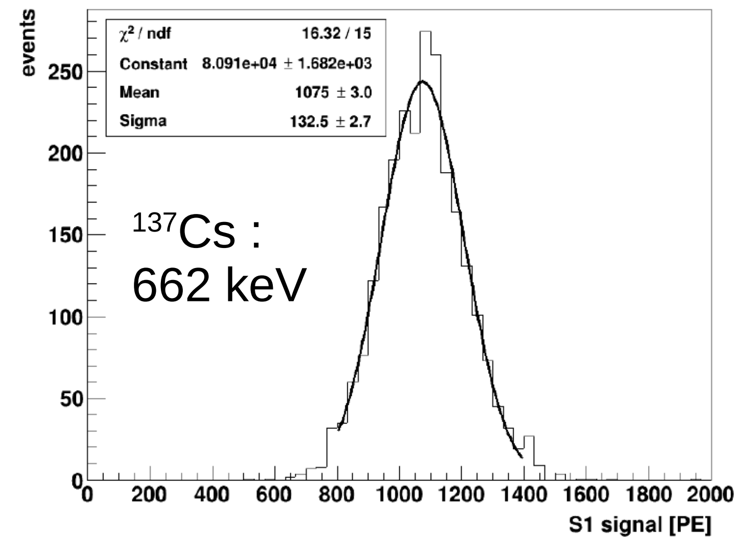
$$= E_{\mathrm{nr}} \langle\mathcal{L}_y(E_{\mathrm{ref}}, \mathcal{E})\rangle \mathcal{L}_{\mathrm{eff}}(E_{\mathrm{nr}}, \mathcal{E}=0) \frac{S_{\mathrm{nr}}(\mathcal{E})}{S_{\mathrm{ee}}(\mathcal{E})}$$

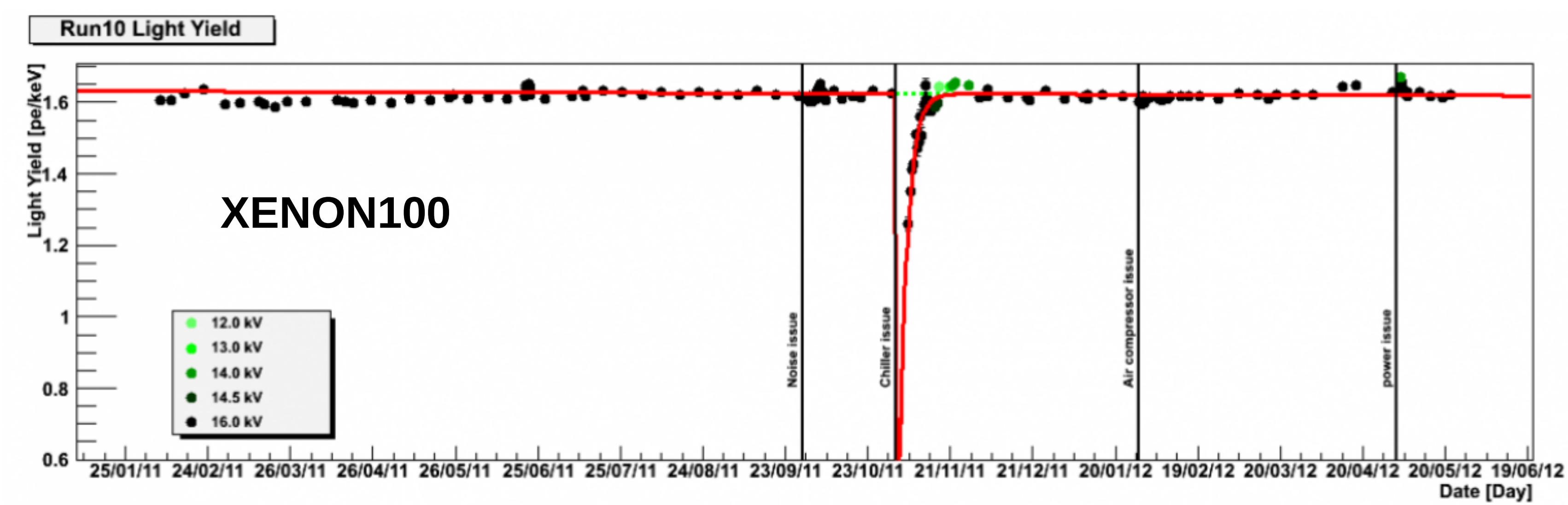
Scintillation signal

Recoil energy

Light yield

Relative scintillation yield





Secondary scintillation signal

Number of generated electrons

Electrons extraction yield

$$s2_i(\vec{r}) \approx n_e(E_u, \mathcal{E})\, e^{-t_d/\tau_e}\, \kappa(\mathcal{E}_{\rm gas})\, Y\left(\frac{\mathcal{E}_{\rm gas}}{\rho}, h_{\rm g}\right) \beta_i(x,y)\eta_i$$

Secondary scintillation signal (induced by ionization)

Electrons loss by impurities

Secondary scintillation gain

τ_e ≡ *electron lifetime*

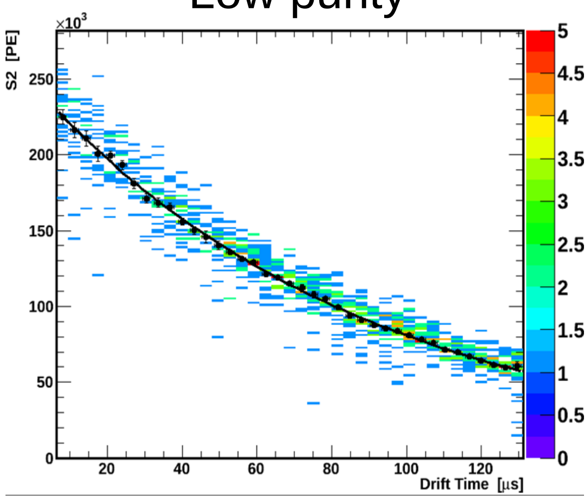
The xenon purity and the electron lifetime

$$dN/dt = -k_S N[S] \qquad N(t) = N(0) \cdot e^{-t/\tau} \qquad \tau = (\sum_i k_{S_i}[S_i])^{-1}$$

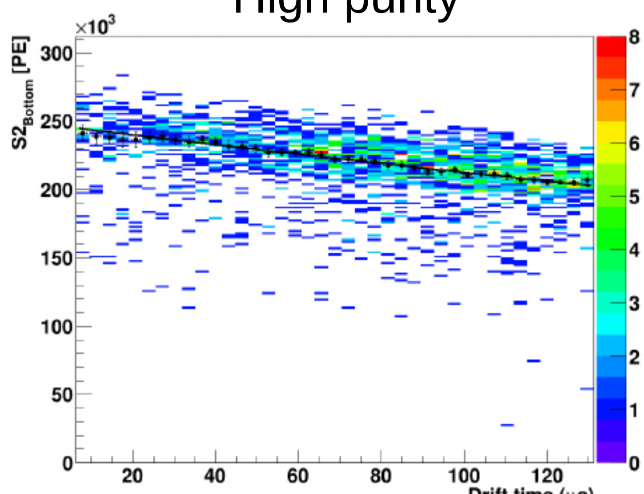
$$[S_{O_2}] = \sum_i \frac{k_{S_i}[S_i]}{k_{O_2}} \qquad N(t)(ppb) = \frac{10^{15} \cdot M(g/mol)}{\tau_e(us) \cdot k_{O_2}(l/mol/s) \cdot \rho(g/l)} = \frac{477}{\tau_e(us)}$$

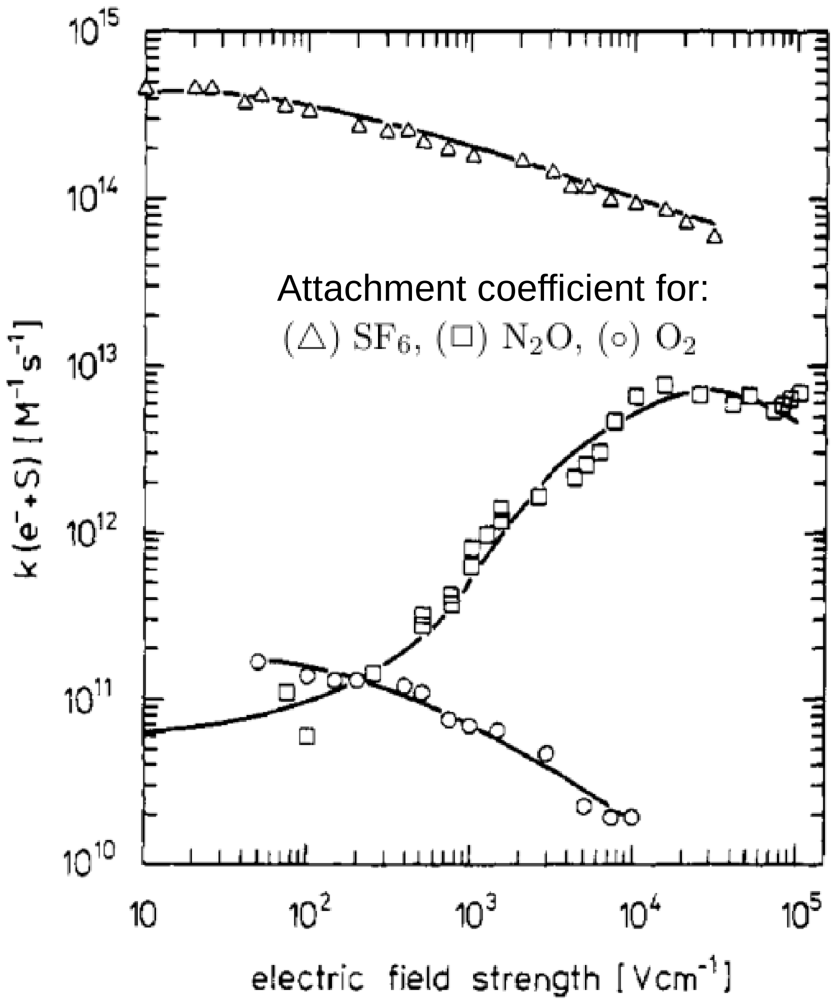
^{137}Cs : 662 keV

Low purity

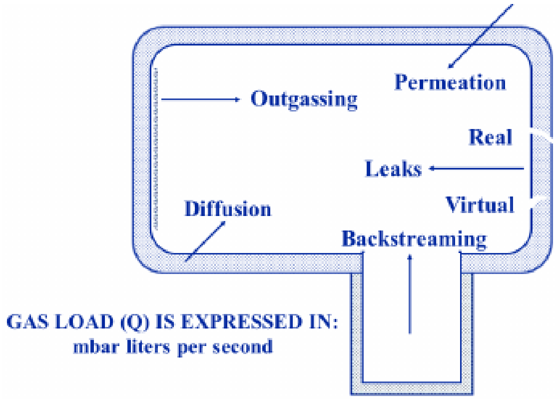


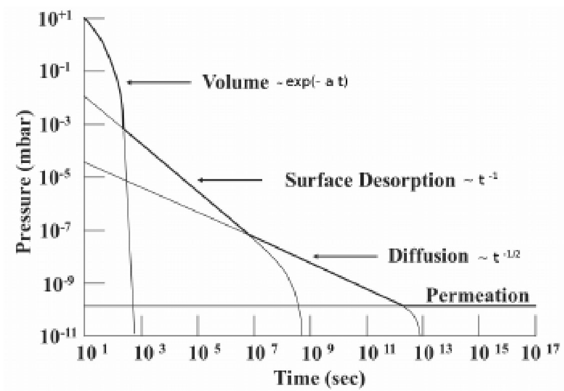
High purity





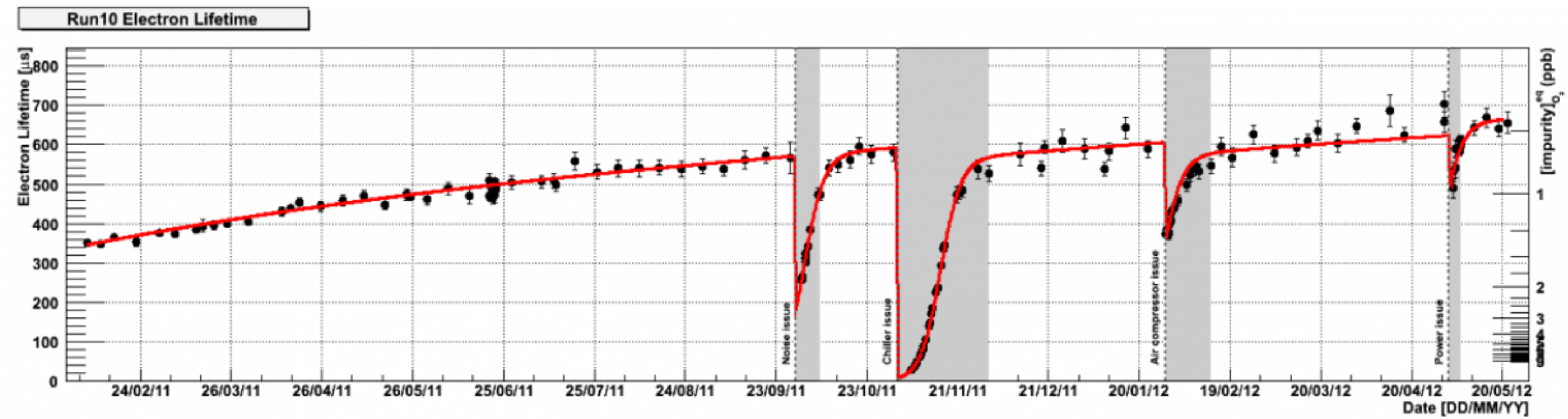
The xenon purity evolution in XENON100





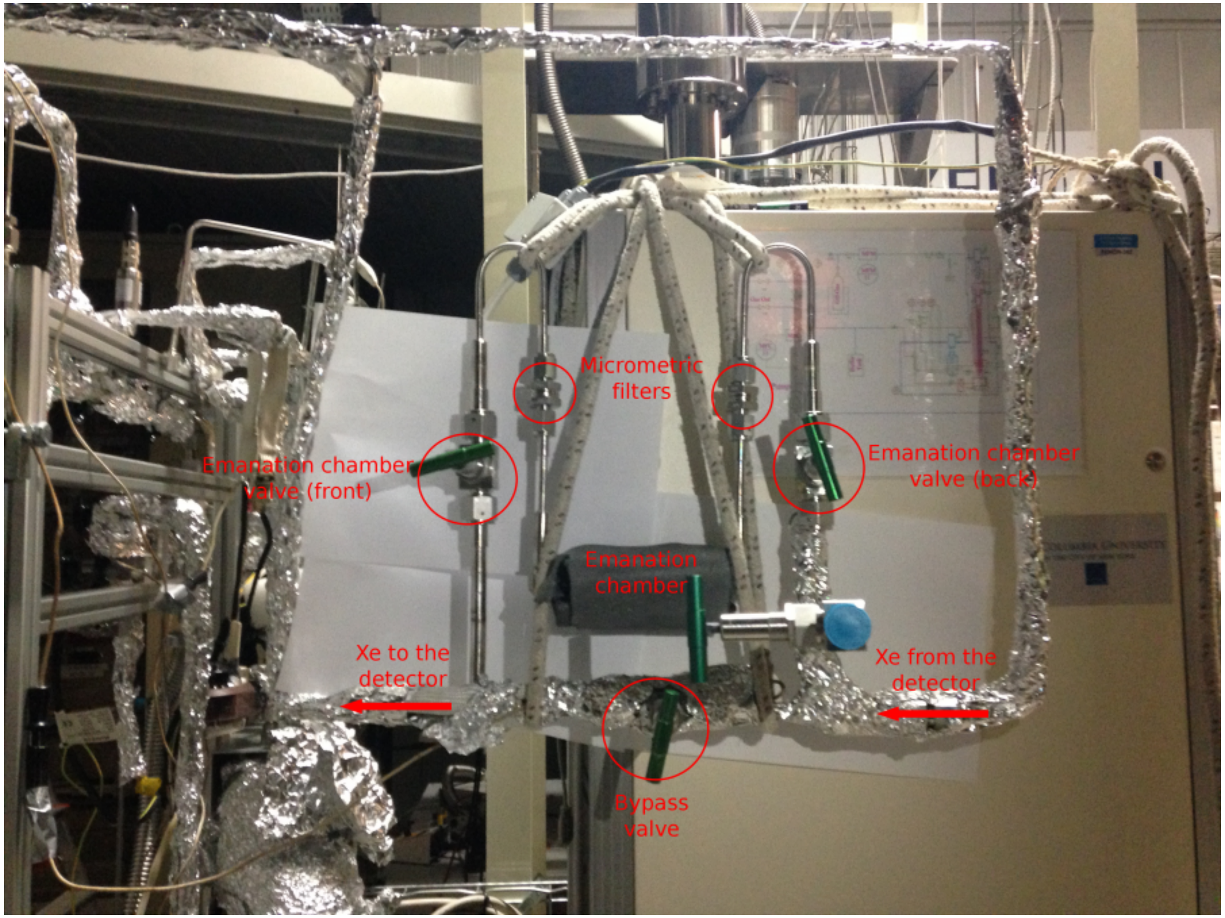
- $\tau_p = (2.870 \pm 0.013) \cdot 10^5 s \sim 79.7h \sim 3.32d$
- $\beta = 0.872 \pm 0.031$

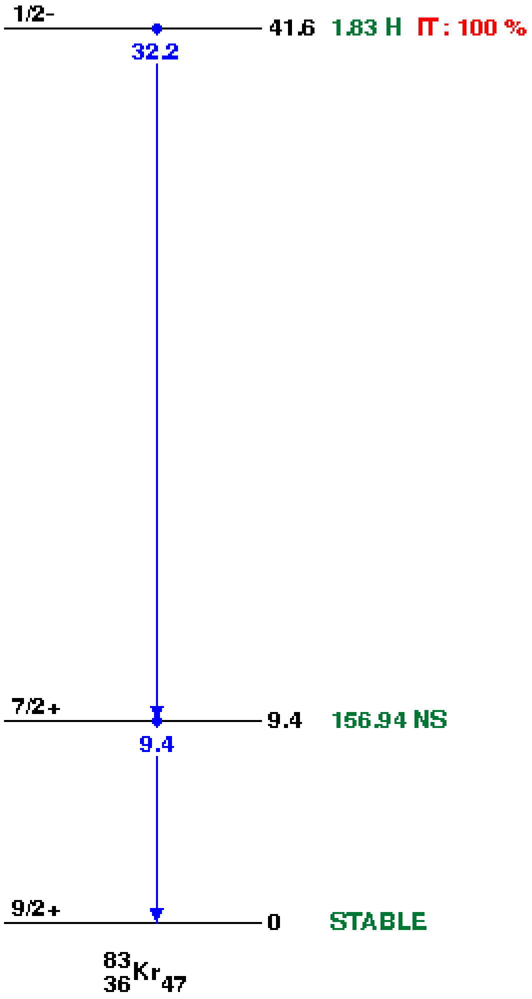
$$\frac{\delta N(t)}{\delta t} = -\frac{N(t)}{\tau_p} + \Phi_\infty + \frac{A}{(t - t_0^{out} + \sum_i \Delta t_i \cdot \delta(t - t_i))^\beta} + \sum_i N_i \cdot \delta(t - t_i)$$



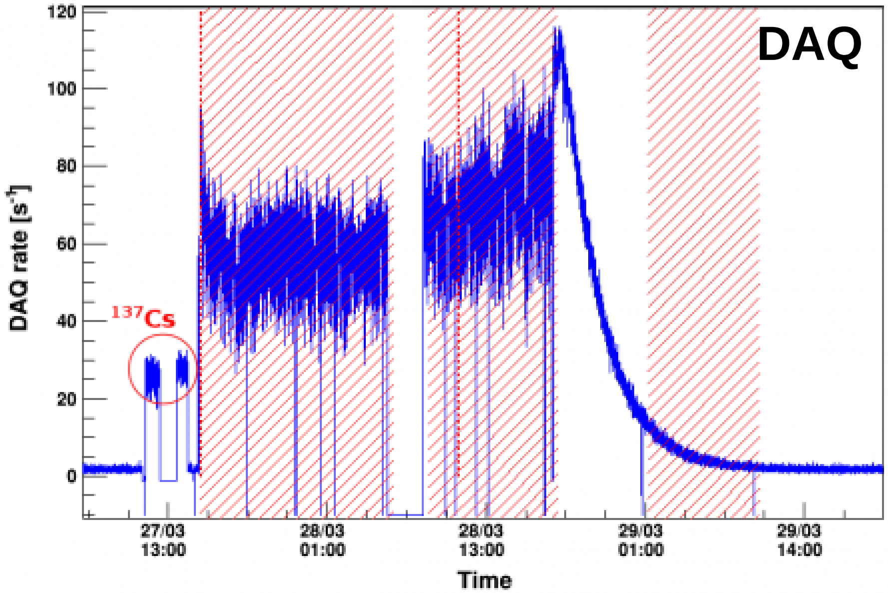
^{83m}Kr calibration in XENON100

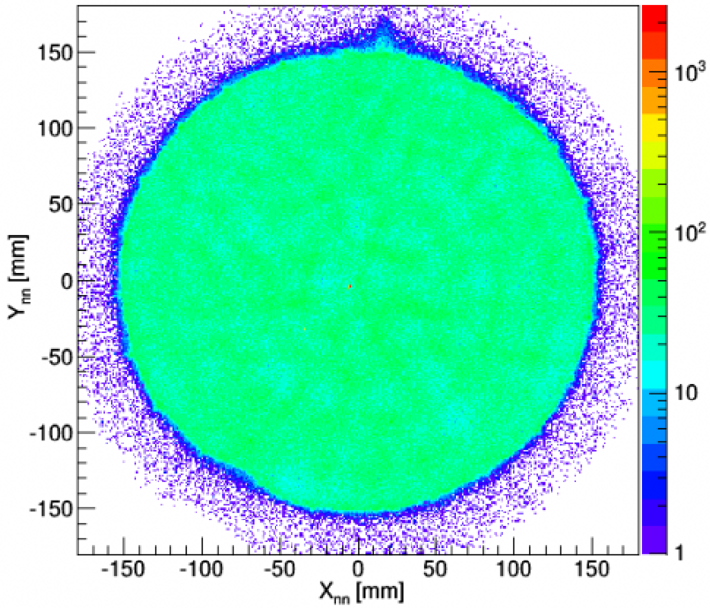
- ^{83}Rb deposited in zeolite spheres
- ^{83}Rb decays (86.2 days) to 41.6keV ^{83m}Kr
- ^{83m}Kr flows into the xenon recirculation system

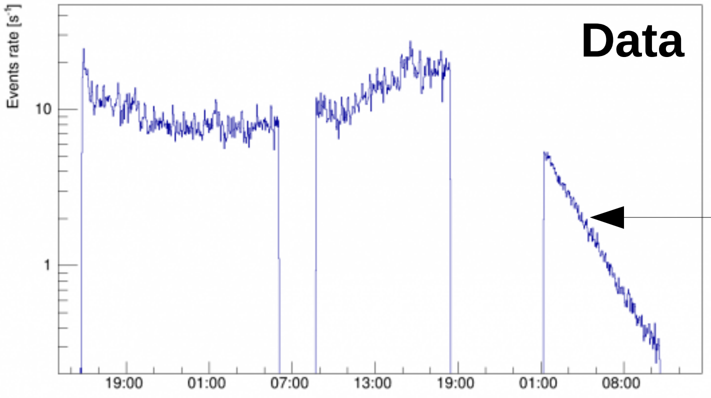




^{83m}Kr calibration first results in XENON100



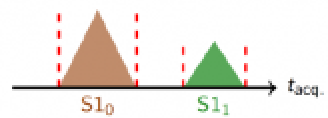




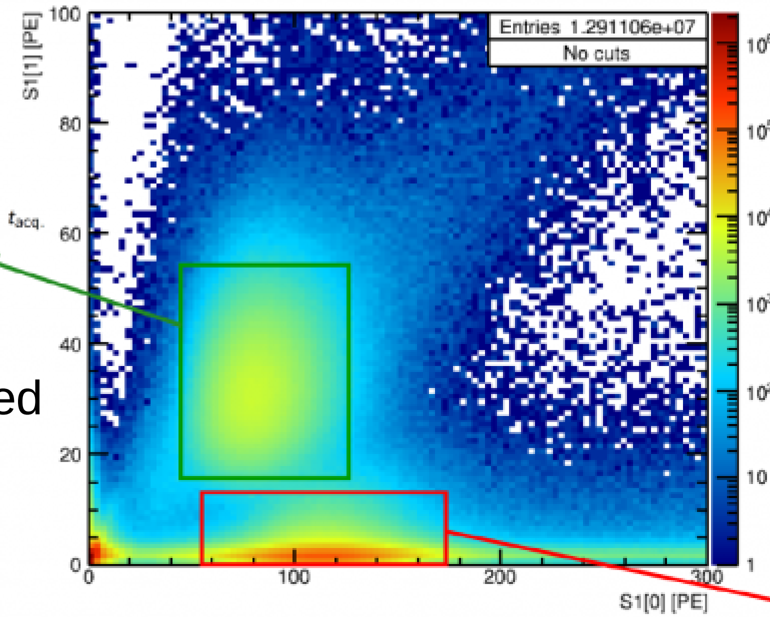
$T_{1/2}$ = 1.87±0.04
(from NuDat 2.6: 1.85±0.05)

Characterization of ^{83m}Kr gamma signals

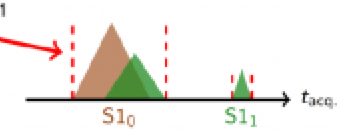
32.2 keV followed by a 9.4 keV peak



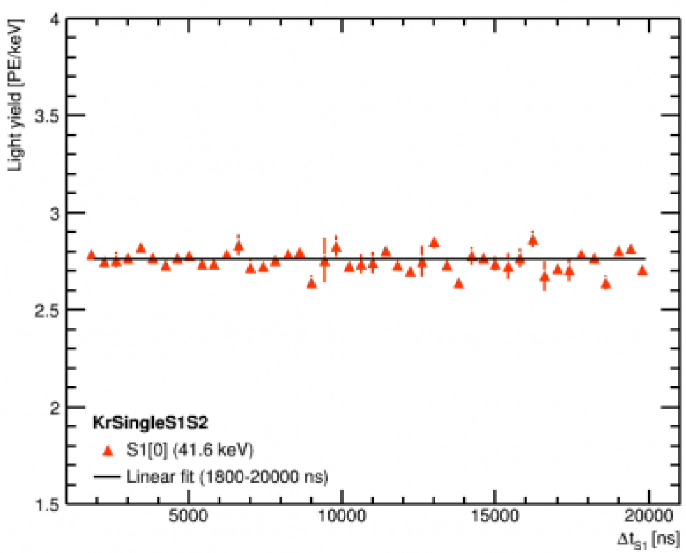
Enough far
to be separated

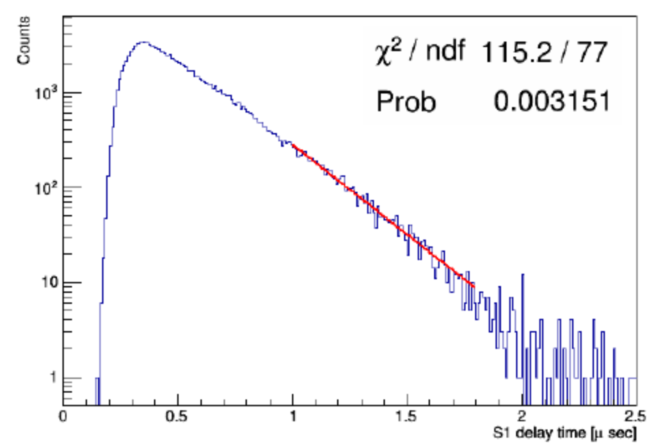


Too close
each other



Extremely stable light yield measurement





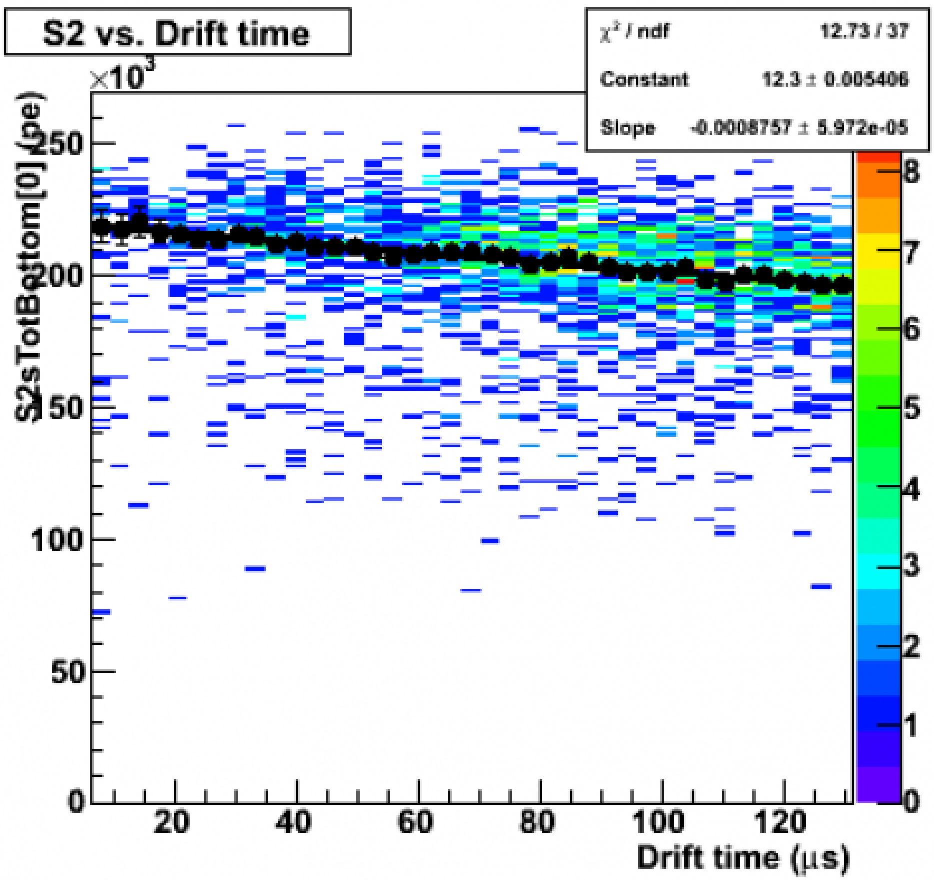
9.4 keV lifetime:

$T_{1/2}$ = (160±3)ns

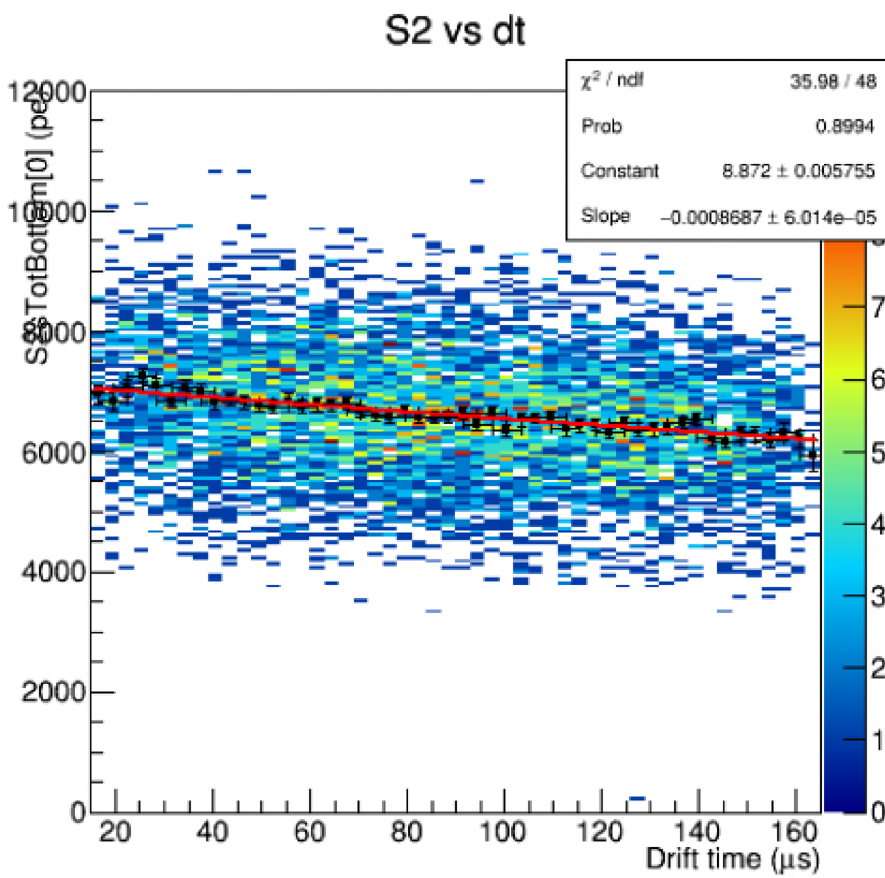
(from NuDat 2.6:
156.9ns)

Electron lifetime measurements : from ^{137}Cs to ^{83m}Kr

^{137}Cs



^{83m}Kr



Uniform spatial distribution (hence also whole z range), no compton, high statistics

Electron lifetime evolution in XENON1T

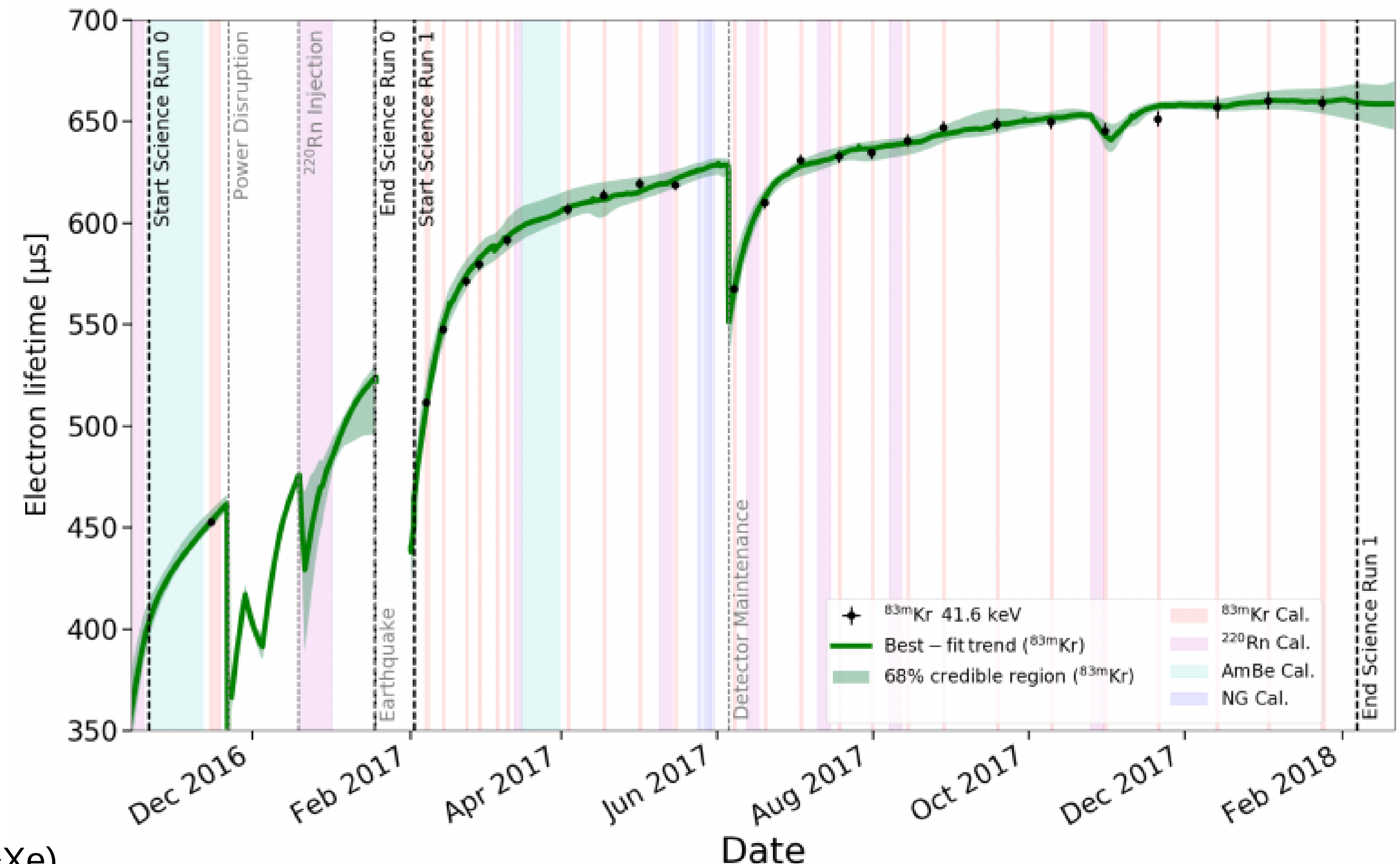
Electron lifetime measured with:

^{222}Rn and ^{218}Po
- it requires no calibration source
- it allows continuous monitoring
- Monochromatic source (alpha):
  - 5.590 MeV (Rn222)
  - 6.114 MeV (Po218)

^{220}Rn
- internal calibration: uniform
- Monochromatic source (alpha):
  - 6.404 MeV
- Larger statistic wrt ^{222}Rn

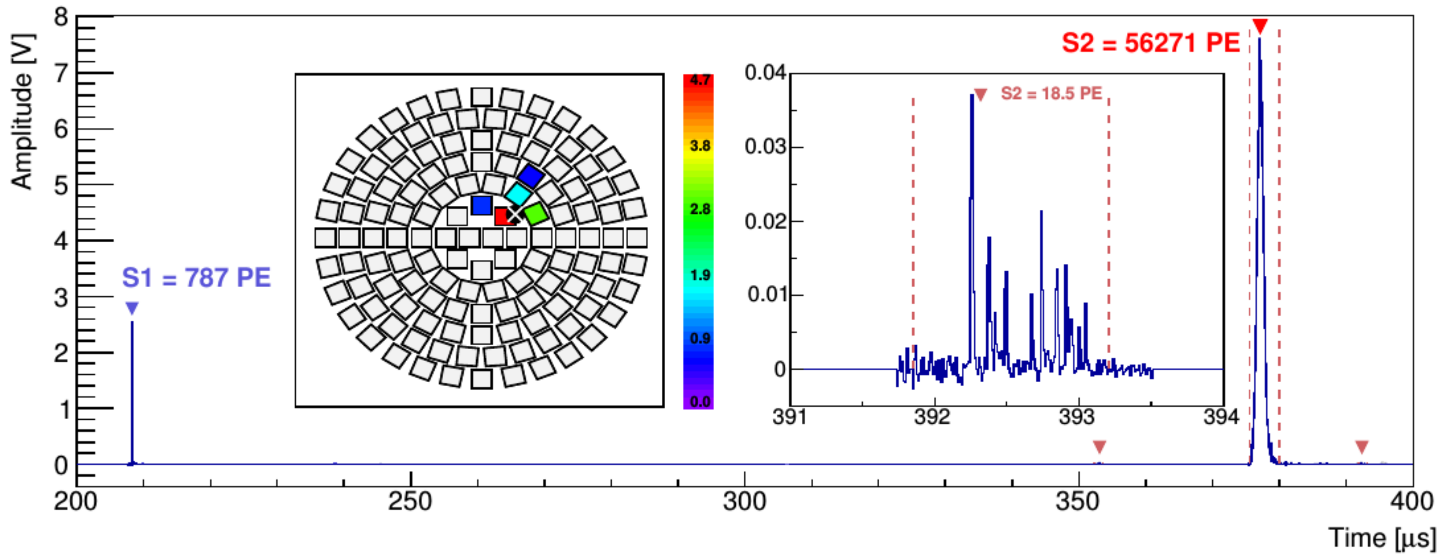
^{83m}Kr
- internal calibration: uniform
- 24h calibration twice per month
- more precise due to high stats
- Energies:
  - 9.2, 32.2, 41.6 keV (sum)

AmBe and Neutron gun
- Xe deactivation lines
  - 39.6 keV (^{129}Xe), 80.2 keV (^{131}Xe),
  - 236.1 keV (^{129m}Xe), 163.9 keV (^{131m}Xe)



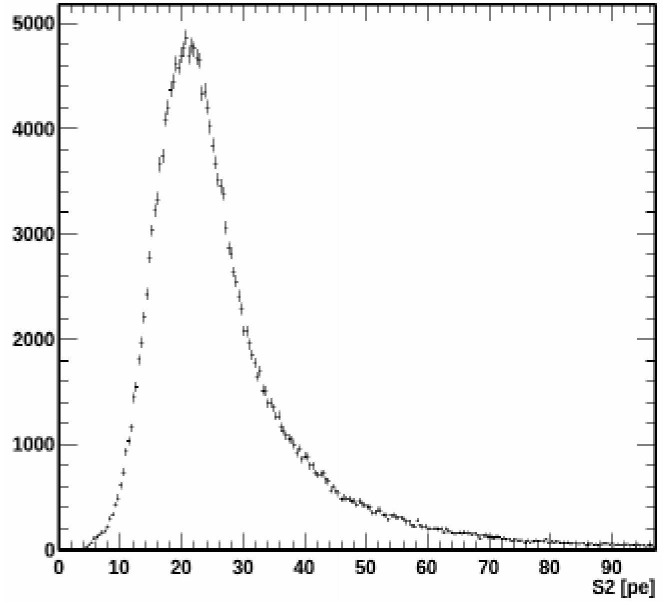
Single electrons charge signals

Low-energy secondary scintillation signal

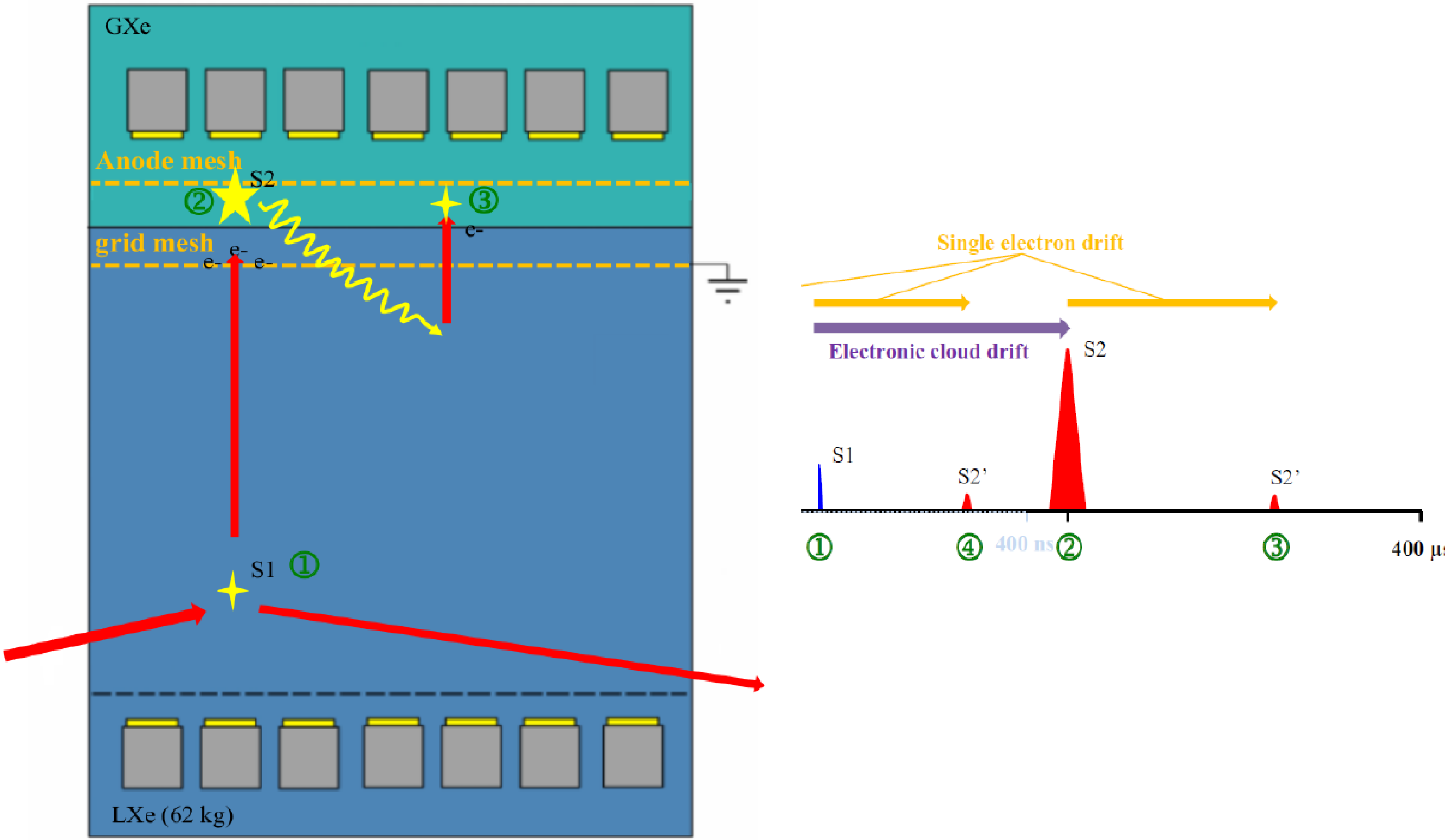


Waveform of a triggered event

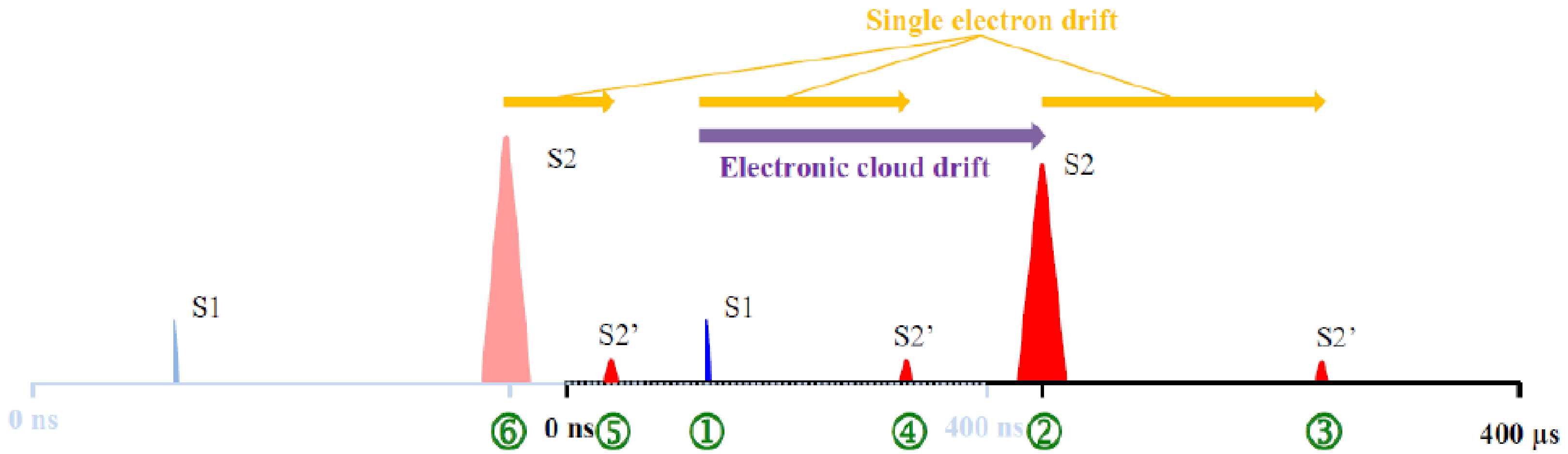
Low energy spectrum



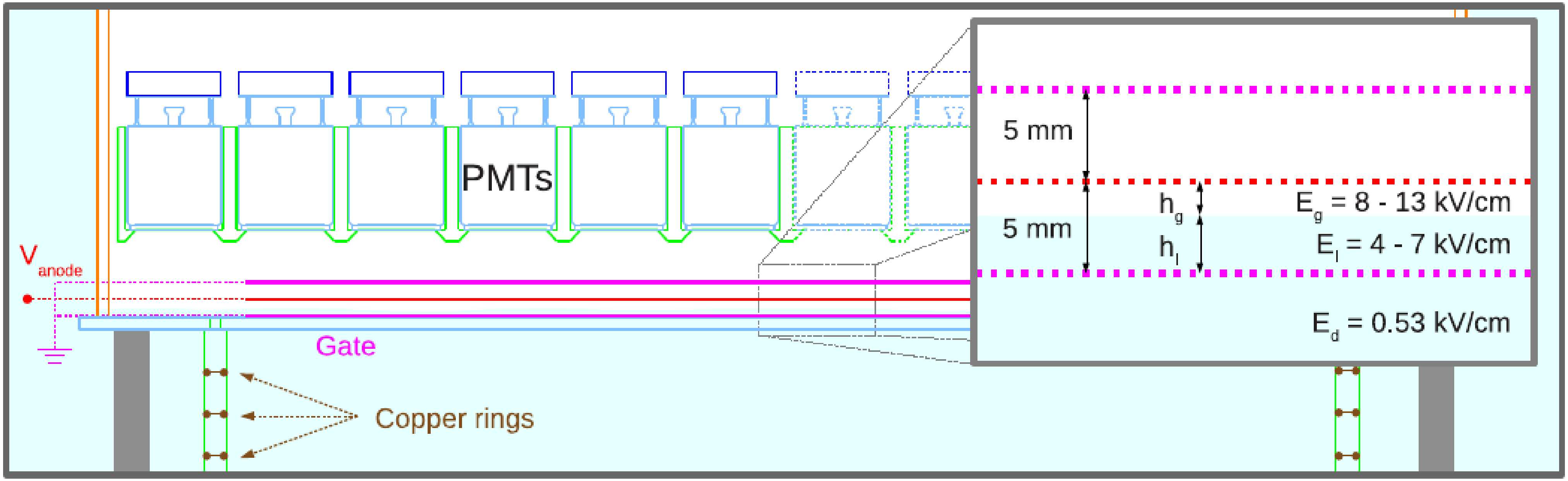
Single electrons responsible of low energy signal

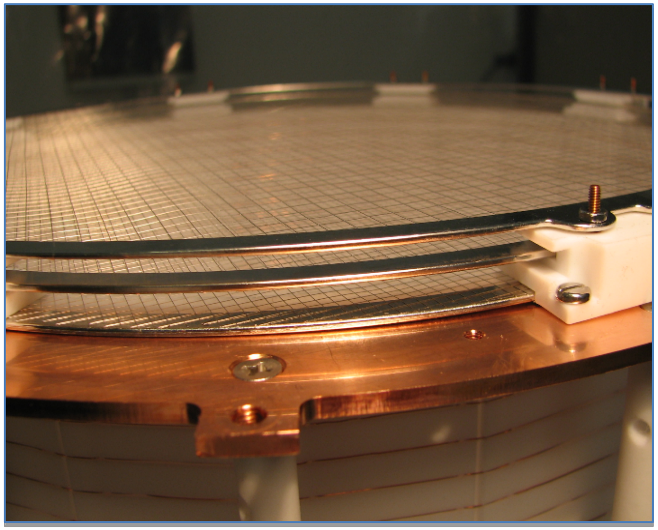


Single electrons responsible of low energy signal



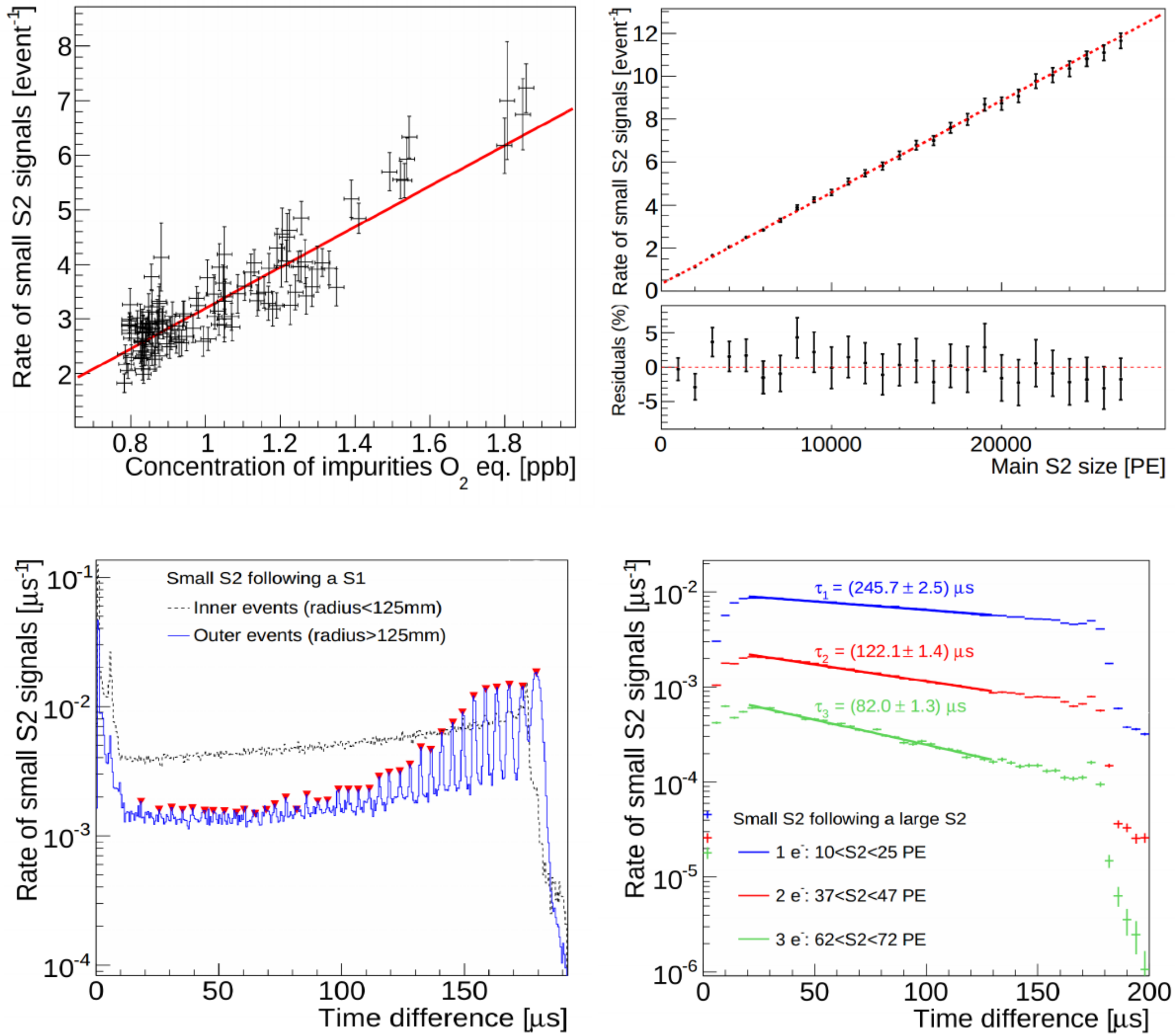
Single electrons responsible of low energy signal



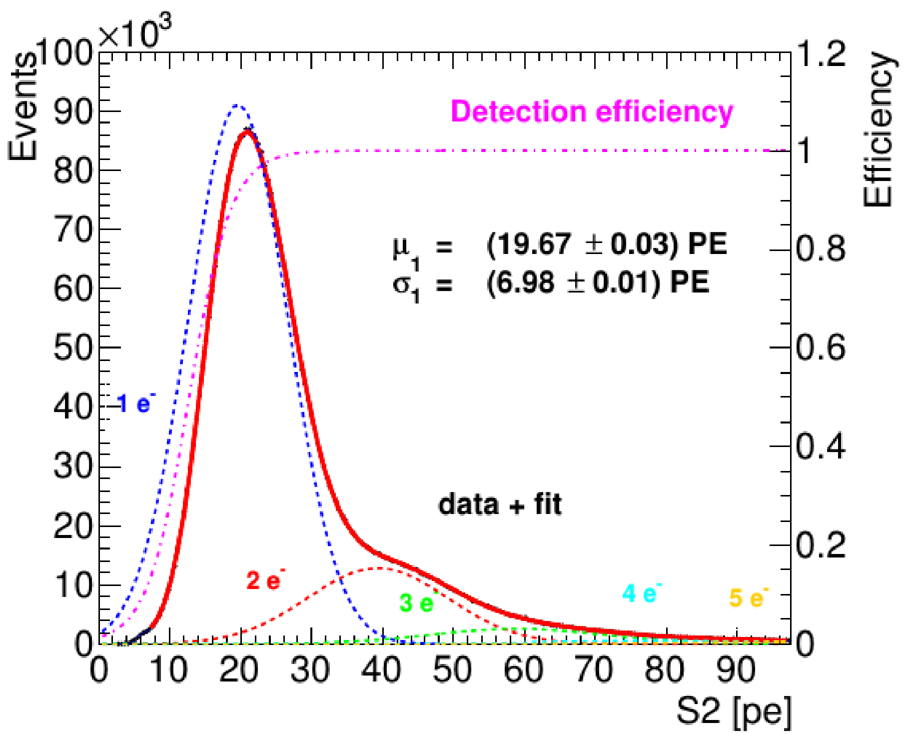


Xe XENON Dark Matter Project

Evidences of single electrons origin



Secondary scintillation gain



$$\mu_i = i\mu_1$$

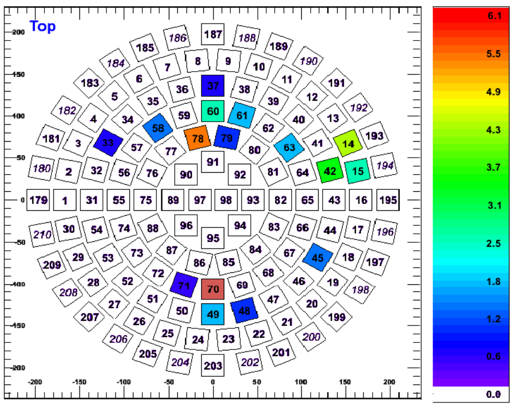
$$\sigma_i = \sqrt{i}\sigma_1$$

μ_1 = secondary scintillation gain

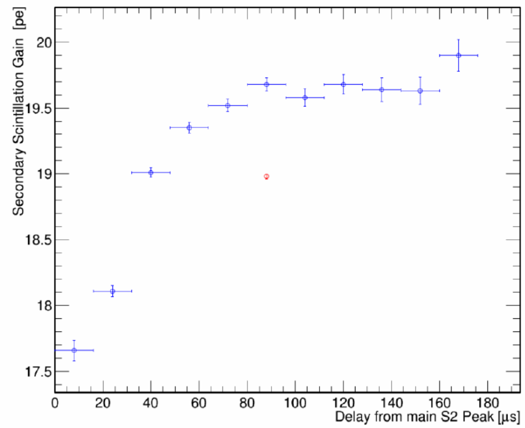
$$f(E) = \frac{1}{e^{\frac{a-E}{b}} + 1} \sum_{i=1}^{n} A_i \, e^{-\frac{1}{2}\left(\frac{E-\mu_i}{\sigma_i}\right)^2}$$

Deep study and cross checks

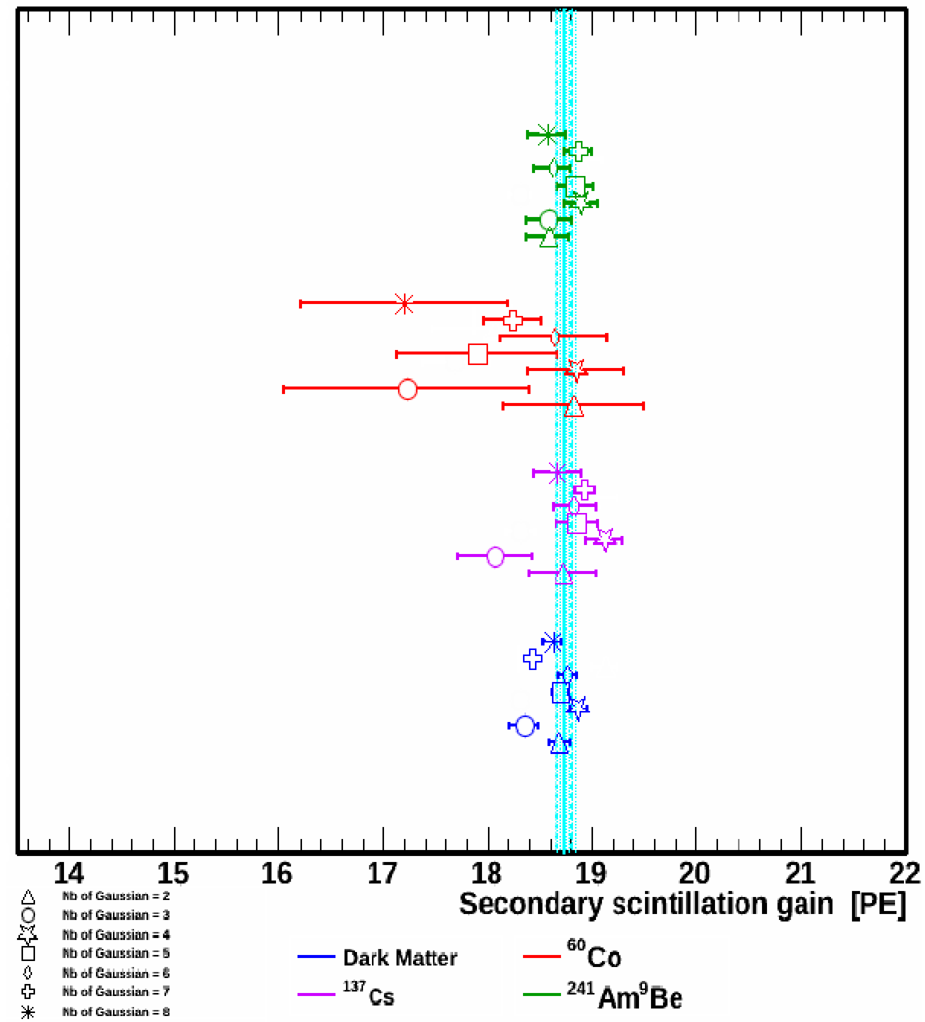
X,Y distribution of multi-e$^-$

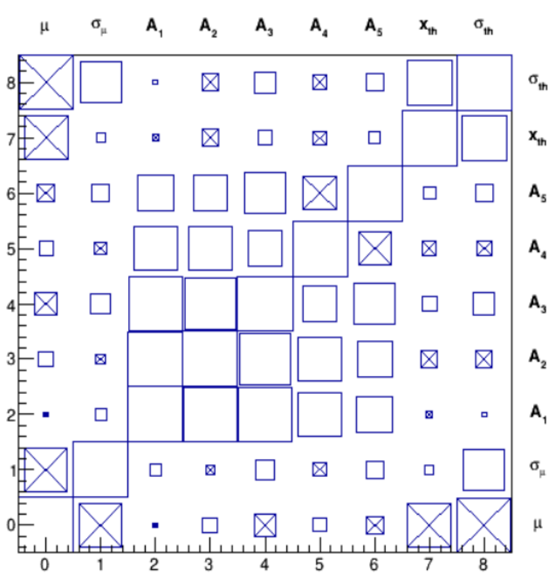


Bias from main signal



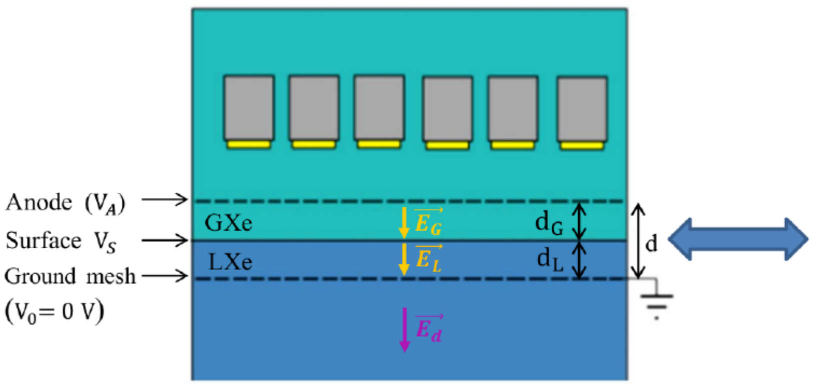
Independence from source and fit choices

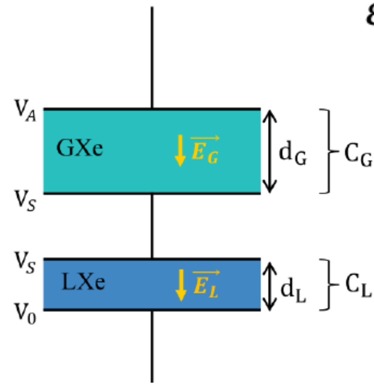




Parameters cross-correlations

Modeling the electric field and electrons trajectories

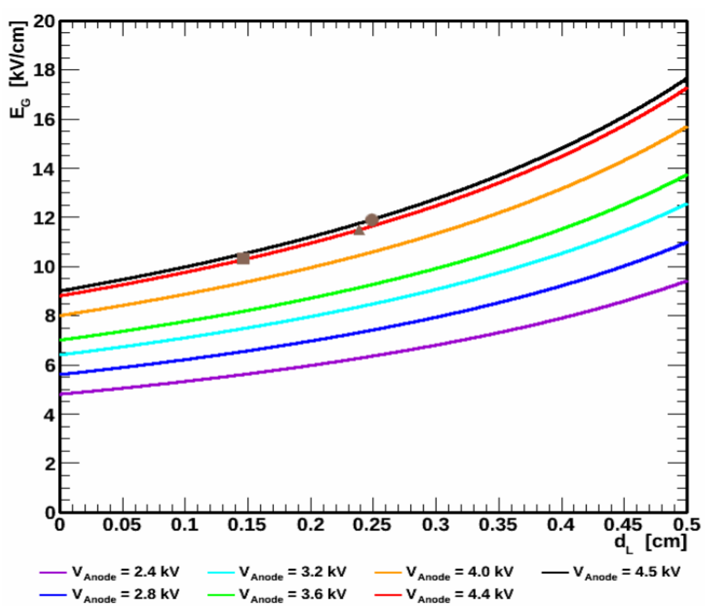


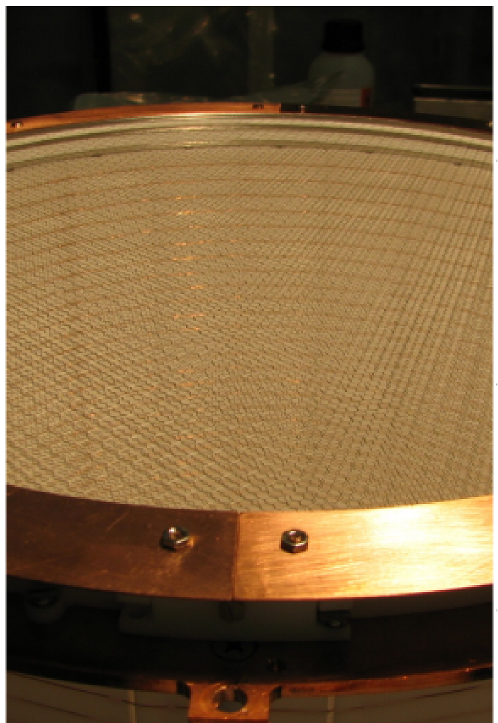


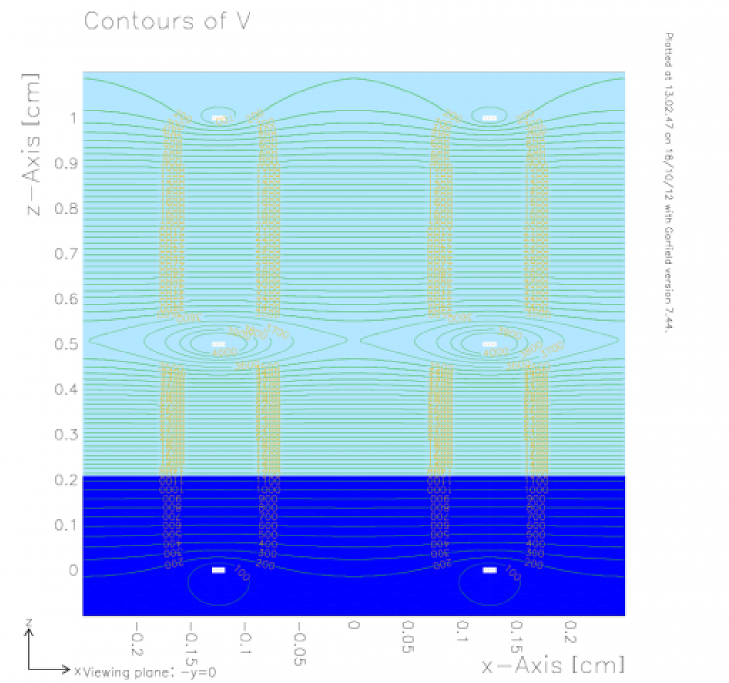
$$\varepsilon_i = \varepsilon_0 \times \varepsilon_{r,i} \quad i = L, G \qquad C_i = \frac{\varepsilon_i \, S}{d_i} \quad i = L, G$$

$$E_L = \frac{\Delta V}{\varepsilon_{r,L}\,(d - d_L) + d_L}$$

$$E_G = \frac{\varepsilon_{r,L}\,\Delta V}{\varepsilon_{r,L}\,(d - d_L) + d_L}$$





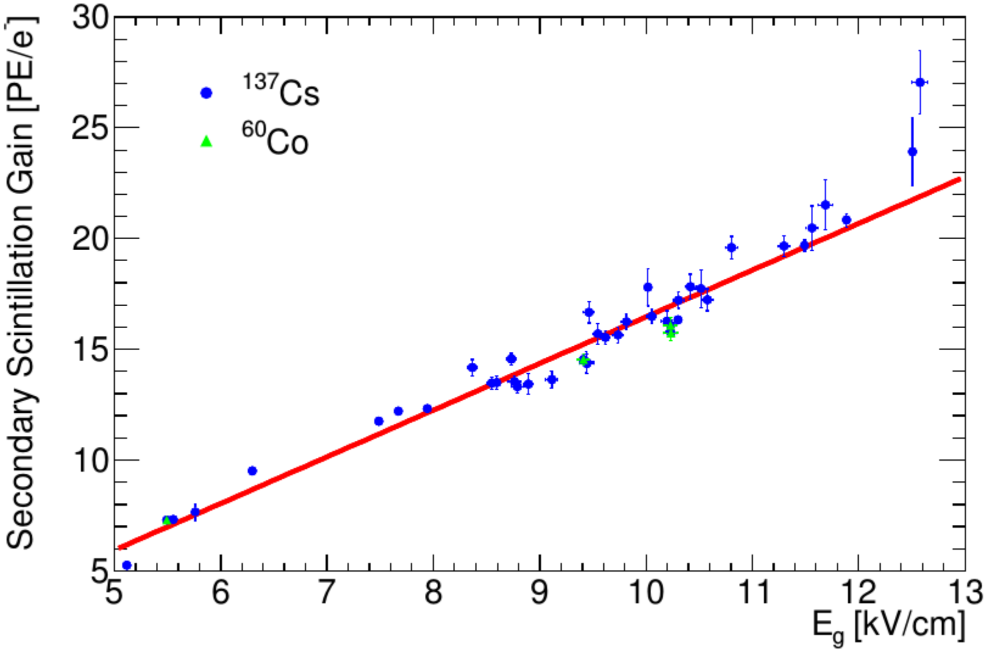


Detector characterization using single electrons

$$s2_i(\vec{r}) \approx n_e(E_u, \mathcal{E})\, e^{-t_d/\tau_e}\, \kappa(\mathcal{E}_{\mathrm{gas}})\, Y\left(\frac{\mathcal{E}_{\mathrm{gas}}}{\rho}, h_{\mathrm{g}}\right) \beta_i(x,y)\eta_i$$

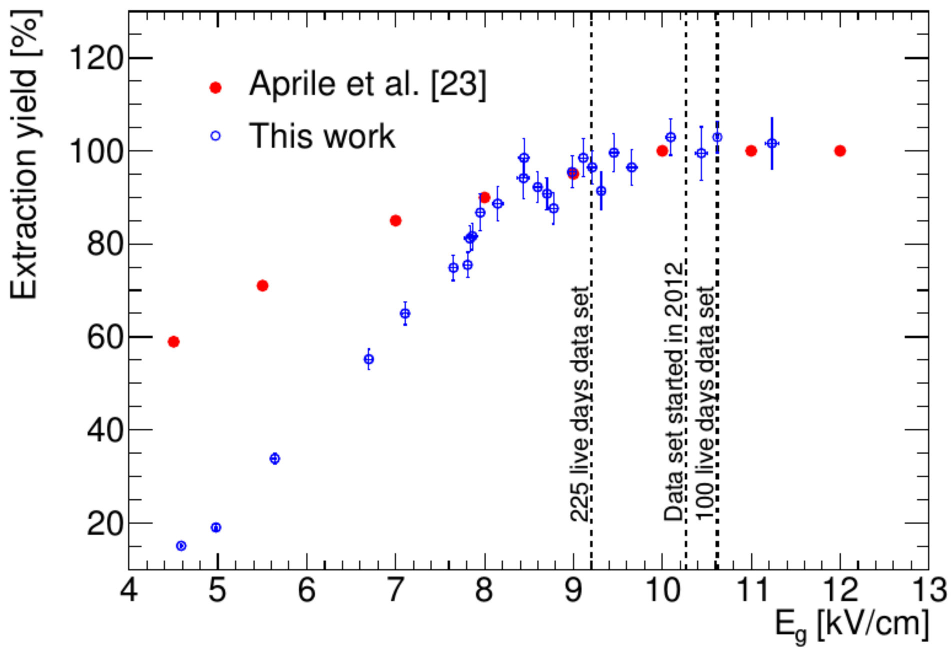
$$Y = (a\frac{E_g}{P_g} + b)\ h_g\ P_g$$

$$\kappa = \frac{G_{S2}\ [PE/eV] \times W\ [eV/e^-]}{Y\ [PE/e^-]}$$



$$a = (151 \pm 19)\,\mathrm{photons/e^-/kV}$$

$$b = -(147 \pm 19)\,\mathrm{photons/e^-/cm/bar}$$



Extraction yield at ~100% during all XENON100 runs

A sort of summary . . .

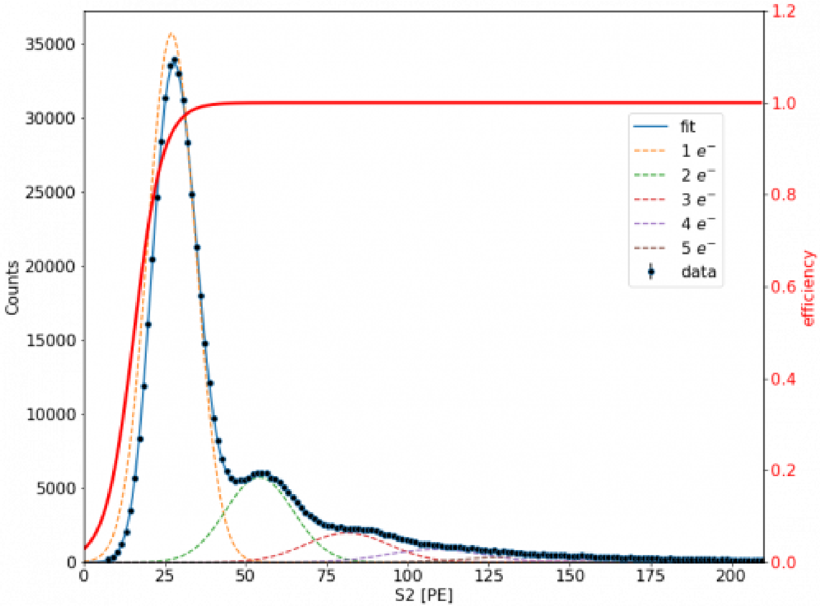
$$s2_i(\vec{r}) \approx n_e(E_u, \mathcal{E})\, e^{-t_d/\tau_e}\, \kappa(\mathcal{E}_{\text{gas}})\, Y\left(\frac{\mathcal{E}_{\text{gas}}}{\rho}, h_{\text{g}}\right) \beta_i(x,y)\eta_i$$

Electron lifetime

Extraction yield

Secondary scintillation gain

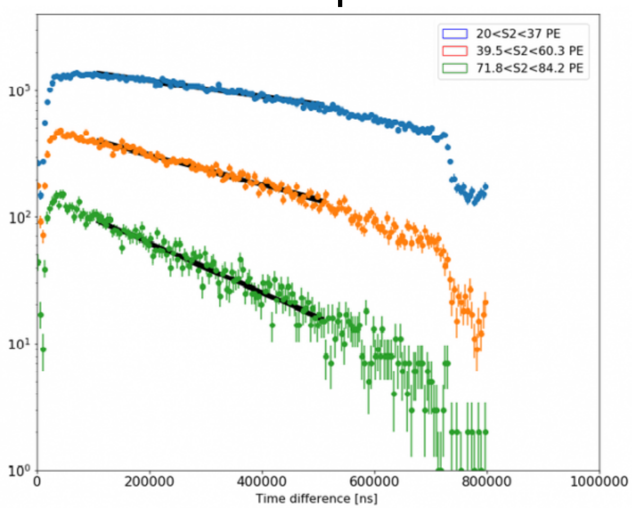
Continuing these analyses for XENON1T



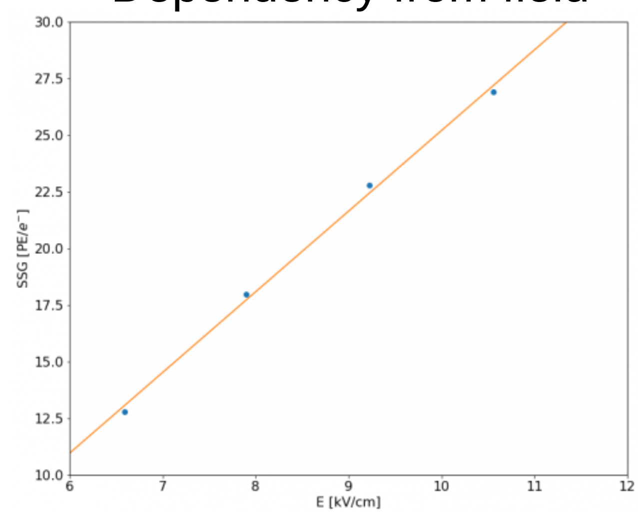
PhD Thesis, Jean-Philippe Zopounidis, LPNHE

χ^2/ndf	1.02
μ	$27.108^{+0.040}_{-0.041}\quad PE/e^-$
σ	$7.366^{+0.016}_{-0.016}\quad PE/e^-$
T	$4.38^{+0.08}_{-0.08}\quad PE/e^-$
S_{tr}	$15.57^{+0.15}_{-0.15}\quad PE/e^-$

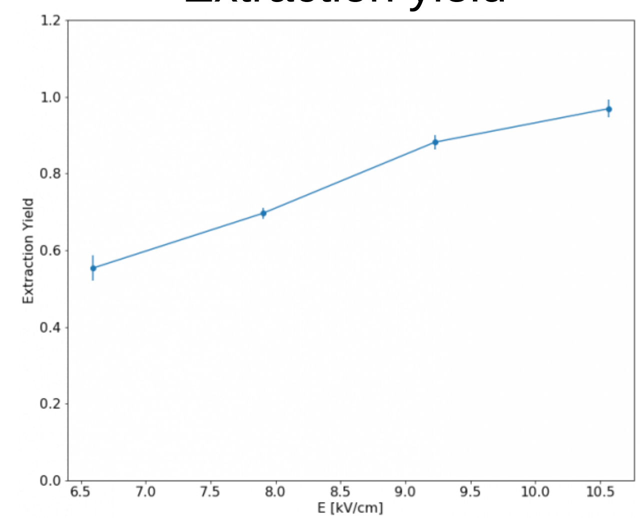
Rate from multiple electrons



Dependency from field



Extraction yield



Still a lot of questions to be answered . . .

Using single electrons to measure x.y dependency of ionization signal

Using single electrons to monitor the ionization gain stability

Origin of single electrons:

- Photoionization from impurities
- Photoionization from metal surfaces
- Trapped electrons
- Long-lived excited states
- Thin film field emission (“Malter effect” : Phys. Rev., 50:48–58)

...and, why not:

- sub-GeV EL dark matter signal

Dedicated working groups in XENON1T are studying all of this and LPNHE is joining them

XENON100 → XENON1T → XENONnT → DARWIN

Xenon-based TPC are excellent to be scaled up to larger sizes and improve the sensitivity to dark matter search

But still it does not come for free. Some studies and R&D are necessary to beat ourselves at each generation

In this context, I focused my work in past 8 years in:

HARDWARE:

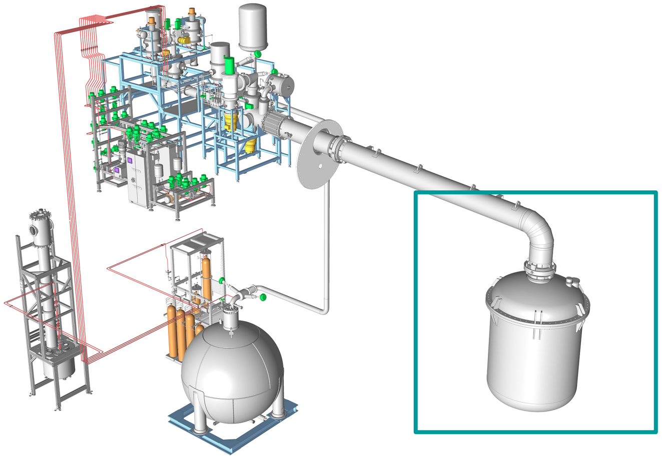
Liquid xenon handling: storage and recovery systems

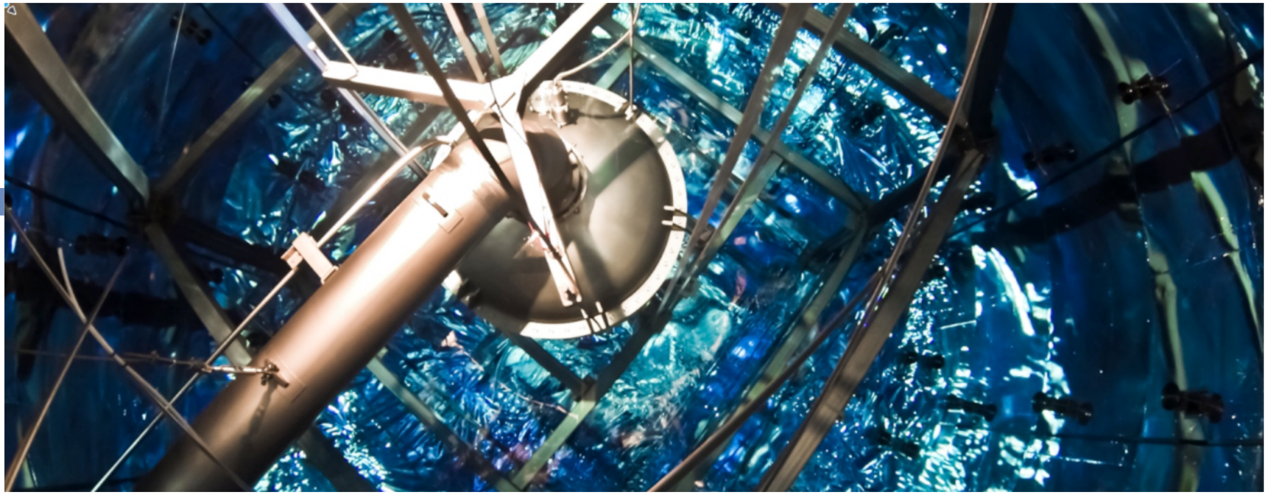
CALIBRATION AND ANALYSIS:

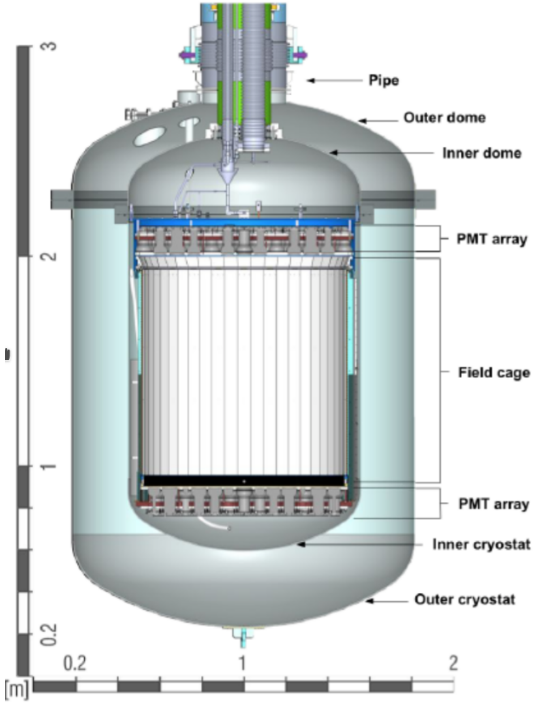
Improving our knowledge on proportional scintillation signal, that is crucial for most of analysis channels


Thanks !
Luca Scotto Lavina
CNRS
October 22nd, 2018, HDR defense, LPNHE
つづく

Cryostat

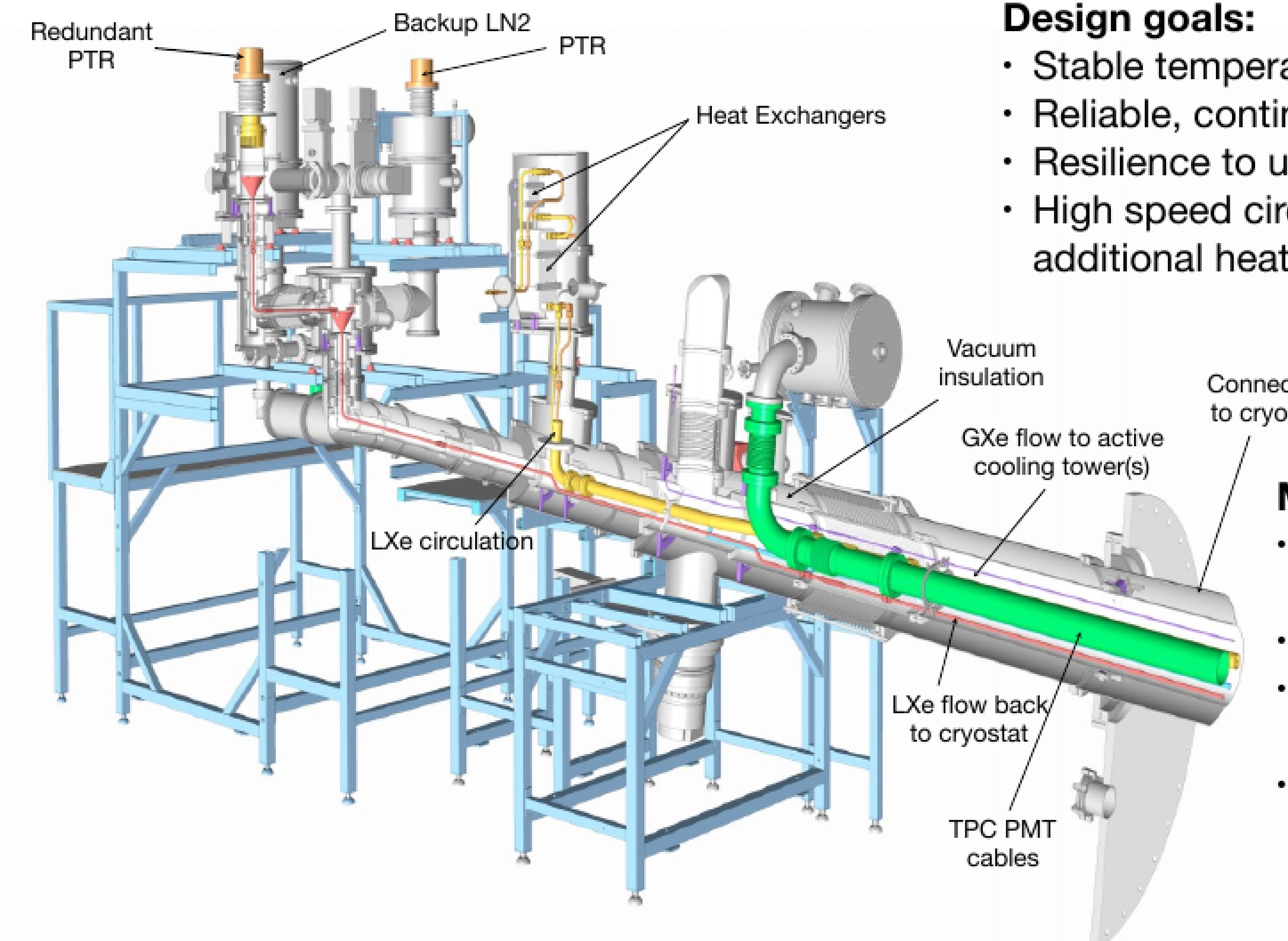





Pipe
Outer dome
Inner dome
PMT array
Field cage
PMT array
Inner cryostat
Outer cryostat
3
2
1
0.2
0.2
1
2
[m]

Cooling system

Goal: liquefy 3300 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.



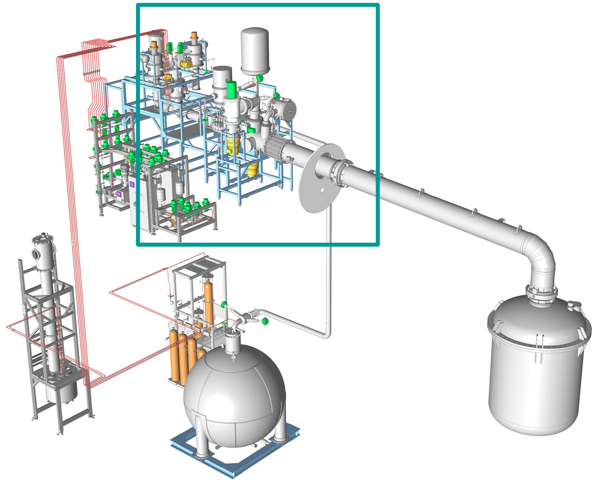
Design goals:

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

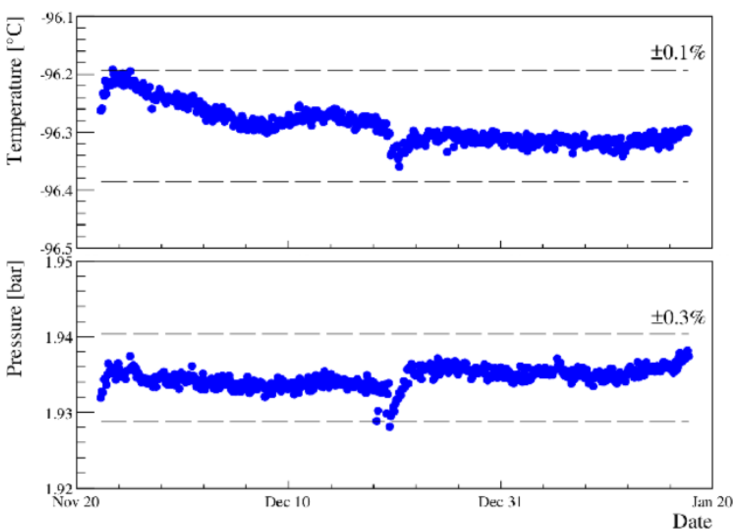
Main features:

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

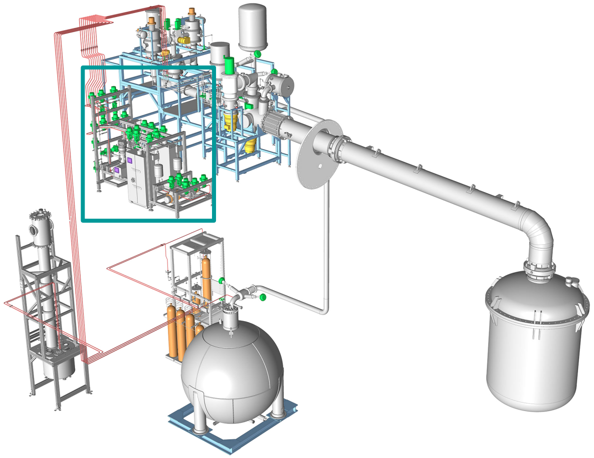
Cooling system



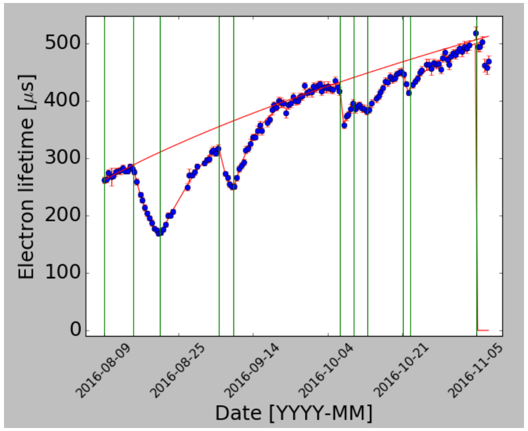
- LXe temperature stable at -96.27 °C, RMS 0.04 °C
- Gxe pressure stable at 1.934 bar, RMS 0.001 bar



Xenon purification

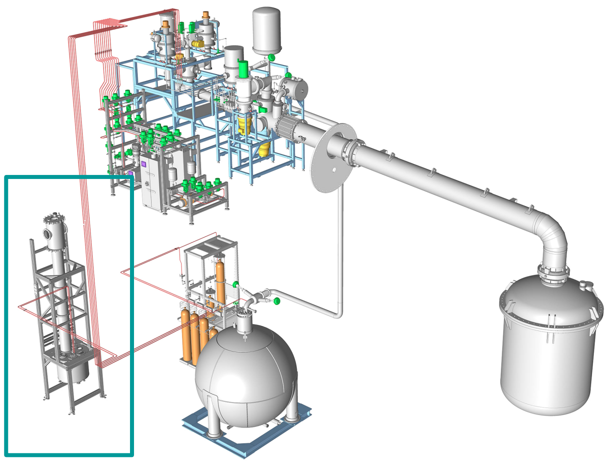


Goal: remove electronegative impurities below 1 ppb (O_2 equivalent) in the Xe gas fill and from outgassing of detector's components with continuous circulation of Xe gas at high speed through hot getters

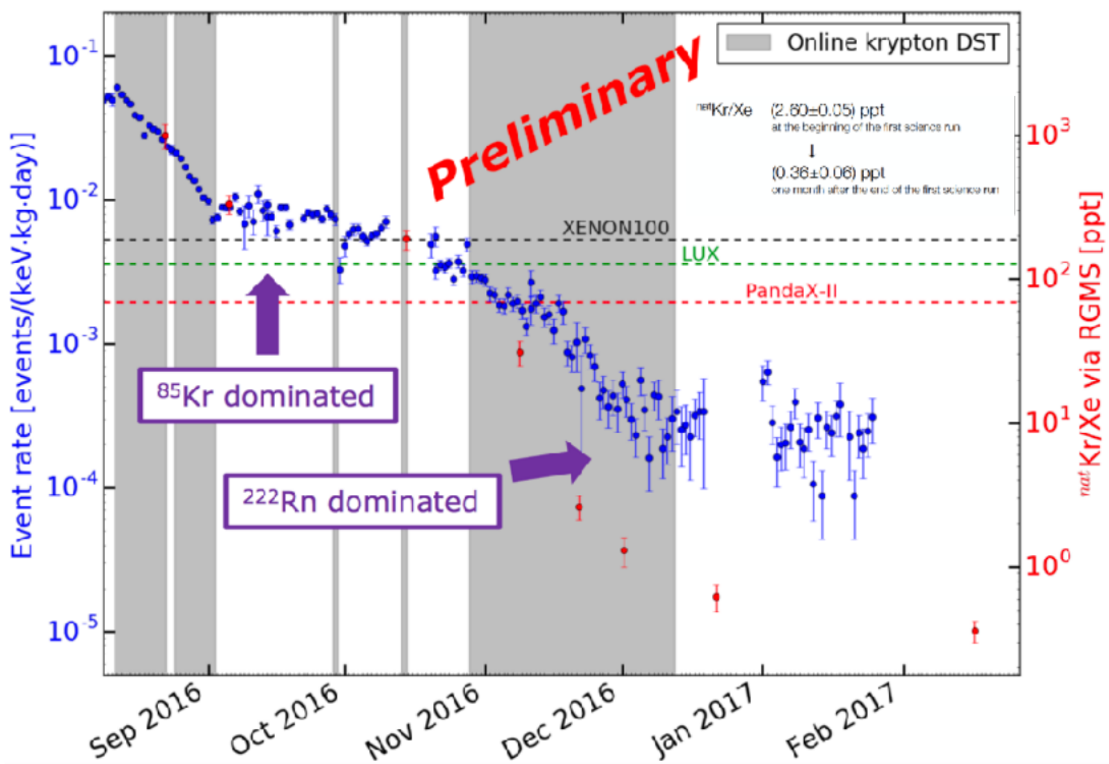


Guillaume Bonnet, Stage M1

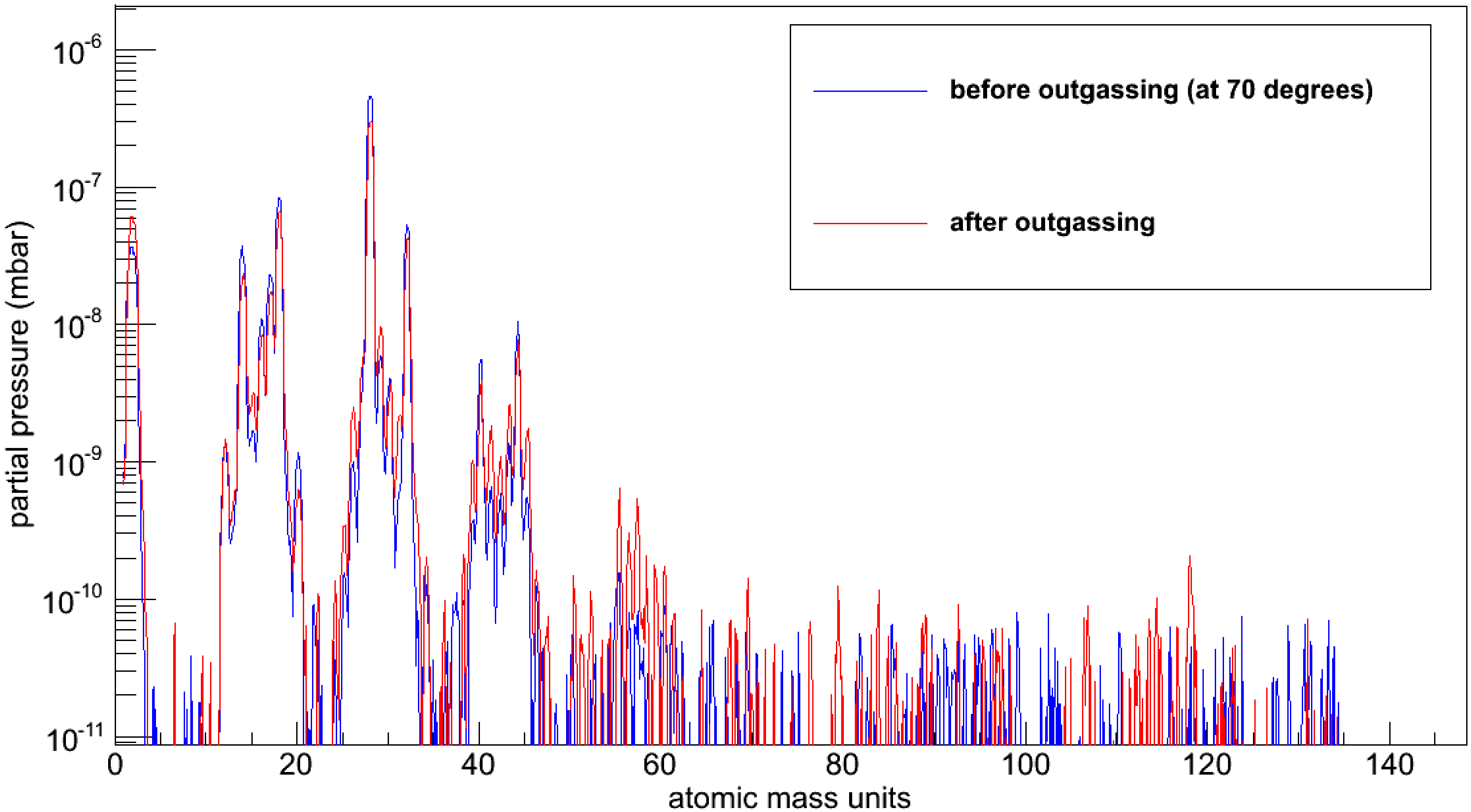
Krypton reduction



Eur. Phys. J. C77 (2017) no.5, 275, arXiv:1702.06942



RGA measurements



RGA measurements : zoom