Purification & Storage

Neutrinoless double beta decay search in Xe - next-generation experiment workshop

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Hypothesis

0vbb Goal is 10^{28} Years

2 options considered here:

- **90% 136-xenon enriched**
- **nEXO**-like experiment
  - 5t
  - 1,3 m ⌀ x 1,3m h

- SNOLAB
  - Active mine
  - Access constrained (vertical shaft)
  - Lab is a clean room
  - *3,000m²*

- **Natural xenon (8,9% in 136)**
- **XLZD**-like experiment
  - 100 t
  - 3,5 m ⌀ x 3,5 m h

- LNGS
  - Easy access (trucks can drive in)
  - Dedicated to underground science
  - *18,000m²*

Electronegativity impurity in LXe

- H_2O: resides on metal surfaces
  - Light attenuation at scintillation wavelength
  - Uniform reduction of S1 signal

- O_2: resides within porous material such as PTFE
  - High electron attenuation; capturing drift electrons
  - Depth dependent loss of S2 signal
  - Quantified by **electron drift lifetime**:

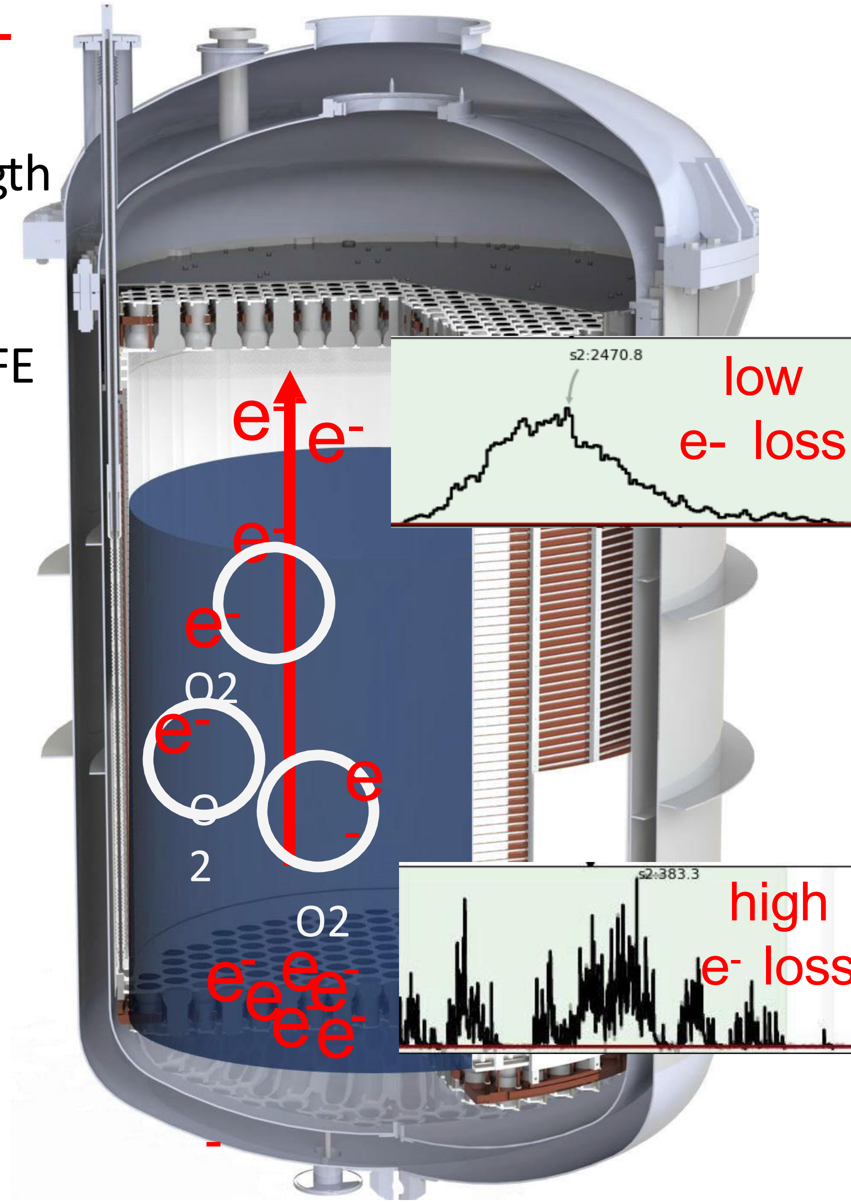
$$\tau_e = \frac{1}{k_{O_2} C_{O_2}}$$

C_{O_2}: O_2 concentration, k_{O_2}: rate constant

  - Number of S2 electrons N_e lost at drift time t:

$$N_e(t) = N_e(0).\, e^{-\frac{t}{\tau_e}}$$

- Impact on Energy resolution, S2-only analysis,…



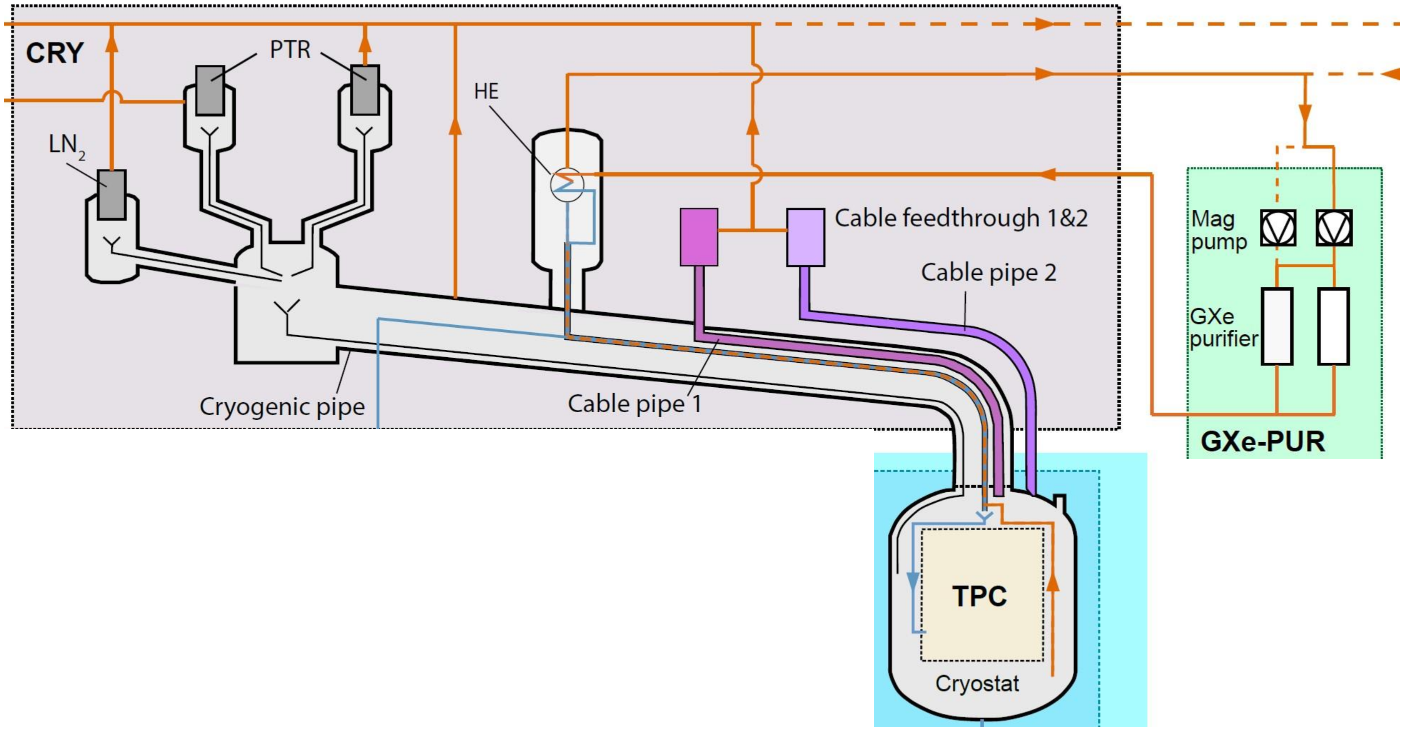
XENON1T/nT Gas Purification

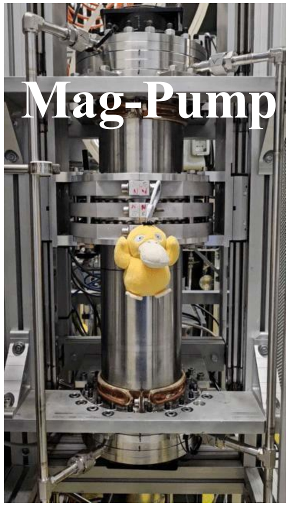
x_∞: impurity at equilibrium
Λ: total impurity source inflow
$\boldsymbol{\tau_p}$: flow turnaround time from TPC
ε: purifier efficiency
n: total LXe

- General purification performance equation:

$$x_\infty = \frac{\Lambda \tau_p}{n\varepsilon}$$

- Hot getter purifiers (zirconium)
- Magnetic GXe pumps (mag-pumps): 22-36 kg/h ~ 60-100 slpm

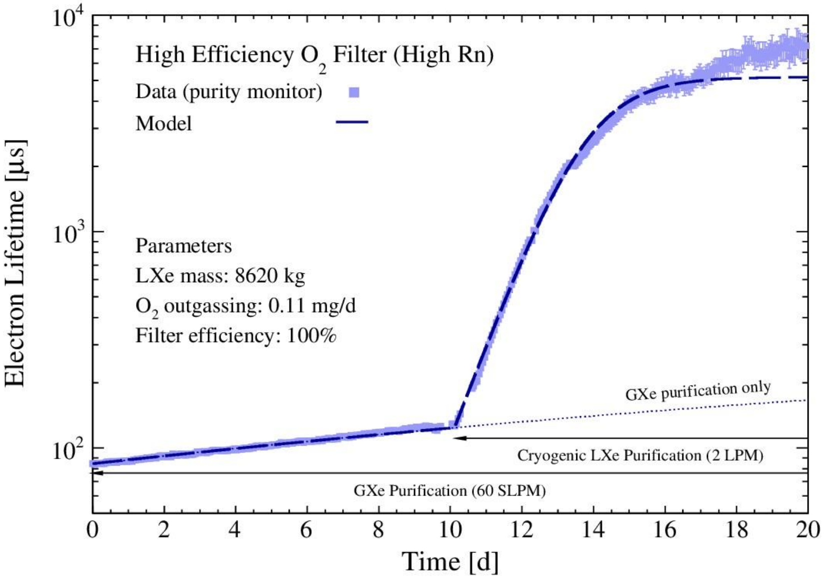




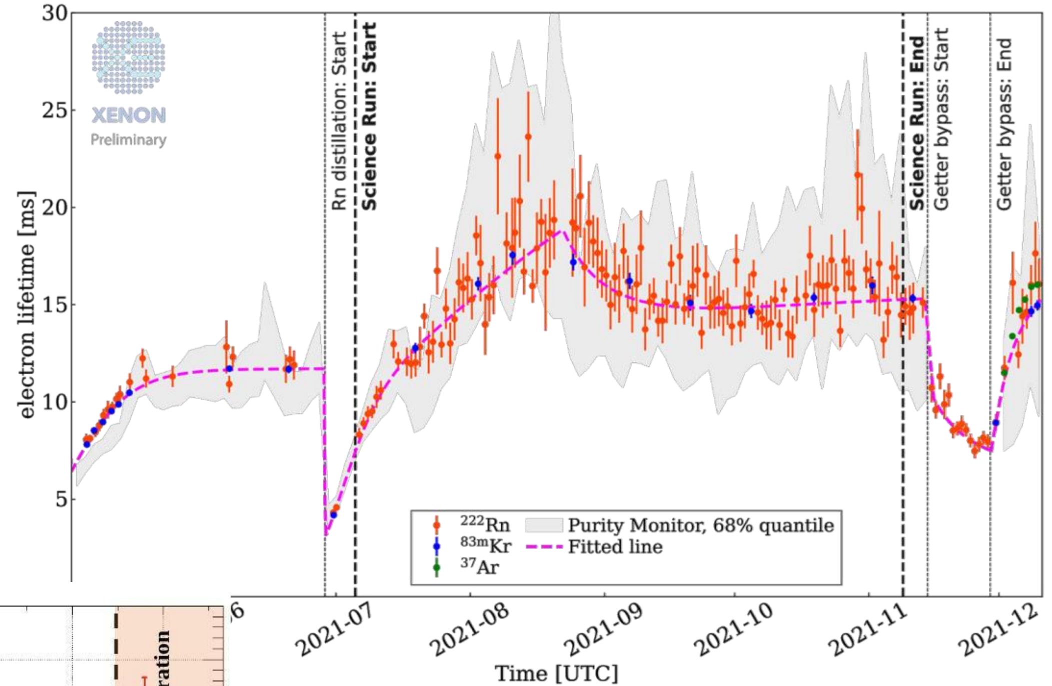
XENONnT Liquid Purification

- Magnetically coupled cryogenic rotor pumps: 180-720 kg/h ~ 1-4 LPM *Barber-Nichols*
- Purifiers:
  - copper catalyst on high-surface-area alumina (Q5): *high ε, higher radon emanation*
  - pellets of non-evaporable getter alloy (St707): *lower ε, low radon emanation*

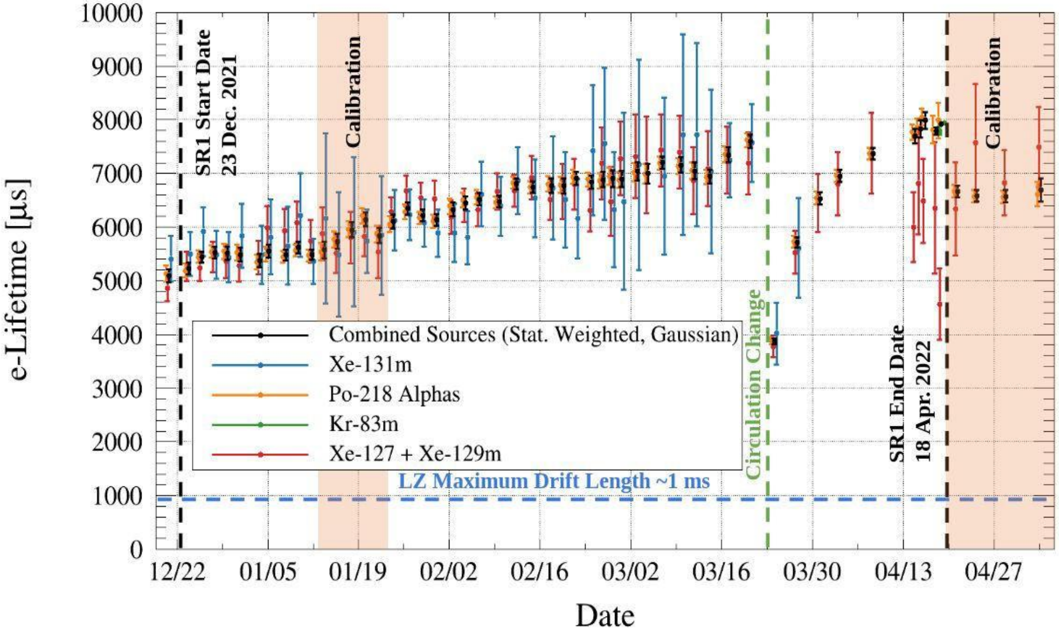
More LXe outside Water Tank
➔ Need extra xenon
➔ Possible 137Xe activation



Purification



LZ >7 ms (gas)



XENONnT ~15ms (liquid)
(650μs gas, XENON1T)

Storage approaches

- Usually expressed as the last thing to think about
- "Easy since we have efficient bottles"
- nat-Xenon or enr-Xenon is similar
- No Loss

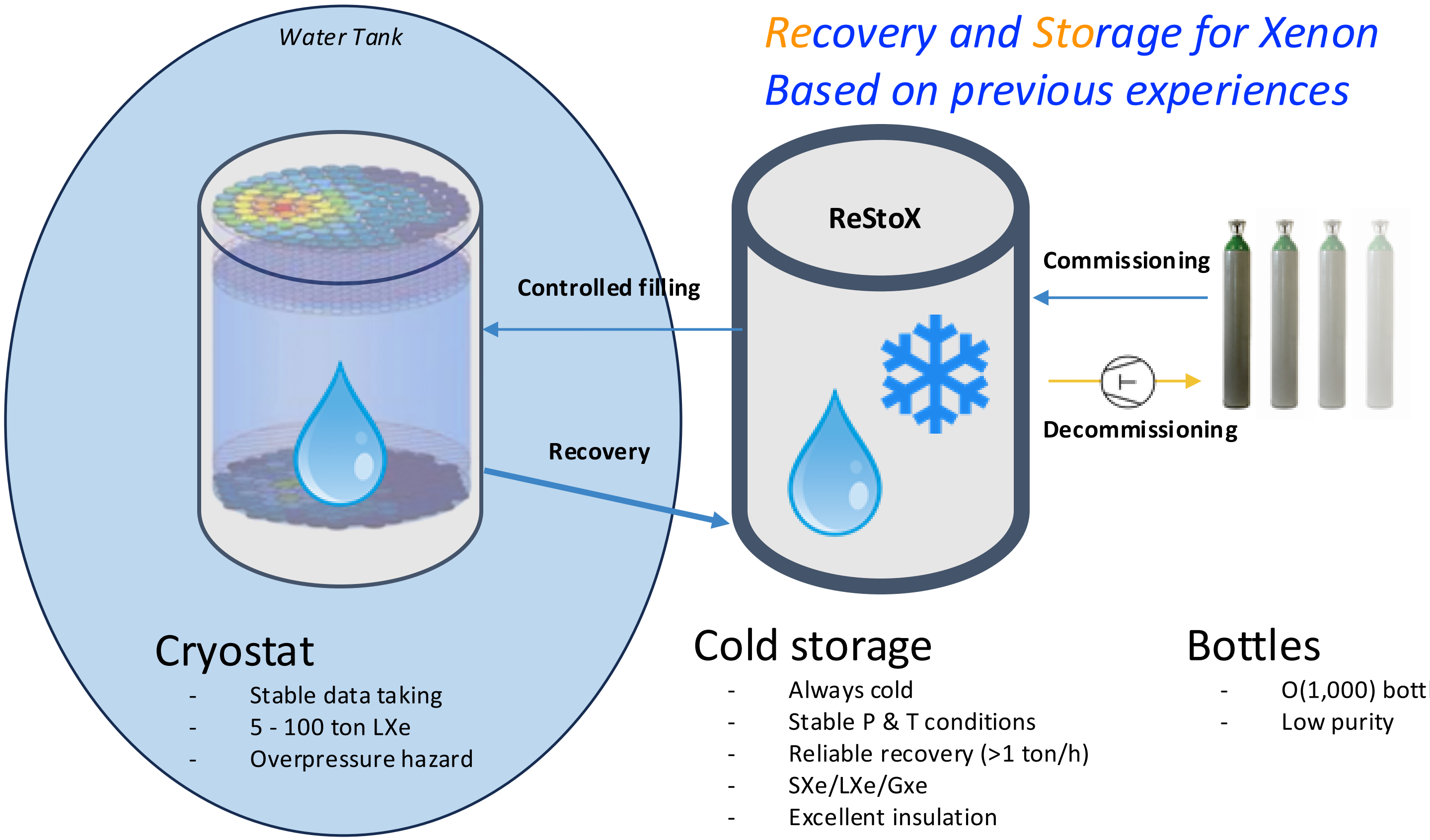
- Standard bottles are not meant to cryopump LXe with LN2
- 5 t of LXe = 100 x (50 kg bottles) !
    - 100 connections !
    - 13 m^2 with 8 bottles / m^2
- 100 t = 2 000 bottles !
    - 2 000 connections !
    - 250 m^2 with 8 bottles / m^2

Transfer from / to storage

Key functionalities	Operating Modes
A) Initial storage	1) Empty / Warm / Under Vacuum 2) Ready to receive Xe from bottles *before or after pre-purification* 3) During the construction of the detector, safely store and manage Xe. 4) Continuous purification through getters
B) Filling the detector	5) Distribution & Pre-cooling the TPC 6) Filling Xe into the detector
C) Level adjustment & Distribution	7) Easy transfer to the experiment 8) Distribution for other subsystem too
D) Recovery	9) Standby : always cold (LN2 T°) for recovery (cryo-pumping) 10) Recovery from detector (voluntary or emergency-triggered)

A new concept of storage : ReStoX

Recovery and Storage for Xenon
Based on previous experiences



Cryostat
- Stable data taking
- 5 - 100 ton LXe
- Overpressure hazard

Cold storage
- Always cold
- Stable P & T conditions
- Reliable recovery (>1 ton/h)
- SXe/LXe/Gxe
- Excellent insulation

Bottles
- O(1,000) bottles
- Low purity

- Storage in GXe / LXe / SXe
- High level of purity
- Storage in case of cooling power loss

- Available all time for the experiment (& sub-systems)
  - Construction / Commissioning / Data taking / Maintenance / Decommissioning
  - Cleanliness / Security / Storage & Recovery

ReStoX - Previous experiences

Knowledge of handling large LXe quantity (10t)
Since 2014

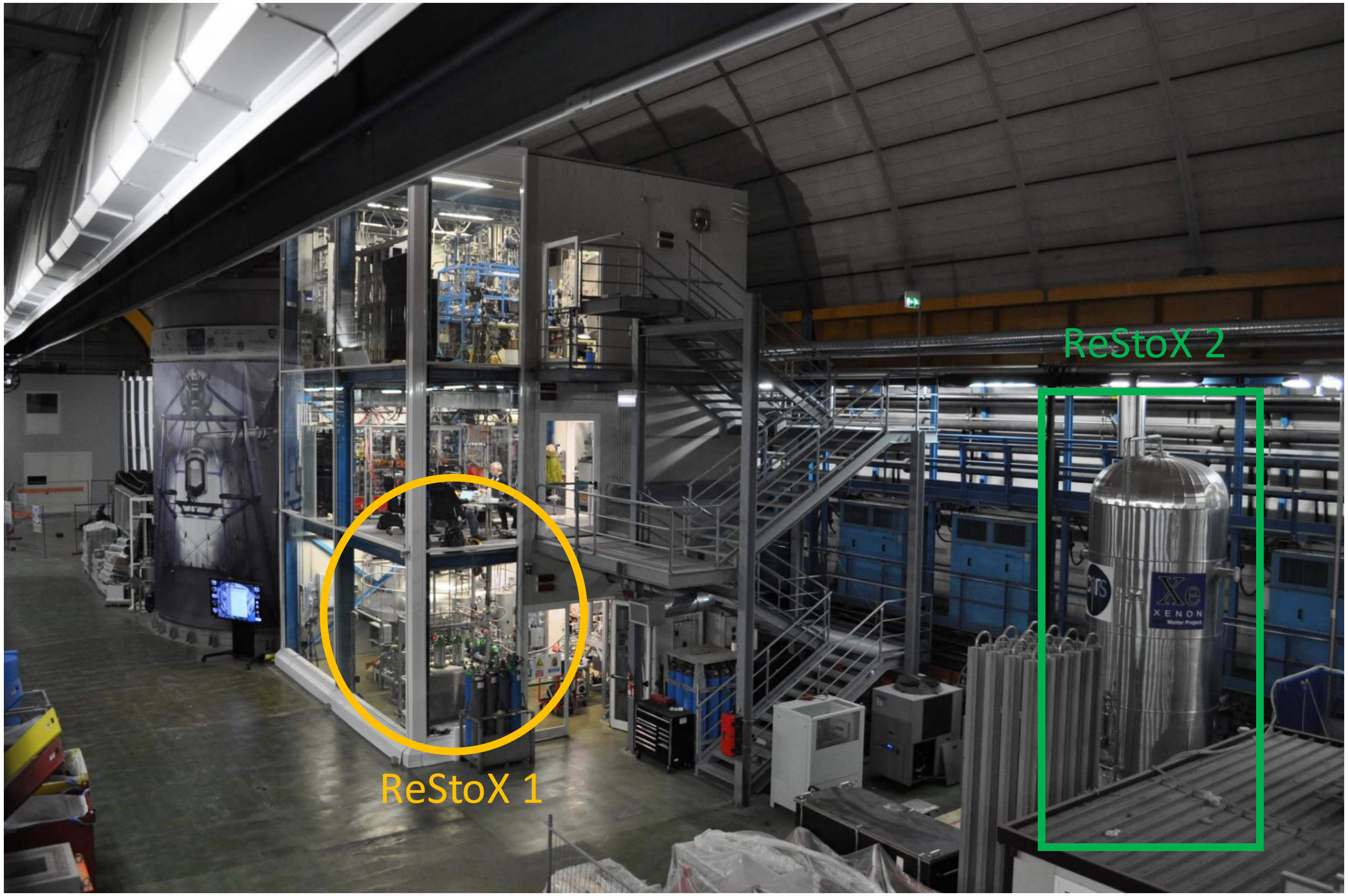
ReStoX are LXe recovering, storage and distribution stations, High Pressure, Safebox

- **ReStoX1 in XENON1T (& XENONnT) – 7,6 t LXe**
  - Columbia University – New York (USA)
  - Mainz University (Germany)
  - Subatech (France)
- **ReStoX2 in XENONnT - 10 t LXe**
  - LAL (France)
  - LPNHE (France)
  - Subatech (France)
- **(nEXO - 5 t LXe-136)**
  - Subatech (France)
- **(XLZD - 100 t LXe-136)**
  - Subatech (France)
- **ReStoX in XEMIS - 200 kg LXe**
  - Air Liquide (France)
  - Subatech (France)

XEMIS

 10

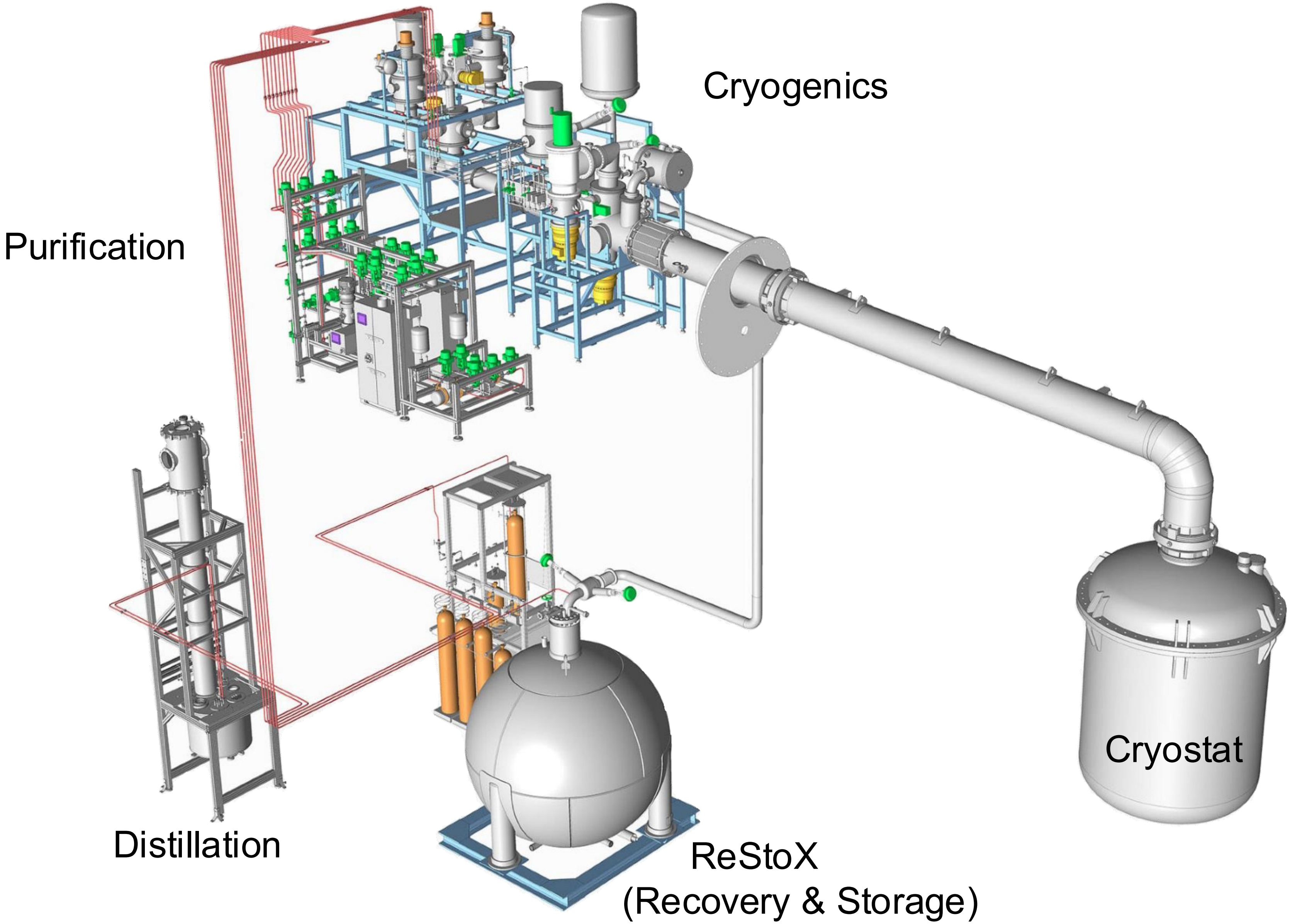
XENONnT facility



ReStoX1: Emergency recovery up to 7.6 tons of LXe
Passive: No active cooling required to keep Xe contained

ReStoX2: Very fast recovery > 1t/h up to 10t.
Passive: No active cooling required to keep Xe contained

XENON1T Plant



ReStoX 1 & 2 - comparison

Table 3.4: Comparison between ReStoX and ReStoX2.

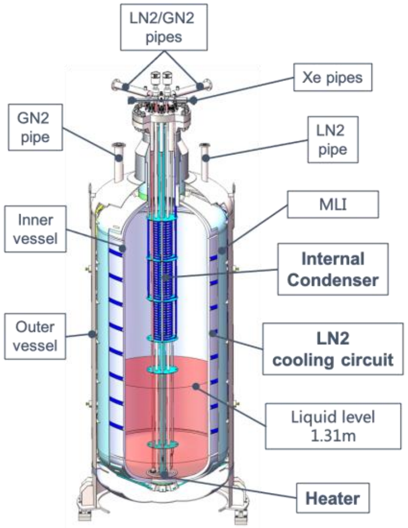
Description	ReStoX	ReStoX2
Dimension	2.1 m ⊘ sphere	(1.45 m, 5.5 m) cylinder
Phase	GXe, LXe, SXe	GXe, LXe, SXe
Maximum pressure	73 bar	71.5 bar
Capacity	7.6 t	10 t
Recovery speed	$\sim$ 50 kg/h	$\sim$ 1000 kg/h
LN_2 consumption in operation	35 kg/d	0 kg/d
LN_2 consumption for recovery	25 kg/h	$\sim$ 8000 kg

FIRST-X in PandaX

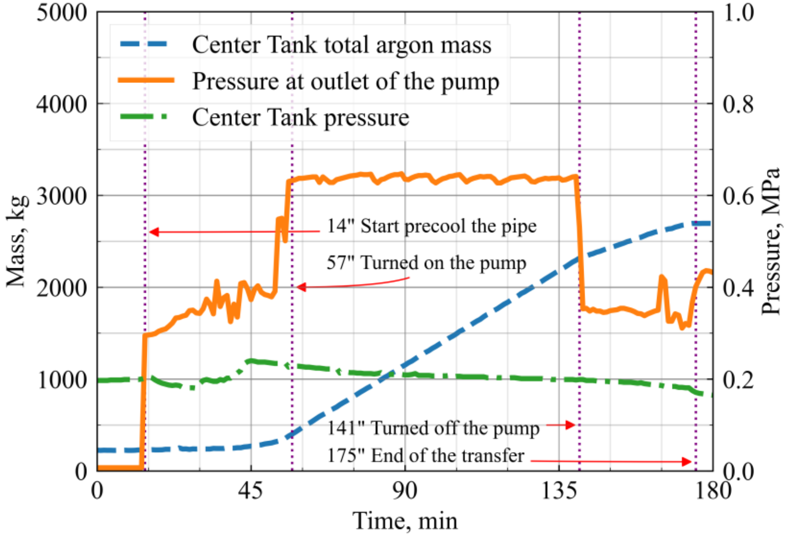
Filling, Recovery, and Storage of Xenon

JINST 18 P05028 - arXiv:2301.06044

5x (6 t)



1390 kg/h LAr = 2140 kg/h LXe



Comparison between ReStoX & cylinders

Feature	ReStoX	Bottles
Connections	Few	Many
Cleaning	Limited	Extensive
Xe weight measurment	Easy & All time	Problematic
Monitoring P & T	All time	partially
Control P & T	Condenser & heater	partially
Footprint underground	Limited	~ 6,000 bottles
LN2 consumption for recuperation	Very efficient = already cold with excellent insulation	High loss
N2 boil off	Dedicated tube	In the cavern
0_2 alams	None	Many (maybe)
Purification during storage	Easy	Feasible
Power failure	Pneumatic logic & Slow control	Pneumatic logic possible
Welding failure	Dramatic	Problematic

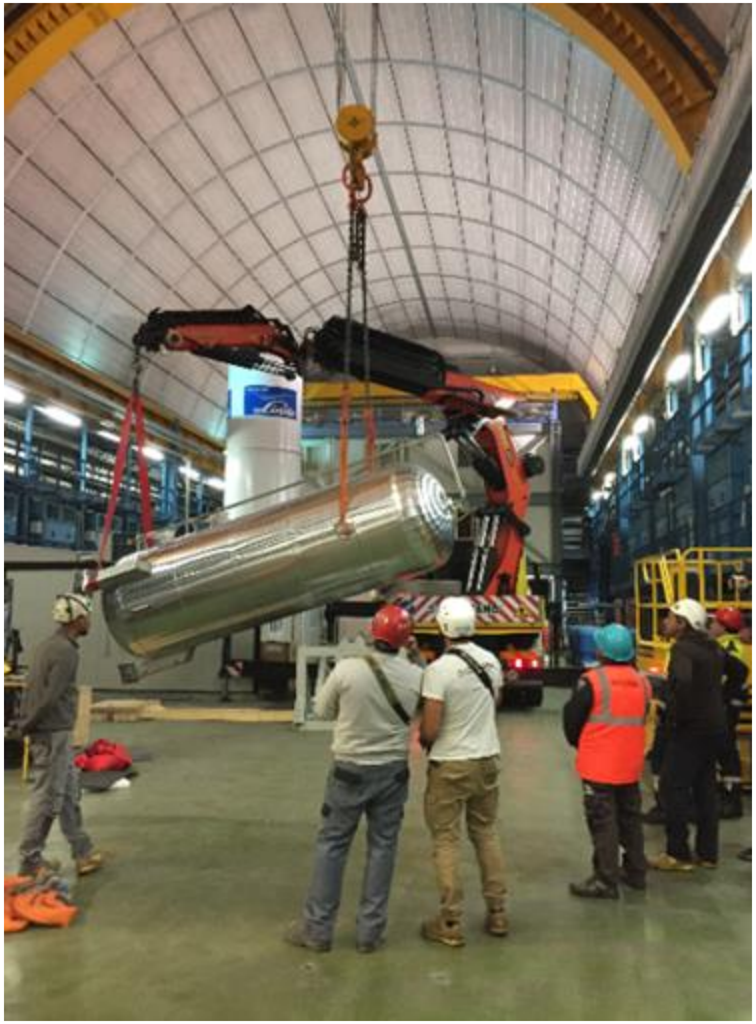
What about 5 - 100 t ?

Where : LNGS-like or SNOLAB-like laboratory?

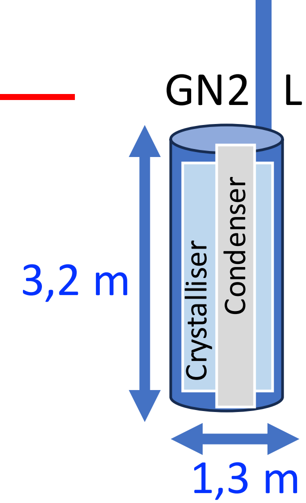
- Trucks can access to LNGS
- Elevator is the only access to SNOLAB
  size ~ 3.2m x 1.3m

- Design has to optimize a variety of factors :
  - Size
  - Cleanliness
  - Ease of use
  - Price
  - …

ReStoX 2 Delivery @ LNGS



What about 5 t @SNOLAB ?



Option 1

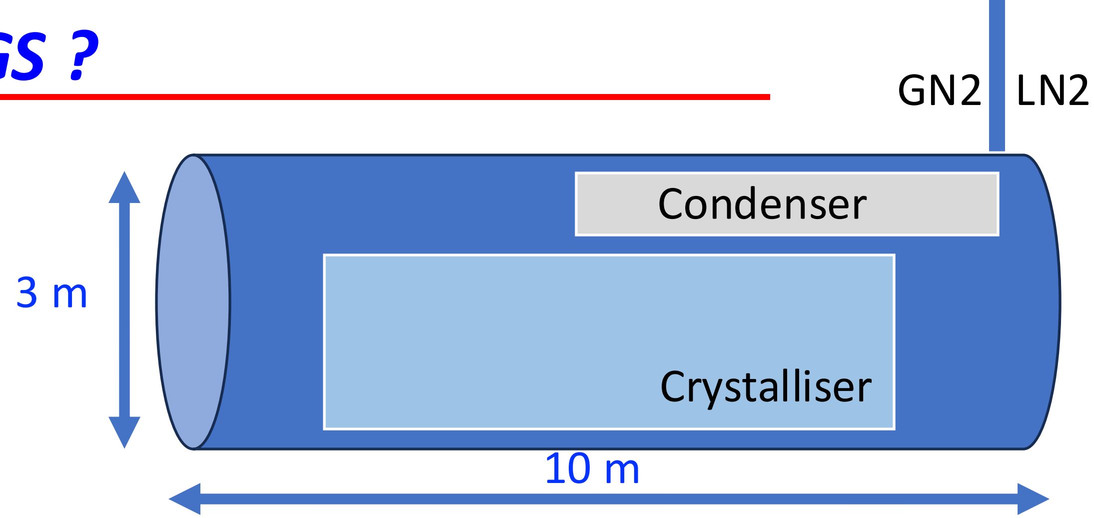
ReStoX Drawn for 5t (nEXO-like)

- Transportable through the shaft to go underground ➔ 2,5 t
- Electropolished with highest standard
- Pressure tested before delivery

Connect 2 Vessels 2x (2,5t ReStoX)

Underground footprint < 5 m^2

What about 100t @LNGS ?



Option 2

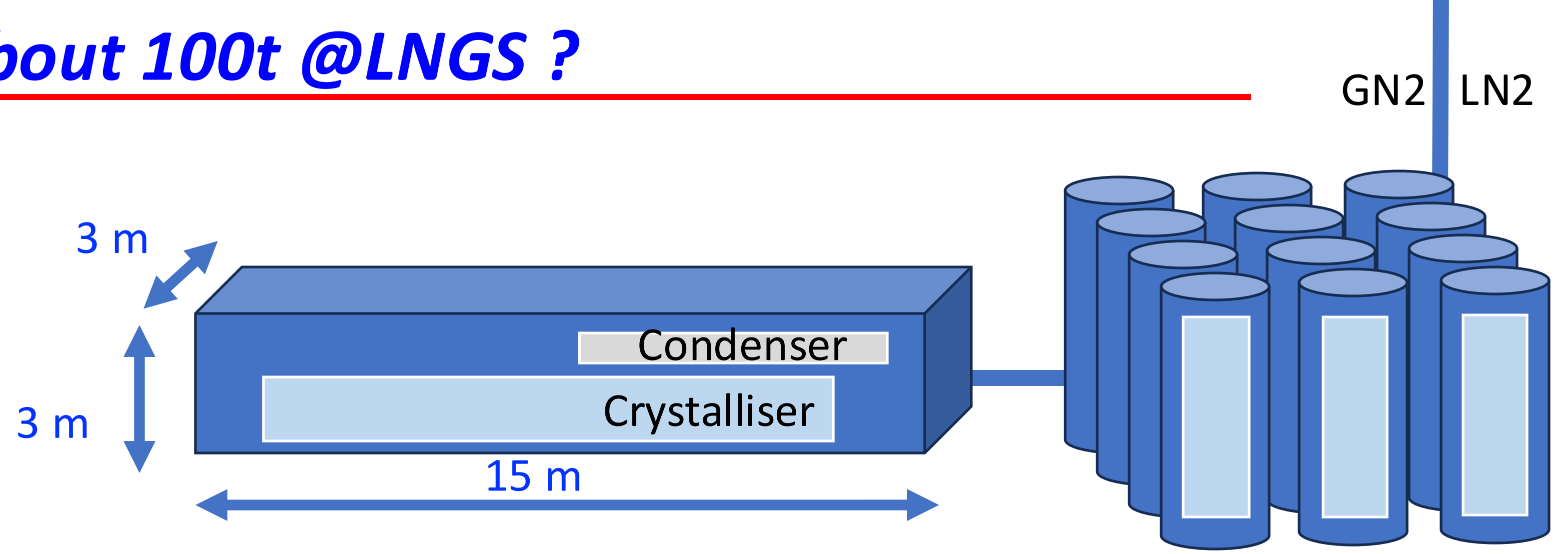
ReStoX Drawn for 50t (DARWIN-like)

- Transportable on a truck to go underground
- Electropolished with highest standard
- Pressure tested before delivery

Can imagine 2x (50t ReStoX) for XLZD

Underground footprint < 100 m²

What about 100t @LNGS ?



Option 3

1 ReStoX for standard operation – low pressure (10 bars)

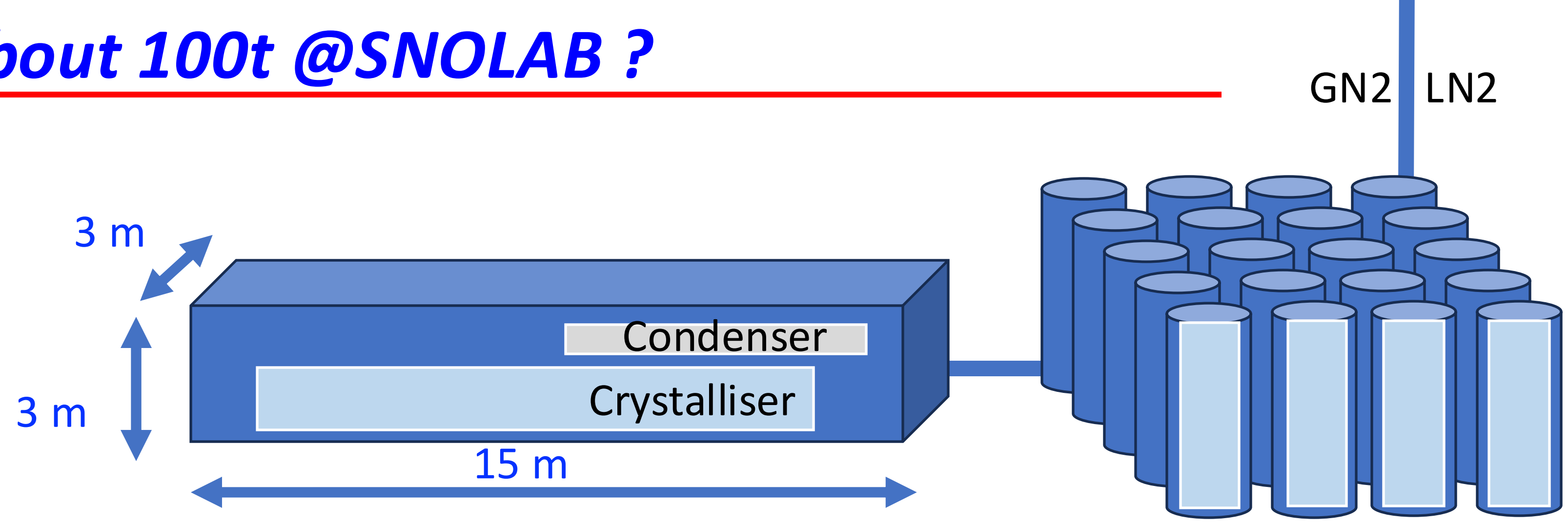
(4m x 4m x 20m already used for LAr)

Can be transported or built underground
High purity standard garantied

+ 10 x 10t ReStoX2 for emergency & long term storage

Underground footprint ~ 100 m^2

What about 100t @SNOLAB ?



Option 4

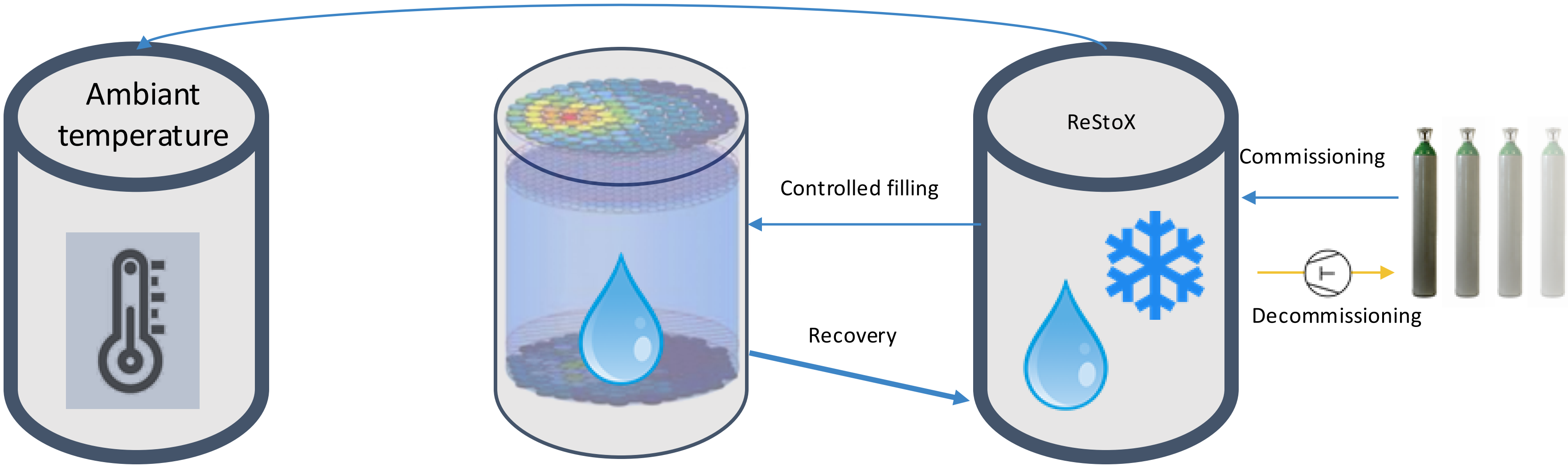
1 ReStoX for standard operation – low pressure (10 bars)

Can be transported or built underground
High purity standard garantied

+ 40 x 2,5t ReStoX for emergency & long term storage

Underground footprint ~ 100 m^2

Summary



Extra storage
- Extra volume

Cryostat
- Stable data taking
- 5 – 100 tons LXe
- Overpressure hazard

Cold storage
- Always cold
- Stable P & T conditions
- Reliable recovery (>>1 ton/h)
- SXe/LXe/Gxe
- Excellent insulation

Bottles
- O(1000) bottles
- Low purity

- Cryopumping transfer
- Safe-box for the (enr)-Xe in any conditions.
- Key Component of the Xe handling system
- Dynamic / active / flexible part of the system.
- LN2 cooling with permanent access.

- Mature design already tested on installations.
- In use in the XENON1T/nT since 2014 no loss nor major issue to be reported.
- Answer to all storage and distribution issues.
- Gravitational recovery possible

Features of bottle's storage

Feature	Bottles
Connections	Many
Cleaning	Extensive
Xe weight measurment	Problematic
Monitoring P & T	partially
Control P & T	partially
Footprint underground	~ 1,000 bottles
LN2 consumption for recuperation	High loss
N2 boil off	In the cavern
0_2 alams	Many (maybe)
Purification during storage	Feasible
Power failure	Pneumatic logic possible
Welding failure	Problematic

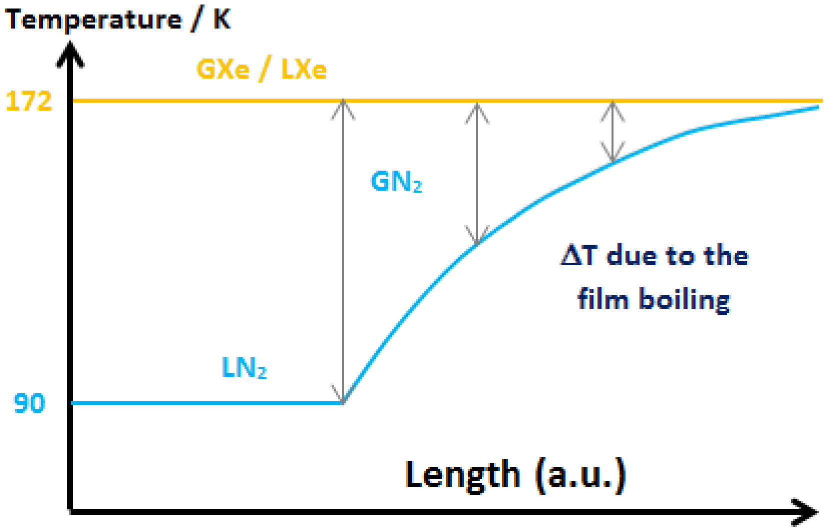
XEMIS project

- XEnon Medical Imaging System (XEMIS)
  - Hospital facility for low activity small animal imaging

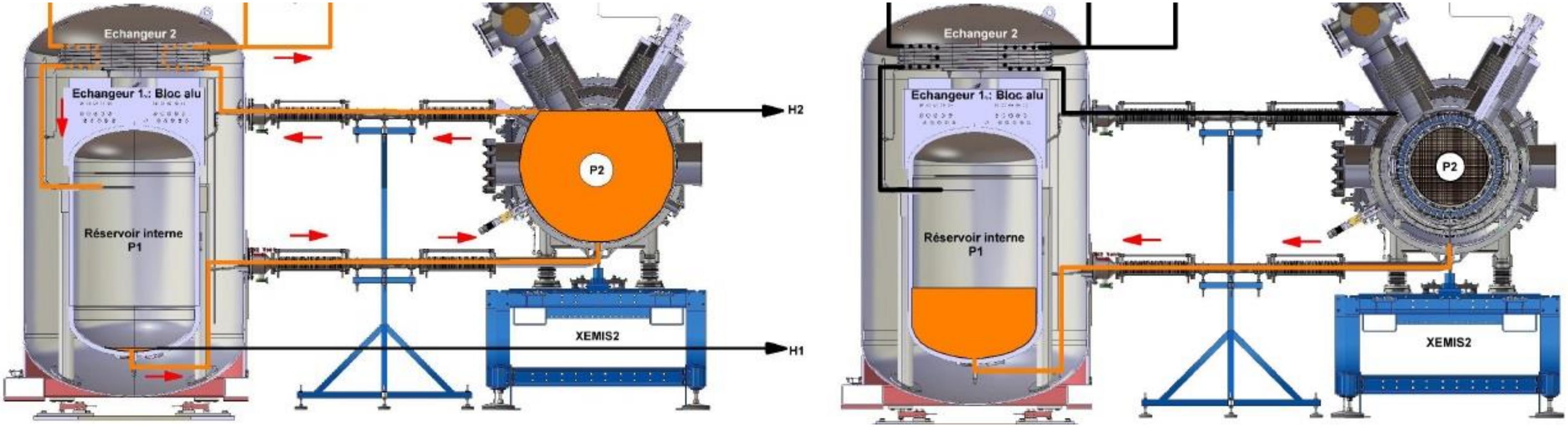
- Compact set with 3 components
  - Closed loop with 200 kg of Xenon

ReStoX for XEMIS

- ❑ Double walled vacuum & perlite insulated shell
- ❑ Internal capacity of 280 L for storing 200 kg of Xe up to 71 bar a in any condition
- ❑ Two exchangers (E001 and E002)
  - ❑ E001 (LN_2/Xe): from 0,1 kW to 11 kW
  - ❑ E002 (Xe/Xe): interface hot and cold parts, up to 250 W

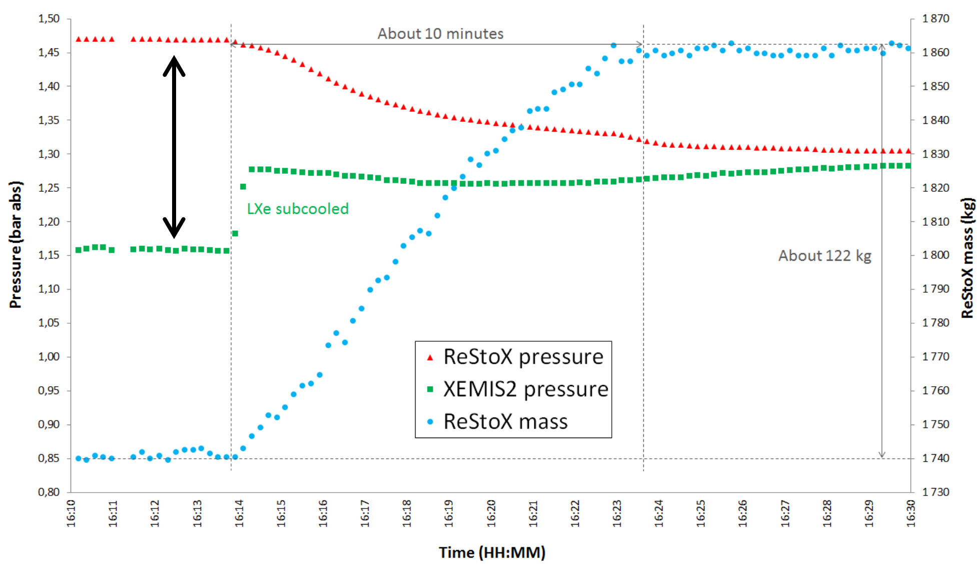


Gravitational recovery



BEFORE AFTER

L. Virone et al., Nucl. Instrum. Meth. Volume 893, (2018)



Equivalent to 732 kg/h