JAGIELLONIAN UNIVERSITY IN KRAKÓW

Filling of the LEGEND cryostat

as an opportunity for

liquid argon optical properties study.

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for the LEGEND LAr purification team

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Plan

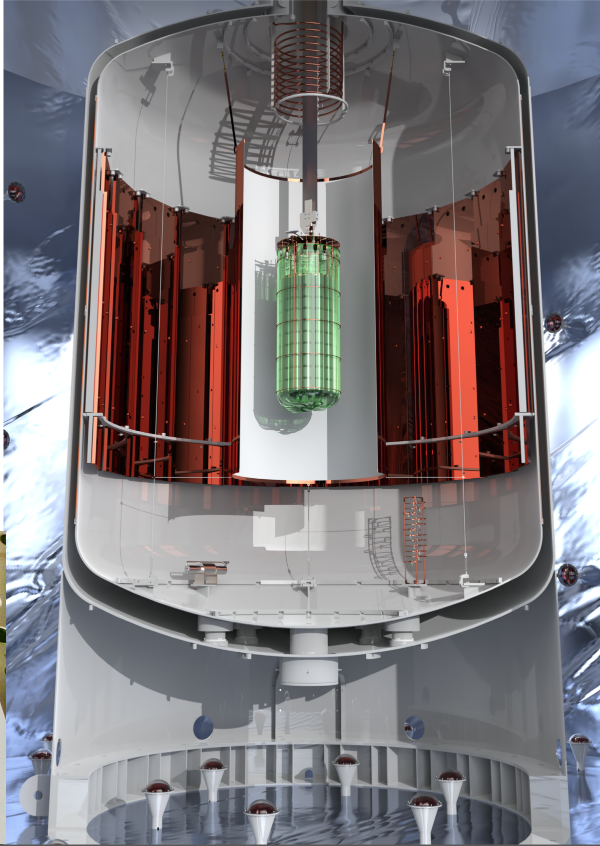
- LEGEND-200 in LNGS - LAr instrumentation
- Purification system design - LLArS
- Filling and purifying
- Nitrogen contamination - optical properties analysis

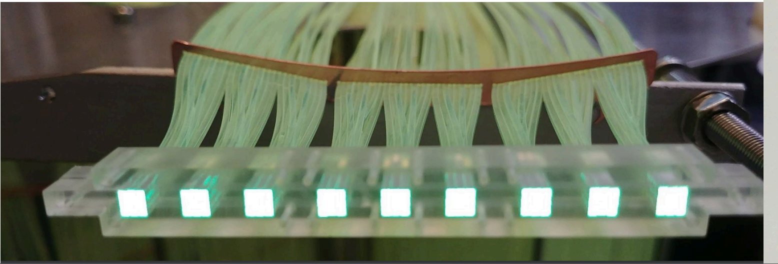
LEGEND - Quasi-background-free search for $0\nu\beta\beta$ decay in ^{76}Ge

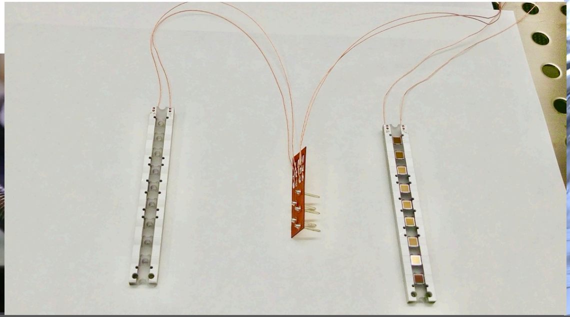
LEGEND-200 in LNGS (Italy):

90 tons ($65 m^3$) of LAr serve as a cooling medium for the germanium detectors and as an instrumented shielding.

Liquid Argon detector system is composed of low-background wavelength shifting light guiding fibres connected to SiPMs detecting scintillation light of argon.



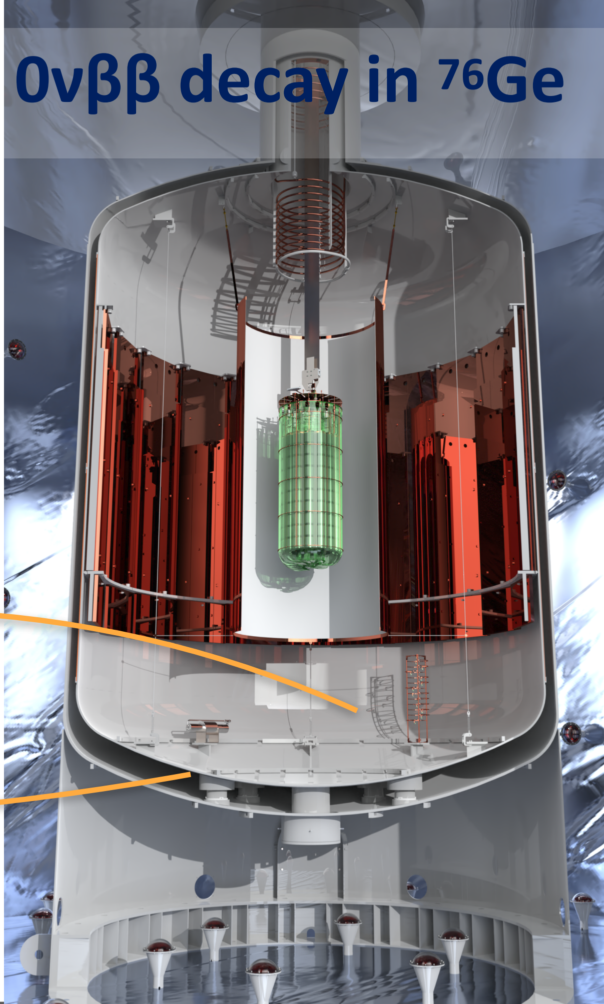




LEGEND - Quasi-background-free search for 0νββ decay in ^{76}Ge

LEGEND-200 in LNGS (Italy):

https://legend-exp.org/

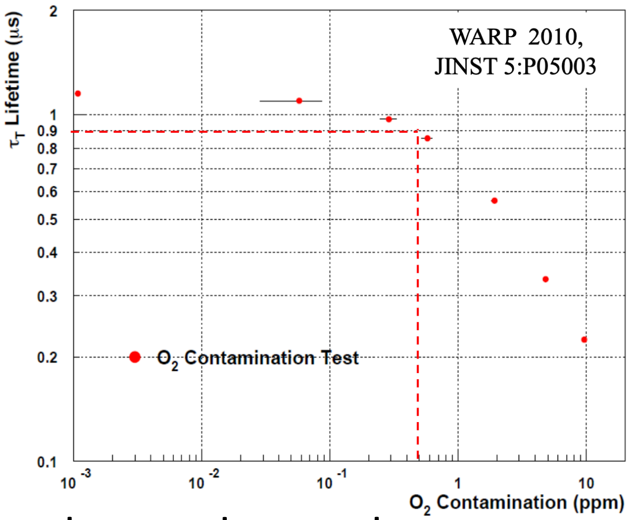


Legend LAr Purification System (LLArS) - motivation

Efficient LAr veto requires very pure LAr (LY, att. length, τ_{trip} ~ 1.3 μs).

What does „very pure argon" mean?

Specifica	4.8	5.0	5.3	5.5	5.6	6.0
Titolo Argon (Ar) % vol.:	>99,998	>99,999	>99,9993	>99,9995	>99,9996	>99,9999
Azoto (N_2):	<10	<5	<3	<1,5	<1	<0,5
Acqua (H_2O):	<5	<3	<2	<1	<1	<0,5
Ossigeno (O_2):	<3	<2	<1	<1	<0,7	<0,5
Idrocarburi (C_nH_m):	<0,5	<0,2	<0,1	<1	<0,1	<0,1
Ossido di carbonio(CO):					<0,1	<0,1
Anidride carbonica (CO_2):					<0,1	<0,1



Even best commercially available LAr quality (6.0) may not be good enough.

⇒ Purification is needed !

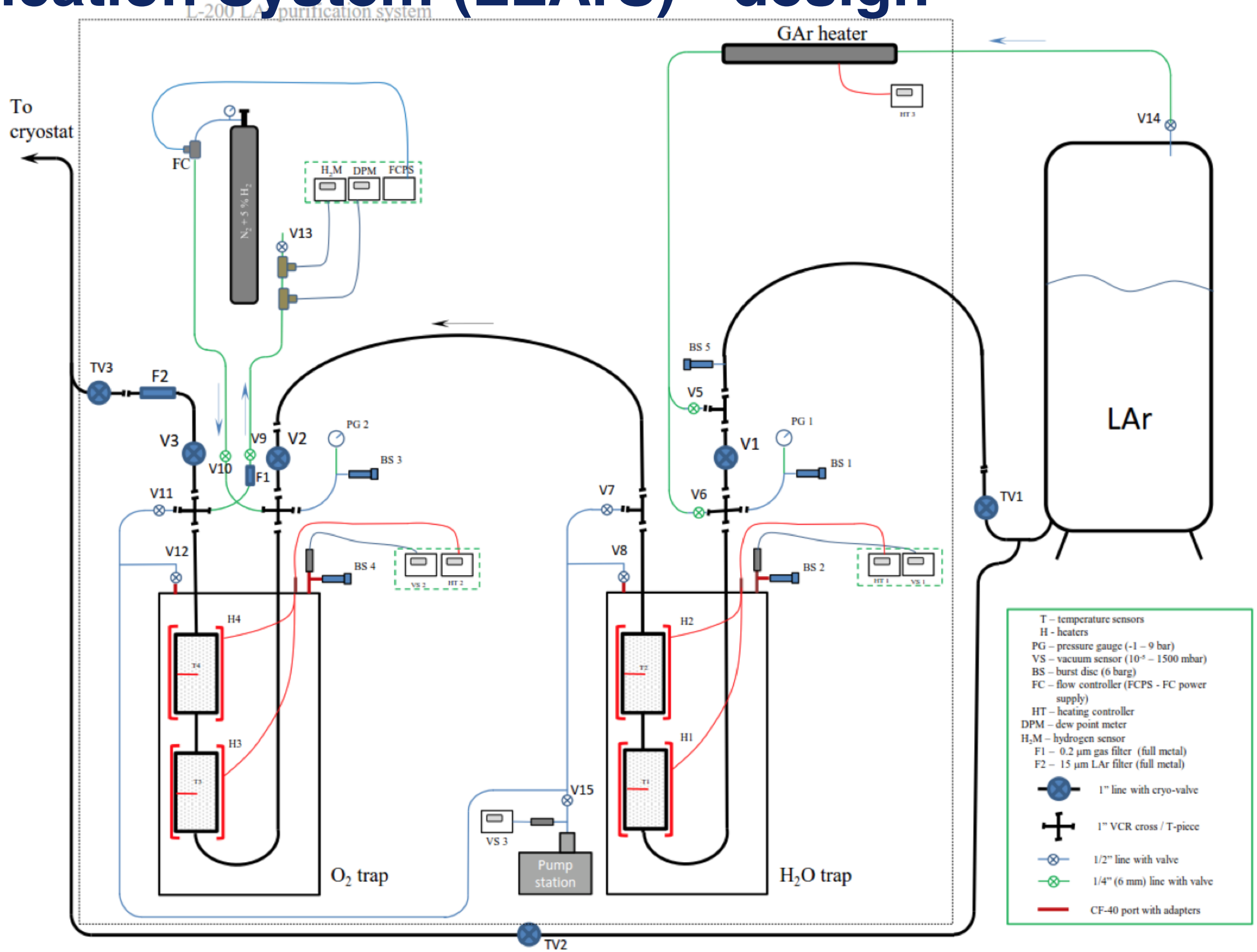
Legend LAr Purification System (LLArS) - requirements

- Purification in the liquid phase (~ 91 tons of LAr to be filled into the LEGEND cryostat)
- System optimized for removal of **oxygen** and **water**
- **Initial** concentrations of contaminants $\leq$ **1 ppm**
  defined LAr purity with the vendor 'L-200 quality' was as: O_2, N_2, H_2O $\leq$ 1 ppm (confirmed by a certificate)
- Purification of min. 8 tons of LAr **in one go** (capacity of the LAr storage tank in LNGS)
- Continuous purification during filling of the cryostat:
  LLArS placed **between** the **storage tank** and the LEGEND-200 **cryostat**
- **LAr quality monitored** during filling (LLAMA inside the cryostat)

Legend LAr Purification System (LLArS) - design

1. trap: oxygen removal:
   10 kg of Cu-0226 S
   Regeneration using heat and H_2

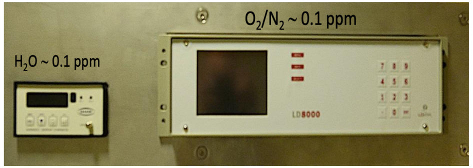
2. trap: water and nitrogen removal
   8 kg of molecular sieve MS 4 A
   Regeneration by heating



Legend LAr Purification System (LLArS) - monitoring

Gas Analyzer :

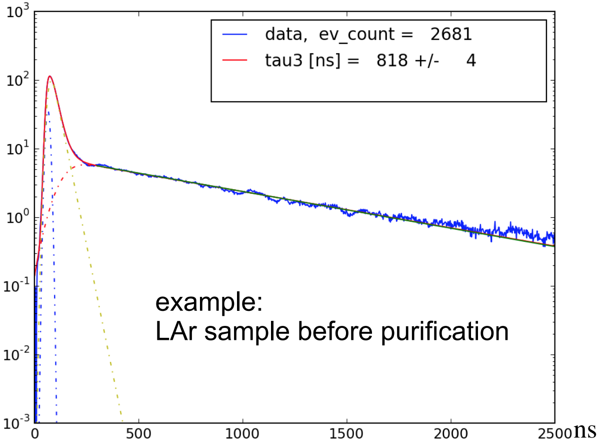
H_2O, N_2, O_2 at 0.1 ppm level - continuous monitoring



Scintillation Analyzer (SA):

LAr triplet lifetime measurement τ_{trip} - sampling after each regeneration of LLArS and during cooling phase of the filling (before LLAMA could be operational)

- 60L metal-sealed dewar, CF-160top flange
- LAr viewed by two 2” TPB-coated PMTs
- PMT's signal readout with linear amplifiers
- PMT's HV supply
- Temperature sensors – LAr level monitor
- DAQ unit (K. Pelczar):
  PC with 14 bit, 400MHz digitizer
- Pulse shape analysis determining long component τ_3



LLArS assembling and tests

- Small scale tests and system development at Jagiellonian Uni.

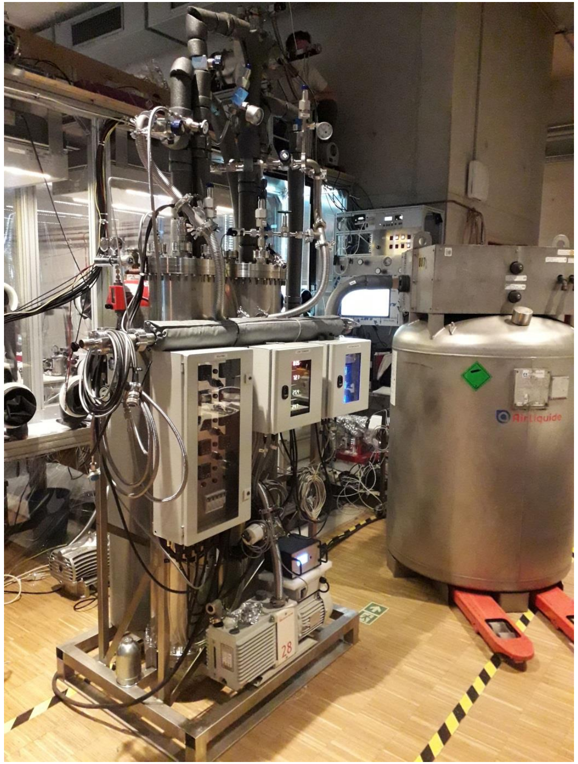
- Assembling full LLArS and precommissioning test at TU Munich using SCARF cryostat.

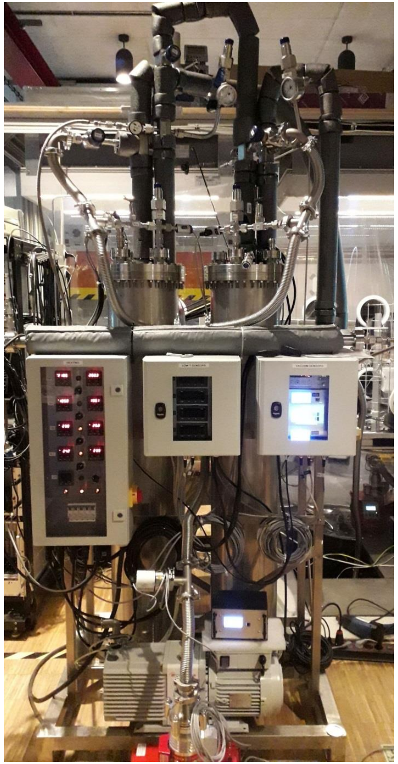
Before purification:

τ_{trip} = 0.65 μs (O_2 = 2.3; N_2 = 3.7; H_2O = 0.3 [ppm])

After purification:

τ_{trip} = (1.31 ± 0.04) μs



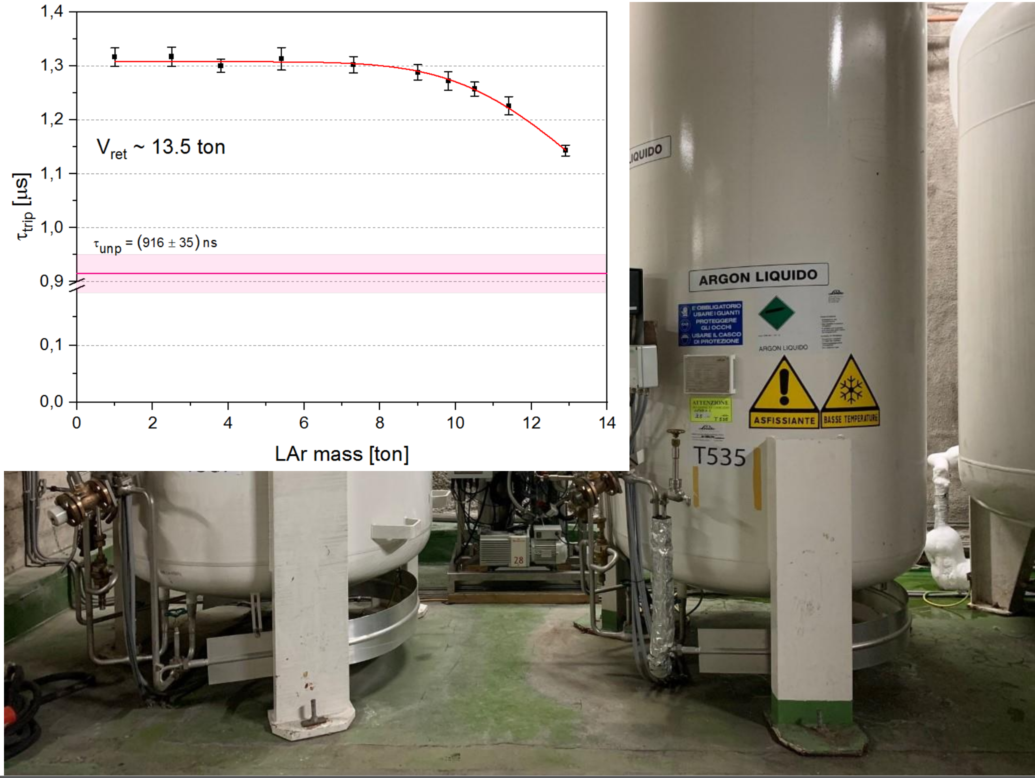


‘Filling and purifying’ operation

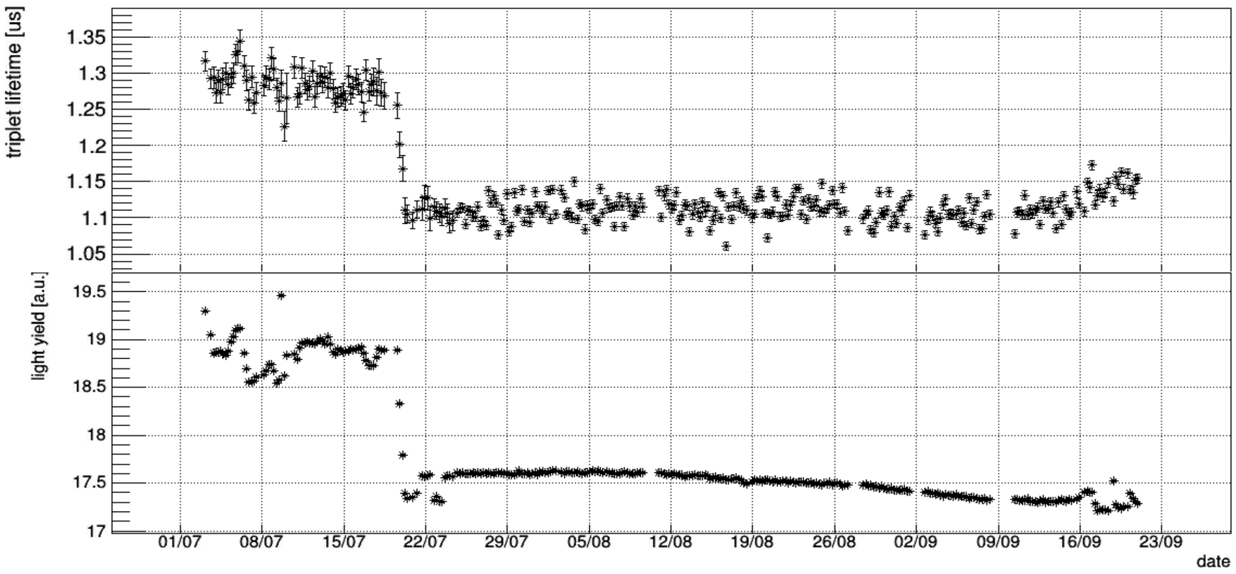
- LLArS to LNGS in March 2021,
- cryostat filling from Jun to Sep 2021.
  70% of the cryostat capacity filled in 4 weeks;
  topping up - 2 weeks

‘Filling and purifying’ operation

- LLArS to LNGS in March 2021,
- cryostat filling from Jun to **Sep 2021.**
  70% of the cryostat capacity filled in 4 weeks; topping up - 2 weeks
- cooling phase used to test the capacity of LLArS - sampling by SA - regeneration needed after ~10 t. (as designed)
- August 2021 - break for investigation of the accidental nitrogen doping.
- since October 2021 LEGEND-200 cryostat is fully filled with LAr and commissioning is ongoing.



LAr properties monitoring during filling - Use of LLAMA



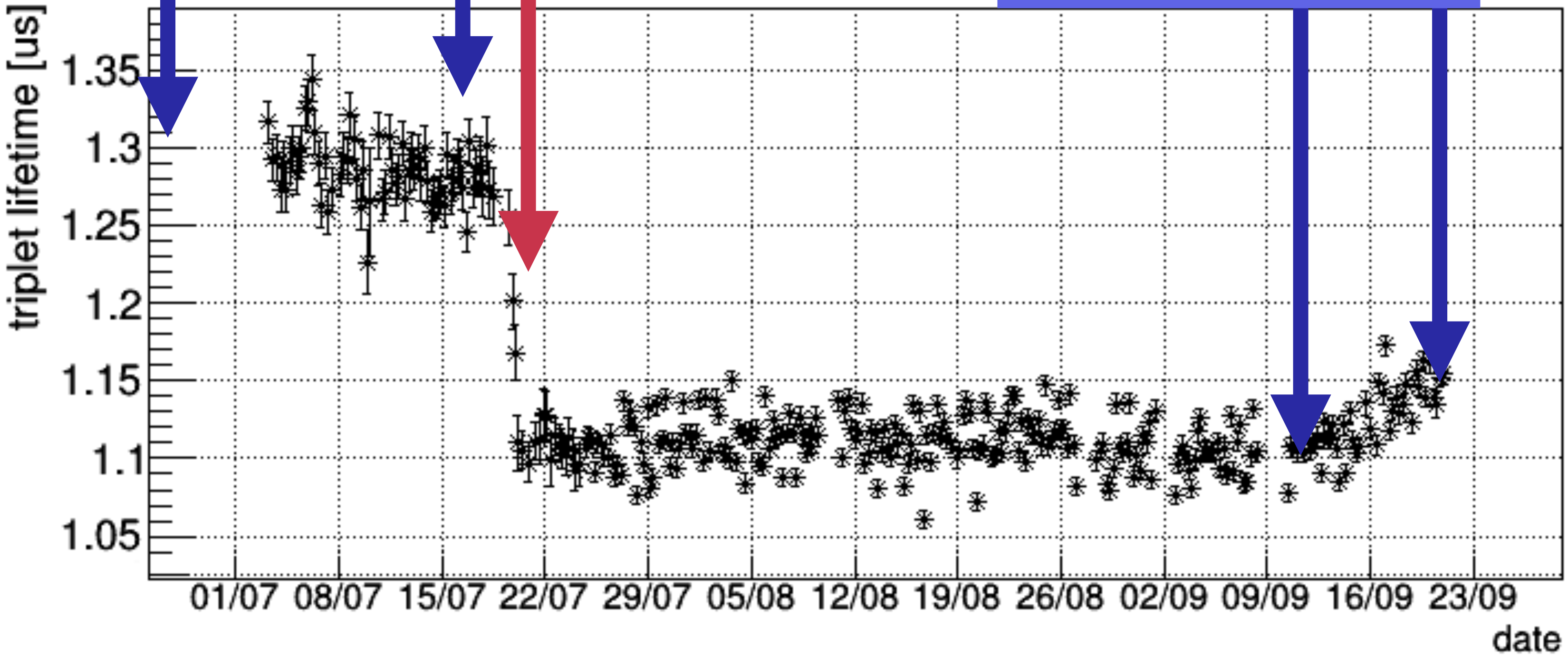
- **LLAMA**
  (LEGEND LAr Monitoring Apparatus),
  13 SiPMs at various distances to the triggered LAr scintillation light source, measuring LAr triplet lifetime, light yield and attenuation length.

Cooling
No LAr inside the cryostat - no data from LLAMA

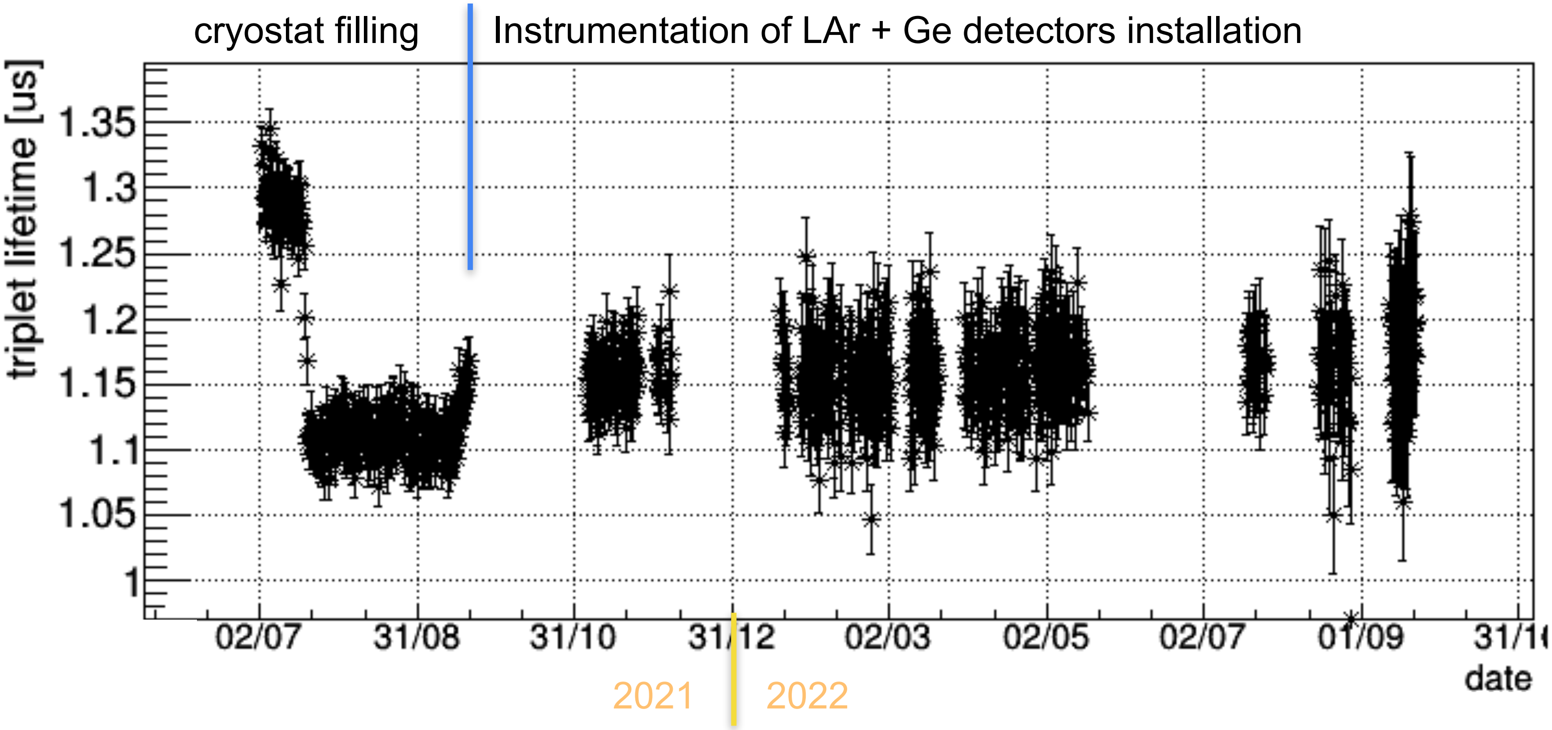
Filling and purifying
τ_3 **=1.29 µs;**
62 t of pure LAr inside.

N_2 contamination incident.
τ_3 **=1.10 µs**
LAr flow stopped;
Investigation and analysis,
68 t of LAr inside

Filling up
processing additional ~30 t of LAr; finally **90 t inside** the LEGEND-200 cryostat;
LAr light properties improve as expected: τ_3 **=1.15 µs;**



A year of LAr monitoring during the commissioning process



Accidental nitrogen doping:

62 000 kg of Purified LAr inside the cryostat (containing traces of inpurities)

6 100 kg of N_2 contaminated LAr added in course of 17 hours (containing nitrogen at 10 ppm level).

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62 000 kg of Purified LAr inside the cryostat (containing traces of inpurities)

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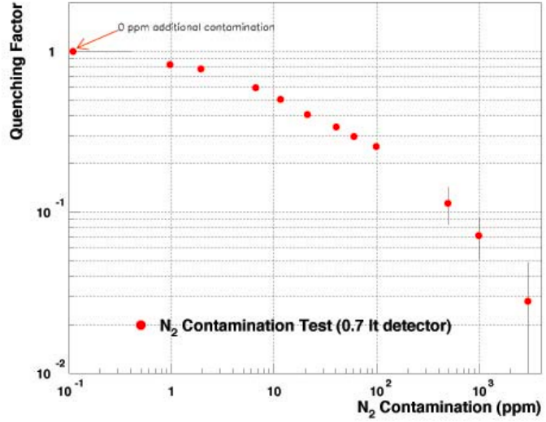
- Decrease of τ_3 and light yield observed by LLAMA.
- N_2 level increase in time is estimated using the known inflow (~350 kg/h) of the N_2 contaminated LAr during the cryostat filling.
- LLArS was not able to remove the high N_2 content.

N_2 increase with flow rate of 0.06 ppm/h giving 0.9 ppm of N_2 increase in total.

[*JINST* 5 (2010) P06003]



Optical properties analysis based on LLAMA data

(Mario Schwarz)

Assuming:

$$I(t) = \frac{R_1}{\tau_1} e^{-t/\tau_1} + \frac{R_2}{\tau_2} e^{-t/\tau_2} + \frac{1 - R_1 - R_2}{(1 + t/\tau_3)^2} \frac{1}{\tau_3}$$

Model for pure argon

Singlet (~ 8ns) triplet (~ 1300 ns)

Intermediate

[G. Ribitzki et al, Phys. Rev. E **50**, 3973 (1994)]

Idea:

1. use of ‘stable’ periods before and after contamination:

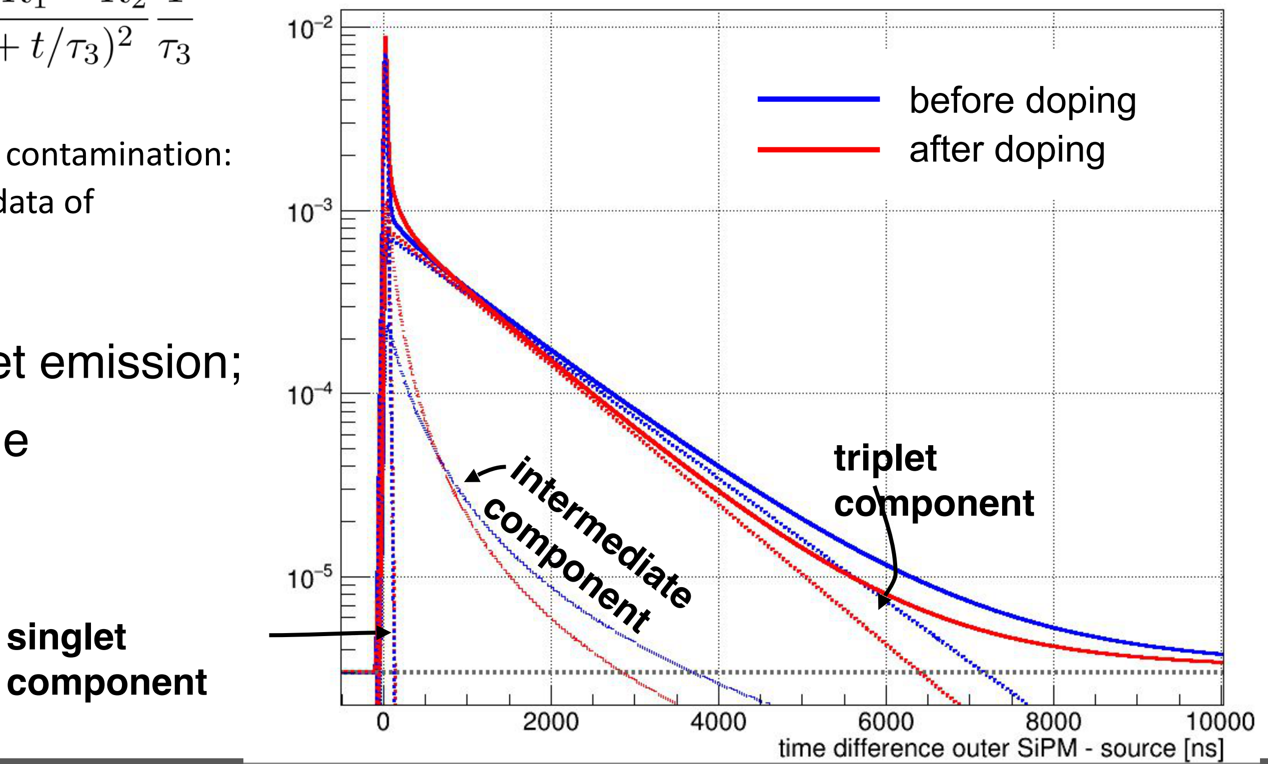
   enable comparison with high statistics data of **contaminated and pure argon.**

Optical properties analysis - stable contamination level

$$I(t) = \frac{R_1}{\tau_1} e^{-t/\tau_1} + \frac{R_2}{\tau_2} e^{-t/\tau_2} + \frac{1 - R_1 - R_2}{(1 + t/\tau_3)^2} \frac{1}{\tau_3}$$

- use of 'stable' periods before and after contamination: enable comparison with high statistics data of **contaminated and pure argon.**

- N_2 quenches long-lived triplet emission;
- influence on singlet negligible

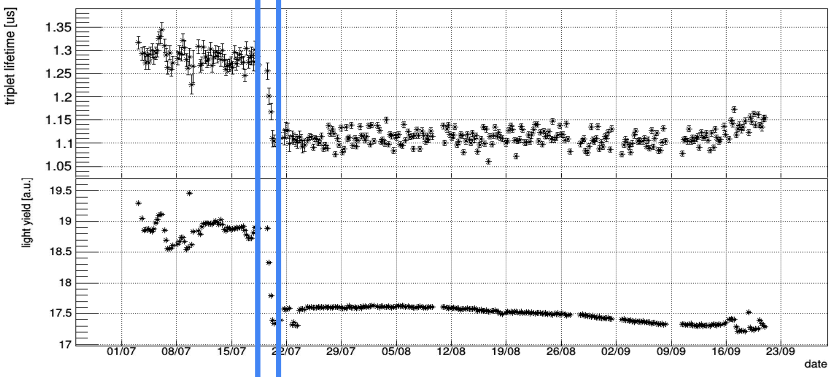


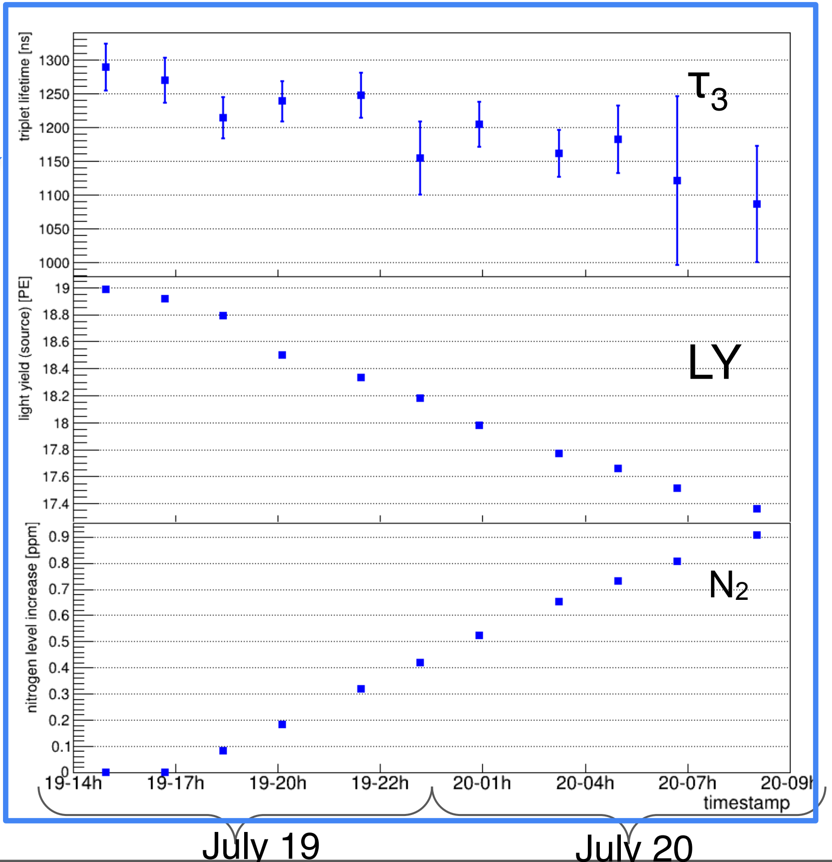
Optical properties analysis - evolution / slow N_2 doping

Idea:

2. Analysis of small 'time slices' to see the **evolution** of the properties during the doping:

i.e. redefine new sets from 'continuous' LLAMA data and perform separate fits.



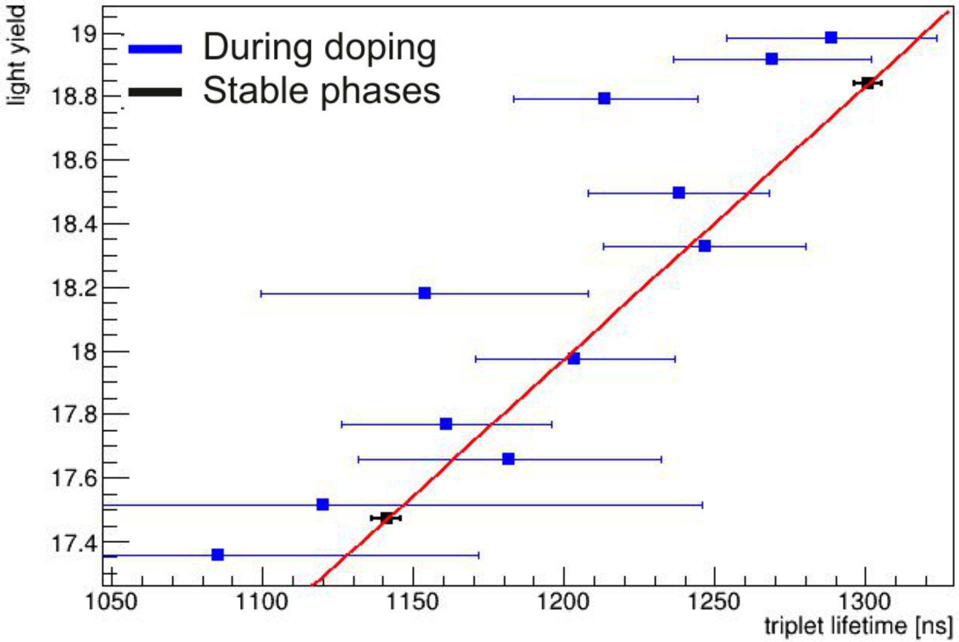


LAr scintillation model verification

Idea:
3. Check the relation between the LY and τ_{trip}

- Linear relation between **light yield** and **triplet state lifetime** for LAr with the presence of nitrogen impurities is shown.

- Points based of high-statistic data sets (before and after spoiling) are in agreement with data points obtained during spoiling.



Conclusions

- LLArS system allows to obtain LAr of very high purity. About 62 tons of LAr was purified and filled into the LEGEND cryostat with quality characterised by τ_{trip} ~ 1.3 µs
- The capacity of traps and operation of LLArS was tested in a large scale and proved to be predictable and stable. Average filling rate: 350 kg/h
- Argon purity is stable in the LEGEND-200 cryostat τ_{trip} ~ 1.15 µs
- If needed, the Ar circulation and purification in the loop mode is possible.
- Best quality data was obtained by LLAMA in the region of interest for the study of LAr scintillation (< 1ppm of nitrogen).
- The spoiling event served as a valuable proof-of concept for LLAMA instrument (in view of LEGEND 1000)
- The nitrogen contamination incident was investigated and explained bringing into the light important risk assessment points (in view of LEGEND 1000)

BACKUP