PC57.155 - WG Guide DGA in Ester-Immersed Transformers

A Working Group with the Insulating Fluids Sub Committee –

Oct 28, 2024

Fall 2024 – St Louis, MO

IEEE Patent Policy

The patent policy and the procedures used to execute that policy are documented in the:

- ***IEEE-SA Standards Board Bylaws*** **(http://standards.ieee.org/develop/policies/bylaws/sect6-7.html#6)**
- ***IEEE-SA Standards Board Operations Manual*** **(http://standards.ieee.org/develop/policies/opman/sect6.html#6.3)**

Material about the patent policy is available at ***http://standards.ieee.org/about/sasb/patcom/materials.html***

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Agenda – for approval

A. Welcome & Introduction

B. Attendance and Establishment of Quorum

C. Call for Patent Disclosure

D. IEEE Copyright Policy

E. Approval of Spring 2024 Minutes

F. Working Group Activities

1. Task Force 4: Task Force 4 – Jinesh Malde - Updates on the Annexes B to F
2. Task Force 3 – Stu Chambers - Updates on the general document
3. Task Force 2 – Alan Sbravati → No updates
4. Task Force 1 – Lance Lewand → Luiz Cheim: 20 min, Toni Melin: 10 min

5 . General discussion → 15 min

H. Old Business / New Business

I. Adjournment

List of members

- Paul Boman
- Jeremiah Bradshaw
- Edward Casserly
- Jonathan Ceatham
- Stuart Chambers
- Luiz Cheim
- Roberto Da Silva
- Stephanie Denzer
- Zack Draper
- James Dukarm
- Todd Felton
- Bruce Forsyth
- Rainer Frotscher
- Miguel Garcia
- Alireza Gorzin
- Attila Gyore
- Robert Harper
- Traci Hopkins
- Egon Kirchenmayer
- Lance Lewand
- Chao Li
- Cesar Lizcano
- Tiffany Lucas
- Jinesh Malde
- Brian McBride
- Toni Mellin
- Nick Perjanik
- Timothy Raymond
- Scott Reed
- Yuri Rossini
- Mickel Saad
- Amitabh Sarkar
- Alan Sbravati
- Mauricio Soto
- Markus Stank
- Evanne Wang
- Zachery Weiss
- Deanna Woods

38 Members
Quorum 19

Approval of Spring 2024 Minutes

- Comments?

Task Force 4 – Annexes B to F (Jinesh)

Annexes

- Annexes B-F rearranged:
- Annex B - Stray Gassing
  - B.1 ASTM D7150 stray gas results
  - B.2 Stray gassing due to UV light exposure
  - B.3 Stray gassing due to material compatibility
- Annex C – Pyrolysis
  - C.1 Laboratory pyrolysis experiment information
  - C.2 EPRI laboratory pyrolysis and arcing experiment information
-

Annexes

- Annexes D - Theory
  - D.1 Enthalpy of formation
  - D.2 Causes of gas formation
- Annex E – Method of Analysis
  - E.1 Duval Triangle analysis method
  - E.2 Duval Pentagon analysis method
- Annex F – Case Studies
  - F.1 In-service transformers
  - F.2 Failed Transformer
  - F.3 Retrofilled Transformer

Task Force 3 – Main Text Updates (Stu)

Task Force 2 – Annex A & NEI (Alan)

No updates

Task Force 1 – Data Analysis

(Lance Lewand)

Overall Updates

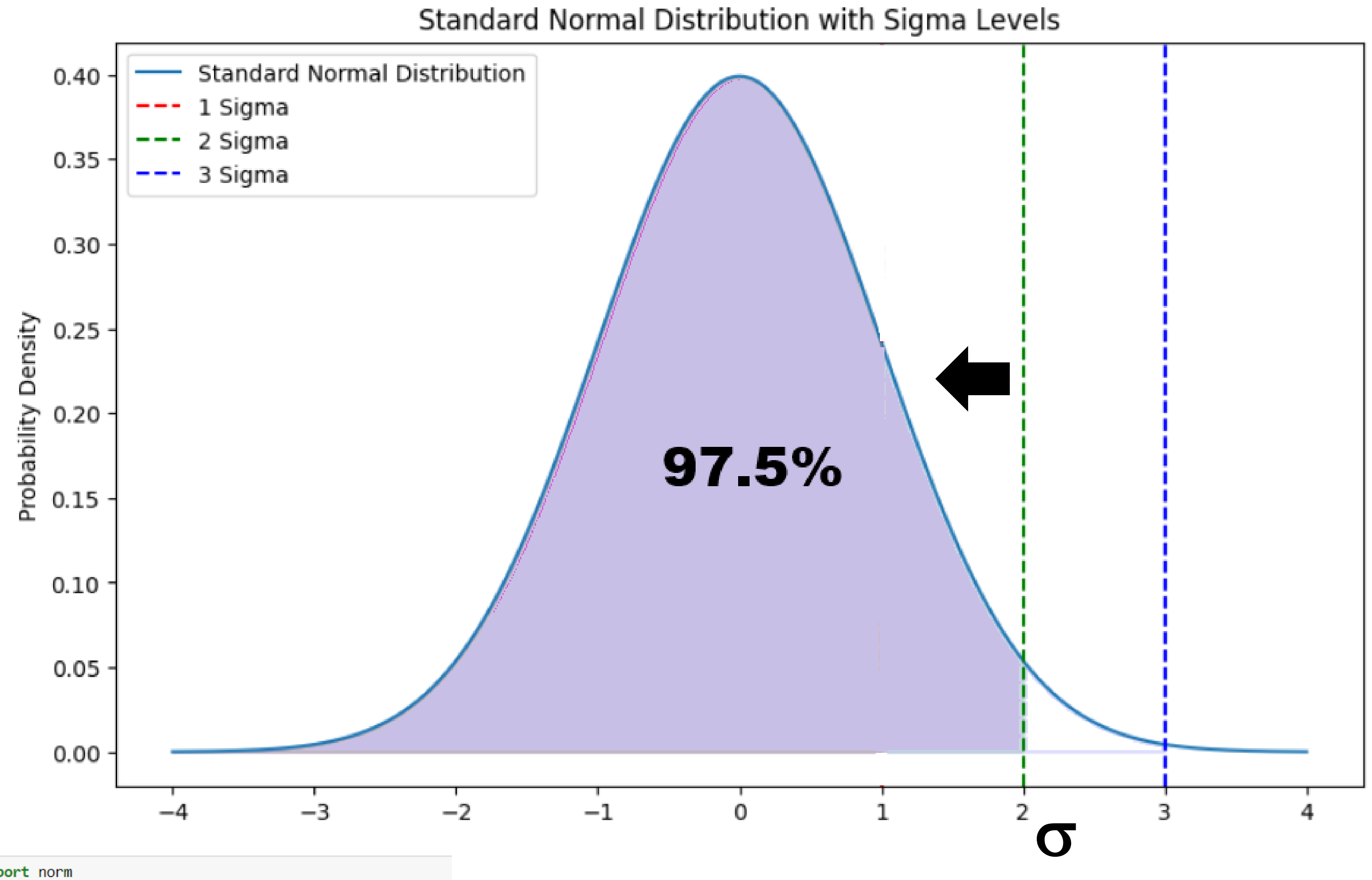
- We received an outstanding number of DGA records both through IEEE SA and directly.
  - Offline measurement = ~71k records (less than 3 records in 1 day)
  - Online measurements = ~39k records (more than 3 records in 1 day)
- Very limited information other than the DG contents
- Data has been completely anonymized, formatted, and duplications removed.
  - Offline measurement = 62,748 records
  - Online = pending

Task Force 1 – Data Cleaning

- **What has been done?**
  - Adjusting fluid types: LO_Ester, HO_Ester, and SY_Ester
    - LO Ester = FR3, VG-100, Midel eN 1204 (4 records only), Midel eN 1215 / HO Ester = Biotemp
    - No further differentiation for Natural Esters (NEs) was possible due to lack of data
  - Cooling types: harmonized (available in 8% of the records)
  - Voltage classes: ≤ 4.16kV, ≤ 13.8kV, ≤ 69kV, > 69kV (available in 16%)
  - Application: only available in 1.4% of the records
- **Open questions:**
  - Checking for outliers: discussion regarding possible criteria
  - Sealed vs Free-breathing units

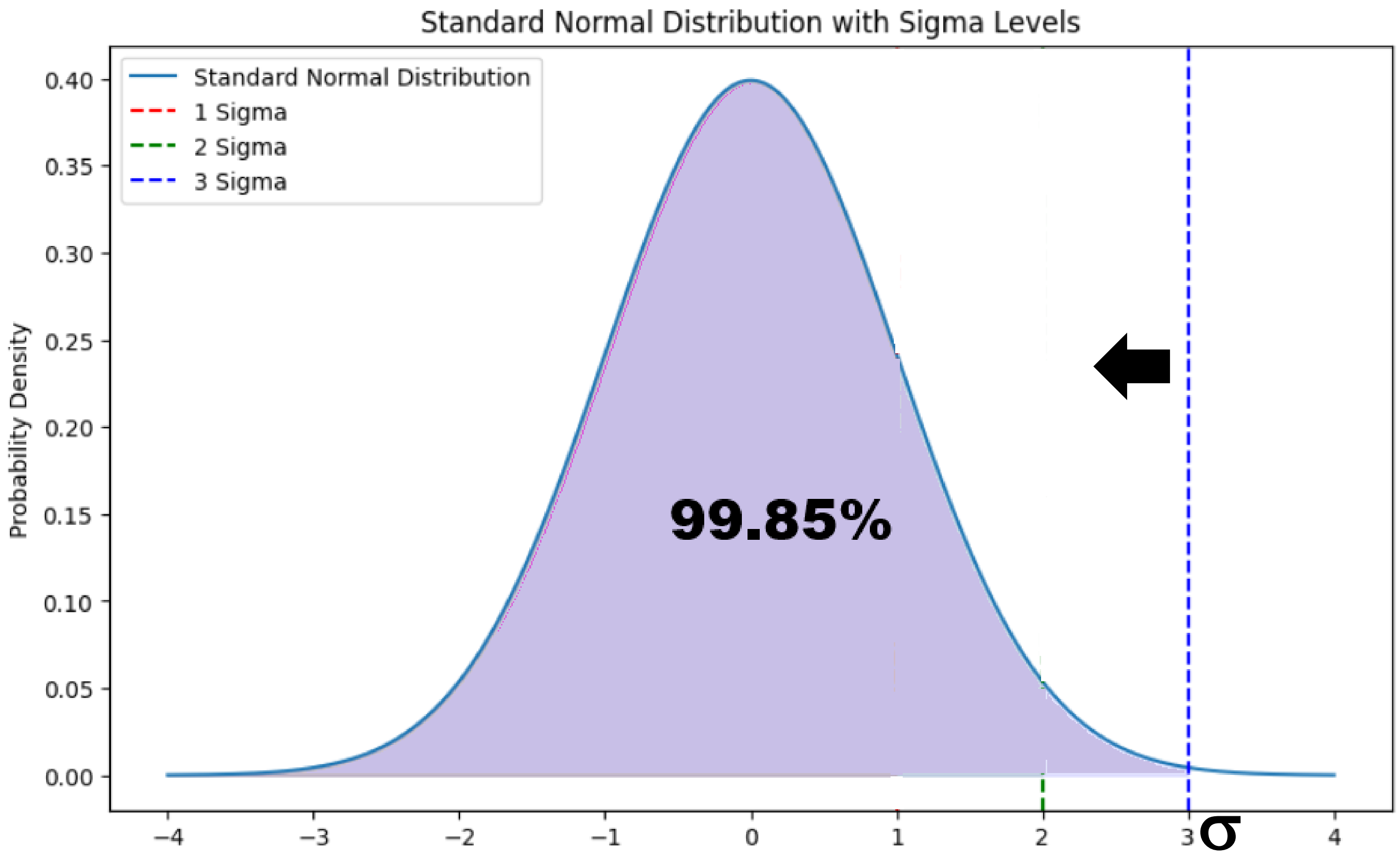
Task Force 1 – Outliers

- There is no information on whether the records refer to normal operating units or failed ones.
- DG content records mostly fit a log-normal distribution, with a very long right tail.
- Trying to use an approximation of a normal distribution is not an option. Approaches such as “3-Sigma” would not work.
- Alternative is to use the so-called “Boxplot approach”.
- Another approach is to agree upon limits based on the Total Dissolved Combustible Gases (TDCG) and C_2H_2 content.



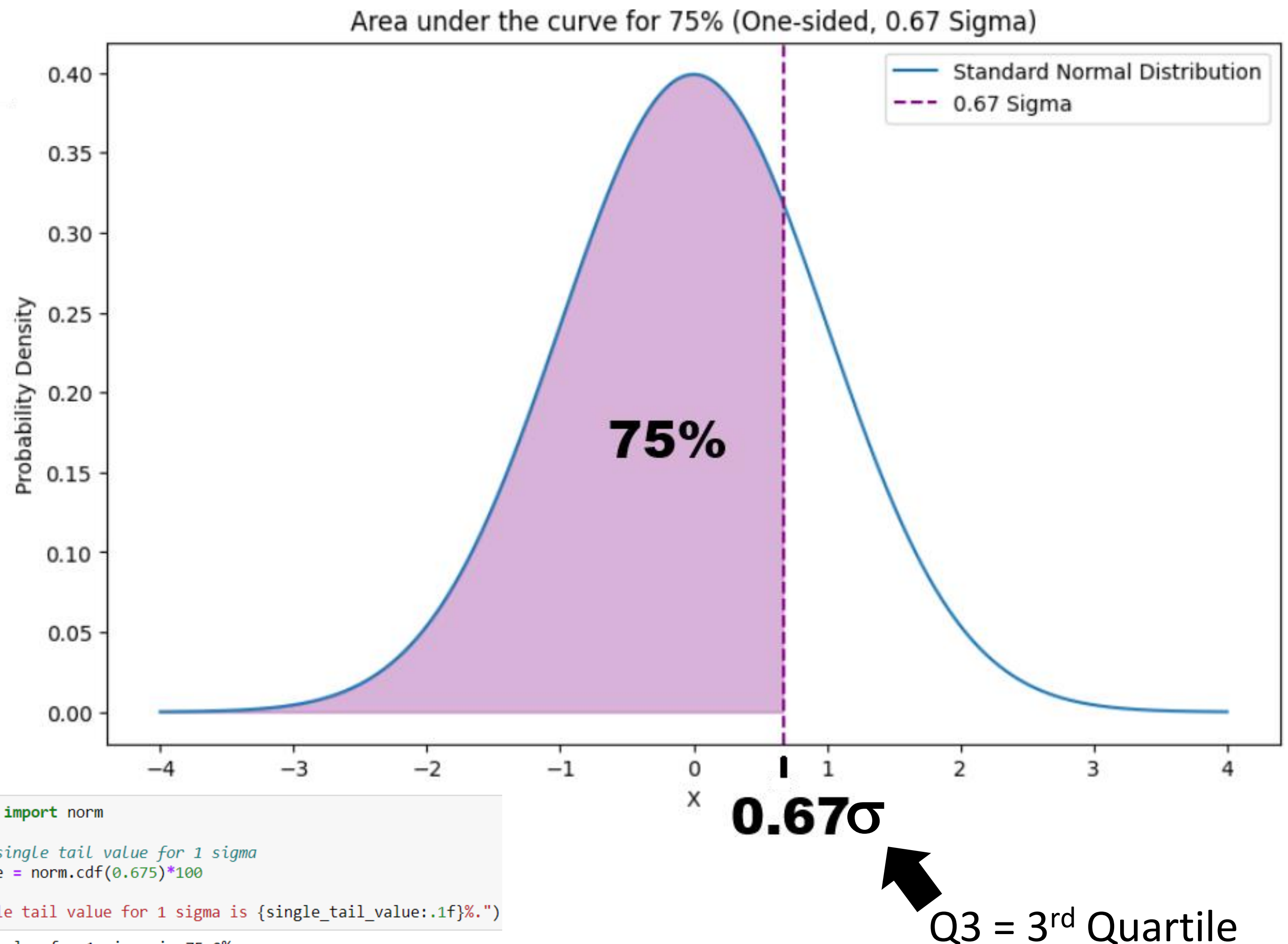

```python
from scipy.stats import norm

# Calculate the single tail value for 1 sigma
single_tail_value = norm.cdf(2)*100

print(f"The single tail value for 1 sigma is {single_tail_value:.1f}%.")
```

```
The single tail value for 1 sigma is 97.7%.
```



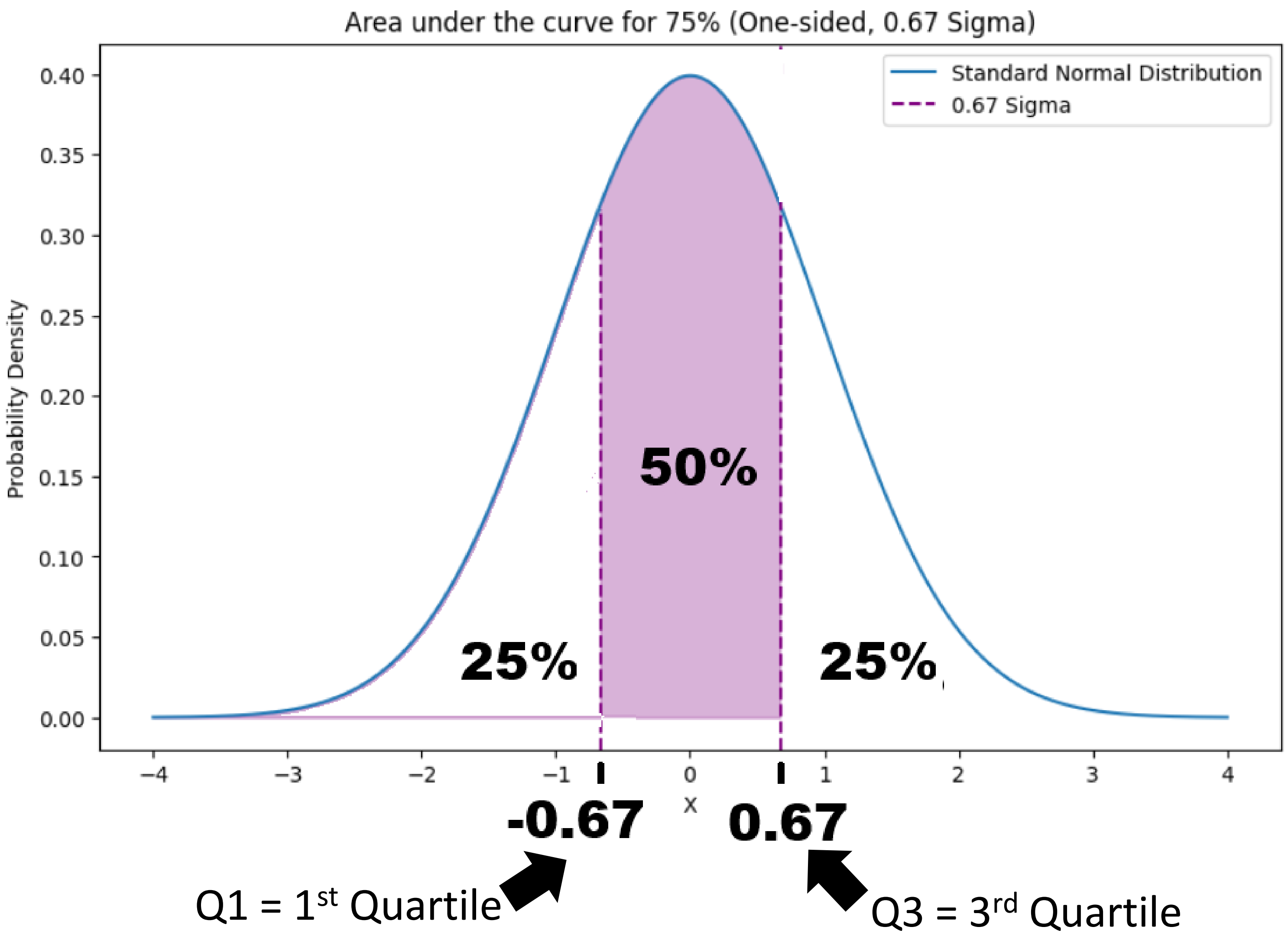

```
from scipy.stats import norm

# Calculate the single tail value for 1 sigma
single_tail_value = norm.cdf(3)*100

print(f"The single tail value for 1 sigma is {single_tail_value:.3f}%.")
```

```
The single tail value for 1 sigma is 99.865%.
```

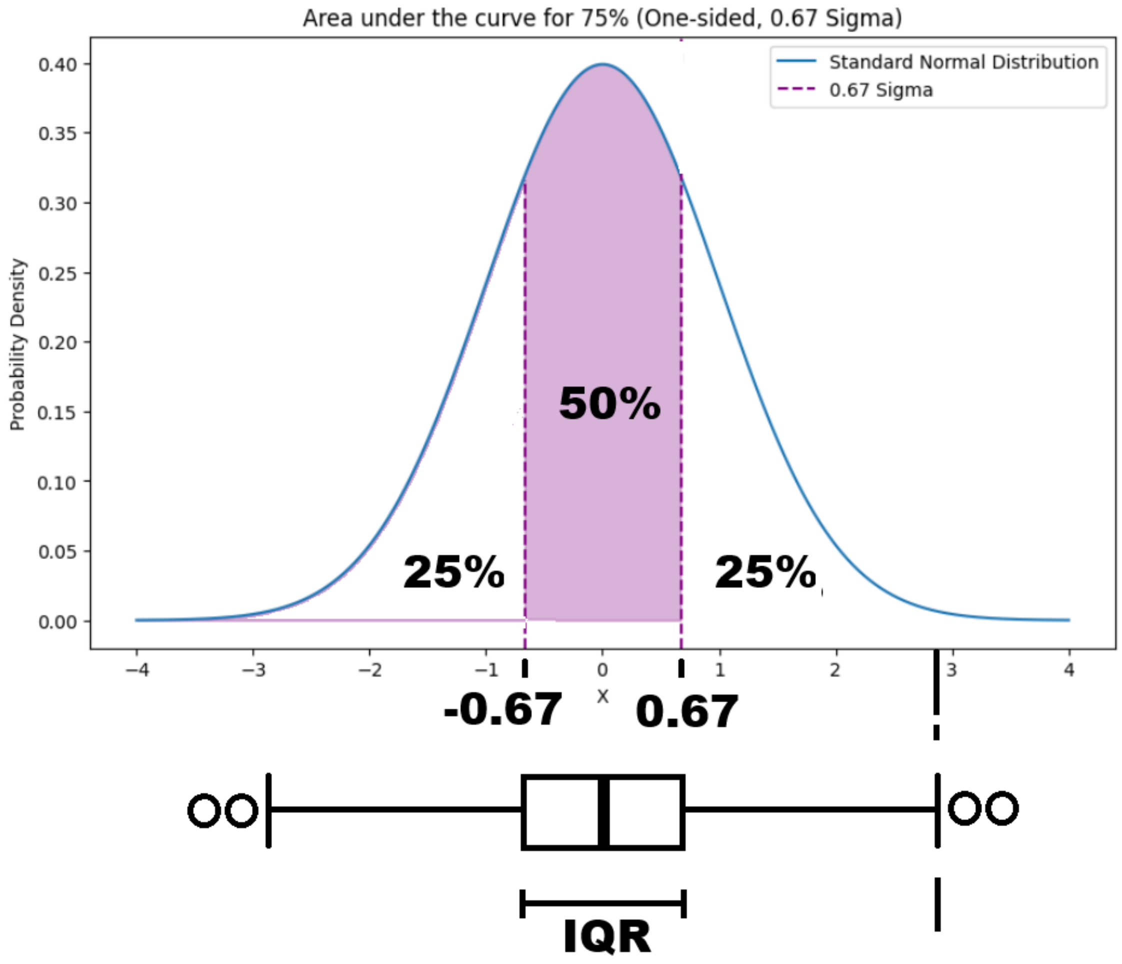



```
from scipy.stats import norm

# Calculate the single tail value for 1 sigma
single_tail_value = norm.cdf(0.675)*100

print(f"The single tail value for 1 sigma is {single_tail_value:.1f}%.")
```

```
The single tail value for 1 sigma is 75.0%.
```



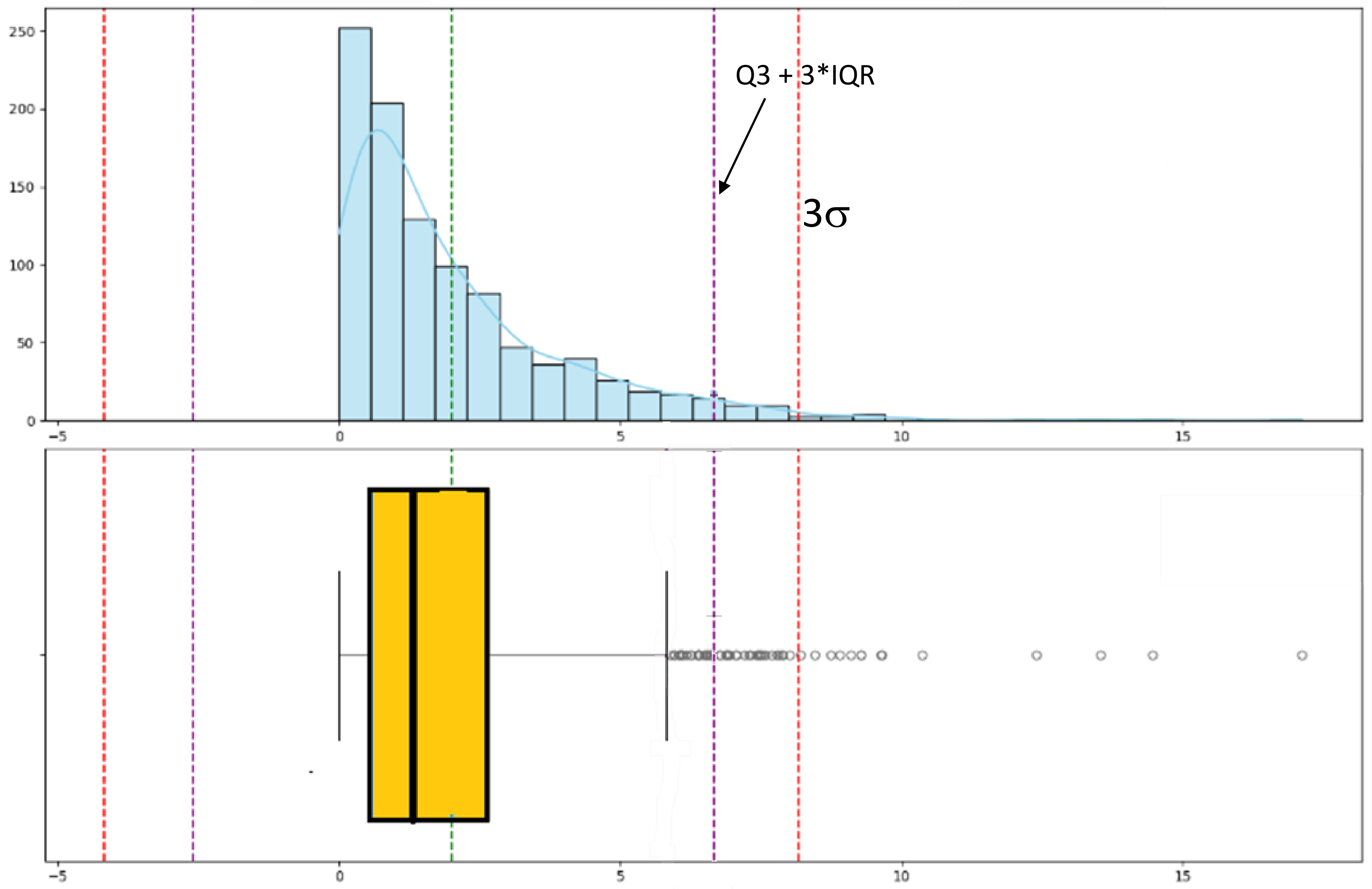
Area under the curve for 75% (One-sided, 0.67 Sigma)
Standard Normal Distribution
0.67 Sigma
Probability Density
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
−4
−3
−2
−1
0
1
2
3
4
X
50%
25%
25%
-0.67
0.67
Q1 = 1st Quartile
Q3 = 3rd Quartile



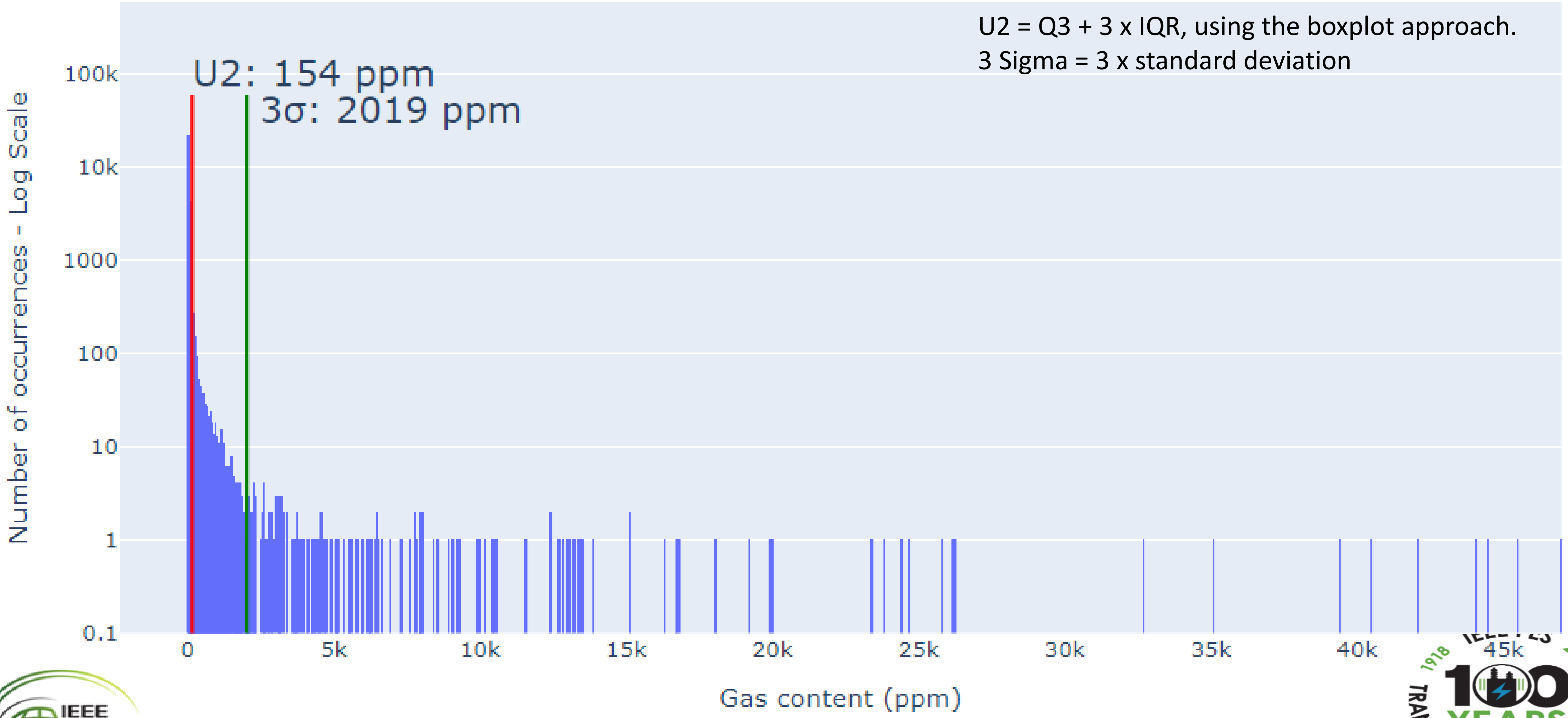
$$Q3 + 1.5IQR = 0.67 + 1.5 \times 1.34 = 2.69$$

$$IQR = 0.67 - (-0.67) = 1.34$$

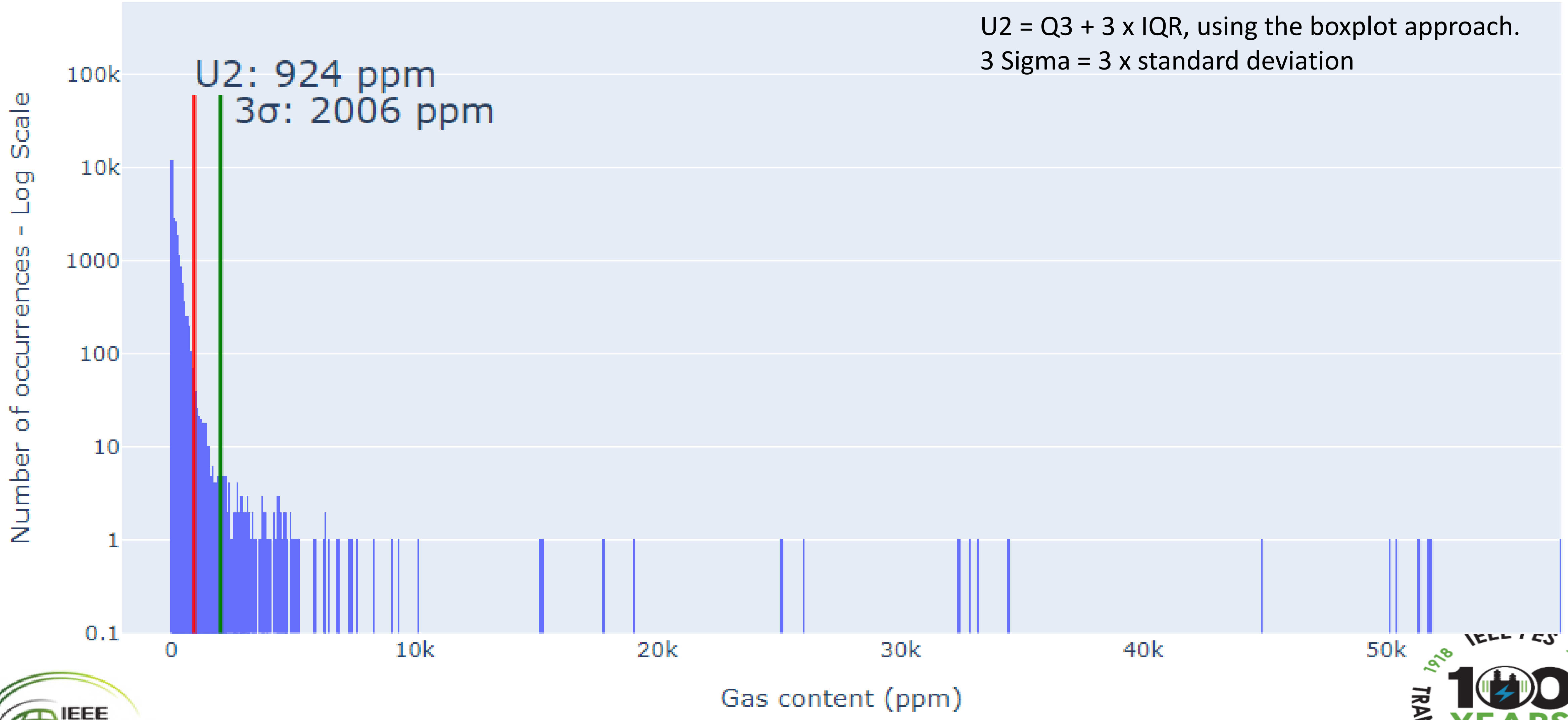
Why 3σ is not always a good idea?



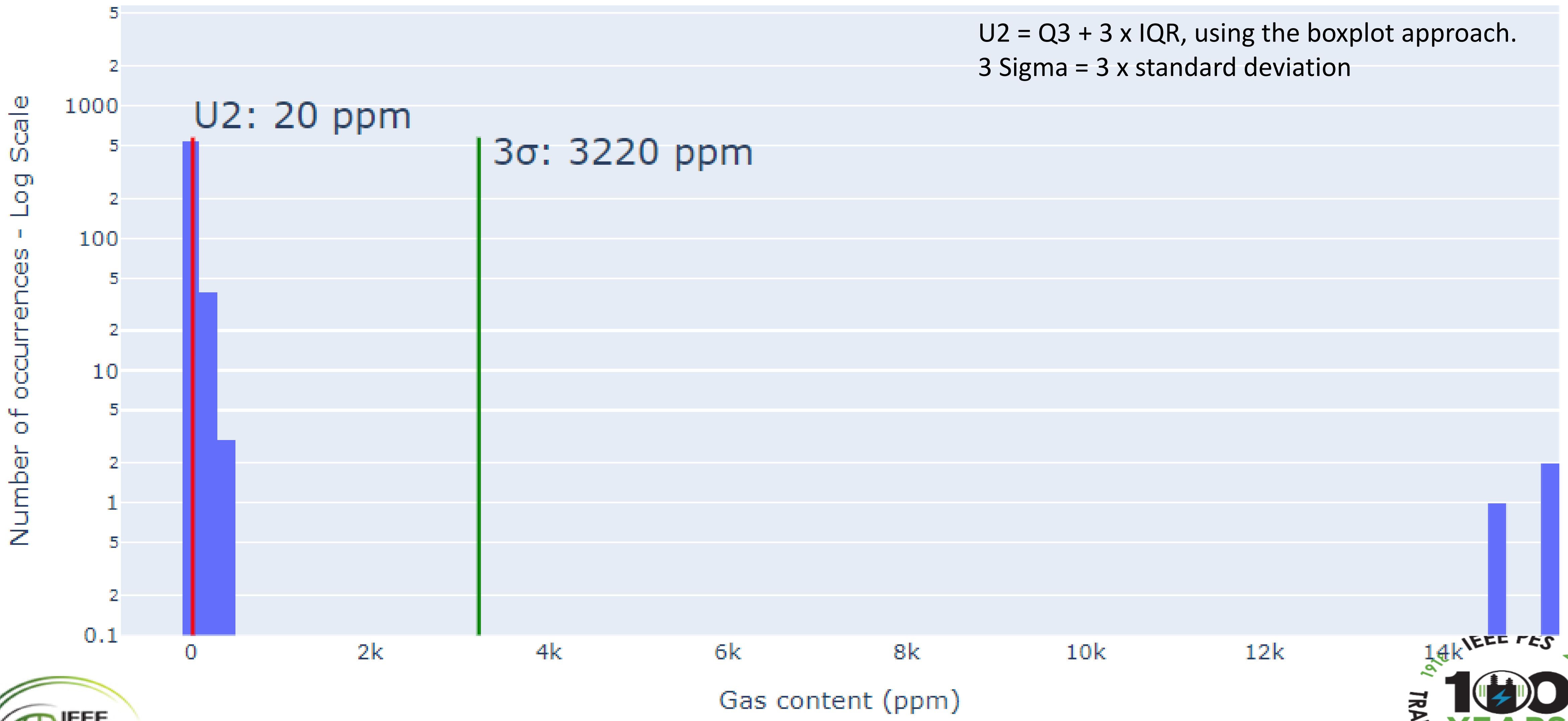
Histogram for the H2 records for LO_ESTER



Histogram for the C2H6 records for LO_ESTER

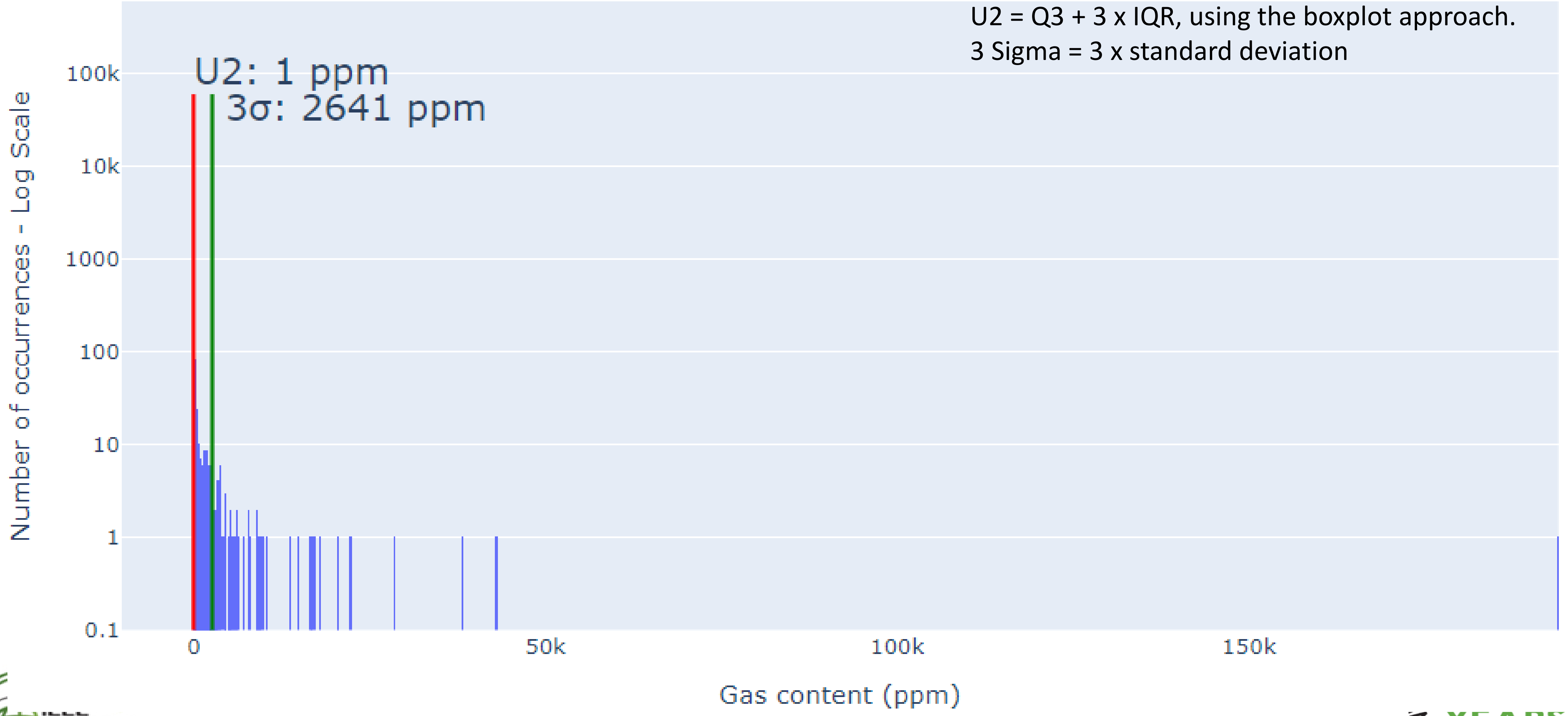


Histogram for the C2H6 records for HO_ESTER

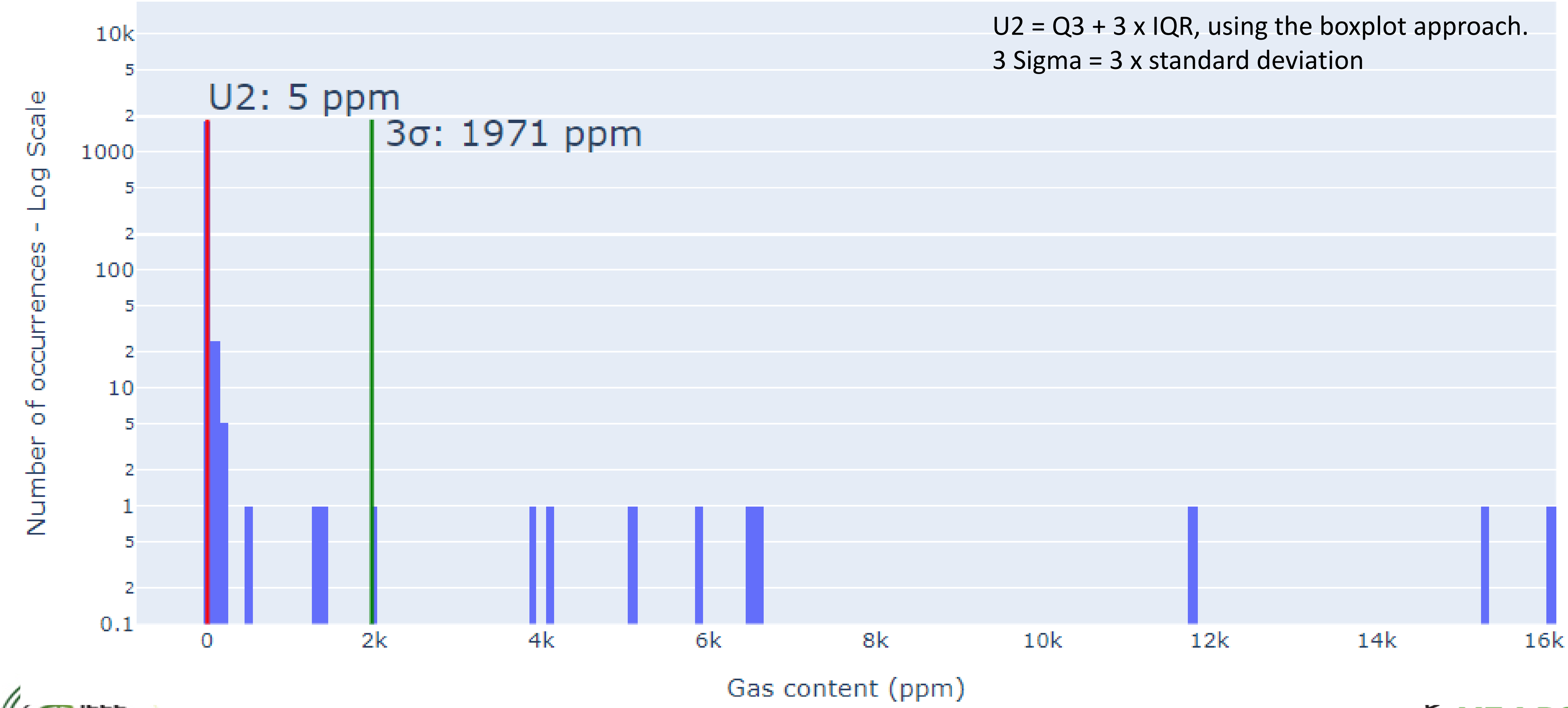


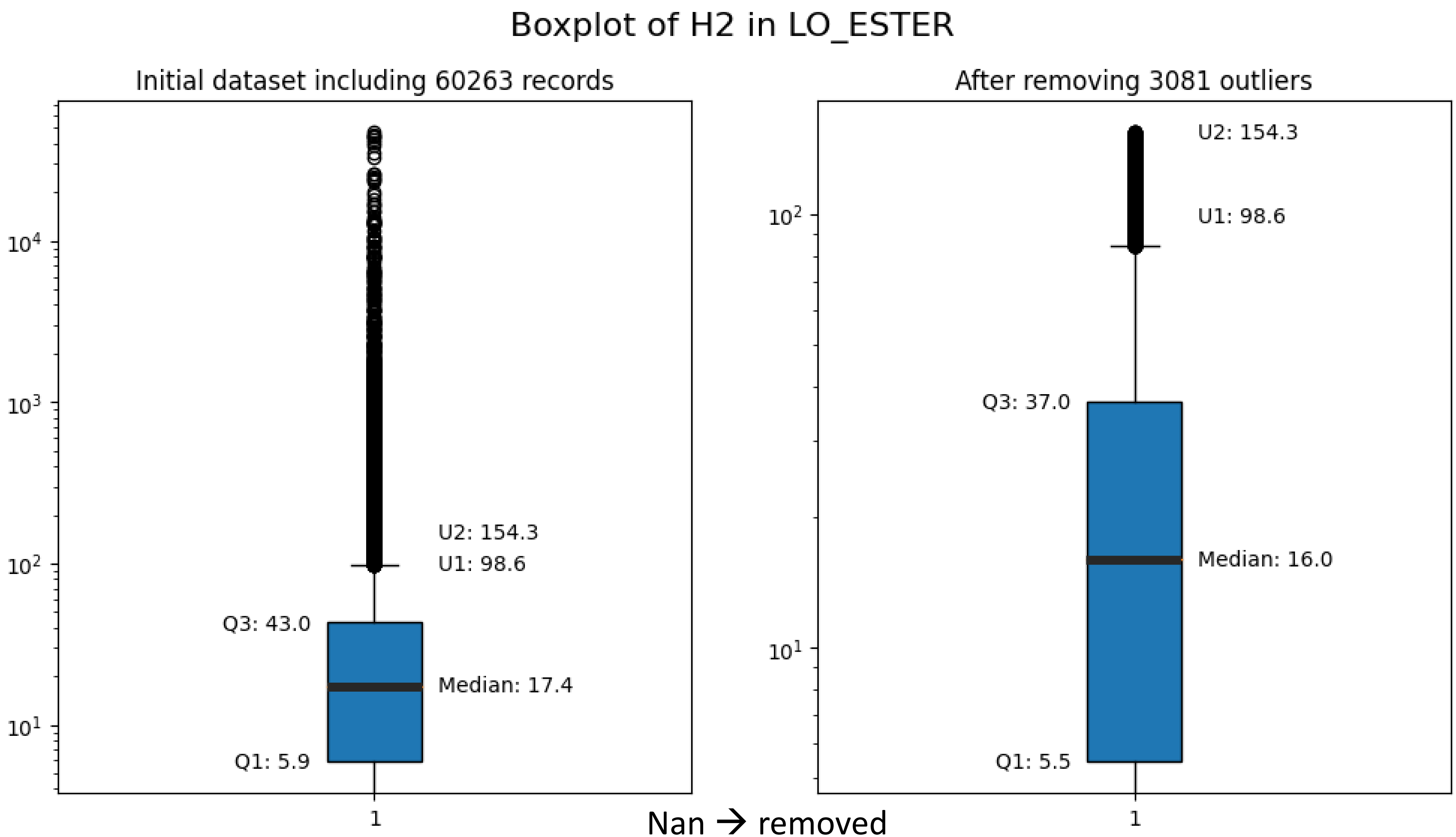
Histogram for the C2H2 records for LO_ESTER

U2 = Q3 + 3 x IQR, using the boxplot approach.
3 Sigma = 3 x standard deviation

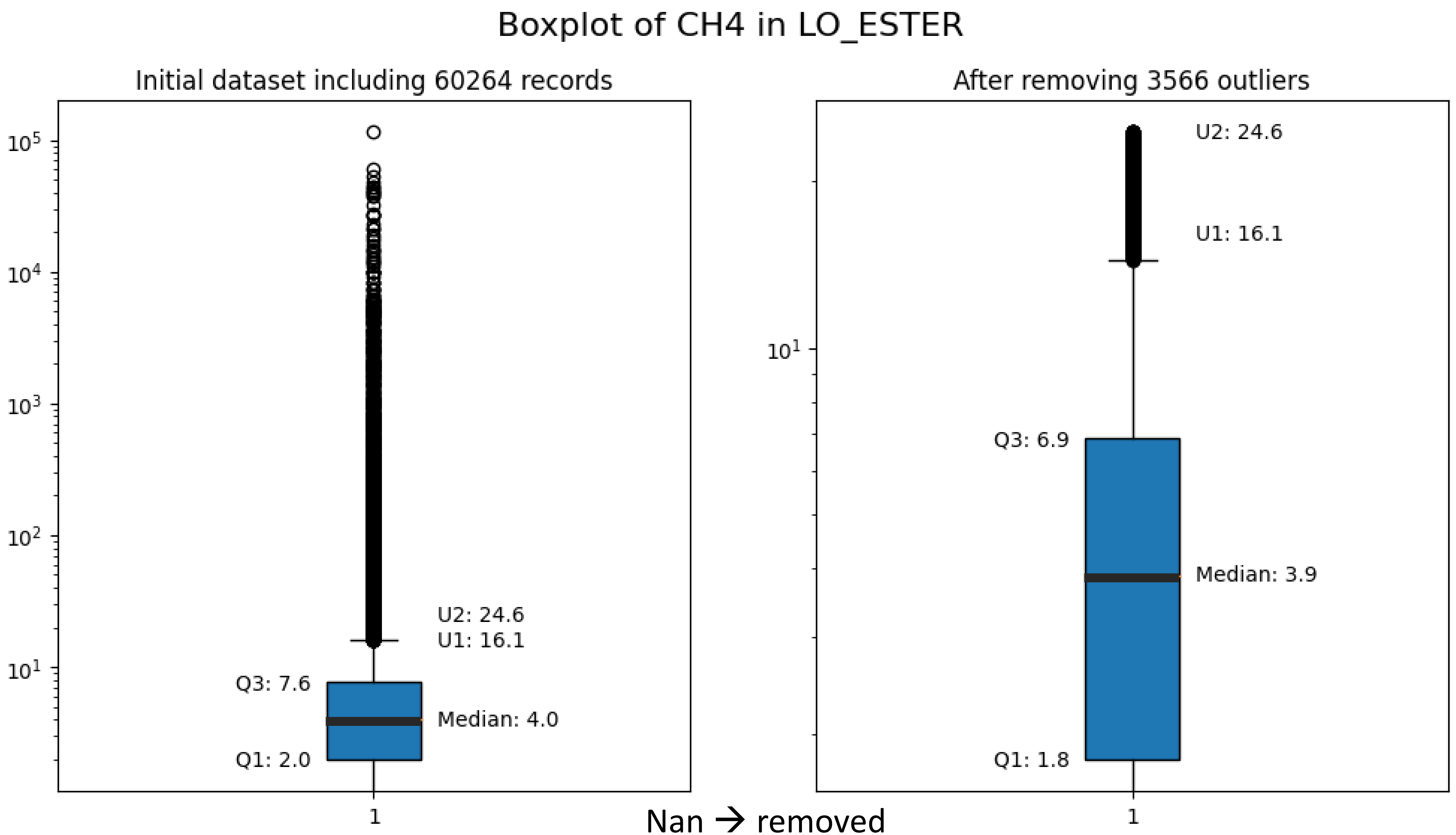


Histogram for the C2H2 records for SY_ESTER

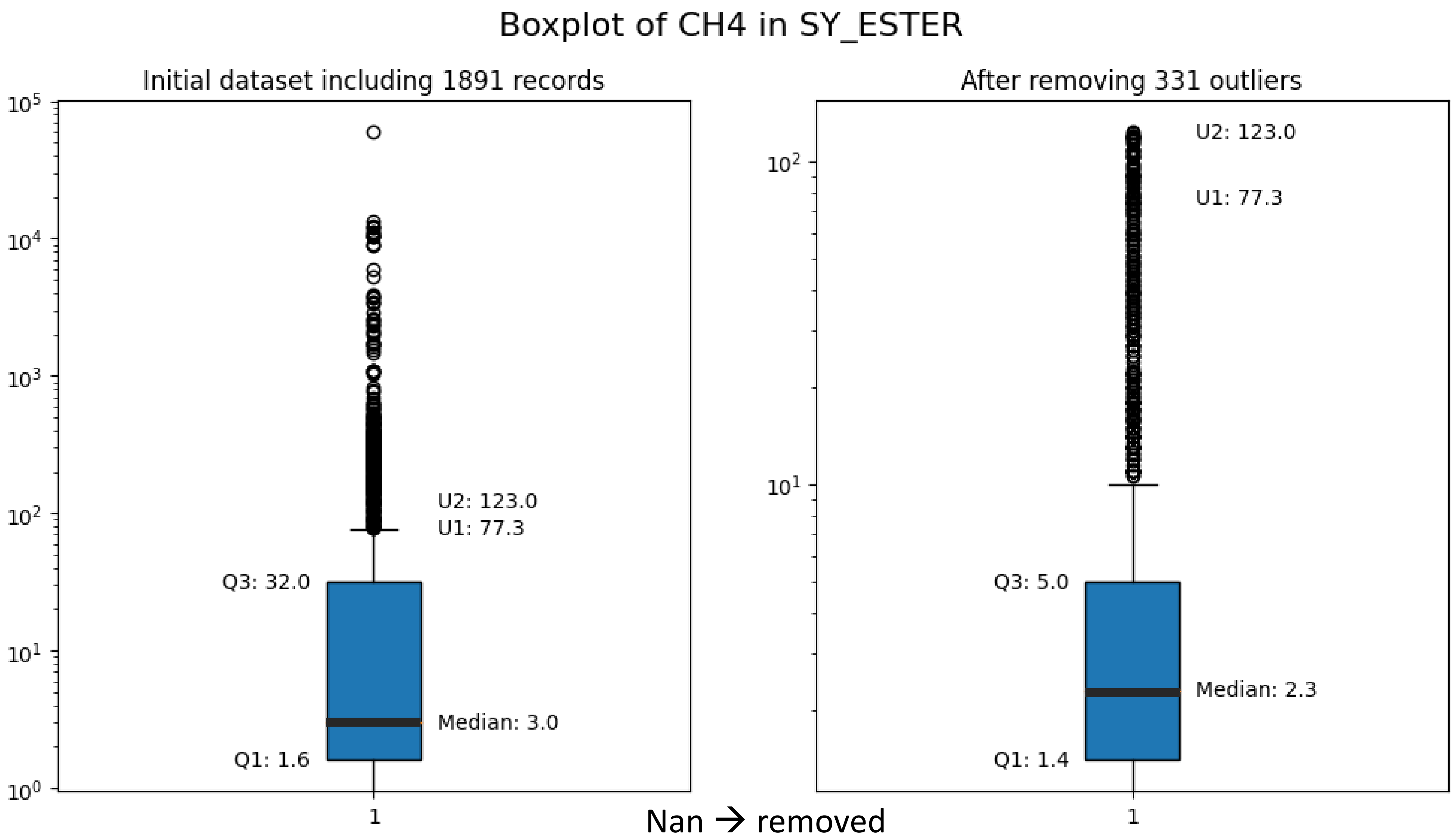




Nan → removed
Values = 0 → kept

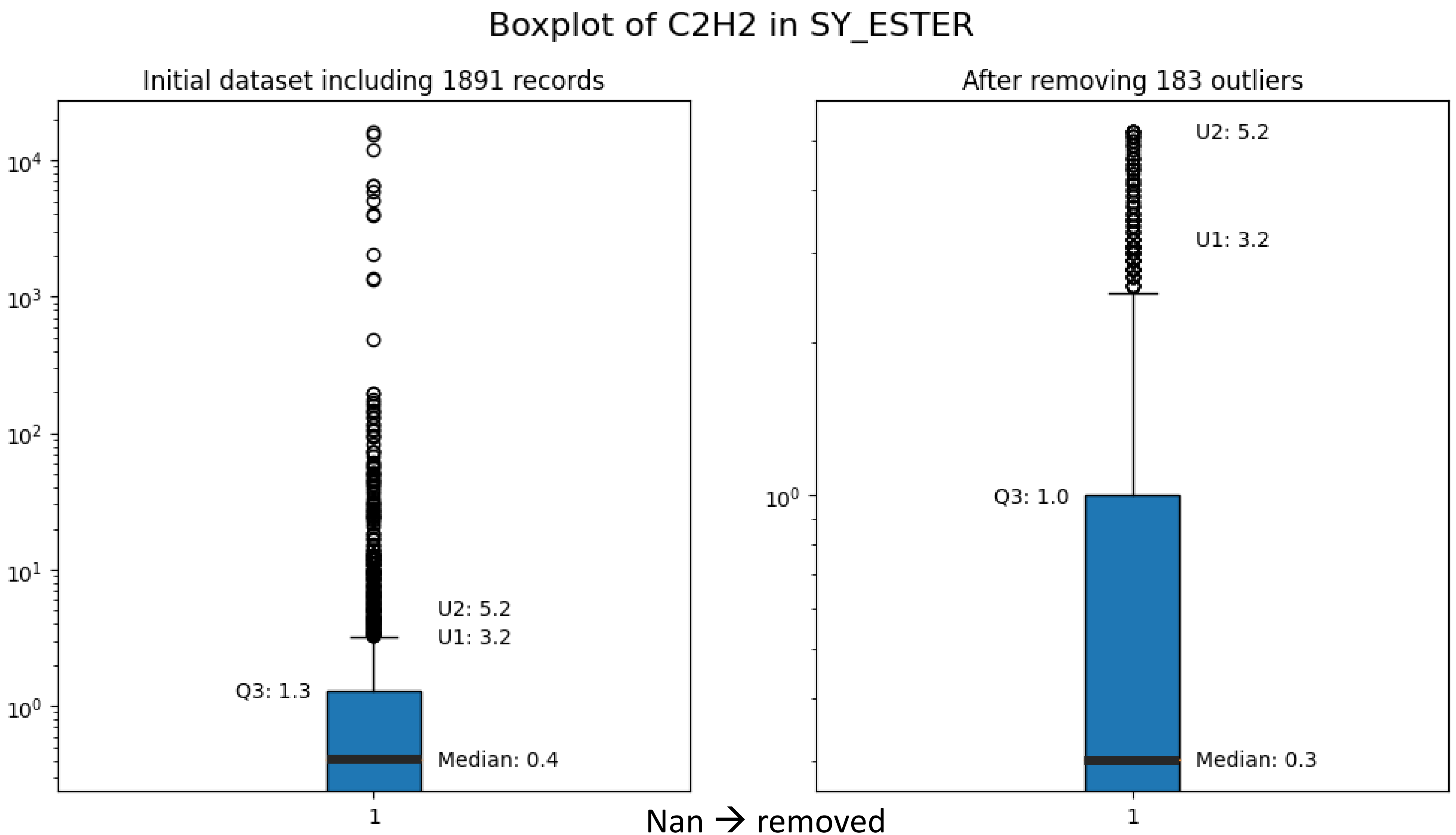


Nan → removed
Values = 0 → kept

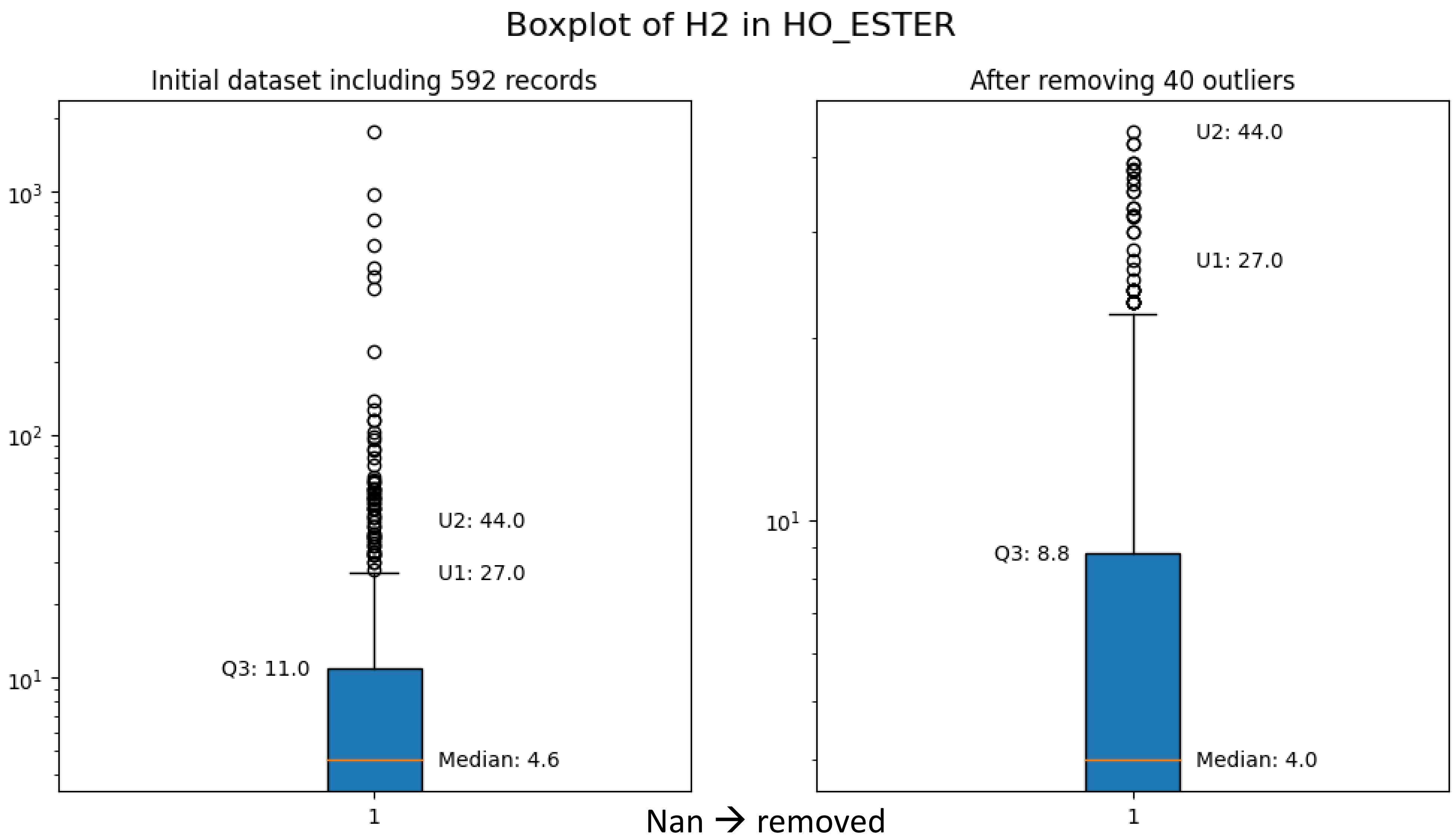


Nan → removed

Values = 0 → kept

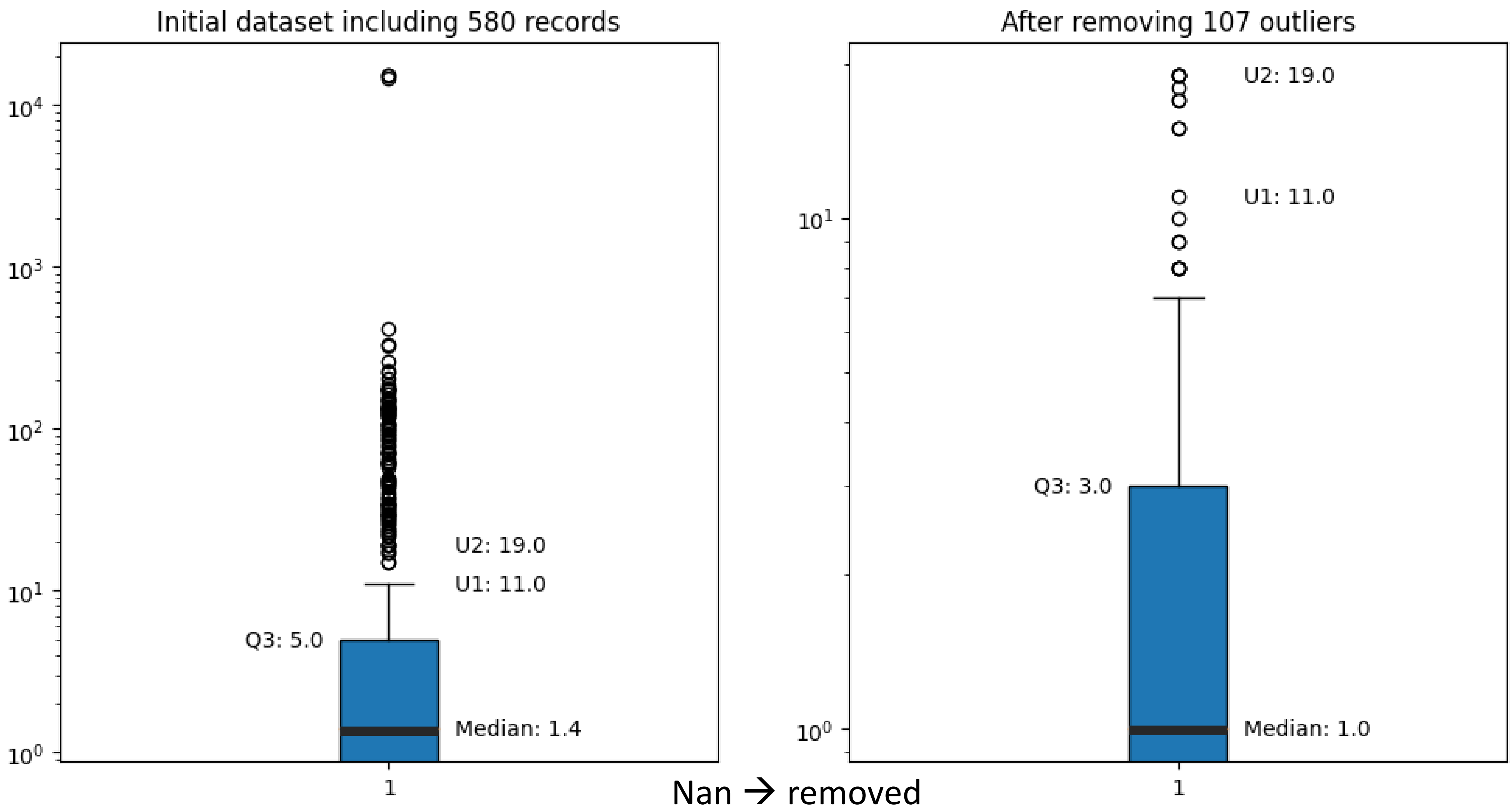


Nan → removed
Values = 0 → kept



Nan → removed
Values = 0 → kept

Boxplot of C_2H_6 in HO_ESTER



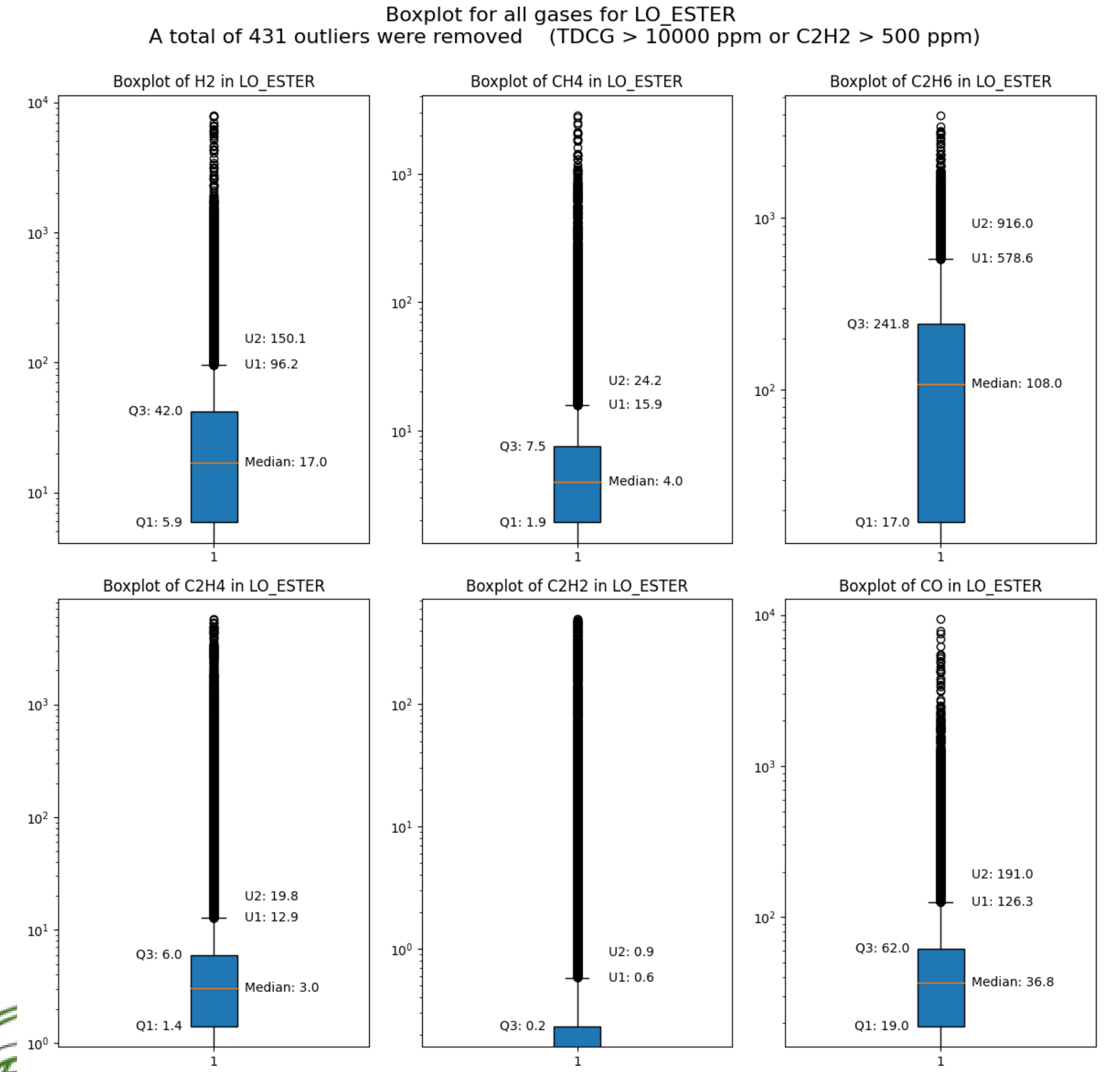
Nan → removed

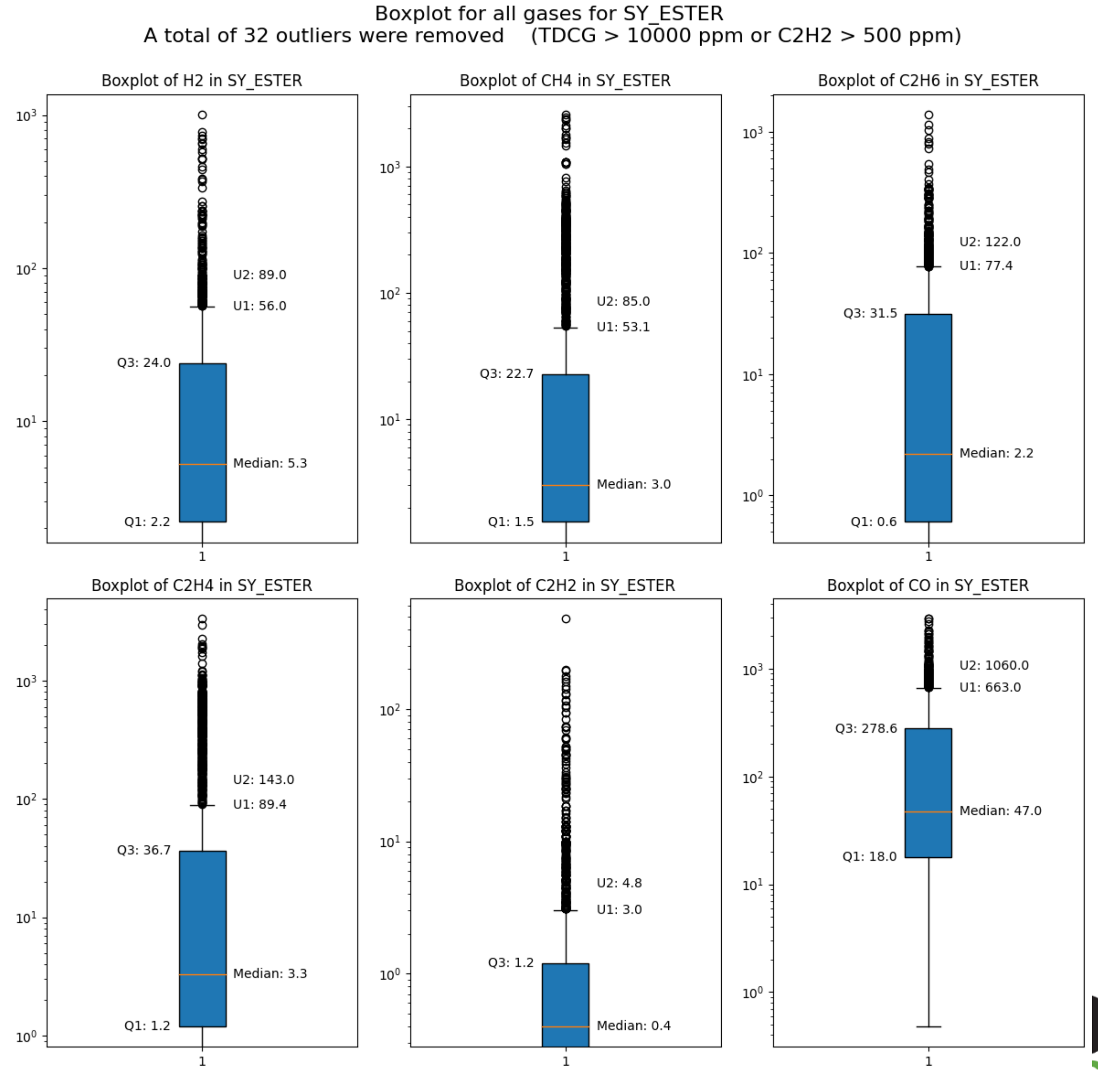
Values = 0 → kept

Results of Outliers elimination using as criteria the TDCG and C_2H_2 content

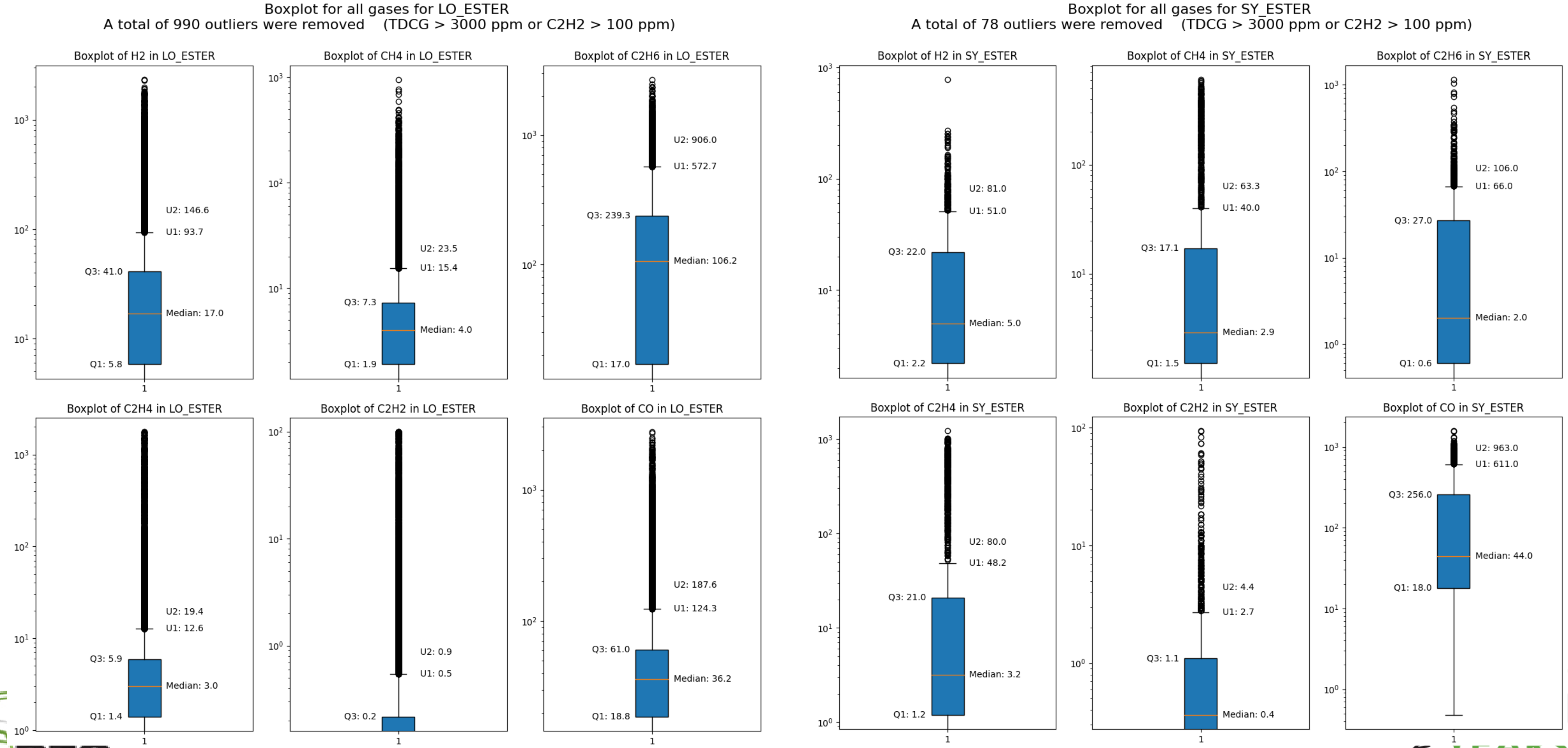
Several values were tried. The presented charts refer to TDCG > 3,000 and C_2H_2 > 100

TDCG criteria for outliers – Only a few cases were removed when the limits were set as TDCG > 10,000ppm or C_2H_2 > 500ppm





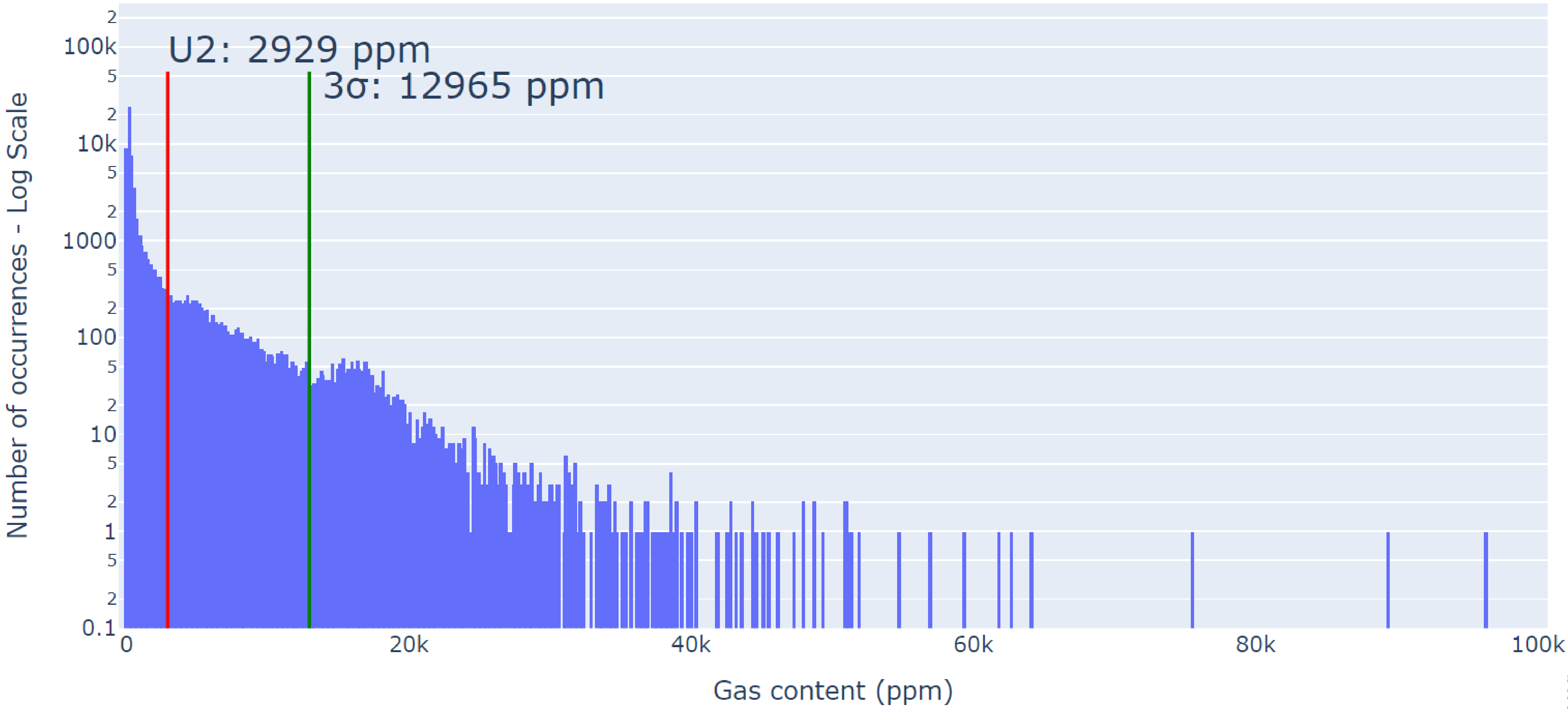
TDCG criteria for outliers – Only a few cases were removed, even when the limits were set as TDCG > 3000ppm or C_2H_2 > 100ppm

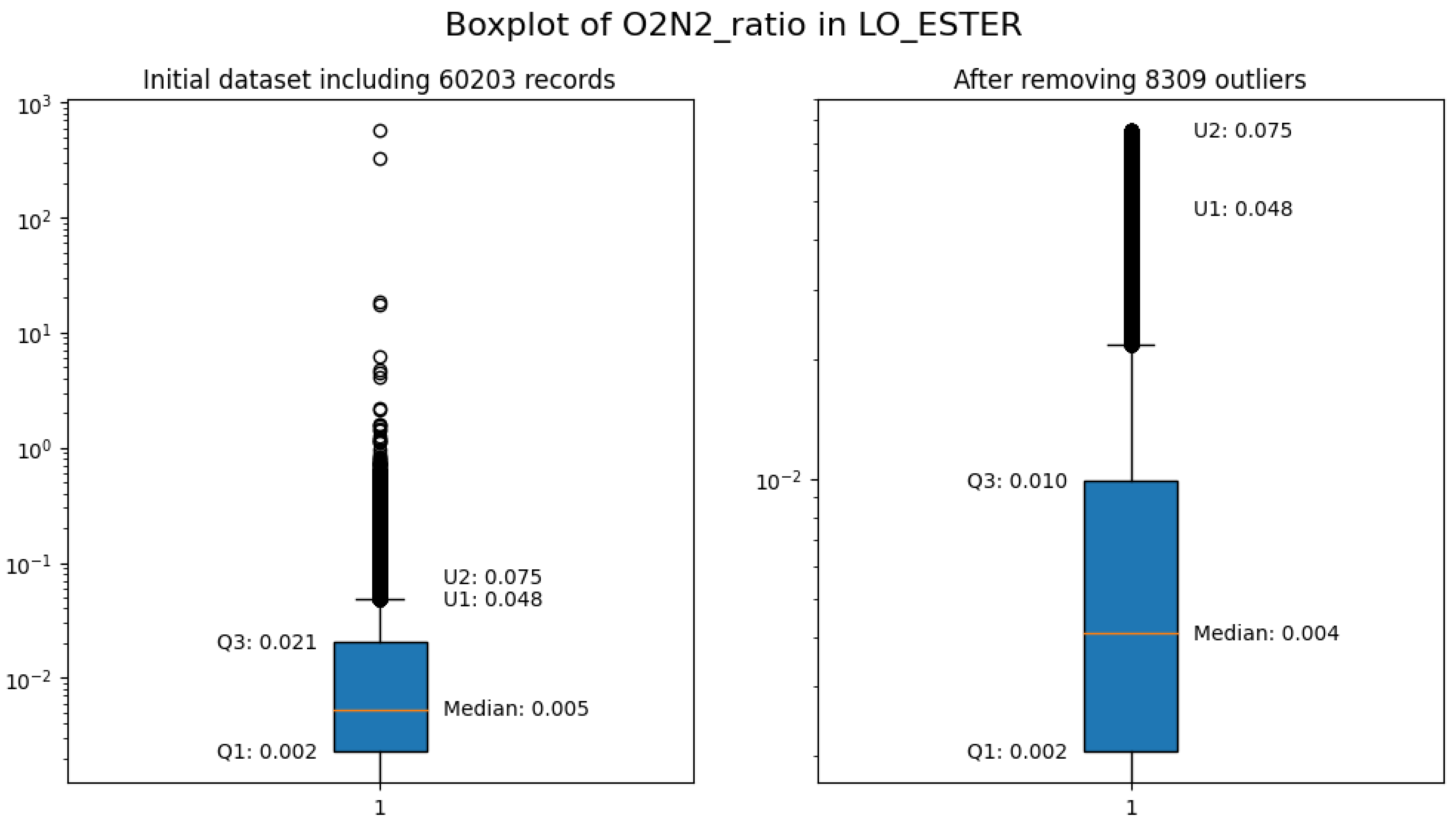


Free-breathing vs Sealed

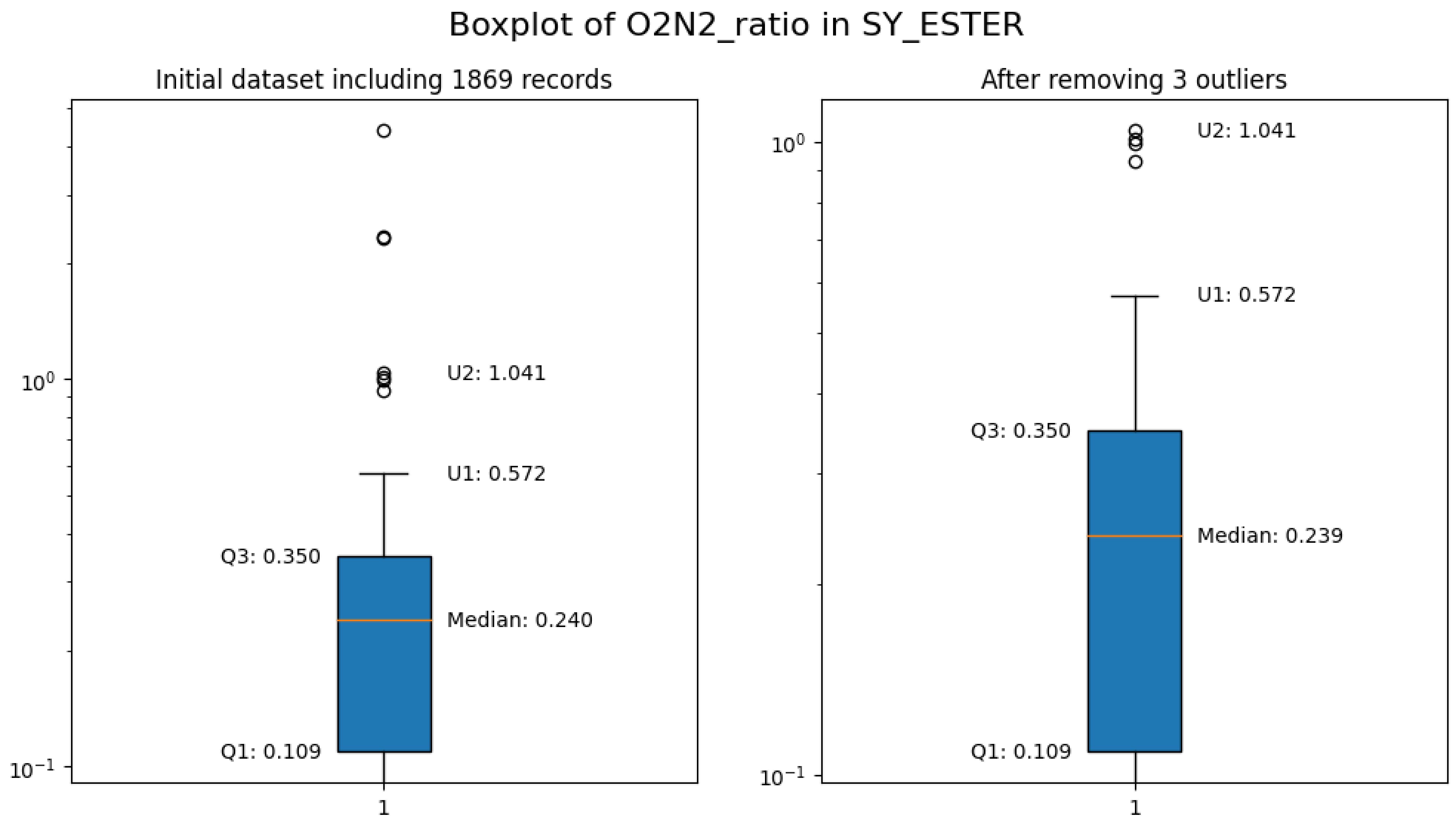
- Supposedly, all the natural ester filled units are sealed.
- The O_2 ratio showed some abnormal behavior
- An assessment of the O_2/N_2 was performed.

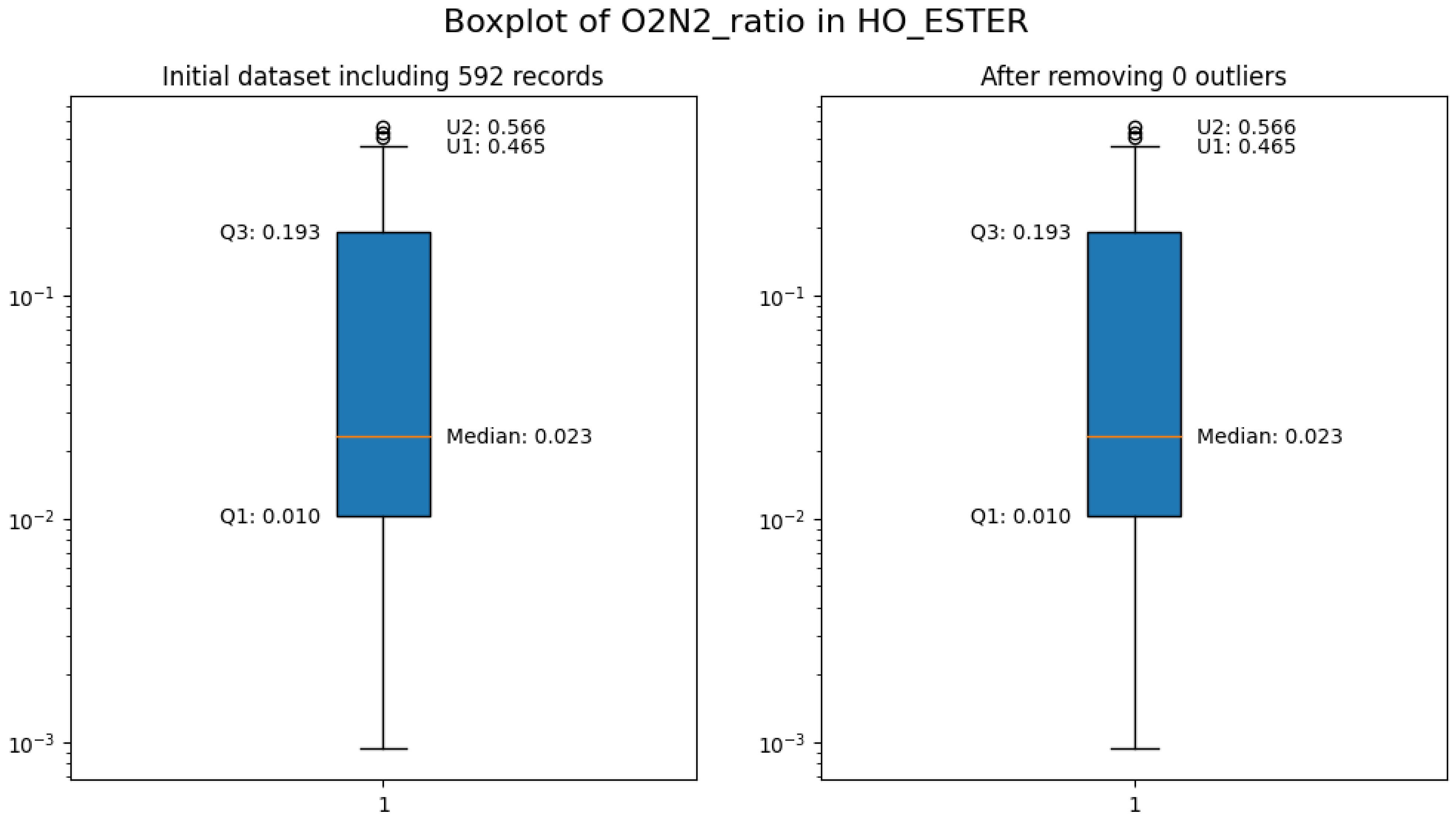
Histogram for the O2 records for LO_ESTER





Boxplot of O2N2_ratio in LO_ESTER
Initial dataset including 60203 records
After removing 8309 outliers
U2: 0.075
U1: 0.048
Q3: 0.021
Median: 0.005
Q1: 0.002
Q3: 0.010
Median: 0.004
Q1: 0.002


Boxplot of O2N2_ratio in SY_ESTER
Initial dataset including 1869 records
U2: 1.041
U1: 0.572
Q3: 0.350
Median: 0.240
Q1: 0.109
10^0
10^{-1}
1
After removing 3 outliers
U2: 1.041
U1: 0.572
Q3: 0.350
Median: 0.239
Q1: 0.109
10^0
10^{-1}
1


Boxplot of O2N2_ratio in HO_ESTER
Initial dataset including 592 records
After removing 0 outliers
U2: 0.566
U1: 0.465
Q3: 0.193
Median: 0.023
Q1: 0.010
10^-1
10^-2
10^-3
1
U2: 0.566
U1: 0.465
Q3: 0.193
Median: 0.023
Q1: 0.010
10^-1
10^-2
10^-3
1

O2/N2 ratio for NEs is very different from mineral oil

- For 75% of the LO_ESTER records, the O2/N2 is equal to or lower than 0.02, a value 10x lower than what was proposed as criteria for mineral oil in C57.104
- For HO_ESTER records, the Q3 value is 0.193, very close to the 0.2 criterium.
- For SY_ESTER, where free-breathing units were expected, the Q3 was 0.35

- The variation of the O2/N2 for LO_ESTER may indicate that some units are non-intentionally free-breathing. The “normal” behavior is for the O2 to be consumed, leading to very low values of O2/N2

- A new “O2/N2” threshold must be defined for LO Esters.

Initial calculations of the Percentiles ("Table 1")

- The following charts present a comparison of the value of the 90^{th}, 95^{th}, and 98^{th} percentiles.
- The original values included in Table 1 were the results for the 90^{th} percentile
- In C57.104, Table 2 uses the 95^{th} percentile.
- The 98^{th} percentile may be used as an "alarm level"

Current values (C57.155)

Table 1—Threshold value for transformers with no previous sample history, summary of 90th percentile values [μL/L (ppm)] with 95% confidence interval from Annex A[8]

Ester Fluid Type	Number of Records		H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO
Soybean	4,378	90th Percentile	112	20	232	18	1	161
		95% C.I.	(105–118)	(19–22)	(219–247)	(17–20)	(1–1)	(150–179)
High Oleic Sunflower	476	90th Percentile	35	25	58	16	0	497
		95% C.I.	(24–45)	(18–30)	(36–84)	(12–23)	(0–0)	(314–583)
Synthetic	157	90th Percentile	64	104	124	150	13	1344
		95% C.I.	(52–82)	(49–135)	(105–362)	(79–215)	(0–33)	(937–1526)

Provisional comparison (red = current values)

Low Oleic Natural Esters

	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO
P90th	112 → 67	20 → 11	232 → 405	18 → 9	1 → 0	161 → 89
P95th	171 → 91	41 →15	389 → 525	36 →12	3 →0	462 → 124
P98th	288 → 119	111 →20	841 → 657	118 →16	10 →1	1,471 → 162

High Oleic Natural Esters

	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO
P90th	35 → 16	25 → 11	58 → 5	16 → 5	0 → 0	497 → 163
P95th	60 → 23	37 → 16	131 → 6	40 → 7	0 → 0	715 → 232
P98th	126 → 35	45 → 22	175 → 11	46 → 10	3 → 0	1,335 → 304

Synthetic Esters

	H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO
P90th	64 → 44	104 → 27	124 → 69	150 → 28	13 → 2	1344 → 603
P95th	88 → 63	144 → 60	474 → 98	230 → 106	42 → 3	1,541 → 769
P98th	100 → 78	179 → 91	592 → 116	325 → 161	51 → 4	1,736 → 920

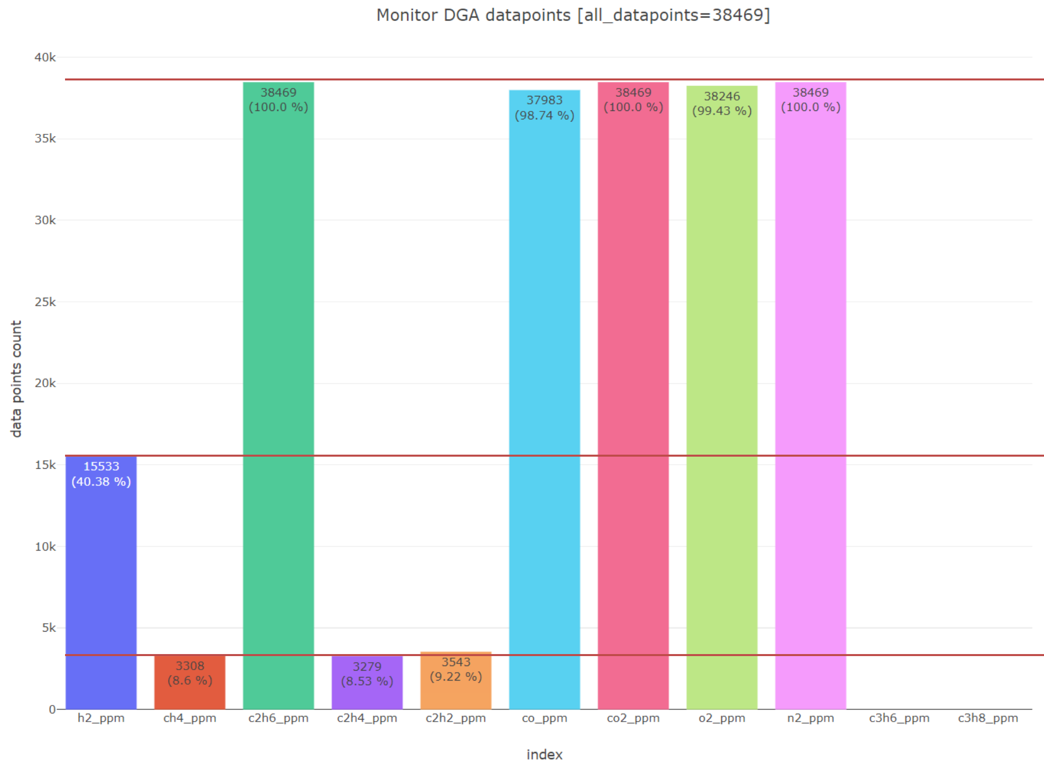
red = values from Annex A of C57.155-2014

C57.155 – Ester DGA monitor data (Toni)

- Extremely odd seeming distribution of gases available in the data
- Monitors should present 0 ppm when detecting no gases not (nan, not a number)

Missing data (not a number):

h2_ppm	22936
ch4_ppm	35161
c2h6_ppm	0
c2h4_ppm	35190
c2h2_ppm	34926
co_ppm	486
co2_ppm	0
o2_ppm	223
n2_ppm	0
c3h6_ppm	38469
c3h8_ppm	38469



60% DGA monitor(s) with only C2H6, CO, CO2, O2, N2

~32% DGA monitor(s) with only H2, C2H6, CO, CO2, O2, N2

~8.5% DGA monitor(s) with All fault gases + N2 + O2

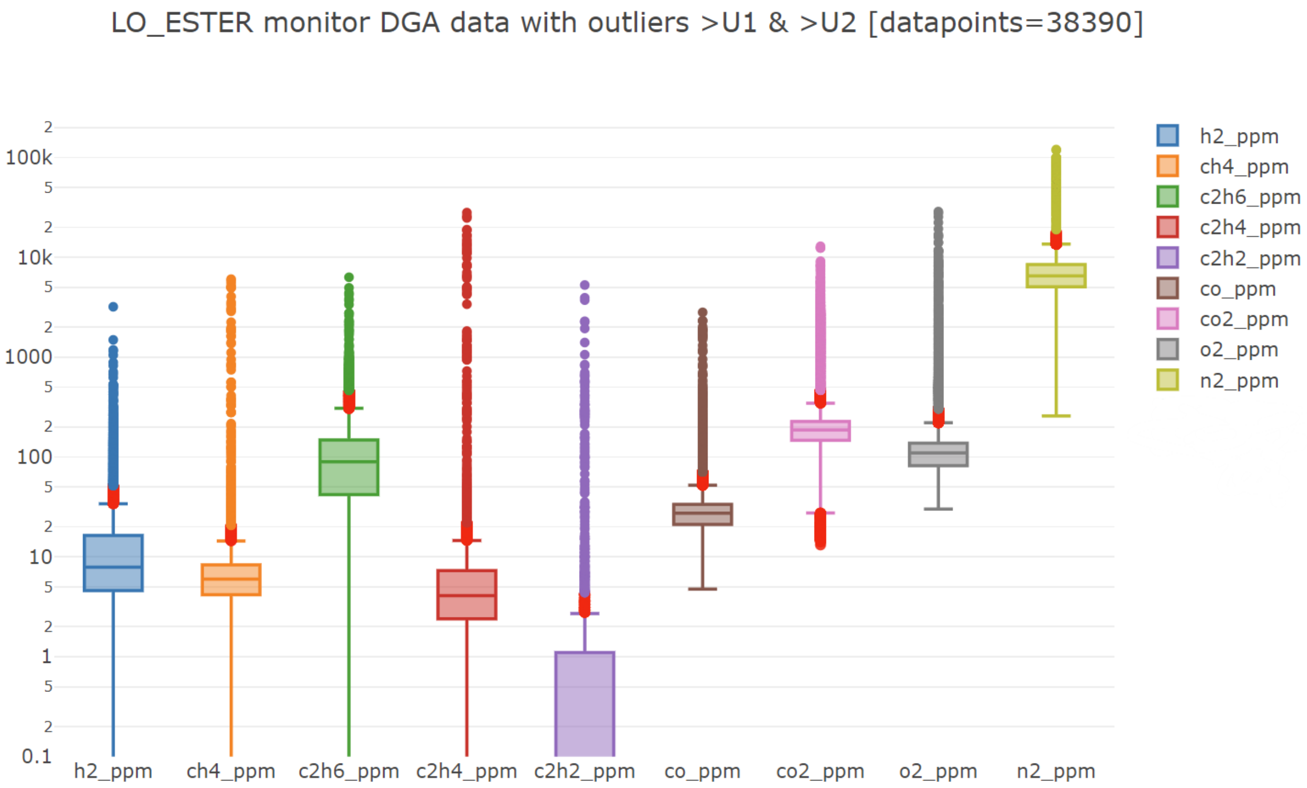
C57.155 – Ester DGA monitor data

– Only low oleic content type ester fluid has sufficient data for any analysis

– Initial statistical data analysis done (no removal of outliers done yet)

Fluid type data:

LO_ESTER	38390
HO_ESTER	44
NaN	35



	H2	CH4	C2H6	C2H4	C2H2	CO	CO2	O2	N2
count	15454	3229	38390	3200	3464	37904	38390	38167	38390
mean	18	36	111	139	13	31	272	160	11104
std	48	309	127	1327	154	47	435	511	15144
min	0	0	0	0	0	5	13	30	258
25%	5	4	42	2	0	21	147	82	5068
50%	8	6	90	4	0	27	187	110	6508
75%	16	8	148	7	1	34	227	138	8473
90%	37	19	174	19	3	41	290	206	13881
95%	71	30	201	36	7	46	844	289	57200
99%	166	503	609	4241	285	98	2421	865	70600
max	3196	6040	6312	28036	5278	2810	12896	28700	120000
IQR	12	4	106	5	1	12	80	56	3405
U1	34	14	307	15	3	52	347	221	13580
U2	52	21	466	22	4	71	466	304	18686