Foto: Försvarsmakten/David Gernes

Source localization capability of a Q_B – Array versus a single state-of-the art system.

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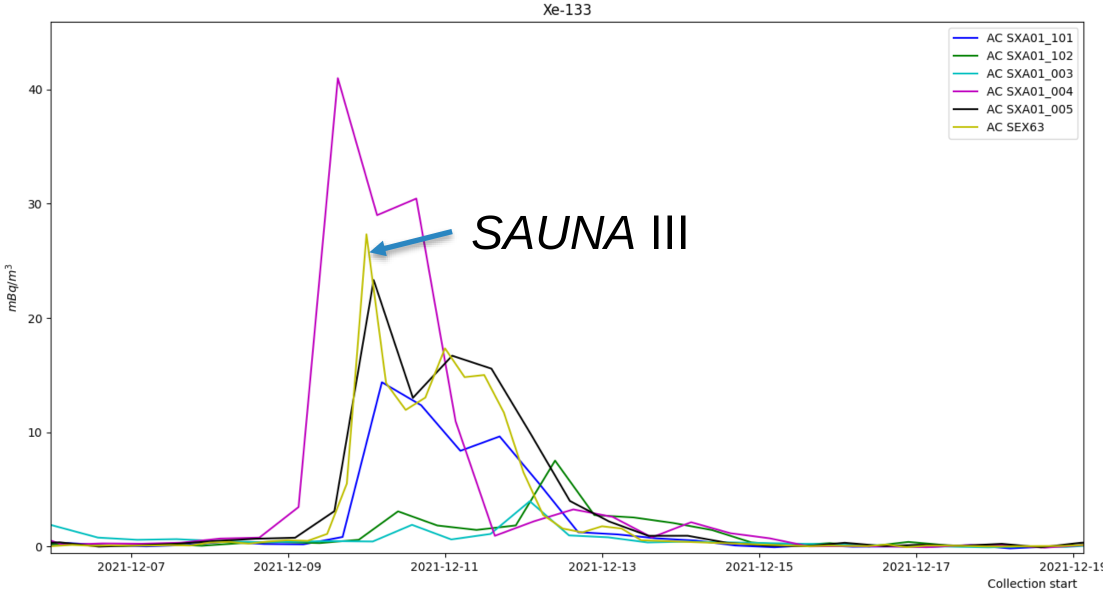
Swedish Defence Research Agency (FOI)

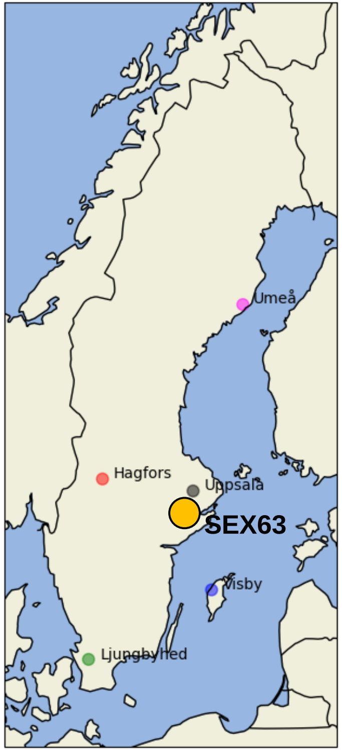
Outline

- Radioxenon sources in Europe
- The Swedish Q_B – Array and SAUNA III
- Evaluating performance and method with simulations
- Examples from real data
- Conclusions

To what extent will higher sensitivity and shorter collection time compensate for multiple sampling locations?



SAUNA III



Radioxenon sources in Europe

- 192 reactors
- 11 Isotope production facilities

  +

- Hospitals
- Research reactors
- …

Suggested task for WOSMIP:
“The WOSMIP list of potential radioxenon emitters”

The Q_B - array

The SAUNA Q_B – array is *the next step in remote sensing of activities involving nuclear fission*.

Has the possibility to increase…

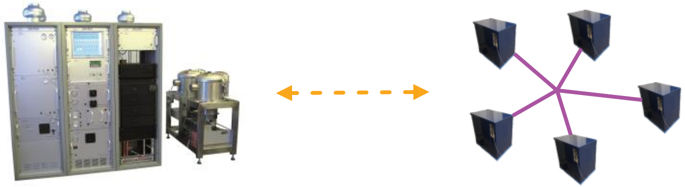
Detection capability by decreasing average source-receptor distance and increasing coverage.

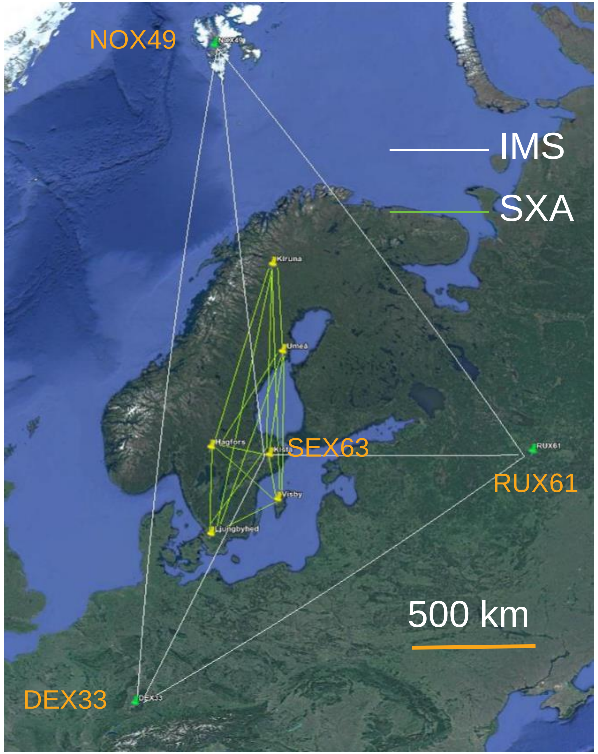
Location capability by increasing number of detecting sensors.

Categorization capability by increase the number of samples.

Redundancy and flexibility

… to a cost comparable to a single state-of the art system like SAUNA III





The Swedish xenon array (units connected by green lines) shown together with nearby IMS radioxenon stations (white lines).

SAUNA III in operation

Testing in Charlottesville, US

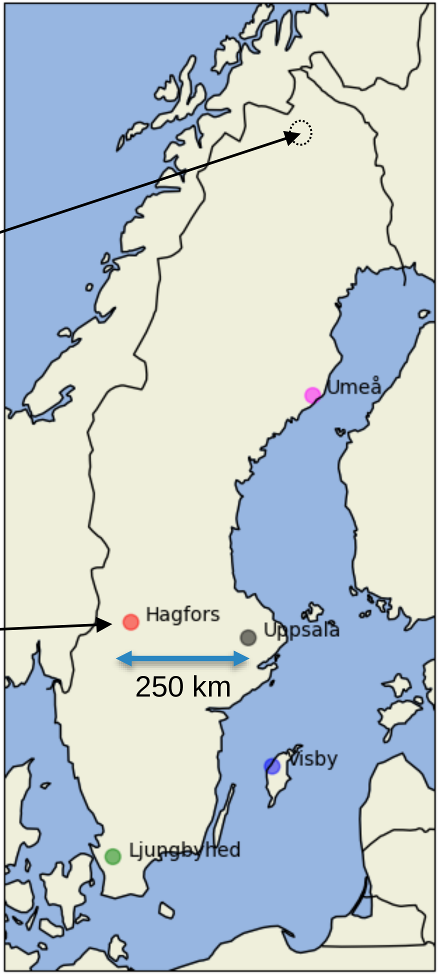
Installation in Stockholm

- After completed acceptance testing, system installed at RN63, Stockholm
- Provides increased verification capability to the IMS
- Offered as an upgrade
- New analysis method and software developed

Array installation

- All five Q_B:s installed and started in May 5, 2021
- The Uppsala unit is now in Leeds for the Xenah - project
- One unit will later be moved from Uppsala to Kiruna in the north of Sweden.

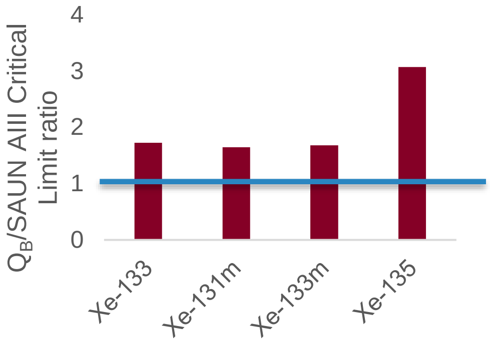
Installation of the first Q_B - unit in Hagfors, Sweden, in November 2020.



SAUNA III vs Q_B – Array

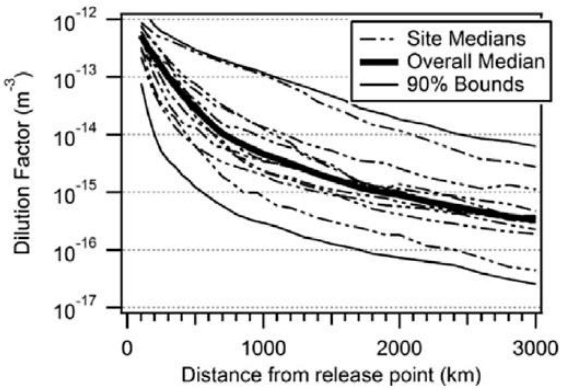
Numbers obtained from the dataset discussed here.
Not nominal values from the manufacturer.

	SAUNA III	**Q_B – Array (x 5)**
Air flow (m^3/h)	7.5	1.9
Median stable xenon volume/sample (ml)	2.74	1.25
Collection time	6 h	12 h
Activity measurement time	6.2 h	10.5 h
Gas background	YES (opt: NO)	NO
Drift correction	YES	YES
Median LC ^{133}Xe (mBq/m^3)	0.087	0.15
Median LC ^{131m}Xe (mBq/m^3)	0.056	0.092
Median LC ^{133m}Xe (mBq/m^3)	0.047	0.079
Median LC ^{135}Xe (mBq/m^3)	0.15	0.46

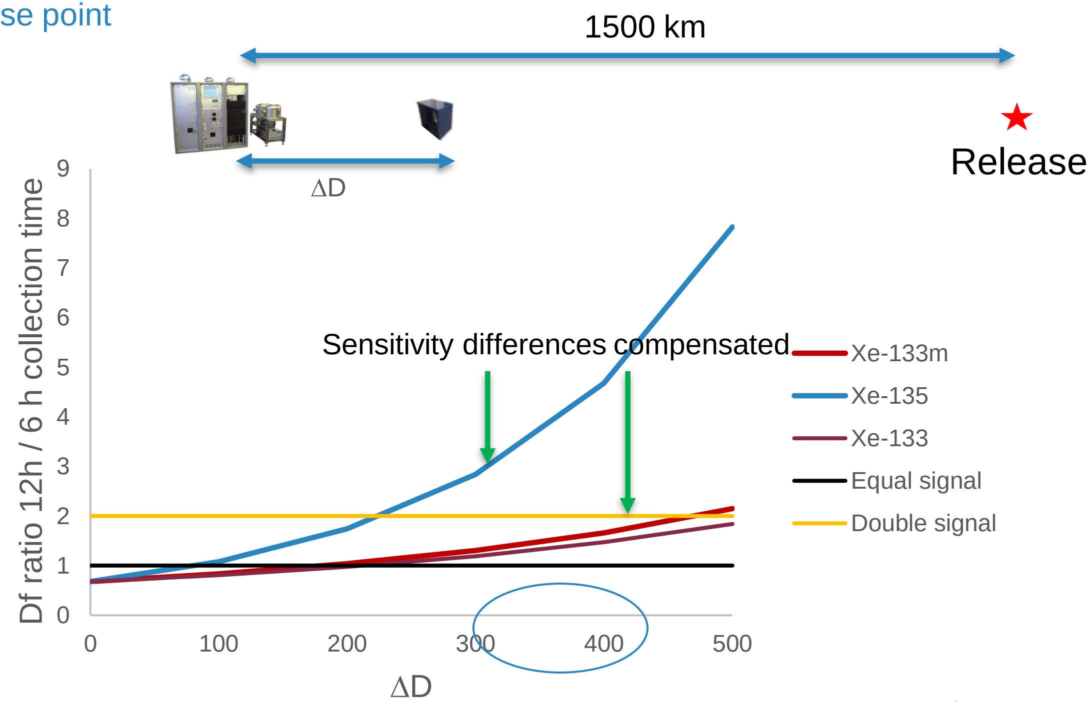


The effect of distance to source

Using published model results*, taking collection time effects into account, the “signal ratio” for a 12h vs. a 6h system was calculated, assuming 1500 km distance from the release point and the 6h – system.

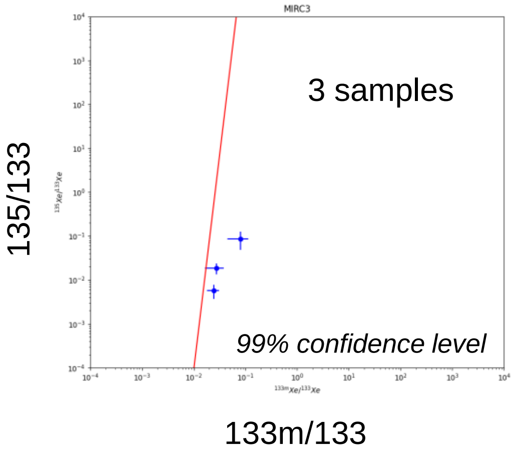


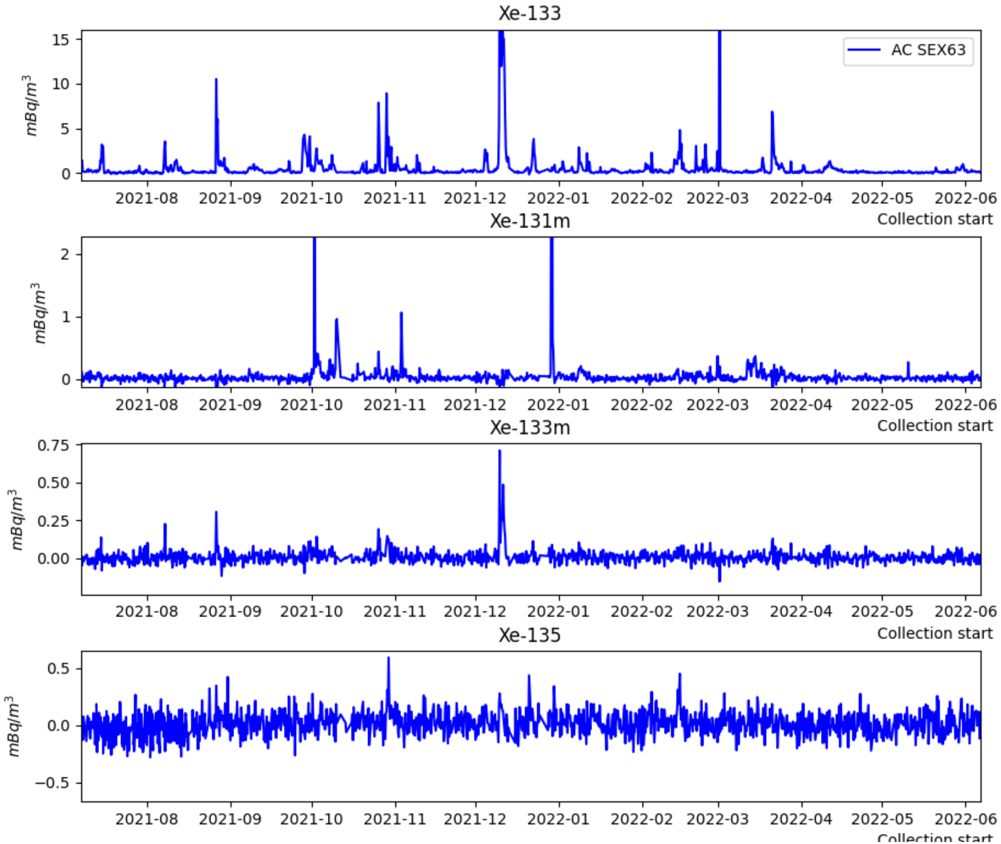
*P. W. Eislinger et.al., Journ. Env. Rad. 148(2015) 123-129



On the average: Q_B = SAUNA III if moved ~ 300-400 km closer to source

SEX63 SAUNA III data
July 2021- June 2022

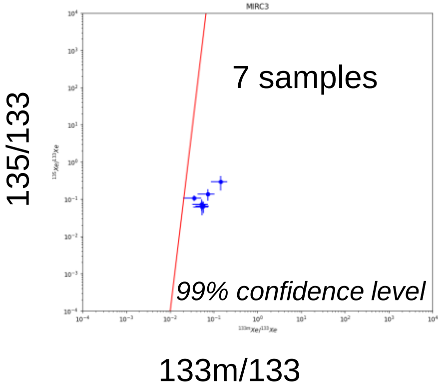


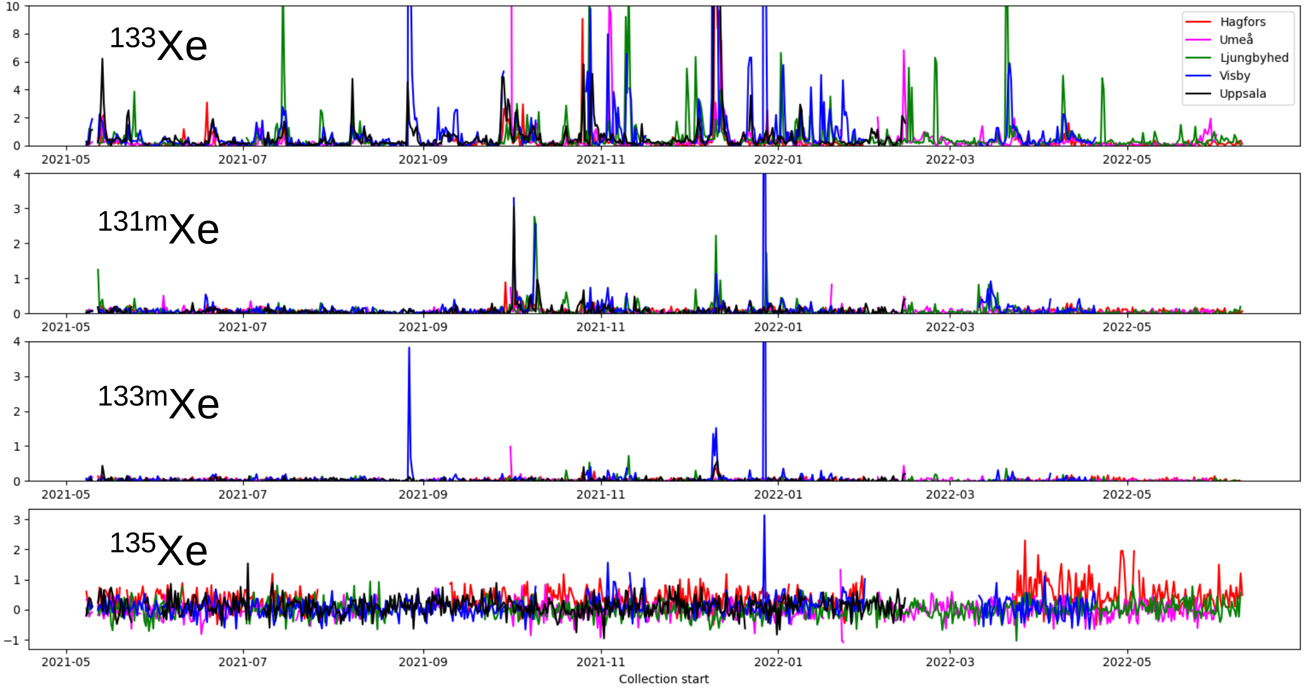


^{133}Xe mean AC: 0.49 mBq/m^3

^{133}Xe 95th percentile AC: 1.6 mBq/m^3

SXA01 data May 2021- June 2022





^{133}Xe mean AC: 0.60 mBq/m^3

^{133}Xe 95th percentile AC: 2.1 mBq/m^3

Evaluating systems performance and method using simulations

Three hypothetical nuclear explosions 1500 – 2000 km from Swedish territory modelled using forward ATM. 1 h release time.

Source term: ^{239}Pu fission with 3 hours ingrowth before 1% released.

	Released activity (Bq)
^{133}Xe	1.115e+13
^{131m}Xe	2.758e+09
^{133m}Xe	1.978e+12
^{135}Xe	7.672e+14

Modelling of measured concentrations

$$C = \frac{N}{\varepsilon B}\,\frac{\lambda^2}{(1-e^{-\lambda t_C})e^{-\lambda t_P}(1-e^{-\lambda t_A})}\,\frac{t_C}{V} = \frac{N}{S} = \frac{n-n_0}{S}$$

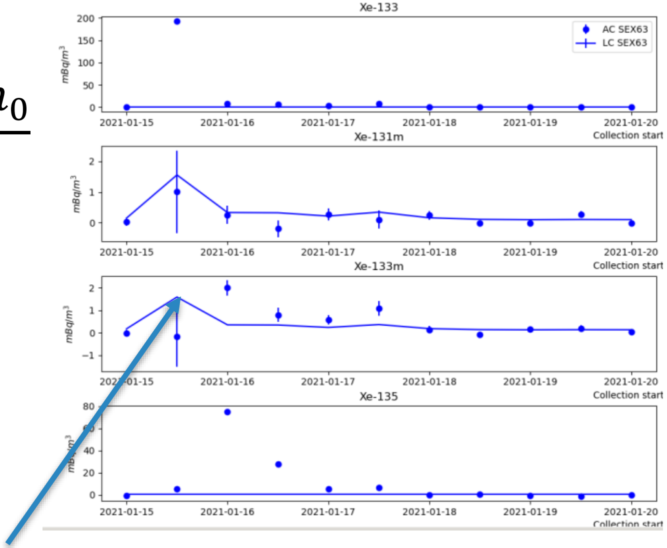
$$\sigma_C^2 = \frac{\sigma_n^2+\sigma_0^2}{S^2} = \frac{n+n_0}{S^2}$$

$$L_C = \frac{k\sigma_0}{S} = \frac{k}{S}\sqrt{n_0}$$

Randomize:

$$n \sim Po(SC+n_0)$$

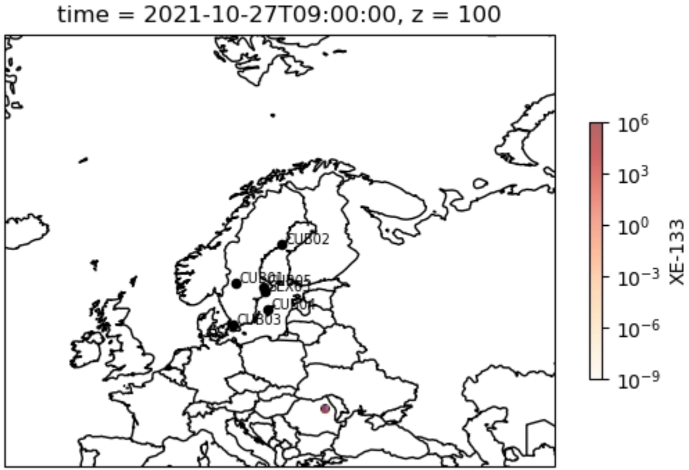
$$C = Po(SC+n_n) - Po(n_0)$$

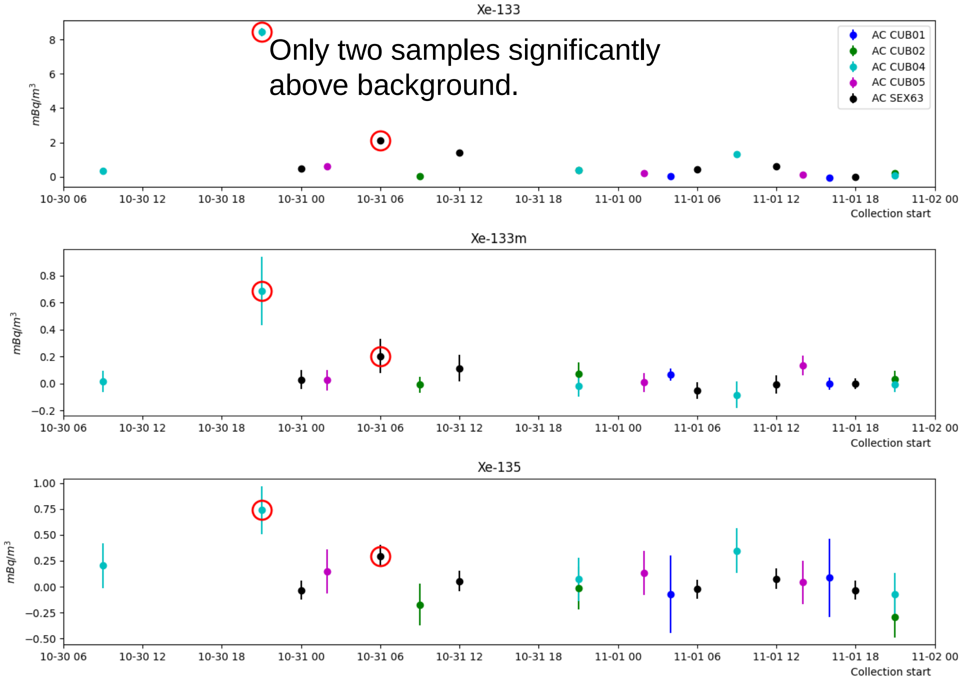


Interference correction for metastables:

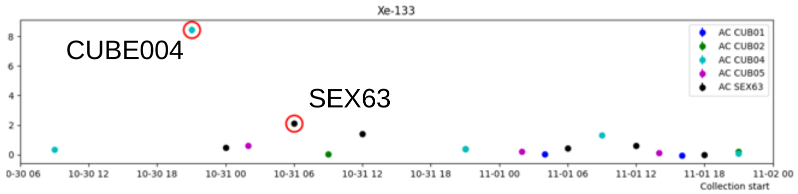
$$n_0' = n_0 + RN_{133}$$

Explosion 1

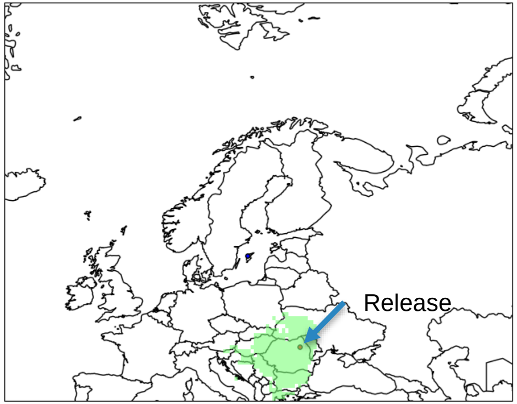



Only two samples significantly above background.

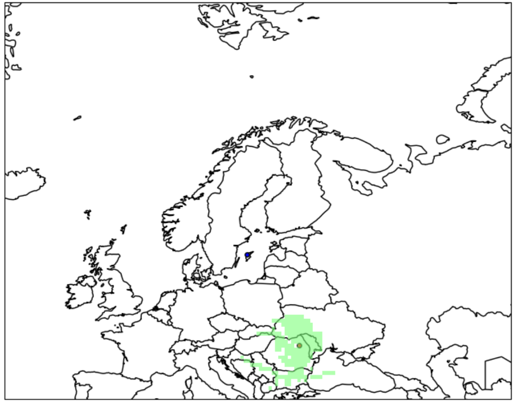
Explosion 1



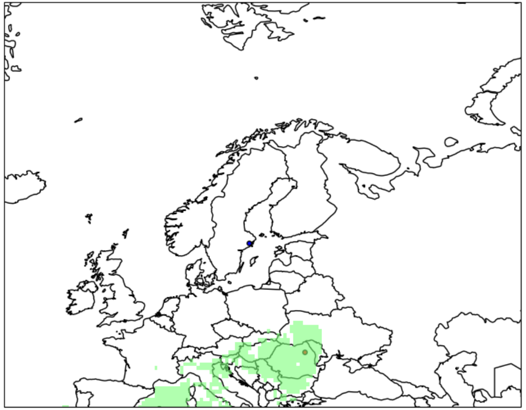
time = 2021-10-27T09:00:00, z = 100



z = 100, time = 2021-10-27T08:00:00



time = 2021-10-27T09:00:00, z = 100



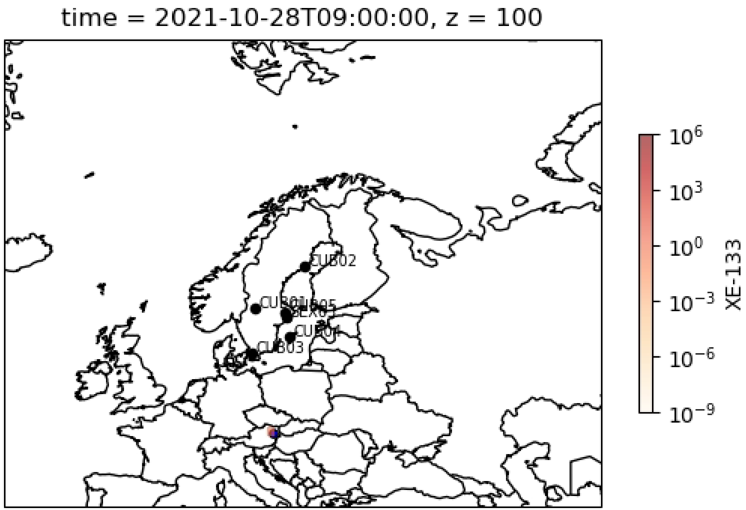
CUBE04 sample FOR at release time.

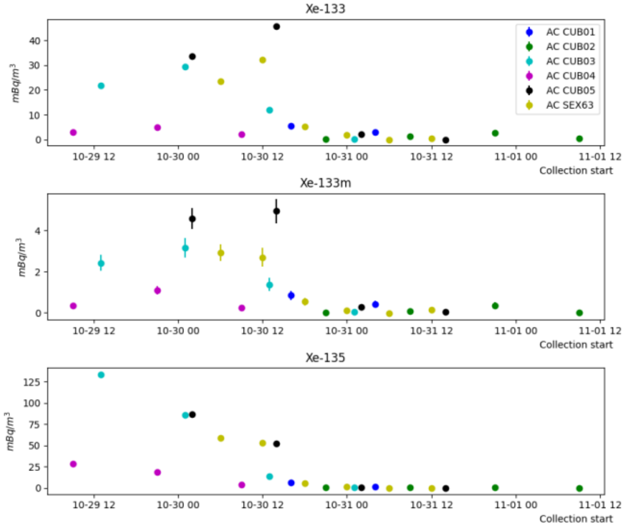
CUBE04 sample, FOR, *one non-detect included*.

SEX63 sample FOR

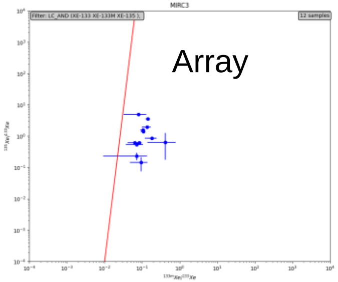
Hit 9 h *later* than CUBE004. Increased FOR area at release time.

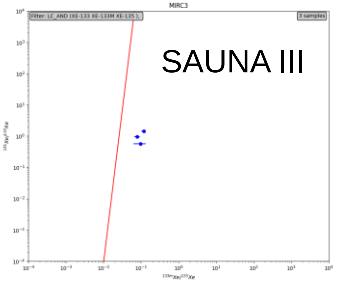
Explosion 2





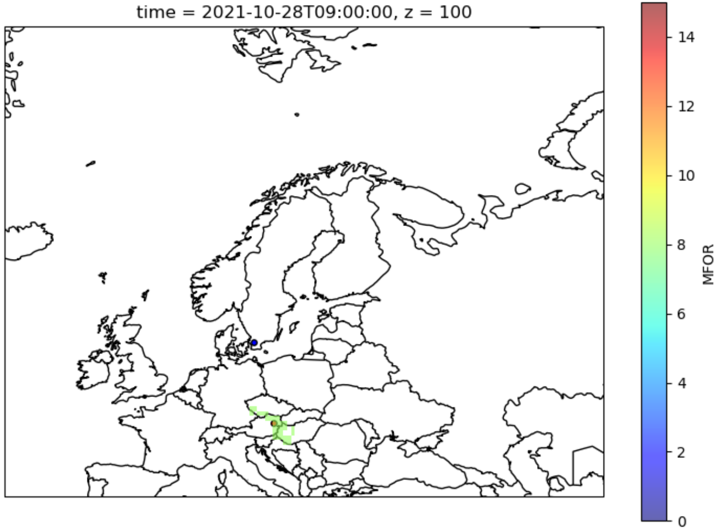
MIRC 3





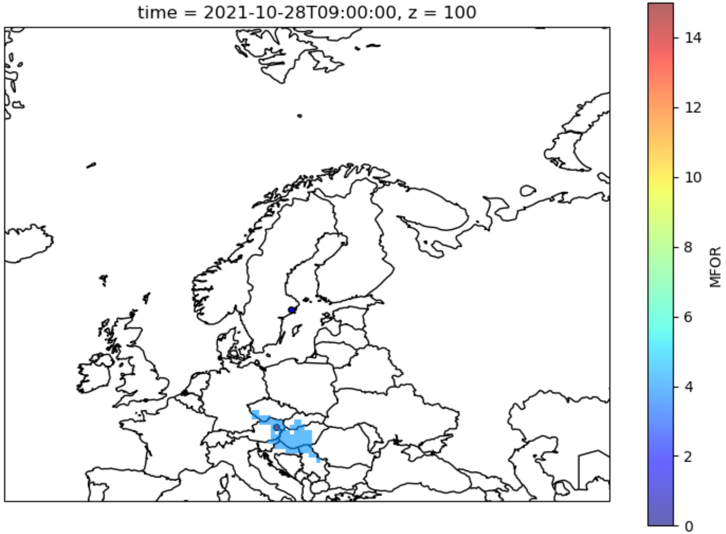
Explosion 2

Array FOR at release time
8 samples



$ST_{133} = 1.4\ E\ {+13}\ Bq$

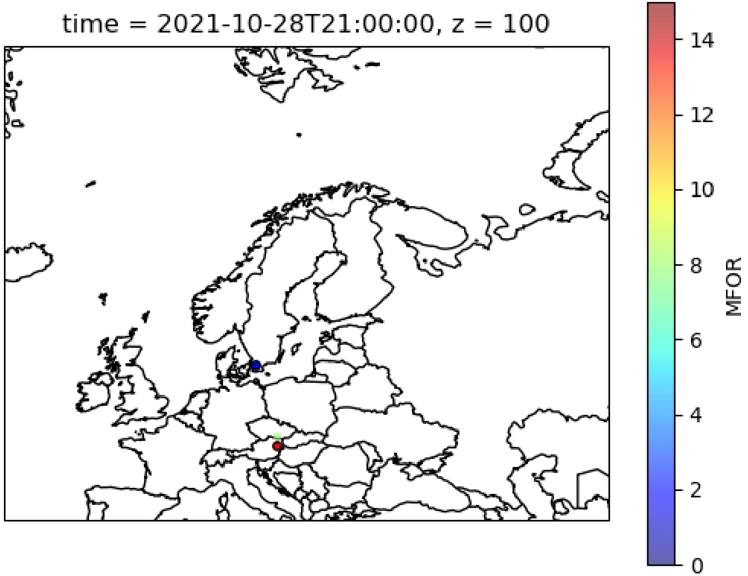
SEX63 FOR at release time
4 samples



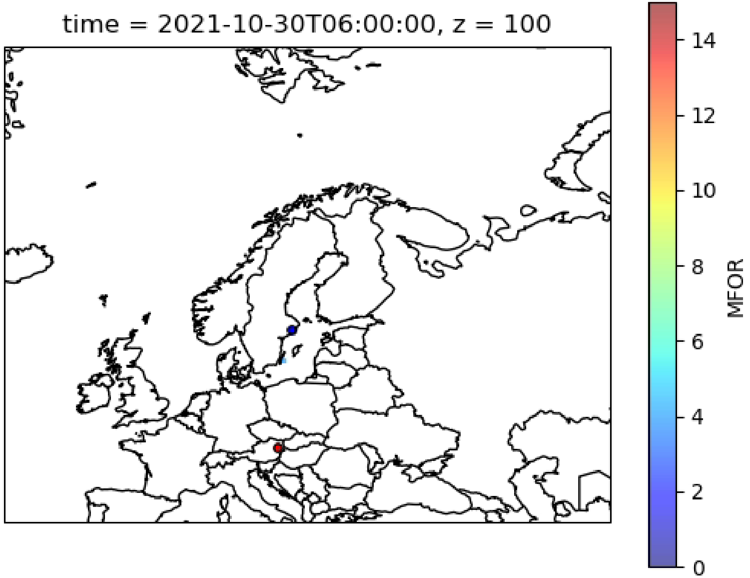
$ST_{133} = 4.5\ E\ {+13}\ Bq$

Explosion 2

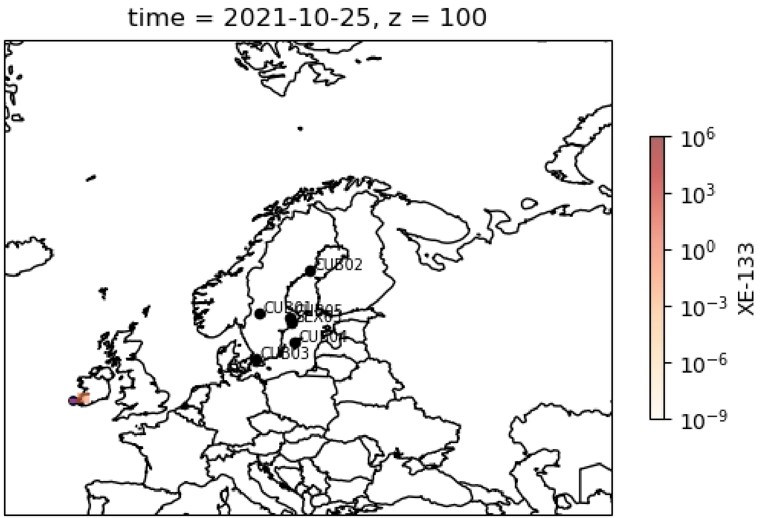
Array FOR

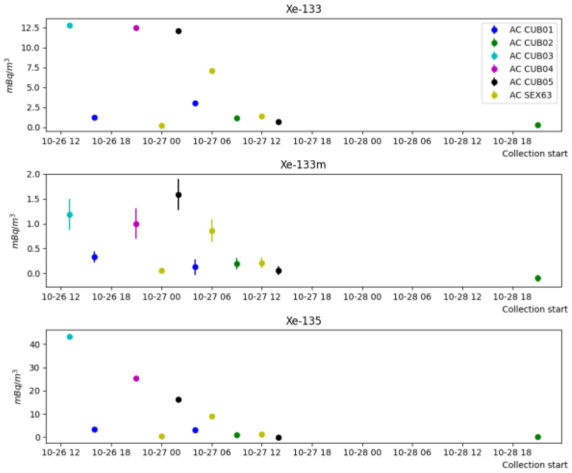


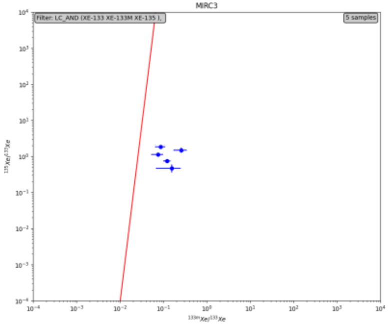
SEX63 FOR



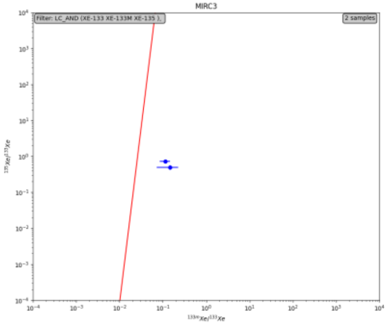
Explosion 3







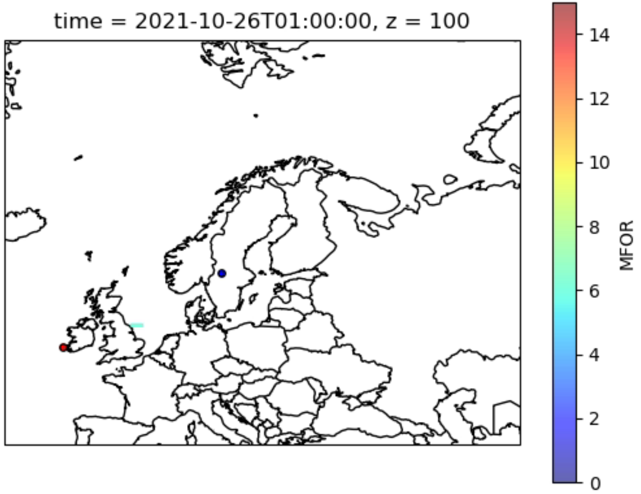
Array



SEX63

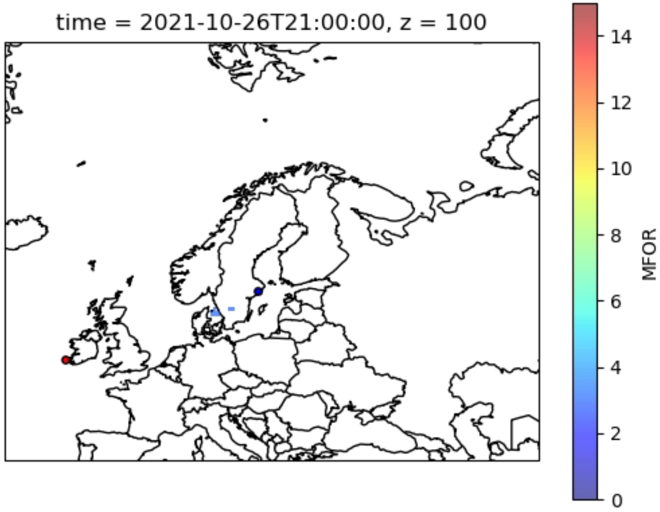
Explosion 3

Array FOR, 6 samples



$ST_{133} = 6.8\ E+12$

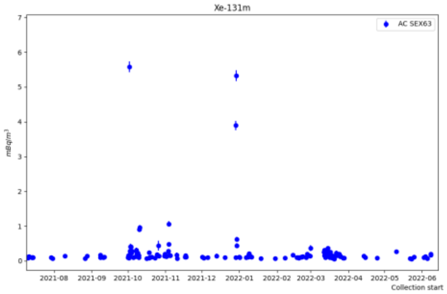
SEX63 FOR, 4 samples



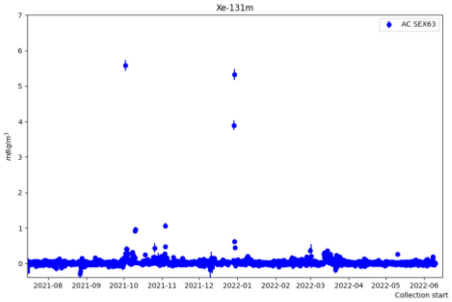
$ST_{133} = 6.2\ E+12$

Where is the ^{131m}Xe – source ?

^{131m}Xe detected

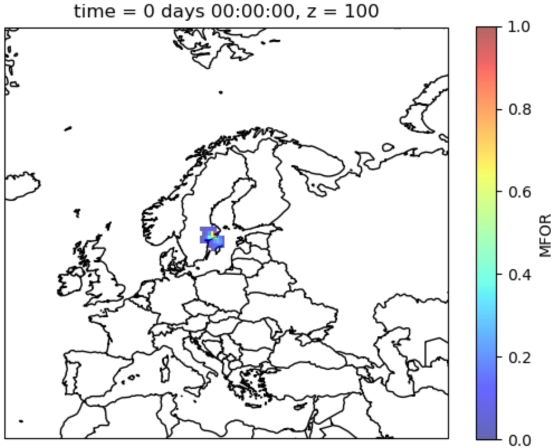


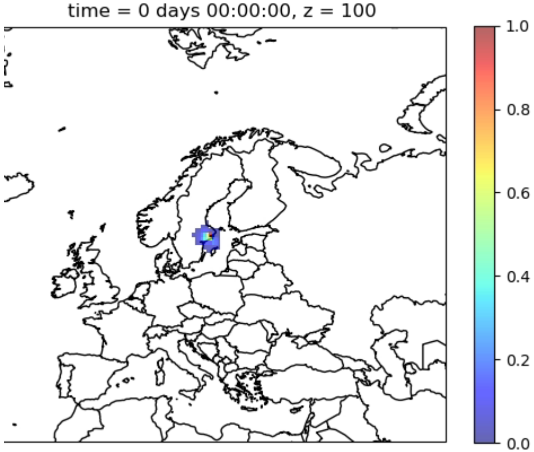
All samples

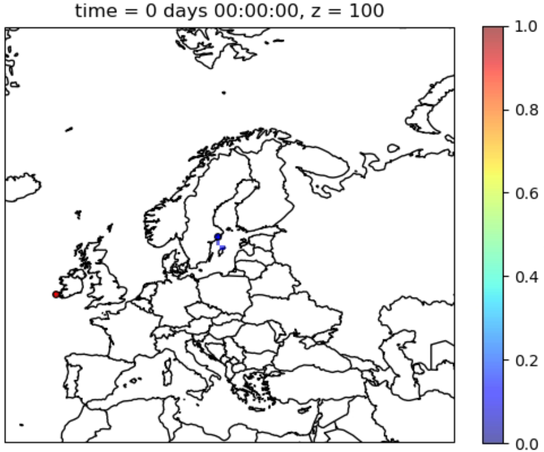


MFOR: Add all FOR:s and normalize to number of samples. SAUNA III – data used.

Subtracted MFOR

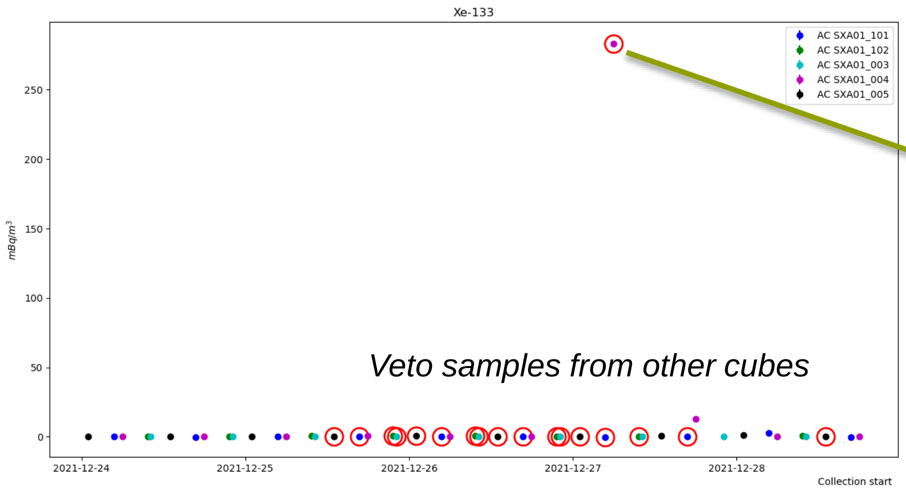






Improved location analysis using array data with non-detections

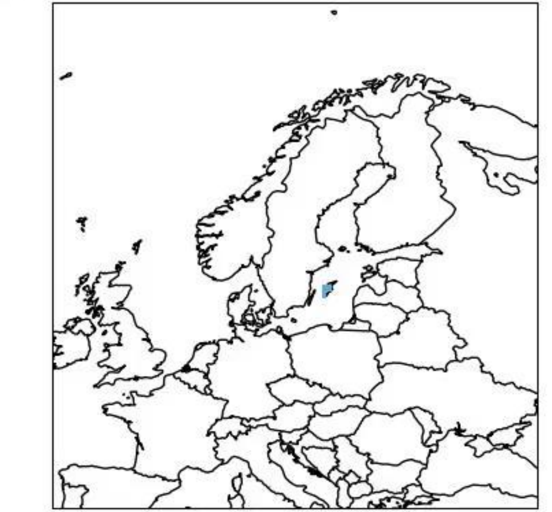
- On Dec 27, 2021, a single sample containing 283 mBq/m^3 was measured in CUBE04 at Visby, Gotland.
- FOR greatly reduced using non-detects from other units



Veto samples from other cubes

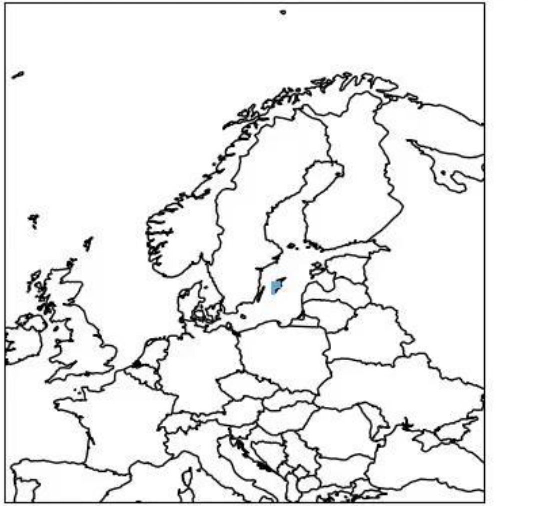
FOR for sample

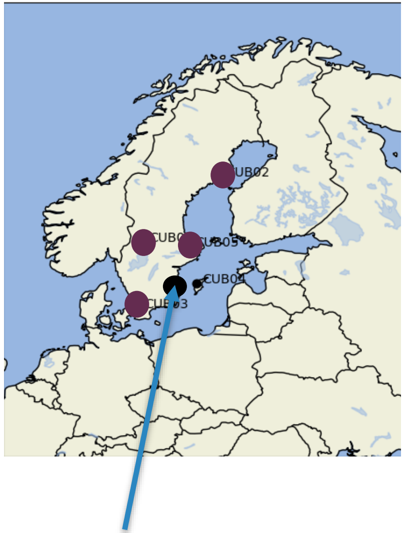
time = 2021-12-27T17:00:00, for, Max: 1.000e



FOR using non-detects

time = 2021-12-27T18:00:00, for, Max: 1.000e+00

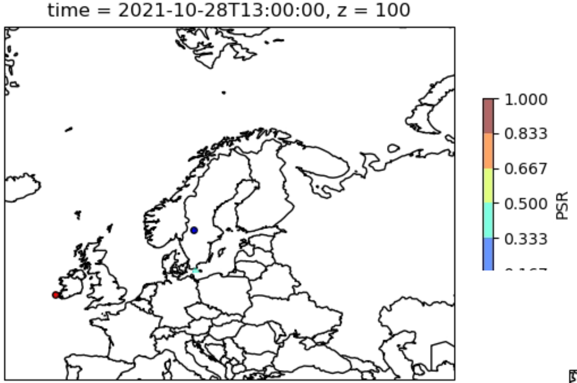




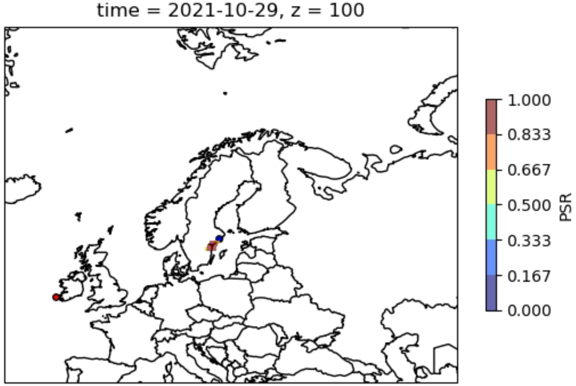
Confirmed source,
Oskarshamn NPP

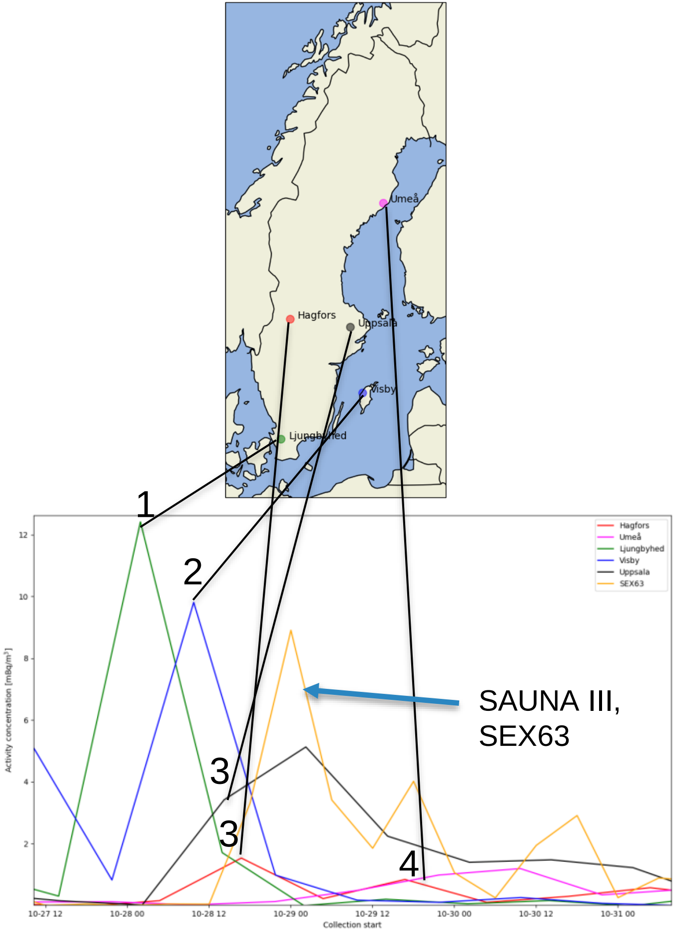
Plume in Oct 2021

Array



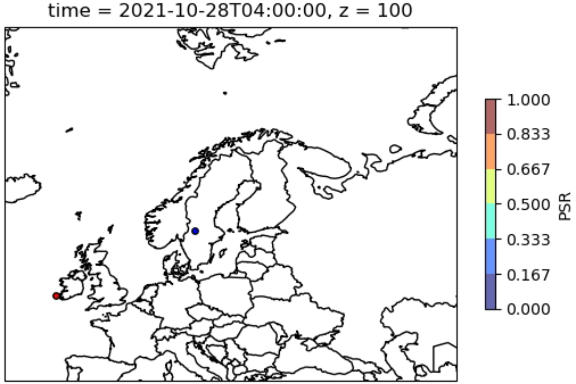
SAUNA III

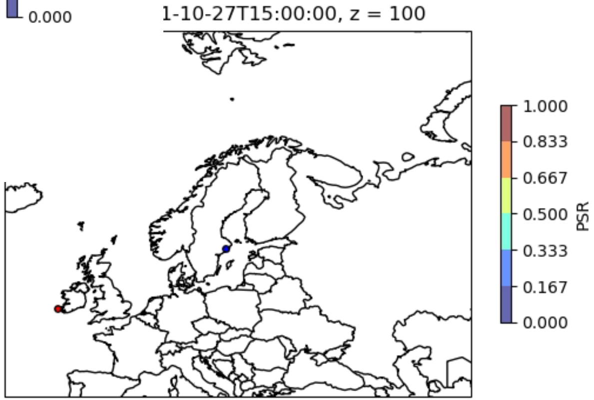


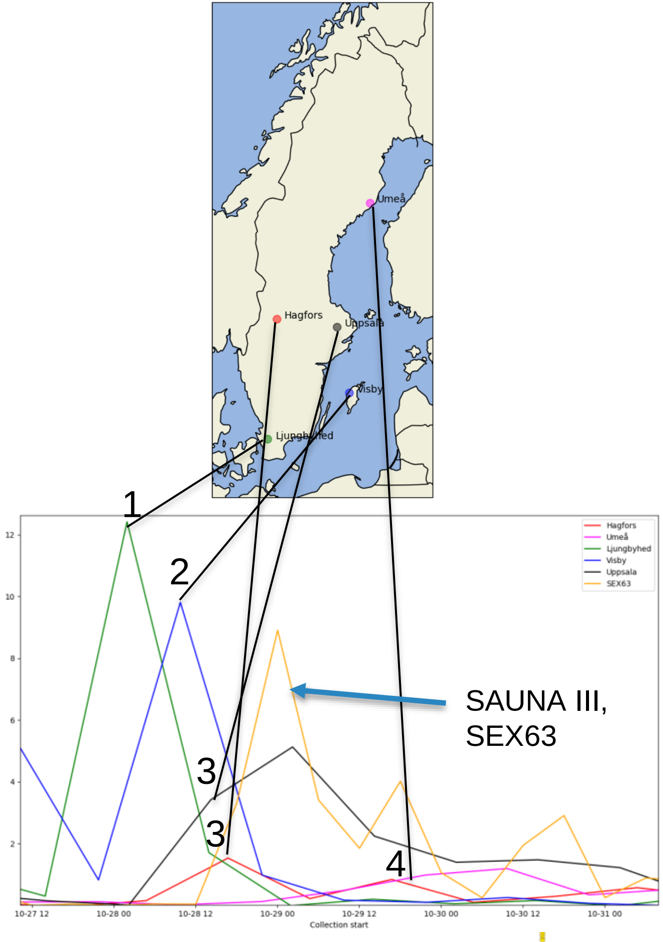


SAUNA III,
SEX63

Plume in Oct 2021



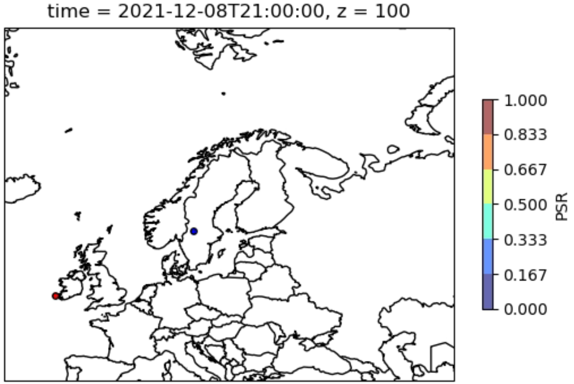




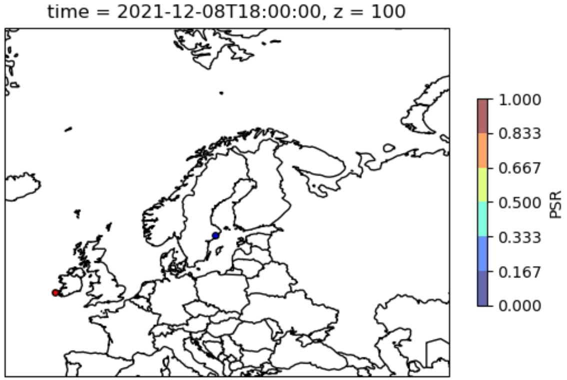
SAUNA III,
SEX63

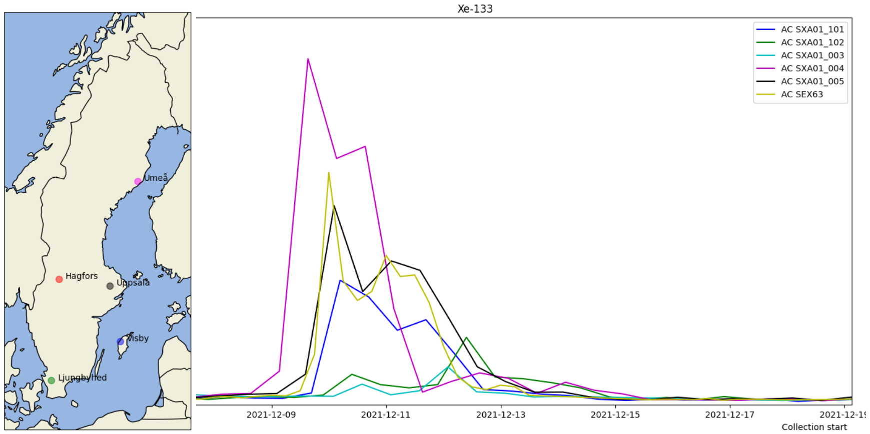
Plume detected in December 2021

Array 13 samples


time = 2021-12-08T21:00:00, z = 100

SEX63 8 samples

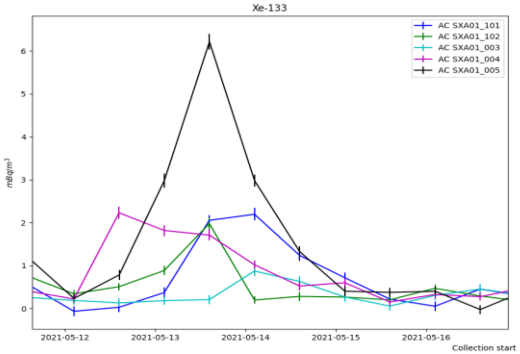

time = 2021-12-08T18:00:00, z = 100


Xe-133

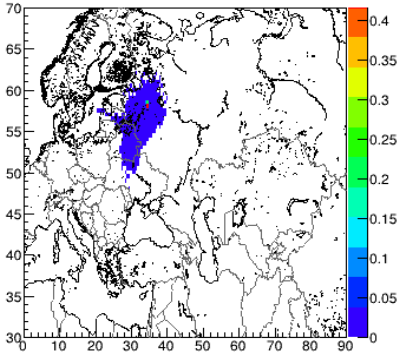
A last example:

Continuous source Bayesian PDF

Array:

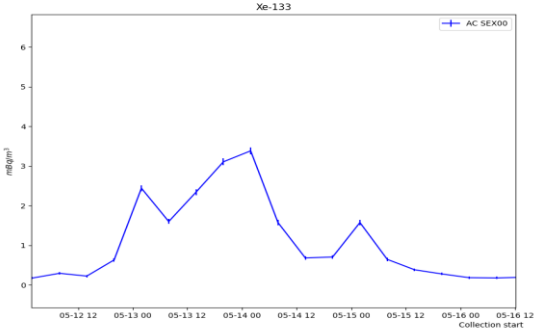


Continuous source Bayesian PDF

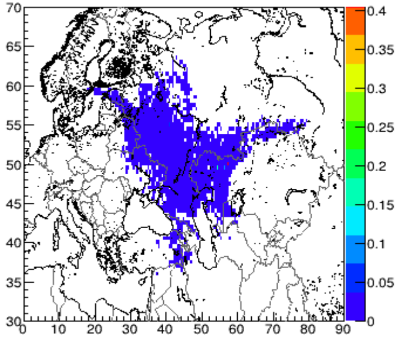


Time-independent (cont. source) Det: 19 NonDet: 0

SAUNA III:



Continuous source Bayesian PDF



Time-independent (cont. source) Det: 11 NonDet: 0

Conclusions

- For a release 1500 km away, a single Q_B – system will on the average have the same performance as a SAUNA III if placed 300-400 km closer, thanks to higher signal.
- This is not a complete study, but for the cases looked at the Swedish Array has higher verification performance compared to the single SAUNA III – system.
- Location (FOR and PSR sizes) is generally smaller for the Array.
- Multiple sampling locations allow for
  1) *Exclusion of nearby sources*
  2) *Large reduction of the FOR using non-detects.*
  3) *Reduced ATM-uncertainty due to shorter travelling times.*
- The Array has already helped identifying an additional release source in Sweden.