SnT 2021
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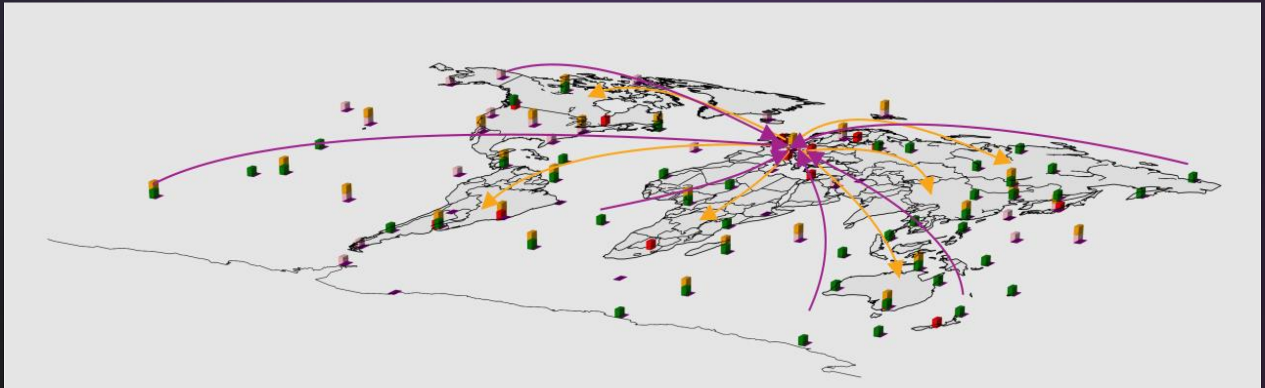
PREPARATORY COMMISSION

The IMS radionuclide network- a unique machine not yet fully exploited

Anders Ringbom
Swedish Defence Research Agency (FOI)



ORAL PRESENTATION

FOI

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The IMS RN network is unique

- The only global detection system for atmospheric radioactivity
- Raw data as well as analyzed data is globally distributed.
- The sensors have higher time resolution than in other networks
- Many particulate stations are automatic
- It contains a network of noble gas stations (all automatic)

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But..

- The system was designed 30 years ago
- Releases from UG tests shown to be smaller than expected
- The knowledge of the global background was limited at the time, in particular for xenon
- The design did not take the entire verification process into account
- The number of stations, as well as their placement, was the result of negotiations

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Outline

- The verification mission
- The RN signal
- The measurement system
- Observations and experience the last 20 years
- Future development

Special thanks to:

Kurt Ungar
Harry Miley
Johan Kastlander
Hakim Gheddou

However, all views expressed are my own

Anders Ringbom, Swedish Defence Research Agency (FOI), anders.ringbom@foi.se

The verification mission

To detect nuclear explosions by performing:

Detection → Location → Categorization

The analysis shold be *consistent* and *coherent*

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The verification mission

Prove with enough confidence that a nuclear test occurred, applying a set of pre-defined criteria

~~Find a nuclear explosion scenario that can explain the observations~~

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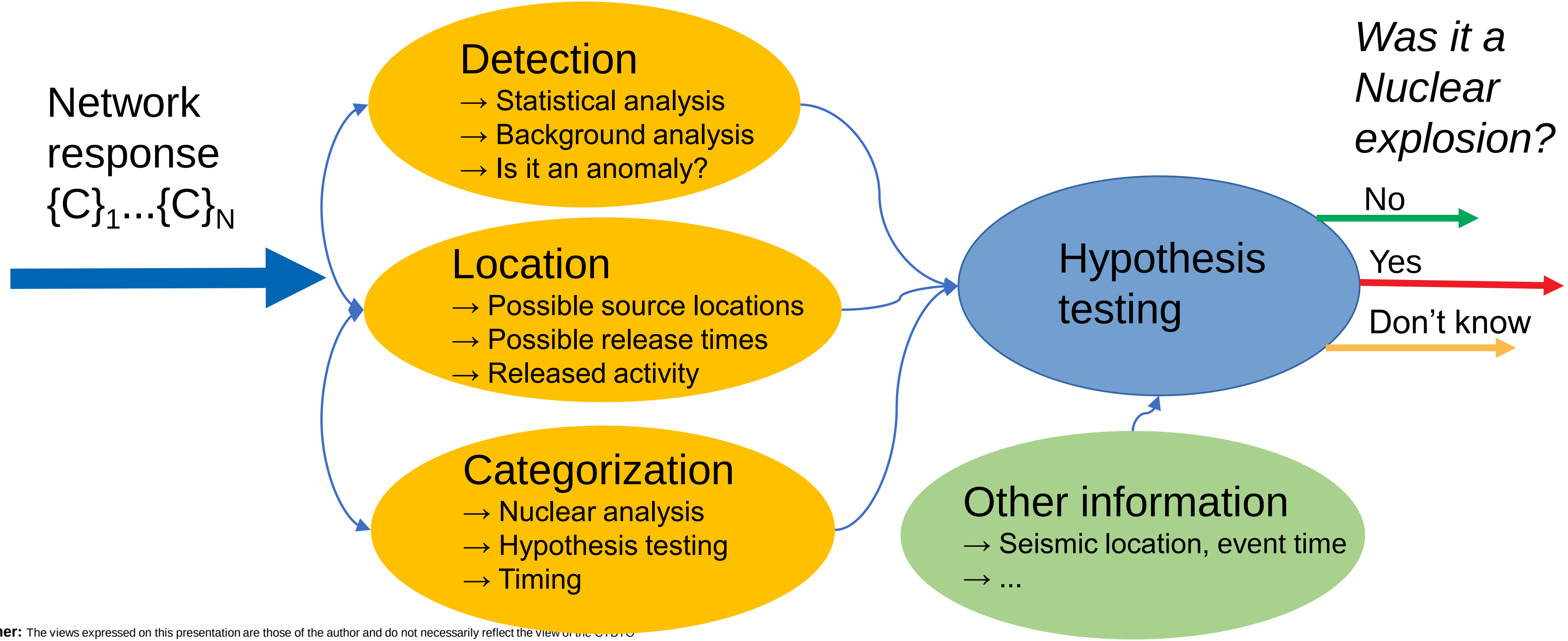
The RN verification process



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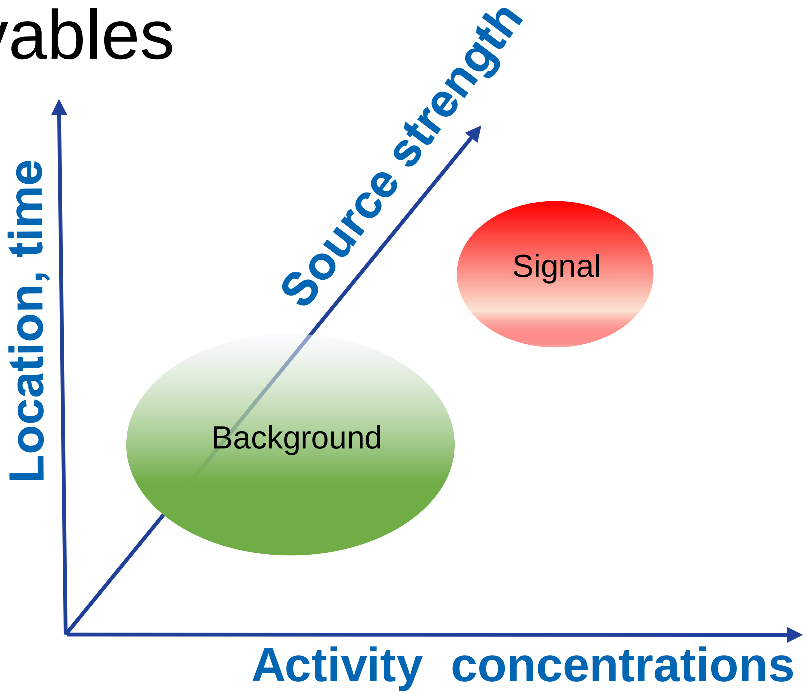
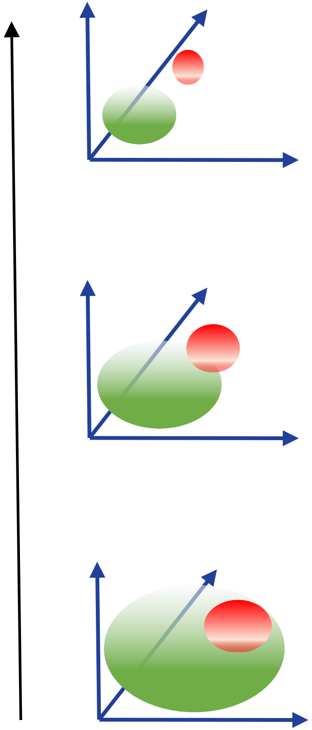
Signal vs background in space of observables



Improving the verification system



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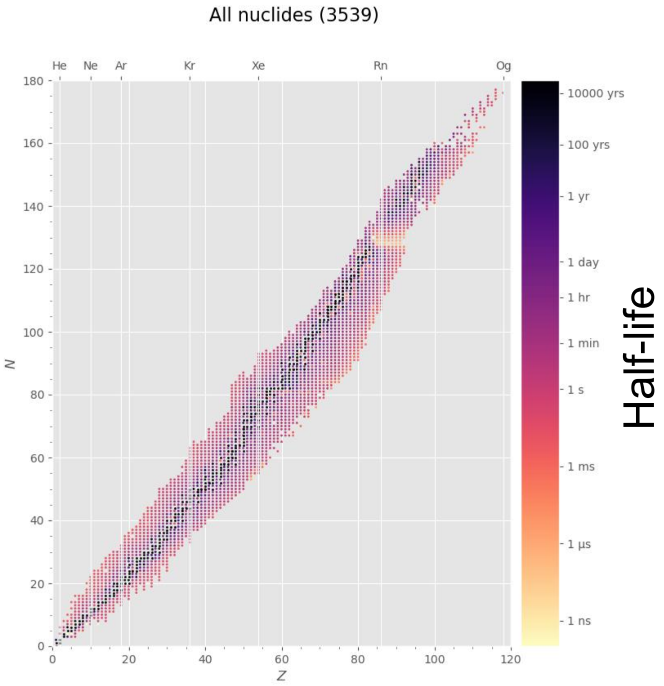
The RN – signal.
What is relevant for CTBT?

- Radionuclides formed in a nuclear explosion in high enough quantities
- Half-lives long enough to allow them to be transported and measured
- Detectable gamma radiation
- List should be agreed among member states



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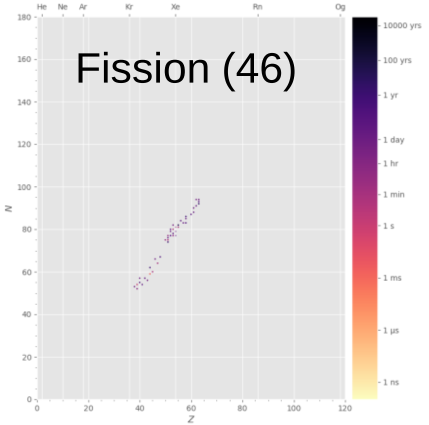
88 CTBT-relevant radionuclides



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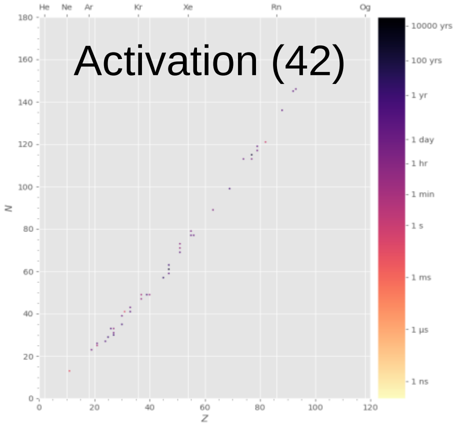

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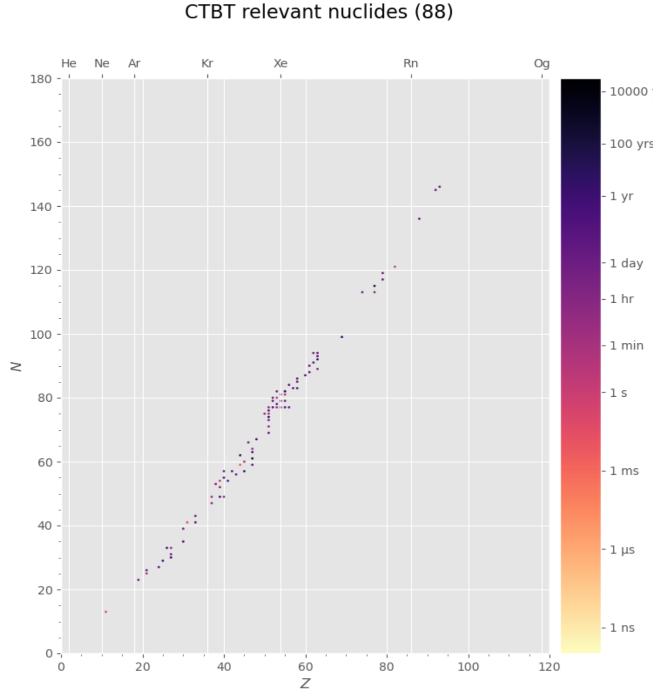

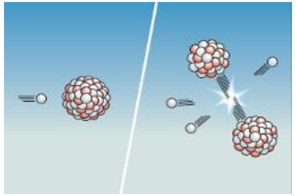

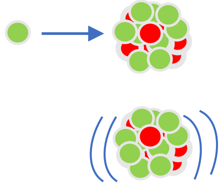

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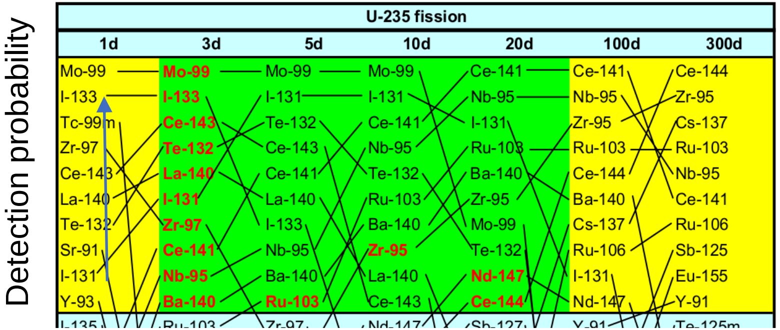
The signal – 88 CTBT-relevant radionuclides

- But some nuclides are more probable to detect than others
  Depends on for example production yield, branching ratios, and volatility
- The most probable scenario is an underground NE.



* K M Matthews, NRL-report 2005/1

Defines ”signficant” nuclides

Tabulated from DOE/NV-317

Noble Gas				Volatile above 600° C				Refractory			
Isotope	Number	$T_{1/2}$	Cum. Yield	Isotope	Number	$T_{1/2}$	Cum. Yield	Isotope	Number	$T_{1/2}$	Cum. Yield
^{131m}Xe	10	11.8 d	.0451	^{131}I	131	8.03 d	3.22	^{99}Mo	3	65.9 h	5.94
^{133}Xe	310	5.25 d	6.72	^{132}I	13	2.30 h	4.67	^{99m}Tc	1	6.01 h	5.23
^{133m}Xe	169	2.20 d	0.192	^{133}I	109	20.8 h	6.72	^{139}Ba	6	82.9 m	6.34
^{135}Xe	271	9.14 h	6.60	^{134}I	6	52.5 m	7.64	^{140}Ba	19	12.8 d	5.98
				^{135}I	88	6.58 h	6.30	^{140}La	17	1.68 d	5.98
				^{132}Te	13	3.20 d	4.66				
				^{137}Cs	10	30.1 y	6.22				
				^{138}Cs	29	32.5 m	6.65				
				^{139}Cs	1	9.27 m	6.32				

Harry Miley, Paul Eslinger, Ramesh Sarathi, *Impact of environmental background on atmospheric monitoring of nuclear explosions*, talk at WOSMIP remote II, 2021

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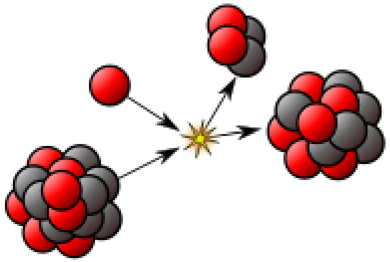
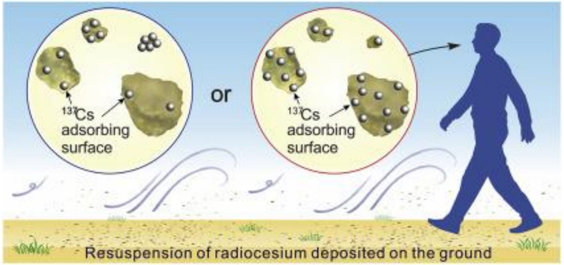
The radionuclide background

- Background from re-suspended soil: Rn and Th, ^{40}K, ^{238}U
- Cosmogenic: ^{7}Be (spallation of N,O), $^{22,24}Na$ (spallation of ^{40}Ar)
- Anthropogenic: IPFs, NPPs, research, industry, accidents, historical tests
- Background from the detector itself



Forsmark NPP, Sweden



N. Kaneyasu, *et.al.*, https://doi.org/10.1016/j.jenvrad.2017.03.001

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The machine

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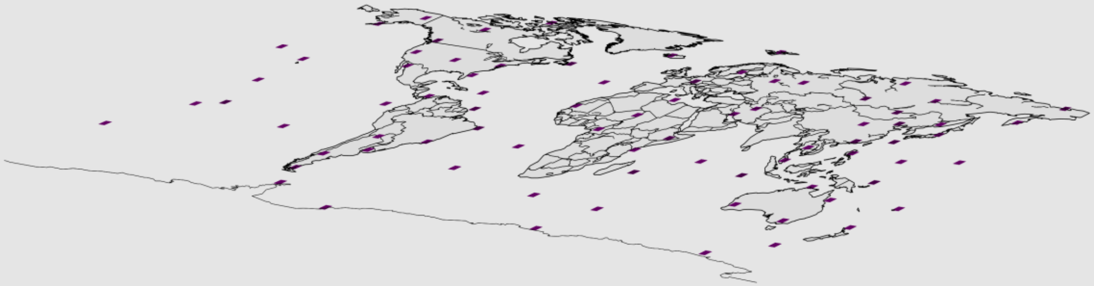
79 (80) globally distributed sites



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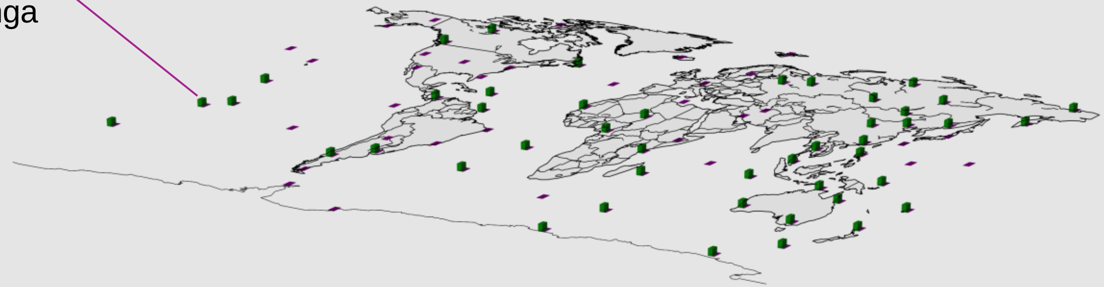
46 certified manual particulate stations

Collection time:	24 h
Decay time:	24 h
Measurement time:	24 h
Air flow:	> 500 m^3/h
Sensitivity	< 10-30 $\mu Bq/m^3$ for ^{140}Ba

RN23, Raratonga



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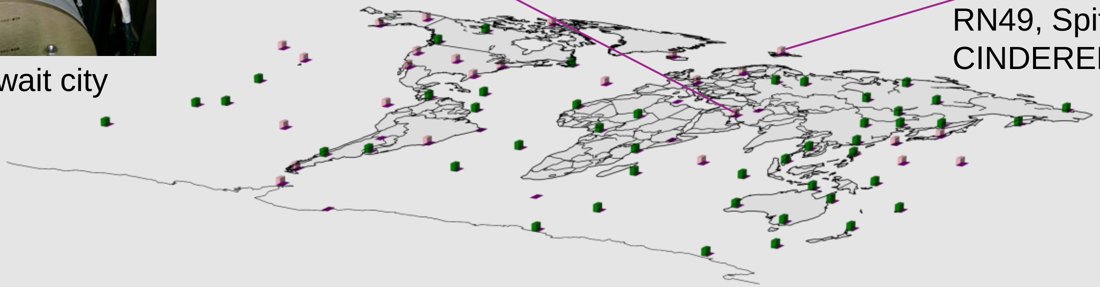
27 certified automatic particulate stations

RN40, Kuwait city
RASA

RN49, Spitzbergen
CINDERELLA



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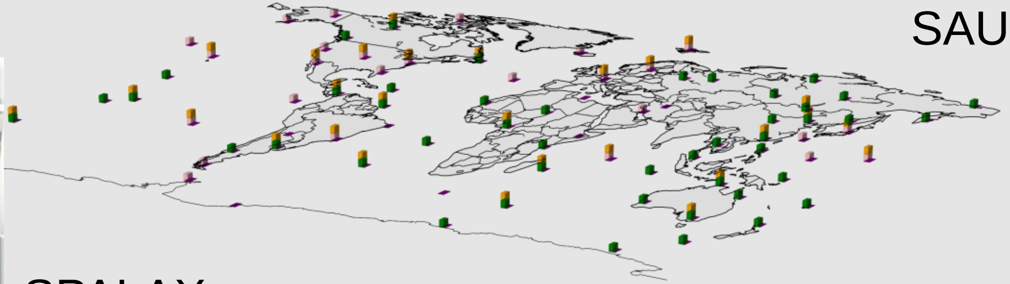
26 certified noble gas stations

Collection time:	12 or 24 h
Decay time:	~6 h
Measurement time:	11 or 24 h
Air flow:	> 1 m^3/h
MDC ^{133}Xe:	~0.3 mBq/m^3

SAUNA II



SPALAX

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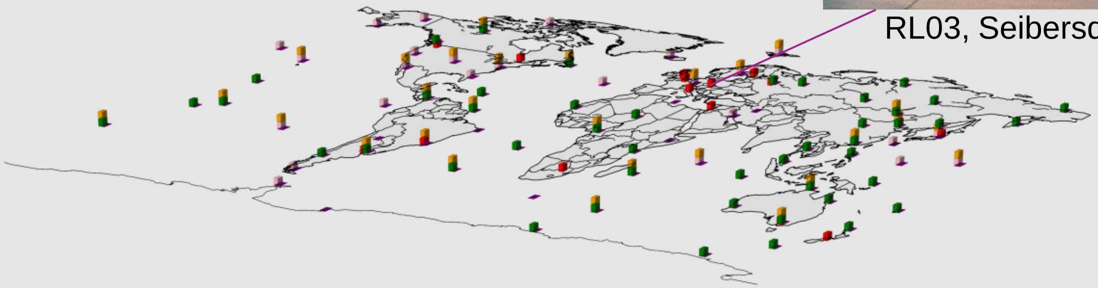
16 radionuclide laboratories

Re-meaures archive filters or bottles
Generally more sensitive measurements than at stations



RL03, Seibersdorf

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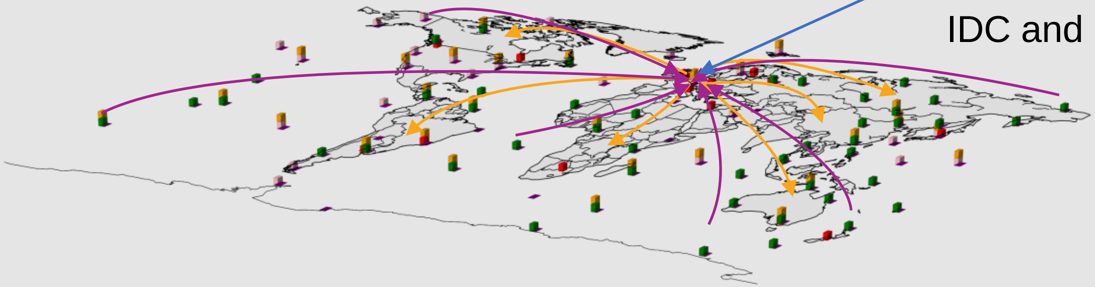
The IMS RN network 2021



IDC and NDCs

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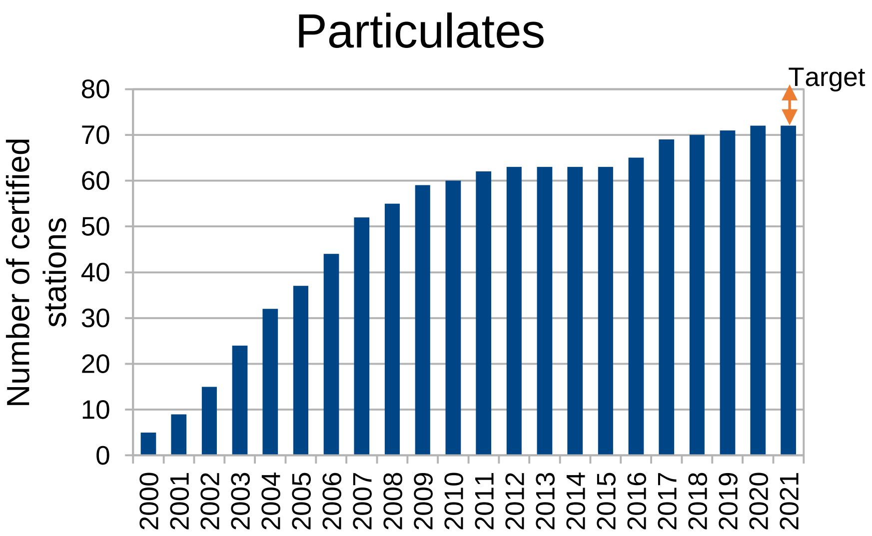
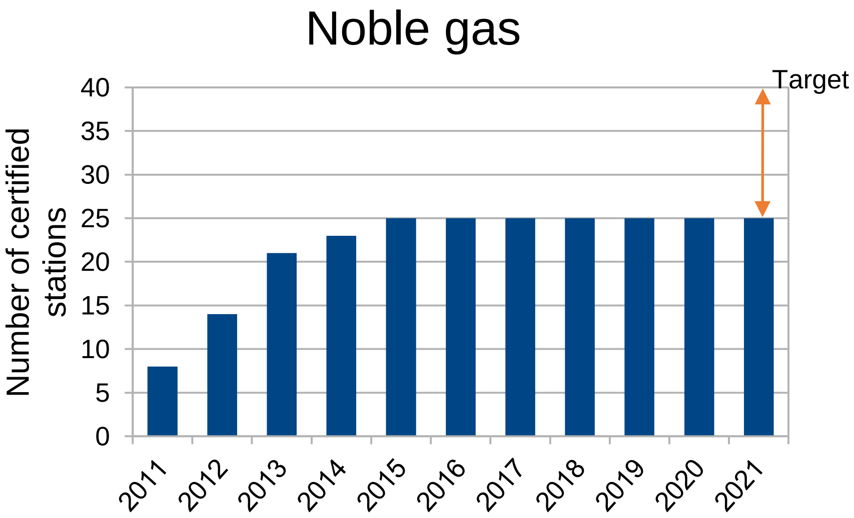
Station certification history





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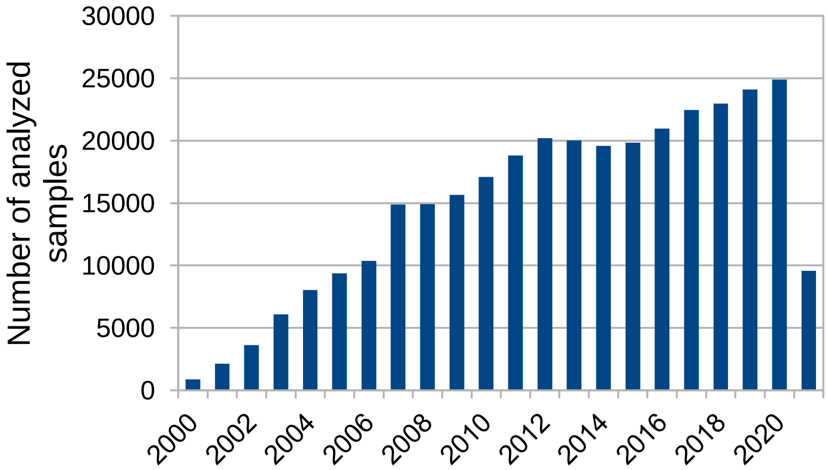
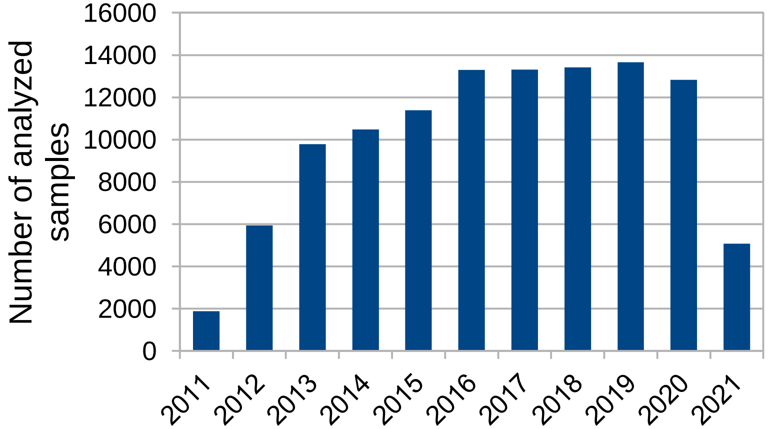
Sample analysis history

Particulate



Noble gas



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Examples of observations the last 20 years

Data extracted from the Swedish NDC, but using the results from the IDC reviewed analysis

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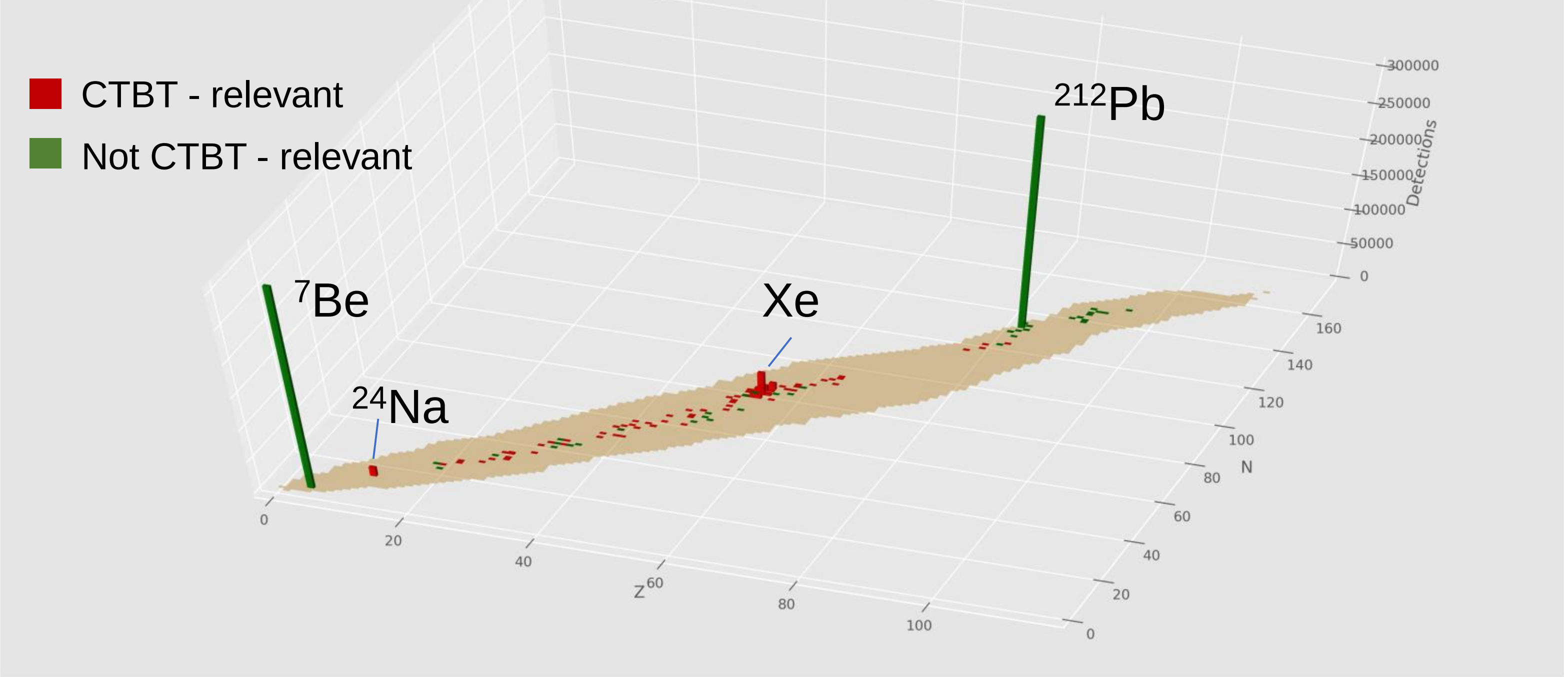
All reported detections 2000 - 2021



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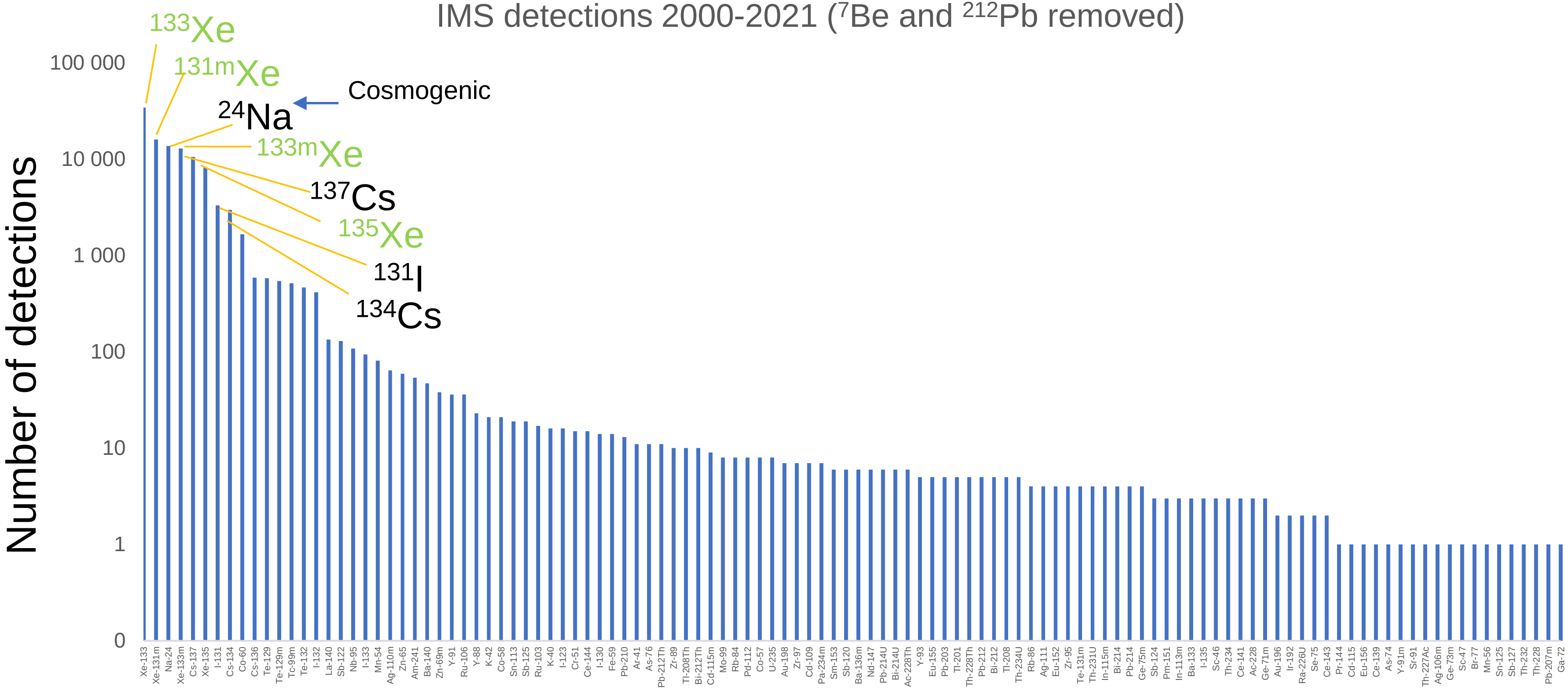
IMS detections 2000-2021 (^{7}Be and ^{212}Pb removed)



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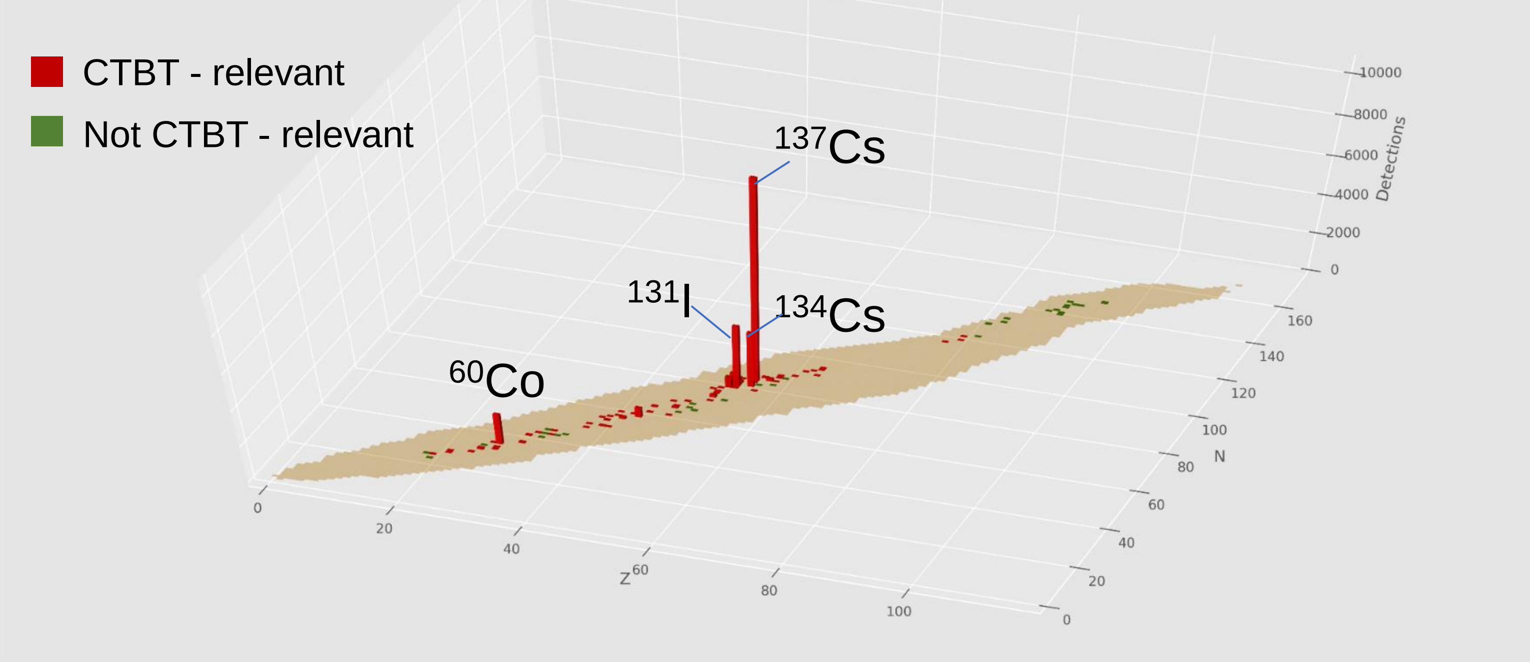
Detections 2000 – 2021, except ^{7}Be, ^{212}Pb, ^{24}Na, and Xe



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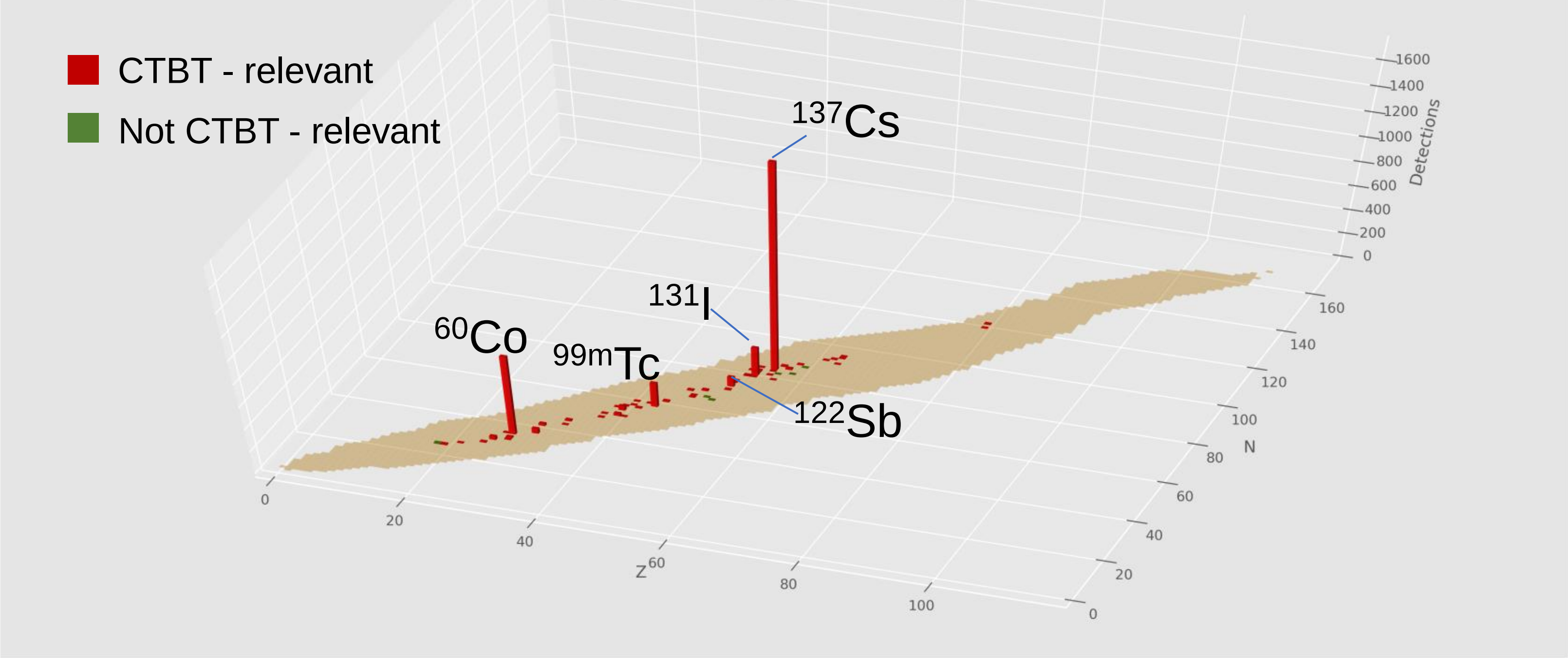
Detections 2000 – 2010, except ^{7}Be, ^{212}Pb, ^{24}Na, and Xe



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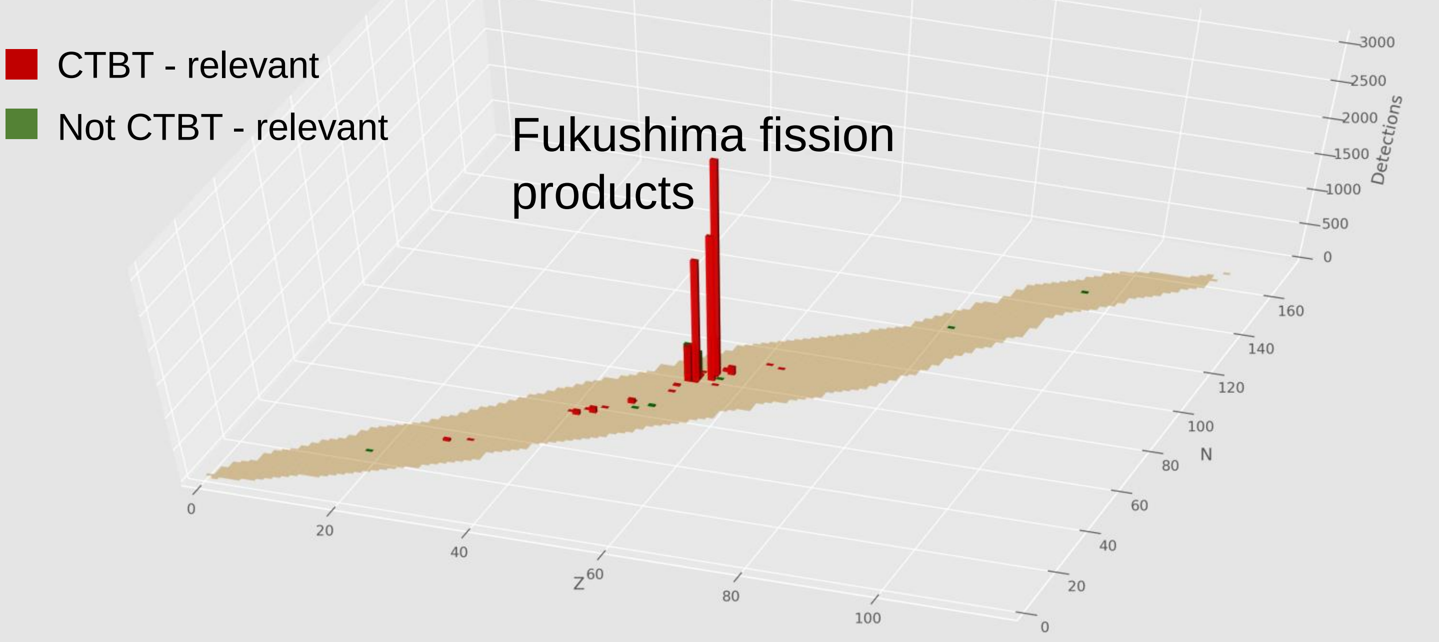

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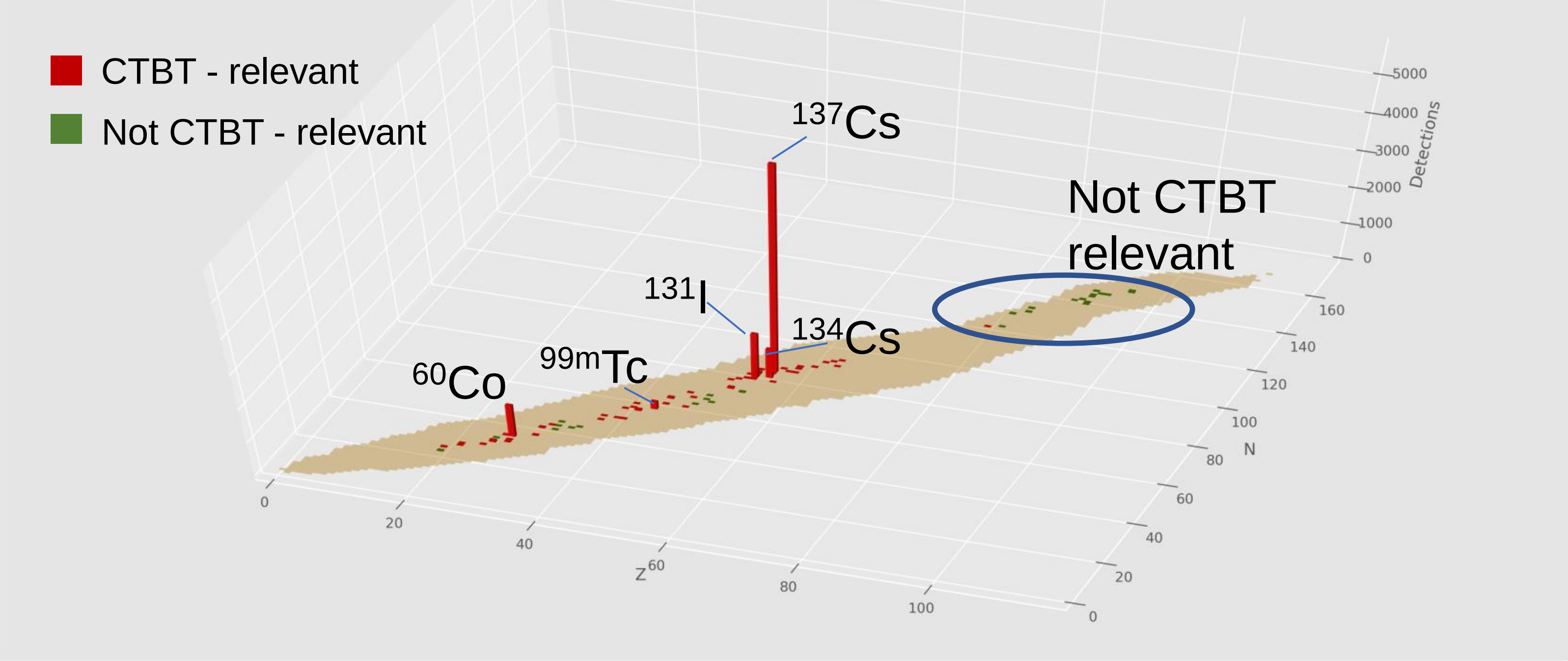

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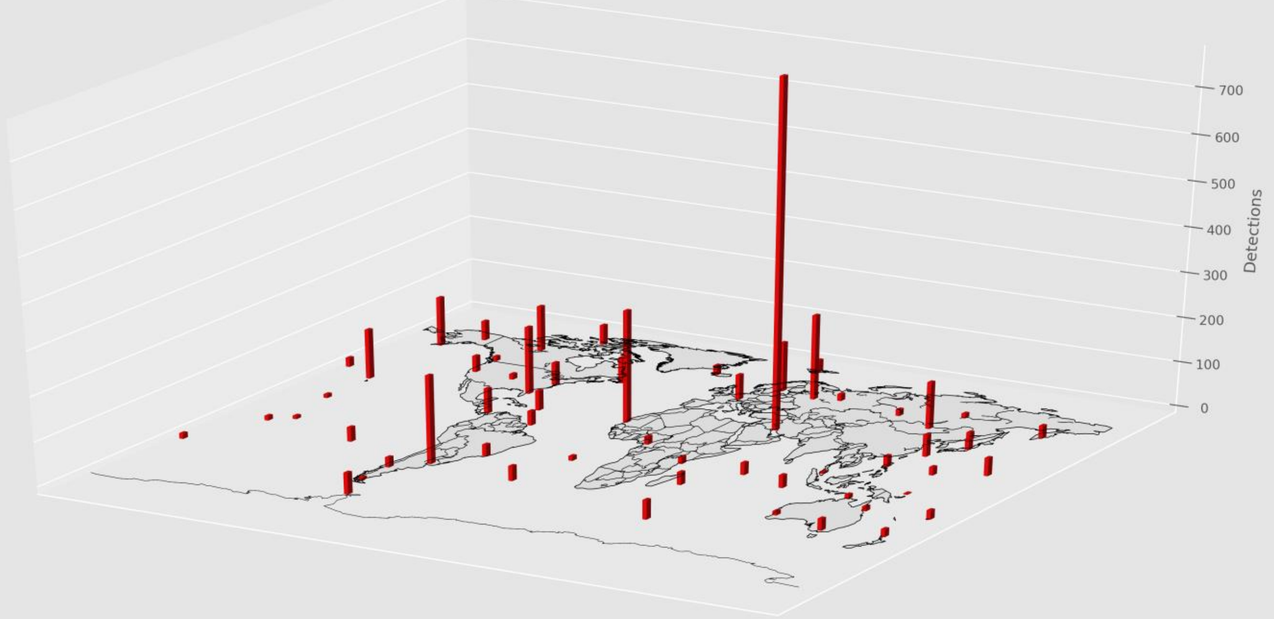

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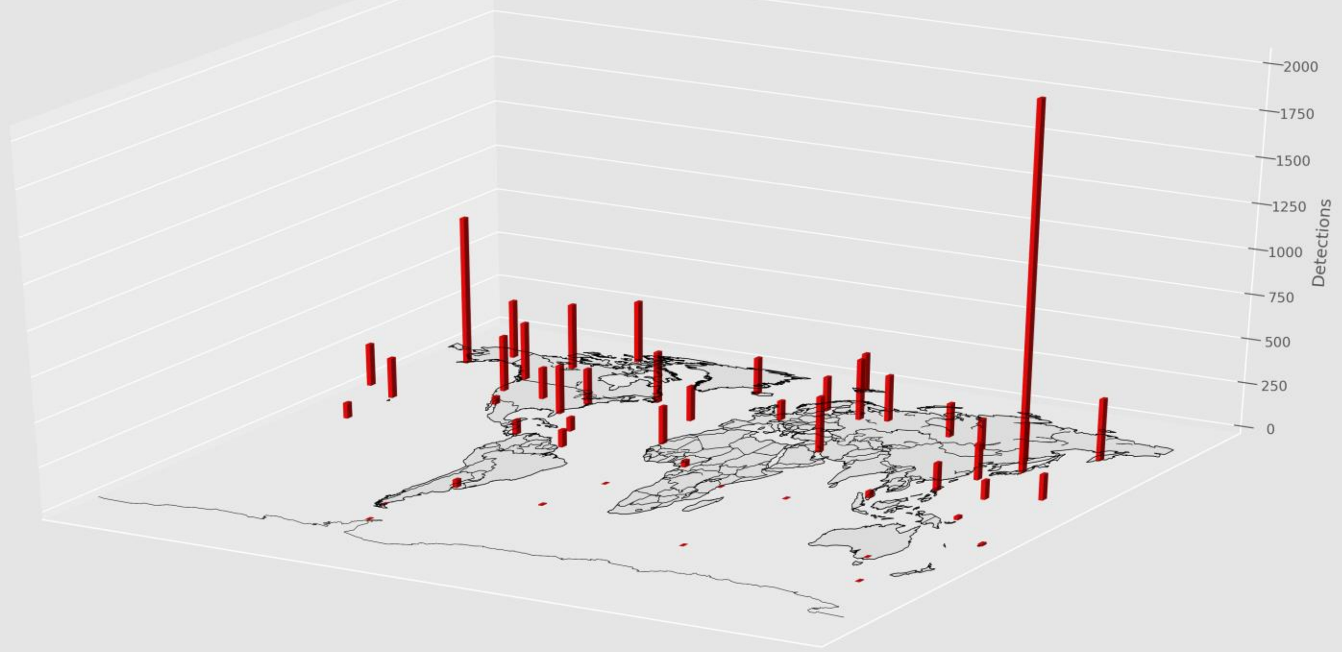

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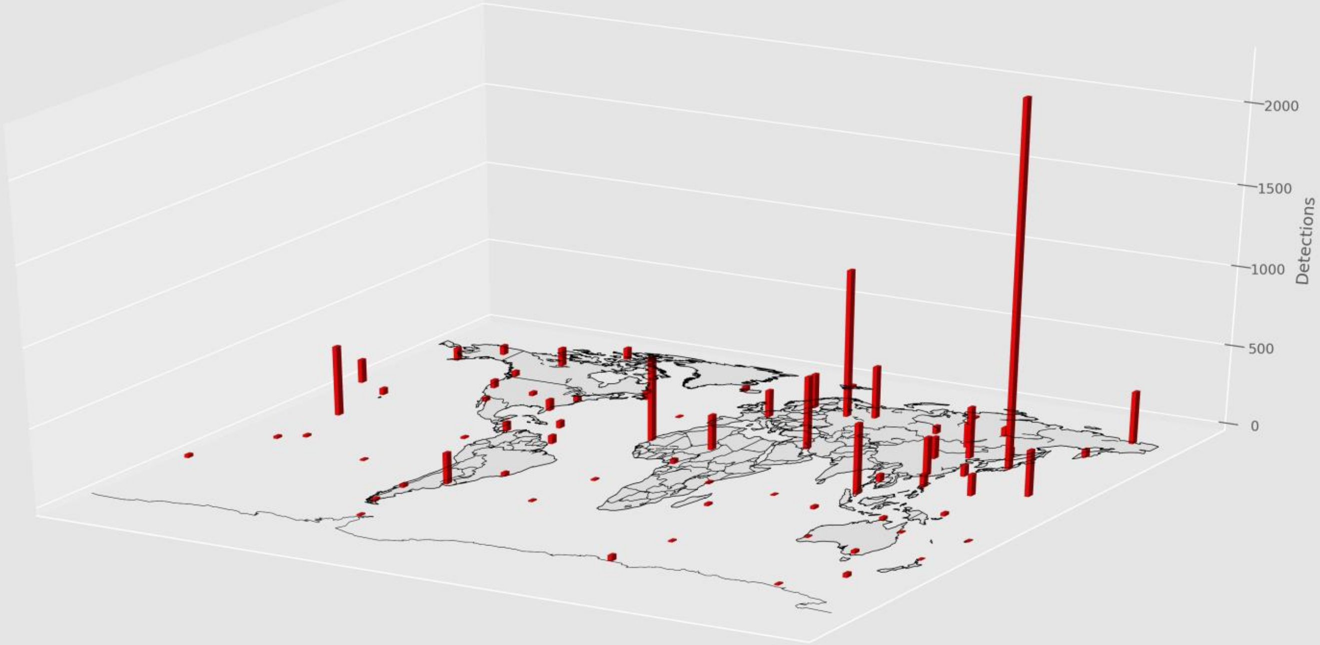

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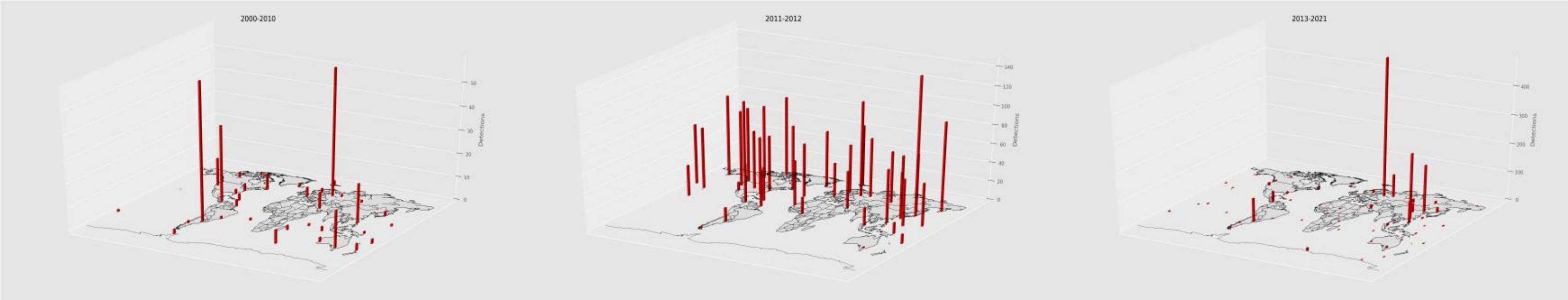
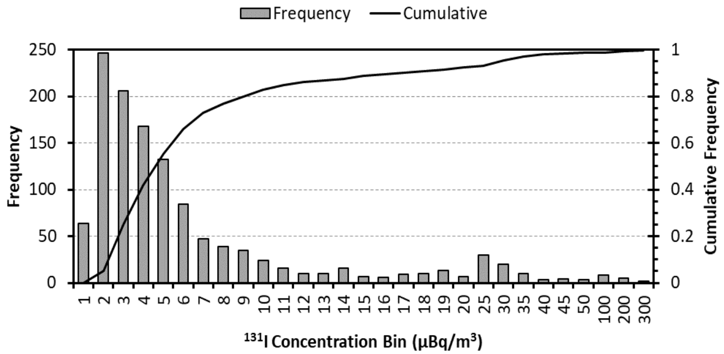
^{131}I – an important fission product with high background

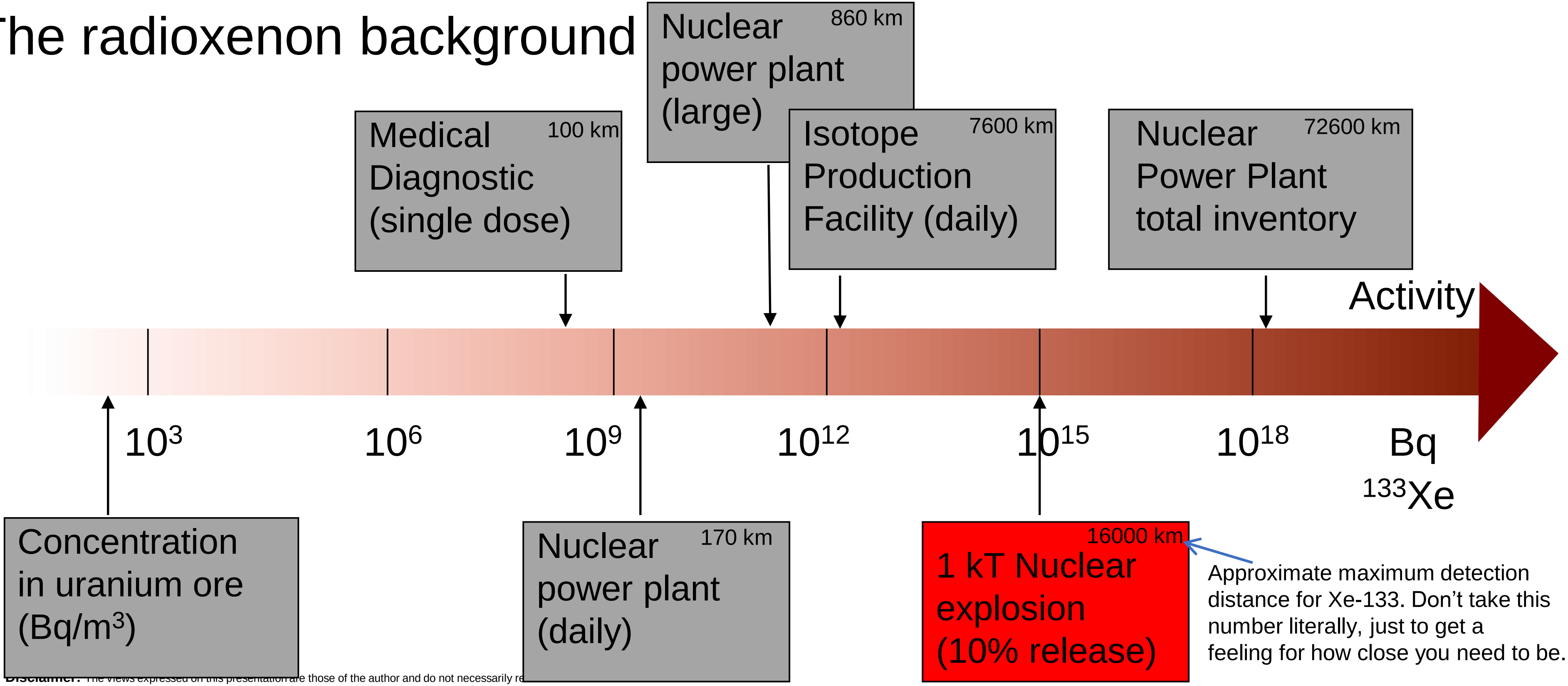


- Iodine the aerosol most likely to escape an UG test
- Observed frequently in IMS
- Many sources still unknown



Harry Miley, Paul Eslinger, Ramesh Sarathi, *Impact of environmental background on atmospheric monitoring of nuclear explosions*, talk at WOSMIP remote II, 2021

The radioxenon background



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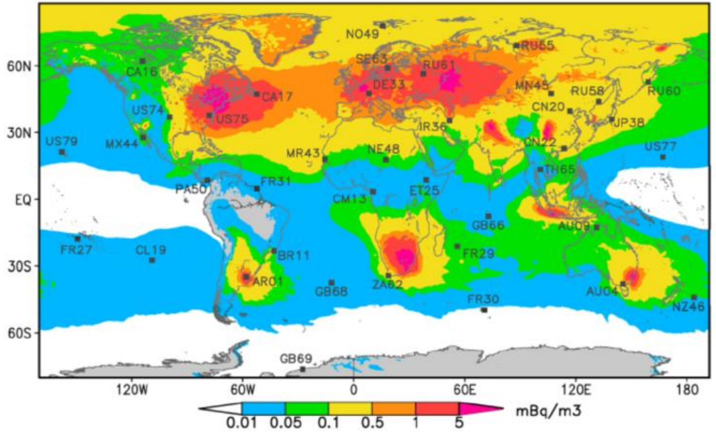
The radioxenon background

- The background is global, but variation between stations is high
- Many sources known, but not all
- The isotopic ratios can be close to NW ratios
- The background sources can mix with a true signal and disturb the ratios
- Pure ^{135}Xe observations
- Pure ^{131m}Xe observations



Map from : Achim, P., S. Generoso, M. Morin, P. Gross, G. Le Petit, and C. Moulin (2016), Characterization of Xe-133 global atmospheric background: Implications for the International Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty, J. Geophys. Res. Atmos., 121,4951–4966, doi:10.1002/2016JD024872

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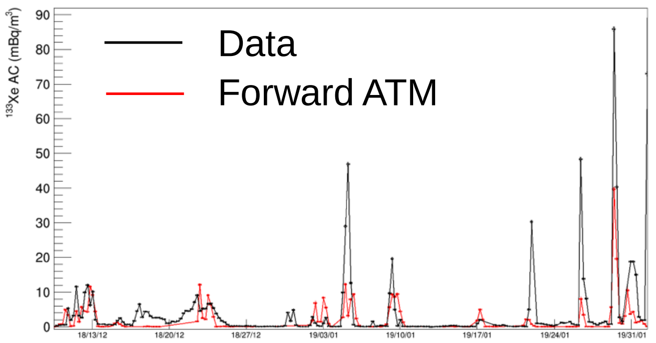
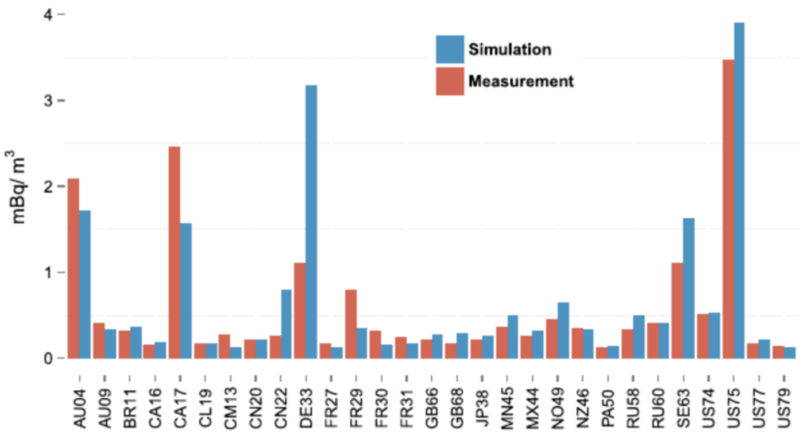
The radioxenon background

- The *average behaviour* of the radioxenon background can today be explained using known sources and ATM
- Individual cases more difficult



A. Ringbom et.al., https://doi.org/10.1007/s00024-020-02425-z



Graph from: Achim, P., S. Generoso, M. Morin, P. Gross, G. Le Petit, and C. Moulin (2016), Characterization of Xe-133 global atmospheric backg round: Implications for the International Monitoring System of the Comprehensive Nuclear-Test-Ban Treaty, J. Geophys. Res. Atmos., 121,4951–4966, doi:10.1002/2016JD024872

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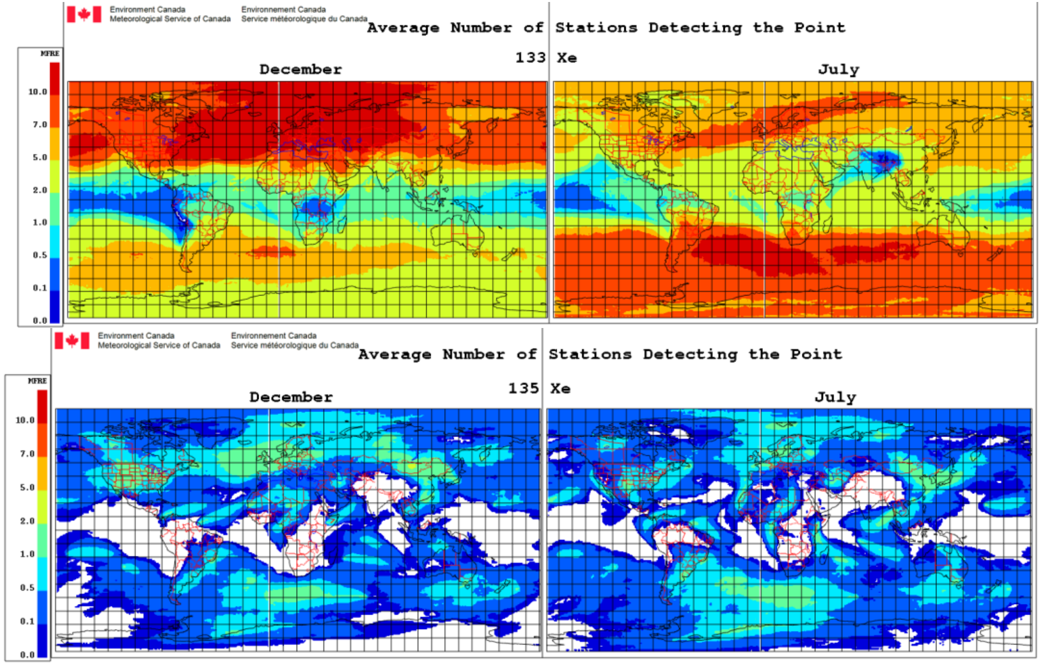
Network coverage for radioxenon

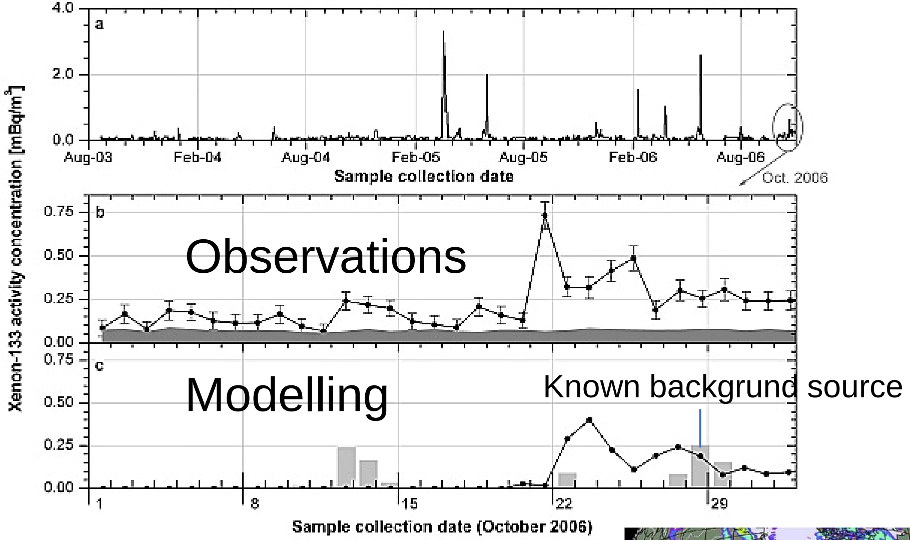
^{133}Xe
1.06×10^{15} Bq

^{135}Xe
3.91×10^{14} Bq

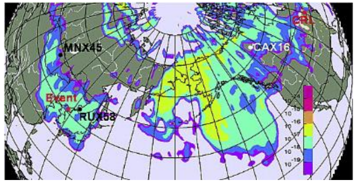


R. D'Amours and A. Ringbom, International Scientific Studies (ISS), Vienna, June 10-12, 2009

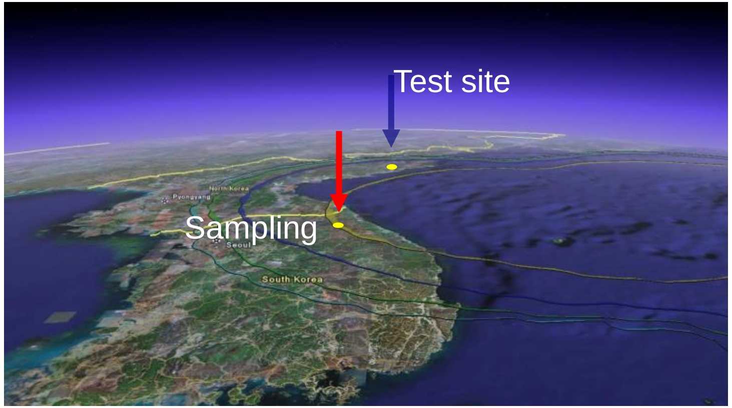
DPRK I - Yellowknife, Canada, October 2006

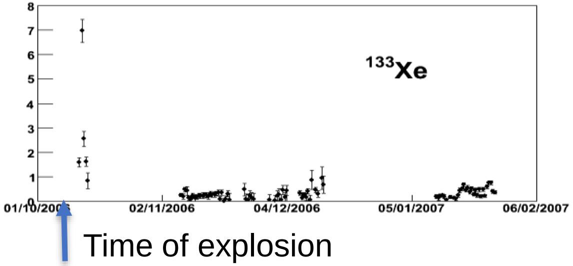


P. Saey et.al, Geophysical Research Letters, Volume: 34, Issue: 20, First published: 16 October 2007, DOI: (10.1029/2007GL030611)



DPRK I – Measurement in ROK by Sweden and ROK





A. Ringbom et.al., Journal of Radioanalytical and Nuclear Chemistry 282(3):773-779

The IMS radionuclide network- a unique machine not yet fully exploited

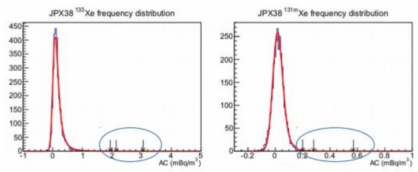
Anders Ringbom, Swedish Defence Research Agency (FOI), anders.ringbom@foi.se

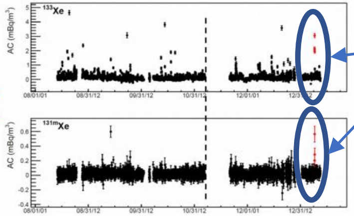
DPRK III – Takasaki & Ussuriysk, April 2013

Estimated release ~10^{12} Bq ^{133}Xe

Observed activity concentrations $C_i(t)$

Statistical analysis



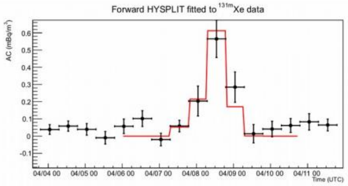


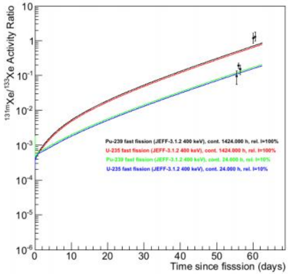
Observations

Extracted signal $C_{i,x}(t)$ + backward ATM model $D_i(x,y,z,t)$

Source location
Source strength

Isotopic ratios





Assumed release(s) + forward ATM model $D_i(x,y,z,t)$

*"Radioxenon detections in the CTBT international monitoring system likely related to the announced nuclear test in North Korea on February 12, 2013", Ringbom, et.al., http://dx.doi.org/10.1016/j.jenvrad.2013.10.027

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Status of RN IMS – some conclusions

- The network is close to be complete, but important to get remaining radioxenon stations installed and certified
- Not all CTBT-relevant radionuclides are as relevant as others
- The background for particulates is relatively low, with a few exceptions.
- The radioxenon background is global and variable.
- Important to continue to identify background sources for xenon and iodine.
- The network xenon detection coverage needs to increase
- The released activity from a NT was overestimated when the network was designed. 33% of the DPRK tests detected.
- The methods used for location needs to be improved, including uncertainty estimates in ATM modelling.

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Future development

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The future development should be guided by a *network perspective,* based on a *scenario analysis* and using the *entire verification process*.*

Network verification power = (D + L + R + T)/4

D - detection power
L - location power
R – rejection power
T – timing power

Example of result from an analysis using the network perspective:

The same IMS xenon detection power for a 1 kT explosion is reached using 40 systems OR 80 systems with 30 times lower sensitivity.

***FOI-R—3856—SE, *The impact of system characteristics on Noble Gas network verification capability*.**

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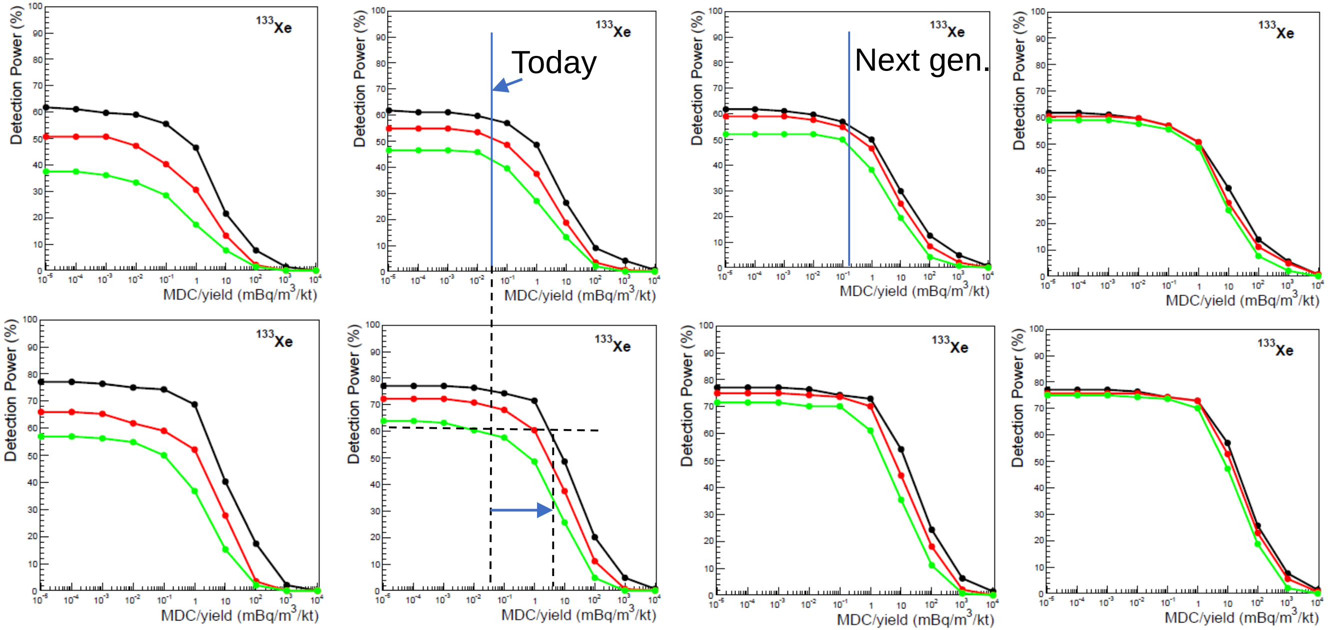
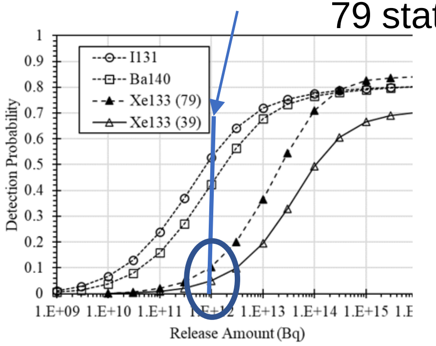
*Detection power** ^{133}Xe

39 stations

79 stations



Xe levels observed from DPRK



Harry Miley, Paul Eslinger, Ramesh Sarathi, talk at WOSMIP, 6/21/2021

Higher release or sensitivity

*FOI-R—3856—SE, *The impact of system characteristics on Noble Gas network verification capability*.

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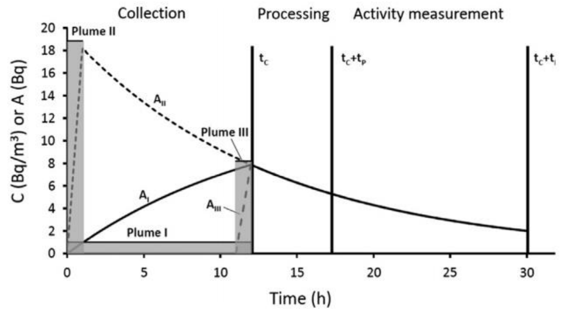
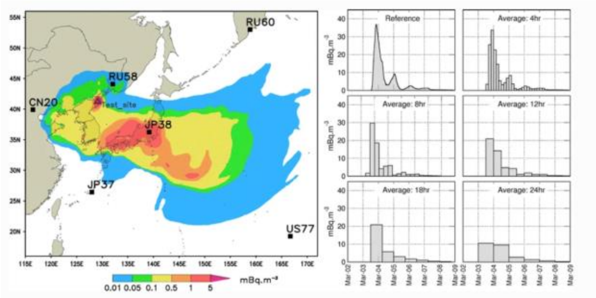
Impact of shorter collection time

- Increased number of samples
- Increased information on plume shape
- Better source location, but remains to be quantified.



A. Axelsson, A. Ringbom, Appl. Rad. Isot. 92 (2014) 12-17



Le Petit, G., Cagniant, A., Morelle, M. *et al.* Innovative concept for a major breakthrough in atmospheric radioactive xenon detection for nuclear explosion monitoring. *J Radioanal Nucl Chem* **298,** 1159–1169 (2013). https://doi.org/10.1007/s10967-013-2525-8

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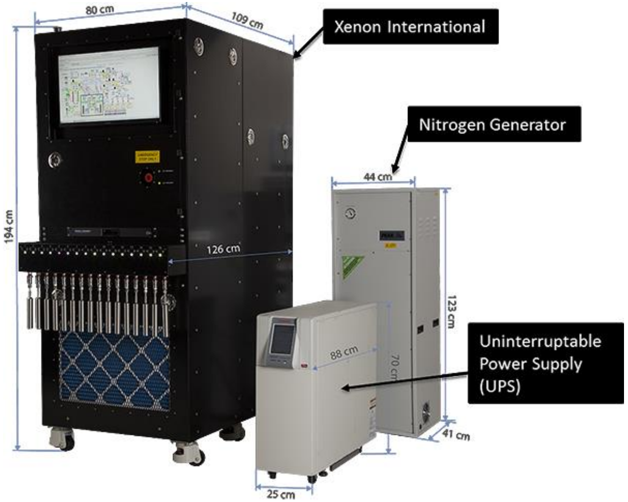
Next generation IMS NG systems

SAUNA III, Sweden

SPALAX NG, France



Xenon International, US

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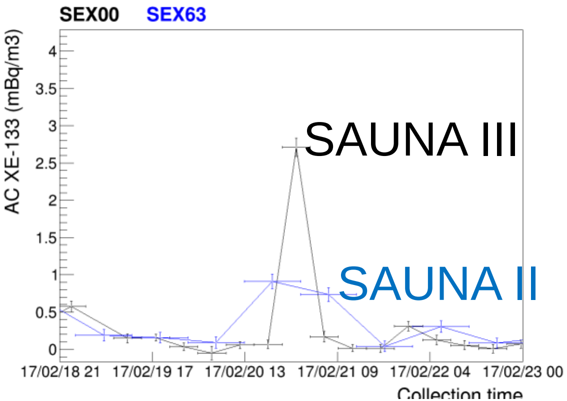
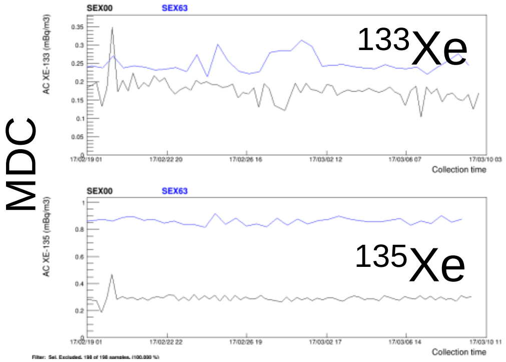
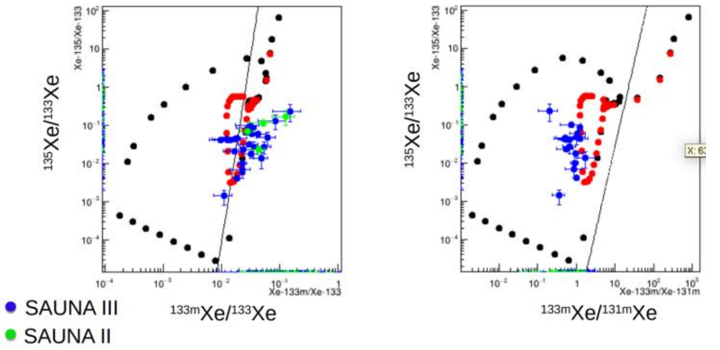
Next generation radioxenon systems



Increased time resolution



Improved sensitivity



More samples

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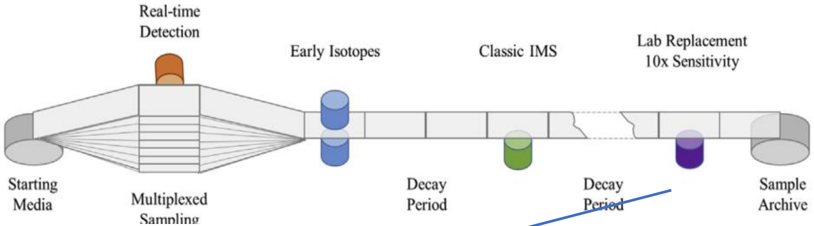
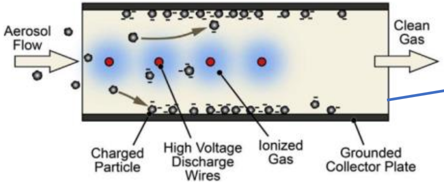
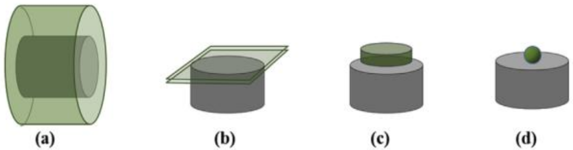
Development of particulate samplers

- Shorter sampling intervals
- Higher air flow
- Electrostatic precipitation (ESP)
- Dual gamma and/or gamma-gamma coincidence



$$MDC \cong C' \sqrt{\frac{e^{-\lambda_B t_d} \times \frac{(1-e^{-\lambda_B t_C})}{\lambda_B}}{e^{-\lambda_A t_d} \times \frac{(1-e^{-\lambda_A t_C})}{\lambda_A}}} \frac{\sqrt{[^{212}Pb] \times FWHM}}{V \times t_C \times \varepsilon\delta\Omega}$$





H. Miley et.al., Design considerations for future radionuclide aerosol monitoring systems Journal of Environmental Radioactivity, Volumes 208–209, 2019, 106037, ISSN 0265-931X, https://doi.org/10.1016/j.jenvrad.2019.106037

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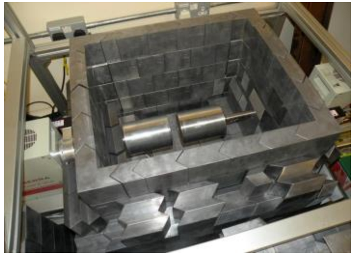
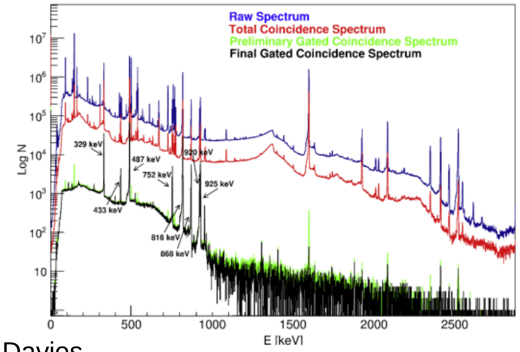
Increased laboratory capabilities – coincidence detector systems

AWE

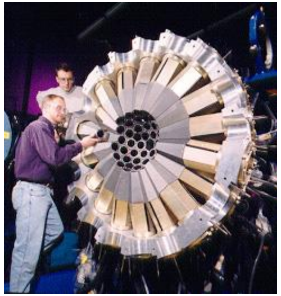




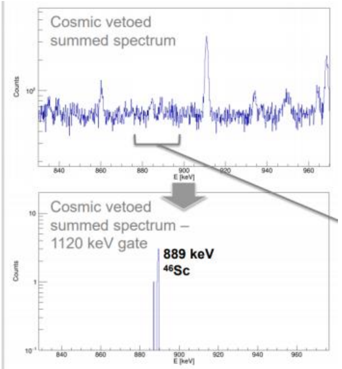
R. Britton, M. J. Jackson, A. V. Davies,
http://dx.doi.org/10.1016/j.jenvrad.2015.07.025
See also poster P3.1-303

- Improved sensitivity (veto, coincidence, and summing)
- Reduce biases from sample inhomogenities
- Redundancy
- New data formats: list-mode

Gammaspere



Argonne Physics Division - Low Energy Physics (anl.gov)



Health Canada,
Pawel Mekarski,
Dec 17, 2020

Disclaimer: The views expressed on this presentation are those of the author and do not necessarily reflect the view of the CTBTO

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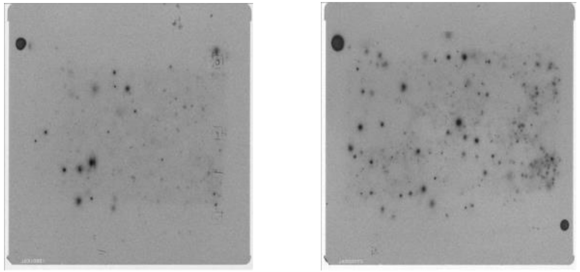
Increased laboratory capabilities – radiography

^{106}Ru, measured in Sweden 2017

IMS station in Takasaki, March 24 , 2011 $^{134,137}Cs$



- Information on production process
- Particle size distribution important for ATM
- Input how to interpret measured activity concentrations

Pictures provided by K. Ungar, Health Canada

Pres. No.: I04-717

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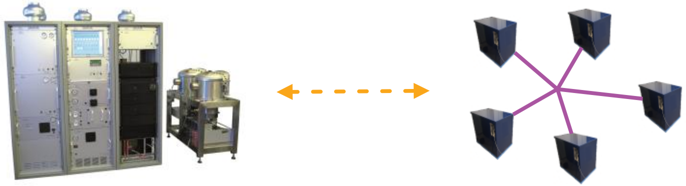
The SAUNA Q_B – array is the next step in remote sensing of activities involving nuclear fission that can improve..

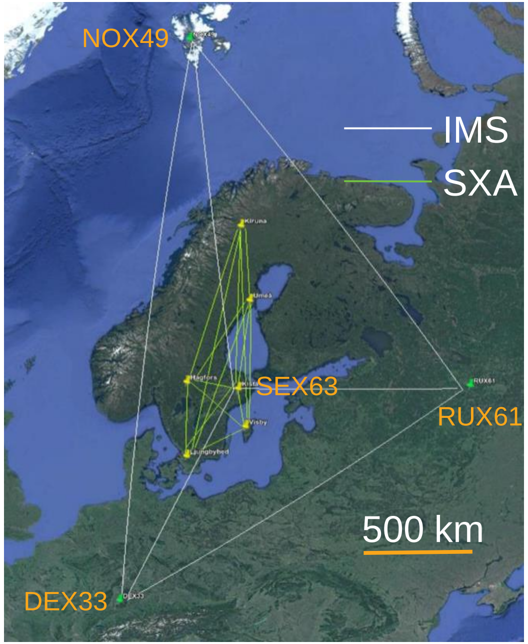
Detection capability by decreasing average source-receptor distance and increasing coverage.

Location capability by increasing number of detecting sensors.

Categorization capability by increase the number of samples.

… at the same cost as 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).

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Five Q_B- array installed and running since May 5, 2021

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

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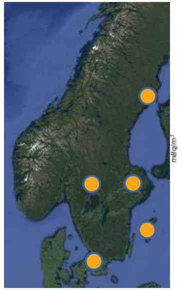
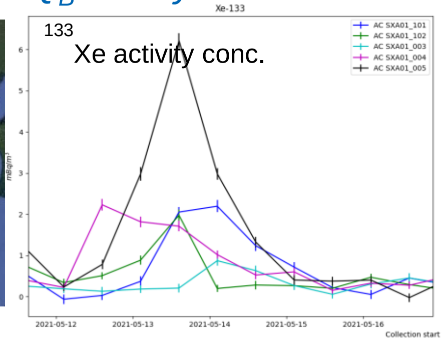
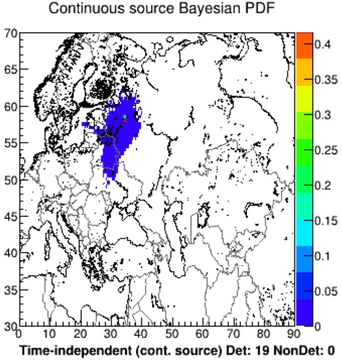
Example of the Q_B – array and SAUNA III detecting the same xenon plume

- A 2.5-day wide plume of ^{133}Xe hit Sweden in the middle of may 2021.
- All five Q_B- units in the array were affected, as well as the FOI SAUNA III in Stockholm.
- A Bayesian location analysis* was performed on the two data sets (19 Q_B – samples and 11 SAUNA III - samples), assuming a continuous source.
- The area of the resulting source location probability distribution is considerable smaller for the Q_B- array.

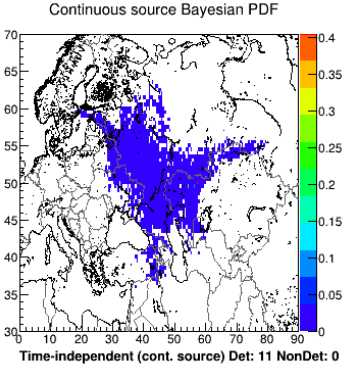
Q_B - array







SAUNA III



*A. Ringbom and A. Axelsson, Poster at SnT2015, T1.3-P1.

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Some thoughts for the future

- Development of equipment should take the entire verification process into account
- The next generation NG systems will improve categorization, detection and source term estimation
- Aerosol detection, including labs, is very sensitive, but there is still potential for improvement
- Upgrading IMS stations with array technology would be a major step
- Work can still be done on nuclear data and source term modelling
- Also true for network analysis, including ML and other techniques