Preliminary Evaluation of Two Beta-Gamma Radioxenon Detection Systems

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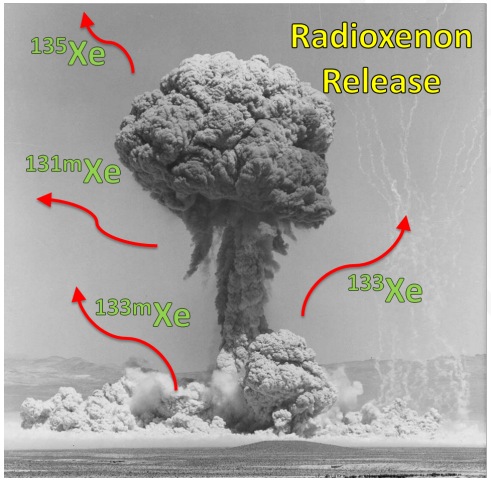
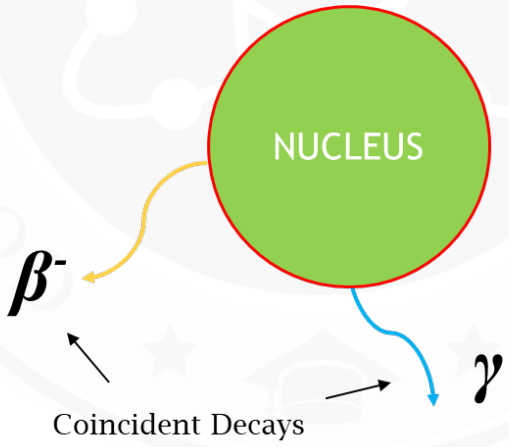
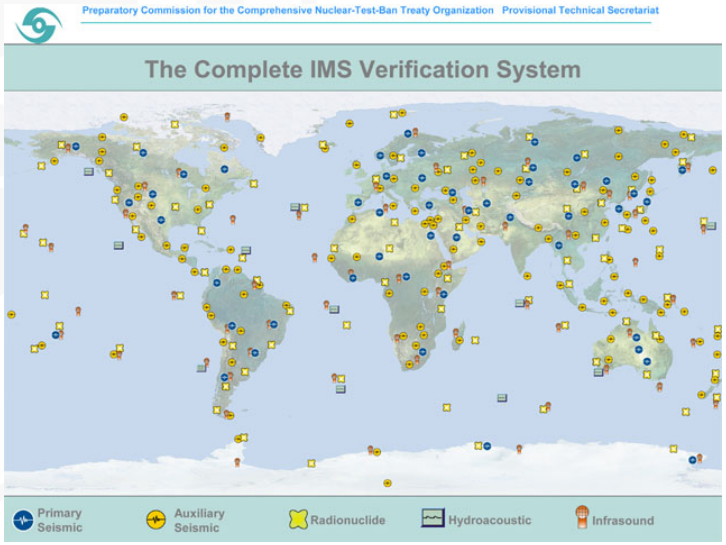
Motivation

- Clandestine nuclear threats
  - 4 isotopes (^{131m}Xe, ^{133}Xe, ^{133m}Xe, ^{135}Xe)
  - Min Detectable Concentration (MDC):
    - < 1 mBq/m^3 air
  - Beta-Gamma Coincidence
- Atmospheric Radioxenon Detection
  - Comprehensive Test Ban Treaty Organization (CTBTO)
  - International Monitoring System (IMS)



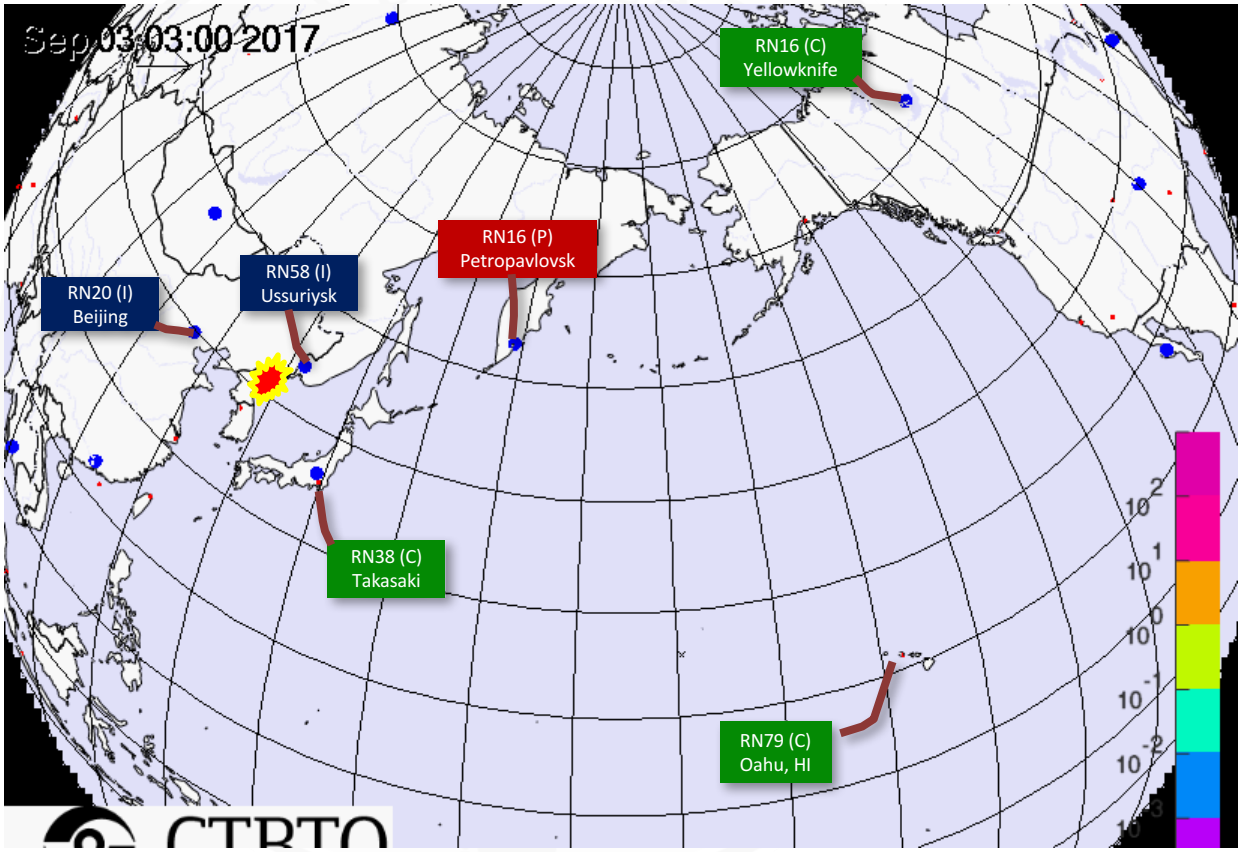




The atmospheric transport simulation below is based on the hypothesis that a release of radionuclides occurred immediately and continuously from the location of the seismic detection.

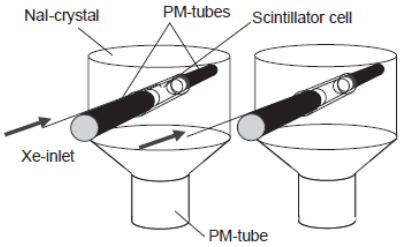
RN: Radionuclide Stations with Nobel Gas System

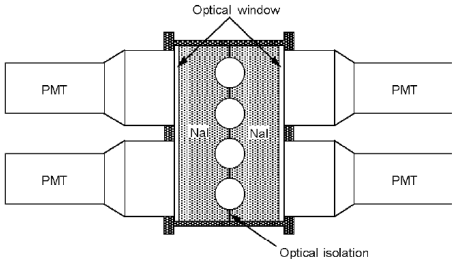
C: Certified
I: Installed
P: Planned

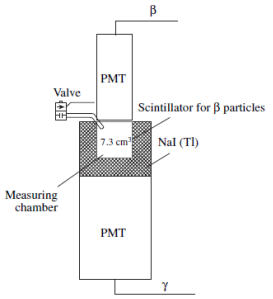


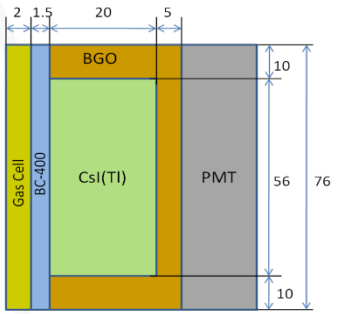
Previous Radioxenon Detection Systems

- Beta-gamma systems
  - Organic, Inorganic, PMTs
  - SAUNA (Sweden)
  - ARSA (USA)
  - ARIX (Russia)
  - Phoswich (USA)
- Other detection systems
  - SPALAX- HPGe (France)
- Drawbacks
  - Memory effect
  - Gain matching
  - High maintenance
  - Bulky cooling systems
  - List mode data collection



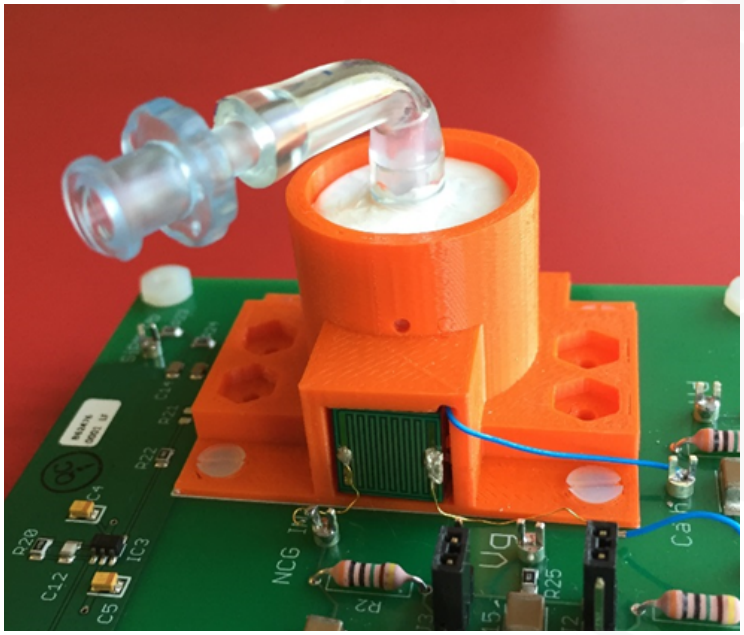




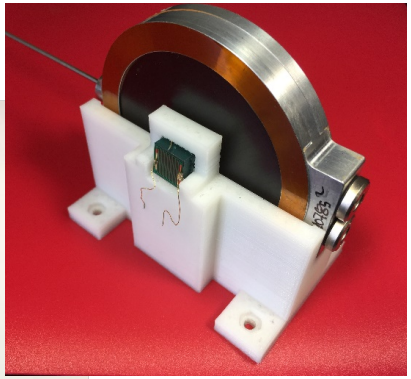


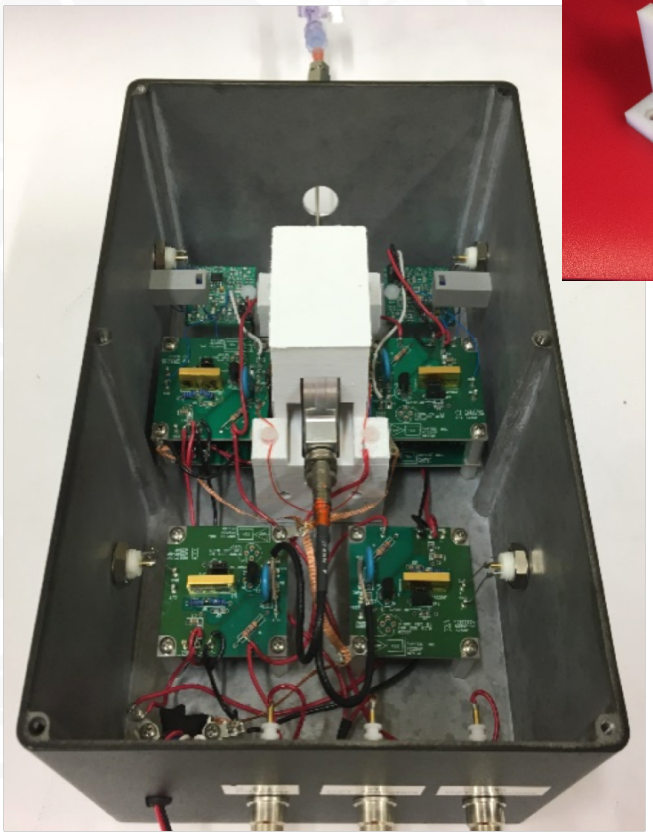
Two Prototype Radioxenon Detectors

- CASP
  - CZT, an Array of Silicon Photomultipliers, and a Plastic Scintillator



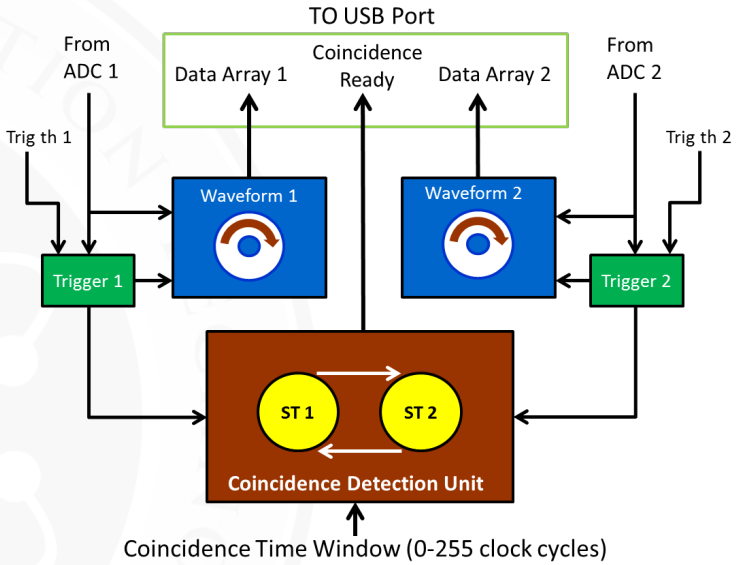
- PIPS-CZT
  - PIPSBox and two coplanar CZT

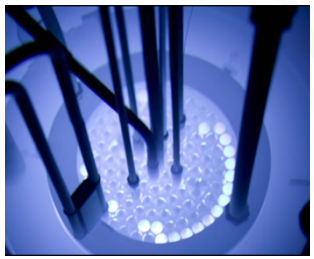




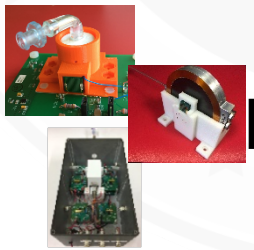
Digital Pulse Processing

- Processing in digital domain
  - High-speed coincidence discrimination conducted in onboard FPGA in real-time
  - USB transfer to PC
    - Specified data; avoidance of time-stamp
  - Fully developed in-house; 100% flexibility
- MATLAB user interface
  - Easy adjustments of FPGA parameters
    - Filters, timing windows, gain, etc.
  - Pulse display and spectra

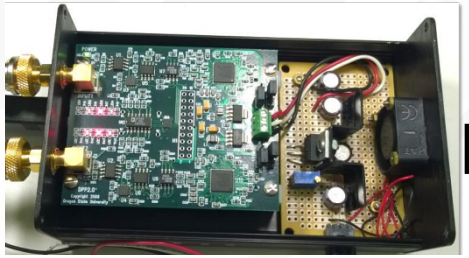




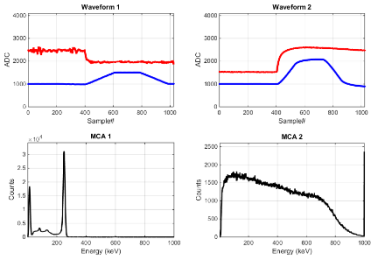
Irradiation



Injection and Detection

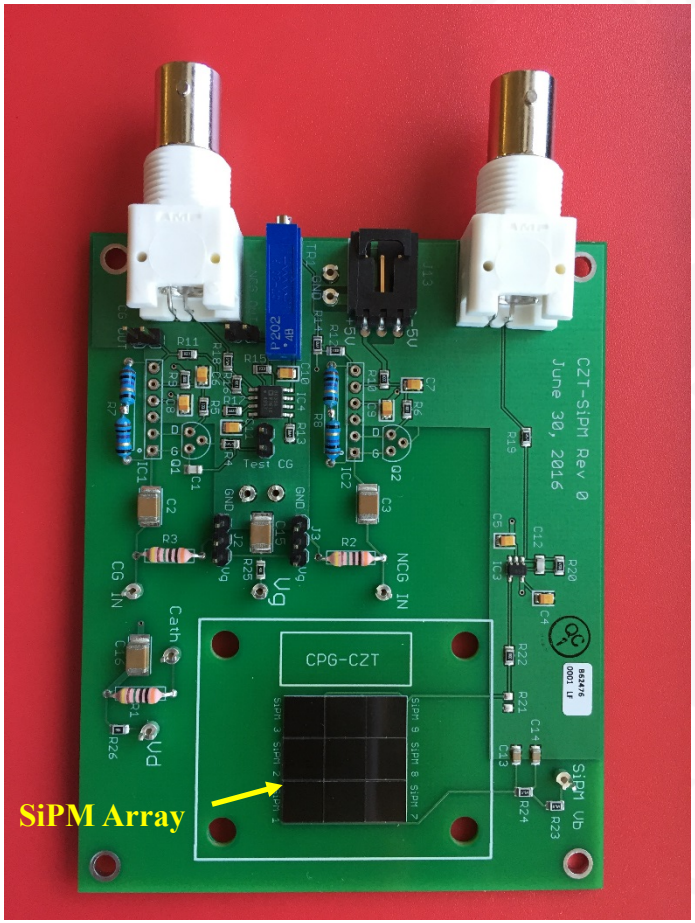


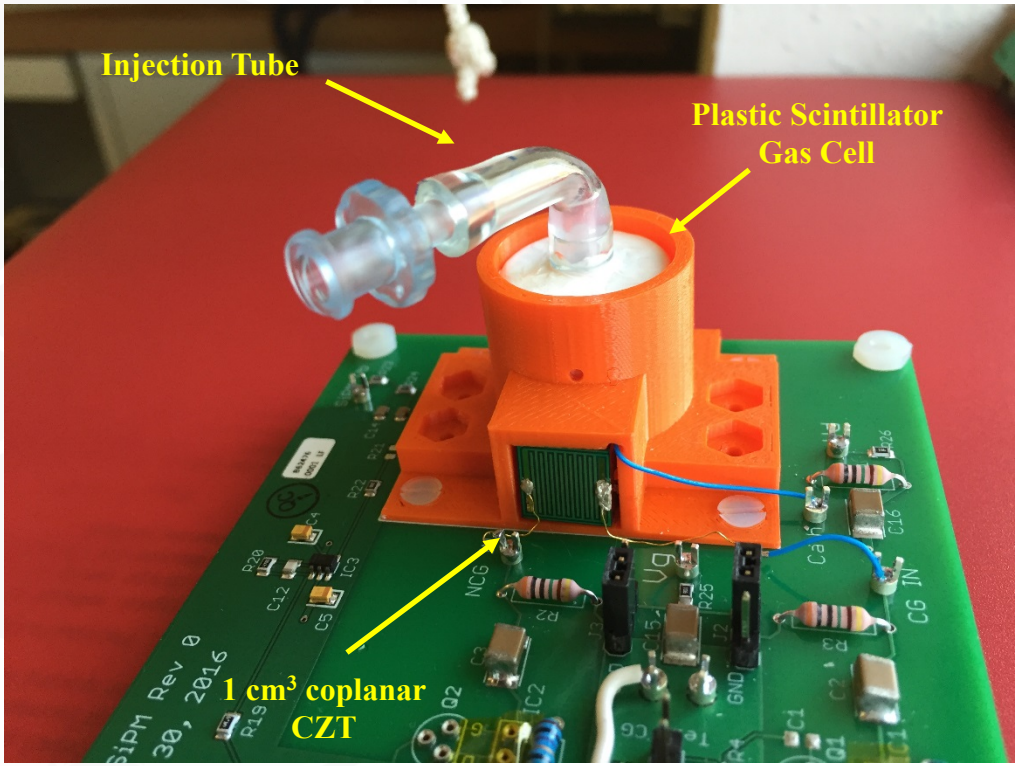
FPGA-based digital pulse processor



MATAB User Interface

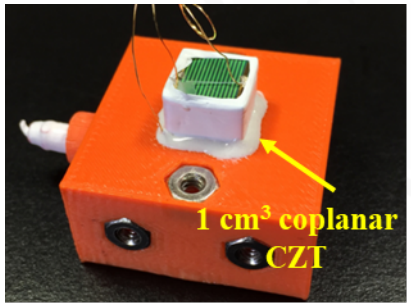
CASP: CZT, Array of SiPMs, and a Plastic

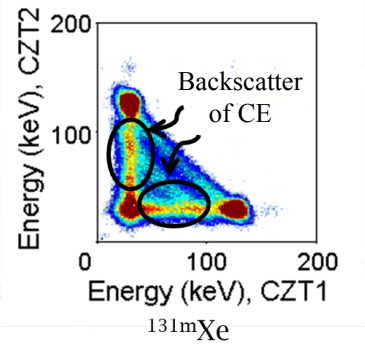


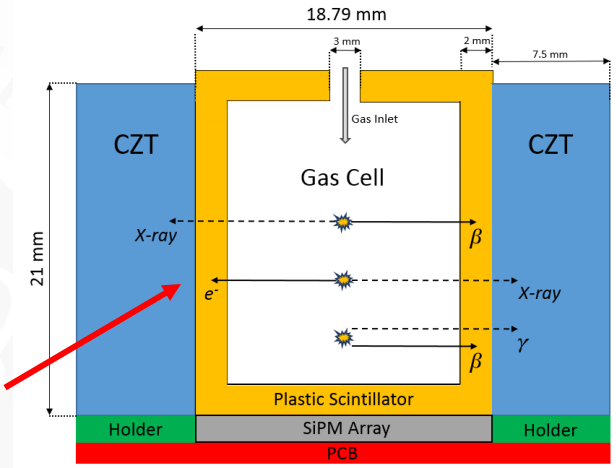


Second Prototype- CZT, Array of SiPMs, and a Plastic Scintillator (CASP)

- Plastic scintillator gas cell
  - Low Z
  - Near 4π solid angle for electrons
  - Light collection by array of SiPMs
    - Compact, low voltage, rugged
- Tight ROIs
  - Adjacent coplanar CZT
    - High resolution photopeaks
- 30 keV detection
  - PCB mounted electronics
    - Low noise







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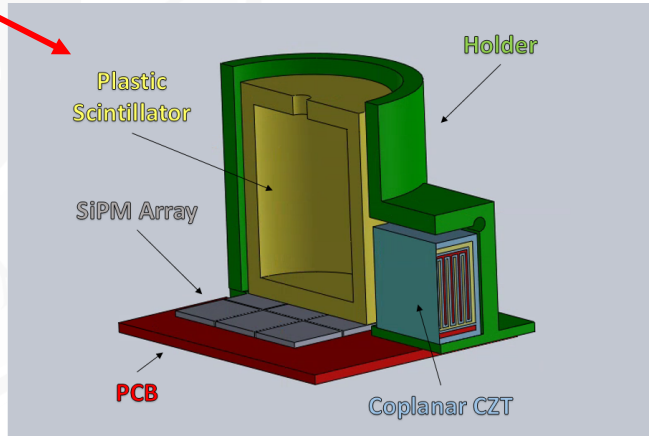
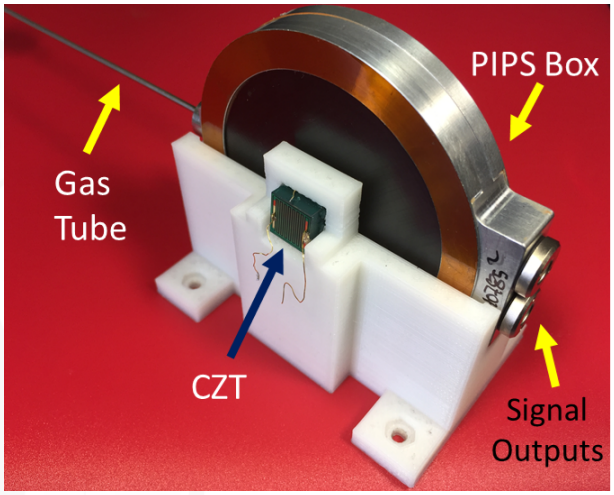
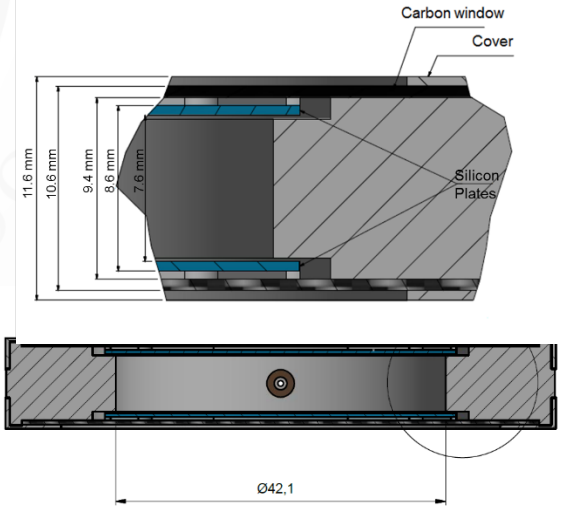


Third Prototype- PIPS-CZT

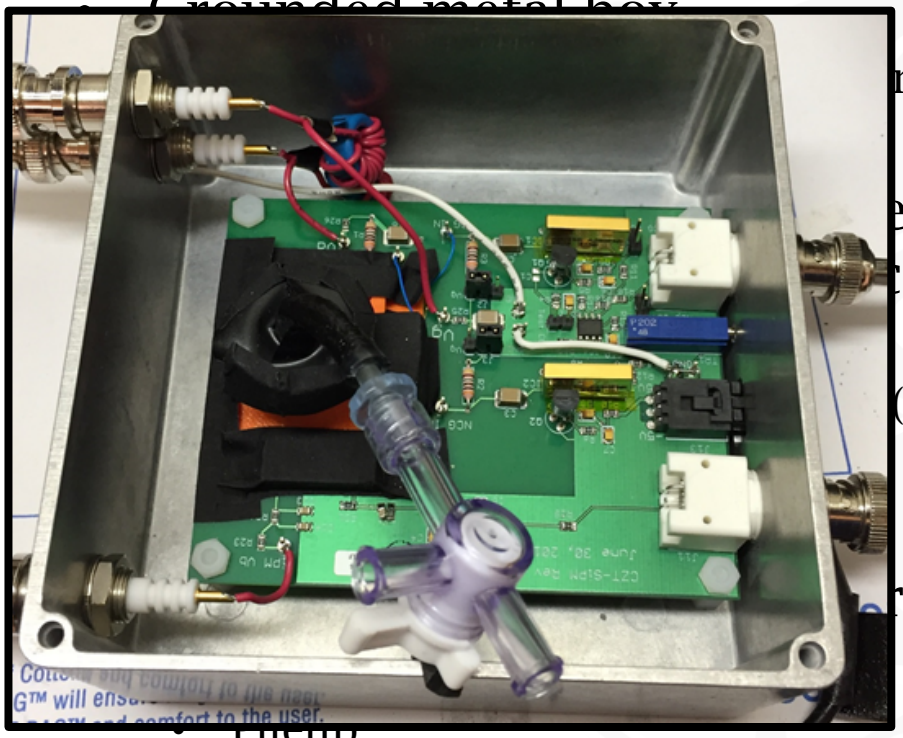
- Electron detection: PIPSBox
  - Passivated Implanted Planar Silicon (PIPS)
    - Two independent silicon plate detectors
    - Gas cell between parallel plates
  - Compact
    - Surface area = 1200 mm^2 each
    - Thickness = 0.5 mm each
      - 0.6 mm carbon window passes X-rays
  - Superior energy resolution = Better MDC
  - Mitigation of memory effect???
  - Low background
- Potential triple-coincidence
- Cutting edge technology
  - PNNL- PIPS x HPGe
  - French CEA- PIPS x SPALAX

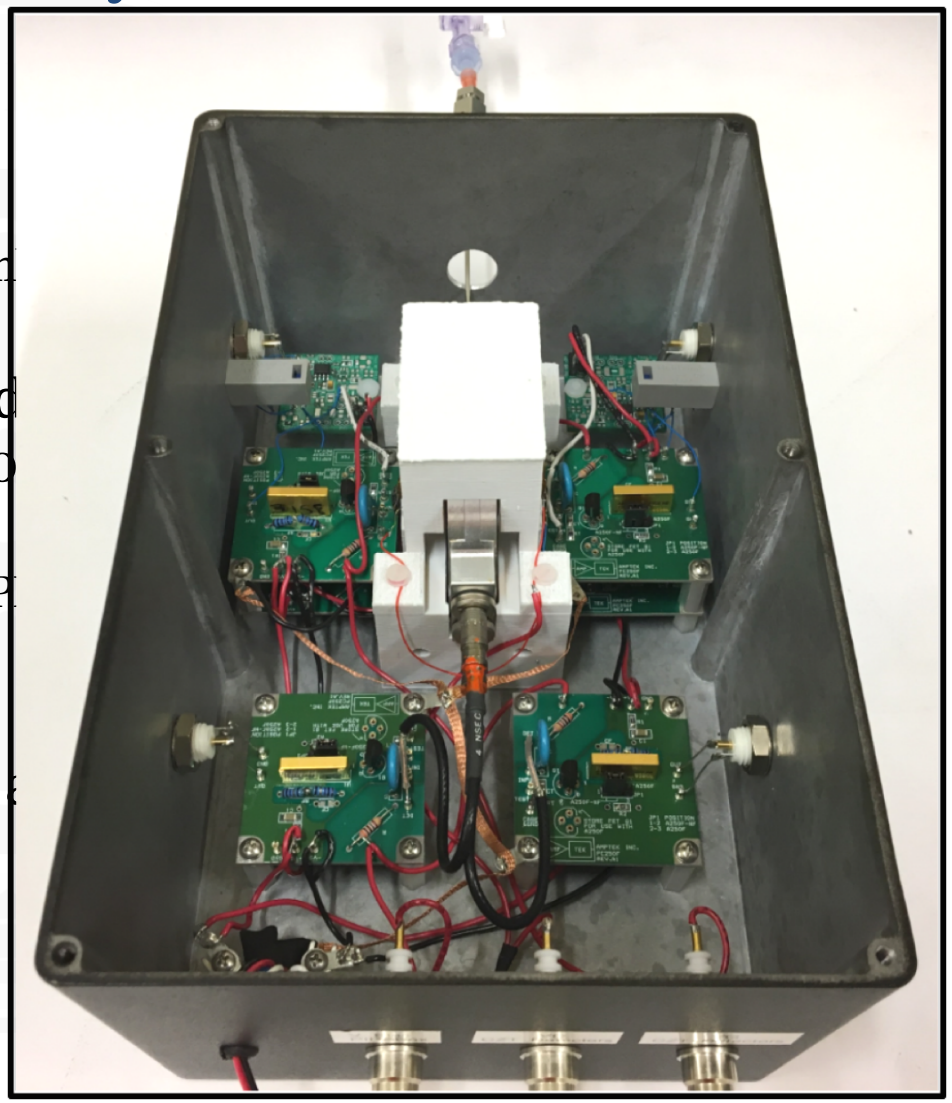




Experimental Setup- System

- Full-coverage light sealing
- Grounded metal box
- Pileup
  - Impurities
- Prototype Configurations

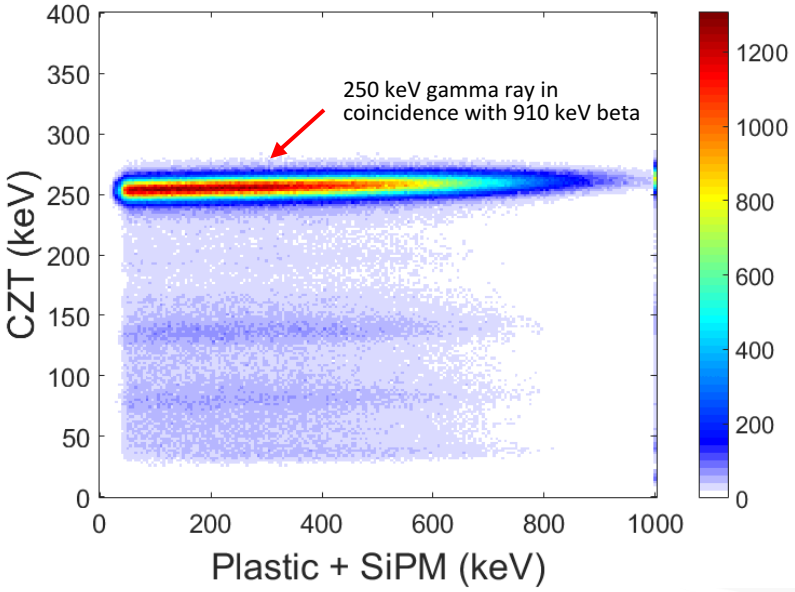




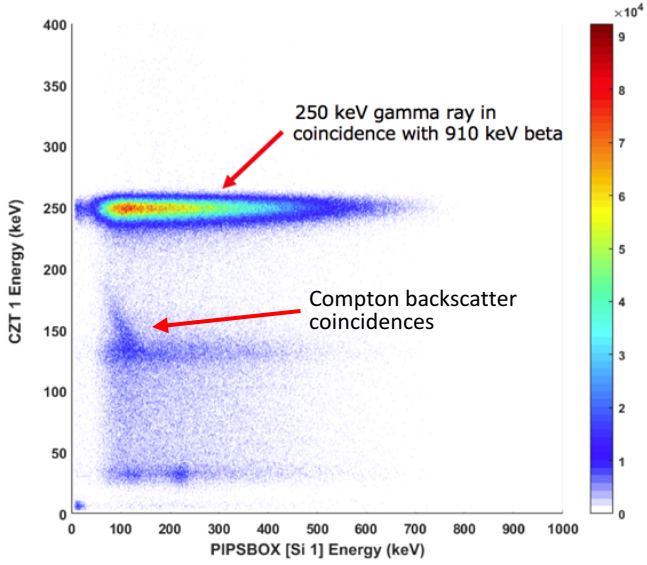
Results- ^{135}Xe

Properties	^{135}Xe
Half-Life (hours)	9.14
Gamma (keV)	250
Max Beta (keV)	905

Energy Resolution (FWHM, %)		
	CASP	PIPS-CZT
250 keV Gamma	5.7%	5.09%



CASP

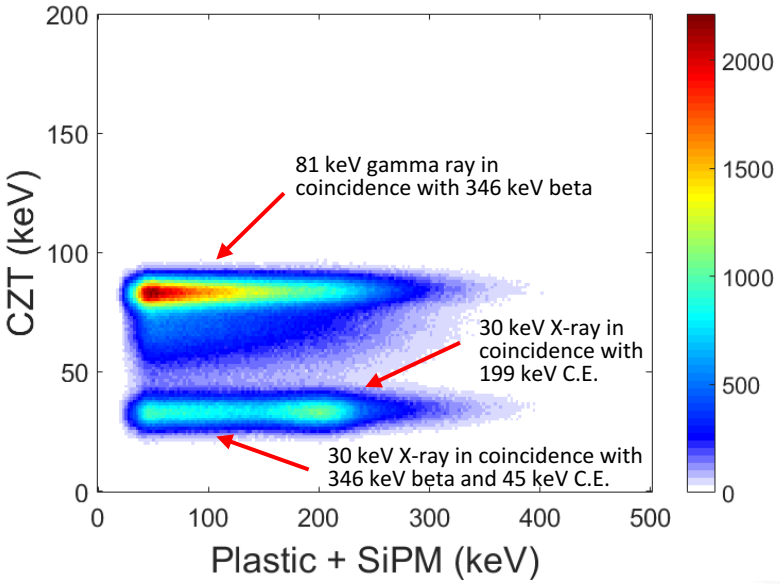


PIPS-CZT

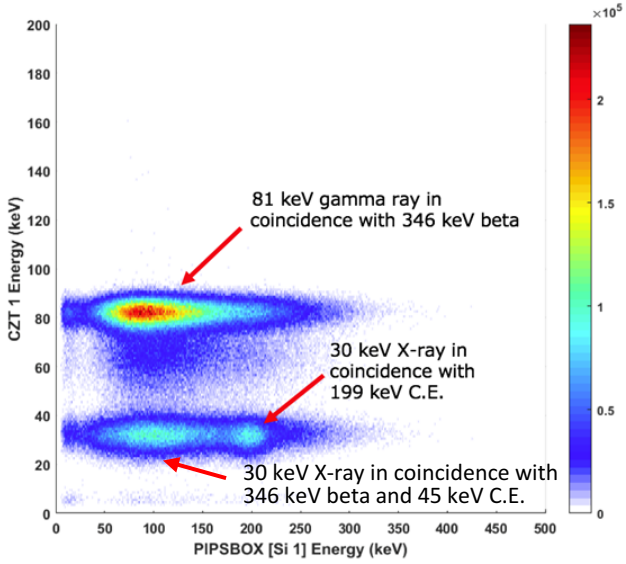
Results- $^{133/133m}Xe$

Properties	^{133}Xe	^{133m}Xe
Half-Life (days)	5.243	2.19
X-Ray (keV)	30	30
Gamma (keV)	81	-
Max Beta (keV)	346	-
Conversion Electron (keV)	45	199

Energy Resolution (FWHM, %)		
	CASP	PIPS-CZT
30 keV X-ray	33.9%	30.0%
81 keV Gamma	11.0%	12.19%
199 keV CE	23.3%	12.95%

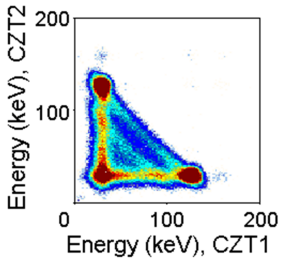


CASP



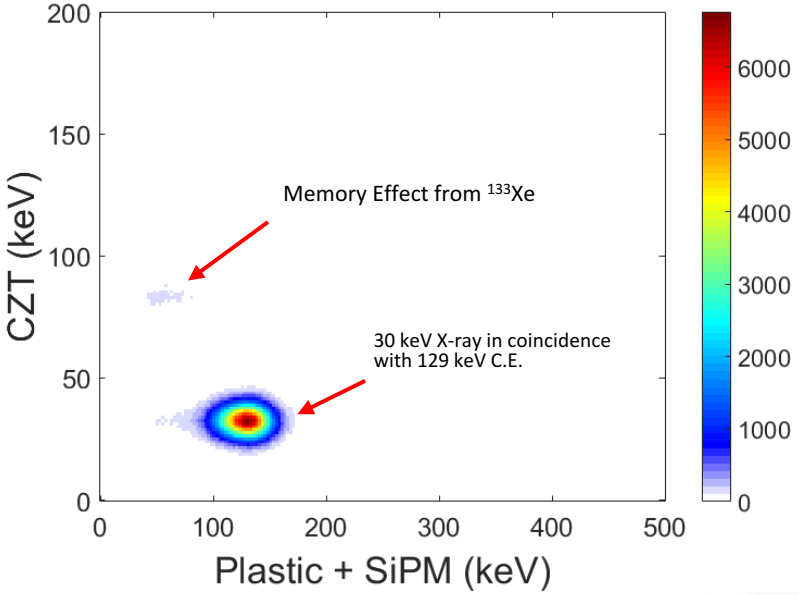
PIPS-CZT

Results- ^{131m}Xe

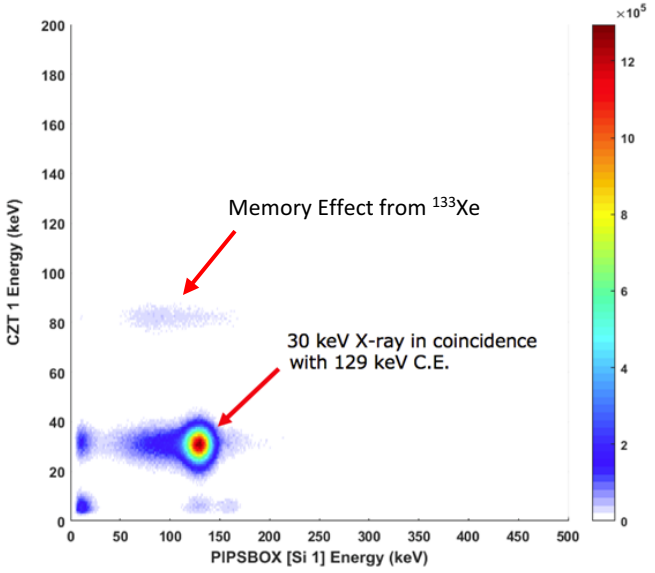


Properties	^{131m}Xe
Half-Life (days)	11.93
X-Ray (keV)	30
Conversion Electron (keV)	129

Energy Resolution (FWHM, %)		
	CASP	PIPS-CZT
30 keV X-ray	35.9%	30.0%
129 keV CE	23.7%	17.7%



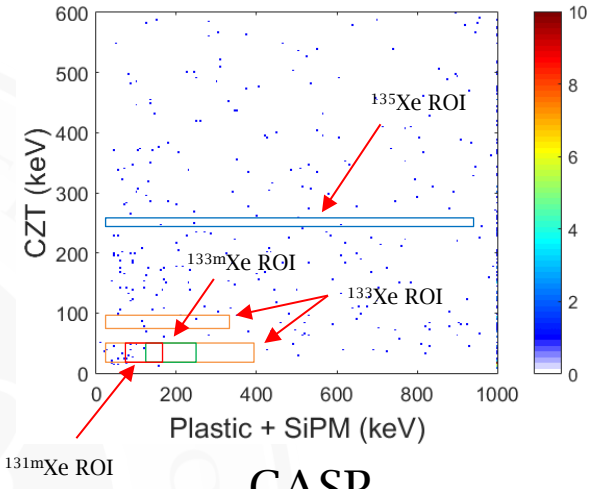
CASP



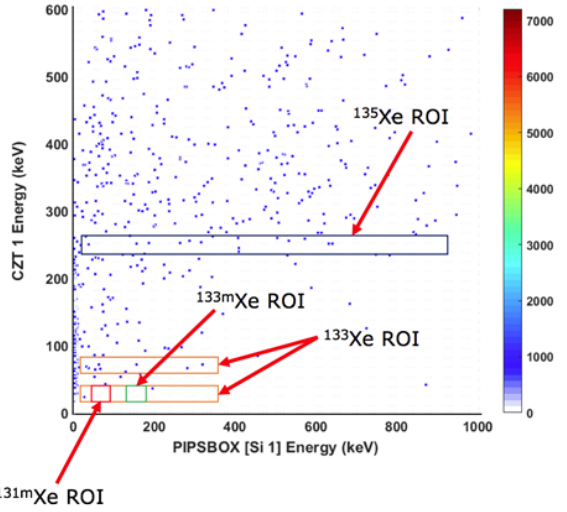
PIPS-CZT

Results- Background

- Background measurement
  - 48 hour, full lead cave
    - **CASP -> 99.8% background rejection rate**
    - **PIPS-CZT -> 99.9% background rejection rate**
- Most coincidences fall outside ROIs



CASP



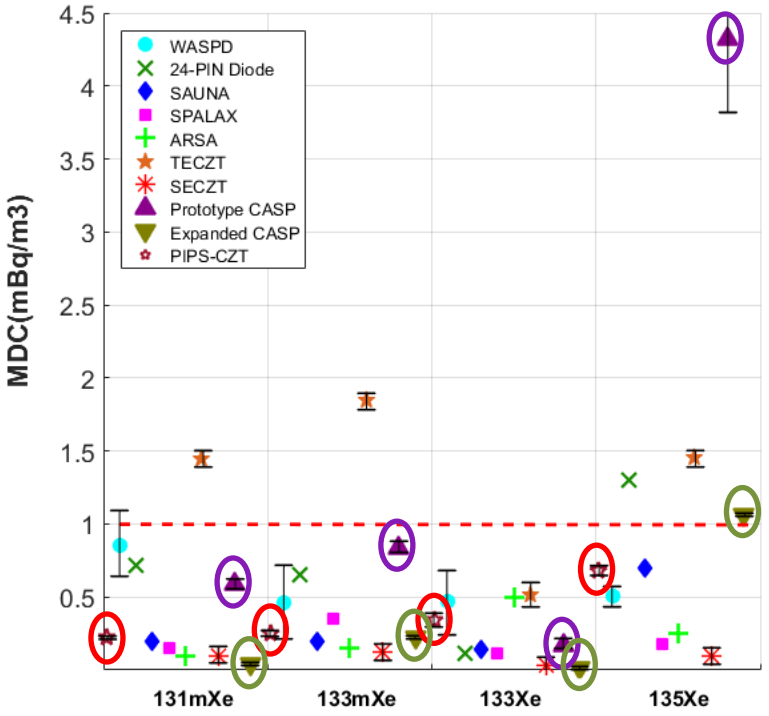
PIPS-CZT

		CASP [1] [2]	PIPS-CZT	TECZT [3] [4]
Background Rate (counts/s)	Total (all events)	**1.79**	**4.83**	0.02
	Coincidence Events	**0.00355**	**0.0055**	0.0036
Coincidence/ Total		**0.002**	**0.001**	0.018

		WASPD [5]	Phoswich [5]	SAUNA [6][7]	ARSA [6][8]	BGW [9][10]
Background Rate (counts/s)	Total (all events)	1.26	3.29	7.5-12	30	5.5
	Coincidence Events	0.02	0.06	0.03	0.1	0.025
Coincidence/ Total		0.0159	0.0182	0.004-0.0025	0.0033	0.0045

Results- MDC

- Prototype CASP achieves < 1 mBq/m^3 for $^{133/133m}$Xe
  - 2x2x1 cm^3 four-element version expected to achieve MDC of < 1 mBq/m^3 for three of the four radioxenons
    - MCNP6 simulations
- PIPS-CZT achieves < 1 mBq/m^3 for all radioxenons of interest



Radioxenon Isotope	MDC (mBq/m^3) CASP System, One 1 x 1 x 1 cm^3 CZT	MDC (estimated) (mBq/m^3) CASP System, Four 2 x 2 x 1 cm^3 CZTs	MDC (mBq/m^3) PIPS-CZT, One 1 x 1 x 1 cm^3 CZT
^{131m}Xe	0.5855 ± 0.0311	0.0442 ± 0.0023	0.22 ± 0.016
^{133}Xe	0.8383 ± 0.0269	0.226 ± 0.0008	0.34 ± 0.062
^{133m}Xe	0.1693 ± 0.0177	0.0129 ± 0.0007	0.25 ± 0.016
^{135}Xe	4.3211 ± 0.5702	1.059± 0.009	0.68 ± 0.045

Conclusions and Outlook

- Deterrence of undeclared nuclear activities
  - Detection of clandestine nuclear explosions (CTBTO/IMS)
  - Atmospheric radioxenon at low concentrations
  - Compact, room temperature, real-time
- CASP Prototype
  - MDC of < 1 mBq/m^3 for ^{133}Xe
  - Removal of CE backscatter
- PIPS-CZT Prototype
  - MDC of < 1 mBq/m^3 for all radioxenon of interest
  - New technology, higher CE resolution
- Problems and Future work
  - Quantify memory effect
  - Determine absolute efficiency

Sources

[1] S. A. Czyz and A. T. Farsoni, “A radioxenon detection system using CdZnTe, an array of SiPMs, and a plastic scintillator,” *Journal of Radioanalytical and Nuclear Chemistry*, vol. 313, no. 1, pp. 131–140, Jul. 2017.

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