DE LA RECHERCHE À L'INDUSTRIE

www.cea.fr

WORKSHOP ML IN2P3/IRFU

École des Ponts ParisTech

APPLICATION OF BAYESIAN CONVOLUTIONAL NEURAL NETWORK TO SPECTRAL IDENTIFICATION OF RADIONUCLIDES FOR NUCLEAR MONITORING

DANIEL Geoffrey[1,2], LIMOUSIN Olivier[1], MAIER Daniel[1], CERAUDO Francesco[1], MEURIS Aline[1]

[1]AIM, CEA, CNRS, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité
[2]École des Ponts ParisTech

January 23rd 2020

CONTEXT

Nuclear safety monitoring:

- Decomissionning and dismantling
- Post-accidental scenes

Nuclear security: radiation portal monitor

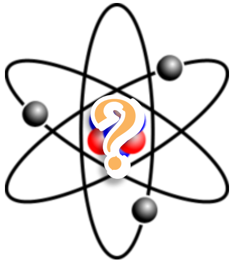
Characterization of radiological scenes

→ **Identification of the radionuclides in the scene**

→ **Proportion of each identified radionuclide**

YOSHIKAZU TSUNO / POOL / AFP

Fukushima accident



CALISTE DETECTOR

CdTe semi-conductor crystal

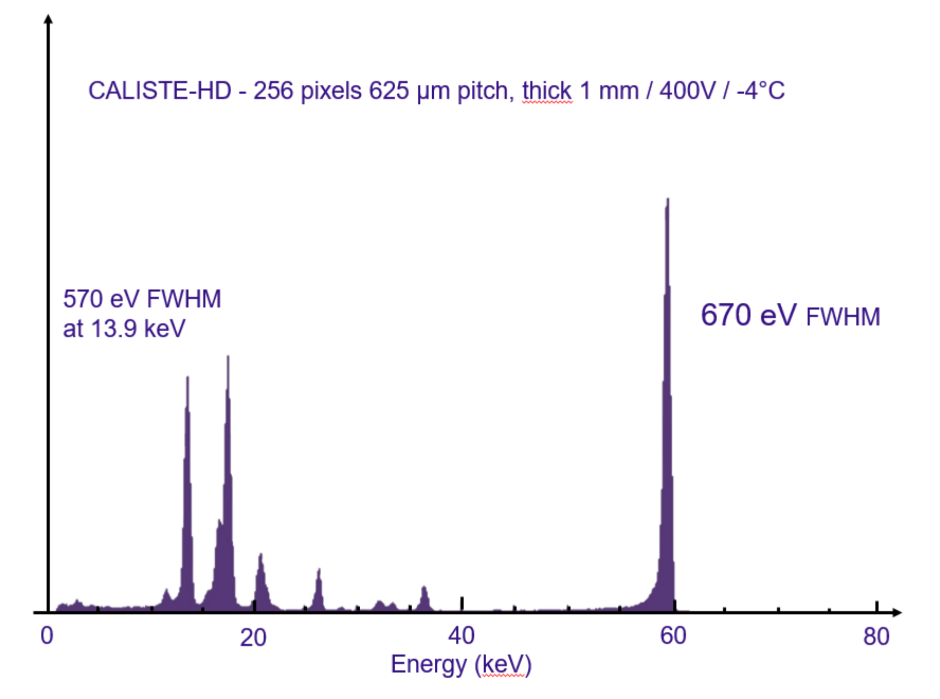
Miniature pixelated spectro-imager

Works at **nearly room temperature**: high performance at -15°C
Low power consumption: 200 mW

First developments for **astrophysical** application
→ STIX: Spectrometer Telescope Imaging X-rays
Observation of Bremstrahlung from accelerated electrons near the Sun

Different versions of Caliste: Caliste-SO, Caliste-HD, Caliste-O…

From space applications to **industrial** applications:
→ Medical application: breast tumor cells detection
→ **Nuclear safety application**



^{241}Am Spectrum

Caliste Family

geoffrey.daniel@cea.fr

CALISTE HD

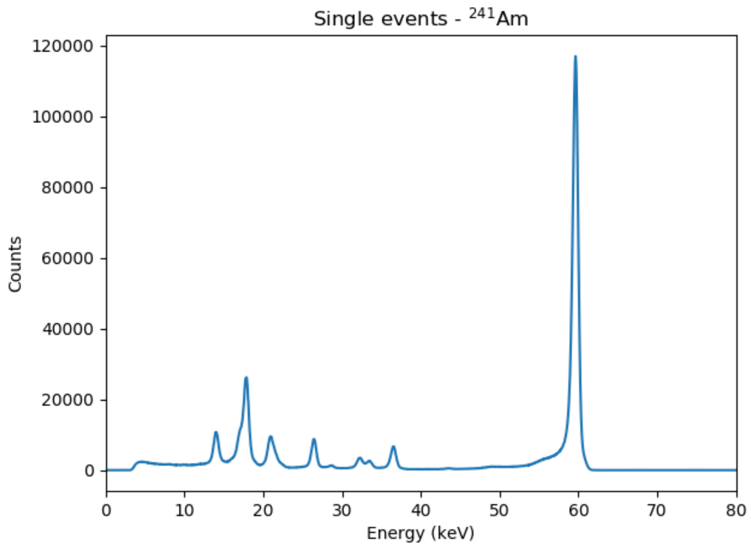
Pixelated detector 16 x 16 pixels
625 μm pixel pitch
1 mm thickness
Surface: 1 cm²
Other versions available

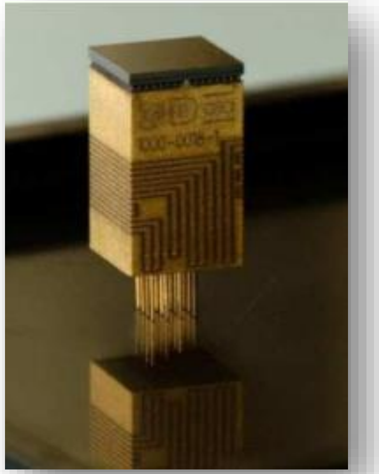
Imaging: Coded mask and Compton localisation

High **energy range**: from 2 keV to 1 MeV

High energy resolution
670 eV FWHM at 60 keV (1,1 %)
4,1 keV FWHM at 662 keV (0,62 %)

Spectroscopy: Radioactive sources identification





Caliste-HD (CEA Irfu)

WIX-HD Camera
Mass: 1 kg

OUR PROBLEM: SPECTRAL IDENTIFICATION

Input : Calibrated event list

Select / All / Invert	FRAME 1I	MULTIPLICITY 1B	MULT 1B	TIME 1D	PIXEL 1B	X 1I	Y 1I	TYPE 1I	ENERGY 1D
	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify	Modify
1	0	1	0	0.000000000000E+000	128	0	8	1	9.794309200000E+001
2	1	1	0	3.062956094742E+000	145	1	9	1	9.333808000000E+001
3	2	1	0	3.107777595520E+000	126	14	7	1	5.661259000000E+001
4	3	1	0	3.311278343201E+000	176	0	11	1	1.204386400000E+002
5	4	1	0	4.261723756790E+000	117	5	7	1	5.908343000000E+001
6	5	1	0	4.685714244843E+000	155	11	9	1	3.126330300000E+001
7	6	1	0	7.426927089691E+000	134	6	8	1	2.661225810000E+002
8	7	2	0	7.764491081238E+000	242	2	15	255	1.749924320000E+002
9	8	2	1	7.764491081238E+000	243	3	15	255	2.266542400000E+001
10	9	1	0	8.099779129028E+000	226	2	14	1	2.673193900000E+001
11	10	2	0	8.122672319412E+000	119	7	7	255	3.066022800000E+001
12	11	2	1	8.122672319412E+000	135	7	8	255	1.780166800000E+001
13	12	1	0	8.208755016327E+000	252	12	15	1	4.416408700000E+001
14	13	1	0	8.331153392792E+000	254	14	15	1	7.991901300000E+001
15	14	1	0	8.772984504700E+000	47	15	2	1	1.588442560000E+002
16	15	1	0	9.839590549469E+000	59	11	3	1	2.487148740000E+002
17	16	1	0	9.900824785233E+000	191	15	11	1	2.493642300000E+001
18	17	1	0	1.208127880096E+001	239	15	14	1	6.909980000000E+001
19	18	1	0	1.288081645966E+001	10	10	0	1	2.669001630000E+002
20	19	1	0	1.323039579391E+001	97	1	6	1	1.040922665000E+003
21	20	1	0	1.323042392731E+001	97	1	6	1	5.778931210000E+002
22	21	1	0	1.323045206070E+001	97	1	6	1	1.885572170000E+002
23	22	1	0	1.470239663124E+001	120	8	7	1	1.665020800000E+001
24	23	1	0	1.472033309937E+001	77	13	4	1	7.437592800000E+001
25	24	1	0	1.529405093193E+001	52	4	3	1	8.464667200000E+001
26	25	1	0	1.603019905090E+001	217	9	13	1	5.825263600000E+001
27	26	1	0	1.623439192772E+001	169	9	10	1	3.984854400000E+001
28	27	1	0	1.637744331360E+001	202	10	12	1	5.378394600000E+001
29	28	1	0	1.652689838409E+001	48	0	3	1	3.205725600000E+001

Outputs

Which **radioelements**? → Classification

In which **proportions**? → Regression

With **uncertainties**?

Some constraints:

- **Real-time** computation
- Identification for **low-statistics** of photon
- Independent on **operational conditions** (temperature, high-voltage… → impact on calibration)
- Not sensitive to environmental conditions (presence of absorbing materials or diffusing materials)

DATA TRANSFORMATION

Input

Calibrated event list

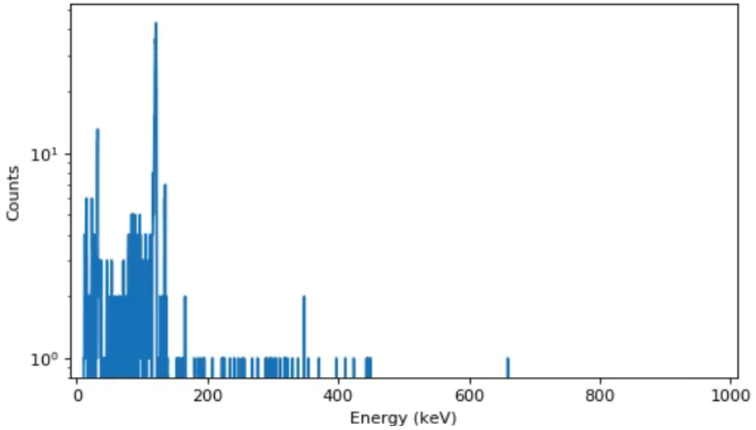
Select	FRAME 1I	MULTIPLICITY 1B	MULT 1B	TIME 1D	PIXEL 1B	X 1I	Y 1I	TYPE 1I	ENERGY 1D
1	0	1	0	0.000000000000E+000	128	0	8	1	9.794309200000E+001
2	1	1	0	3.062956094742E+000	145	1	9	1	9.333808000000E+001
3	2	1	0	3.107777595520E+000	126	14	7	1	5.661259000000E+001
4	3	1	0	3.311278343201E+000	176	0	11	1	1.204386400000E+002
5	4	1	0	4.261723756790E+000	117	5	7	1	5.908343000000E+001
6	5	1	0	4.685714244843E+000	155	11	9	1	3.126330300000E+001
7	6	1	0	7.426927089691E+000	134	6	8	1	2.661225810000E+002
8	7	2	0	7.764491081238E+000	242	2	15	255	1.749924320000E+002
9	8	2	1	7.764491081238E+000	243	3	15	255	2.266542400000E+001
10	9	1	0	8.099779129028E+000	226	2	14	1	2.673193900000E+001
11	10	2	0	8.122672319412E+000	119	7	7	255	3.066022800000E+001
12	11	2	1	8.122672319412E+000	135	7	8	255	1.780166800000E+001
13	12	1	0	8.208755016327E+000	252	12	15	1	4.416408700000E+001
14	13	1	0	8.331153392792E+000	254	14	15	1	7.991901300000E+001
15	14	1	0	8.772984504700E+000	47	15	2	1	1.588442560000E+002
16	15	1	0	9.839590549469E+000	59	11	3	1	2.487148740000E+002
17	16	1	0	9.900824785233E+000	191	15	11	1	2.493642300000E+001
18	17	1	0	1.208127880096E+001	239	15	14	1	6.909980000000E+001
19	18	1	0	1.288081645966E+001	10	10	0	1	2.669001630000E+002
20	19	1	0	1.323039579391E+001	97	1	6	1	1.040922665000E+003
21	20	1	0	1.323042392731E+001	97	1	6	1	5.778931210000E+002
22	21	1	0	1.323045206070E+001	97	1	6	1	1.885572170000E+002
23	22	1	0	1.470239663124E+001	120	8	7	1	1.665020800000E+001
24	23	1	0	1.472033309937E+001	77	13	4	1	7.437592800000E+001
25	24	1	0	1.529405093193E+001	52	4	3	1	8.464667200000E+001
26	25	1	0	1.603019905090E+001	217	9	13	1	5.825263600000E+001
27	26	1	0	1.623439192772E+001	169	9	10	1	3.984854400000E+001
28	27	1	0	1.637744331360E+001	202	10	12	1	5.378394600000E+001
29	28	1	0	1.652689838409E+001	48	0	3	1	3.205725600000E+001

Histogram of measured energies
Classical way for these studies

Choices: binning, range, single events, sum spectrum of all pixels

Vector of counts → Spectrum

0	25	100	50	12	….	4	0	0	0



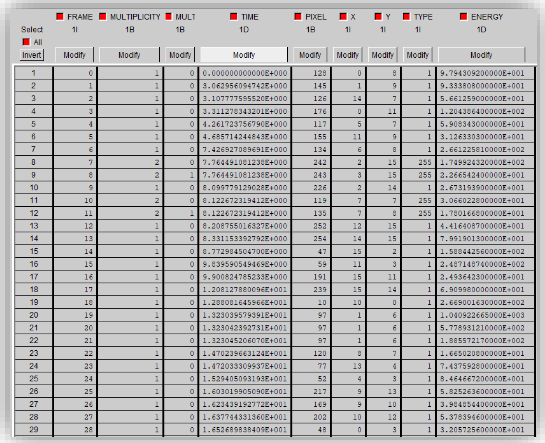
Normalization

Log-normalization, max = 1

Input of ML algorithm

DATA TRANSFORMATION

Calibrated event list



	FRAME 1I	MULTIPLICITY 1B	MULT 1B	TIME 1D	PIXEL 1B	X 1I	Y 1I	TYPE 1I	ENERGY 1D
1	0	1	0	0.000000000000E+000	128	0	8	1	9.794309200000E+001
2	1	1	0	3.062956094742E+000	145	1	9	1	9.333808000000E+001
3	2	1	0	3.107777595520E+000	126	14	7	1	5.661259000000E+001
4	3	1	0	3.311278343201E+000	176	0	11	1	1.204386400000E+002
5	4	1	0	4.261723756790E+000	117	5	7	1	5.908343000000E+001
6	5	1	0	4.685714244843E+000	155	11	9	1	3.126330300000E+001
7	6	1	0	7.426927089691E+000	134	6	8	1	2.661225810000E+002
8	7	2	0	7.764491081238E+000	242	2	15	255	1.749924320000E+002
9	8	2	1	7.764491081238E+000	243	3	15	255	2.266542400000E+001
10	9	1	0	8.099779129028E+000	226	2	14	1	2.673193900000E+001
11	10	2	0	8.122672319412E+000	119	7	7	255	3.066022800000E+001
12	11	2	1	8.122672319412E+000	135	7	8	255	1.780166800000E+001
13	12	1	0	8.208755016327E+000	252	12	15	1	4.416408700000E+001
14	13	1	0	8.331153392792E+000	254	14	15	1	7.991901300000E+001
15	14	1	0	8.772984504700E+000	47	15	2	1	1.588442560000E+002
16	15	1	0	9.839590549469E+000	59	11	3	1	2.487148740000E+002
17	16	1	0	9.900824785233E+000	191	15	11	1	2.493642300000E+001
18	17	1	0	1.208127880096E+001	239	15	14	1	6.909980000000E+001
19	18	1	0	1.288081645966E+001	10	10	0	1	2.669001630000E+002
20	19	1	0	1.323039579391E+001	97	1	6	1	1.040922665000E+003
21	20	1	0	1.323042392731E+001	97	1	6	1	5.778931210000E+002
22	21	1	0	1.323045206070E+001	97	1	6	1	1.885572170000E+002
23	22	1	0	1.470239663124E+001	120	8	7	1	1.665020800000E+001
24	23	1	0	1.472033309937E+001	77	13	4	1	7.437592800000E+001
25	24	1	0	1.529405093193E+001	52	4	3	1	8.464667200000E+001
26	25	1	0	1.603019905090E+001	217	9	13	1	5.825263600000E+001
27	26	1	0	1.623439192772E+001	169	9	10	1	3.984854400000E+001
28	27	1	0	1.637744331360E+001	202	10	12	1	5.378394600000E+001
29	28	1	0	1.652689838409E+001	48	0	3	1	3.205725600000E+001

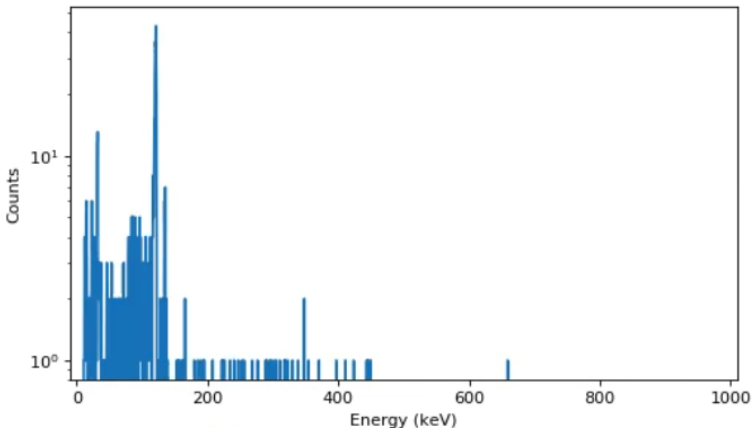
Input

Histogram of measured energies
Classical way for these studies

Choices: binning, range, single events, sum spectrum of all pixels

Vector of counts → Spectrum

0	25	100	50	12	….	4	0	0	0



Normalization

Log-normalization, max = 1

Input of ML algorithm

Convolutional Neural Network

Output of ML algorithm

Output

List of sources: ^{137}Cs, ^{57}Co

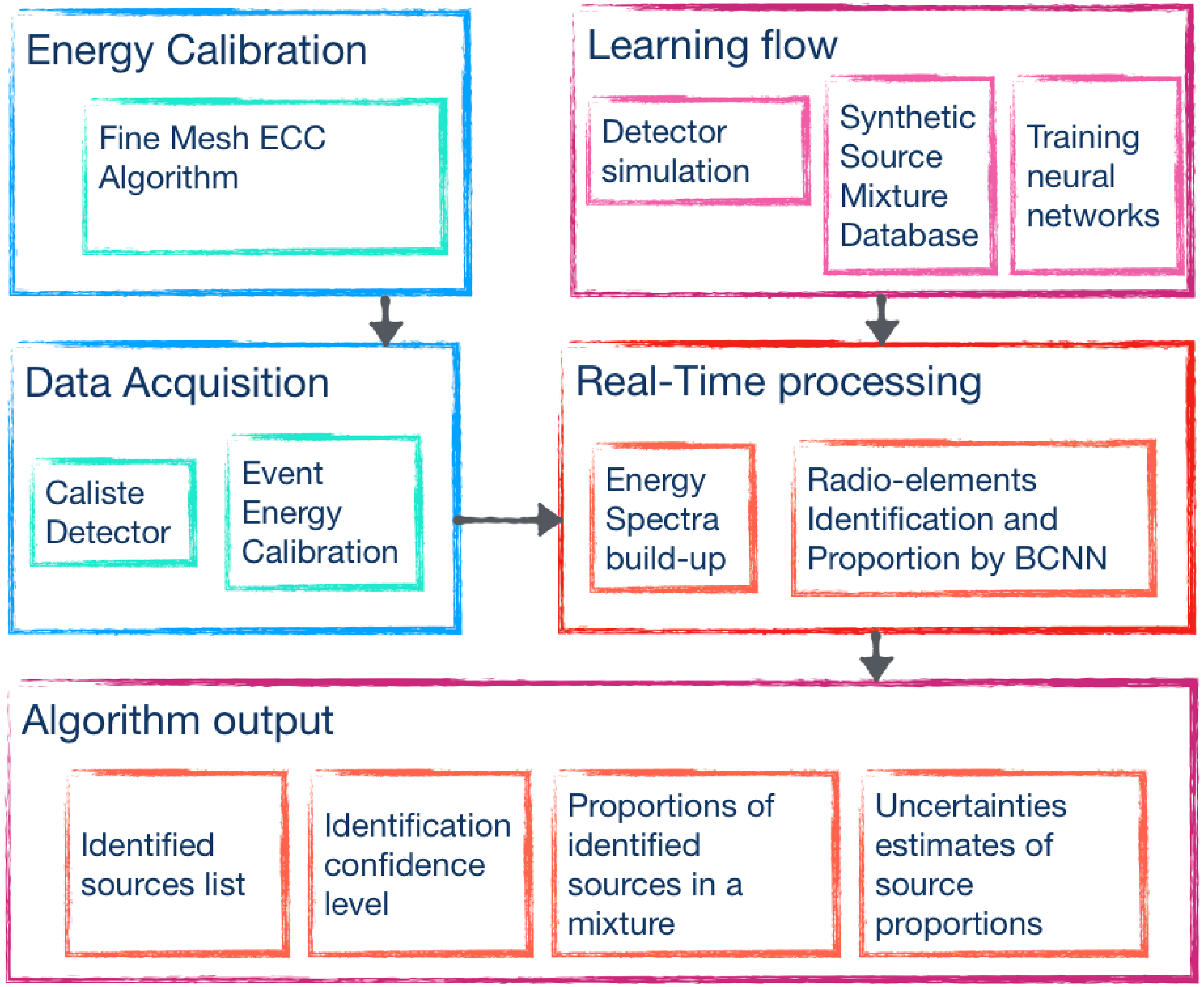
Proportions of the detected photons: ^{137}Cs: 30%, ^{57}Co: 70%

Mathematical representation

^{241}Am	^{133}Ba	^{57}Co	^{137}Cs	^{152}Eu	^{22}Na
0	0	1	1	0	0
0	0	0,7	0,3	0	0

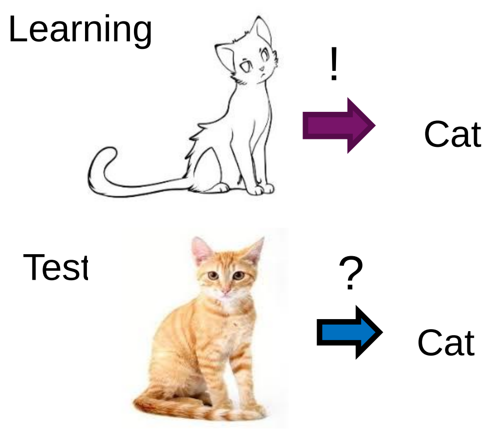
geoffrey.daniel@cea.fr

PIPELINE TO SOLVE OUR PROBLEM



Use of **synthetic** data:

- Sources we do not have in lab
- Control the environment (put absorbing/diffusing materials)
- Voluntary decalibration → operational conditions
- Mixture creation (control the proportions)
- **Physical model of the detector** is required



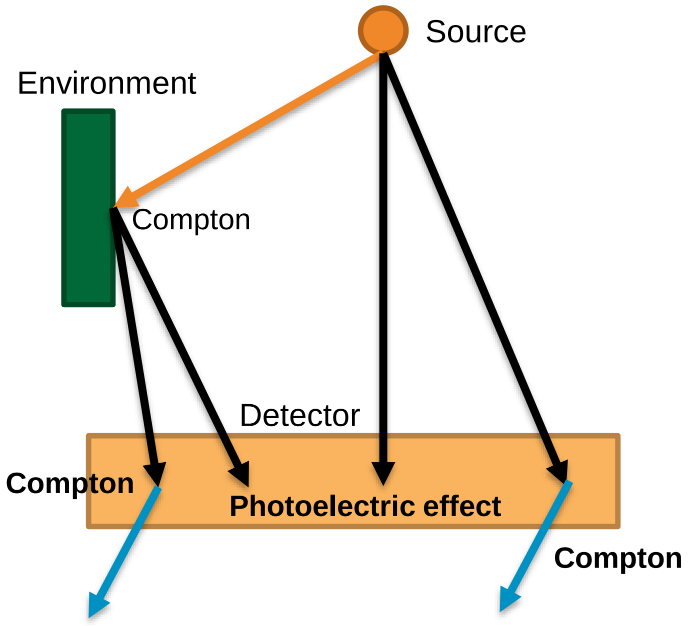
geoffrey.daniel@cea.fr

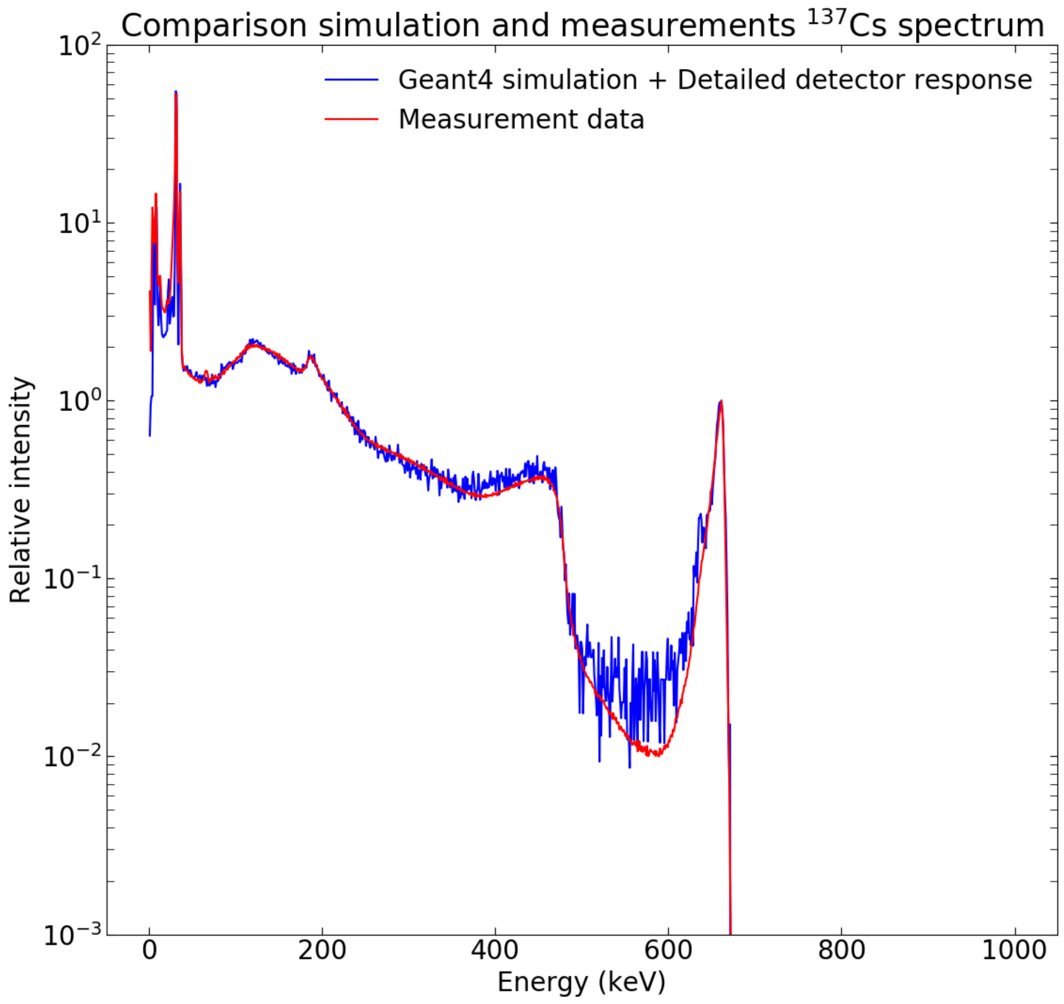
Detailed Geant4 model

- Photoelectric absorption: total absorption of the energy of the photon (+ fluorescence)
- Compton diffusion: partial energy deposition and diffusion of the photon
- Modelisation of direct environment: multiple Compton scattering

Detector response modelisation

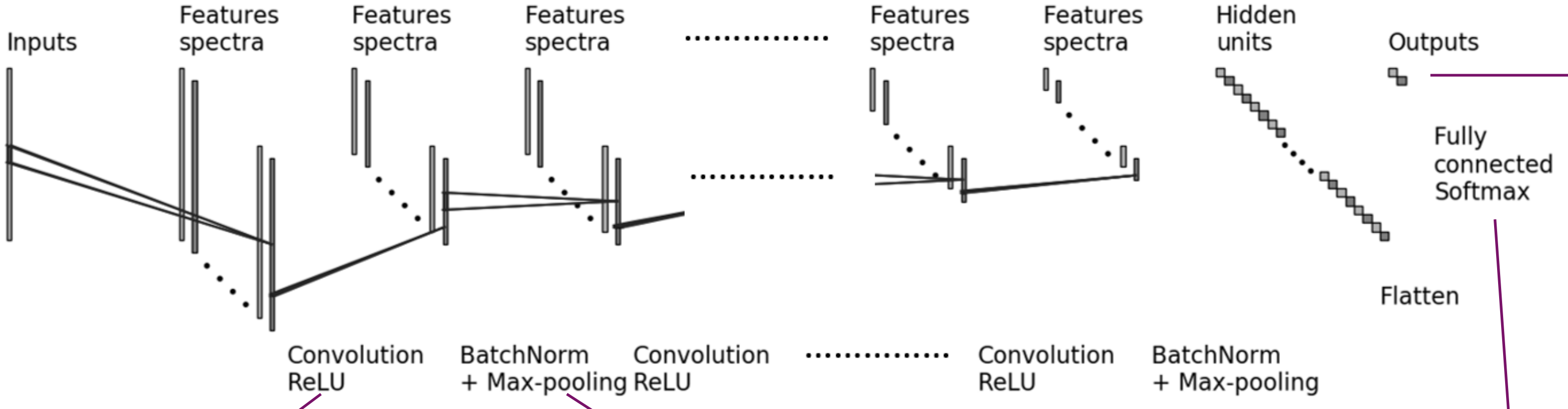
- Statiscal fluctuations of electrons/holes pair creation
- Charge loss modelisation (3D)
- Electronic noise





geoffrey.daniel@cea.fr

CONVOLUTIONAL NEURAL NETWORK



Convolution part:
Characteristics extraction

Pooling:
→ Dimension reduction
→ Search for more global features

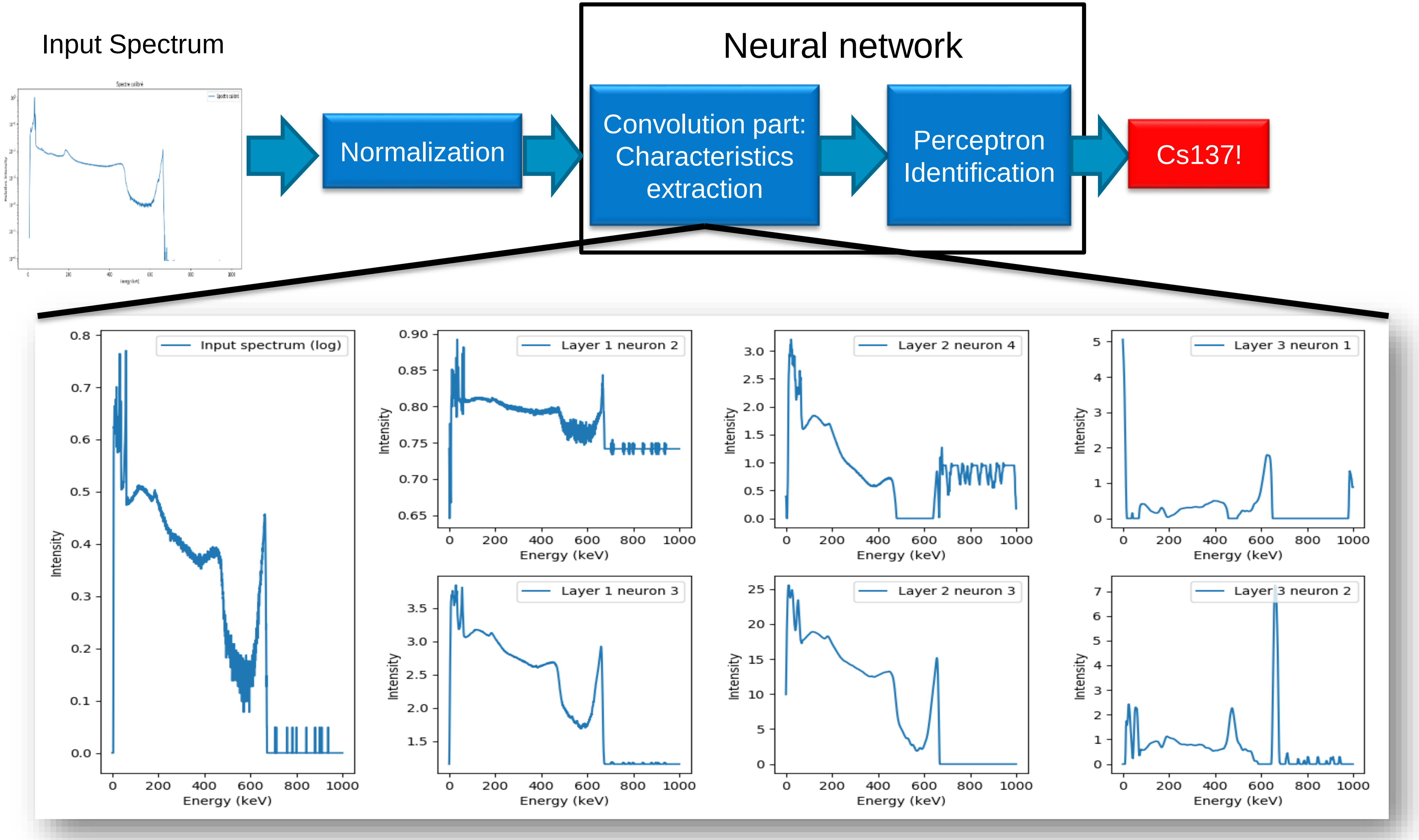
Fully connected:
Identification

One identification network for each radio-element:
→ Use separated networks for each radio-element: characteristics extraction more efficient
→ Better performances on synthetic learning

One network to evaluate proportions for each radio-element:
→ Use separated networks for identification and evaluation of proportions
→ Discriminate presence or absence of sources with small proportions

Network creation:
→ Dedicated architecture
→ Methodological: simple network then complexification, monitoring of performance (error rate) until performance did not improve
→ Cost function: binary cross-entropy (classification), MSE (proportion)

CONVOLUTIONAL NEURAL NETWORK



PERFORMANCE

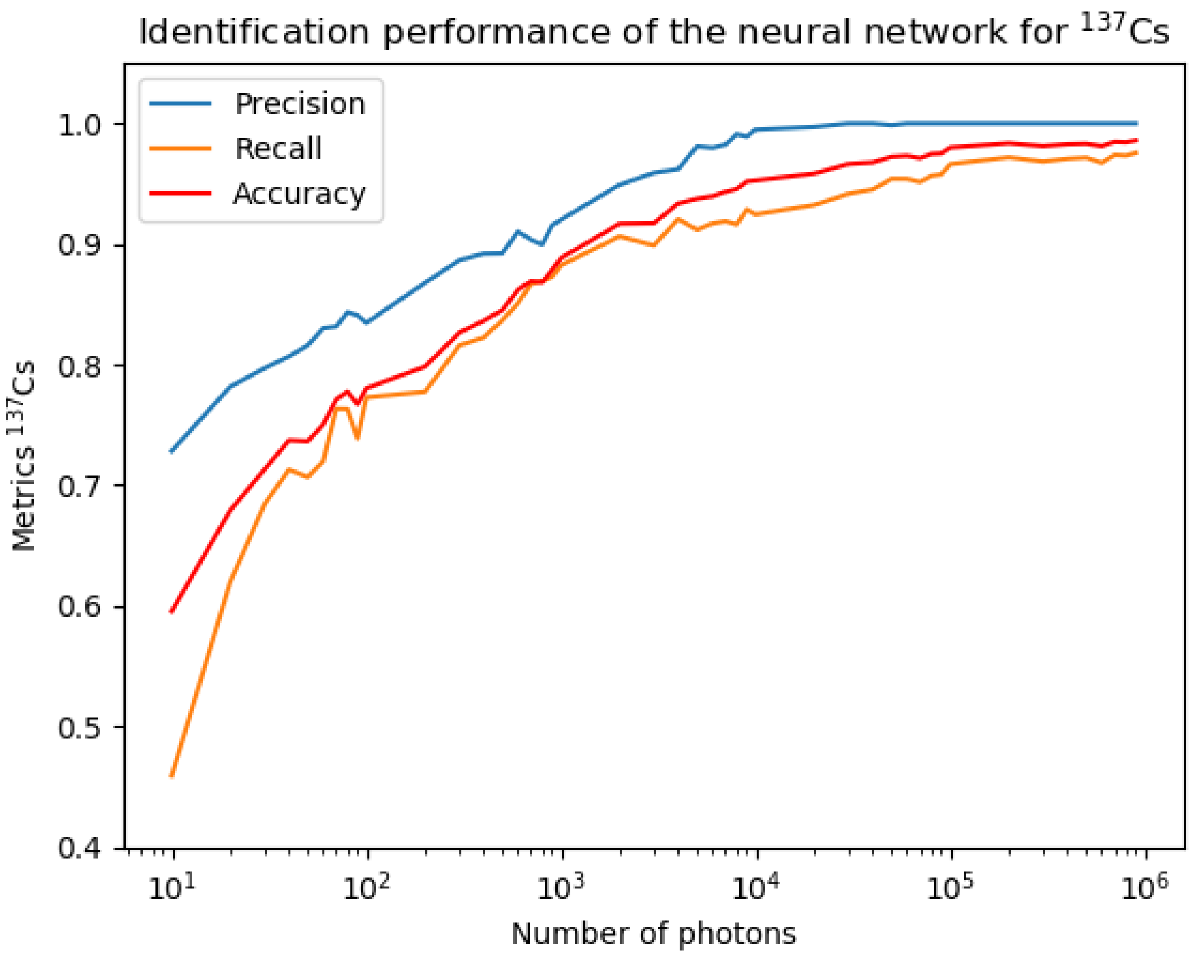
Precision: False positive influence
Recall: False negative influence
Accuracy: Right identification rate

Accuracy:

- > 80 % with more than 200 photons
- > 90 % with at least 1000 photons
- > 95 % with at least some thousands of photons

- Similar performance for other radionuclides: ^{241}Am, ^{133}Ba, ^{57}Co, ^{152}Eu, ^{22}Na

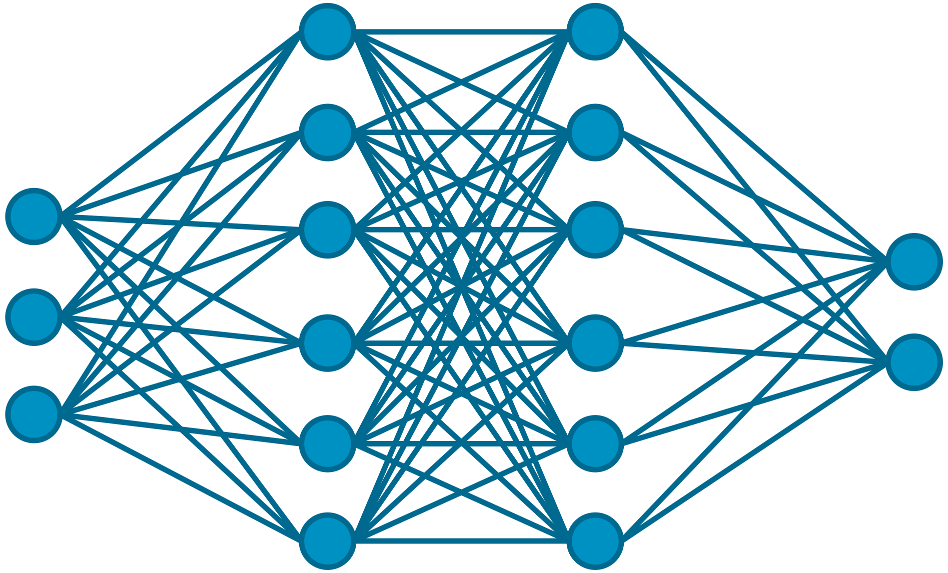
Test on real data of mixtures with **random decalibration**

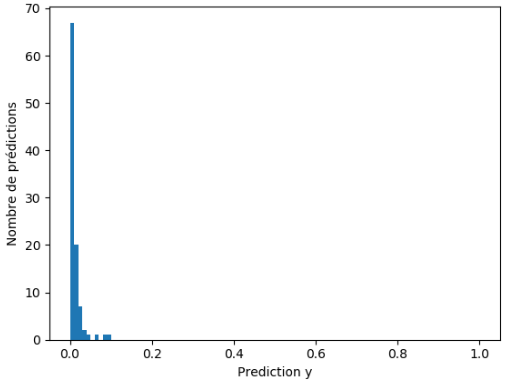


HOW TO MEASURE UNCERTAINTY?

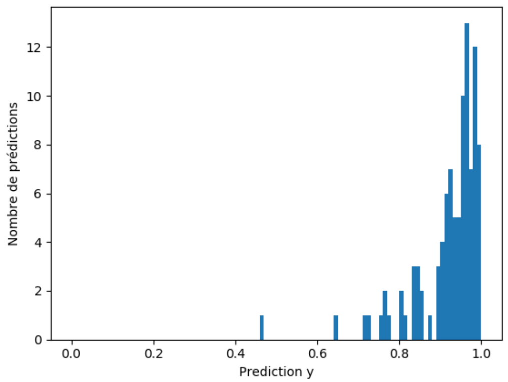
Idea: **bayesian neural network**
Weights learned are not fixed: we want to learn a **distribution** $W \sim \mathcal{N}(\mu, \sigma)$ → Prediction Y is a **distribution**
In practice: really complex to implement

Approximation by **dropout**: random extinction of the neurons → Different tests on the same example, different answers

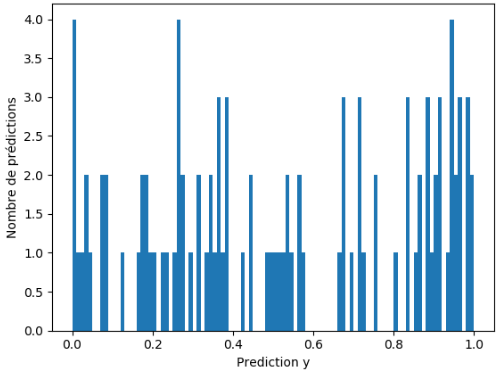




Very low uncertainty

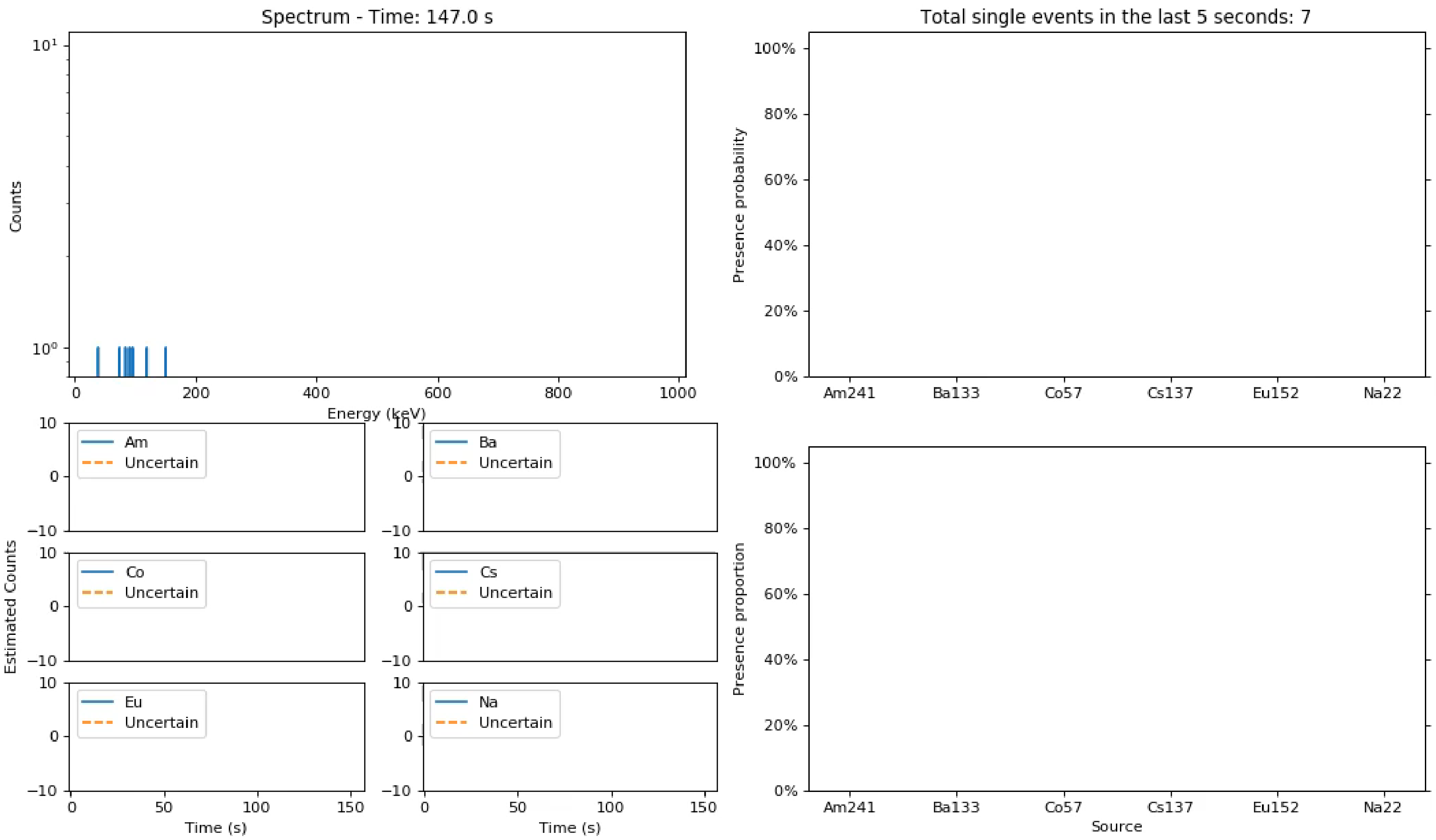


Low uncertainty

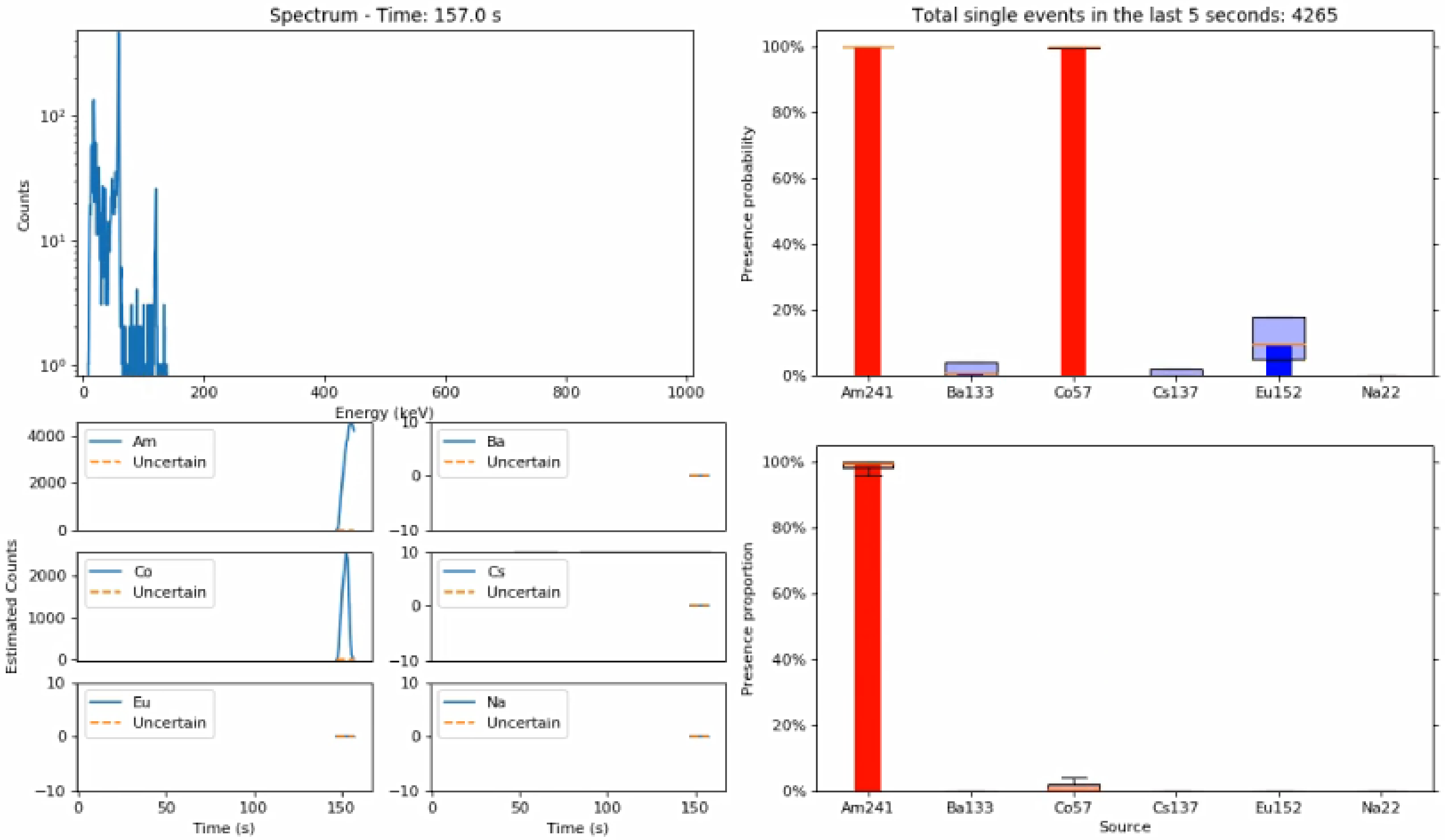


Very high uncertainty

EXAMPLE: VIDEO



EXAMPLE: VIDEO



CONCLUSION AND OUTLOOKS

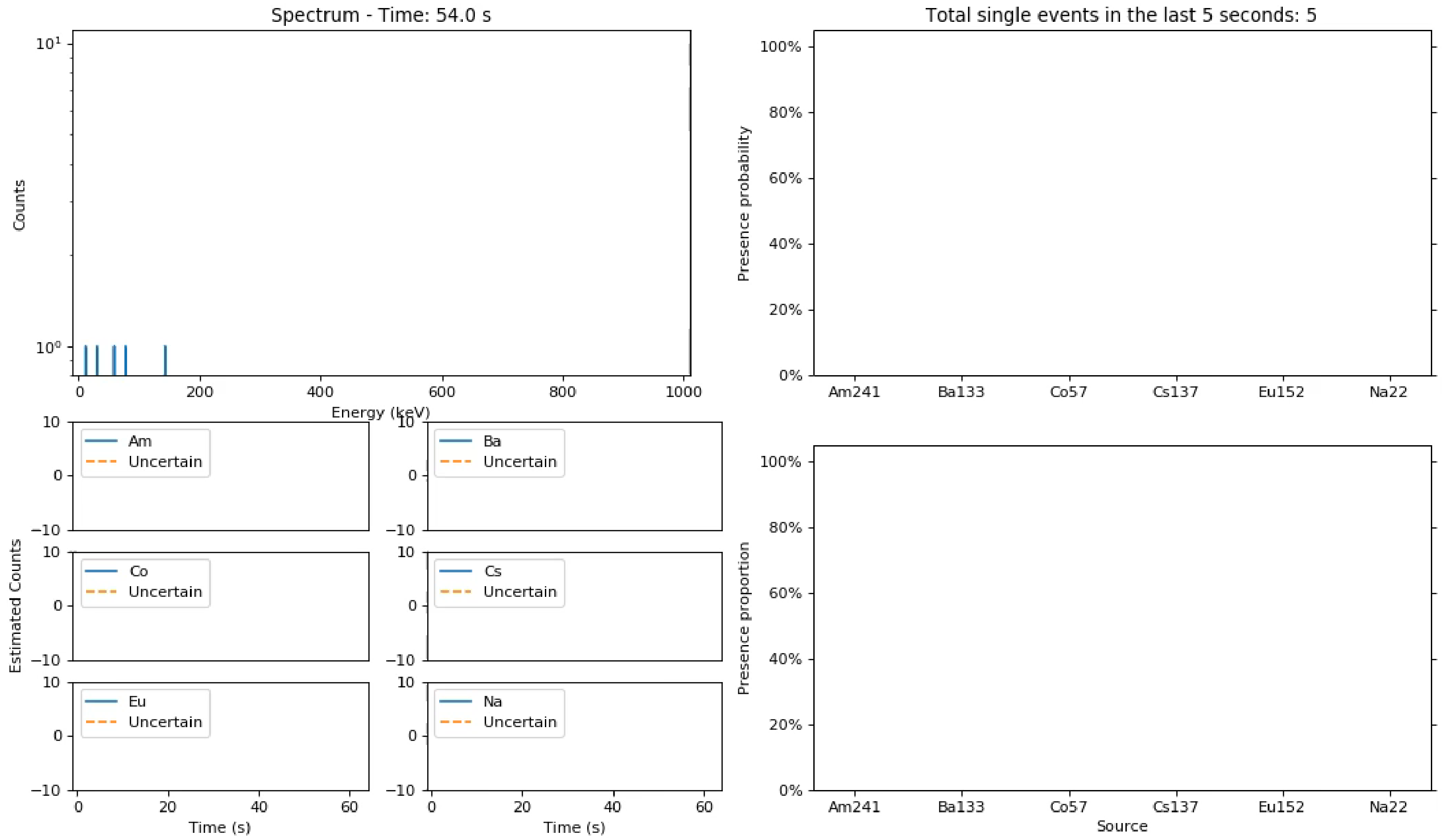
- **Identification and proportion determination** of radioelements
  - Performed thanks to Deep learning algorithms
  - Training on synthetic data sets
- **Uncertainties** on the predictions
- **Real-time** measurements processing and low-statistics acquisition
- Not sensitive to **decalibration**

And now:

- **More sources** in the library (but still limited for the test set)
- **Embedded** implementation in FPGA
- Evaluation and qualification campaigns in different environments → Adaptation of the CNN architecture to the situation (more complex environment, deeper architecture)

geoffrey.daniel@cea.fr

Thank you!


Spectrum - Time: 54.0 s
Counts
Energy (keV)
Total single events in the last 5 seconds: 5
Presence probability
Am241
Ba133
Co57
Cs137
Eu152
Na22
Estimated Counts
Am
Ba
Co
Cs
Eu
Na
Uncertain
Time (s)
Presence proportion
Source

REFERENCES

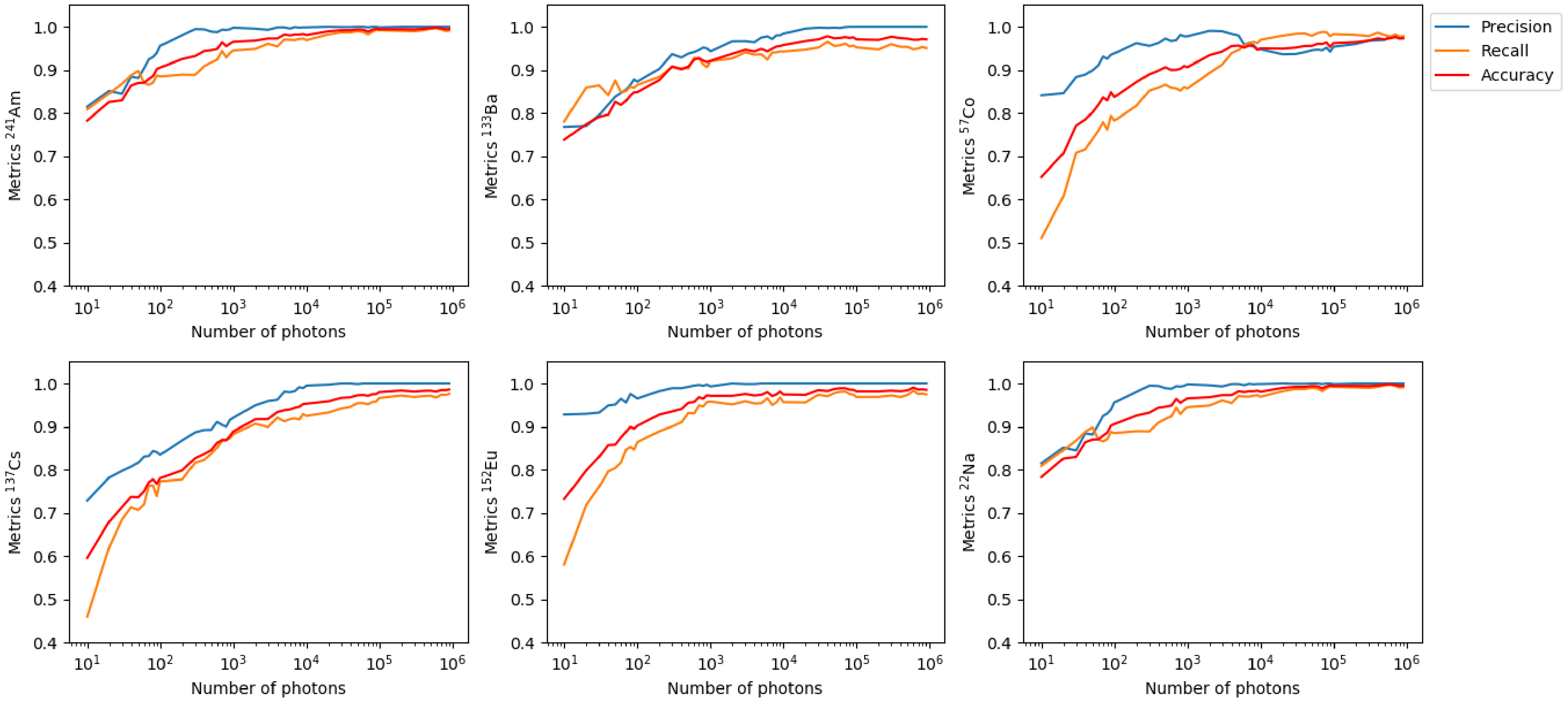
[1] *Second generation of portable gamma camera based on Caliste CdTe hybrid technology,* D. Maier et al., NIM-A (2017)

[2] *Caliste HD: A new fine pitch Cd(Zn)Te imaging spectrometer from 2 keV up to 1 MeV,* A. Meuris et al., IEEE-NSS (2011)

[3] *A Review on Deep Convolutional Neural Network,* N. Aloysius, M. Geetha, International Conference on Communication and Signal Processing (2017)

[4] *Dropout as a Bayesian Approximation: Representing Model Uncertainty in Deep Learning*, Y. Gal, Z. Ghahramani, Proceedings of the 33 rd International Conference on Machine Learning (2016)

GLOBAL PERFORMANCE



EXAMPLE: VIDEO 1