Spatio-temporal detection and tracking of thermal events on the PFCs of W7-X

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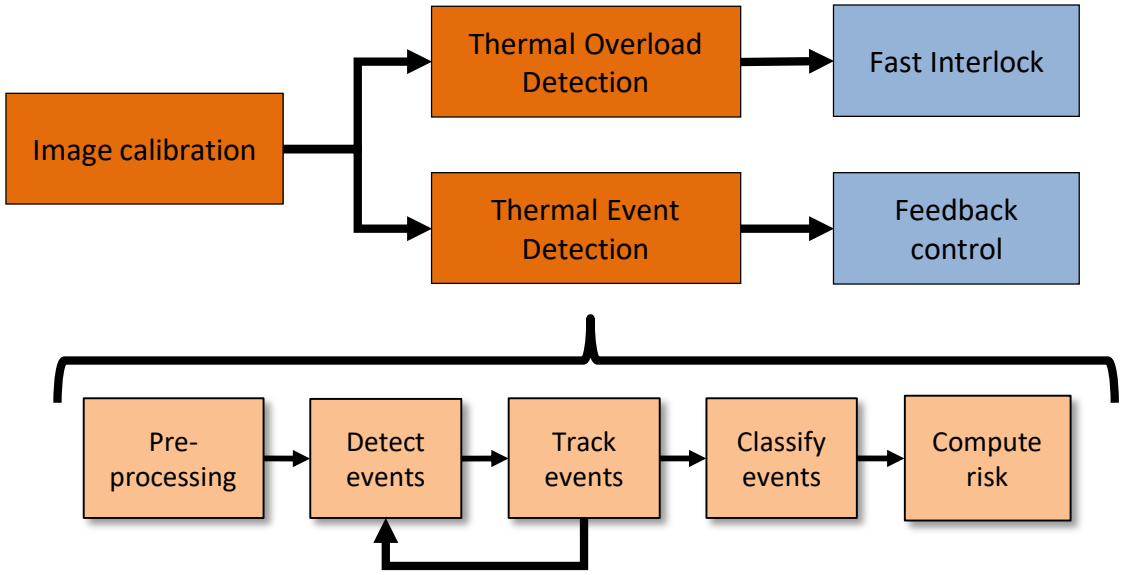
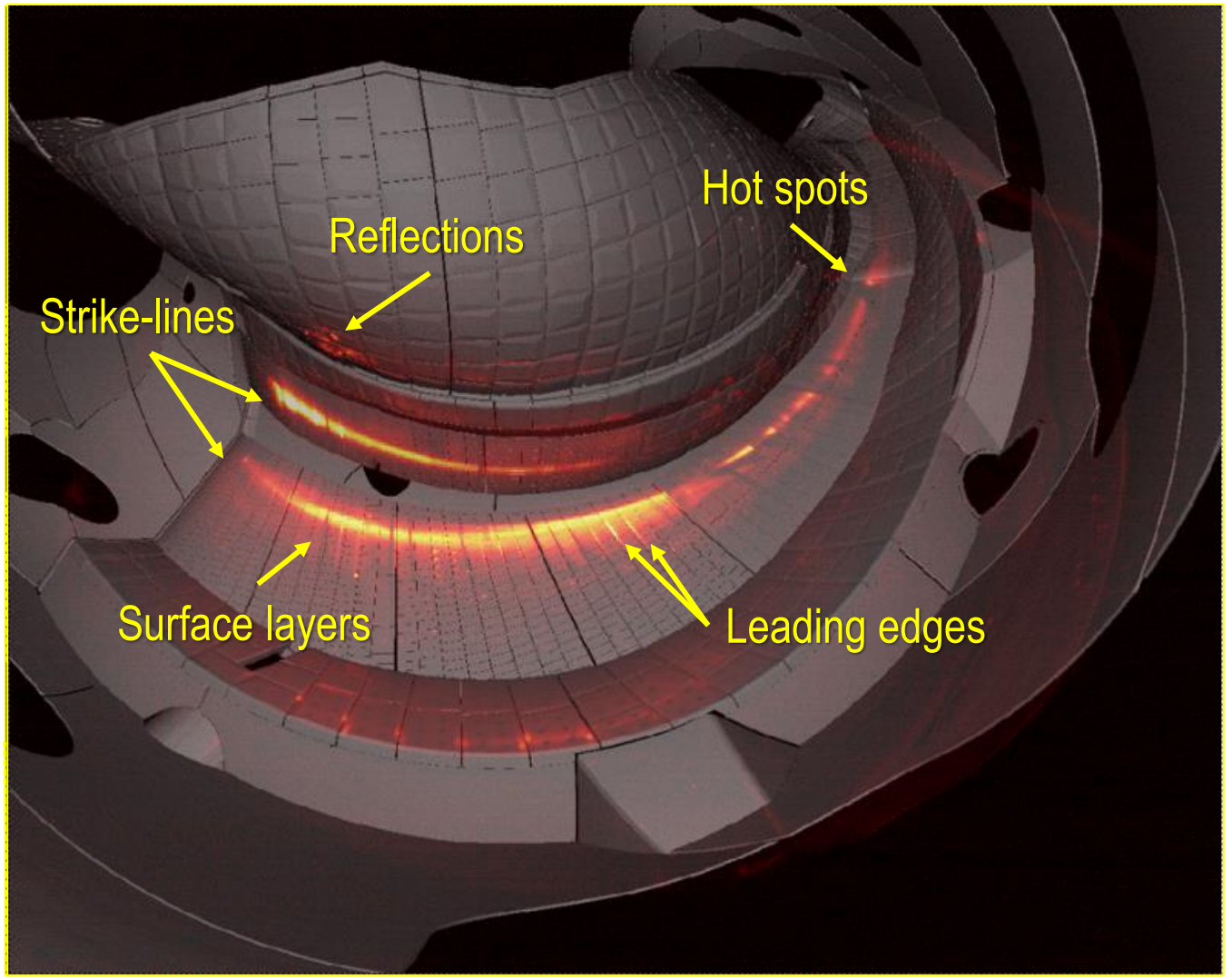
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Outline

- Protection of W7-X plasma facing components
- The annotation problem
- Thermal event segmentation
- Thermal event classification
- Thermal event tracking
- Conclusions

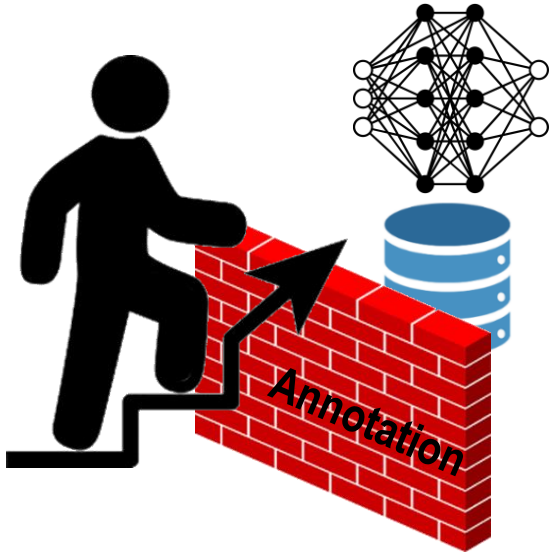
W7-X Plasma Facing Components protection

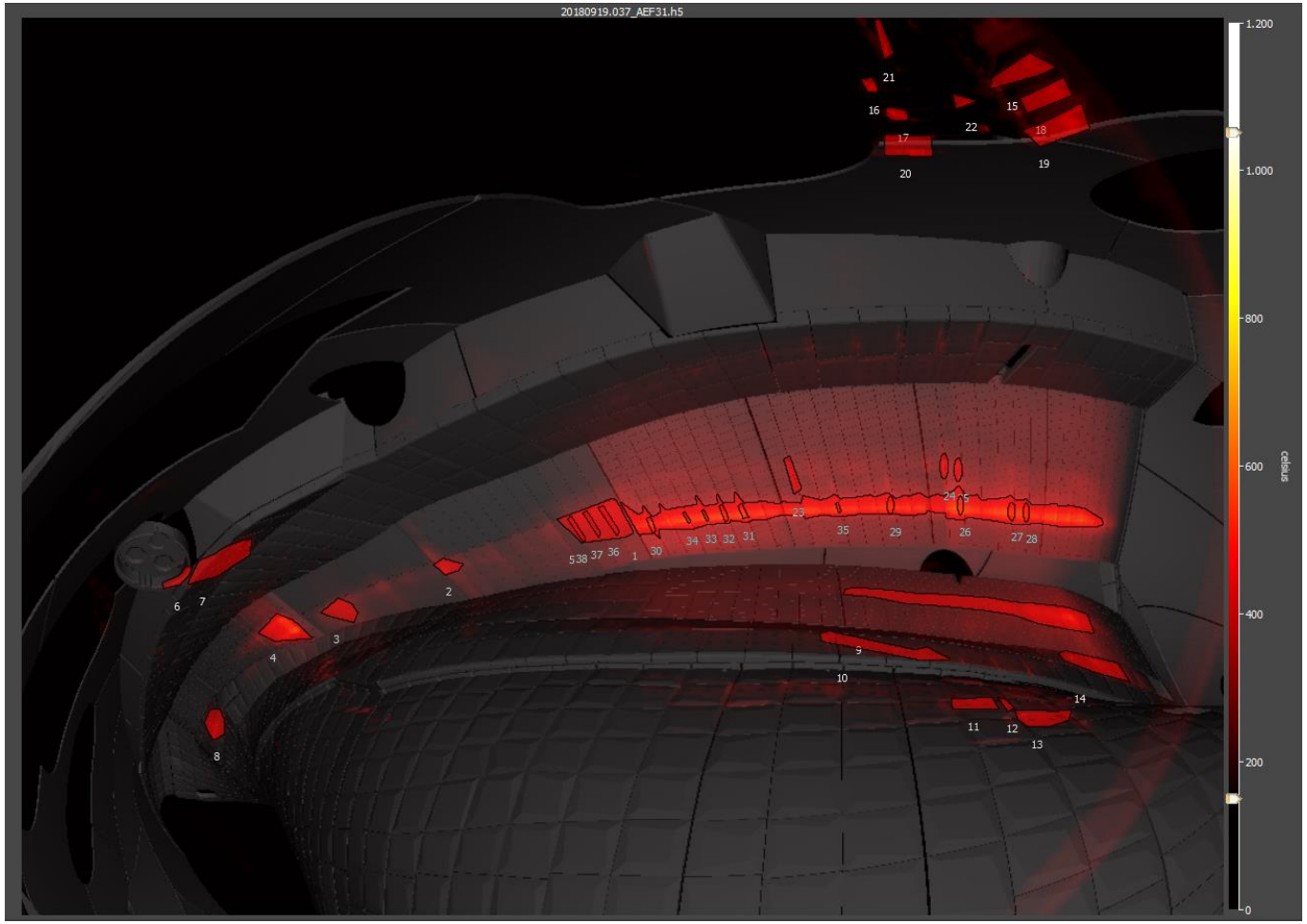




The annotation hurdle

- Deep Learning requires **large annotated datasets**
- Annotation for **video segmentation** is **very costly** (contours of events for each frame of 15.000 videos)

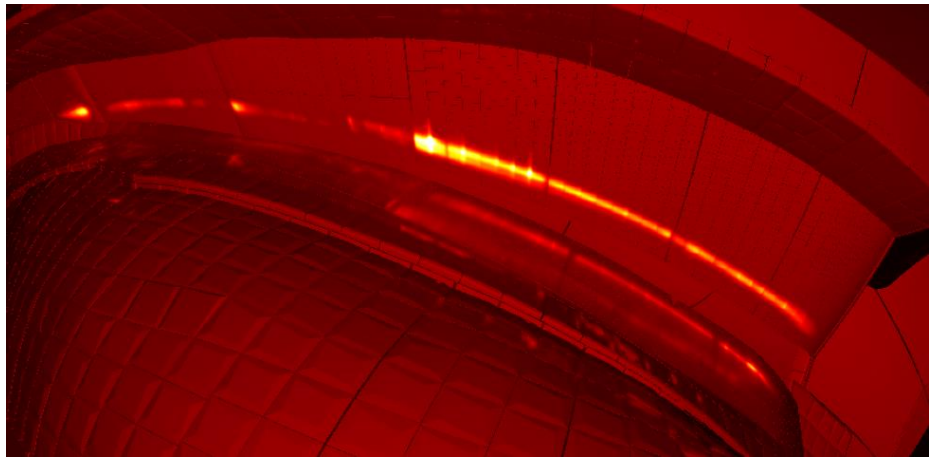




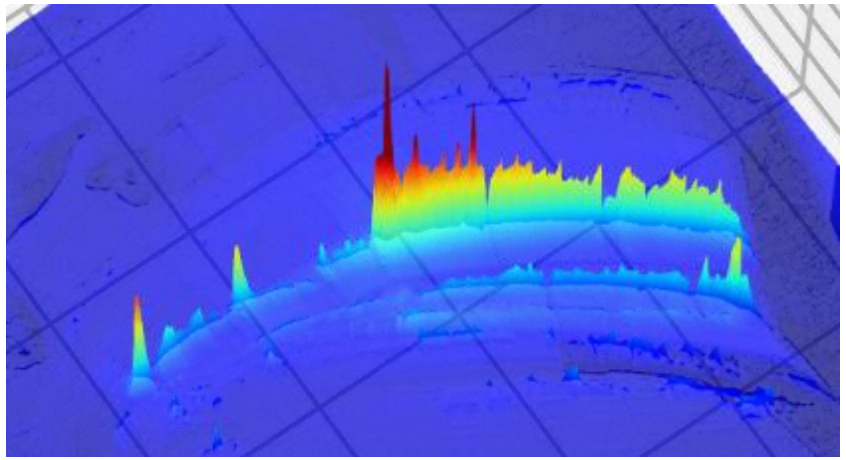
- **Automated** image-processing tools
  - **Segmentation** and **tracking** of events
  - Little training
  - Support annotation of large datasets for DL*

* E. Grelier, et al. Deep Learning and Image Processing for the Automated Analysis of Thermal Events on the First Wall and Divertor of Fusion Reactors, IAEA-TM FDPVA 2021.

Max-Tree Transform

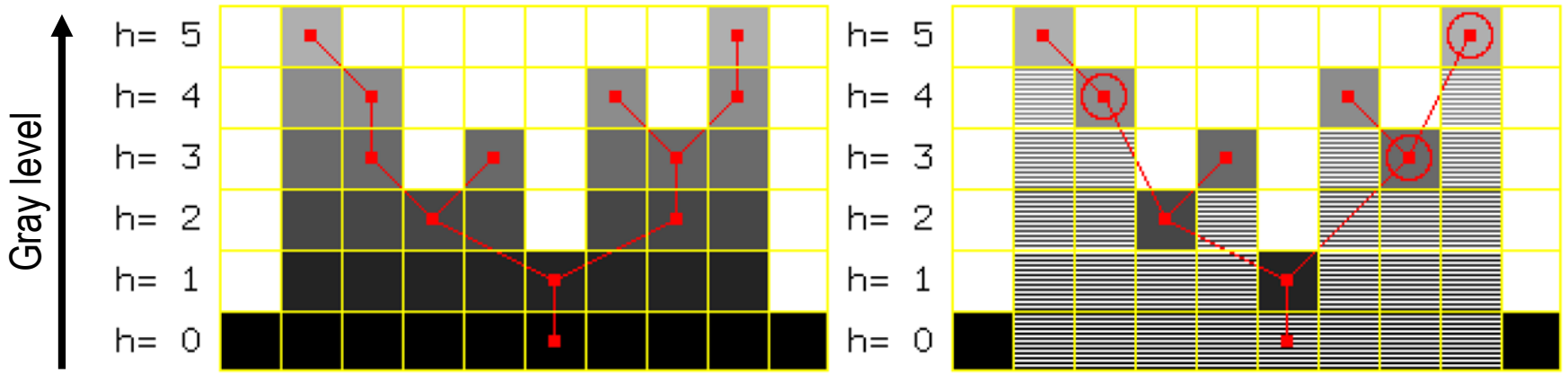


Infrared image



Infrared image as topographic relief

- **Max-Tree***: ***hierarchical*** *(graph) representation of all the* ***connected components*** *that can be extracted from an image by* ***thresholding*** *at all possible gray level values and it structures them by* ***inclusion***



1D image = [0, 5, 4, 2, 3, 1, 4, 3, 5, 0]

Max-tree transform

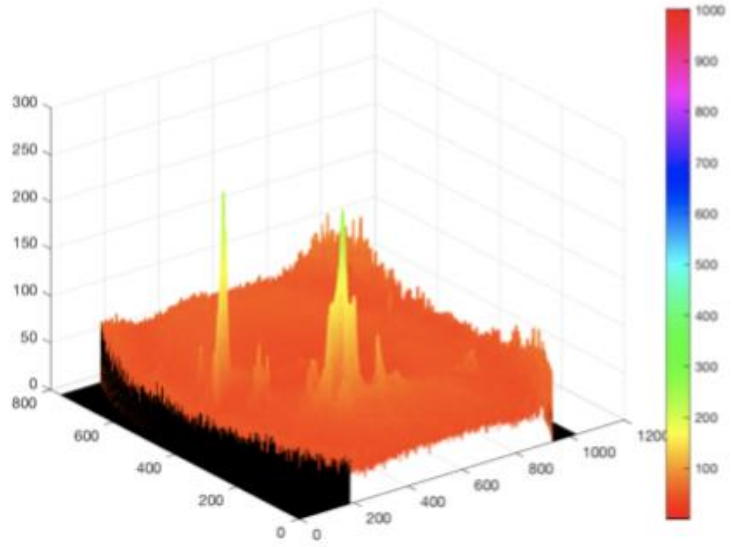
- Nodes are populated with **Attributes**
- **Tree pruning** based on descriptors

Segmentation

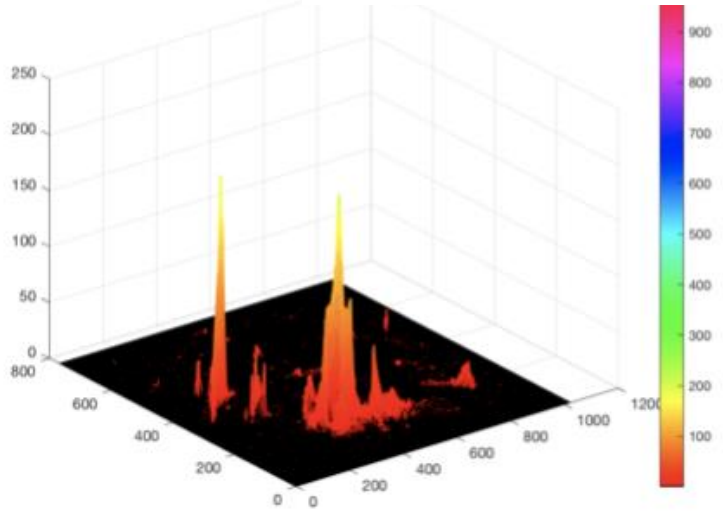
* Salembier, P., et al. Antiextensive Connected Operators for Image and Sequence Processing. *IEEE Transactions on Image Processing*, 7(4), 555-570, 1998.

Thermal Event Segmentation

- **Field of View** mask
- **Background subtraction**
- Morphological Reconstruction by **Top-Hat**
- **Quantization**: reduce computational cost of Max-Tree (n=5) $x_{quant} = n \cdot round(\frac{x}{n})$

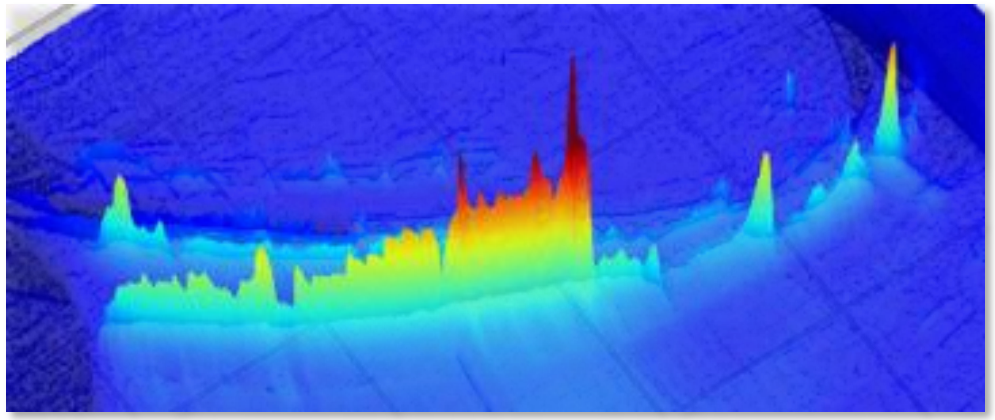


(a) Image with FOV mask applied

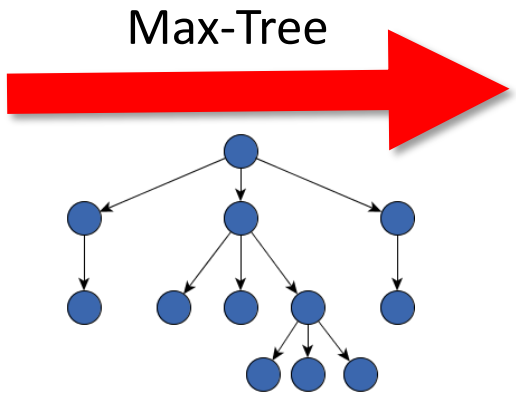


(b) Reconstruction by Top-Hat image

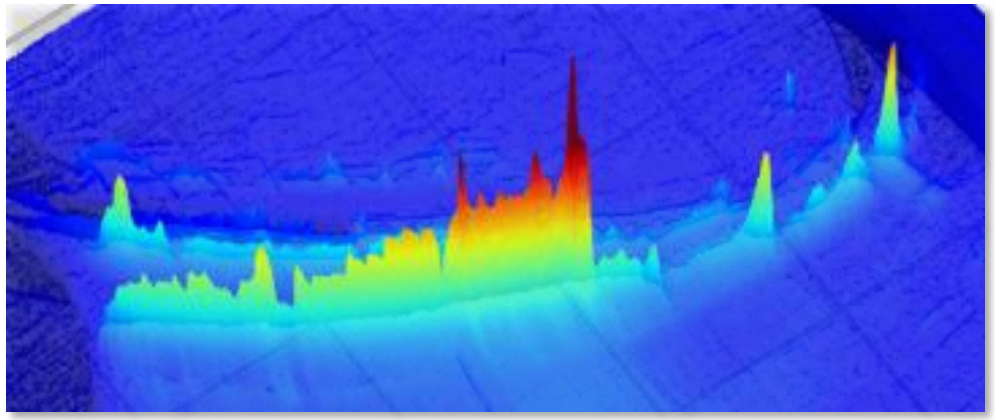
Thermal Event Segmentation



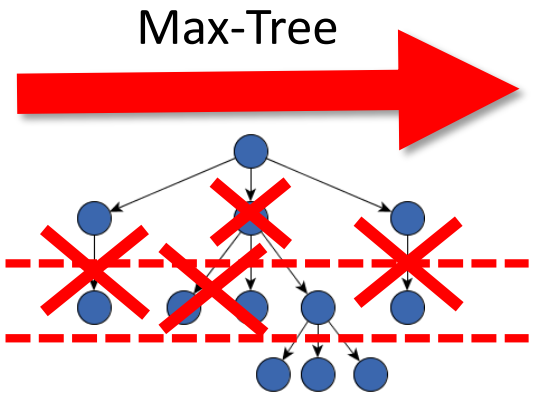
Original termal image



Thermal Event Segmentation

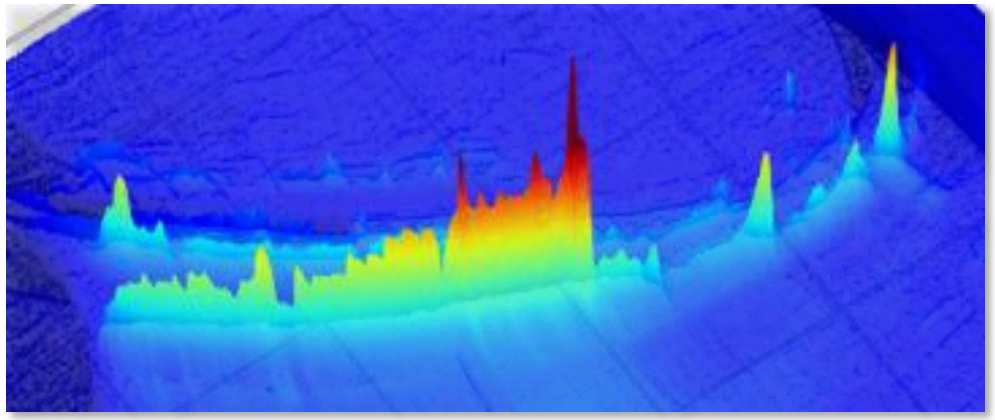


Original termal image

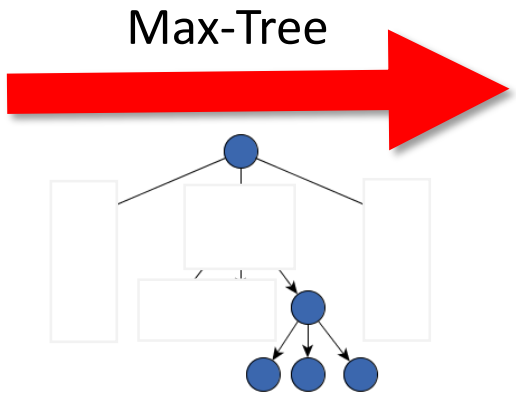


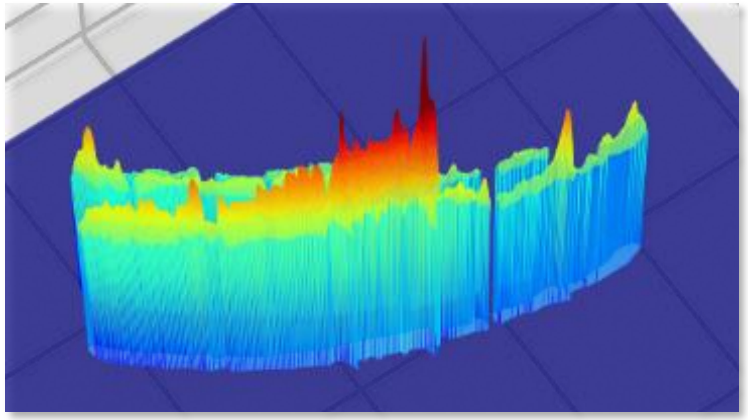
- Populate nodes with **descriptors**
- Find local **maxima** of the image (leaves of the tree)
- **Prune branches** below an absolute minimum temperature → removes small hot spots
- **Remove nodes** below a temperature offset from the branch maximum → removes background noise

Thermal Event Segmentation



Original termal image



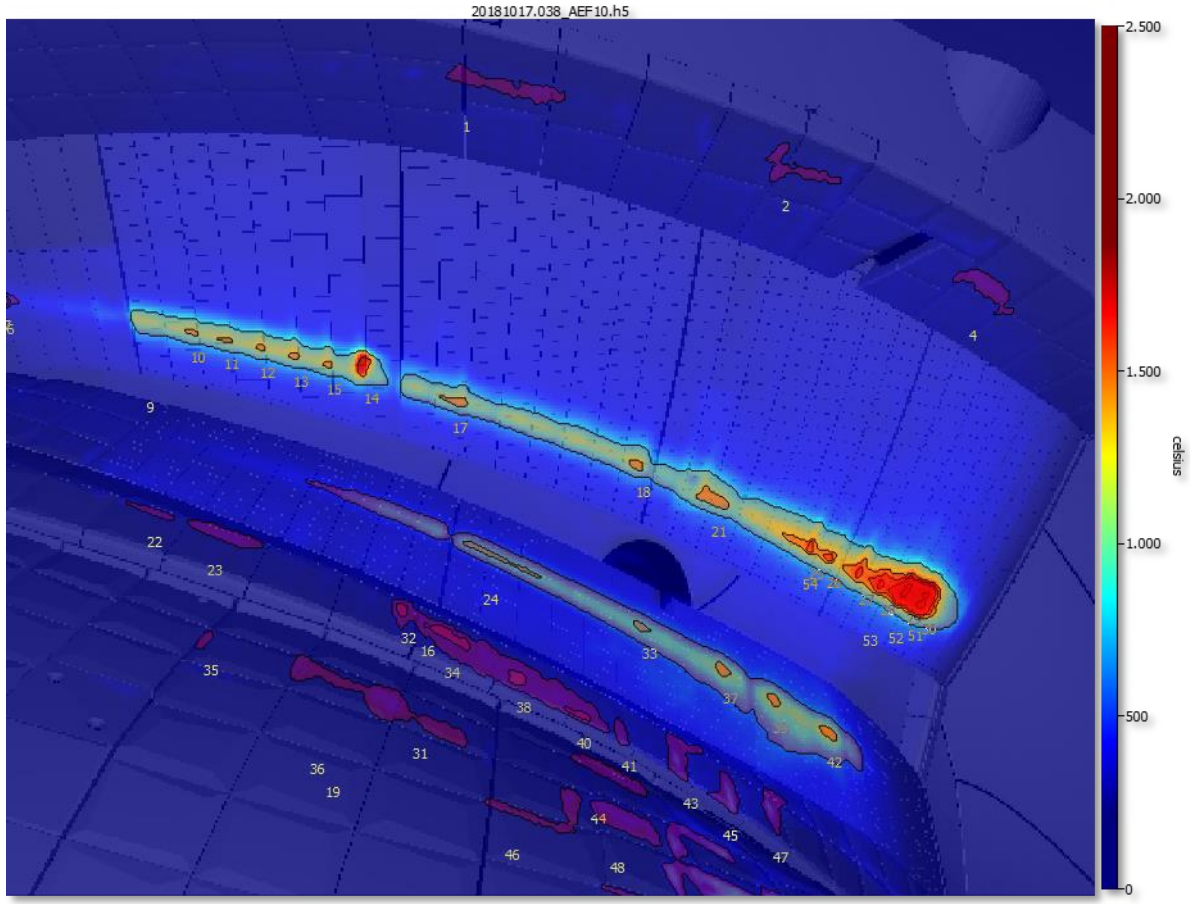


strike-line segmentation

- Populate nodes with **descriptors**
- Find local **maxima** of the image (leaves of the tree)
- **Prune branches** below an absolute minimum temperature → removes small hot spots
- **Remove nodes** below a temperature offset from the branch maximum → removes background noise
- **Inverse transform** → segment by absolute threshold > 0

Thermal Event Segmentation

Pre-processing → Max-Tree computation → Attribute Population → **Segmentation** → Classification



- Dataset:
  - 14 sequences
  - **133 manually labelled** regions

Image	F_2score	Image	F_2score
20171114.053 AEF20	0.743	20181009.041 AEF10	0.752
20171207.014 AEF40	0.675	20181017.038 AEF10	0.797
20180807.029 AEF11	0.755	20171121.013 AEF10	0.841
20180823.037 AEF31	0.840	20180904.016 AEF10	0.528
20180904.007 AEF10	0.700	20180927.025 AEF20	0.633
20180905.030 AEF20	0.807	20180918.019 AEF21	0.970
20180919.037 AEF31	0.558	20181018.041 AEF50	0.834
Mean			**0.745**

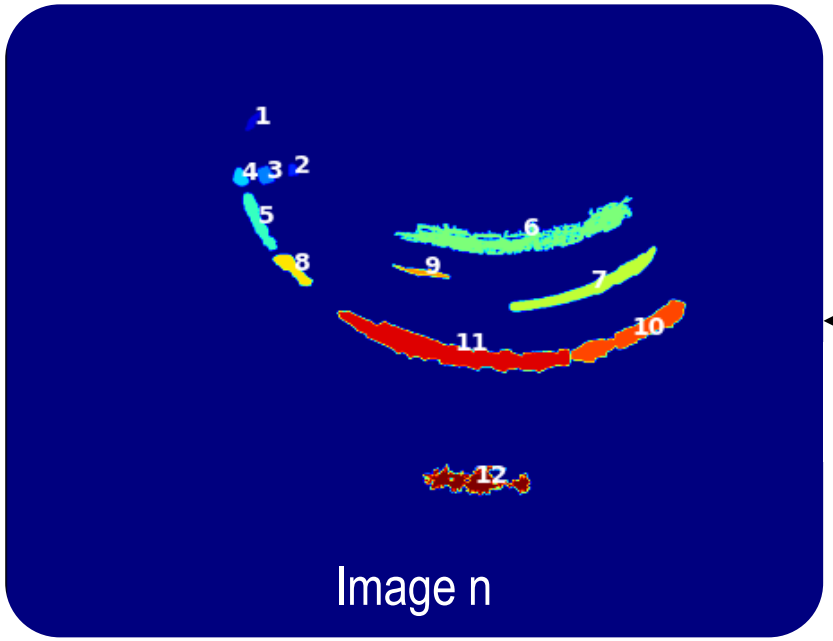
$$F_2 = \frac{5 \cdot Precision \cdot Recall}{4 \cdot Precision + Recall}$$

Thermal Event Classification

- Regions classified as **Hot-Spot or Strike Line**
- Dataset (133 manually labeled events):
  - **50% Training - 50% Test** Split of the regions
  - 5-fold cross validation
  - Still too **small** for **a Deep learning** approach
- Several **classical classifiers** have been tested:
  - Decision Trees
  - SVM
  - K-NN
- Shape **descriptors**:
  - Area
  - Circularity
  - Orientation

	Training		Test	
Classification Model	Accuracy	F_1 score	Accuracy	F_1 score
Fine Tree	0.930	0.939 0.943	0.782	0.769 0.787
Cubic SVM	0.948	0.945 0.949	0.796	0.783 0.802
Quadratic SVM	**0.925**	**0.902** **0.907**	**0.868**	**0.846** **0.884**
Fine KNN	1.000	1.000 1.000	0.836	0.815 0.850
Bagged Tree	1.000	1.000 1.000	0.821	0.804 0.832

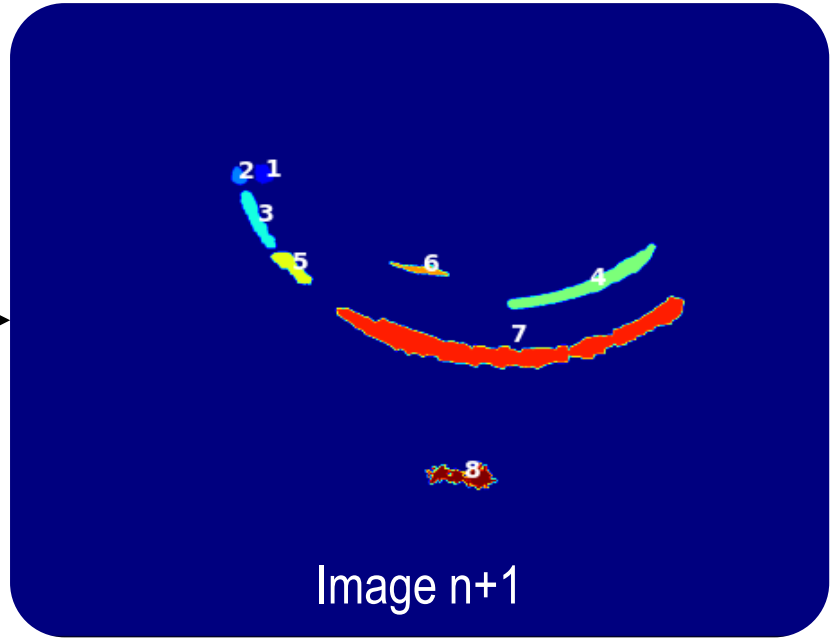
Thermal Event Tracking



20181018.041_AEF50

Jaccard index

$$J(A,B) = \frac{|A \cap B|}{|A \cup B|}$$



- **Temporal events**:
  - Appears
  - Disappears
  - Splits
  - Merges
  - Shape changes
  - Shifts
  - No change

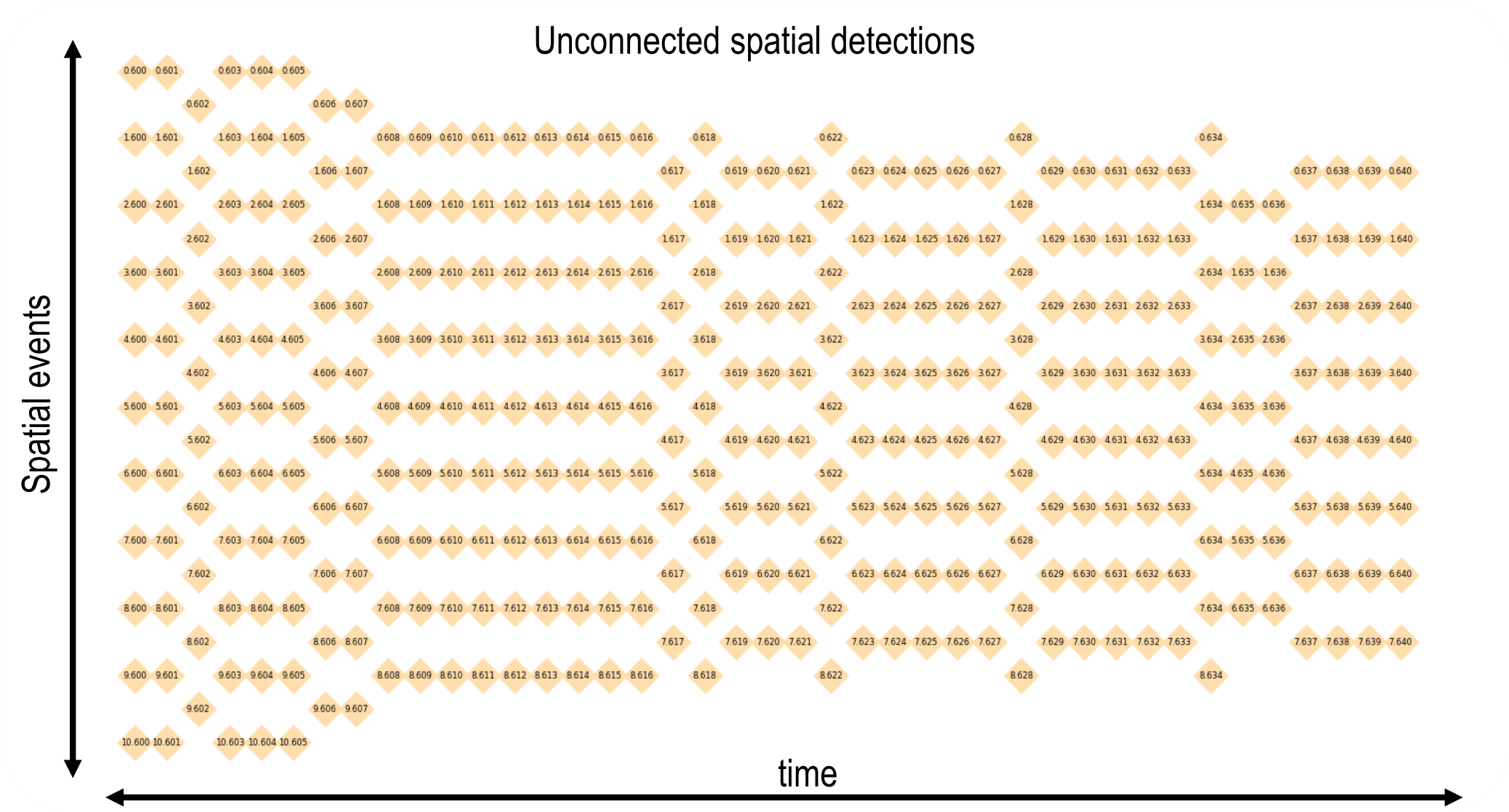
Jaccard Matrix

Labels image n

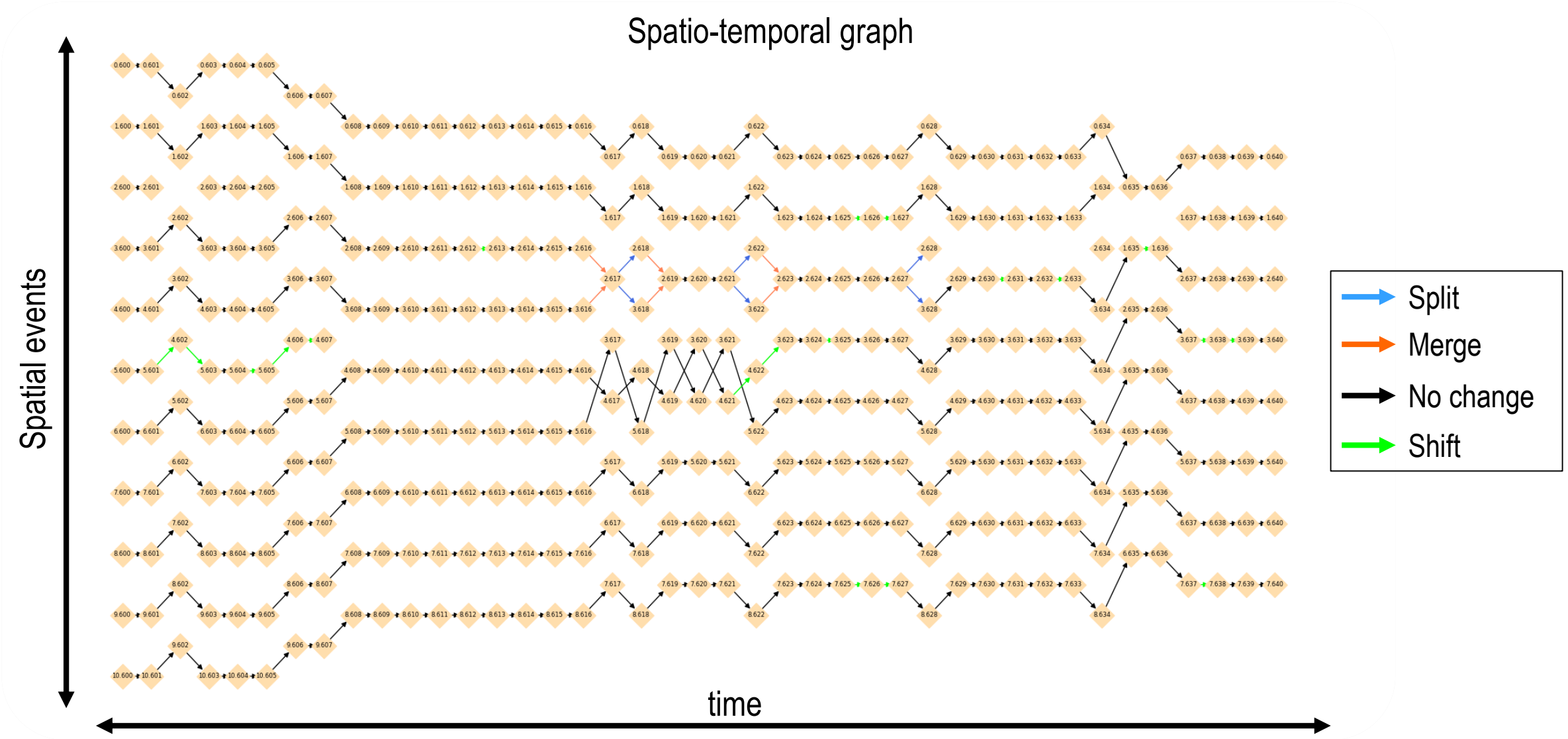
Labels image n+1

	0	1	2	3	4	5	6	7	8	9	10	11	12
0	0.98896	0.00028	0.00020	0.00000	0.00002	0.00000	0.00827	0.00000	0.00000	0.00000	0.00000	0.00000	0.00118
1	0.00007	0.00000	0.00000	0.87500	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2	0.00000	0.00000	0.00000	0.00000	0.96118	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
3	0.00015	0.00000	0.00000	0.00000	0.00000	0.90264	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
4	0.00027	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.93140	0.00000	0.00000	0.00000	0.00000	0.00000
5	0.00014	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.87238	0.00000	0.00000	0.00000	0.00000
6	0.00012	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.81818	0.00000	0.00000	0.00000
7	0.00033	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.31216	0.66195	0.00000
8	0.00003	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.60087

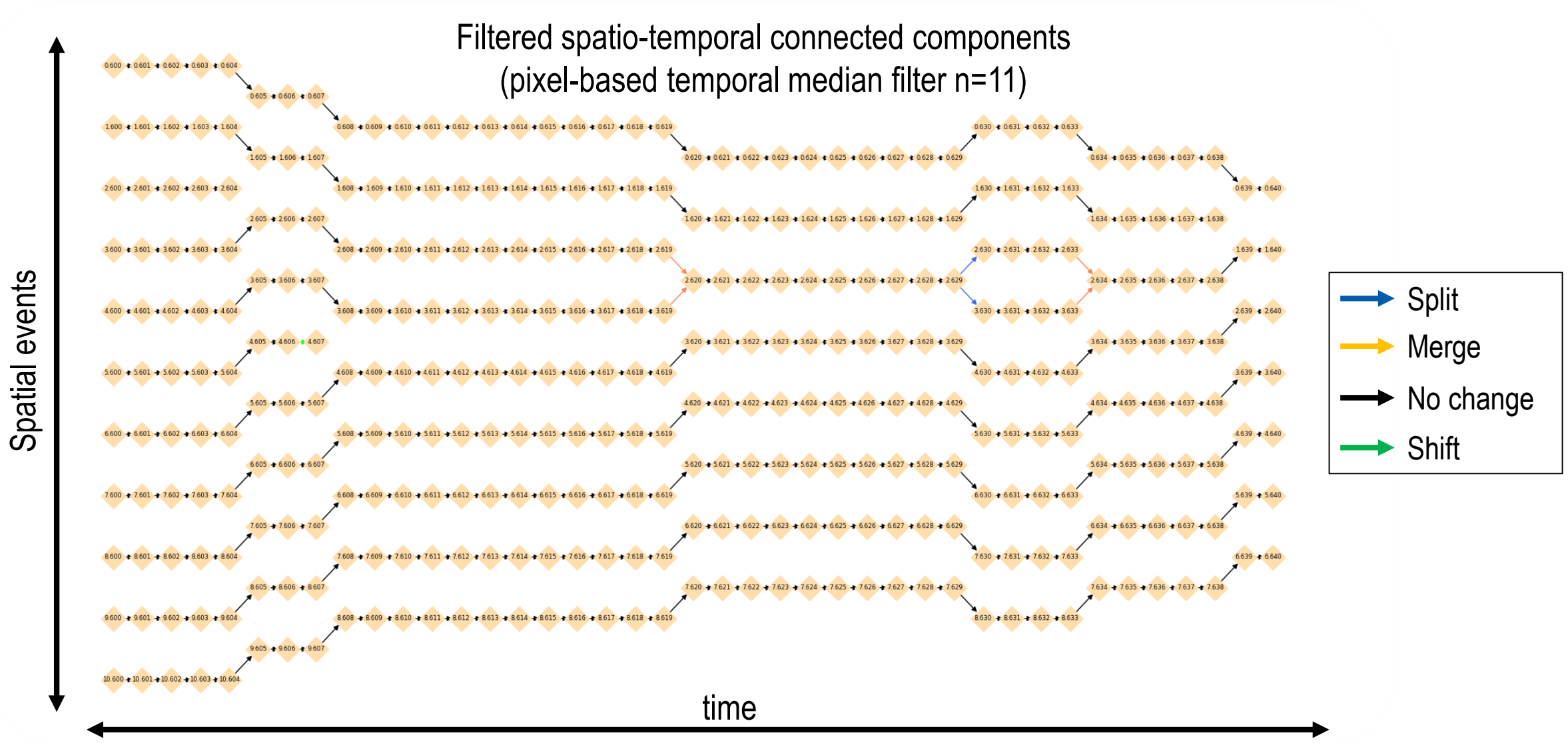
Thermal Events Tracking



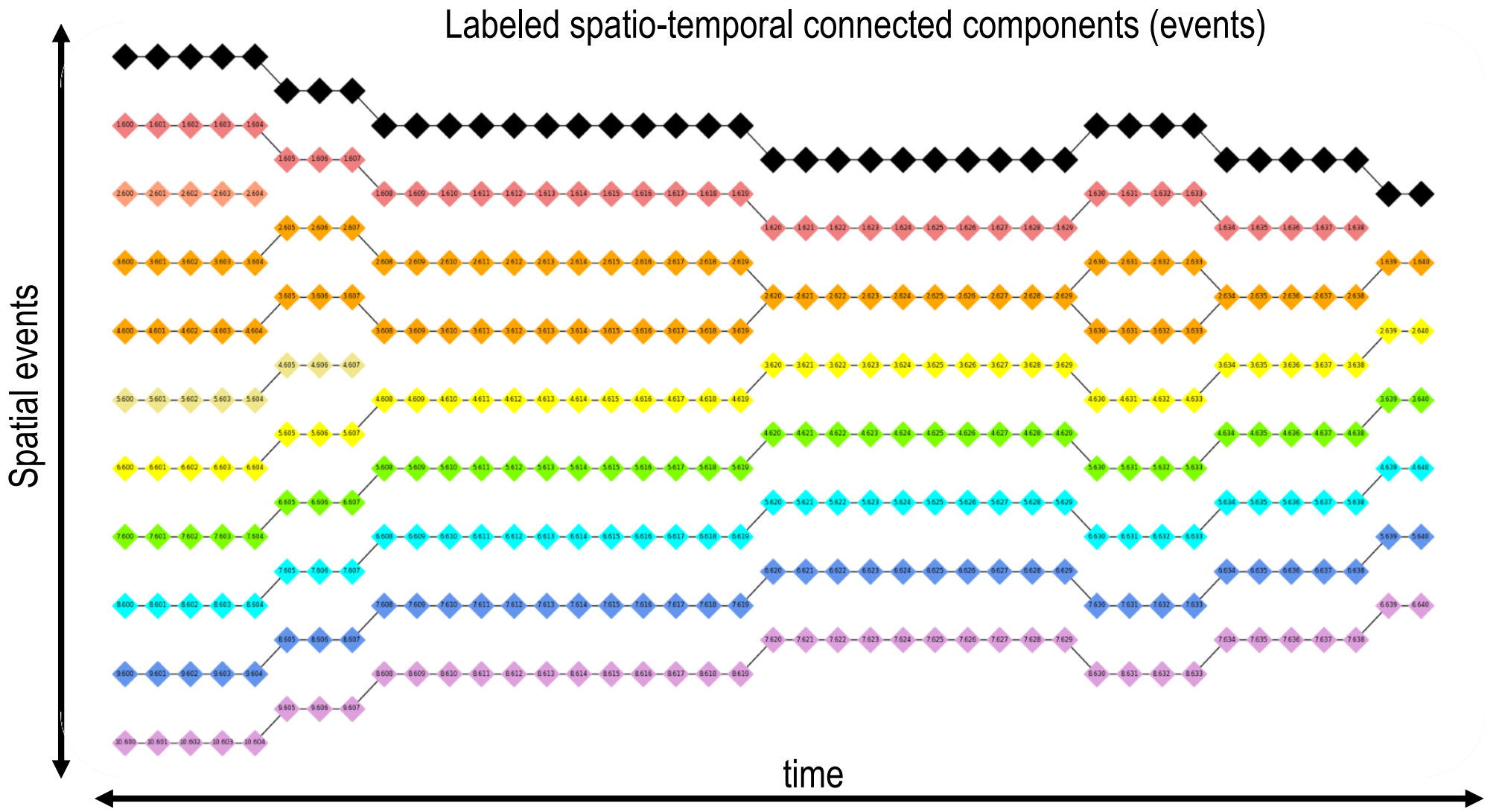
Thermal Events Tracking



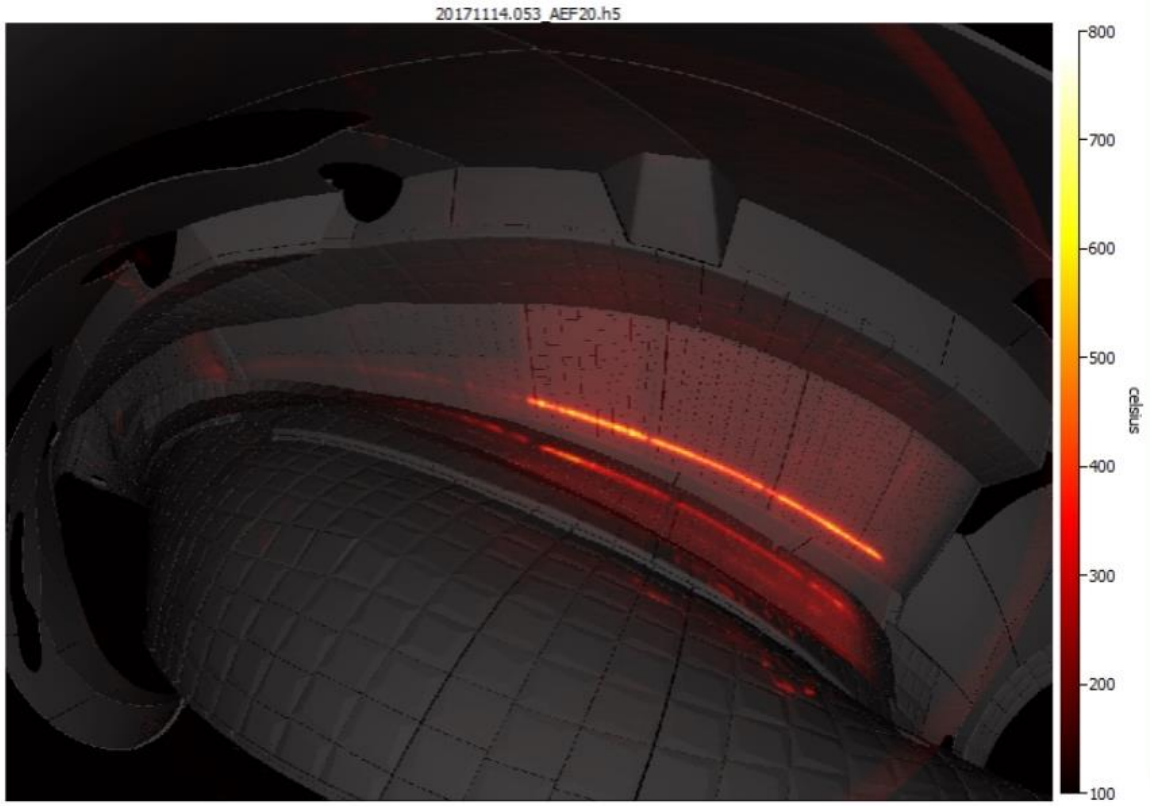
Thermal Events Tracking



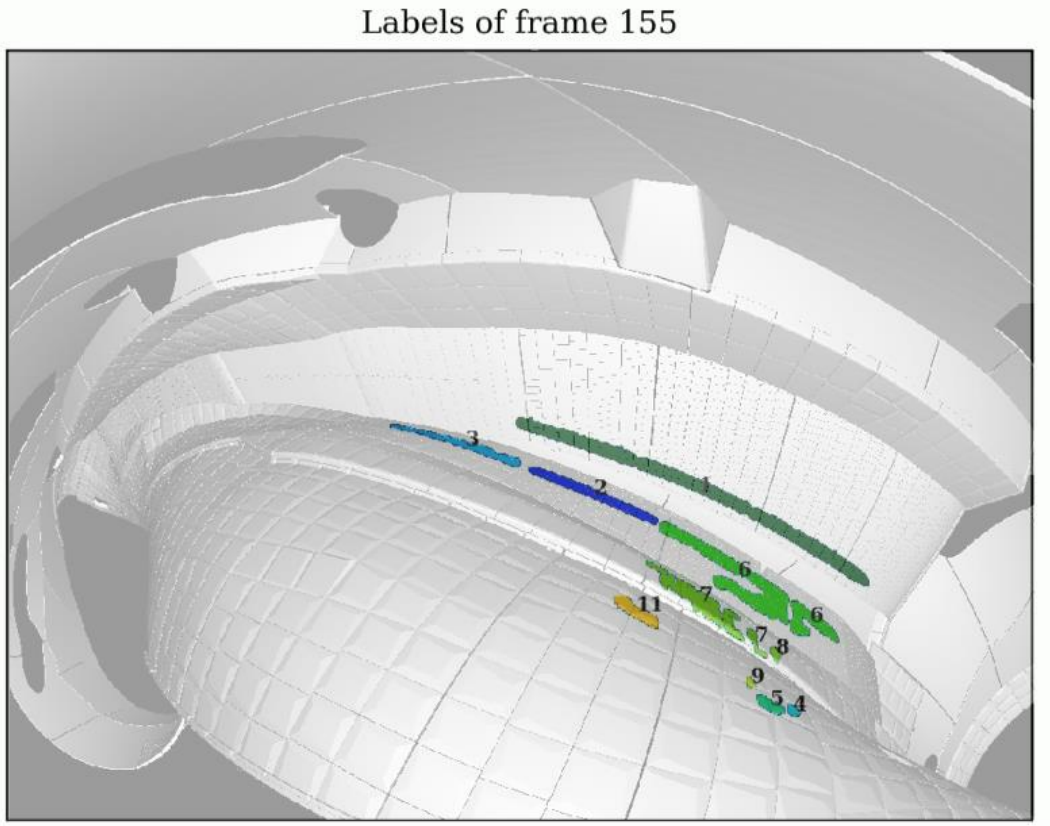
Thermal Events Tracking



Thermal Events Tracking



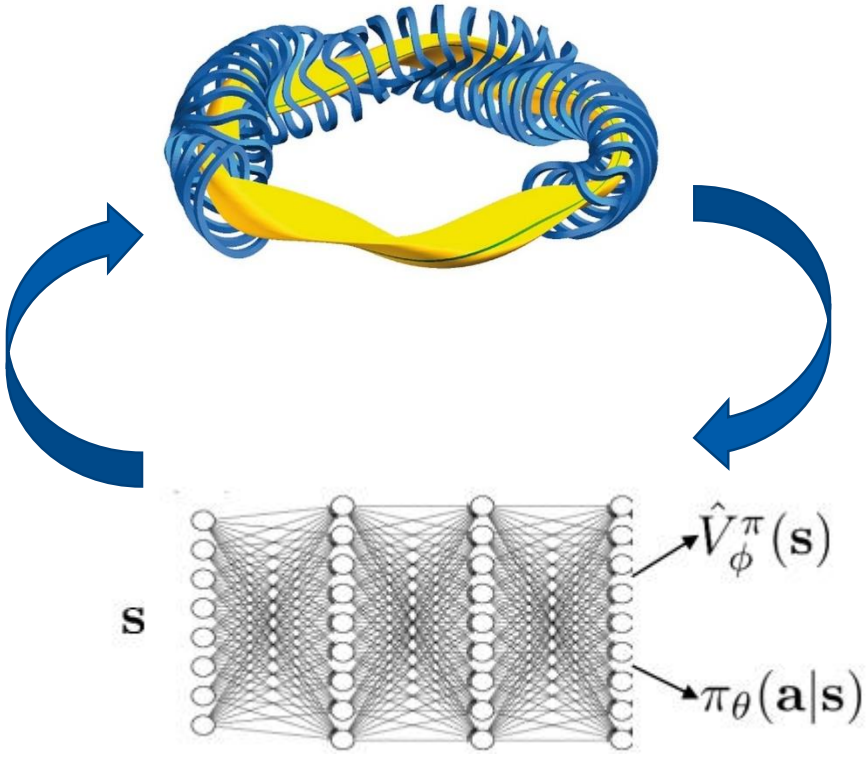
Infrared sequence



Segmentation and tracking of thermal events

Conclusions

- **Automated** image-processing tools for **segmentation** and **tracking** of events
- The **Max-Tree** allows a **precise and hierarchical** segmentation of thermal events
- A **spatio-temporal graph** is used to improve temporal **tracking** coherence
- **Little training**
- **Early protection**
- Support **annotation** of large datasets for DL



Roadmap towards **feedback control of thermal loads:**

- **W7-X OP 2.1** (High-heat-flux divertor and water-cooled PFCs)
  - **Basic protection** with image processing techniques
  - Validation of **segmentation** and **tracking** algorithms
- **W7-X OP2.2-OP2.4** (Steady-state, 30 min, 18 GJ)
  - Build large **annotated datasets**
  - **Deep models** for **advanced feedback control**
  - ECRH and NBI, strike-line control and detachment

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