MPI-Parallel Machine Learning Algorithms for the Analysis of High-Speed Video Data

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DLR

Outline

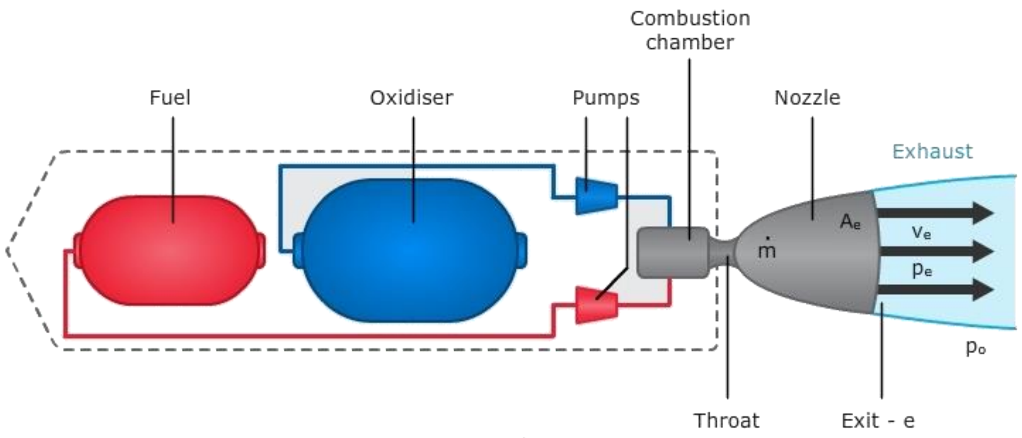
1. Rocket engine combustion analysis at DLR

2. Helmholtz Analytics Toolkit (Heat) for distributed ML

3. Results
   a) Spectral Clustering
   b) Anomaly Detection

Rocket engine combustion analysis

- **Aim:** Cost reduction of rocket engines, be competitive with e.g. Space-X



Traditional liquid rocket engine:

- 2 pumps transporting fluid fuel and oxidizer at very high pressure and flow
- Advantages
  - Burning rate can be controlled precisely
- Disadvantages
  - Pumps are mechanically very complex
  - Expensive

Rocket engine combustion analysis

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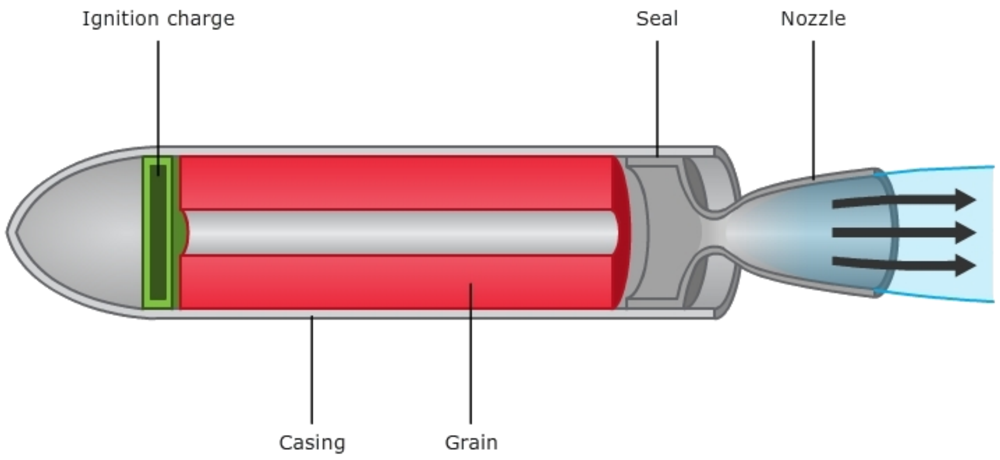
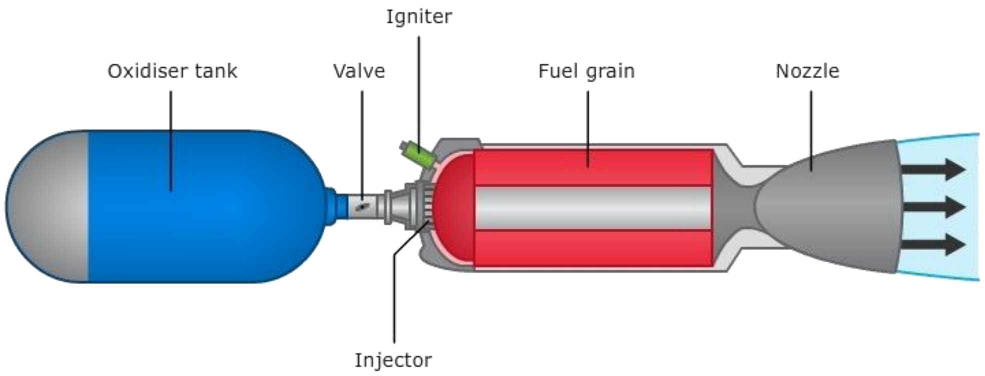


Solid propellant rocket engine

- Fuel and oxidizer are mixed in solid form
- Advantage
  - Cheap
- Disadvantage
  - Burning rate can not be varied during flight

Rocket engine combustion analysis

- **Aim:** Cost reduction of rocket engines, be competitive with e.g. Space-X



Hybrid rocket engine

- Pressurized fluid oxidizer
- Solid fuel
- A valve controls, how much oxidizer gets into the combustion chamber

- Advantages
  - Cheap
  - Controllable

Experiments on new hybrid rocket fuels at DLR

- DLR investigates new hybrid rocket fuels on a paraffin basis at Institute of Space Propulsion in Lampoldshausen.
- About 300 combustion tests were performed with single-slab paraffin-based fuel with 20° forward facing ramp angle + gaseous oxygen.
- Combustion is captured with high-speed video camera with 10 000 frames / second

Fig. 1: Fuel slap configuration before (top) and after (bottom) combustion test

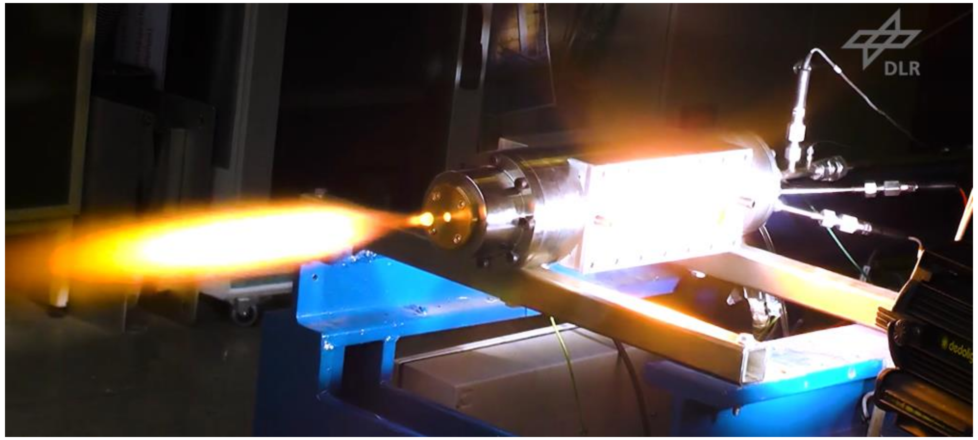


Fig. 2: Hybrid rocket engine combustion chamber

Video extract of test 284	fuel	oxidizer mass flow	CH*-filter	duration
Ignition, steady combustion, extinction	pure paraffin 6805	50 *g*/*s*,	yes, i.e. only wavelengths emitted from CH* are filmed	3 s = 30 000 frames

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Heat

- Heat = Helmholtz Analytics Toolkit

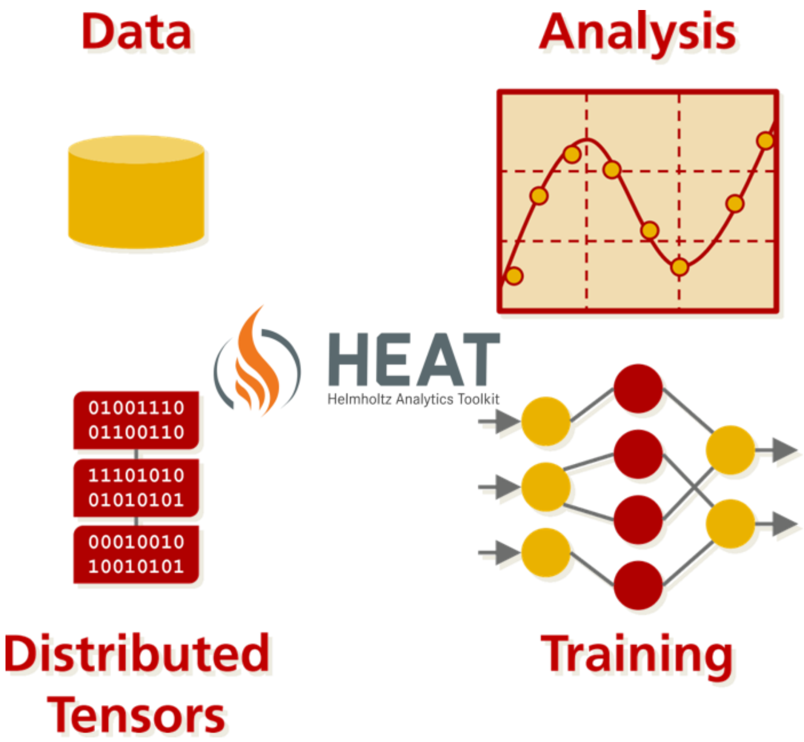
- Developed by three Helmholtz research organizations in Germany:
    - Research Center Juelich (FZJ)
    - Karlsruhe Institute of Technology (KIT)
    - German Aerospace Center (DLR)

- Python library for **parallel**, **distributed** data analytics and machine learning

- **Aim:** Bridge data analytics and **high-performance computing**

- Open Source licensed, MIT

https://github.com/helmholtz-analytics/heat



Scope

Facilitating analysis of Helmholtz applications

Bringing HPC and Machine Learning / Data Analytics closer together

Ease of use

Design

HEAT
Helmholtz Analytics Toolkit

- k-means
- SVM
- Deep Learning

And more machine learning algorithms

PyTorch

- Tensor Linear Algebra
- Automatic Differentiation
- NumPy-like interface
- GPU support

mpi4torch

- Automatically Differentiated Node-Node Communication using MPI

Core Idea: Data Distribution

HeAT Tensor

Server#1 PyTorch Tensor#1	Server#2 PyTorch Tensor#2	Server#3 PyTorch Tensor#3

split=1

Server#1 PyTorch Tensor#1
Server#2 PyTorch Tensor#2
Server#3 PyTorch Tensor#3

HeAT Tensor

split=0

Example:

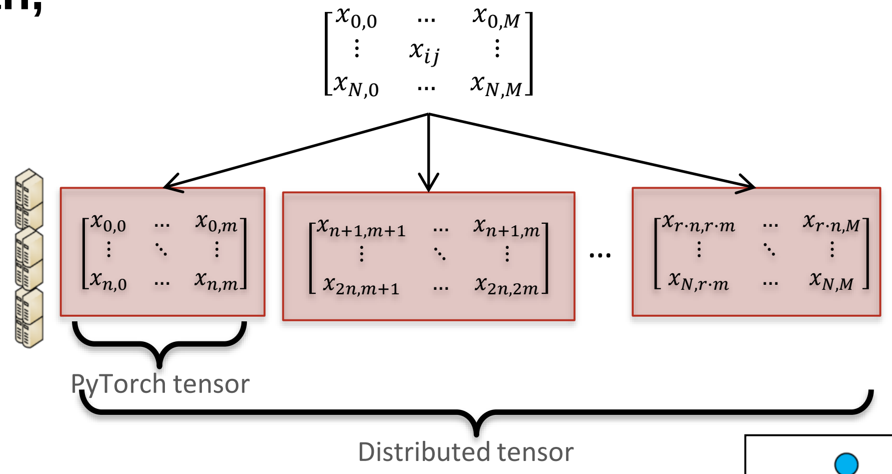
```
import heat as ht
# construct a range tensor
>>> range_data = ht.arange(6, split=1)
```

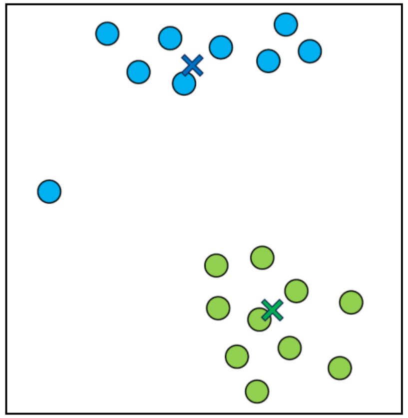
Server#1 [0, 1]	Server#2 [2, 3]	Server#3 [4, 5]

```
>>> range_data.mean()
2.5
>>> range_data.argmax()
5
```

Functionality achieved

- Implementation of a **distributed parallel tensor math,** NumPy-compatible, based on PyTorch
- Some linear algebra routines
- **Parallel data I/O** via HDF 5 and NetCDF
- Development of **mpi4torch** to enable **automatic differentiation** of distributed PyTorch code
- Multiple methods (clustering, classification, regression)
- Data-parallel training of neural nets (new DASO algorithm)





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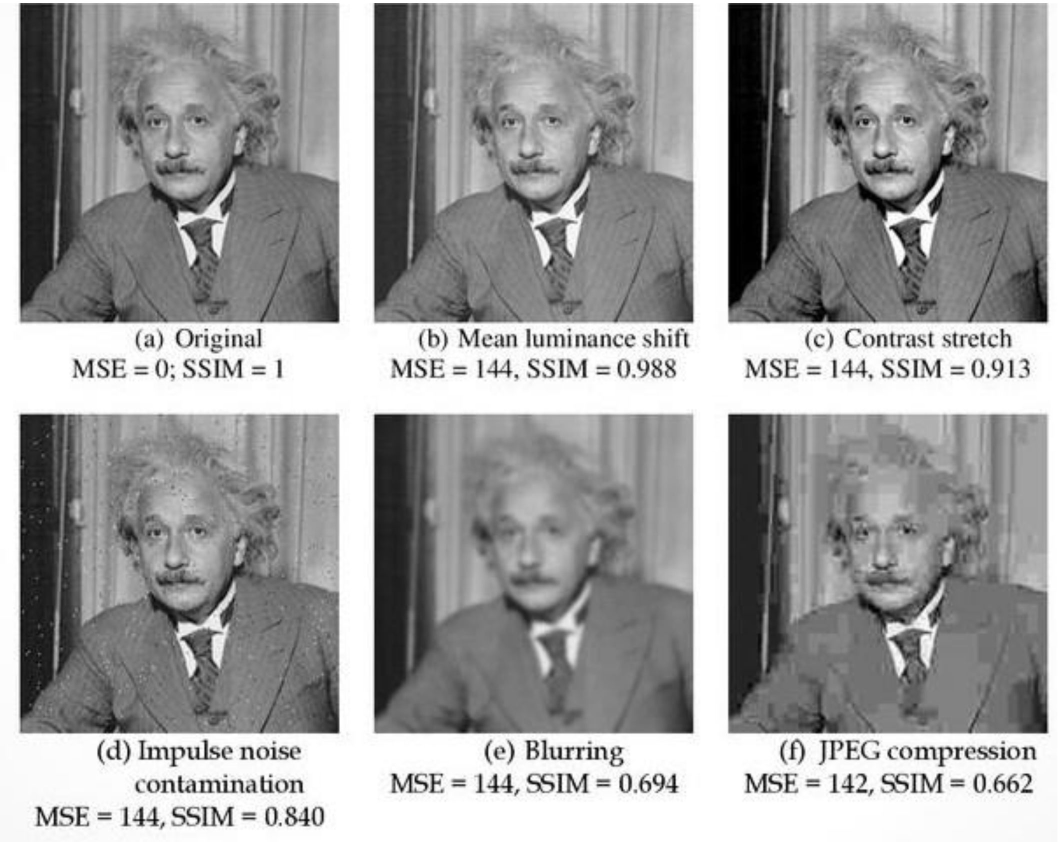
Dissimilarity measure for image data

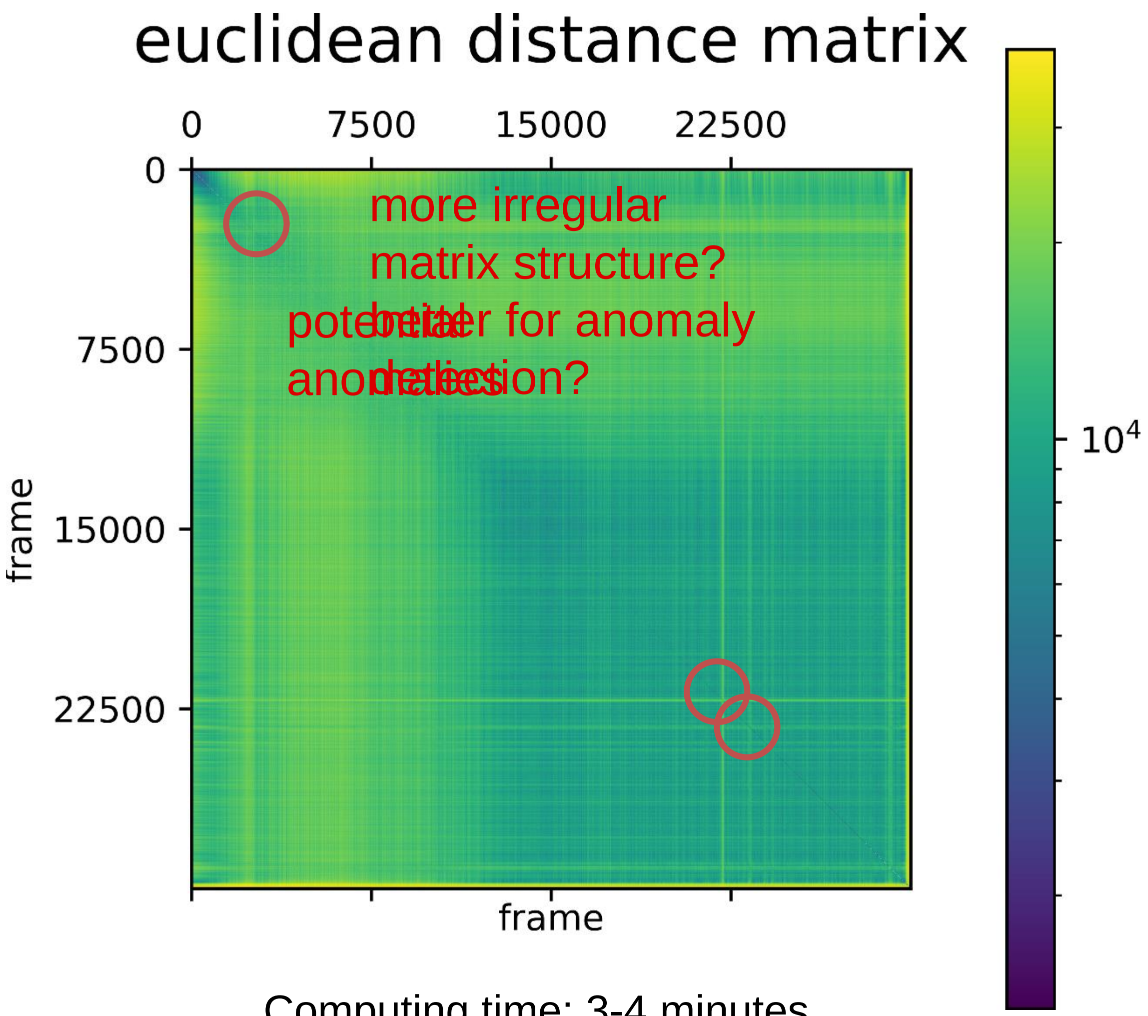
- Algorithms often require pairwise dissimilarity of images (matrix of size nr_of_images x nr_of_images).
- Standard approaches such as mean squared error (MSE) / discrete L^2-norm often differ from human recognition.
- Advanced dissimilarity measures such as structural similarity (SSIM) often perform better (considers luminance, contrast and structure) but are much more expensive.
- Structural similarity (SSIM)/ structural dissimilarity (DSSIM) is not a distance metric.



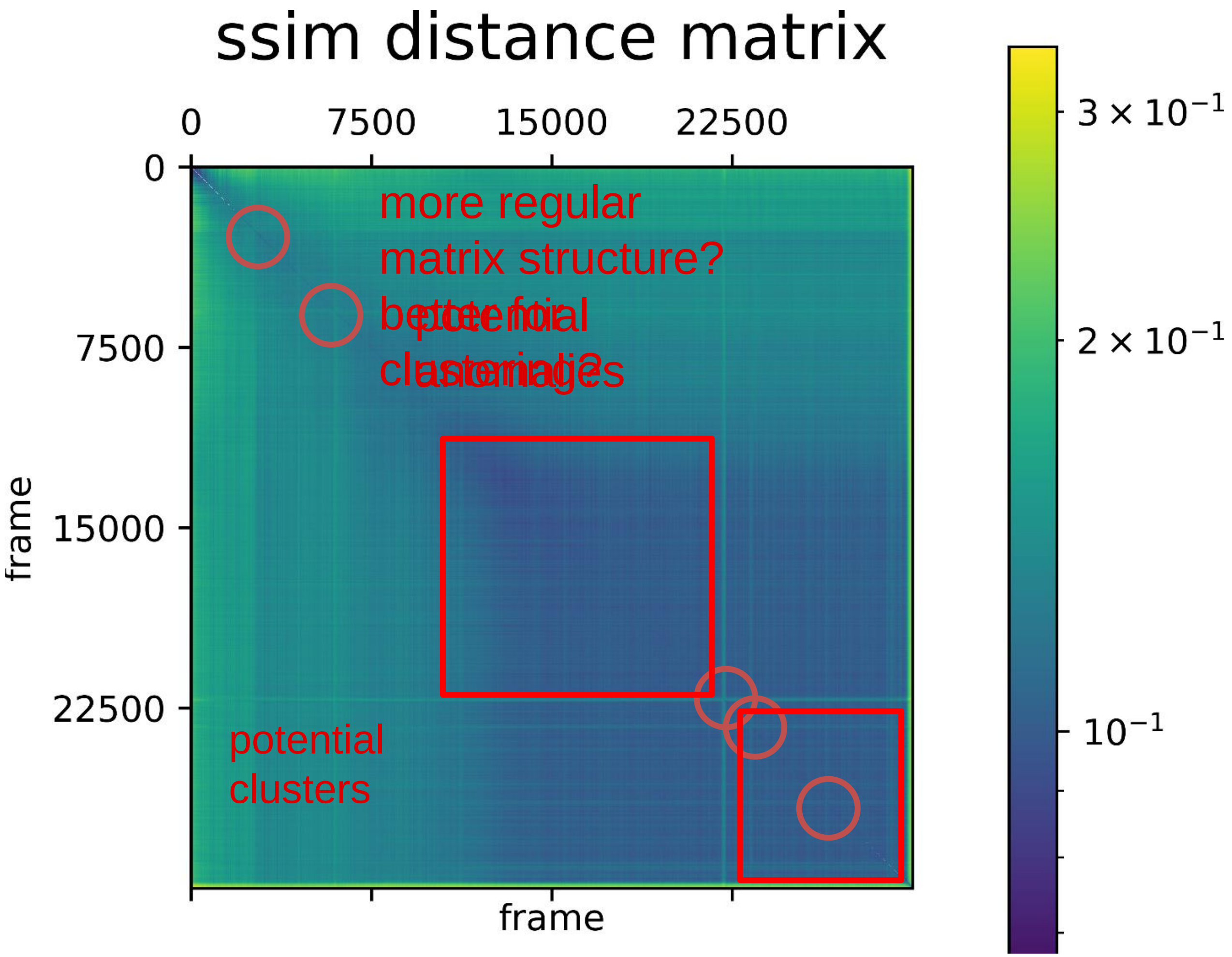
Example: (b)-(f) with same MSE, SSIM decreases*

*https://nsf.gov/news/mmg/mmg_disp.jsp?med_id=79419&from=

Pairwise distance matrices for test 284

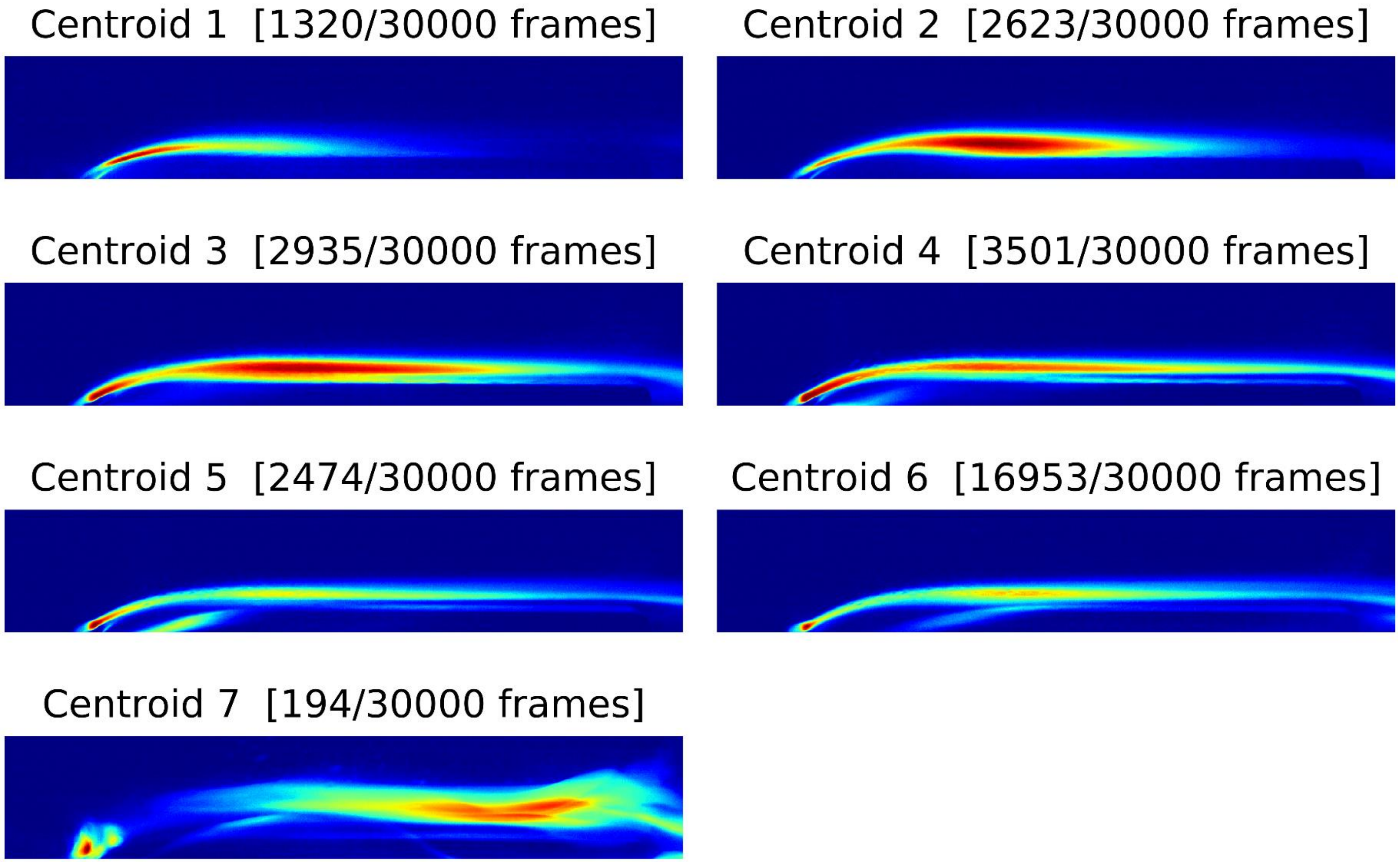


Computing time: 3-4 minutes



Computing time: 5 days (OpenMP parallel, 56 cores)
one comparison ≈ 0.1 s (scikit-image)

Spectral Clustering of test 284

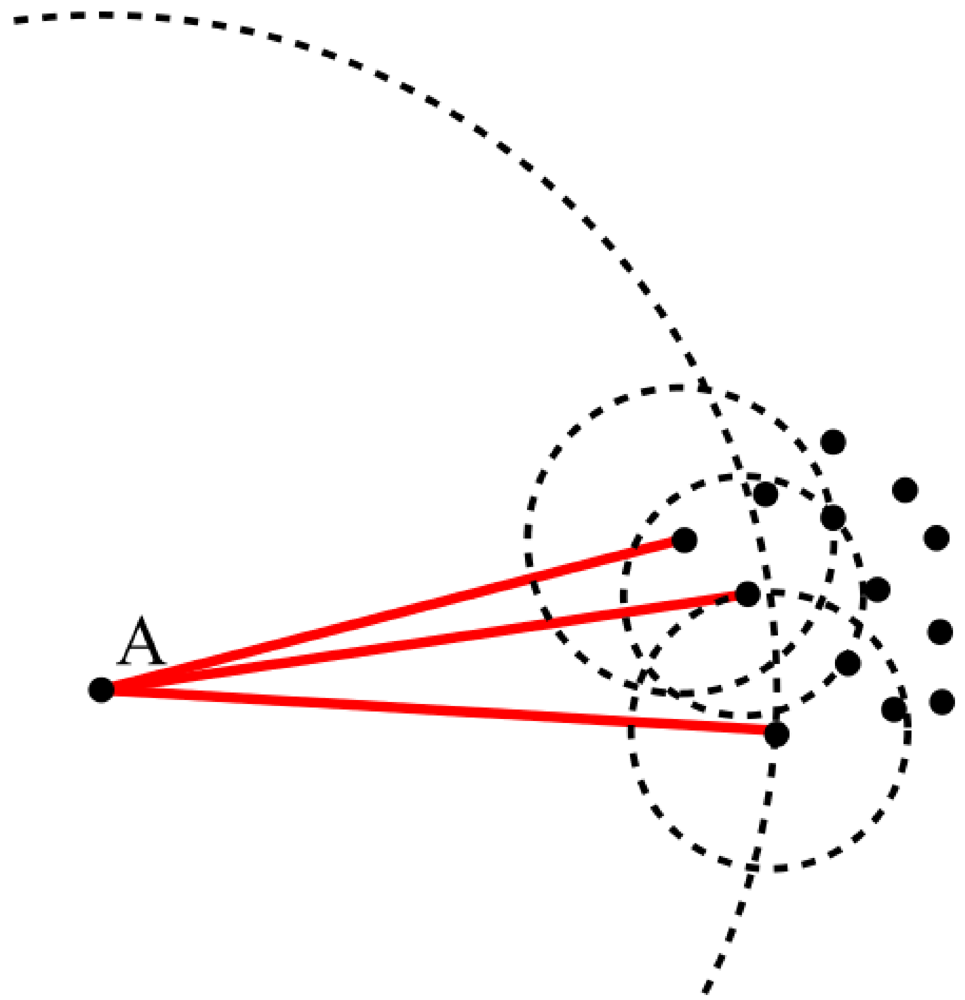


- **Fig. 1**: Results of spectral clustering with ssim affinity matrix.
- Using an Euclidean affinity matrix leads to a separation of the extinction phase into various clusters.
- Note that the number of clusters *k* is a hyperparameter of the clustering algorithm.

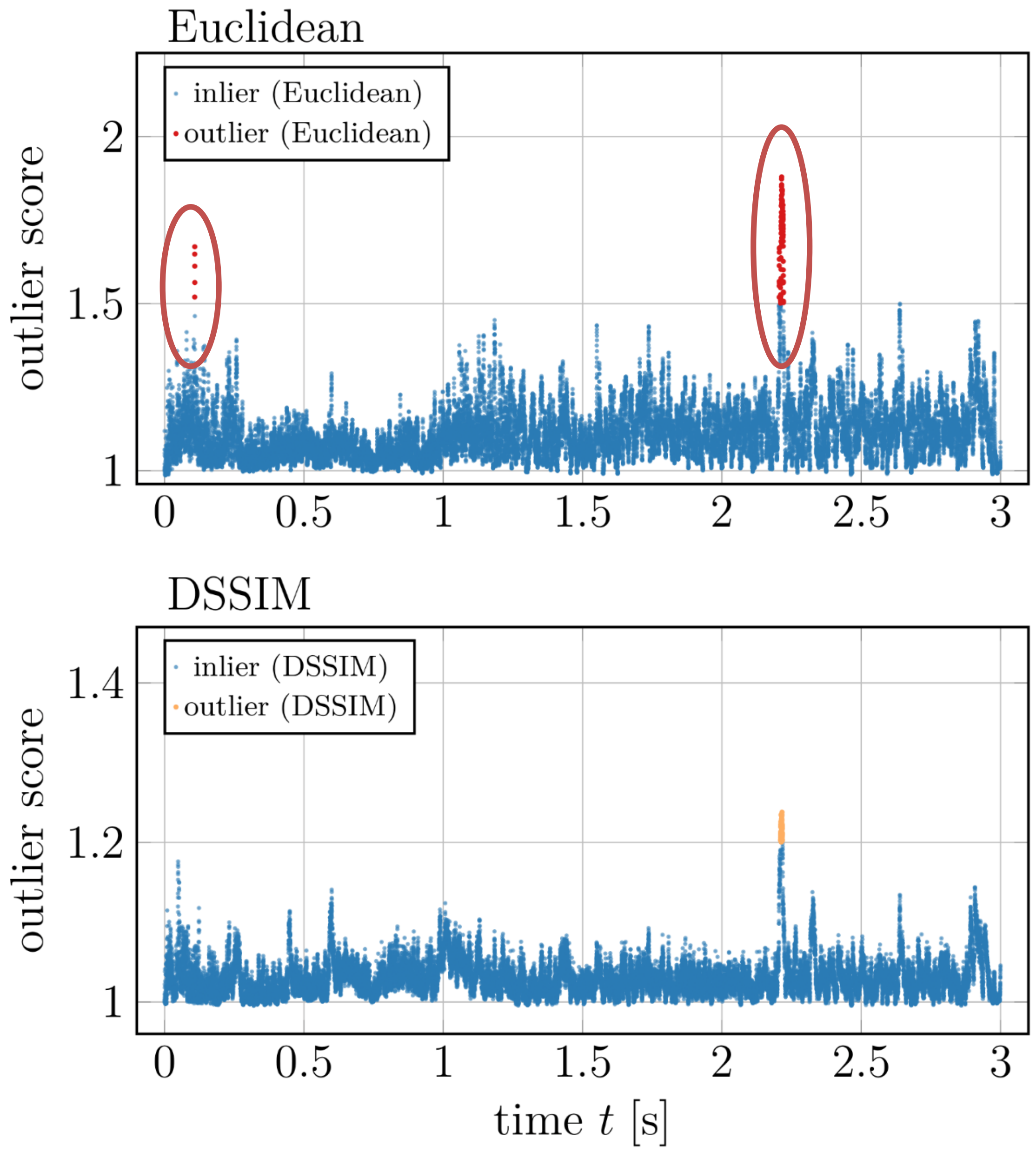
A. Rüttgers, A. Petrarolo, M. Kobald, Clustering of paraffin-based hybrid rocket fuels combustion data. *Exp. Fluids*, 61:4 (2020)

Anomaly Detection: Local Outlier Factor (LOF)

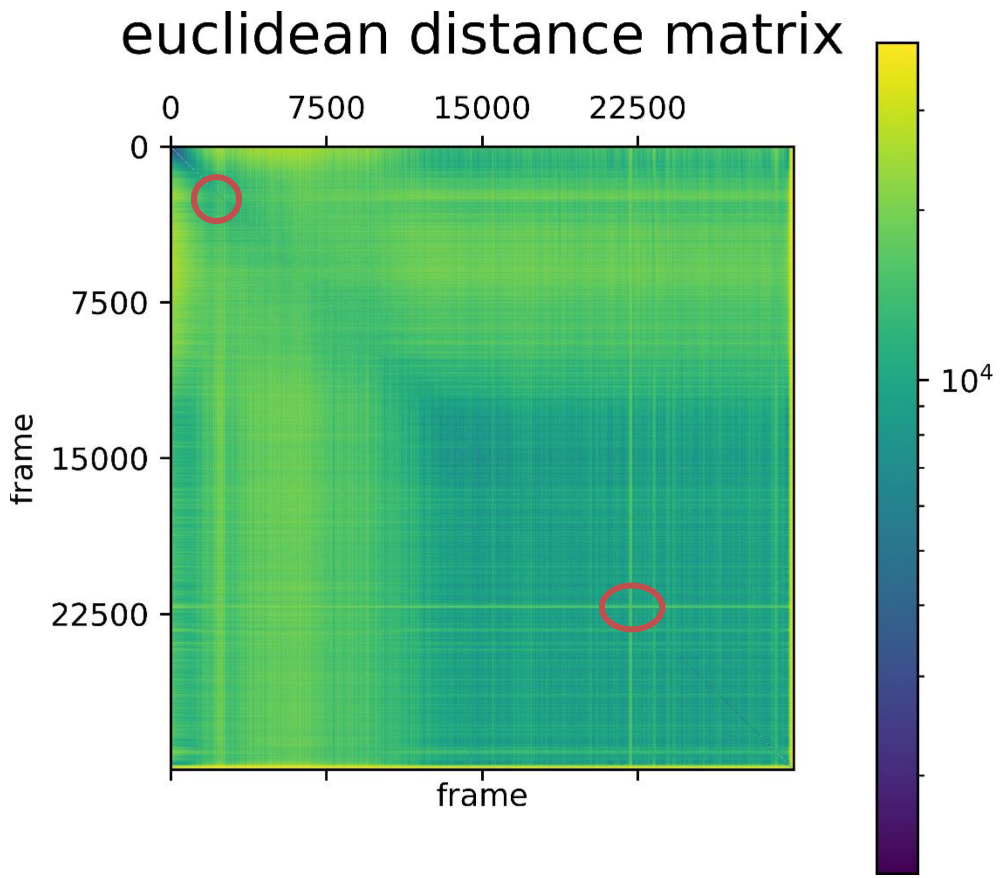
- Algorithm that bases on local density of data points.
- Shares some concepts with clustering algorithms such as DBSCAN and OPTICS.
- Does not show a decision boundary, i.e. cannot directly be used on new data (not necessary here).
- **Core idea:** Compare local density of an object to the local densities of its neighbors.
  → distance matrices from clustering are reused
- Ratio „Density of neighbors / local density of an objects"
  - ≈ 1.0 means similar density as neighbors
  - > 1.0 means lower density than neighbors (outlier candidate)



Point density with respect to k=3 closest neighbors

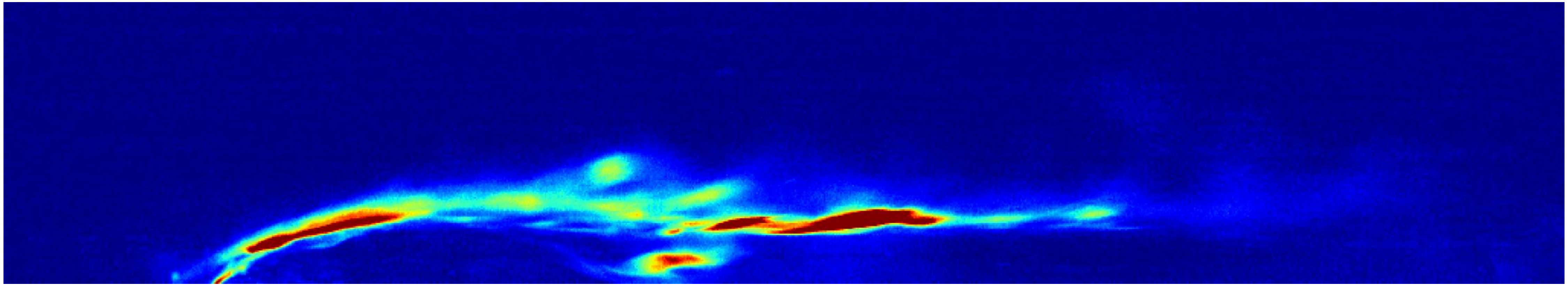


- Euclidean distance norm returns larger outlier score values (due to irregular matrix?).
- SSIM and Euclidean distance share some anomalies but there are differences.

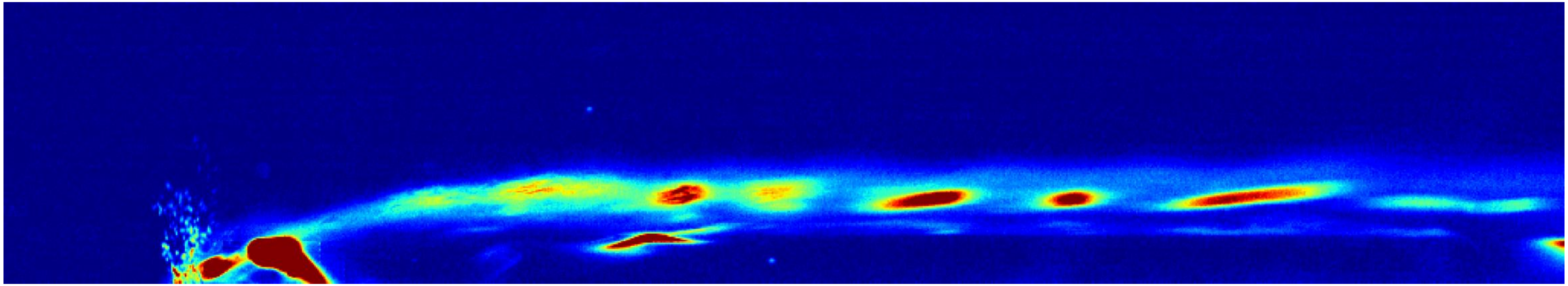


A. Rüttgers, A. Petrarolo, Local Anomaly Detection in Hybrid Rocket Combustion Tests. *Exp. Fluids*, 62:136 (2021)

Peak outliers of Euclidean metric (test 284)

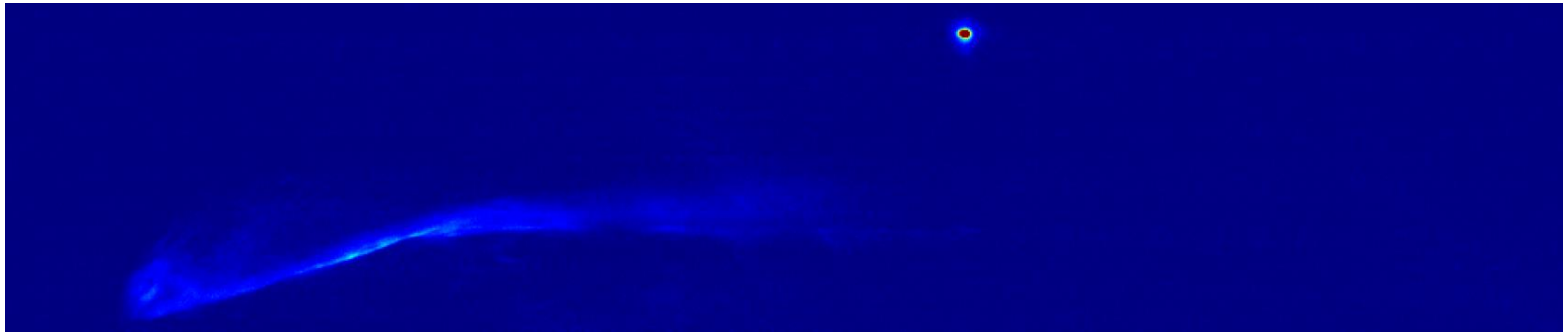


Flame fluctuations in ignition phase at t = 0.1078 s



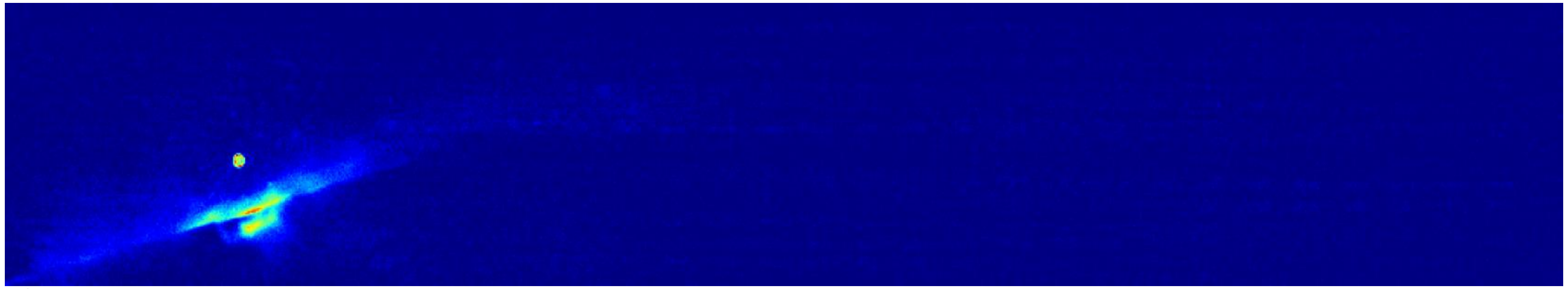
Droplet detection towards end of combustion at t = 2.2055 s

Some outliers found in other combustion tests



Test 291:
satellite droplet at t = 0.0253 s

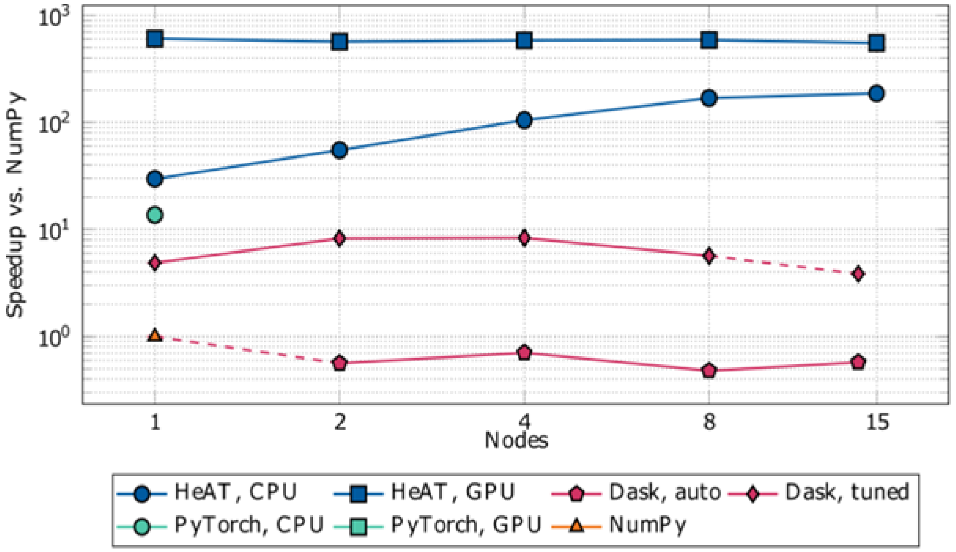
Test 296:
satellite droplet at t = 0.0017 s



Test 296:
satellite droplet at t = 0.0223 s

Conclusion and outlook

- Compute intensive clustering and anomaly detection on large data (e.g. rocket combustion image data) is possible using our software Heat
- Outperforms DASK, PyTorch and Scikit-Learn on distributed data
- Allows deep insights into the combustion process, e.g. to identify different phases and irregularities during combustion
- further insights are possible if datasets are combined (e.g. anomaly detection in spectral and image data).
- Heat currently used for a variety of applications, e.g.
  - Structural prediction of Proteins and RNA (project ProFiLe)
  - Classification of Land-Cover
  - Temporal prediction of physical system with Reservoir Computing



Runtime Speed-Up on distributed data

M. Götz et al., HeAT - a Distributed and GPU-accelerated Tensor Framework for Data Analytics. *2020 IEEE International Conference on Big Data* (2020) pp. 276-287

Thank you for your attention!

DLR