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Classifying low-Z materials with muon scattering tomography for border security

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European Commission

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CosmoPort

EU-funded project aiming to improve scanning at borders (postal centres)

Technical	Customs/law enforcement
GSCAN FONDAZIONE BRUNO KESSLER KEMEA	REPUBLIC OF ESTONIA ESTONIAN TAX AND CUSTOMS BOARD TULLI ΕΛΛΗΝΙΚΗ ΑΣΤΥΝΟΜΙΑ ΑΑΔΕ Independent Authority for Public Revenue (IAPR) State Revenue Service Republic of Latvia

European Commission
Horizon 2020
European Union funding
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Material classification exercise

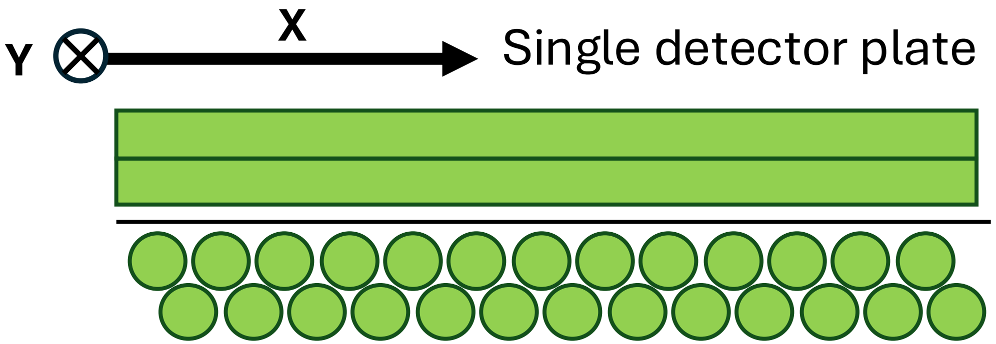
- Aimed to demonstrate separation of low-Z materials by combining MST and machine learning

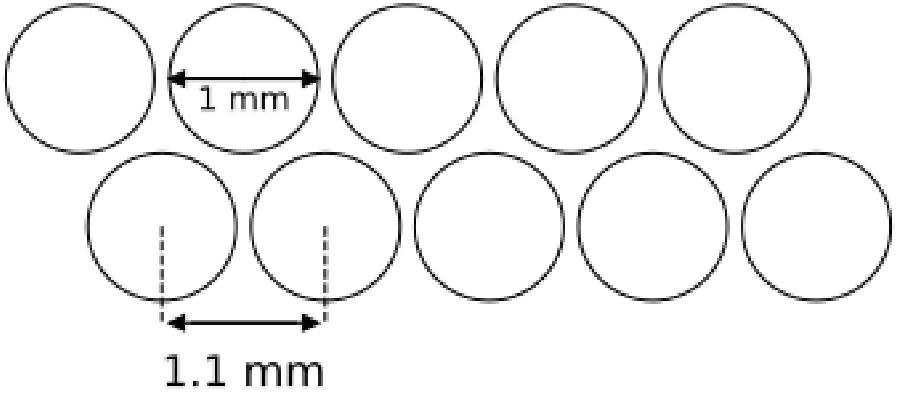
- Real measurements were made using a prototype detector and used to train classification algorithms to discriminate materials

Further details available in existing publication[1]

Prototype detector design

- Prototype scintillating fibre detector by GScan OÜ (in 2021)
- Basic hodoscope design: 3 detector plates, with two double-layered fibre mats each
- From sim study[2]: average reconstruction error is ~0.1 mm, corresponding angular resolution ~1 mrad





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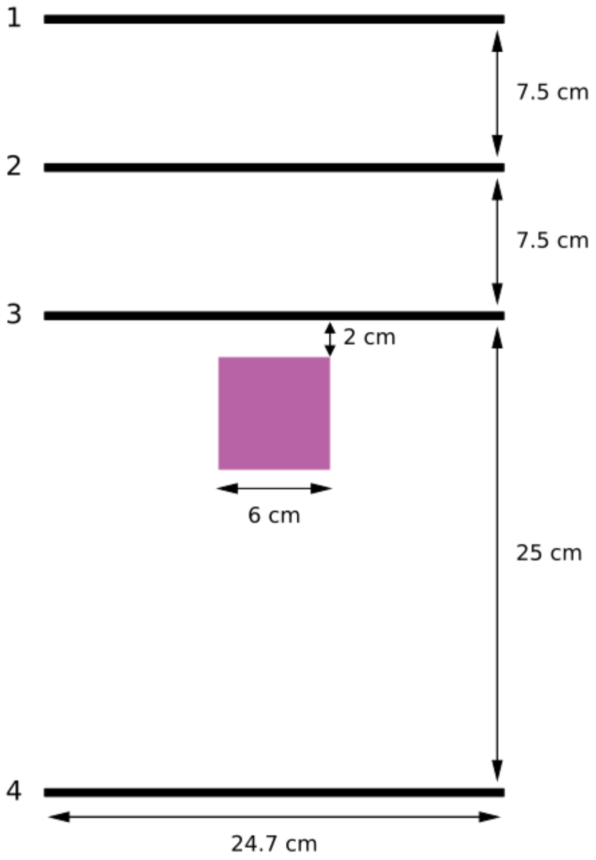
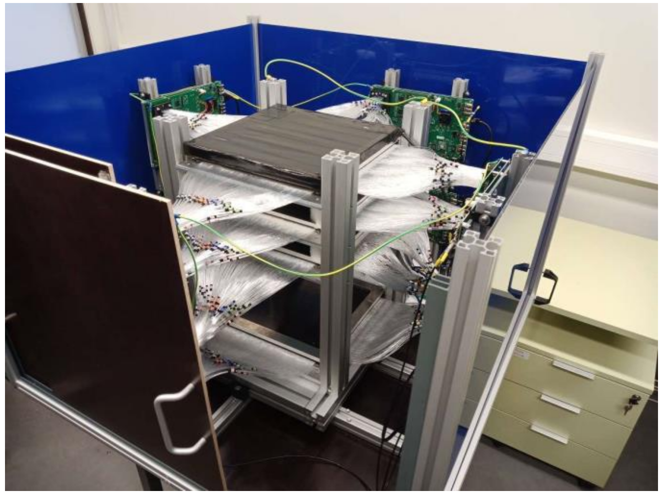
Experimental setup

- Prototype detector consists of 3 detector planes above volume of interest (VOI) and 1 below

- Position measurement samples 2 cm below top hodoscope





Measurement samples

- 6 cm side length cubes of material
- Measure each material for 8 hours in 30 minute segments for 16 samples per material

Material	Weight / g
Air	-
AW5754 Aluminium	574.2
C30/37 Concrete	512.0
Glass	514.8
Water	256.9
Ammonium nitrate with sulphur pellets (NH_4NO_3)	199.6
PENO plastic explosive	342.0
Plexiglass	251.6
15 mm FF Birch Plywood	147.6
S355MC Steel	1684.9

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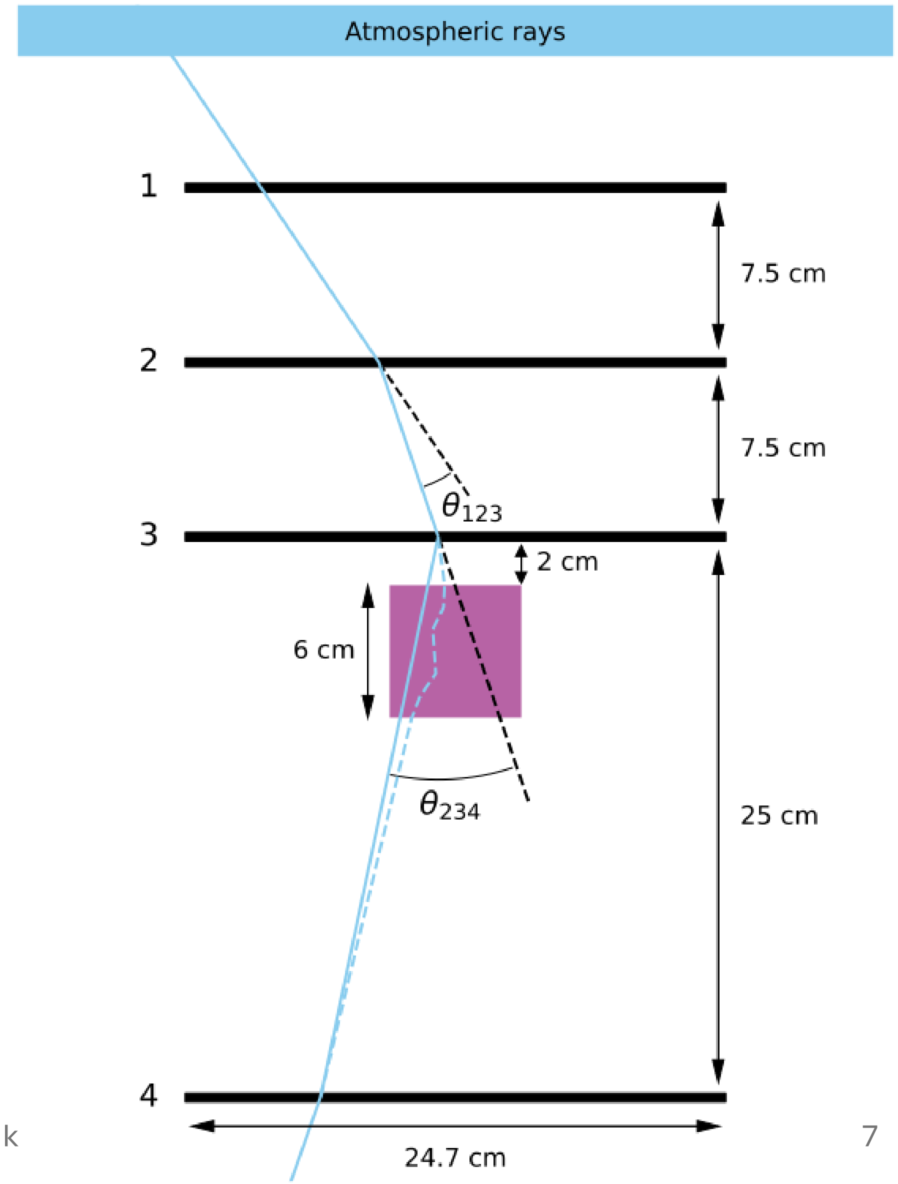
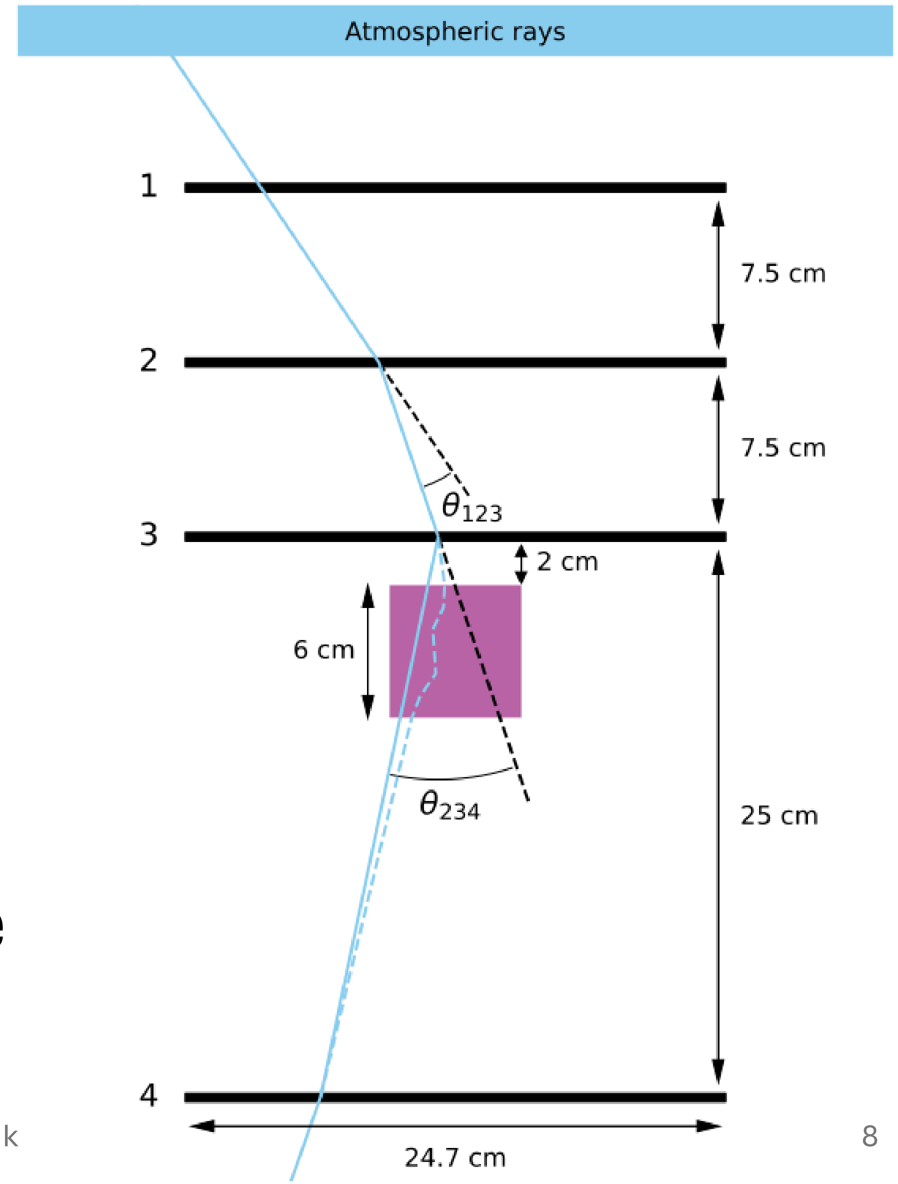
Data processing

- Approximate muon track through volume by straight line through VOI
- Use 3 filter groups based on θ_{123} to group electrons, electron/muon mixture, and muons
- Find events traversing each voxel in VOI (using 0.5 cm voxels)



Data processing

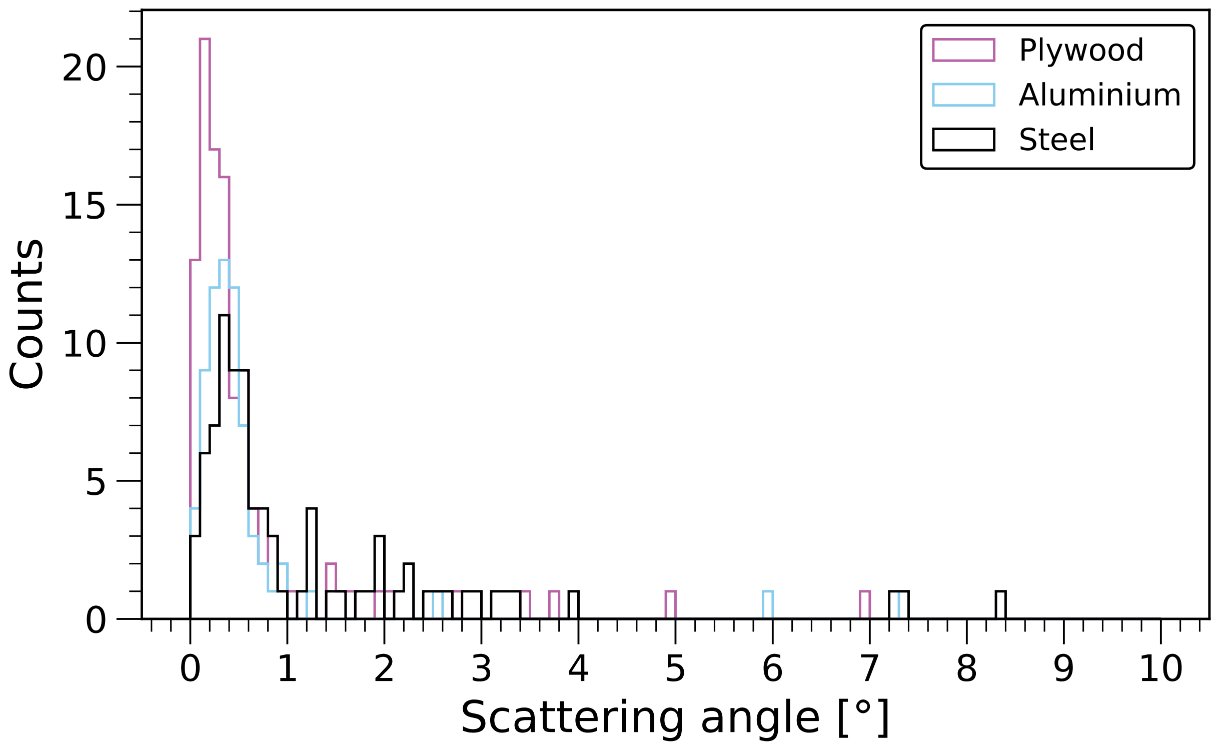
- For each voxel intersecting the known object position, compute quantities including (but not limited to):
    - Average scattering angle
    - Average track length in voxel
    - Average scattering angle per unit track length
- Repeat for each filter group and plane combination (123 and 234)



Object histograms

- Aggregate quantities across all voxels in object
- ML algorithm inputs are normalised histograms
- Separate in 15-fold cross-validation, so per material in each fold:
  - 10 training samples
  - 1 validation sample
  - 1 test sample

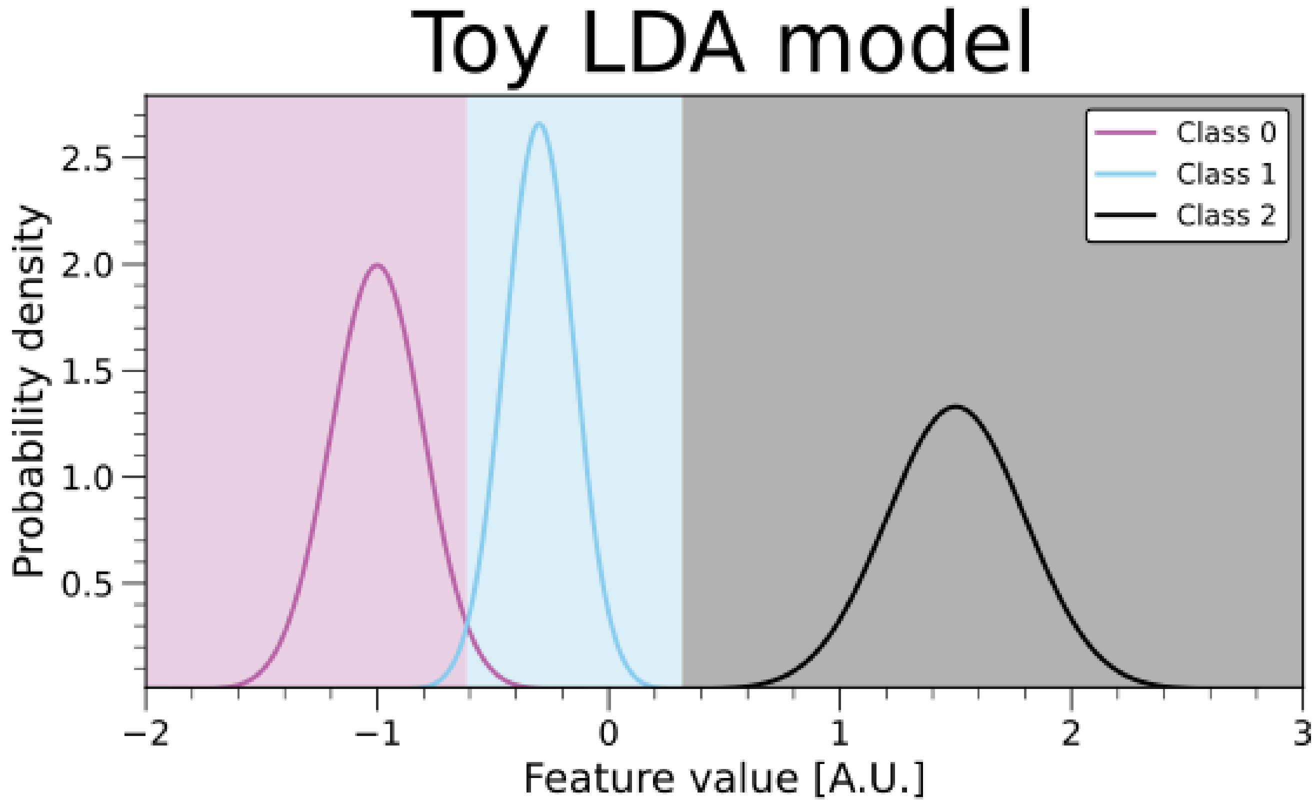
Example unnormalised $\overline{\theta_{234}}$ histograms



Material classification methods

For this exercise, use **linear discriminant analysis (LDA):**

- Model each class with multivariate Gaussian, **minimise** in-class variance and **maximise** class separation
- At prediction, select class with highest likelihood for the sample
- Try both multiclass and 1 vs 1 LDA methods



Shaded regions show what class would be predicted

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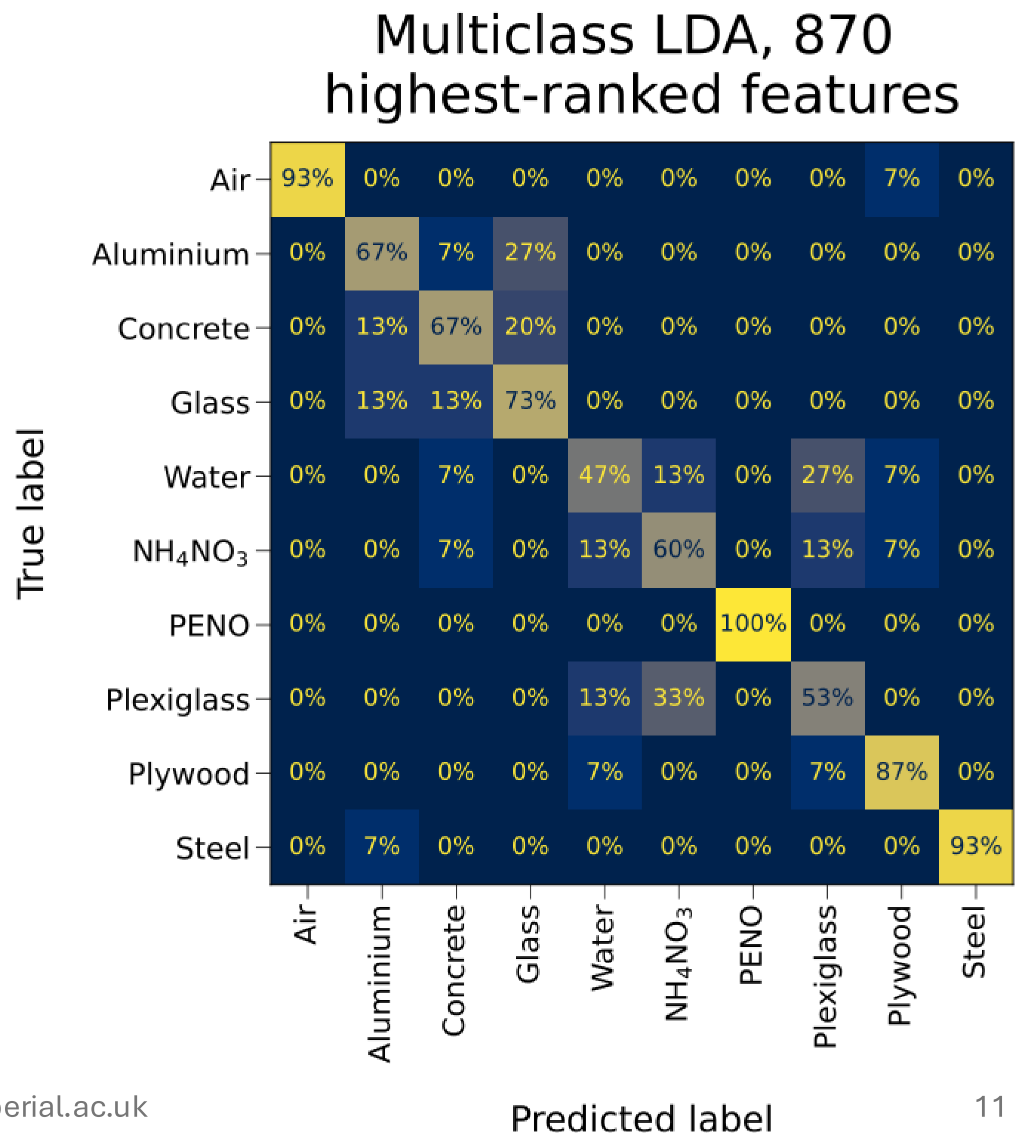
Multiclass LDA

- Multiclass training scheme: simultaneously fit all class Gaussian models
- Optimise number of features based on feature importance scoring (see paper for details[1])
- Average test set accuracy across all folds is **74.0%**



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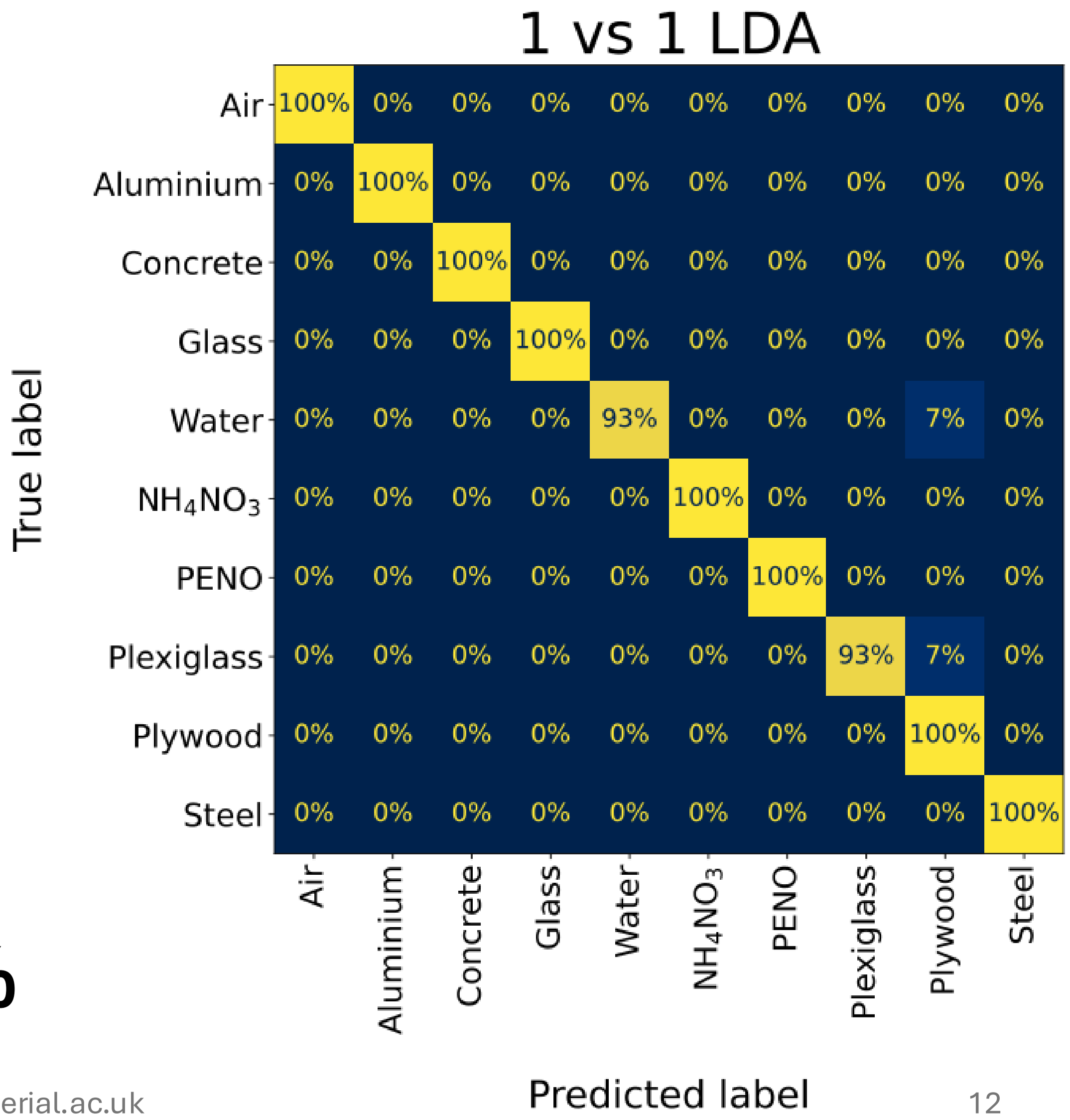
1 vs 1 LDA

- 1 vs 1 training scheme: train an LDA classifier for each pair of classes
- Final prediction is most voted class among all classifiers
- Optimise feature count per classifier
- Same CV scheme as multiclass

Average test accuracy = 98.7%



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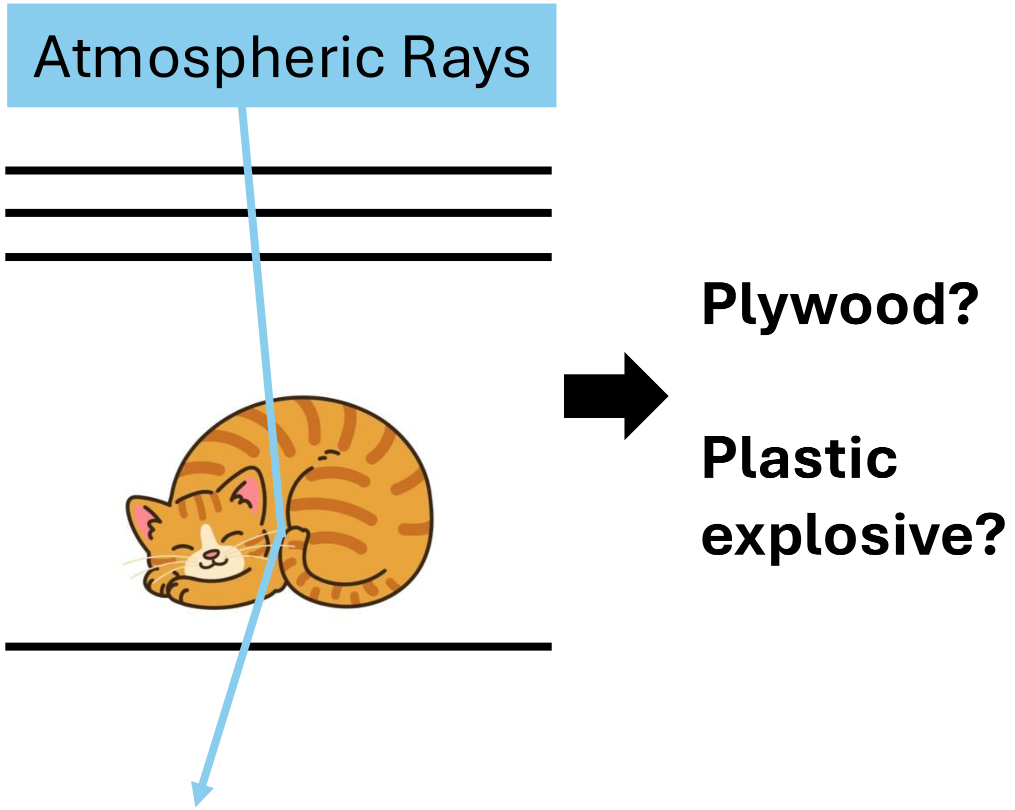
Limitations of this exercise

- Limited tomography device, so needed ground truth to identify object voxels
- Simple experimental scenario, not realistic
- Reliance on seen materials for classification, difficult to generalise



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Subsequent developments

- Dedicated CosmoPort scanner in a trailer (two full hodoscopes), sized for postal roll cages
- Piloting measurement campaigns with customs partners
- Extensive simulation validation and generation of synthetic datasets

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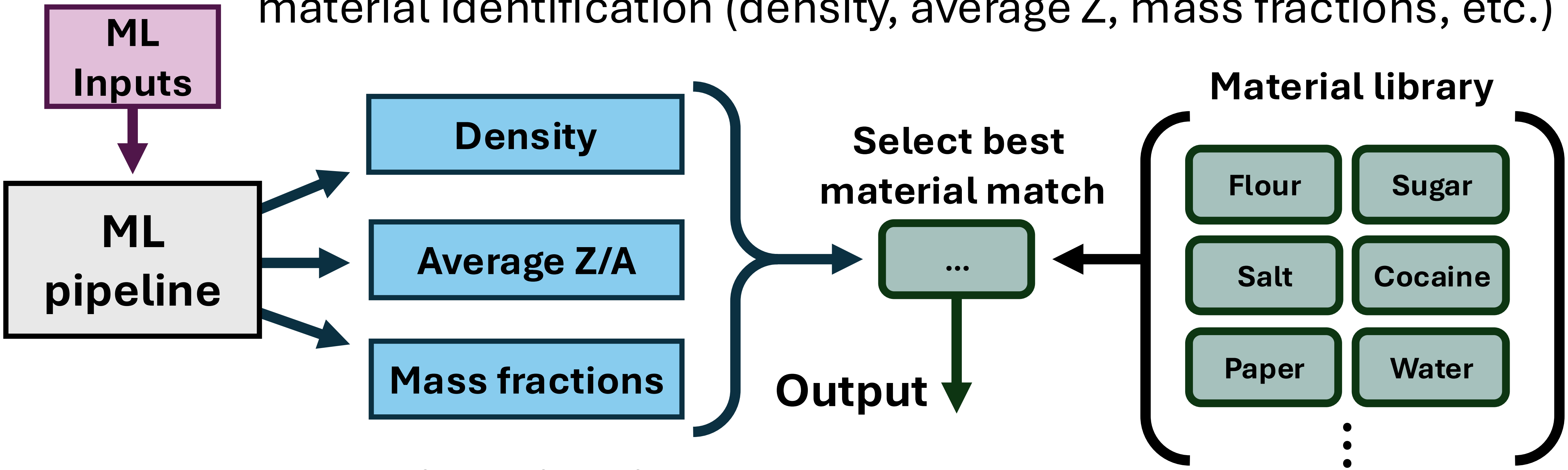
Next steps

Development of ML methods to improve **generalisation** of material identification (density, average Z, mass fractions, etc.)



Example processing pipeline

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Summary

- A prototype scintillating fibre detector was built with position reconstruction error ~ 0.1 mm, corresponding angular resolution ~ 1mrad
- ML models were trained using 30 minute scans of low-Z material cubes, achieving **98.7%** average accuracy
- Improvements to detector & methods are ongoing, with the (eventual) aim of generalised material identification

Thank you!

[1] N. Reed *et al* 2025 *JINST* **20** P07032
[2] G. Anbarjafari *et al* 2021 arXiv:2102.12542 **[physics.ins-det]**

Bonus Slides

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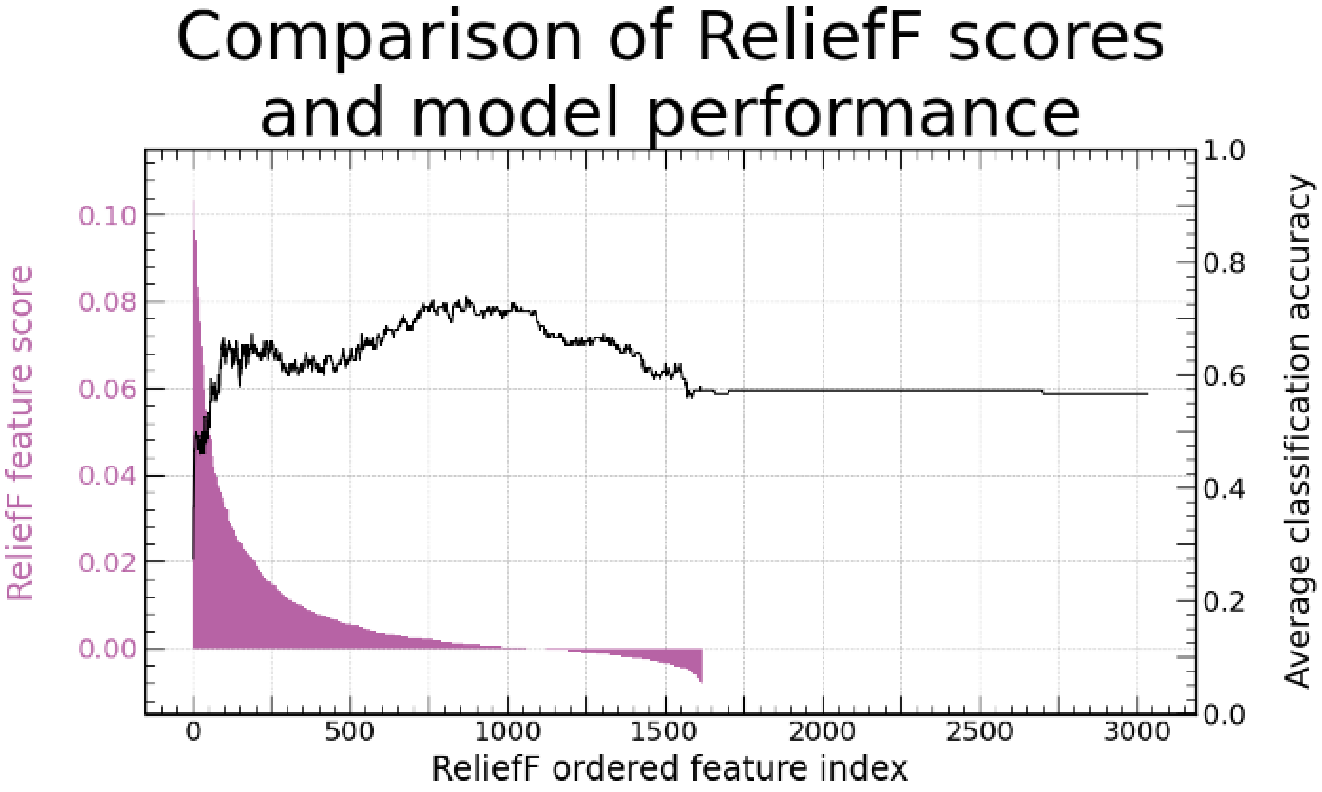
Feature importance

- Use ReliefF feature importance algorithm to calculate score per feature quantifying discrimination power
- Use top N ReliefF-ordered features to train, optimise N for best validation accuracy



Multiclass LDA feature count optimisation