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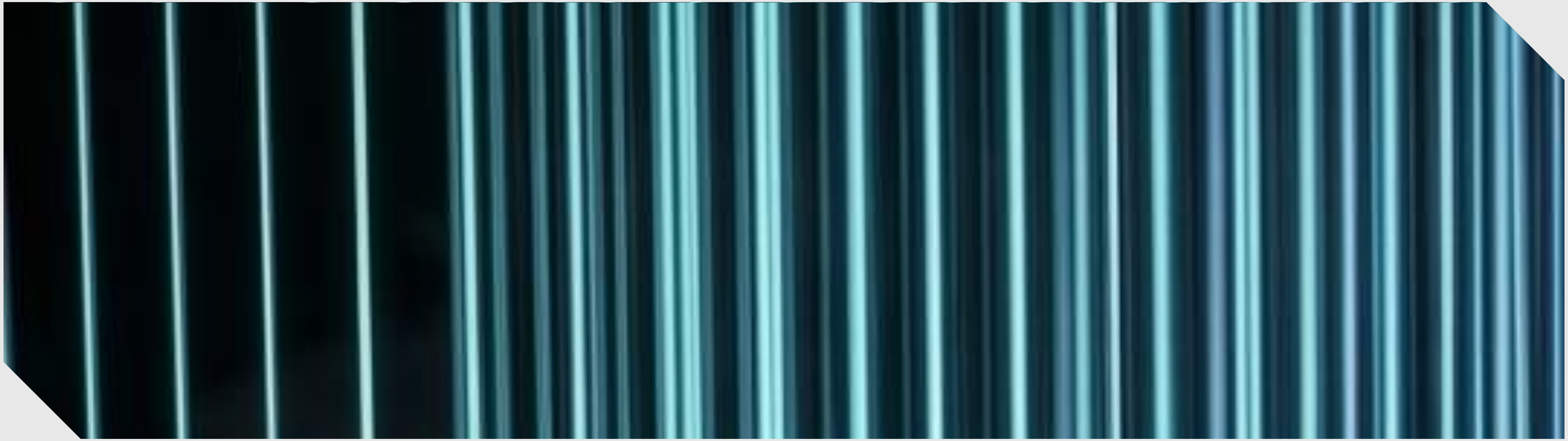


ANALYSIS OF EXPERIMENTAL DATA FROM THE THOMSON SPECTROMETER

Department of Laser Physics and Photonics
Supervisor: Doc. Ing. Ondřej Klimo

CZECH TECHNICAL UNIVERSITY IN PRAGUE

ARTEM SHELAMANOV

PRESENTER

ARTEM SHELAMANOV

3rd year international Bachelor student

SPECIALIZATION

Physical engineering - computational physics

ALSO...

4+ YOE as ML/AI R&D Engineer at Neuroforge

DEPARTMENT OF LASER PHYSICS AND PHOTONICS

FACULTY OF NUCLEAR SCIENCES AND PHYSICAL ENGINEERING CTU IN PRAGUE

BACHELOR THESIS ASSIGNMENT

Assignment for the thesis “Analysis of experimental data from the Thomson spectrometer”

ION ACCELERATION

01

Review the fundamentls of ion acceleration.

THOMSON SPECTROMETER

02

Study principles of Thomson spectrometer.

SOFTWARE DEVELOPMENT

03

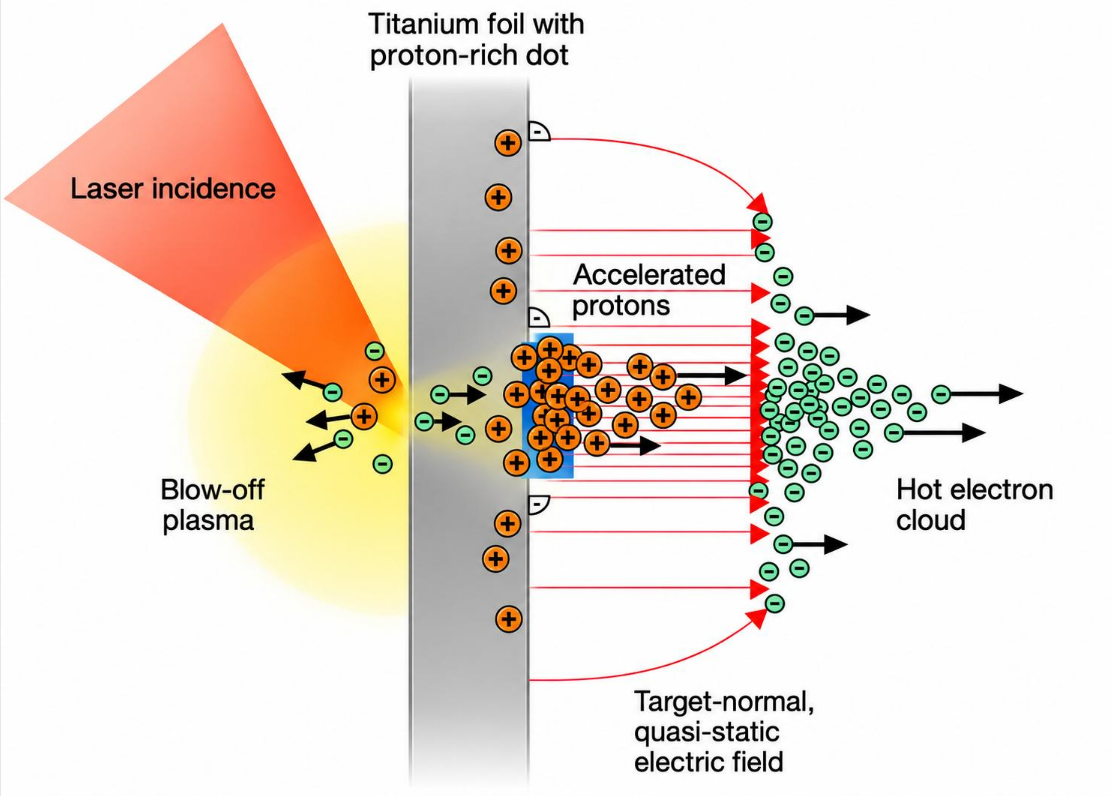
Develop a software tool for processing and analysis of images from Thomson spectrometer.

ANALYSIS OF DATA

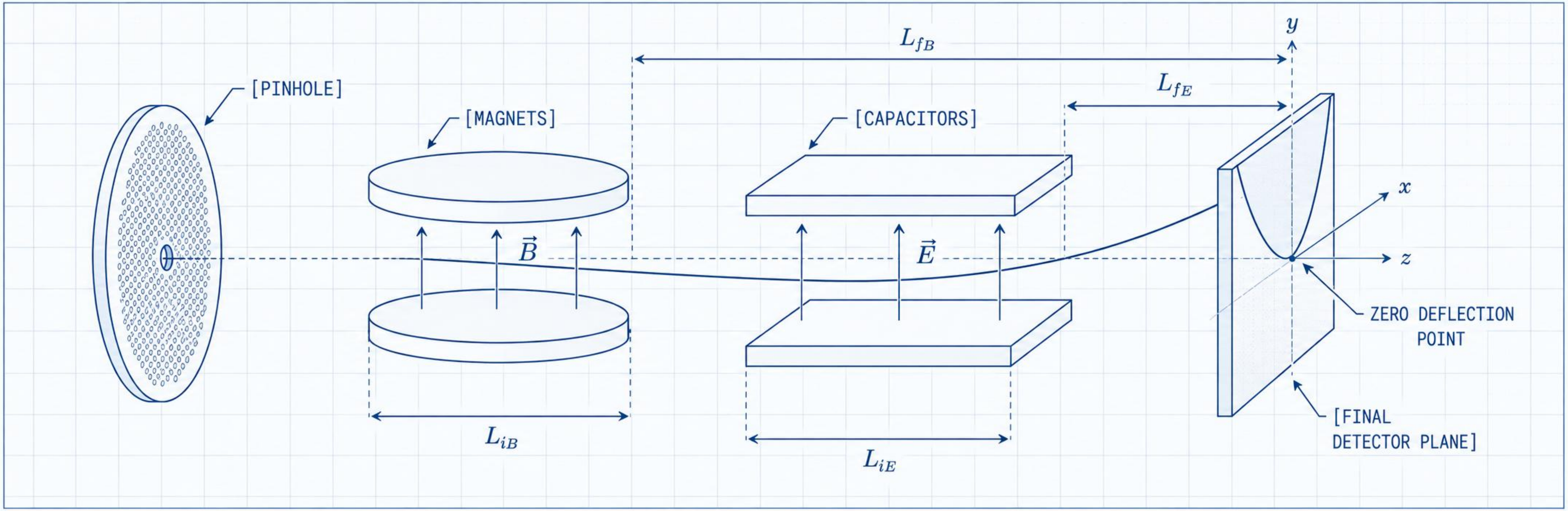
04

Test the developed tool on synthetic data and apply the tool on analysis of experimental data from the PALS laser facility.

TNSA LASER-SOLID INTERACTION



1. High-intensity laser pulse interacts with solid target.
2. Burst of relativistic electrons is created from the target rear surface.
3. Dense cloud of electrons forms, creating a strong temporary electric field.
4. This strong electric field accelerates surface ions from the target's rear, forming an ion beam.



Ions with different mass to charge ratios and
different velocity/energy get deflected differently.

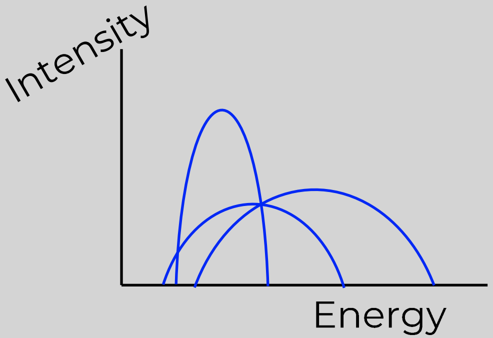
THOMSON SPECTROMETER

MAIN GOAL OF THE THESIS

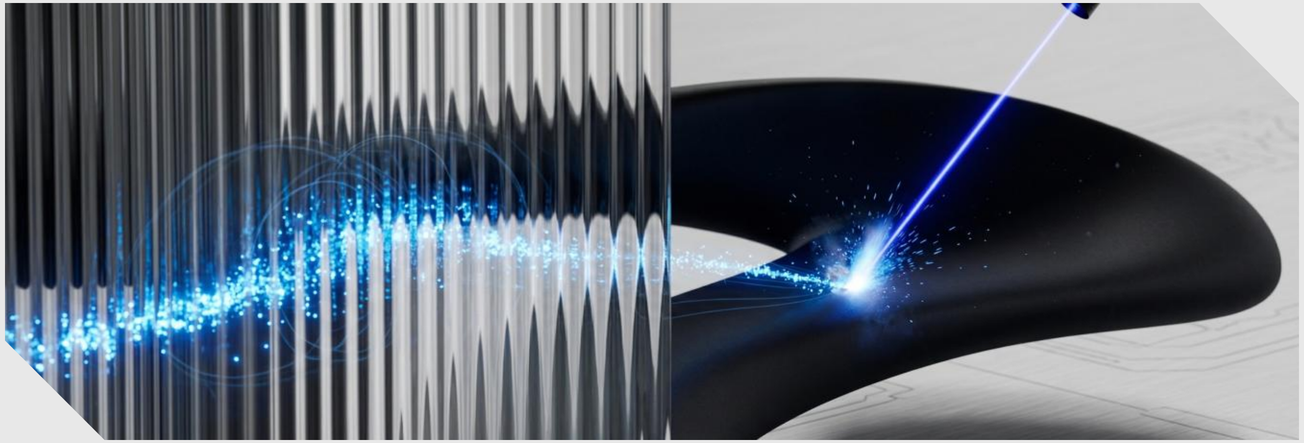
ION SPECIES

O1+, O2+, O3+
H1+
Si3+, Si4+

SPECTRA



THESIS MOTIVATION



01

SOLID COMPOSITION

Get information about the composition of the solid the laser interacts with.

02

LASER AND PLASMA

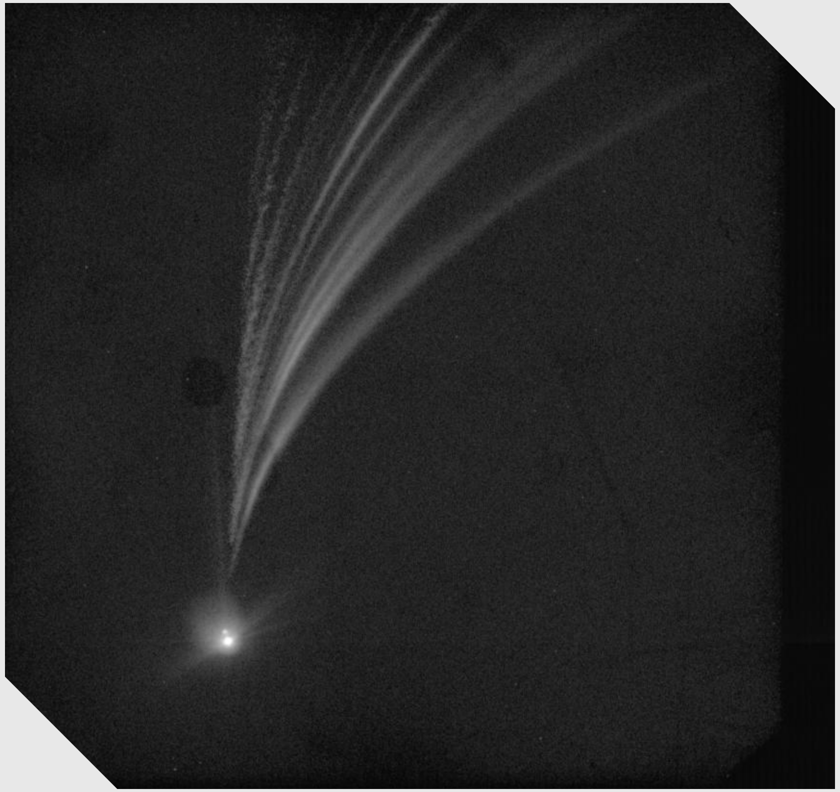
Investigate laser-solid and laser-plasma interactions. Analyze plasma and charged particles behaviour.

03

AUTOMATION

Reduce manual work and time needed to analyze detector images, minimize human errors and bias.

PROBLEM STATEMENT – WHAT'S SO HARD?

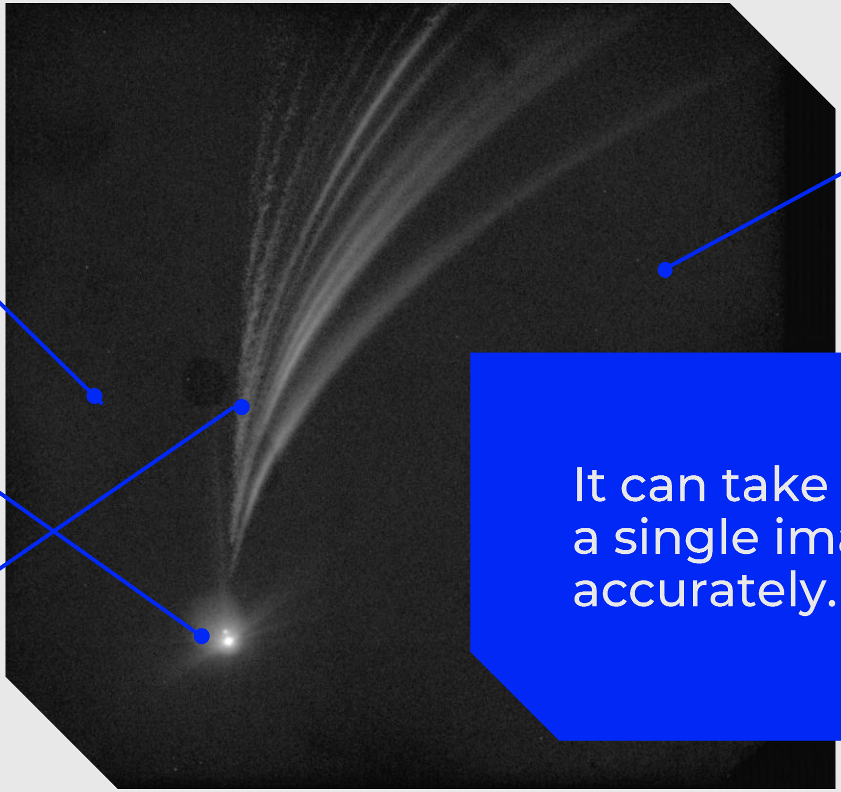


PROBLEM STATEMENT – WHAT'S SO HARD?

Images are noisy

No clear shared origin for parabolas

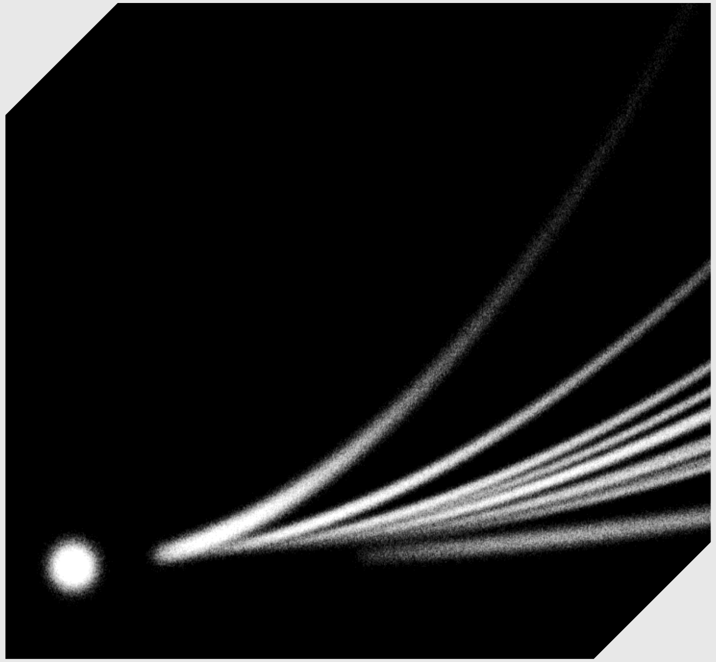
Parabolas are not following $y=Cx^2$



The whole image is rotated, tilted and distorted

It can take hours to analyze a single image manually accurately.

PROBLEM STATEMENT: SYNTHETIC IMAGE



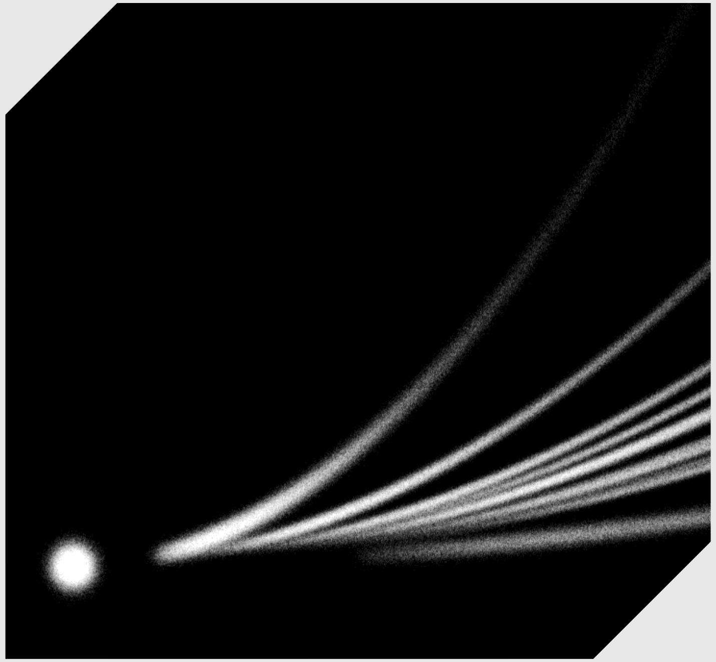
SYNTHETIC IMAGE

Clear bright spot, clear smooth parabolas; 01

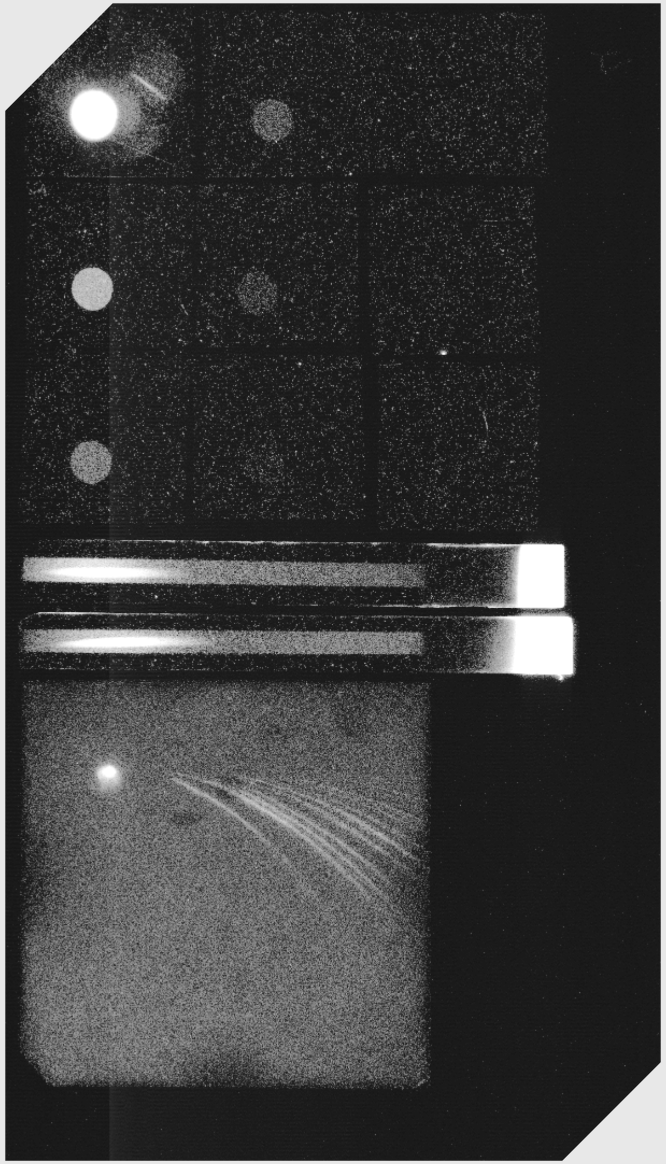
No background noise, no tilts or rotation; 02

It is very easy to extract parabolas and fit them with one function. 03

PROBLEM STATEMENT: EXPERIMENTAL IMAGE



SYNTHETIC IMAGE



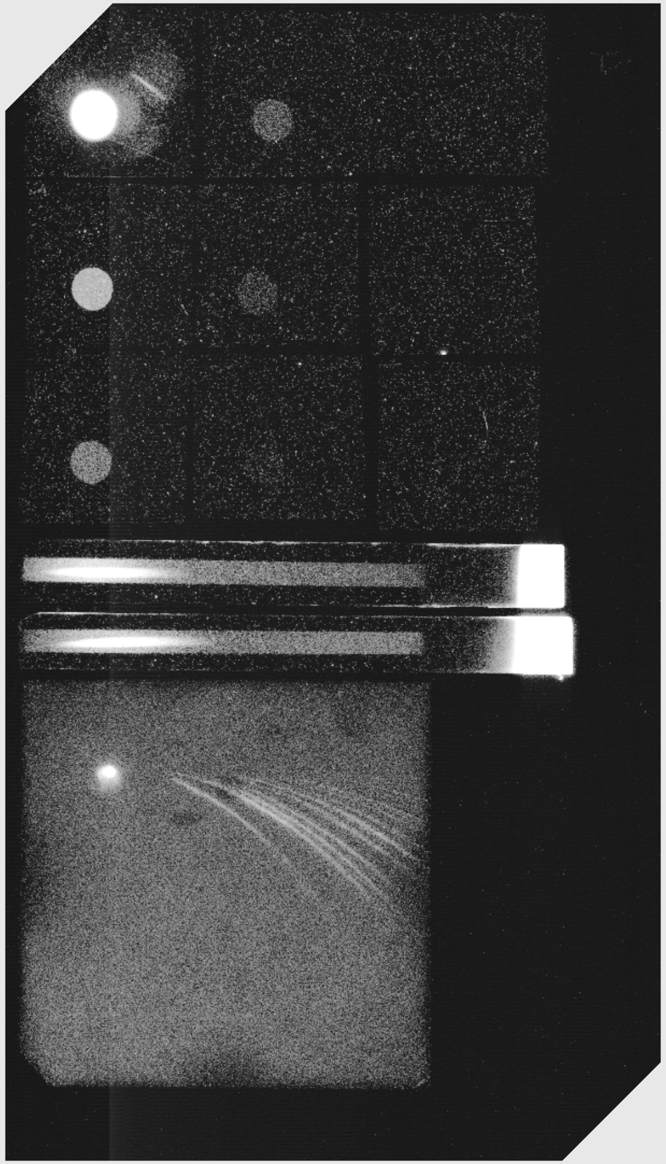
EXPERIMENTAL IMAGE

PROBLEM STATEMENT: EXPERIMENTAL IMAGE

01 Bright spot has some “halo” around it, sometimes there are ghost bright spots;

02 Background noise is as intense as some parabolas; actual parabolas take only some part of the image;

03 Parabolas are messy, they are interrupted, not smooth.



EXPERIMENTAL IMAGE

SOLUTION: A ROBUST COMPUTER VISION ALGORITHM

01
Crop, rotate, flip

02
Denoising, smoothing

03
Extract lines, filtering

04
Origin+params fitting

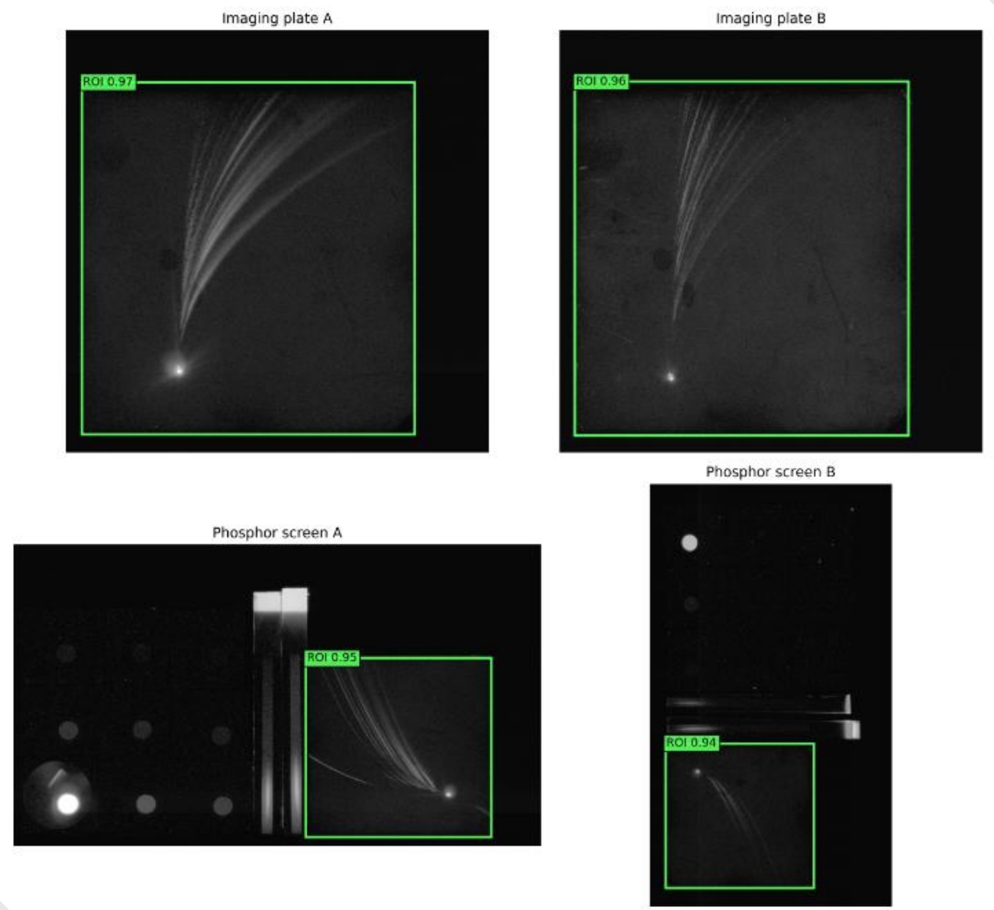
05
Calculating q/m + spectra

MAIN IDEAS

Minimize manual work, minimize human errors and experimental imperfections.

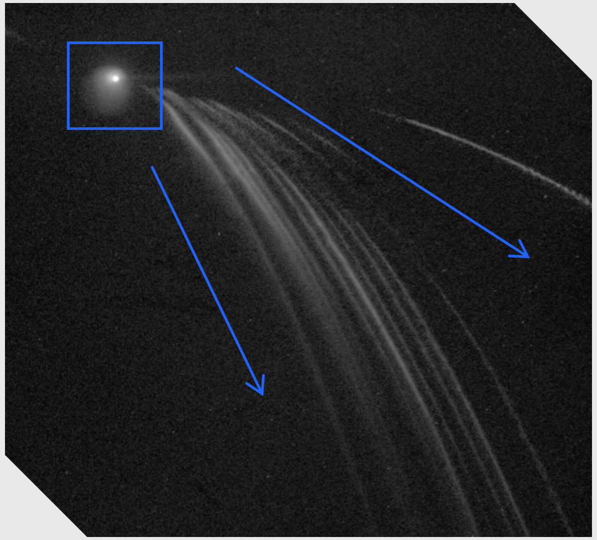
STEP 1 – CROPPING WITH YOLO AI MODEL

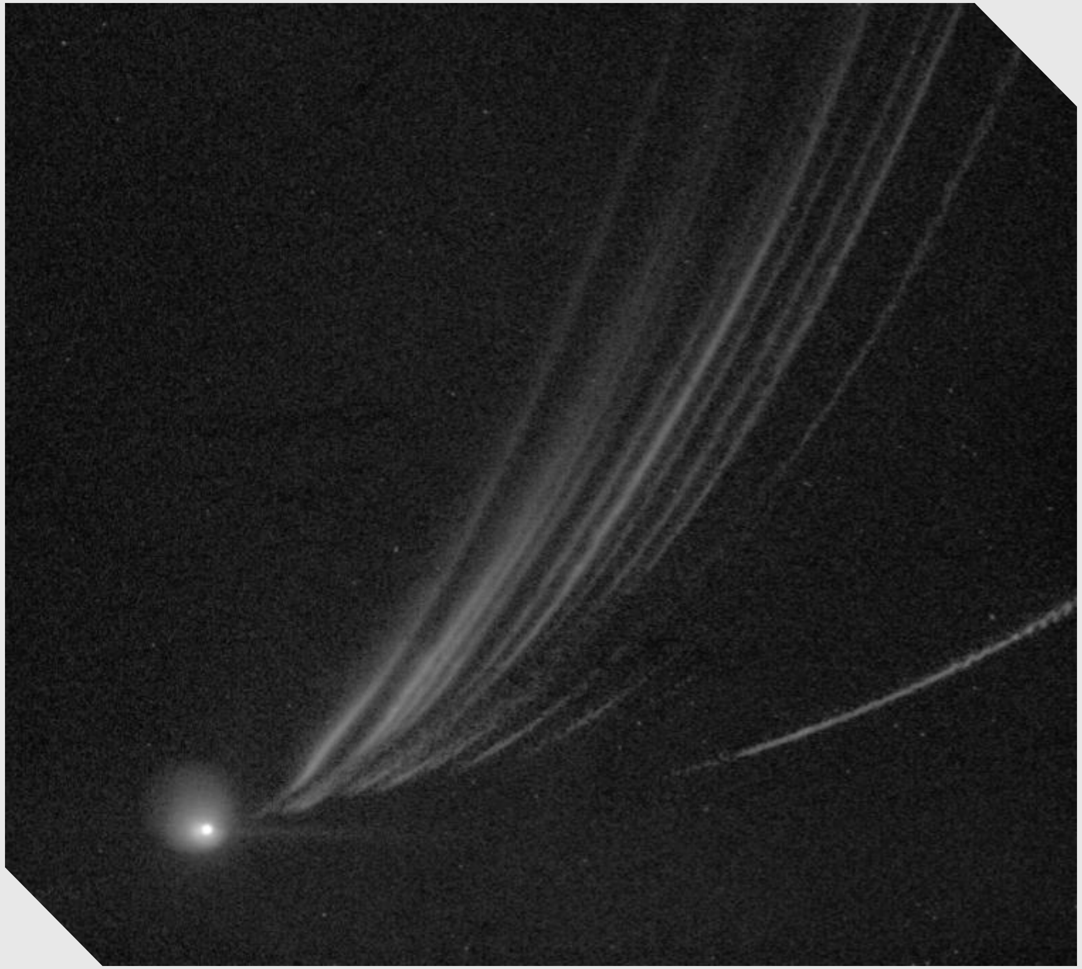
Cropping: Fine-tuned YOLOv26 object detection model



STEP 1 – ROTATION AND FLIPPING

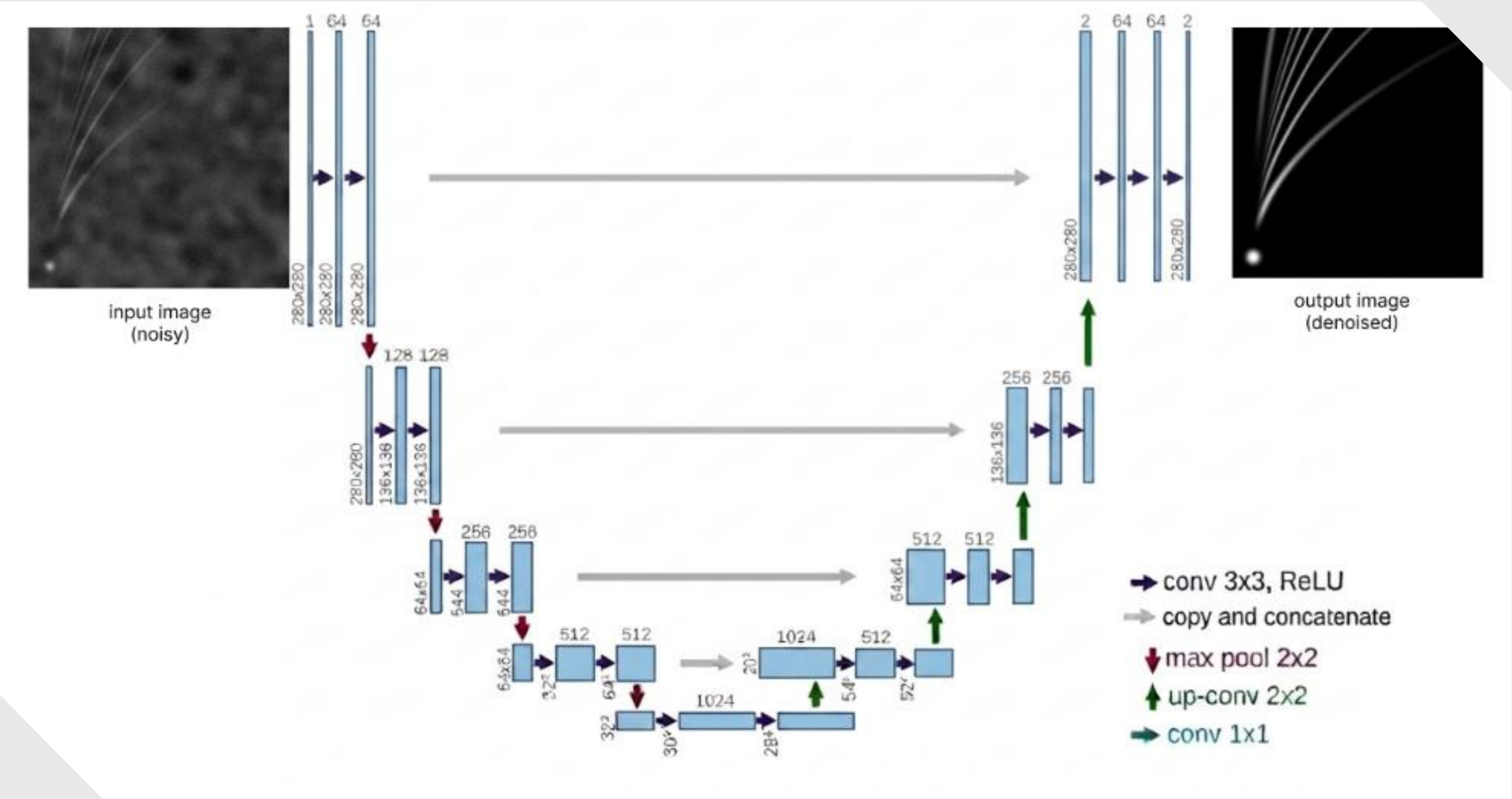
Find brightest spot + identify overall “momentum” of intensity (white pixels)





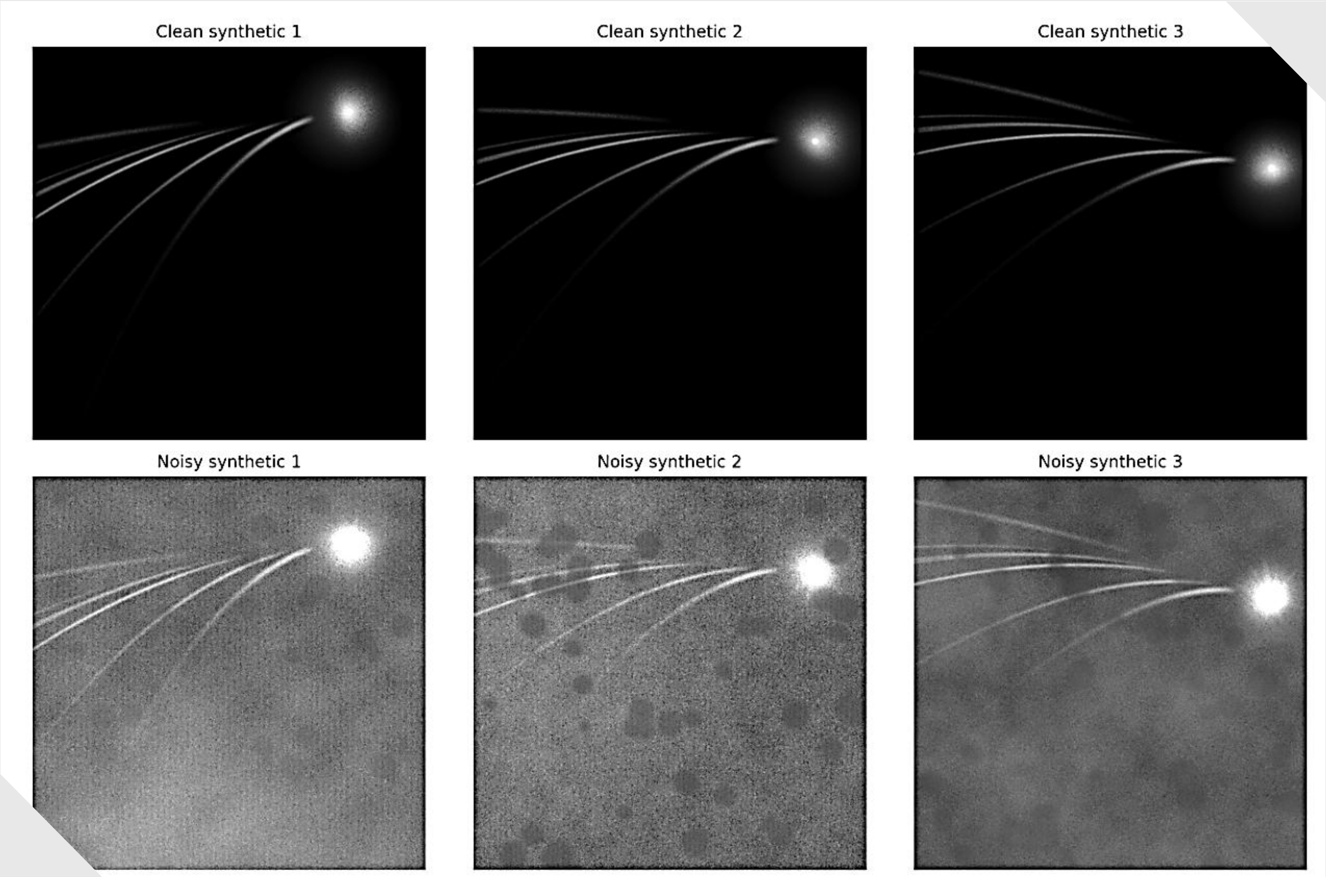
STEP 2 – DENOISING WITH UNET

Synthetic dataset + artificial noise -> removes noise and enhances lines.
UNet – ML architecture commonly used for image processing.



STEP 2 – DENOISING DATASET

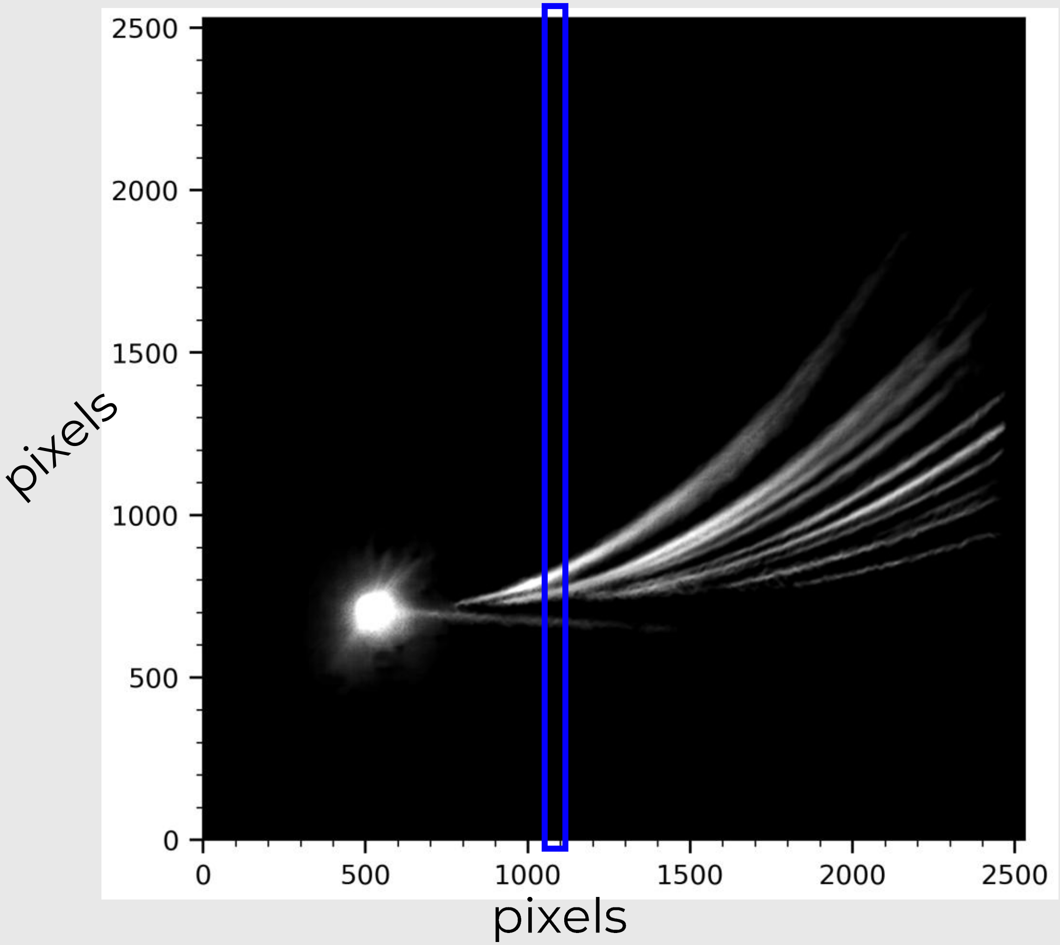
Synthetic dataset: 10 different kinds of noise, random intensity for each. Clean image vs noisy image.

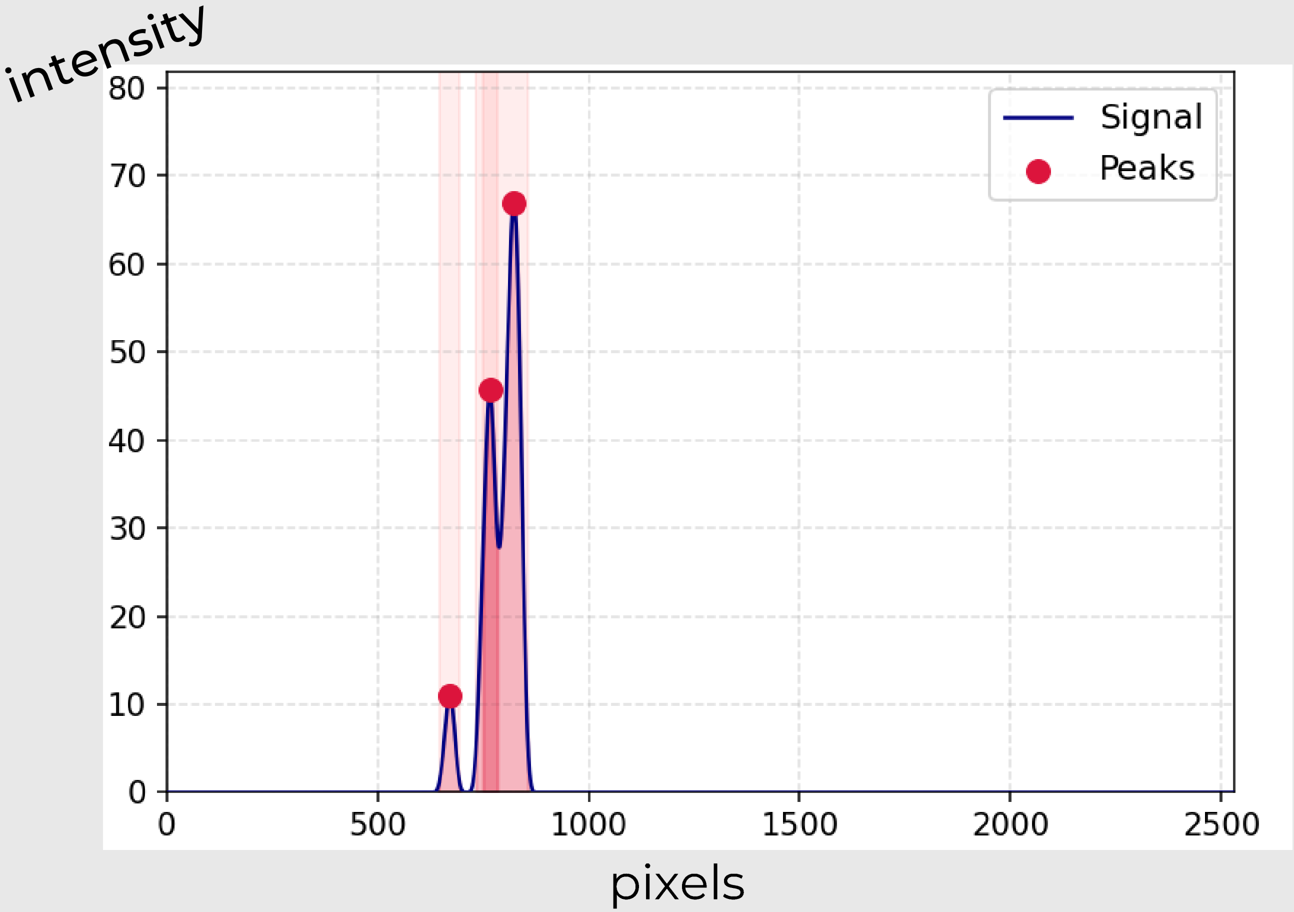


STEP 2 – DENOISING WITH UNET

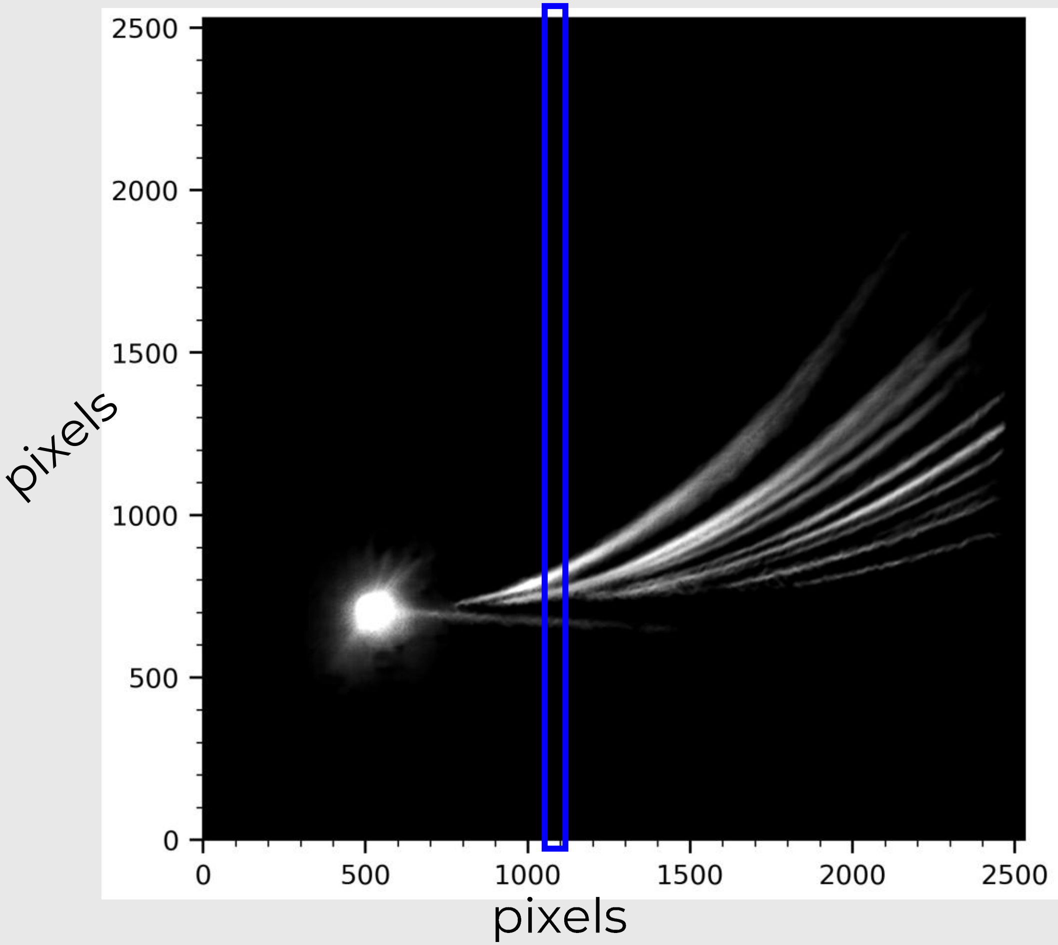
Example of denoising an experimental image using the denoising model. The model removes any noise while keeping all the traces.

STEP 3 – PEAKS EXTRACTION

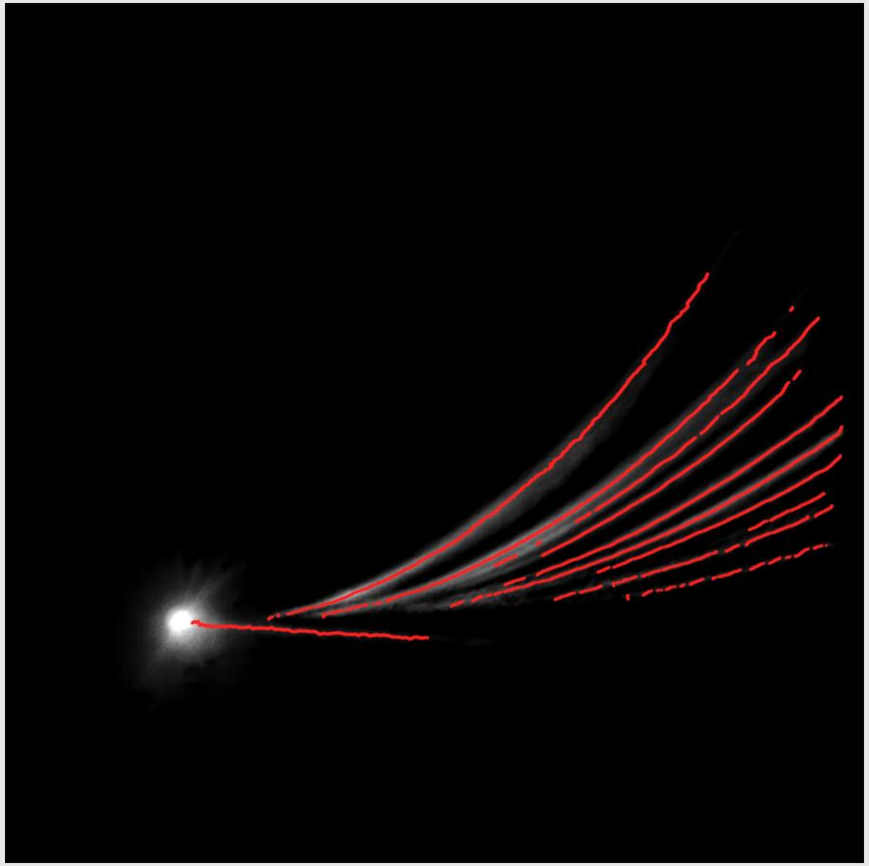


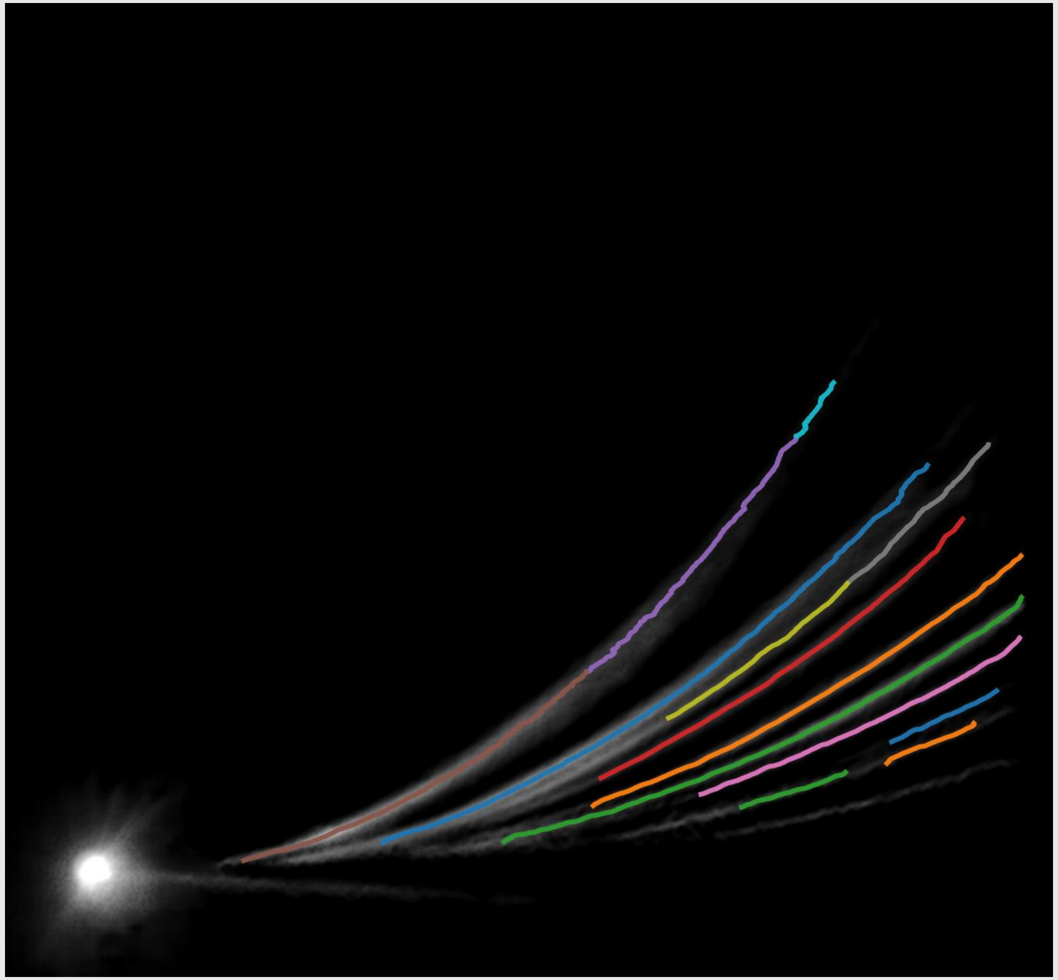


STEP 3 – PEAKS EXTRACTION

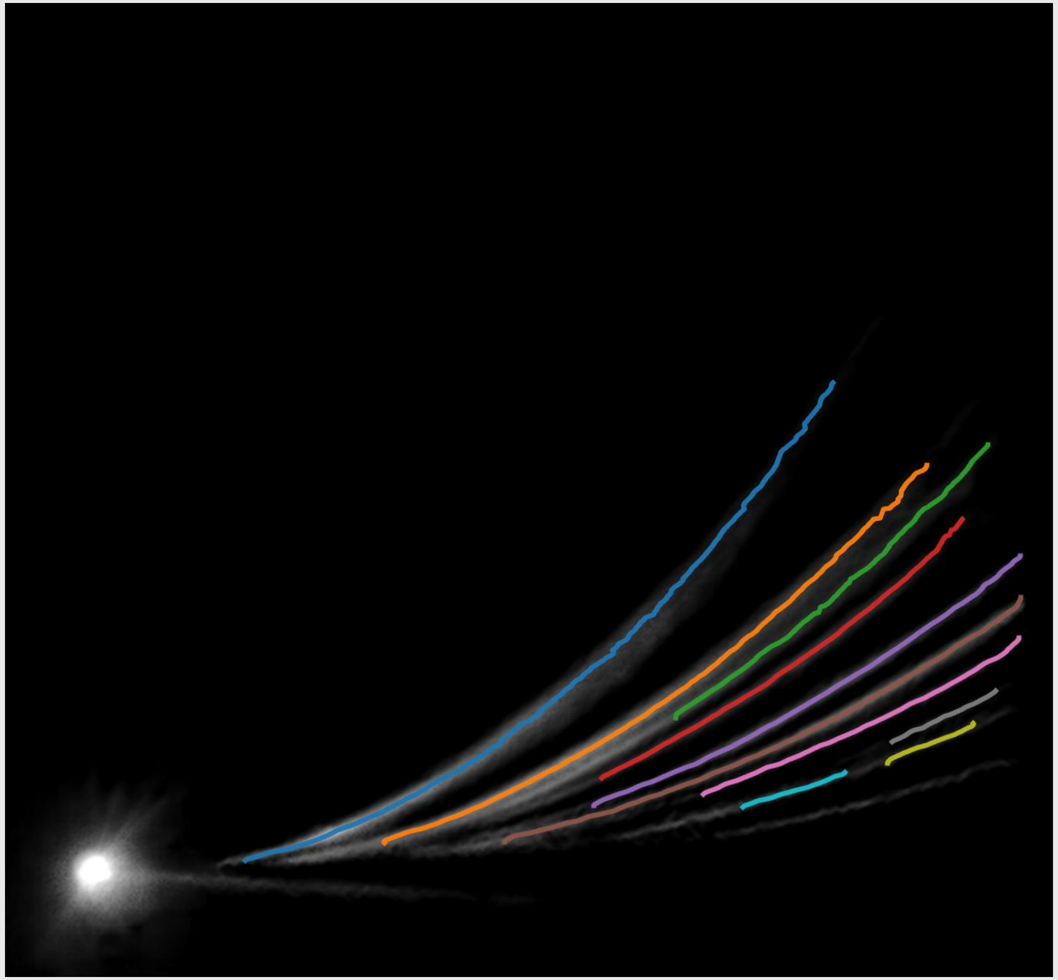


Extracted peaks (points)





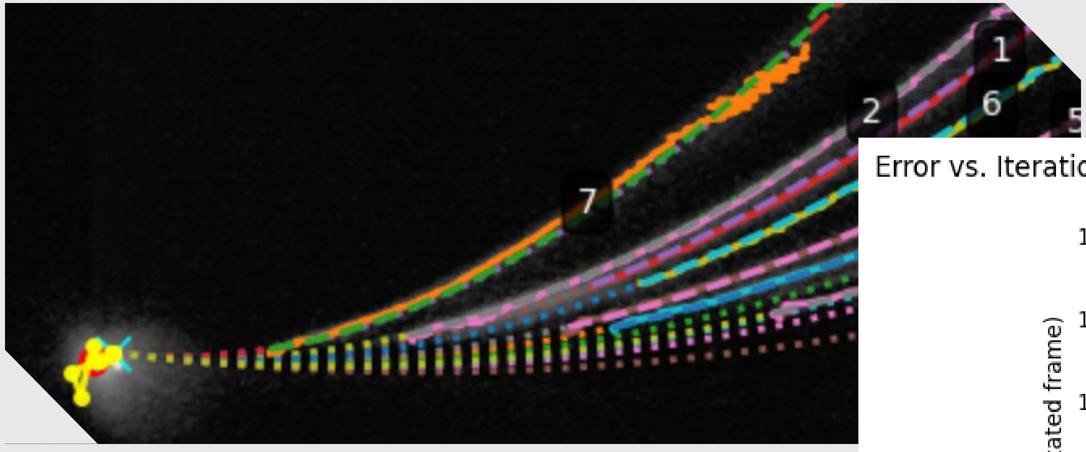
Extracted lines from points – denoised, filtered, merged

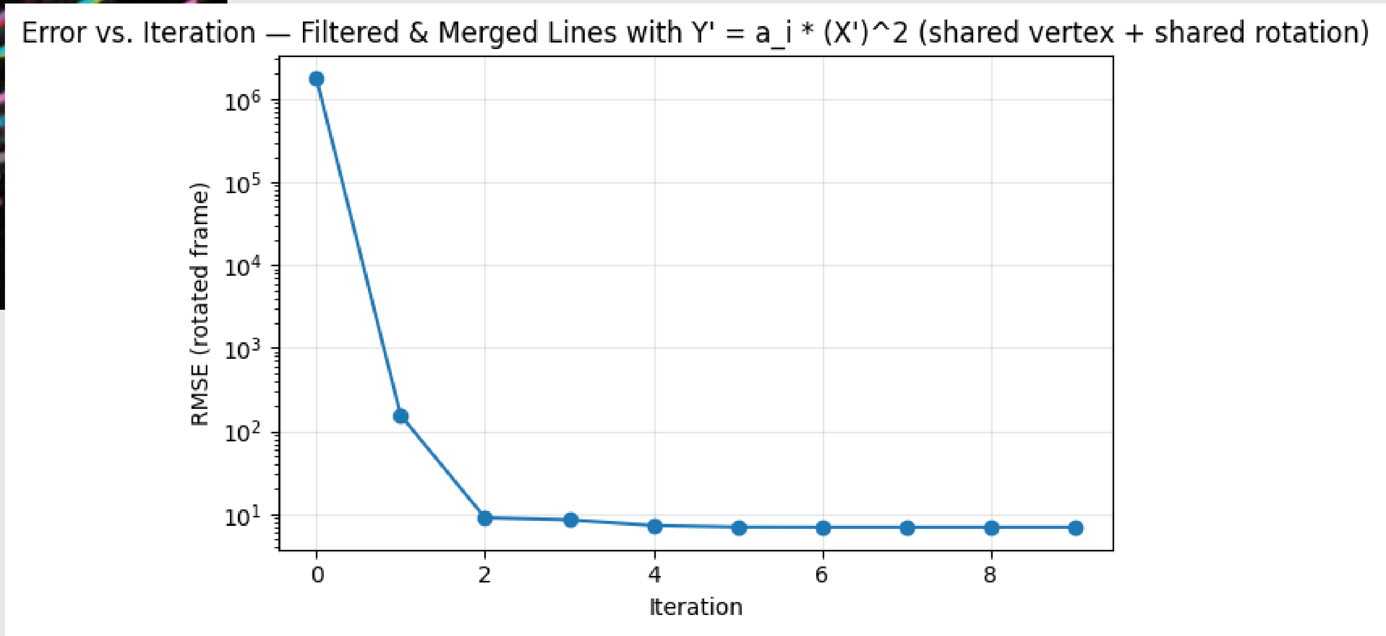


Second merge step – fitting the lines by their slope

STEP 4 – PARAMETERS FITTING

Fitting tilts, rotation, parabola initial spot, radial distortion, and q/m ratios.





STEP 4 – FITTING PARAMETERS

These parameters are fitted based on the extracted lines.

TILTS – GRID SEARCH

01

Two parameters are initiated, which account for tilts around two axes. Other parameters are fitted using these tilts.

RADIAL DISTORTION

02

Two parameters are fitted to minimize distortion.

ROTATION, INITIAL SPOT

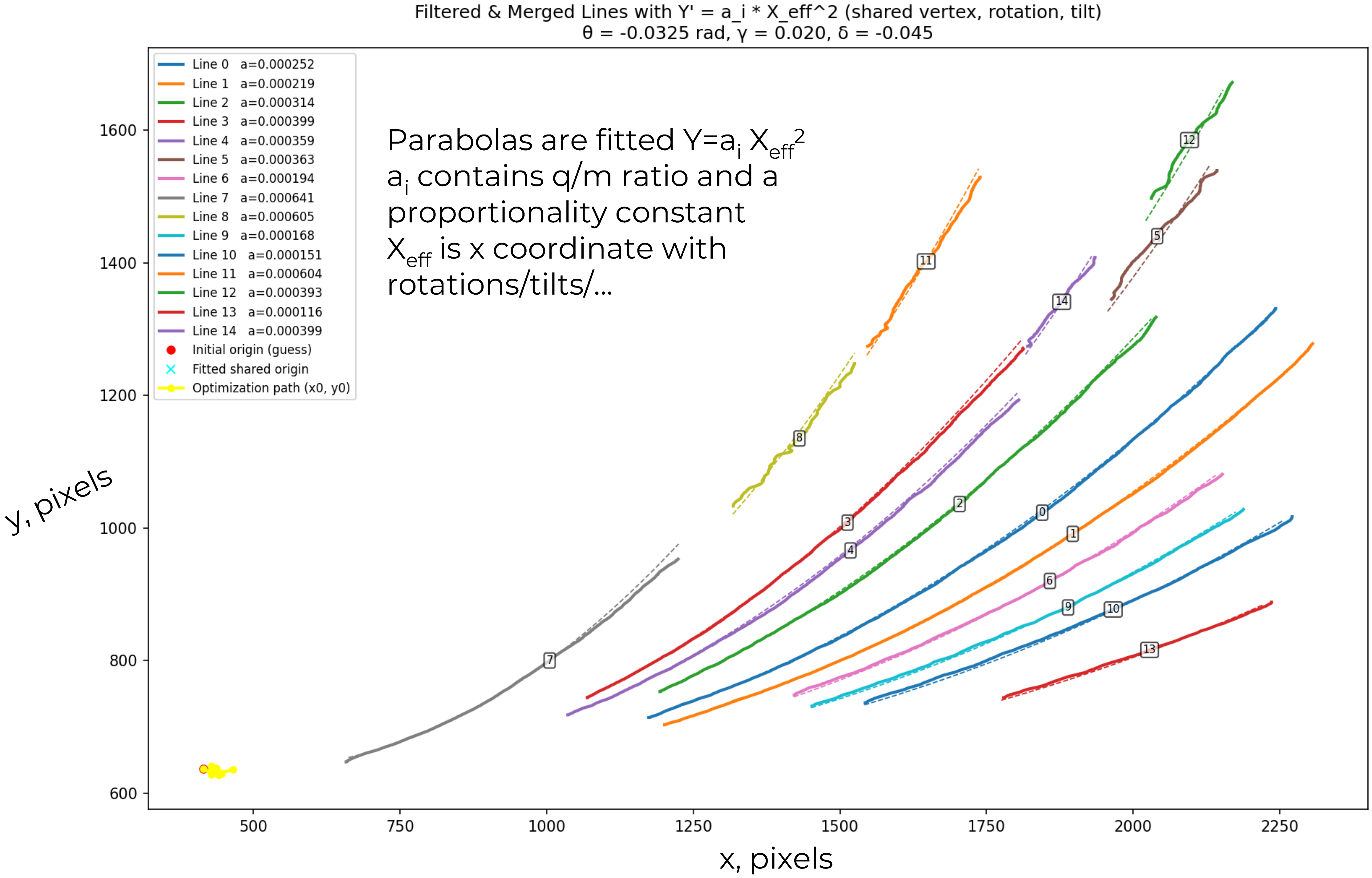
03

Three parameters are fitted to identify overall image rotation and the common origin for all parabolas.

PARABOLAS

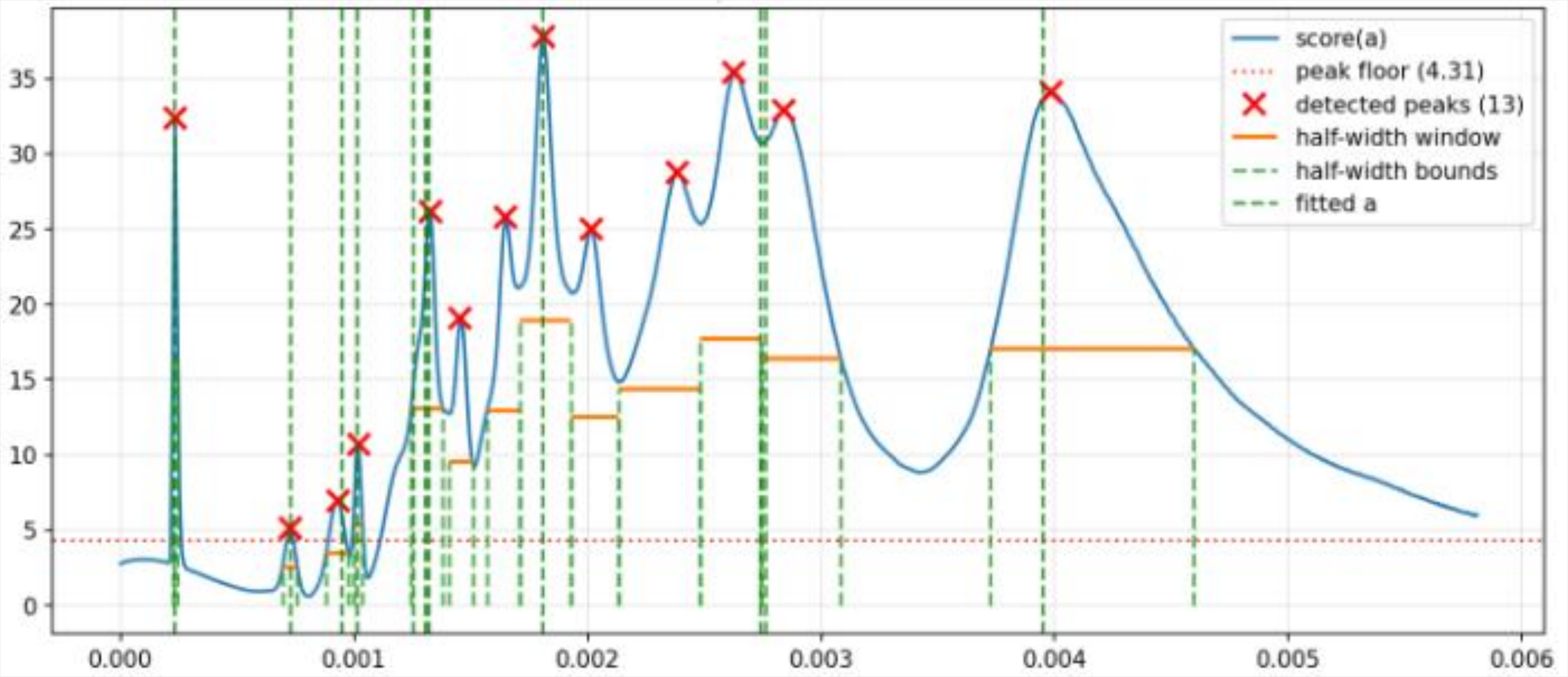
04

With all parameters above fixed, charge to mass ratio is fitted for each line to find exact parabola formulas.


Filtered & Merged Lines with Y' = a_i * X_eff^2 (shared vertex, rotation, tilt)
θ = -0.0325 rad, γ = 0.020, δ = -0.045
Line 0 a=0.000252
Line 1 a=0.000219
Line 2 a=0.000314
Line 3 a=0.000399
Line 4 a=0.000359
Line 5 a=0.000363
Line 6 a=0.000194
Line 7 a=0.000641
Line 8 a=0.000605
Line 9 a=0.000168
Line 10 a=0.000151
Line 11 a=0.000604
Line 12 a=0.000393
Line 13 a=0.000116
Line 14 a=0.000399
Initial origin (guess)
Fitted shared origin
Optimization path (x0, y0)
Parabolas are fitted $Y=a_i X_{eff}^2$
a_i contains q/m ratio and a proportionality constant
X_{eff} is x coordinate with rotations/tilts/…
y, pixels
x, pixels

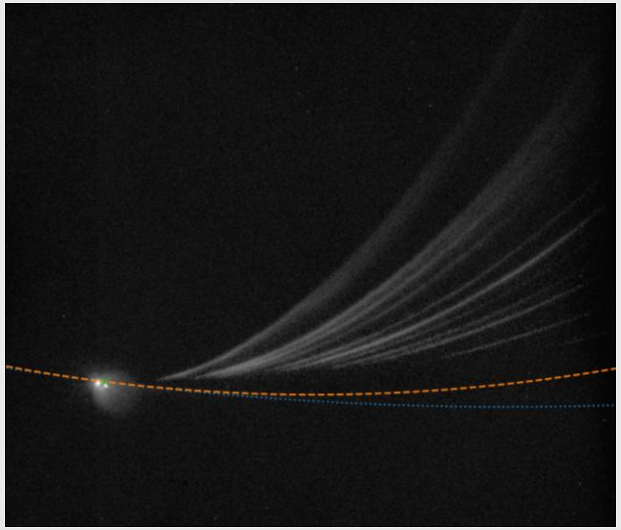
STEP 5 – SPECTRA FOR EACH SPECIES

Integrated intensity

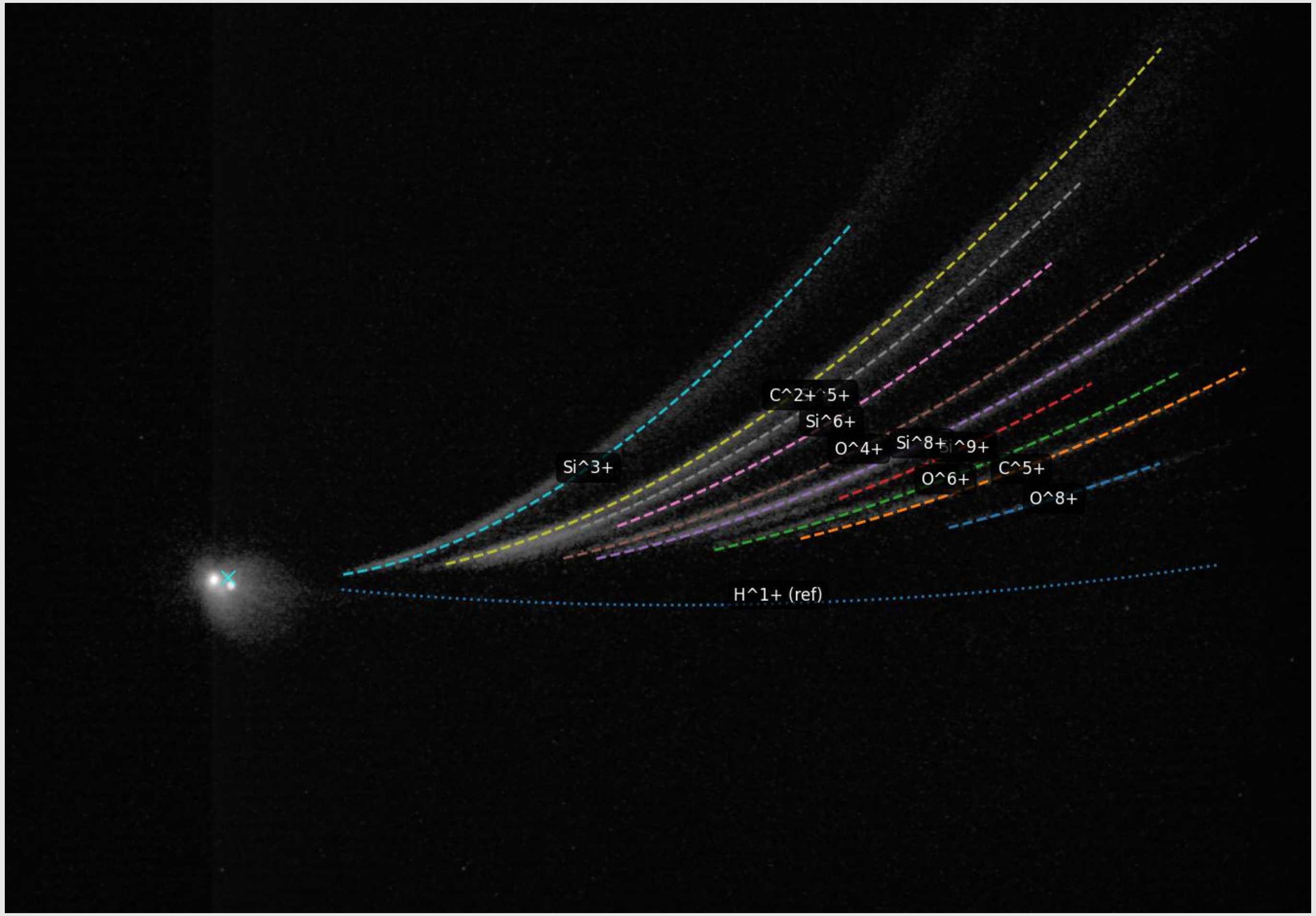


a – constant
containing q/m ratio;
600 points used

STEP 5 – SPECIES CLASSIFICATION

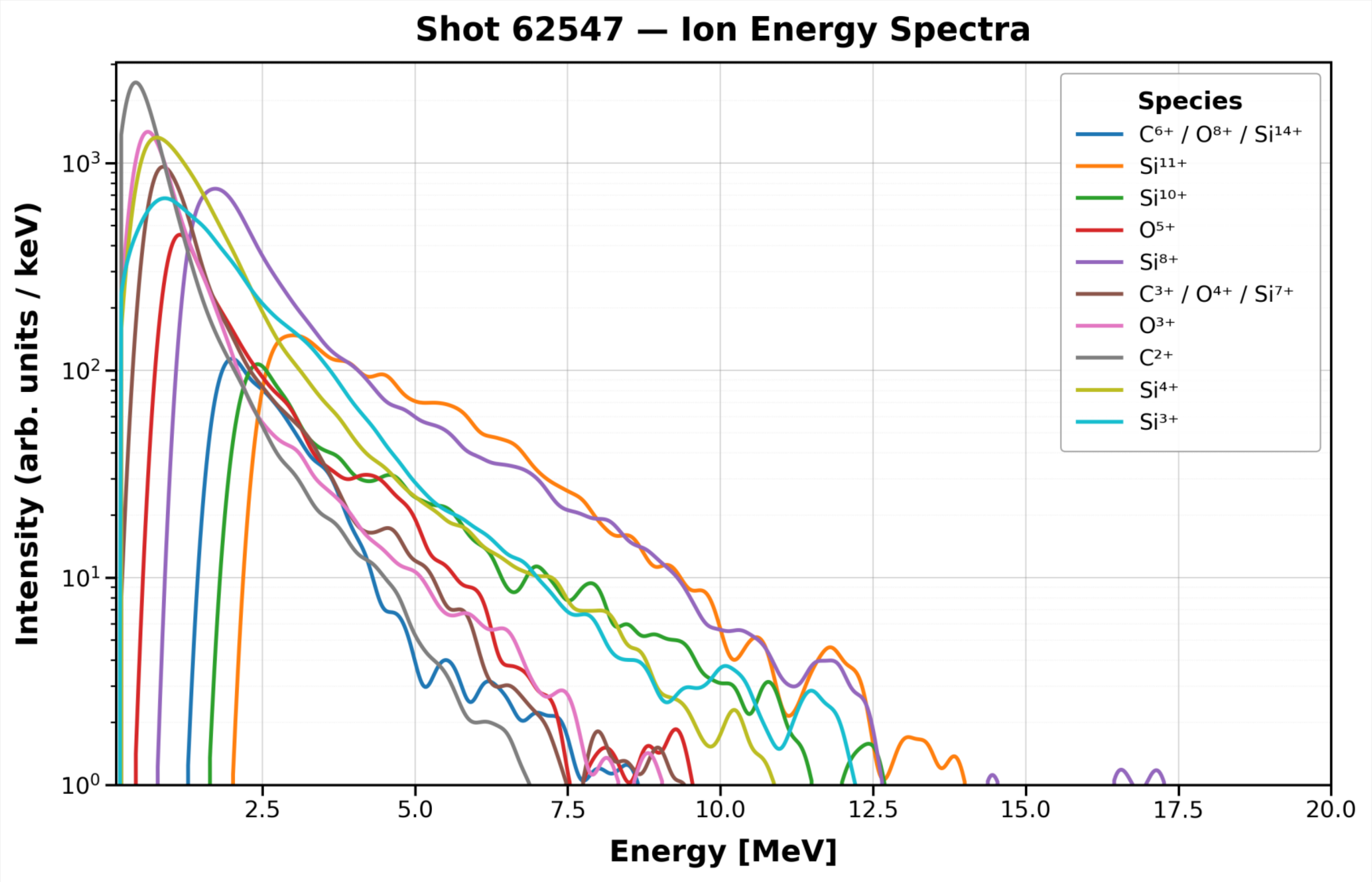


Analytical reference parabola (Hydrogen)

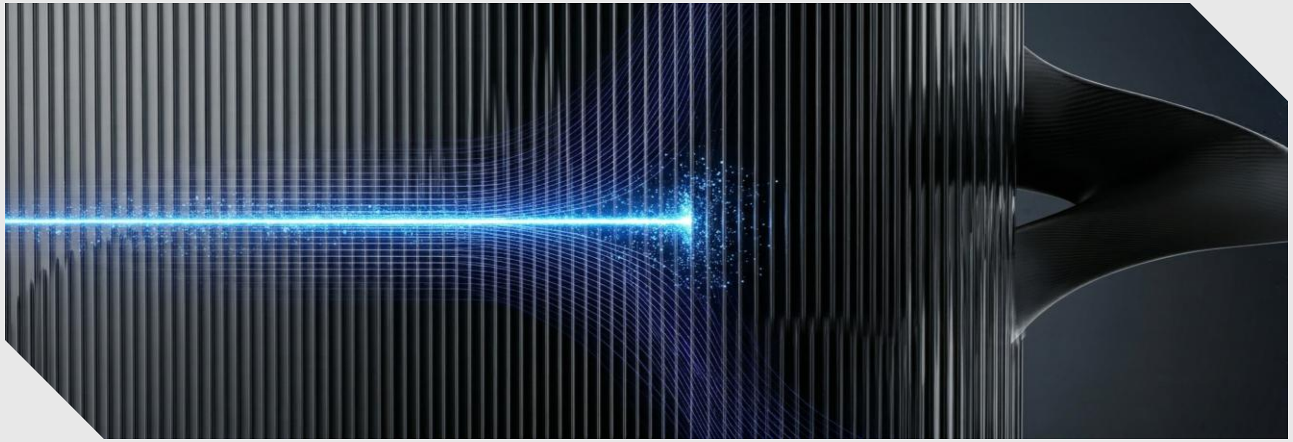


Classified parabolas

STEP 5 – SPECTRA FOR EACH SPECIES



ALGORITHM EVALUATION



01

RMSE

For evaluating fits, we use root mean squared error in pixel value between fitted parabolas and extracted lines.

02

SPECIES

Compare how many species were identified in an image, how many parabolas were unidentified.

03

Q/M ERROR

On synthetic dataset, we can also evaluate error in charge to mass ratio identification.

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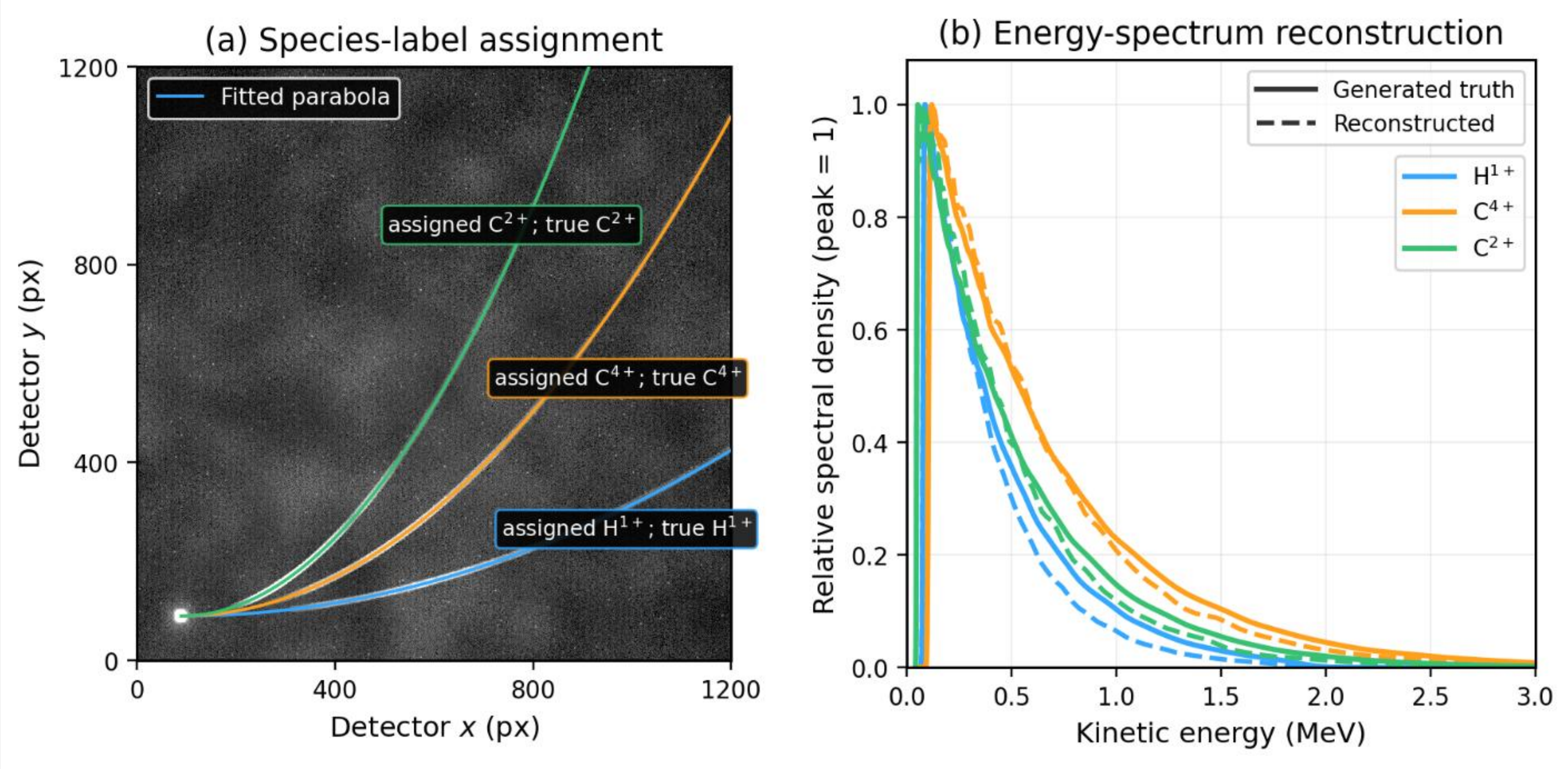
ALGORITHM EVALUATION

On main dataset, on average **9 out of 10** parabolas are found and correctly identified per image. Average error in px is around 1 pixel for clean images and 6 pixels for noisy images - smaller than the width of the parabolas.

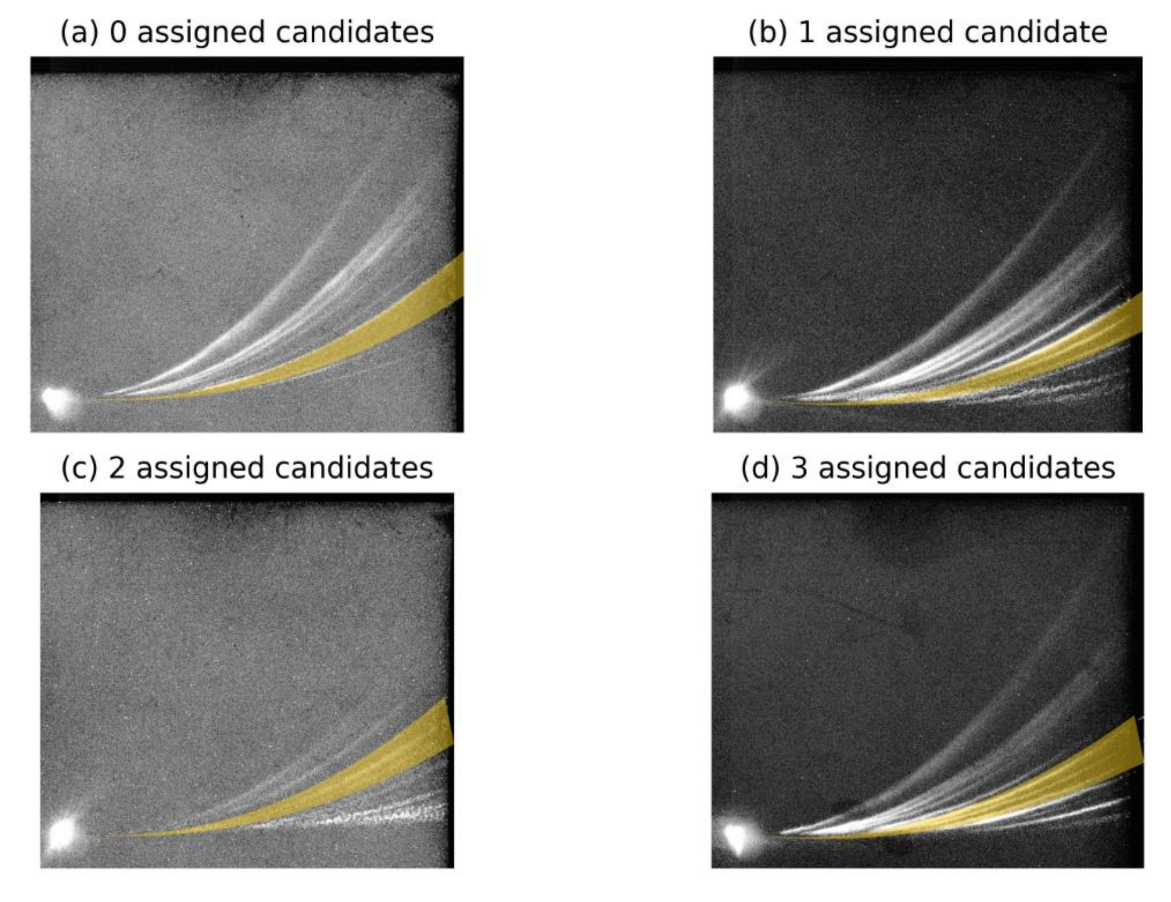
Metric	Transformed clean	Transformed with added noise	Experimental
Images completed	30/30	30/30	76/76
Detected parabolas	196	183	634
Parabolas assigned a candidate mass-to-charge ratio	195 (99.5%)	182 (99.5%)	623 (98.3%)
True positives / false positives / false negatives	188 / 8 / 13	172 / 11 / 29	not available
Mean image-level precision	96.0%	89.8%	not available
Mean image-level recall	93.1%	86.1%	not available
Mean matched-ratio relative m/q error	2.86%	2.62%	not available
Mean image-level RMSE	1.14 px	6.10 px	6.37 px

ALGORITHM EVALUATION

Comparison of the spectra, scaled by the maximum point.



EXPERIMENTAL DATA

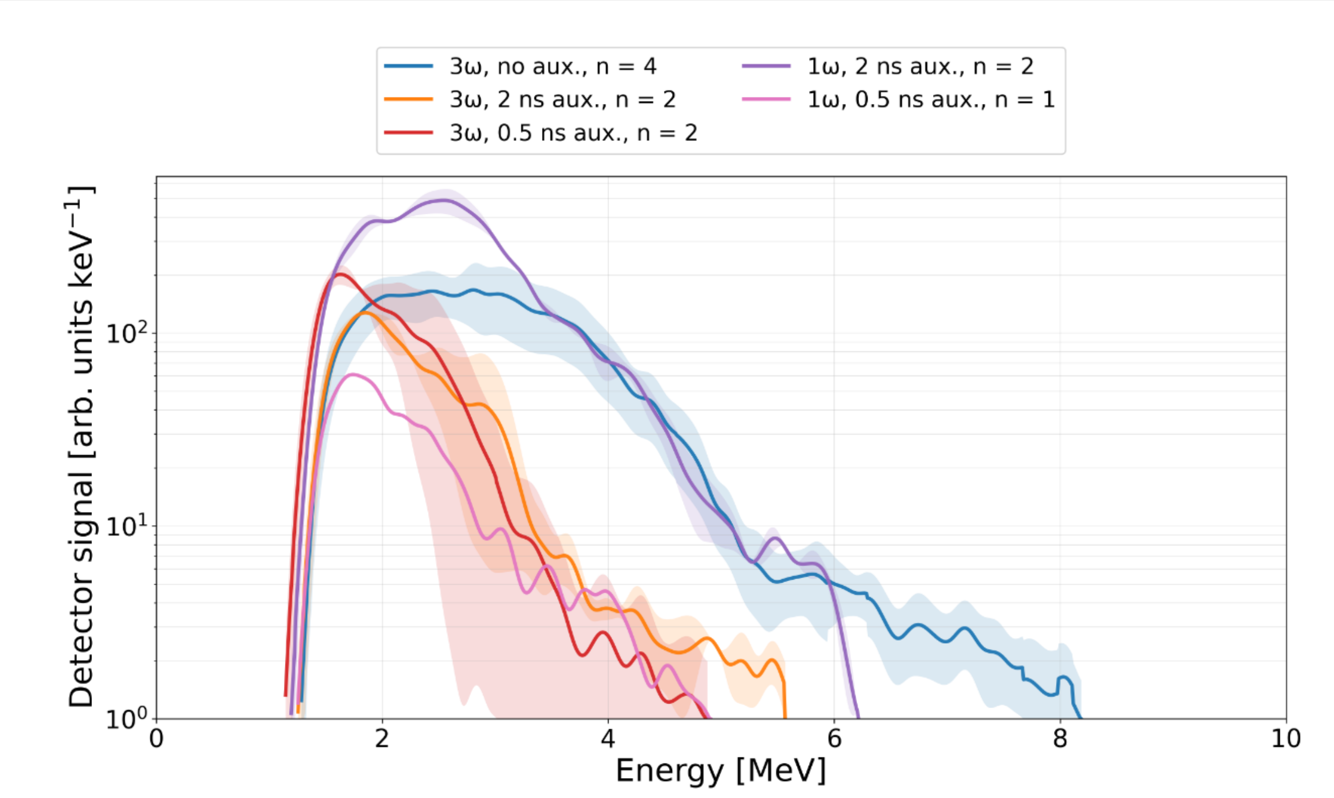


Algorithm was used on a subset from experimental data from PALS – from a pulsed laser experiment on SiO_2 targets, with main setup having two laser pulses: a main beam, and an auxiliary beam, with a time delay between them. Pulses had either fundamental or third harmonic frequencies.

A range of q/m ratios was defined, approximately corresponding to values around Si8+. In this region, a parabola with q/m closest to Si8 was extracted.

DATA ANALYSIS

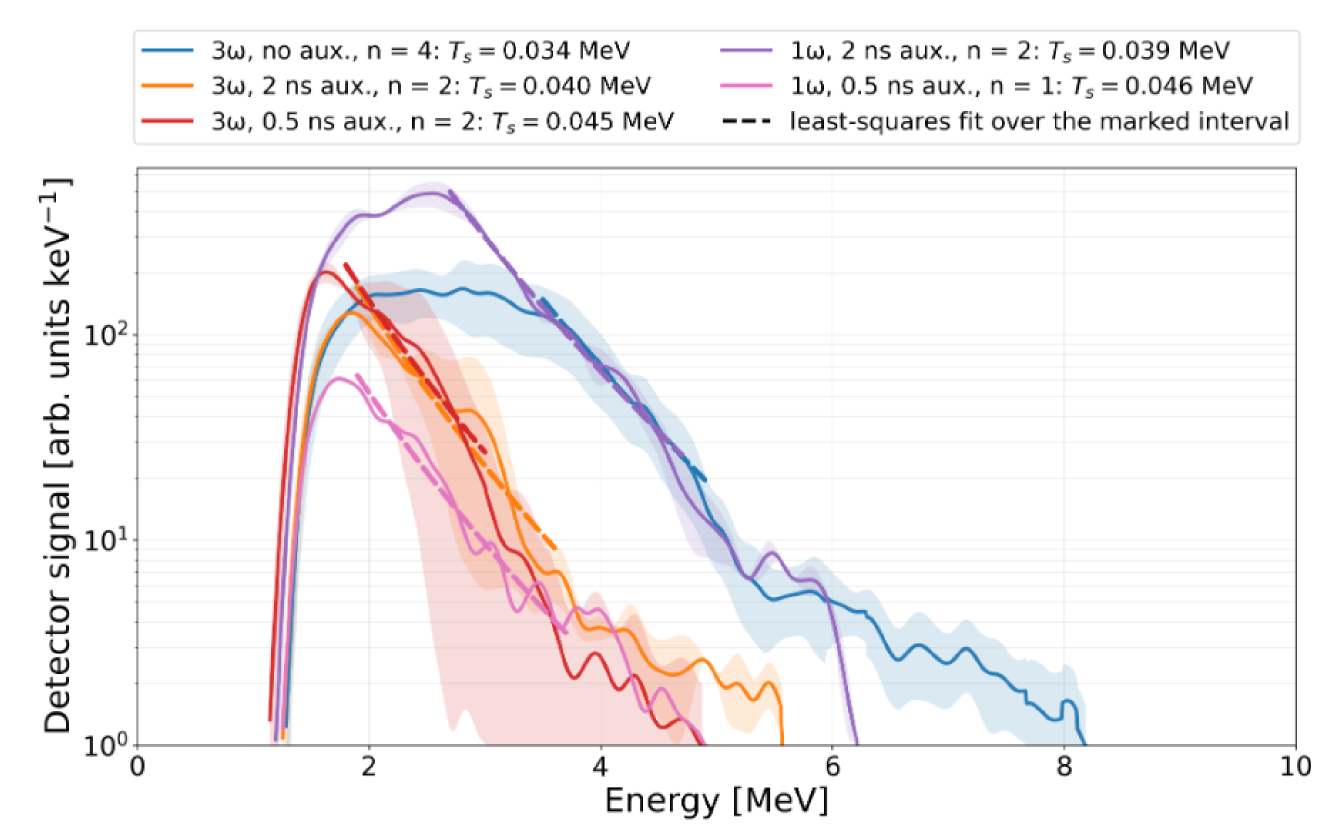
The results for different laser setups were compared, with 3rd harmonic frequency and no auxiliary beam and 1st harmonic frequency, auxiliary beam with 2ns delay producing the most ions.



Condition	Ion-number indicator	Ion-energy indicator [MeV]
3ω, no aux.	3.76 ± 1.20	10.76 ± 3.57
3ω, 2 ns aux.	1.35 ± 0.29	3.01 ± 0.78
3ω, 0.5 ns aux.	1.90 ± 0.53	3.83 ± 1.47
1ω, 2 ns aux.	7.74 ± 0.14	20.05 ± 0.35
1ω, 0.5 ns aux.	0.63	1.39

DATA ANALYSIS

The effective ion temperature was compared for different experimental setups, reaching similar values. Additionally, the cutoff energies differ significantly across the setups.

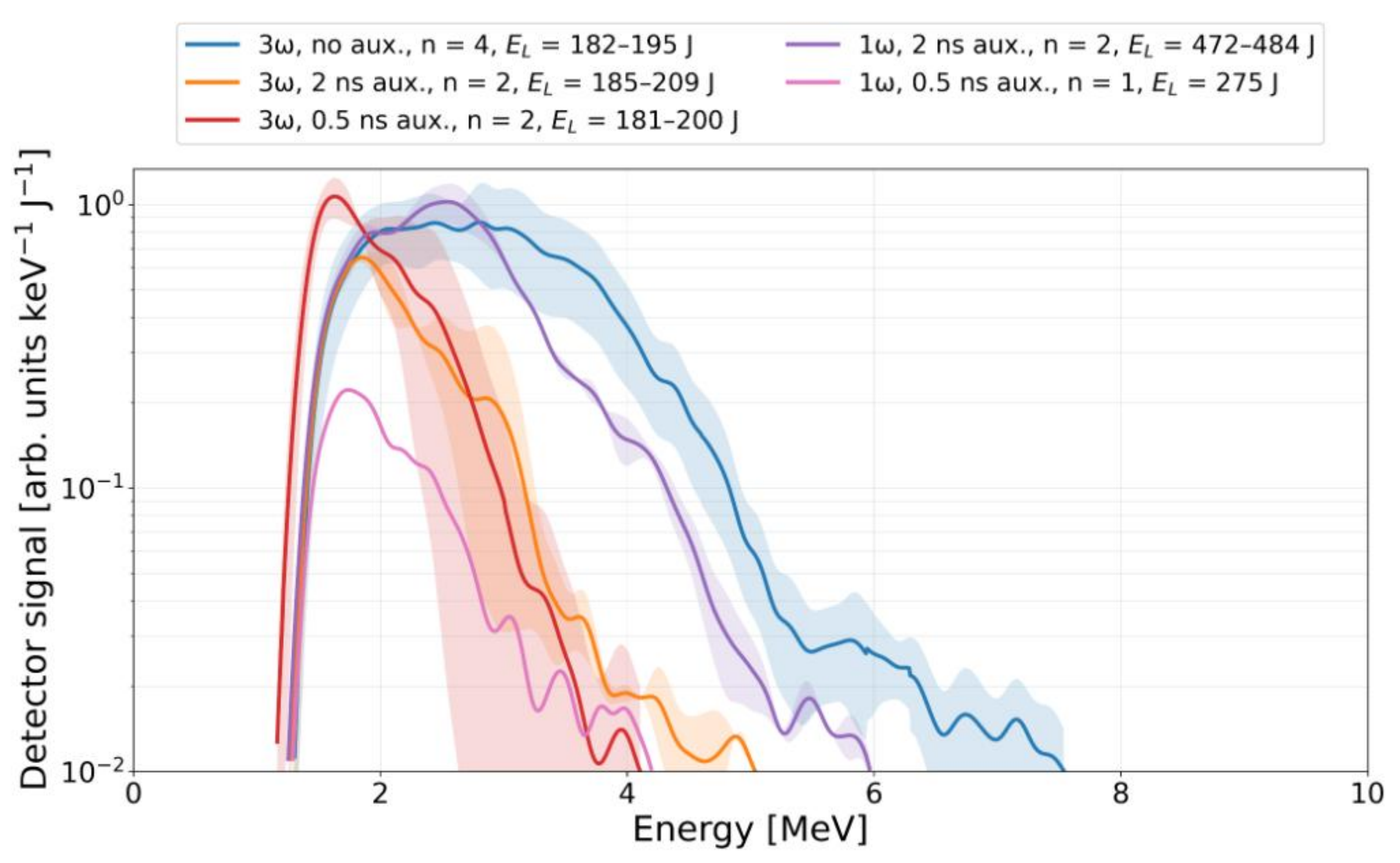


$$\frac{dN}{d\varepsilon_i} \simeq \frac{K_1}{\sqrt{\varepsilon_i T_h}} \exp\left(-\sqrt{\frac{K_2 \varepsilon_i}{T_h}}\right)$$

Setup	T_s [MeV]	Cutoff energy
3ω, no aux.	0.034 (0.006)	8.2
3ω, 2 ns aux.	0.040 (0.007)	5.6
3ω, 0.5 ns aux.	0.045 (0.014)	4.9
1ω, 2 ns aux.	0.039 (0.003)	6.2
1ω, 0.5 ns aux.	0.046 (0.004)	4.9

DATA ANALYSIS

After normalization by laser energy, 3ω without the auxiliary pulse gives the highest detector-signal indicators per joule.

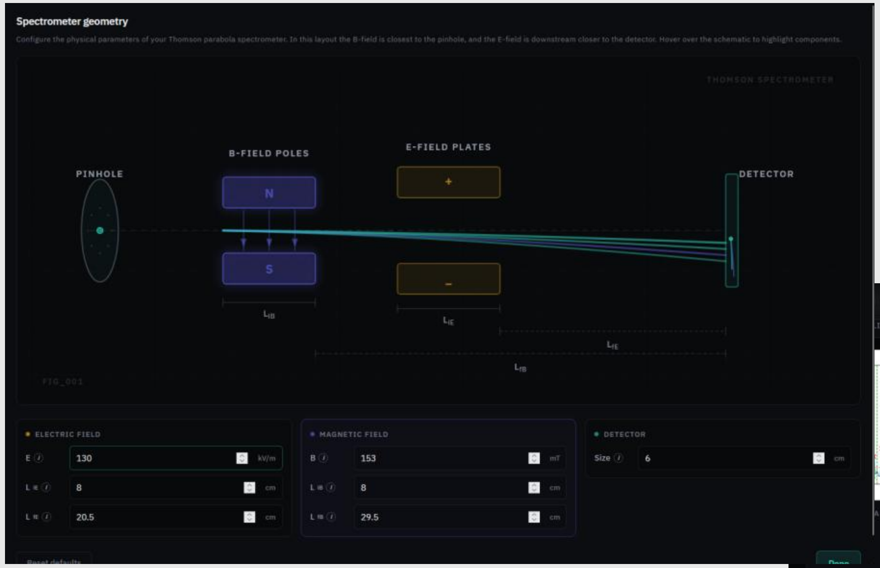


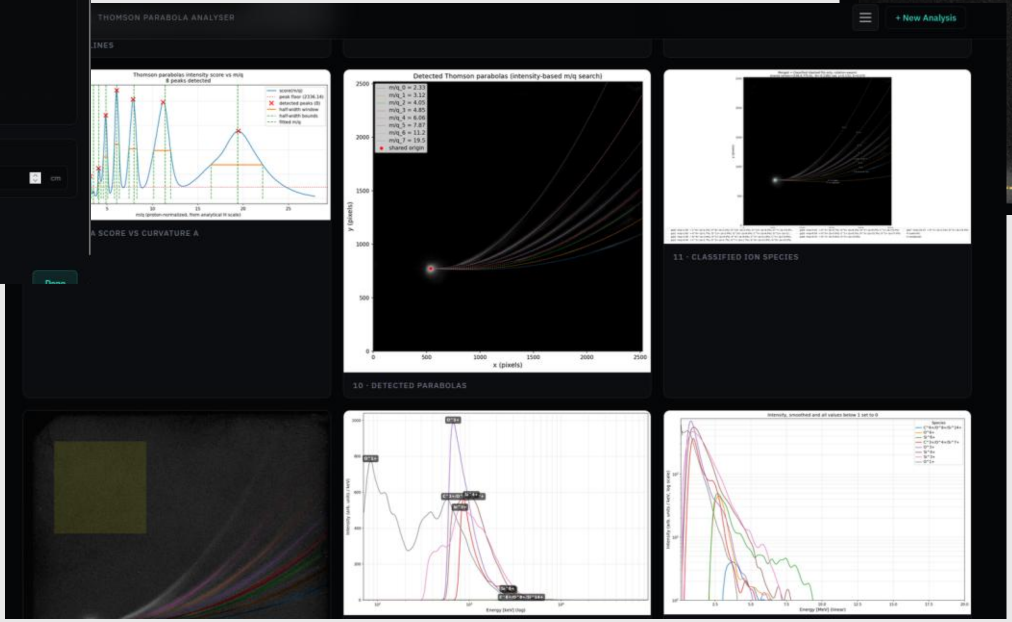
$$I_{0,s} = \sum_j w_{s,j}, \quad I_{1,s} = \sum_j E_{s,j} w_{s,j},$$

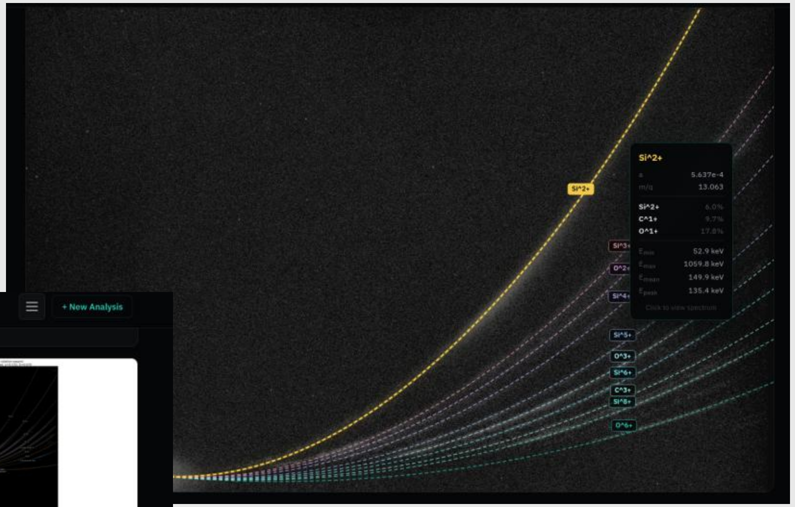
Condition	Ion-number indicator per joule	Ion-energy indicator per joule [MeV]
3ω, no aux.	1.95 ± 0.61	5.58 ± 1.82
3ω, 2 ns aux.	0.68 ± 0.10	1.51 ± 0.30
3ω, 0.5 ns aux.	0.99 ± 0.23	1.97 ± 0.67
1ω, 2 ns aux.	1.62 ± 0.05	4.20 ± 0.13
1ω, 0.5 ns aux.	0.23	0.51

BONUS: A WEBSITE FOR EASE OF USE

https://thomson-parabolas.shelamanov.com/results/d21f39cb-2a78-403f-b49a-aa814887c08f







MAIN ISSUES IDENTIFIED

IDEAL SPECTROMETER 01

The software assumes that the Thomson spectrometer is ideal, with no temporal/spatial shifts and other defects.

NO ABSOLUTE CALIBRATION 02

Amplitudes are relative detector-signal indicators, not calibrated ion yields. Reliable calibration was available only for H.

IDENTICAL Q/M 03

If two different ion species have same q/m, they can’t be reliably separated because of TPS geometry.

SUMMARY AND CONCLUSIONS

Some images and visualizations were created with help of Generative AI.

THOMSON SPECTROMETER
01

We are studying images produced by Thomson spectrometer. It's a device for getting q/m ratios + spectra.

DATA ANALYSIS
02

Analysing detector images is extremely hard and time consuming.

THIS THESIS
03

We developed an algorithm that automates all the steps, and extracts data reliably, mitigating human error.

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FUTURE PROSPECTS

SPECIES IDENTIFICATION 01

Improve fitting, take into account more potential experimental imperfections. Improve species identification.

SIMULATION 02

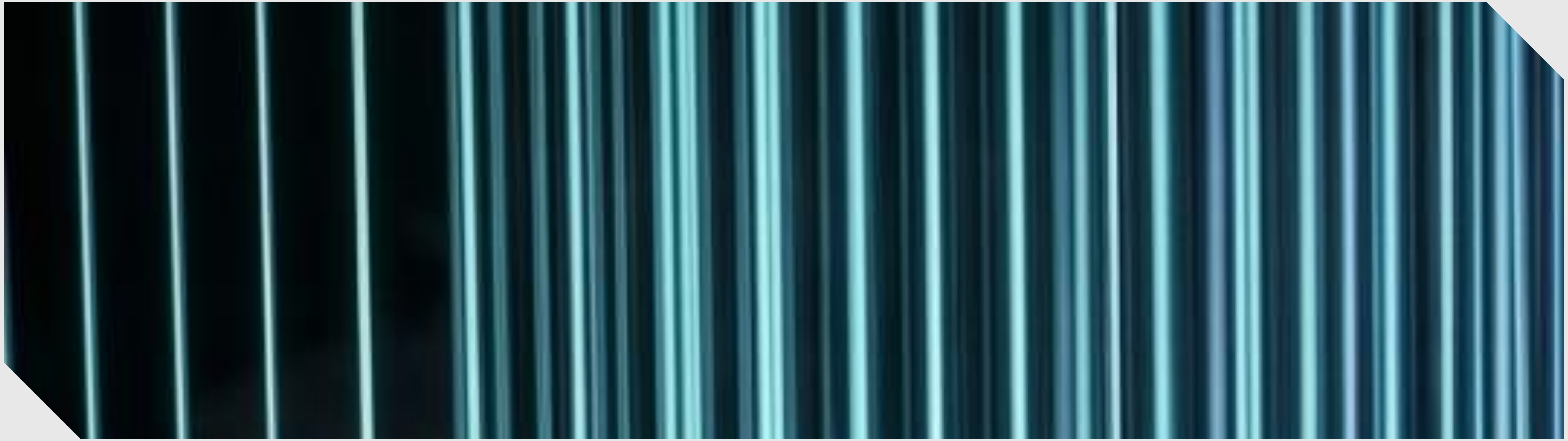
TNSA laser-solid interaction could be simulated using PIC methods.

SYNTHETIC DATA 03

Improve quality of the synthetic data generator, understand principles. Solve an inverse problem: parabolas -> species.

OTHER LABORATORES 04

Reach out to other laboratories. Ask them for their Thomson spectrometer images, use them to make pipeline more robust.



THANK YOU!

Reach out if there are any questions:
SHELAART@CVUT.CZ

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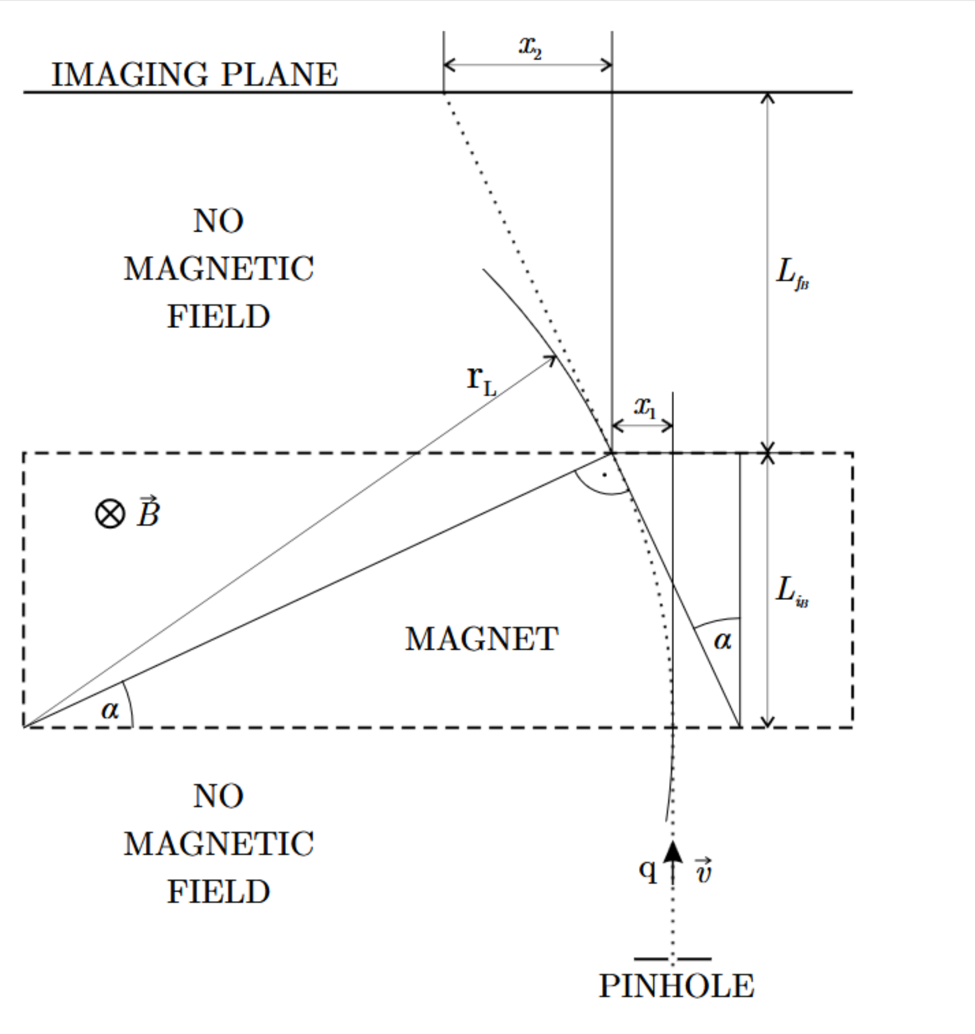
THOMSON PARABOLA CALCULATIONS

$$x = \frac{qBL_{i_B}}{mv}\left(\frac{L_{i_B}}{2} + L_{f_B}\right)$$

$$y = \frac{qEL_{i_E}}{mv^2}\left(\frac{L_{i_E}}{2} + L_{f_E}\right)$$

$$y = \frac{q}{m} \cdot \frac{EL_{i_E}\left(\frac{L_{i_E}}{2} + L_{f_E}\right)}{B^2 L_{i_B}^2 \left(\frac{L_{i_B}}{2} + L_{f_B}\right)^2} \cdot x^2$$



*Diagnostics Systems for Laser-Accelerated Particle Beams - Jan Prokupek

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SPECTRA CALCULATIONS

$$x = \frac{qBL_{i_B}}{mv}\left(\frac{L_{i_B}}{2} + L_{f_B}\right)$$

$$v = \frac{qBL_{i_B}}{mx}\left(\frac{L_{i_B}}{2} + L_{f_B}\right)$$

$$\mathcal{E} = \frac{1}{2}mv^2.$$

We have exact formulas for x coordinate. From it, we can calculate velocity, and from velocity we can calculate energy. Thus we get dependence of energy on coordinate.

x - coordinate on the image.