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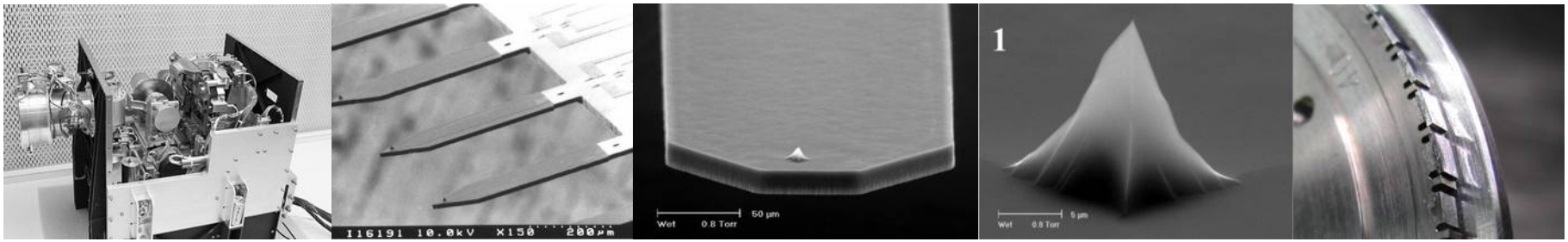
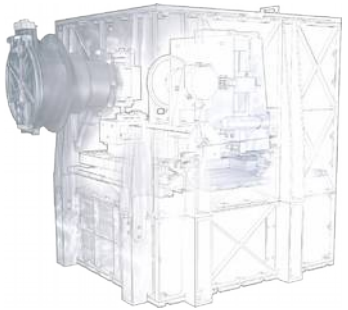
Micro-Imaging Dust Analysis System



Cometary dust at the nanometre scale
Results from the MIDAS atomic force microscope on Rosetta

Mark S. Bentley



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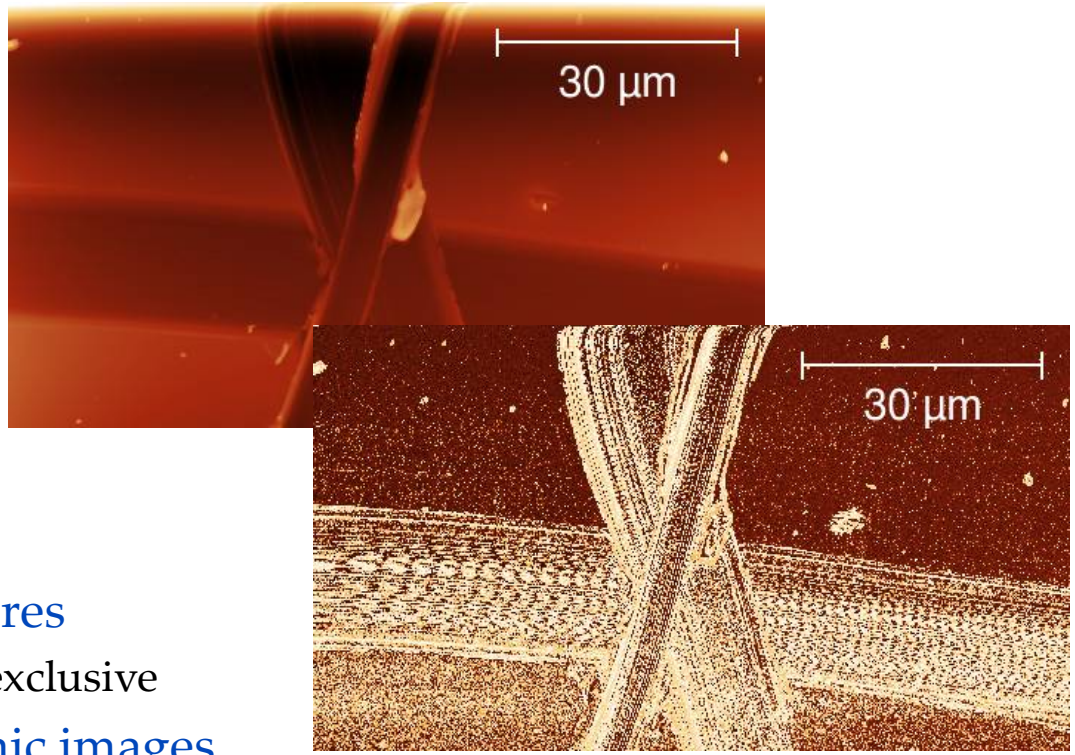
What is MIDAS?

- MIDAS consists of:
  - dust collection and handling system
  - Atomic Force Microscope (AFM)
- Why AFM?
  - analysis of particles < diffraction limit
  - no sample preparation required
    - but strong limitations on sample size
  - relatively robust
- Dust collected during passive exposures
  - collection and scanning and mutually exclusive
- Data are nm-resolution 3D topographic images
  - other modes: phase imaging, magnetic force microscopy



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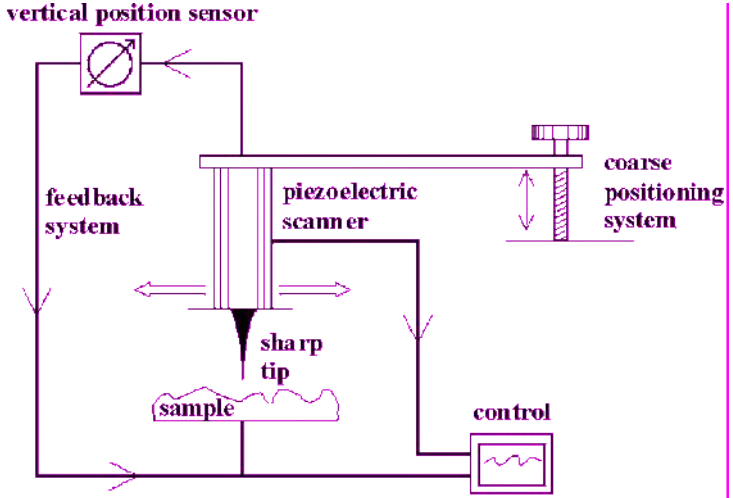
What is AFM?

- A sharp (~10 nm) tip is mounted on an oscillating cantilever
- Various forces act on the tip as it moves towards the sample
- Cantilever frequency / amplitude responds to these forces
- The tip is rastered over the sample to build a 3D image



Parameter	Performance
Lateral resolution	3.8 nm (open loop) 1.4 nm (closed loop)
Height resolution	0.16 nm
Max height	~8 µm
Scan field	min: ~1 µm, max: ~100 µm
Image size	32 x 32 – 512 x 512
Working modes	Contact and dynamic (tapping), magnetic, phase

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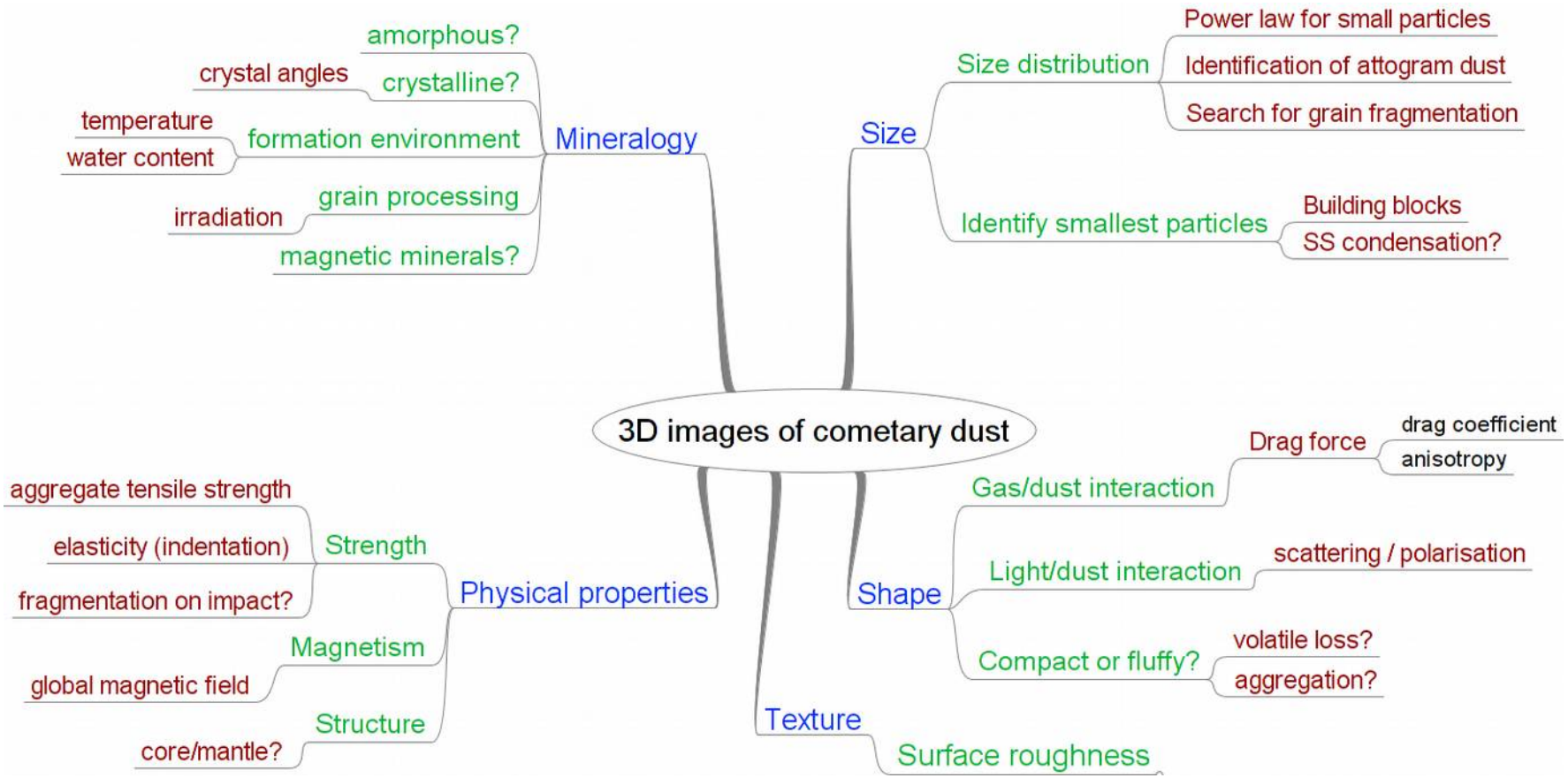
Science with MIDAS



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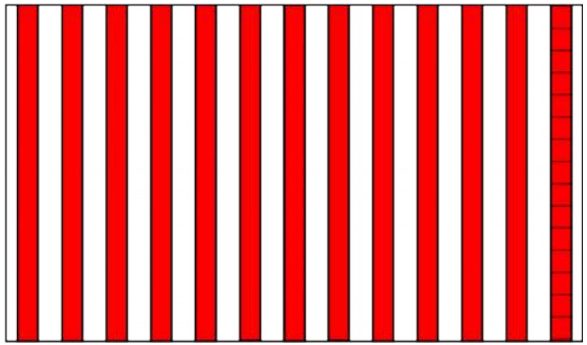
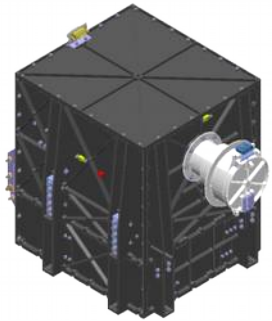
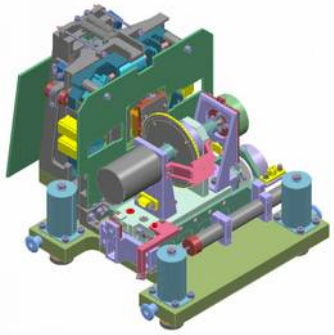
MIDAS vs a regular AFM



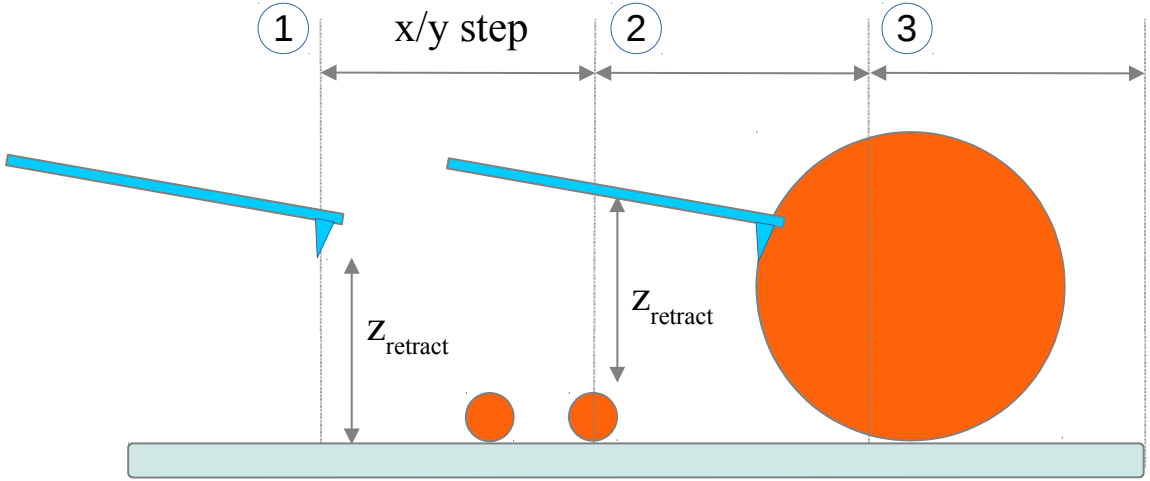




1.4 x 2.4 mm

61 available

3 calibration



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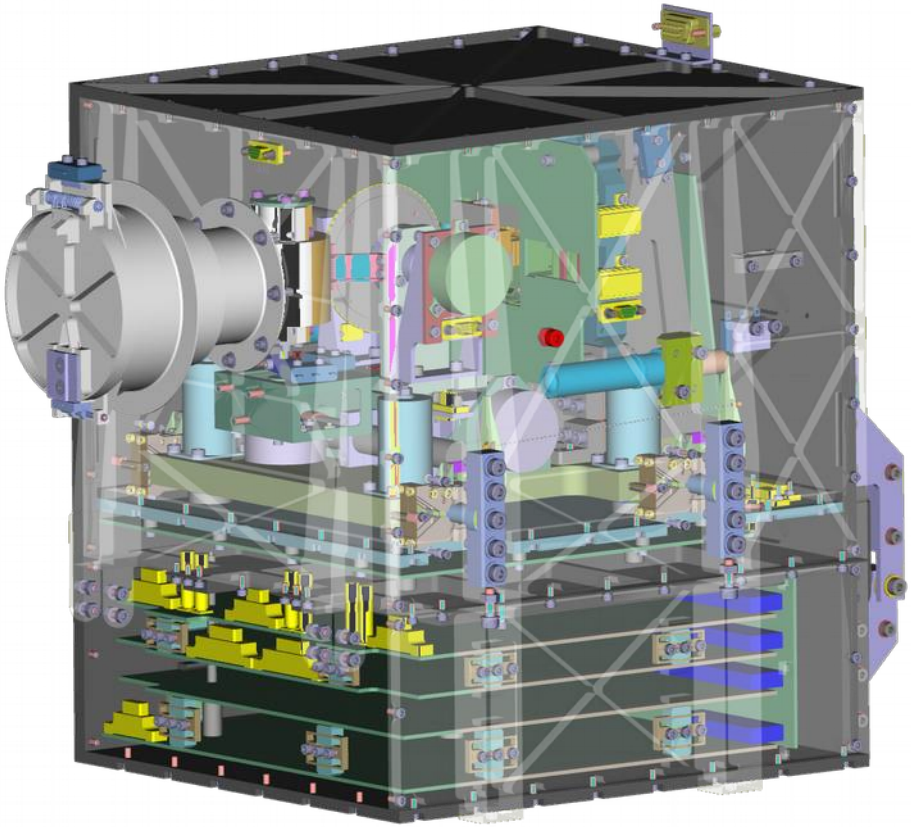
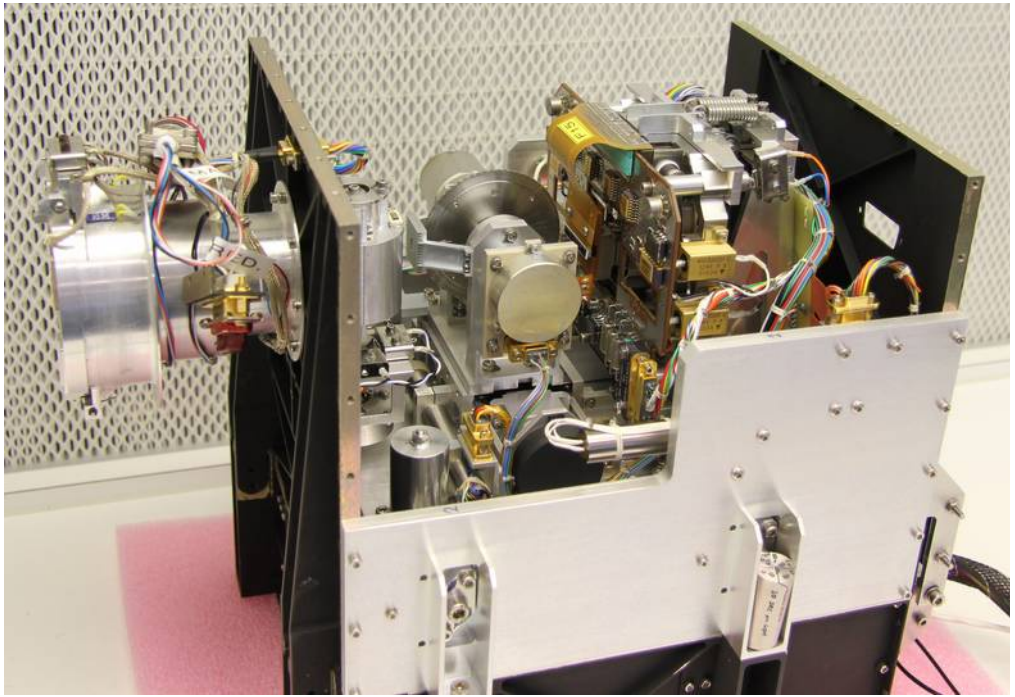
The instrument





Total mass: 8180 g, Peak power: 18.3 W

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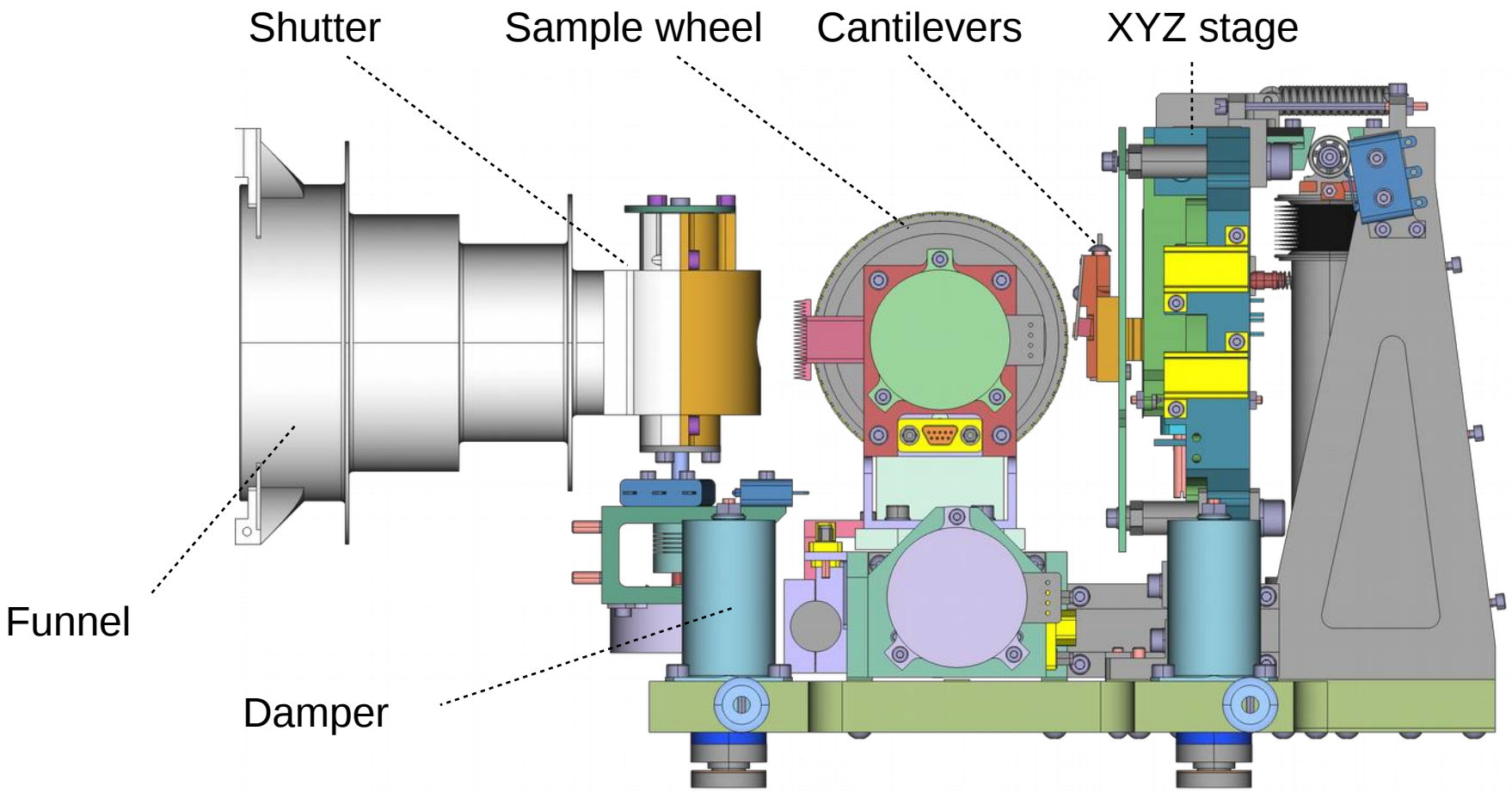
The instrument



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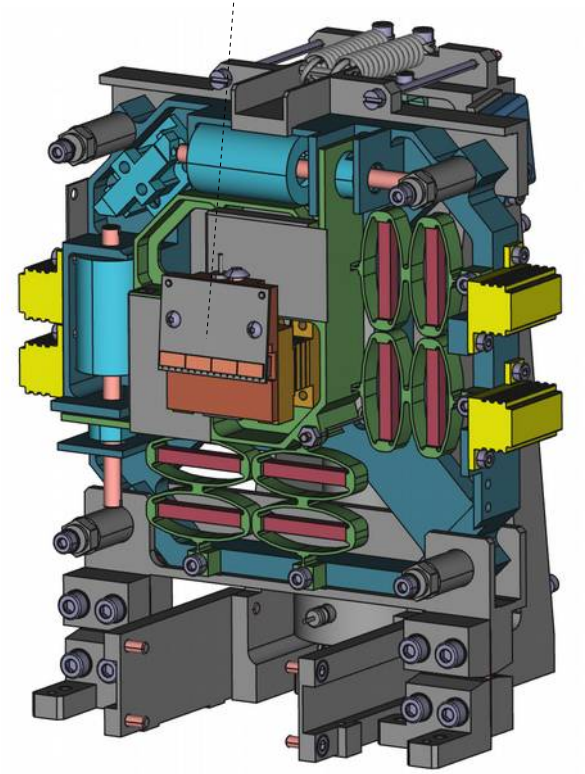
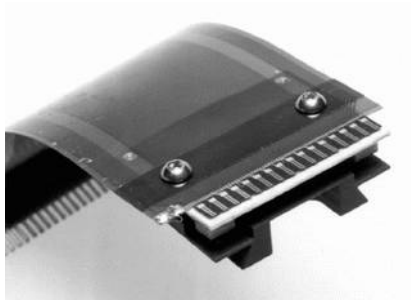
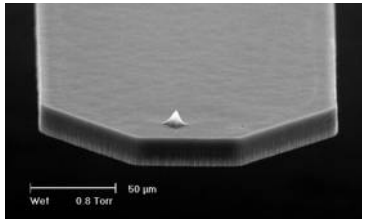
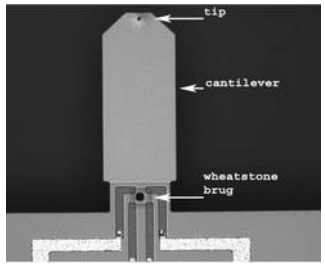
The instrument

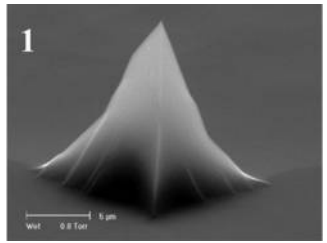
Cantilevers

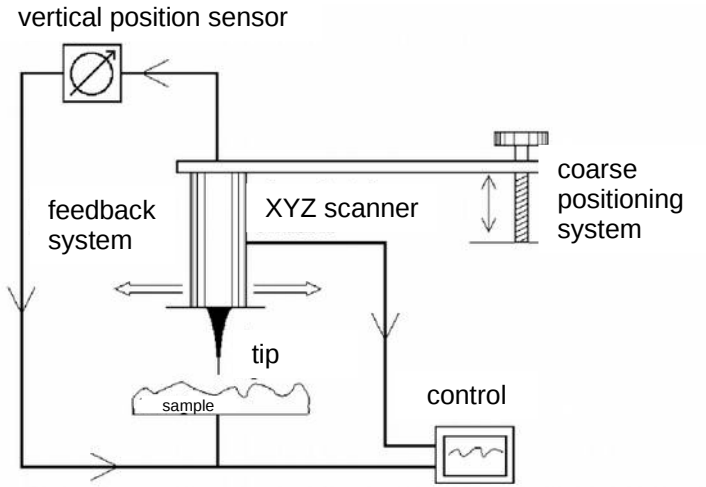




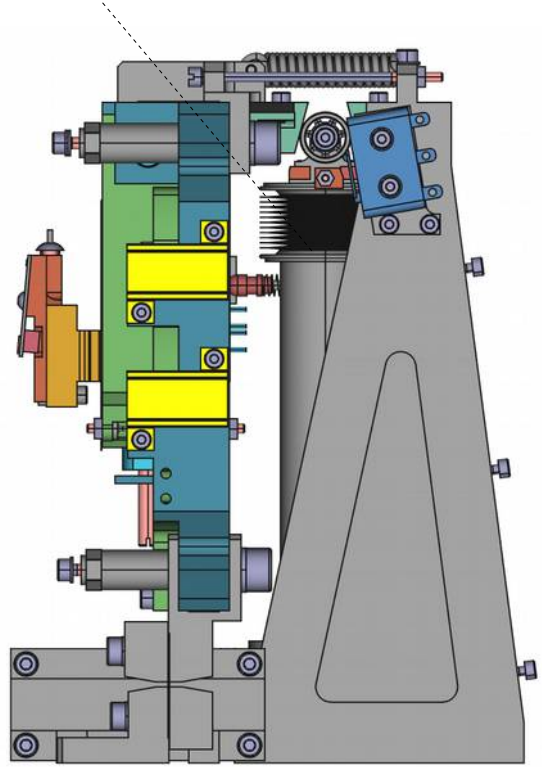








Approach stage



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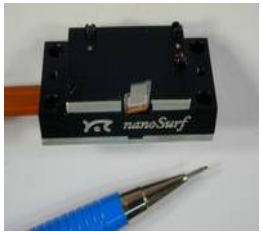
History of MIDAS and AFM

AFM invented – 1986
Atomic resolution – 1987
1st commercial AFM – 1989

Micro-fabricated tips – 1991
Tapping mode commercialised – 1993
Phase imaging – 1999

Theory ~ 2000
Phoenix Mars AFM launched – 2007
Phoenix operations – 2009



1980
1990
2000
2010
2020

1994 – MIDAS conceived
1995 – Proposal submitted

2001 – FM delivery
2003 – Refurbishment in Kourou
2004 – Launch and commissioning

2014 – Re-commissioning, pre-scans
2015 – Prime mission
2016 – Extended mission

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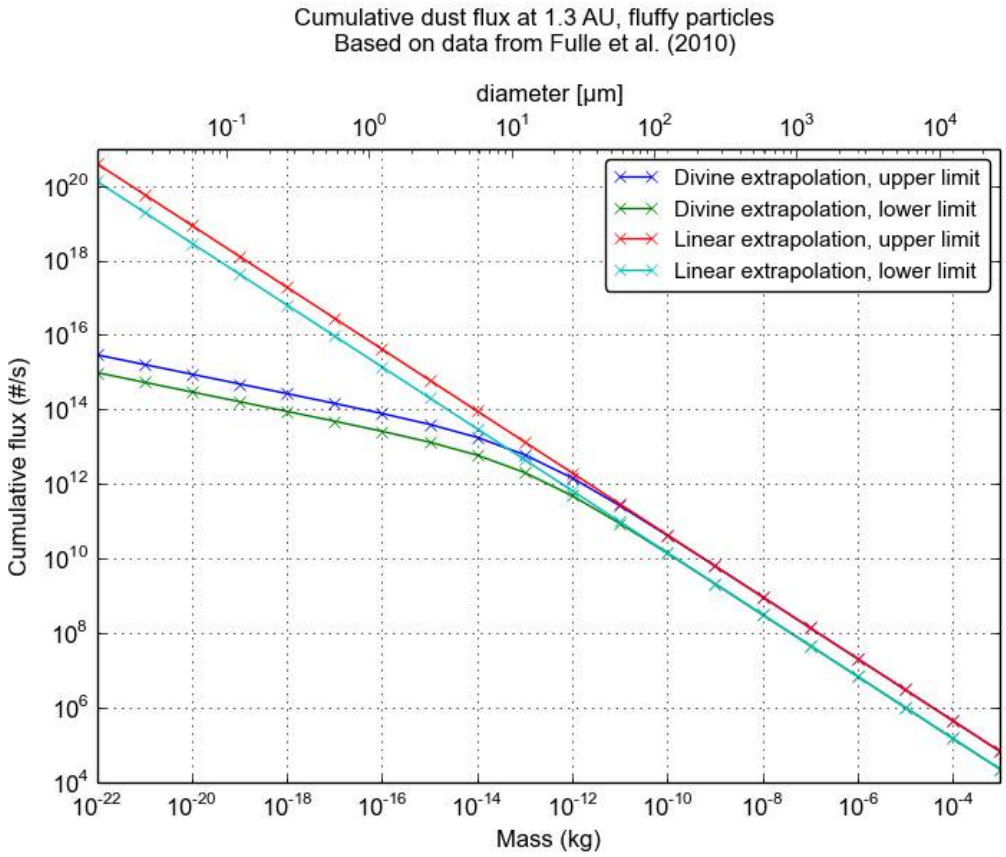
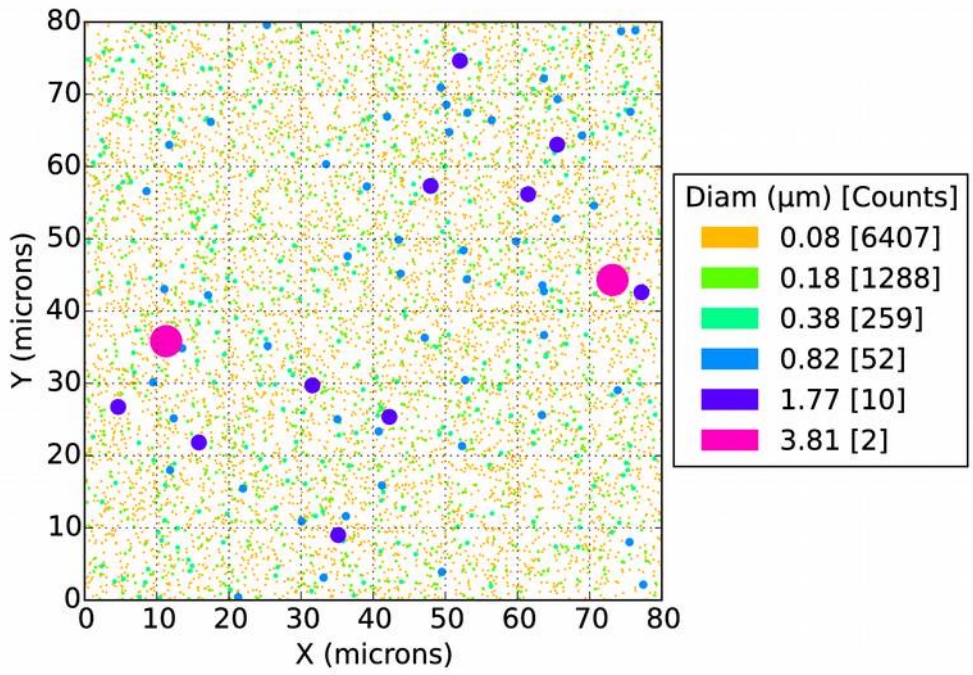
Expectations and scan strategy





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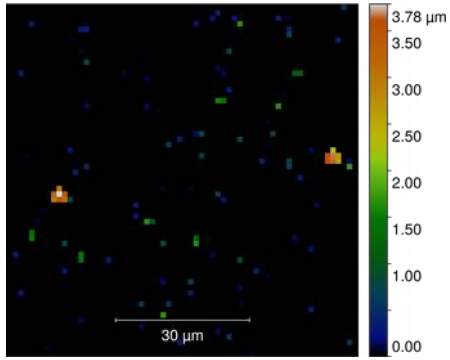
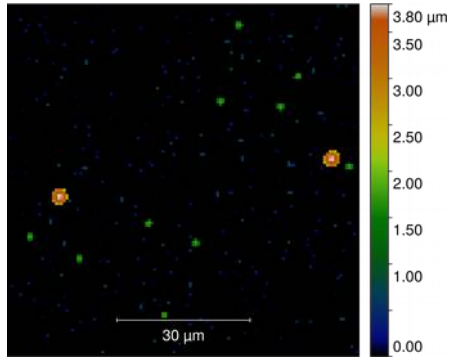
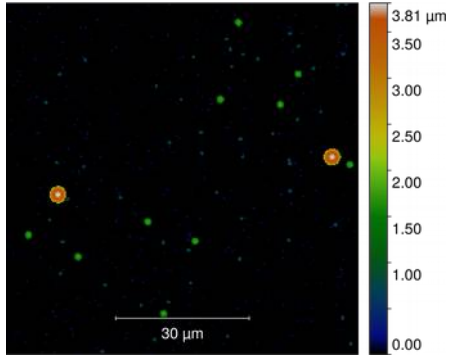
Expectations and scan strategy



64 x 64



128 x 128



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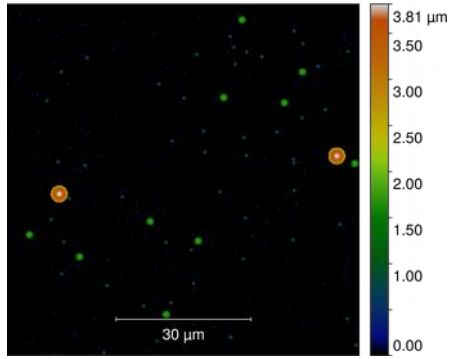

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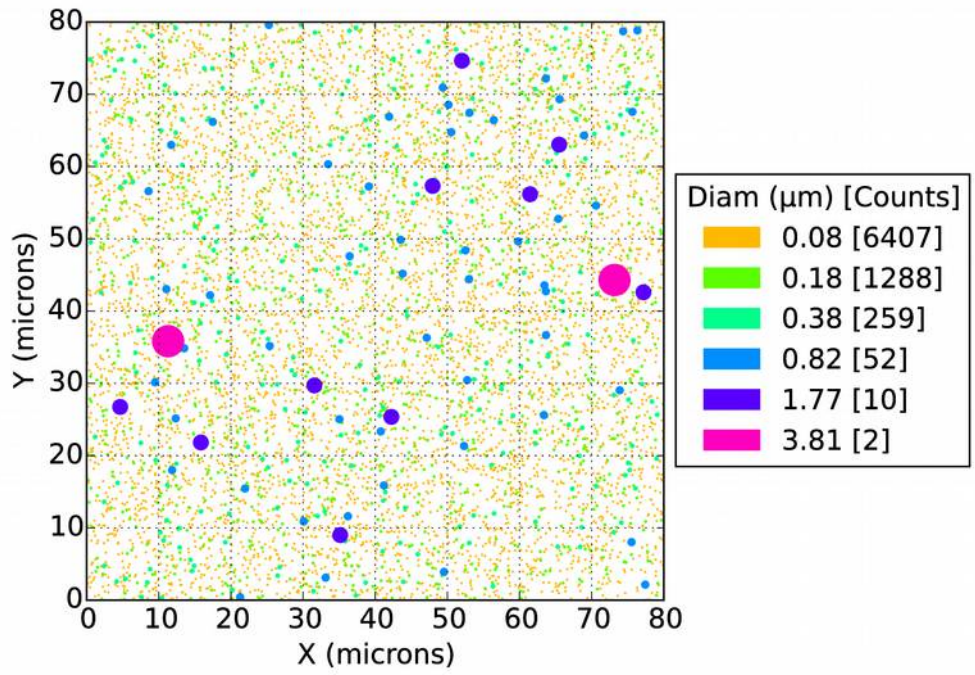

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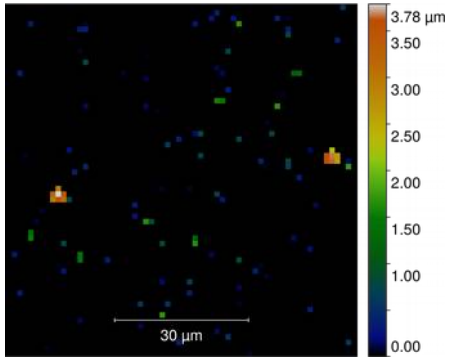
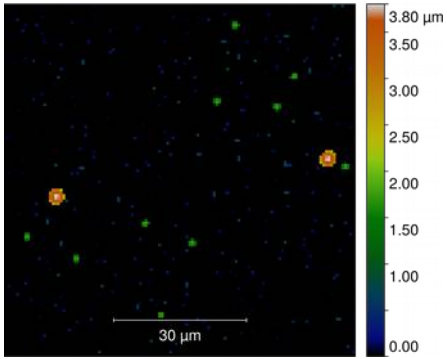
Expectations and scan strategy



64 x 64



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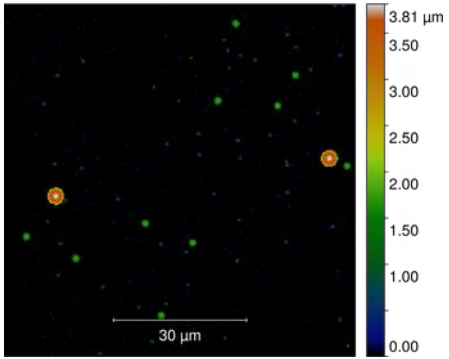

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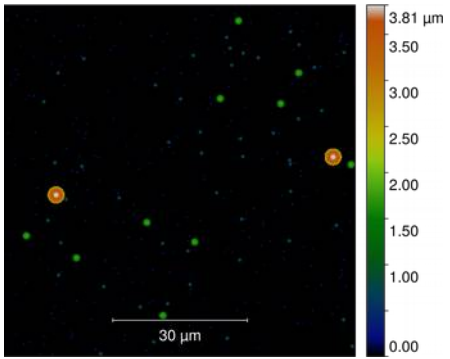

512 x 512

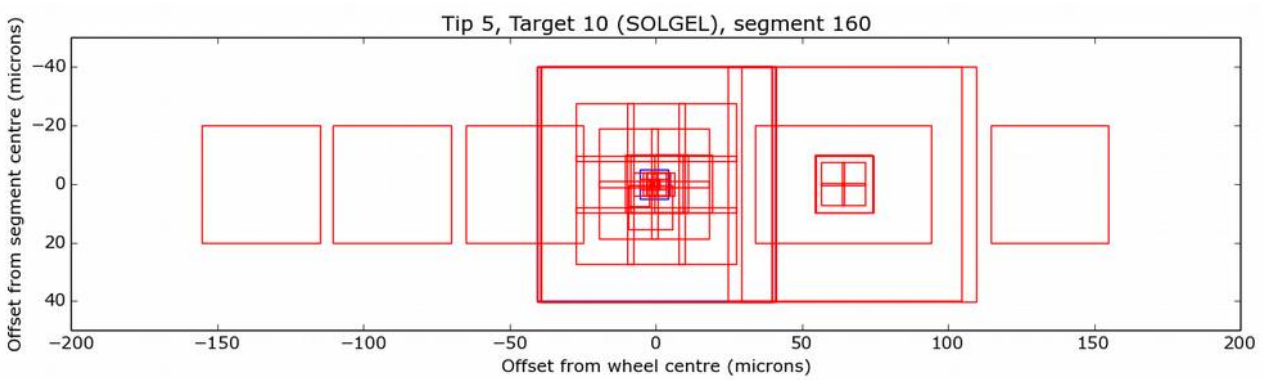

Image size (pix)	*Step size (nm)*	*Duration (hh:mm:ss)*
64 x 64	1250.9	4:42:38
128 x 128	625.5	9:39:15
256 x 256	312.7	20:14:00
512 x 512	156.4	44:10:04

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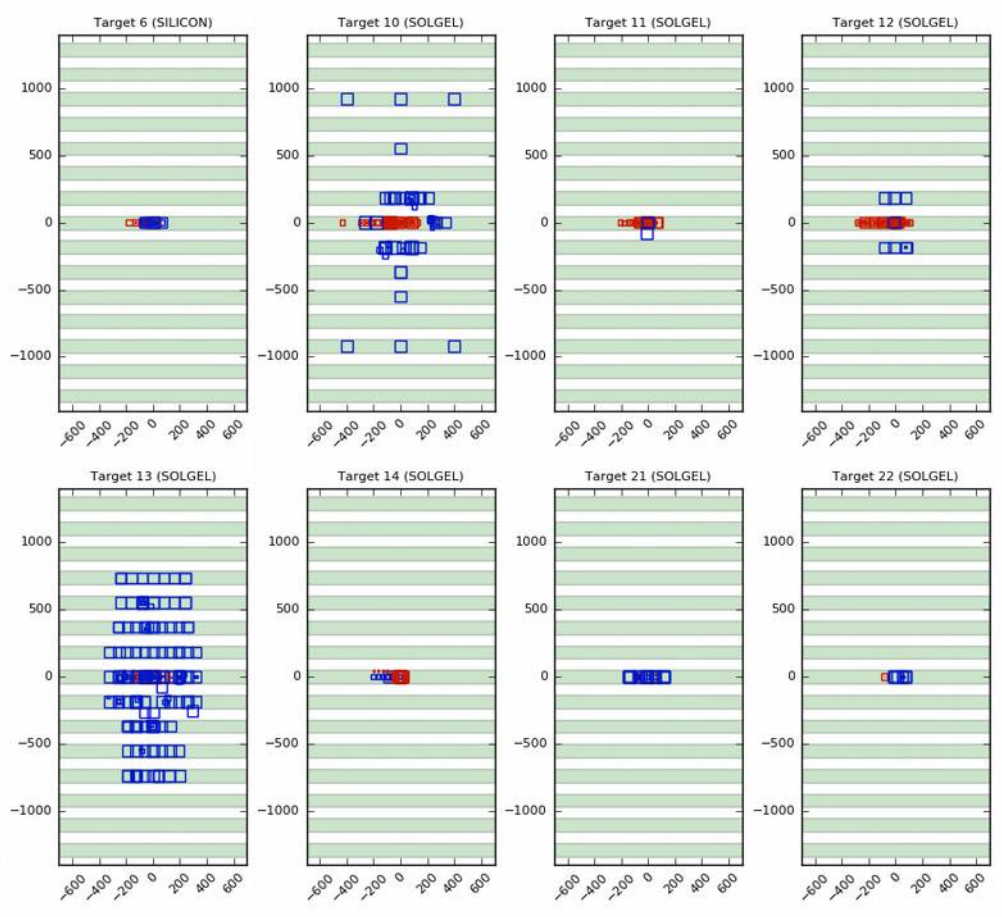
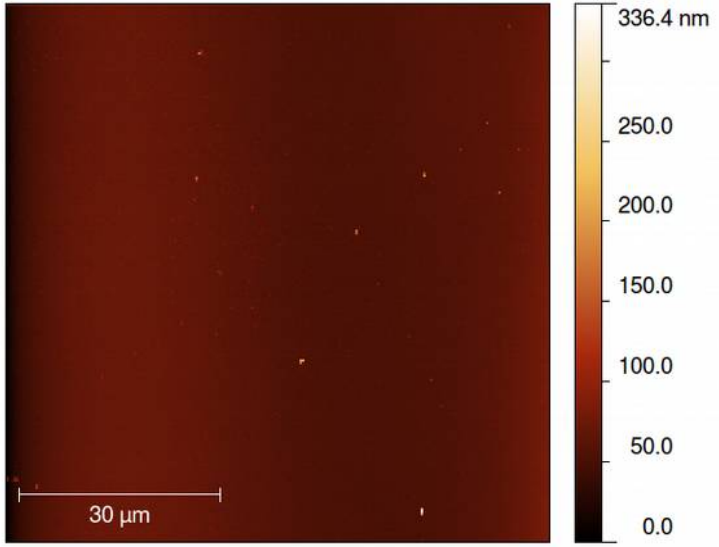
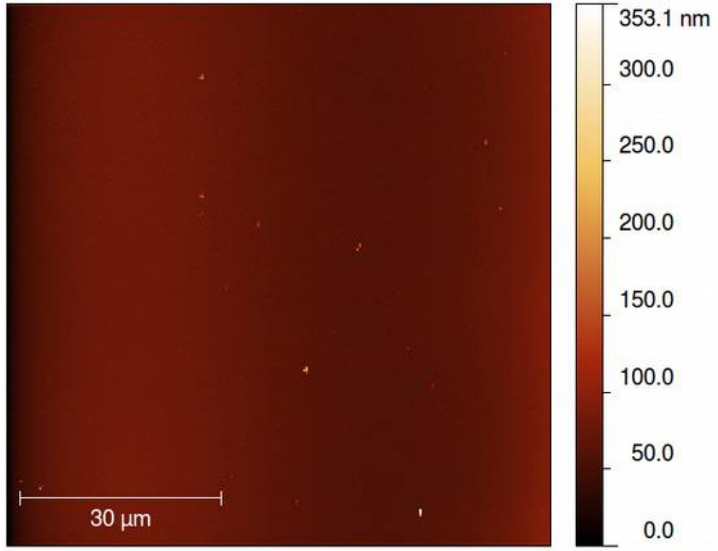
Exposed target coverage



Please wait...

- First exposure of 4 days in mid September 2014
  - no obvious new particles
  - contamination is clear (but also useful for image registration)
    - before and after scans critical!





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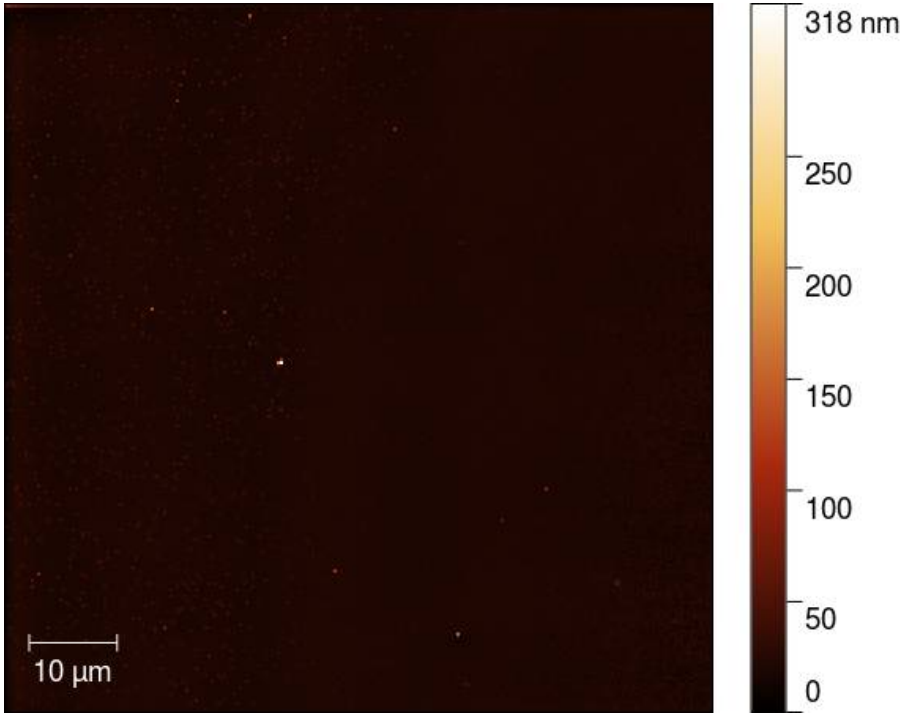
First contact

SCAN_MD_M009_S027_2014-11-05T173245Z_TGT10



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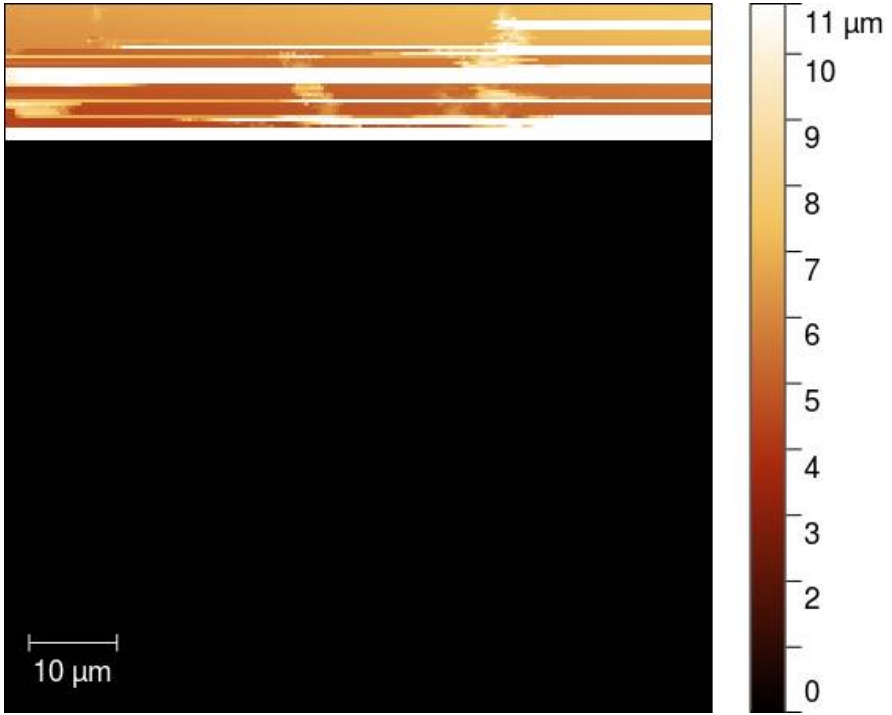

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First contact

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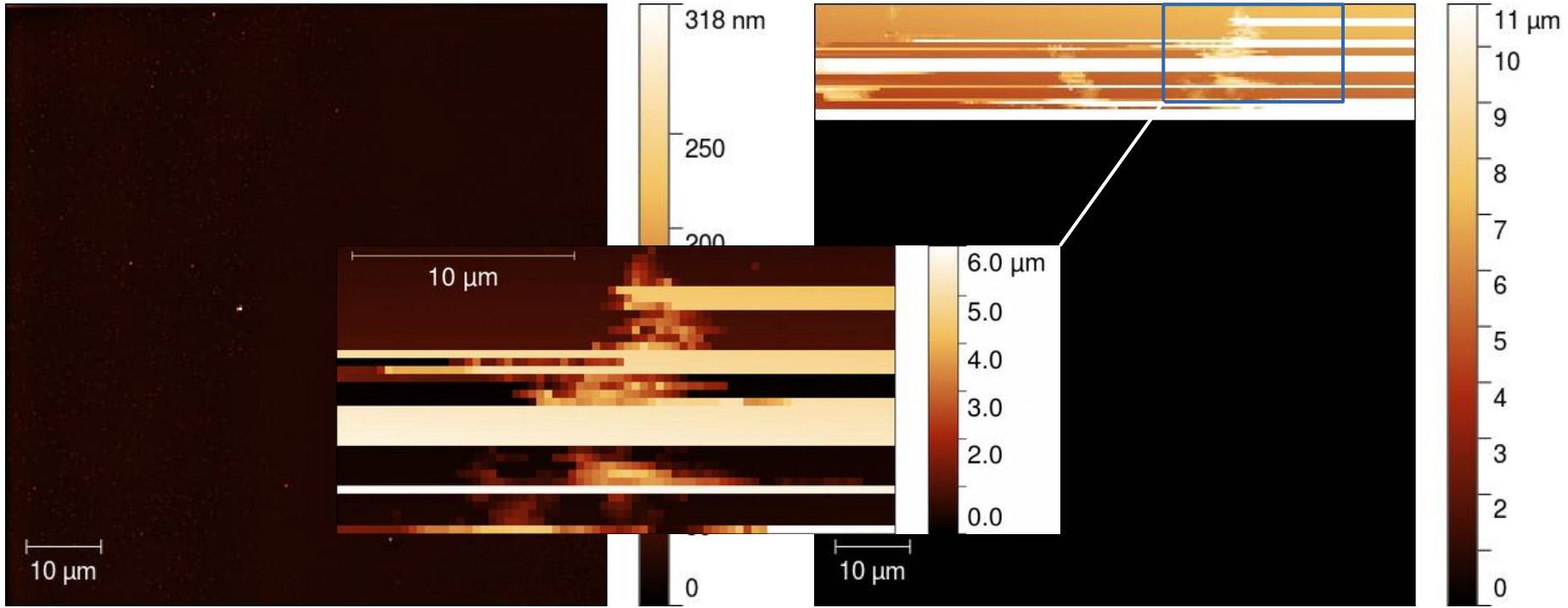

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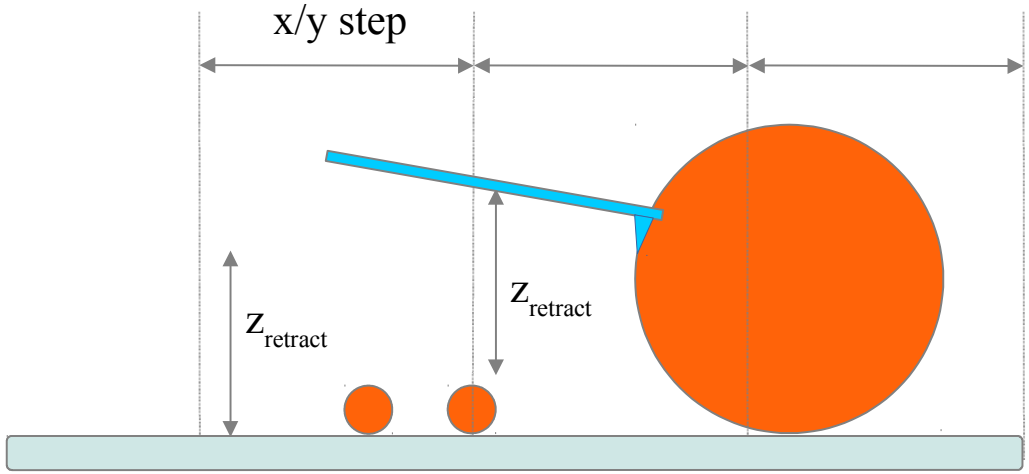
First contact



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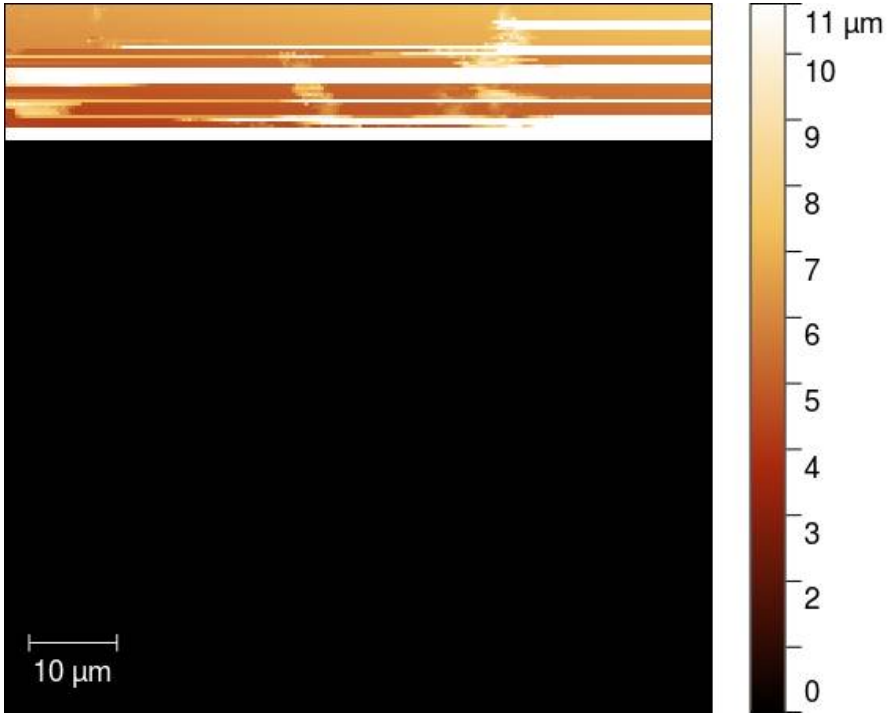

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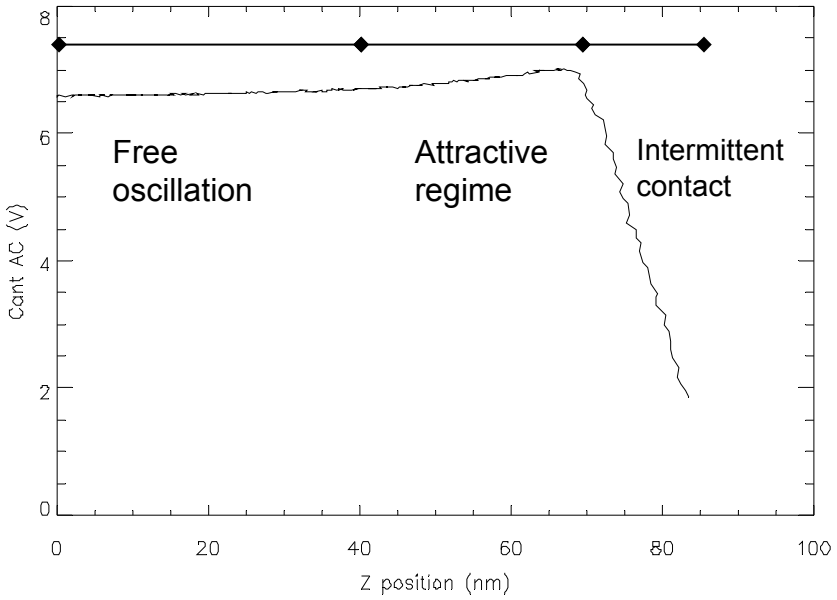
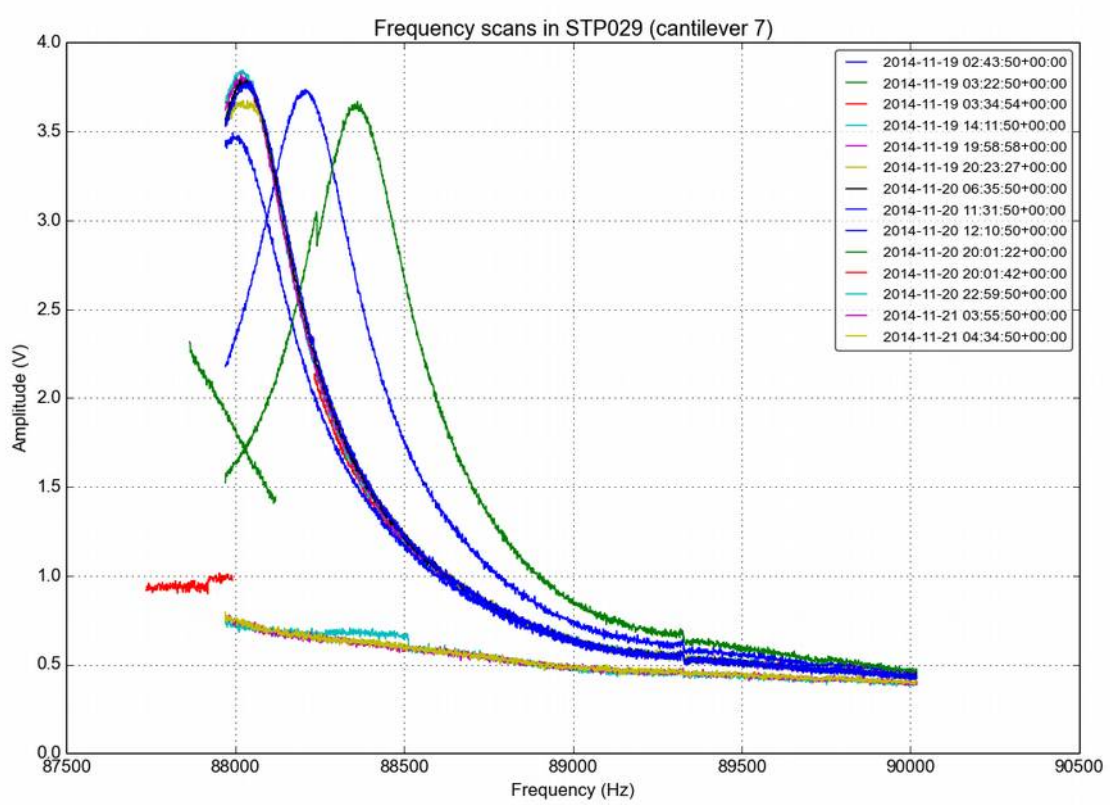
Measuring mass and temperature





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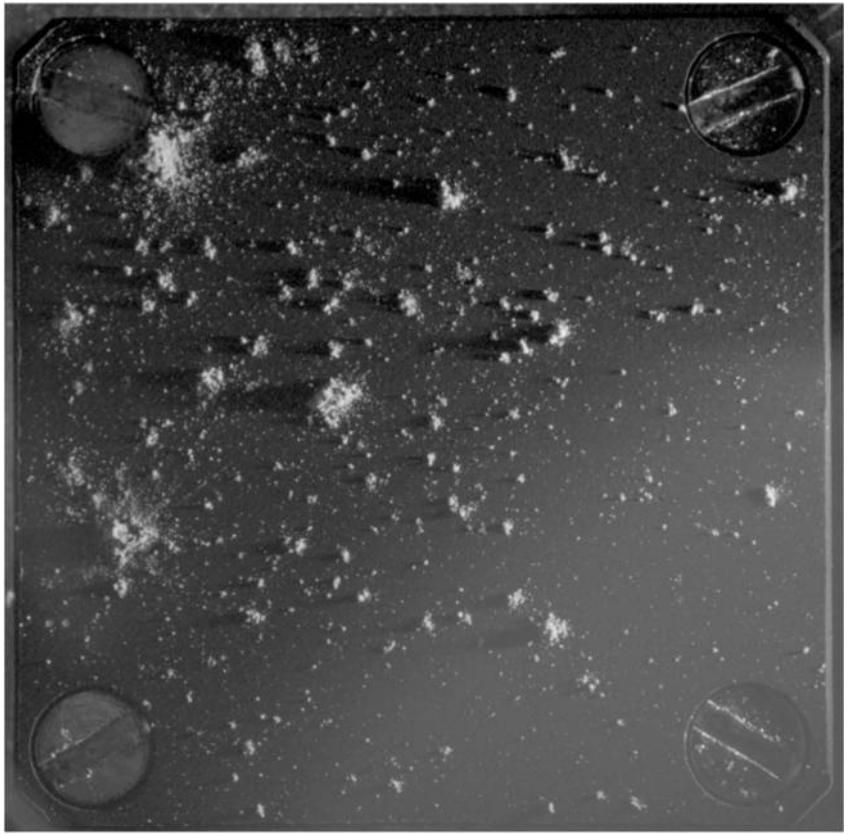
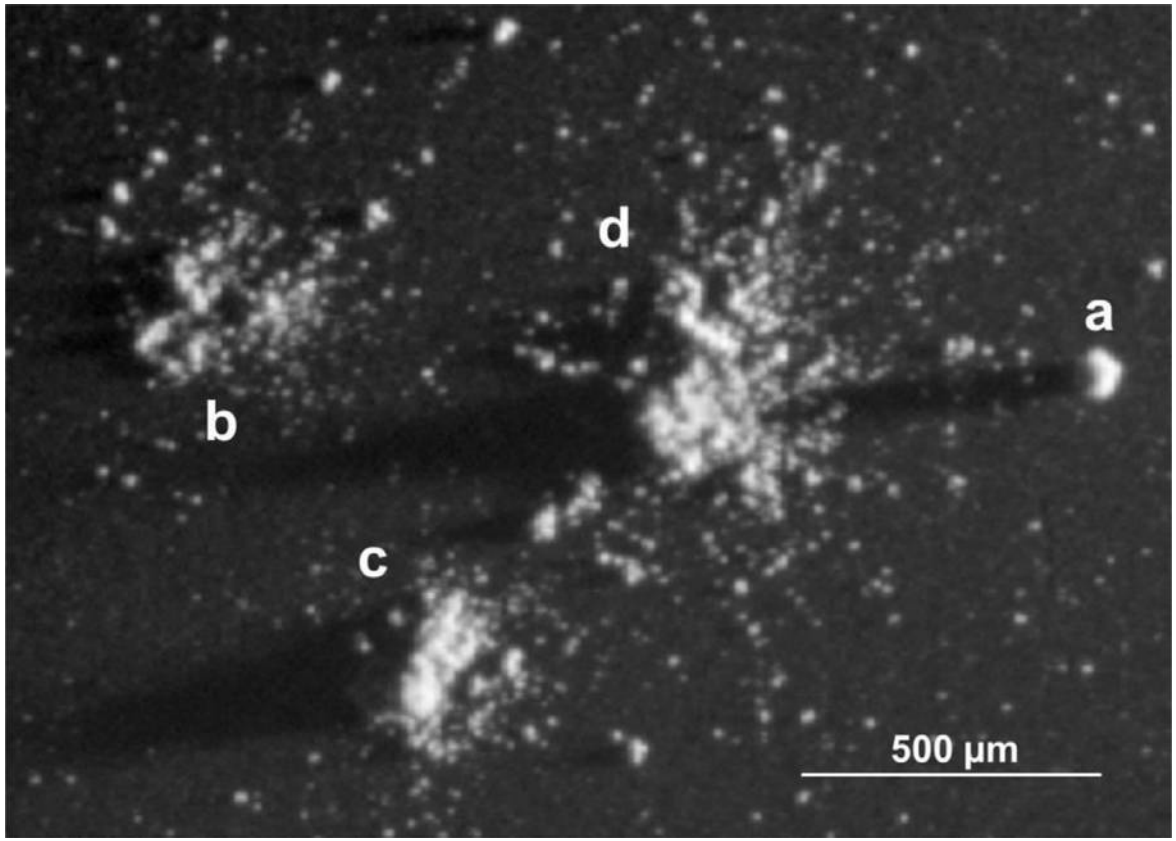
COSISCOPE





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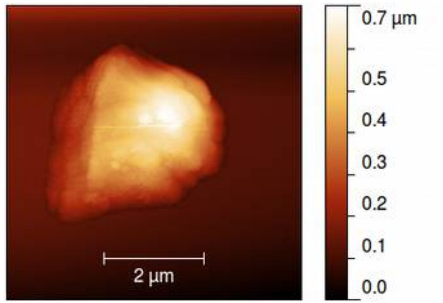
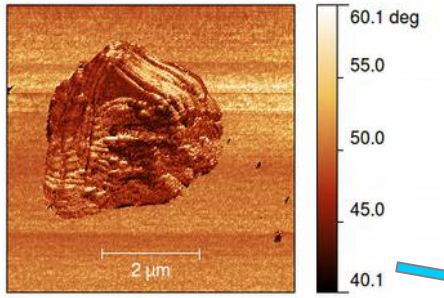
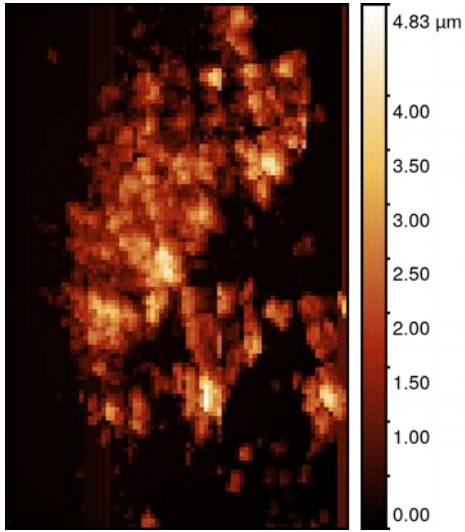
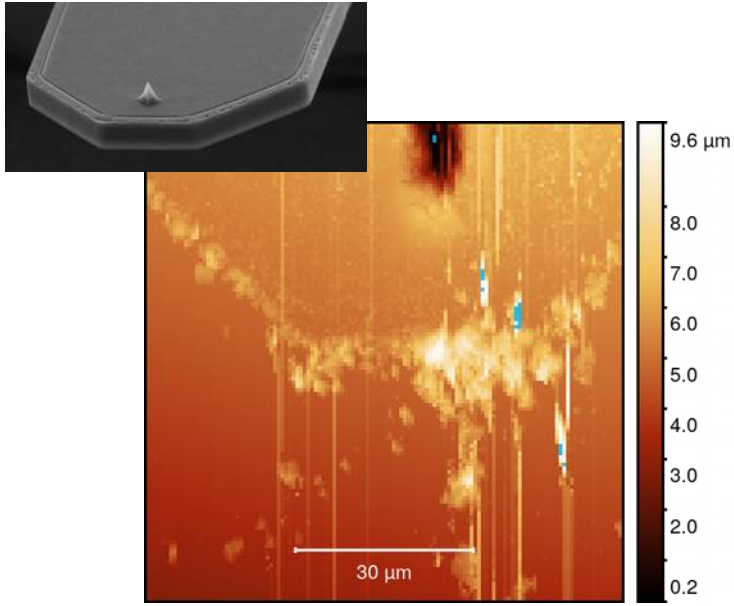
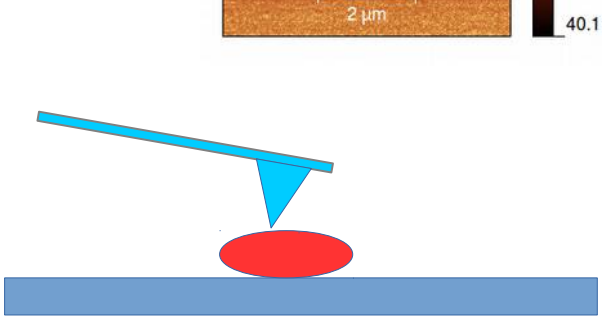
Large vs. small, single vs. aggregate

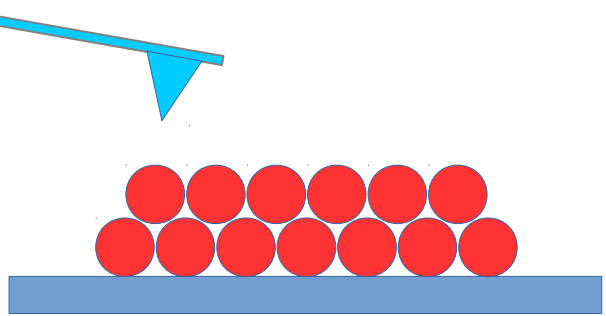


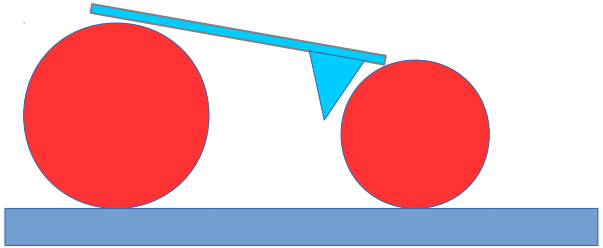












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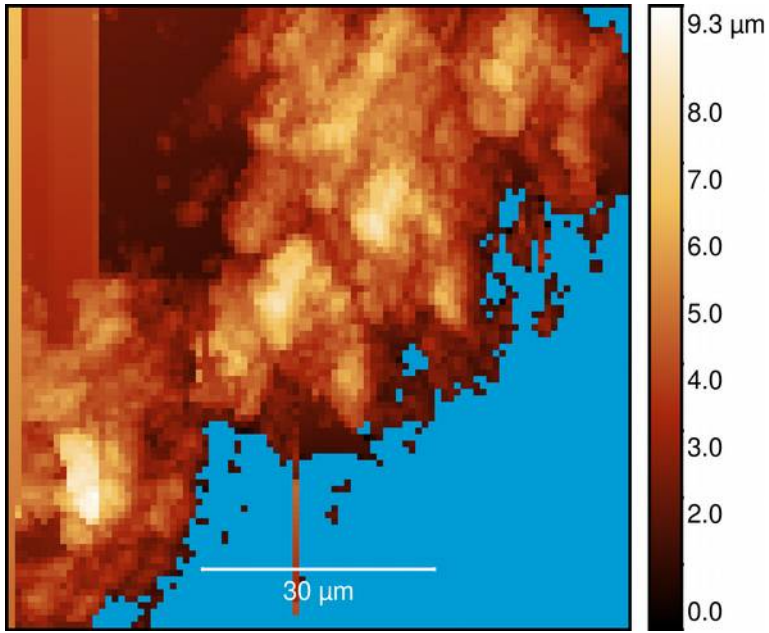
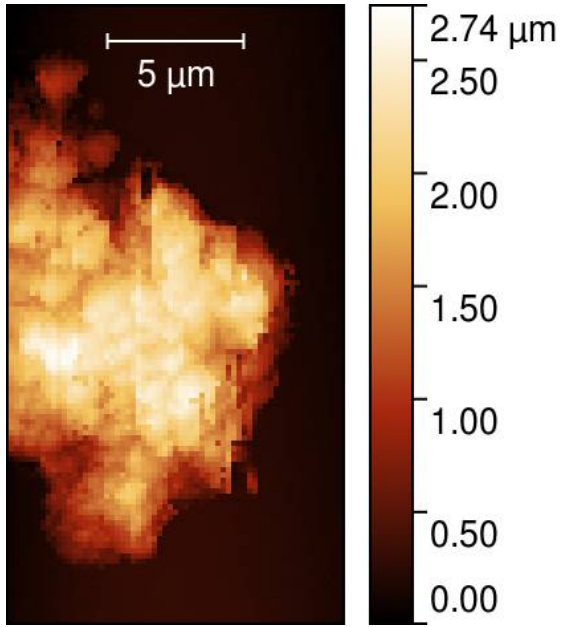
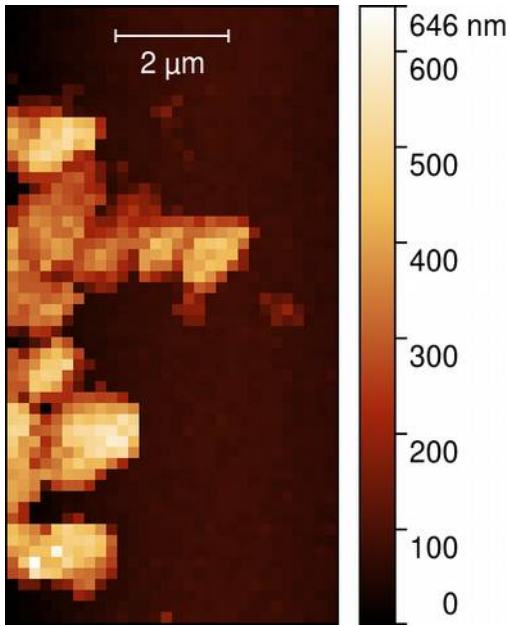
The learning curve







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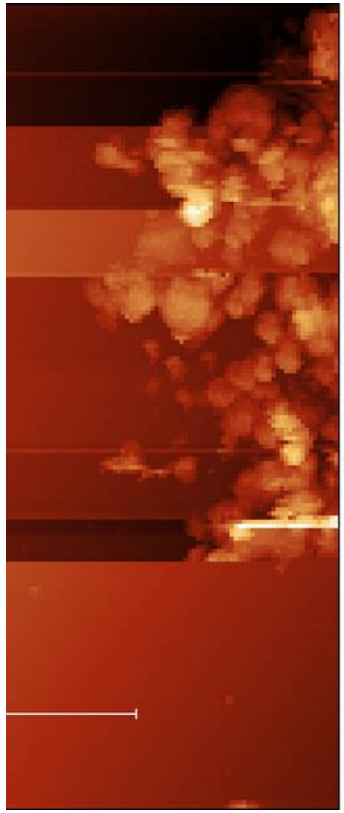
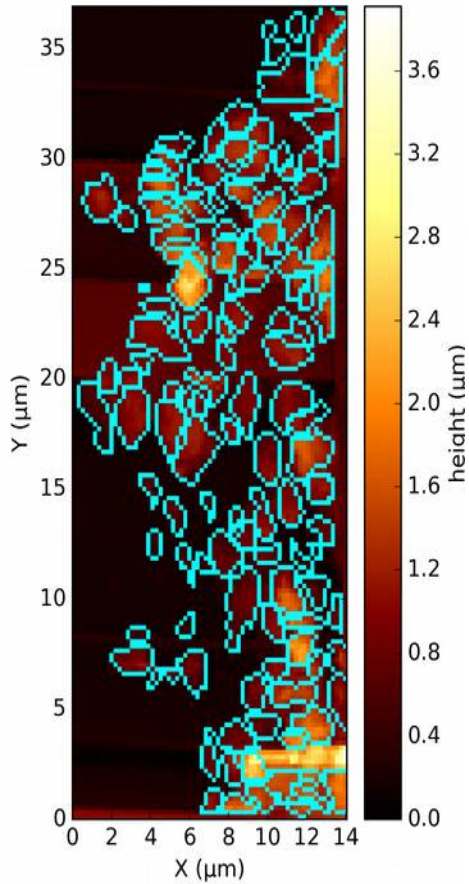
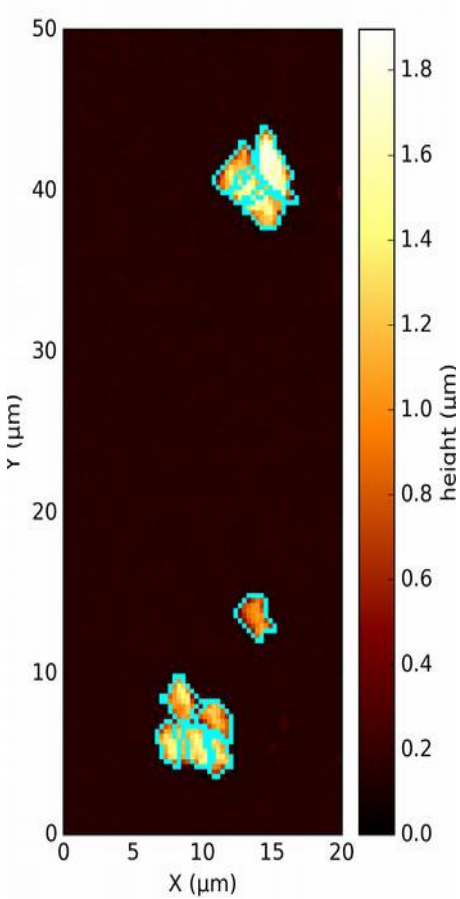
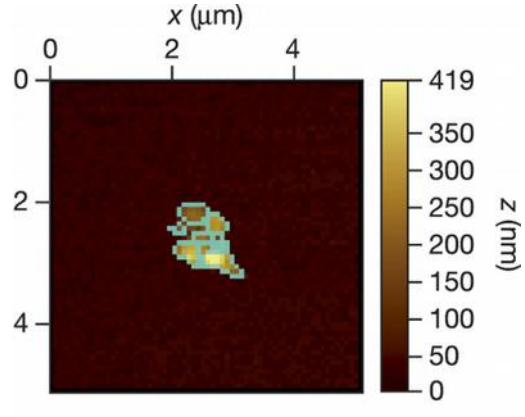
Aggregates of aggregates









Bentley, M.S. et al., 2016. Aggregate dust particles at comet 67P/Churyumov–Gerasimenko. Nature, 537(7618), pp.73–75.

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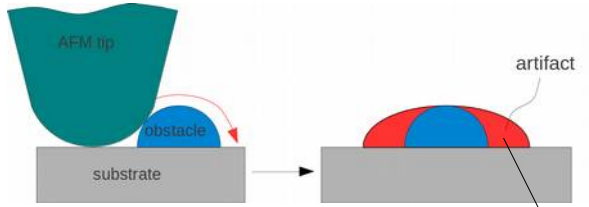
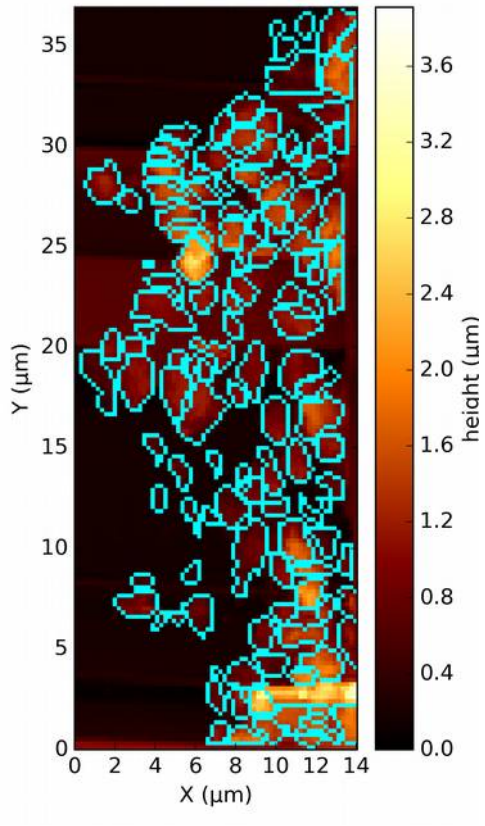
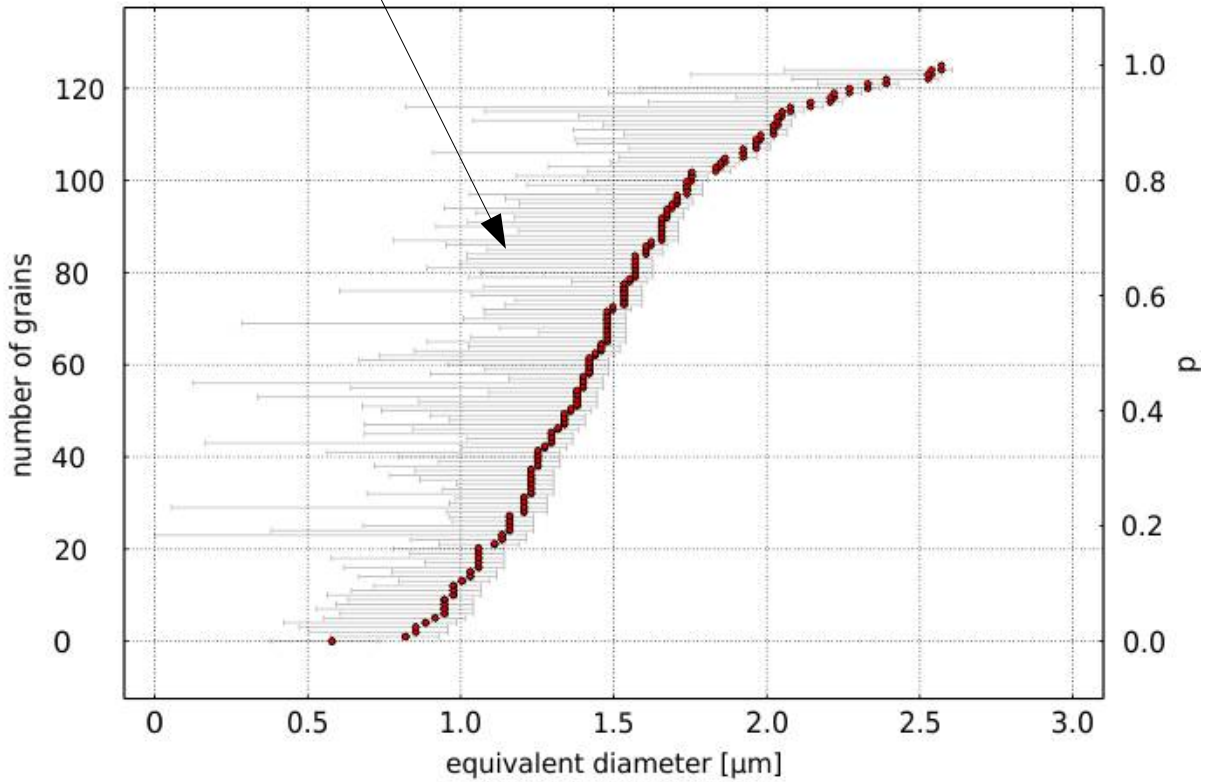
Grain size distribution







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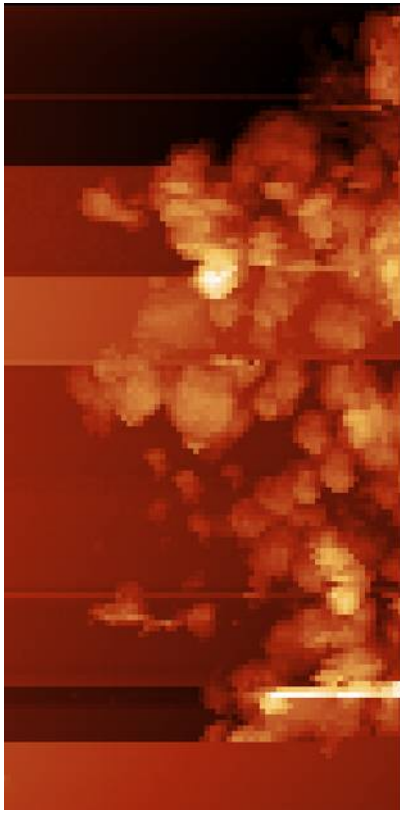
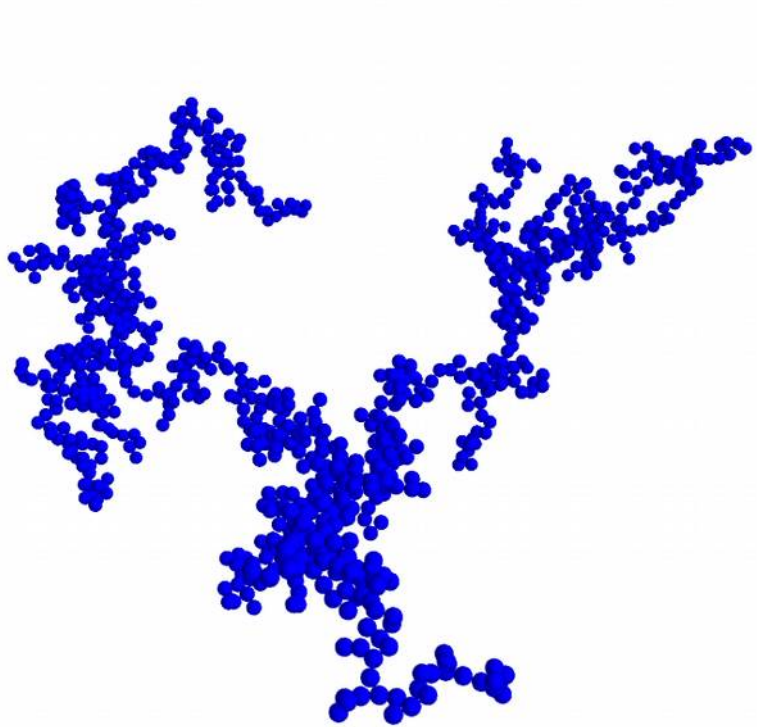
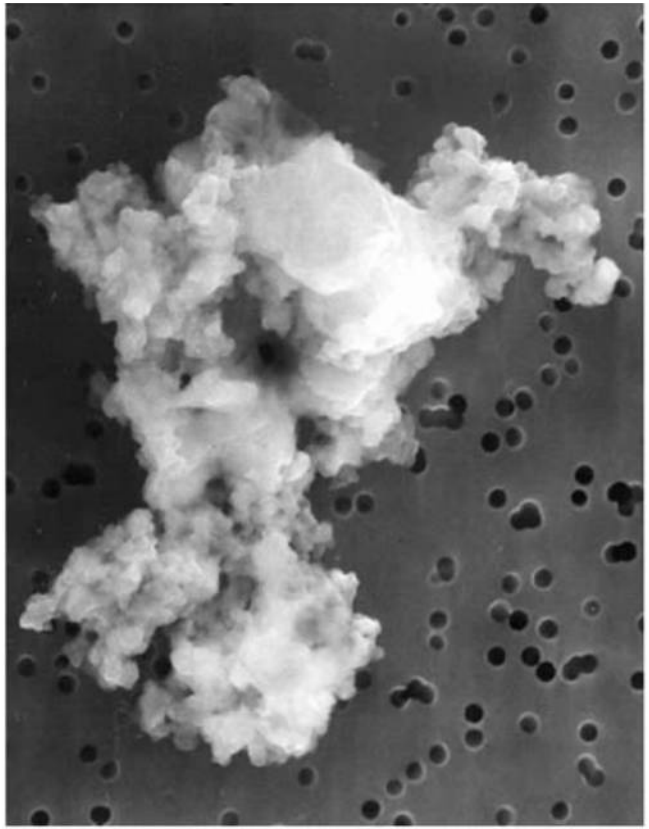
Comparing to....





BCCA, 1024 monomers



Int. Microbiol.

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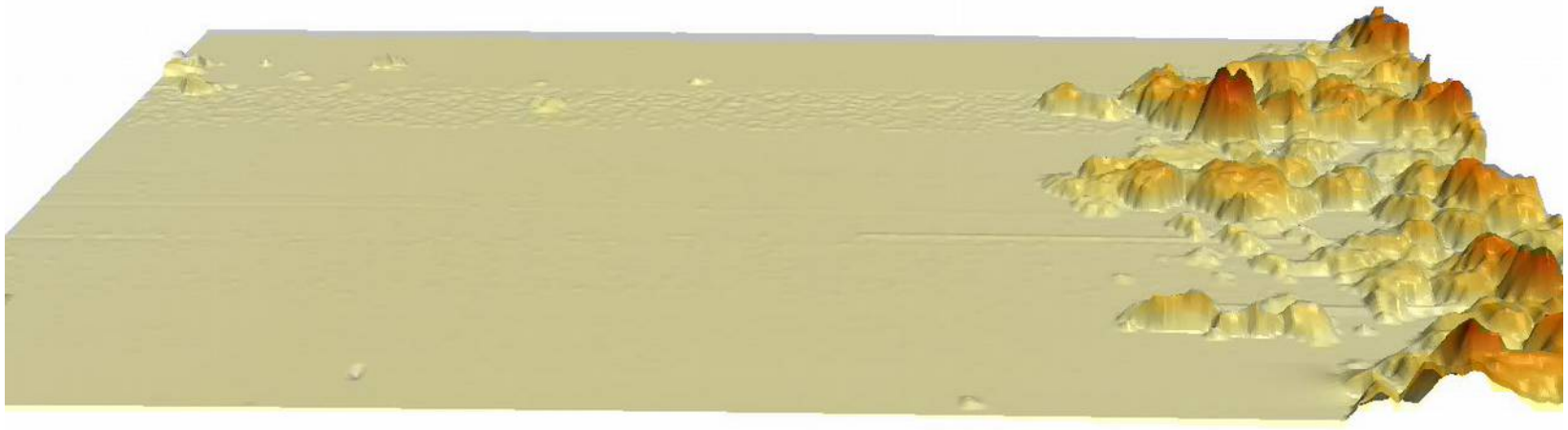
https://goo.gl/wymYg2

Aggregates of aggregates



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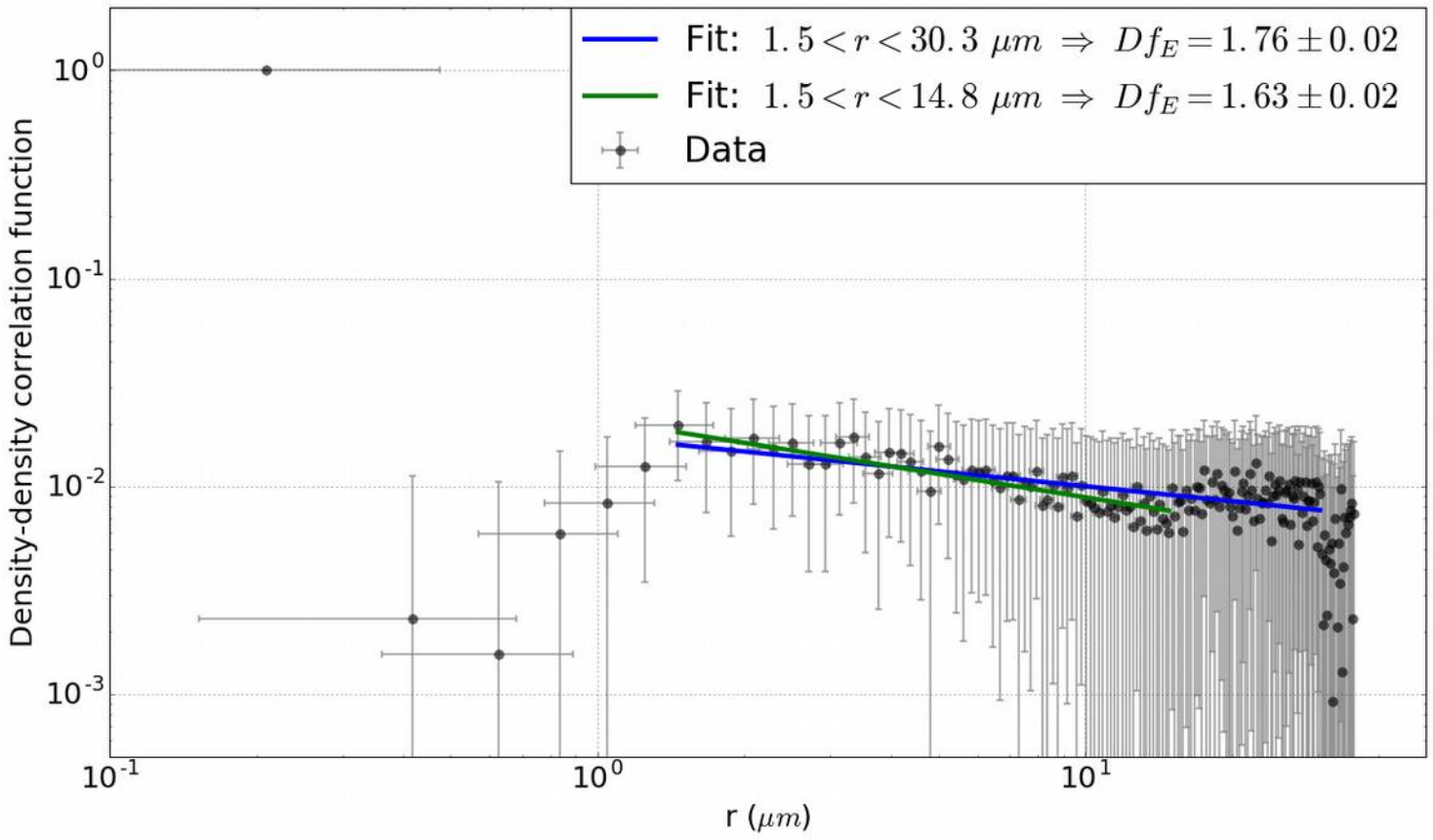
“Frozen fractals…”



Mannel, T. *et al.* 2016. “Fractal Cometary Dust – a Window into the Early Solar System.” Monthly Notices of the Royal Astronomical Society 462 (Suppl 1): S304–11. doi:10.1093/mnras/stw2898.

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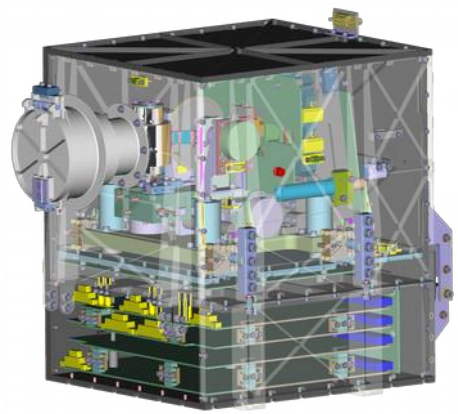
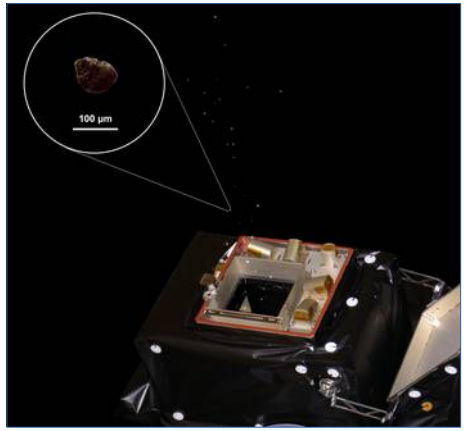
Fluffy, fractal, particles



Single fractal particle

$D_f \approx 1.7 \pm 0.2$

Size ~40 µm



Population of fluffy particles

$D_f \approx 1.78$ (inferred)

Sizes up to 2.5 mm

Fractal dust in µm to mm sizes

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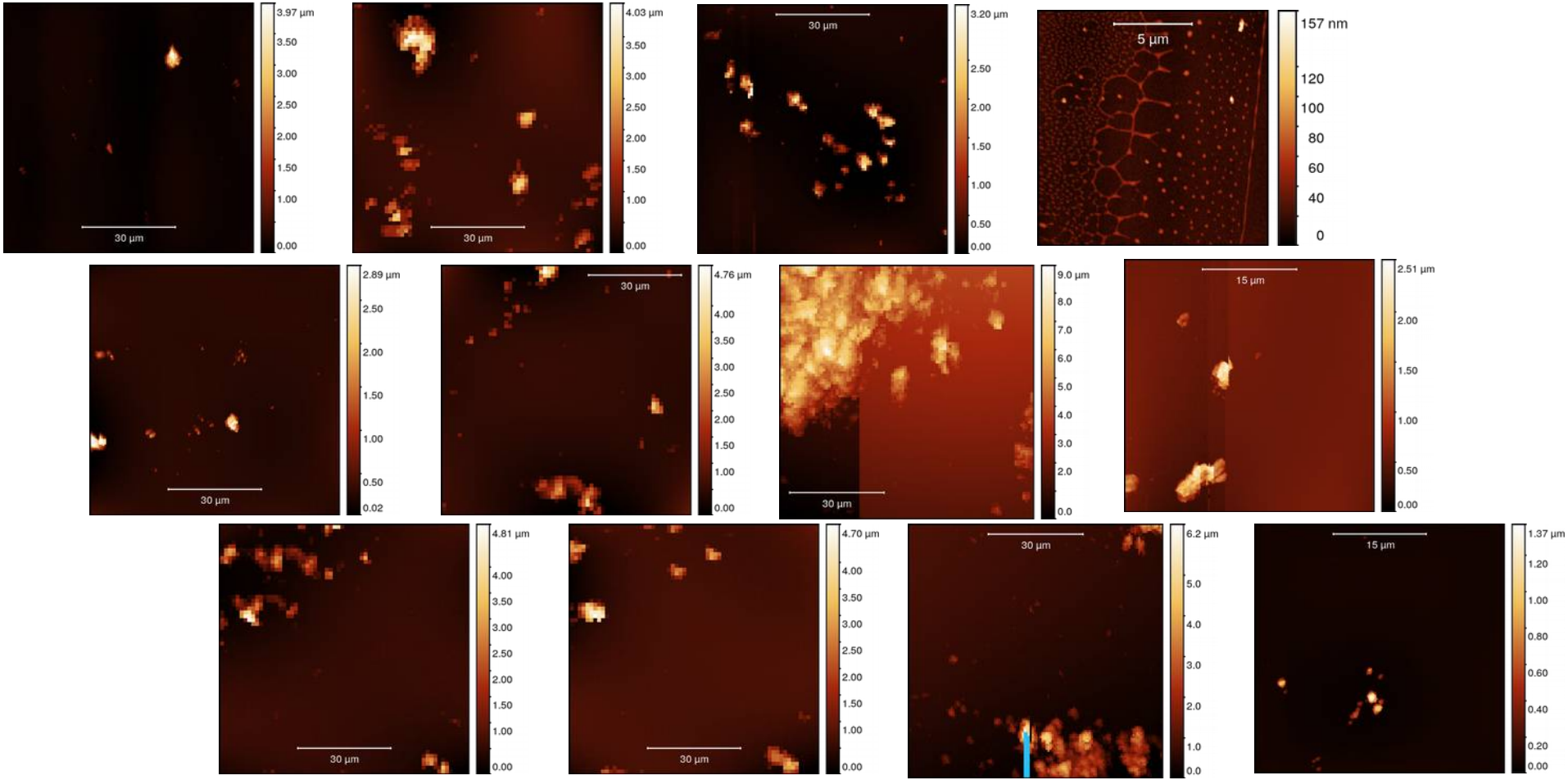
February 2016 outburst



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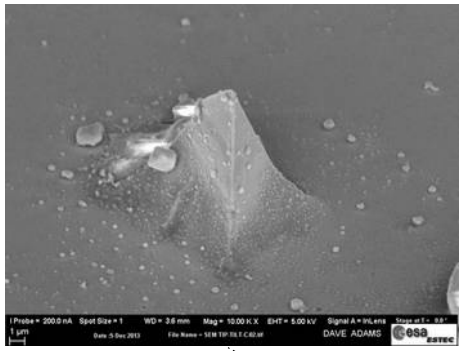
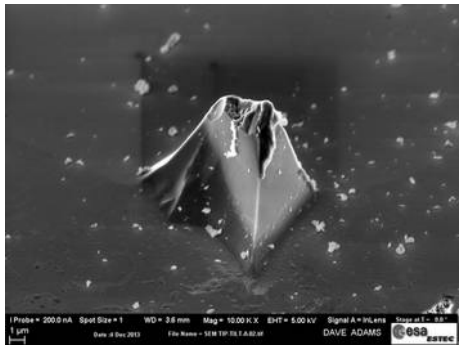
Flight Spare tip wear

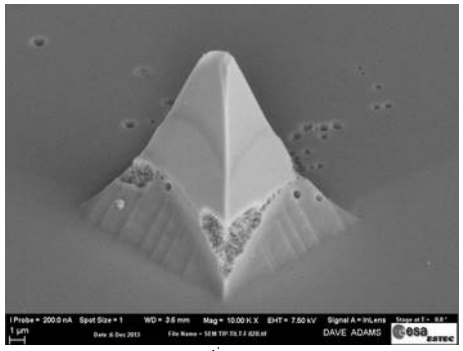
Contaminated

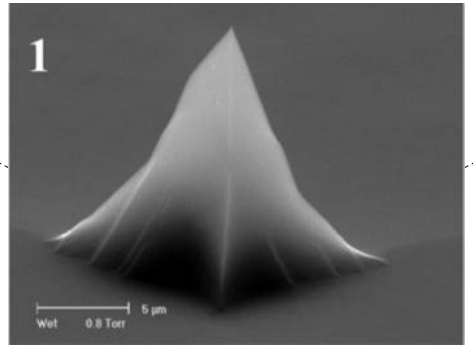


Broken



Blunt





Unused

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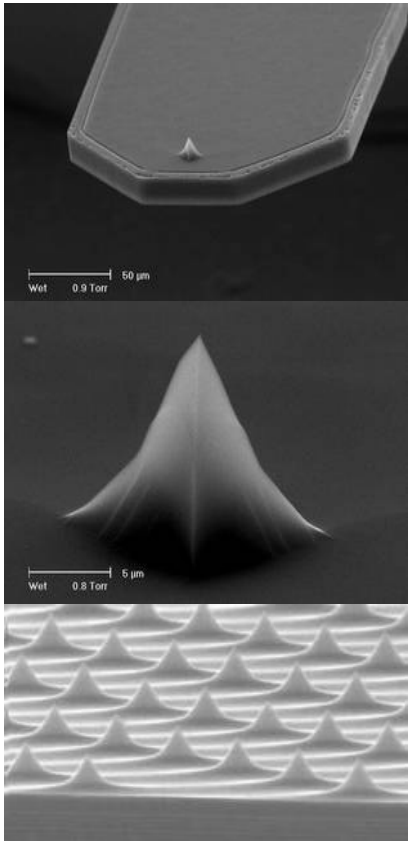
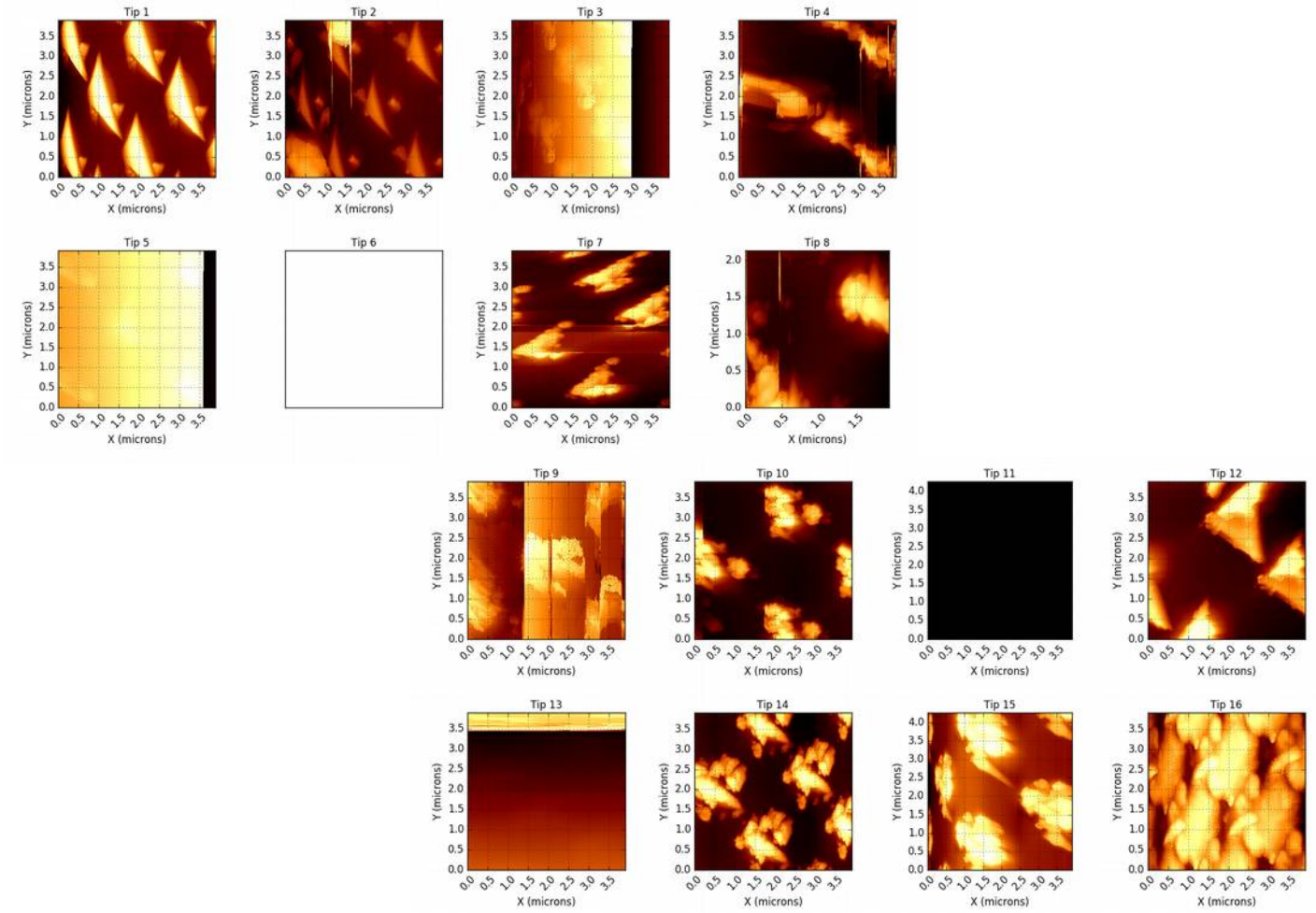
Tip ~~contamination~~ science





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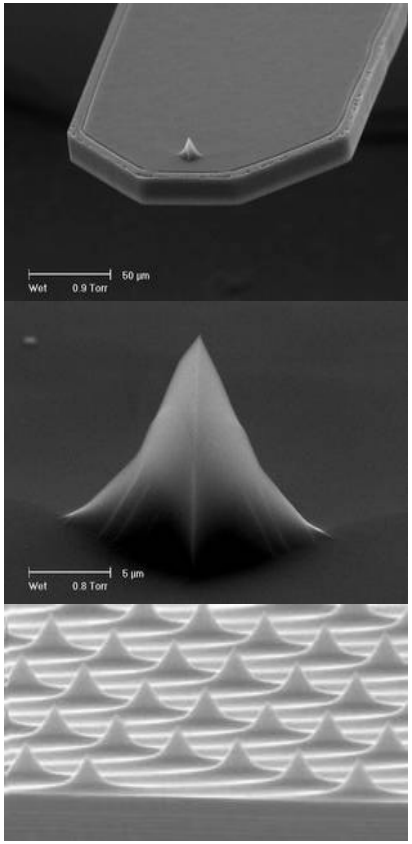
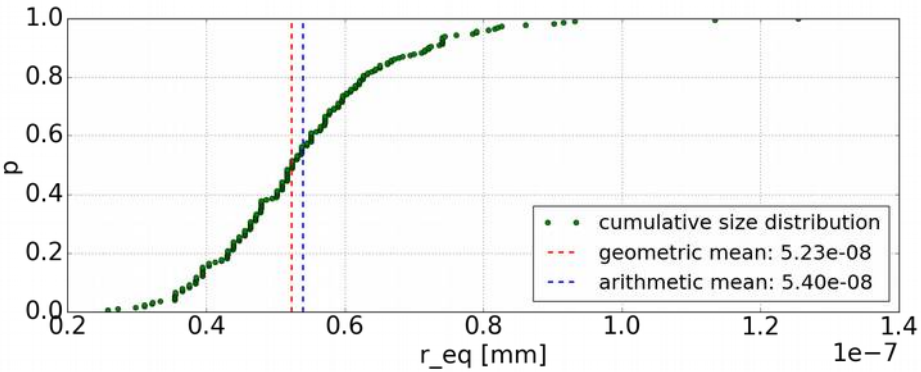
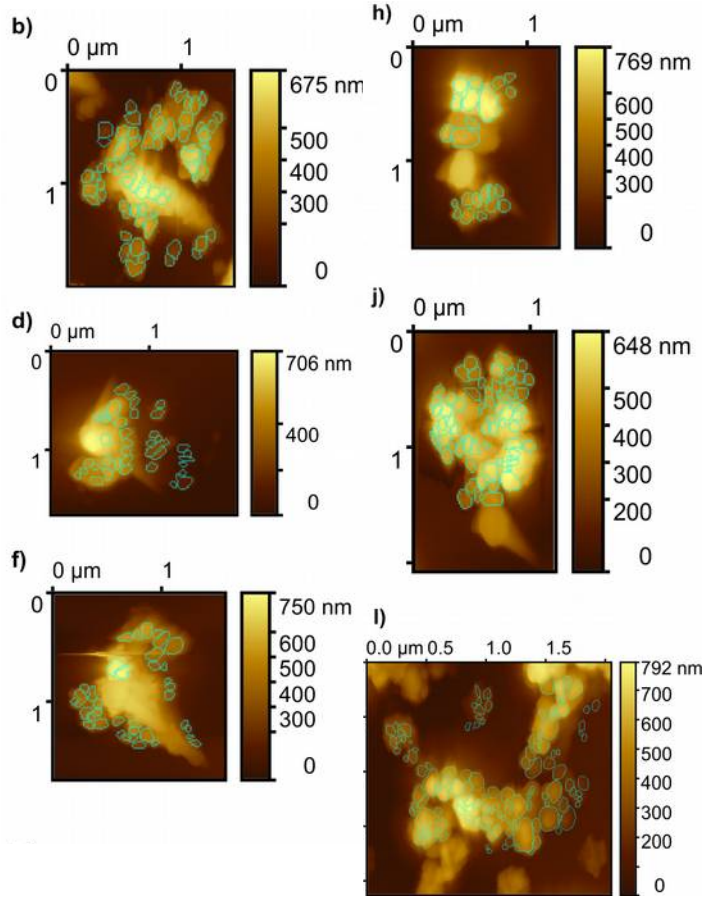
Smallest building blocks (?)





Smallest blocks: 28 ± 4 nm



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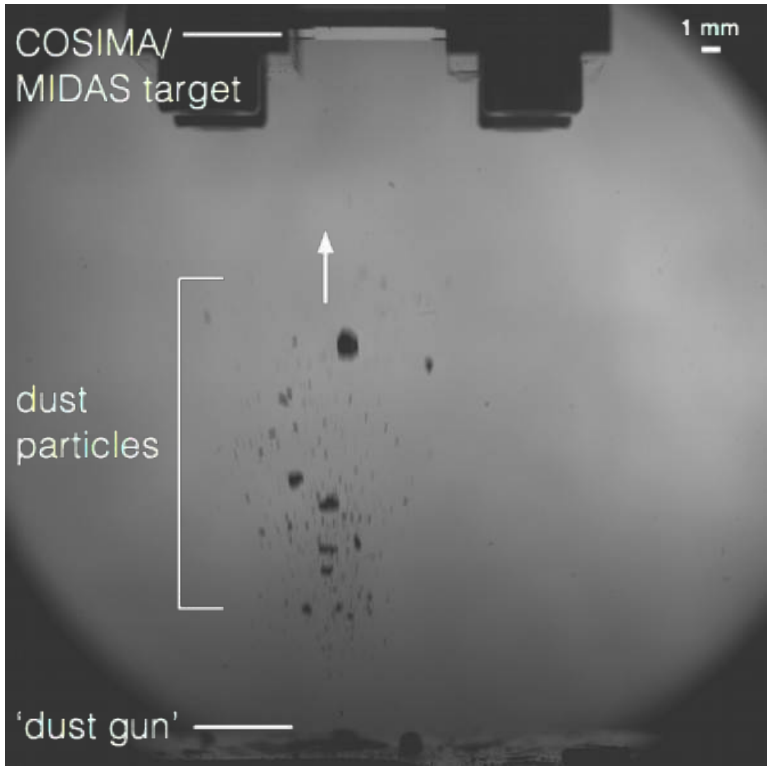
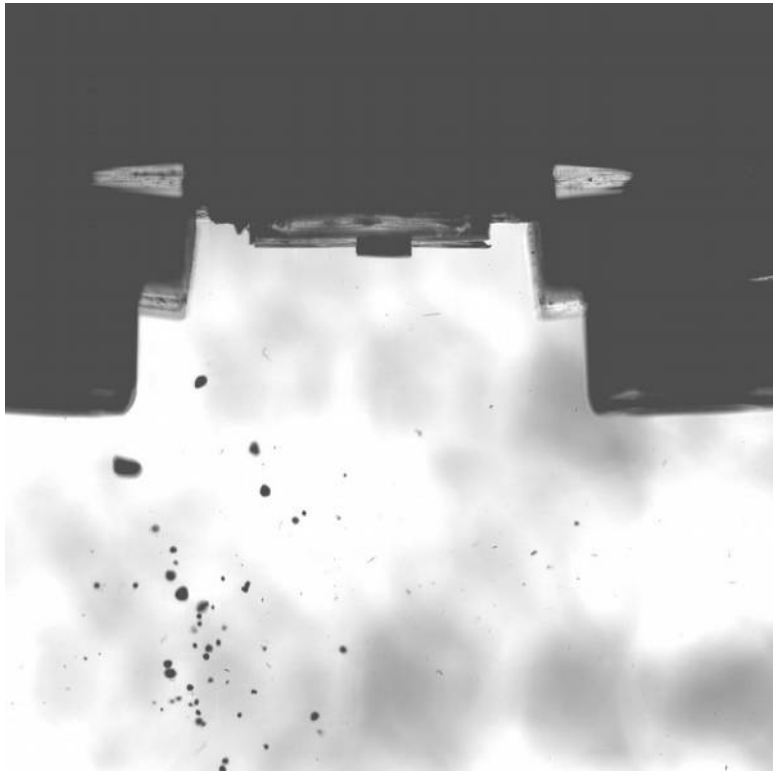
Impact experiments





Courtesy of Lucas Ellerbroek

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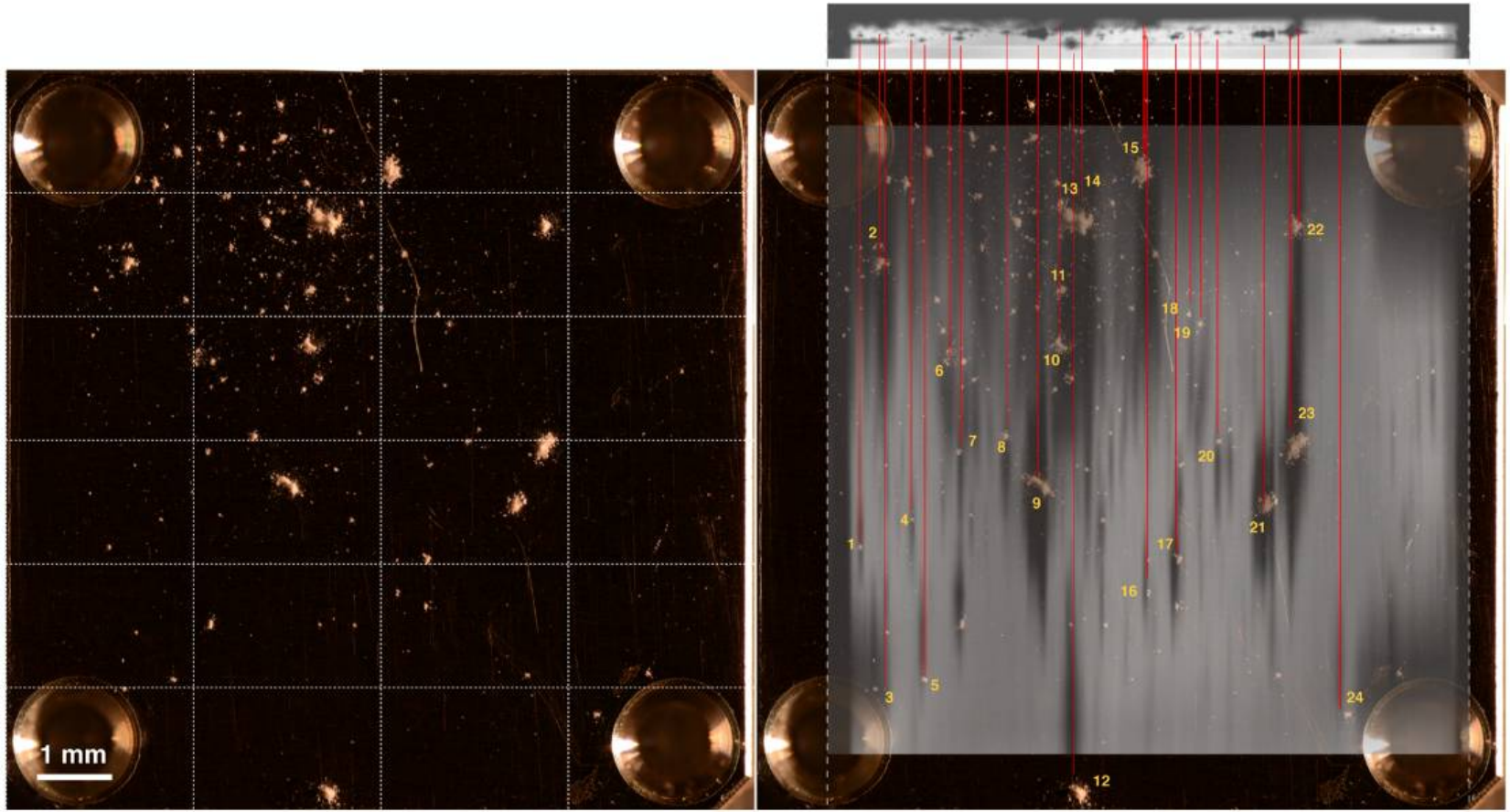
Impact experiments



Ellerbroek *et al.*, MNRAS469,S204–S216 (2017)

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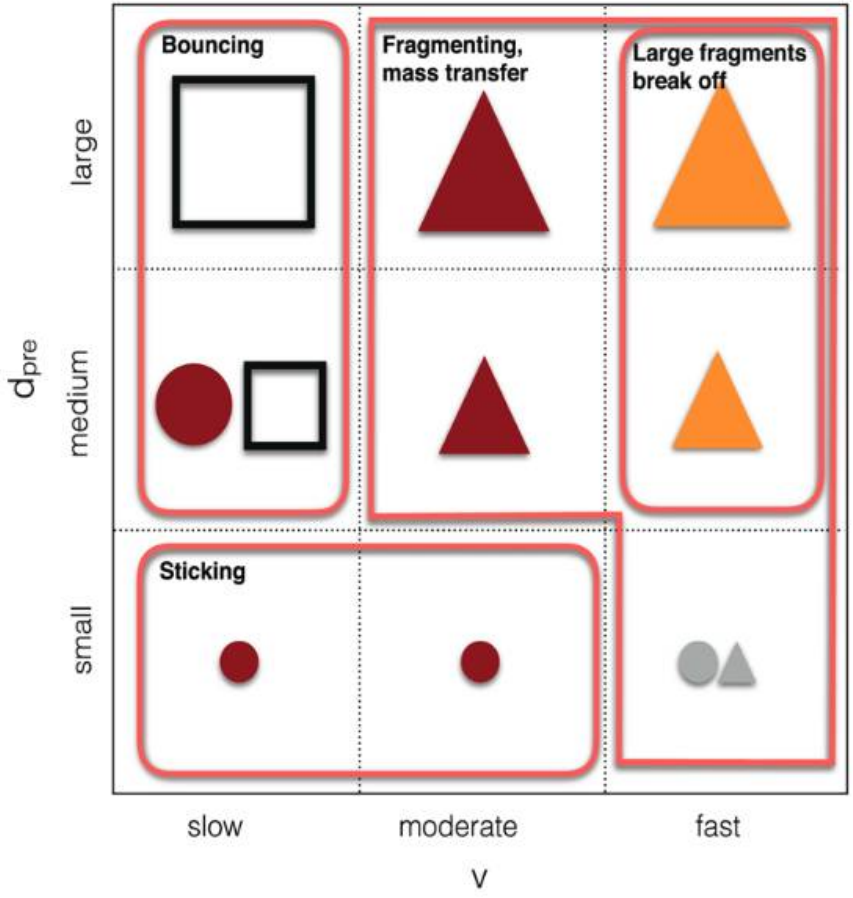
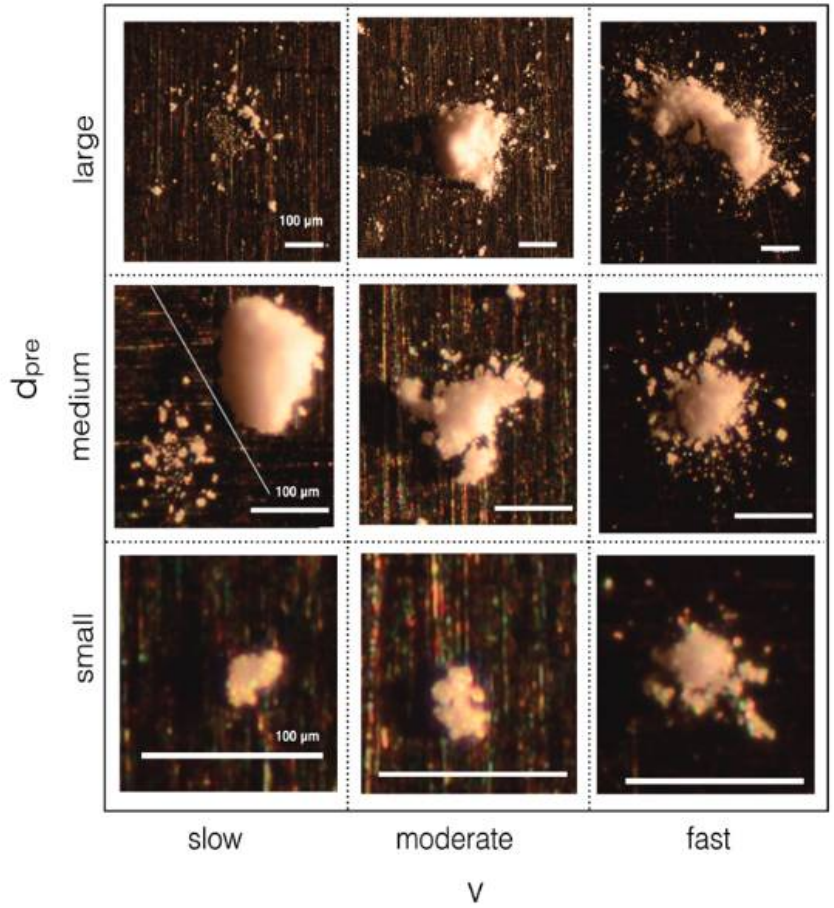
Impact experiments





Ellerbroek *et al.*, MNRAS469,S204–S216 (2017)

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The “big” picture

- Very few “small” (sub-μm) particles close to the nucleus
- Aggregates “all the way down”
  - as far as we can see…
- Grains are typically elongated by a factor of ~few
- Particles have a low profile
  - grains re-arranged on impact?
- Particles easily disrupted and stick to tip
  - low tensile strength and/or organic coating?

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Science – "To Do"

Analysis

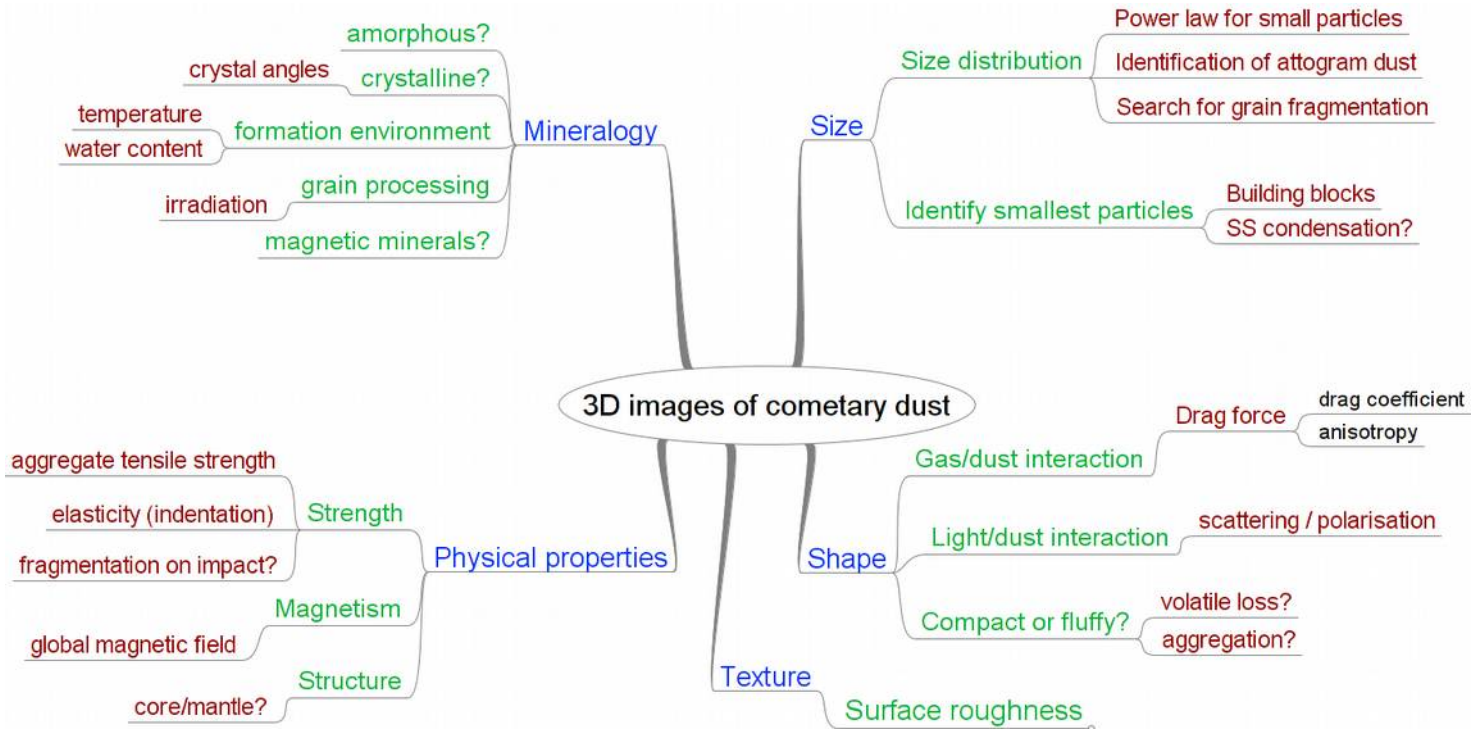
Calibration & deconvolution
Morphological description (shape, size, roughness, fractal dimension etc.)

Modelling

Aggregate impact
Tensile strength
Heat flow
Gas permeability

Experiments

Aggregate impact
Tip magnetisation
Applied tip/sample force



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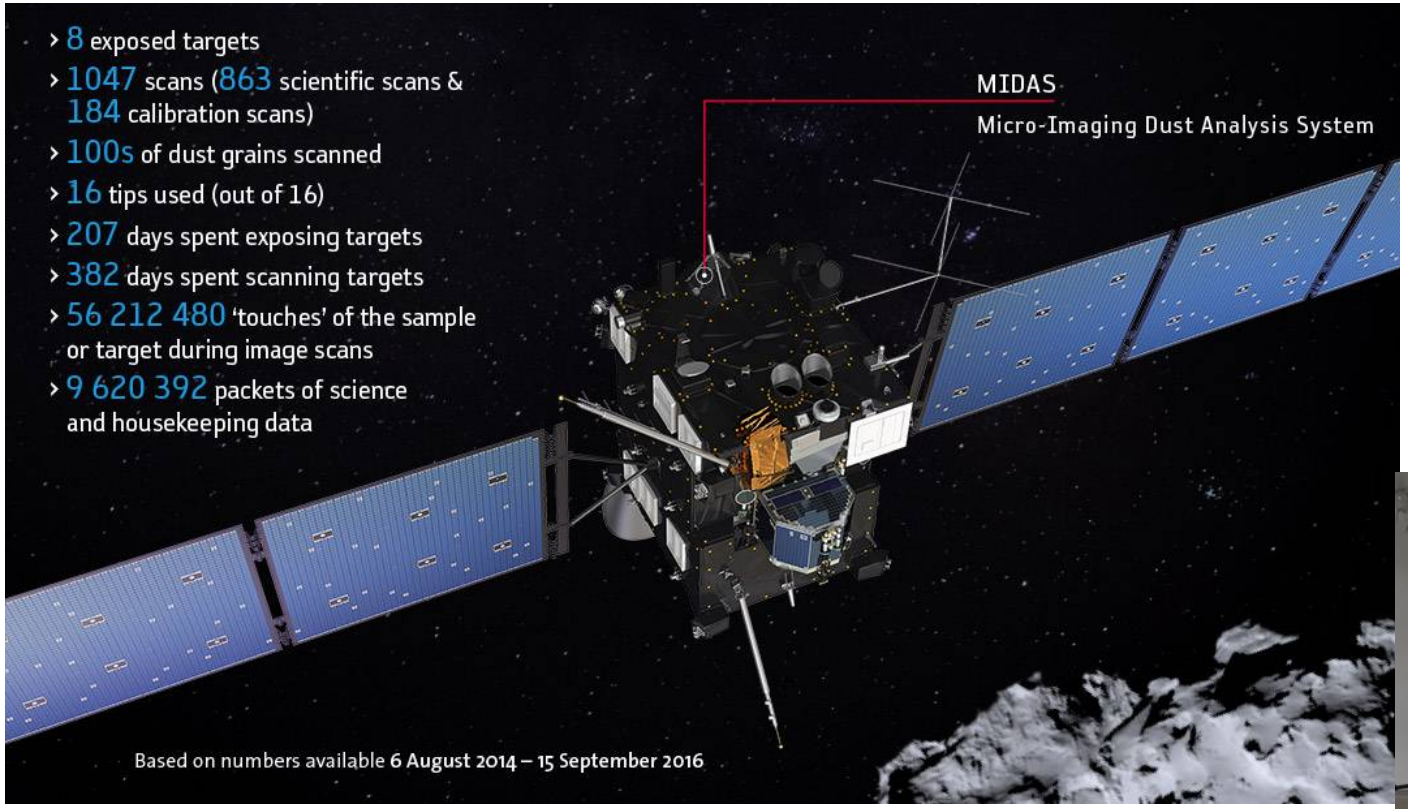
Vital stats and thanks!



Thanks to ESA ESTEC/ESAC/RMOC and the entire MIDAS team, past and present!