GWADW

Scattered light workshop

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Stray light from dust in Virgo

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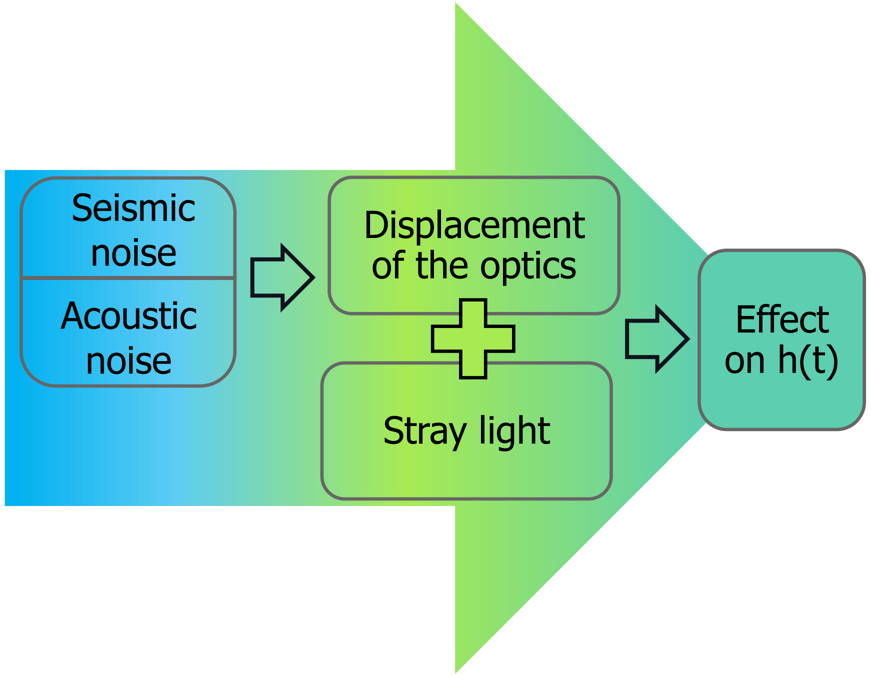
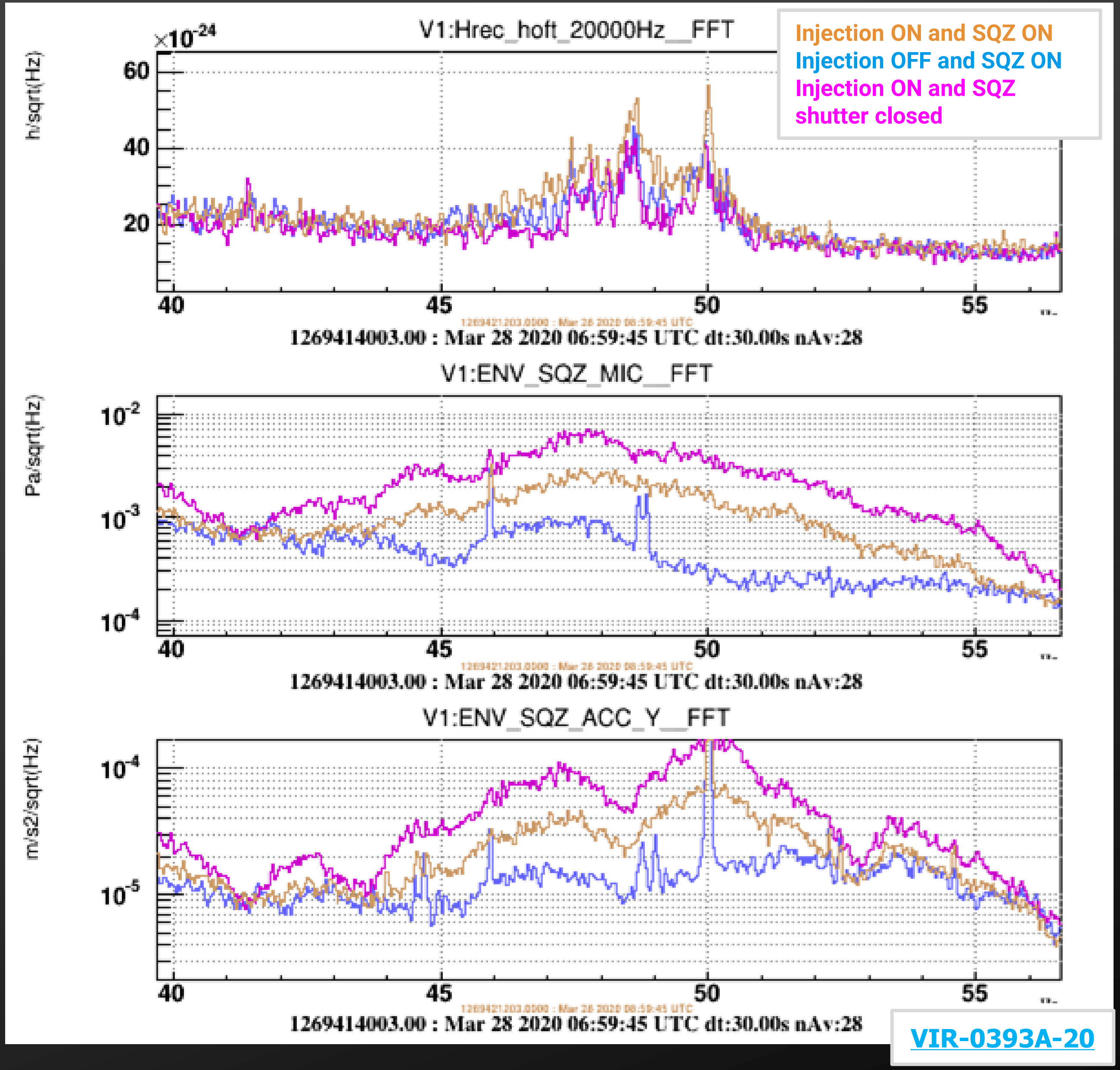
Stray light problem

- Stray light injects additional noise into the ITF: currently visible as bumps and peaks at low f
- Need to develop mitigation strategies by finding the main scatterers & quantify the stray light power
- Tapping/shaking tests help find mechanical resonances
- Stray light simulations can provide estimates of the fraction of stray light that couples back into the ITF & its main sources





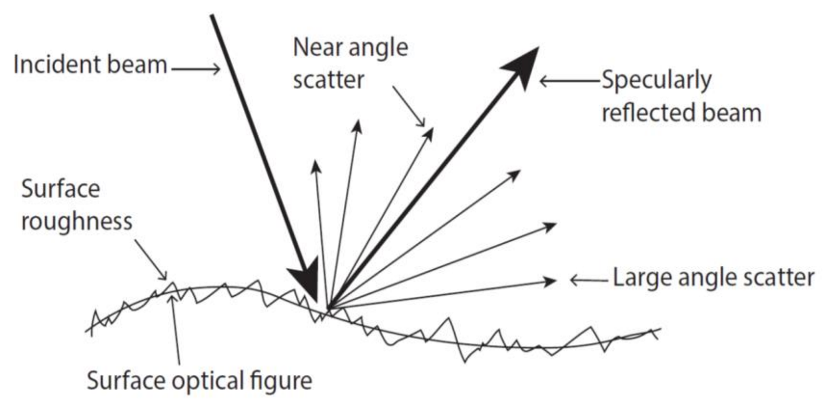
Stray light sources

Main sources:

- **Surface roughness**
- **Dust contamination**

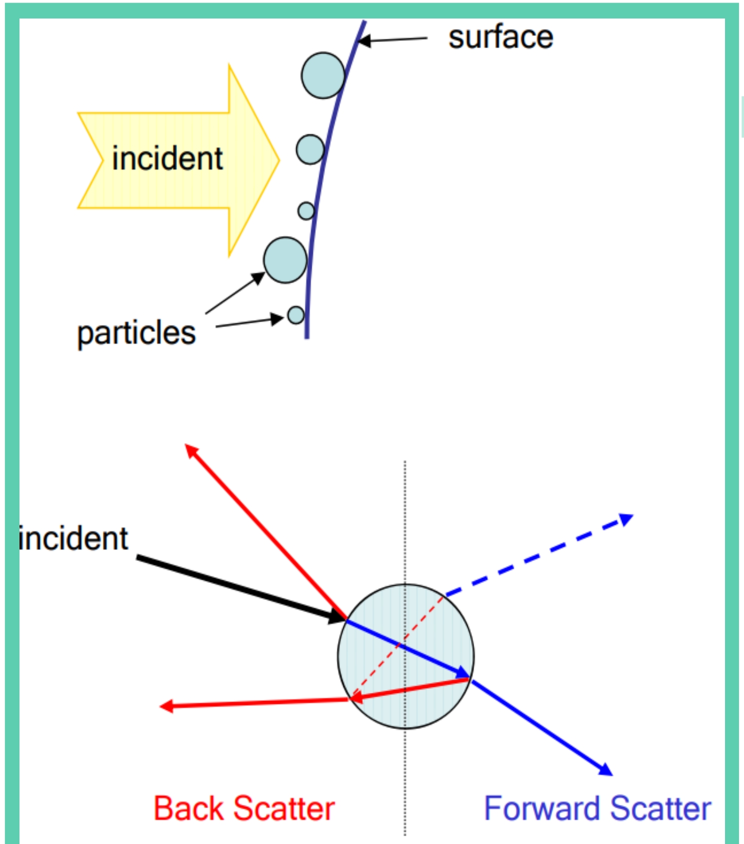
Optics have extremely low roughness -> dust can be the leading contributor to stray light in Virgo

Surface roughness



Scattering due to non-perfectly smooth surfaces

Dust contamination



Dust scattering is described by **Mie Theory:**

- Particles are considered spherical & dielectric
- Their surface distribution function ***f(D)*** is modeled
- Particles produce both forward and back scatter components

Dust particle distribution ***f(D)*** in clean environments is usually modeled via IEST CC21246D:

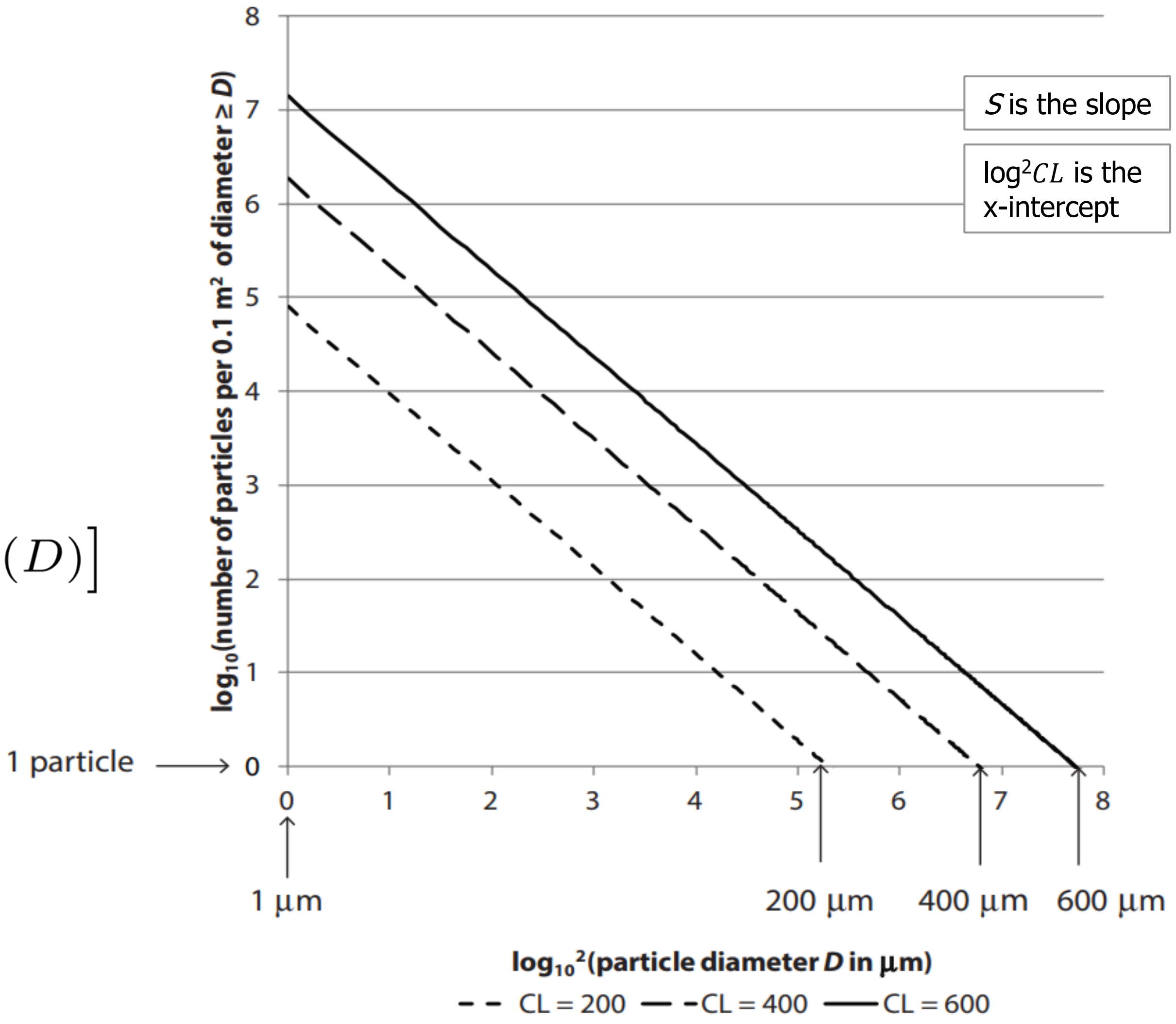
$$f(S, \mathrm{CL}, D) = -\frac{d}{dD} N_p(S, \mathrm{CL}, D)$$

$$N_p(S, \mathrm{CL}, D) = 10^{|S|\left[\log_{10}^2(\mathrm{CL}) - \log_{10}^2(D)\right]}$$

N_p is the **number of particles**/0.1m^2 with diameter ≥ D

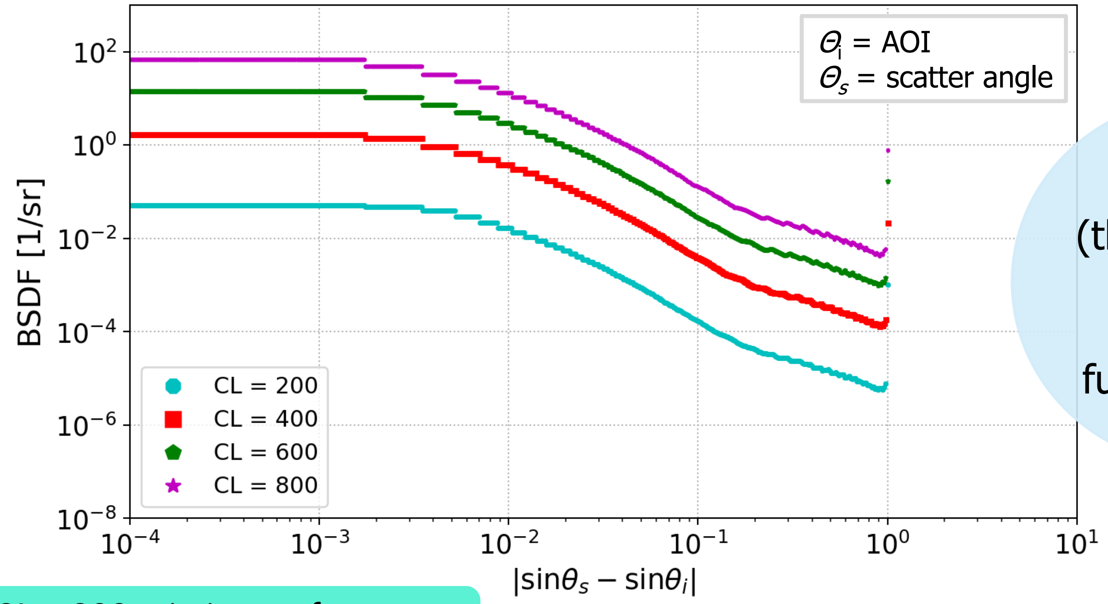
S is the particle distribution **slope** (S = -0.926 in IEST, experimental data not very much in agreement)

CL is the **cleanliness** level of the surface: in IEST it's equivalent to the maximum particle size/0.1m^2 (x-intercept)

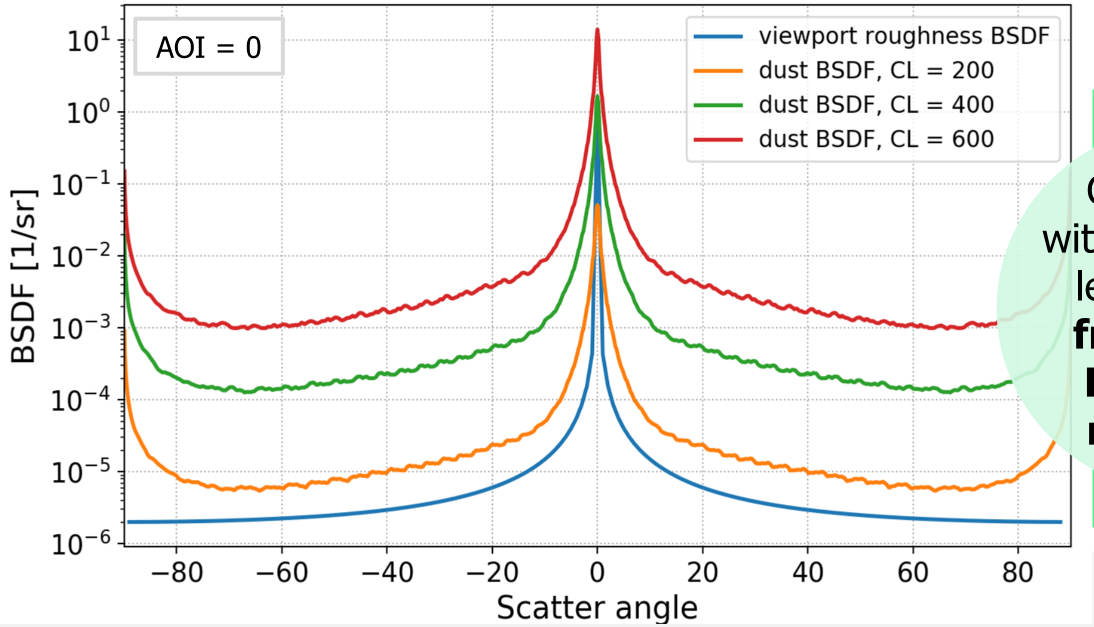


Dust particles distribution

Dust particles scattering



- CL < 200 pristine surface
- CL = 600 visibly clean surface
- CL > 1000 visibly dirty surface



The **BSDF** (the scattering property) is a strong function of CL

In Virgo **no measurements of CL:**

Need to directly measure it

Comparison with standard CL levels: **BSDF from dust » BSDF from roughness**

If modeled with IEST CC21246D the CL is calculated as:

$$\log_{10} \mathrm{CL} = [1.08(\log_{10} h + \log_{10} \rho + \log_{10} t + 0.773 \log_{10} \mathrm{X_c} - 1.248)]^{1/2}$$

The CL depends on the parameters:

- Optics orientation h (1 for horizontal, 0.1 for vertical)
- Air changes/hour ρ
- Surface exposure time t
- Air cleanliness class X_c

In principle, these parameters *may* be measured → In *real* environments too many variables not under control → A direct measurement of particles distribution is more reliable

Dust contamination monitoring campaign

MOTIVATION & PURPOSE

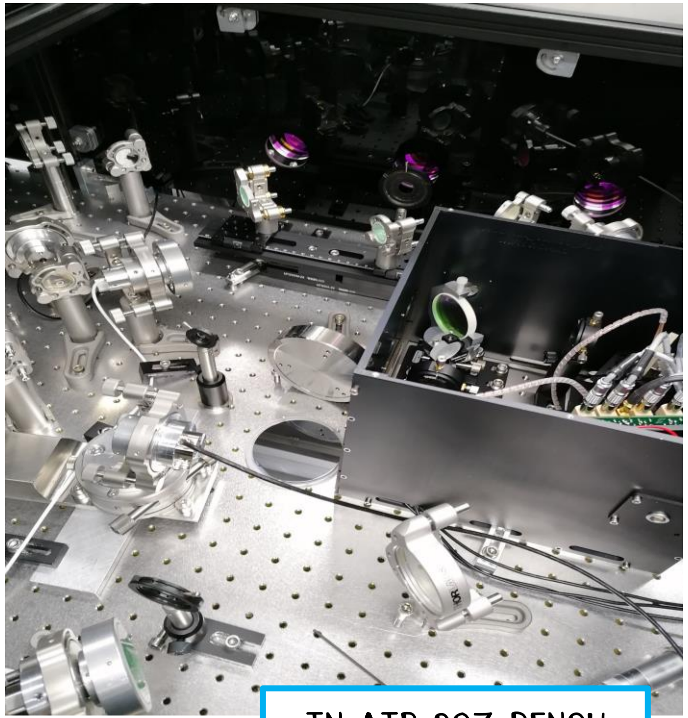
- Have reasonable cleanliness (CL) estimates
- Produce realistic estimates of stray light from dust

GOALS

- Monitor level of cleanliness of optics in different environments and over time
- Highlight critical situations and adopt mitigation strategies

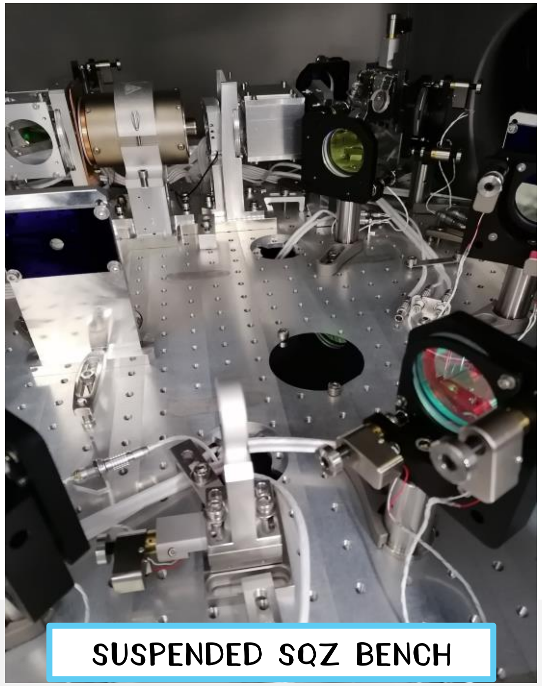
METHOD

- Expose clean silicon wafers next to optics in representative locations (first in the squeezing environment SQZ)
- Take pictures of exposed wafers to extract particle size distribution

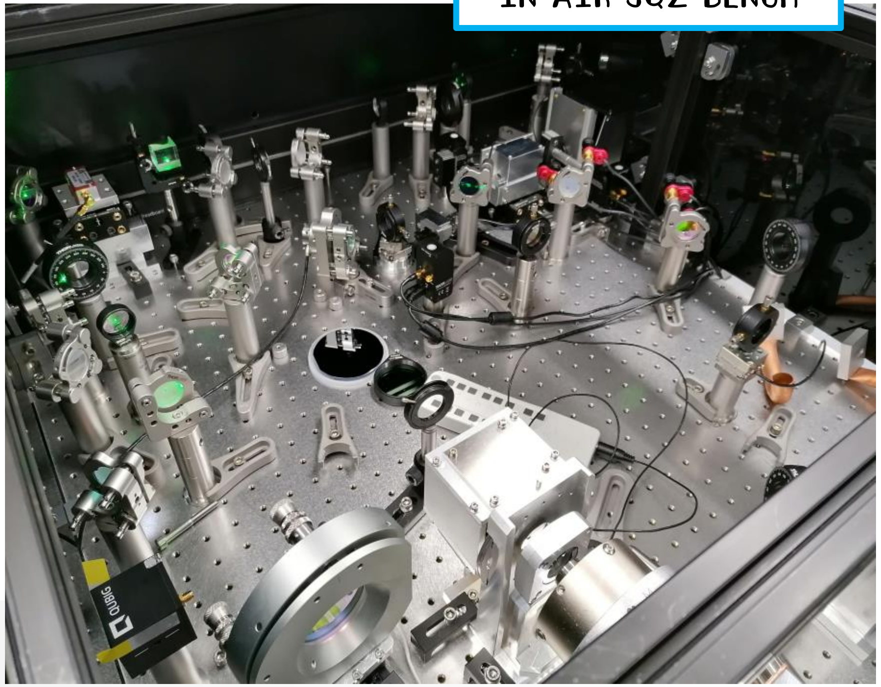


IN-AIR SQZ BENCH

SQZ CLEANROOM



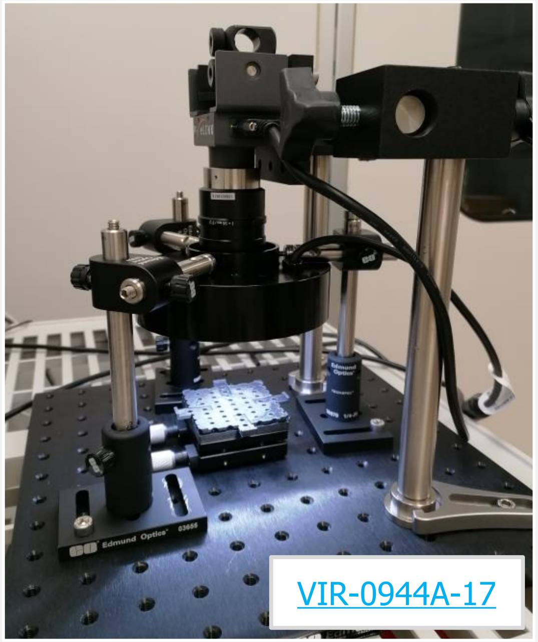
SUSPENDED SQZ BENCH



Dust images

CAMERA SYSTEM

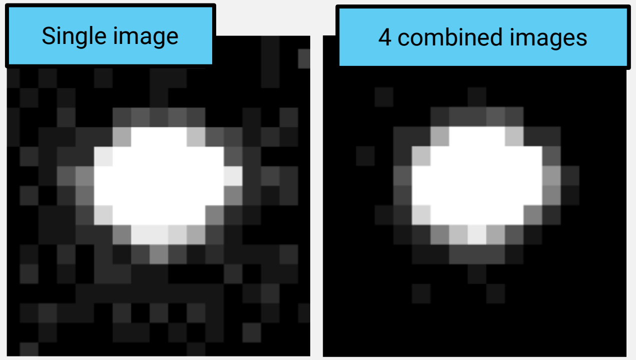
- Images of wafers taken via camera system in ISO 3 Clean Room
- Camera with resolution ~5 μm is mounted over an illuminating LED ring
- Wafers' area of 2.8x1.8 cm is imaged
- Correspondence pixel-μm is determined



VIR-0944A-17

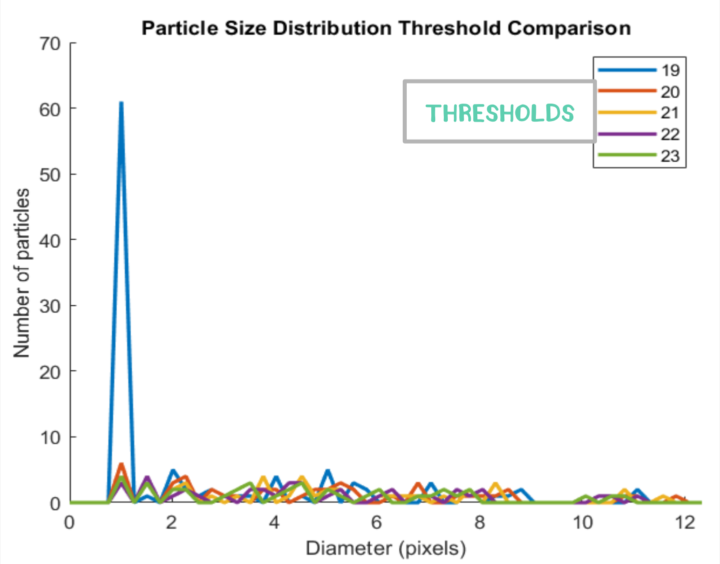
IMAGES ACQUISITION

- Optimal values for numerical aperture and height of illuminating LED ring were set
- Multiple identical images for noise-averaging purposes are taken
- Images are acquired via **PixeLINK Image Capture** (freeware)



IMAGES PROCESSING

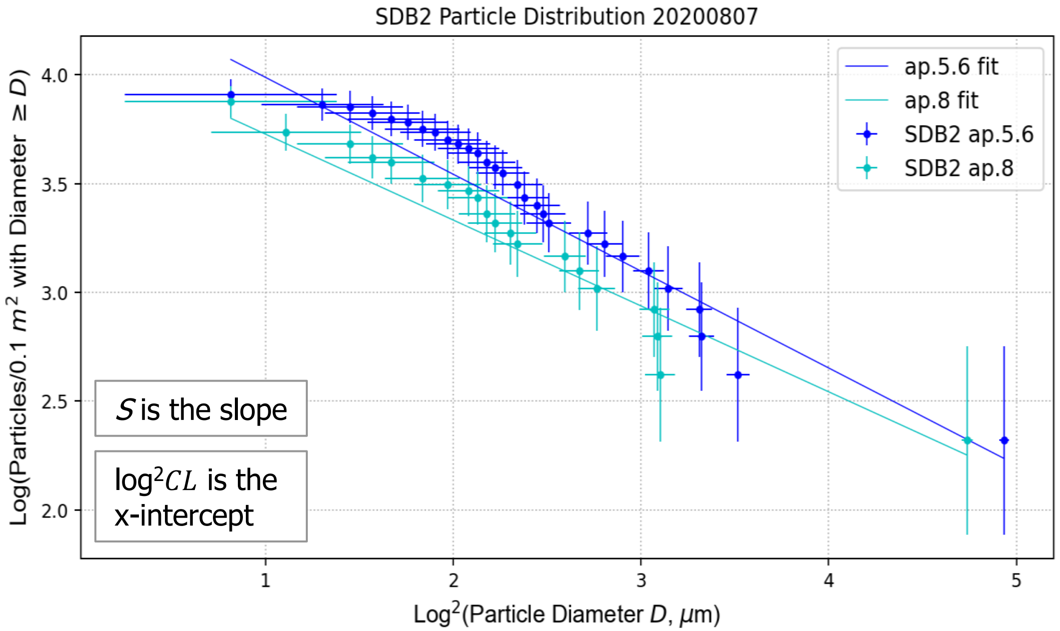
- **ImageJ**: images are combined as projection of image stacks
- LIGO **MATLAB** code to count particles and determine diameters (set the luminosity **threshold**, below which pixels are considered background and discarded)



Details are in LIGO-G2001405

Analyses of O3 wafers

First we analyzed wafers placed in the SQZ environment employed during the third observation run O3



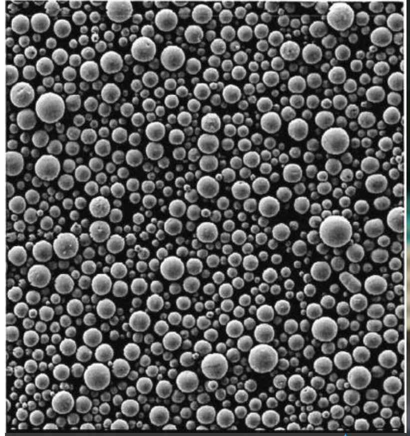
Position	Camera aperture	-Slope	CL
SDB2	5.6	0.45 ± 0.02	1429 ± 170
SDB2	8	0.39 ± 0.03	1702 ± 320
EDB	5.6	0.53 ± 0.02	881 ± 60
EDB	8	0.48 ± 0.02	998 ± 110
SQZVertical	5.6	0.38 ± 0.05	1312 ± 410
SQZVertical	8	0.42 ± 0.04	918 ± 200
WS1	5.6	0.34 ± 0.02	1642 ± 300
WS1	8	0.28 ± 0.03	2678 ± 800

Fits results are displayed in the table

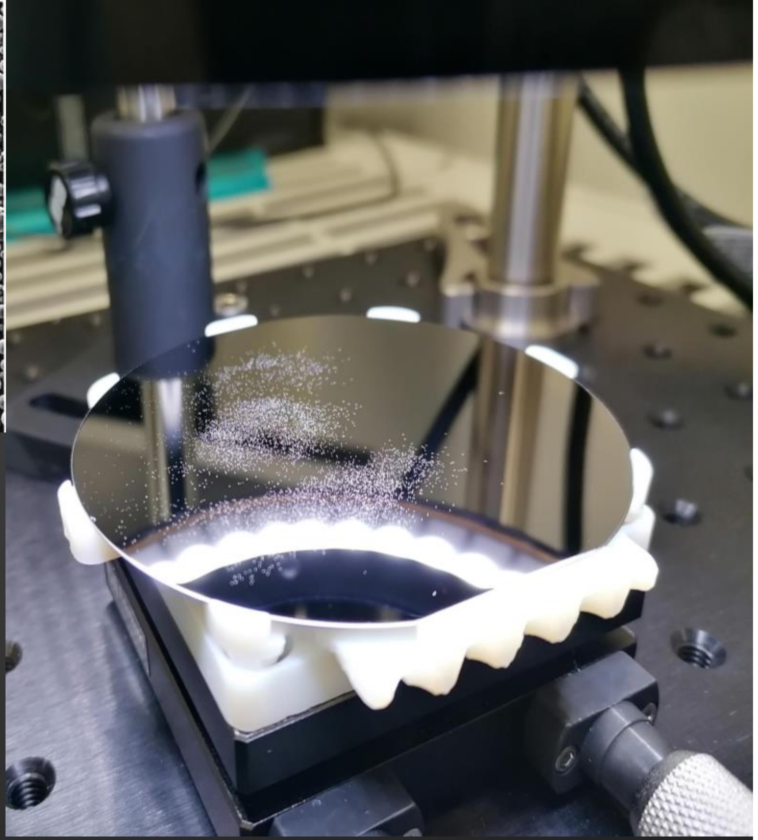
- Wafers placed horizontally except SQZVertical (placed vertically)
- Wafers exposed for a month except WS1 (exposed for a week)

Comment & Conclusions

- Fit results are **similar** in spite of wafers' variety of placement locations
- Overall: CL **higher** than standard values considered in initial analyses
- Saturation effect visible at small diameters in the data distributions (especially for smaller apertures) due to camera resolution
- Fit **not** in agreement with IEST model: other theoretical particle distribution include Gaussian and uniform
- **SQZVertical** and **WS1** are not cleaner than the others, as one would expect (possible handling process "spoiled" the wafers in a similar way?)



MOLYBDENUM MORPHOLOGY



TITANIUM POWDER ON A CLEAN WAFER

Images acquisition: fine tuning

Calibrated metal-based powder (Molybdenum & Titanium)

Use calibrated powder to determine **best** correct camera system **parameters** by taking pictures with different:

- Exposure time
- Camera aperture
- Focus

Extract particle counts via MATLAB code:

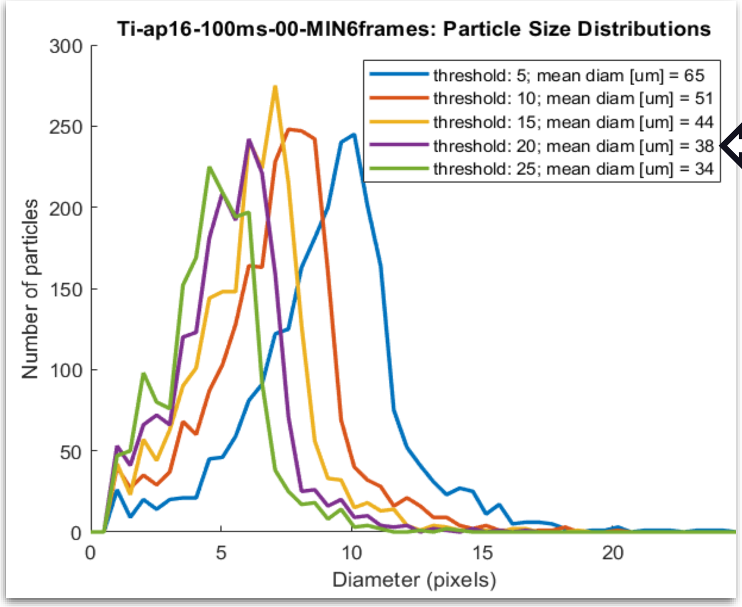
For each image, code will output particle size distribution as a function of luminosity threshold

Determine best values of parameters:

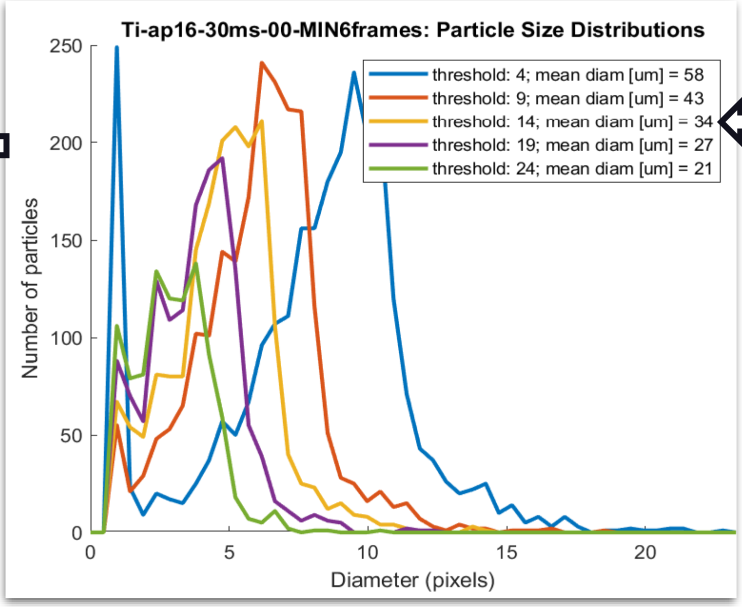
Analyze distributions and find the ones more **similar** to the known one

Images acquisition: fine tuning

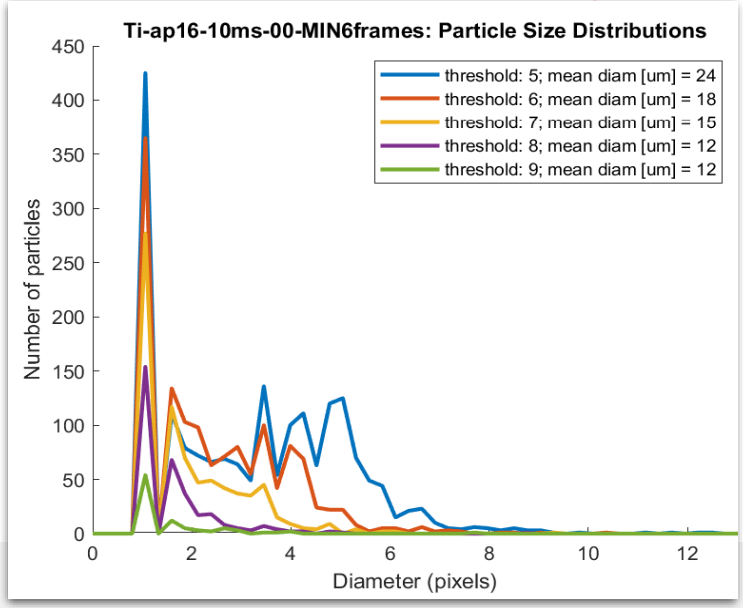
EXPOSURE TIME 100 MS



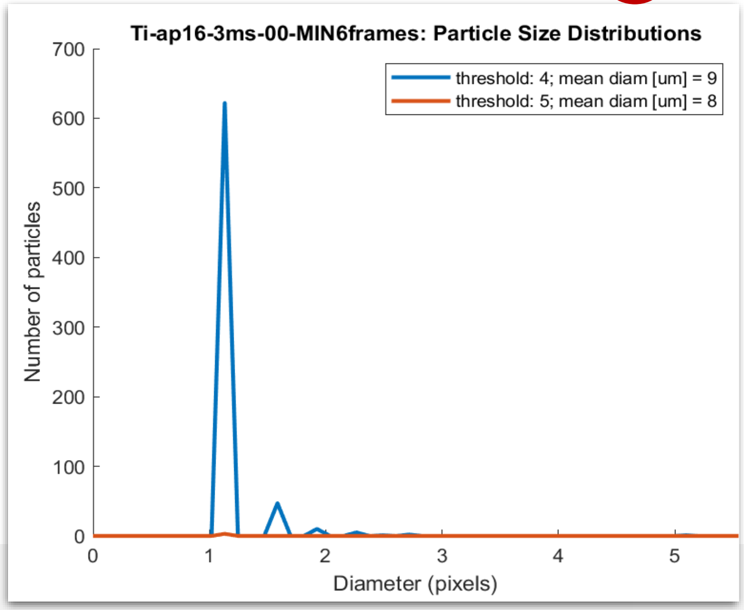
EXPOSURE TIME 30 MS



EXPOSURE TIME 10 MS



EXPOSURE TIME 3 MS



Example of analysis: Titanium particle distributions with calibrated **mean diameter = 38 μm** for 4 different exposure times

Curves in each graph are distribution for different luminosity thresholds

Legend displays the computed mean diameter for each curve

Calibrated Titanium particles mean diameter = 38 μm: exposure time > 30 ms works better

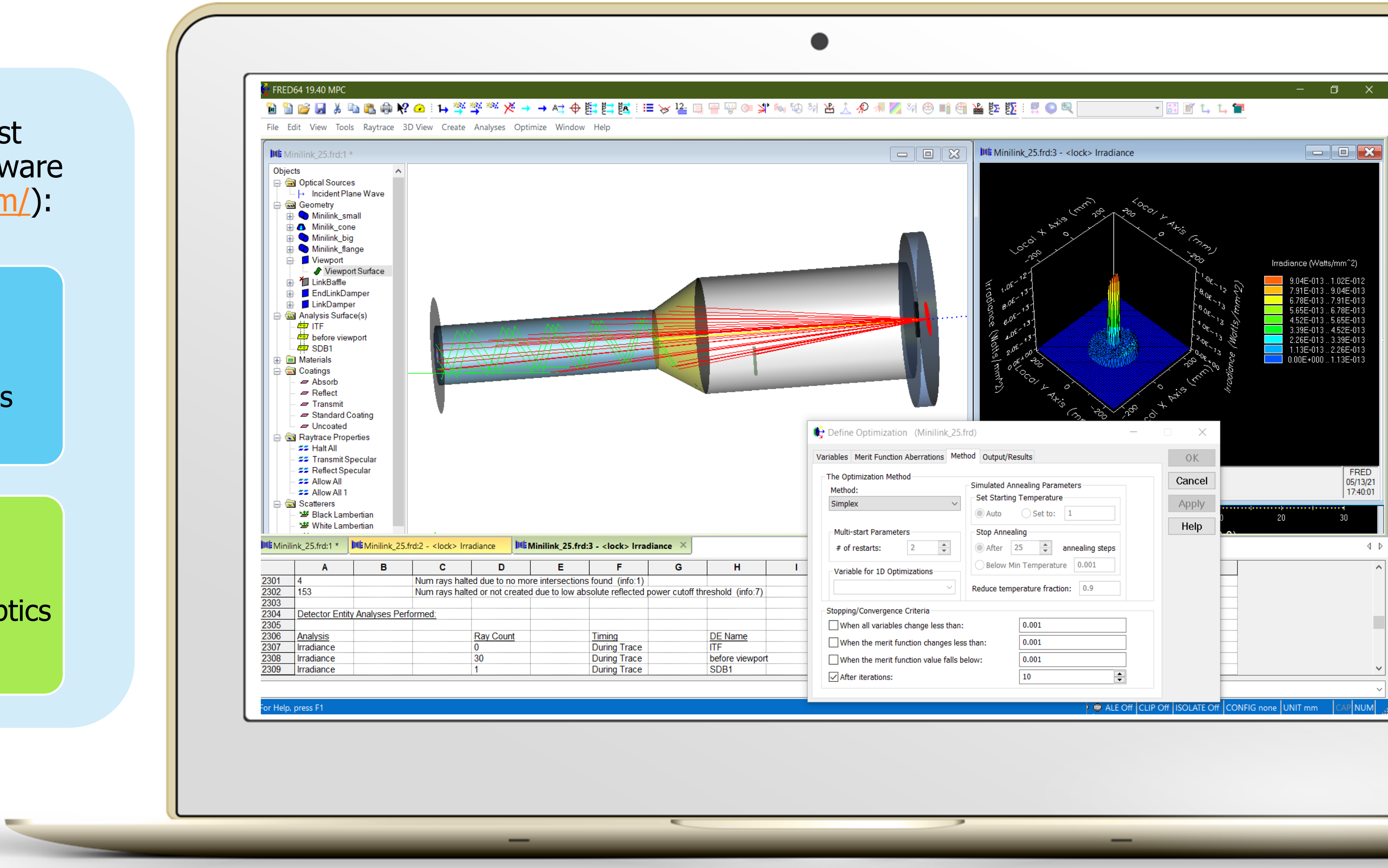
Analyses just started, more **WORK IN PROGRESS**

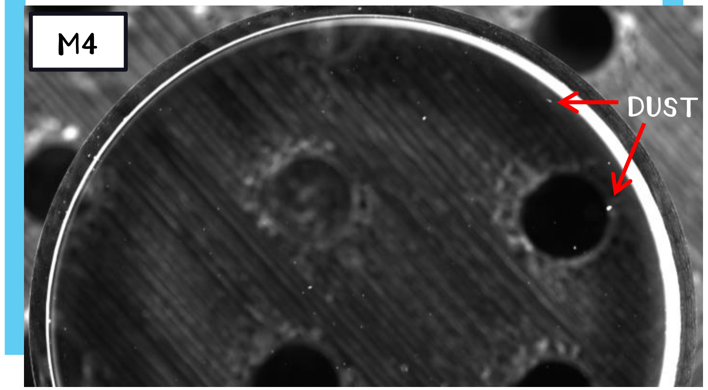
Dust scattering simulations

Simulations of stray light from dust are performed via FRED Optical Software Engineering (https://photonengr.com/):

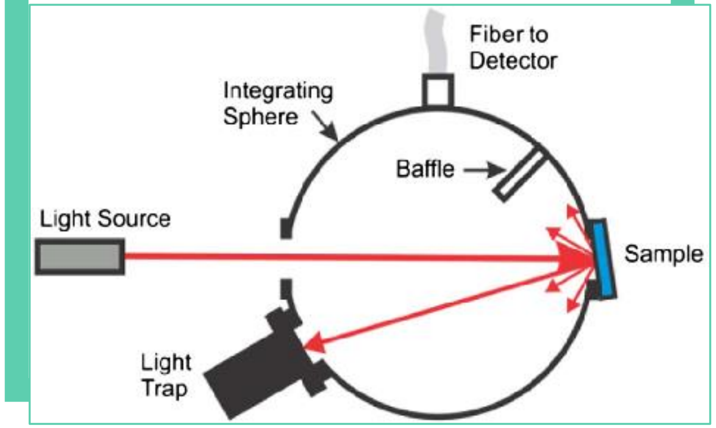
Particle distributions from wafers' images will be the **input** values for the simulations

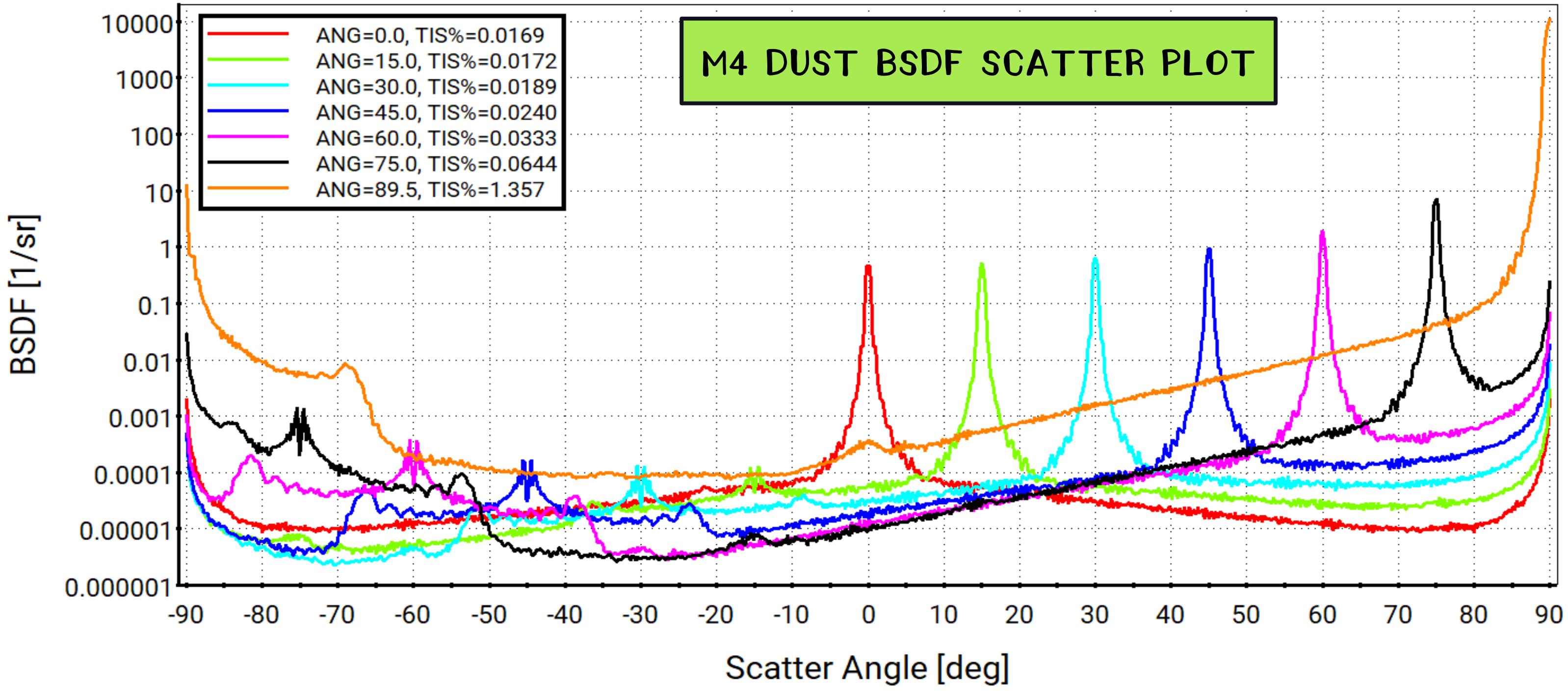
Wafer -> particle distribution -> scattering model to apply to nearby optics





Extract dust distributions of two mirrors used in O3 in SQZ → Put the distributions in FRED and derive dust BSDF & **TIS** → Measure TIS directly at 0° AOI with an Integrating Sphere → Results obtained @0° AOI are **comparable** (table)





Mirror	Integrating Sphere TIS [ppm]	Dust Analyses TIS [ppm]
M4	258(4)	169
M5	241(12)	228

Dust scattering simulations

Conclusions

PRELIMINARY STUDIES

- Dust is projected to be a **major** source of scattering in SQZ
- Dust distribution on optics difficult to model, better **measure** it

DUST IMAGES WITH CAMERA SYSTEM

- We have identified a procedure for determining surface particulate contamination in a cleanroom environment
- Preliminary studies on O3 wafers: found **CL** values are much higher than standard values (which are up to CL = 1000)
- Preliminary studies on O3 wafers: experimental data **distributions** not in agreement with IEST STD CC1246D: this could suggest a need for more data, shortcomings in IEST's ability to represent our environment, or handling contamination
- Dust images with **calibrated** distribution of powder can aid setting right parameters for imaging system and will allow to increase the accuracy of measured distributions

Future work

DUST IMAGES WITH CAMERA SYSTEM

- Analyze dust images of samples placed in SQZ environment during O4 Commissioning
- Setup numerical **simulations** of stray light from dust, once reliable particle distributions are derived
- Investigate other particle distributions available in FRED to fit the data

CALIBRATION WITH SAMPLED DUST

- Analyze images from different areas of wafers
- Study the criticality of **focus**
- Use other calibrated parameters like 10 & 90 **percentiles** to help differentiate between curves
- Calculate **integrals** of curves to determine total #particles
- Develop a strategy to discern between **threshold** values and determine the right one
- Explore other types of combinations in **ImageJ** (e.g. use sum rather than minimum intensity projections)

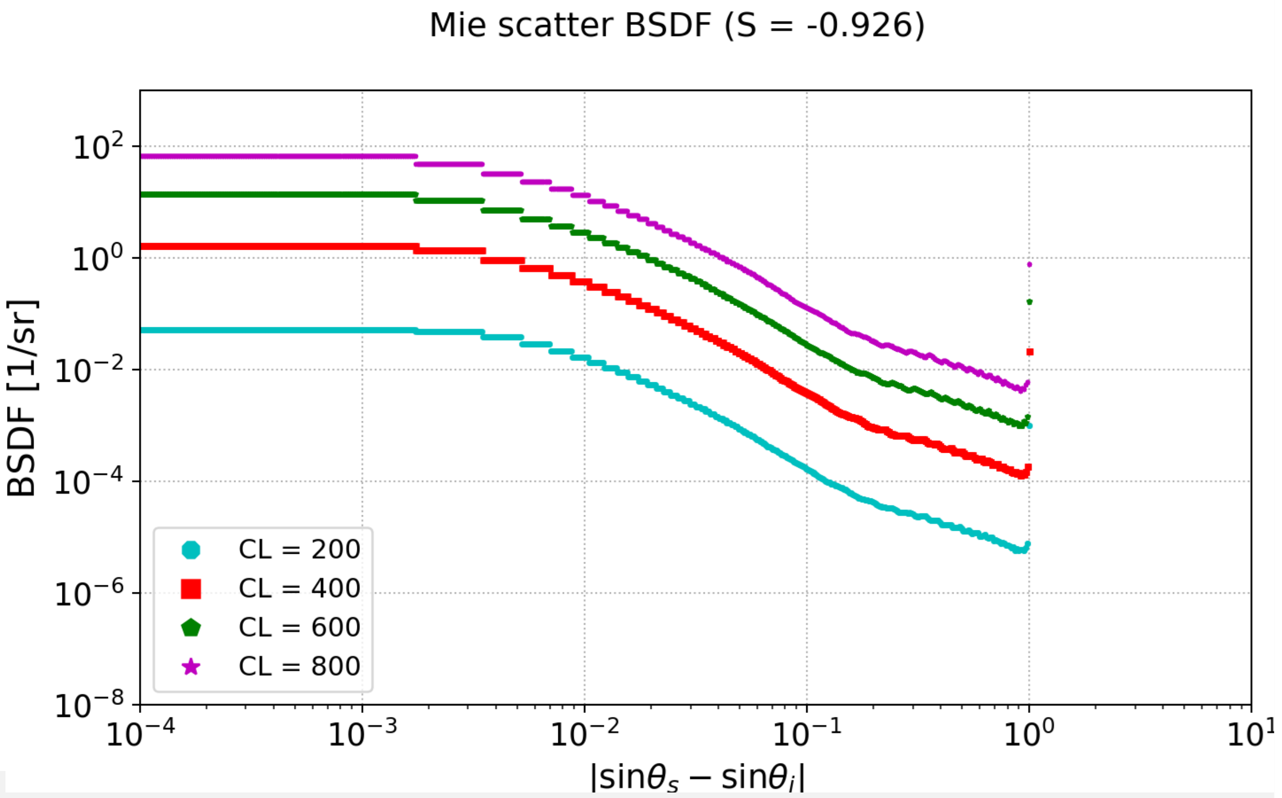
Additional slides

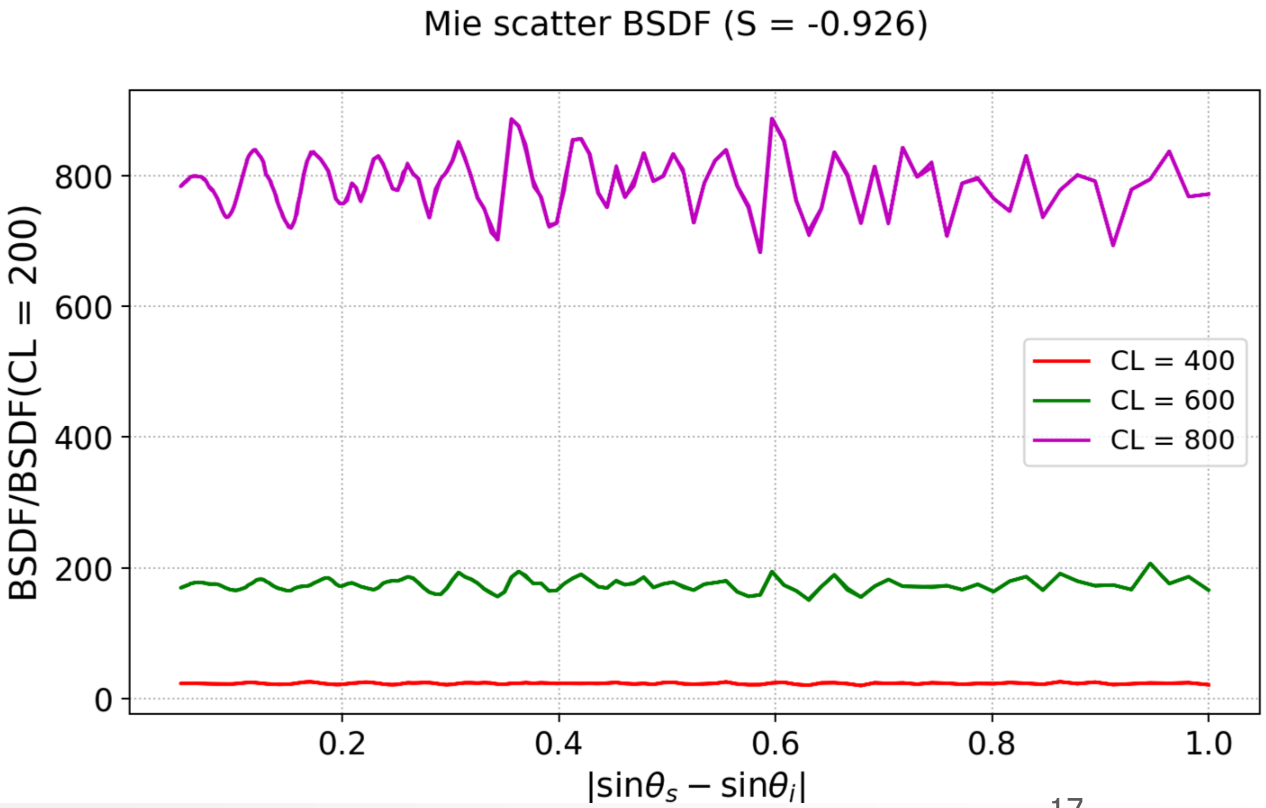
Surface cleanliness level CL

In order to see how much the BSDF is affected by the choice of the CL, we plotted the BSDF as a function of CL for a fixed value of the particle distribution slope *S*

By taking the ratio between the BSDF for each CL value and the BSDF for CL = 200, a scale factor can be derived:

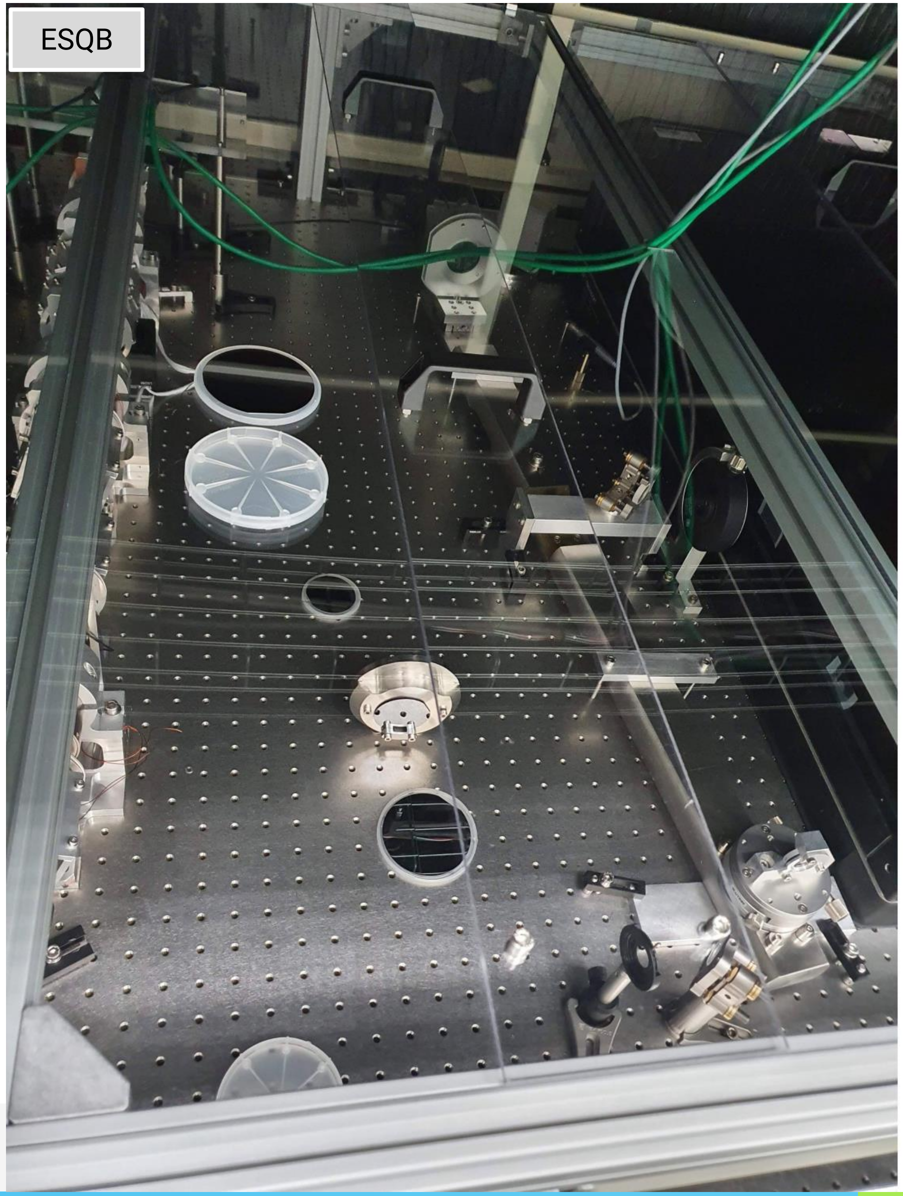
- CL = 400: scale factor = 23
- CL = 600: scale factor = 174
- CL = 800: scale factor = 787



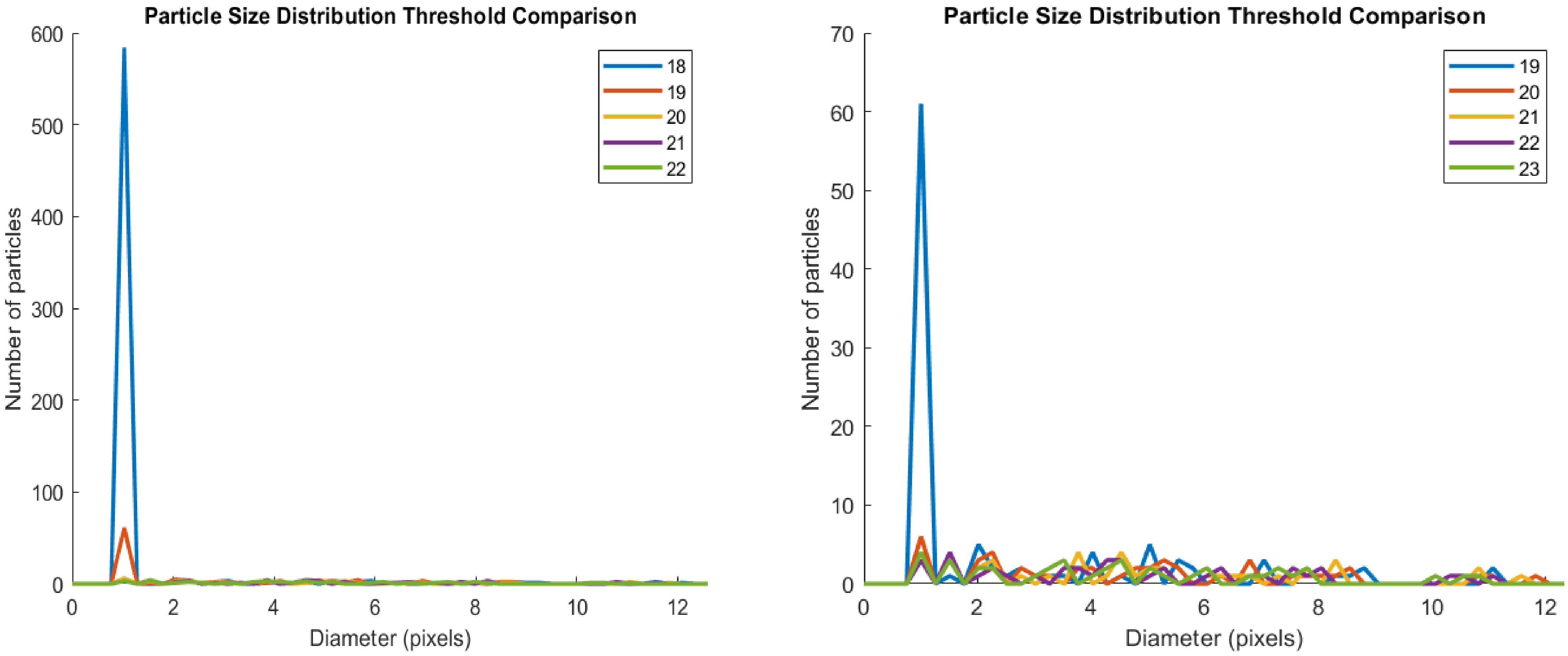


Wafers in O3 (SQZ environment)

- WS1: on ESQB, one week exposure
- SQZVertical: on ESQB, vertical
- SDB2: on top of threshold of tower structure, behind detection bench minitower
- EDB: on on top of external detection bench (EDB)

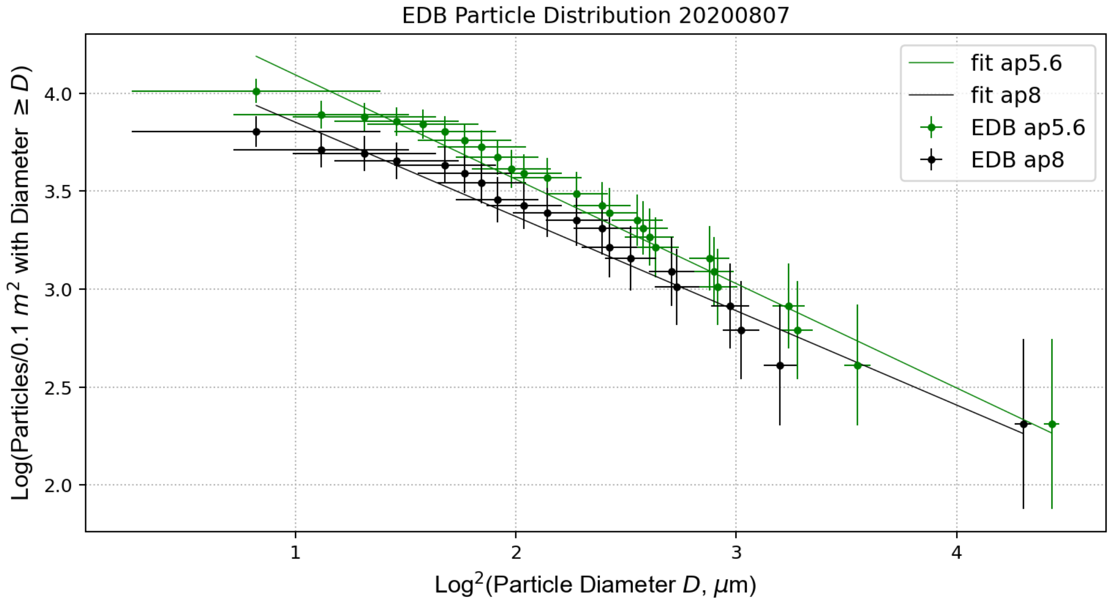


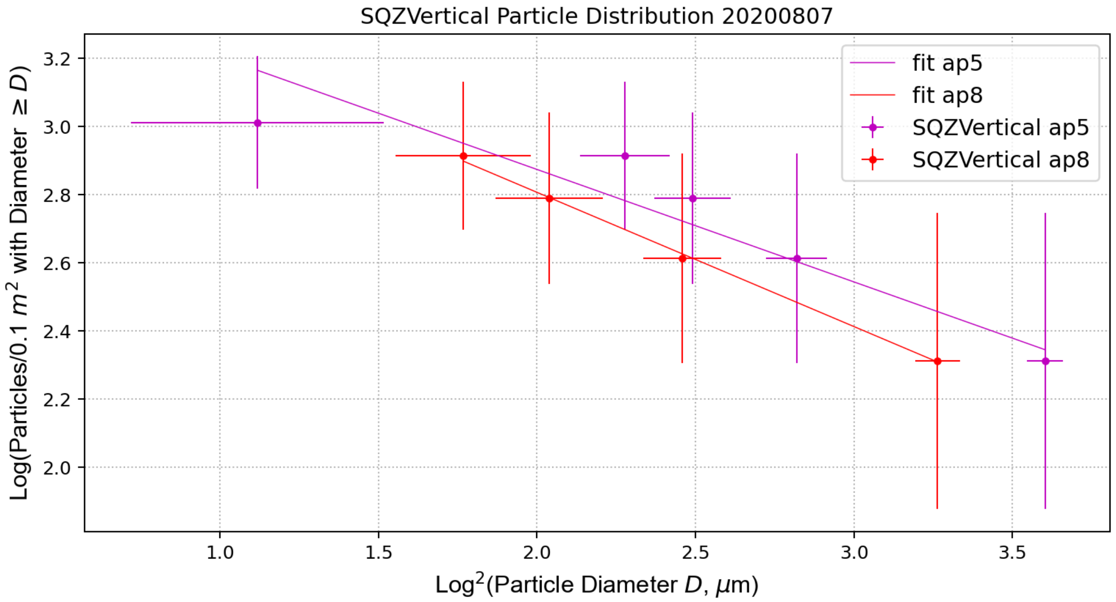
LIGO MATLAB code

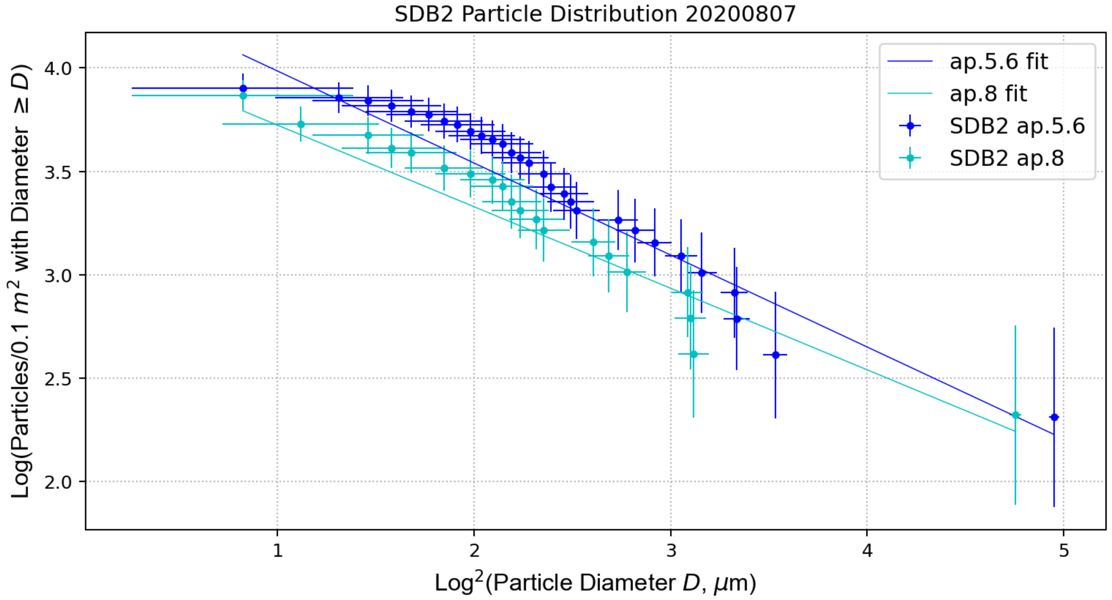


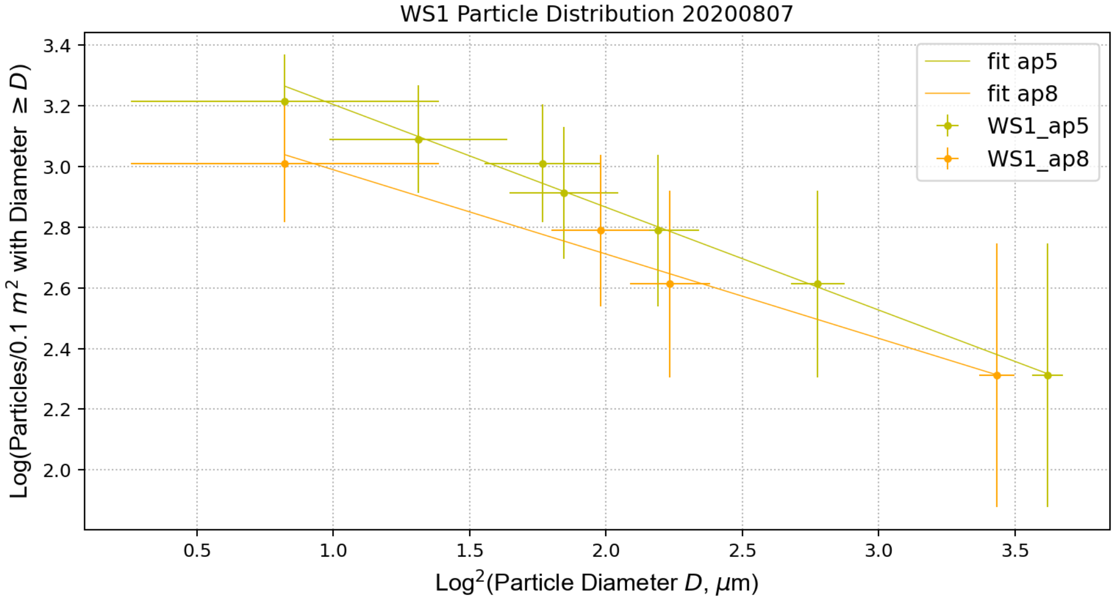
- Lower thresholds tends to overestimate the number of particles (by counting background pixels as real particles) and their diameter
- Higher thresholds tends to underestimate the number of particles and their diameter
- A compromize is needed to be found

Wafers in O3 (SQZ environment)









M4 & M5 particle distributions

Mirror	|Slope|	CL
M4	0.378 ± 0.008	2786 ± 143
M5	0.460 ± 0.008	1703 ± 69