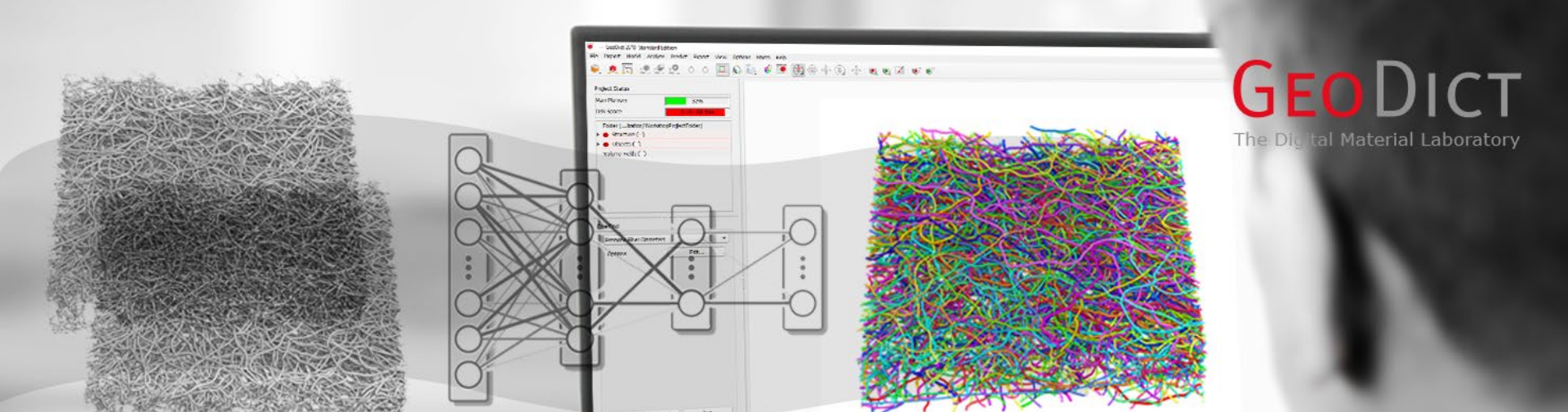




# MACHINE LEARNING-BASED SEGMENTATION AND IDENTIFICATION OF FIBER AND BINDERS IN $\mu$ CT IMAGES OF FIBROUS MEDIA

FiltXPO 2020

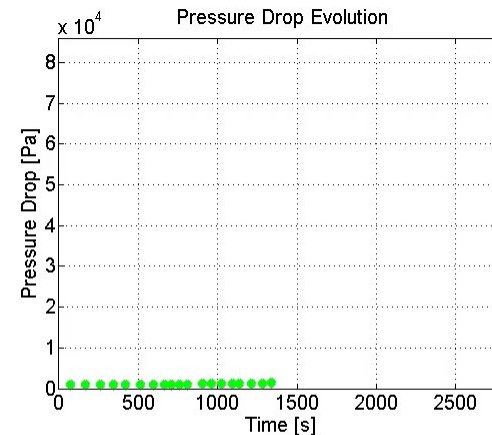
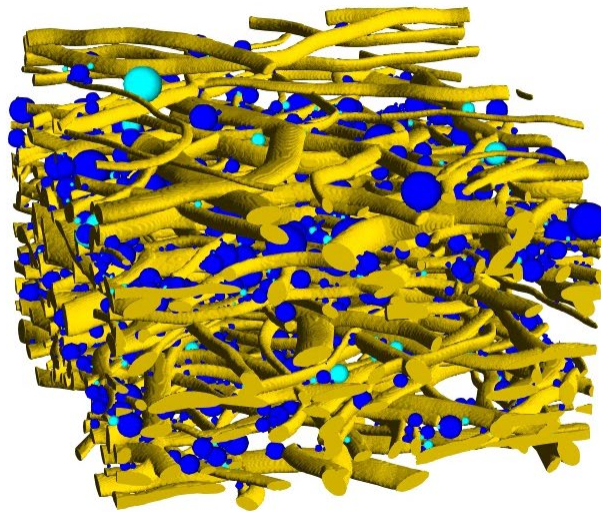
Chicago, February 27<sup>th</sup>, 2020

Andreas Wiegmann, Andreas Grießer, Rolf Westerteiger, Mehdi Azimian,  
Math2Market GmbH, Germany

# WHY DIGITALLY DESIGN FILTER MEDIA?

GEODICT

- It saves time: Media modelling and filtration simulation are much faster than manufacturing and experiments
- It saves money: Media modelling and process simulation are cheaper than manufacturing and experiments
- Fewer prototypes
- Better results





# DOES DIGITAL DESIGN REQUIRE A DIGITAL TWIN? GEODICT

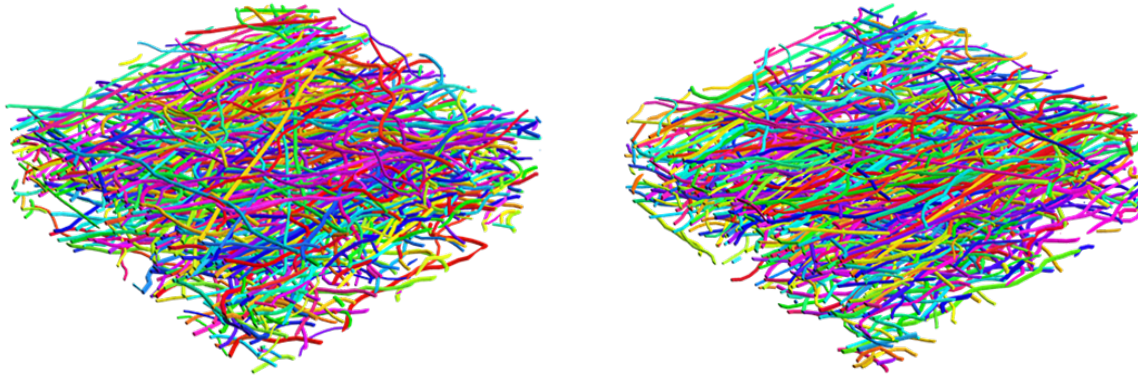


# NO!

- We see segmented  $\mu$ CT scans of 2 cutouts of a filter media.
- Both are “digital twins” of the real media
- Yet they differ
- They are data, not information
- And they cannot be used for filter media design!

# DIGITAL DESIGN REQUIRES A STATISTICAL TWIN! (THE MATERIAL ANALOGUE OF A DIGITAL TWIN)

GEODICT

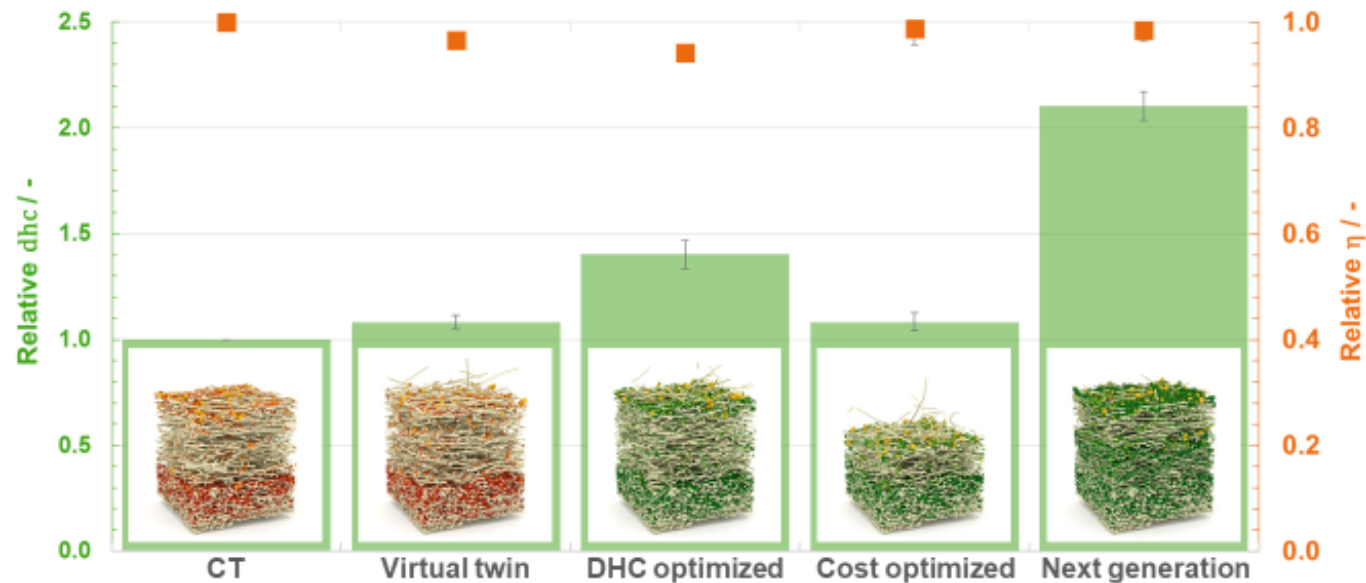


- Now we see the individual fibers
- We know their stats
  - diameters
  - orientations
  - porosities
  - ...
- Their statistics are the same
- We can modify the stats to optimize filter media!

# CLIENT BENEFIT – NEXT GENERATION FILTER MEDIA FOUND BY COMPUTER SIMULATIONS

GEODICT

Optimization of a virtual filter media prototype  
Pushing the limits 2.0 – next generation



11

Kaiserslautern, September 27th, 2017  
Simulation-driven development and optimization of virtual filter media prototypes

**MANN+**  
**HUMMEL**

# TRADITIONAL FILTER MEDIA DEVELOPMENT: EXPENSIVE AND LENGTHY PROTOTYPE TESTS



## Experiments on real media

Filter media  
prototyping



measure

Properties

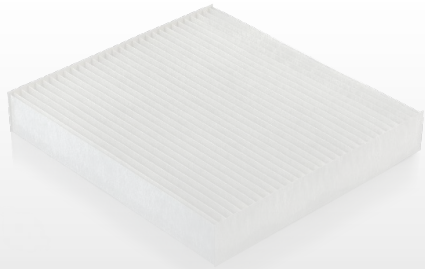
## Desired Properties

- Pore size distribution
- Pressure drop, permeability
- Filter efficiency
- Dust holding capacity
- Producibility
- Manufacturing costs
- ...

≠



# MODERN FILTER MEDIA DEVELOPMENT: DIGITAL MATERIAL LABORATORY - FAST & ECONOMICAL



Experiments on real media

Filter media  
prototyping



measure

Properties

## Desired Properties

- Pore size distribution
- Pressure drop, permeability
- Filter efficiency
- Dust holding capacity
- Producibility
- Manufacturing costs
- ...



Simulation on material model

Digital model

generate

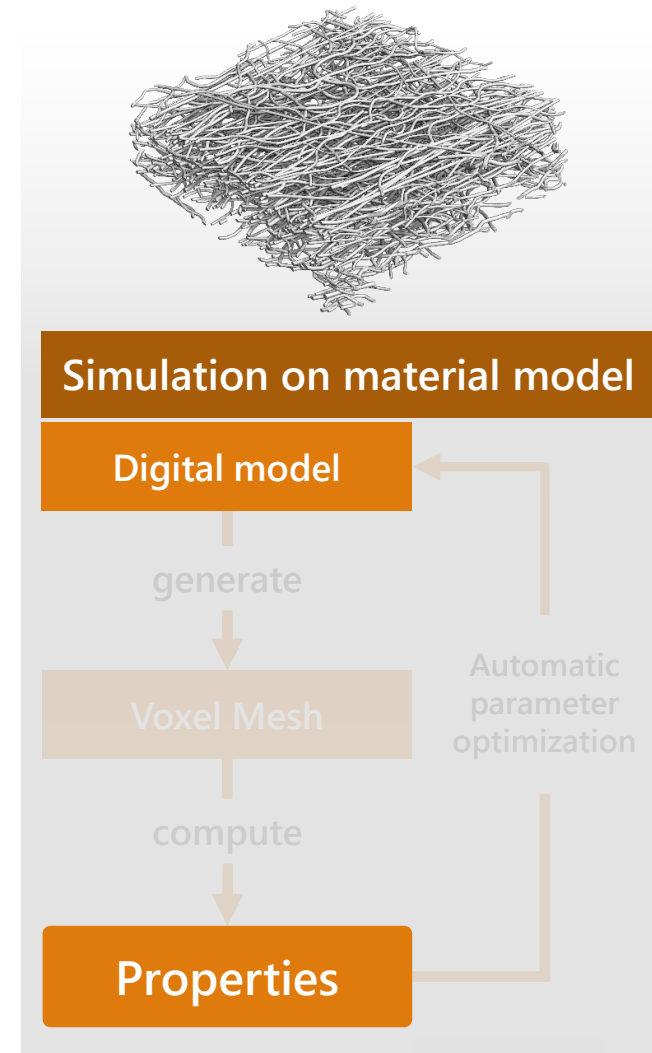
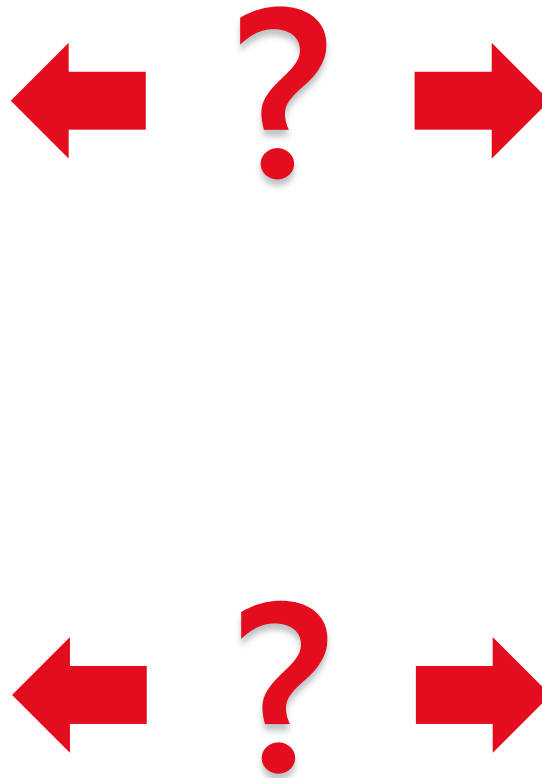
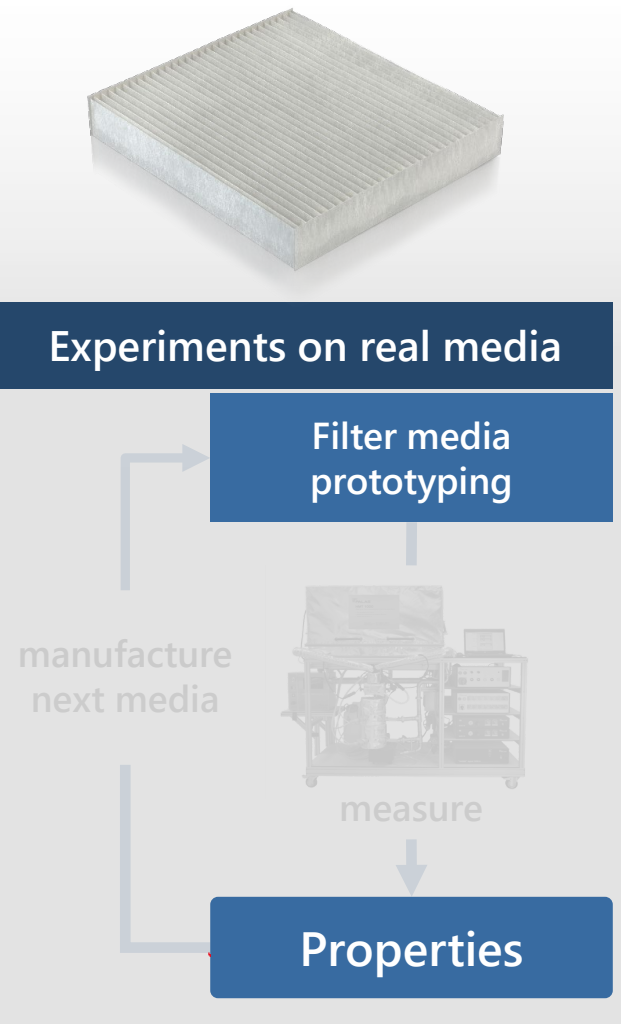
Voxel mesh

compute

Properties

Automatic  
parameter  
optimization

≠





## Experiments on real media

Filter media  
prototyping



measure

Properties



How can we prove  
that the **material model**  
is correct?



## Simulation on material model

Digital model

generate

Voxel Mesh

compute

Properties

Automatic  
parameter  
optimization



## Experiments on real media

Filter media  
prototyping



measure

Properties

How can we prove  
that the **property  
computation** is correct?



## Simulation on material model

Digital model

generate

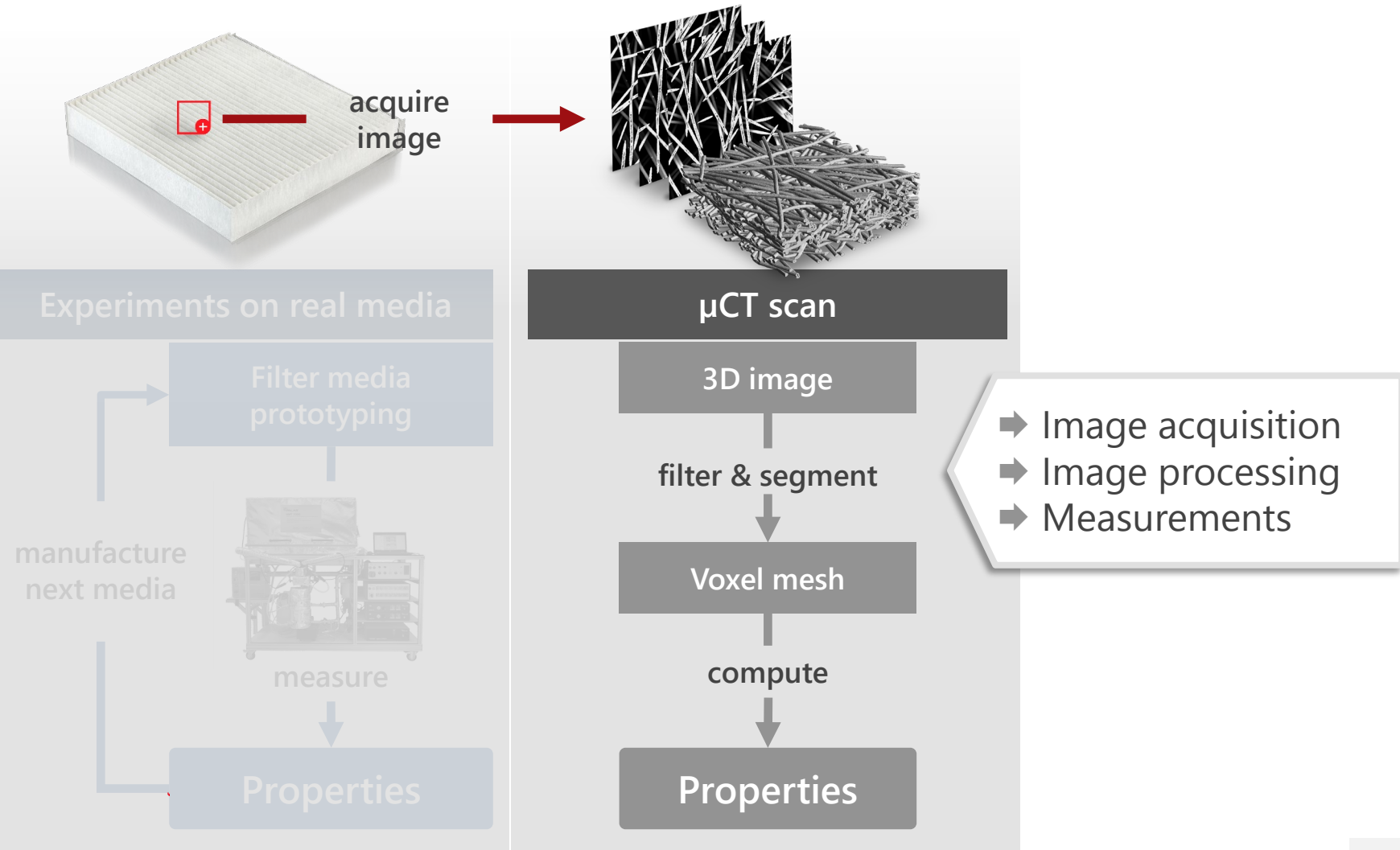
Voxel Mesh

compute

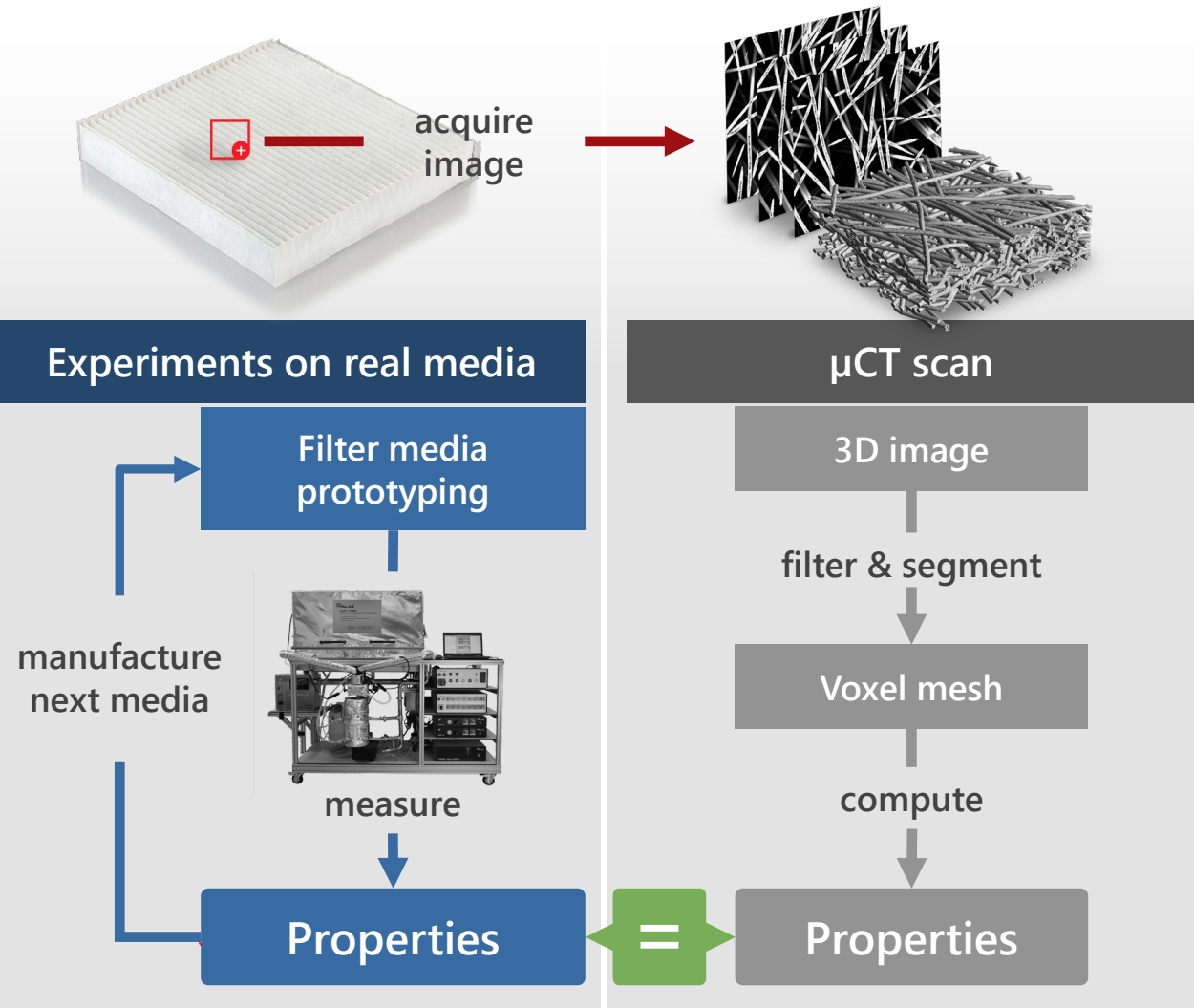
Properties

Automatic  
parameter  
optimization

# STEP 1: COMPUTE MATERIAL PROPERTIES

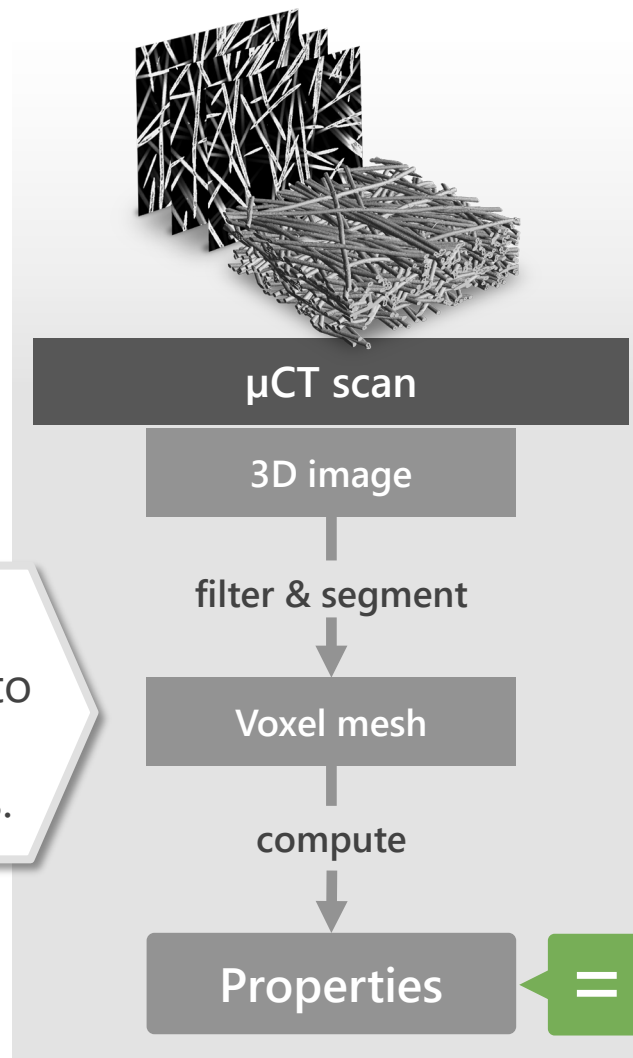


# STEP 1: COMPUTE MATERIAL PROPERTIES

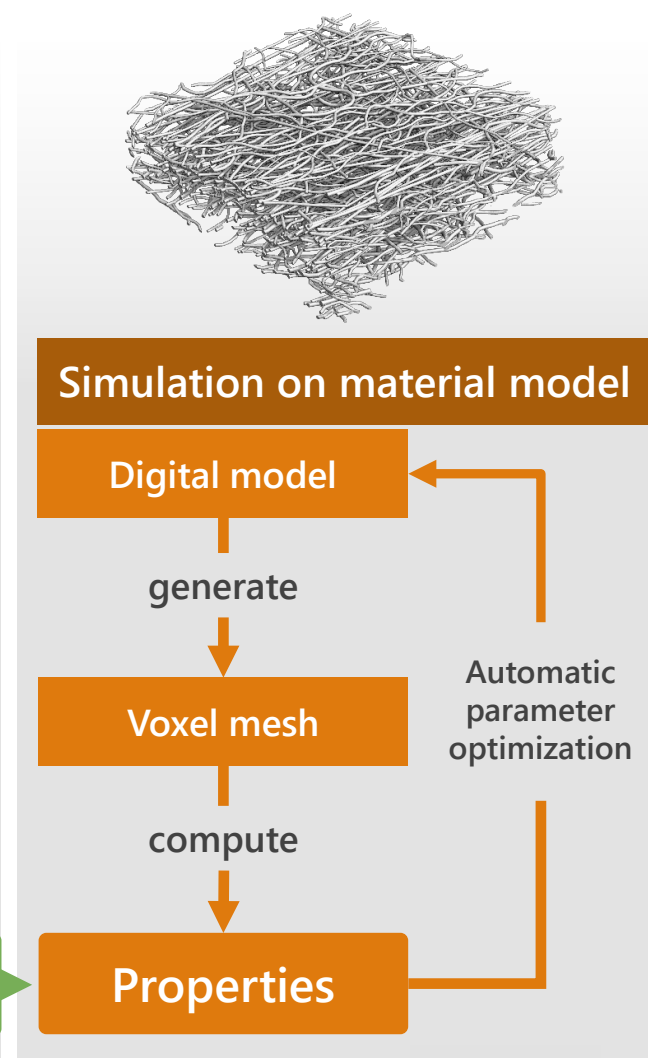




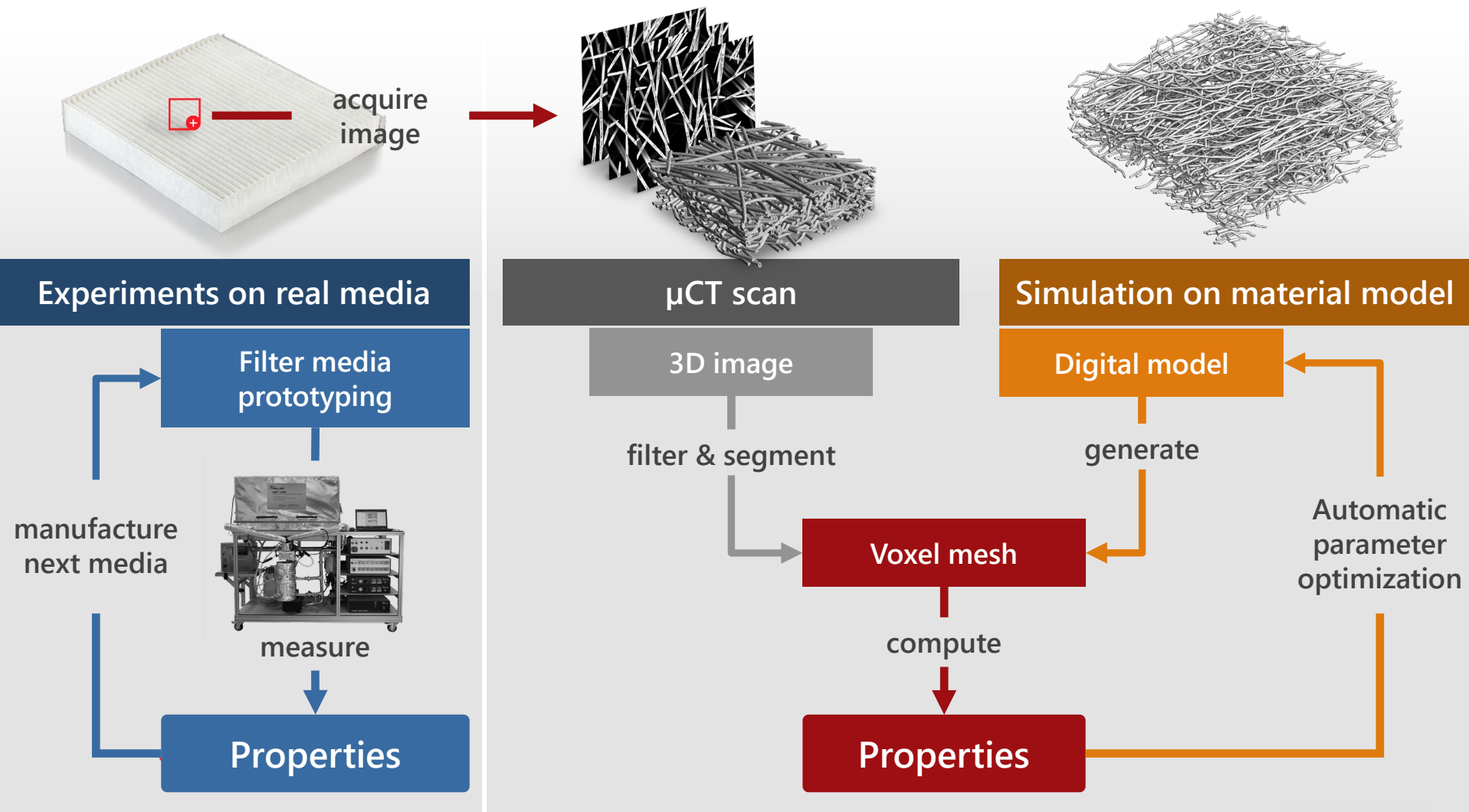
## STEP 2: CREATE THE DIGITAL MATERIAL MODEL



3D images and **digital models** are converted into **Voxel meshes** to achieve synergies for calculations.



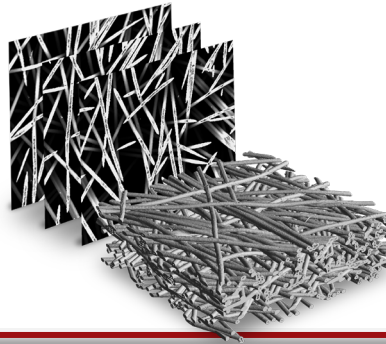
## STEP 2: CREATE THE DIGITAL MATERIAL MODEL



# FIRST MODELS ARE OFTEN 3D IMAGES

GEODICT

## Computer Tomography



## Experiments on real media

Filter media  
prototyping



measure

Properties

manufacture  
next media

## $\mu$ CT scan

3D image

filter & segment

Voxel mesh

compute

Properties

## Simulation on material model

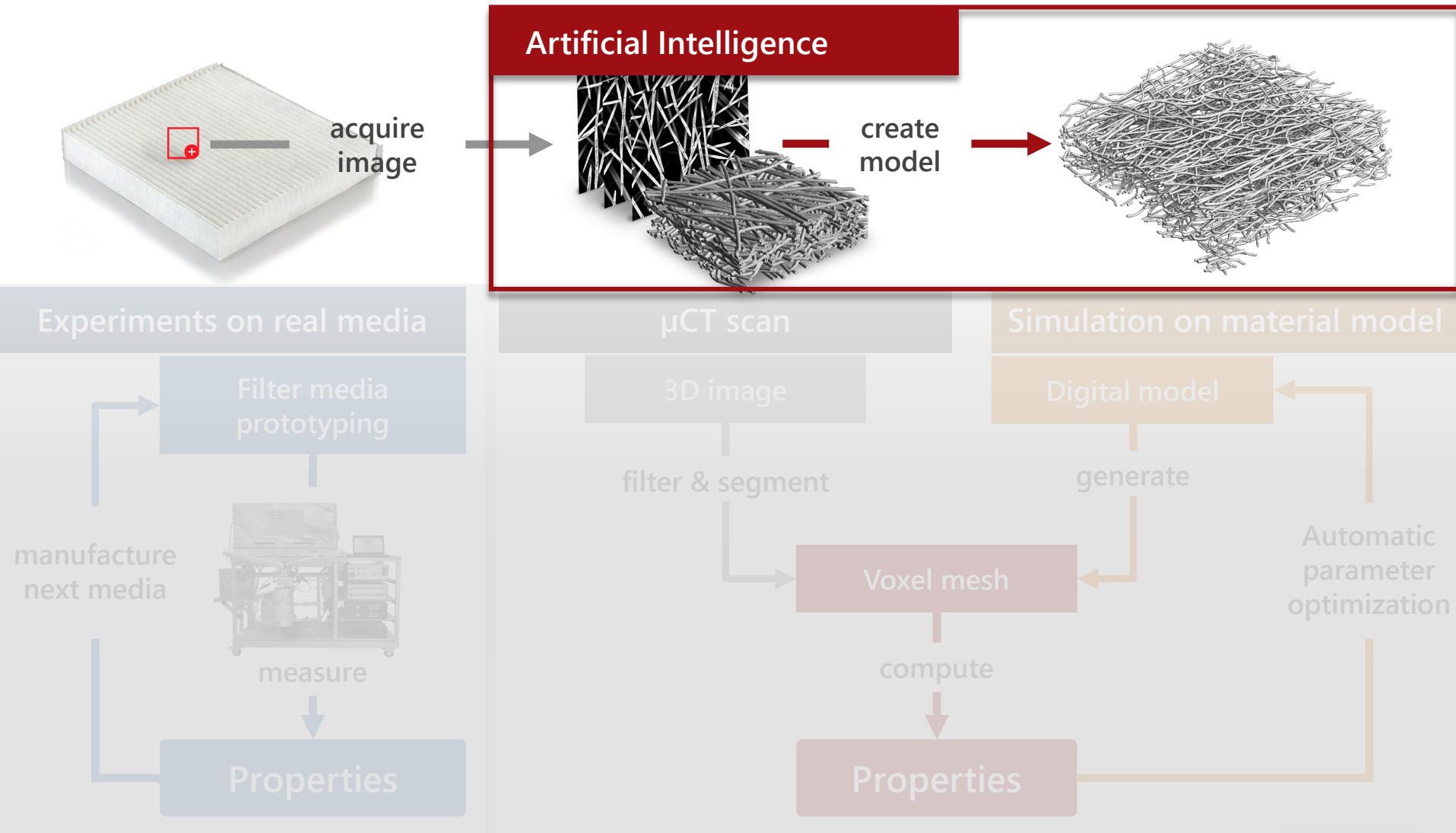
Digital model

generate

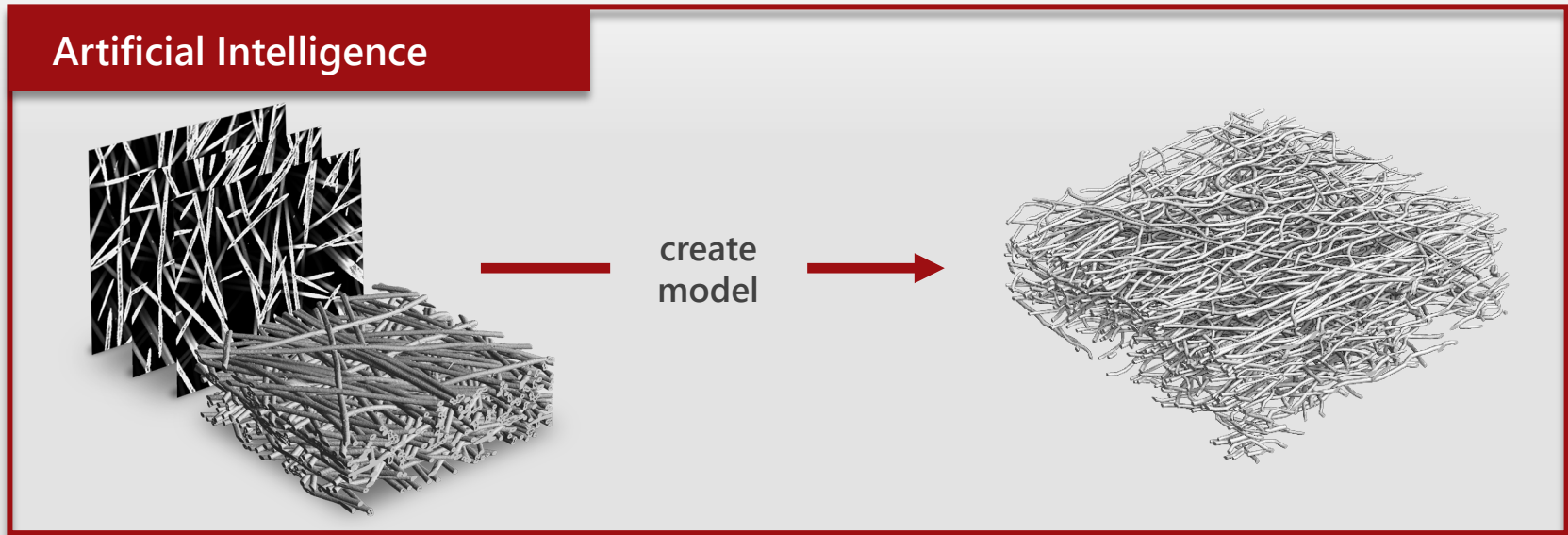
Automatic  
parameter  
optimization

# GET MODELS FROM 3D IMAGES

GEODICT



# THIS PREVIOUSLY MANUAL STEP IS FACILITATED BY AI



# BENEFITS OF AI TO CREATE DIGITAL MODELS DIRECTLY FROM THE $\mu$ CT SCAN



## Without AI

- M2M employees necessary  
➔ data leave client premises
- Single fiber detection insufficient
- Days to find model parameters
- Object-based characterization costly and only partly possible
- High costs with less automation and uncertain results



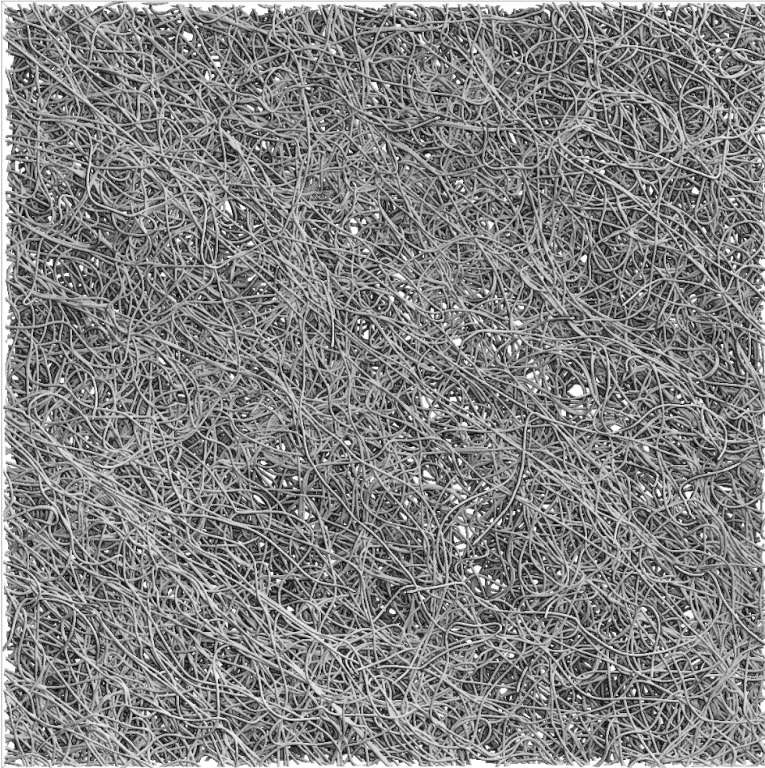
## With AI

- No M2M personnel required  
➔ data remain at client
- AI finds fibers in hours
- AI finds model parameters in hours
- Object-based characterization easily and generically possible
- Low costs with complete automation and guaranteed results

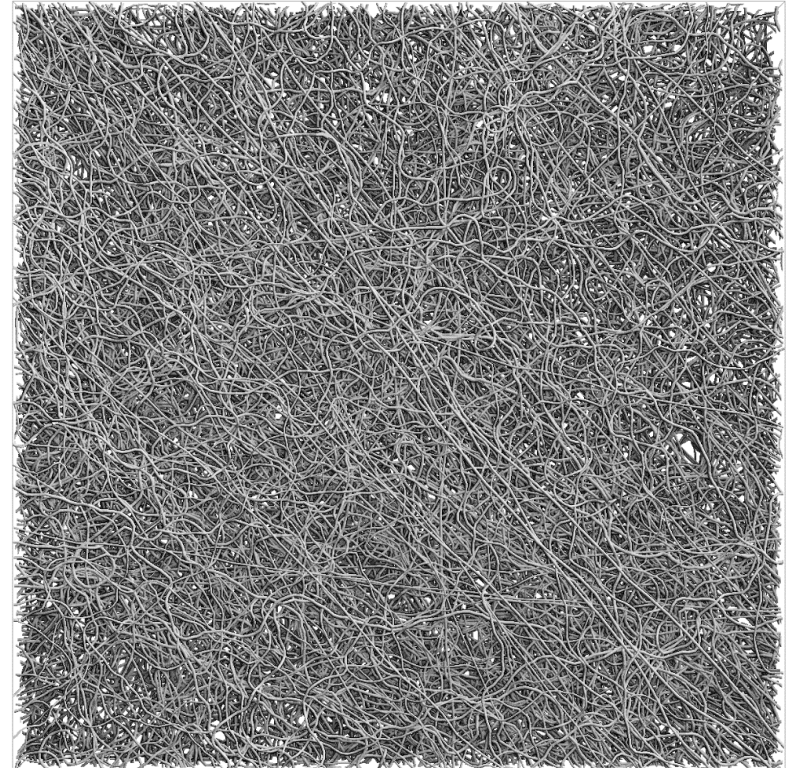


# CT-SCAN VS STATISTICAL TWIN GENERATED IN GEODICT

GEODICT



μCT-scan

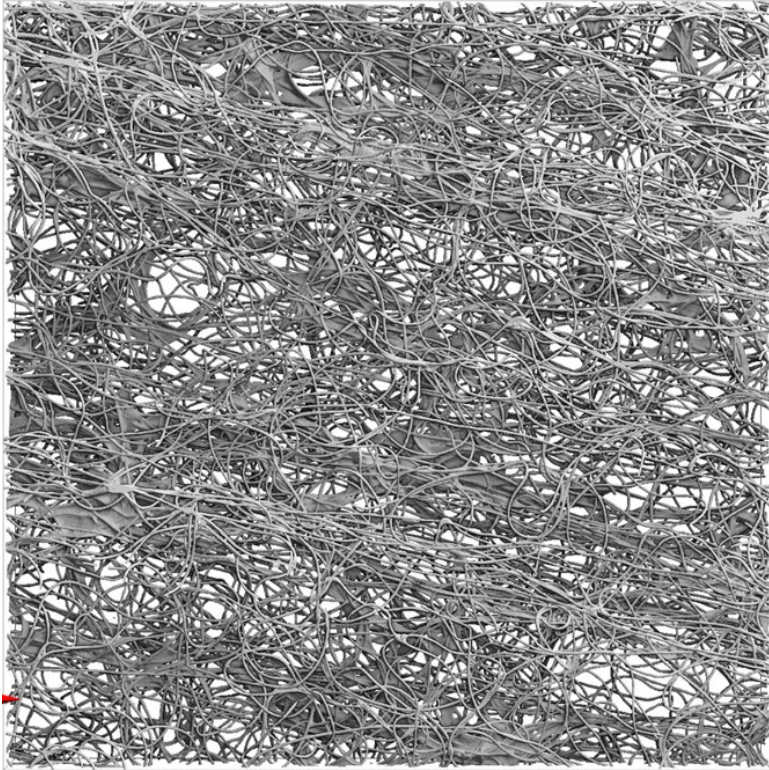


Statistical Twin

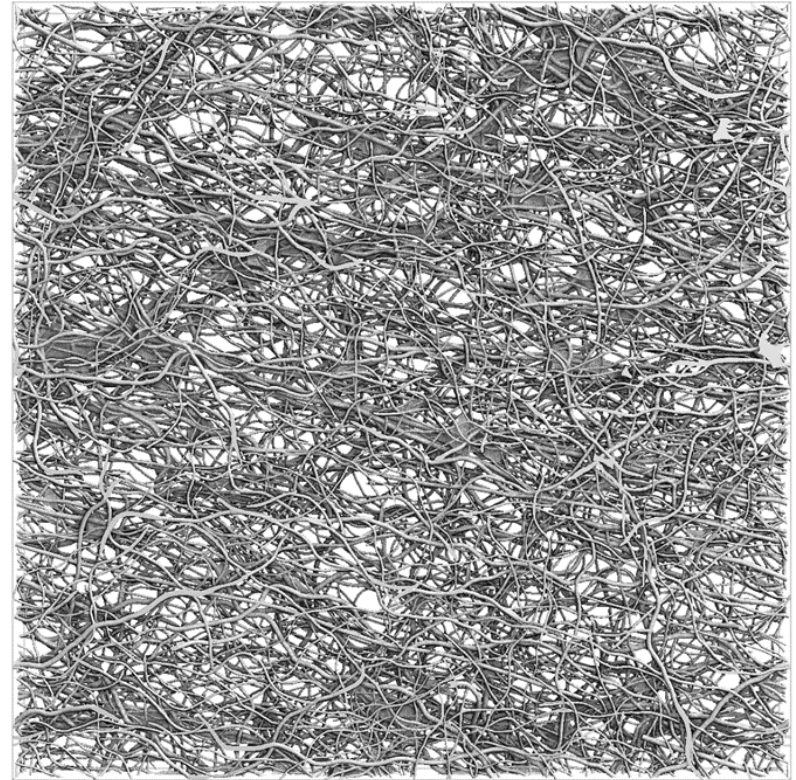


# CT-SCAN VS STATISTICAL TWIN GENERATED IN GEODICT

GEODICT



μCT-scan

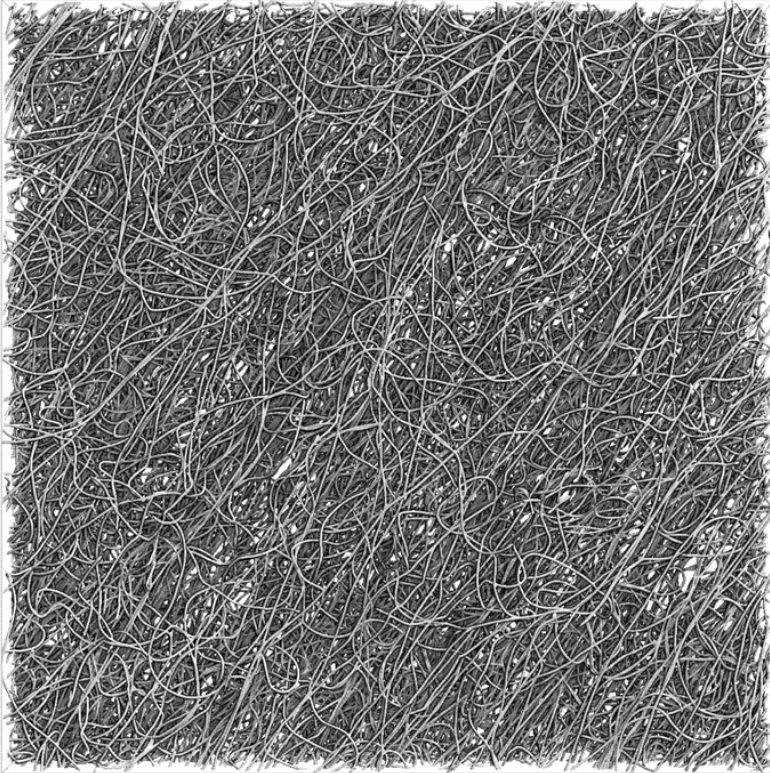


Statistical Twin

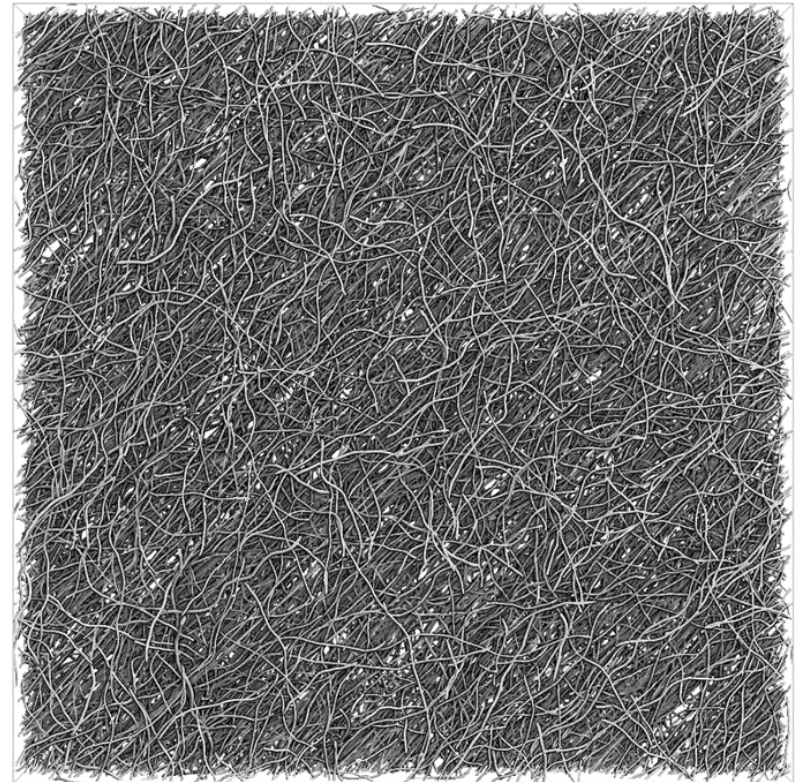


# CT-SCAN VS STATISTICAL TWIN GENERATED IN GEODICT

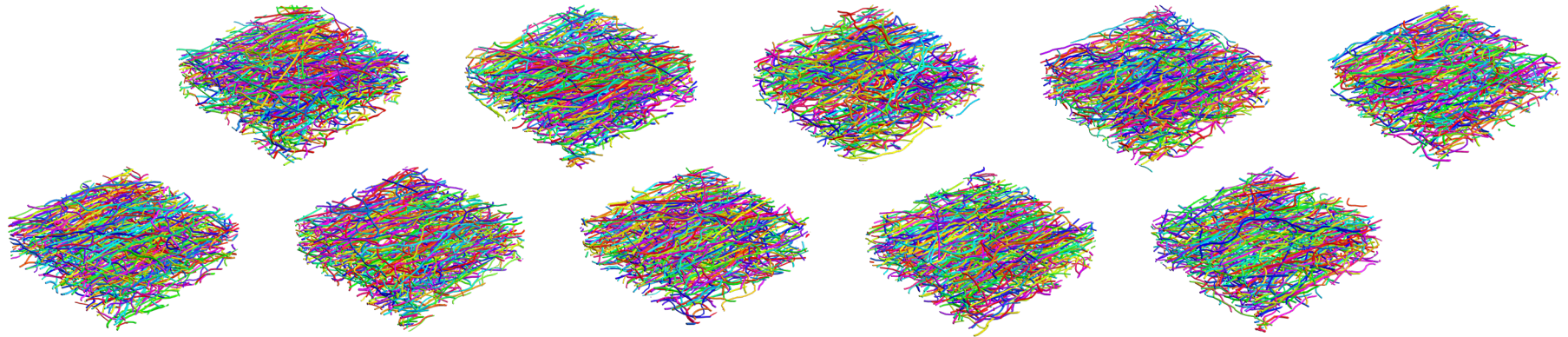
GEODICT



$\mu$ CT-scan



Statistical Twin



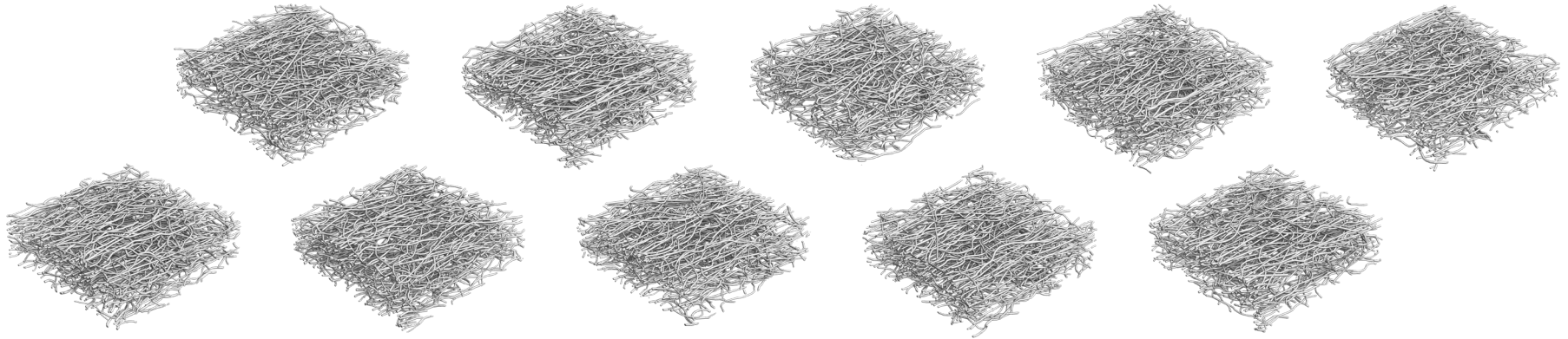
Training Data: Use GeoDict's unique fiber modelling capabilities:

- Modeled 10 Statistical siblings (512x512x256 Voxels) as training data
- Varied fiber curvature, orientation, length and diameter



Corresponds to  $\sim 1/2$  billion solid voxels as training points

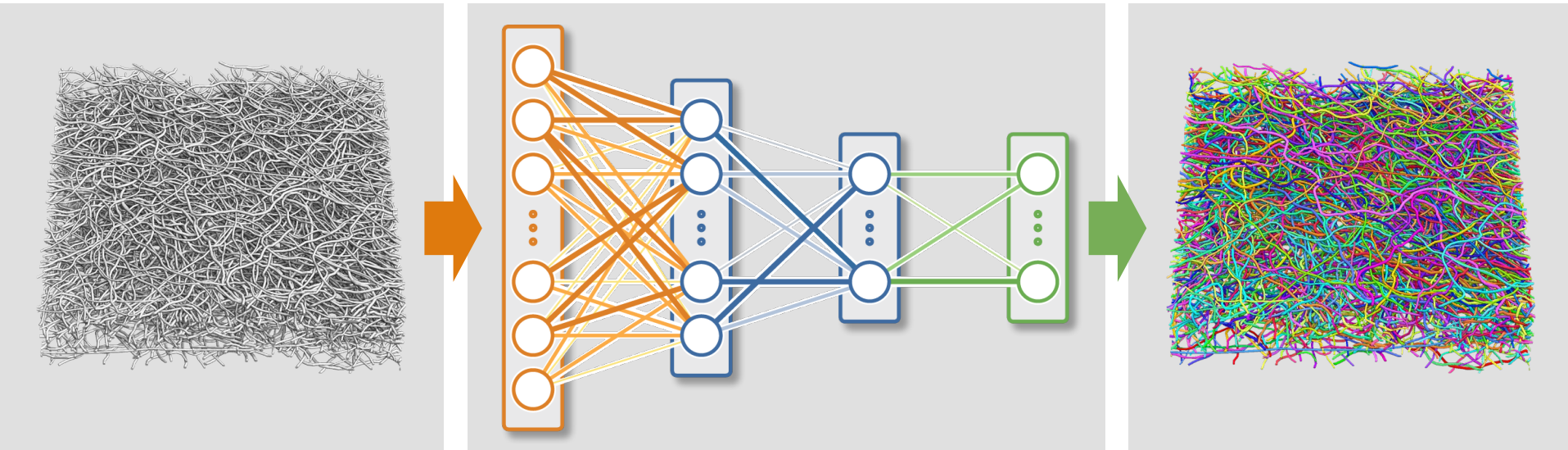




**Training Data: Then make the models look like binarized scans!**

- All fibers in the models get the same gray value, just as in the segmented 3D scans

# NEURAL NETWORK (N.N.) TRAINING & USAGE PHASES

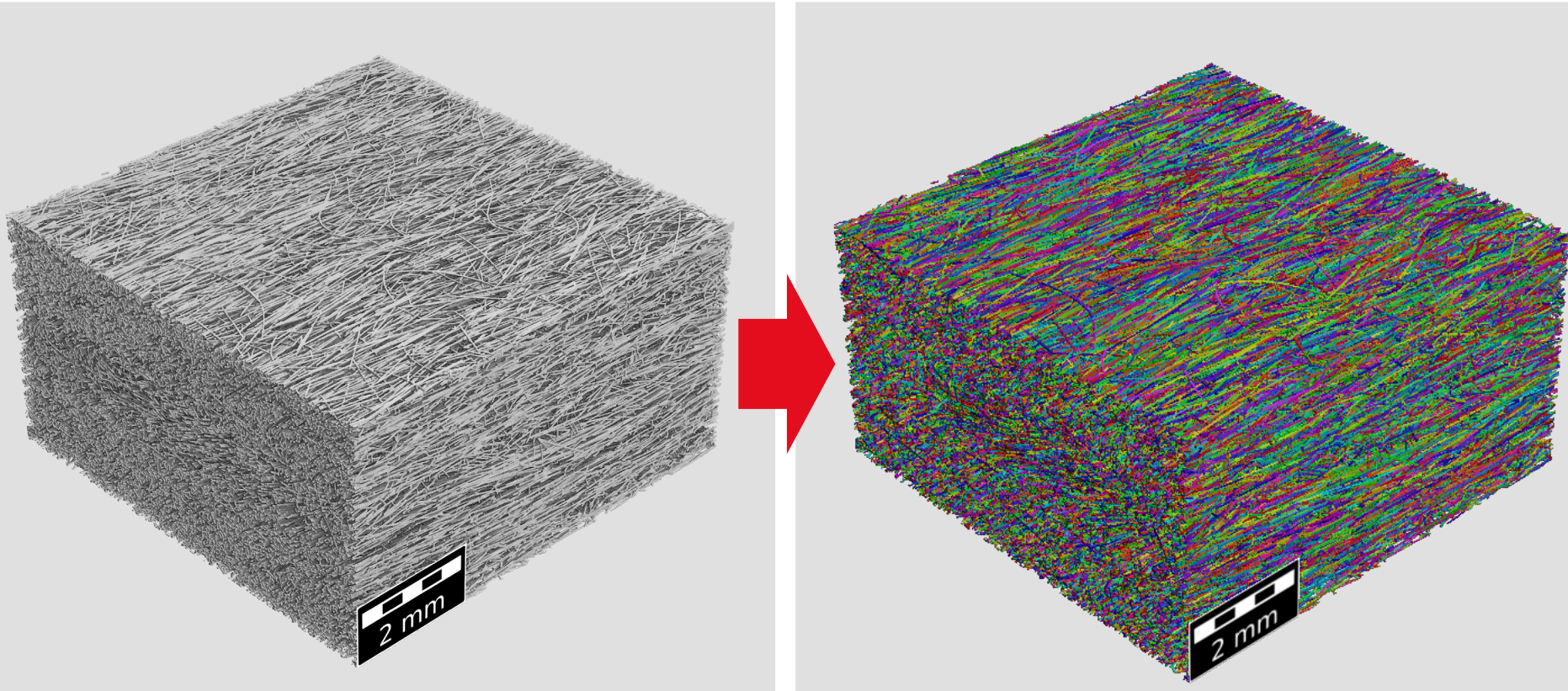


**Training:** N.N. learns edge weights from input and output

- input: Statistical Twin data: binarized version
- output: Statistical Twin data: labeled fibers version

**Usage:** N.N. predicts labeled output from input using weights

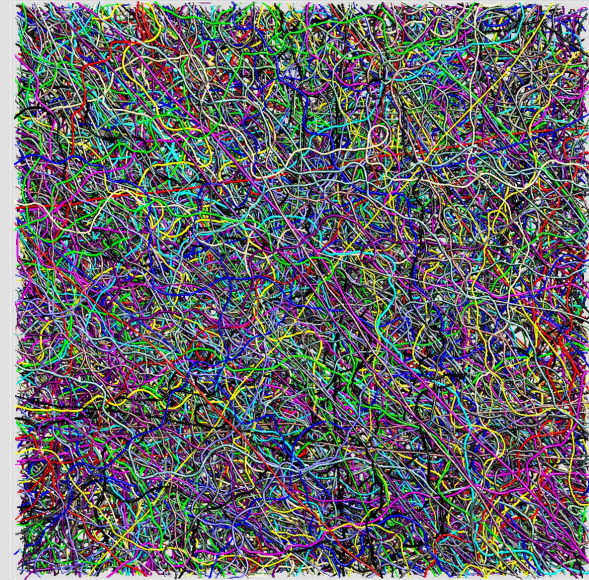
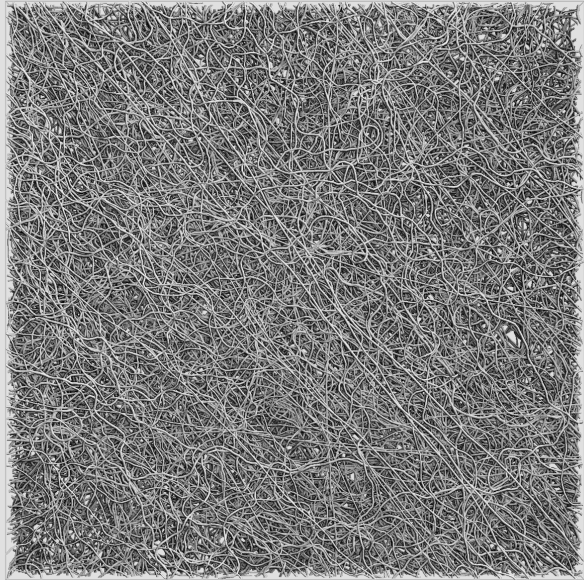
- input: 3D scan data: binarized
- output: 3D scan data: labeled fibers



Input: segmented  $\mu$ CT scan

Output: labeled fibers





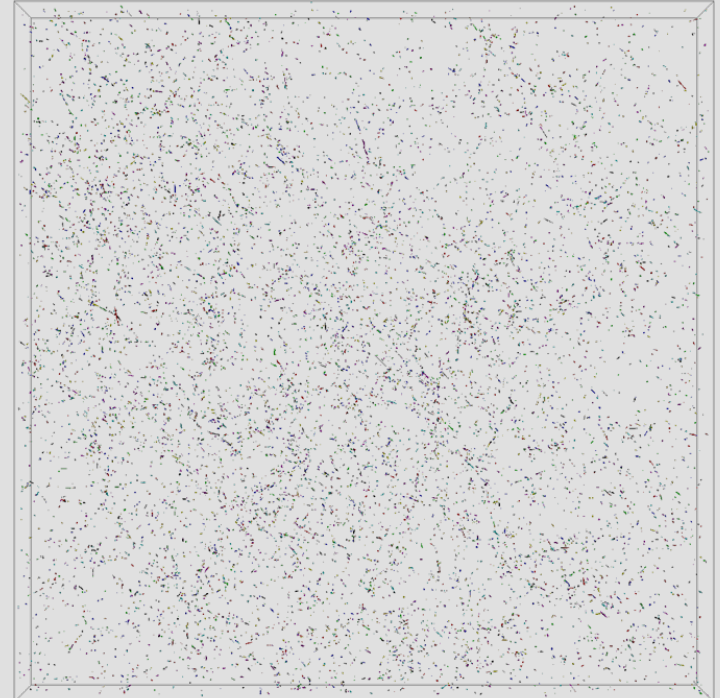
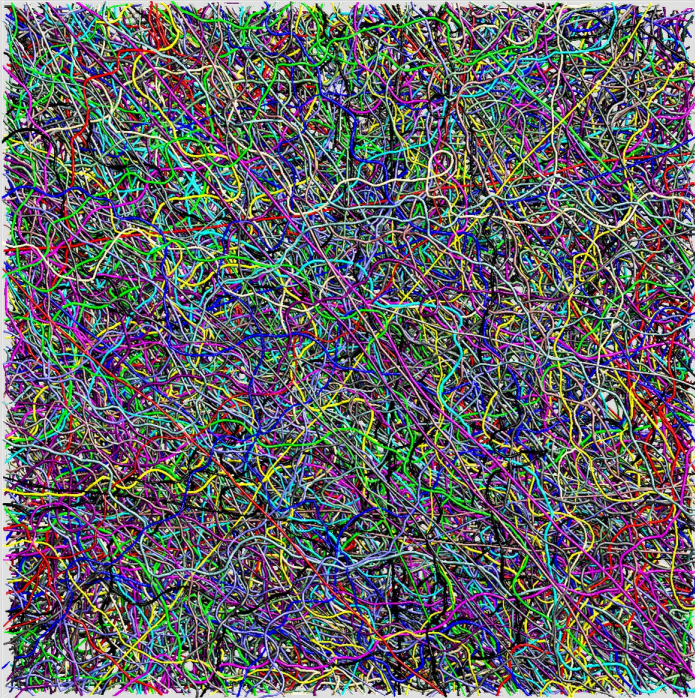
Input: segmented  $\mu$ CT-Scan

Output: labeled fibers

- Grammage / volume percentages:  
total, binder separate or fibers separate
- Binder distribution in through-plane and in-plane directions
- Size-distribution of binder points
- Total number of binder blobs/components
- Output of binder or fibers as triangulation (.stl), CAD (.dxf), etc.
- Number of contact points per fiber
- Length of individual fibers
- Curvature distribution along individual fibers
- Fiber orientation distribution

# DETECTION OF 14995 BOND POINTS

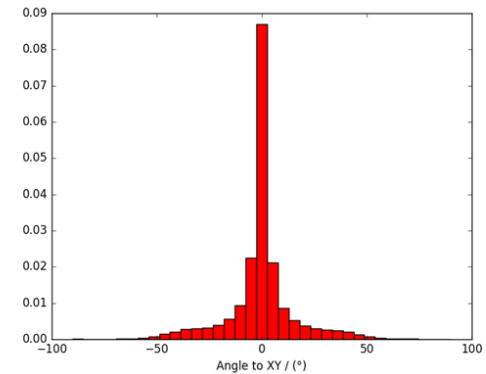
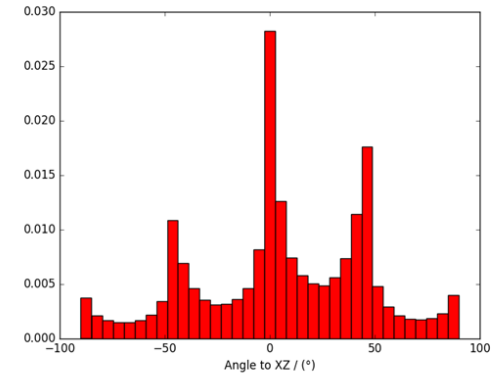
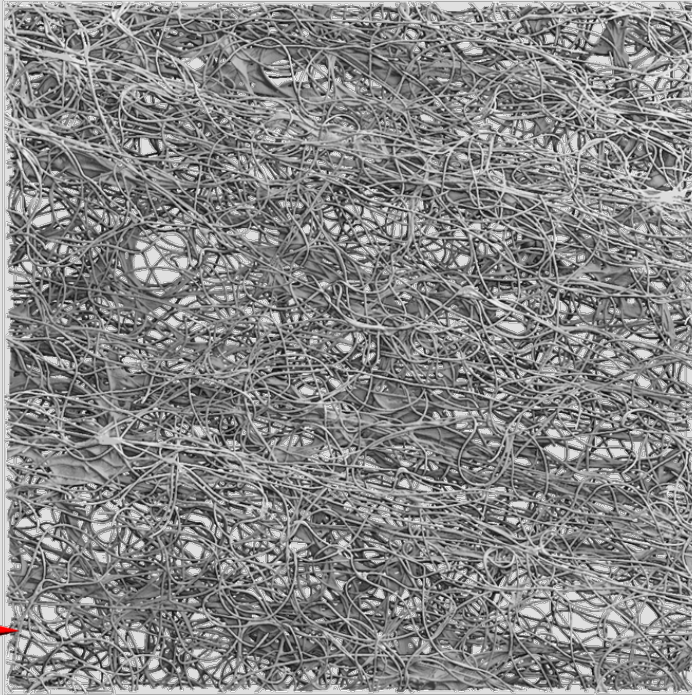
GEODICT



Input: labeled individual fibers

Output: labeled individual  
bonds





Input: segmented CT scan

Output: orientation plots

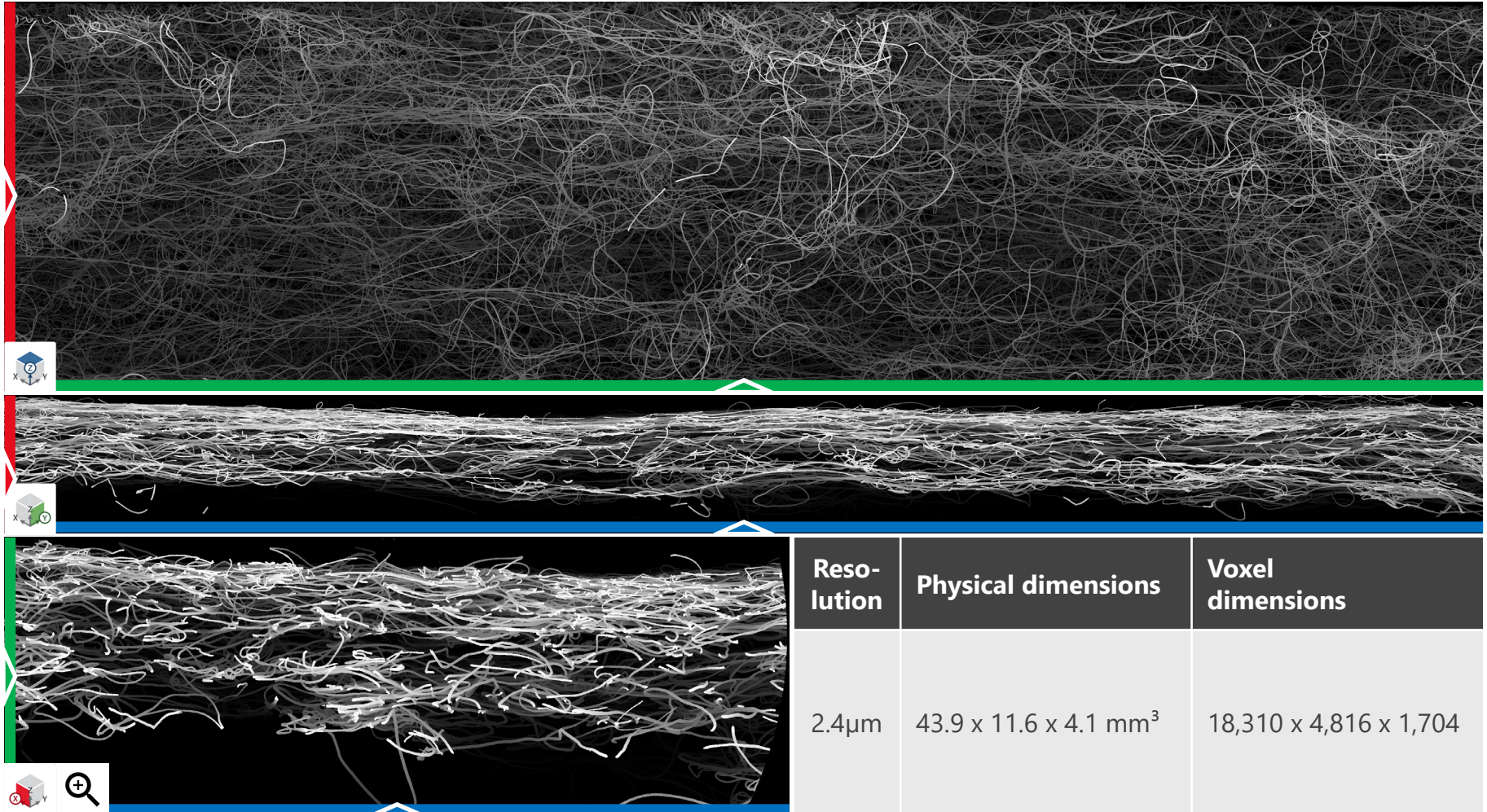


# ANALYSIS OF 2 LARGEST SAMPLES SO FAR

| Sample Name | Resolution | Physical dimensions  | Domain sizes in voxels                |
|-------------|------------|----------------------|---------------------------------------|
| A           | 2.4μm      | 43.9 x 11.6 x 4.1 mm | 18,310 x 4,816 x 1,704 = 150 Giga Vox |
| B           | 2.7μm      | 42.2 x 10.9 x 4.8 mm | 15,619 x 4,032 x 1,796 = 113 Giga Vox |

- Carded nonwoven samples
- Scanned and stitched together by Bruker microCT
- Analyzed by Math2Market on workstation with 1TB of memory

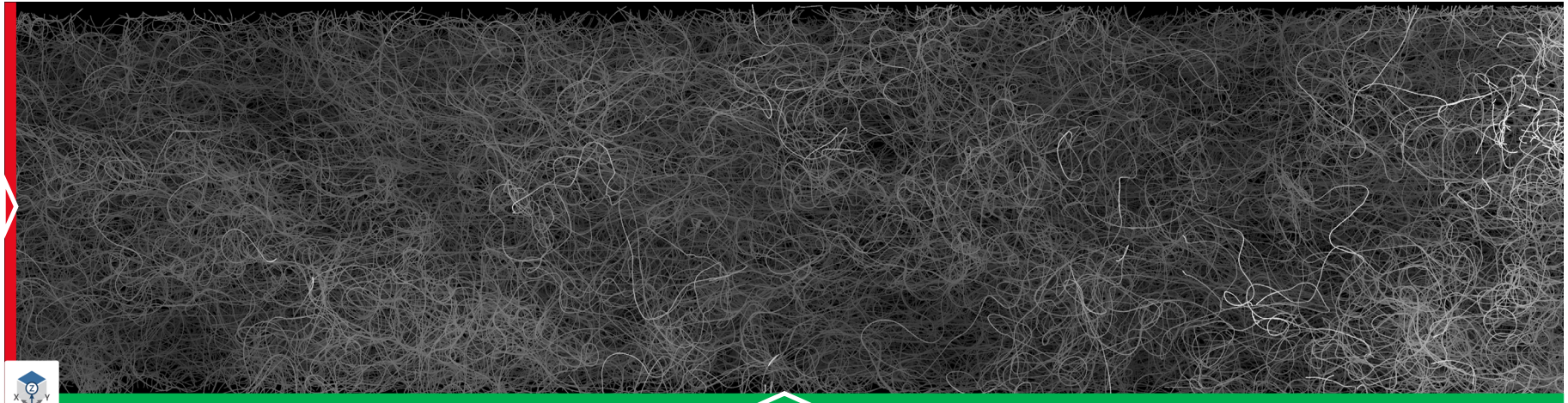
# SAMPLE A – SEM VIEW



| Resolution | Physical dimensions               | Voxel dimensions       |
|------------|-----------------------------------|------------------------|
| 2.4μm      | 43.9 x 11.6 x 4.1 mm <sup>3</sup> | 18,310 x 4,816 x 1,704 |



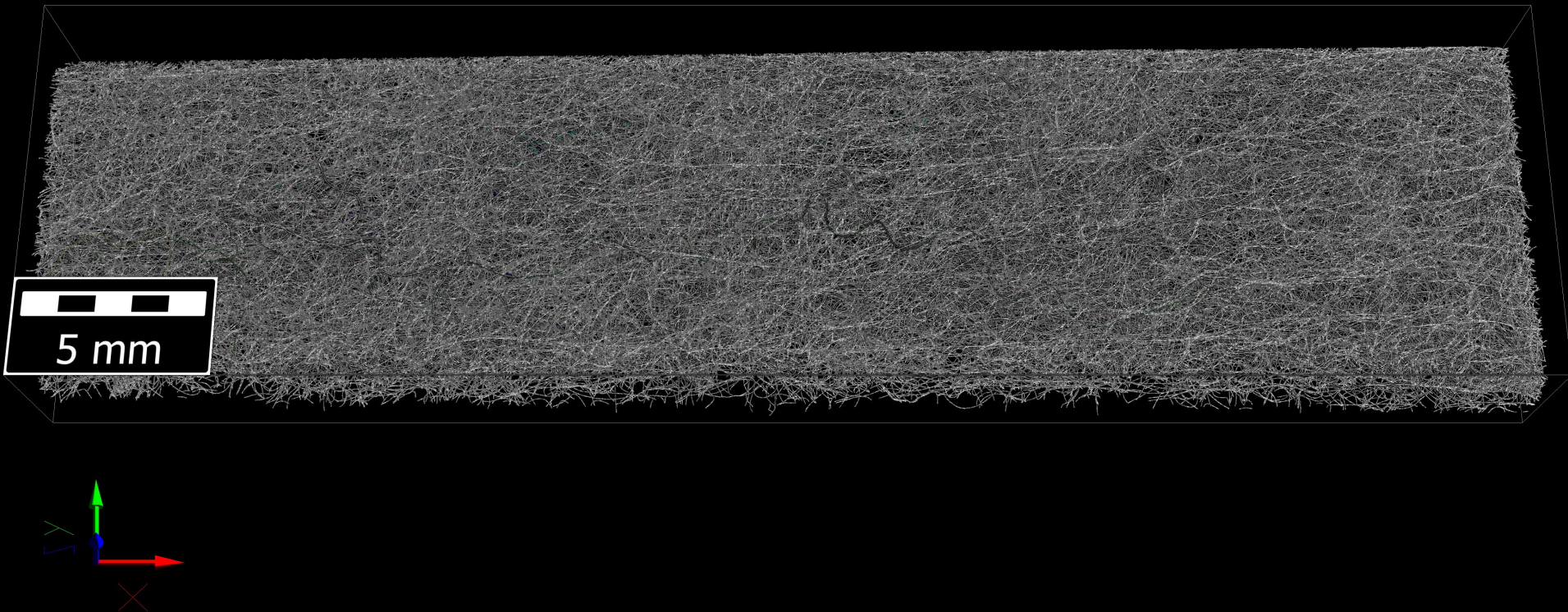
# SAMPLE B – SEM VIEW



| Resolution  | Physical dimensions               | Voxel dimensions       |
|-------------|-----------------------------------|------------------------|
| 2.7 $\mu$ m | 42.2 x 10.9 x 4.8 mm <sup>3</sup> | 15,619 x 4,032 x 1,796 |

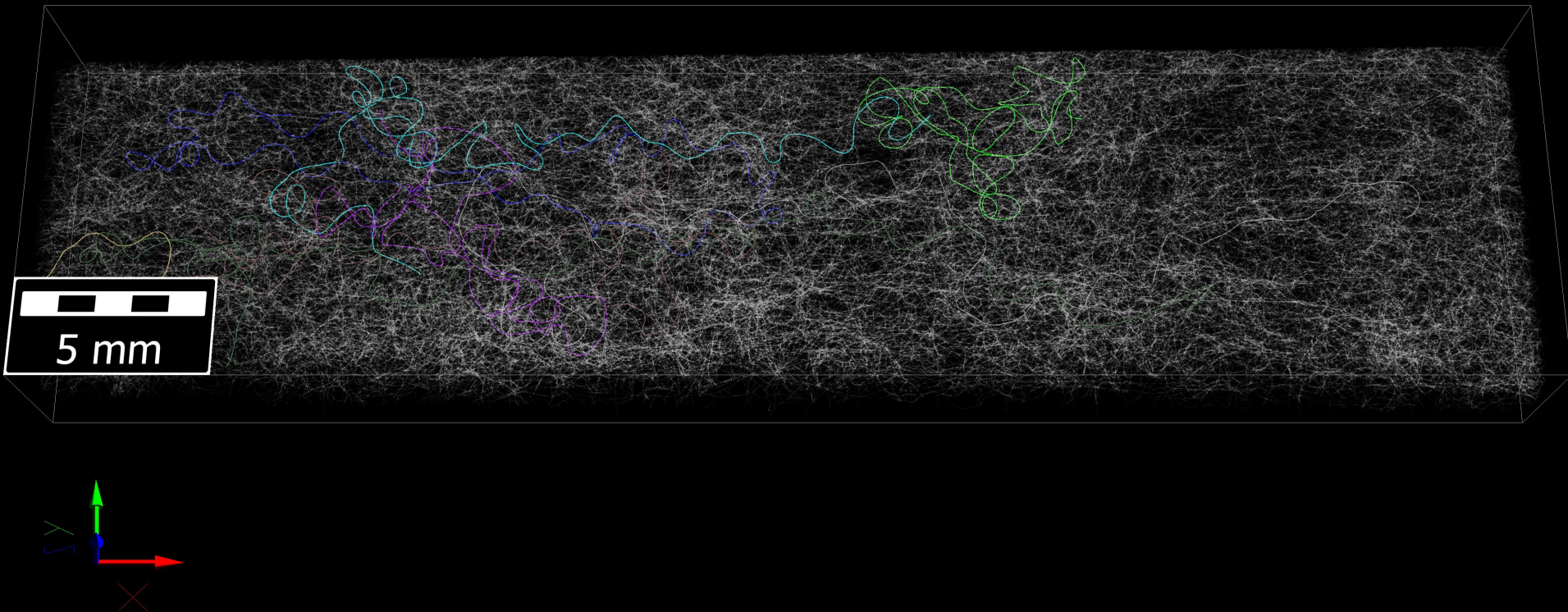






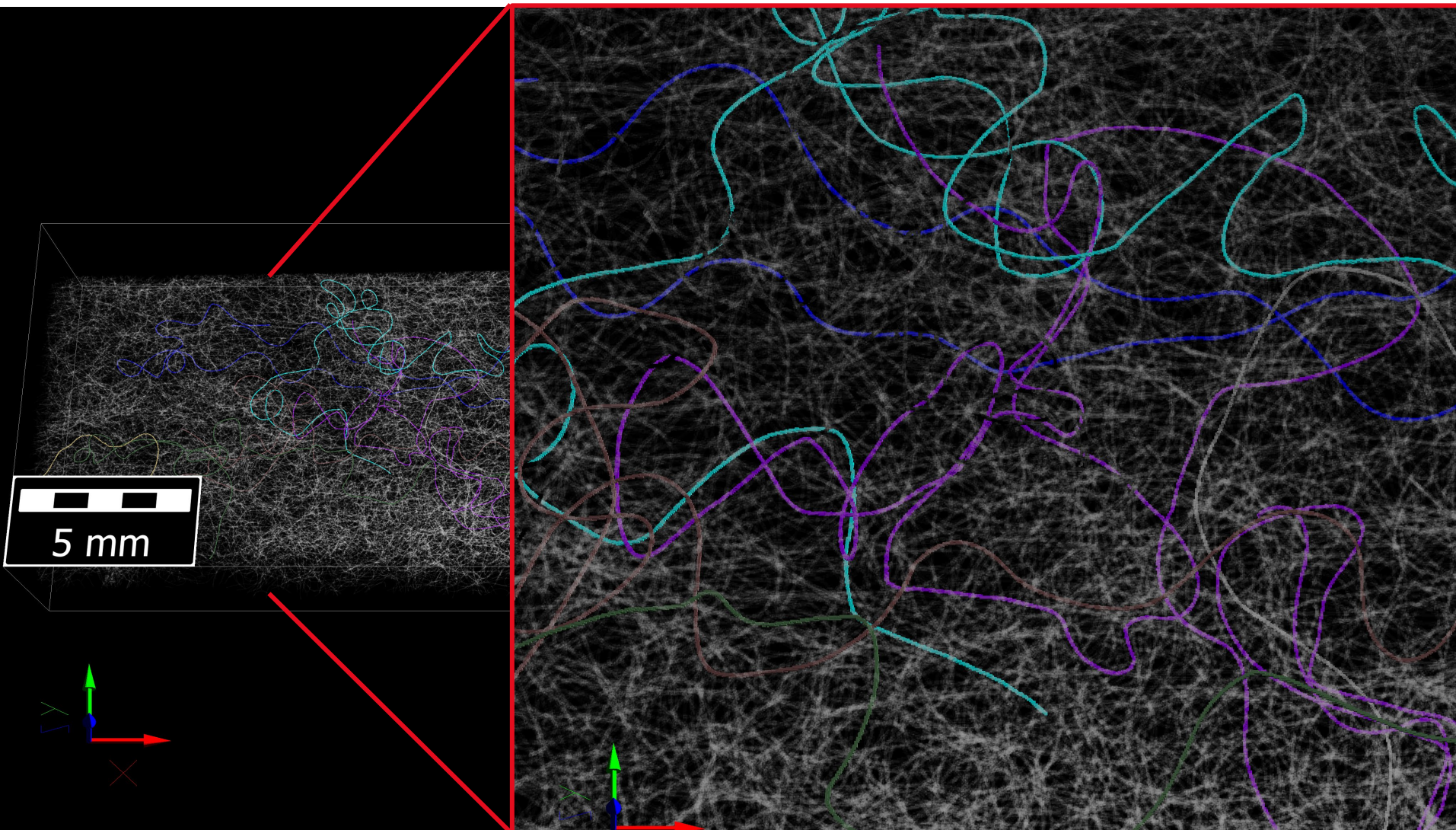
# SAMPLE B: SELECTED HIGHLIGHTED FIBERS

GEODICT





# ZOOM ON HIGHLIGHTED FIBERS



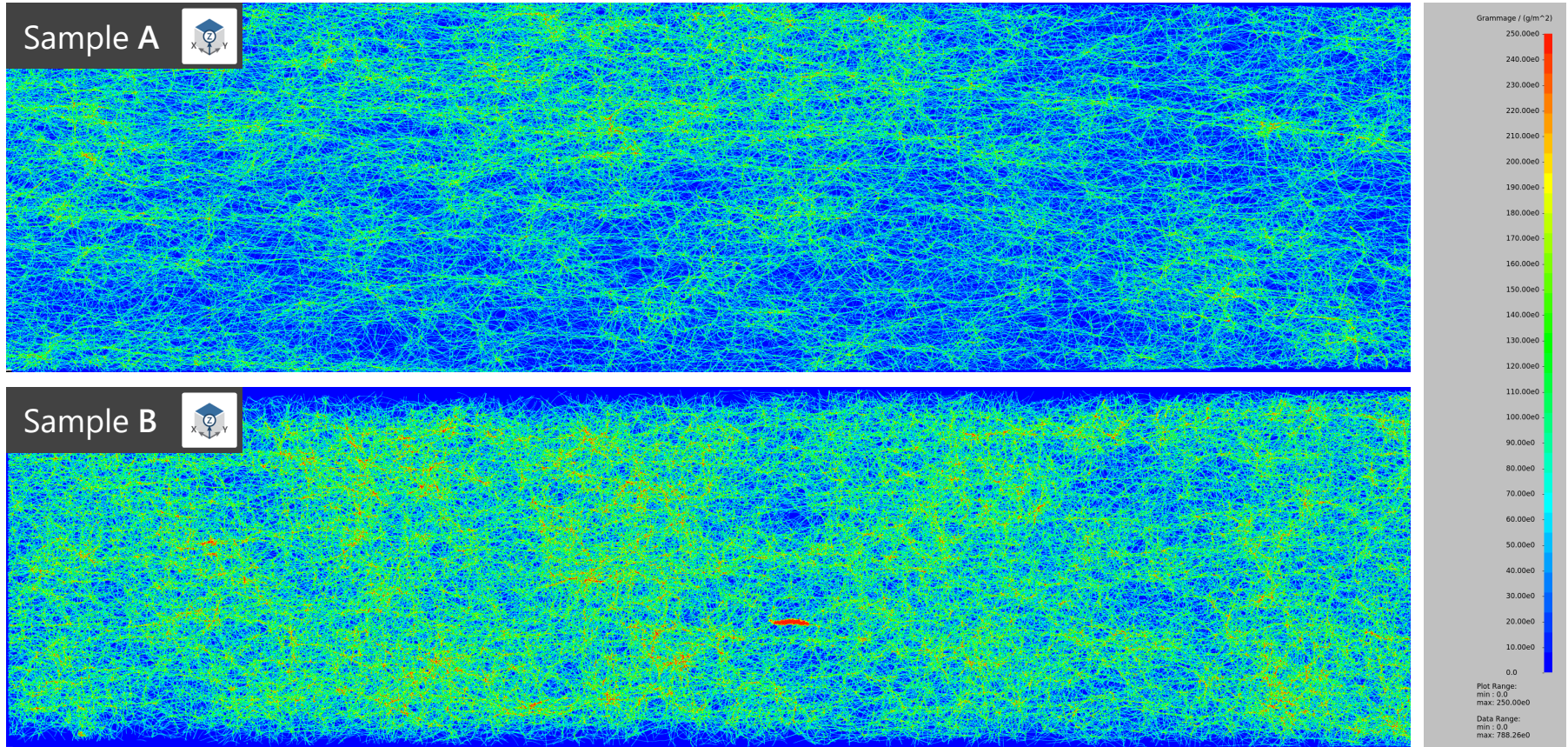
# SAMPLE B: TRACKING OF THE LIGHT-BLUE FIBER

GEODICT





# DENSITY MAP (CLOUDINESS)





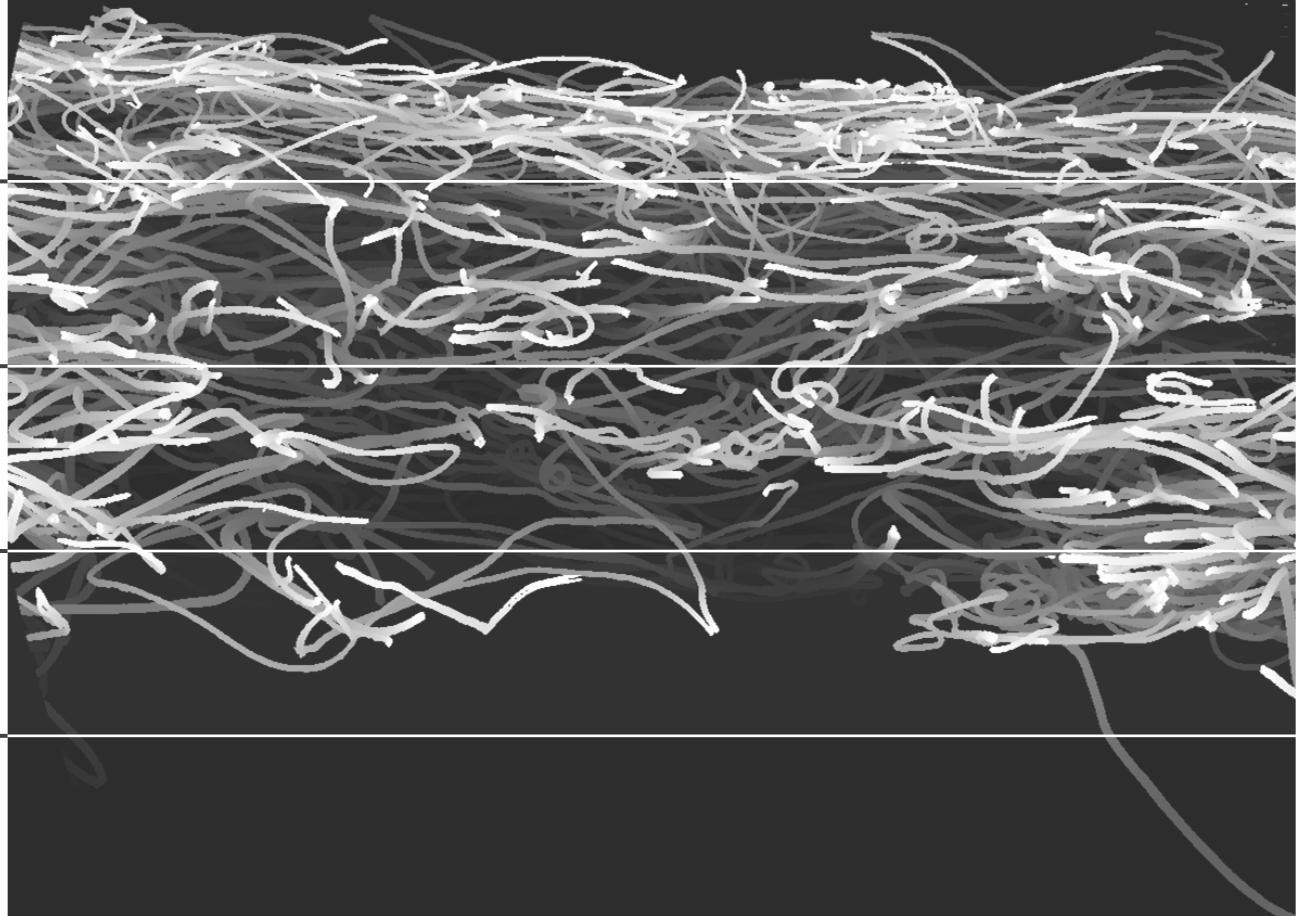
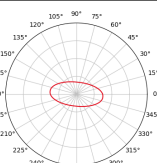
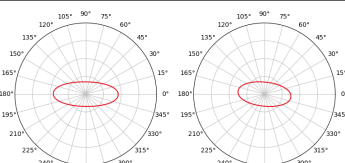
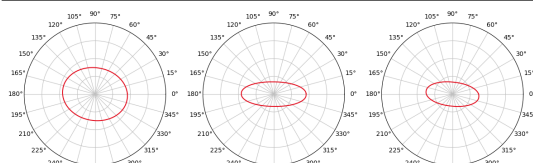
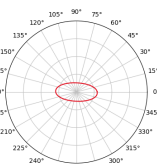
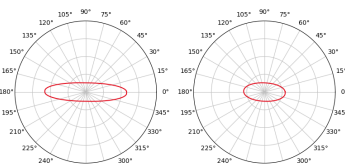
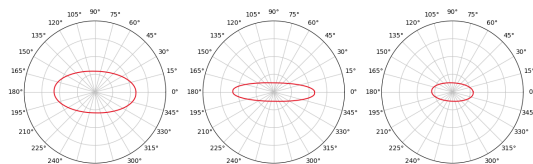
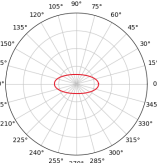
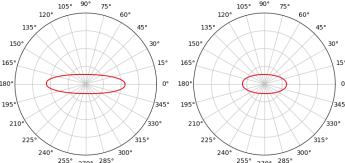
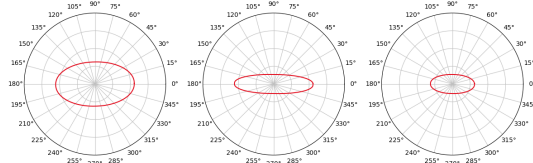
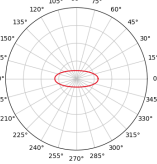
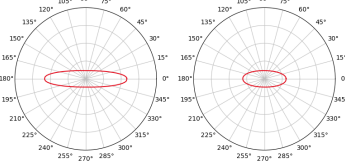
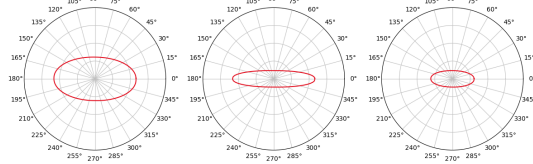
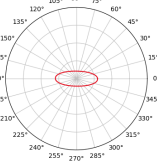
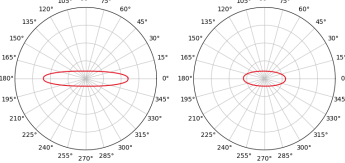
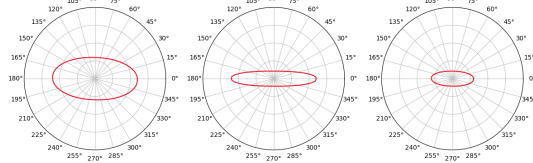
# FIBER ORIENTATIONS – SAMPLE A

XY

XZ

YZ

View of a section of the surface in the direction of the X axis.



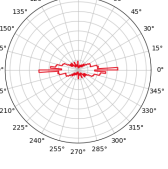
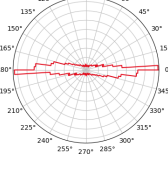
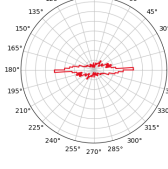
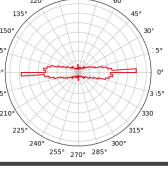
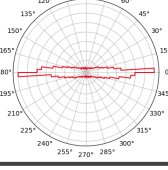
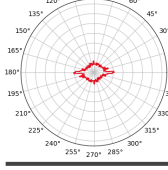
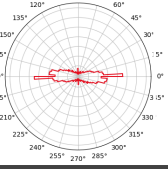
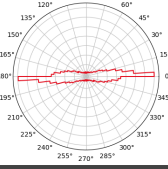
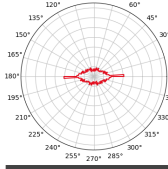
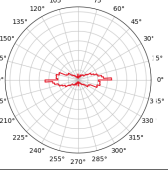
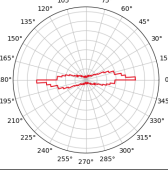
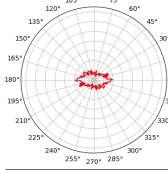
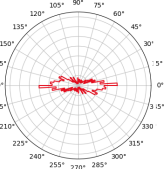
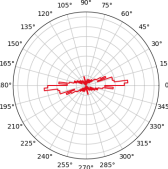
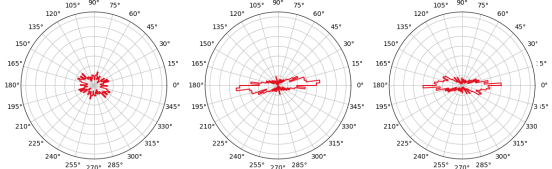
# FIBER ORIENTATIONS – SAMPLE B

XY

XZ

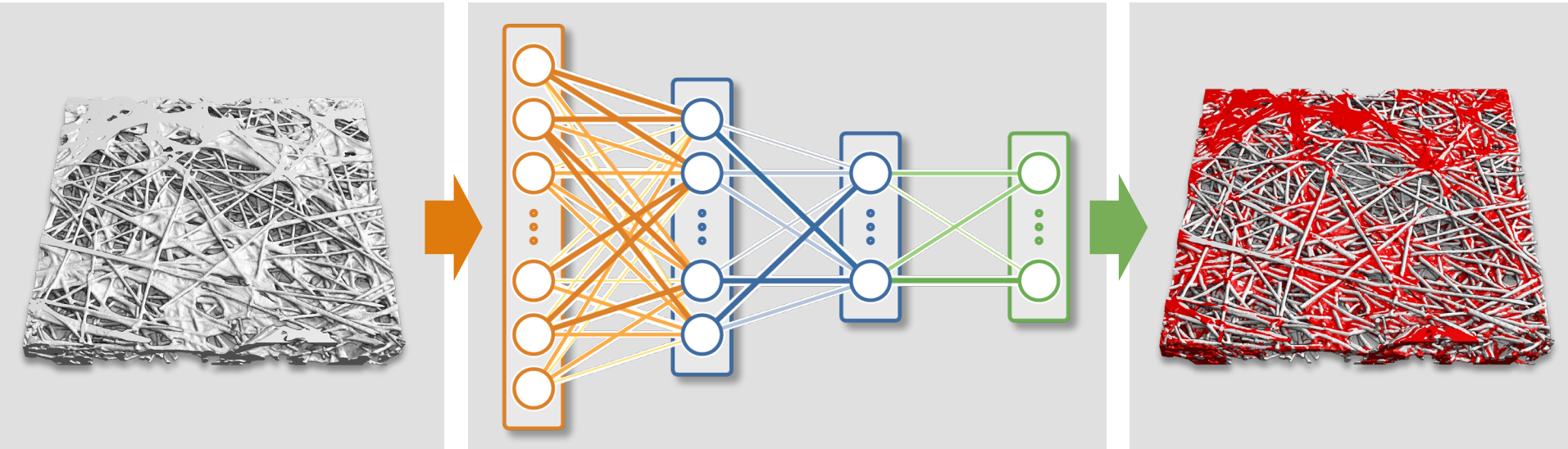
YZ

View of a section of the surface in the direction of the X axis.





# NEURAL NETWORK (N.N.) TRAINING & USAGE PHASES



**Training:** N.N. learns edge weights from input and output

- input: Statistical Twin data: binarized version
- output: Statistical Twin data: labeled binder and fibers version

**Usage:** N.N. predicts labeled output from input and edge weights

- input: 3D scan data: binarized
- output: 3D scan data: labeled binder and fibers

# TORAY PAPER TGP-H-030, 05% WET PROOFING

GEODICT



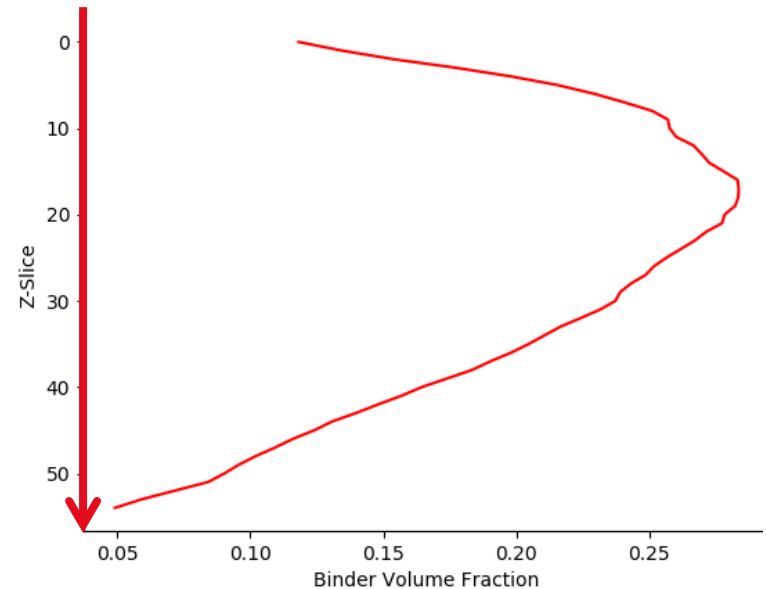
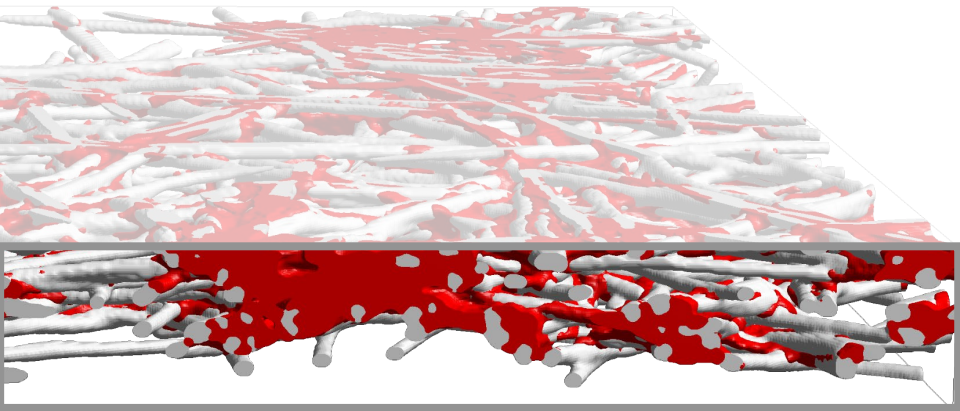
# BINDER IDENTIFICATION IN GAS DIFFUSION LAYER

Crossection in X-Direction:

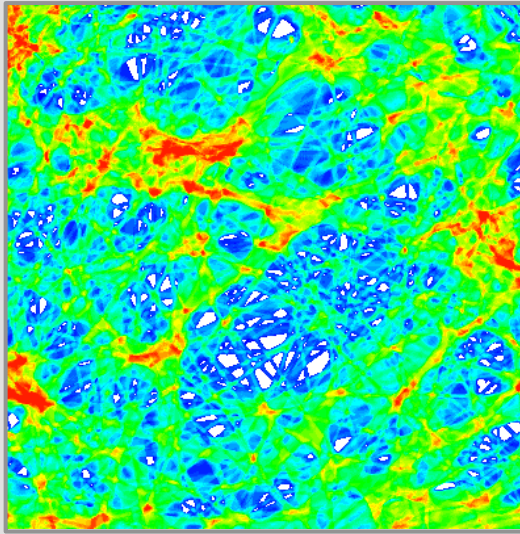


Idea: Maybe create 3D Statistical Twins from 2D images using AI in the future?

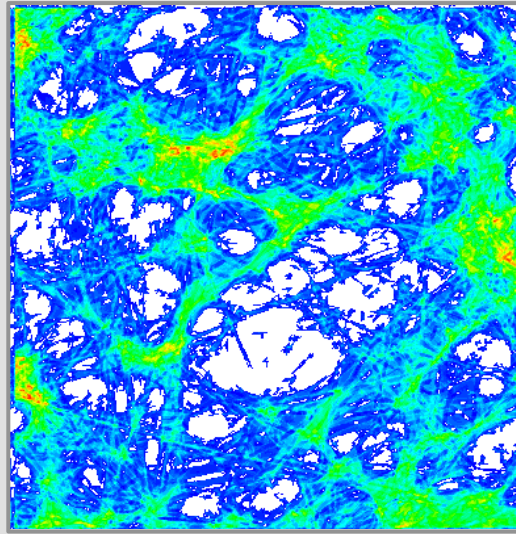




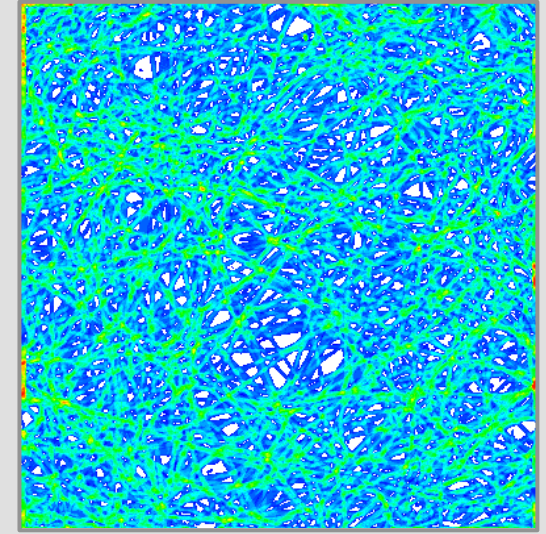
- In production, binder is applied to the top of the fiber and, then, intrudes into deeper layers
- After labelling binder voxels, we can compute the distribution of binder in through direction (right)



Both materials



Binder only



Fibers only

Scale: White: 0% volume fraction, Red: 7.2% volume fraction

- Neural networks separate binder and fibers and identify individual fibers
  - based on learning shapes
- N.N. can label multi-material scans where materials can not be separated by thresholding or classical image processing
- N.N. require training data consisting of segmented and labeled scans
- These can be created easily using material models from GeoDict
  - Models continuously improve, e.g. by improving the binder model
- We continue to improve the capabilities by
  - Increasing the fidelity
  - Speeding up the computations
  - Extending the capabilities to other types of materials
  - Placing the capability to train N.N.s in your hands



# THANKS TO THE MATH2MARKET TEAM ...

# GEODICT



... and our partners & clients around the world.

# Creating statistical twins and the digital design of filter media have just gotten a lot easier!

Statistical Twins for

- Granular filter media,
- Woven filter media,
- Open cell foams
- etc. etc.

can all be found by this technology!

