Statistical Analysis for Quantification and Visualization of Spatial Variability in Features of Uncertain Data

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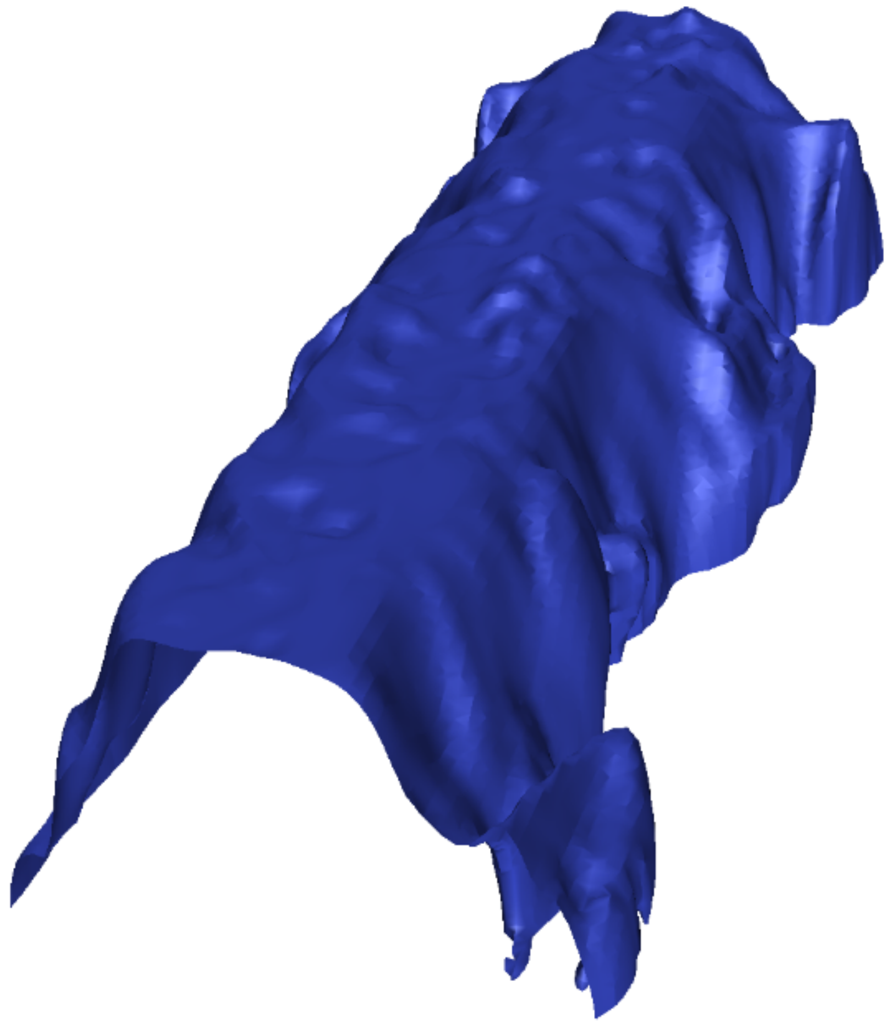
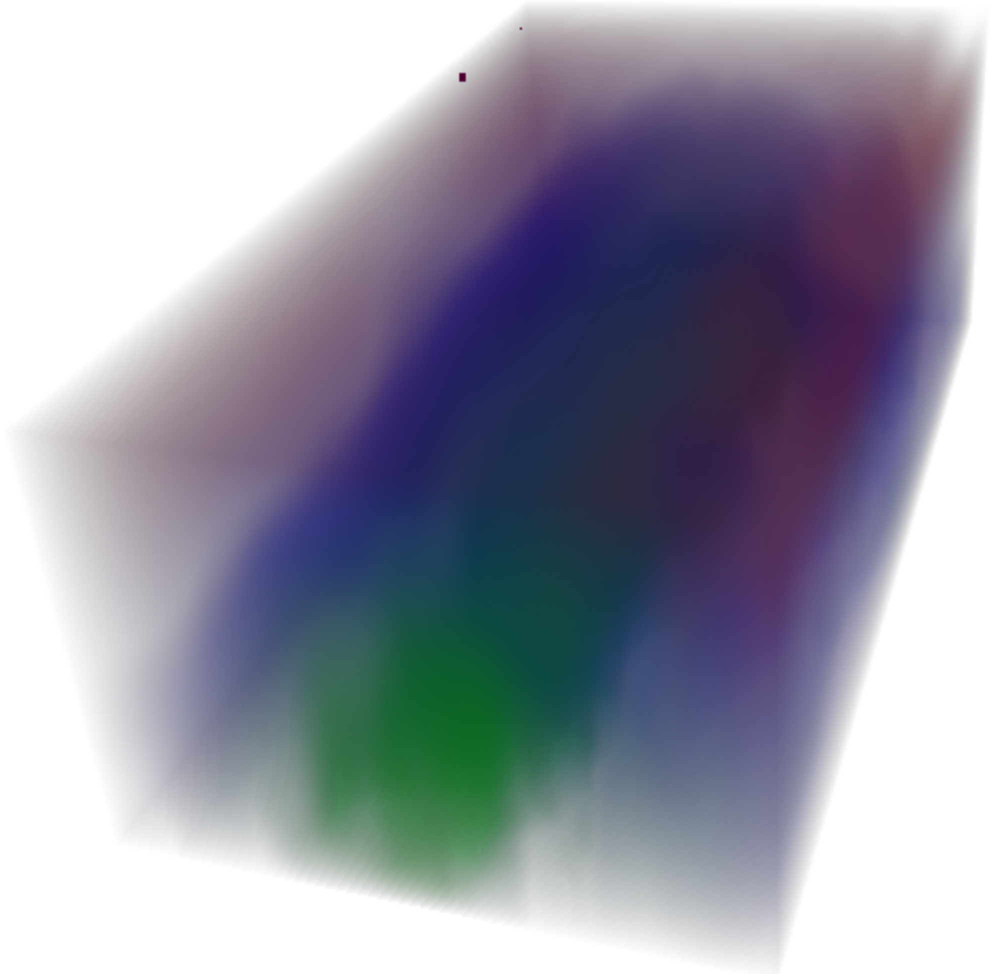
Outline

- Uncertainty visualization for large-scale data
  - Level-set extraction using marching square/cubes
  - Direct volume rendering using ray casting
- Application of uncertainty visualization
  - Deep brain stimulation
- Conclusion and future work

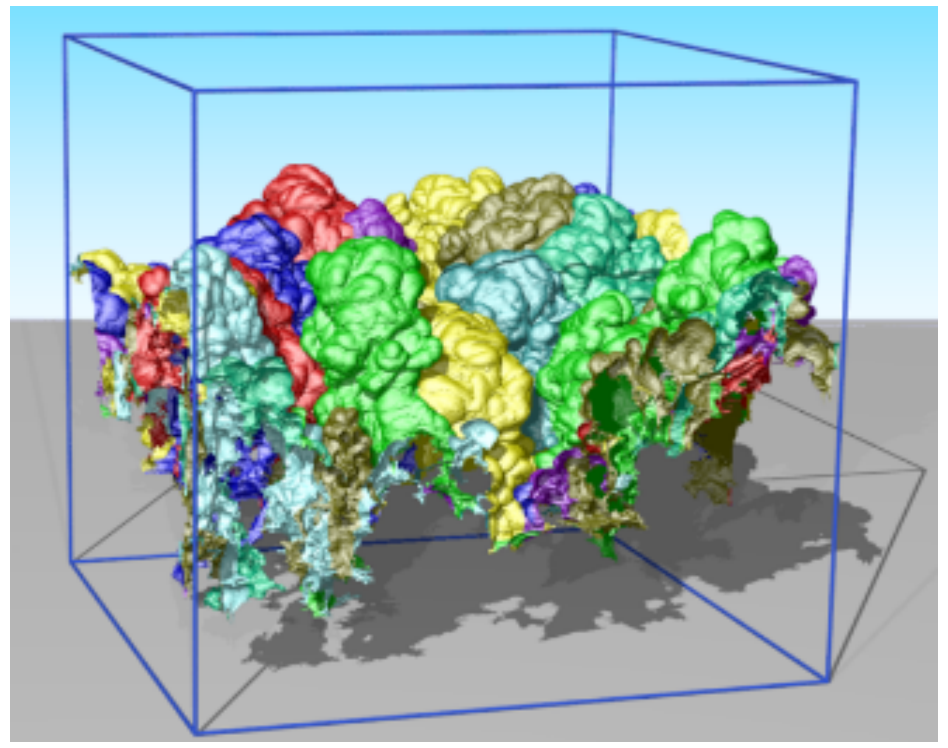


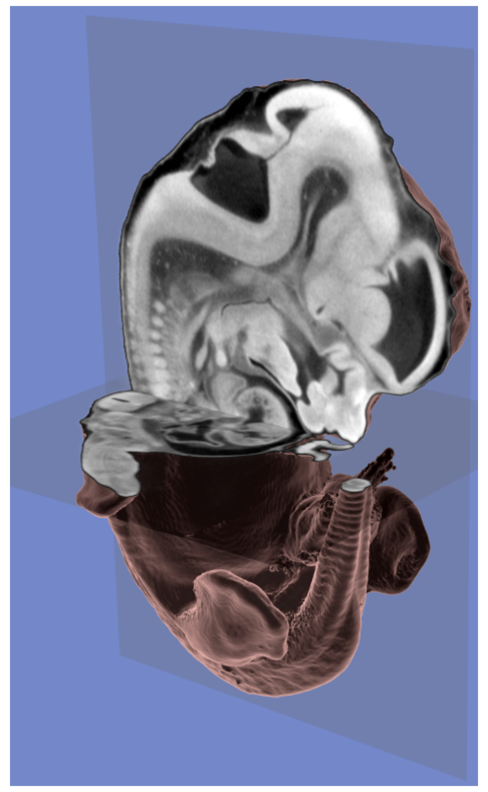
Level-set visualization

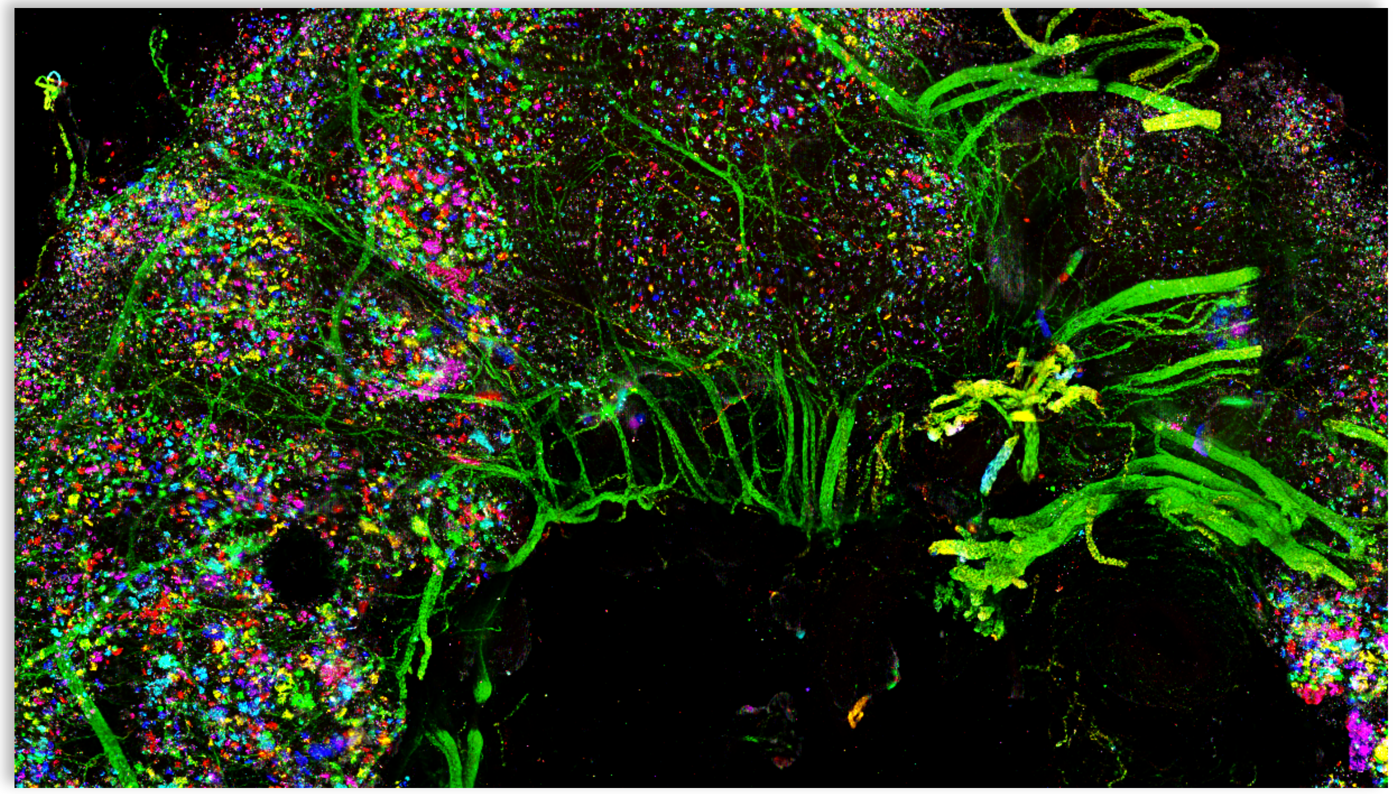


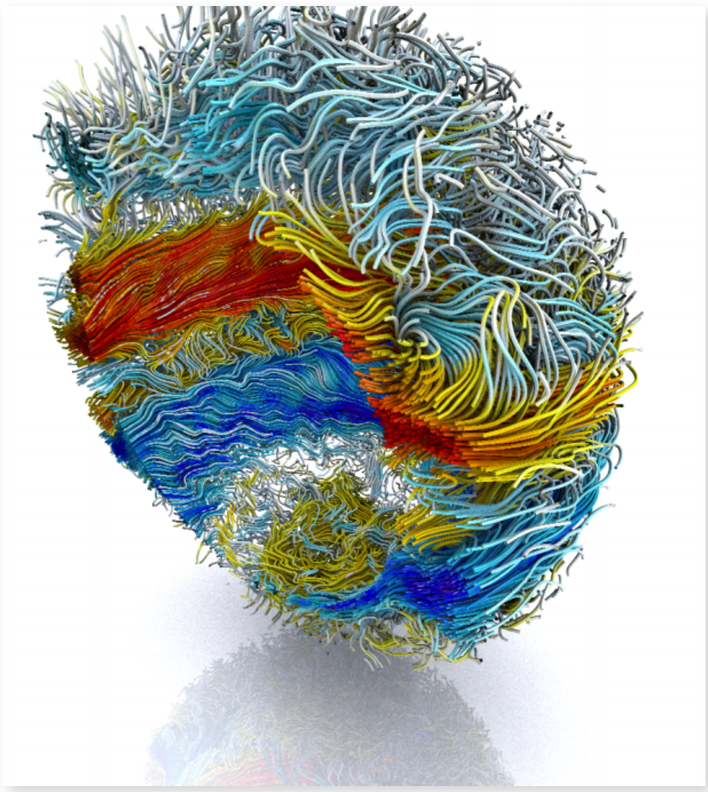
Direct volume rendering

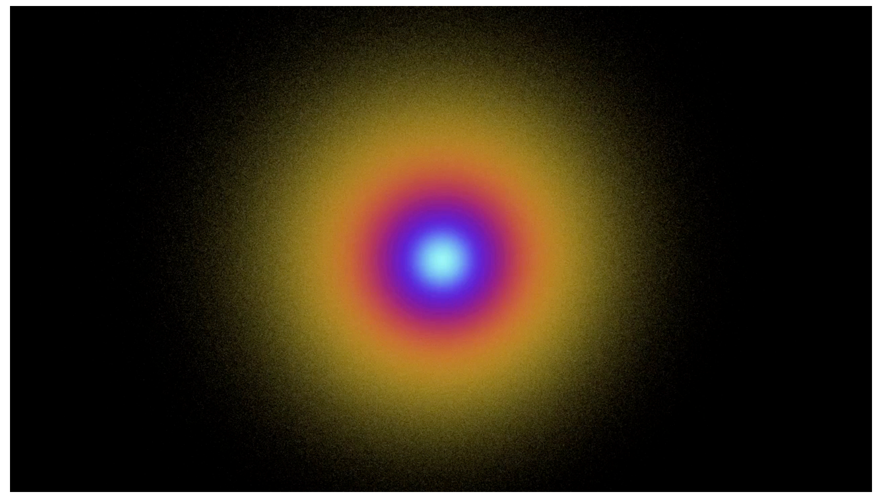
Large-Scale Visualizations

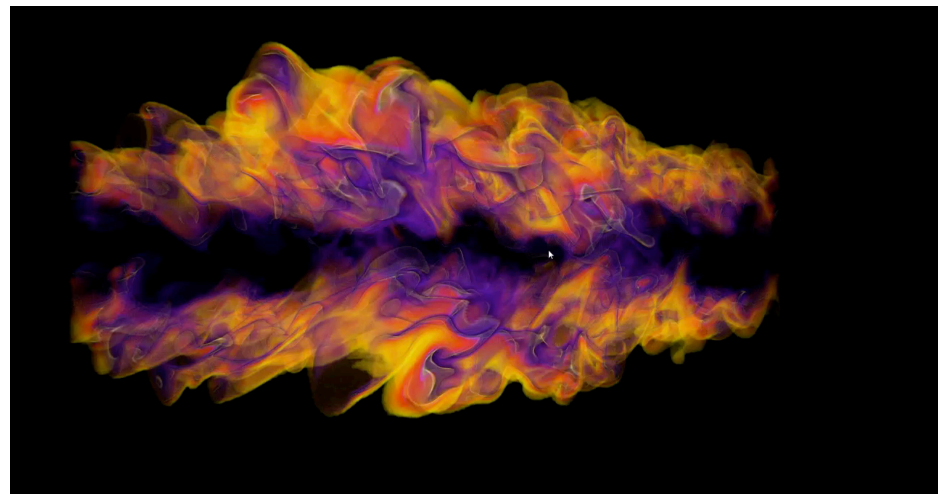


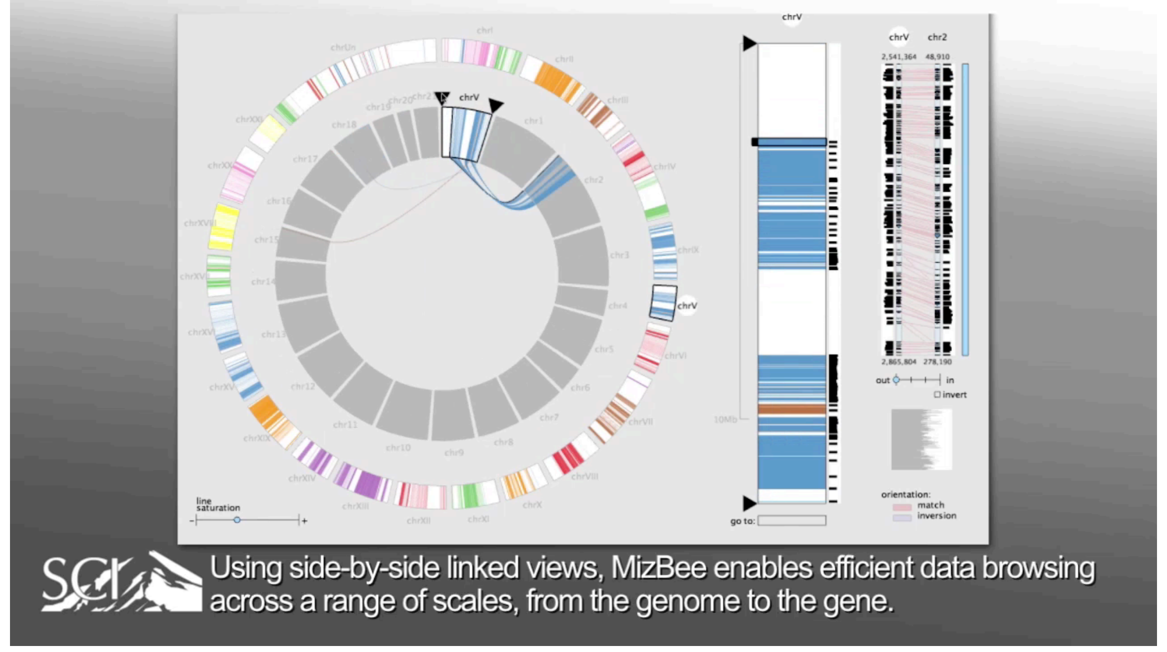


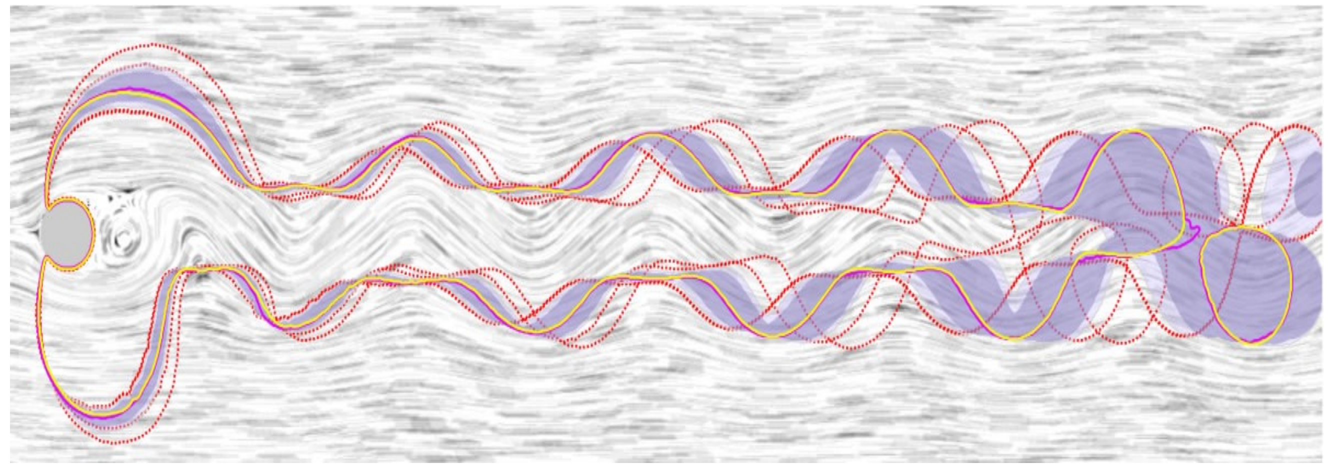


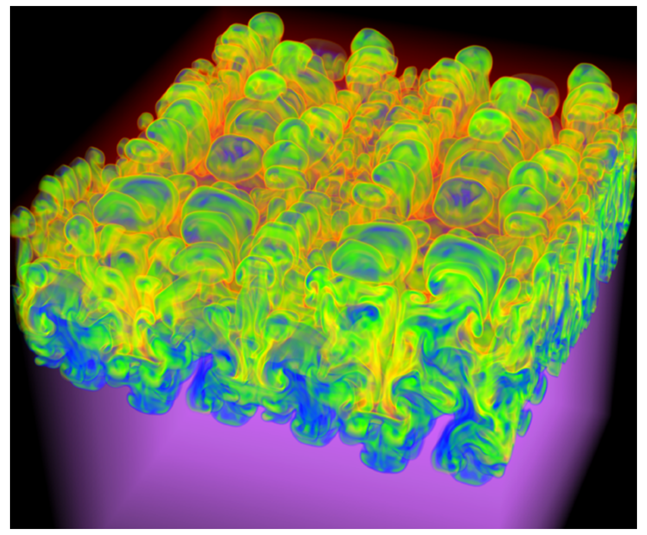


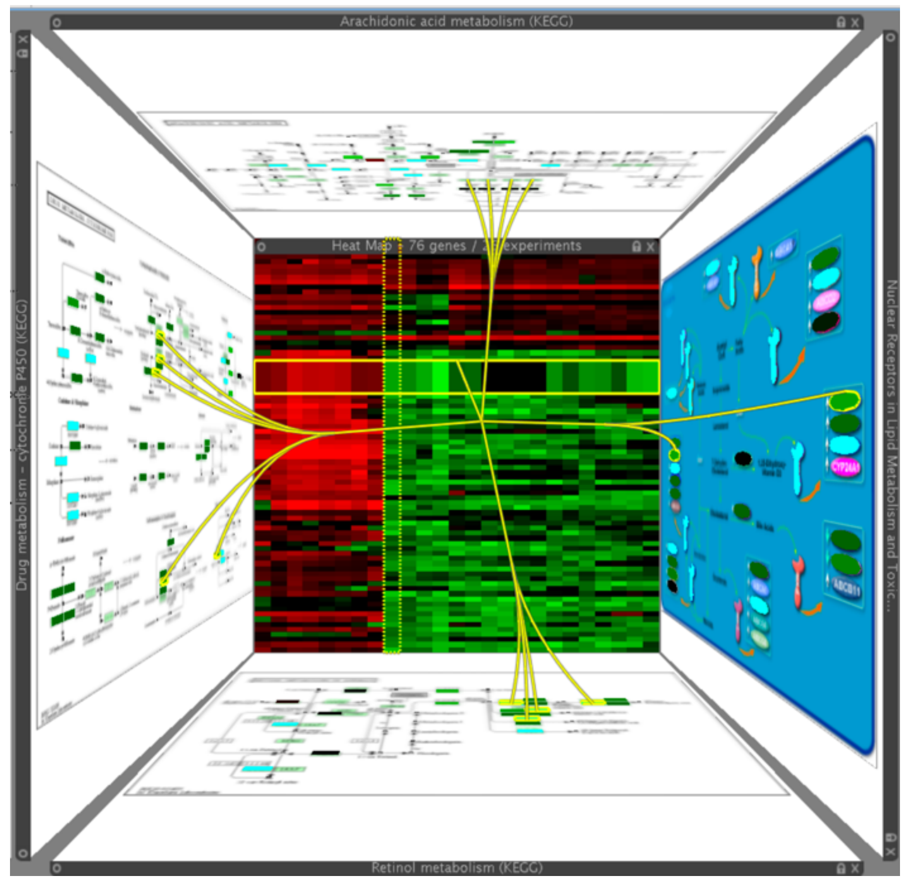


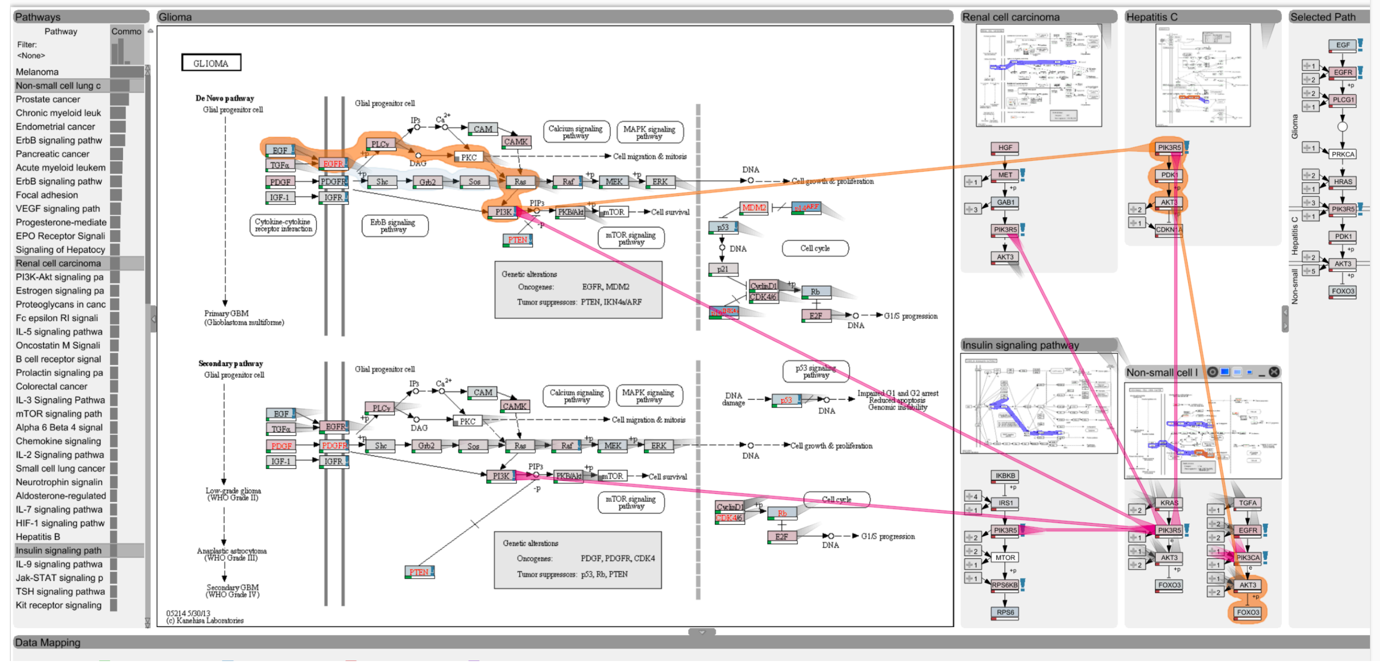


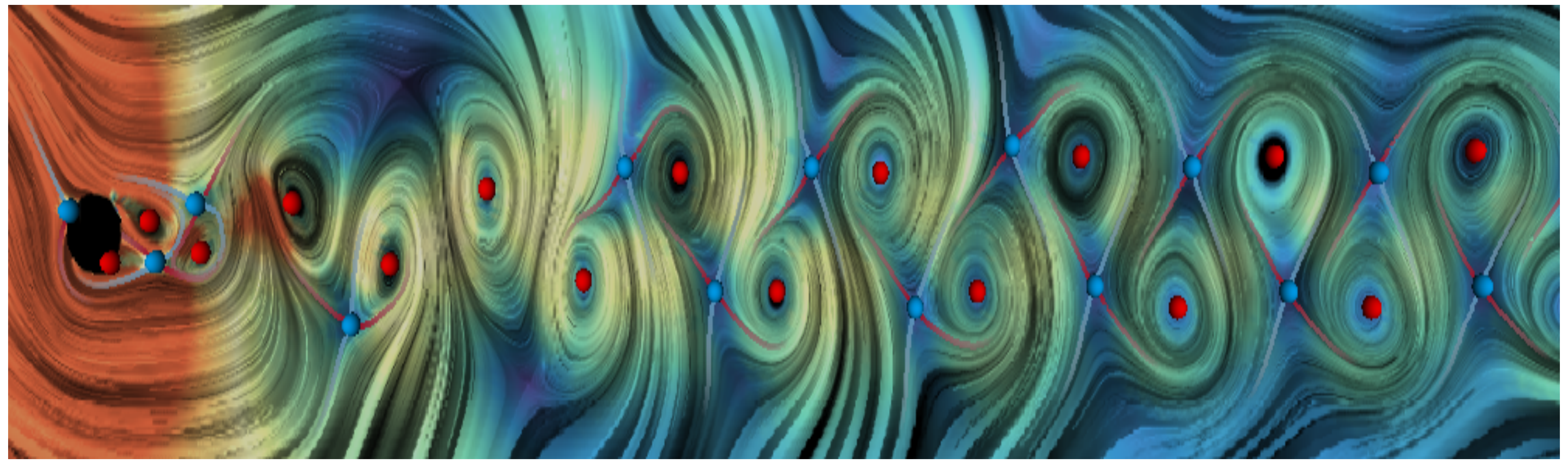






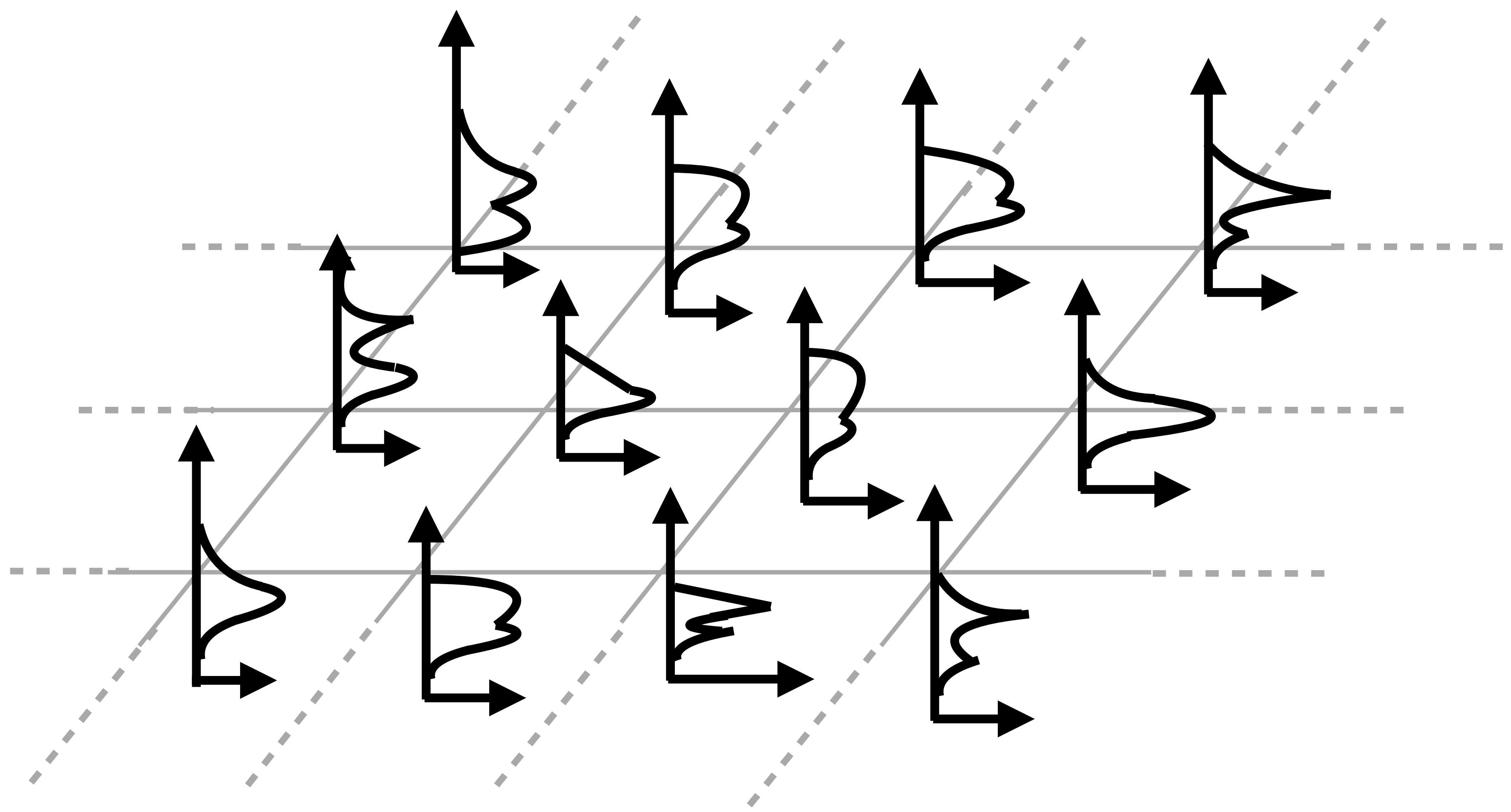






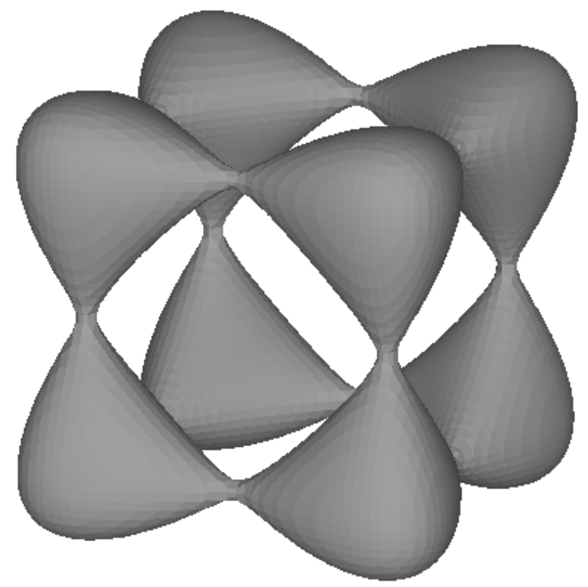
Data Reduction and Distributions

Distributions: Hixel representation/ in-situ statistical summaries for large-scale data [Thompson et al., 2011, Lehmann and Jung, 2014, Hazarika et al., 2018]



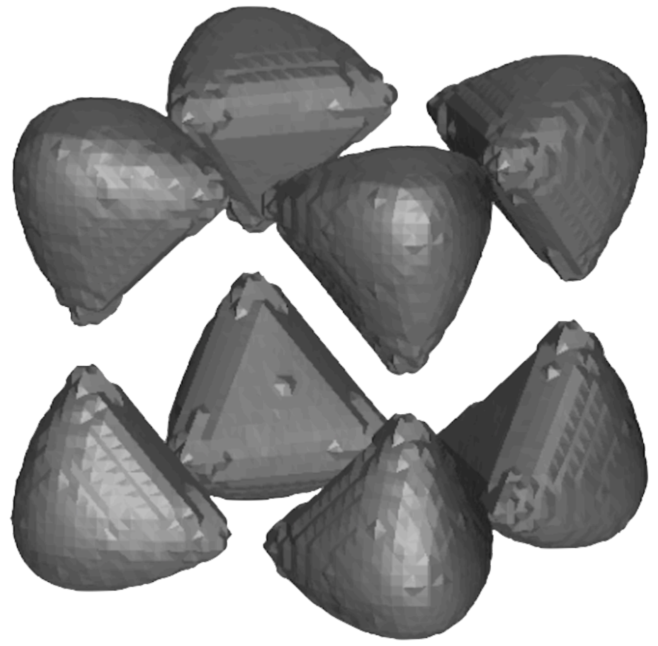
Ensemble Data: Multiple simulations for PDE solutions (Store Min/Max, Approximate distributions from samples)

Data Reduction and Distributions



Groundtruth

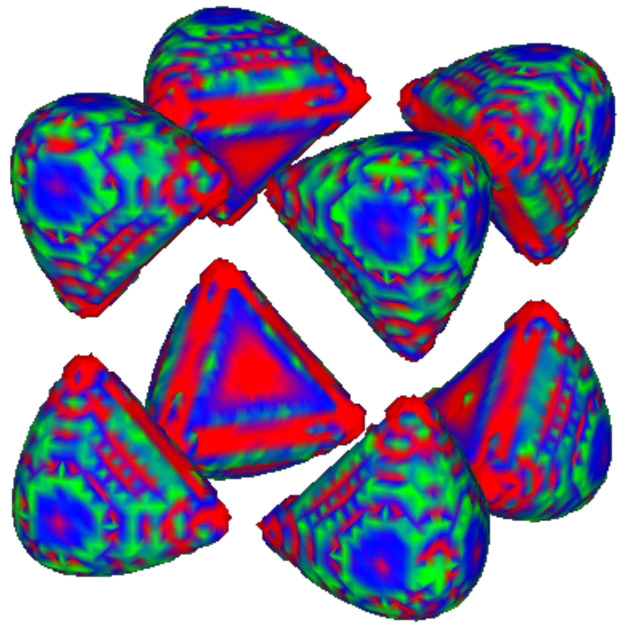
Memory consumption = 100*X



Mean

Memory consumption = X

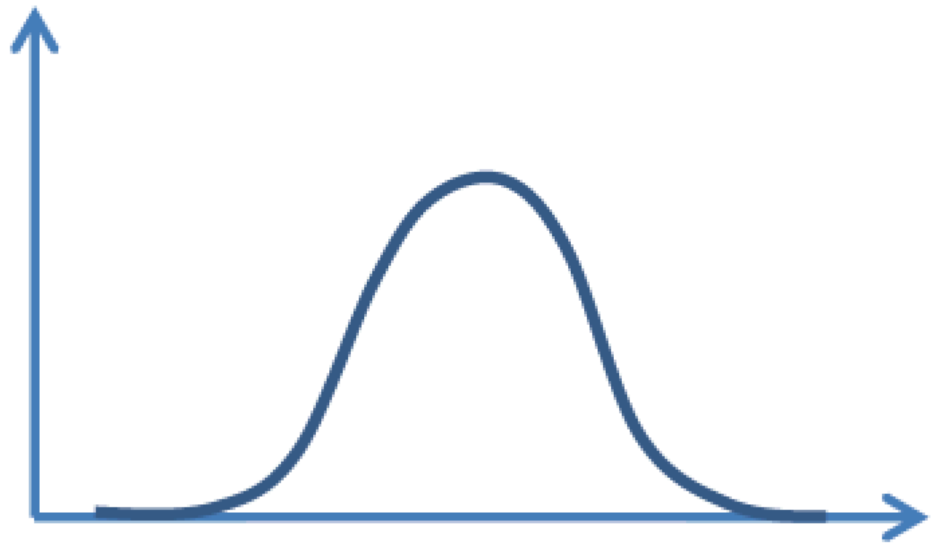
Brick size = 100



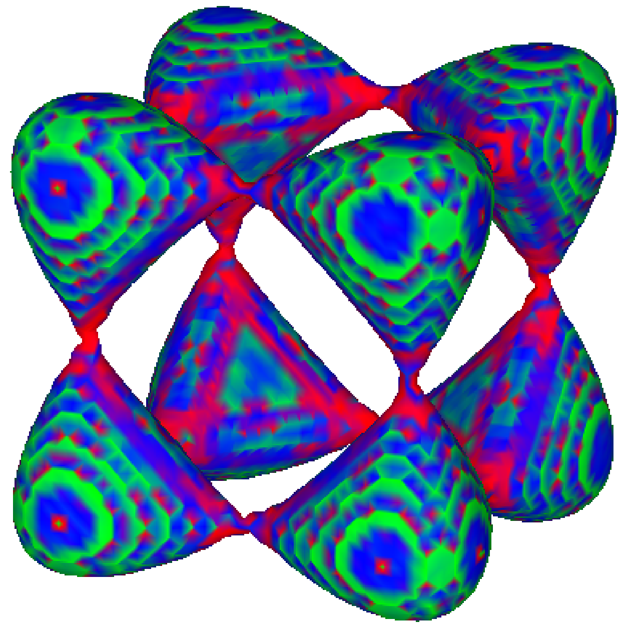
Parametric

Memory consumption = 2X

Uniform

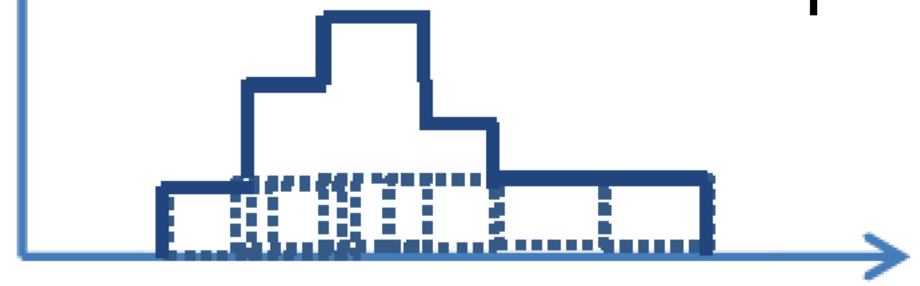


Gaussian



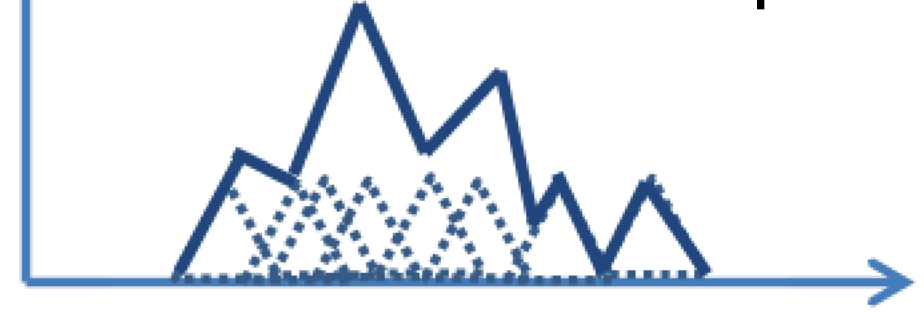
Nonparametric

Memory consumption = b*X



Uniform kernel

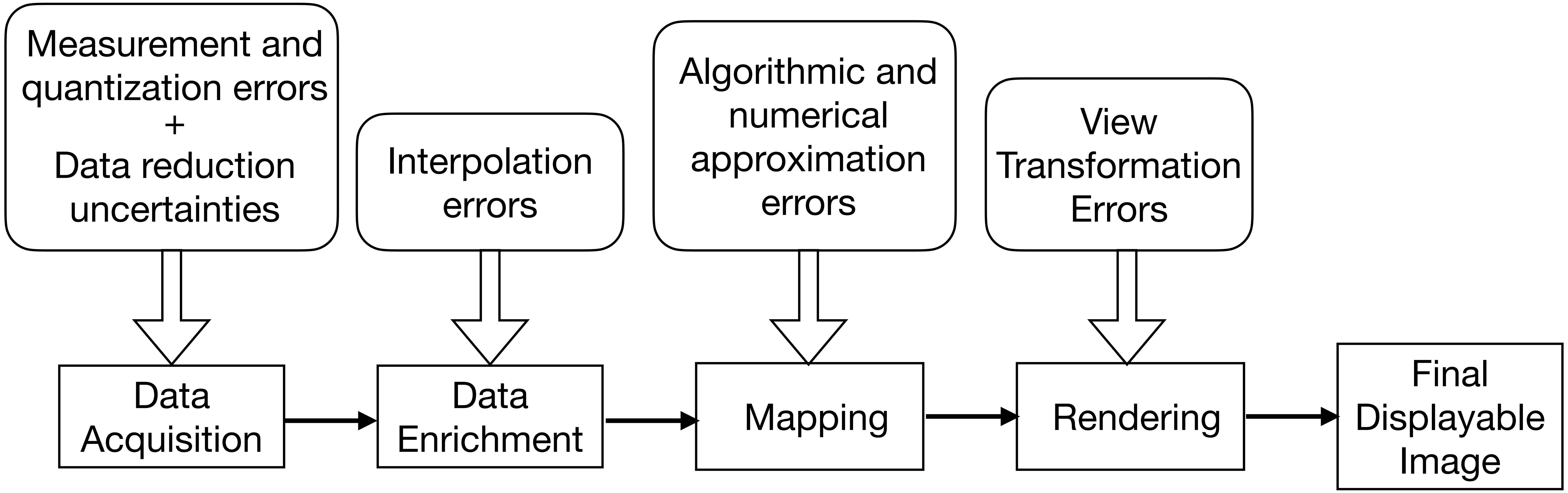
b = # representative samples per brick



Triangular kernel

Why Visualize Uncertainty? [Johnson and Sanderson, 2004]

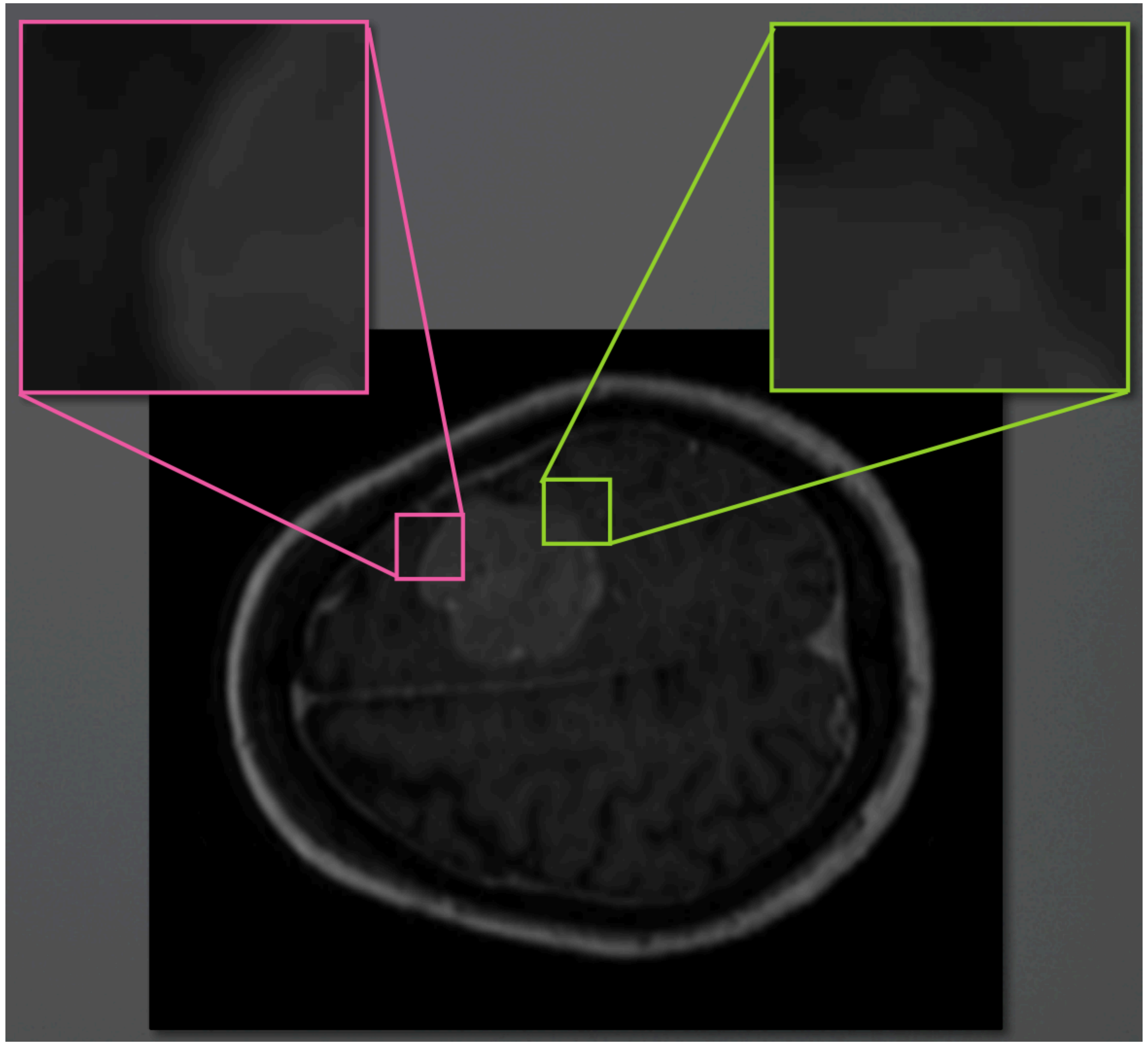
Minimize risks associated with scientific decisions



The Visualization Pipeline
[Brodlie et al., 2012]

Why Visualize Uncertainty?

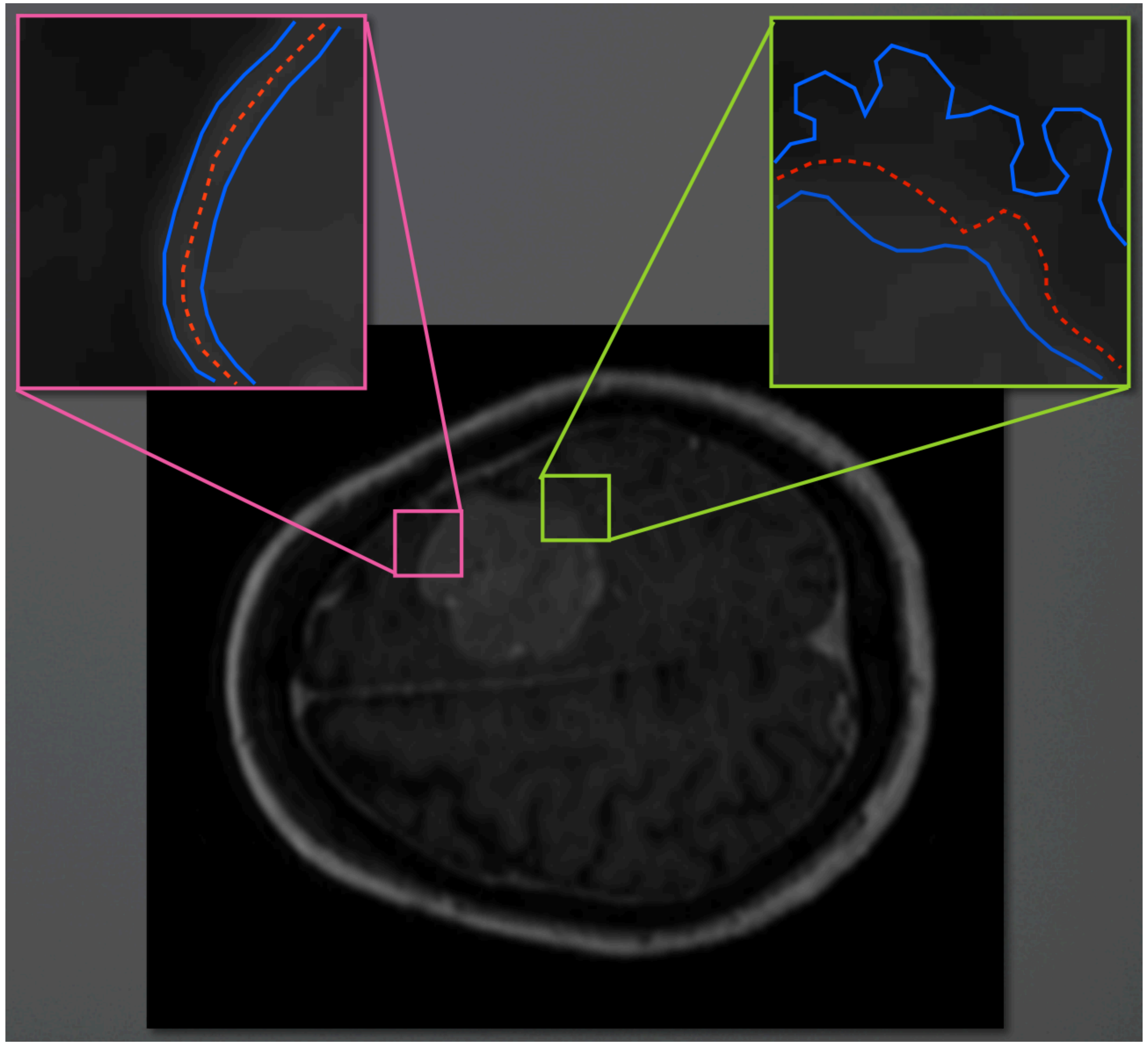
Can you identify a tumor boundary?



Whole brain atlas: http://www.med.harvard.edu/AANLIB/home.html

Why Visualize Uncertainty?

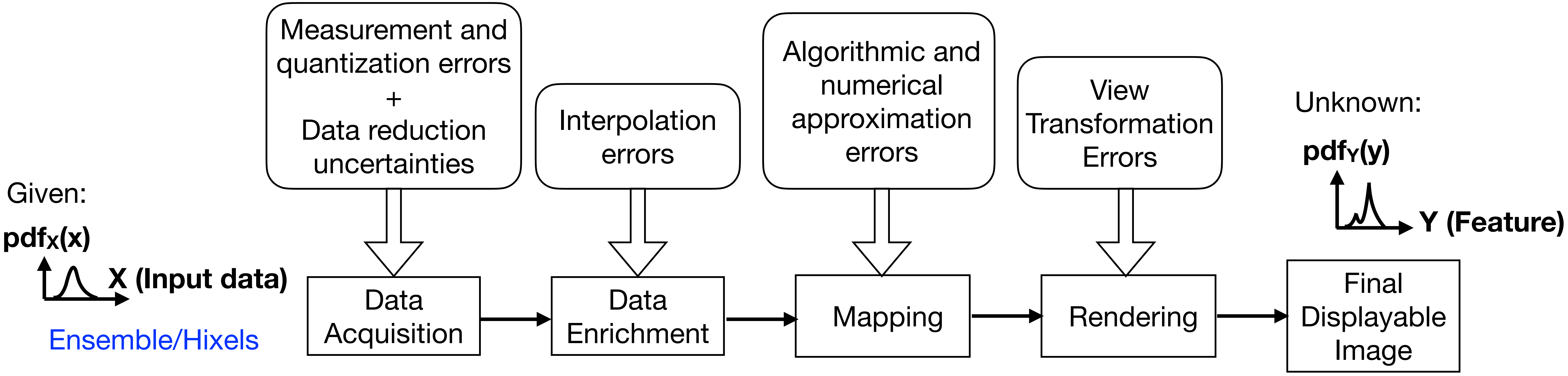
Can you identify a tumor boundary?



Whole brain atlas: http://www.med.harvard.edu/AANLIB/home.html

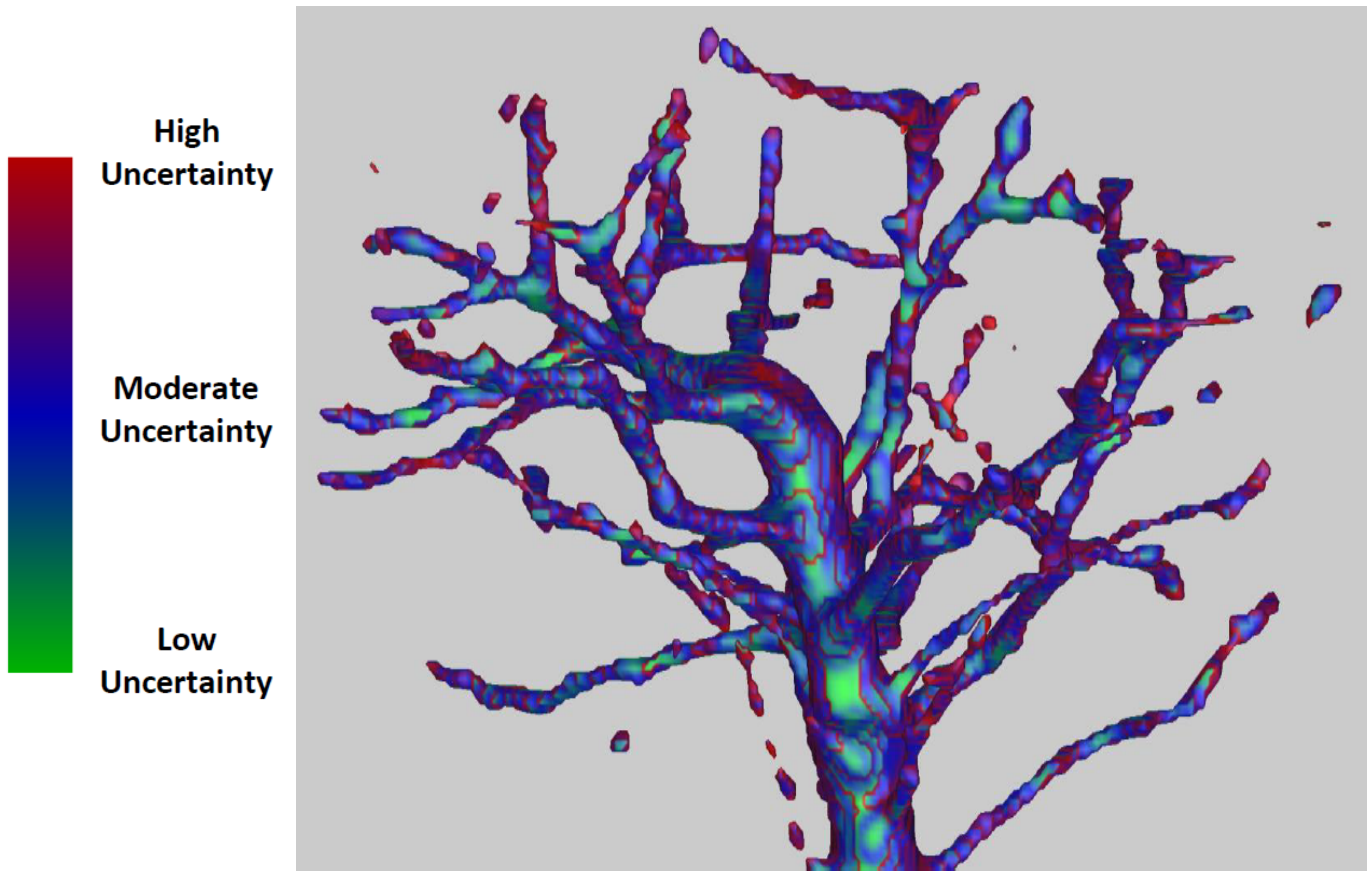
Uncertainty Quantification (Statistical Approach)

Monte Carlo (easy but expensive) vs. Analytical (difficult but fast)

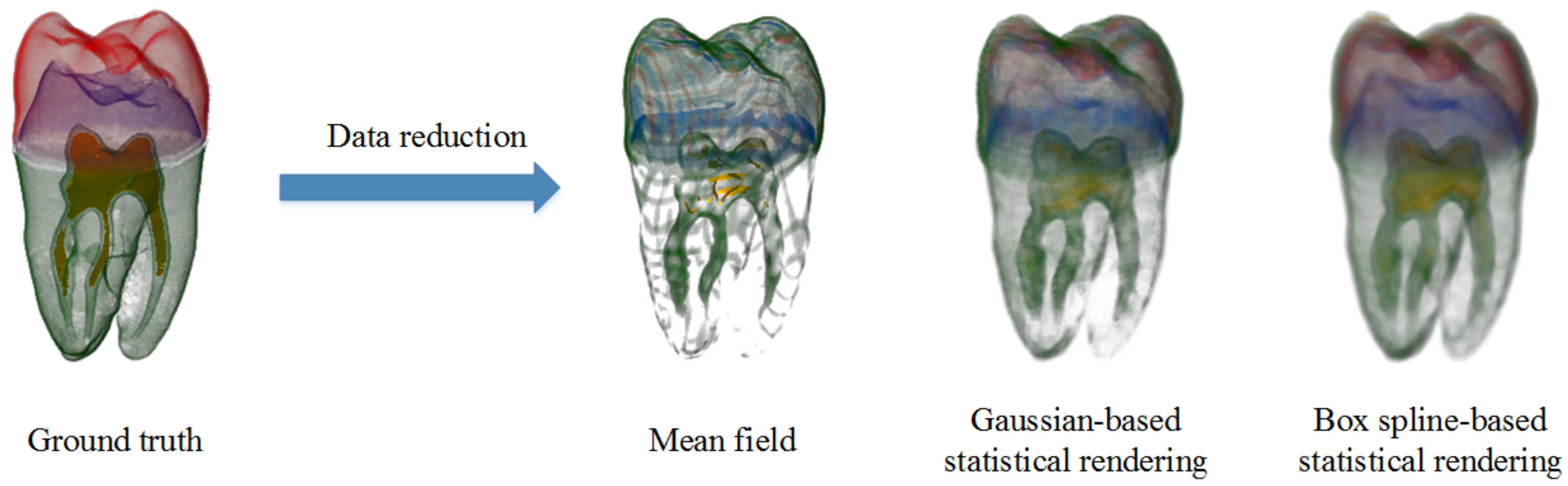


The Visualization Pipeline

Our Work

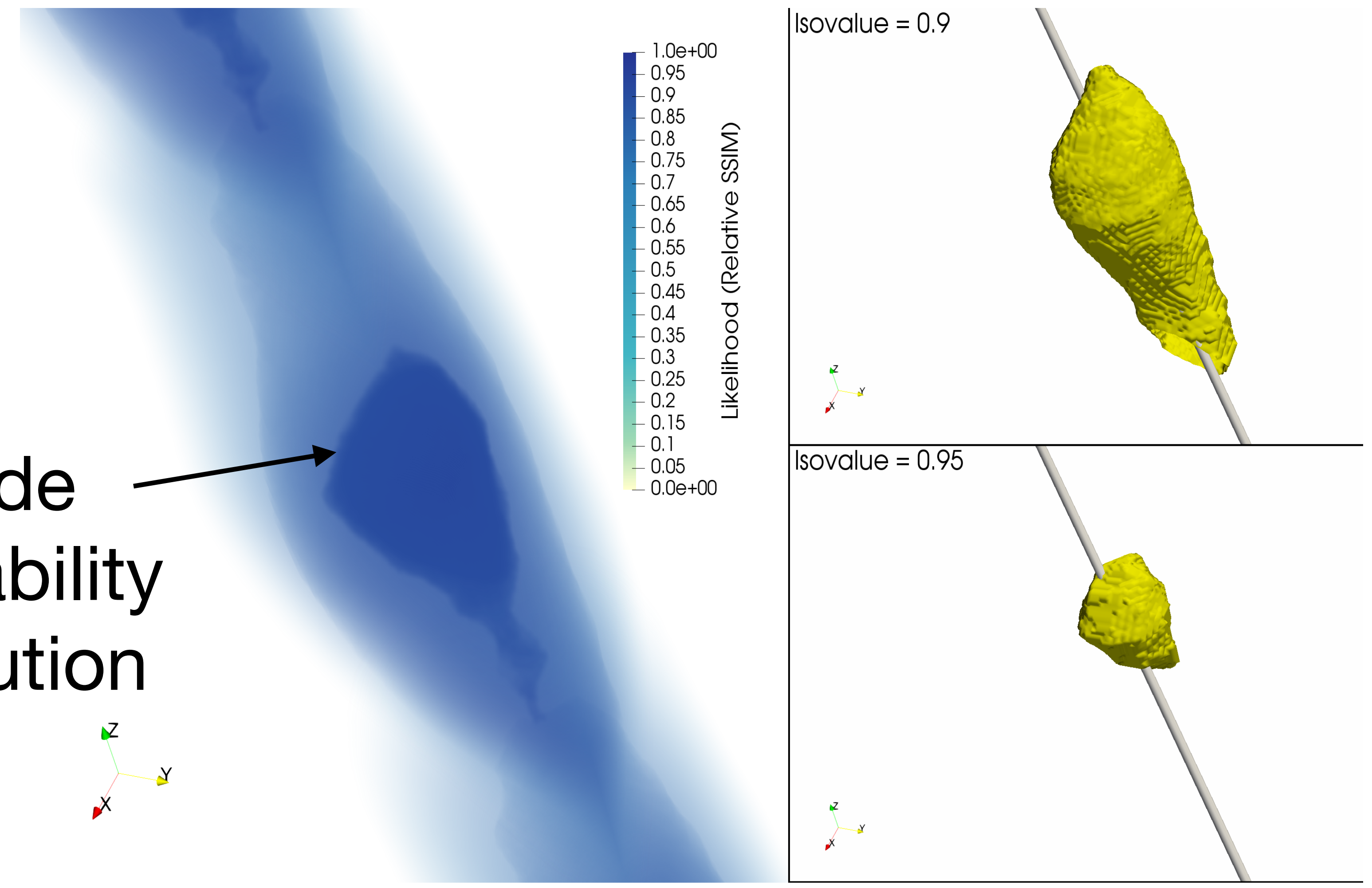


Level sets in distribution data



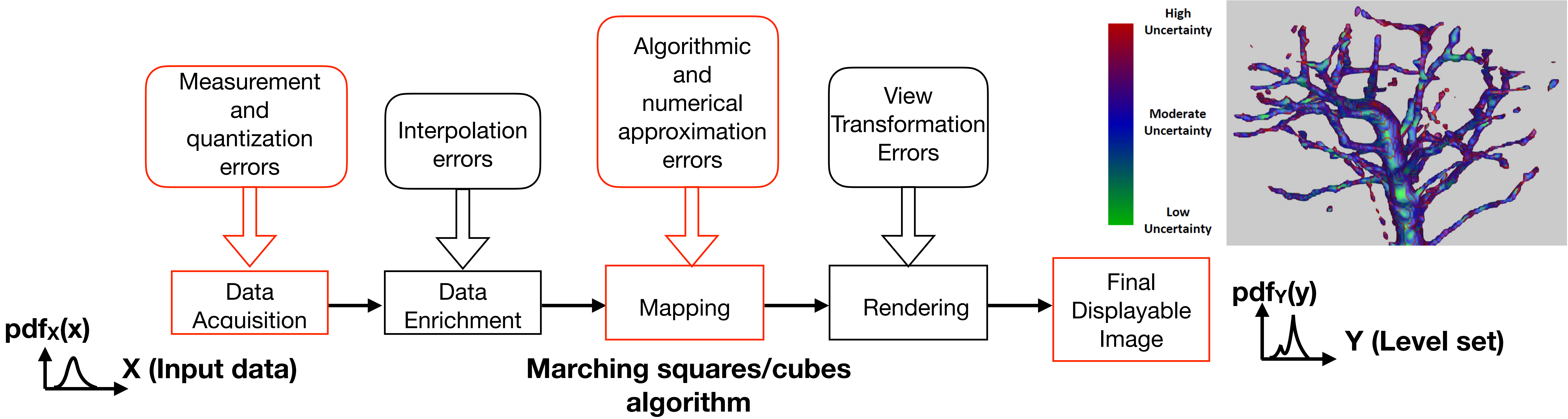
Direct volume rendering
of distribution data

DBS electrode
positional variability
for finite-resolution
Imaging

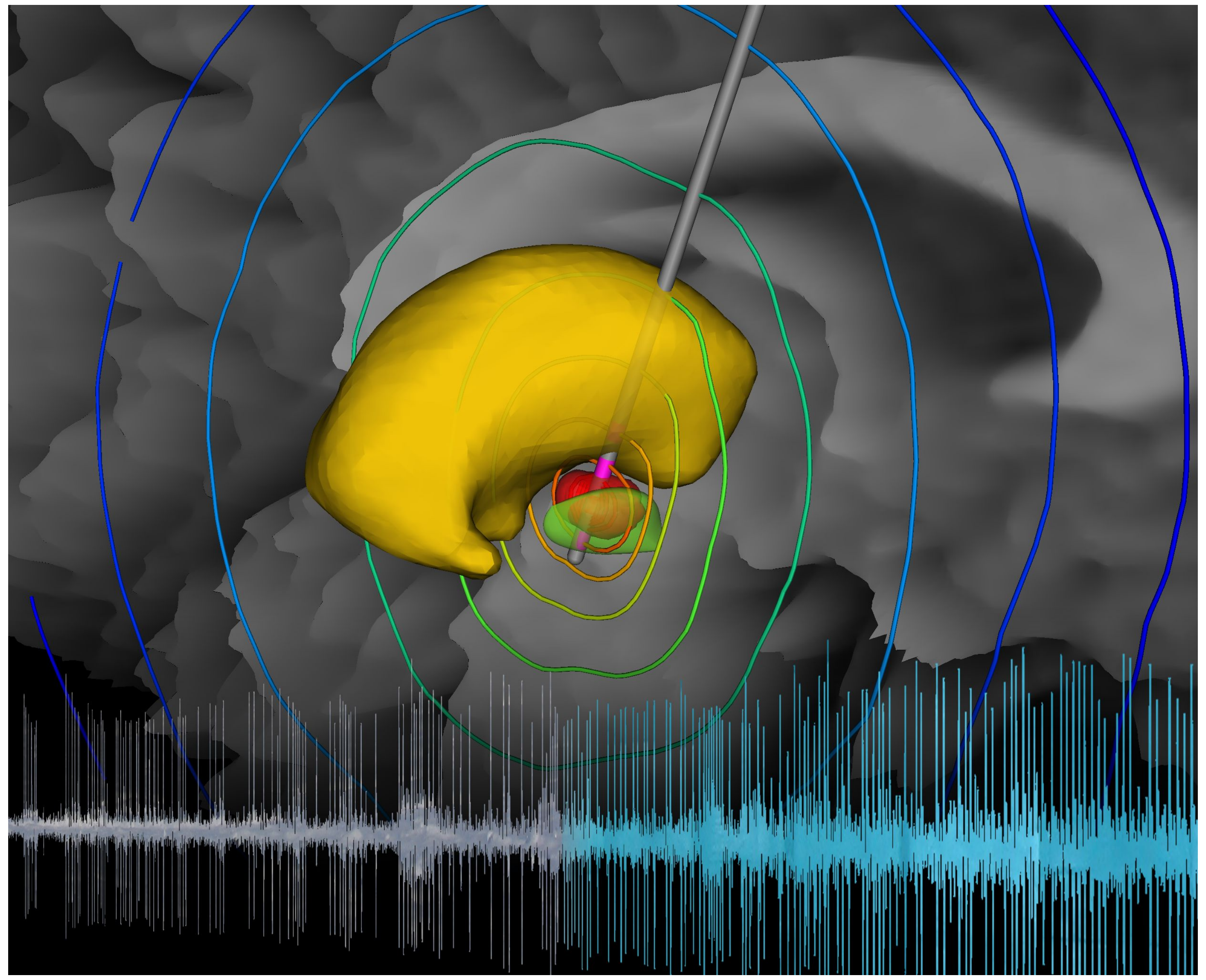


Level-Set Extraction in Uncertain Data

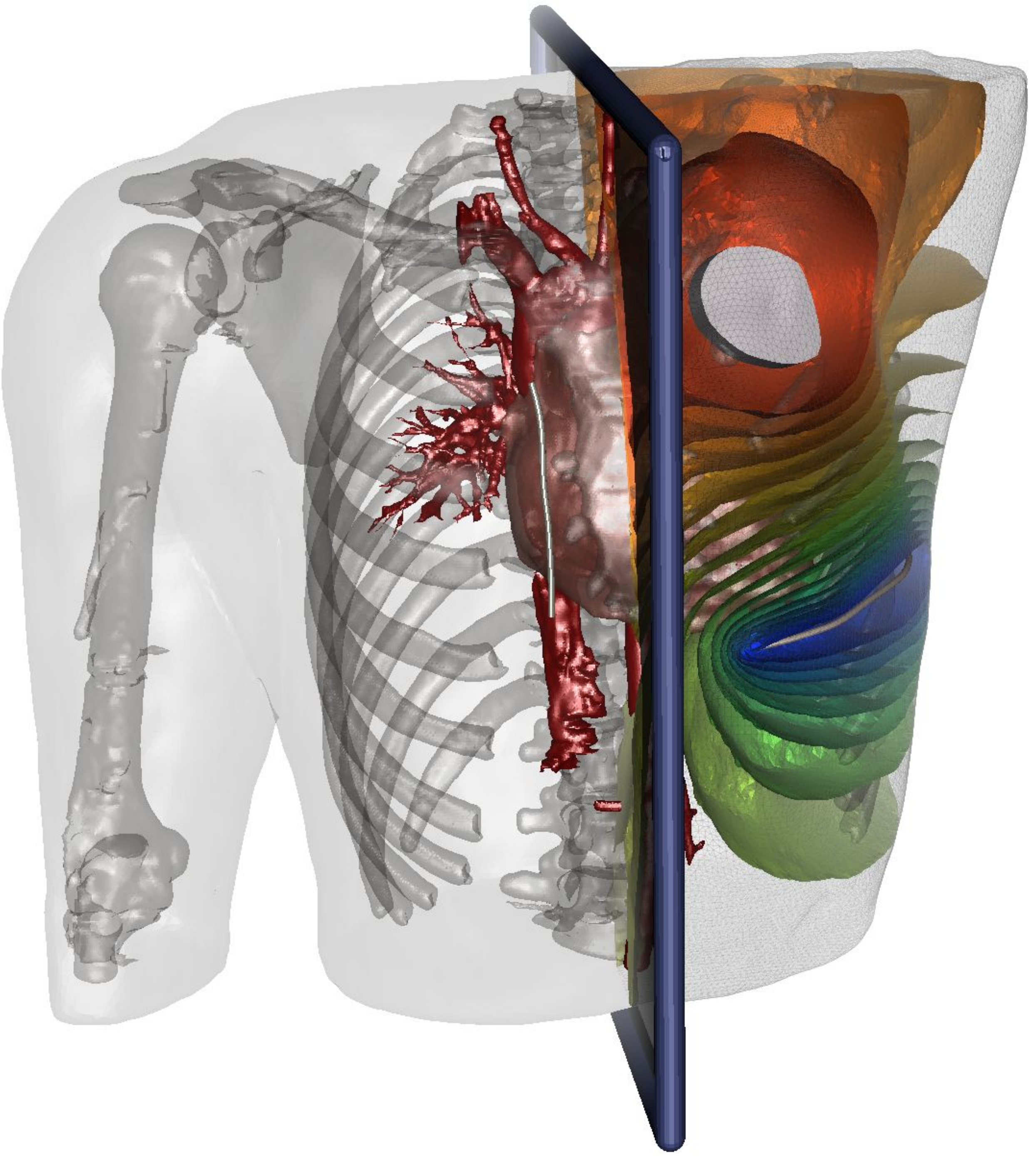
- Level sets and uncertainty
- Marching squares/cubes algorithm in certain vs. uncertain data (our contribution!)
- Results



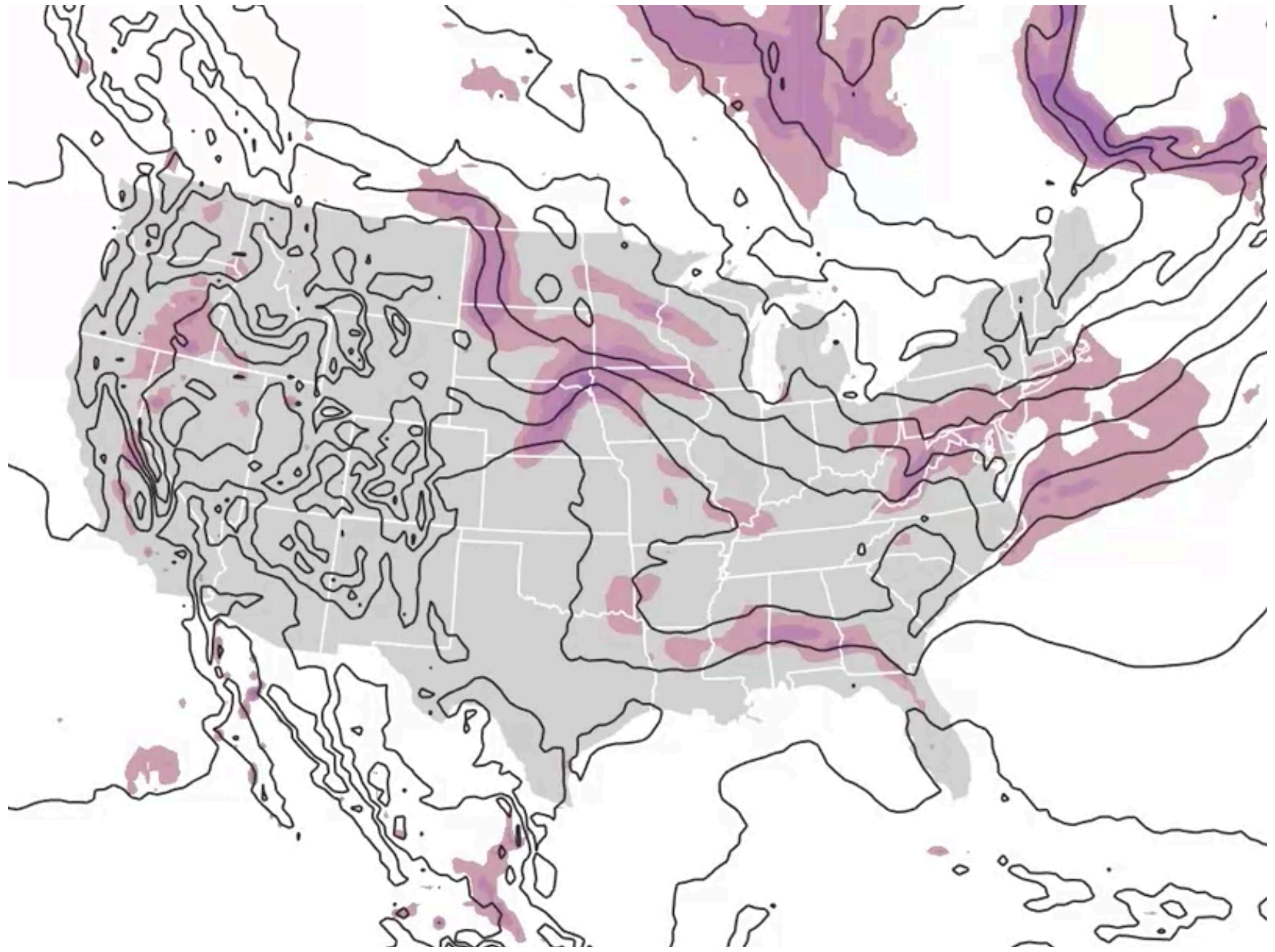
Level-Set Visualization



Deep Brain Stimulation (DBS)



Bioelectric-field Simulation

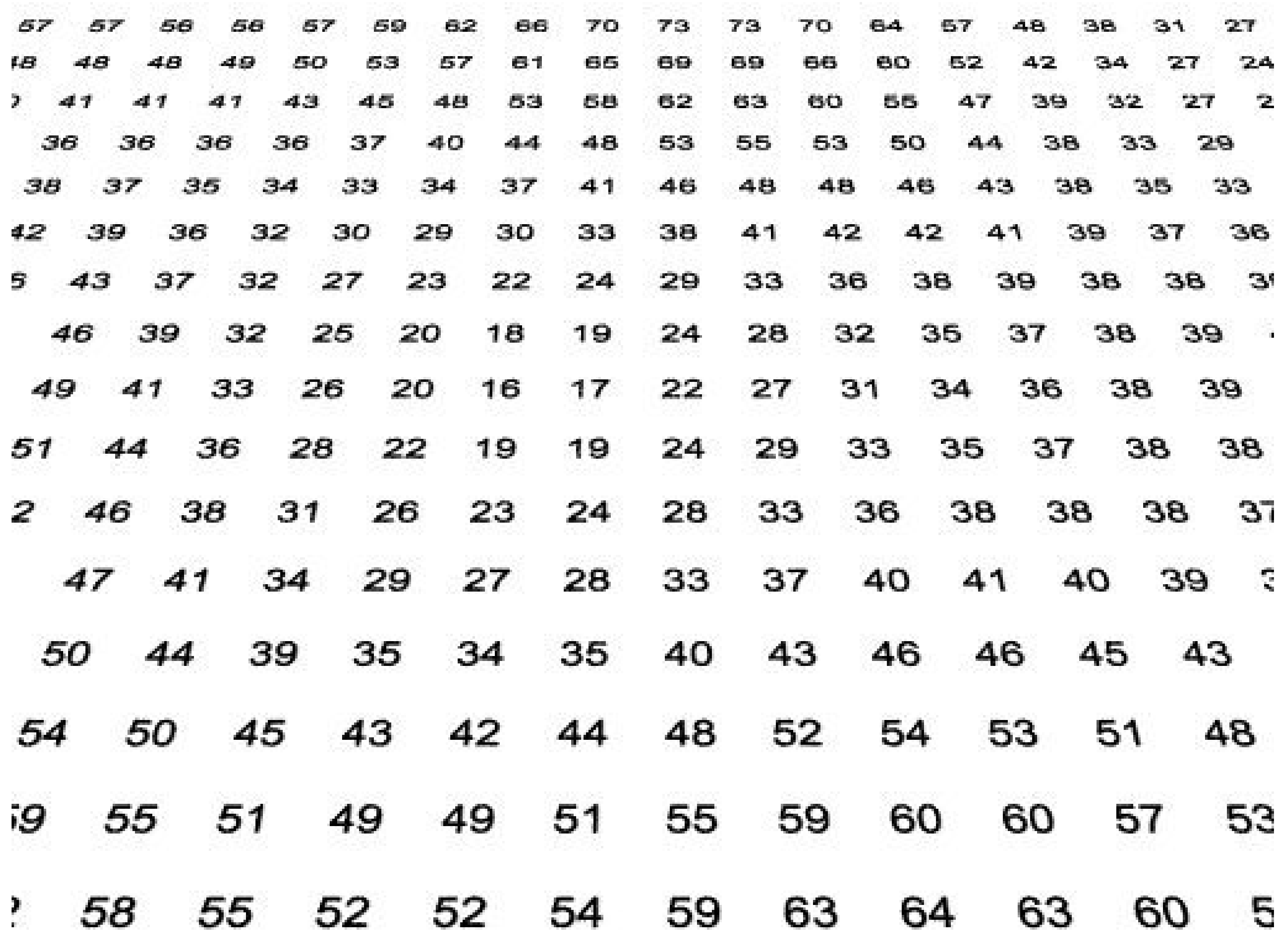


Temperature Field

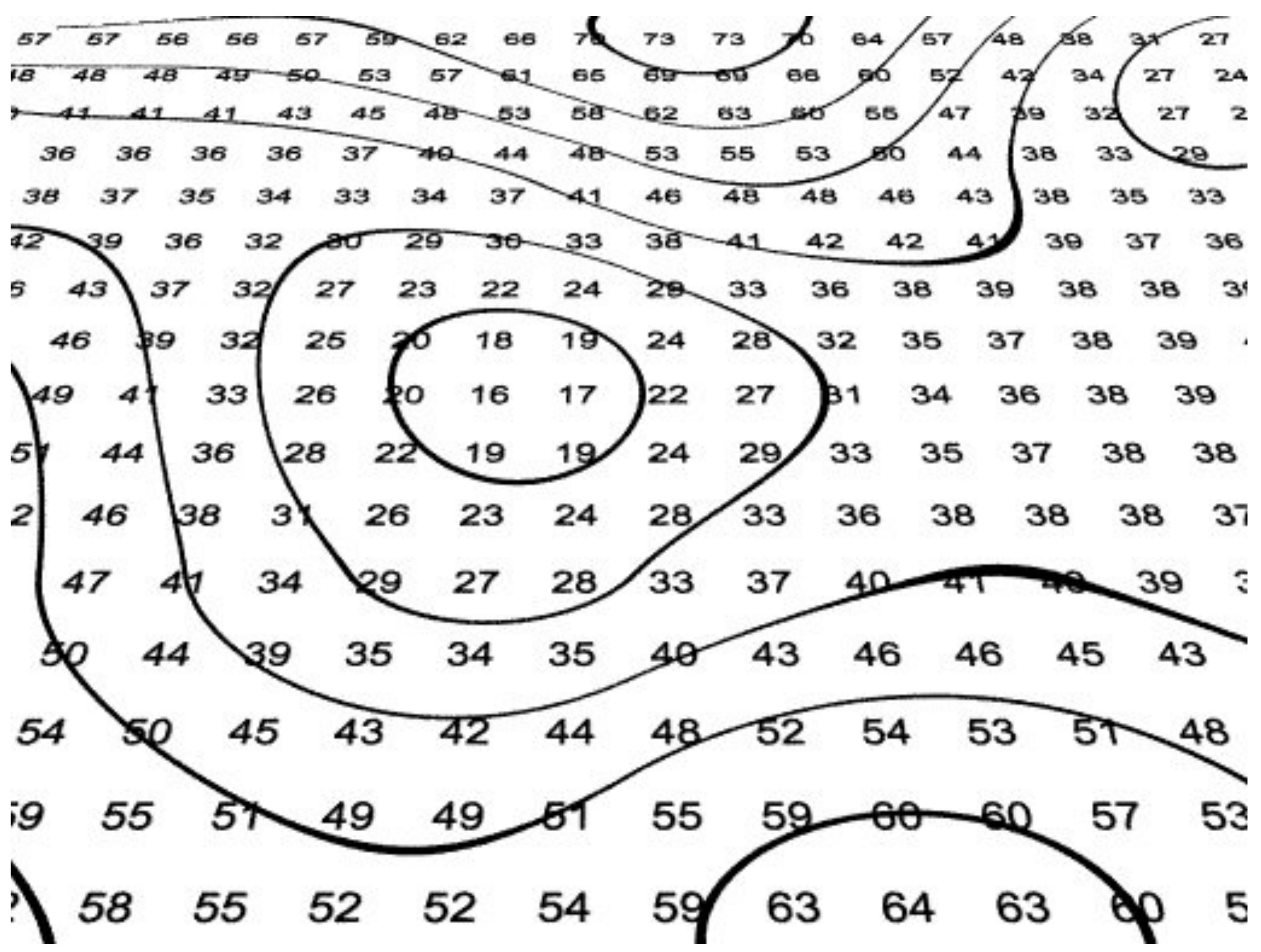
Level-Set Extraction

The inverse problem: The level-set *S* corresponding to the isovalue *k* is given by:

$$S = \{x \in \mathbb{R}^n | f(x) = k\} \text{, where } \quad f : \mathbb{R}^n \rightarrow \mathbb{R}$$



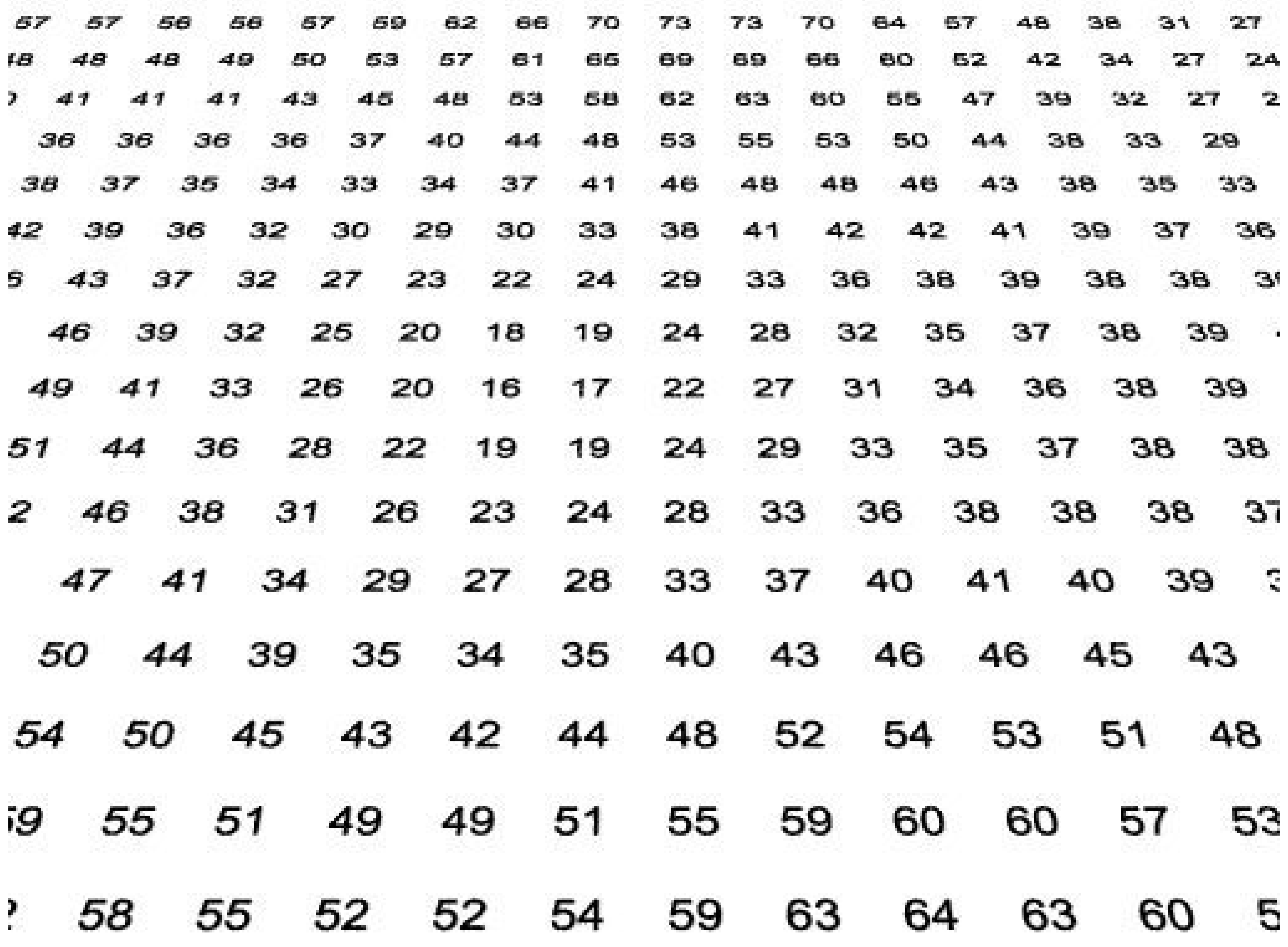
Input: Scalar Field



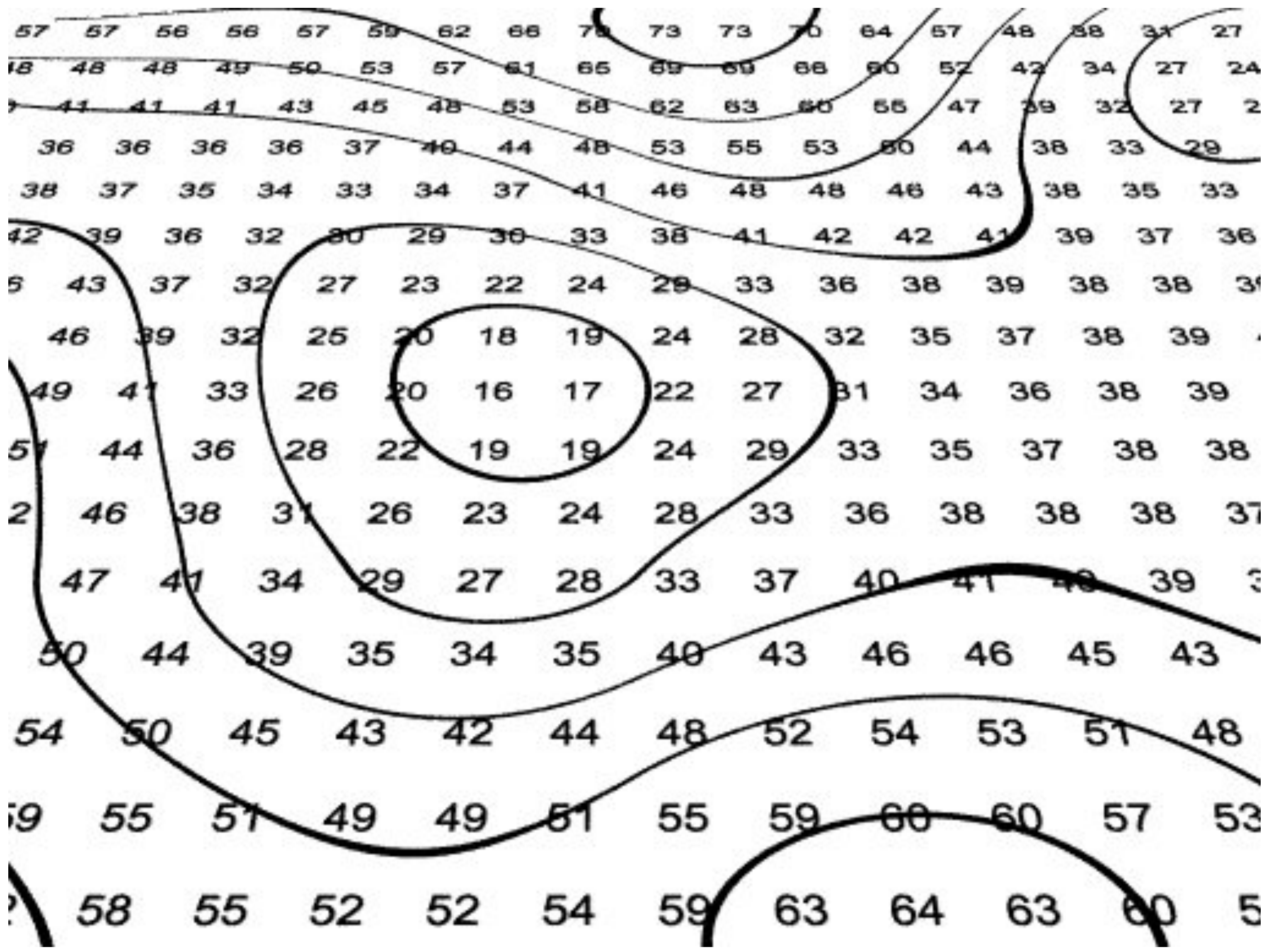
Output: Level-Sets Visualization

Level-Set Extraction in Uncertain Data

Research Question: Analysis of topological and geometric variations in level sets for uncertain scalar field



Input: Noisy Scalar Field

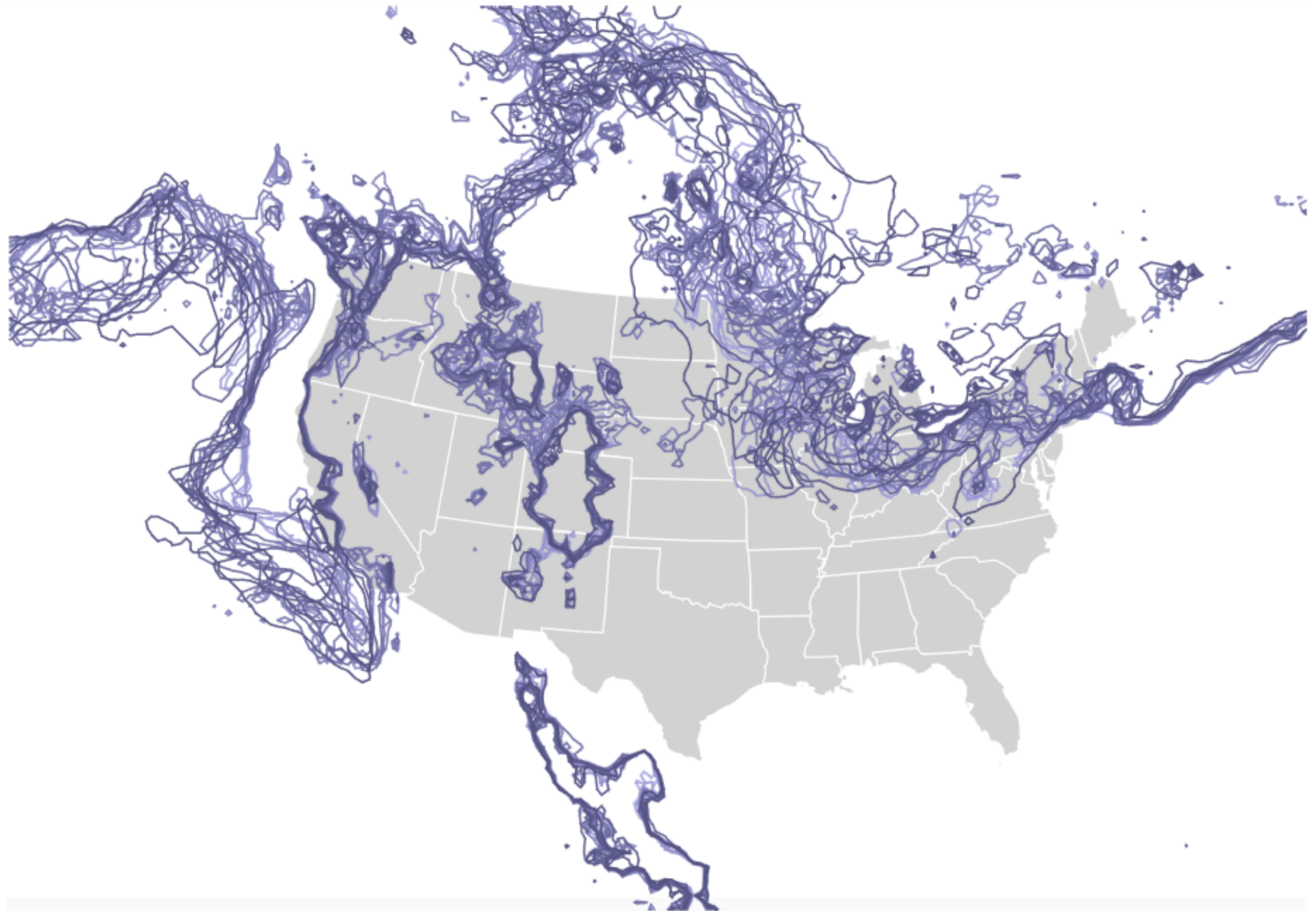


Output: Level-Sets Visualization

May not represent the true level sets!

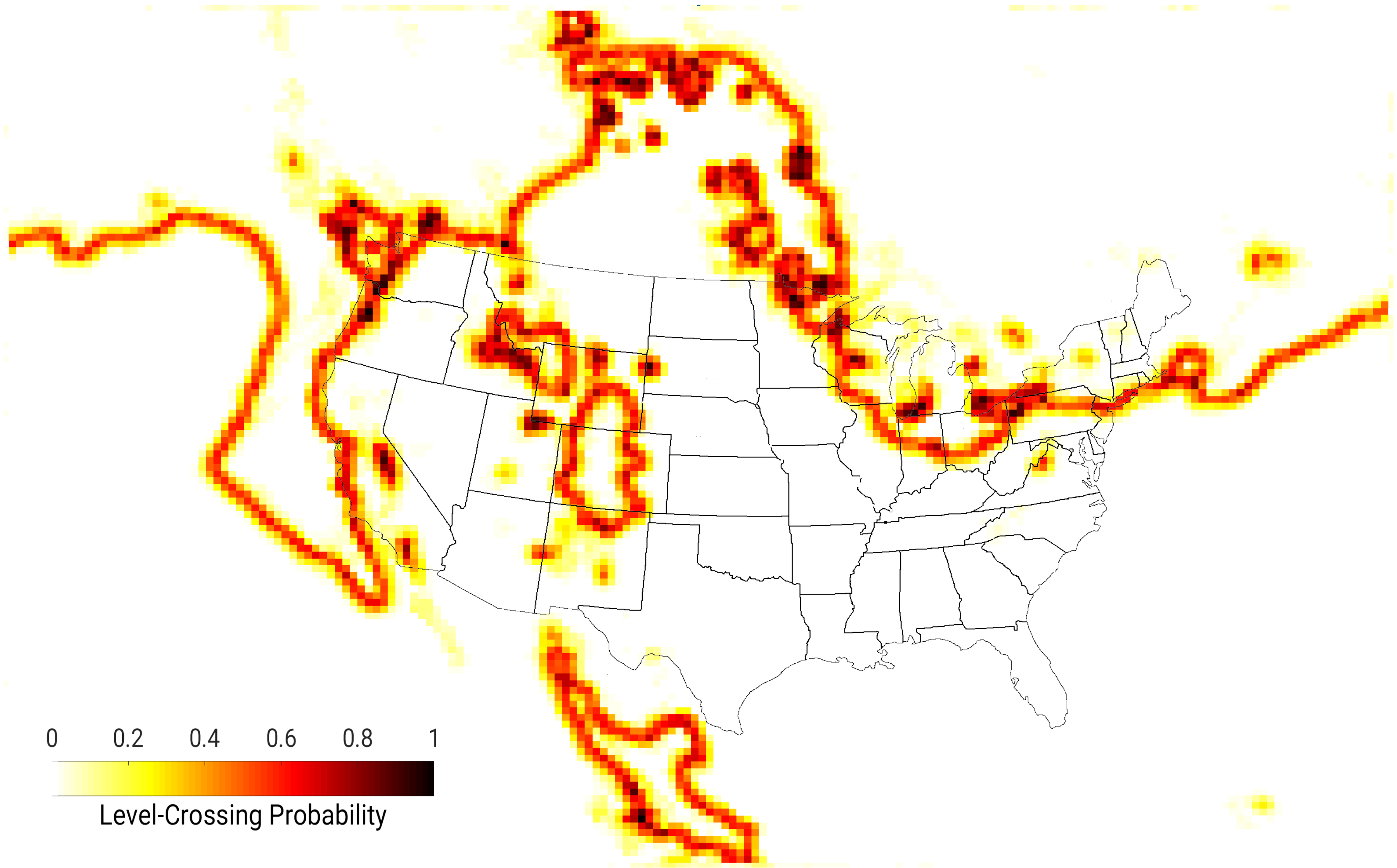
Visualization of Level-Sets in Uncertain Data

Spaghetti plots
[Potter et al., 2009]

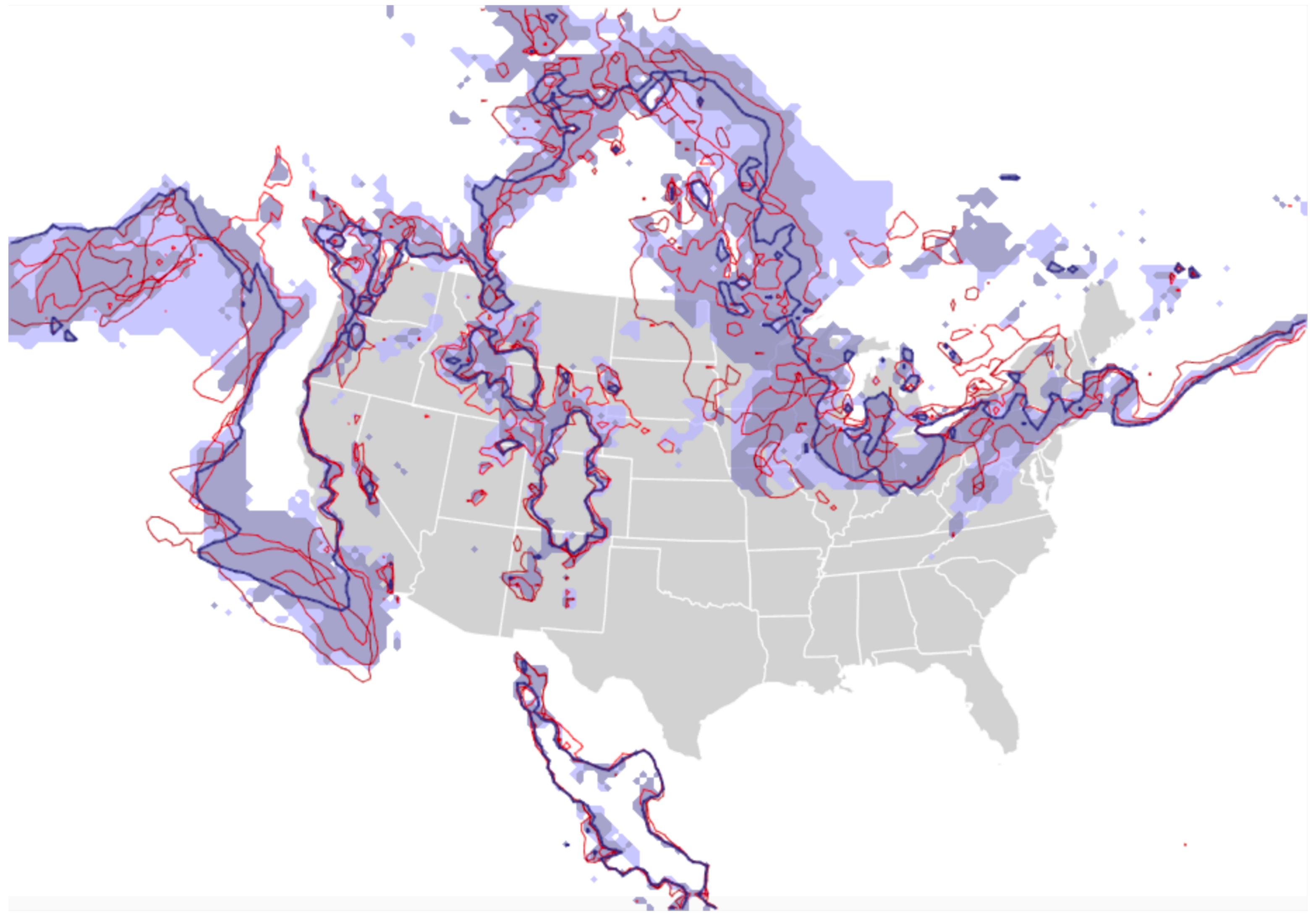


Visualization software: The WeaVER
[Quinan and Meyer, 2016]

Probabilistic marching cubes
[Pöthkow et al., 2011]



Contour/Surface boxplots
[Whitaker et al., 2013; Genton et al., 2014]



The visualization of uncertain temperature field
isovalue (k) = 60°F

Marching Squares/Cubes Algorithm for Level-Set Extraction

[Lorenson and Cline, 1987]

Bill Lorensen

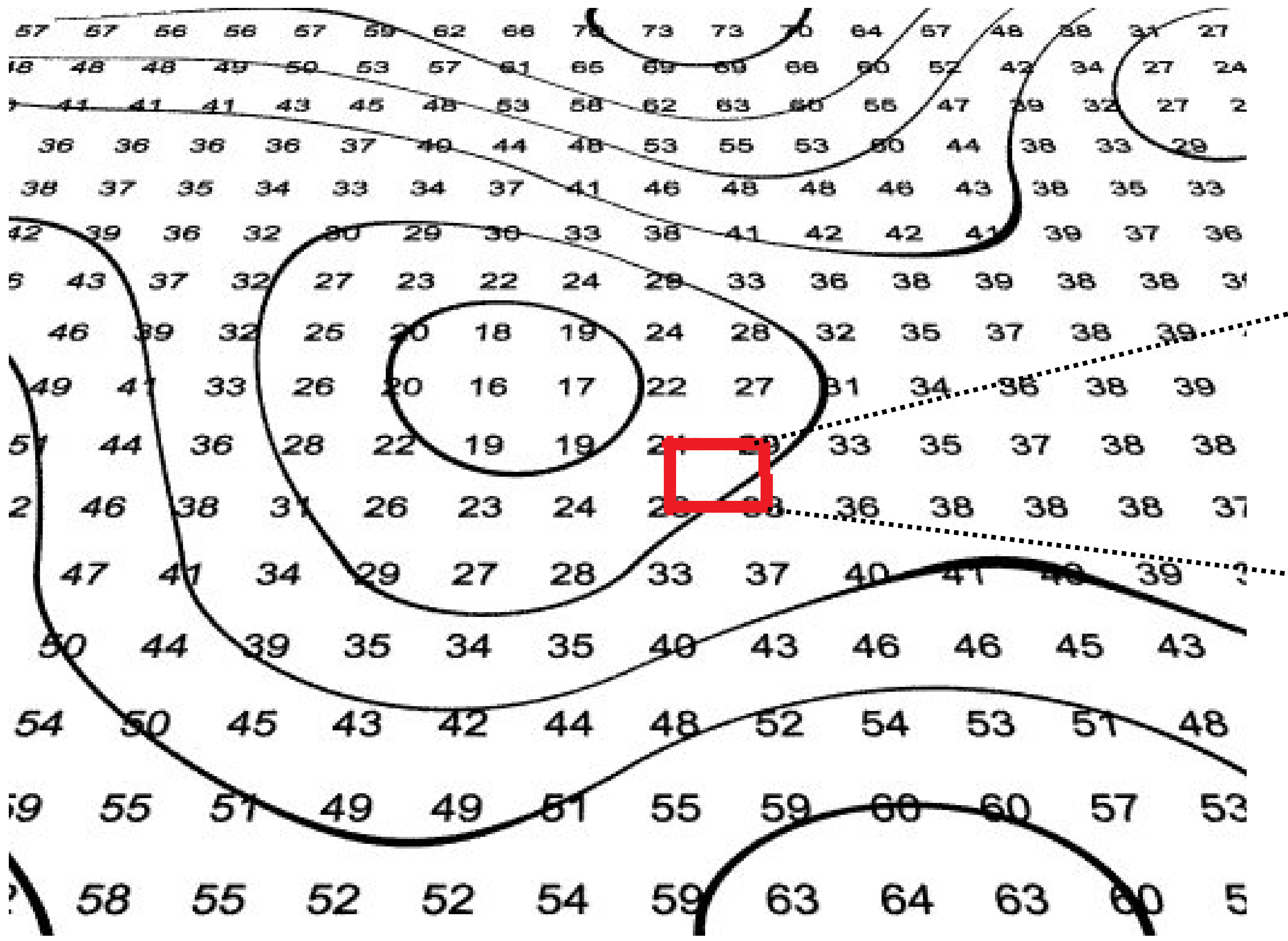
FOLLOW

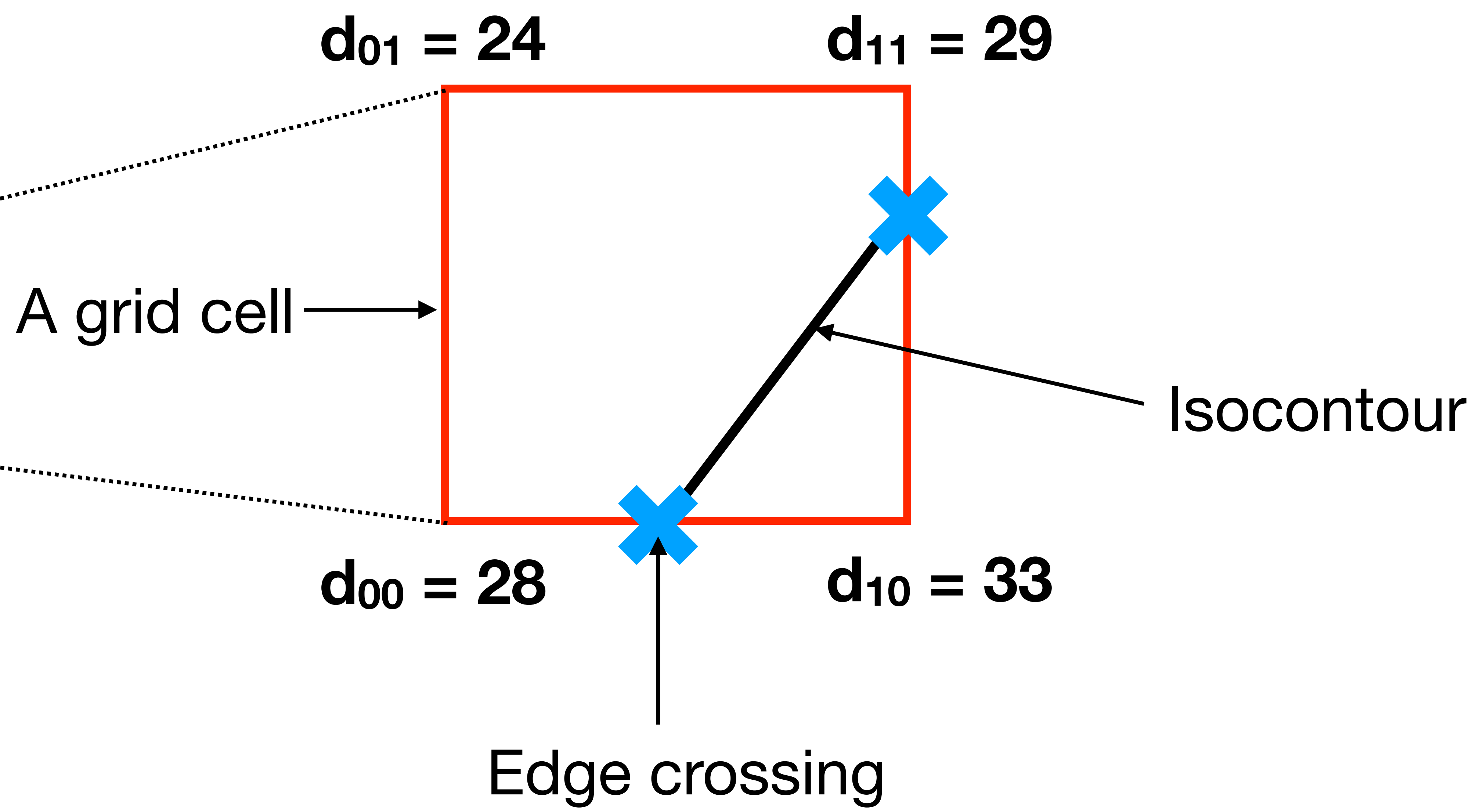
GE Global Research (retired)
Verified email at nycap.rr.com - Homepage

TITLE	CITED BY	YEAR
Marching cubes: A high resolution 3D surface construction algorithm WE Lorensen, HE Cline ACM siggraph computer graphics 21 (4), 163-169	14722	1987
Object-oriented modeling and design J Rumbaugh, M Blaha, W Premerlani, F Eddy, WE Lorensen Prentice-hall 199 (1)	11422	1991

Marching Squares Algorithm (MSA)

- Bilinear interpolation: prediction of unknown data values within a grid cell
- For each cell:
  - Extract isocontour topology (Which edges are crossed?)
  - Compute geometry (Where on the edge?)



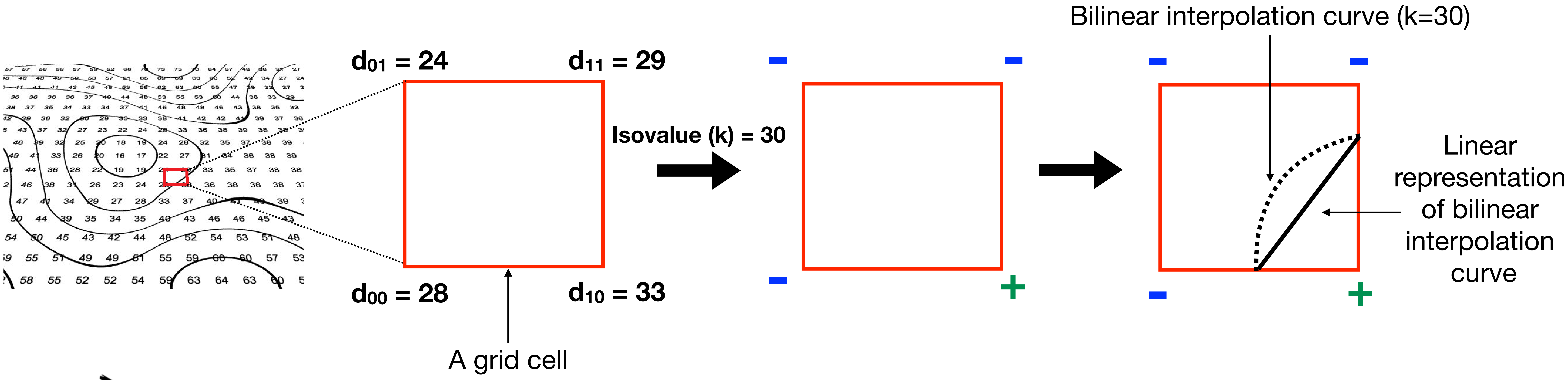


MSA: The Topology Step (which edges?)

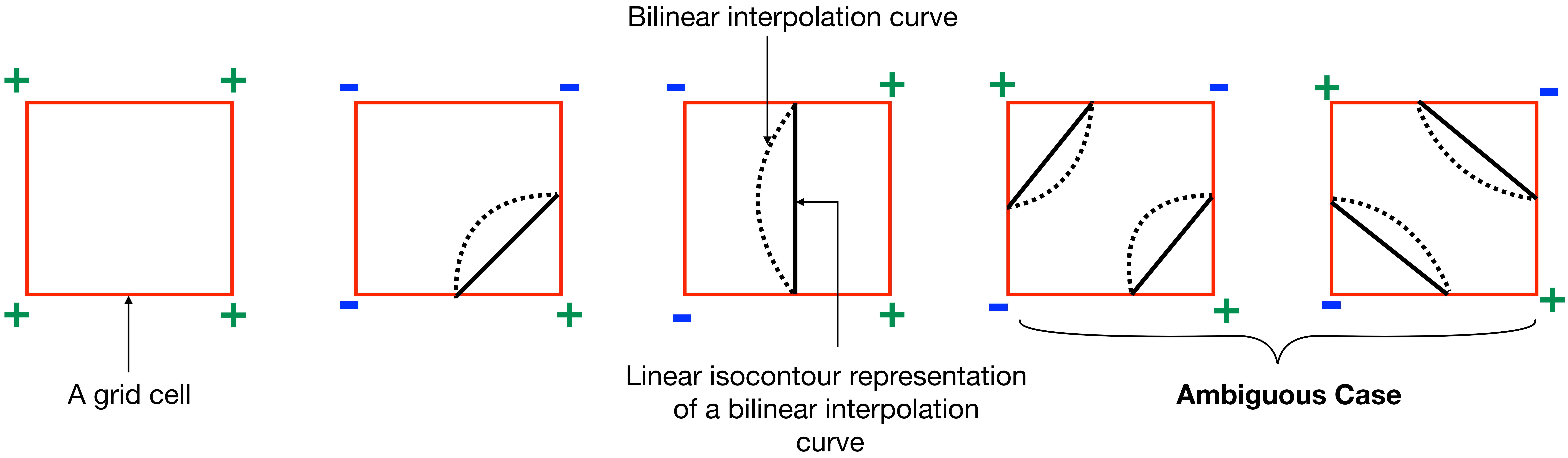
Data (d_{xy}) > Isovalue (k) : Positive vertex (+)
Data (d_{xy}) < Isovalue (k) : Negative vertex (−)

Bilinear interpolation function:

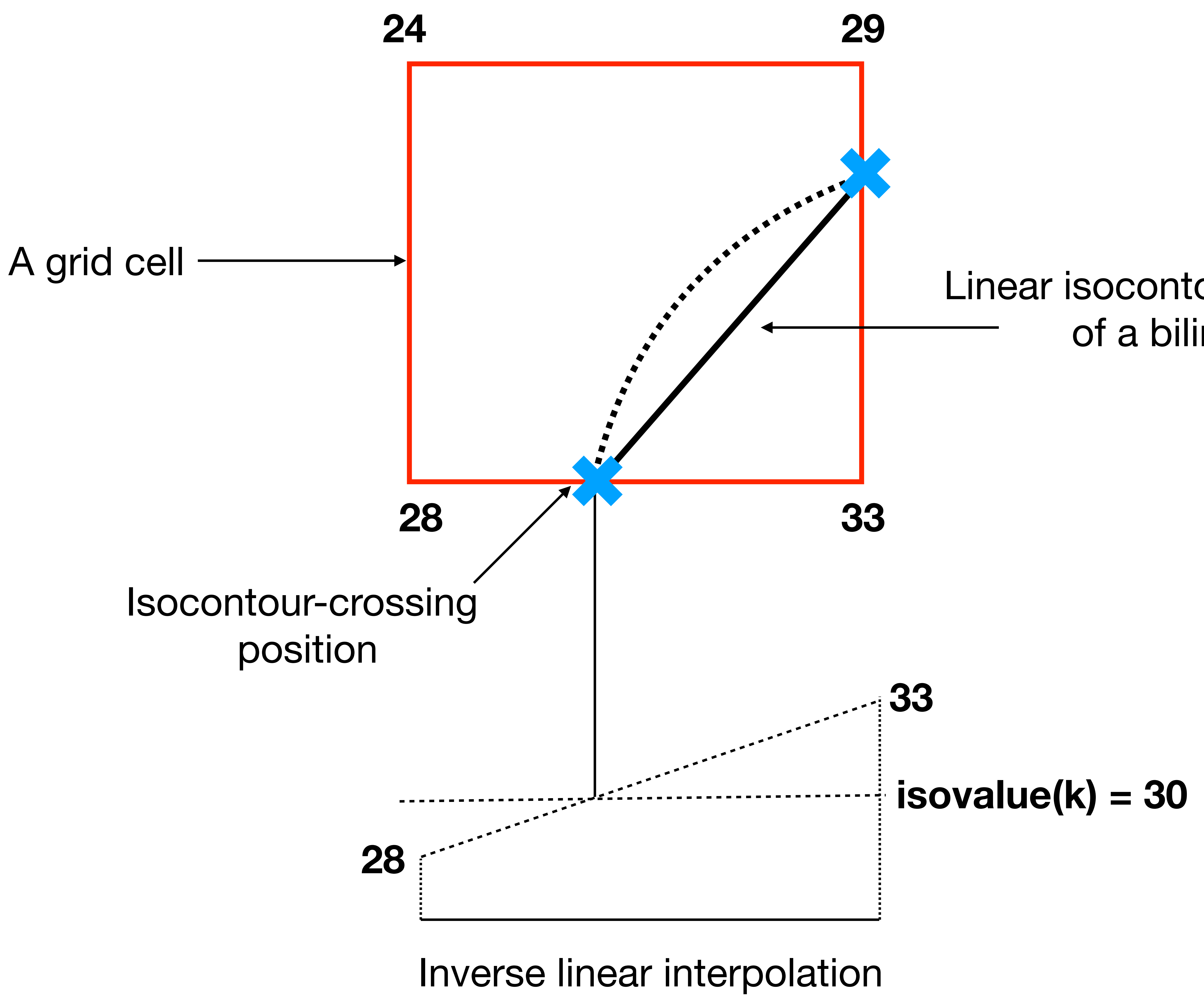
f: [0,1]x[0,1] → *R*
f(x,y) = ax + by + cxy + d (the equation of hyperbola!)**, where**
$a = d_{10} - d_{00}$, $b = d_{01} - d_{00}$
$c = d_{00} + d_{11} - d_{01} - d_{10}$, $d = d_{00}$



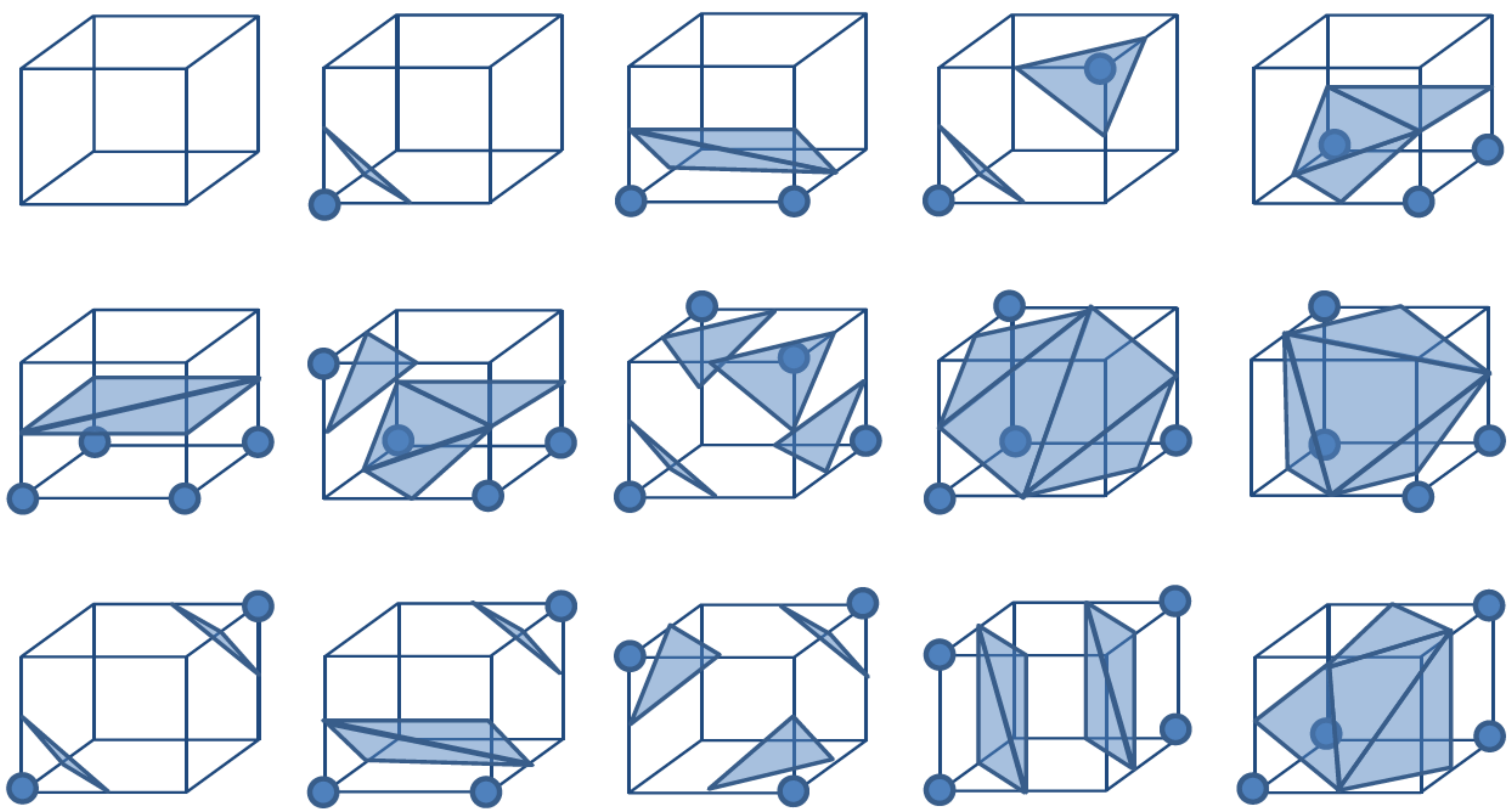
MSA: Topological Cases (which edges?)

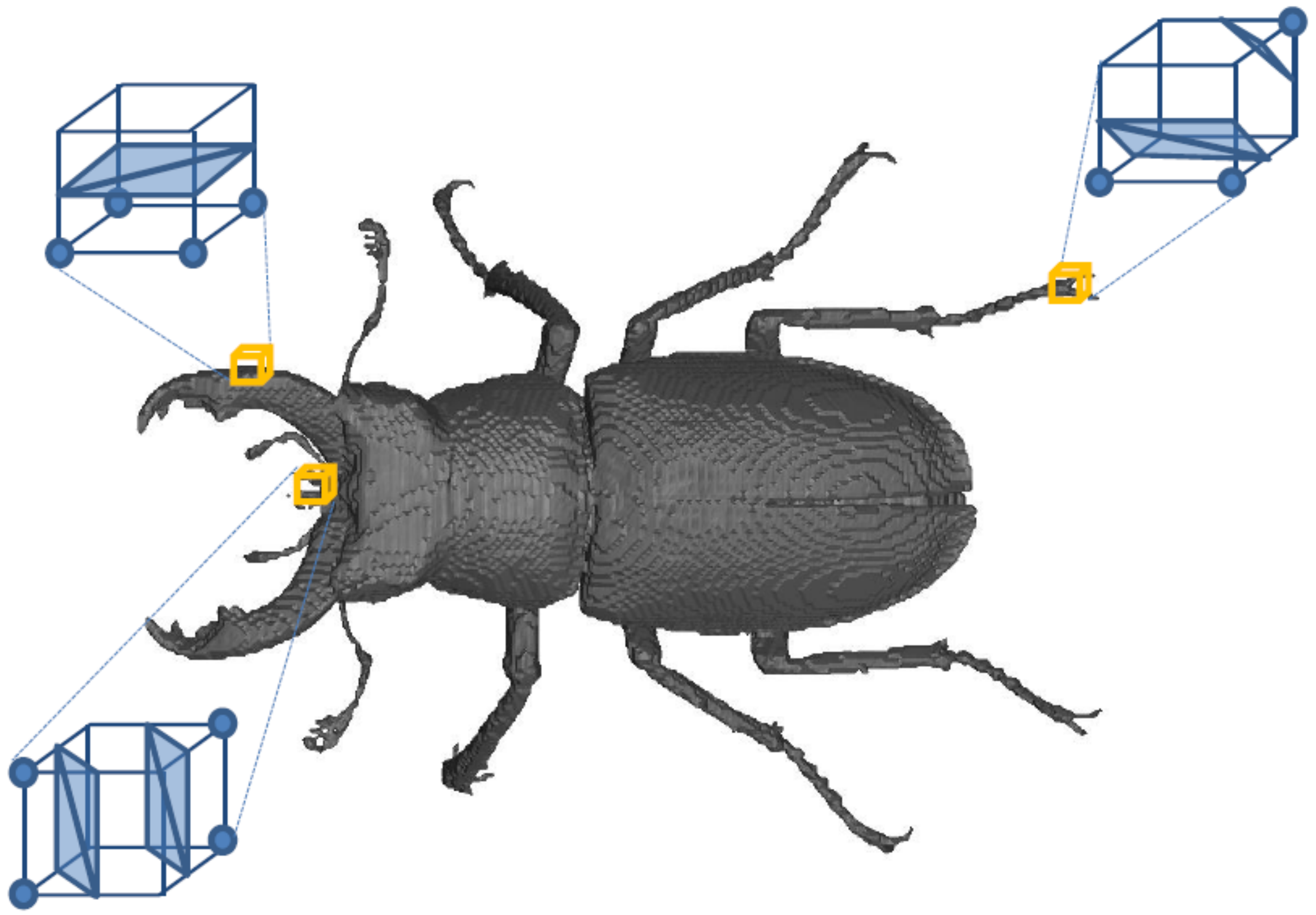


MSA: The Geometry Step (where on the edge?)

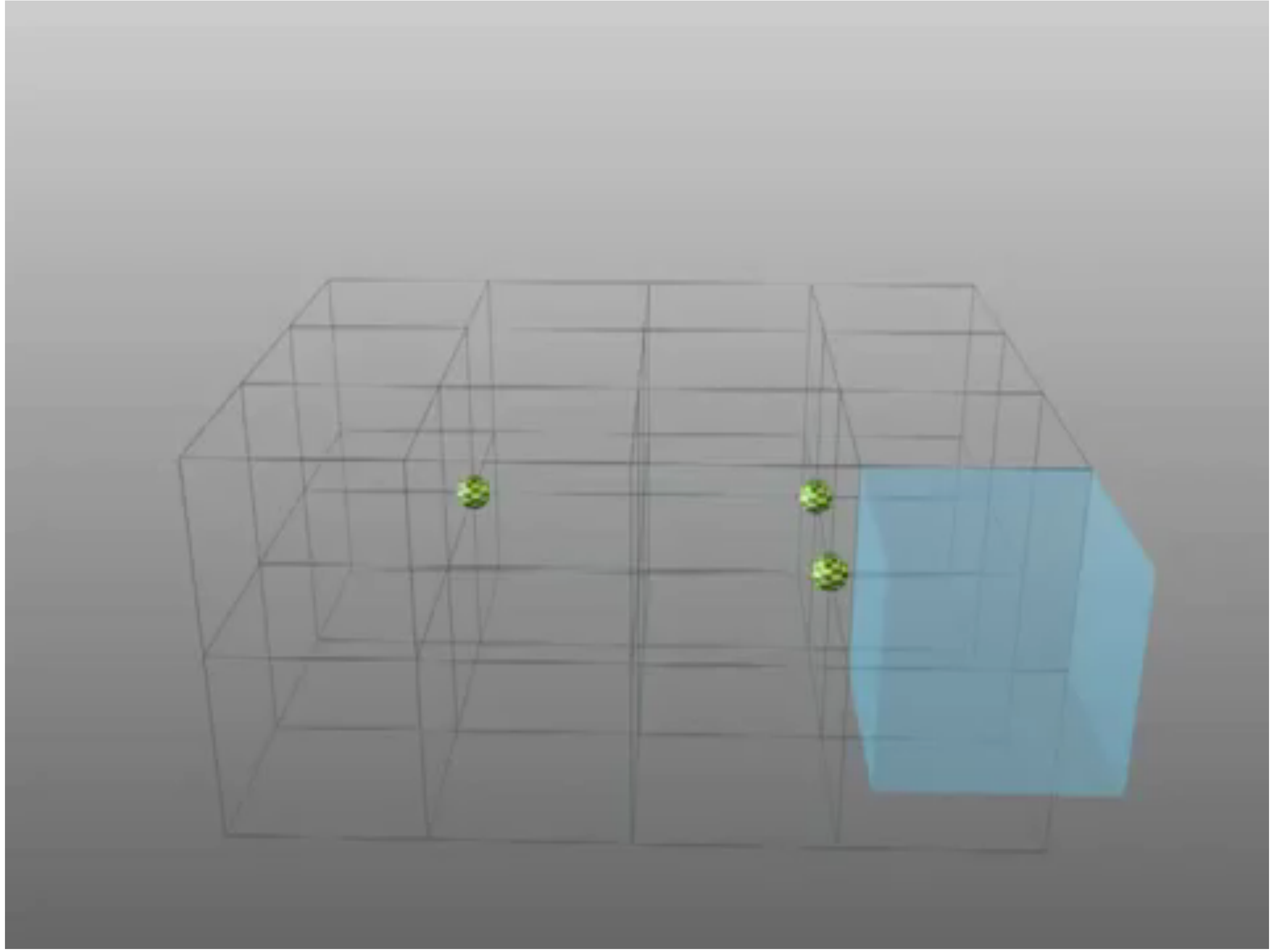


Marching Cubes Algorithm (MCA): Topological Cases





Marching Cubes Algorithm in Action!

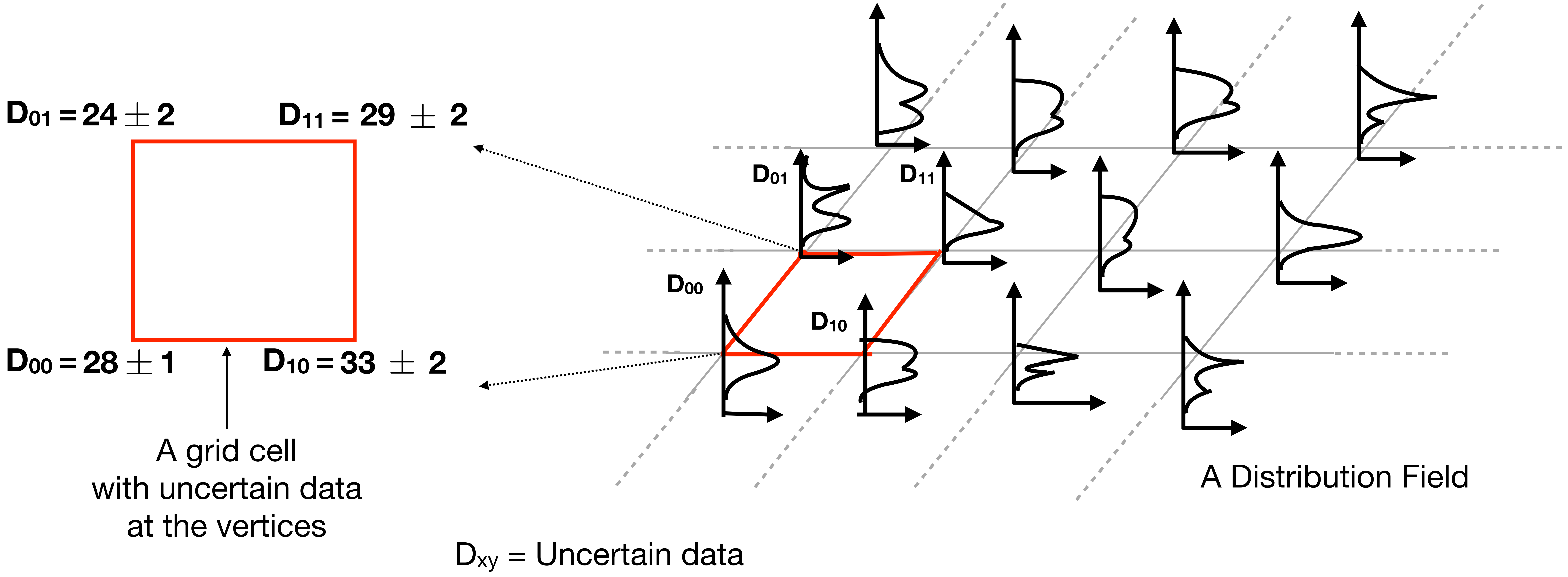


https://www.youtube.com/watch?v=LfttaAepYJ8

Marching Squares/Cubes Algorithm for Level-Set Extraction in Uncertain Data

MSA for Uncertain Data (our contribution!)

- Topological (which edges) uncertainty resolution
- Geometric (where on the edges) uncertainty resolution

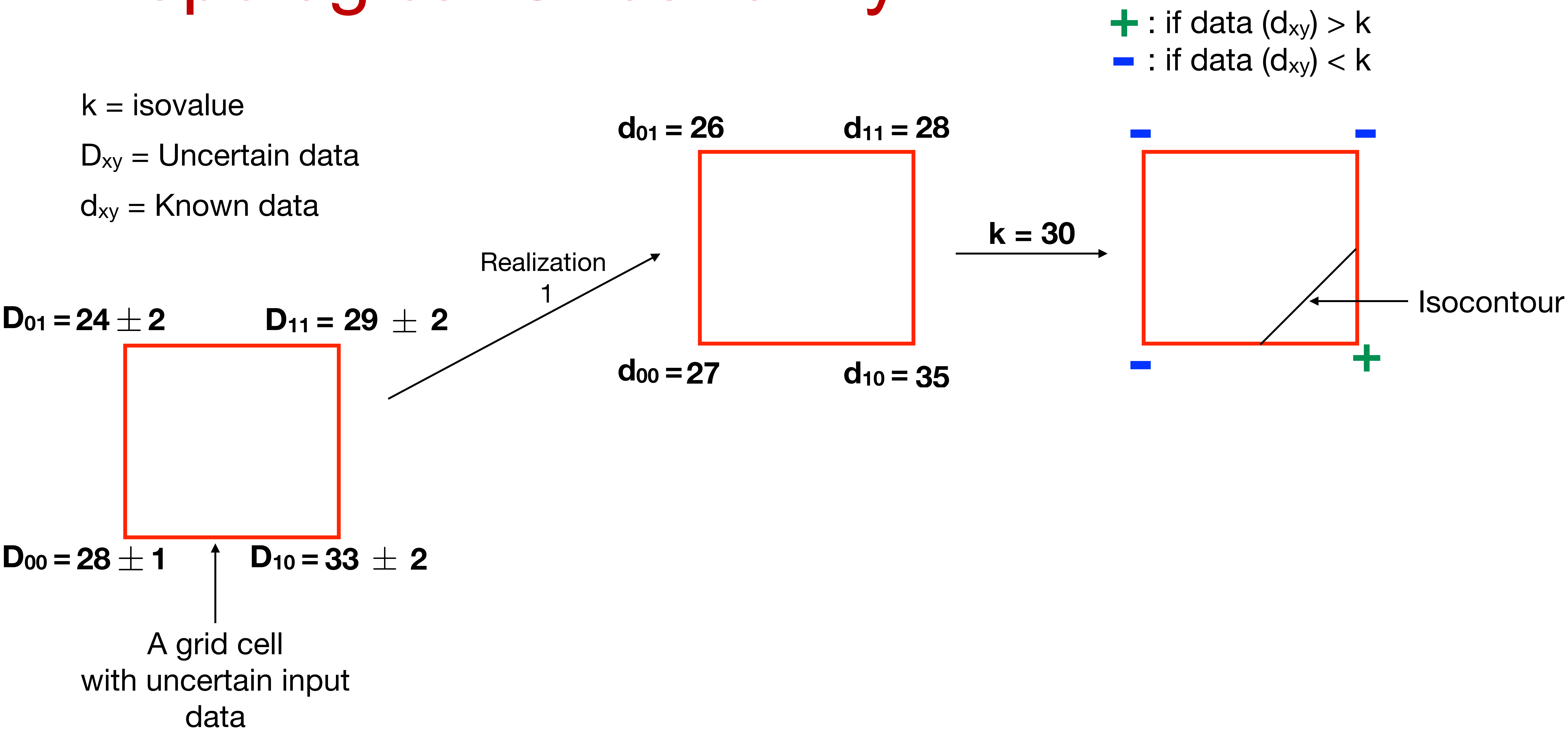


MSA: Topological Uncertainty

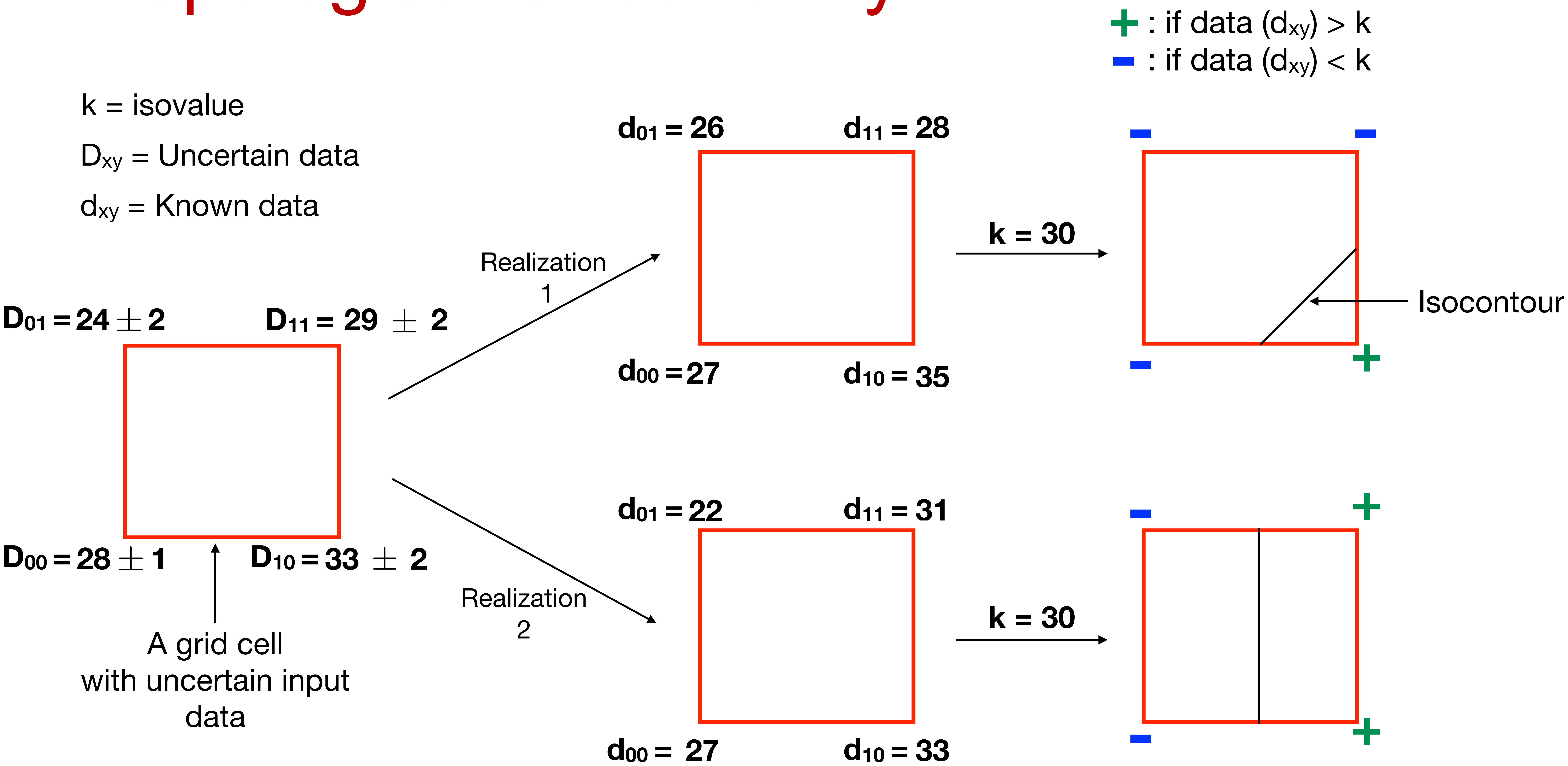
k = isovalue

D_{xy} = Uncertain data

d_{xy} = Known data



MSA: Topological Uncertainty

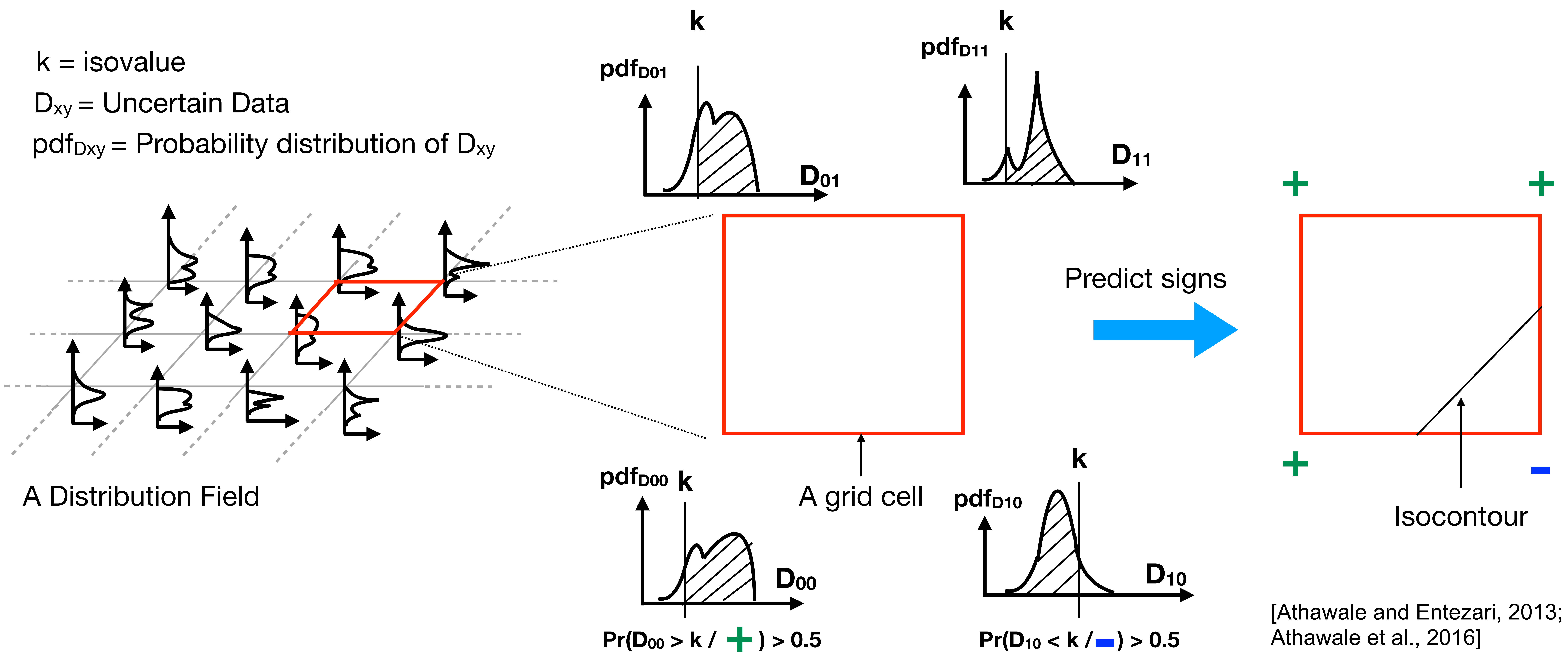


MSA: Topological Uncertainty Resolution

k = isovalue

D_{xy} = Uncertain Data

$pdf_{D_{xy}}$ = Probability distribution of D_{xy}



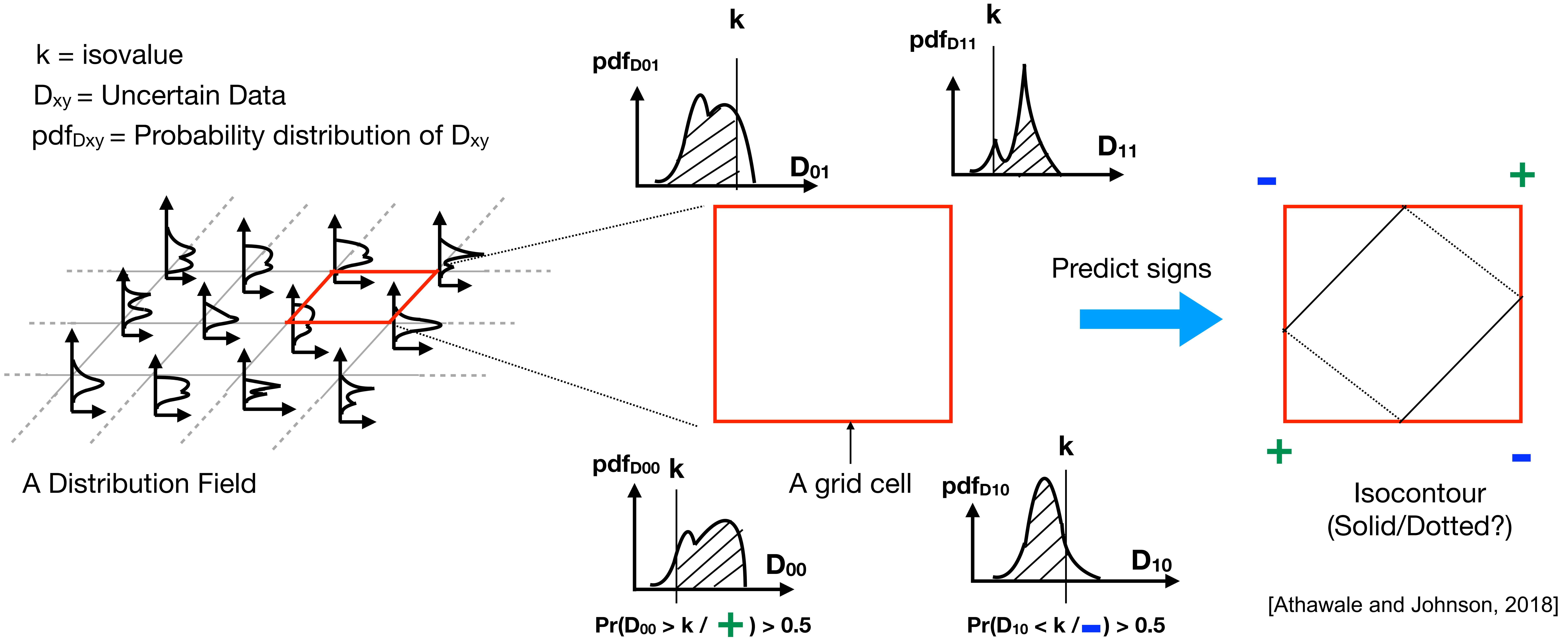
[Athawale and Entezari, 2013; Athawale et al., 2016]

MSA Ambiguous Case: Topological Uncertainty Resolution

k = isovalue

D_{xy} = Uncertain Data

$pdf_{D_{xy}}$ = Probability distribution of D_{xy}



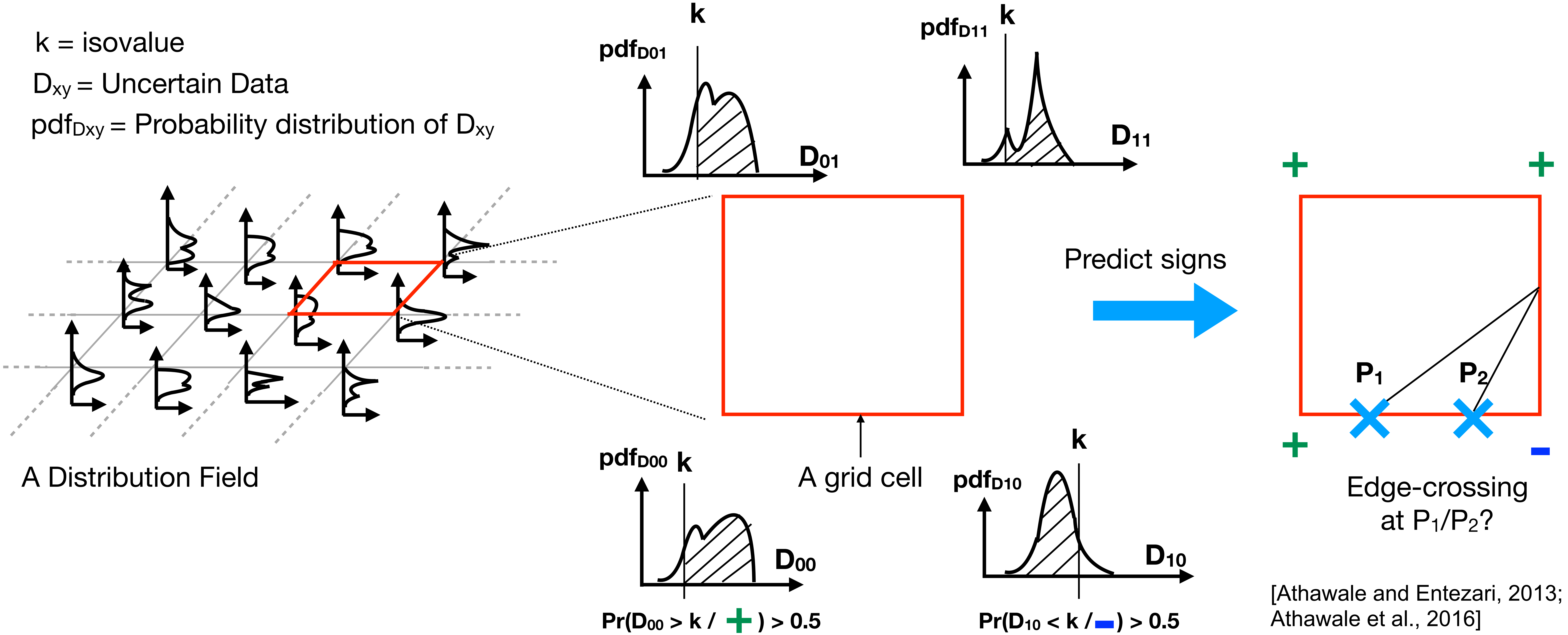
[Athawale and Johnson, 2018]

MSA: Geometric Uncertainty

k = isovalue

D_{xy} = Uncertain Data

$pdf_{D_{xy}}$ = Probability distribution of D_{xy}

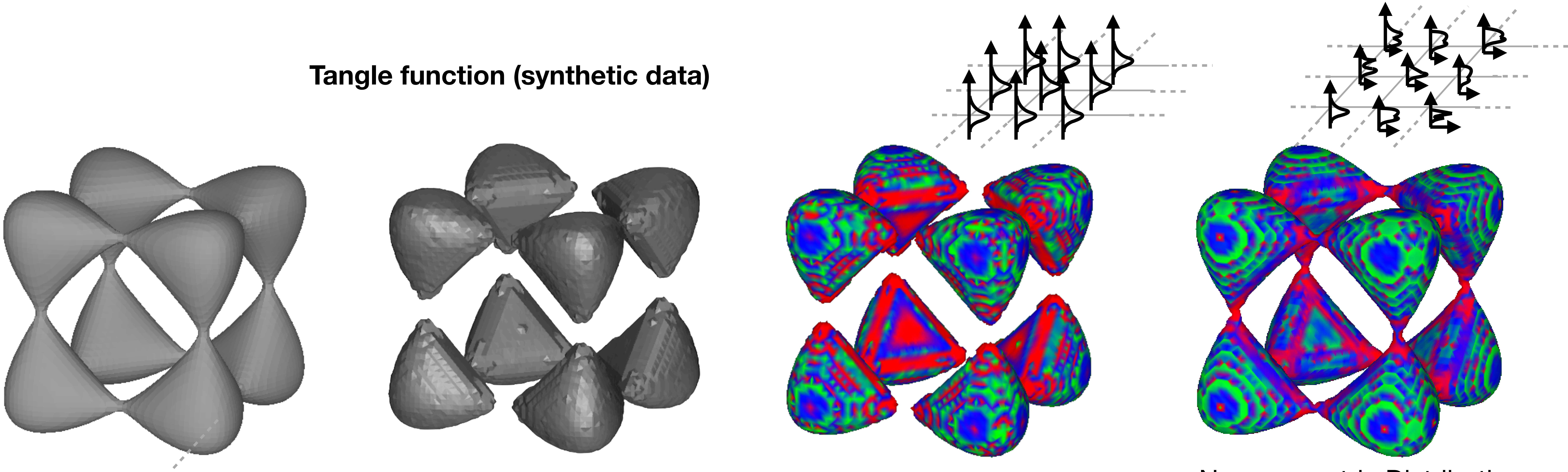


[Athawale and Entezari, 2013; Athawale et al., 2016]

Results: Visualization of Uncertain Level Sets

Isosurface Extraction in Uncertain Data

Tangle function (synthetic data)



Groundtruth

Mean Field

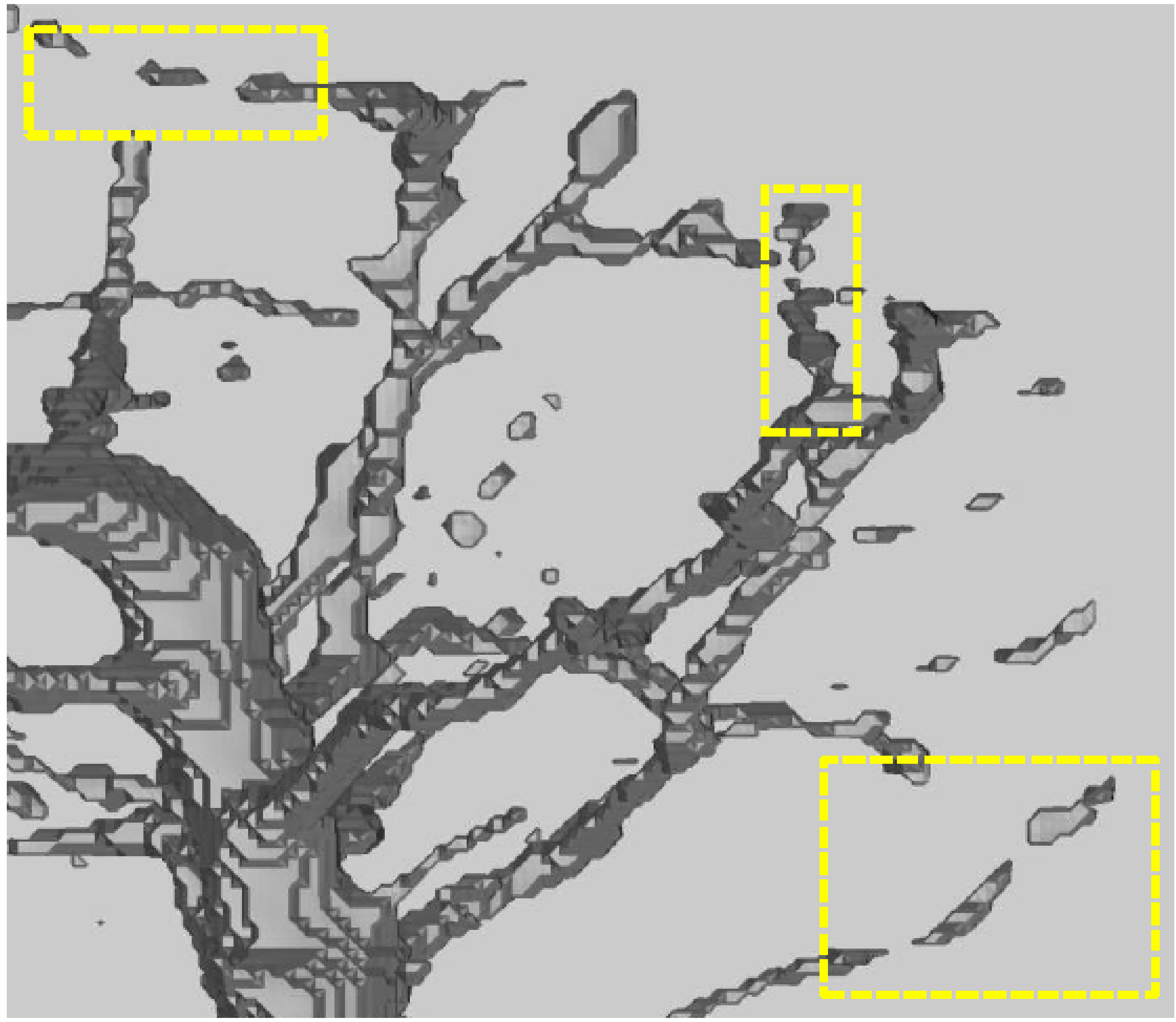
Parametric Distribution Field

Nonparametric Distribution Field

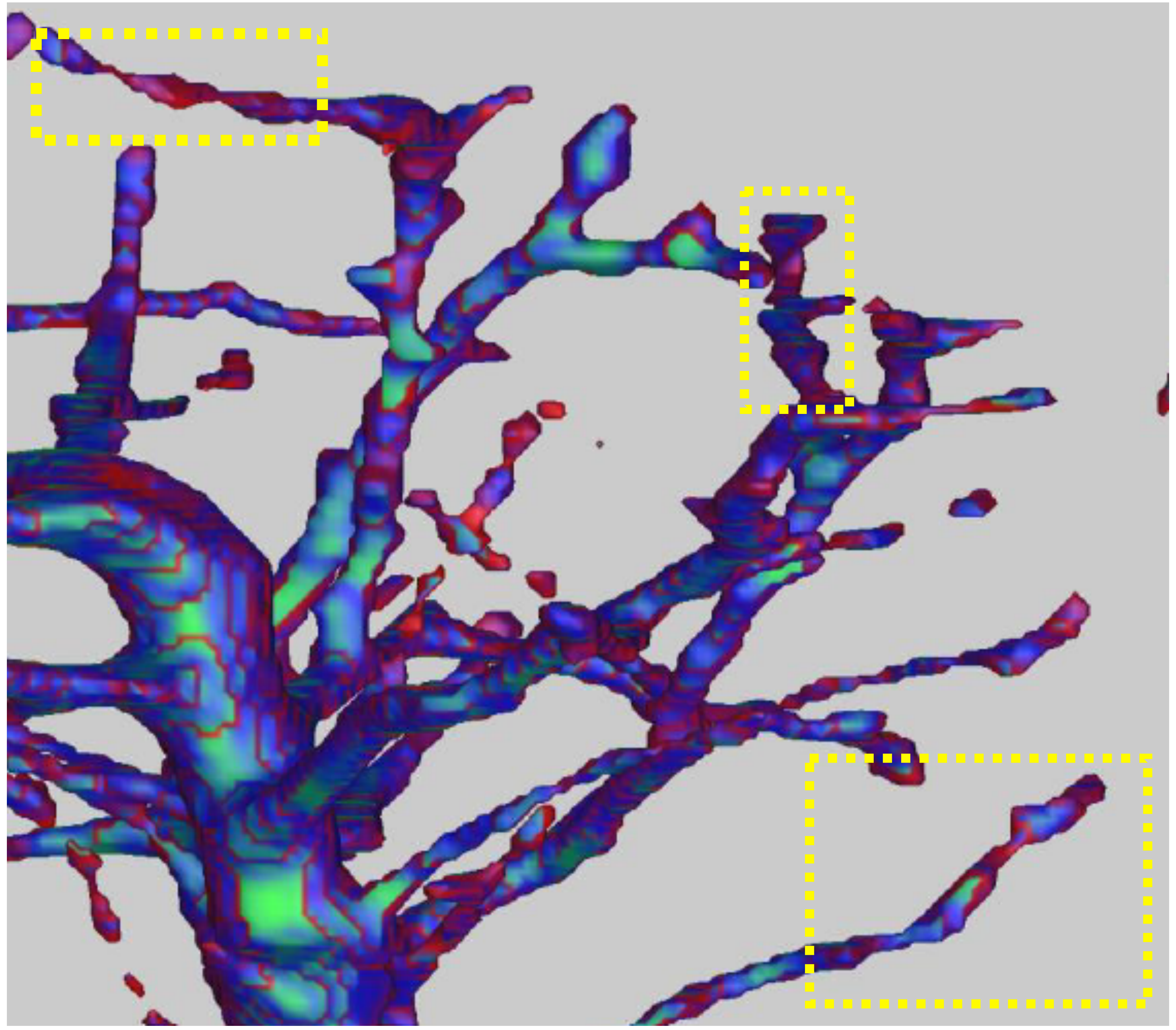
(Visualization software: The Geomview,
Developer: The Geometry Center at the University of Minnesota)

Isosurface Extraction in Uncertain Data

Bonsai tree (real data)



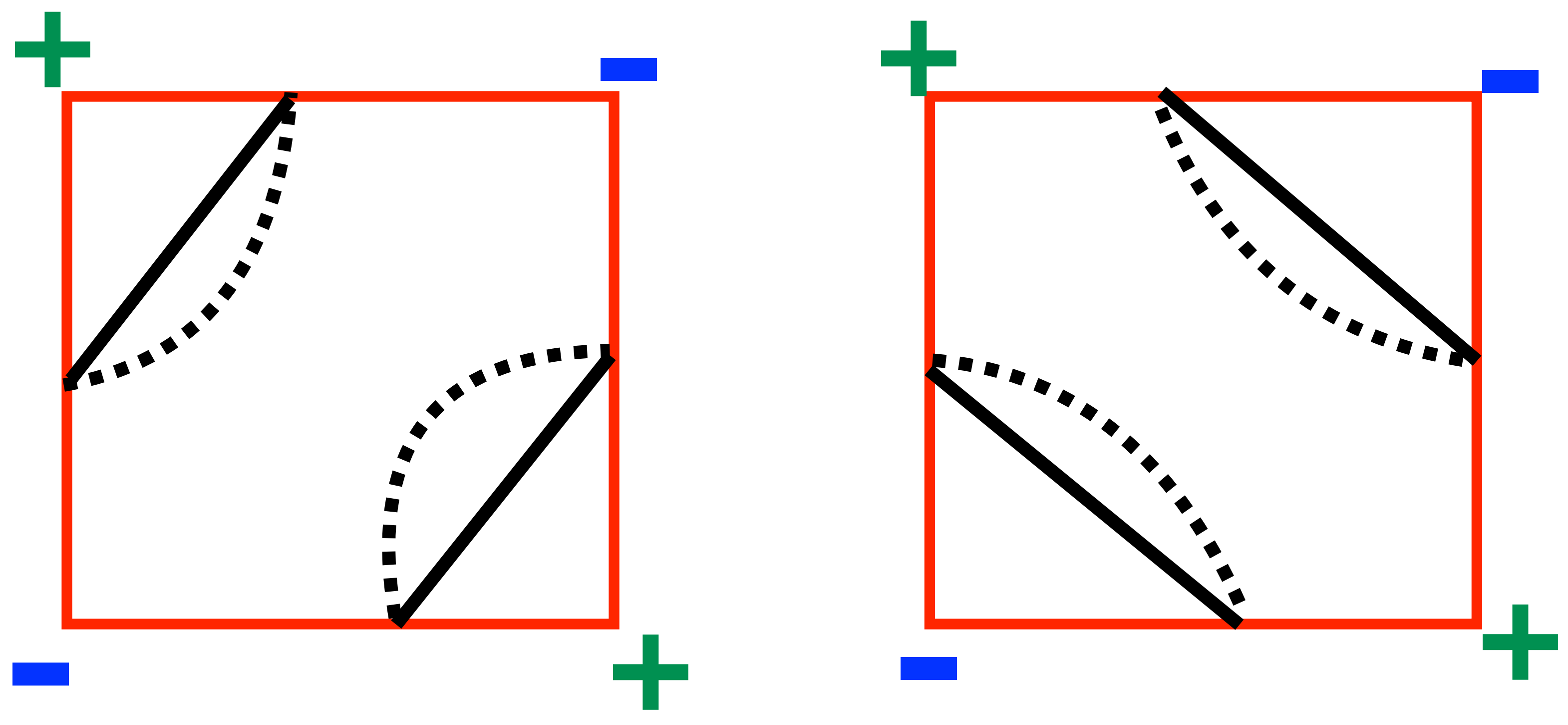
Parametric



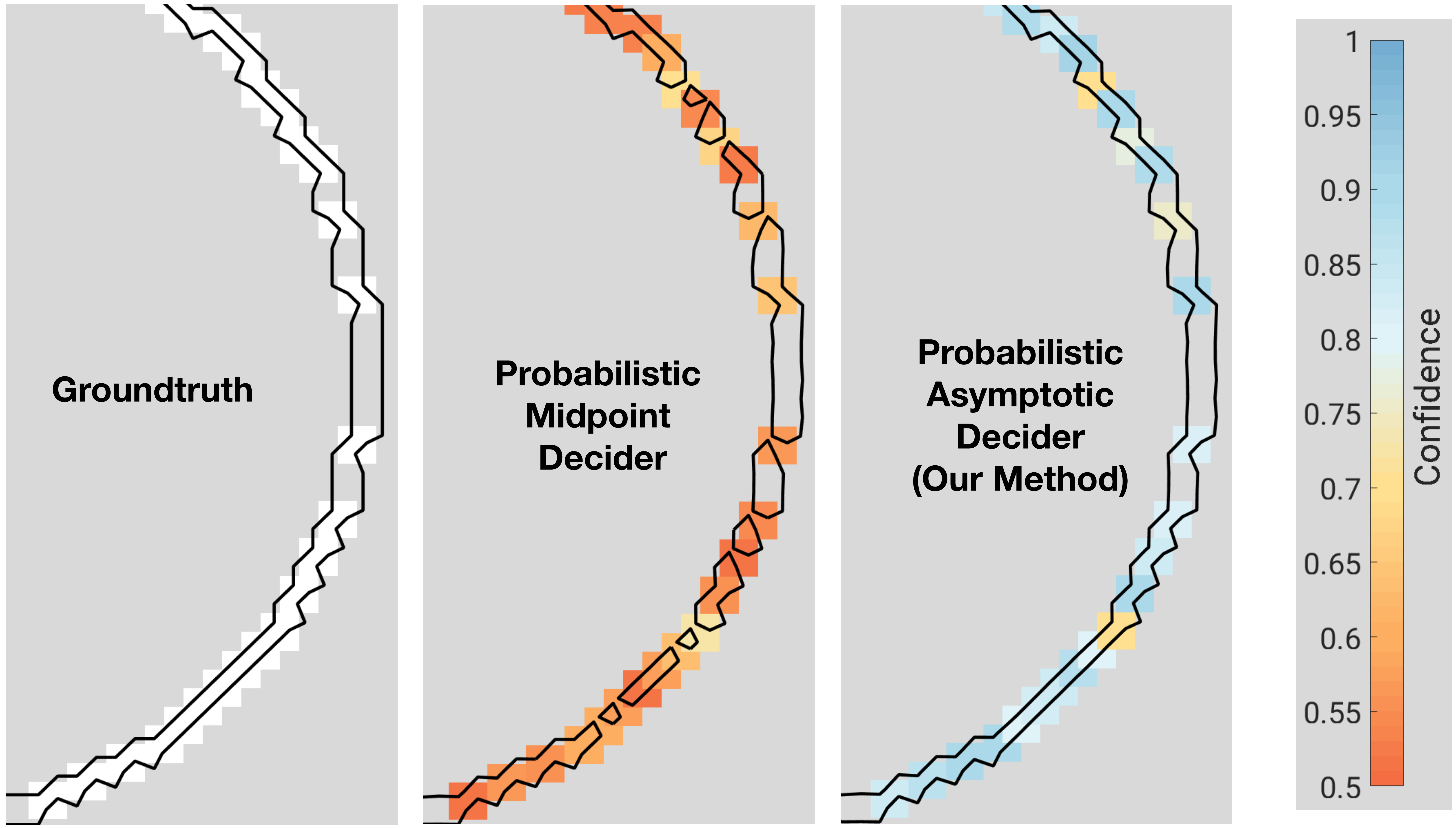
Nonparametric

MSA Ambiguous Case Resolution in Uncertain Data

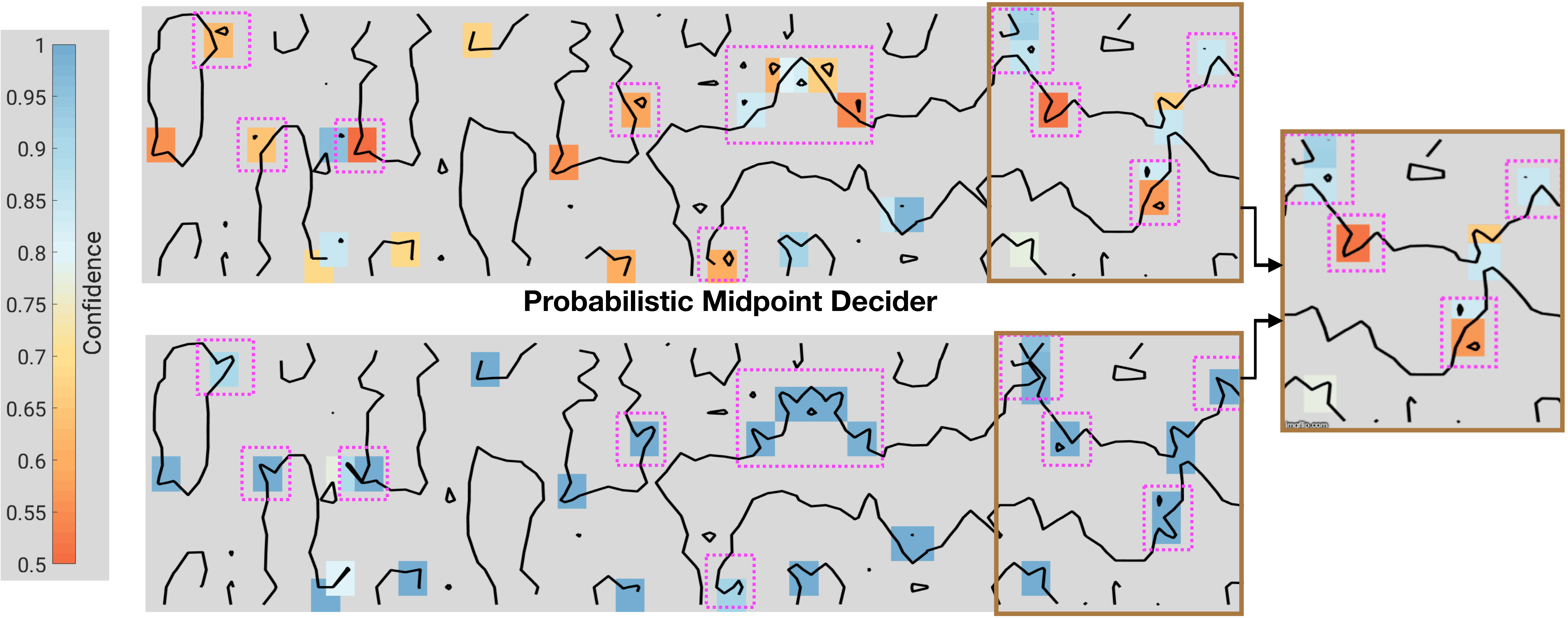
Concentric circles (synthetic data)



MSA ambiguous case



Isocontour Visualizations (Kàrmàn Vortex Street)

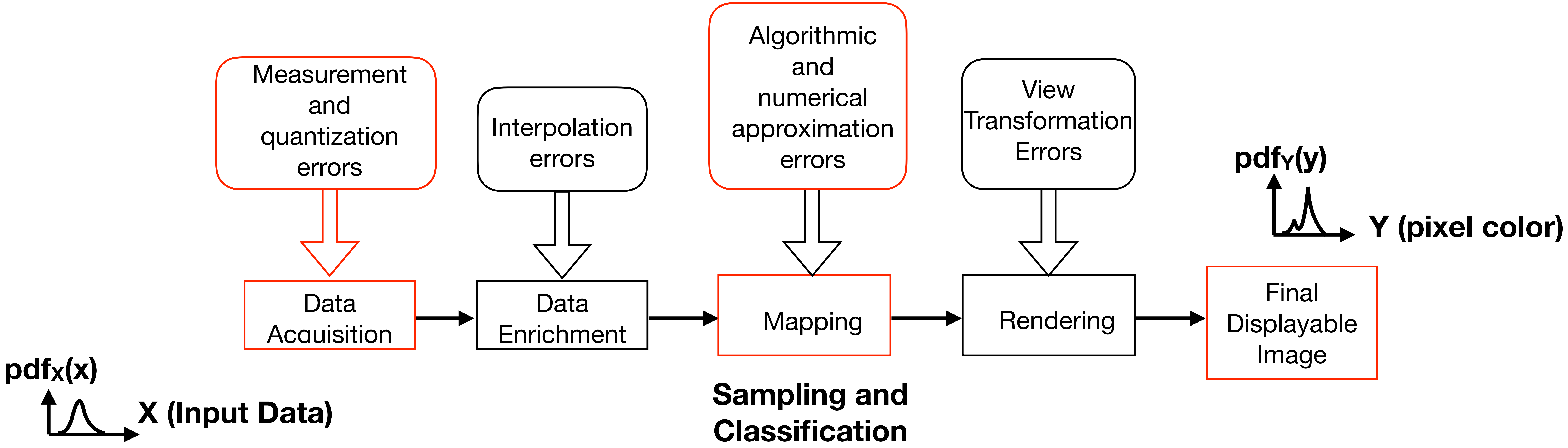


Probabilistic Asymptotic Decider (Our Method)

The flow simulation dataset is courtesy of the Gerris project [Popinet, 2003]

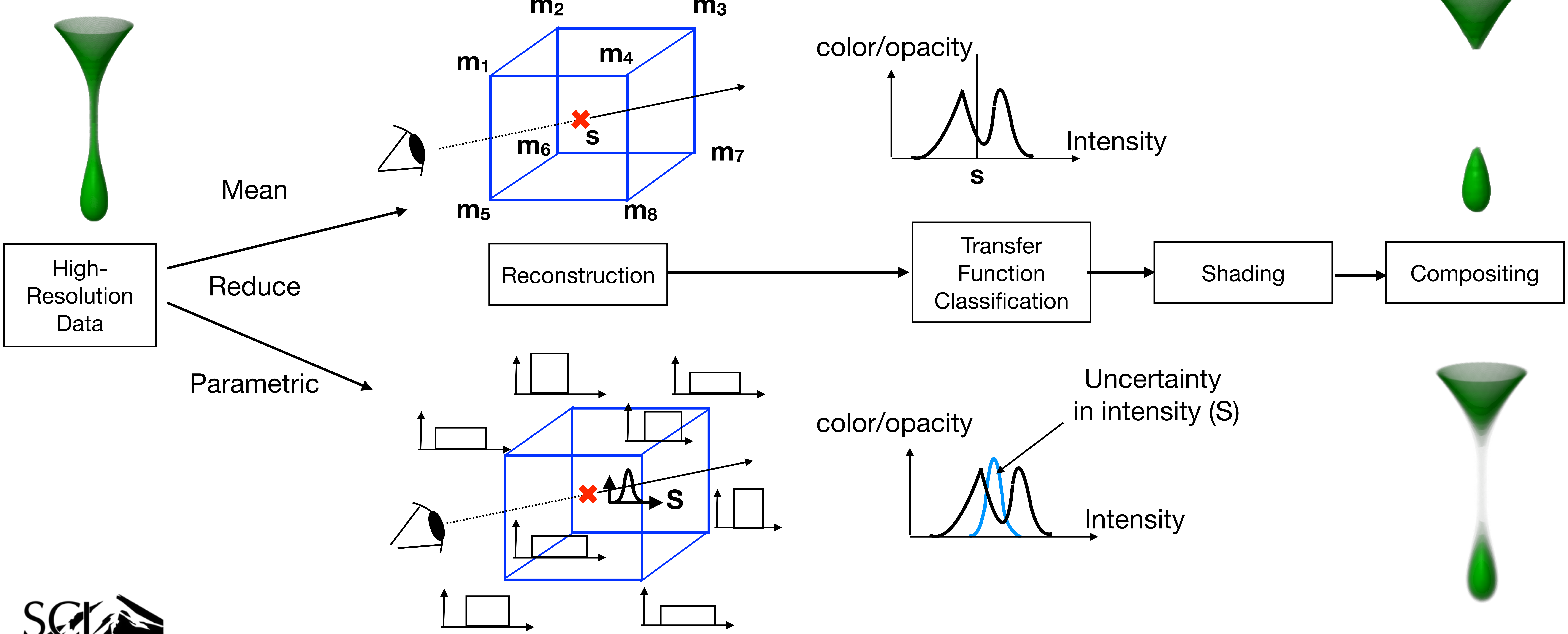
Direct Volume Rendering (DVR) of Uncertain Data

- Ray casting and transfer functions for certain vs. uncertain data
- Results

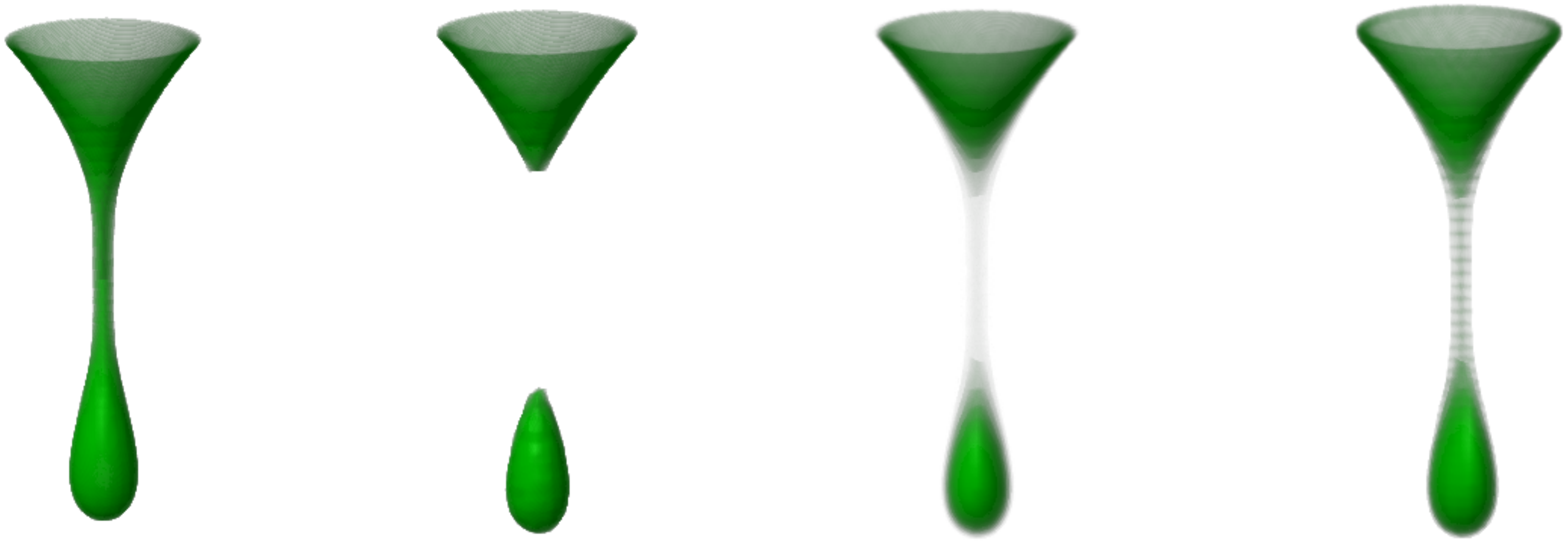


DVR of Certain vs. Uncertain Data [Sakhaee and Entezari, 2017]

The teardrop function [Knoll et al., 2009]

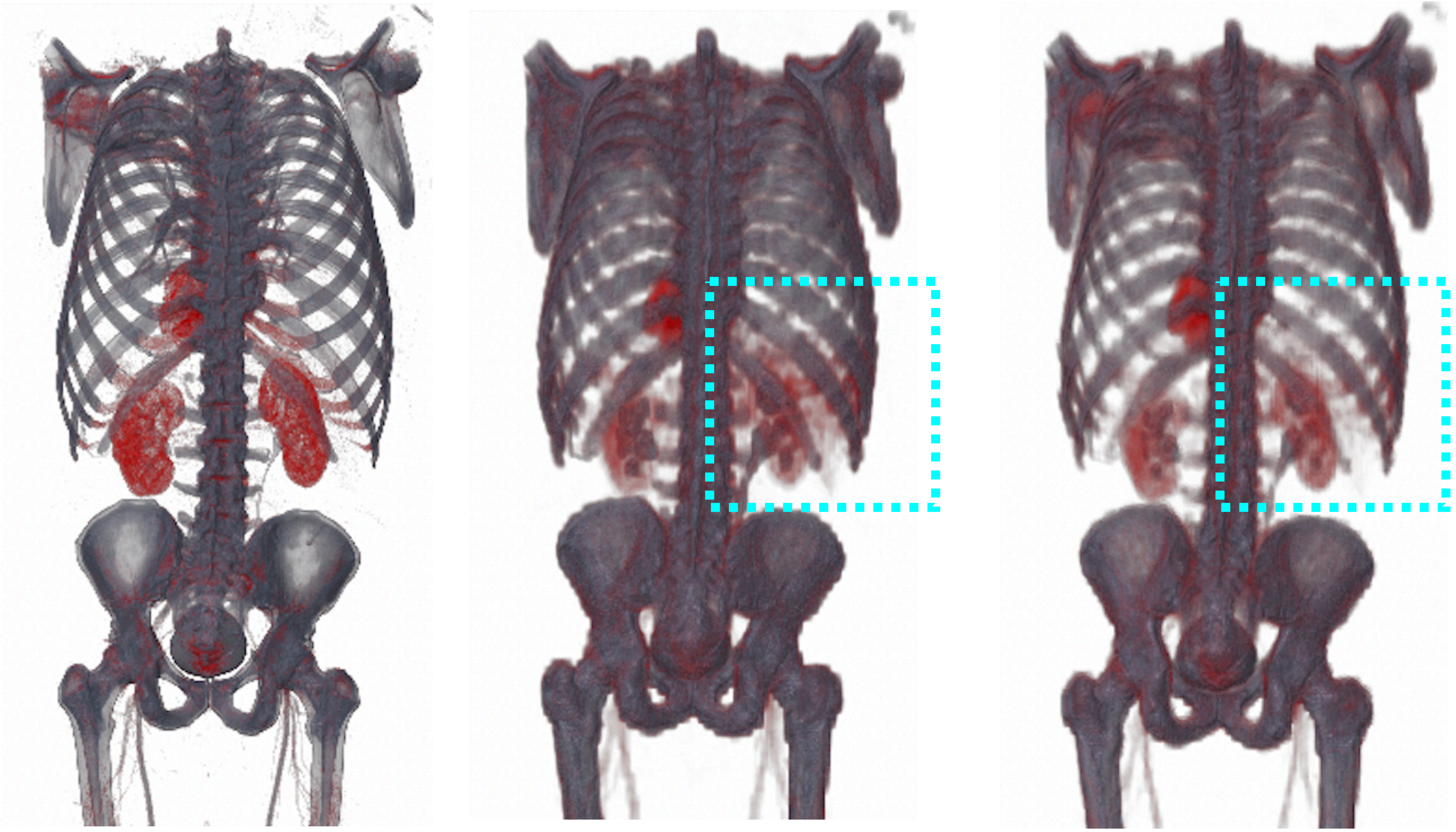


DVR of Certain vs. Uncertain Data (Nonparametric)



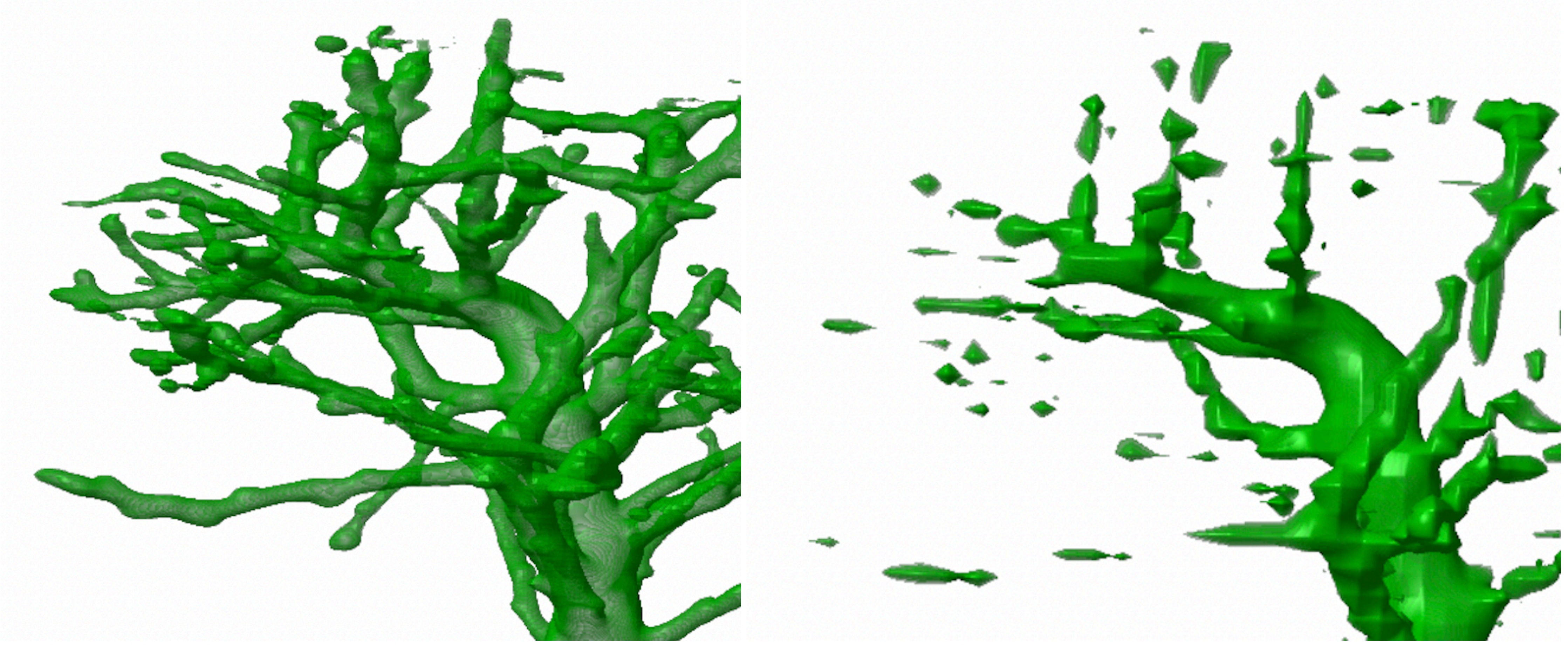
Groundtruth **Mean** **Parametric** **Nonparametric (New)**

DVR of Certain vs. Uncertain Data (Nonparametric)

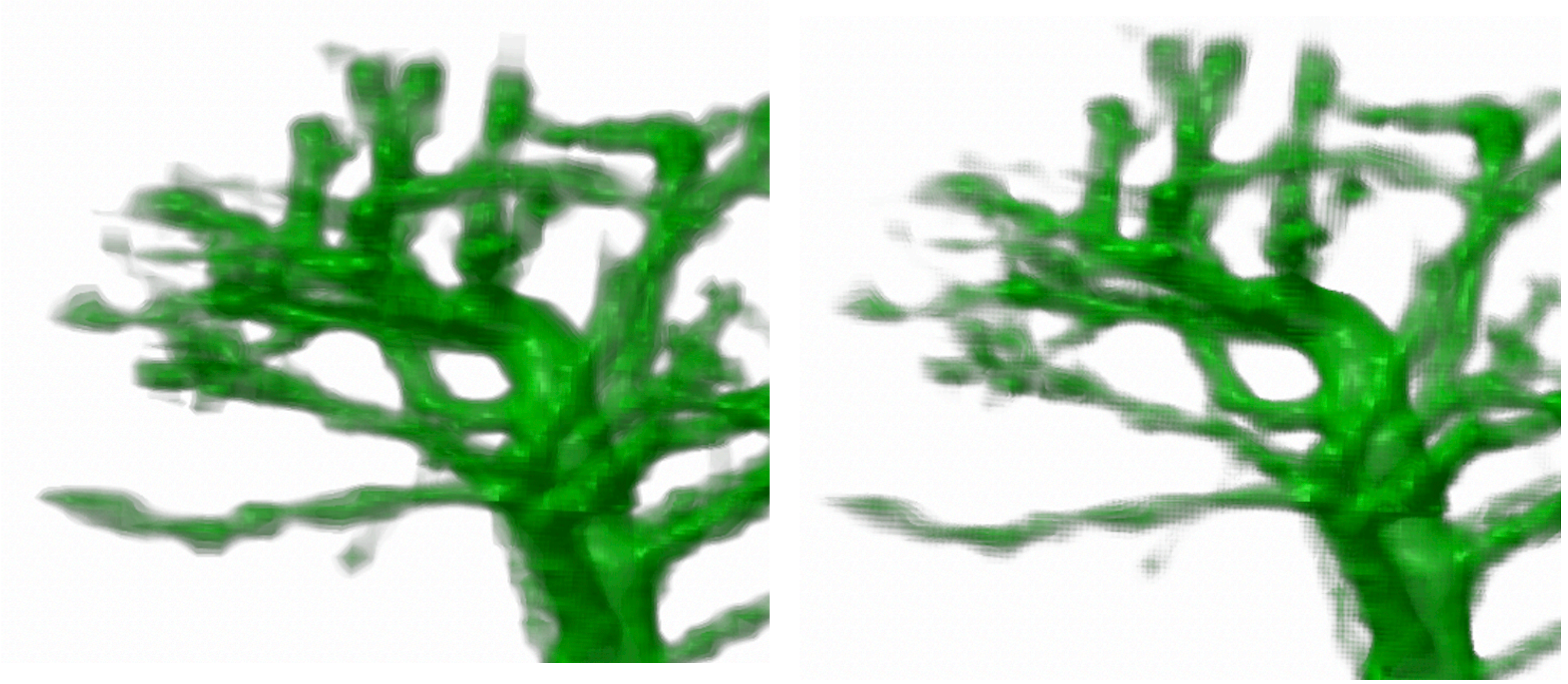


Groundtruth Parametric Nonparametric (New)

Osirix OBELIX dataset
(http://medvis.org/datasets/)



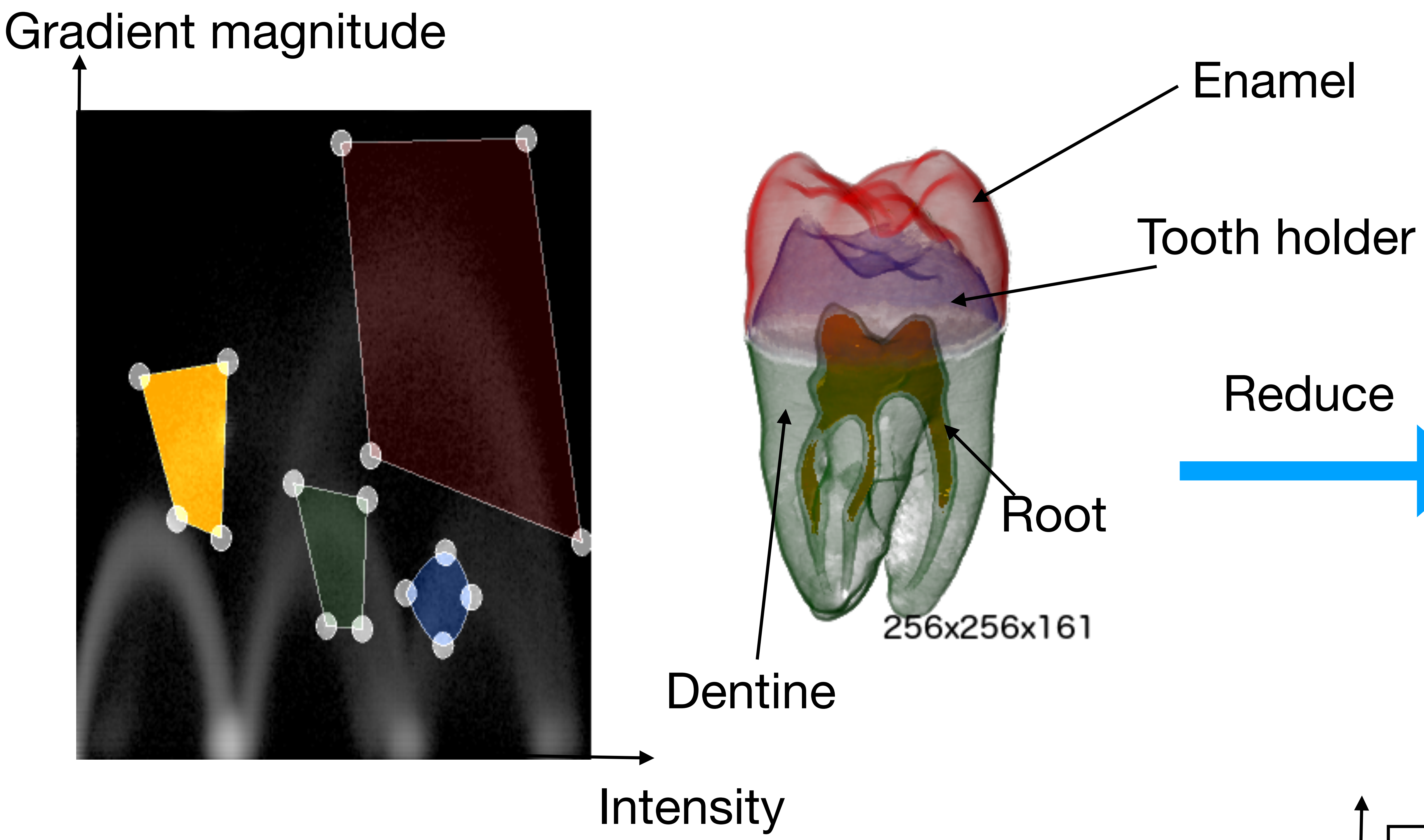
Groundtruth Mean

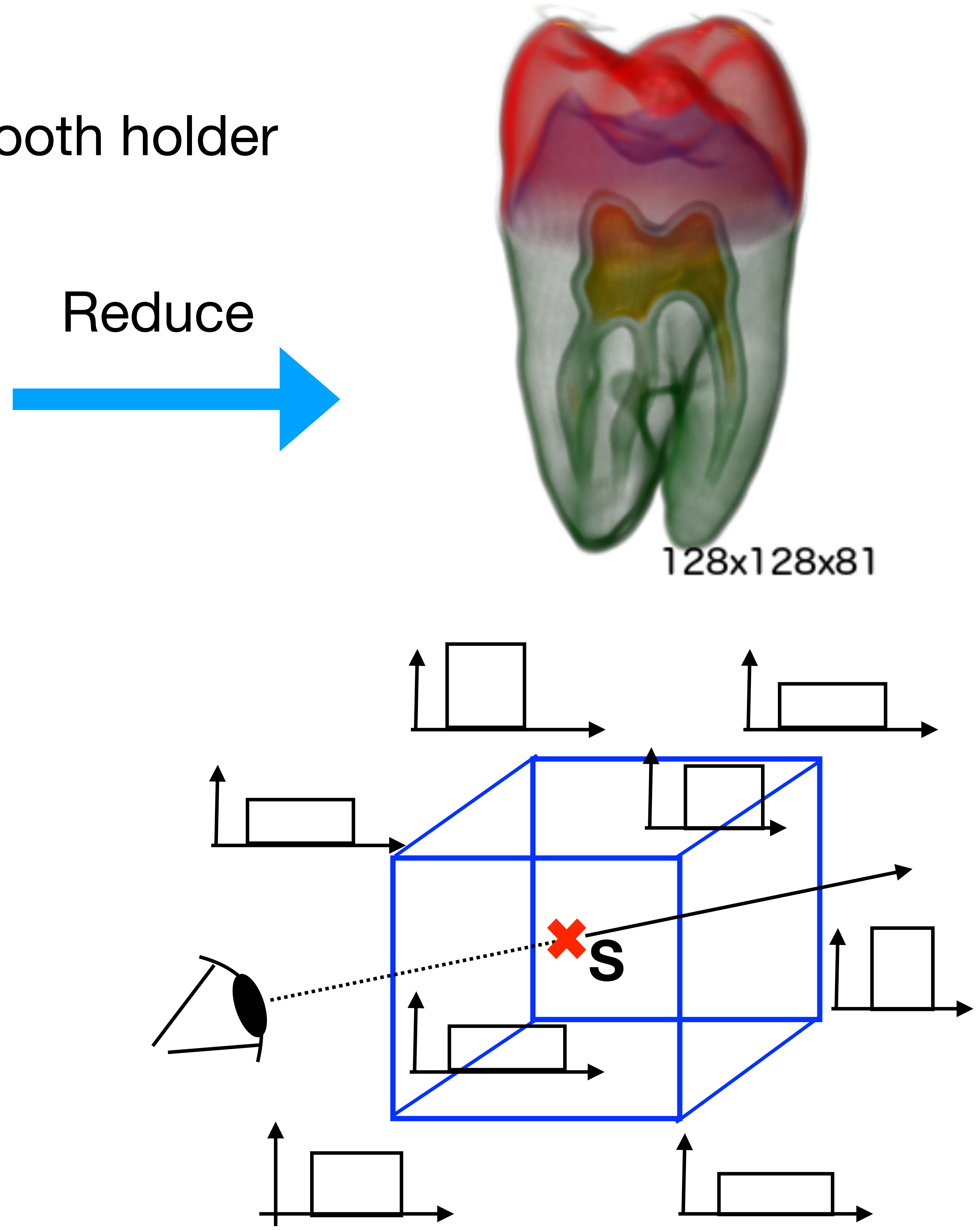


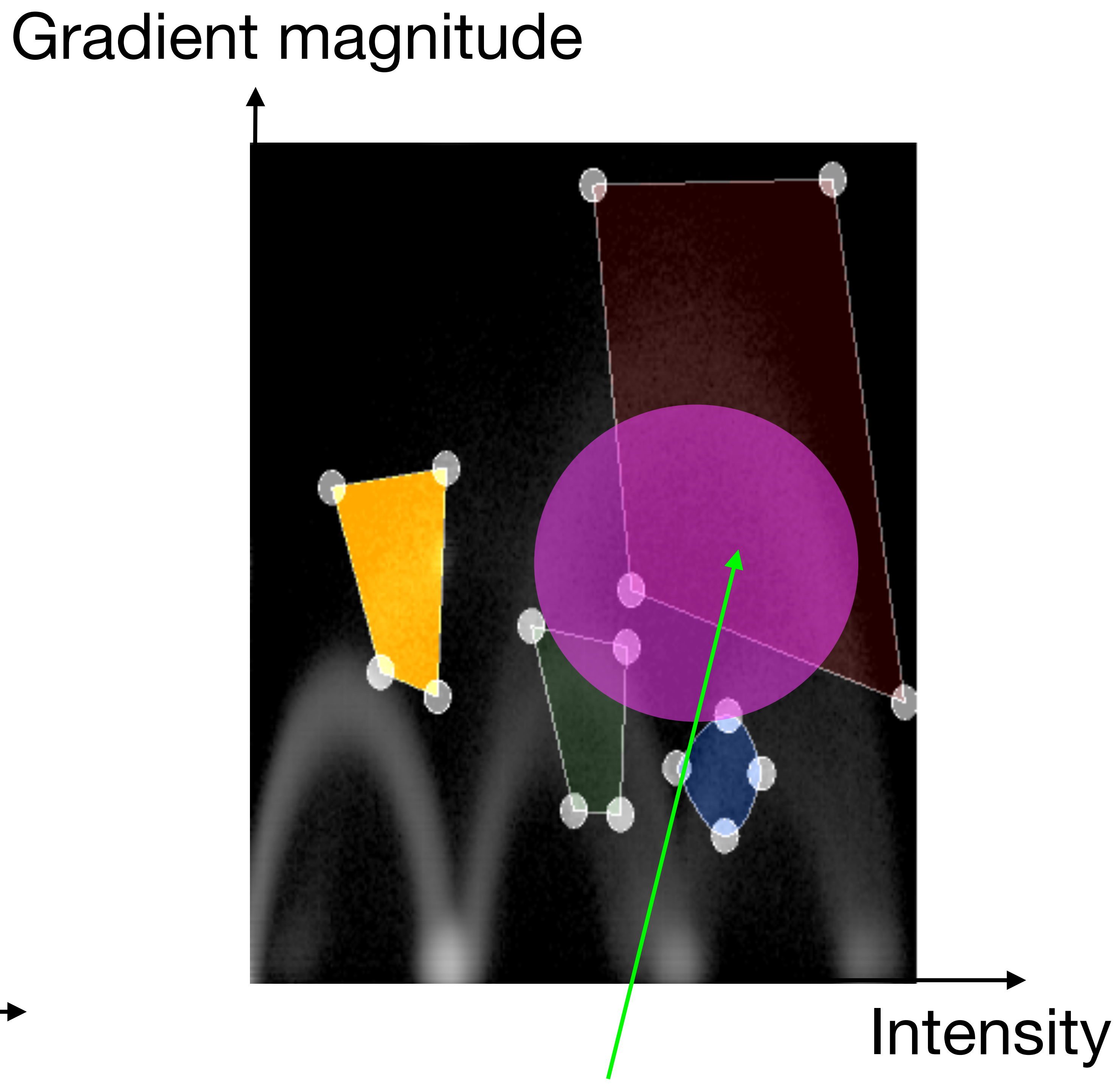
Parametric Nonparametric

Bonsai tree dataset

DVR of Certain vs. Uncertain Data (2D Transfer Functions [Kniss et al., 2002])

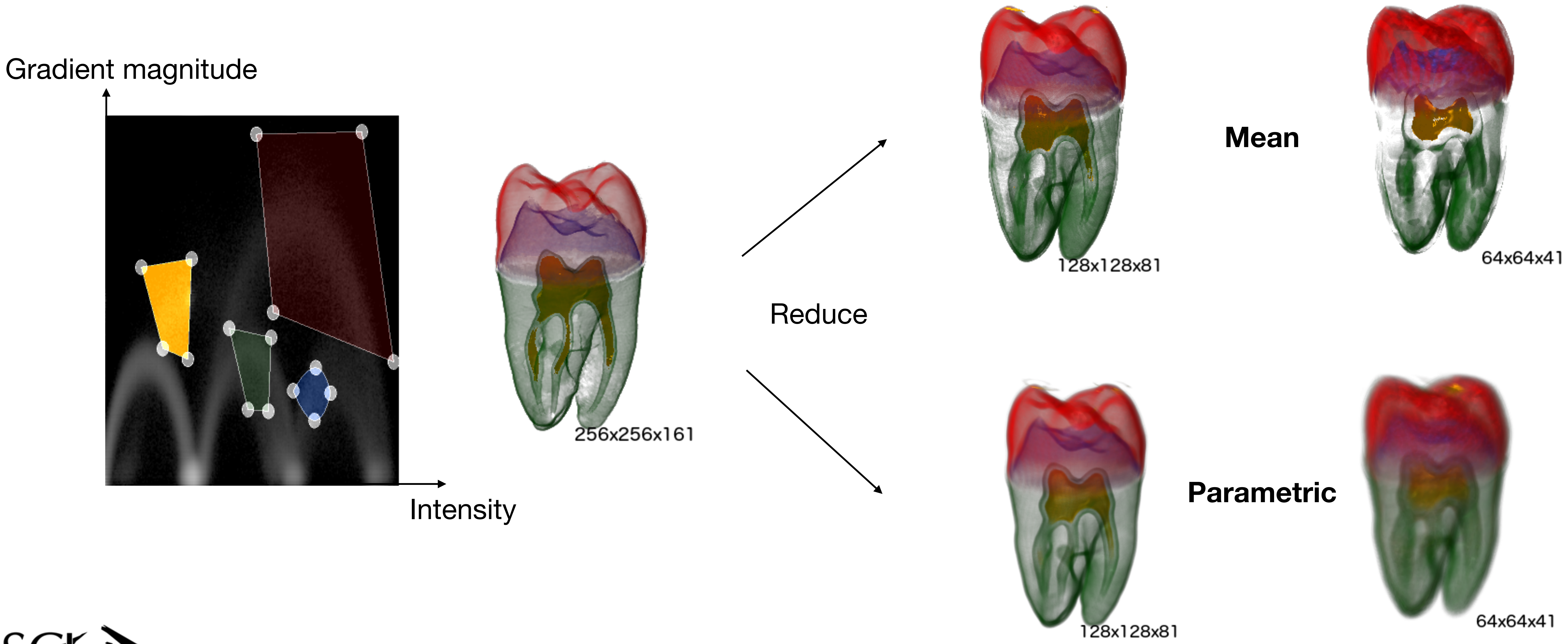






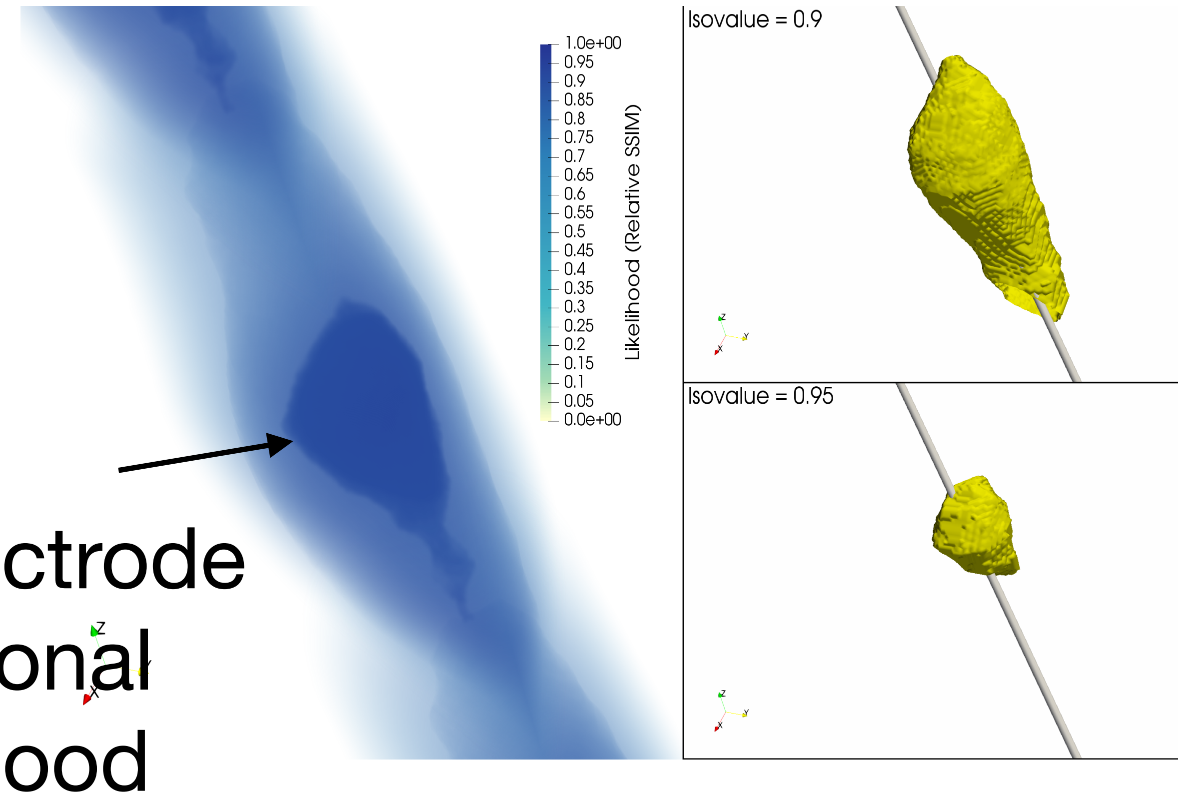
Probability density of S:
The material for the sample
is most likely to be Enamel

DVR of Certain vs. Uncertain Data (2D Transfer Functions [Kniss et al., 2002])

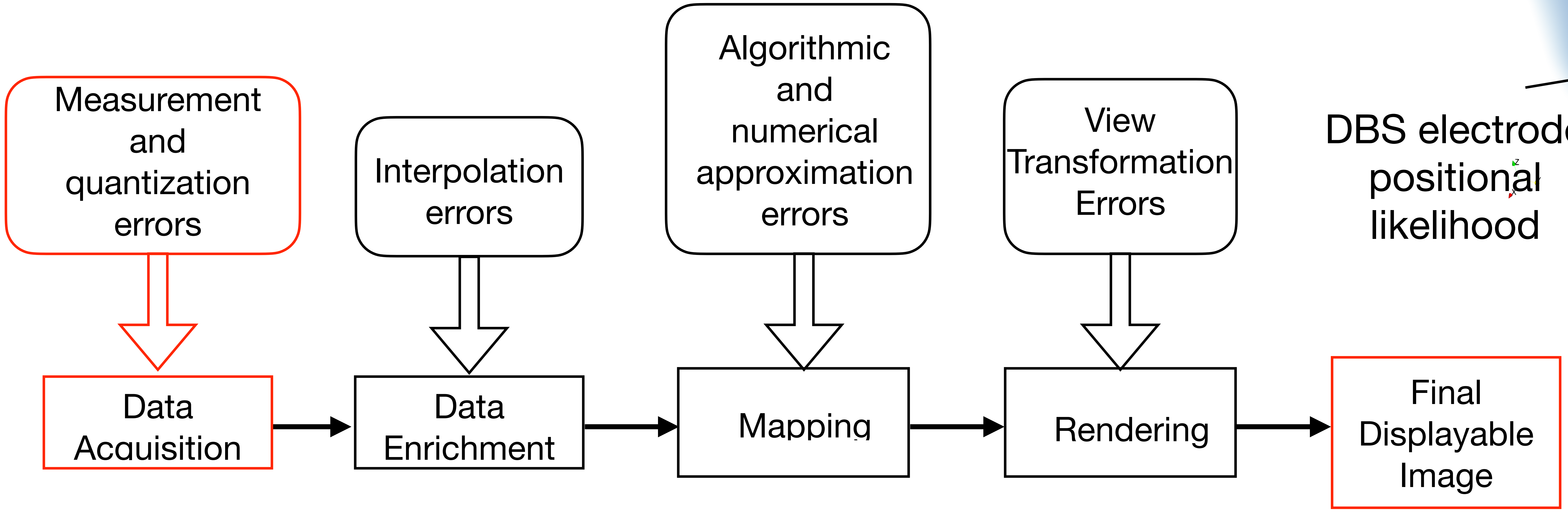


Uncertainty Quantification in DBS Electrode Positions

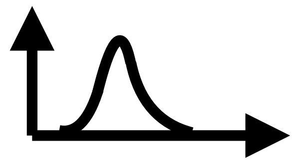
- Deep Brain Stimulation (DBS)
- MRI/CT imaging for understanding DBS electrode position
- Uncertainty in electrode positions (discretization uncertainties)
- Results



DBS electrode positional likelihood

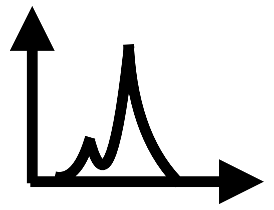


pdf$_X$(x)



X (A finite-resolution image of a DBS electrode implanted in patient brain)

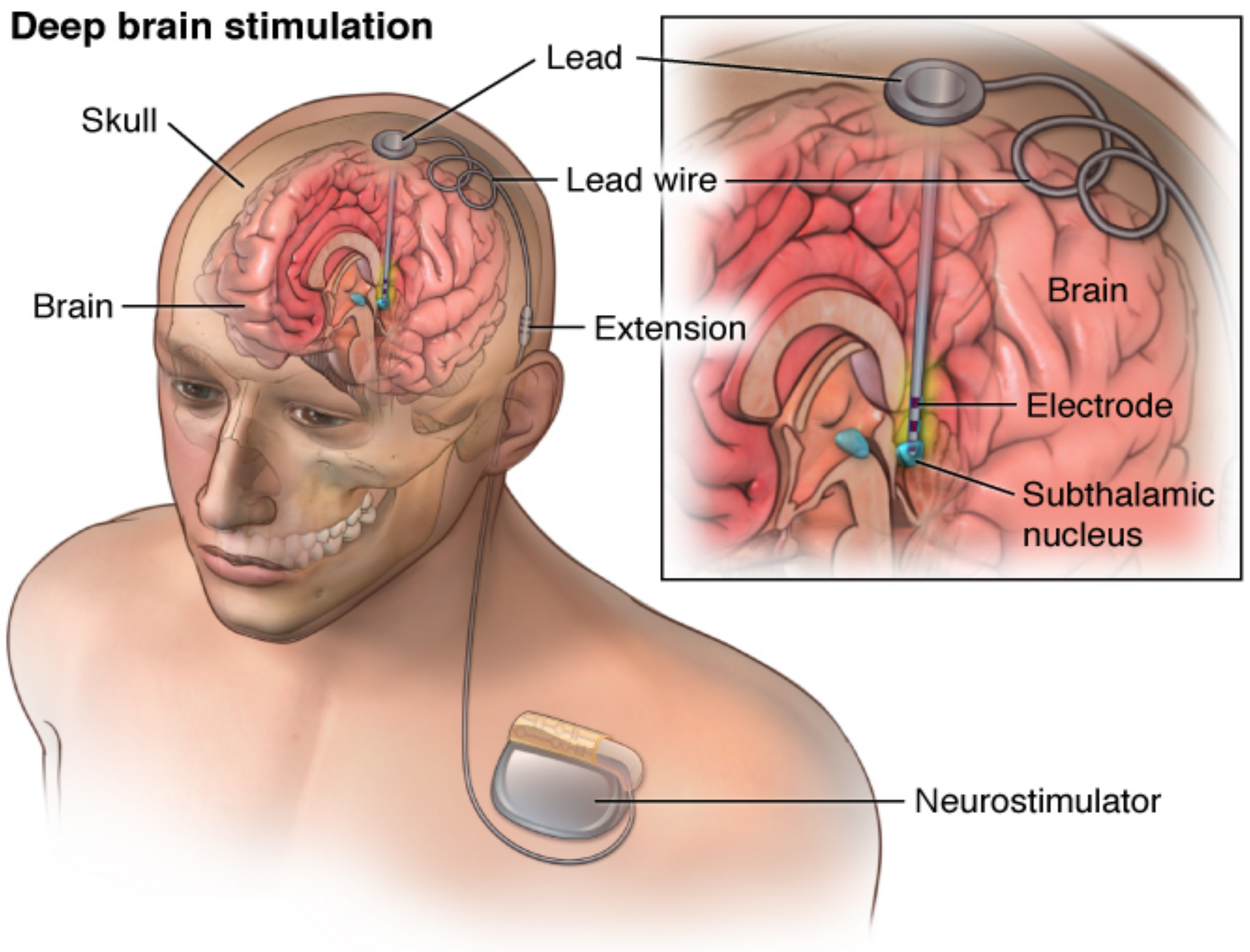
pdf$_Y$(y)



Y (DBS electrode position)

DBS: Surgical Portion

- Treatment of movement disorders
  - Parkinson's disease, essential tremor, and dystonia
- Food & Drug Administration (FDA) approved
  - Parkinson's disease and essential tremor: 1997
  - Dystonia: 2003



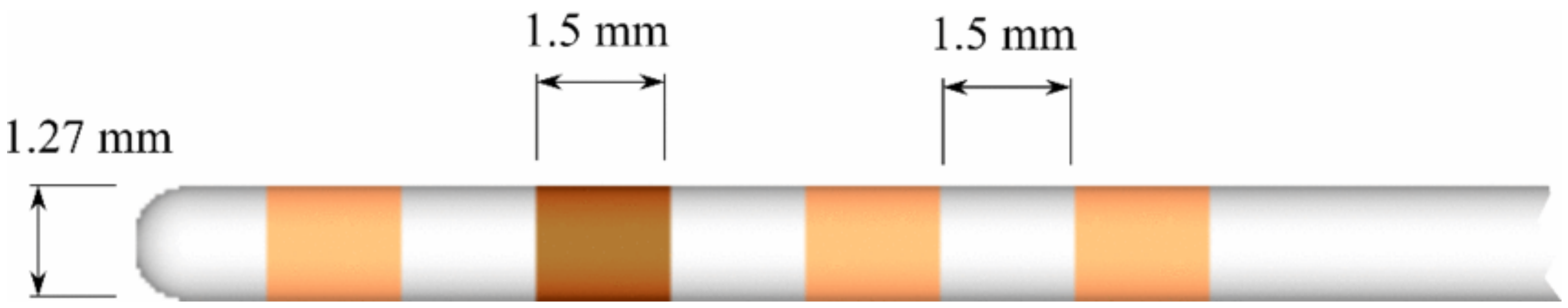
DBS: Post-Surgical Portion

- Treatment of movement disorders
  - Parkinson's disease (PD), essential tremor, and dystonia
  - Possible side effects: speech disturbances, depression, mood changes
- Exploration of DBS stimulation settings for optimal patient response (time consuming step!)
  - Voltage
  - Pulse width
  - Frequency

Stimulation settings depend upon the electrode positions with respect to neural structures!

DBS Electrode and Stimulation Settings

Medtronic DBS electrode Mo. 3387



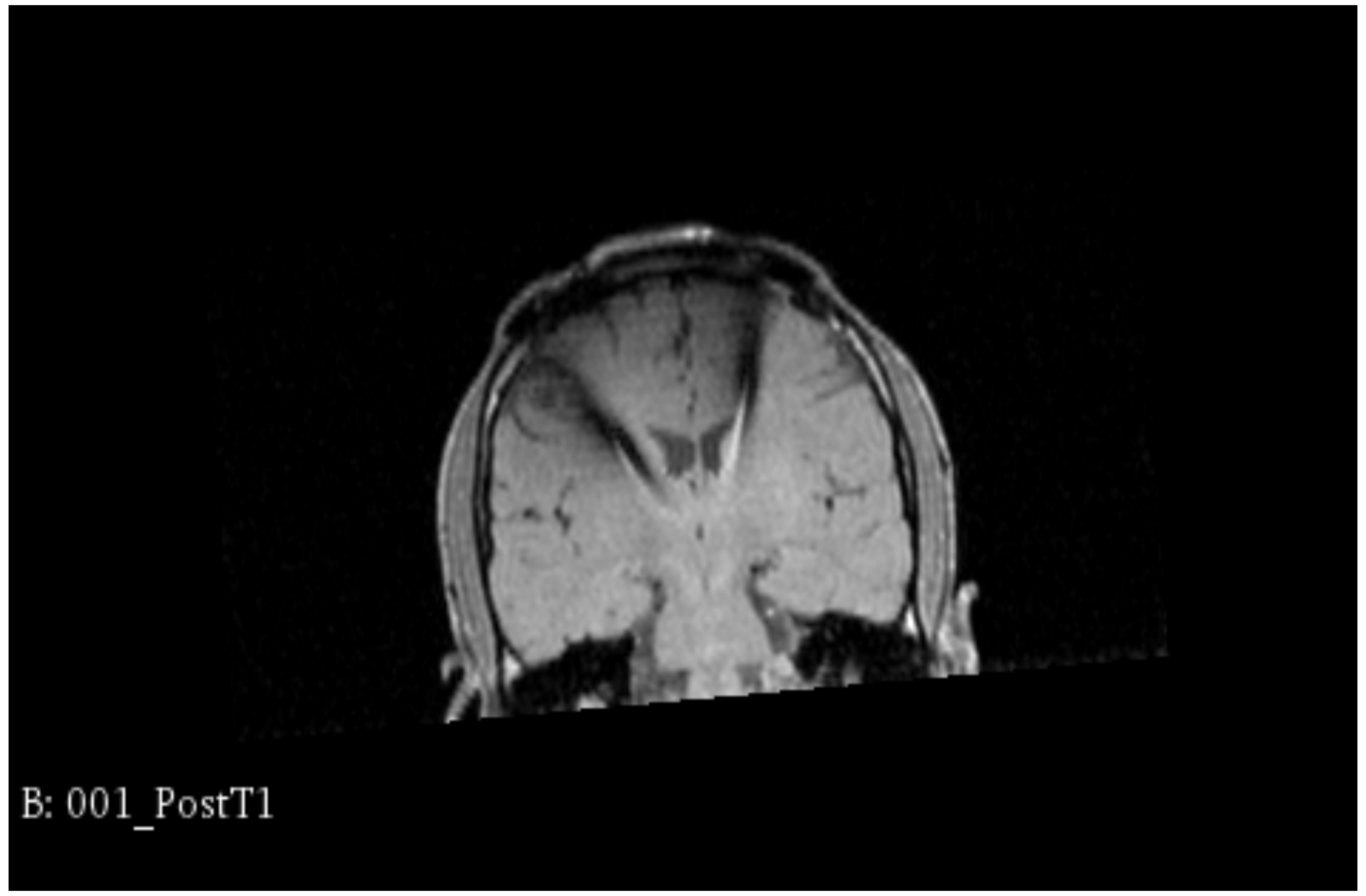
Voltage: 1-5 V
Frequency: 120-185 Hz
Pulse width: 60-200 μs
Contacts can be configured as: Cathode(-)/Anode(+)/Off
Stimulation mode: Monopolar or Bipolar

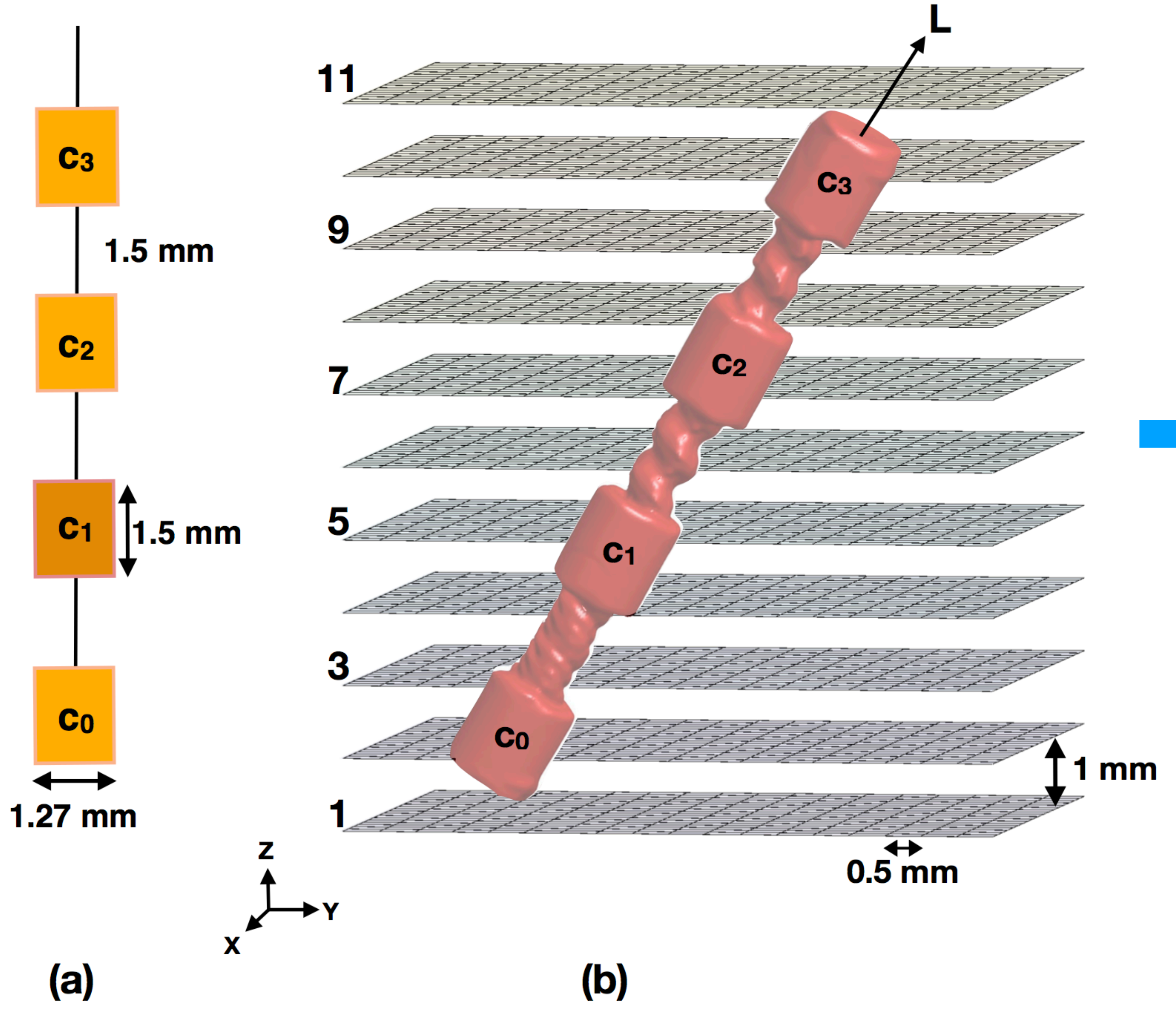
Therapeutic response is sensitive to the position of stimulation in human brain and the stimulation pattern.

Research Question

- Analysis of discretization errors and positional uncertainty in DBS electrodes

Can we determine the exact electrode positions by looking at a following scan?



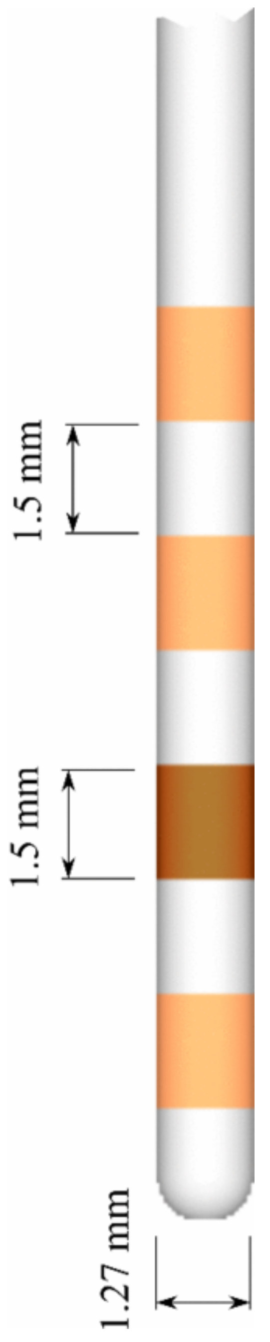


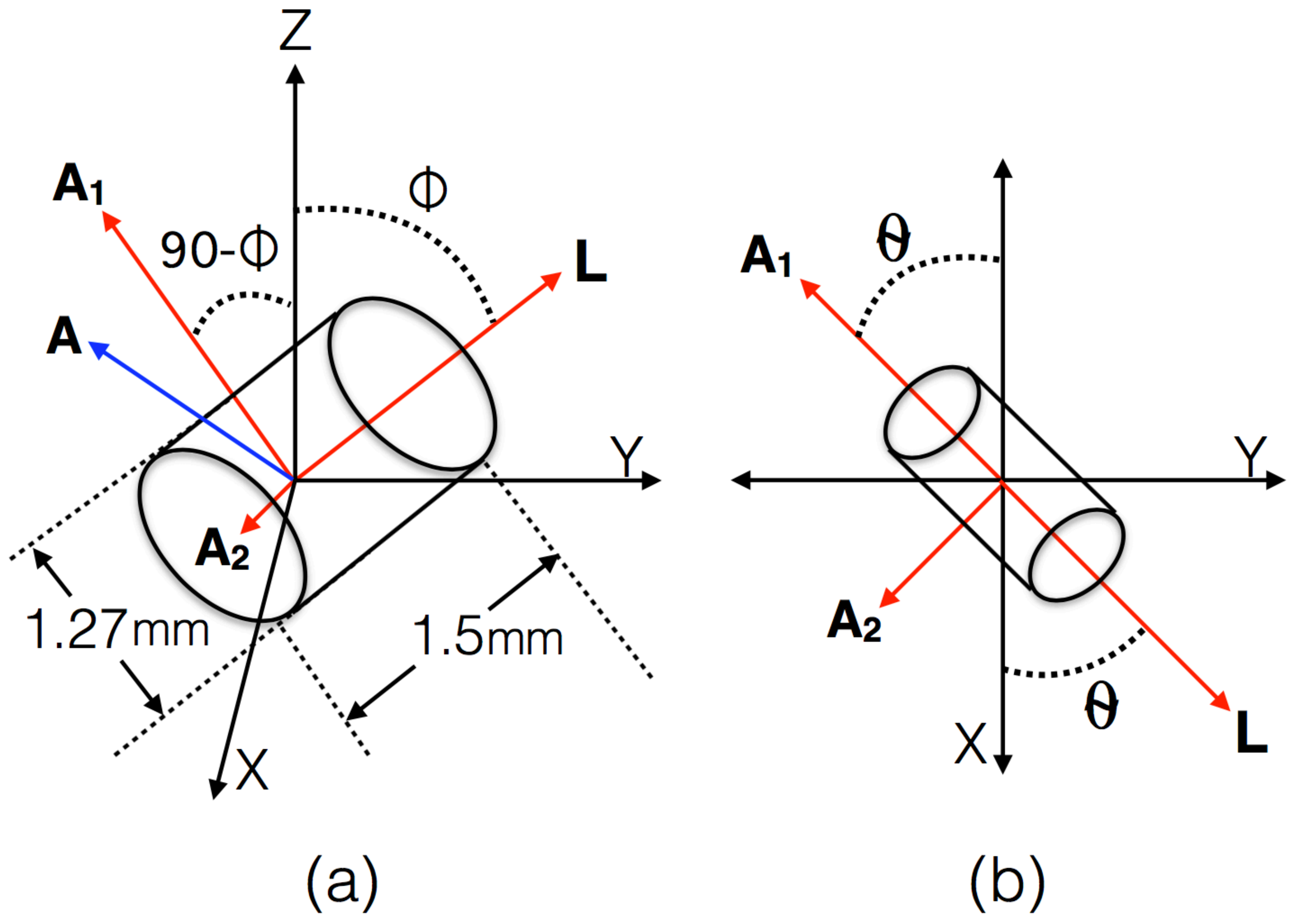
Input: Finite-resolution CT image

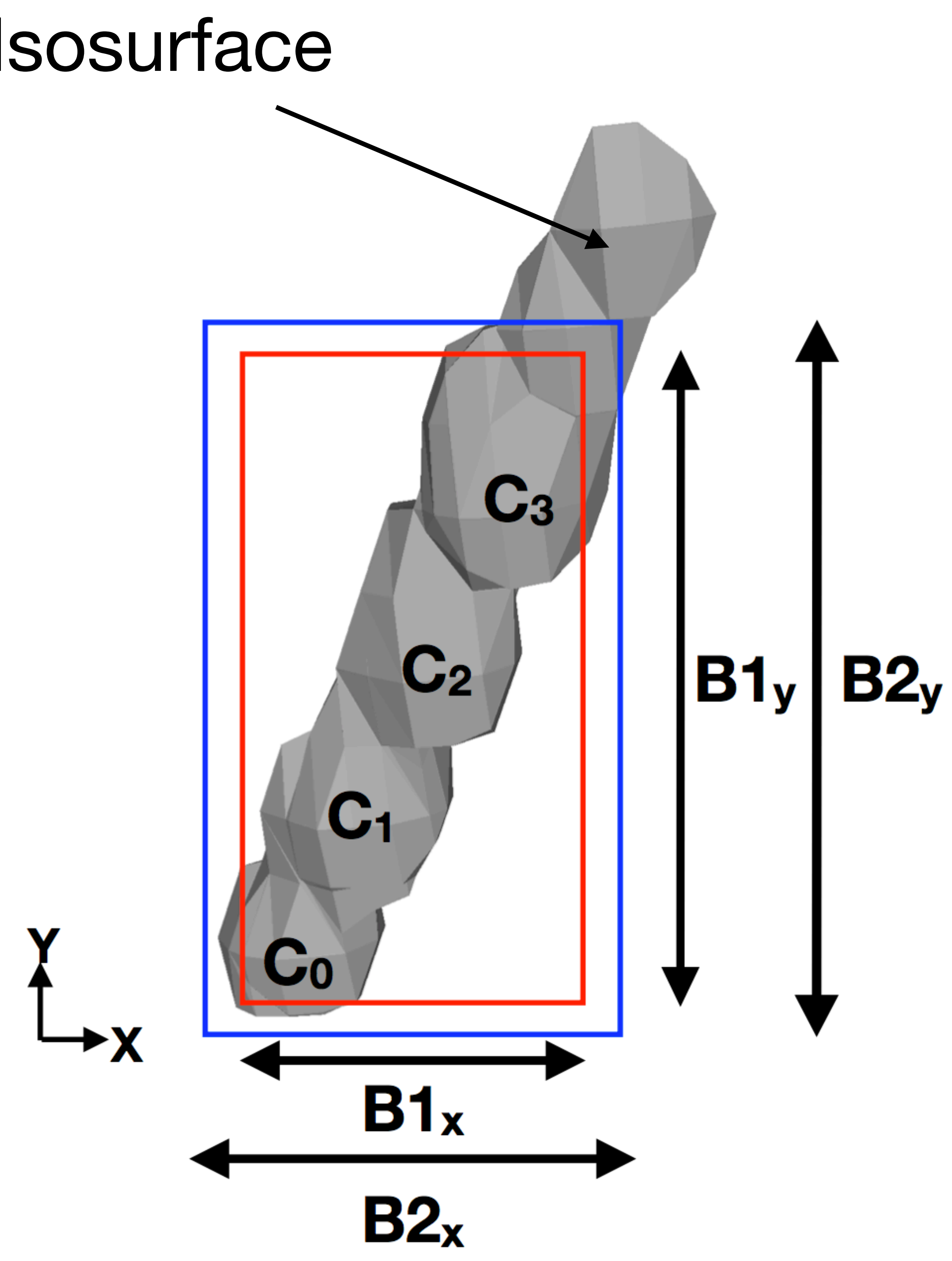
1) Uncertainty in direction **L** / Longitudinal uncertainty?

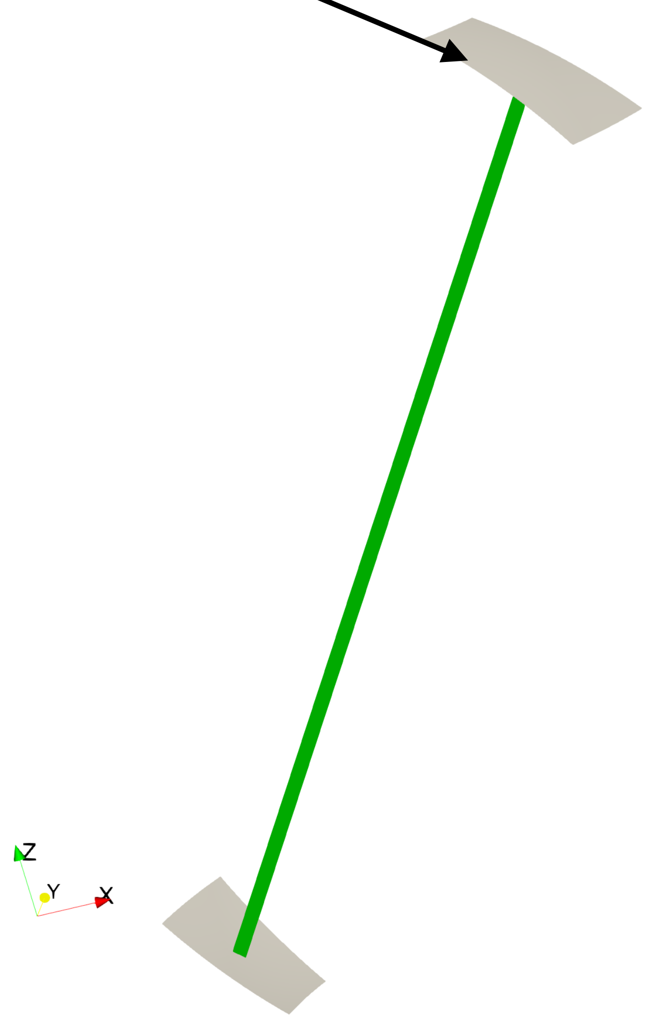
2) Translational Uncertainty?

Longitudinal Uncertainty Quantification









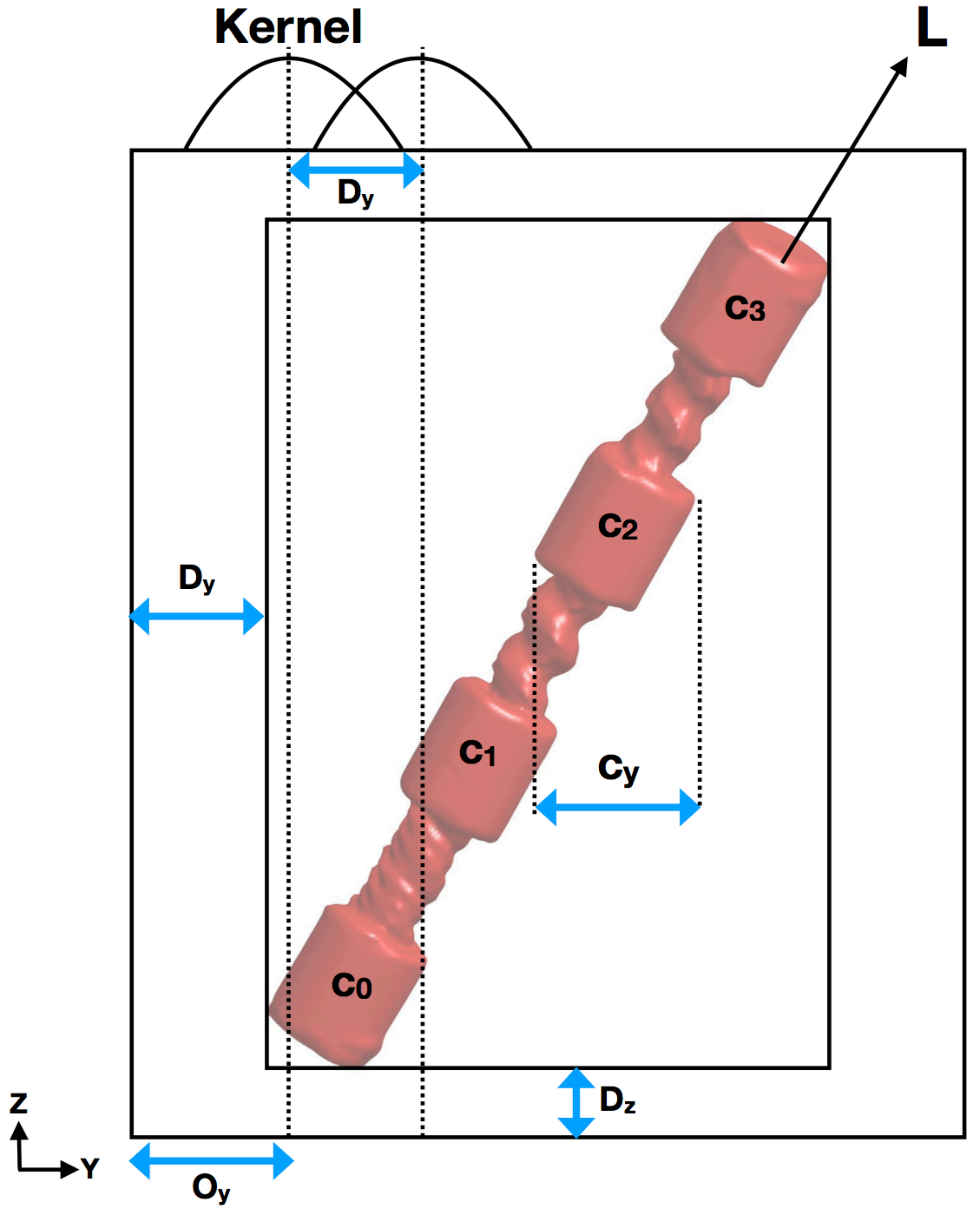
1) Closed-form DBS electrode stretch along X, Y, and Z be Sx, Sy, and Sz, respectively.

→ 2) Let B1 and B2 denote uncertainty in stretch of four electrodes computed from image space

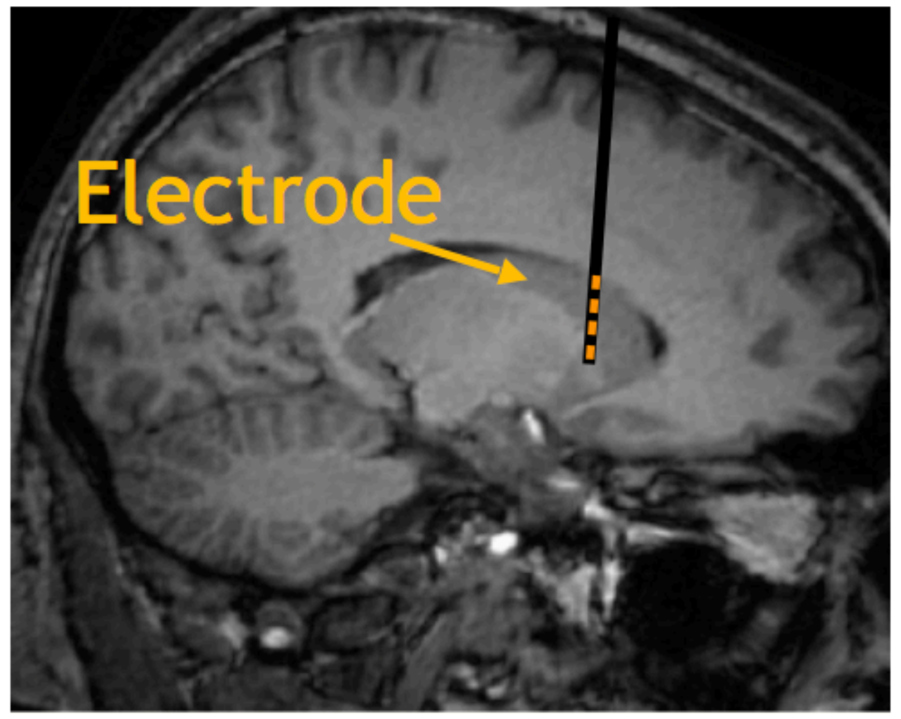
→ 3) Compute likelihood of arbitrary direction L by matching Sx, Sy, and Sz with B1x and B1y

[Athawale et al., 2018]

Translational Uncertainty Quantification



High-resolution image taken outside the patient brain (Imaging resolution: H)



Post-operative brain image

Low-resolution image taken when implanted in the patient brain (Imaging resolution: P)

[Athawale et al., 2018]

Draw a sample with imaging resolution P

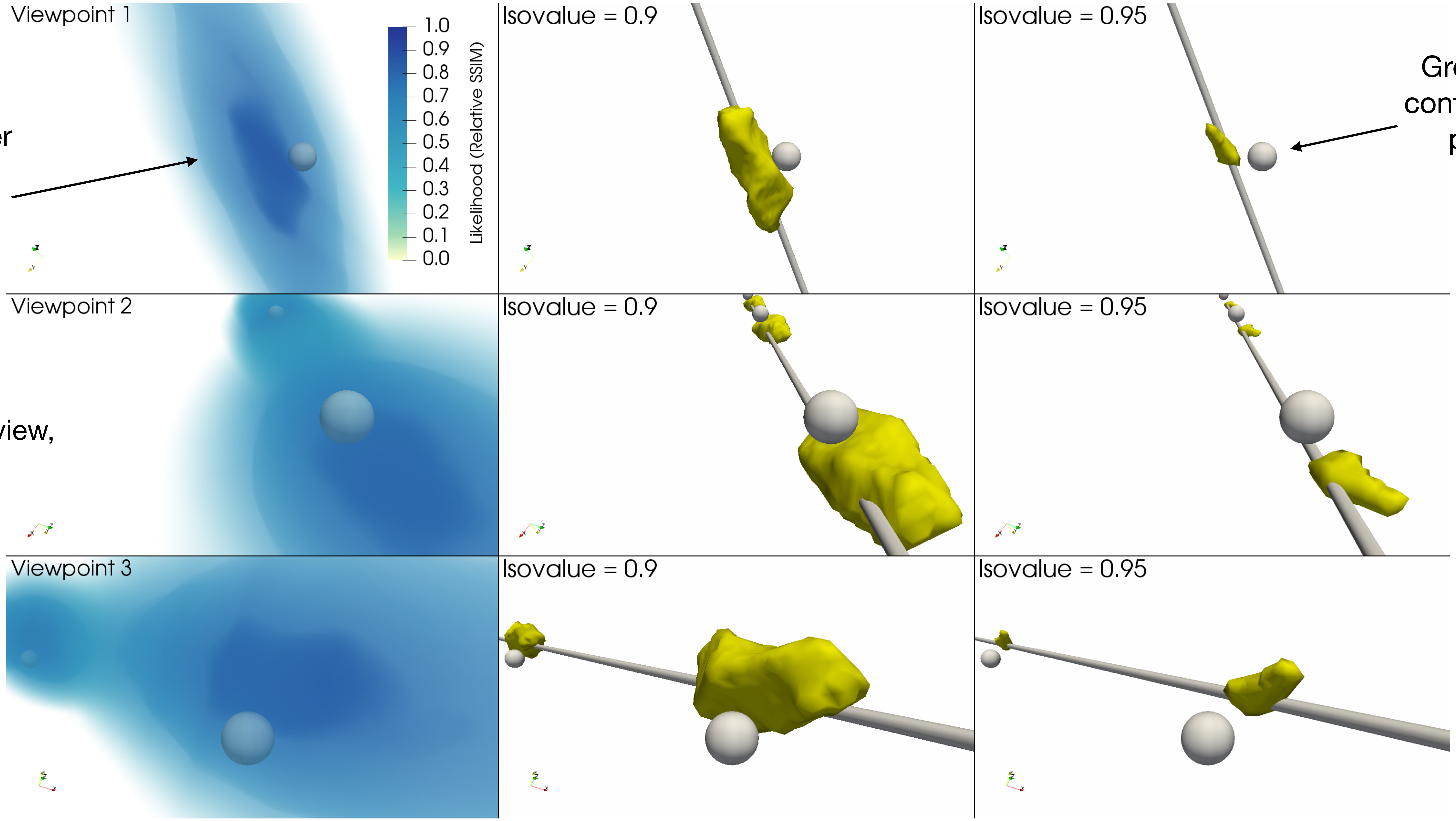
Contact position is exactly known for a drawn sample

compare (sample, post-operative image)

Results: Visualization of Uncertain DBS Electrode Positions

Synthetic Data: Uncertain DBS Contact Centers

Contact-center positional likelihood



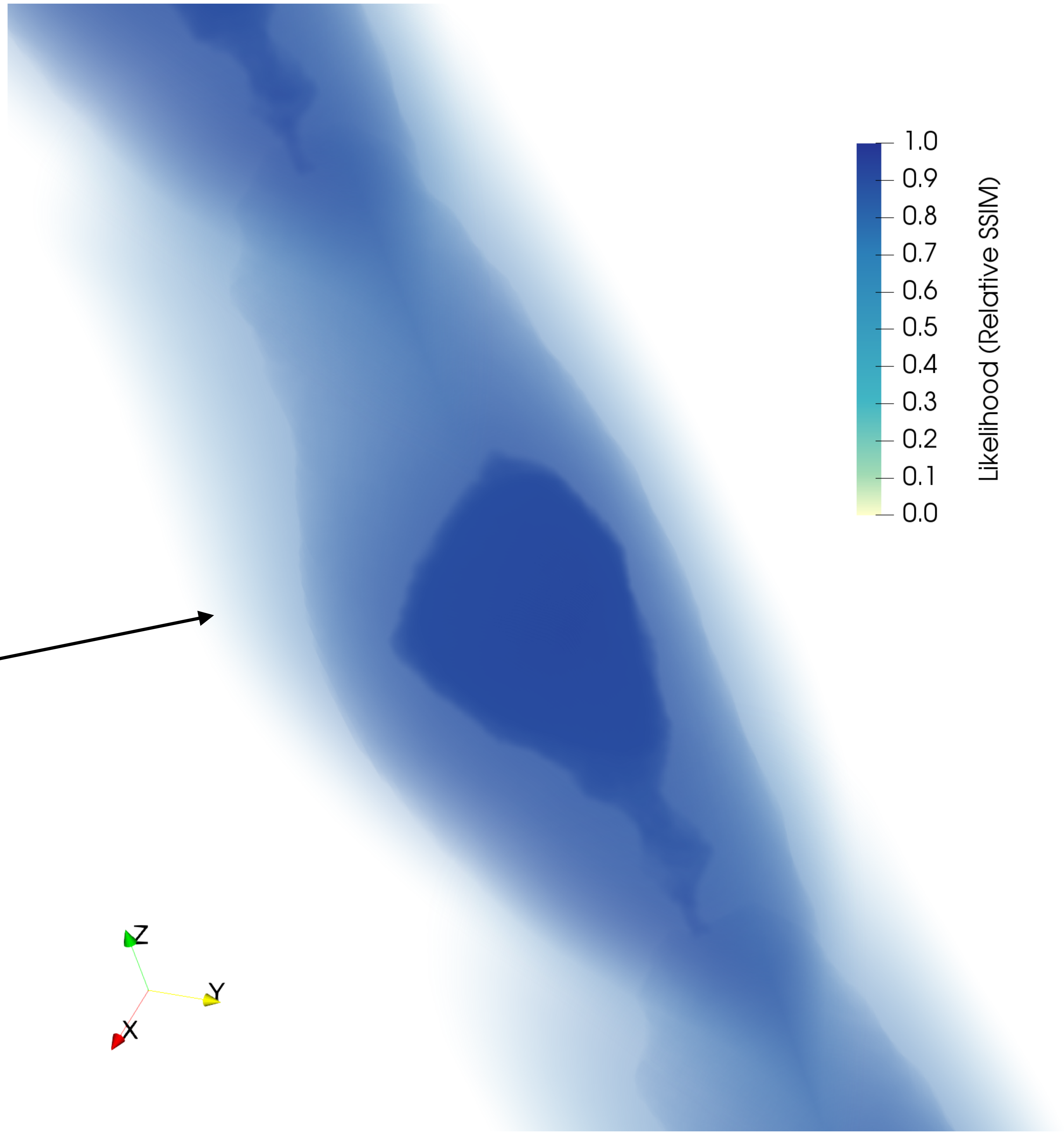
Groundtruth contact-center position

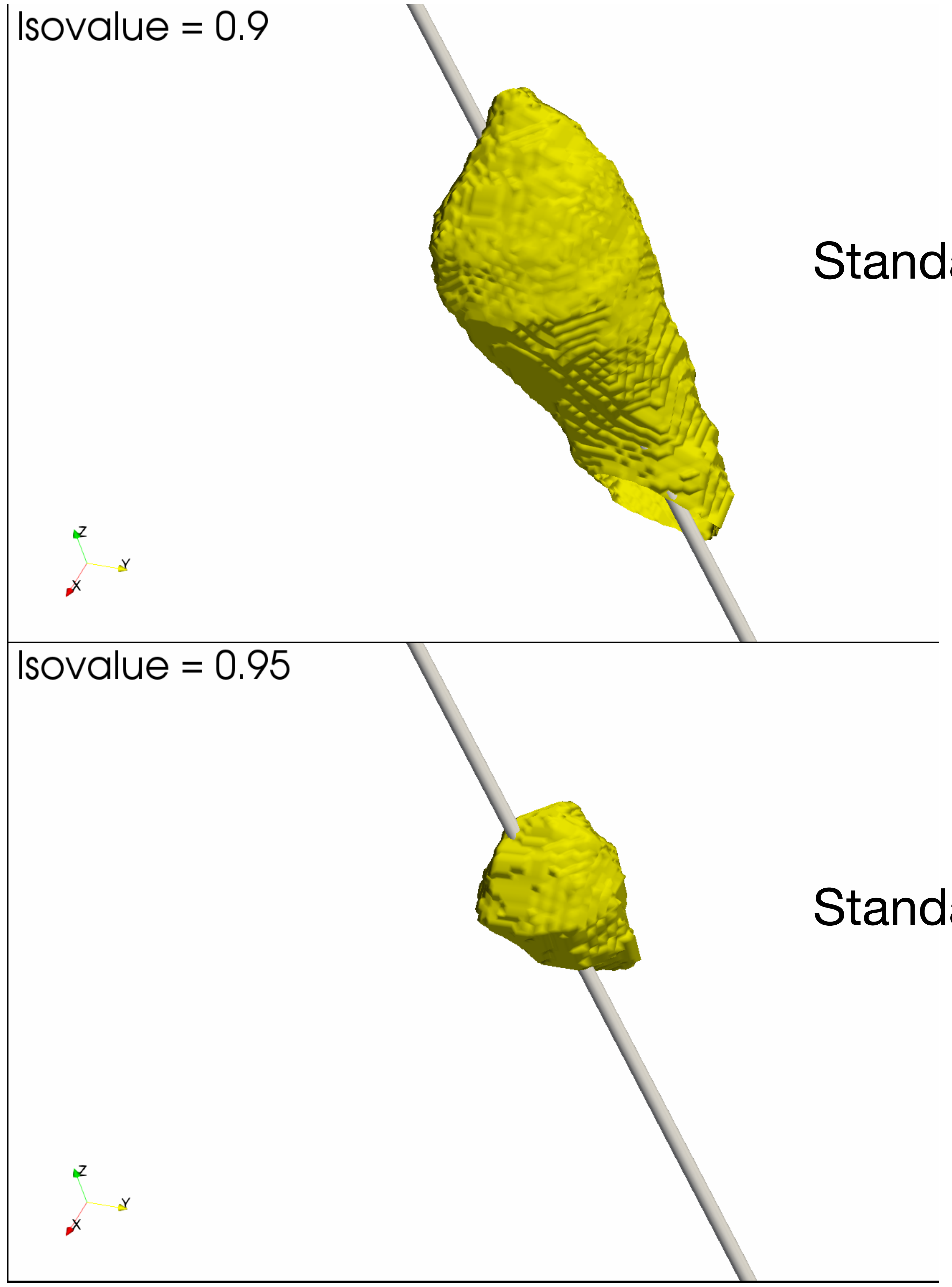
(Visualization software: The Paraview, Ahrens et al., 2005)

Standard deviation = 0.38 mm Standard deviation = 0.28 mm

Real Data: Uncertain DBS Contact Centers

Contact-center positional likelihood





Standard deviation = 0.71 mm

Standard deviation = 0.48 mm

Conclusions

- Uncertainty visualization for large-scale data
  - Marching squares/cubes algorithm
  - Ray casting for direct volume rendering
  - Distribution-based analysis: analytical approach
- Uncertainty quantification in DBS electrode positions for finite-resolution brain imaging
  - Distribution-based analysis: Monte Carlo sampling

Publications

- B. Ma, T. M. Athawale, E. Sakhaee, C. R. Johnson, and A. Entezari; **Nonparametric Models for Direct Volume Rendering of Uncertain Data Using Multidimensional Transfer Functions** (submitted to EuroVis 2019).

- T. M. Athawale and C. R. Johnson; **Probabilistic Asymptotic Decider for Topological Ambiguity Resolution in Level-Set Extraction for Uncertain 2D Data**, *IEEE Transactions on Visualization and Computer Graphics (TVCG), Special Issue on IEEE VIS Conf*, vol.25, no. 1, pp. 1163-1172, Jan. 2019.

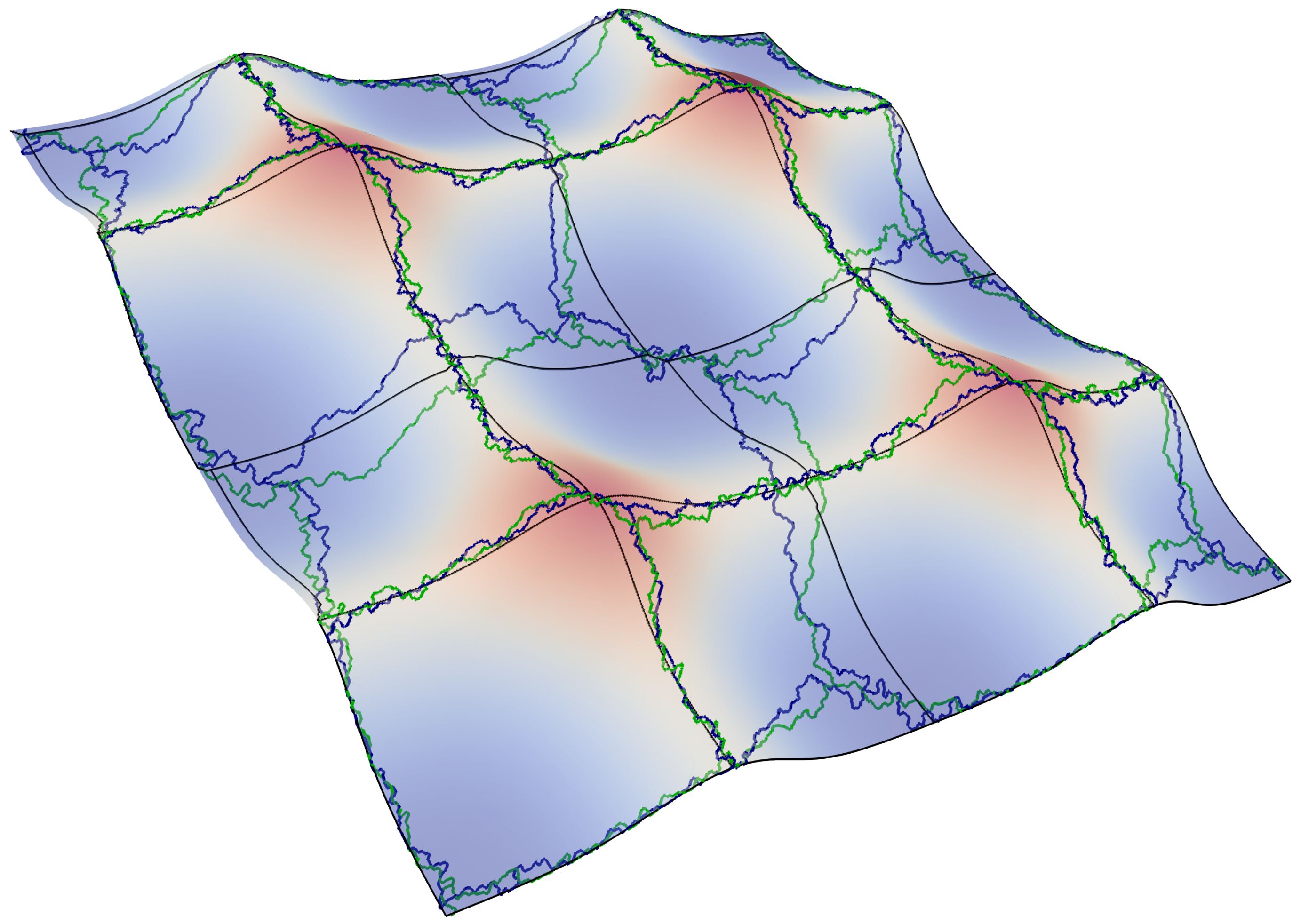
- T. M. Athawale, K. A. Johnson, C. R. Butson, and C. R. Johnson; **A Statistical Framework for Visualization of Positional Uncertainty in Deep Brain Stimulation Electrodes.**, *Computer Methods in Biomechanics and Biomedical Engineering: Imaging & Visualization*, pp. 1-12, Oct. 2018.

- T. M. Athawale, E. Sakhaee, and, A. Entezari; **Isosurface Visualization of Data with Nonparametric Models for Uncertainty**, *IEEE Transactions on Visualization and Computer Graphics (TVCG), Special Issue on IEEE VIS Conf*, vol.22, no.1, pp.777-786, Jan. 2016.

- T. M. Athawale and A. Entezari.; **Uncertainty Quantification in Linear Interpolation for Isosurface Extraction**, *IEEE Transactions on Visualization and Computer Graphics (TVCG), Special Issue on IEEE VIS Conf*, vol.19, no.12, pp.2723-2732, Dec. 2013.

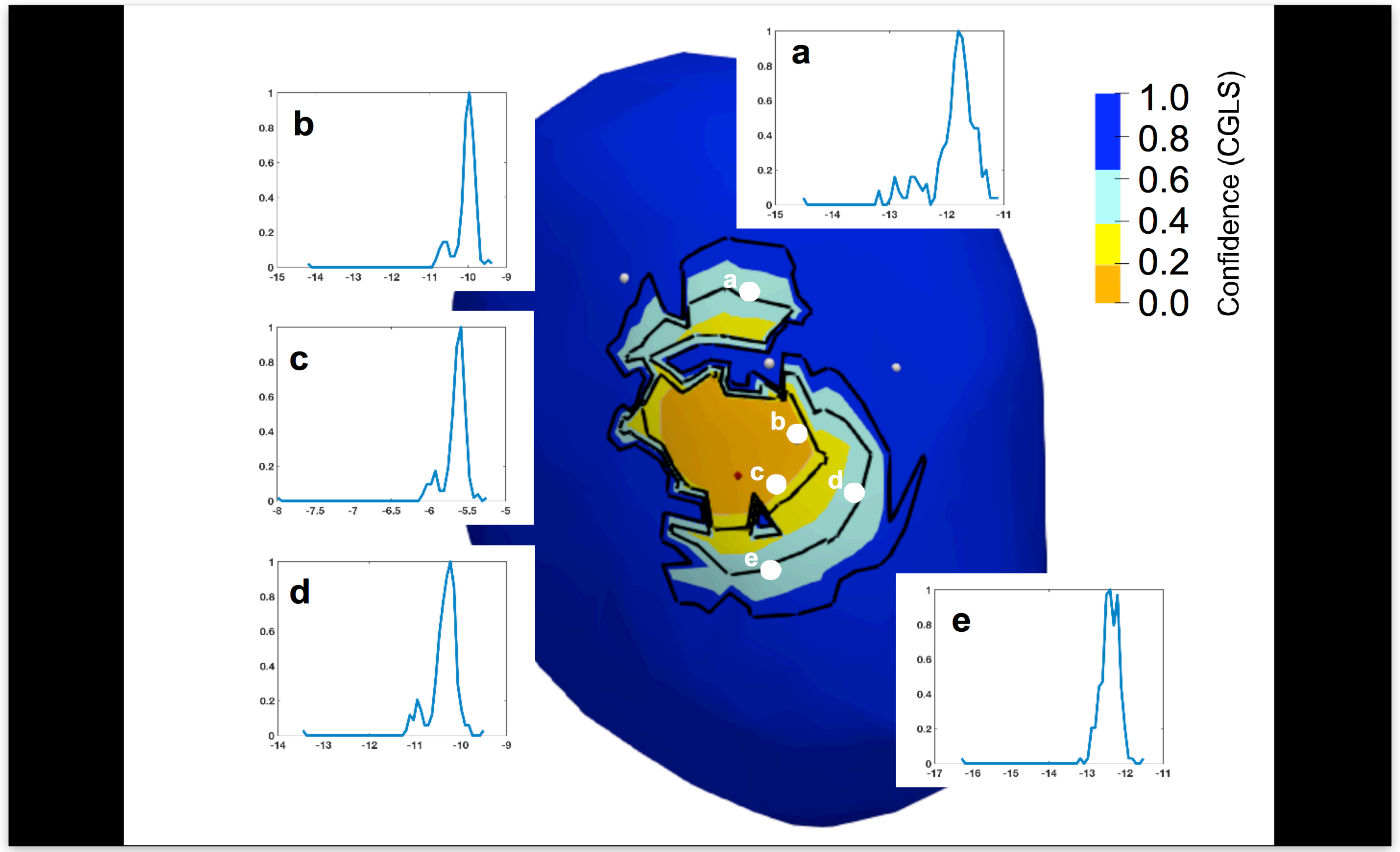
Future Work

- Positional uncertainty quantification in topological features/segmentations



The Visualization of Uncertain Morse-Smale Complexes
(Visualization software: The Topology Toolkit (TTK) [Tierny et al., 2017])

- Positional uncertainty in sources of arrhythmia for noisy ECG recordings



Positional Likelihood of Sources of Arrhythmia

Thank you for your attention!

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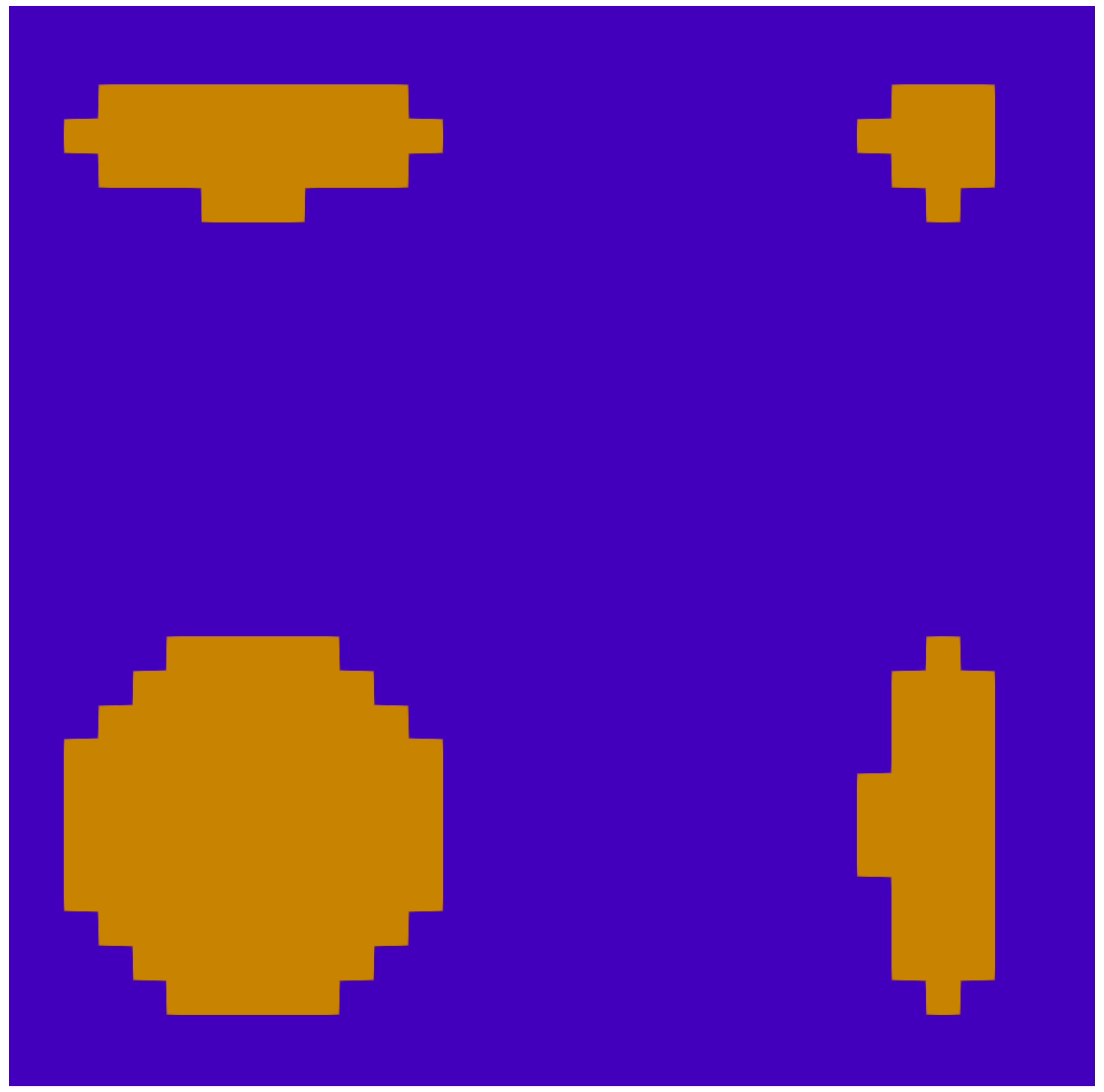
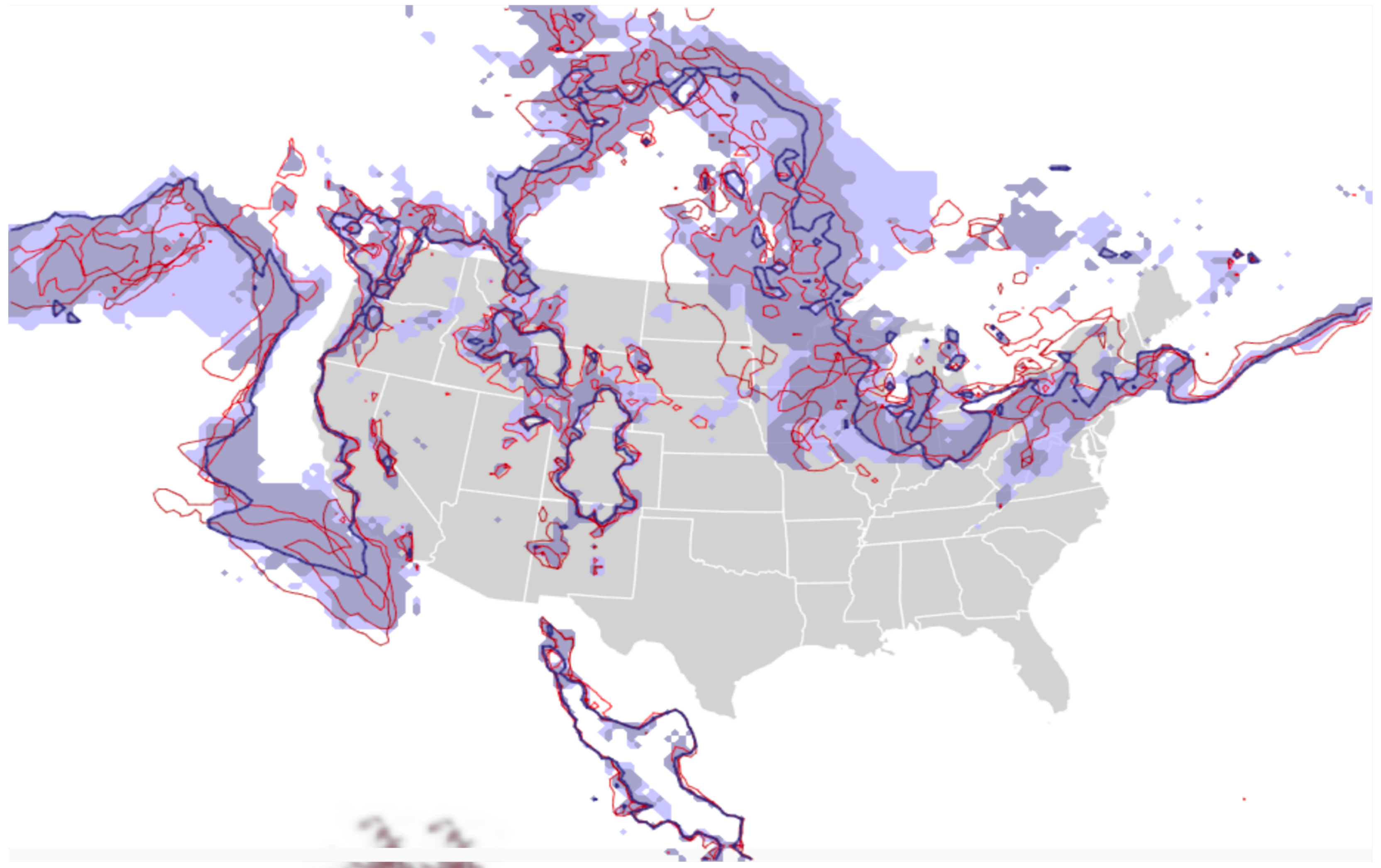
For any questions, please contact at:

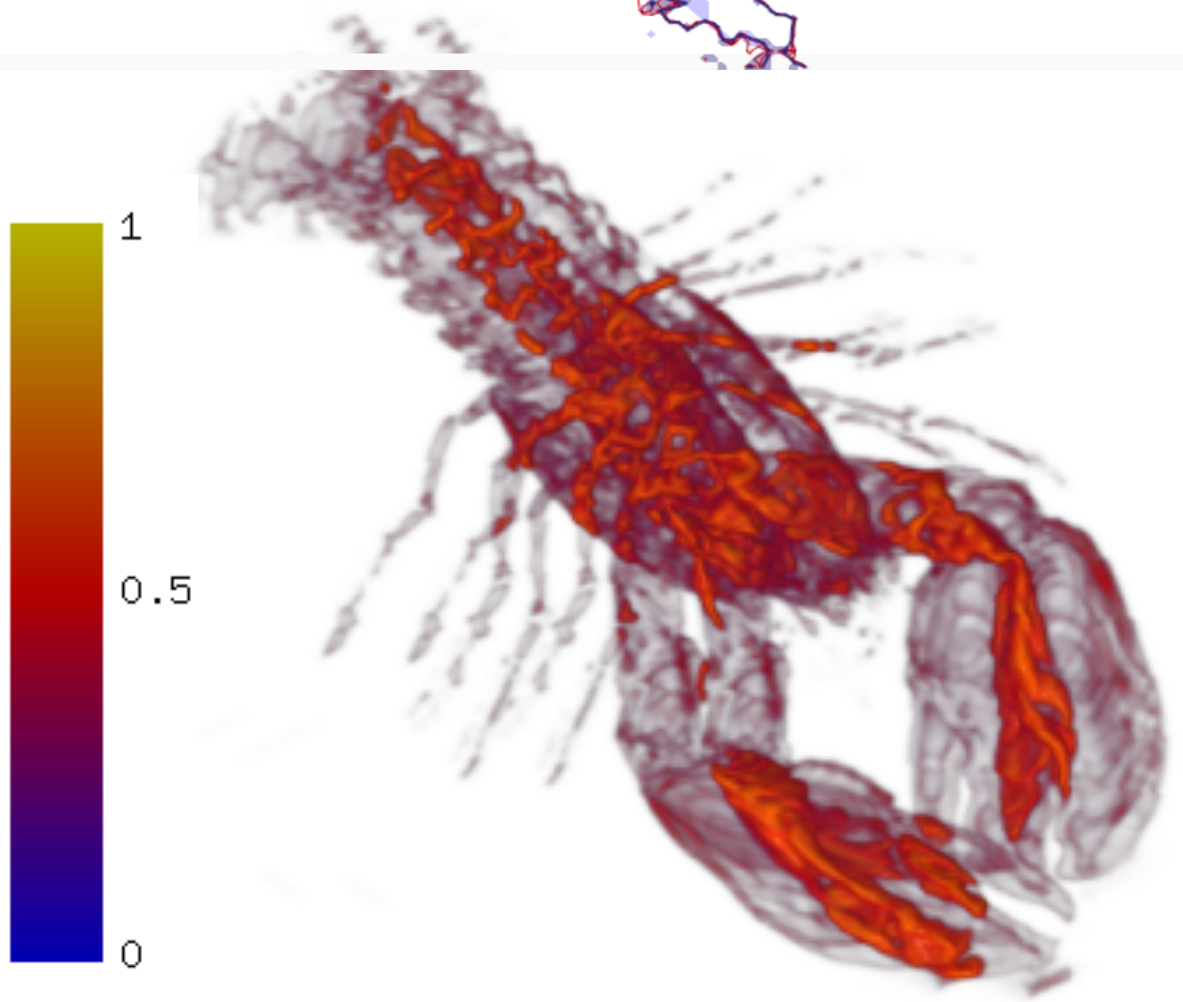
Email: tushar.athawale@gmail.com

Uncertainty Visualization: Related Work

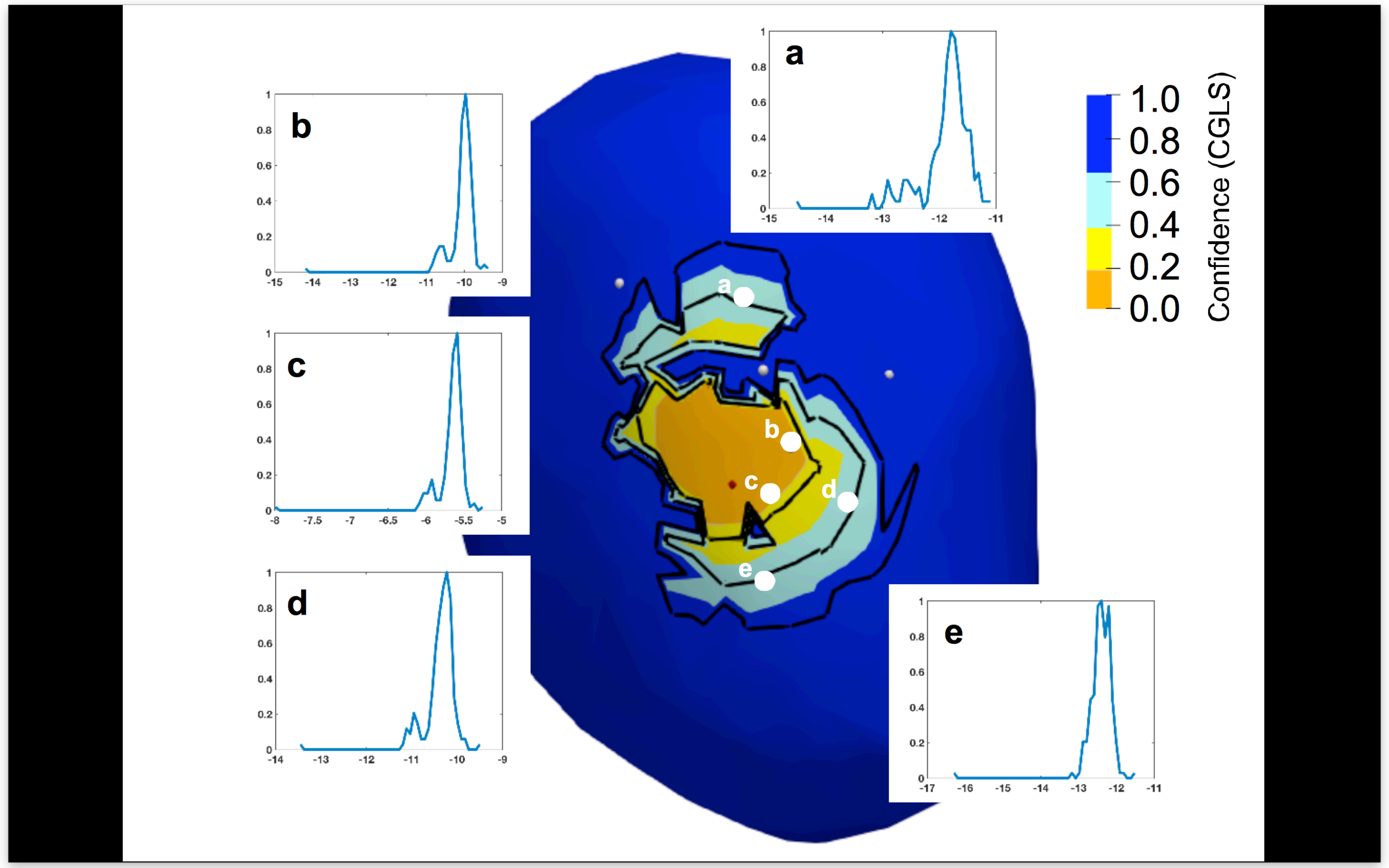


Mandatory Critical Points
[Günther el al., 2014]





Uncertain Level sets
[Pöthkow et al., 2011, Whitaker et al., 2013]



Interactive PDF queries
[Potter et al., 2011]