OAK RIDGE National Laboratory

Uncertainty Visualization of 2D/3D Scientific Data for Trusted Analysis and Decision-Making

Tushar M. Athawale

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

My Educational and Job Journey

University of Florida (2010 – 2015)
Thesis: Uncertainty quantification for isosurface visualization

MathWorks (2015 – 2016)

SCI Institute, University of Utah
(2016 – 2021)

Oak Ridge National Laboratory
(2021-Present)

Oak Ridge National Laboratory

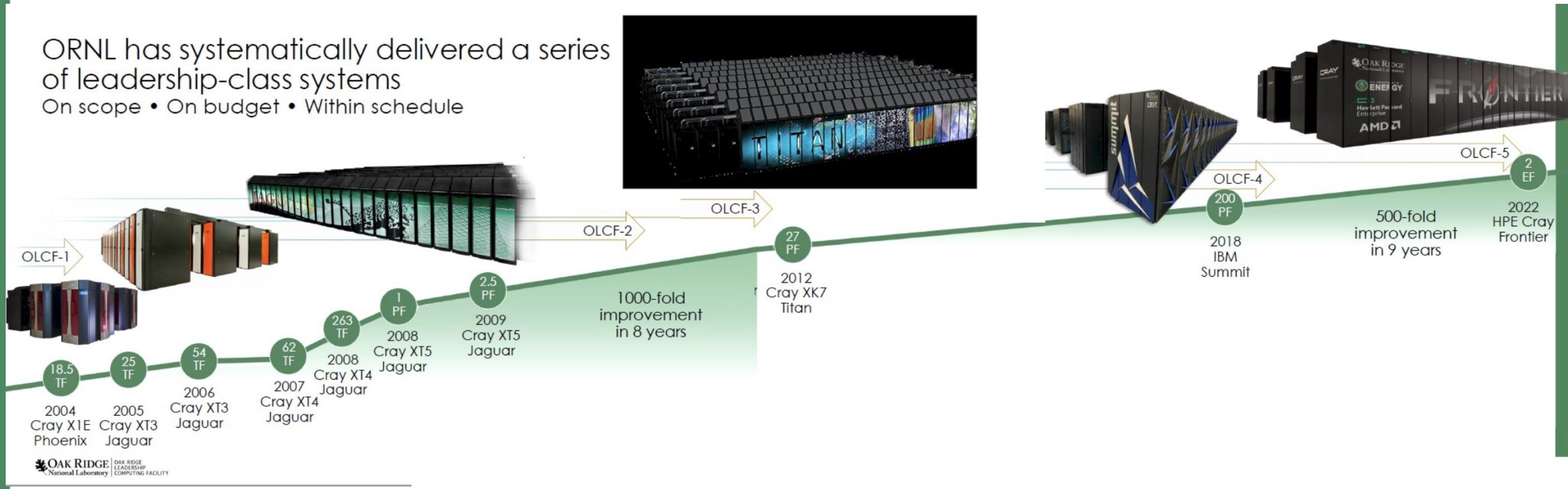
https://www.ornl.gov/directorate/ccsd

- Staff ~ 6000
- Home to the first exascale supercomputer

<u>Computing and Computational Sciences Directorate (CCSD)</u>

- National Center for Computational Sciences (NCCS)
- Computer Science and Mathematics Division (CSMD)
- Computational Science and Engineering (CSED)

Supercomputers at ORNL



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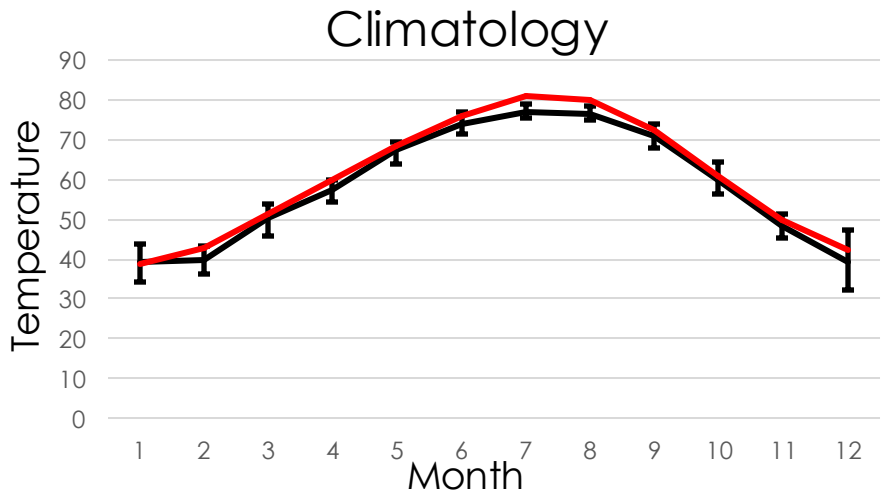
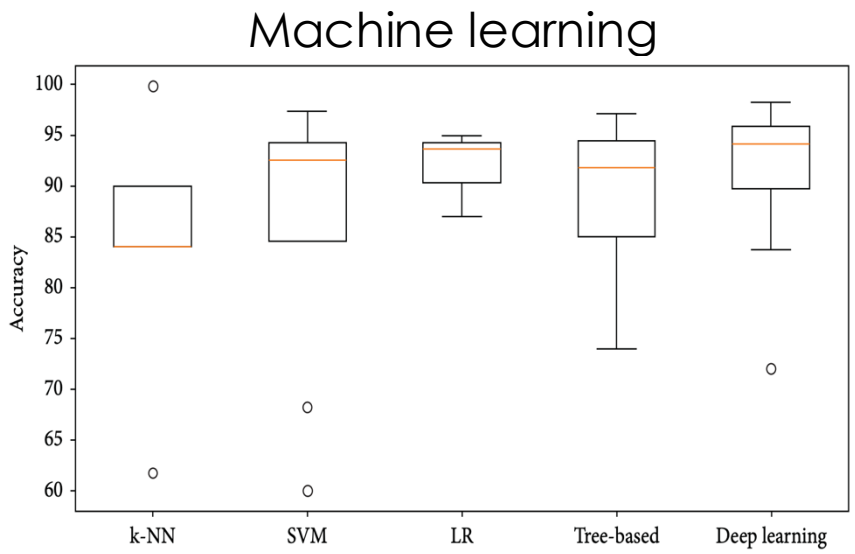
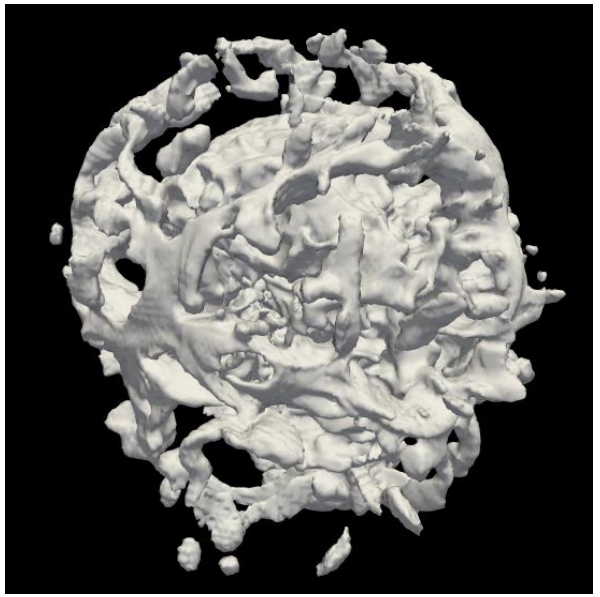
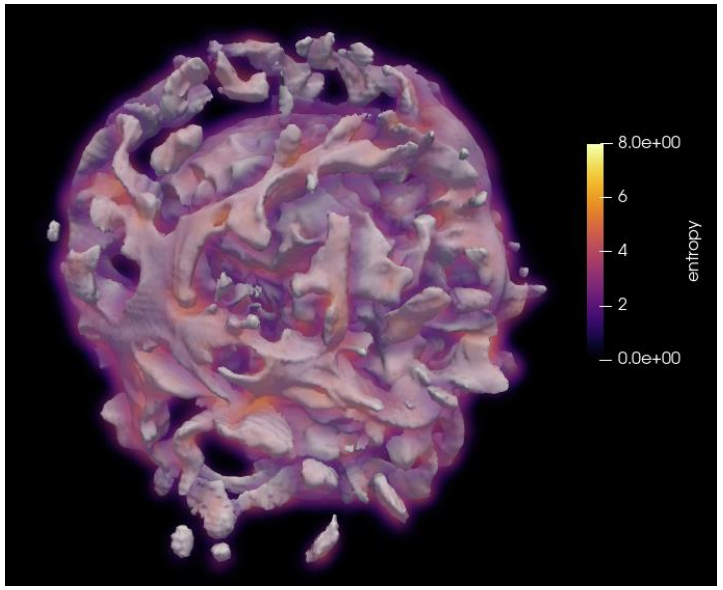
How Often Do We See Error Bars in 2D/3D Visualizations?





Supernova dataset

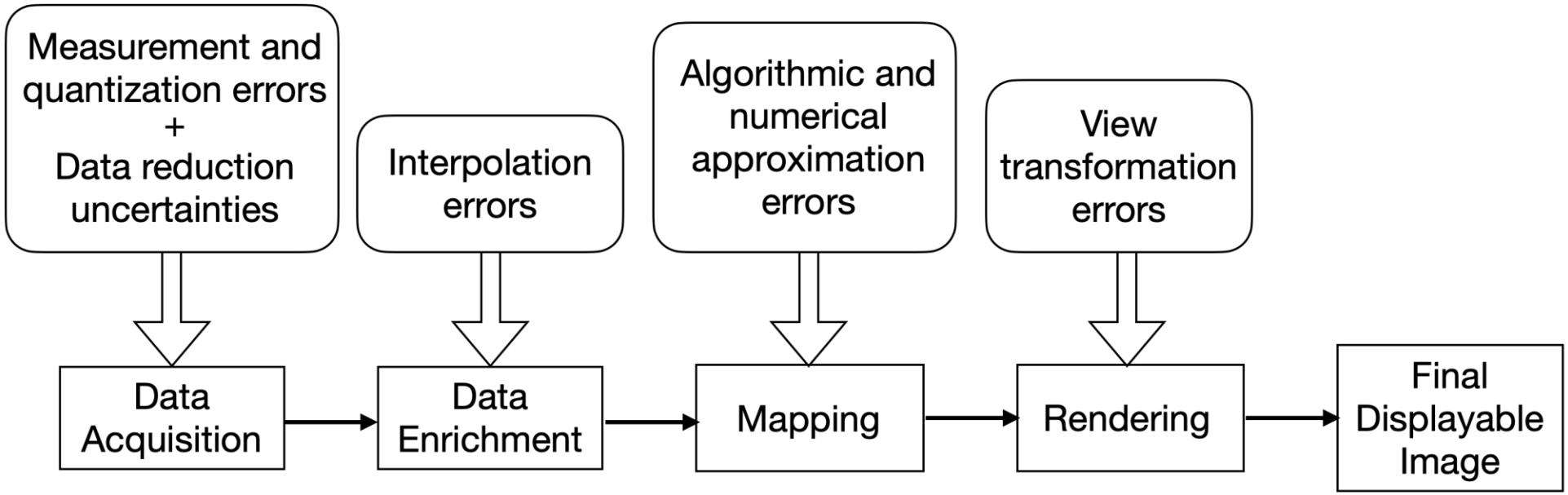




Isosurface without uncertainty

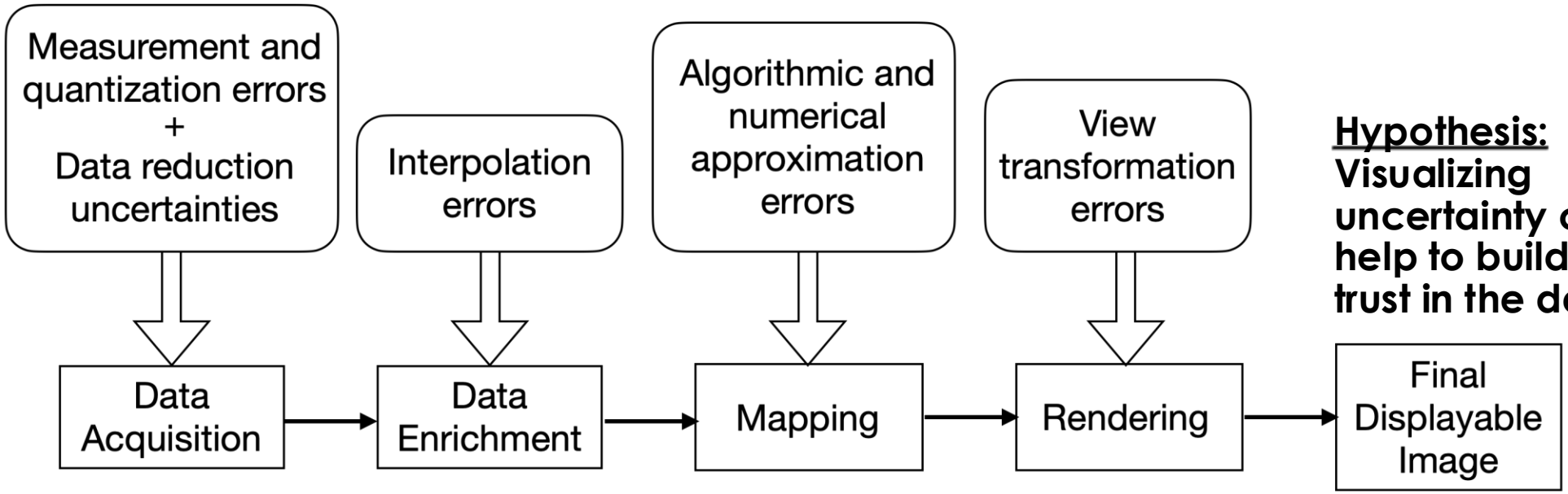
Isosurface with uncertainty

Why Should We Visualize Uncertainty?



The Visualization Pipeline

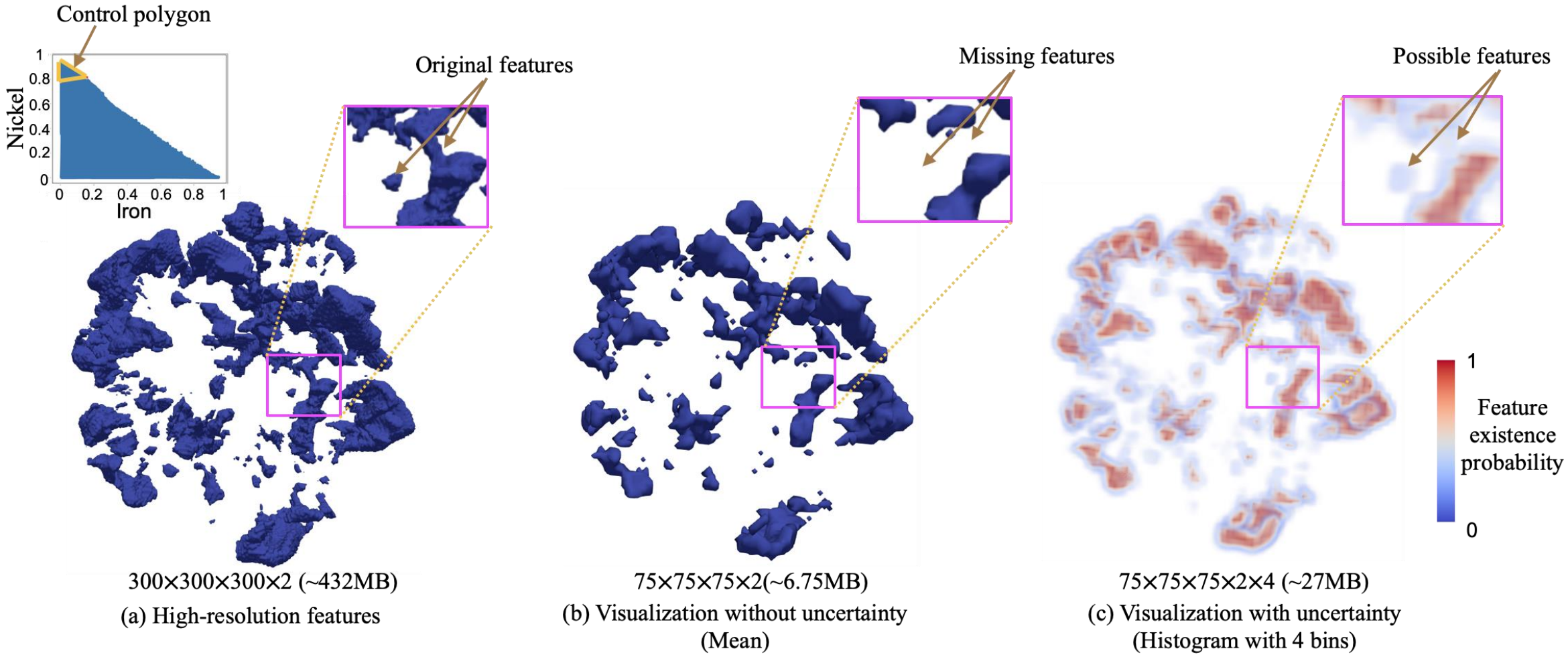
Why Should We Visualize Uncertainty?



The Visualization Pipeline

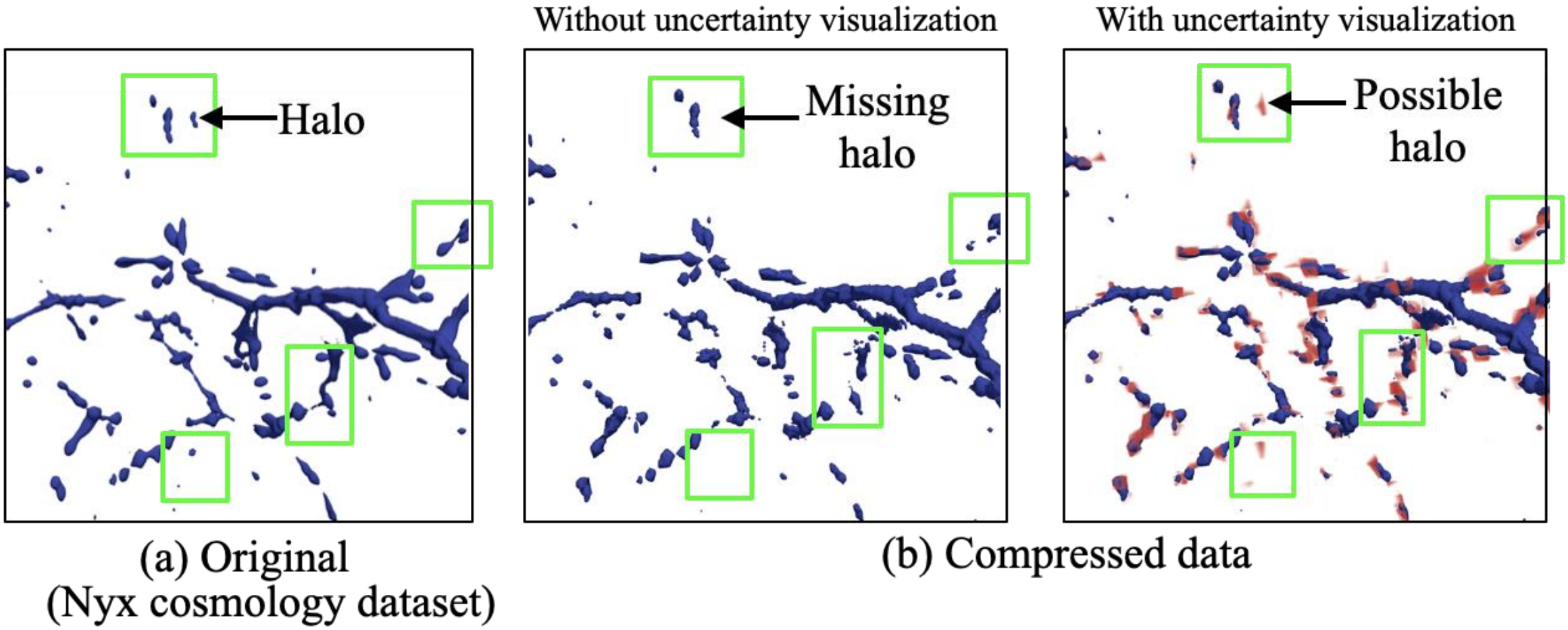
<u>Hypothesis:</u>
Visualizing uncertainty can help to build trust in the data

Uncertainty Visualization for Trustworthy Analysis



[Athawale et al., Fiber Uncertainty Visualization of Bivariate Data for Parametric and Nonparametric Noise Models, IEEE VIS 2022]

Uncertainty Visualization for Trustworthy Analysis

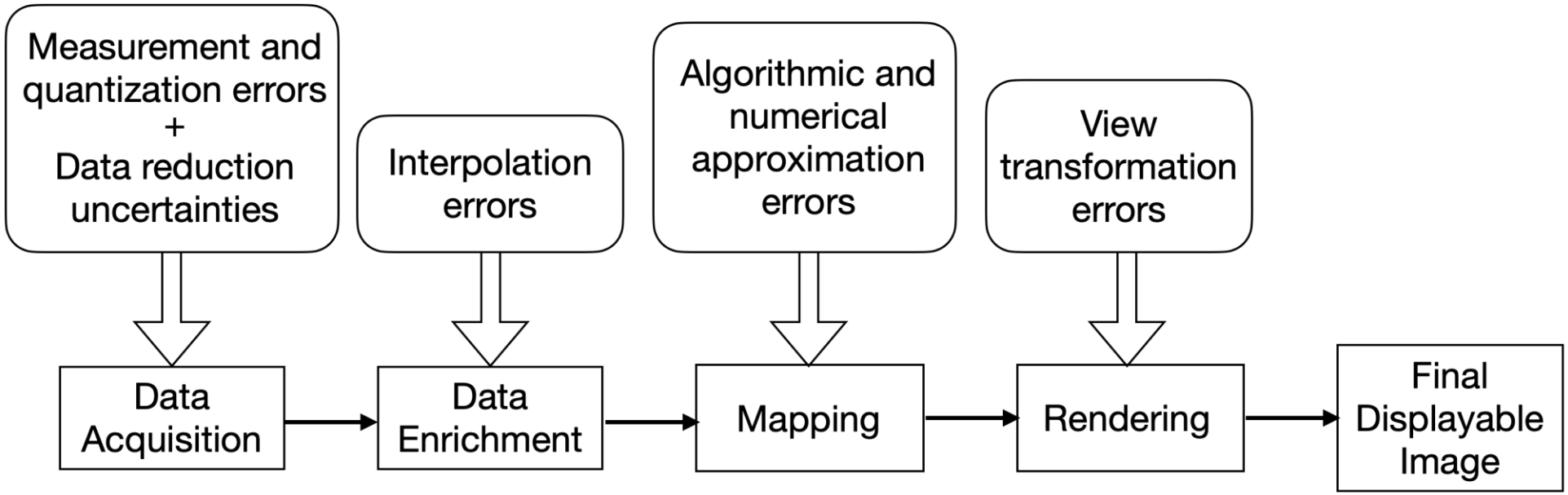


[Athawale et al., Uncertainty Visualization of Marching Squares and Marching Cubes Topology Cases, IEEE VIS 2021]

Uncertainty Visualization: Top Research Challenge

[A. T. Pang, C. M. Wittenbrink, and S. K. Lodha, “Approaches to Uncertainty Visualization”, 1997]
[C. R. Johnson and A. R. Sanderson, “A Next Step: Visualizing Errors and Uncertainty”, 2004]

Challenge: Lack of theory in uncertainty visualization because of the complexities related to uncertainty propagation, cost overhead, rendering, perception, cognition, decision-making



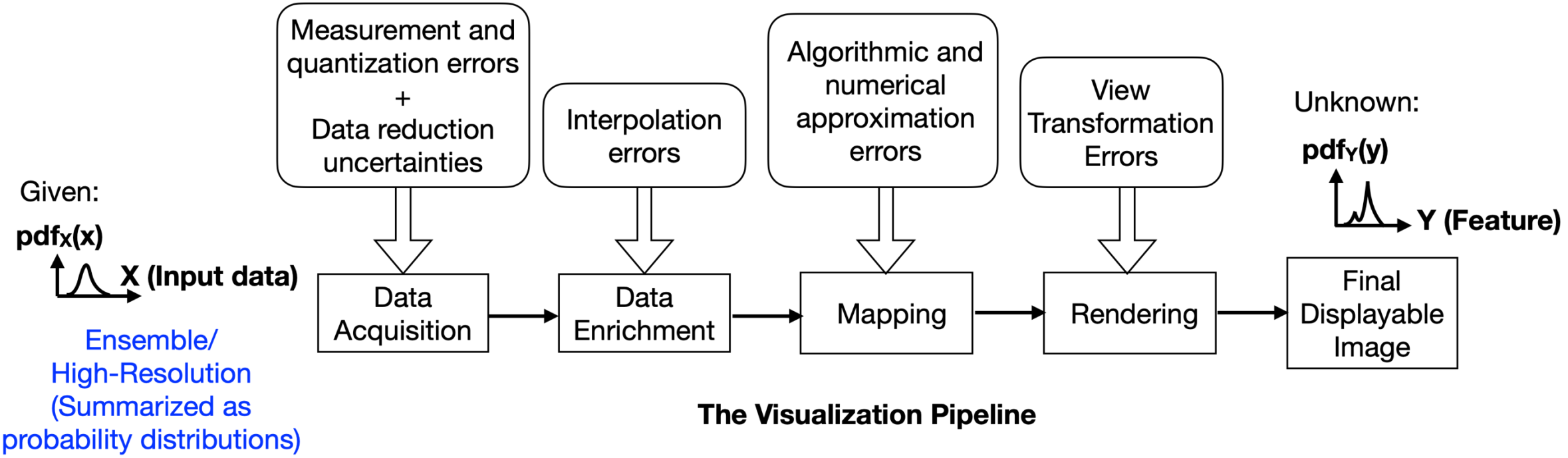
The Visualization Pipeline

[K. Brodlie, R. A. Osorio, and A. Lopes, “A Review of Uncertainty in Data Visualization”, 2012]
[A. Kamal et al., “Recent Advances and Challenges in Uncertainty Visualization”, 2021]

Our Approach to Uncertainty Visualization

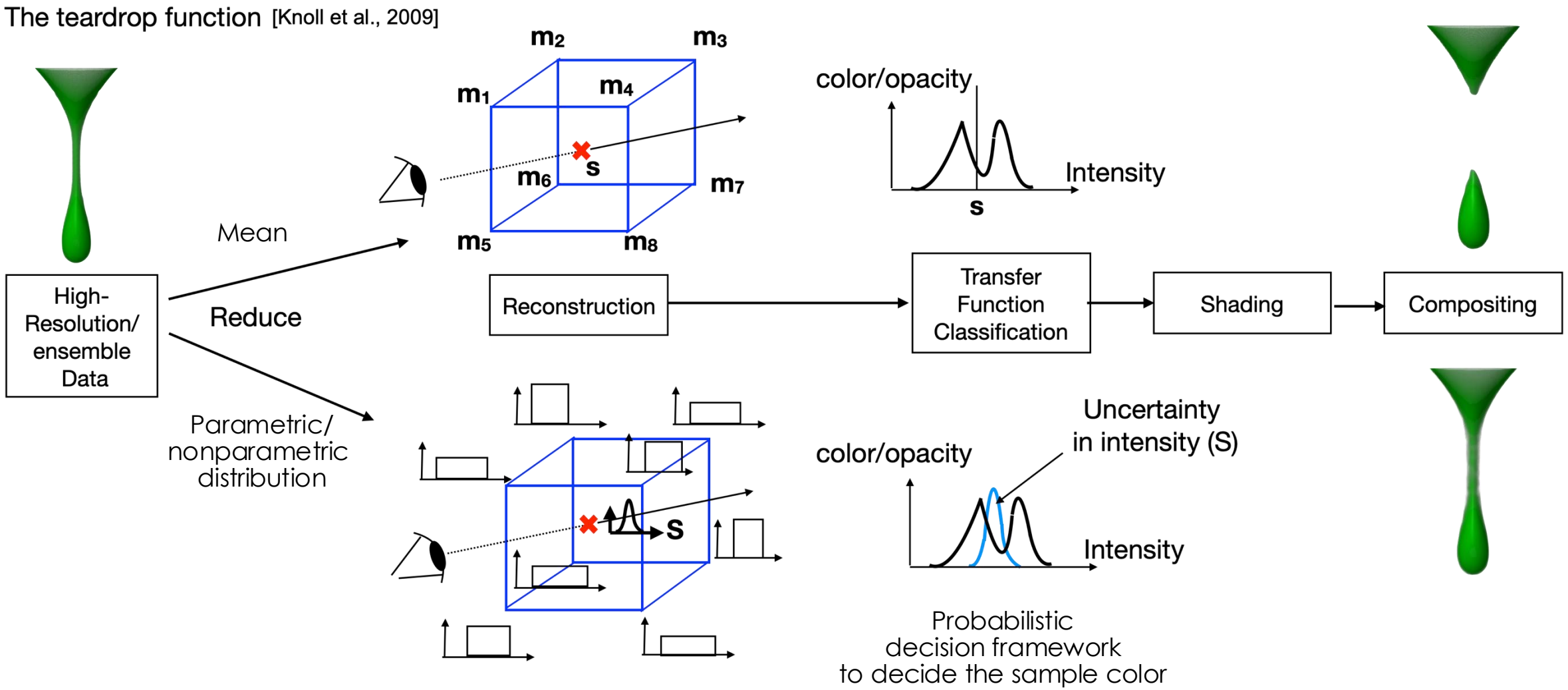
Monte Carlo (easy but expensive) vs. **Analytical** (difficult but fast)

(State of the art) (Our approach)

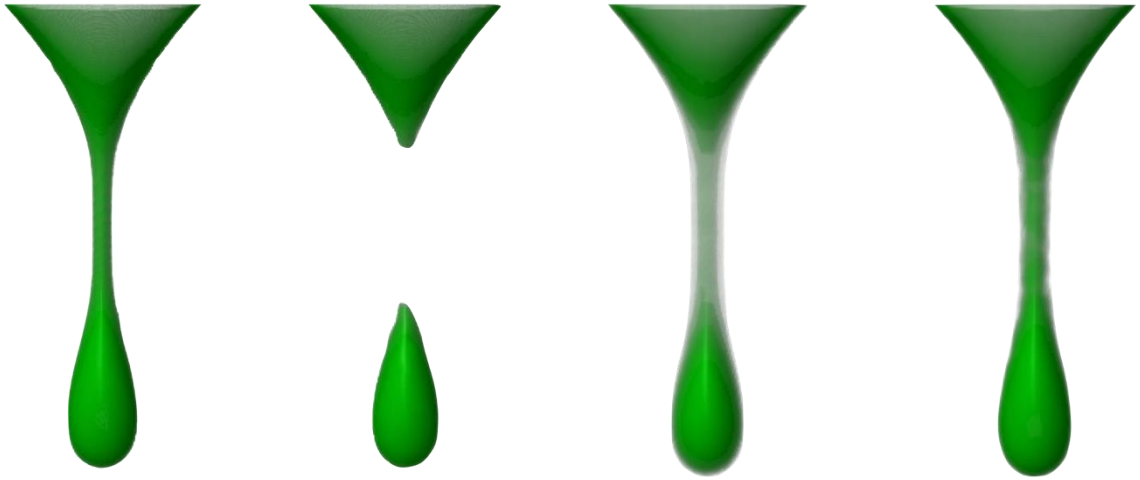


Uncertainty-Aware Direct Volume Rendering

Uncertainty-Aware Direct Volume Rendering (Analytical Approach)



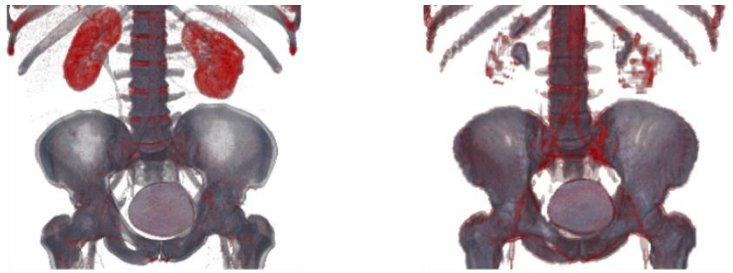
Uncertainty-Aware Direct Volume Rendering



(a) Ground truth | (b) Mean | (c) Parametric [Sakhaee and Entezari, 2017] | (d) Nonparametric (Our contribution) [Athawale et al., 2020]

The teardrop function (ensemble dataset)

Visualization software: Voreen (http://voreen.uni-muenster.de)



(a) Ground truth (512x512x1559) | (b) Mean (64x64x195)

(c) Parametric (64x64x195) x 2 [Sakhaee and Entezari, 2017]

(d) Nonparametric (64x64x195) x b (our contribution) [Athawale et al., 2020]

b = # histogram bins

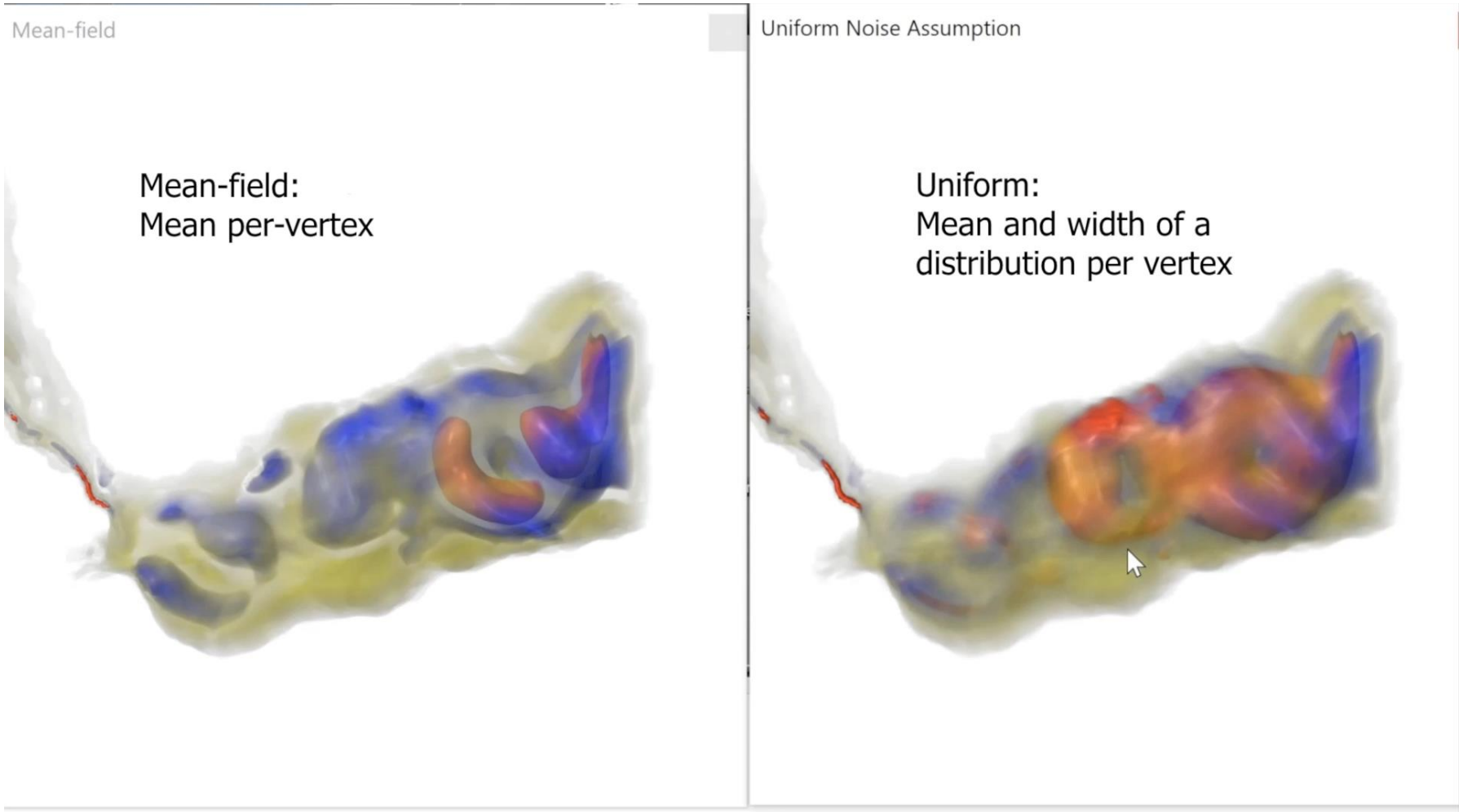
Osirix OBELIX dataset (http://medvis.org/datasets/)

The Red Sea Eddy Simulations

IEEE SciVis Contest 2020:

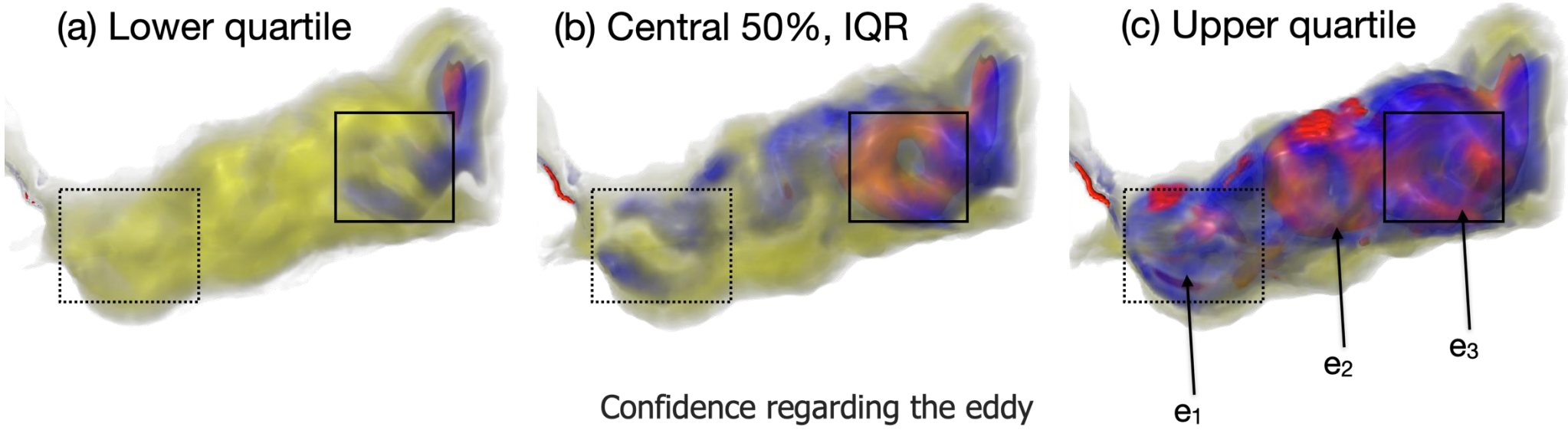
- Kaust Supercomputing Core Lab
- Large-scale eddy simulations (~1.5 TB)
- https://kaust-vislab.github.io/SciVis2020/

Uncertainty-Aware Volume Rendering: Interactive Exploration



Quartile View: Uncertainty Visualization

Rendering uncertainty for 3D or high-dimensional data sets is an open research challenge.

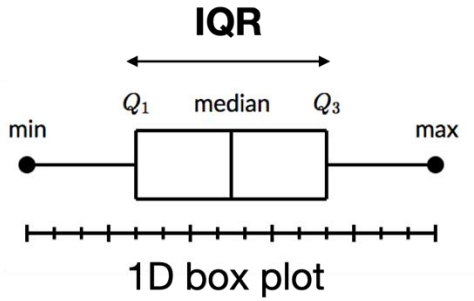


Confidence regarding the eddy presence/position:

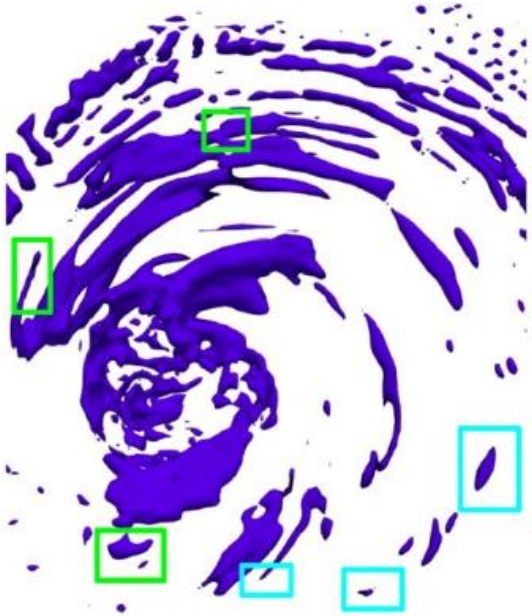
e_1: Low

e_2: Moderate

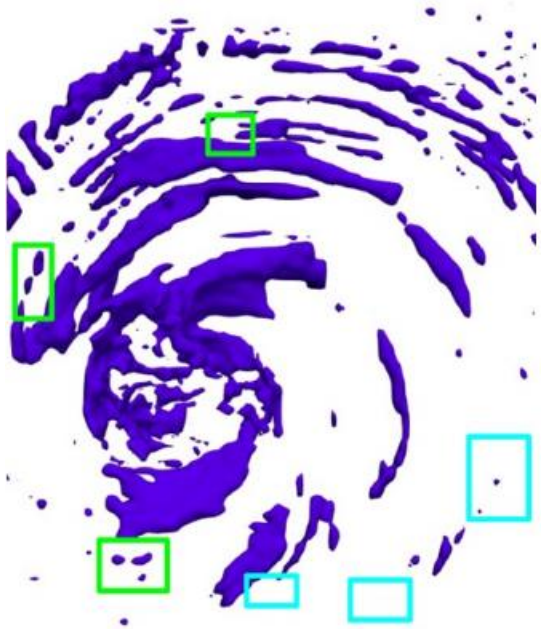
e_3: High



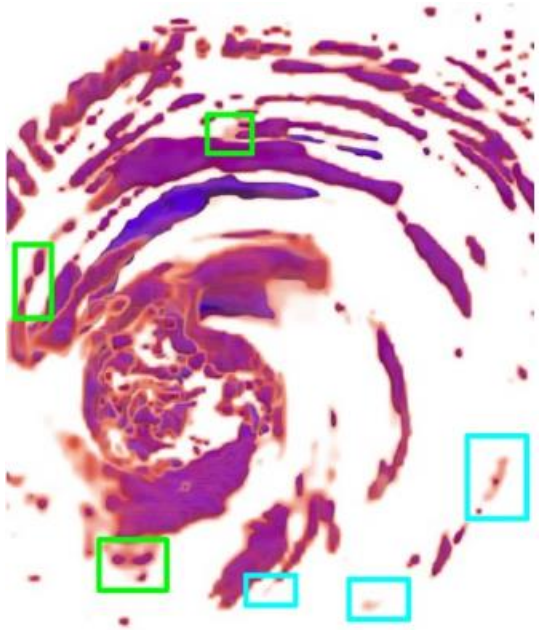
Uncertainty in Surface-Based Visualization of Univariate Data



Original data



Decompressed data without uncertainty visualization



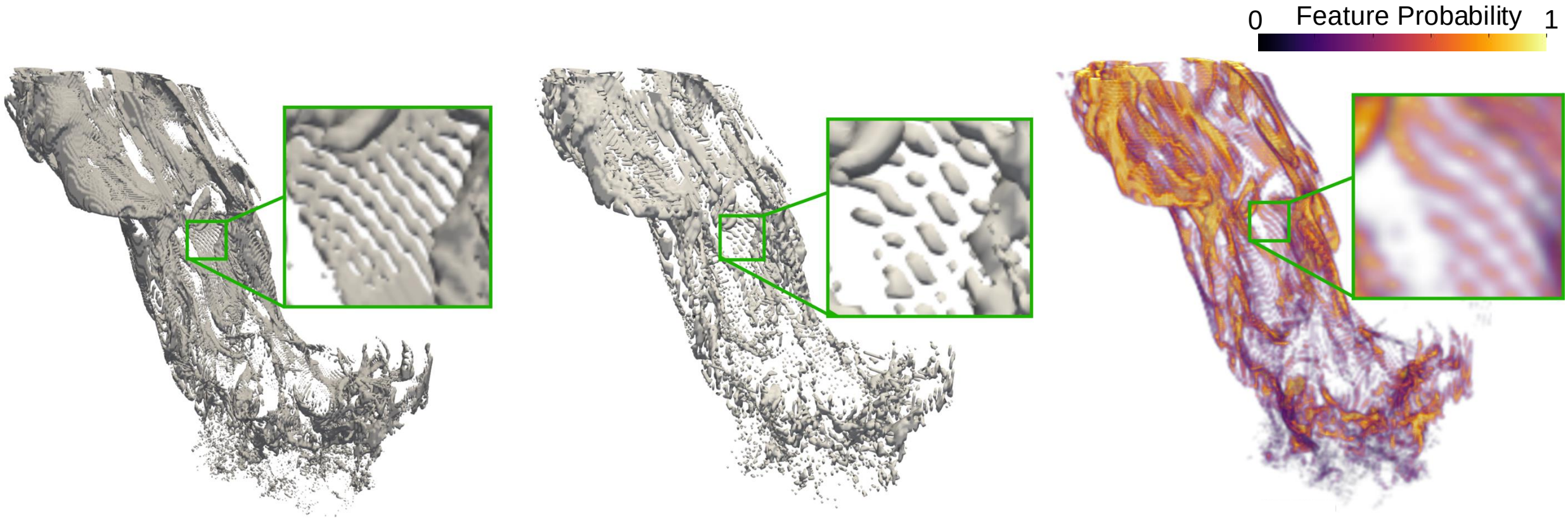
Decompressed data with uncertainty visualized in red

[Wang et al., Supercomputing 2024]

Uncertainty Visualization of Multivariate Data

Visualization of Trivariate Uncertain Data

Velocity magnitude:(0.1, 0.5), temperature:(0.2, 0.25), and pressure:(30000, 400000)



Original data
(490x280x240)

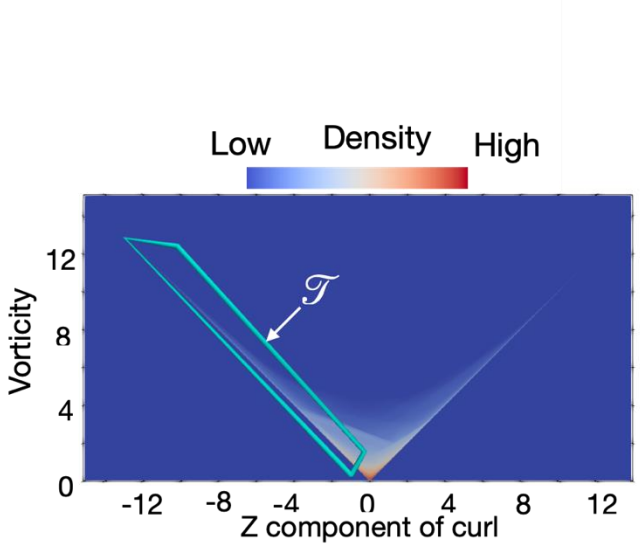
Visualization without uncertainty
(245x140x120)

Visualization with uncertainty
(245x140x120x2)

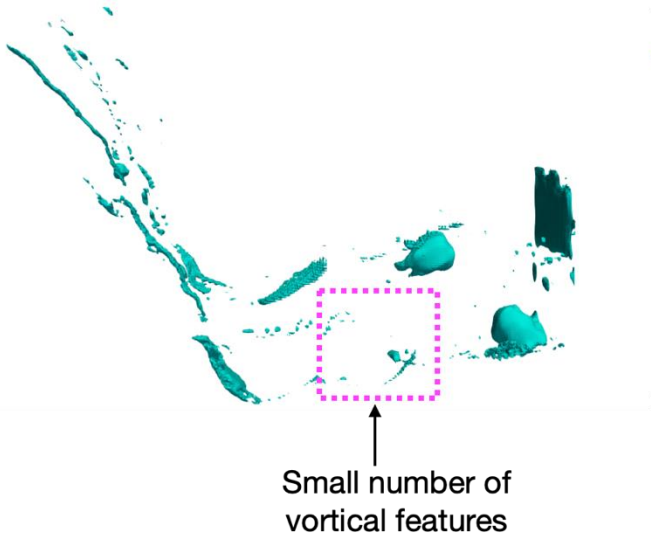
[Hari et al., 2024 IEEE Workshop on Uncertainty Visualization]

Uncertainty Visualization: Oceanology

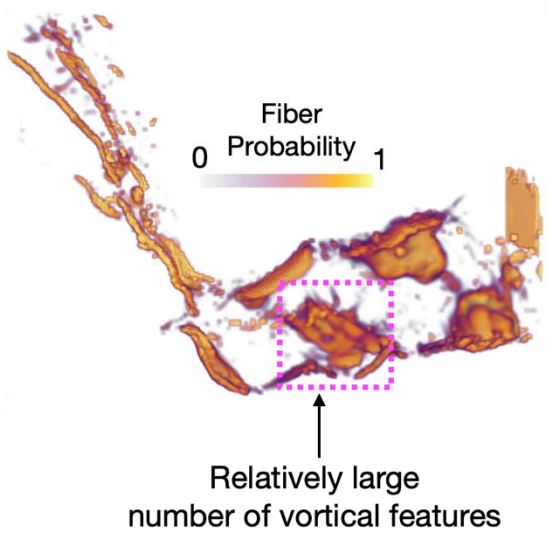
Eddies play a major role in transporting energy and biogeochemical particles in oceans [Zhan et al., "Eddies in Red Sea: A statistical and dynamical study", 2014]



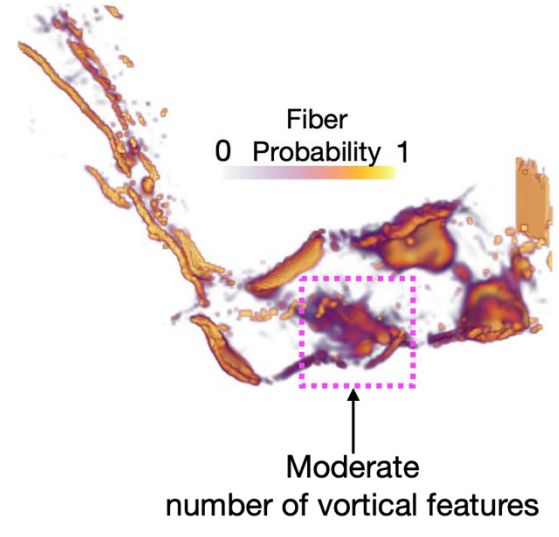
(a) Continuous scatterplot



(b) Mean-field fiber surface



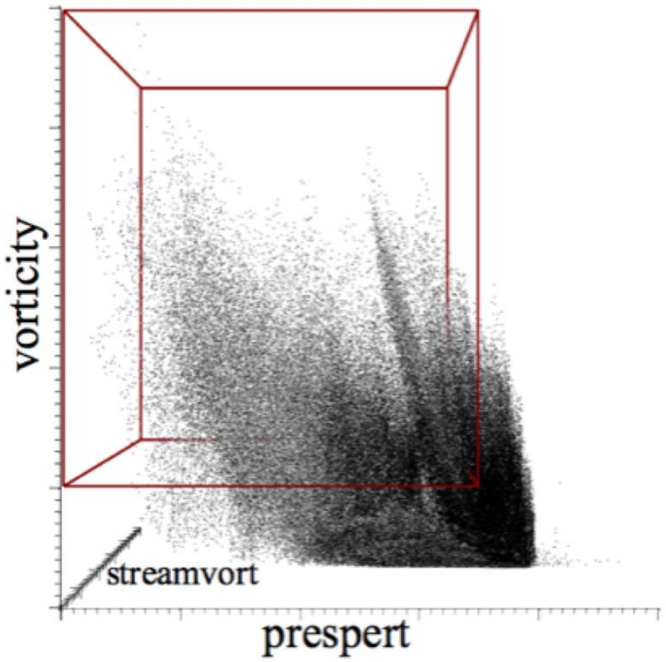
(c) Parametric

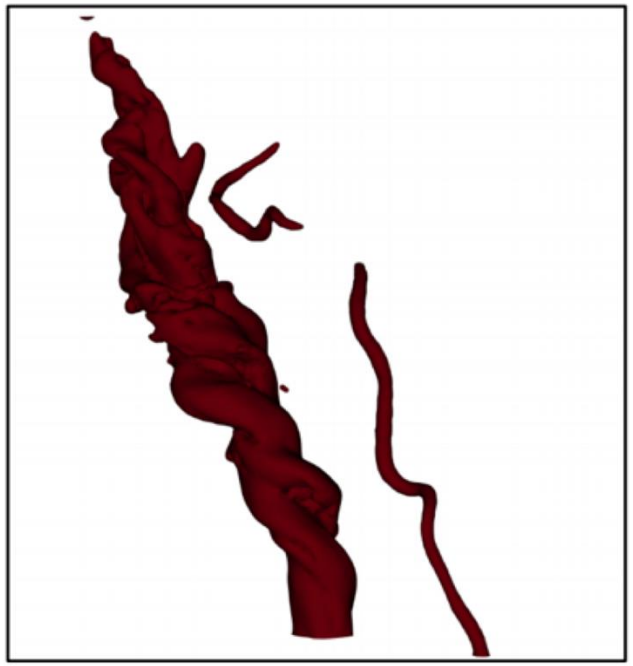


(d) Nonparametric

[T. M. Athawale, C. R. Johnson, S. Sane, and D. Pugmire, "Fiber Uncertainty Visualization for Bivariate Data With Parametric And Nonparametric Noise Models", IEEE VIS 2022]

Uncertainty Visualization of Feature Level-Sets





Feature level-sets
[Jankowai, 2018]

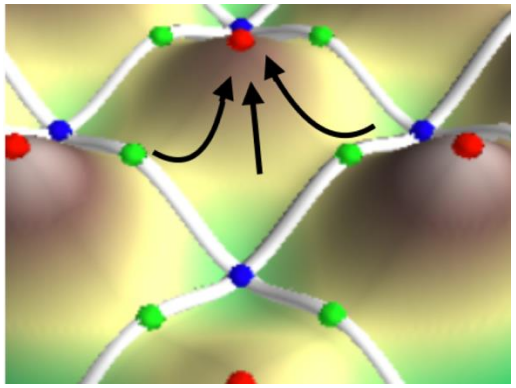
Feature confidence level-sets
[Sane, Athawale, and Johnson, 2021]

Visualization software: VisIt [Childs et al., 2012]

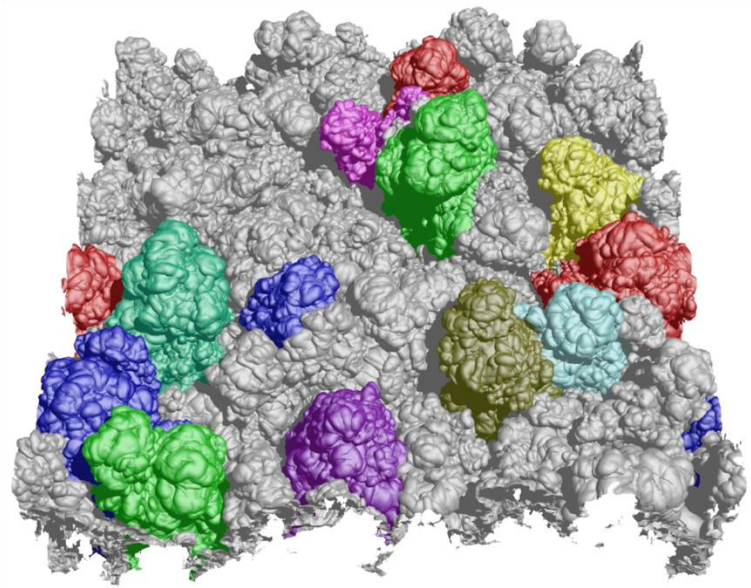
Uncertainty Visualization of Topological Features

Morse Complex Visualizations

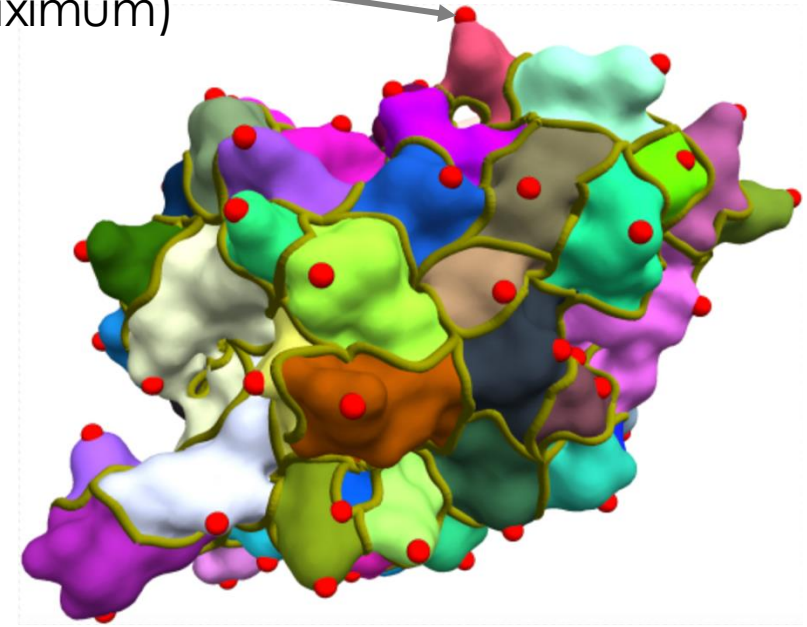
Topological descriptors of gradient flows of a scalar field



Critical point
(local maximum)

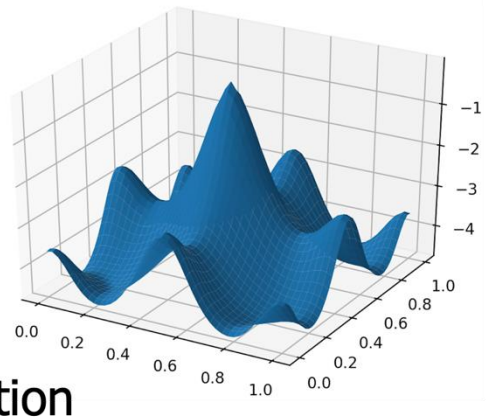


Understanding structure of turbulent mixing layers [Laney et al. 2006]



Segmenting molecular surfaces
[Natarajan et al., 2006]
[Shivashankar et al., 2012]

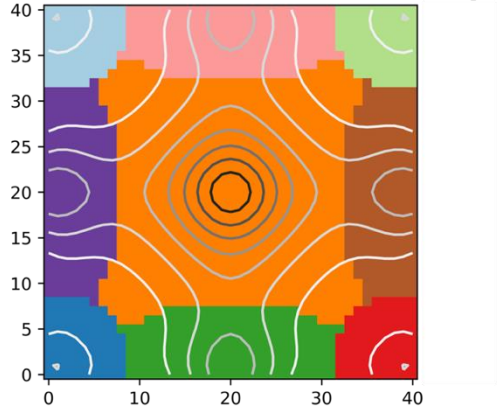
Effect of Noise on Morse Complexes



Ackley function
[Ackley, 1987]

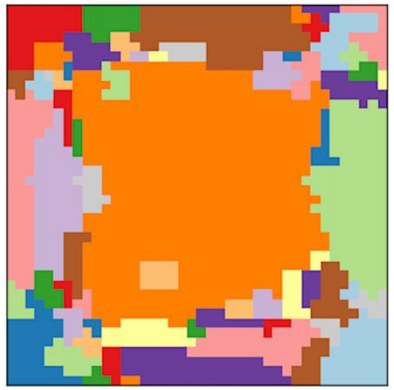
Morse complex extraction

Ground truth Morse complex

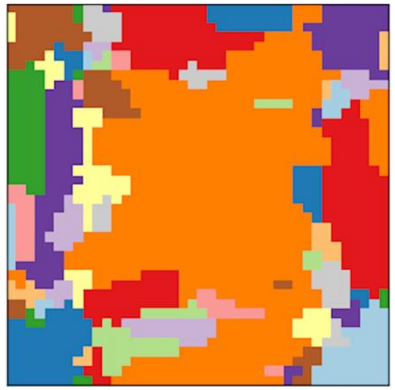


Mix noise and
extract Morse complex

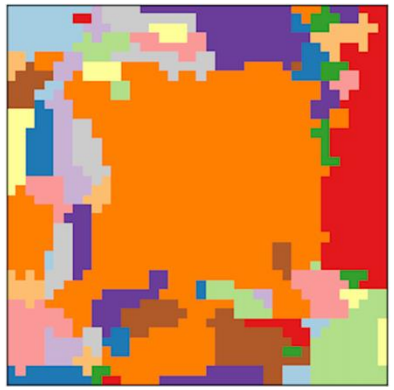
Ensemble member 1



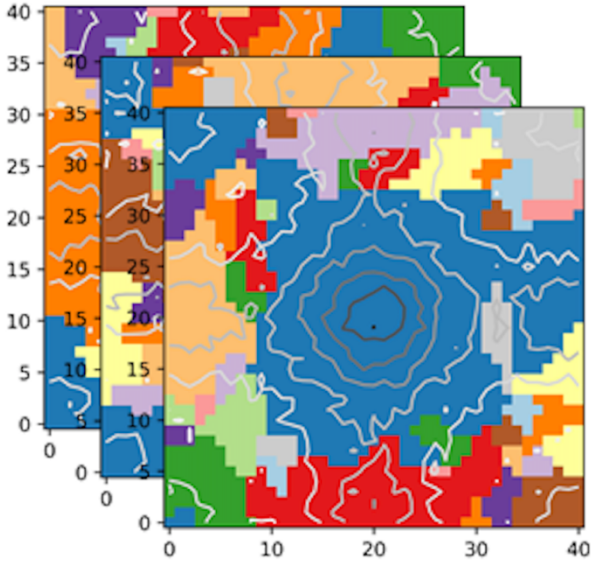
Ensemble member 2



Ensemble member 3



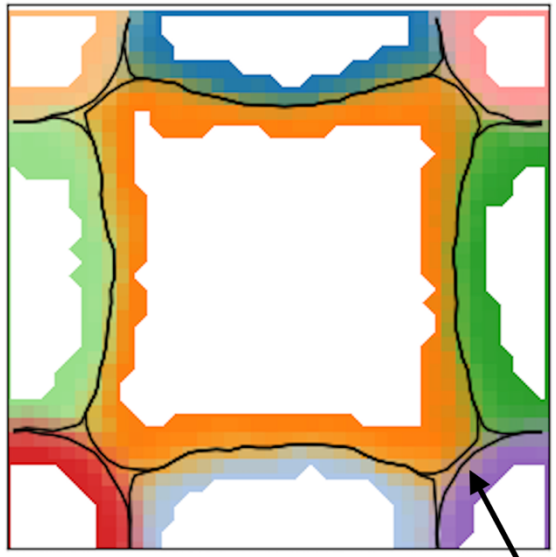
Morse Complex Uncertainty



Ensemble of Morse Complexes

Agreement Regions

+

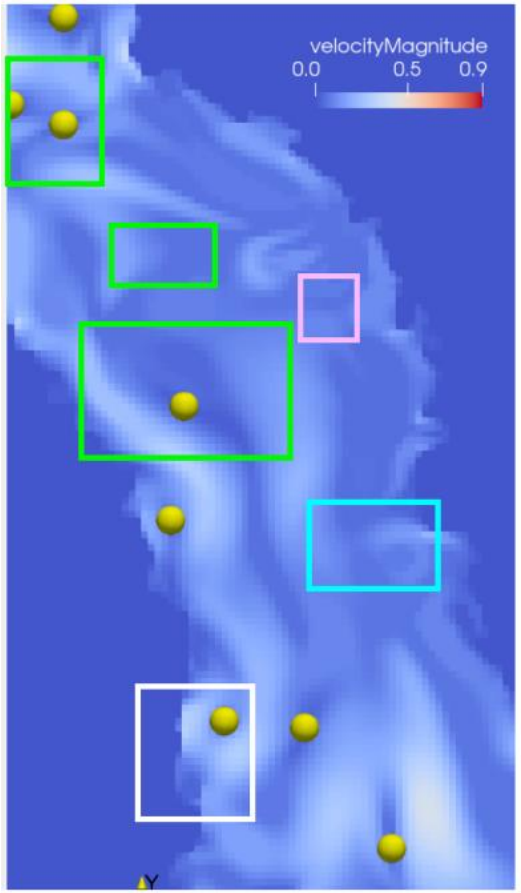


Uncertainty Regions

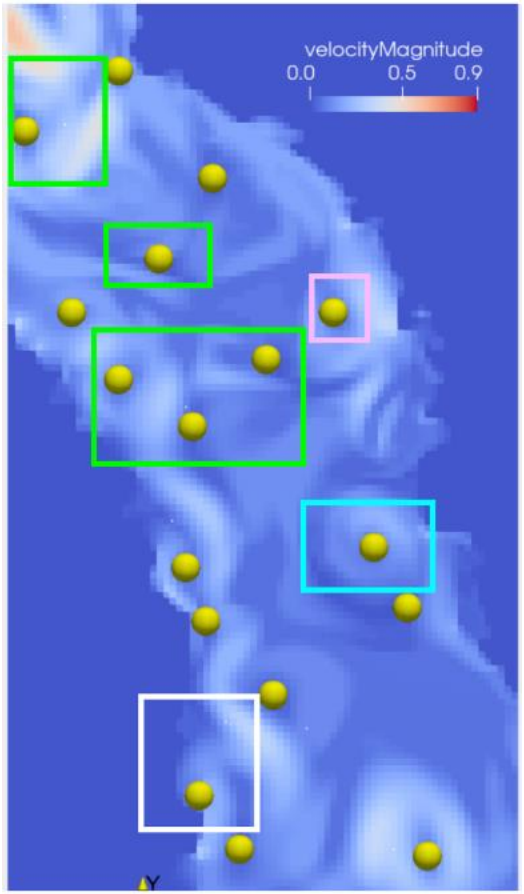
Expected boundaries

[T. M. Athawale, D. Maljovec, L. Yan, C. R. Johnson, V. Pascucci, and B. Wang, TVCG, 2022]

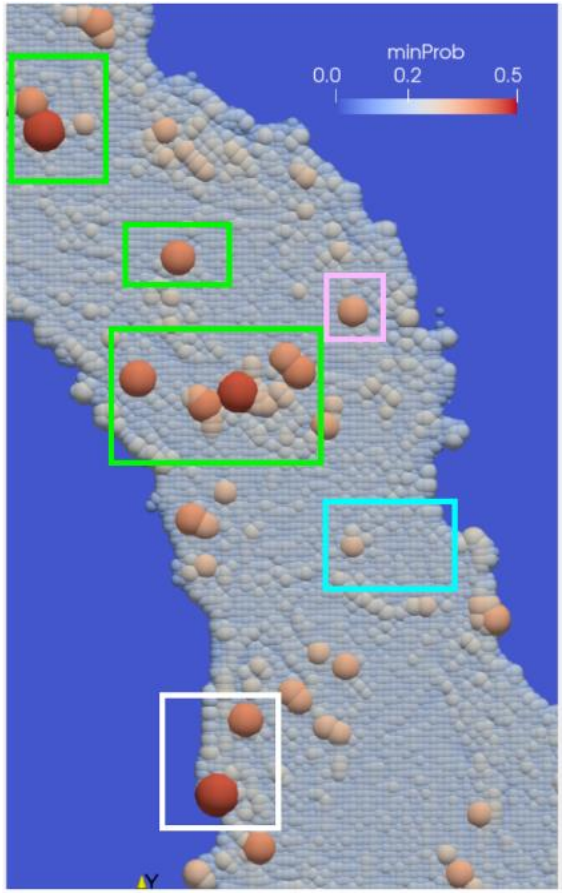
Uncertainty Visualization of Critical Points



Ensemble member **1**
(Vortex cores in yellow)



Ensemble member **n**
(Vortex cores in yellow)

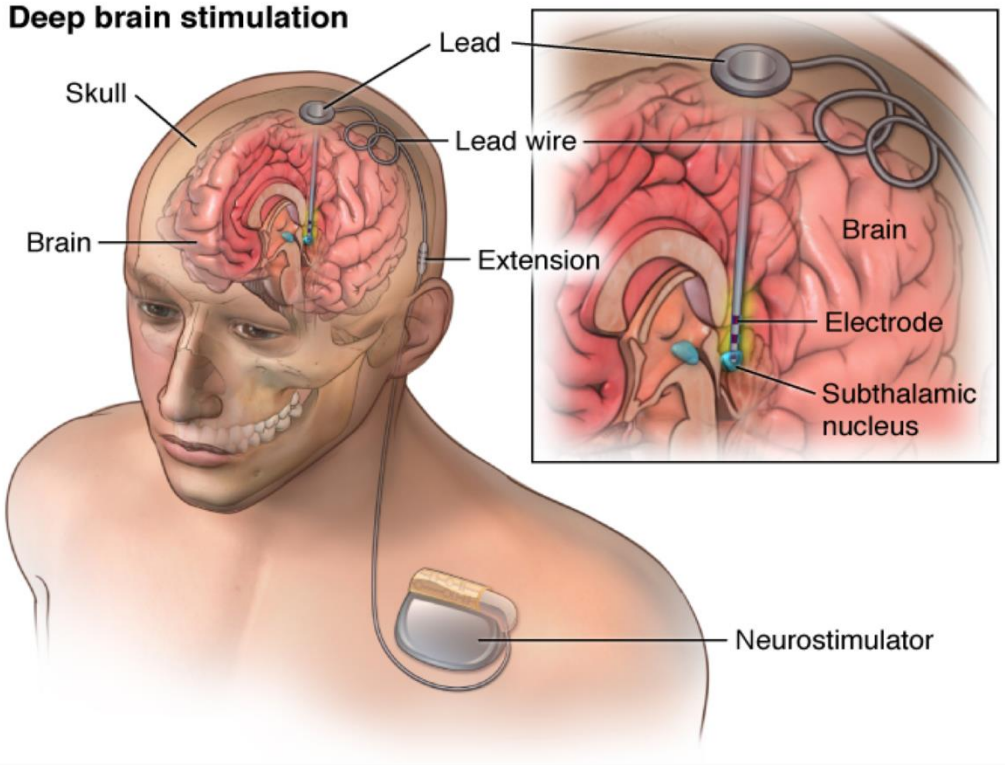


Uncertainty visualization
(Vortex core position probabilities)

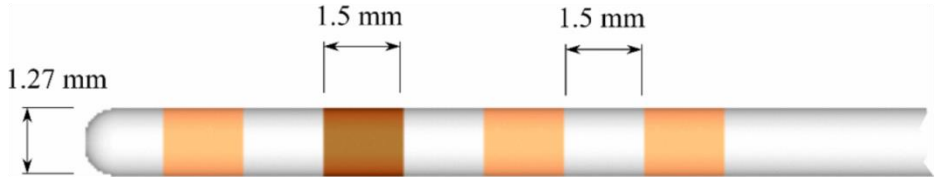
[Athawale et al., IEEE TVCG, 2025]

Uncertainty Visualization of Domain-Specific Data

Deep Brain Stimulation (DBS)



Medtronic DBS electrode Mo. 3387

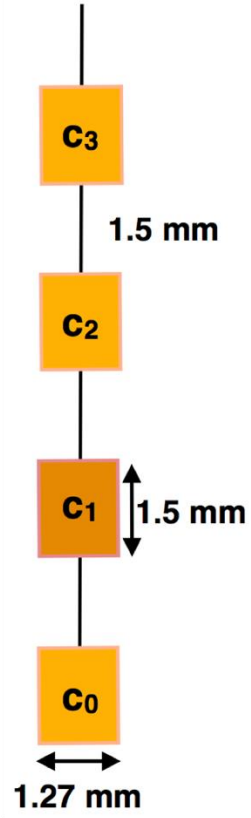


Voltage: 1-5 V
Frequency: 120-185 Hz
Pulse width: 60-200 μs
Contacts: Cathode(-)/Anode(+)/.Off

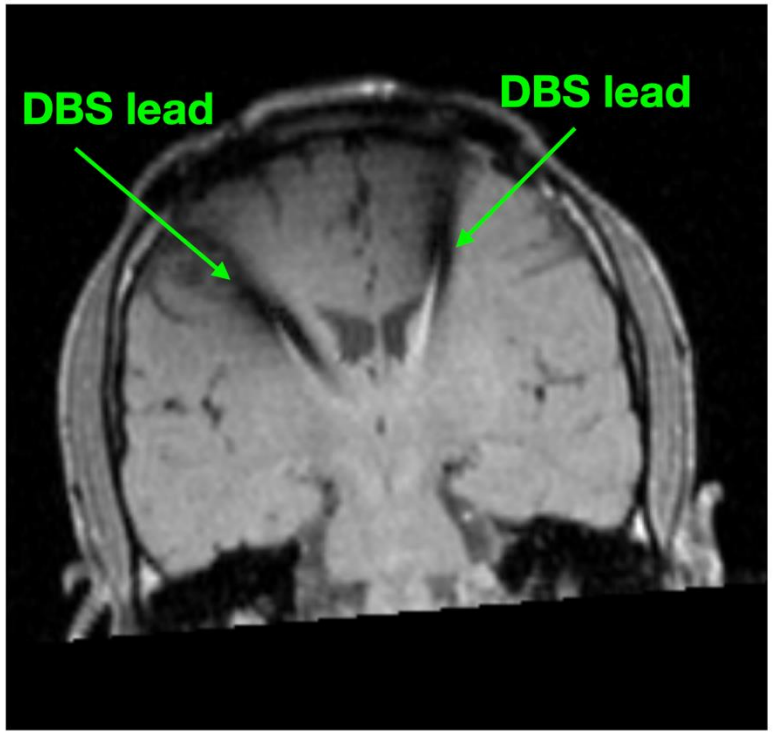
Knowledge of precise electrode positions in the patient brain is essential in order to set optimal patient-specific stimulation pattern.

Patient Head Image with Implanted Electrodes

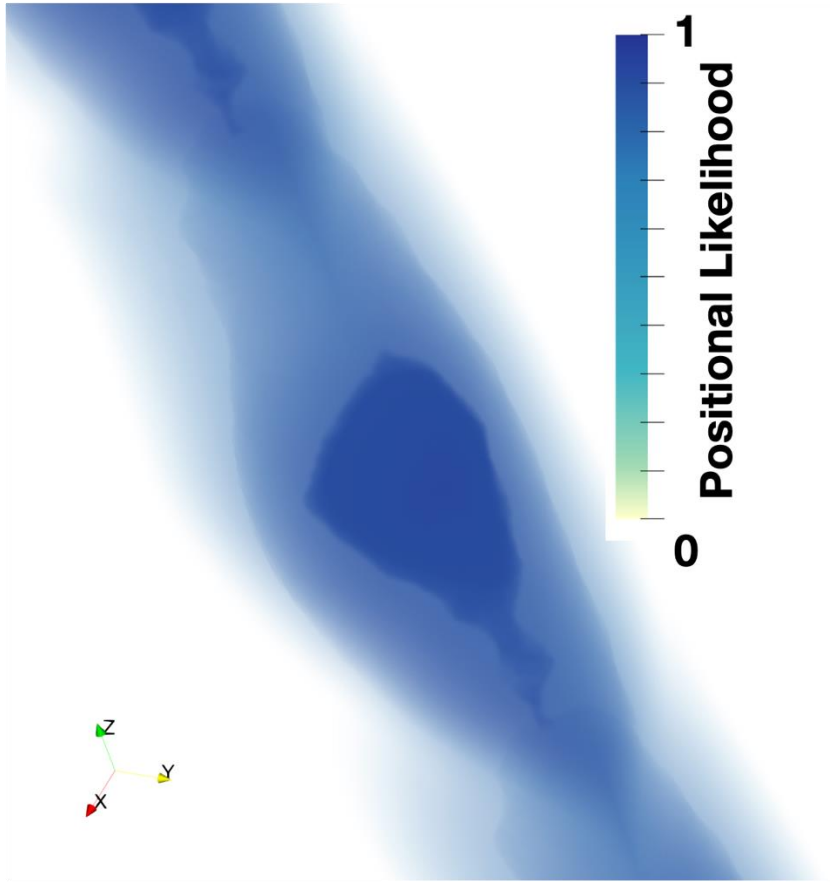
DBS lead schematic



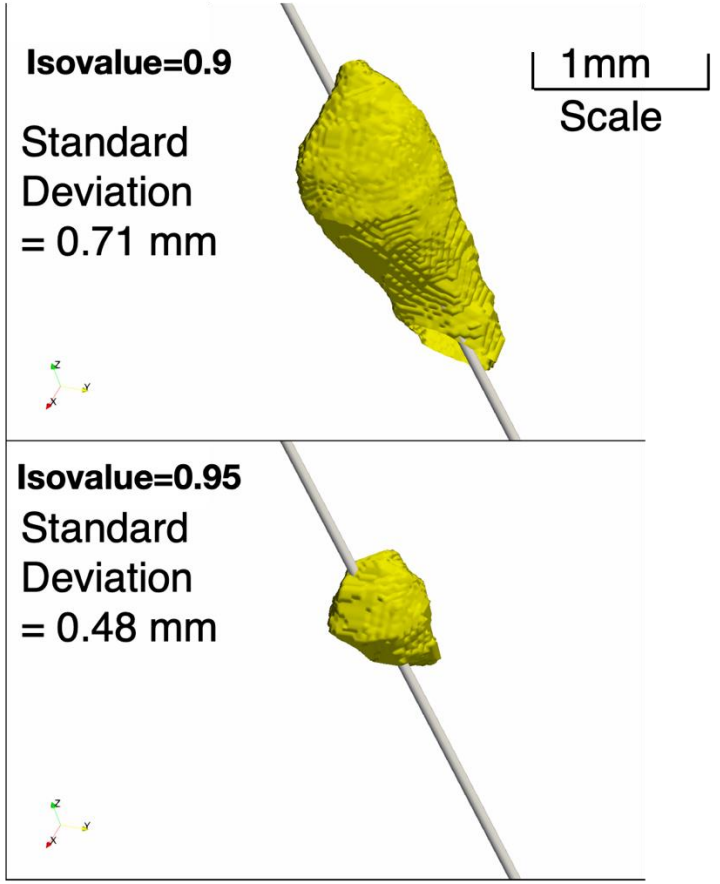
Post-surgery MRI to capture electrode positions



Uncertainty Visualization of Implanted Electrodes



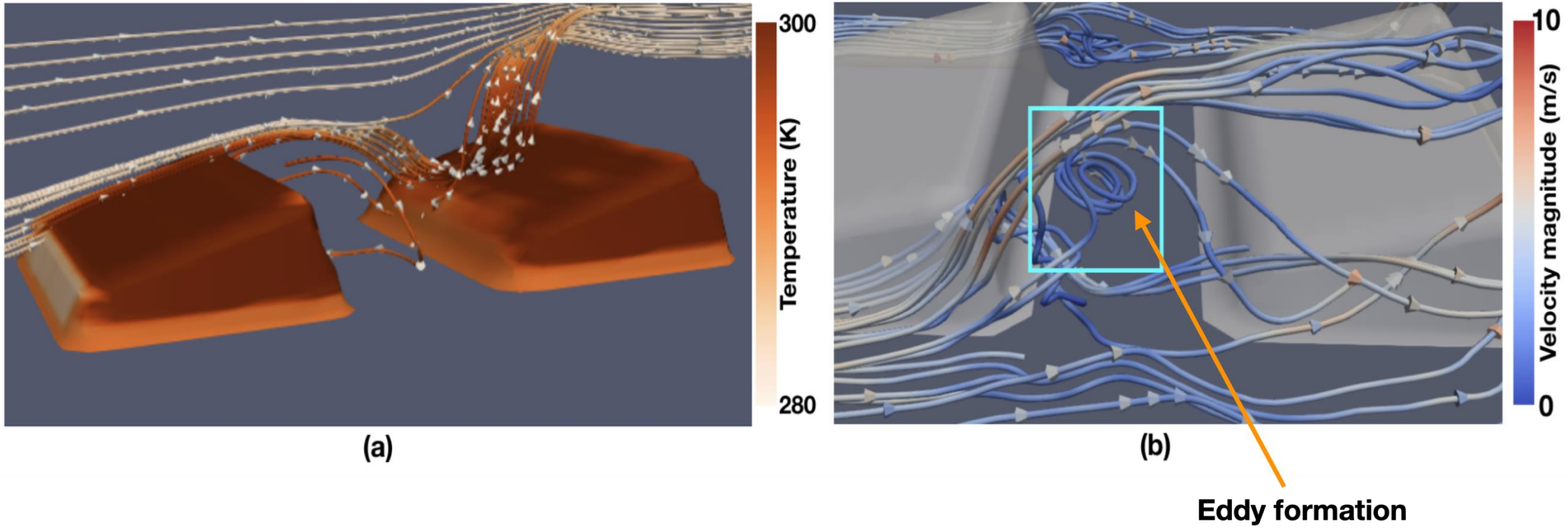
The volume visualization



The confidence visualization

[Athawale et al., 2019]

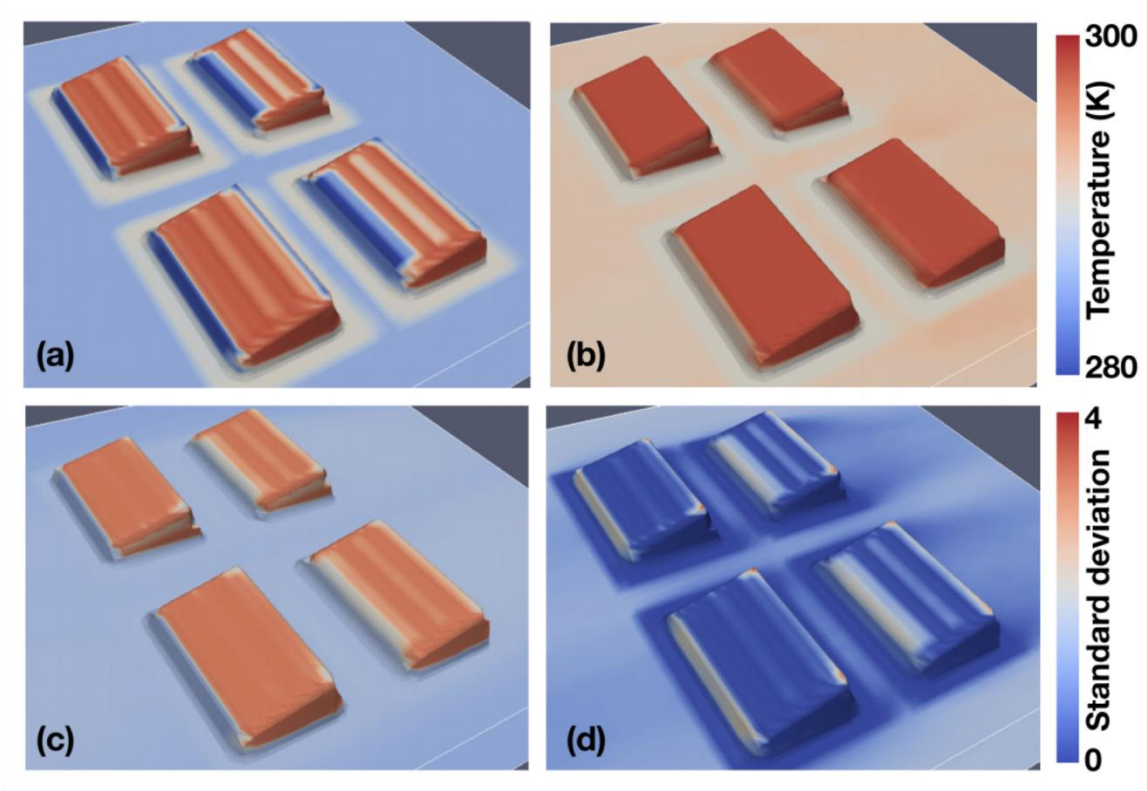
Wind Flow Near Solar Panels



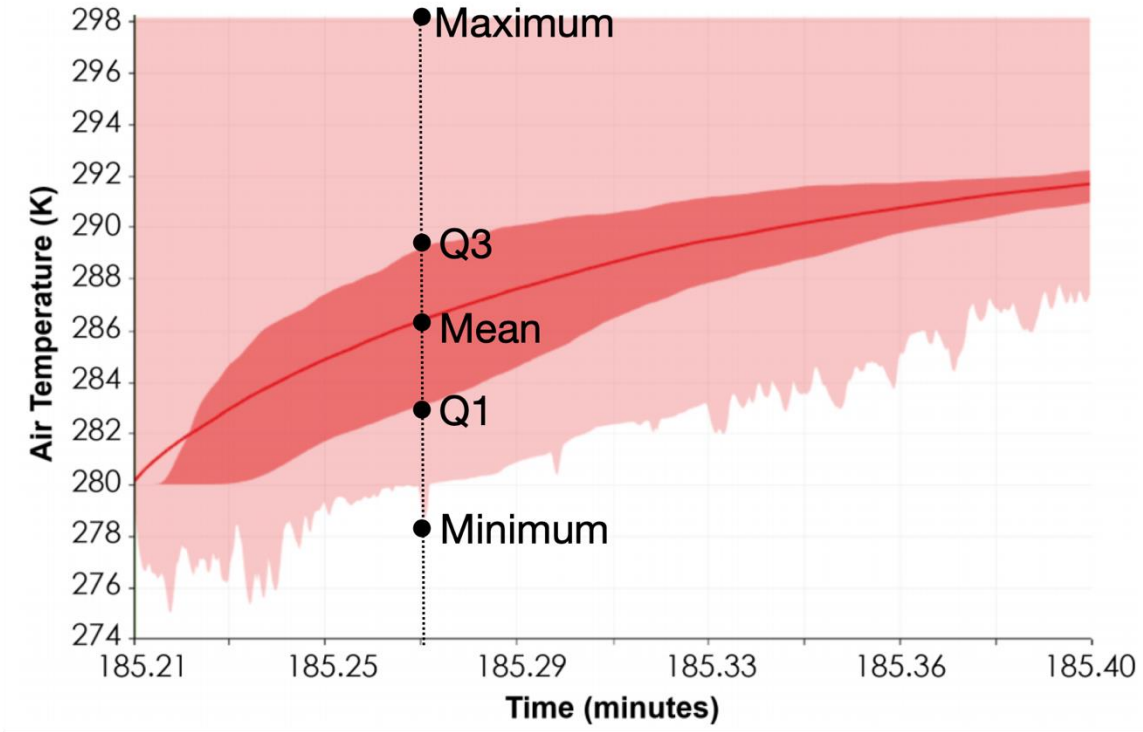
[Athawale, Staninslawski, Sane, and Johnson, 2021]

Visualization software: ParaView [Ahrens et al., 2005]

Temperature Variation Analysis

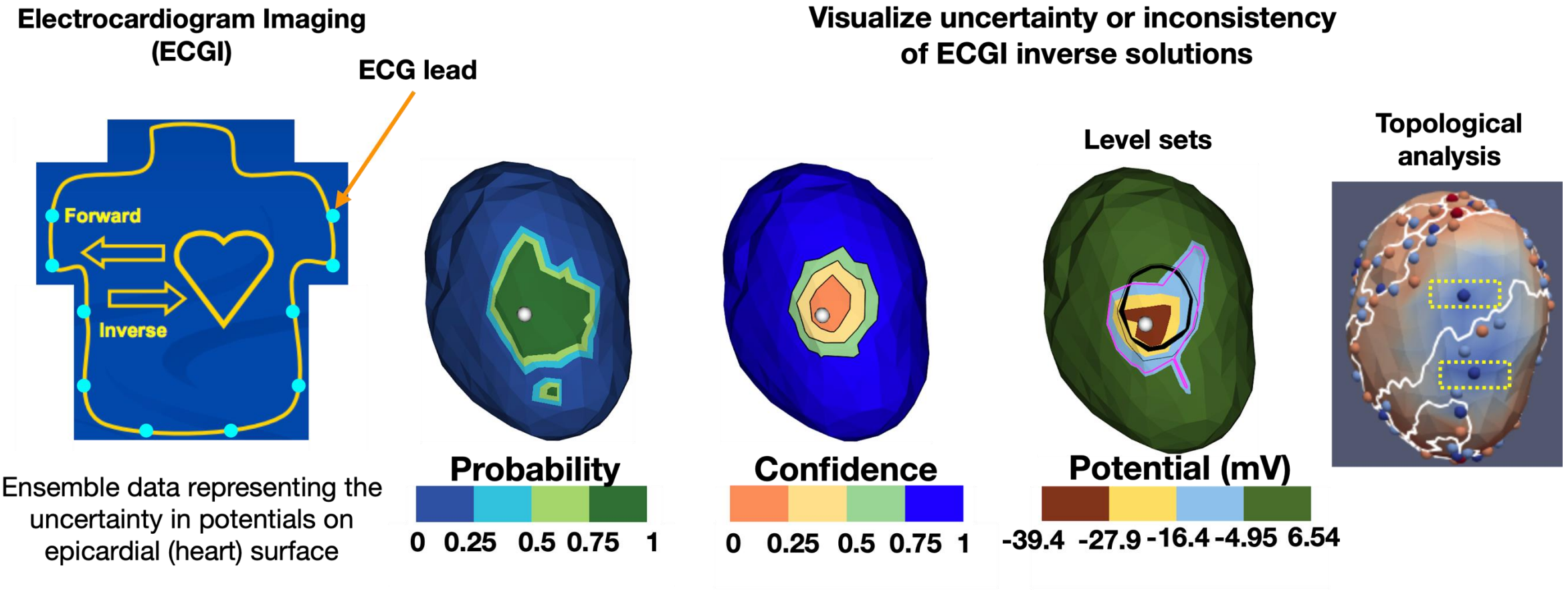


(a) Minimum, (b) Maximum, (c) Mean, (d) Standard Deviation



Quartile plot

Electrocardiographic Imaging (ECGI)



[Njeru, Athawale, France, Johnson, 2022]

Addressing Cost Overhead of Visualizing Uncertainty

Addressing Cost Overhead of Visualizing Uncertainty

EUROVIS 2024/ C. Tominski, M. Waldner, and B. Wang *Short Paper*

Data-Driven Computation of Probabilistic Marching Cubes for Efficient Visualization of Level-Set Uncertainty

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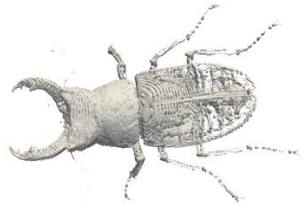
[2]Scientific Computing and Imaging Institute, University of Utah, USA

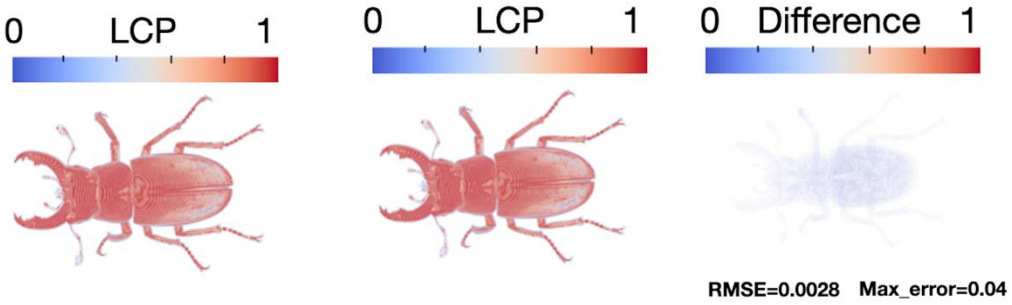
Abstract

Uncertainty visualization is an important emerging research area. Being able to visualize data uncertainty can help scientists improve trust in analysis and decision-making. However, visualizing uncertainty can add computational overhead, which can hinder the efficiency of analysis. In this paper, we propose novel data-driven techniques to reduce the computational requirements of the probabilistic marching cubes (PMC) algorithm. PMC is an uncertainty visualization technique that studies how uncertainty in data affects level-set positions. However, the algorithm relies on expensive Monte Carlo (MC) sampling for the multivariate Gaussian uncertainty model because no closed-form solution exists for the integration of multivariate Gaussian. In this work, we propose the eigenvalue decomposition and adaptive probability model techniques that reduce the amount of MC sampling in the original PMC algorithm and hence speed up the computations. Our proposed methods produce results that show negligible differences compared with the original PMC algorithm demonstrated through metrics, including root mean squared error, maximum error, and difference images. We demonstrate the performance and accuracy evaluations of our data-driven methods through experiments on synthetic and real datasets.

Data size = 680 MB



(a) Without uncertainty

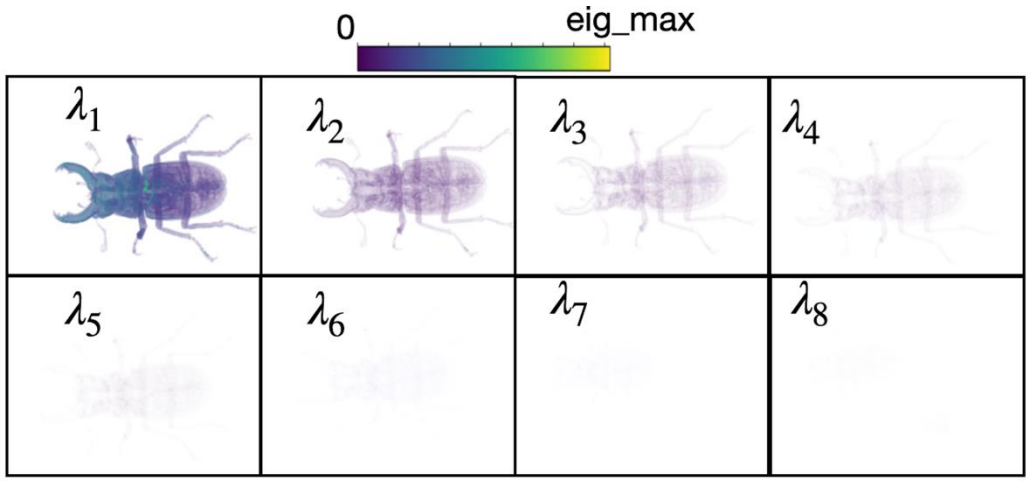


(b) PMC (Reference)

27.18 seconds

(c) PMC (Eigenvalue-based)
1.63X faster than the reference

16.72 seconds

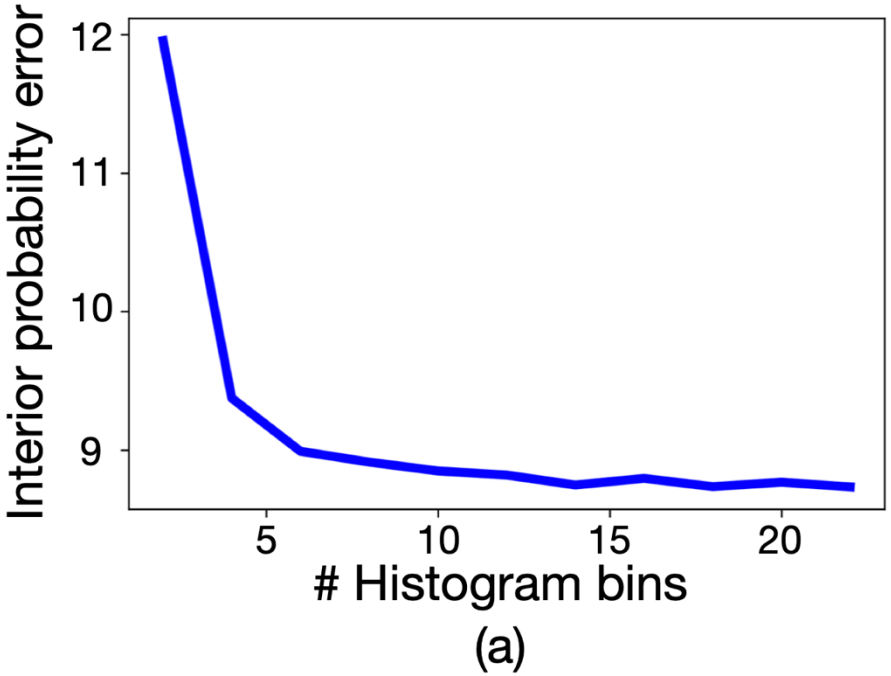


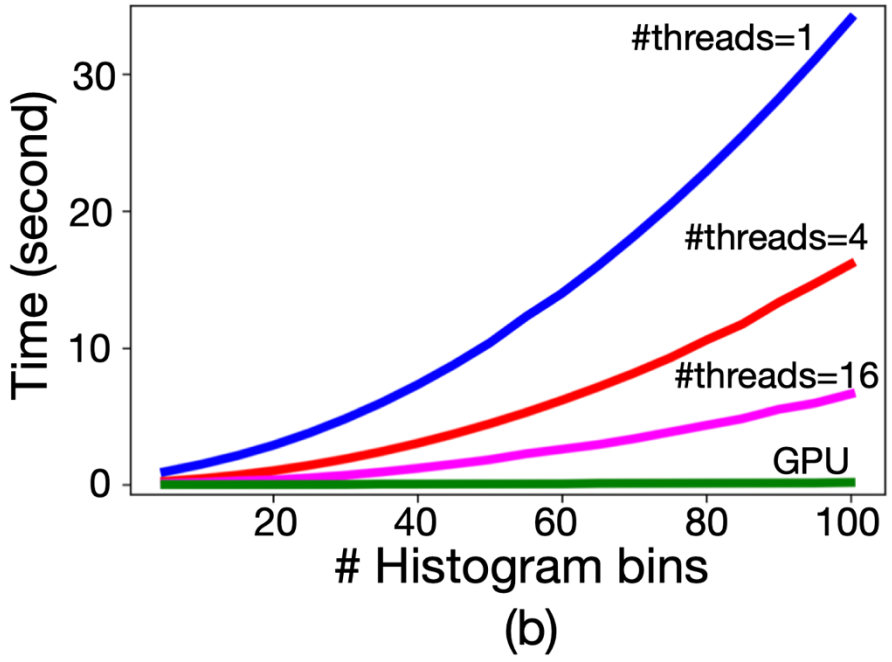
OAK RIDGE National Laboratory

Addressing Cost Overhead of Visualizing Uncertainty

Create scalable algorithms

The GPU CUDA (NVIDIA V100 graphics card) and C++ openMP (Power9 CPU) implementations





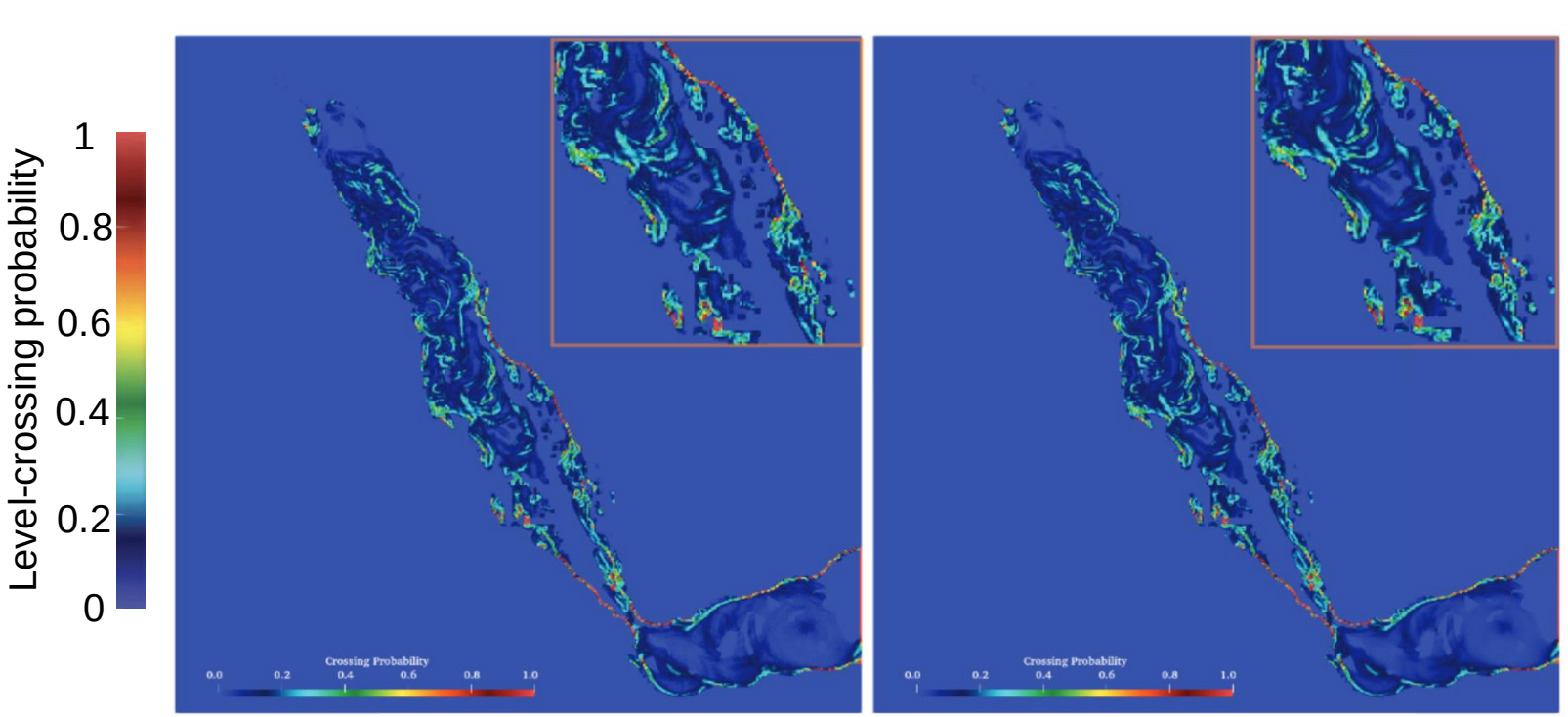
Accuracy (a) Vs. Timing (b) Curves

The computing resources are courtesy of the Summit Supercomputer at the Oak Ridge National Laboratory.

[Athawale et al., Fiber Uncertainty Visualization of Bivariate Data for Parametric and Nonparametric Noise Models, IEEE VIS 2022]

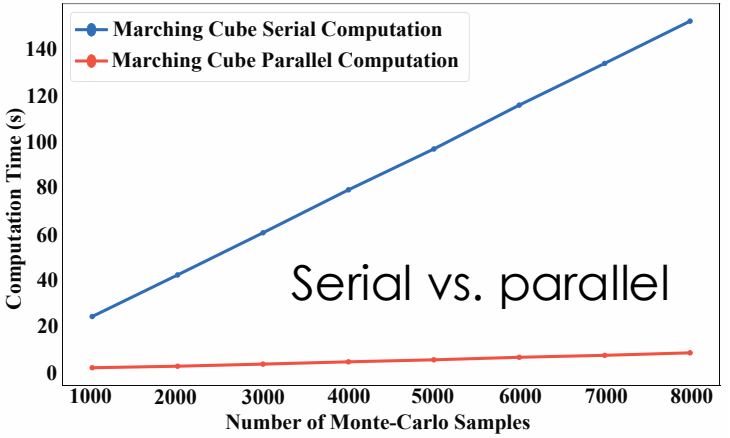
Future work: Machine Learning for Uncertainty Visualization

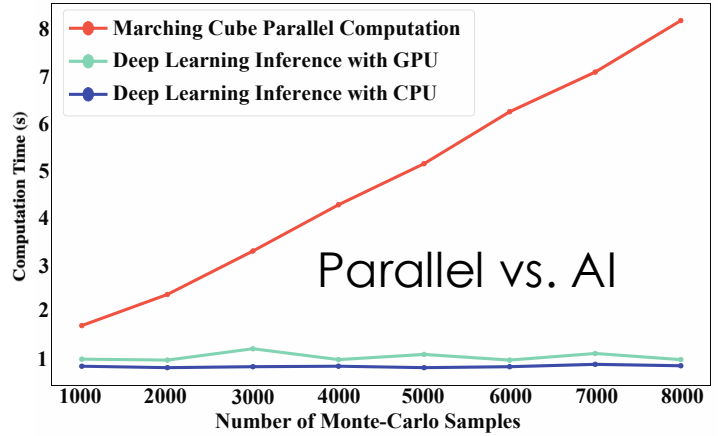
Learn uncertainties pertinent to isosurfaces from a bunch of time steps and predict uncertainty for future time steps



Monte Carlo

Machine Predicted (170X faster)





[M. Han, T. M. Athawale, D. Pugmire, and C. R. Johnson, IEEE VIS 2022 short papers]

Open Research Challenges

- Theoretical research in uncertainty visualization for 2D/3D/high-dimensional data
- Devising uncertainty-aware decision frameworks to perform optimal algorithmic decisions, reduce uncertainty, and enhance quality of visualizations
- Handling cost overhead of visualizing uncertainty
- Effective rendering of uncertainty
- Assessing perception, cognition, and decision-making quality under uncertainty

Opportunities at ORNL

Faculty and Undergraduate Students

Impacting students at a pivotal point in their education, WDTS undergraduate student programs strive to transform STEM learning into STEM careers. Working alongside researchers at the DOE national labs, student interns are not only able to imagine themselves as scientists — they become scientists. Visiting faculty expand their research horizons and invigorate their STEM teaching through new collaborations.

- Science Undergraduate Laboratory Internships (SULI)
- Community College Internships (CCI)
- Visiting Faculty Program (VFP)

Graduate Students

Graduate students can further advance their doctoral thesis research by accessing cutting-edge instrumentation and expertise at DOE national laboratories. Students become scientists in residence, collaborating with national lab scientists and engineers to answer their most challenging research questions and establishing a one-of-a-kind network for their future careers.

- Office of Science Graduate Student Research (SCGSR)

Frontier (currently, 2nd fastest supercomputer)

- The first supercomputer to break exascale barrier!
- Frontier uses 9,472 AMD Epyc 7713 "Trento" 64 core 2 GHz CPUs (606,208 cores) and 37,888 Instinct MI250X GPUs (8,335,360 cores).
- Consumes around 21 megawatts (MW) (which is equivalent to the power needed for 15,000 single-family homes),

Thank you!

This research used resources of the Oak Ridge Leadership Computing Facility at the Oak Ridge National Laboratory, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC05-00OR22725.

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