Fast HARDI Uncertainty Quantification and Visualization with Spherical Sampling

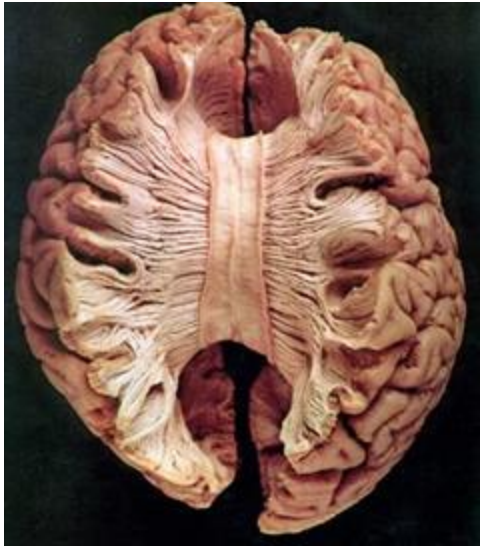
Tark Patel[1], Tushar M. Athawale[2], Timbwaoga A.J. Ouermi[1], Chris R. Johnson[1]

1 – Scientific Computing & Imaging Institute, Utah, USA
2 – Oak Ridge National Lab, Tennessee, USA

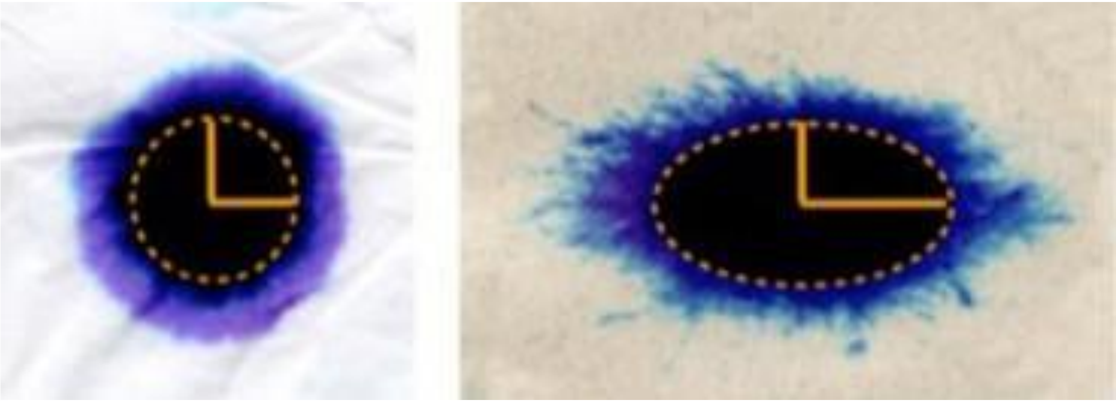
EuroVis 2025 Full Paper

EUROVIS 2025 LUXEMBOURG

Introduction



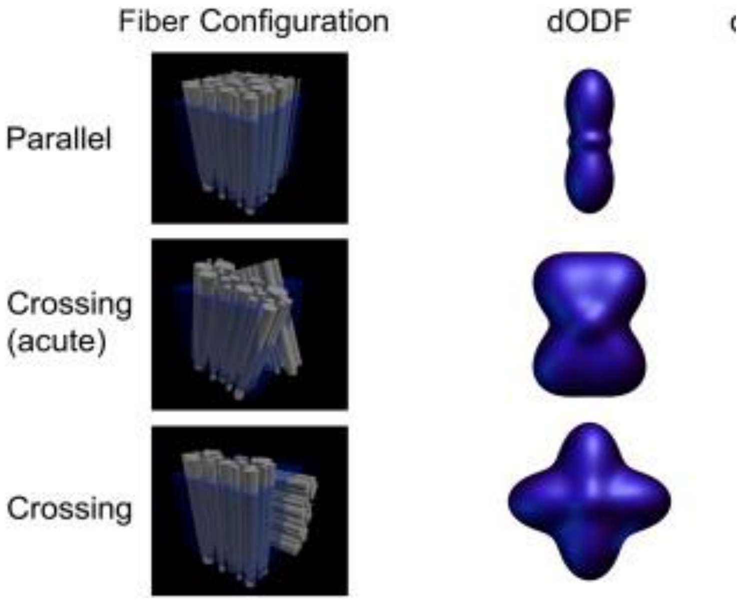
Neural tracts have anisotropic diffusion

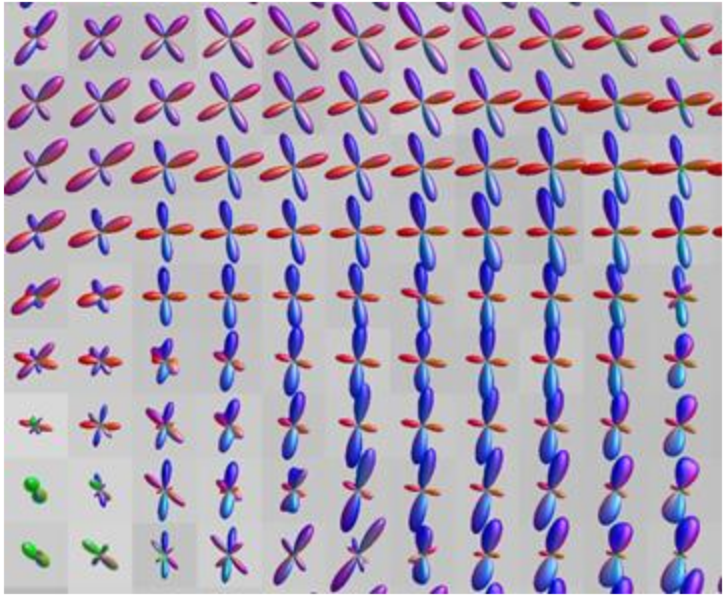


Drops of dye in Kleenex and newspaper show the diffusivity through Brownian Motion

mriquestions.com/iso-anisotropic-diffusion

Diffusion MRI





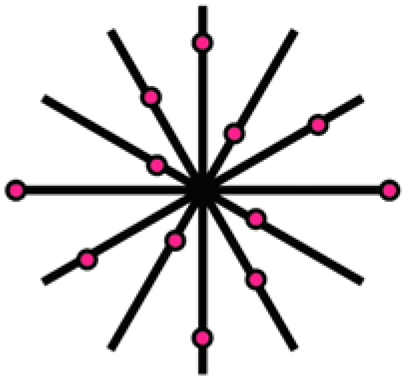
Diffusion MRI measures the diffusivity function per voxel

Directly visualized as glyphs

[Sotiropoulos & Zalesky 2017]

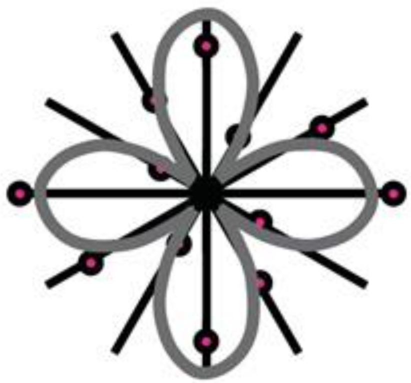
Measuring and Modeling

Discrete Measurements



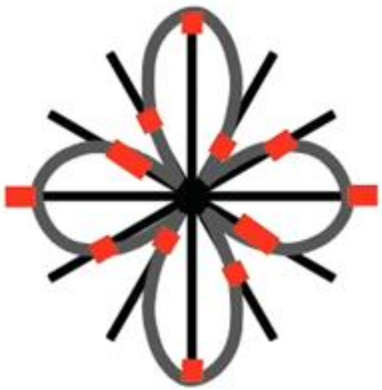
Diffusion magnitude along gradient vectors

Modeling



Estimate function from samples

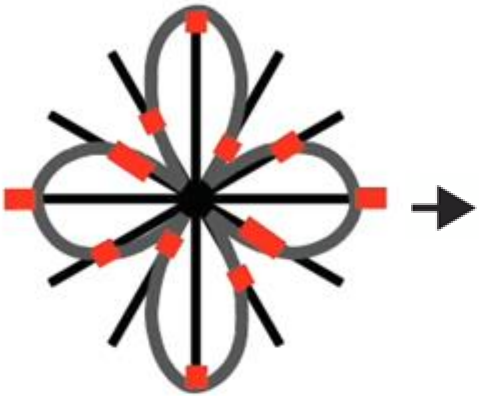
Compute Residuals



Red bars denote residual magnitude

Bootstrapping

Compute Residuals

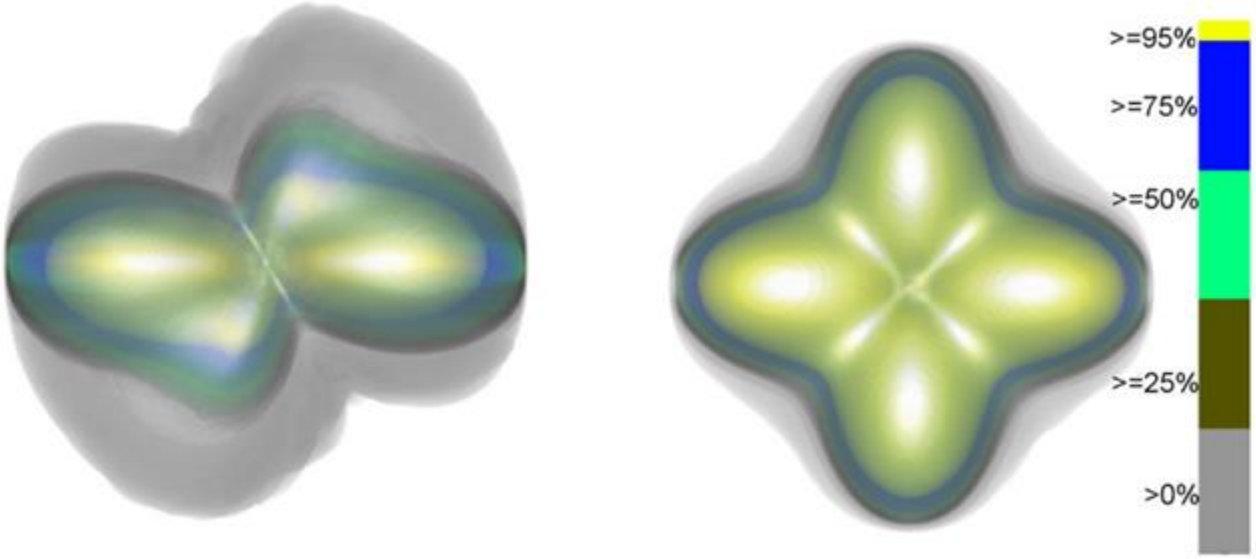


Bootstrapping

Red bars denote residual magnitude

- Bootstrapping simulates multiple acquisitions
- Each simulation randomly perturbed by residuals
- The ensemble encodes uncertainty

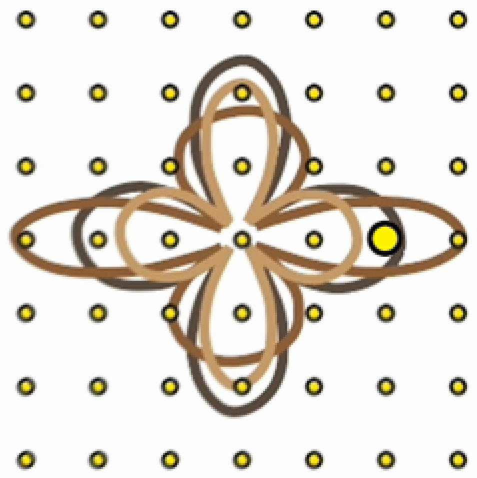
Shape Inclusion Probability



- Directly shows the variation of the bootstrap ensemble
- High cost to compute, store, and render

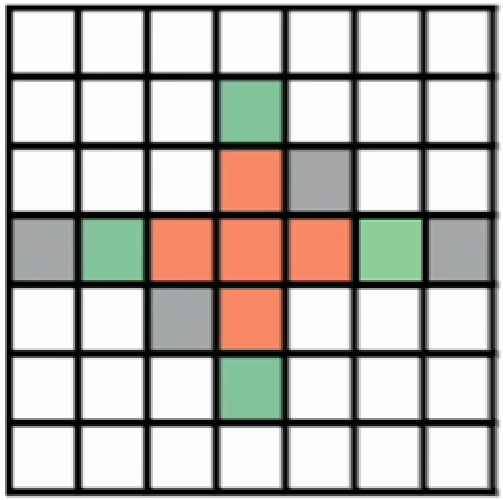
Volume Sampling

- Samples SIP function on structured grid
- Entire ensemble is evaluated to compute one voxel



Yellow dots denote sampling points

[out in in] = 0.67
SIP



Volume rendered with transfer function

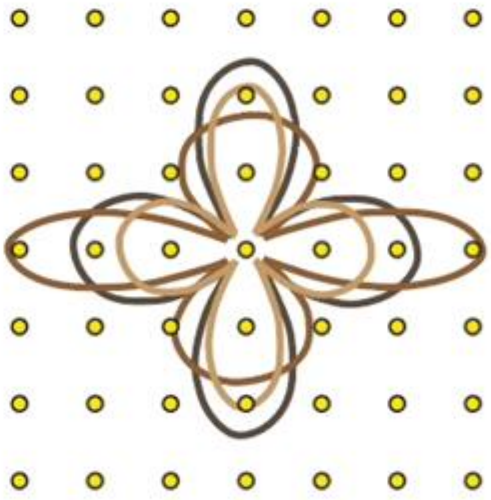
Our Contributions

EUROVIS 2025
LUXEMBOURG

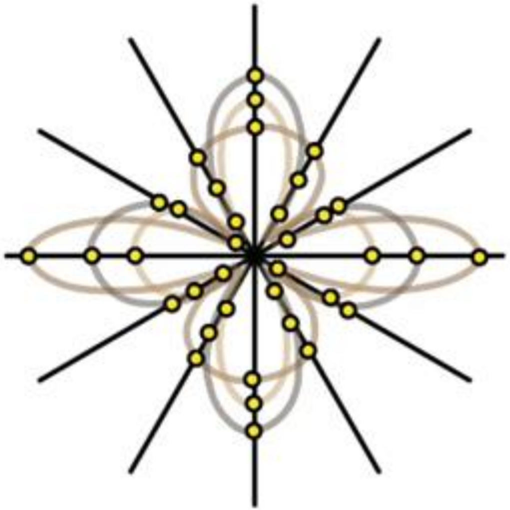
Volume Sampling vs Spherical Sampling

- Evaluates SIP values directly at boundaries
- Needs much less samples

Volume Sampling

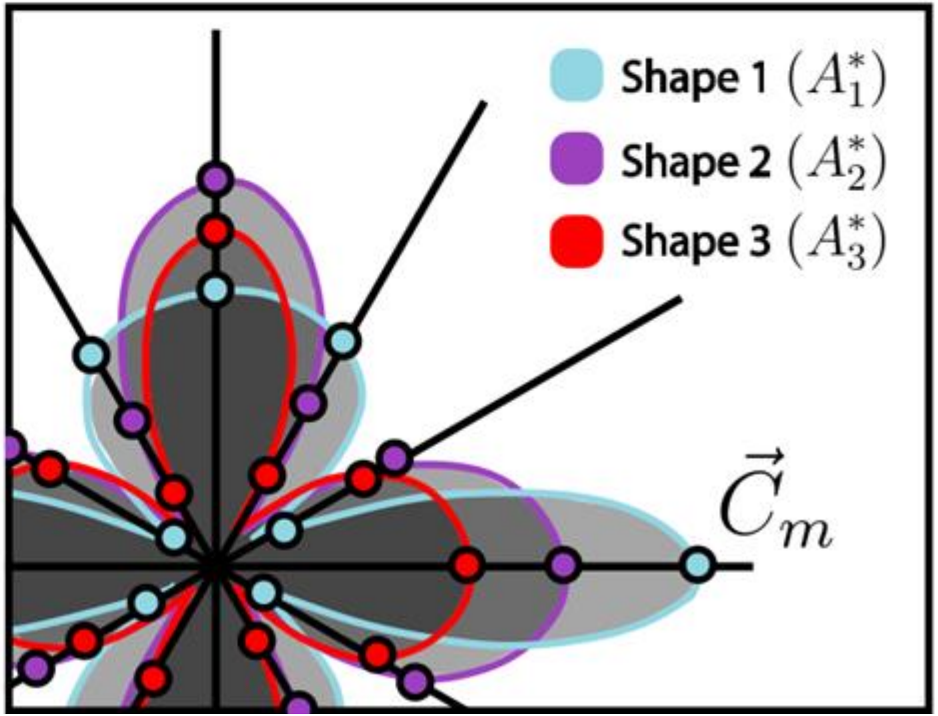


Spherical Sampling



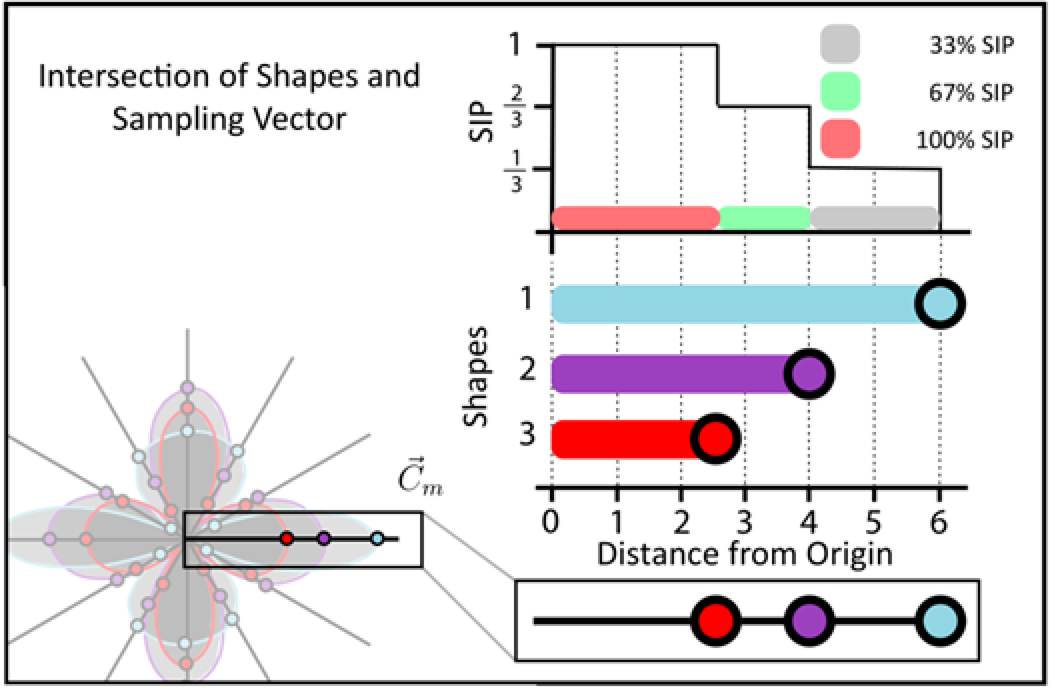
Spherical Sampling

- Sampling vectors are roughly distributed evenly
- Each shape intersects a vector exactly twice
- Each shape is evaluated once per sampling vector



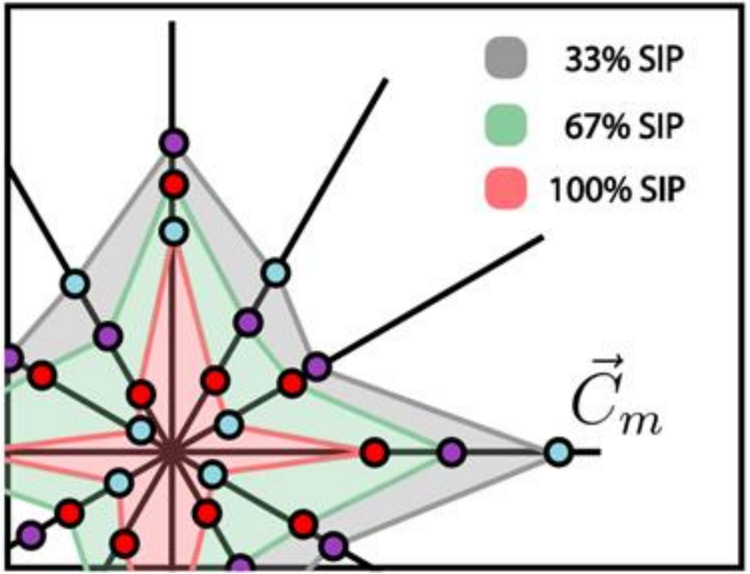
Spherical Sampling

- SIP function changes at vertices
- Sorting each vector’s samples gives isolevels in order
- Isosurfaces easily extracted from array access (Ex. 2nd element of length 3 array corresponds to 67% SIP)

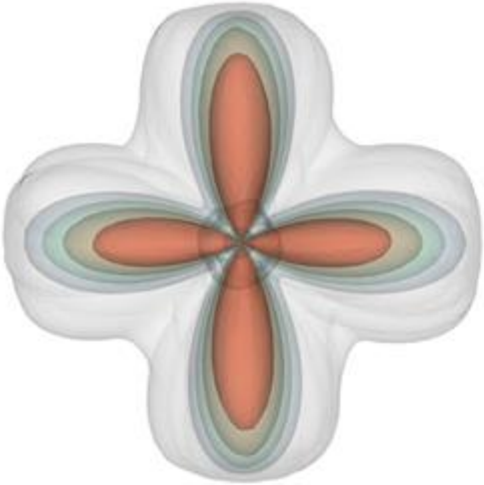


SIP Isosurface Extraction

- SIP isosurfaces are derived from the shapes' vertices
- All isolevels are computed simultaneously



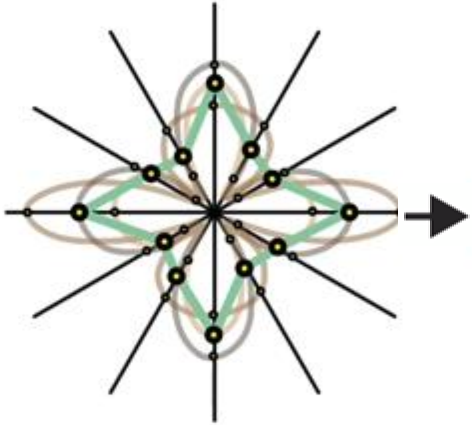
Mesh Rendering



SIP Modeling

- Each isosurface is modeled
- Modeling requires much less samples
- Reduces memory
- Enables ray tracing

Spherical Sampling



Single isosurface

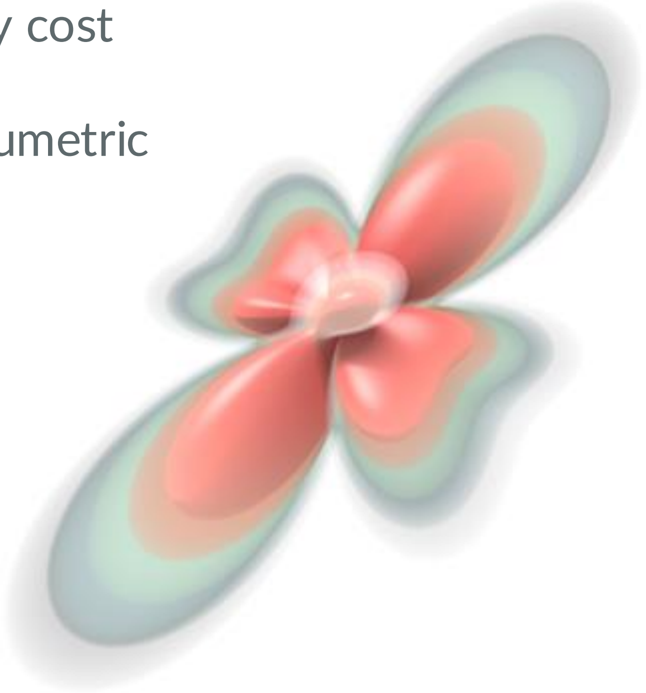
Modeling

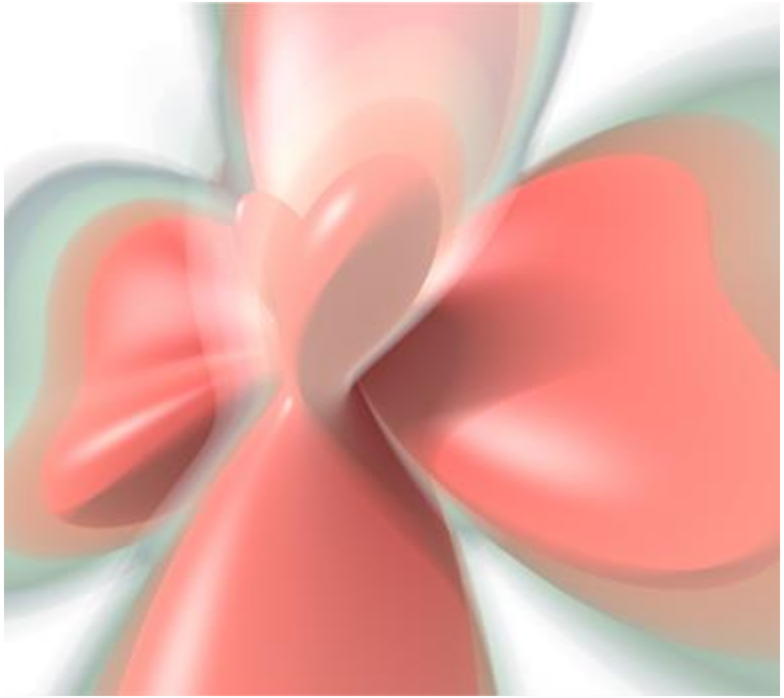
Represented in SH basis

Ray Tracing

Ray Tracing

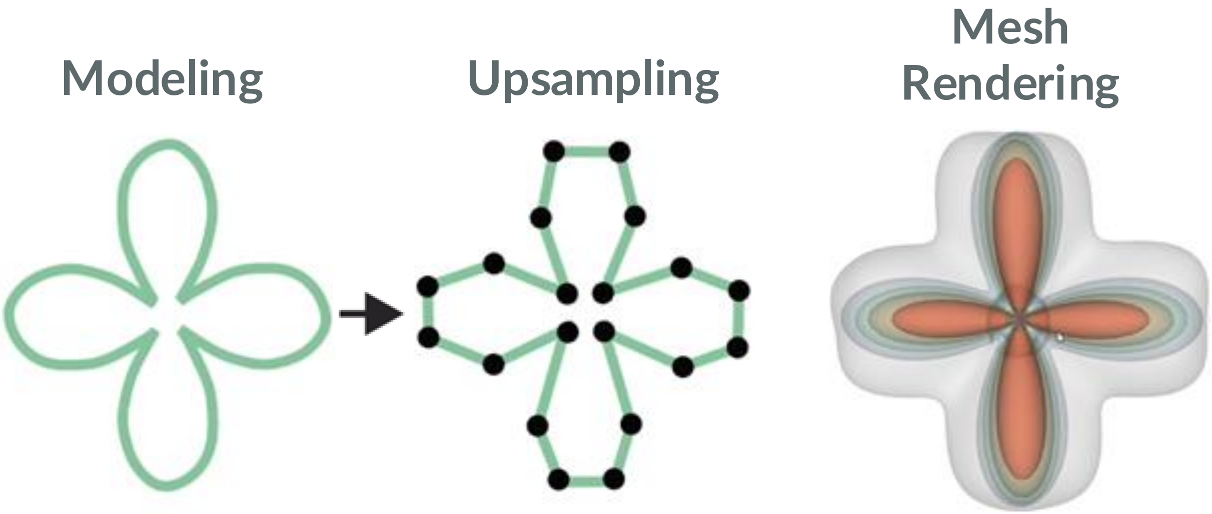
- Low memory cost
- Multiple volumetric regions





SIP Upsampling

- Modeling allows efficient upsampling
- Quickly creates high resolution meshes
- Triangle meshes are easy to visualize



Black dots are vertices of upsampled isosurface

Evaluation

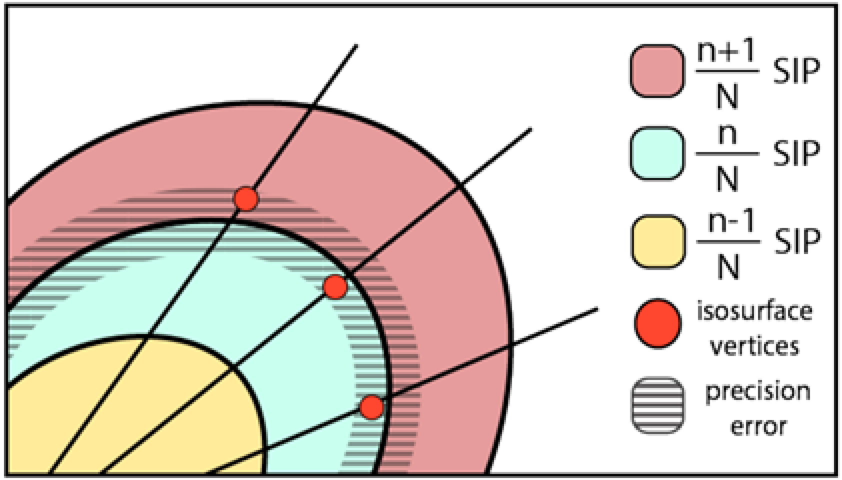
EUROVIS 2025
LUXEMBOURG

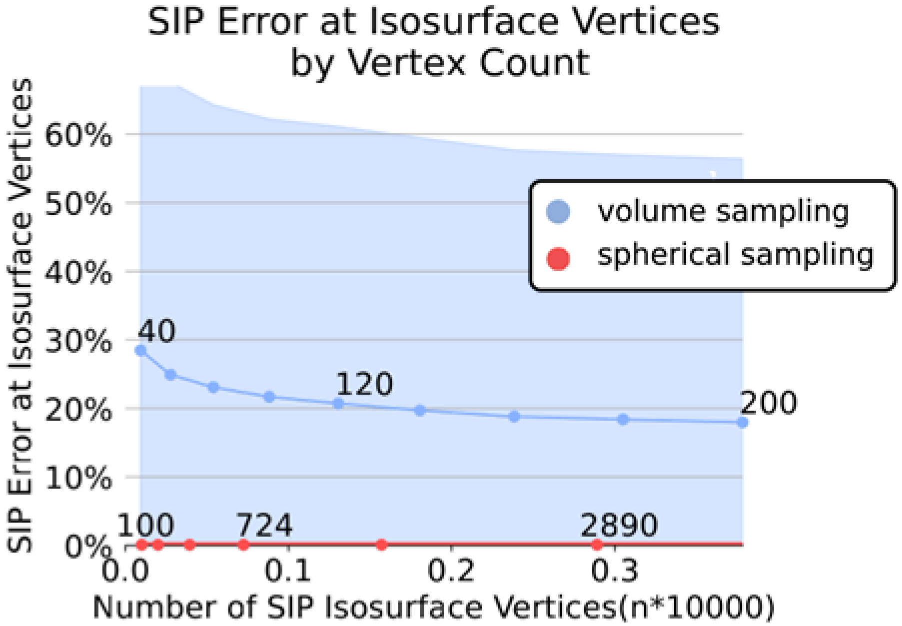
Speed

- Up to 8164X faster
- Previous method can take days to months
- New methods are usable in clinically feasible times

SIP Interval Modeling	Single Voxel	Data Slice (81,106)
Volume ($R=100^3$)	2 min	12 days
Volume ($R=200^3$)	12 min	2 months
Spherical ($M = 500$)	114 ms	12 min
Spherical ($M = 1{,}000$)	215 ms	24 min
Upsampling ($SH = 4$)	31 ms	5 min
Upsampling ($SH = 8$)	85 ms	13 min

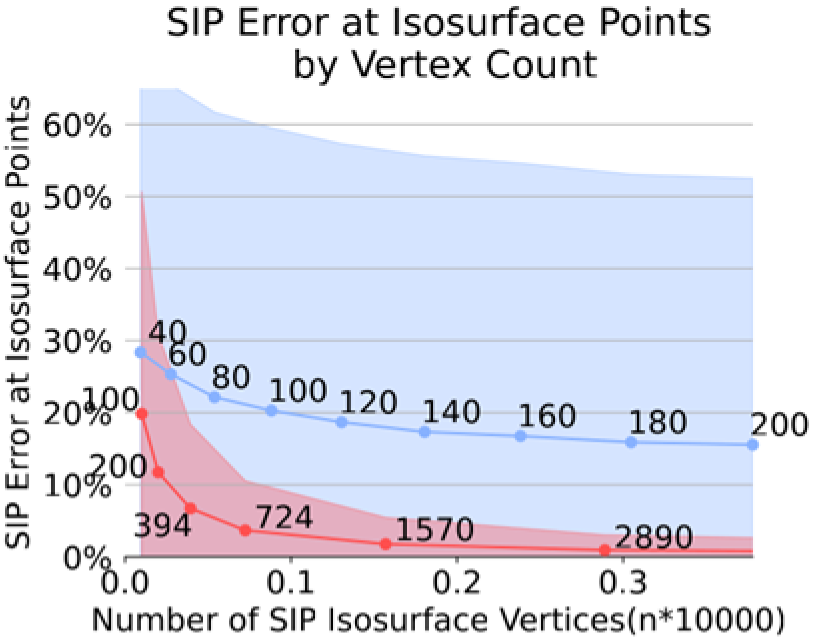
Accuracy

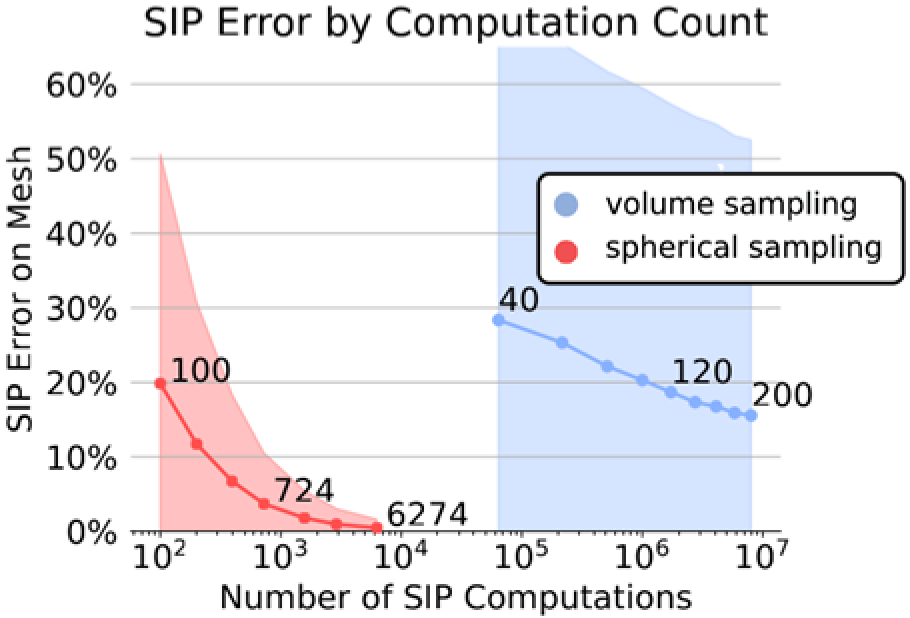




- Error is minimal at SIP boundaries
- Good choice for modeling

Accuracy





- Error of the mesh converges as resolution increases with respect to resolution (left) and compute time

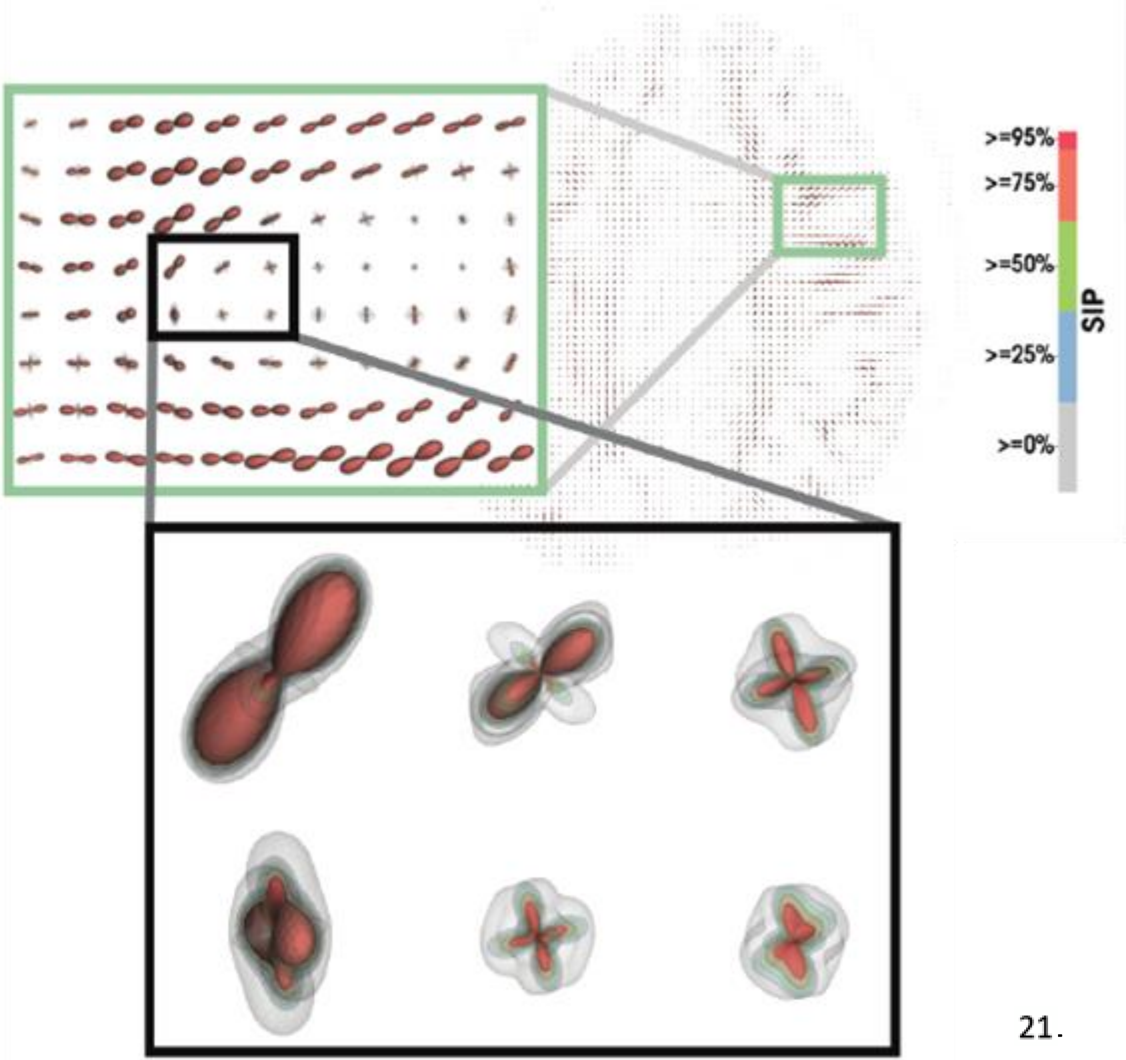
Memory

- Up to 37282x memory reduction
- Polygon mesh and model representation may alleviate storage constraints

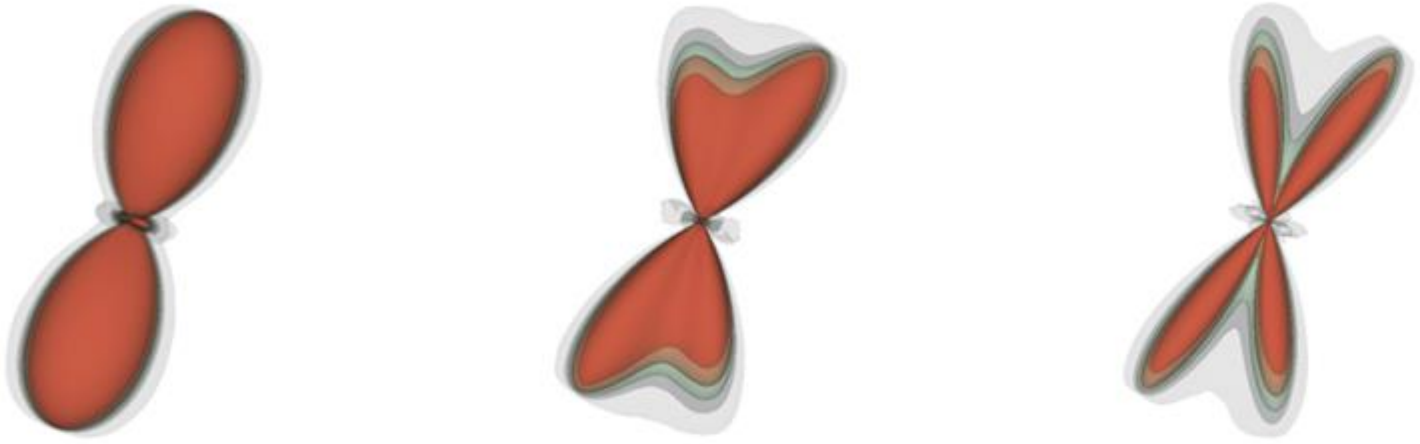
Technique	Single Voxel	Data Slice (81,106)
Volume (R=100^3)	4 MB	34 GB
Volume (R=200^3)	32 MB	268 GB
Polygon Mesh (M=500)	10 KB	84 MB
Polygon Mesh (M=1,000)	20 KB	168 MB
Polygon Mesh (M=10,000)	200 KB	2 GB
Model (SH=4)	300 B	3 MB
Model (SH=8)	900 B	8 MB

Brain Data

- The example is a slice (81x106) of the Stanford HARDI data set
- Computed in 13 minutes with upsampling
- Clinically feasible time



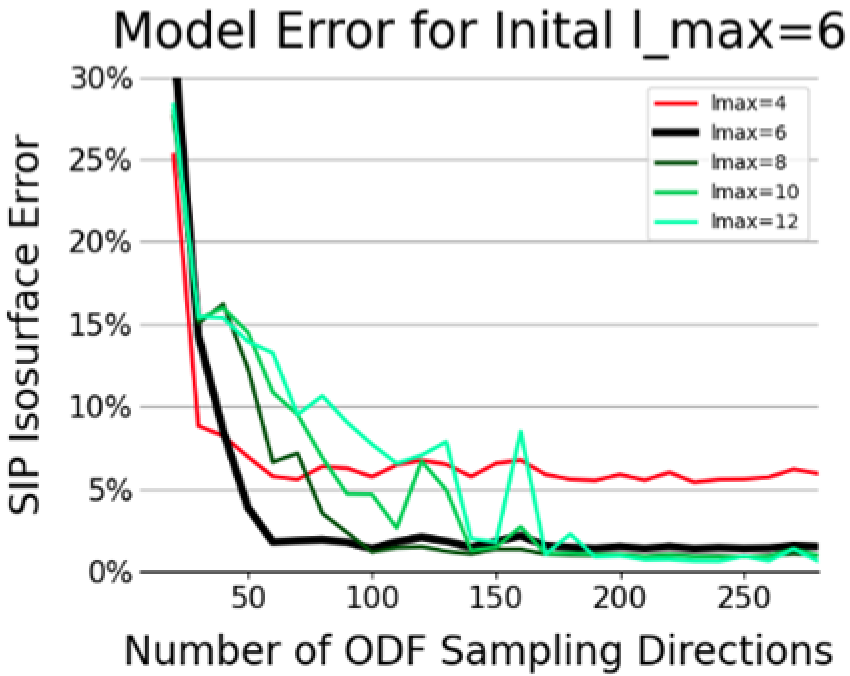
SH Degree & Discernibility

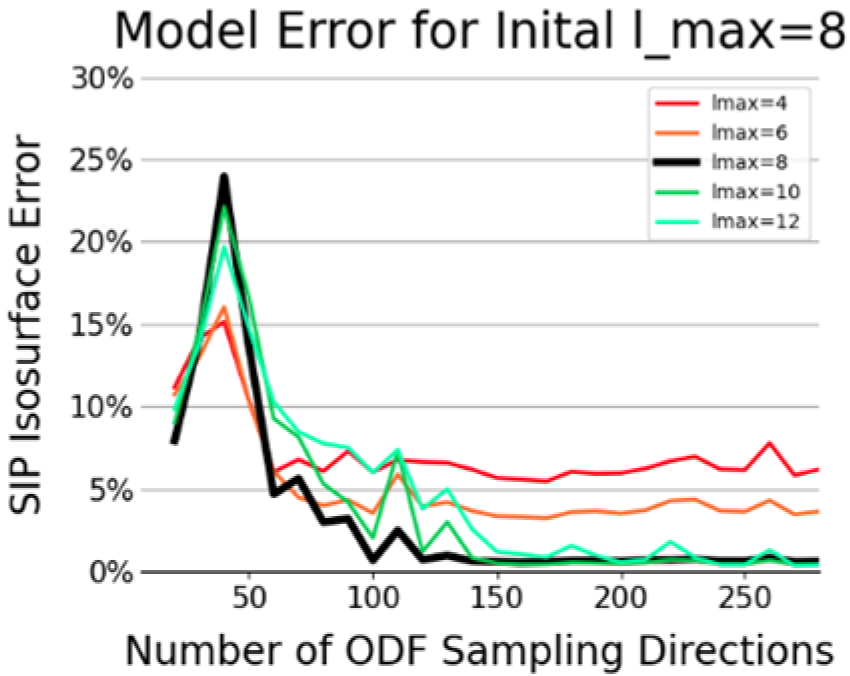


(a) $l_{max} = 4$ (b) $l_{max} = 8$ (c) $l_{max} = 12$

- Higher SH complexity of initial model discerns smaller angles

SIP Modeling Accuracy





- SIP Modeling error converges as samping vectors increase
- SIP model complexity must be greater or equal to initial model complexity

Future Work

- GPU acceleration
- Uncertainty-aware tractography
- Adaptive modeling complexity

Thanks for your attention


Tark
Patel


Tushar M.
Athawale


Timbwaoga A.J.
Ouermi (TAJO)


Chris R.
Johnson

Paper

Funded by U.S. Department of Energy (No. DE-AC05-00OR22725) and Intel Center of Excellence

tpat@sci.utah.edu