Reconstruction and Visualization of Fiber and Laminar Structure of the Human Heart

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Summary

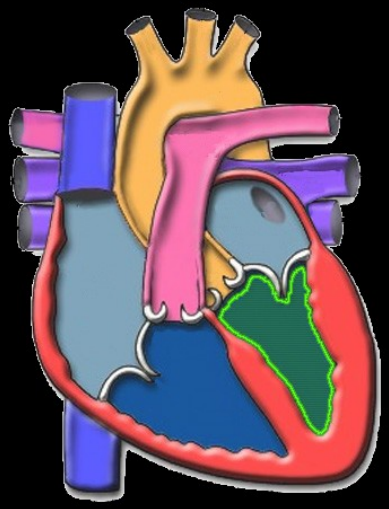
1. Structure of the heart
   - Geometry of the heart
   - Fiber Organisation
   - Sheet organization
2. Diffusion Tensor
   - Introduction
   - Role
   - Available Data
3. Visualization Methods
   - Color Encoding
   - Fiber Direction
   - Tensor Visualization
1. Fiber Tracking
   - Integration Step
   - Interpolation
   - Filtering
   - Sense of the propagation
   - Results
2. Sheet Structure
   - Method
   - Results
3. Conclusion

Summary

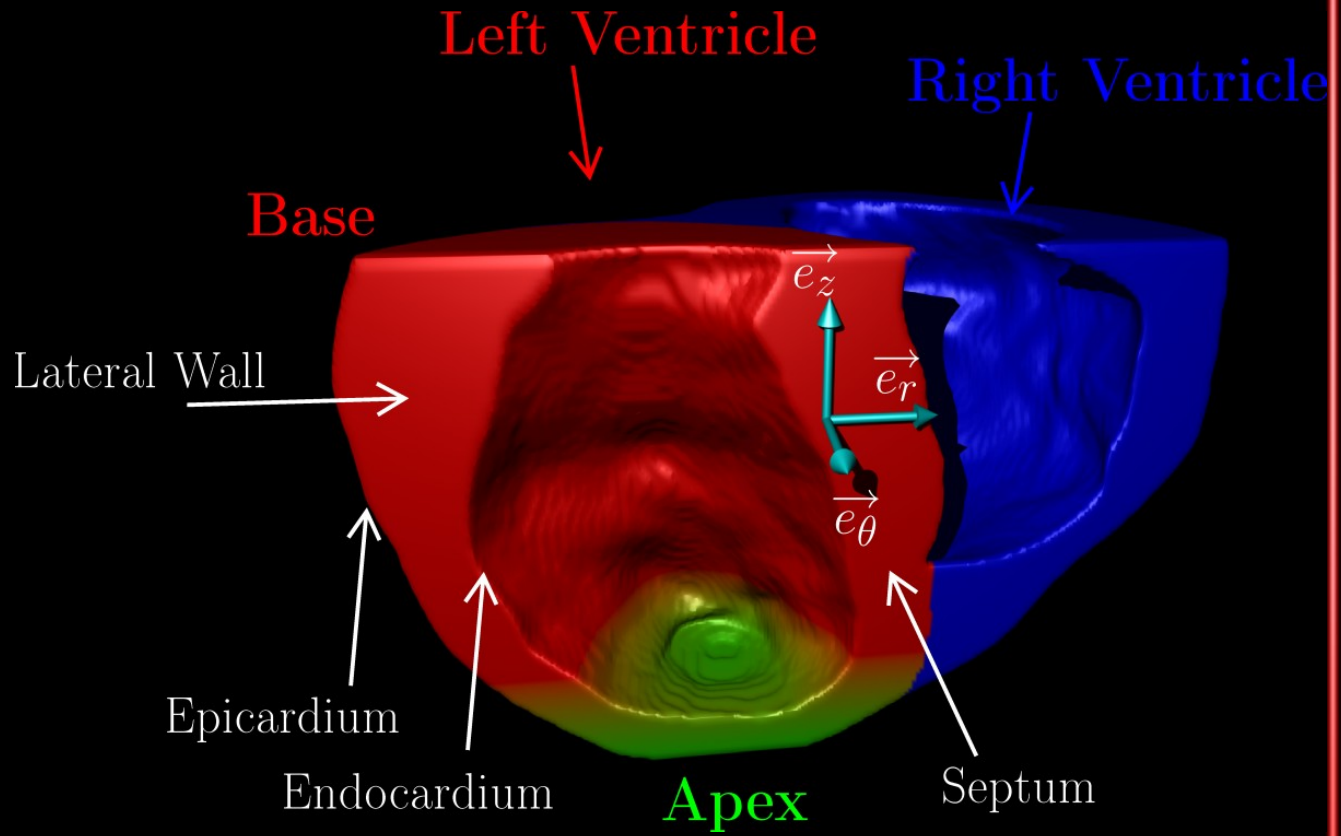
1. Structure of the heart
   - Geometry of the heart
   - Fiber Structure
     - General orientation
     - Physical Constitution
     - Spatial Arrangement
   - Sheet organization
     - Spatial Arrangement
     - Physical Constitution
   - Role of the study
2. Diffusion Tensor
3. Visualization Methods
4. Fiber Tracking
5. Sheet Structure
6. Conclusion

1. Structure of the heart

- **Geometry of the heart**
  - Approximate by a portion of ellipsoid

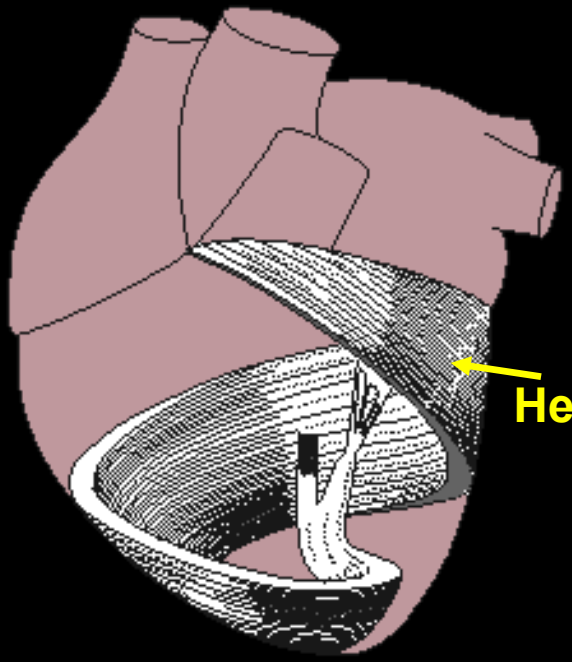


Texas Heart Institute :
http://www.tmc.edu/thi/anatomy.html

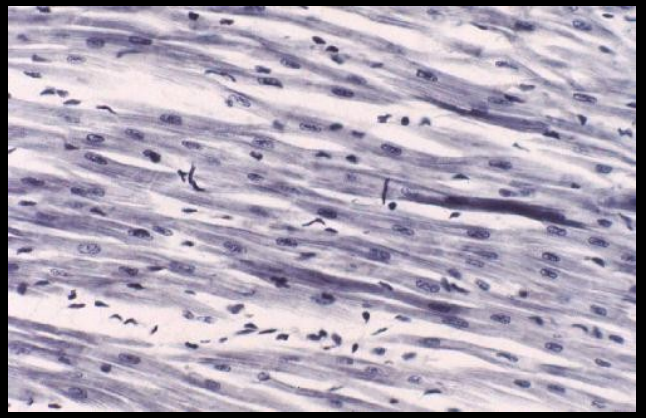


1. Structure of the heart

- **Fiber Structure**
  - General Orientation



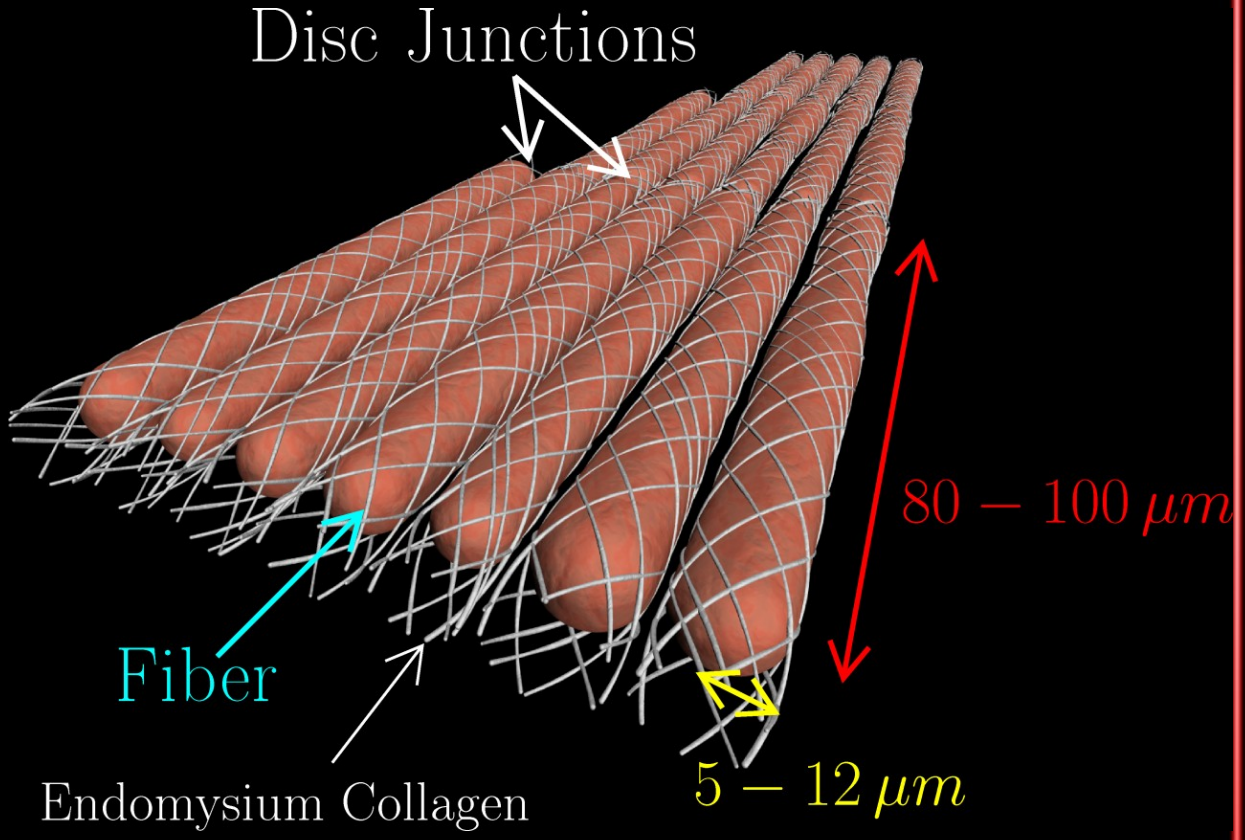
Microscopic view of the cells : myocytes



1. Structure of the heart

- **Fiber Structure**
  - **Physical Constitution**

Constitution of the fibers and myocardial Collagen :

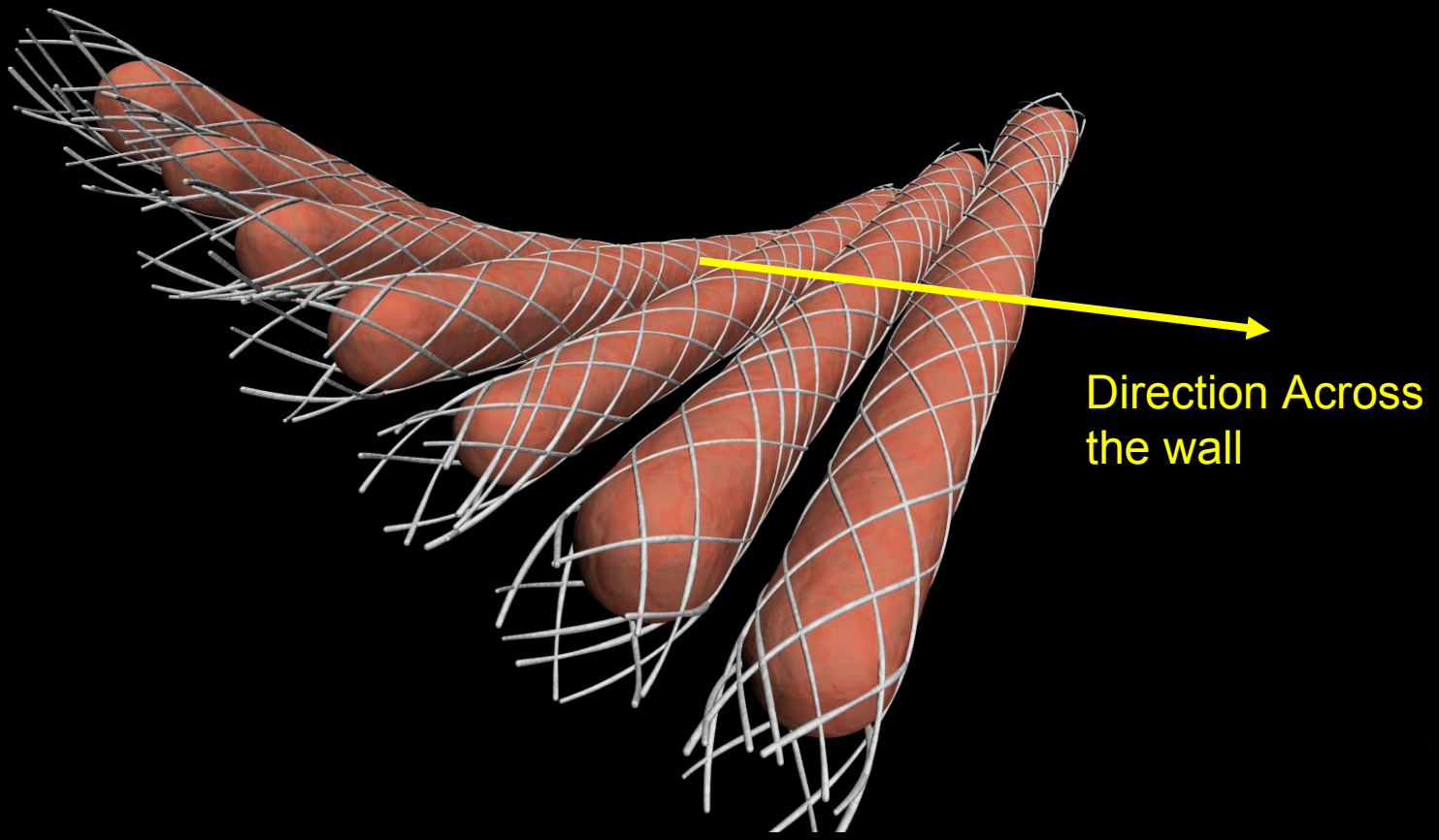


•Disc junctions : continuity of information between cells

•Role of Collagen : prevent slipage, rupture and overstretch. Mainly Type I and III (62%).

1. Structure of the heart

- **Fiber Structure**
  - Spatial Arrangement (I)

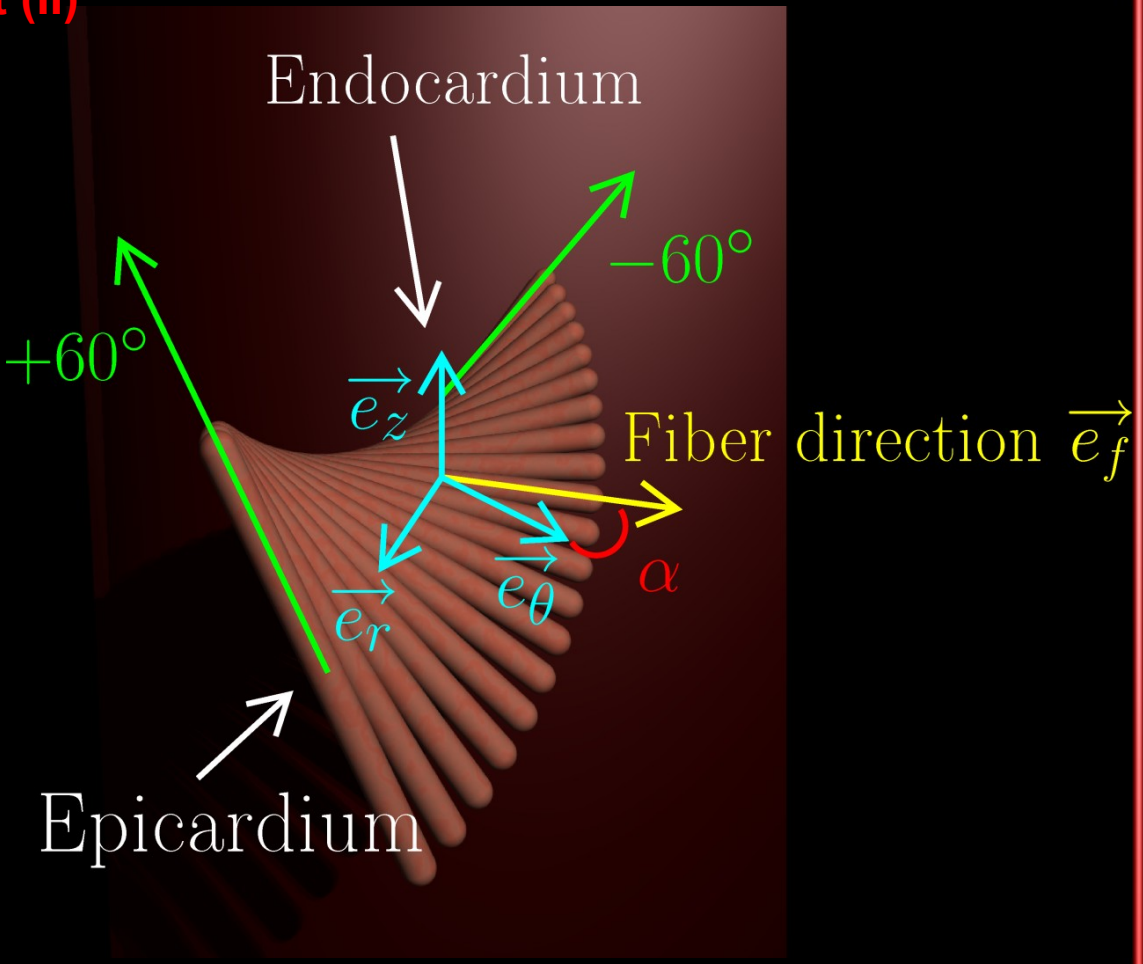


1. Structure of the heart

- **Fiber Structure**
  - Spatial Arrangement (II)

•Fiber direction changing from +60º (epicardium) to -60º (endocardium) across the wall

•Define fiber angle α



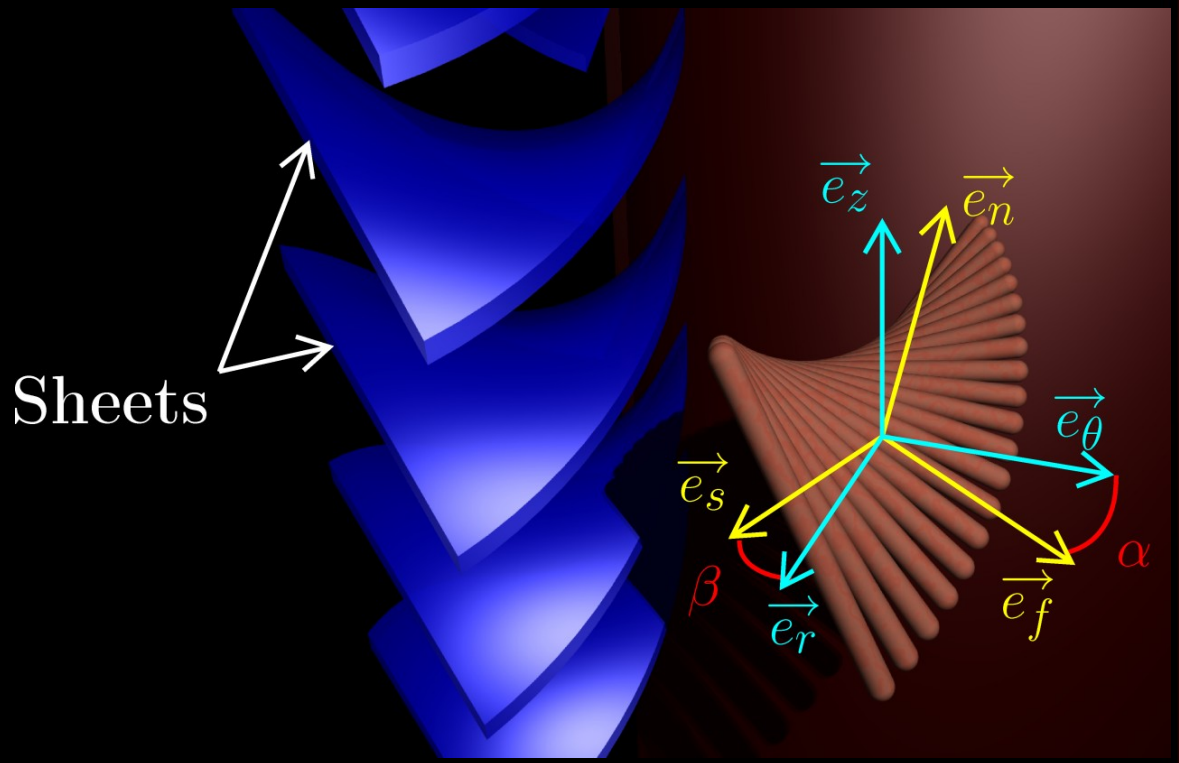
1. Structure of the heart

- **Sheet Structure**
  - **Spatial Arrangement**

Higher 3 Dimensional Structure

•Arrangement of fibers in Sheets stacked form apex to base

•Define a sheet angle β

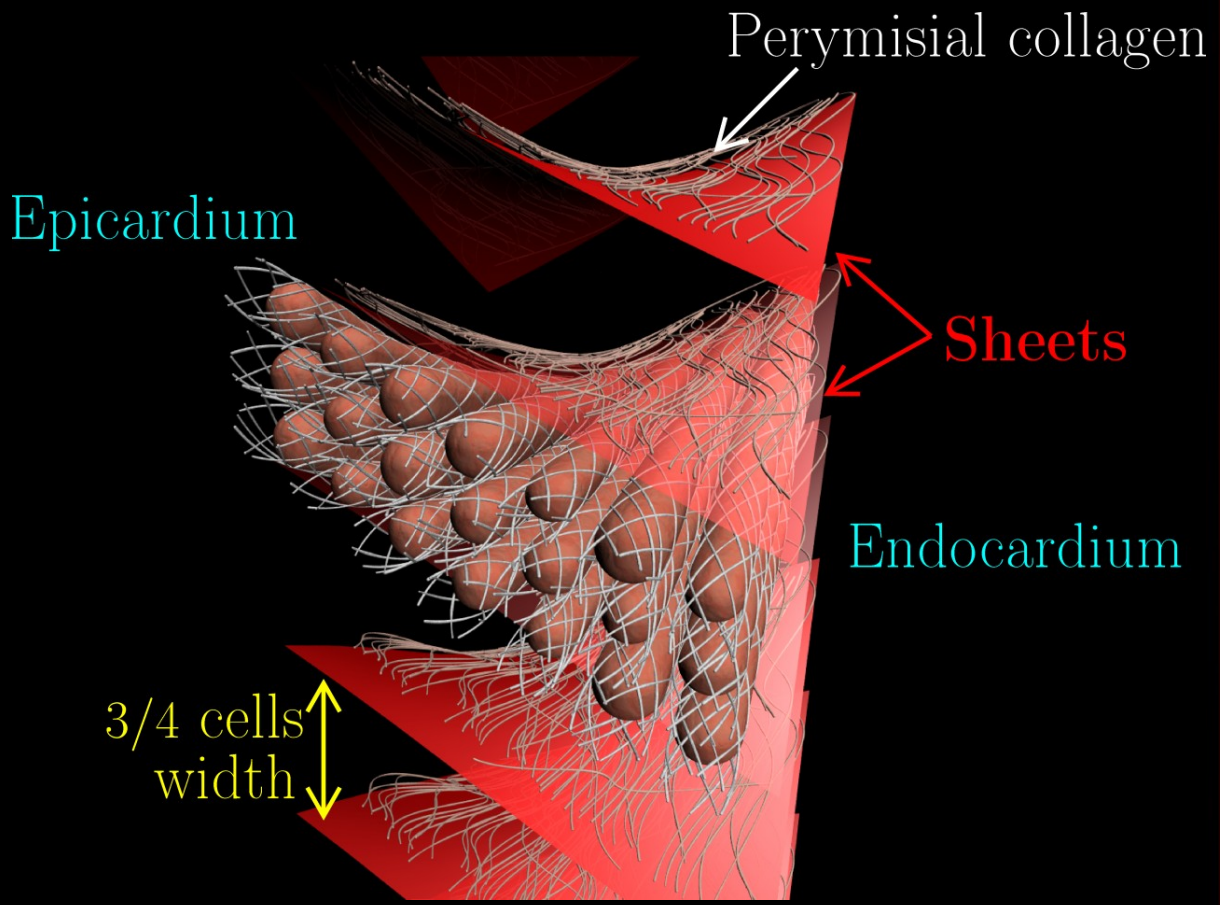


1. Structure of the heart

- **Sheet Structure**
  - **Physical Constitution**

•Physical separation by Perimysial Collagen. Mainly Type I (72%) and III.

•Fibers lie in the sheet



1. Structure of the heart

- **Role of the Study**

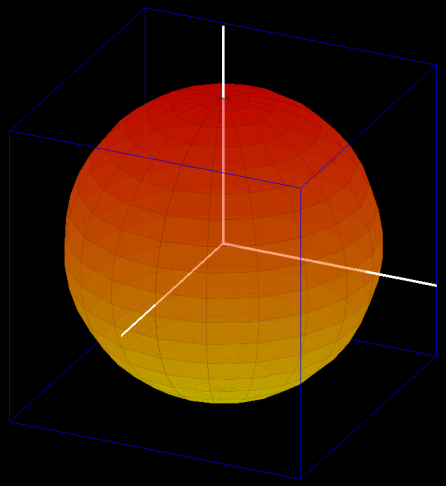
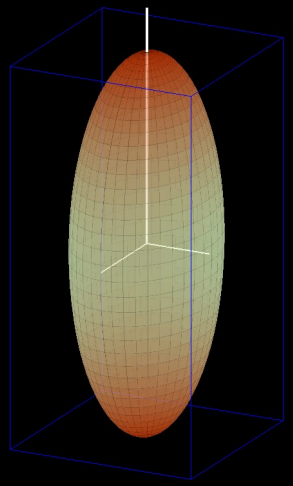
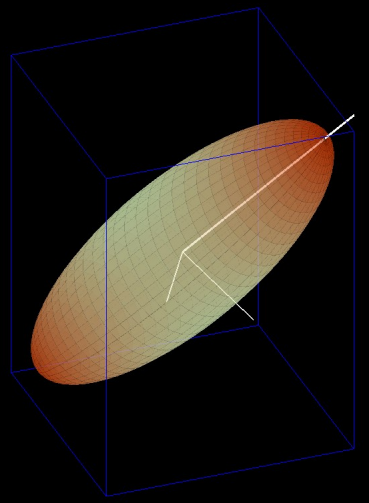
	Fiber	Sheet
Goal	•Visualizing the precise orientation of the fiber •Comparing with the standard model (+60º/-60º) •Study interesting regions like apex: compare with Band Theory (Torrent-Guasp)	•Visualization of the laminar structure.
Reasons	•Twisting motion of the heart. •Precise model of the morphology. •Electrical Model.	•Better understanding of the structure •Orthotropic distribution of Stress and Strain •Remodelling after infarct

Summary

1. Structure of the heart
2. Diffusion Tensor
   - Introduction
     - Einstein formulation of diffusion
     - Eigenvalue decomposition
   - Role
     - Largest Diffusion direction
     - Other directions
     - Overview of the vectors
   - Available data
     - Data Set
     - Normal MRI
     - Diffusion MRI
3. Visualization Methods
4. Fiber Tracking
5. Sheet Structure
6. Conclusion

2. Diffusion Tensor

- **Introduction**
  - Einstein formulation of diffusion

Isotropic	Constant Anisotropic	Anisotropic
		
$D = \begin{pmatrix} \lambda & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda \end{pmatrix}$	$D = \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix}$	$D = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{pmatrix}$

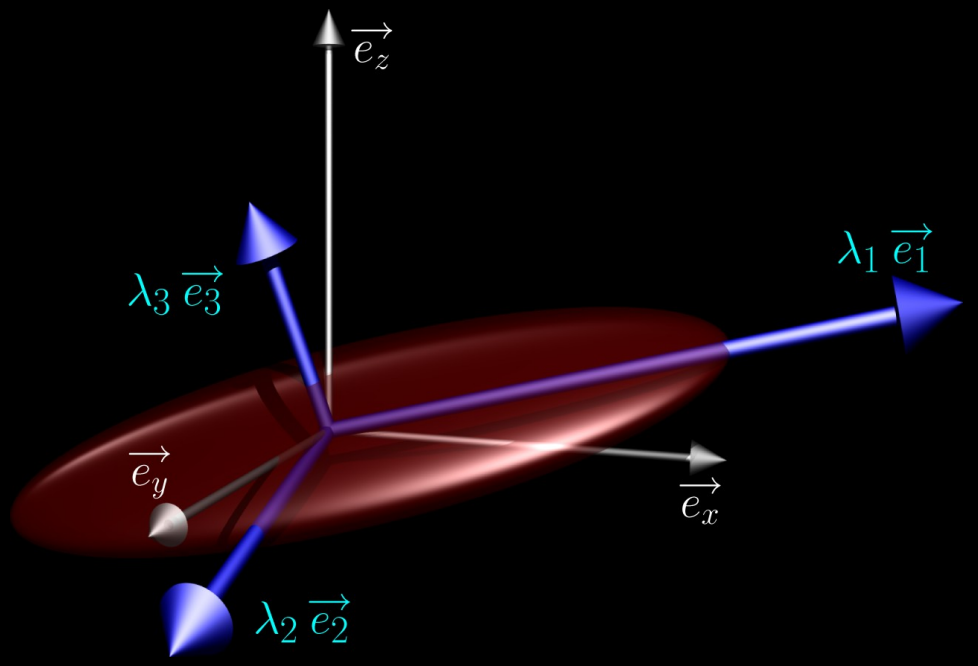
2. Diffusion Tensor

- **Introduction**
  - Eigenvalue decomposition

$$D = \begin{pmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{pmatrix}$$

$$D = R.\Lambda.R^T$$

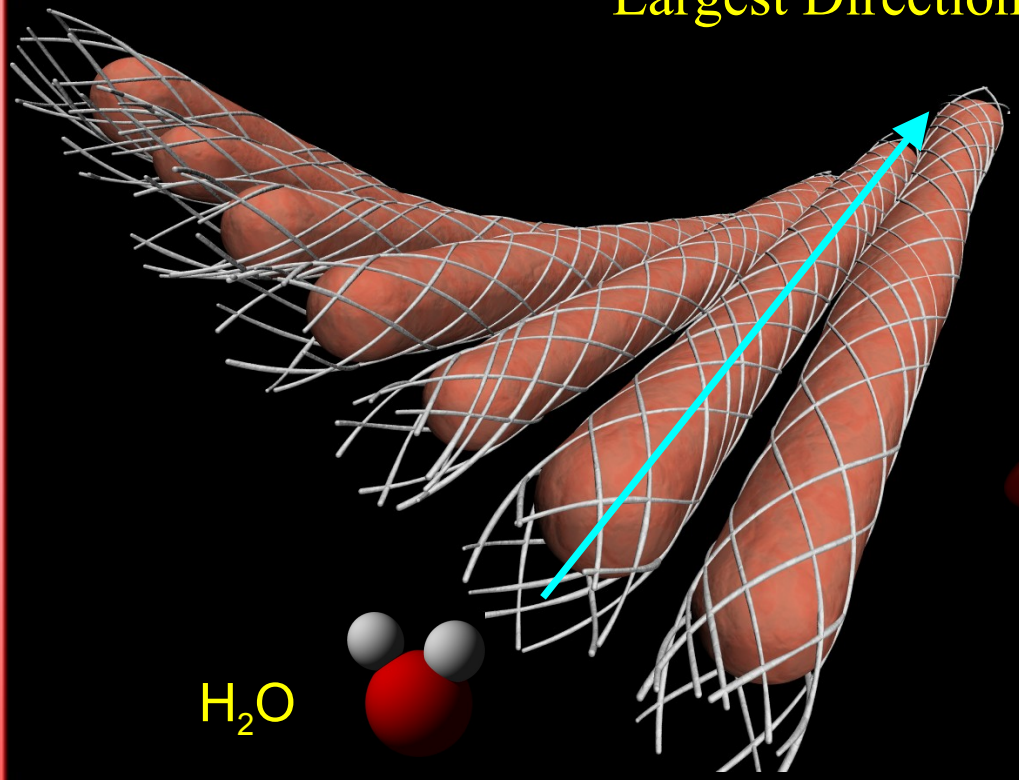
$$\begin{cases} R = \left[\overrightarrow{e_1}, \overrightarrow{e_2}, \overrightarrow{e_3}\right] \\ \Lambda = \mathrm{diag}\left(\lambda_1, \lambda_2, \lambda_3\right) \end{cases}$$

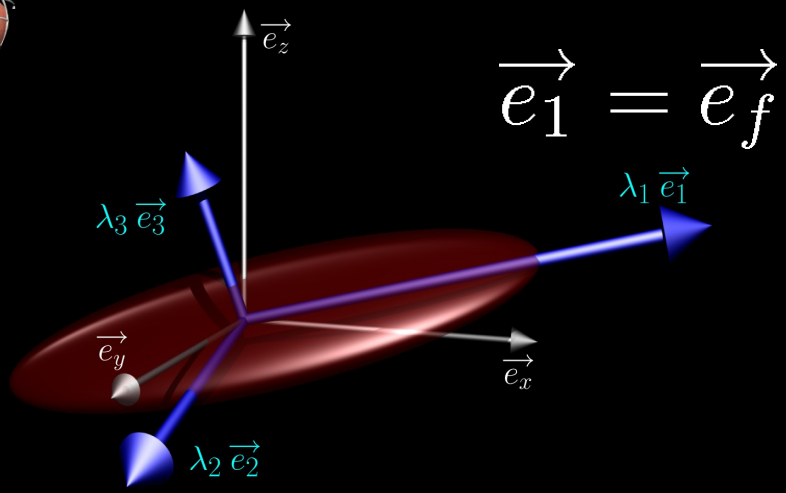


2. Diffusion Tensor

- **Role**
  - **Largest Diffusion direction**

Largest Direction in the Fiber Direction





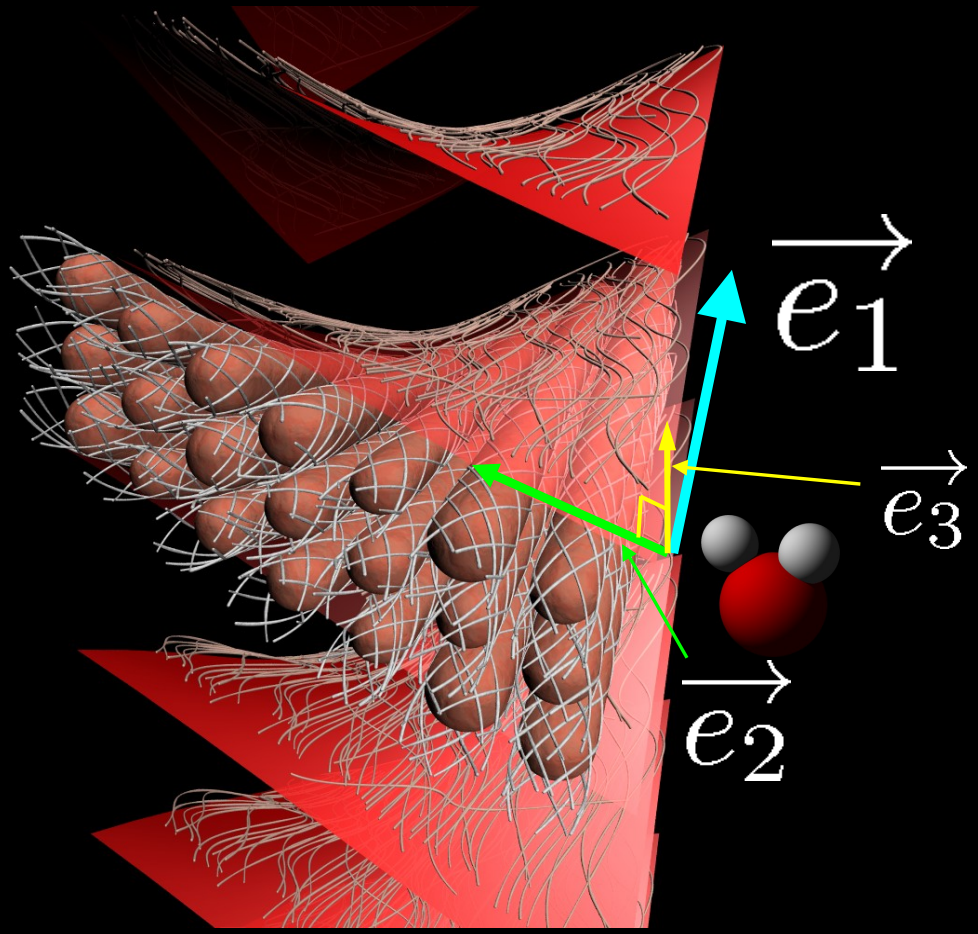
2. Diffusion Tensor

- **Role**
  - Other directions

•Sheet act like a Barrier

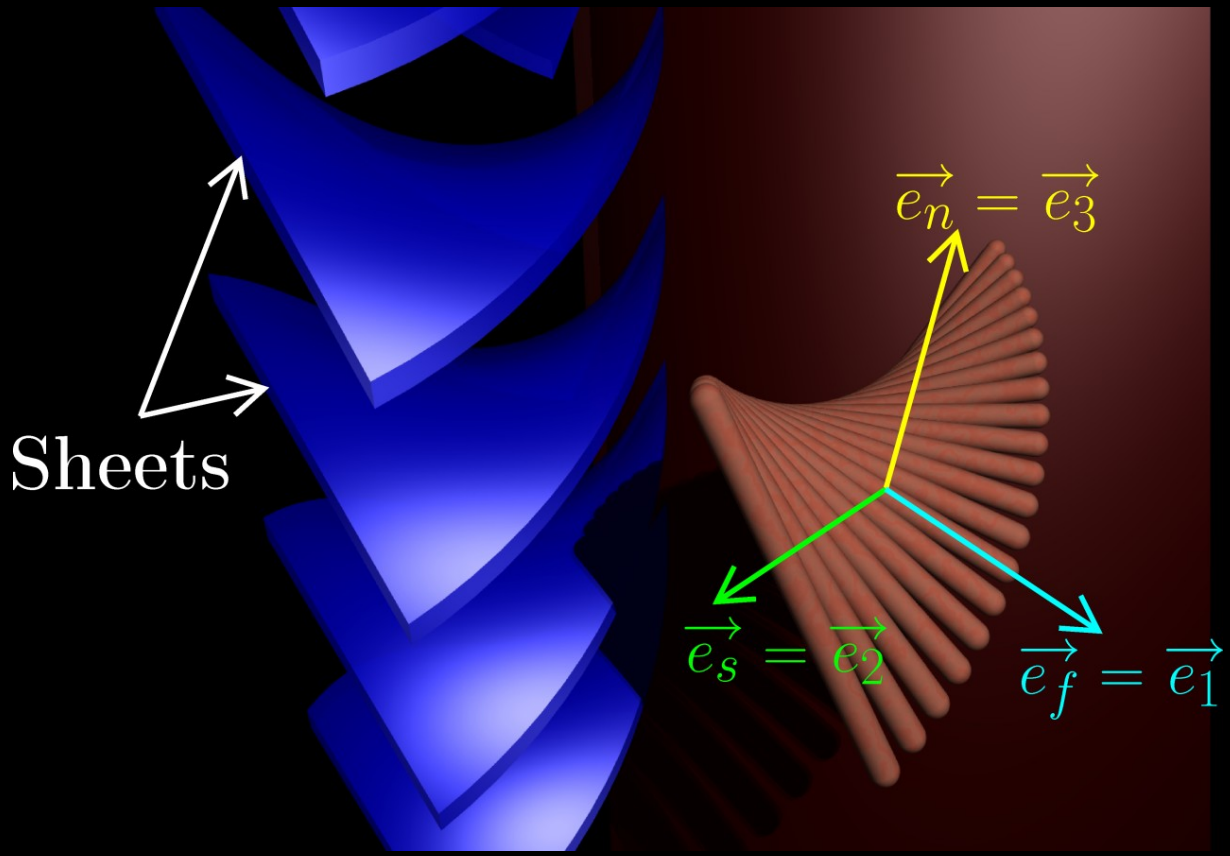
•Second component inside the sheet

•Smallest component normal to it



2. Diffusion Tensor

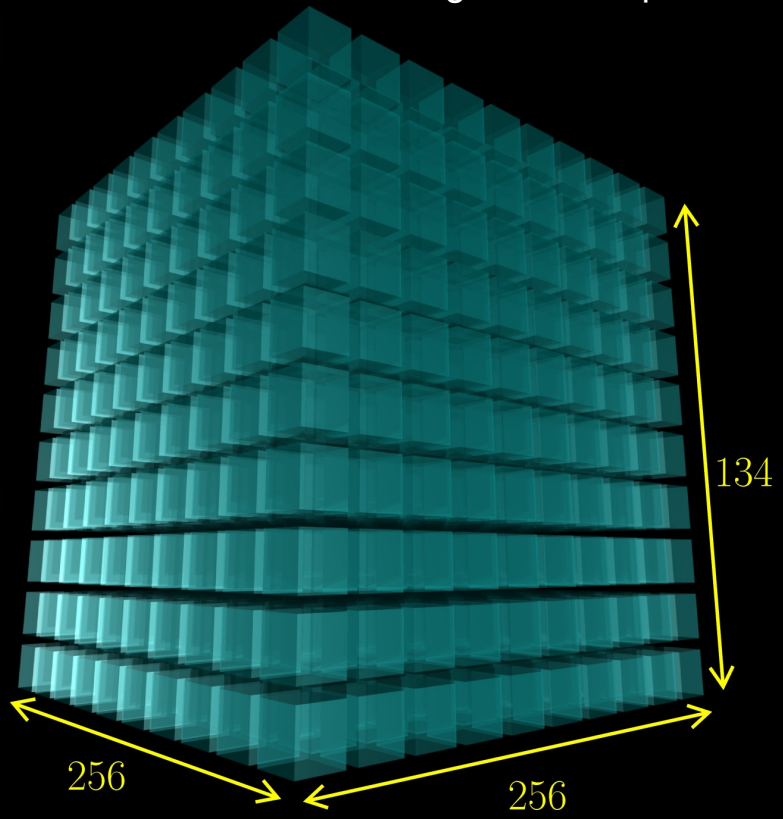
- **Role**
  - Overview of the vectors

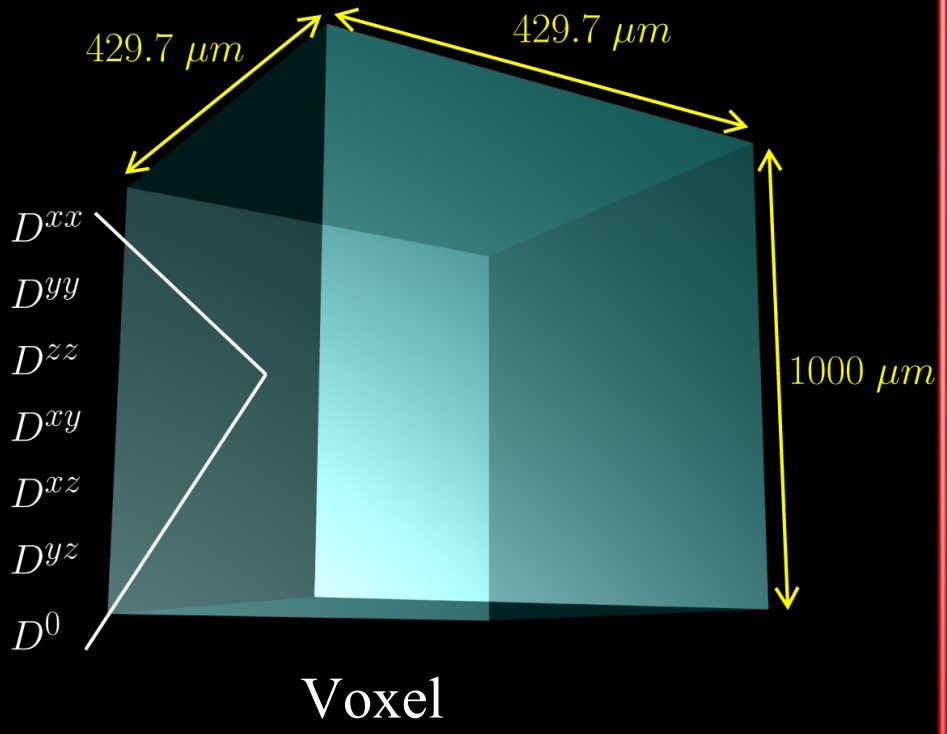


2. Diffusion Tensor

- **Available data**
  - **Data Set**

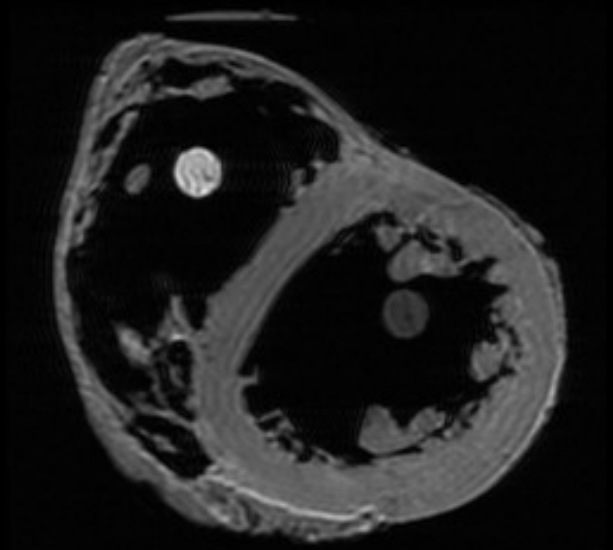
Raimond Winlsow at The Center for Cardiovascular Bioinformatics and Modeling. Johns Hopkins.



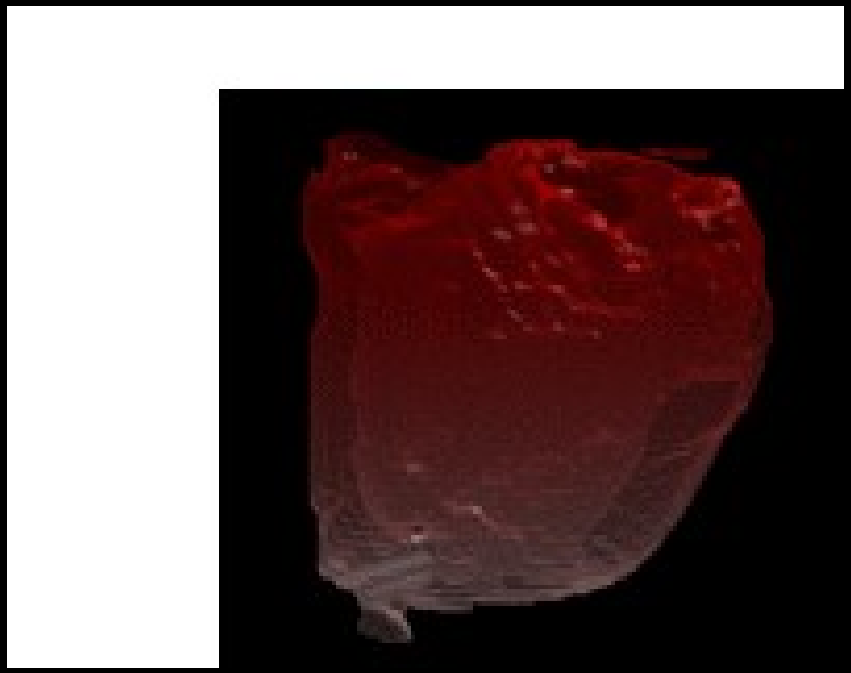


2. Diffusion Tensor

- **Available data**
  - **Normal MRI**



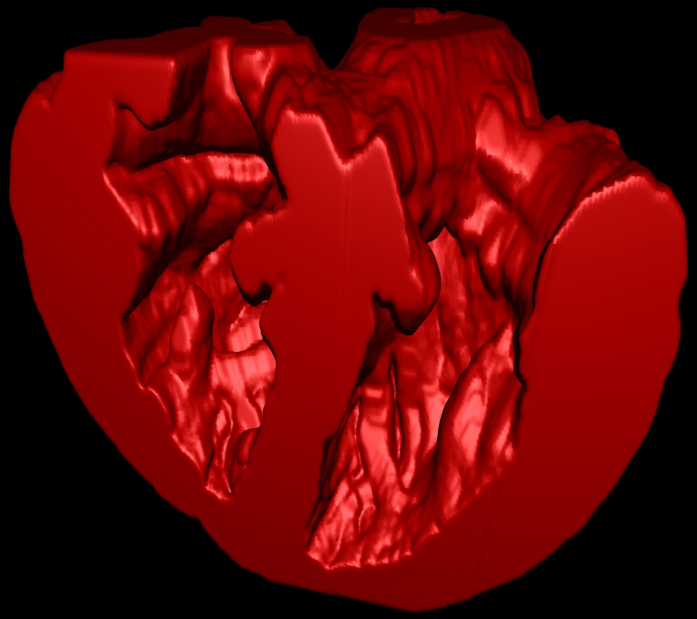
134 slices



2. Diffusion Tensor

- **Available data**
  - **Normal MRI**

Enables the Segmentation



Cut in the full heart
(automatic segmentation)

Keep the ventricles only
(manual segmentation)

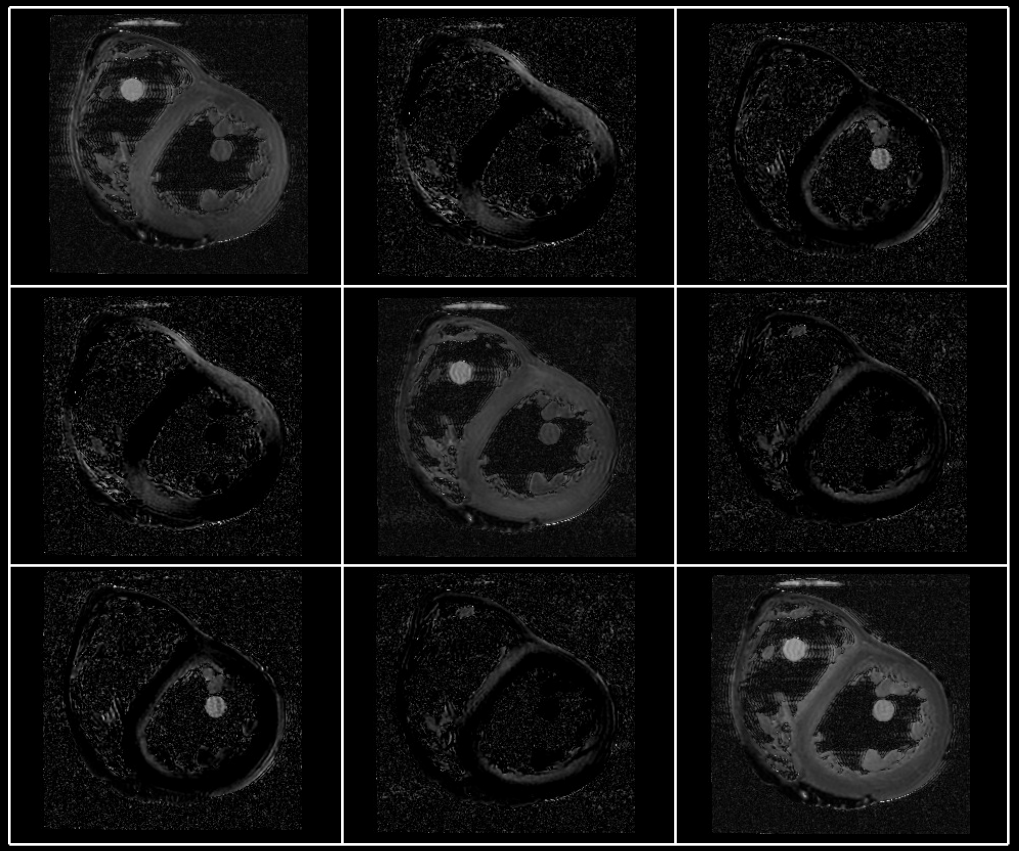
2. Diffusion Tensor

- **Available data**
  - **Diffusion MRI**

9 Components

6 independants

60h acquisition



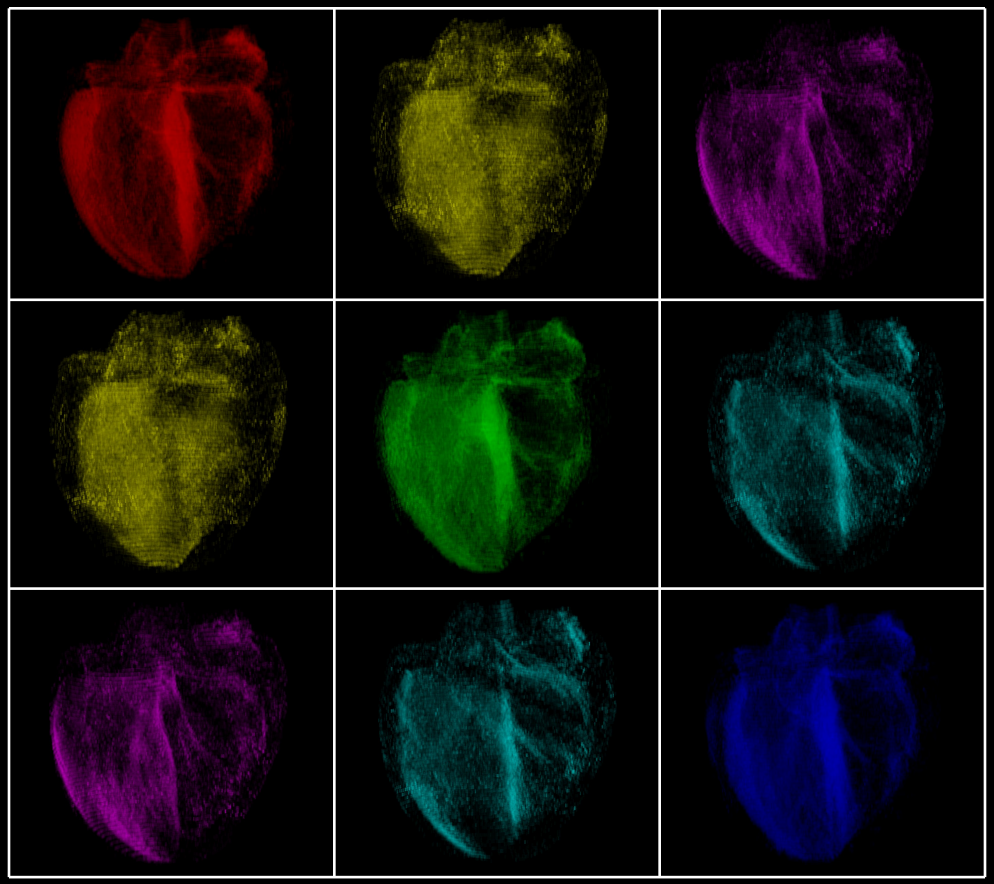
Summary

1. Structure of the heart
2. Diffusion Tensor
3. Visualization Methods
   - Color Encoding
     - Diffusion Coefficient
     - First Component
     - Circumferential direction
     - Fiber angle
   - Fiber direction visualization
   - Tensor Visualization
     - Ellipse Representation
     - Glyph amelioration
4. Fiber Tracking
5. Sheet Structure
6. Conclusion

3. Visualization Methods

- **Color Encoding**
  - Diffusion coefficient

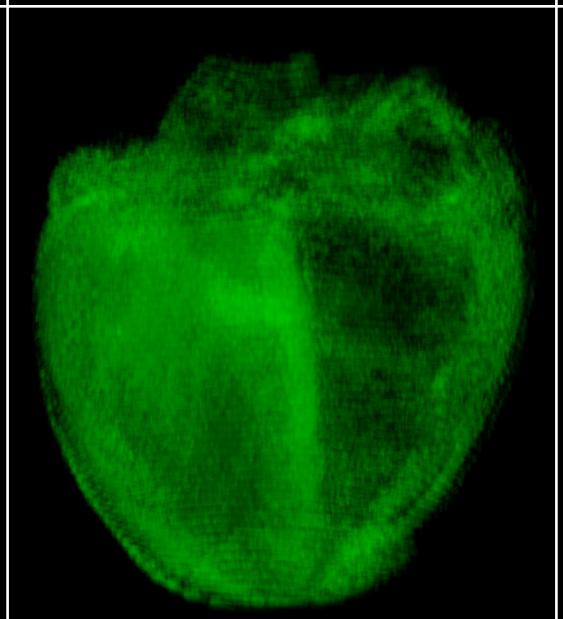
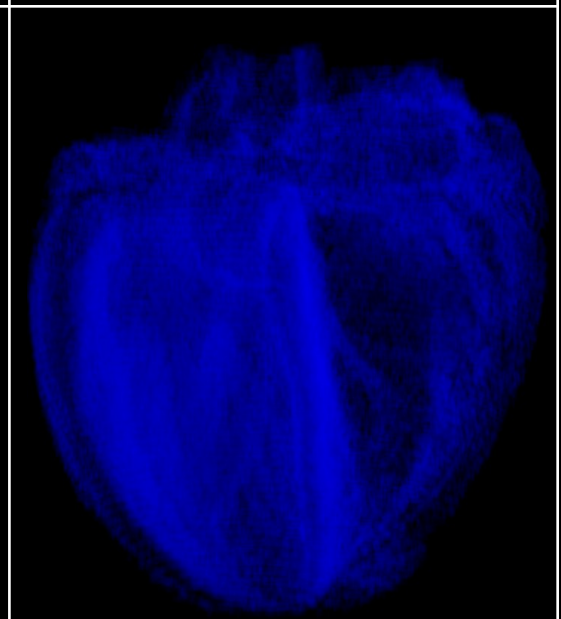
Too Complex



3. Visualization Methods

- **Color Encoding**
  - **First Component (I)**

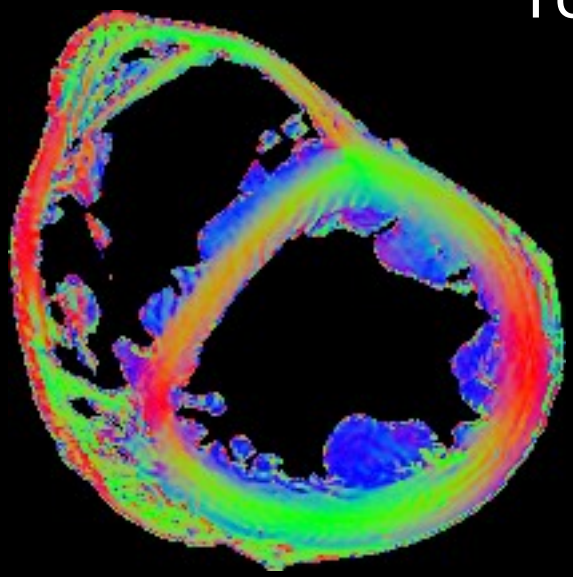
$$D = R.\Lambda.R^T \qquad R = \left[\overrightarrow{e_1}, \overrightarrow{e_2}, \overrightarrow{e_3}\right]$$ Need to have a link

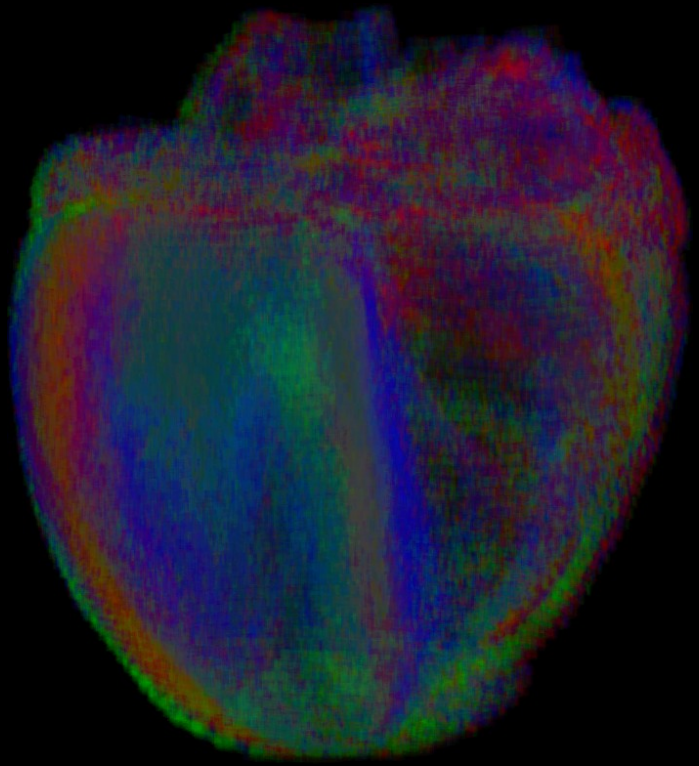
X component	Y component	Z component
		

3. Visualization Methods

- **Color Encoding**
  - First Component (II)

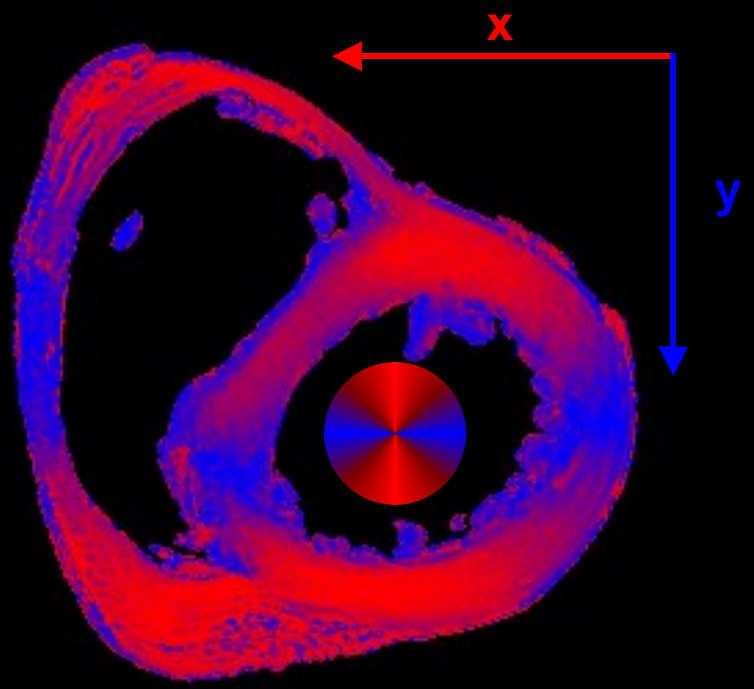
Too Complex



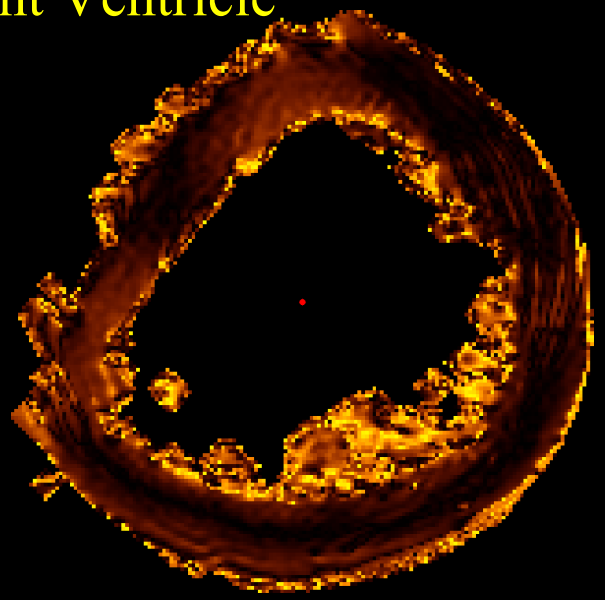


3. Visualization Methods

- **Color Encoding**
  - Circumferential direction (l)

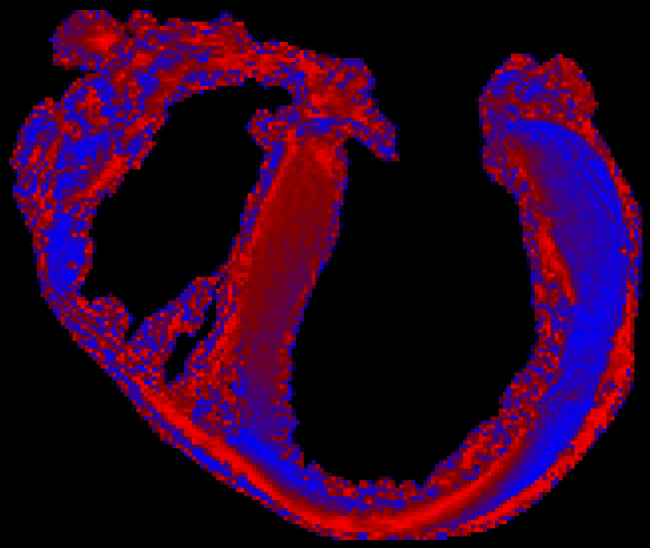


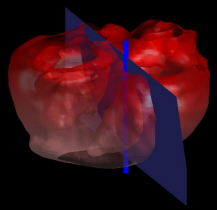
Modification of the circumferential direction at the junction with the Right Ventricle

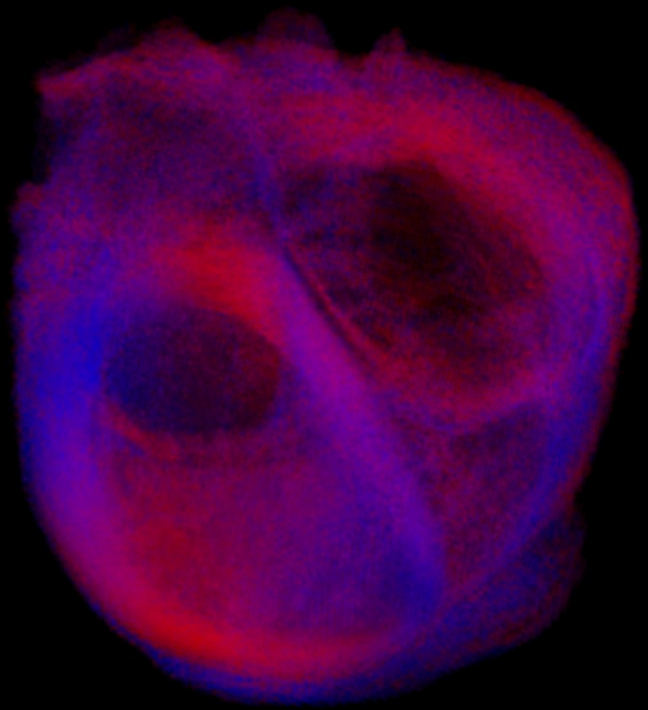


3. Visualization Methods

- **Color Encoding**
  - Circumferential direction (II)

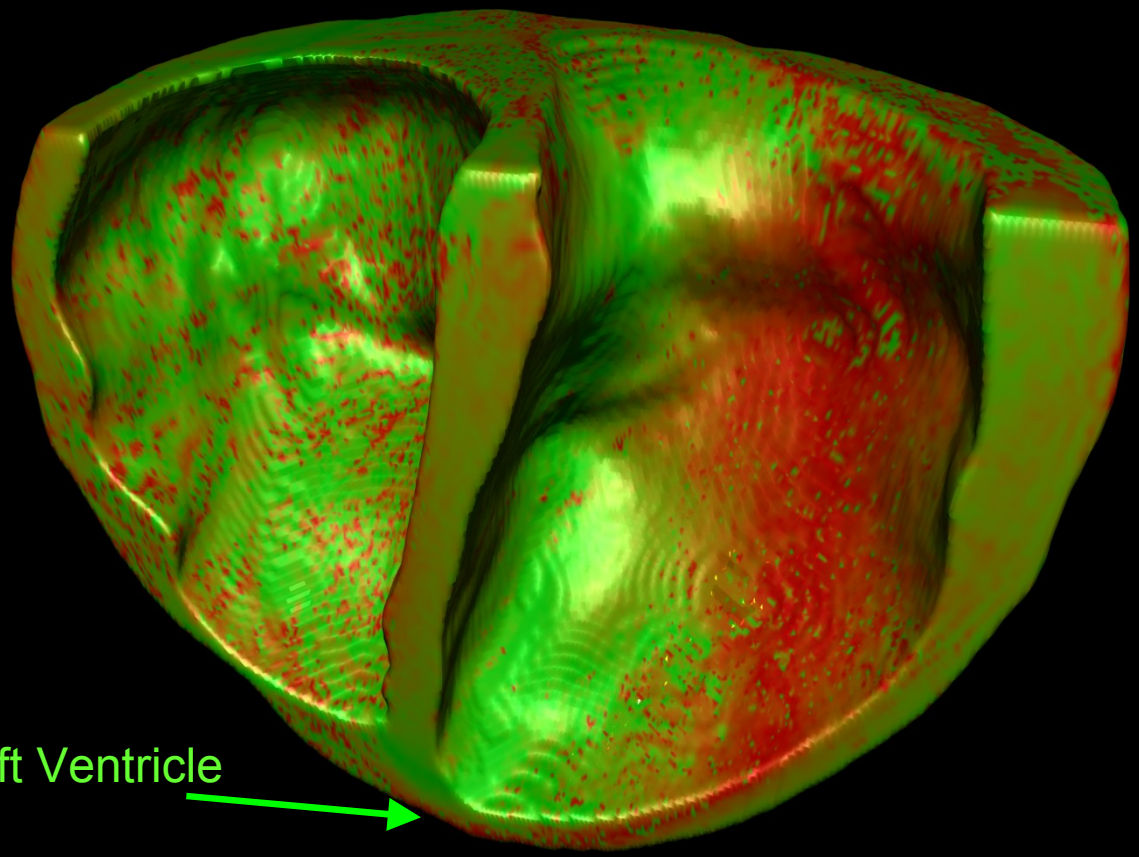






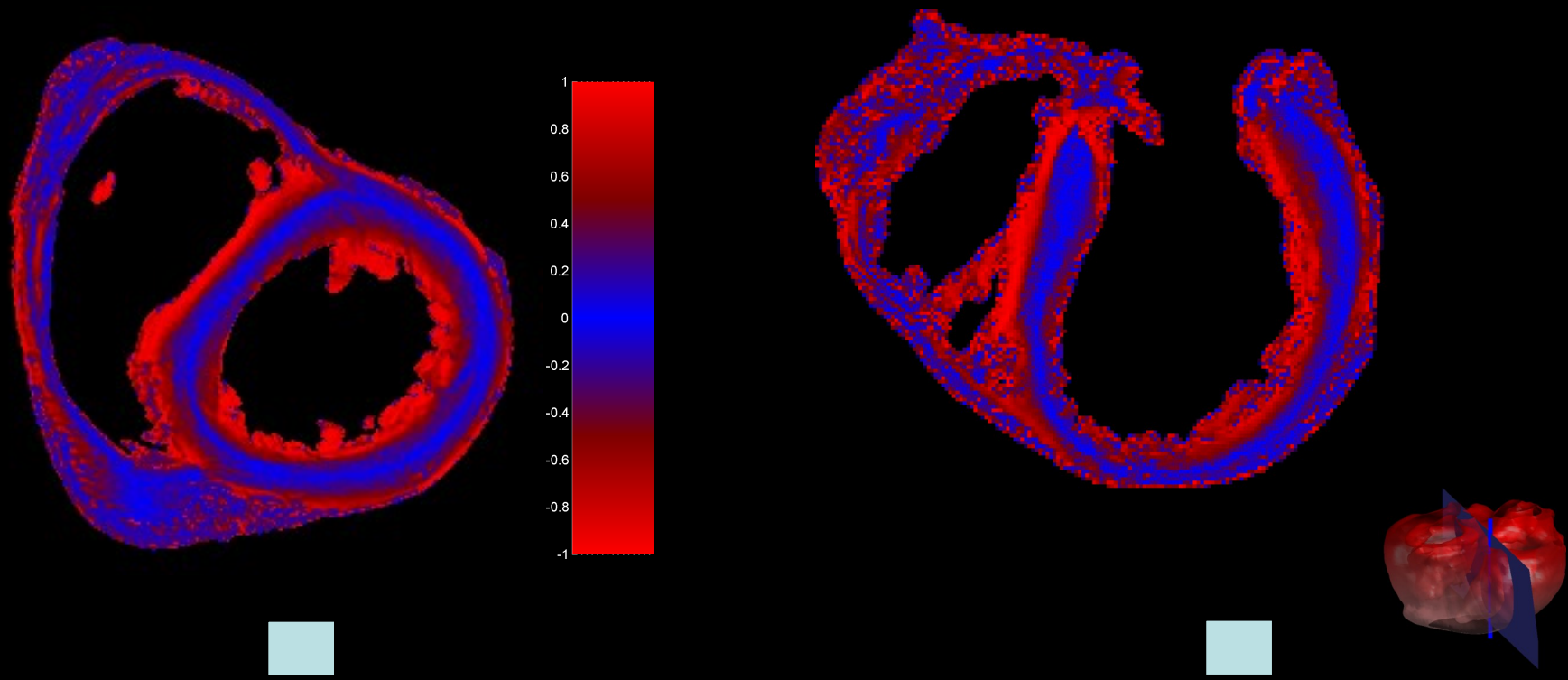
3. Visualization Methods

- **Color Encoding**
  - **Circumferential direction (III)**



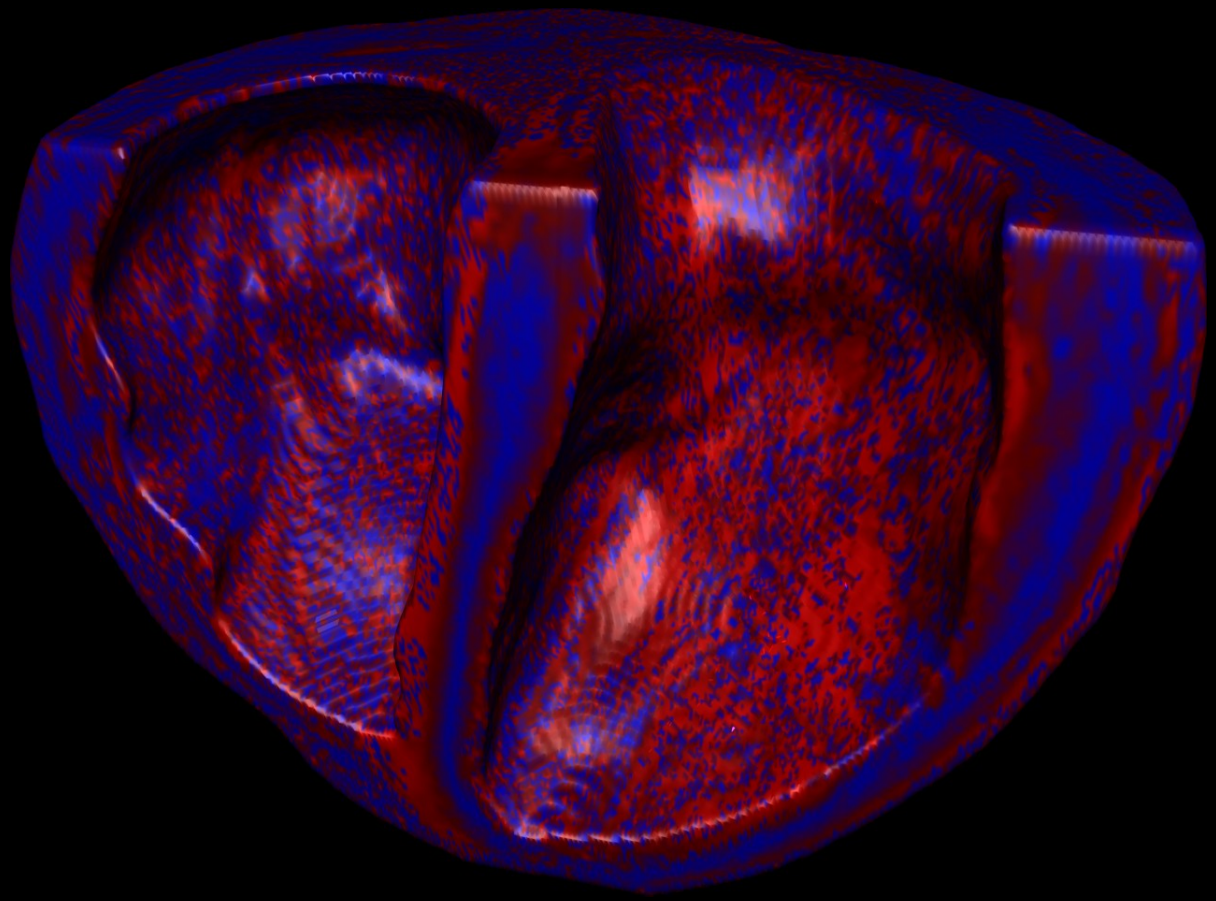
3. Visualization Methods

- **Color Encoding**
  - Fiber angle (l)



3. Visualization Methods

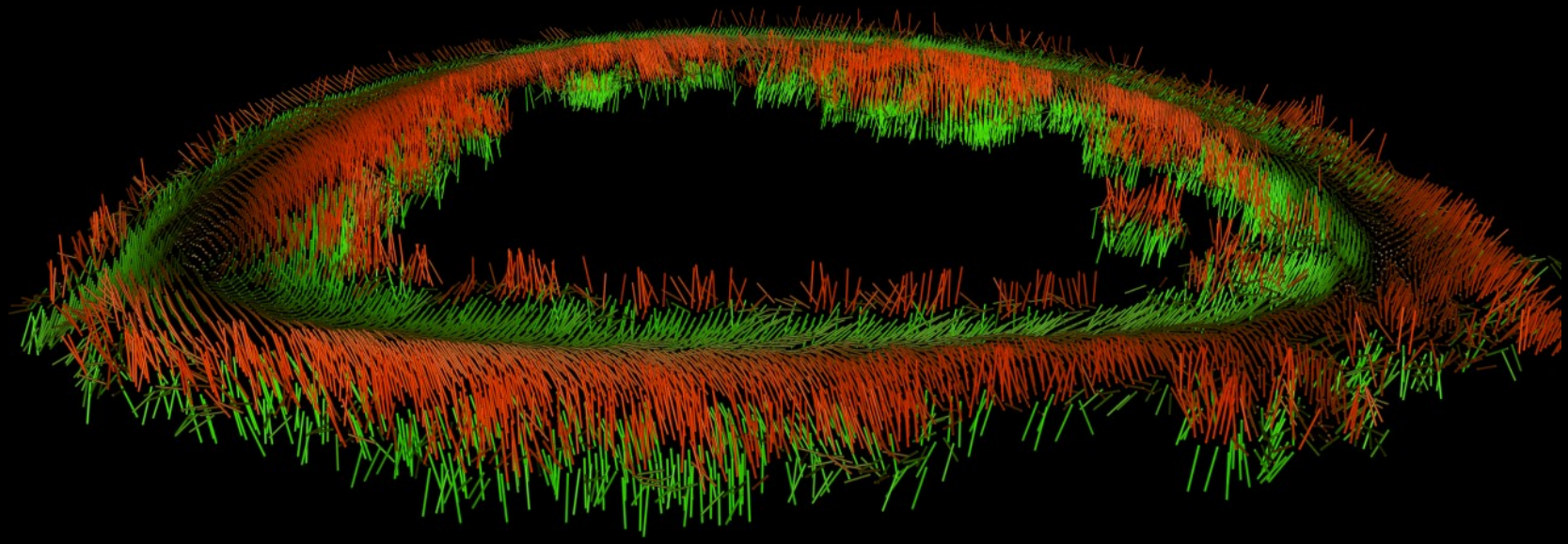
- **Color Encoding**
  - Fiber angle (II)



3. Visualization Methods

- **Fiber Direction Visualization**

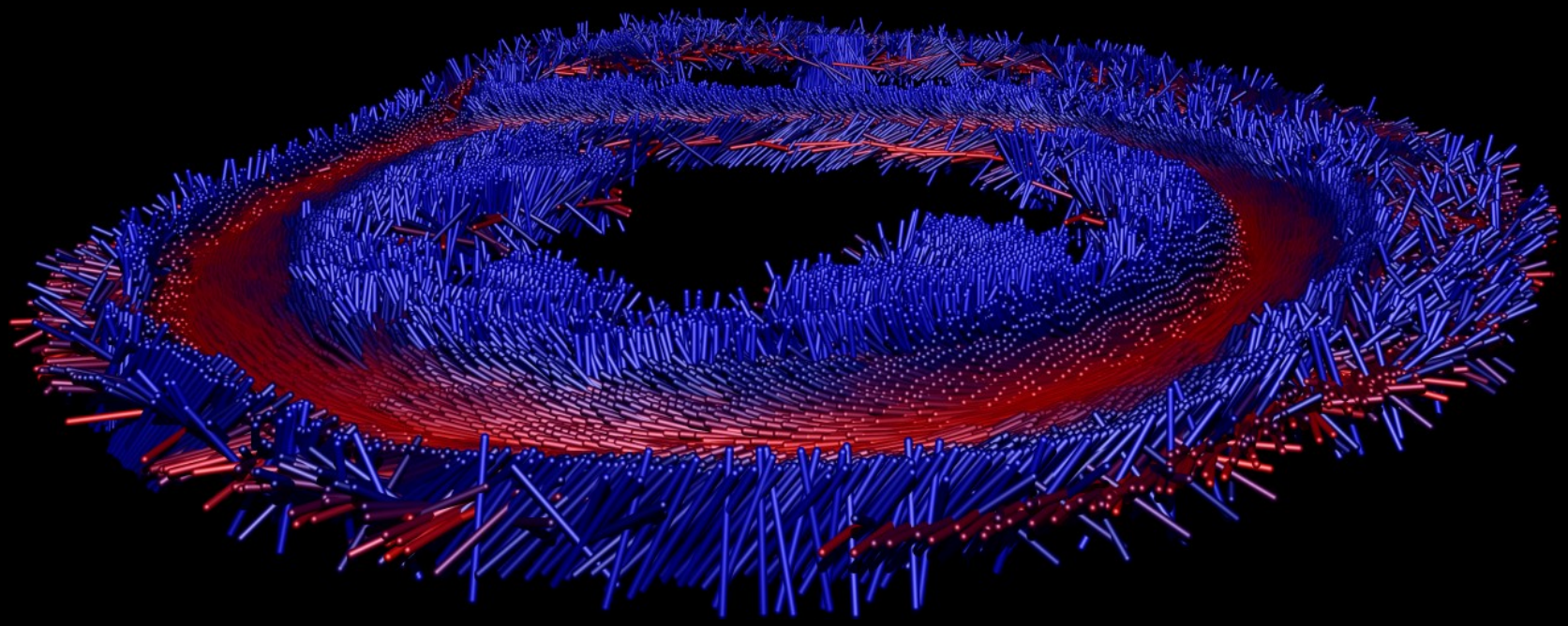
For each positions the fiber direction is Drawn



3. Visualization Methods

- **Fiber Direction Visualization**

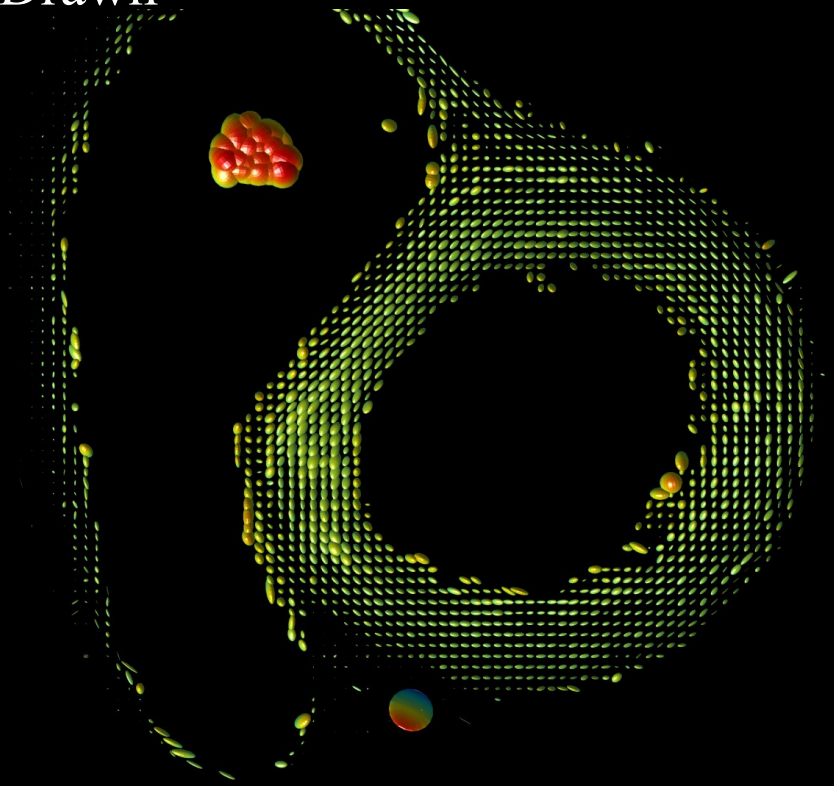
Can be mixed with the color encoding

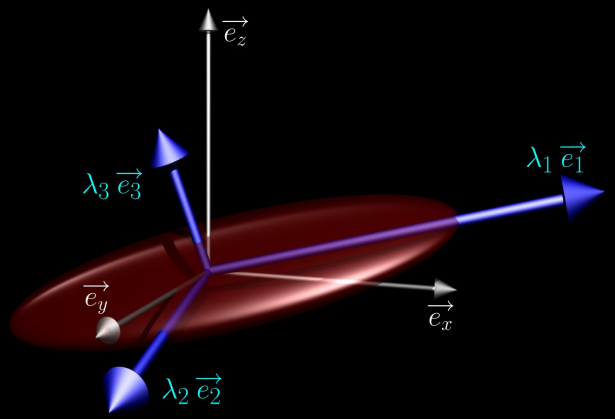


3. Visualization Methods

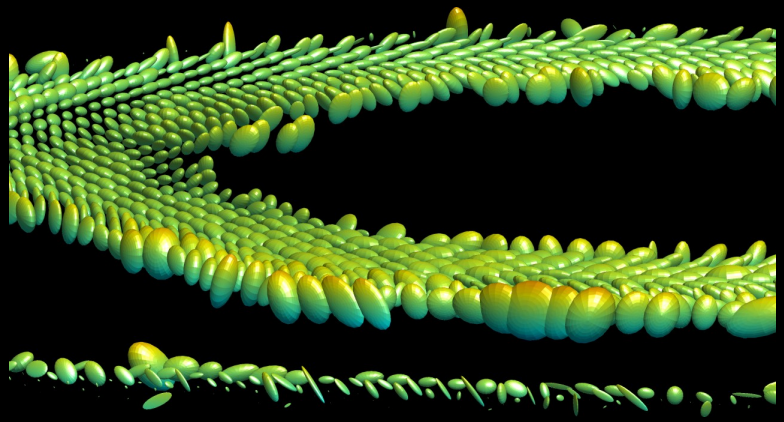
- **Tensor Visualization**
  - **Ellipse Representation**

For each positions the tensor is Drawn



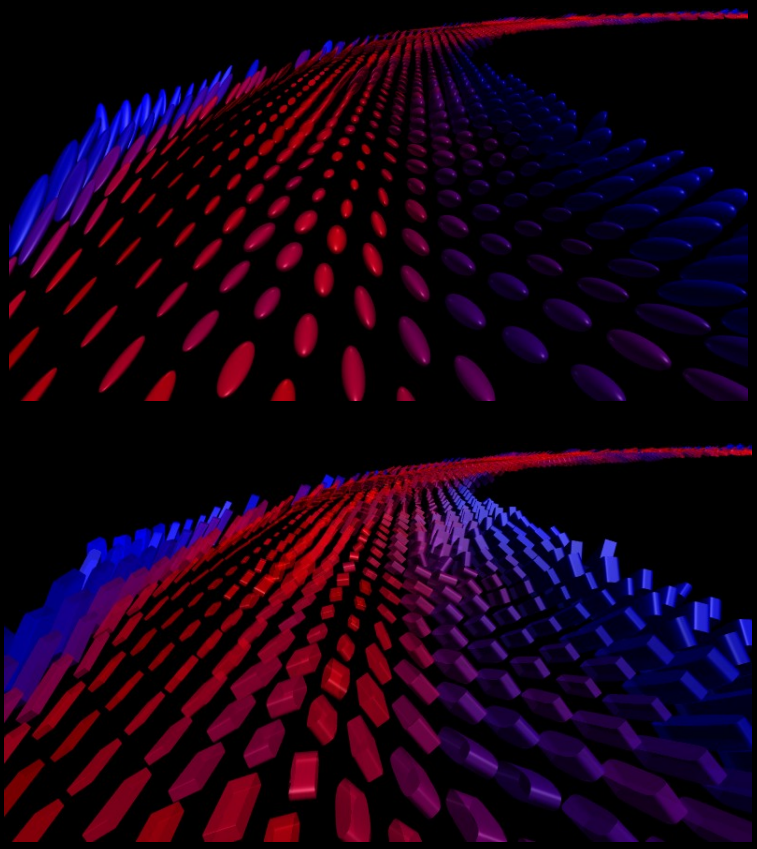


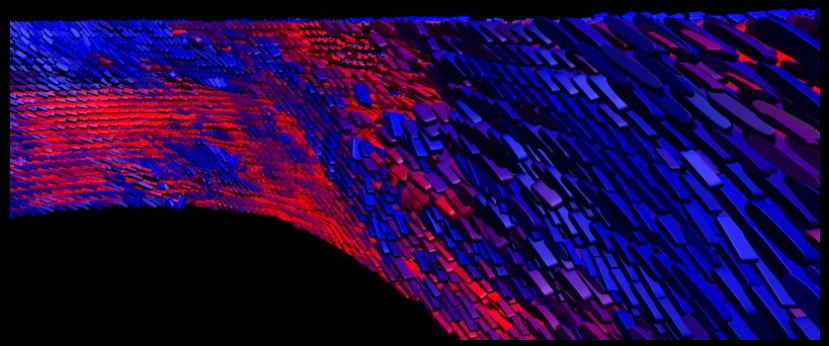
Problem of low anisotropy



3. Visualization Methods

- **Tensor Visualization**
  - Glyph amelioration



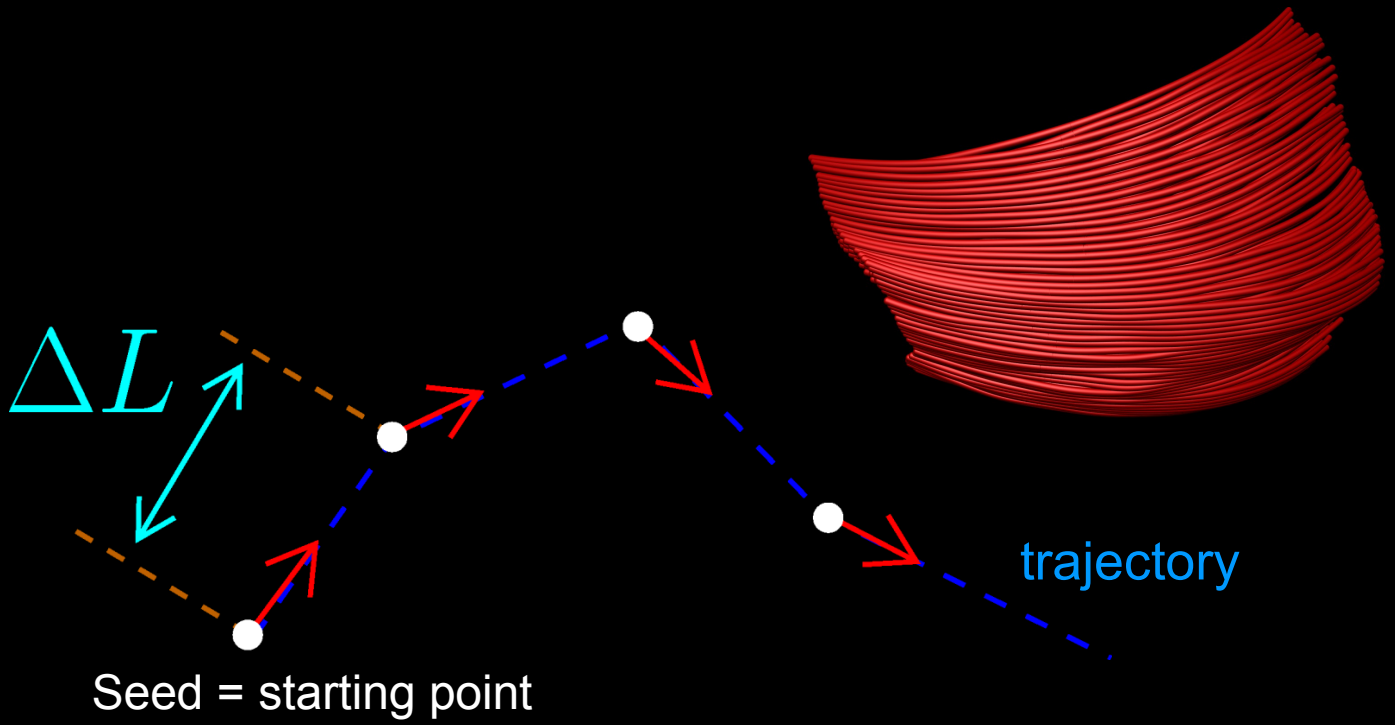


Summary

1. Structure of the heart
2. Diffusion Tensor
3. Visualization Methods
4. Fiber Tracking
   - Introduction
   - Integration Step
   - Interpolation
   - Filtering of the data
     - Noise
     - MLS Method
   - Sense of the propagation
   - Results
     - Helicoidal wrapping
     - Smooth fiber angle change
     - Apex
5. Sheet Structure
6. Conclusion

4. Fiber Tracking

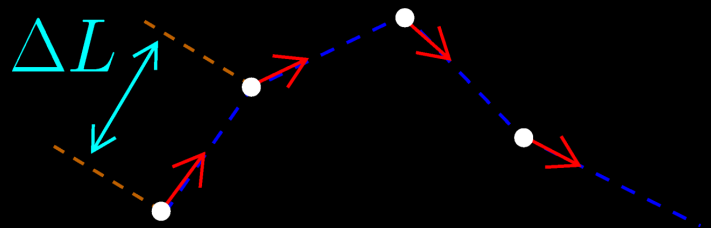
- **Introduction**



$$s(t) = s(0) + \int_0^t \mathbf{e}_1\Big(s(\tau)\,\mathrm{d}\tau\Big)$$

4. Fiber Tracking

- **Integration Step**



ODE form : first order, non-linear

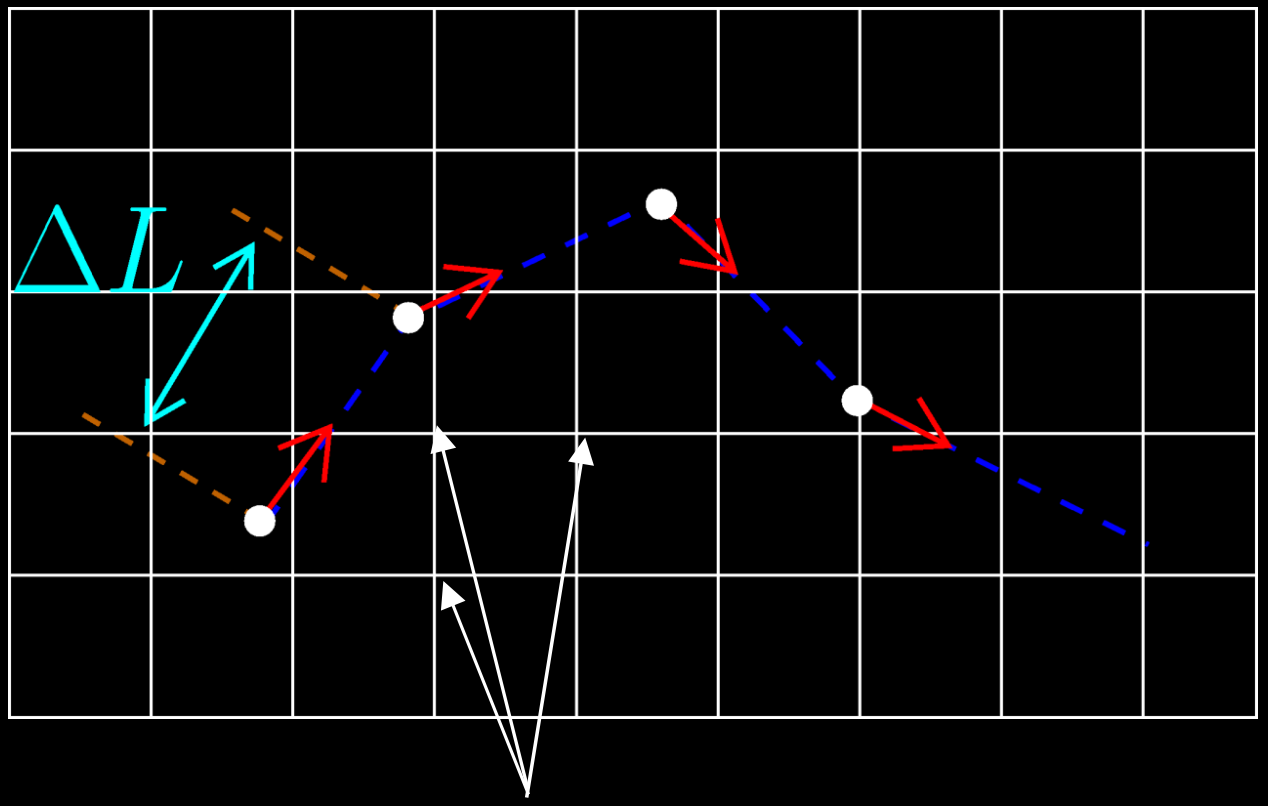
$$\begin{cases} s'(t) = \mathbf{e}_1\Big(s(t)\Big) \\ s(0) = \mathbf{x}_0 \end{cases}$$

Use Runge-Kutta : order 5 (Dormand-Prince)

$$\mathbf{s}(t+\Delta t) = \mathbf{s}(t) + \Delta t \sum_i a_i \, \mathbf{k}_i$$

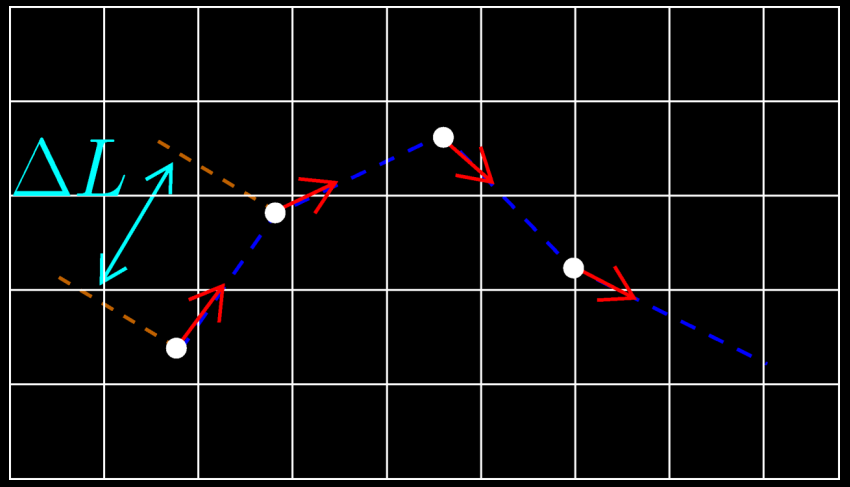
4. Fiber Tracking

- **Interpolation**



4. Fiber Tracking

- **Interpolation**



Problem of interpolation :

$$\| \overrightarrow{e}_1(\mathbf{x}_i) \| = 1$$

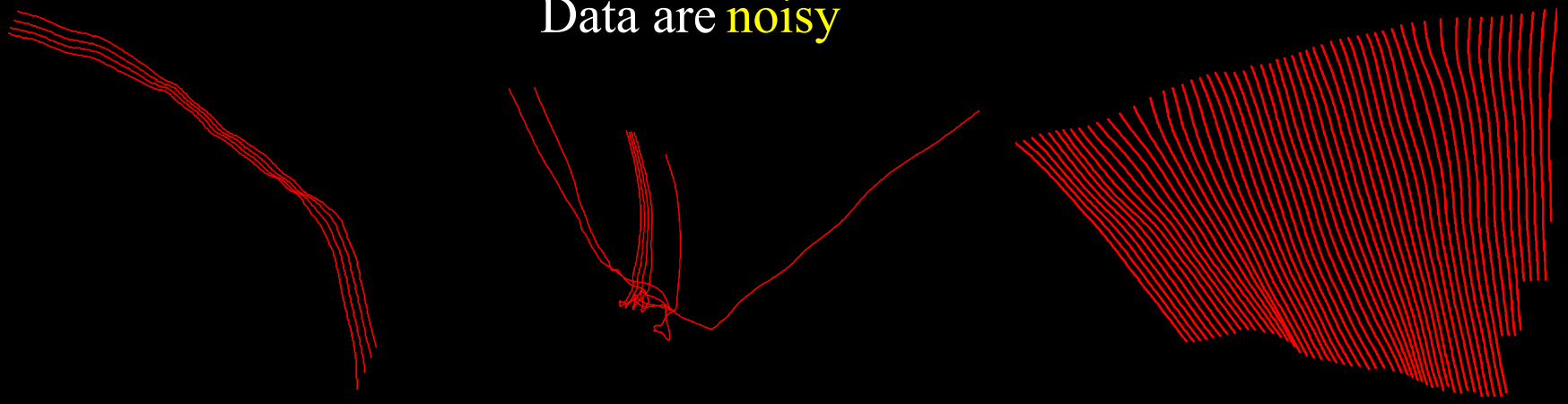
$$\left\| \sum_i a_i \overrightarrow{e}_1(\mathbf{x}_i) \right\| \neq 1 \quad \rightarrow \quad \sum_{i,j} a^{i,j} D^{ij} = R.\Lambda.R^T$$

Normalized vectors

4. Fiber Tracking

- **Filtering of the data**
  - **Noise**

Data are noisy

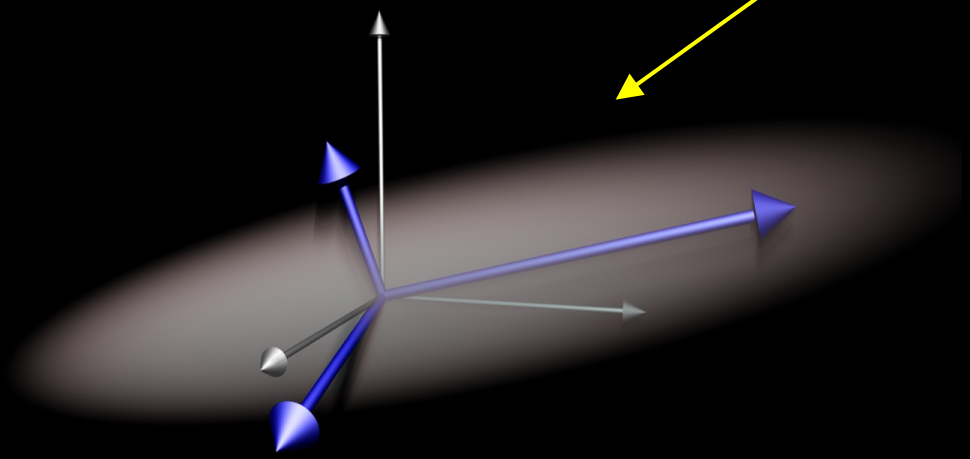


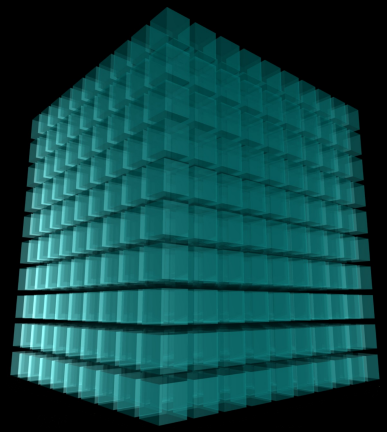
Gaussian filter will destroy the Anisotropy

4. Fiber Tracking

- **Filtering of the data**
  - MLS (Moving Least Square) method (I)

Minimization : $$E(\mathbf{x}) = \int_{\mathbf{y}\in\mathbb{R}^3} G(\mathbf{y}-\mathbf{x})\left(\tilde{D}(\mathbf{y}-\mathbf{x}) - D(\mathbf{y})\right)^2 \mathrm{d}\mathbf{y}$$





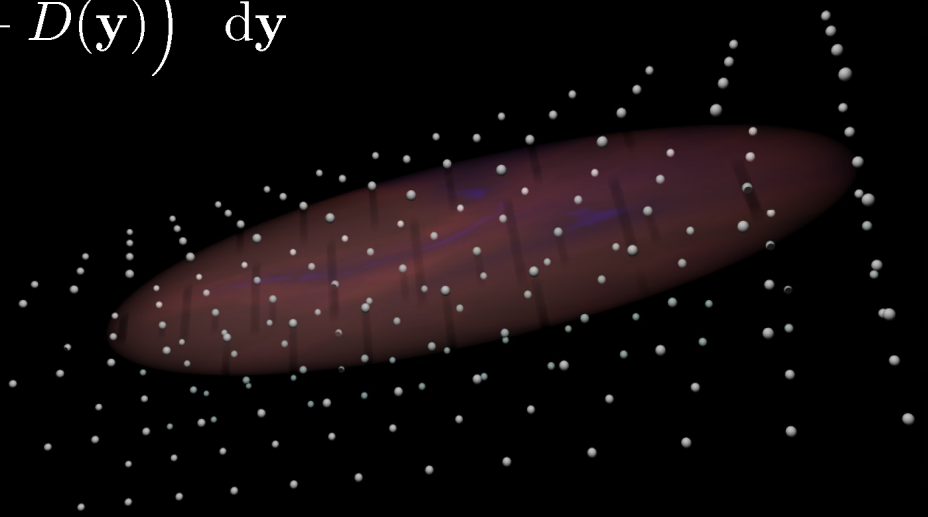
4. Fiber Tracking

- **Filtering of the data**
  - **MLS (Moving Least Square) method (II)**

$$E(\mathbf{x}) = \int_{\mathbf{y}\in\mathbb{R}^3} G(\mathbf{y}-\mathbf{x})\left(\tilde{D}(\mathbf{y}-\mathbf{x}) - D(\mathbf{y})\right)^2 \mathrm{d}\mathbf{y}$$

Approximated by a polynome

$$\tilde{D}^{\alpha_1\alpha_2}(\Xi) = \sum_{k_1=k_2=k_3=0}^{k_1+k_2+k_3<N} a^{\alpha_1\alpha_2}_{k_1k_2k_3}\ \xi_1^{k_1}\ \xi_2^{k_2}\ \xi_3^{k_3}$$



4. Fiber Tracking

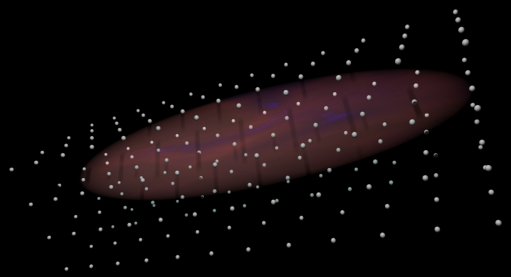
- **Filtering of the data**
  - **MLS method (III)**

Solve a linear system at each iteration :

$$\forall (\alpha_1, \alpha_2) \in [\![0,2]\!] \ , \ \sum_{k_1,k_2,k_3} M_{k_4k_5k_6,k_1k_2k_3} \ a^{\alpha_1\alpha_2}_{k_1k_2k_3} = b^{\alpha_1\alpha_2}_{k_4k_5k_6}$$

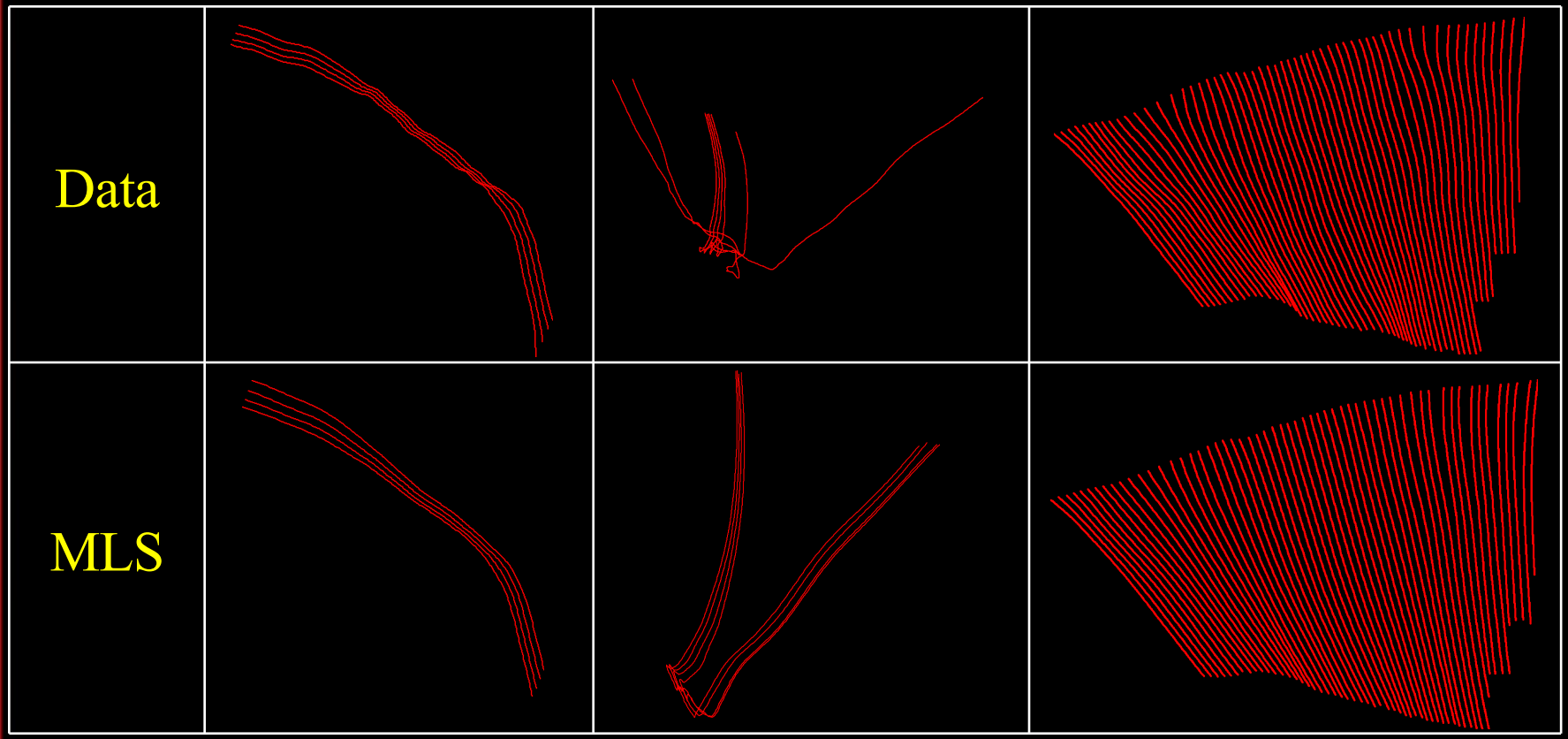
$$\begin{cases} M_{k_1k_2k_3,k_4k_5k_6} = \displaystyle\int_{\Xi\in\mathbb{R}^3} \xi_1^{k_1+k_4} \xi_2^{k_2+k_5} \xi_3^{k_3+k_6} \, G(\Xi) \, \mathrm{d}\Xi \\ b^{\alpha_1\alpha_2}_{k_4k_5k_6} = \displaystyle\int_{\Xi\in\mathbb{R}^3} D^{\alpha_1\alpha_2}(\Xi) \, \xi_1^{k_4} \xi_2^{k_5} \xi_3^{k_6} \, G(\Xi) \, \mathrm{d}\Xi \end{cases}$$

Numerical integration :
Gaussian quadrature



4. Fiber Tracking

- **Filtering of the data**
  - **MLS method (IV)**

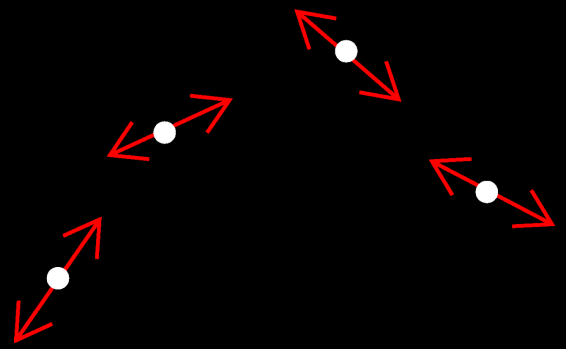


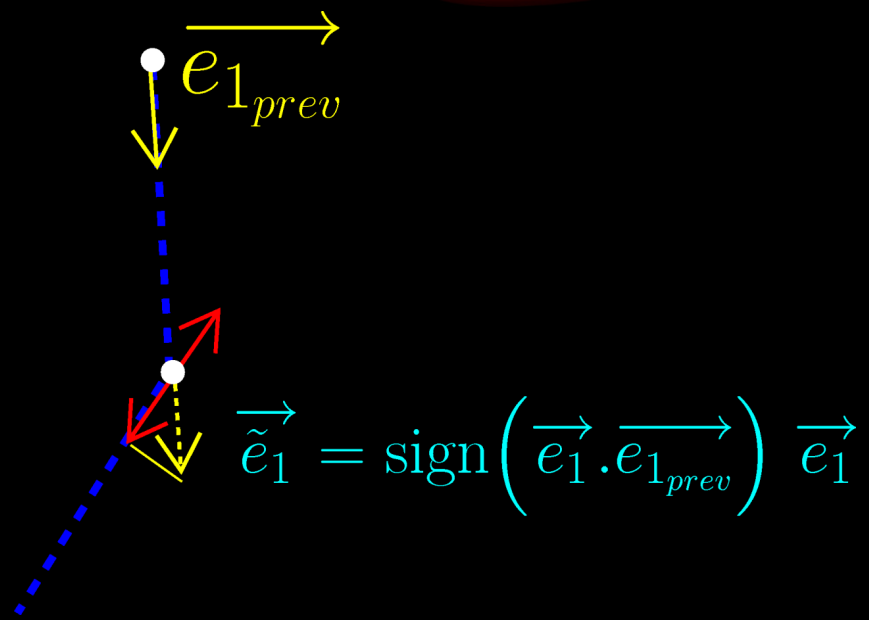
4. Fiber Tracking

- **Sense of the propagation**

$$D = R.\Lambda.R^T$$

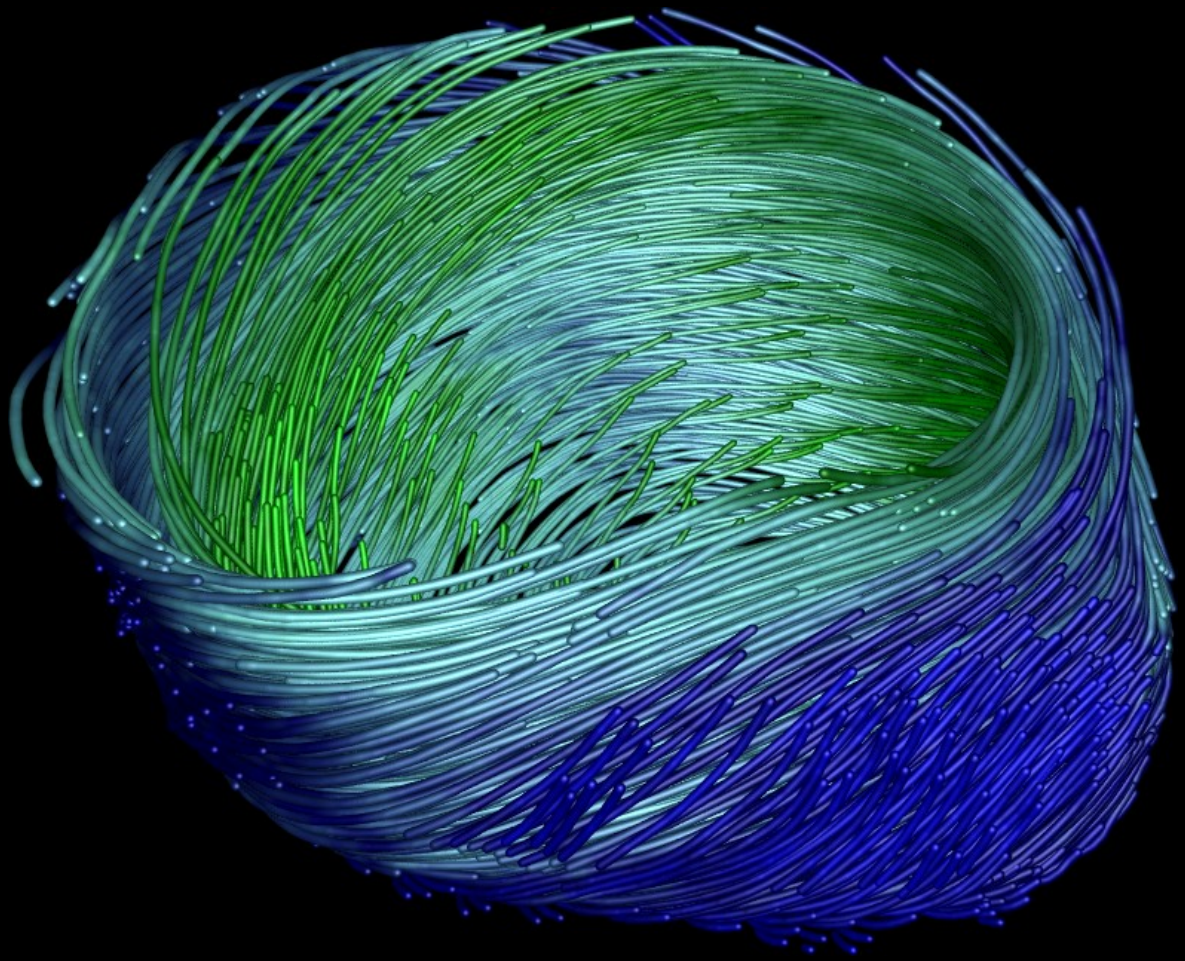
Diffusion has no sign





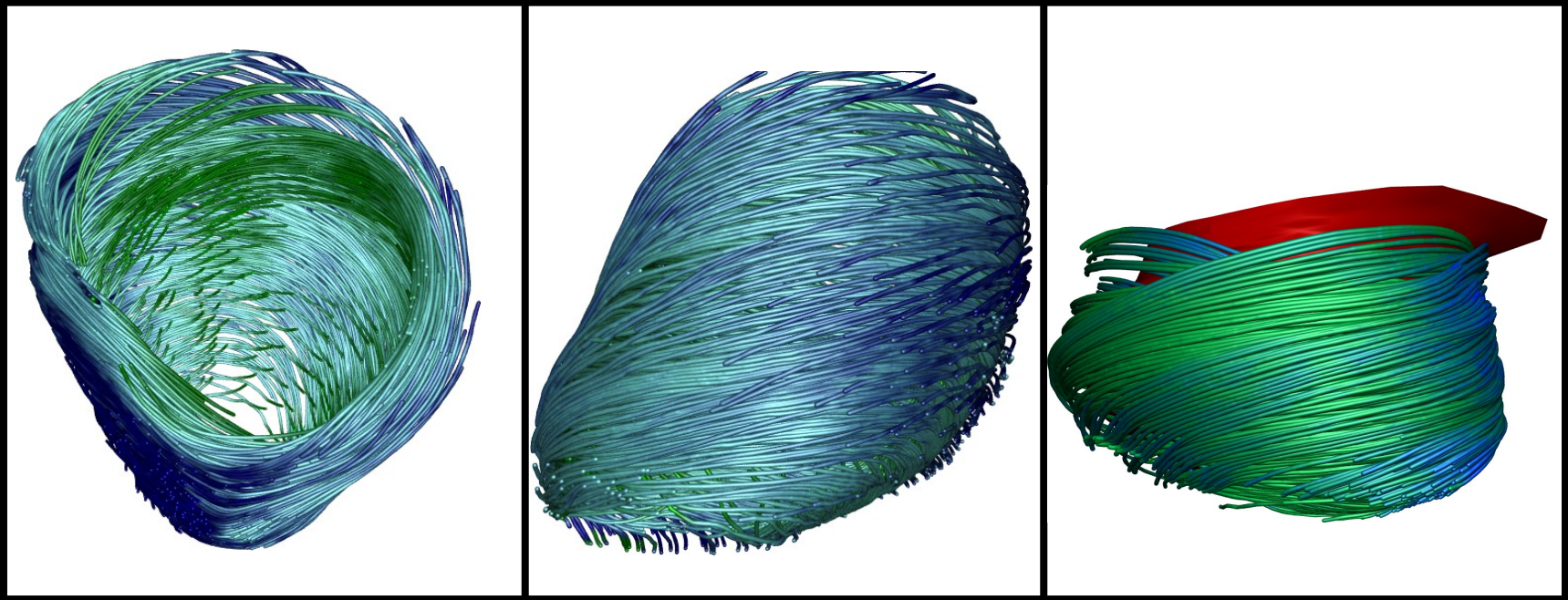
4. Fiber Tracking

- **Results**



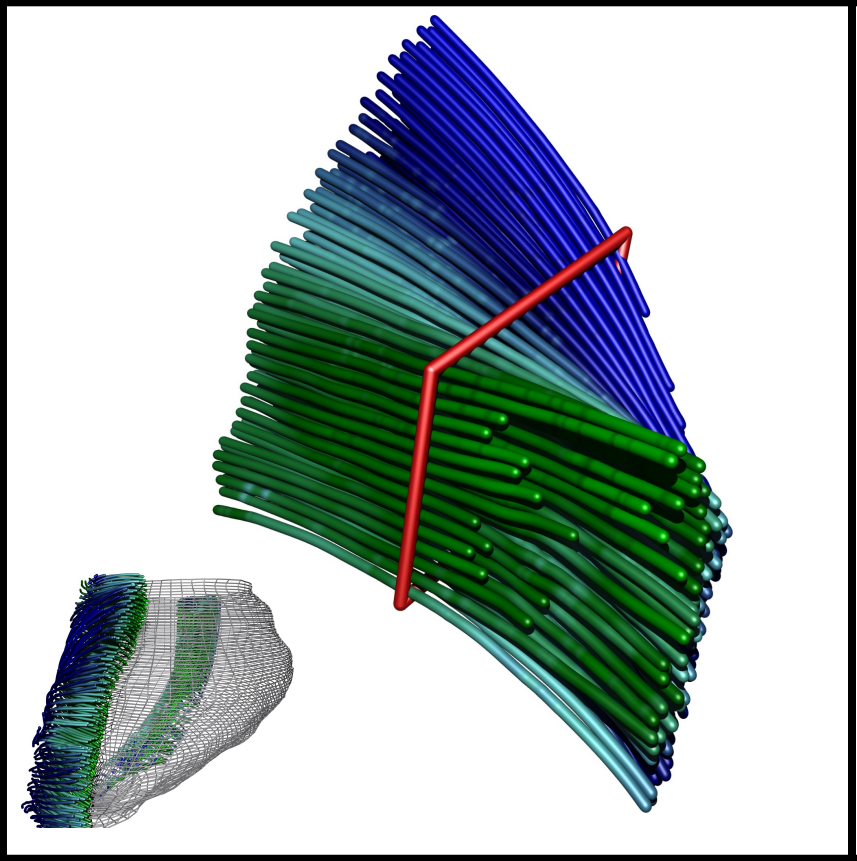
4. Fiber Tracking

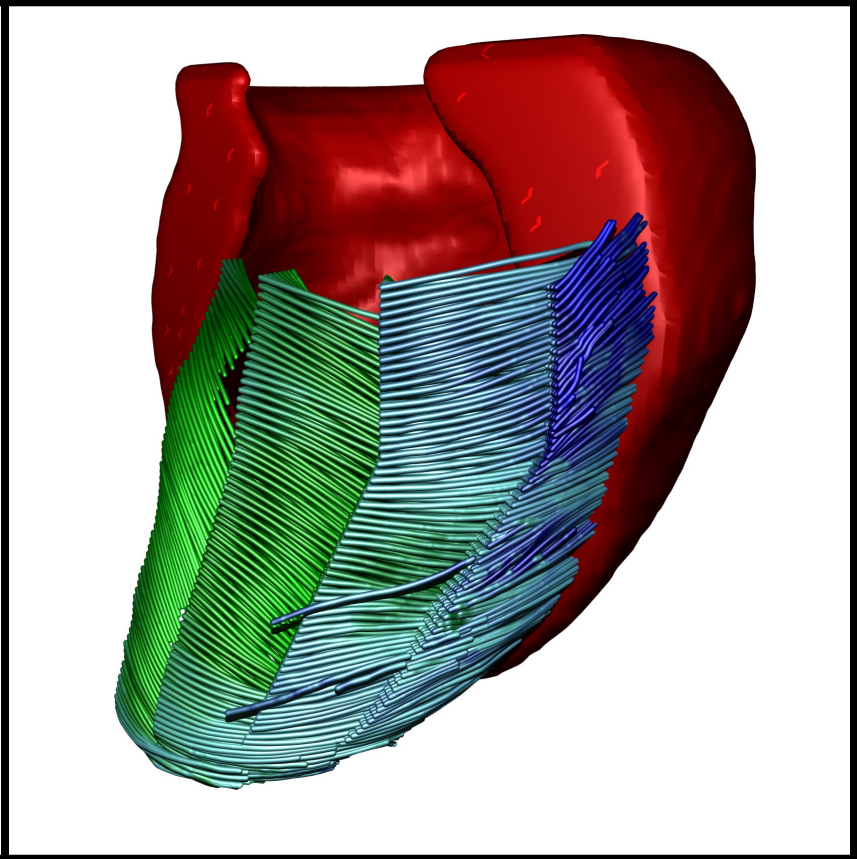
- **Results**
  - Helicoidal wrapping



4. Fiber Tracking

- **Results**
  - Smooth fiber angle change

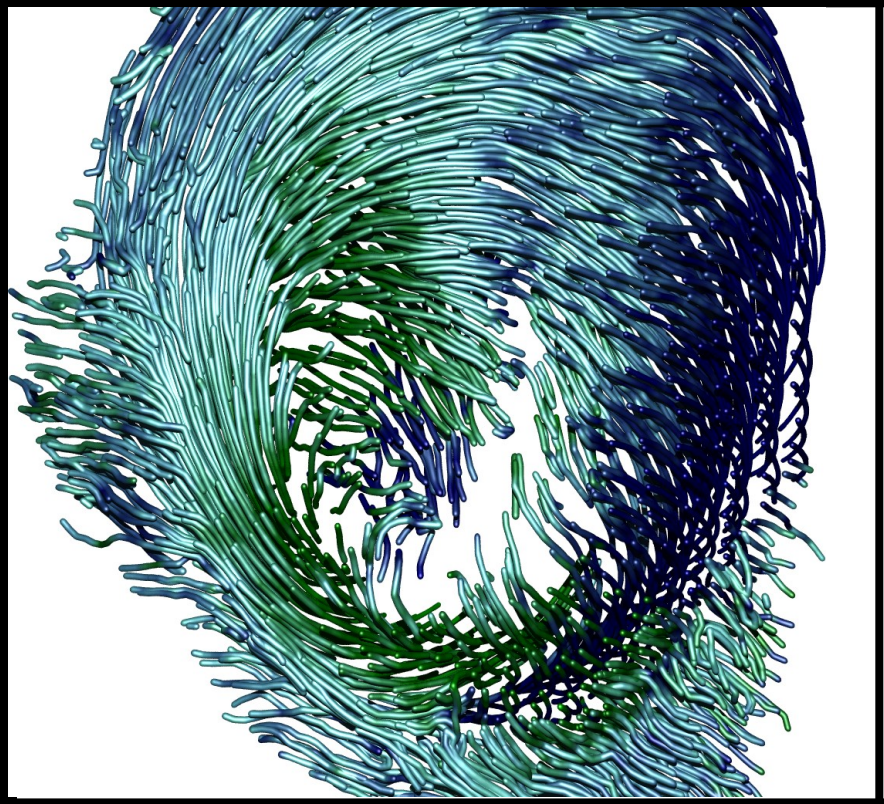


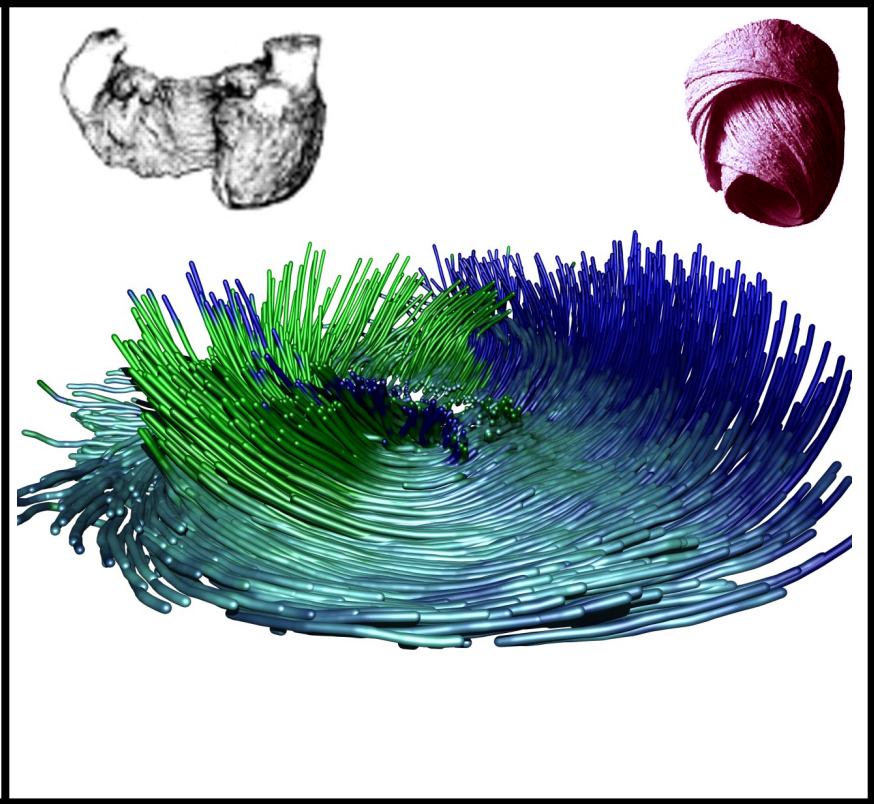


4. Fiber Tracking

- **Results**
  - **Apex**

Torrent-Guasp et al. Cardio-Thoracic surgery 2005



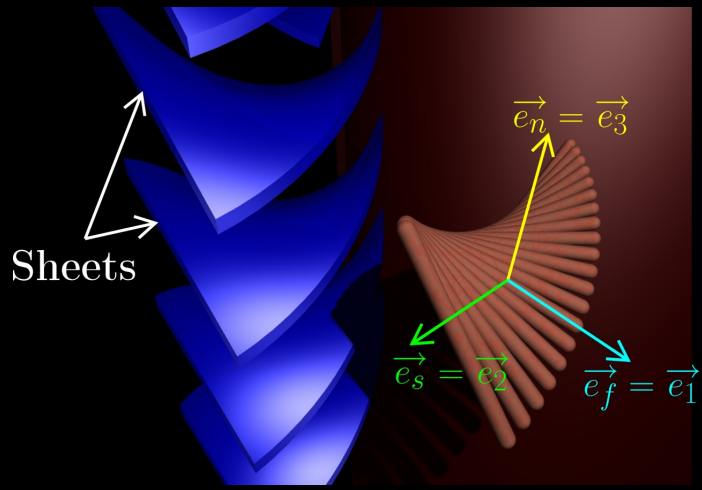


Summary

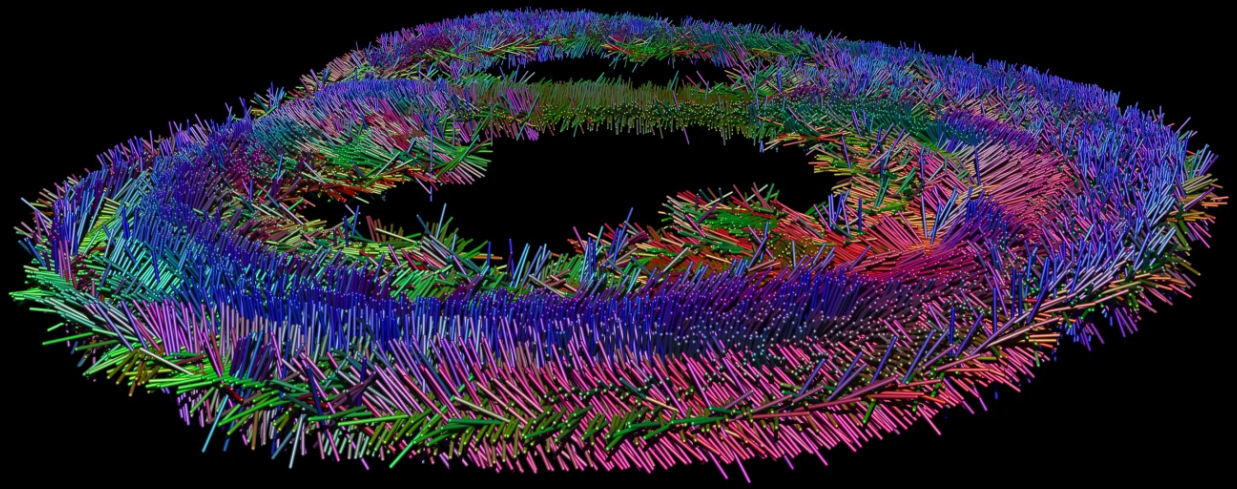
1. Structure of the heart
2. Diffusion Tensor
3. Visualization Methods
4. Fiber Tracking
5. Sheet Structure
   - Introduction
   - Method
     - Choice of the cross section direction
     - Perpendicular direction
   - Results
     - Sheet reconstruction
     - Fiber relation
     - Laminar structure
     - Apex
6. Conclusion

5. Sheet Structure

- **Introduction**



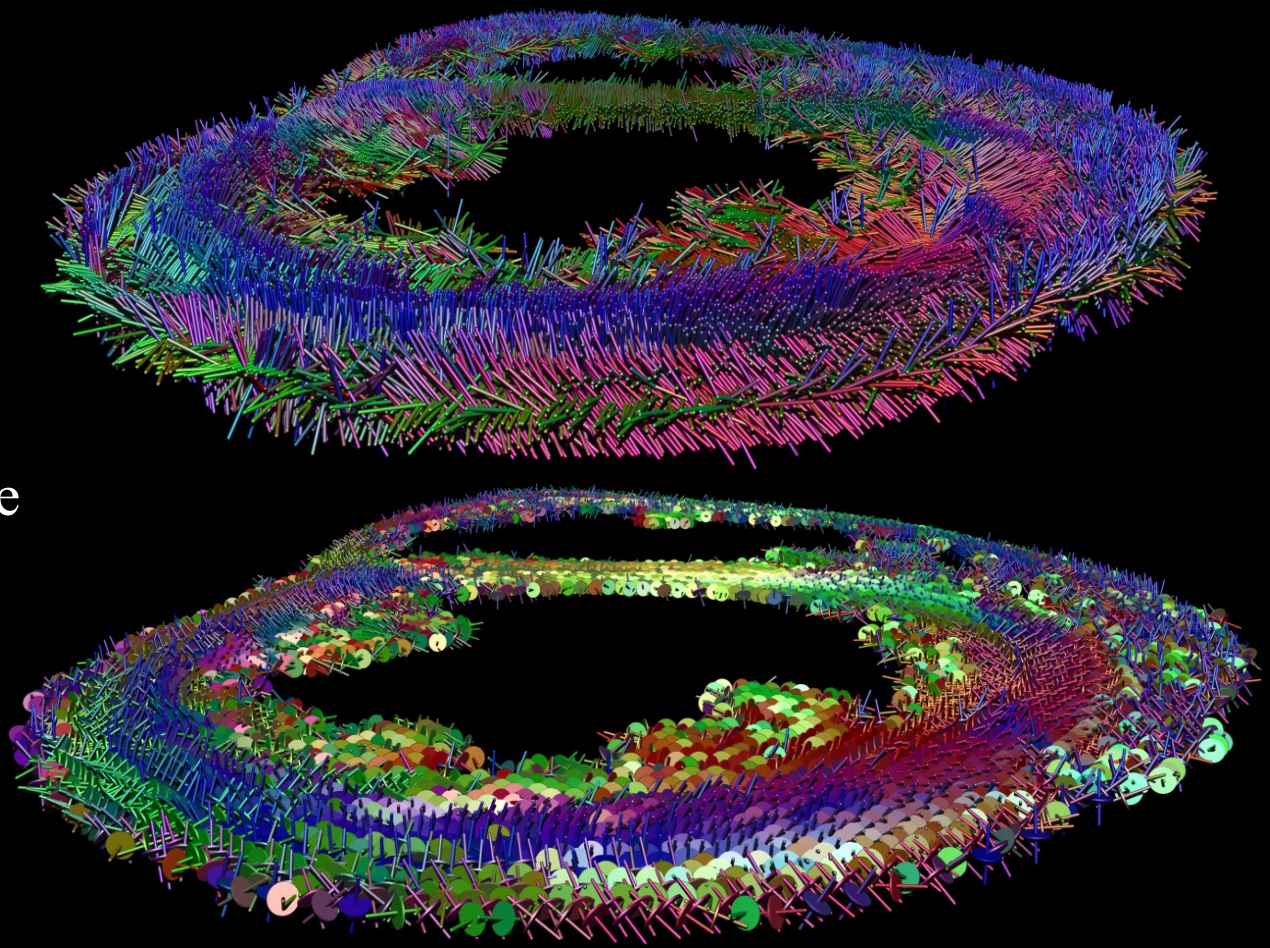
Slice of normal vectors



5. Sheet Structure

- **Introduction**

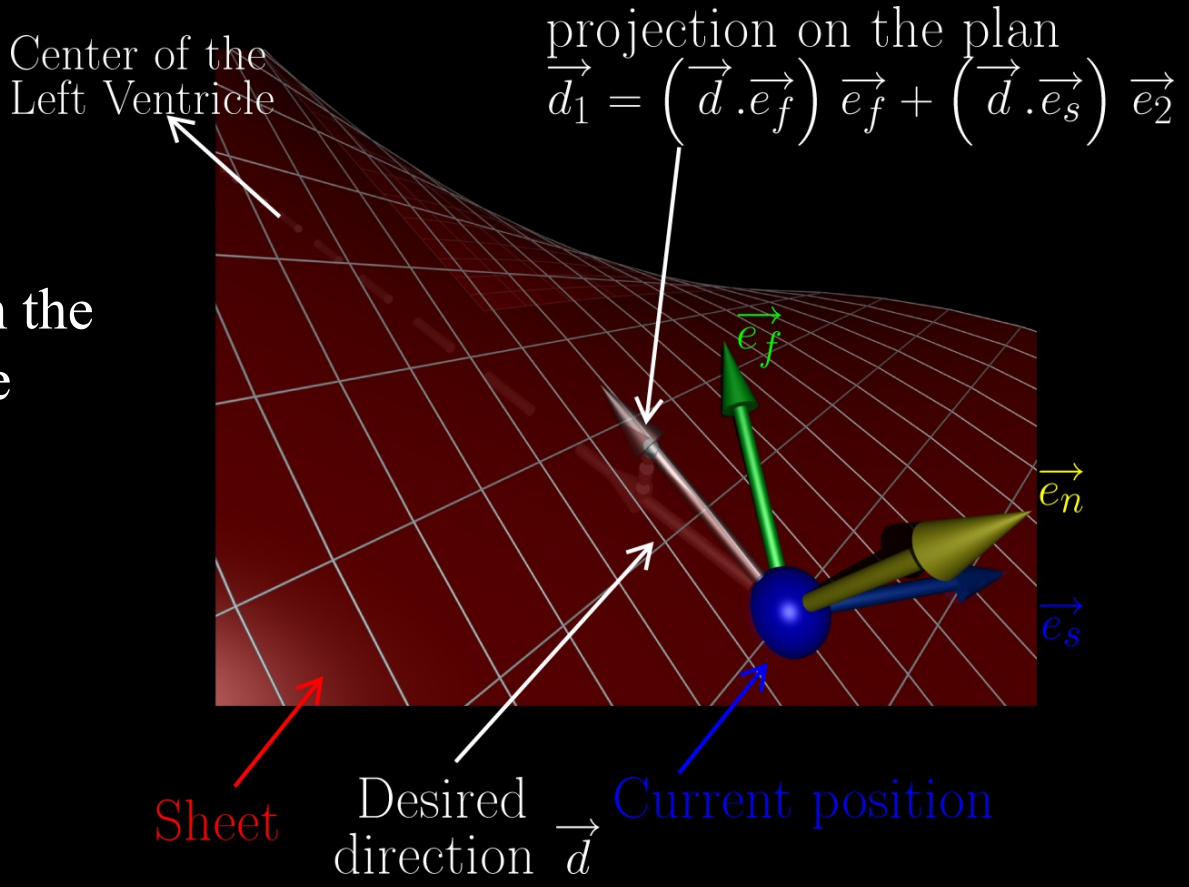
The normal vector defines the tangent plane



5. Sheet Structure

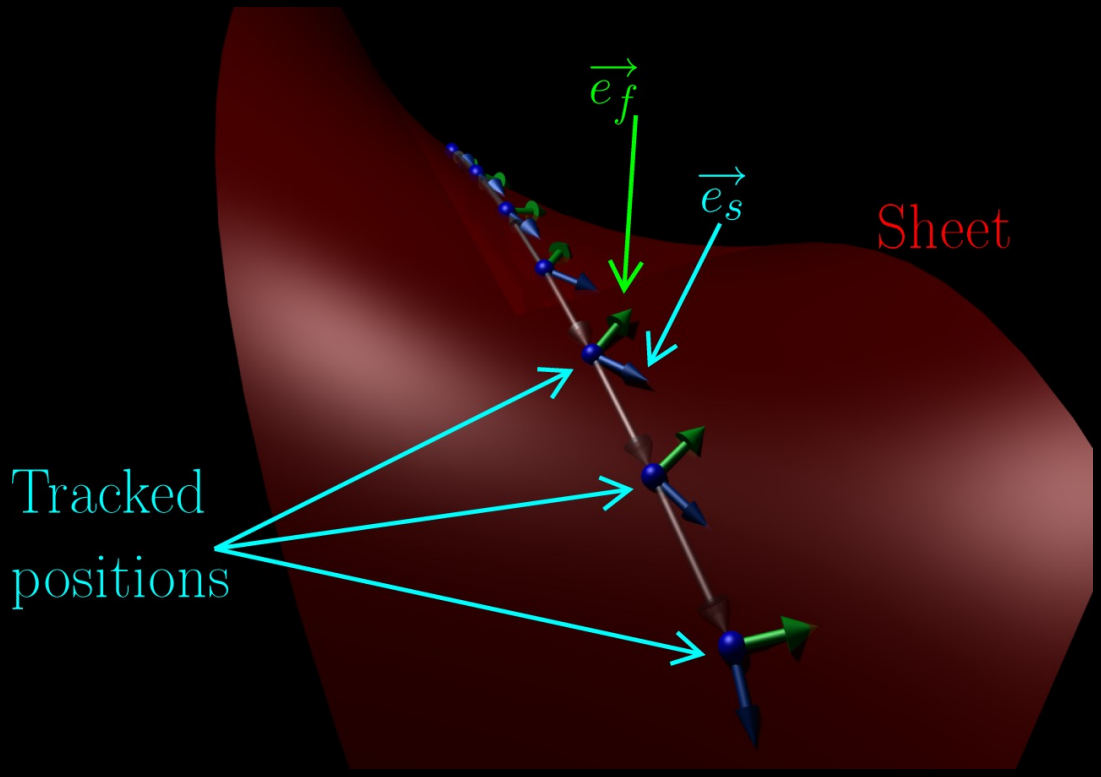
- **Method**
  - **Choice of cross section direction**

Projection on the tangent plane



5. Sheet Structure

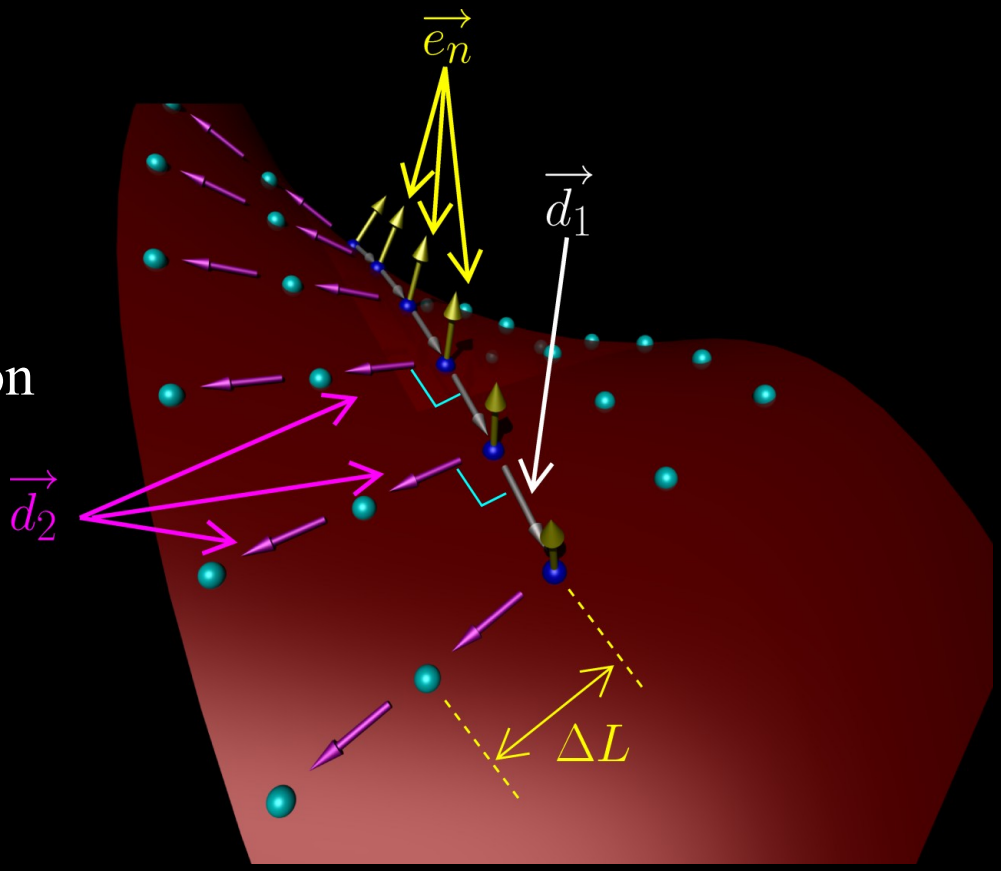
- **Method**
  - Choice of cross section direction



5. Sheet Structure

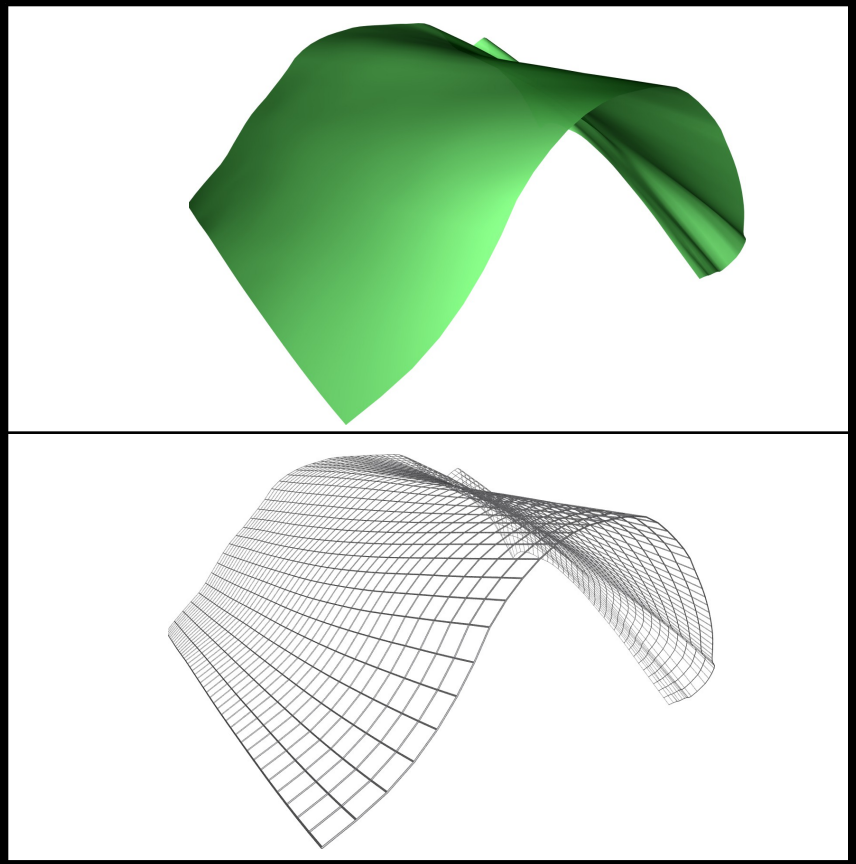
- **Method**
  - **Perpendicular direction**

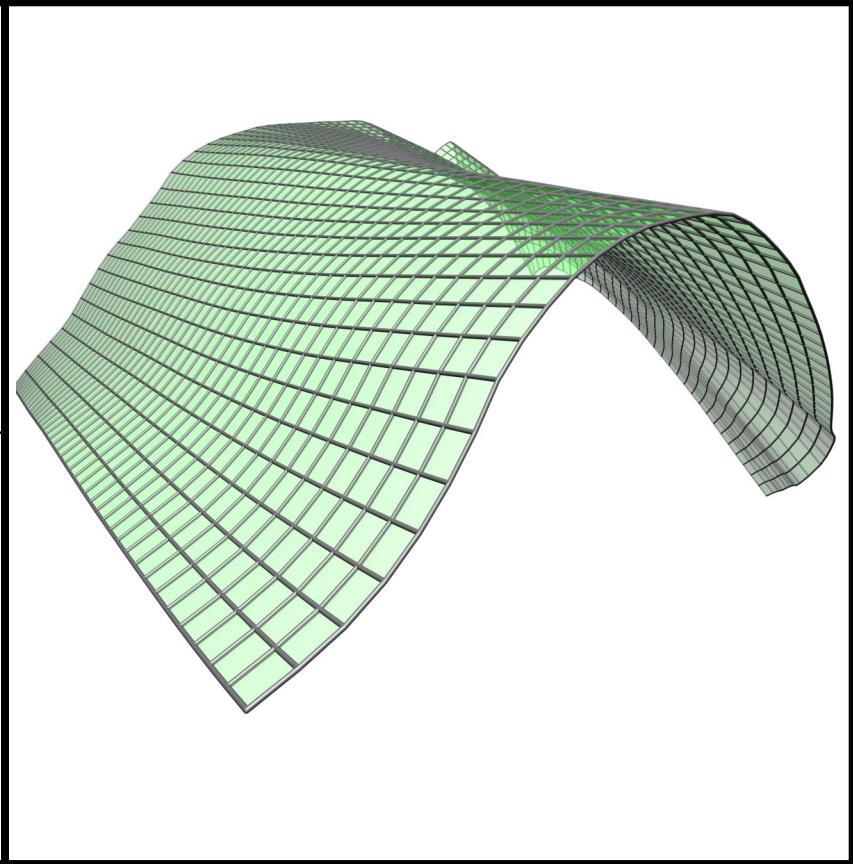
Rotate the previous direction around the normal



5. Sheet Structure

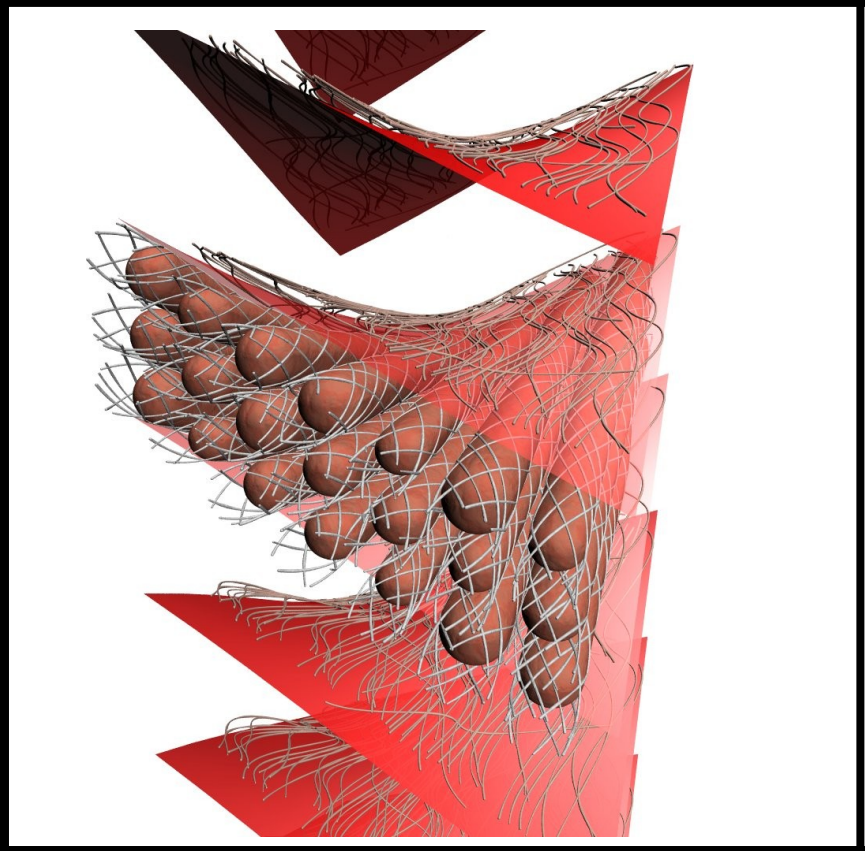
- **Results**
  - **Sheet reconstruction**

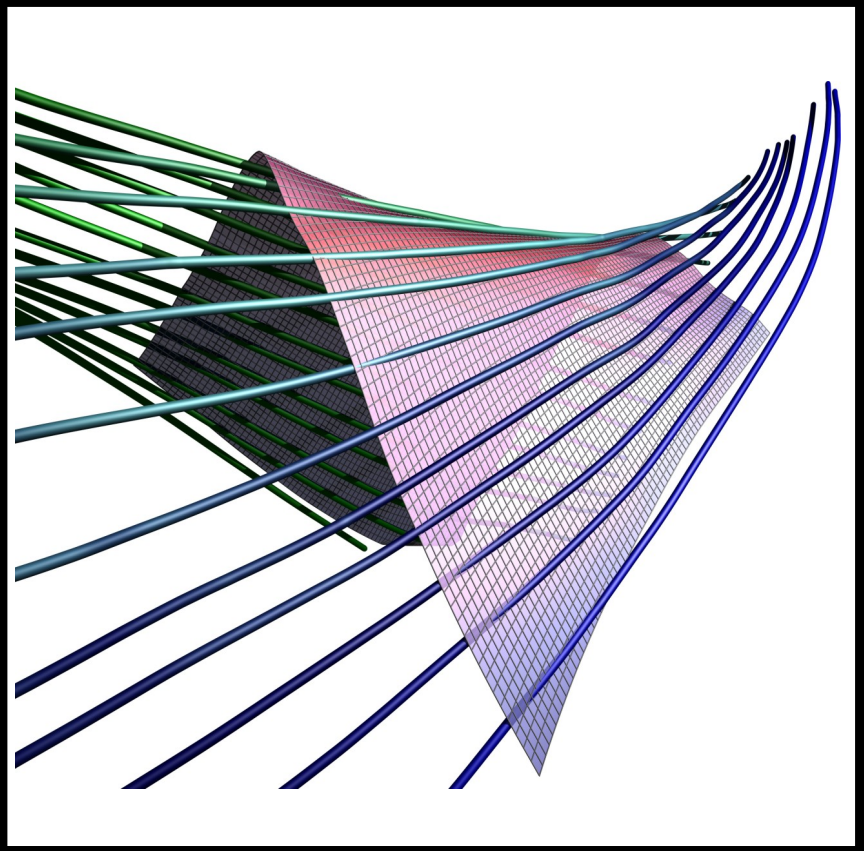




5. Sheet Structure

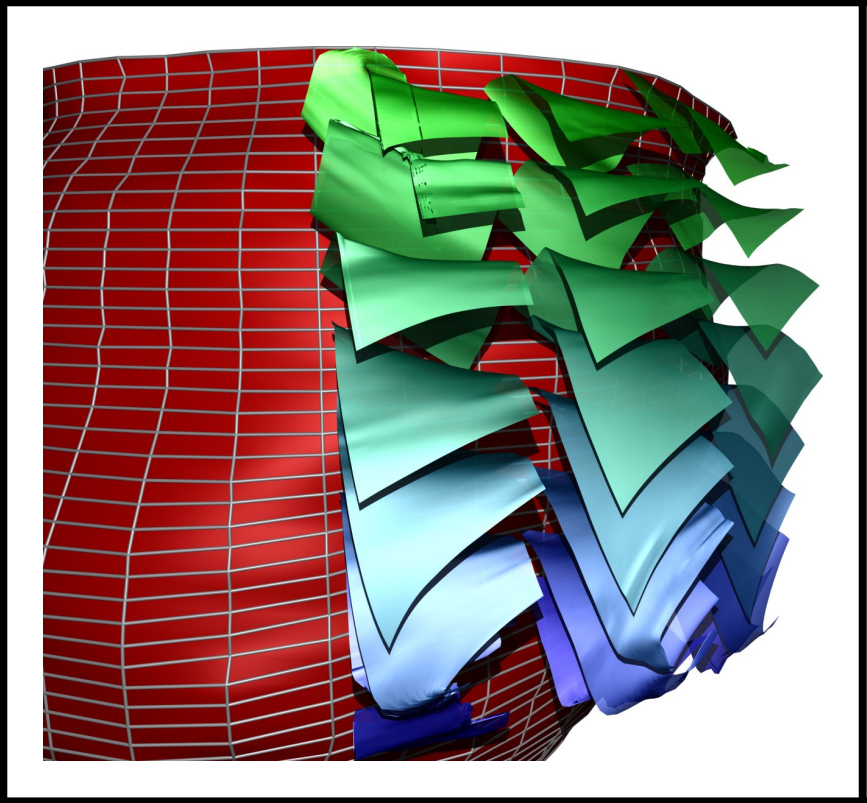
- **Results**
  - Fiber relation

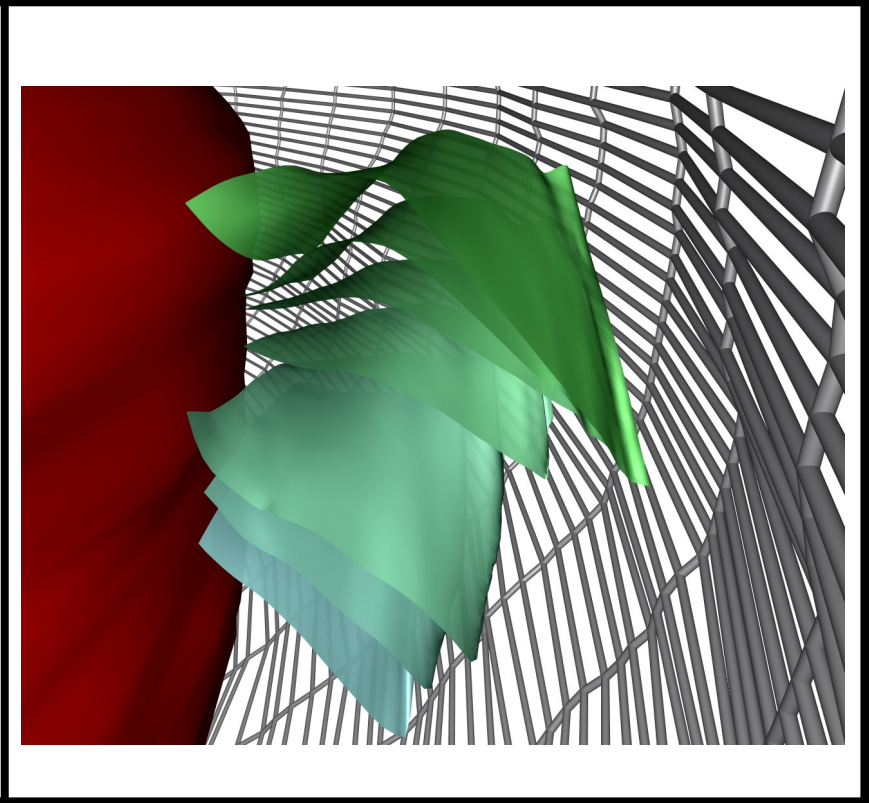




5. Sheet Structure

- **Results**
  - Laminar Structure

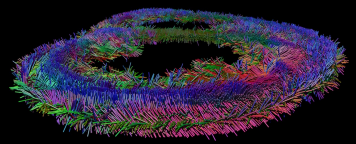


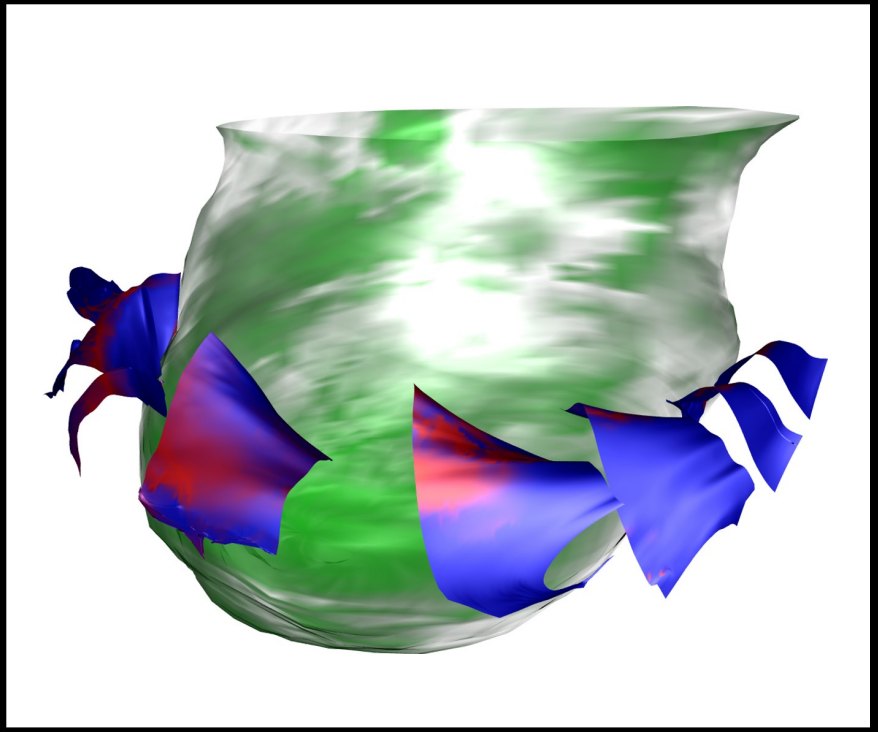


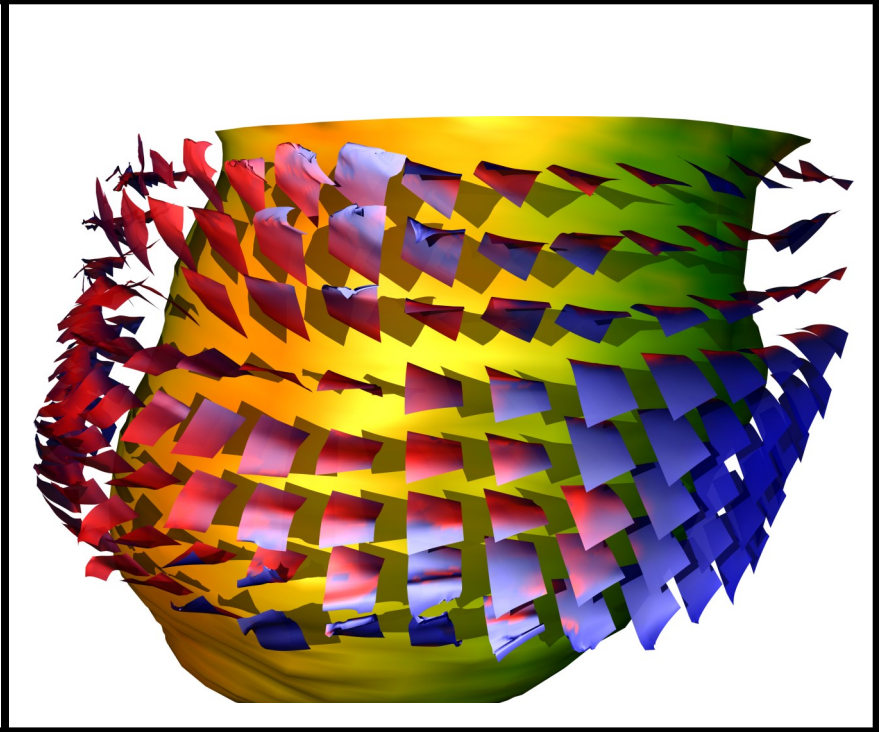
5. Sheet Structure

- **Results**
  - **Laminar Structure**

The structure is complex

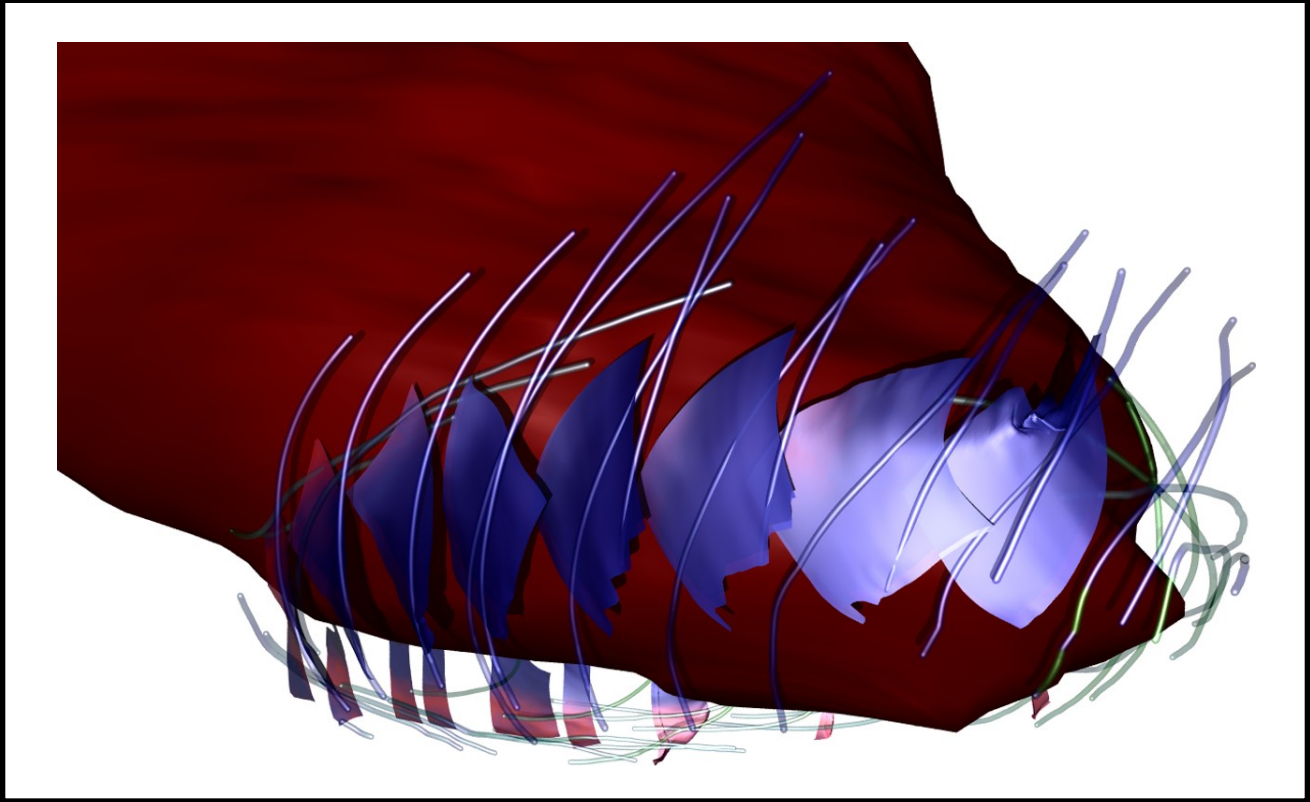






5. Sheet Structure

- **Results**
  - Apex

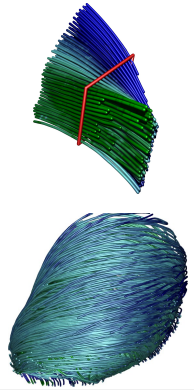
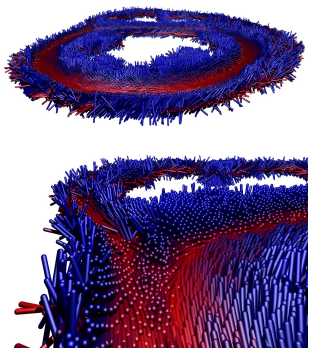


Summary

1. Structure of the heart
2. Diffusion Tensor
3. Visualization Methods
4. Fiber Tracking
5. Sheet Structure
6. Conclusion
   - Fiber Tracking
   - Sheet Reconstruction

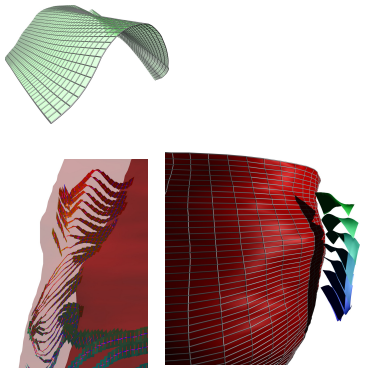
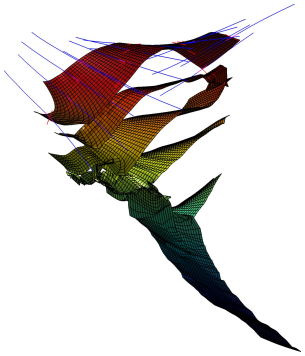
6. Conclusion

- **Fiber Tracking**

Results	•Smooth Results with MLS •Fit to the model (goes to +90º to -90º)	
Future Work	•Fiber tracking in the whole heart (papillary muscles, right ventricle) •Validation of the Band Theory (Torrent-Guasp)	

6. Conclusion

- **Sheet Reconstruction**

Results	•Smooth in the some regions •Correspond to the measurements in those regions	
Difficulties And future work	•Geometry is complex (cross section is not always the best direction) •Noise level (inversion, noise at the boundaries) •Need a check on the normal direction	

Acknowledgment

- Arkadiusz Sitek
- Grant T Gullberg