DT-MRI

- Measurement & Biology basics
- Tensor Shape & Orientation
- Data Inspection with Glyphs
- Fiber Tracking and Analysis
- Current Issues and Work

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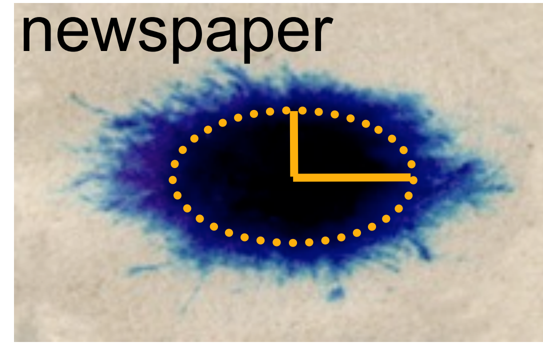
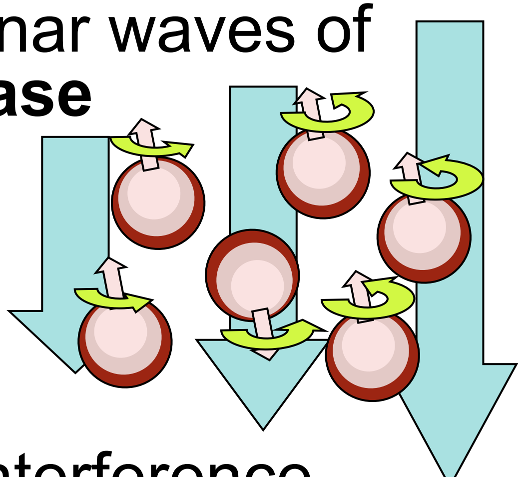
Diffusion-weighted MRI (DW-MRI)

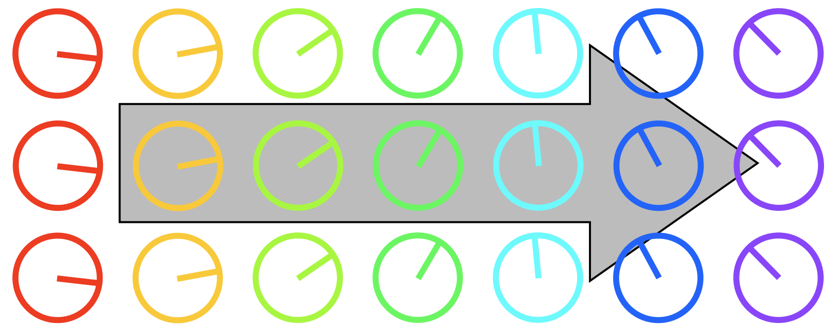
Brownian motion of one material through another

Anisotropy: diffusion rate depends on direction

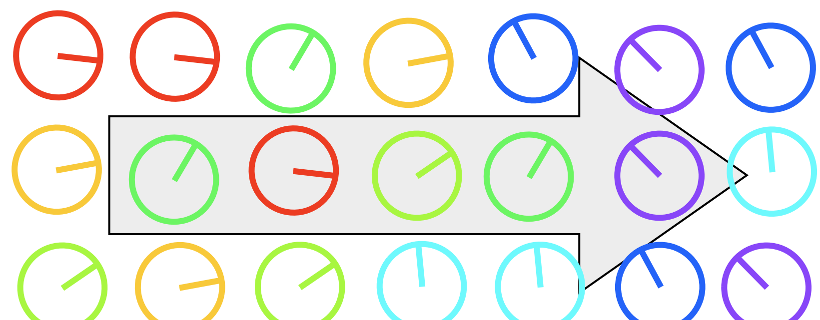


Magnetic gradients create spatial planar waves of proton **phase**

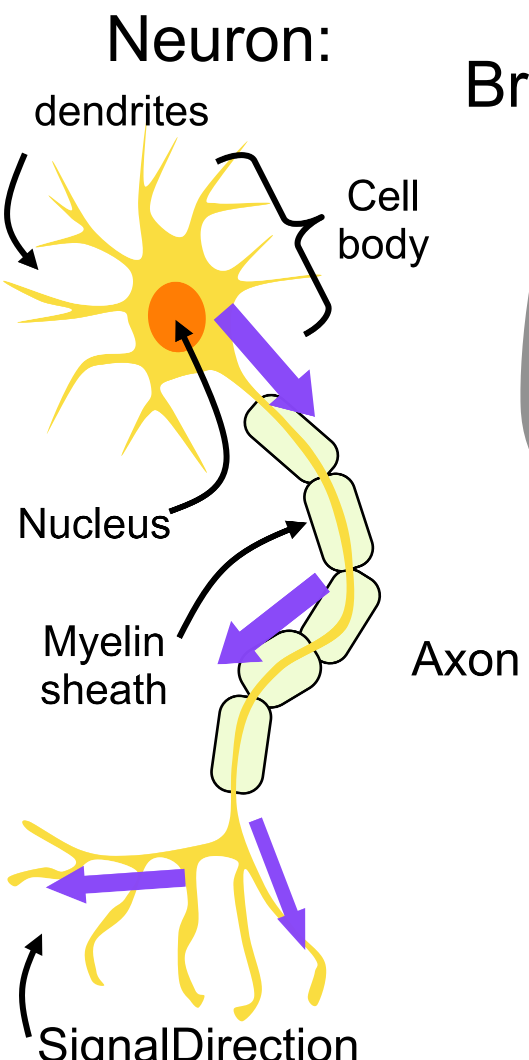


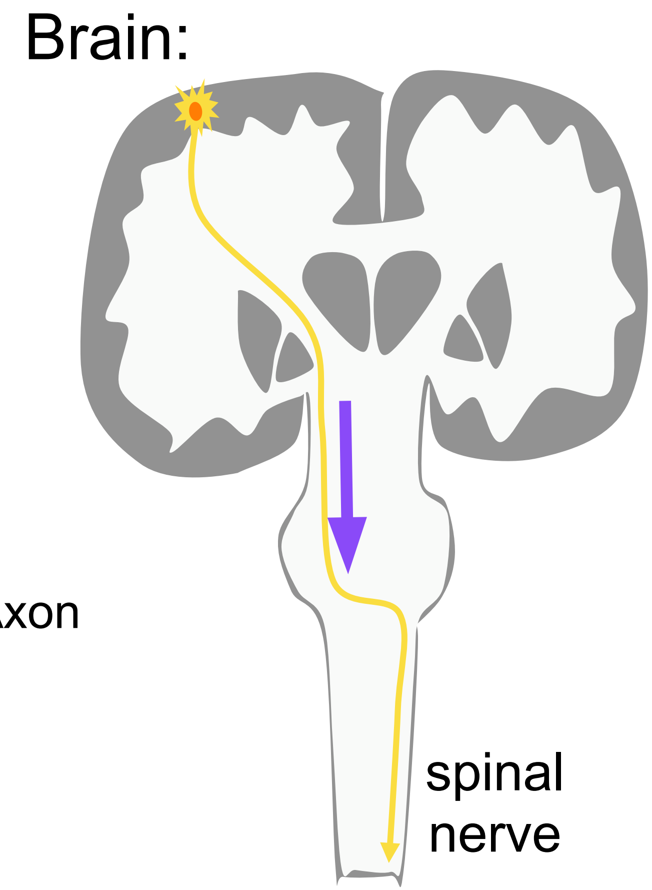


Destructive interference measures diffusion along gradient direction only



Underlying Biology (Simplified!)

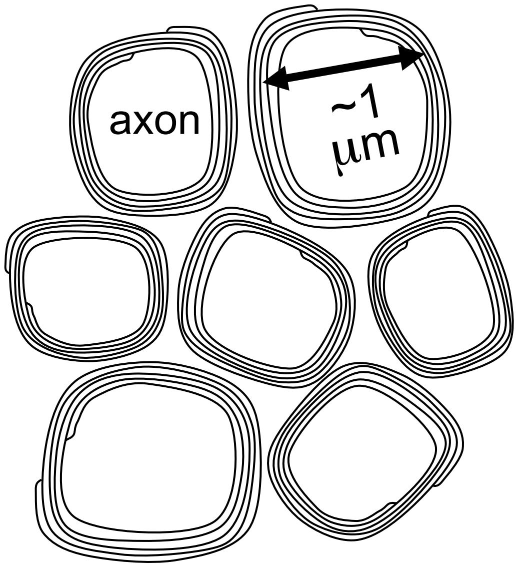




- Gray matter (cortex + nuclei): cell bodies
- White matter: axons
- Myelin sheath speeds signal conduction
- Axon + sheath = nerve fibers
- Major white matter pathways aggregate many fibers into bundles

Scales in anisotropy of DW-MRI

Fiber bundle
Cross-section:



Microstructure of bundles directionally constrains water diffusion along fiber direction (LeBihan et al. 1985)

Intra- vs. extra-cellular diffusion?

Diffusion lengths with the time-scale of MR measurement (TE ~= 100ms) on order of 10μm

Apparent diffusion coefficient: ADC

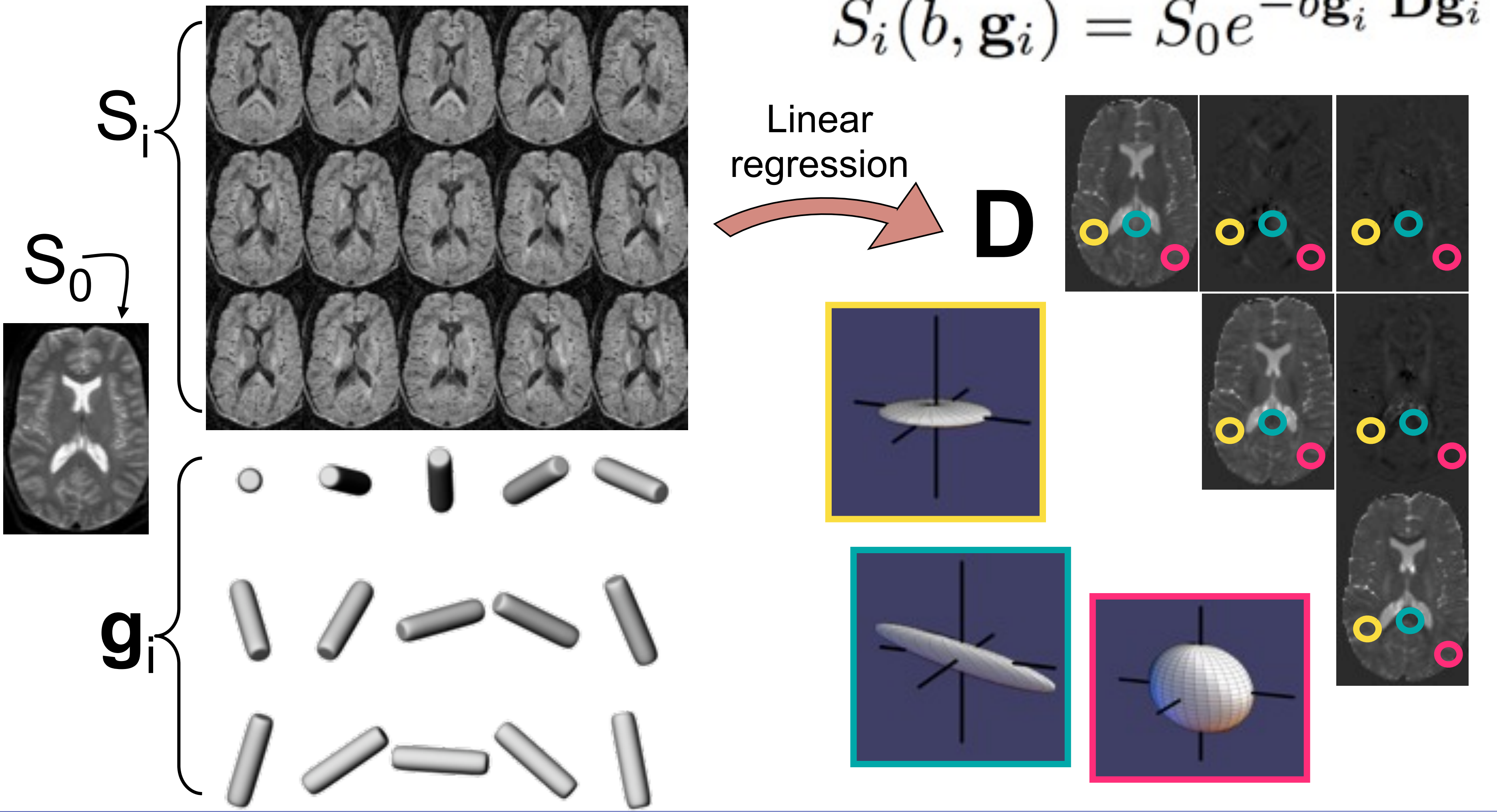
Voxels on the order of 1mm

⇒ **Two to three orders of magnitude away from measuring axons**

Multiple DWI → Tensor Estimate

Single Tensor Model (Basser et al. 1994)

$$S_i(b, \mathbf{g}_i) = S_0 e^{-b\mathbf{g}_i^T \mathbf{D} \mathbf{g}_i}$$



Applications

Images from Virtual Hospital (www.vh.org)

- Neuroanatomy (in vivo)
- Neurosurgery: tumor/ tract relationship
- Ischemic stroke: detection
- Degenerative diseases: ALS, Multiple Sclerosis
- Psychiatric disorders: Schizophrenia, Autism

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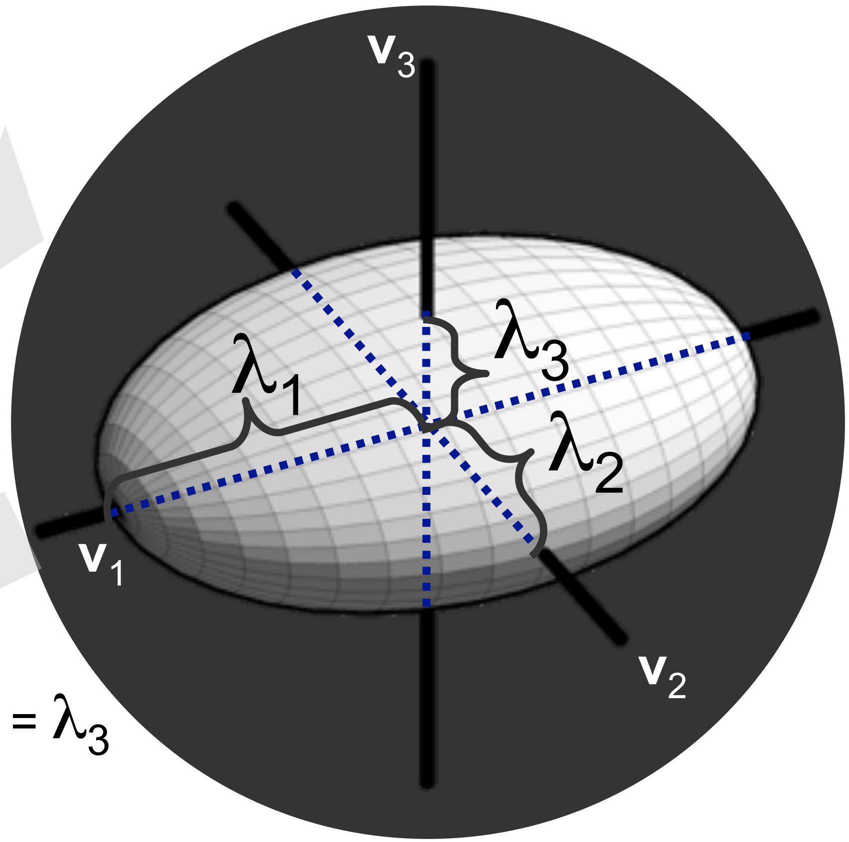
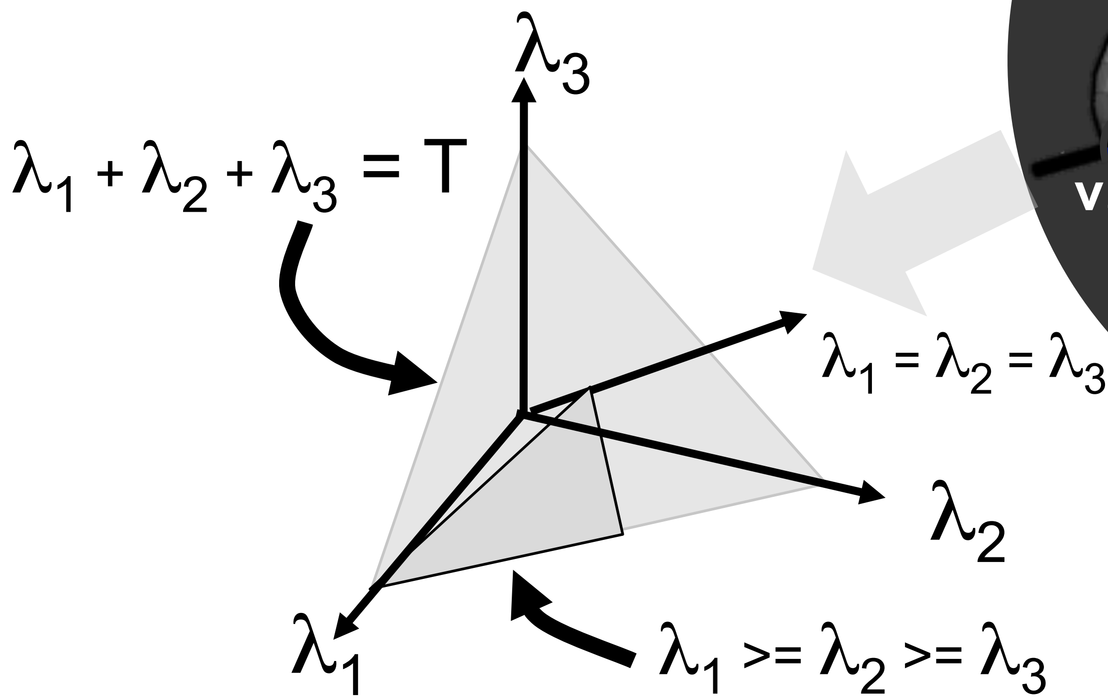
Eigenvalues == Shape

$$D = R \Lambda R^{-1}$$

$$= \begin{bmatrix} \mathbf{v}_1 & \mathbf{v}_2 & \mathbf{v}_3 \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \begin{bmatrix} \mathbf{v}_1 \\ \mathbf{v}_2 \\ \mathbf{v}_3 \end{bmatrix}$$

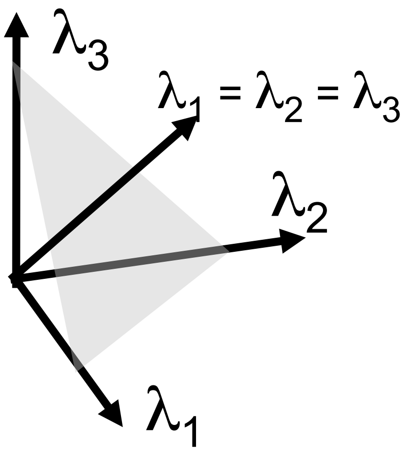




Tensor shape always has 3 degrees of freedom

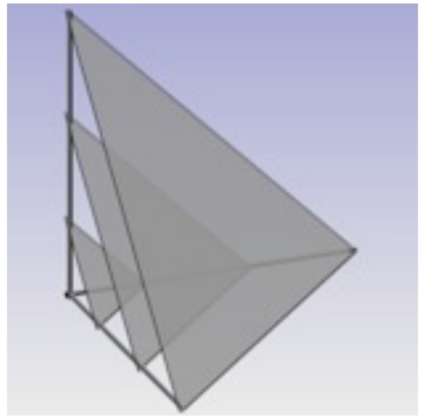
Tensor invariants as orthogonal shape parameterizations

Cylindrical or spherical coordinates
(Ennis & Kindlmann 2005)

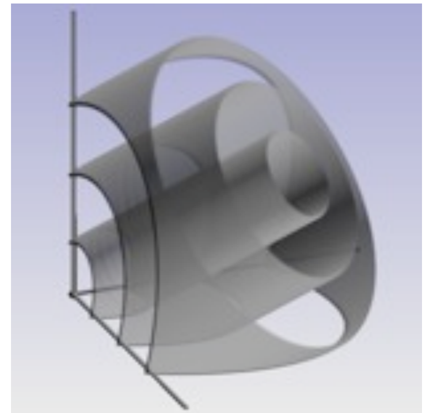


tr(**D**) = Dxx+Dyy+Dzz
|**D**| = sqrt(tr($\mathbf{D}^T\mathbf{D}$))

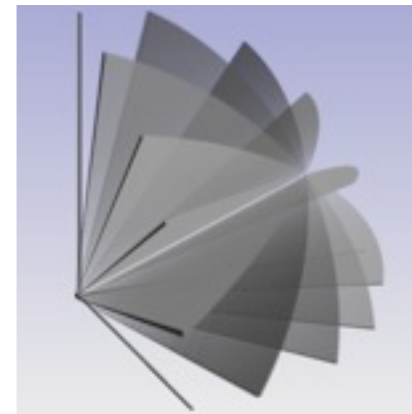
E = deviatoric(**D**)
= **D** - trace(**D**)*$\mathbf{I}$/3



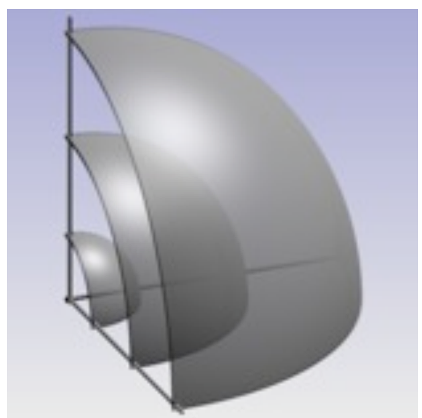
tr(**D**)



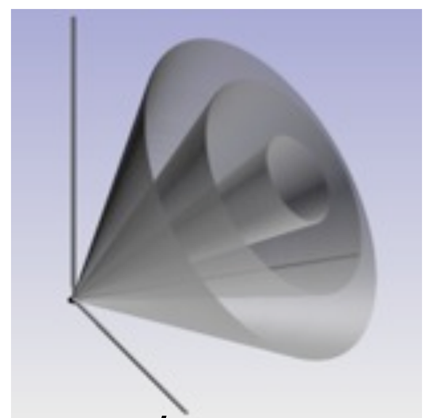
|**E**|



mode(**E**)
= det(**E**/|**E**|)
(Criscione '00)
Mode measures
Linear vs. planar
anisotropy



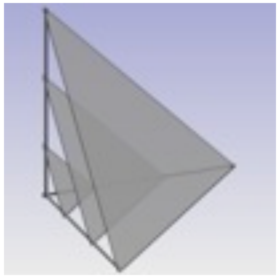
|**D**|



|**E**|/|**D**| ~= FA
FA = **Fractional Anisotropy**

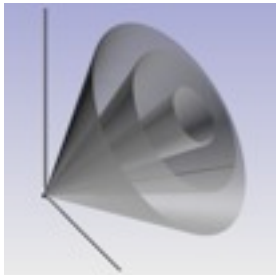
Biological Meaning of Tensor Shape

Size: **bulk mean diffusivity** (“ADC”)



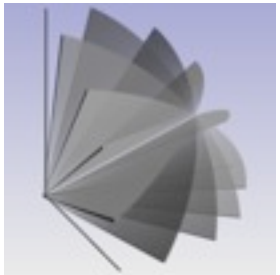
- ADC strictly speaking diffusivity along **one** direction
- Note: same across gray+white matter, high in CSF
- Indicator of acute ischemic stroke

Anisotropy (e.g. FA): directional microstructure



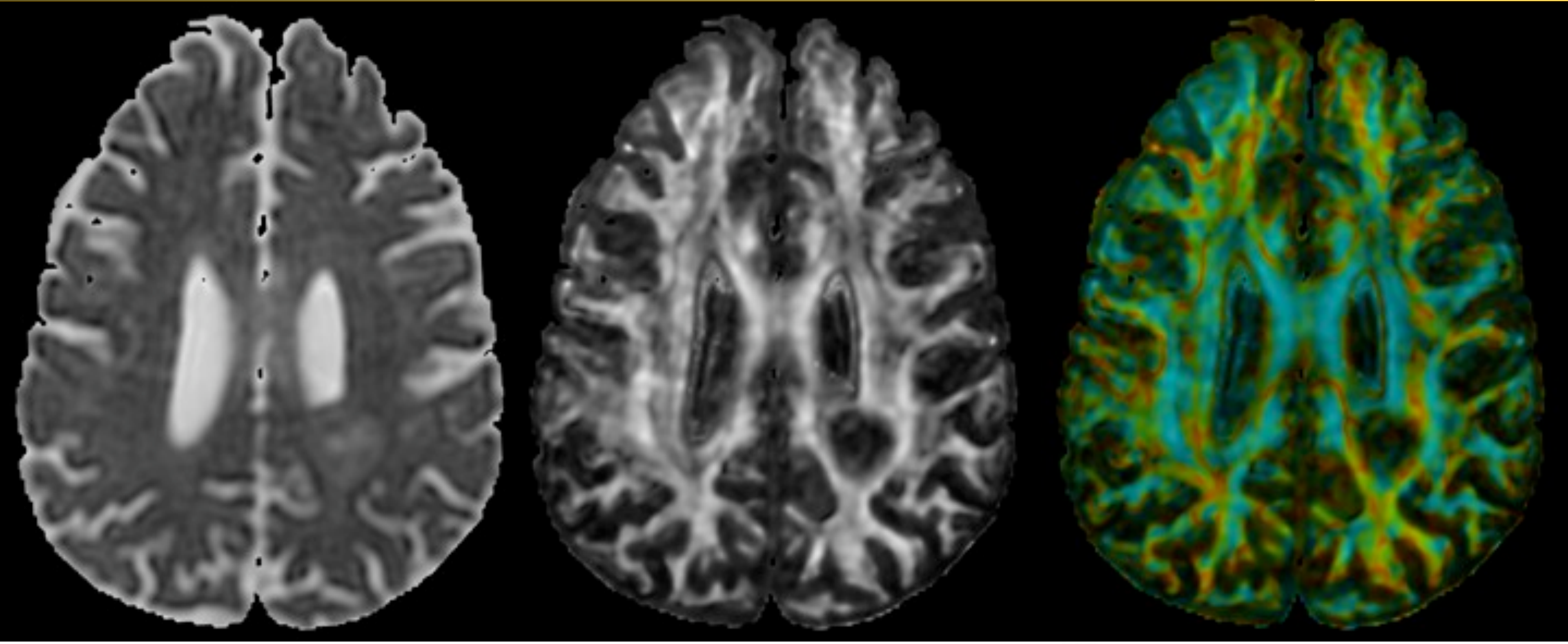
- High in white matter, low in gray matter and CSF
- Increases with myelination, decreases in some diseases (Multiple Sclerosis)

Mode: linear versus planar



- Partial voluming of adjacent orthogonal structures
- Fine-scale mixing of diverse fiber directions
- Tensor fitting error increases with planarity (Tuch 2002)

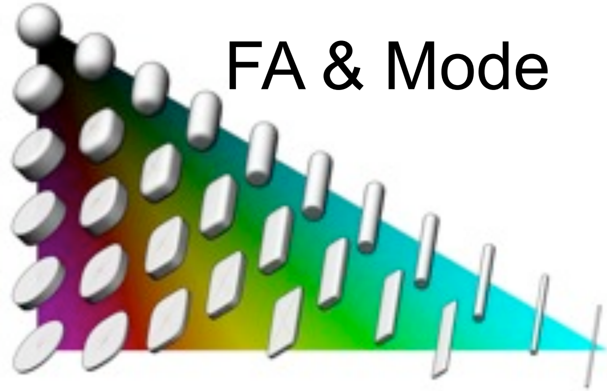
Tensor shape on one slice



Trace

Fractional Anisotropy

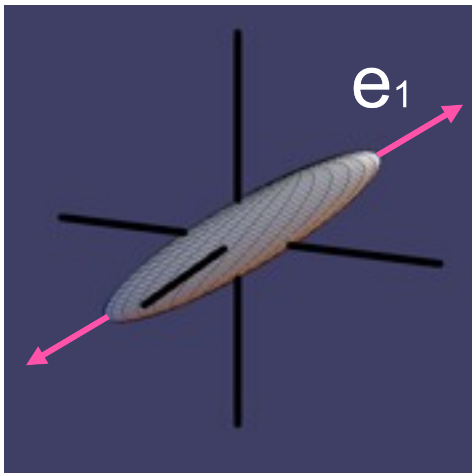
FA & Mode

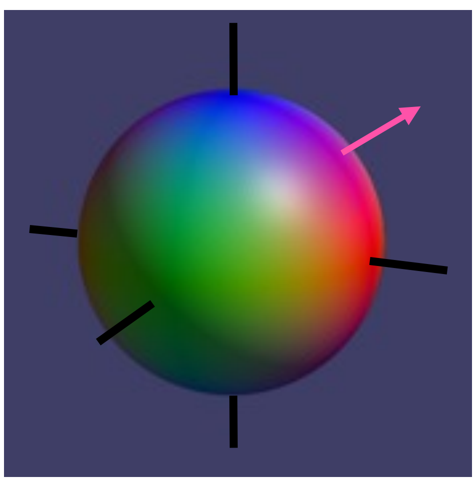


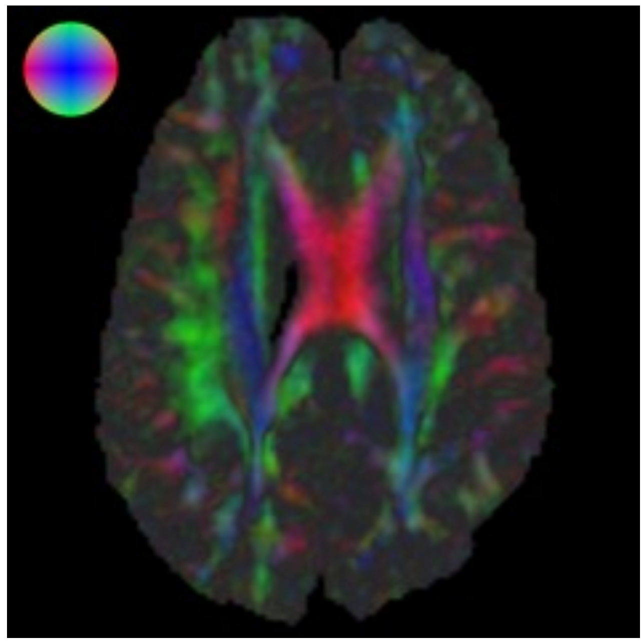
"Anisotropy" is a bivariate quantity

Tensor Orientation: 1st Eigenvector

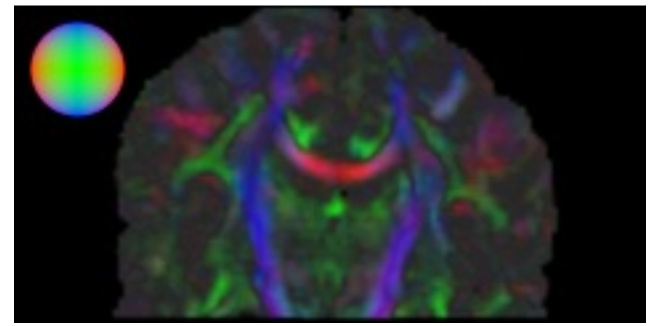
Principal eigenvector gives axon bundle direction



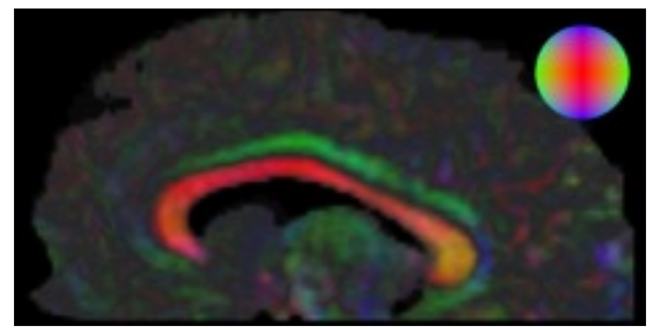




Axial



Coronal



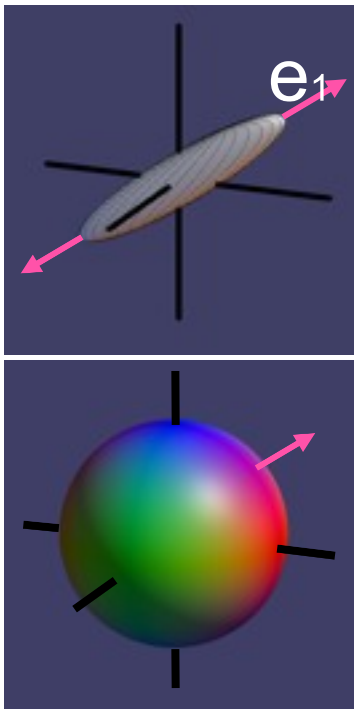
Sagittal

R=$| \mathbf{e}_1 \cdot x |$

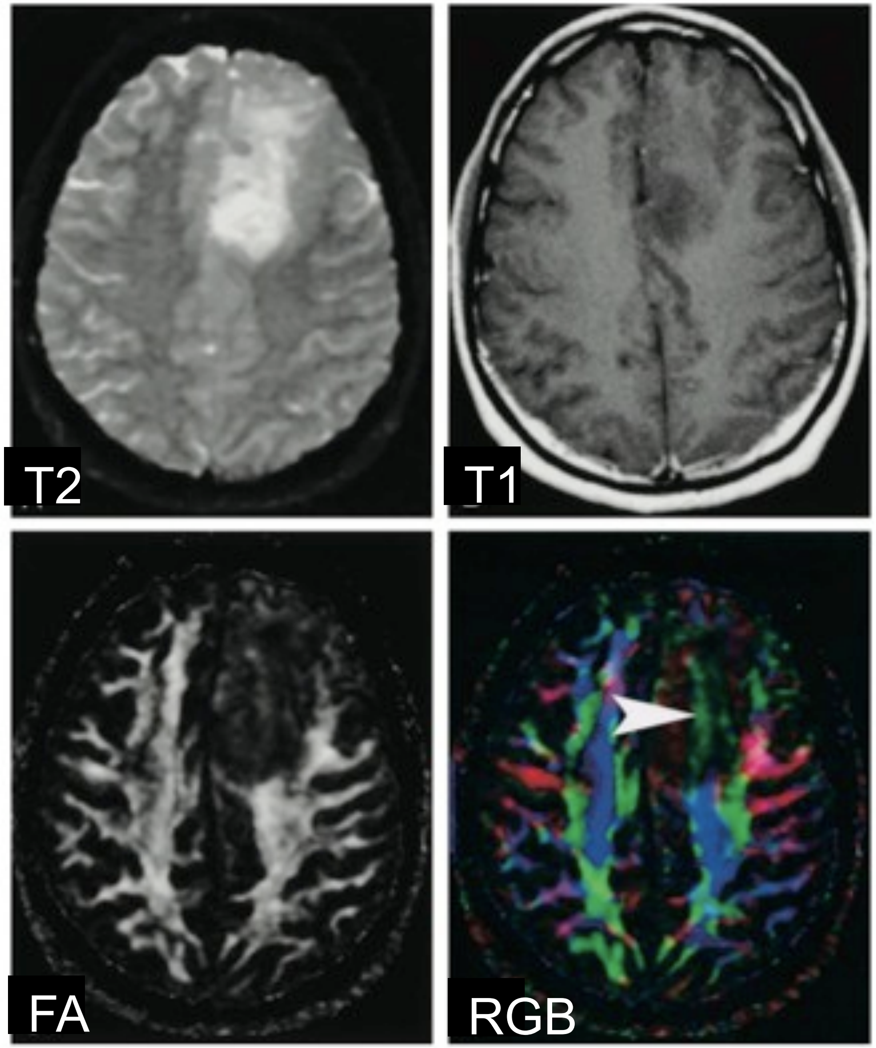
G=$| \mathbf{e}_1 \cdot y |$ (Pajevic & Pierpaoli, 1999)

B=$| \mathbf{e}_1 \cdot z |$

RGB maps for tumors



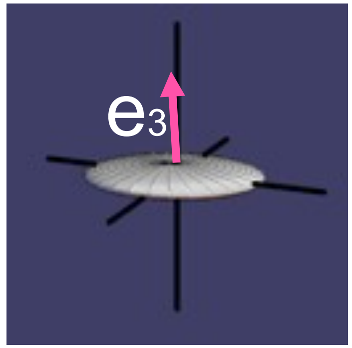
Jellison et al. 2004

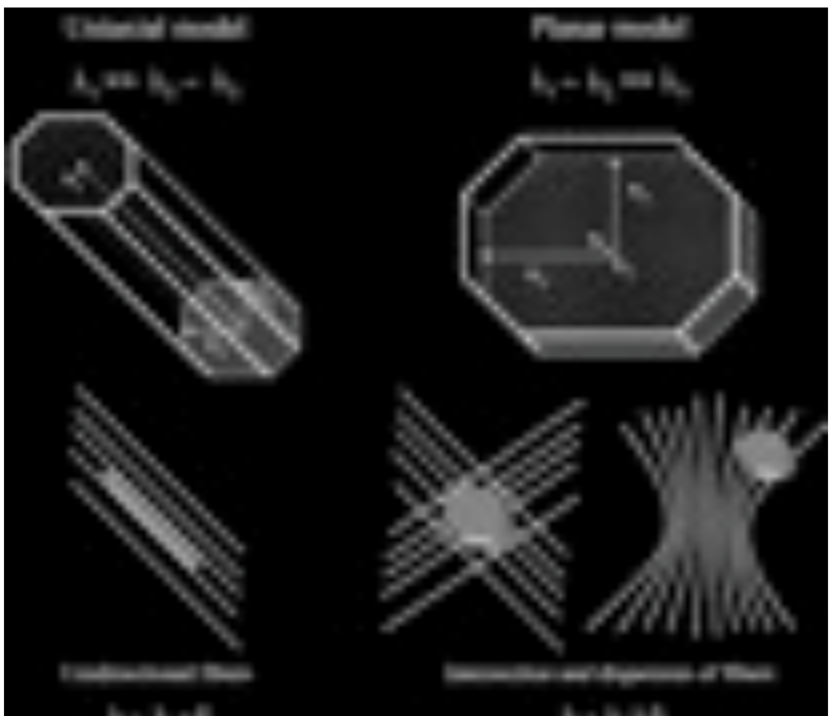


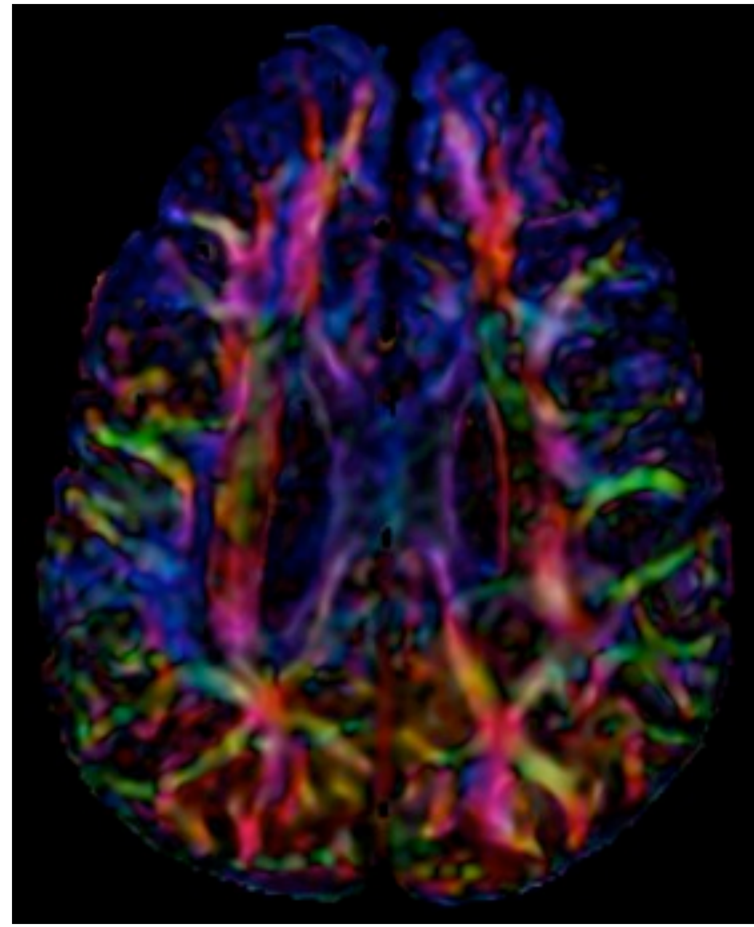
- Allows view of affected region in and around tumor
- 2D views still common for brain surgery planning
- RGB map illustrates changes in white matter

Tensor Orientation: 3rd Eigenvector

Minor eigenvector: direction of **least** diffusion







Significant and coherent planar anisotropy, e.g. around tumor

Wiegell et al. 2000

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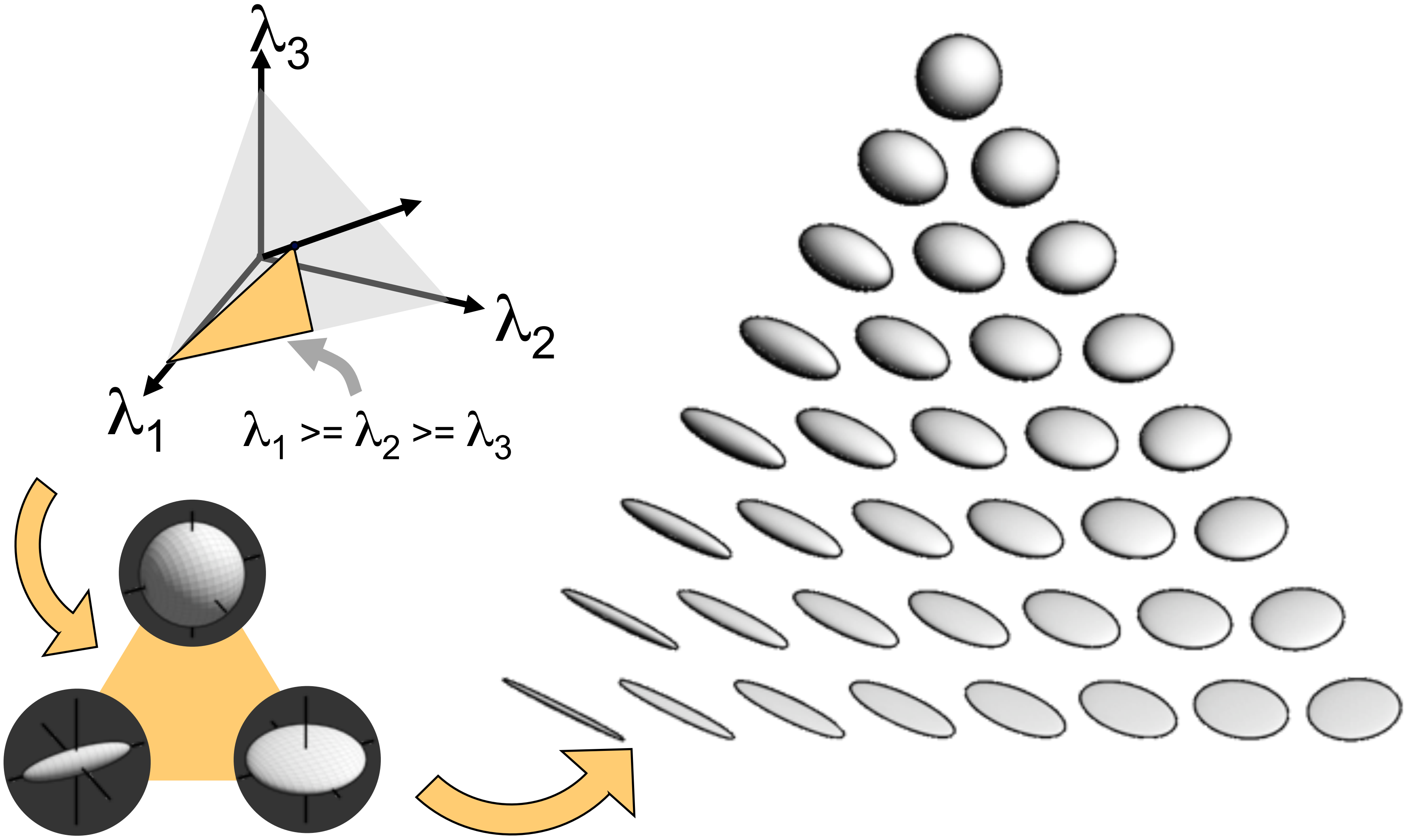
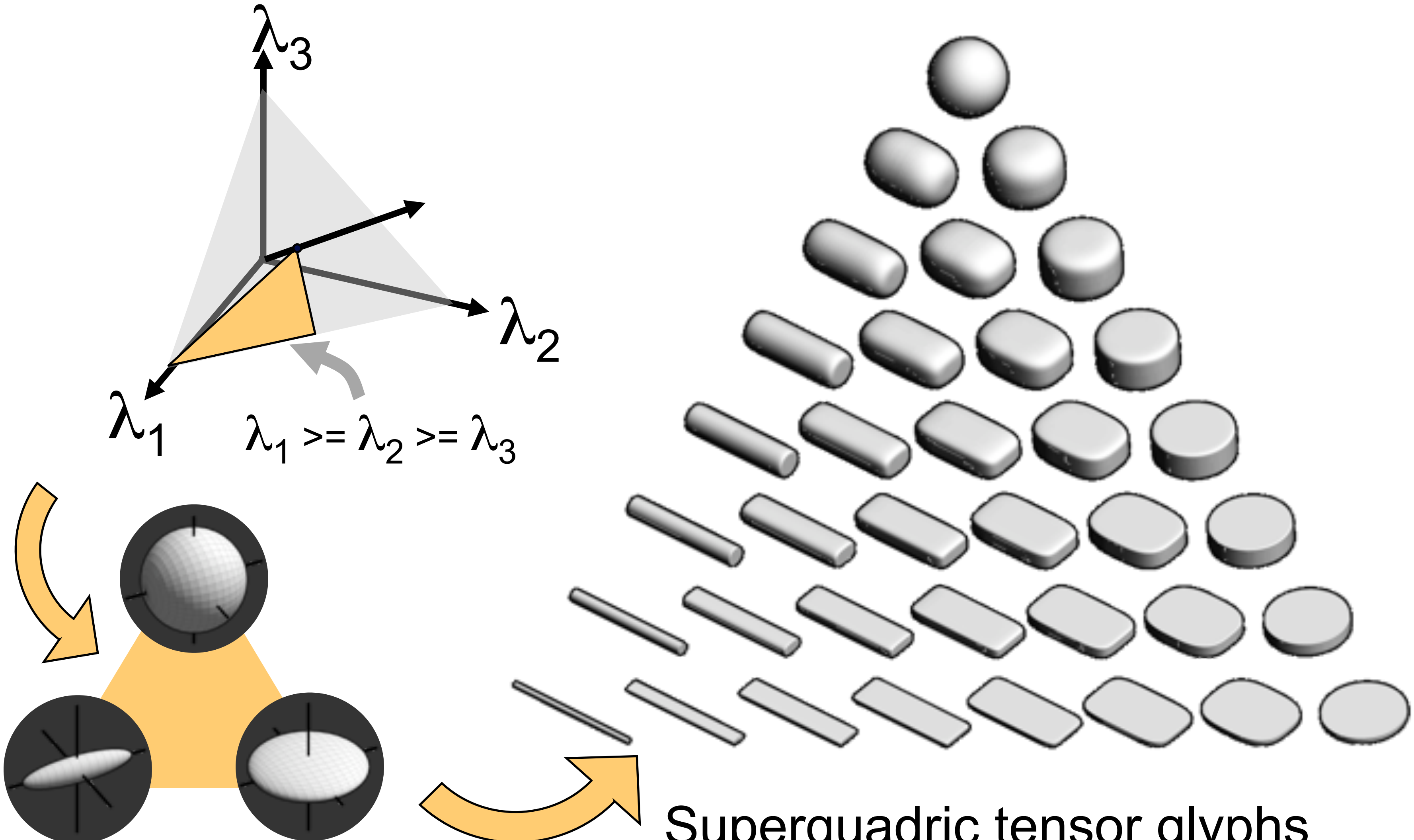
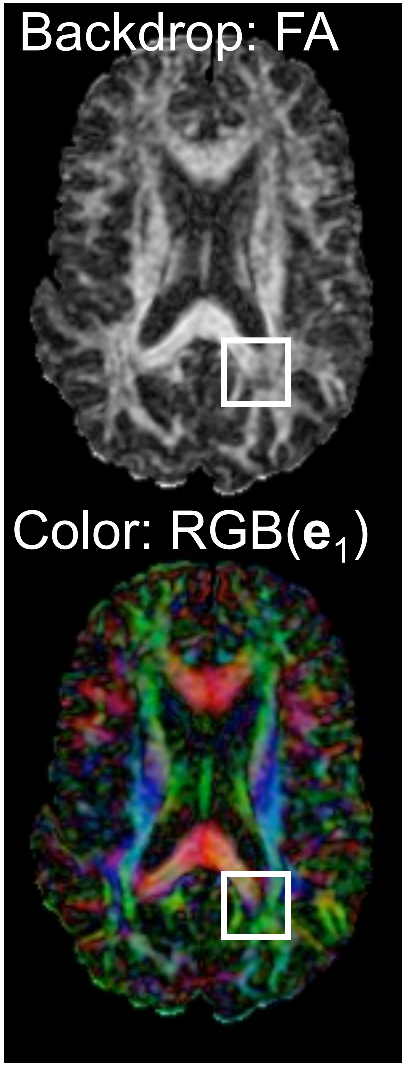
Glyphs for Range of Tensor Shape

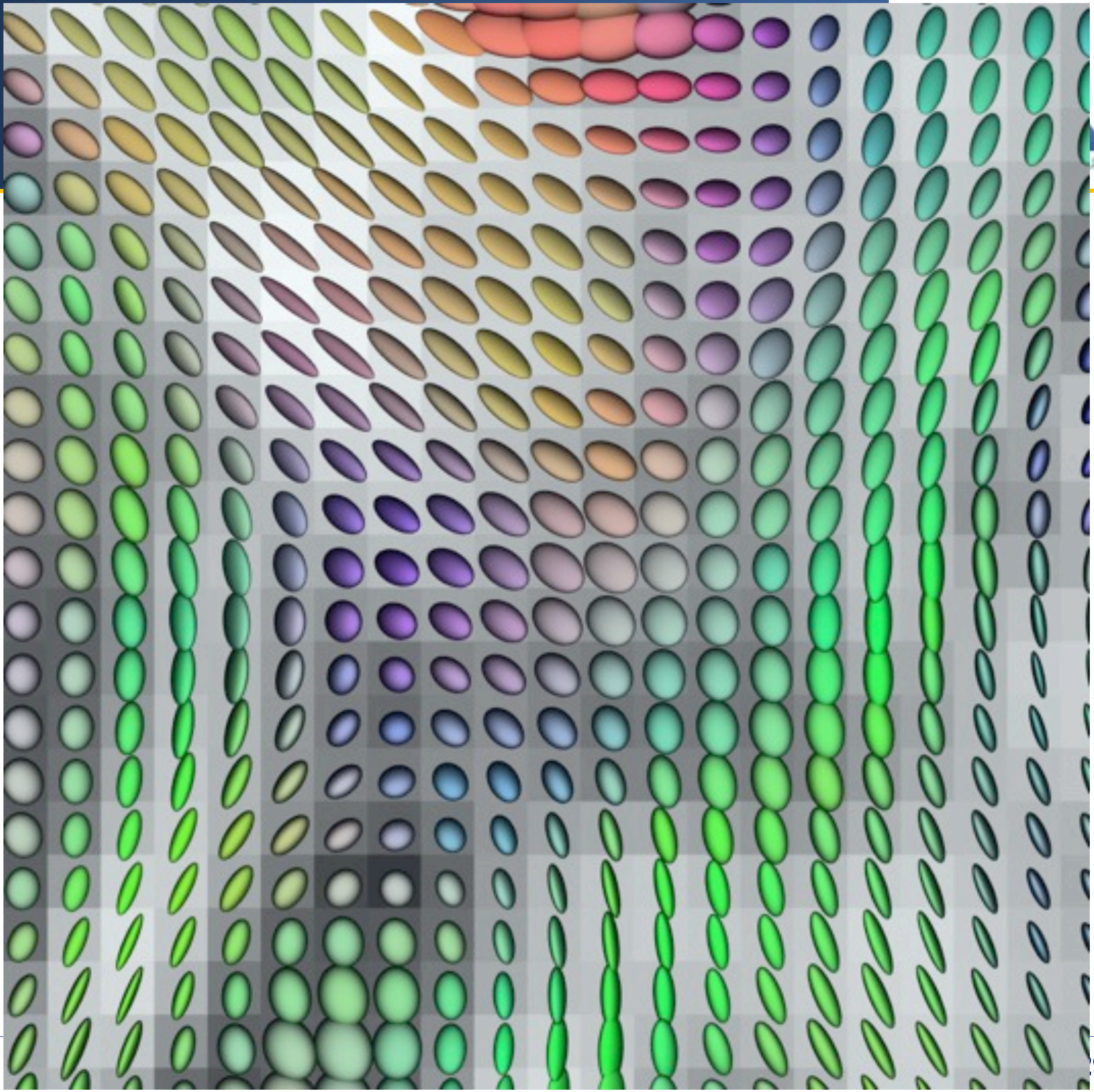


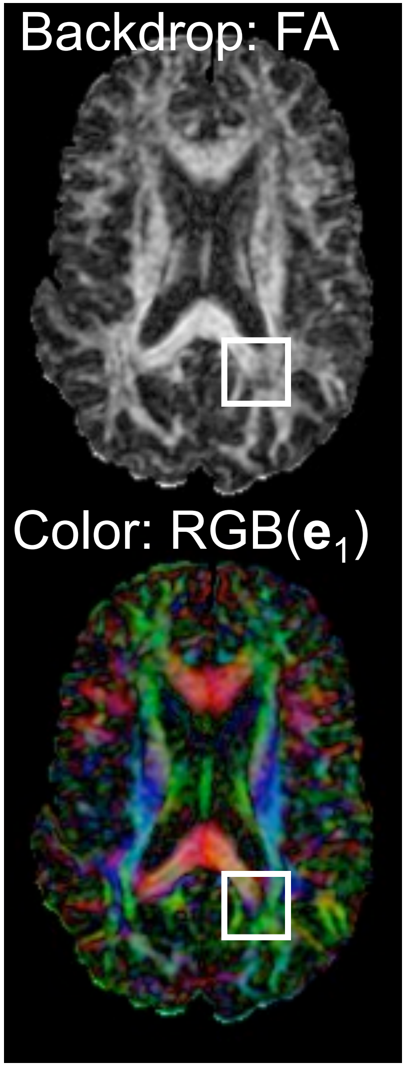
Glyphs for Range of Tensor Shape

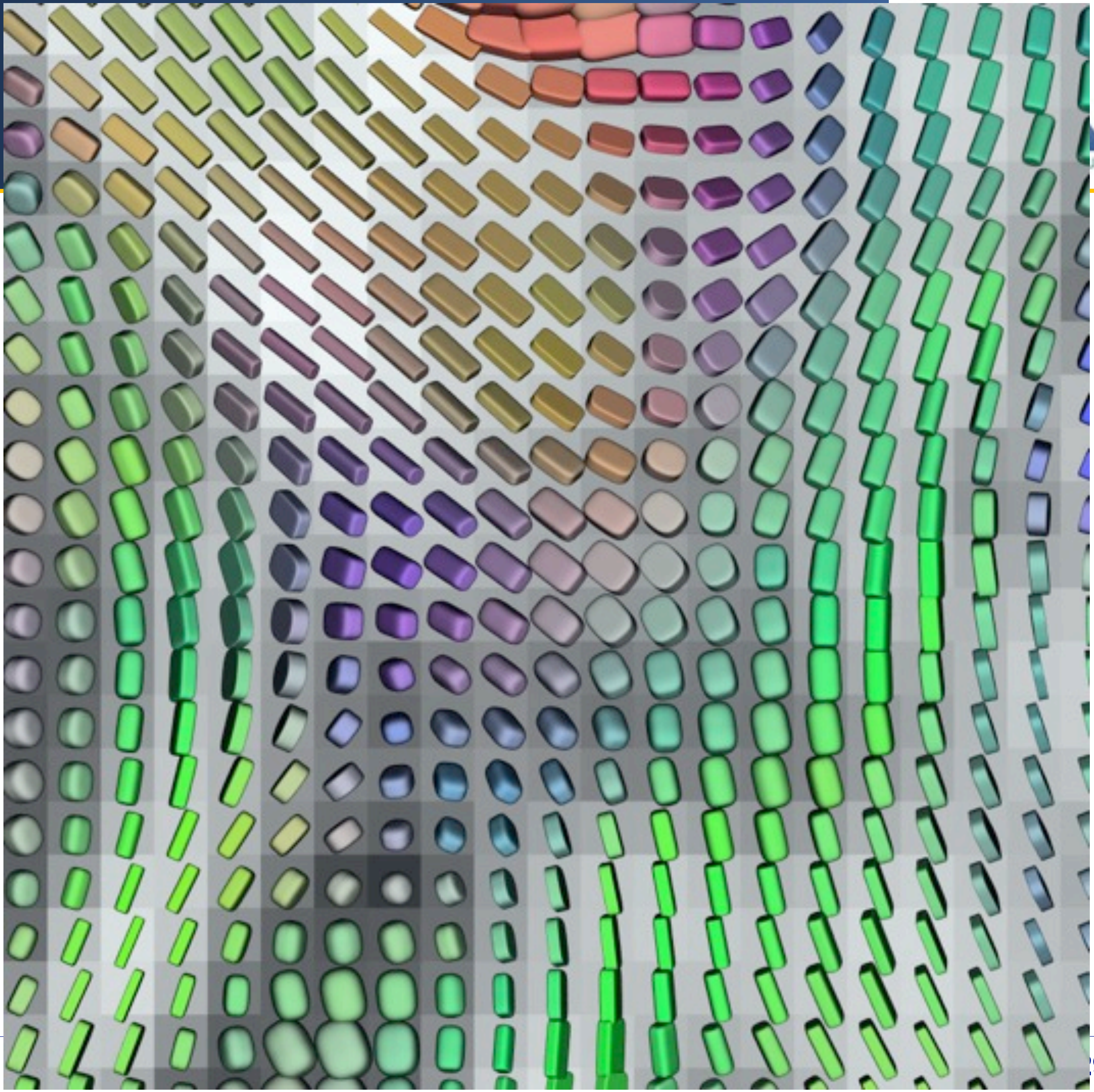


Superquadric tensor glyphs
(Kindlmann '04)


Backdrop: FA
Color: RGB($\mathbf{e}_1$)




Backdrop: FA
Color: RGB($\mathbf{e}_1$)

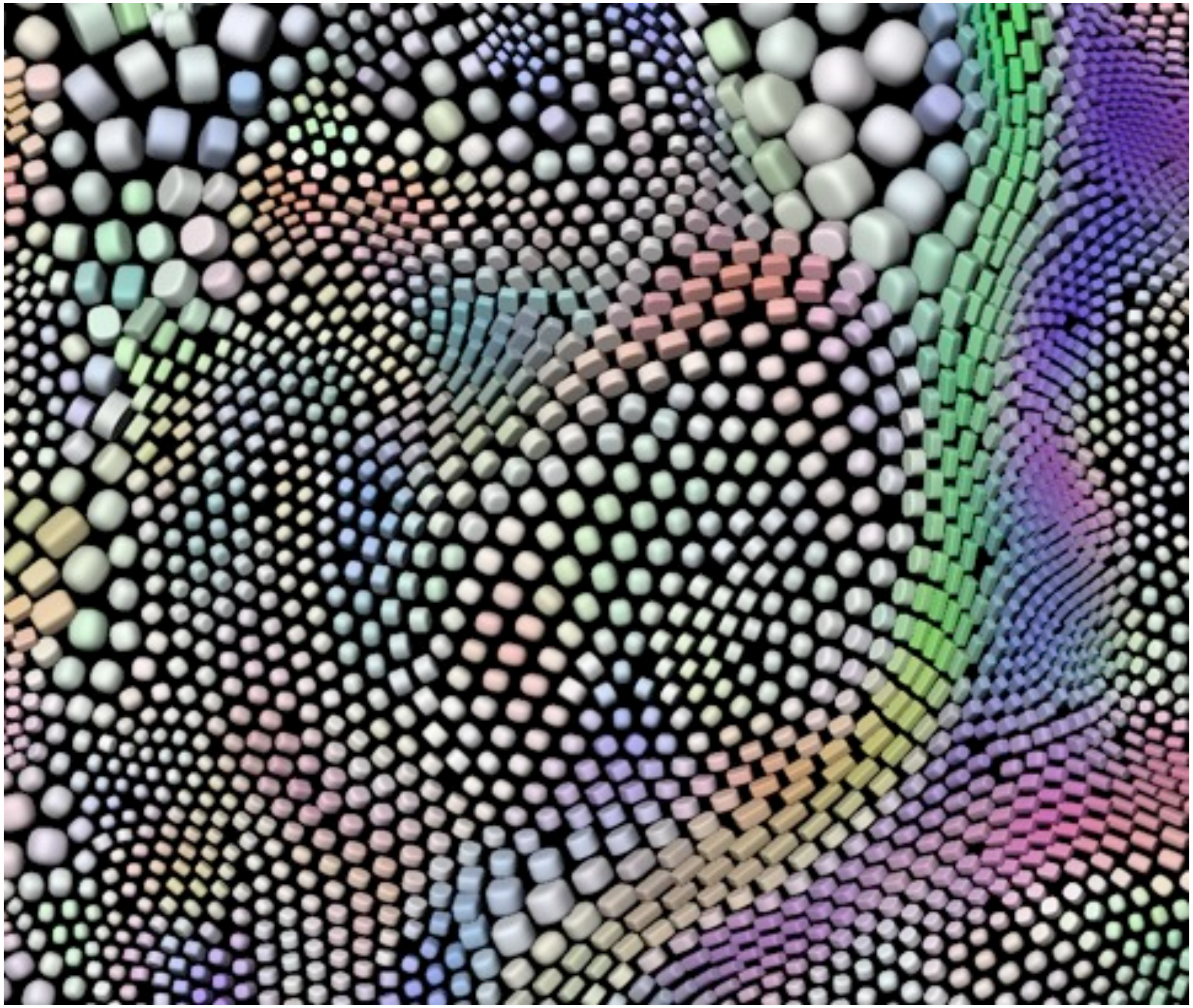


Glyph Placement

Particle systems (from graphics and anisotropic mesh generation) to “pack” glyphs (Kindlmann & Westin Vis’ 06)

Ongoing work with neurosurgeon

Friday, 10:45 -11:45
Vector/Tensor Visualization II



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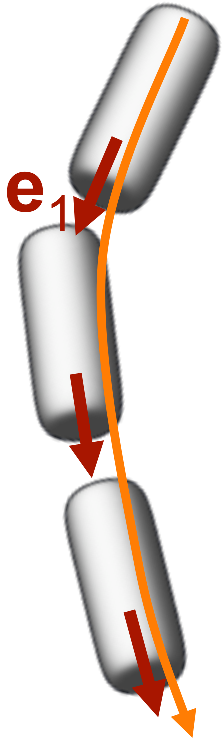
Fiber tractography (Basser 1999)

Path integration along principal eigenvector

Idea/Fantasy: follow paths of individual axons!

- Reality: 2-3 orders of magnitude too coarse

Essentially same as simplified hyperstreamlines (Delmarcelle 1993)



(demo anisotropy
isosurfaces + glyphs
+ fiber tracking)

Fiber Tracking Issues

- Tensor Field Interpolation/Filtering
- Integration quality, step size
  - Eigensolve at every sample non-trivial
- Seedpoint selection determines path
- Termination criteria
- Parameter space → Reproducibility, Validation

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Current Issues and Work

Single Tensor Model limited: fiber crossings

→ High Angular Resolution Diffusion Imaging

Spatial Resolution still somewhat coarse

→ Parallel imaging, better post-processing

Tractography validation not common

→ Histological comparison

Fusion with other modalities: fMRI, MEG

→ Wide open visualization research problem!

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