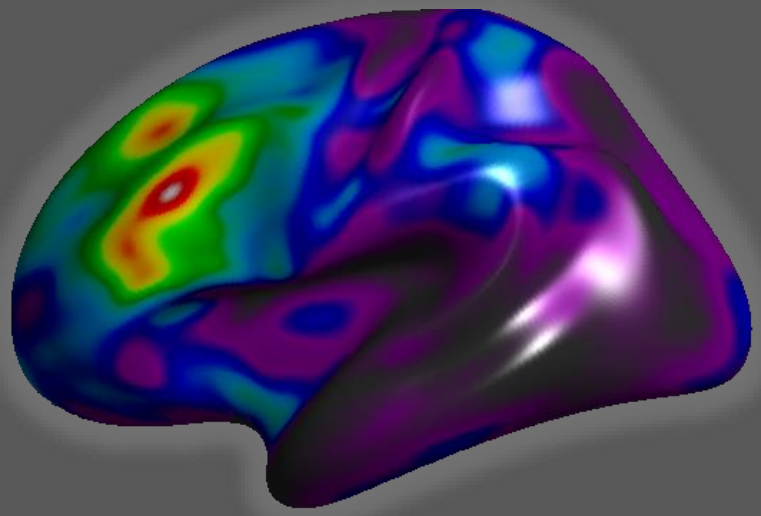


The basics of mesh processing in neuroimaging

Successive steps in a classical pipeline

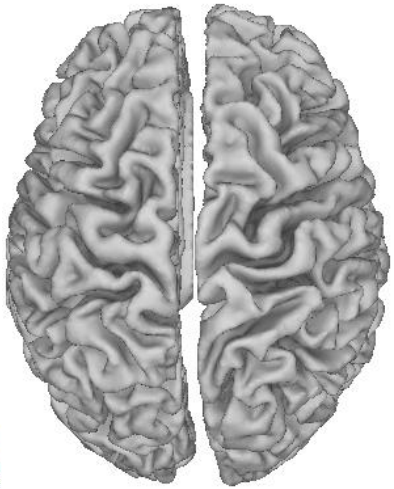
Guillaume Auzias

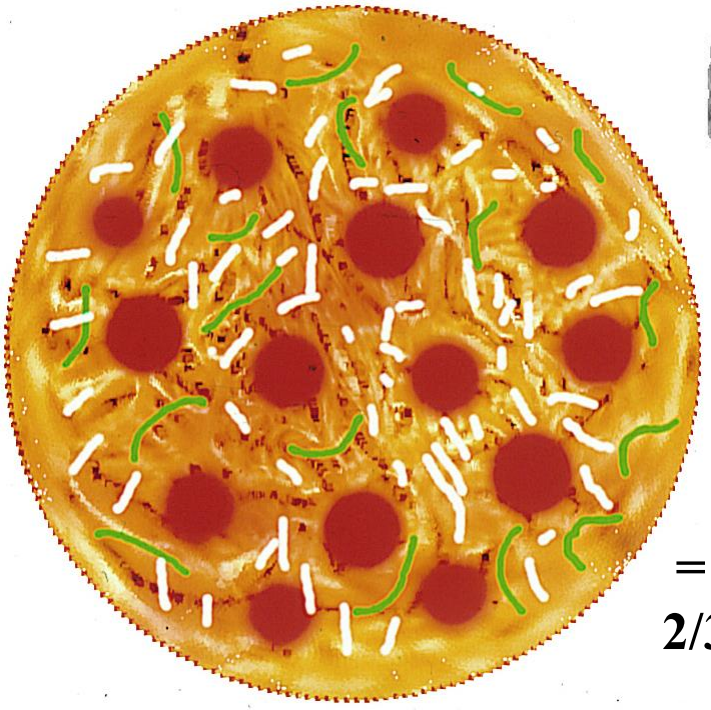
2022-02-24

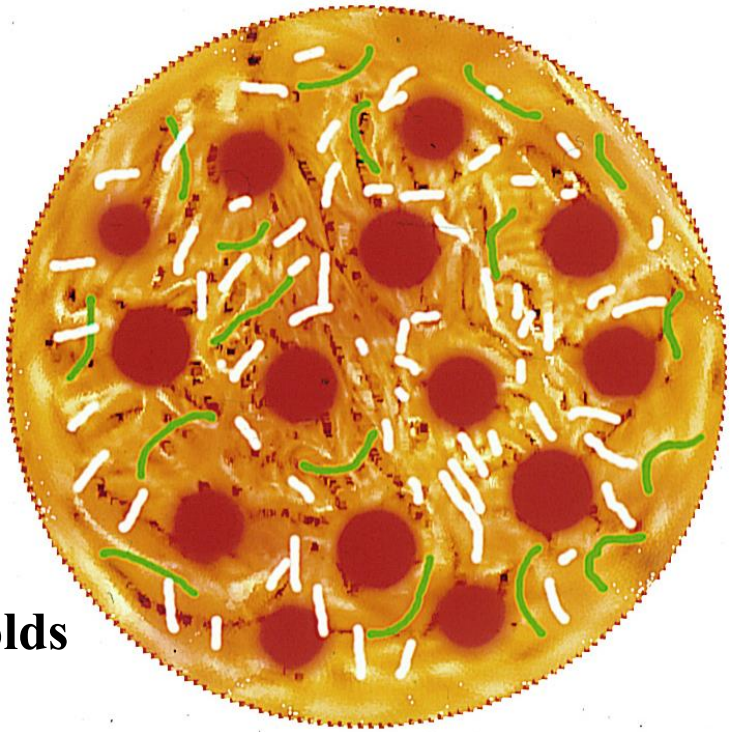
RMN

The essentials of cortical surface analysis: Each brain is unique and complex

Average surface area = 960 cm sq. (~1900 cm sq. for two hemispheres)







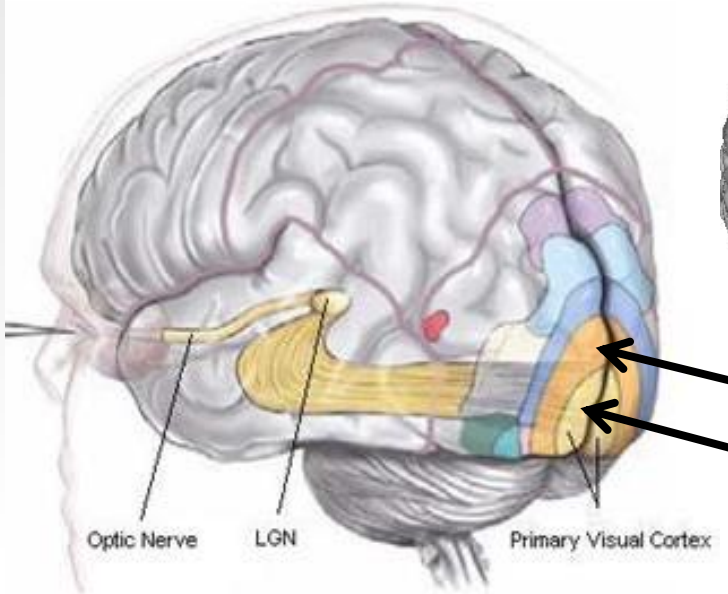
= two 13” pizzas!
2/3 hidden in the folds

150 ~more than 250 areas
Each cortical area ~ one 3 cm pepperoni!

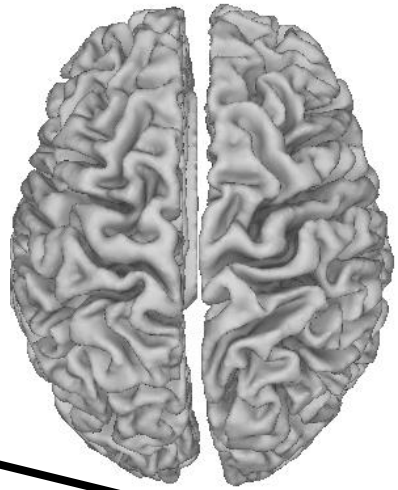
Slide DC Van Essen

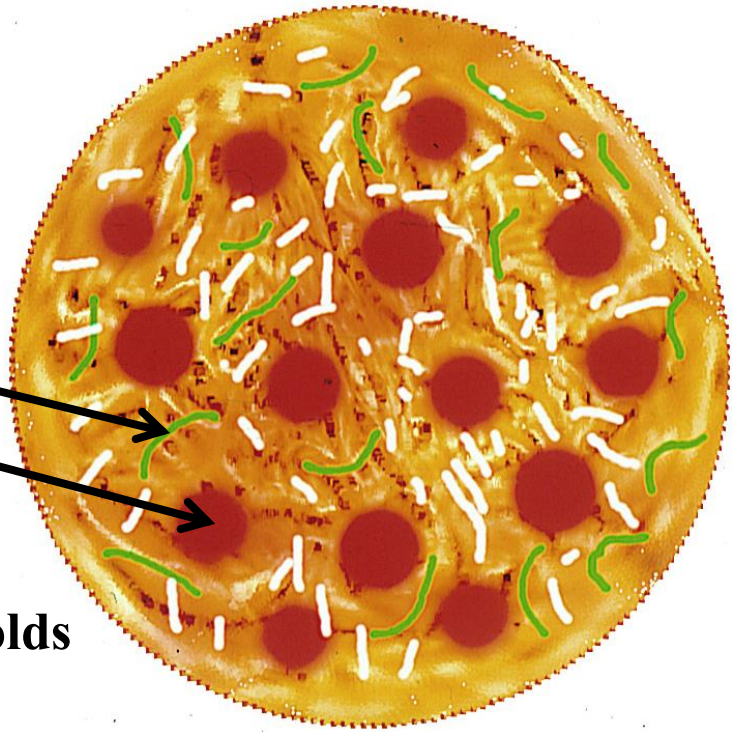
The essentials of cortical surface analysis: Each brain is unique and complex

Average surface area = 960 cm sq. (~1900 cm sq. for two hemispheres)



http://scien.stanford.edu





= two 13” pizzas!
2/3 hidden in the folds

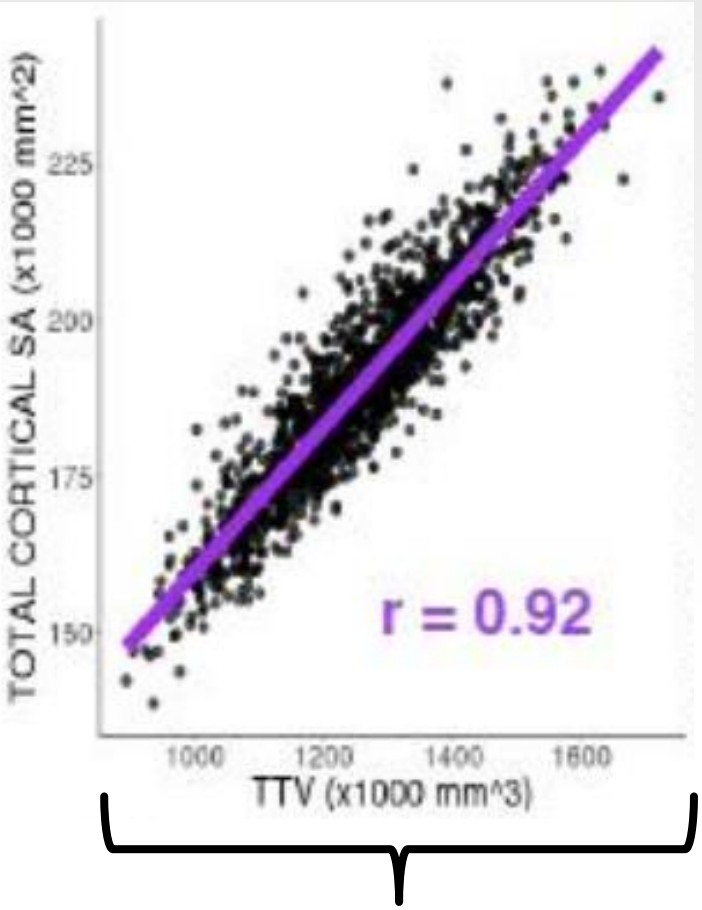
150 ~more than 250 areas
Each cortical area ~ one 3 cm pepperoni!

Slide DC Van Essen

The essentials of cortical surface analysis: variations across individuals: 2 folds magnitude!

1373 subjects 8~23 years

150~300 mm^2

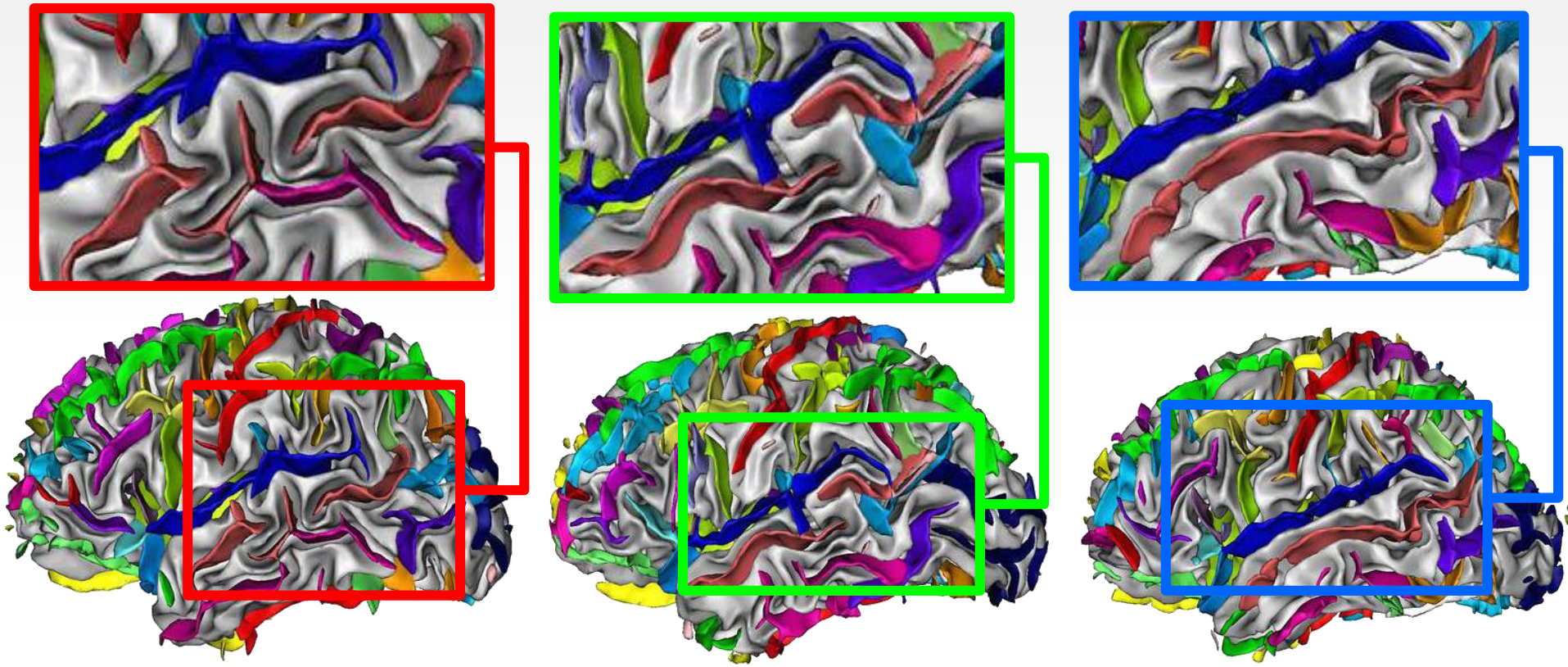


1000~2000 mm^3

Reardon et al., *science*, 2018

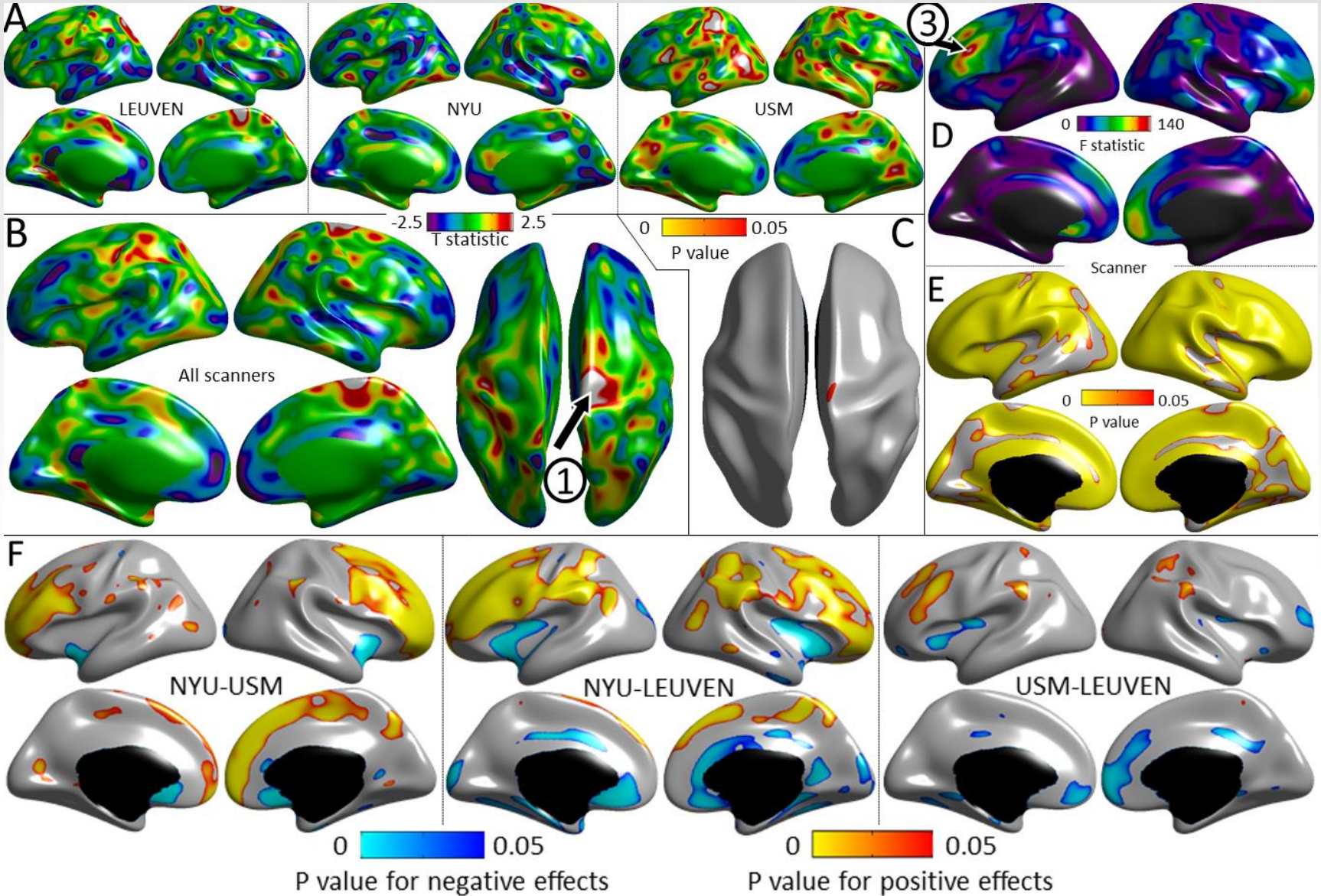
The essentials of cortical surface analysis: Cortical geometry is complex and variable

- Defining correspondences across brains:
  - remains an open issue
  - multiple approaches/softwares



Neuroimaging pipelines enable surface-based statistical analysis

Auzias et al., IEEE JBHI, 2015



Successive steps in a classical pipeline

- Segmentation of the white mesh
- Topology correction
- Mesh deformation to get the pial mesh
- Mapping onto a sphere
- Spherical registration
- Remeshing / interpolation across meshes
- Volume to mesh interpolation
- Smoothing on the surface
- Computing statistics across meshes

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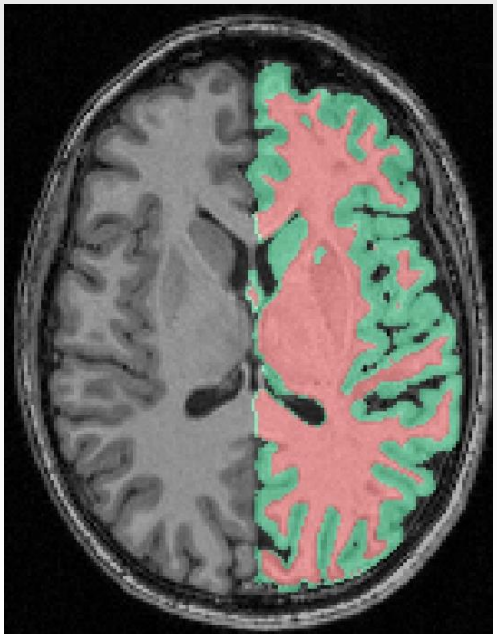
Segmentation of the *white* (G/W) surface mesh

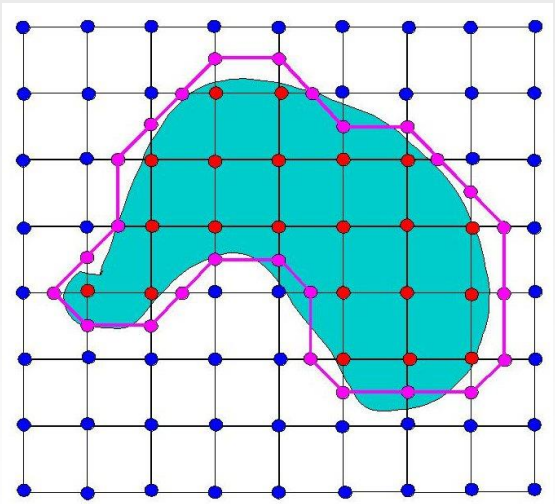
- Aim: extract a triangular mesh (2D surface) corresponding to an iso-intensity value in the 3D volume

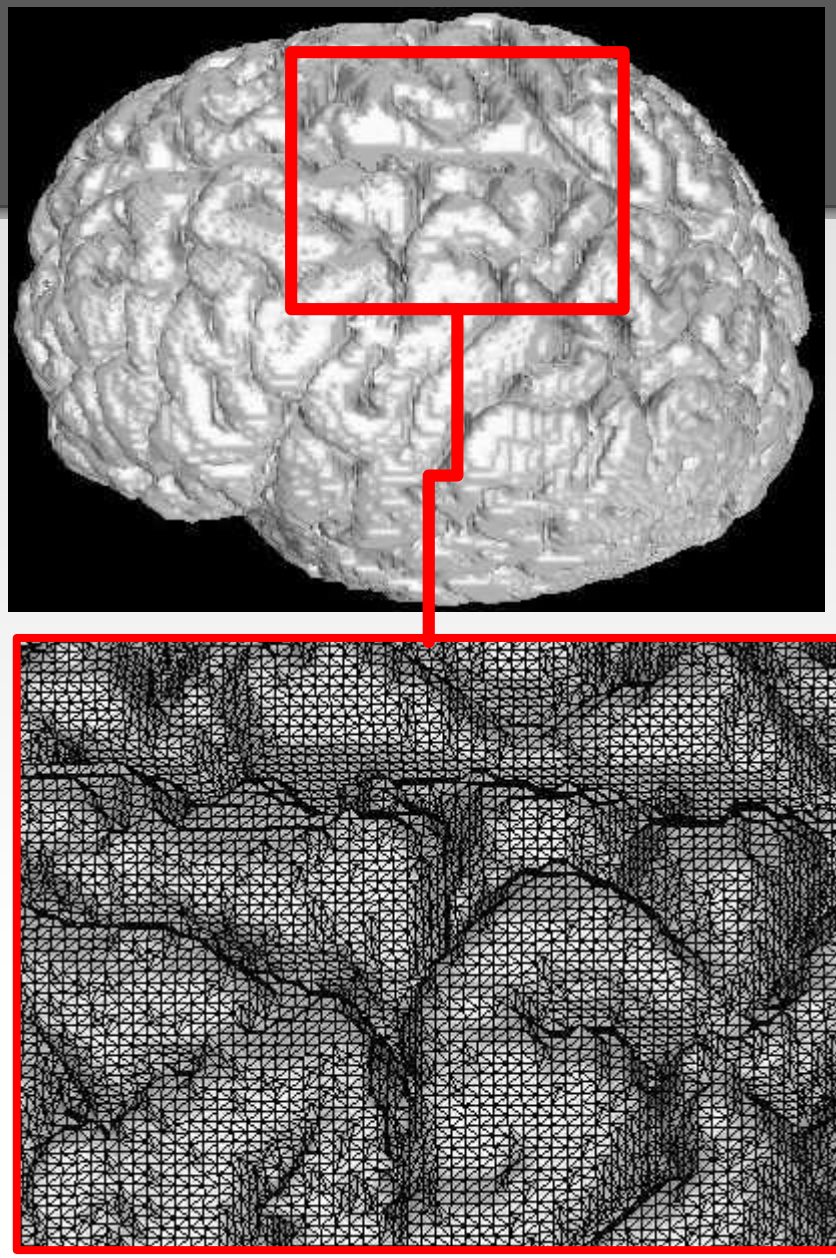
- Get a surface representation of the interface **between grey and white tissues**
  - ?h.white surface in freesurfer / HCP

volume to mesh

- Marching cubes







No constraint on the **topology**
Not well suited for the pial (cortex/CSF) surface

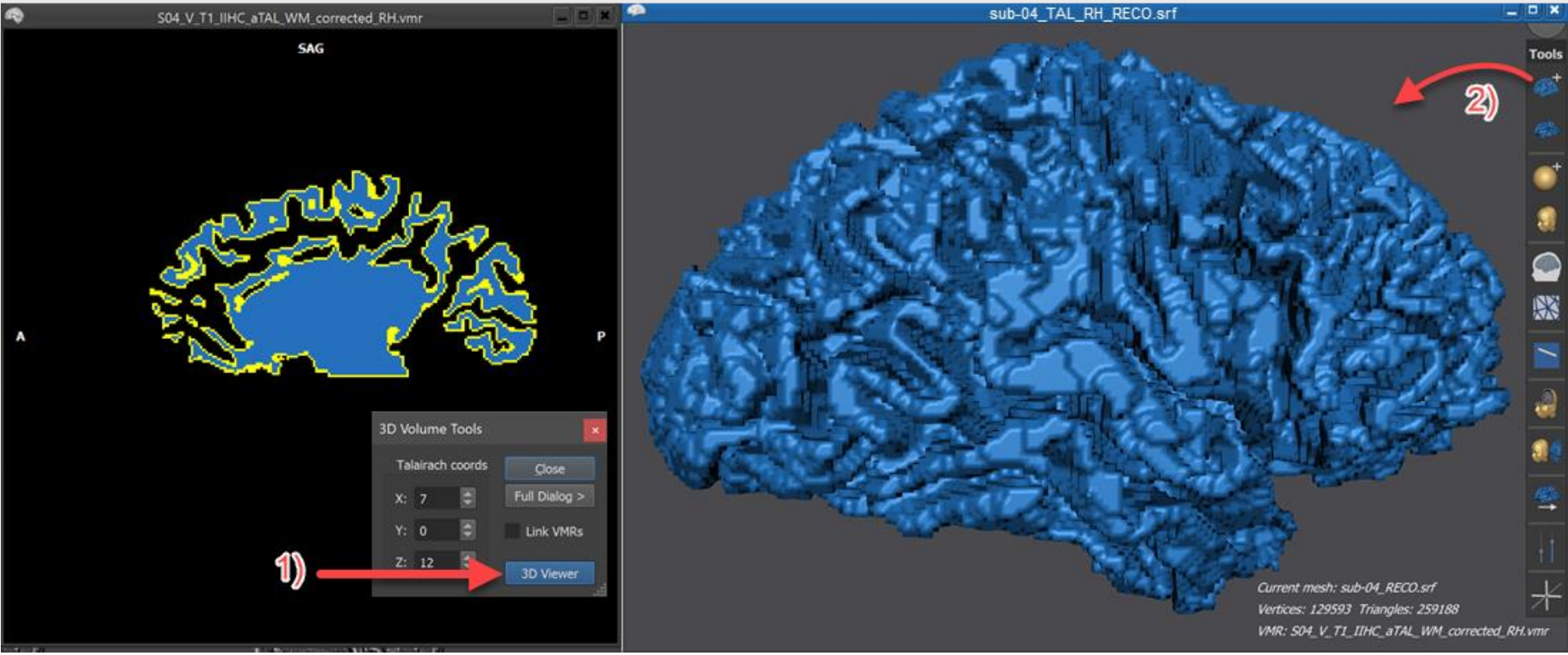
Works well for white surface

A bit of smoothing required…

http://users.polytech.unice.fr/~lingrand/MarchingCubes/presGene.html

volume to mesh

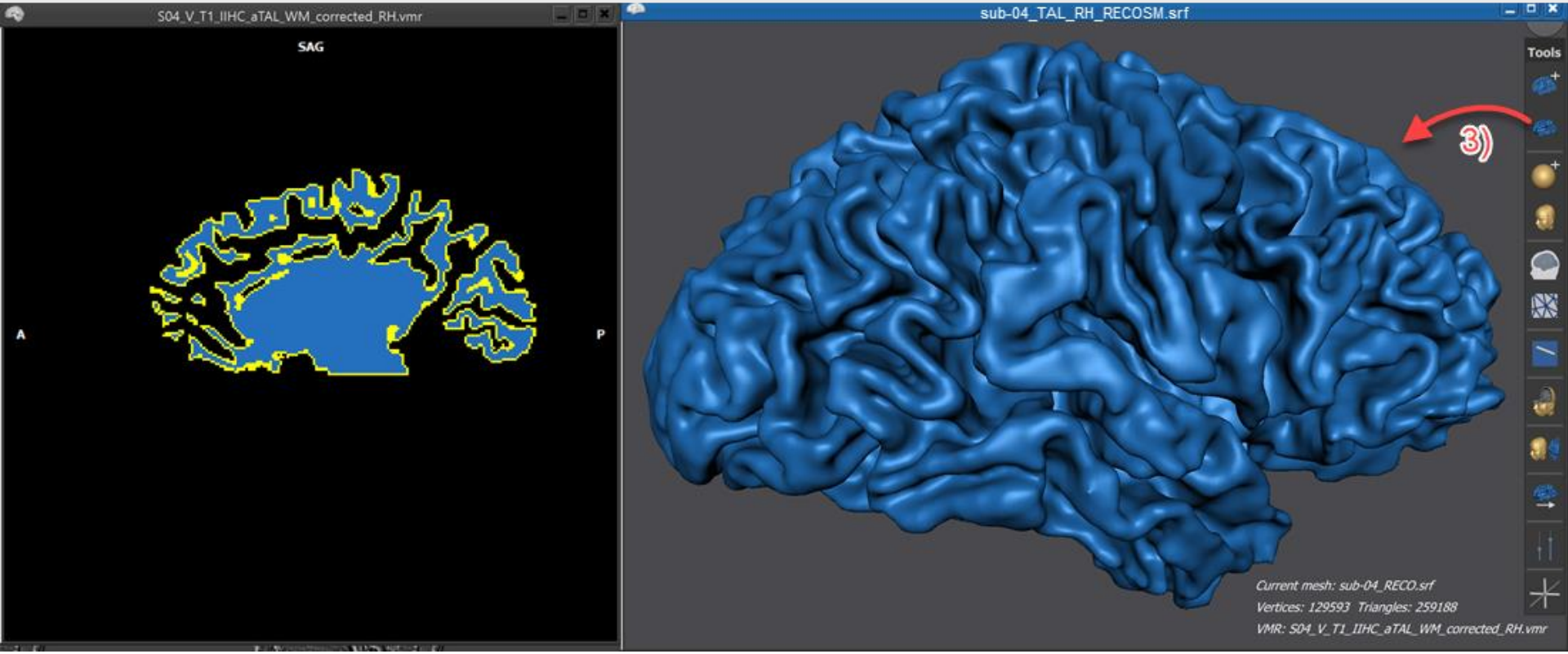
- Marching cubes



https://download.brainvoyager.com/bv/doc/UsersGuide/CortexBasedAlignment/PreparingAMeshForCBA.html

volume to mesh

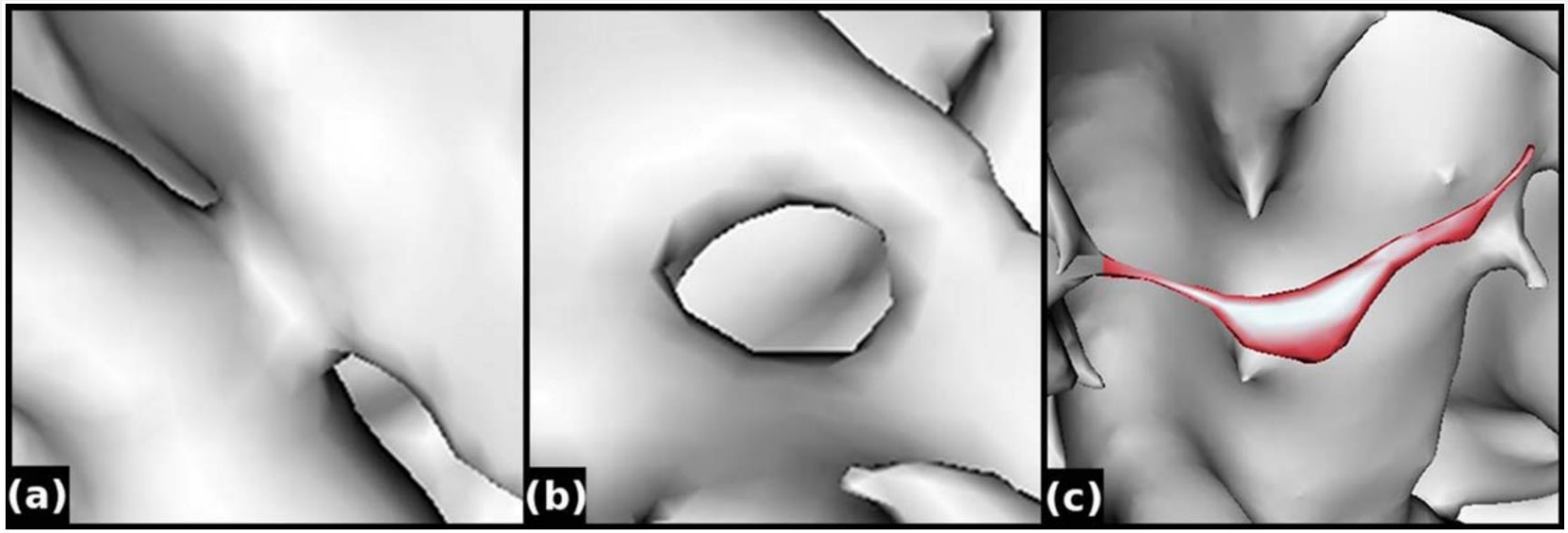
- Marching cubes + smoothing



https://download.brainvoyager.com/bv/doc/UsersGuide/CortexBasedAlignment/PreparingAMeshForCBA.html

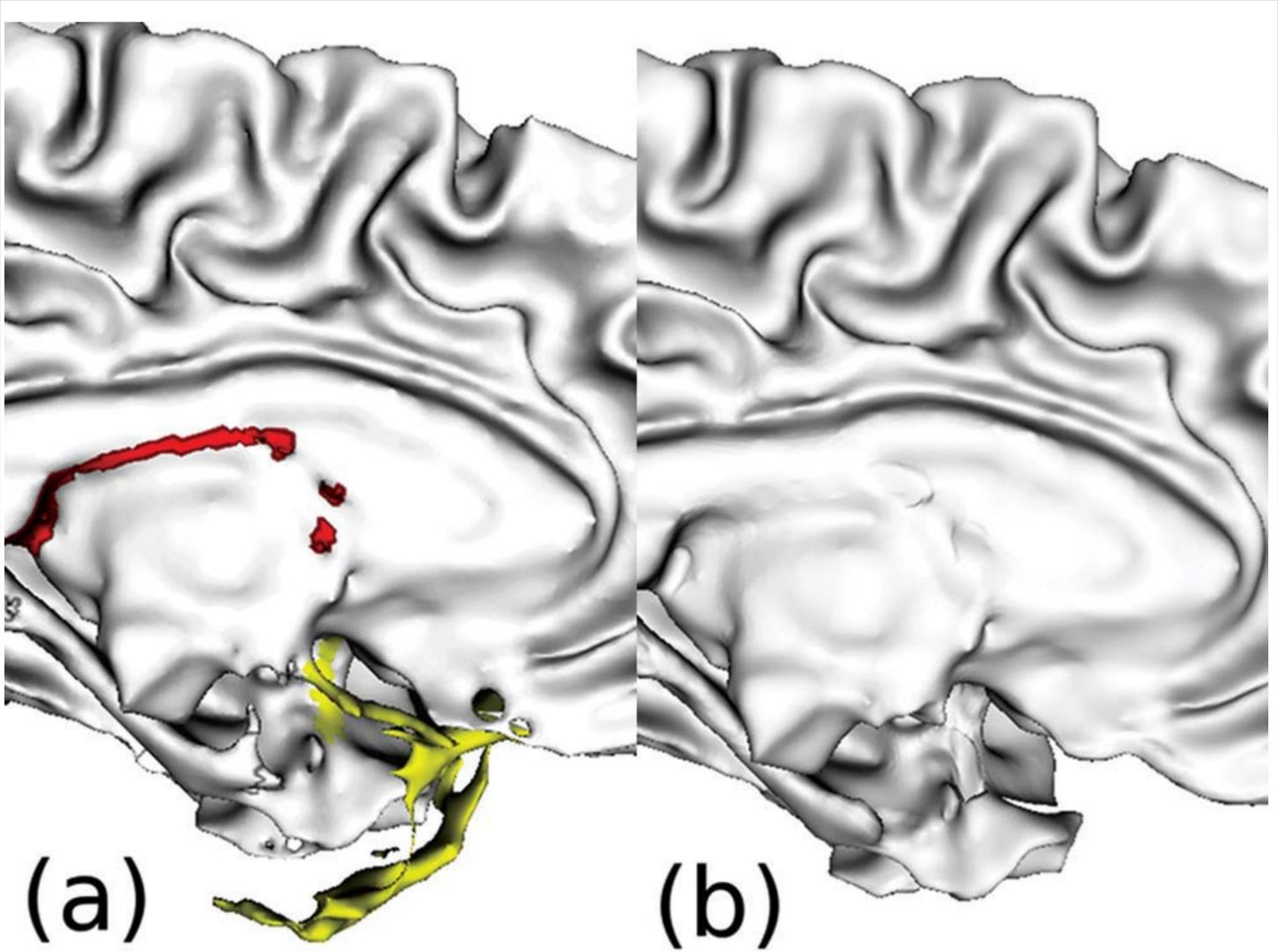
Topology correction

- Correct topological defects so that the mesh can be mapped onto a sphere without any flipped triangle / hole / handle



- Defects correspond to segmentation errors, i.e. geometry is not biologically plausible

Topology correction

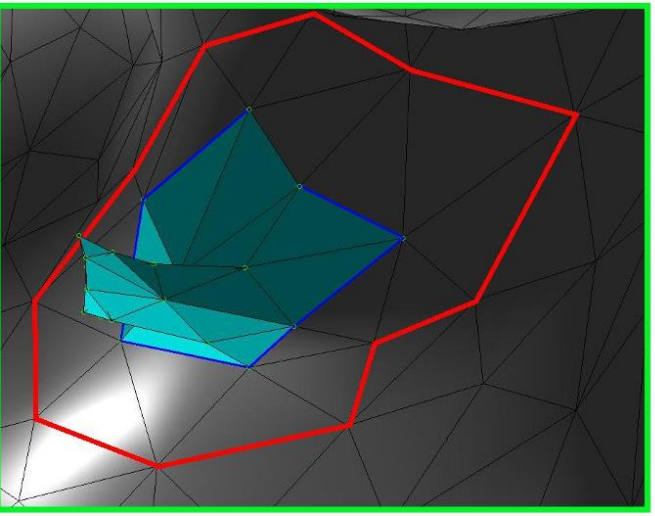
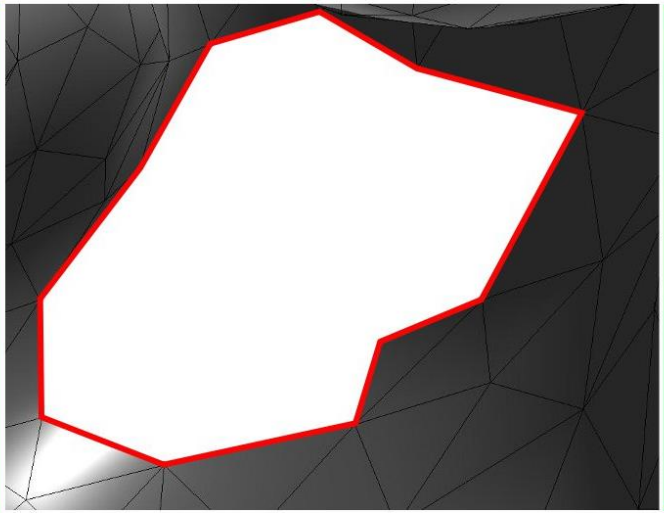
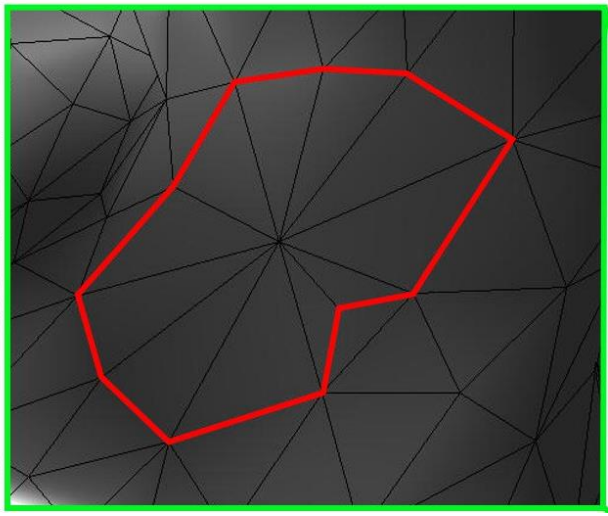


Yotter et al., Human Brain Mapping, 2010

https://brain-slam.github.io/slam/

Implemented in the python package SLAM

- Curvature-based defect detection
- Mapping-based defect detection
- Mesh surgery (cut and close)

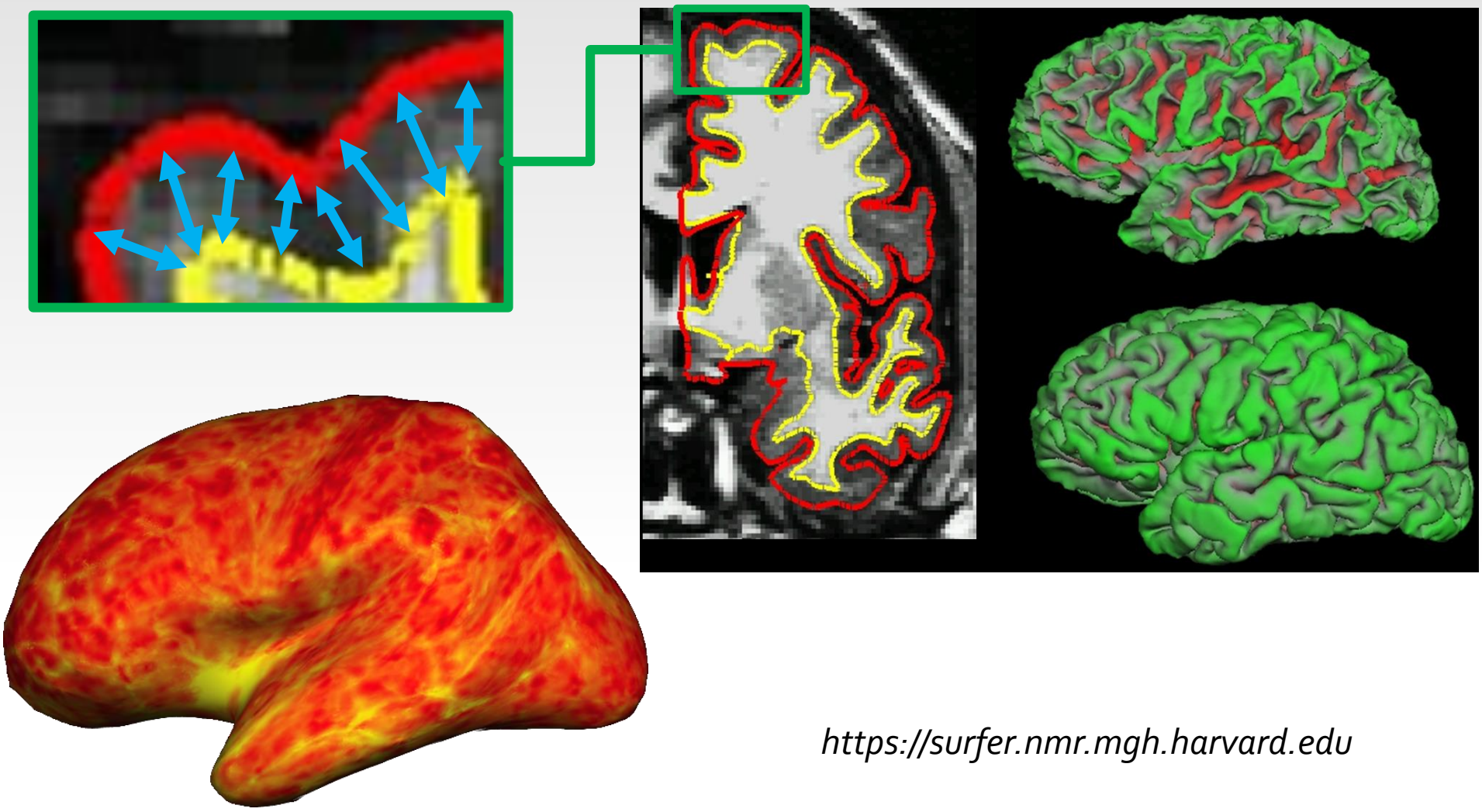
Surface deformation

- Get a topologically correct pial surface

- Vertex correspondence between white and pial surfaces

  ➡ estimation of cortical thickness

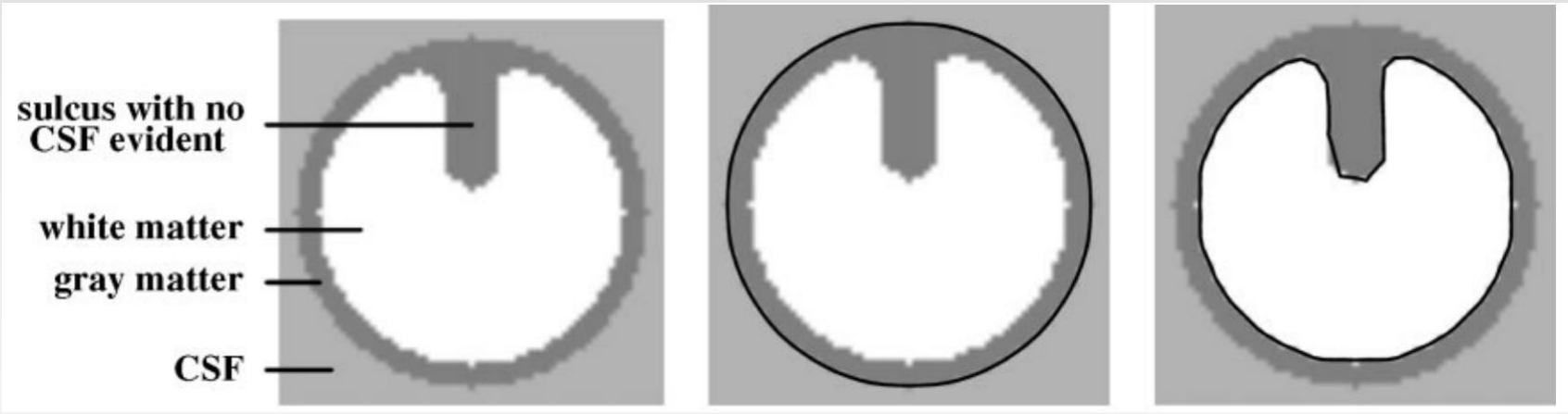
Surface deformation



https://surfer.nmr.mgh.harvard.edu

Mc Donald et al., Neuroimage, 2000
Schuh et al., ISBI, 2017

Surface deformation



- Internal & tangential forces + self-intersections

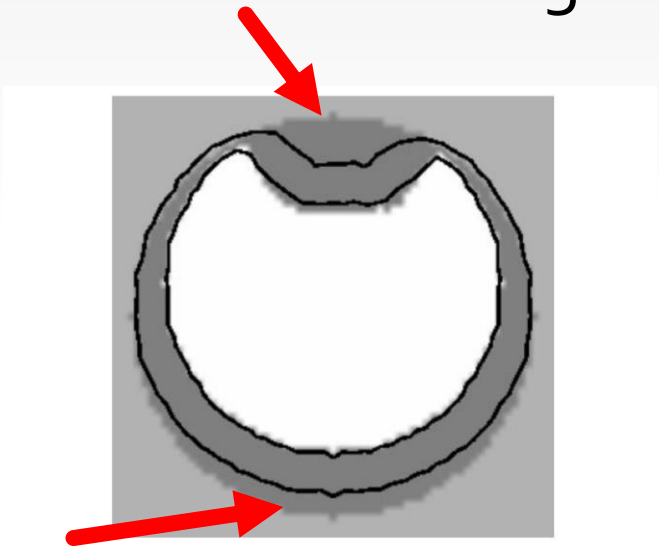
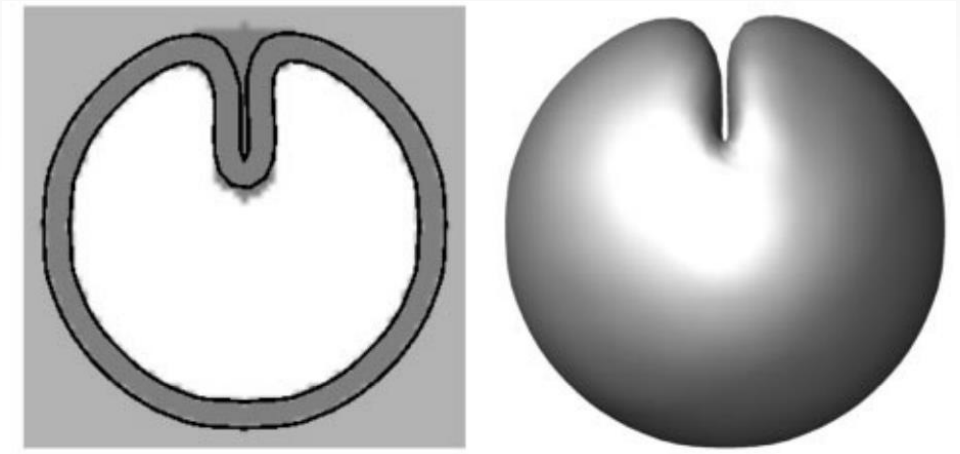


FIG. 5. Response of ASP to gray thickness outside normal range. Here the phantom's cortical thickness varied from 1 to 15 mm, i.e., far beyond normal values. The algorithm constrained the thickness to between 2 and 6 mm.



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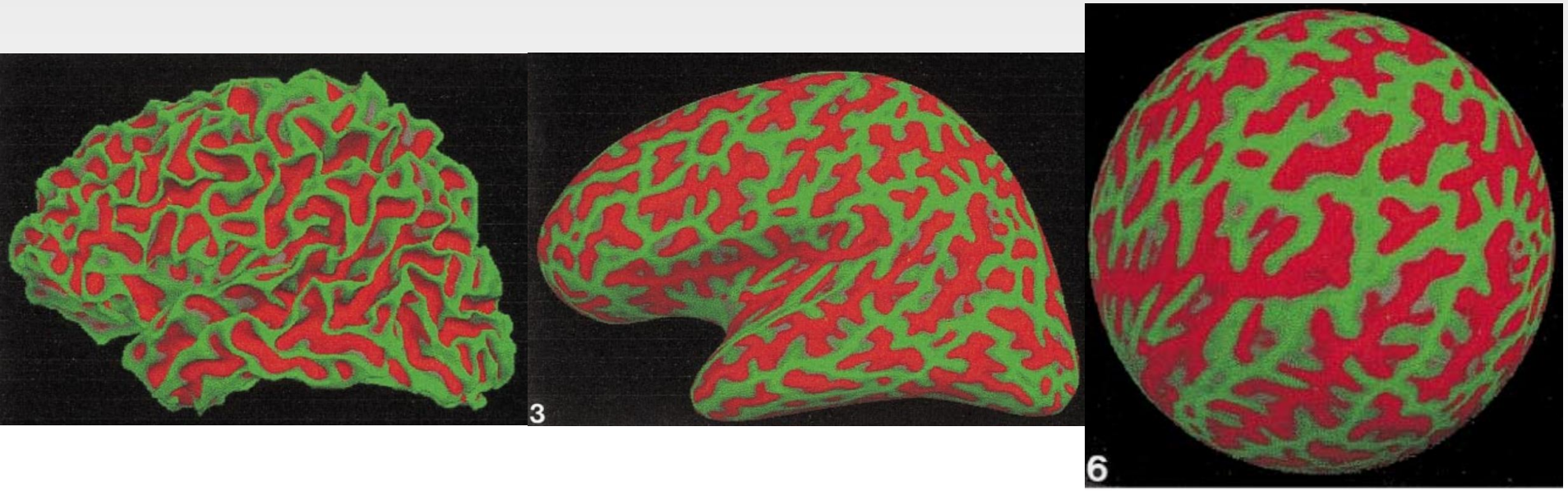
Mapping onto a sphere

- Map onto a canonical space common to all surfaces (i.e. subjects)
- Parameterization (latitudes/longitudes)

Mapping onto a sphere

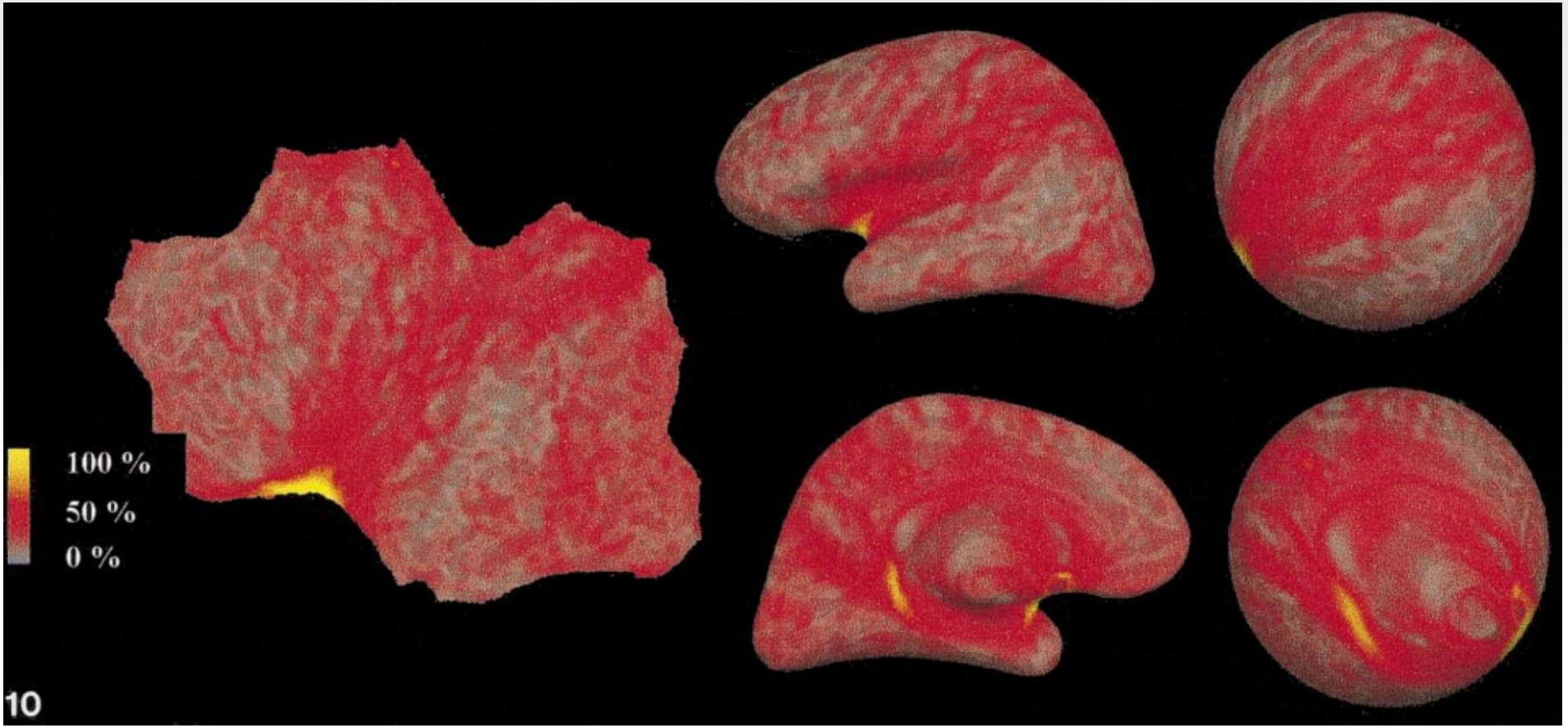
- Freesurfer : inflation + projection



Fischl et al., NeuroImage, 1999

Mapping onto a sphere

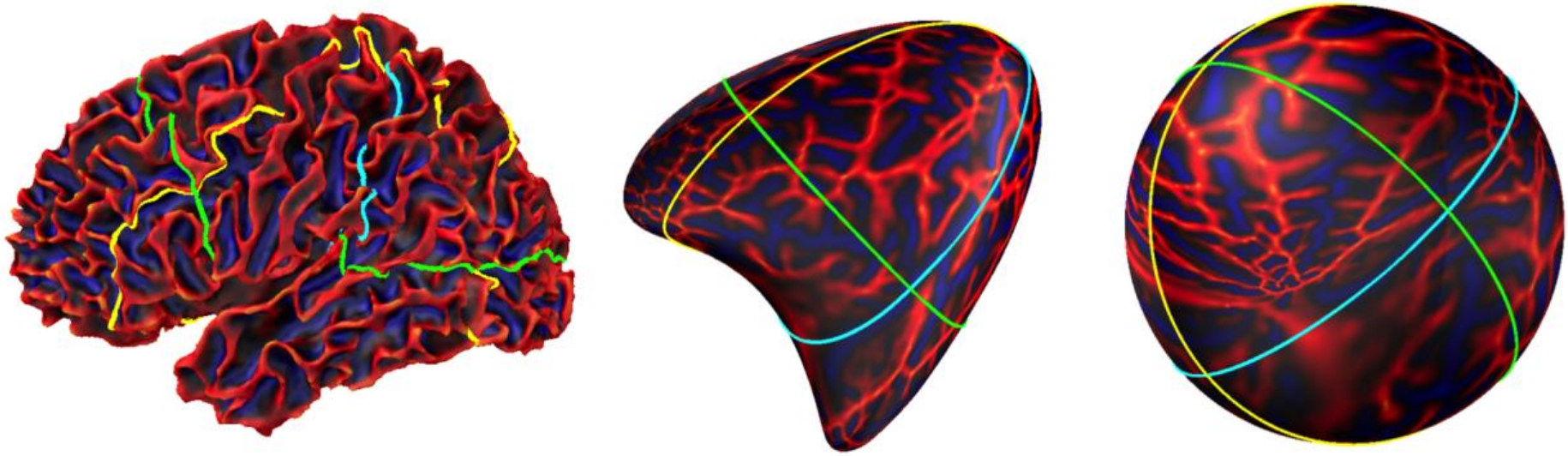
- Freesurfer : inflation + projection ➡ **distortions**!



Fischl et al., NeuroImage, 1999

Mapping onto a sphere

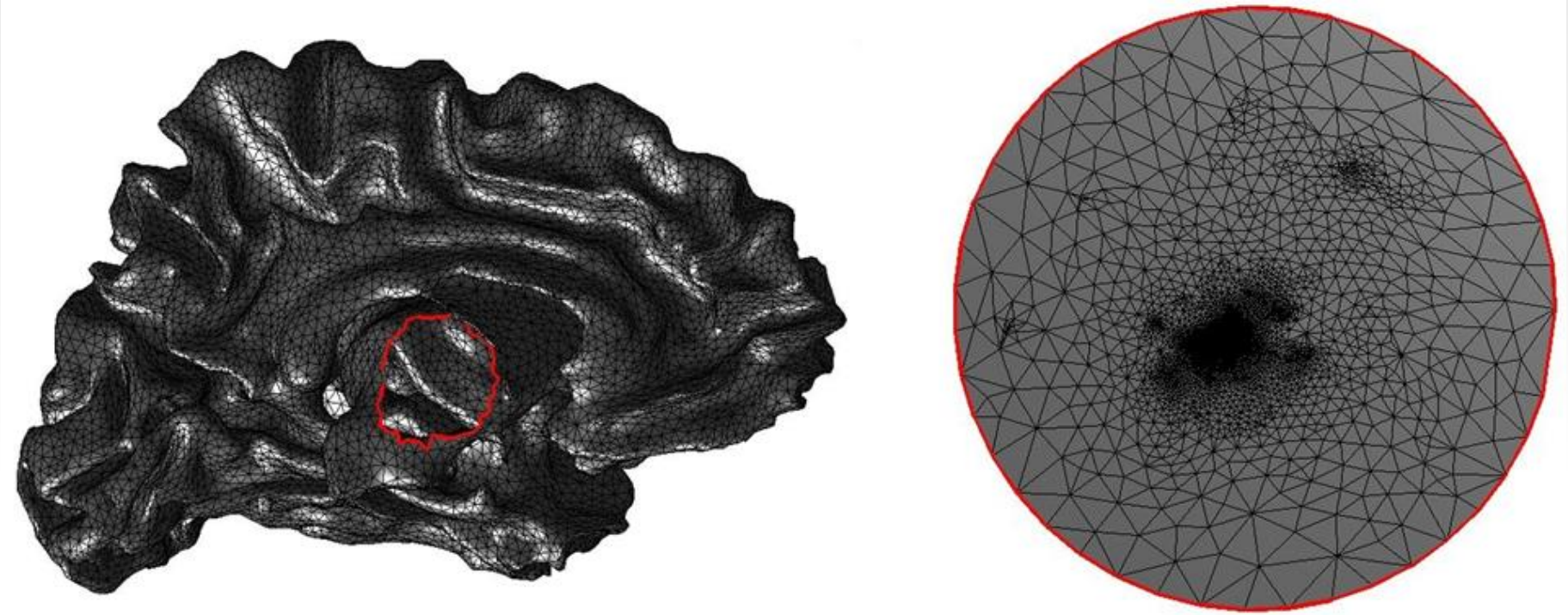
- Based on spectral decomposition



$$\begin{array}{ccccc} \mathcal{M} & \longrightarrow & \mathbb{R}^3 & \longrightarrow & \mathbb{S}^2 \\ p & \longmapsto & \big(\Phi_1(p), \Phi_2(p), \Phi_3(p)\big) & \longmapsto & \dfrac{\big(\Phi_1(p), \Phi_2(p), \Phi_3(p)\big)}{\sqrt{\Phi_1(p)^2+\Phi_2(p)^2+\Phi_3(p)^2}} \end{array}$$

Mapping onto a sphere

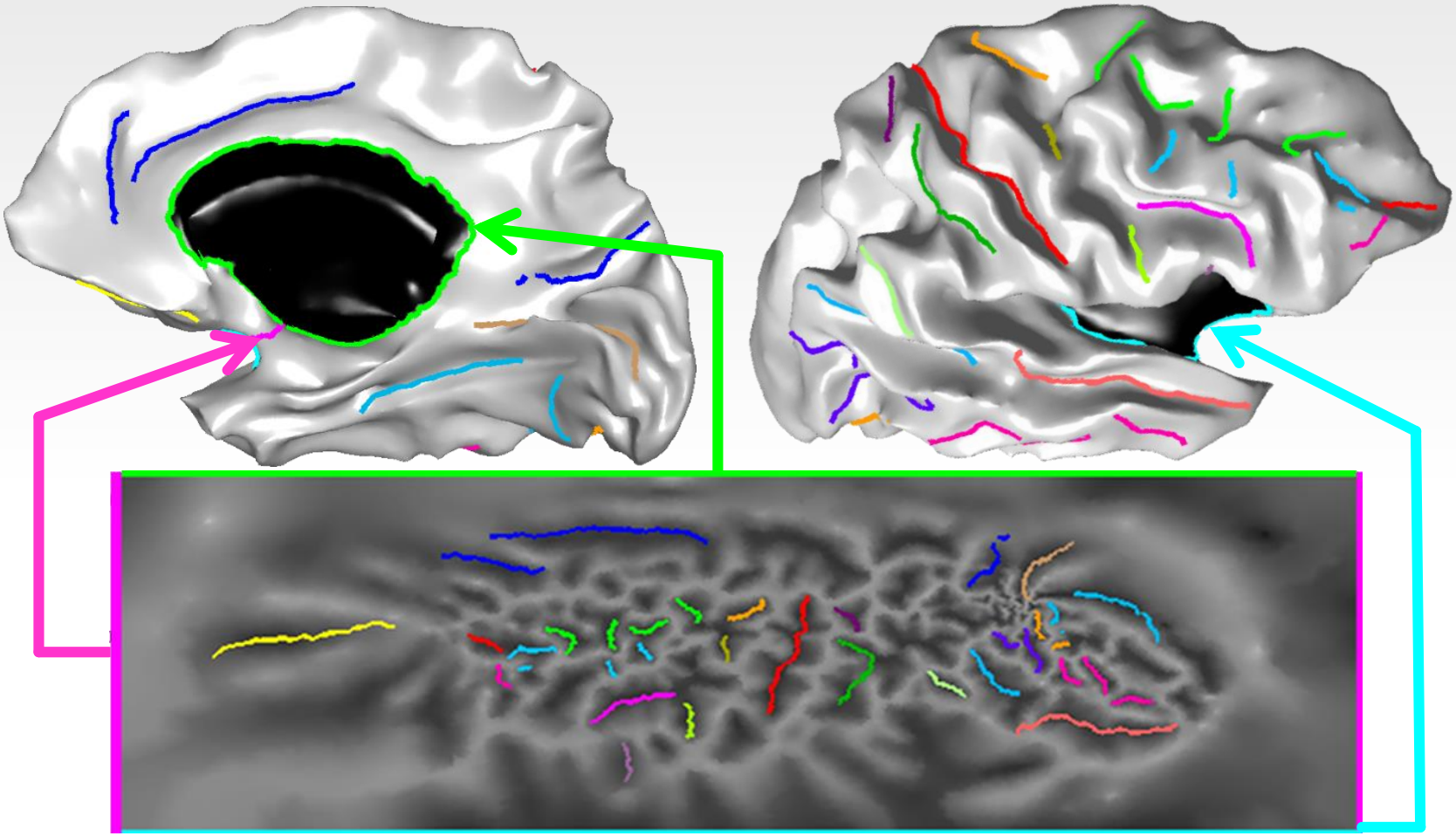
- Alternative options: disk



Keywords: conformal mapping

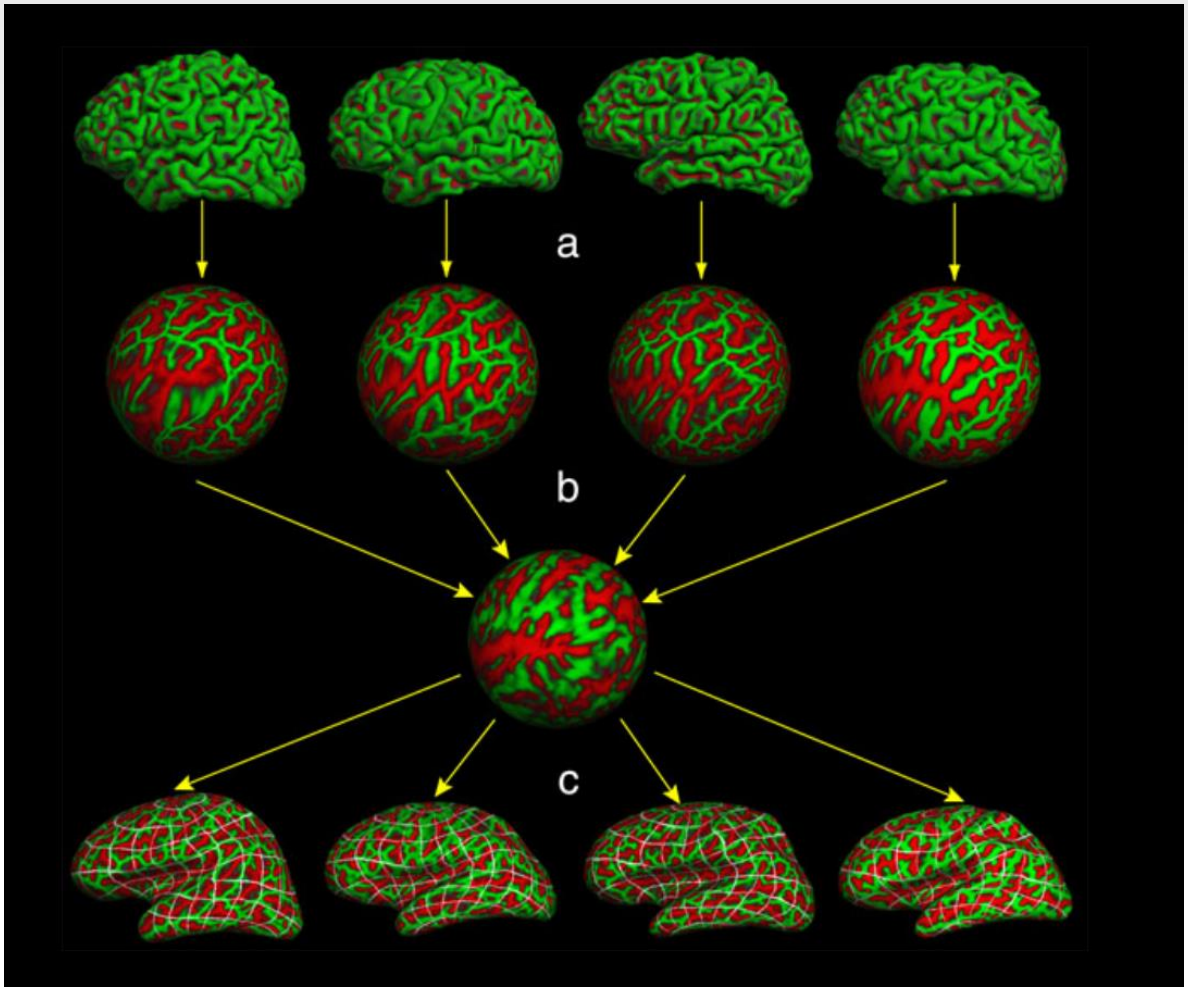
Mapping onto a sphere

- Alternative options: rectangle (HIPHOP)



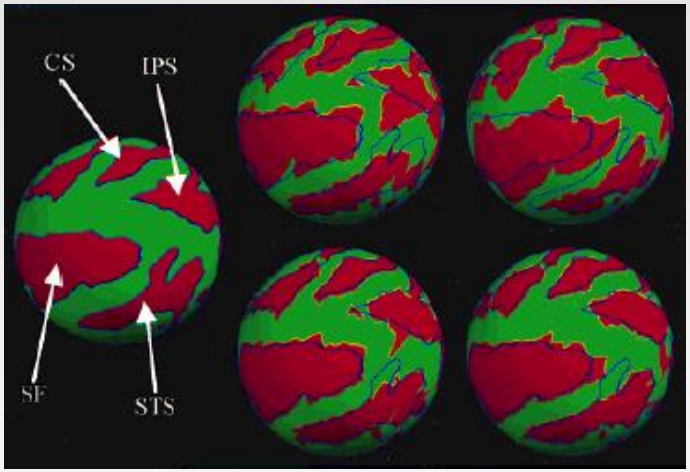
Spherical registration

- Align anatomical / functional / … features
- Vertex-to-vertex correspondence across surfaces

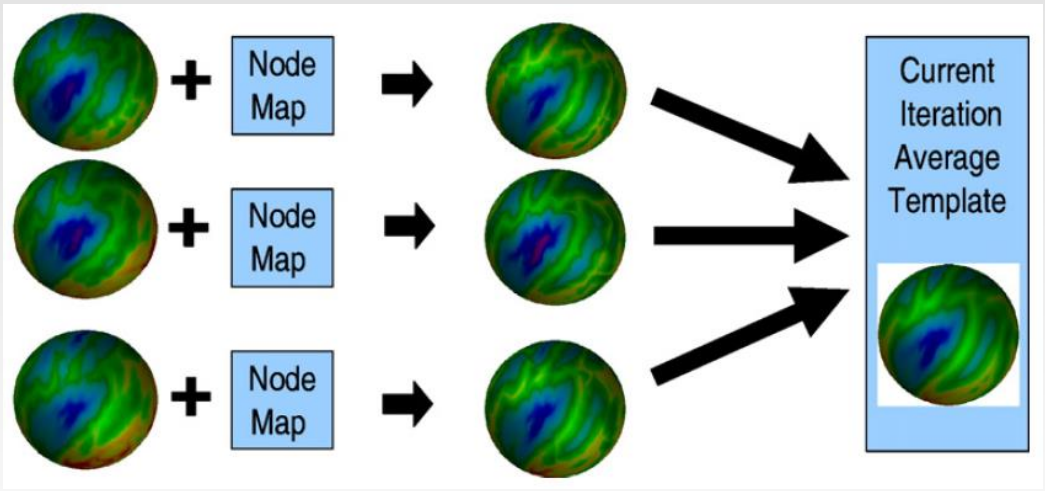


> 30 surface-based methods (>50 volume-based) See e.g. Gholipour et al., IEEE *TMI*, 2007

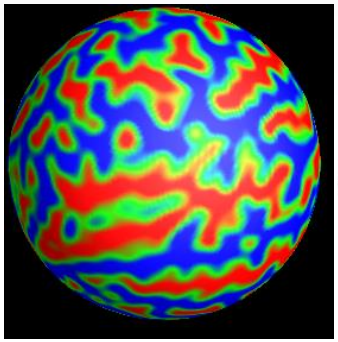
Brain registration is a very active field



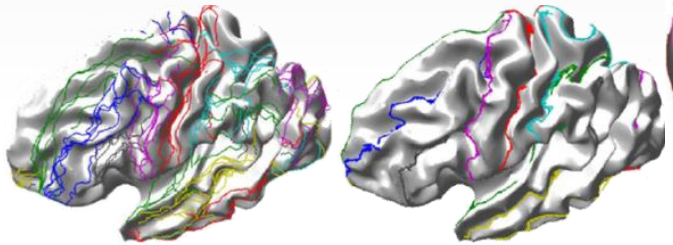
FREESURFER
Fischl et al, *Hum Brain Mapp*, 1999



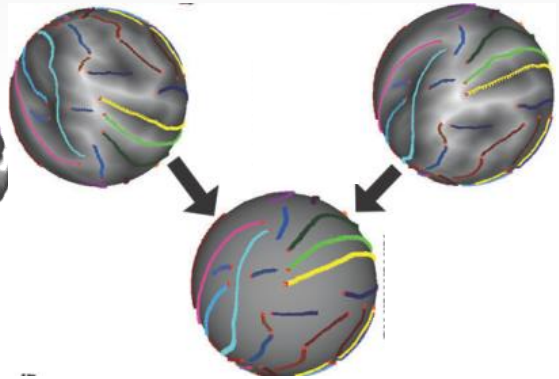
Lyttelton et al, *NeuroImage, 2007*



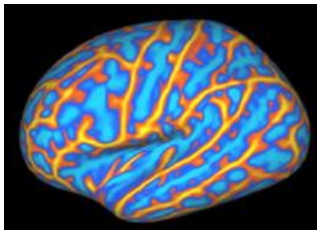
Yeo et al.,
IEEE TMI, 2010



Joshi et al,
IEEE TMI, 2007



CARET, Van Essen,
NeuroImage, 2005



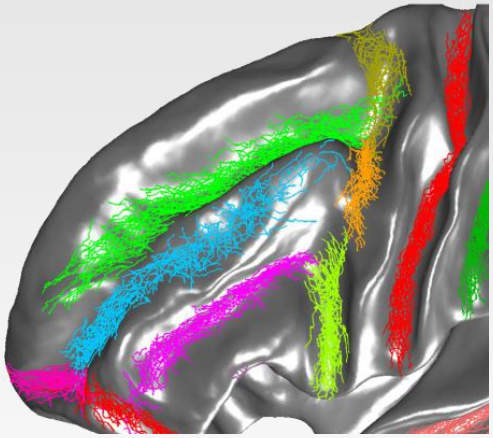
Robinson et al,
NeuroImage, 2014

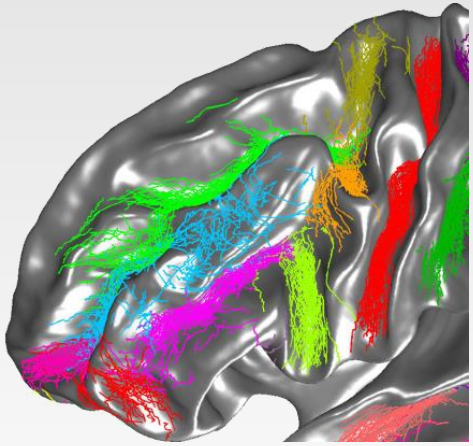
See also Auzias et al., *IEEE TMI*, 2011 & 2013

Auzias et al., *IEEE TMI*, 2013

Differences between methods outcome

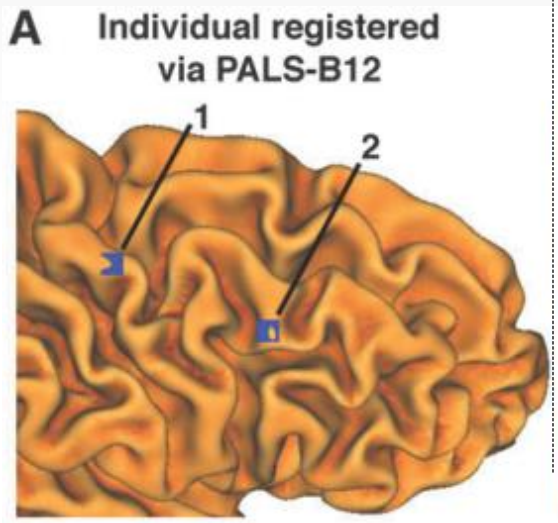
HIP-HOP

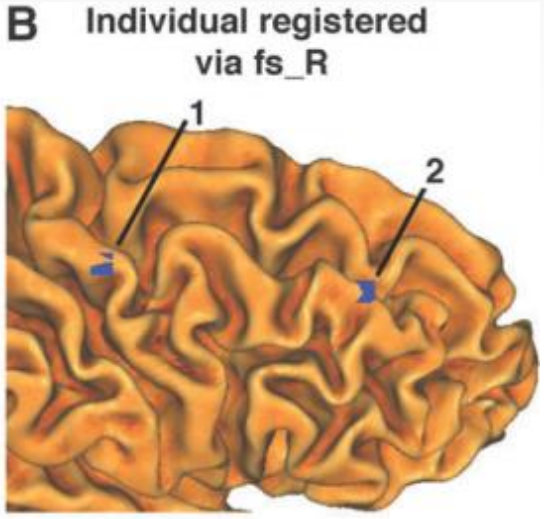




Freesurfer

CARET





Freesurfer

Van essen et al, *Cereb Cortex*, 2011

Differences between methods outcome

Freesurfer : alignment driven by sulcal depth and curvature

curvature

≠

labelled sulci

≠

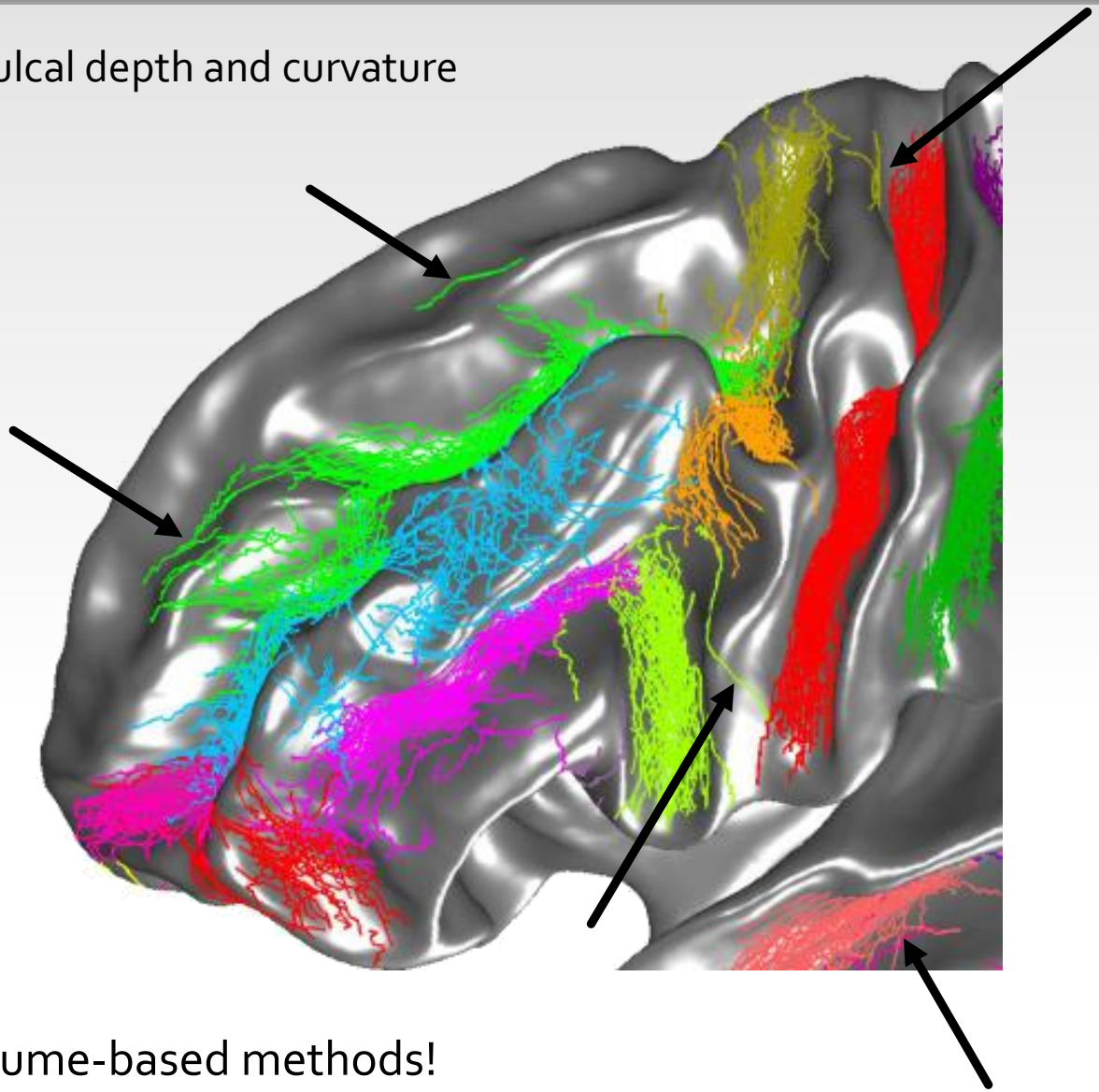
myelin

≠

functional areas or activations

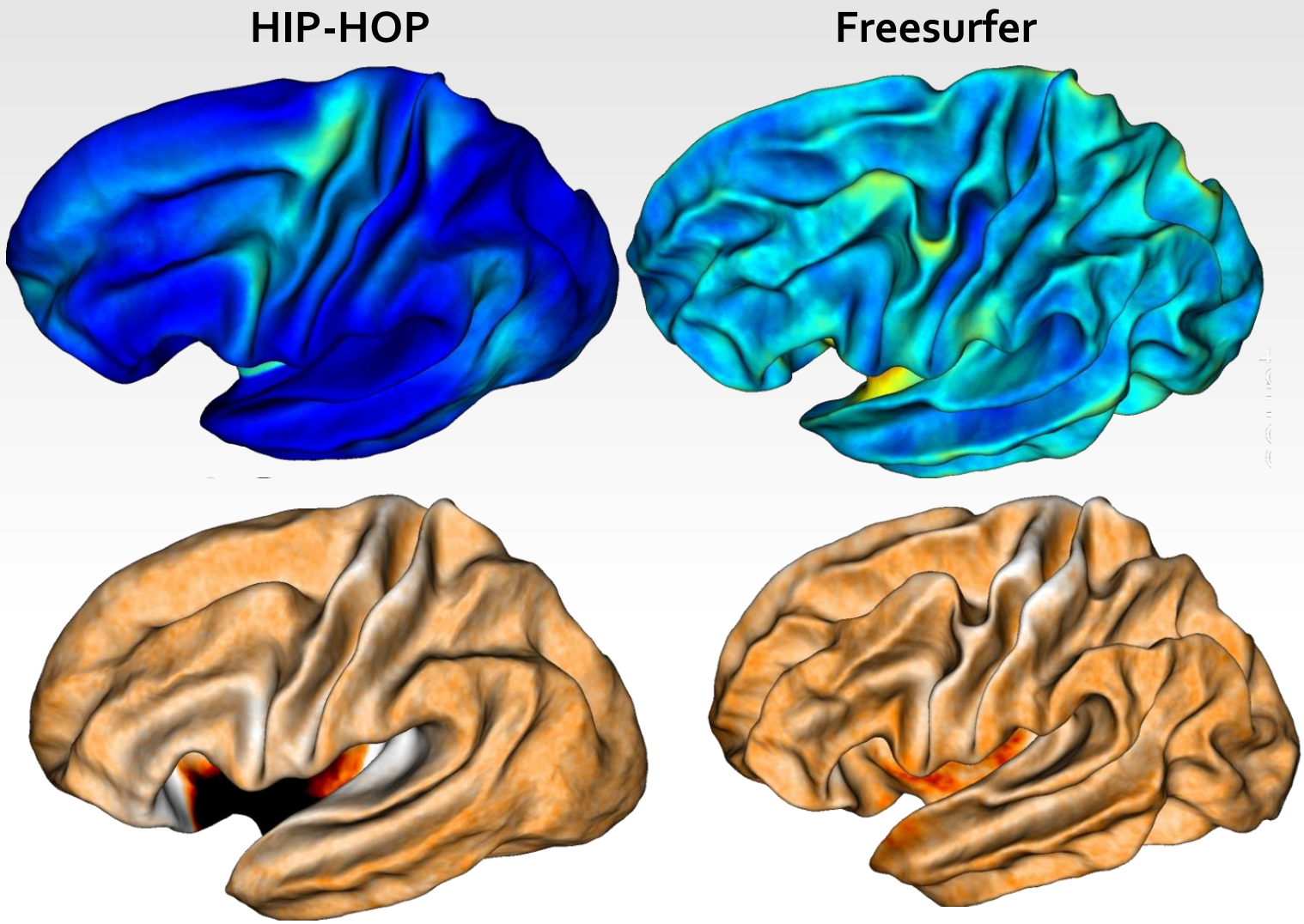
≠

sulcal depth



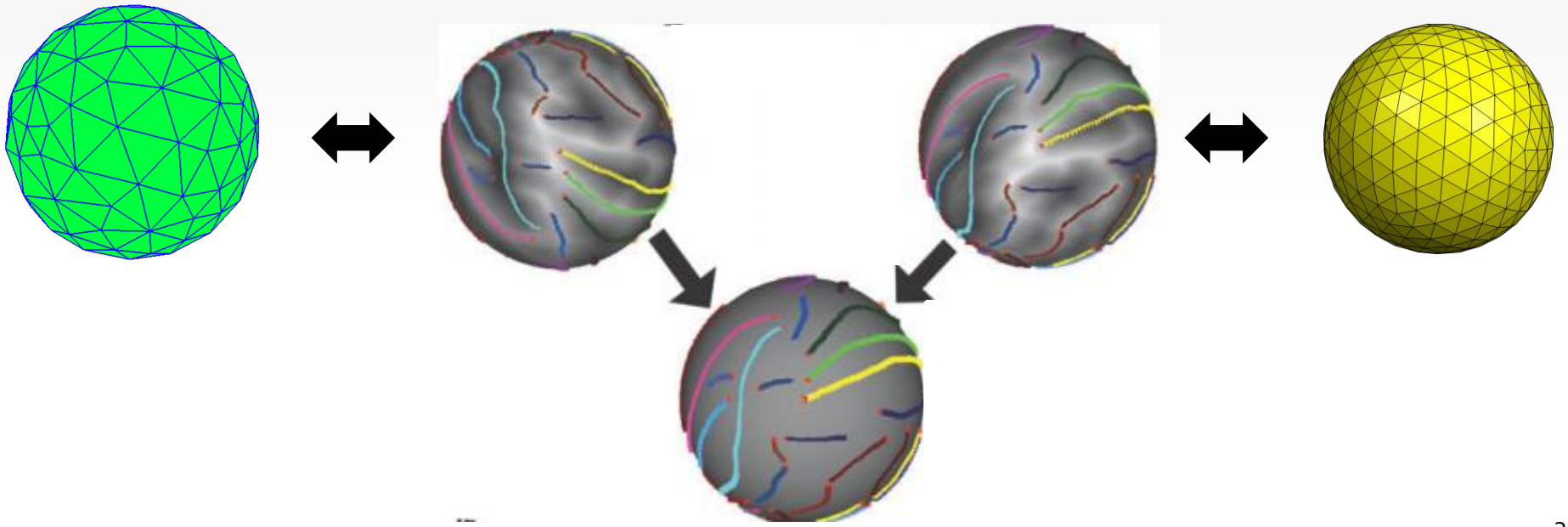
Also true for volume-based methods!

Registration = distortions

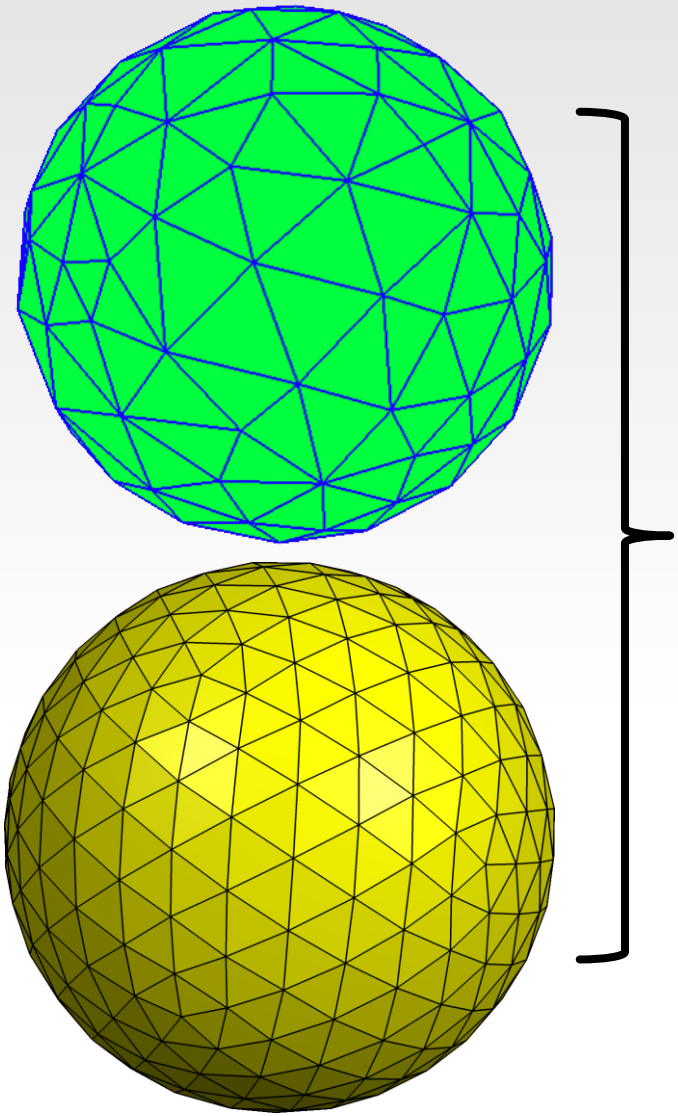


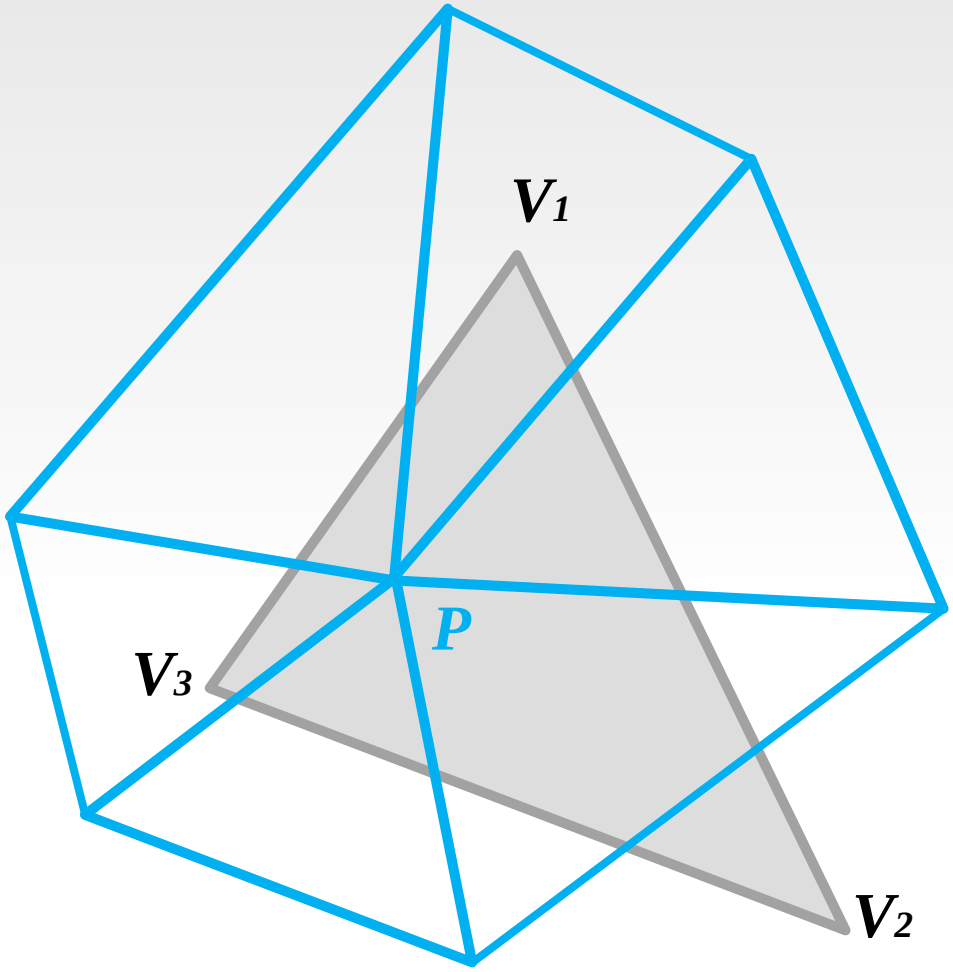
Remeshing = interpolation across meshes

- Transfer information across meshes
  to a common domain
- Change the spatial resolution
- Compute an average surface



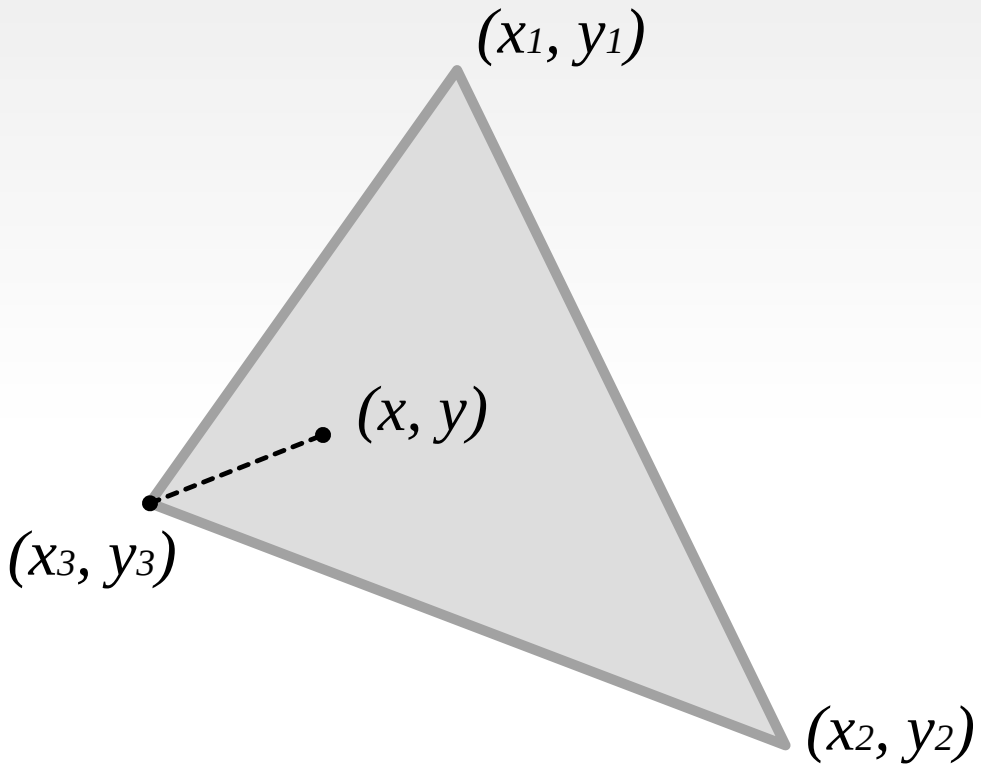
Remeshing = interpolation across meshes





Remeshing = interpolation across meshes

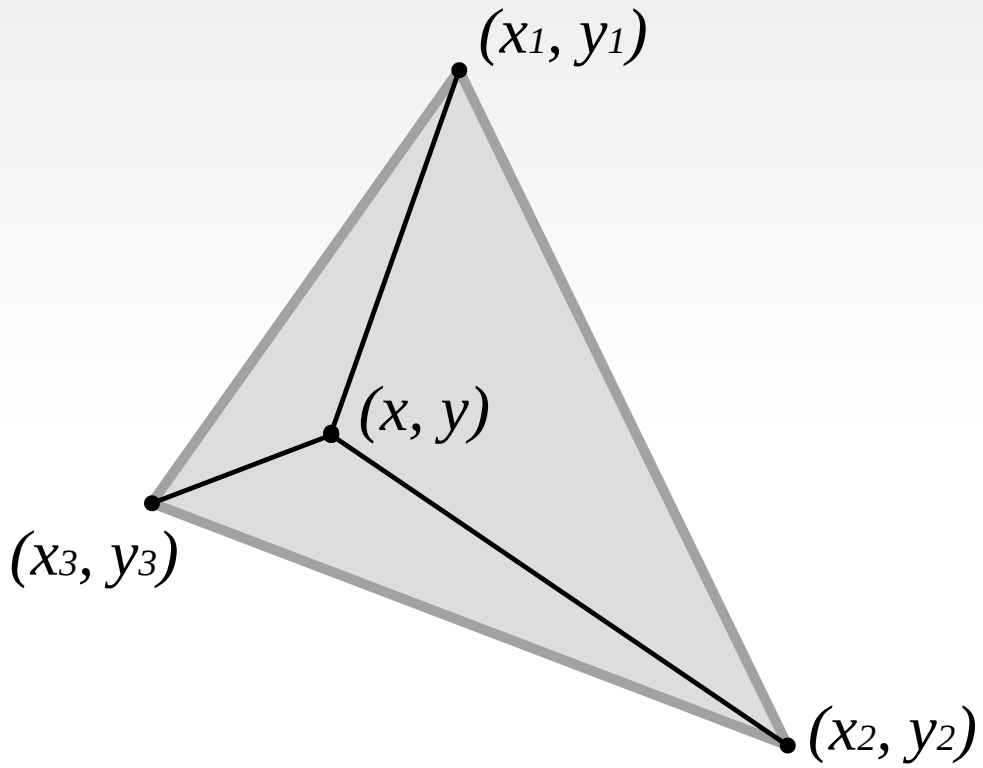
- Nearest neighbor interpolation:
- Associate the value of the closest point



Remeshing = interpolation across meshes

- Linear interpolation:
- Barycentric coordinates

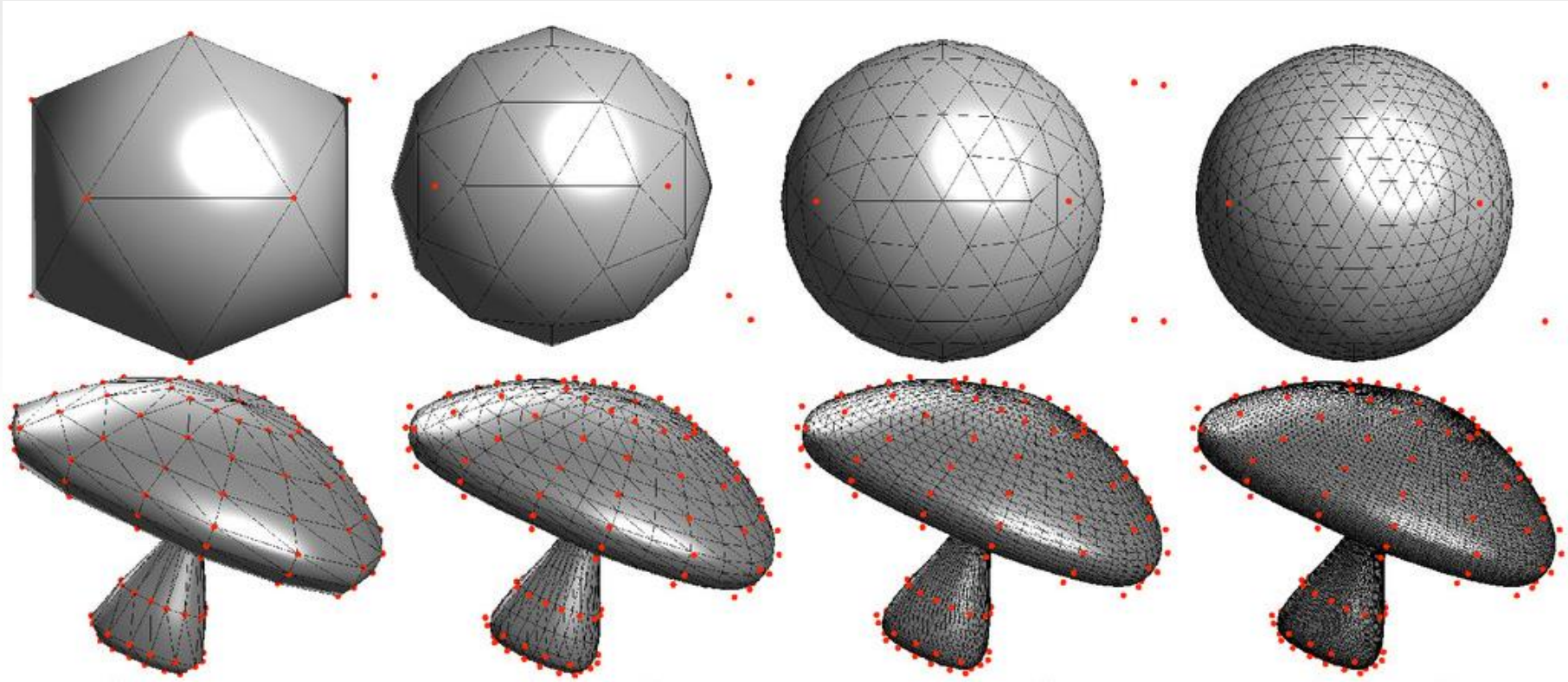
$$x = \lambda_1 x_1 + \lambda_2 x_2 + \lambda_3 x_3$$
$$y = \lambda_1 y_1 + \lambda_2 y_2 + \lambda_3 y_3$$



https://en.wikipedia.org/wiki/Barycentric_coordinate_system

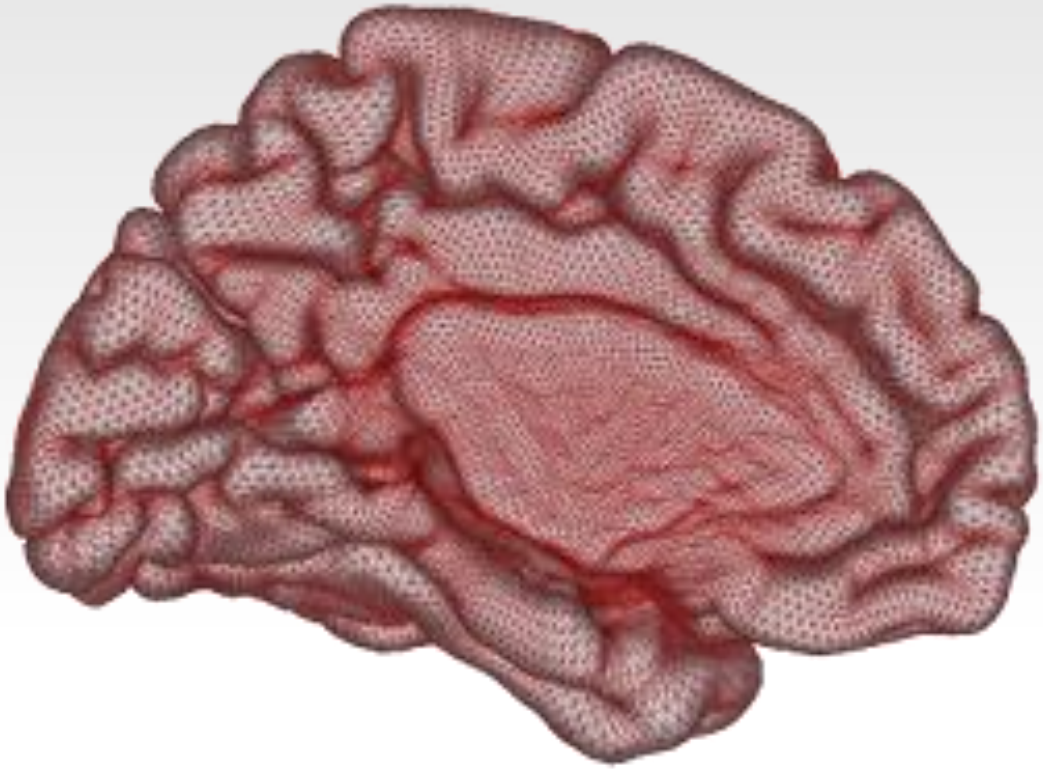
Remeshing = interpolation across meshes

- Change the spatial resolution

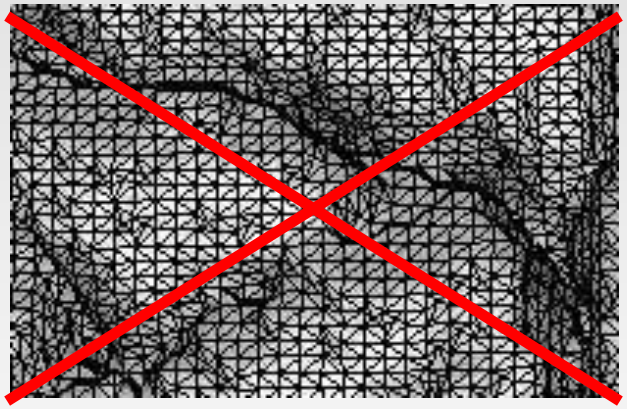


Excellent courses from G.Peyré

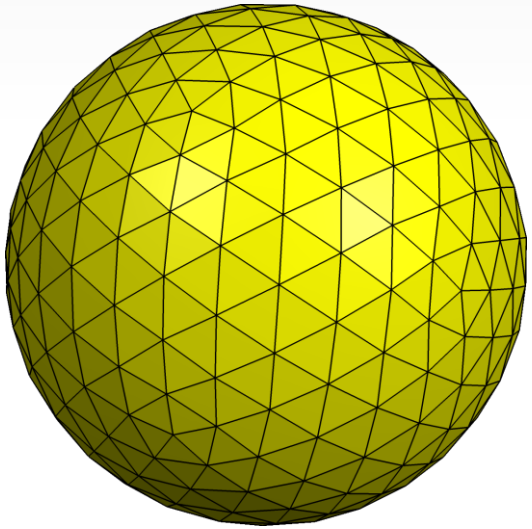
Remeshing = interpolation across meshes



https://mcin.ca/technology/civet/

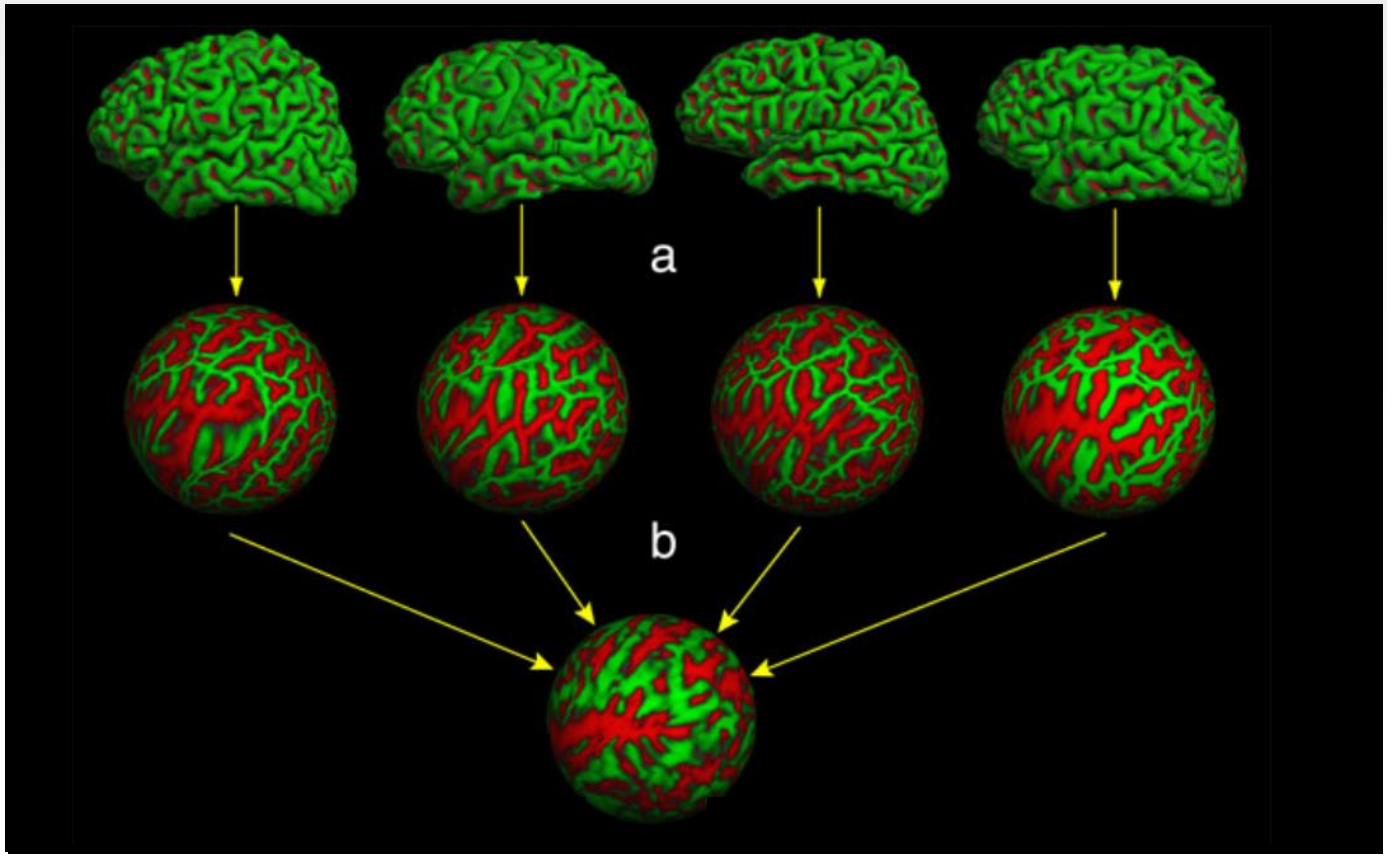


-Too regular for a marching cubes
-Heterogeneous triangle size
-> Remeshed using an icosahedron



Computing statistics across meshes

- Compare features across meshes
- E.g. 2 groups of subjects



Successive steps in a classical pipeline

- Segmentation of the white mesh
- Topology correction
- Mesh deformation to get the pial mesh
- Mapping onto a sphere
- Spherical registration
- Remeshing / interpolation across meshes
- **Volume to mesh interpolation**
- **Smoothing on the surface**
- **Computing statistics across meshes**

Volume to mesh interpolation/projection

Operto et al., *Neuroimage*, 2008

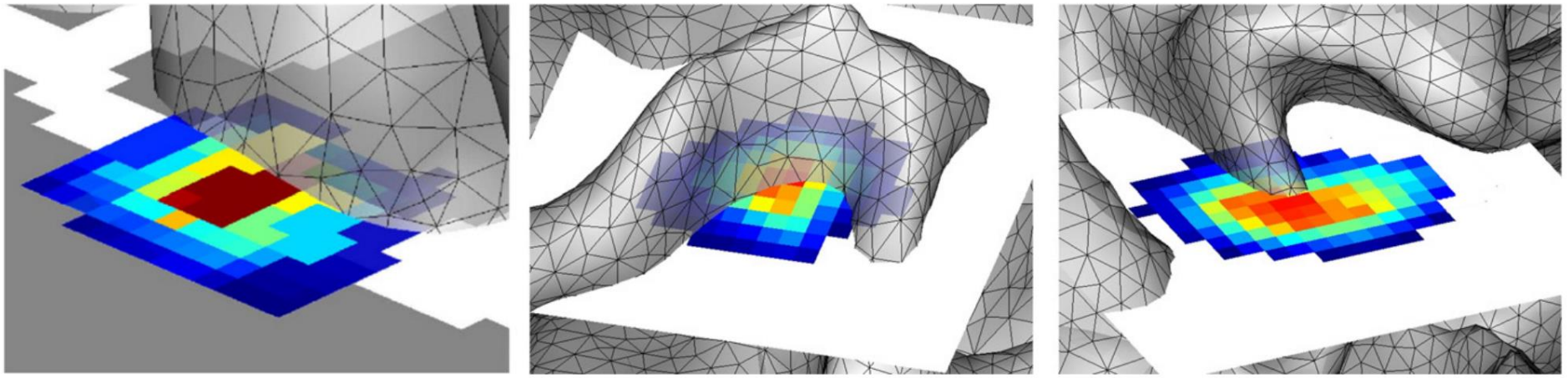
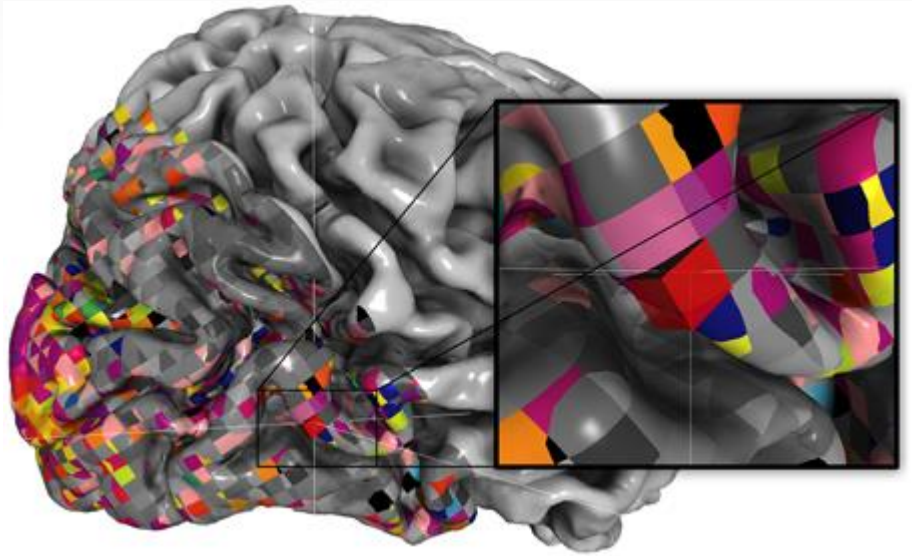


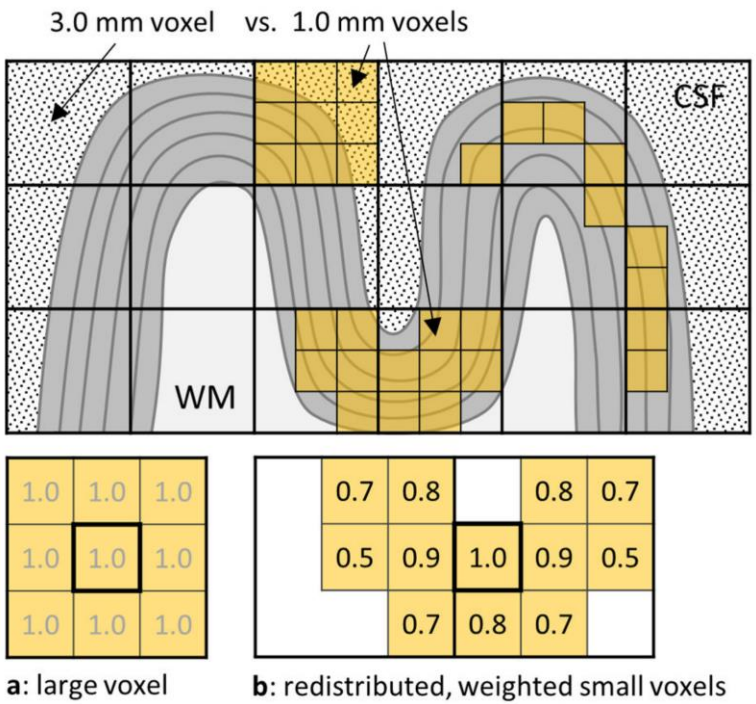
Fig. 6. Convolution kernels obtained for nodes on real cortical meshes. The kernel on the left shows a superimposed cortical mask.

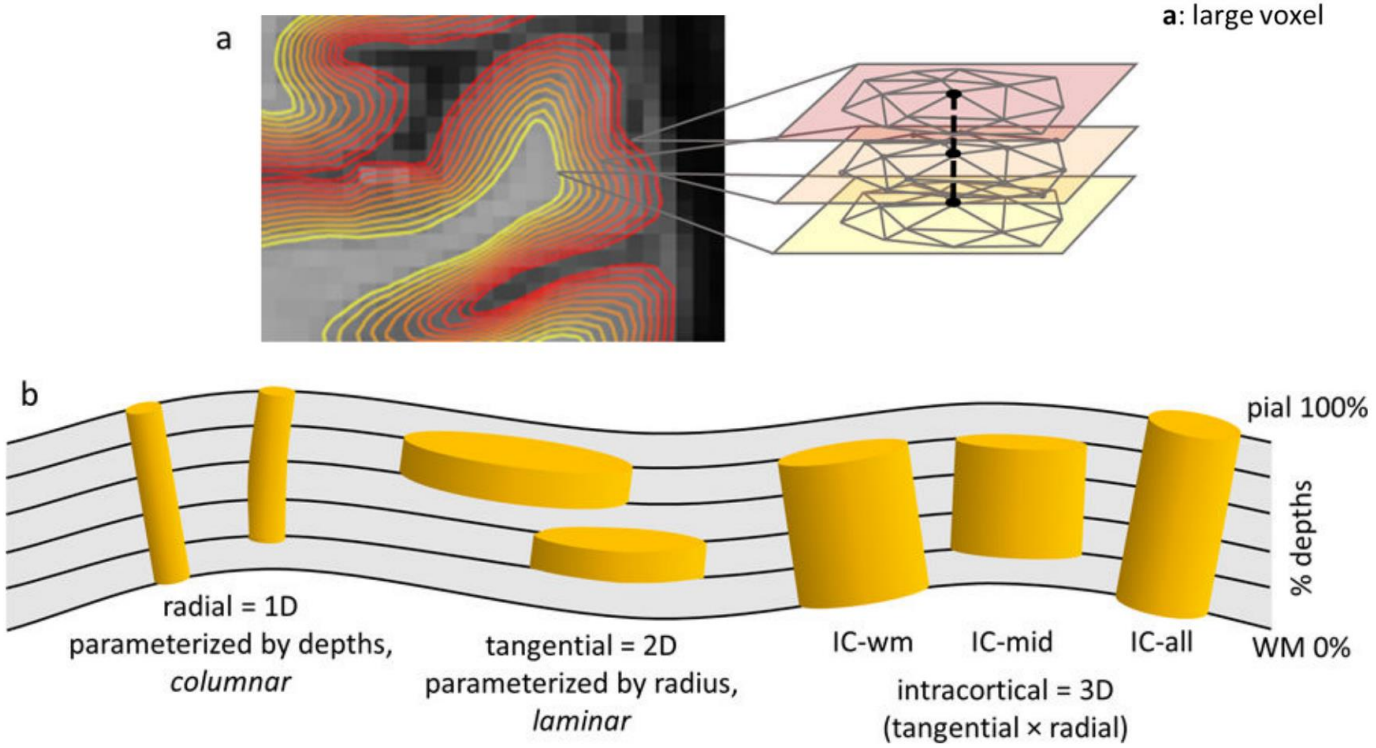


Gao et al., *Front. NeuroInf.*, 2015
Pycortex
https://gallantlab.github.io/pycortex/index.html

Smoothing on the surface

Al Blazejewska et al., *Neuroimage*, 2019





Computing statistics on meshes

- Available tools
  - Freesurfer tksurfer
  - Surfstat (matlab)
  - CAT 12
  - Nilearn?

Control False positives
Multiple comparisons

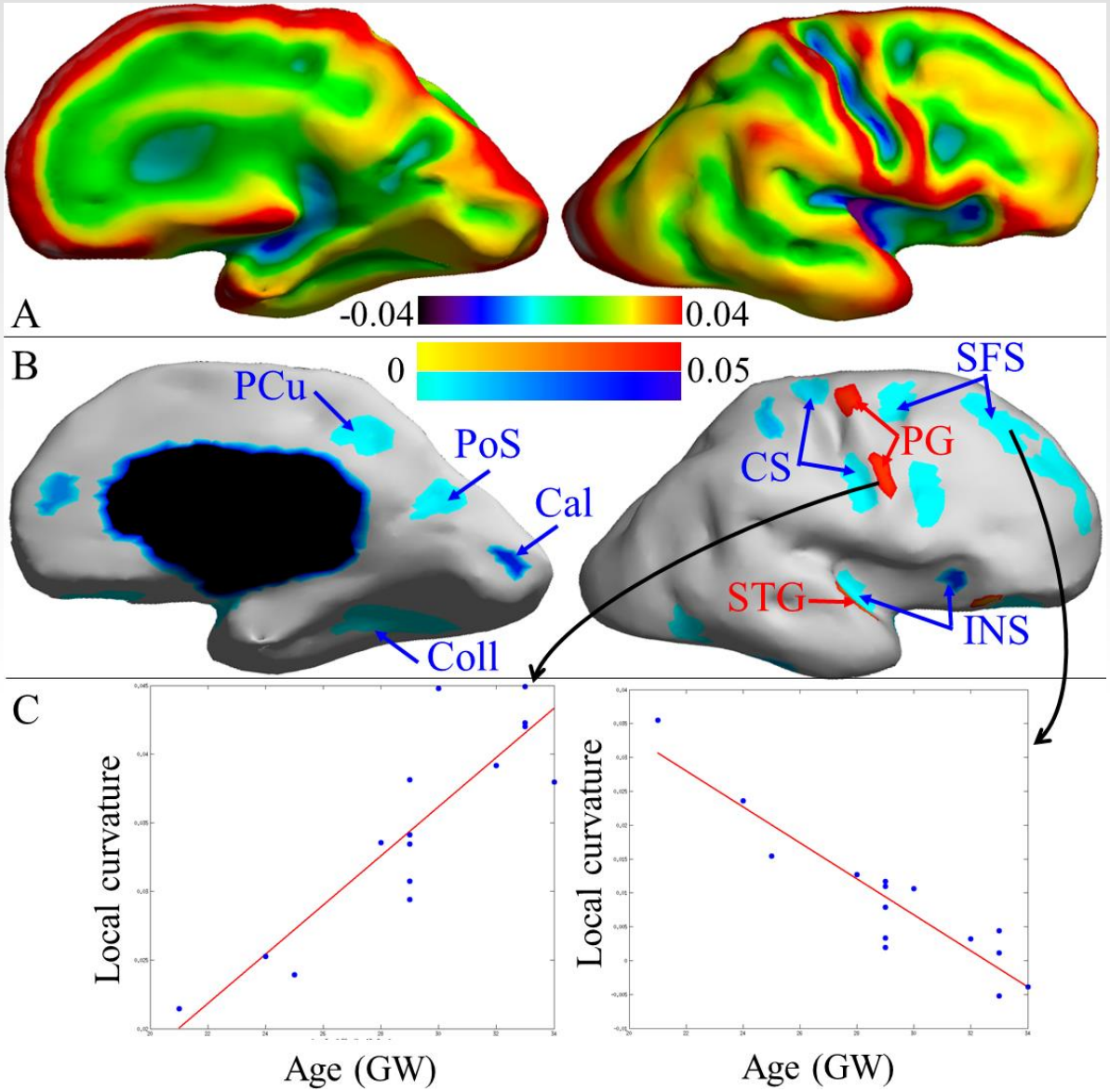
Greve et al., *Neuroimage*, 2018

Andy W. K. Yeung,*Frontiers in Human Neuroscience, 2018*

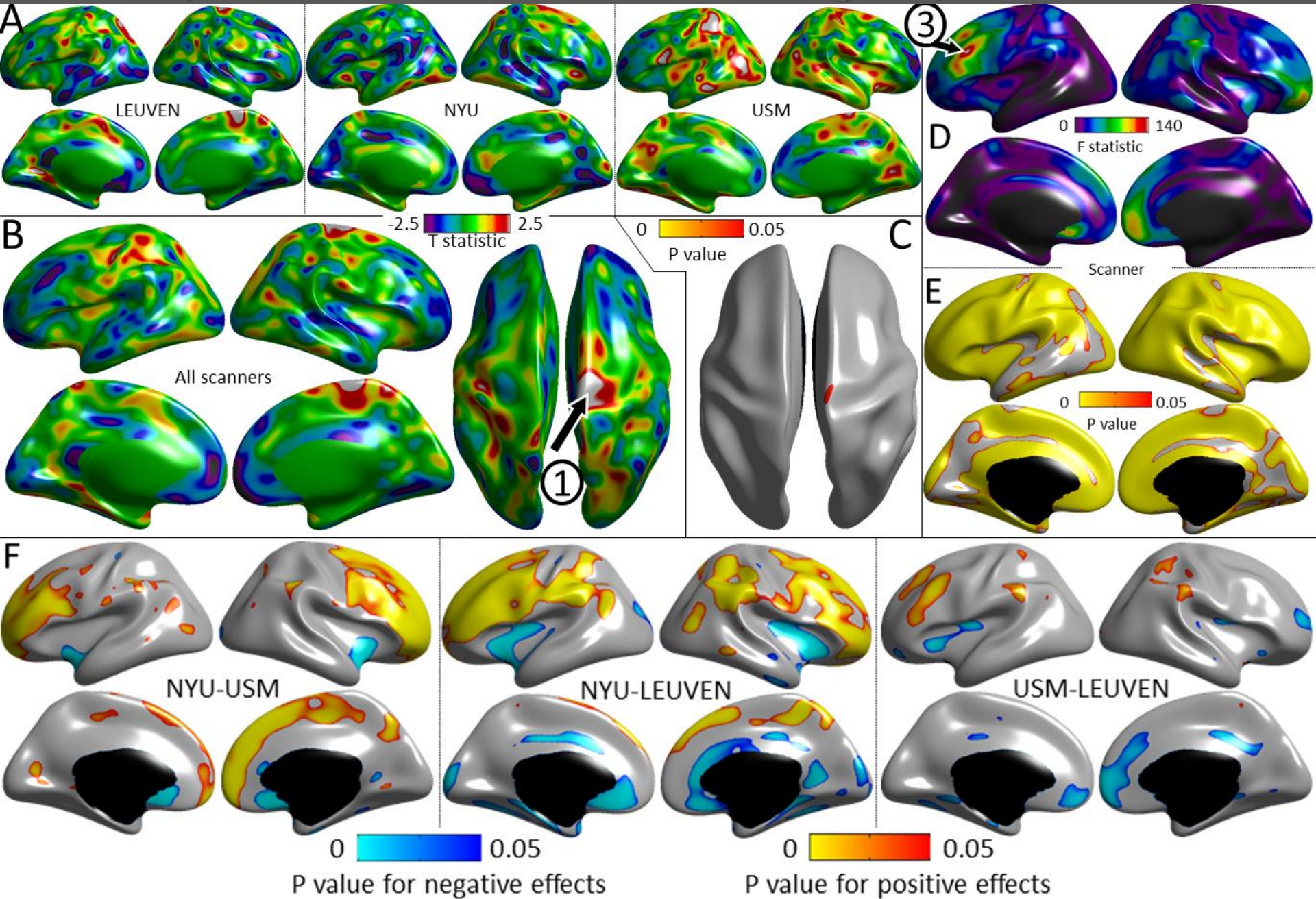
Evolution of Cortical folding with GA

15 Fetuses
21-34 wk GA

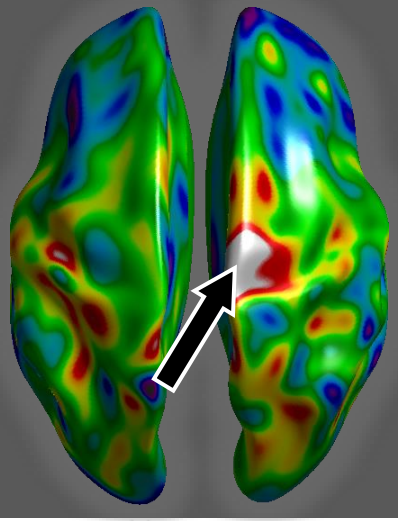
Auzias et al., *IEEE ISBI*, 2015

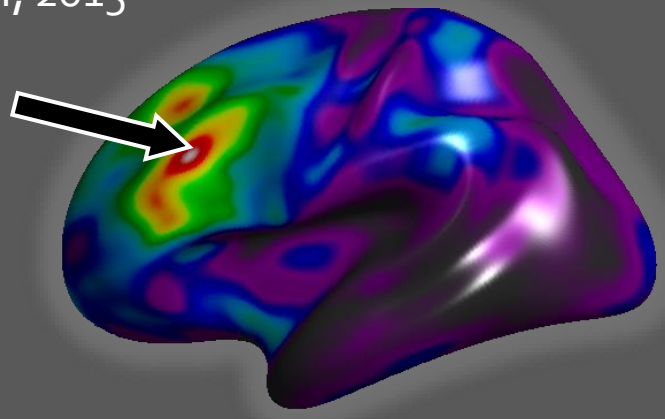


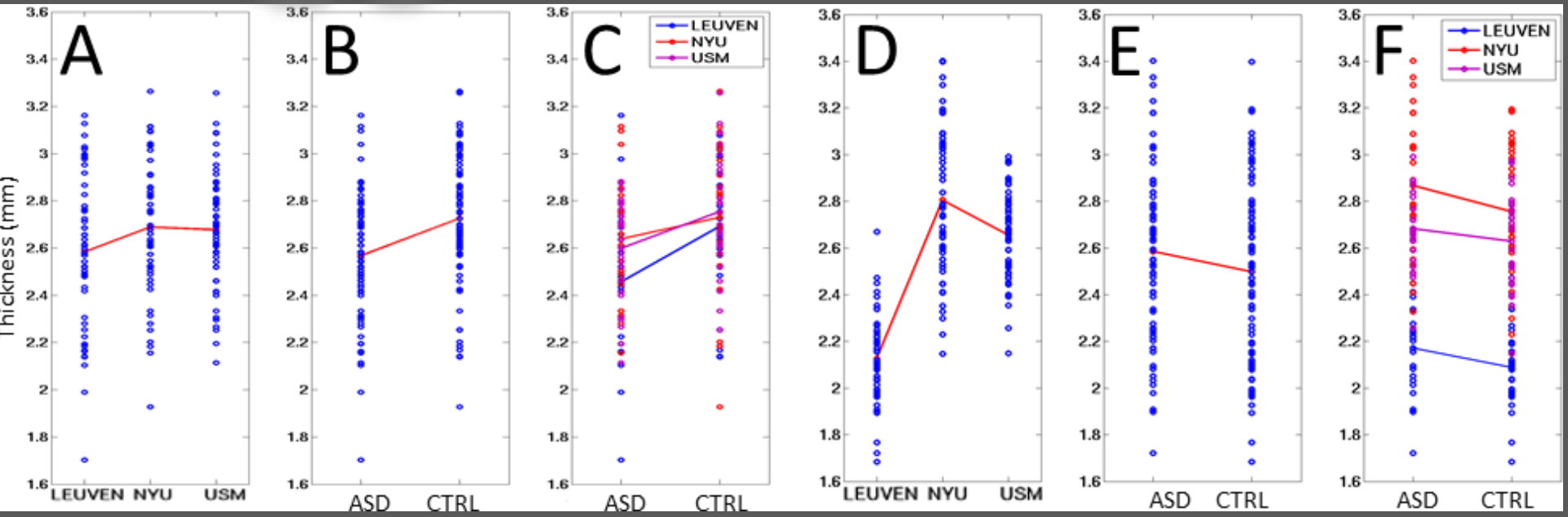
Compare cortical thickness across groups and scanners



Auzias et al., IEEE JBHI, 2015







Diagnostic group: η^2=0.35, p<0.0001
scanner : η^2=0.07, p=0.14
Age: η^2=0.49, p<0.0001
age-by-scanner η^2=0.08, p=0.12

Diagnostic group: η^2=0.01, p=0.0284
Scanner: η^2=0.77, p<0.0001
Age: η^2=0.15, p<0.0001
age-by-scanner: η^2=0.05, p<0.0001

Recap
Successive steps in a classical pipeline

- Segmentation of the white mesh
- Topology correction

} Imprecisions

- Mesh deformation to get the pial mesh — Distortions
- Mapping onto a sphere — Distortions
- Spherical registration — Distortions / Bias
- Remeshing / interpolation across meshes — Interpolation errors
- Volume to mesh interpolation — Interpolation errors
- Smoothing on the surface
- Computing statistics across meshes — Interpretation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