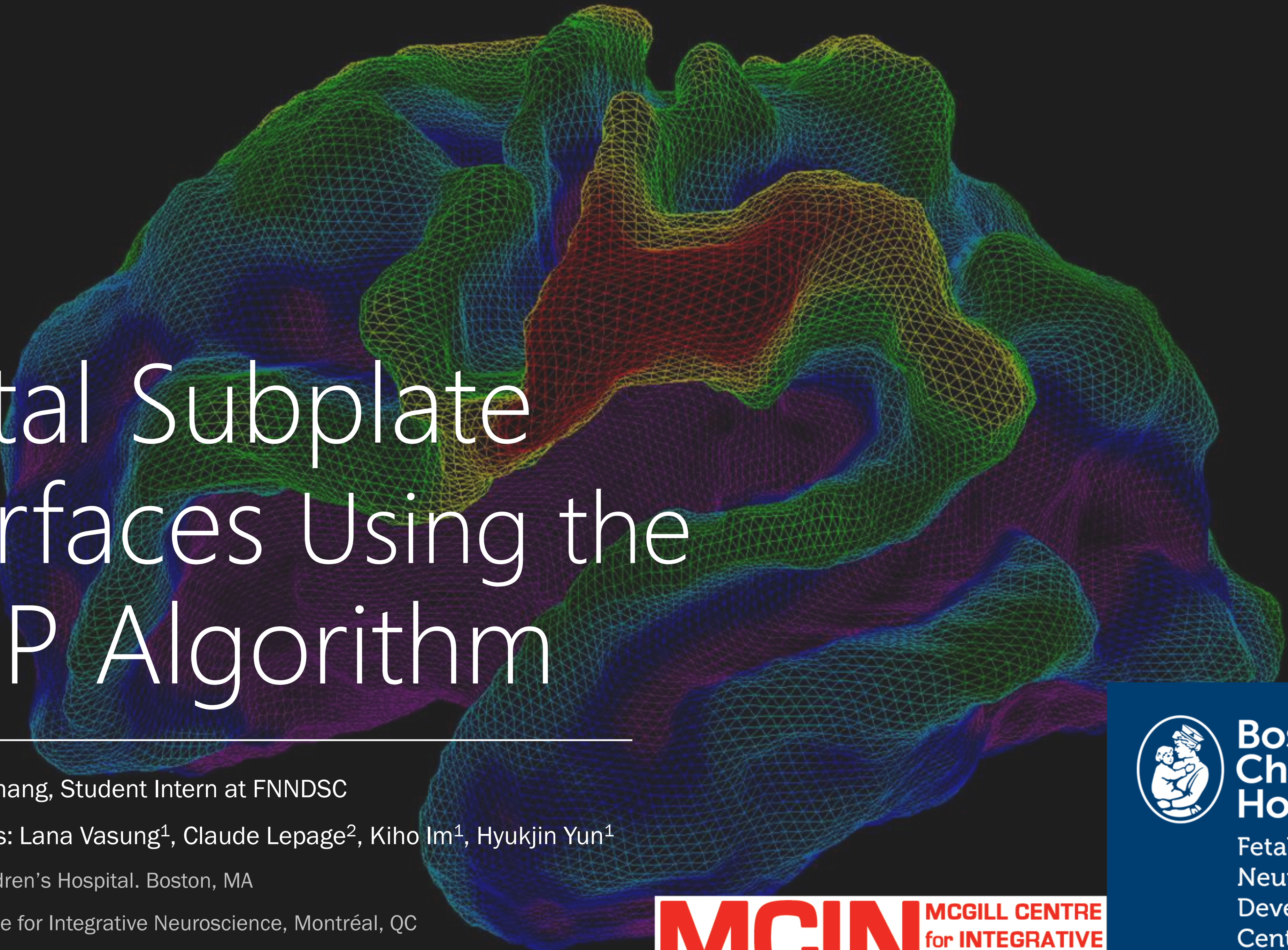


Fetal Subplate Surfaces Using the ASP Algorithm

Jennings Zhang, Student Intern at FNNDSC

Supervisors: Lana Vasung[1], Claude Lepage[2], Kiho Im[1], Hyukjin Yun[1]

[1]Boston Children's Hospital. Boston, MA

[2]McGill Centre for Integrative Neuroscience, Montréal, QC

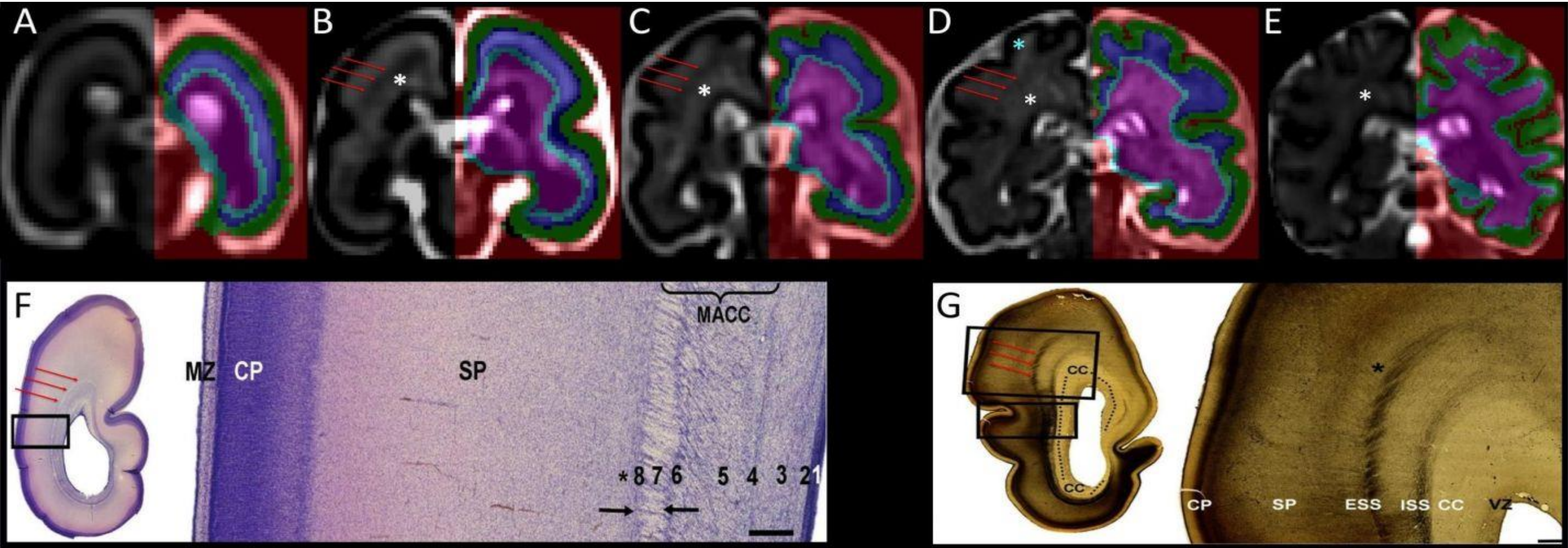
MCIN MCGILL CENTRE for INTEGRATIVE NEUROSCIENCE

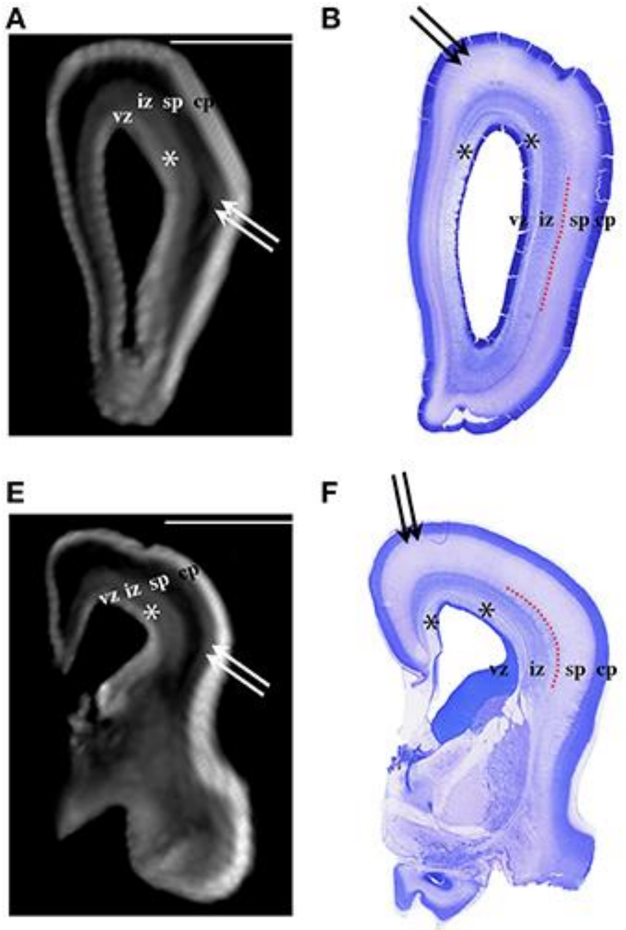
Boston Children's Hospital

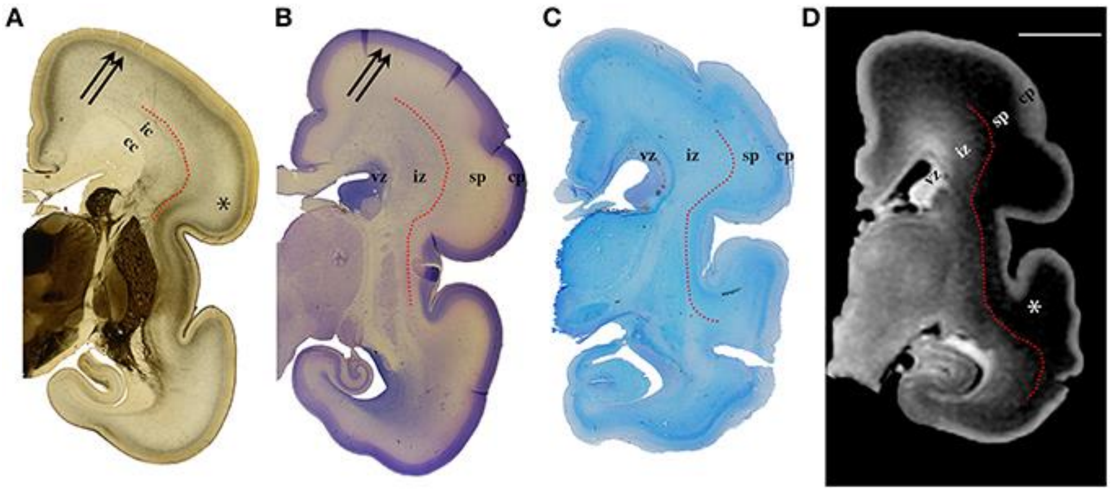
Fetal-Neonatal Neuroimaging and Developmental Science Center

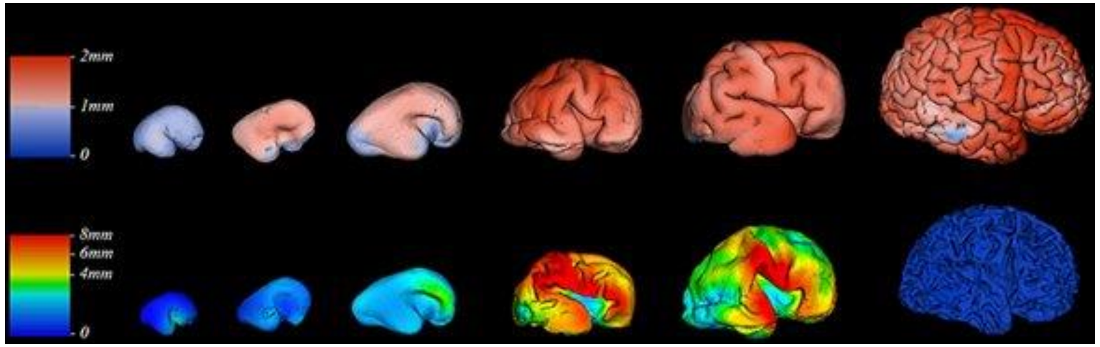
Transient Fetal Sublayers

- Temporary subcortical layers
- Subplate (SP) neurons guide thalamocortical fibers and corticogenesis
- Subplate zone visible on MRI between 15-32 gestational age
- Disappears after 32 GA





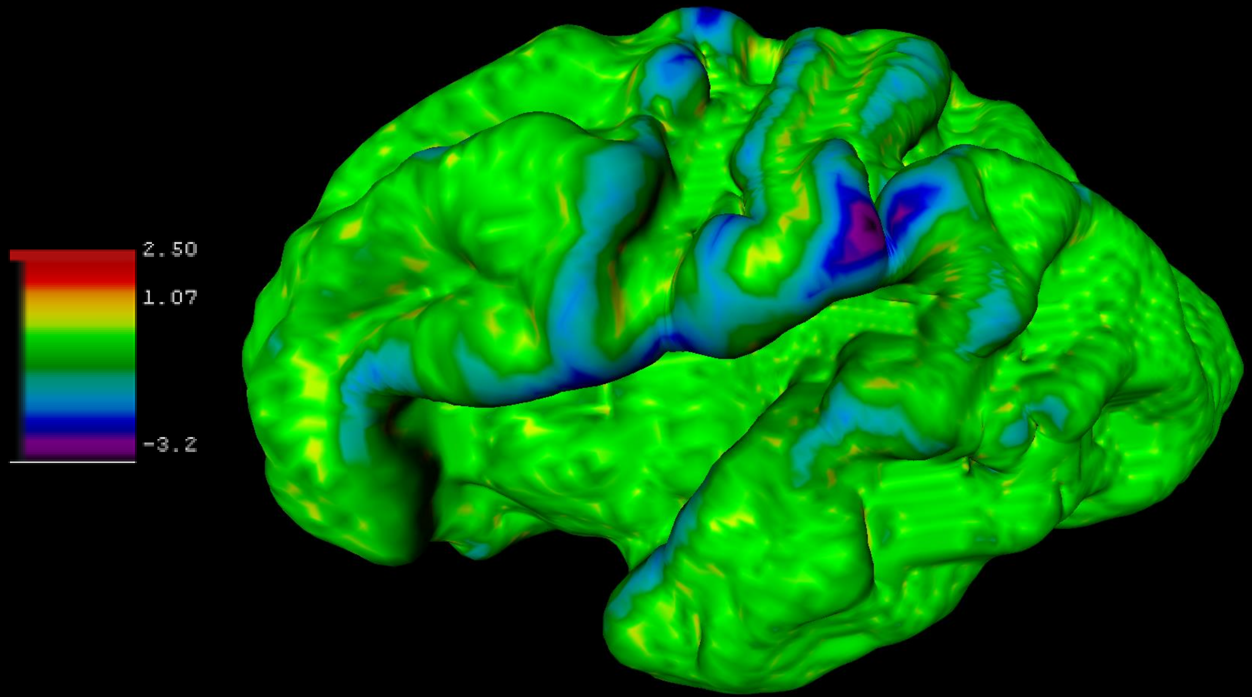


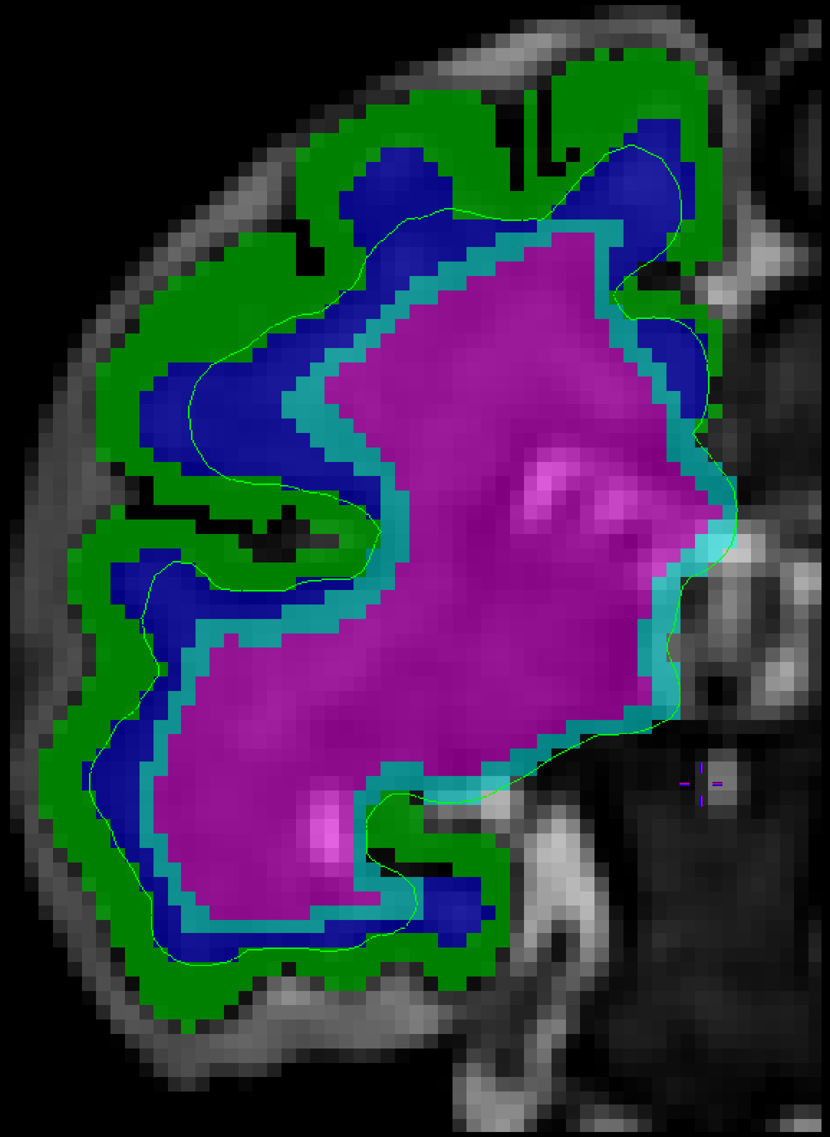


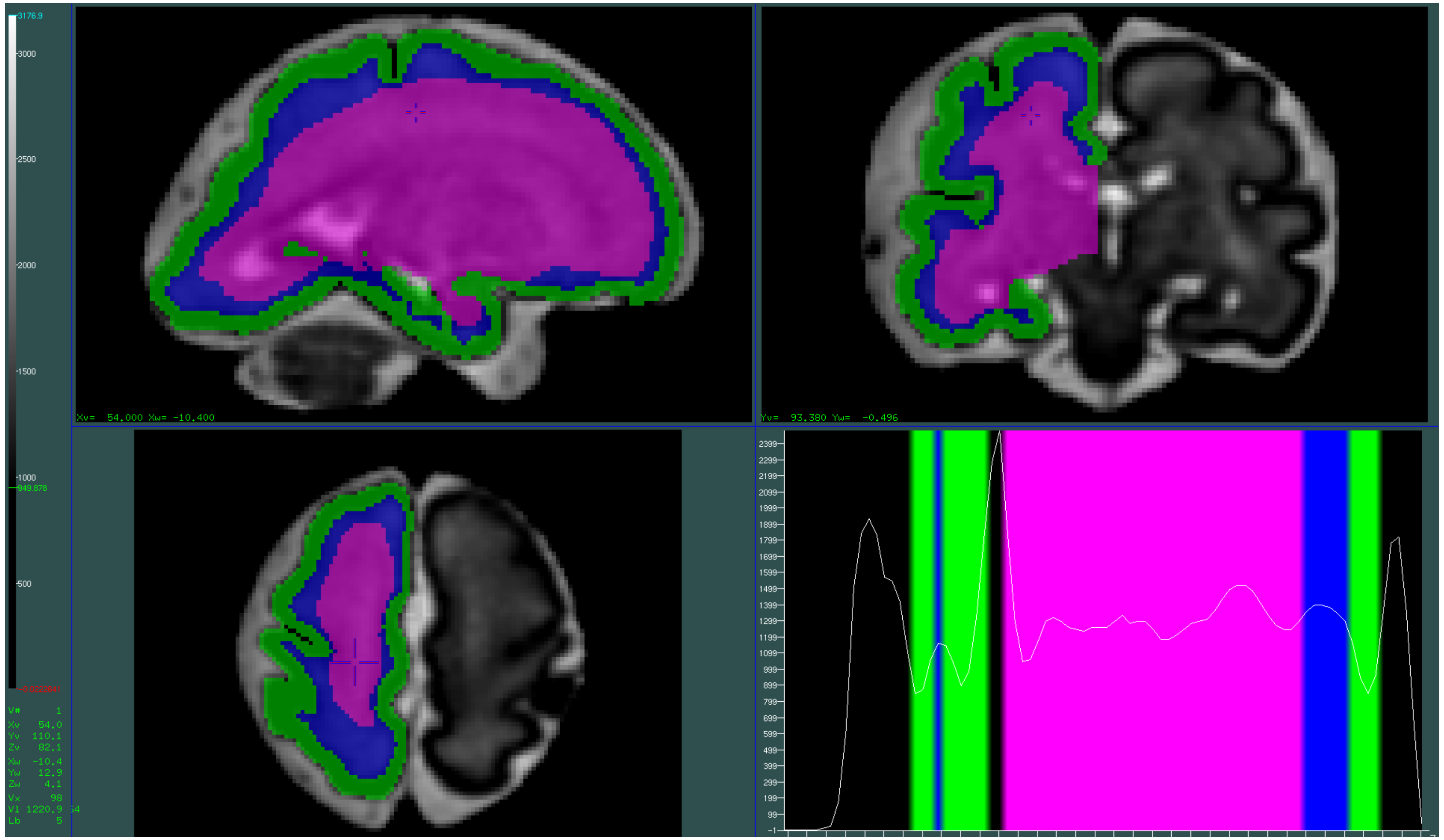
Vasung, L., Lepage, C., Radoš, M., Pletikos, M., Goldman, J.S., Richiardi, J., Raguž, M., Fischi-Gómez, E., Karama, S., Huppi, P.S. and Evans, A.C., 2016. Quantitative and qualitative analysis of transient fetal compartments during prenatal human brain development. *Frontiers in neuroanatomy*, *10*, p.11.

Old Pipeline

- Ex-vivo post-mortem
- Errors with 26-32 GA







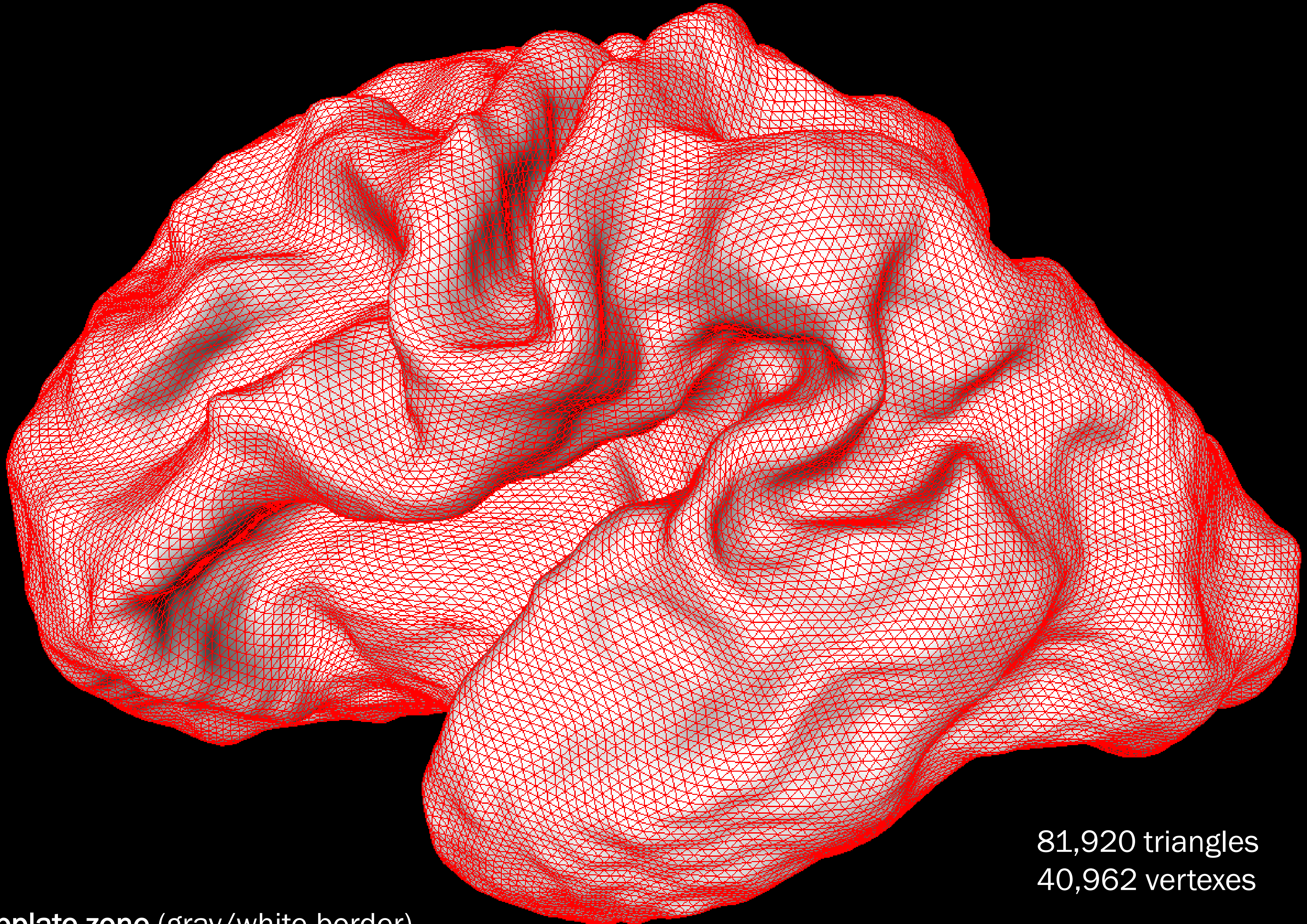
In-utero MRI Pipeline

Data Acquisition

1. T2-weighted MRI scan
   42 Subjects, 14 with subplate
2. Automatic segmentation
   Post-processing resolution: 0.8 mm
3. Manual corrections
   Operational bottleneck

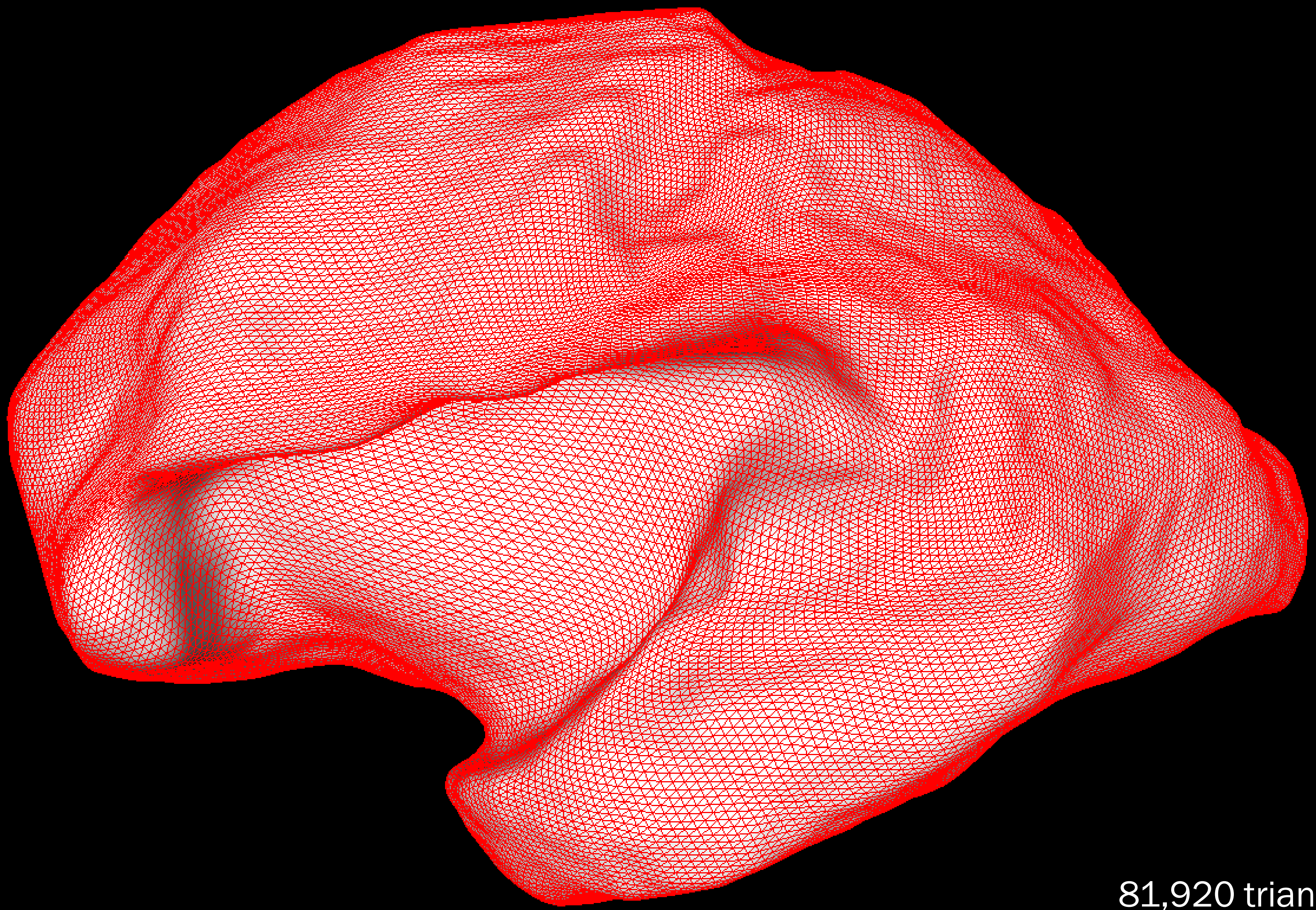
Surfaces

4. Extract white/gray boundary
   marching_cubes.pl
5. Fit WM surface out to CP
   CLASP
6. **Fit WM surface down to IZ**
   surface_fit



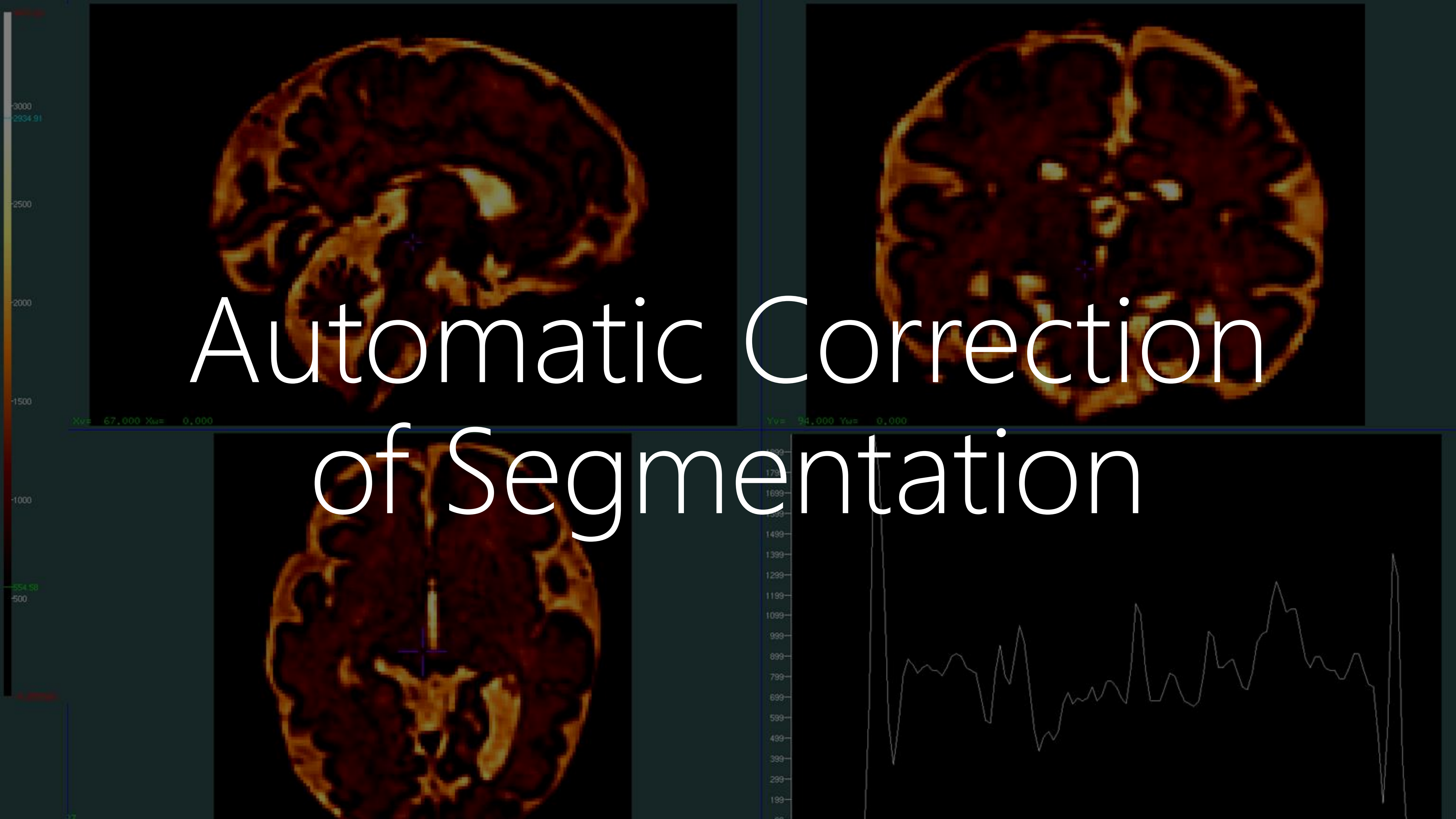
81,920 triangles
40,962 vertexes

Surface of **subplate zone** (gray/white border)



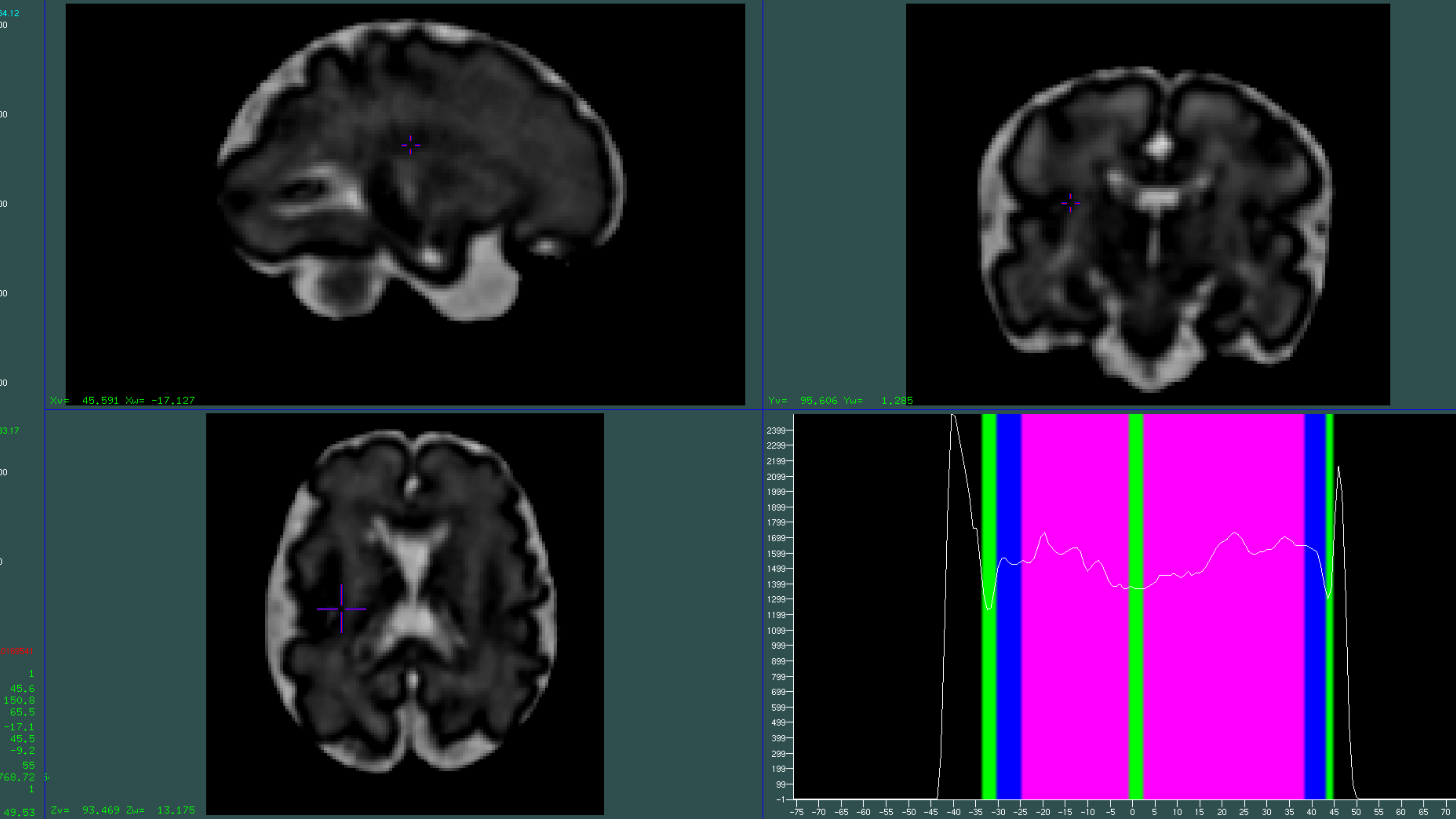
Surface of **intermediate zone**

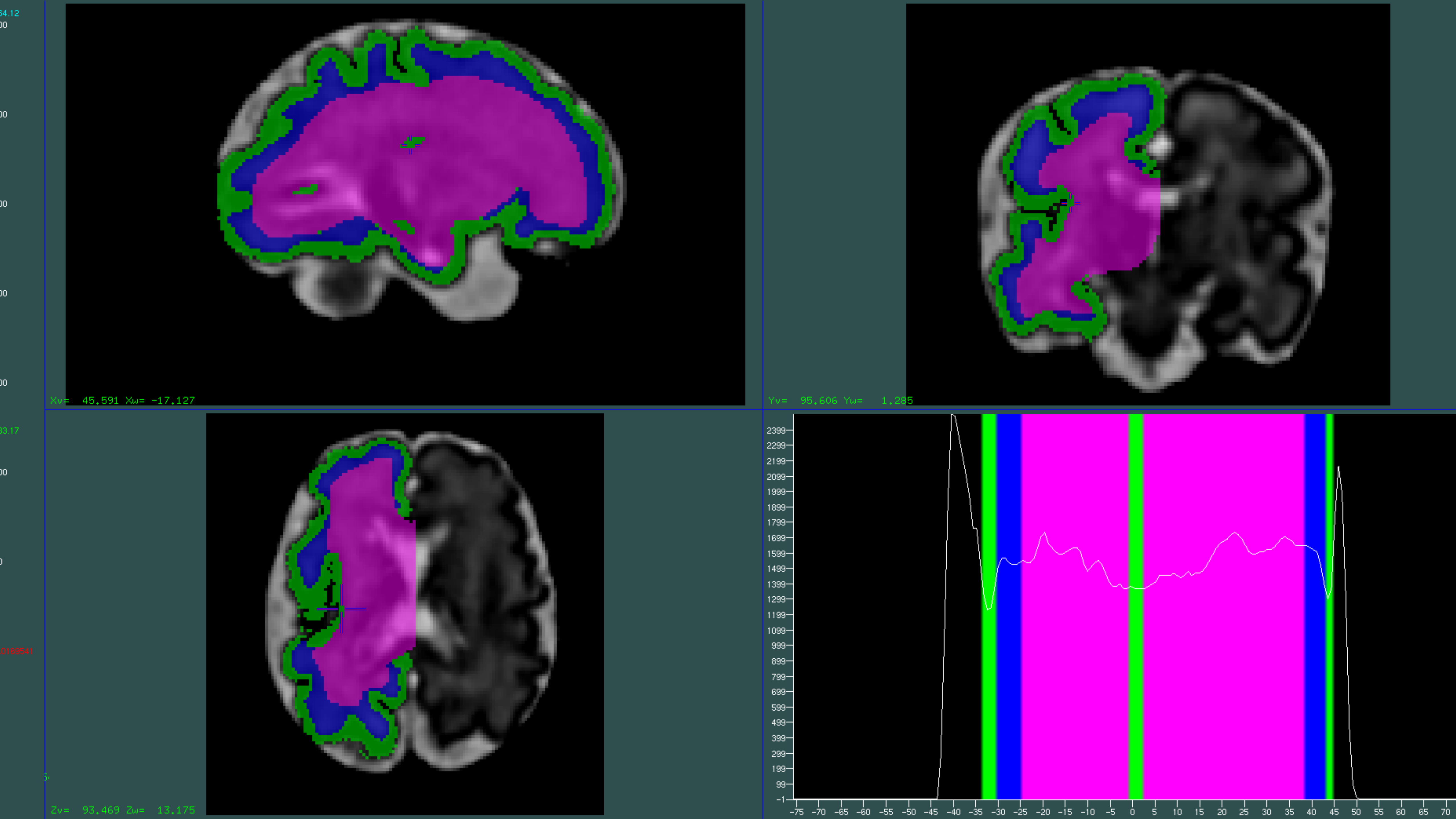
Automatic Correction of Segmentation

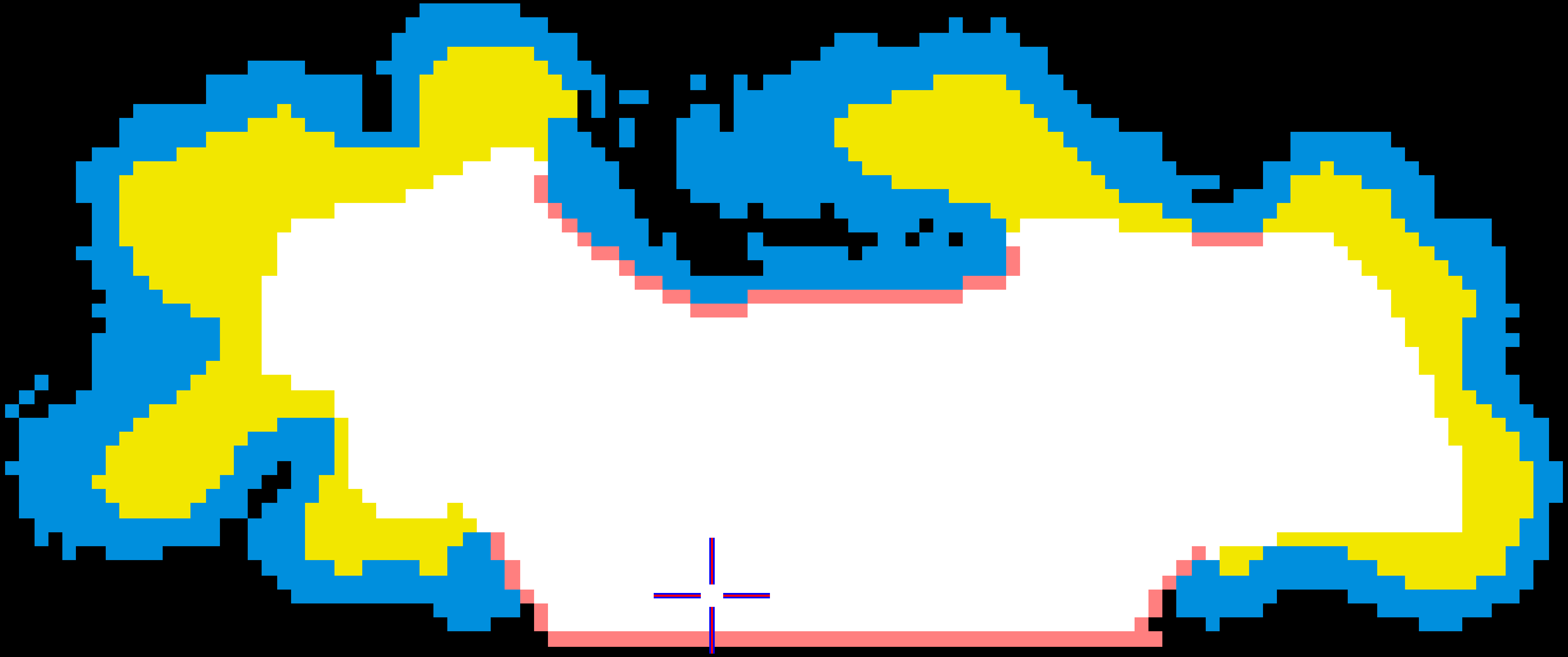


patch.sh

Files	Input: Final_Labels_{LEFT,RIGHT}.mnc Output: patched segmentation volume (*.mnc)
Algorithm	Mark regions where subplate is discontinuous Fill one voxel inside the subplate/intermediate zone boundary
Outcome	Discontinuous subplate on lateral surface is corrected (biologically accurate)


Xv= 45.591 Xw= -17.127
Yv= 95.606 Yw= 1.285
Zv= 93.469 Zw= 13.175
1
45.6
150.8
65.5
-17.1
45.5
-9.2
55
768.72
1
49.53
2399
2299
2199
2099
1999
1899
1799
1699
1599
1499
1399
1299
1199
1099
999
899
799
699
599
499
399
299
199
99
-1
-75 -70 -65 -60 -55 -50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50 55 60 65 70


Xv= 45.591 Xw= -17.127
Yv= 95.606 Yw= 1.285
Zv= 93.469 Zw= 13.175



diemesh.py

Files

Input: labels.mnc, surface.obj

Output: exclusion_mask.txt

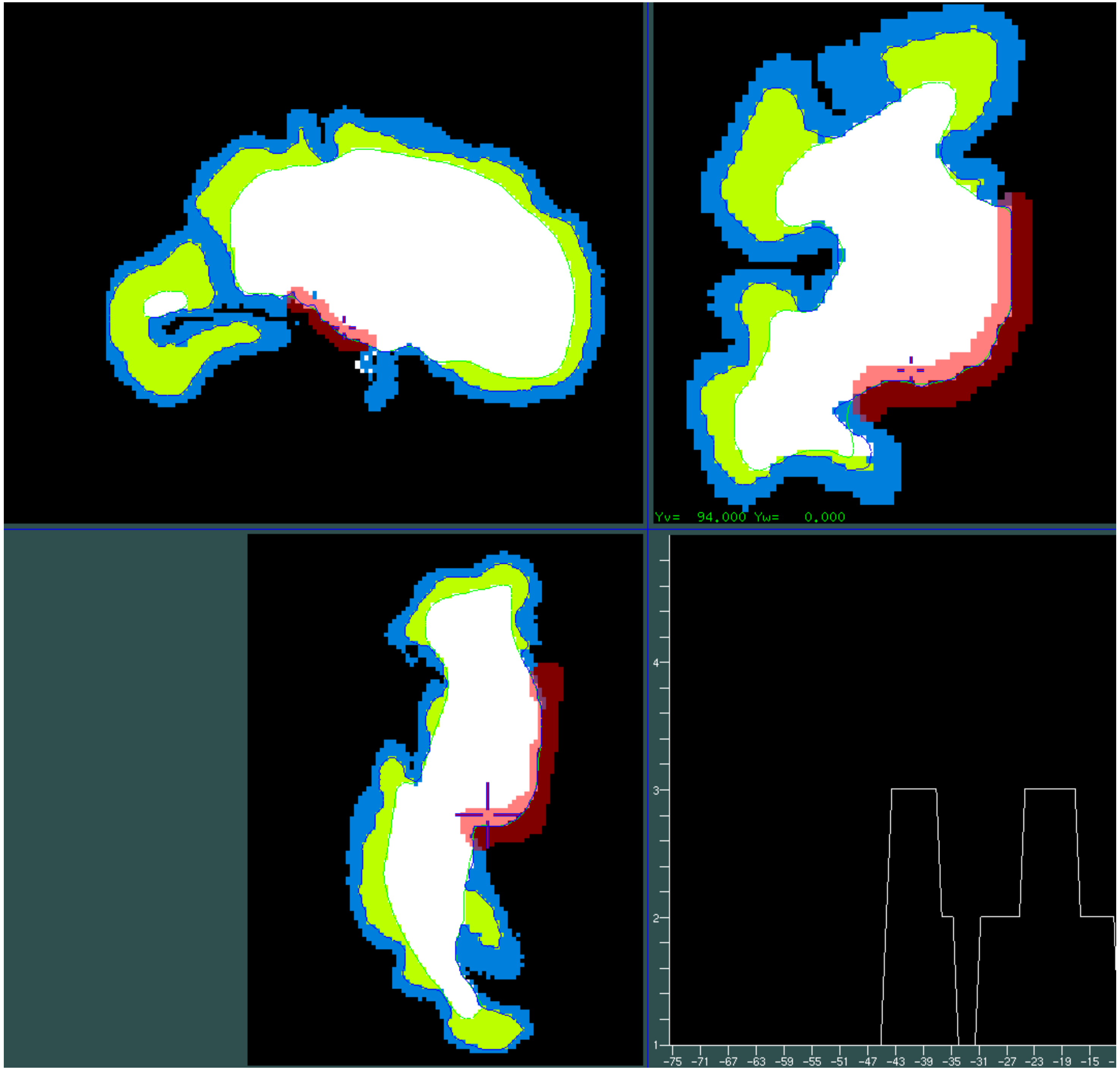
Algorithm

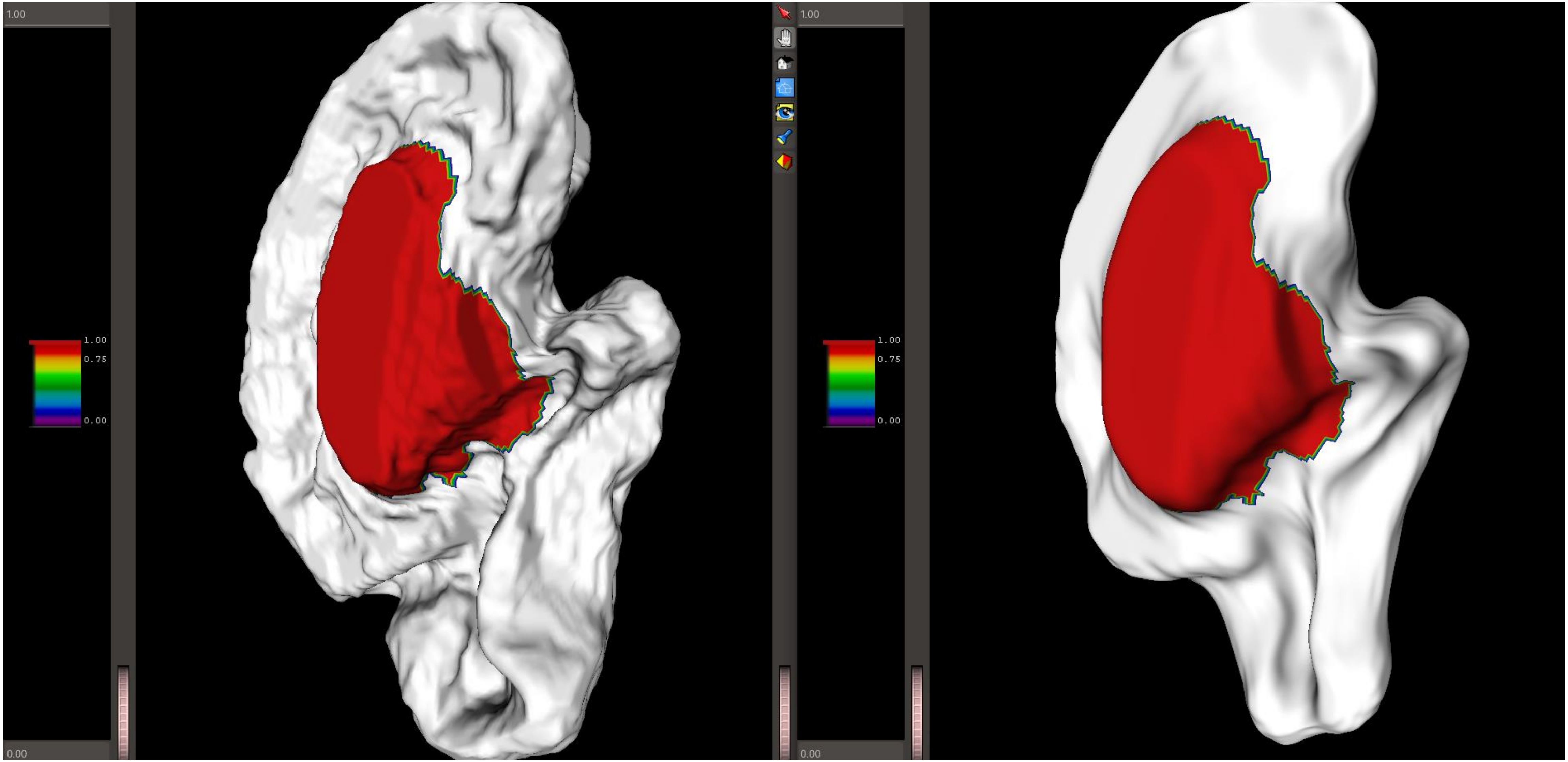
Find boundary where the intermediate zone is in direct contact with background/CSF

Mark nearby vertexes to be excluded

Result

Text file denotes which vertexes to exclude from calculations

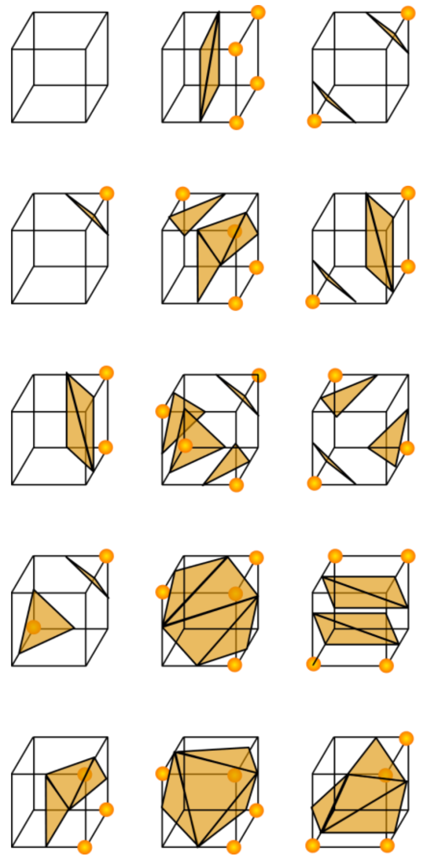

Yv= 94.000 Yw= 0.000
4
3
2
1
-75 -71 -67 -63 -59 -55 -51 -47 -43 -39 -35 -31 -27 -23 -19 -15



IZ Segmentation in Contact with Background/CSF

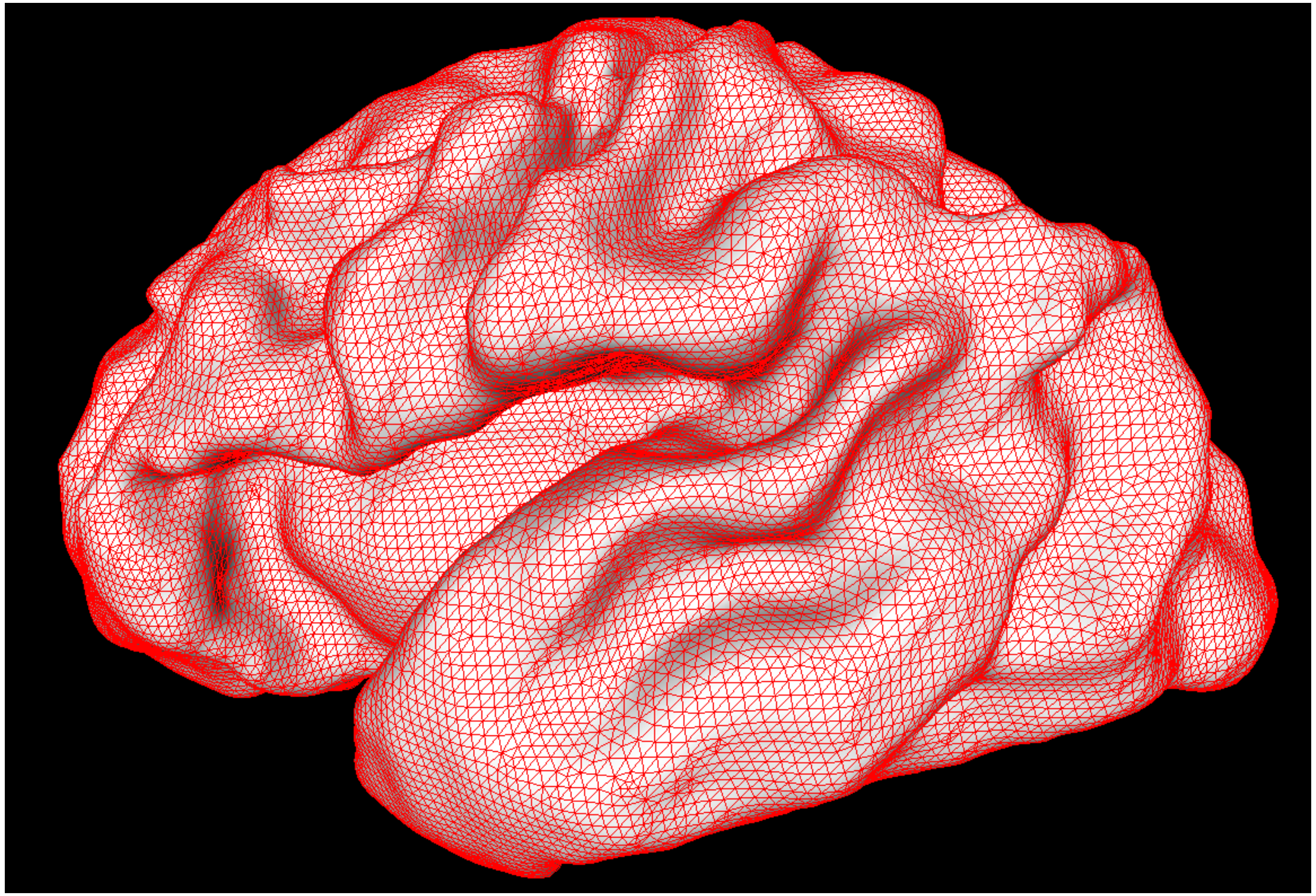
Surface Reconstruction using Marching Cubes

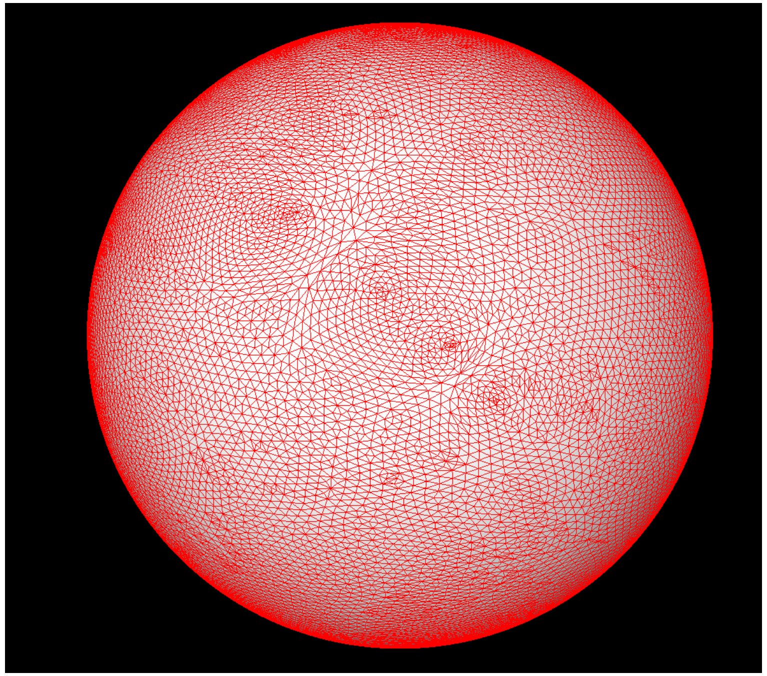
Surface Reconstruction: Marching Cubes

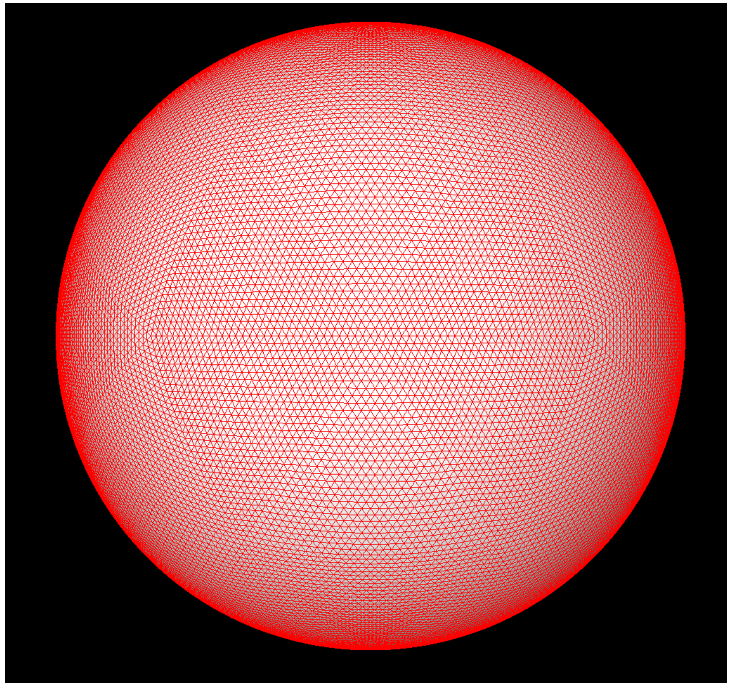


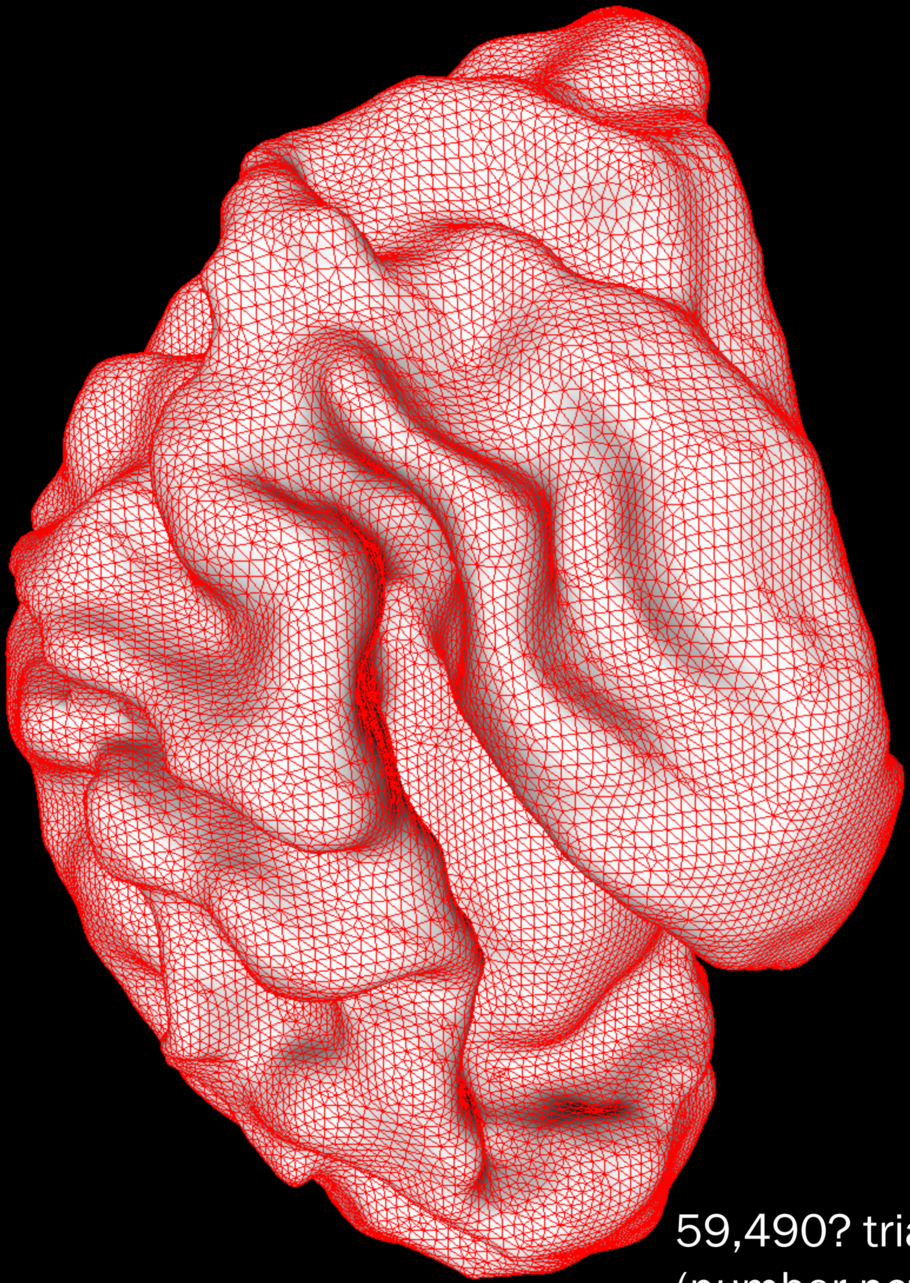
By Jmtrivial - Own work, GPL, https://commons.wikimedia.org/w/index.php?curid=1282165

Sphere Interpolation

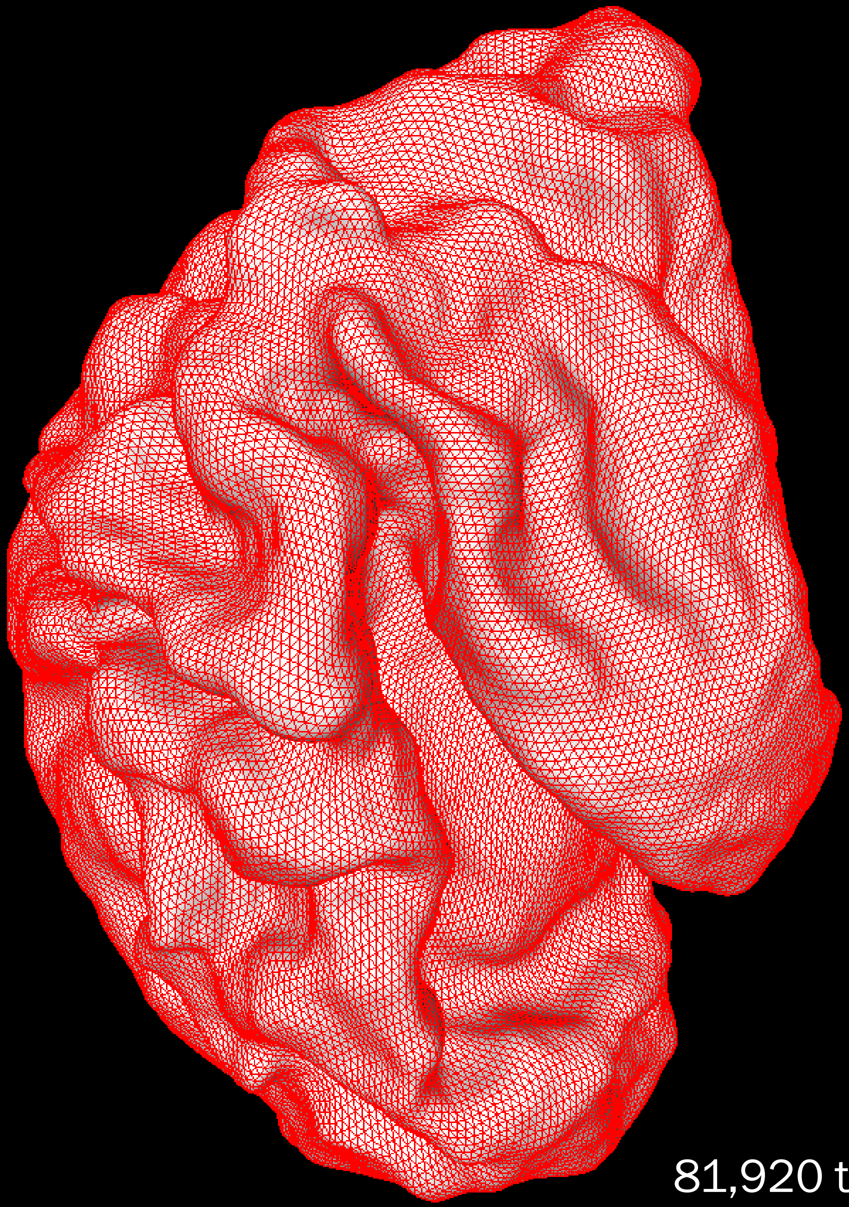








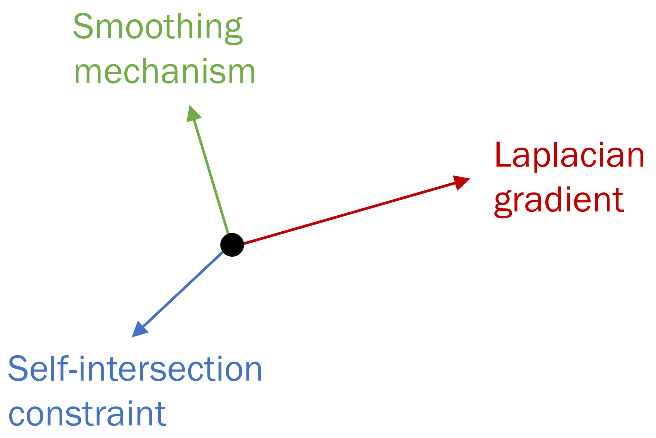
59,490? triangles
(number not consistent)

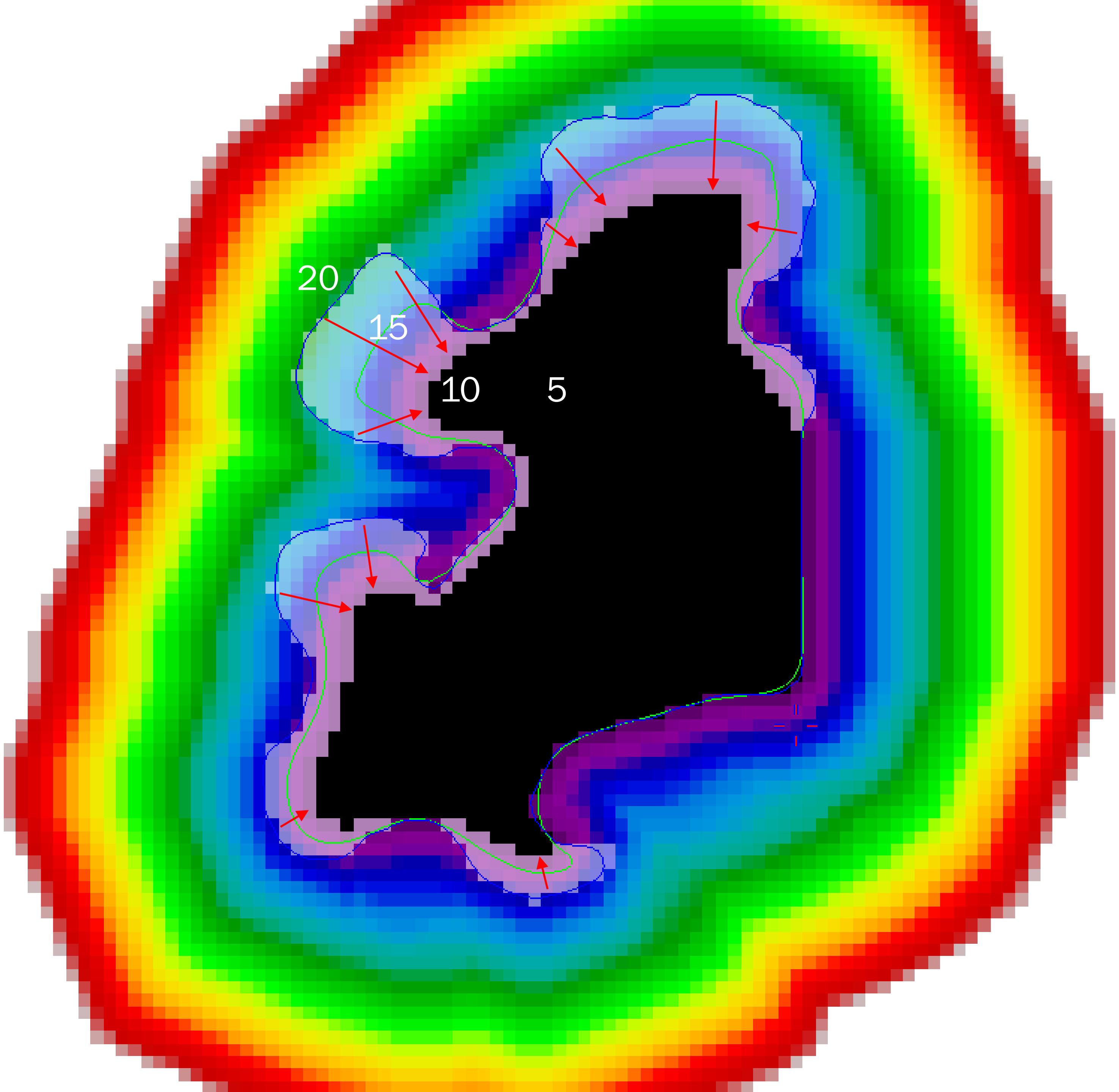


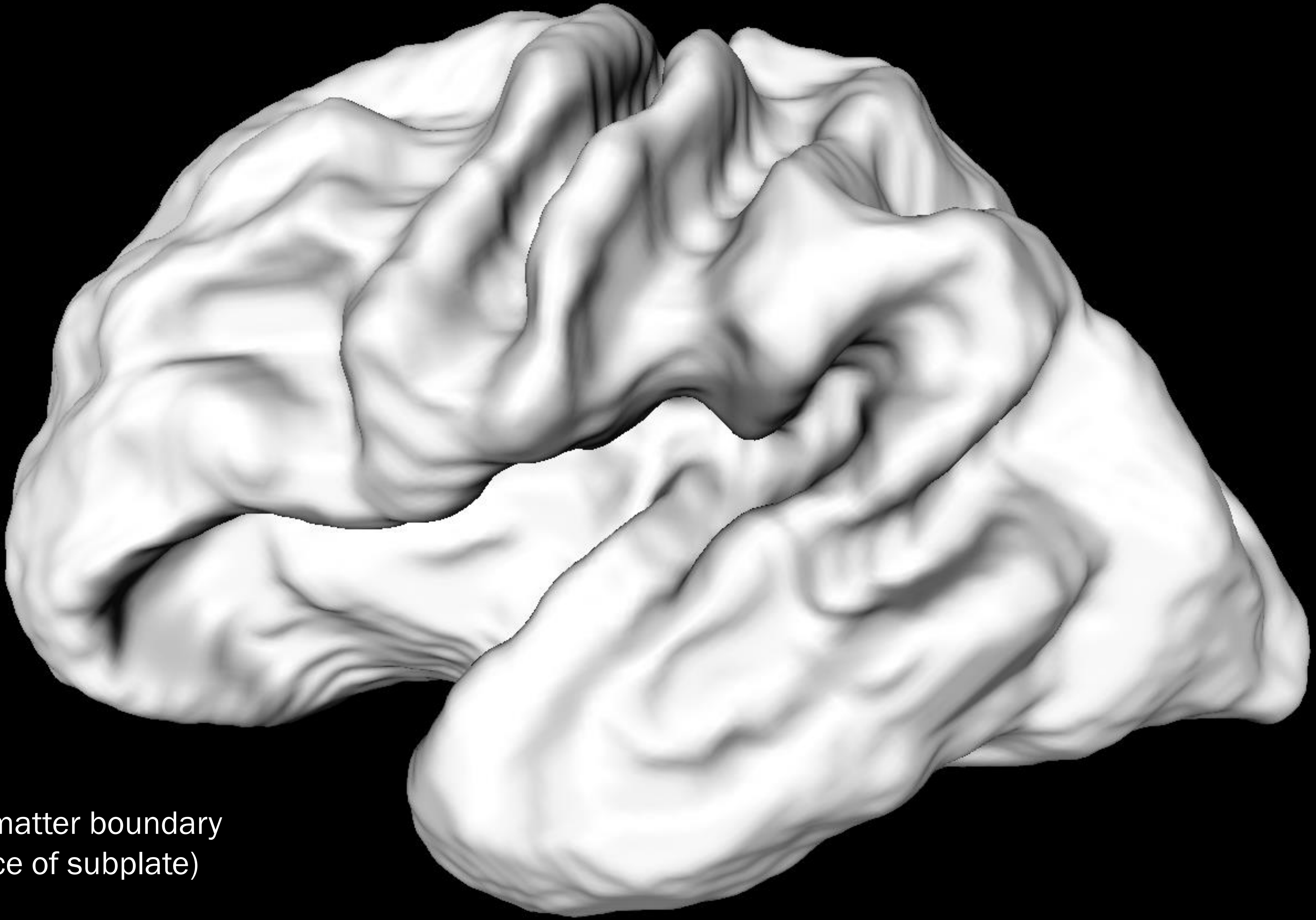
81,920 triangles
Standard connectivity

Mesh Deformation with a Radial Distance Map

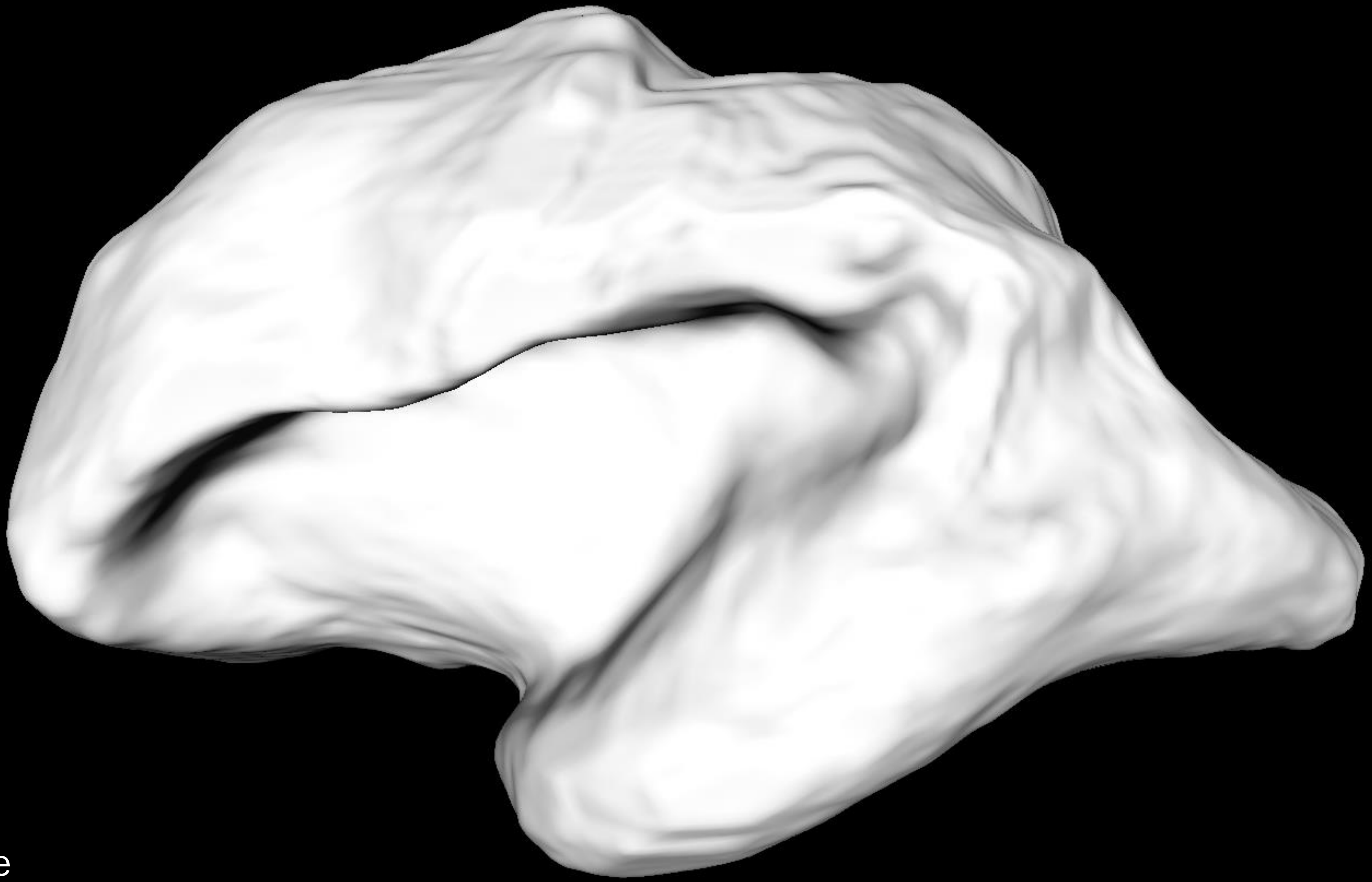
- Voxel intensities indicate distance from target surface
- Mesh vertexes take discrete steps in direction of gradient







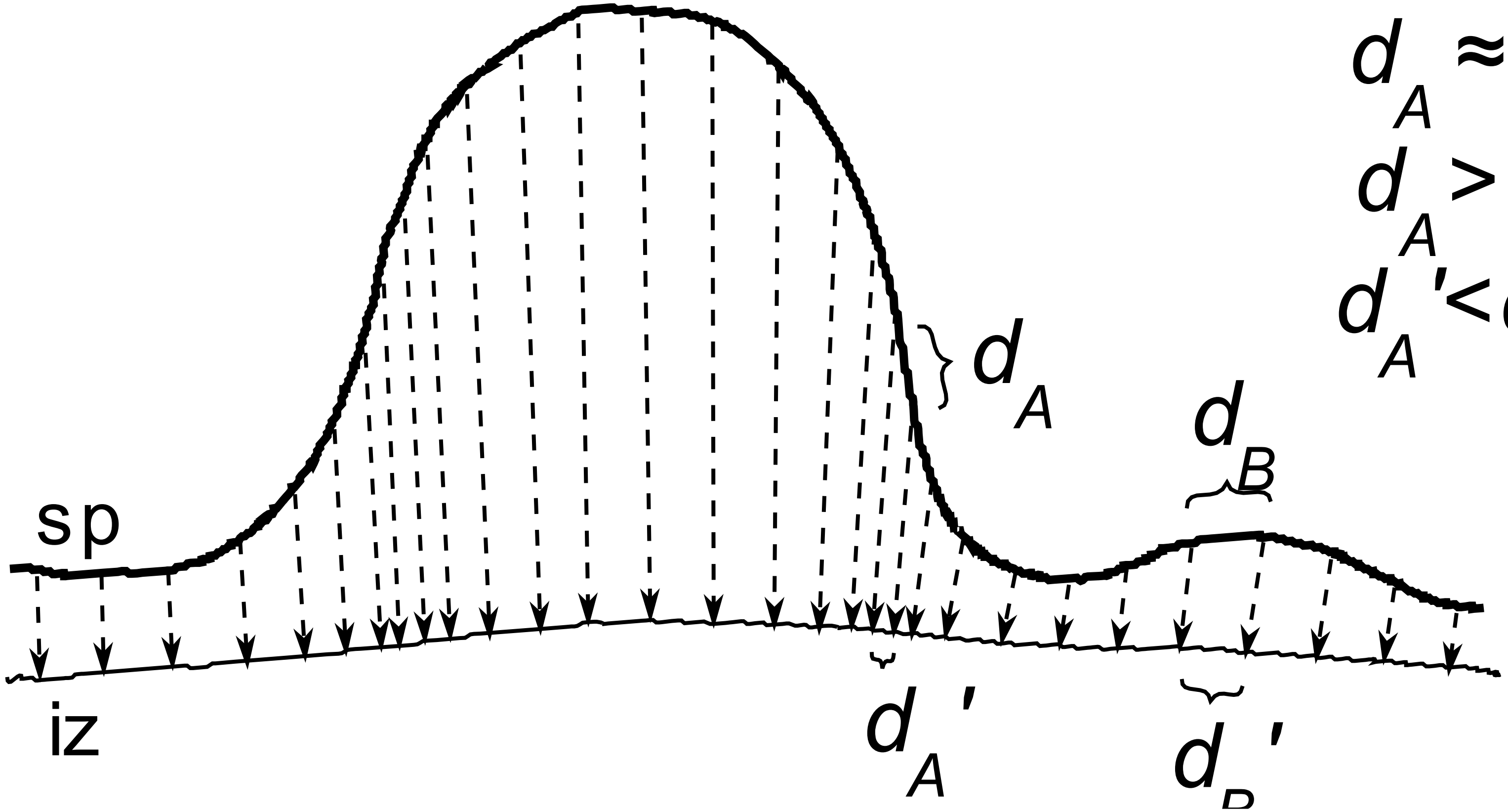
Gray/white matter boundary
(outer surface of subplate)

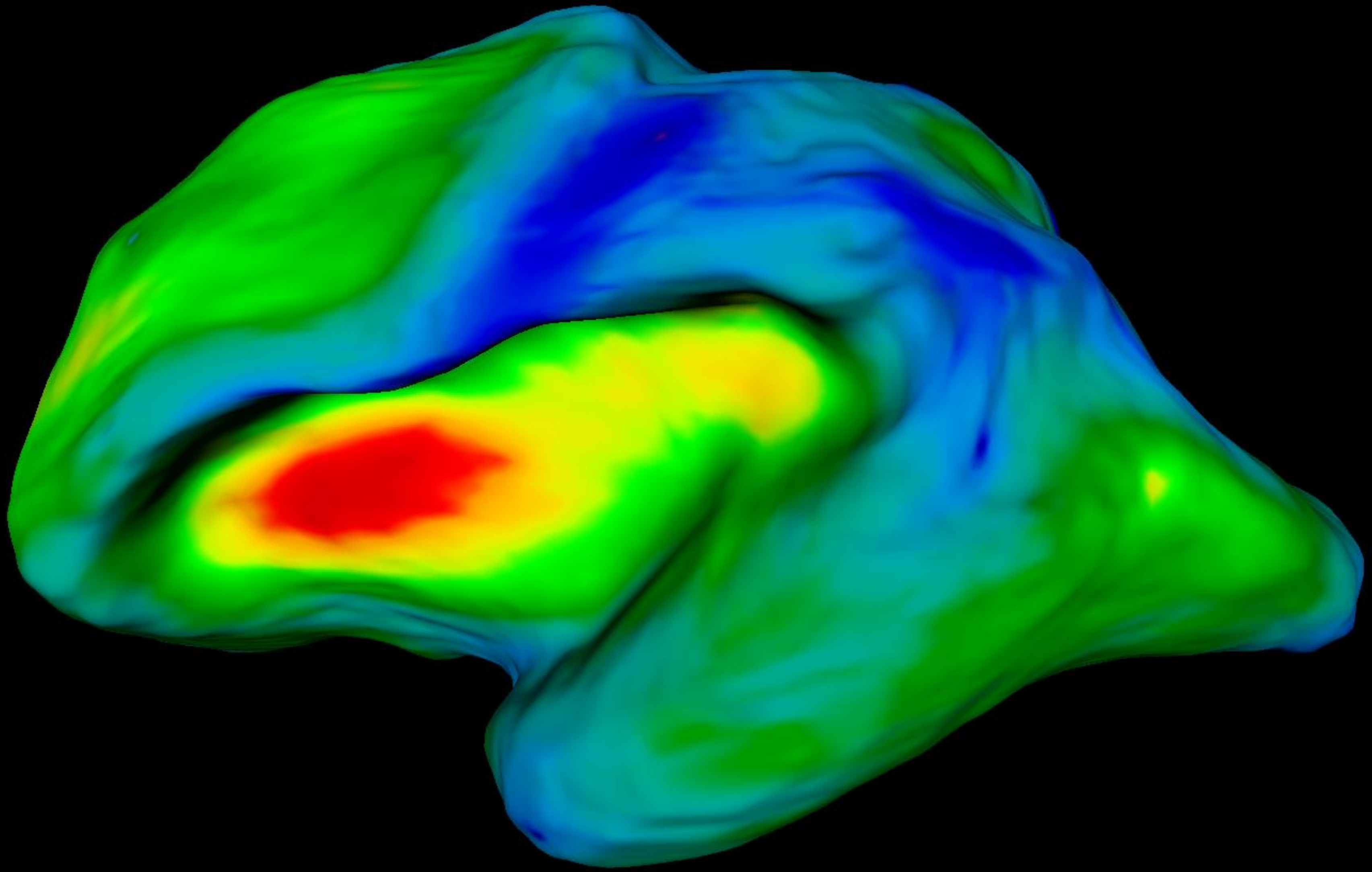


Intermediate zone
(inner surface of subplate)

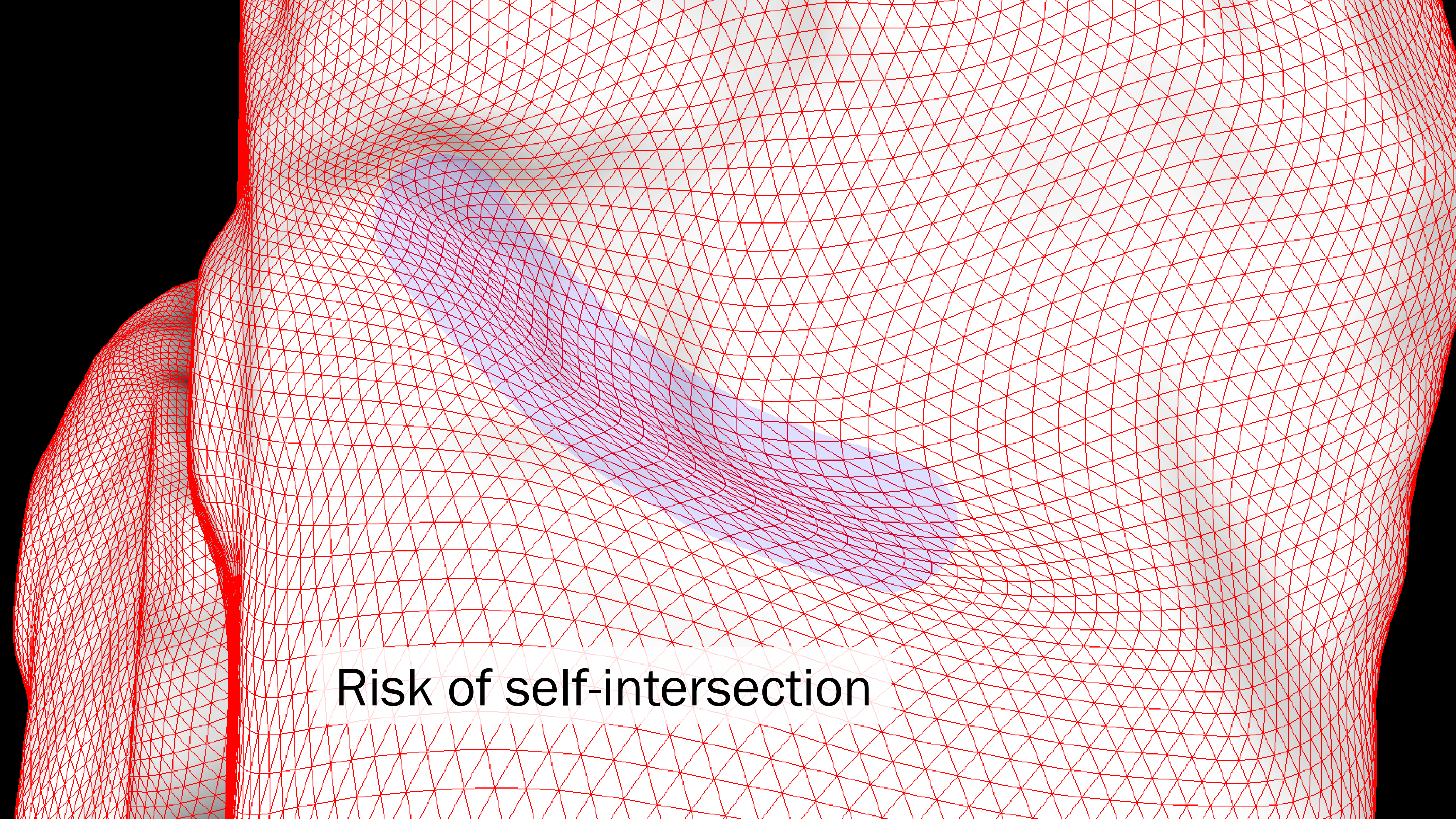
Convoluted Morphology to Flat Inner Surface

Sharp increase in vertex density where the change in thickness is severe



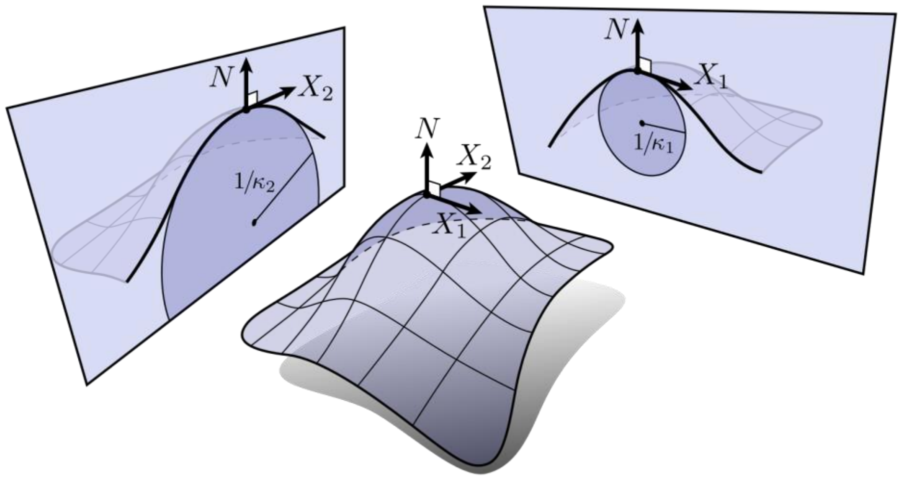


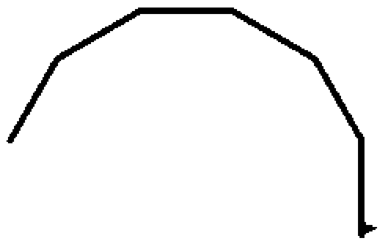
depth_potential –area_simple


Risk of self-intersection

Mesh Quality

First Derivative of Curvature as a Definition of Smoothness Error





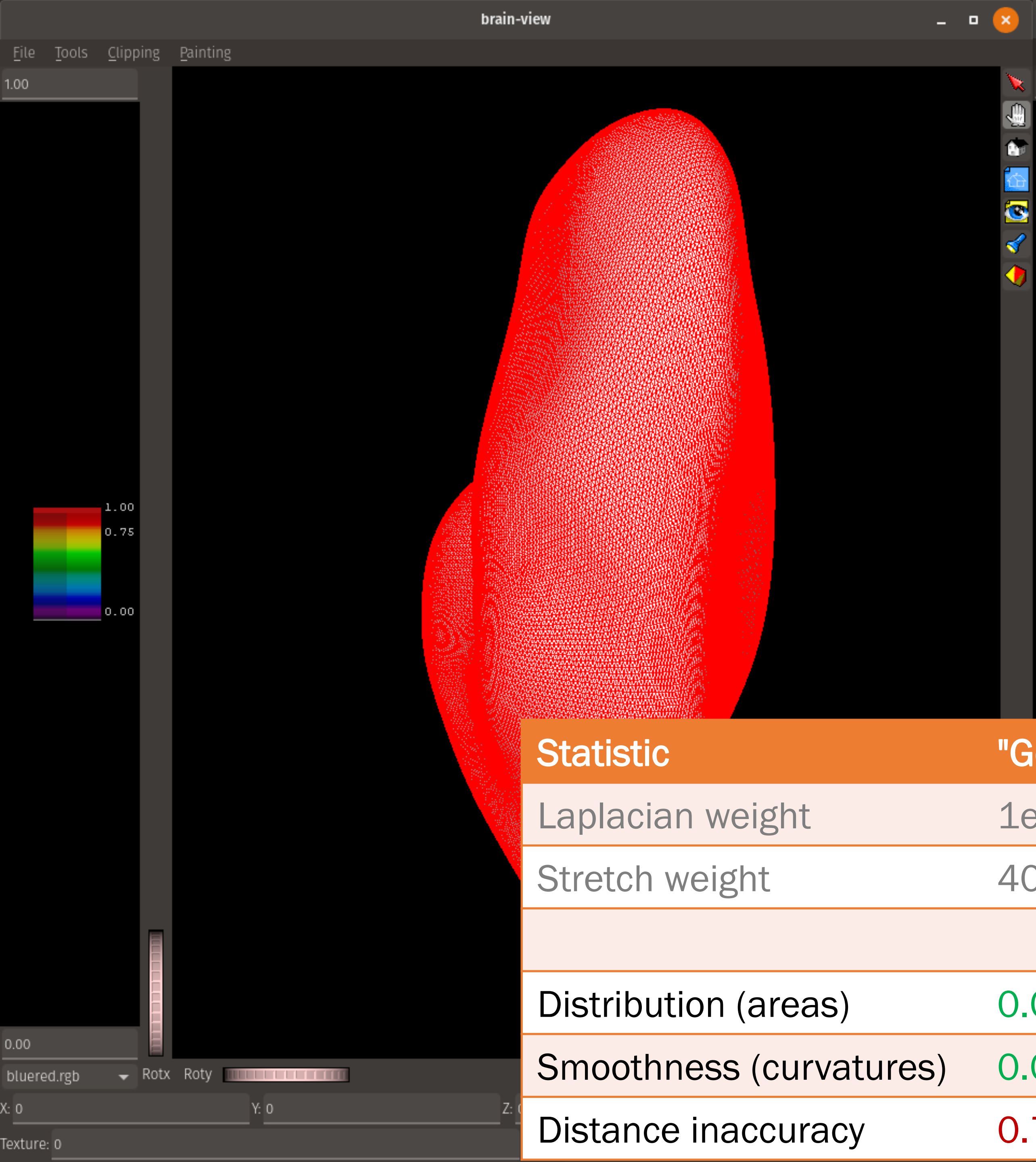
Smooth
H=20
S=0

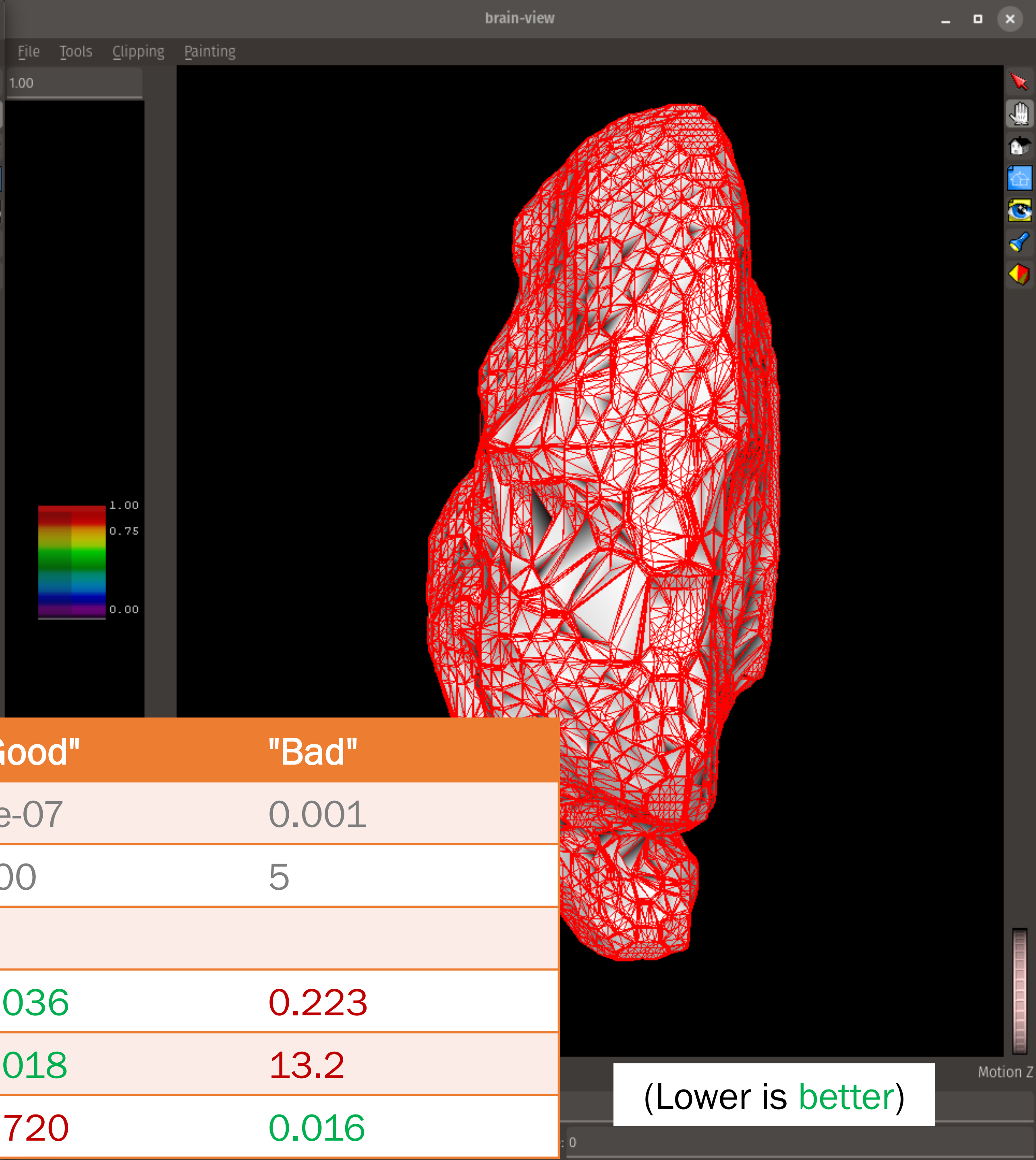
Not smooth
H=20
S=40

$$H = \frac{\kappa_1 + \kappa_2}{2}$$

$$S = \left|\frac{\Delta H}{\Delta v}\right|$$

Same curvature at each point, but one surface can be said to be smooth, the other is not.



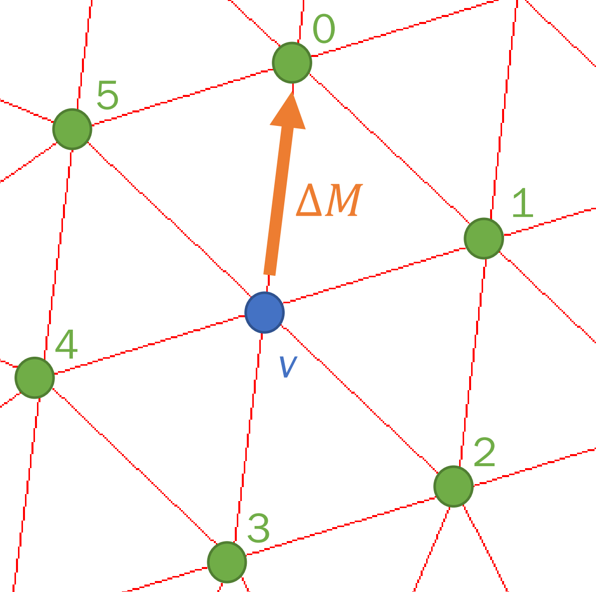


Statistic	"Good"	"Bad"
Laplacian weight	1e-07	0.001
Stretch weight	400	5
Distribution (areas)	0.036	0.223
Smoothness (curvatures)	0.018	13.2
Distance inaccuracy	0.720	0.016

(Lower is better)

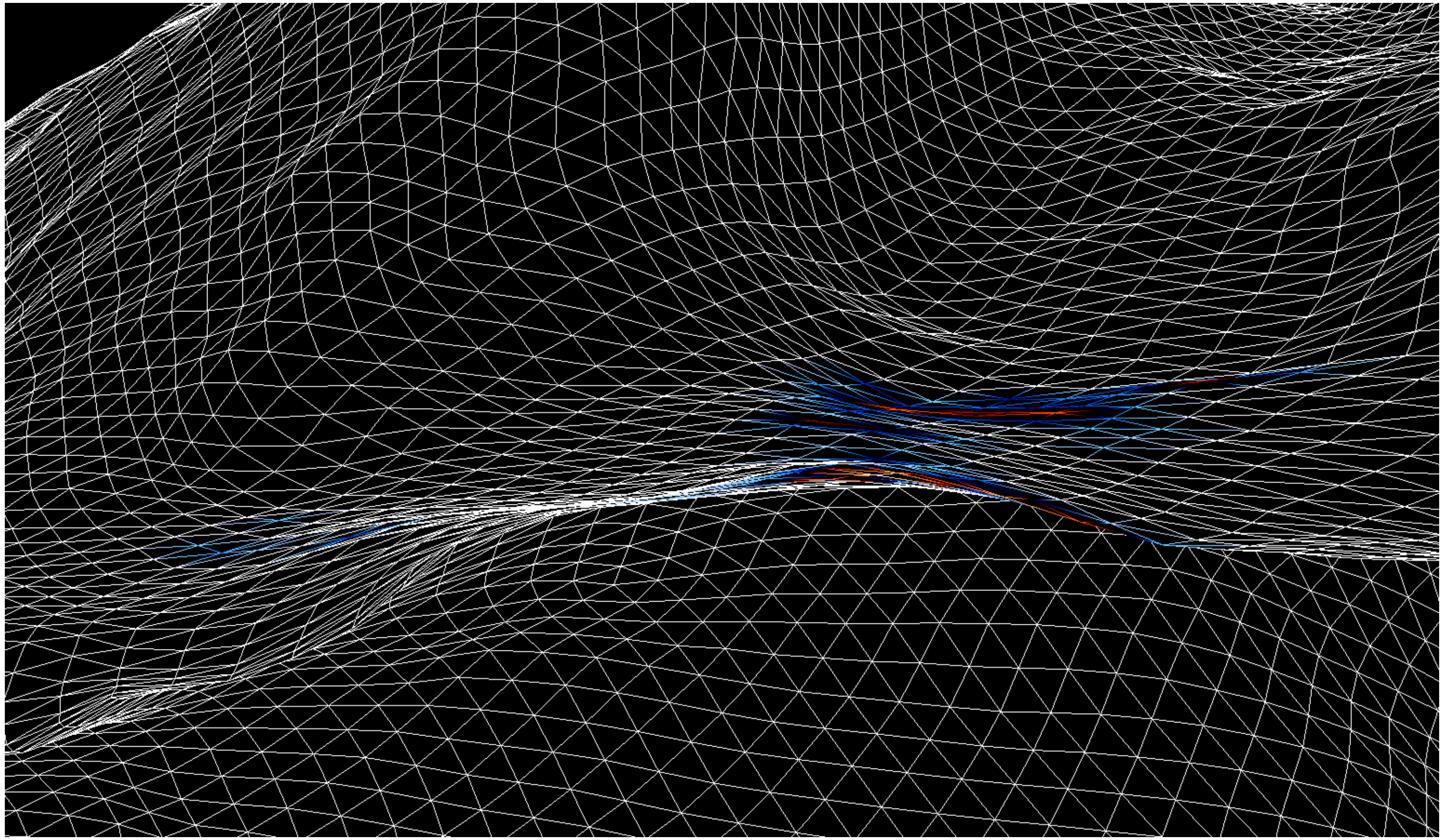
pybicpl

- Python support for MNI .obj file format
- File read and write
- Vertex neighbor graph to calculate local changes in metric



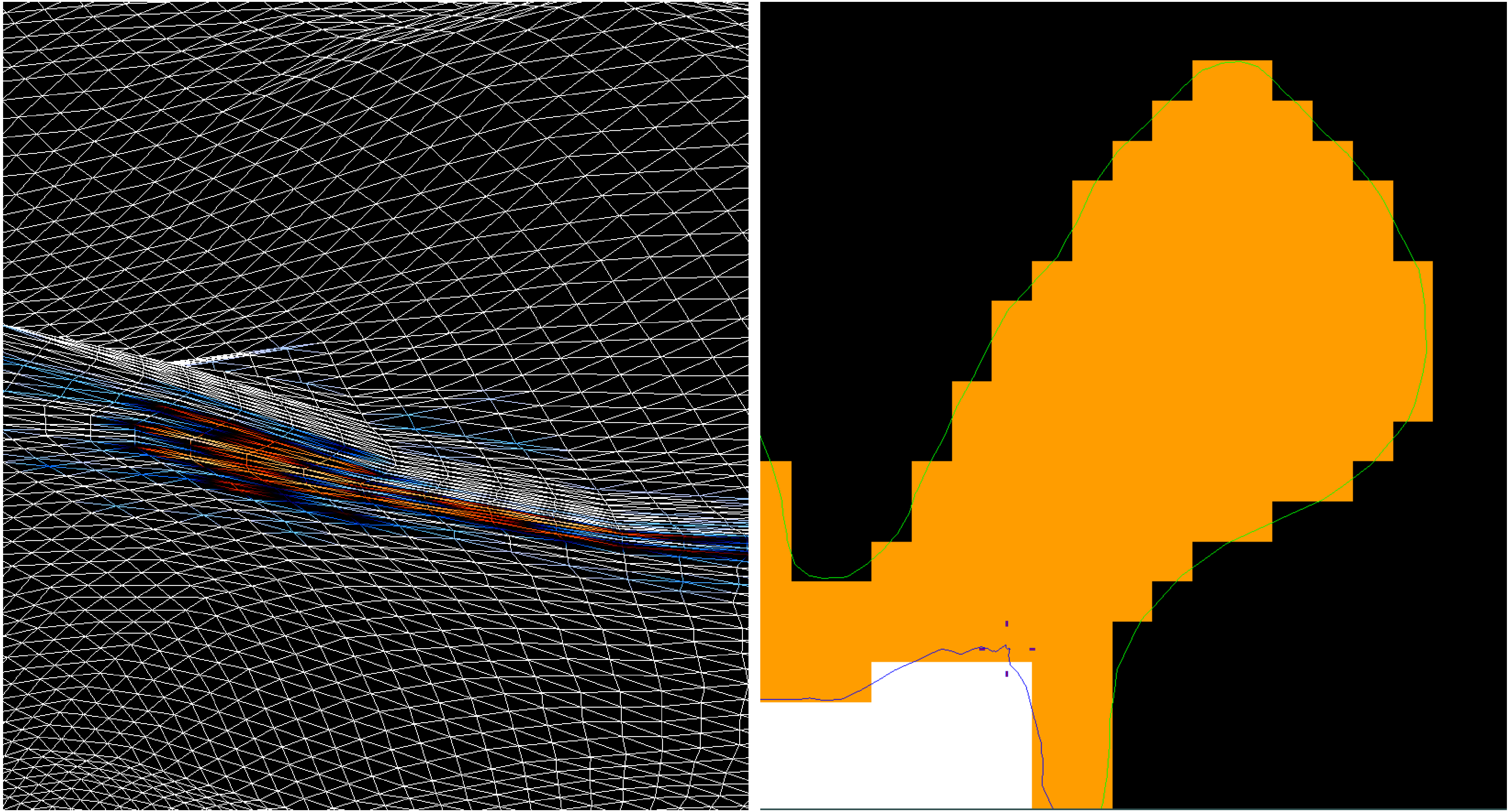
$$\Delta M = |M_v - M_0|$$

$$\mu_V = \frac{|M_v - M_0| + |M_v - M_1| + |M_v - M_2| + |M_v - M_3| + |M_v - M_4| + |M_v - M_5|}{6}$$

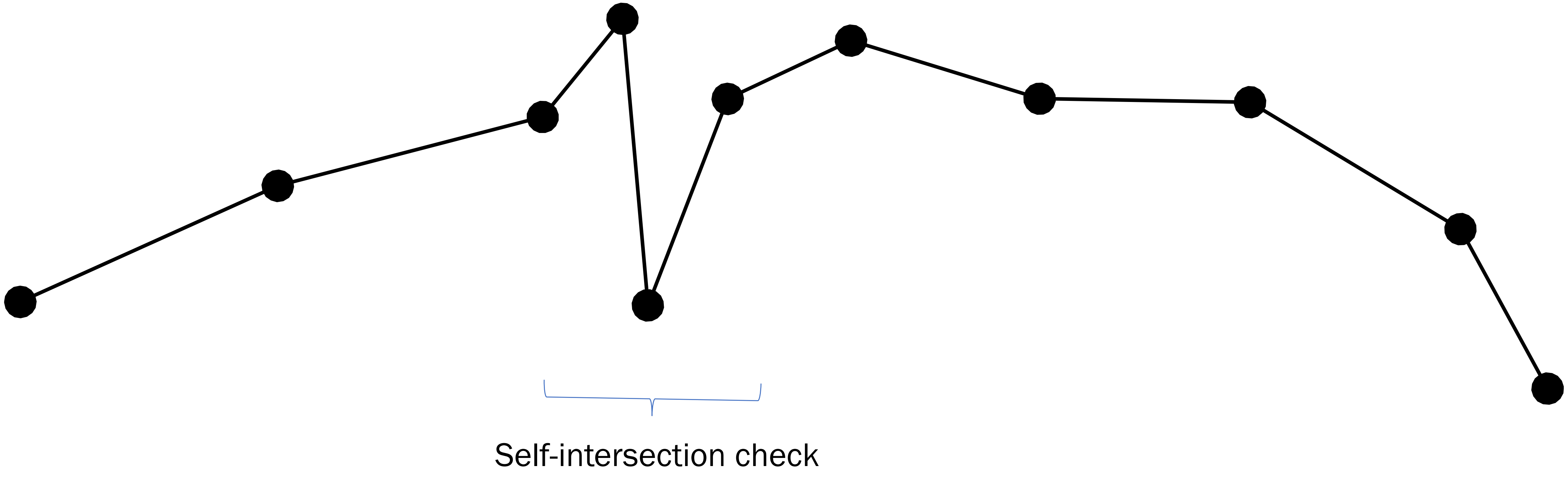


Smoothness Error

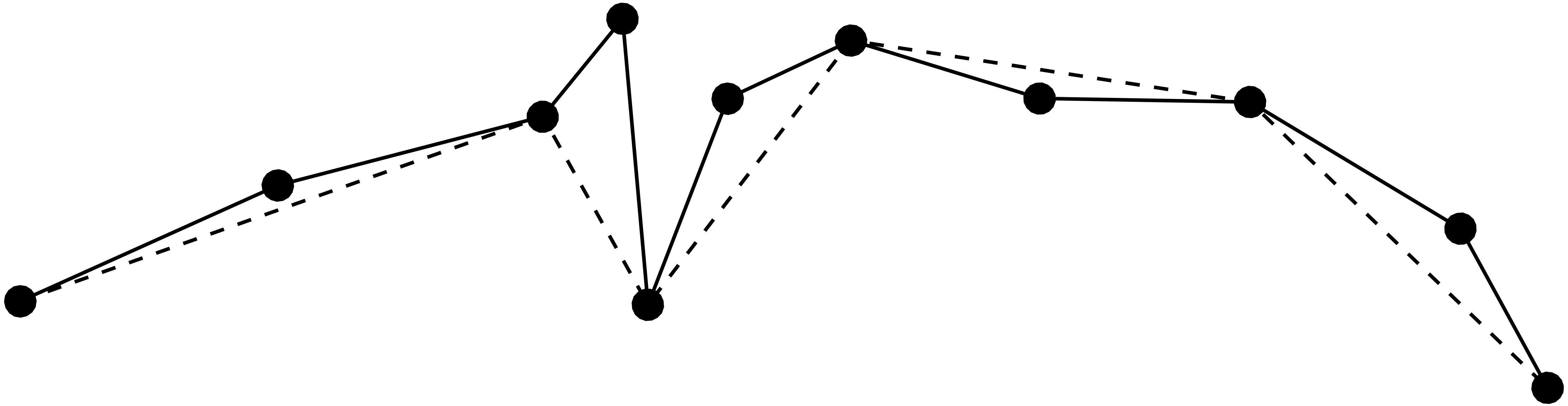
- Local neighborhood difference average of mean curvature
- Metric of surface *quality*
- Highlights problematic creases visually



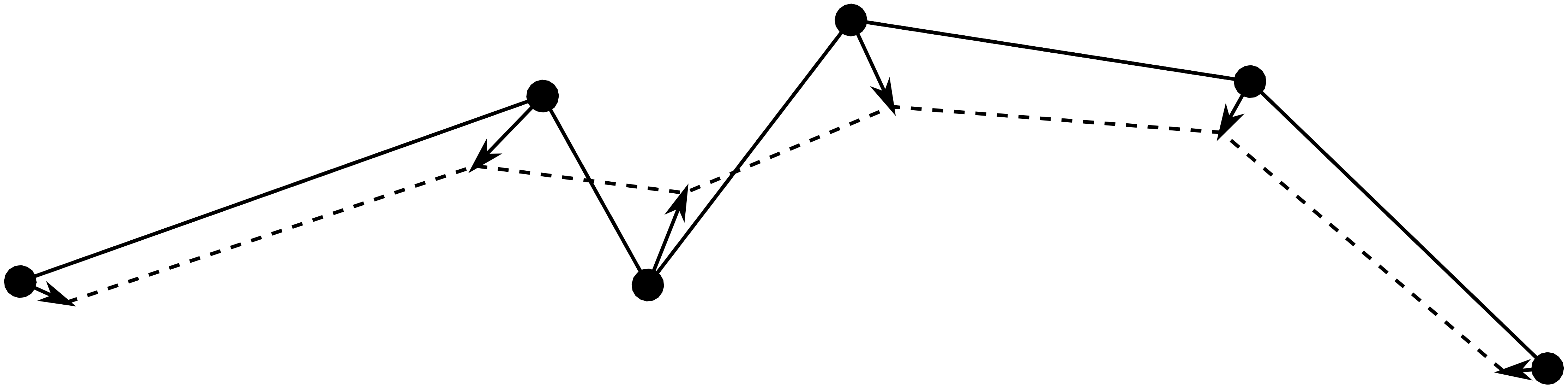
Self-intersection Check Causes Crinkles



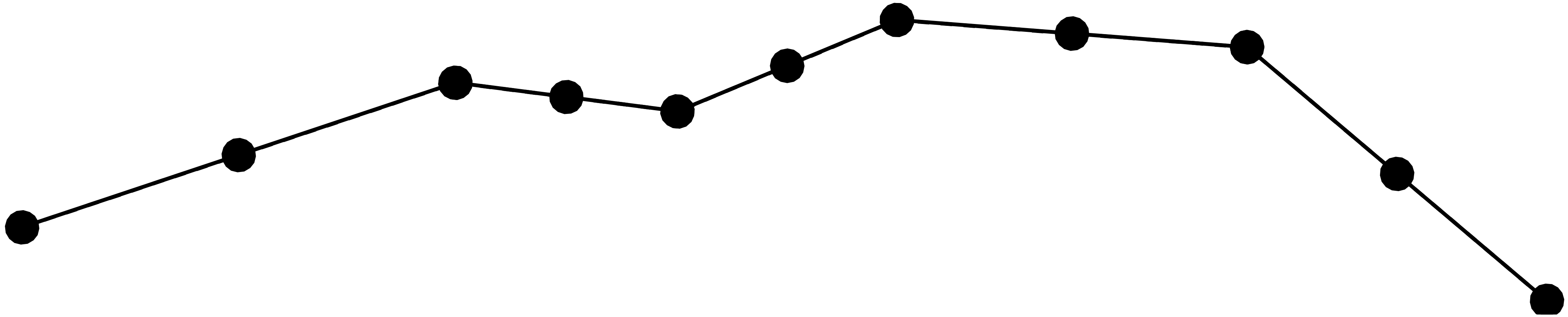
Downsizing Number of Polygons



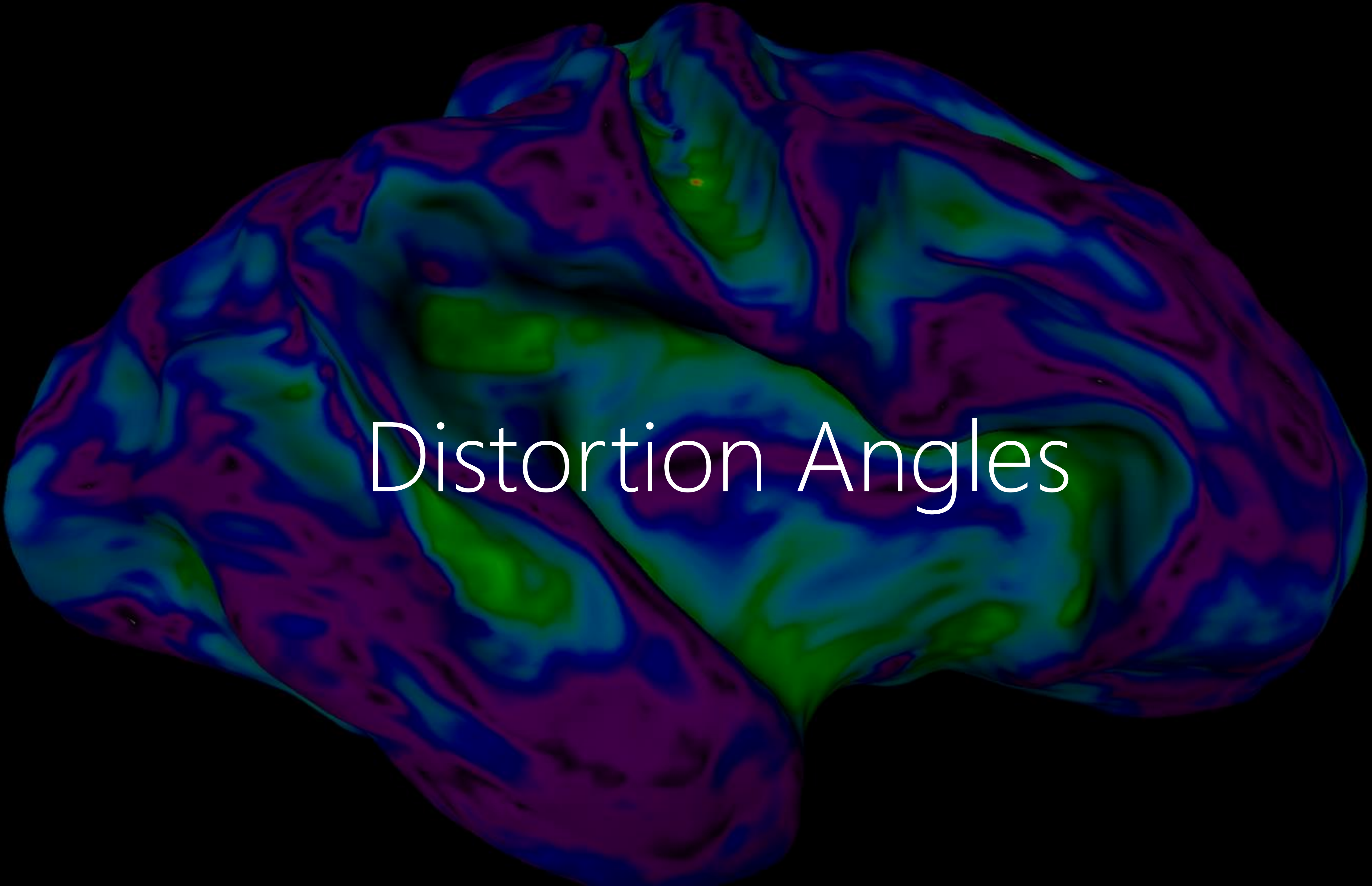
Safer to Fit

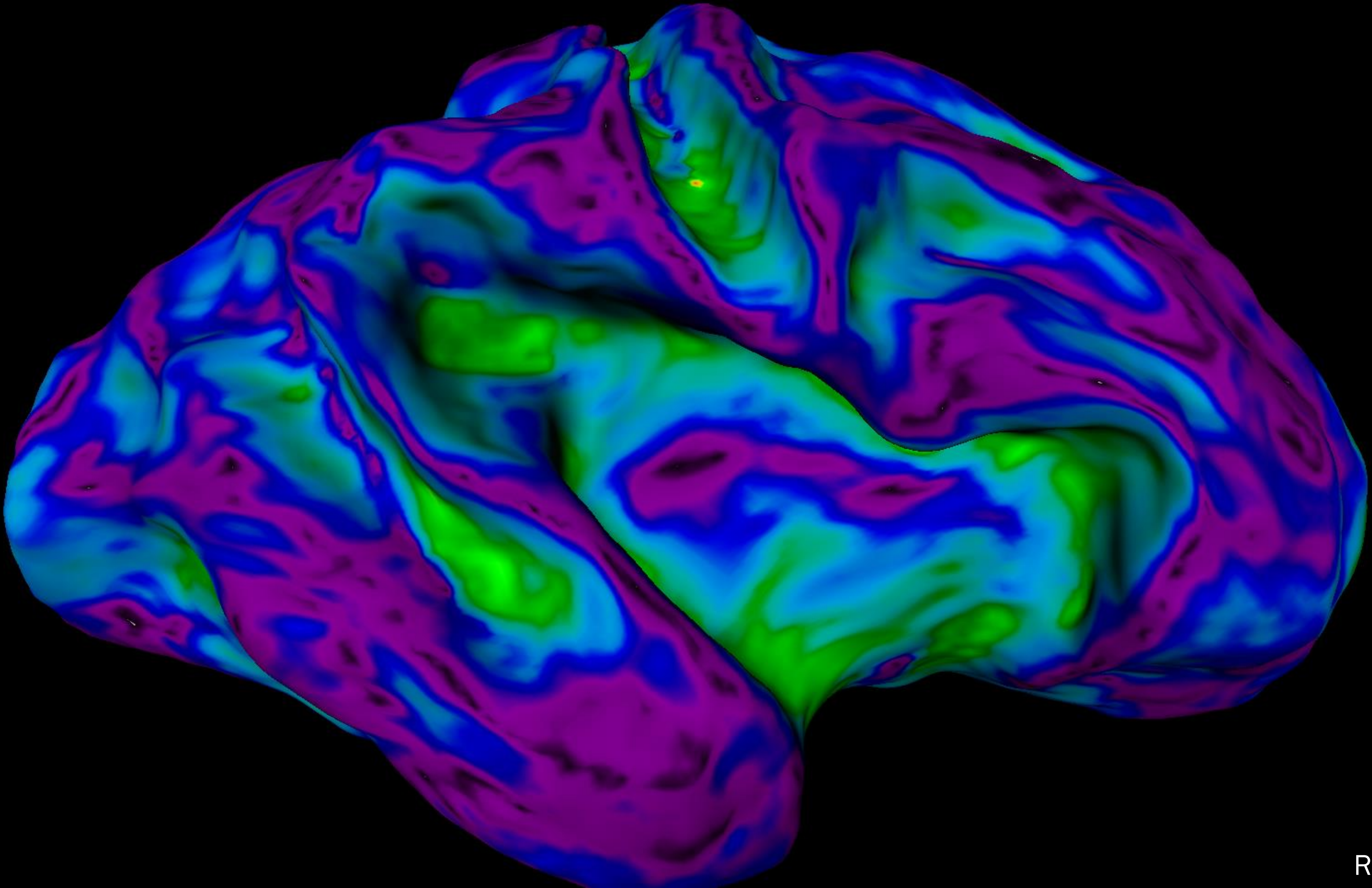


Subdivision to Restore 81,920 Polygons

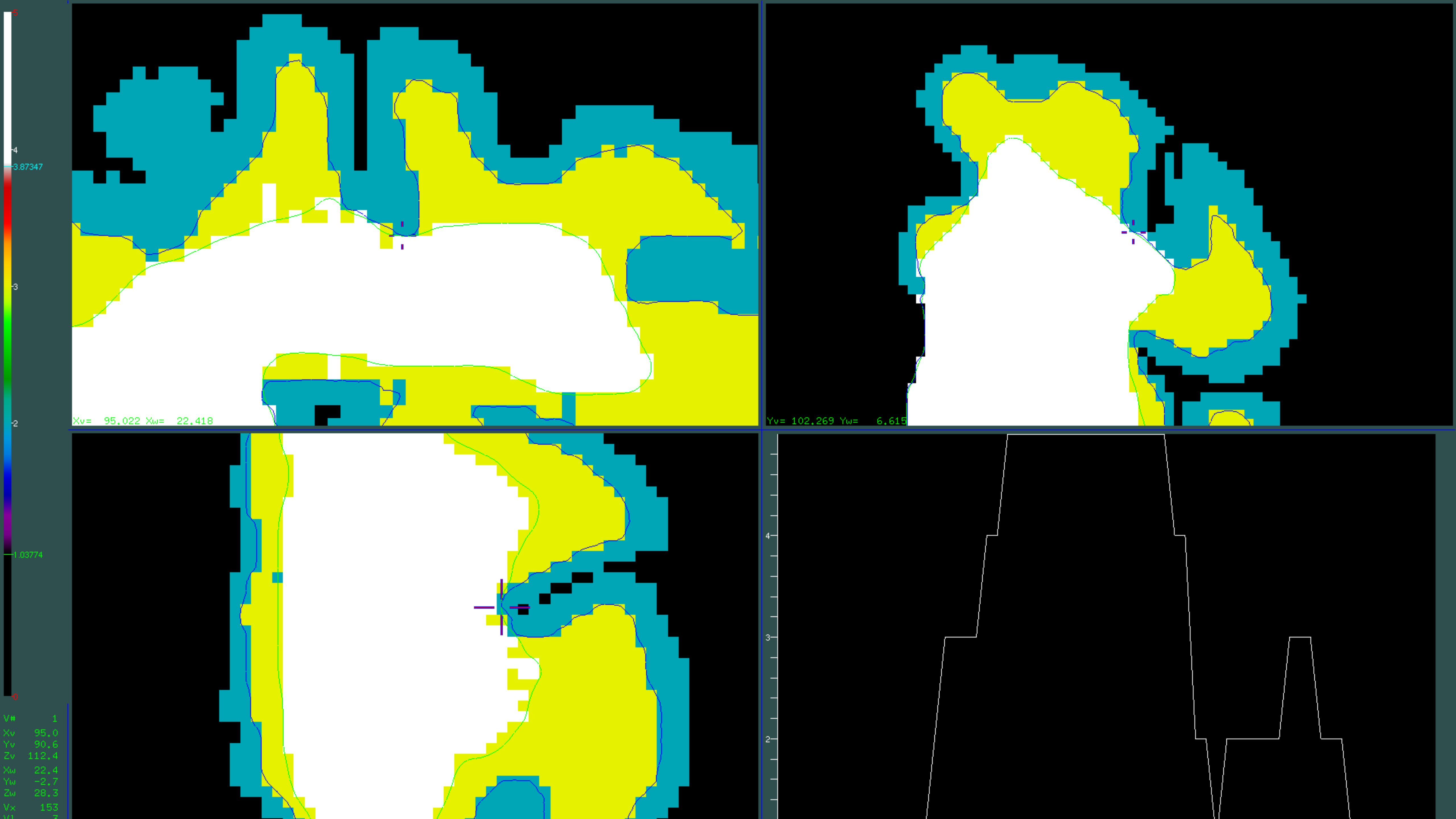


Distortion Angles

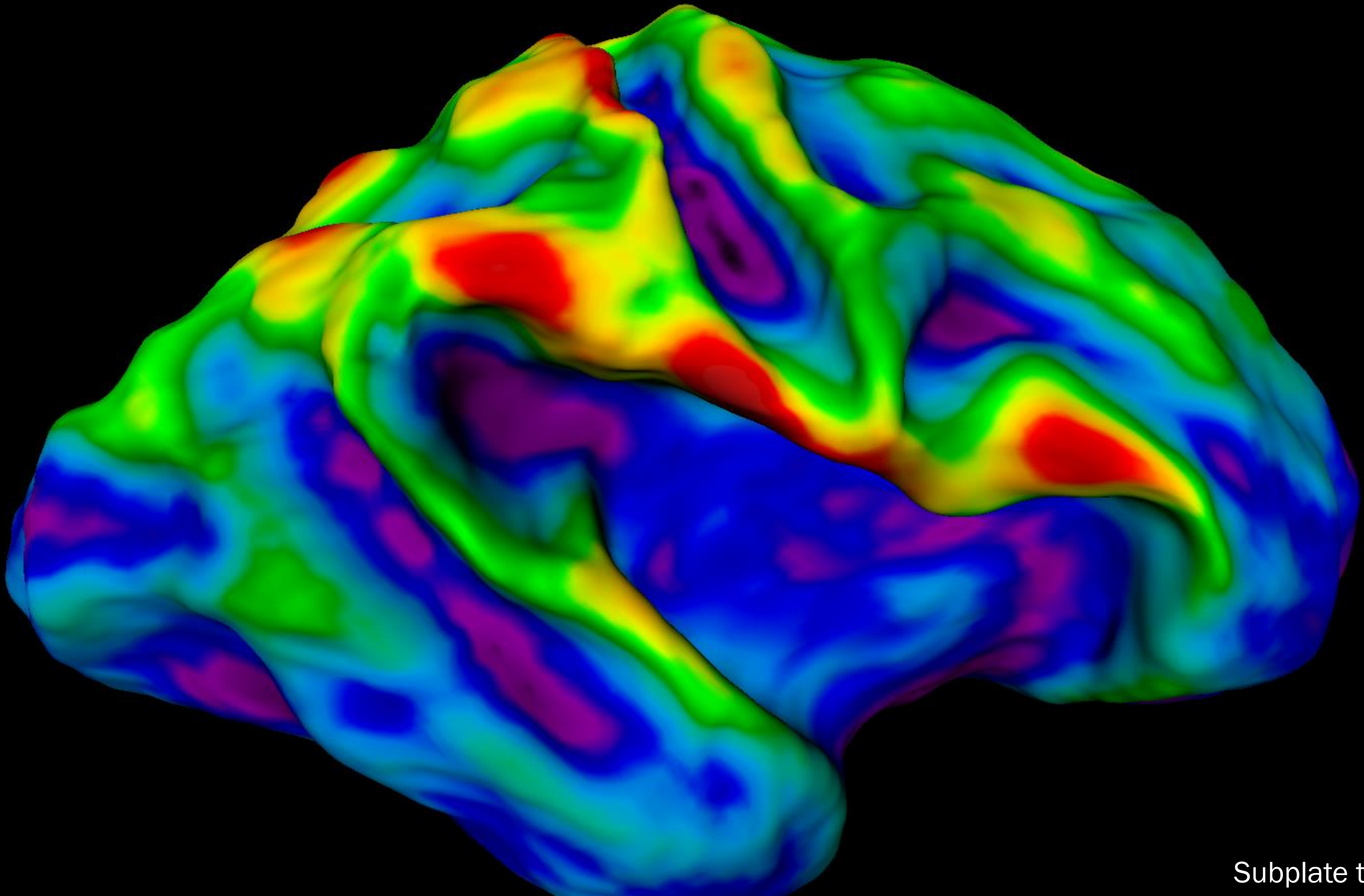




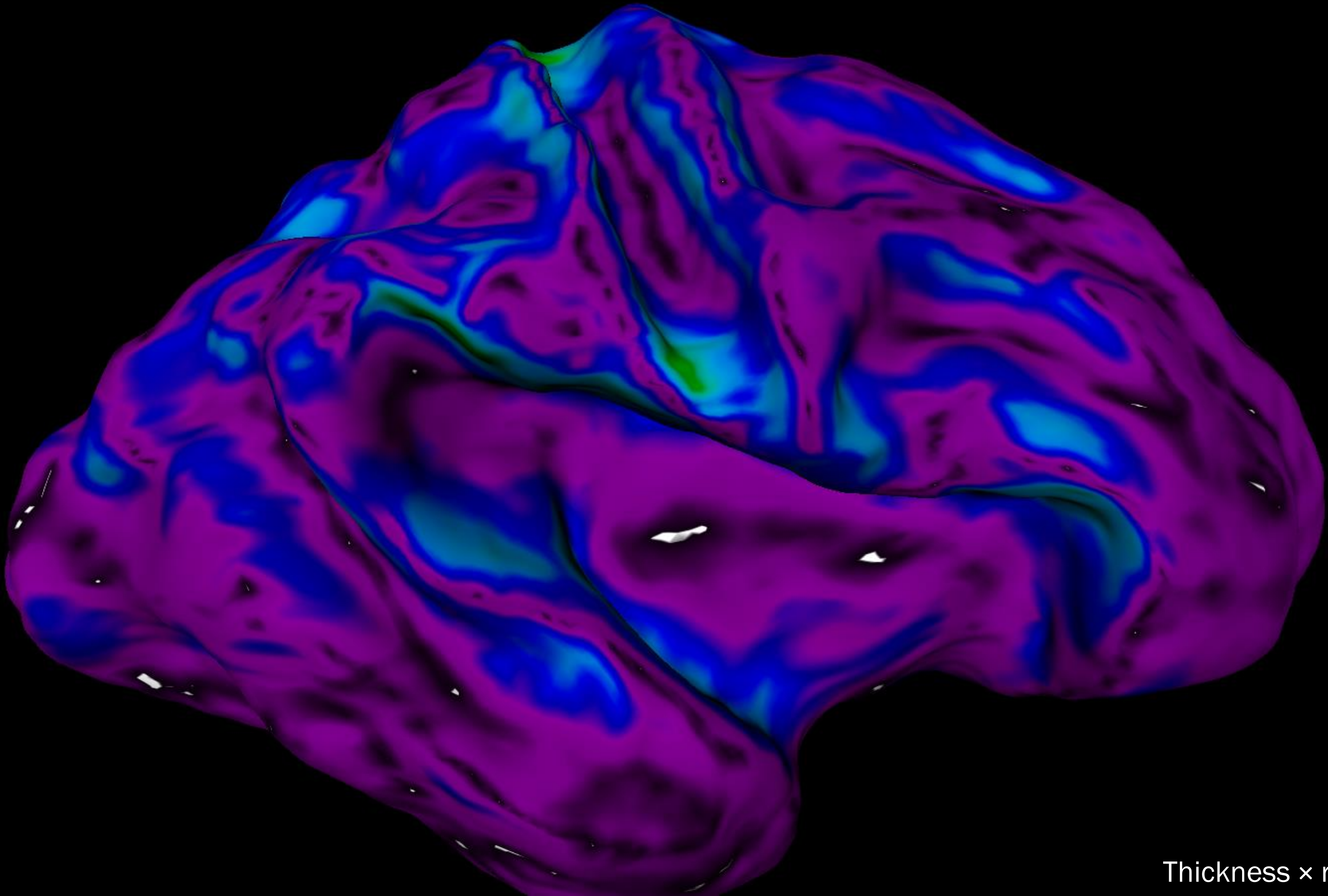
Raw angles



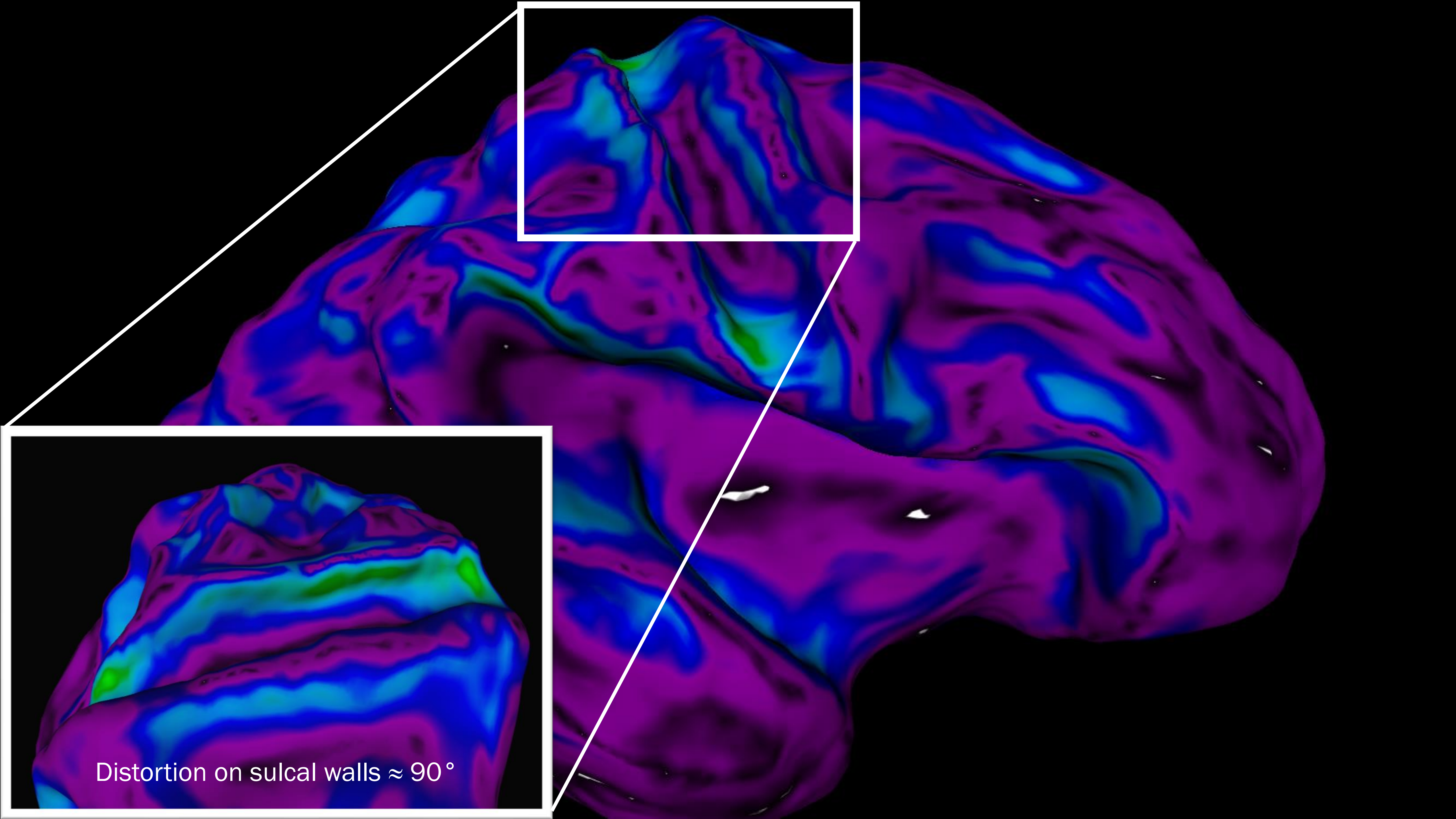
Xv= 95.022 Xw= 22.418
Yv= 102.269 Yw= 6.615
4
3.87347
3
2
1.03774
V# 1
Xv 95.0
Yv 90.6
Zv 112.4
Xw 22.4
Yw -2.7
Zw 28.3
Vx 153
4
3
2

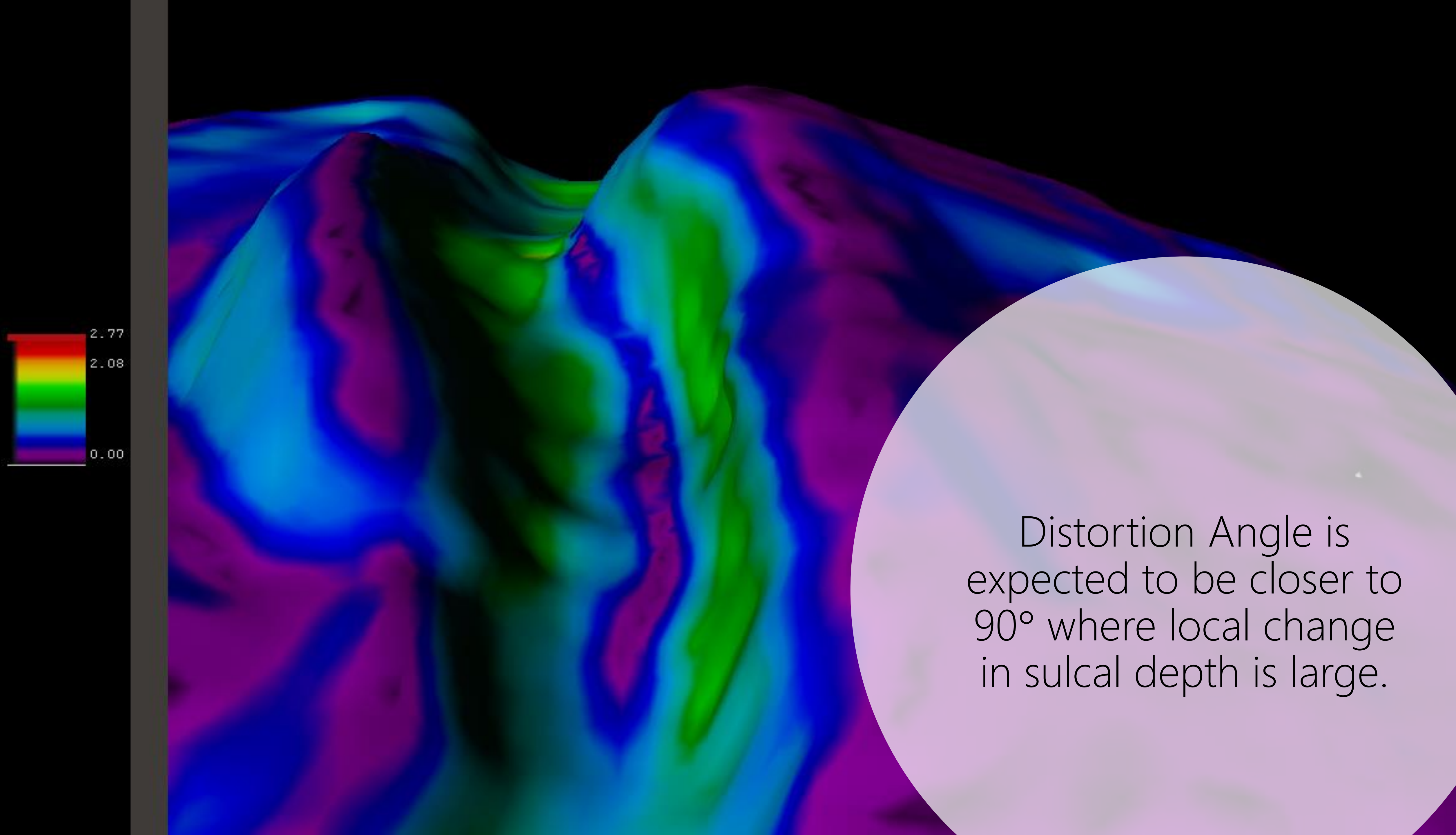


Subplate thickness



Thickness × raw angles


Distortion on sulcal walls ≈ 90°



Distortion Angle is expected to be closer to 90° where local change in sulcal depth is large.

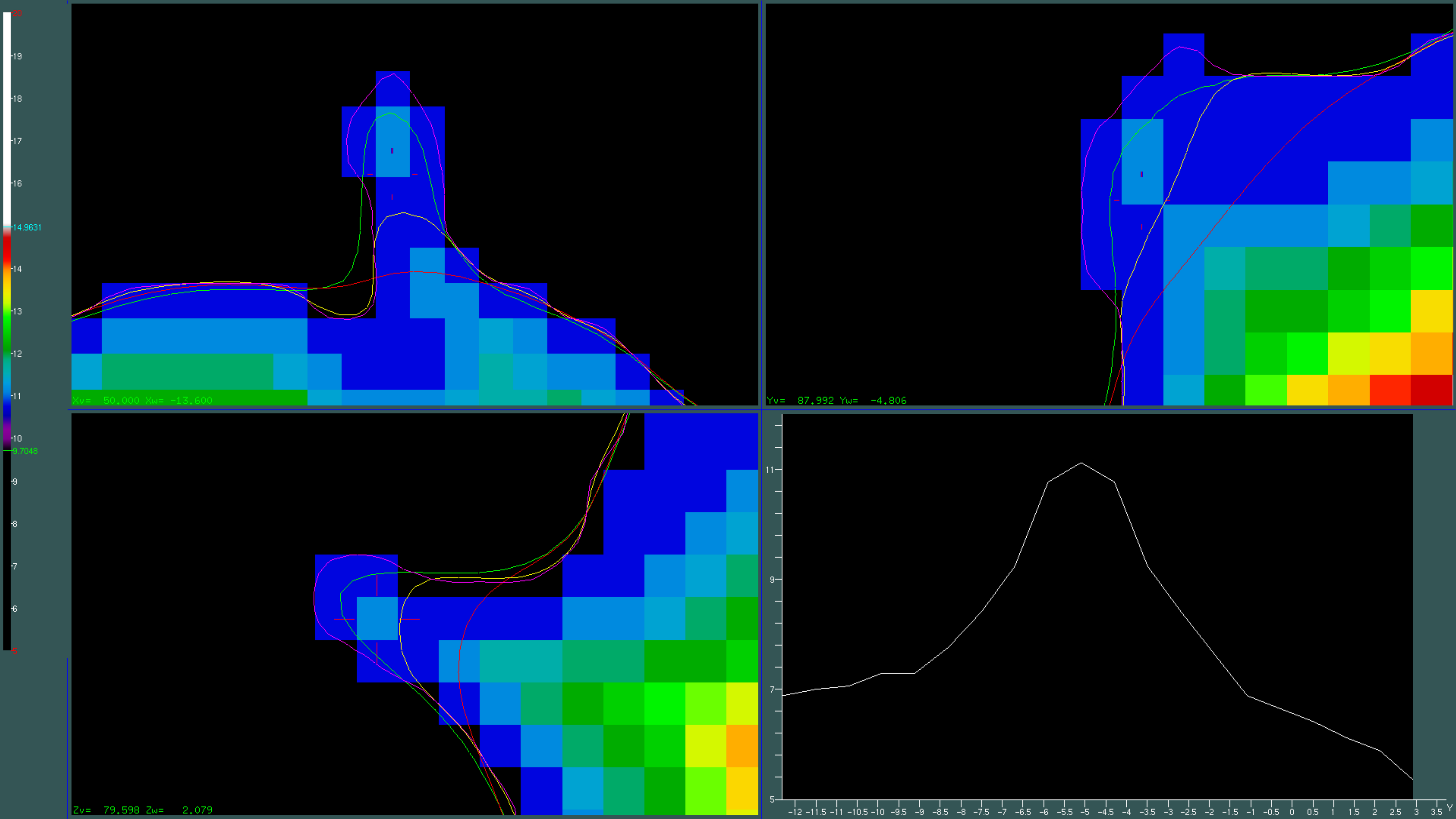
```
echo Step 81920: 400 / 500    sw=20,  Schedule row 1 / 1
surface_fit -mode two -surface  wm_81920.obj wm_81920.obj -stretch 20 /tmp/mcubes-BxAMKi/w
hite_model_tmp.obj -.9 0 0 0 -laplacian /tmp/mcubes-BxAMKi/simple_chamfer.mnc 8e-06 0  10
0   -self_intersect 1 0.01  -self_intersect 7.74263682681127 0.009  -self_intersect 59.948
4250318941 0.008  -self_intersect 464.158883361278 0.007  -self_intersect 3593.81366380462
 0.006  -self_intersect 27825.5940220712 0.005  -self_intersect 215443.469003188 0.004  -s
elf_intersect 1668100.53720006 0.003  -self_intersect 12915496.6501488 0.002  -self_inters
ect 100000000 0.001  -step 0.1  -fitting 100 5 0.001  -ftol 1e-06  -stop 0.001 1000
Surface 0:  Using model /tmp/mcubes-BxAMKi/white_model_tmp.obj scaled by 0.380078 for stre
tch lengths
phi_res(40962) = 0.13144  min = 9.0146  max = 11.4842
Initial:             0.0151582  S:0.01008 I:1.592e-08 (0.006554) L:0.005078
Iter    1: 0.0151580     S:0.01008 I:2.818e-08 (0.00619) L:0.005078
phi_res(40962) = 0.131439  min = 9.01465  max = 11.4842
Iter    2: 0.0151578     S:0.01008 I:3.711e-08 (0.006261) L:0.005078
phi_res(40962) = 0.131438  min = 9.01471  max = 11.4842
Iter    3: 0.0151575     S:0.01008 I:4.817e-08 (0.006114) L:0.005078
phi_res(40962) = 0.131436  min = 9.01479  max = 11.4842
Iter    4: 0.0151536     S:0.01008 L:0.005074
phi_res(40962) = 0.131427  min = 9.01516  max = 11.4842
Iter    5: 0.0151531     S:0.01008 I:4.825e-08 (0.005883) L:0.005074
phi_res(40962) = 0.131424  min = 9.0153  max = 11.4842
Iter    6: 0.0151527     S:0.01008 I:4.375e-08 (0.00617) L:0.005074
phi_res(40962) = 0.131422  min = 9.01539  max = 11.4842
Iter    7: 0.0151519     S:0.01008 I:2.862e-08 (0.006469) L:0.005073
phi_res(40962) = 0.131418  min = 9.01559  max = 11.4843
Iter    8: 0.0151515     S:0.01008 I:1.773e-07 (0.005305) L:0.005073
phi_res(40962) = 0.131414  min = 9.01574  max = 11.4843
Iter    9: 0.0151500     S:0.01008 I:2.015e-09 (0.007842) L:0.005072
phi_res(40962) = 0.131407  min = 9.01604  max = 11.4843
Iter   10: 0.0151500     S:0.01008 I:5.083e-09 (0.007399) L:0.005072
phi_res(40962) = 0.131407  min = 9.01606  max = 11.4843
Iter   11: 0.0151498     S:0.01008 I:4.713e-08 (0.005894) L:0.005072
phi_res(40962) = 0.131406  min = 9.01611  max = 11.4843
Iter   12: 0.0151493     S:0.01008 I:7.93e-09 (0.006954) L:0.005072
phi_res(40962) = 0.131404  min = 9.01621  max = 11.4843
Iter   13: 0.0151487     S:0.01008 I:4.497e-10 (0.008339) L:0.005072
phi_res(40962) = 0.1314  min = 9.01634  max = 11.4843
Iter   14: 0.0151511     S:0.01008 I:7.277e-08 (0.00594) L:0.005074
phi_res(40962) = 0.131398  min = 9.01641  max = 11.4843
Iter   15: 0.0151510     S:0.01008 I:6.551e-08 (0.005848) L:0.005074
phi_res(40962) = 0.131398  min = 9.01643  max = 11.4843
Iter   16: 0.0151507     S:0.01008 I:3.695e-08 (0.006264) L:0.005074
phi_res(40962) = 0.131396  min = 9.01651  max = 11.4843
Iter   17: 0.0151504     S:0.01008 I:4.417e-08 (0.005925) L:0.005074
phi_res(40962) = 0.131394  min = 9.01659  max = 11.4844
Iter   18: 0.0151497     S:0.01008 I:3.774e-10 (0.008431) L:0.005073
```

ASP Parameters

Stretch, Laplacian, Self →

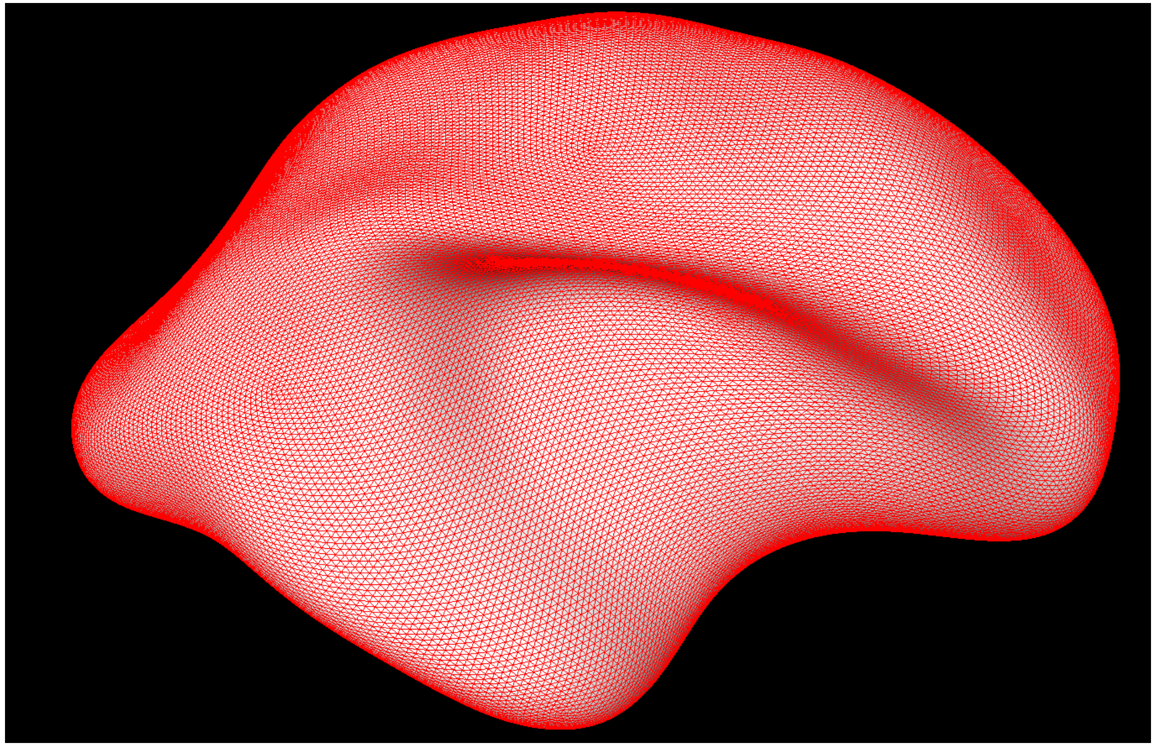
Accuracy, Quality, Error

```
#  size    sw  n_itr  inc   l_w  iso   si   l_s   iw    self  t chamfer_algo
# -----  ---  -----  ---  ----  ---  ---- ----  ----   ----- --  --------
  20480,  40,  100,  50,  2e-5,  10, 0.30,  1,  1.0,   0.10, 0, $simple,
   5120,   2,  200,  50,  2e-4,  10, 0.10,  2,  1.0,   0.02, 0, $simple,
  20480,  10,  200,  50,  5e-5,  10, 0.05,  1,  0.1,  0.001, 1, $simple,
  81920,  20,   50,  50,  3e-6,  10, 0.05,  0,  0.1,  0.001, 0, $simple,
```

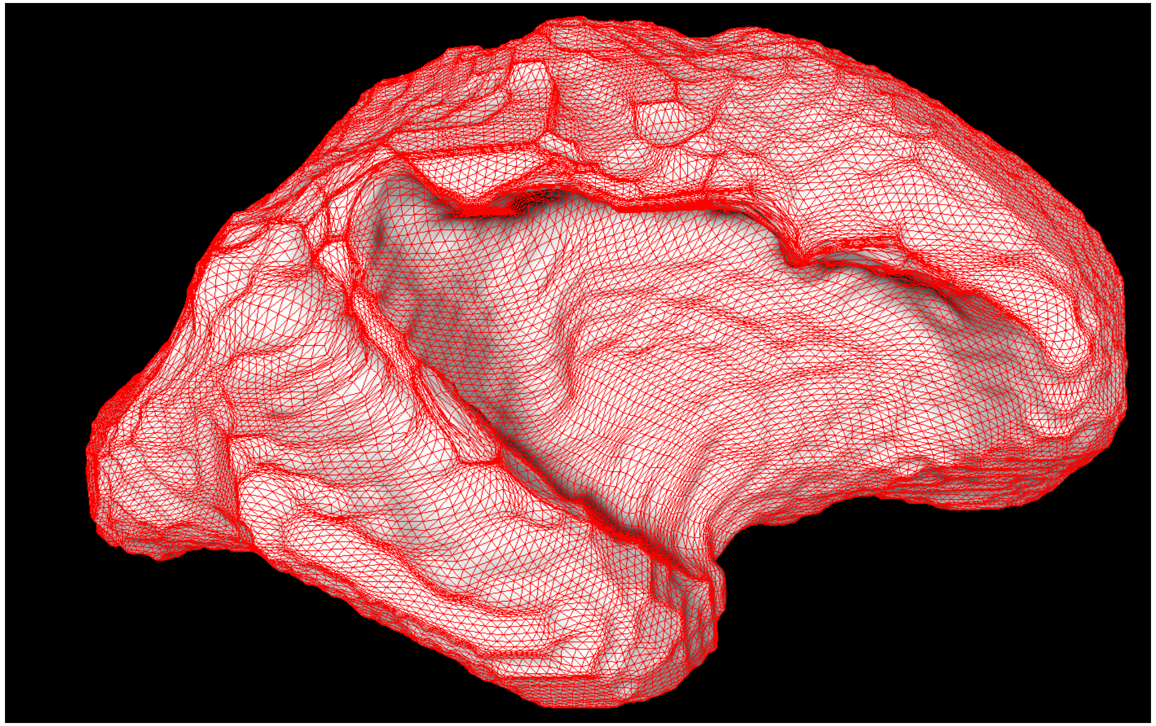


20
19
18
17
16
14.9631
14
13
12
11
10
9.7048
9
8
7
6
5
Xv= 50.000 Xw= -13.600
Yv= 87.992 Yw= -4.806
Zv= 79.598 Zw= 2.079
11
9
7
5
-12 -11.5 -11 -10.5 -10 -9.5 -9 -8.5 -8 -7.5 -7 -6.5 -6 -5.5 -5 -4.5 -4 -3.5 -3 -2.5 -2 -1.5 -1 -0.5 0 0.5 1 1.5 2 2.5 3 3.5 Y

Laplacian Weight (l_w)



1.0e-7



1.0e-3

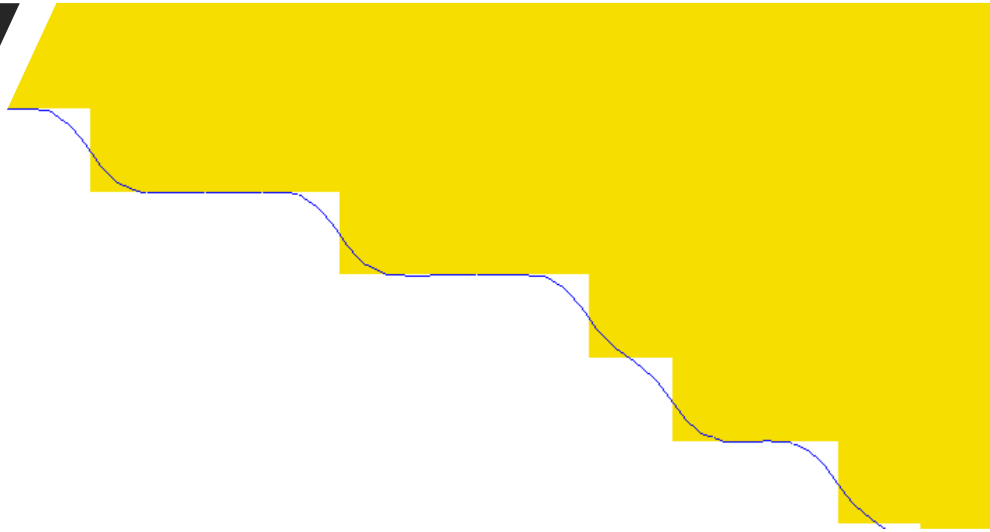
Laplacian Weight

Large Value

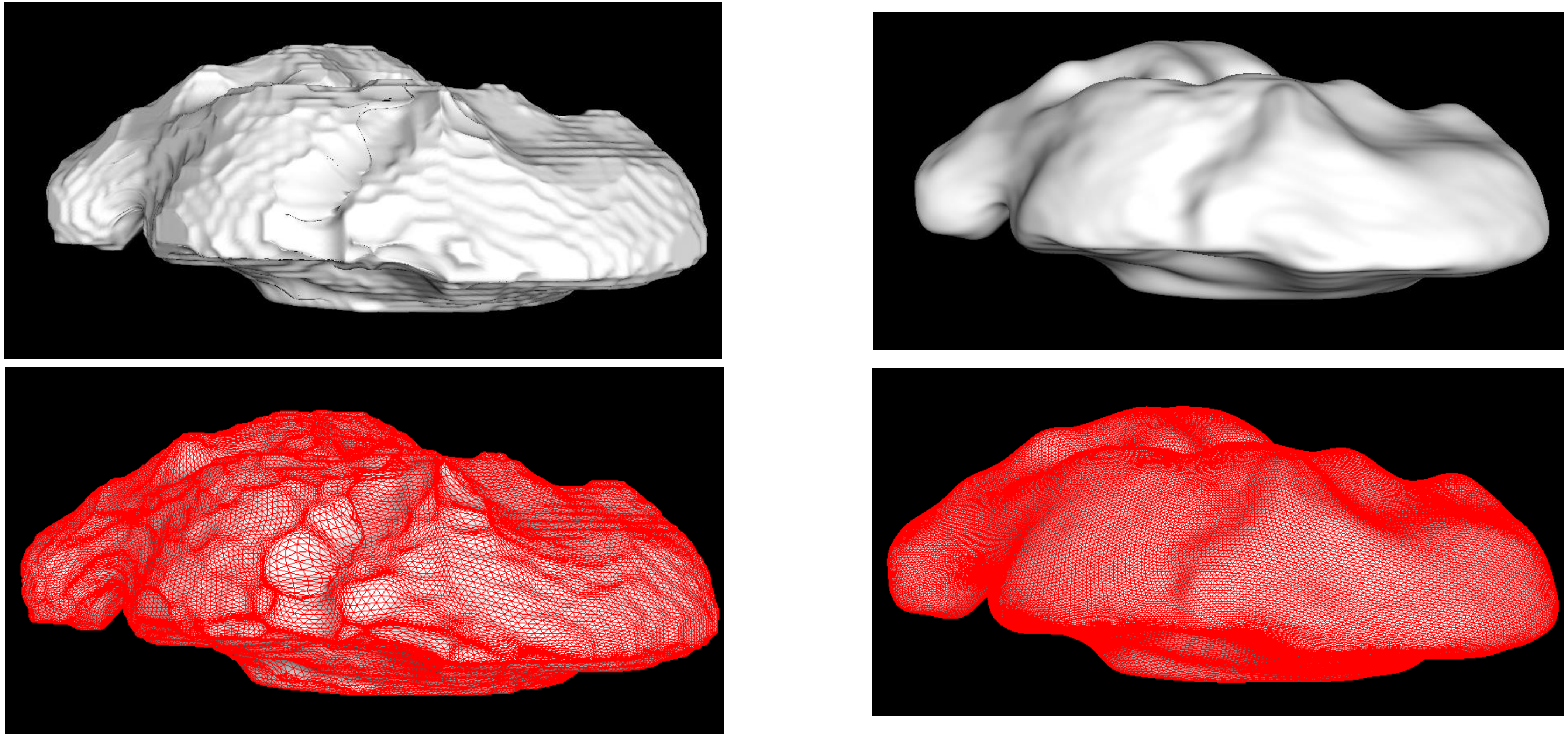
- Tighter fit
- Bumpy surface
- Risk of sharp angles

Small Value

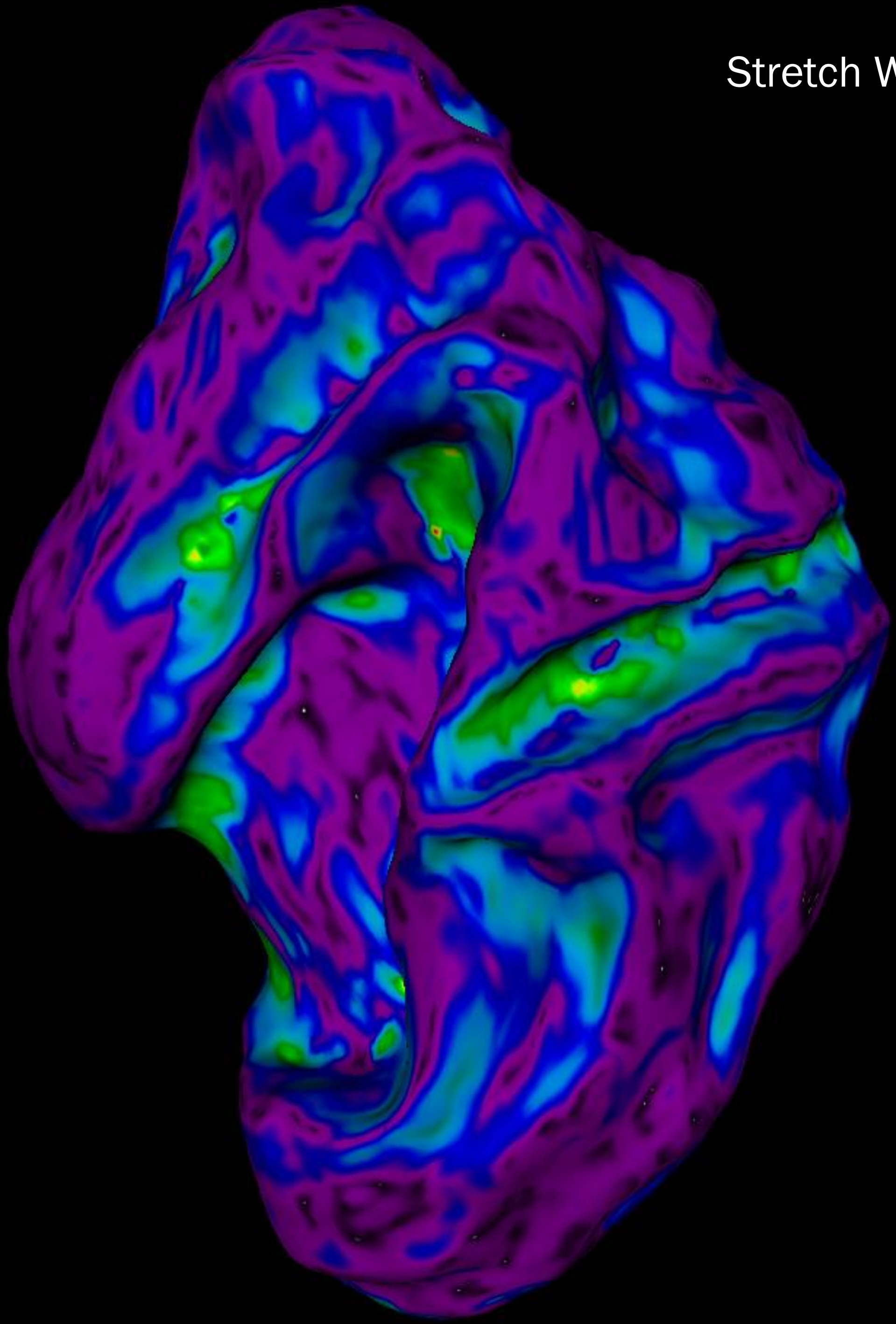
- Smoother Surface
- Unlikely to crease
- Less Accurate



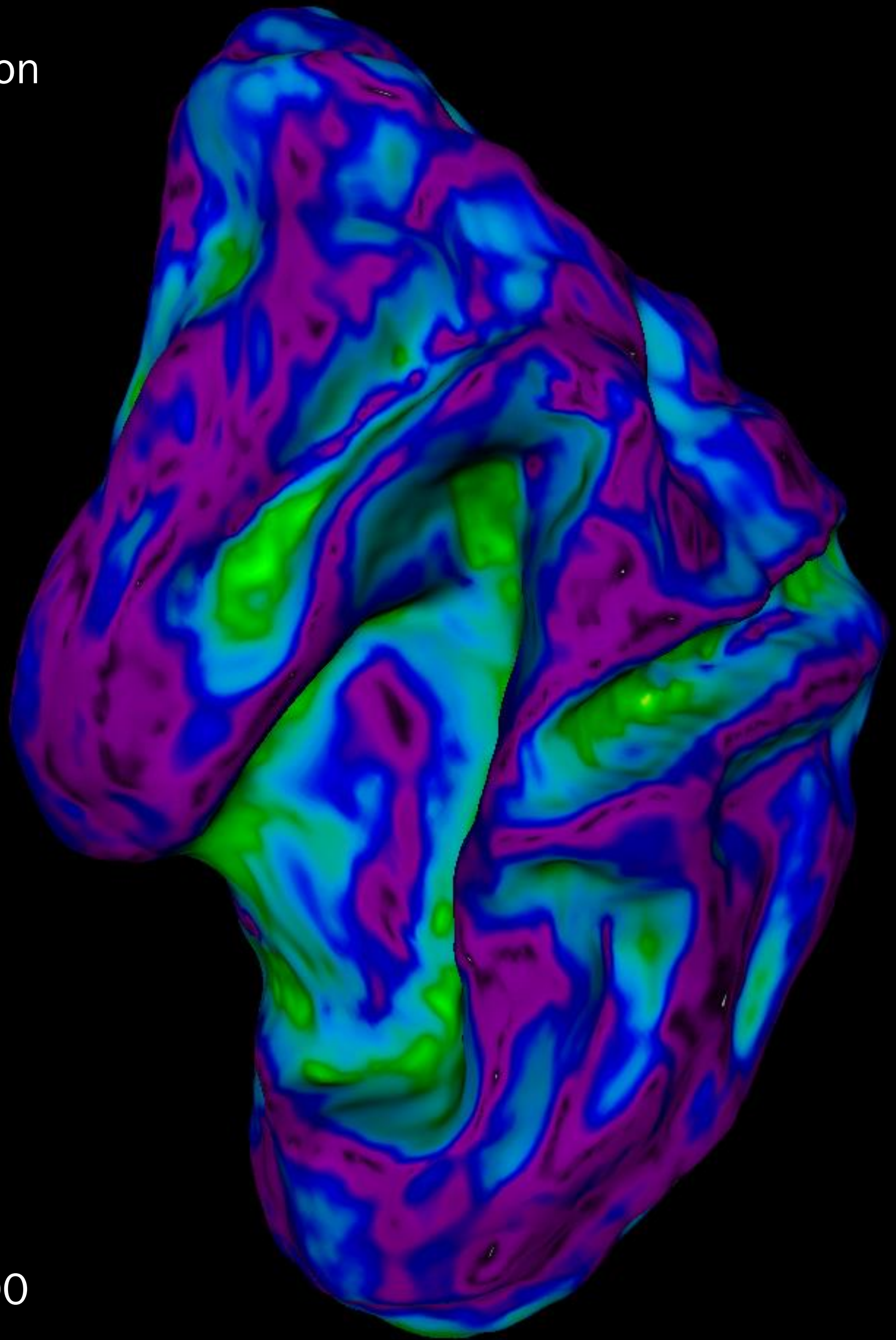
Stretch Weight Regulates Vertex Distribution



Stretch Worsens Distortion



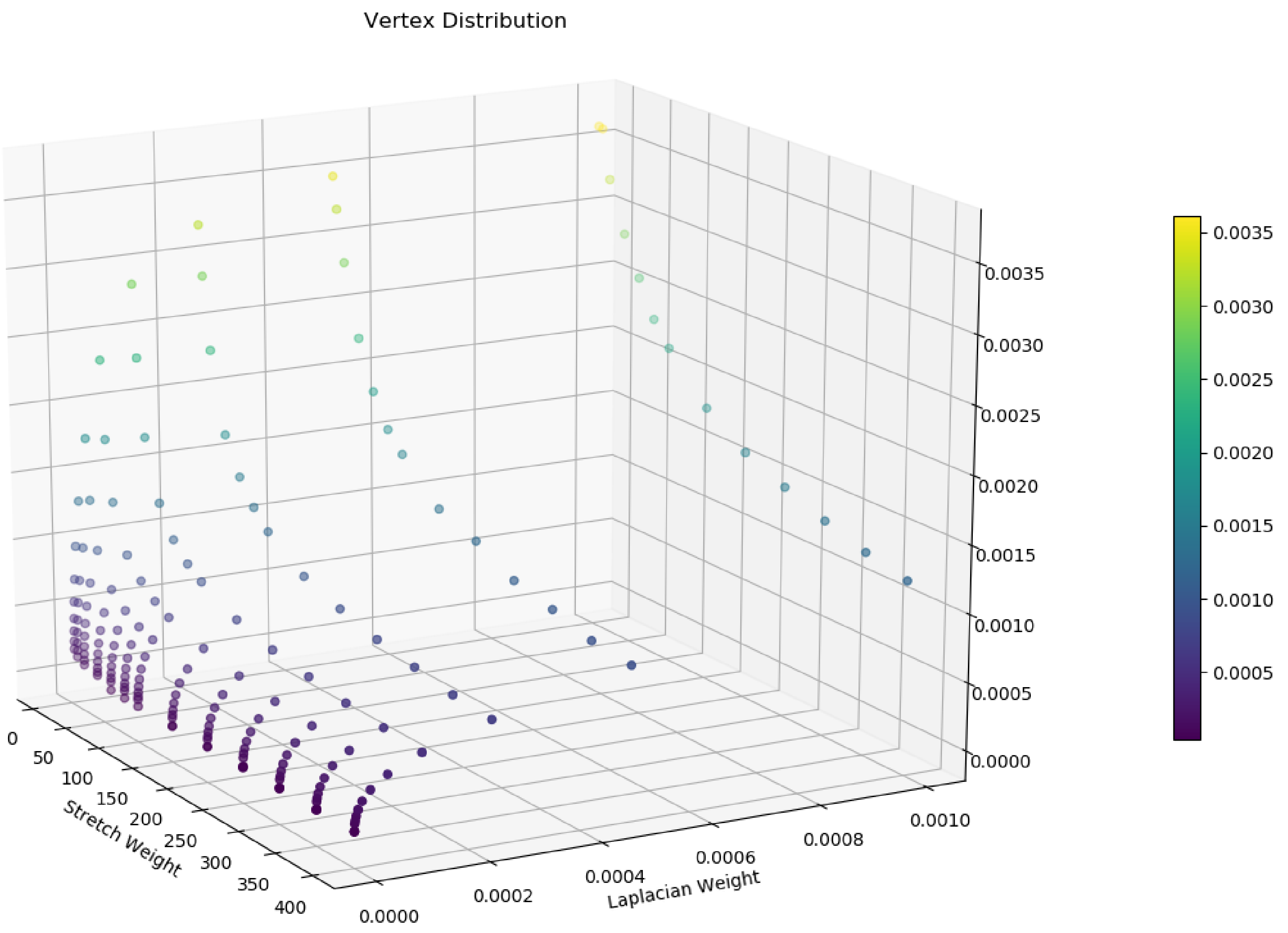
sw=40



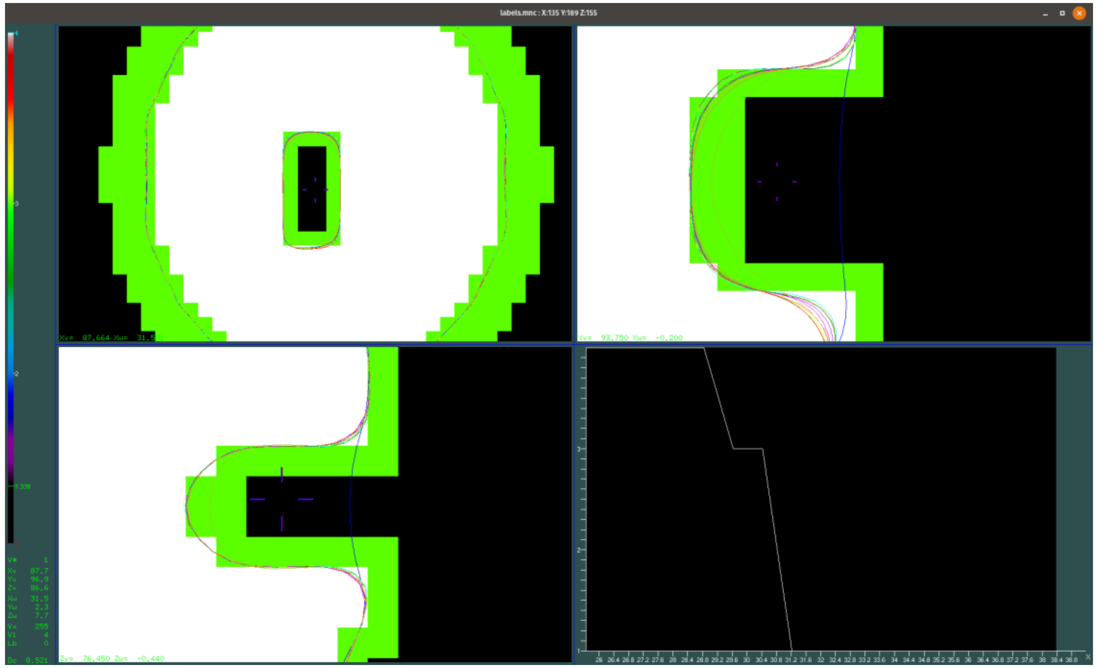
sw=400

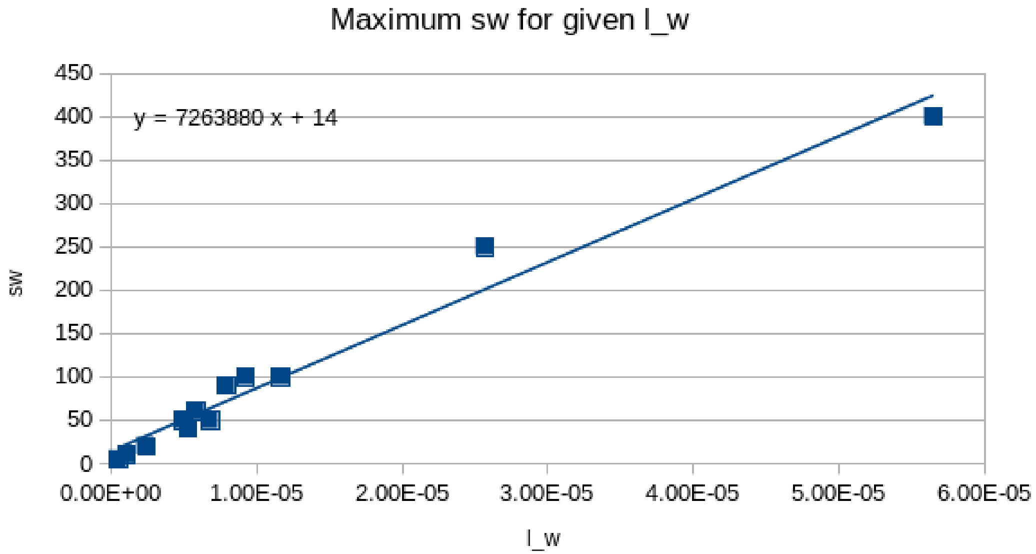
sw versus l_w

- Python scripts to run many jobs (like 9,000) in parallel
- Multi-threaded data processing
- Averages data while deallocating individual points
- Results are cached
- Multi-variable relations visualized with matplotlib



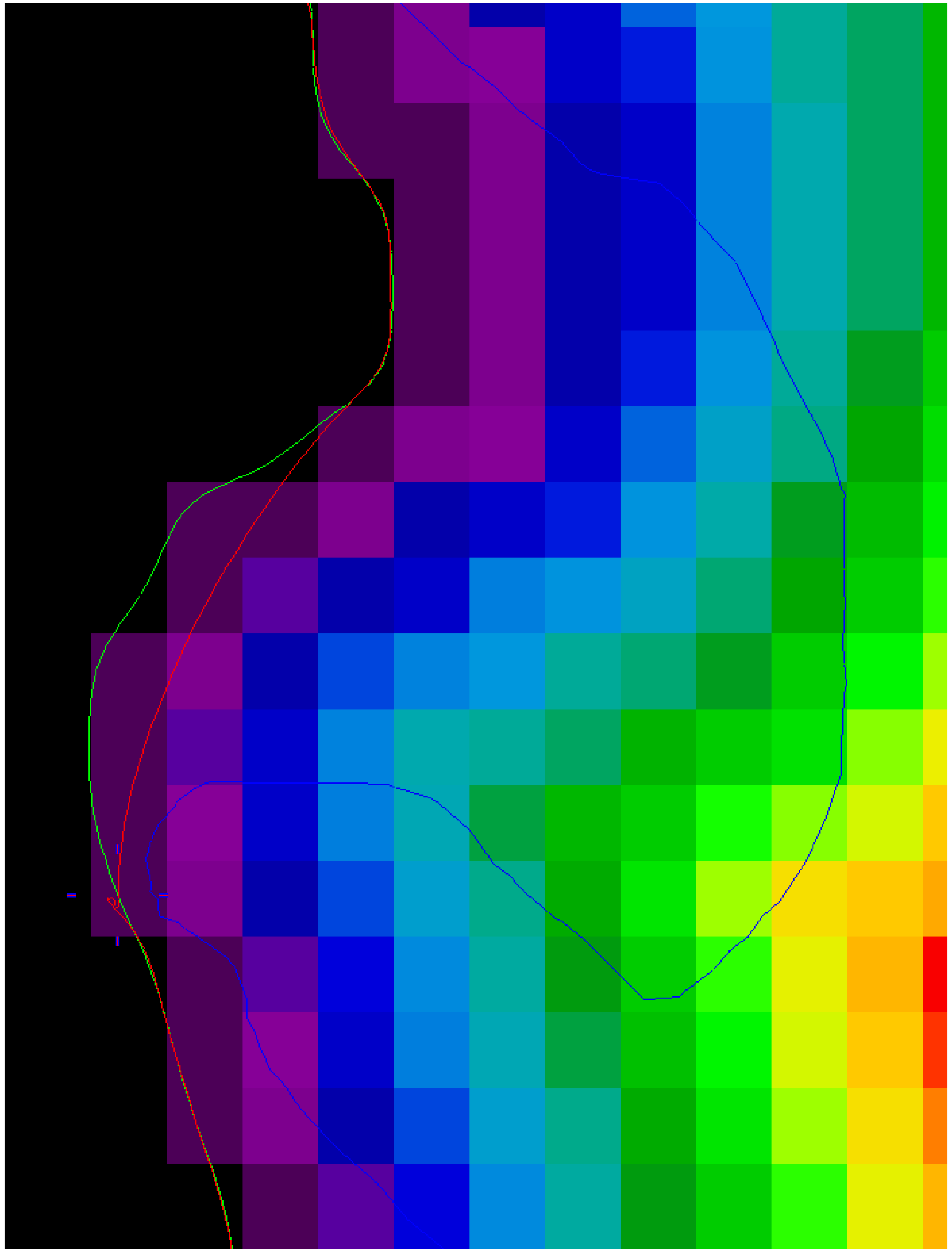
Artificial Sulci for Maximum sw



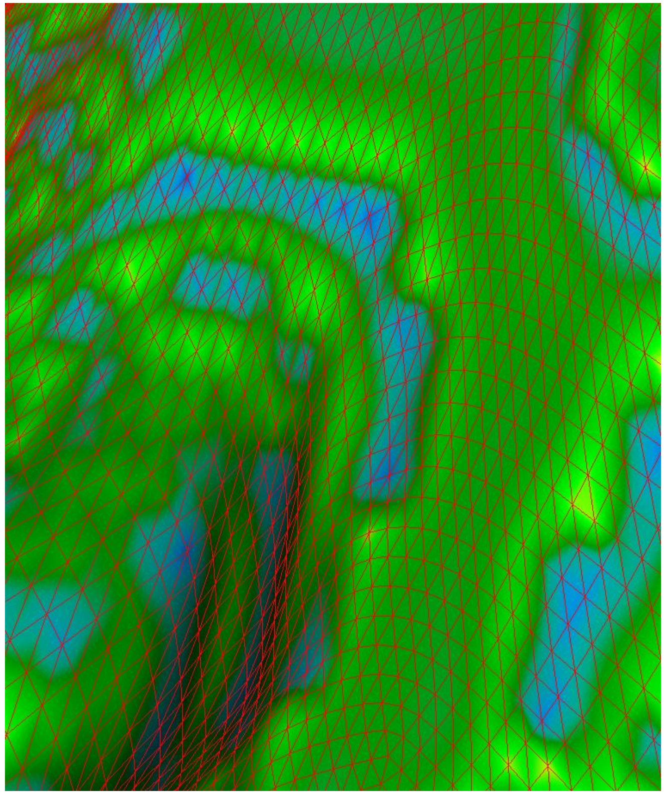


"Sulci" intrusion is
8 voxels long
2 voxels wide
4 voxels deep
(1 voxel = 0.8 mm)

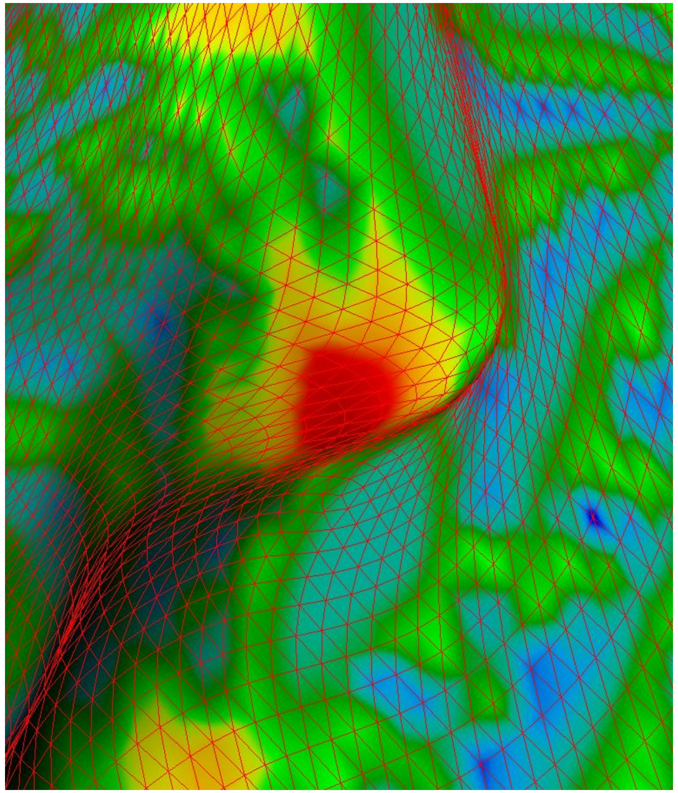
Low l_w overcomes folding



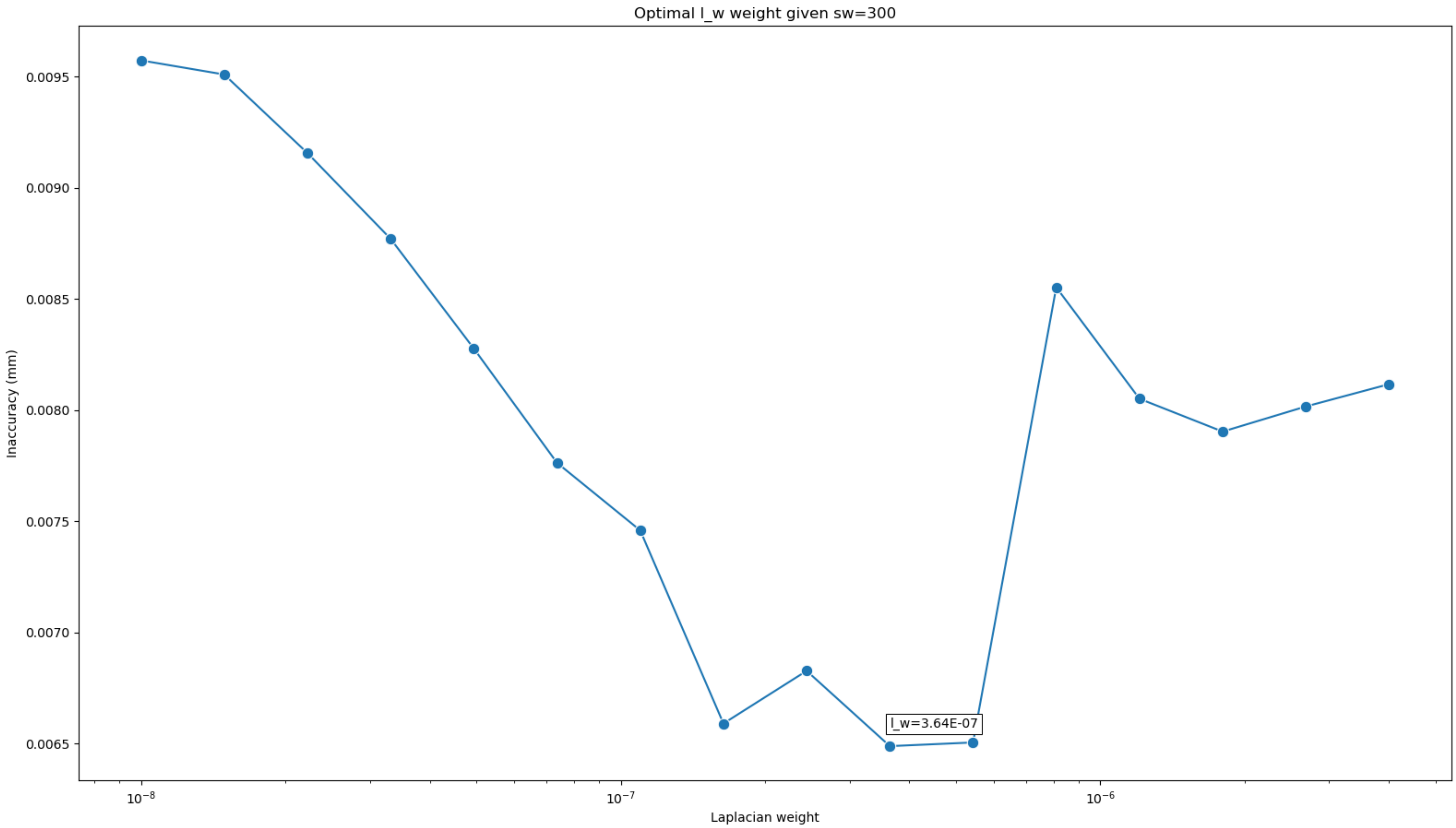
0010_s2 right



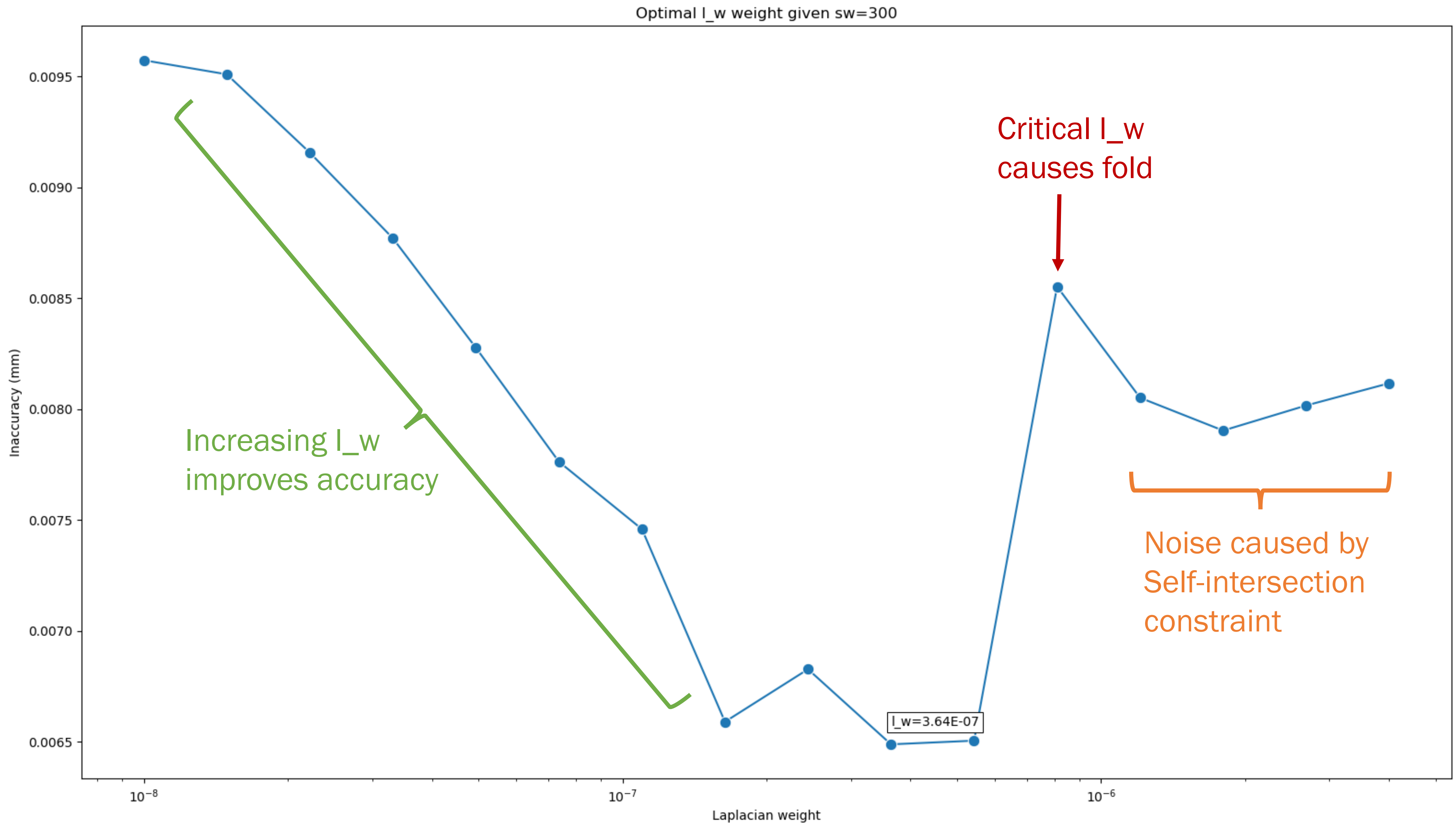
Green



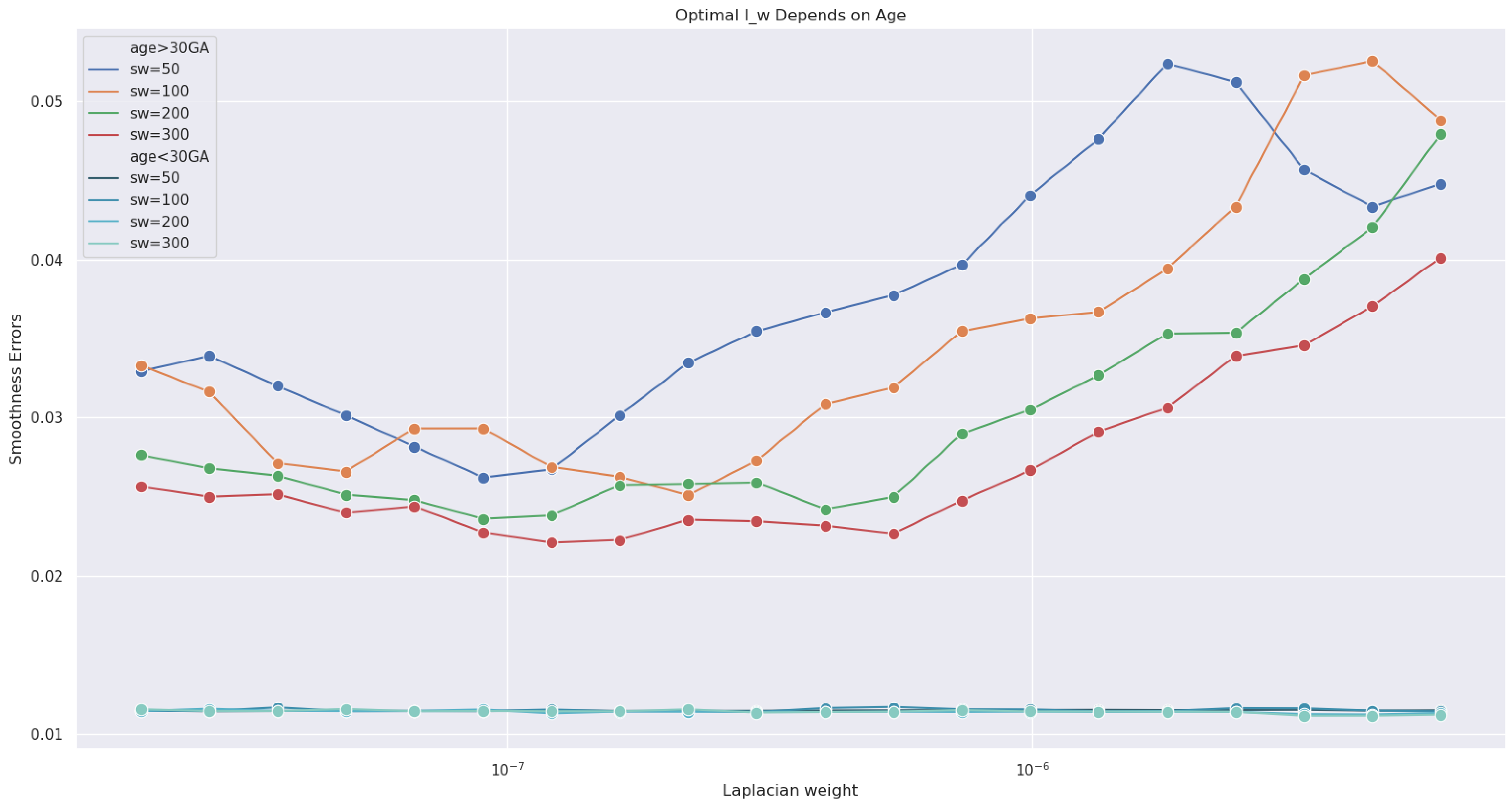
Red



Optimal l_w weight given sw=300
Inaccuracy (mm)
0.0095
0.0090
0.0085
0.0080
0.0075
0.0070
0.0065
l_w=3.64E-07
10^{-8}
10^{-7}
10^{-6}
Laplacian weight

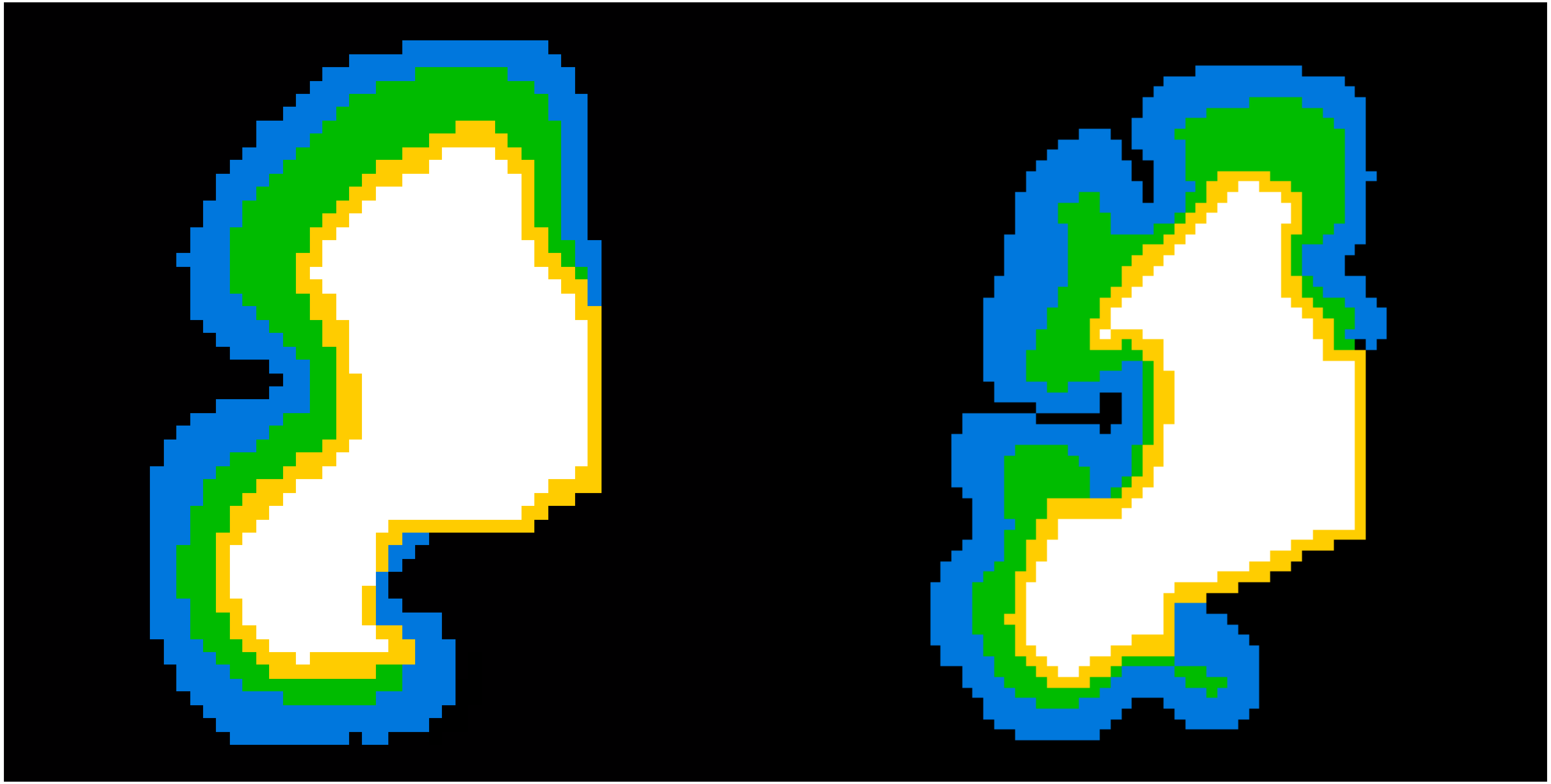


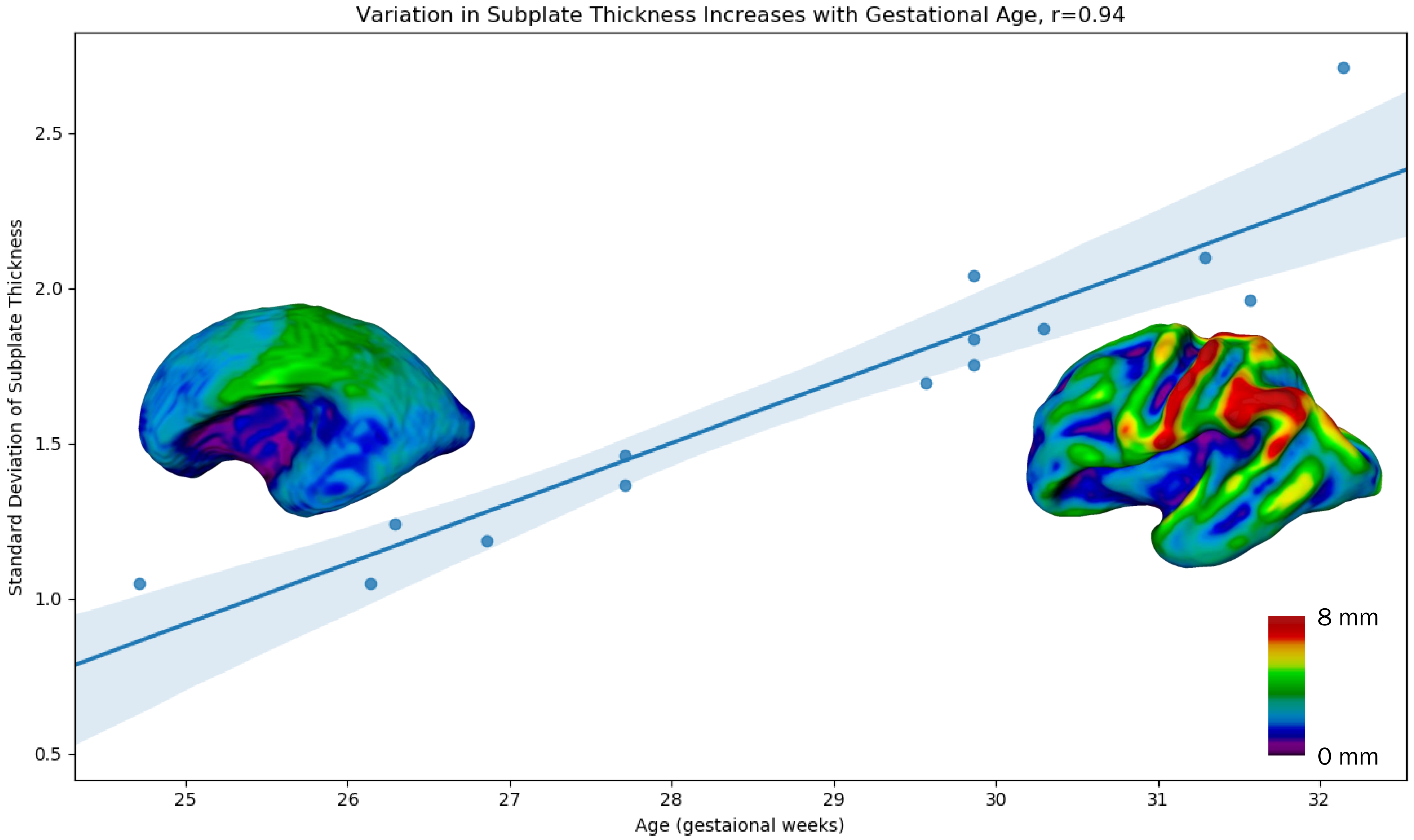
Optimal l_w weight given sw=300
0.0095
0.0090
0.0085
0.0080
0.0075
0.0070
0.0065
Inaccuracy (mm)
10^{-8}
10^{-7}
10^{-6}
Laplacian weight
l_w=3.64E-07
Critical l_w
causes fold
Increasing l_w
improves accuracy
Noise caused by
Self-intersection
constraint



Optimal l_w Depends on Age
age>30GA
sw=50
sw=100
sw=200
sw=300
age<30GA
sw=50
sw=100
sw=200
sw=300
0.05
0.04
0.03
0.02
0.01
Smoothness Errors
10^{-7}
10^{-6}
Laplacian weight

Gyrification





Variation in Subplate Thickness Increases with Gestational Age, r=0.94
Standard Deviation of Subplate Thickness
2.5
2.0
1.5
1.0
0.5
25
26
27
28
29
30
31
32
Age (gestaional weeks)
8 mm
0 mm

parm.py: Spherical Parametric Functions

Spherical Function given by $r(\theta, \varphi)$

→ **.obj mesh** using a *Python script*

→ **MINC** volume using `surface_mask2`

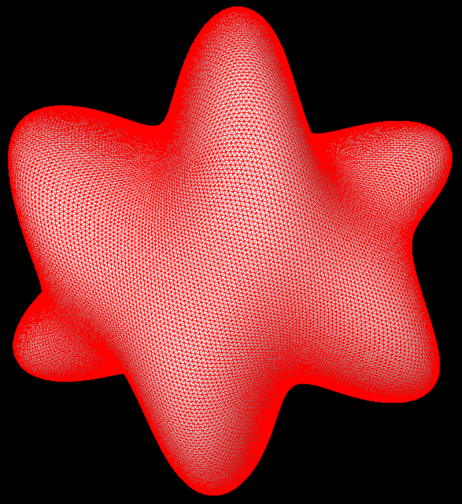
$$r(\theta, \varphi) = 20 + 5\sin(6\theta)\, sin\varphi$$

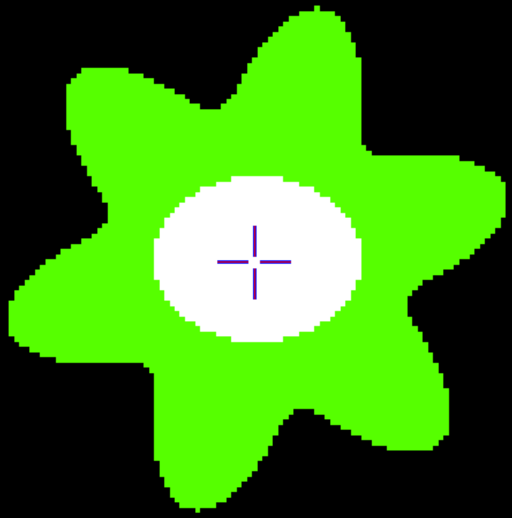
W: size

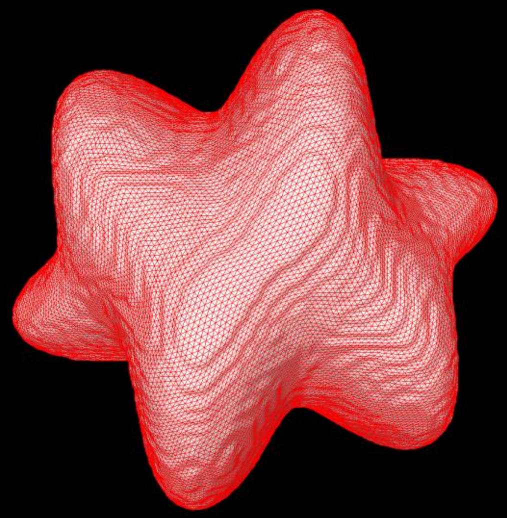
C: number of “gyri”

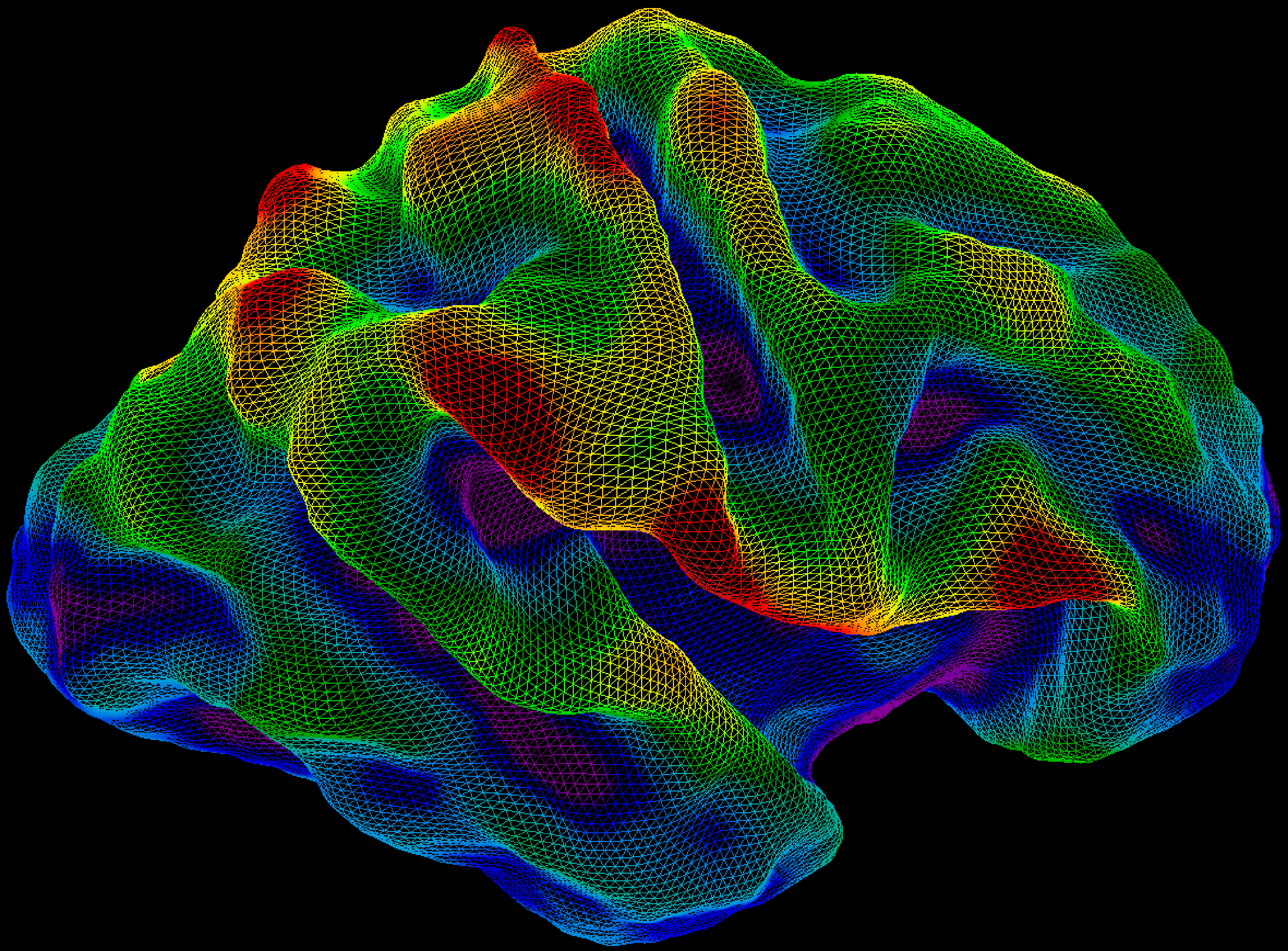
D: amplitude (akin to sulcal depth)

$$\left.\begin{array}{l} x(\theta, \varphi) \\ y(\theta, \varphi) \\ z(\theta, \varphi) \end{array}\right\}$$









cortical_thickness -tlink iz_81920.obj wm_81920.obj subplate_thickness.txt