

Creating statistical atlases of modern primate endocranial morphology using non-rigid deformation analysis of high-resolution CT images

P. Thomas Schoenemann^{1,2}, Janet Monge^{2,3},
Ralph L. Holloway⁴, Brian B. Avants⁵, and James C. Gee⁵

¹Department of Anthropology, Indiana University,

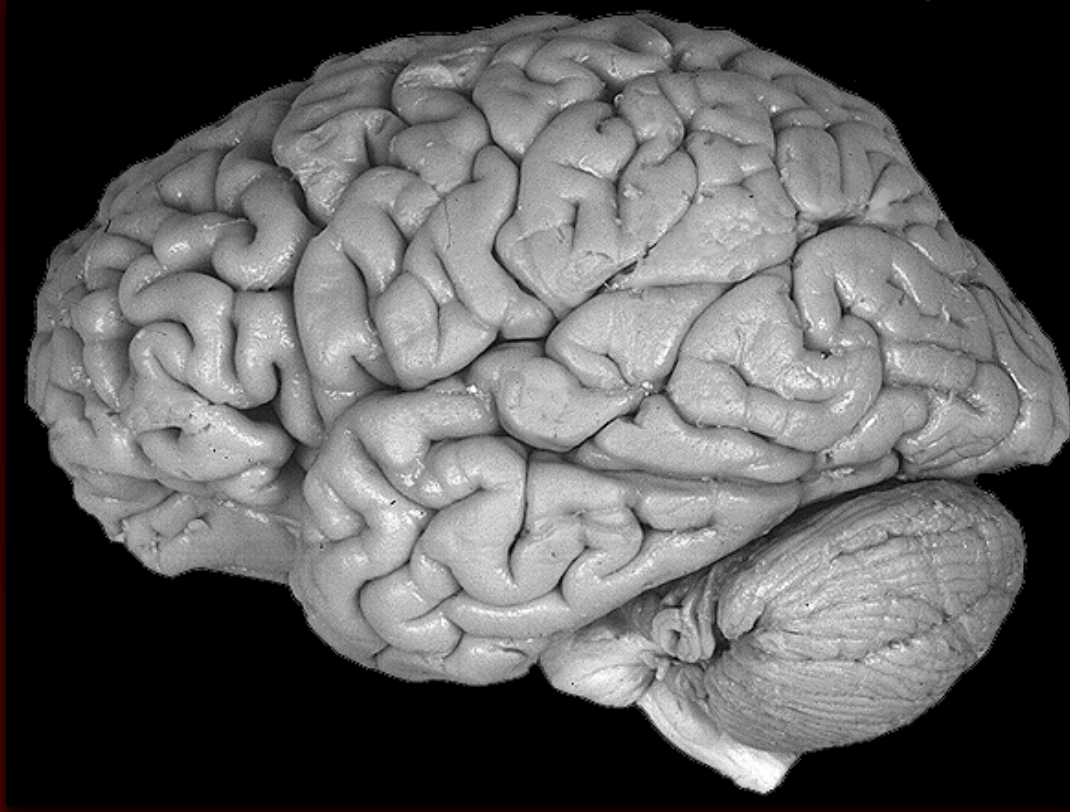
² Museum of Archaeology and Anthropology, University of Pennsylvania,

³Department of Anthropology, University of Pennsylvania,

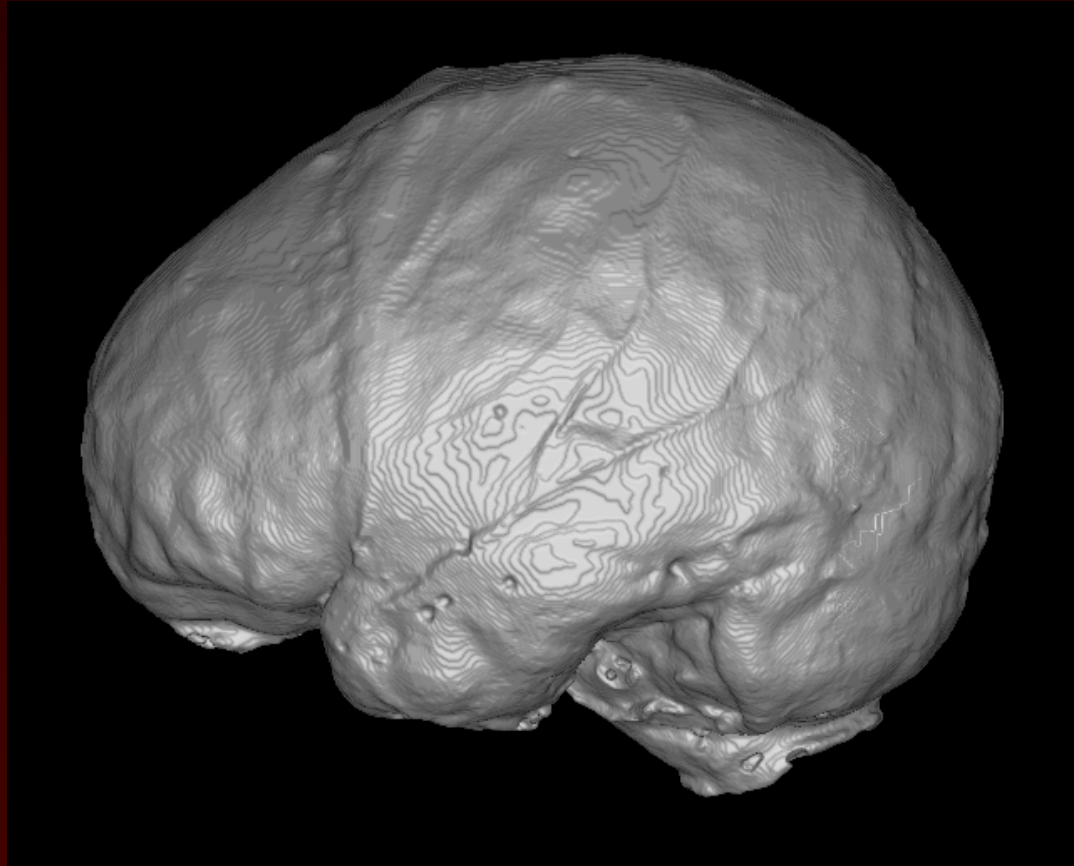
⁴Department of Anthropology, Columbia University,

⁵Department of Radiology, University of Pennsylvania

What we'd *like* to study in fossils:



What we are *able* to study in fossils:

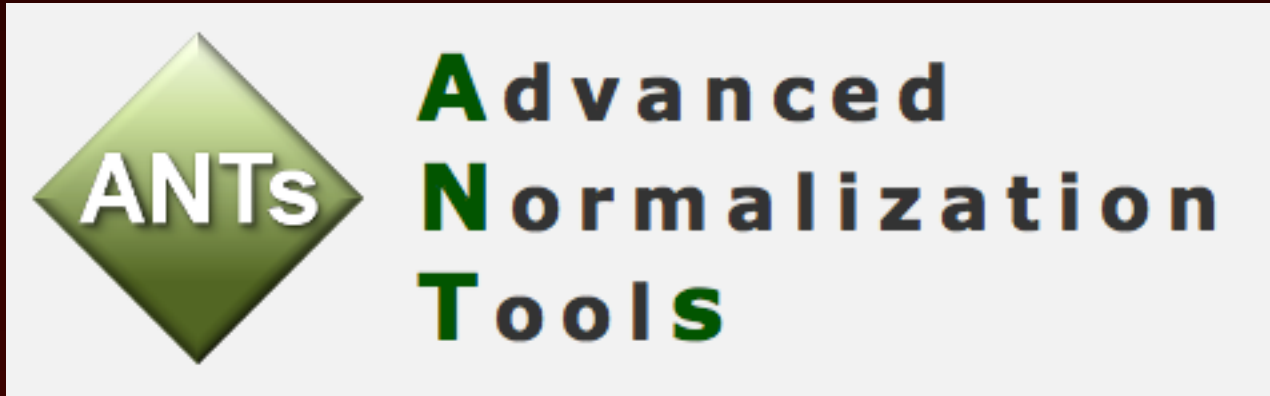


- only fossil evidence of brain evolution
- very complicated morphological shape

Goal of the present study:

- Create average endocrania for different species that can be used as reference standards by other researchers
- Replicate the study by MacLeod, Falk, Mohlberg, and Zilles (2003, “Patterns of surface shape in great ape endocasts”) using alternative methods
- Describe variation at each point in the samples
- Illustrate the usefulness of freeware software tools available for these analyses

Software tools used for this study:



<http://www.picsl.upenn.edu/ANTs/>

Many powerful, flexible tools for image analysis

Freeware

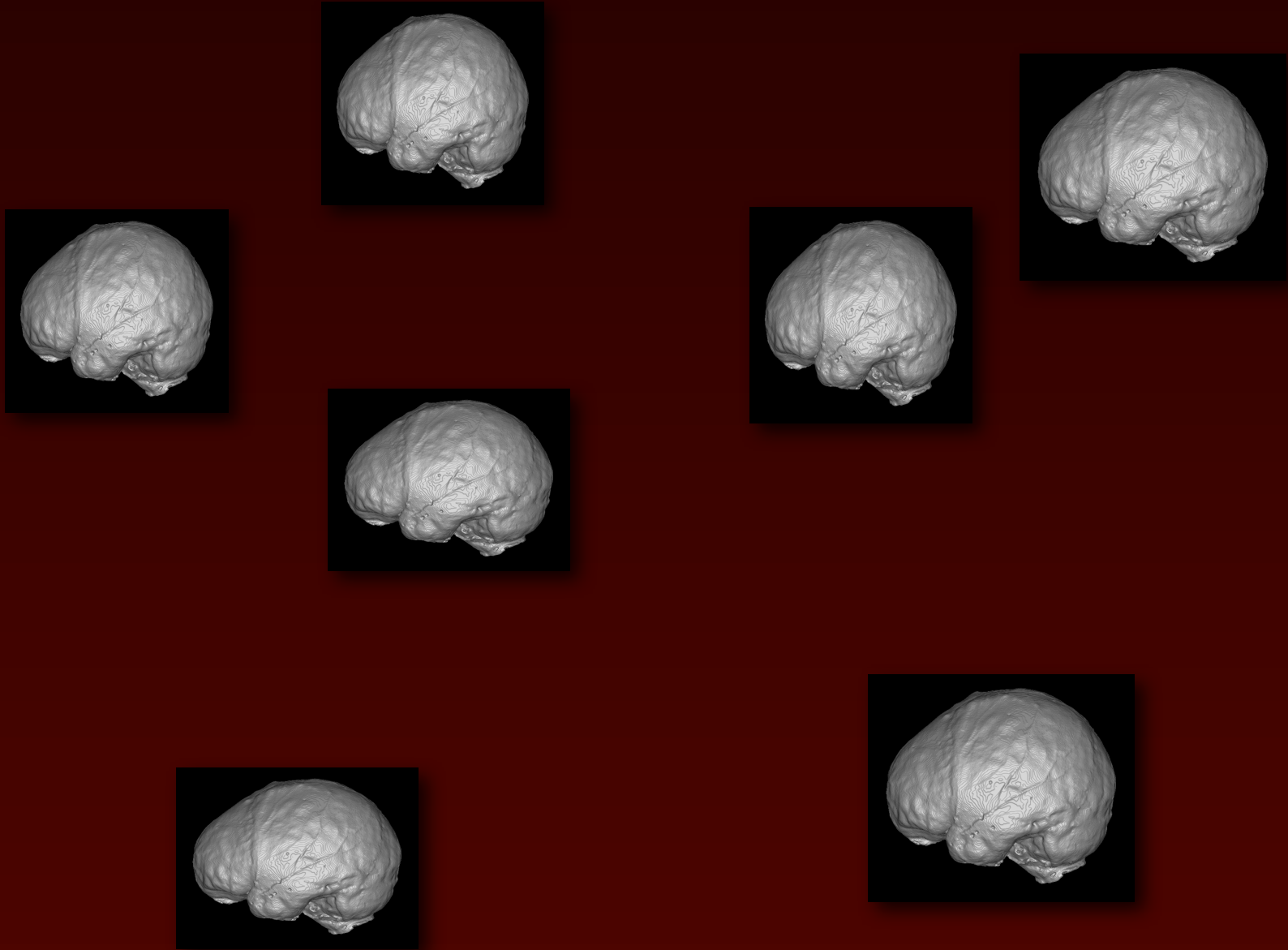
Binaries and source code available

Can be compiled on Windows, Linux, Mac OS X

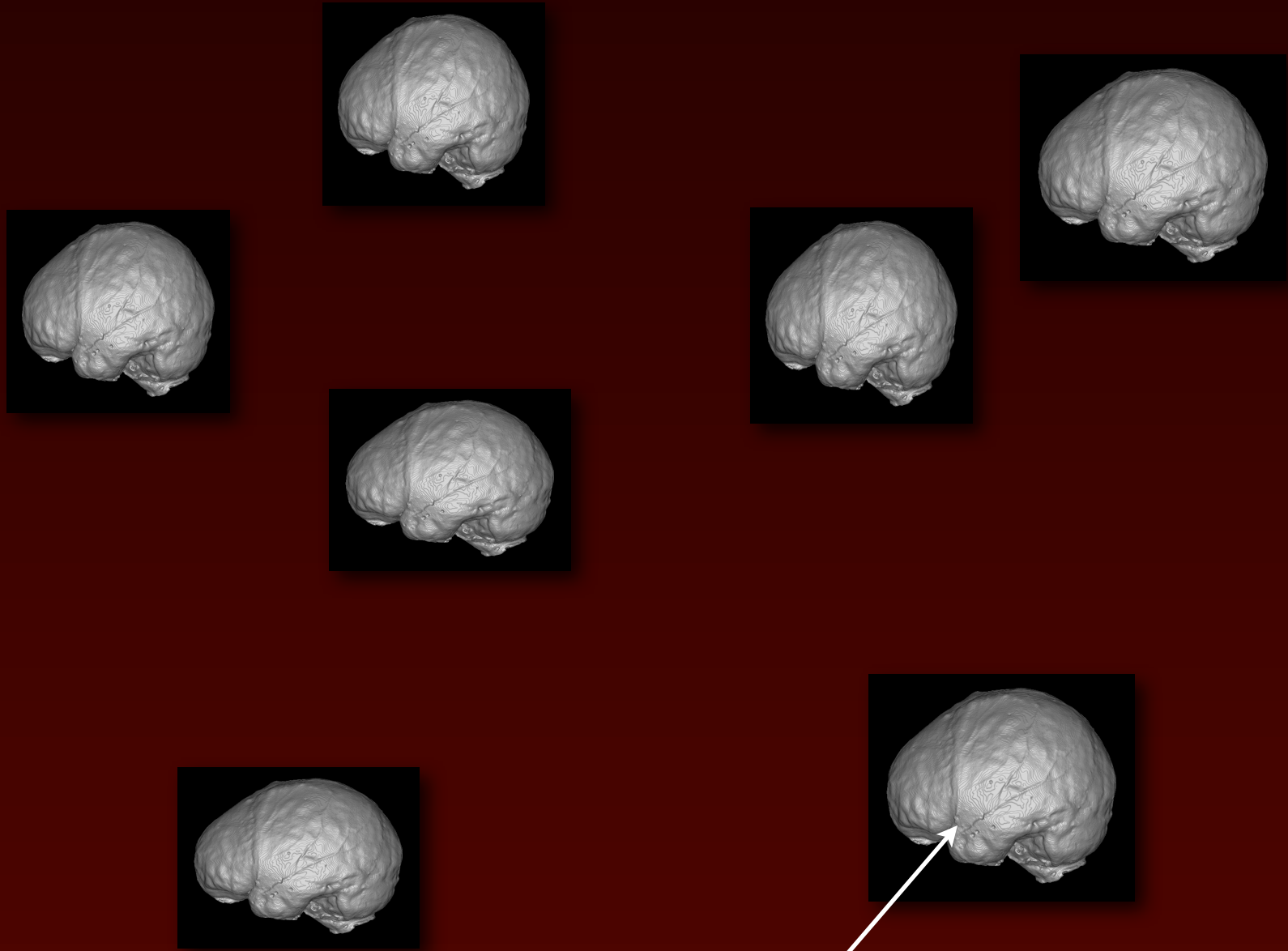
Basic method used to create average endocrania:

1. rigidly align images
2. choose initial template image (e.g., simple average)
3. morph each individual image into template (affine + diffeomorphic registration)
4. average distortion maps
5. use average distortion maps to integrate the diffeomorphism forward in time (i.e., 'move' template in the average direction), creating an updated template
6. repeat steps 3-5 until average distortion maps indicate one has reached the 'center' of the study population's shape space

Step 1: align images in 3D space (rigid rotation)

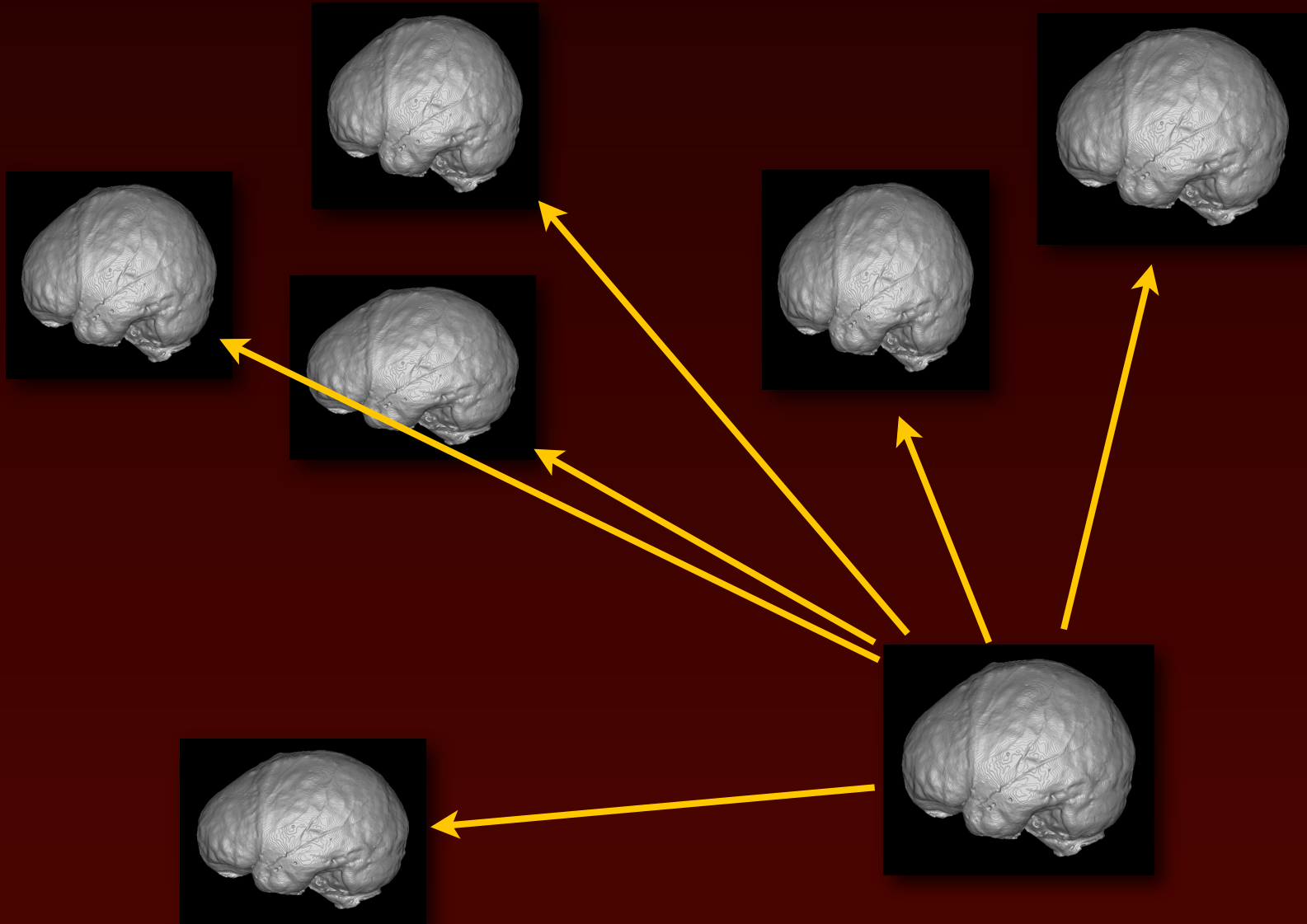


Step 2: create a starting template (e.g., choose one at random)



initial template

Step 3: morph template into each individual



Each arrow represents a separate 3D mapping

What exactly are the mappings?

Volumes representing vectors in 3D space indicating the directions and distances that voxels in the target (template) image are mapped to voxels in the subject image

i.e.:

X-vector file

Y-vector file

Z-vector file

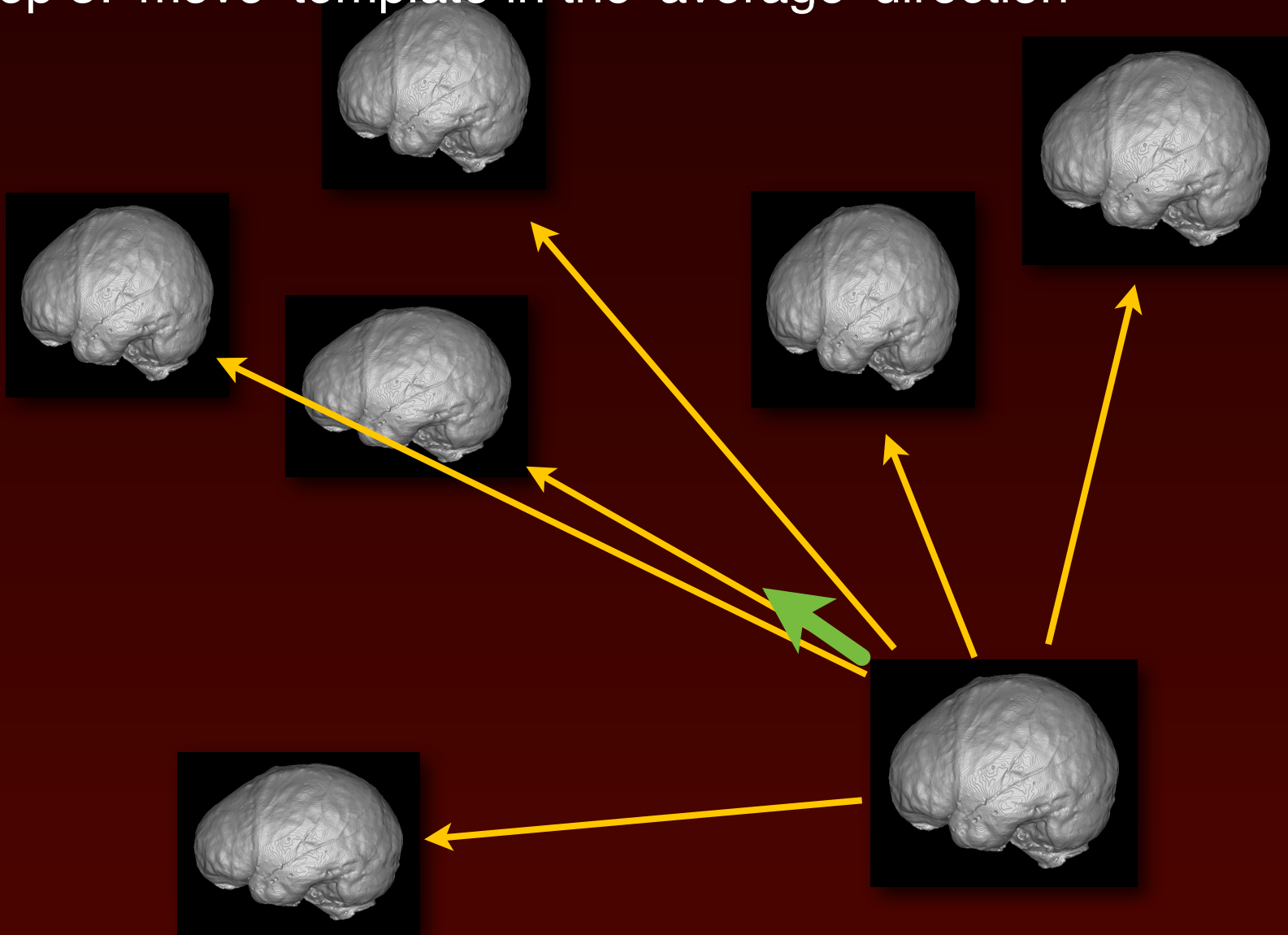
Step 4: average the distortion maps

Averaging the X-vector files gives the average distance the template is in the X dimension from the individuals in the population.

Averaging the Y-vector files gives the average distance the template is in the Y dimension from the individuals in the population.

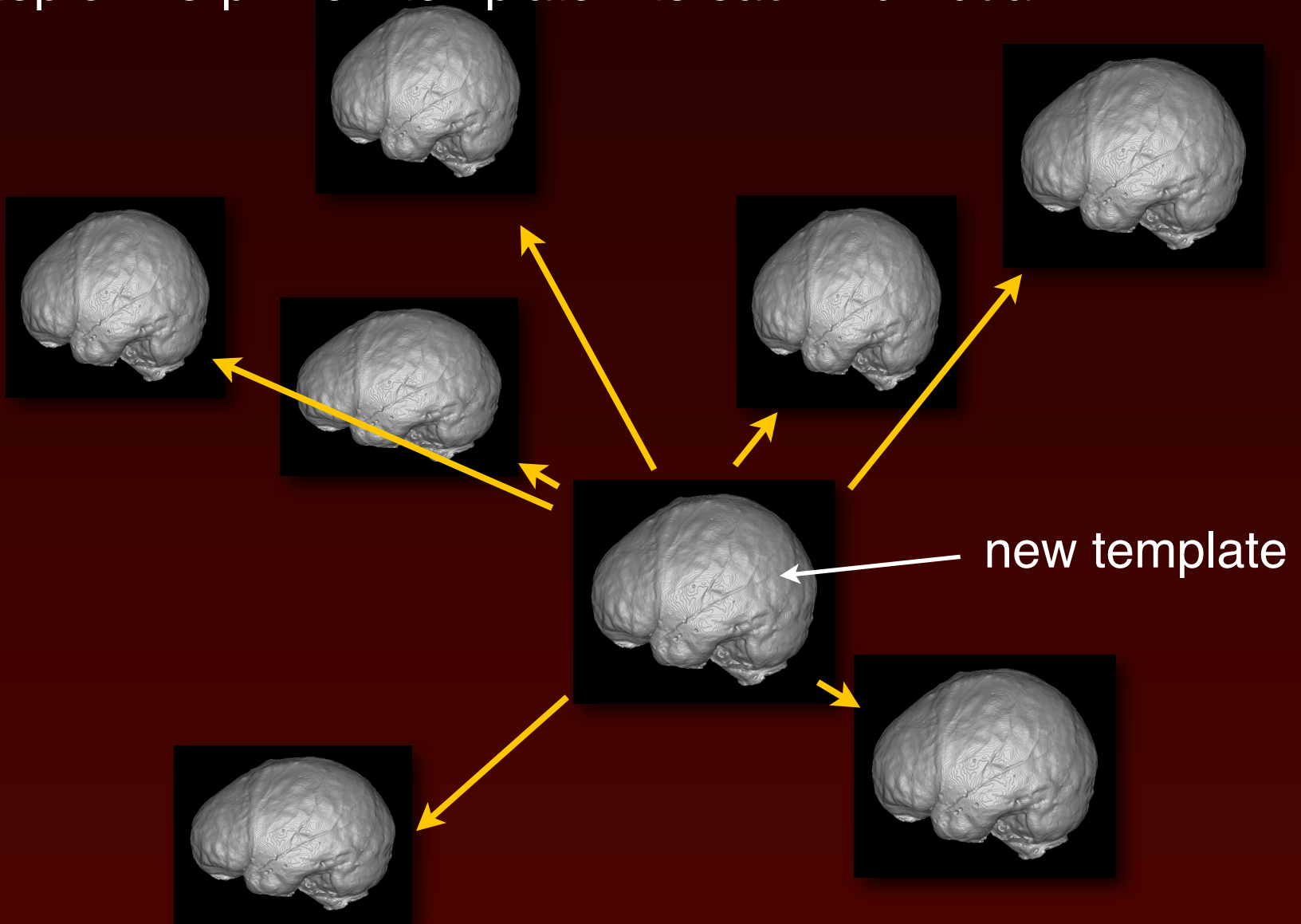
Averaging the Z-vector files gives the average distance the template is in the Z dimension from the individuals in the population.

Step 5: 'move' template in the 'average' direction



Average mapping (**green arrow**) points towards average shape

Step 6: morph new template into each individual



Repeat this process until the template doesn't change in subsequent iterations

This effectively moves the template into the average shape space of the population

Present study sample

CT scans of latex/plaster endocasts from Ralph Holloway's collection:

18 *Homo sapiens*

33 *Pan troglodytes*

33 *Pan paniscus*

38 *Gorilla gorilla*

Average *Homo sapiens* endocranial shape

superior

anterior

right lateral



inferior

posterior

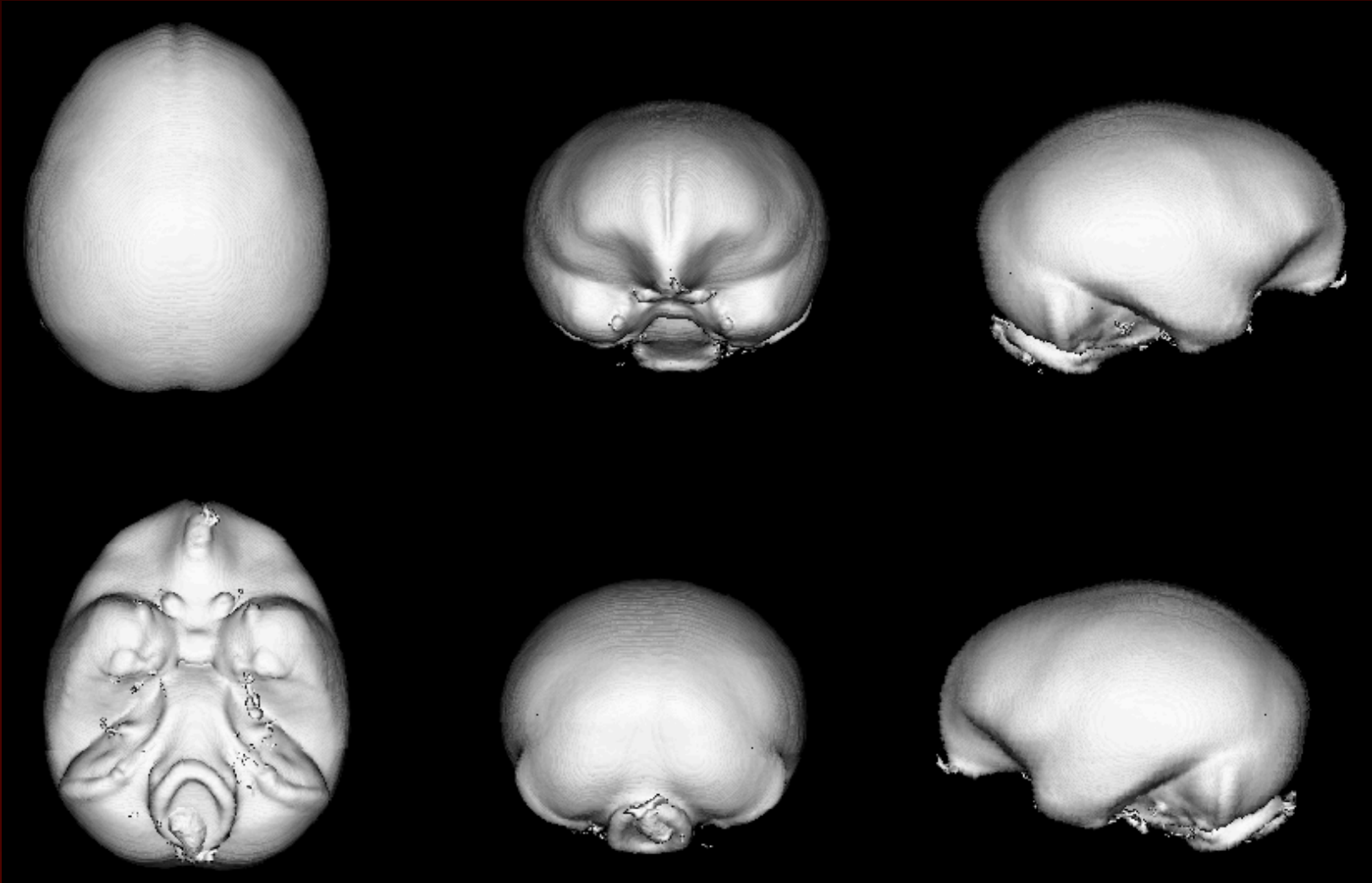
left lateral

Average *Pan troglodytes* endocranial shape

superior

anterior

right lateral



inferior

posterior

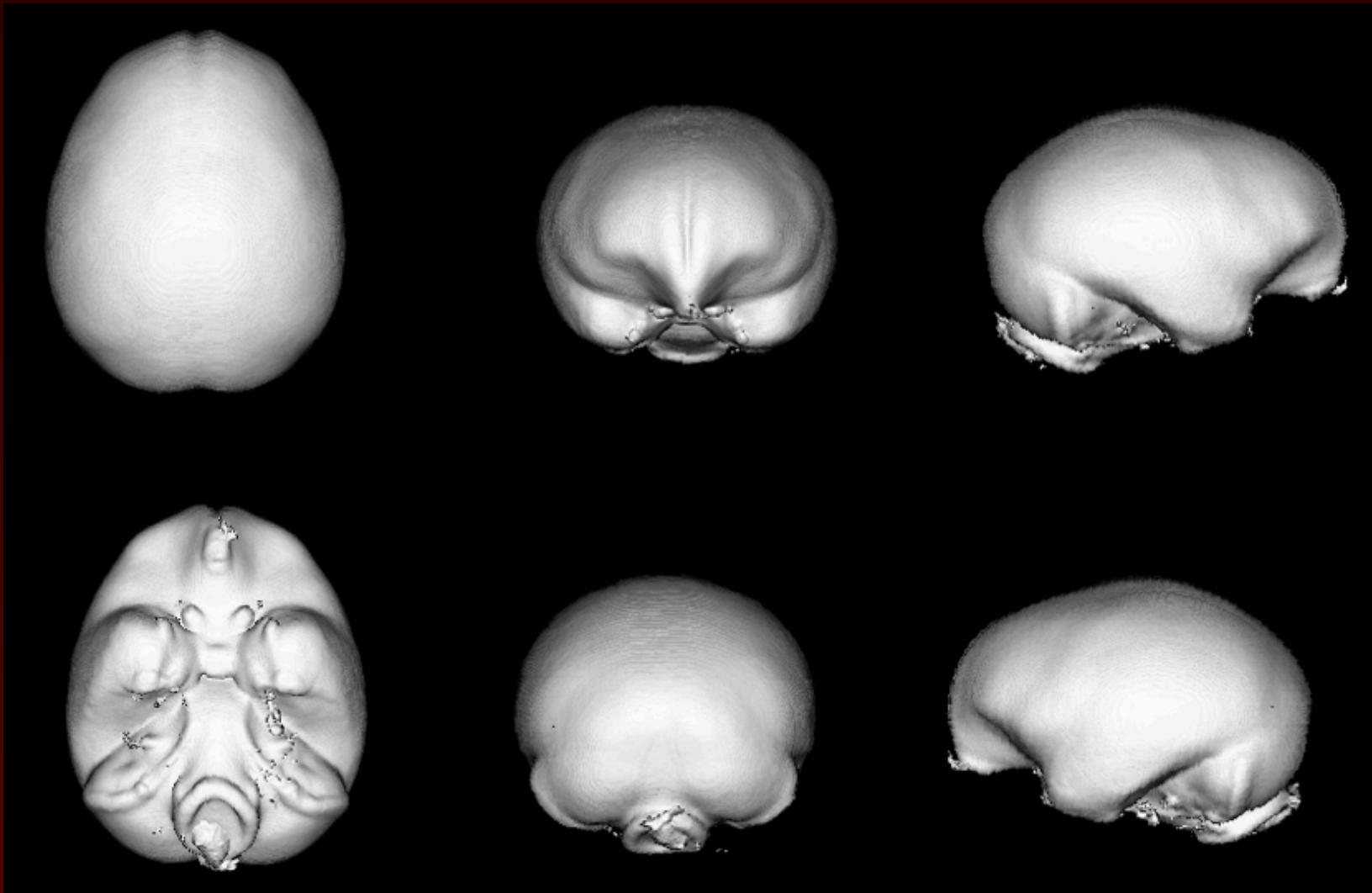
left lateral

Average *Pan paniscus* endocranial shape

superior

anterior

right lateral



inferior

posterior

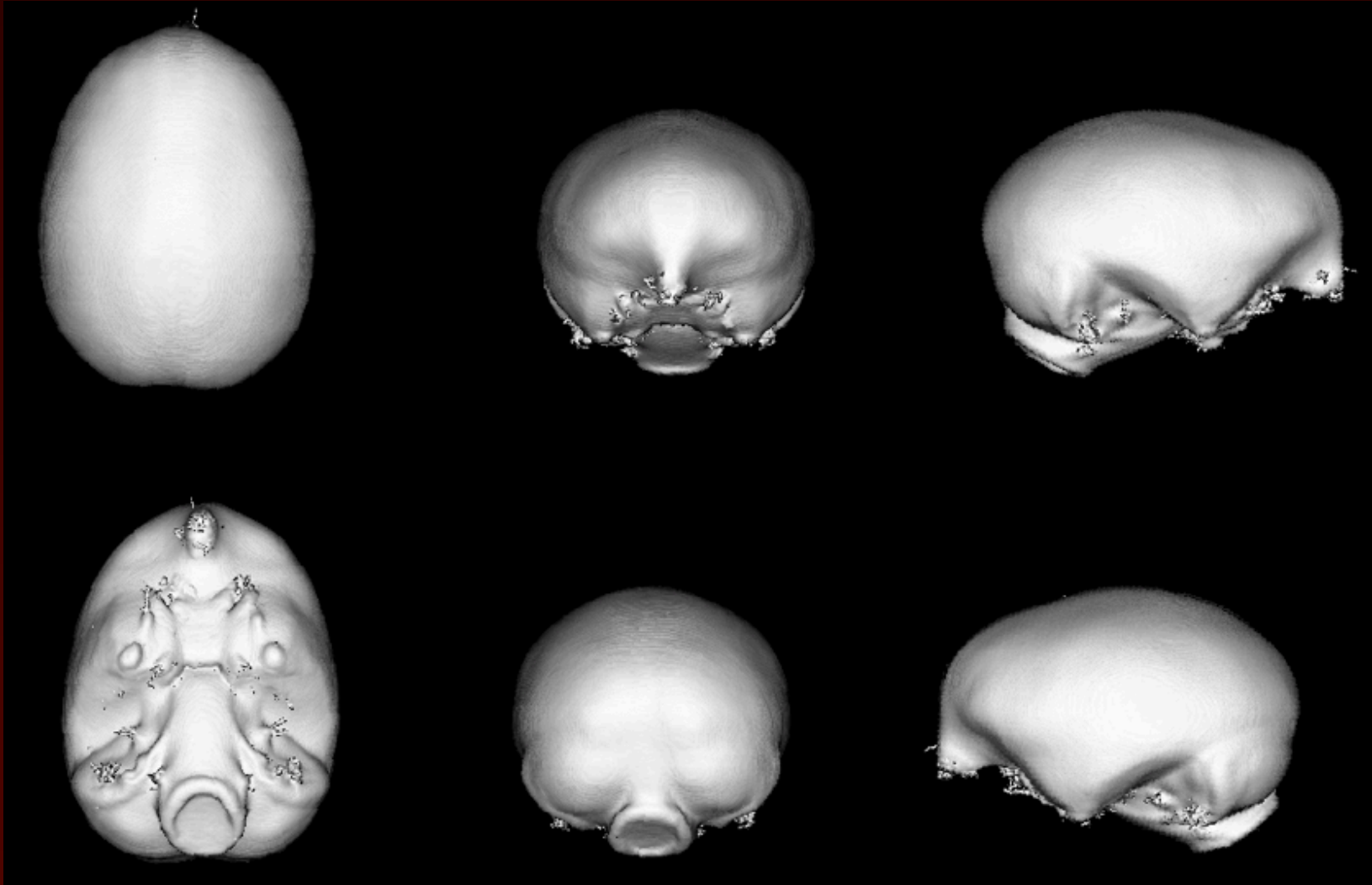
left lateral

Average *Gorilla gorilla* endocranial shape

superior

anterior

right lateral



inferior

posterior

left lateral

Note:

The template is itself an actual image, which can therefore be (virtually) measured and compared (using freeware software tools) to real specimens (e.g., fossils)

The file itself can be easily transferred to other researchers

Additional possible analyses:

Degree of localized scaling can be calculated for each voxel of a given distortion map for an individual. These values are mathematically known as Jacobians.

A Jacobian map thus represents a detailed mathematical description of how an individual is different from the average shape for that species

These can be color coded in various ways to highlight differences between an individual and the average

Additional benefits

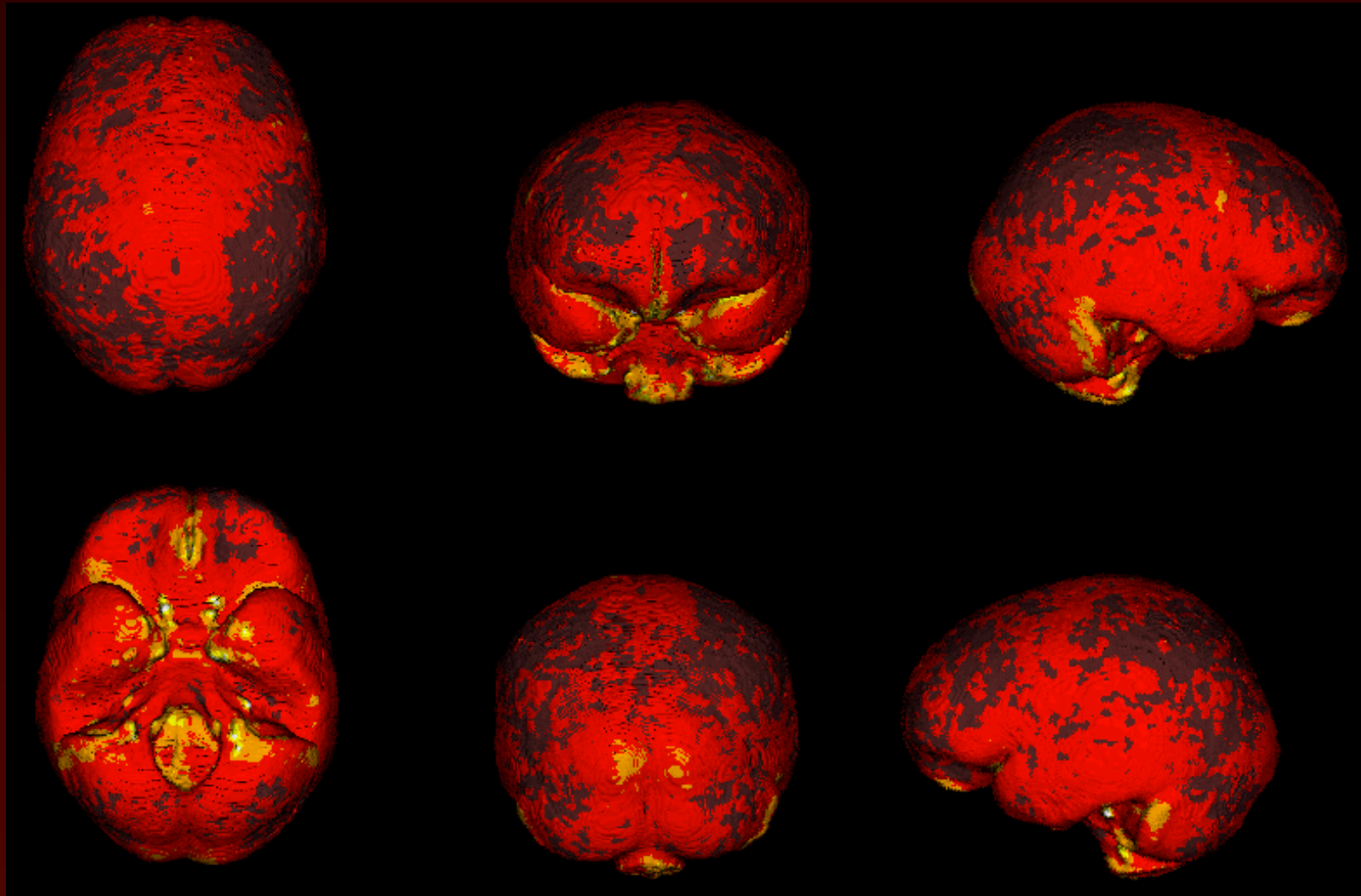
Degree of variation in Jacobians (i.e., scaling factors) can easily be calculated, thereby highlighting the locations where the shape is most variable across individuals in a population

Standard deviations of log Jacobians for *Homo sapiens*

superior

anterior

right lateral



inferior

posterior

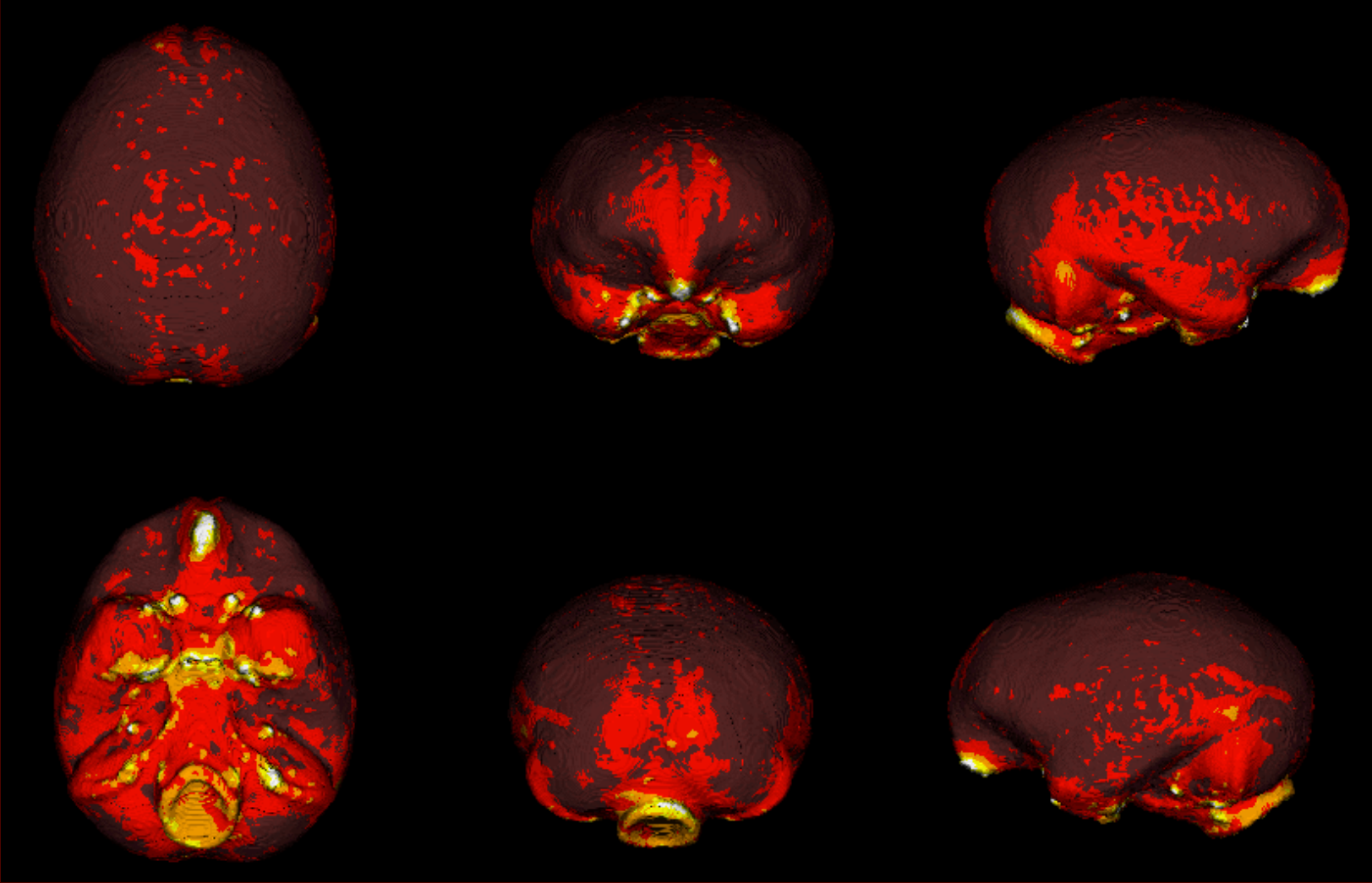
left lateral

Standard deviations of log Jacobians for *Pan troglodytes*

superior

anterior

right lateral



inferior

posterior

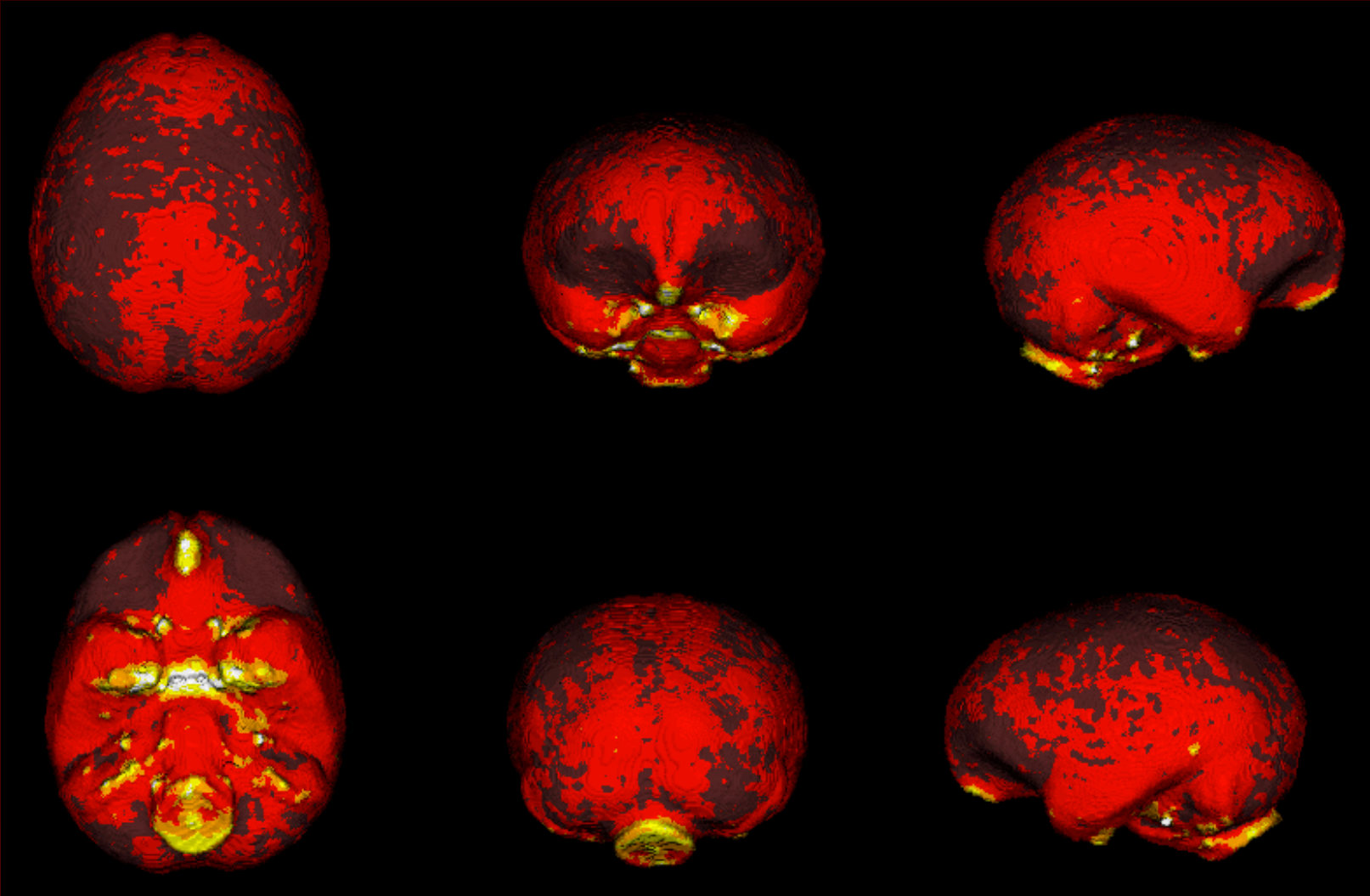
left lateral

Standard deviations of log Jacobians for *Pan paniscus*

superior

anterior

right lateral



inferior

posterior

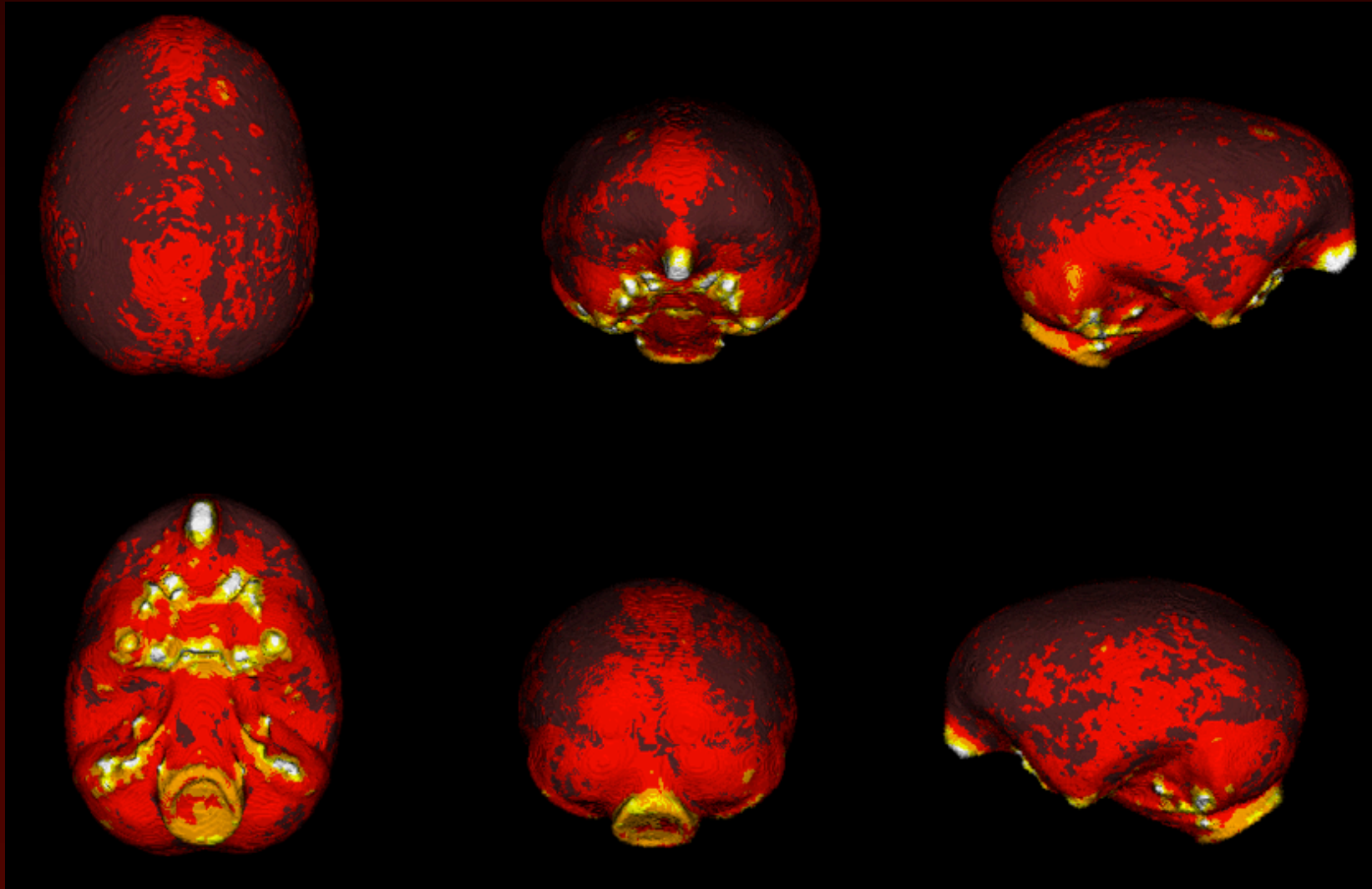
left lateral

Standard deviations of log Jacobians for *Gorilla gorilla*

superior

anterior

right lateral



inferior

posterior

left lateral

Note:

Inferior areas are most variable because of the numerous foramen found there, in which latex filled to different extents

In these samples, inferolateral temporal lobe and lateral cerebellar areas appear to be most variable locations with respect to localized size differences

Further benefits:

Average species templates can be morphed into each other, resulting in detailed mathematical descriptions of where species differ from each other, and by how much

Acknowledgements:

- Felicia Jefferson and staff at the Hospital of the University of Pennsylvania CT facility
- Samantha Cox and Jen Rosado at Penn for help scanning the specimens
- Robert Mahaney for help preprocessing the scans for analysis
- Open Research Scan Archive (<http://plum.museum.upenn.edu/~orsa/ORSA/Welcome.html>)