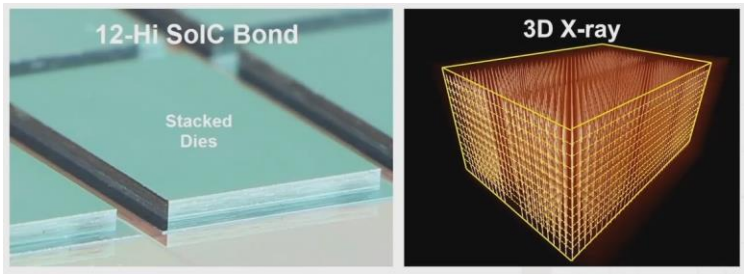
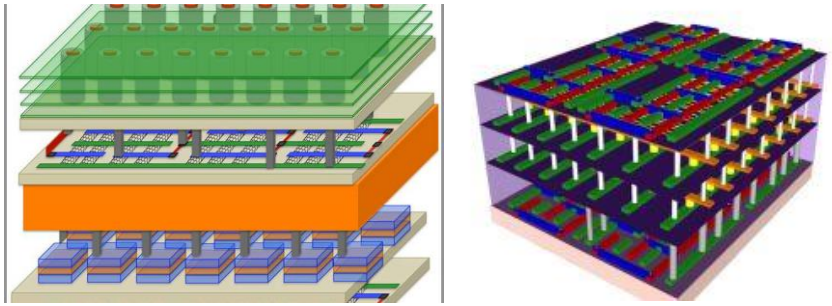
What cortical folding patterns could tell us about individual brains?

J.-F. Mangin, Neurospin, CEA

3D Chip design



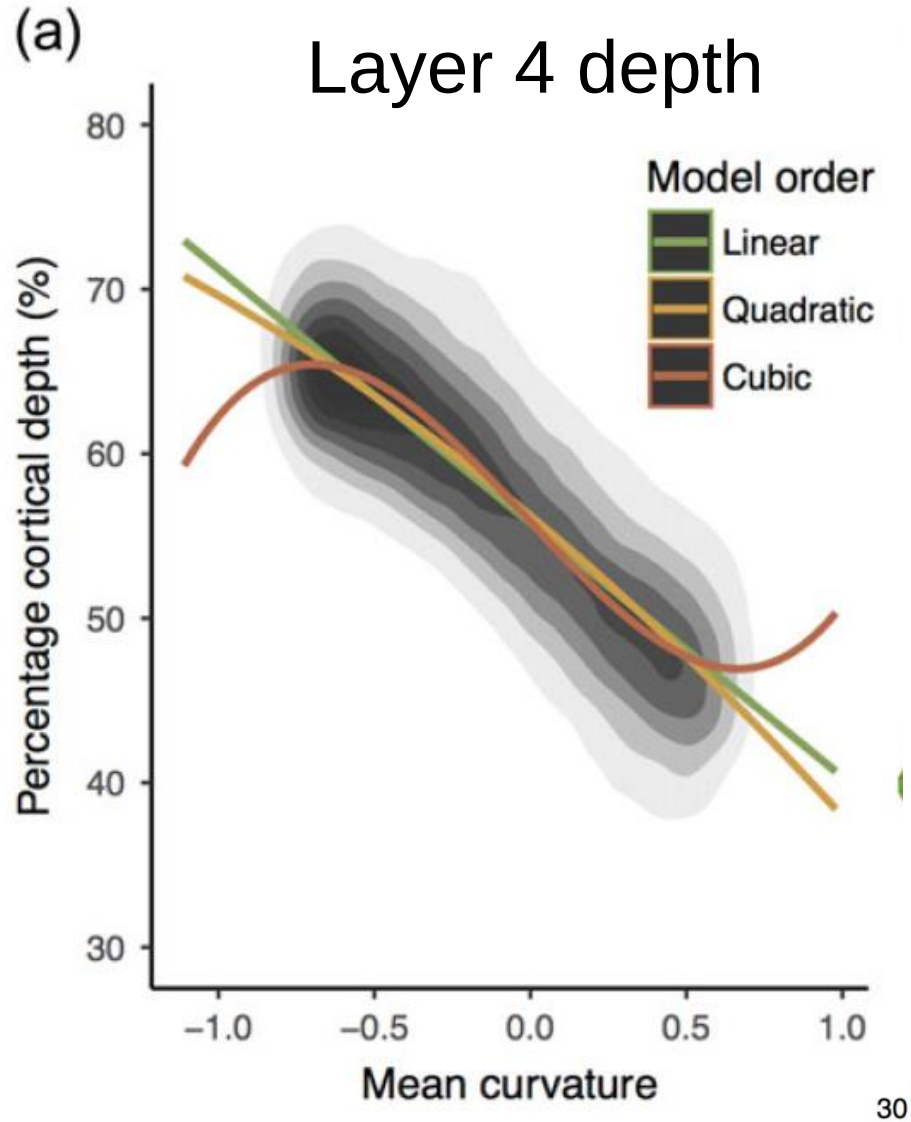


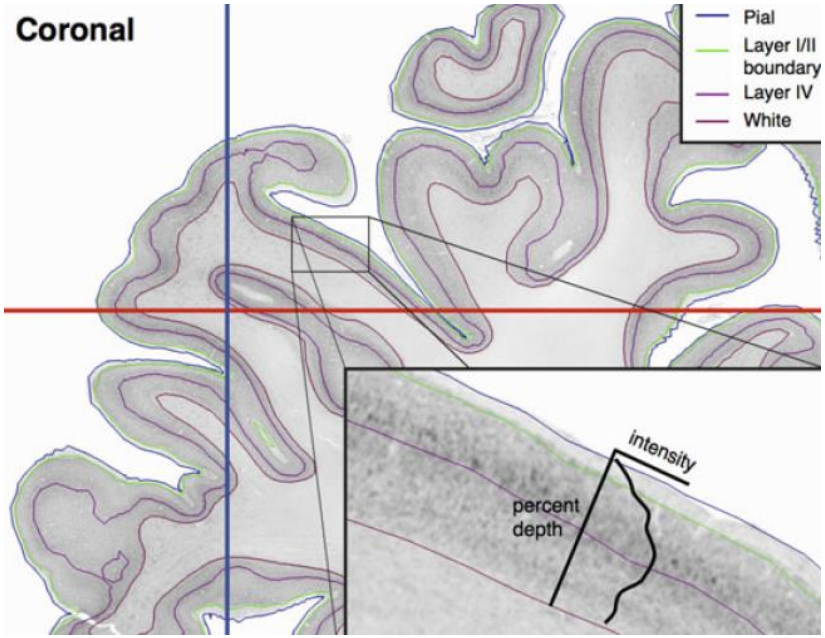
Nature solution

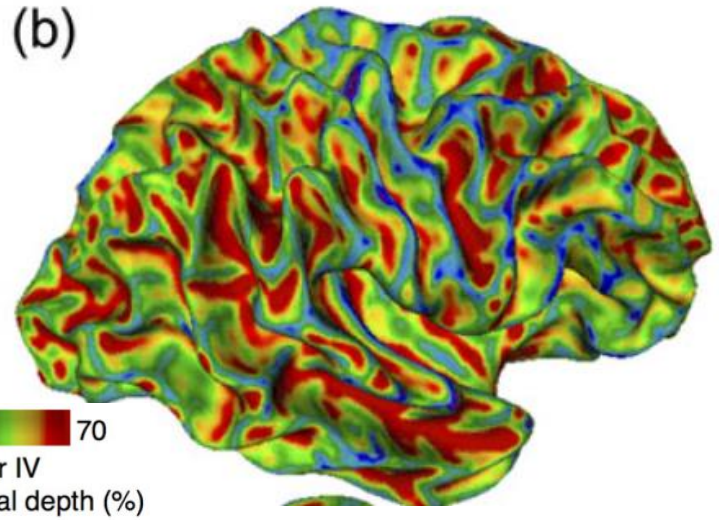
Most folding patterns are meaningless

Nature had to stick more cortical surface into our skulls! So what?

Laminar structure depends on cortex curvature

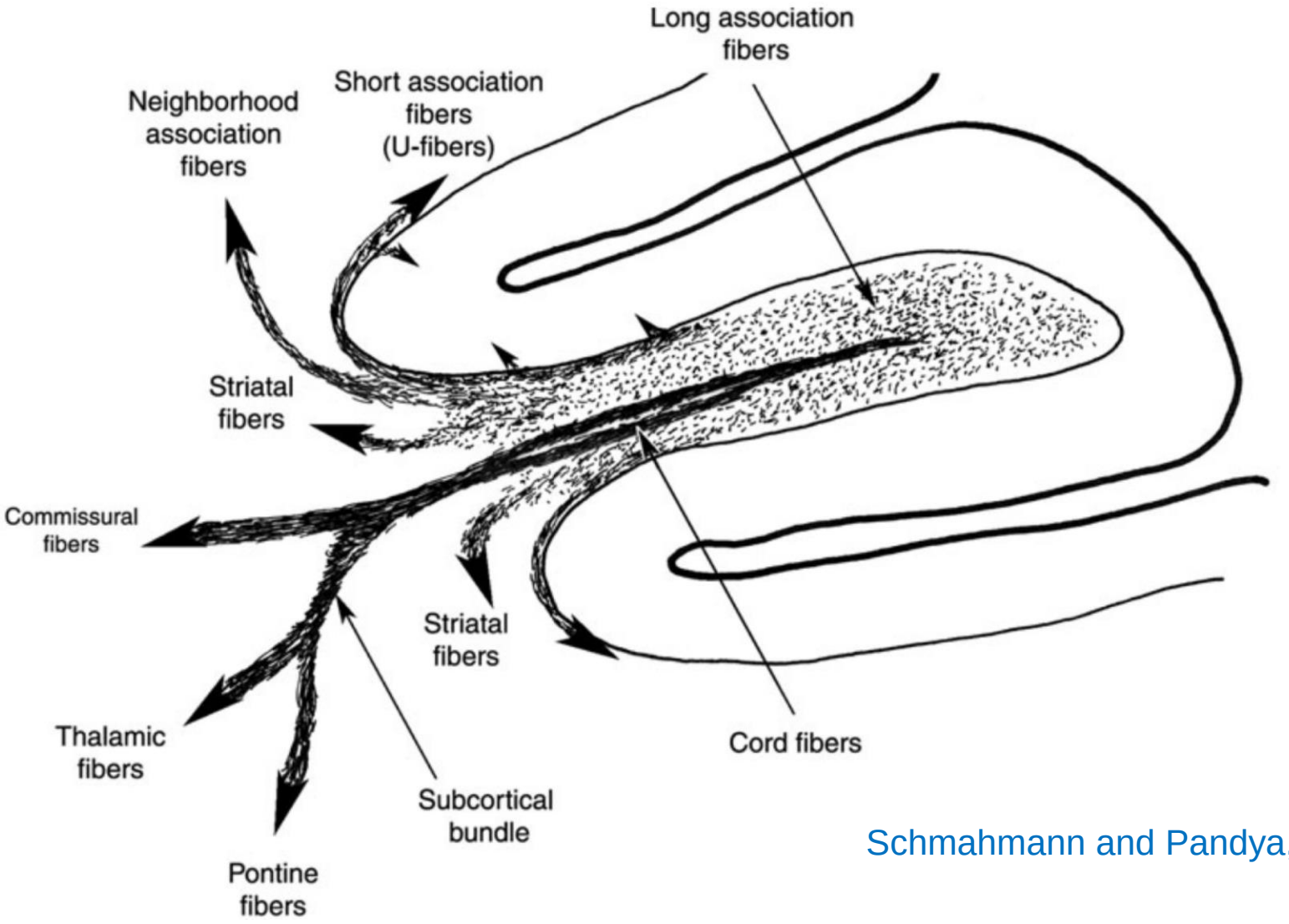






Wagstyl et al., Cereb. Cortex, 2018

Is there some organization in gyral blades?



Schmahmann and Pandya, 2006

Folding patterns = invariants after birth?

Cachia et al., Dev. Cog. Neurosci., 2016

Folding…

3 months

Aging

Alzheimer disease

Adolescence

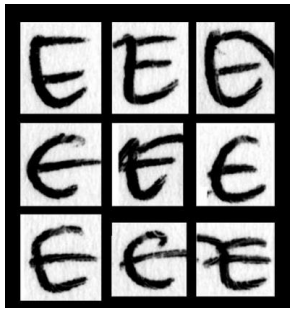
In utero

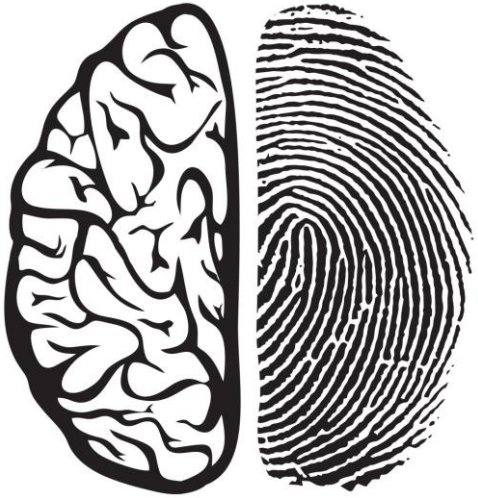
Accelerated unfolding

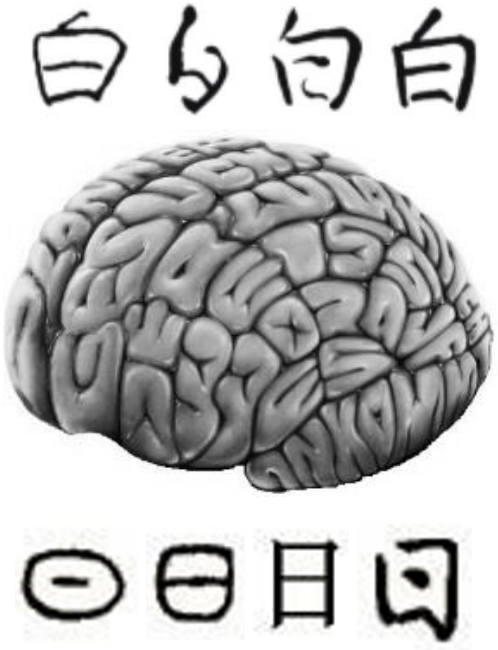
Unfolding

Mangin et al.,
Current Opinion Neurology, 2010

Are folding patterns a proxy of architectural variability?







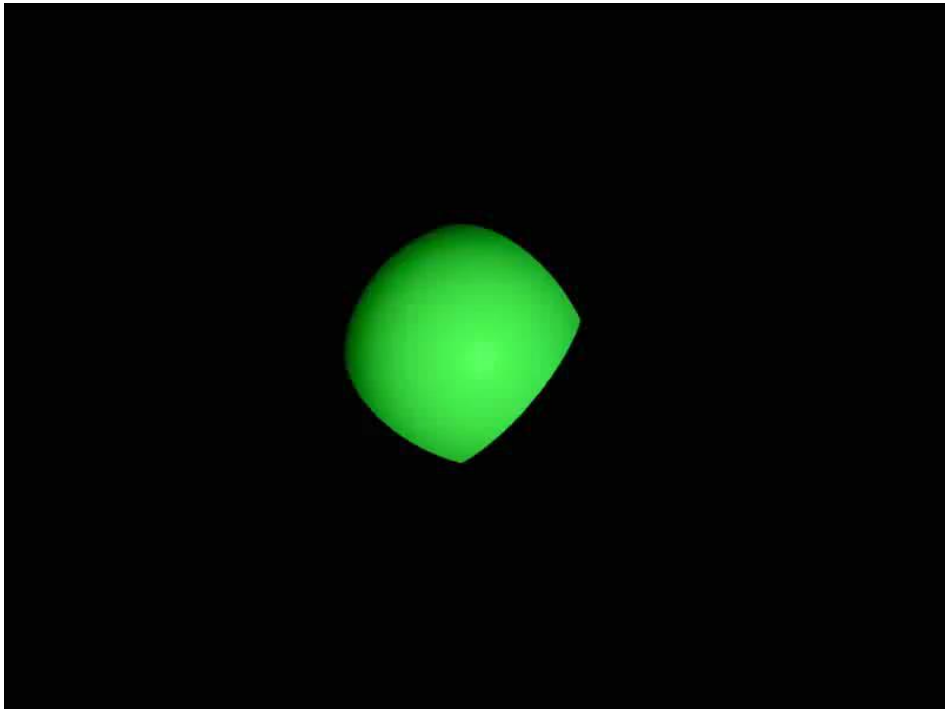
A finger print

Billions of brains

A hidden language?

Folding processes

1D (protein)



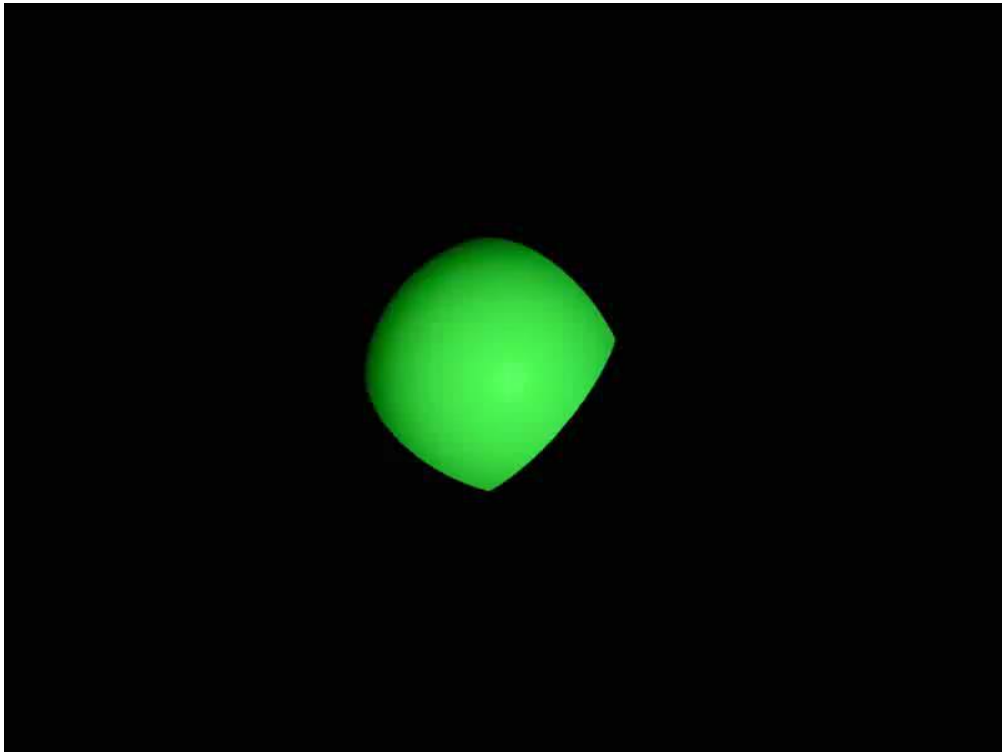
2D (cortex)
this is not a brain…

Tallinen et al., PNAS, 2014

Physicists may have found the rules of cortical tectonics

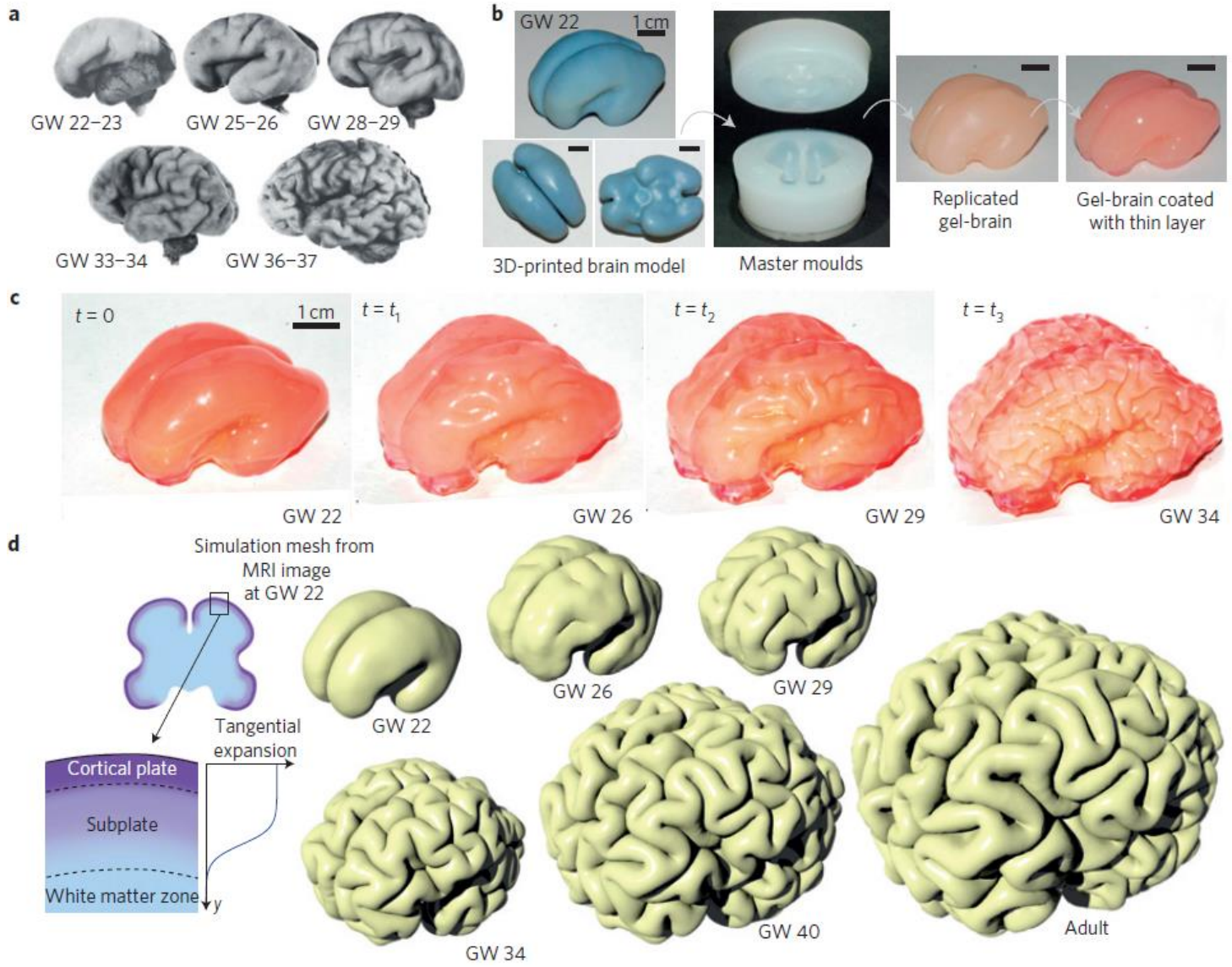
This is not a brain

Tallinen et al., PNAS, 2014



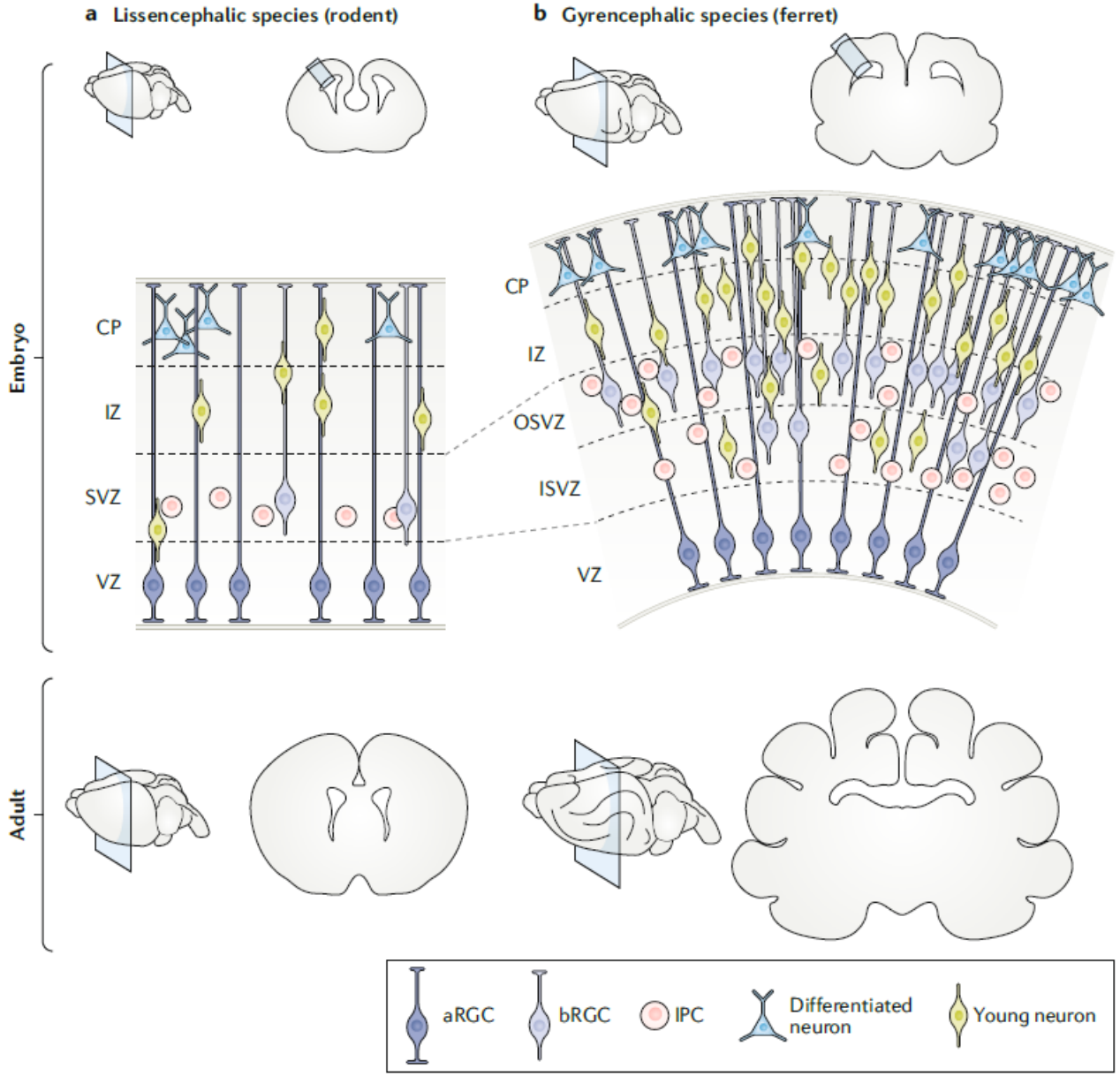
Tangential expansion
of the gray matter
constrained by the white matter

Getting closer and closer



Tallinen et al., Nature Physics, 2016

To be folded or not folded



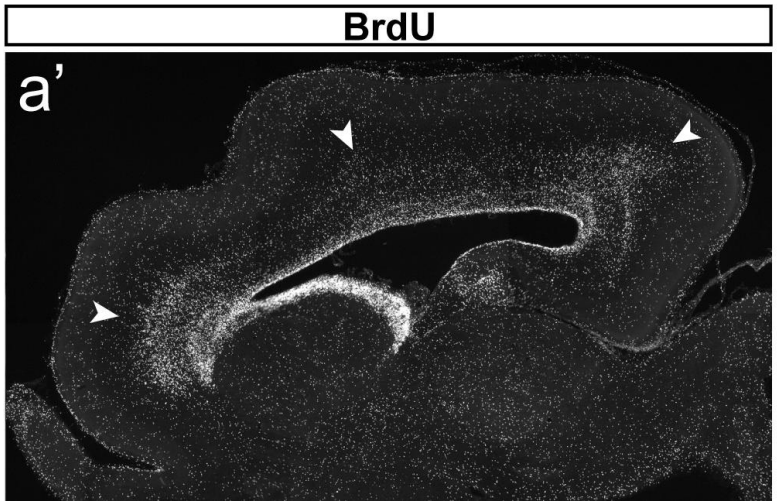
Divergence of the radial fiber scaffold

Llinares et al., 2019

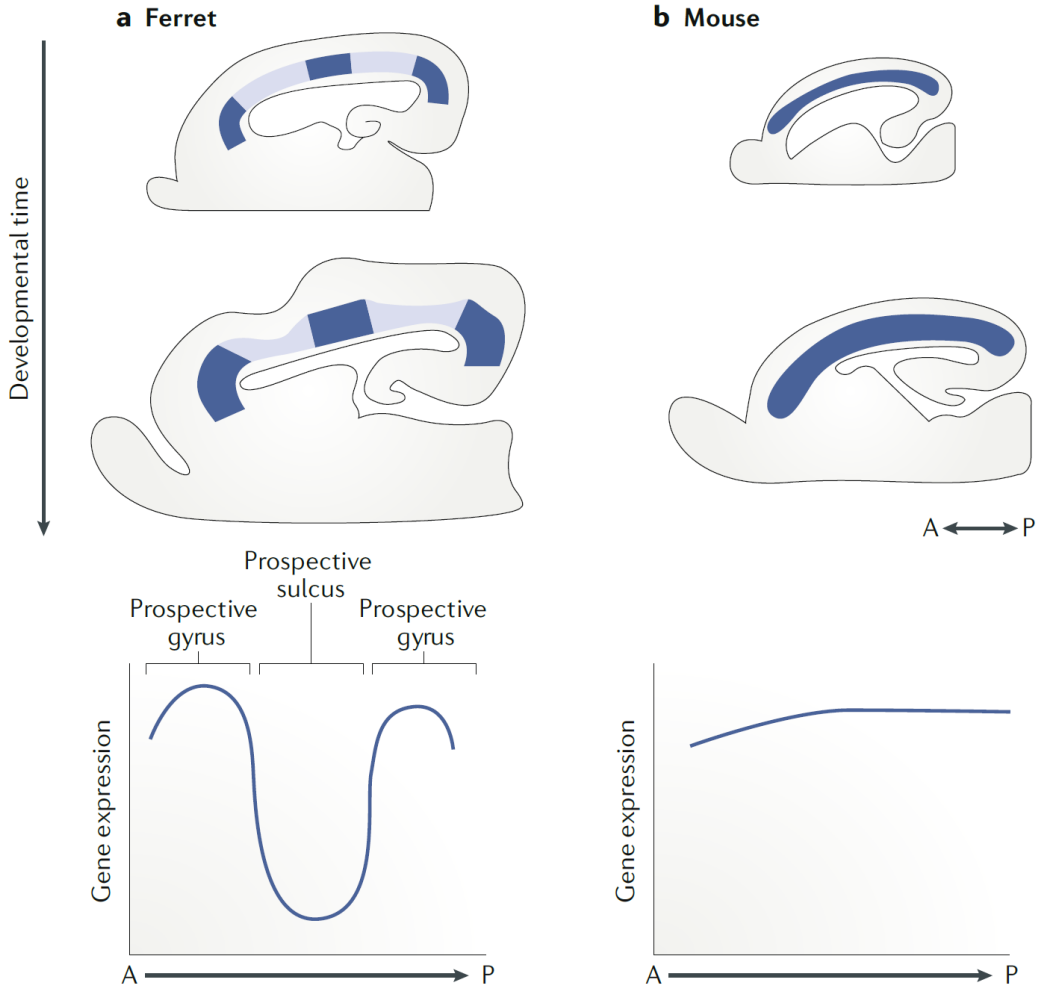
A protomap during neurogenesis?

Ferret.

Accumulation of progenitors at the level of protogyri

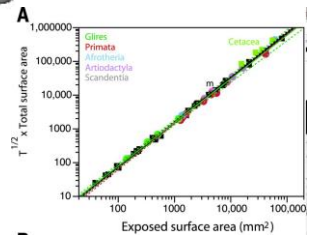


Reillo I, **Borrell V** , 2011



Llinares et al., 2019

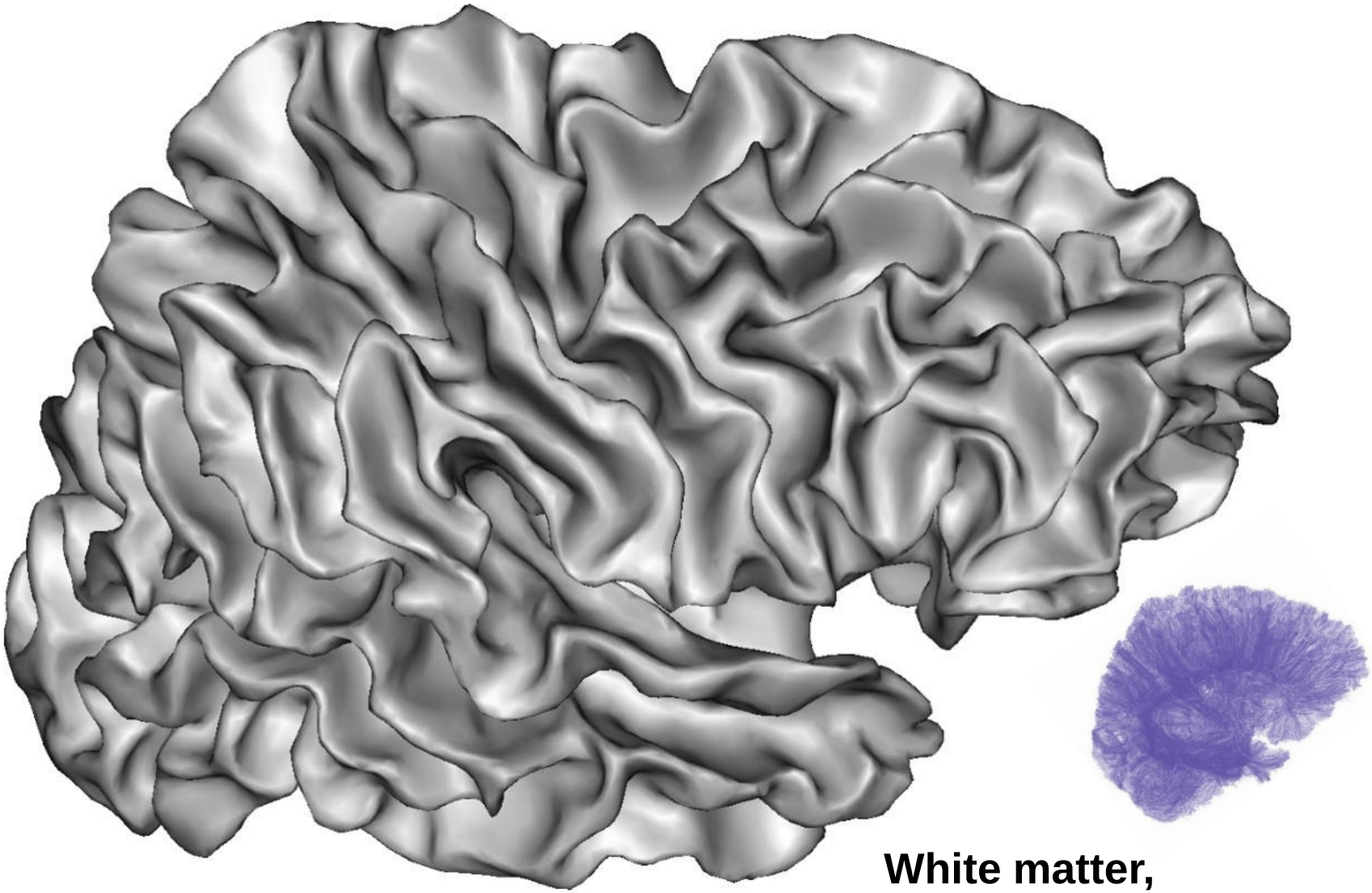
My own brain…



A folding wavelength?

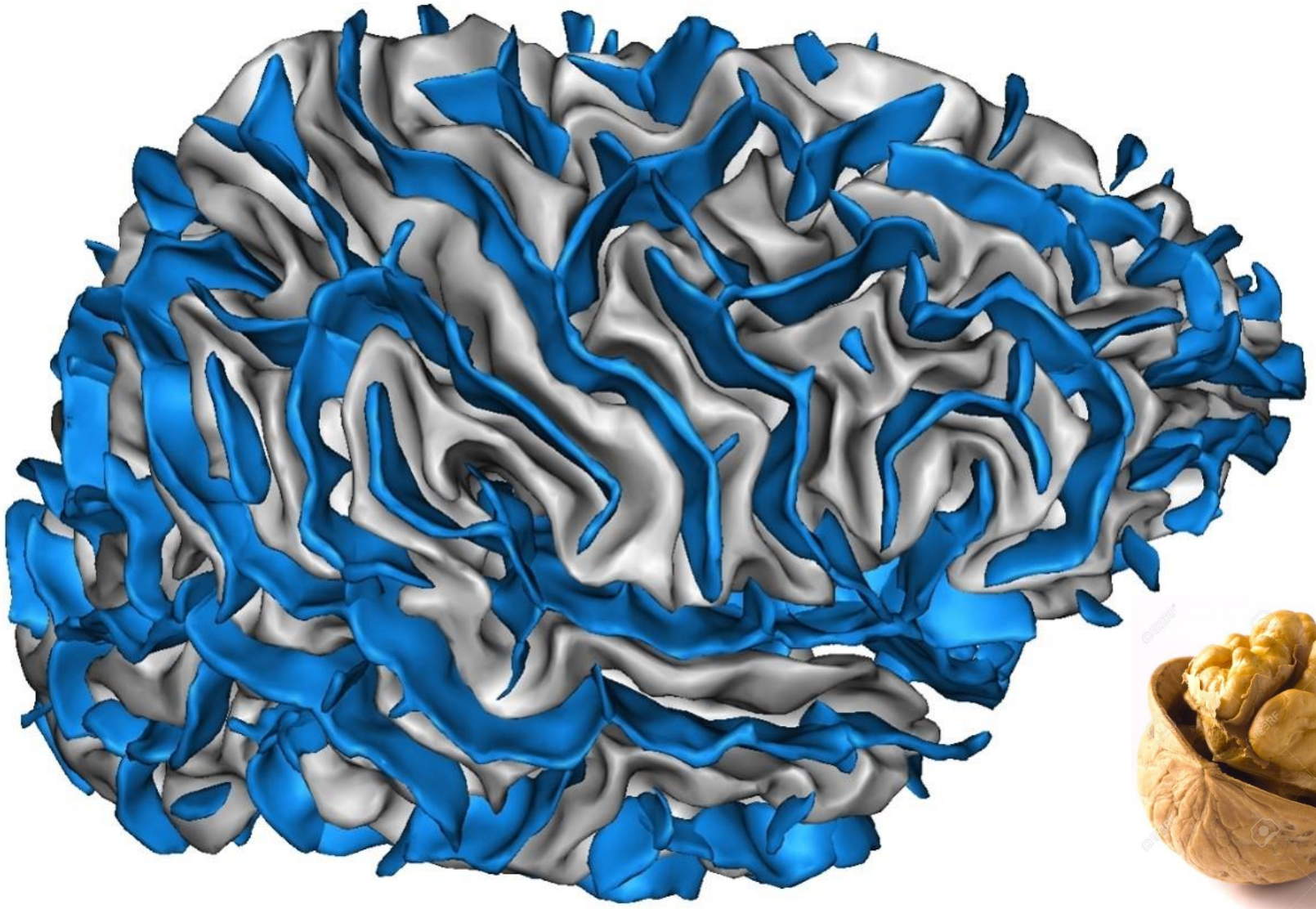
see Mota et al., Science, 2015

Peeling of the cortical mantle



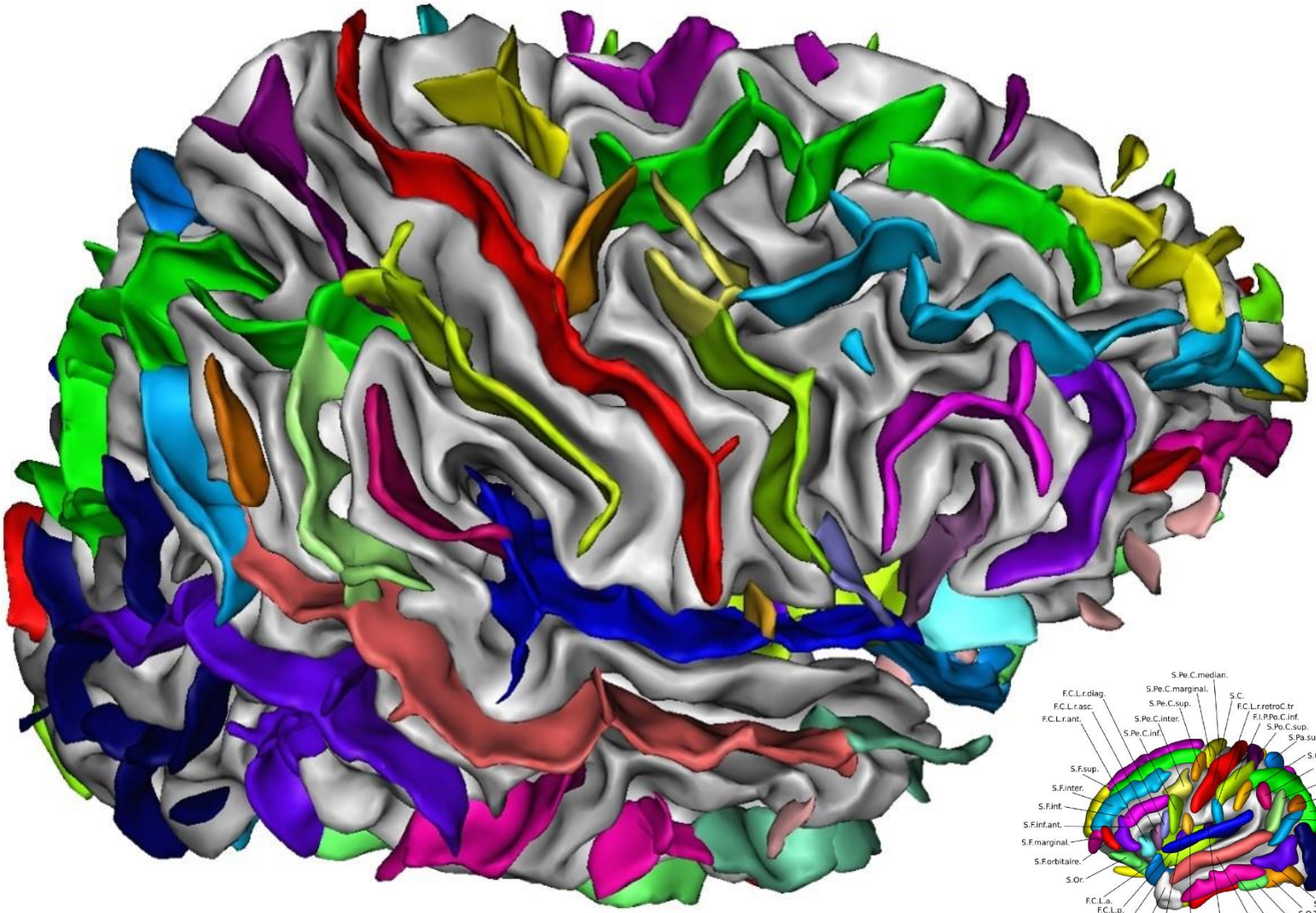
White matter,
the world of long axons

A negative cast



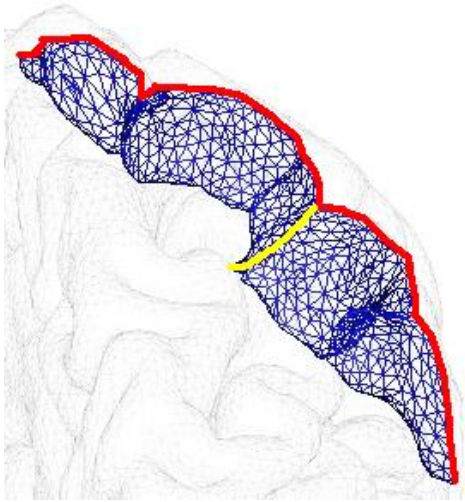
A watershed-based strategy positions this skeleton in the CSF

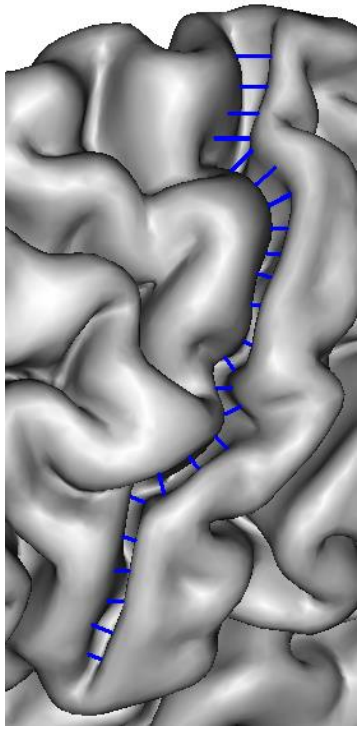
Automatic identification of sulci

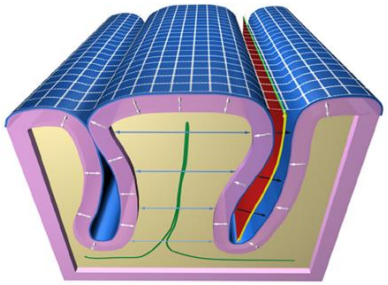


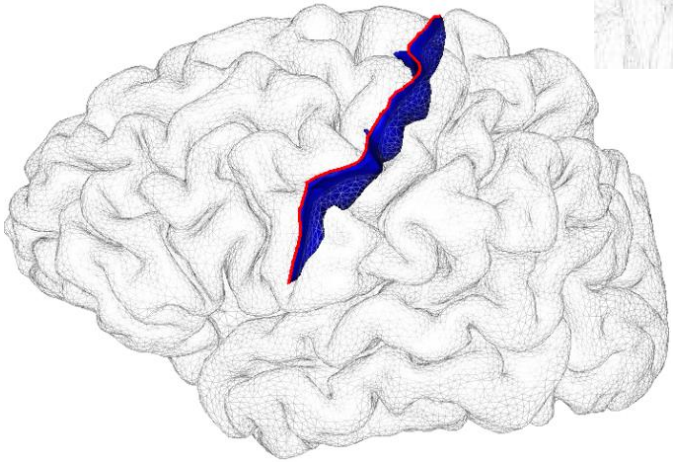
50000 processed brains

Sulcus geometry



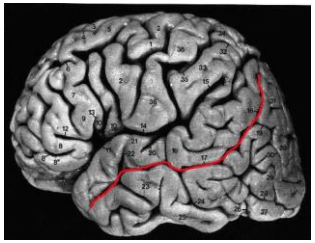




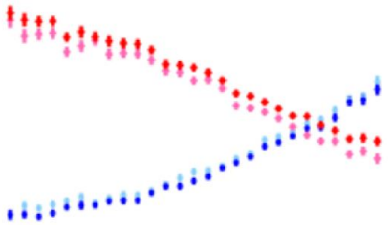


Length, depth, surface area, width…

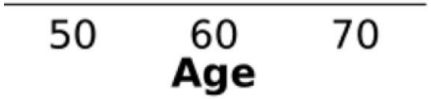
Sulcus width increases during aging



STS thickness

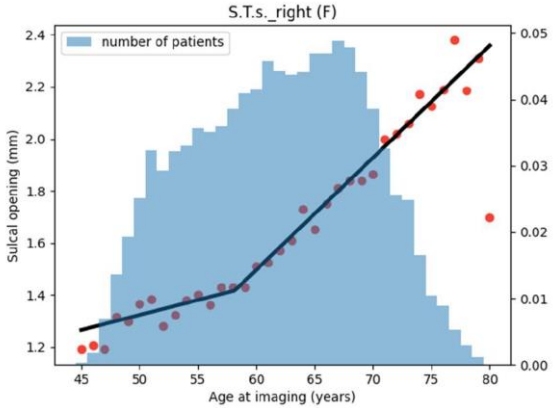


STS width

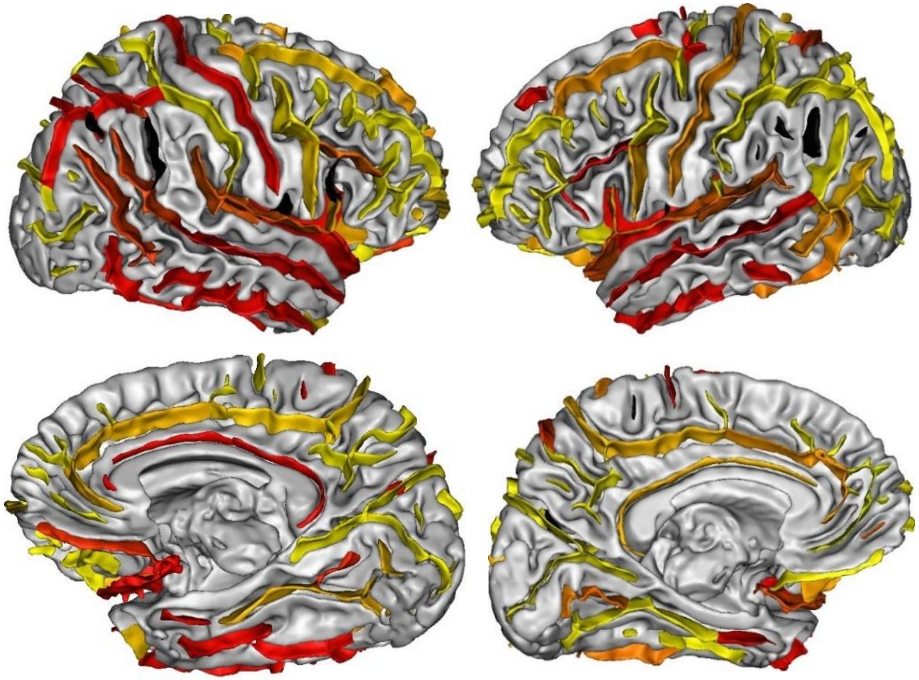


Le Guen et al., BASF, 2019

STS width 90th percentile (UKBiobank)

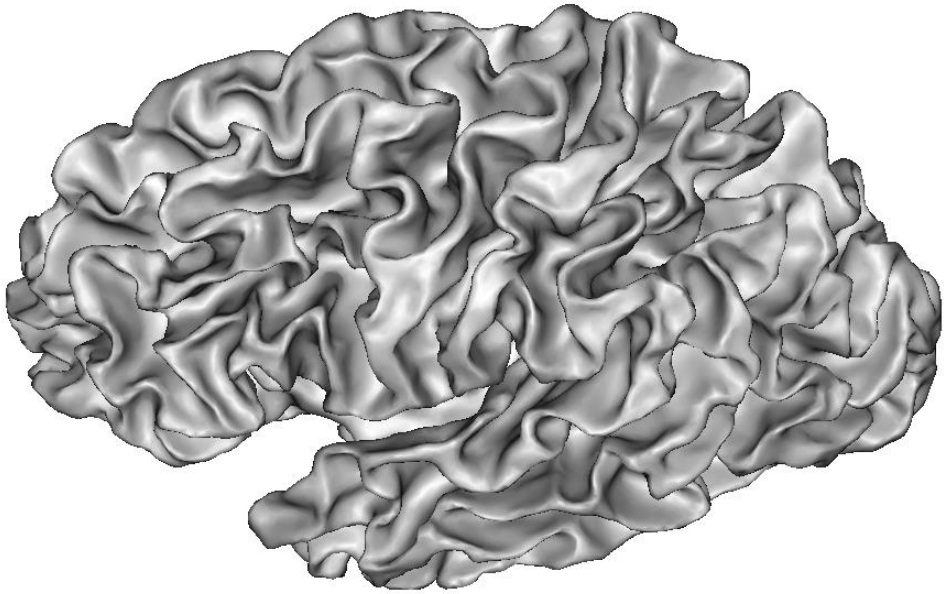


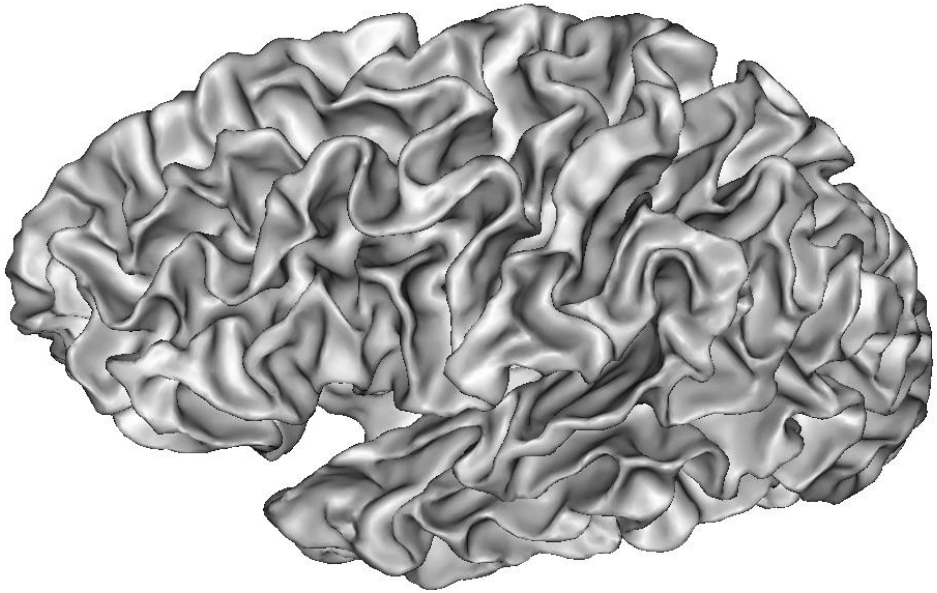
Shu-Quartier-Dit-Maire et al., OHBM, 2022



Bouteloup et al., AAIC,
Prediction of incident dementia in outpatients attending French memory clinics
2018

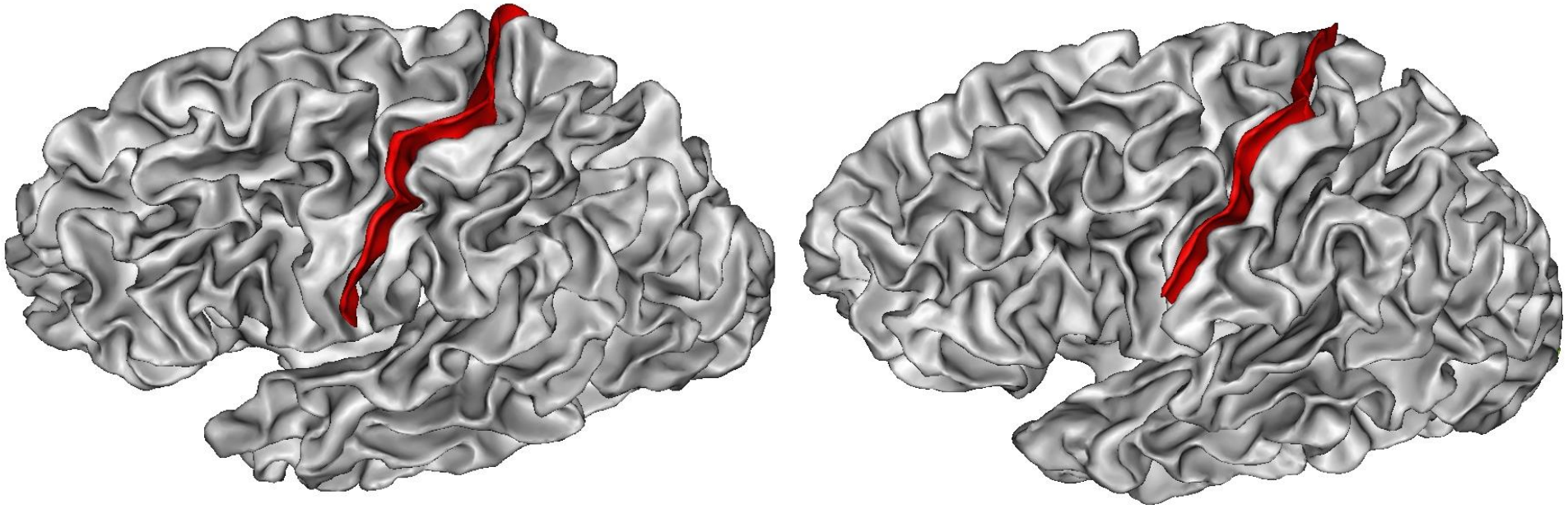
Two different brains…





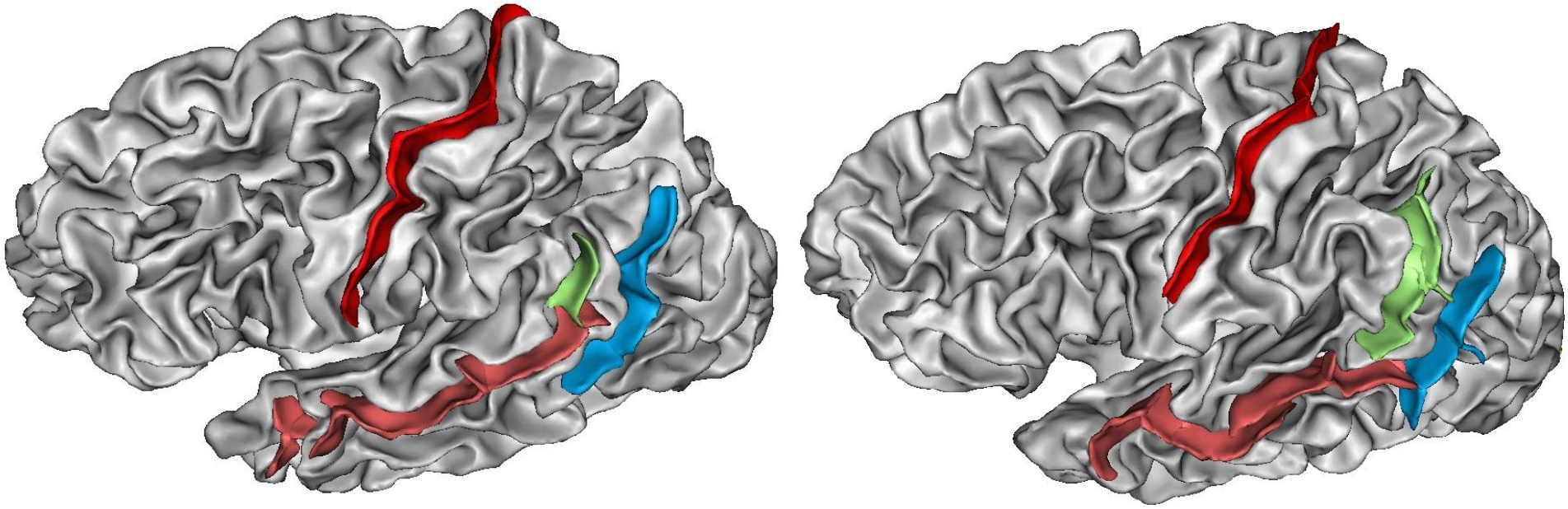
Cortical surface convoluted geometry

Two different brains…



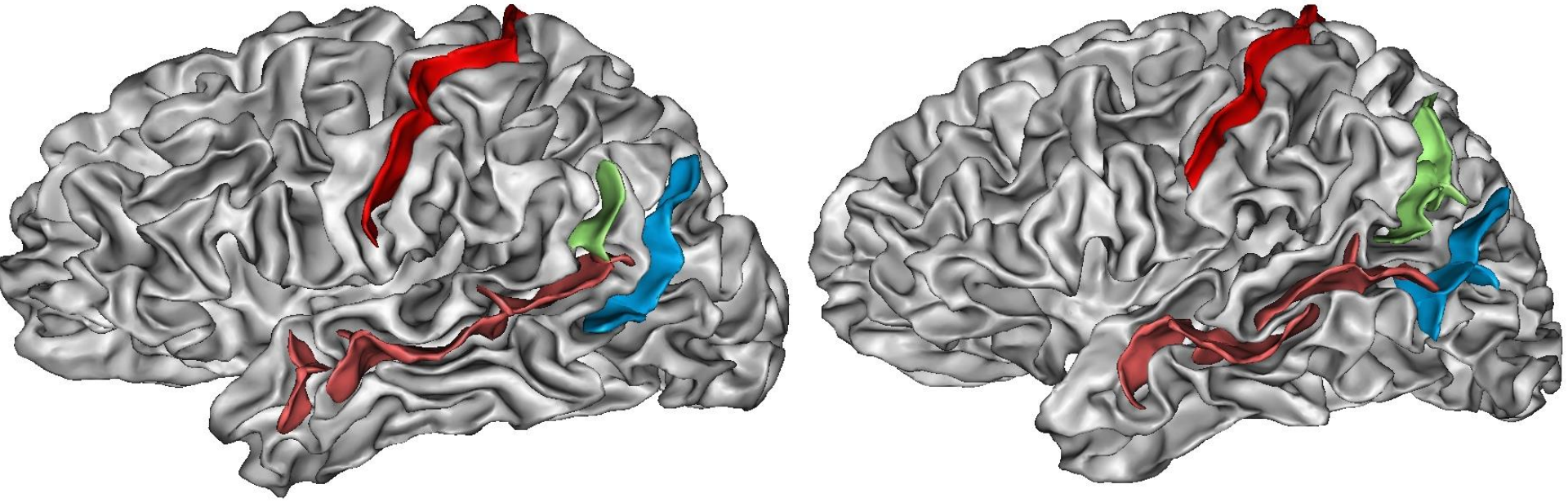
Central sulcus, an island of stability

Two different brains…



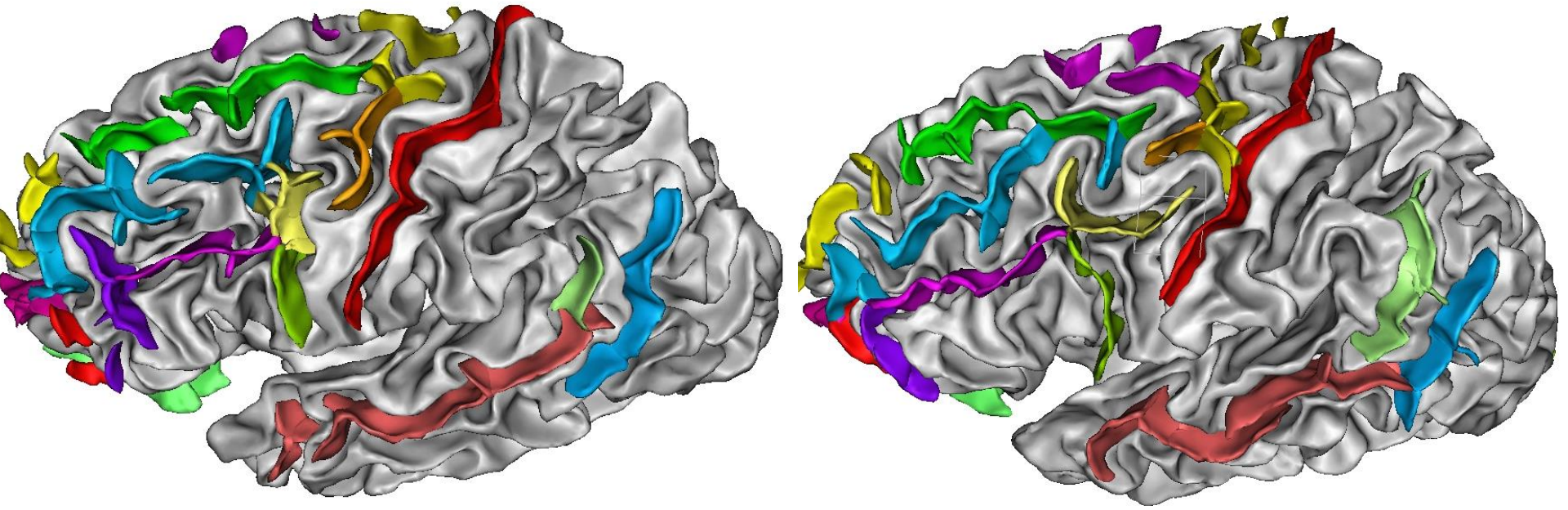
Superior temporal sulcus, more troubles

Two different brains…



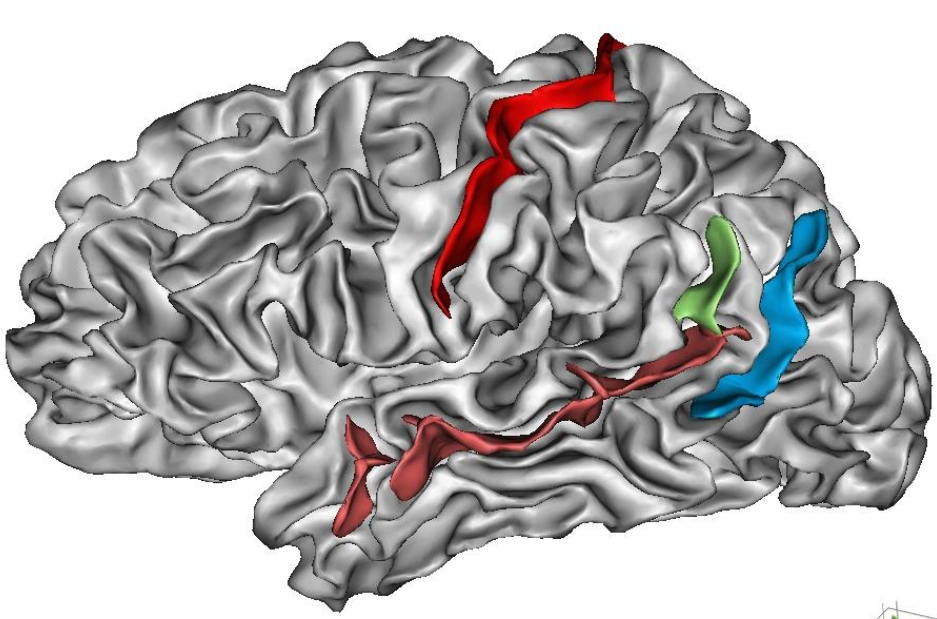
Superior temporal sulcus: a world of interruptions

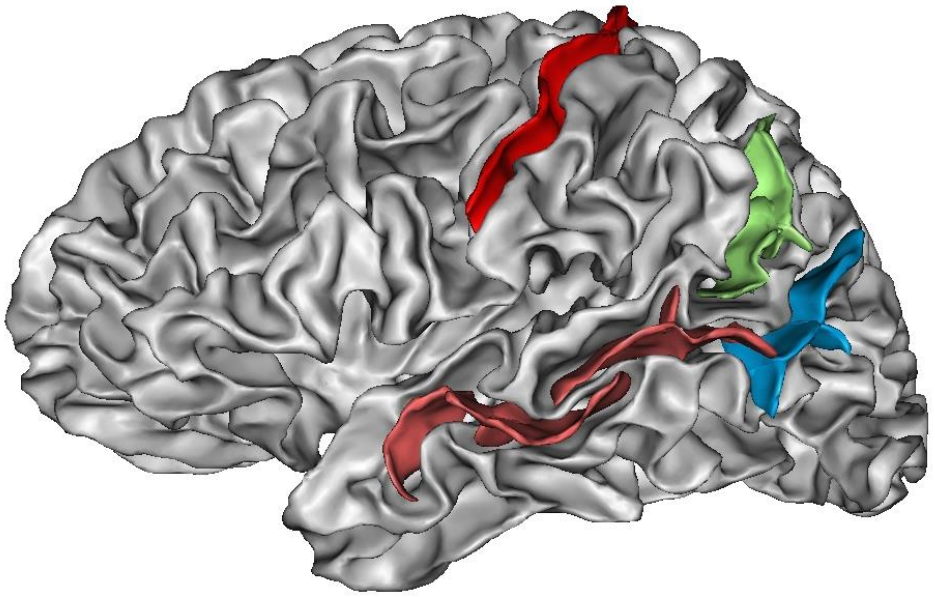
Two different brains…

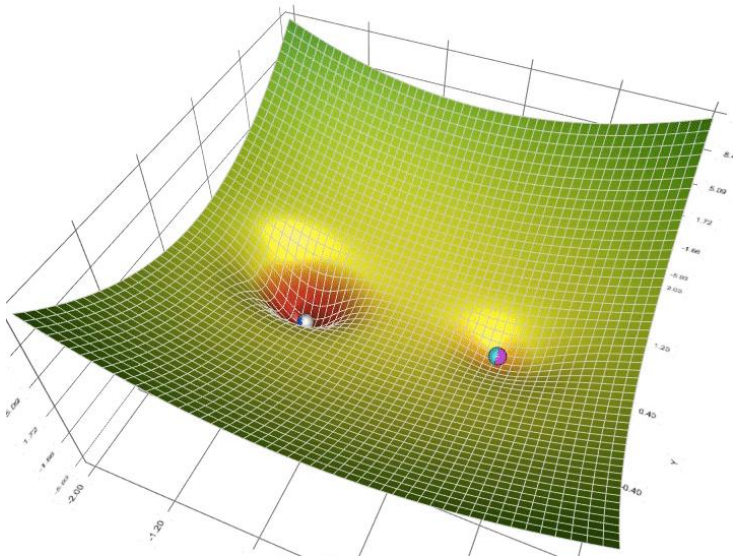


Frontal lobe: almost a nightmare

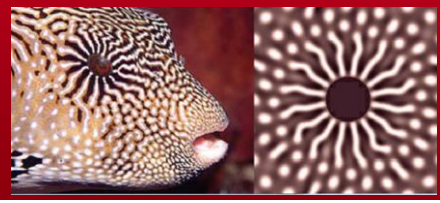
Two different attractors of folding dynamics ?





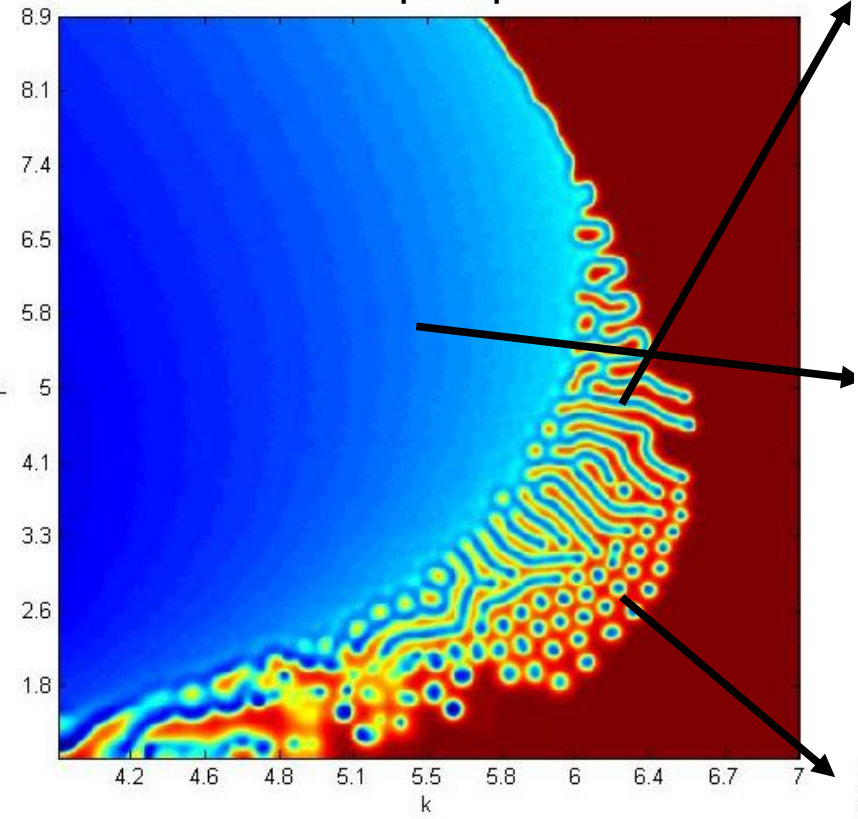


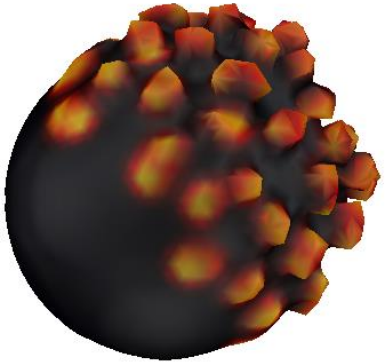
Türing morphogenes…



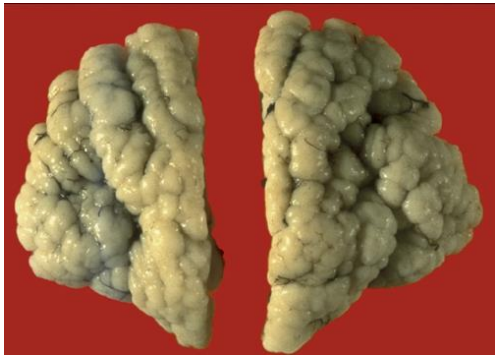
Phase diagram

Global perspective





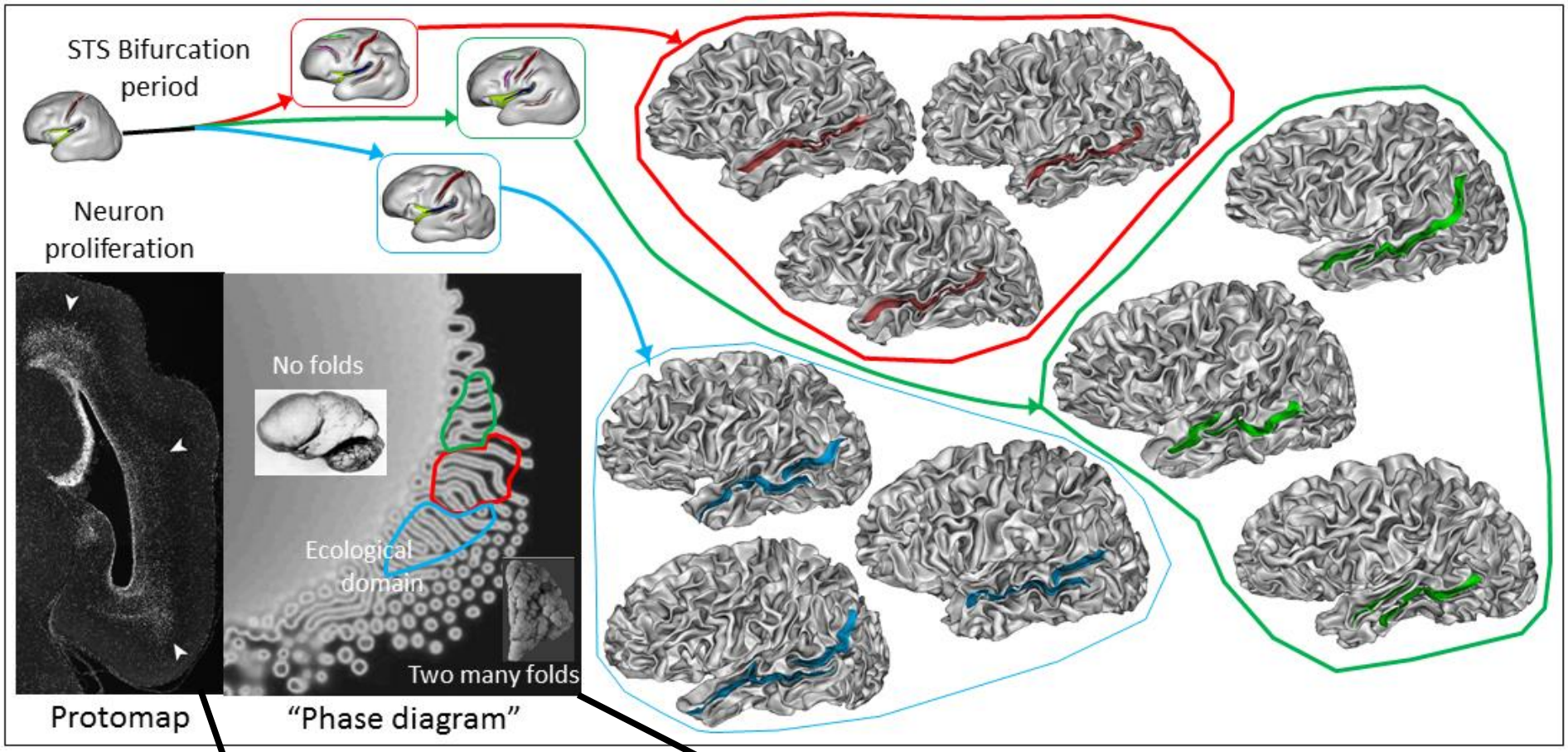
Lissencephalia



Polymicrogyria

Lefèvre and Mangin,
PLOS Comput. Biol, 2010

Folding patterns as attractors of the folding dynamics



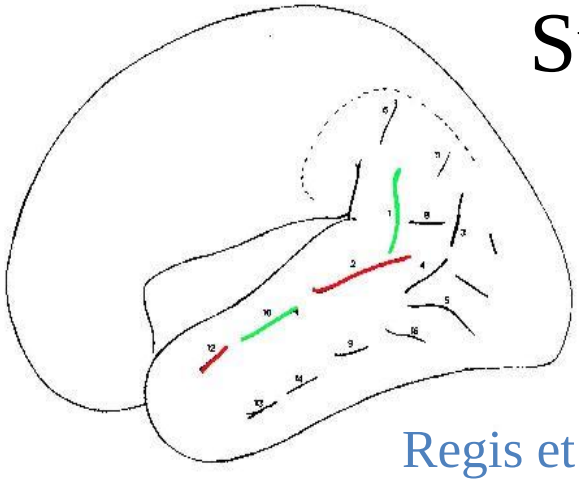
Reillo I, **Borrell V** , 2011 (Ferrets)

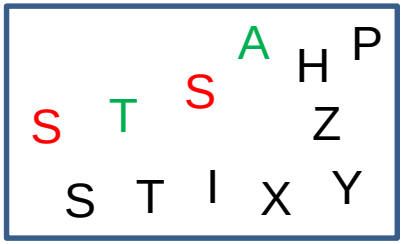
Phase diagram (regional perspective)

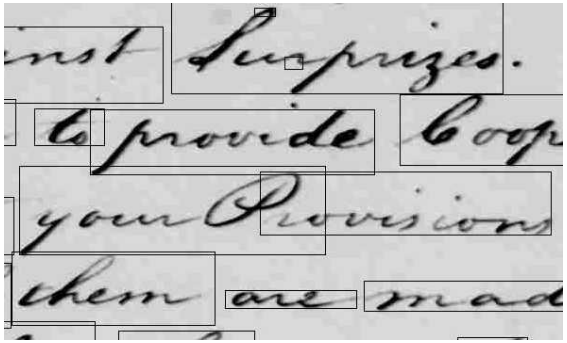
Lefèvre 2010

An alphabet behind the folding patterns ?

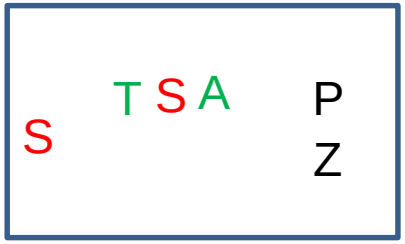
Sulcal roots : atomic units / Letters?

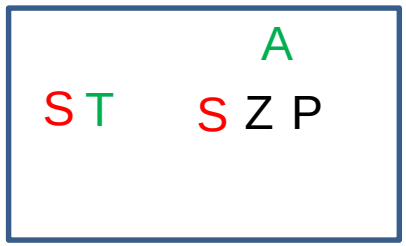


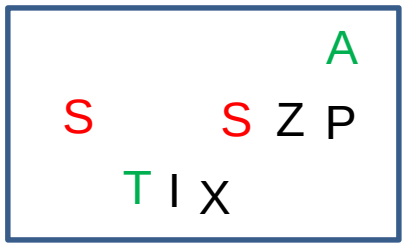


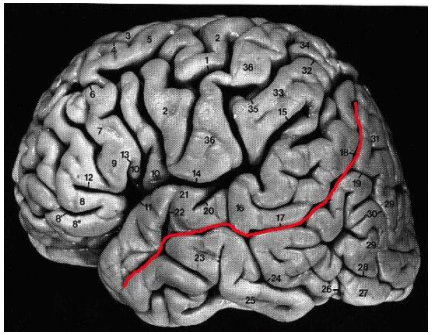


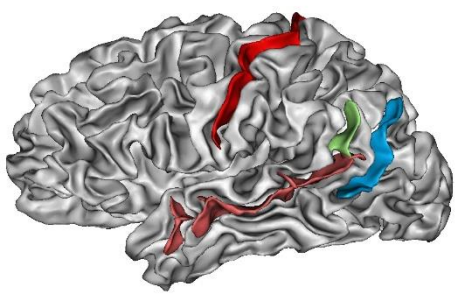
Regis et al., 1994, 2005

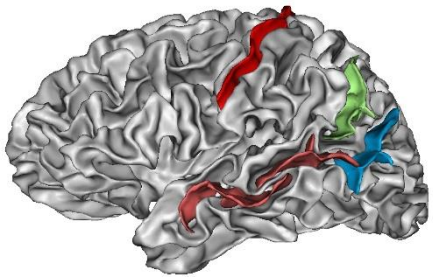


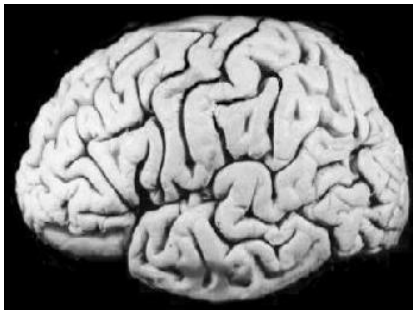






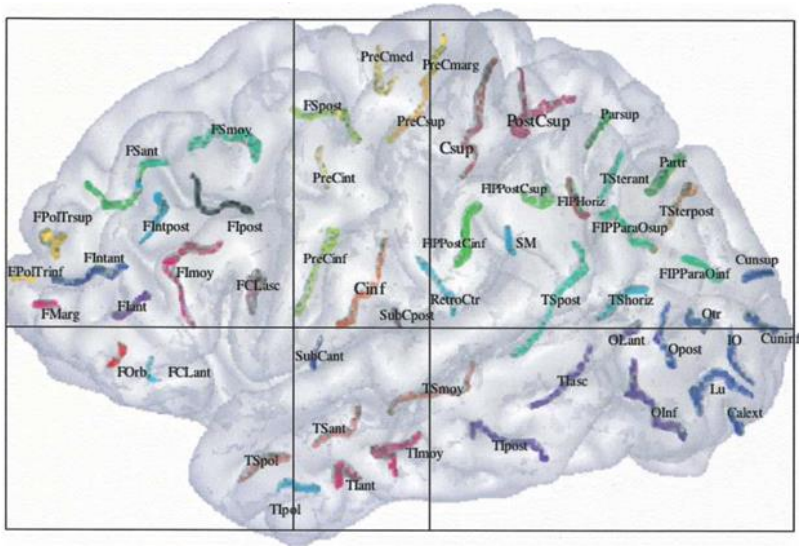




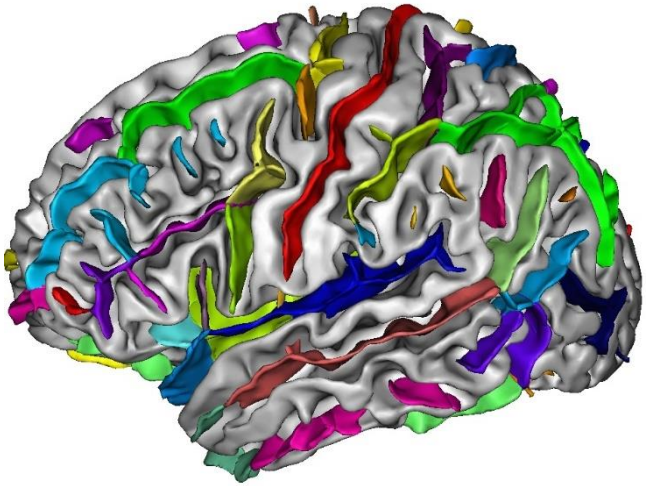


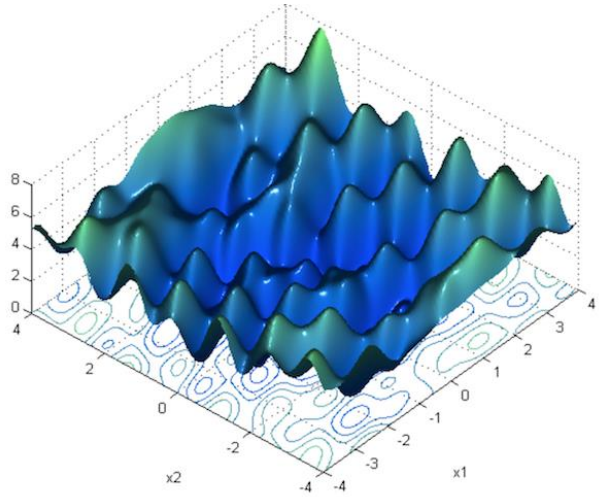
A combinatorial explosion with a probability distribution

Sulcal roots map

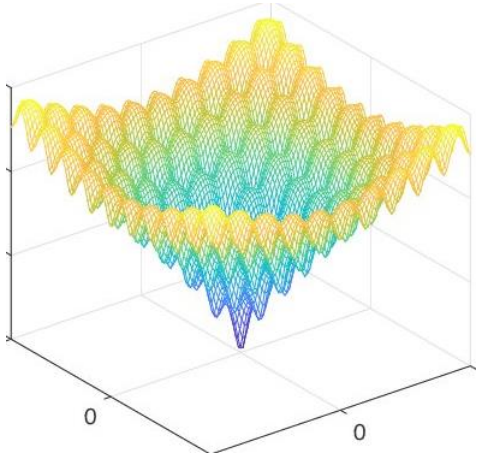


Sulci of icbm average (152 brains)





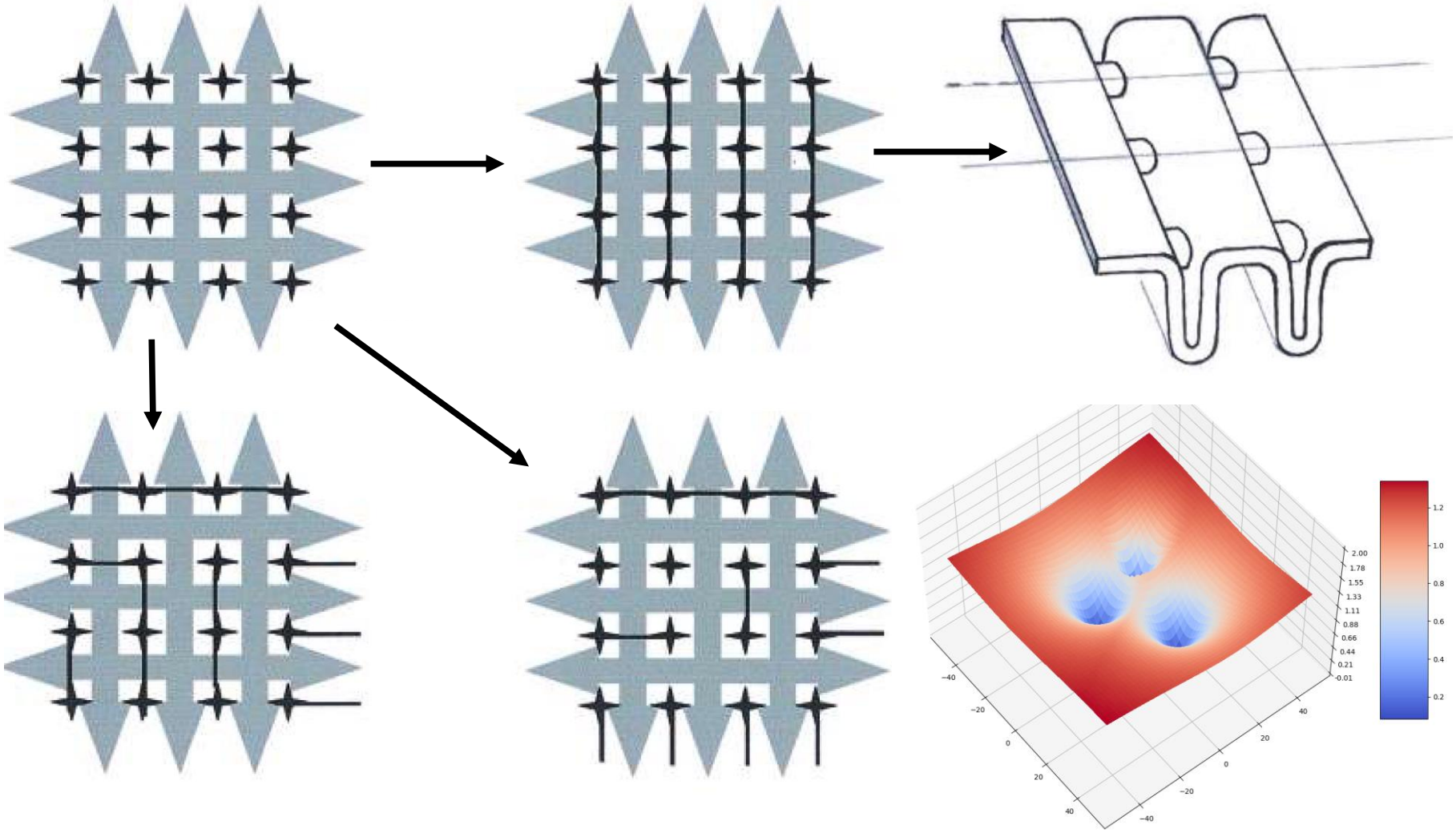
A funnel-like distribution?



Régis et al., 2005

Deep or superficial « plis de passage »

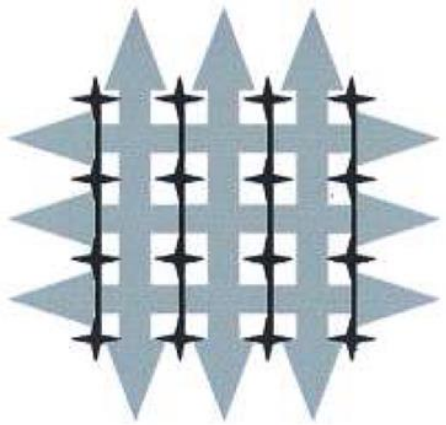
The meridian/parallel model & 3 frequent instances

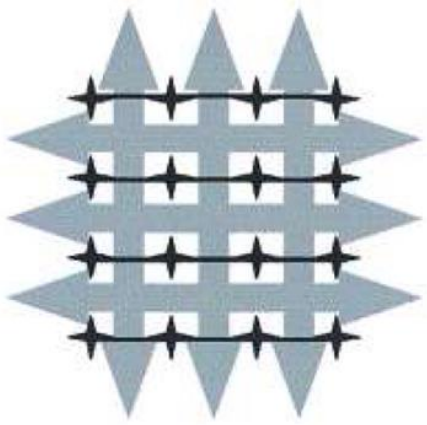


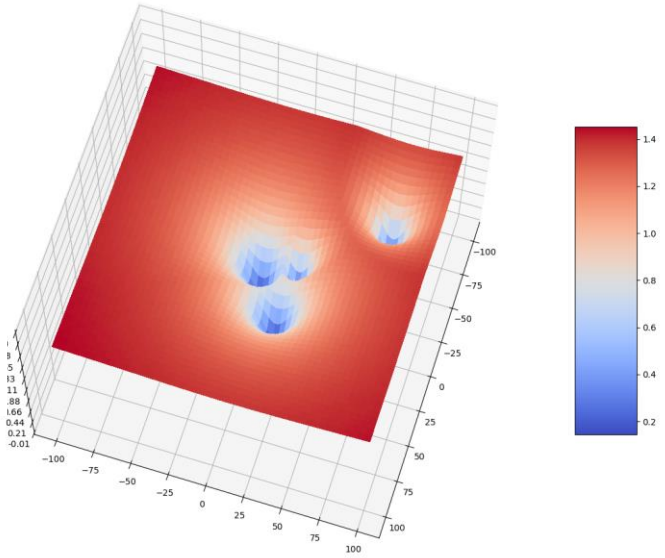
Régis et al., 2005

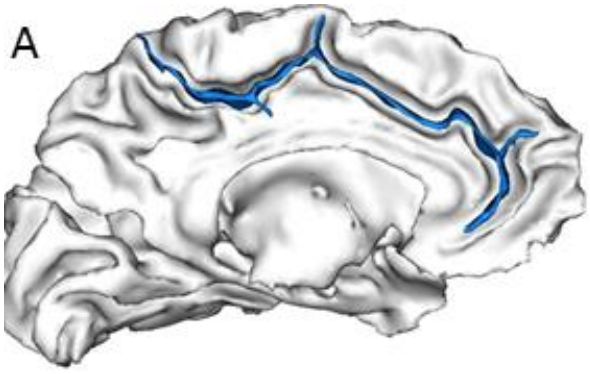
Rare patterns may reveal abnormal development

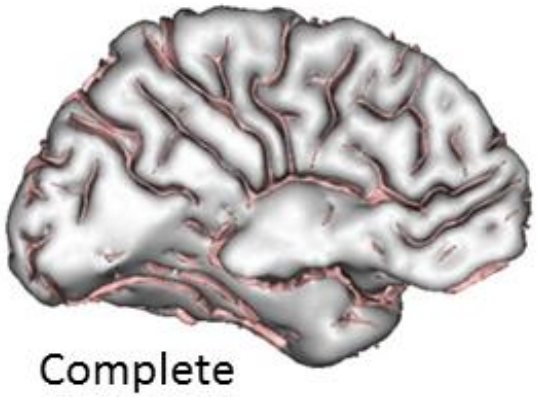
A rare instance (meridian versus parallel organization)









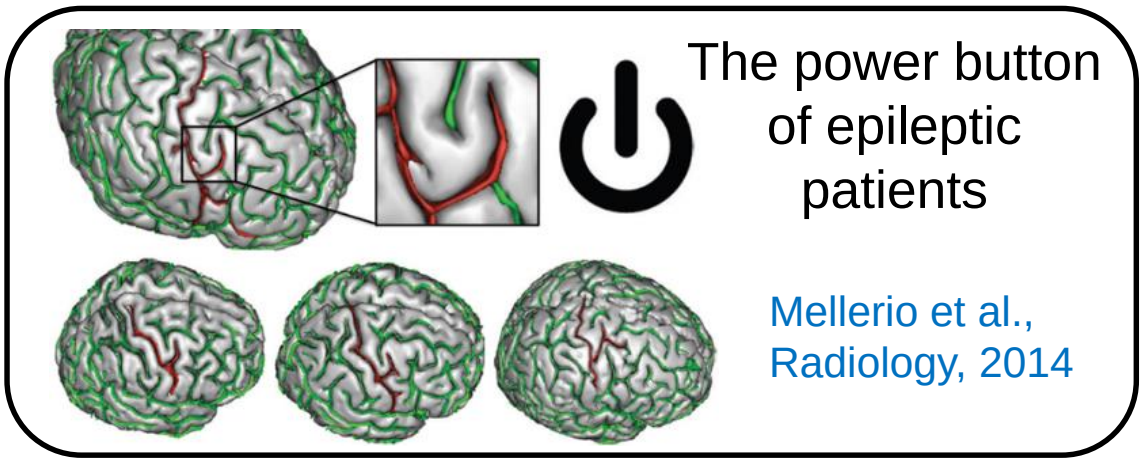


Cingulate sulcus

Corpus callosum agenesis

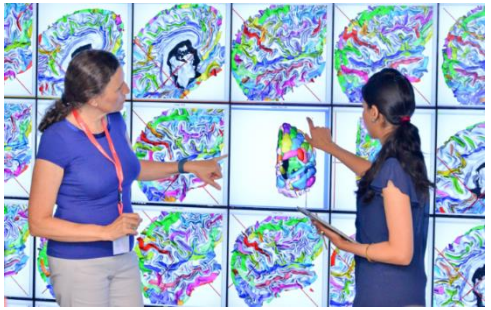
Towards a dictionary of the folding patterns

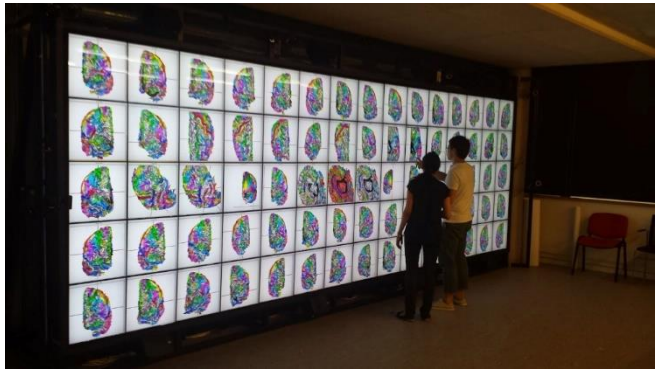
Lost in folding patterns

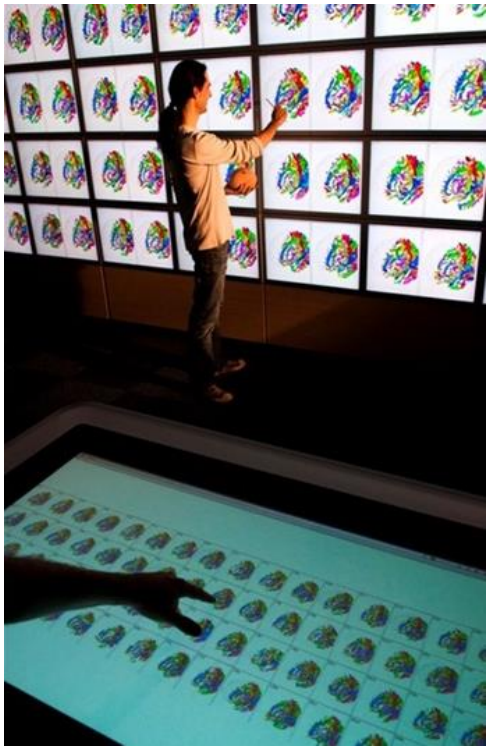


The power button of epileptic patients

Mellerio et al., Radiology, 2014

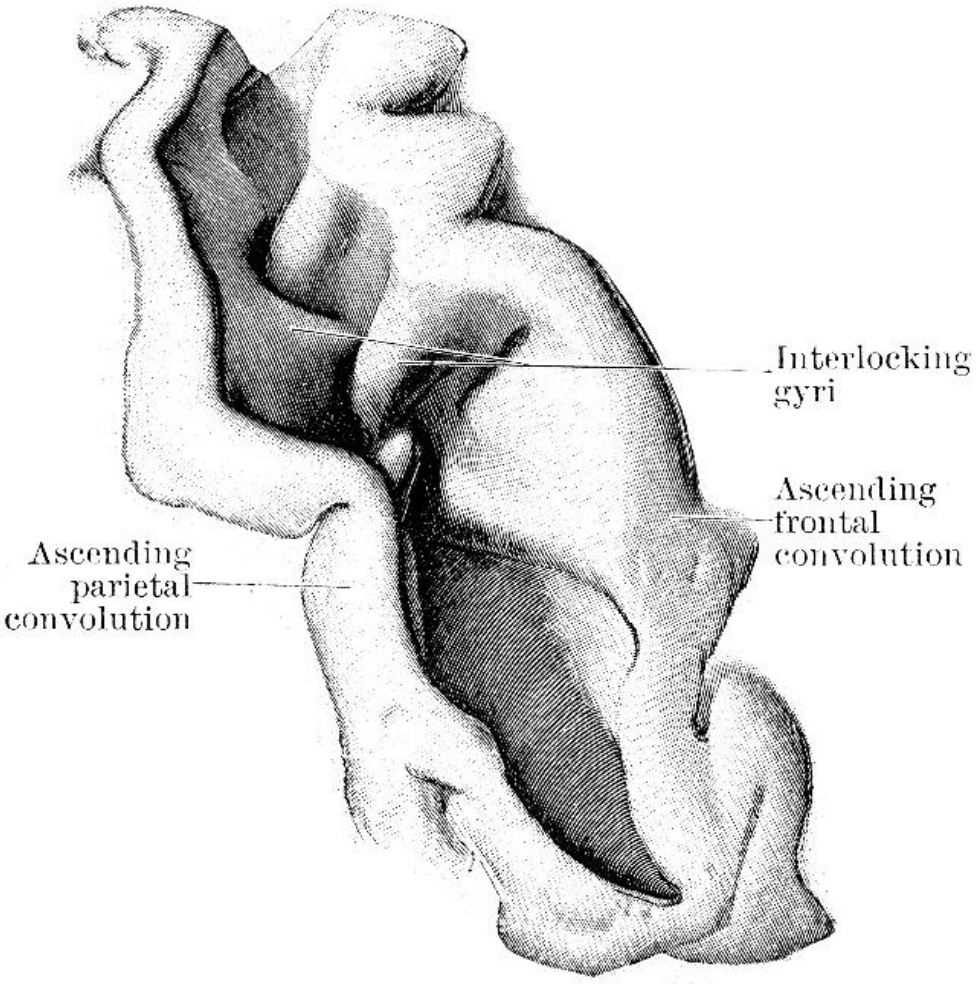




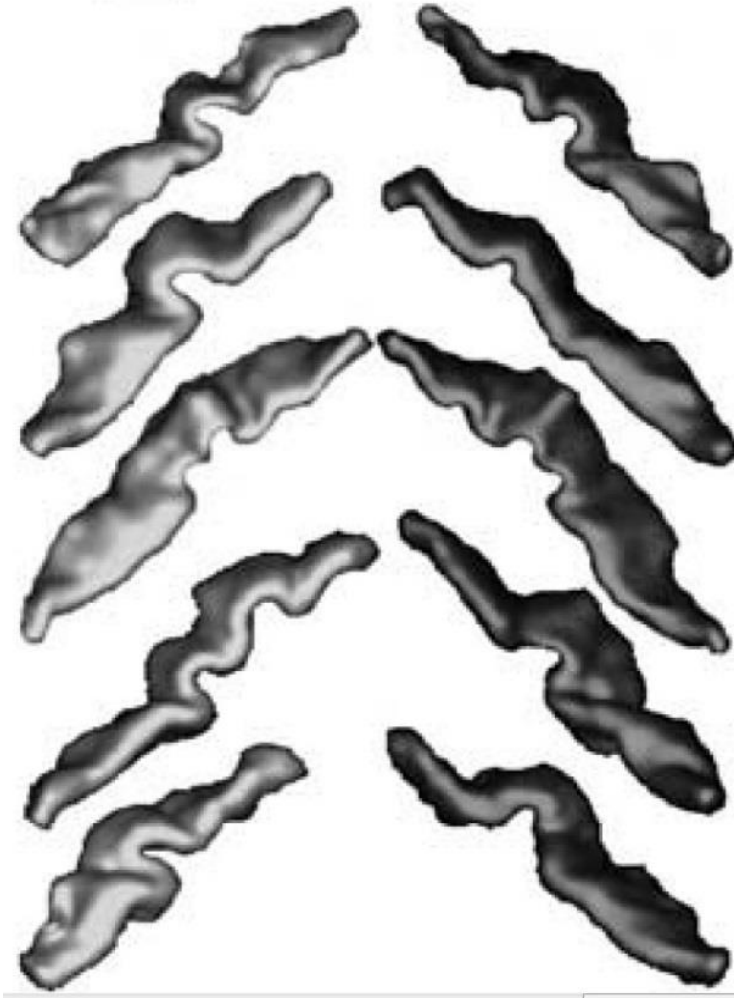


Equipex Digiscope:
Plateformes Wild & Wilder,
LRI, université Paris 11 / Mandelbrot,
Maison de la simulation, Saclay

The good old central sulcus

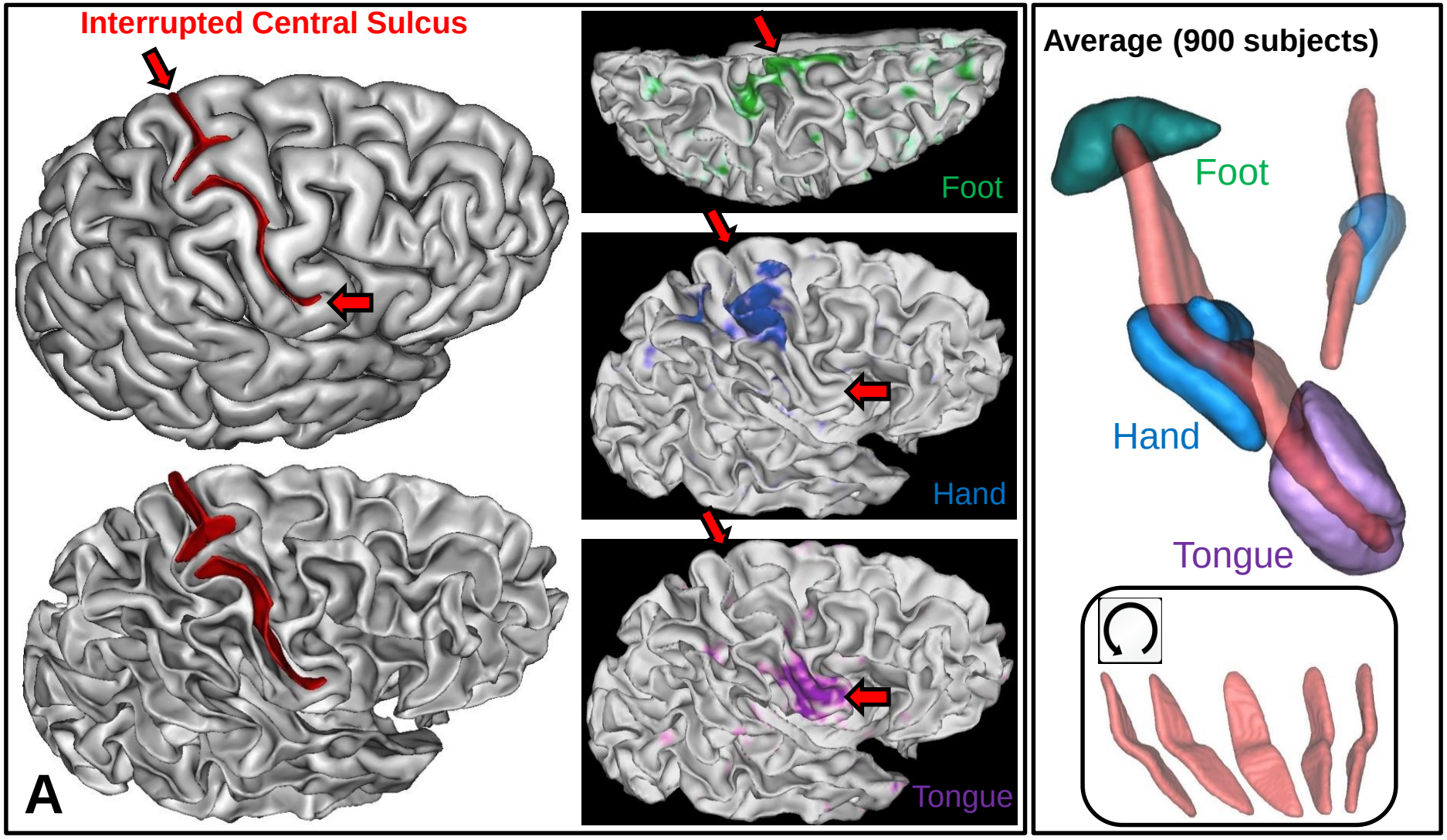


Central sulcus, Cunnigham, 1890



Central sulci from under (Mangin et al., 2004)

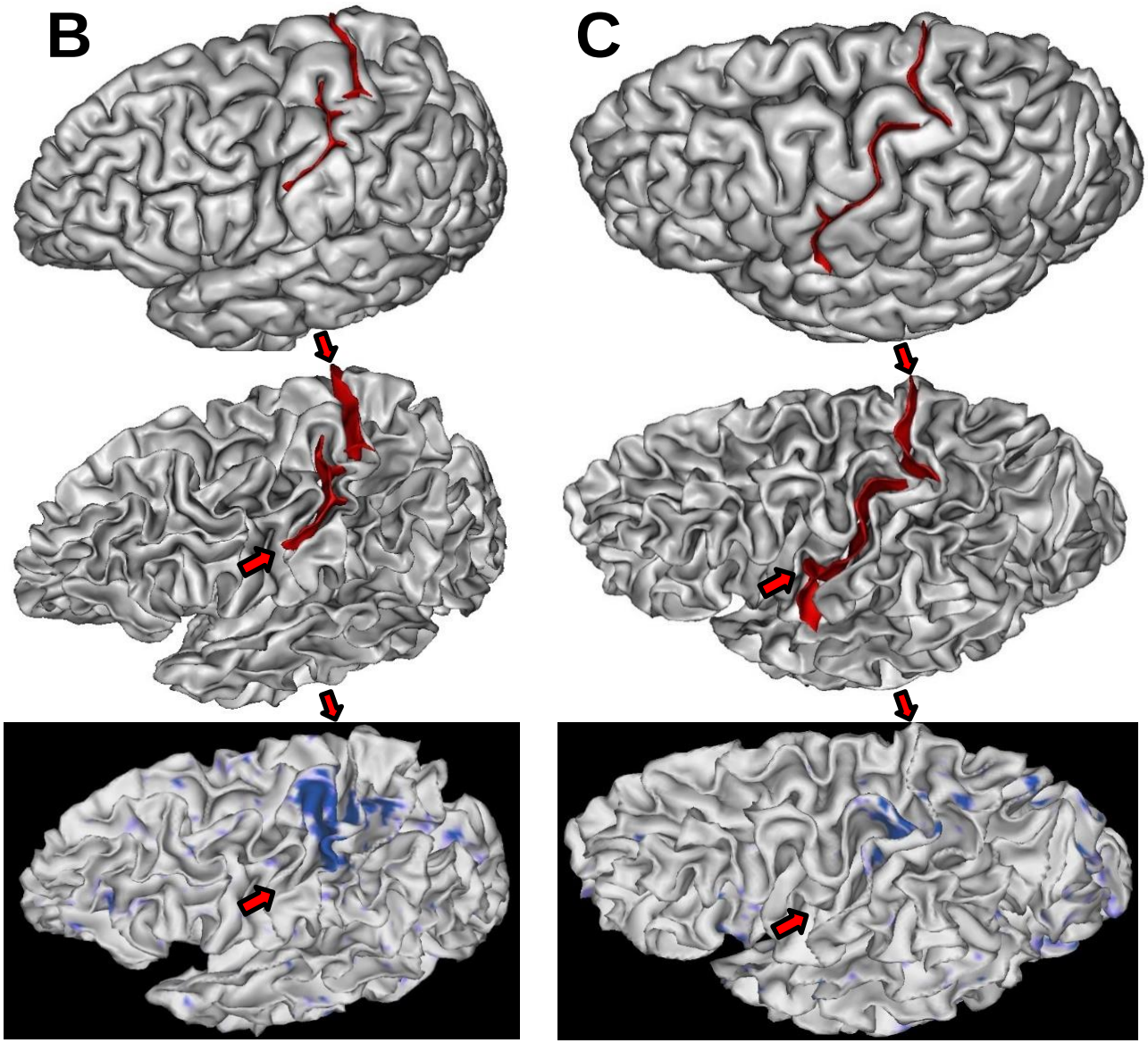
HCP dataset (1000 subjects)



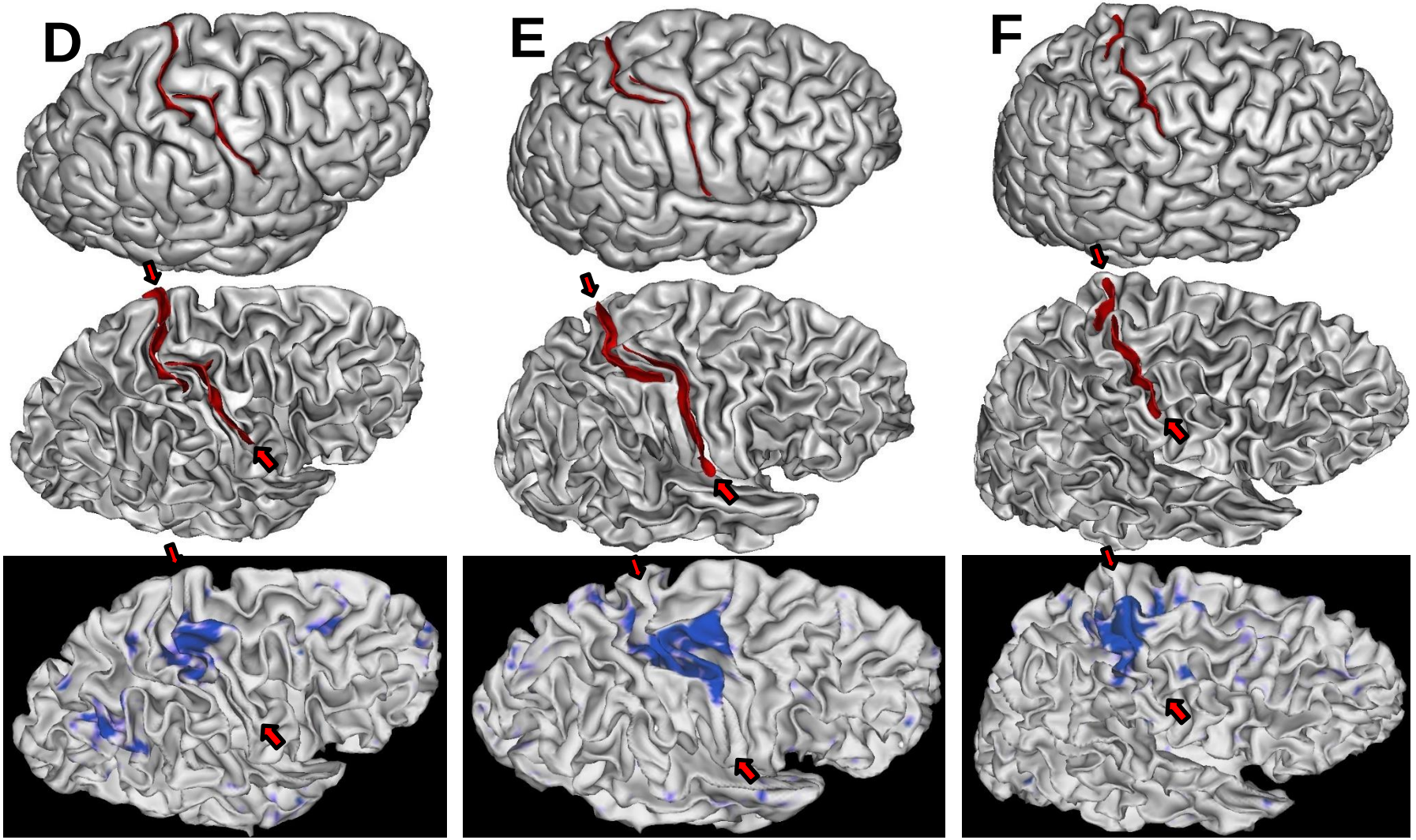
Mangin et al., 2019

10 interrupted central sulci

Left hemisphere

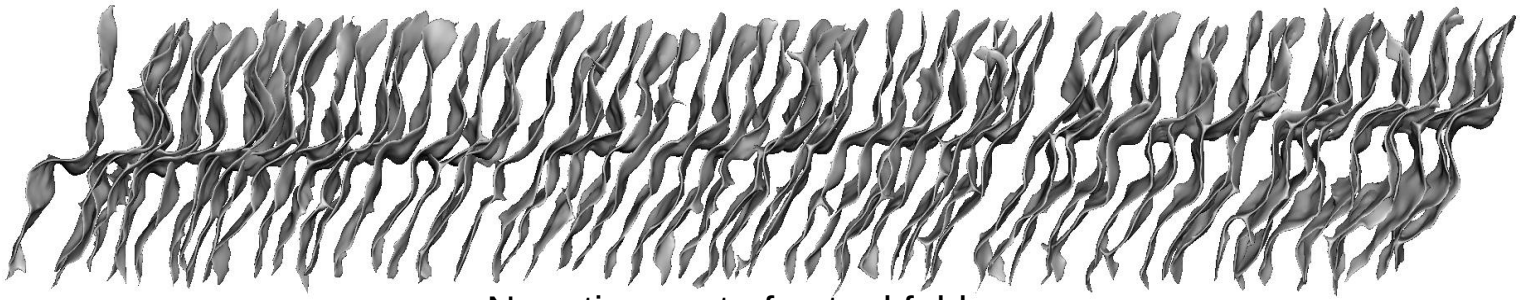


Right hemisphere

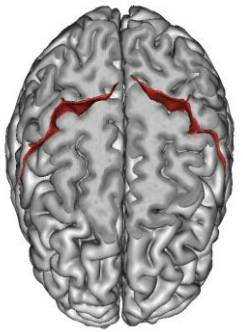


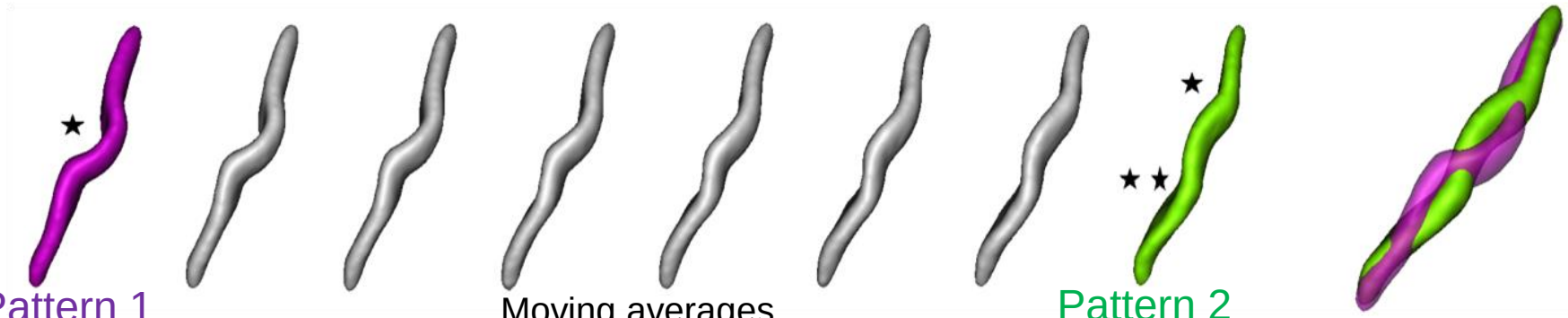
Geometry driven machine learning

A one dimensional manifold (isomap)



Negative cast of actual folds

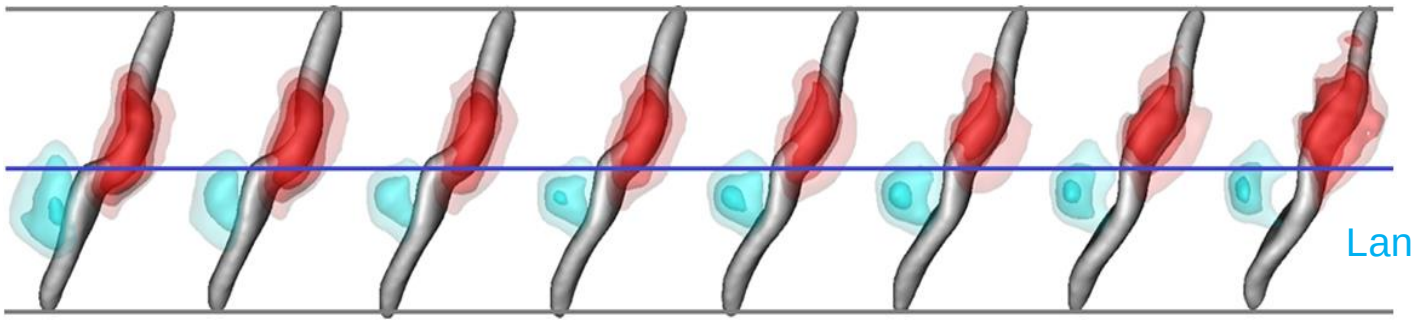




Pattern 1

Moving averages

Pattern 2



Hand

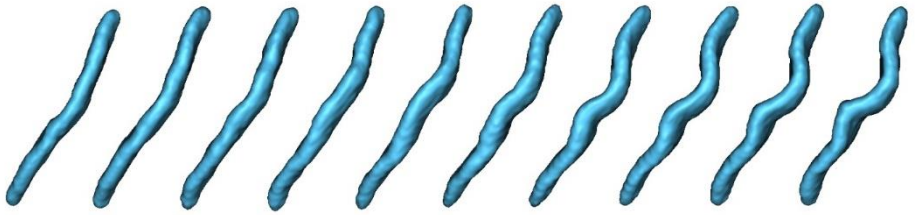
Functional activations

Language (55B?)

Sun et al., Brain Struct. And Function, 2016

Abnormal folding patterns

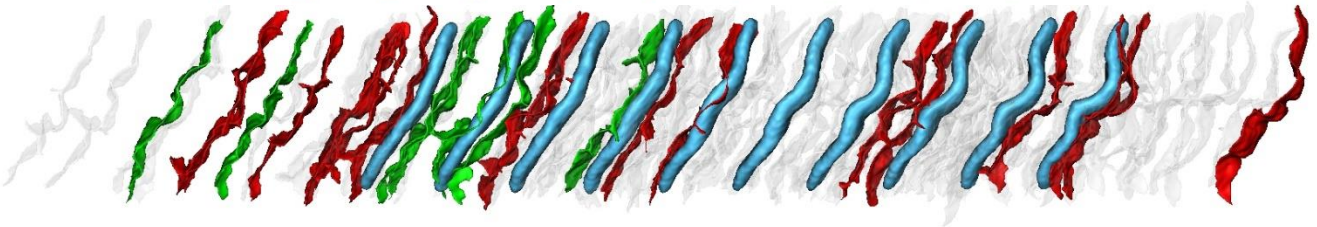
Manifold in a population gathering **one-handers** and two-handed controls



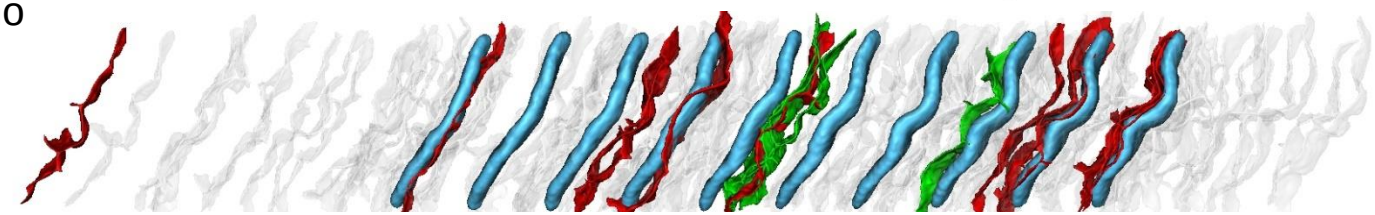
Left sulcus (right hand missing)

Right sulcus (left hand missing)

Individuals **born without** a hand

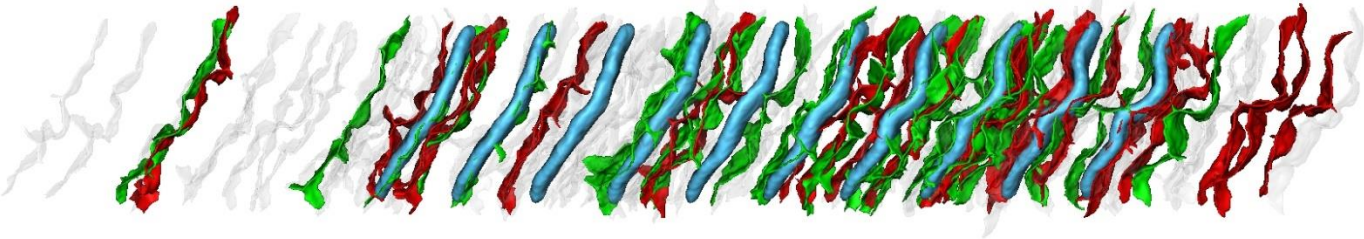


Individuals who have **lost** their hand as adults



Sun et al., HBM 2017

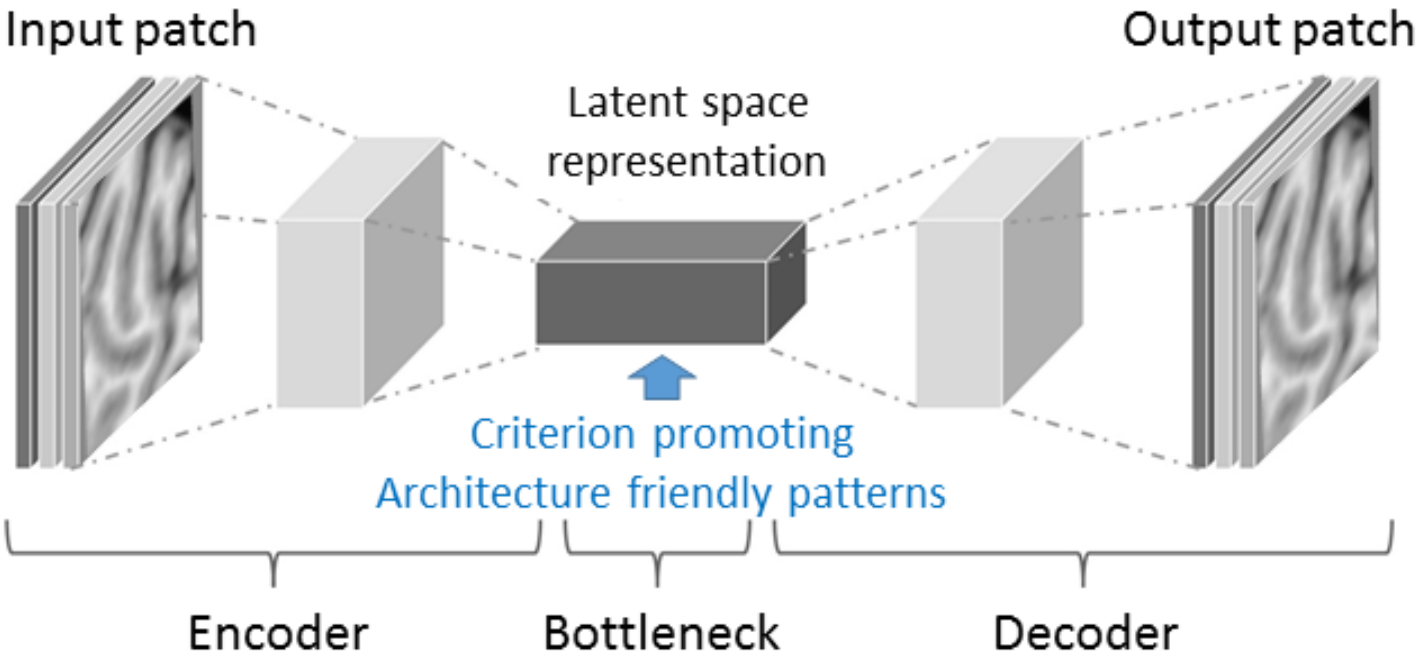
Two-handed **controls**

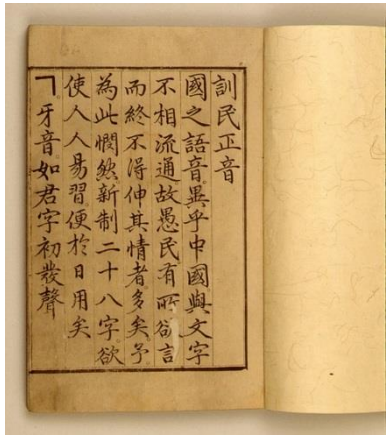


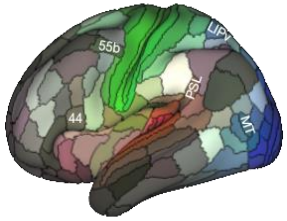
Colab. T. Makin

The unsupervised data driven path

Let us get rid of the old nomenclatures!







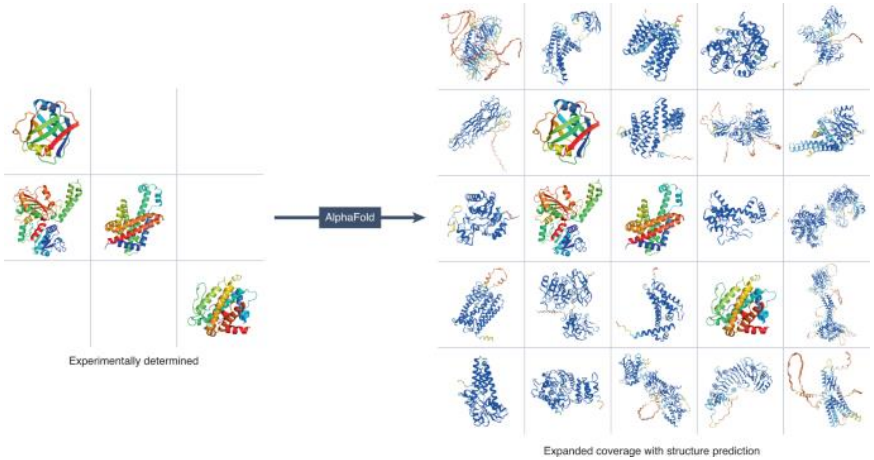
Glasser et al., Nature, 2016

Self-supervised + Task-driven learning of the dictionary

The unsupervised data driven path

Modern AI

180,000 proteins with known 3D structures from expensive experiments

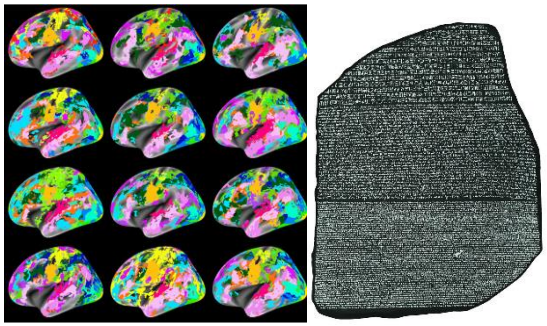


AlphaFold Open Access Protein Structure Database

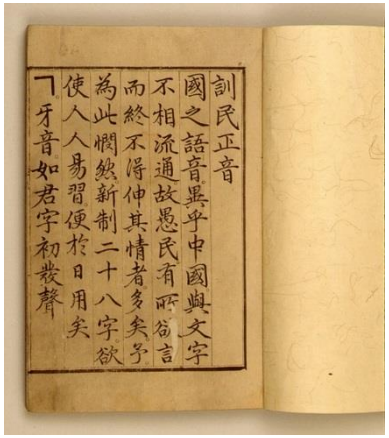
200 million known proteins in UniProt

Jumper et al., 2022

Brain research datasets (a few 100000s)



Cortical ideogram dictionary

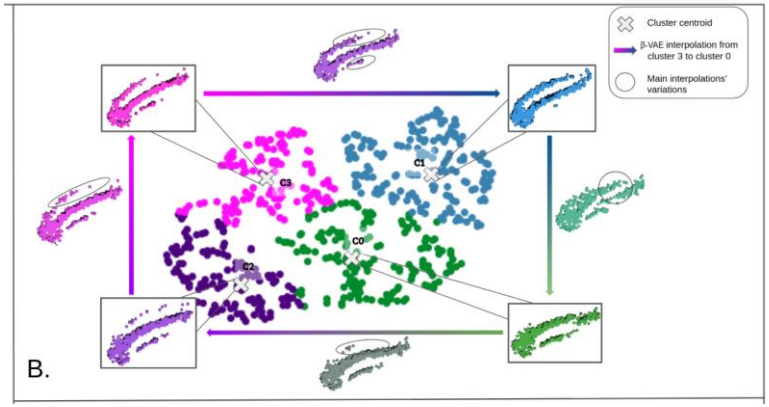


訓民正音

國之語音異乎中國與文字不相流通故愚民有所欲言而終不得伸其情者多矣予為此憫然新制二十八字欲使人人易習便於日用矣

ㄱ牙音如君字初發聲

Predictions for our 7 billion brains



Guillon, Chavas et al., MICCAI 2022

Questions?