Visual Computing in Connectomics

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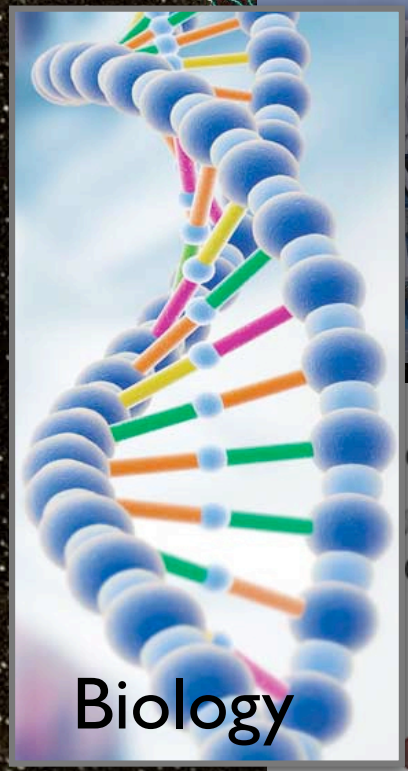
Scientific Data Explosion

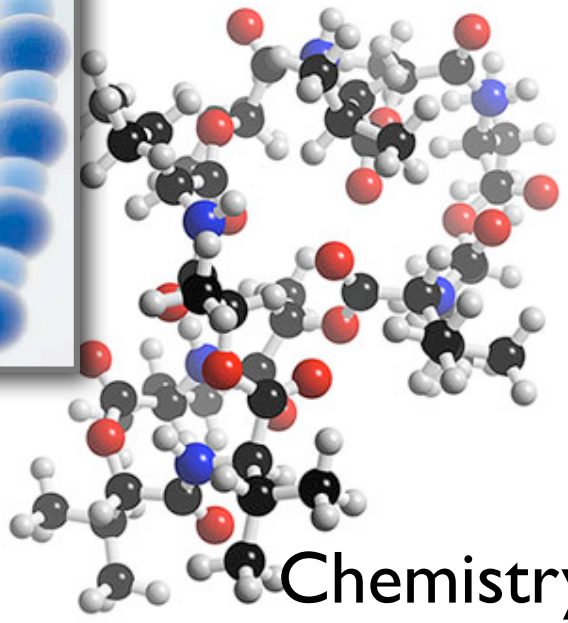
Astronomy

Microscopy



Biology

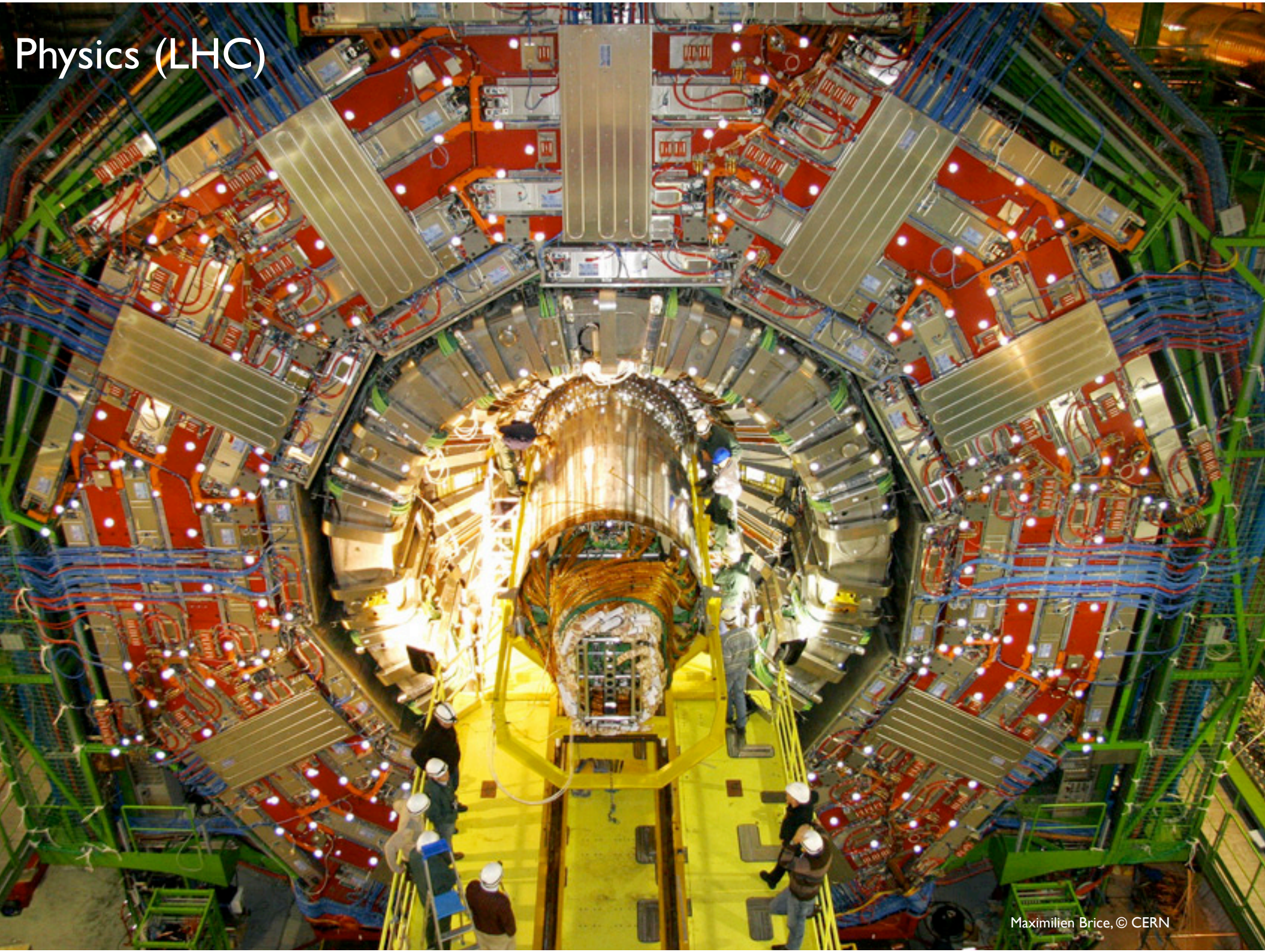
Medicine



Chemistry

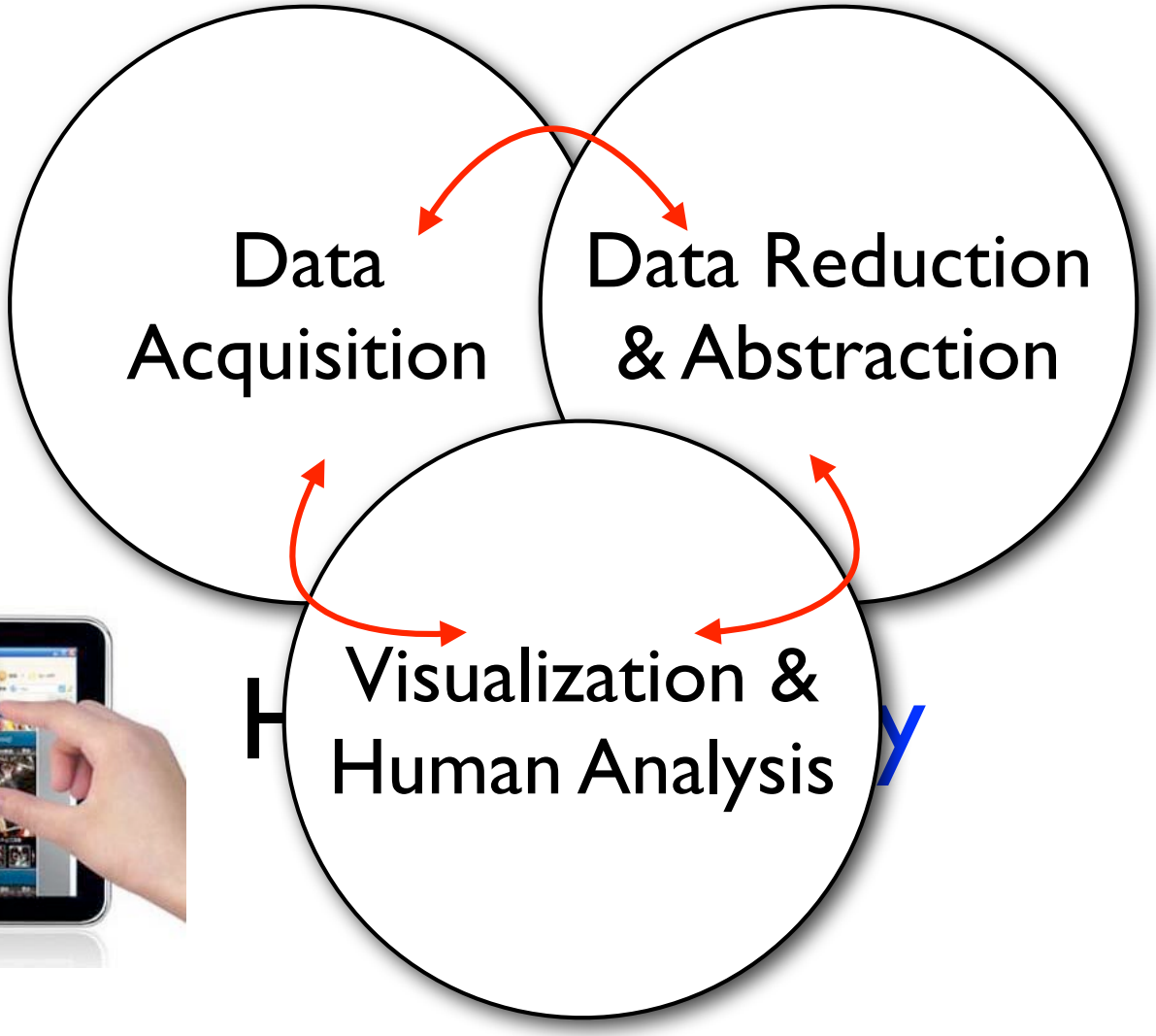
Social Sciences

Physics (LHC)



Maximilien Brice, © CERN

Challenges


Data
Acquisition
Data Reduction
& Abstraction
Visualization &
Human Analysis

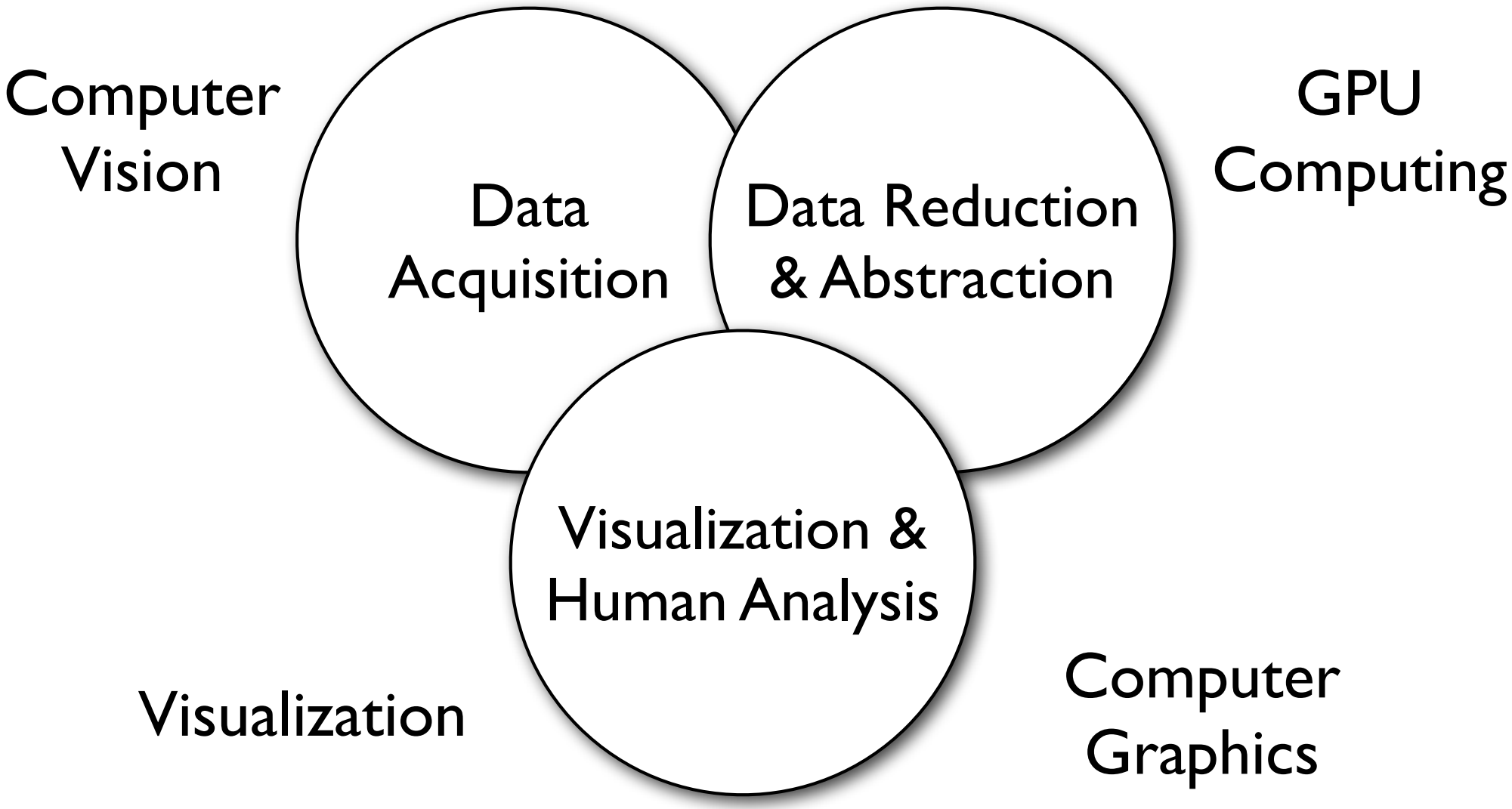
Visual Computing

Data Acquisition

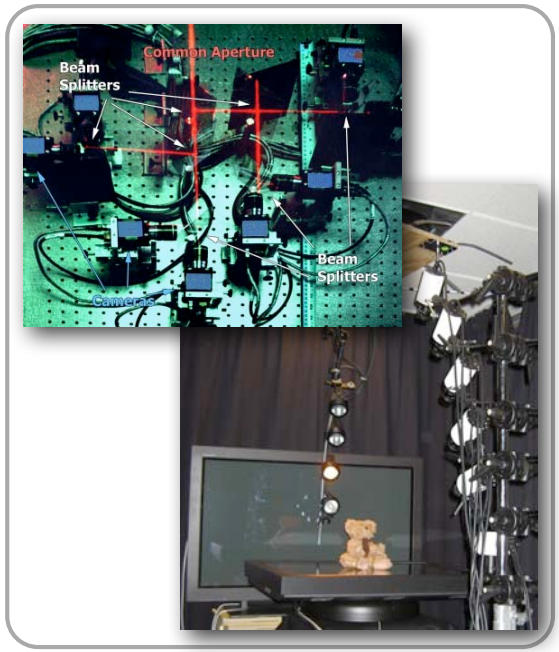
Data Reduction & Abstraction

Visualization & Human Analysis

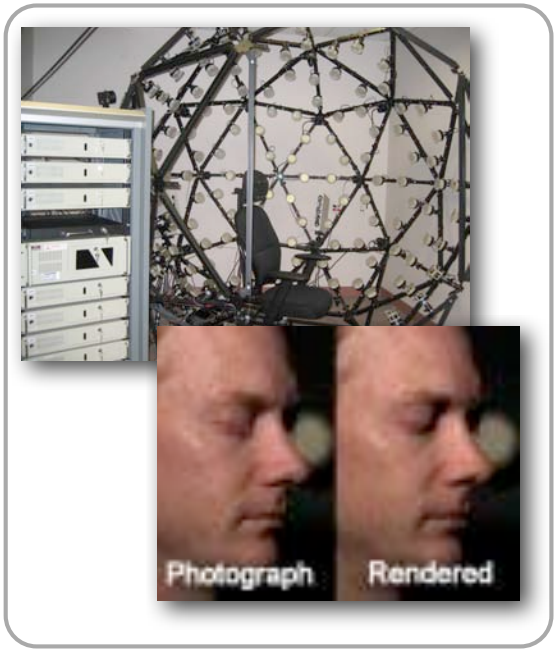
Visual Computing



Data Acquisition



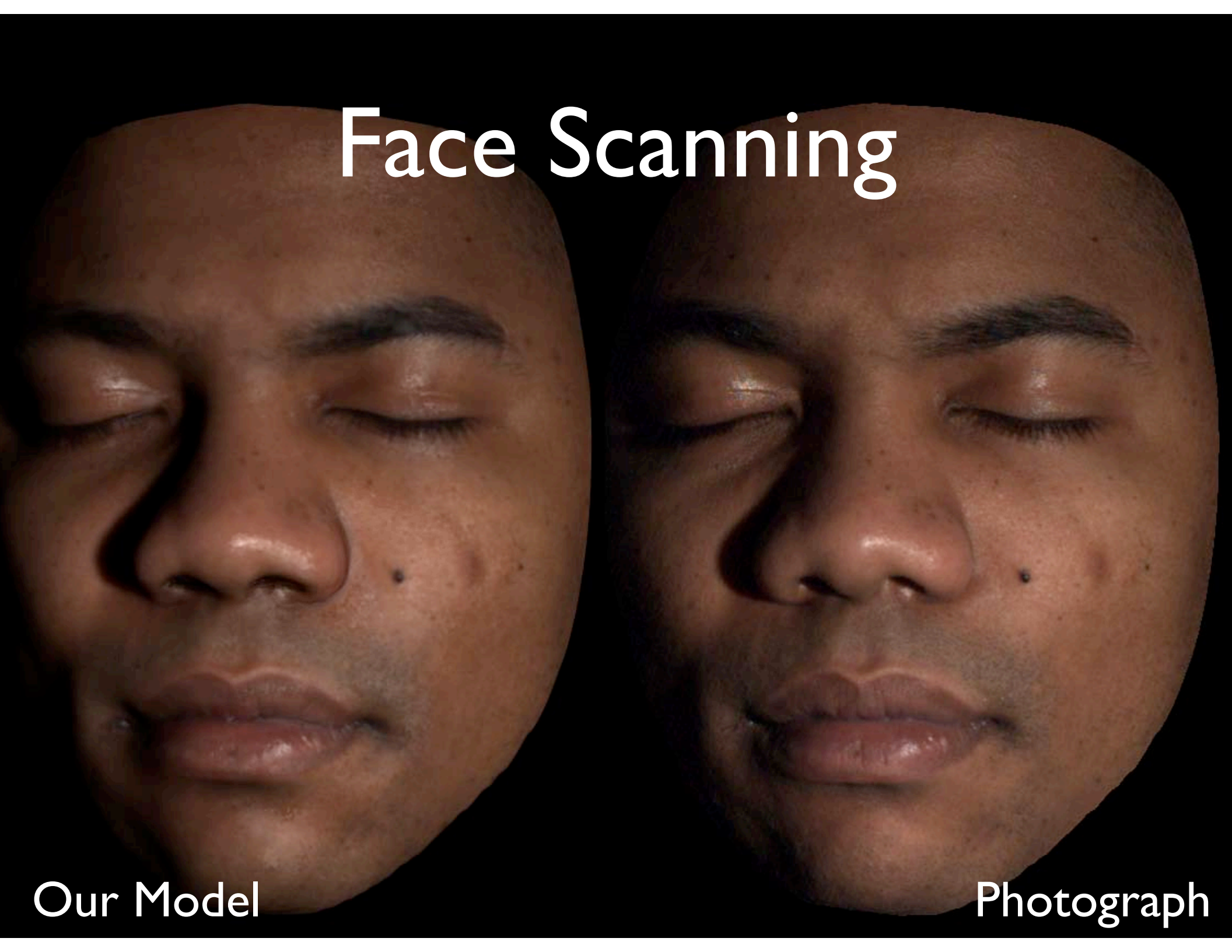
Computational Photography



Face Scanning

Material Measurements

Face Scanning

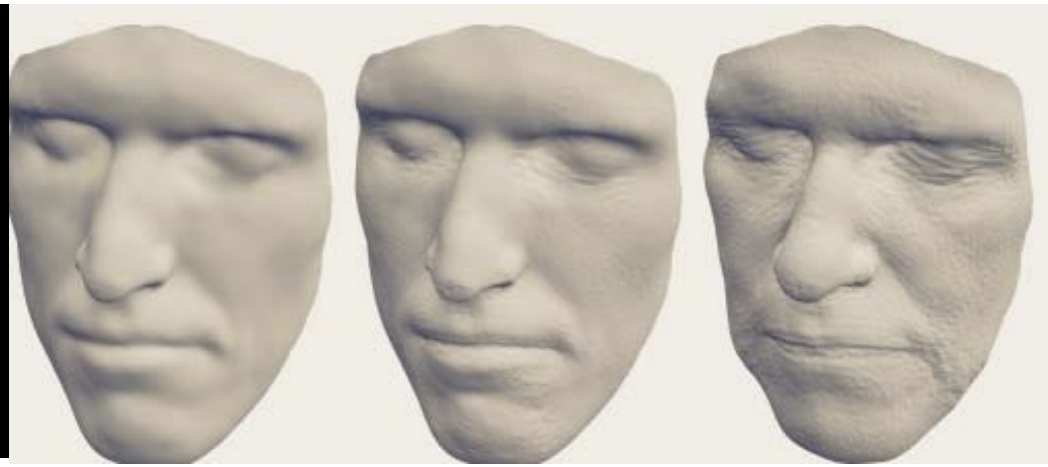


Face Scanning Dome

Face Database

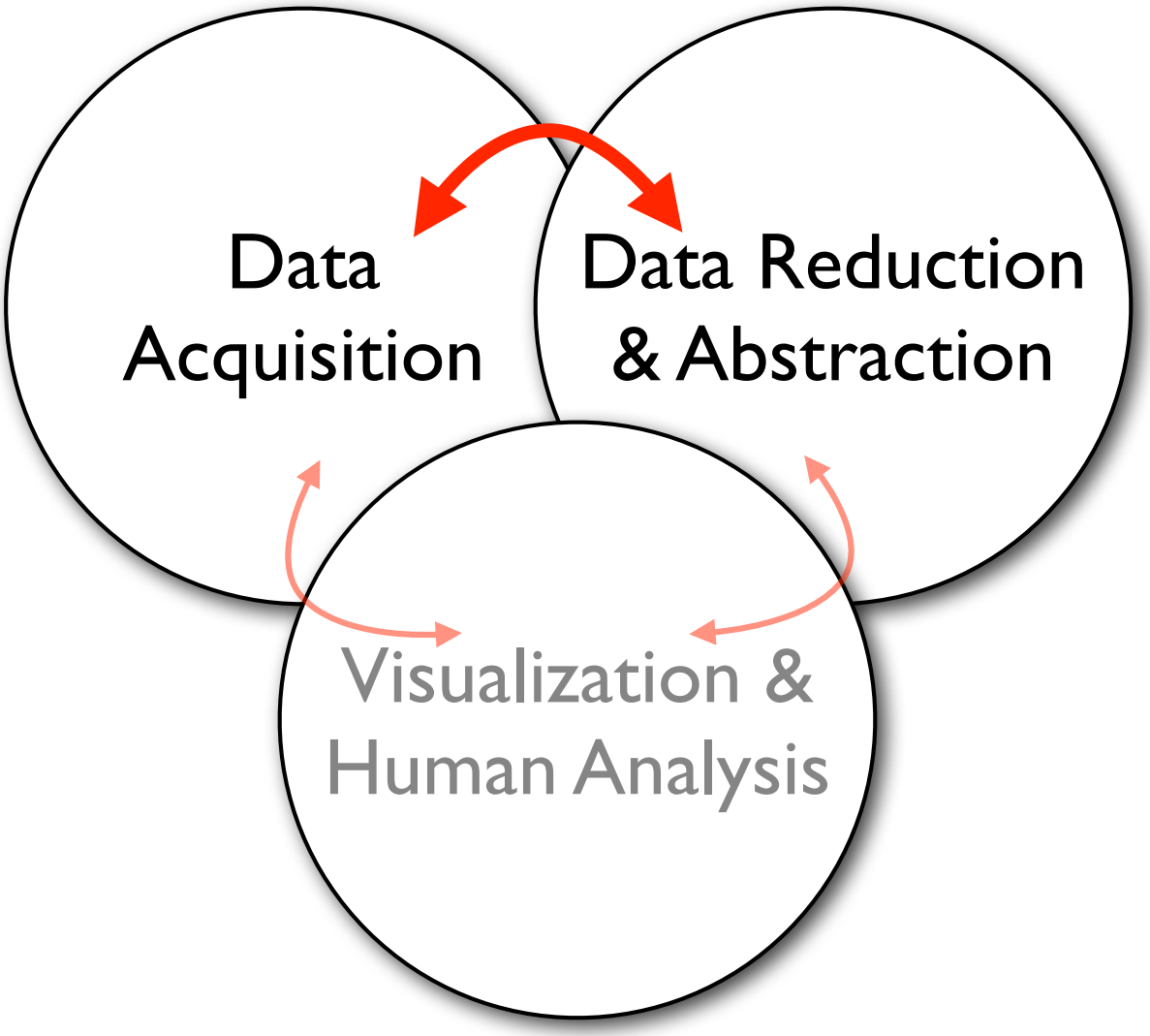
- ~500 subjects
- ~12 TB of data
- Statistical models of facial appearance

[Weyrich et al., SIGGRAPH 2006]



[Golovinskiy et al., SIGGRAPH 2006]

Visual Computing



Data Reduction & Abstraction

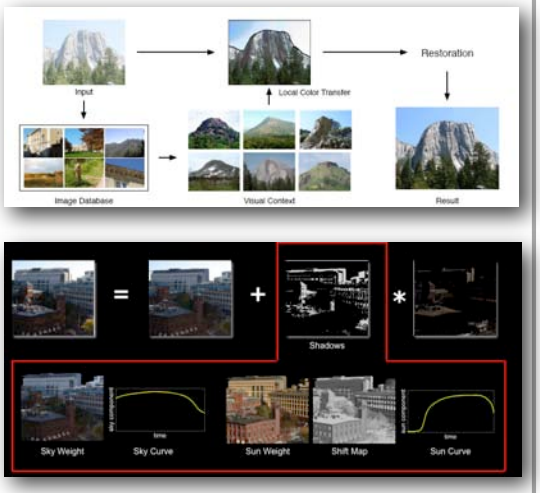
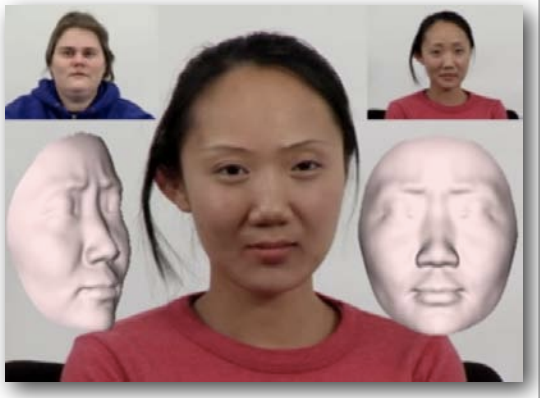
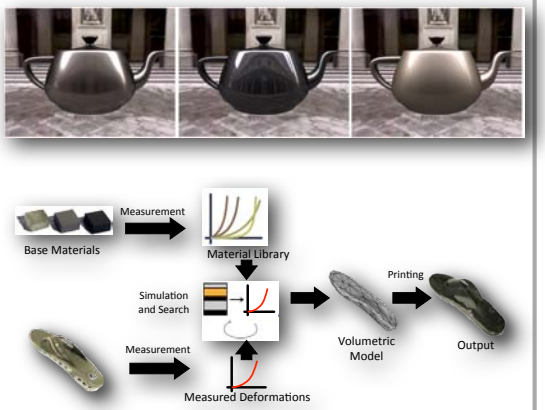


Image & Video Analysis



Face Models



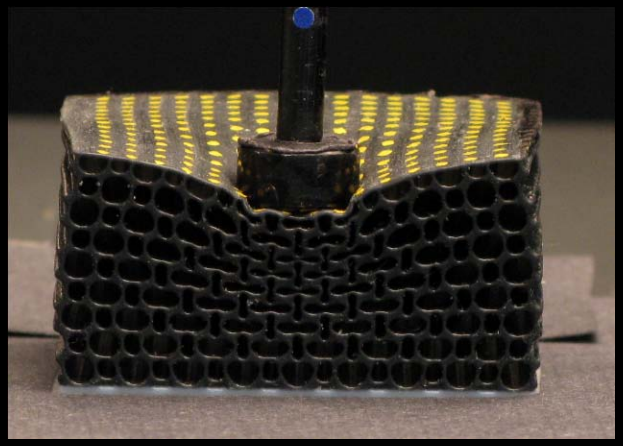
Material Models

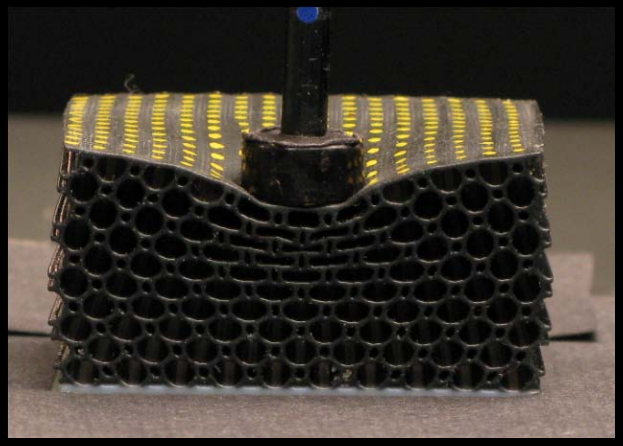
Material Design & Fabrication

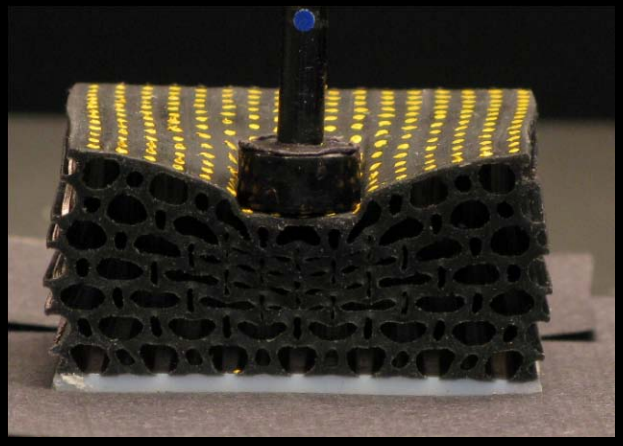
Real Object

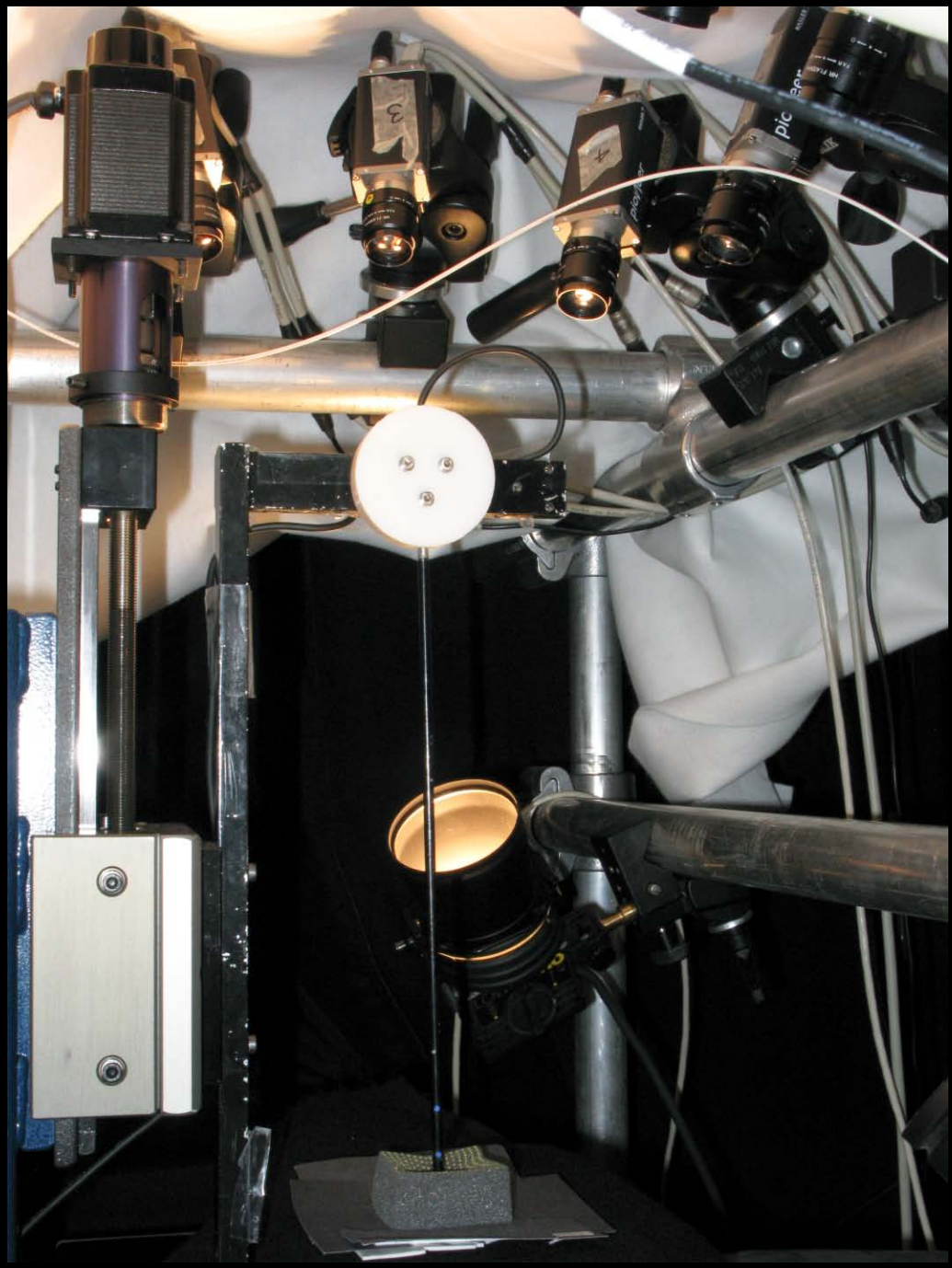
Reproduction

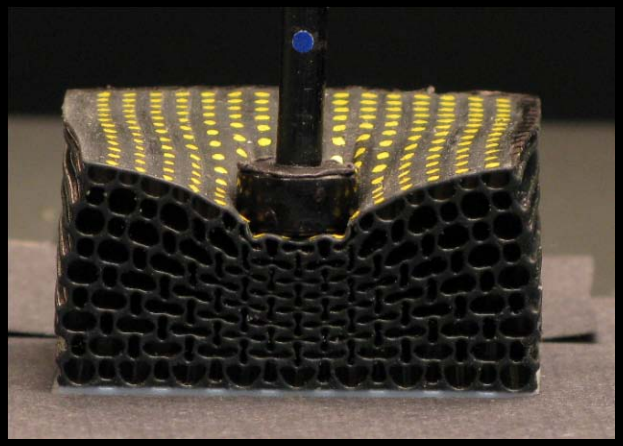
[Bickel et al., SIGGRAPH 2010]

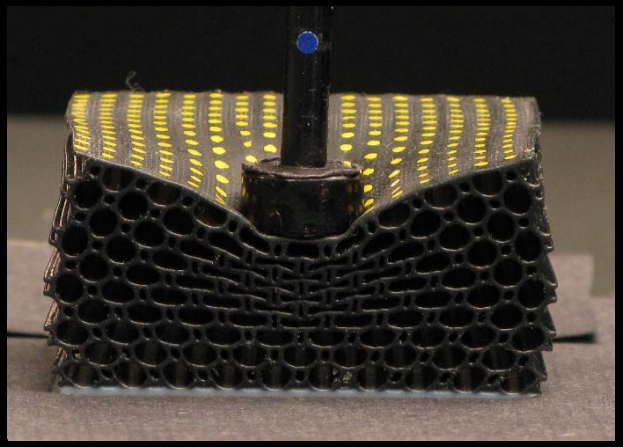


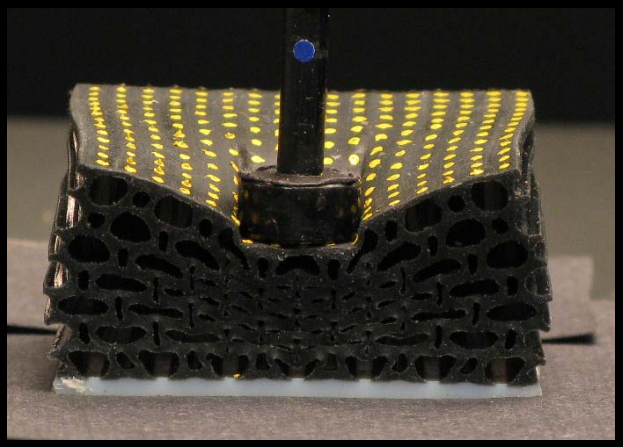


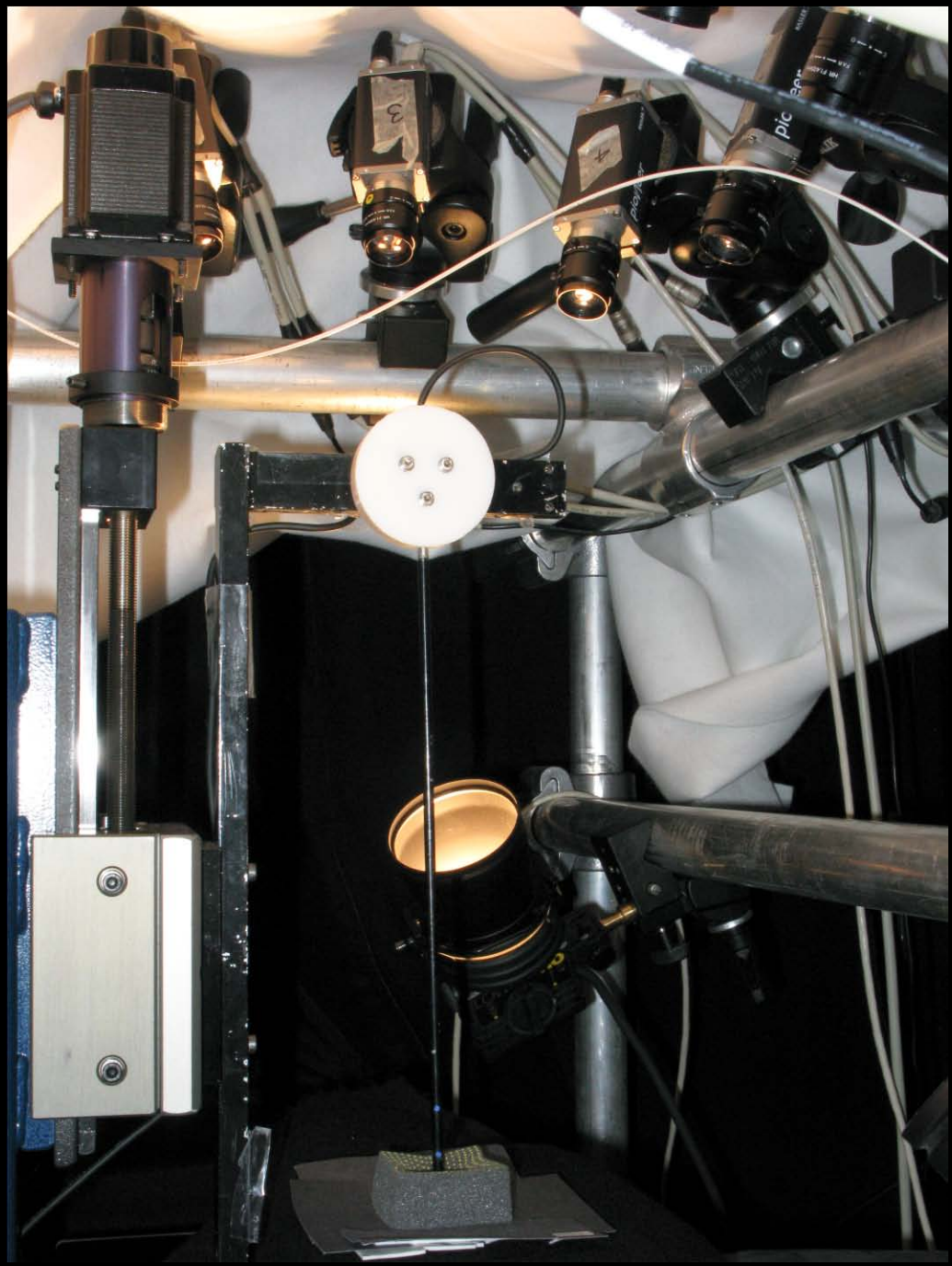


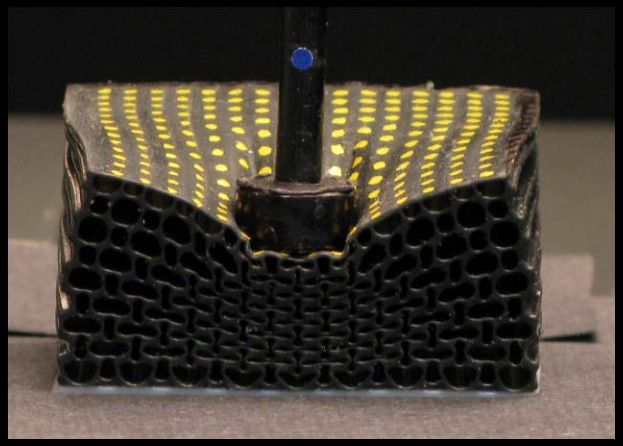


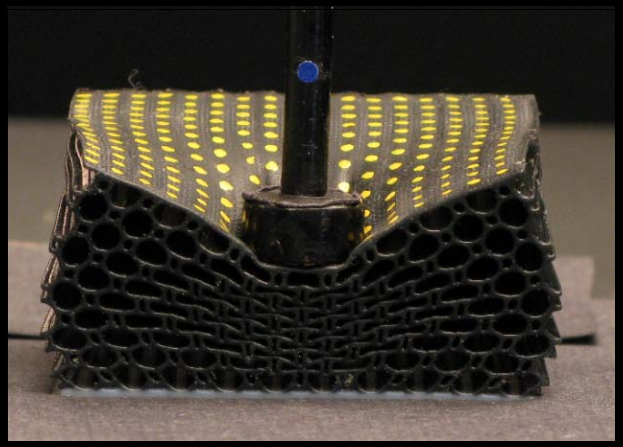


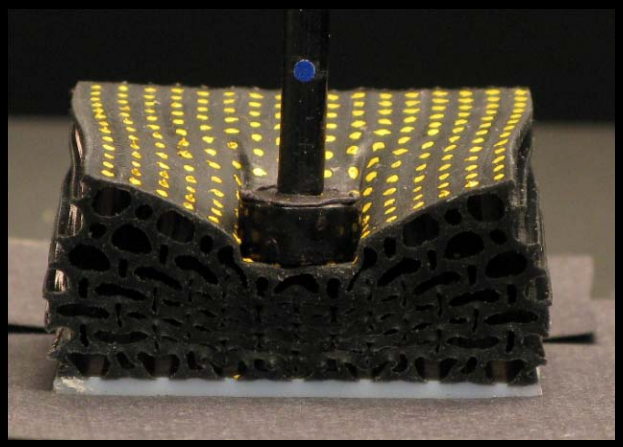


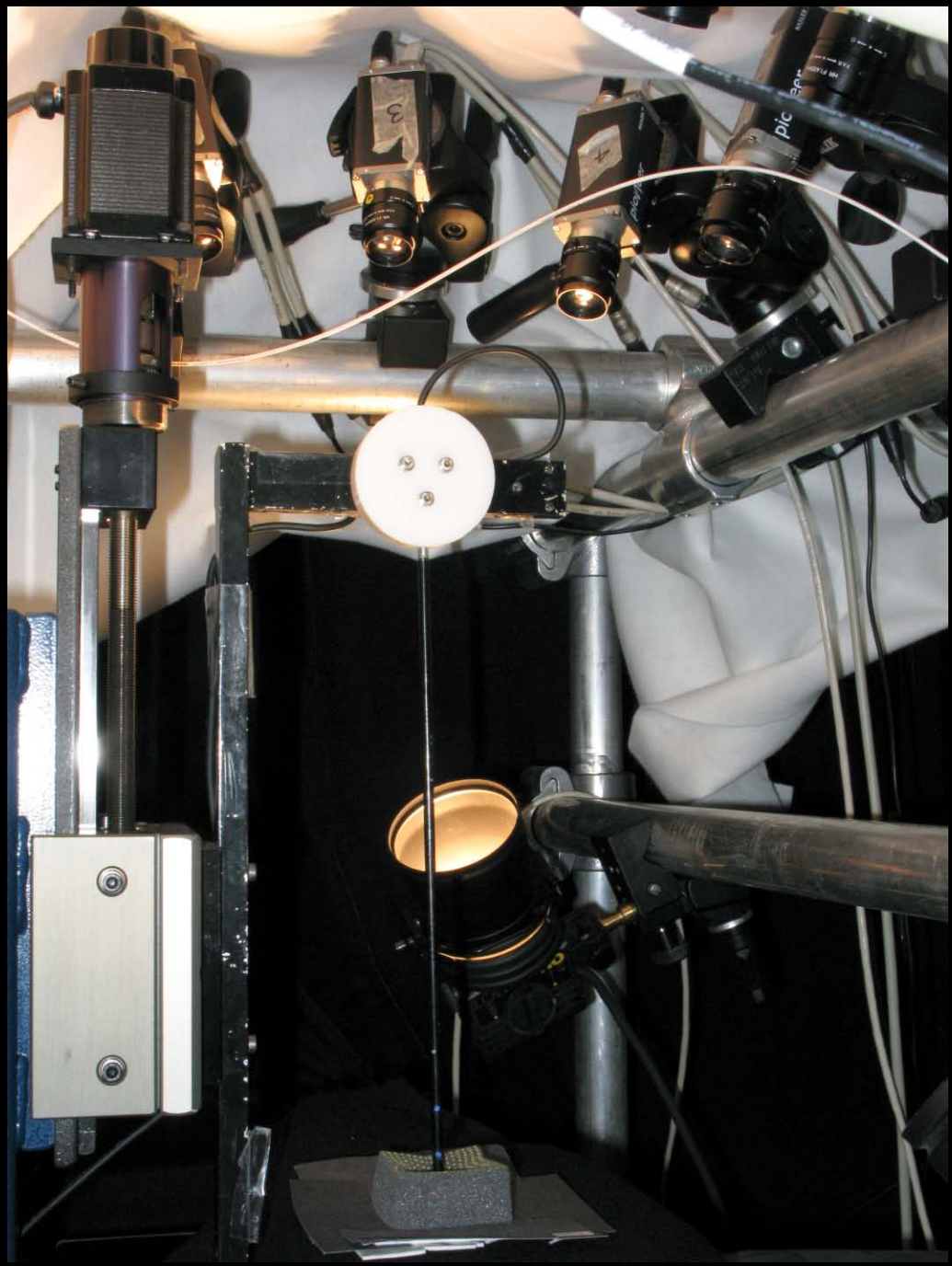


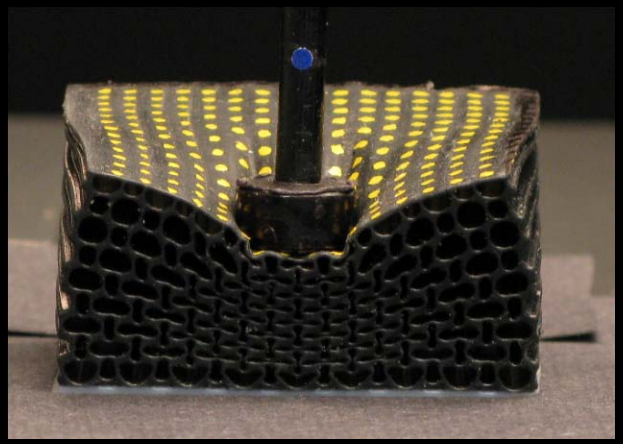


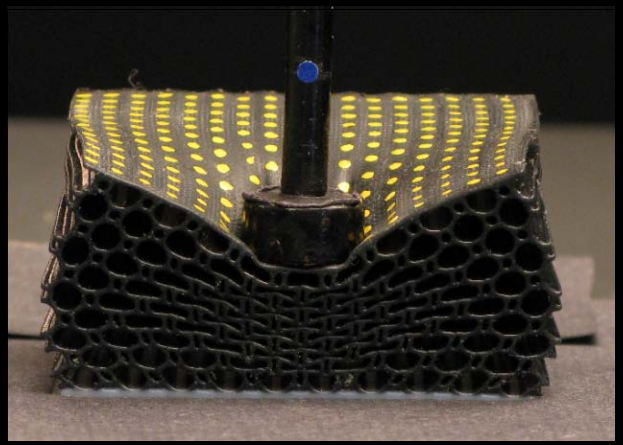


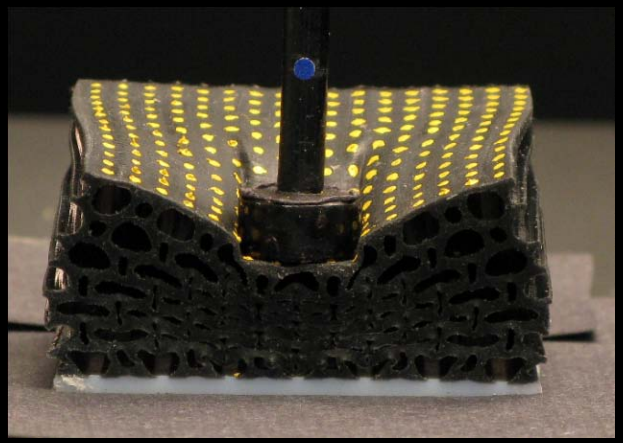


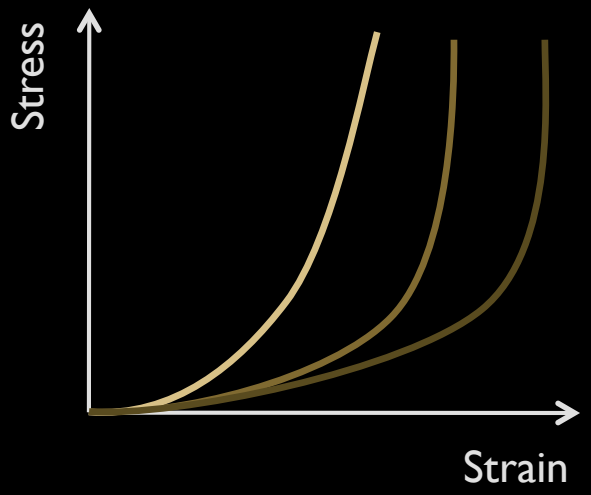


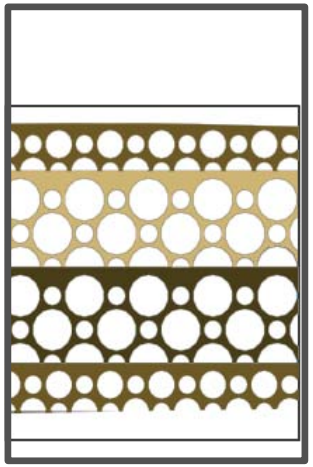


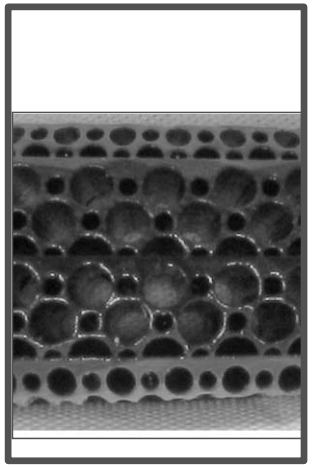






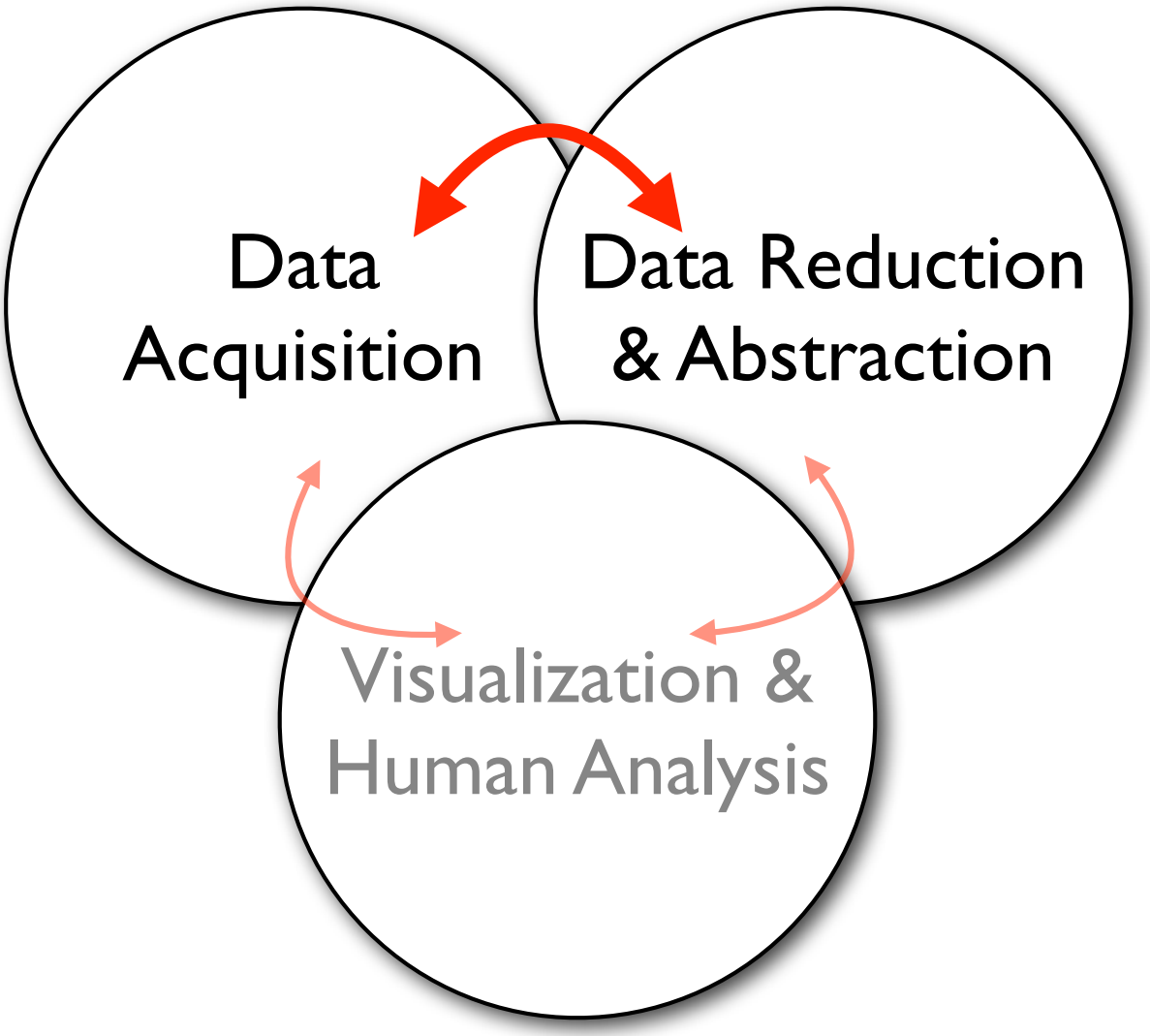

Stress
Strain



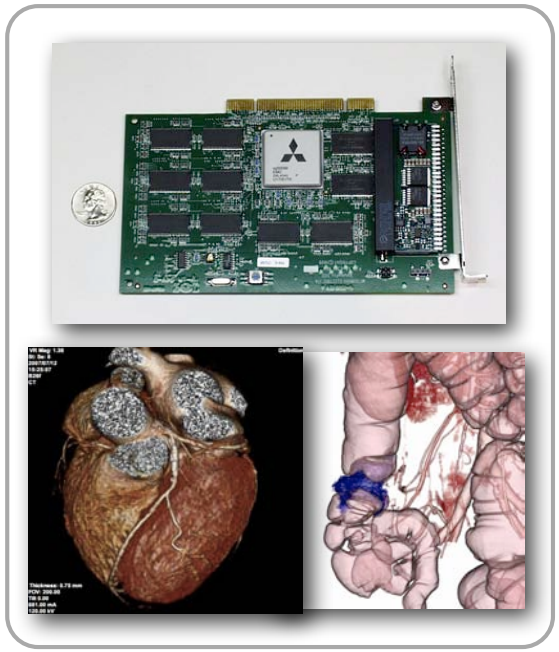


[Bickel et al., SIGGRAPH 2010]

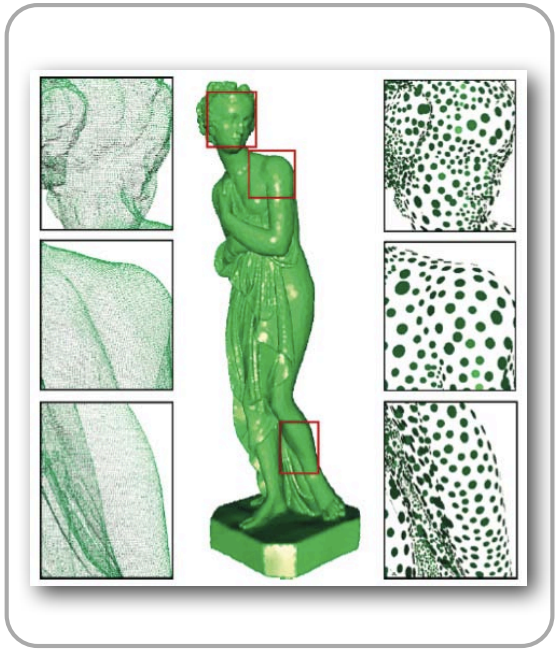
Visual Computing



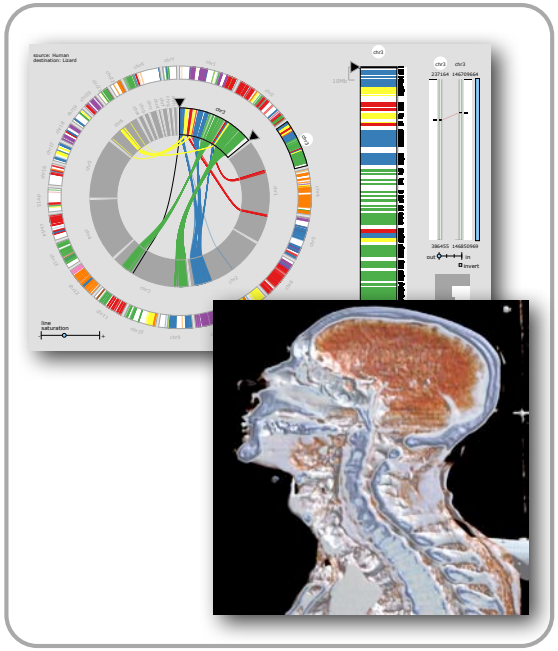
Visualization



VolumePro Hardware



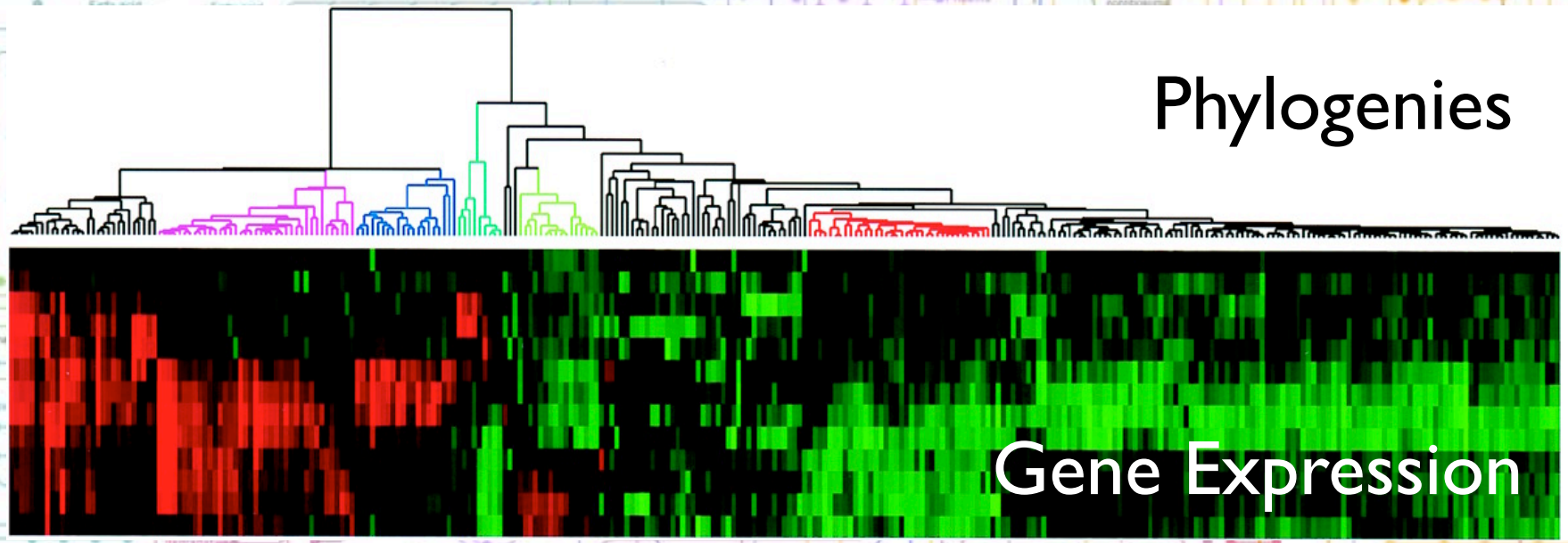
Point-Based Graphics



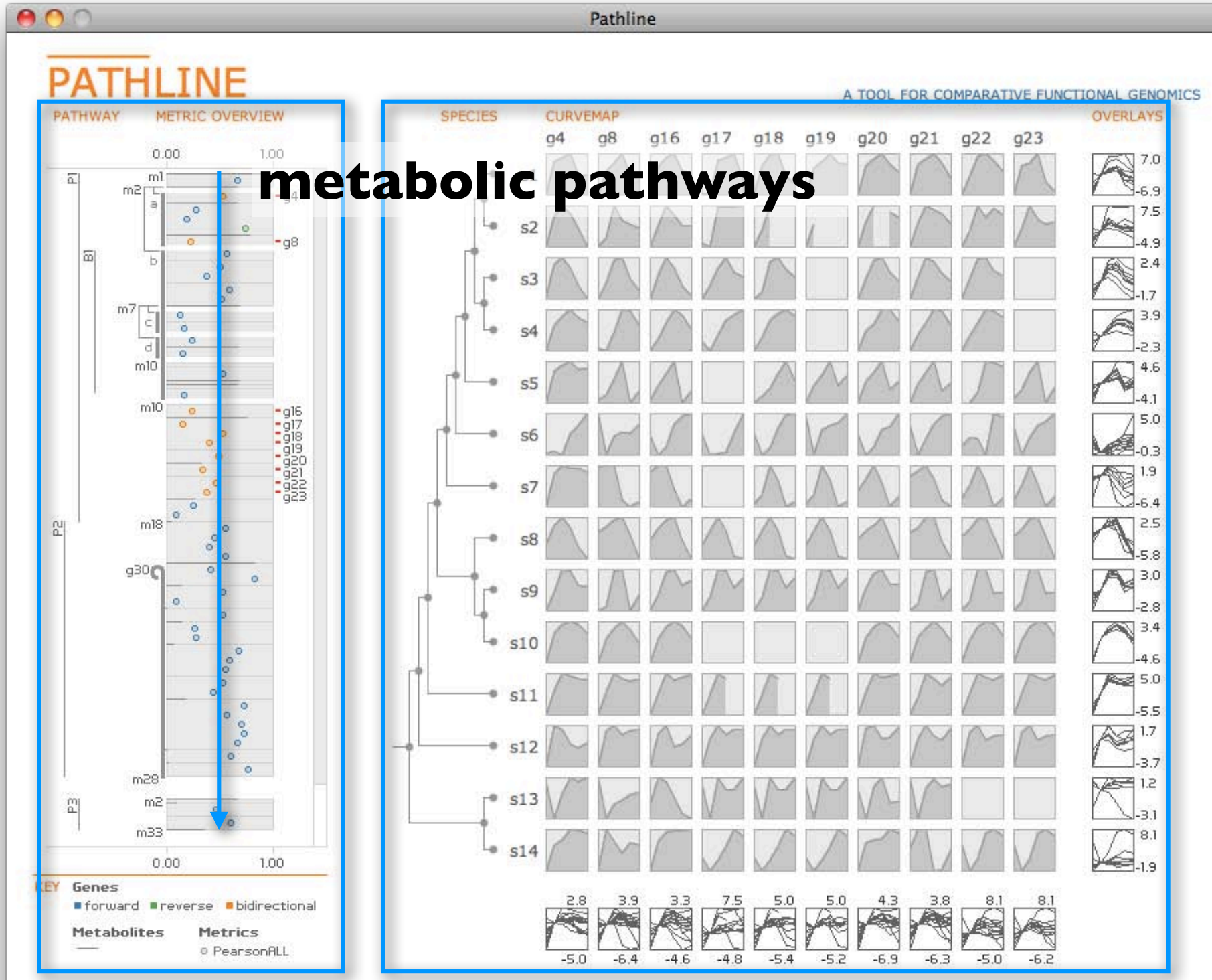
Bio-Medical Visualization

Functional Genomics

How do genes work together to perform different functions in the cell?

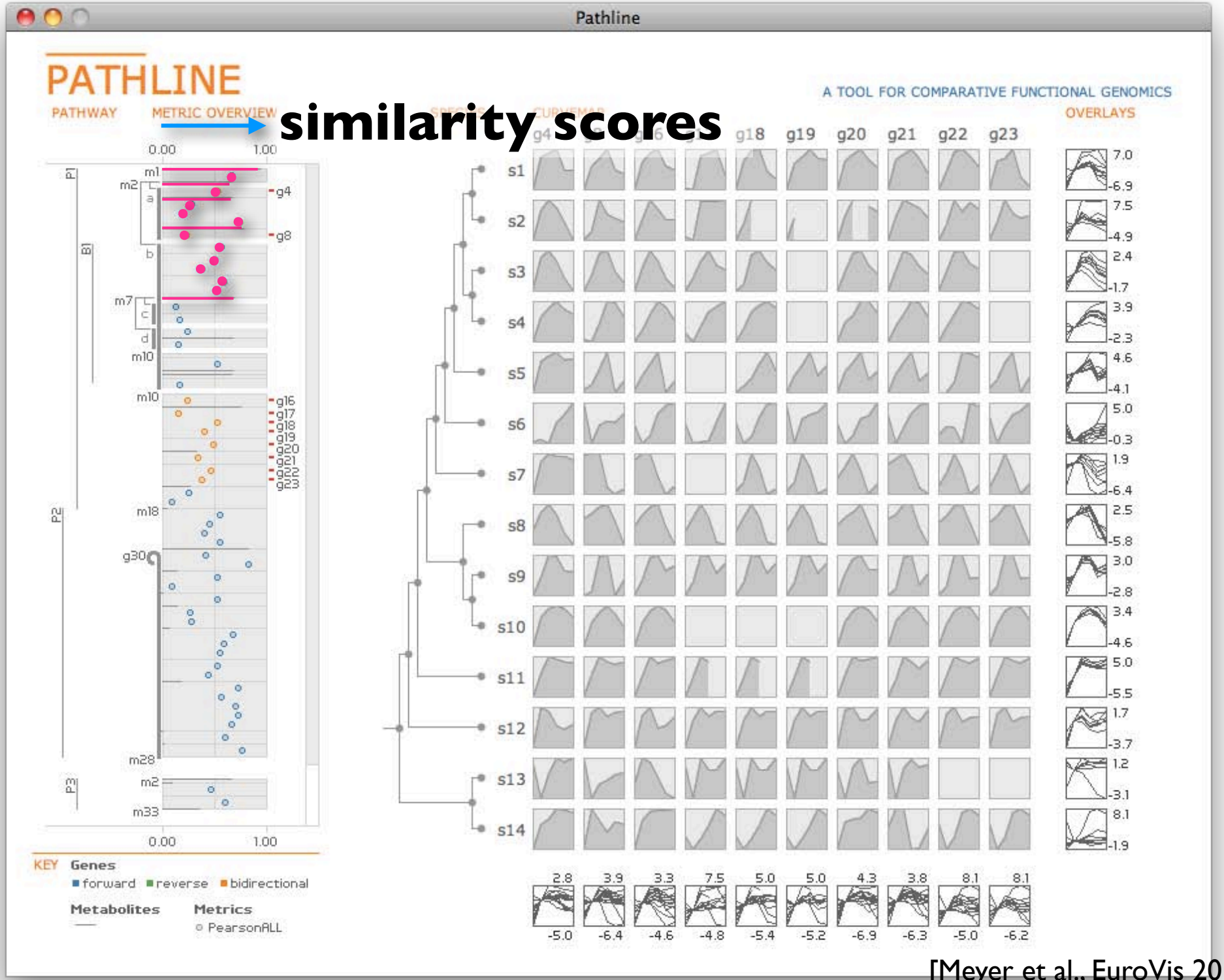


Metabolic Pathways

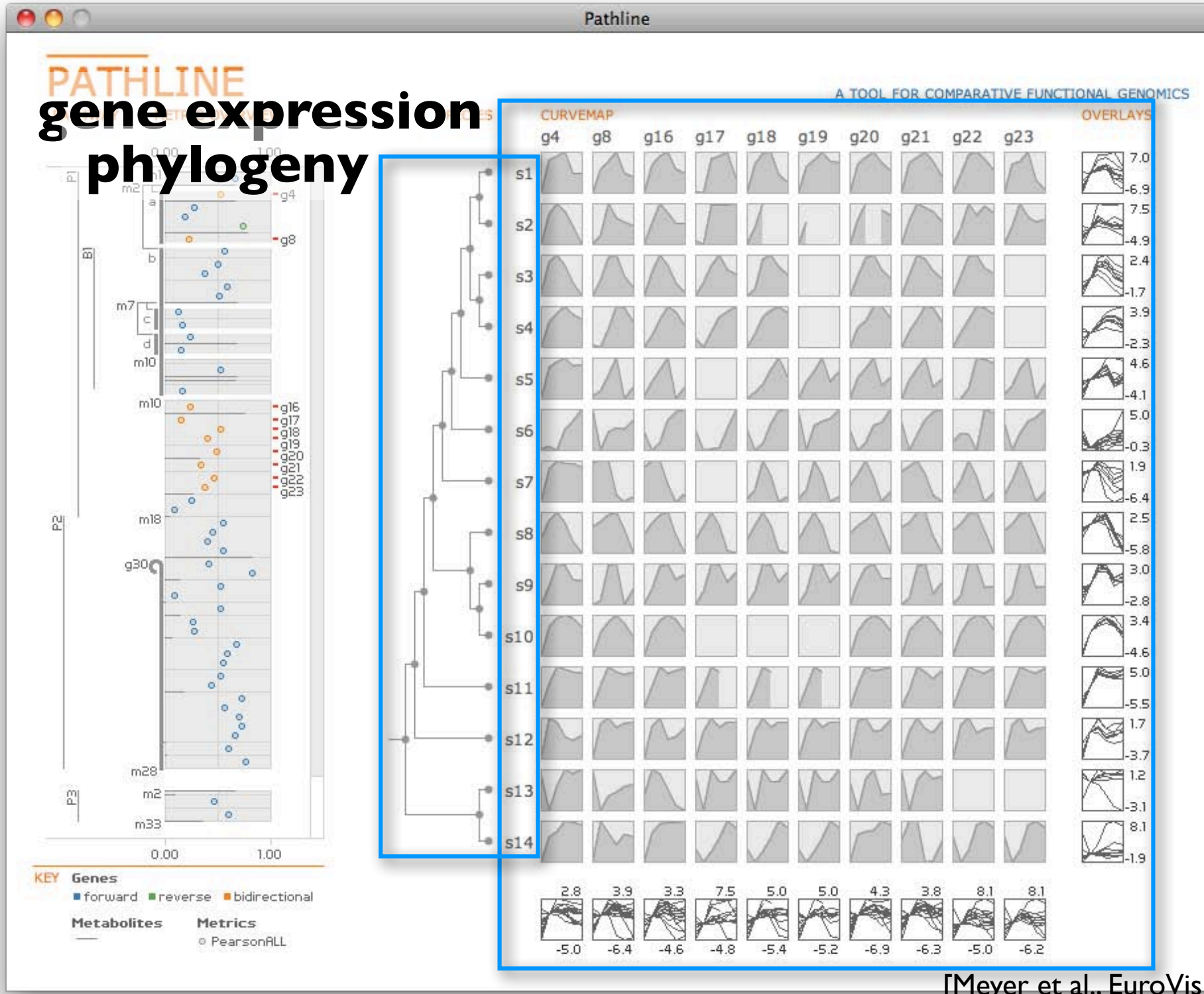


metabolic pathways

[Meyer et al., EuroVis 2010]



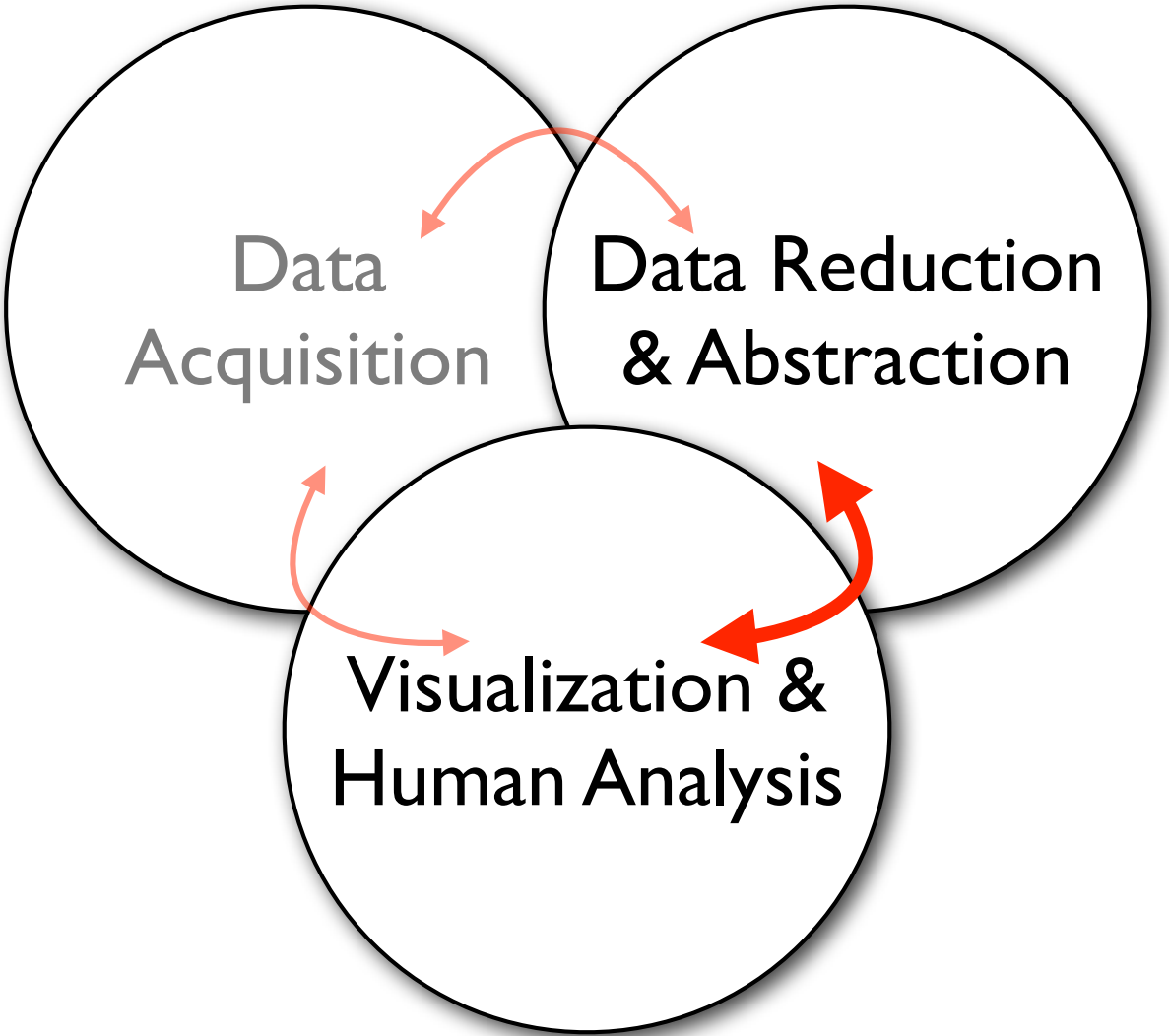
[Meyer et al., EuroVis 2010]



gene expression phylogeny

[Meyer et al., EuroVis 2010]

Visual Computing



Metabolomics and Integrative Systems Biology Analysis of the Evolution of the Diauxic Shift in Ascomycota fungi,
M. Styczynski et al., in preparation.

Visual Computing Group

Dr. Won-Ki Jeong
Dr. Verena Kaynig
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Moritz Baecher
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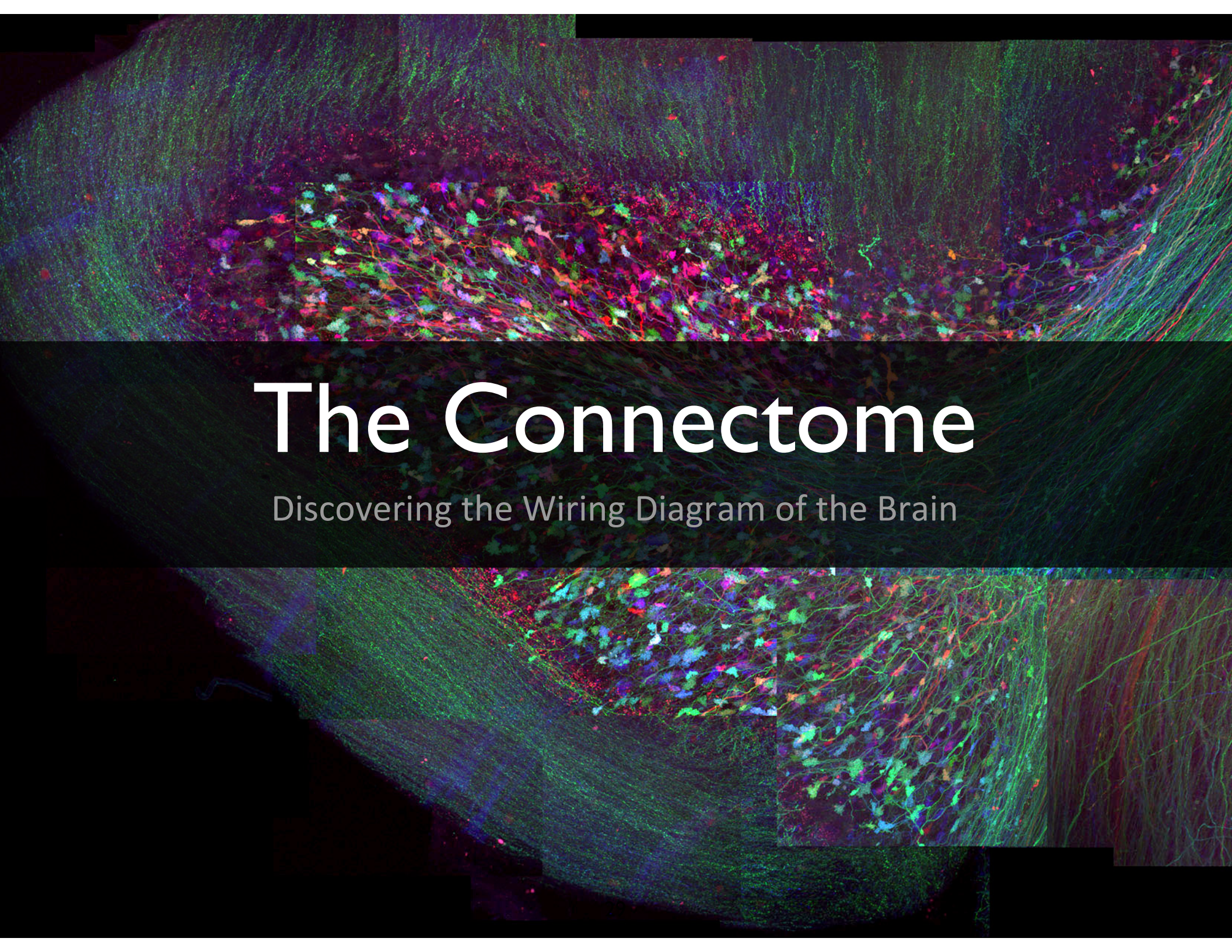
Kevin Dale
Amanda Peters
Mike Roberts
Kalyan Sunkavalli
Amelio Vazquez



The Connectome

Discovering the Wiring Diagram of the Brain

Collaborators

Harvard Center for Brain Science

- Prof. Jeff Lichtman & Prof. Clay Reid


KAUST

- Prof. Markus Hadwiger, Dr. Johanna Beyer

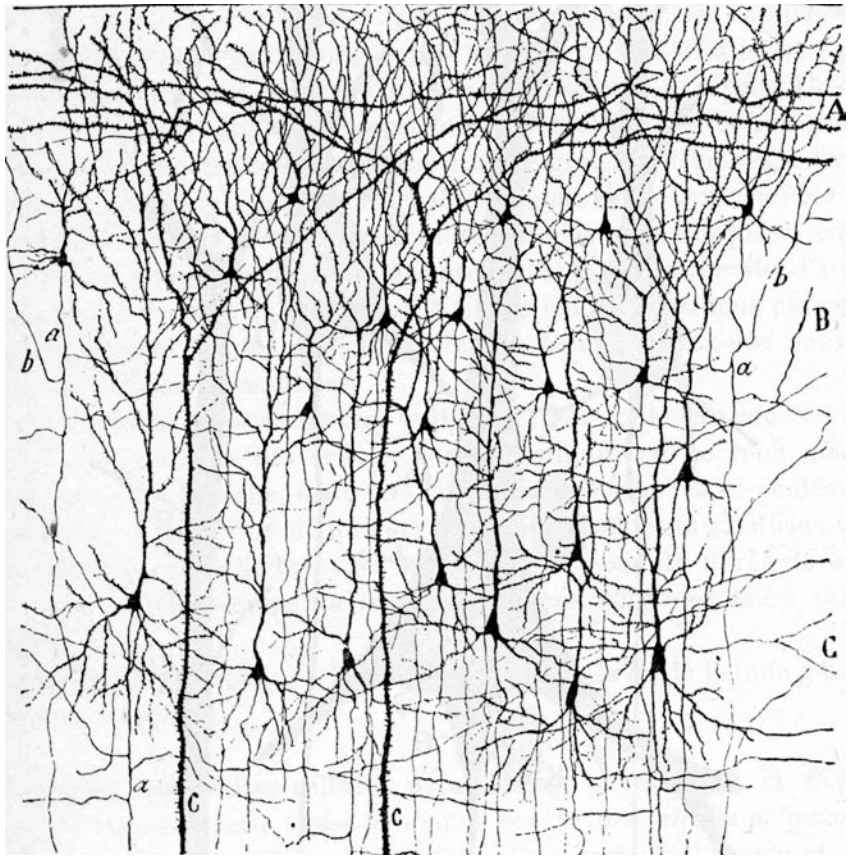

SEAS

- Dr. Won-Ki Jeong
  Dr. Verena Kaynig-Fittkau
  Amelio Vazquez
  Mike Roberts
  N

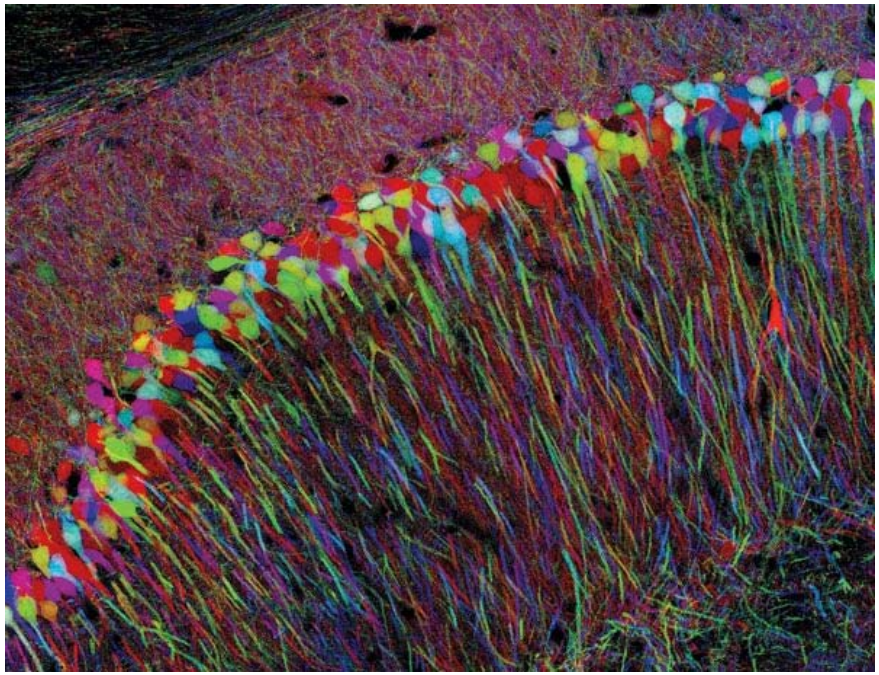



The Scientific Challenge

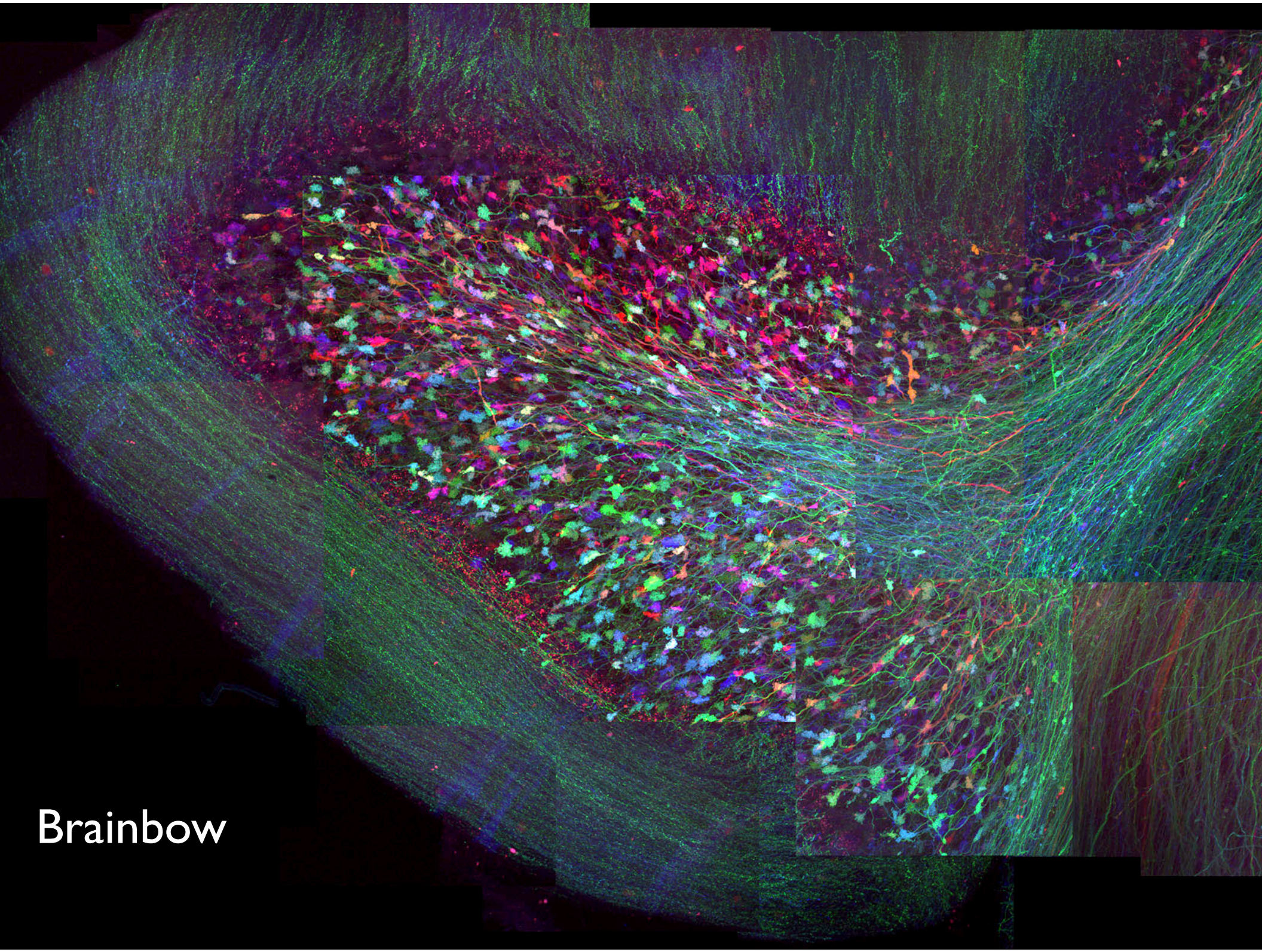
How is the mammalian brain wired?



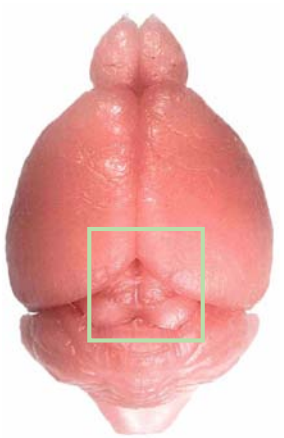
Ramón y Cajal, 1905

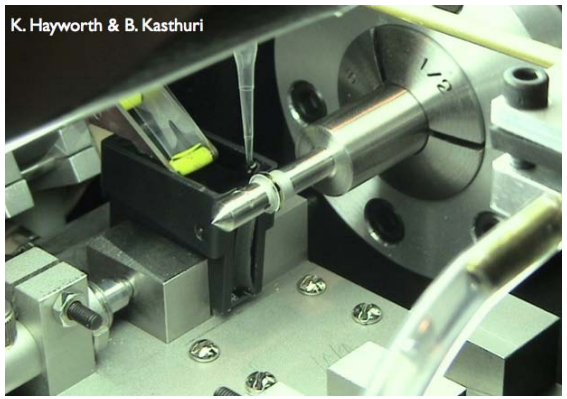


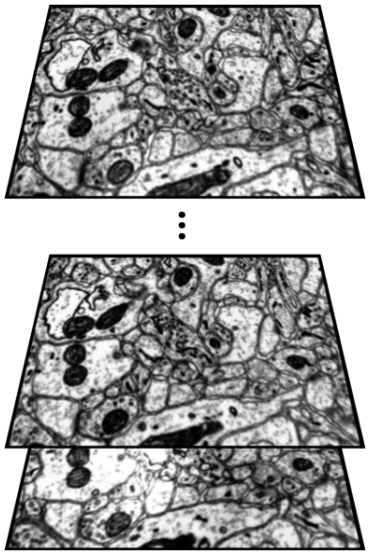
Harvard Center for Brain Science

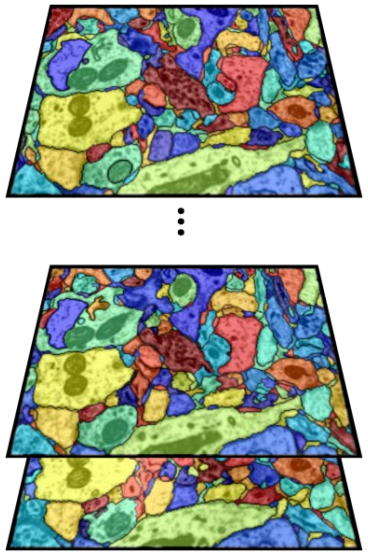

Brainbow

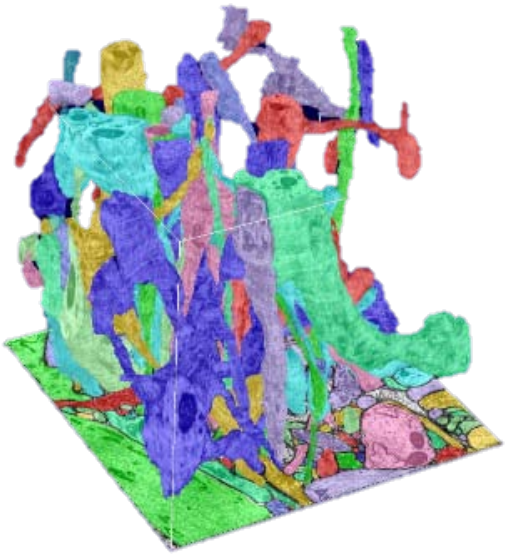
Connectome Workflow



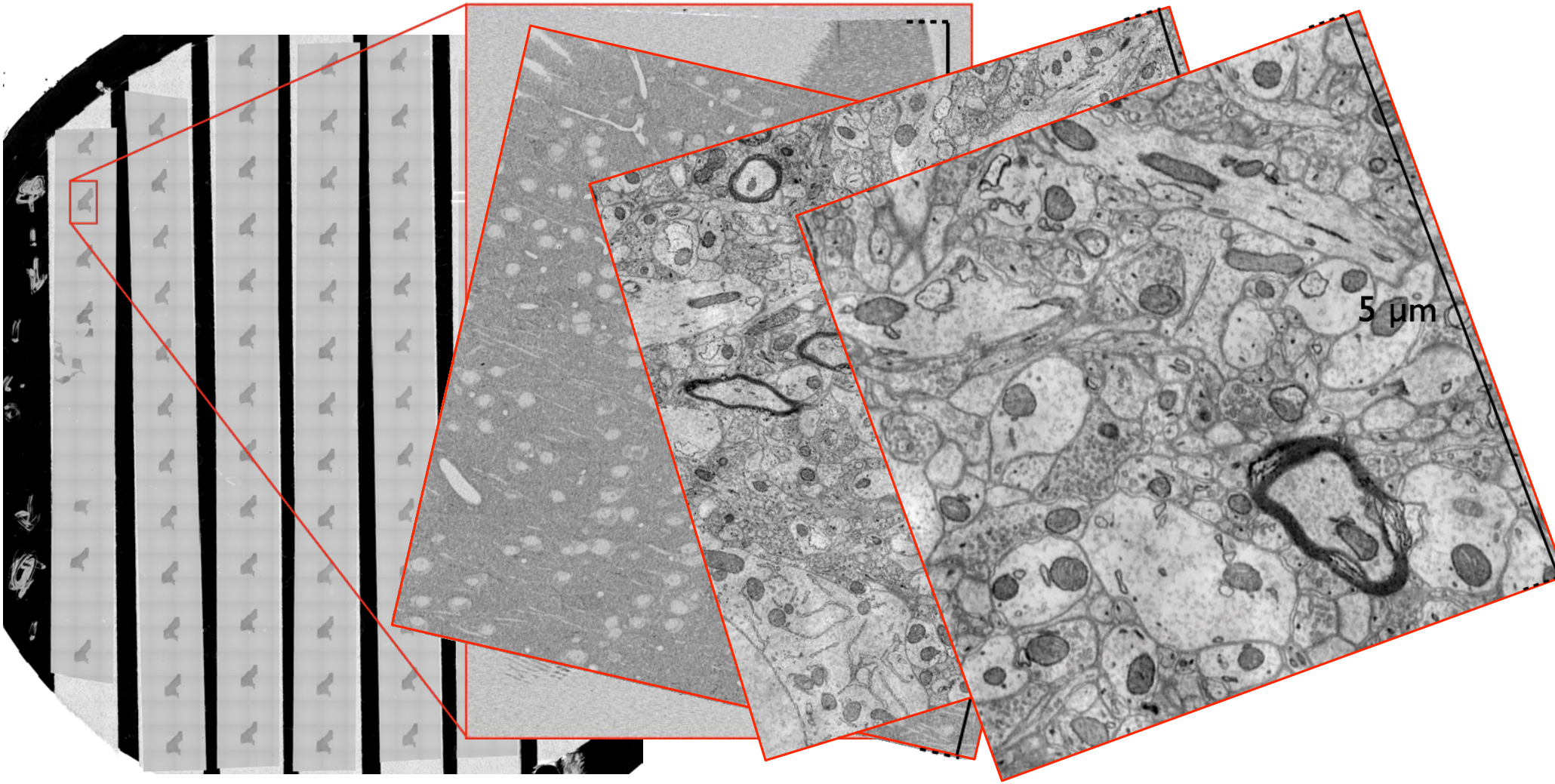




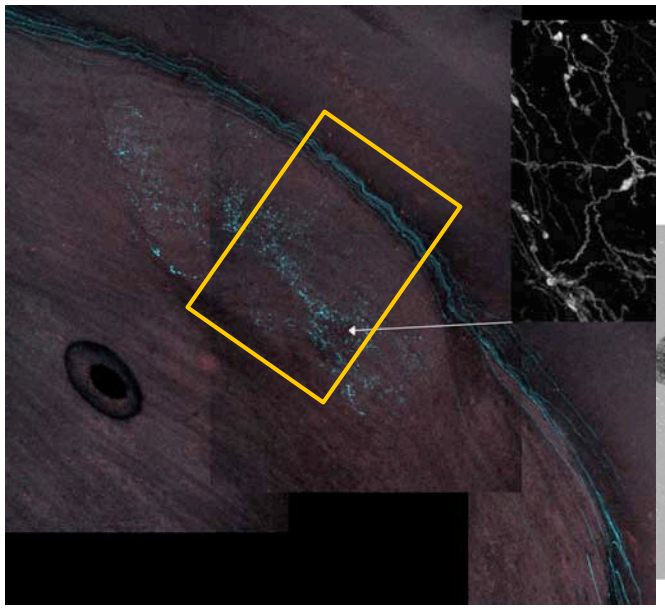


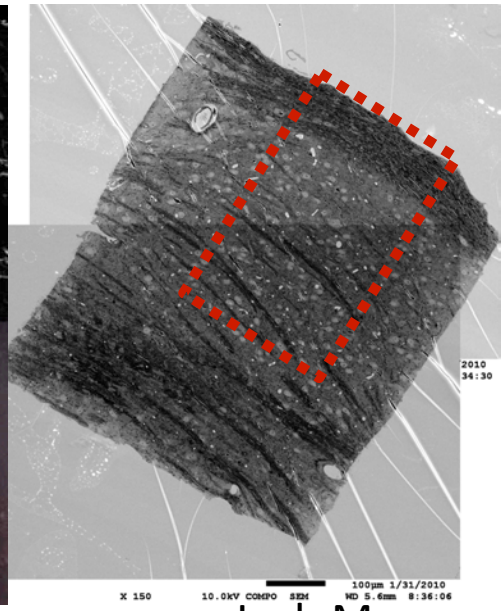


Electron Microscopy



The Data Challenge





Josh Morgan

- Pixel resolution: 3-5 nm
- Slice thickness: 30-50 nm
- 1 mm^3: 200k x 200k pixels x 20k slices

  40 Gpixels x 20k = 800 TB

CS Challenges

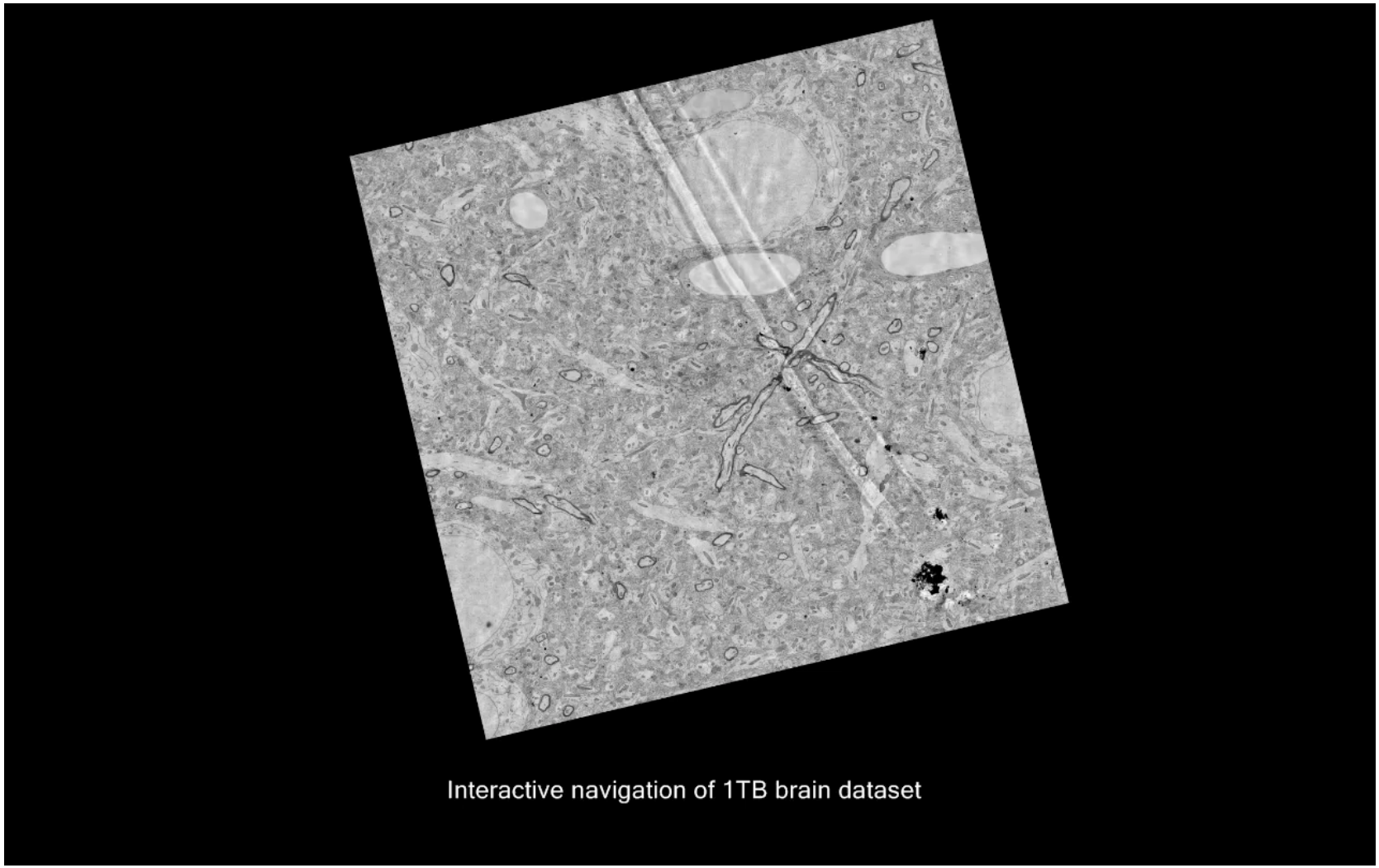
- Stitching and alignment of overlapping tiles
- 3D registration of sections
- Visualization
- 3D reconstruction
- Synapse detection
- Network analysis

CS Challenges

- Stitching and alignment of overlapping tiles
- 3D registration of sections
- **Visualization**
- **3D reconstruction**

- Synapse detection
- Network analysis

Neurotrace



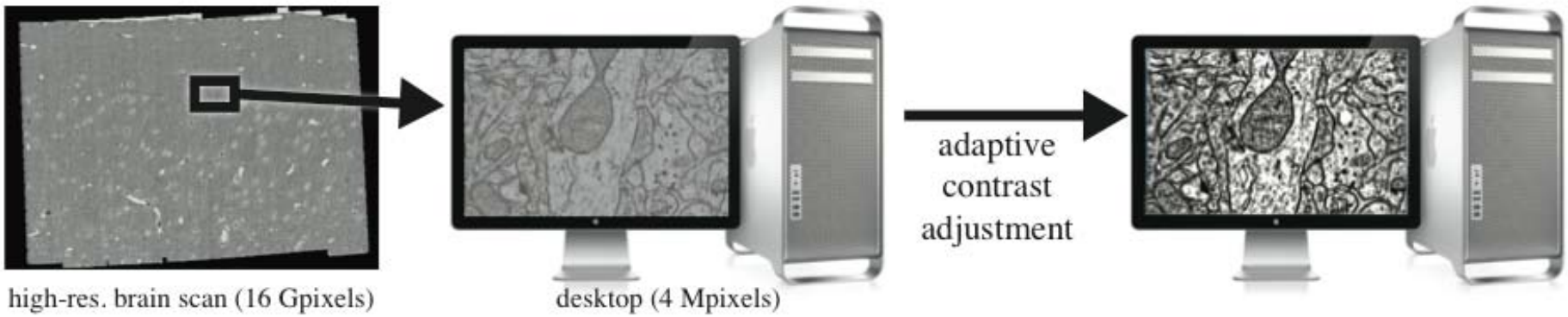
[Jeong et al., TVCG 2009]

Existing Methods

- Global image pyramid (e.g., Photoshop)
- Preprocessing required
- Not optimal for integration of new image tiles

Display-Aware Processing

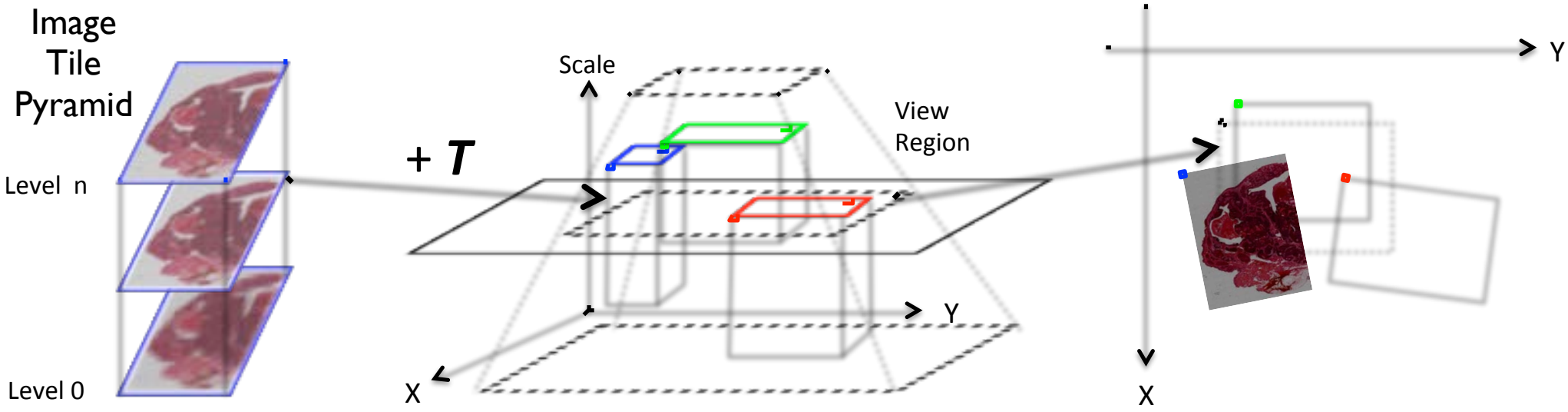
- Take into account and process only the visible pixels
- Design choice: Displayed image computed on-the-fly each time



[Jeong et al., ICCP 2011]

Reference Space

- Virtual coordinate system for images
- On-the-fly resampling of *only* visible pixels

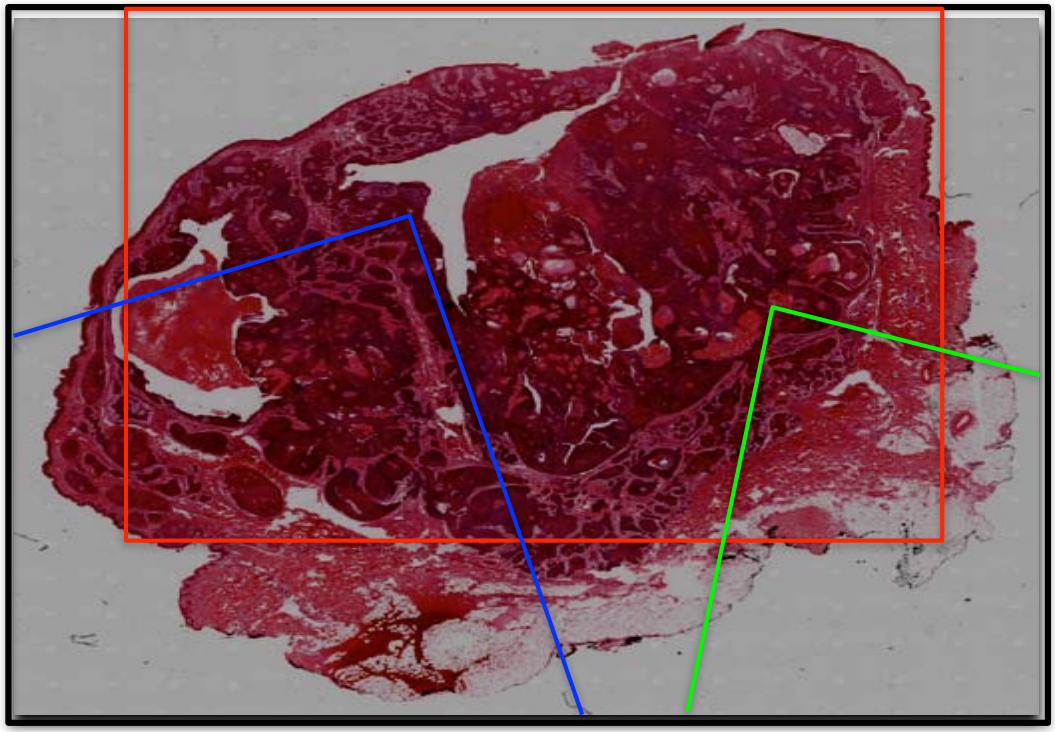


Data Space (Virtual) Reference Space Screen Space

[Jeong et al., ICCP 2011]

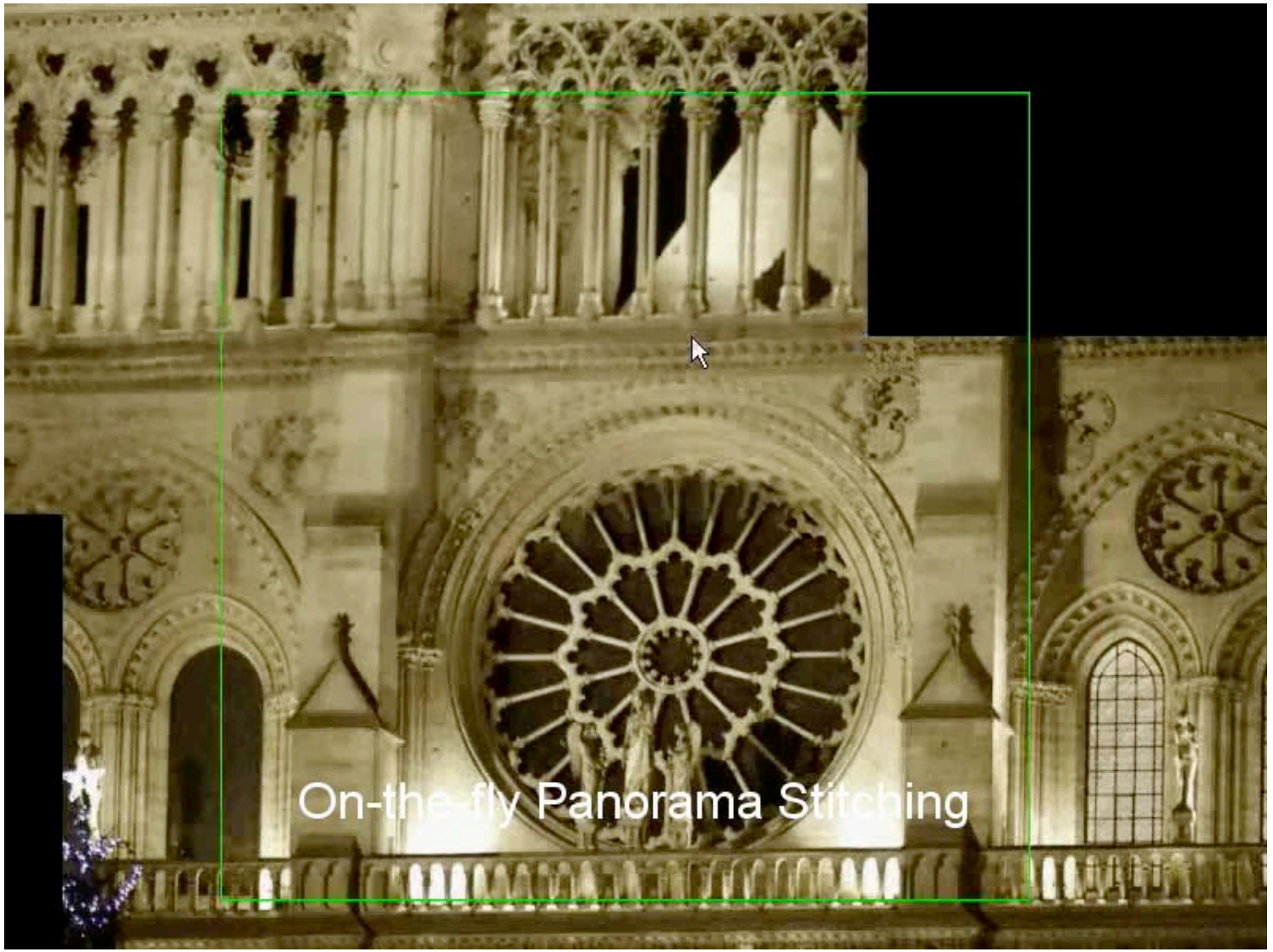
Display Space

- GPU-accelerated resampling
- Display-aware operations
  - Alignment
  - Blending
  - Color editing



[Jeong et al., ICCP 2011]

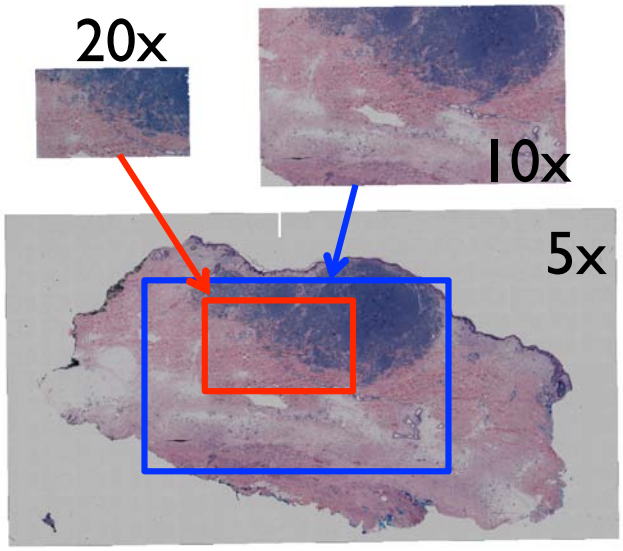
GPU Image Alignment

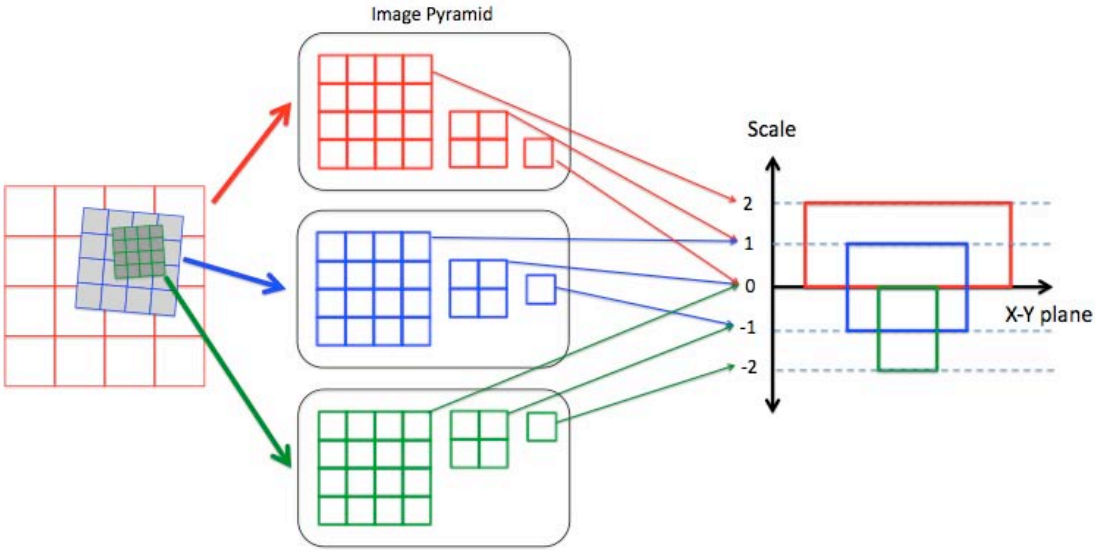


[Jeong et al., ICCP 2011]

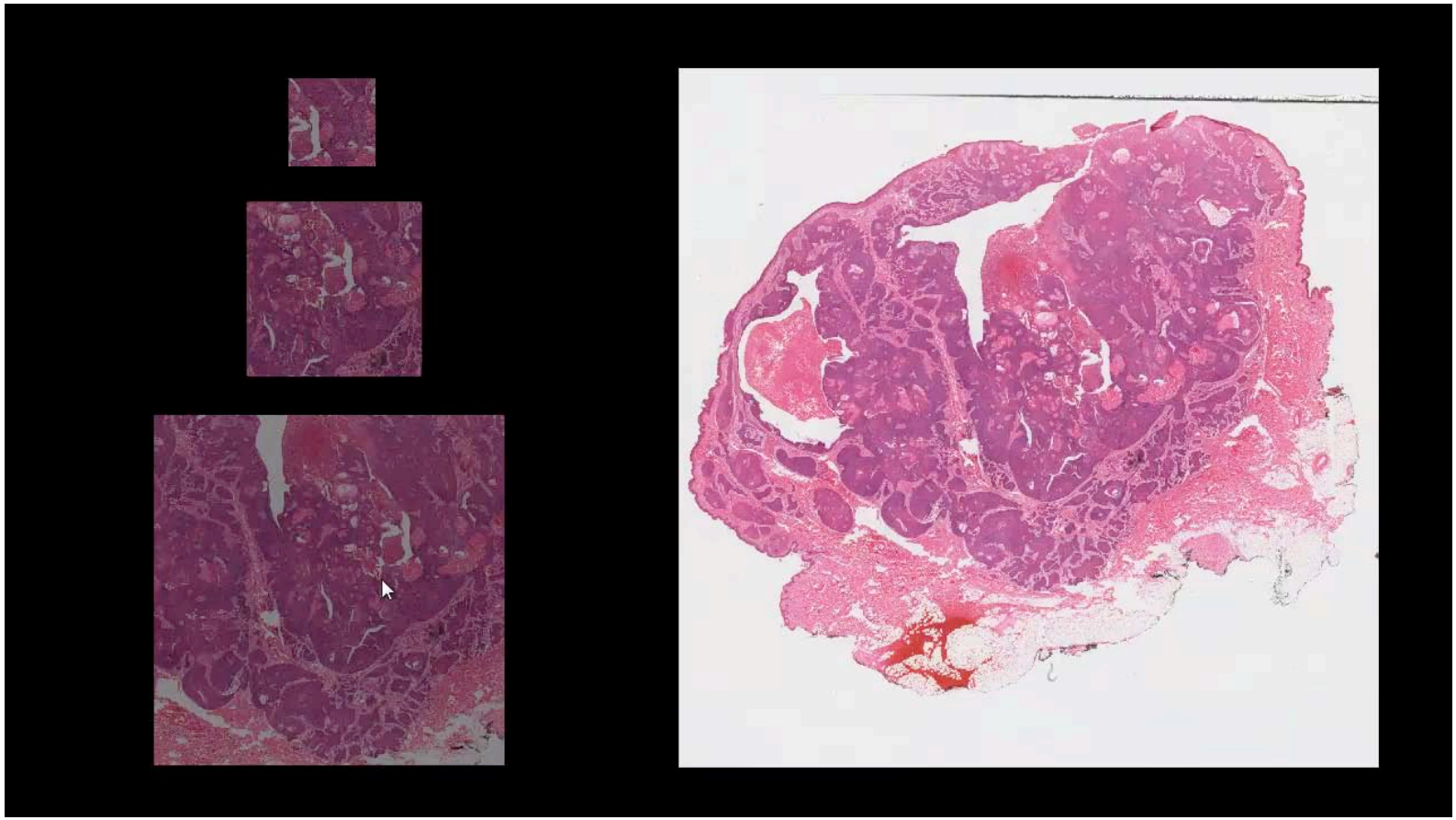
Adaptive Image Hierarchy

- Nested images with varying *resolutions*



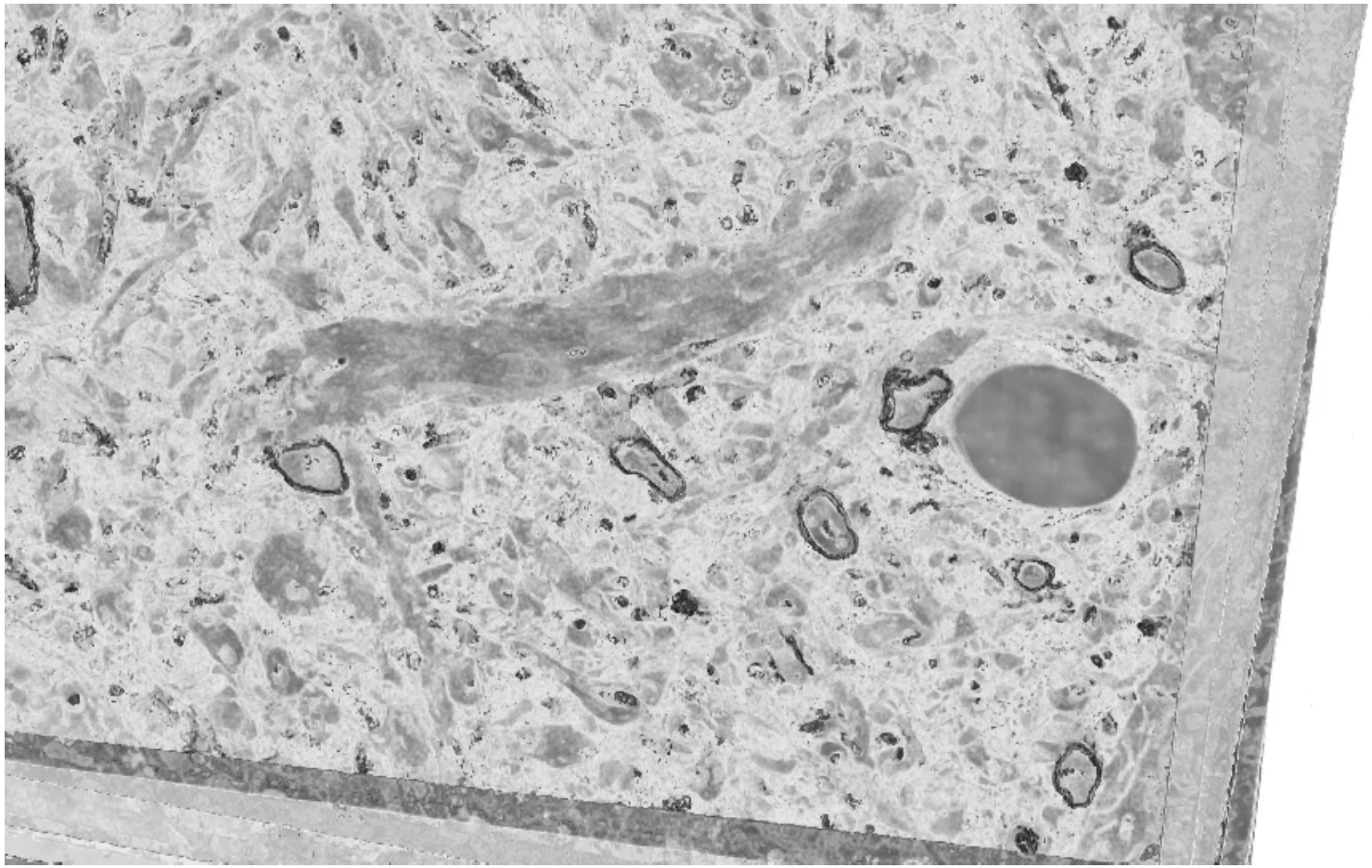


Adaptive Image Hierarchy



Volume Visualization

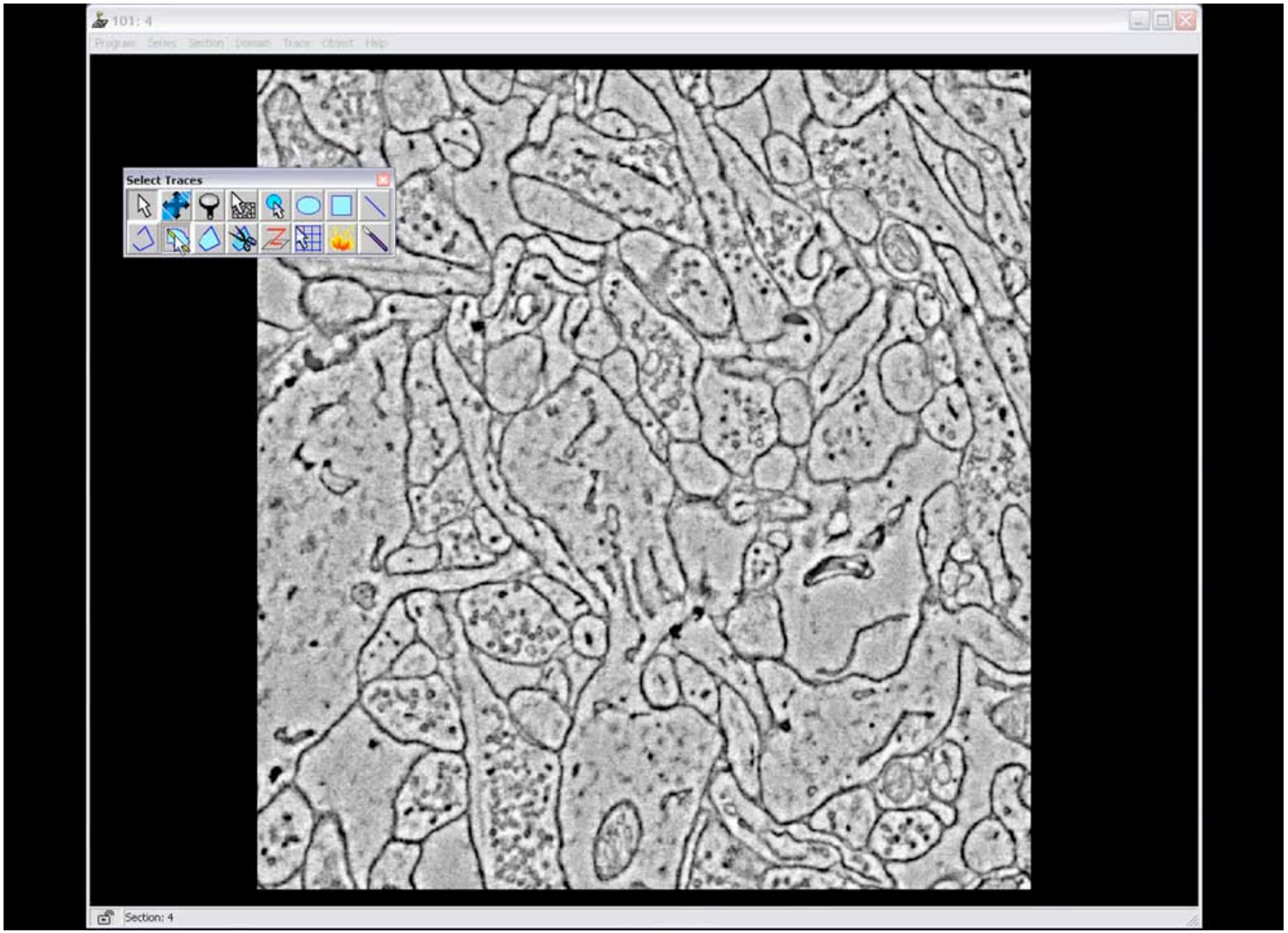
21,494 X 25,790 X 1850 = 955 GB



CS Challenges

- Stitching and alignment of overlapping tiles
- 3D registration of sections
- Visualization
- **3D reconstruction**
- Network analysis

Manual Reconstruction



[Reconstruct]

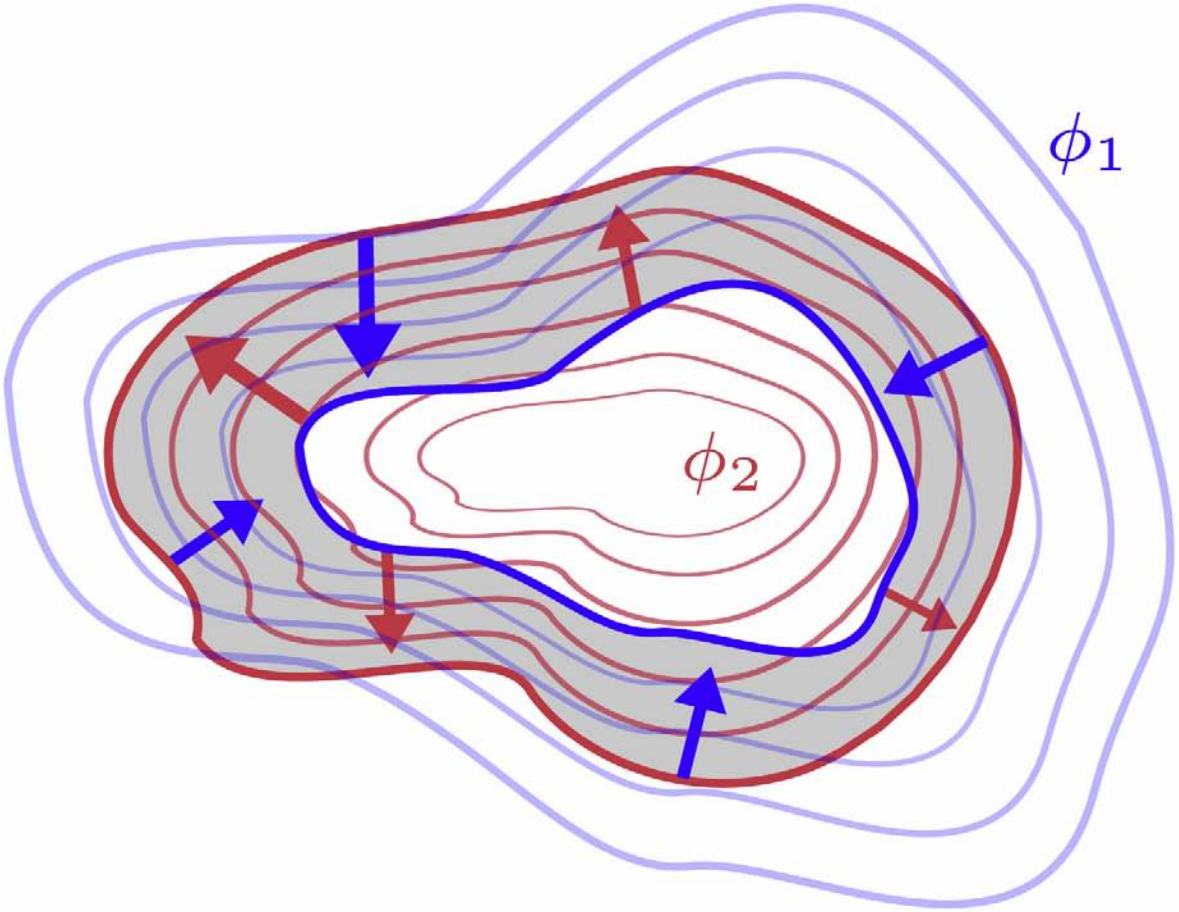
Active Ribbons

Section 1

[Vazquez et al., CVPR 09]

Active Ribbons

Implicit deformable model based on multiphase level sets and force fields



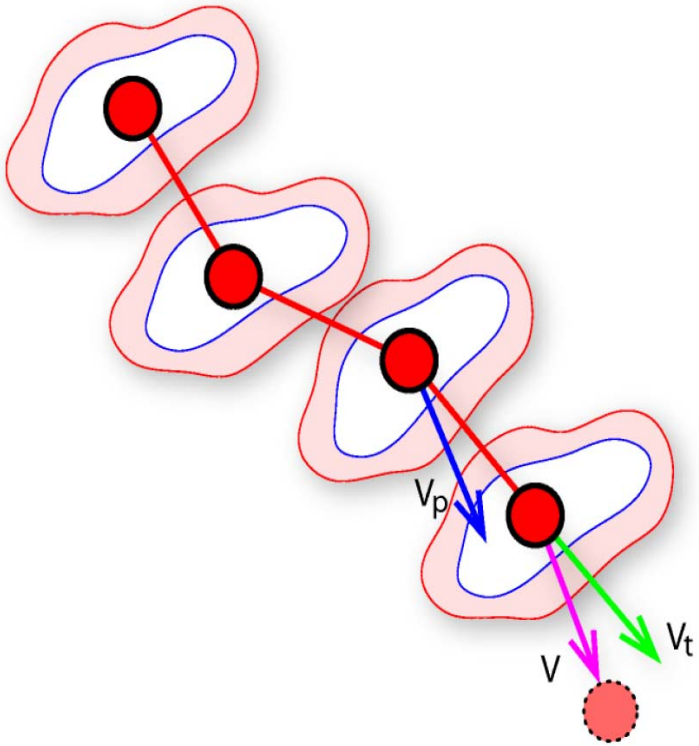
$$v_1 = \frac{\nabla \phi_2}{\sigma_1}$$

$$v_2 = -\frac{\nabla \phi_1}{\sigma_2}$$

[Vazquez et al., CVPR 09]

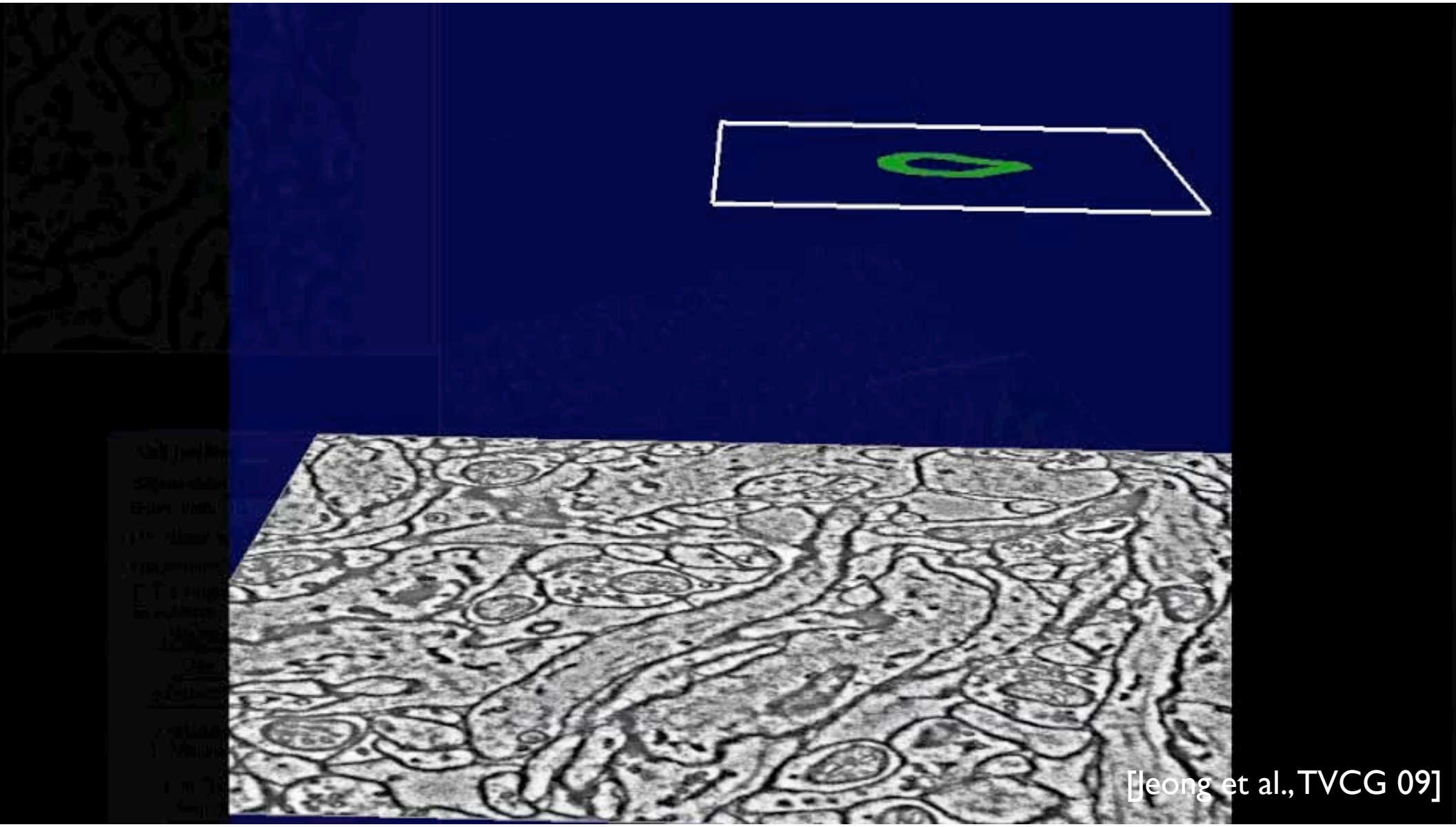
GPU Processing

Real-time editing and 3D tracking, 0.5 s/section



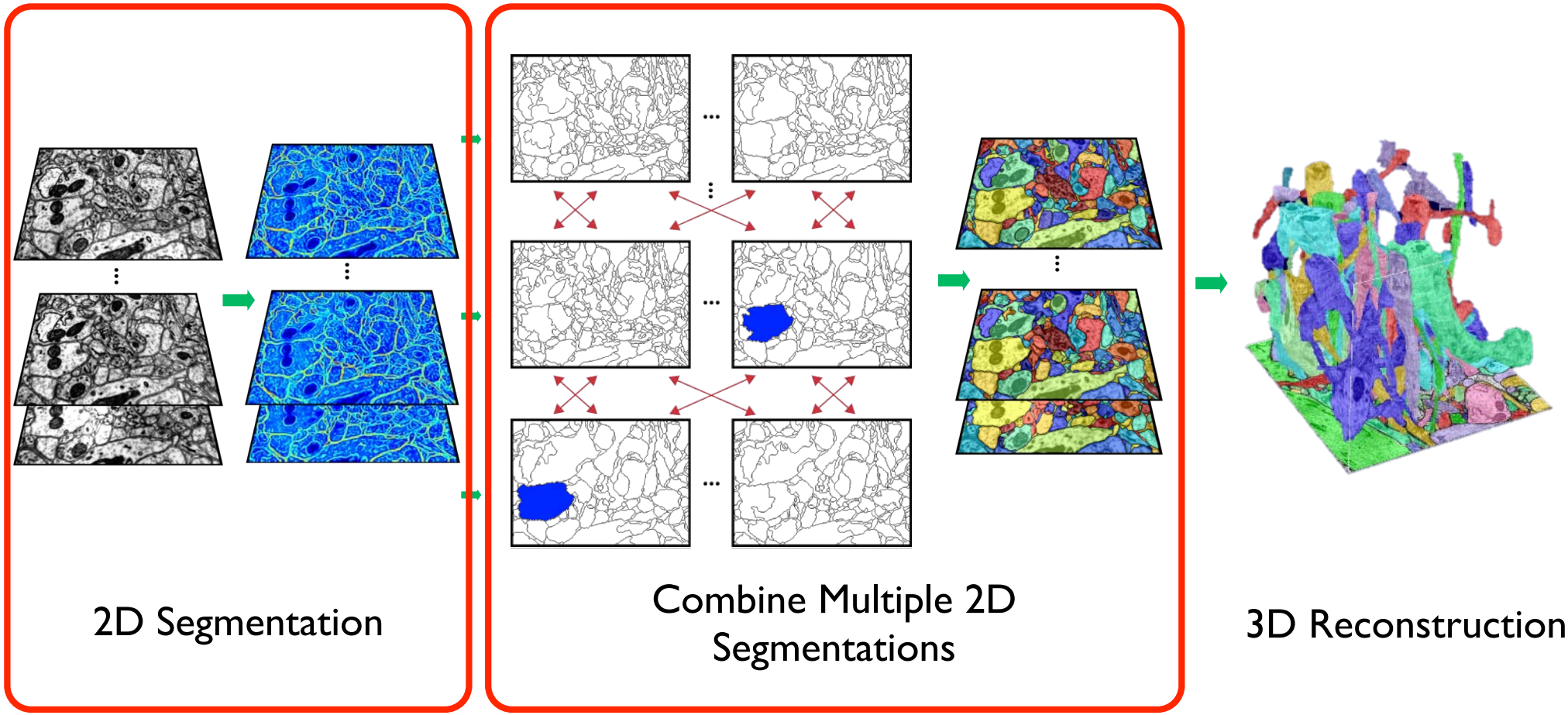
[Jeong et al., TVCG 09]

User-Guided Reconstruction



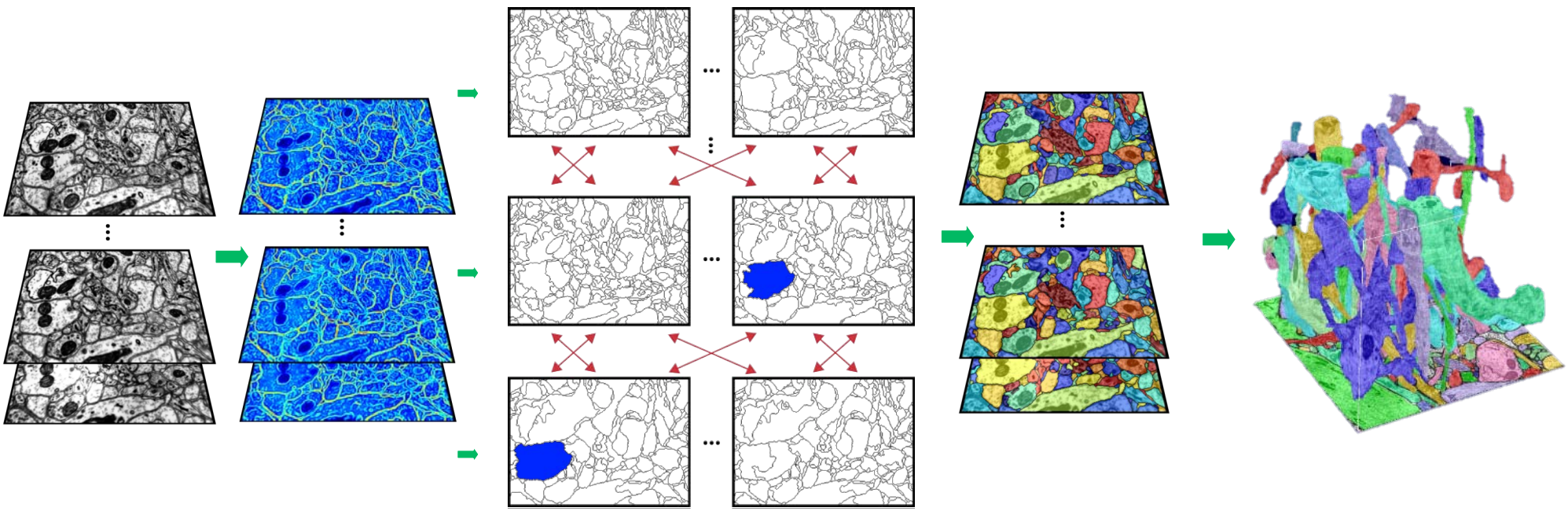
[Jeong et al., TVCG 09]

Automatic Reconstruction



[Kaynig et al., CVPR 10]
[Vazquez et al., ICCV 2011]

Automatic Reconstruction



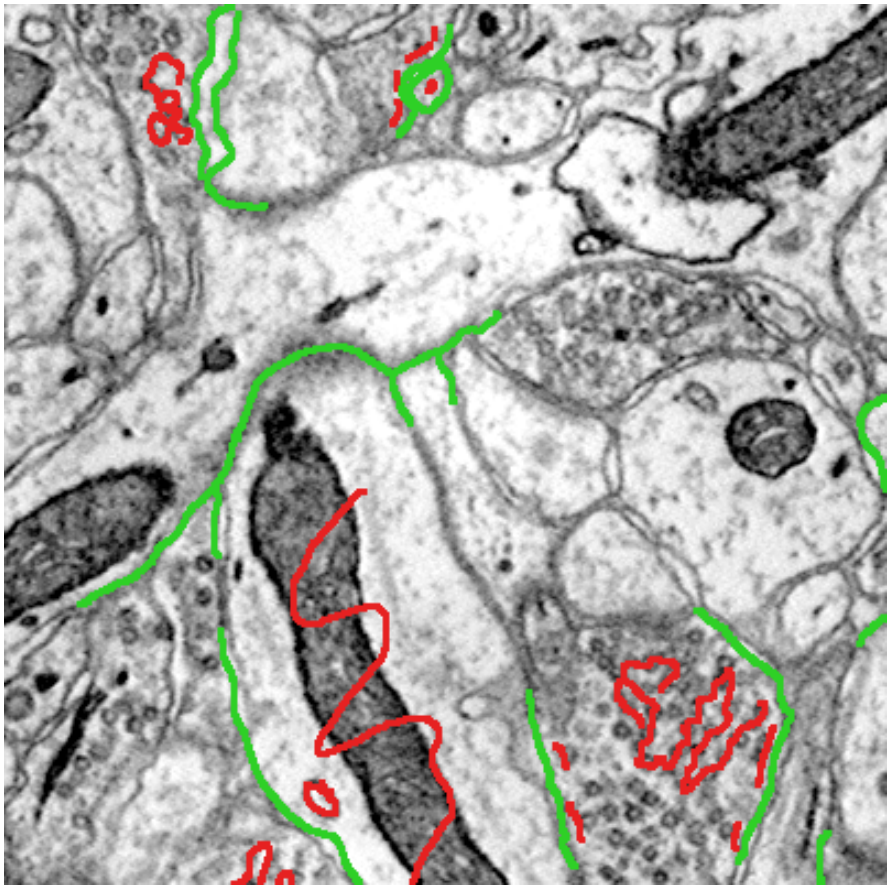
Membrane probability maps

Enumerate and evaluate combinations

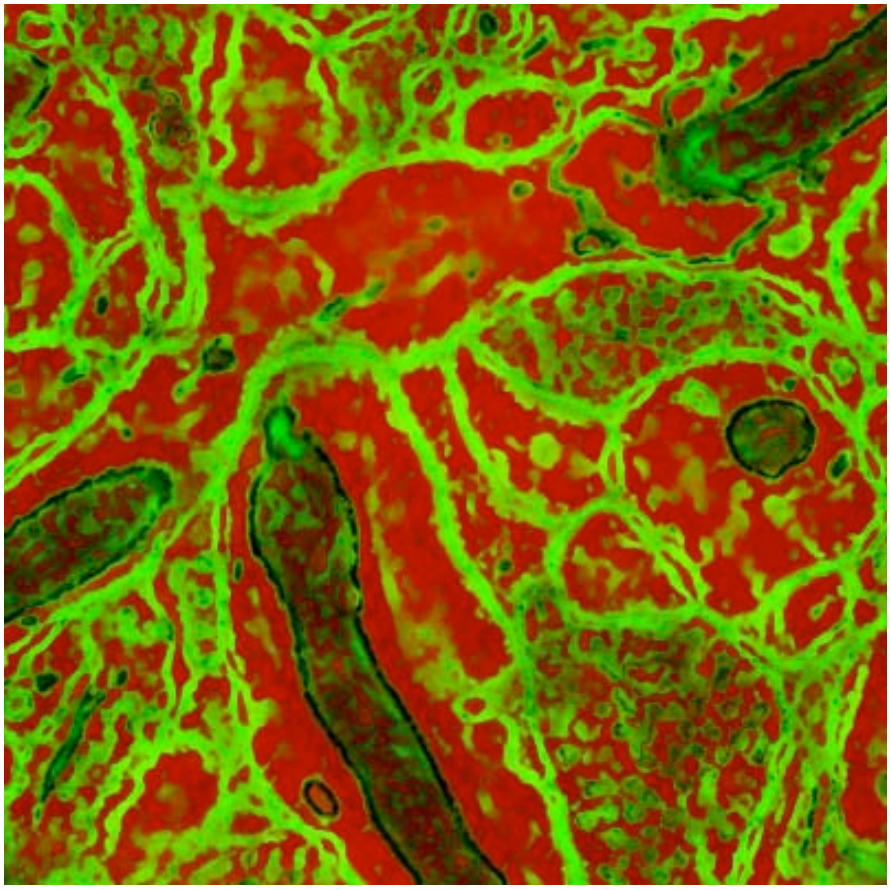
Globally consistent 3D reconstruction

[Kaynig et al., CVPR 10]
[Vazquez et al., ICCV 2011]

Sparse Interactive Annotation

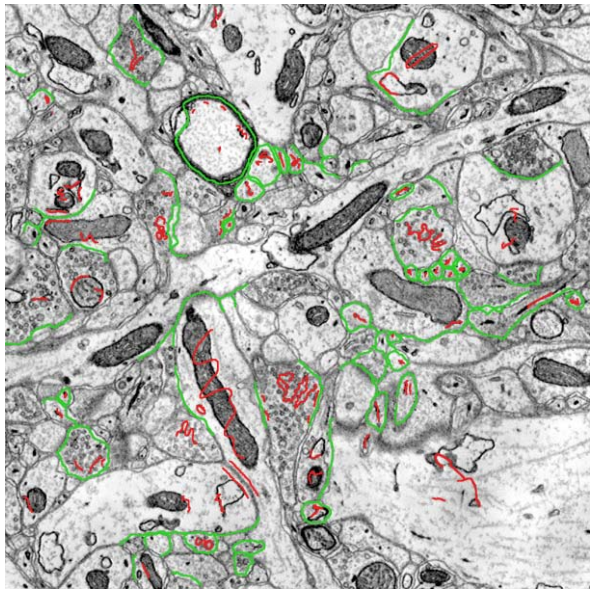
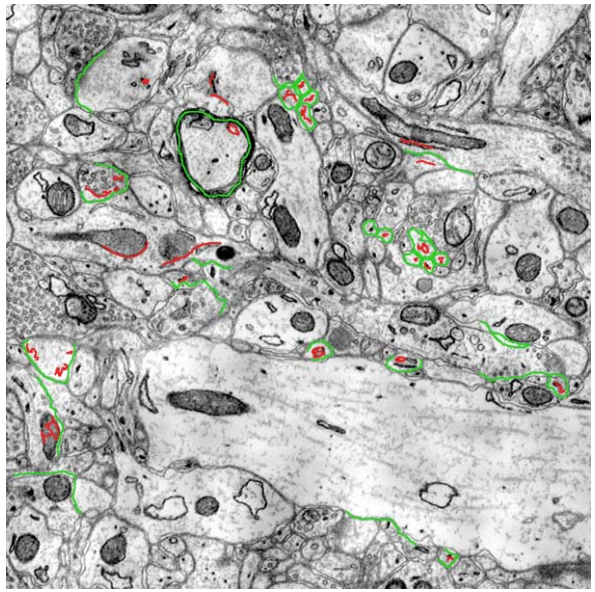
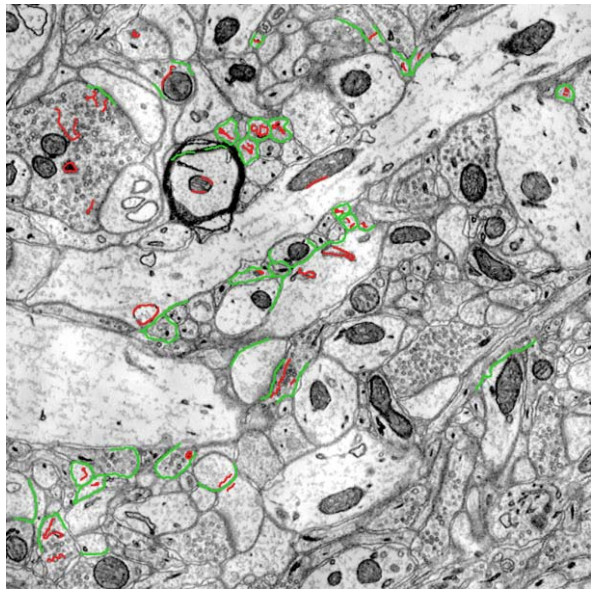
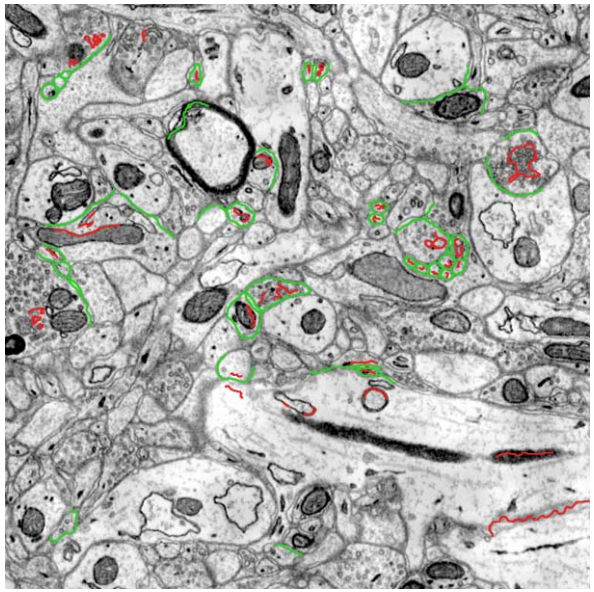
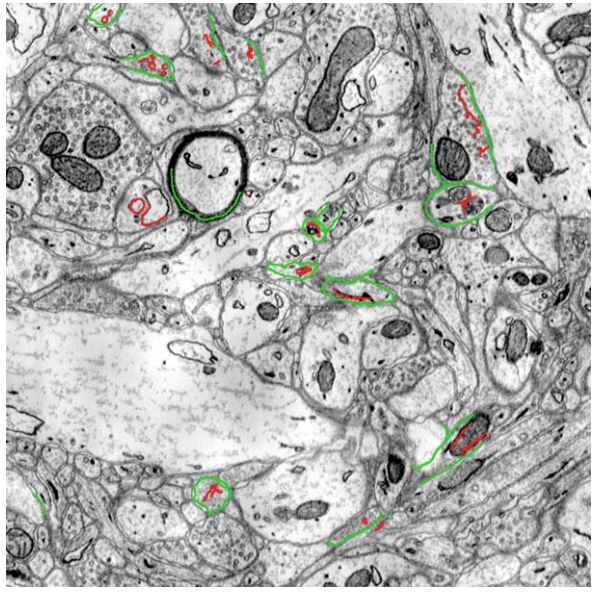
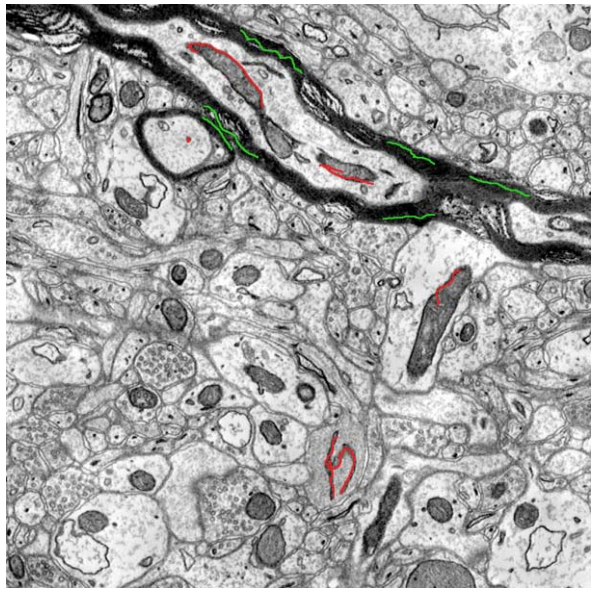


Manual annotation

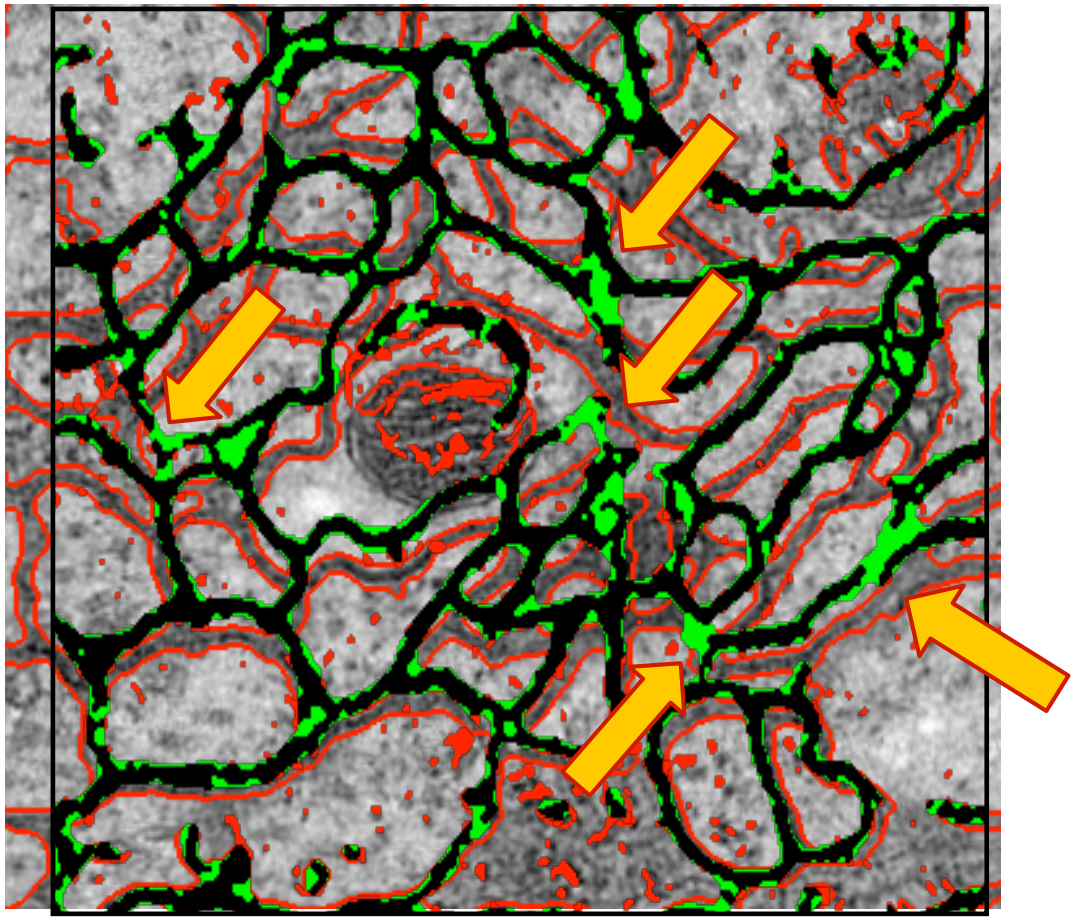


Visual feedback from classification

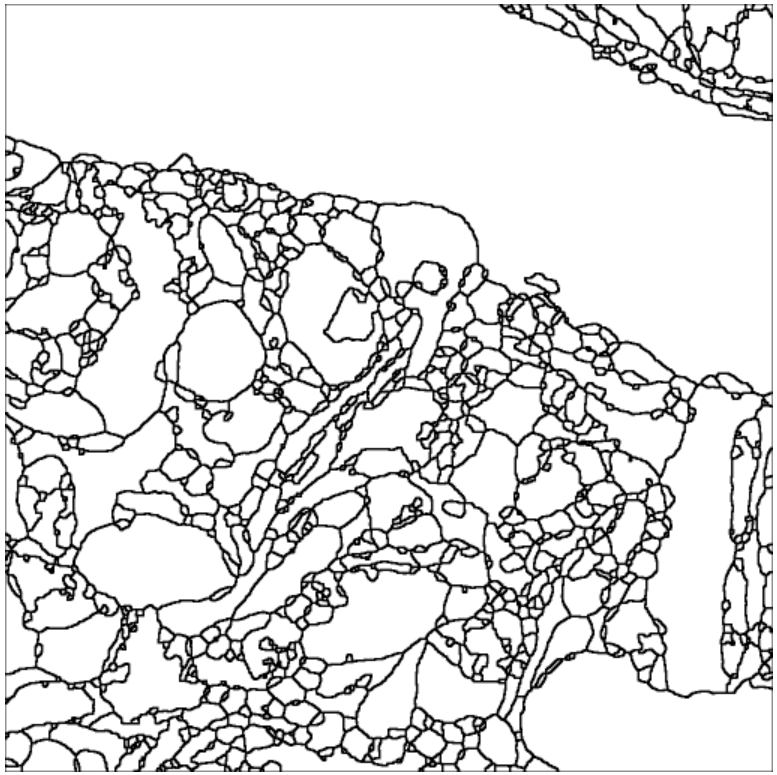
The whole training set! (<1% annotated)

Qualitative Evaluation



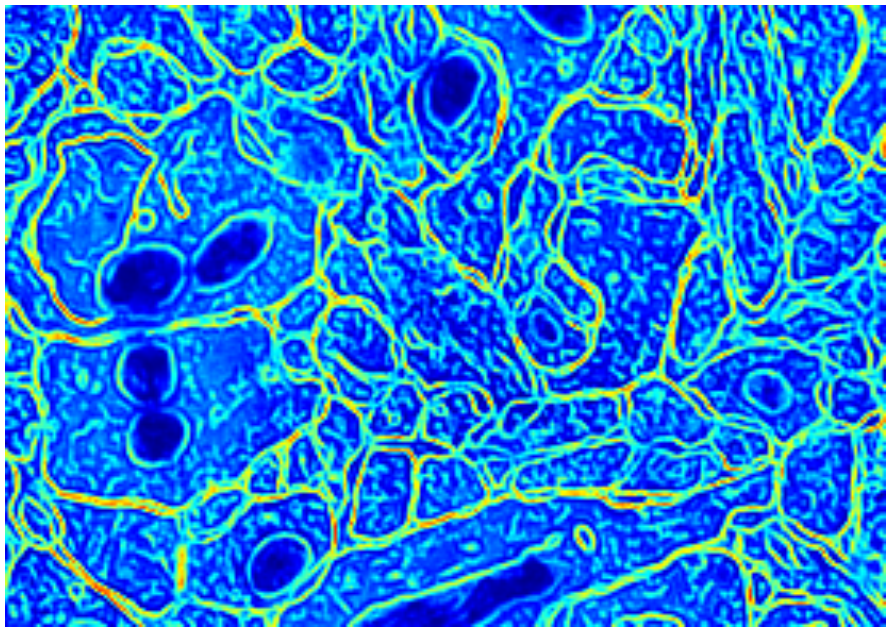
Gap Completion

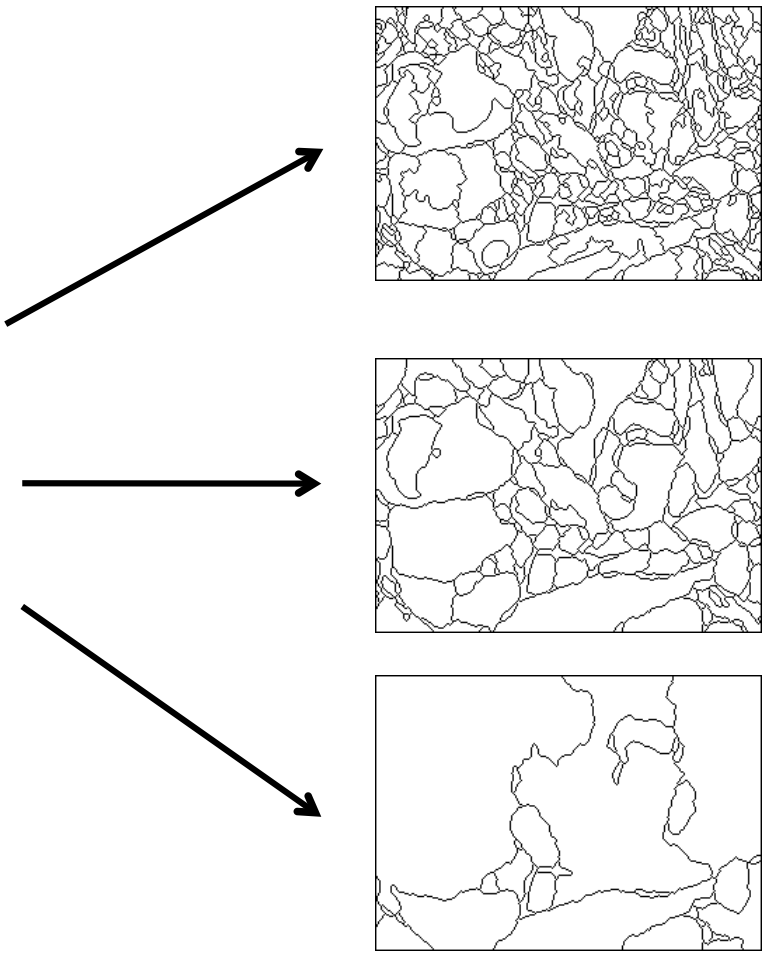


$$E(y) = \sum_{p \in P} E_{rf}(y_p) + \lambda_{gc} \sum_{p \in P, q \in N_2(p)} E_{gc}(y_p, y_q) + \lambda_s \sum_{p \in P, q \in N_2(p)} E_s(y_p, y_q)$$

[Kaynig et al., CVPR 10]

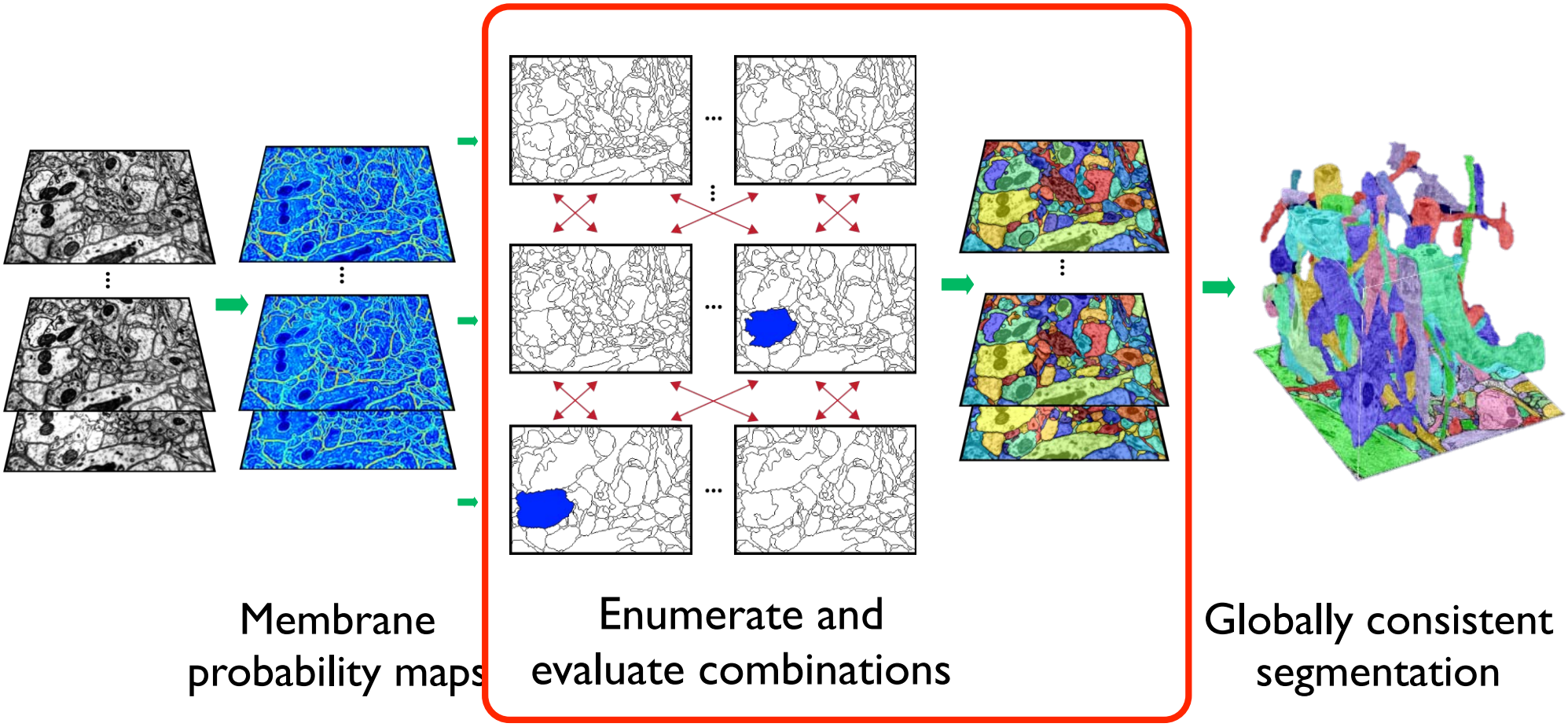
Multiple Segmentations





Closed contours

The Pipeline



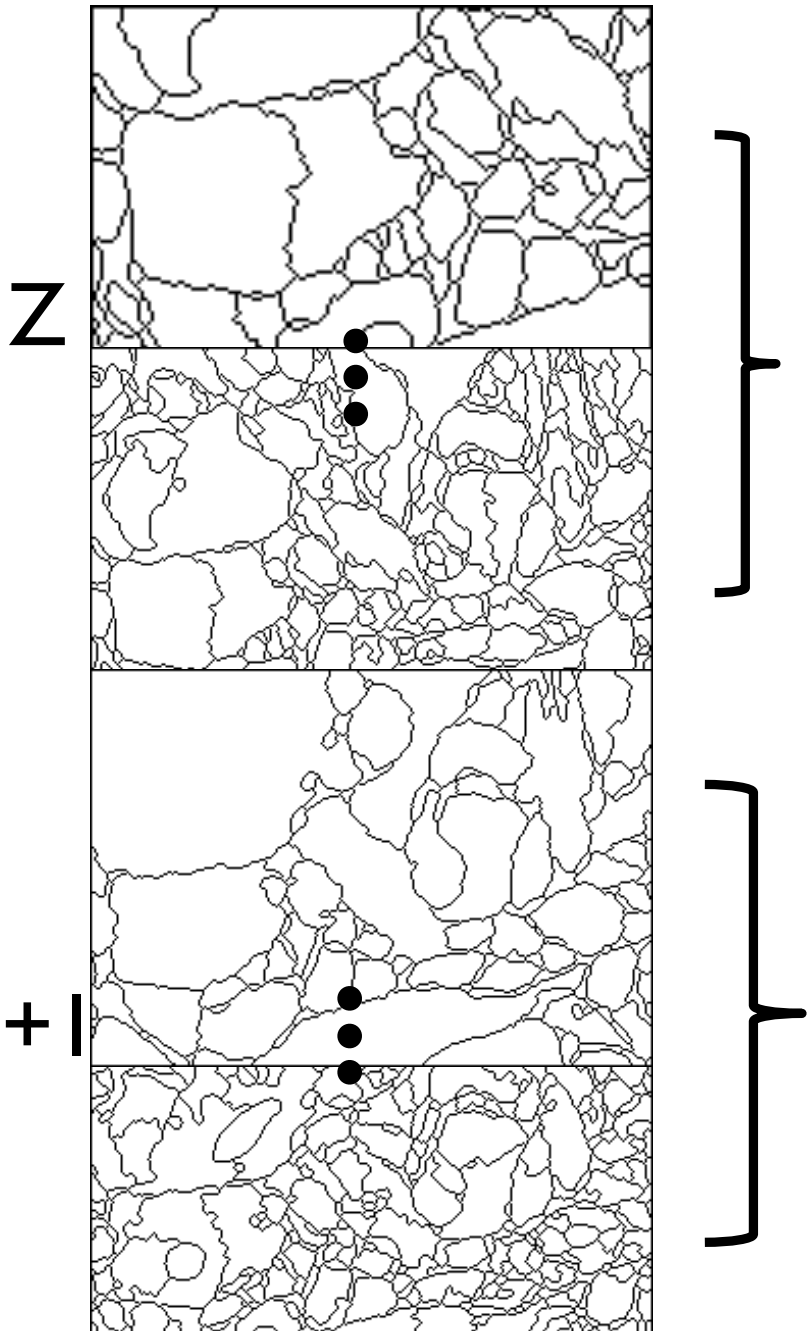
Membrane probability maps

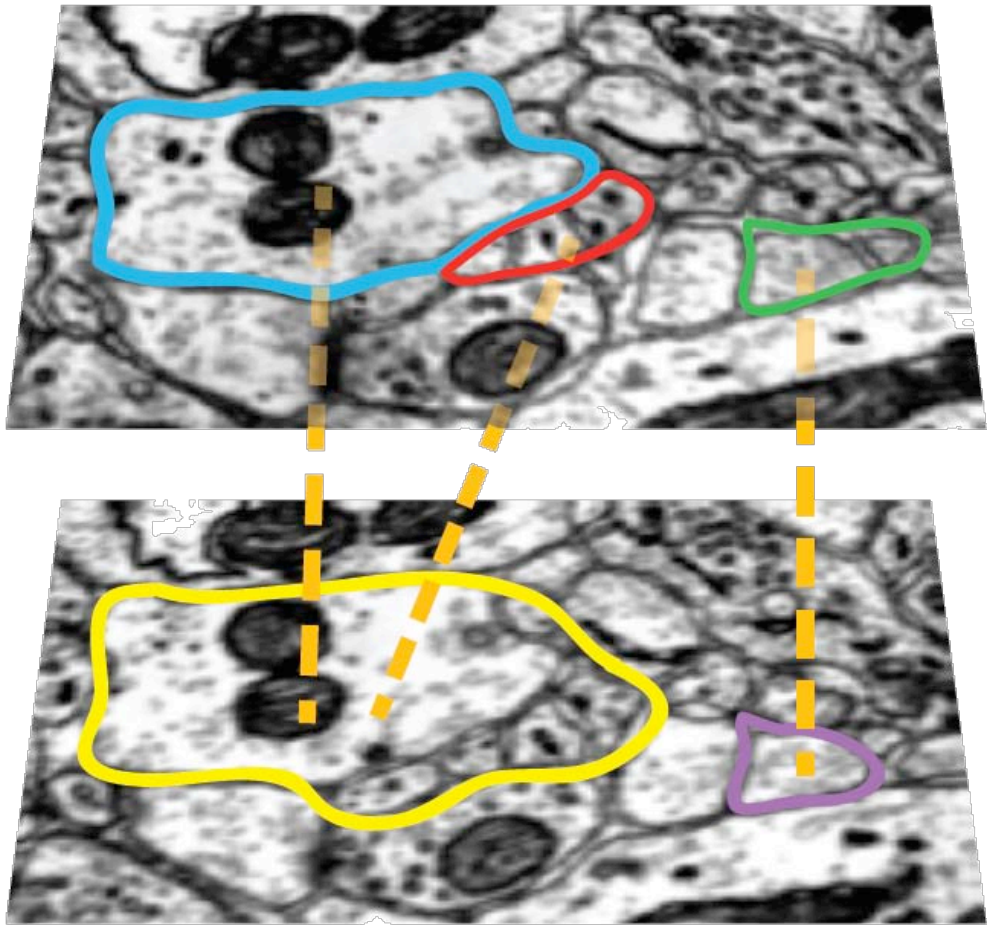
Enumerate and evaluate combinations

Globally consistent segmentation

[Kaynig et al., CVPR 10]
[Vazquez et al., ICCV 2011]

Enumerate 3D links

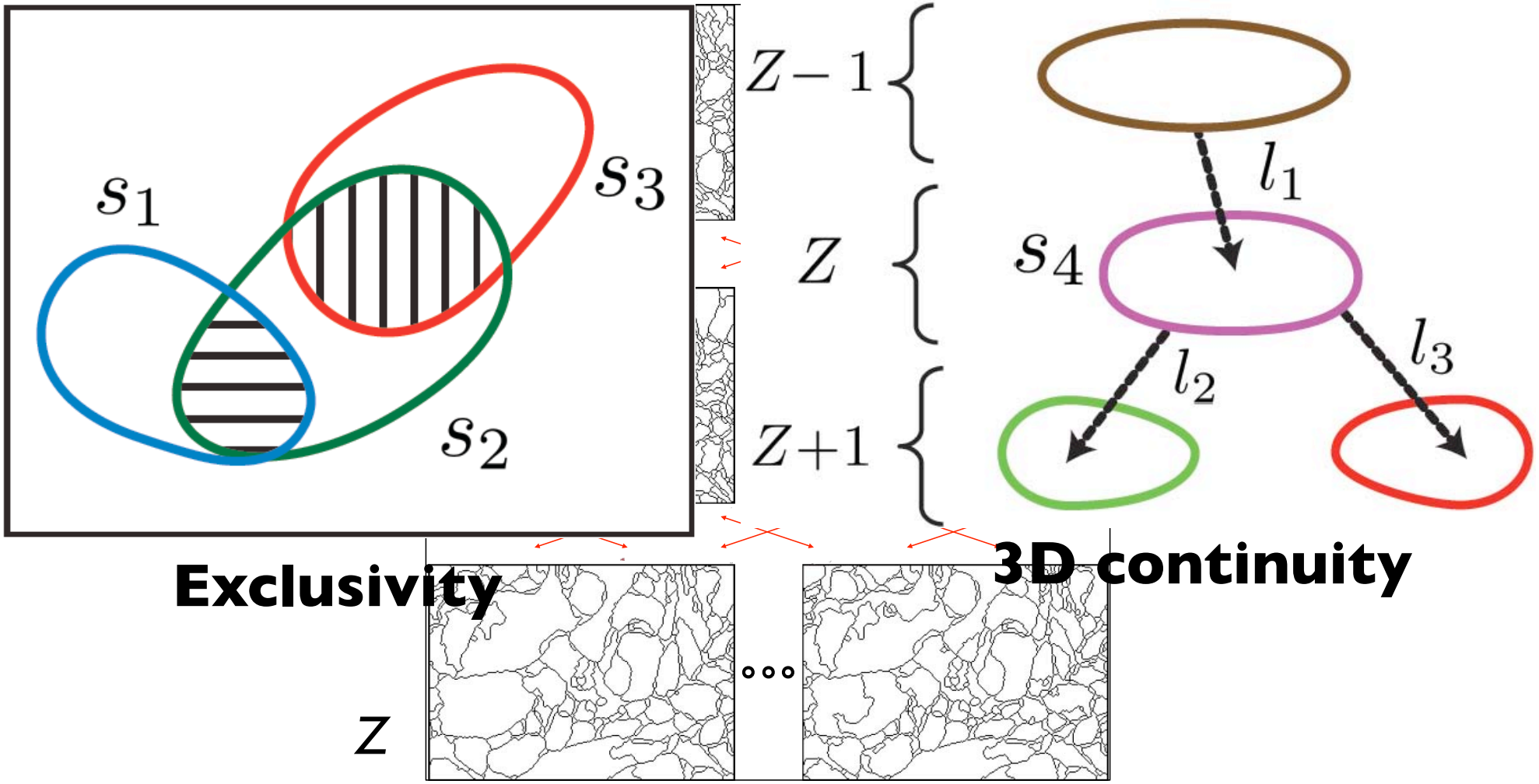




Assign a score to each
2D segment and 3D link

Modeling Fusion

Find the selection of segments and links
that gives us the total highest score



Modeling Fusion

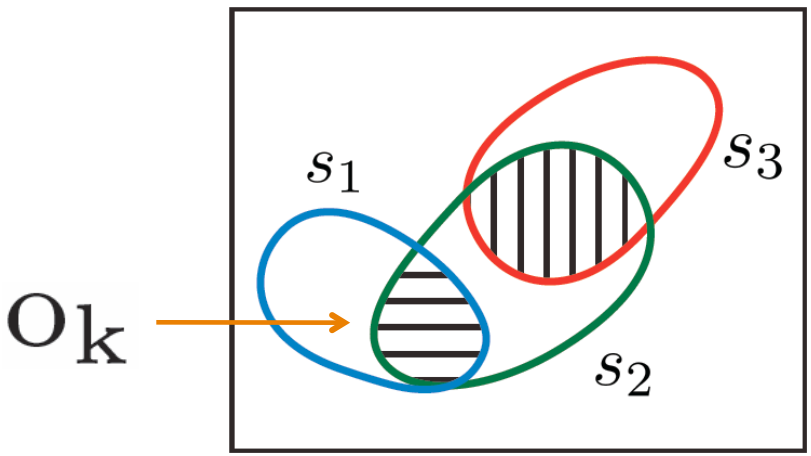
$$\arg\max_{\mathbf{s},\mathbf{l}} \sum_{i=1}^{S} \theta_{s_i} s_i + \sum_{j=1}^{L} \theta_{l_j} l_j$$

Fitness of segment i

Fitness of link j

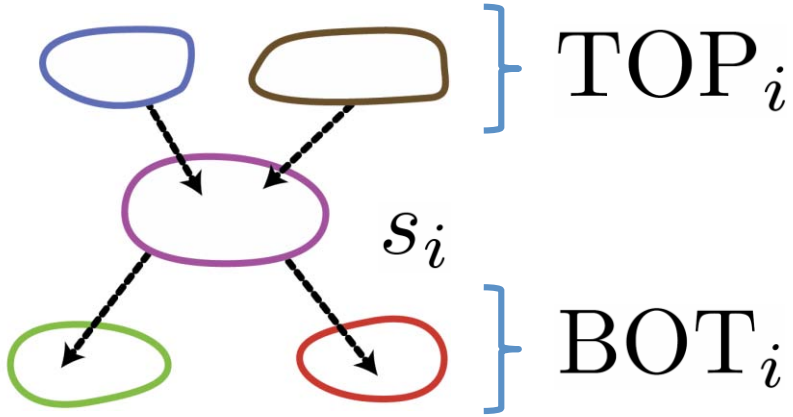
Subject to:

Exclusivity



$$\sum_{i \in O_k} s_i \leq 1$$

3D continuity

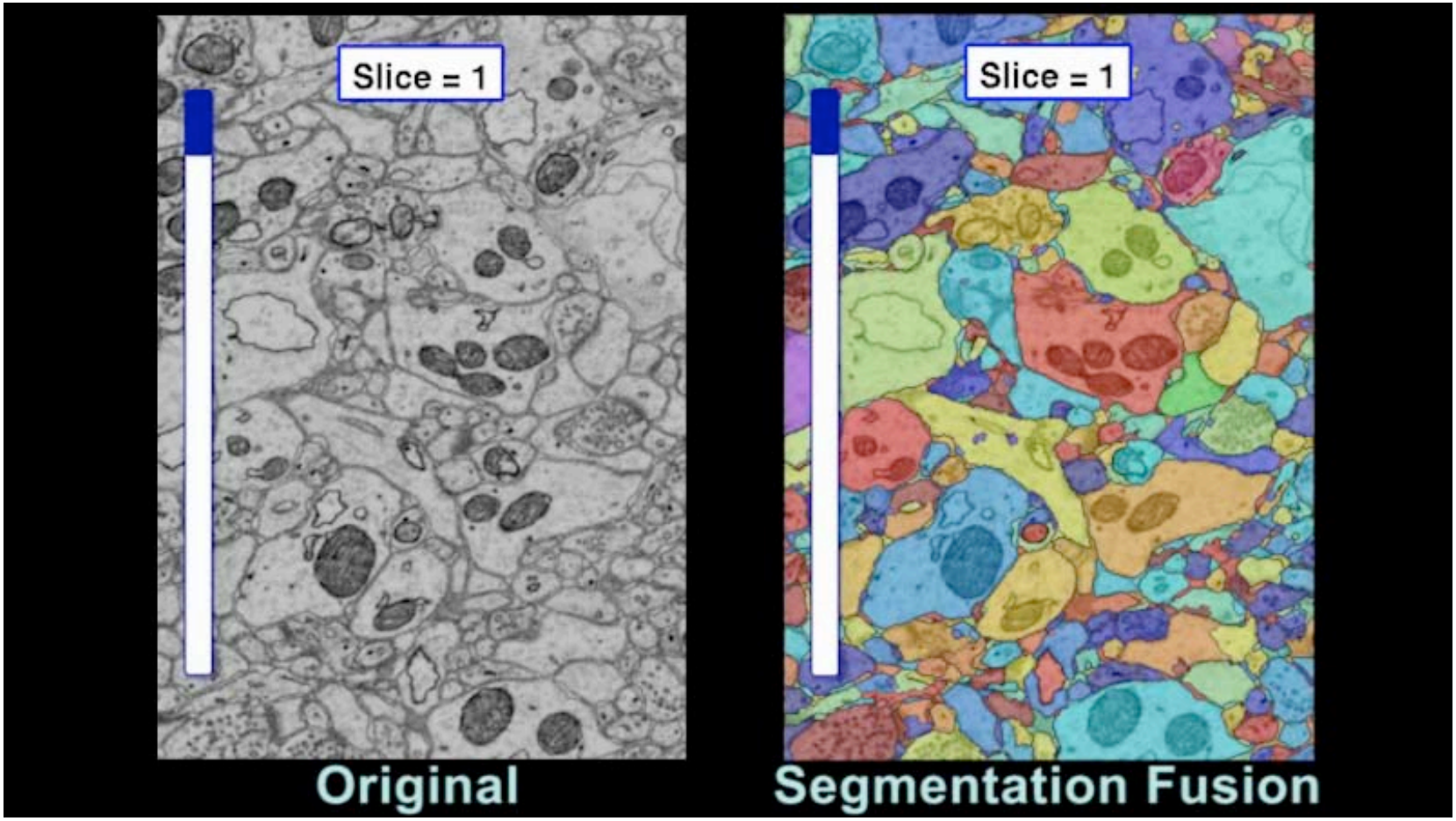


$$\sum_{j \in \mathrm{TOP_i}} l_j \leq s_i, \quad \sum_{j \in \mathrm{BOT_i}} l_j \leq s_i$$

Solving Fusion

- Constrained optimization using ILP solver
- Enumerating links is the slowest part
- 1000 x 1000 x 20 volume takes 30 mins
- Total time, including boundary probability maps, about 1 hour
- Match sub-blocks solving the assignment problem (max. weighted bipartite matching)

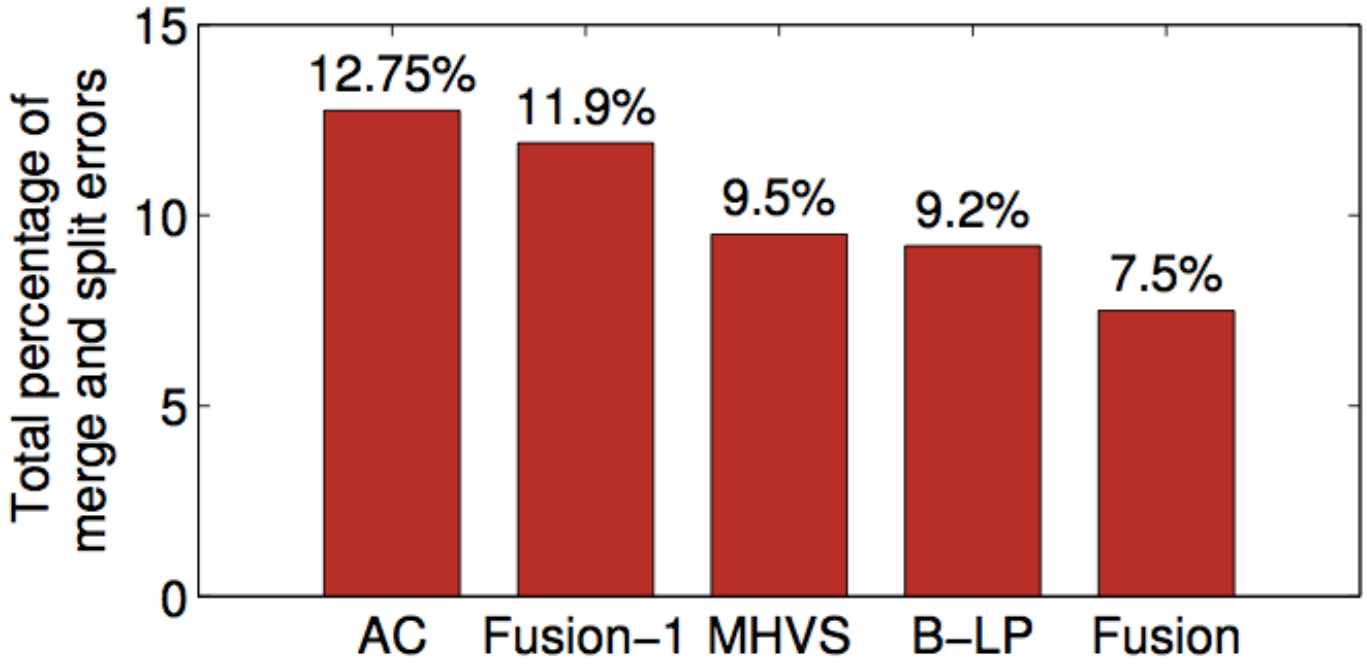
Results

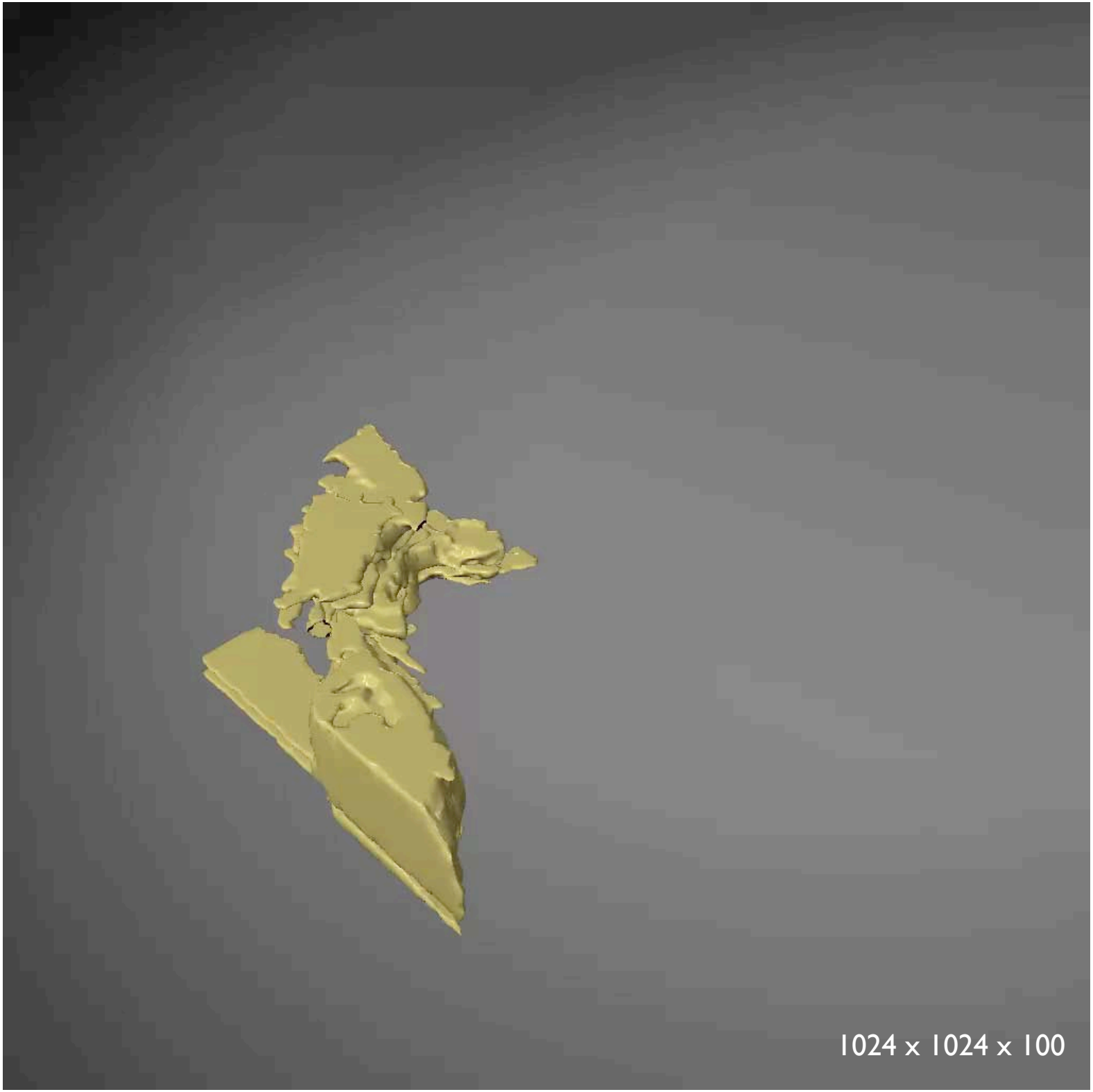


1,000 x 1,000 x 9

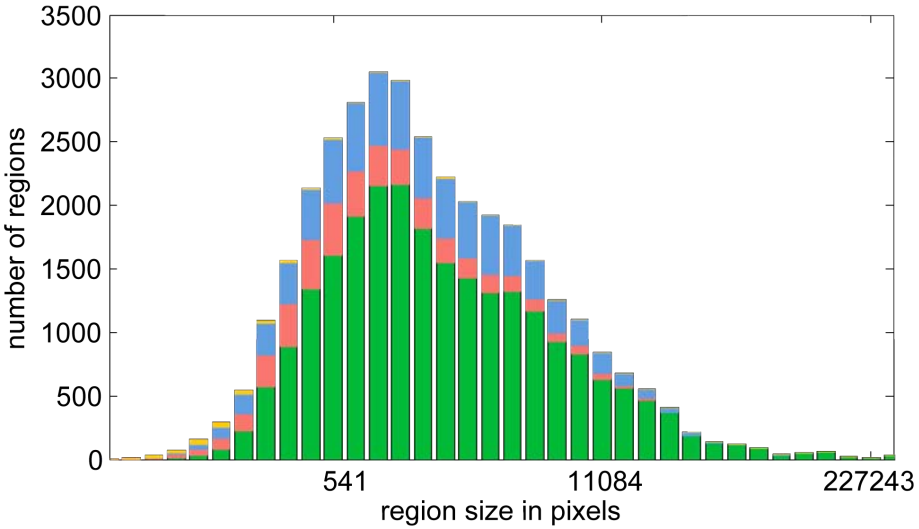
[Vazquez et al., ICCV 2011]

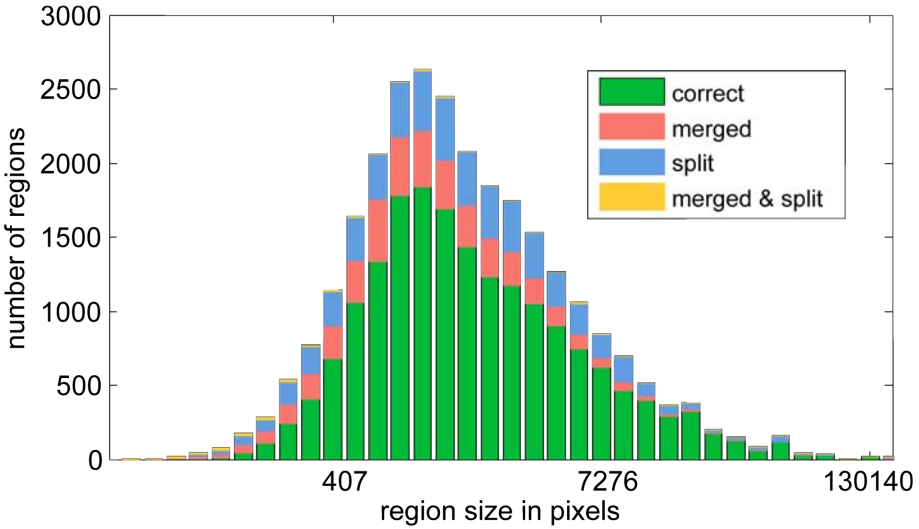
Error Comparison




1024 x 1024 x 100

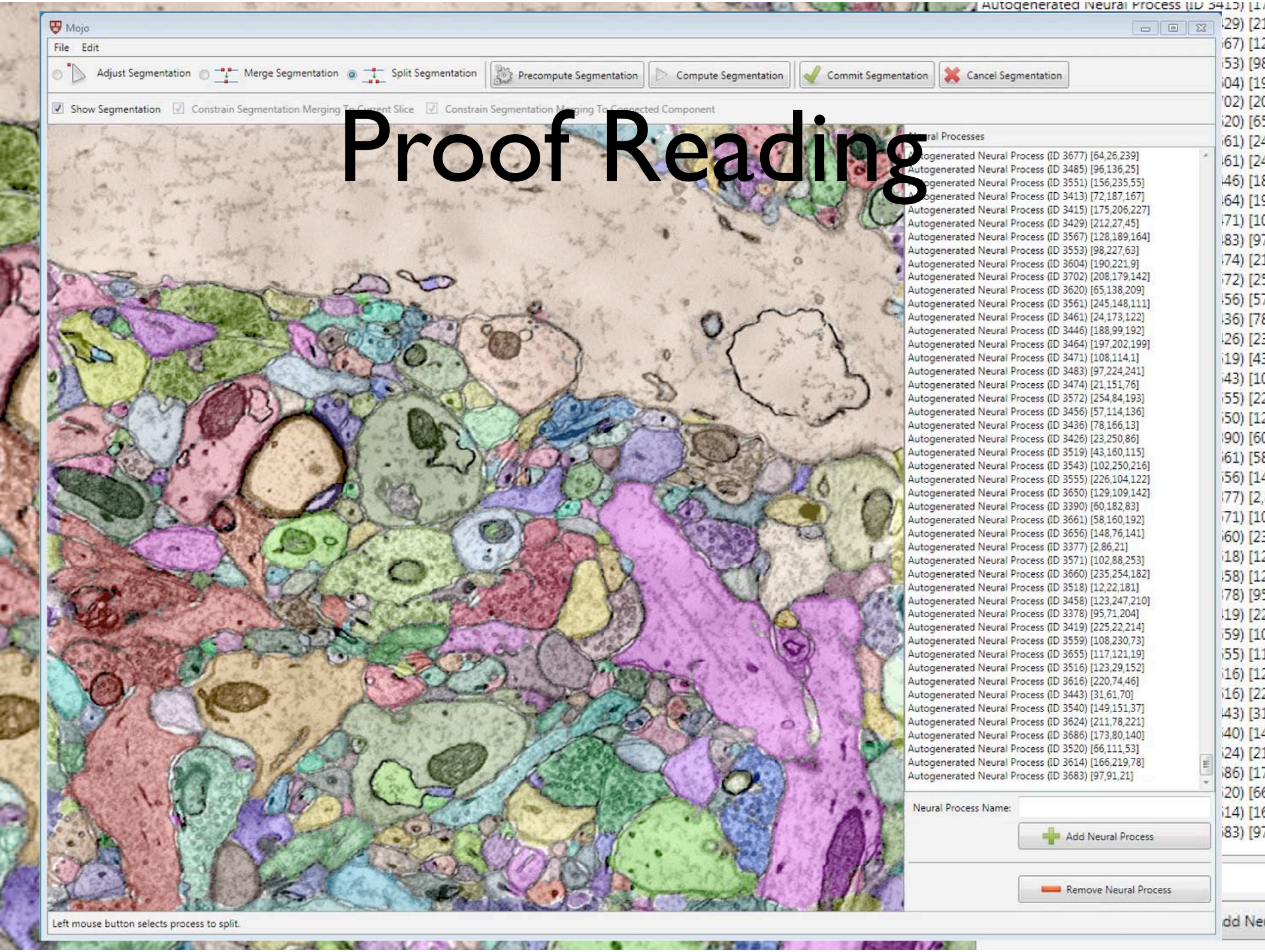
Quantitative Evaluation





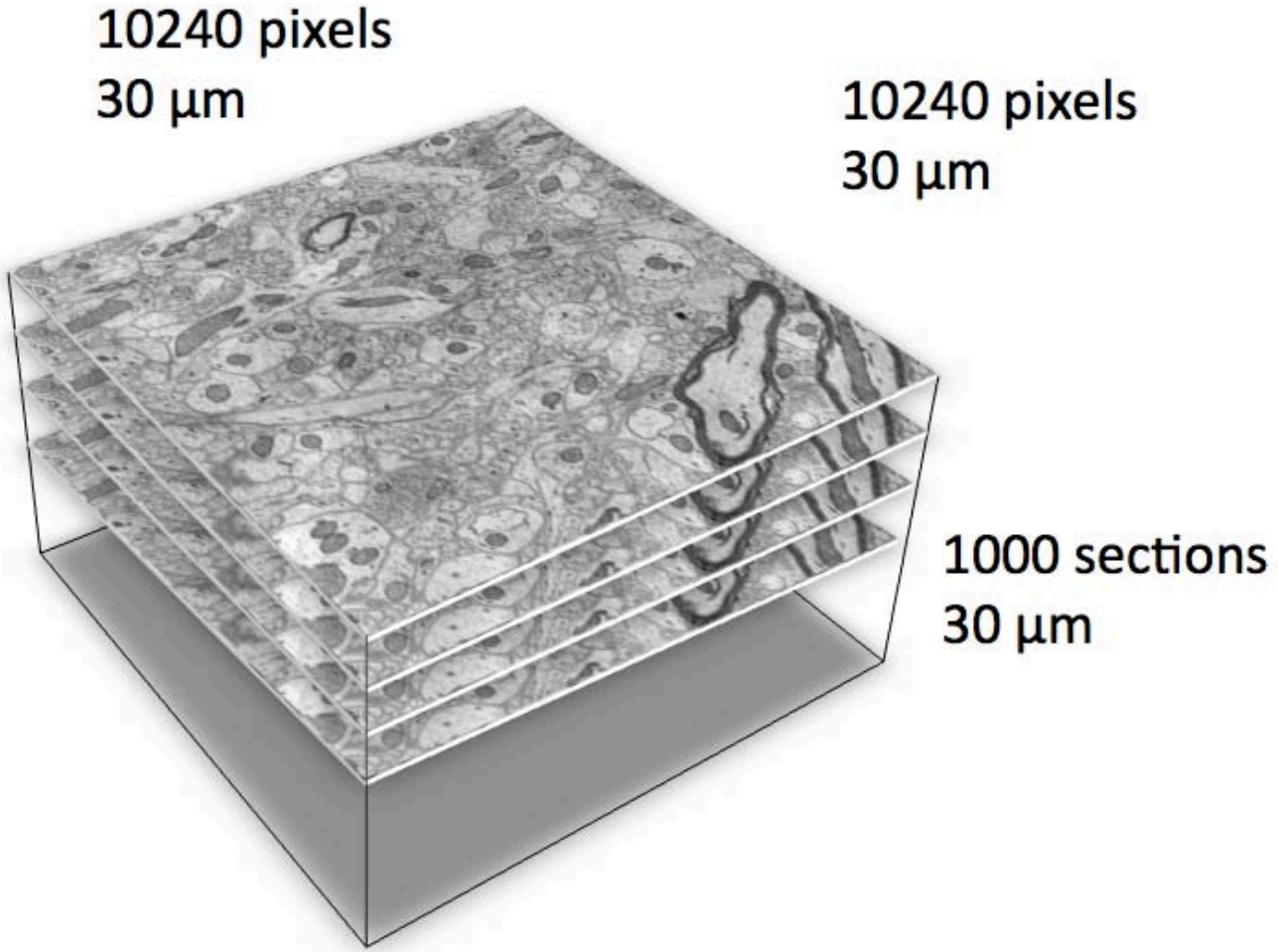
150 sections at 1024x1024 pixels
including 6 training images
correct segmentation covers:
69% ±4 of all regions
82% ±5 of all pixels

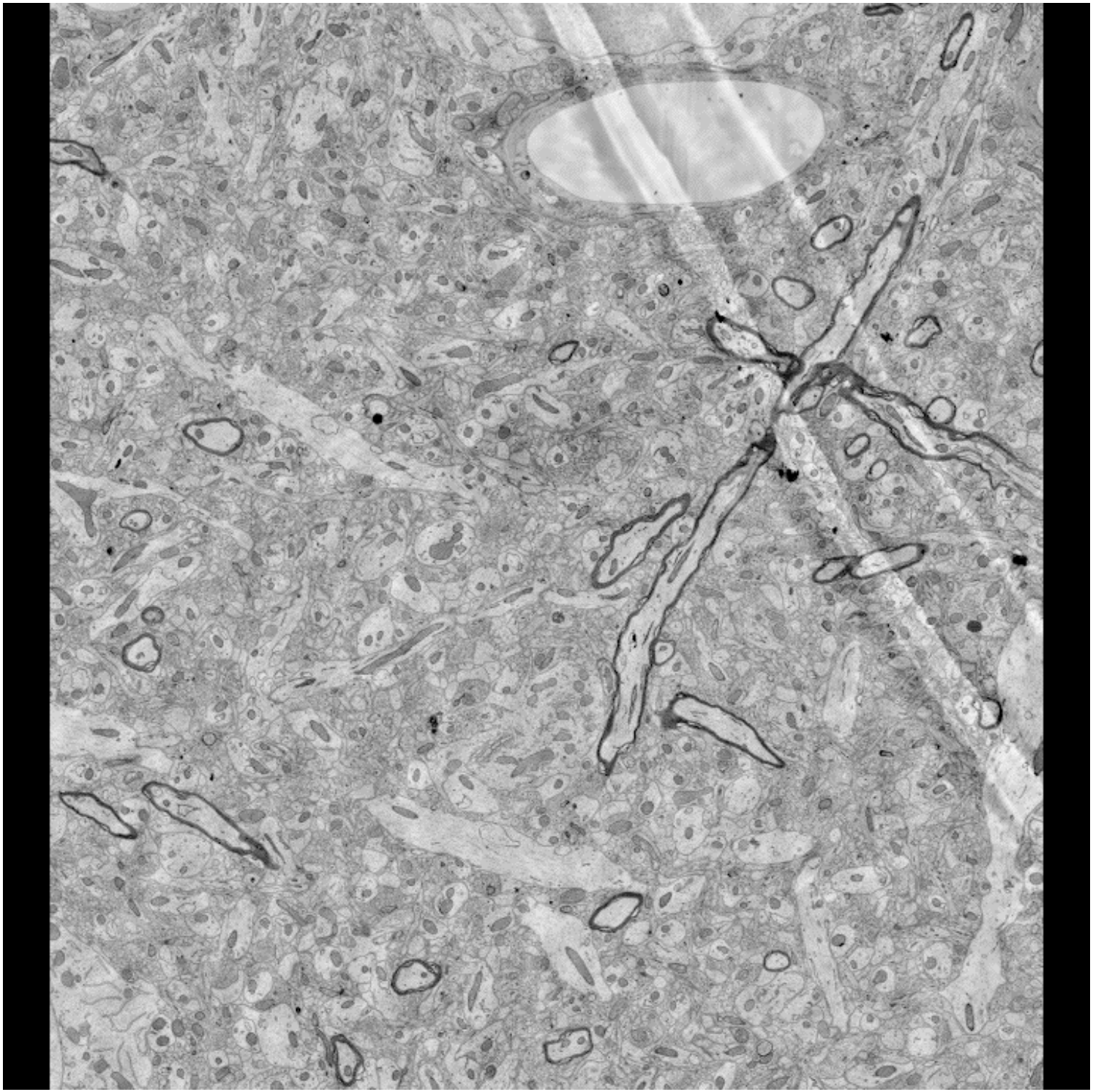
100 sections at 1024x1024 pixels
completely test performance
correct segmentation covers:
68% ±4 of all regions
71% ±7 of all pixels

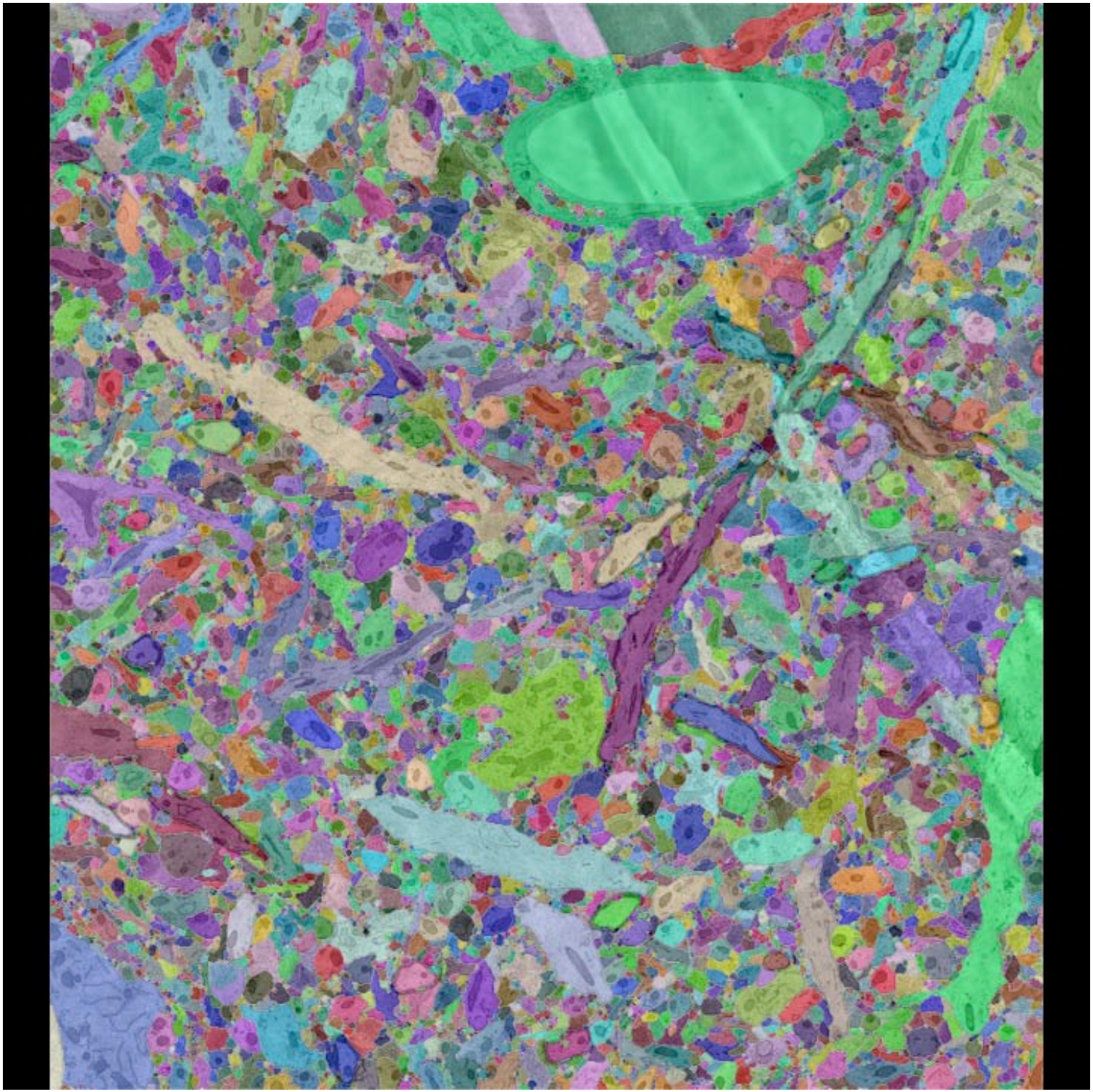

Mojo
File Edit
Adjust Segmentation
Merge Segmentation
Split Segmentation
Precompute Segmentation
Compute Segmentation
Commit Segmentation
Cancel Segmentation
Show Segmentation
Constrain Segmentation Merging To Current Slice
Constrain Segmentation Merging To Connected Component
Proof Reading
Autogenerated Neural Process (ID 3677) [64,26,239]
Autogenerated Neural Process (ID 3485) [96,136,25]
Autogenerated Neural Process (ID 3551) [156,235,55]
Autogenerated Neural Process (ID 3413) [72,187,167]
Autogenerated Neural Process (ID 3415) [175,206,227]
Autogenerated Neural Process (ID 3429) [212,27,45]
Autogenerated Neural Process (ID 3567) [128,189,164]
Autogenerated Neural Process (ID 3553) [98,227,63]
Autogenerated Neural Process (ID 3604) [190,221,9]
Autogenerated Neural Process (ID 3702) [208,179,142]
Autogenerated Neural Process (ID 3620) [65,138,209]
Autogenerated Neural Process (ID 3561) [245,148,111]
Autogenerated Neural Process (ID 3461) [24,173,122]
Autogenerated Neural Process (ID 3446) [188,99,192]
Autogenerated Neural Process (ID 3464) [197,202,199]
Autogenerated Neural Process (ID 3471) [108,114,1]
Autogenerated Neural Process (ID 3483) [97,224,241]
Autogenerated Neural Process (ID 3474) [21,151,76]
Autogenerated Neural Process (ID 3572) [254,84,193]
Autogenerated Neural Process (ID 3456) [57,114,136]
Autogenerated Neural Process (ID 3436) [78,166,13]
Autogenerated Neural Process (ID 3426) [23,250,86]
Autogenerated Neural Process (ID 3519) [43,160,115]
Autogenerated Neural Process (ID 3543) [102,250,216]
Autogenerated Neural Process (ID 3555) [226,104,122]
Autogenerated Neural Process (ID 3650) [129,109,142]
Autogenerated Neural Process (ID 3390) [60,182,83]
Autogenerated Neural Process (ID 3661) [58,160,192]
Autogenerated Neural Process (ID 3656) [148,76,141]
Autogenerated Neural Process (ID 3377) [2,86,21]
Autogenerated Neural Process (ID 3571) [102,88,253]
Autogenerated Neural Process (ID 3660) [235,254,182]
Autogenerated Neural Process (ID 3518) [12,22,181]
Autogenerated Neural Process (ID 3458) [123,247,210]
Autogenerated Neural Process (ID 3378) [95,71,204]
Autogenerated Neural Process (ID 3419) [225,22,214]
Autogenerated Neural Process (ID 3559) [108,230,73]
Autogenerated Neural Process (ID 3655) [117,121,19]
Autogenerated Neural Process (ID 3516) [123,29,152]
Autogenerated Neural Process (ID 3616) [220,74,46]
Autogenerated Neural Process (ID 3443) [31,61,70]
Autogenerated Neural Process (ID 3540) [149,151,37]
Autogenerated Neural Process (ID 3624) [211,78,221]
Autogenerated Neural Process (ID 3686) [173,80,140]
Autogenerated Neural Process (ID 3520) [66,111,53]
Autogenerated Neural Process (ID 3614) [166,219,78]
Autogenerated Neural Process (ID 3683) [97,91,21]
Neural Process Name:
Add Neural Process
Remove Neural Process
Left mouse button selects process to split.

Jeff's Challenge

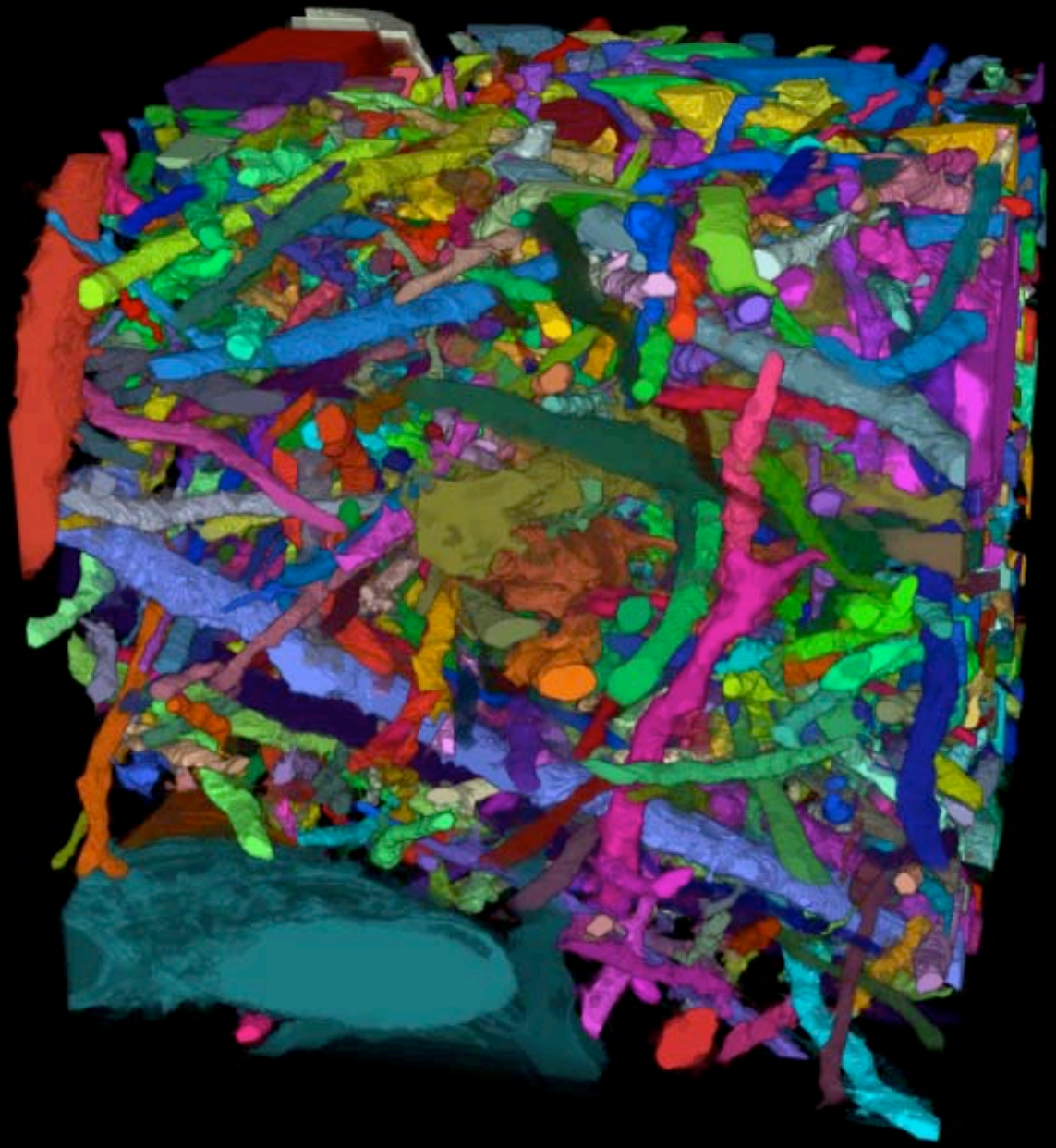
Automatic 3D reconstruction for largest EM stack **ever**

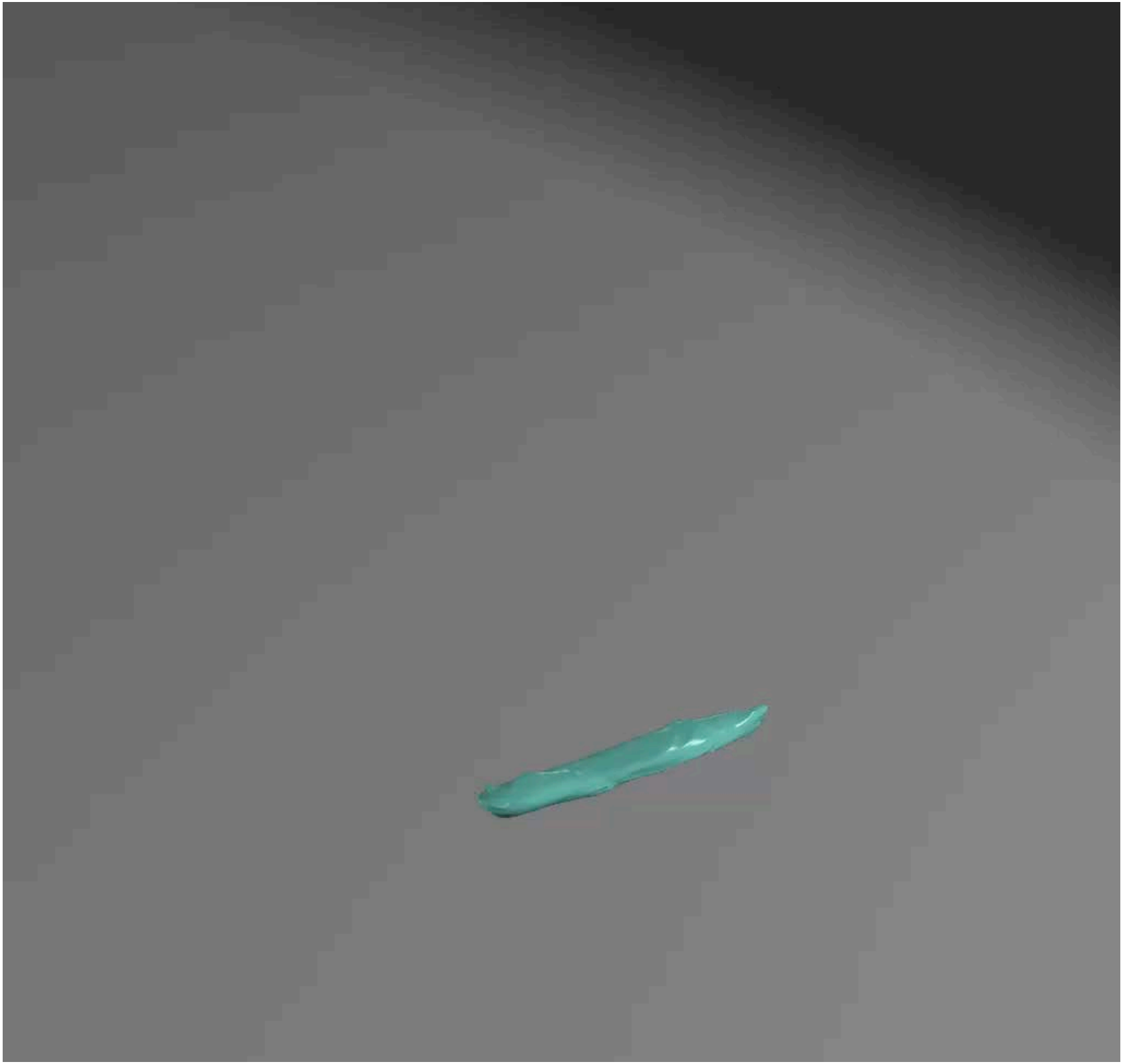


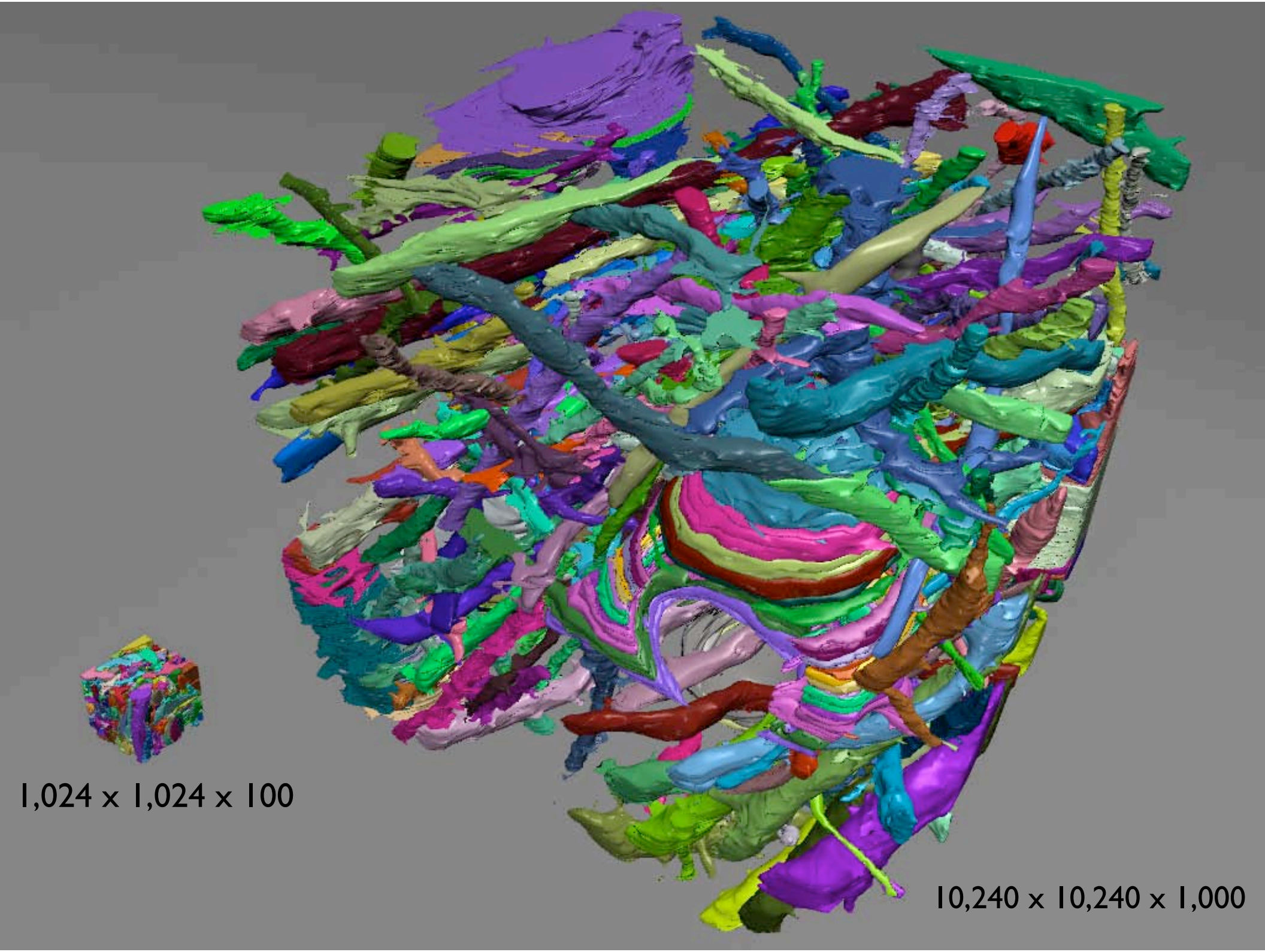




All objects containing at least 100 sections

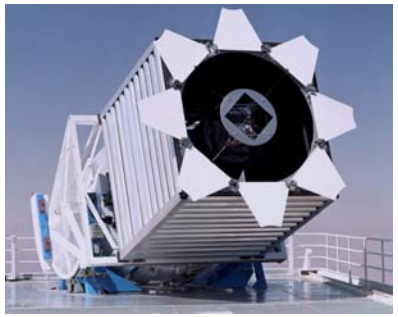


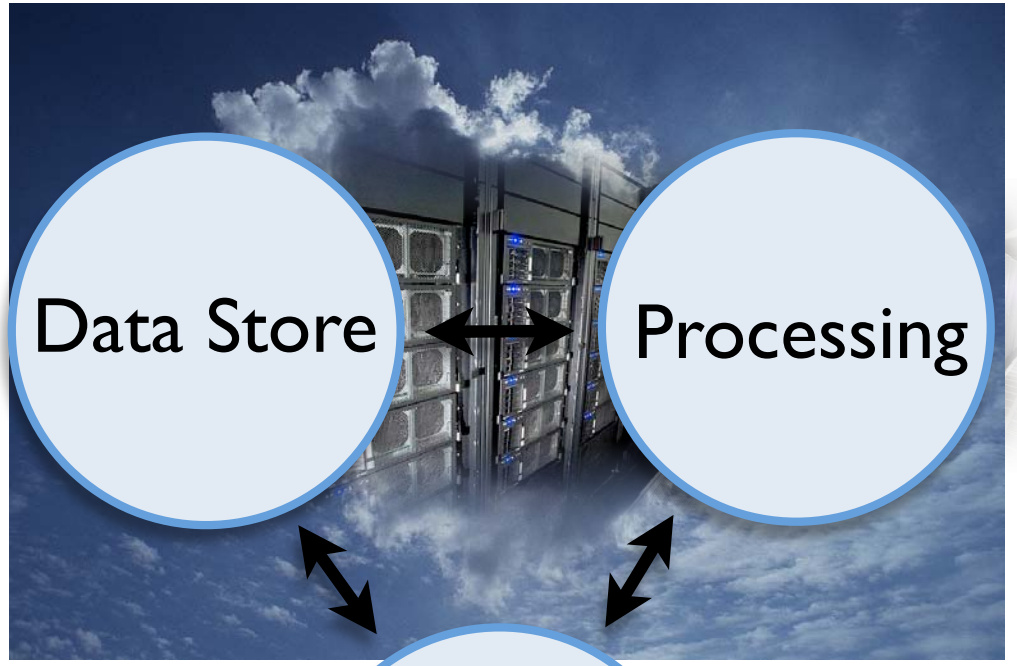


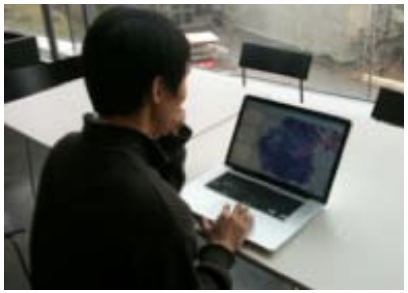

1,024 x 1,024 x 100
10,240 x 10,240 x 1,000

Future Work

Distributed Image Analysis & Visualization

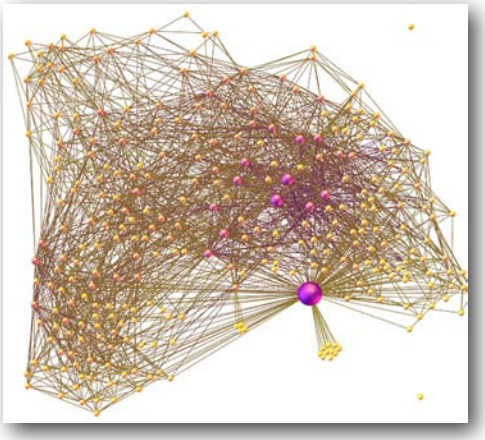






Human Analysis

CBS



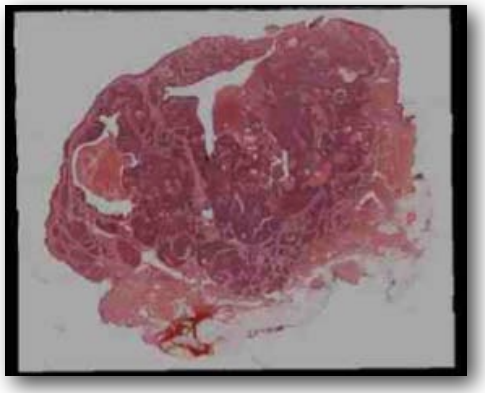
Network Visualization

MGH

Radiation Oncology

GSD

Building Energy Usage

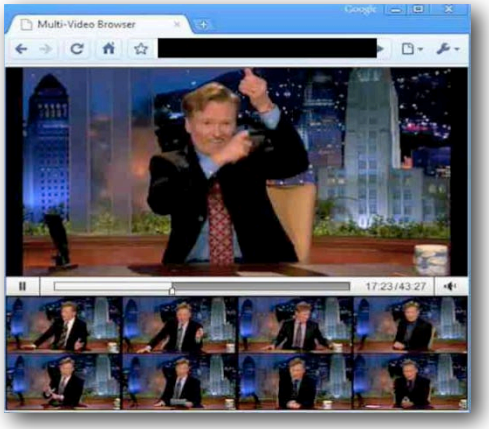


Digital Pathology

Beth Israel

Object Replication

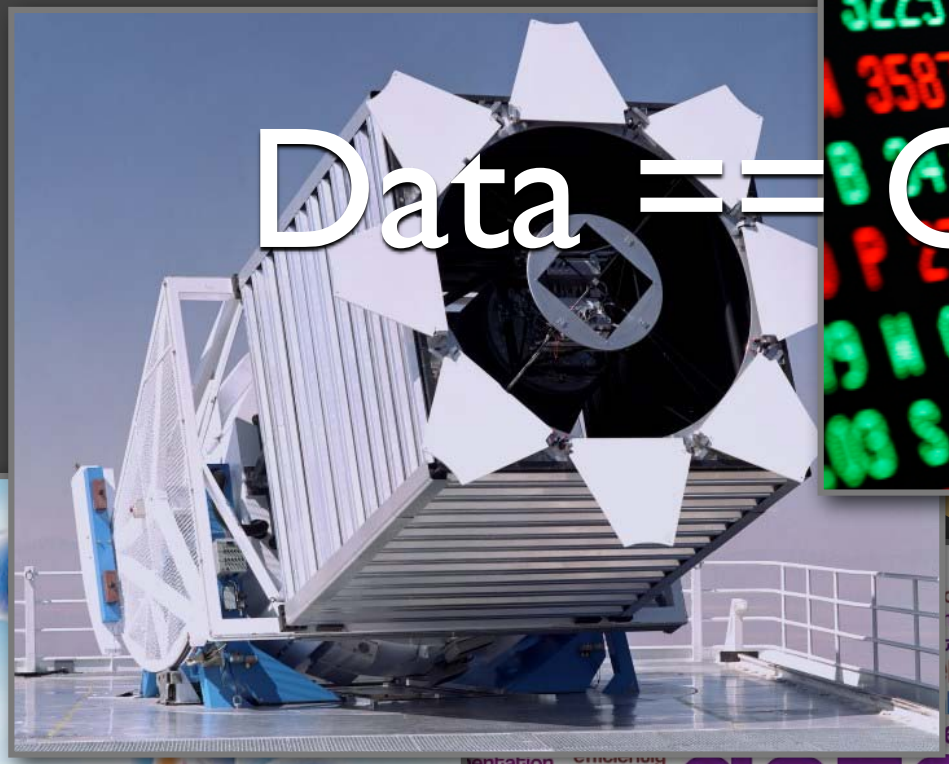
Disney Research



Video Browsing

IQSS

Data == Opportunities




Thank you!
http://gvi.seas.harvard.edu/pfister