

**CROSS**



# Polyphorm

Nature-inspired reconstruction  
and visualization of transport networks

**Oskar Elek**  
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**Joseph Burchett**  
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**Angus Forbes**  
UCSC



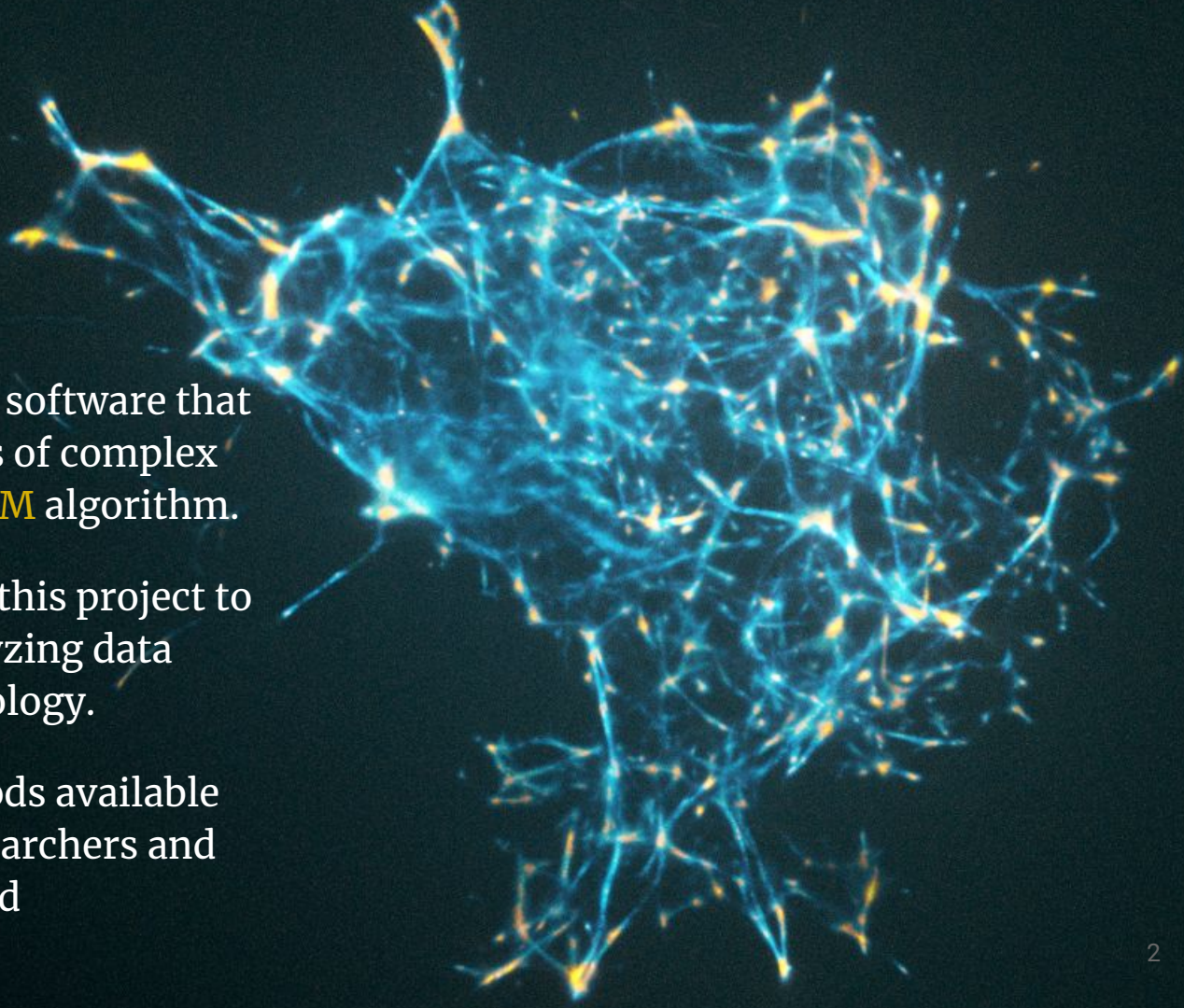
**Carlos Maltzahn**  
UCSC/CROSS



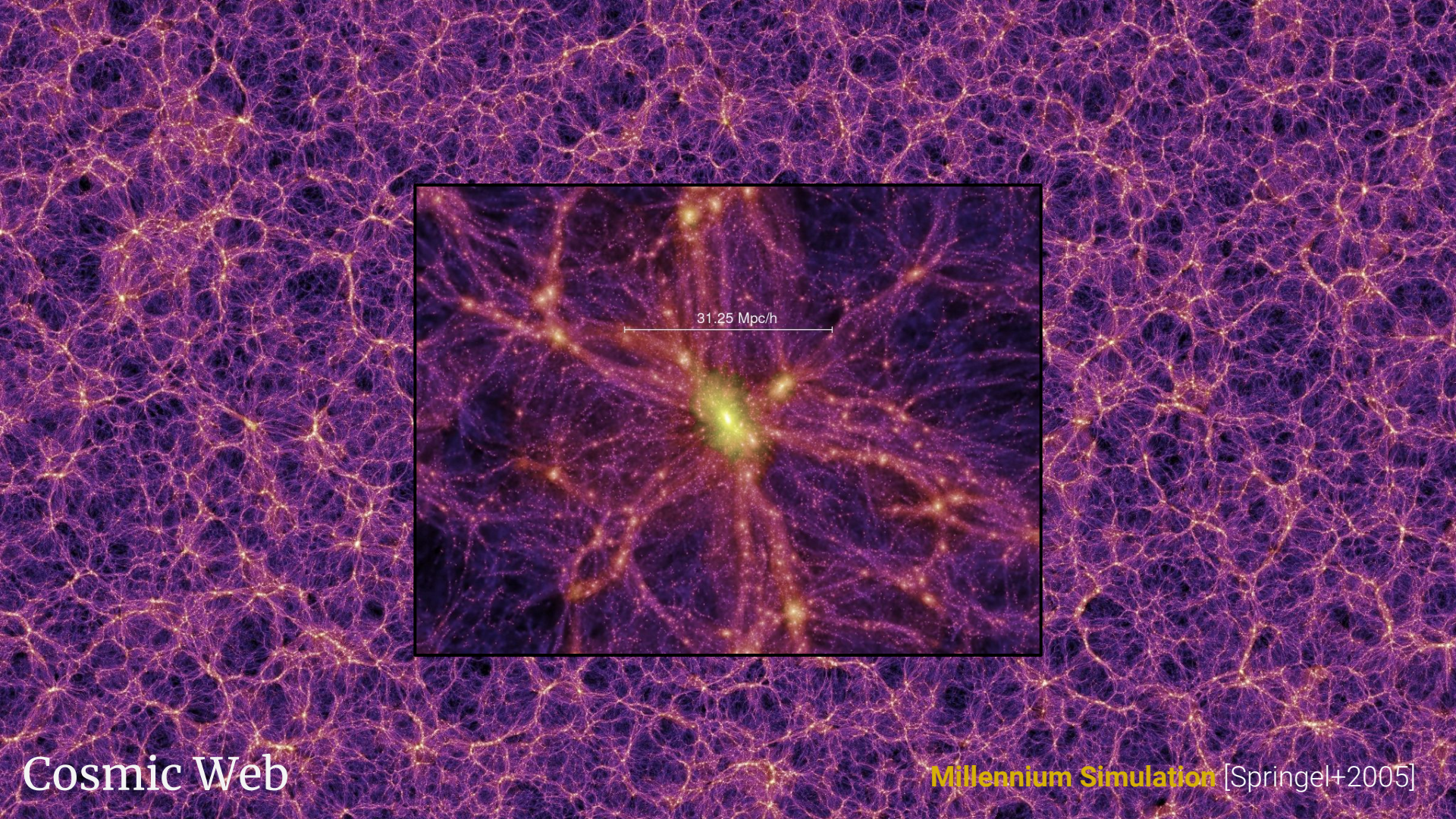
**Polyphorm** is an open source software that enables new types of analysis of complex scientific data using the **MCPM** algorithm.

In the past 2.5 years we used this project to make breakthroughs in analyzing data from astrophysics and cosmology.

**PolyPhy** will make our methods available to a wider community of researchers and data scientists as a redesigned multi-platform Python port.



# Polyphorm and MCPM



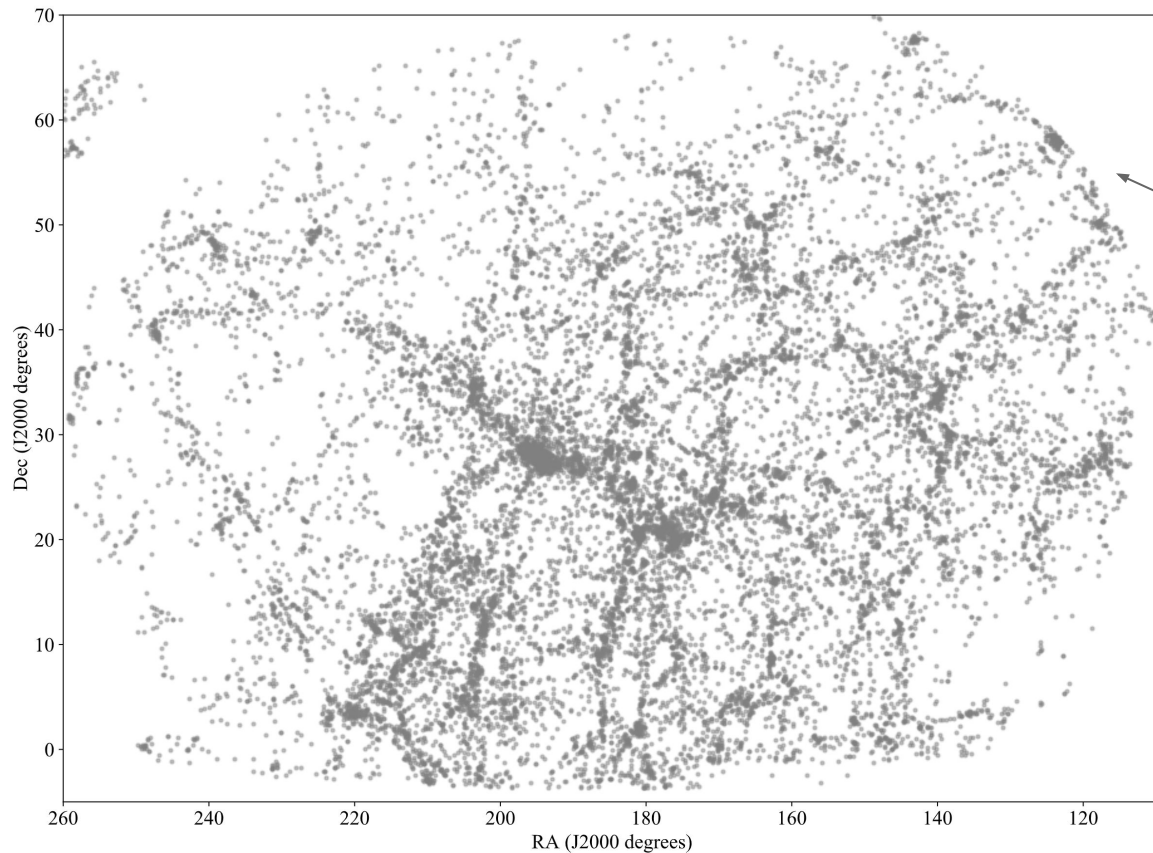
Cosmic Web

Millennium Simulation [Springel+2005]



Cosmic Web: Where is it?

Hubble Deep Field



**Sloan Digital Sky Survey**

37.6k galaxies (3D points)

Redshifts .018 to .038

...density of data not sufficient to reconstruct the Cosmic Web without additional considerations

# Cosmic Web: Where is it?

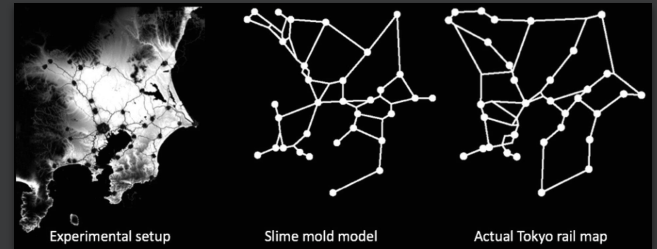


Unicellular, multi-nuclear protist

Searches its environment by climbing **chemical marker gradients** (emitted by food and also itself)

Amazing range of behaviors - look up "BBC slime mold" for a great time-lapse

Forms approximate **optimal transport networks** over available food sources (NP-hard)



[Tero+2010]

**Physarum Polycephalum** – model organism

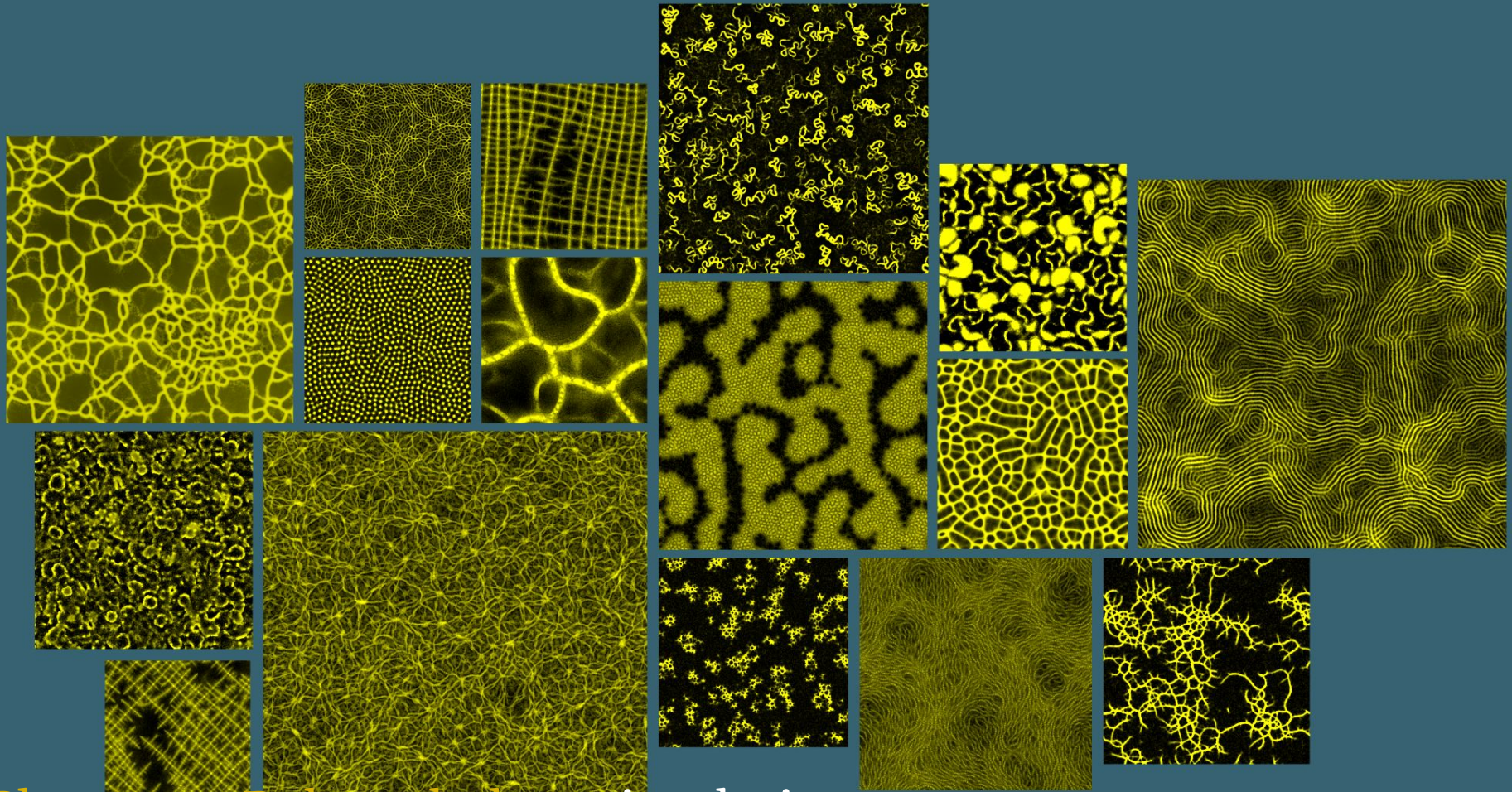
**Sage Jensen's simulation art (2018)**

**Based on work of Jeff Jones (2010)**

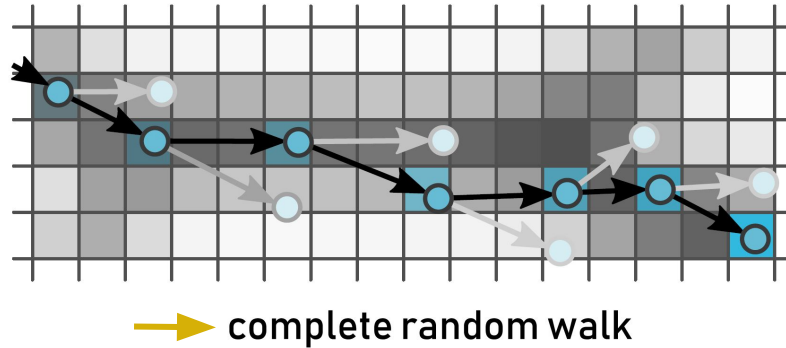
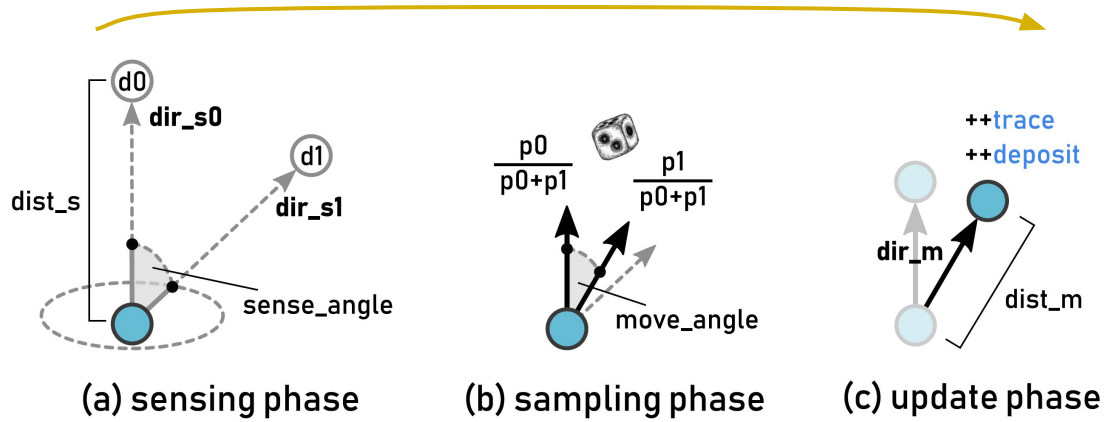


**Physarum Polycephalum** simulation

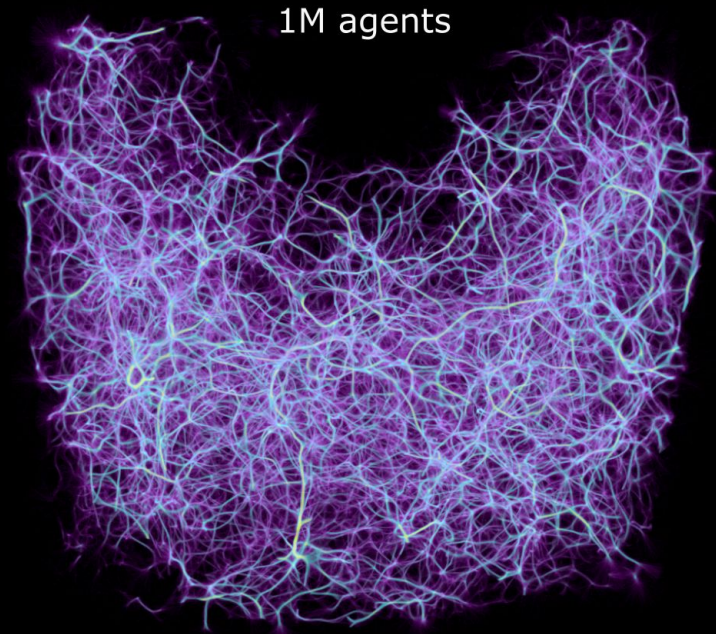
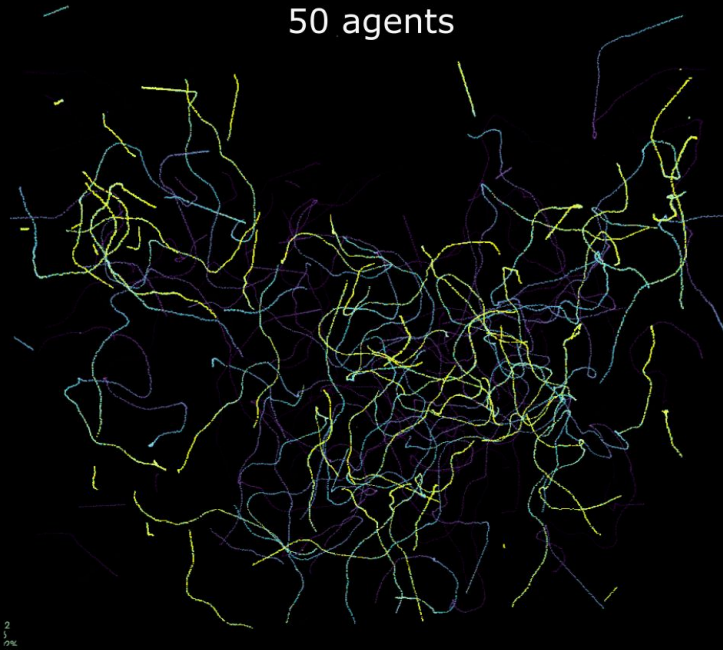




Physarum Polycephalum simulation

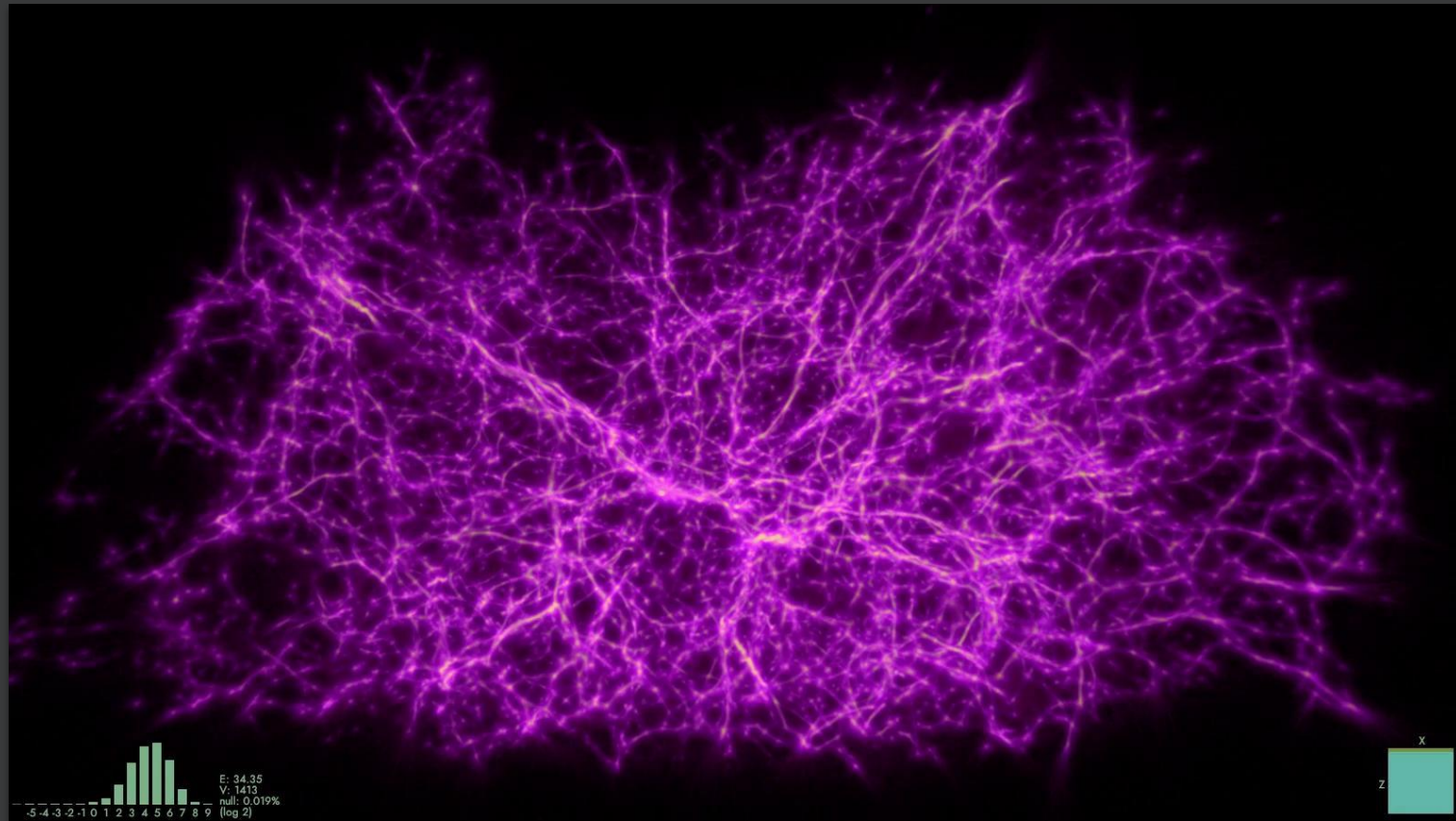


3D “trace” density fields (Bolshoi-Planck dataset, 450k objects)



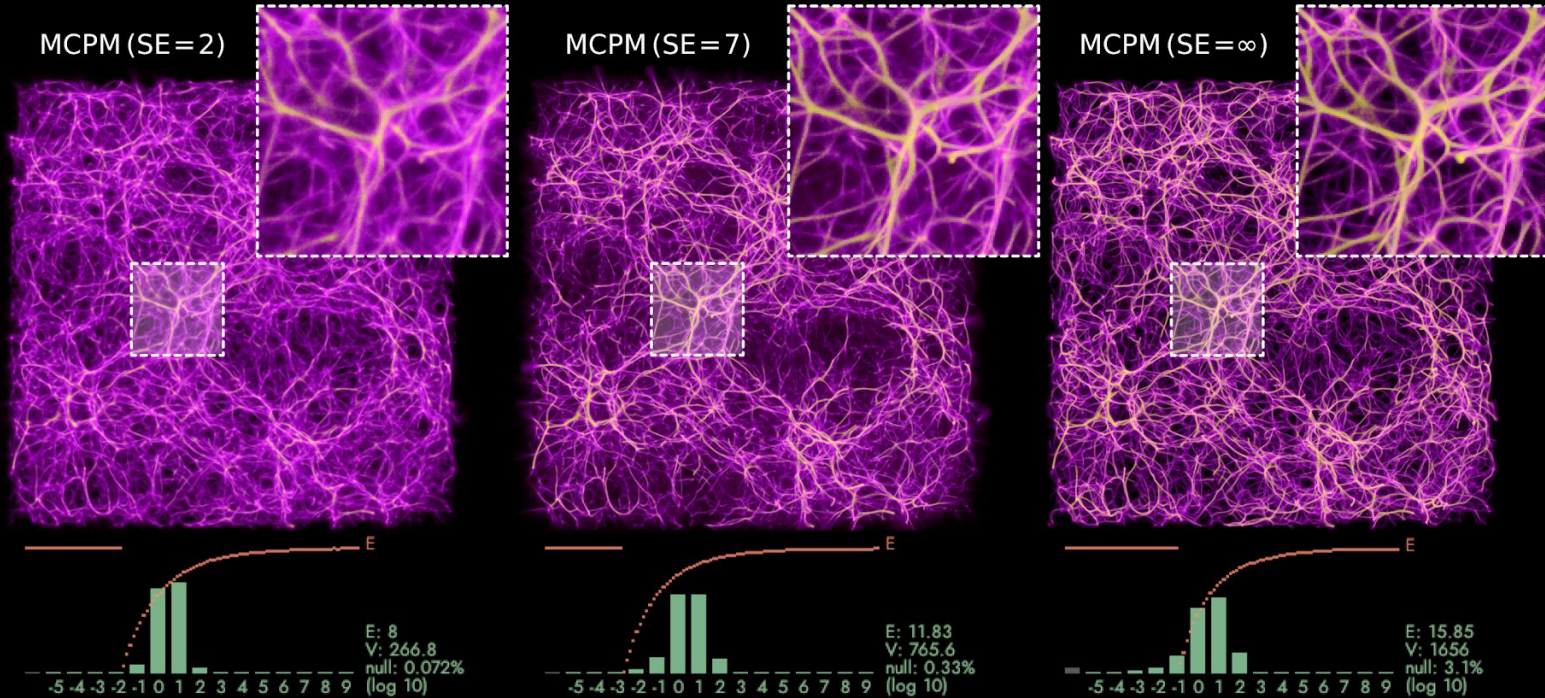
**Monte Carlo Physarum Machine: Agent parallelism**

Sloan Digital Sky Survey (SDSS) data, 300 Mpc wide, 37.6k galaxies



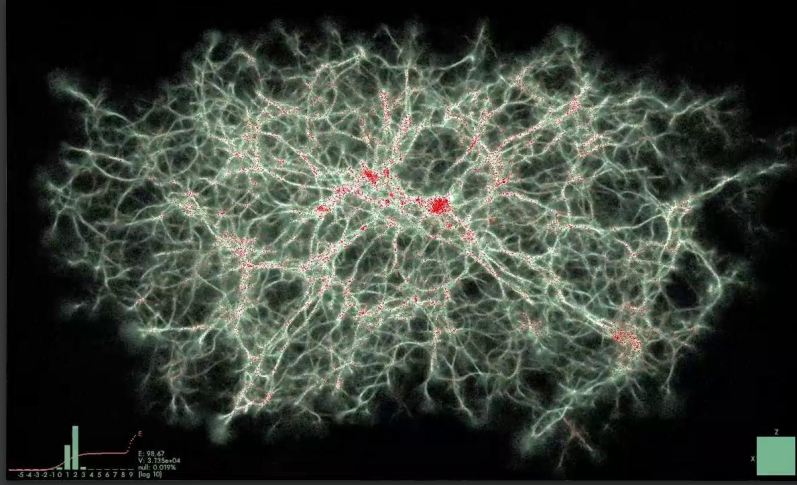
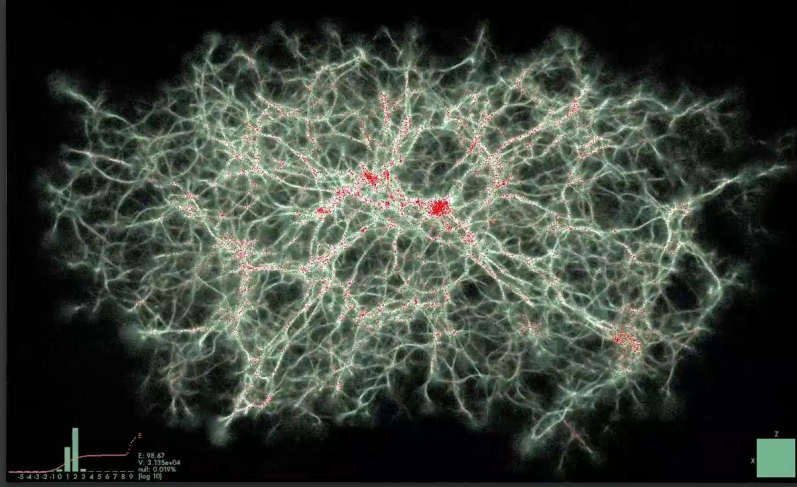
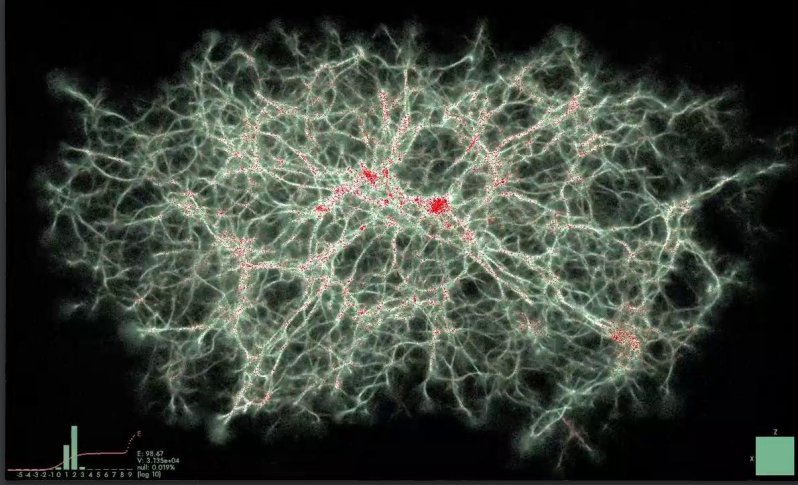
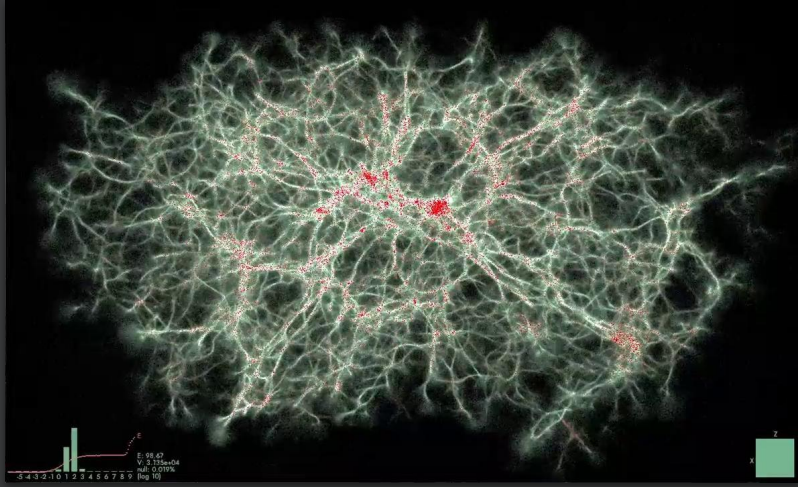
**Monte Carlo Physarum Machine:** Real-time fitting

## 3D "trace" density fields (Bolshoi-Planck dataset, 450k objects)

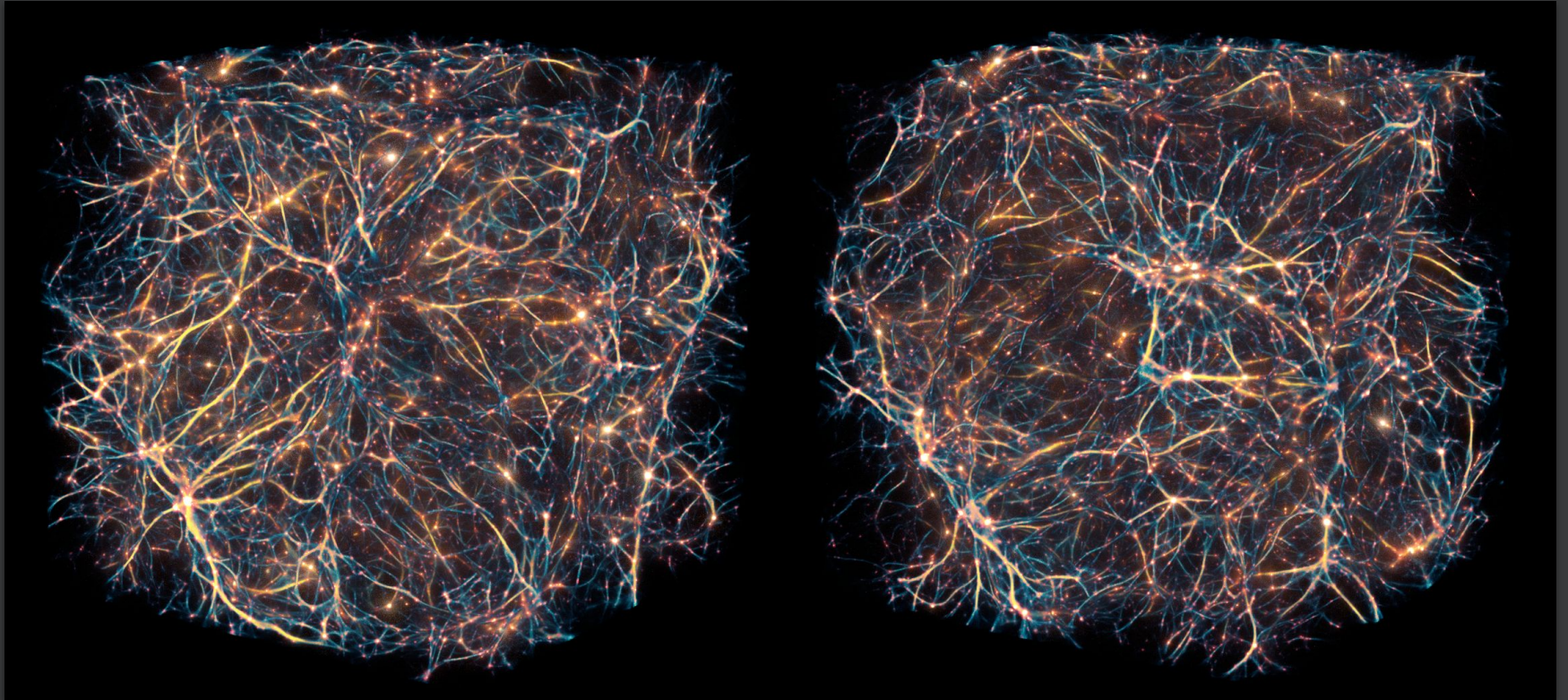


**Monte Carlo Physarum Machine: Probabilistic sampling**

# Polyphorm: Interactive Vis



Physically plausible global illumination (using path-tracing) in Illustris TNG-100 data



**Polyphorm:** Aesthetics

with David Abramov @ Vis Astro Data Challenge 2020

What can Polyphorm/MCPM do?



■ **Burchett J.N., Elek O., Tejos N., Prochaska J.X., Tripp T.M., Bordoloi R., Forbes A.G.**

*Revealing the dark threads of the Cosmic Web*

The Astrophysical Journal Letters, **2020**, Vol. 891(2)

■ **Elek O., Burchett J.N., Prochaska J.X., Forbes A.G.**

*Polyphorm: Structural analysis of cosmological datasets via interactive Physarum polycephalum visualization*

Transactions of Visualization and Computer Graphics, **2021**, Vol. 27(2), Presented at VIS 2020

■ **Simha S., Burchett J.N., Prochaska J.X., Chittidi J.S., Elek O., Tejos N. et al.**

*Disentangling the Cosmic Web toward FRB 190608*

The Astrophysical Journal, **2020**, Vol. 901(2)

■ ■ **Zhou H., Elek O., Anand P., Forbes A.G.**

*Bio-inspired structure identification in language embeddings*

Visualization for Digital Humanities, **2020**

■ **Burchett J.N., Abramov D., Elek O., Forbes A.G.**

*Volumetric Reconstruction for Interactive Analysis of the Cosmic Web*

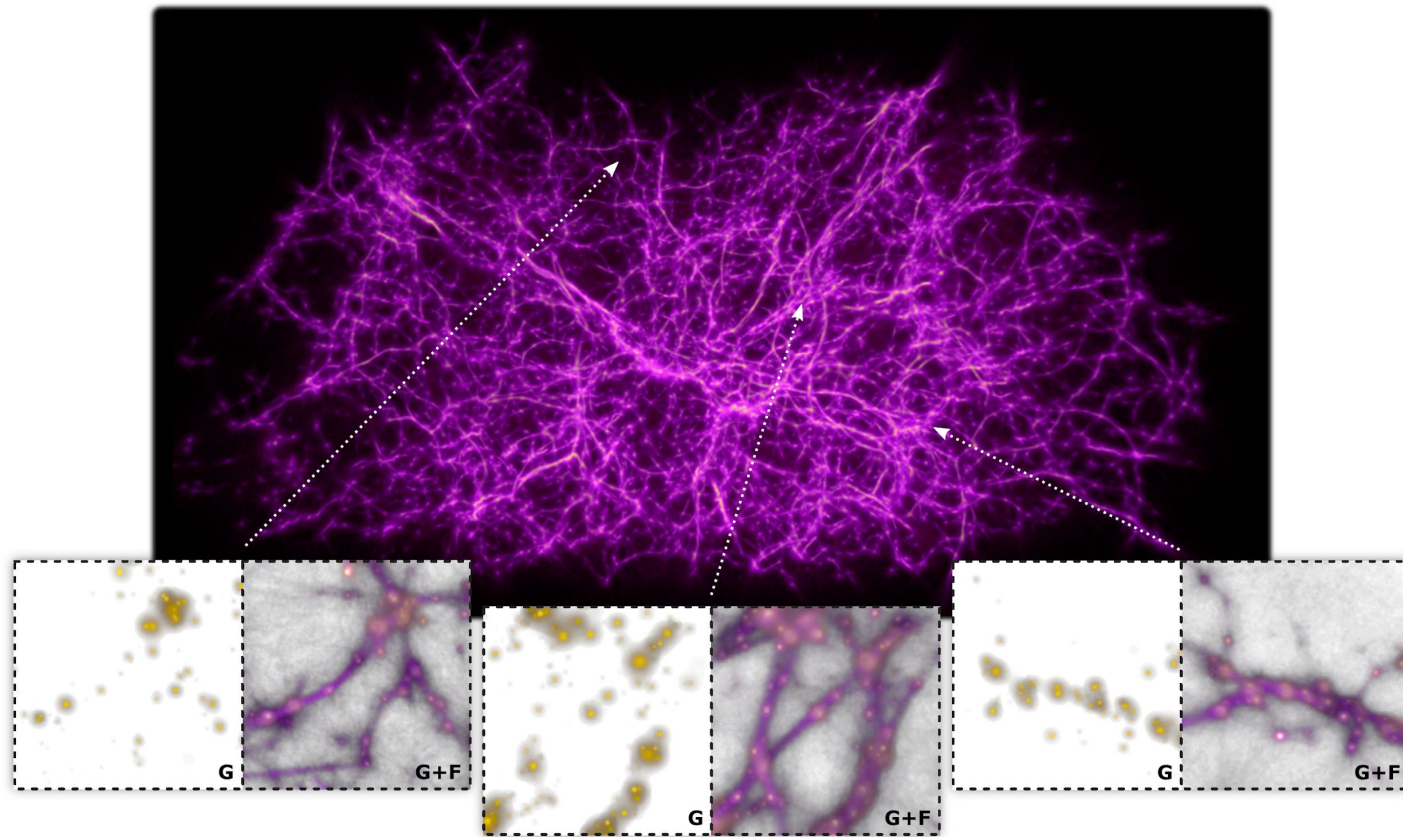
IEEE Vis Astro, **2020**, Winner of the DataVis Challenge

■ **Elek O., Burchett J.N., Prochaska J.X., Forbes A.G.**

*Monte Carlo Physarum Machine: Characteristics of Pattern Formation in Continuous Stochastic Transport Networks*

Artificial Life Journal, **2021**, Vol. 27(4), Will be presented at ALIFE 2022

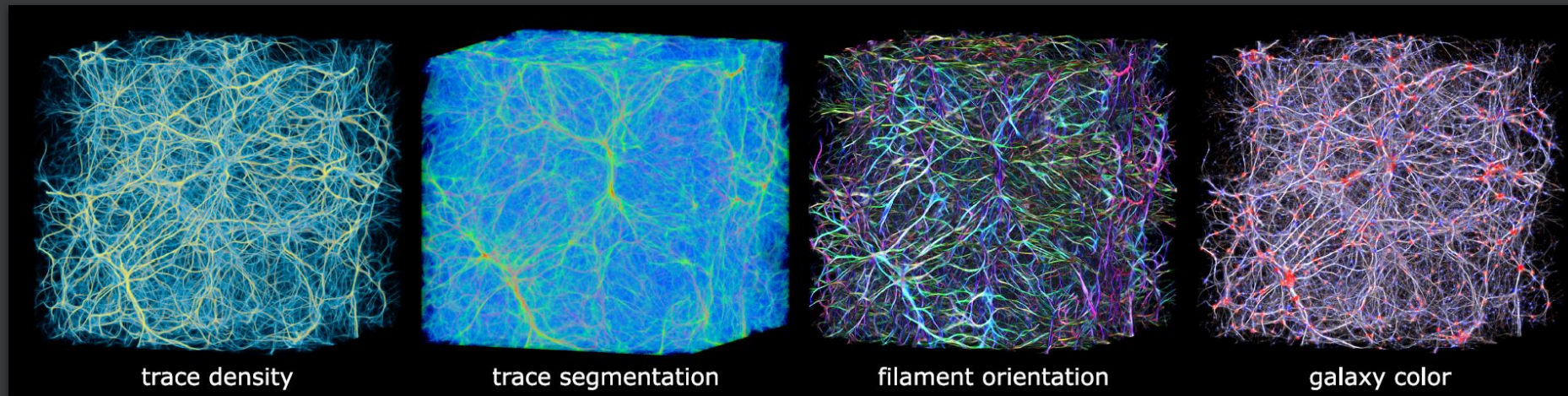
- Astronomy & cosmology
- Data visualization
- Procedural modeling
- Computational linguistics



Covered by:

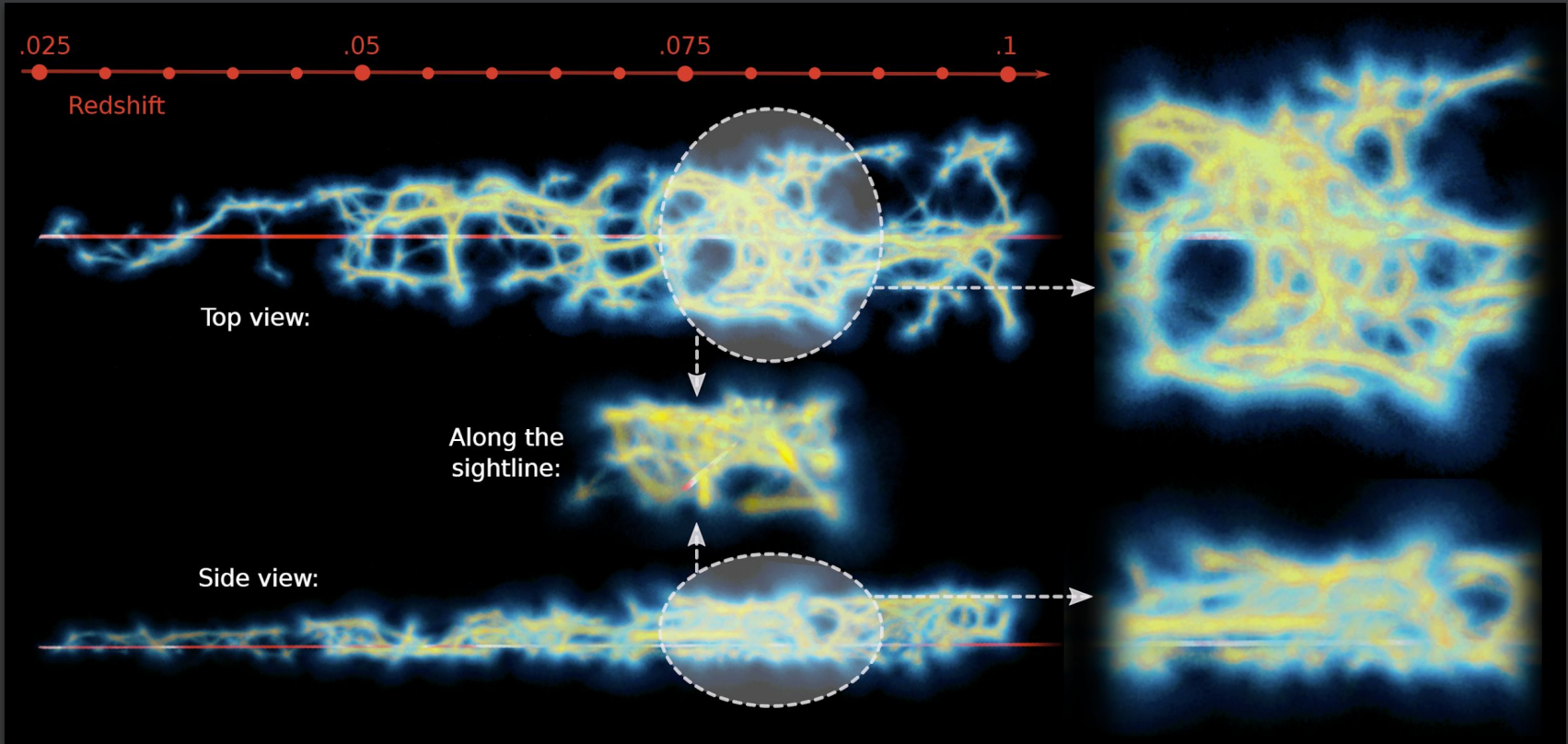
- Hubble ST
- NASA
- ESA
- Ars Technica
- Planetary Society
- Popular Science
- SciShow
- Seeker
- Forbes
- Inverse
- Astronomy
- Universe Today
- Discover
- Reddit
- Space
- Entrepreneur

Illustris TNG simulation,  $100^3$  Mpc volume, 4M halos



**Polyphorm:** Structural insights

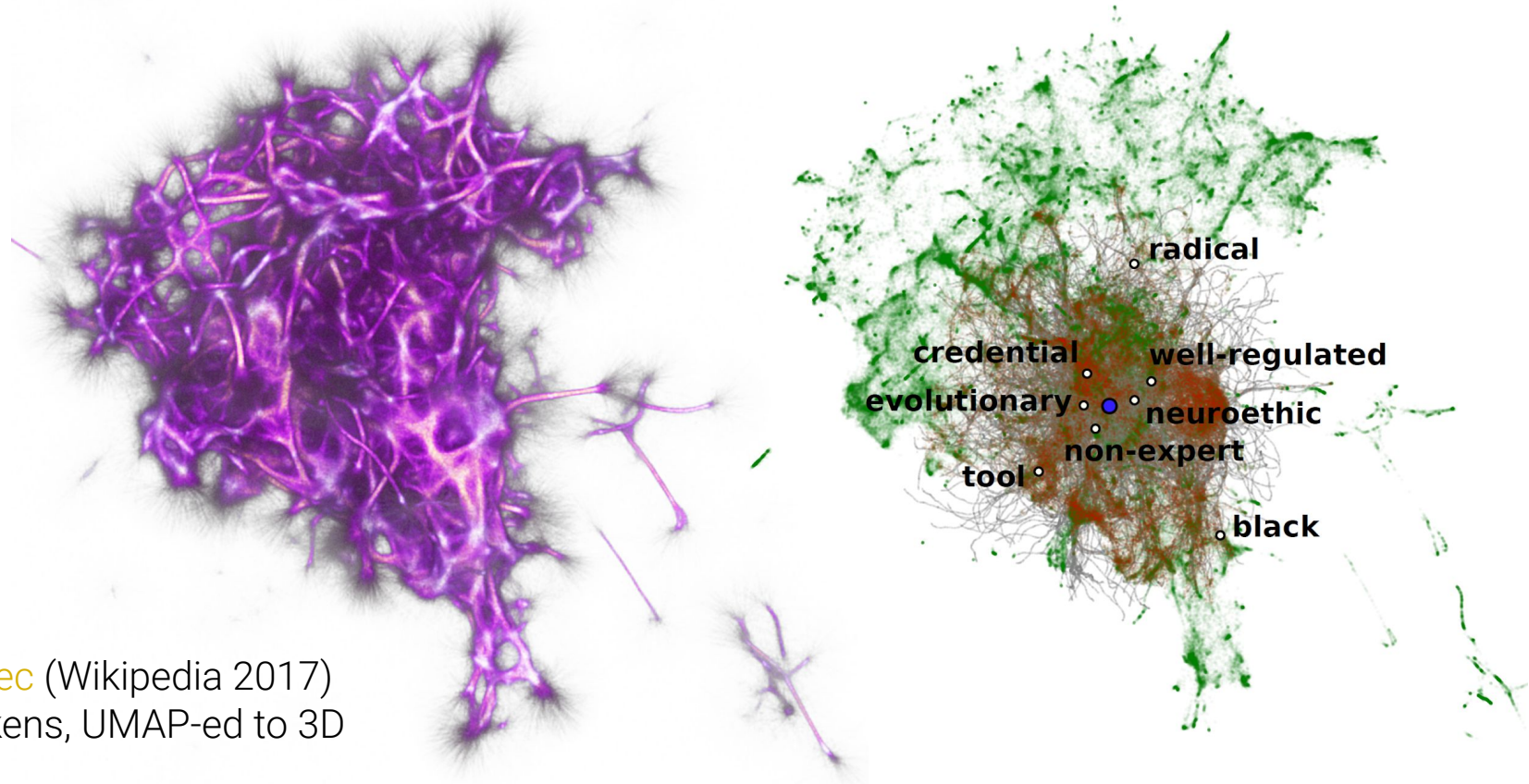
with David Abramov @ Vis Astro Data Challenge 2020



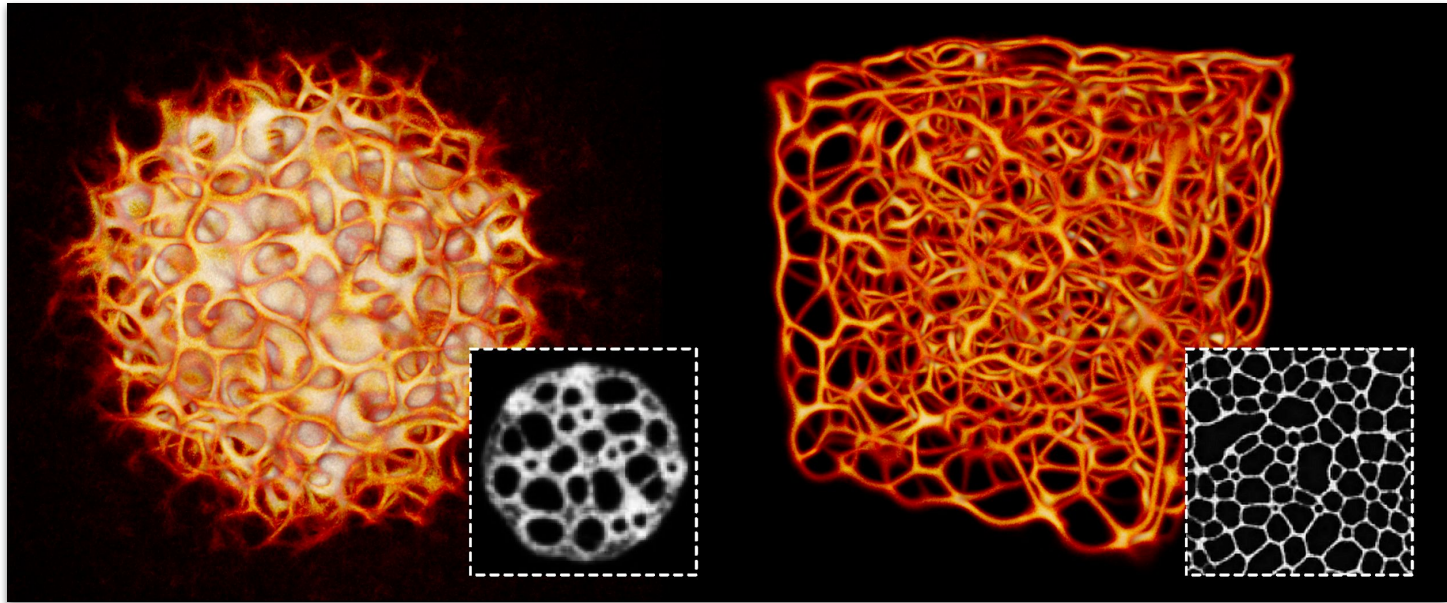
# Cosmic Web towards a Fast Radio Burst

Simha et al.: Disentangling the Cosmic Web towards FRB 190608 (Astrophysical Journal Letters, 2020)

# Exploring the geometry of latent high-dimensional **word embedding spaces**



**word2vec** (Wikipedia 2017)  
300k tokens, UMAP-ed to 3D

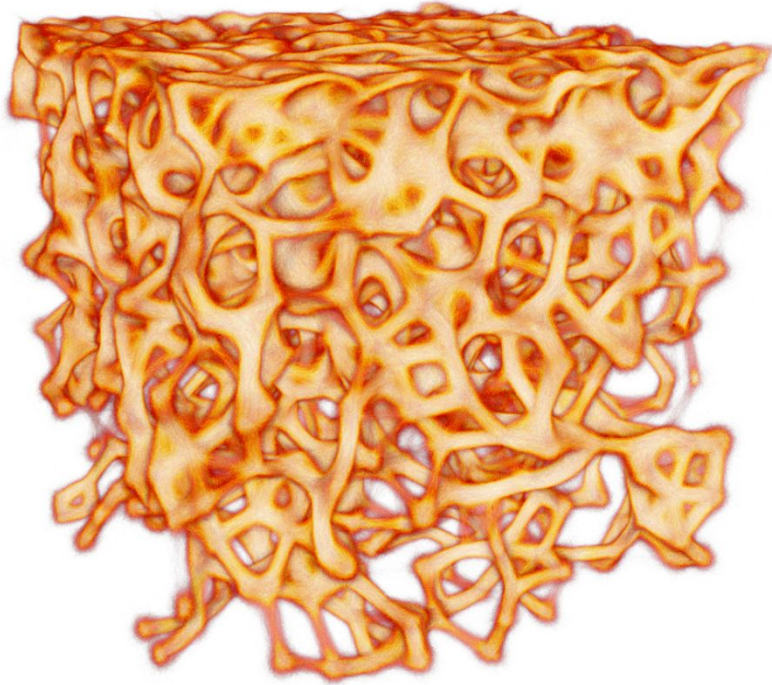


■ Elek O., Burchett J.N., Prochaska J.X., Forbes A.G.

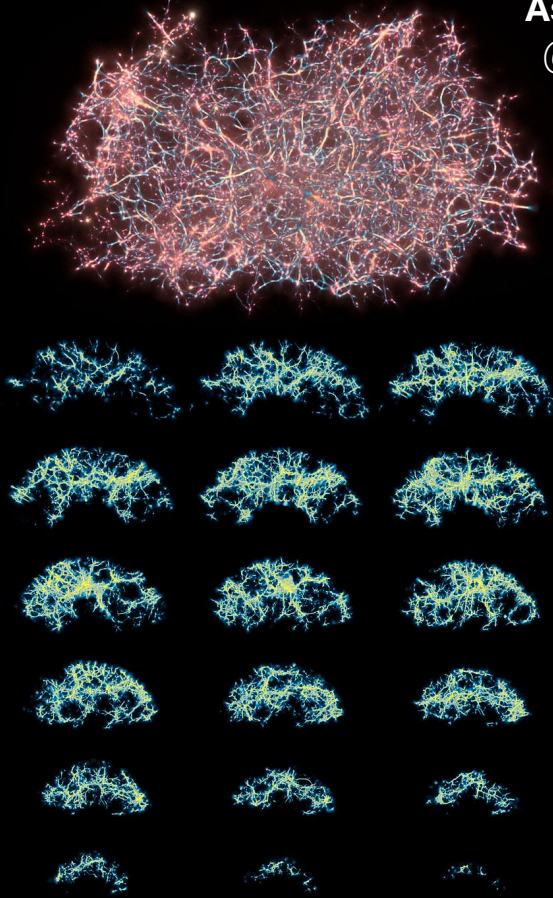
*Monte Carlo Physarum Machine: Characteristics of Pattern Formation in Continuous Stochastic Transport Networks*

Artificial Life Journal, **2021**, Vol. 27(4), Will be presented at ALIFE 2022

Building bio-inspired scaffoldings for 3D printing (with Drew Ehrlich and Milad Hakimshafaei)



**As Above - So Below**  
@ MAH Santa Cruz



**Colleen Flanigan's**  
sculpture **Zoe**



**Physarum Telam** with  
**Issei Mori** @ ALIFE  
[tinyurl.com/PhysarumTelam](http://tinyurl.com/PhysarumTelam)

**Art and outreach**



- First fully 3D simulation of Physarum networks
- Probabilistic 'Monte Carlo' sampling and continuous density reconstruction
- Natively parallelizable method, real-time on a single GPU, converges in 1-2 minutes
- Interactive visualization and expert supervision of the reconstruction process
- Easy to interpret and explain to non-experts

# Future of MCPM: PolyPhy

# CROSS

CENTER FOR RESEARCH IN  
OPEN SOURCE SOFTWARE



We have partnered with UCSC's **CROSS** to develop **PolyPhy** as an open source data-scientific software

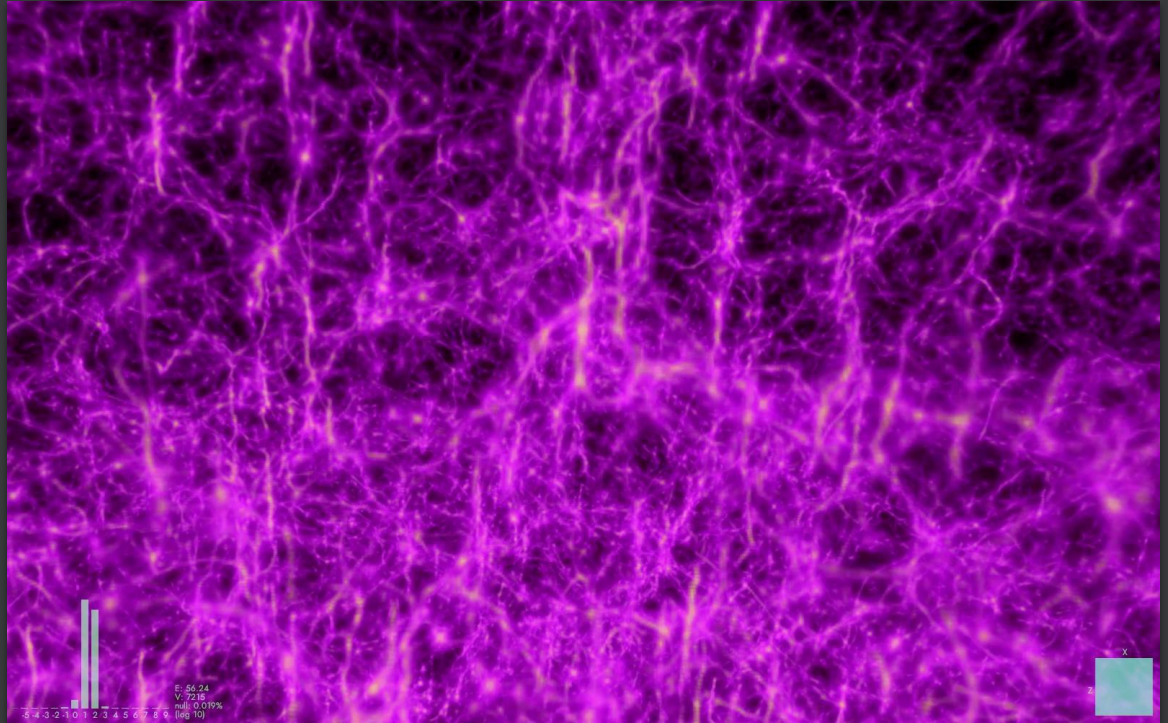
## Project objectives:

1. Develop **PolyPhy** for 3D and high-D data
2. Explore new scientific use cases
3. Build a community of domain experts and data scientists centered around this methodology

320k+ SDSS galaxies, redshift < 0.1

Expanding our search range to higher redshifts + cross-verification of the MCPM model with other modalities

Building on wide-sky surveys: SDSS and LRG

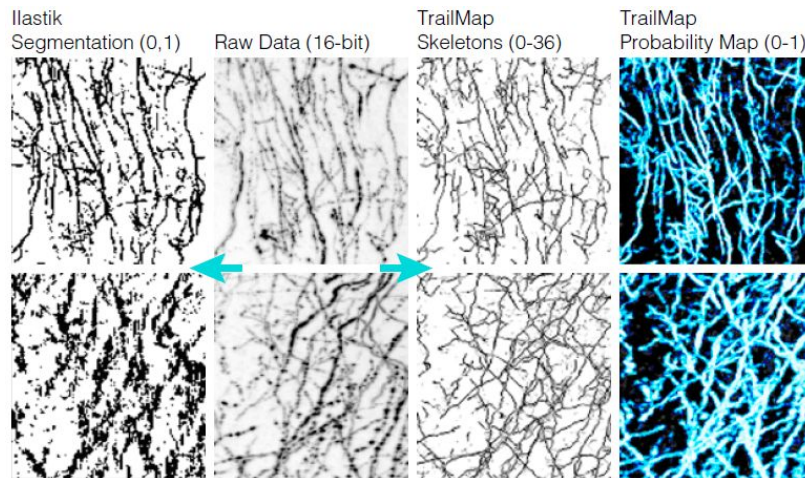
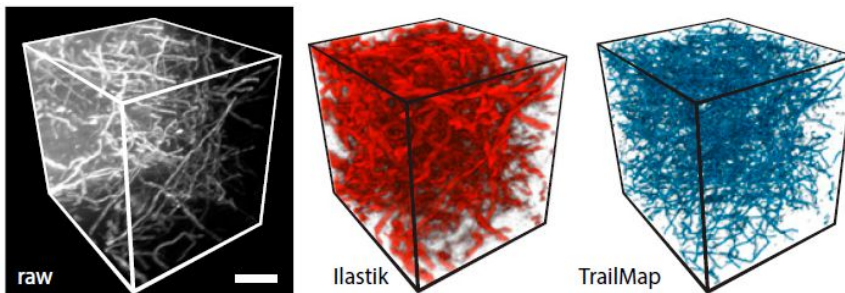


Astronomy and cosmology

## Using Polyphorm for reconstructing 3D maps of neuronal networks

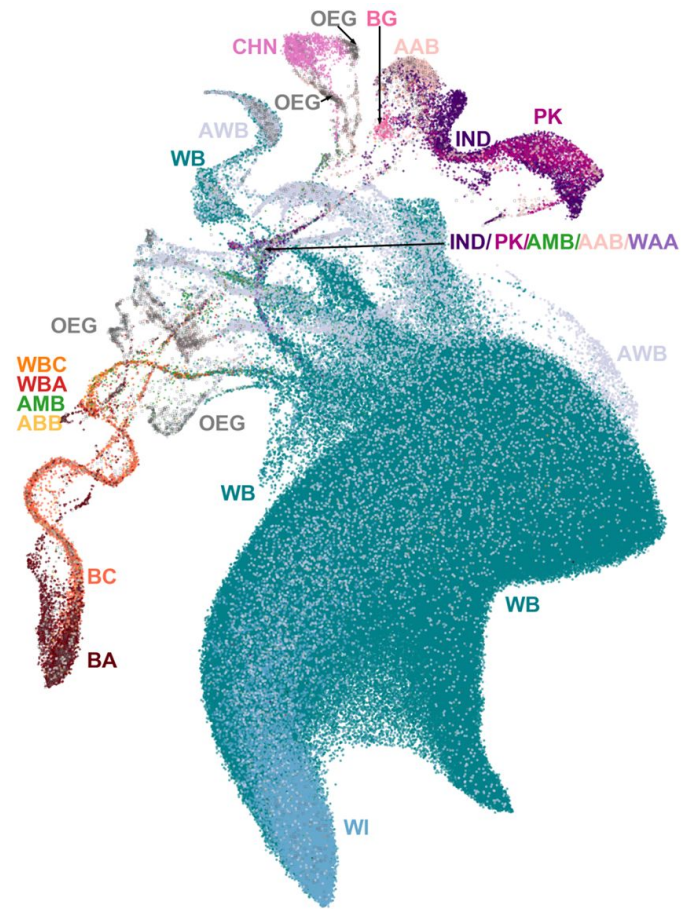
Extension of the MCPM algorithm to  
operate on density fields rather than  
point clouds as input data

Friedmann et al.: Mapping Mesoscale Axonal Projections in the  
Mouse Brain Using A 3D Convolutional Network @ PNAS 2019



## Mapping genomic data of large human populations

Examining dispersion and clustering of genetic markers corresponding to distinct geographic or ethnic groups



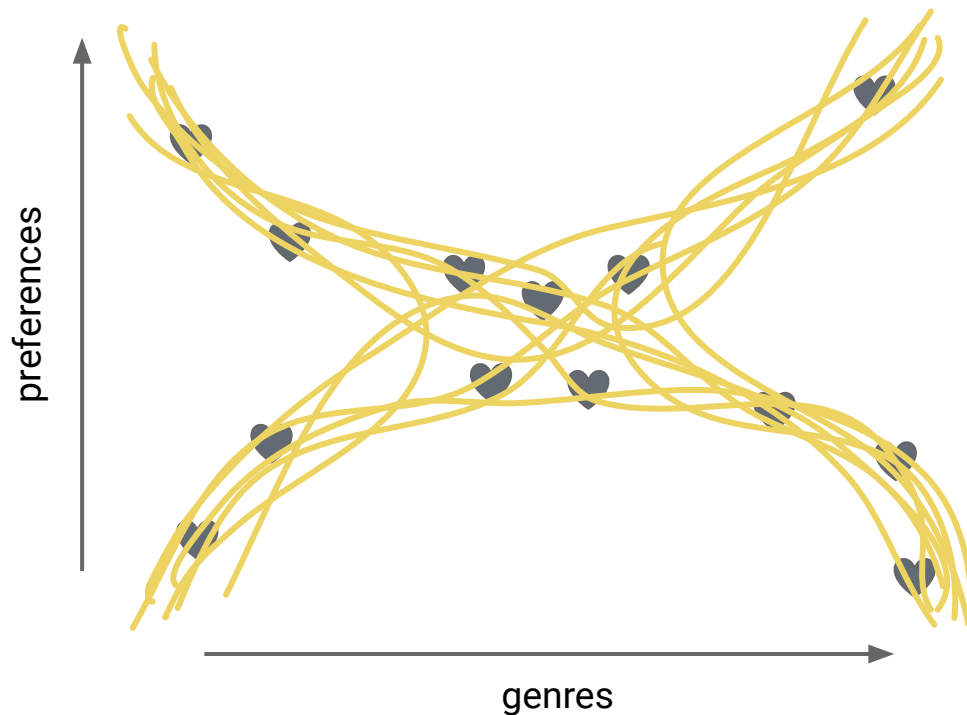
Diaz-Papkovich et al.: UMAP reveals cryptic population structure and phenotype heterogeneity in large genomic cohorts @ PLOS Genetics 2019

The recommender system problem:

*"If I listen to some specific songs on Spotify, what others might I be interested in?"*

Required tasks/queries:

- similarity
- interpolation
- extrapolation



1. How would you design a toolkit with such tight coupling between simulation and visualization?
2. Would you use **PolyPhy** for your science? How?
3. Any insights into the existing use cases?





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Research



Polyphorm

