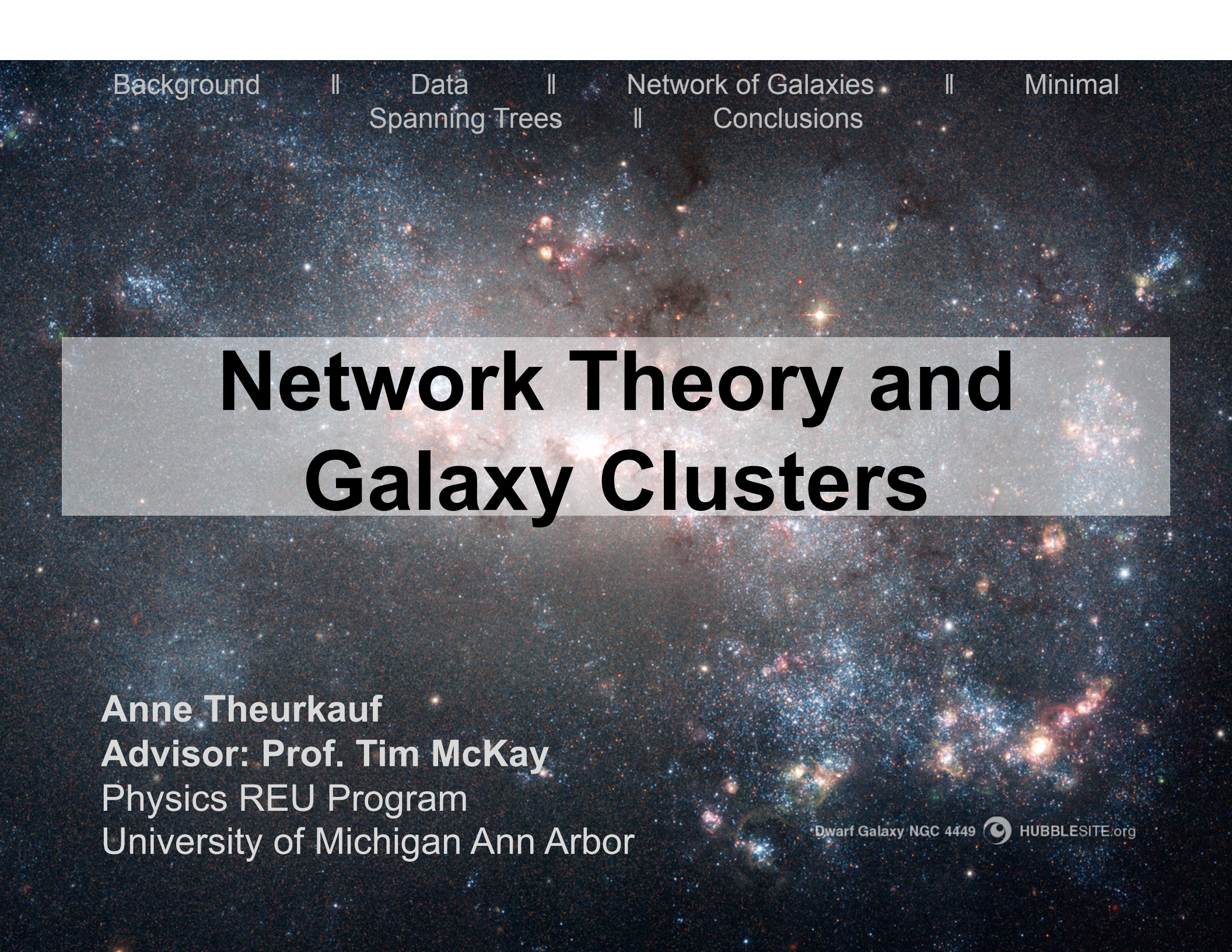
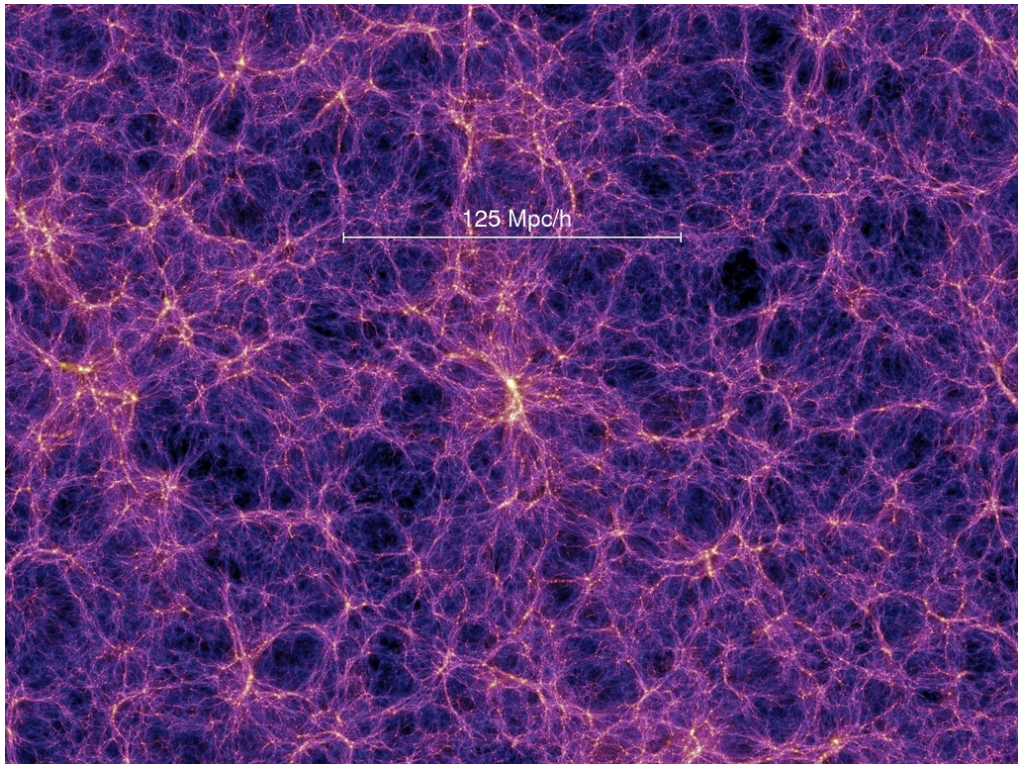
Network Theory and Galaxy Clusters

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Large Scale Structure

- Foamy
  - Galaxy Clusters
  - Galaxy Filaments
- Structure can help us understand subjects like dark energy, dark matter, gravity, etc.



Network Theory

- Prof. Mark Newman
- A network consists of nodes and edges
- Example: food chain, links in web pages, etc.




facebook
December 2010

Simulated Data

- **R**e-simulated **HA**lo **P**opulation for **S**tatistical **O**bservable–mass **D**istribution stud**Y** (Rhapsody)
- Resolved n-body simulation: provides information on the galaxies in clusters (position, luminosity, etc.)
- Comparing simulation to observation can be used to test theory

Problems Addressed

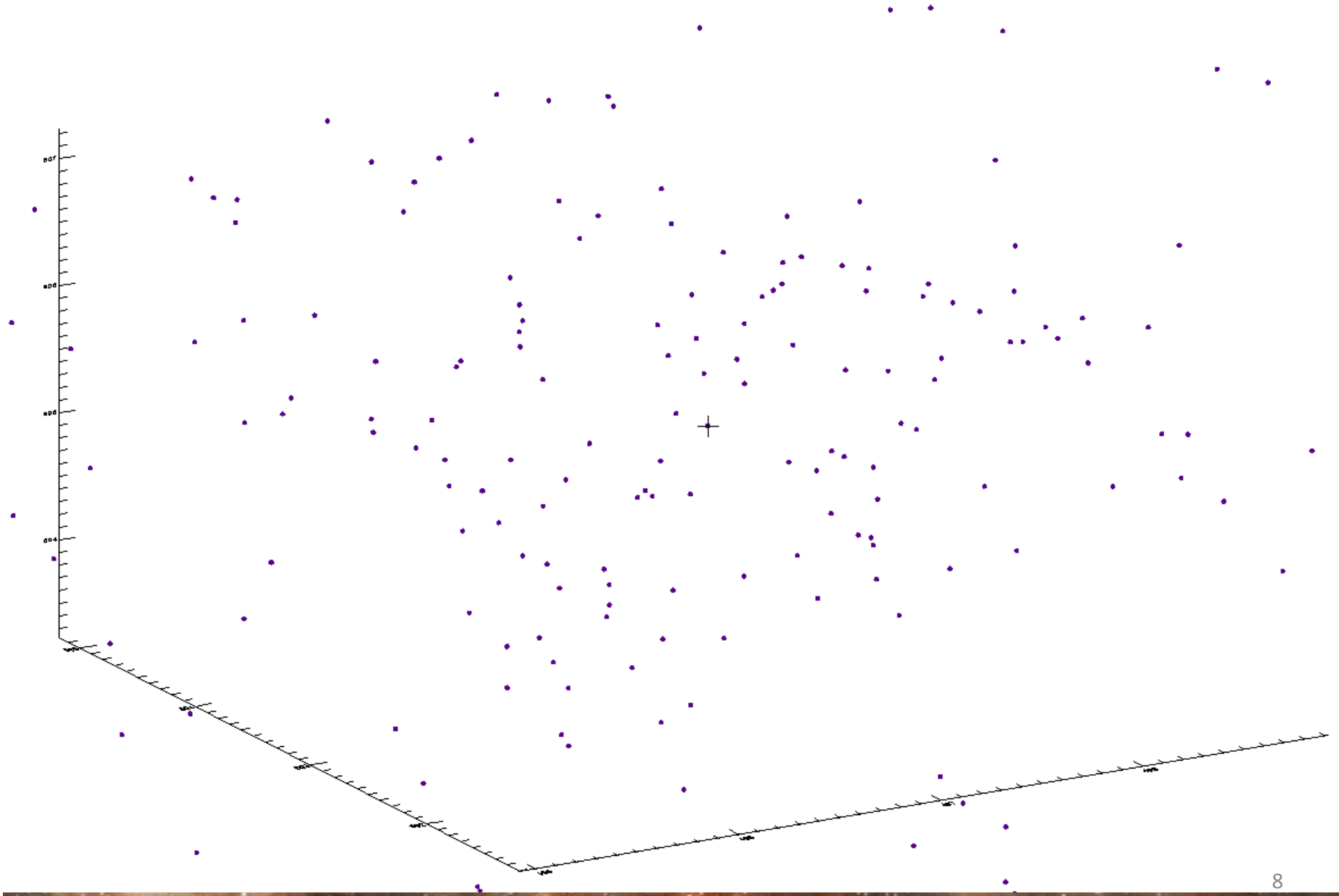
- Finding the center of a cluster
  - Ambiguity: the center cannot always be clearly identified
  - Making accurate predictions in 2 dimensional projections

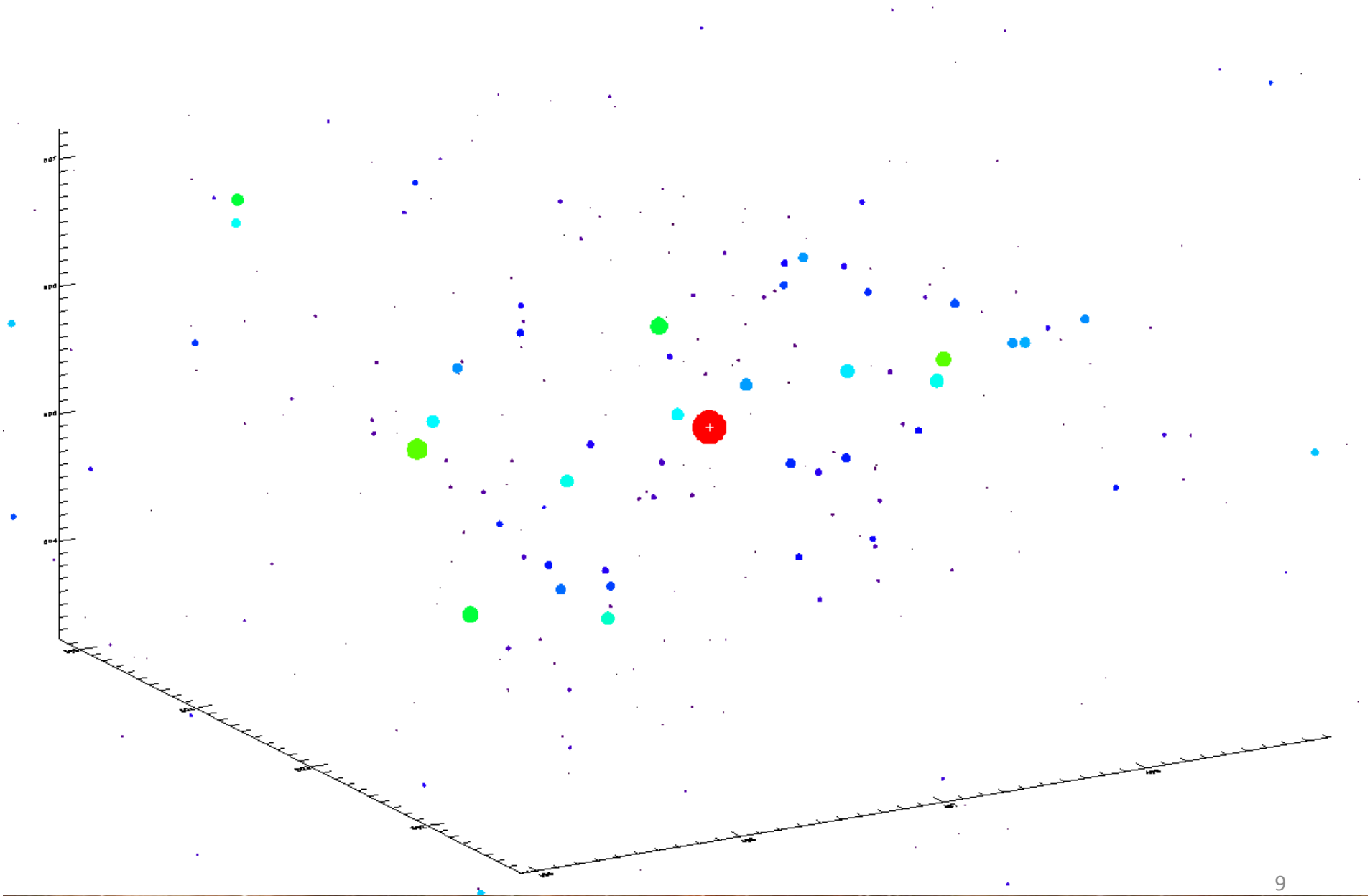
A Network of Galaxies

- Nodes: galaxies
- Links: gravitational potential

$$link\ weight = \frac{L_i * L_j}{r_{ij}}$$

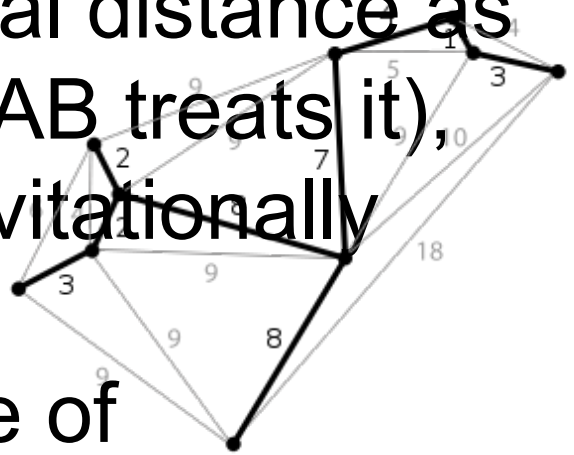
- Every node is connected to every other node
- Degree: we defined the degree of a node to be the sum of the weights of all of its links, this can be used as an indication of the center of a cluster

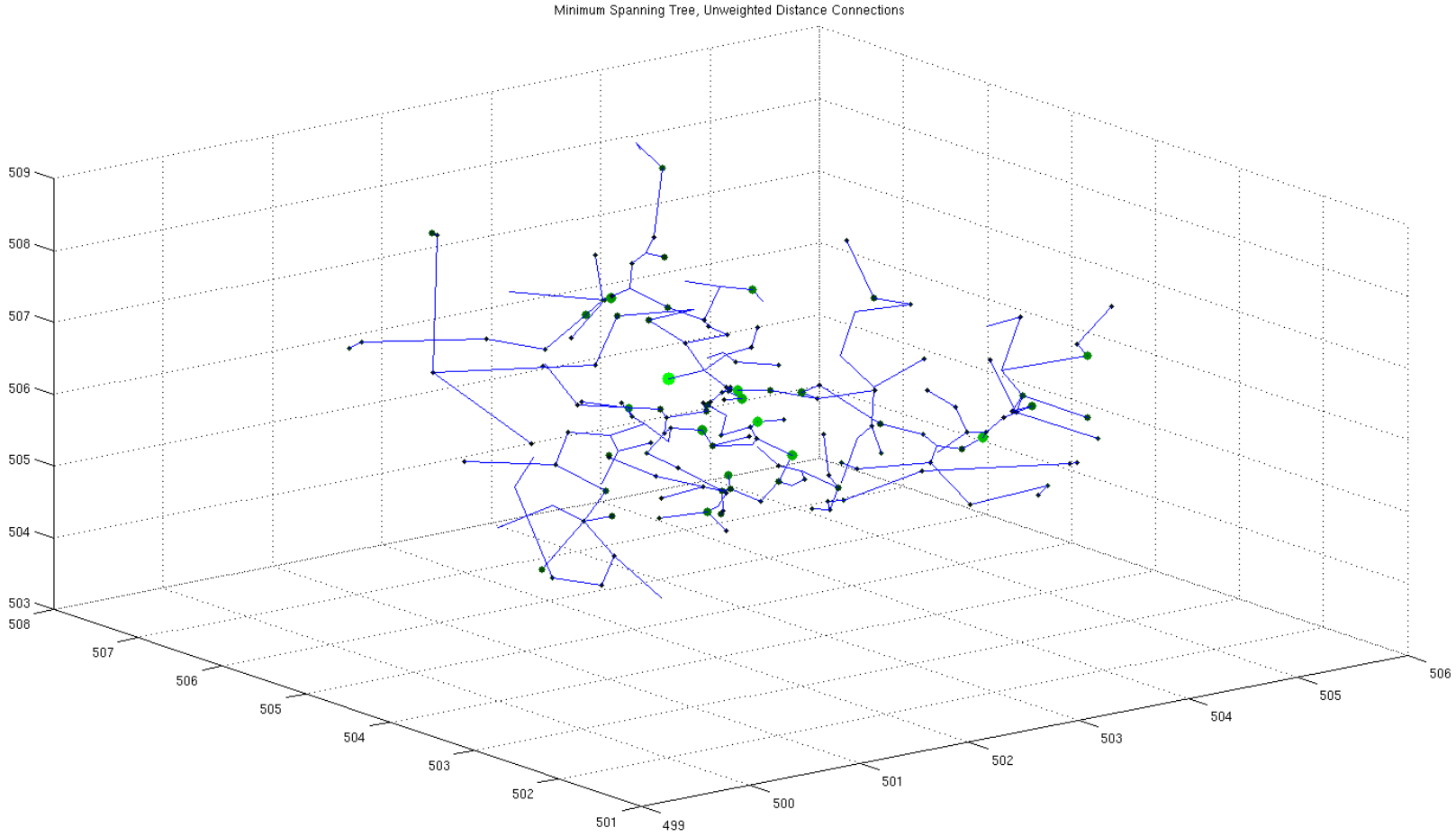


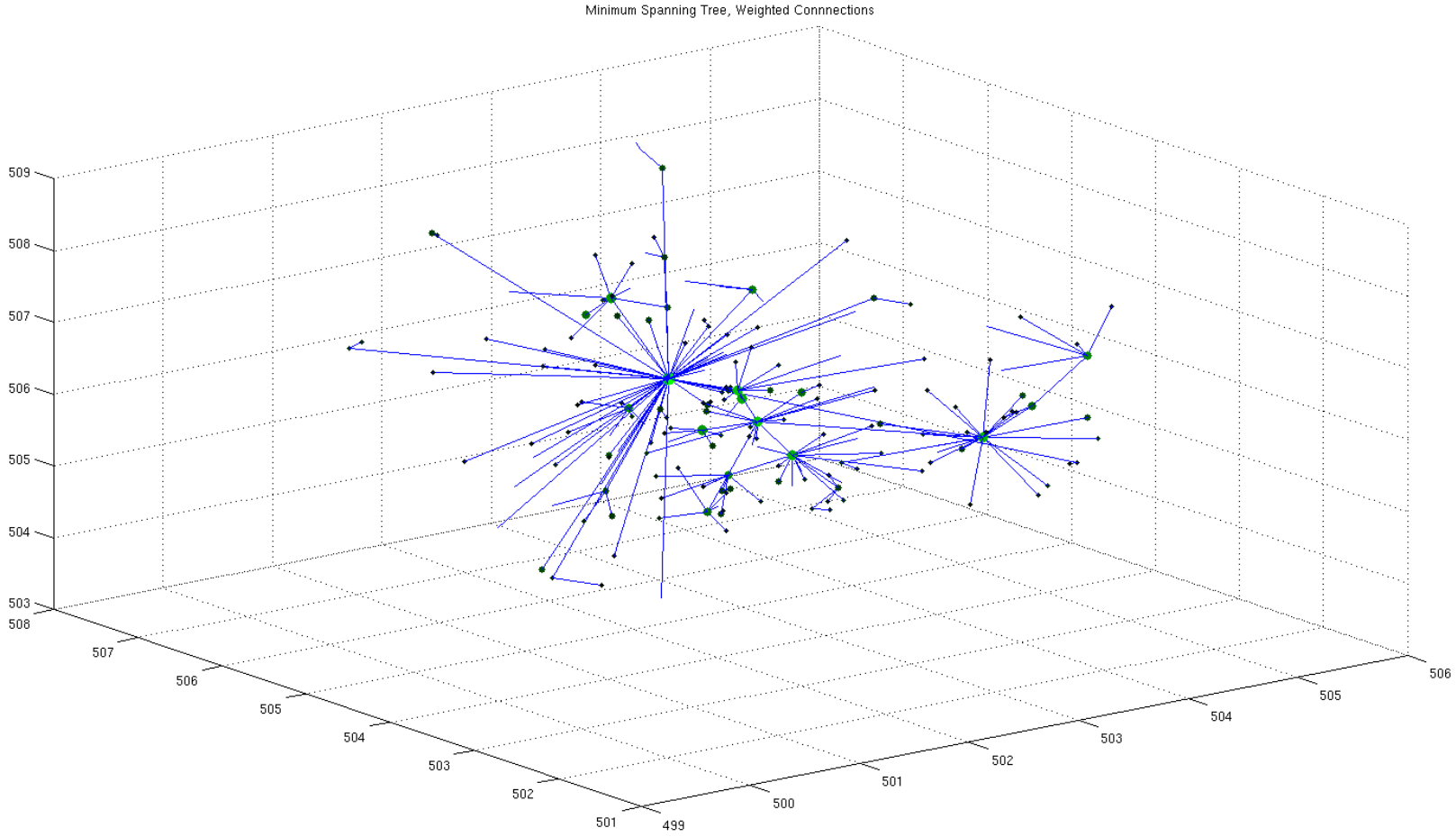


Minimal Spanning Trees

- A minimal spanning tree is a series of links that connect every node in a network with out creating any loops and minimizes the total of the weight of the links
- Typically MST's use physical distance as the links (this is how MATLAB treats it), however using gravitationally weighted links more clearly reflects the structure of our galaxy network




Minimum Spanning Tree, Unweighted Distance Connections
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Minimum Spanning Tree, Weighted Connnections
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Why Use MST's?

- Simplification:
  - The MST only uses a subset of the links
- Structure:
  - The MST can reveal clustering in a network while preserving the overall structure
  - The connections selected by the MST may be used to relate to other characteristics, such as the centrality of a halo

Degree Measures

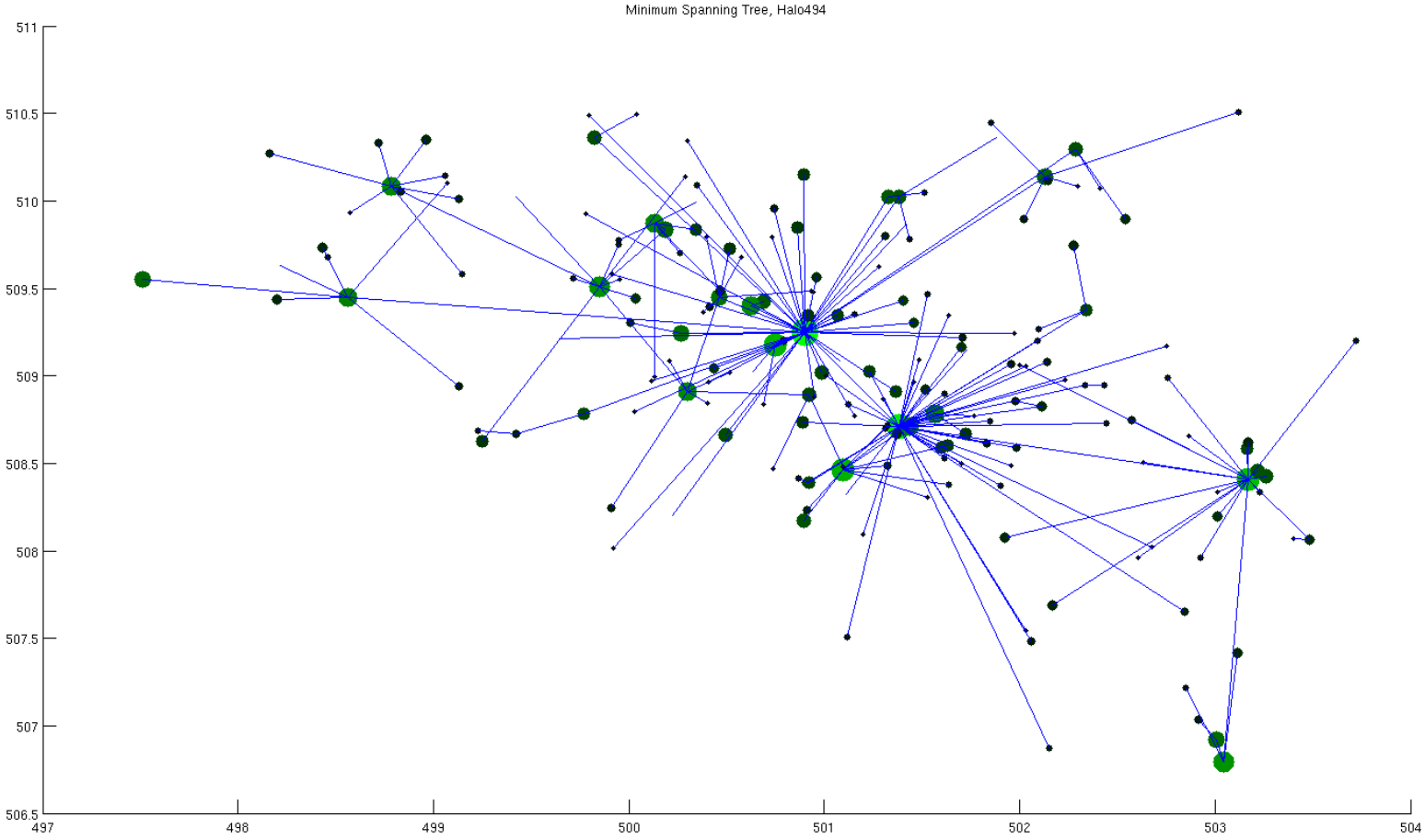
- The degree of a node in an MST can be measured in two ways:
  1. The sum of the weights of its links
  2. The number of links

Number of Links

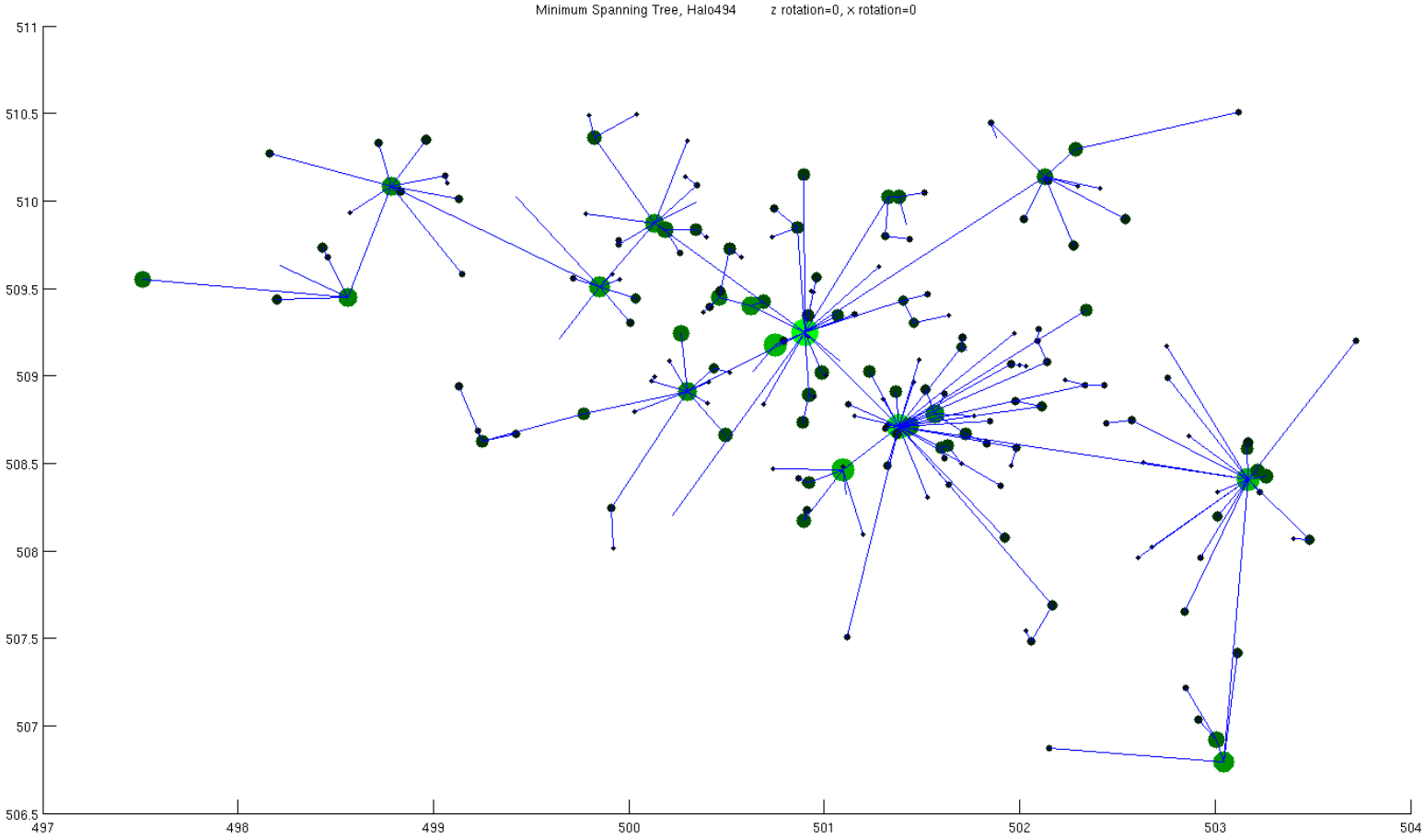
- Percent of clusters with correctly predicted centers:
  - Using total degree: **87.85%**
  - Using weight of links in MST: **88.79%**
  - Using # of links in MST: **98.13%**
- Using the number of links eliminates outliers when a pair of relatively unimportant nodes lie very close together

2 Dimensions

- Observation comes in 2 dimensions, not 3
  - Distances are distorted in 2-dimensional projections
- We took the 3D simulated data and projected it into 2D for 100 rotations
- Average percent of rotations when correct center is picked:
  - Using total degree: **89.03%**
  - Using # of links in MST: **95.34%**
- Lowest percent of rotations when correct center is picked for one cluster
  - **21.82%**



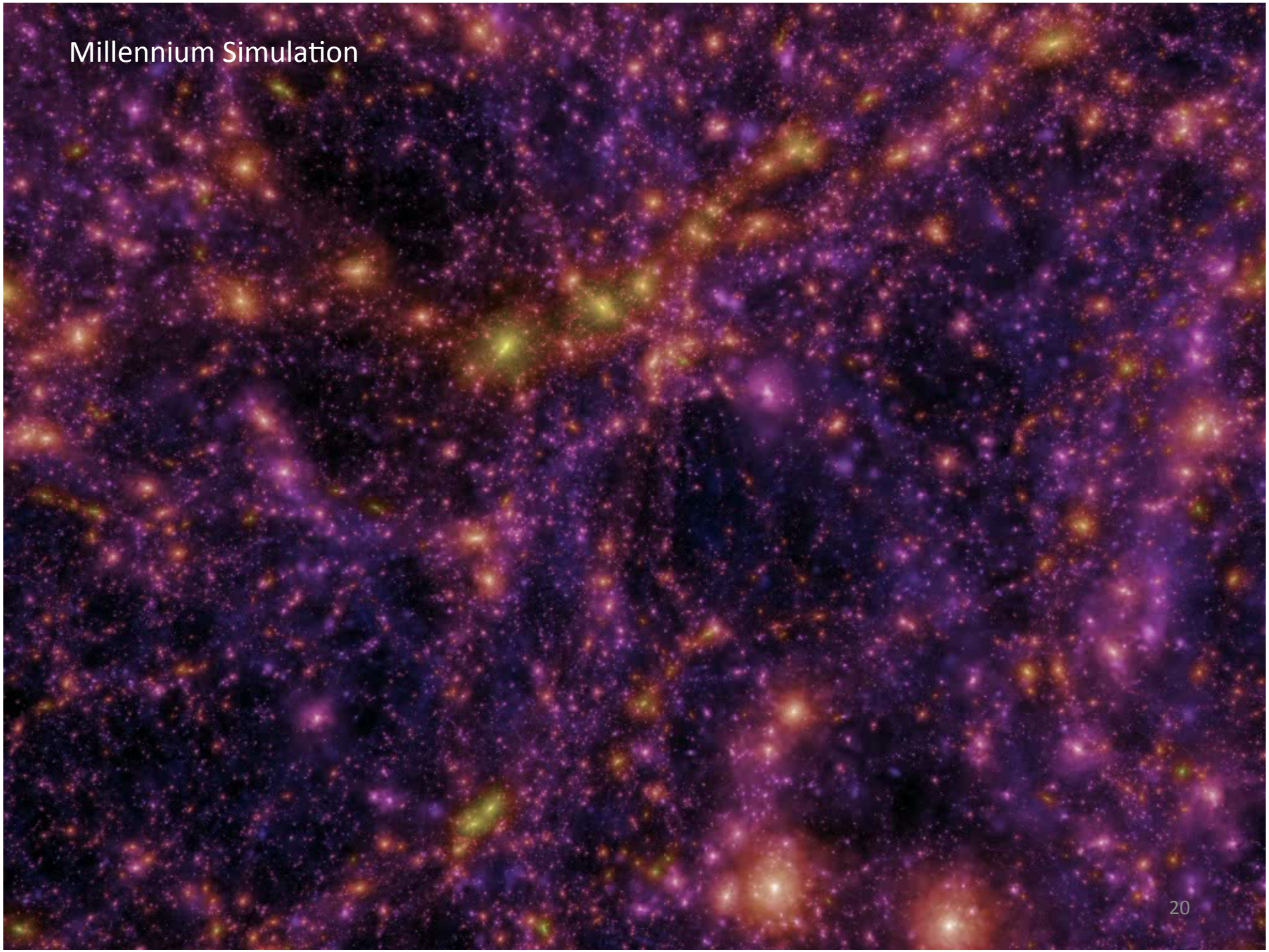
3D Links Projected into 2D



2D Uncorrected Projection

Conclusions

- The number of links in the MST is a reliable indicator of the center of a cluster
- Further work must be done in correcting 2D distances
- Further work can be done in determining whether a cluster has 2 or more possible centers


Millennium Simulation

Rhapsody, Formation of Galaxy Cluster

Acknowledgments

- My advisor, Prof. Tim McKay, and all the member of his lab, especially my research partner Blythe Moreland
- The REU Program at University of Michigan and the NSF for sponsoring it

Image Sources

Sllide # 4:

Butler, Paul. *Visualizing Friendships*. Digital image. Facebook, 13 Dec. 2010. Web. <http://www.facebook.com/notes/facebook-engineering/visualizing-friendships/469716398919>.

Slide # 1:

HST. *Dwarf Galaxy NGC 44449*. Digital image. NASA, n.d. Web. <http://hubblesite.org/gallery/wallpaper/pr2007026a/>.

Slide Backgrounds:

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Slide # 21:

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Slide # 10:

"Minimum Spanning Tree." *Wikipedia*. Wikimedia Foundation, 30 July 2012. Web. 03 Aug. 2012. <http://en.wikipedia.org/wiki/Minimum_spanning_tree>.

Slide # 3:

Newman, M. E. J. "Communities, Modules and Large-scale Structure in Networks."*Nature Physics* 8 (2011): 25-31. Print.

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Springel Et Al. (Virgo Consortium). Digital image. *The Millennium Simulation Project*. The Virgo Project, 2005. Web. <http://www.mpa-garching.mpg.de/galform/virgo/millennium/>.