Title: Fast and Accurate Mocks: Getting the Most from Large Scale Structure Surveys

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Abstract: Generation of accurate mock observations tailored specifically to upcoming surveys such as Advanced ACT, CHIME, and LSST is a key technical challenge in cosmology. Traditional approaches involving N-body simulation are fraught with difficulties due to increasingly large survey volumes and depths. Typically, statistical ensembles can only be realized for a few carefully-chosen parameters, limiting exploration to a significantly restricted cosmological model space. We have developed a new massively parallel algorithm to generate accurate halo masses and positions in a fraction (~1e-3 to 1e-2) of the time taken by N-body simulations. I will present a suite of simulated full sky cluster Sunyaev-Zelâ€™dovich maps that have been produced with this approach, and describe the types of virtual large scale structure observations that are now within reach in the coming years.

Fast and Accurate Mocks: Getting the Most from Large Scale Structure Surveys

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Collaborators

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N. Battaglia (Princeton)

Outline

Motivation

Our Approach

Halo Clustering

Full Sky Cluster SZ Maps

Summary & Future Directions

Main Motivation

Data Analysis
&
Theory

Data Analysis for
Large Scale Structure Surveys

Galaxy Surveys

HSC, DES, LSST, Euclid, WFirst

CMB

Planck, Advanced ACTPol, CMB-S4

Intensity Mapping

CHIME, TIAN-LAI, HIRAX, COMA

Simulations for Data Analysis

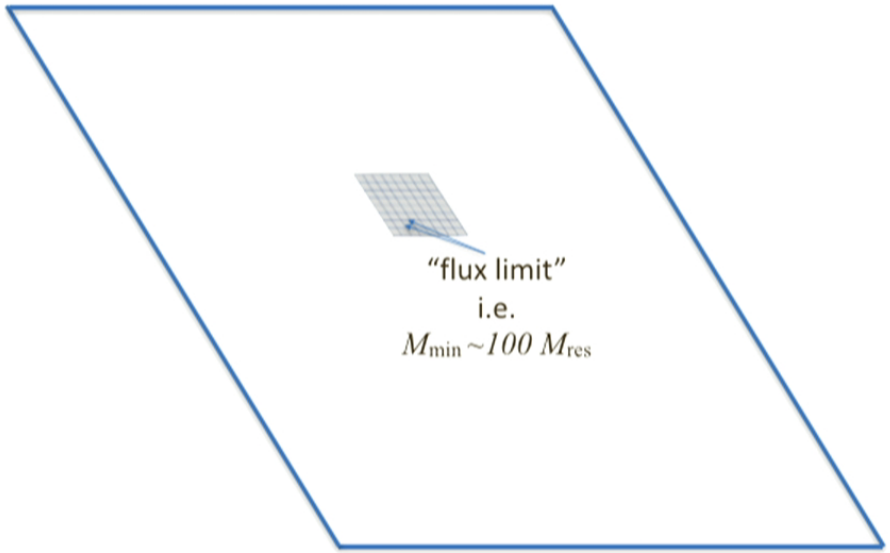
Key Challenges

Speed

&

Dynamic Range

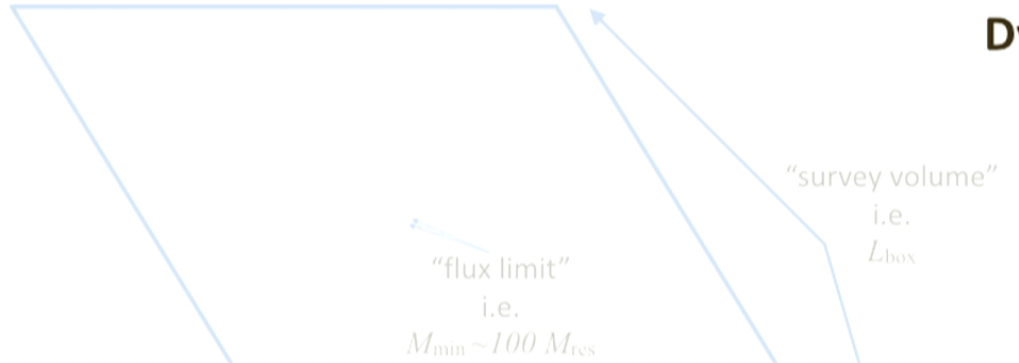
Simulations for Data Analysis
Key Challenges



Dynamic Range

Simulations for Data Analysis
Key Challenges

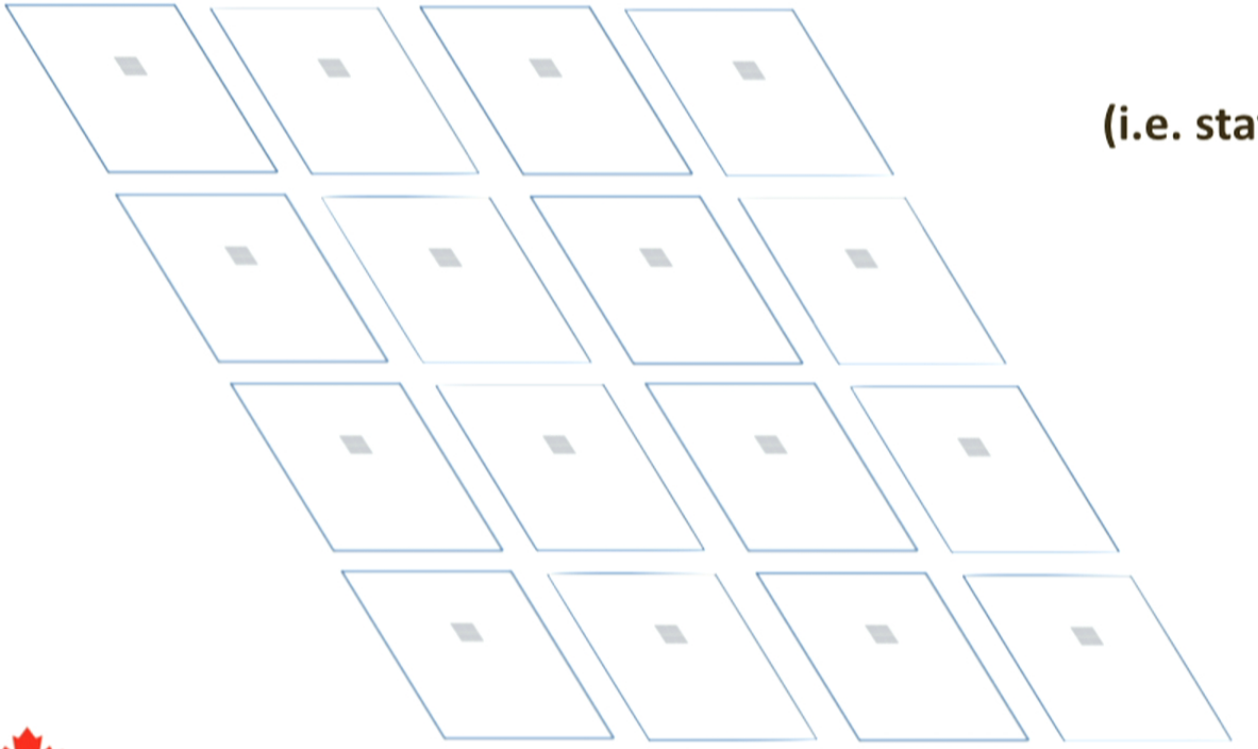
Dynamic Range



$$N \simeq 16{,}000^3 \left(\frac{L_{\rm box}}{10\ {\rm Gpc}}\right)^3 \left(\frac{M_{\rm min}}{10^{12}\ M_\odot}\right)^{-1}$$

Simulations for Data Analysis

Key Challenges



Speed
(i.e. statistics)

Theory of Large Scale Structure

Key Questions

Perturbation Theory vs. **Nonlinear Collapse**

How to Probe

$\delta_{lin}(\boldsymbol{k})$, $D(z)$, $H(z)$

Studying Halo Formation and Clustering

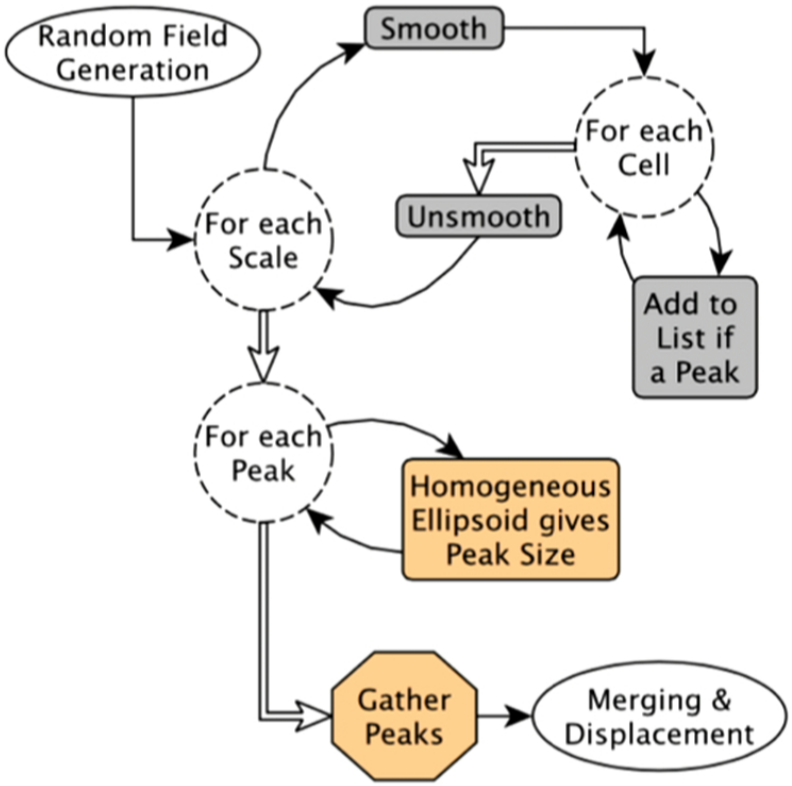
and

Generating Mock Catalogs Efficiently

with

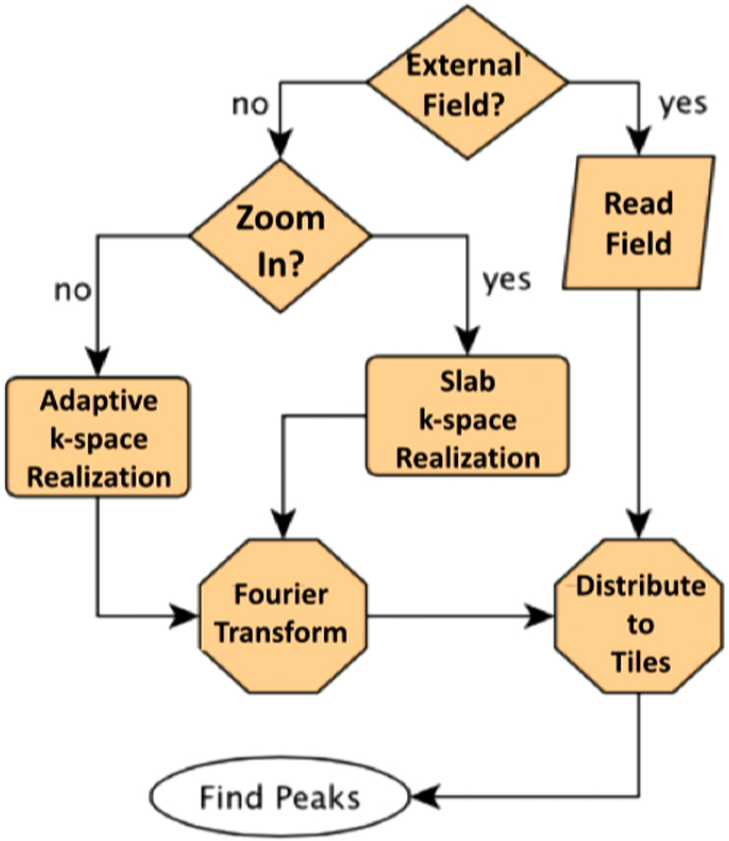
Peak Dynamics & Lagrangian Exclusion

Peak Dynamics & Exclusion



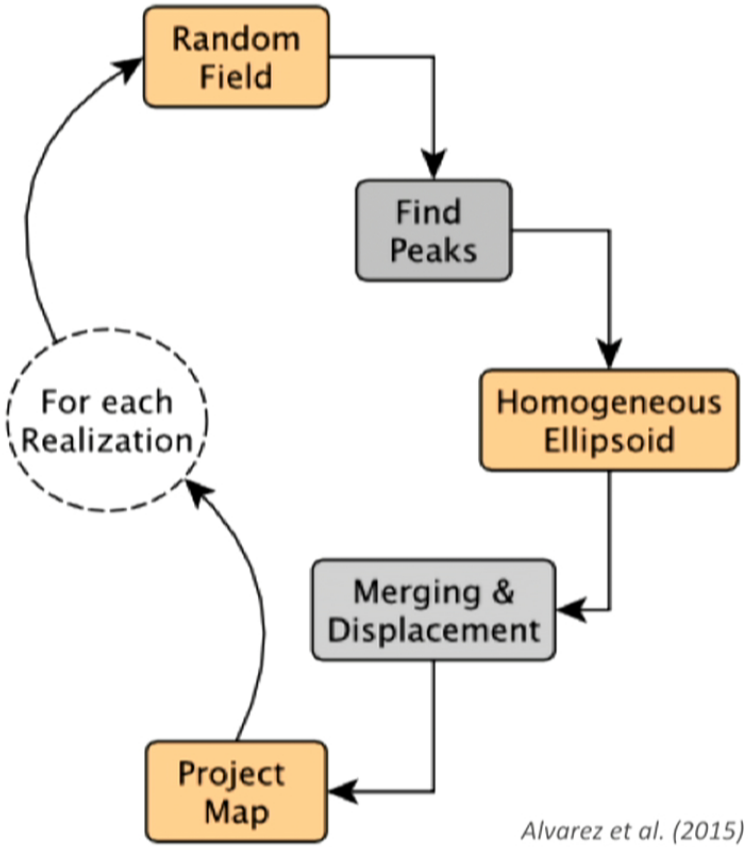
Alvarez et al. (2015)

Random Field & Domain Decomposition



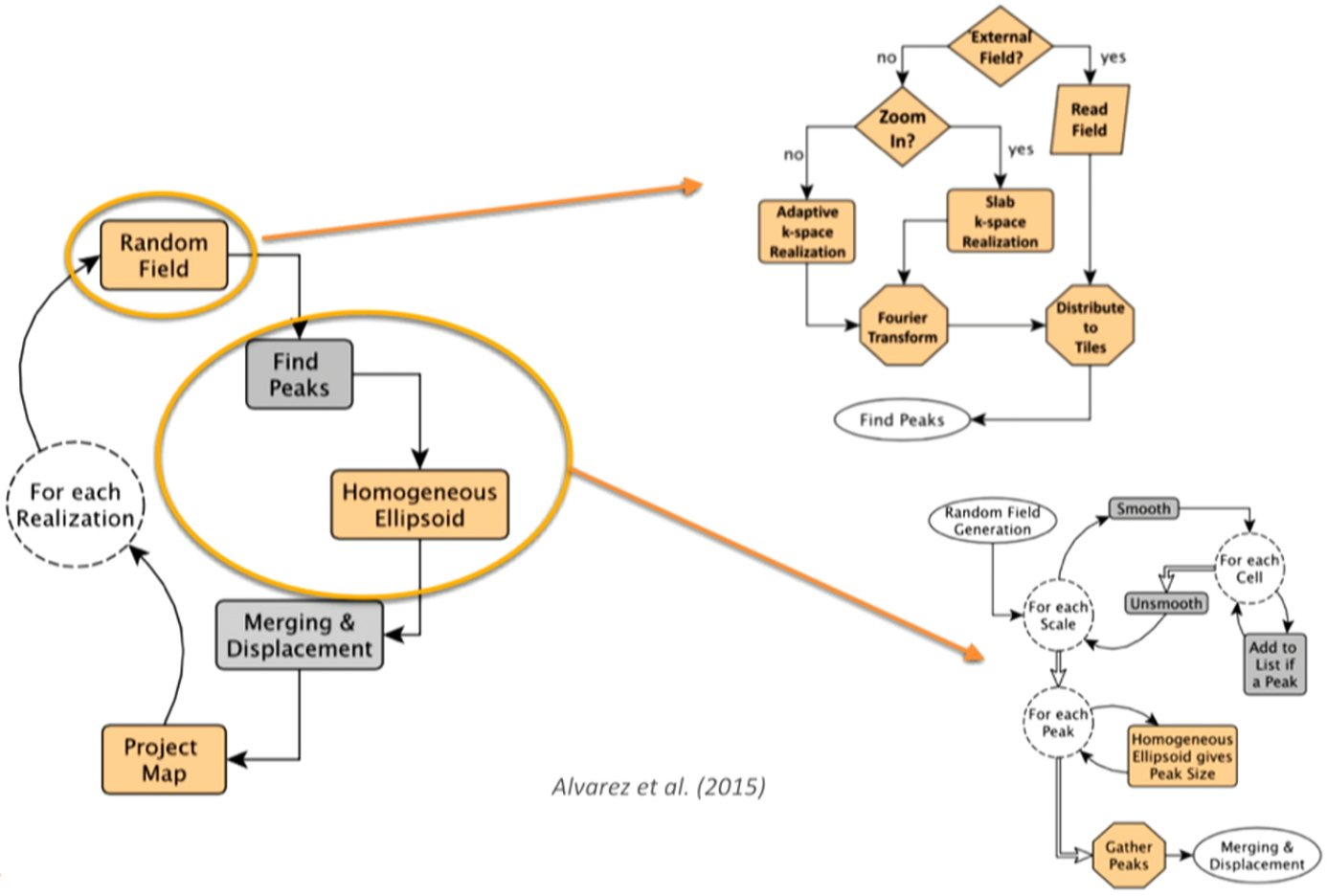
Alvarez et al. (2015)

Monte Carlo Pipeline



Alvarez et al. (2015)

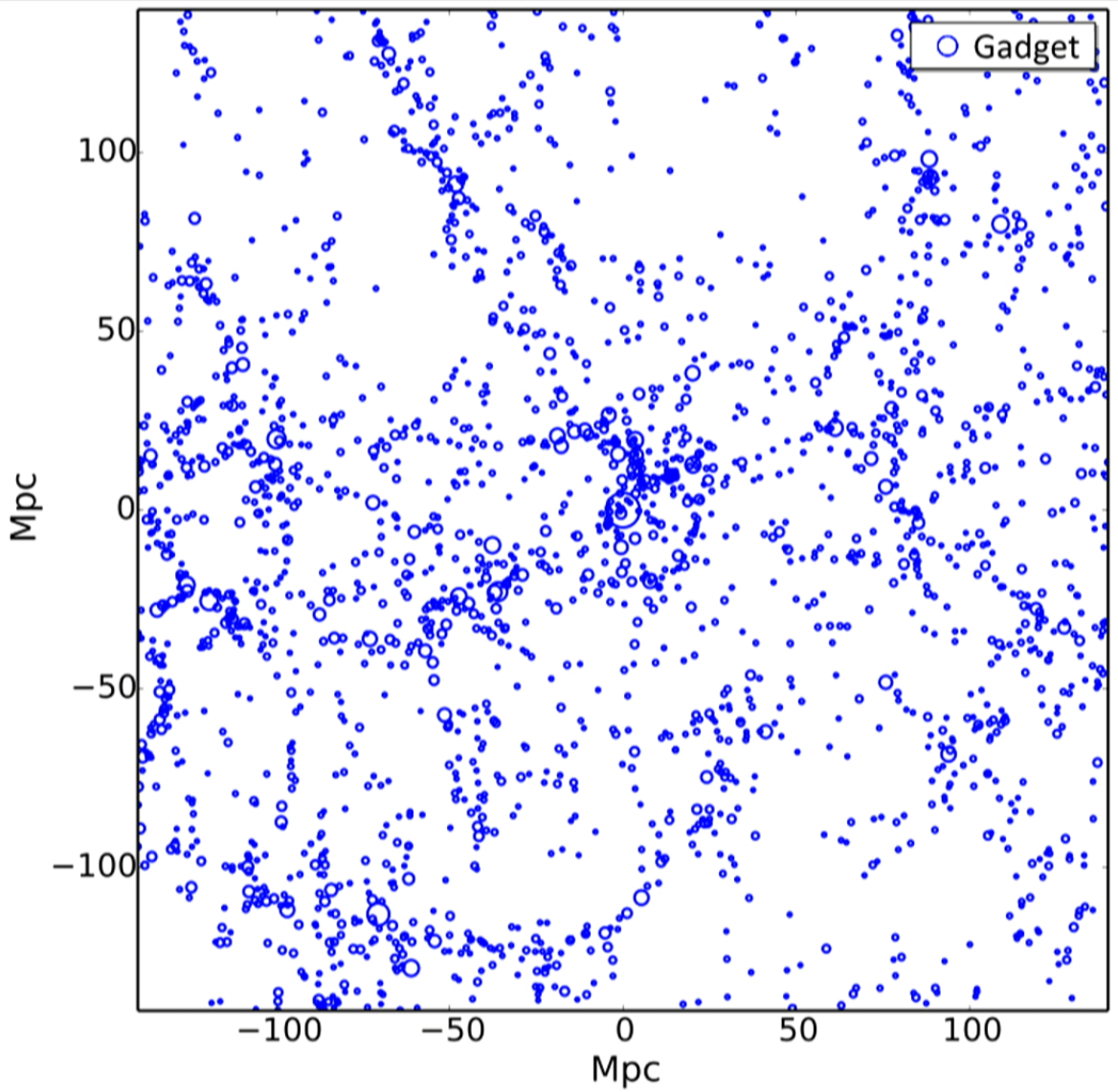
Mock Maps with Peak Patches

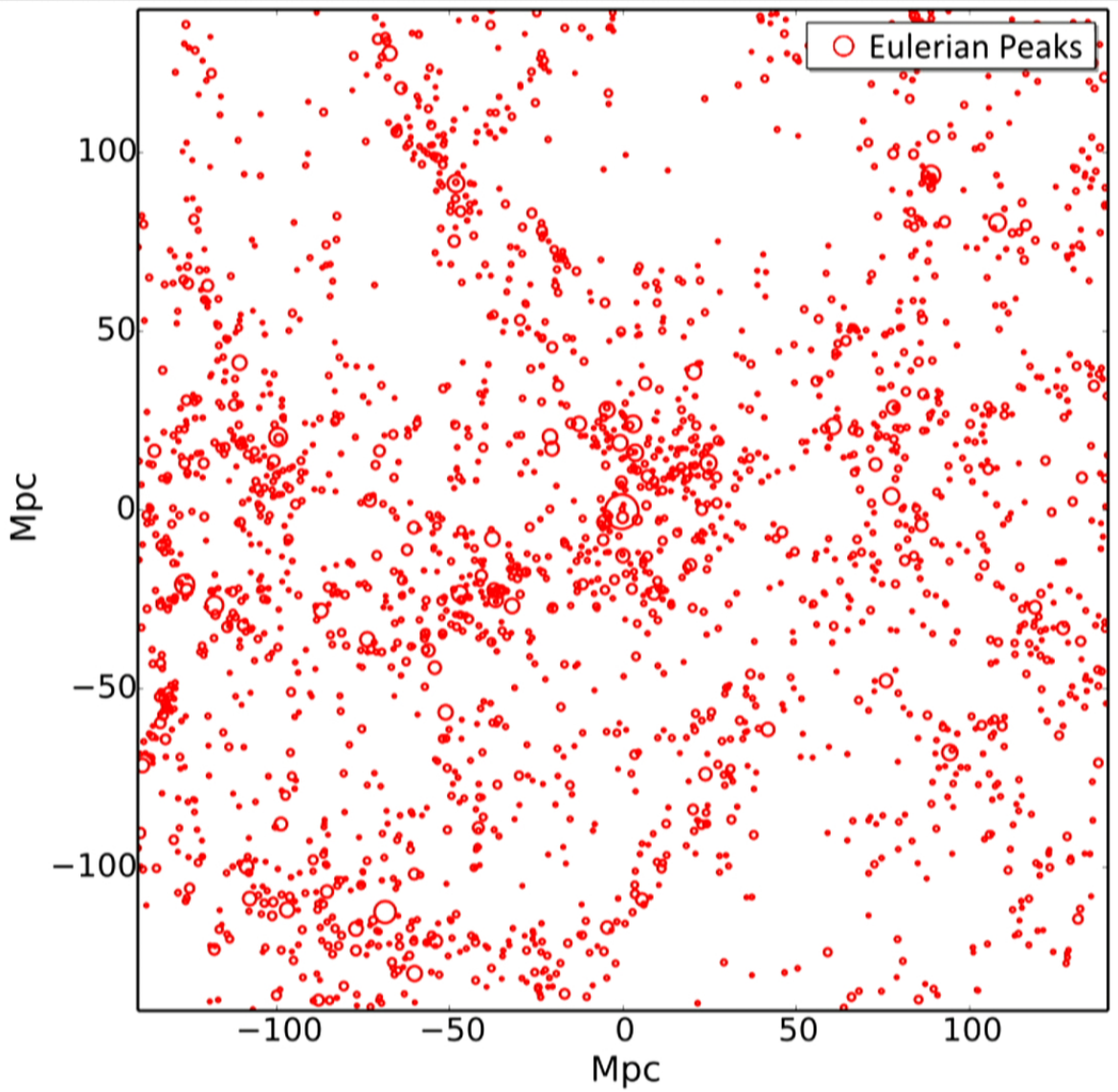


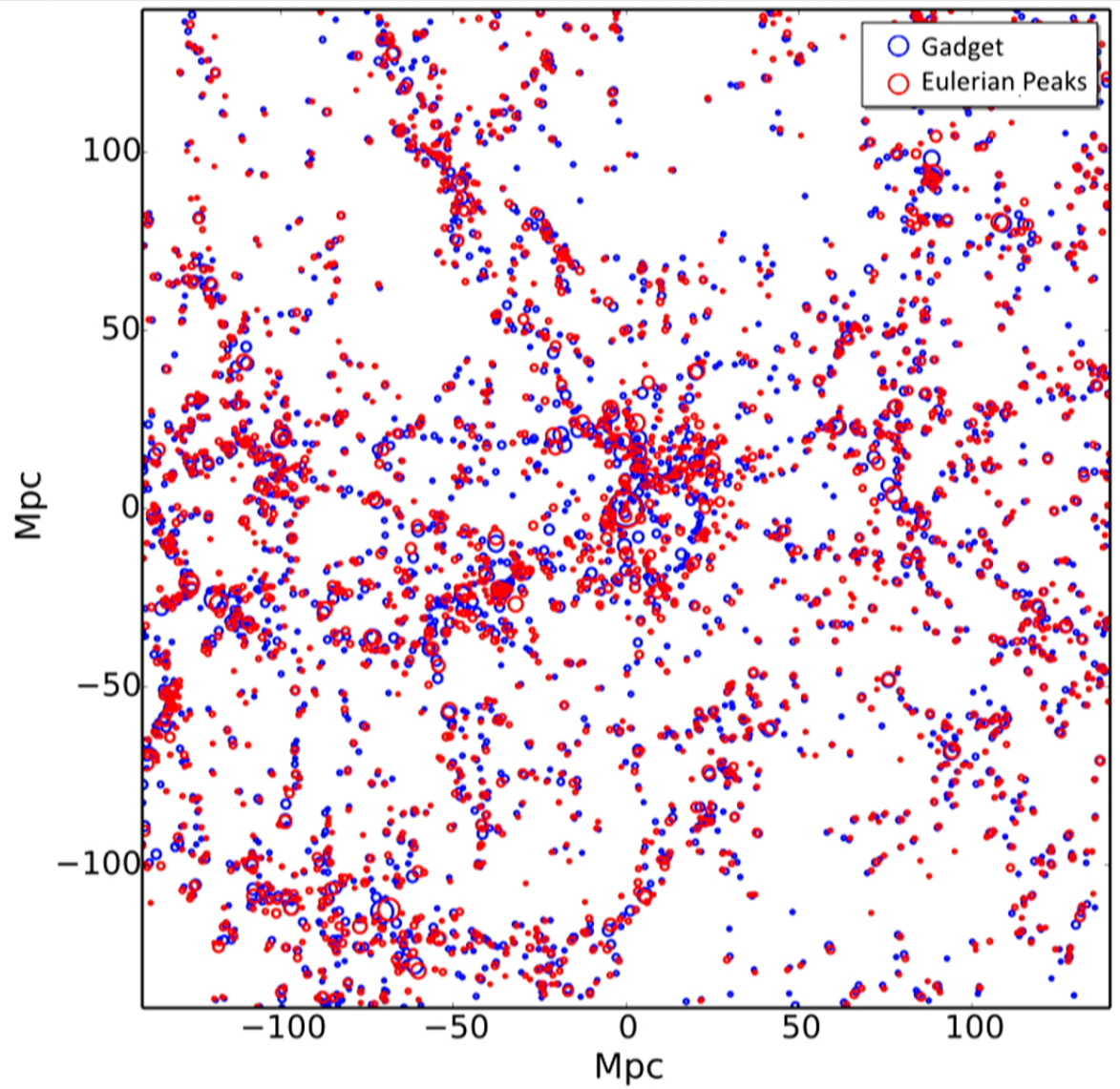
Alvarez et al. (2015)

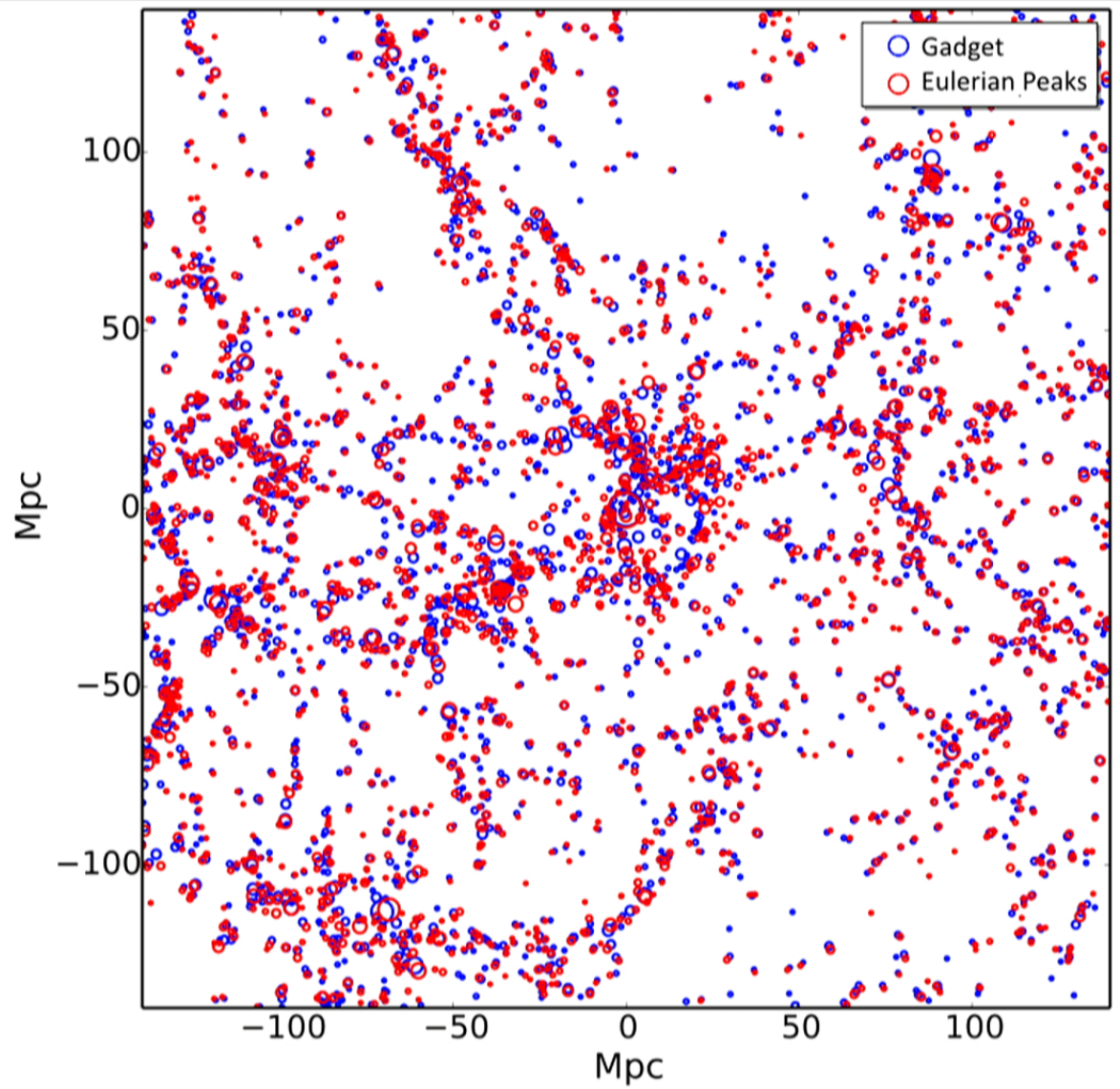
Comparison to N-body

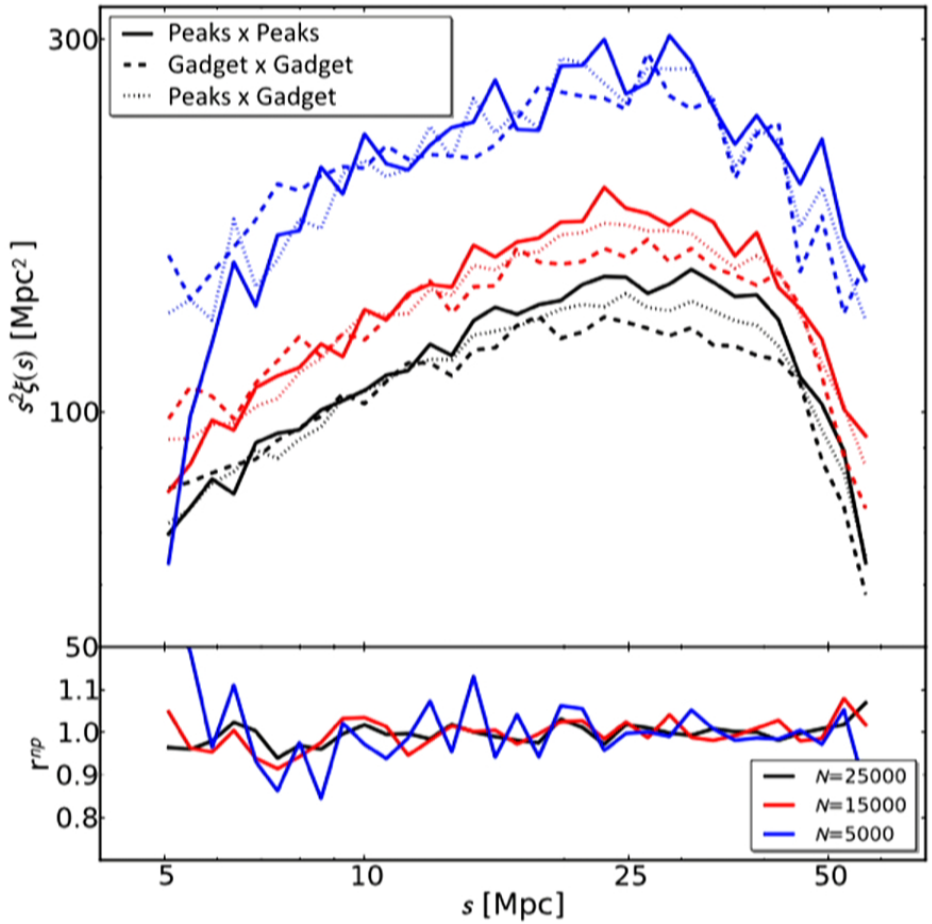
Alvarez et al. (2015)


Gadget
100
50
0
−50
−100
Mpc
−100
−50
0
50
100
Mpc


Eulerian Peaks
100
50
0
−50
−100
Mpc
−100
−50
0
50
100
Mpc


Gadget
Eulerian Peaks
100
50
0
−50
−100
Mpc
−100
−50
0
50
100
Mpc


Gadget
Eulerian Peaks
100
50
0
−50
−100
Mpc
−100
−50
0
50
100
Mpc



Alvarez et al. (2015)

Outline

Motivation

Our Approach

Halo Clustering

Full Sky Cluster SZ Maps

Summary & Future Directions

Halo Clustering Statistics

Gpc box — **1024^3** cells

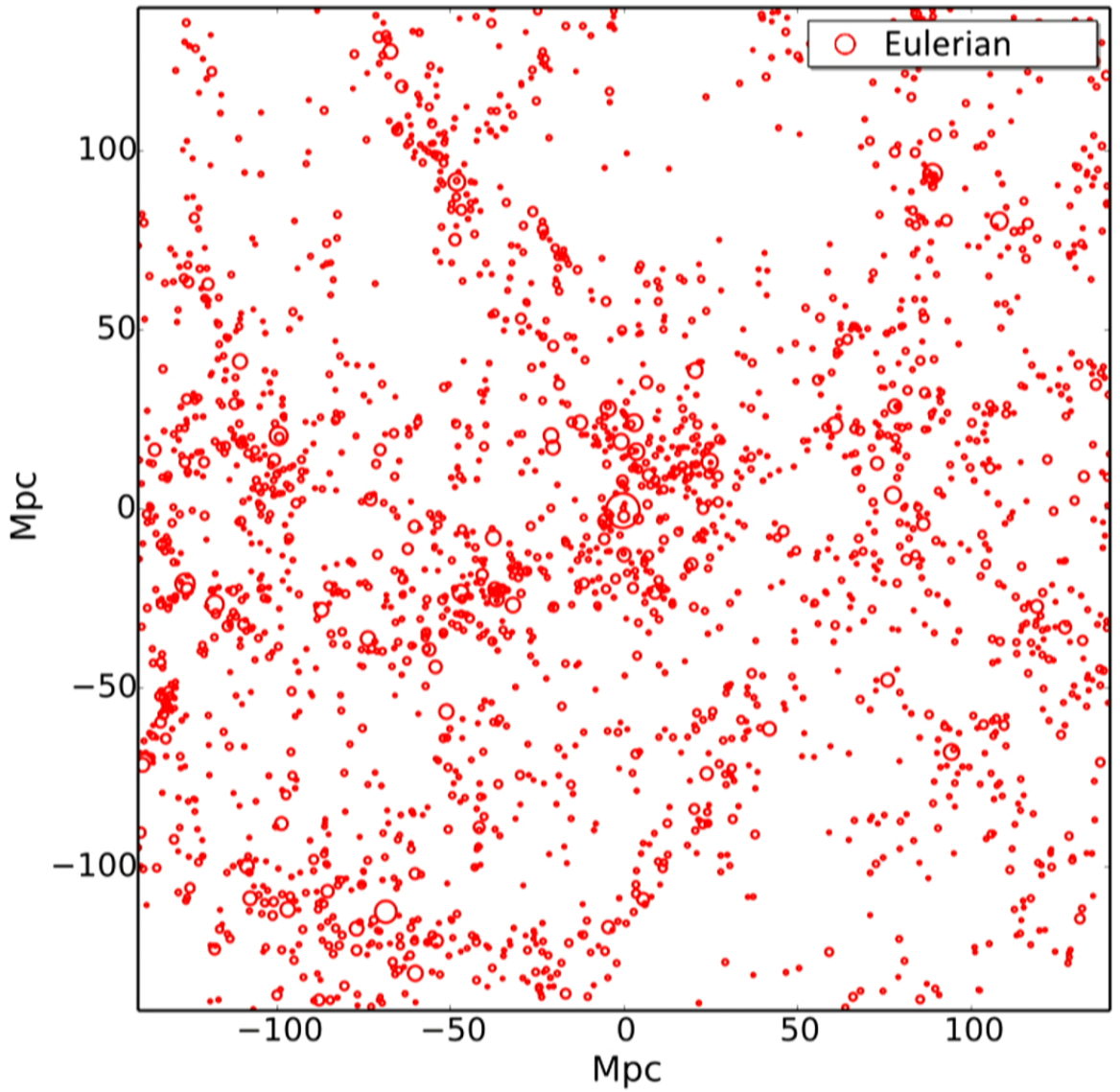
Wall clock ~ **3 mins** each on **64 cores**

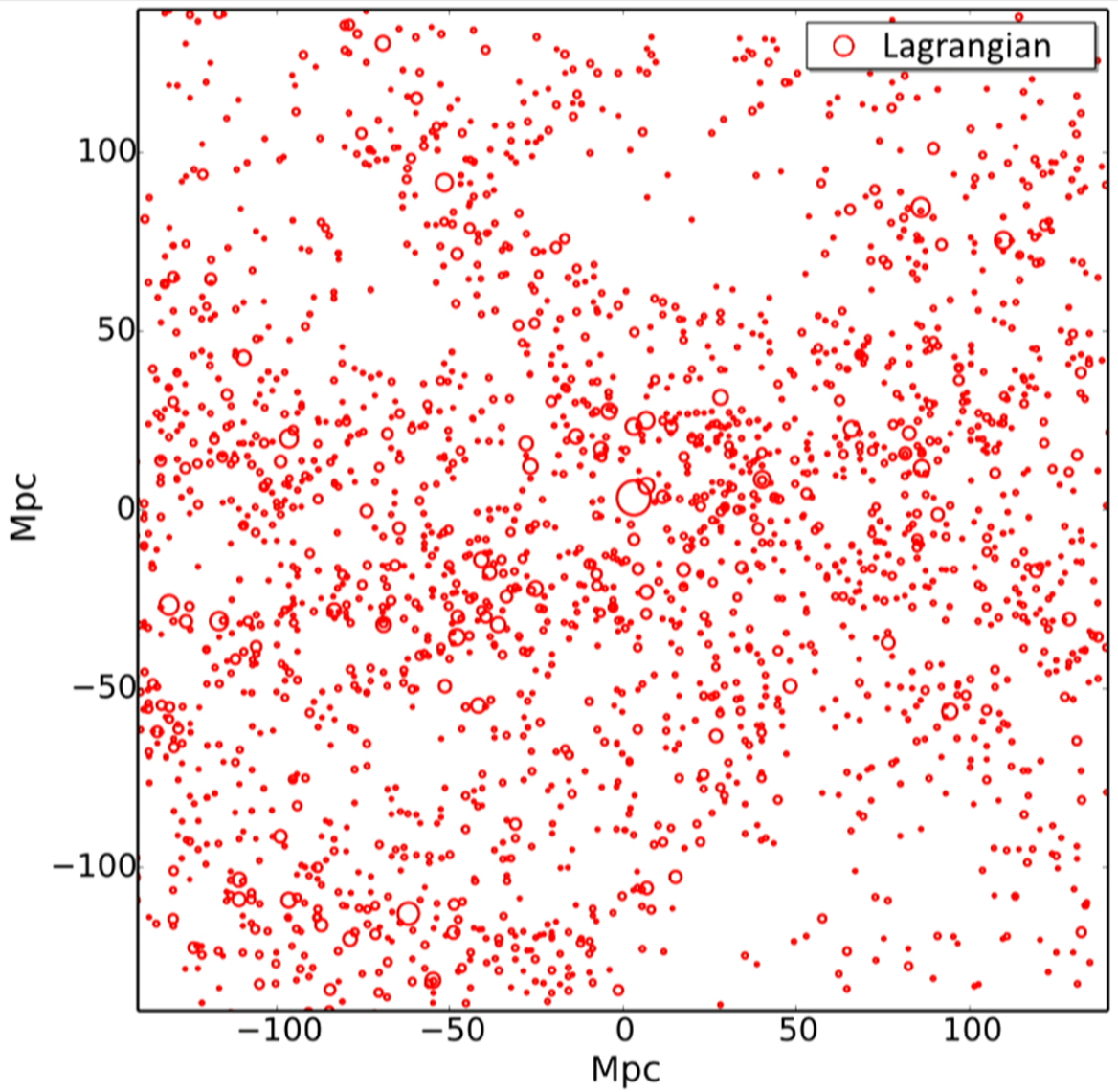
$z=0$ with ~ **10^6 halos**

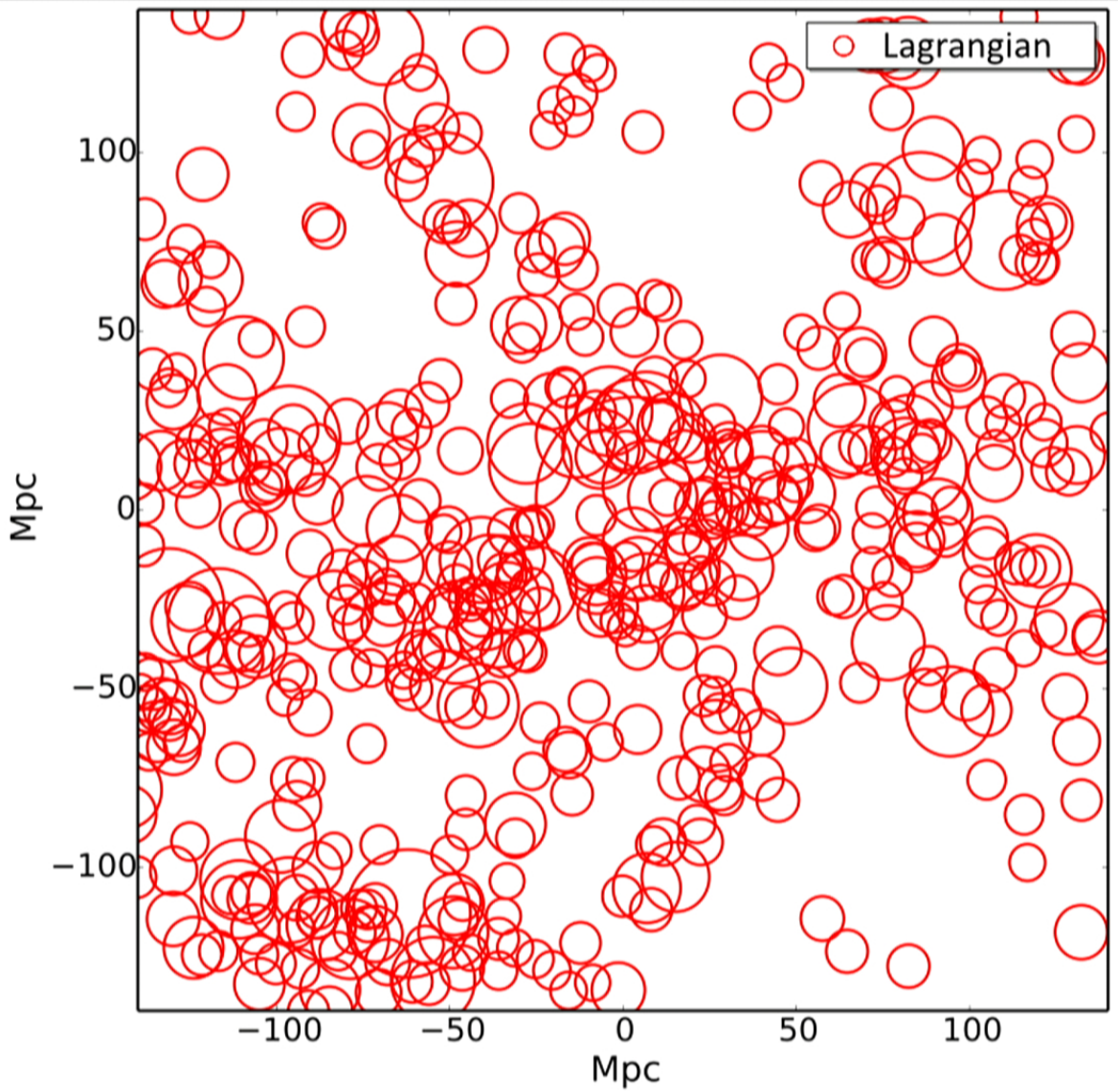
Complete for $M_{halo} > 3 \times 10^{12} M_{sun}$

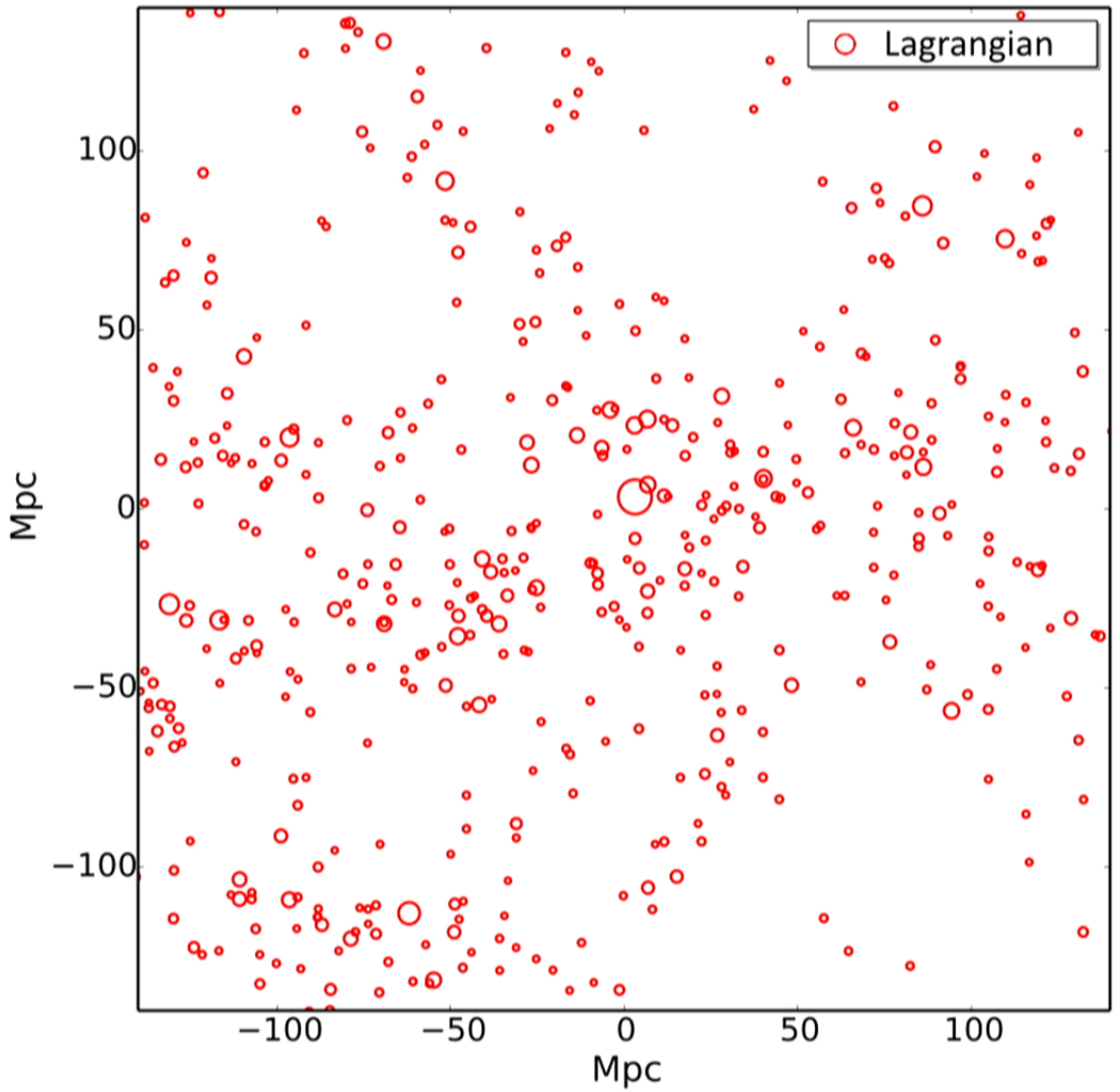
~ 400 realizations

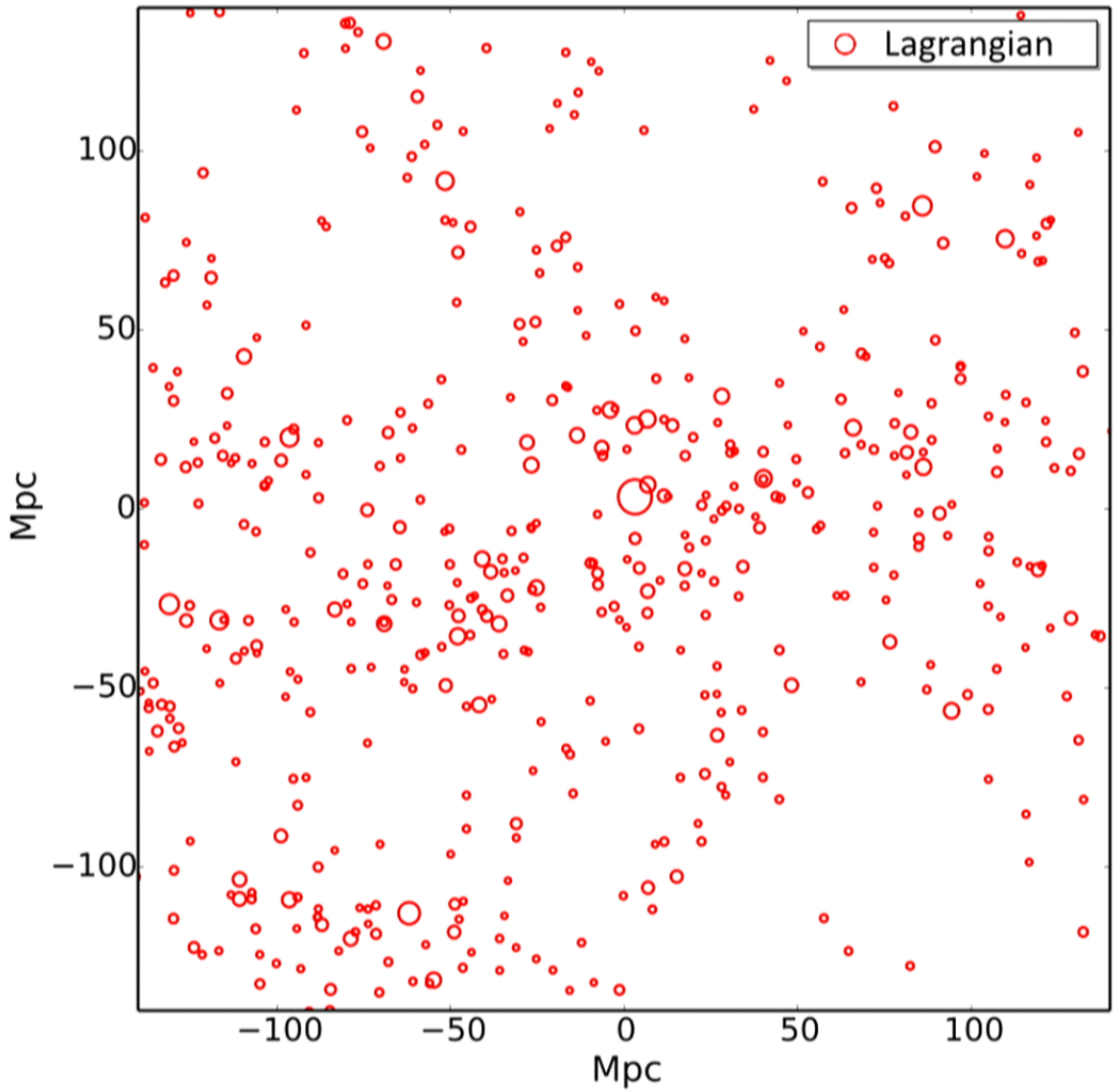
Computed correlation function and its covariance


Eulerian
100
50
0
−50
−100
Mpc
−100
−50
0
50
100
Mpc

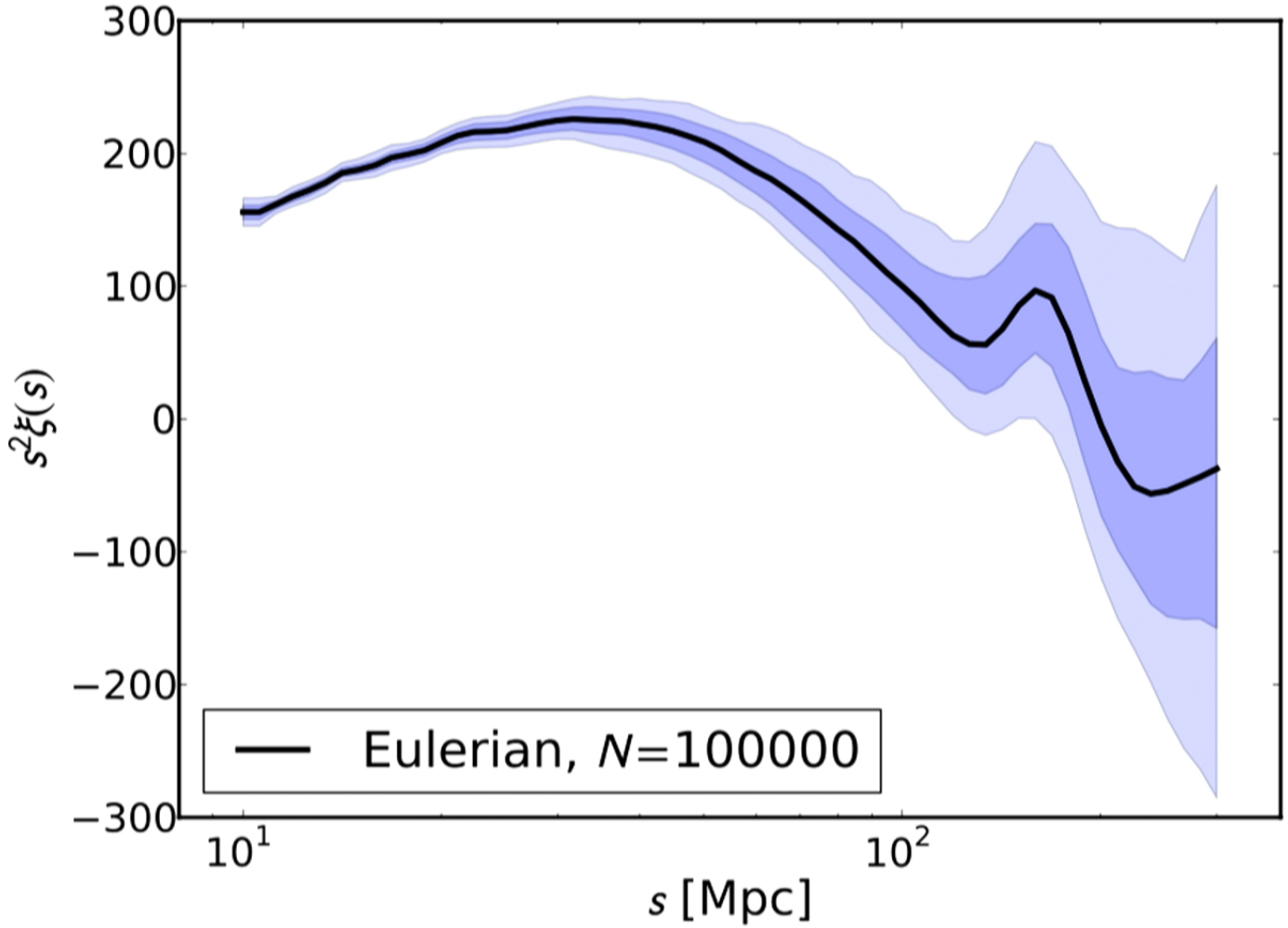

Lagrangian
100
50
0
−50
−100
Mpc
−100
−50
0
50
100
Mpc

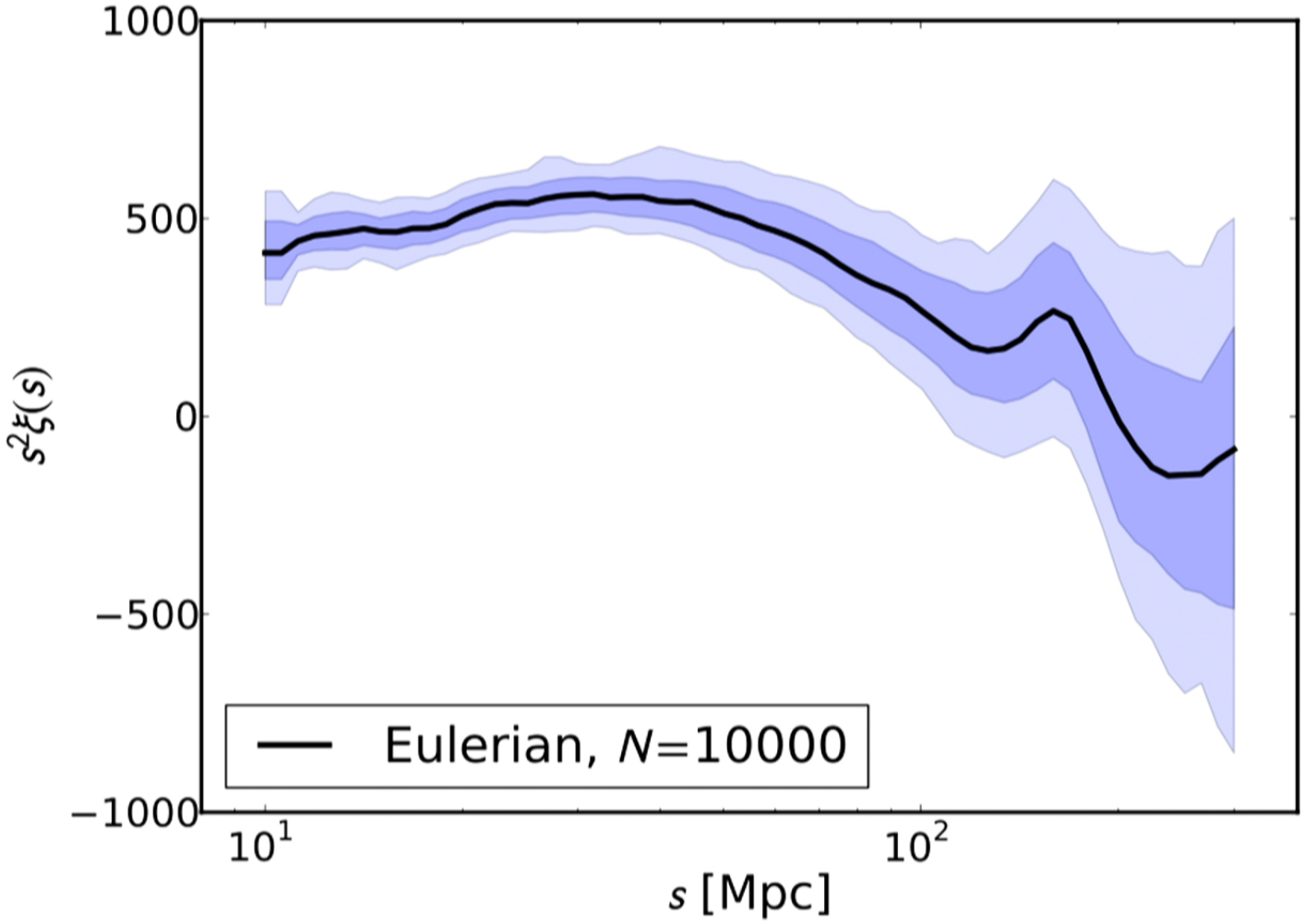

Lagrangian
100
50
0
−50
−100
Mpc
−100
−50
0
50
100
Mpc

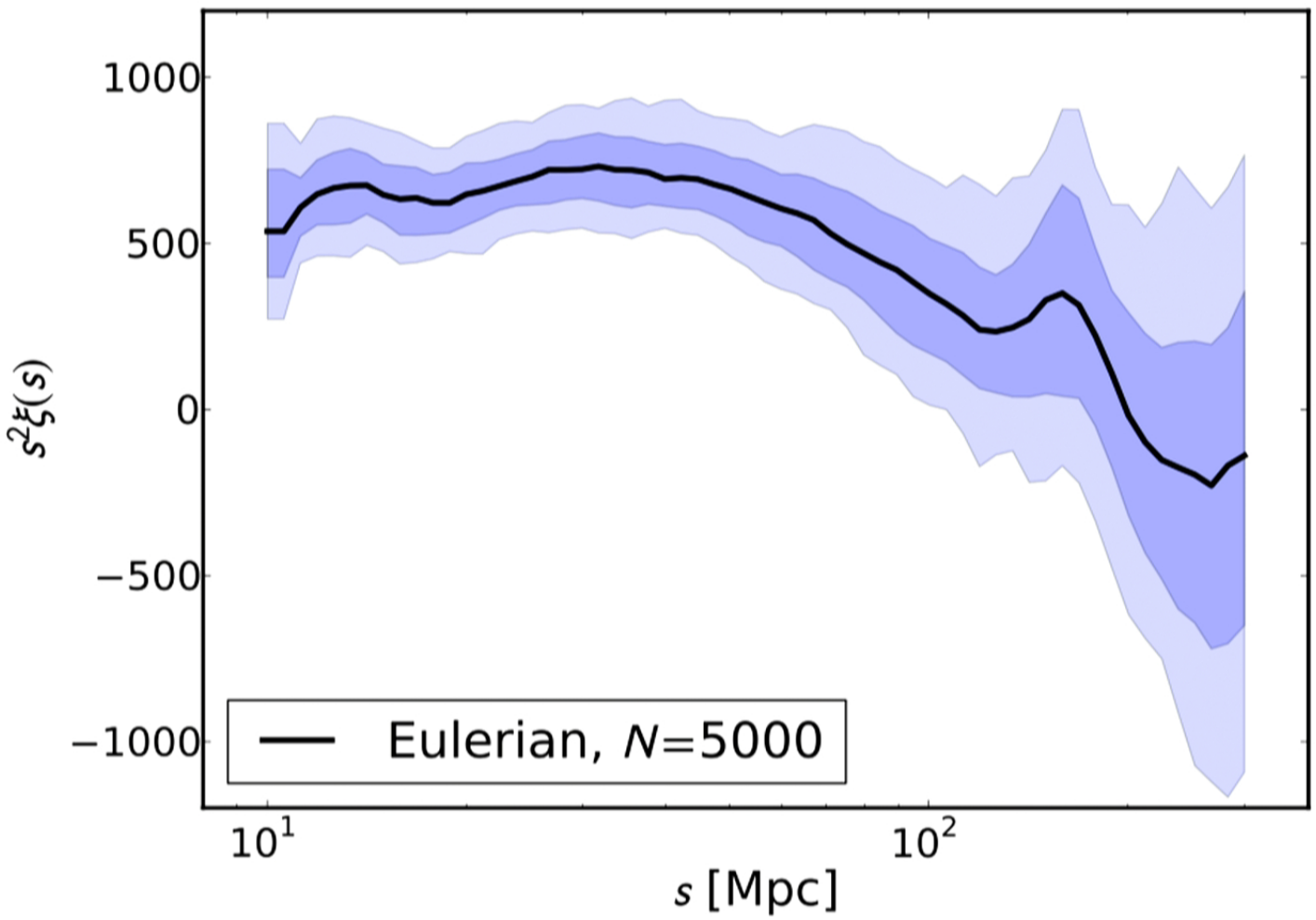

Lagrangian
100
50
0
−50
−100
Mpc
−100
−50
0
50
100
Mpc

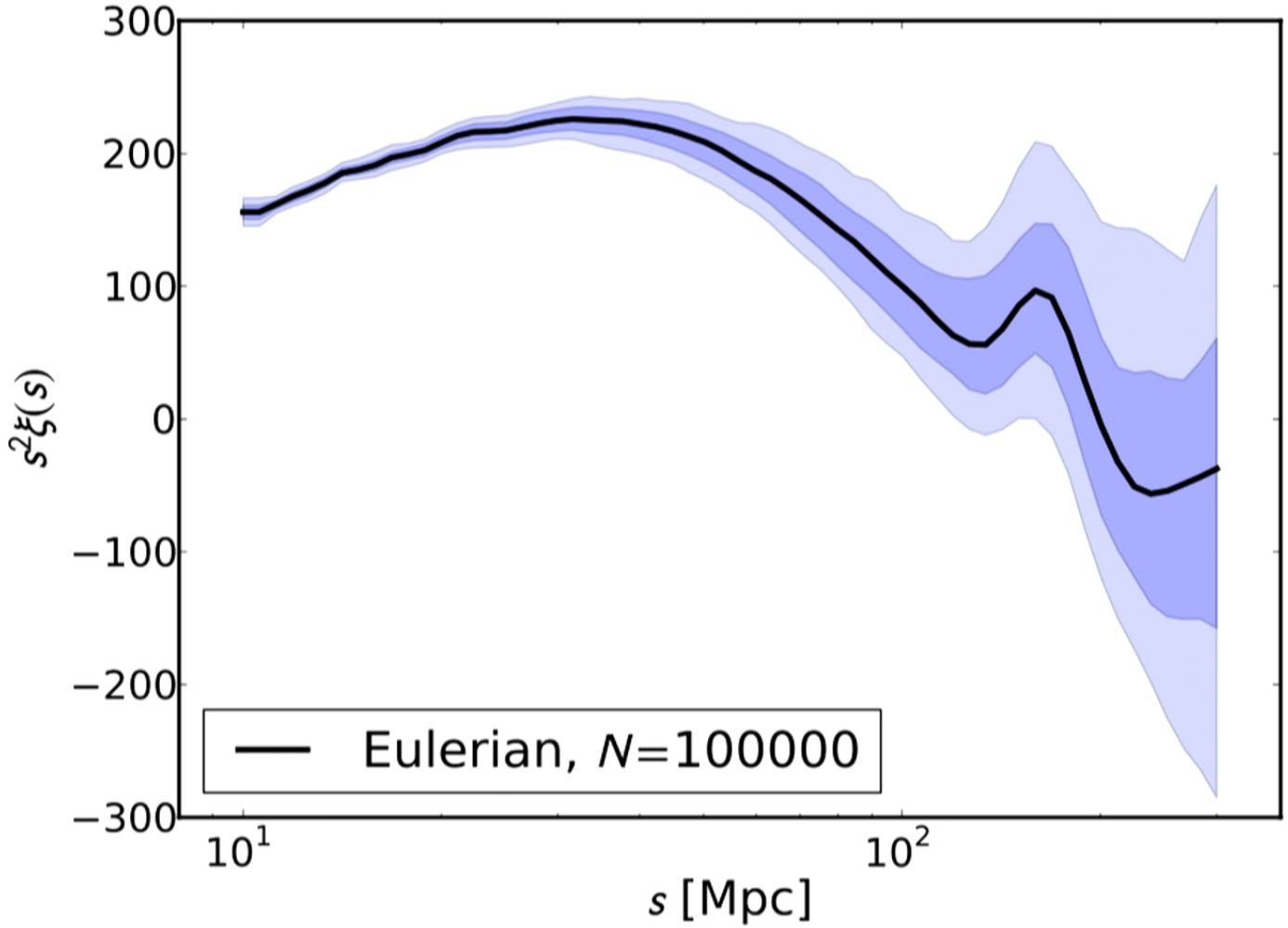

Lagrangian
100
50
0
−50
−100
Mpc
−100
−50
0
50
100
Mpc

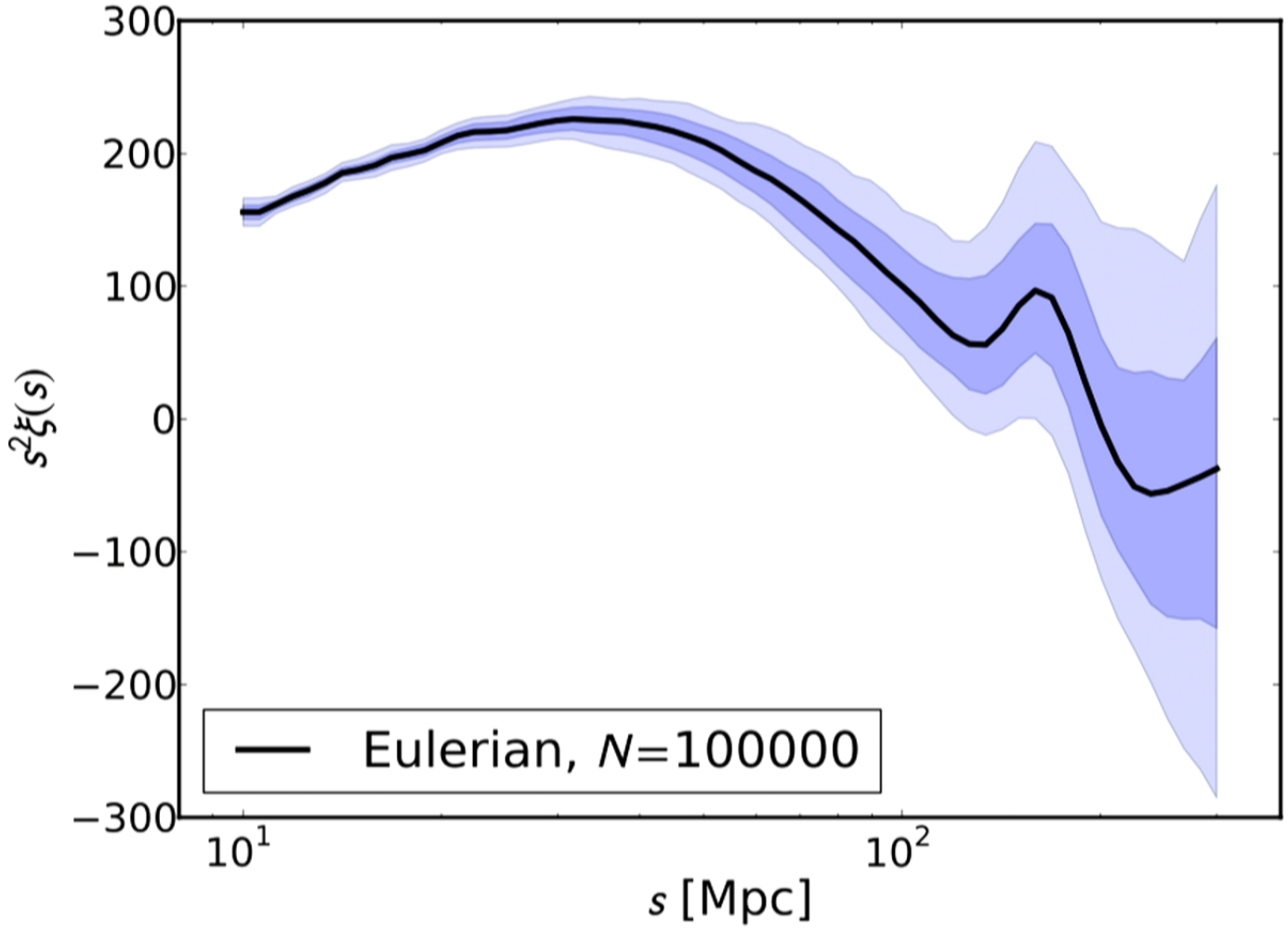
Correlation Function and its Covariance: Eulerian vs Lagrangian Space

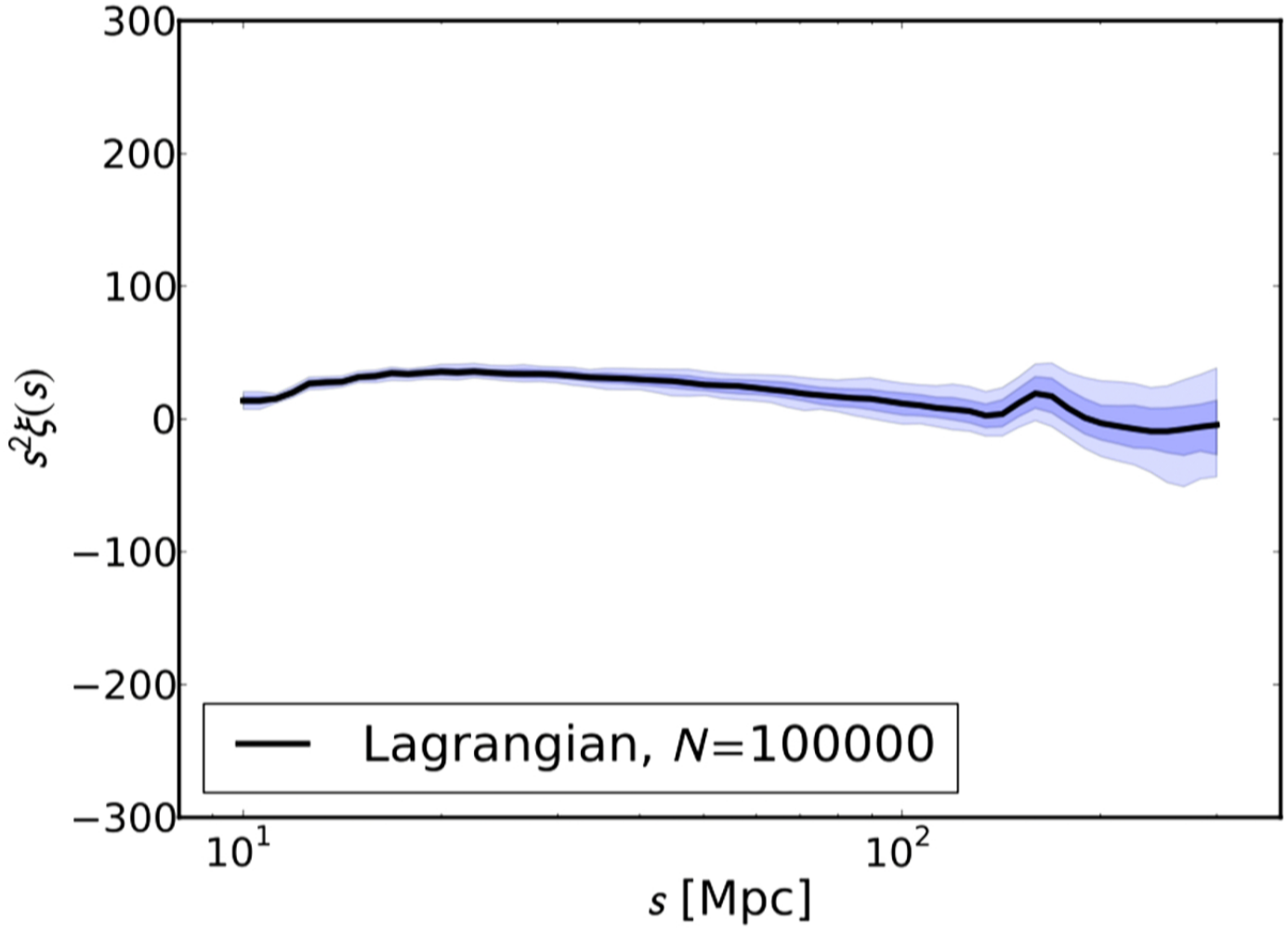

300
200
100
0
−100
−200
−300
$s^2\xi(s)$
10^1
10^2
s [Mpc]
Eulerian, N=100000

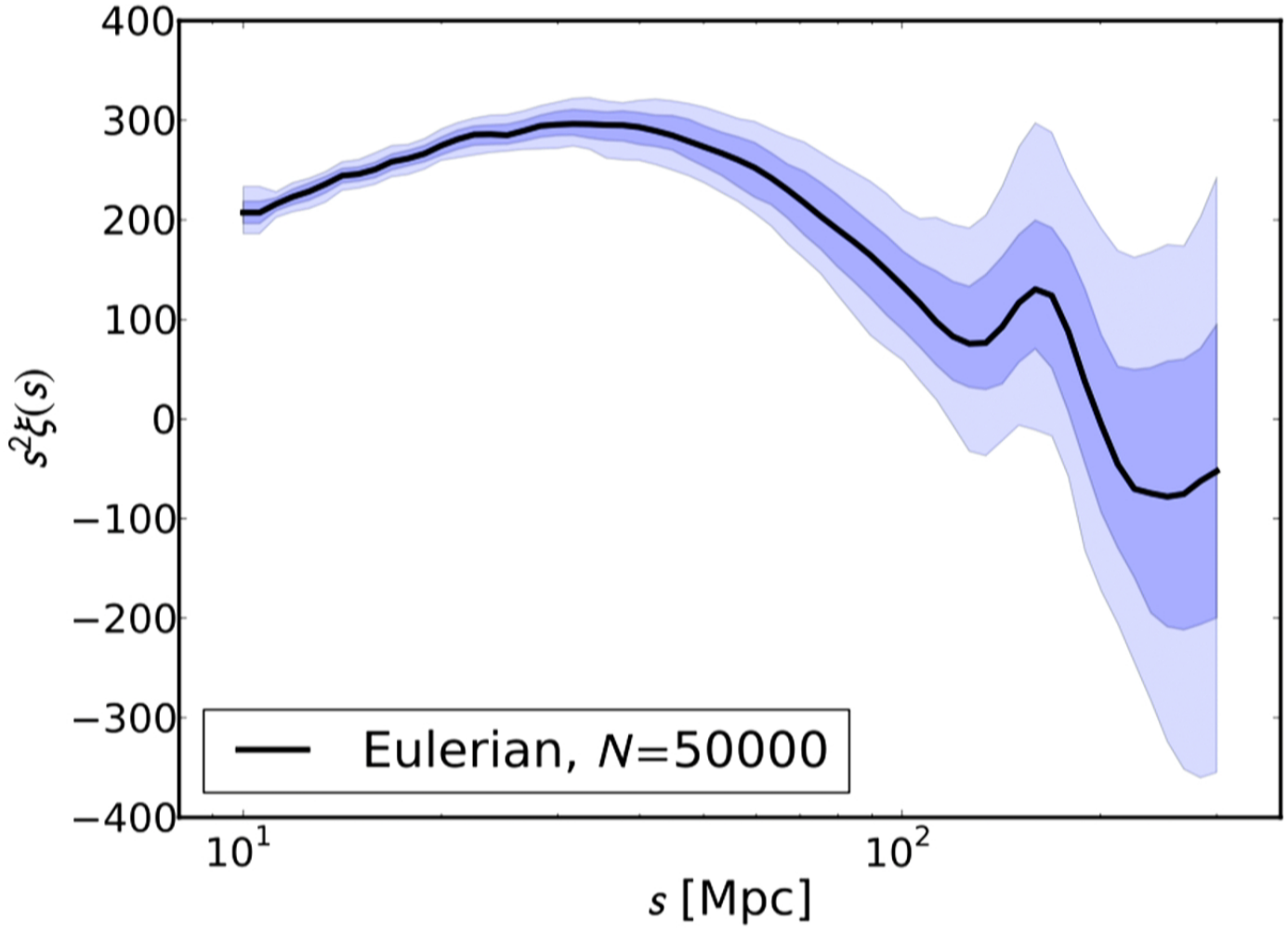

1000
500
0
−500
−1000
$s^2\xi(s)$
10^1
10^2
s [Mpc]
Eulerian, N=10000

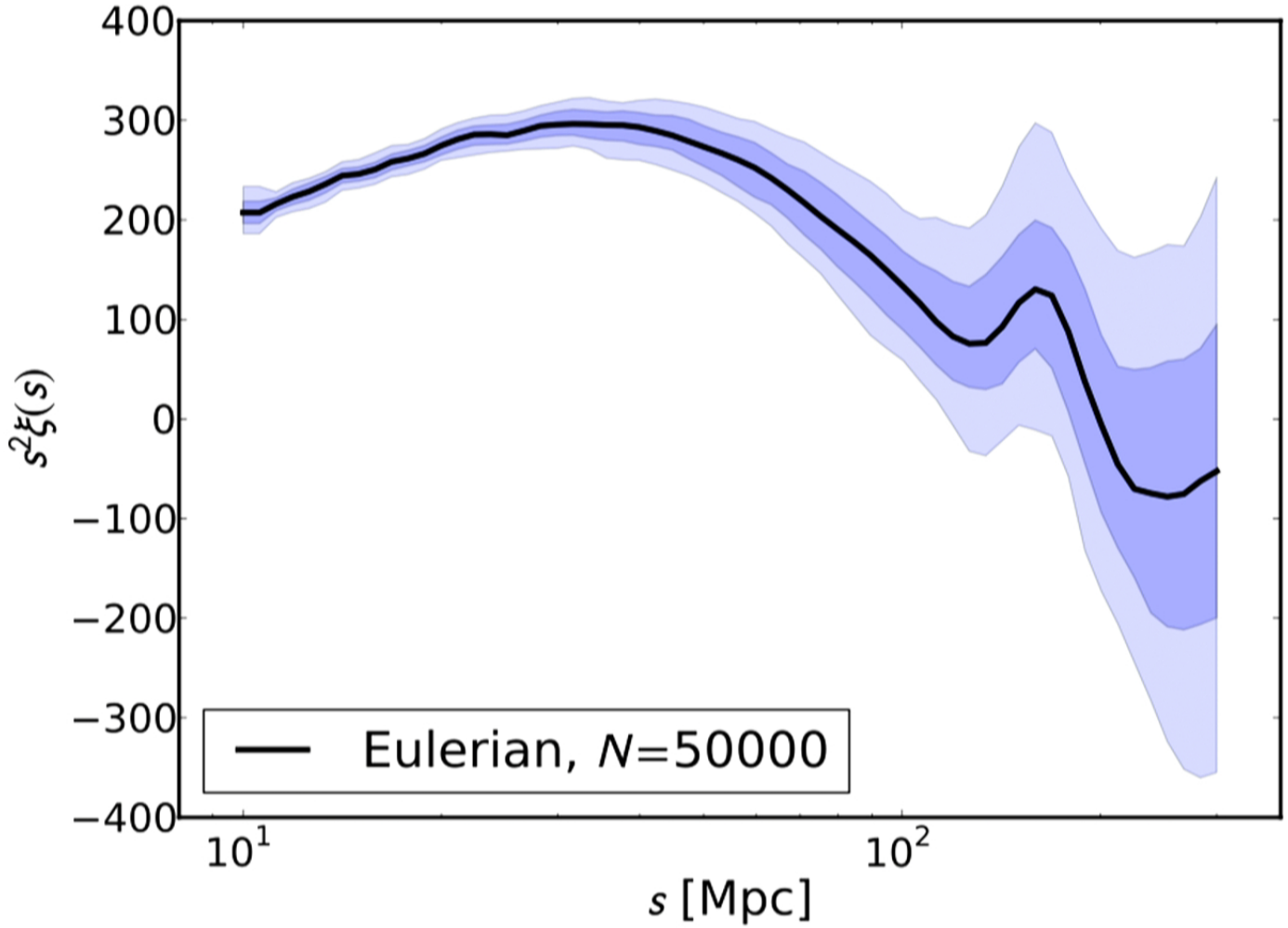

1000
500
0
−500
−1000
$s^2\xi(s)$
Eulerian, N=5000
10^1
10^2
s [Mpc]

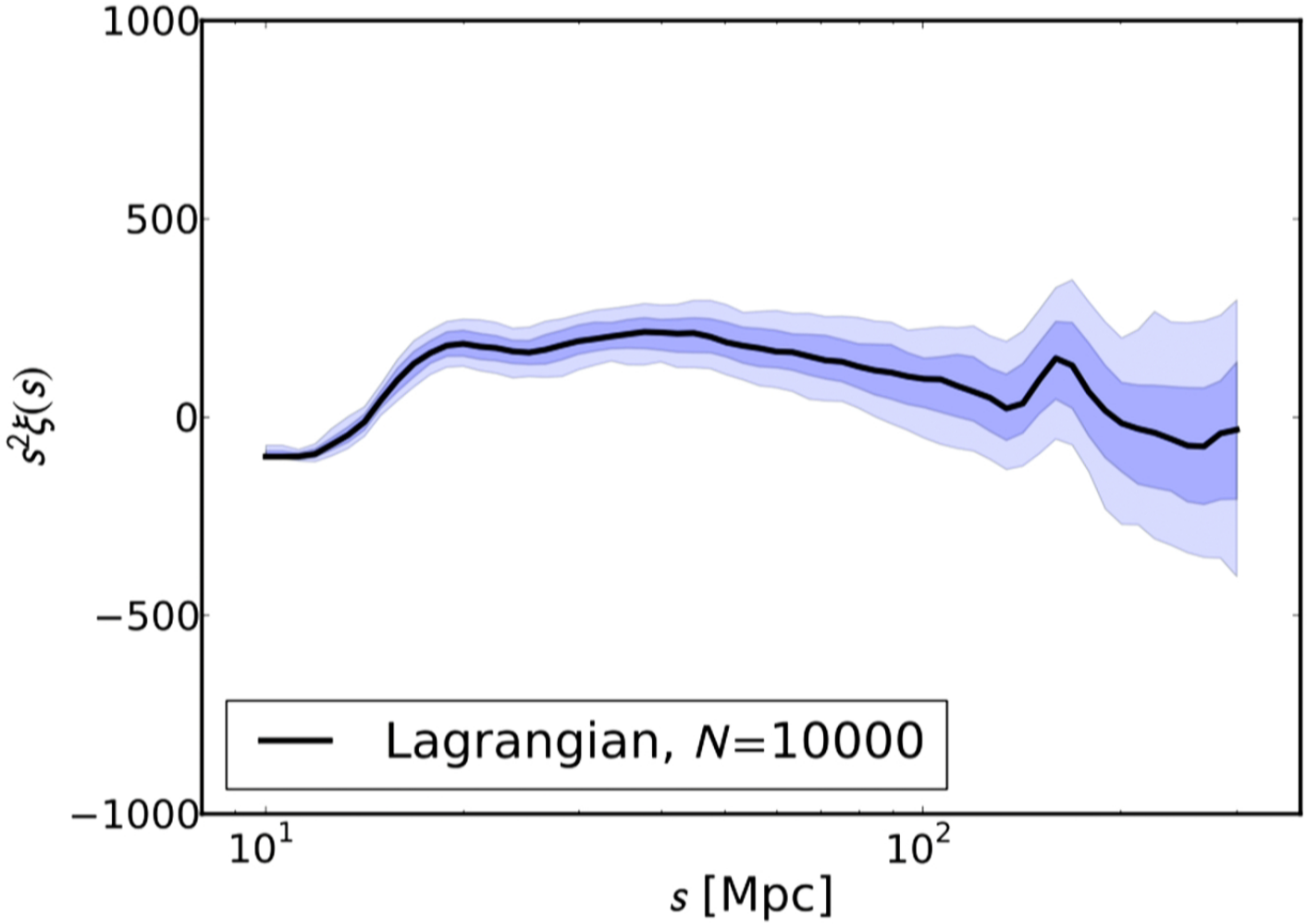

300
200
100
0
−100
−200
−300
$s^2\xi(s)$
10^1
10^2
s [Mpc]
Eulerian, N=100000

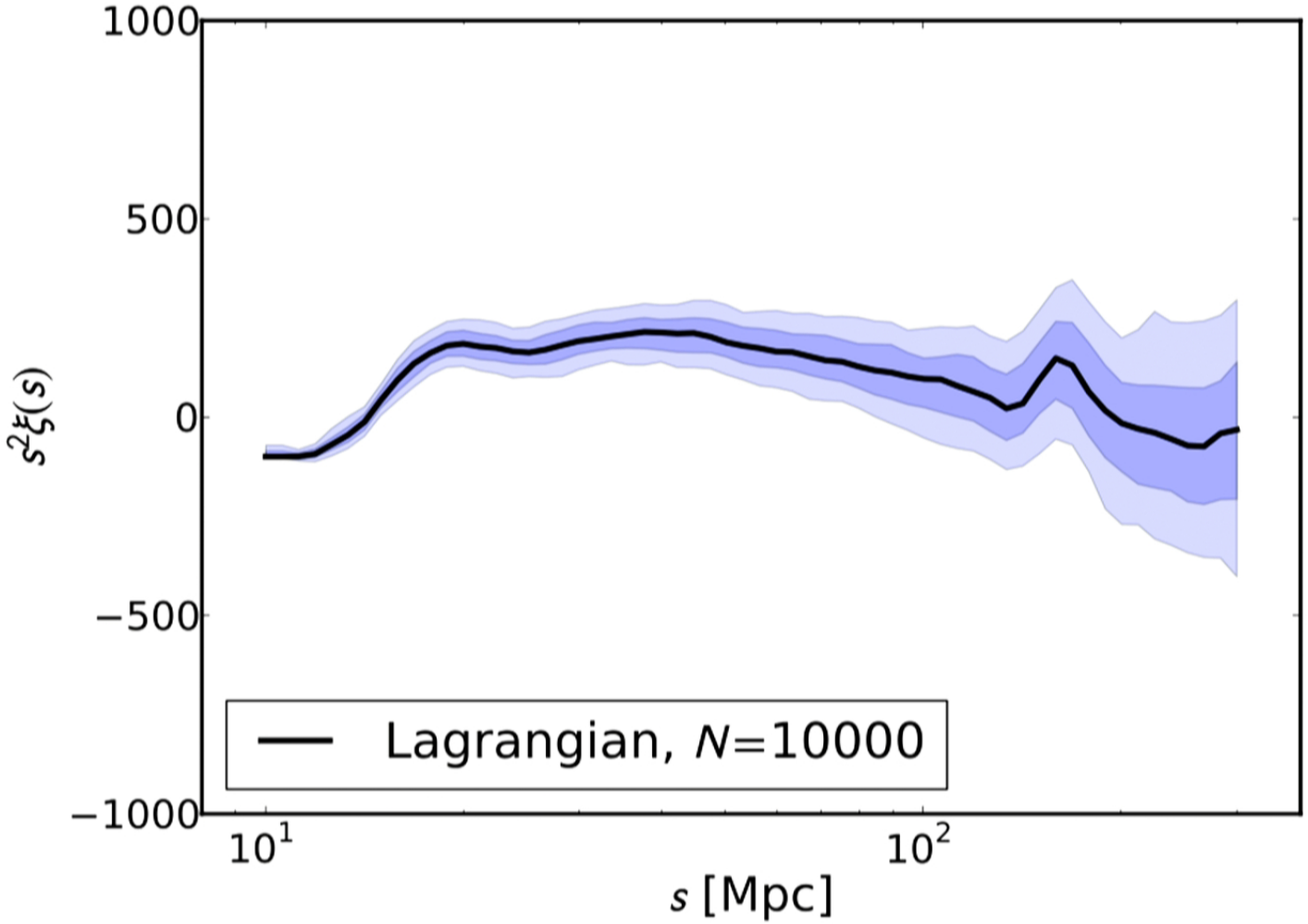

300
200
100
0
−100
−200
−300
$s^2\xi(s)$
10^1
10^2
s [Mpc]
Eulerian, N=100000

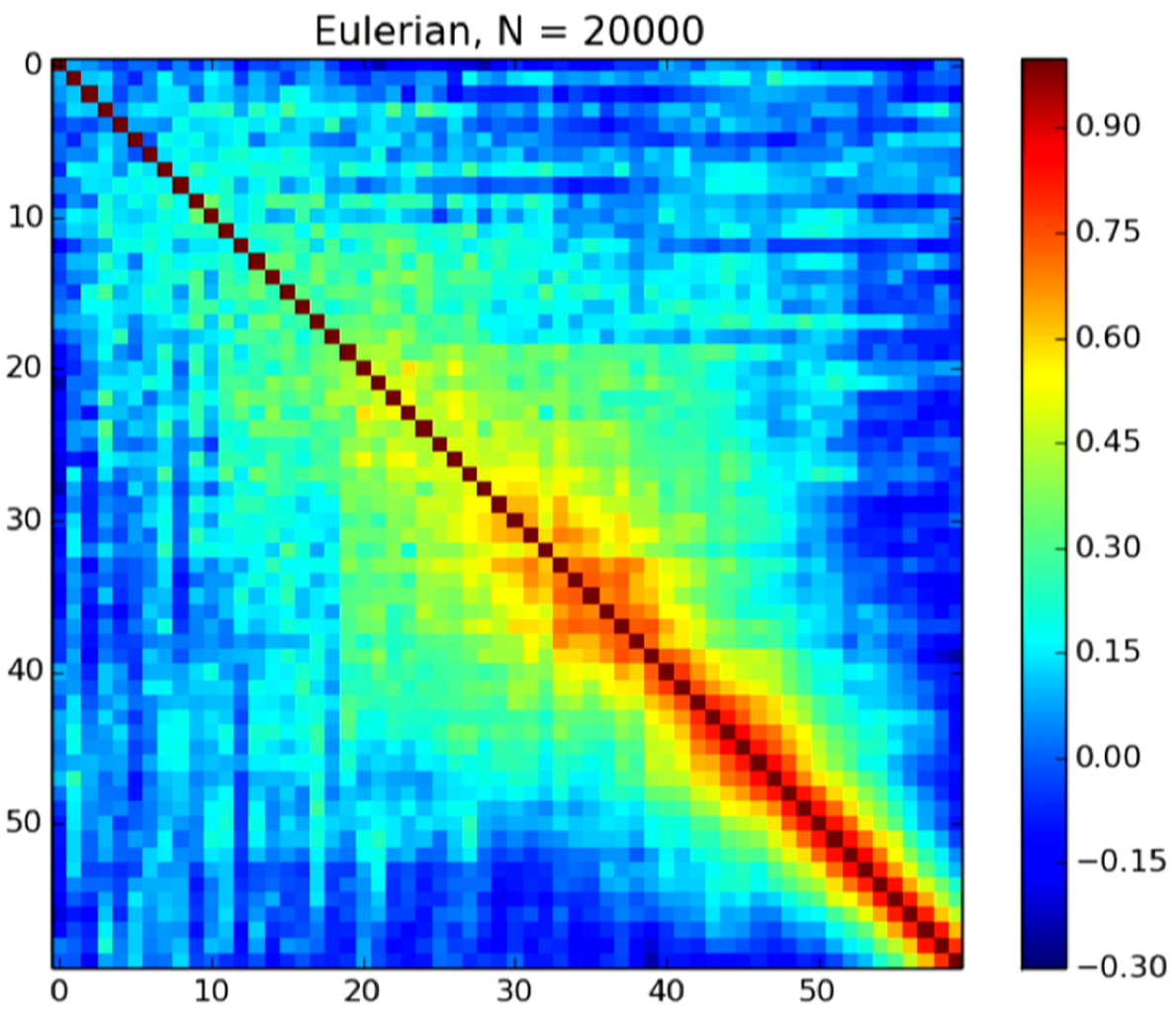

300
200
100
0
−100
−200
−300
$s^2\xi(s)$
10^1
10^2
s [Mpc]
Lagrangian, N=100000

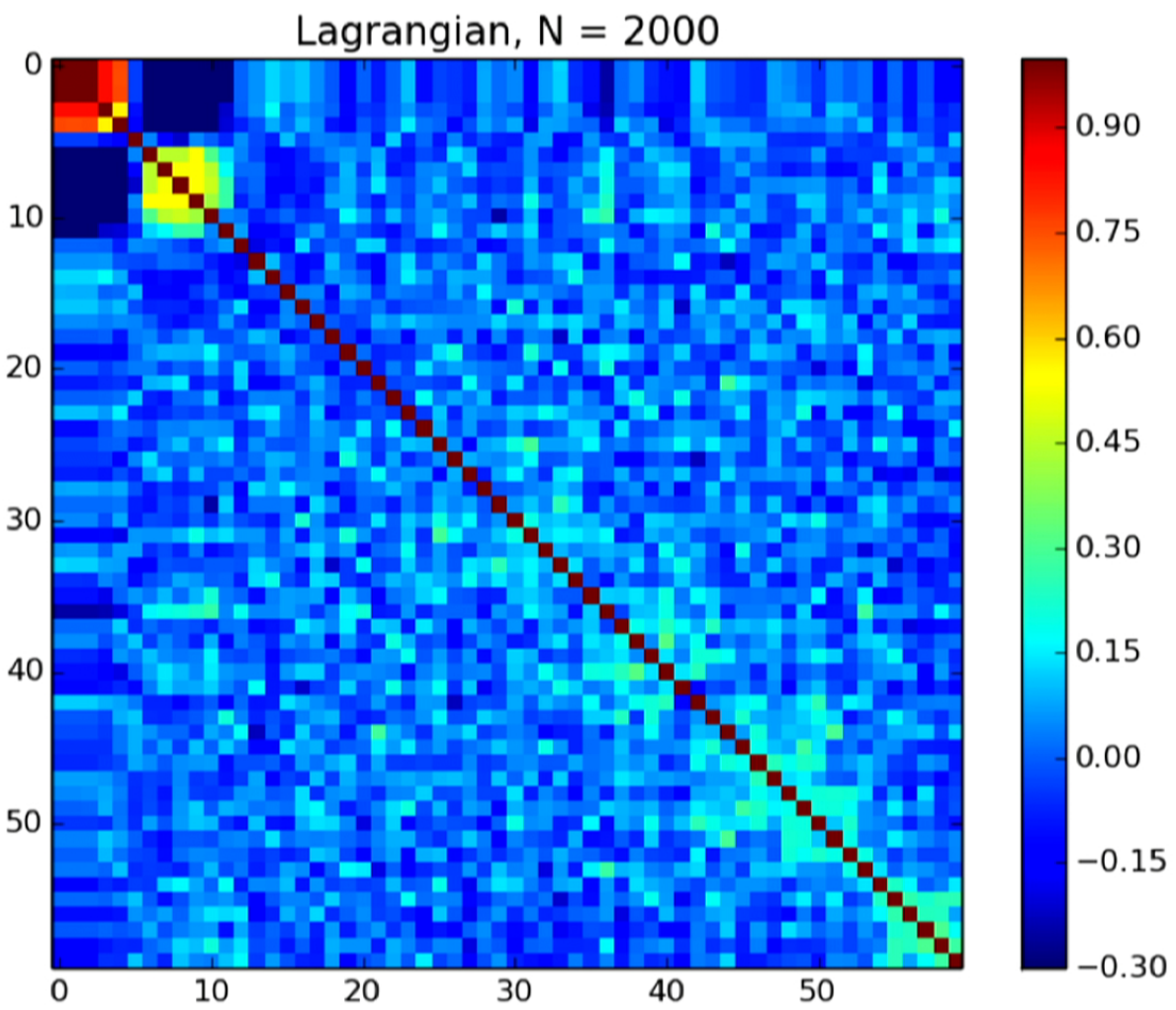

400
300
200
100
0
−100
−200
−300
−400
$s^2\xi(s)$
10^1
10^2
s [Mpc]
Eulerian, N=50000

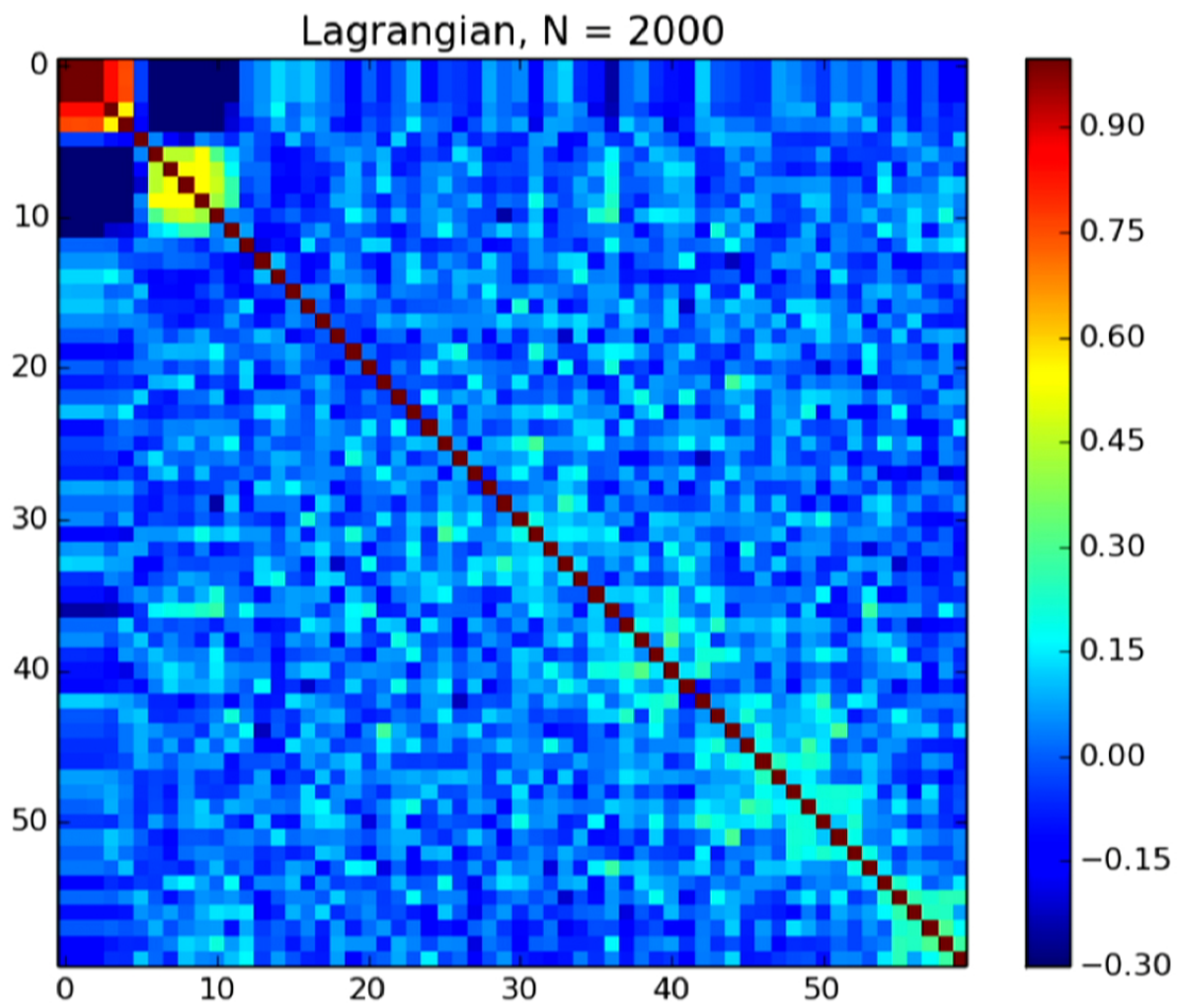

400
300
200
100
0
−100
−200
−300
−400
$s^2\xi(s)$
10^1
10^2
s [Mpc]
Eulerian, N=50000


1000
500
0
−500
−1000
$s^2\xi(s)$
10^1
10^2
s [Mpc]
Lagrangian, N=10000


1000
500
0
−500
−1000
$s^2\xi(s)$
10^1
10^2
s [Mpc]
Lagrangian, N=10000


Eulerian, N = 20000
0
10
20
30
40
50
0
10
20
30
40
50
0.90
0.75
0.60
0.45
0.30
0.15
0.00
−0.15
−0.30


Lagrangian, N = 2000
0
10
20
30
40
50
0
10
20
30
40
50
0.90
0.75
0.60
0.45
0.30
0.15
0.00
−0.15
−0.30


Lagrangian, N = 2000
0
10
20
30
40
50
0
10
20
30
40
50
0.90
0.75
0.60
0.45
0.30
0.15
0.00
−0.15
−0.30

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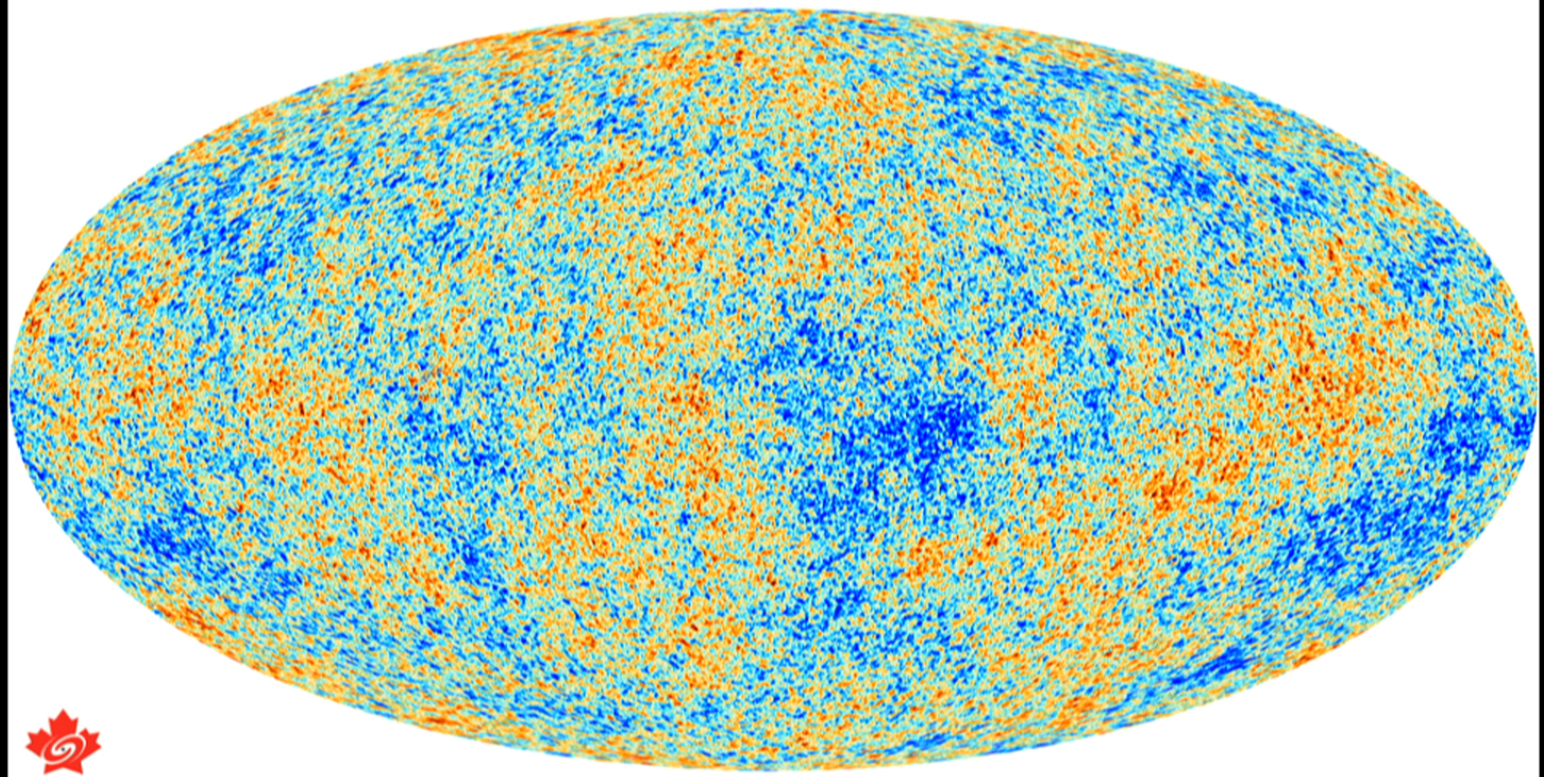
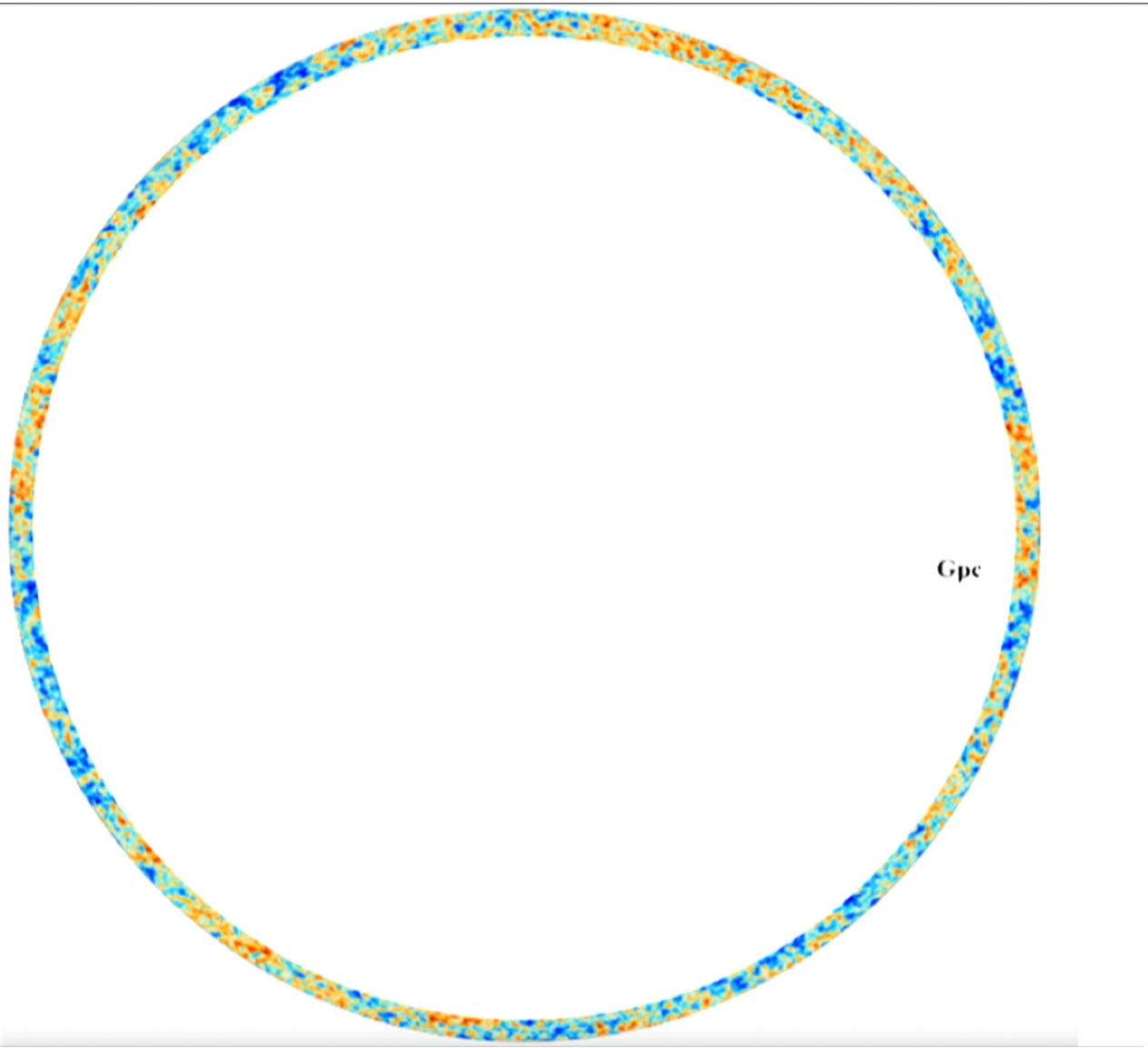
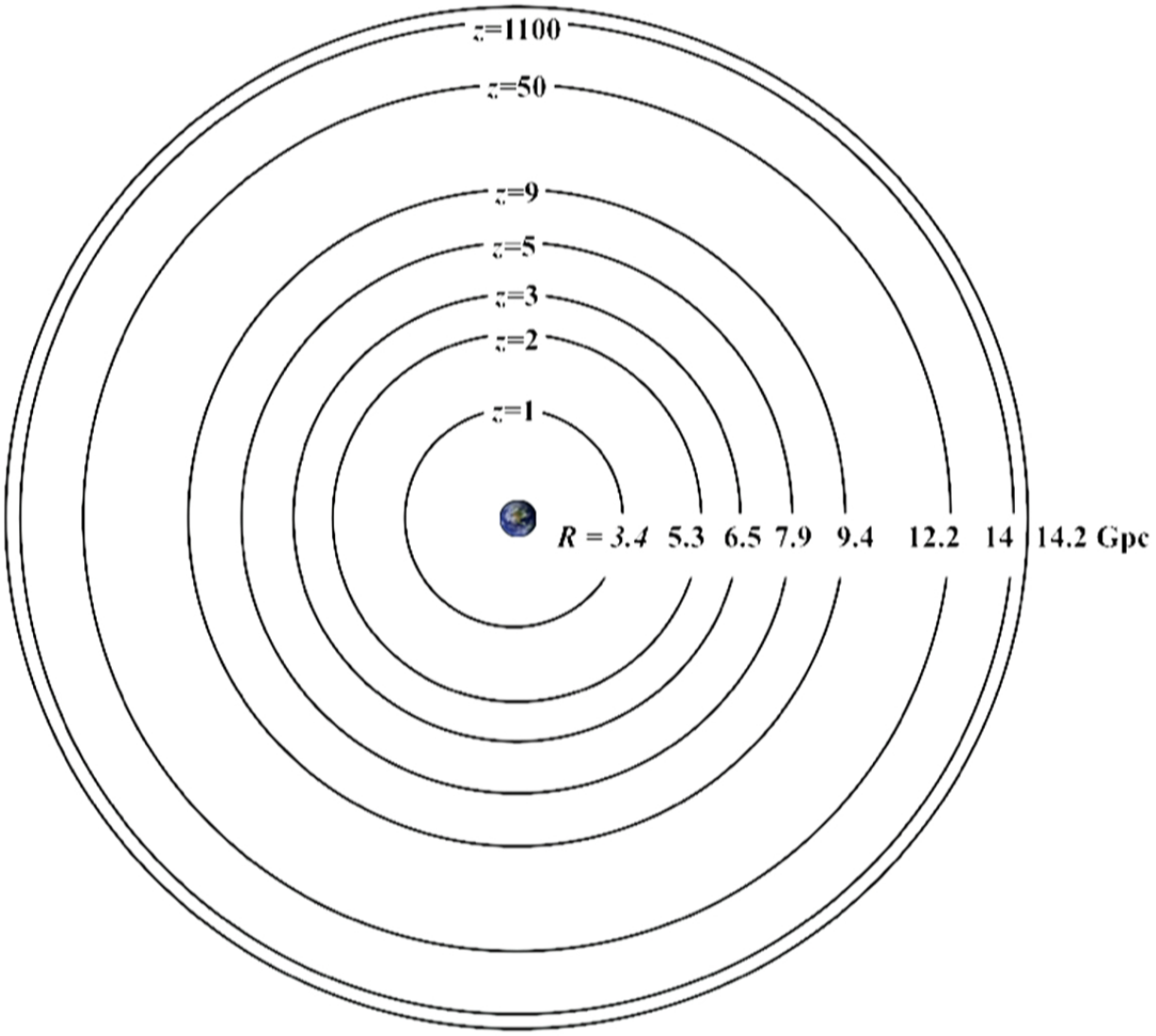
The Galaxy Cluster Sunyaev-Zel'dovich Effect

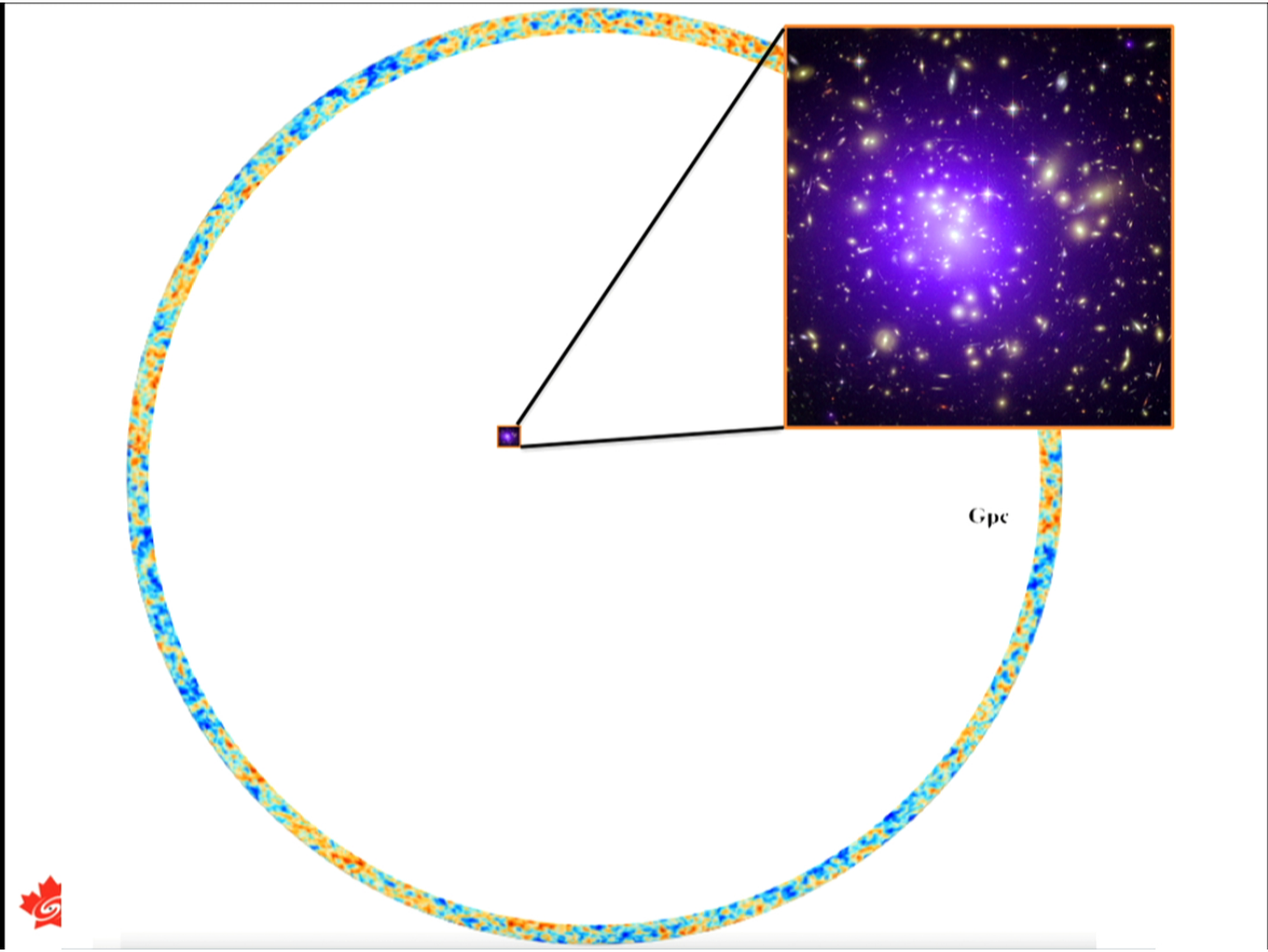
Hot Electrons in Galaxy Clusters
Thomson Scatter the Cosmic Microwave Backround and Create a Spectral Distortion

Cosmic Microwave Background Blackbody Anisotropies as Seen by Planck Satellite



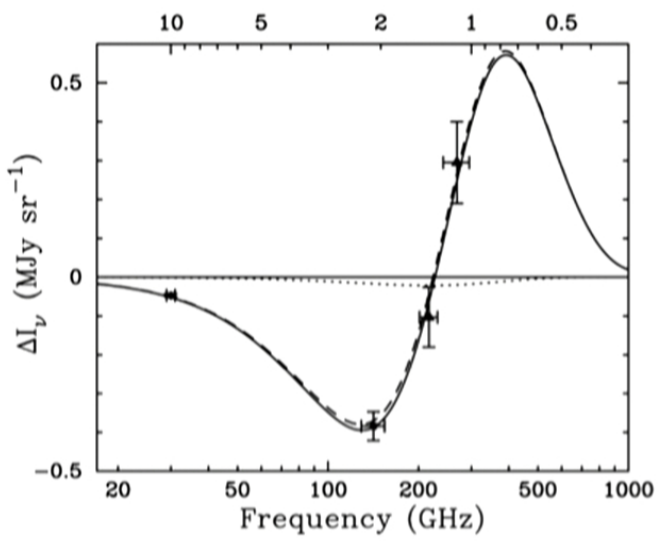

Gpc

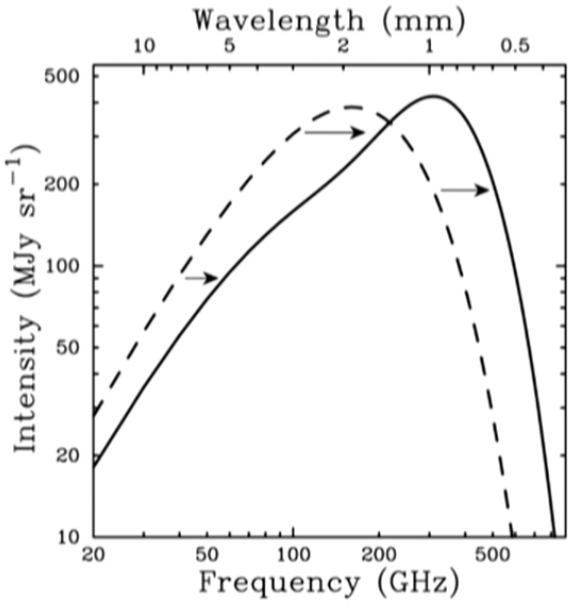

z=1100
z=50
z=9
z=5
z=3
z=2
z=1
R = 3.4 5.3 6.5 7.9 9.4 12.2 14 14.2 Gpc


Gpc

The Cluster SZ Effect

$$\frac{\Delta T}{T} = f(\nu) y = f(\nu) \frac{\sigma_{\mathrm{T}}}{m_{\mathrm{e}} c^2} \int P_{\mathrm{e}}(l) dl$$





Simulating the Galaxy Cluster SZ Effect

8 Gpc box — **4096^3** cells

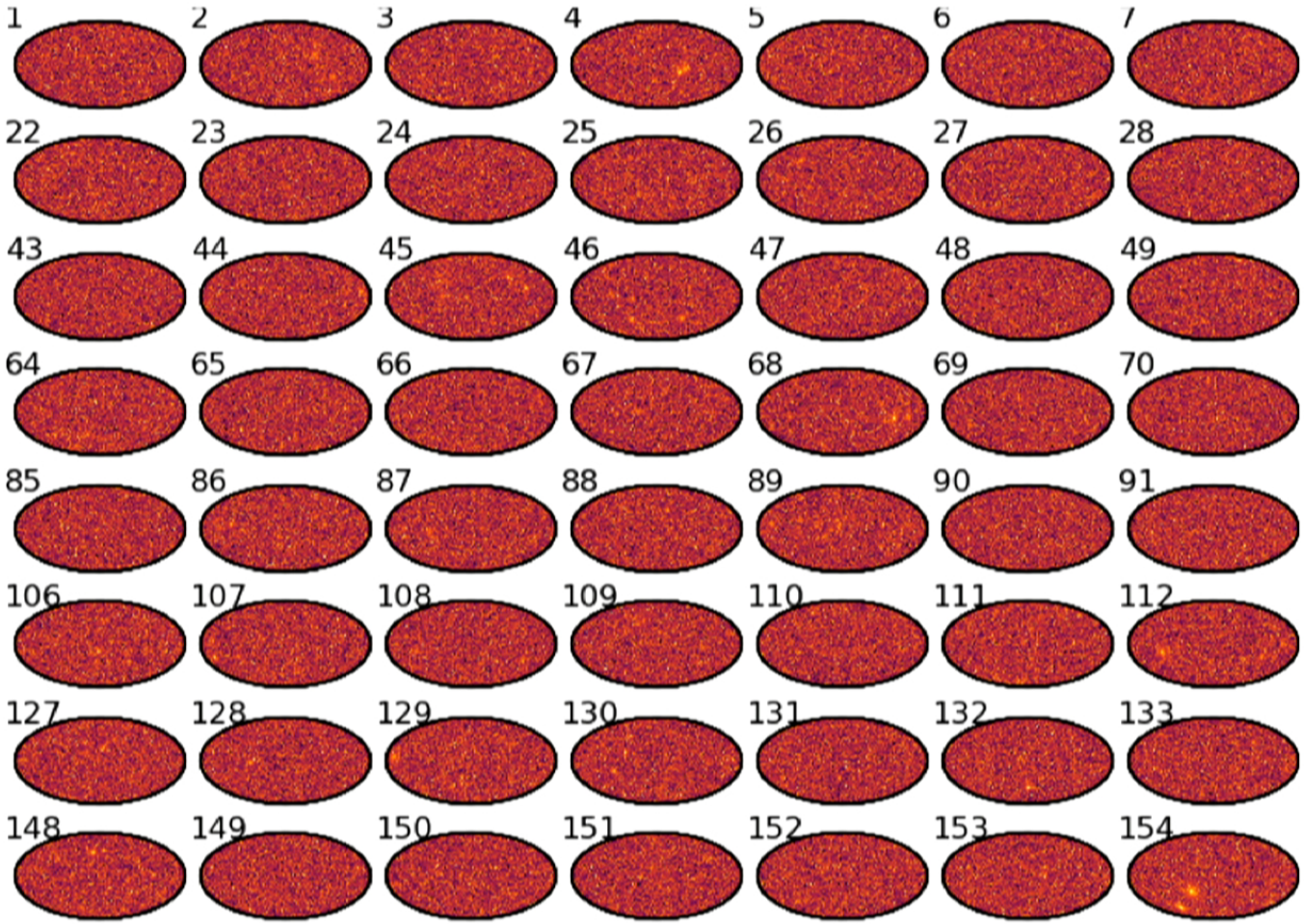
Wall clock ~ **10 mins** each on 1024 cores

Full-sky Light Cone with ~ **6×10^7 halos**

Complete to $z < 1.3$ **and** $M_{\rm halo} > 3 \times 10^{13}\ M_{\rm sun}$

~ 500 maps produced total

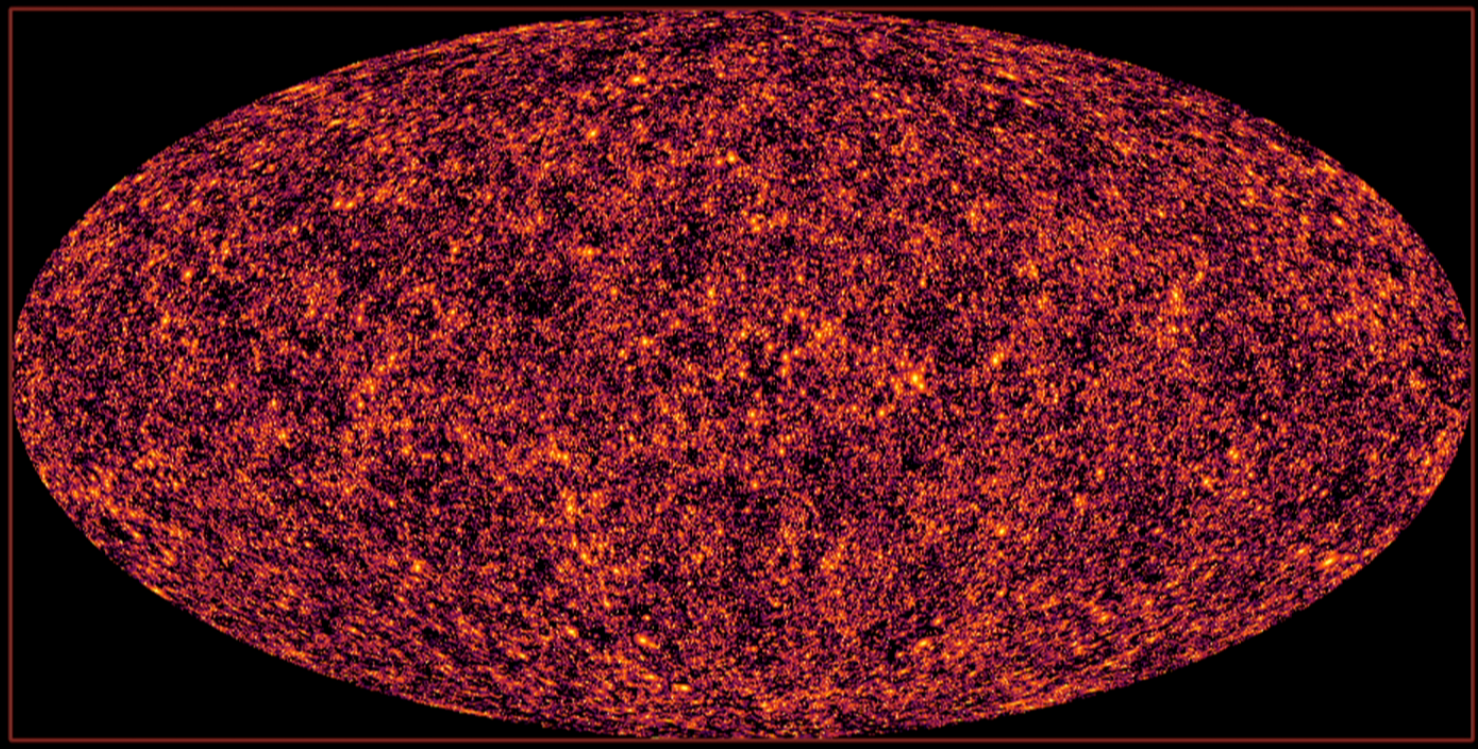
Battaglia et al. (2012) universal pressure profile out to $4R_{200}$

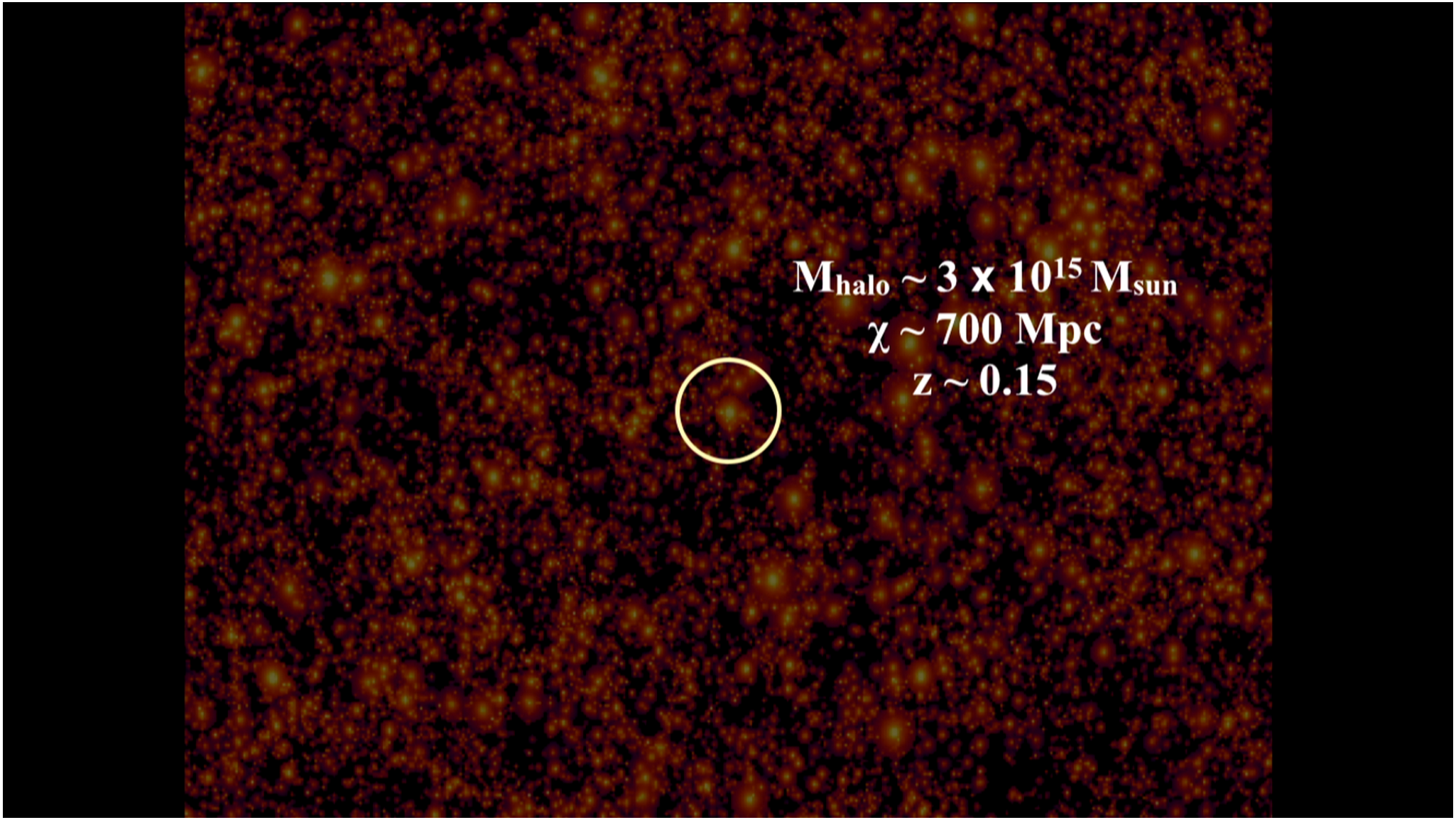


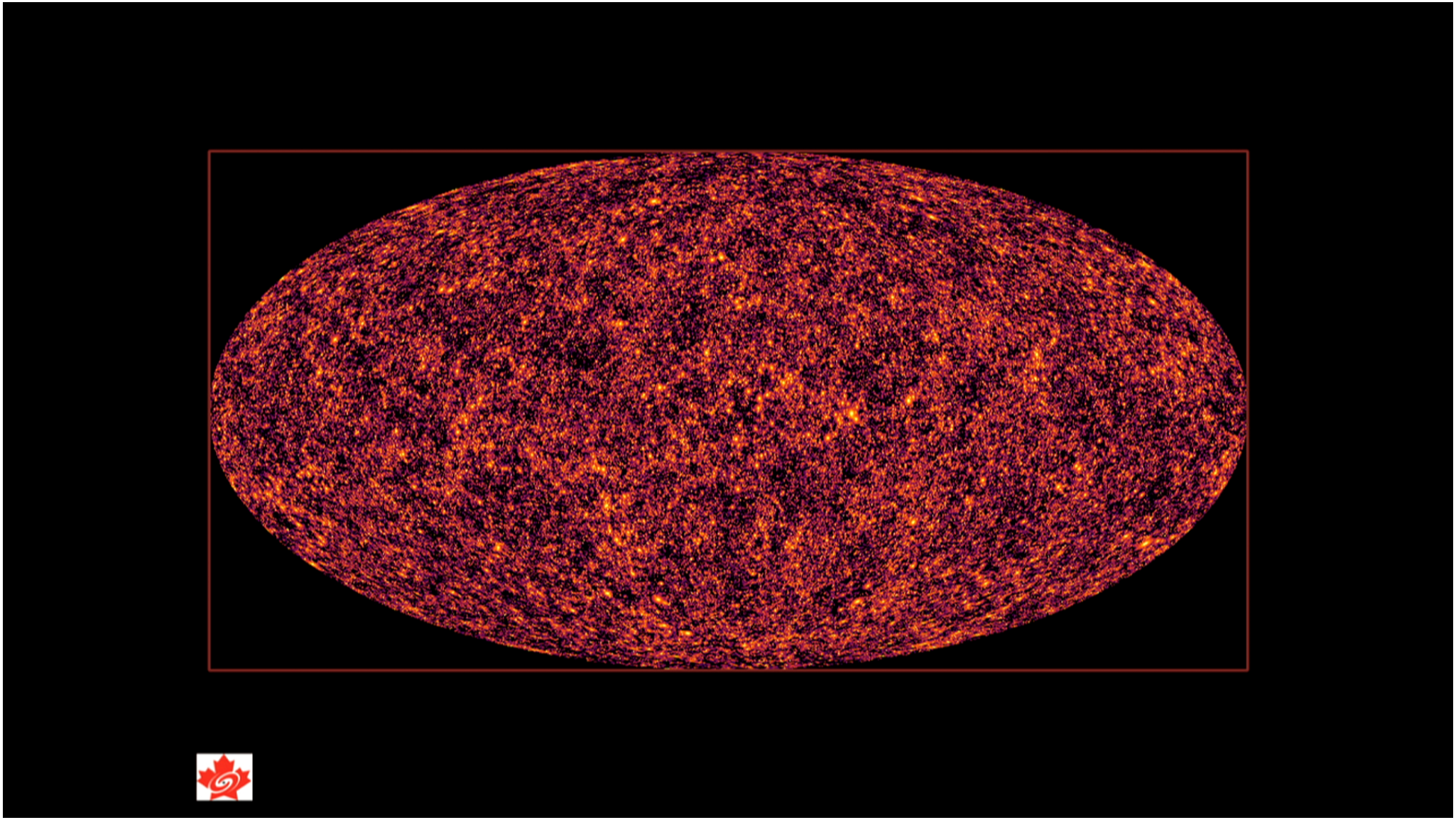
Alvarez et al. (2015)

Compton y for halos at

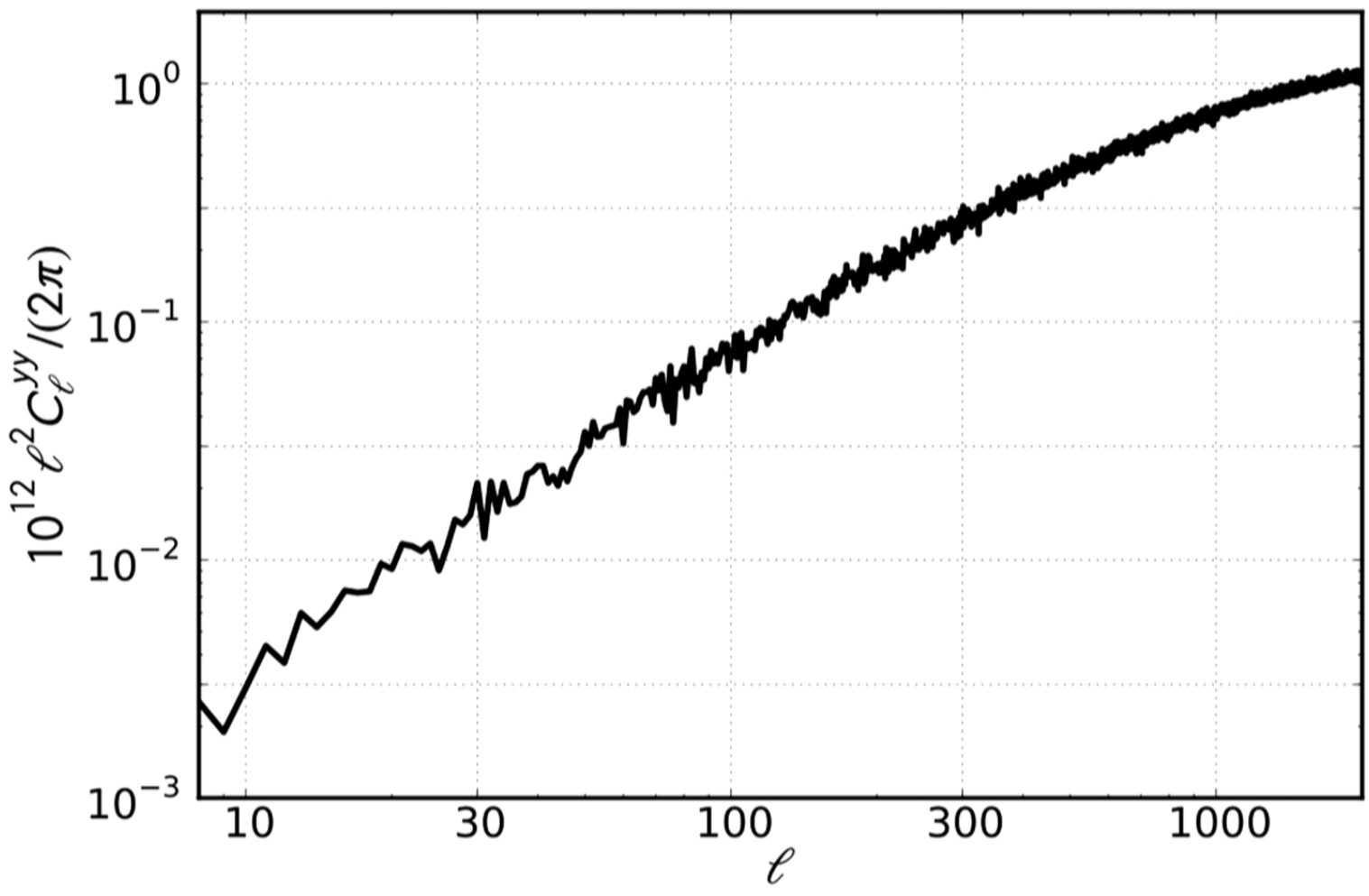
200 Mpc < χ < 1 Gpc

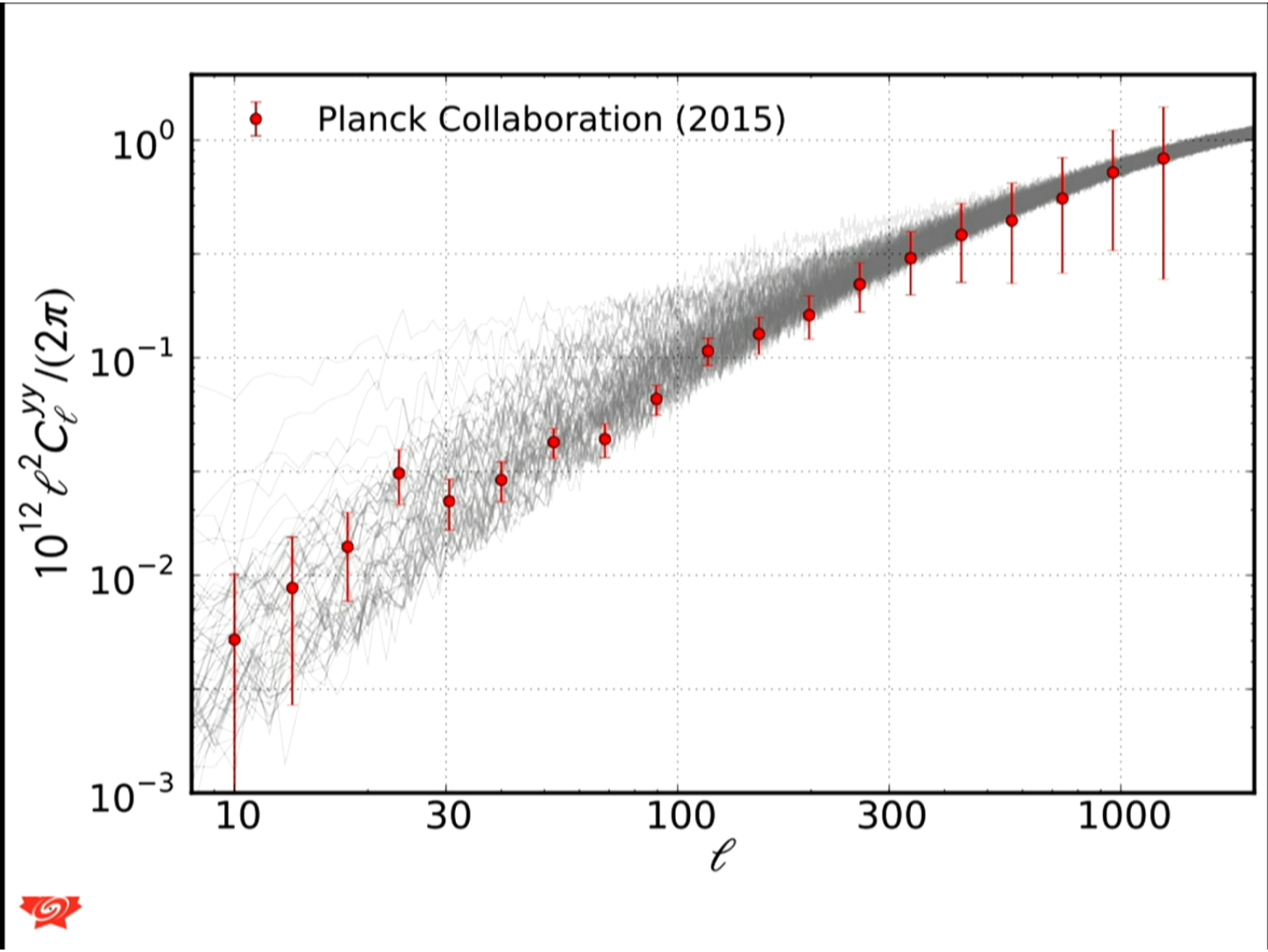


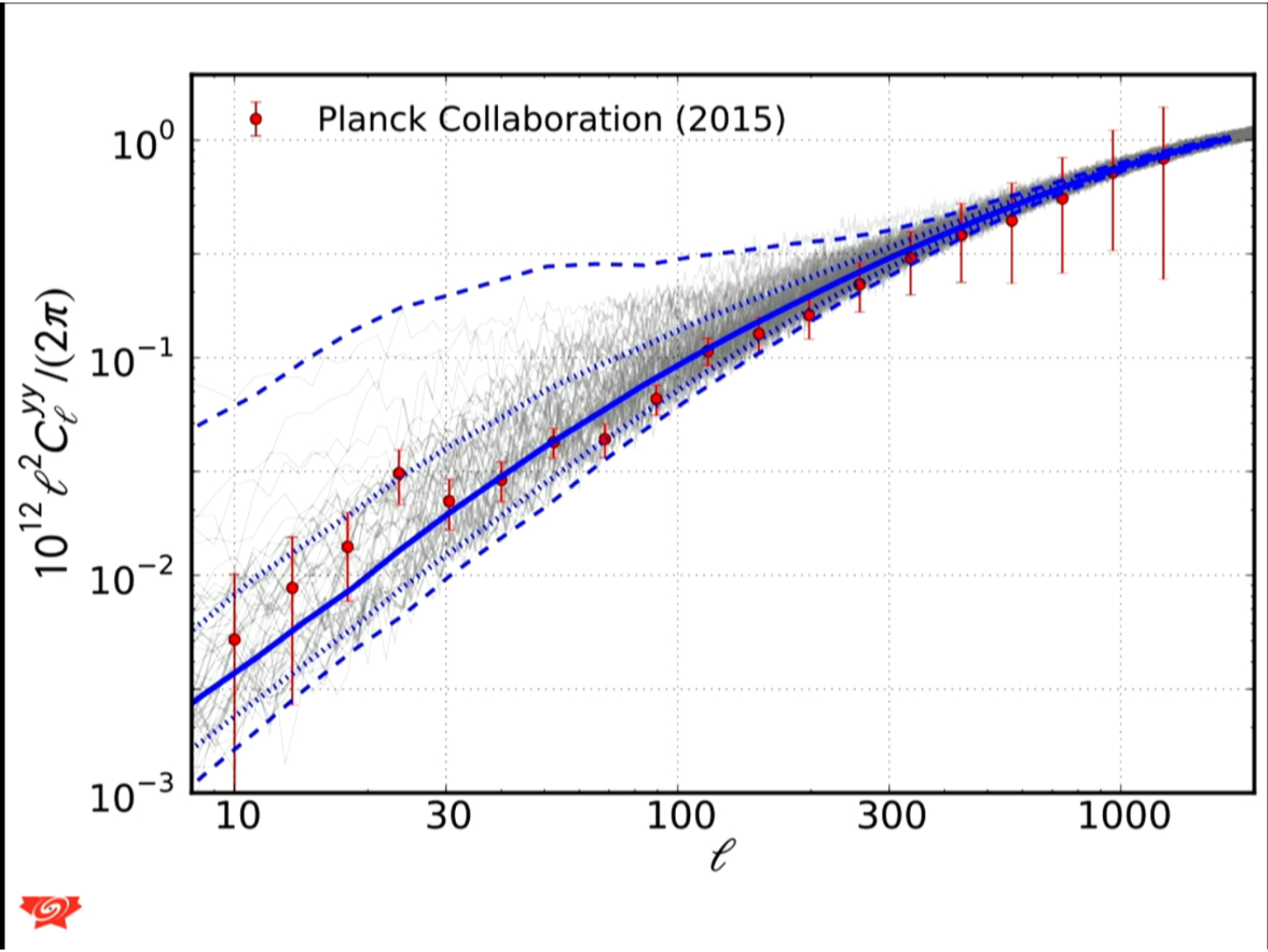

$M_{halo} \sim 3 \times 10^{15} M_{sun}$
$\chi \sim 700$ Mpc
$z \sim 0.15$



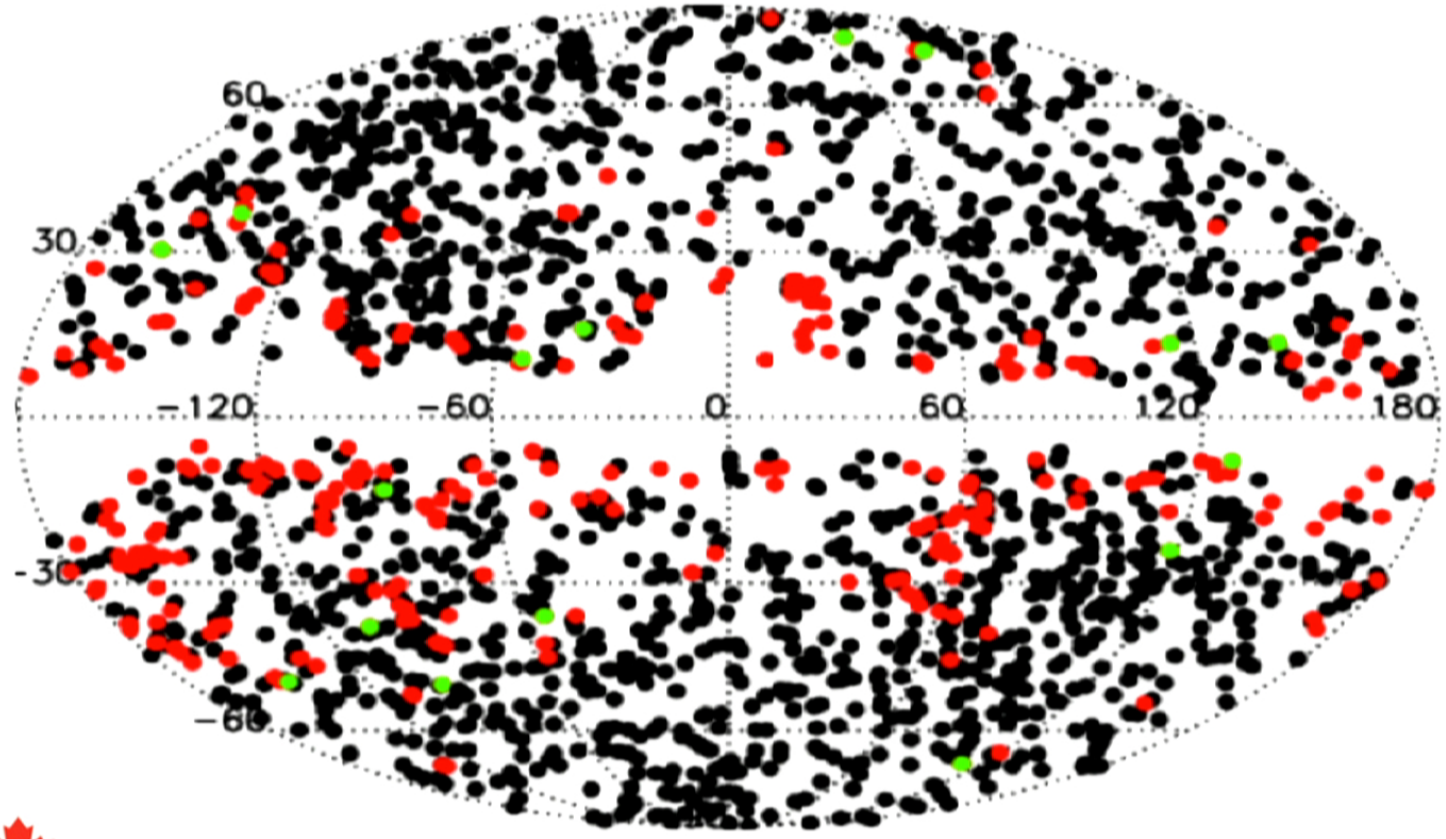
Angular Power Spectrum


$10^{12}\,\ell^2 C_\ell^{yy}/(2\pi)$
10^0
10^{-1}
10^{-2}
10^{-3}
10
30
100
300
1000
ℓ

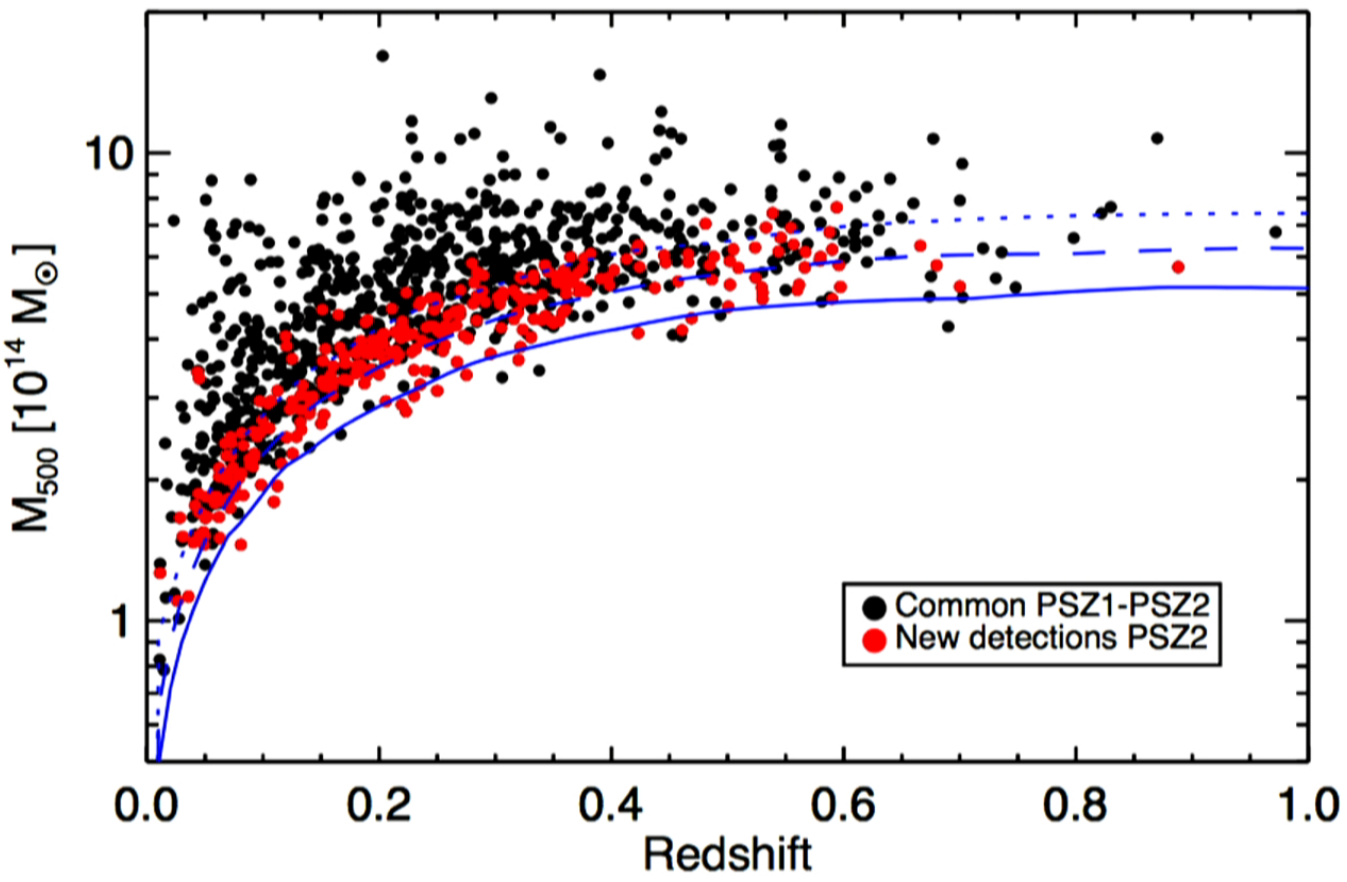

Planck Collaboration (2015)
$10^{12}\ell^2 C_\ell^{yy}/(2\pi)$
10^0
10^{-1}
10^{-2}
10^{-3}
10
30
100
300
1000
ℓ


Planck Collaboration (2015)
$10^{12}\ell^2 C_\ell^{yy}/(2\pi)$
10^0
10^{-1}
10^{-2}
10^{-3}
10
30
100
300
1000
ℓ

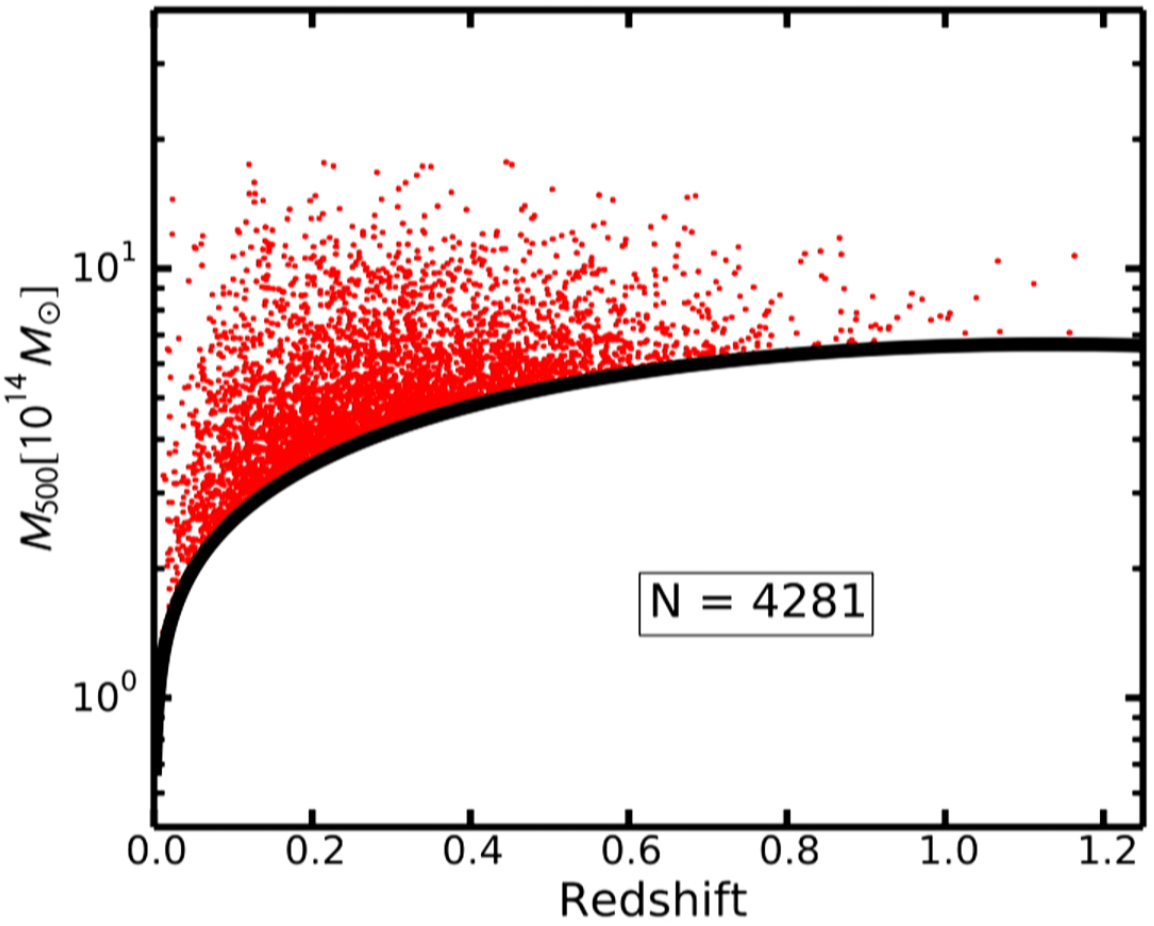
Planck Catalog of SZ Sources



Planck Cluster Selection Function

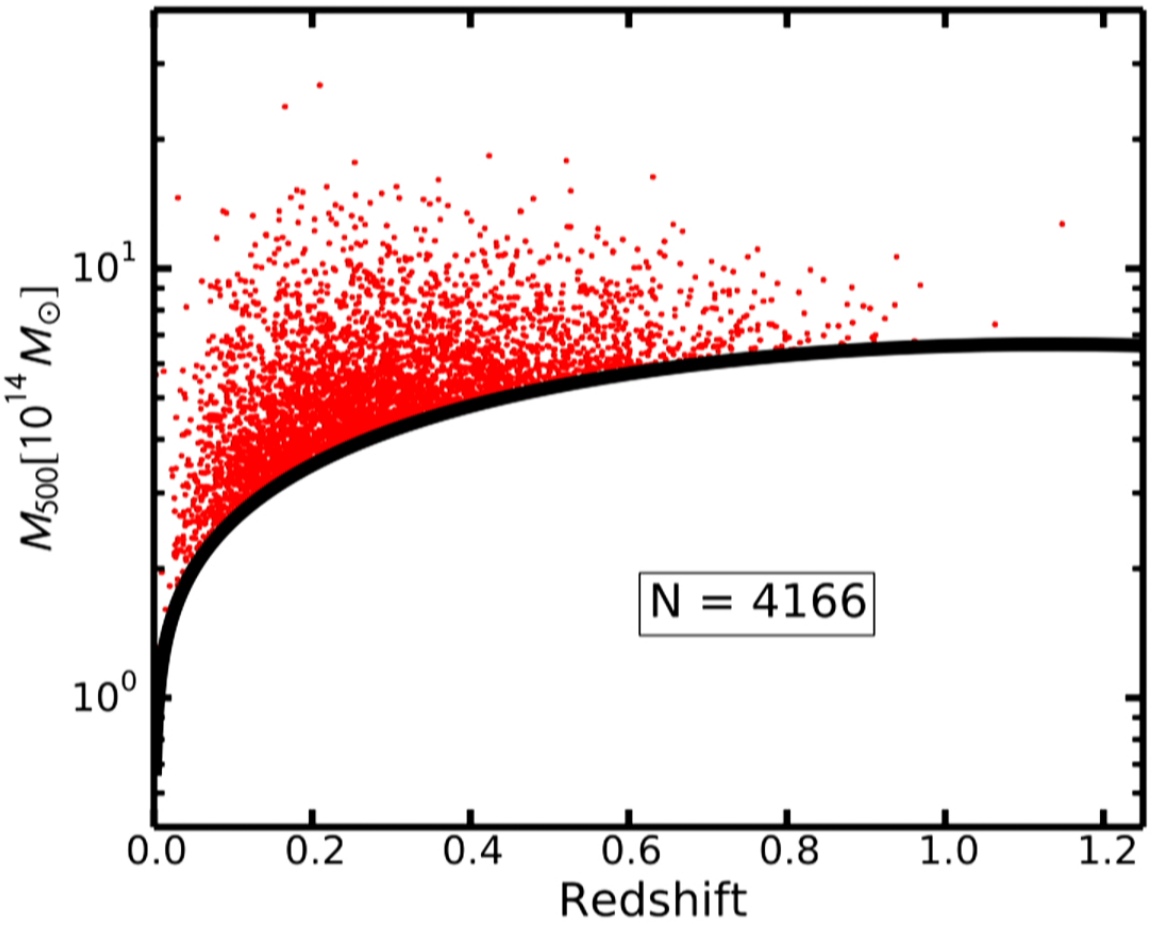


Applying Selection Function to Mocks

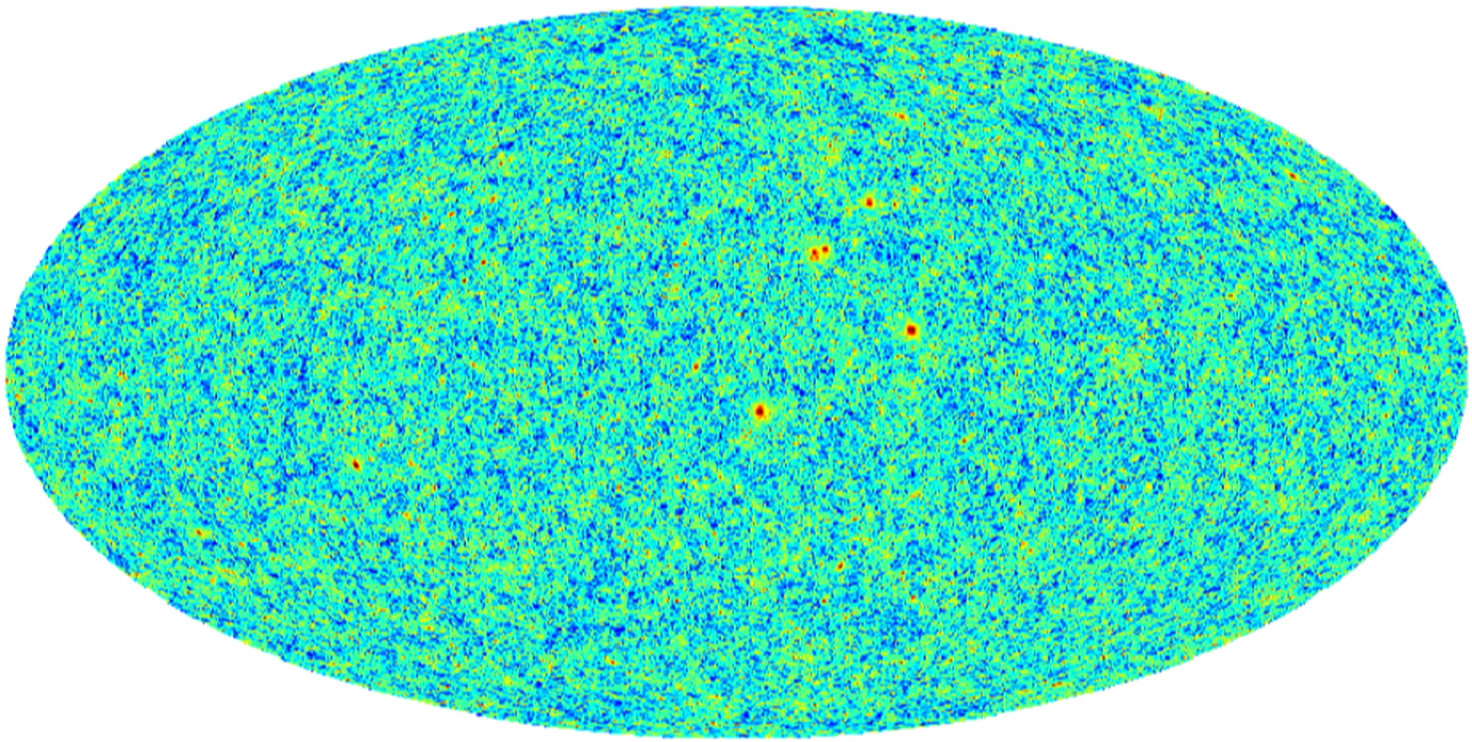


What Happens if we Correlate
Detected Clusters
with ***What is Left*** in the Map?

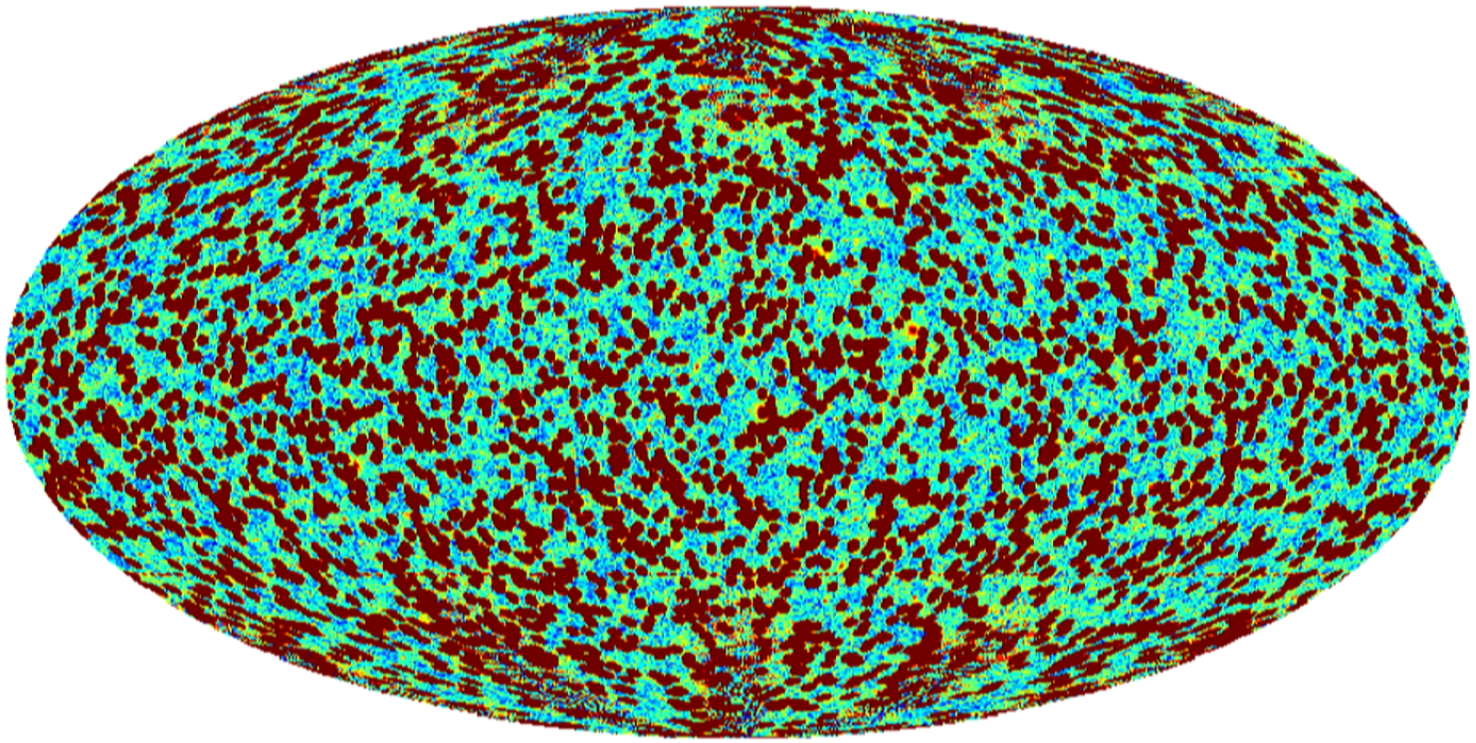
Applying Selection Function to Mocks



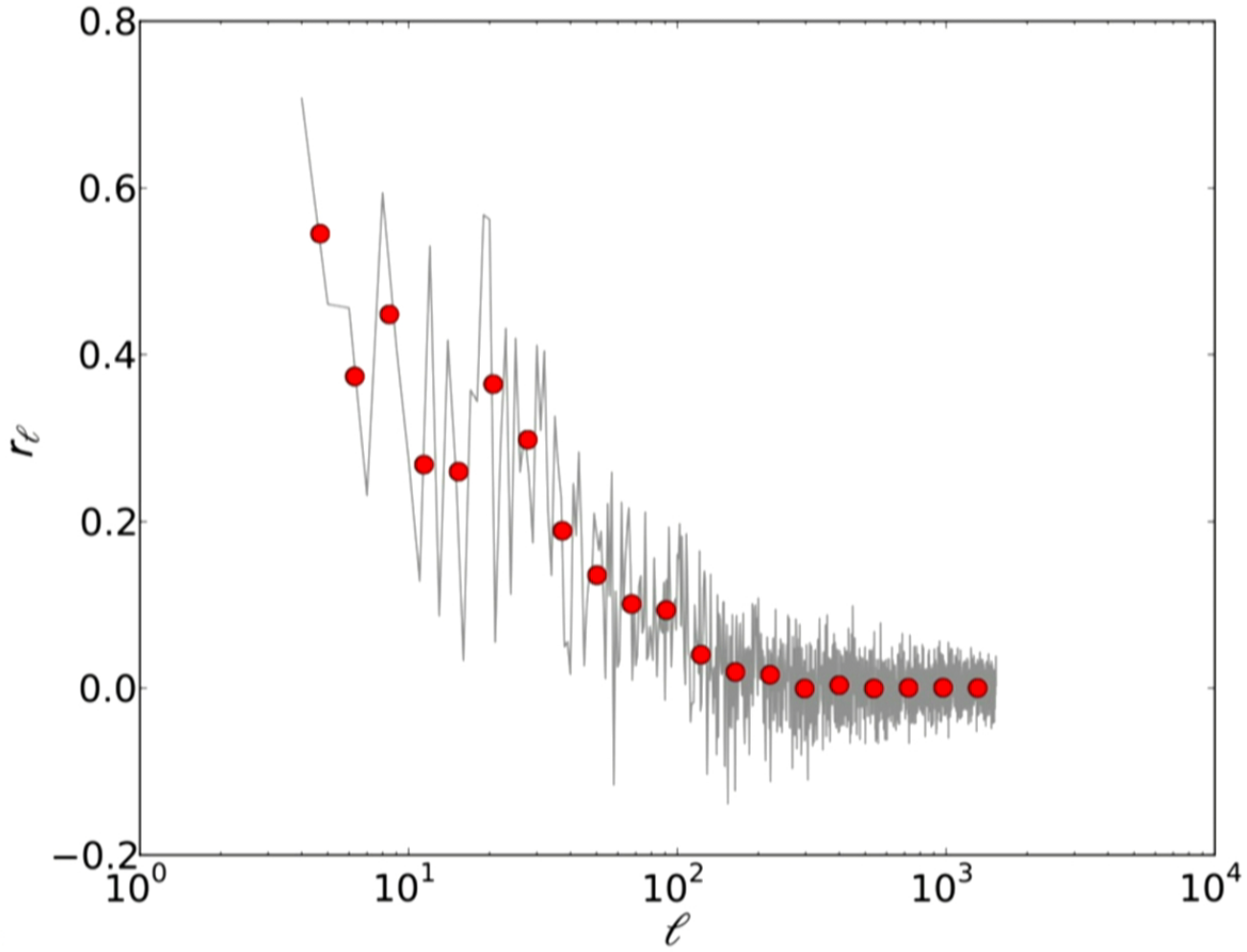
Map with Selected Clusters Removed

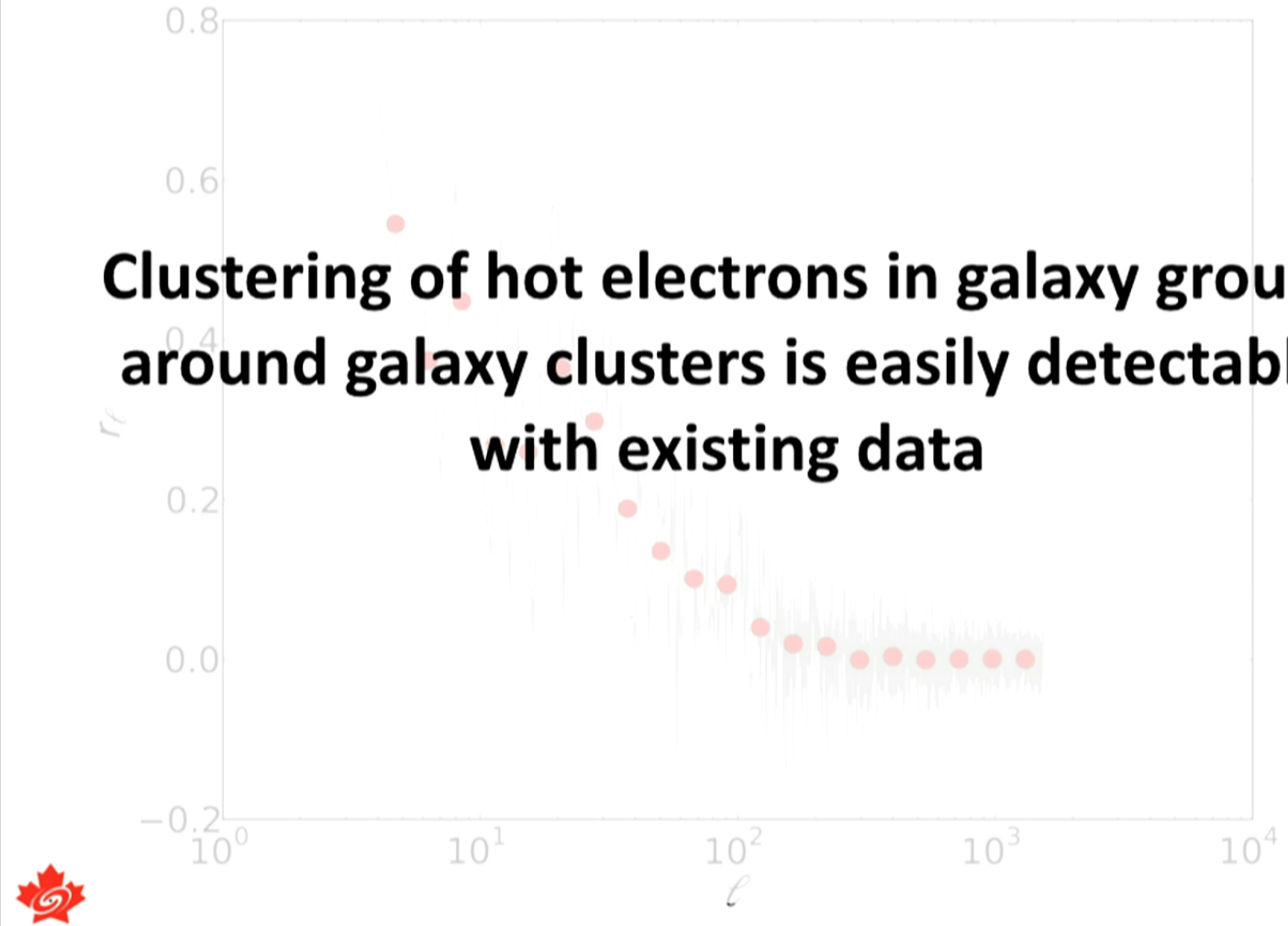


Location of Selected Clusters



Cross-correlation





Clustering of hot electrons in galaxy groups around galaxy clusters is easily detectable with existing data

Outline

Motivation

Our Approach

Halo Clustering

Full Sky Cluster SZ Maps

Summary & Future Directions

Summary

New cosmological surveys require simulations with fast, accurate, and high dynamic ranges

Our **parallel implementation of ellipsoidal peak dynamics** reproduces N-body halo masses and positions **~1000 times faster** and allows **efficient exploration of cosmological theory space**

Exclusion is an Important Effect that happens in **Lagrangian space**

Monte Carlo **all-sky realizations of tSZ maps** and shows for first time that **Clustering of Galaxies is easily detectable with current data**

Future Directions

Cluster **Sunyaev-Zel'dovich** effect, **Non-Gaussianity, Cosmic Infrared Background**, and **Hydrogen and CO/C Intensity Mapping**

Exclusion, **Lagrangian to Eulerian mapping,** and **Calibration**

Parallel ellipsoidal peak dynamics code will be **publicly released**