WE - HERAEUS & NARIT COSMOLOGY SCHOOL

GALAXIES AND BEYOND

COSMOLOGY | GALAXY FORMATION | THE MILKY WAY | COSMOLOGICAL SIMULATIONS | ΛCDM | DARK MATTER | DARK ENERGY | HUBBLE TENSION

13-17.10.2025
CHIANG MAI, THAILAND

FOR MORE INFORMATION
indico.narit.or.th/event/223

APPLICATION DEADLINE 11.07.2025

APPLICATIONS OPEN FOR STUDENTS & EARLY-CAREER RESEARCHERS IN GERMANY AND THAILAND

Successful applicants will receive support for round-trip airfare to Chiang Mai, Thailand, accommodation and full room and board

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MATTHIAS STEINMETZ (AIP)
MICHAEL KRAMER (MPIFR)
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The Simulated Cosmic Web

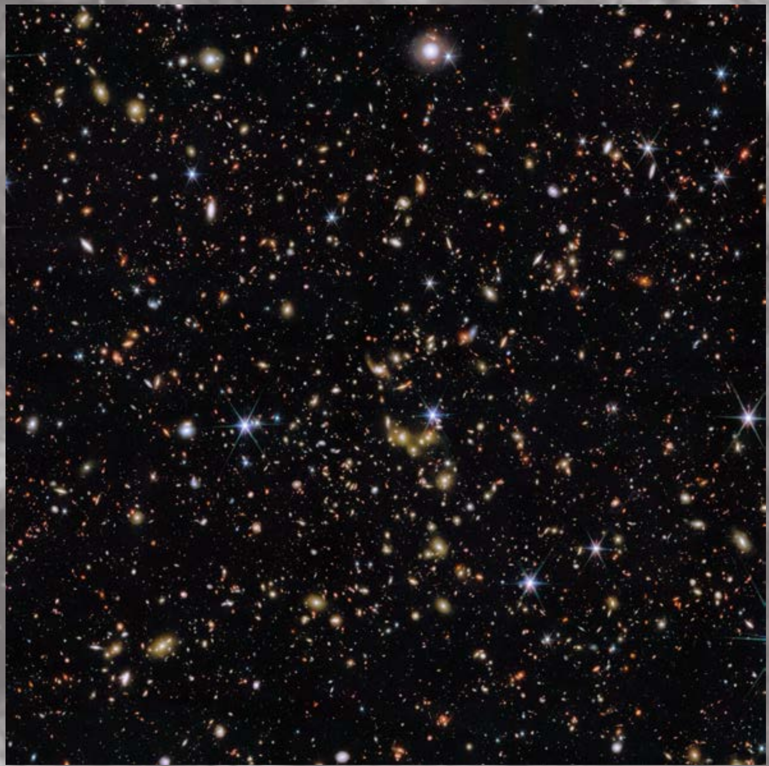
I: Simulating the Universe
II: Simulating the Local Universe

Dr Noam I Libeskind

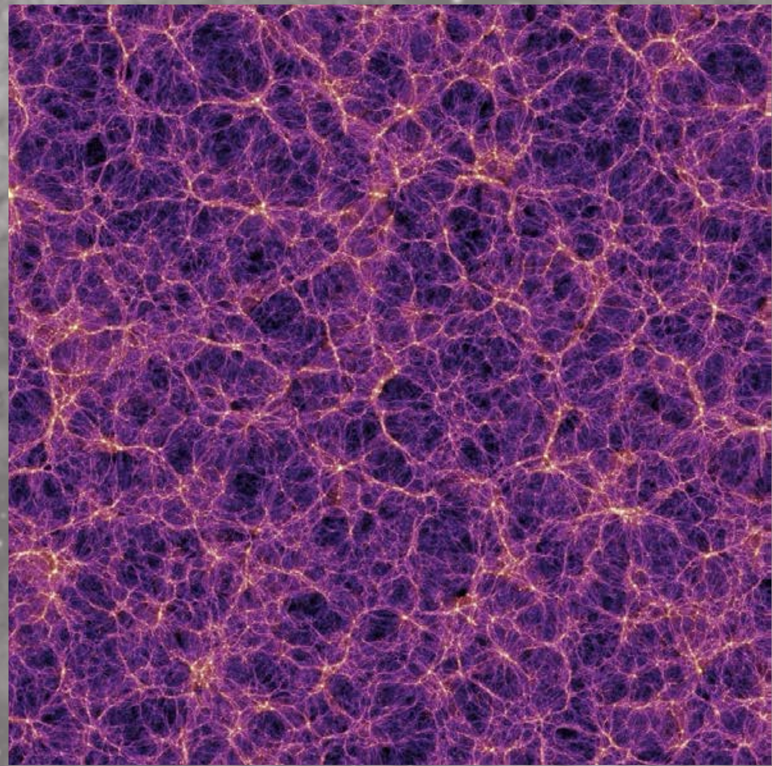
Cosmography and Large-scale structure

AIP
Leibniz-Institut für Astrophysik Potsdam

How do galaxies form in the Universe?



Large cosmological simulations: statistical questions/answers



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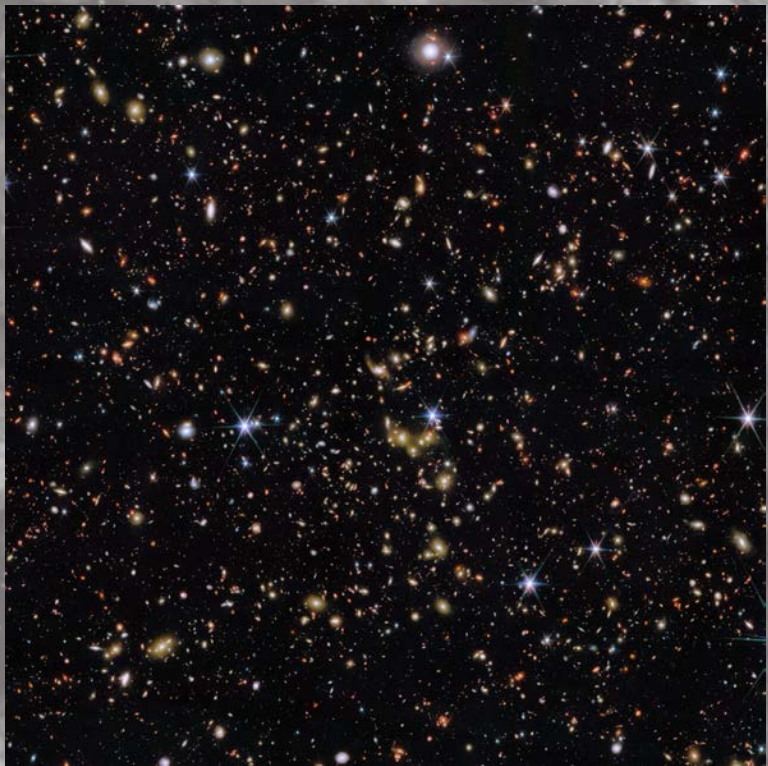

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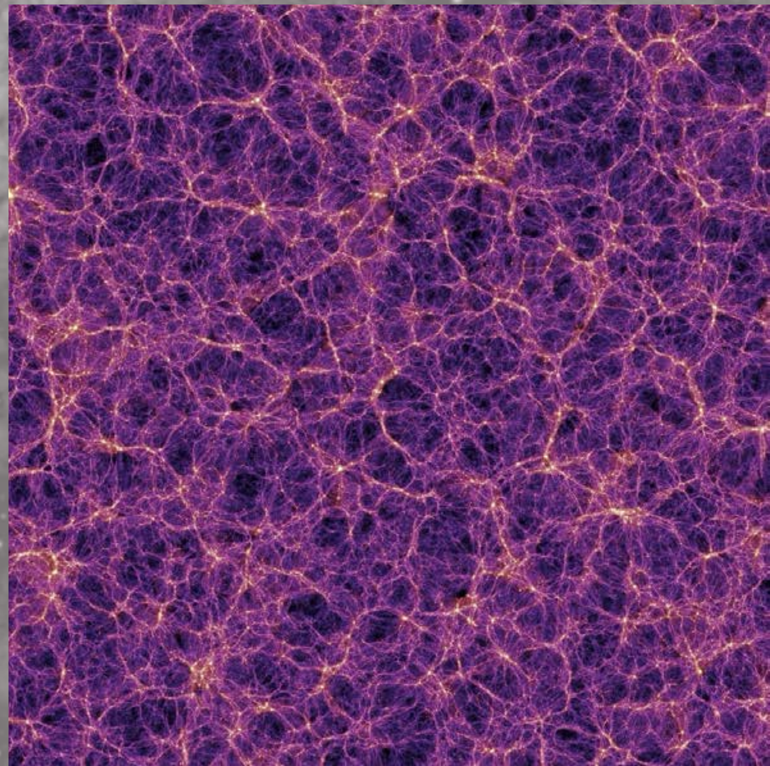

Nature vs Nurture

Which physical process are "universal", which depend on environment

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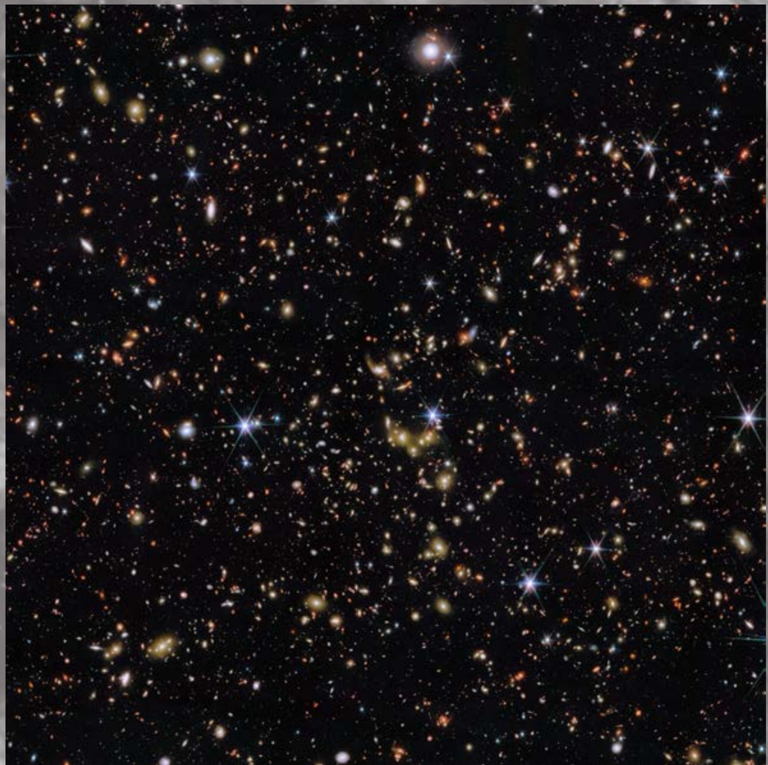

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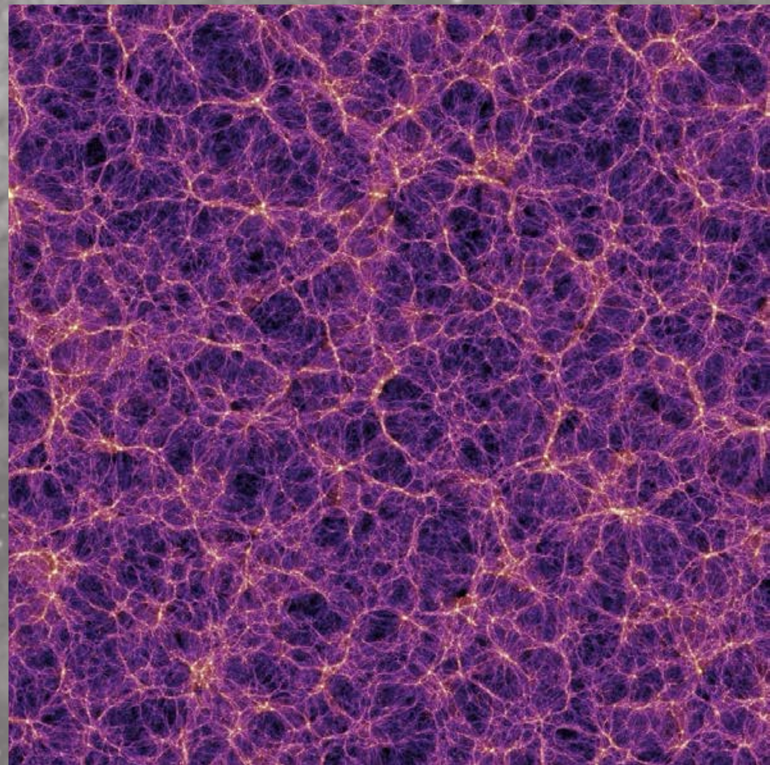


Nature vs *Nurture*

Which physical process are "universal", which depend on environment

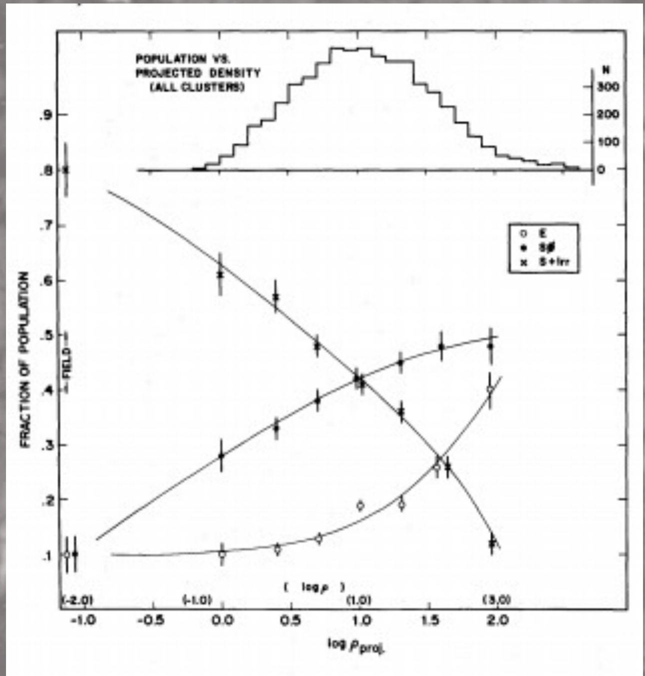
- Star formation
- Gas accretion
- Chemical enrichment

- Mergers
- Tidal interactions
- Environment

How did the Milky Way Form?

Need simulations that model the Milky Ways environment

Why bother with constraining the local environment?



Dressler 1980

Galaxy properties are effected by environment

Morphology – density relationship

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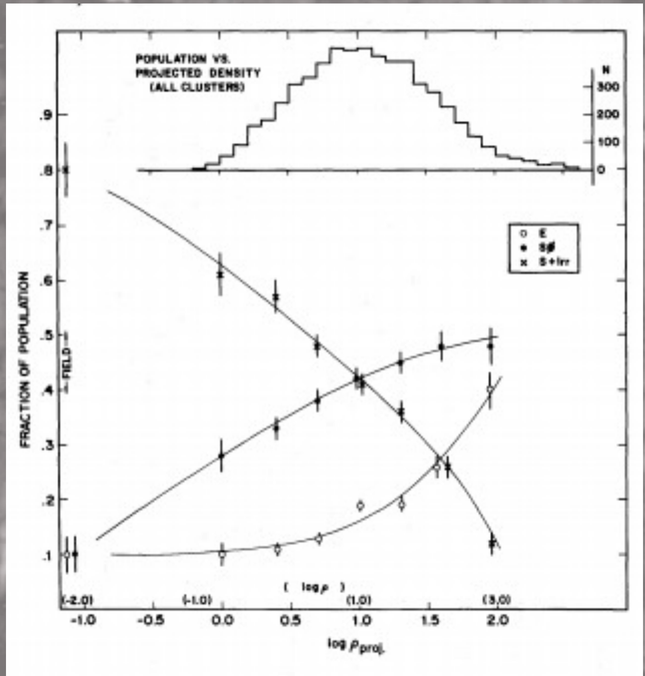

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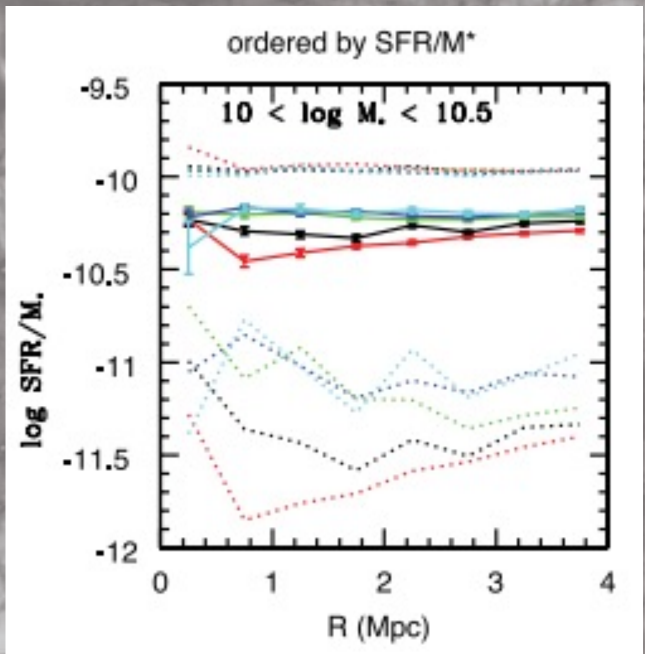
Kauffman et al 2013



Galaxy conformity (Weinman et al 2006)
Neighboring galaxies *conform* to one an other

SSFR conforms out to 4Mpc

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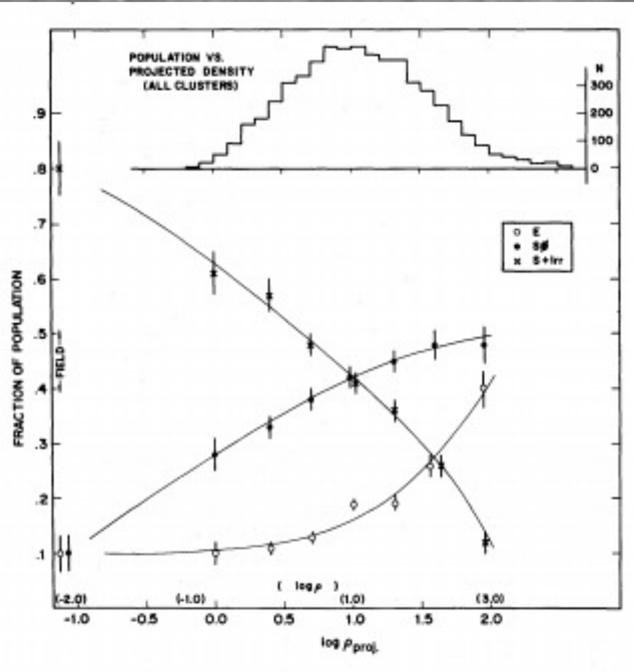

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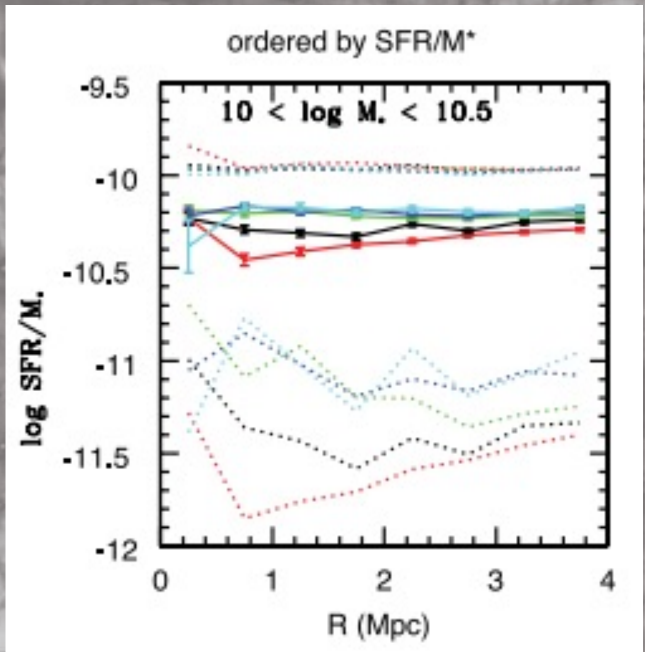

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How do we define or measure a galaxy's environment?

Isolated – few neighbors

Fairly rare

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Groups – Leo Triplet

2-100 galaxies

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Clusters: Coma

100– 1000 galaxies

Distance to Nth nearest neighbor above some Magnitude limit

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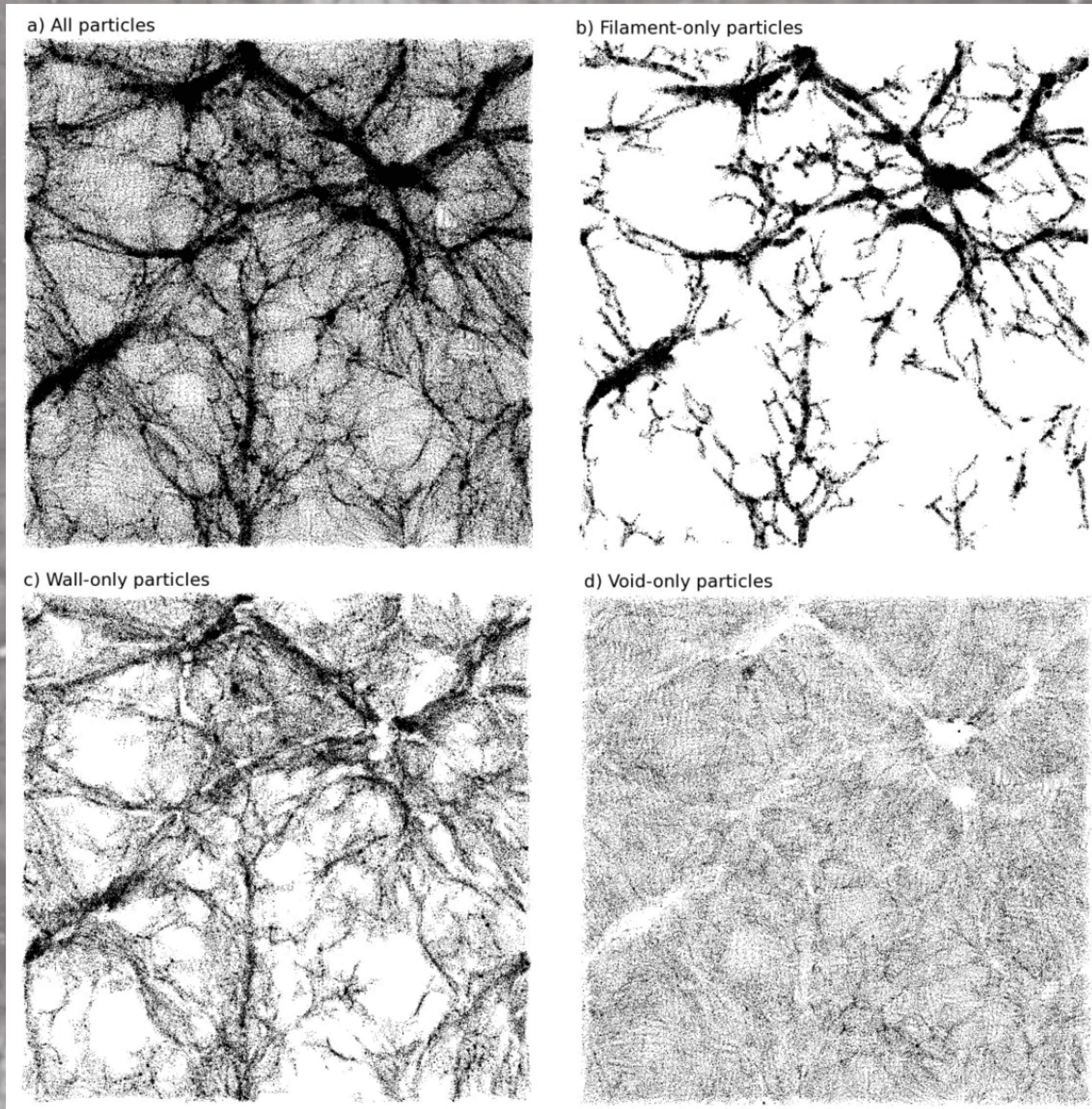

Cautun et al 2020

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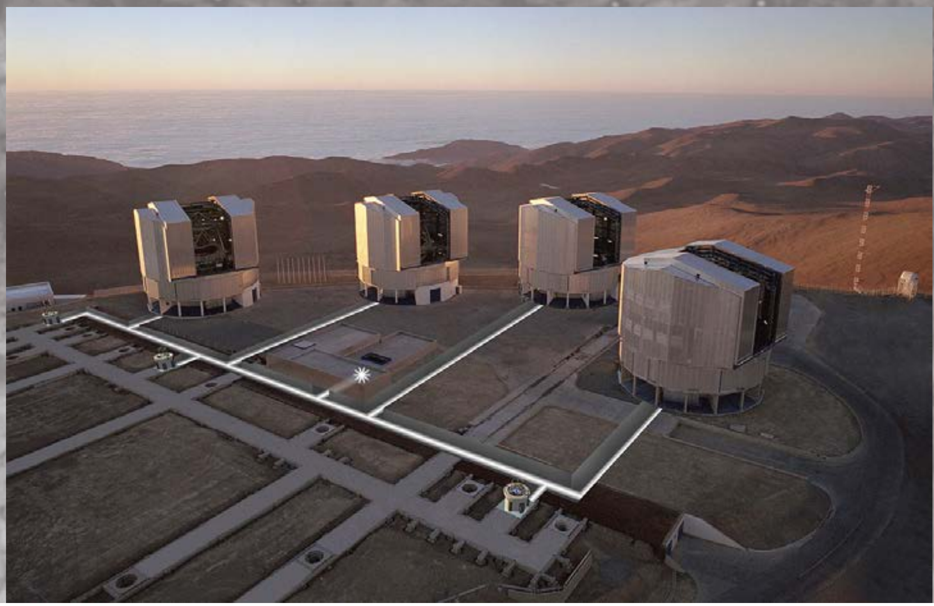
Point a telescope and take a picture



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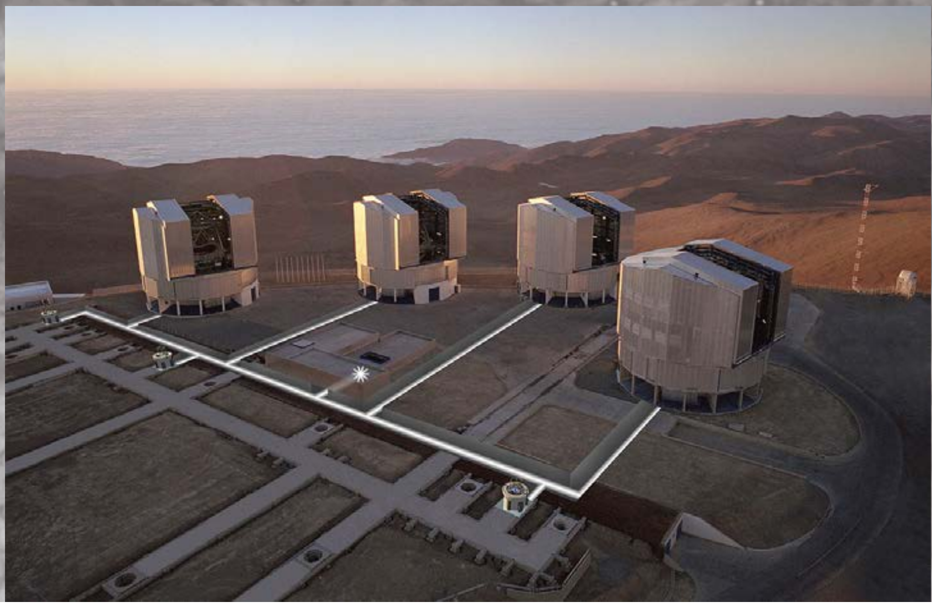
1. "Simple"
2. Traditional
3. Intuitive



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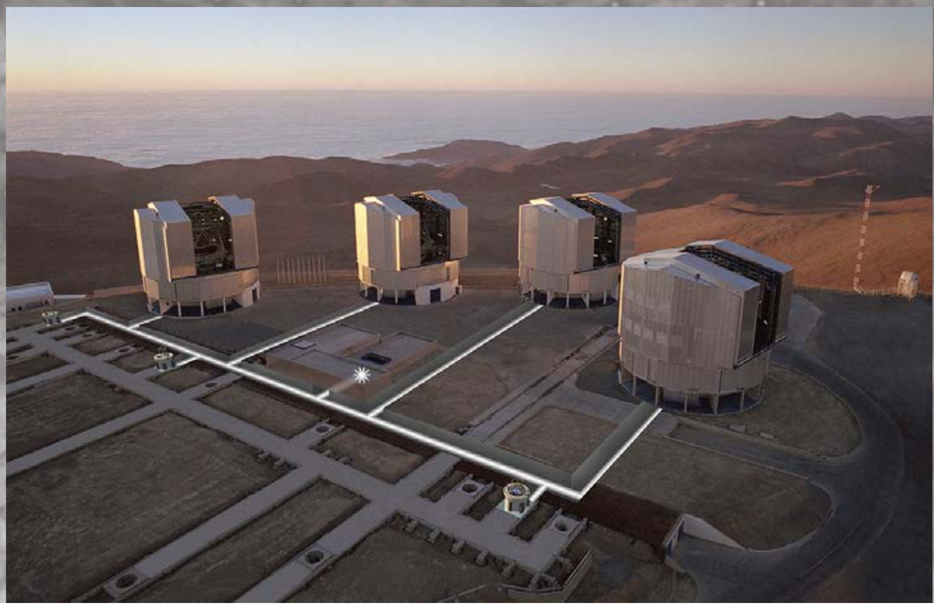

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1. light doesnt trace mass - the universe is full of dark matter

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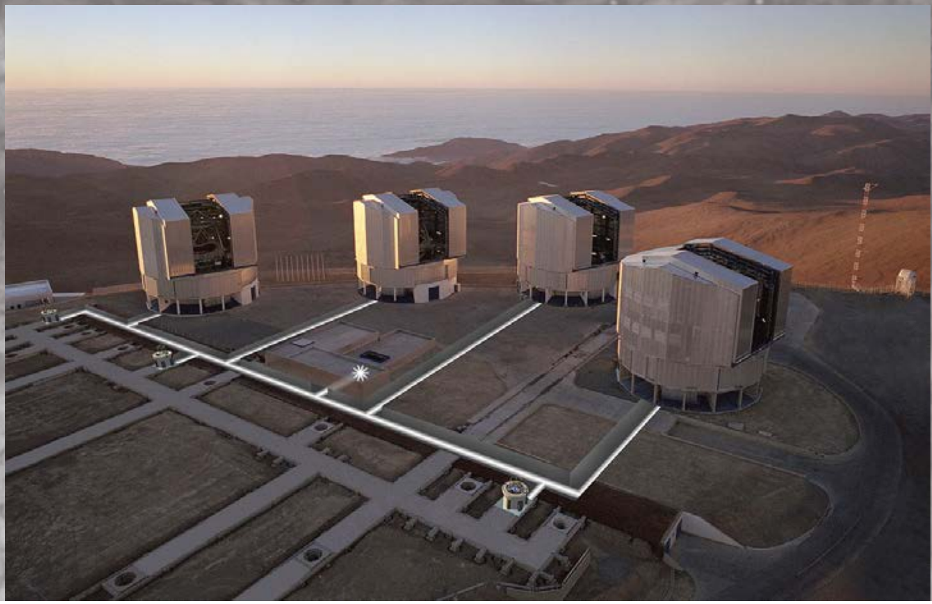

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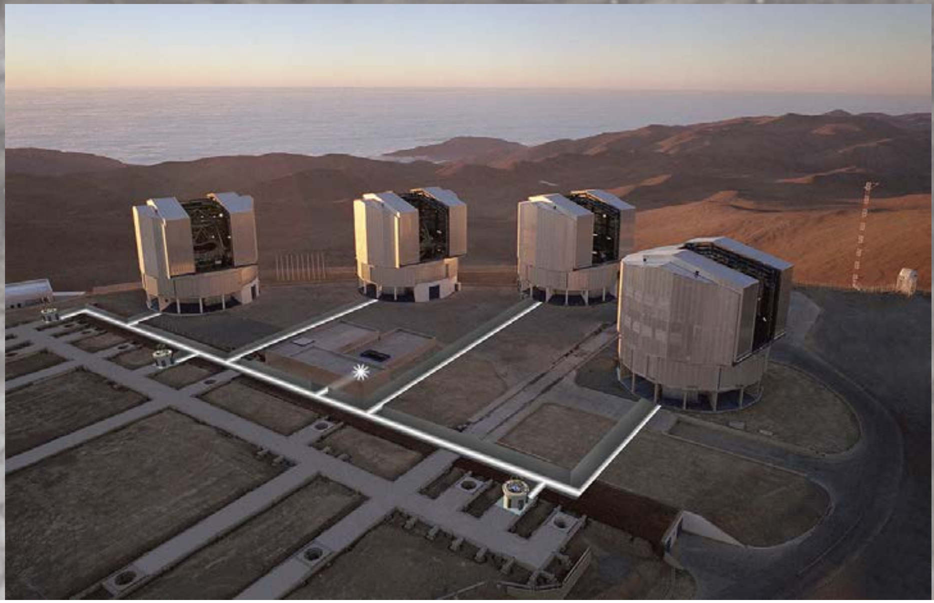

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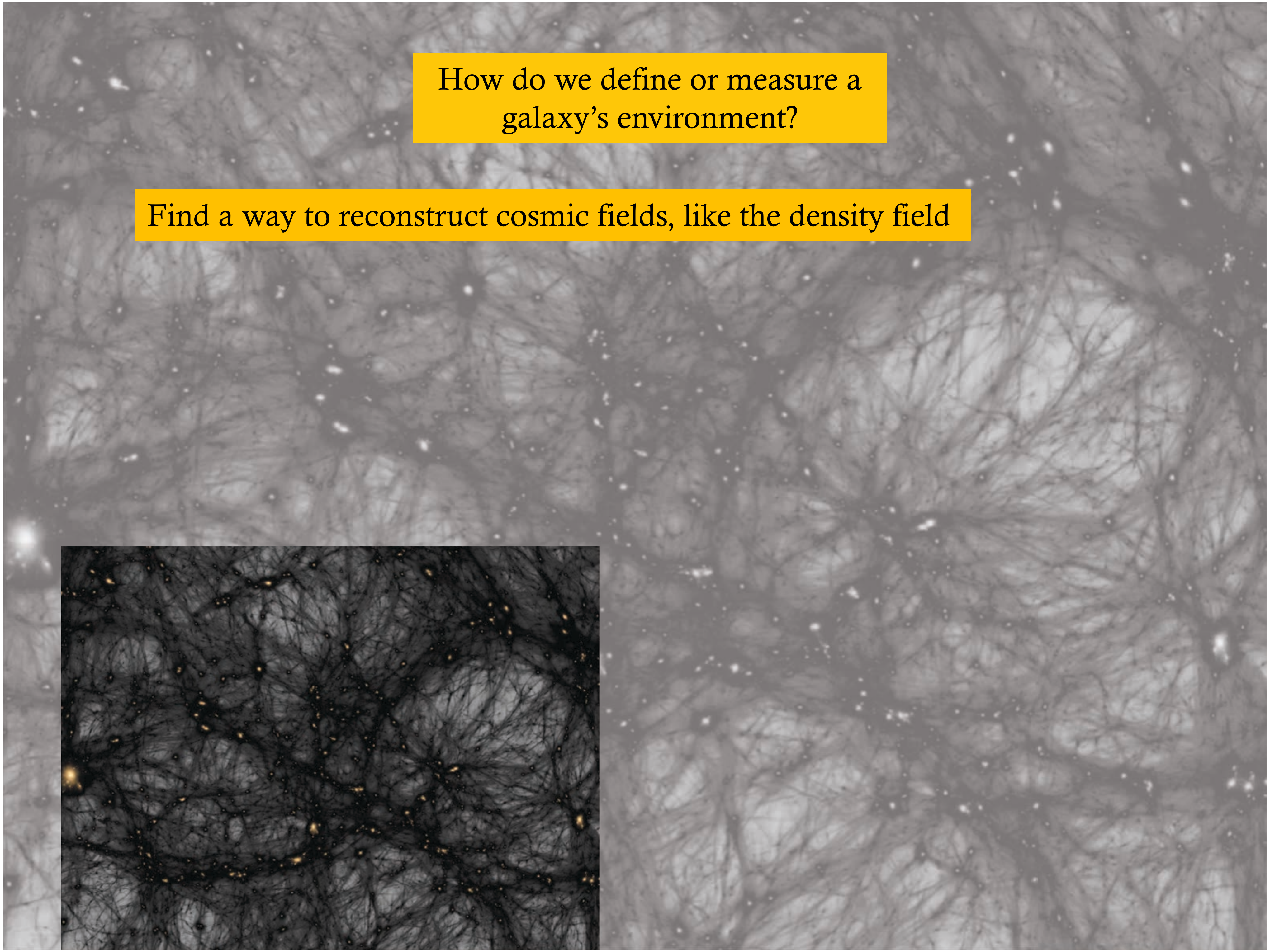
3. Any census of the galaxy distribution depends on how sensitive your telescope is – better telescopes see fainter things

How do we define or measure a galaxy's environment?

Find a way to reconstruct cosmic fields, like the density field



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1. The "truth"

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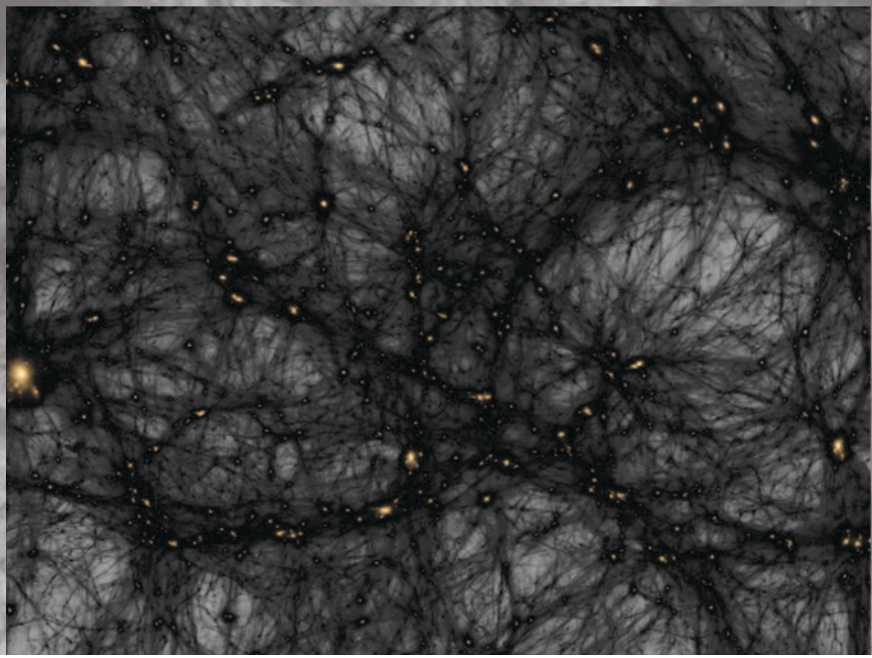

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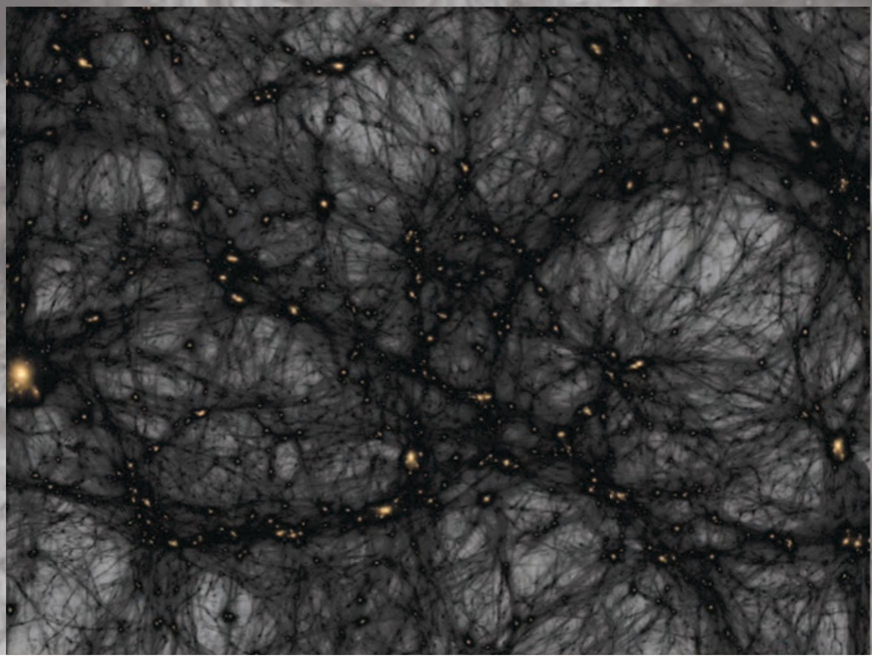


Problems:

1. Complex

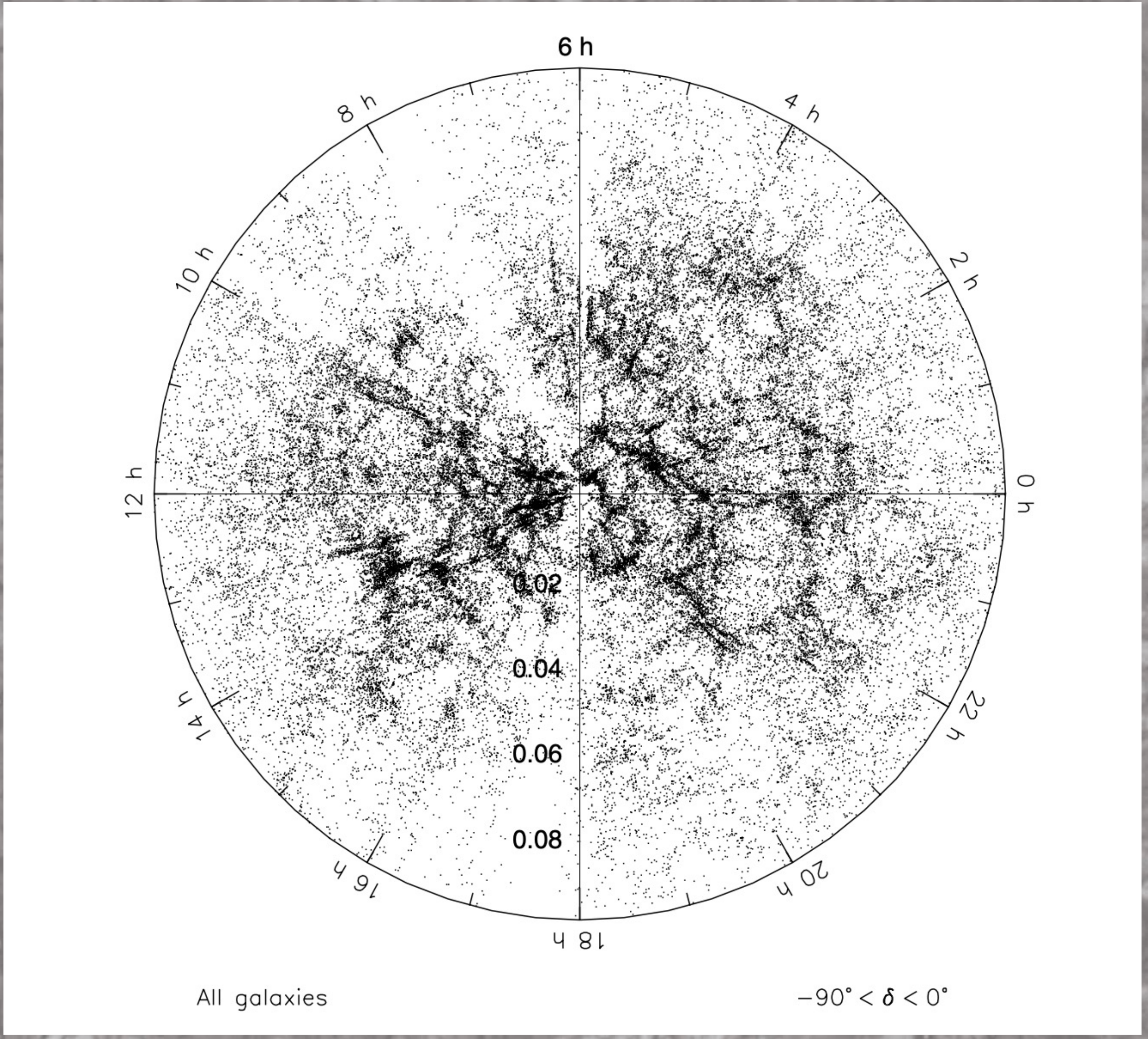
2. Data is poor: inhomogeneous and sparse

3. Data is full of complex biases.

Distortions & Biases

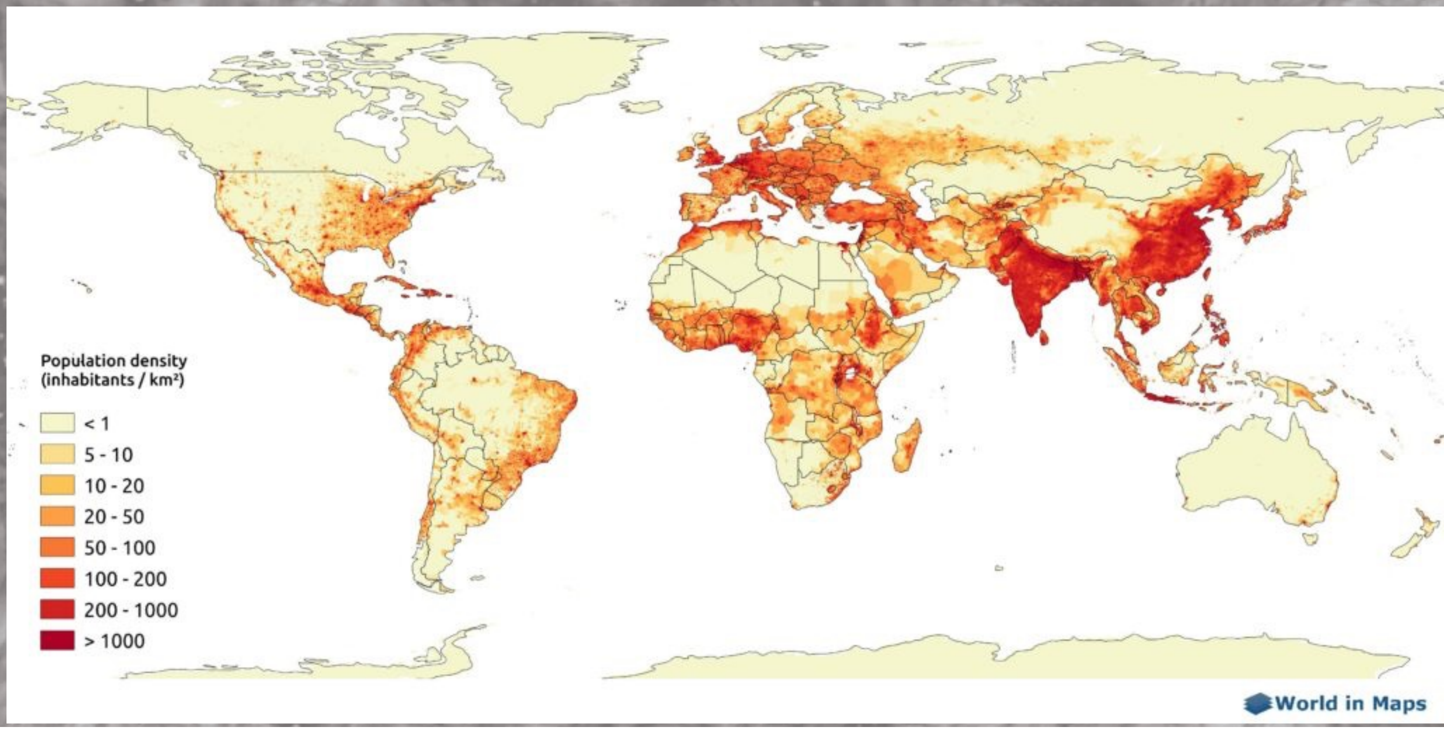
cz is the **full** velocity, so we have all sorts of red shift space distortions

Also: light doesn't trace mass



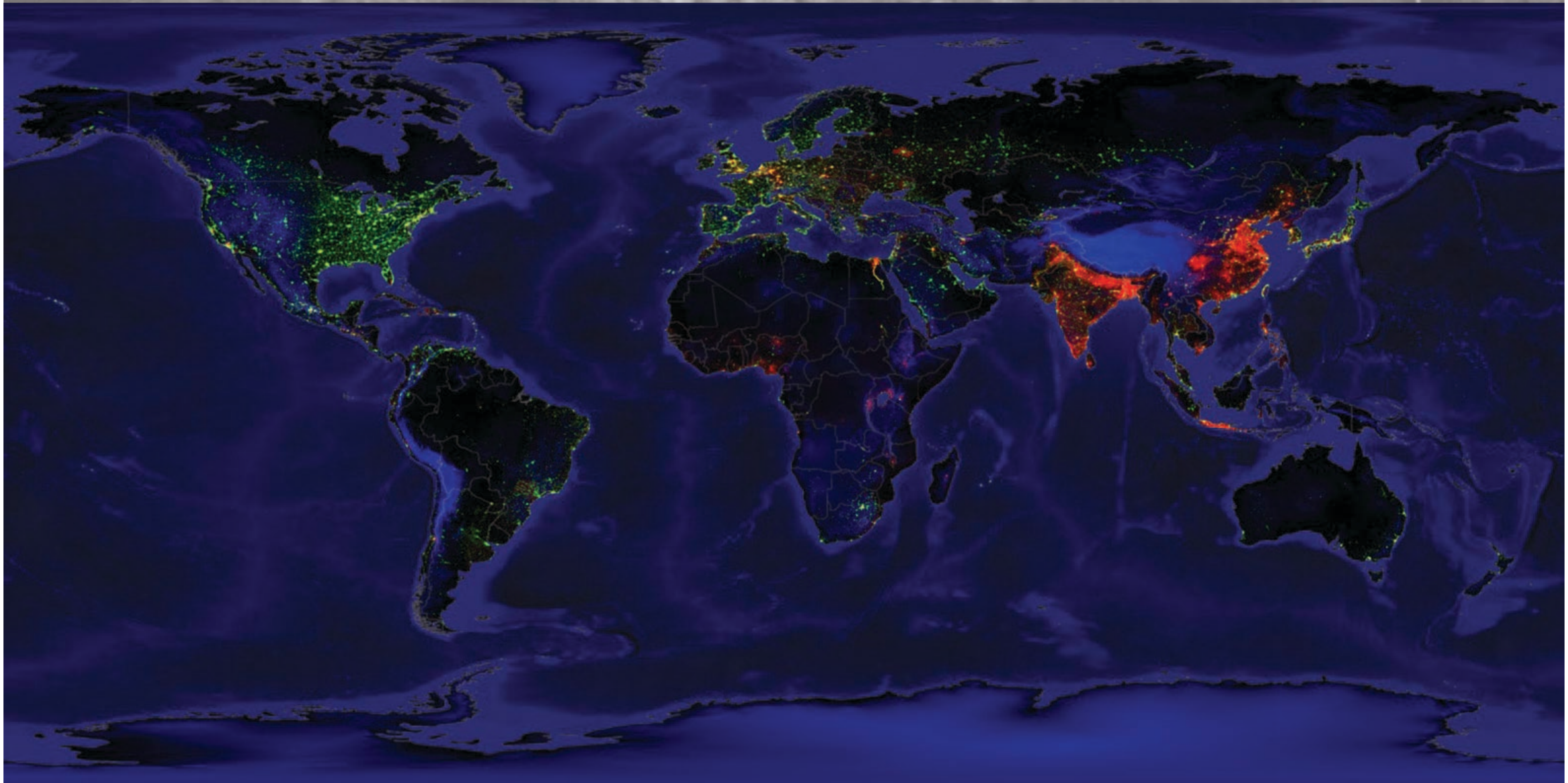
6df Jones et al 2004

Light from the Earth at night



Population density

Bias – light does not trace density



Red – high mass to light

Green – low mass to light

What does trace the density?

The gravitational velocity – mistakenly called the peculiar velocity

$$\nabla^2\Phi = 4\pi G\rho$$

$$\delta = -\boldsymbol{\nabla} \cdot \boldsymbol{v}/H_0 f(\Omega_m),$$

One of the best examples of this is the so-called “backside in fall” of the Virgo cluster

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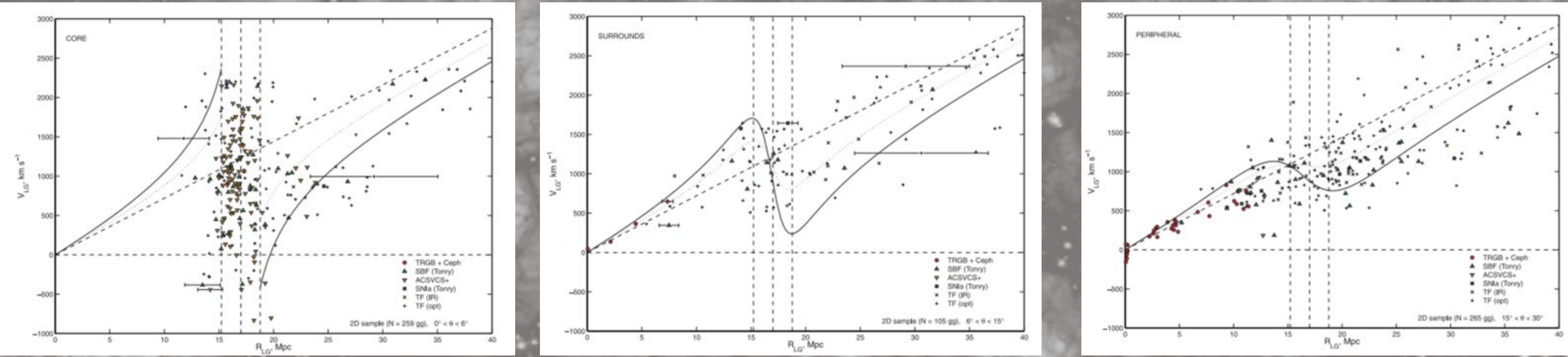

Karatchensev et al 2012

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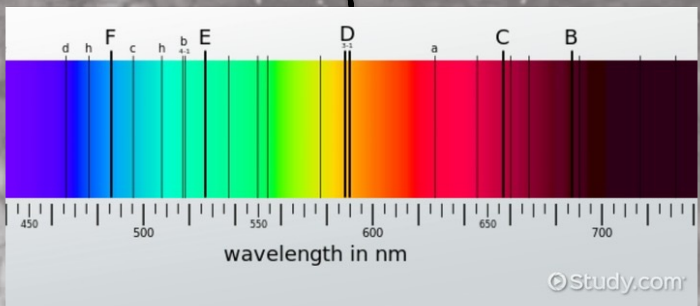
Reconstructing the underlying matter distribution of the Local universe

$$cz = v_{exp} + v_{pec}$$

$$v_{exp} = H_0\, d$$

$$v_{pec} = cz - H_0\, d$$



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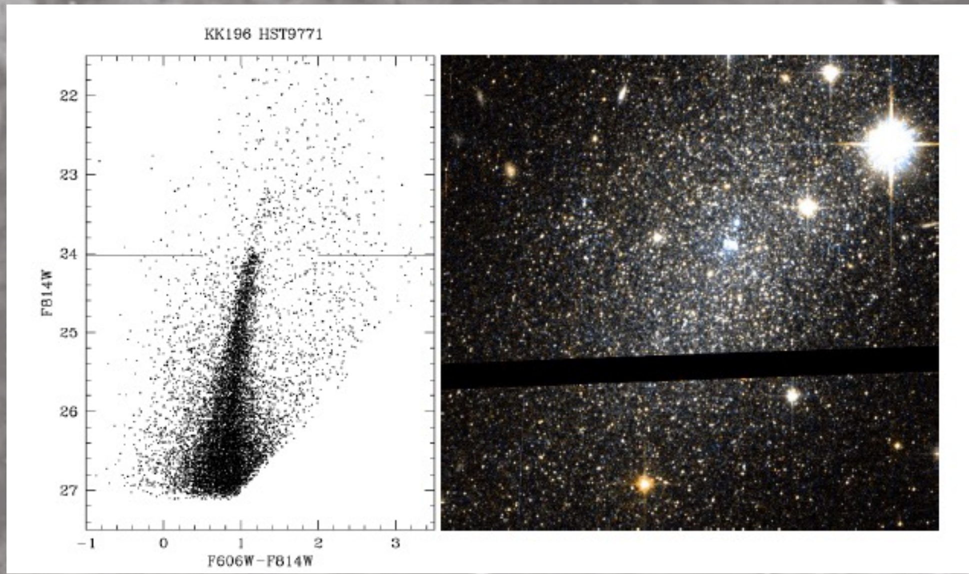

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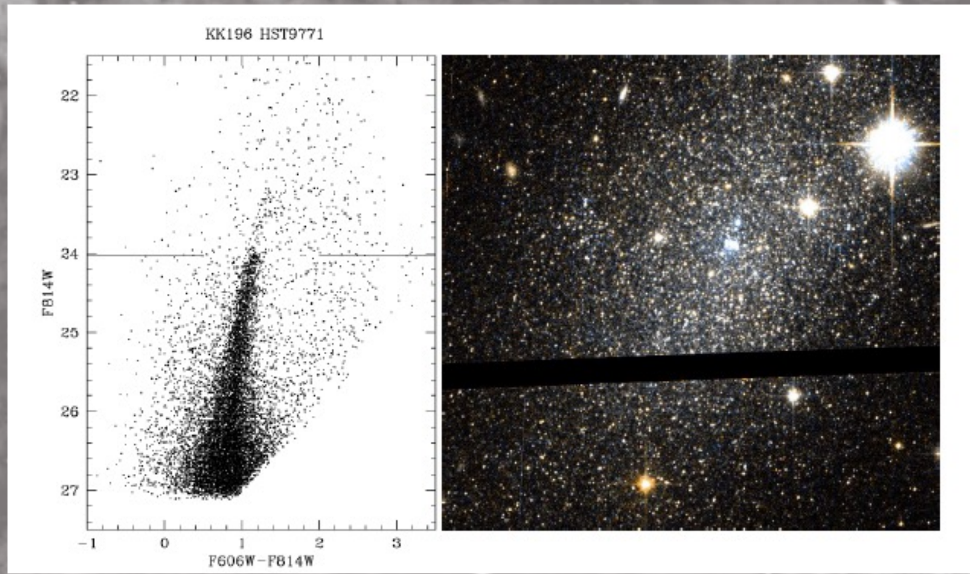
Method	error	distance	Common?
Cepheids	~1%	very local	no
RR Lyrae	~1%	very local	no
TRGB	~5%	local	yes
SBF	~5%	local	yes
SN	1-5%	far	no
Scaling relations	10-30%	far	yes



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This allows us to separate the peculiar velocity from the Hubble expansion

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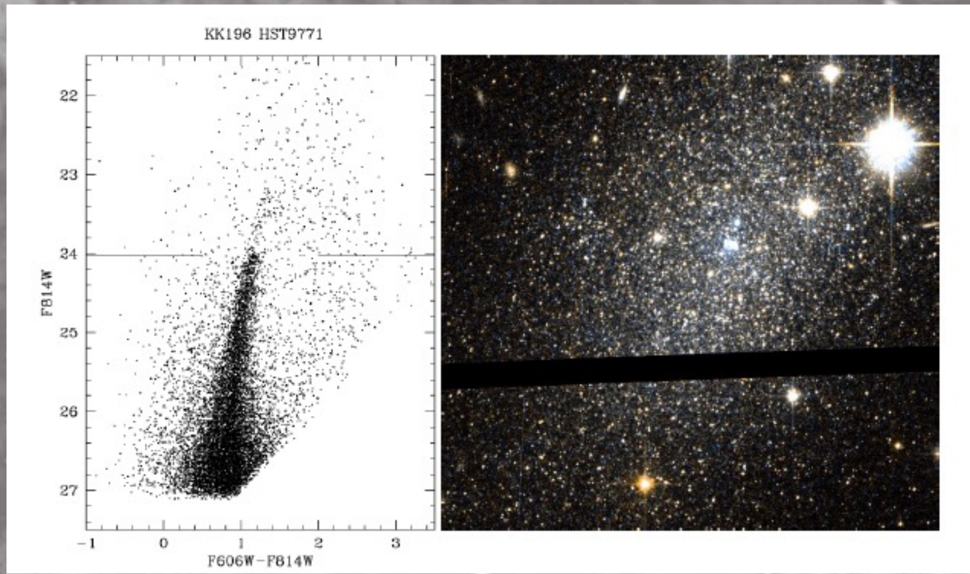

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JWST will increase the *d* where stellar populations are resolved by more than an order of magnitude wrt Hubble.

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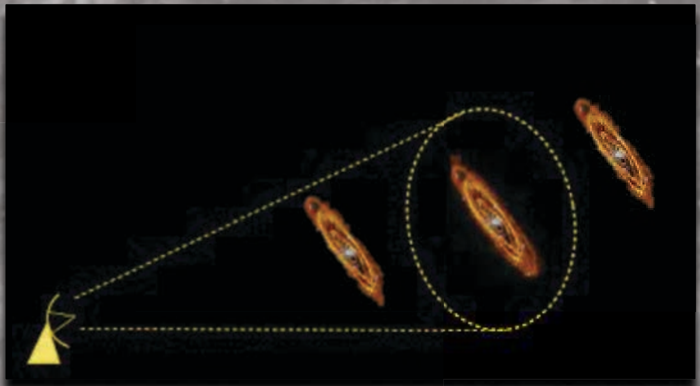
Peculiar velocity at great distances

Issue: errors can be way larger than the signal.

A typical distance estimate based on for example a Tully-Fisher measurement has ~20% error



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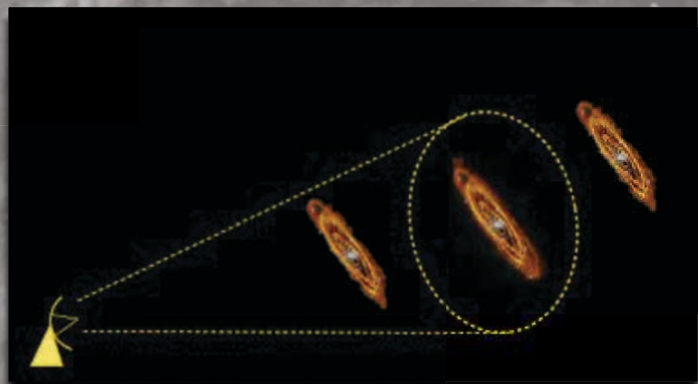
So already $V_{pec} = 0.05\ V_{hubble}$



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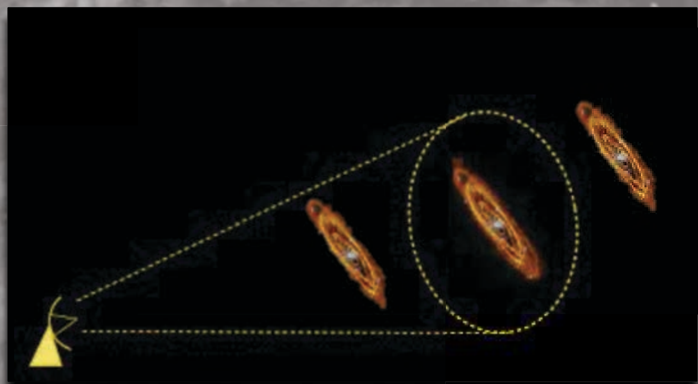
A 20% error on the distance at 100Mpc translates into an error on the peculiar velocity of ±*1400* km/s so $\Delta V_{pec} \sim 20 V_{pec}$



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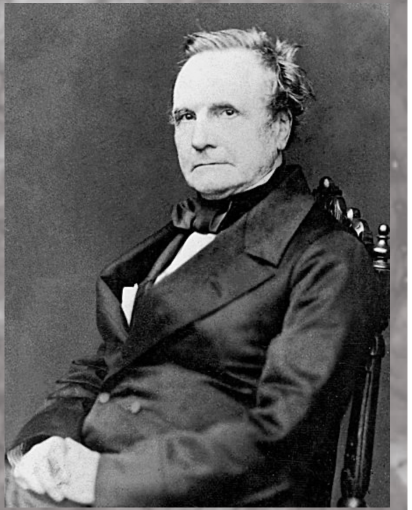

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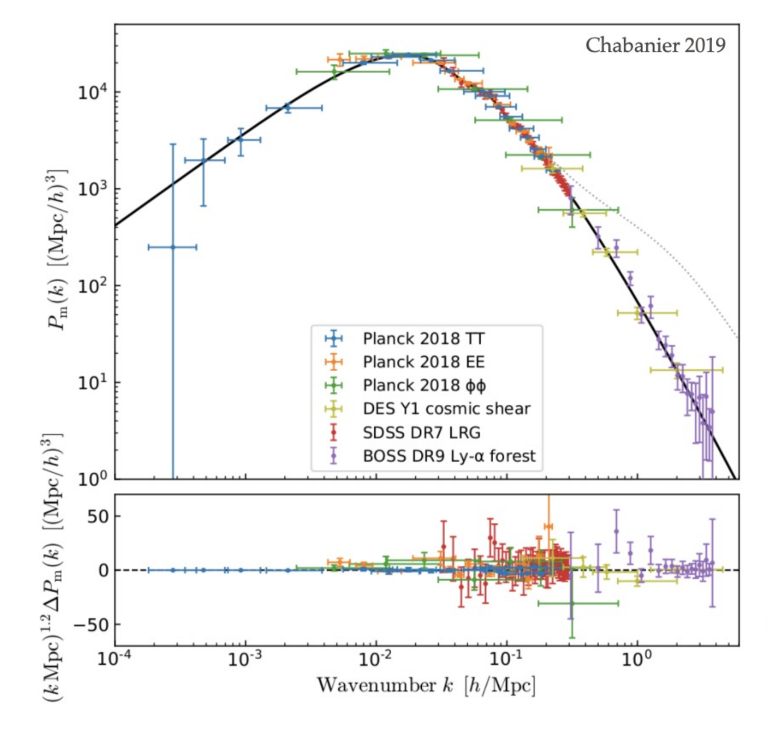

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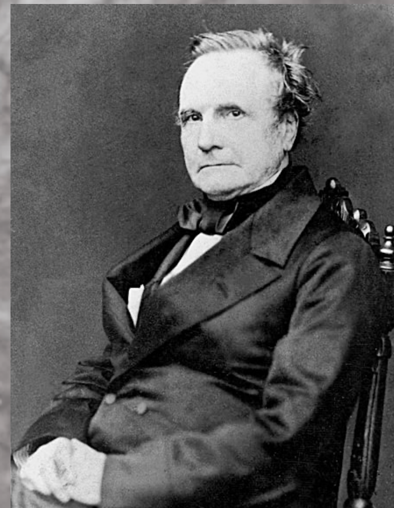

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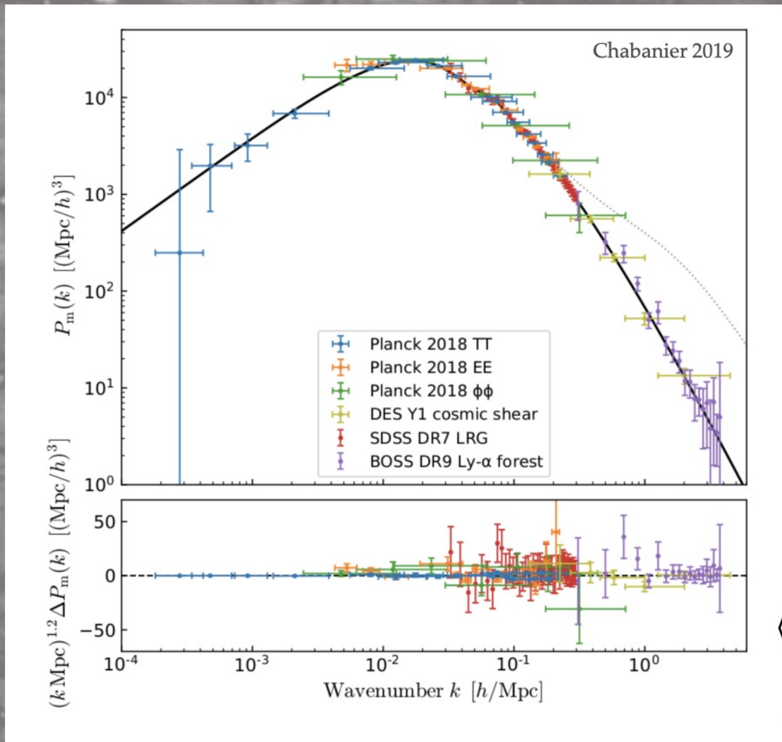

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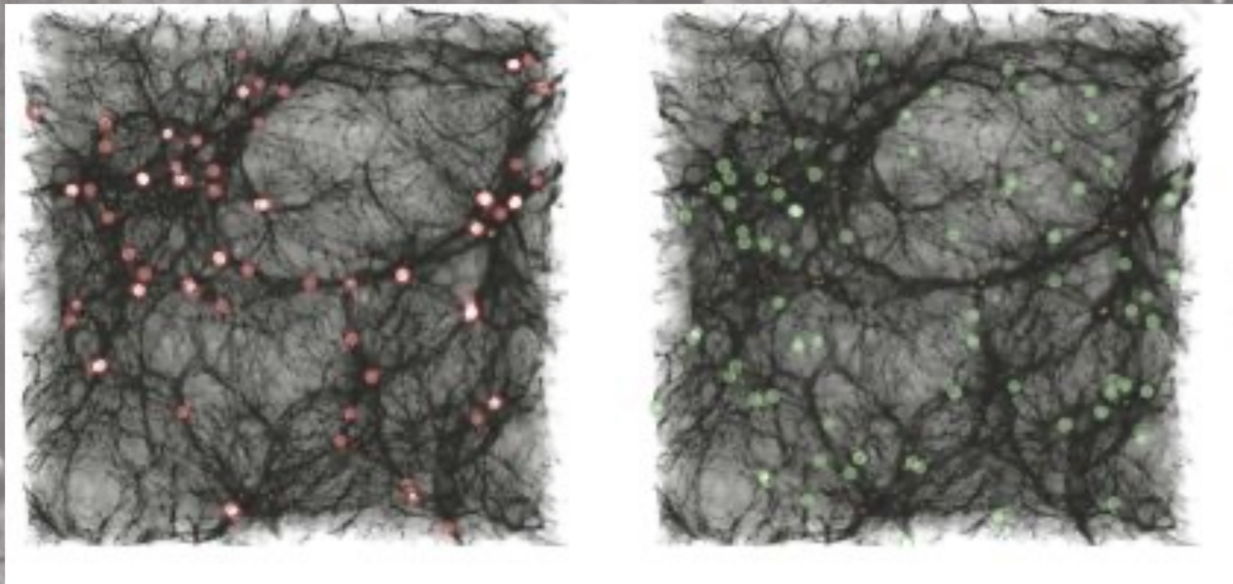
$$\vec{\nabla}\vec{v} = -H_0 f \delta$$

$$\langle v_\alpha^2 \rangle = (f\sigma_8)^2 \frac{k_\alpha^2}{k^4} P_0(k)$$

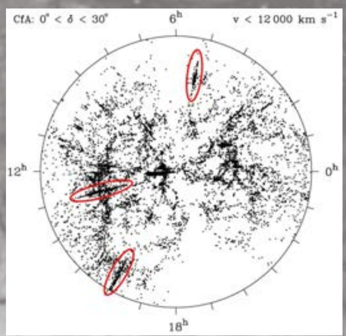
A summary of the challenges faced when trying to map the Universe

Galaxy bias – light doesn't trace matter



"Malmquist bias" – you only see the brightest galaxies at any given distance, given your telescope sensitivity

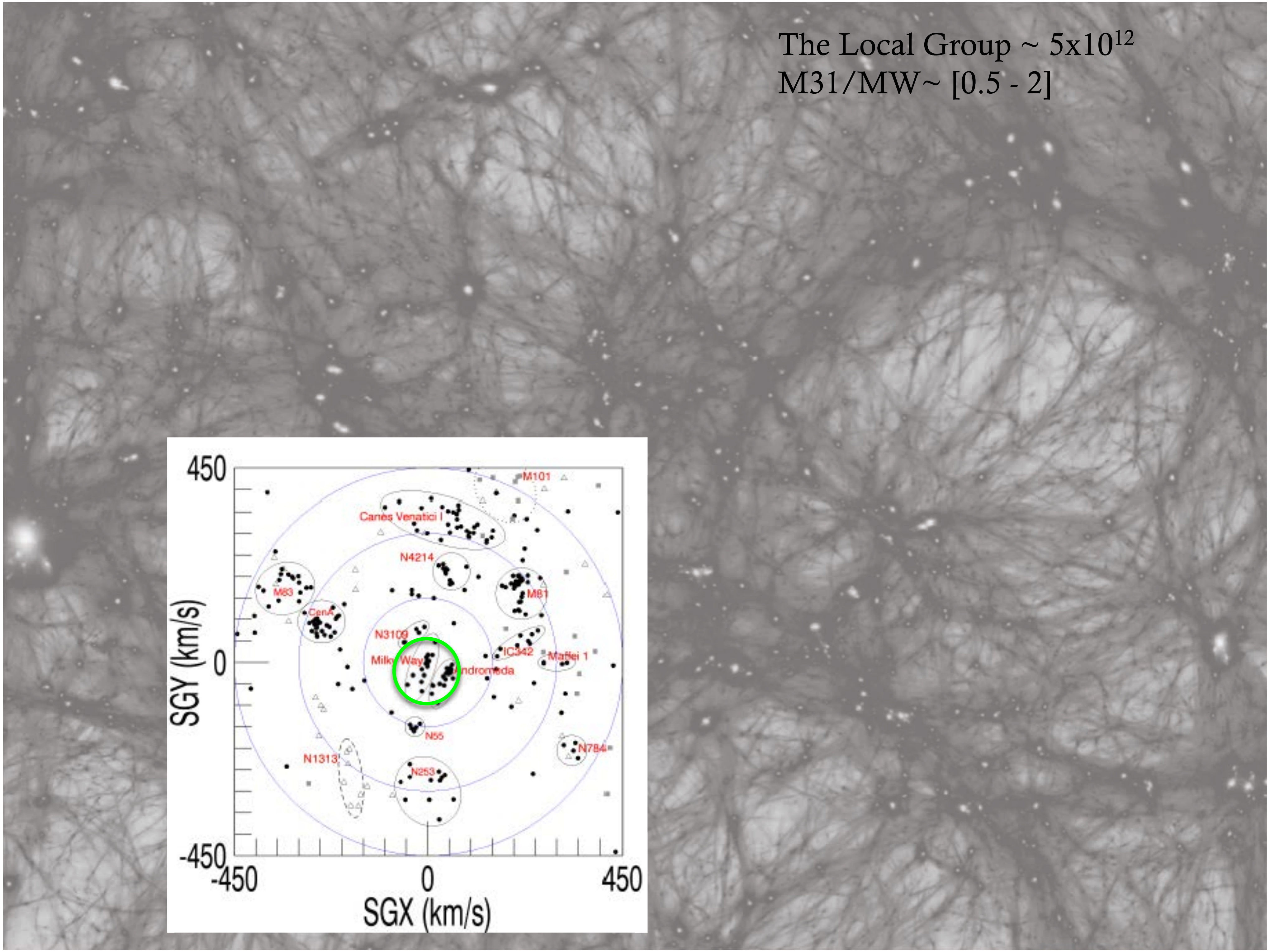
Selection bias and obstructions – incomplete sky coverage, Zone of Avoidance, dust, etc



Red shift space distortions: "fingers-of-god" and the Kaiser effect

Dynamic evolving matter field, changed by competing forces – gravity and expansion

The Local Group ~ 5×10^{12}
M31/MW~ [0.5 - 2]



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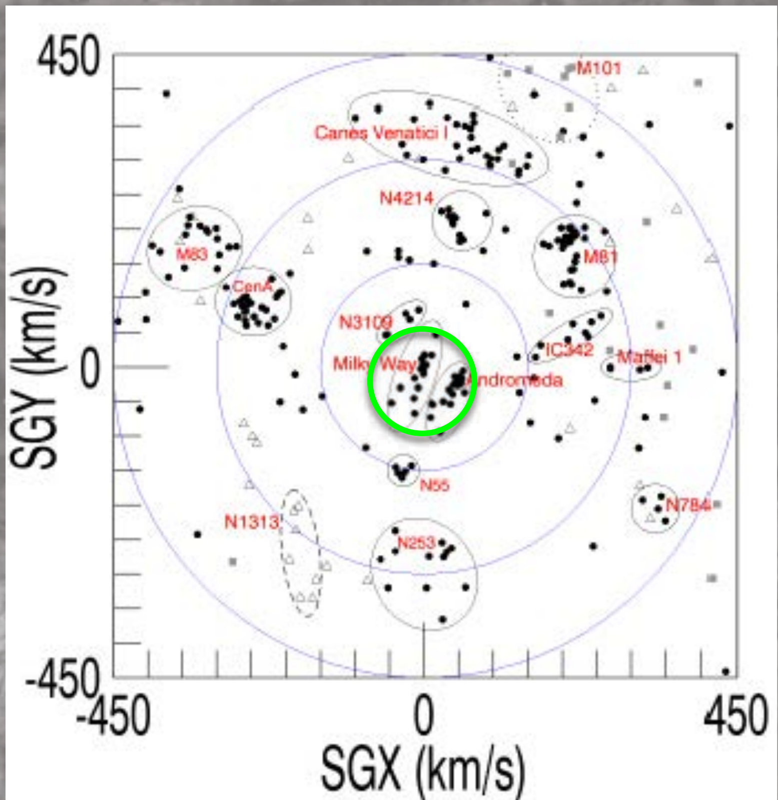
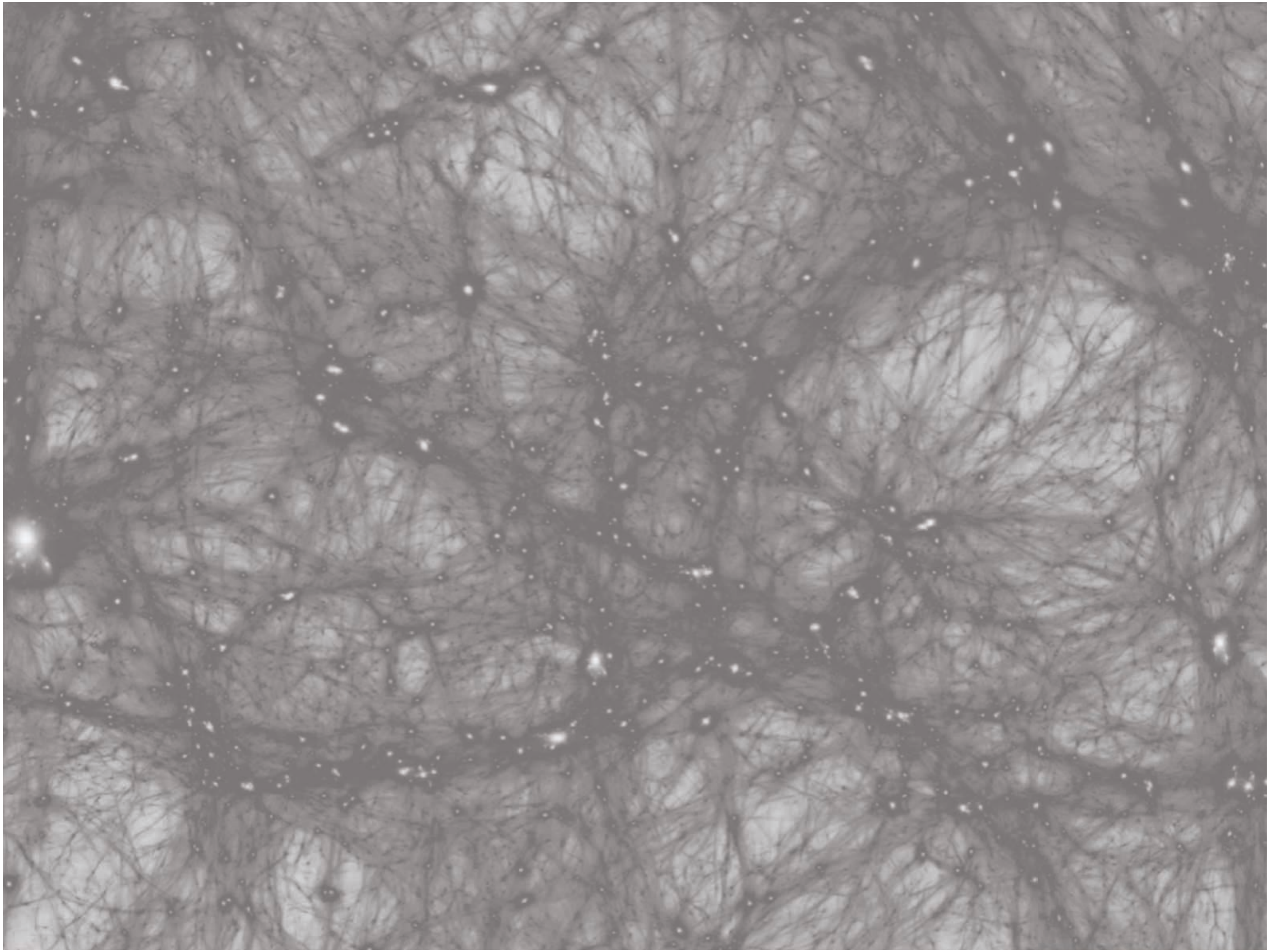
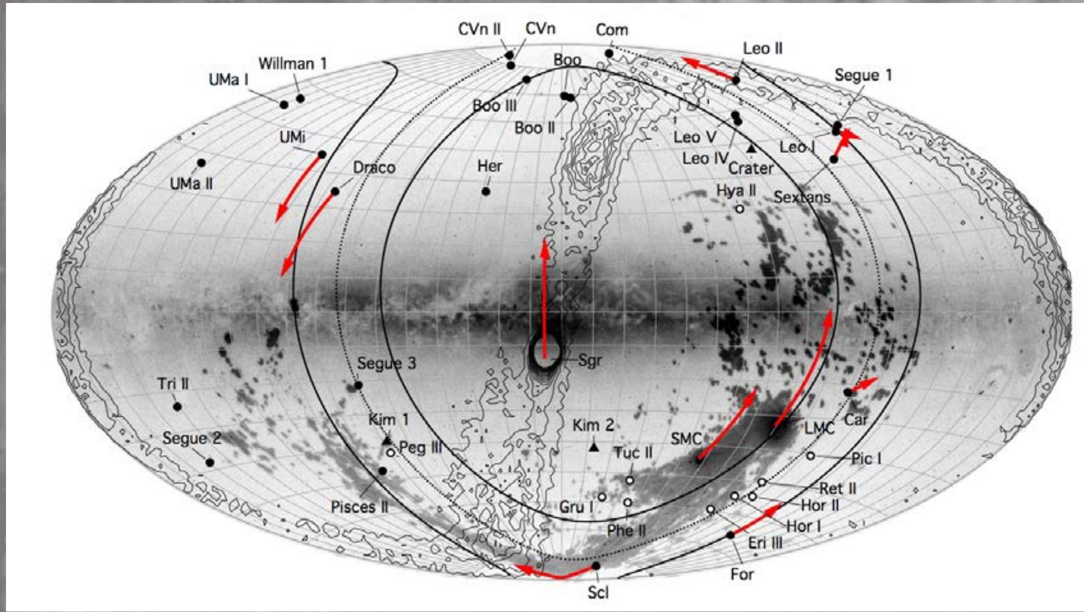
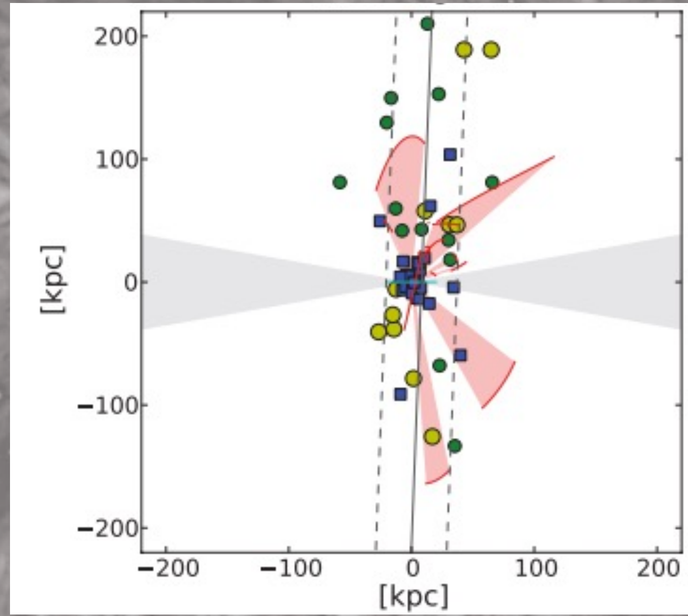






Pawlowski et al 2012



Pawlowski et al 2012

c/a ~ 0.15

N_{sat}=27+ streams …

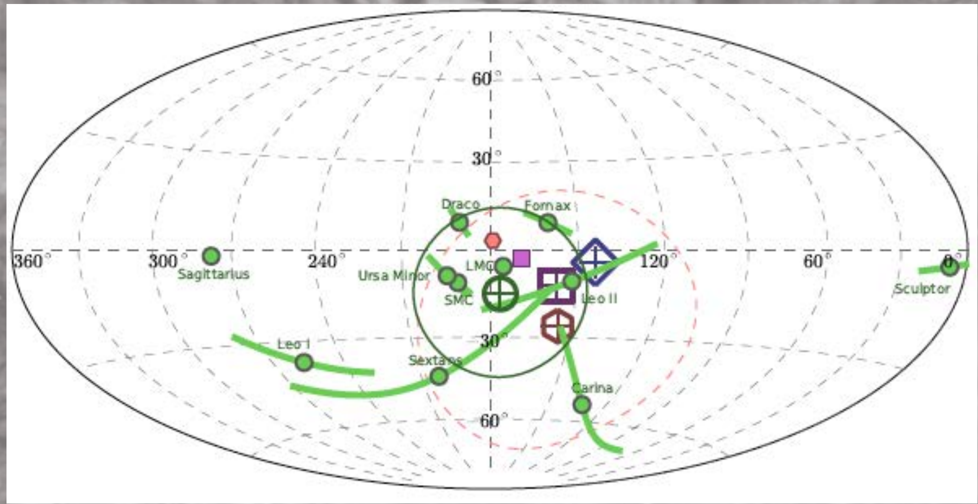
D_{rms}=24kpc

THE FORNAX–LEO–SCULPTOR STREAM*

By D. Lynden-Bell
University of Cambridge

The dwarf spheroidal galaxies Fornax, Leo I, Leo II and Sculptor lie on a great circle as seen from the Galactic centre, and Sculptor, the most tidally fragile, is elongated along that circle. All the dwarf spheroidal satellites of the Milky Way are in one of two streams of tidal débris.

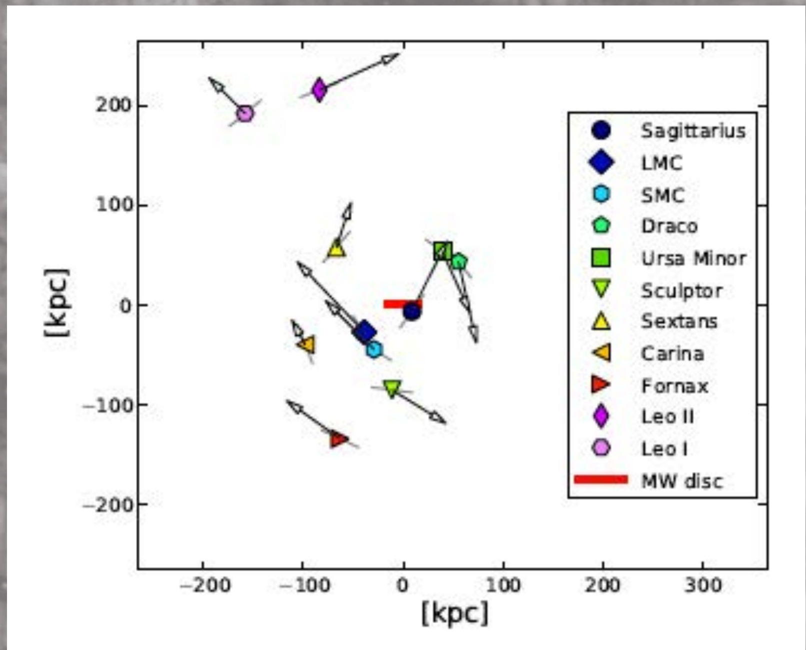
MW satellite velocities - corotating



Metz, Kroupa & Libeskind 2007

"Rotationally stabilized"

Various measures of the plane normal



~ 8 out of 11 orbit in the plane they define

Metz, Kroupa & Libeskind 2007

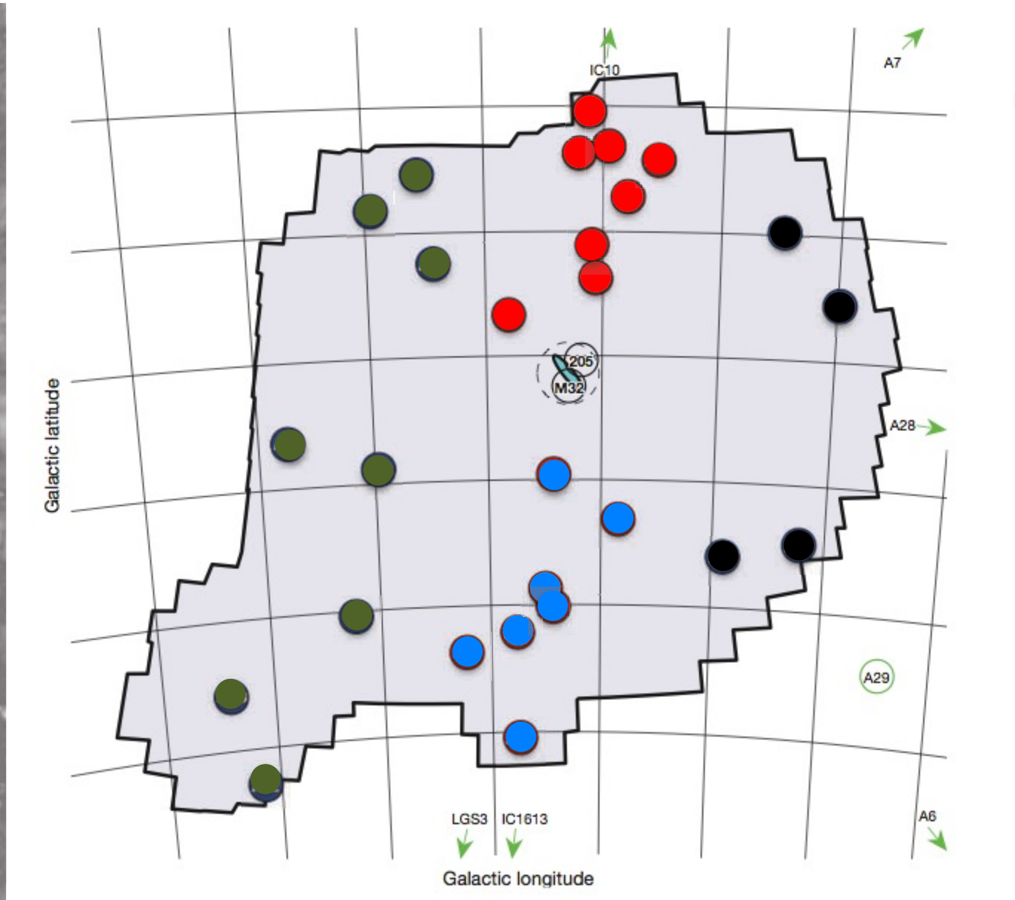
Pawlowski & Kroupa 2013

LETTER

doi:10.1038/nature11717

A vast, thin plane of corotating dwarf galaxies orbiting the Andromeda galaxy

Rodrigo A. Ibata[1], Geraint F. Lewis[2], Anthony R. Conn[3], Michael J. Irwin[4], Alan W. McConnachie[5], Scott C. Chapman[6], Michelle L. Collins[7], Mark Fardal[8], Annette M. N. Ferguson[9], Neil G. Ibata[10], A. Dougal Mackey[11], Nicolas F. Martin[1,7], Julio Navarro[12], R. Michael Rich[13], David Valls-Gabaud[14] & Lawrence M. Widrow[15]



Ibata et al 2013

15 “aligned” satellites

12 “unaligned” satellites

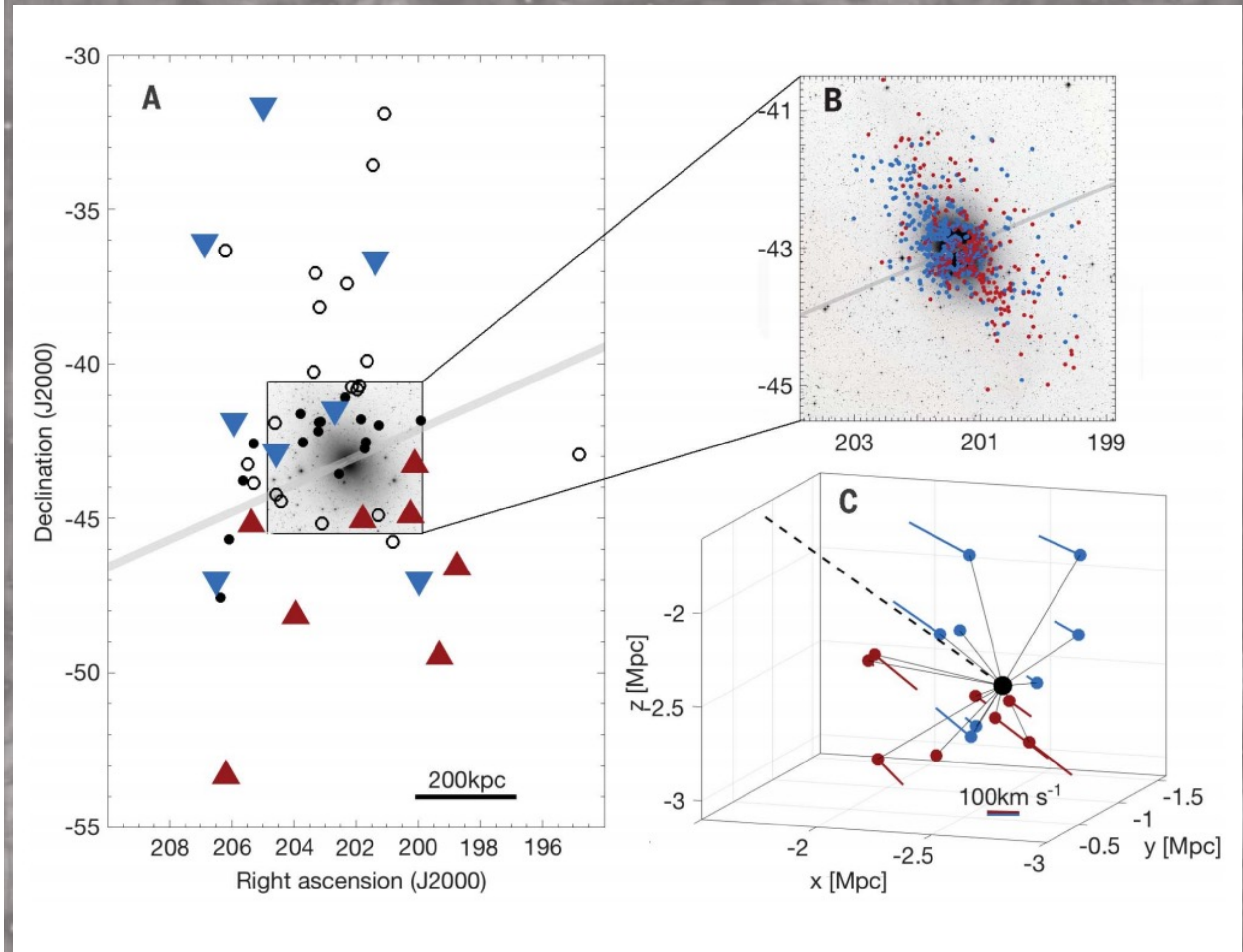
Disk of M31

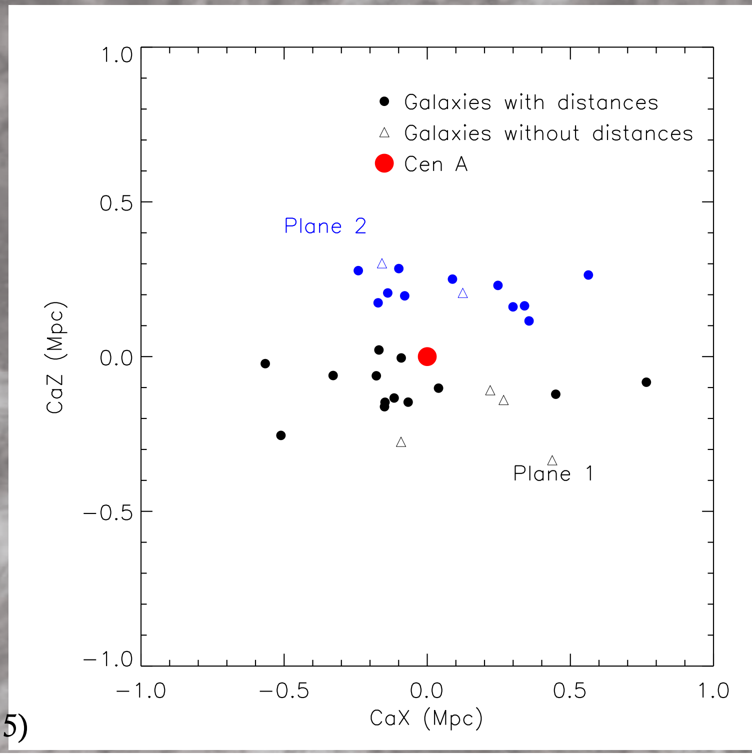
Plane “2”

Half the galaxies (13 out of 27) on plane with $c/a \sim 0.1$ and Δ_{rms}=14kpc

8 out of 12 “left overs” on a plane with Δ_{rms}=12kpc

Centaurus A satellites





Müller *et al* (2018)

Tully +NL *et al* (2015)

M101

M83

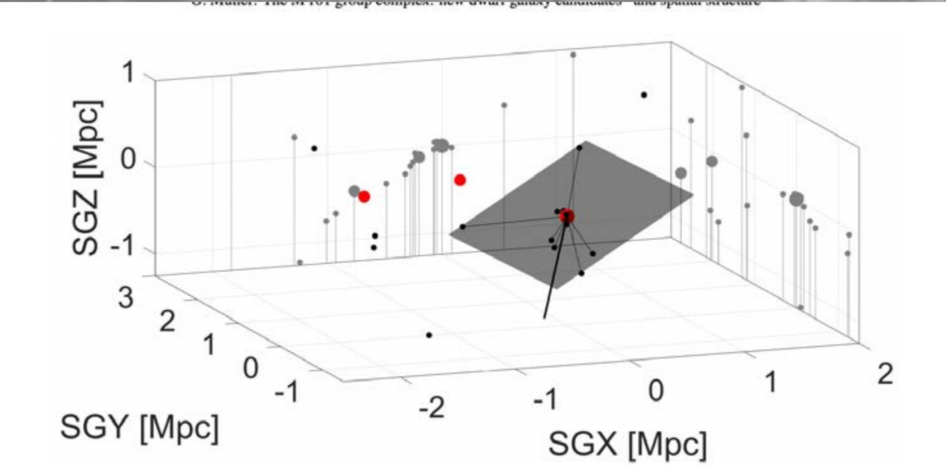
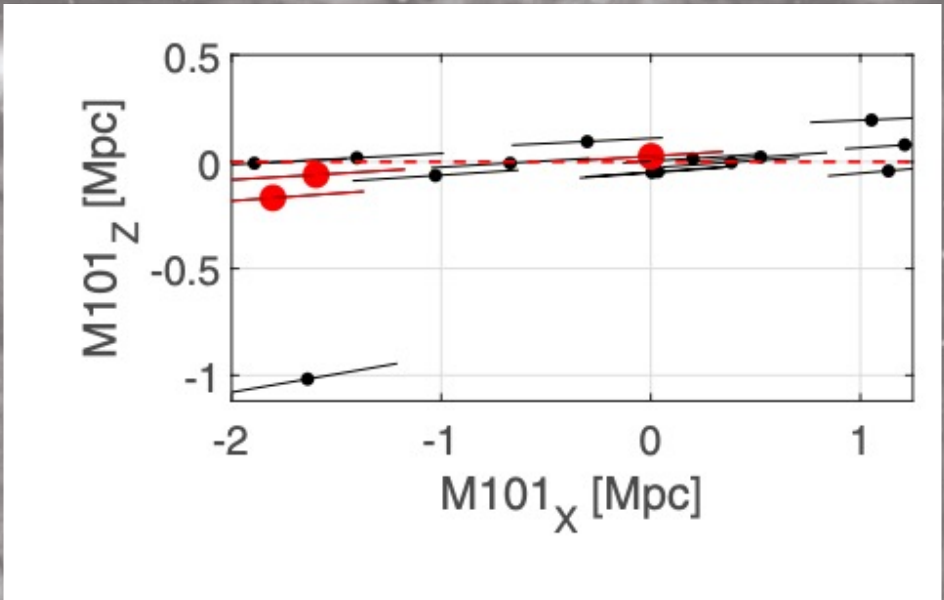
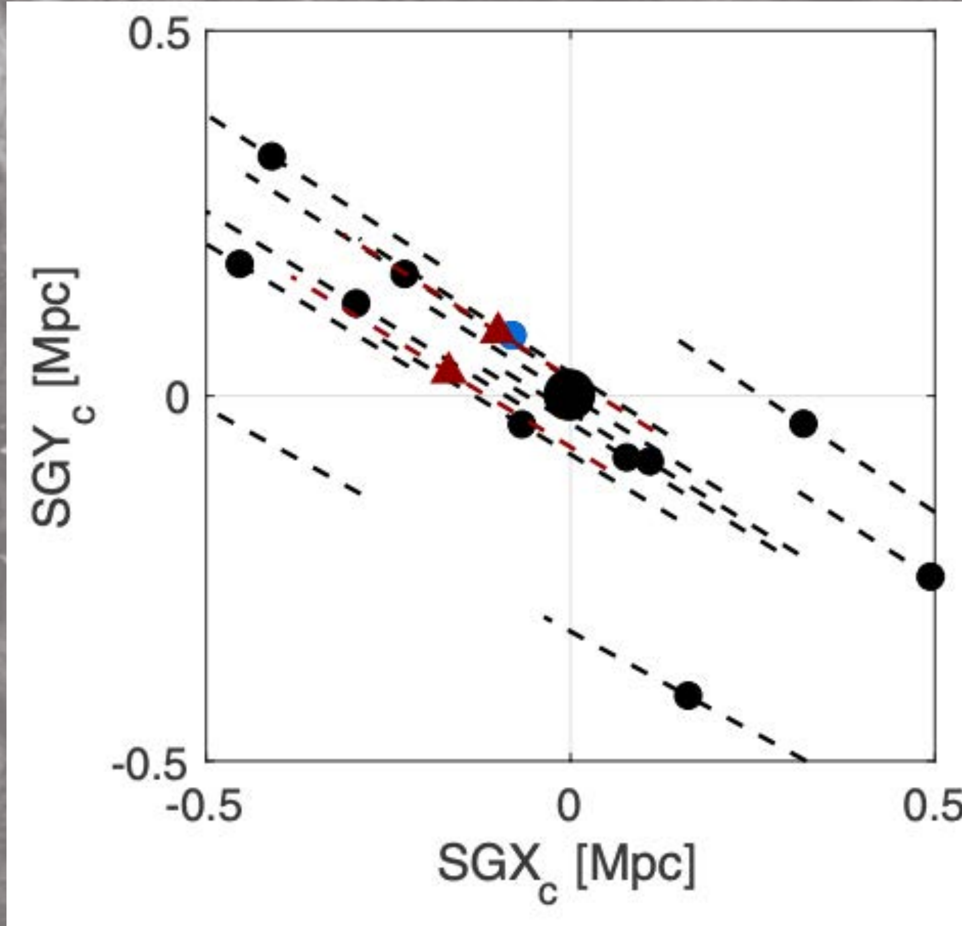


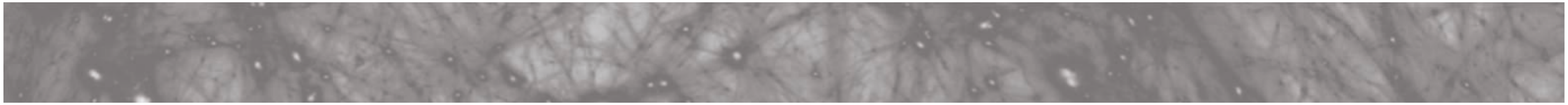
Fig. 7. 3D distribution, in supergalactic coordinates, of all galaxies with distance measurements in the surveyed M 101 group complex, centered at M 101. The red dots correspond to the major galaxies M 101, M 51, and M 63; the black dots indicate dwarf galaxies. The gray dots (shadows) appearing on the SGXSGZ– and SGYSGZ–walls are orthogonal projections. The best-fitting plane through the M 101 subgroup is shown as the gray plane and has a rms of only 46 kpc. The line of sight between the Milky Way and M 101 is indicated by the thick black line pointing downwards.

Müller *et al* 2017



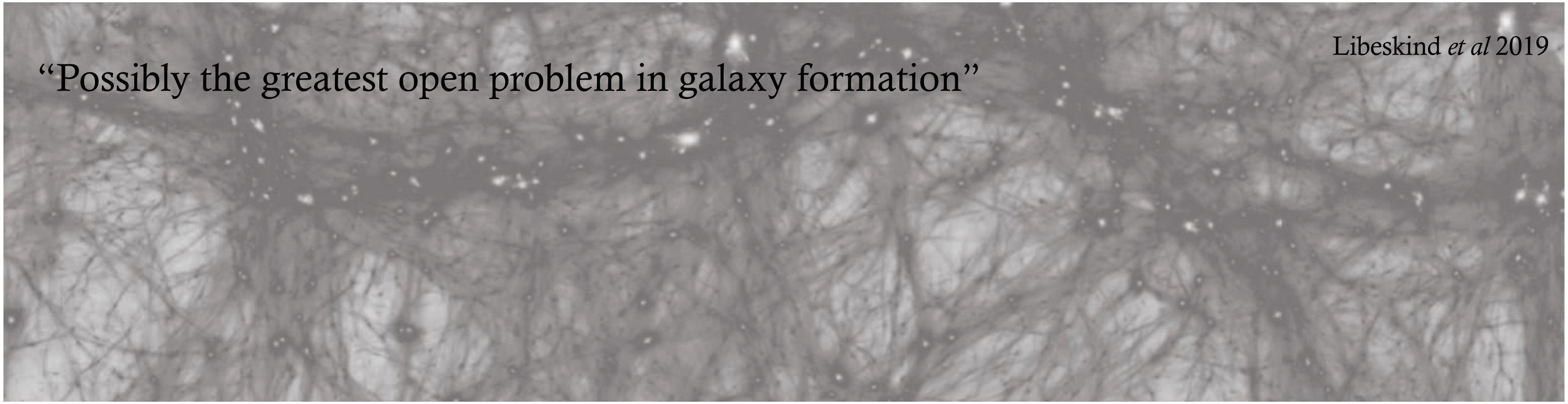


Müller *et al* 2018



Structure	$\hat{n}_x$	$\hat{n}_y$	$\hat{n}_z$	SG_x	SG_y	SG_z	Δ	c/a	$\sigma_{\hat{n}}$	Ref.
MW	0.532	-0.306	-0.789	0.000	0.000	0.000	19.9 ± 0.3	0.209 ± 0.002	0.43^o	[1]
$M31_{P1}$	-0.339	-0.234	0.912	0.688	-0.303	0.167	13.6 ± 0.2	0.107 ± 0.005	0.79^o	[1]
$M31_{P2}$	-0.108	-0.411	0.905	0.688	-0.303	0.167	11.5	0.15	N/P	[2]
$CenA_{P1}$	-0.135	-0.442	0.886	-3.410	1.260	-0.330	73	0.2109 ± 0.004	2^o	[3]
$CenA_{P2}$	0.079	0.323	-0.943	-3.410	1.260	-0.330	46	0.184 ± 0.004	2^o	[3]
M101	0.629	-0.023	-0.778	2.855	5.746	2.672	46	0.03	1.5^o	[4]
M83	-0.654	-0.724	0.221	-4.152	2.601	0.085	20.4	0.097	N/P	[5]
LG_{P1}	0.112	-0.278	-0.954	0.186	-0.188	-0.109	54.8 ± 1.8	0.077 ± 0.003	0.41^o	[1]
LG_{P2}	-0.155	-0.729	-0.667	0.148	-0.409	0.610	65.5 ± 3.1	0.110 ± 0.004	1.72^o	[1]
GNP	0.423	-0.438	-0.793	-0.050	0.873	-0.700	53.4 ± 1.5	0.098 ± 0.004	0.6^o	[6]

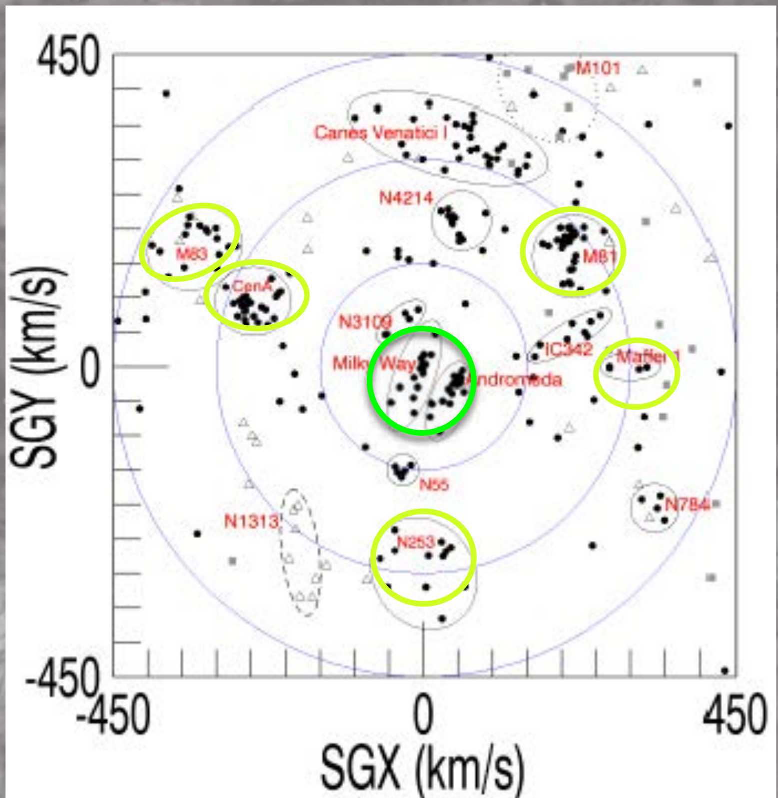
Table 1. Properties of the 10 planar structures examined in this paper. From left to right we present the name of the planar structure (or the name of the galaxy around which it is found); the x, y, z directions, in supergalactic coordinates of the unit normal, $\hat{n}_i$, to the plane; the x, y, z positions in supergalactic coordinates of the centroids, SG_i, of each plane (in units of Mpc); the rms thickness Δ, of the planar structure (in kpc); the ratio of the short to long axis, c/a of the identified planar structure; and the error on the published normal direction ($\sigma_{\hat{n}}$), N/P means that no error was published on this normal. References for these are: [1] Pawlowski et al. 2013, [2] Shaya & Tully 2013, [3] Tully et al. 2015, [4] Müller et al. 2017, [5] Müller et al. 2018, [6] Pawlowski & McGaugh 2014

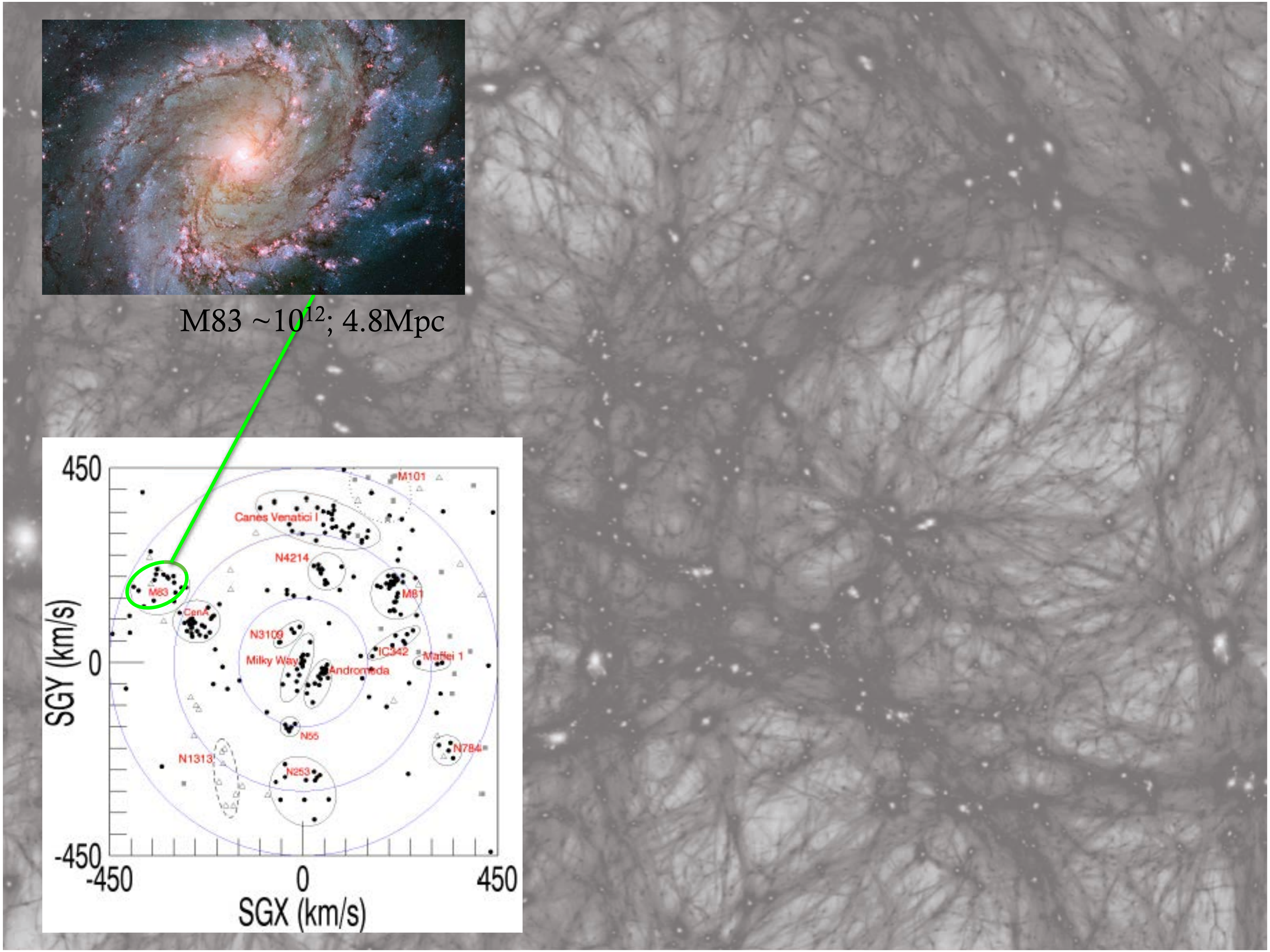


Libeskind *et al* 2019

“Possibly the greatest open problem in galaxy formation”

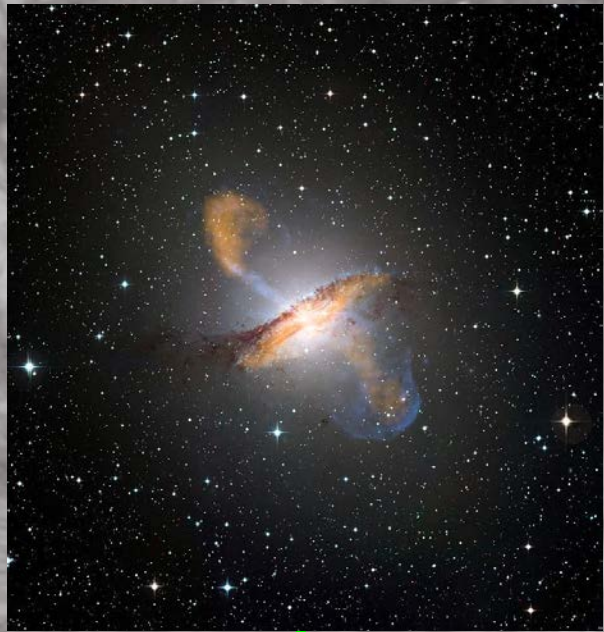
The Local Group ~ $5x10^{12}$
M31/MW~ [0.5 - 2]



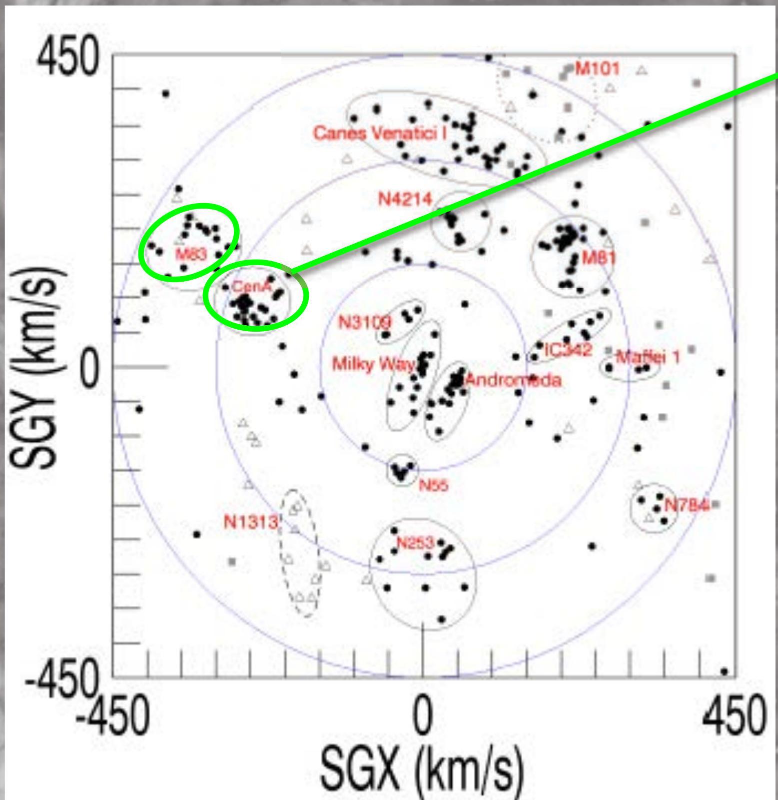


M83 ~10^{12}; 4.8Mpc

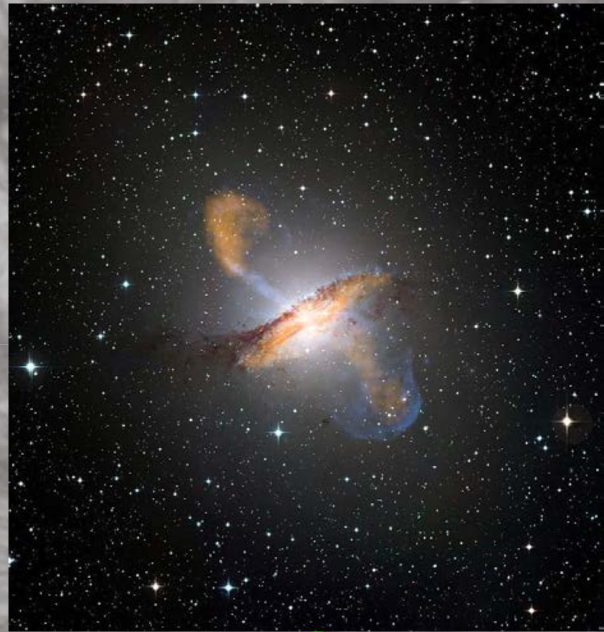
M83 ~10^{12}; 4.8Mpc



Cen A ~$3x10^{13}$; 3.8Mpc

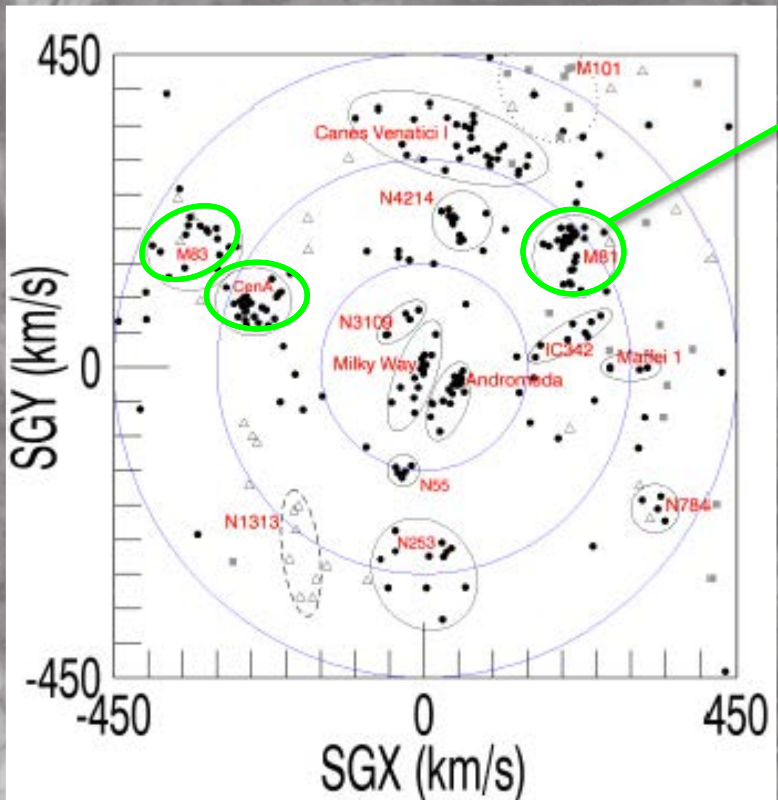


M83 ~10^{12}; 4.8Mpc

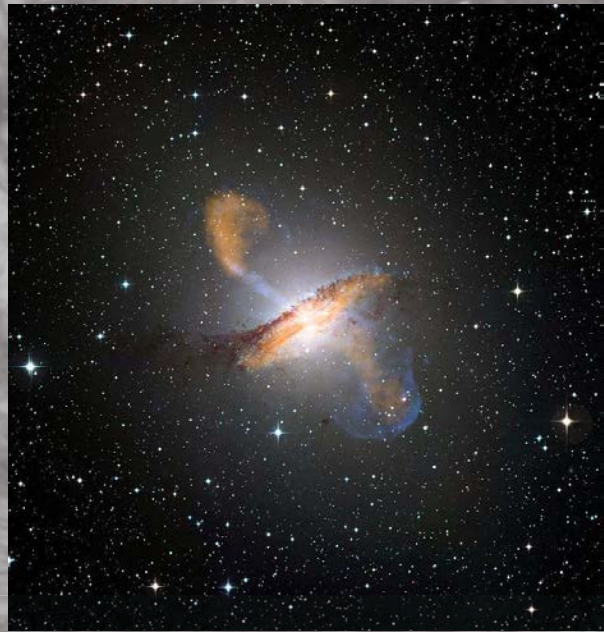


Cen A ~$3x10^{13}$; 3.8Mpc

M81~$3x10^{12}$; 3.6Mpc



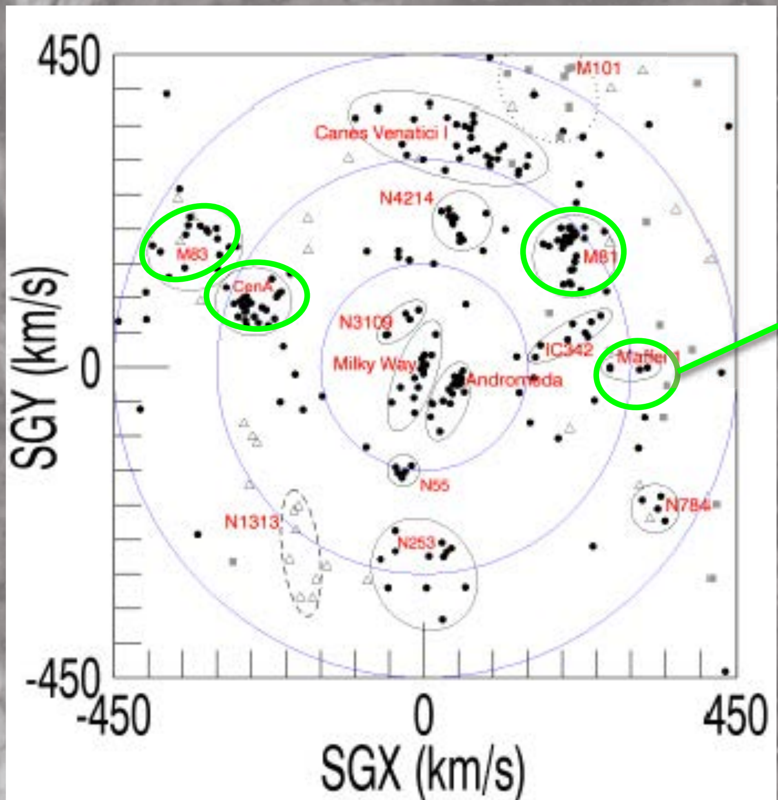
M83 ~10^{12}; 4.8Mpc



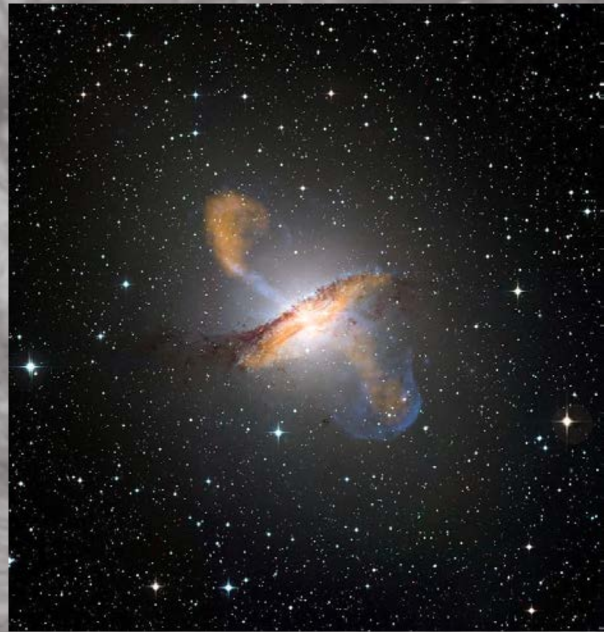
Cen A ~$3x10^{13}$; 3.8Mpc

M81~$3x10^{12}$;
3.6Mpc

Maffei-1 in ZOA ~10^{12}; 2.5-4Mpc



M83 ~10^{12}; 4.8Mpc



Cen A ~3×10^{13}; 3.8Mpc

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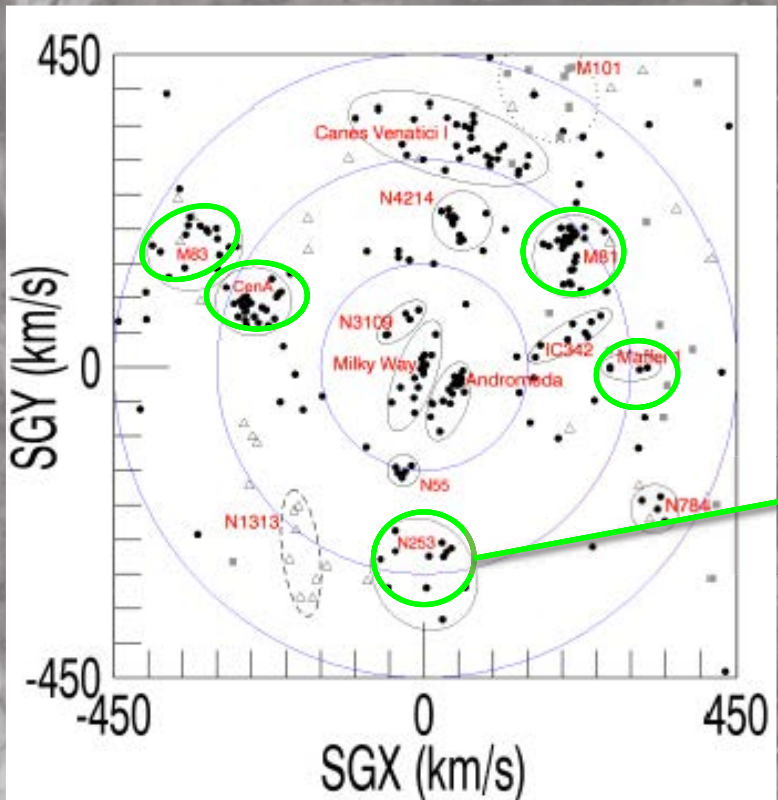
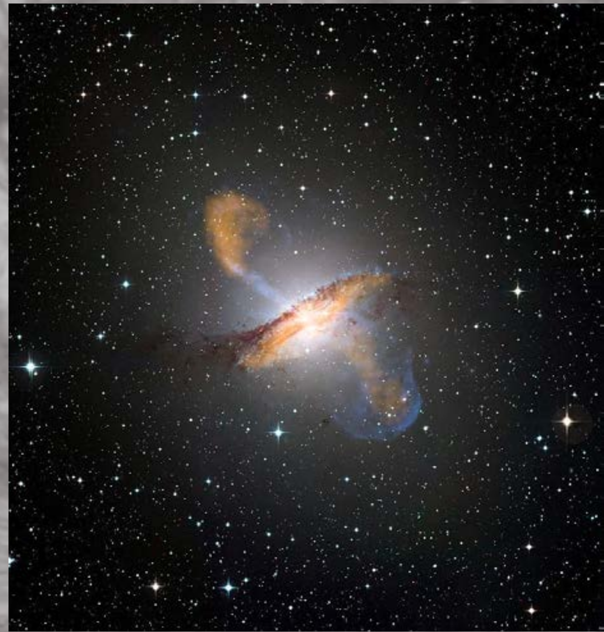
Maffei-1 in ZOA ~10^{12}; 2.5-4Mpc



NGC 253 ~10^{11}; 3.5Mpc

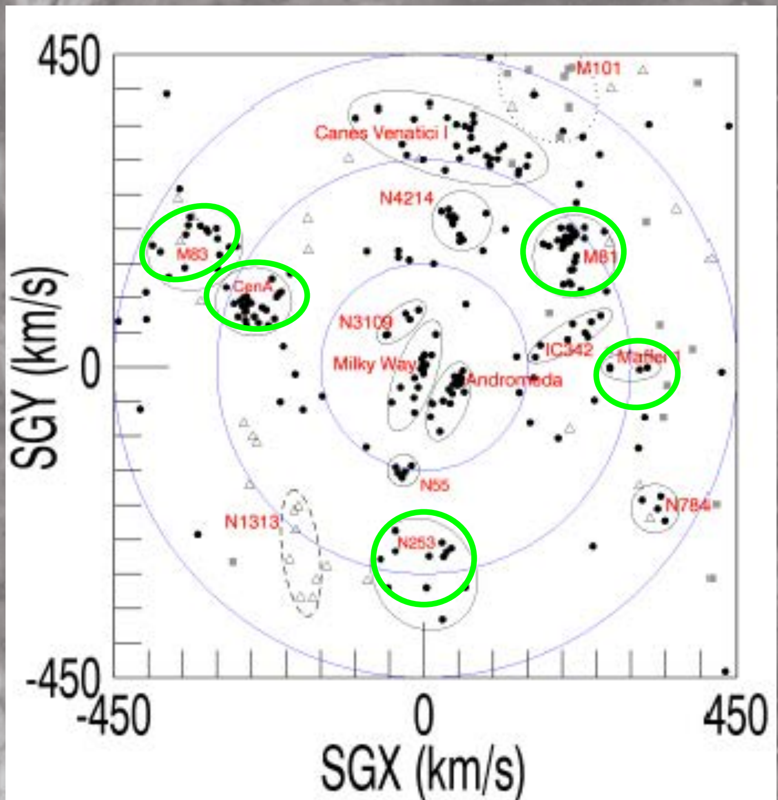
M83 ~10^{12}; 4.8Mpc



Cen A ~$3x10^{13}$; 3.8Mpc

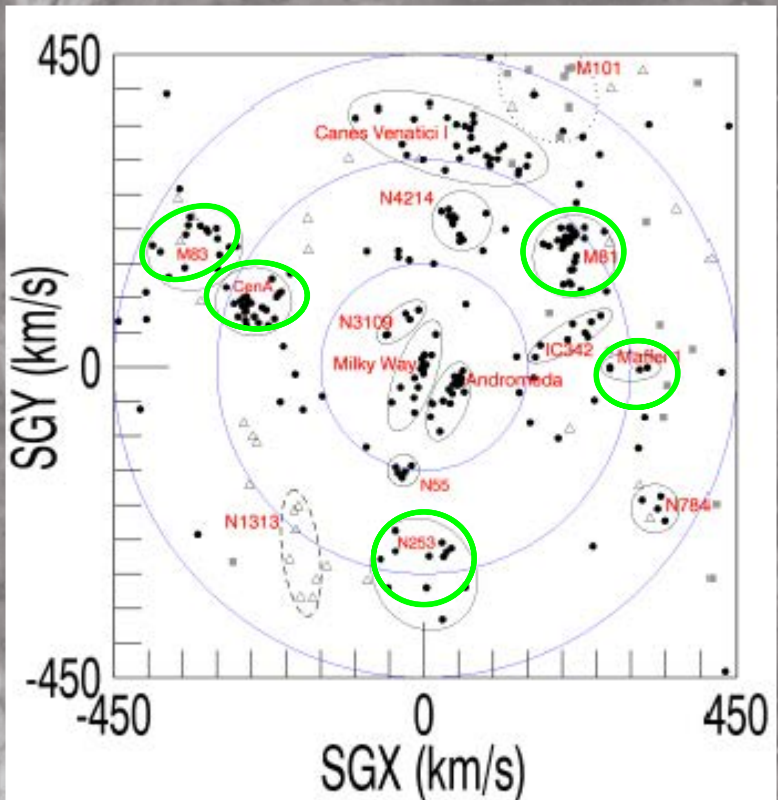
M81~$3x10^{12}$; 3.6Mpc

Maffei-1 in ZOA ~10^{12}; 2.5-4Mpc



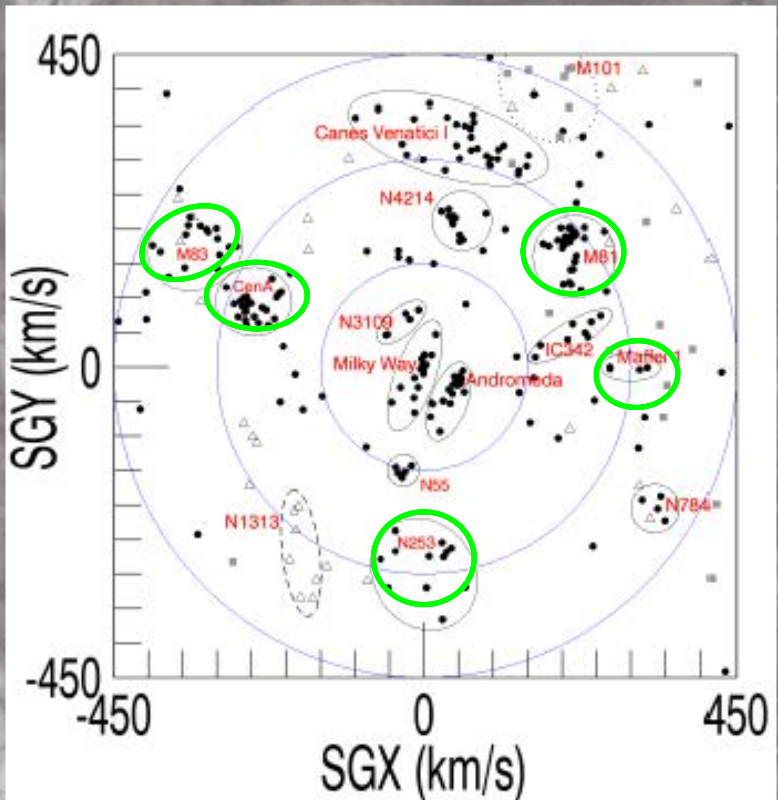
NGC 253 ~10^{11}; 3.5Mpc

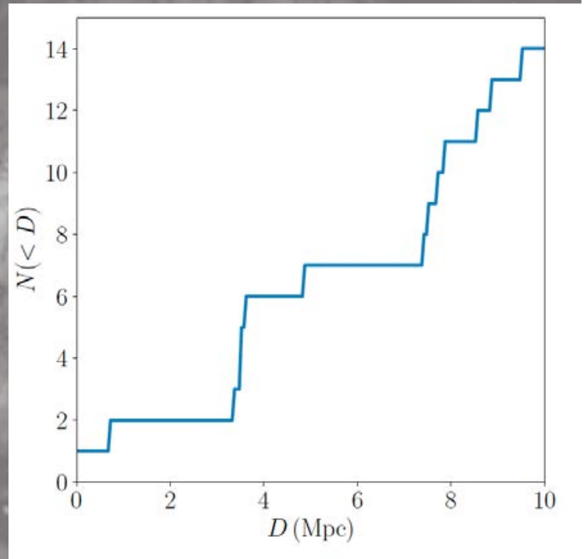
The ~10 giant galaxies at around 5Mpc from the Milky Way constitute the so-called "council of giants" – an odd toroidal arrangements with the MW and Local Group at its center

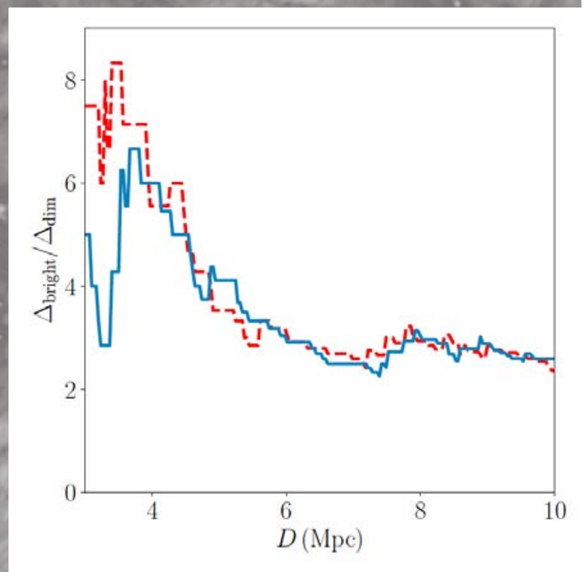


The ~10 giant galaxies at around 5Mpc from the Milky Way constitute the so-called "council of giants" – an odd toroidal arrangements with the MW and Local Group at its center

Neuzil et al
McCall et al







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Neuzil et al
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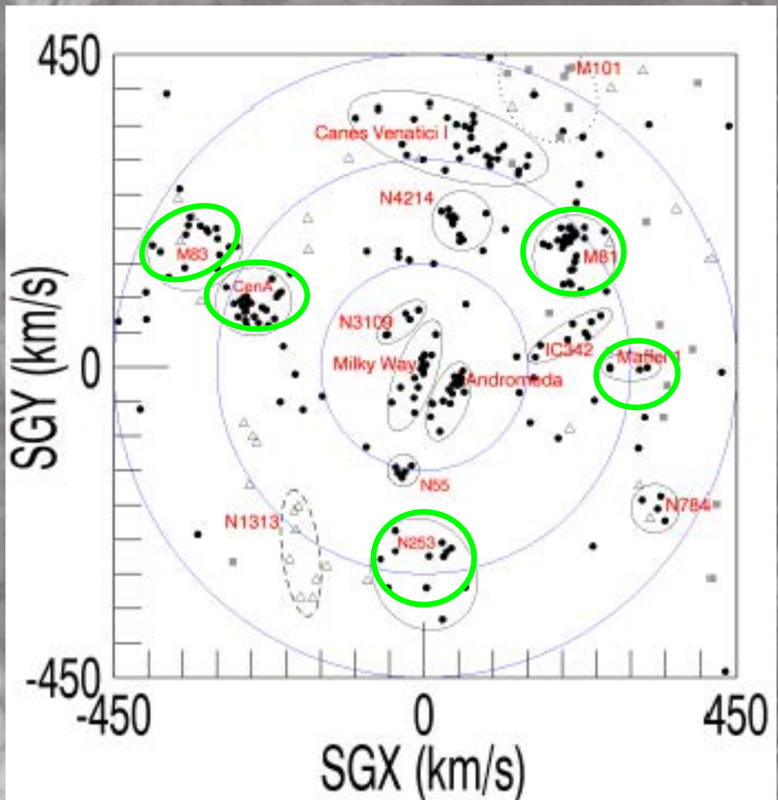

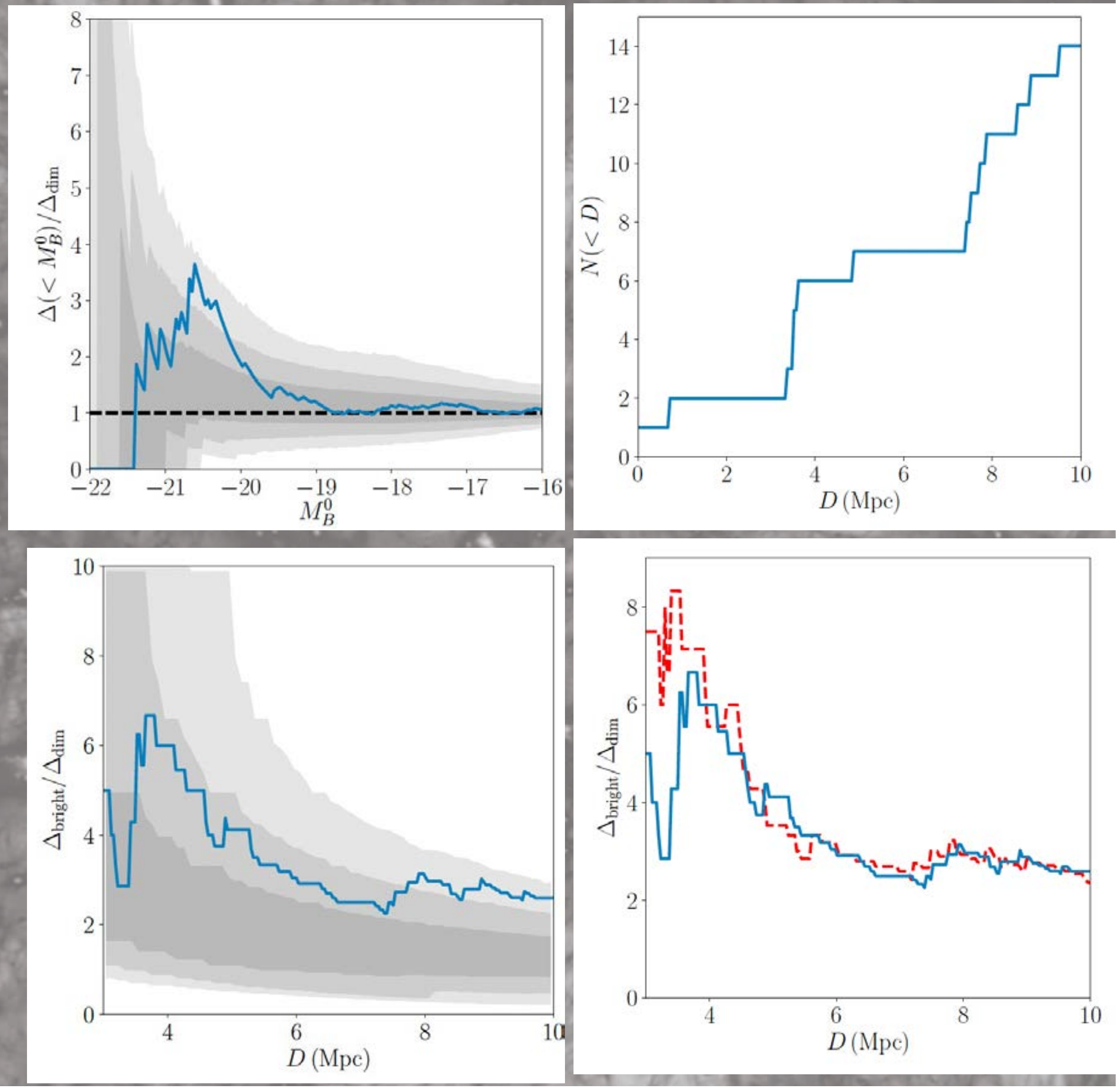

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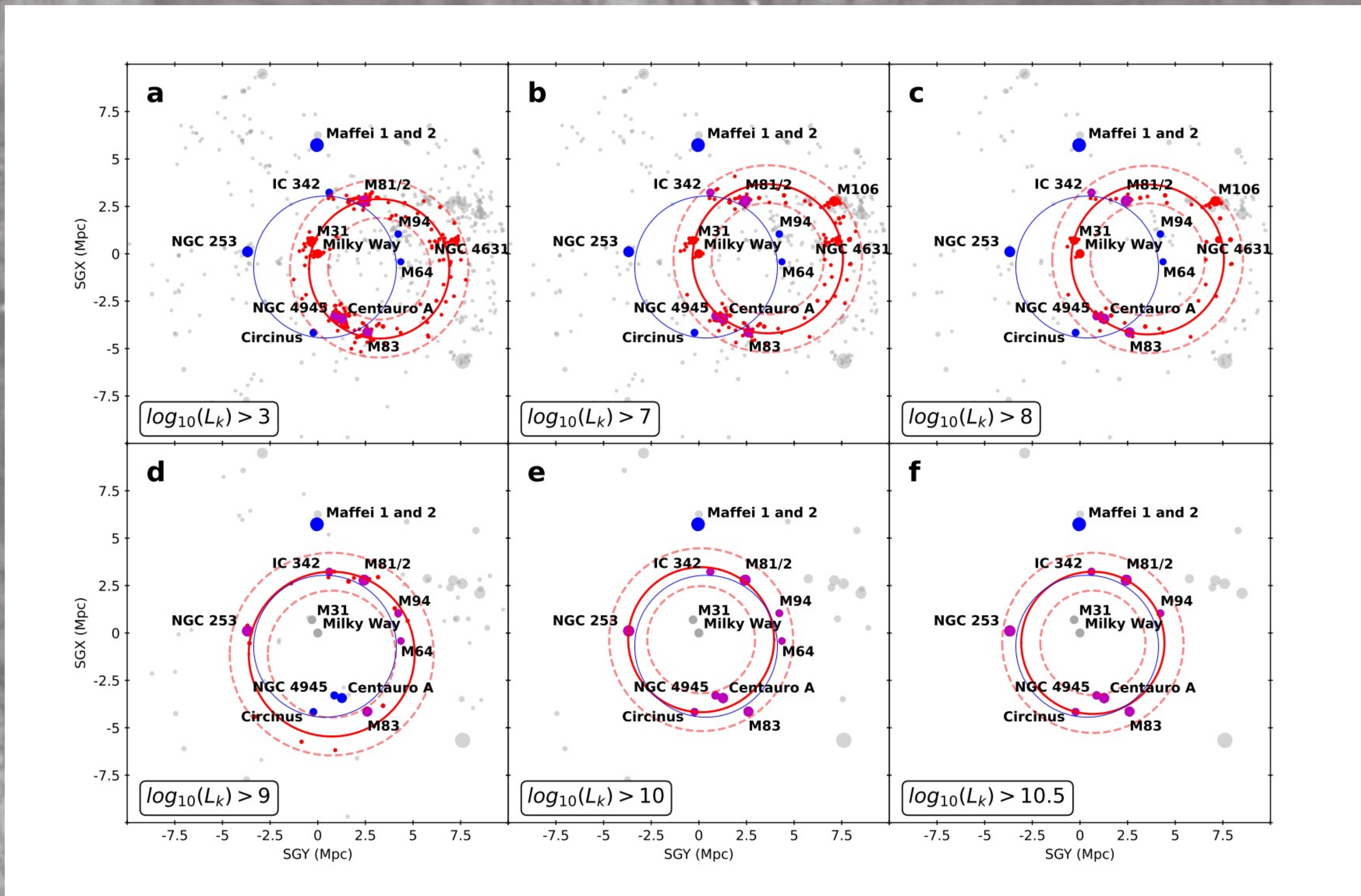
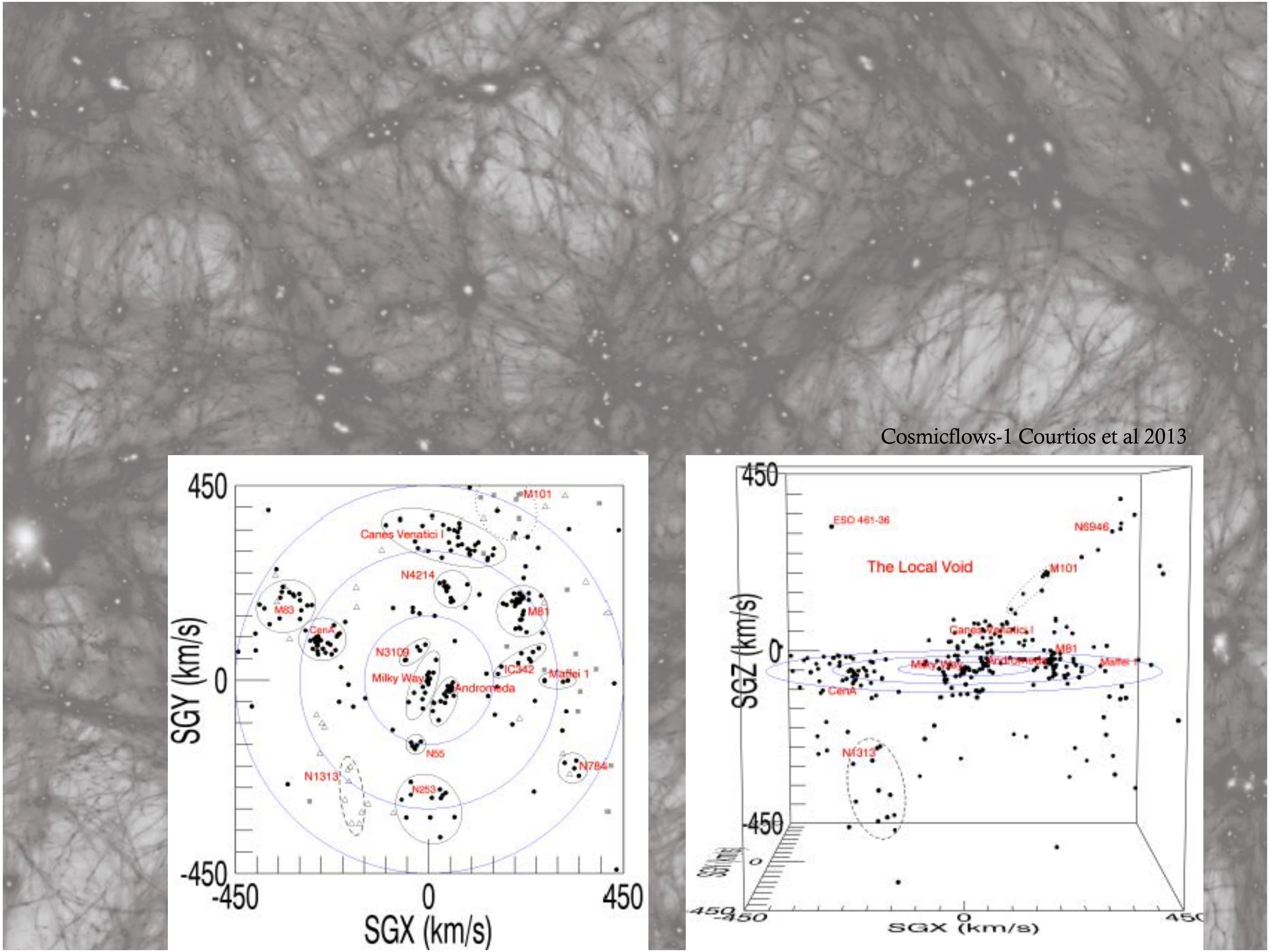


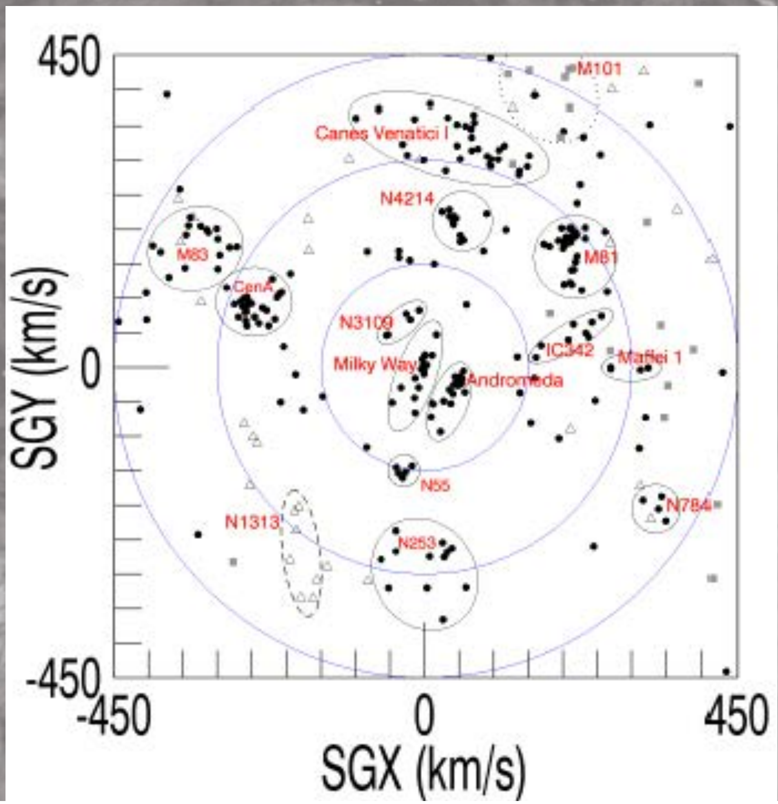
Olex +NL et al 2023

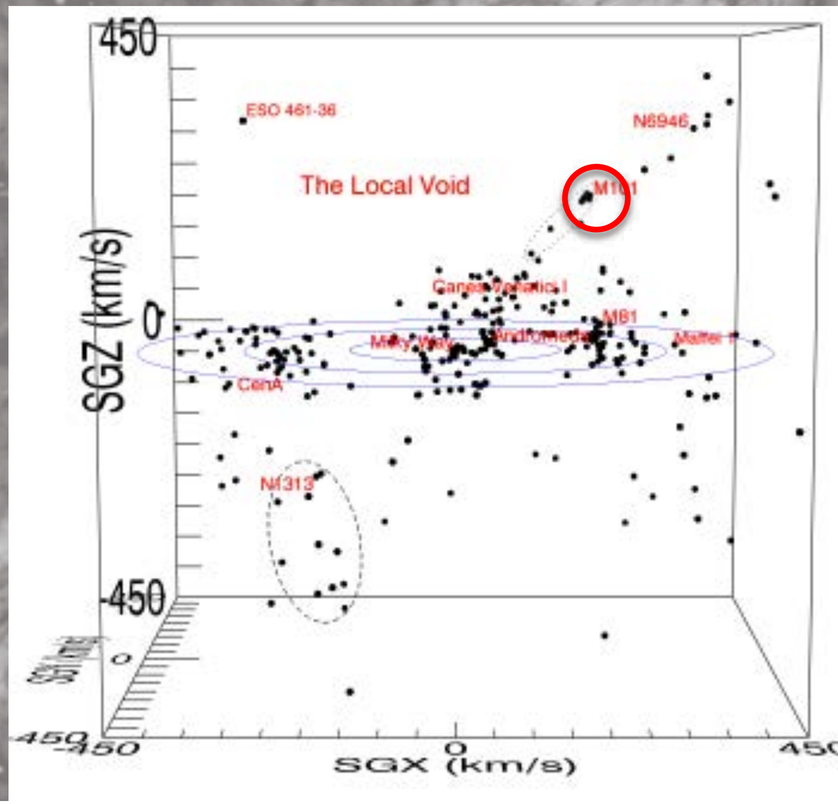


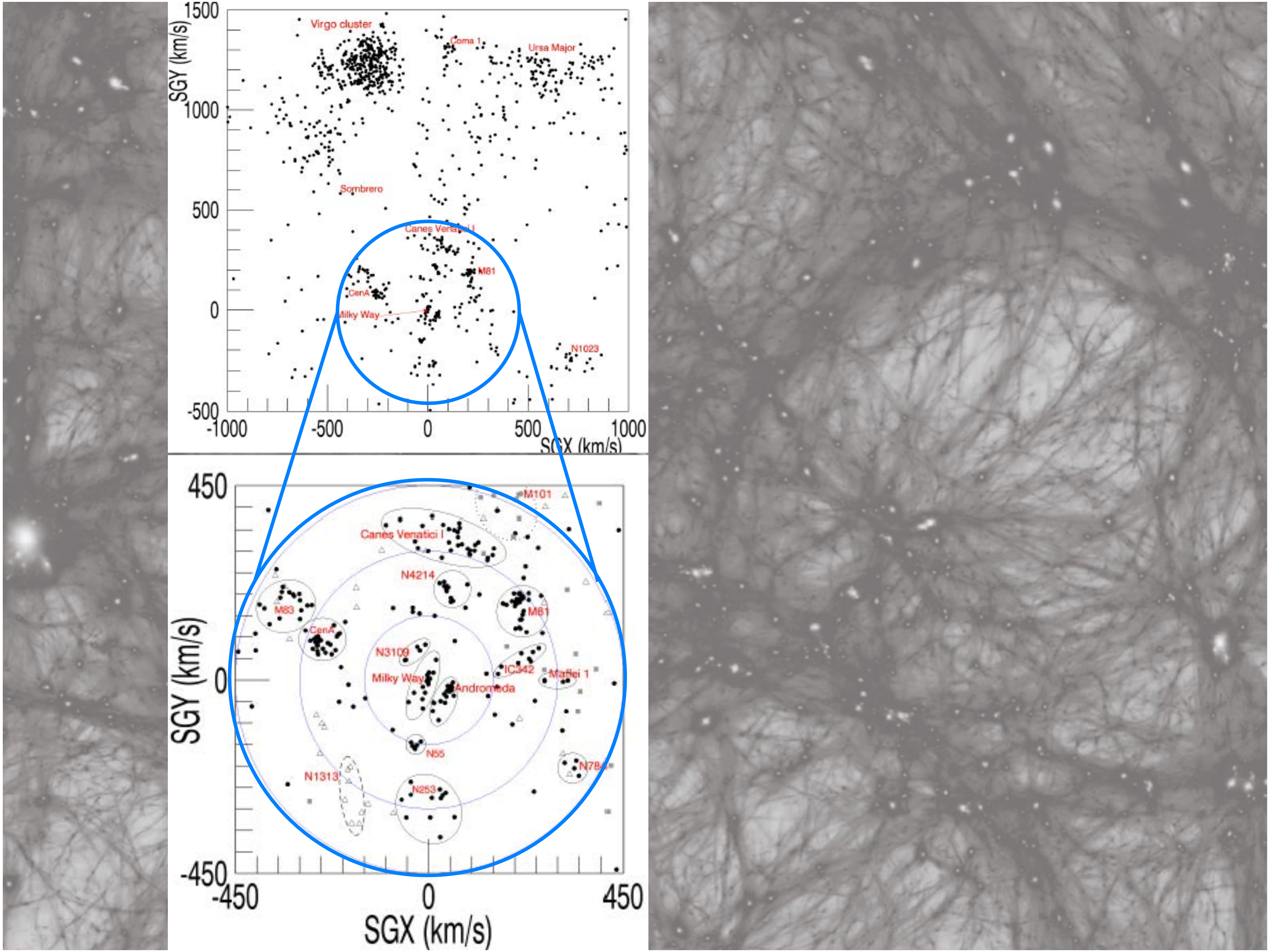
Cosmicflows-1 Courtios et al 2013

M101, “Pinwheel”

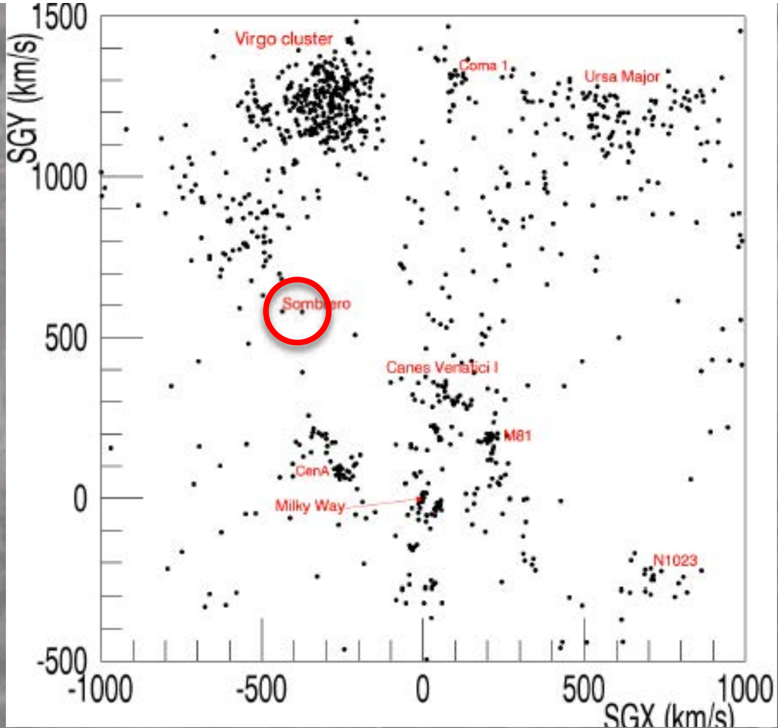
Cosmicflows-1 Courtios et al 2013







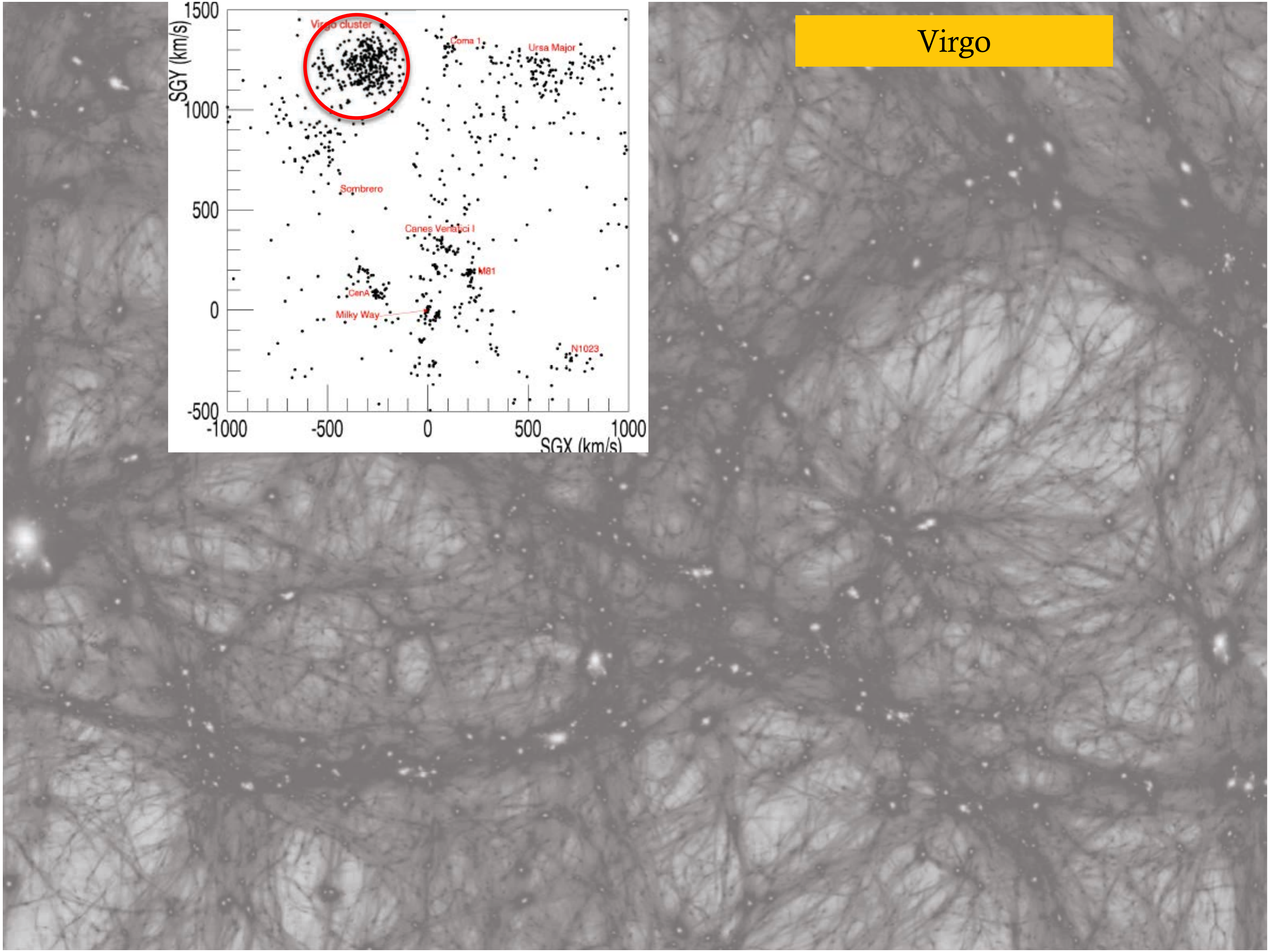
SGY (km/s)
SGX (km/s)
Virgo cluster
Coma 1
Ursa Major
Sombrero
Canes Venatici I
M81
CenA
Milky Way
N1023
-1000
-500
0
500
1000
1500
-500
M101
N4214
M83
N3109
IC342
Maffei 1
Andromeda
N55
N784
N1313
N253
450
-450

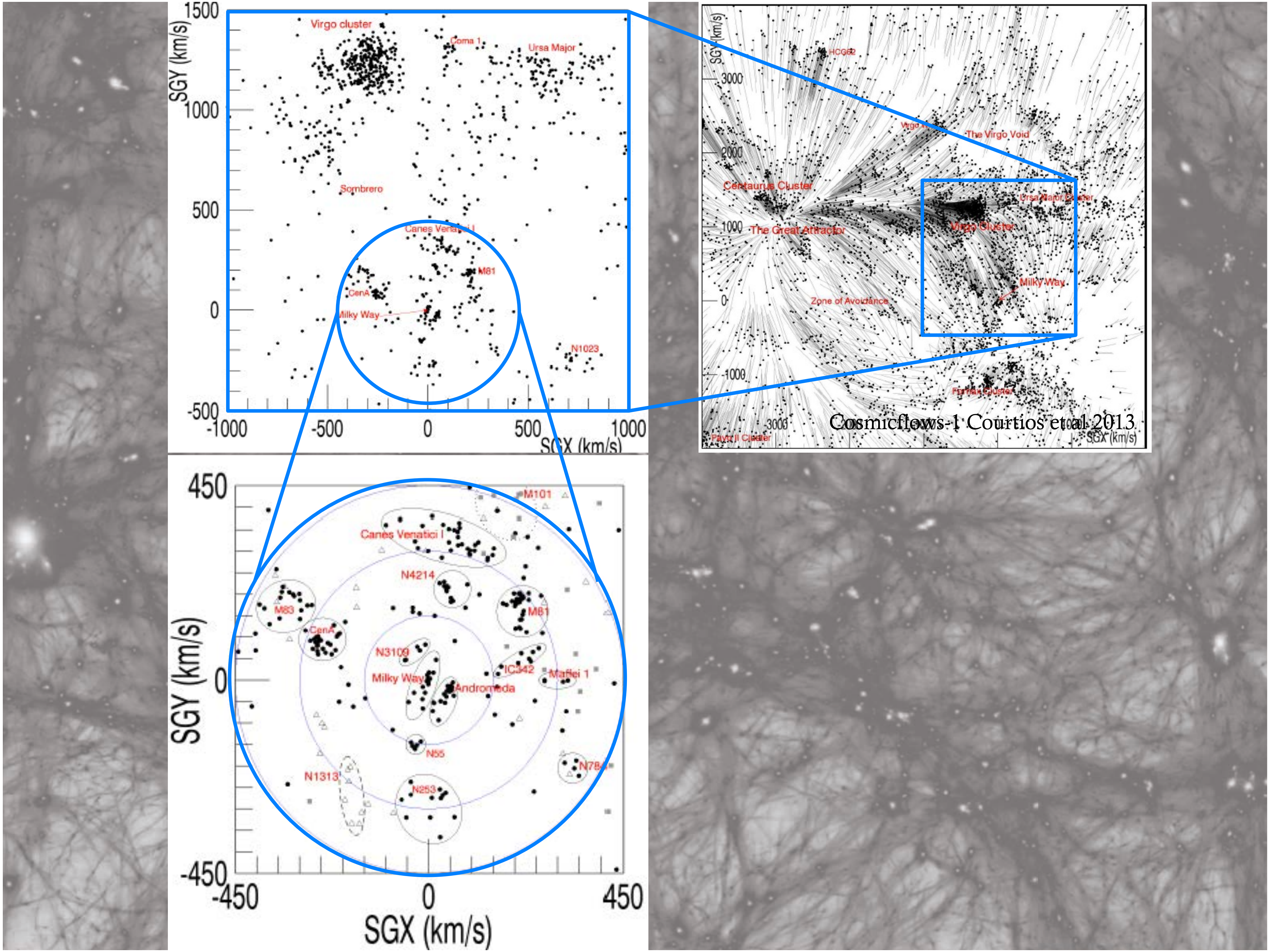


SGY (km/s)
SGX (km/s)
1500
1000
500
0
-500
-1000
-500
0
500
1000
Virgo cluster
Coma 1
Ursa Major
Sombrero
Canes Venatici I
M81
CenA
Milky Way
N1023

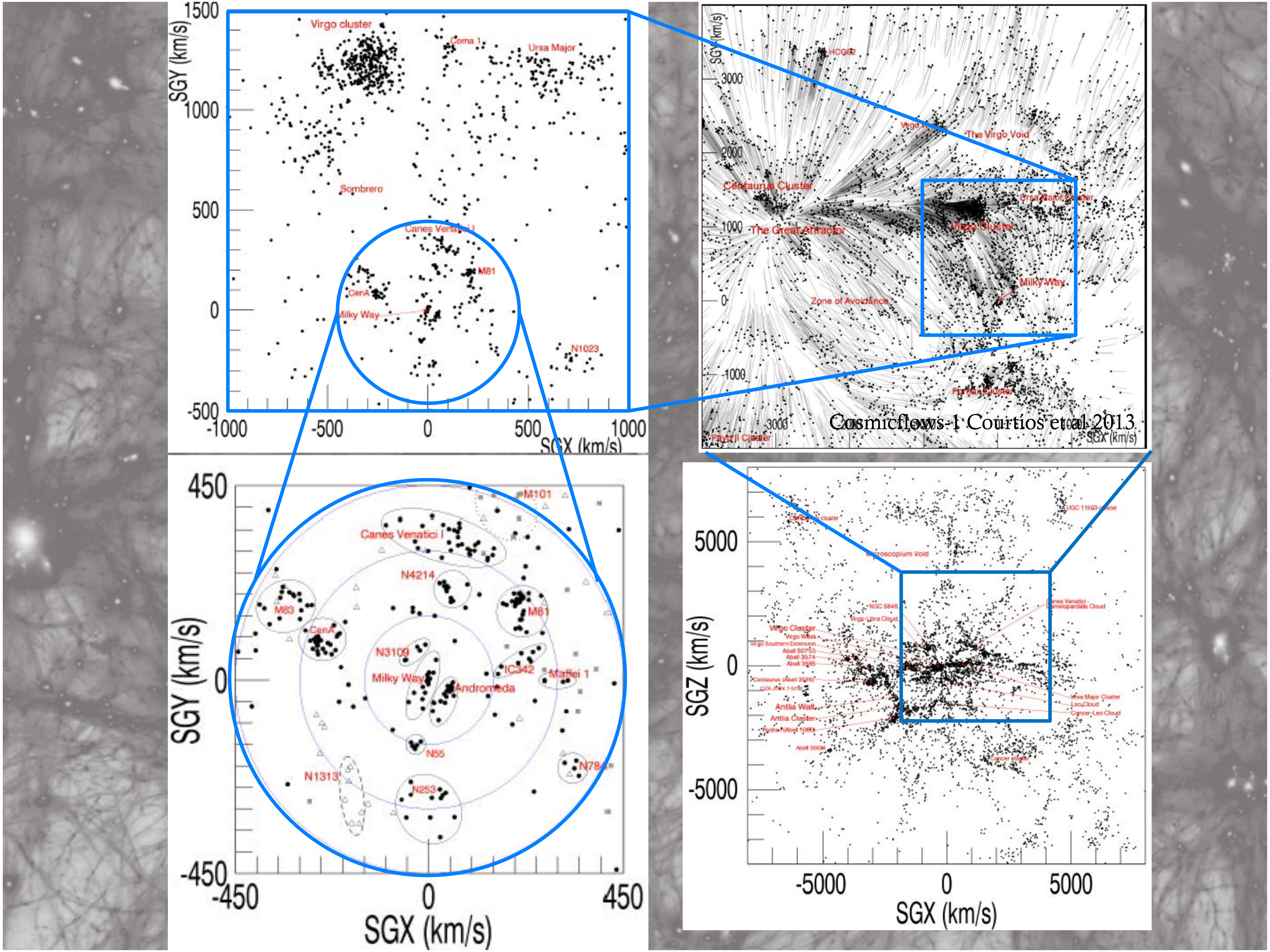
Sombrero

Virgo

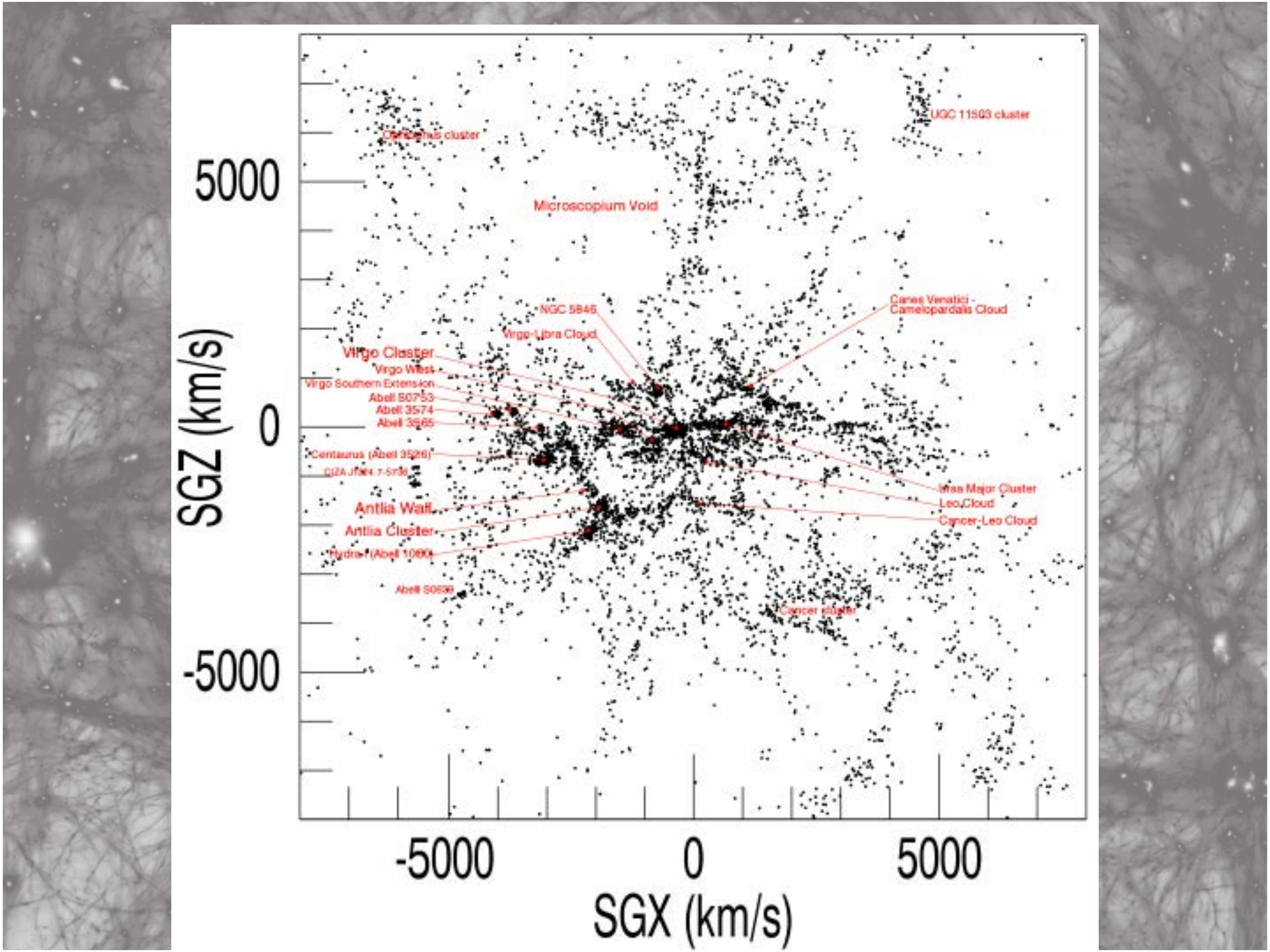

Virgo cluster
Coma 1
Ursa Major
Sombrero
Canes Venatici I
M81
CenA
Milky Way
N1023
SGY (km/s)
SGX (km/s)
1500
1000
500
0
-500
-1000
-500
0
500
1000

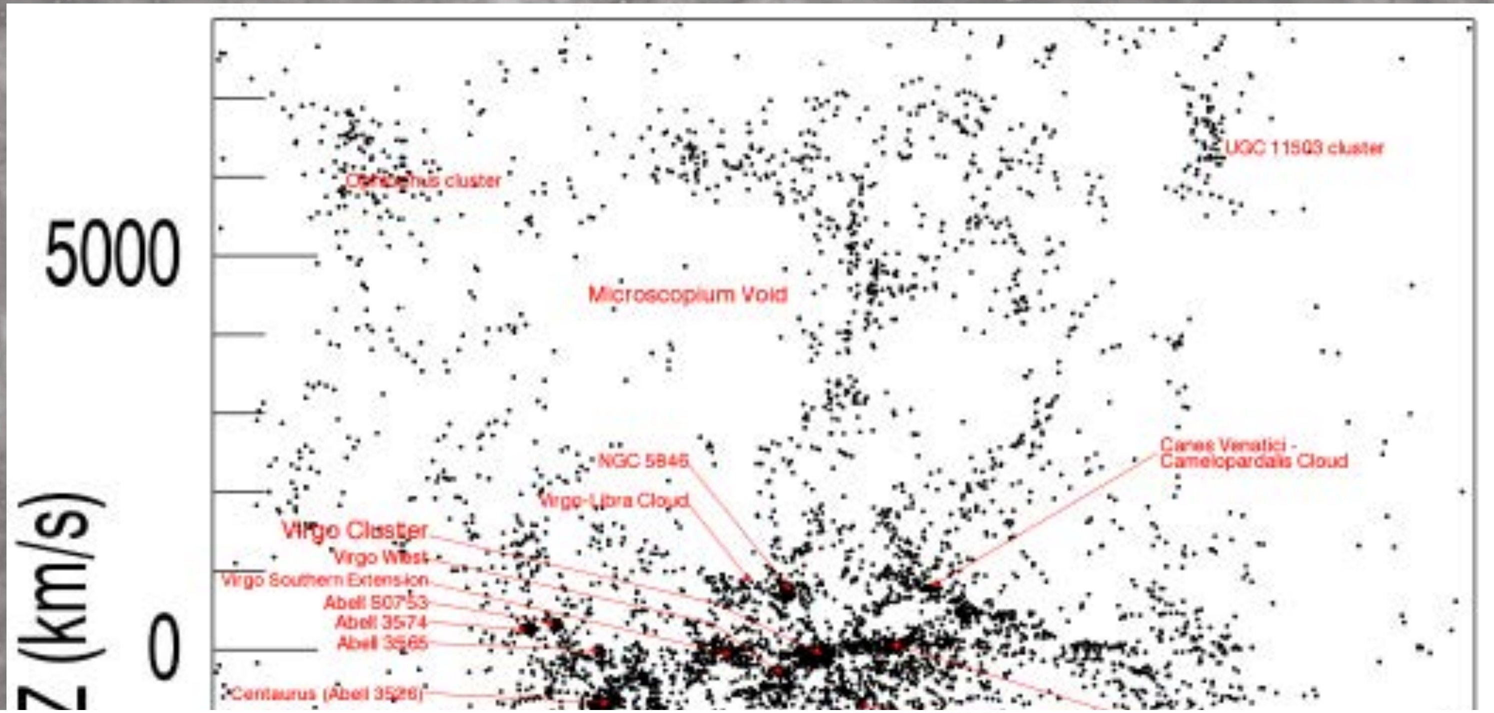


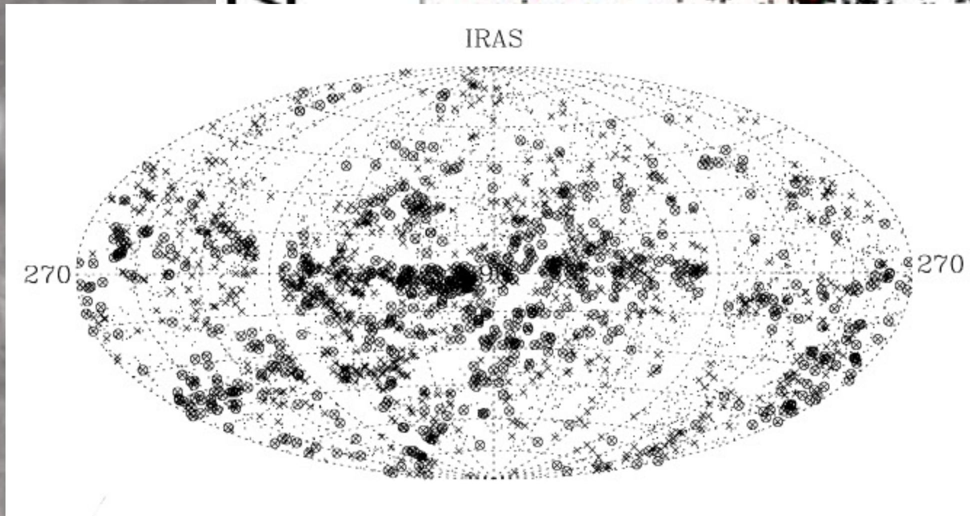
Virgo cluster
Coma 1
Ursa Major
Sombrero
Canes Venatici I
M81
CenA
Milky Way
N1023
SGY (km/s)
SGX (km/s)
HCG62
The Virgo Void
Centaurus Cluster
The Great Attractor
Virgo Cluster
Milky Way
Zone of Avoidance
Cosmicflows-1 Courtios et al 2013
M101
N4214
M83
N3109
Andromeda
IC342
Maffei 1
N55
N1313
N253

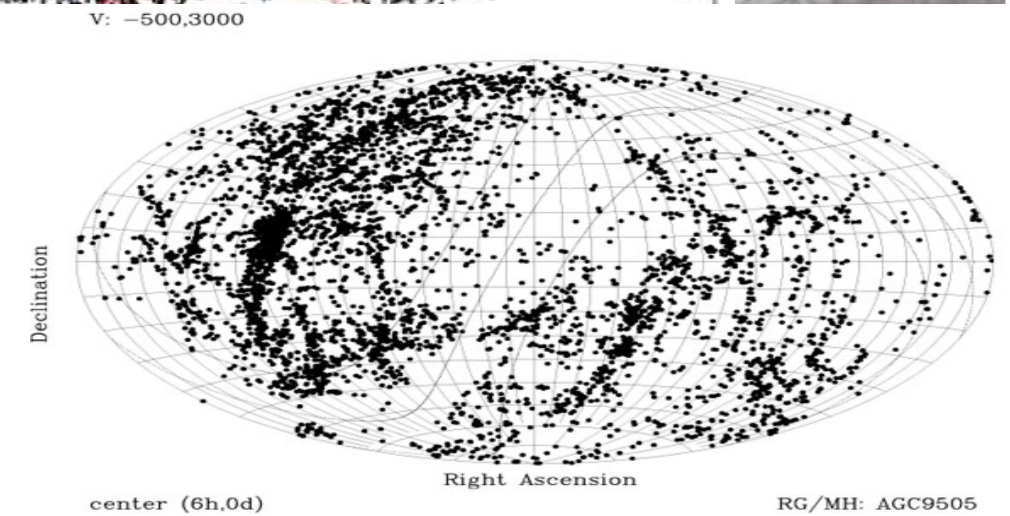


Virgo cluster
Coma 1
Ursa Major
Sombrero
Canes Venatici I
M81
CenA
Milky Way
N1023
SGY (km/s)
SGX (km/s)
Canes Venatici I
M101
N4214
M83
CenA
M81
N3109
Milky Way
Andromeda
IC342
Maffei 1
N55
N1313
N784
N253
HCG62
Virgo
The Virgo Void
Centaurus Cluster
Ursa Major Cluster
The Great Attractor
Virgo Cluster
Milky Way
Zone of Avoidance
Fornax Cluster
Pavo II Cluster
Cosmicflows-1 Courtios et al 2013
SGZ (km/s)
UGC 11503 cluster
Microscopium Void
NGC 5846
Virgo-Libra Cloud
Canes Venatici - Camelopardalis Cloud
Virgo Cluster
Virgo W
Virgo Southern Extension
Antlia Wall
Antlia Cluster
Ursa Major Cluster
Leo Cloud
Cancer-Leo Cloud


UGC 11503 cluster
Microscopium Void
NGC 5846
Virgo-Libra Cloud
Canes Venatici -
Camelopardalis Cloud
Virgo Cluster
Virgo West
Virgo Southern Extension
Abell S0753
Abell 3574
Abell 3565
Centaurus (Abell 3526)
Ursa Major Cluster
Leo Cloud
Cancer-Leo Cloud
Antlia Wall
Antlia Cluster
Hydra-I (Abell 1060)
Cancer cluster
5000
0
-5000
SGZ (km/s)
-5000
0
5000
SGX (km/s)







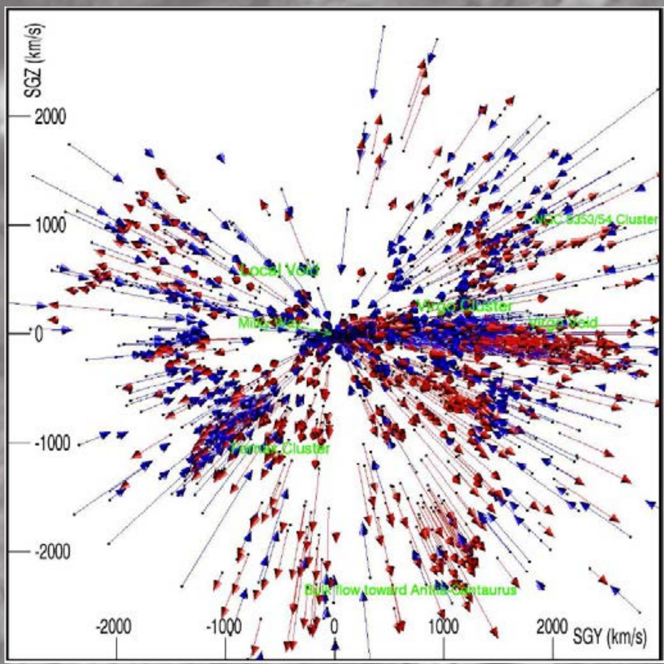
Supergalactic plane:
Lahav et al 2000
de Vaucouleurs 1953

Reconstructing the underlying matter distribution of the Local universe

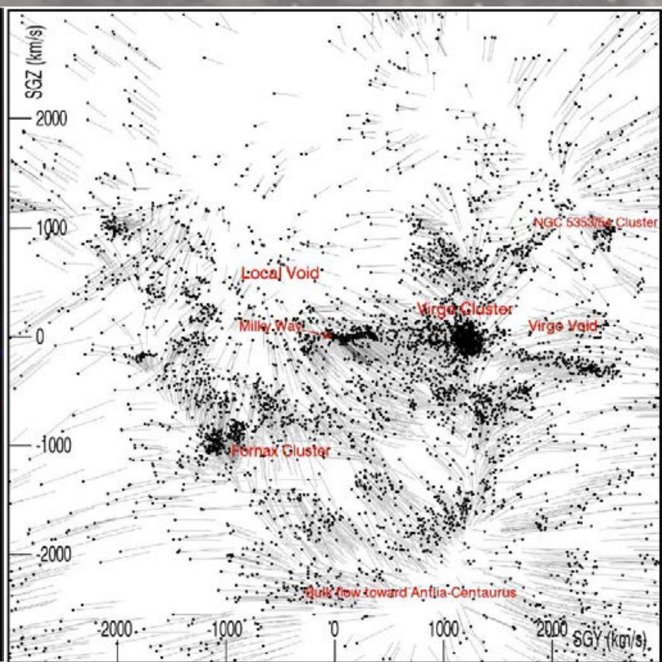
$$\rho \propto -\vec{\nabla} \cdot \vec{v}$$

In the linear regime there is a very simple relationship between density and peculiar velocity

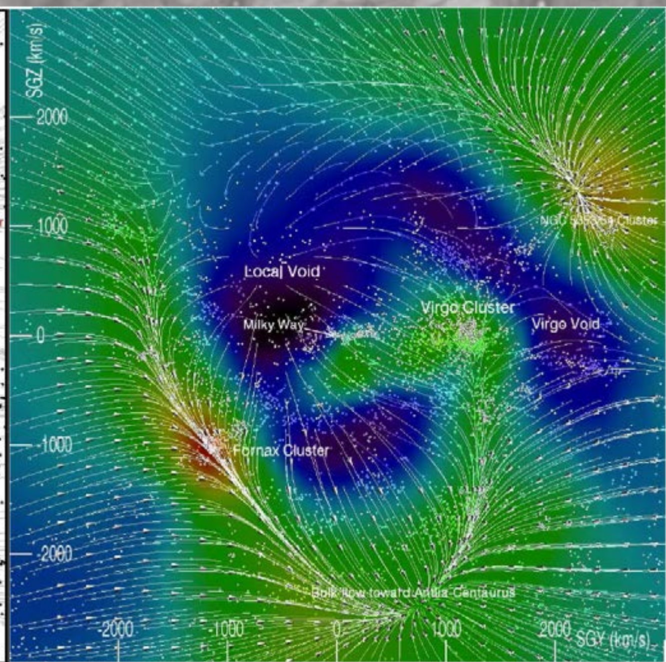
radial peculiar velocity



reconstructed 3D peculiar velocity



Corresponding 3D density field



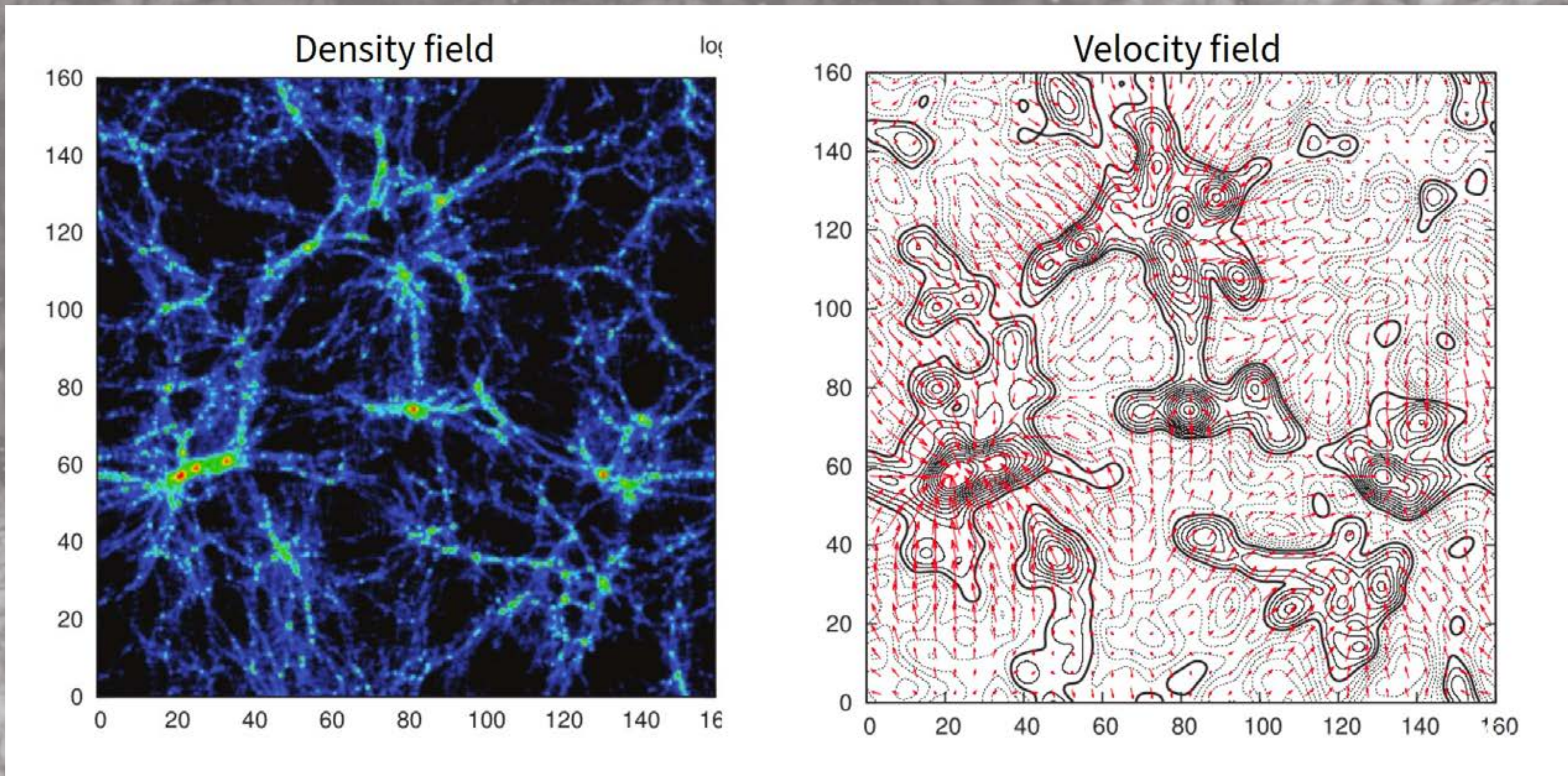
Courtois *et al* 2013

Zaroubi et al 1995

Reconstructing the underlying matter distribution of the Local universe

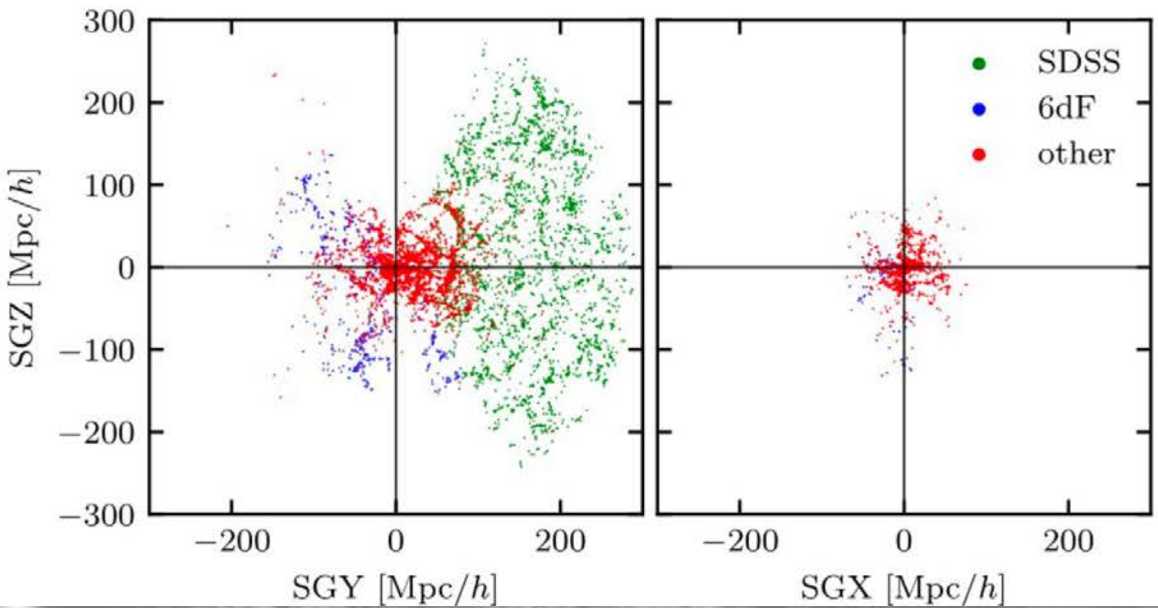
$$\delta = -H_0 f \nabla \cdot v$$

Its all based on the laminar flow, linear relationship between velocity and over-density



Doumler et al 2013

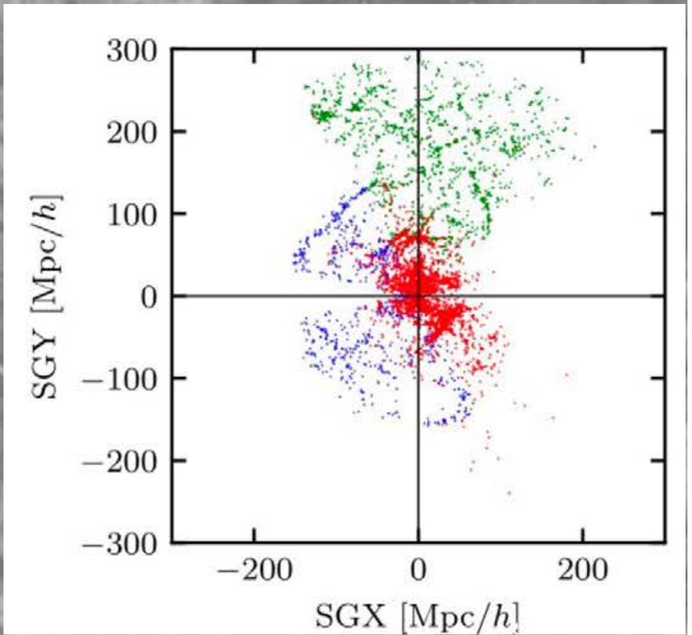
The data: CF4

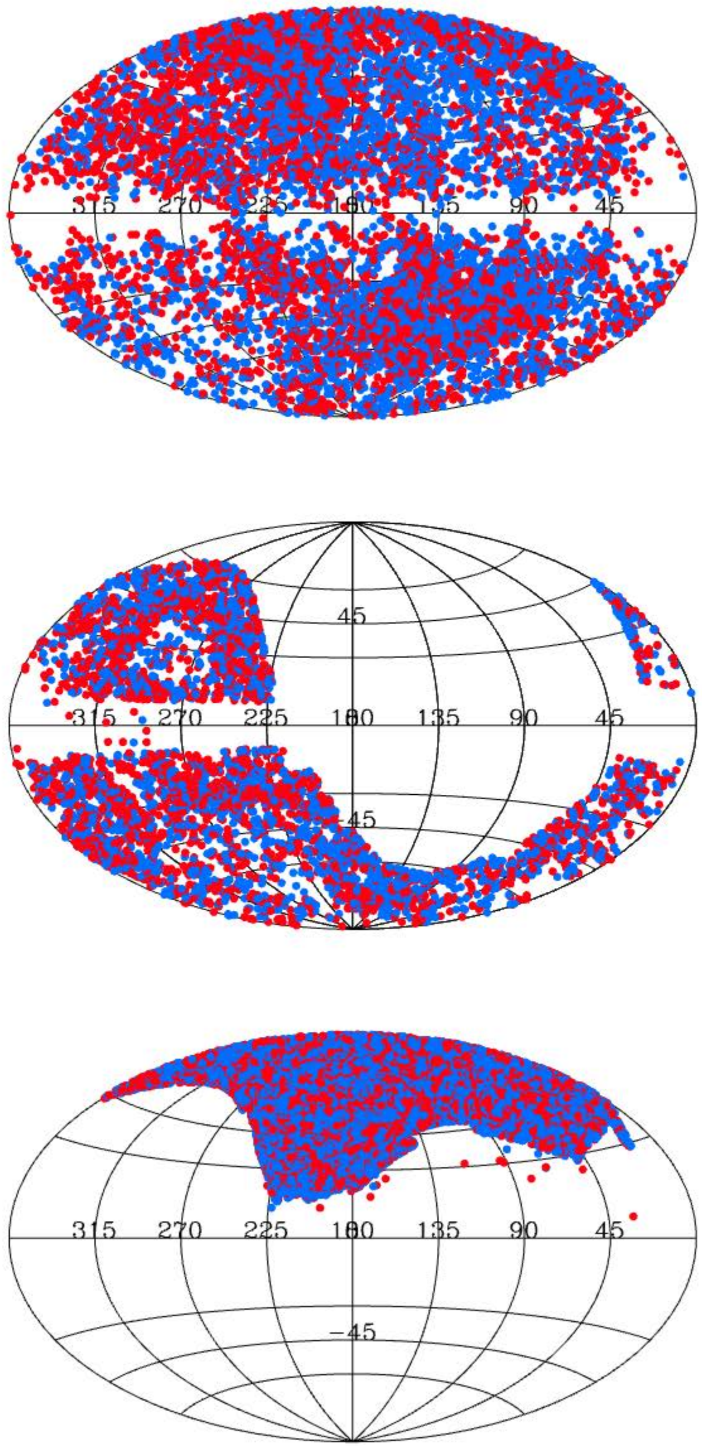


58,000 distances
38,000 groups

Mostly scaling relations but also *better* measures like SN, TRGB, SBF

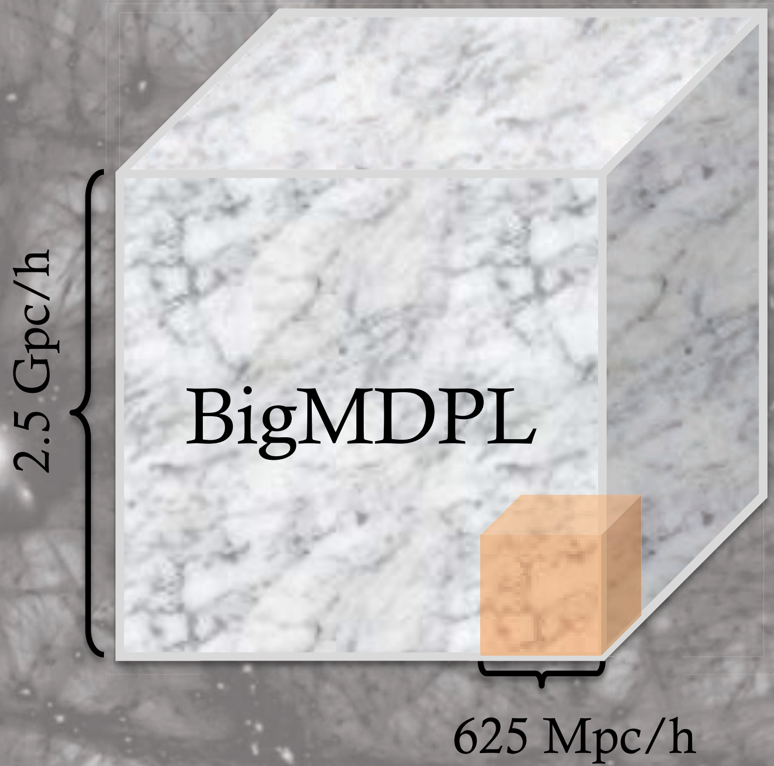
Tully et al 2023





How good are these reconstruction?

Take a simulation, make a mock, apply and check!

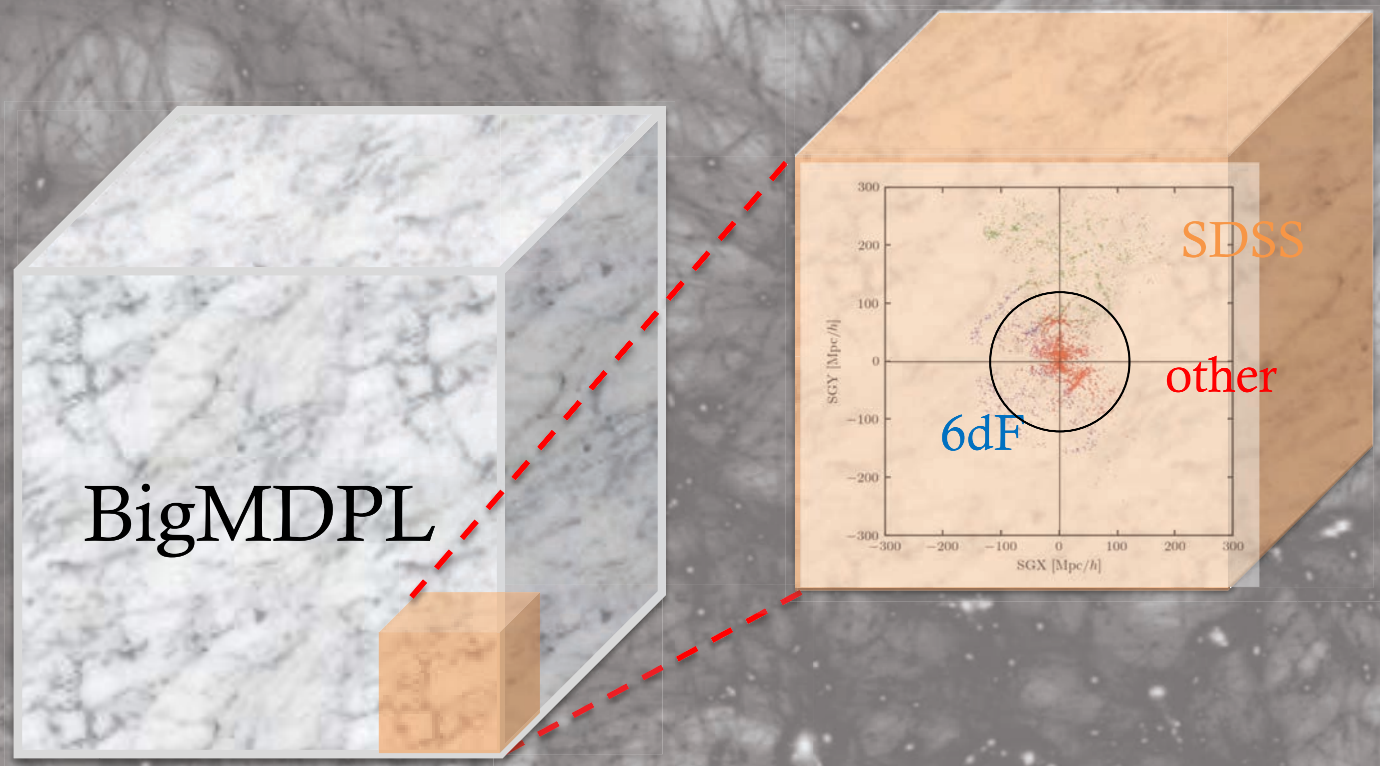


- The BigMultiDark Planck simulation
  - Box size: (2.5 Gpc/h)^3
  - N_particle: 3840^3
  - Mass_res: 2.359*10^10 Msun/h
  - N_halo: ~128M halos

Duangchan et al *in prep*

How good are these reconstruction?

Take a simulation, make a mock, apply and check!



Duangchan et al *in prep*

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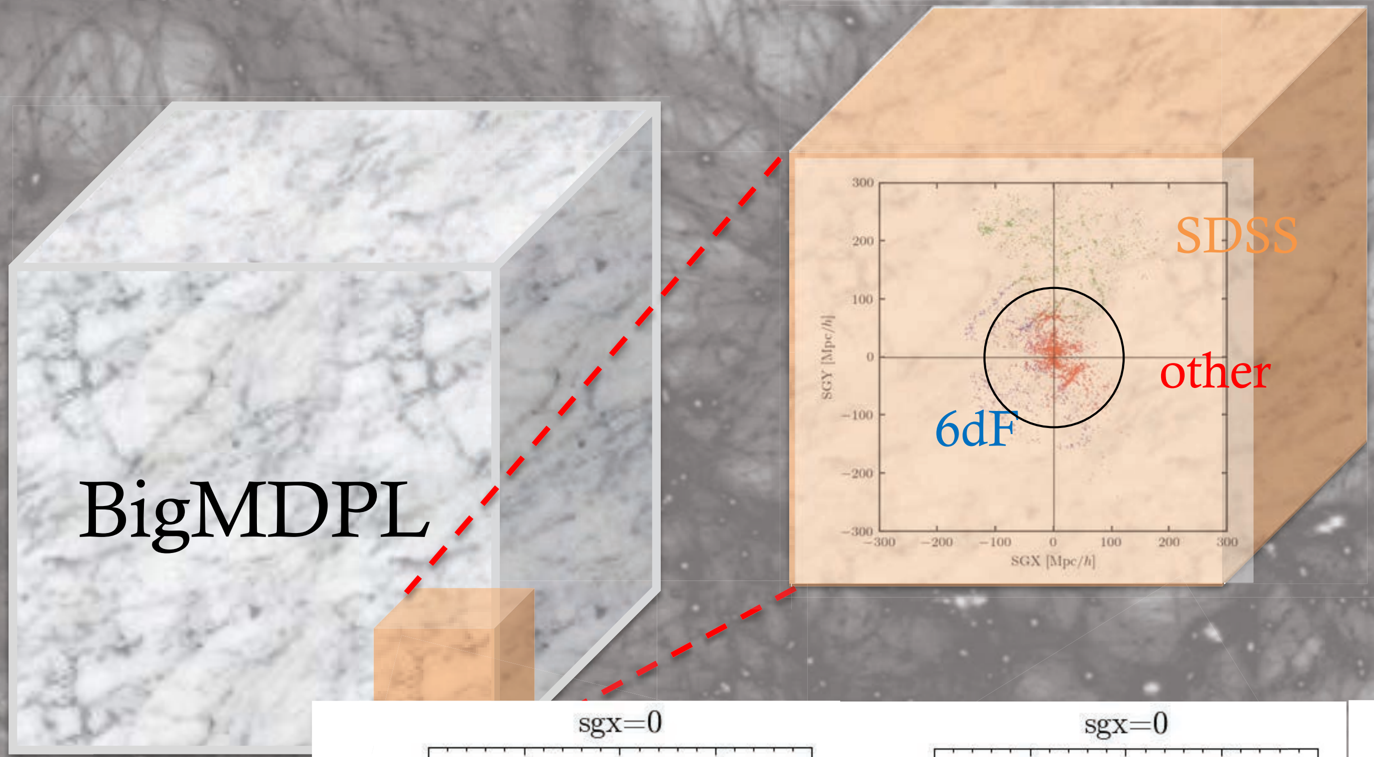
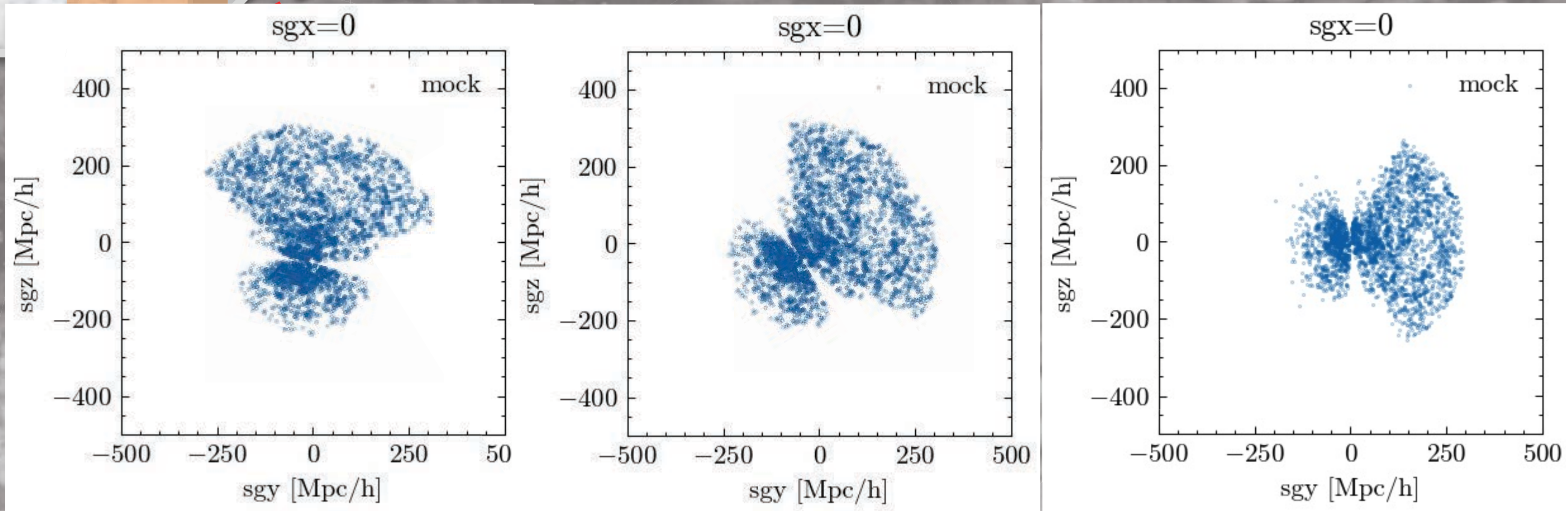
Take a simulation, make a mock, apply and check!

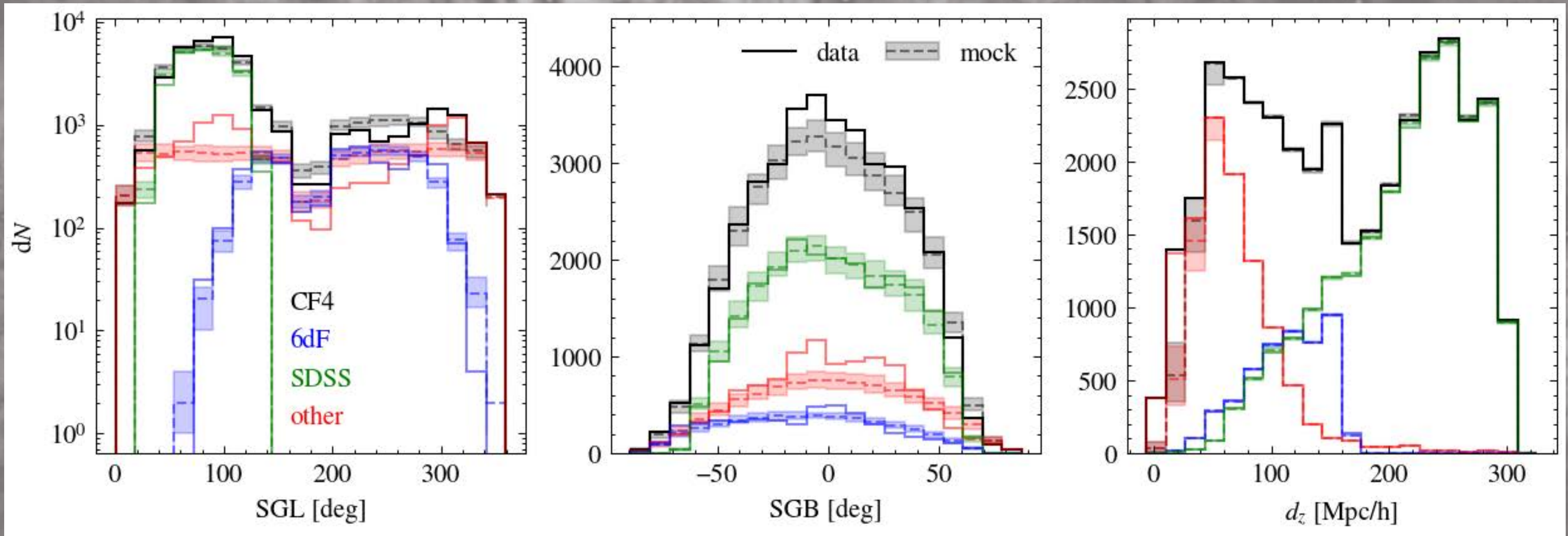


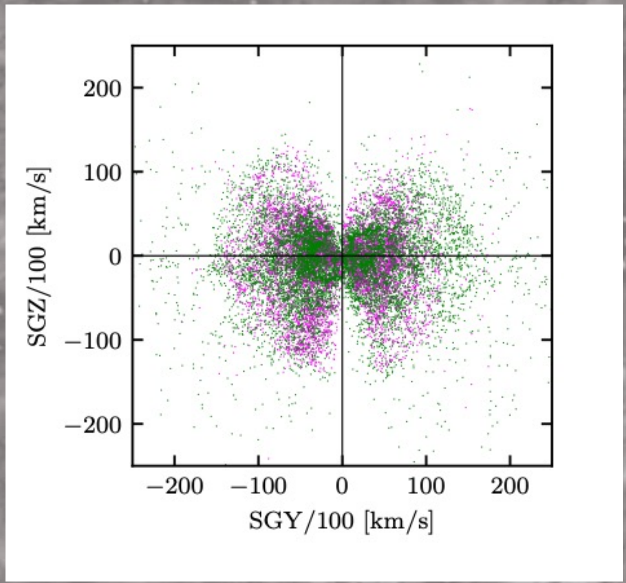


Duangchan et al *in prep*

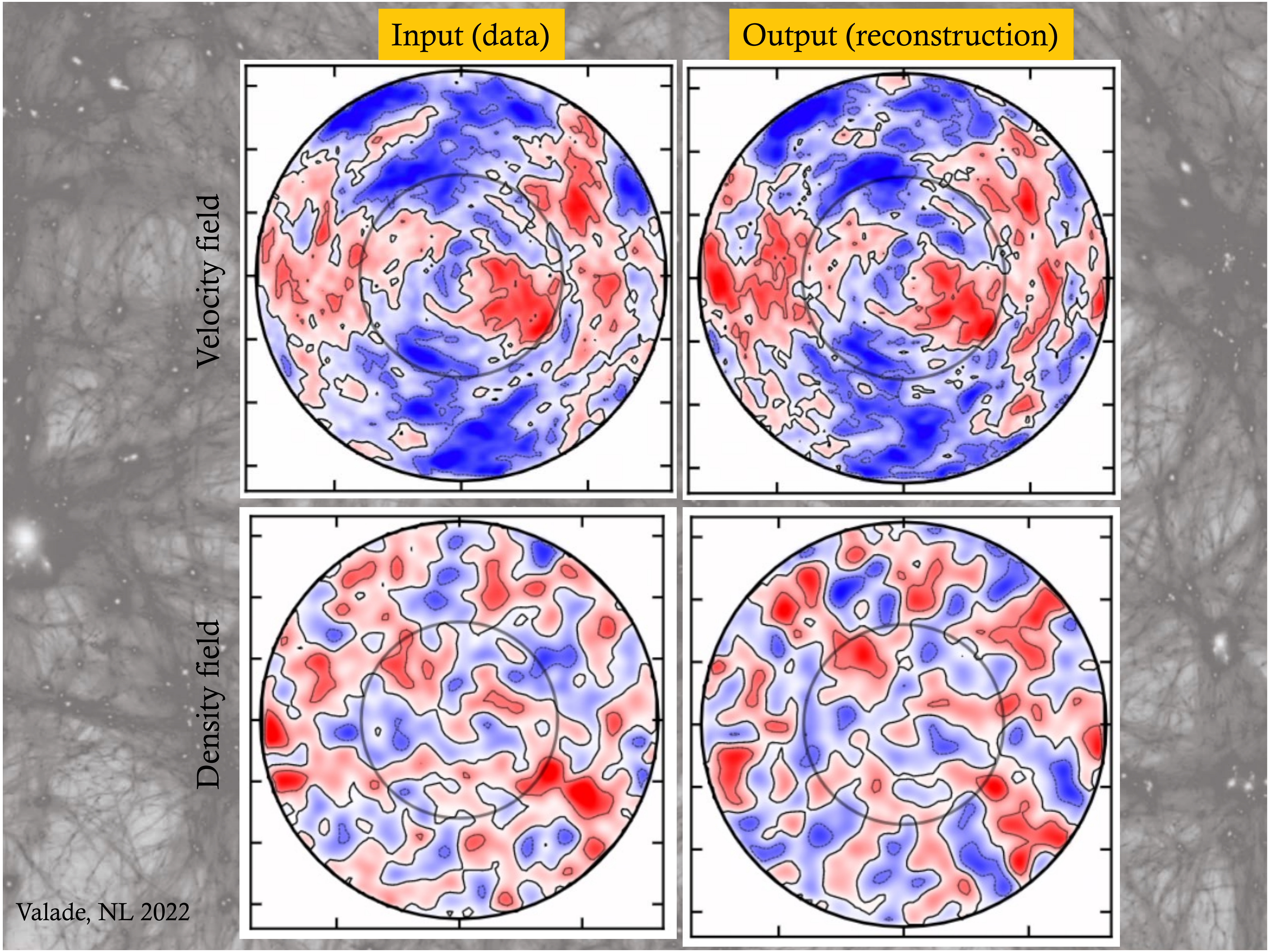
How good are these reconstruction?

Take a simulation, make a mock, apply and check!

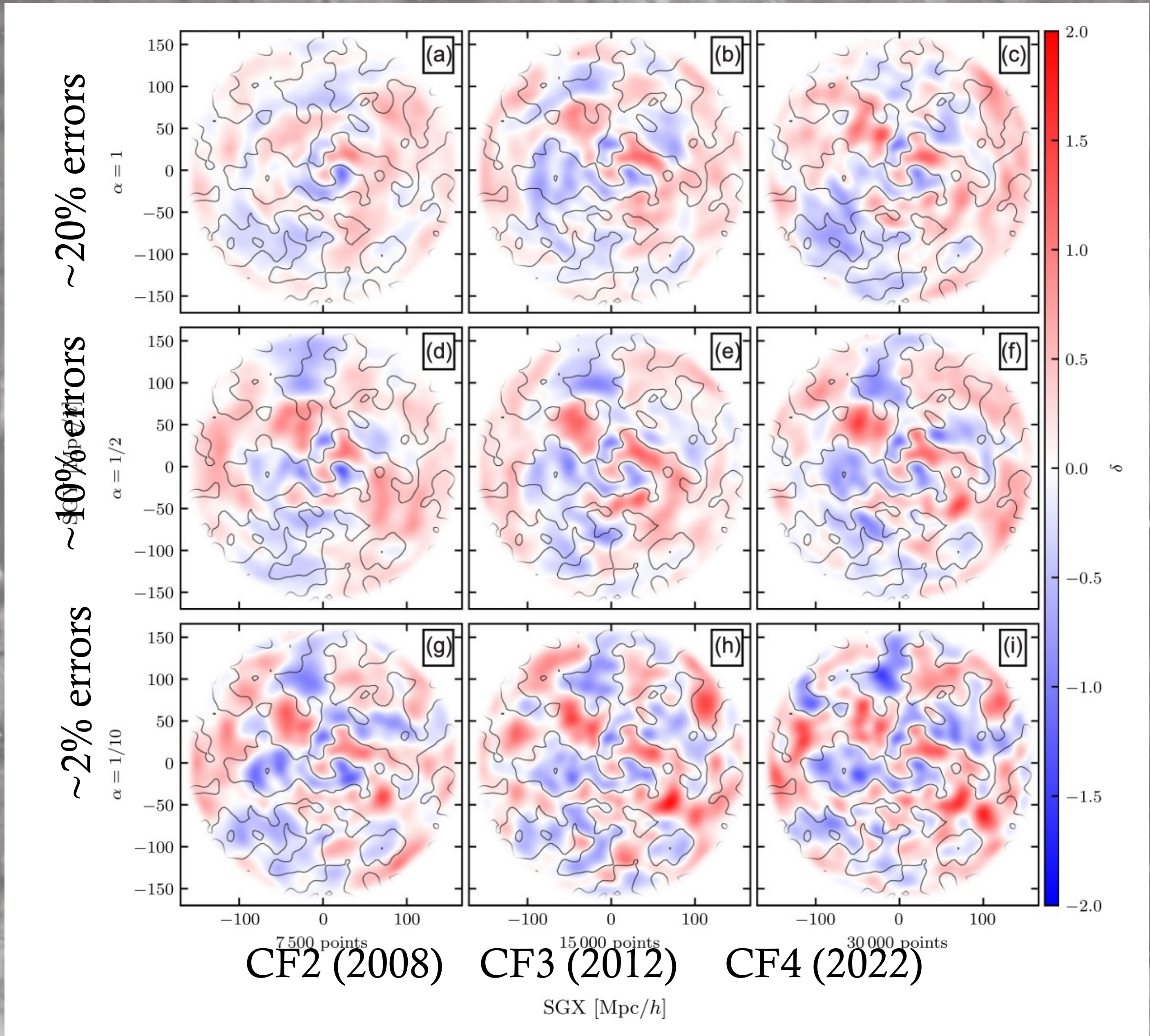




Duangchan et al *in prep*

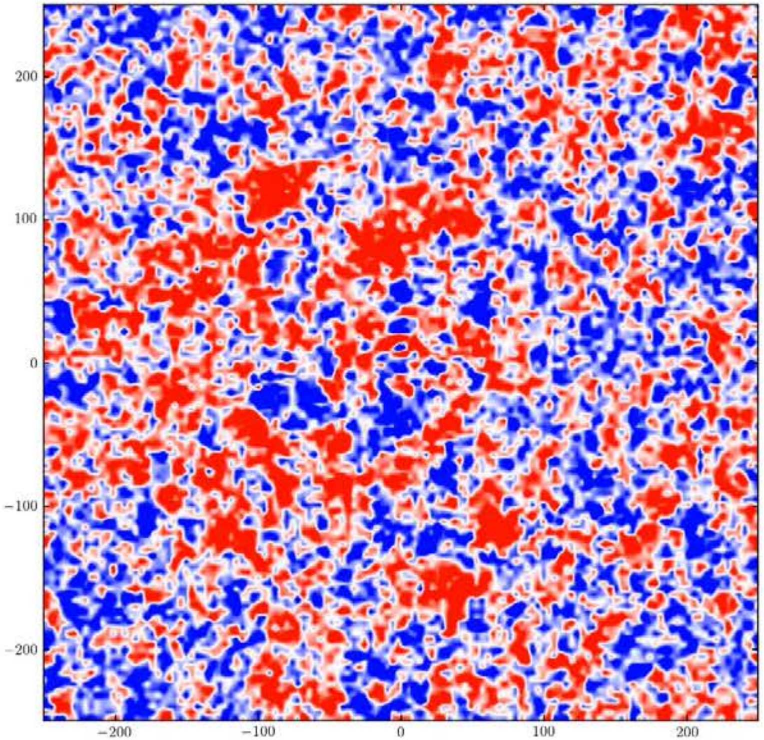

Input (data)
Output (reconstruction)
Velocity field
Density field
Valade, NL 2022

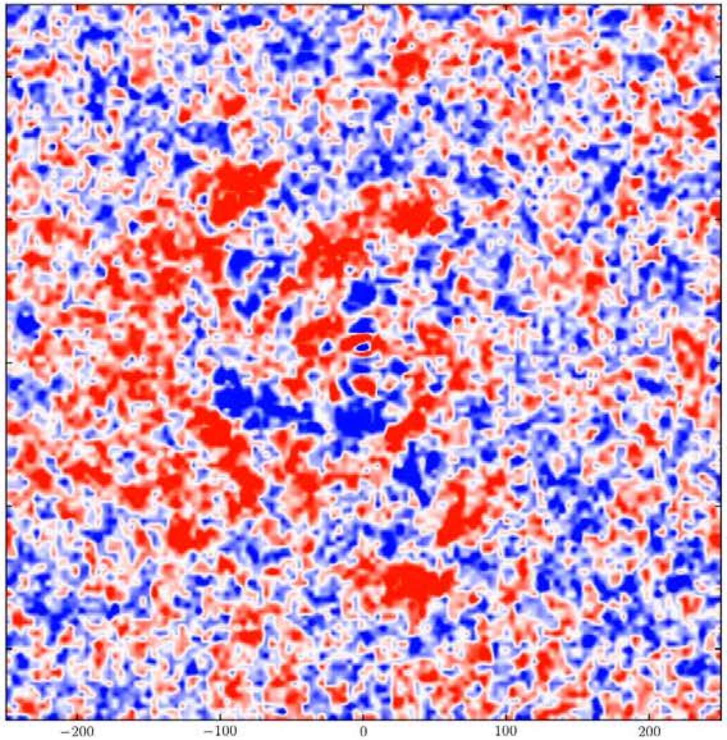
How good are these reconstruction?

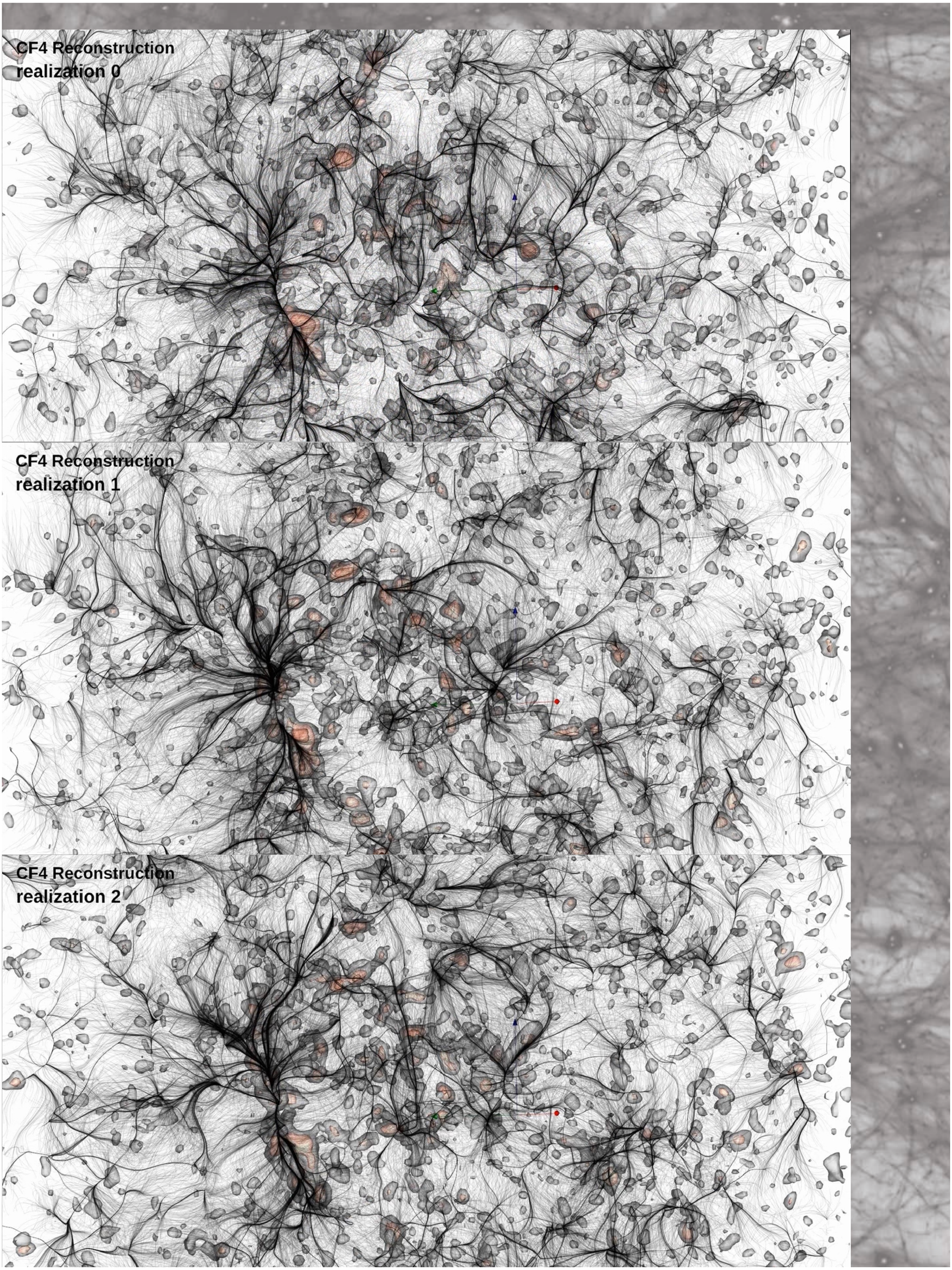


Valade, NL + 2022

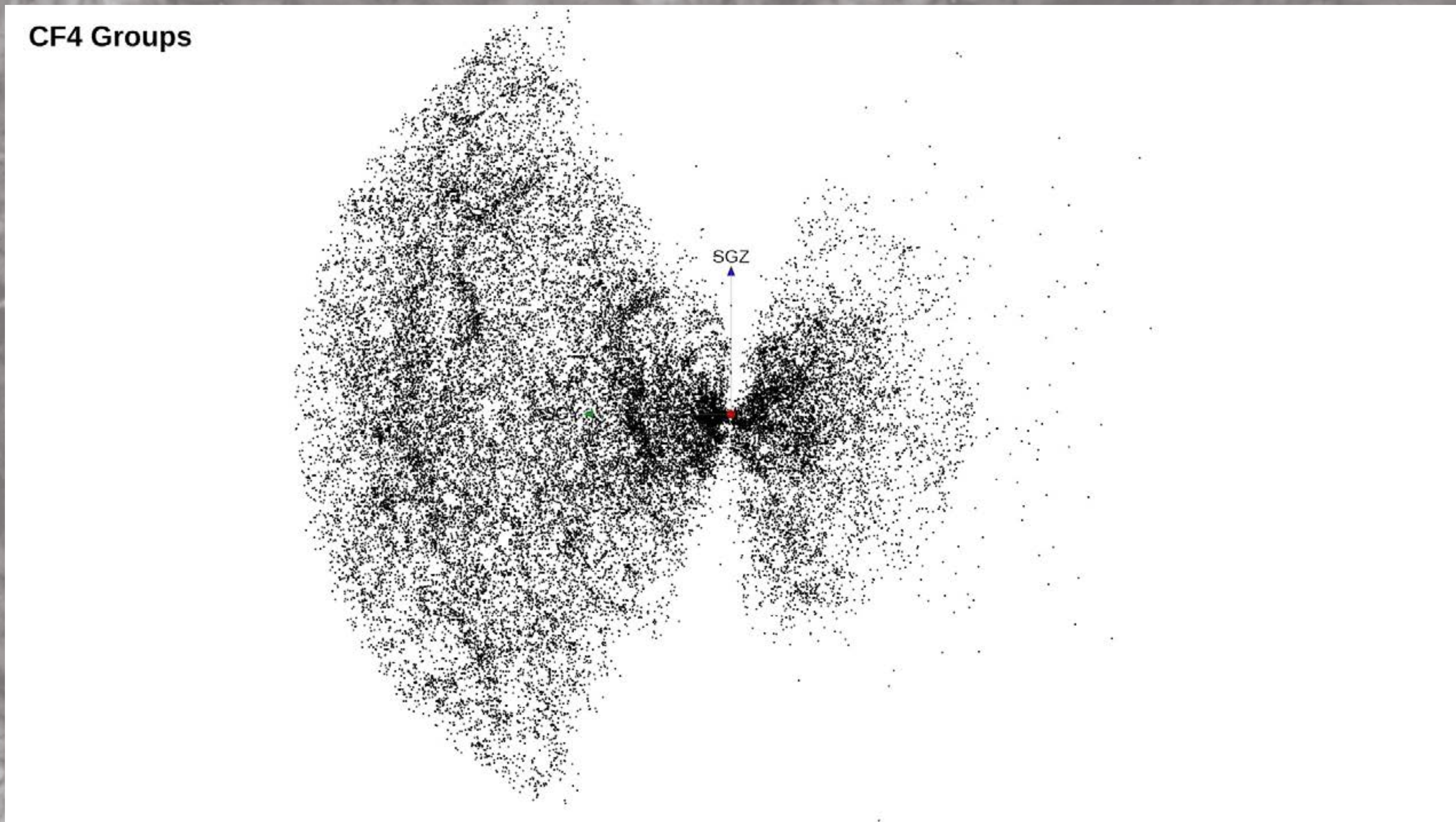
The HAmiltonian Monte carlo reconstruction of the Local EnvironmenT



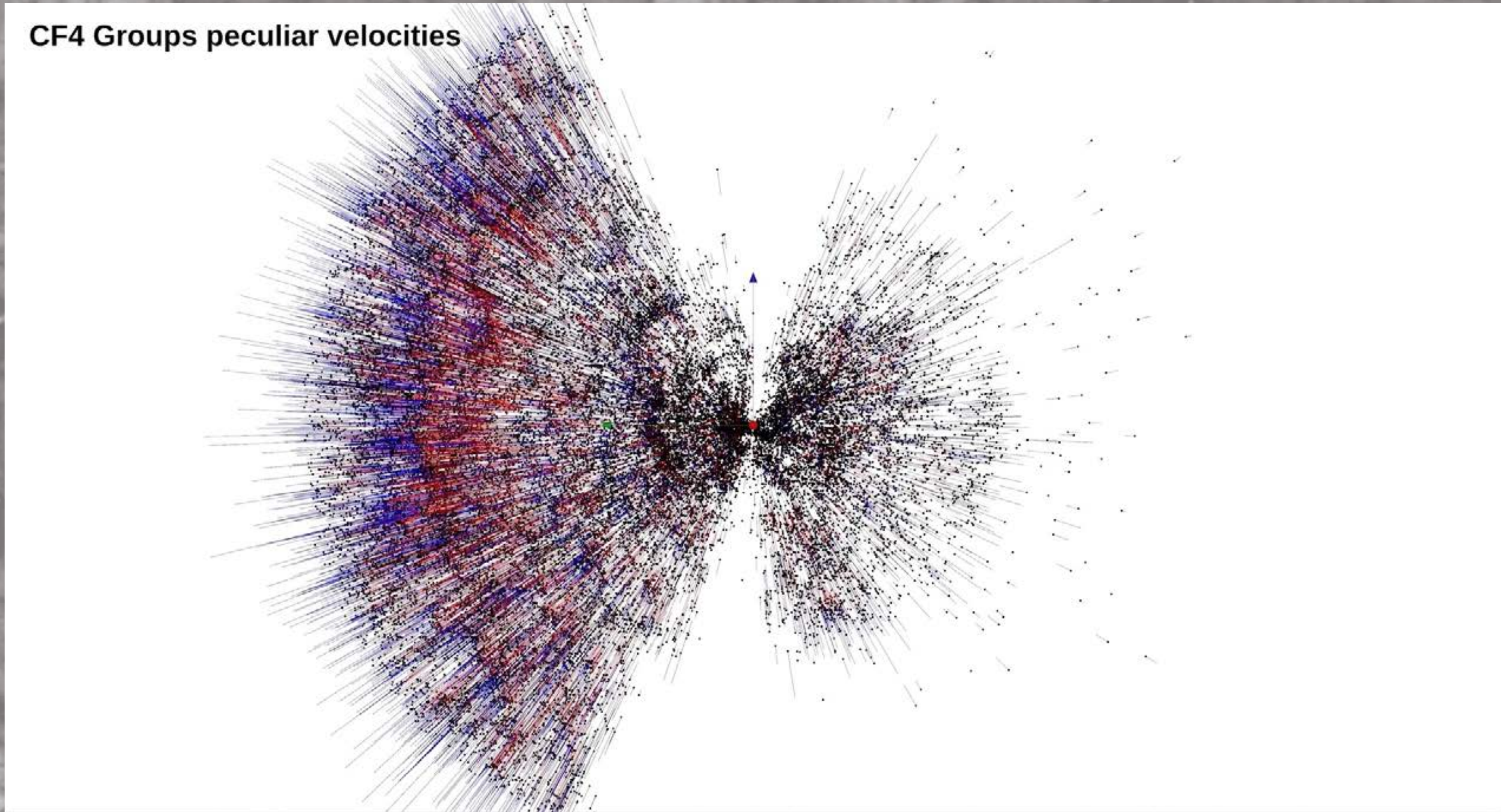



CF4 Reconstruction
realization 0
CF4 Reconstruction
realization 1
CF4 Reconstruction
realization 2

Our starting point is the CF4 set of 50,000 data points, grouped into ~38,000 groups

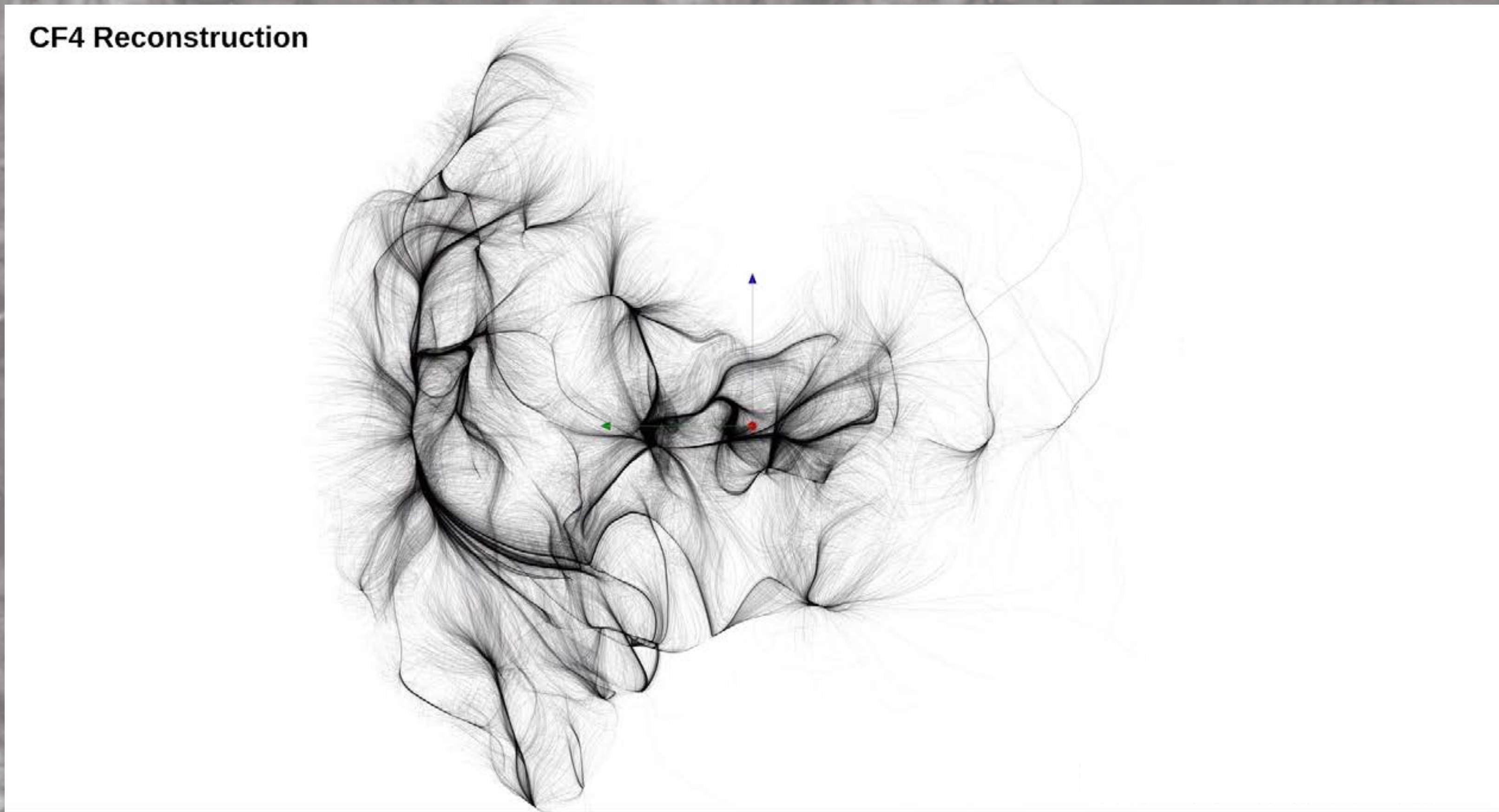


Peculiar Velocity measurements done by standard candles



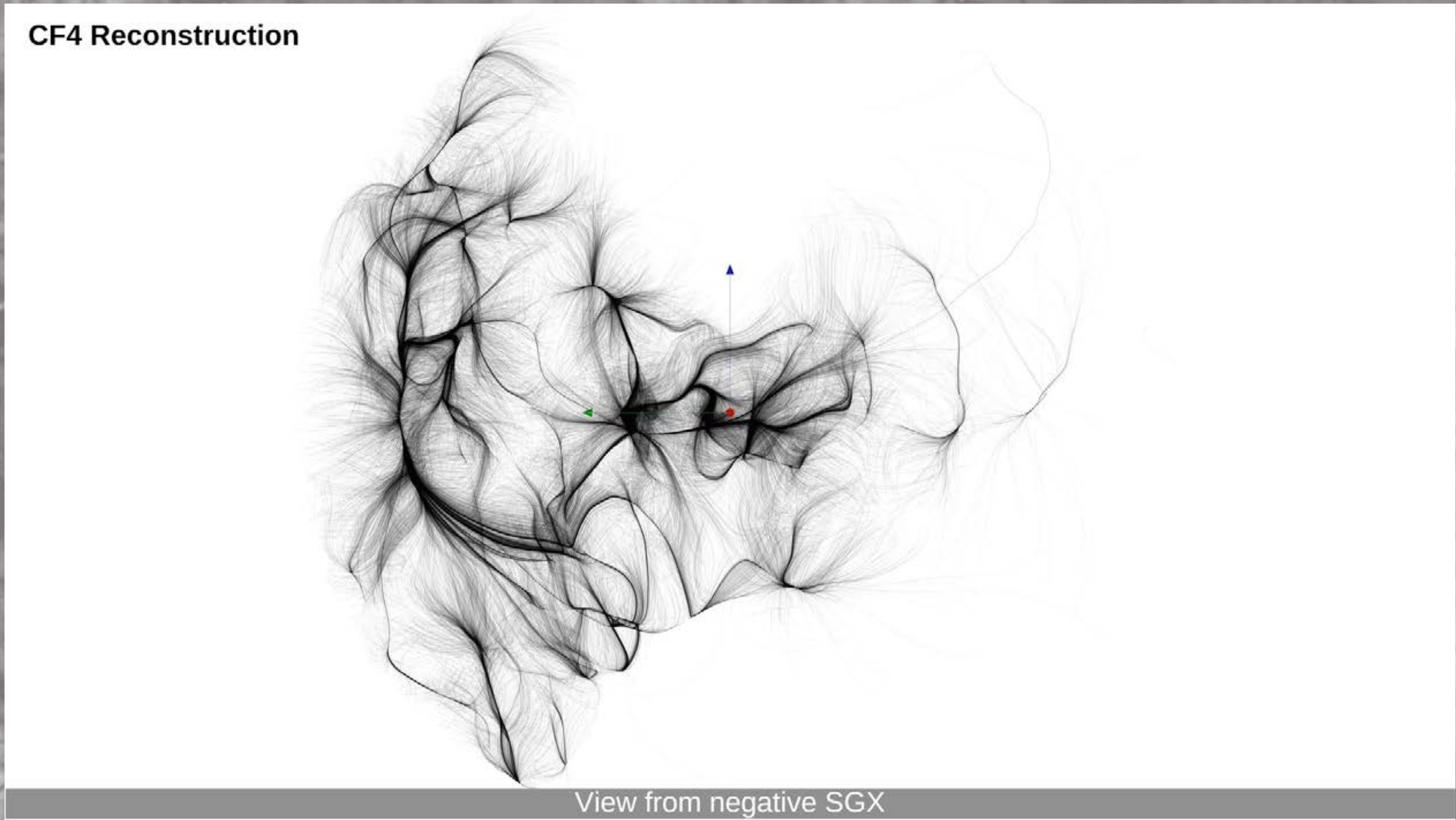
Radial peculiar velocity vectors associated with groups; red outward and blue inward

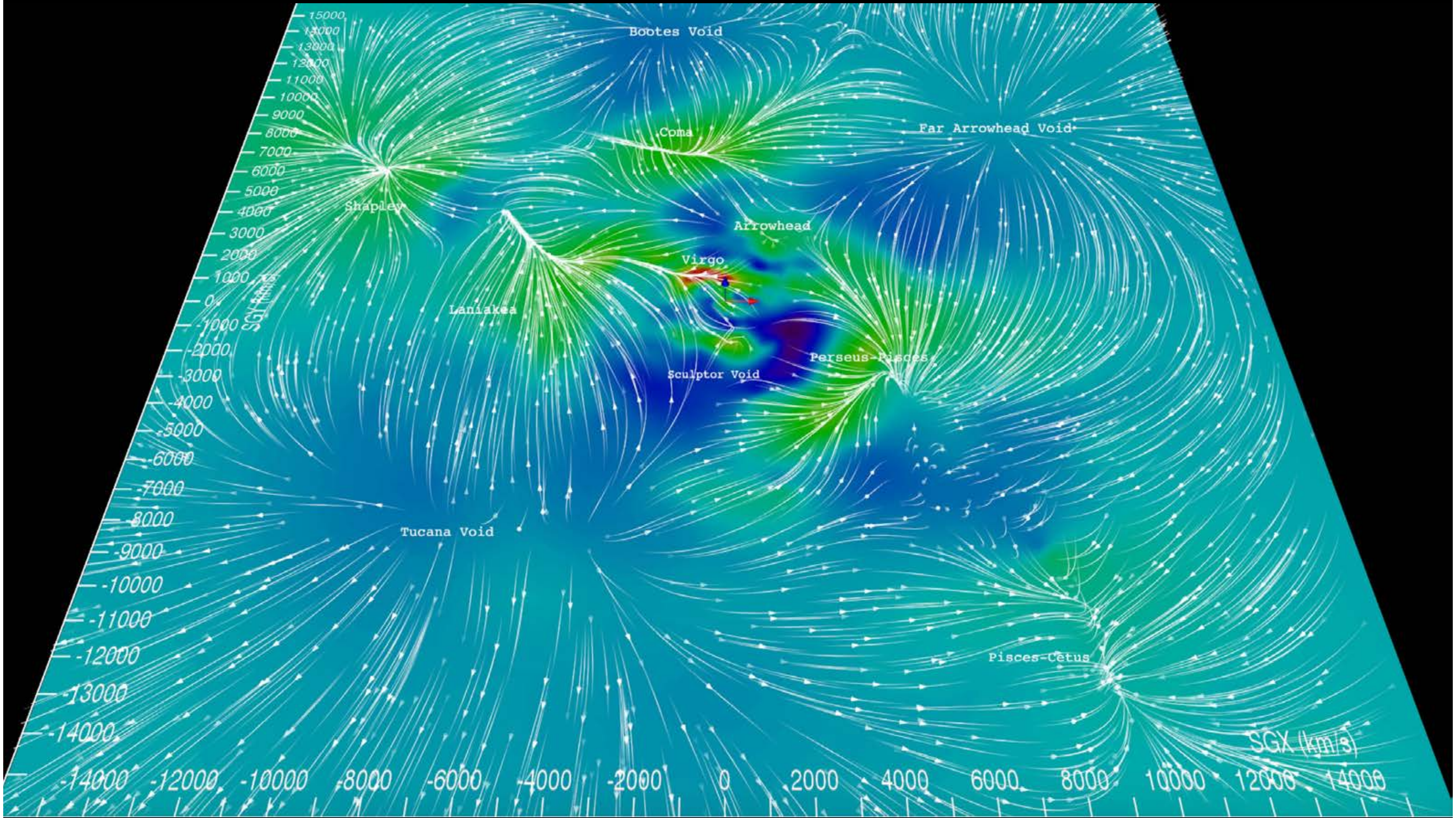
3D Flow lines



Velocity streamlines from model of the peculiar velocity field

Density field and super clusters



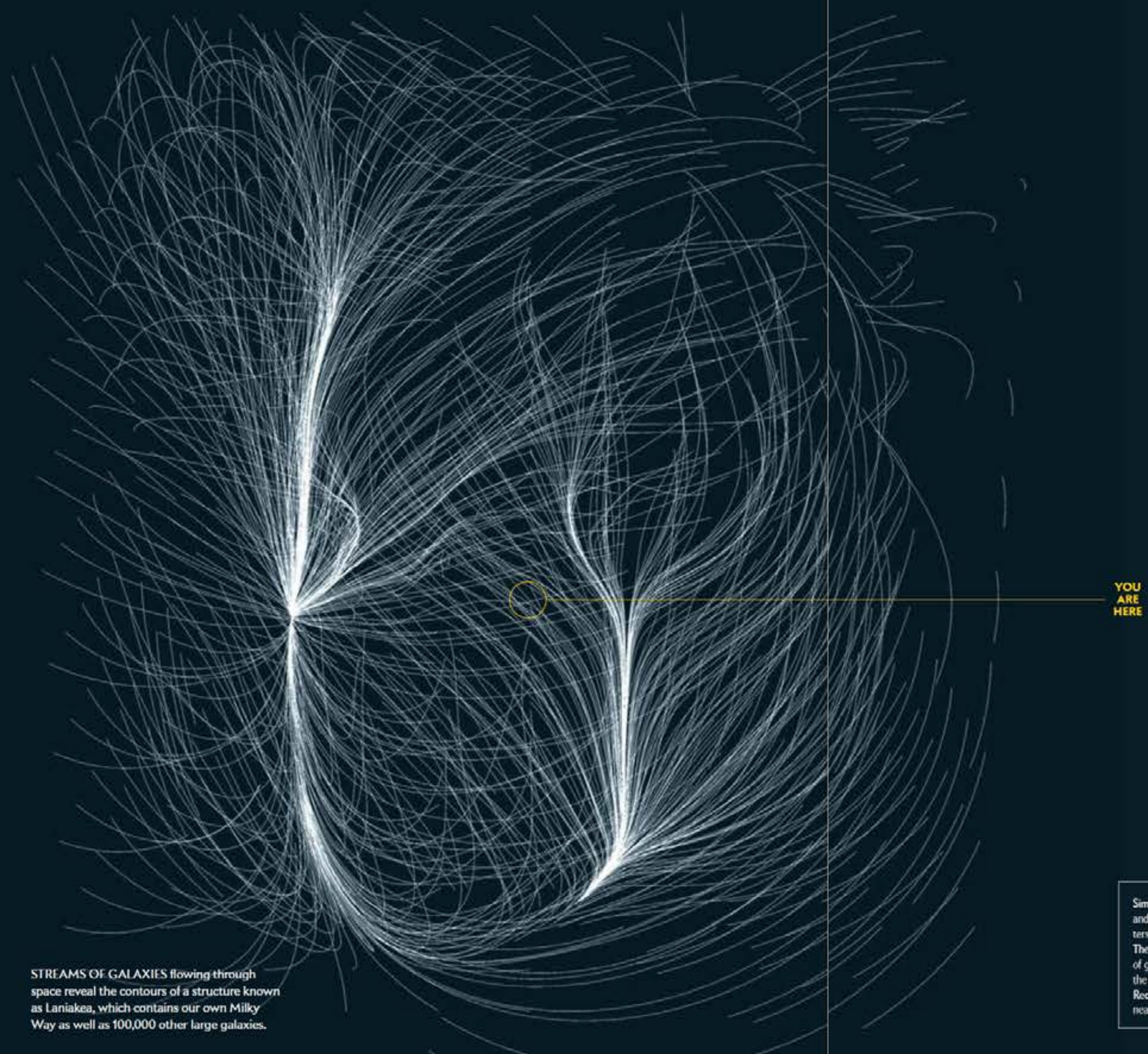

Bootes Void
Coma
Far Arrowhead Void
Shapley
Arrowhead
Virgo
Laniakea
Perseus-Pisces
Sculptor Void
Tucana Void
Pisces-Cetus
SGX (km/s)
SGY (km/s)

ASTRONOMY

Our Place in the Cosmos

The Milky Way turns out to be part of a massive supercluster of galaxies that forms one of the largest known structures in the universe. This discovery is only the beginning of a new effort to map the cosmos

By Noam I. Libeskind and R. Brent Tully



STREAMS OF GALAXIES flowing through space reveal the contours of a structure known as Laniakea, which contains our own Milky Way as well as 100,000 other large galaxies.

IN BRIEF

Similar to how stars clump together into star clusters and galaxies, galaxies themselves gather into clusters, and galactic clusters group into superclusters.

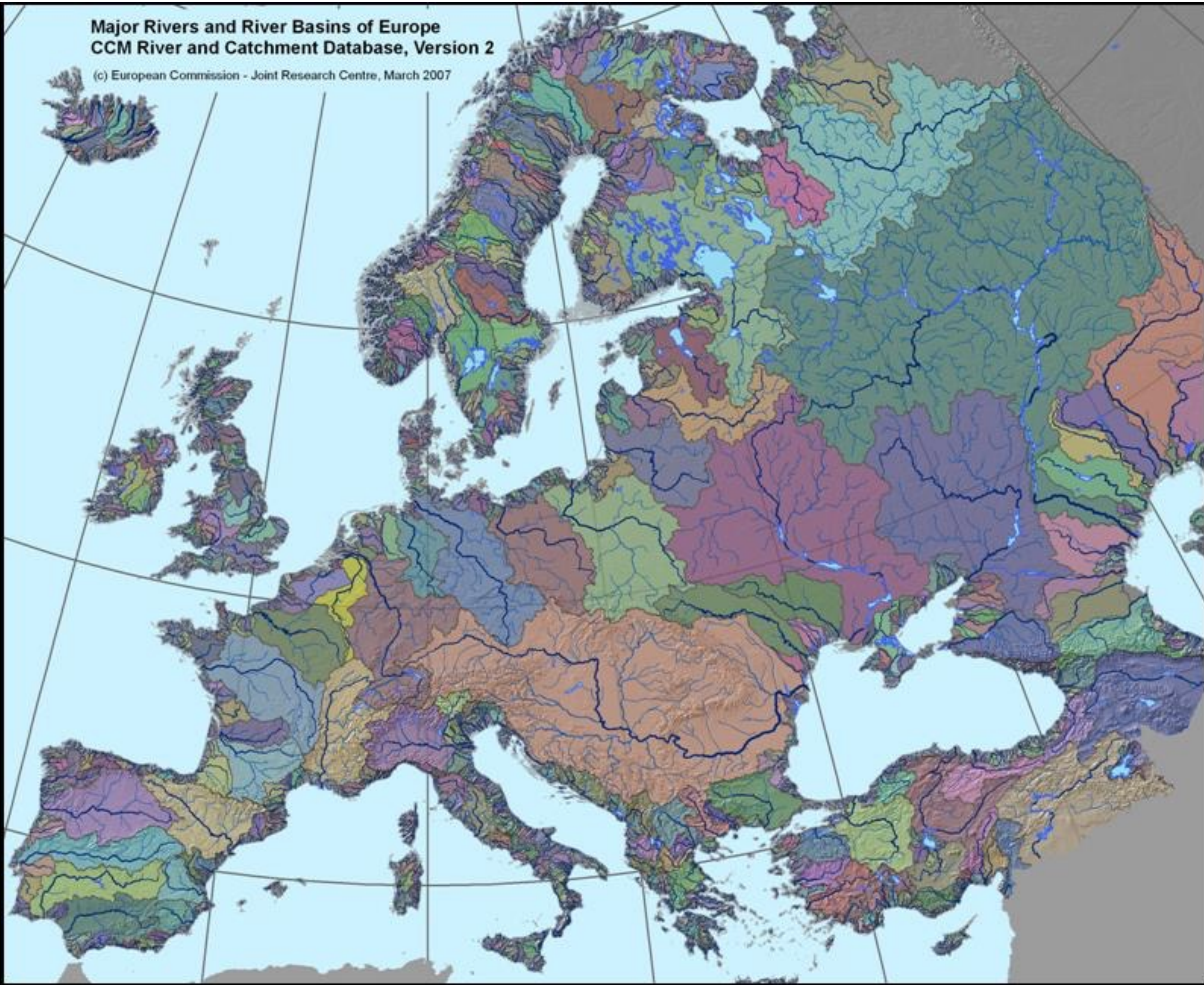
These galactic superclusters are the building blocks of great filaments, sheets and voids that constitute the largest measurable structures in the universe.

Recent studies of the motions of thousands of nearby galaxies have revealed that the Milky Way's home supercluster is far larger than previously thought. Astronomers call this newfound super-sized supercluster "Laniakea."

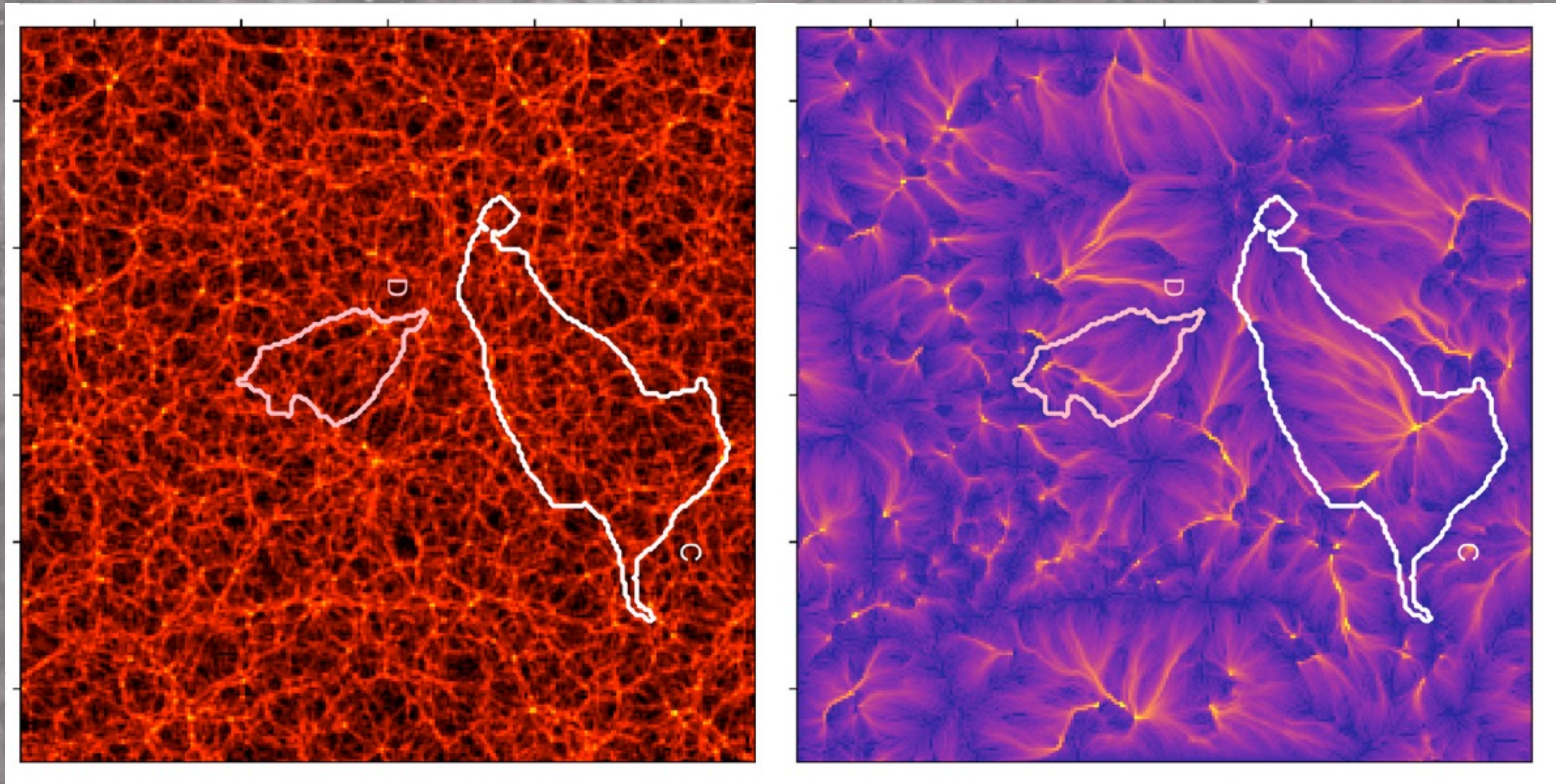
More detailed mapping of Laniakea and its neighboring superclusters could reveal new details about galaxy formation and help researchers solve the dual cosmological mysteries of dark matter and dark energy.

July 2016, ScientificAmerican.com 33

NL & Tully 2016
Scientific American

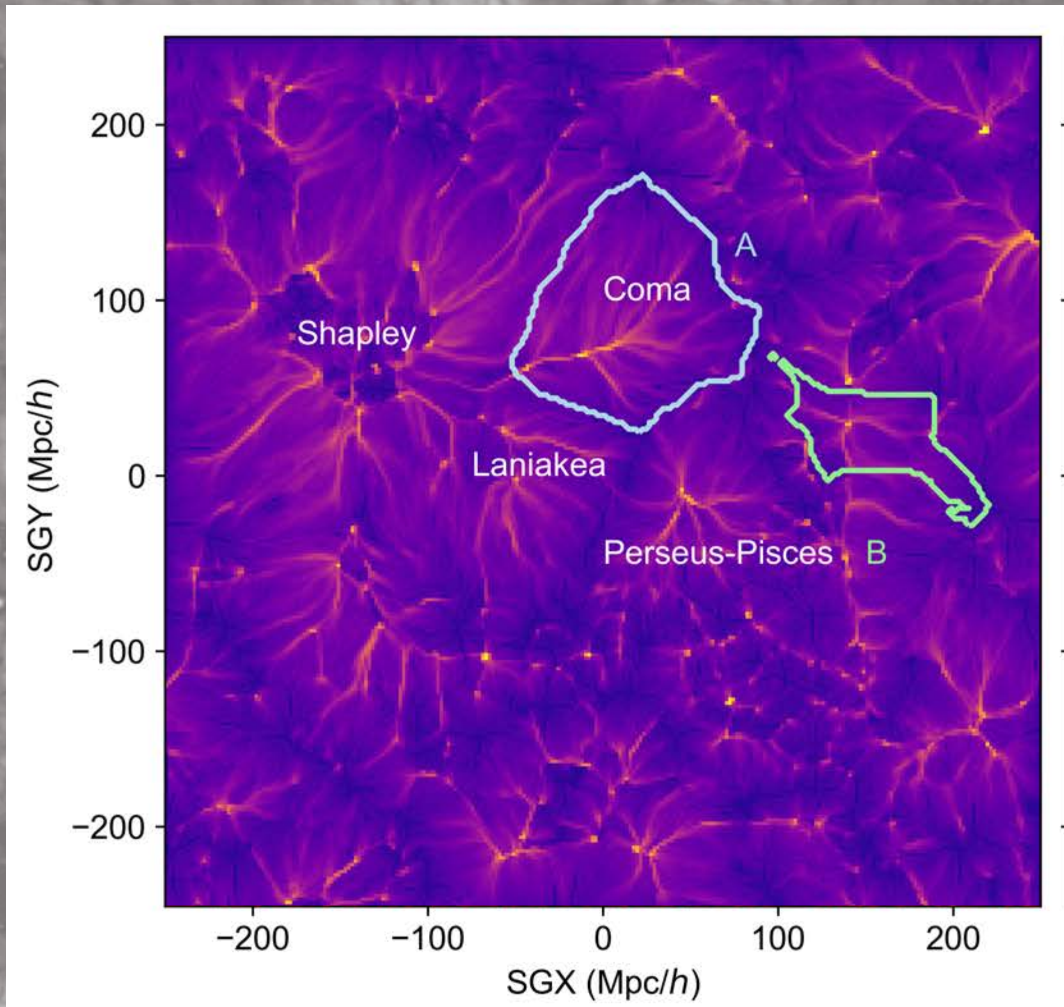

Major Rivers and River Basins of Europe
CCM River and Catchment Database, Version 2
(c) European Commission - Joint Research Centre, March 2007

Identifying watershed basins in the peculiar velocity field

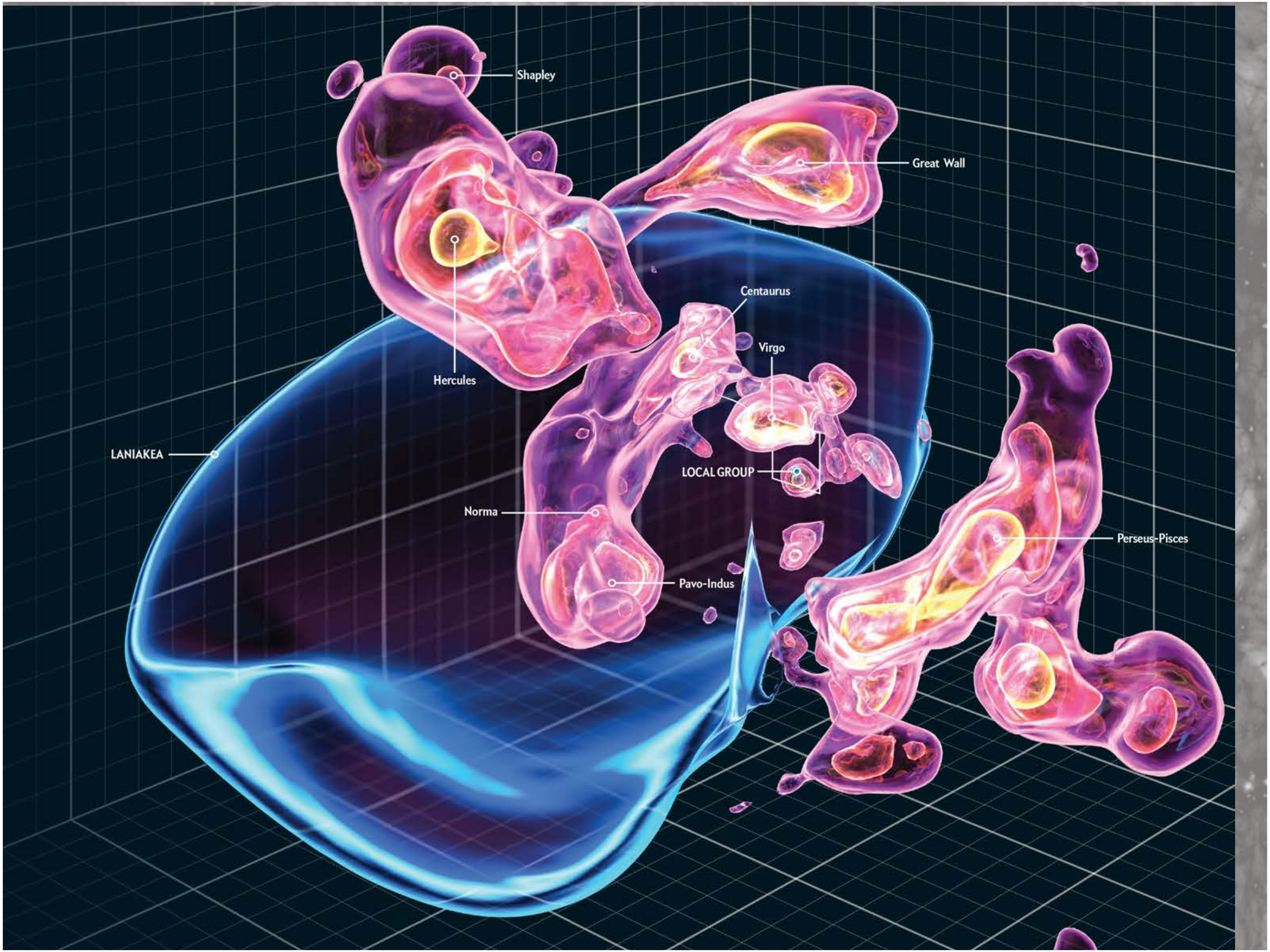


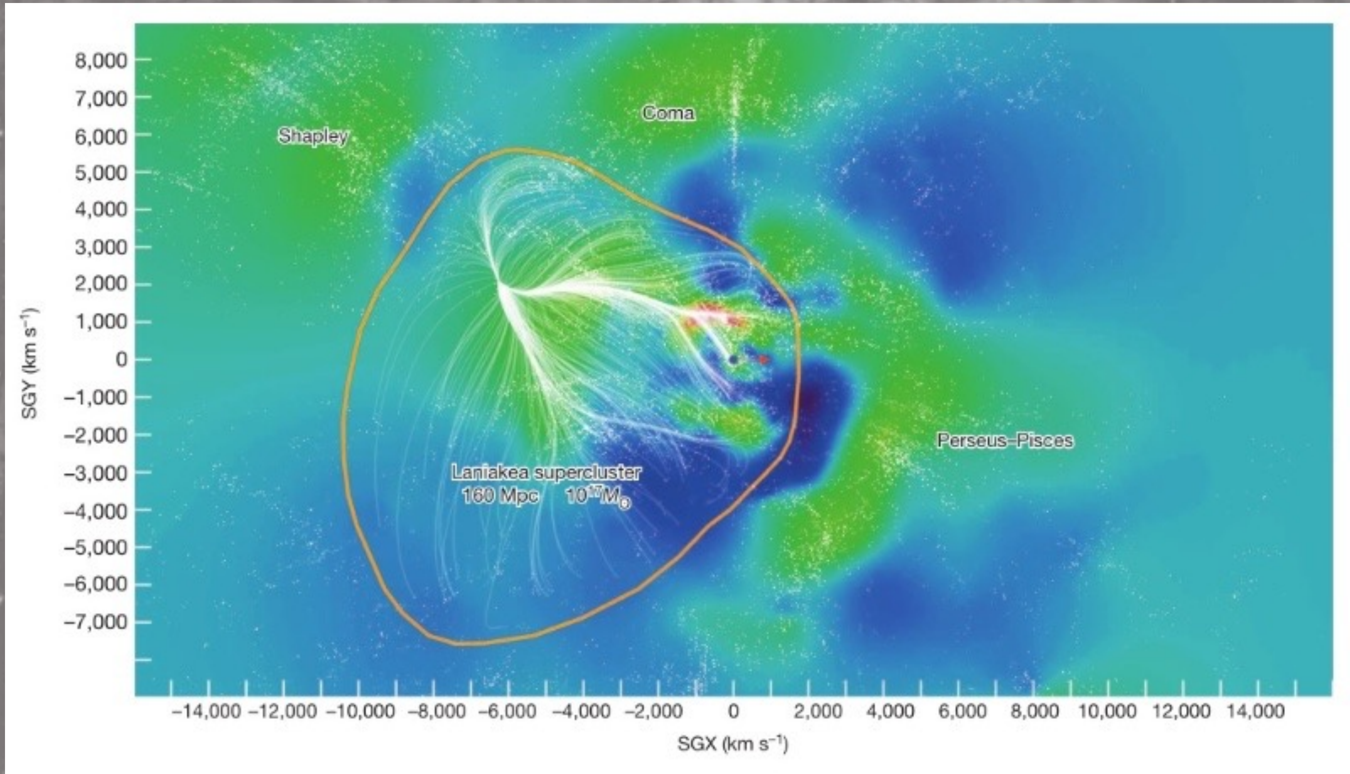
Dupuy + NL et al 2019

Can be used to study structures



Dupuy + NL et al 2020

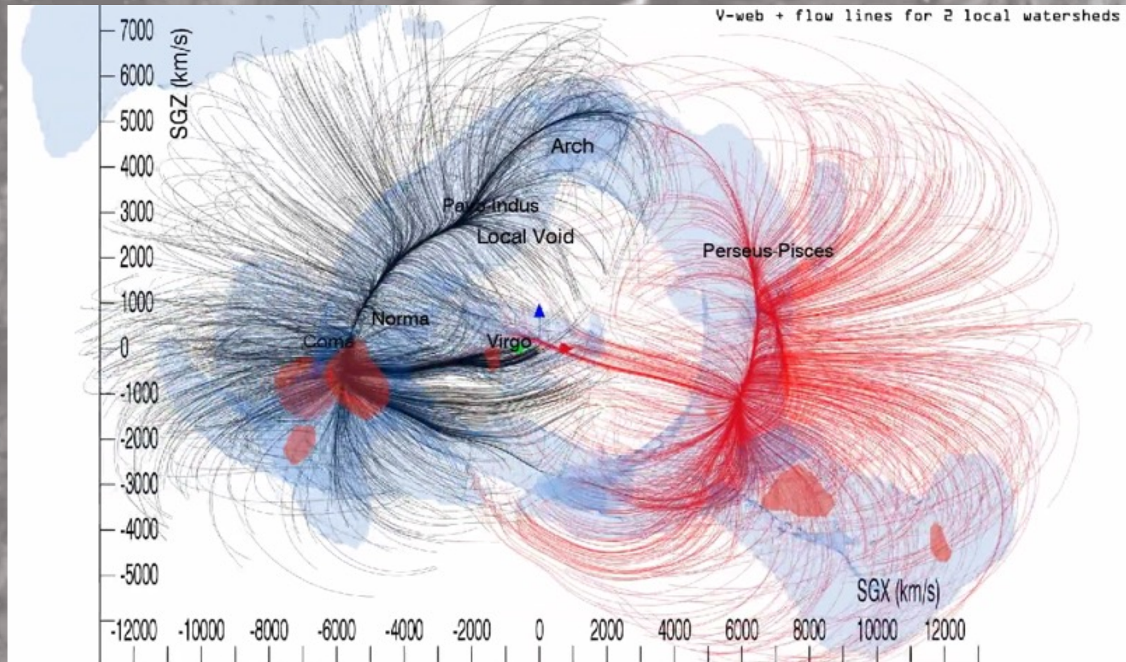

Shapley
Great Wall
Centaurus
Hercules
Virgo
LANIAKEA
LOCAL GROUP
Norma
Perseus-Pisces
Pavo-Indus

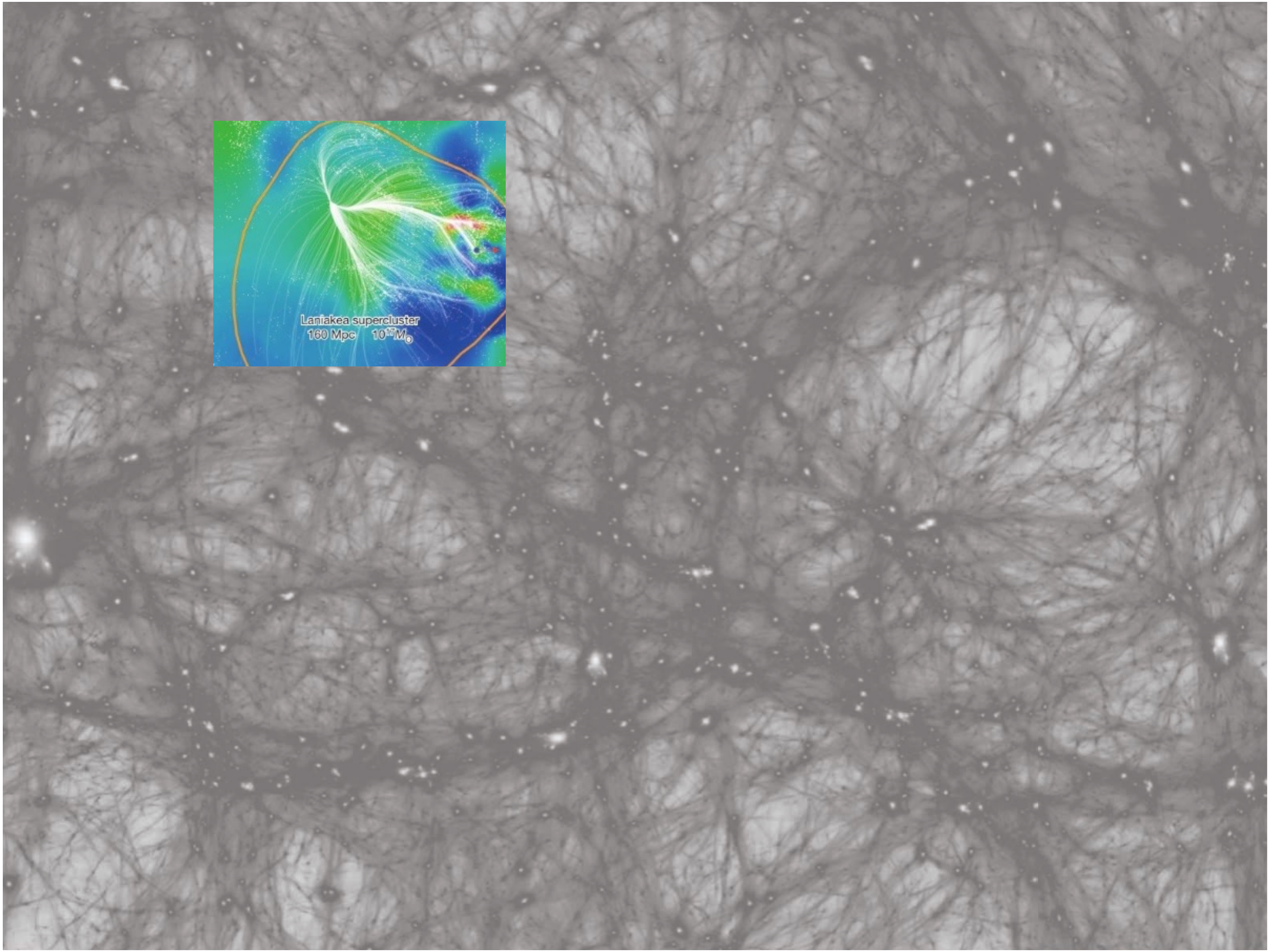


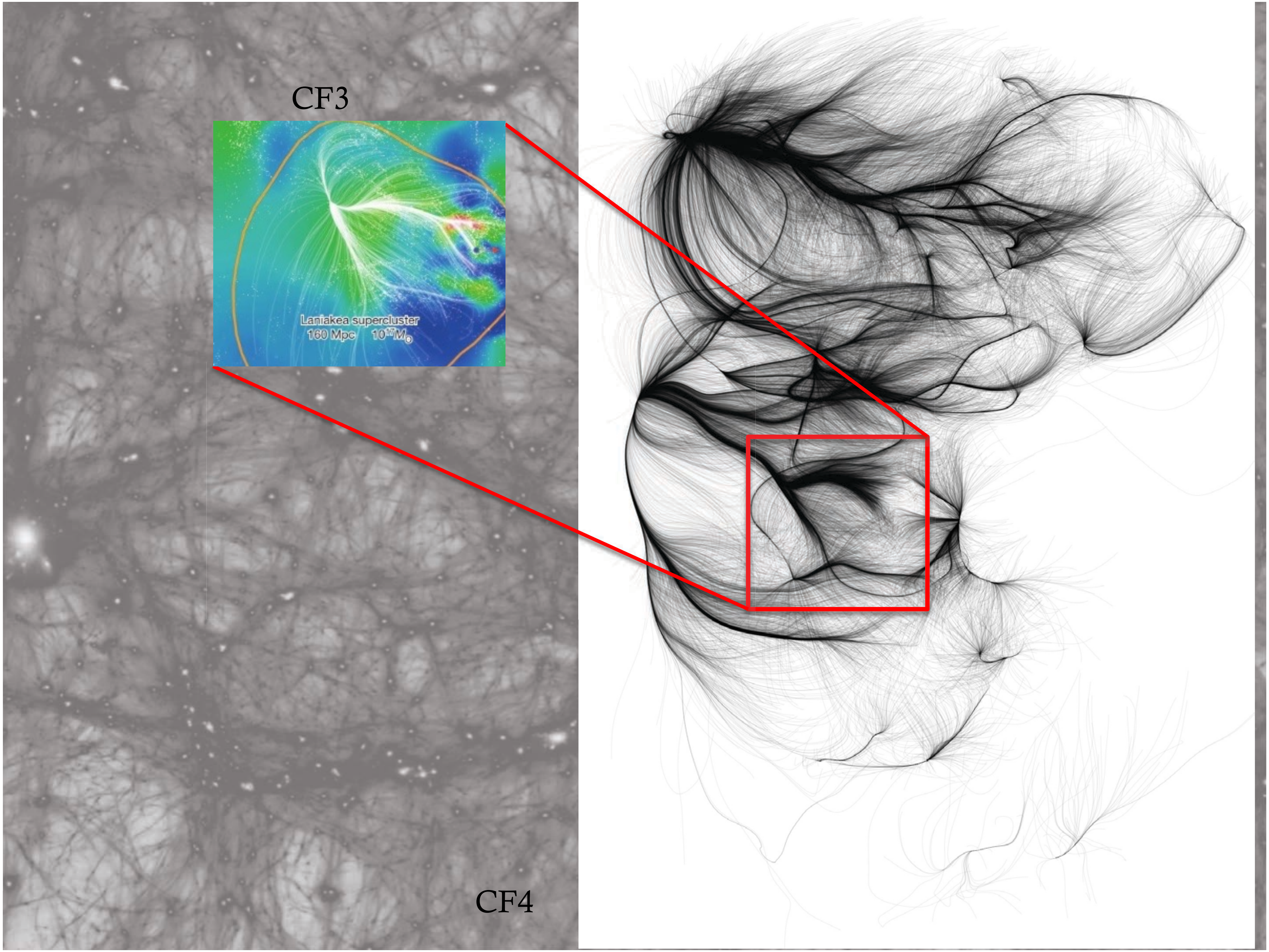
Laniakea "Super-cluster"

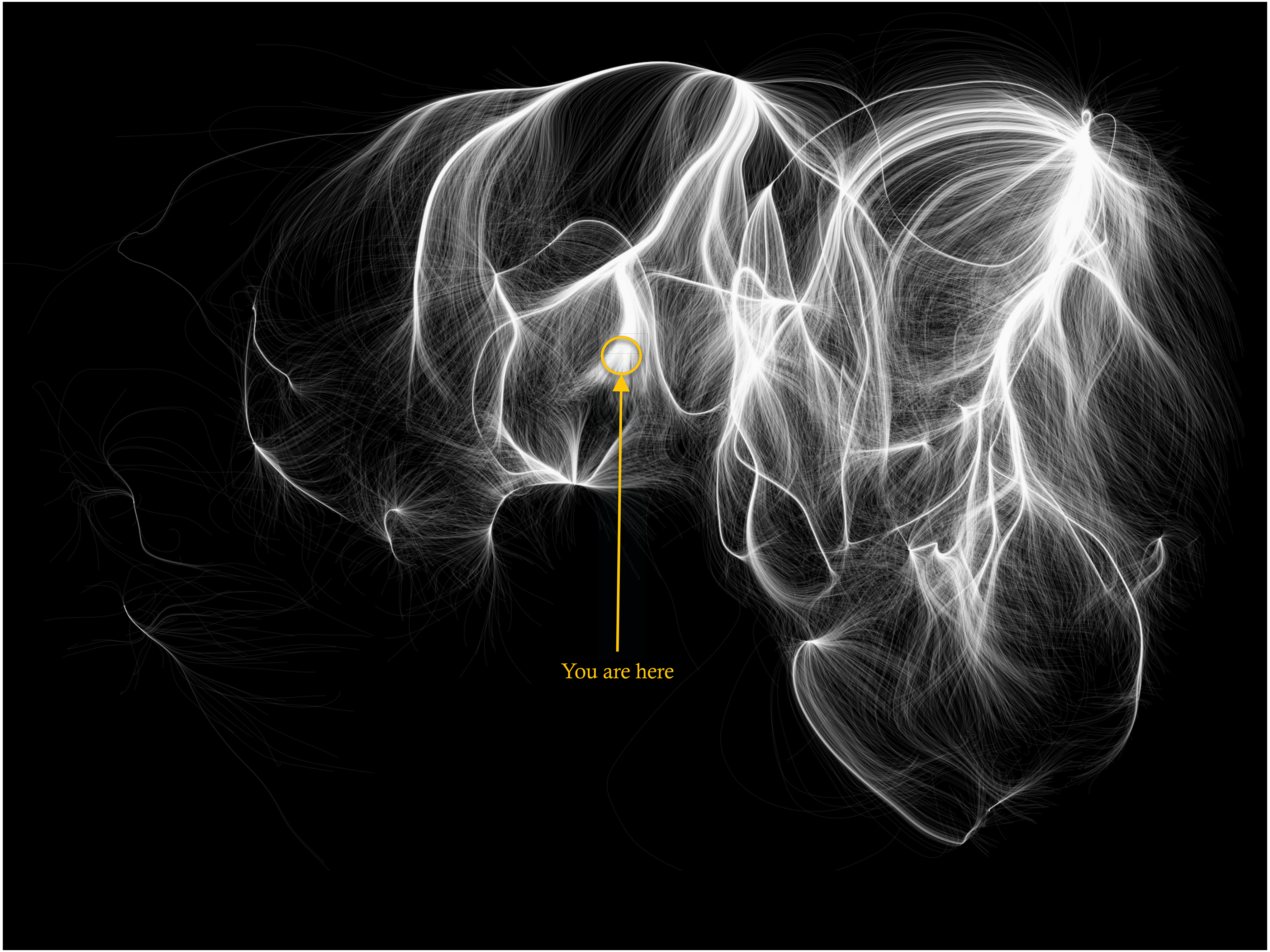
L~100s Mpc

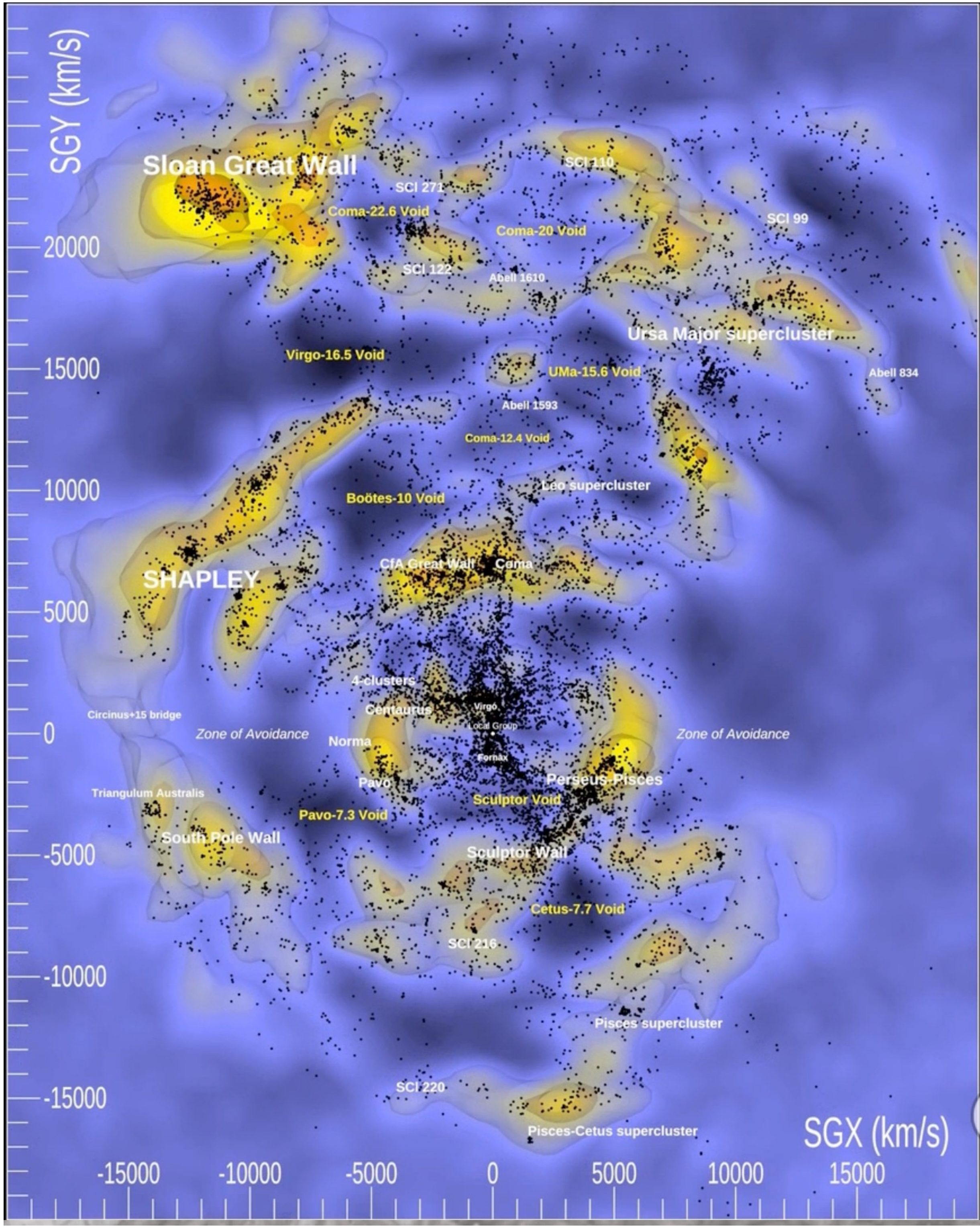
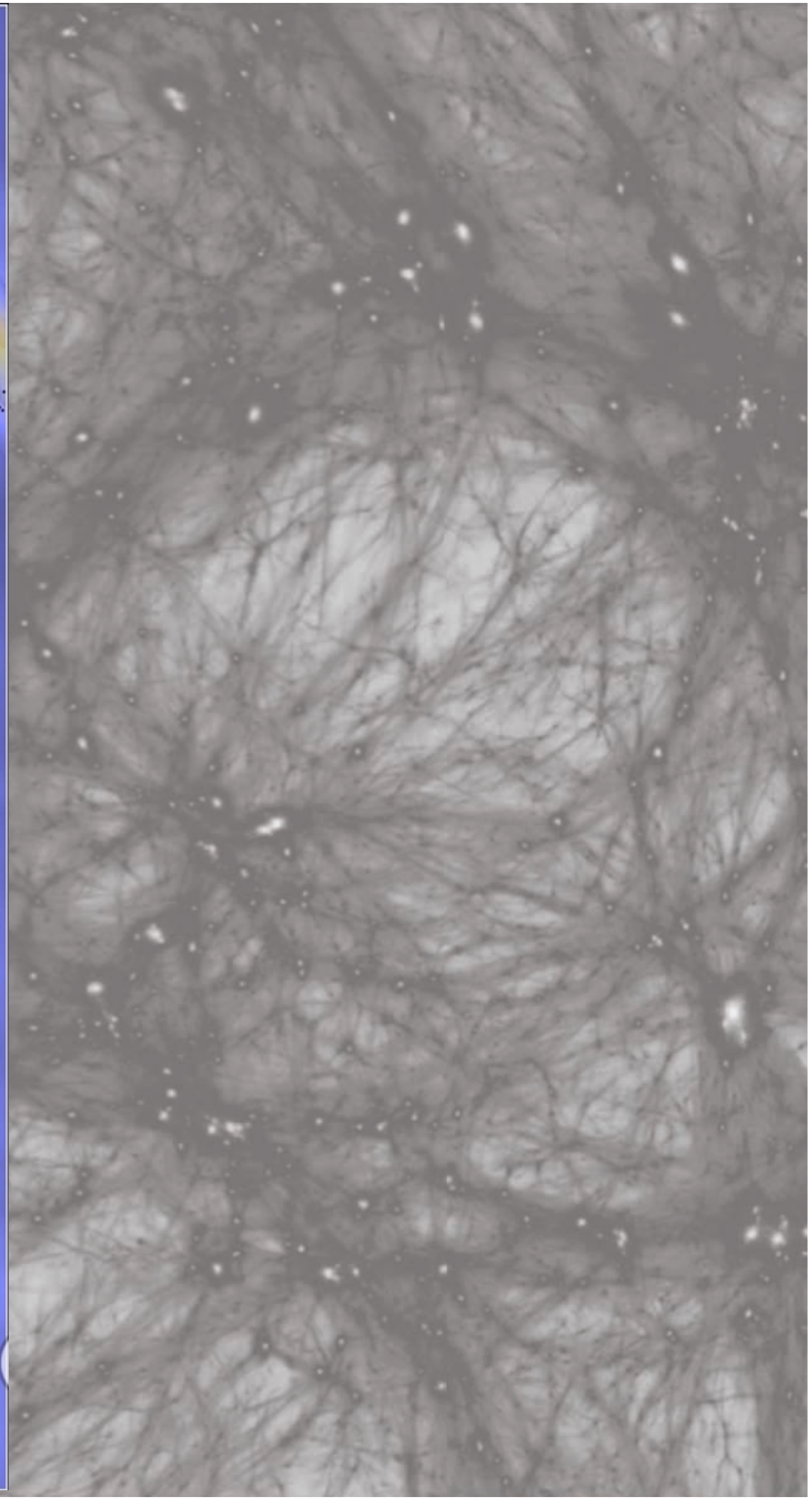
Tully et al 2014

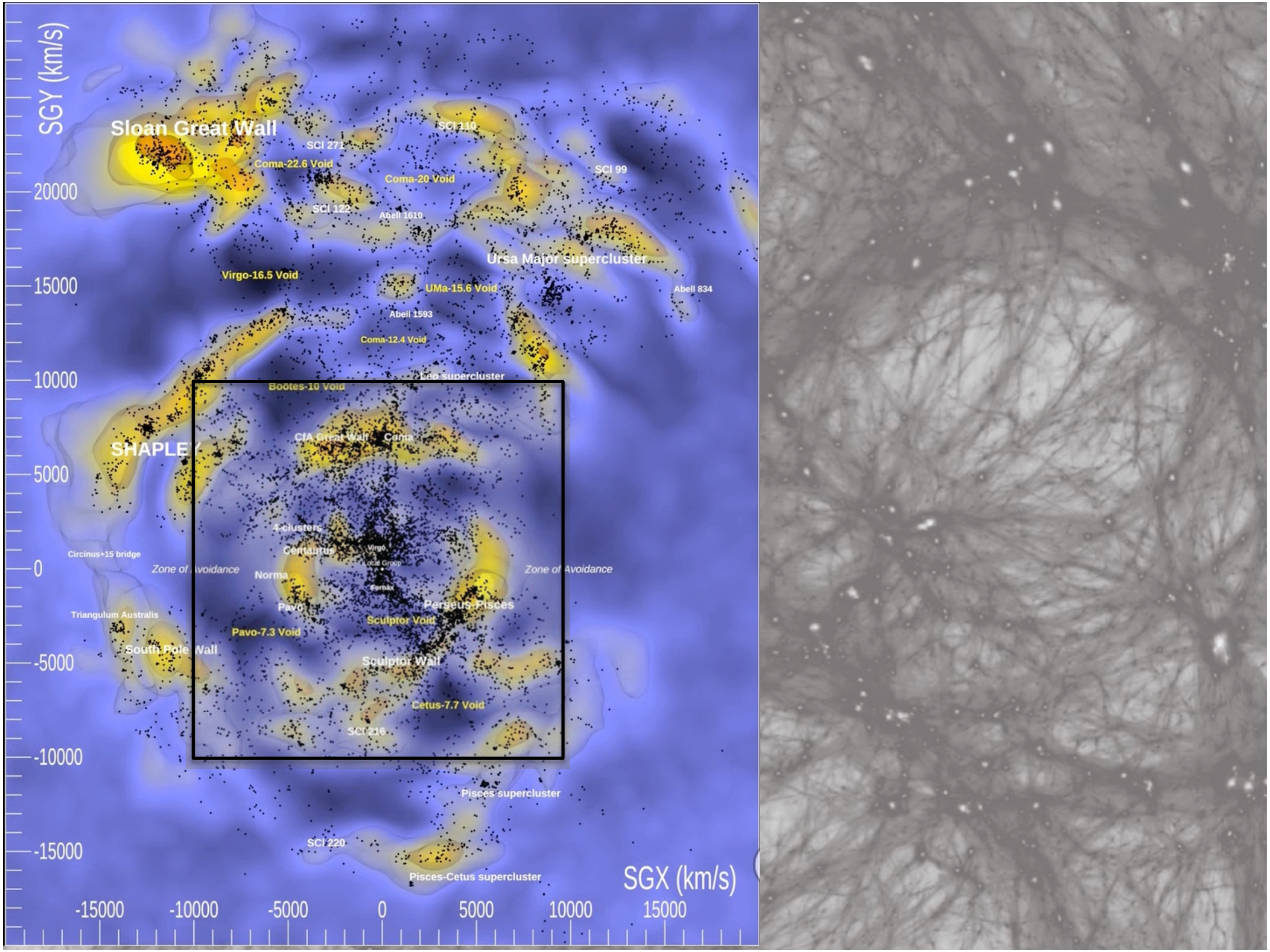



Laniakea supercluster
160 Mpc $10^{17} M_{\odot}$


CF3
Laniakea supercluster
160 Mpc $10^{17}M_{\odot}$
CF4


You are here


SGY (km/s)
SGX (km/s)
20000
15000
10000
5000
0
-5000
-10000
-15000
-15000
-10000
-5000
0
5000
10000
15000
Sloan Great Wall
SCl 271
SCl 110
Coma-22.6 Void
Coma-20 Void
SCl 99
SCl 122
Abell 1610
Ursa Major supercluster
Virgo-16.5 Void
UMa-15.6 Void
Abell 834
Abell 1593
Coma-12.4 Void
Leo supercluster
Boötes-10 Void
CfA Great Wall
Coma
SHAPLEY
4-clusters
Centaurus
Virgo
Local Group
Circinus+15 bridge
Zone of Avoidance
Norma
Zone of Avoidance
Fornax
Pavo
Perseus-Pisces
Triangulum Australis
Sculptor Void
Pavo-7.3 Void
South Pole Wall
Sculptor Wall
Cetus-7.7 Void
SCl 216
Pisces supercluster
SCl 220
Pisces-Cetus supercluster




SGY (km/s)
SGX (km/s)
20000
15000
10000
5000
0
-5000
-10000
-15000
-15000
-10000
-5000
0
5000
10000
15000
Sloan Great Wall
SCI 271
SCI 110
Coma-22.6 Void
Coma-20 Void
SCI 99
SCI 122
Abell 1610
Ursa Major supercluster
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Centaurus
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Zone of Avoidance
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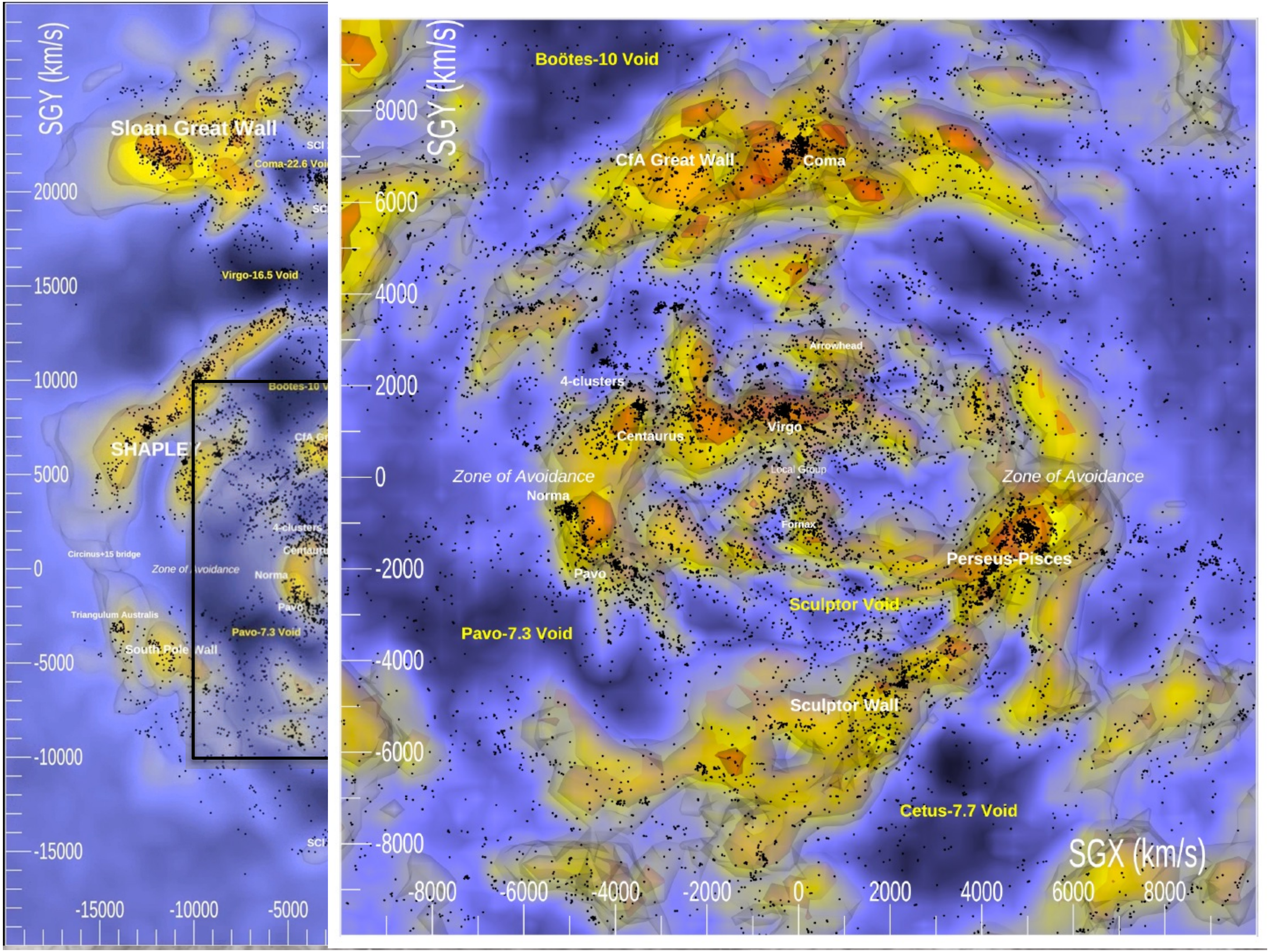
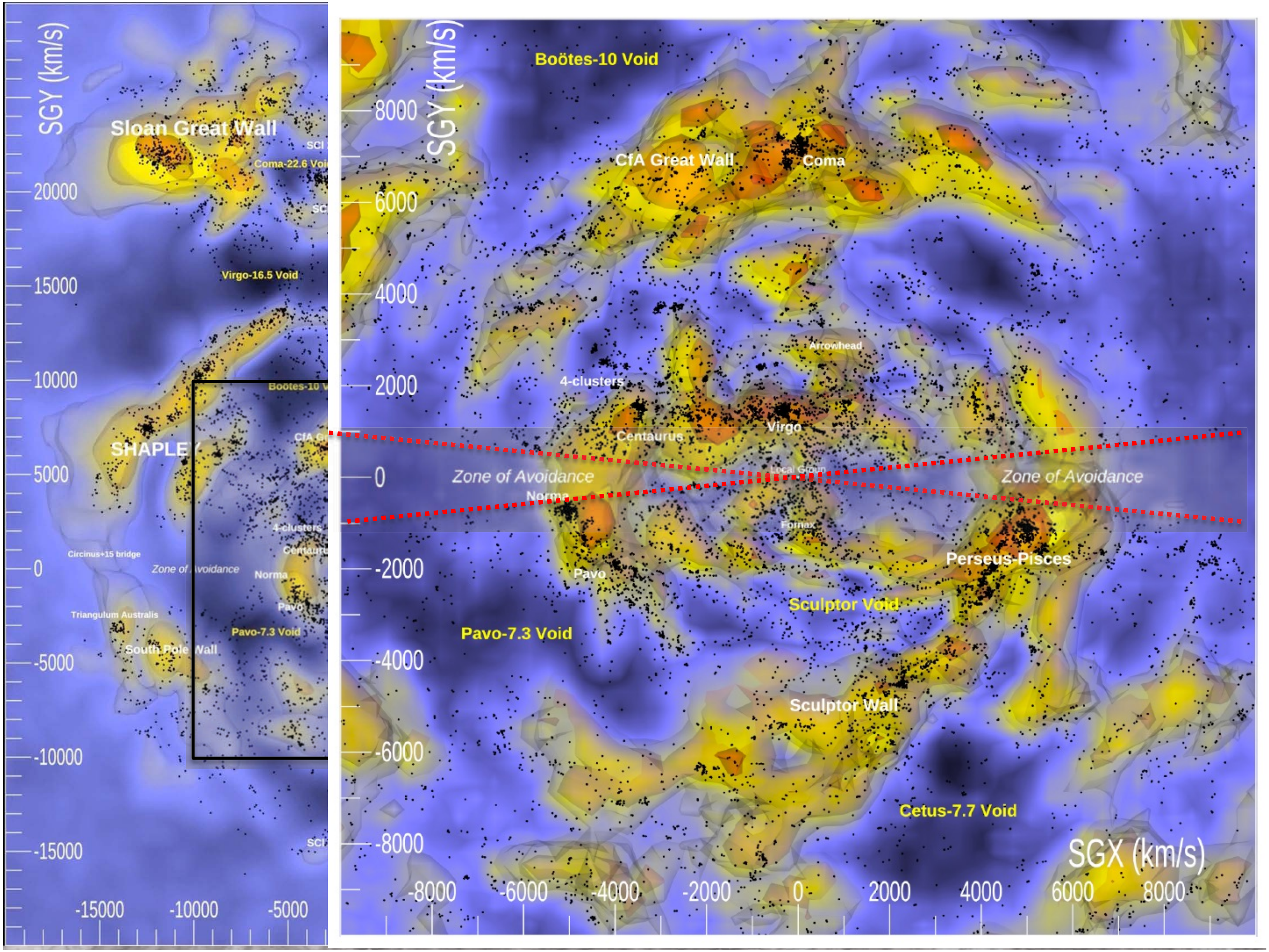
Zone of Avoidance
Triangulum Australis
Pavo
Perseus-Pisces
Sculptor Void
Pavo-7.3 Void
South Pole Wall
Sculptor Wall
Cetus-7.7 Void
SCI 216
Pisces supercluster
SCI 220
Pisces-Cetus supercluster


SGY (km/s)
Sloan Great Wall
20000
15000
Virgo-16.5 Void
10000
5000
Circinus+15 bridge
0
Norma
Pavo
Triangulum Australis
Pavo-7.3 Void
South Pole Wall
-5000
-10000
-15000
-15000
-10000
-5000
Boötes-10 Void
8000
SGY (km/s)
CfA Great Wall
Coma
6000
4000
Arrowhead
2000
4-clusters
Centaurus
Virgo
Local Group
0
Zone of Avoidance
Zone of Avoidance
Norma
Fornax
Perseus-Pisces
-2000
Pavo
Sculptor Void
Pavo-7.3 Void
-4000
Sculptor Wall
-6000
Cetus-7.7 Void
-8000
SGX (km/s)
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000



SGY (km/s)
Sloan Great Wall
Coma-22.6 Void
Virgo-16.5 Void
SHAPLEY
Circinus+15 bridge
Zone of Avoidance
Norma
Triangulum Australis
South Pole Wall
Pavo-7.3 Void
Pavo
4-clusters
20000
15000
10000
5000
0
-5000
-10000
-15000
-15000
-10000
-5000
Boötes-10 Void
CfA Great Wall
Coma
Arrowhead
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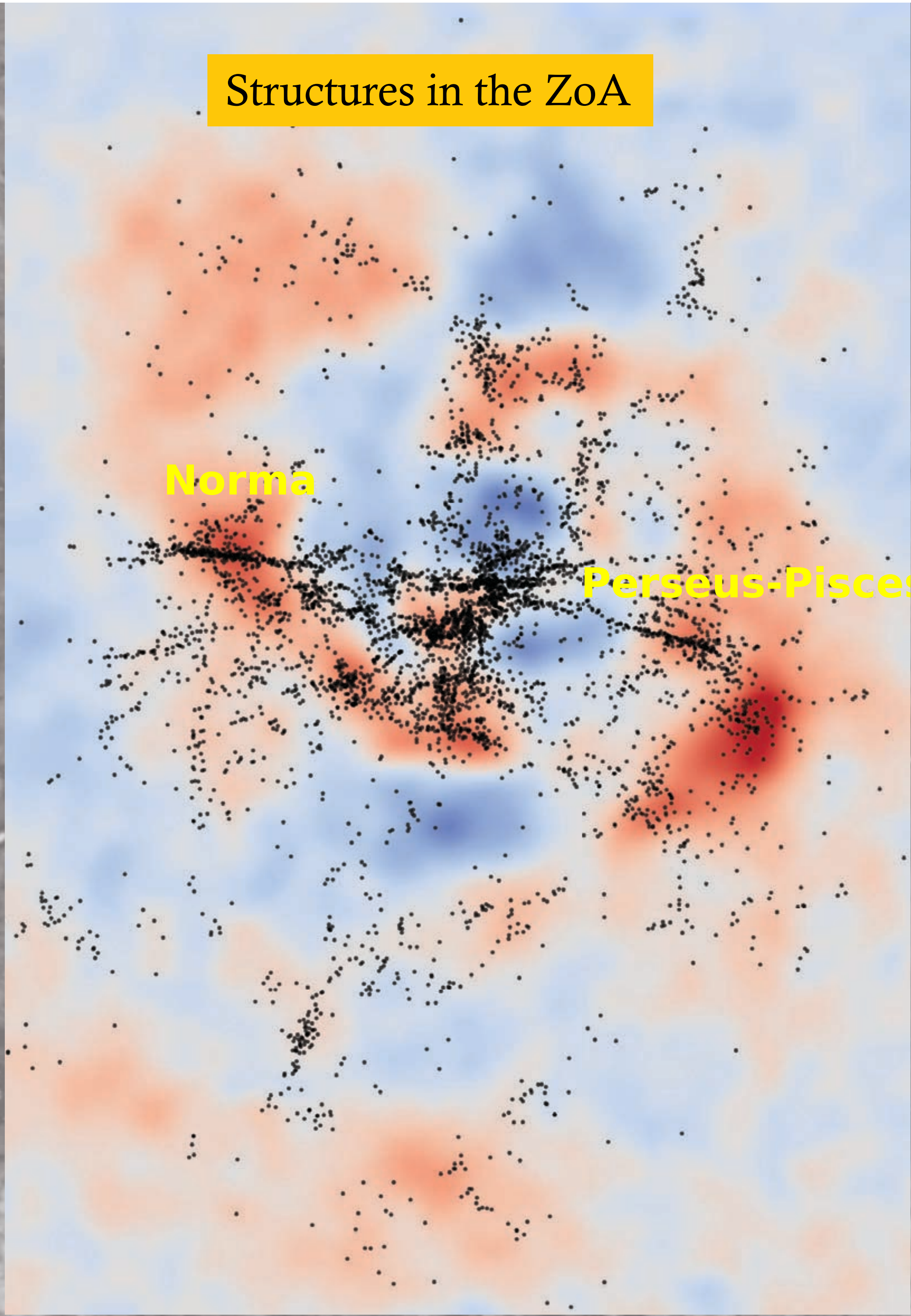
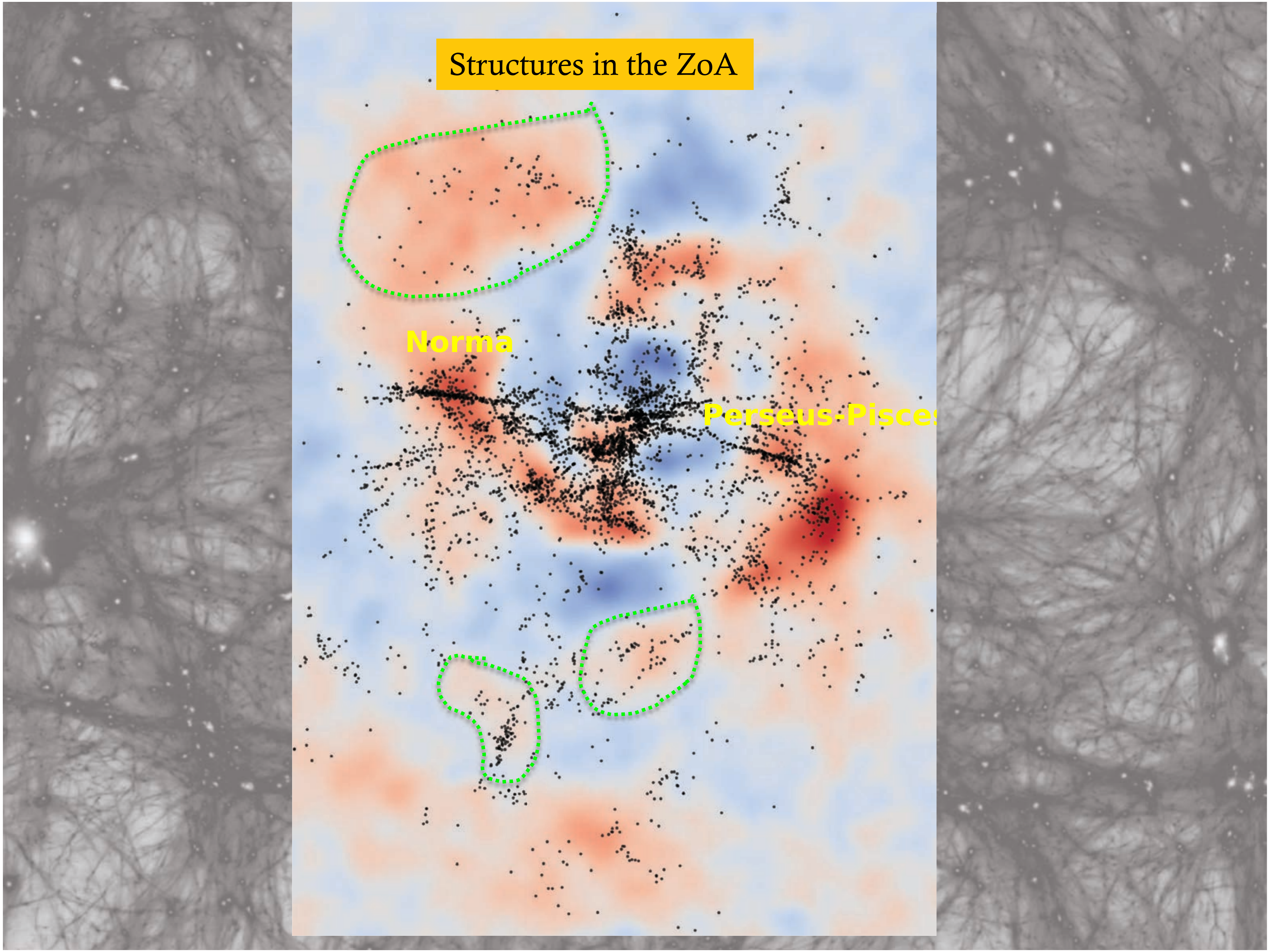
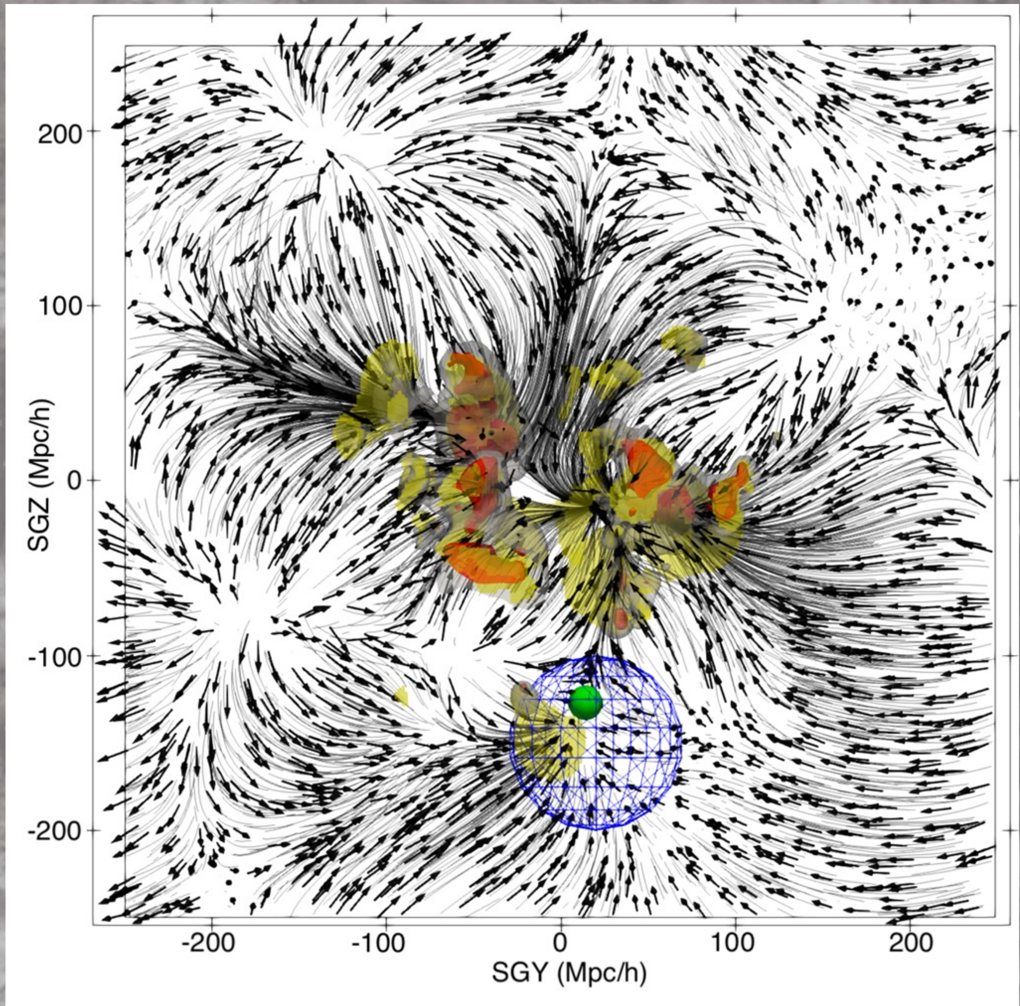
Centaurus
Virgo
Local Group
Zone of Avoidance
Zone of Avoidance
Norma
Fornax
Perseus-Pisces
Pavo
Sculptor Void
Pavo-7.3 Void
Sculptor Wall
Cetus-7.7 Void
SGX (km/s)
8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000

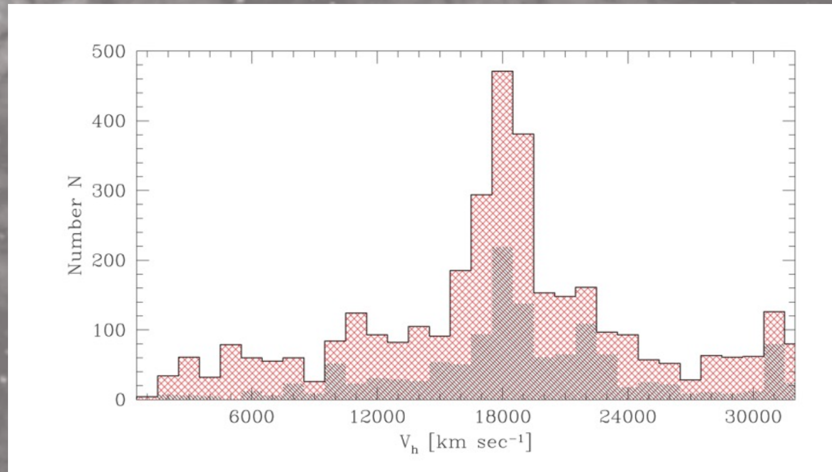
Structures in the ZoA

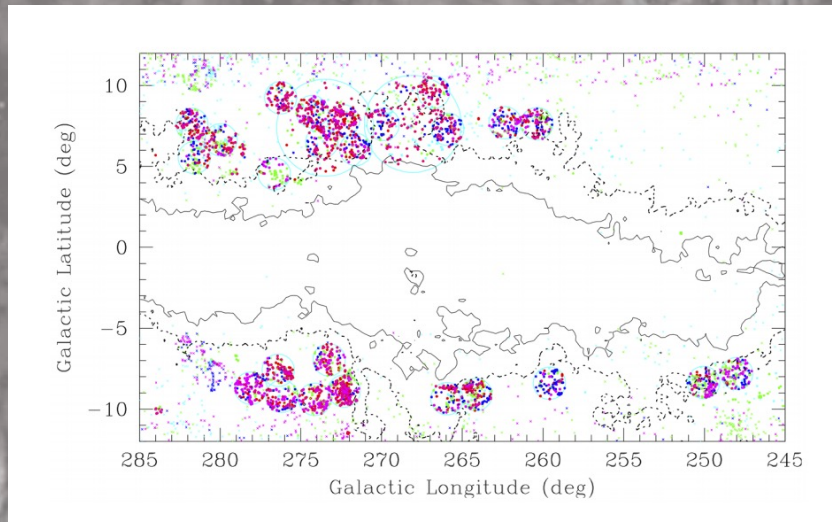



Structures in the ZoA
Norma
Perseus-Pisces

Velo super cluster : in the ZOA

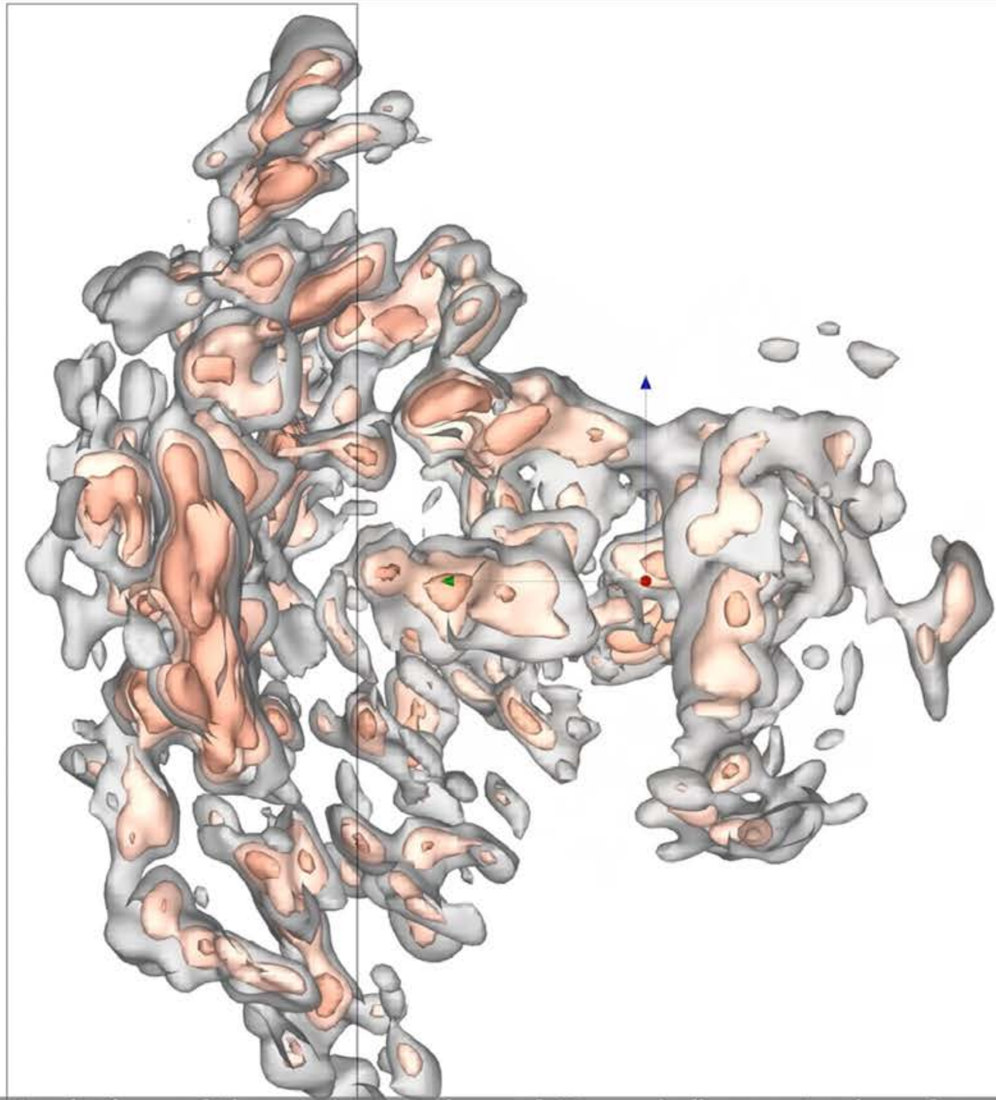




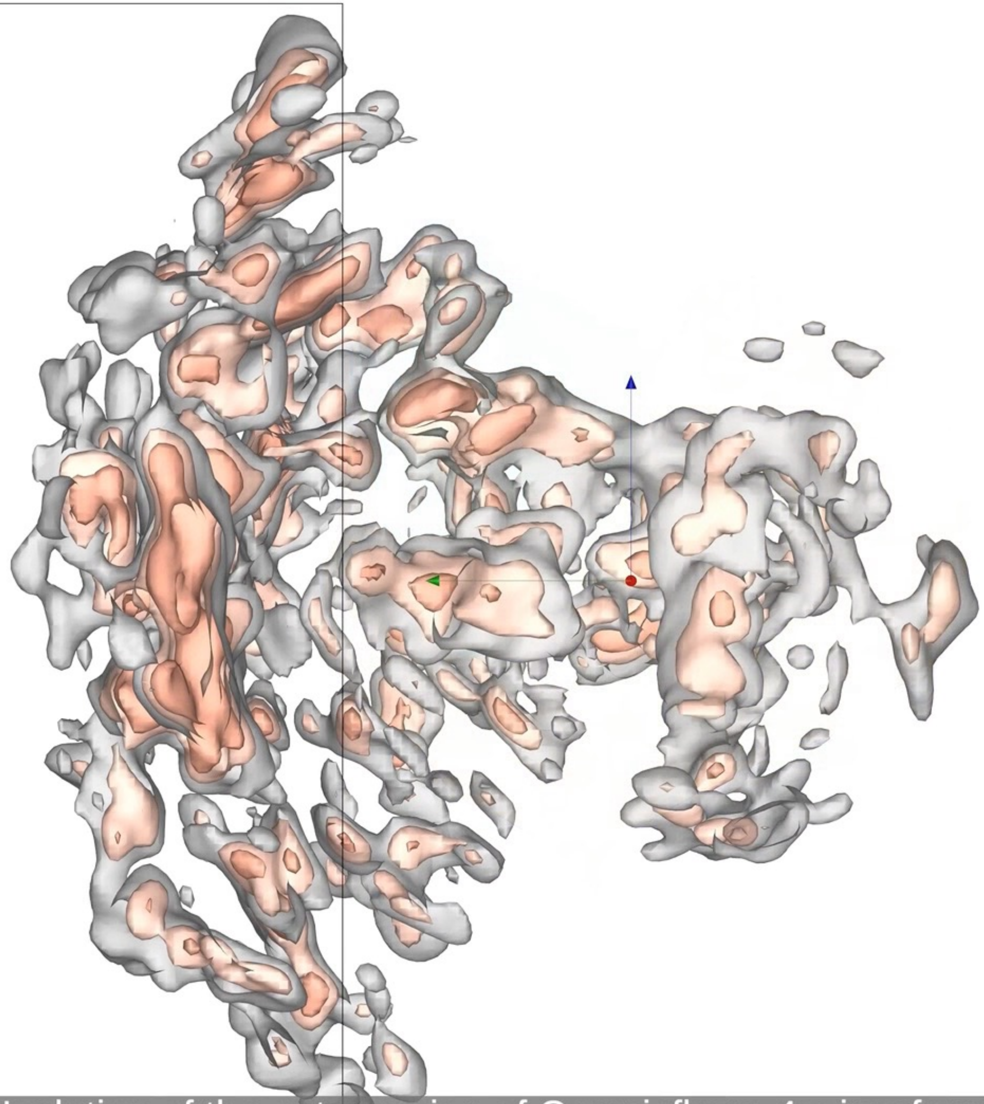


Courtois + NL et al 2019

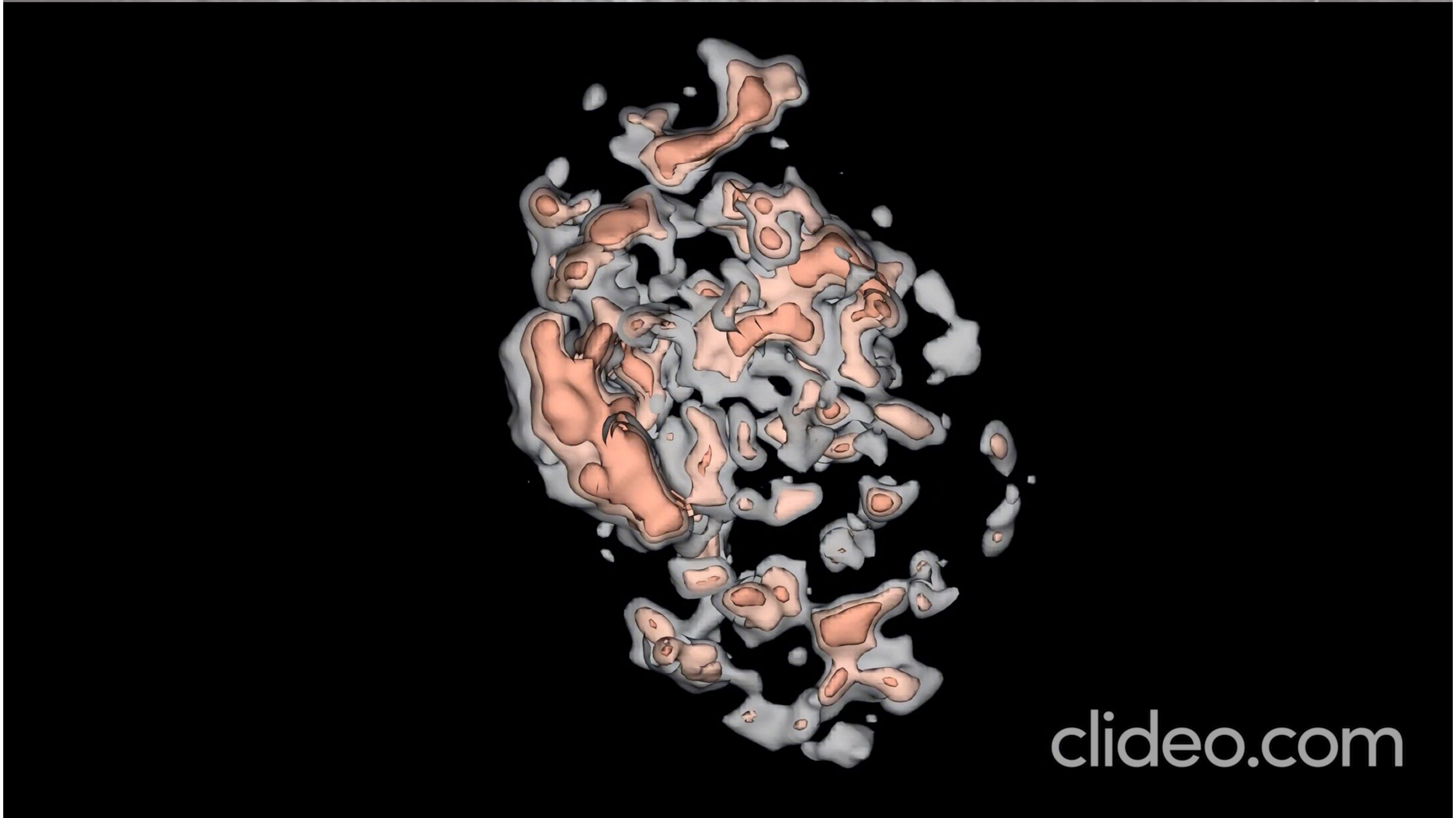
Kraan-Korteweeg 2017



Isolation of the outer region of Cosmicflows-4; view from negative SGX



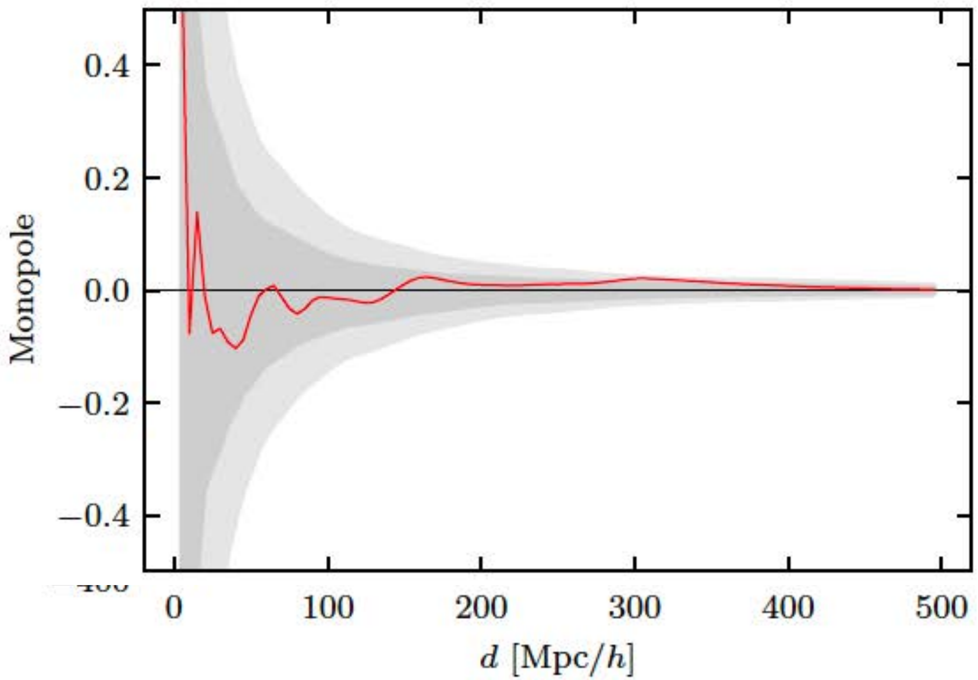
Isolation of the outer region of Cosmicflows-4; view from negative SGX

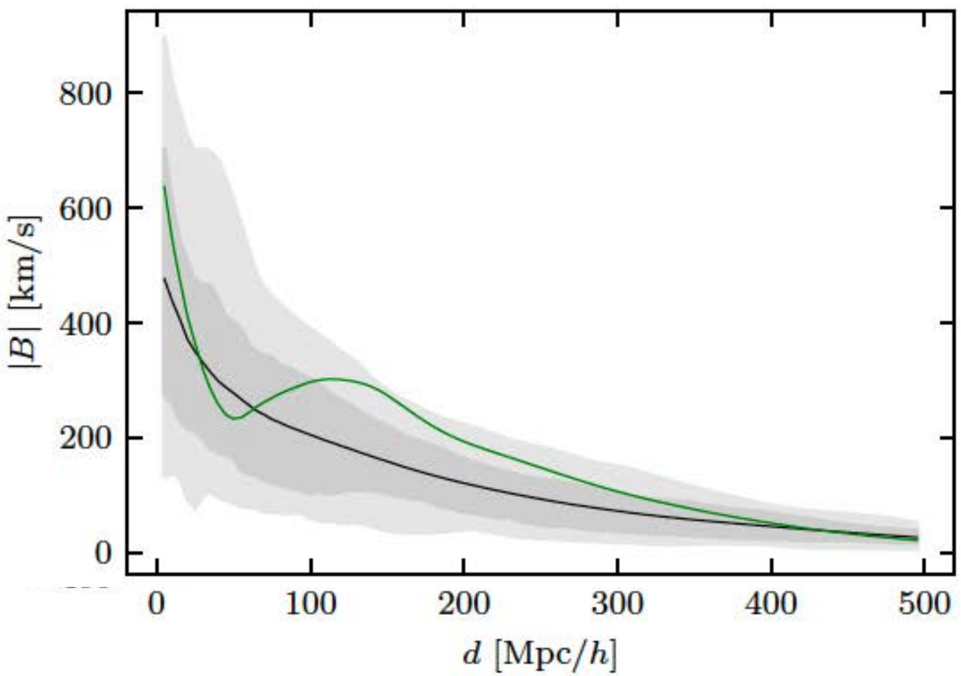

clideo.com

The Bulk Flow

The cosmic monopole

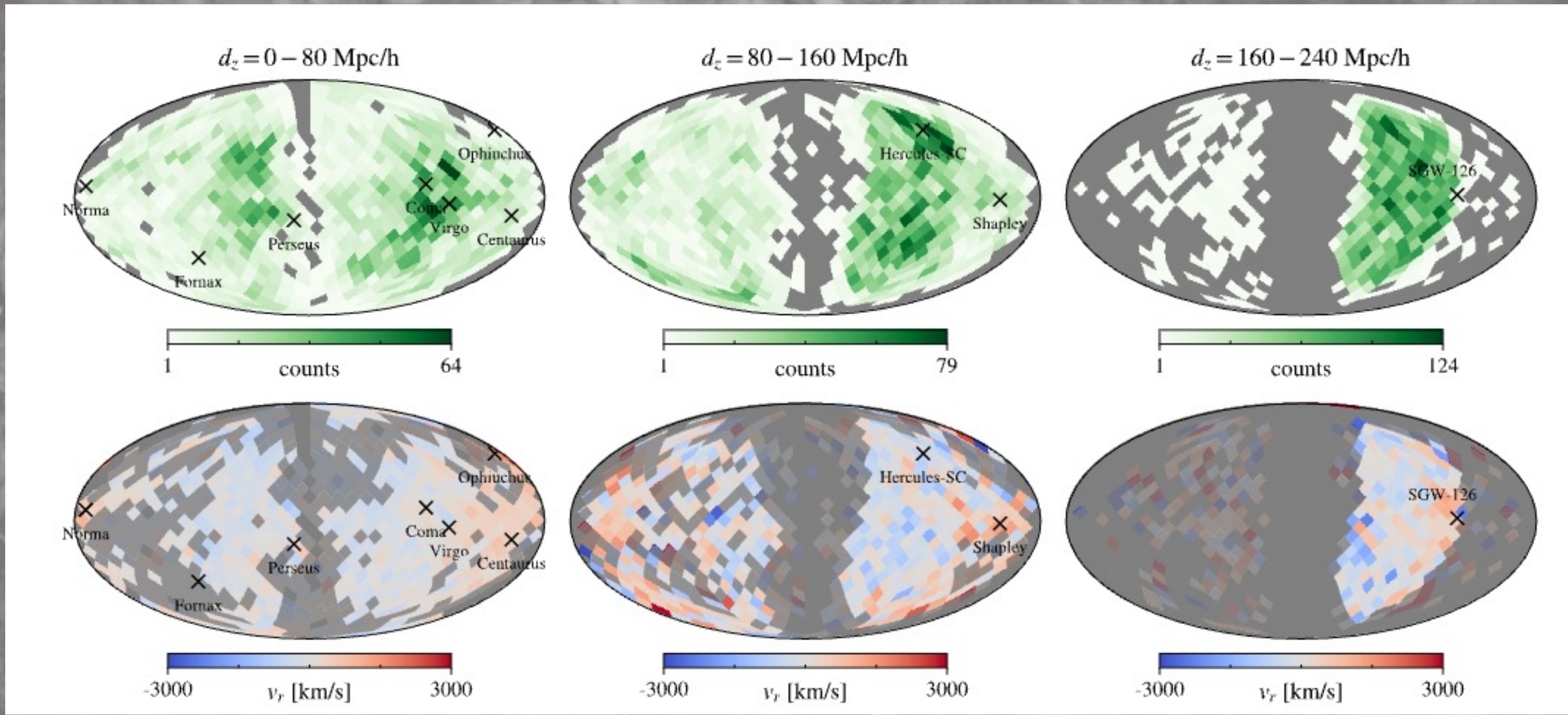
The cosmic dipole (bulk flow)



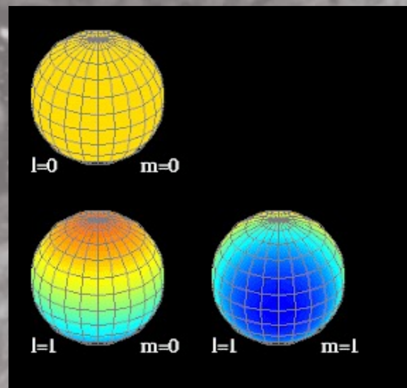


Valade, NL + 2022

Measuring the cosmic velocity field

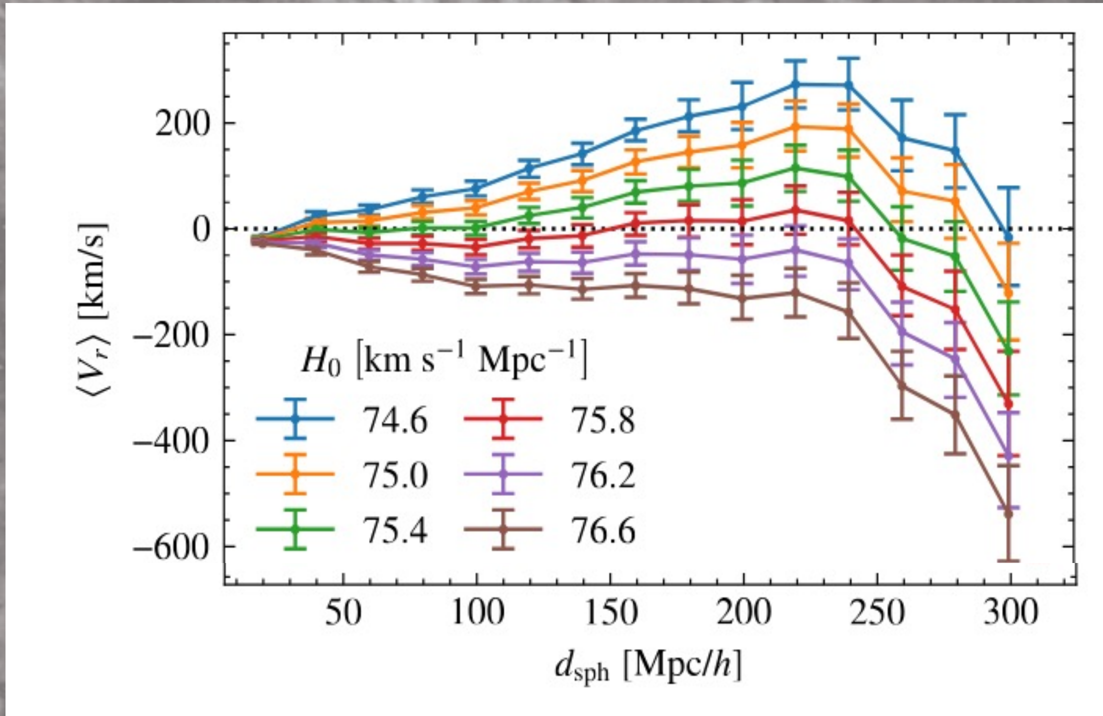


Fit spherical harmonics of the velocity field to shells



Duangchan, NL *in prep*

Measuring the cosmic velocity field



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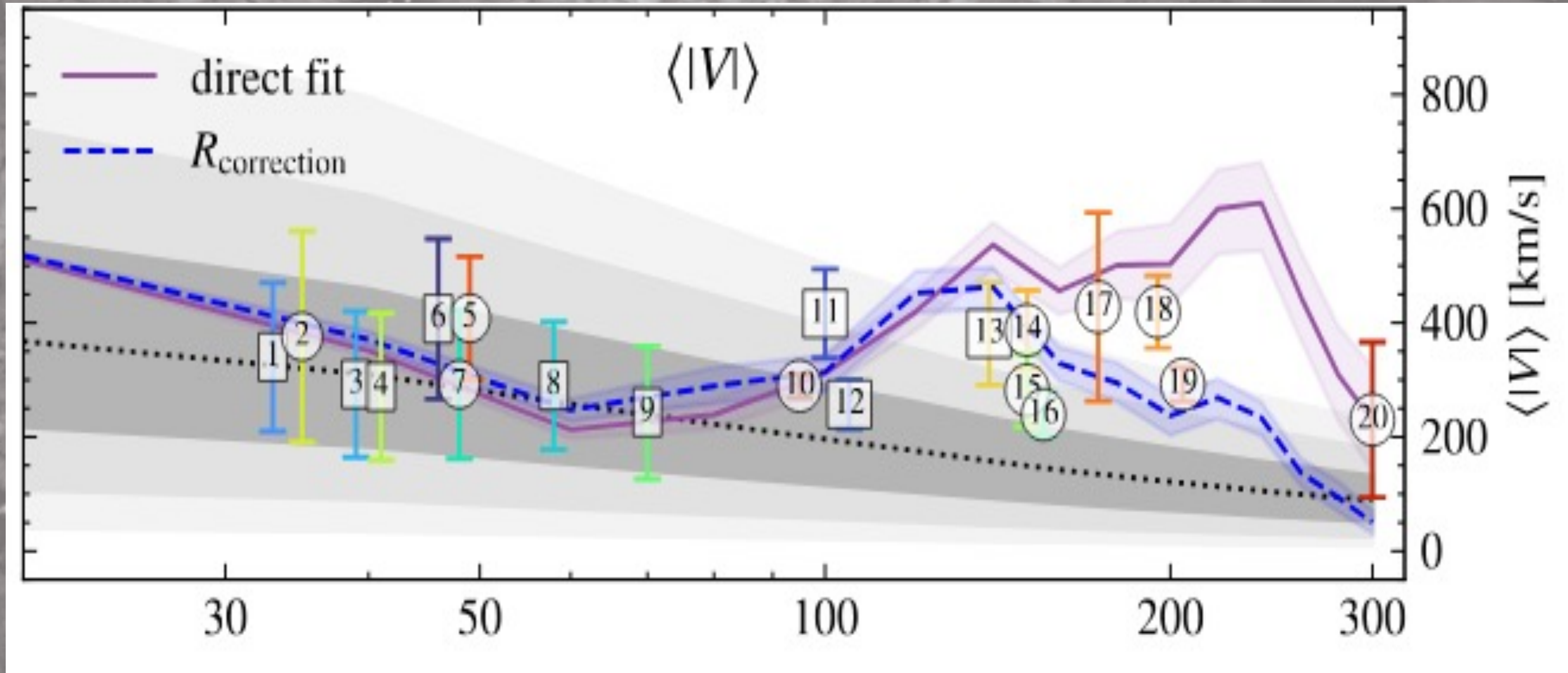
Measuring the cosmic velocity field



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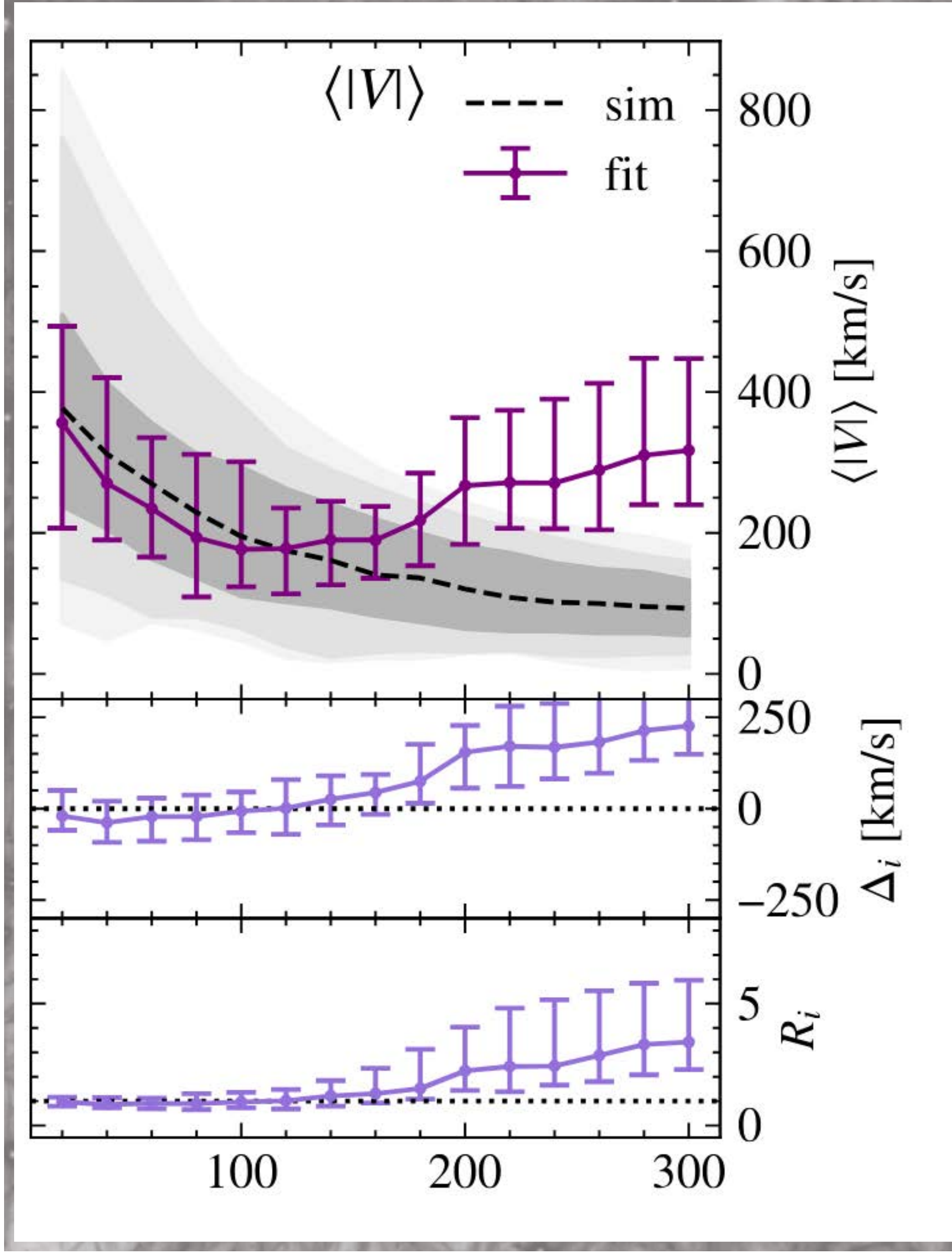

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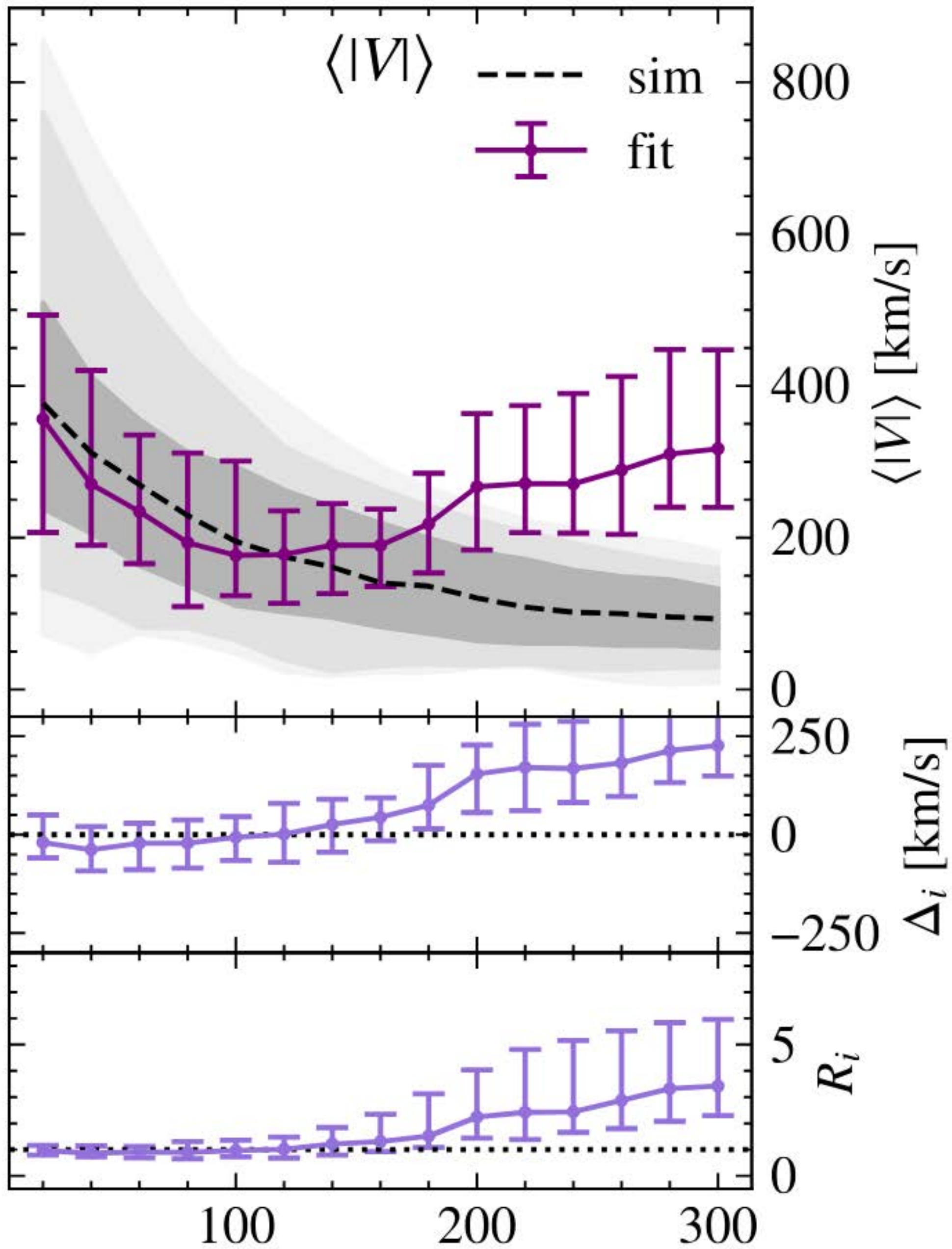

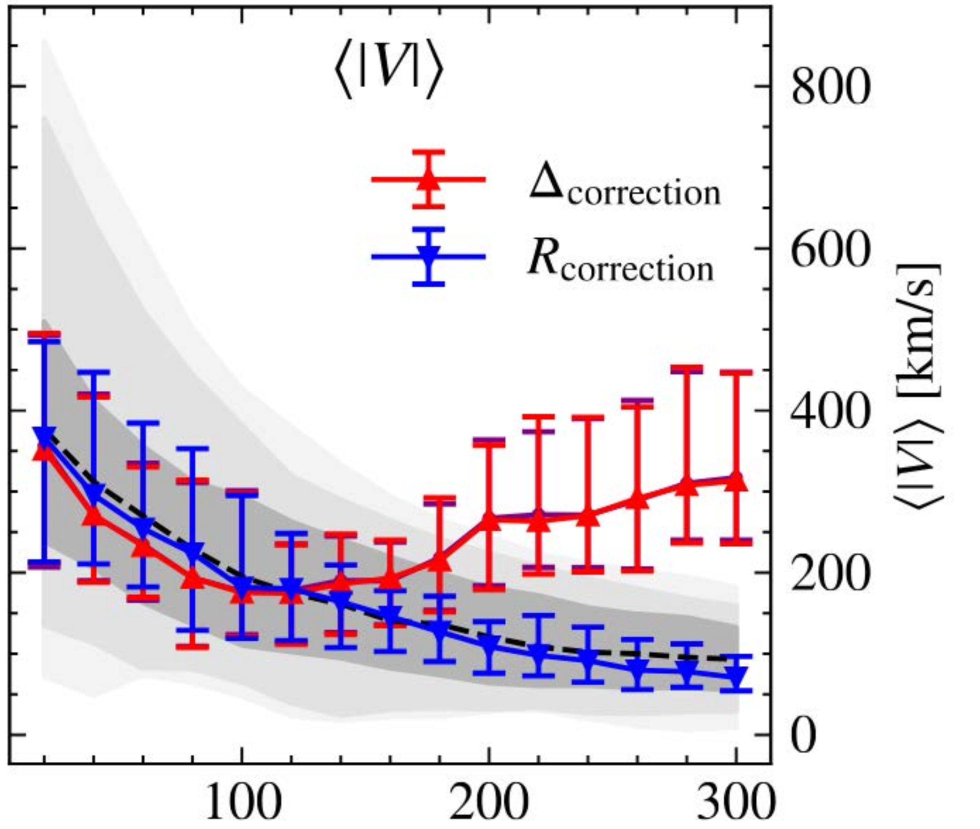

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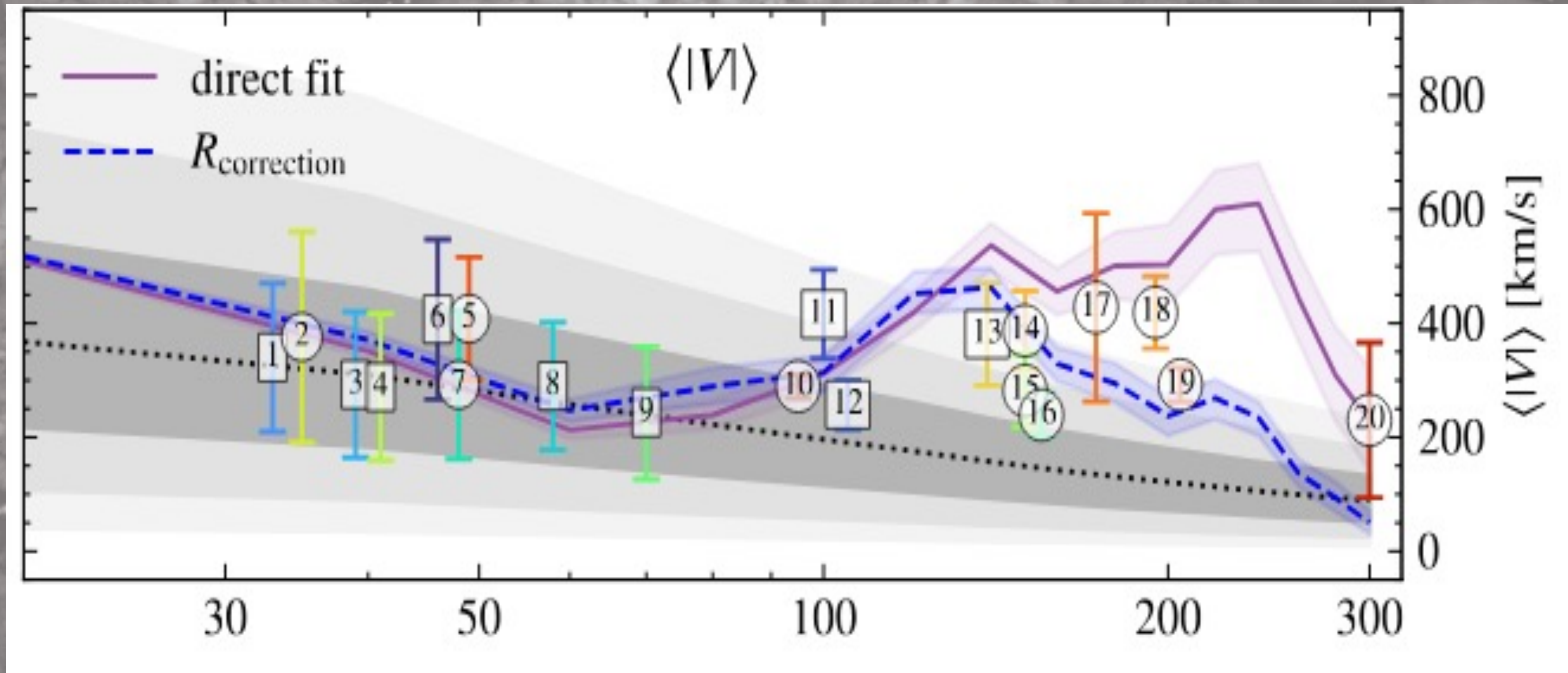

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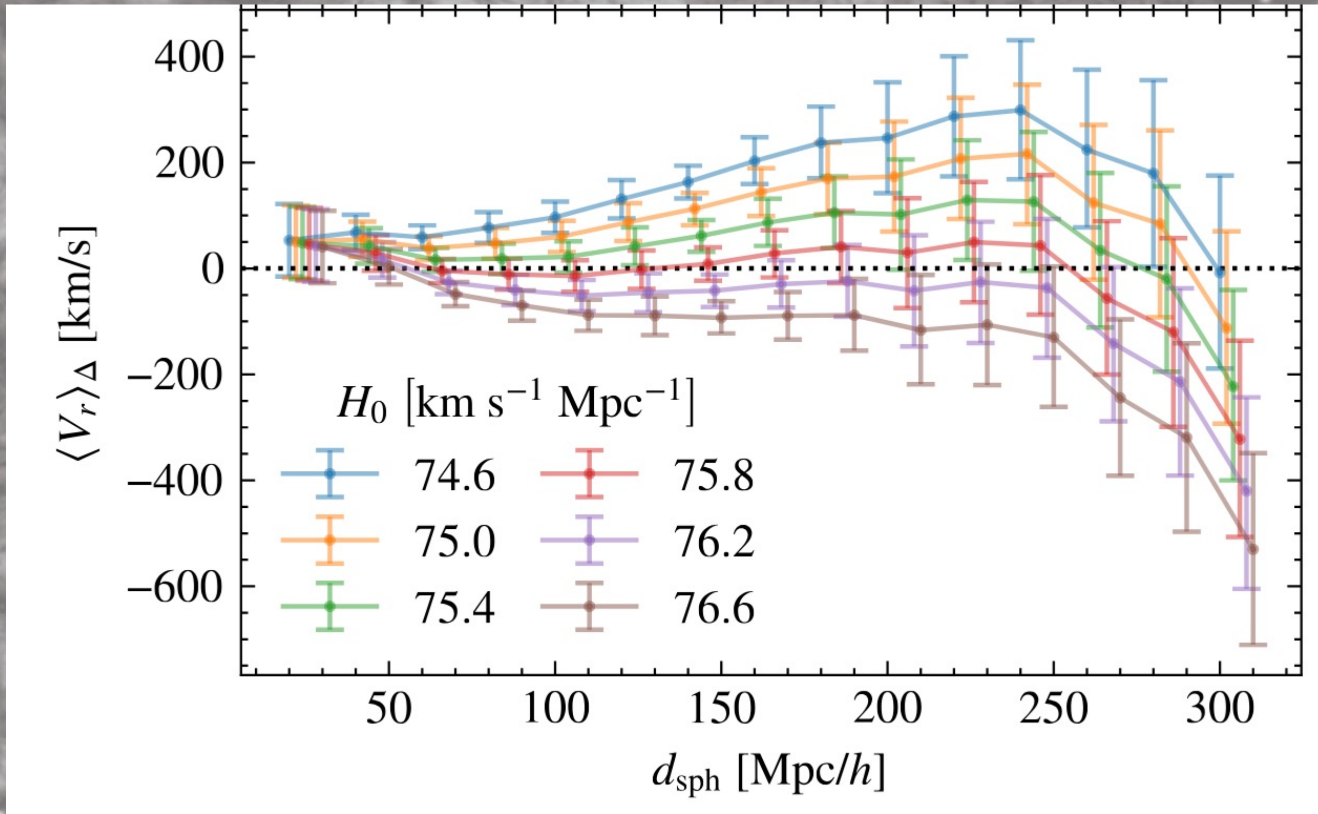
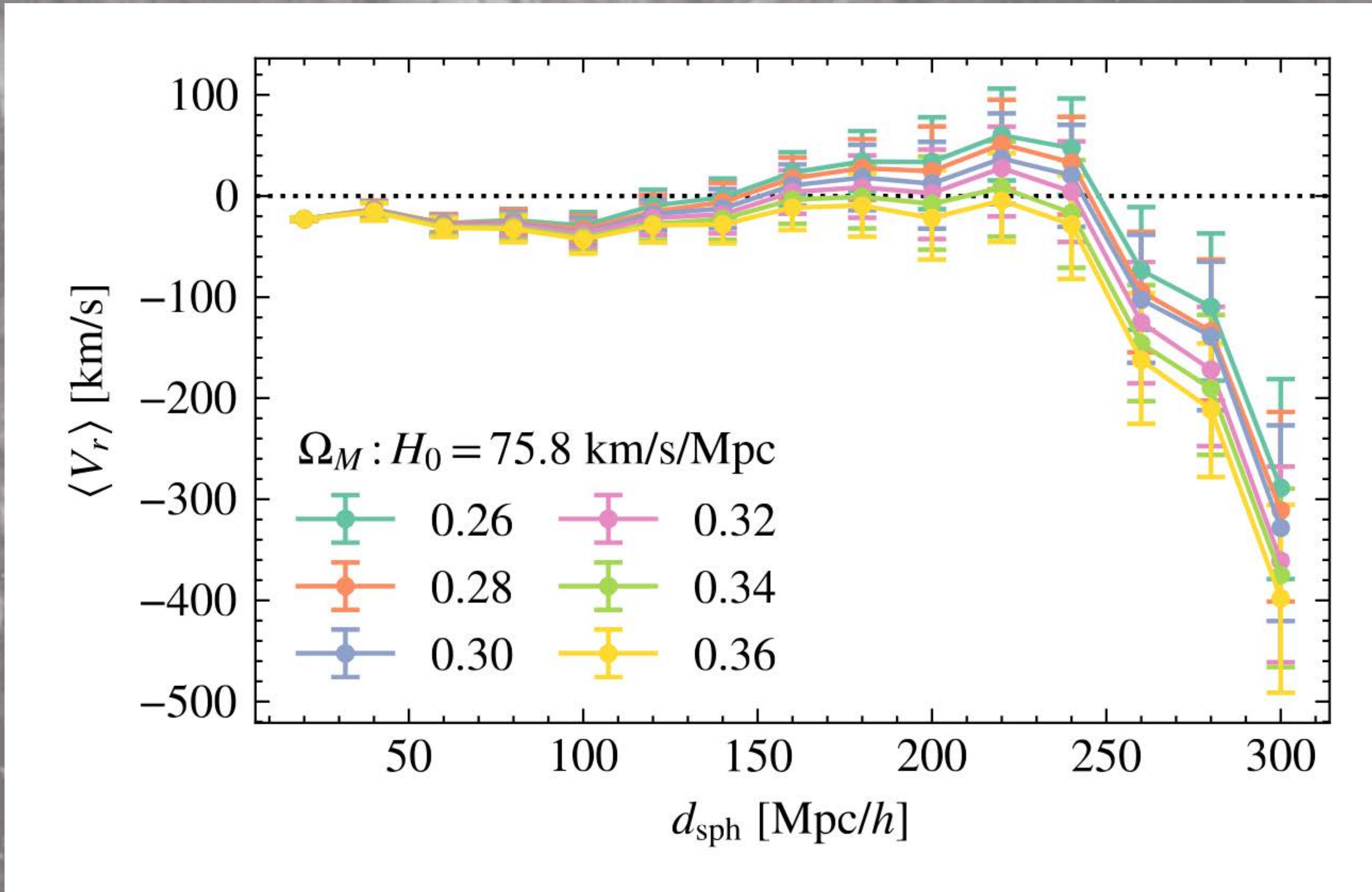
Measuring the cosmic velocity field



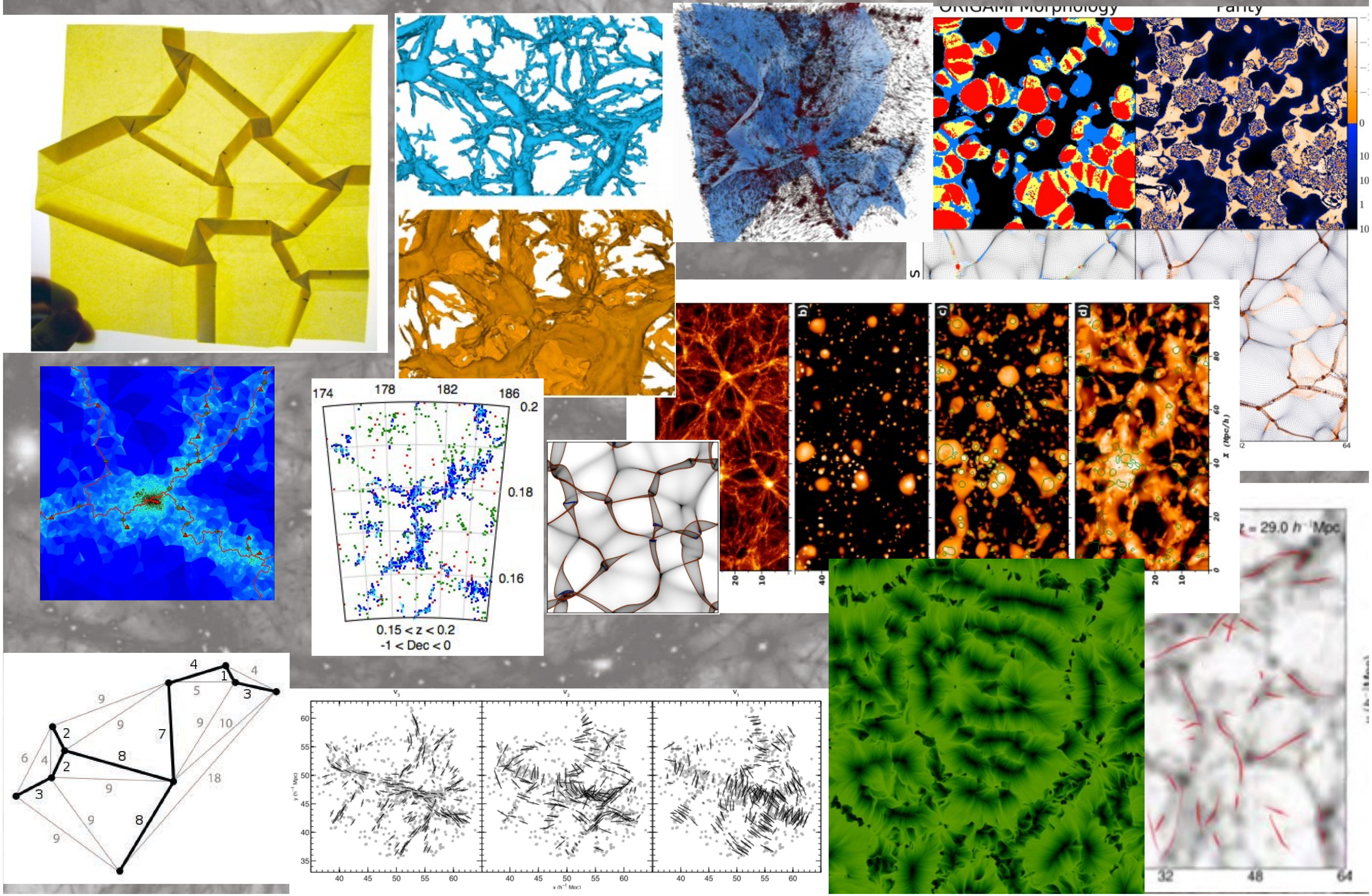
Duangchan, NL *in prep*

Measuring the cosmic velocity field



Duangchan, NL *in prep*

The Cosmic Web



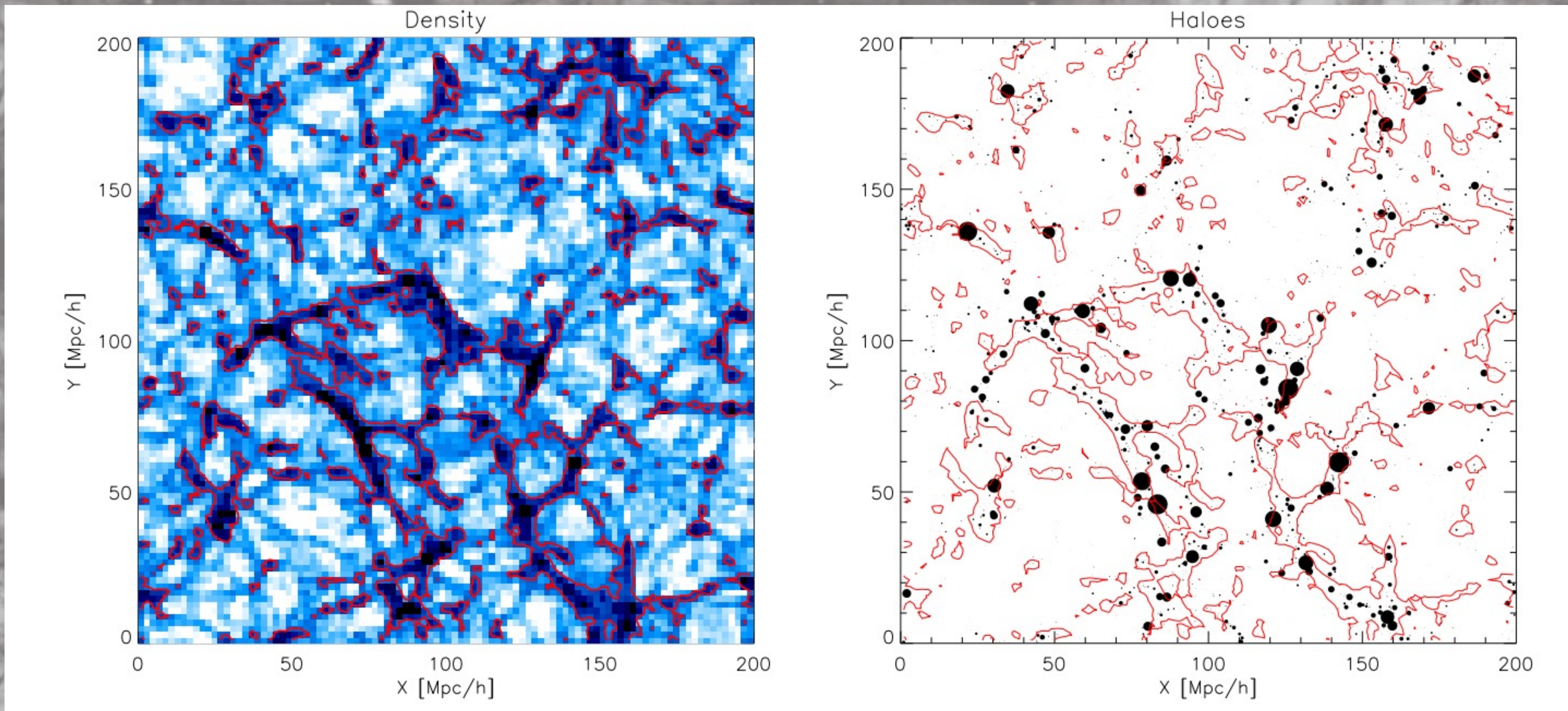
The cosmic web is a vast network of interconnected filaments, nodes, and voids, composed of dark matter, galaxies and gas.

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **473,** 1195–1217 (2018)
Advance Access publication 2017 August 3
doi:10.1093/mnras/stx1976

Tracing the cosmic web

Noam I. Libeskind,[1★] Rien van de Weygaert,[2] Marius Cautun,[3] Bridget Falck,[4] Elmo Tempel,[1,5] Tom Abel,[6,7] Mehmet Alpaslan,[8] Miguel A. Aragón-Calvo,[9] Jaime E. Forero-Romero,[10] Roberto Gonzalez,[11,12] Stefan Gottlöber,[1] Oliver Hahn,[13] Wojciech A. Hellwing,[14,15] Yehuda Hoffman,[16] Bernard J. T. Jones,[2] Francisco Kitaura,[17,18] Alexander Knebe,[19,20] Serena Manti,[21] Mark Neyrinck,[3] Sebastián E. Nuza,[1,22] Nelson Padilla,[11,12] Erwin Platen,[2] Nesar Ramachandra,[23] Aaron Robotham,[24] Enn Saar,[5] Sergei Shandarin,[23] Matthias Steinmetz,[1] Radu S. Stoica,[25,26] Thierry Sousbie[27] and Gustavo Yepes[18]



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doi:10.1093/mnras/stx1976

Tracing the cosmic web

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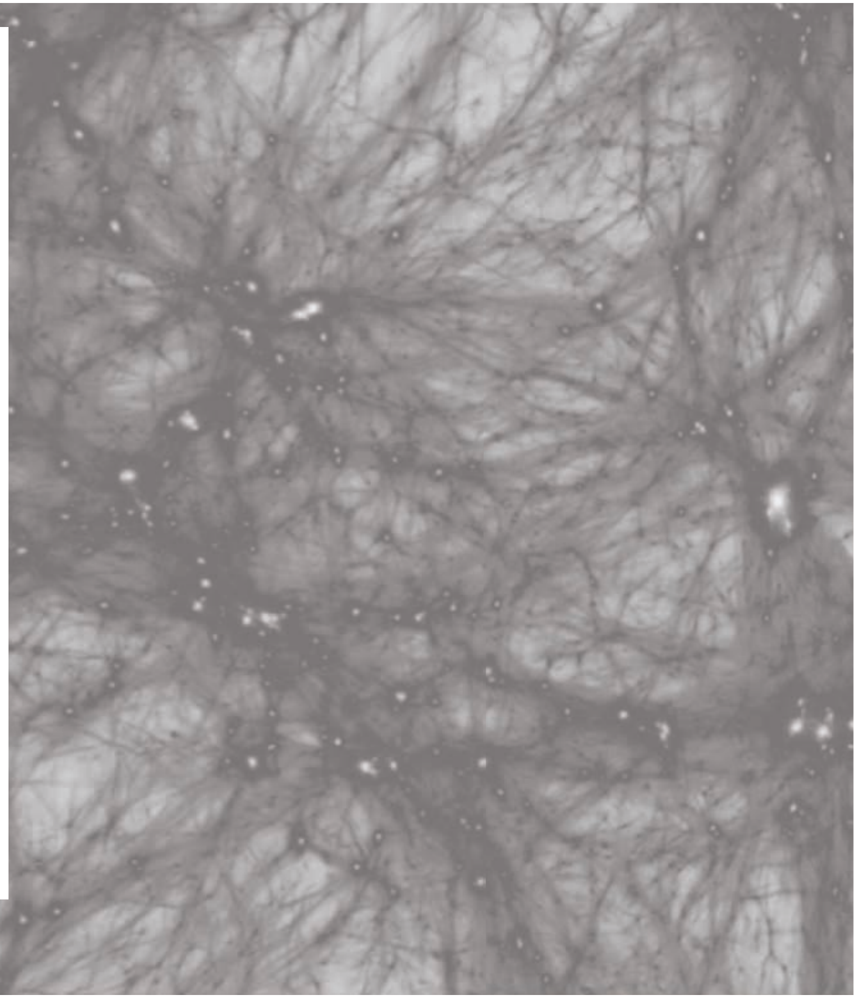
In the spirit of previous structure finder comparison projects (Colberg et al. 2008; Knebe et al. 2011, etc.), we present a comparison of cosmic-web identification codes and philosophies. However, our comparison differs significantly from e.g. the seminal Santa Barbara comparison project (Frenk et al. 1999) or other tests of codes which purport to model the same physical process (e.g. Scannapieco et al. 2012; Knebe et al. 2013). Instead, the methods compared here were developed for very different purposes, to be applied to different kinds of data and with different goals in mind. Some of the methods are based on treating galaxies (haloes) as points; while others were developed to be applied to density or velocity fields. Furthermore, unlike halo finders seeking collapsed or bound objects, there is no robust analytical theory (such as the spherical top hat collapse model of Sheth & Tormen 1999) which we may use as a guide for how we expect different cosmic-web finders to behave. Therefore, we enter into this comparison fully expecting large disagreements between the methods examined.



The cosmic web is a vast network of interconnected filaments, nodes, and voids, composed of dark matter, galaxies and gas.

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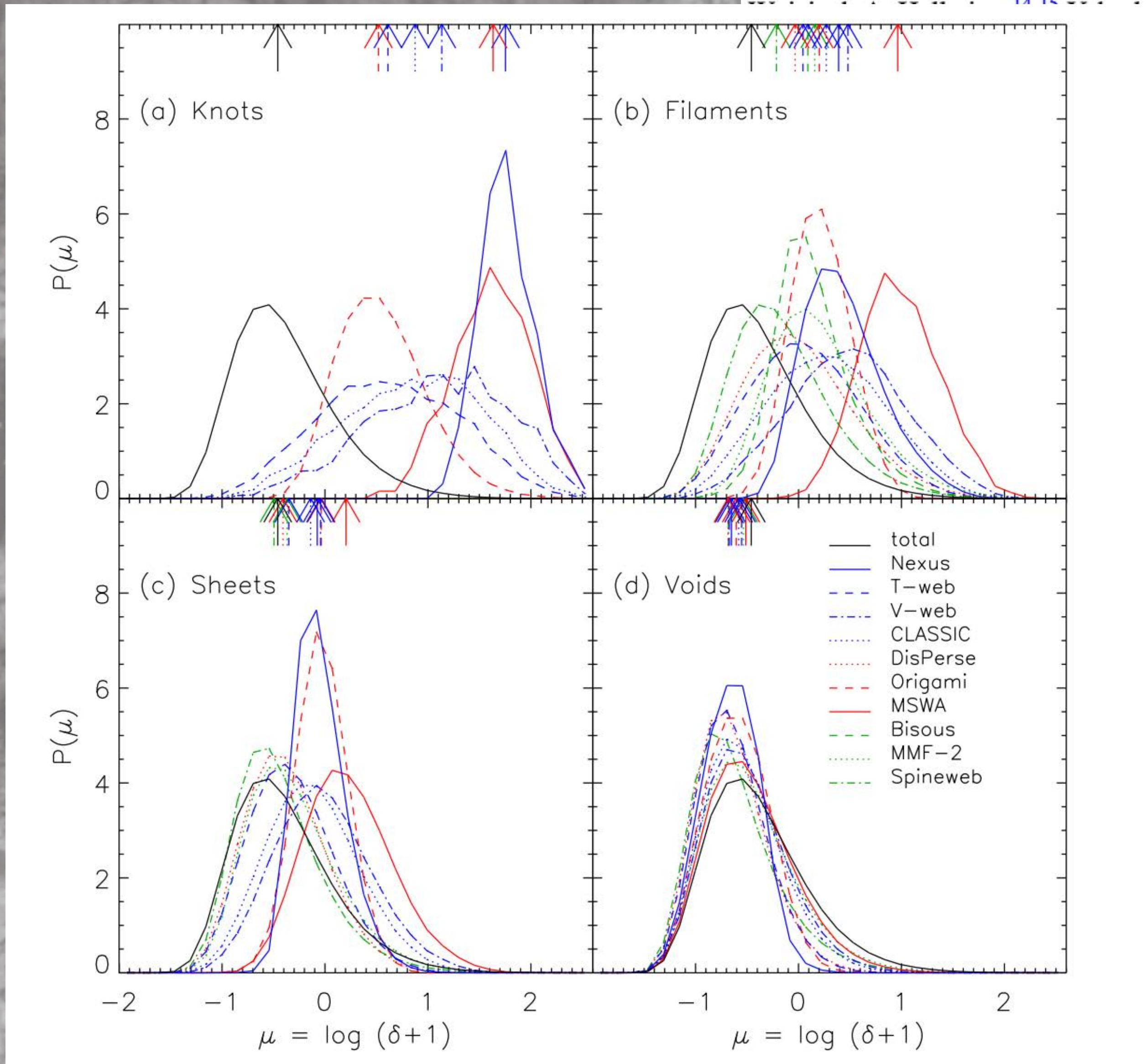

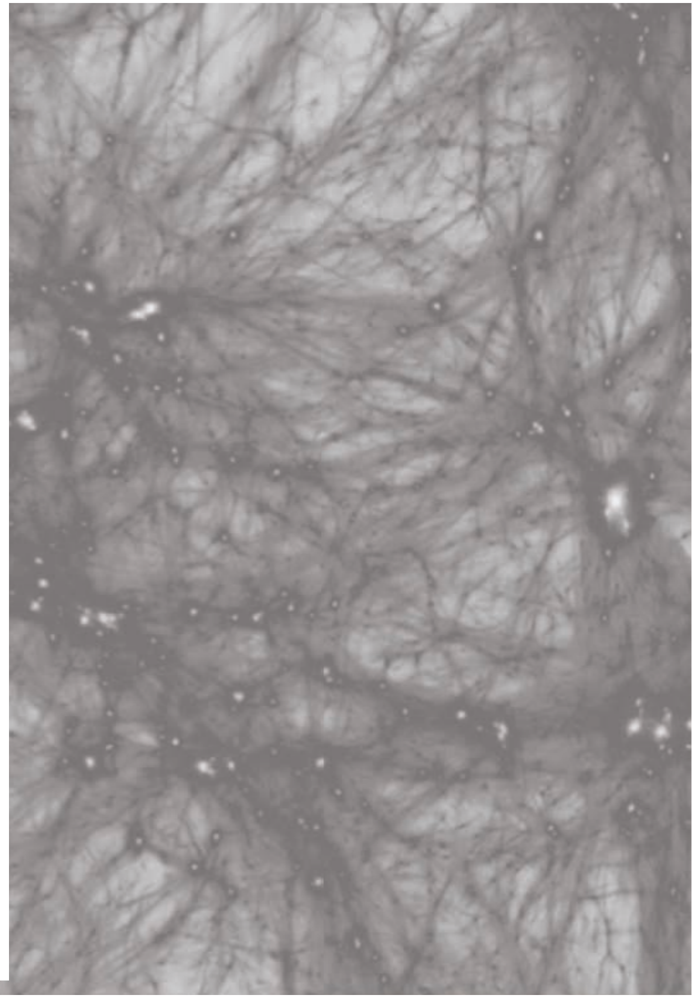

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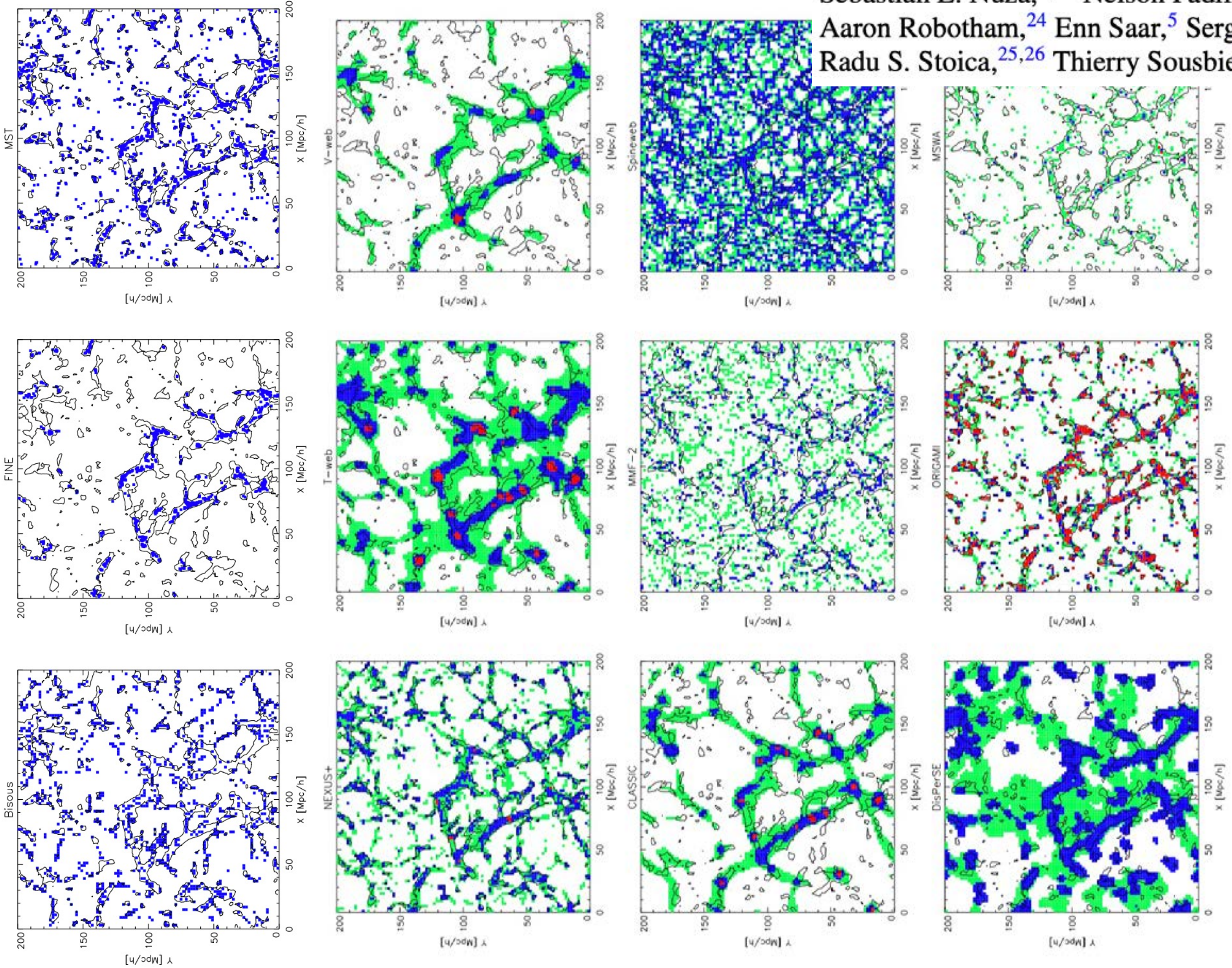

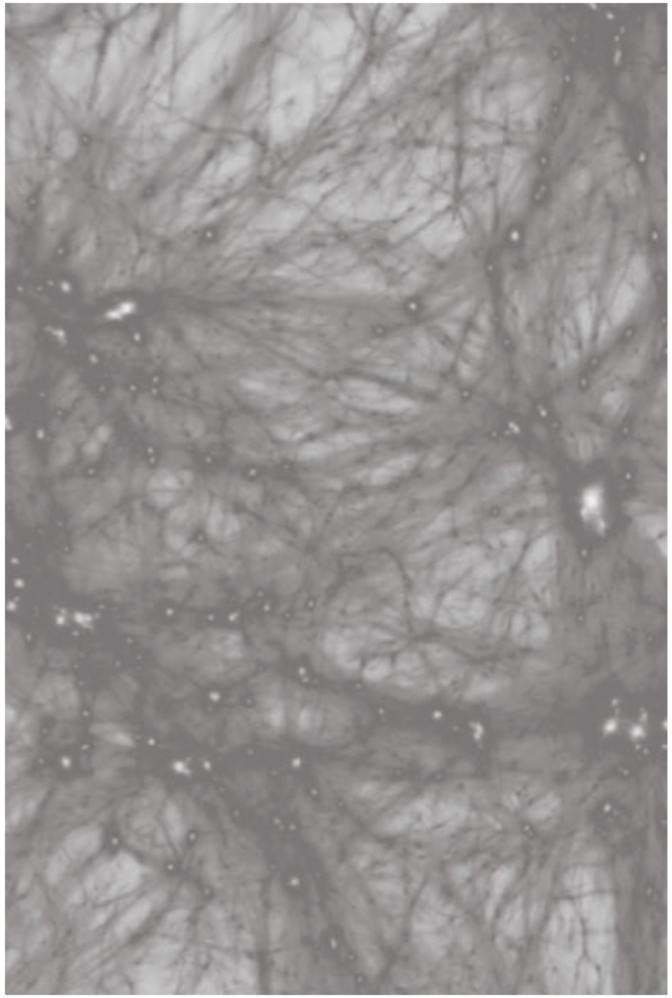

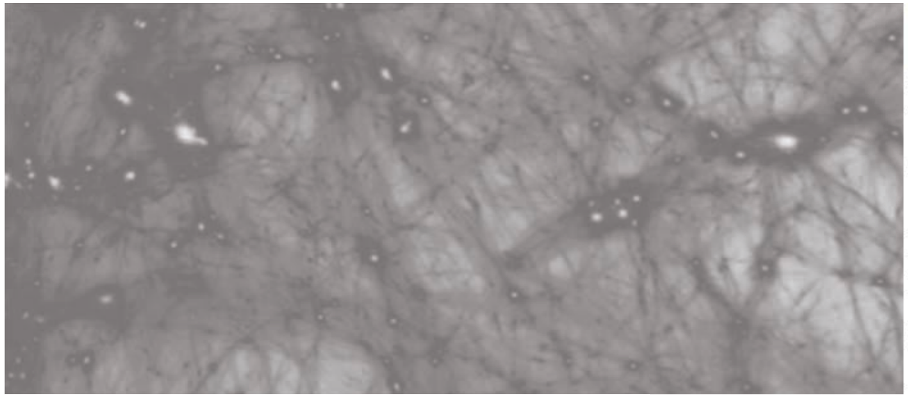

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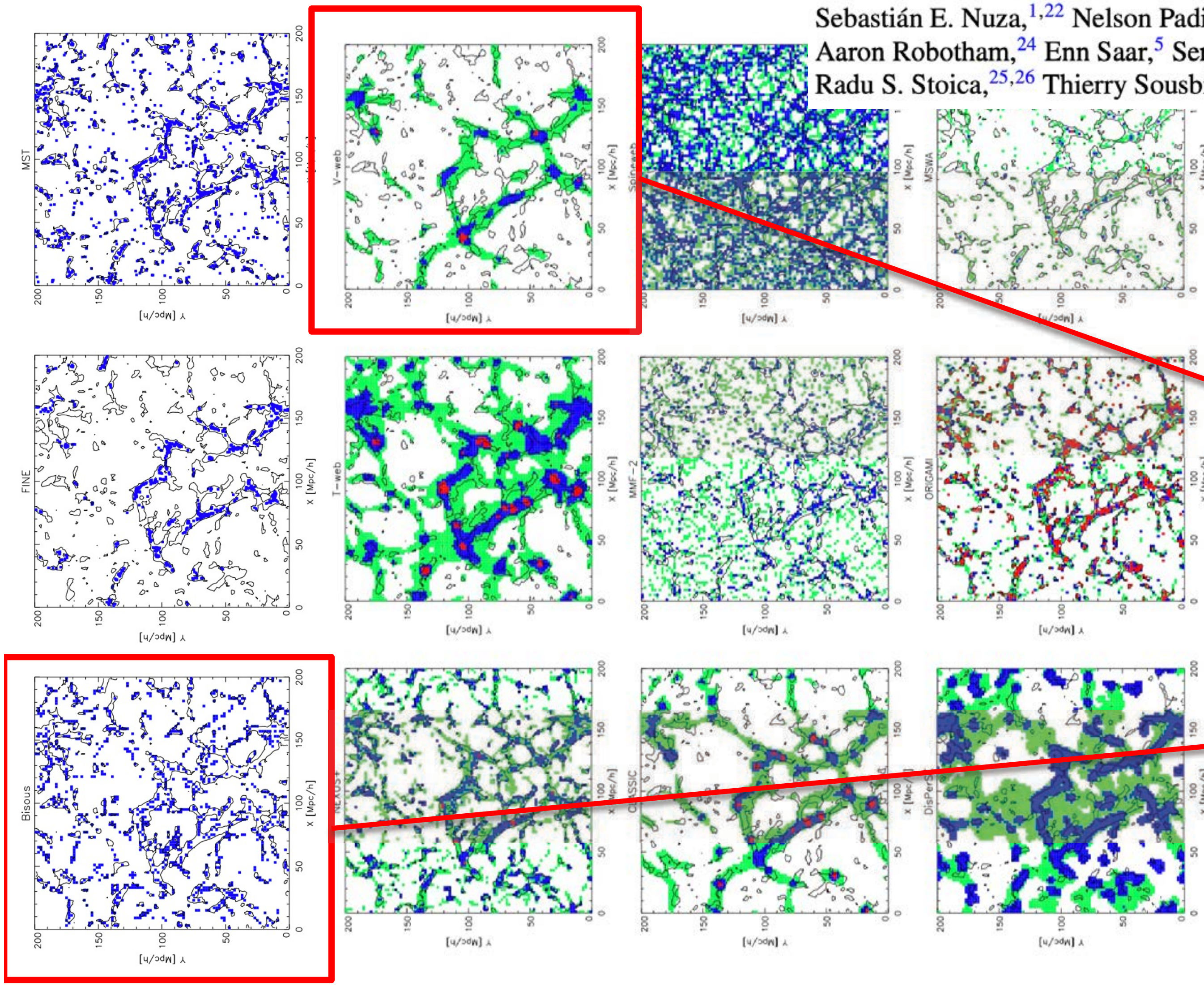
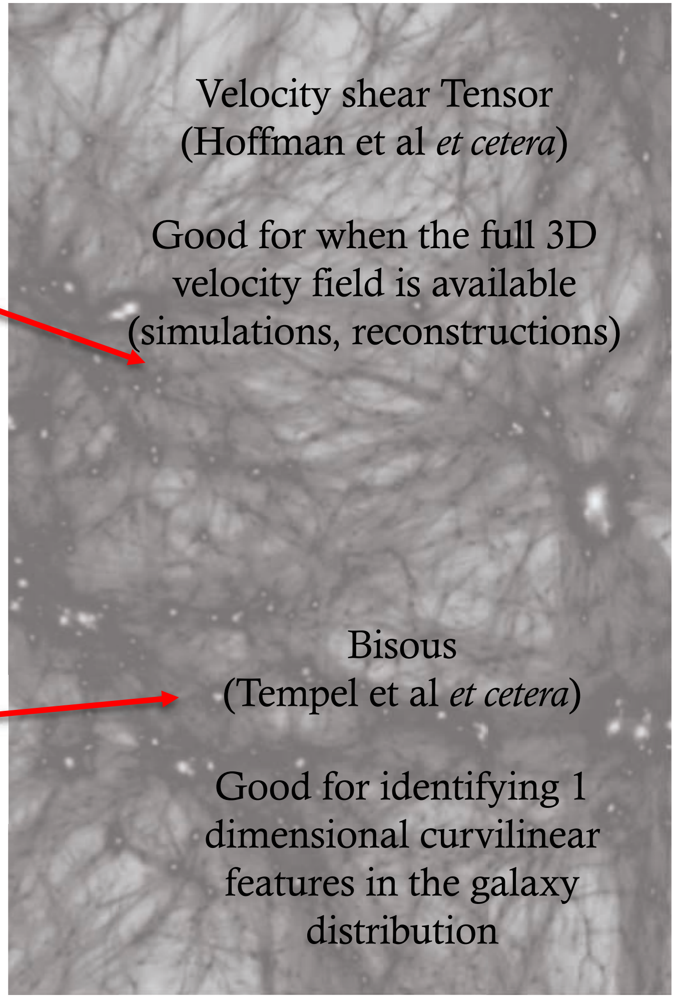




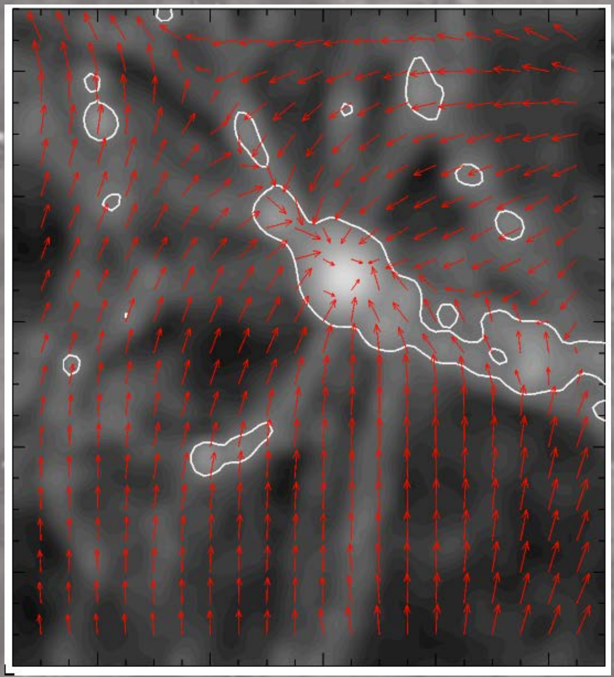
Velocity shear Tensor
(Hoffman et al *et cetera*)

Good for when the full 3D velocity field is available (simulations, reconstructions)

Bisous
(Tempel et al *et cetera*)

Good for identifying 1 dimensional curvilinear features in the galaxy distribution

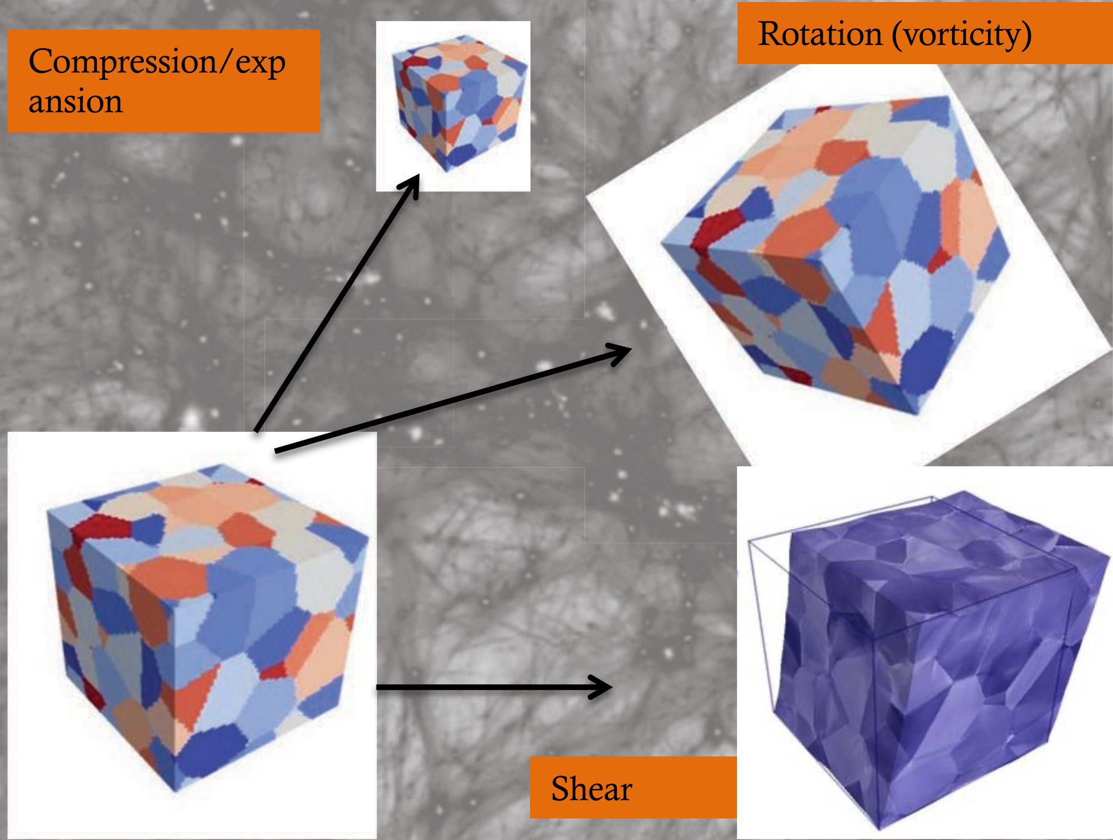
Velocity Shear Tensor

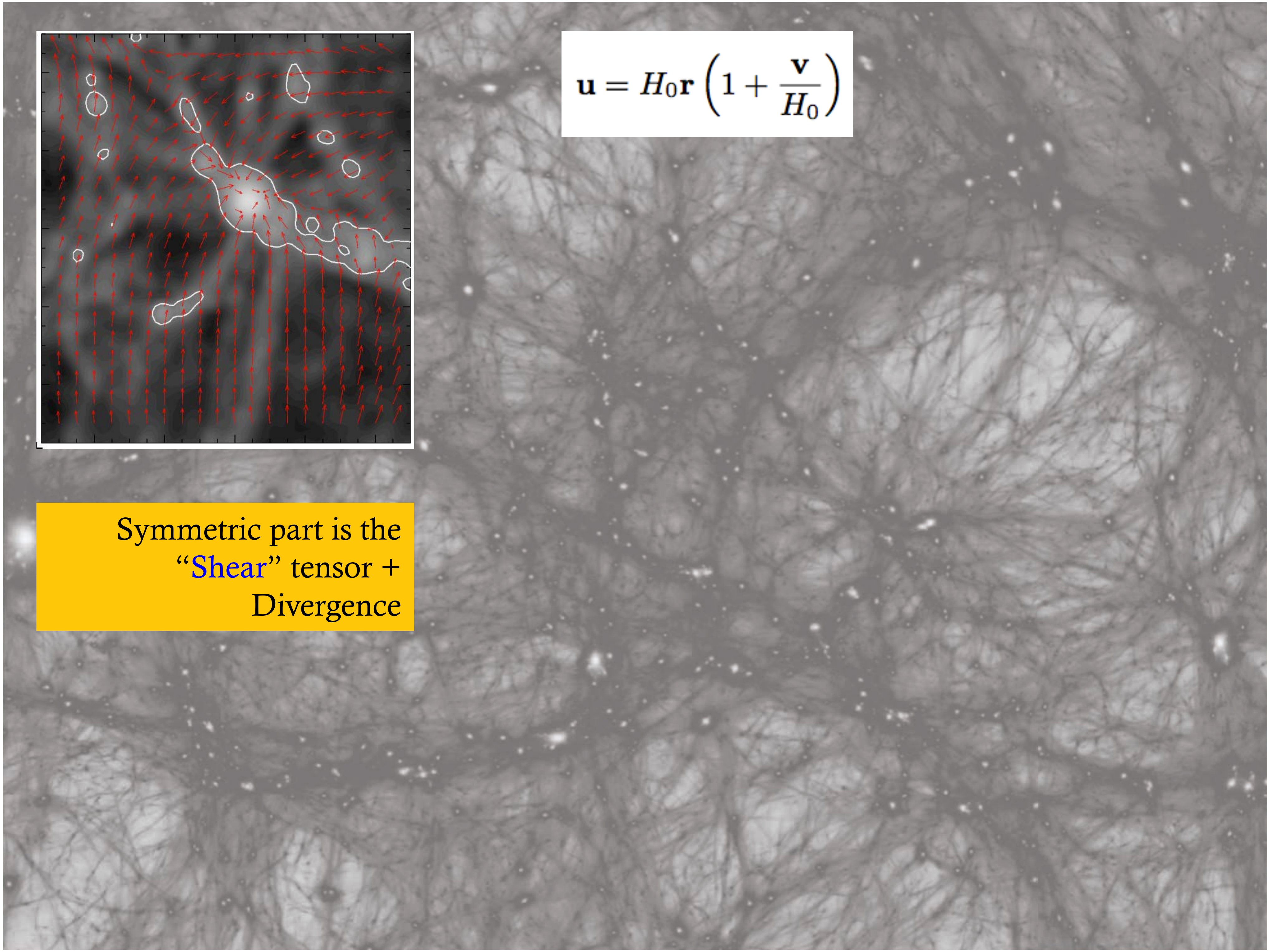


Hoffman et al 2012
Libeskind et al 2012, 2013

Looking at LSS from the point of view of (*peculiar*) velocity.

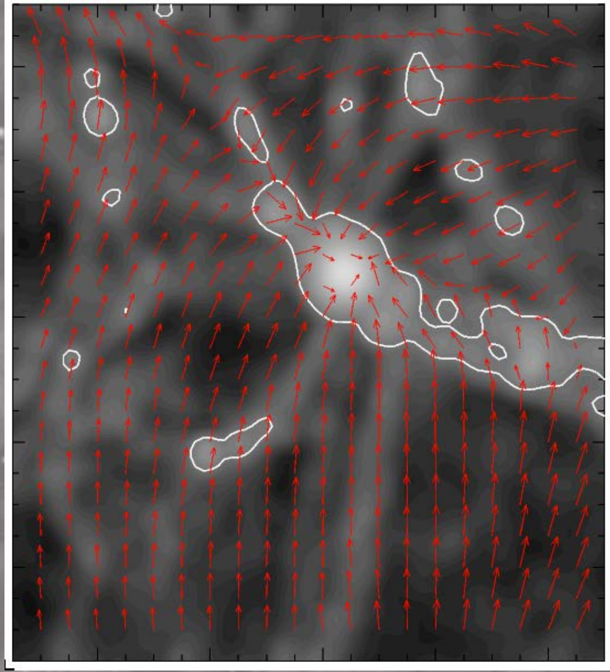
Specifically the deformation of the velocity field – shear, compression and rotation:





$$\mathbf{u} = H_0 \mathbf{r} \left(1 + \frac{\mathbf{v}}{H_0}\right)$$

Symmetric part is the
"Shear" tensor +
Divergence

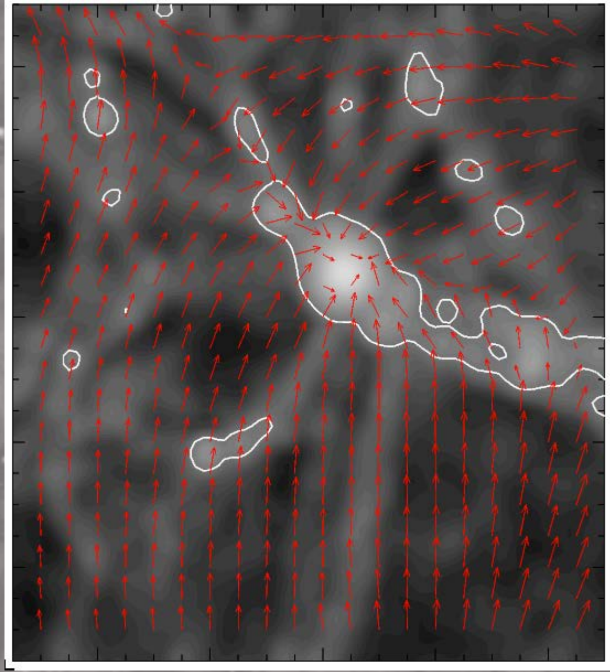


$$\mathbf{u} = H_0 \mathbf{r} \left(1 + \frac{\mathbf{v}}{H_0}\right)$$

$$\begin{aligned}
\mathbf{v}(\mathbf{r}) &= \mathbf{v}(\mathbf{r}_0) + \frac{\partial \mathbf{v}(\mathbf{r})}{\partial r} \mathrm{d}\mathbf{r} \\
&= \mathbf{v}(\mathbf{r}_0) + \begin{bmatrix} \frac{\partial v_x}{\partial x} & \frac{\partial v_x}{\partial y} & \frac{\partial v_x}{\partial z} \\ \frac{\partial v_y}{\partial x} & \frac{\partial v_y}{\partial y} & \frac{\partial v_y}{\partial z} \\ \frac{\partial v_z}{\partial x} & \frac{\partial v_z}{\partial y} & \frac{\partial v_z}{\partial z} \end{bmatrix} \begin{bmatrix} \mathrm{d}\mathbf{x} \\ \mathrm{d}\mathbf{y} \\ \mathrm{d}\mathbf{z} \end{bmatrix} \\
&= \mathbf{v}(\mathbf{r}_0) + \mathbf{S}_{\alpha\beta}\ \mathrm{d}\mathbf{r}
\end{aligned}$$

$$\mathbf{S}_{ij} = \Sigma_{ij} + \Omega_{ij}$$

Symmetric part is the “Shear” tensor + Divergence



$$\mathbf{u} = H_0 \mathbf{r} \left(1 + \frac{\mathbf{v}}{H_0}\right)$$

$$\begin{aligned}
\mathbf{v}(\mathbf{r}) &= \mathbf{v}(\mathbf{r}_0) + \frac{\partial \mathbf{v}(\mathbf{r})}{\partial r} \mathbf{dr} \\
&= \mathbf{v}(\mathbf{r}_0) + \begin{bmatrix} \frac{\partial v_x}{\partial x} & \frac{\partial v_x}{\partial y} & \frac{\partial v_x}{\partial z} \\ \frac{\partial v_y}{\partial x} & \frac{\partial v_y}{\partial y} & \frac{\partial v_y}{\partial z} \\ \frac{\partial v_z}{\partial x} & \frac{\partial v_z}{\partial y} & \frac{\partial v_z}{\partial z} \end{bmatrix} \begin{bmatrix} \mathbf{dx} \\ \mathbf{dy} \\ \mathbf{dz} \end{bmatrix} \\
&= \mathbf{v}(\mathbf{r}_0) + \mathbf{S}_{\alpha\beta}\ \mathbf{dr}
\end{aligned}$$

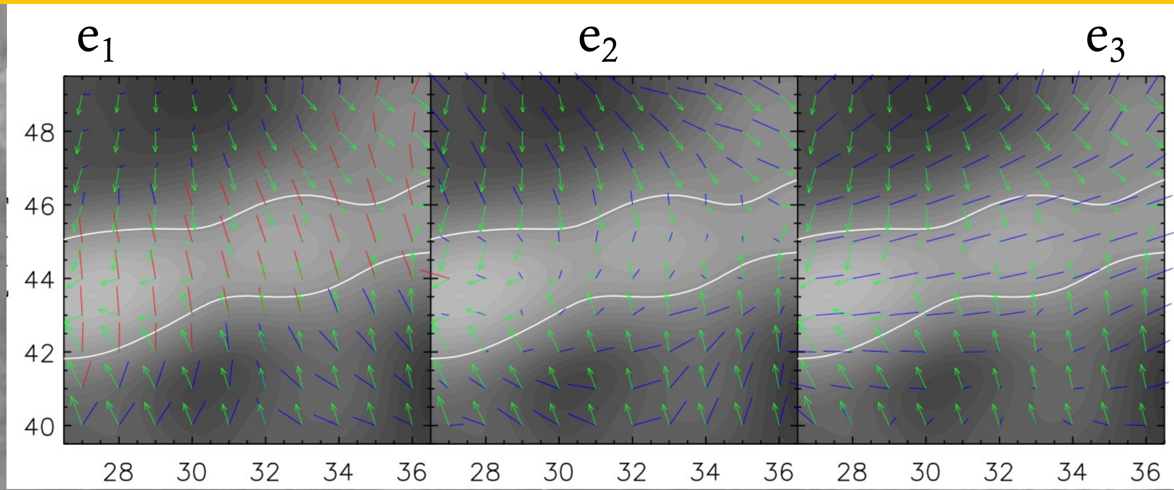
$$\mathbf{S}_{ij} \quad = \quad \Sigma_{ij} + \Omega_{ij}$$

Symmetric part is the "Shear" tensor + Divergence

$$\begin{bmatrix} \frac{\partial v_x}{\partial x} & \frac{1}{2}\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right) & \frac{1}{2}\left(\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x}\right) \\ \frac{1}{2}\left(\frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y}\right) & \frac{\partial v_y}{\partial y} & \frac{1}{2}\left(\frac{\partial v_y}{\partial z} + \frac{\partial v_z}{\partial y}\right) \\ \frac{1}{2}\left(\frac{\partial v_z}{\partial x} + \frac{\partial v_x}{\partial z}\right) & \frac{1}{2}\left(\frac{\partial v_y}{\partial z} + \frac{\partial v_z}{\partial y}\right) & \frac{\partial v_z}{\partial z} \end{bmatrix}$$

$$\begin{bmatrix} 0 & \frac{1}{2}\left(\frac{\partial v_x}{\partial y} - \frac{\partial v_y}{\partial x}\right) & \frac{1}{2}\left(\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}\right) \\ -\frac{1}{2}\left(\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}\right) & 0 & \frac{1}{2}\left(\frac{\partial v_y}{\partial z} - \frac{\partial v_z}{\partial y}\right) \\ -\frac{1}{2}\left(\frac{\partial v_z}{\partial x} - \frac{\partial v_x}{\partial z}\right) & -\frac{1}{2}\left(\frac{\partial v_y}{\partial z} - \frac{\partial v_z}{\partial y}\right) & 0 \end{bmatrix}$$

Full (3D) velocity & density field from Wiener filter reconstructions of the cosmic flows-2 survey

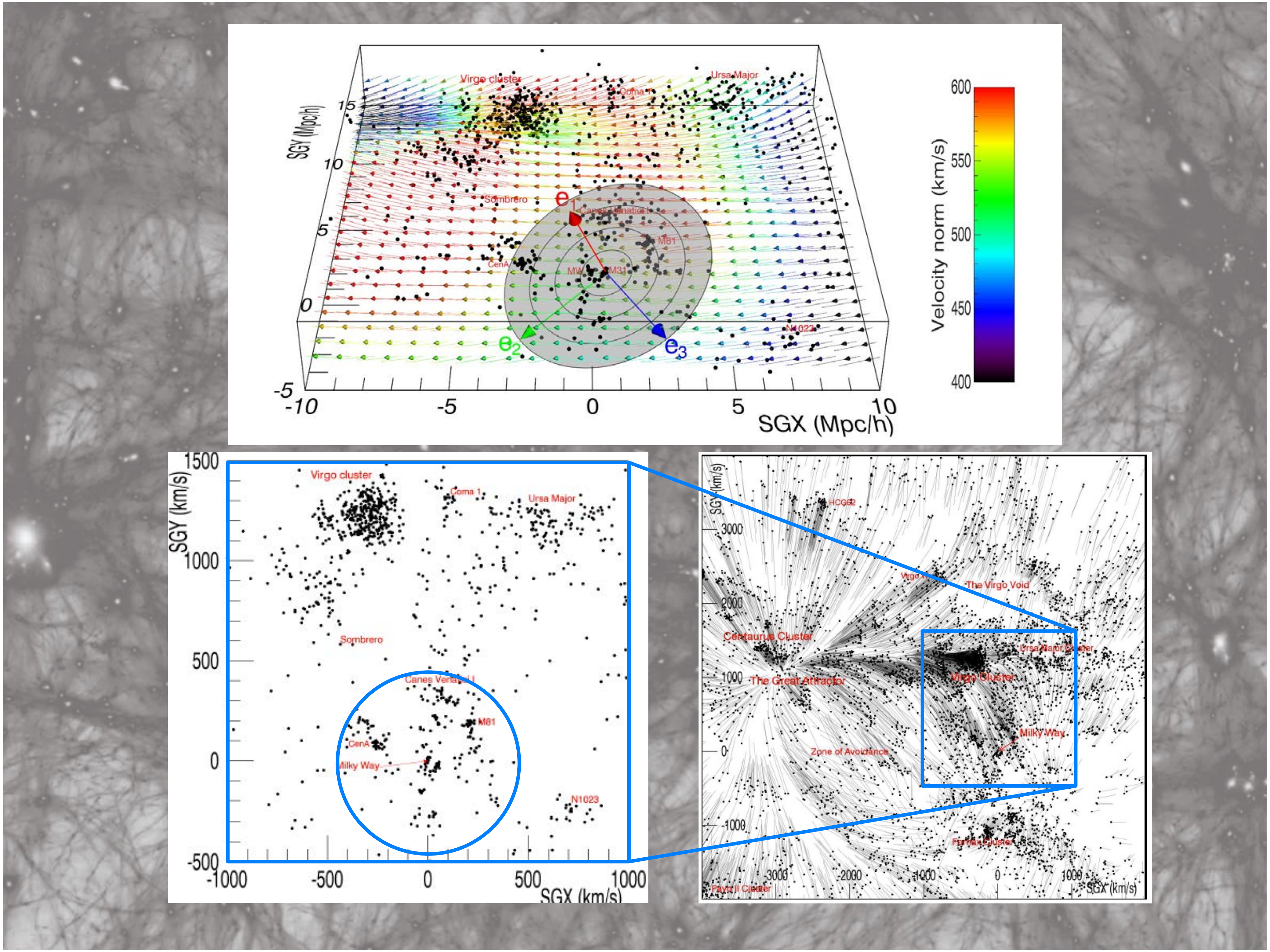


Axis of fastest collapse
Sheet normal

Axis of slowest collapse

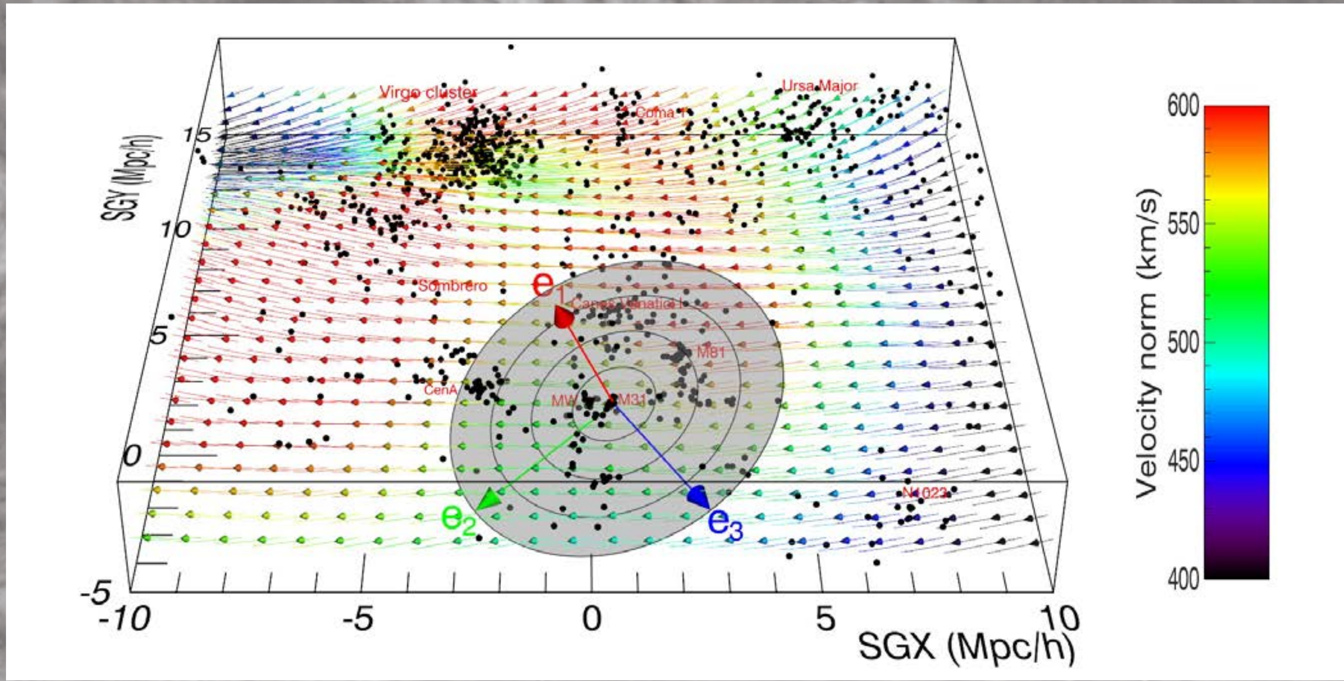
$$\Sigma_{ij} = -\frac{1}{2H(z)}\left(\frac{\partial v_i}{\partial r_j} + \frac{\partial v_j}{\partial r_i}\right)$$

$\lambda_1 > \lambda_2 > \lambda_3$ are the eigenvalues and represent the magnitude of compression (+) or collapse (-)



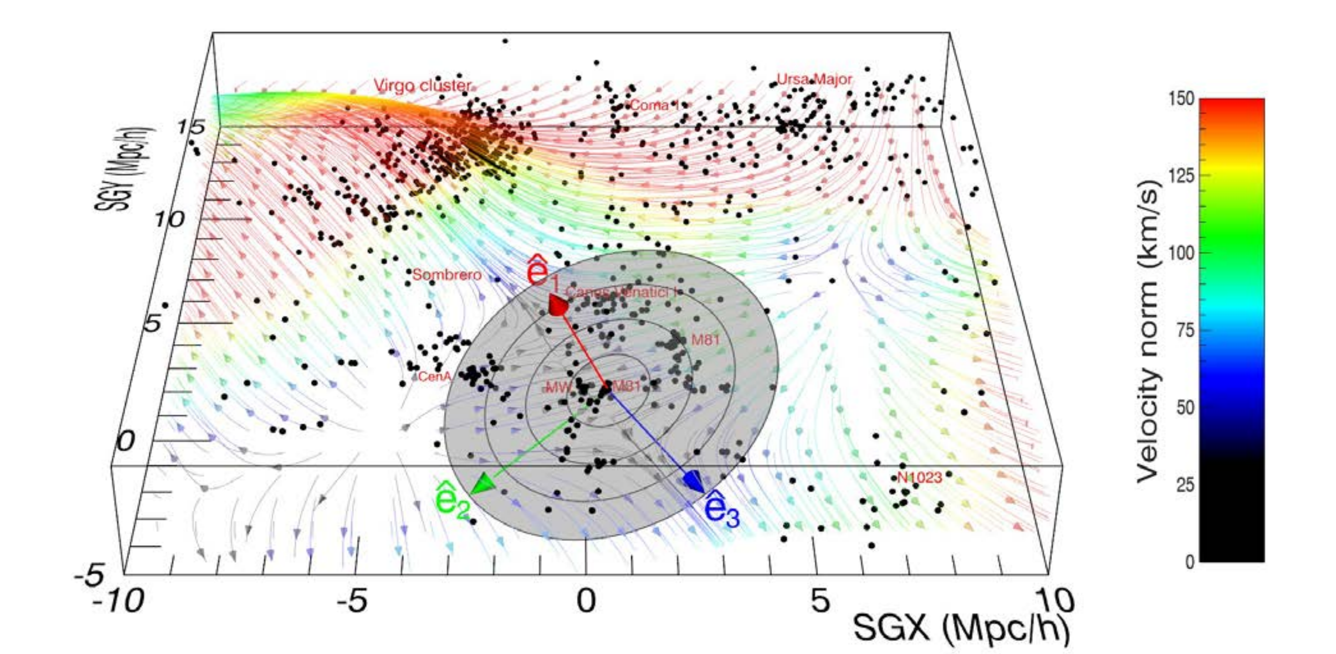
Virgo cluster
Ursa Major
Coma
SGY (Mpc/h)
Sombrero
e1
Canes Venatici I
M81
CenA
MW
M31
e2
e3
N1023
SGX (Mpc/h)
Velocity norm (km/s)
SGY (km/s)
SGX (km/s)
Coma 1
Milky Way
HCG62
The Virgo Void
Centaurus Cluster
The Great Attractor
Ursa Major Cluster
Virgo Cluster
Zone of Avoidance
Fornax Cluster
Pavo II Cluster

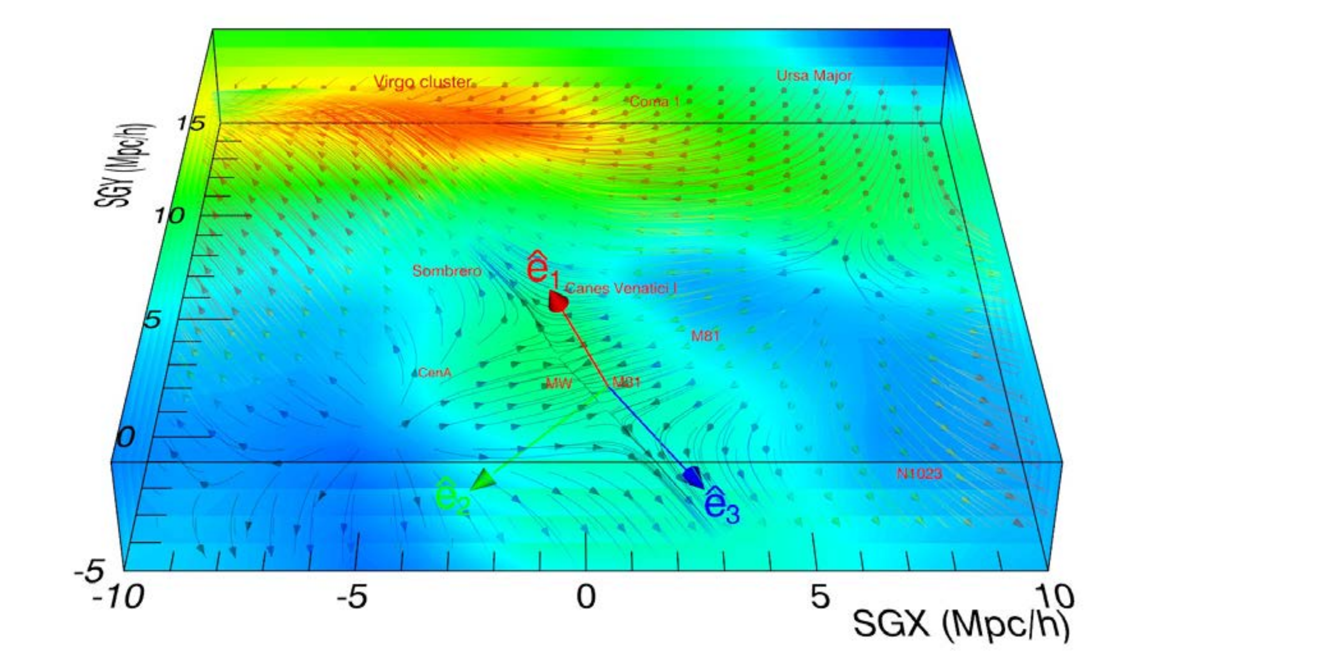
The Local Cosmic Web



Libeskind *et al* 2015,
Nature Physics

The Local Cosmic Web

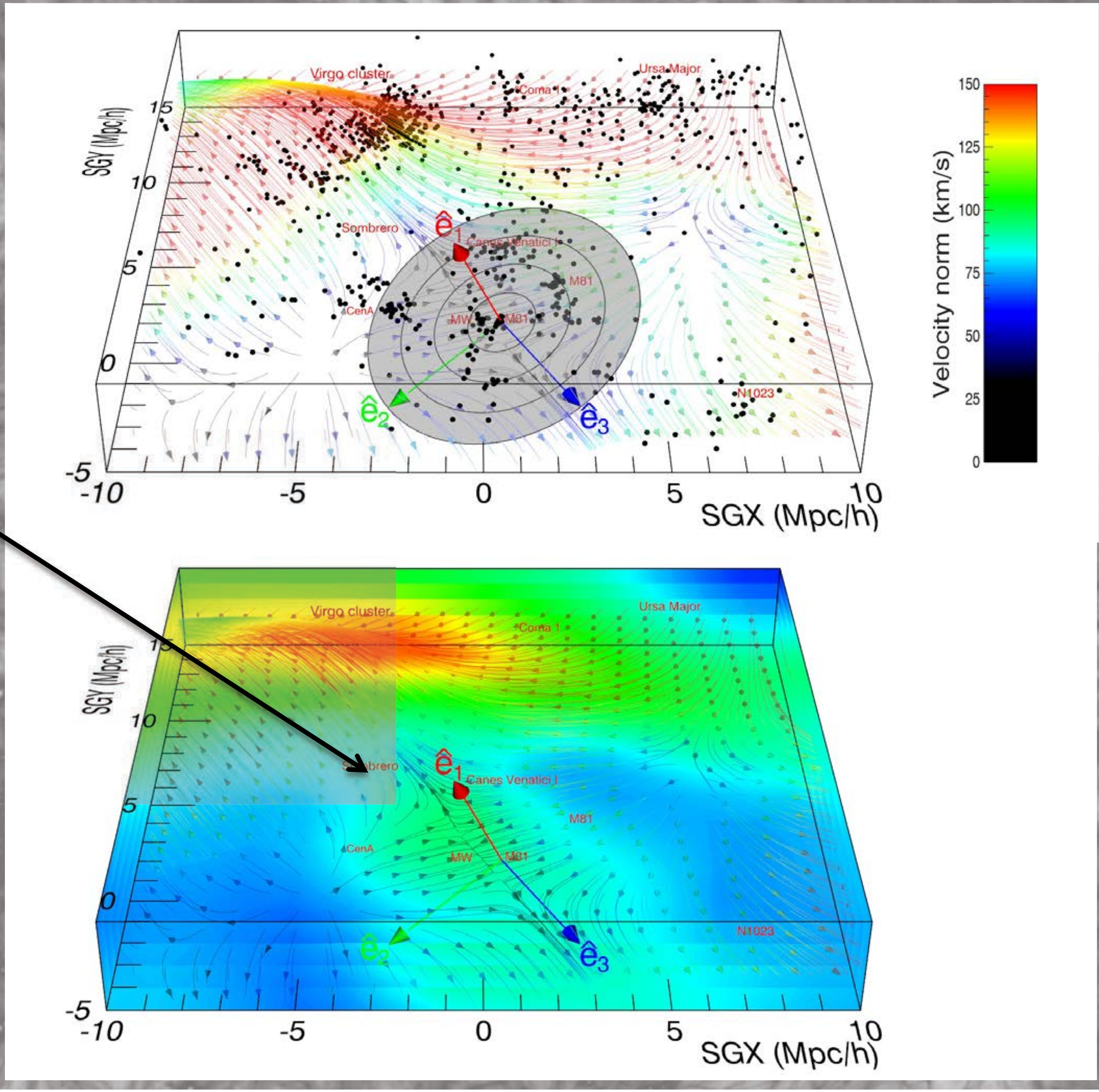




Libeskind *et al* 2015, Nature Physics

The Local Cosmic Web

“Local Filament” stretched by Virgo



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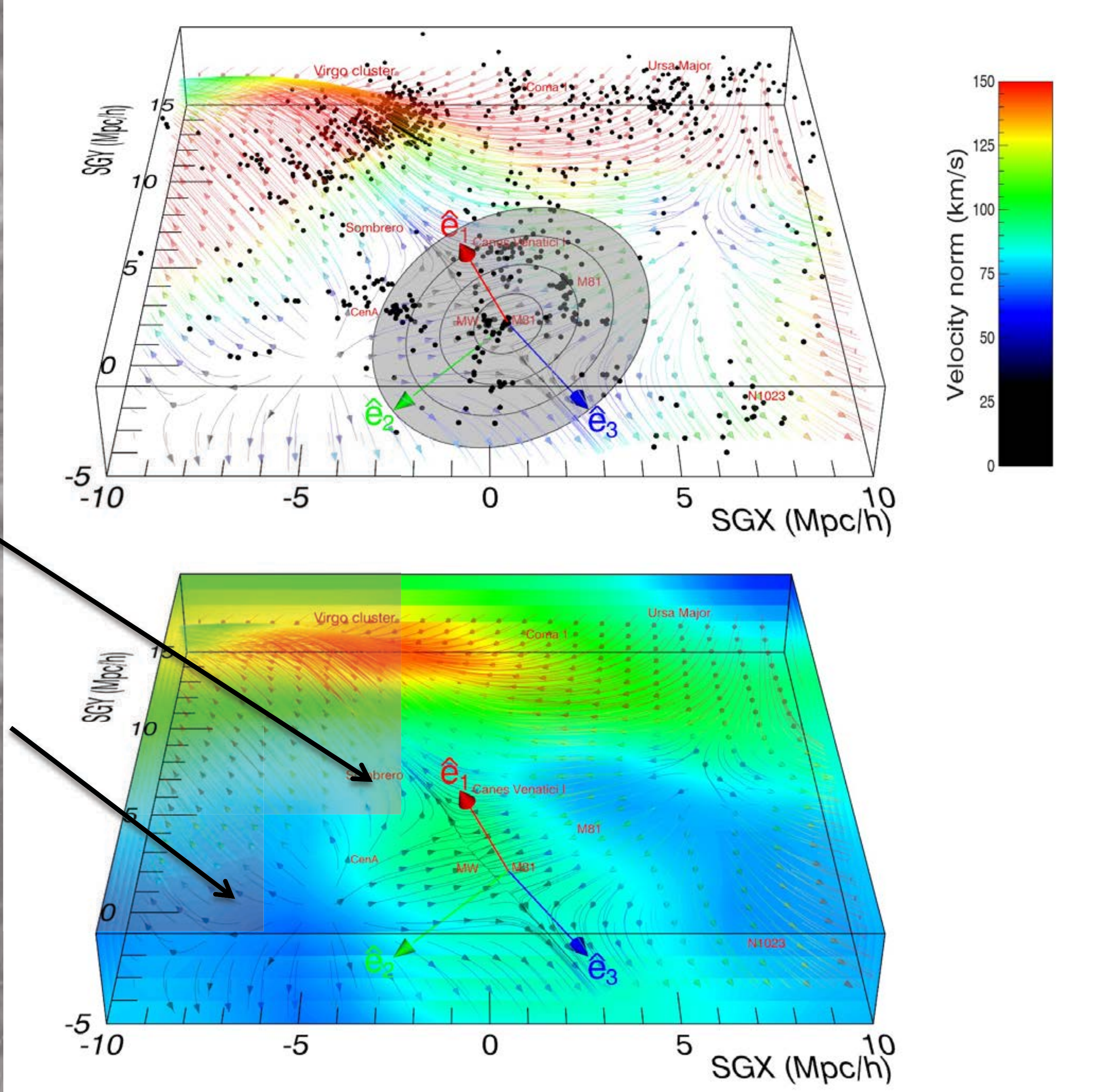
The Local Cosmic Web



"Local Filament" stretched by Virgo

Laterally squashed by a "mini-repeller"

Libeskind *et al* 2015, Nature Physics

The Local Cosmic Web

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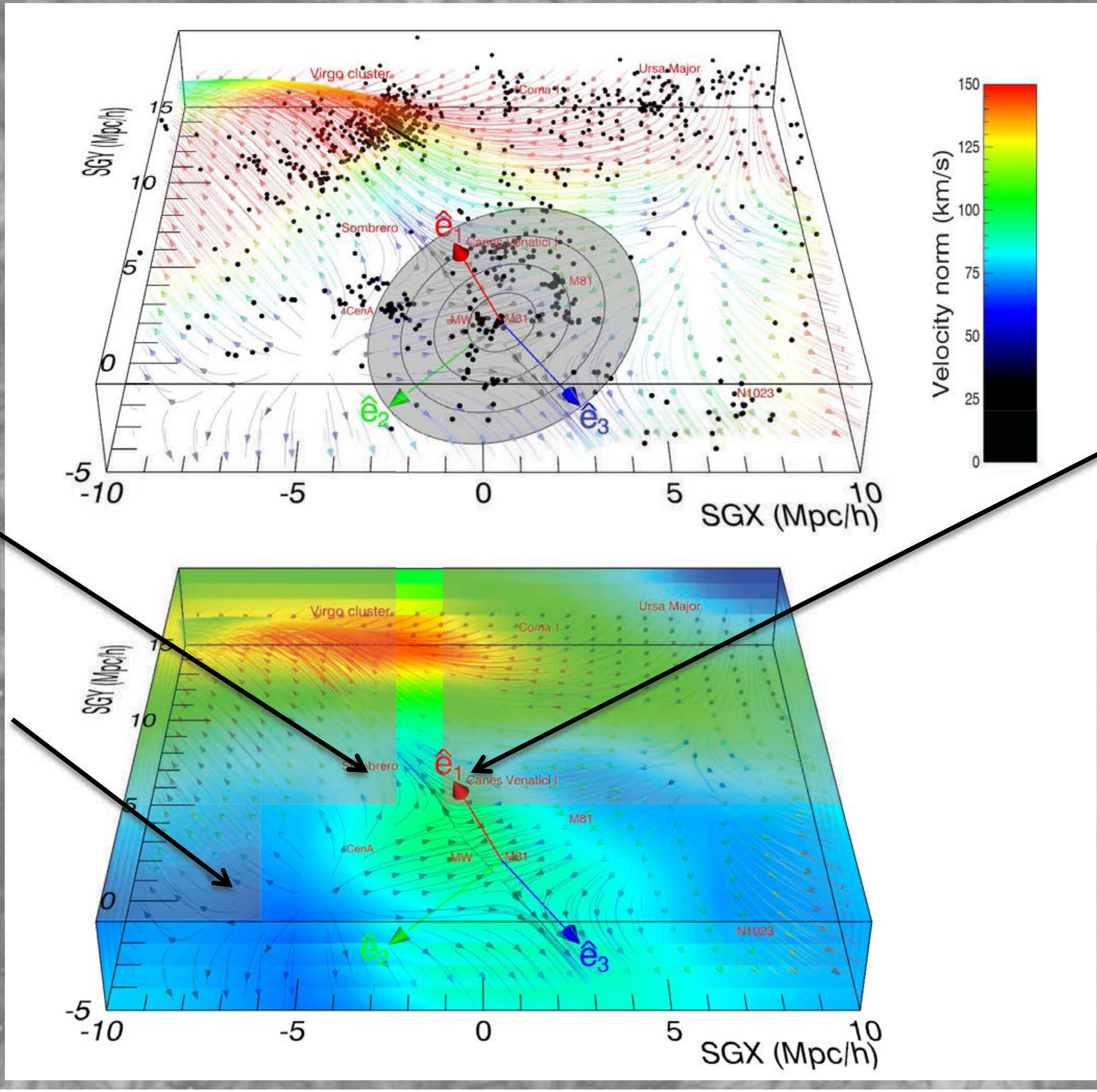
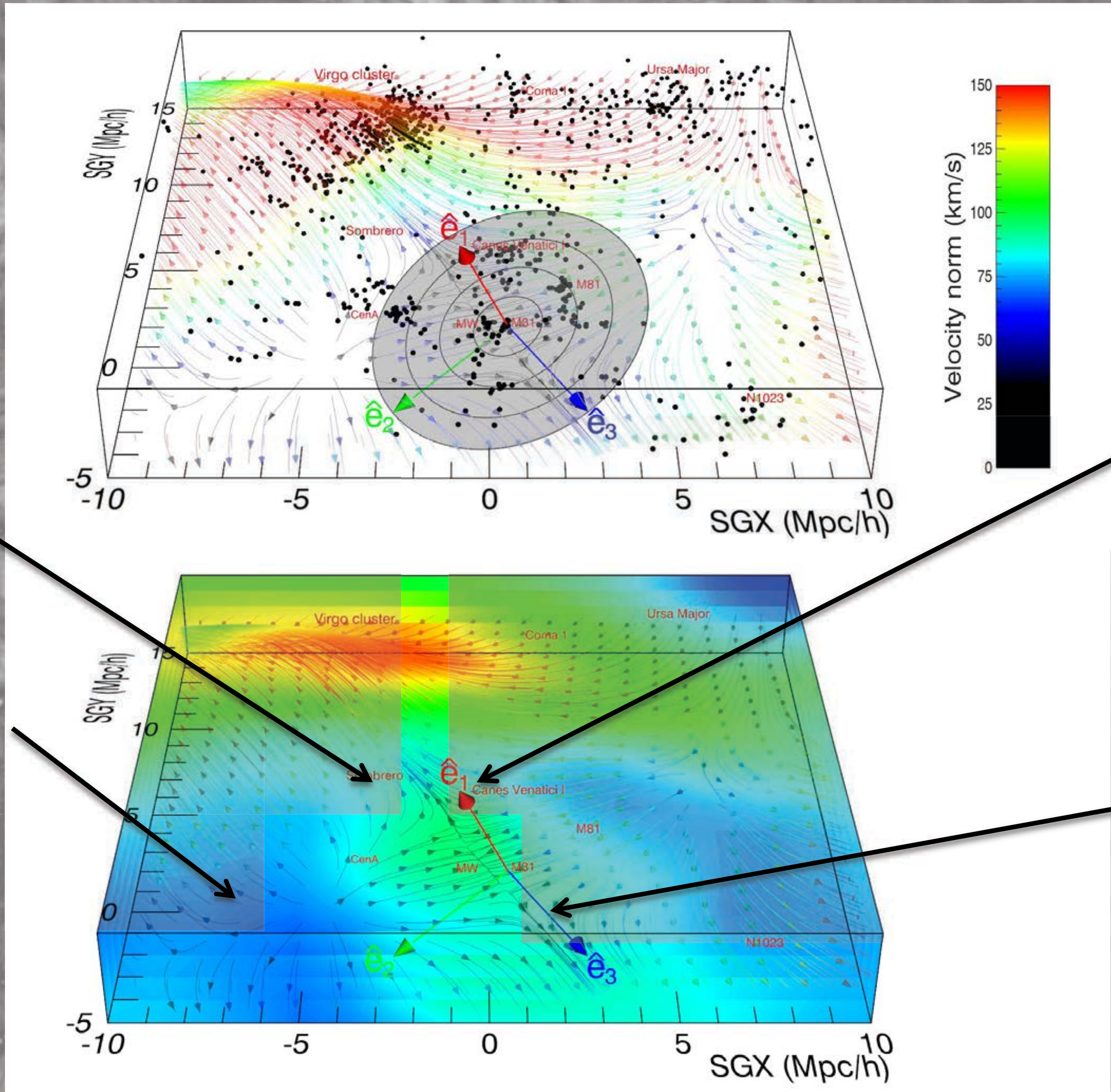


e_1 sheet normal, points to the local void

Libeskind *et al* 2015, Nature Physics

The Local Cosmic Web



"Local Filament" stretched by Virgo

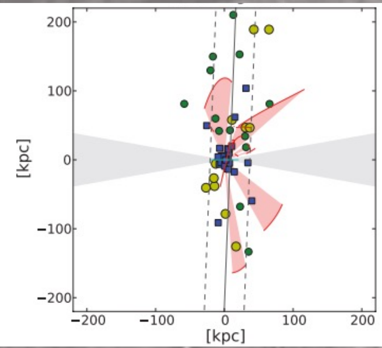
Laterally squashed by a "mini-repeller"

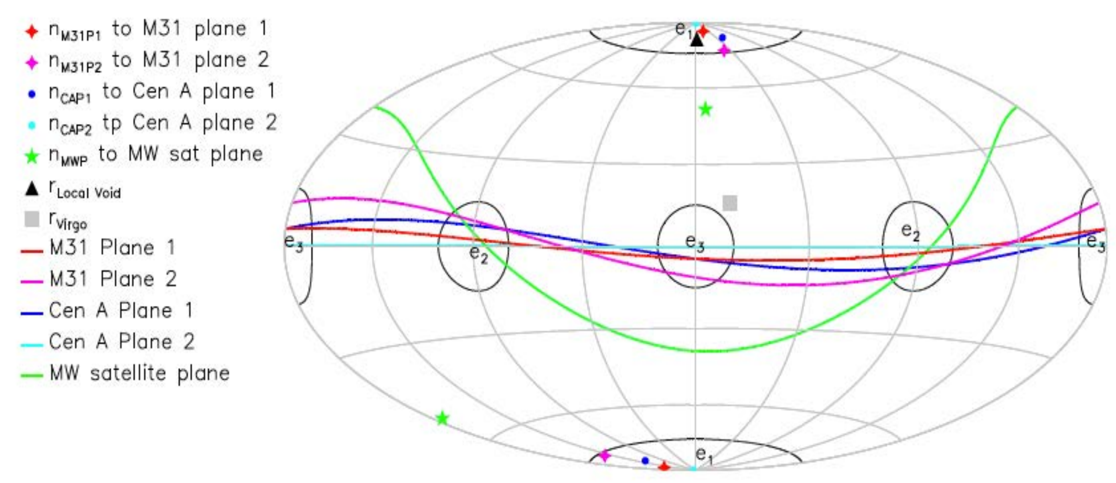
e_1 sheet normal, points to the local void

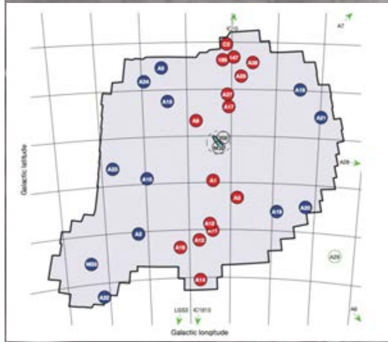
e_3 filament axis, points to Virgo

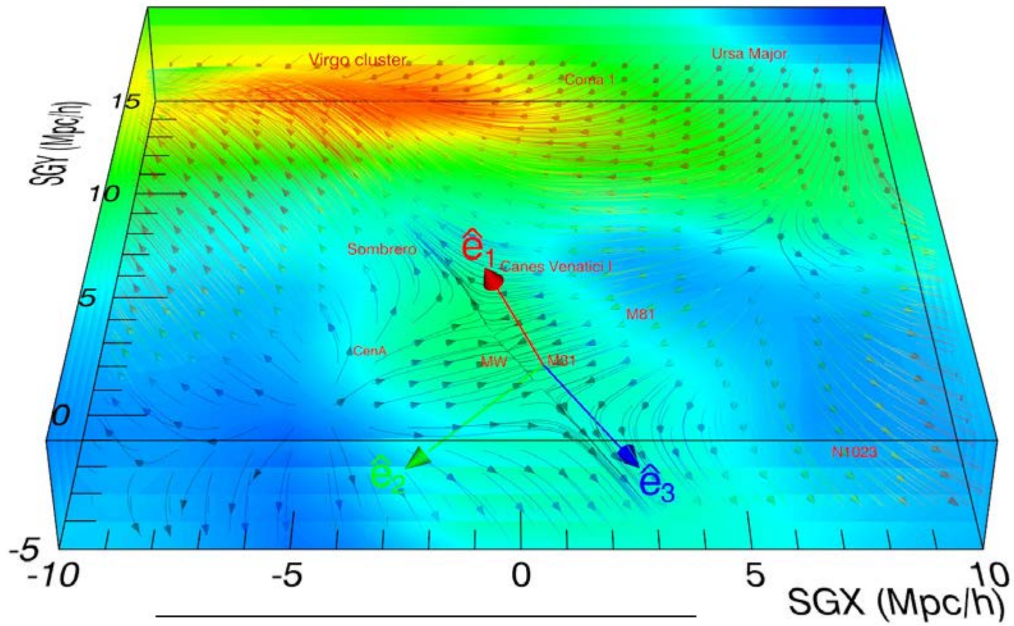
Libeskind *et al* 2015, Nature Physics

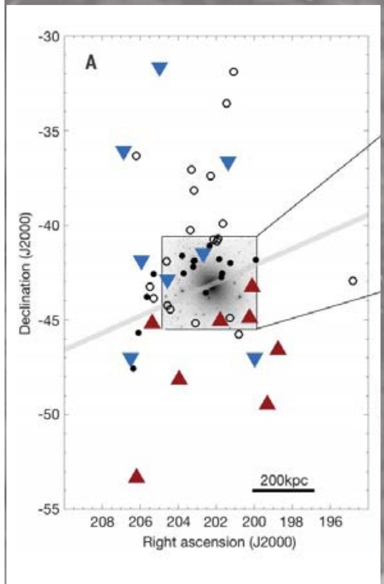
Planes of Satellites

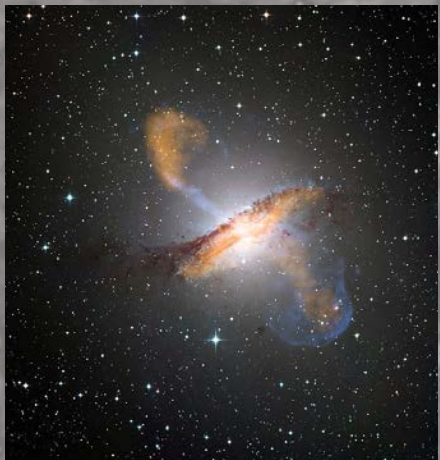








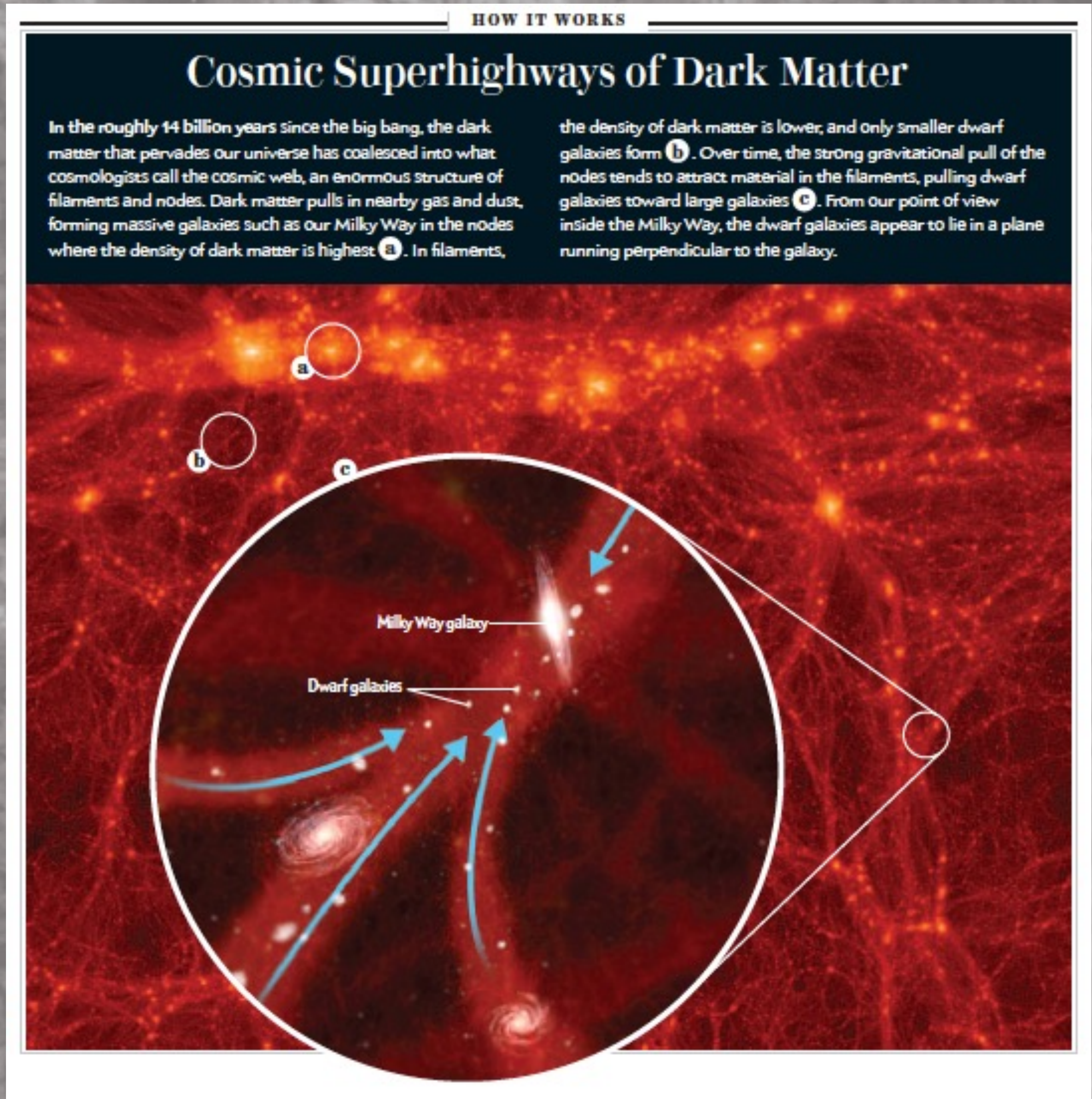




Property	$\lvert\cos\theta\rvert$	deg apart
$\boldsymbol{e}_3 \cdot \hat{r}_{\rm Virgo}$	0.9330	~21.1
$\boldsymbol{e}_1 \cdot \hat{r}_{\rm Virgo}$	0.2733	~74.1
$\boldsymbol{e}_1 \cdot \hat{r}_{\rm LV}$	0.9898	~8.17
$\boldsymbol{e}_1 \cdot \hat{n}_{\rm M31P1}$	0.9968	~4.5
$\boldsymbol{e}_1 \cdot \hat{n}_{\rm M31P2}$	0.9704	~13.9
$\boldsymbol{e}_1 \cdot \hat{n}_{\rm CAP1}$	0.9879	~8.9
$\boldsymbol{e}_1 \cdot \hat{n}_{\rm CAP2}$	0.9999	~0.3
$\boldsymbol{e}_1 \cdot \hat{n}_{\rm MWP}$	0.7801	~38.7

Libeskind *et al* 2015

Satellites and cosmic filaments



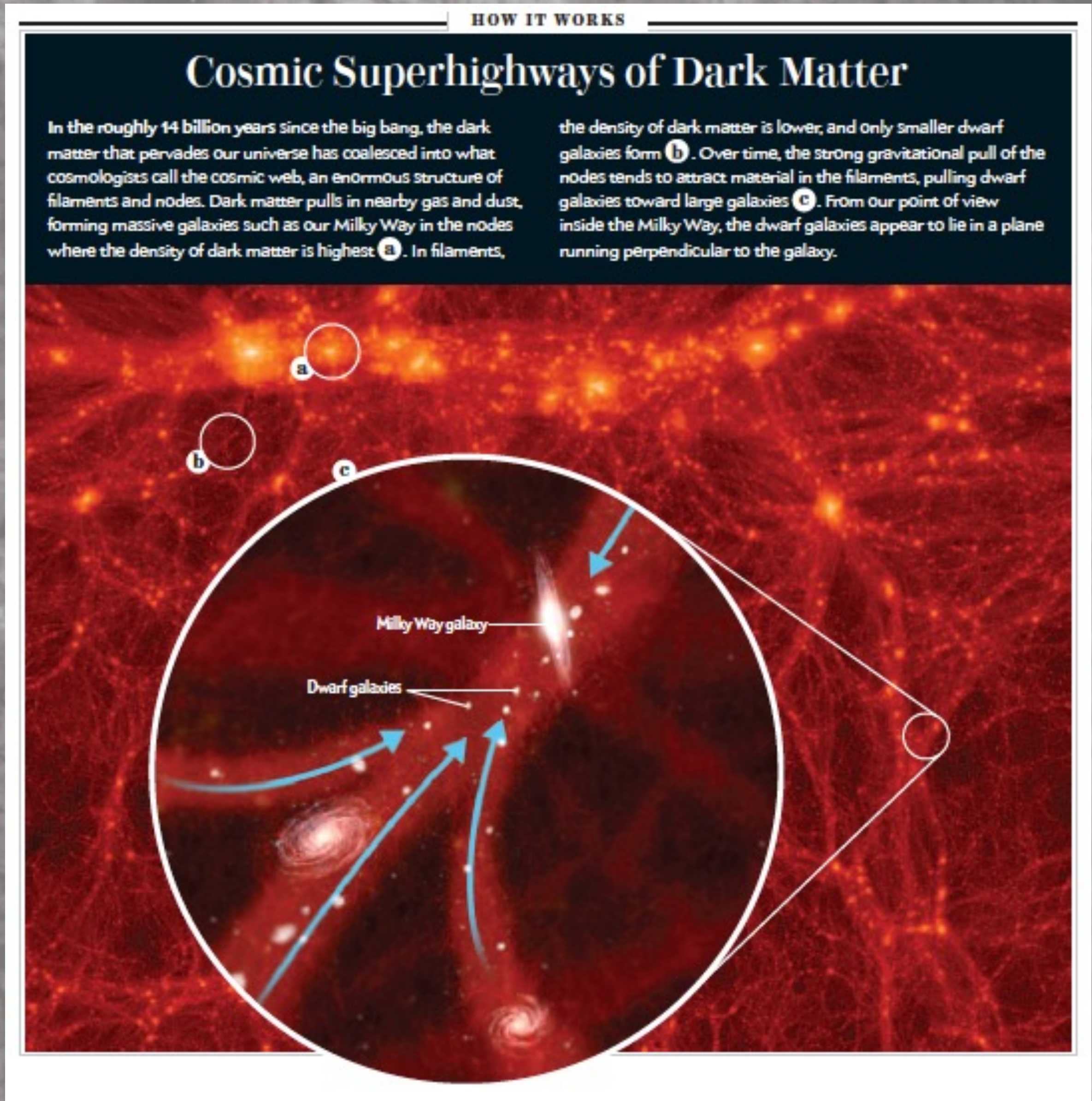
HOW IT WORKS

Cosmic Superhighways of Dark Matter

In the roughly 14 billion years since the big bang, the dark matter that pervades our universe has coalesced into what cosmologists call the cosmic web, an enormous structure of filaments and nodes. Dark matter pulls in nearby gas and dust, forming massive galaxies such as our Milky Way in the nodes where the density of dark matter is highest (a). In filaments, the density of dark matter is lower, and only smaller dwarf galaxies form (b). Over time, the strong gravitational pull of the nodes tends to attract material in the filaments, pulling dwarf galaxies toward large galaxies (c). From our point of view inside the Milky Way, the dwarf galaxies appear to lie in a plane running perpendicular to the galaxy.

Libeskind 2014, *Scientific American*

Satellites and cosmic filaments



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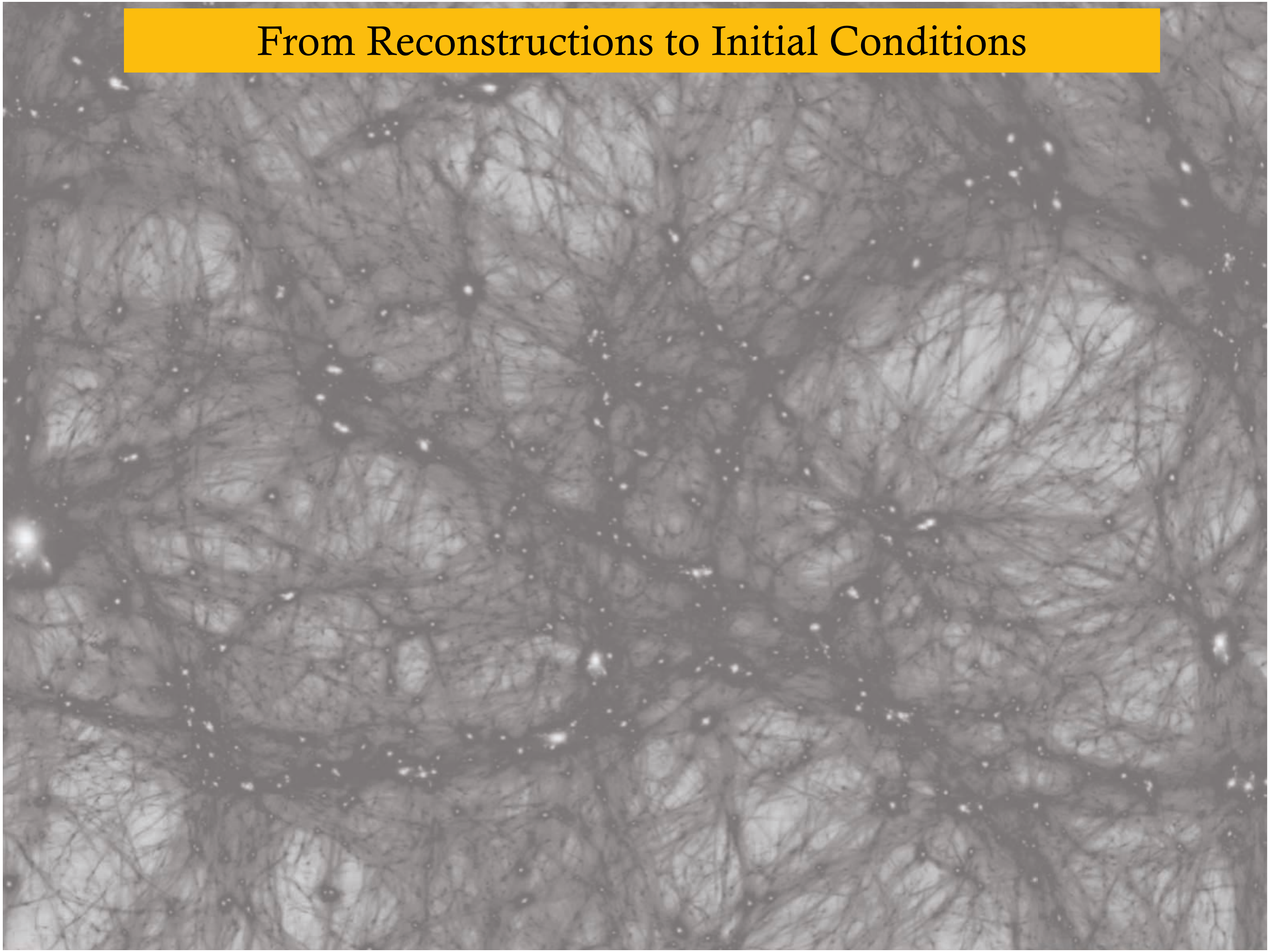
Libeskind 2014, *Scientific American*

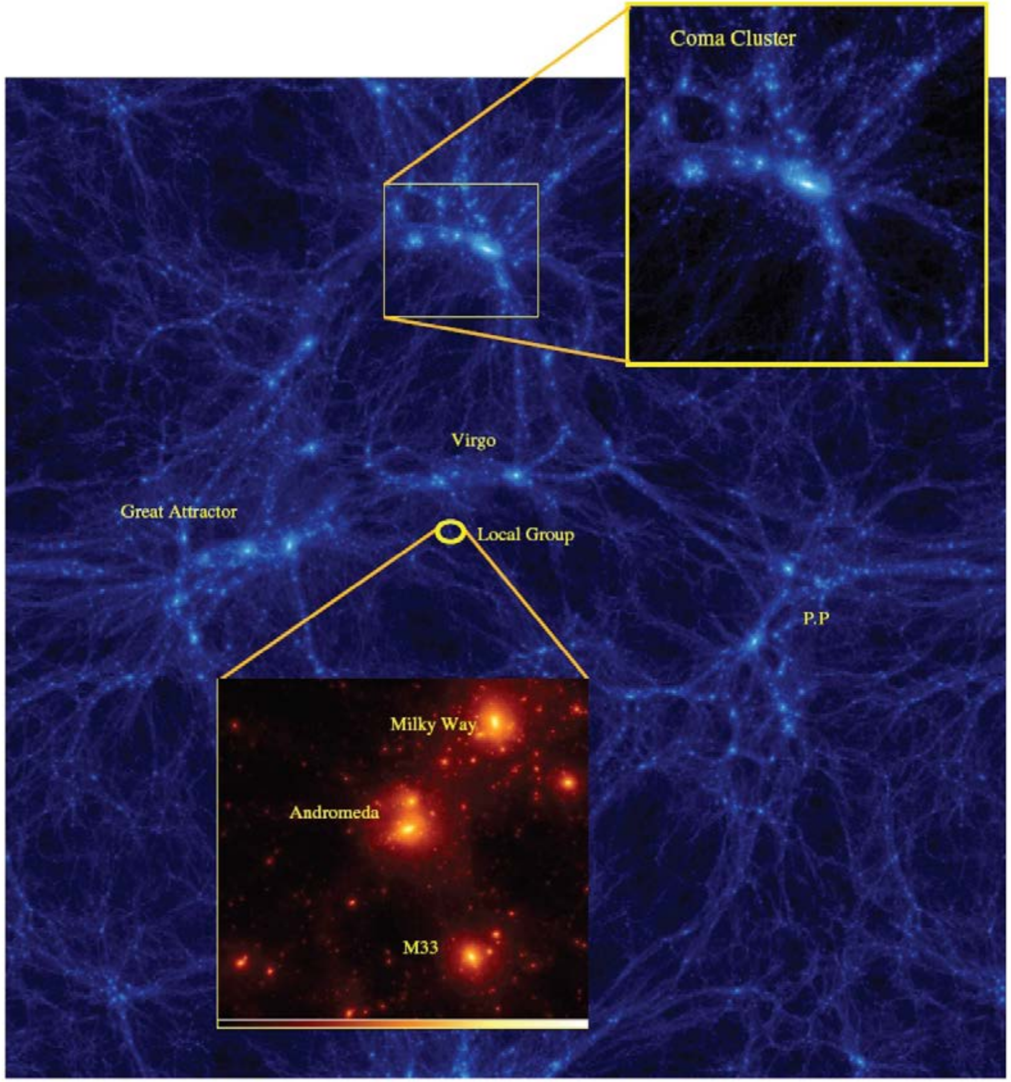
… watch this space

From Reconstructions to Initial Conditions



From Reconstructions to Initial Conditions

Initial conditions can be generated by the Reverse Zeldovich Approximation



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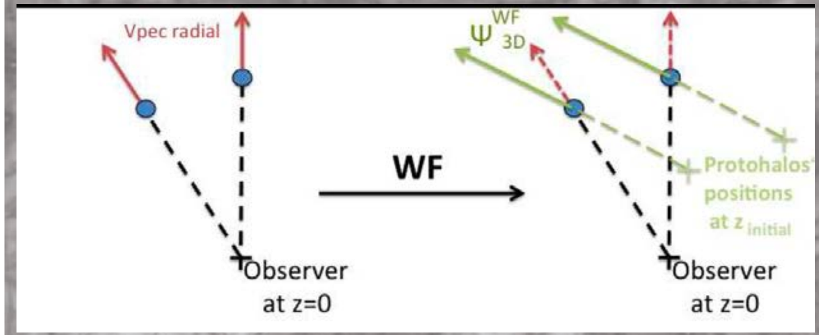

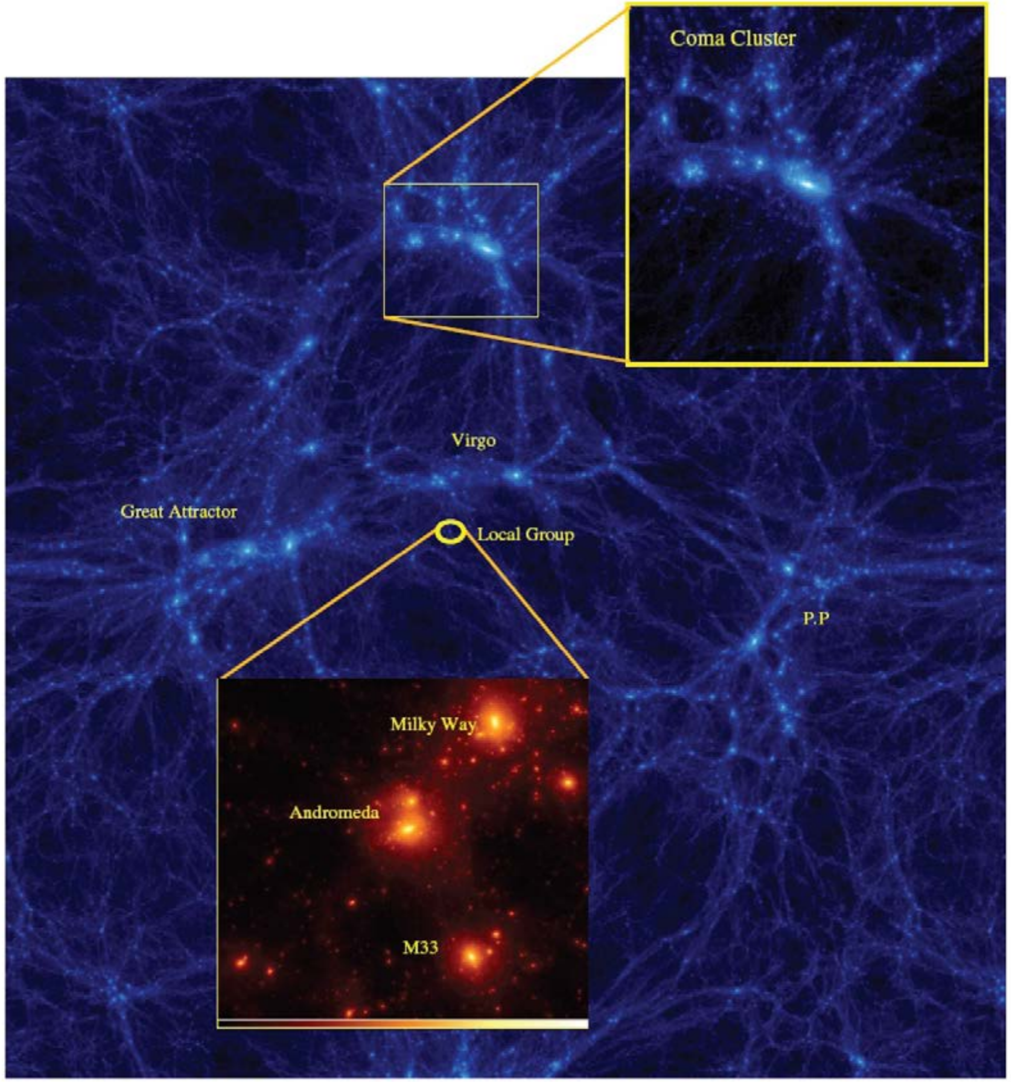

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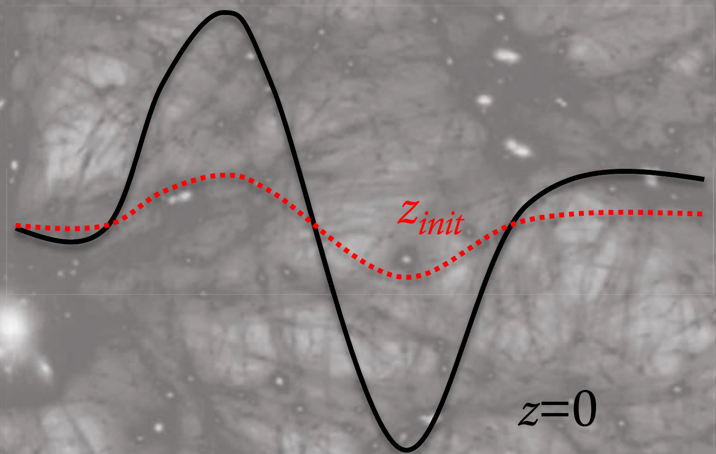

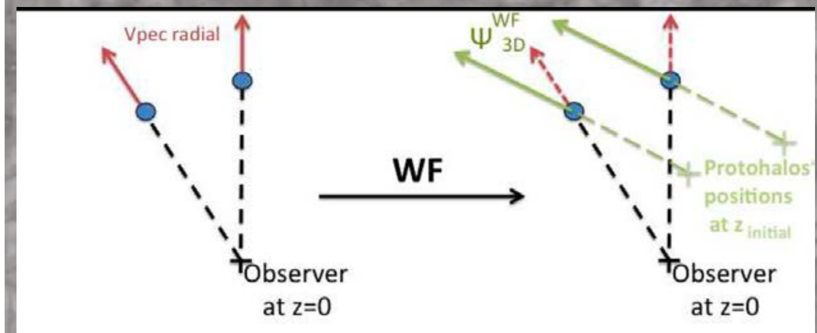

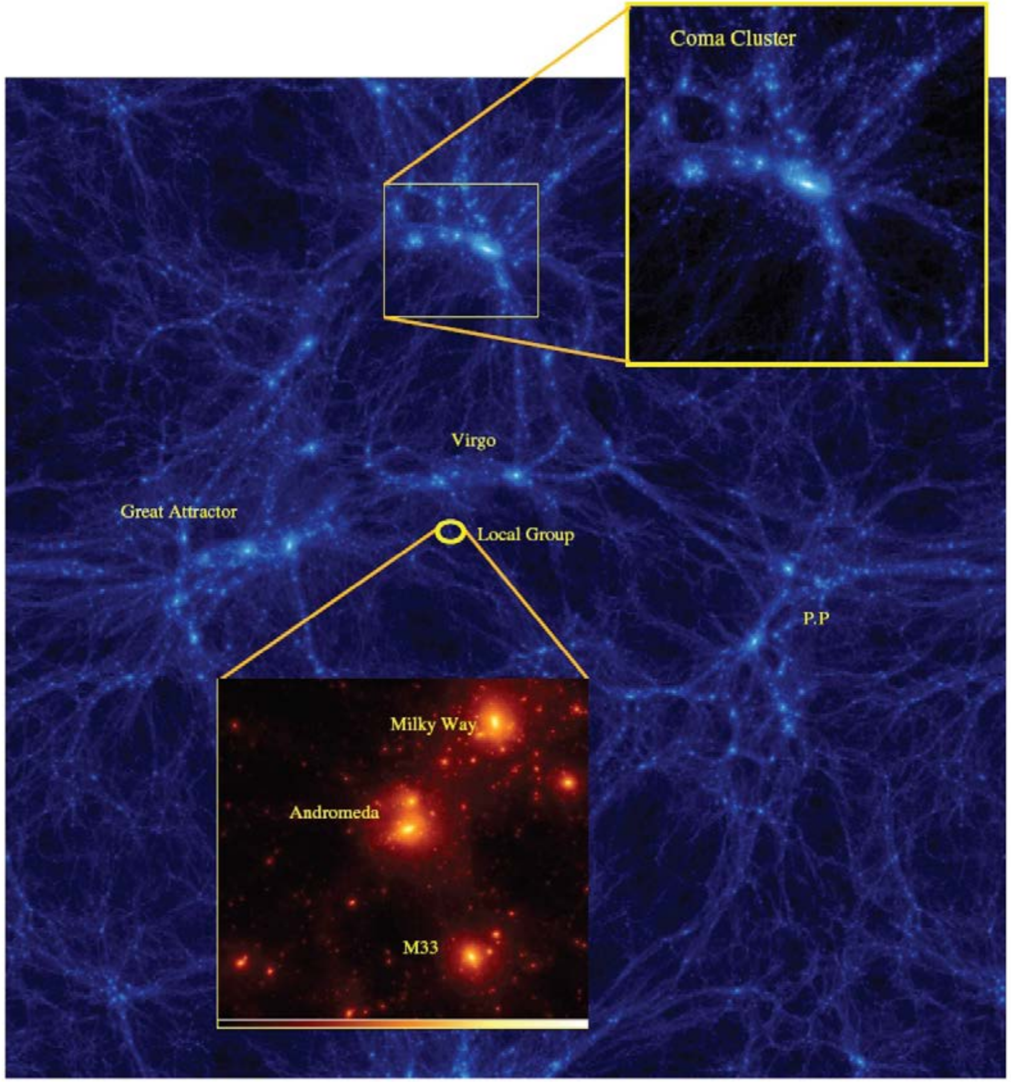

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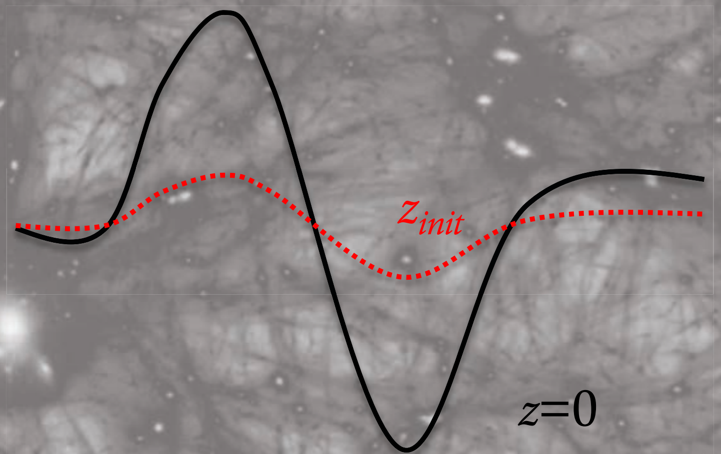
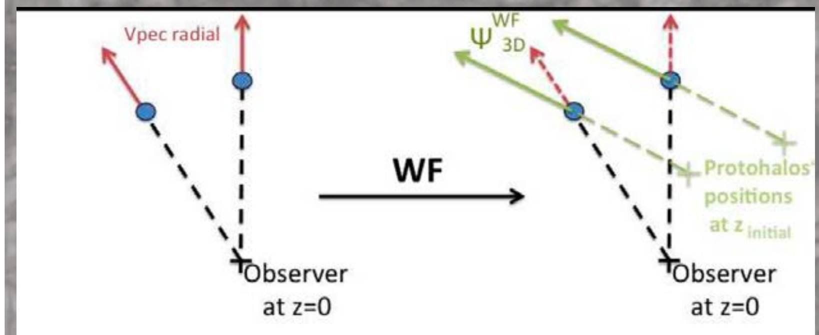
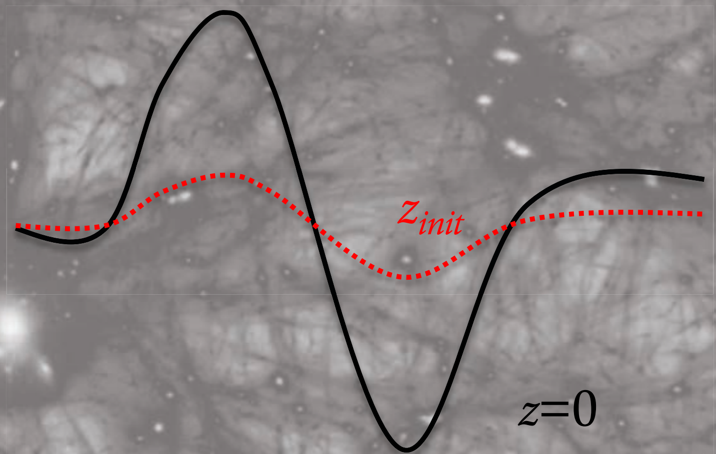
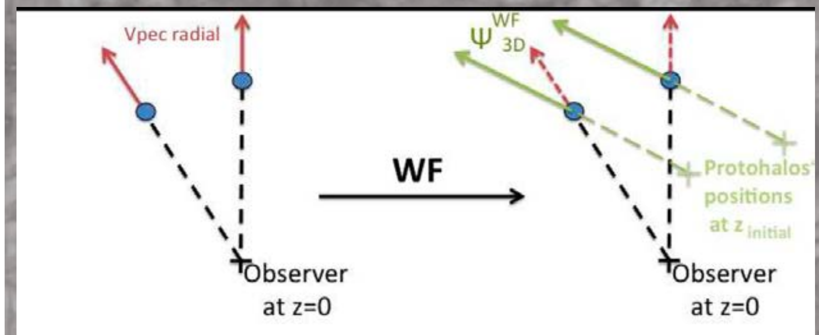




From Reconstructions to Initial Conditions

Initial conditions can be generated by the Reverse Zeldovich Approximation





Need random modes for

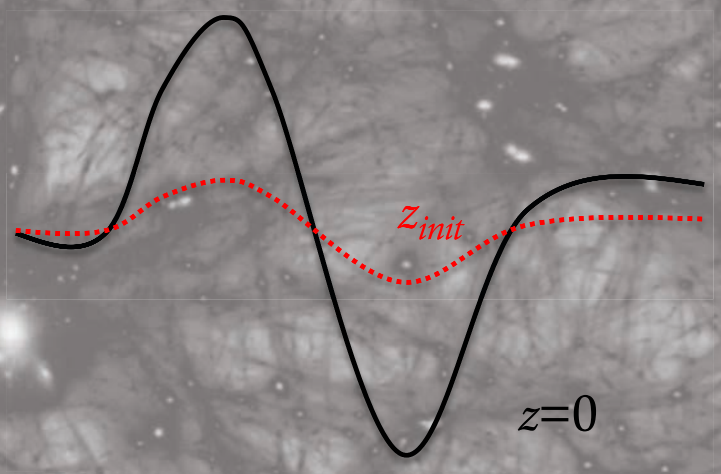
Unobserved regions

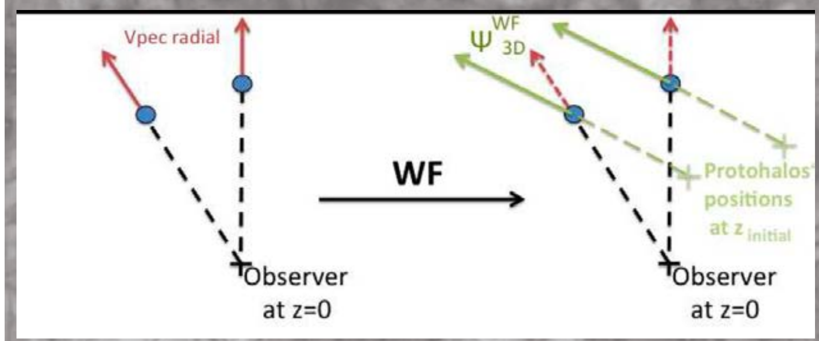
ZoA

Beyond the data

From Reconstructions to Initial Conditions

Initial conditions can be generated by the Reverse Zeldovich Approximation





Need random modes for

ZoA

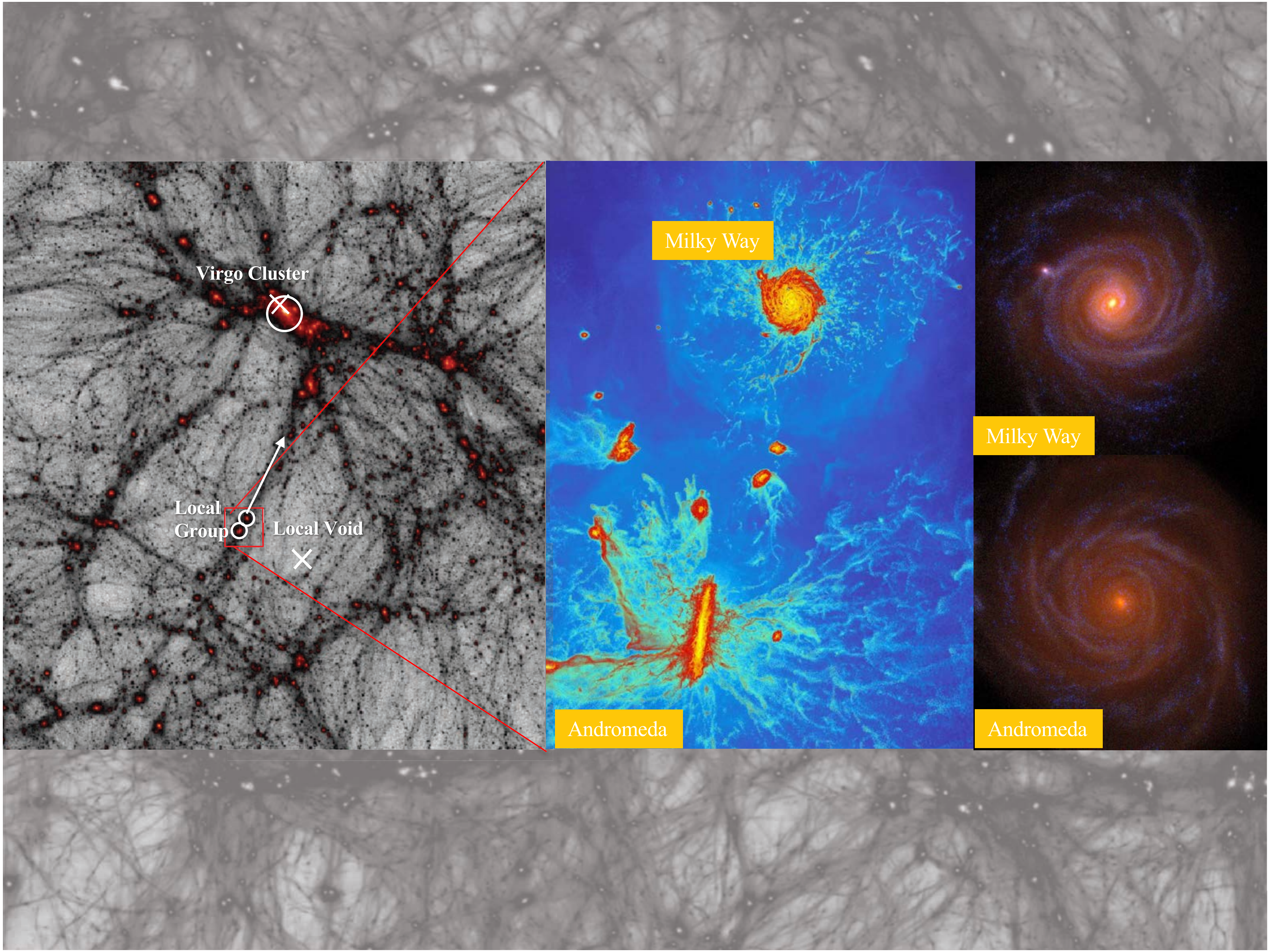
Unobserved regions

Beyond the data

Unconstrained regions

Small scale

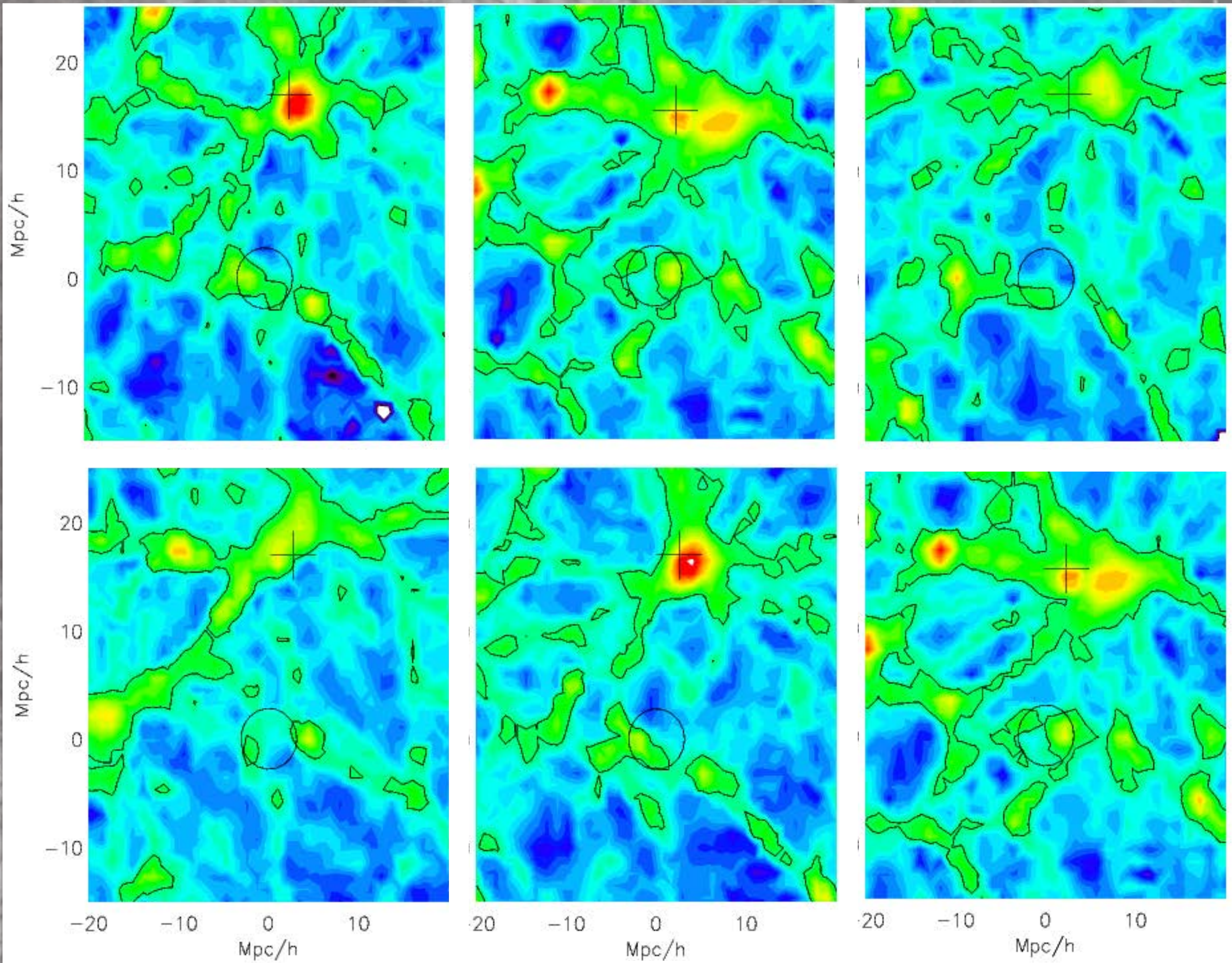
High resolition
Environmental
Simulations of
The
Immediate
Area



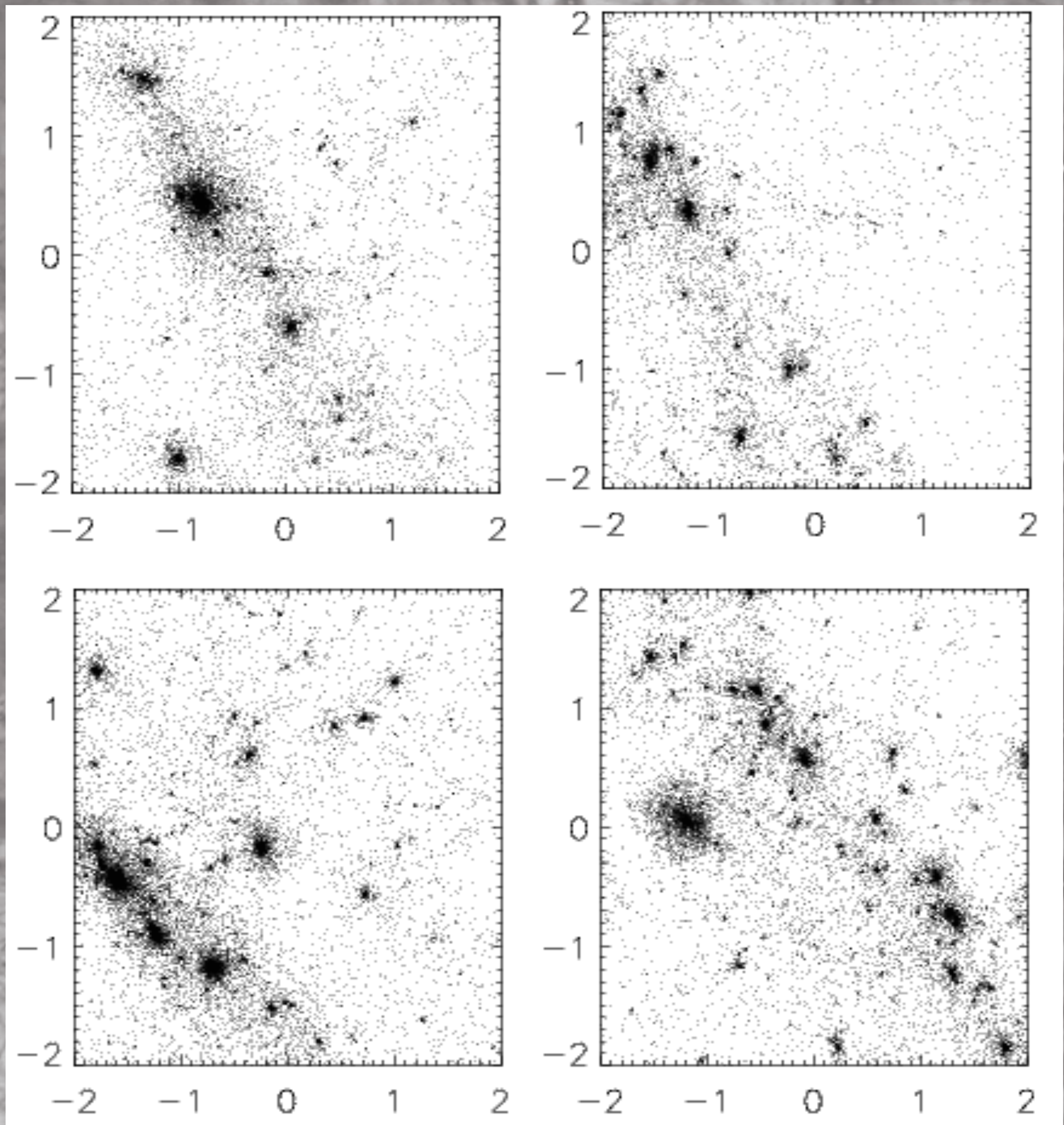
Virgo Cluster
Local Group
Local Void
Milky Way
Andromeda
Milky Way
Andromeda

Hestia:

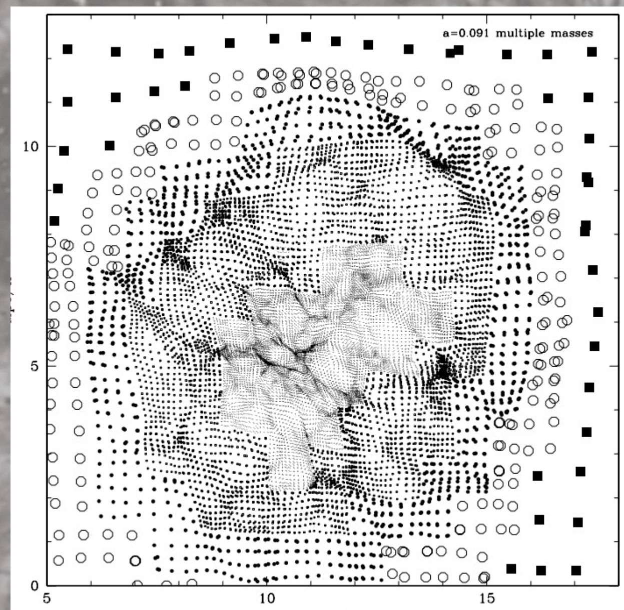
constrained initial conditions for hydrodynamic simulations of the Local Group



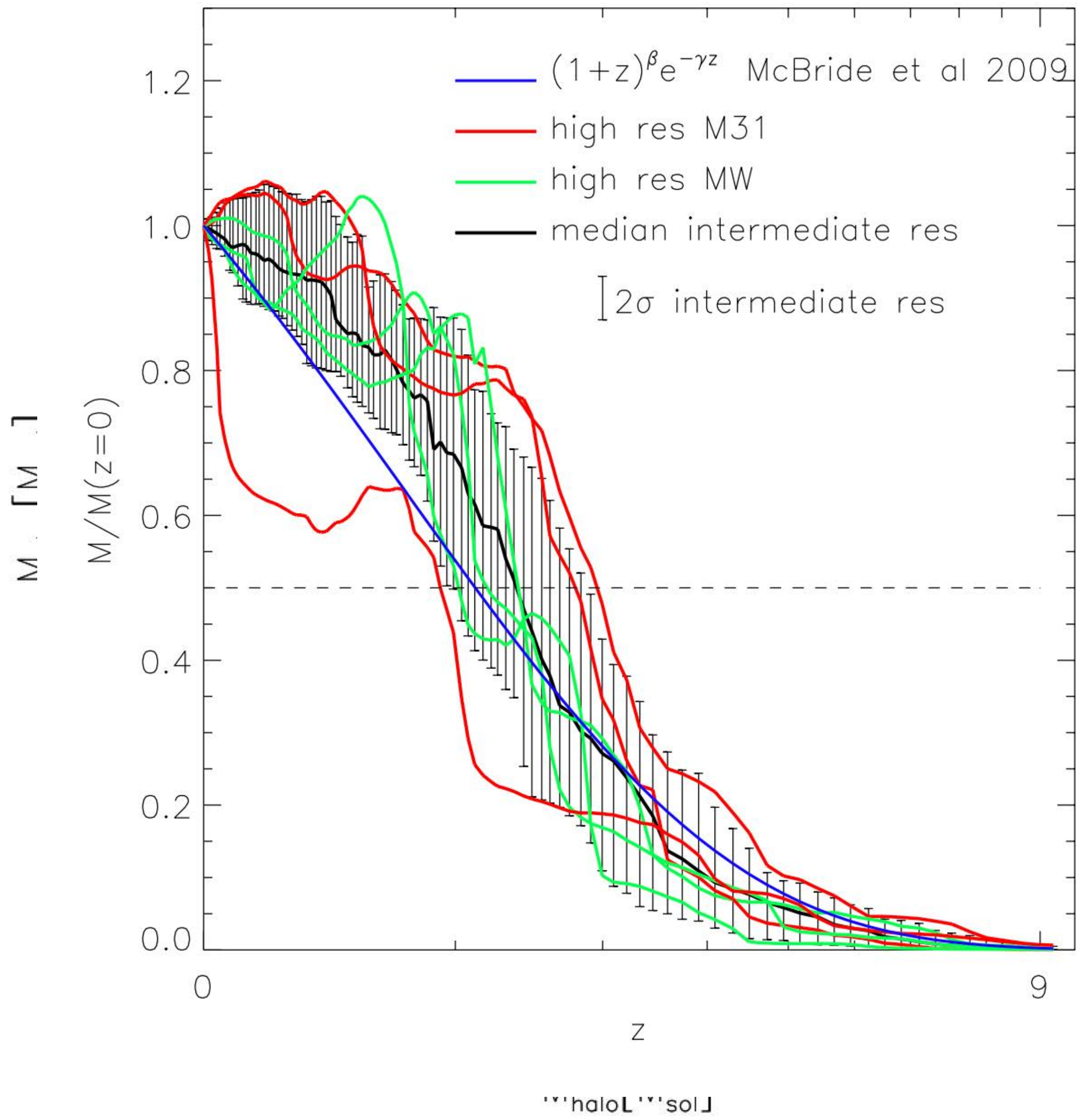
Hestia:
Small scales not constrained



Small scale selection for a LG is done in a “frequentist“ manner. Many low resolution simulations are searched

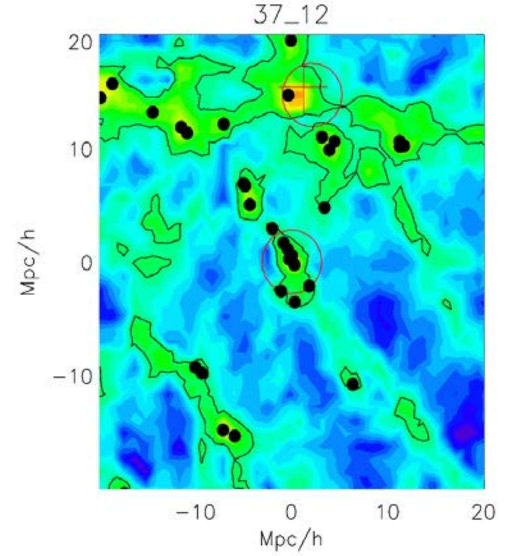


Halo growth seems a bit faster after z=2
When compared with similar mass haloes



What is a "GOOD" Constrained simulation

1. Virgo like cluster (> 2 x $10^{14}M_{sol}$) within 5 Mpc of where Virgo should be (in practice $|d_{sim, virgo} - d_{obs, virgo}| < 3.5$ Mpc)
   1a. No other massive Virgo like cluster closer than the simulated Virgo



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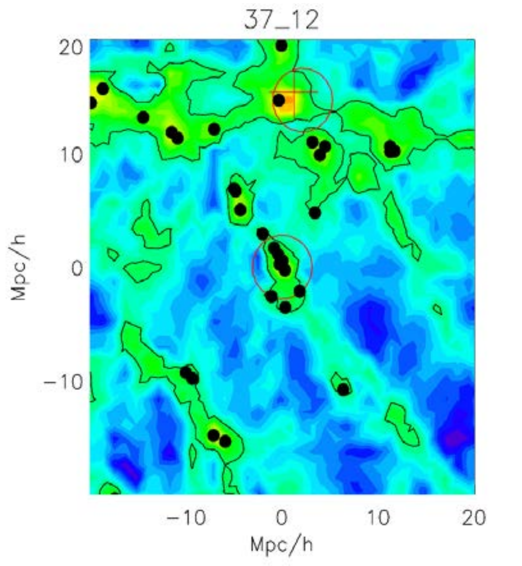

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   1a. No other massive Virgo like cluster closer than the simulated Virgo

2. LG within 5 Mpc of box center
   2a. LG: 2 halos of mass
   $8 \times 10^{11} < M_{MW} < M_{31} < 2.5 \times 10^{12}$
   2b. $M_{MW}/M_{31} > 1/2$
   2c. Separated by
   $500\ \mathrm{kpc} < d_{sep} < 1{,}000\mathrm{kpc}$
   2d. Exclusion: nothing greater than M_{31} within $d_{excl} < 2.5$Mpc of LG c.o.m
   2e. $V_{rad} < 0$ (infalling)

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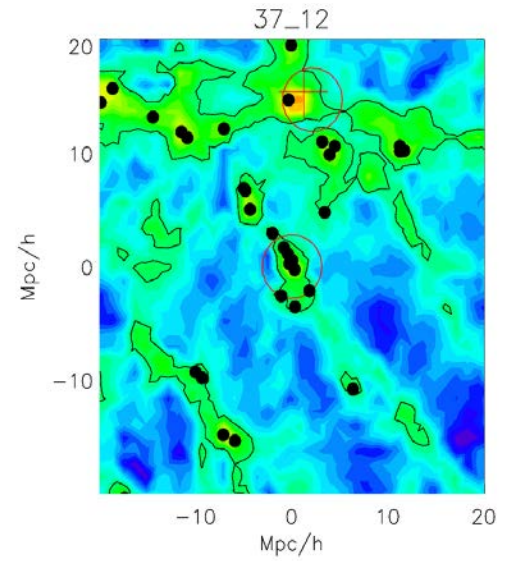
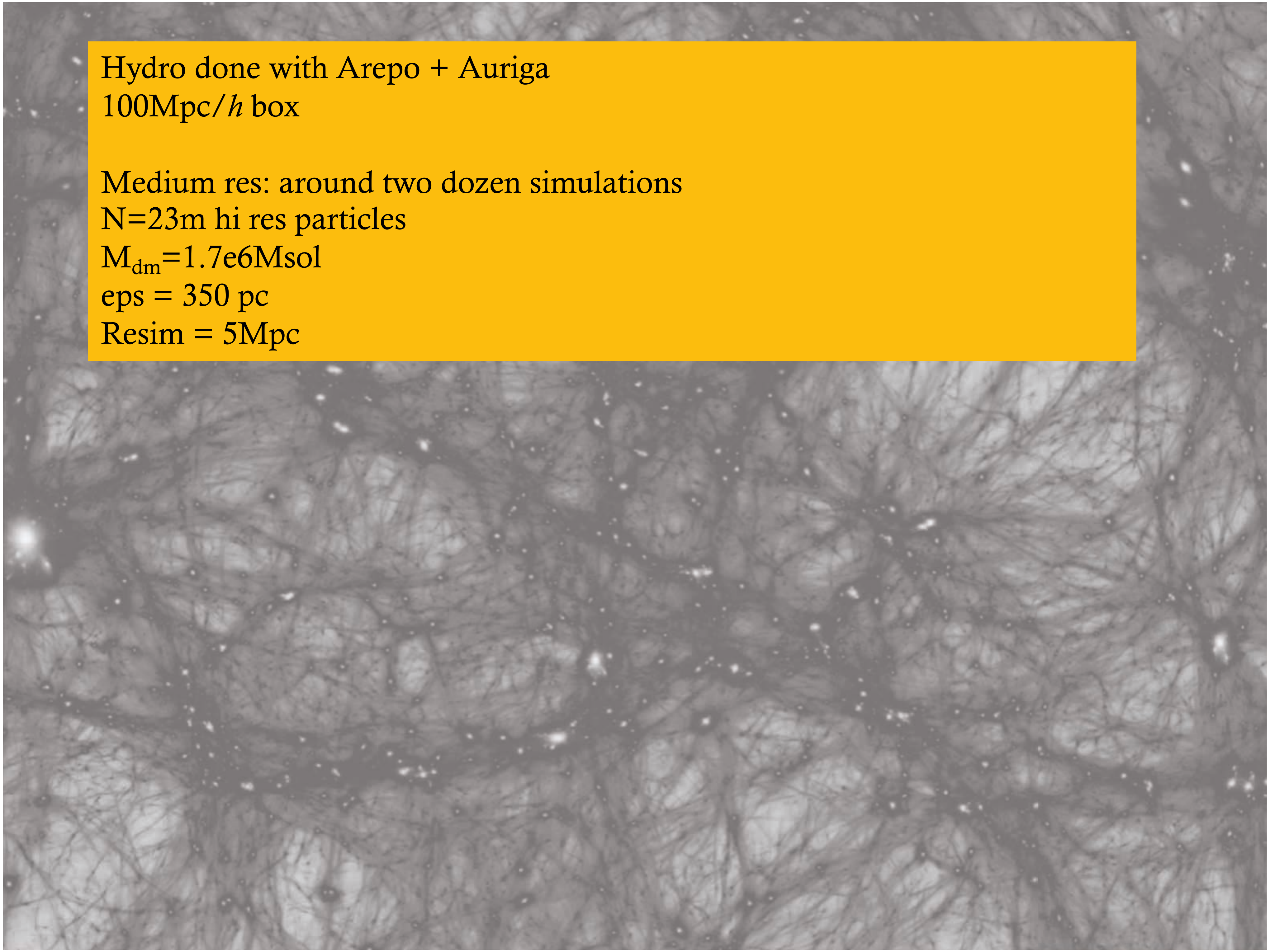
3. $M_{star} > 6\times10^{10} M_{sol}$
4. Disky galaxies

Hyrdo criteria



Hydro done with Arepo + Auriga
100Mpc/*h* box

Medium res: around two dozen simulations
N=23m hi res particles
M_{dm}=1.7e6Msol
eps = 350 pc
Resim = 5Mpc

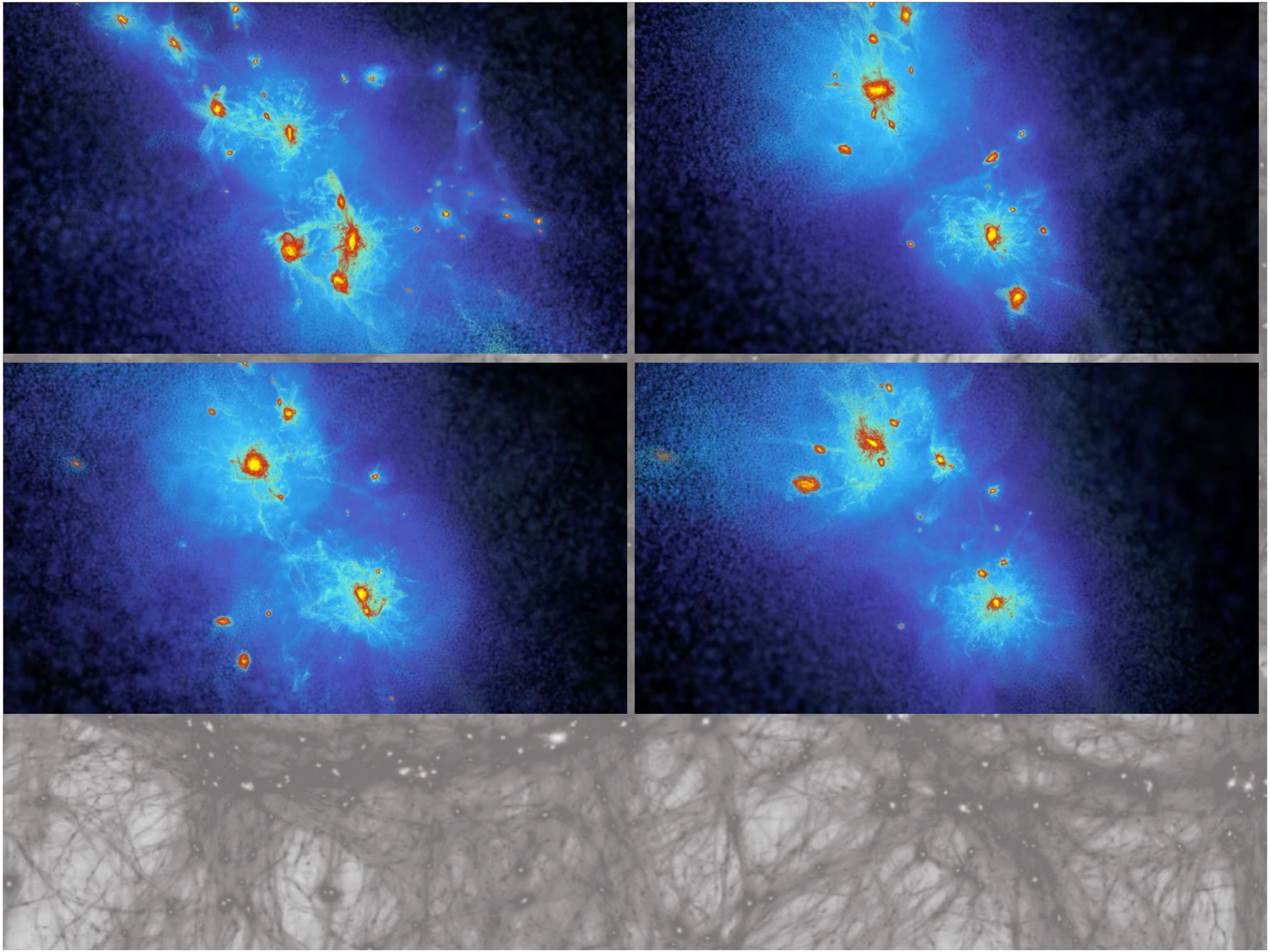


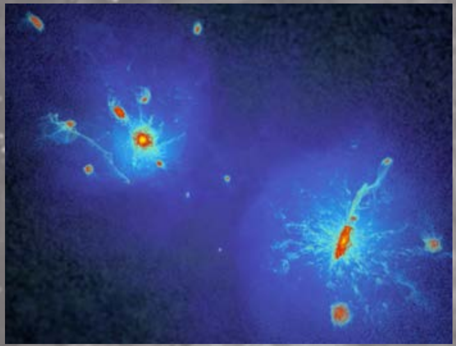
Hydro done with Arepo + Auriga
100Mpc/*h* box

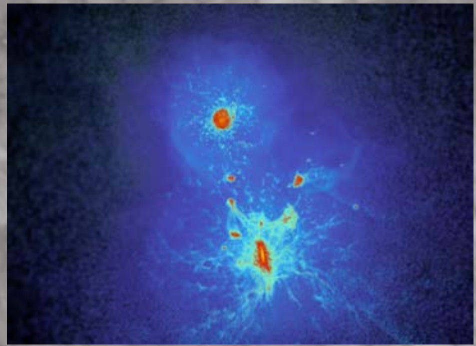
Medium res: around two dozen simulations
N=23m hi res particles
M_{dm}=1.7e6Msol
eps = 350 pc
Resim = 5Mpc

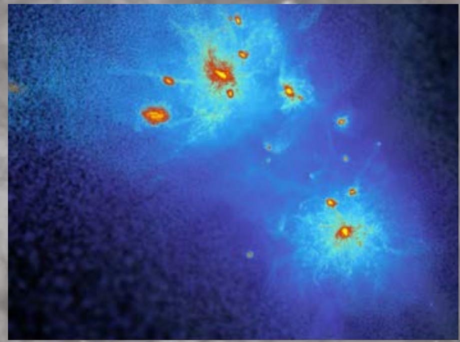
High res: 3 runs
N=187m hi res particles
M_{dm}=2.3e5Msol
eps = 170 pc
Resim = 2.5Mpc

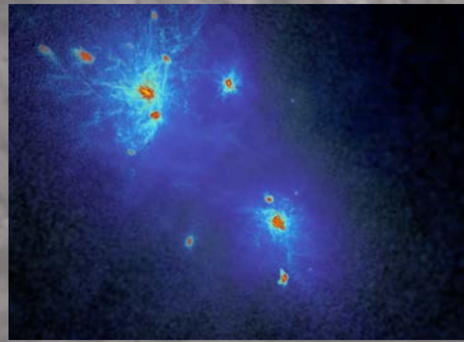
Everything with DMO and hydro





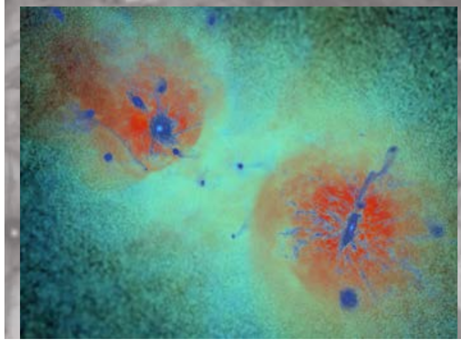


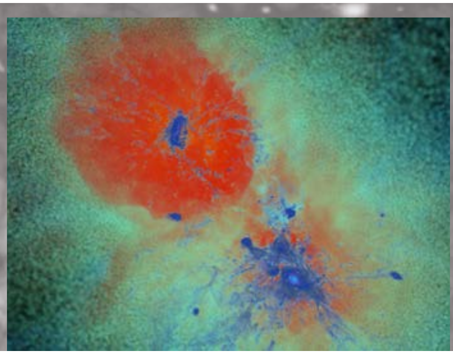


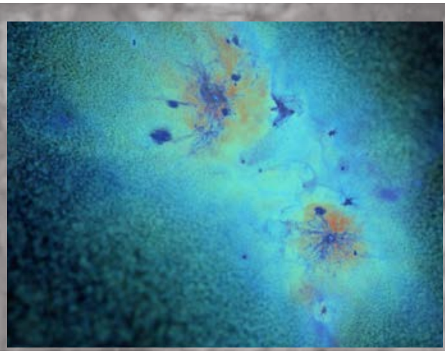


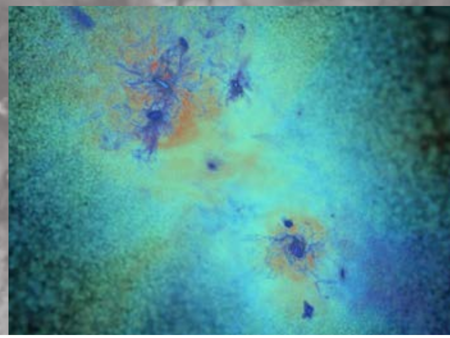
	ID	M_{M31}	M_{MW}	M_{MW}/M_{M31}	$M^{M31}_{star,disc}$	$M^{MW}_{star,disc}$	d_{sep}	v_{rad}	v_{tan}	M_{Virgo}	d_{Virgo}	Δ_{Virgo}
intermediate resolution	9_10	2.06	1.25	0.607	8.13	4.46	857	−61.7	48.3	4.28	1.72	0.648
	9_16	2.07	1.25	0.605	6.49	5.87	752	−68.8	59.5	4.25	1.73	0.727
	9_17	2.27	1.31	0.577	7.94	6.38	1090	−10.3	28.3	4.30	1.72	0.657
	9_18	2.22	1.92	0.863	8.47	6.41	856	−76.1	55.7	4.25	1.71	0.577
	9_19	2.15	1.22	0.566	7.02	4.45	726	−87.3	44.8	4.25	1.72	0.639
	17_10	2.16	2.08	0.961	7.53	9.71	736	−76.4	12.1	3.02	2.00	3.42
	17_11	2.35	1.98	0.845	11.0	6.25	662	−103.9	13.9	3.14	2.00	3.43
	17_13	2.08	1.89	0.910	6.72	7.35	975	−26.9	12.6	3.15	1.99	3.29
	17_14	2.20	2.06	0.938	11.9	6.36	613	−104.4	14.1	3.12	2.00	3.43
	37_11	1.12	1.11	0.993	4.07	5.67	864	−17.0	68.8	3.87	1.59	0.680
	37_12	1.22	0.99	0.812	5.95	4.30	838	−23.4	87.5	3.96	1.59	0.646
	37_16	1.11	1.08	0.973	4.46	4.59	721	−26.6	81.4	3.90	1.60	0.593
	37_17	1.23	0.96	0.785	5.17	4.47	805	−41.1	89.8	3.96	1.59	0.693
high res	9_18	2.13	1.94	0.913	11.4	7.70	866	−74.0	54.0	4.26	1.71	0.565
	17_11	2.30	1.96	0.852	9.90	8.38	675	−102.2	137	3.11	2.00	3.44
	37_11	1.04	1.09	0.980	4.12	5.70	850	−8.86	71.1	3.82	1.57	0.867
Observation		0.6-2.0	1.0-2.1	0.5 – 1	8 – 15	5 – 10	785±25	-110	0 – 60	2.7-8	1.7	
References		[1,2,3,4]	[5,6,7,8,9]		[2,10,11]	[11,12,13]	[14]	[15]	[16,17,18]	[19,20,21]	[20]	

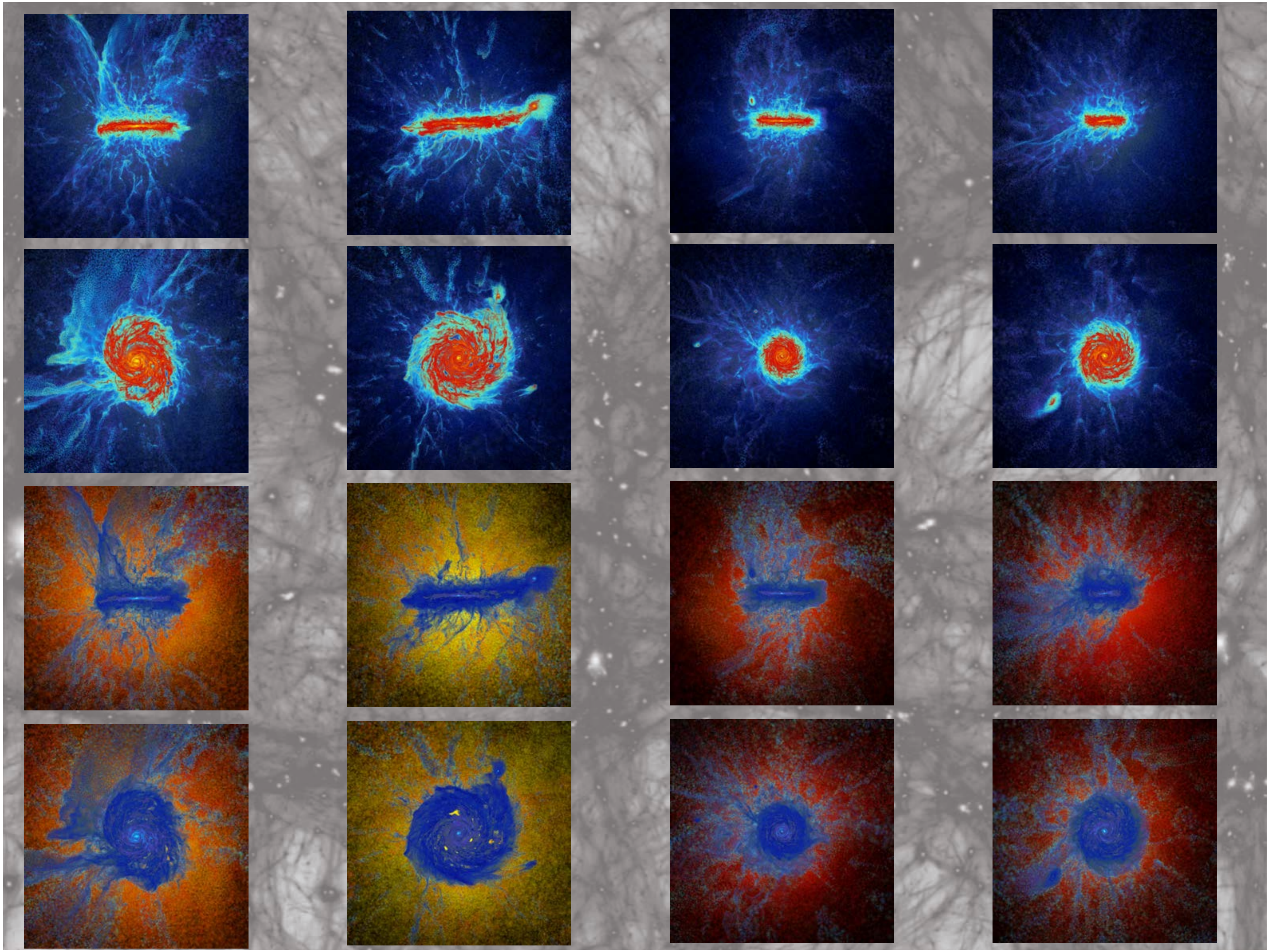
Table 1. $z = 0$ properties of the intermediate resolution (termed "4096") runs. We adopt the convention that the more massive halo is termed M31 while the less massive one is termed the MW. From left column to right we show: the simulation ID; the virial mass of the simulated M_{M31} halo, the virial mass of the simulated M_{MW} halo; the mass ratio of the two; the mass of the stellar disc of M31 (determined as the stars within $0.15r_{vir}$; the mass of the stellar disc of the MW; the separation of the two halos, the radial velocity (negative v_{rad} indicates in-falling motion); and the the tangential velocity. References [1]: Kafle et al 2018; [2] Tamm et al 2012; [3] Diaz et al 2014; [4] Corbelli et al 2010; [5] Posti & Helmi 2018; [6] Hattori et al 2018; [7] Monari et al 2018; [8] Watkins et al 2018; [9] Sick ety al 2014; [10] McMillain et al 2017; [11] Licquia & Newman 2015; [12] Kafle et al 2014; [13]McConnachie et al 2014; [14] Karachentsev & Kashibadze 2006; [15] van den Marel et al 2019; [16] van den Marel et al 2012

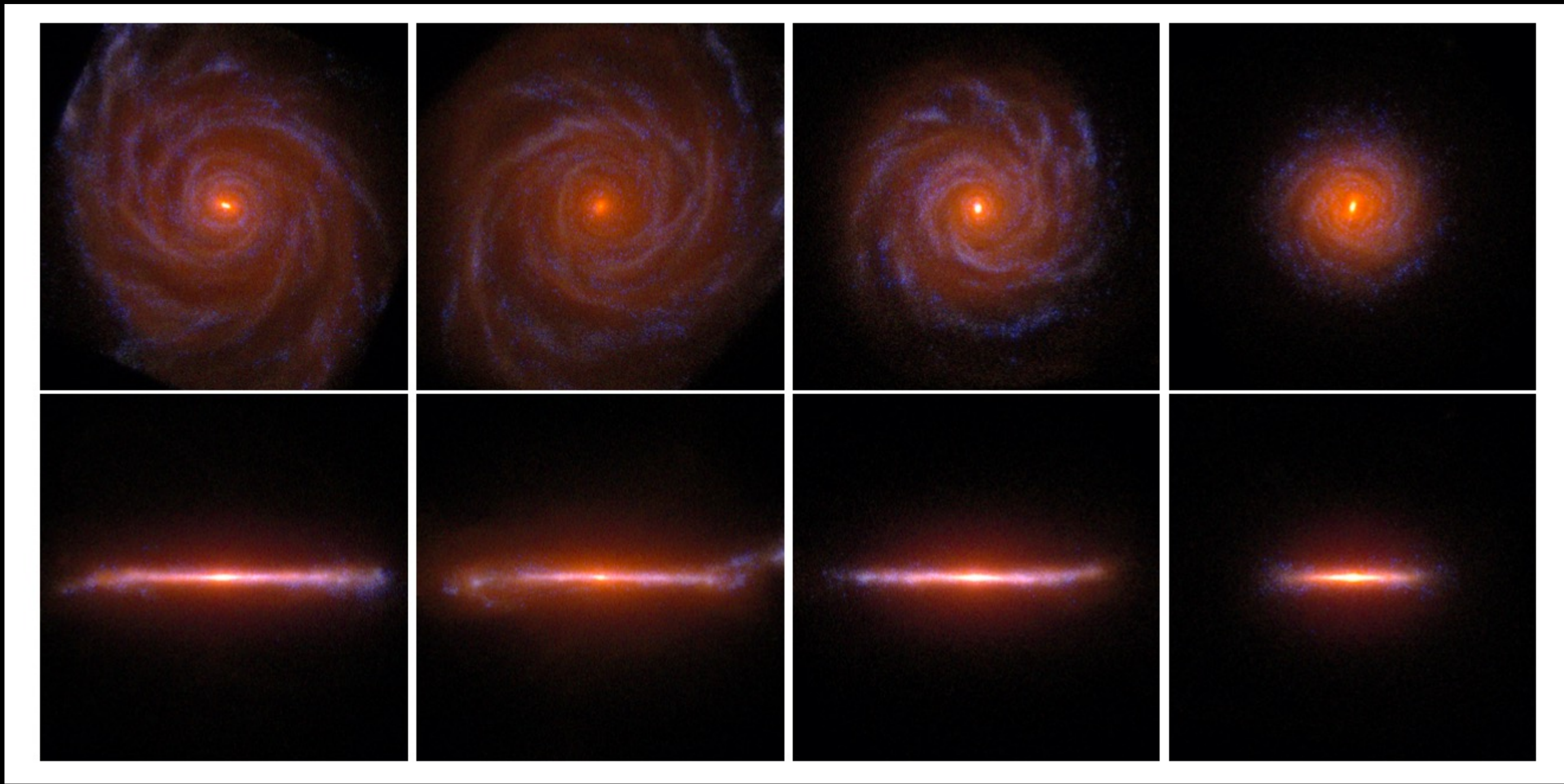


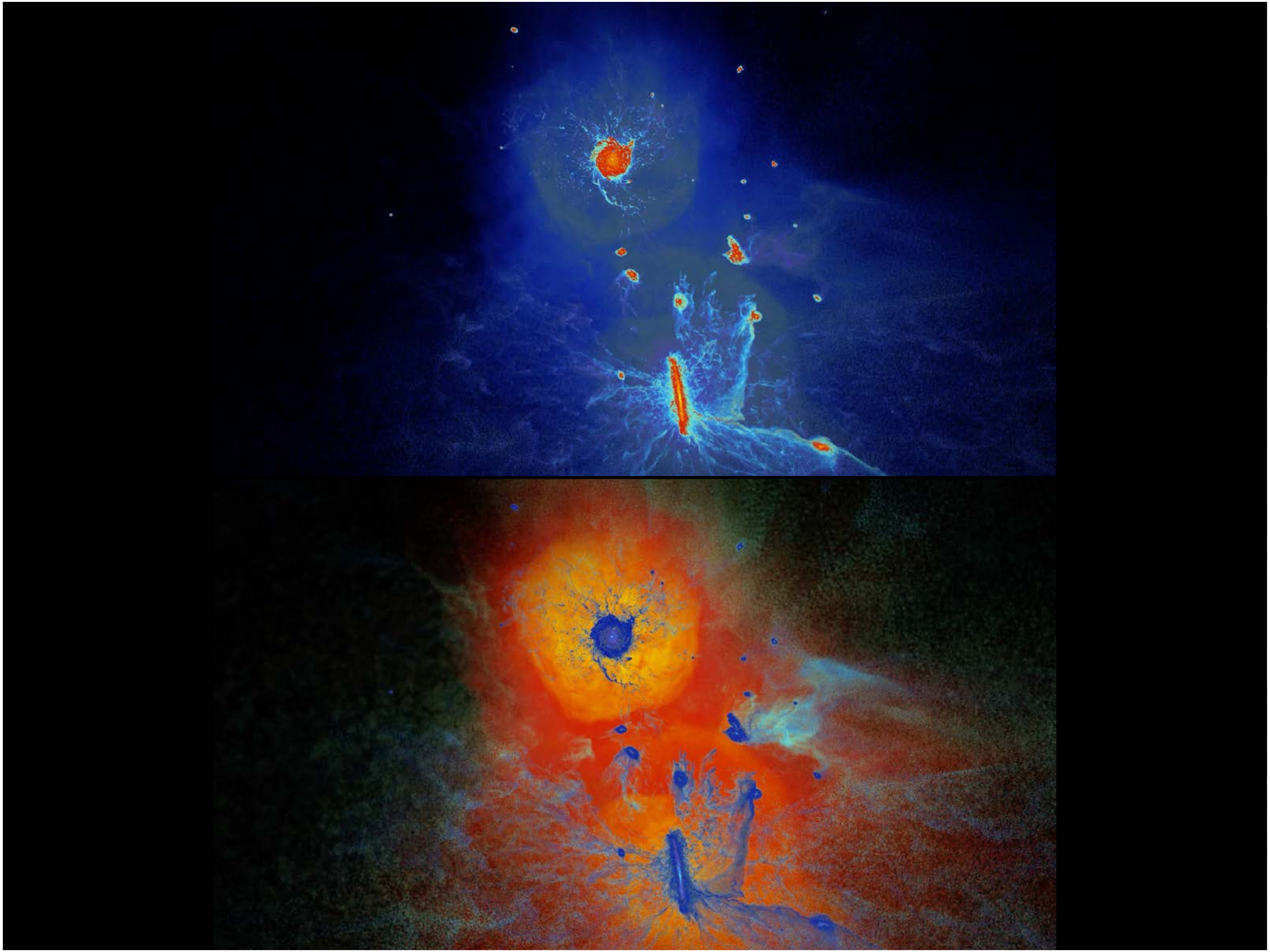




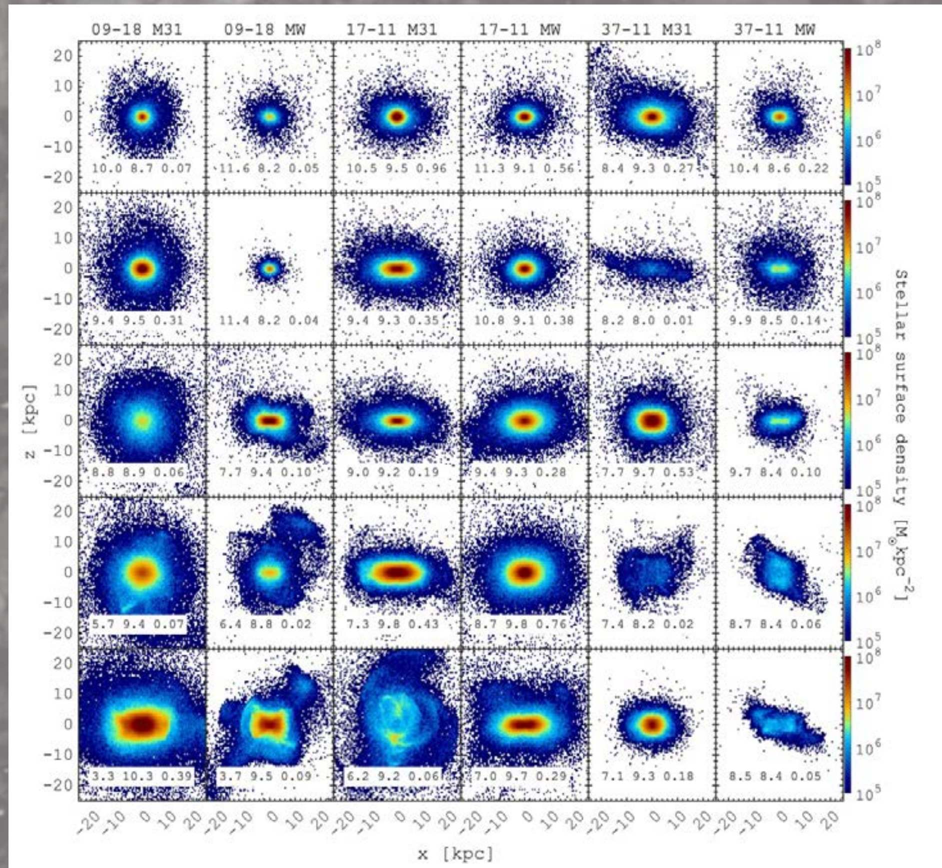








Constrained simulations of the Local Group: An important laboratory for LG science



Khoperskov + NL (2023)

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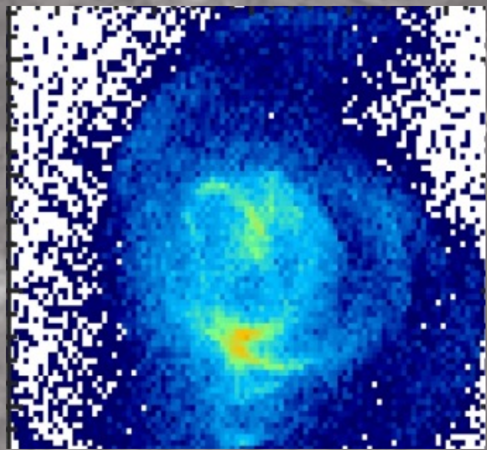

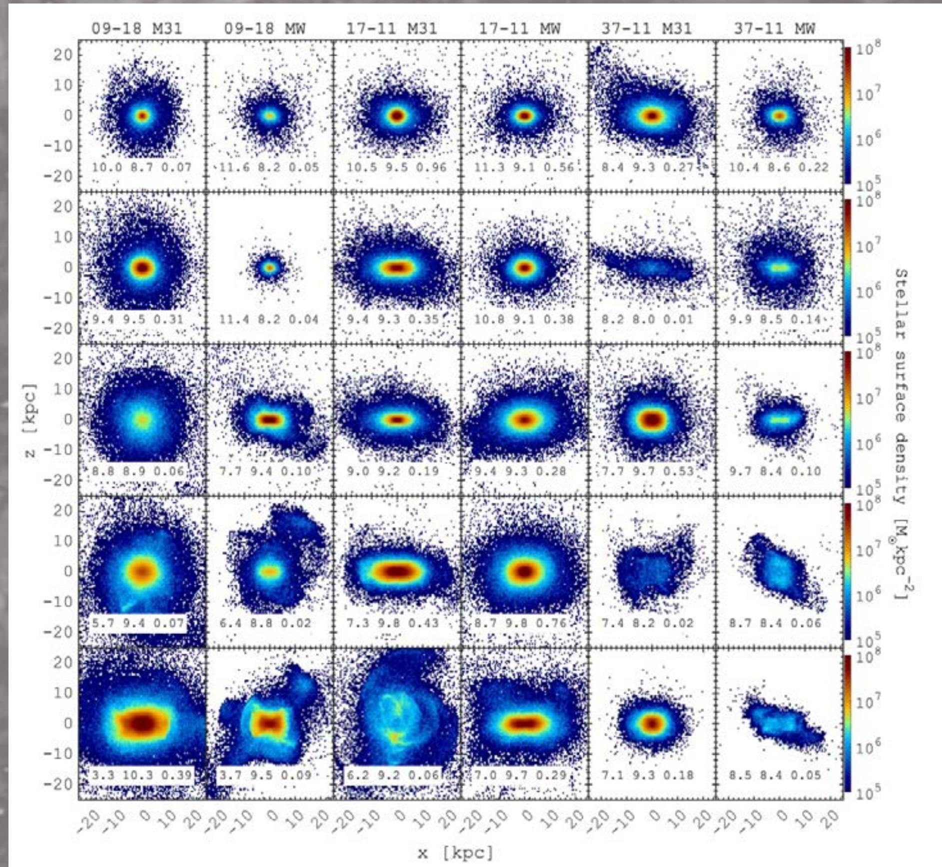

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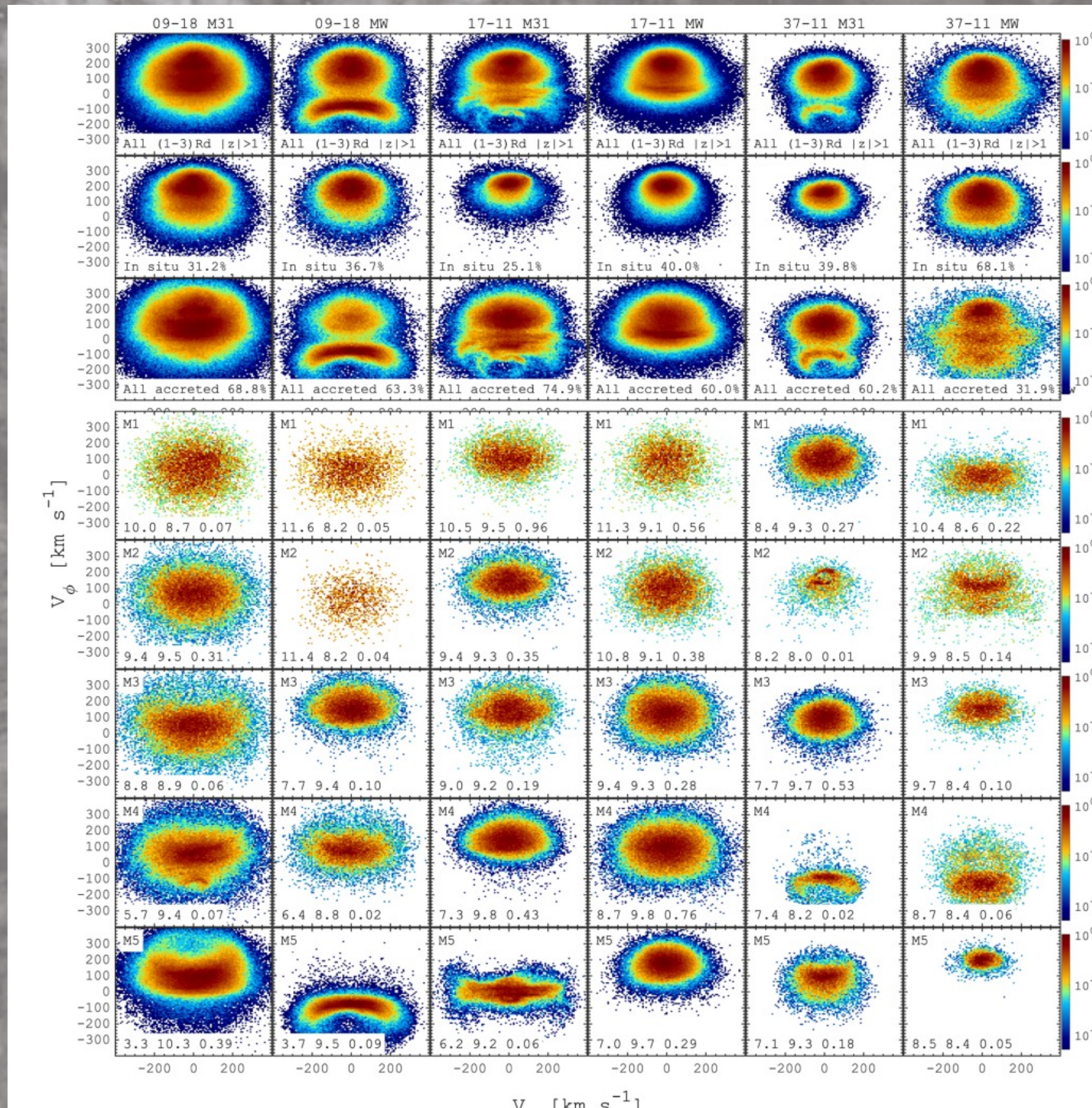

Khoperskov + NL (2023)

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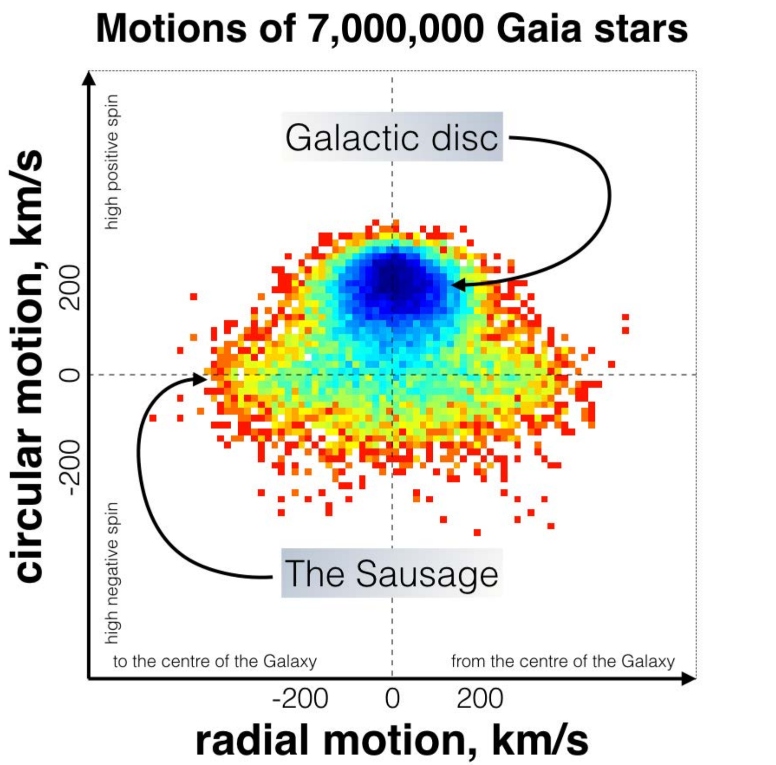
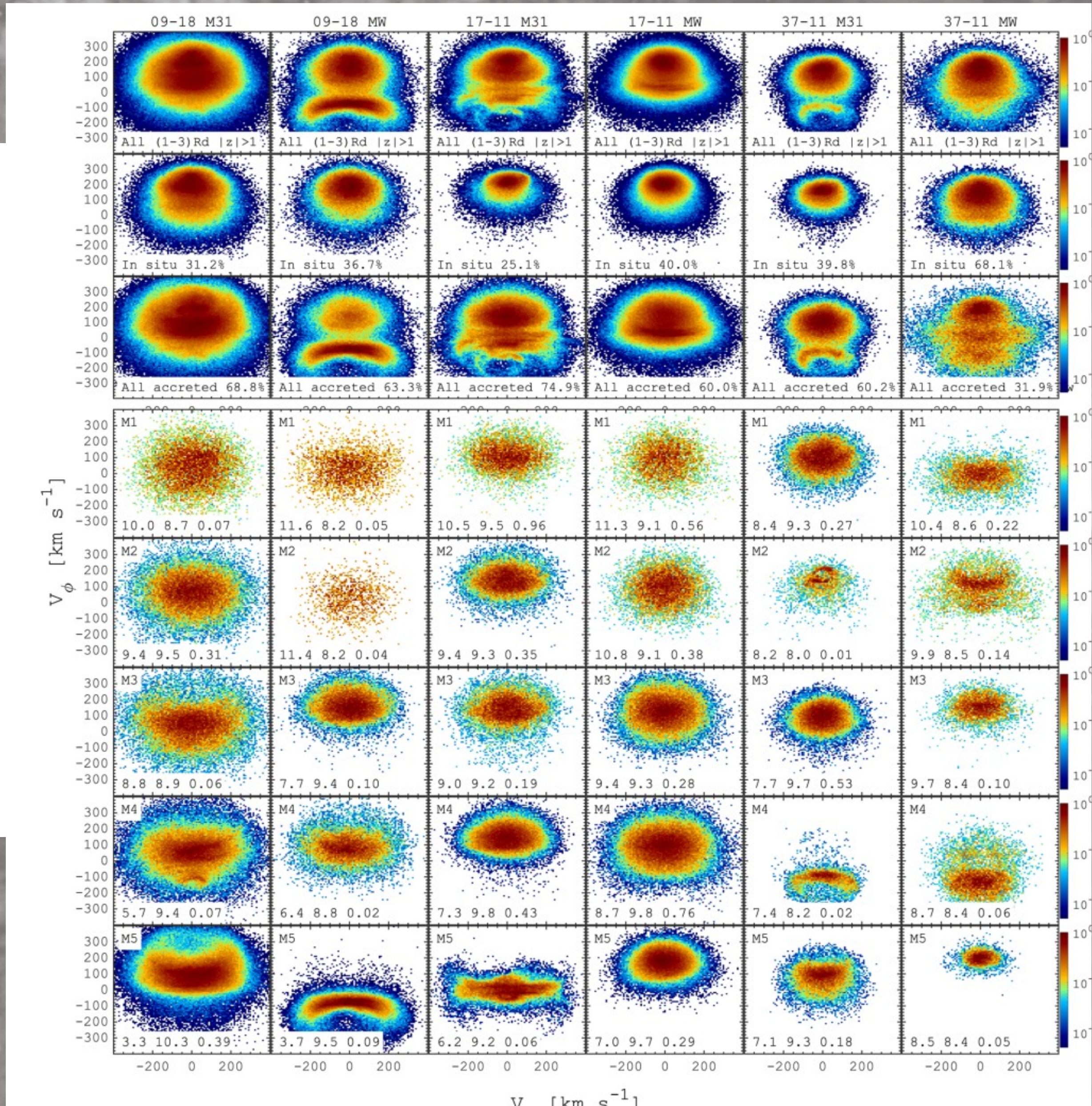
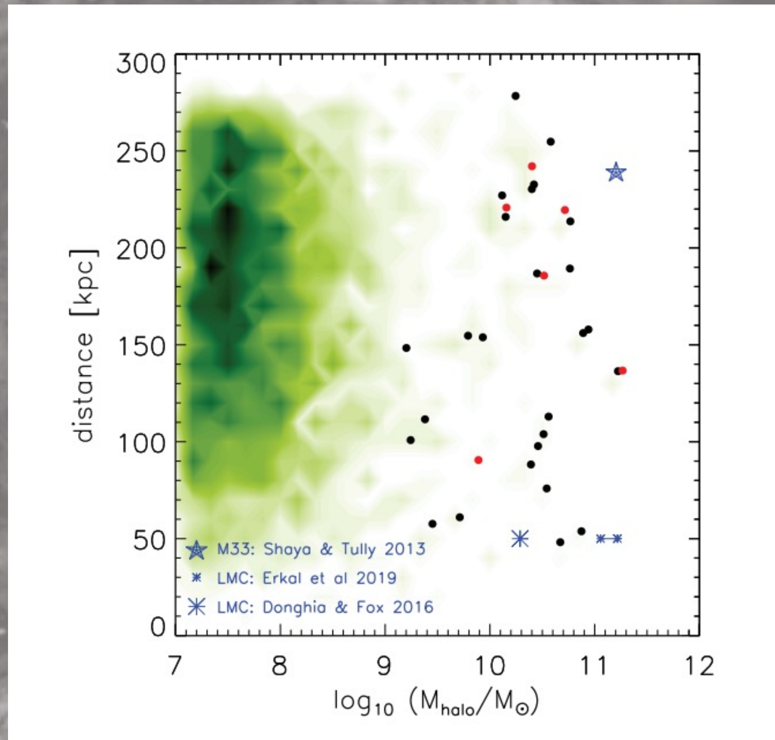




Khoperskov + NL (2023)

Tracking the Magellanic cloud



Muru et al *in prep*

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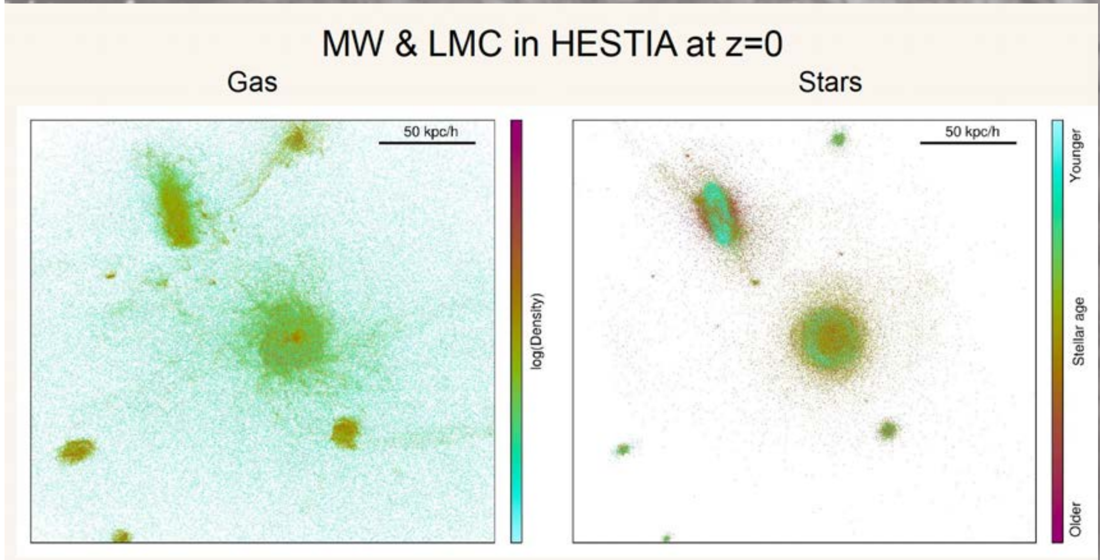

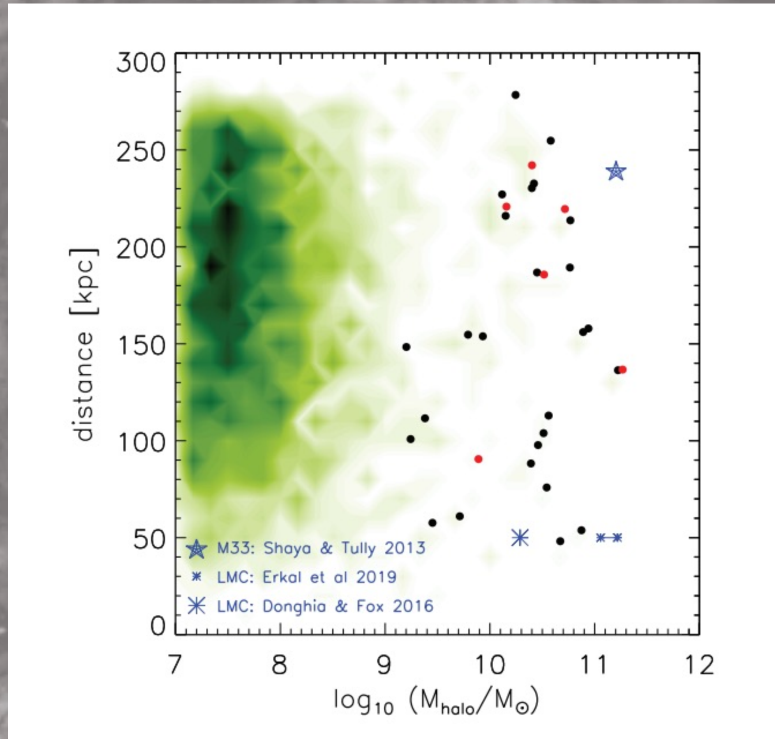

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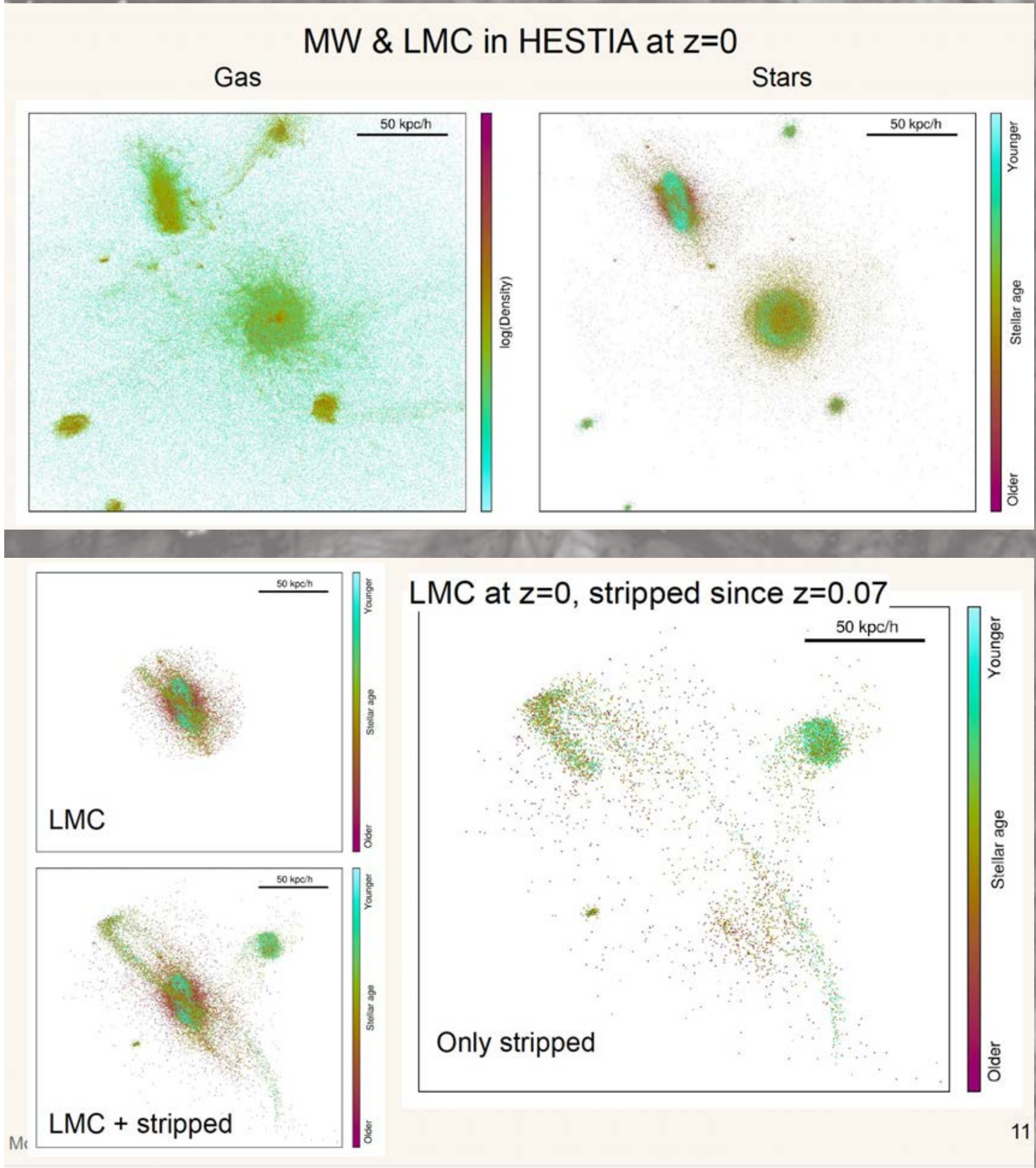

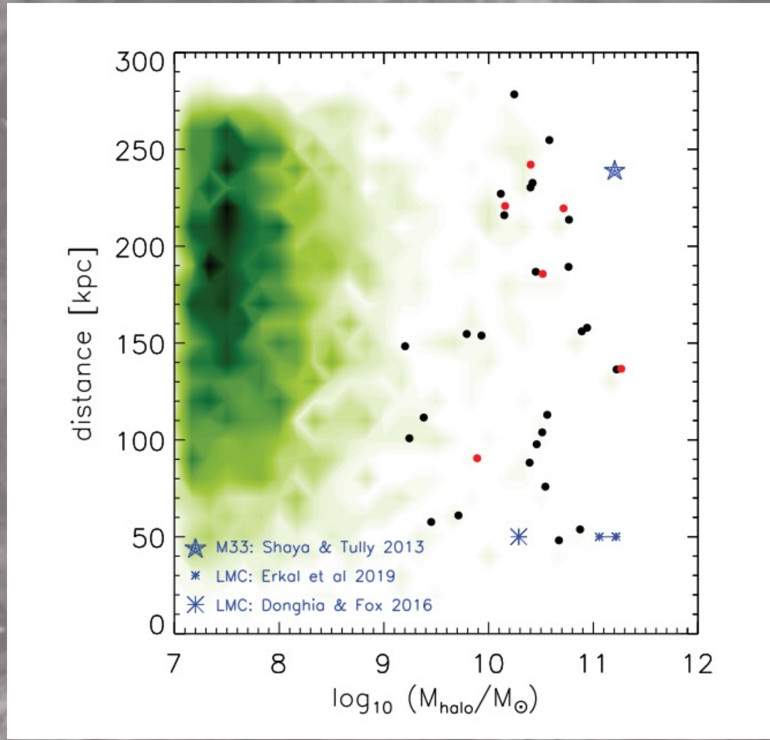

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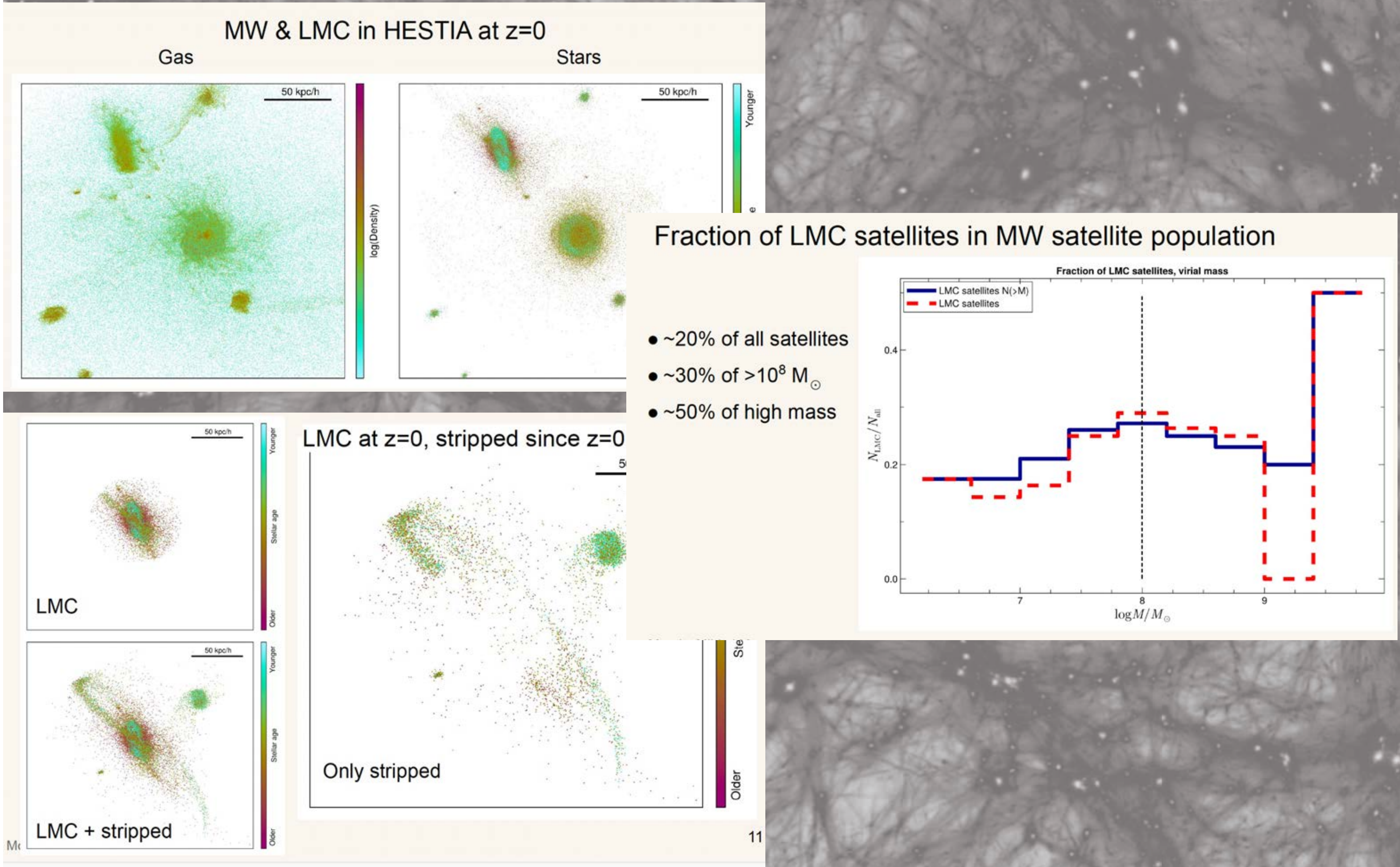

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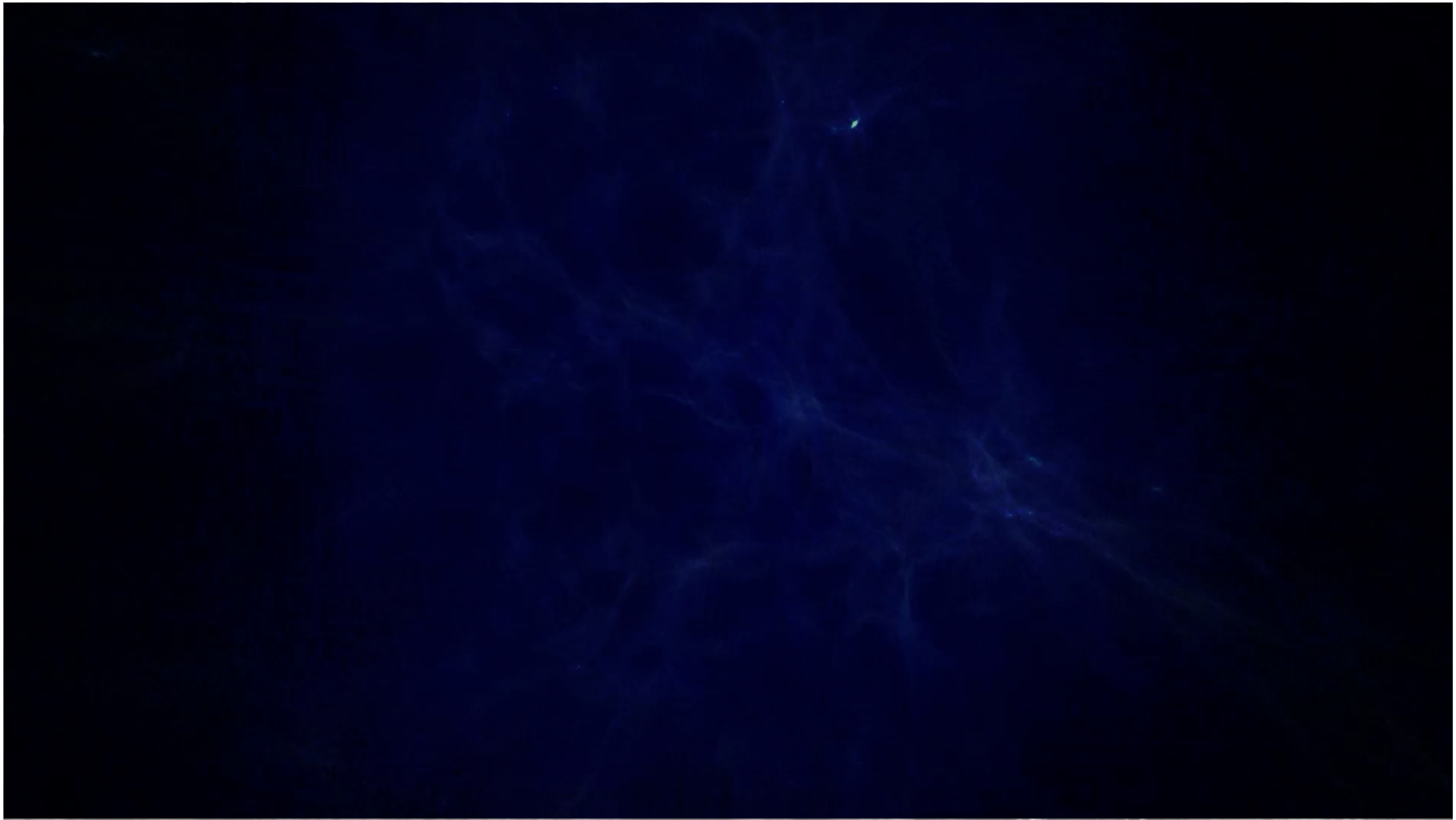
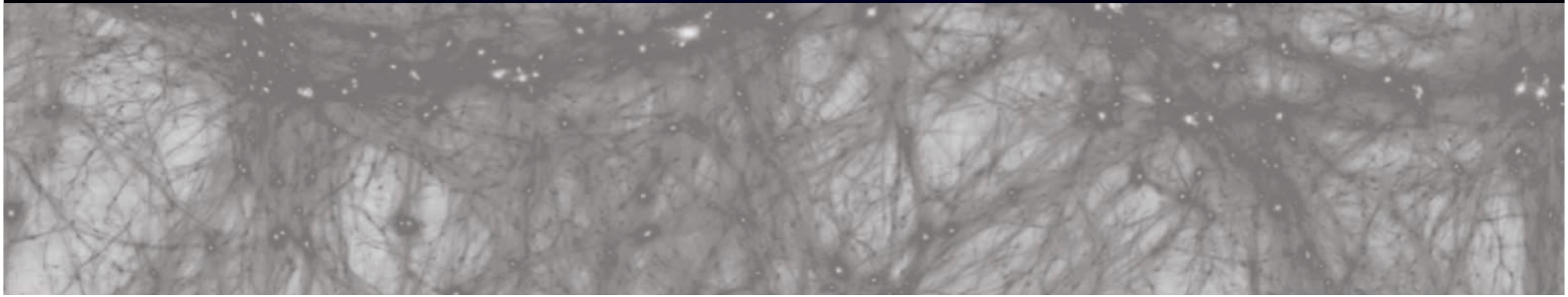
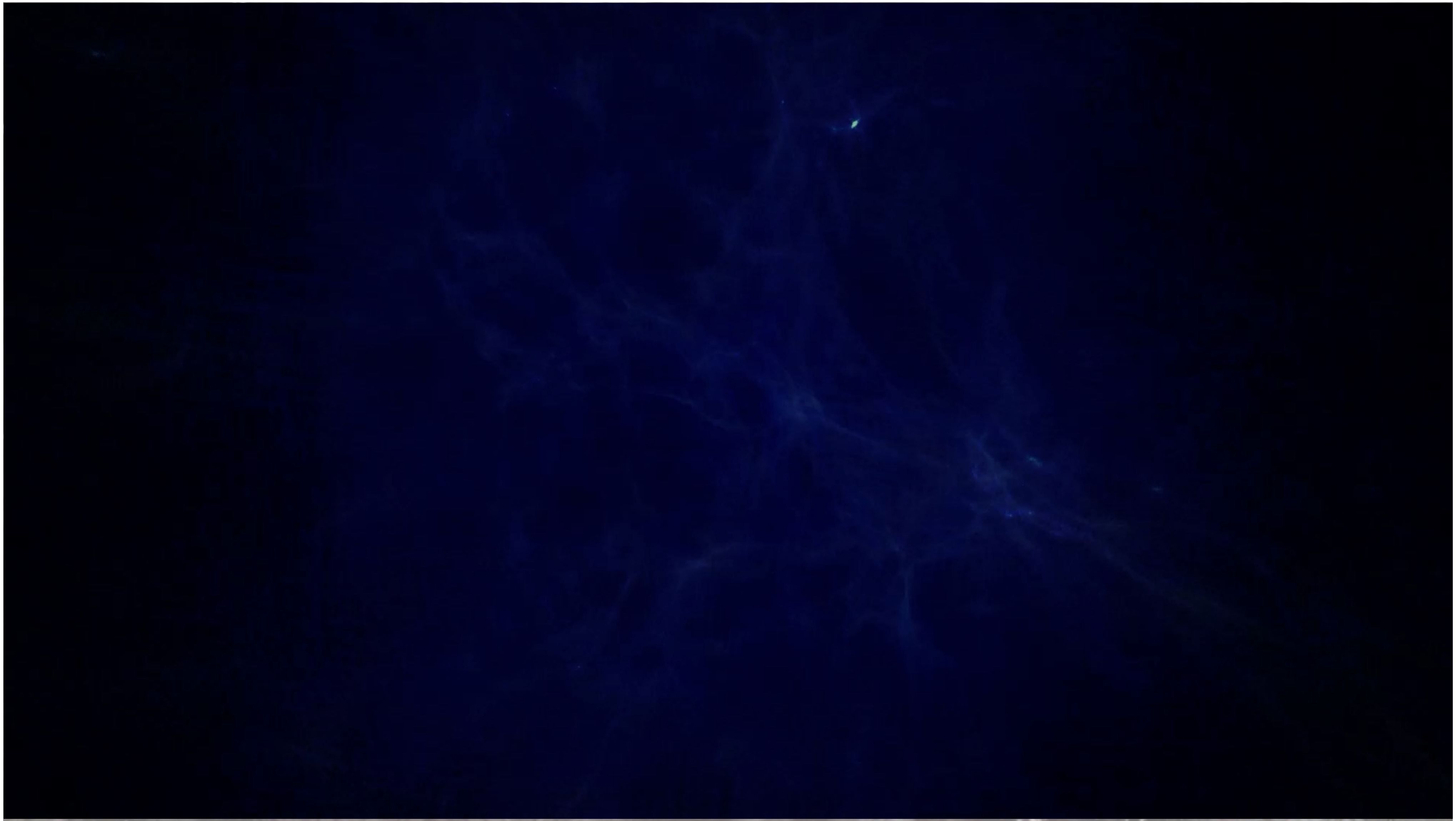
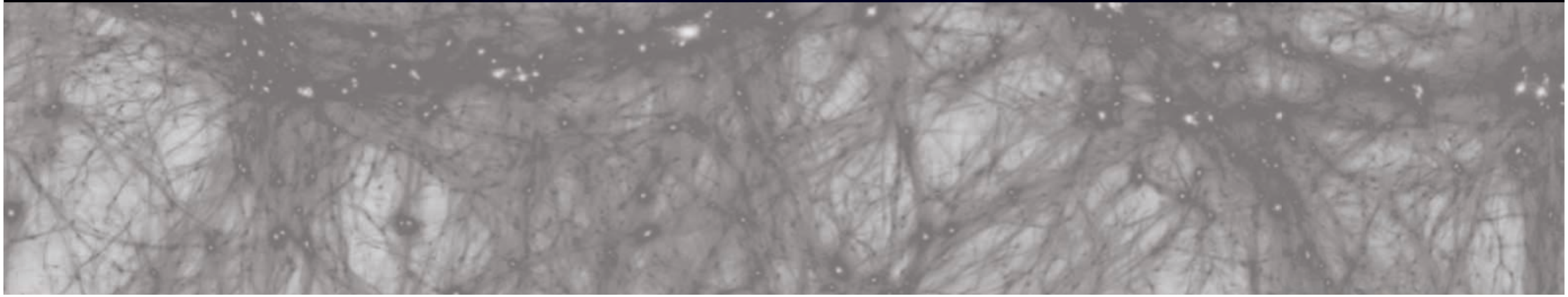
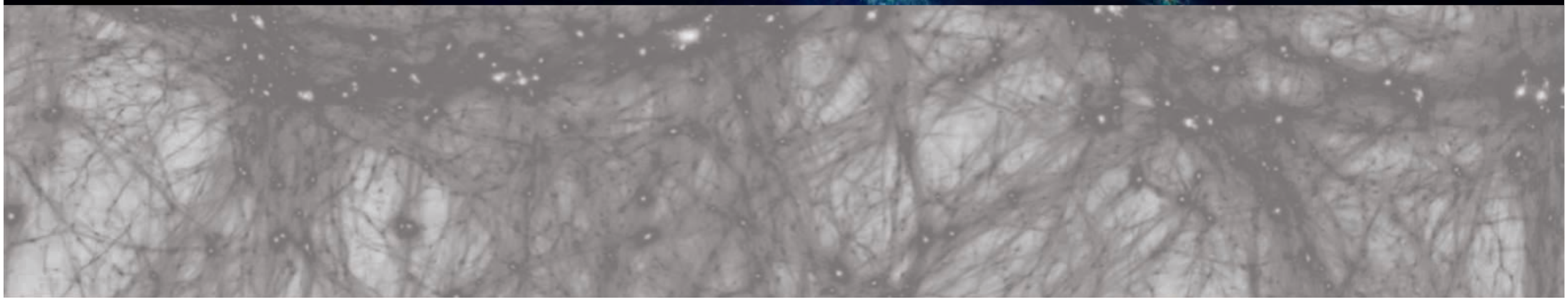
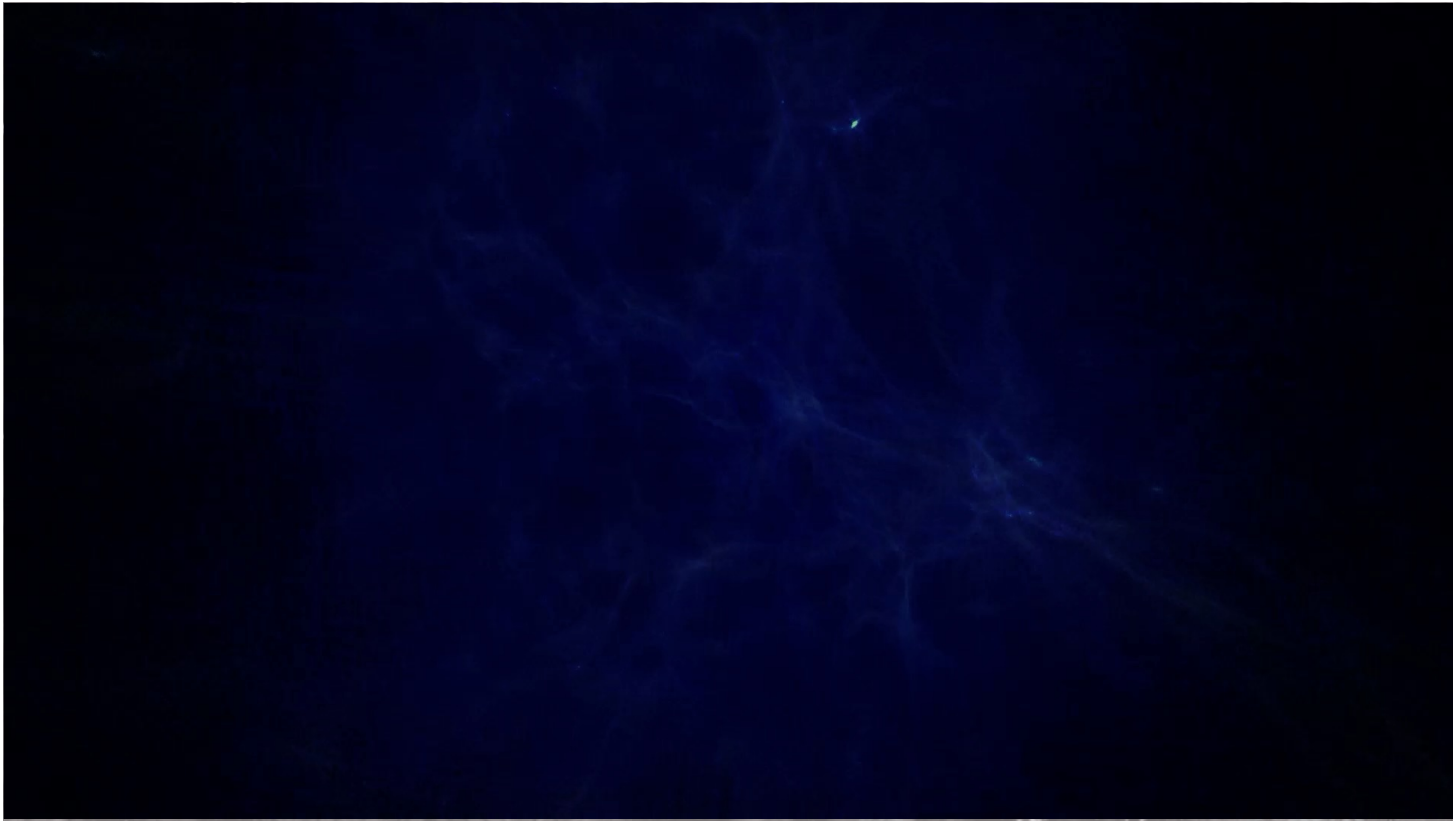
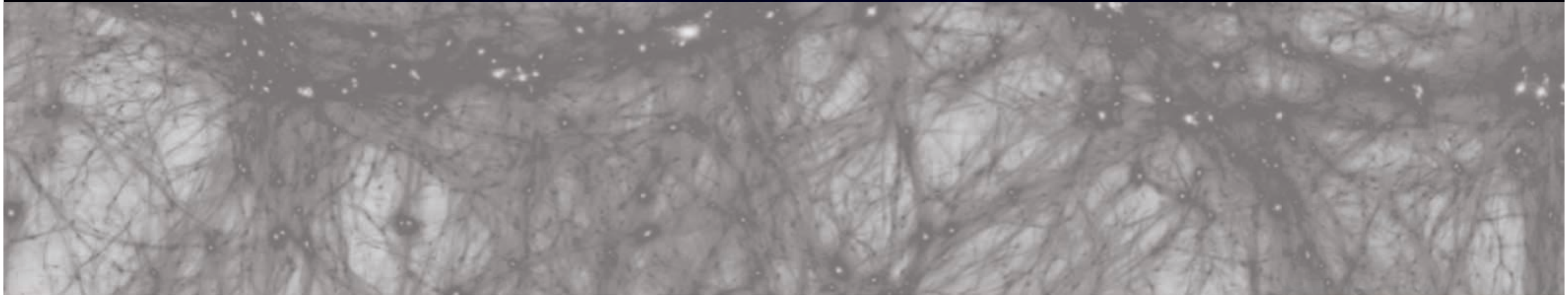


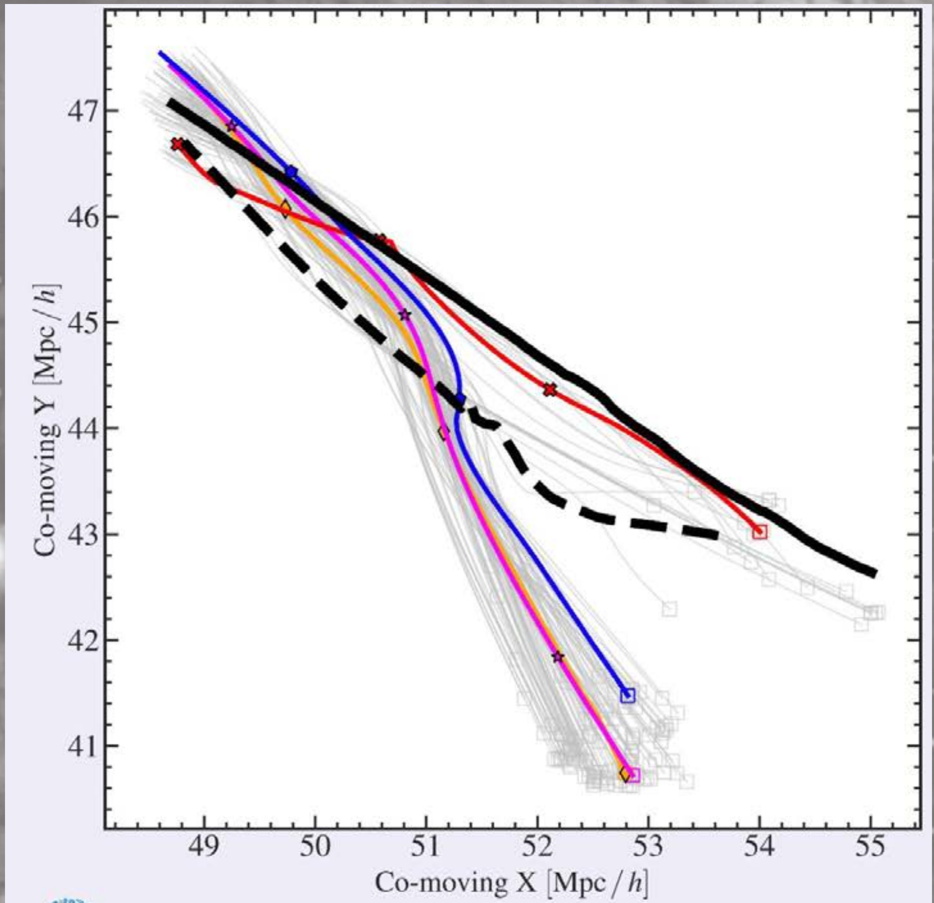


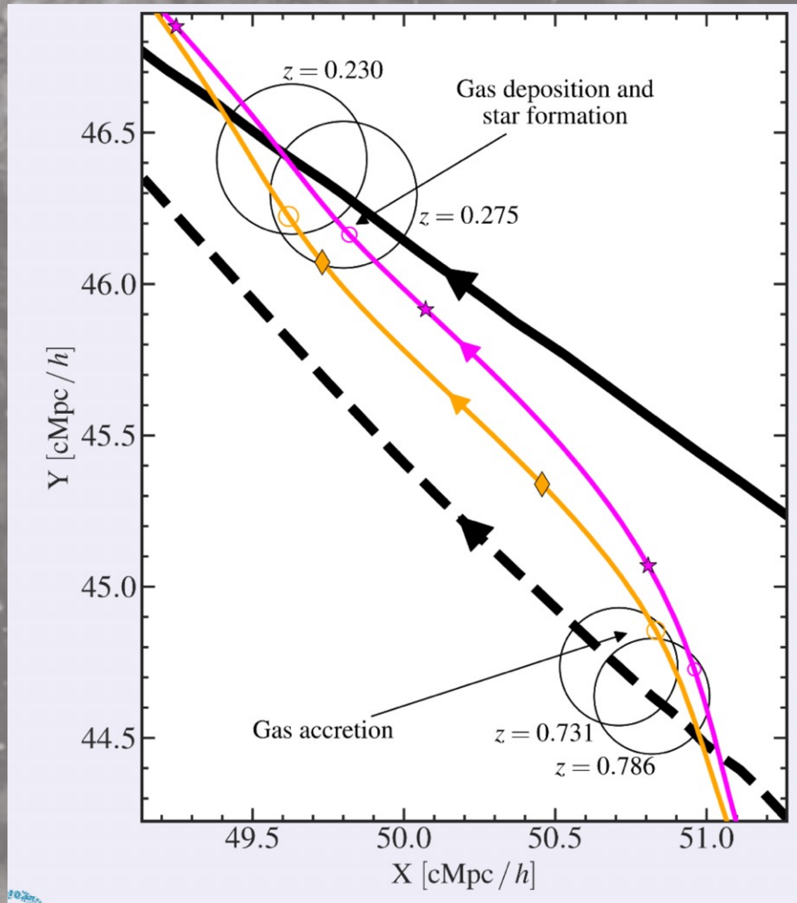



Hermean subhalos of the Local Group

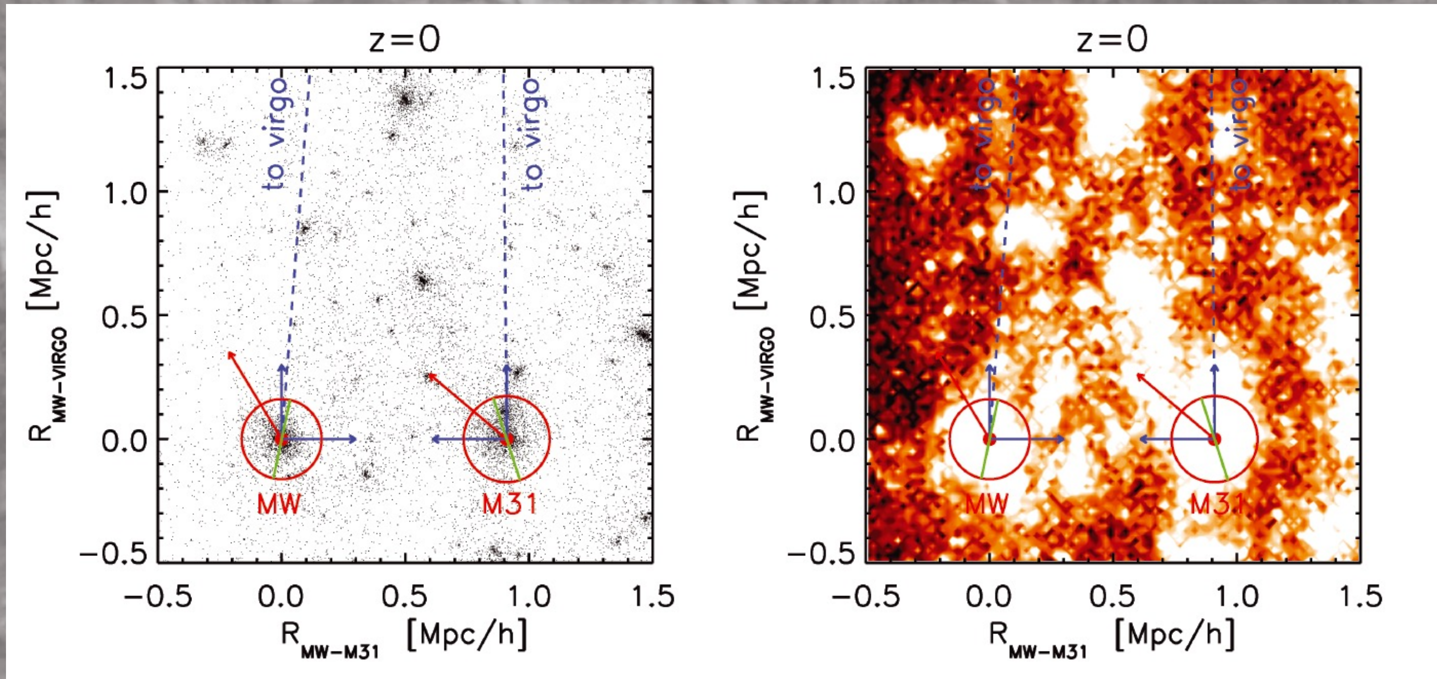




A new class of dwarf galaxy!

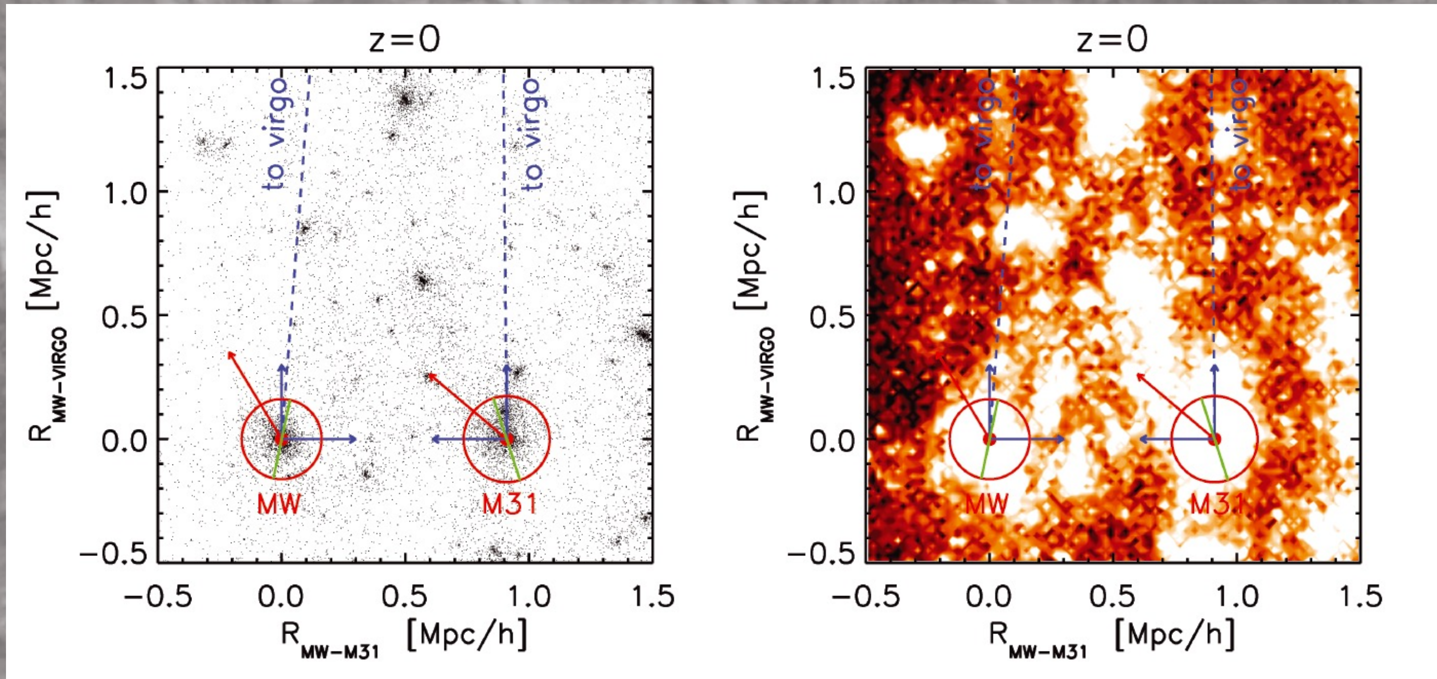
Newton, NL et al 2021

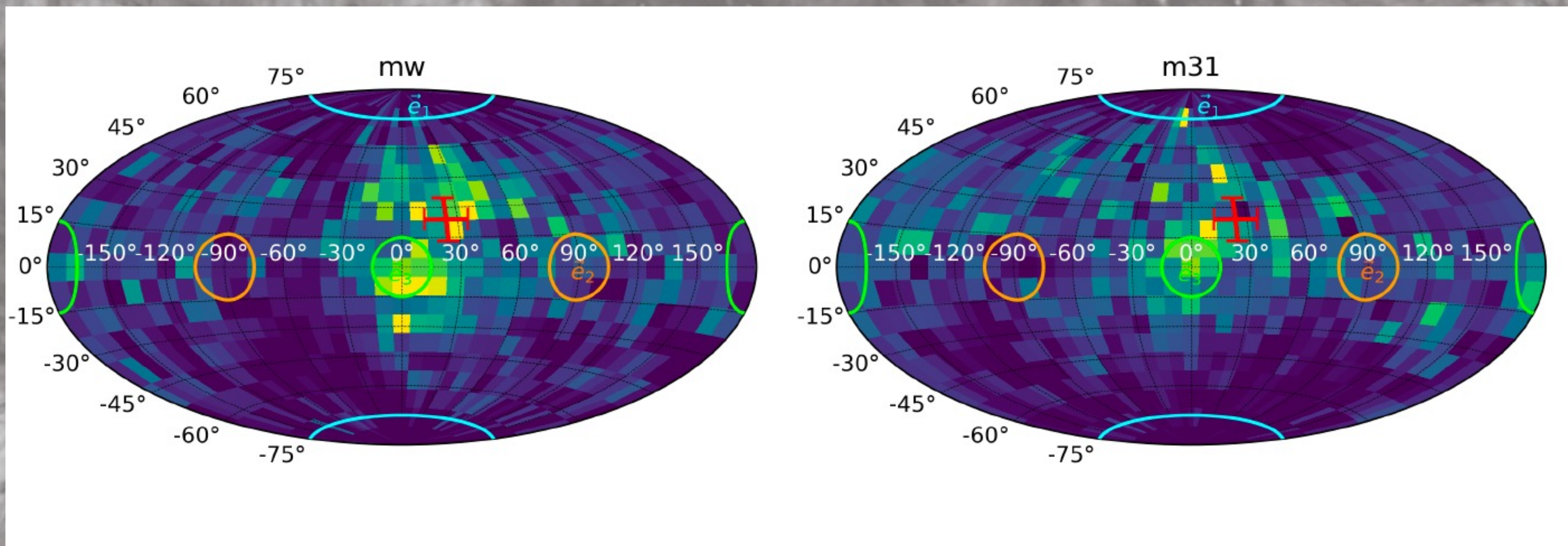
Preferred axes of accretion of LG satellites



Dupuy, NL et al 2021

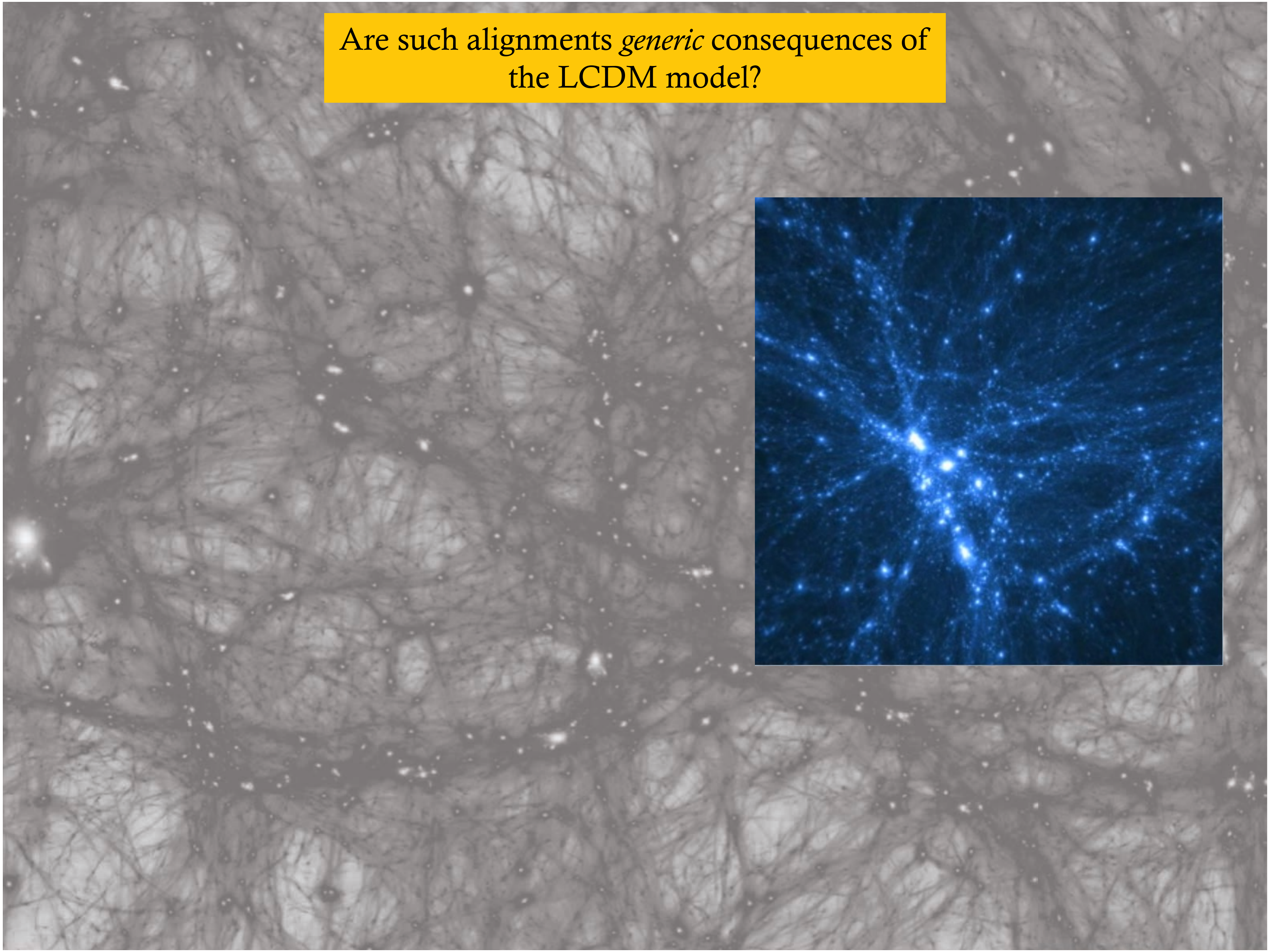
Preferred axes of accretion of LG satellites



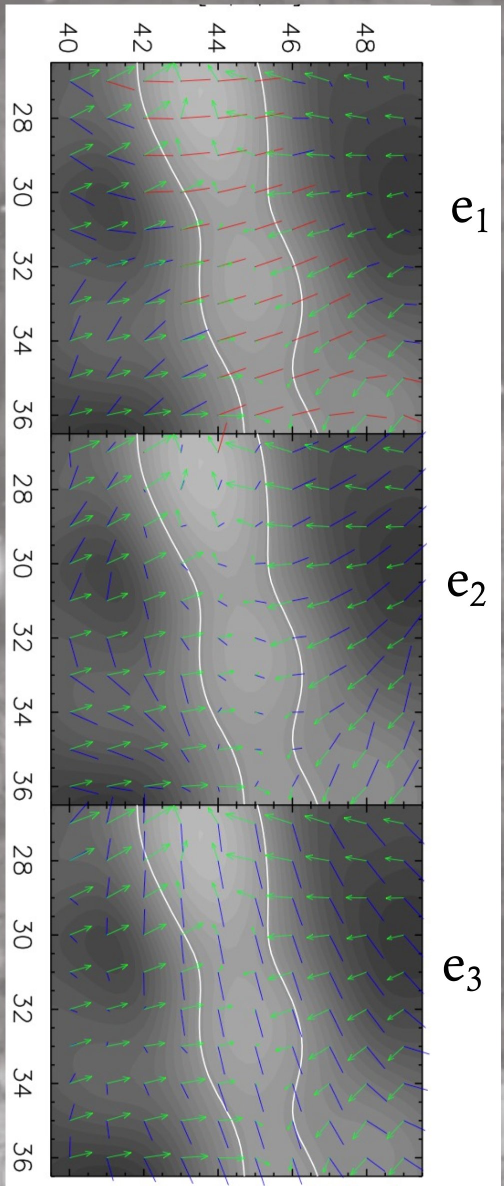


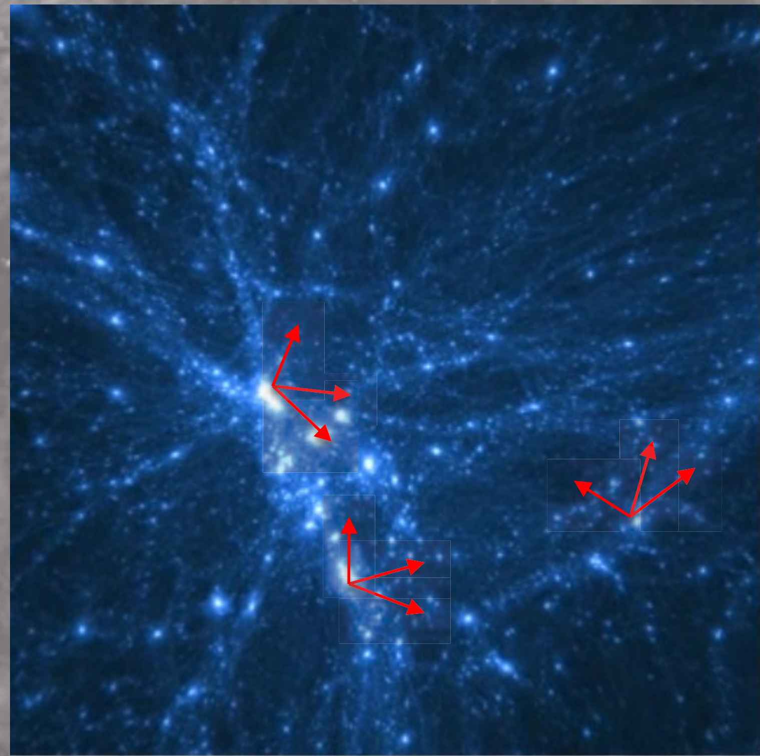
Dupuy, NL et al 2021

Are such alignments *generic* consequences of the LCDM model?

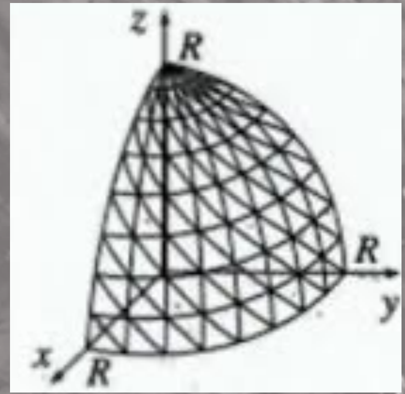


Are such alignments *generic* consequences of the LCDM model?

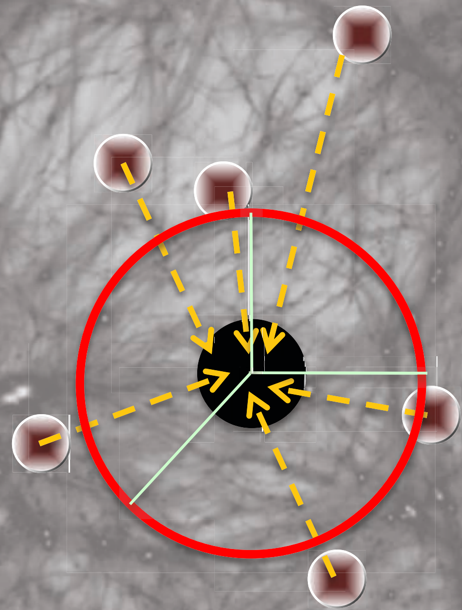


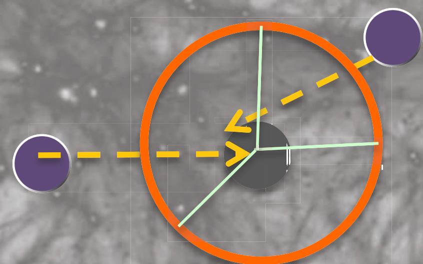


Eigenvectors are degenerate: Only one octant

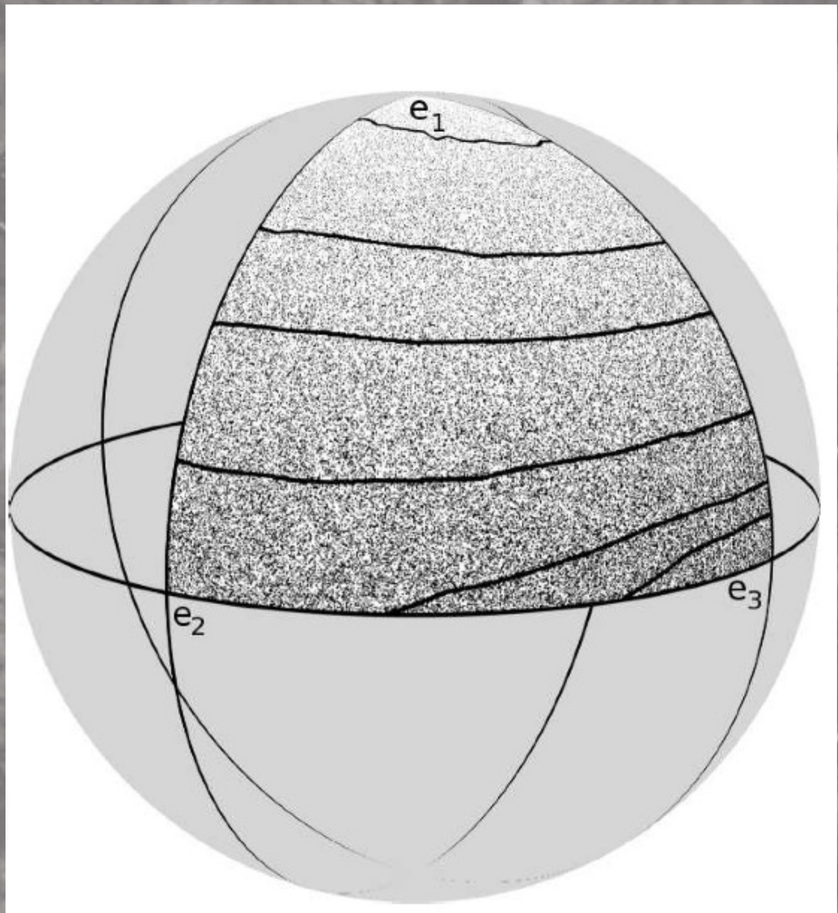


For each accretion event onto each halo at all *z*, we compute the shear *adaptively* on 4, 8, 16r_{vir} scales



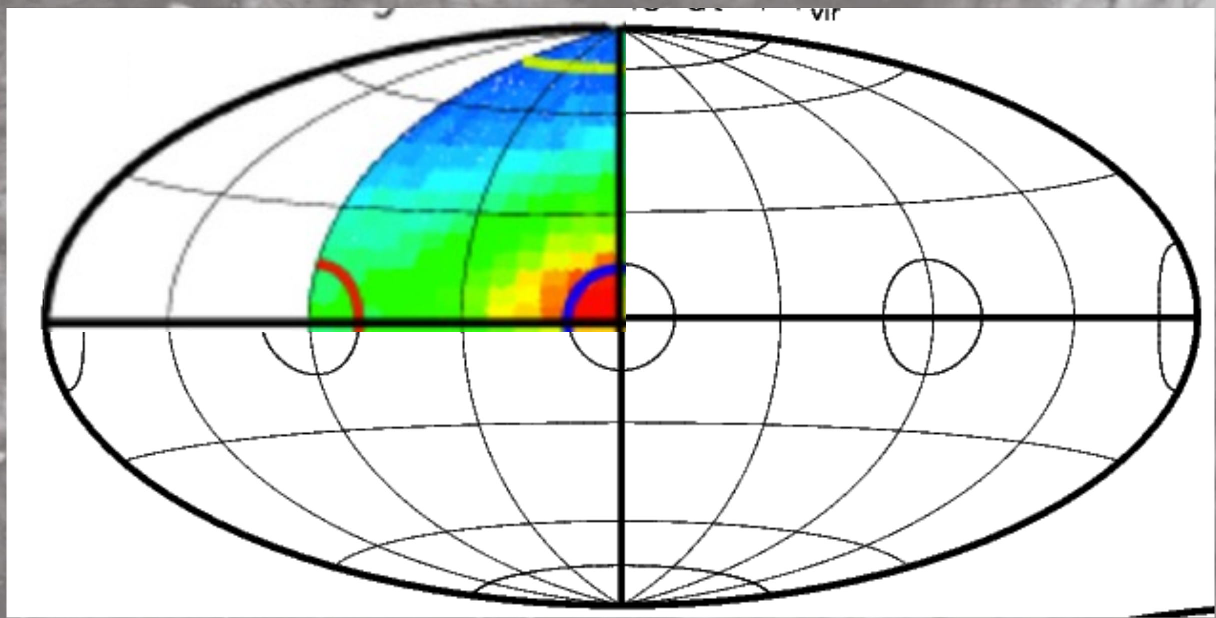


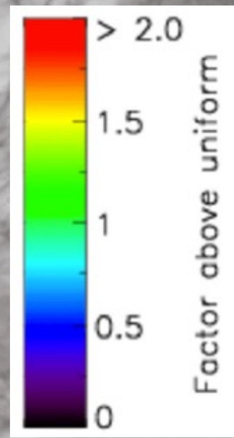
Track all infall points of subhaloes in the Shear eigenframe



Libeskind et al 2014

Infall points of subhaloes in the Shear eigenframe



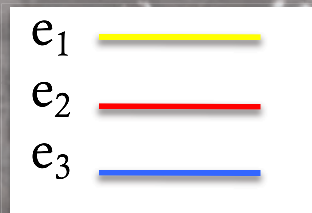


Scale the mass of each halo

Stack, all accretion events, all haloes, all z

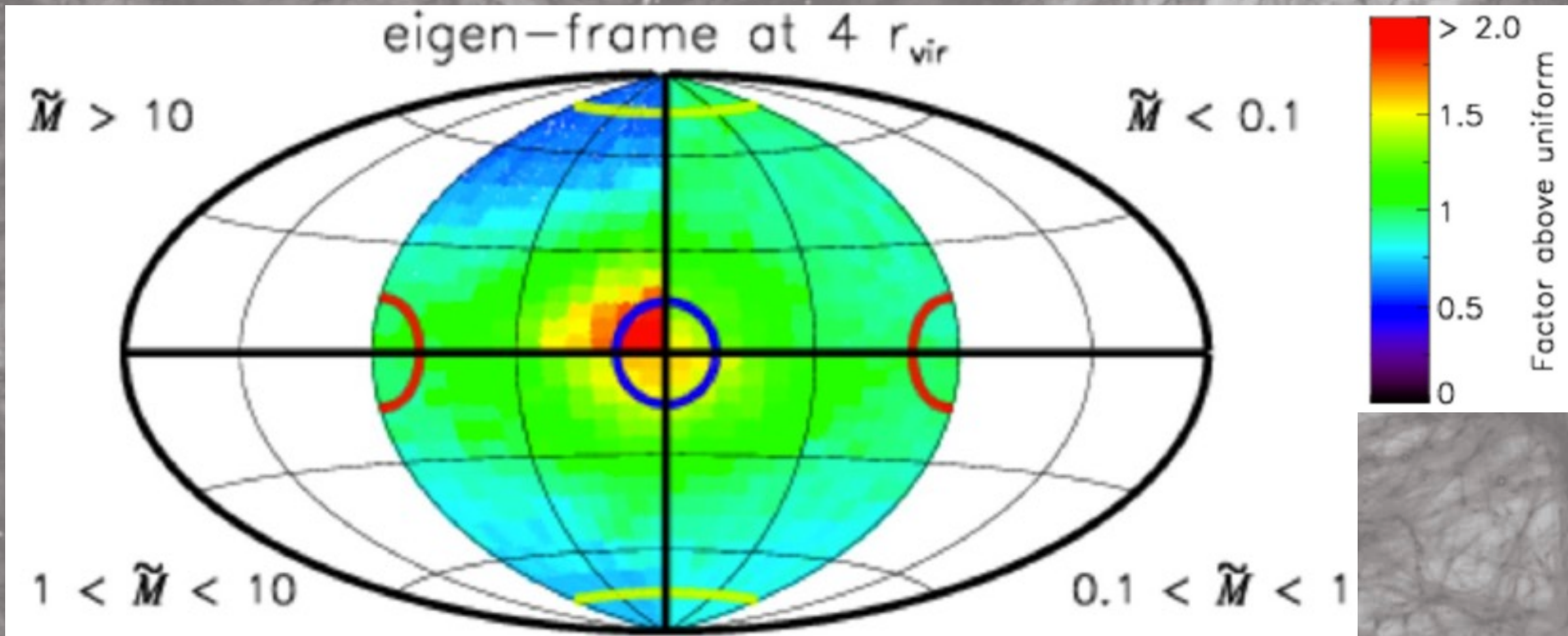
$M_\star$ - Mass scale of collapsing objects at z.

$$\tilde{M} = \frac{M_{\rm vir}}{M_\star}$$



Libeskind et al 2014

Infall points of subhaloes in the Shear eigenframe



All mergers

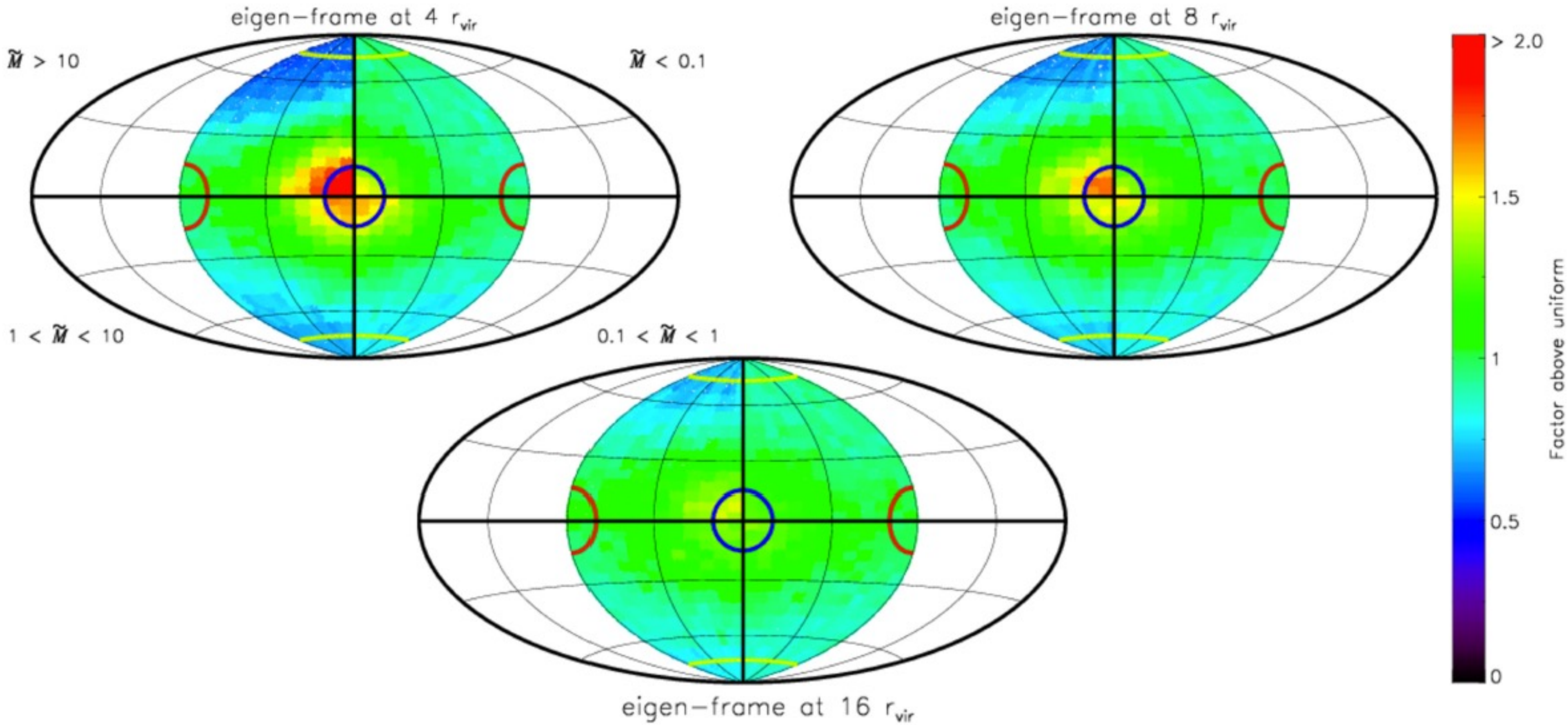
e_1

e_2

e_3

Libeskind et al 2014

Infall points of subhaloes in the Shear eigenframe

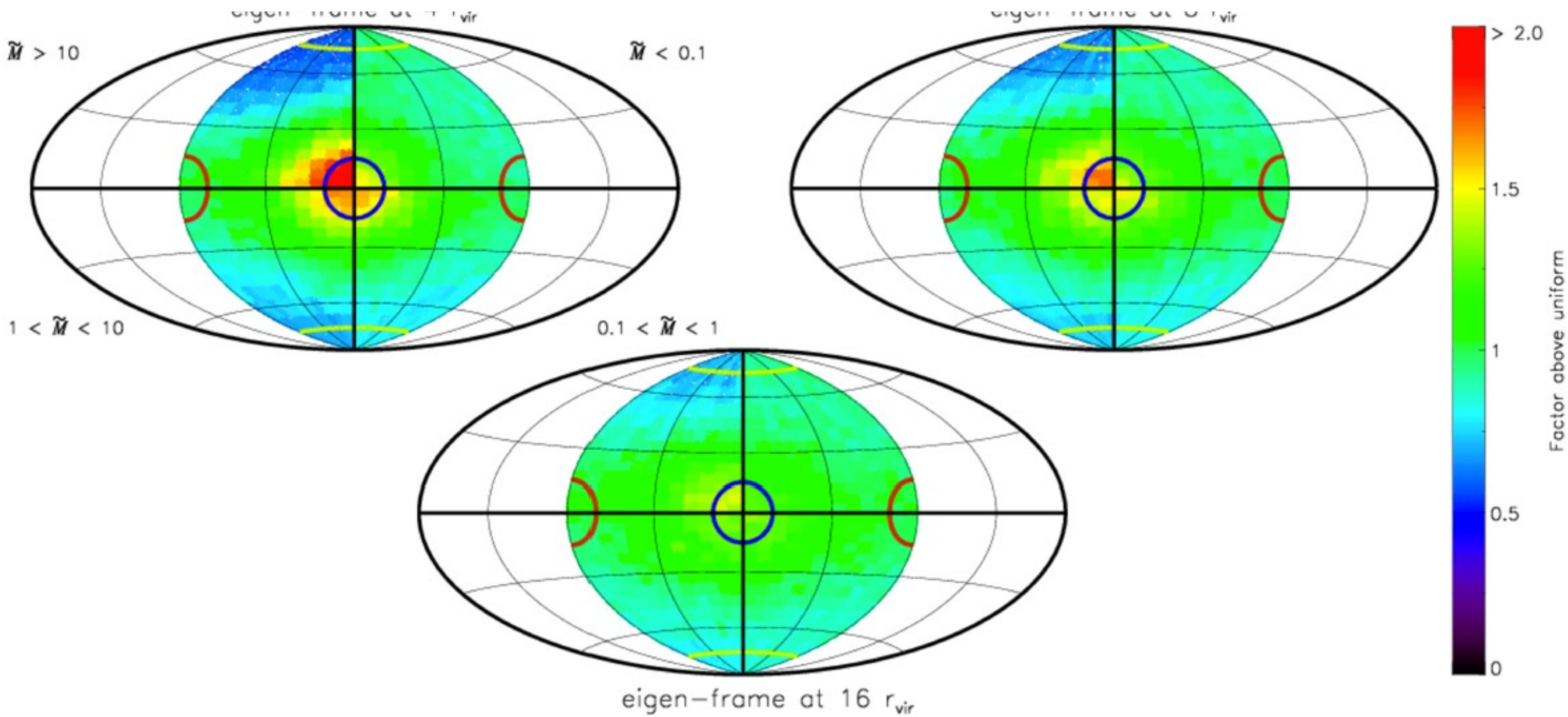


Libeskind et al 2014

Infall points of subhaloes in the Shear eigenframe

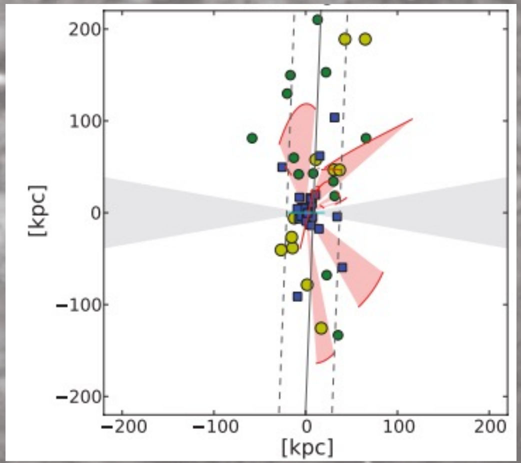
The universal nature of subhalo accretion

Noam I Libeskind[1], Alexander Knebe[2], Yehuda Hoffman[3], Stefan Gottlöber[1]
[1] *Leibniz-Institute für Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany*
[2] *Grupo de Astrofísica, Departamento de Fisica Teorica, Modulo C-8, Universidad Autónoma de Madrid, Cantoblanco E-280049, Spain*
[3] *Racah Institute of Physics, Hebrew University, Jerusalem 91904, Israel*

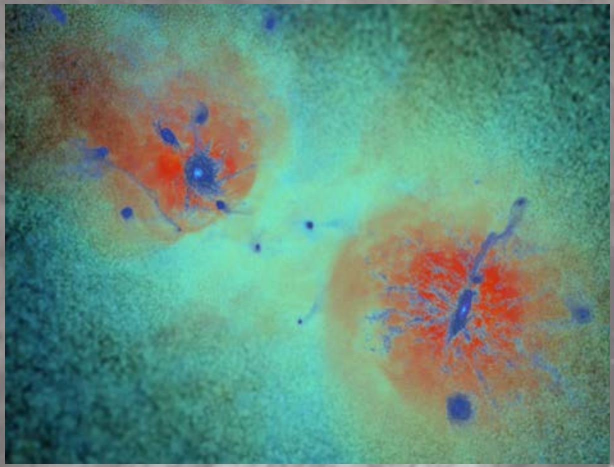


Libeskind et al 2014

MW

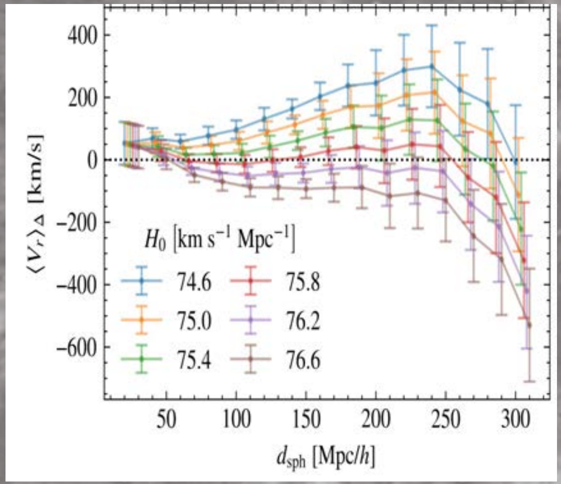


Planes



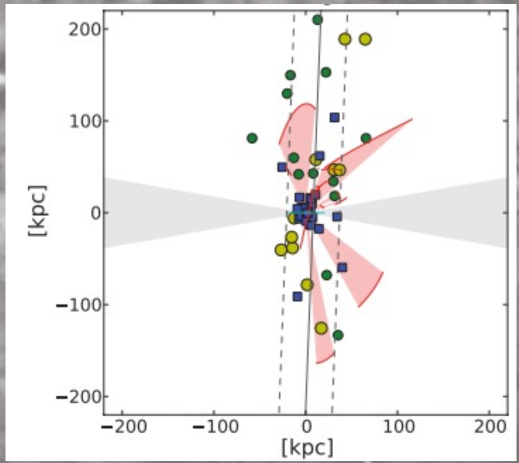
Constrained Simulations of the LG

Cosmography

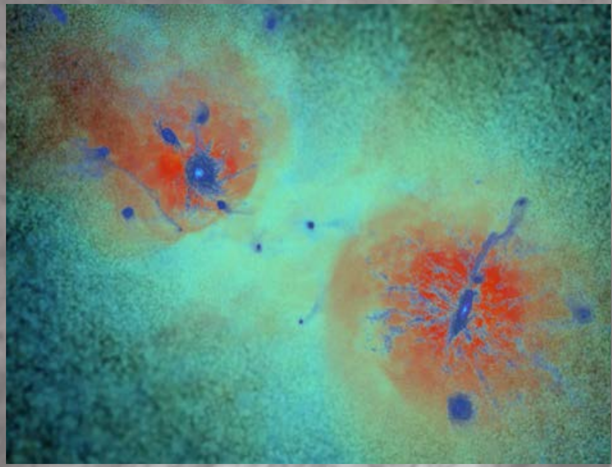


Cosmography for cosmology

MW



Planes



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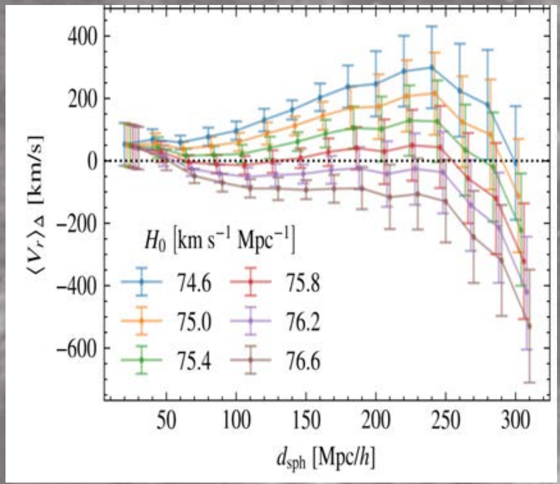
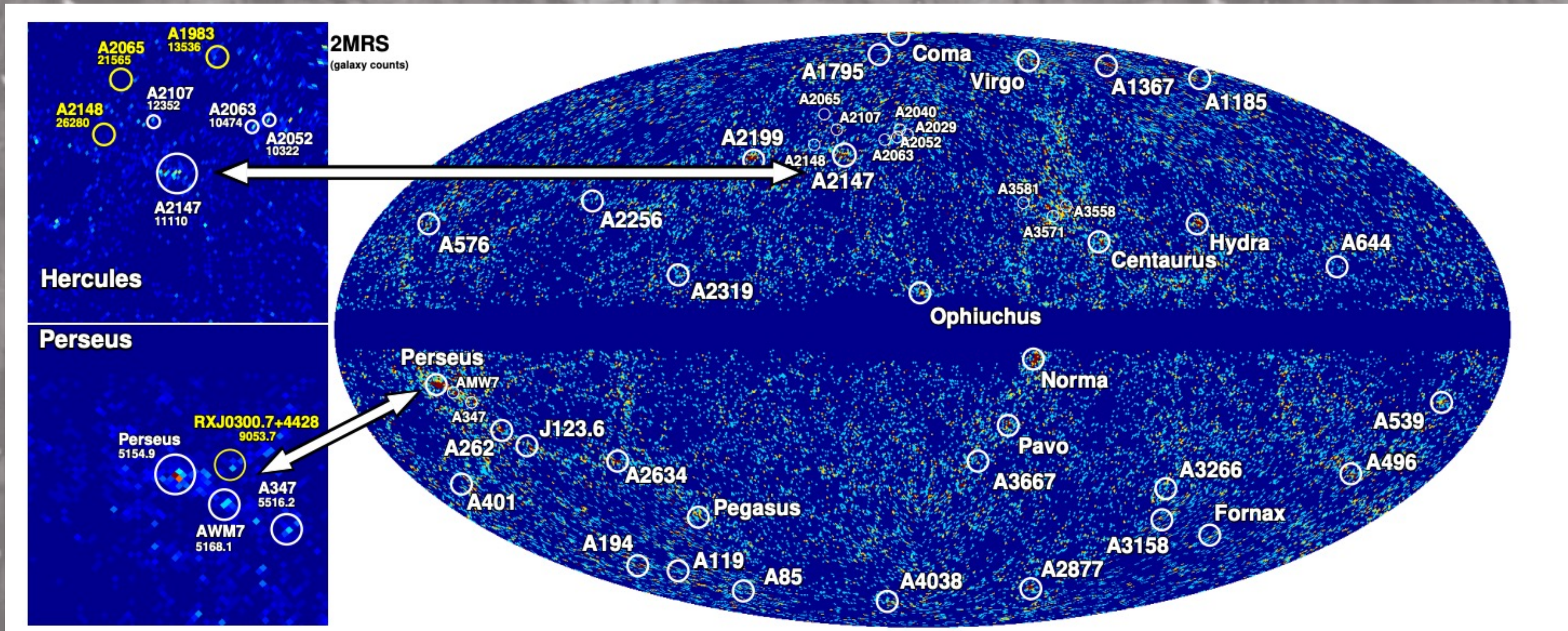


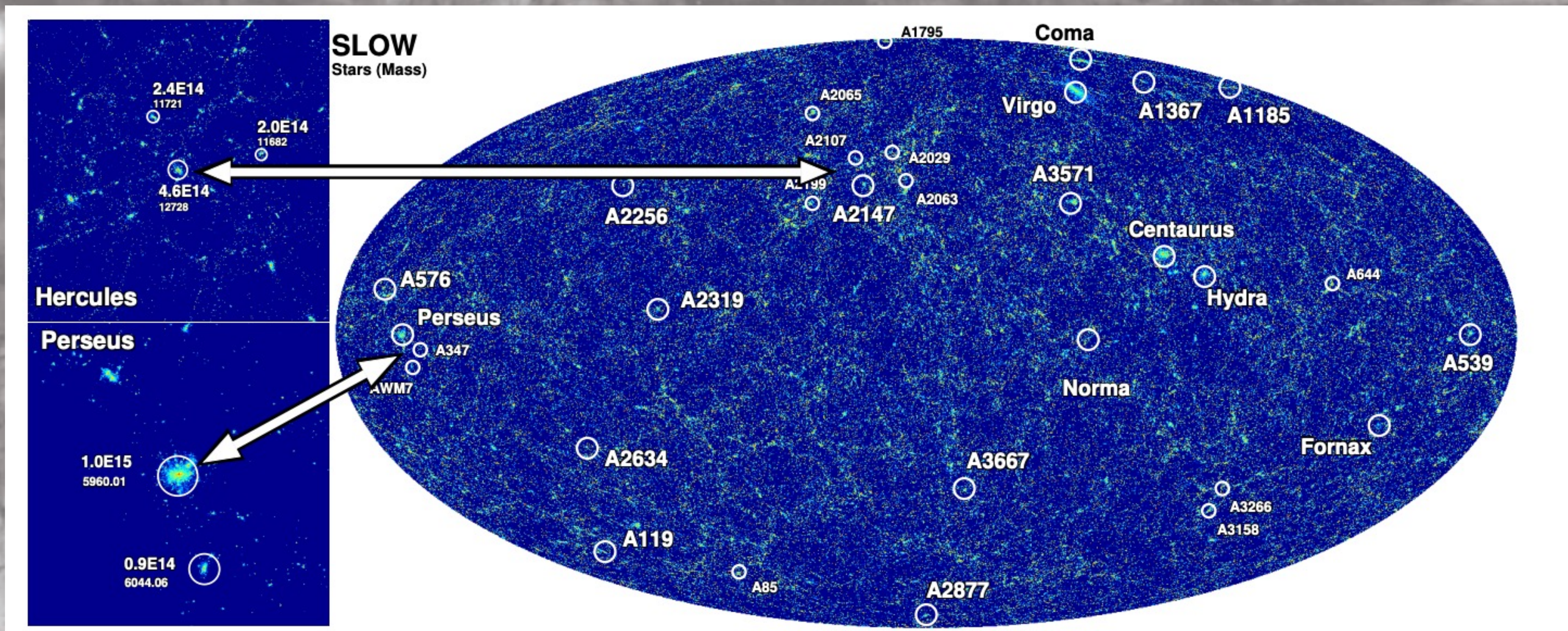
Cosmography for cosmology

Non-linear constrained simulations of the local universe

Aurelien Valade

From dwarfs to clusters

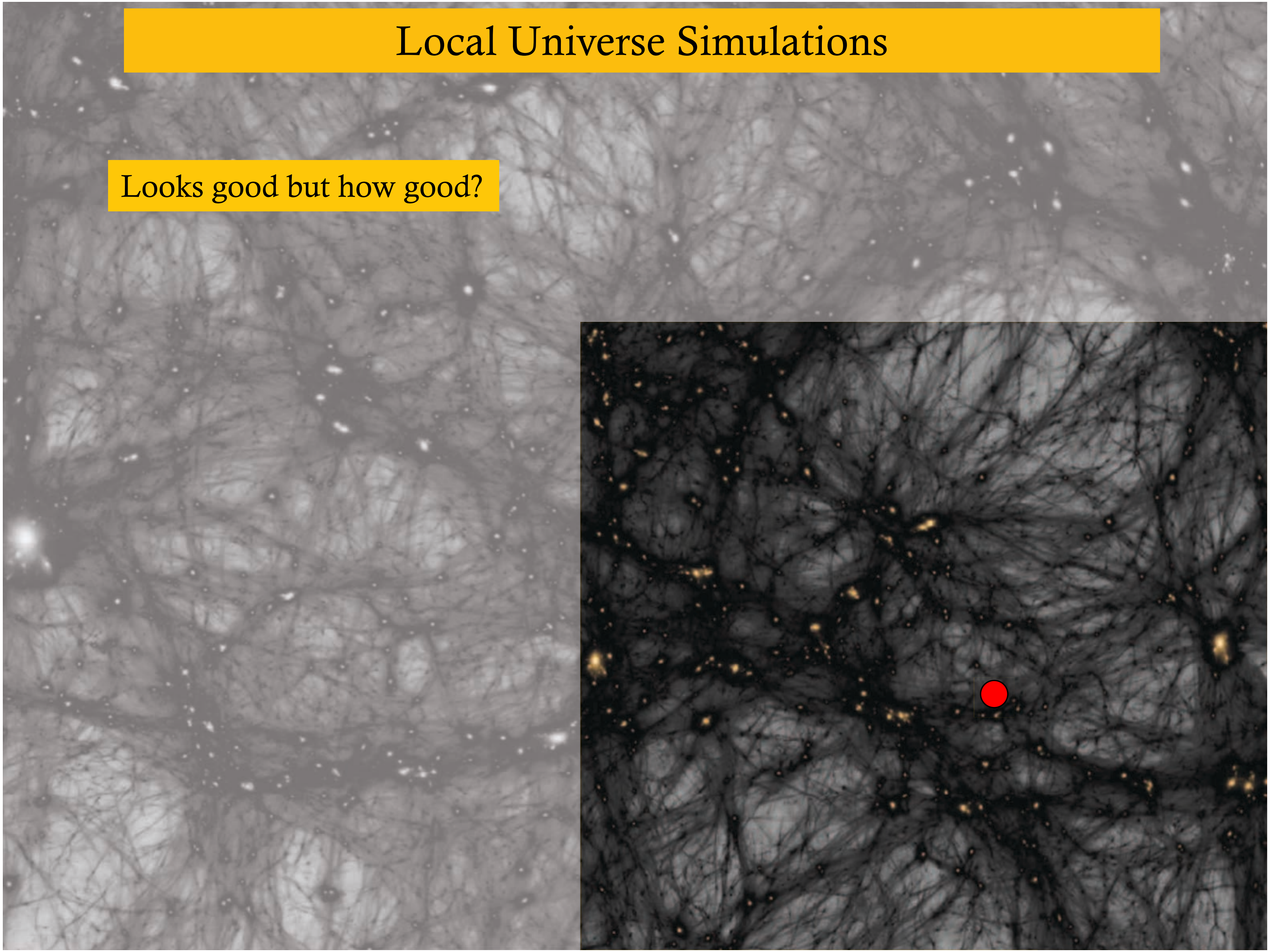




Dolag et al 2023

Local Universe Simulations

Looks good but how good?



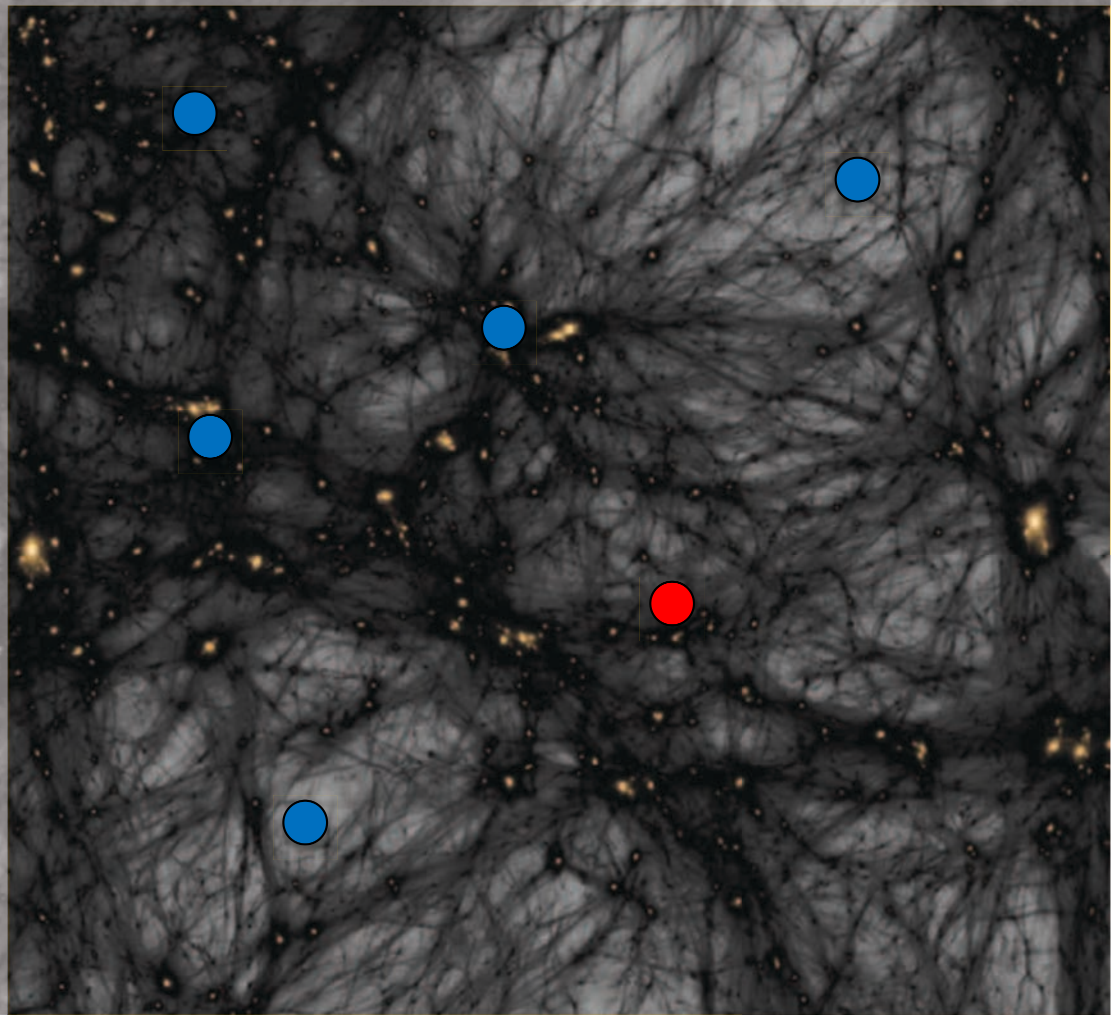
Local Universe Simulations

Looks good but how good?

What is the chance that a random simulation puts a cluster in the "correct" place?

What we need is the probability distribution for a halo of mass $M > 10^{14}$ to be at a distance r from a random observer.

What is the probability that a sphere of radius R contains a halo of mass M?



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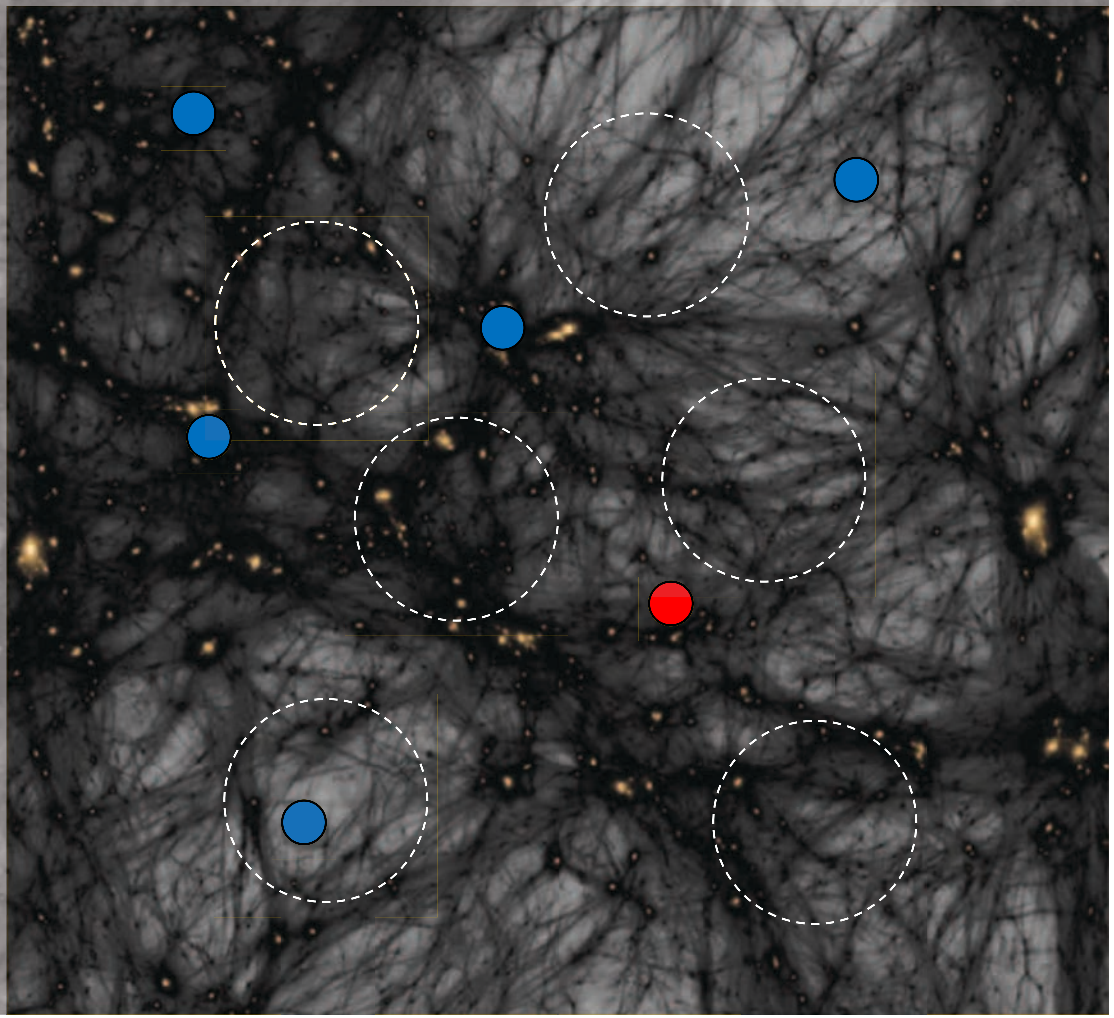

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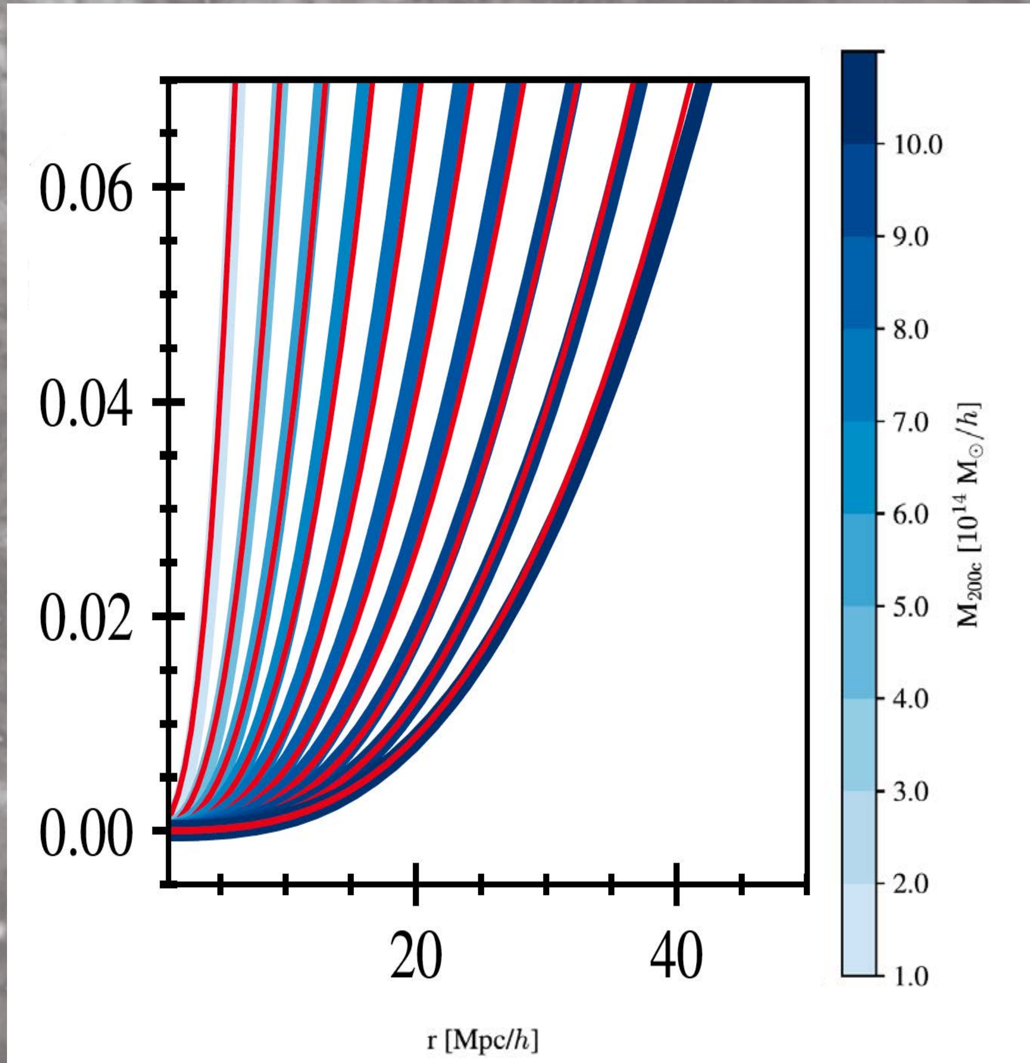


Pfeifer, NL et al 2022

Local Universe Simulations

This gives us a way to "grade" each simulated cluster counterpart depending on the target mass and the target position

A random simulations do not produce a halo of mass of 10^{14} at a distance of 6 Mpc or closer from given spot 95% of the time.

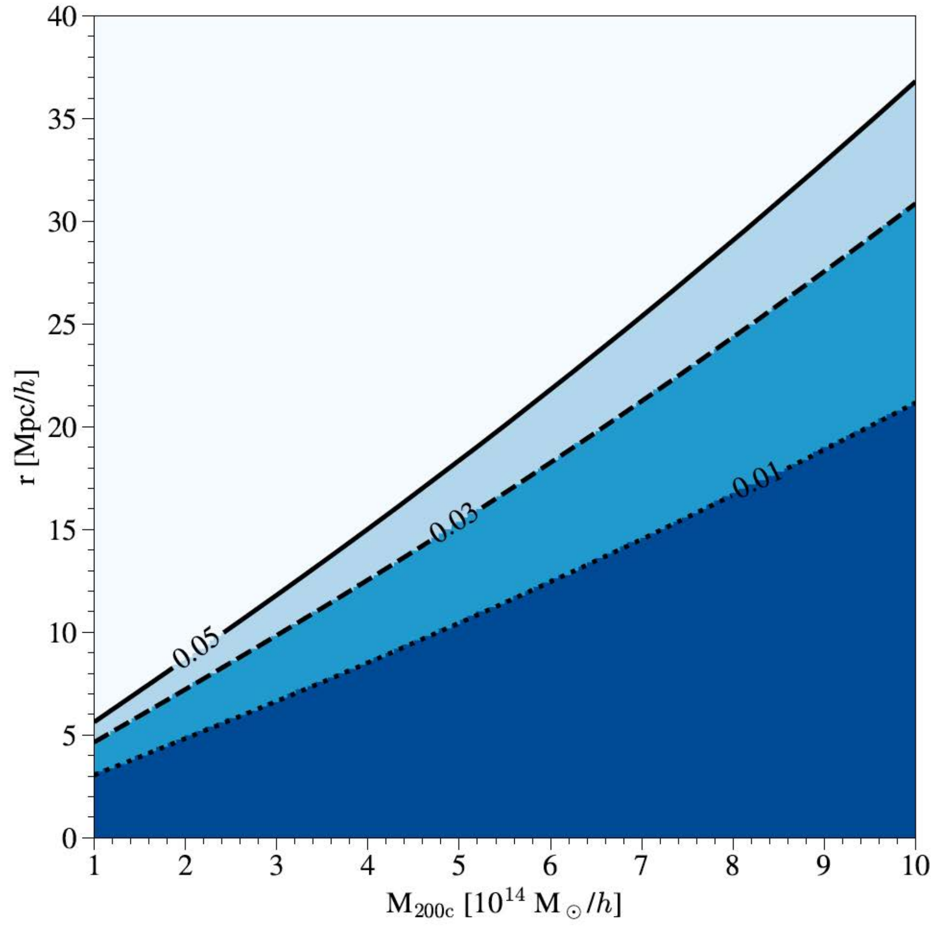
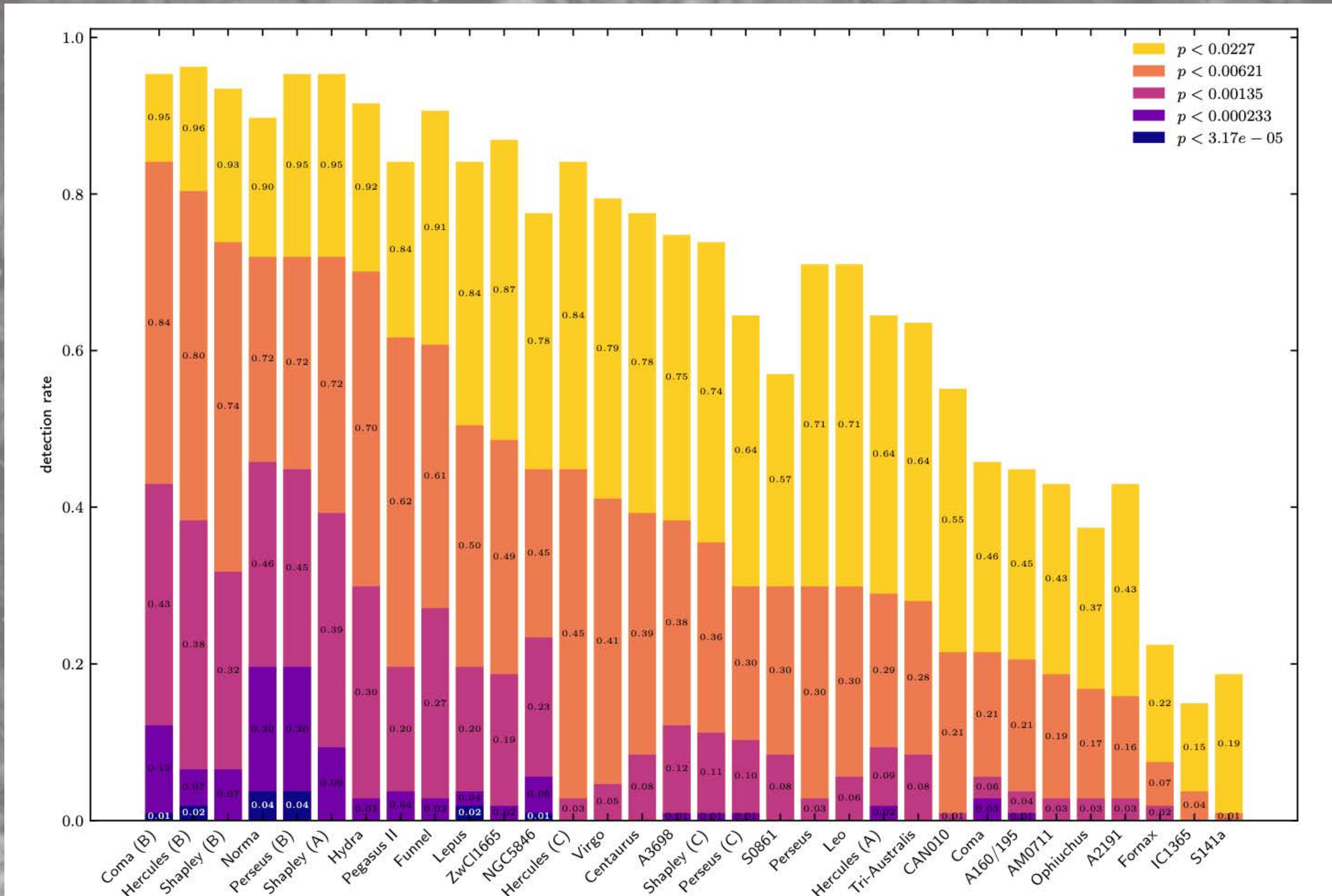


Figure 3. The p-values, calculated from the fits shown in Fig. 2, as a function of lower mass limit and separation. The lines denote contours of constant p and darker shaded areas show lower p-values. The distribution above 10^{15} h^{-1} $M_\odot$ are kept constant as not enough halos of these masses exist in the simulations to produce stable fits.

Pfeifer, NL et al 2022

Non-linear Local Universe Simulations

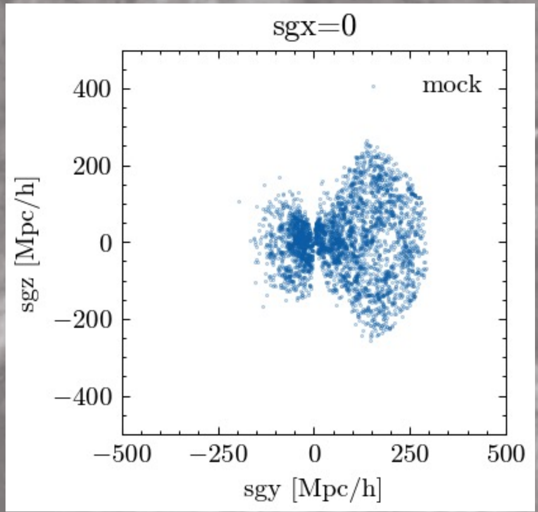


Select the best halo counterpart based on target mass and position.
Then select the best simulation by minimizing *p*

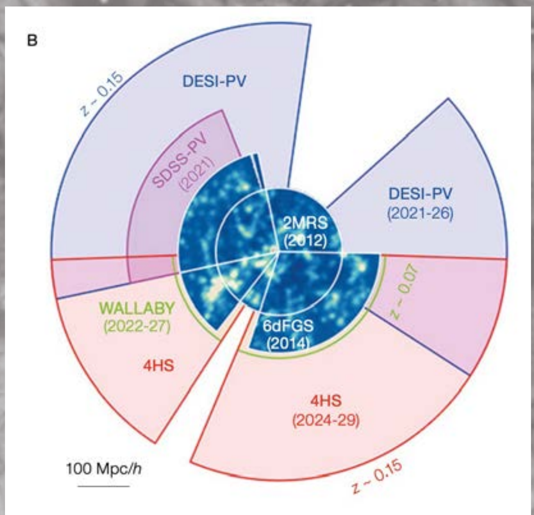
Valade, NL et al *in prep*

The goal of constrained simulations:

Simulate the entire local universe at observational resolution



observations



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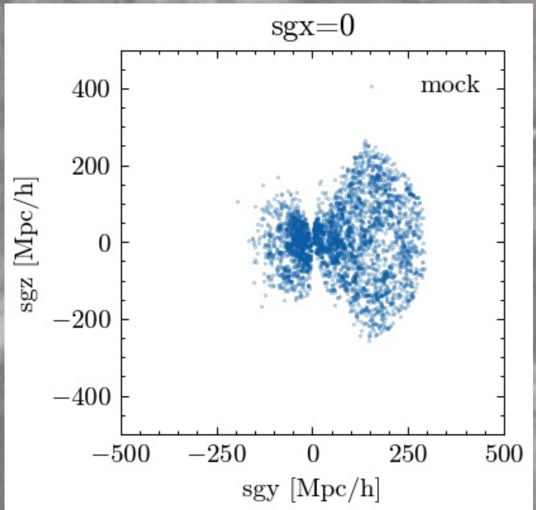
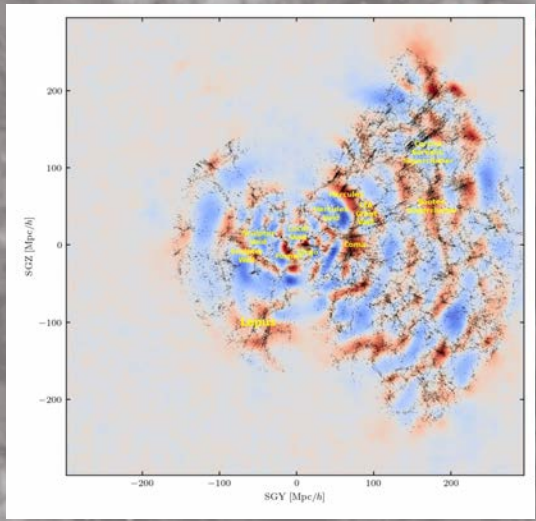
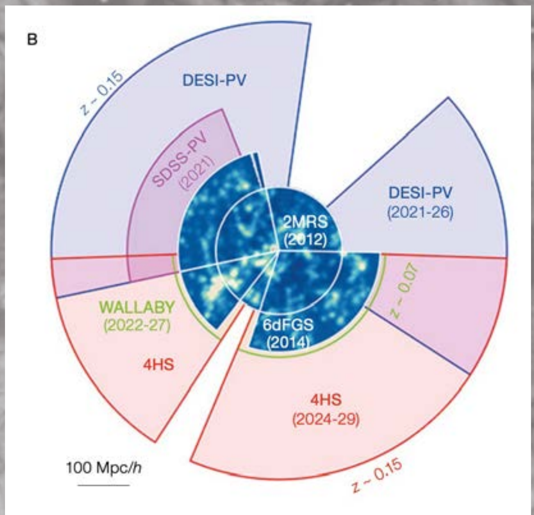


observations



Reconstructions of density and velocity



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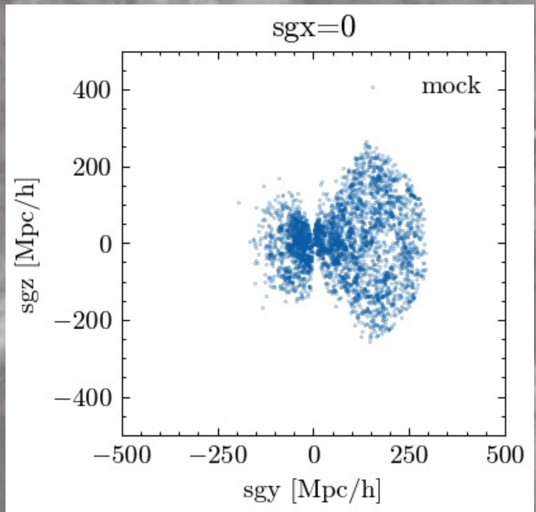
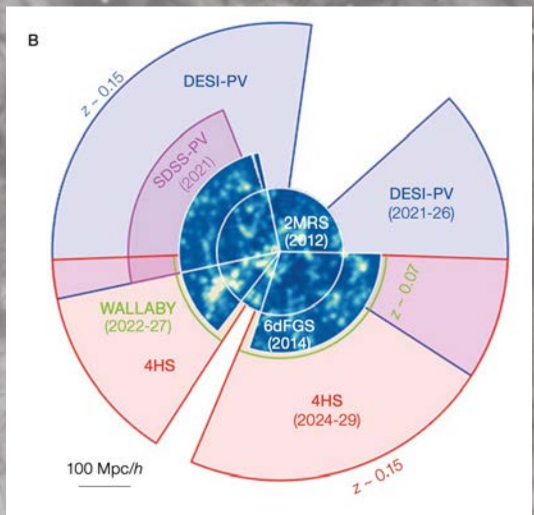
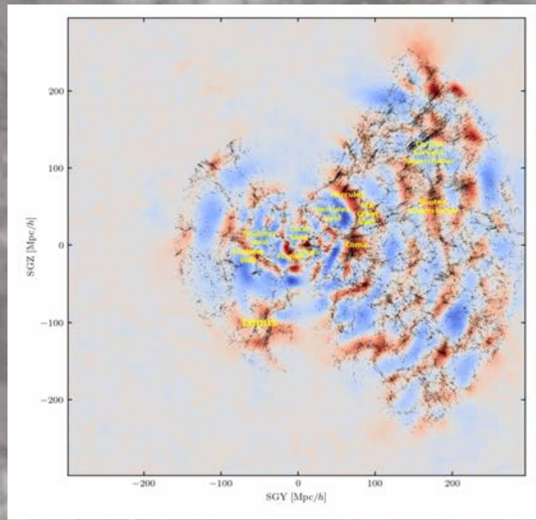


observations





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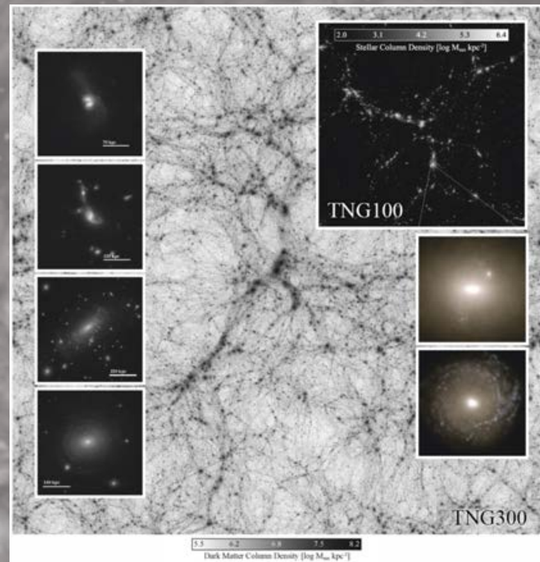

Simulation of all the named members of the Local Universe