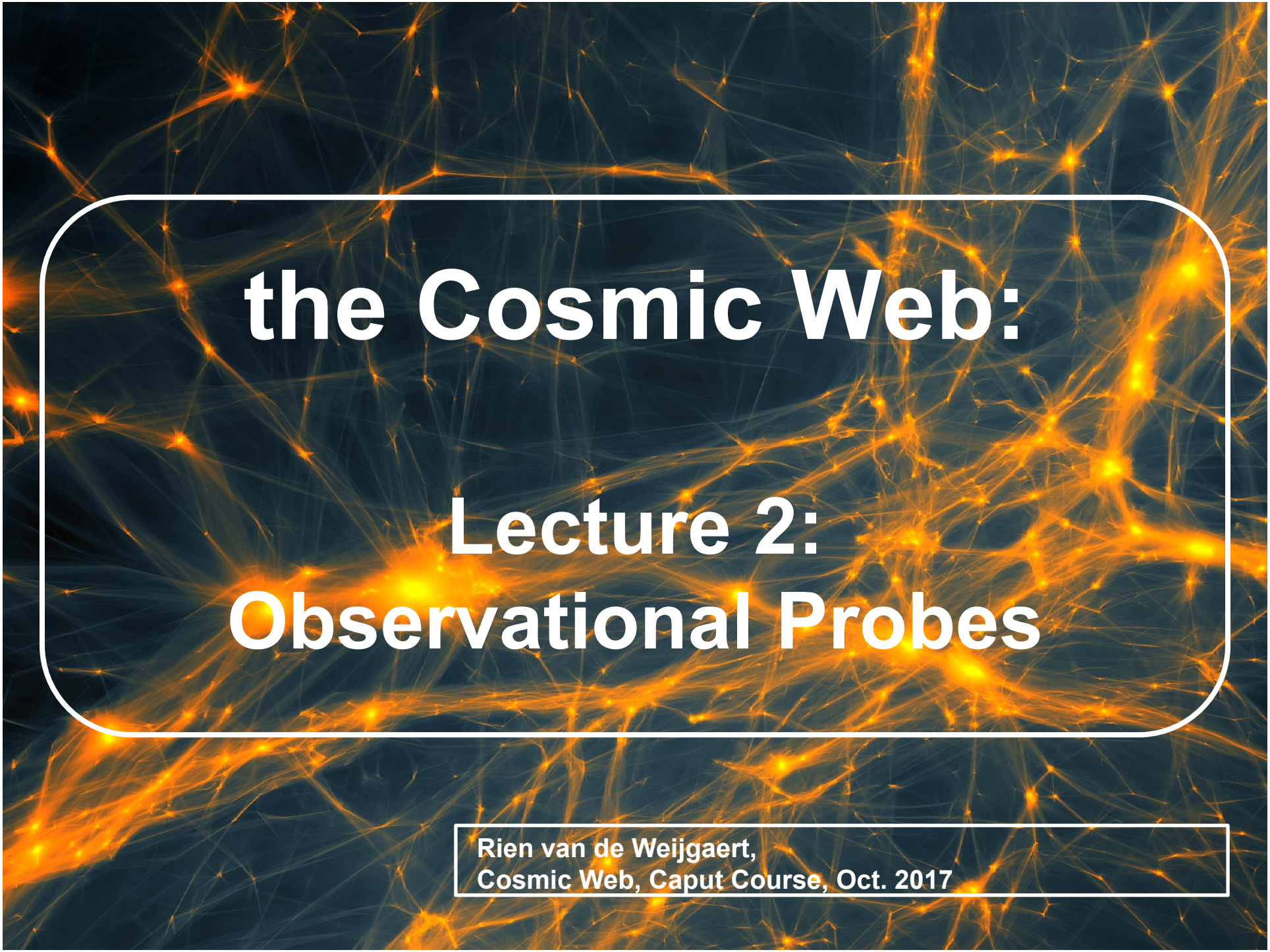


the Cosmic Web:

Lecture 2:
Observational Probes

Rien van de Weijgaert,
Cosmic Web, Caput Course, Oct. 2017

Cosmic Web:

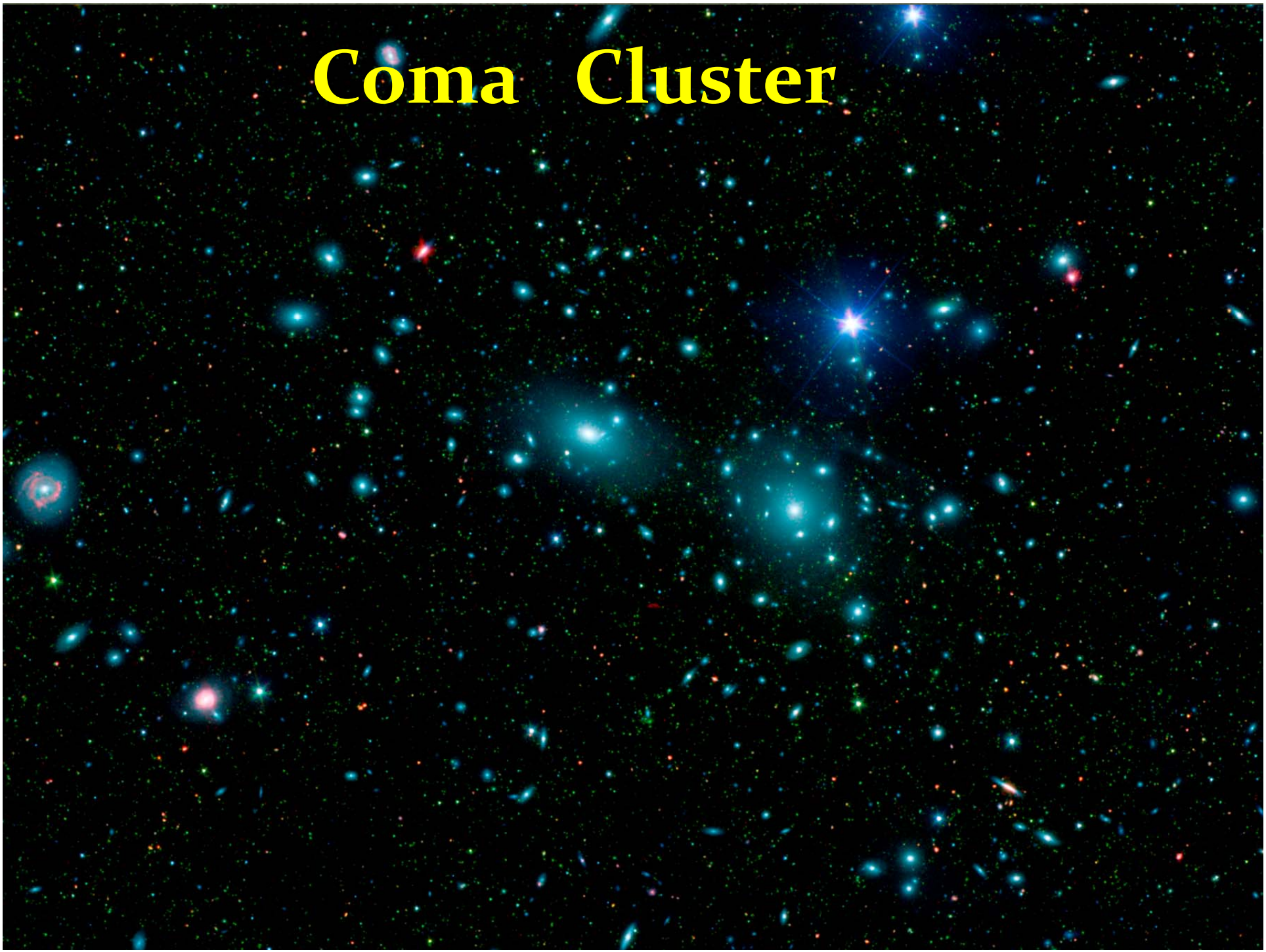
Galaxy & Cluster Distribution

Map of the Universe

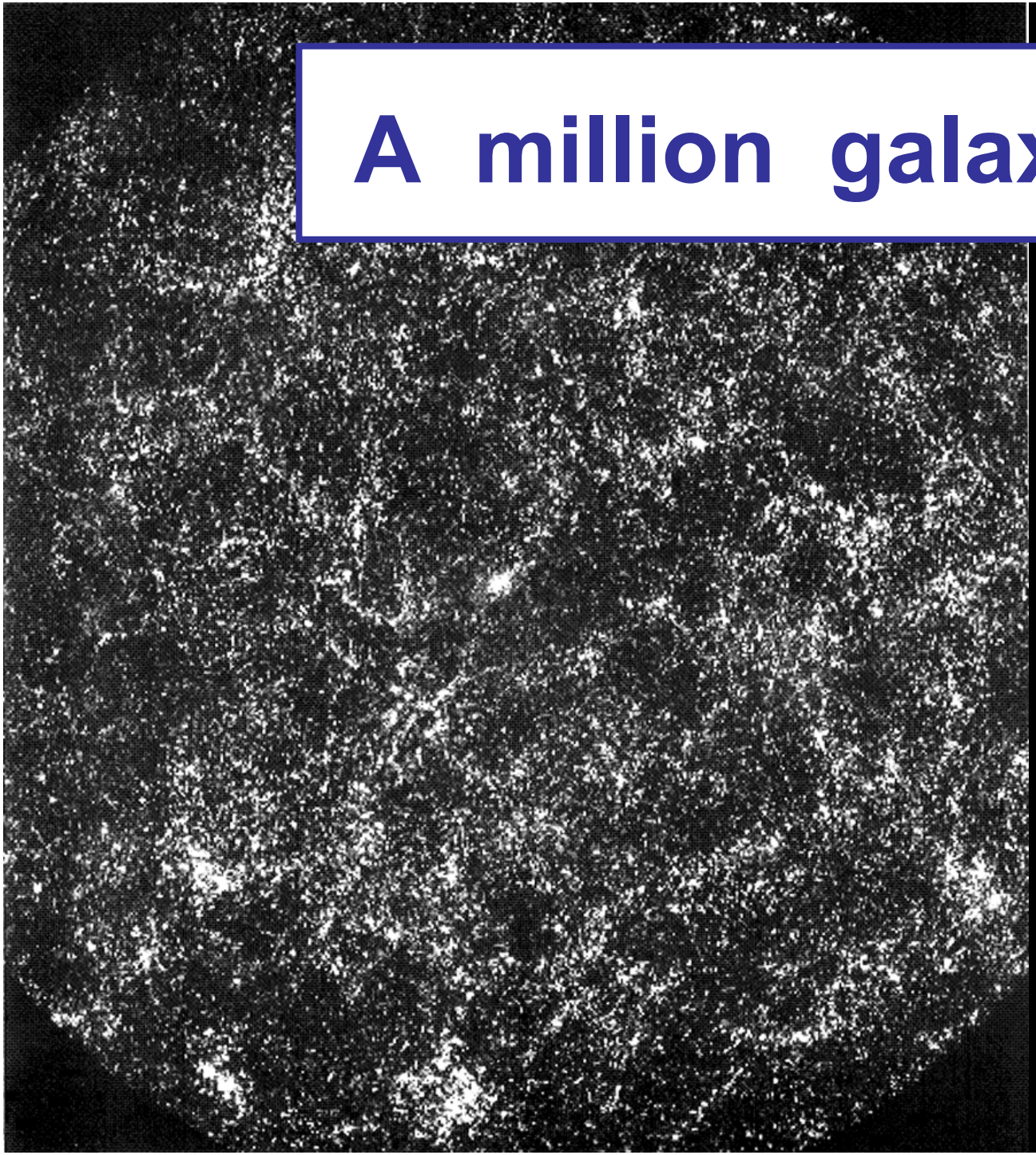
How to map the structures and patterns in the Universe ?

- Use galaxies as beacons
- Map of
  Galaxy positions
- Tracing of structures from distribution of galaxies


... Galaxies ...


Coma Cluster

A million galaxies

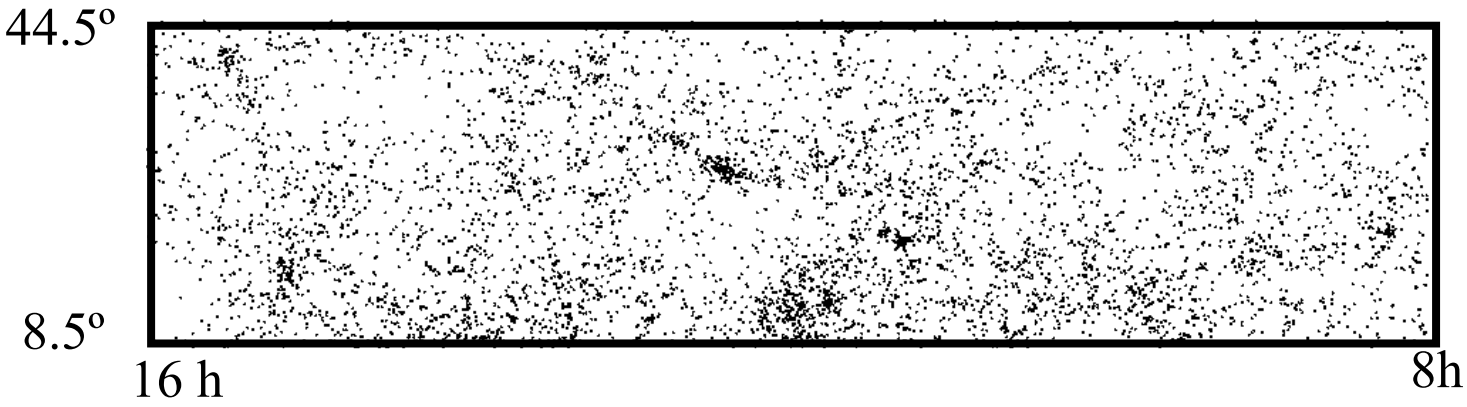


Shane-Wirtanen map:

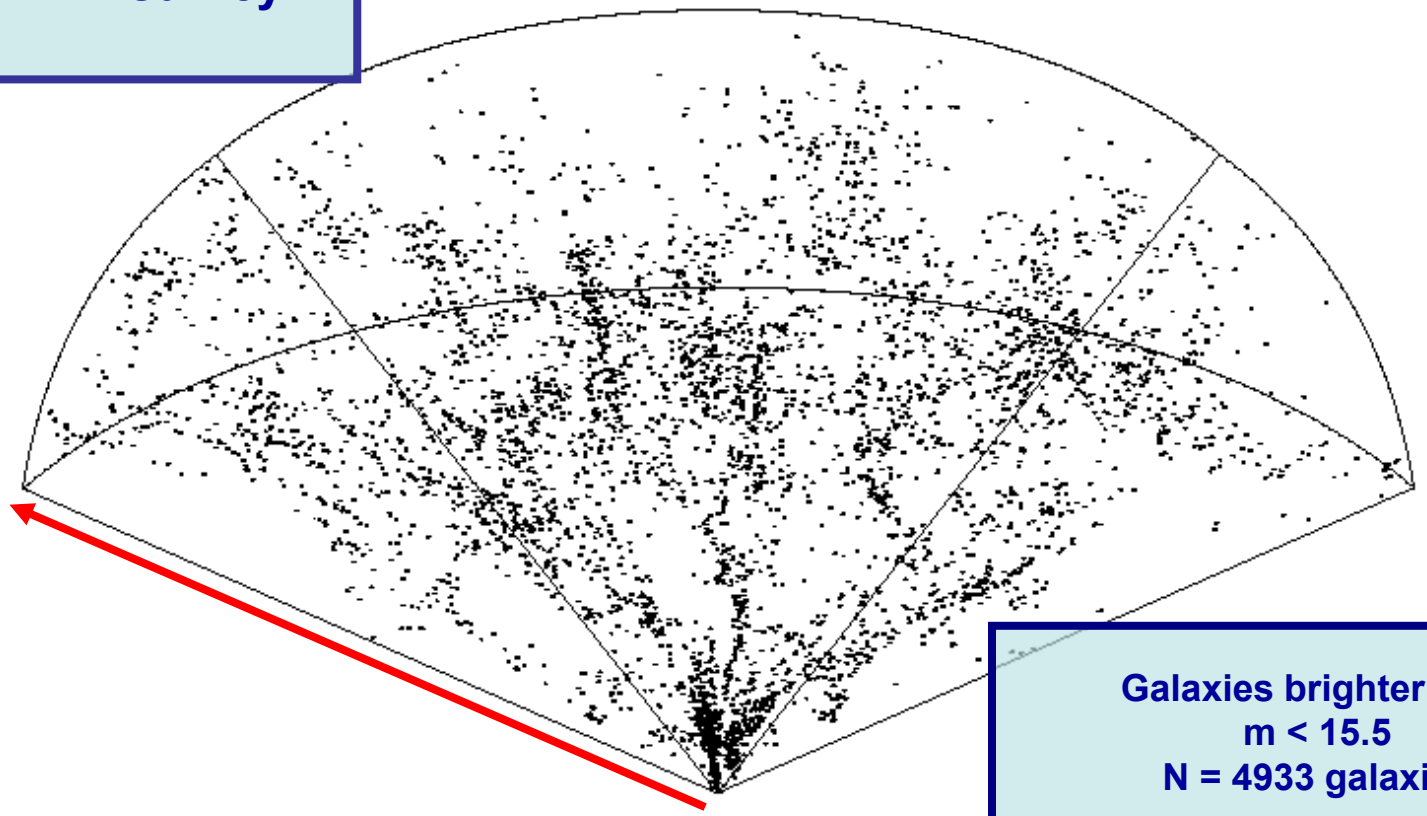
On the basis of the Shane-Wirtanen counts,

P.J.E. Peebles produced a map of the sky distribution of 1 million galaxies on the sky:

- Clearly visible are clusters
- hint of filamentary LSS features, embedding clusters



CfA2 survey



101 Mpc/h

Galaxies brighter than
m < 15.5
N = 4933 galaxies

Figure courtesy: V. Martínez

Redshift Space Distortions

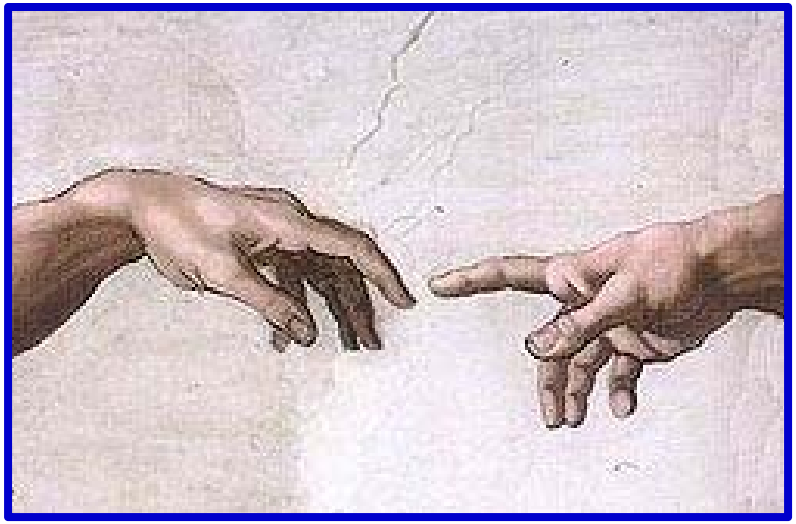
Clusters of galaxies:

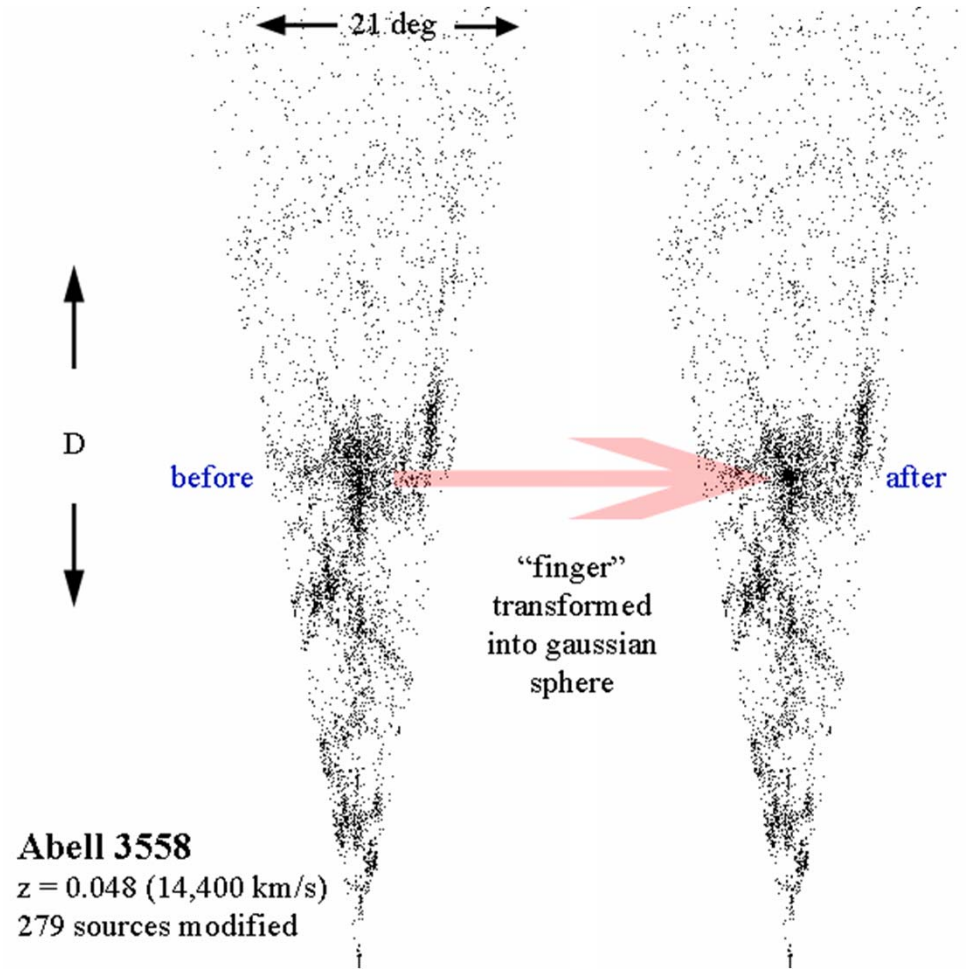
Mass: 10^{14}-10^{15} $M_\odot$
Radius: ~ 1.5 Mpc
Overdensity ~ 1000

Virial (thermal) velocity: ~ 1000 km/s

Internal cluster galaxy velocities visible in projection along line of sight

→ **"Finger of God"**





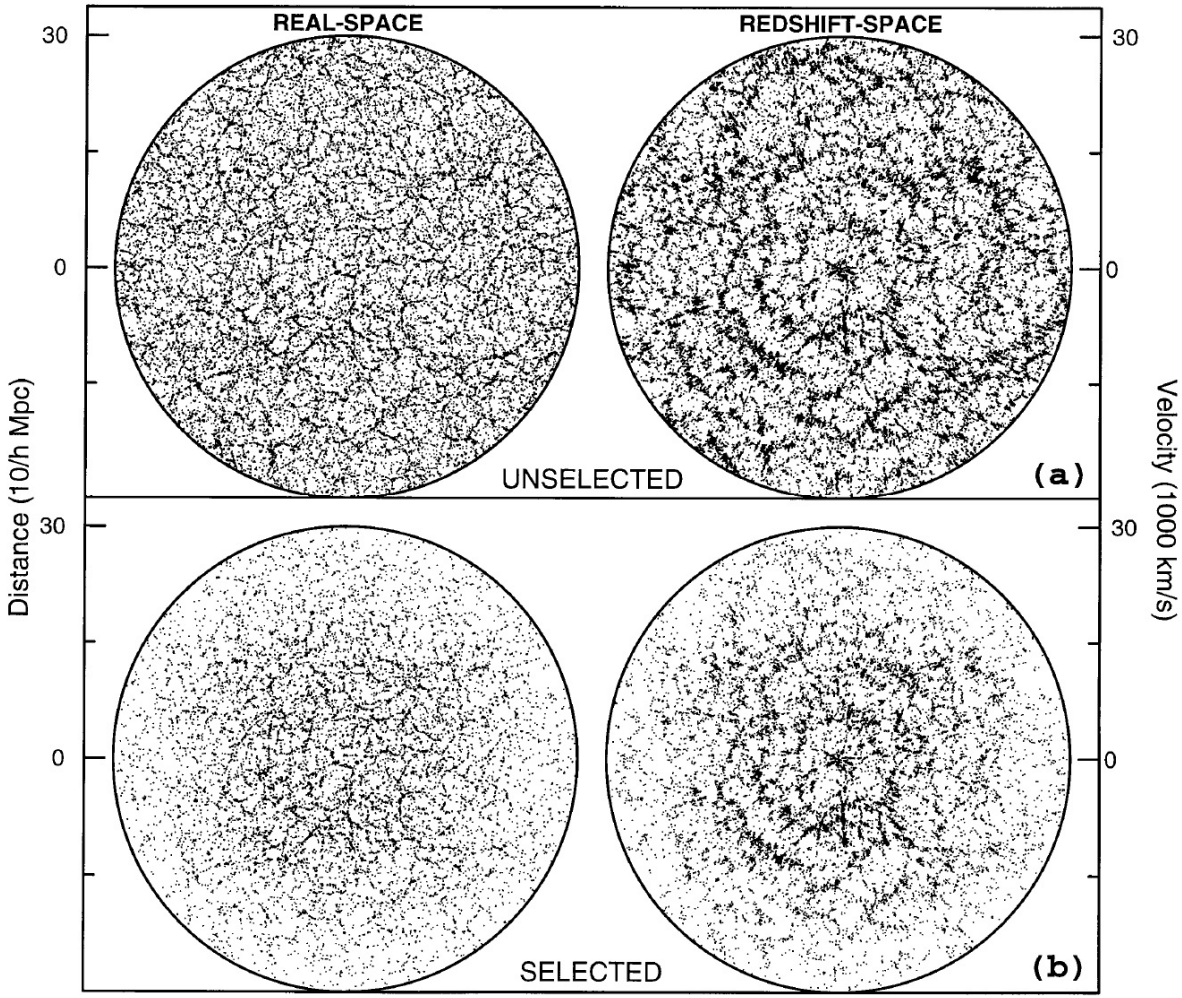
Redshift Maps: distortion @ cosmic flows

Large-Scale Flows:

the induced large scale peculiar velocities of galaxies translate into extra contributions to the redshift of the galaxies

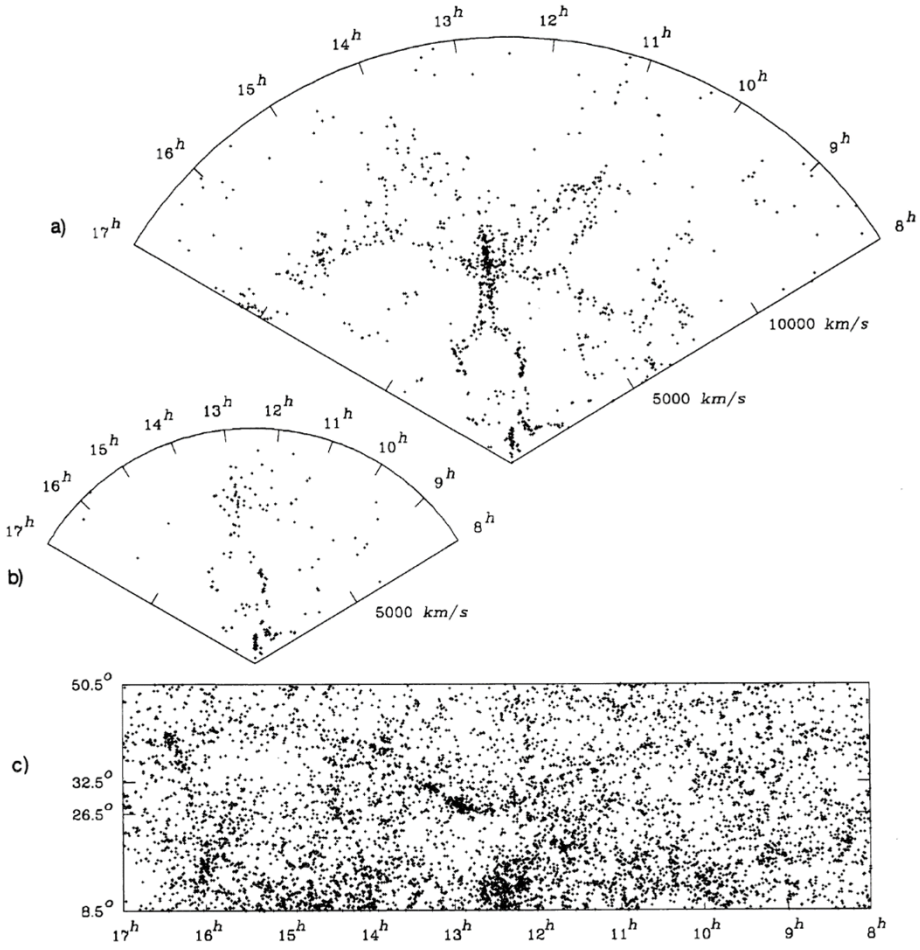
"real space" structure
vs.
"redshift space" structure

- Sharpening of filaments & walls
- Prominent structure near peak radial selection function



Ryden & Melott 1996

“Stickman” & Soapsud

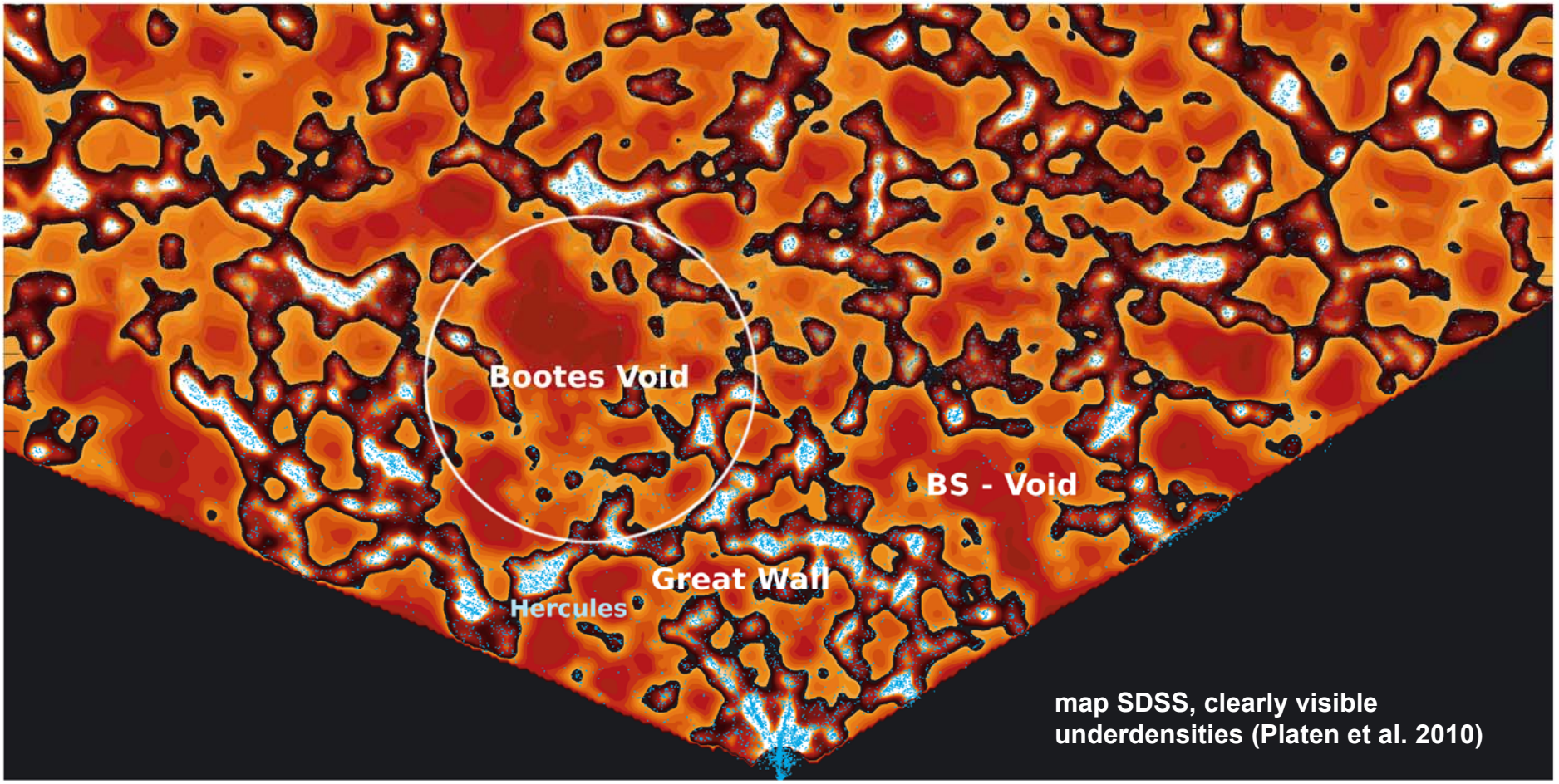


deLapparent, Geller & Huchra, 1986:

“a slice of the Universe”

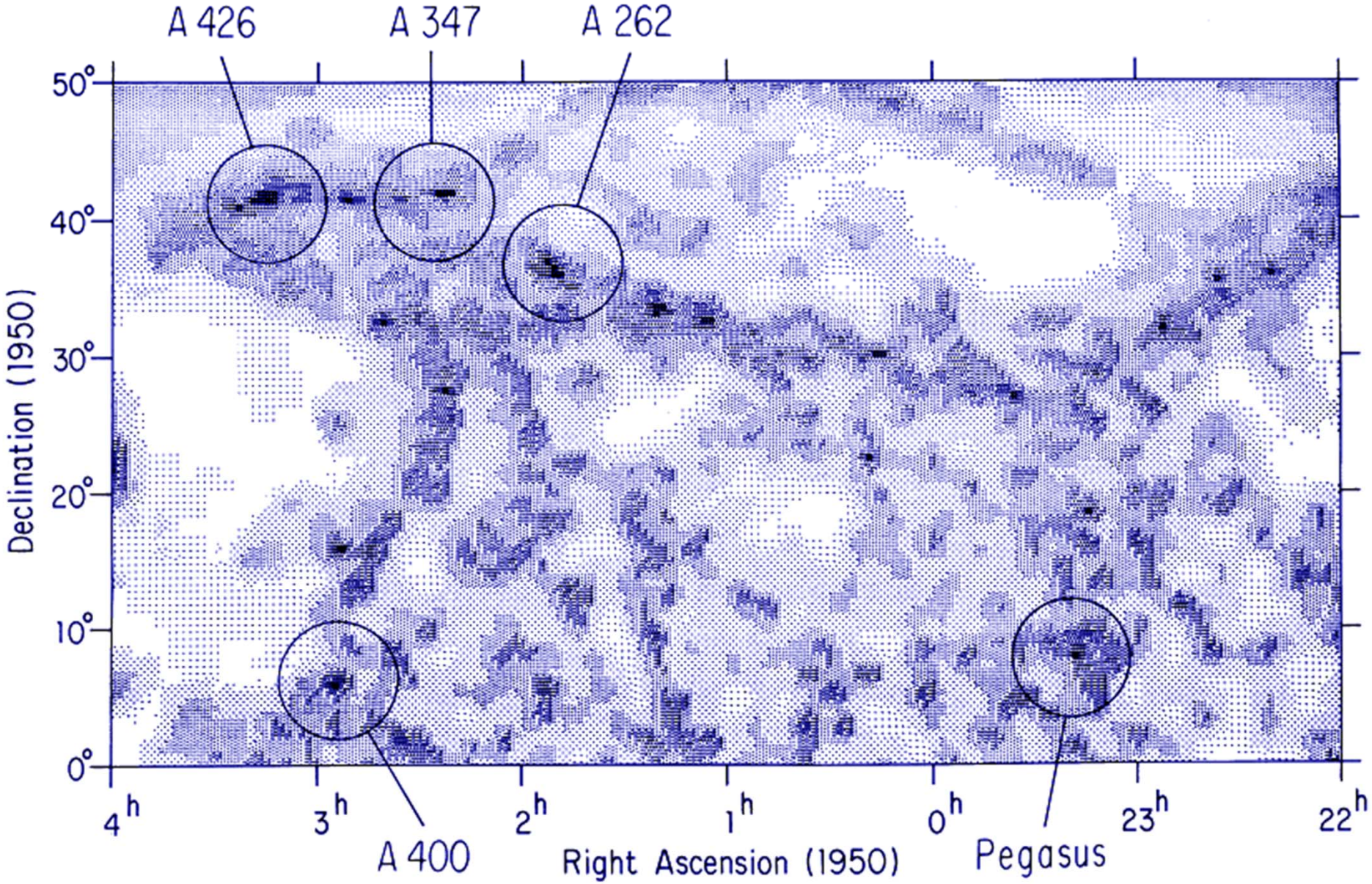
Voids are an integral component of a Galaxy distribution that resembles a soapsud.

SDSS Galaxy Survey

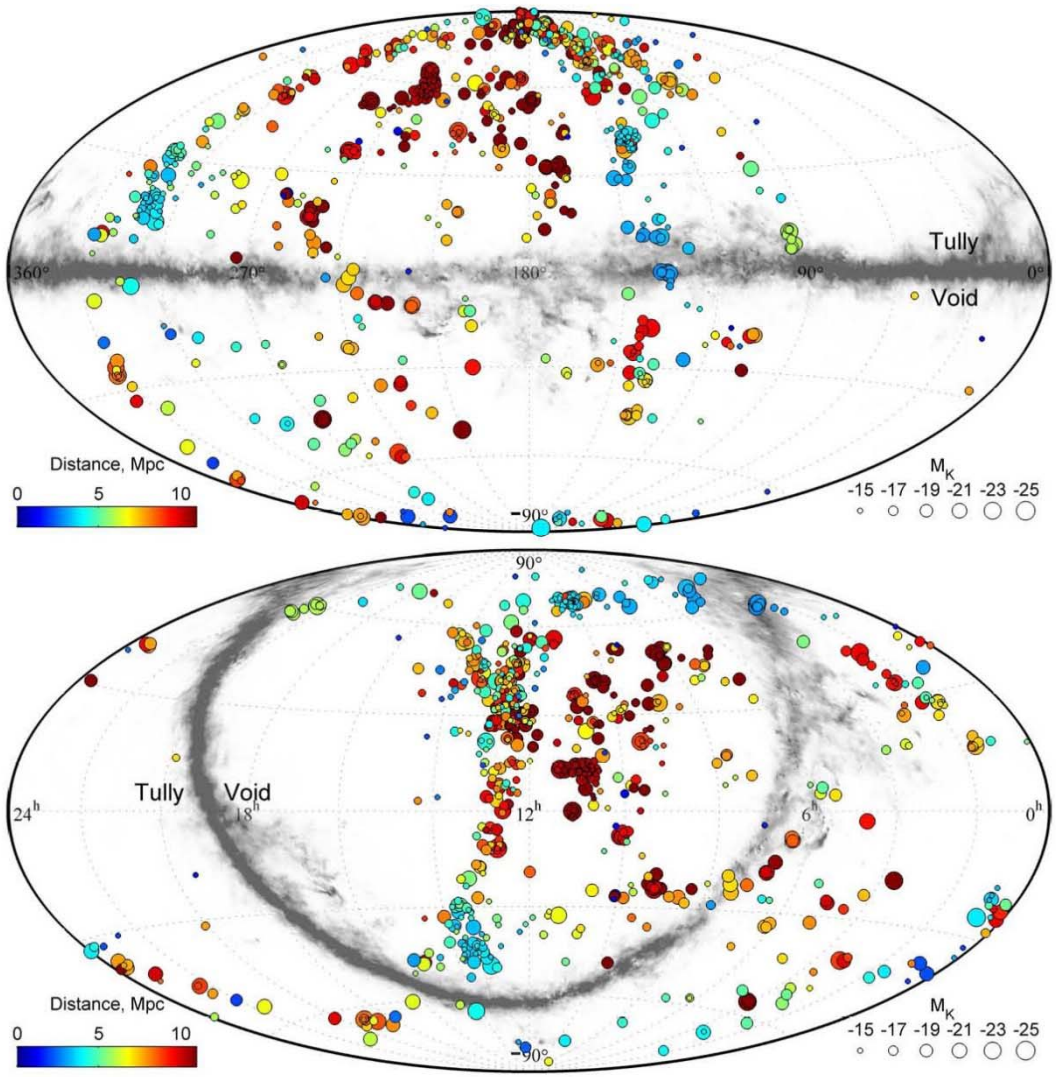


with the advent of large galaxy redshift surveys
– LCRS, 2dFGRS, SDSS, 2MRS –
voids have been recognized as one of the quintessential components of the Cosmic Web

Pisces-Perseus Supercluster



Voids in the Cosmic Web: the Local Void

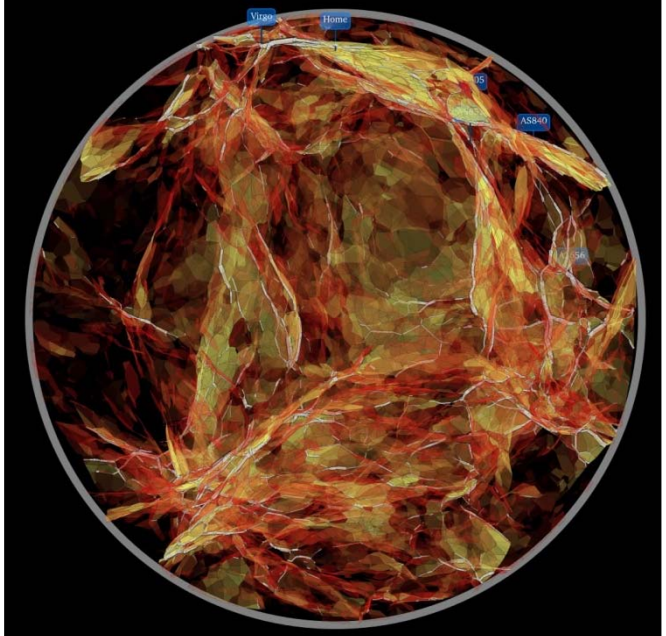


Karachentsev etal.

LV catalog:
galaxies within 10 Mpc reveal beautifully the magnificent

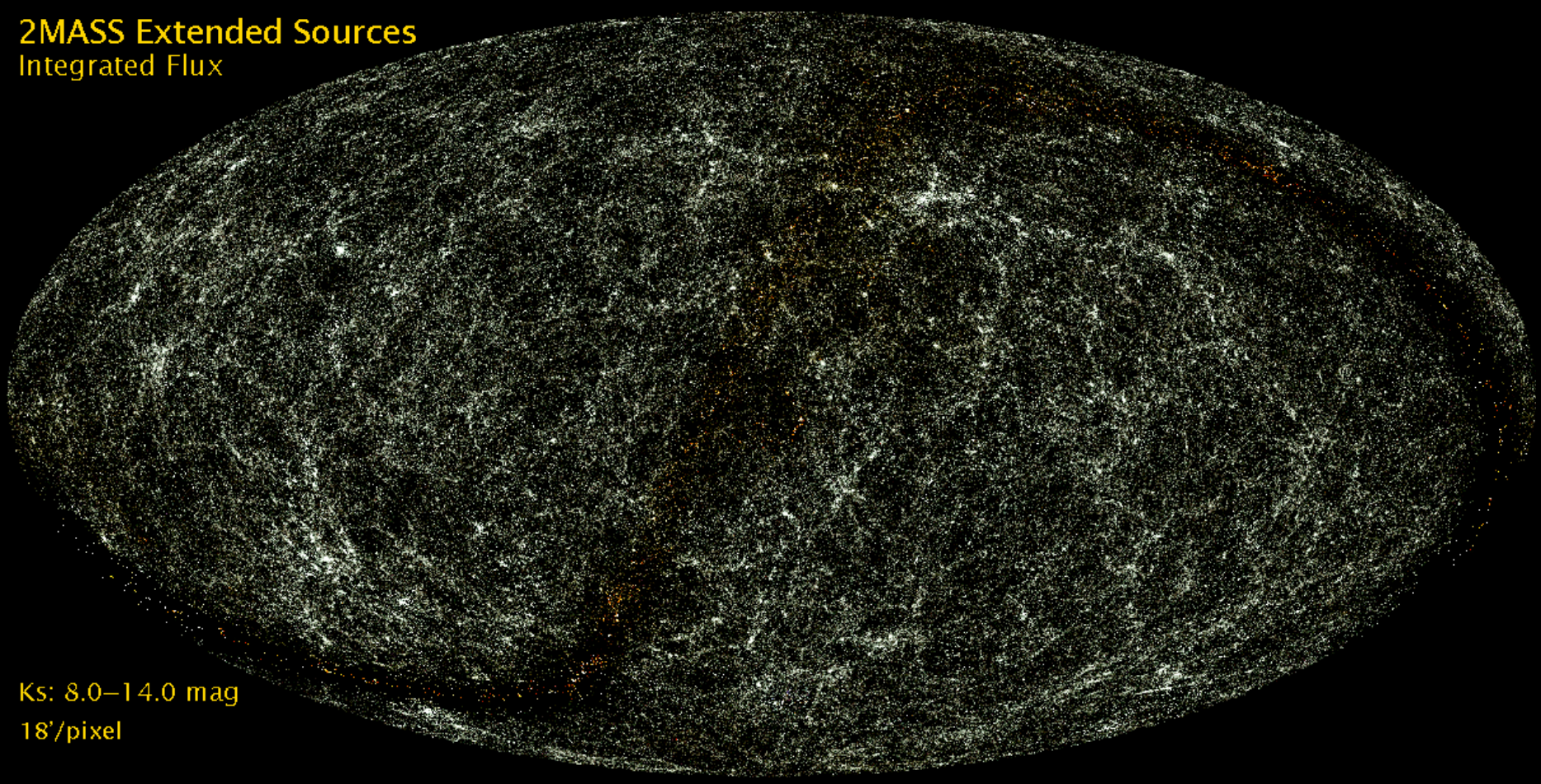
Local Void – Tully Void

KIGEN-Adhesion reconstruction



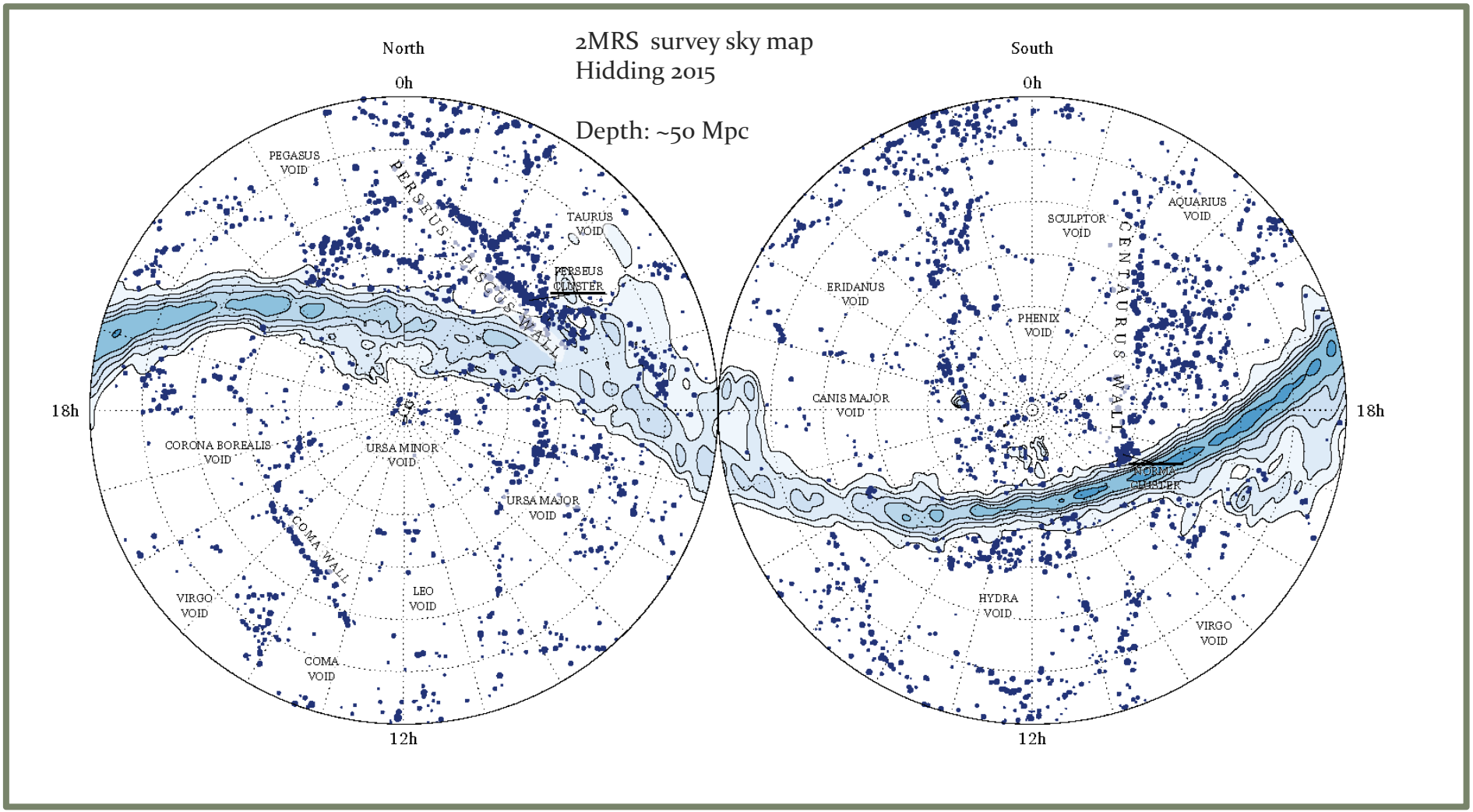
Hidding, vdW, Kitaura & Hess 2016/2017

2MASS: the Local Cosmic Web



Looking around us we already see the unmistakable signatures of an intriguing foamlike matter distribution in our immediate Cosmic Vicinity.

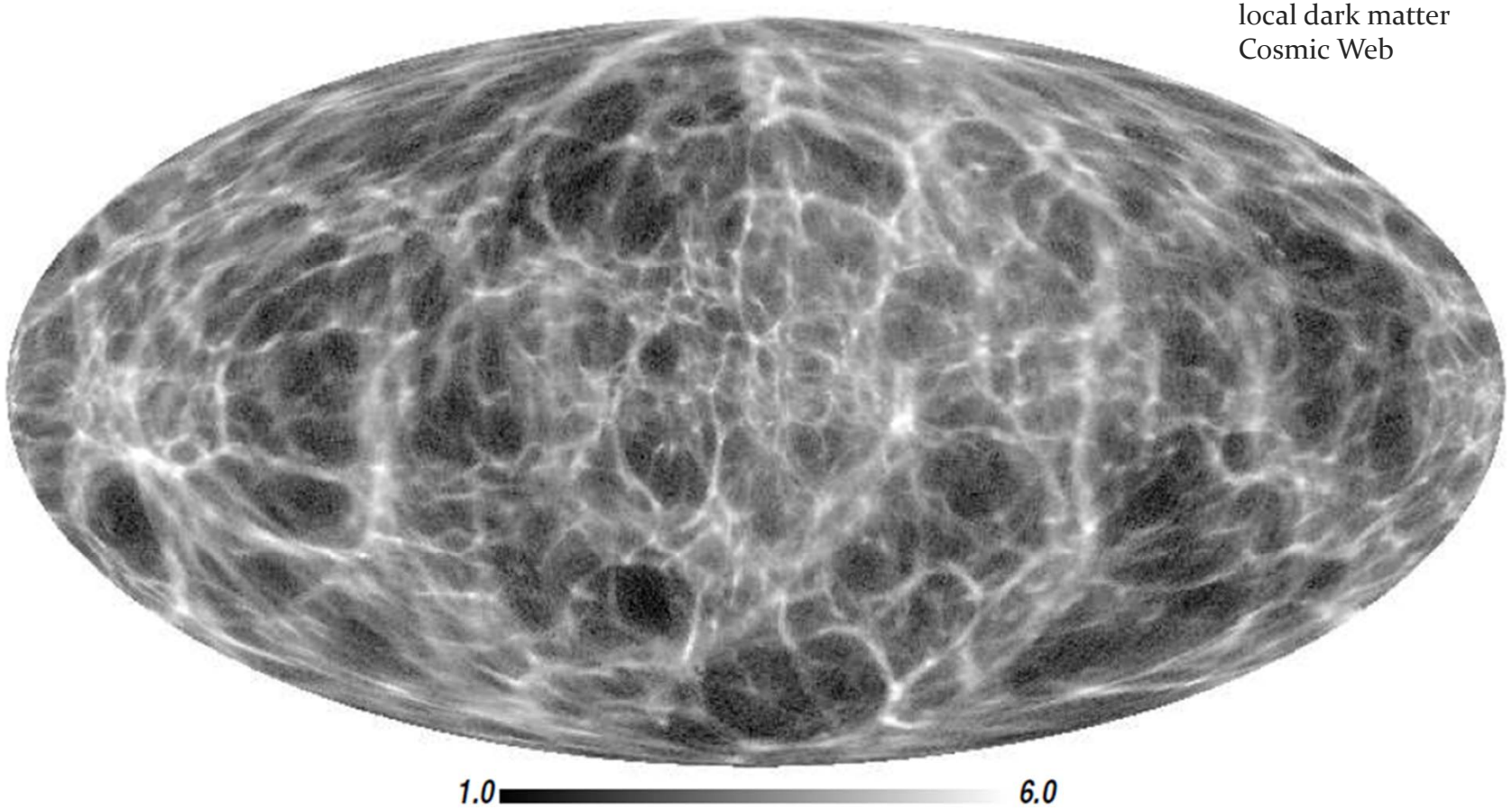
2MRS Local Universe …



local Cosmic Web: 2MRS

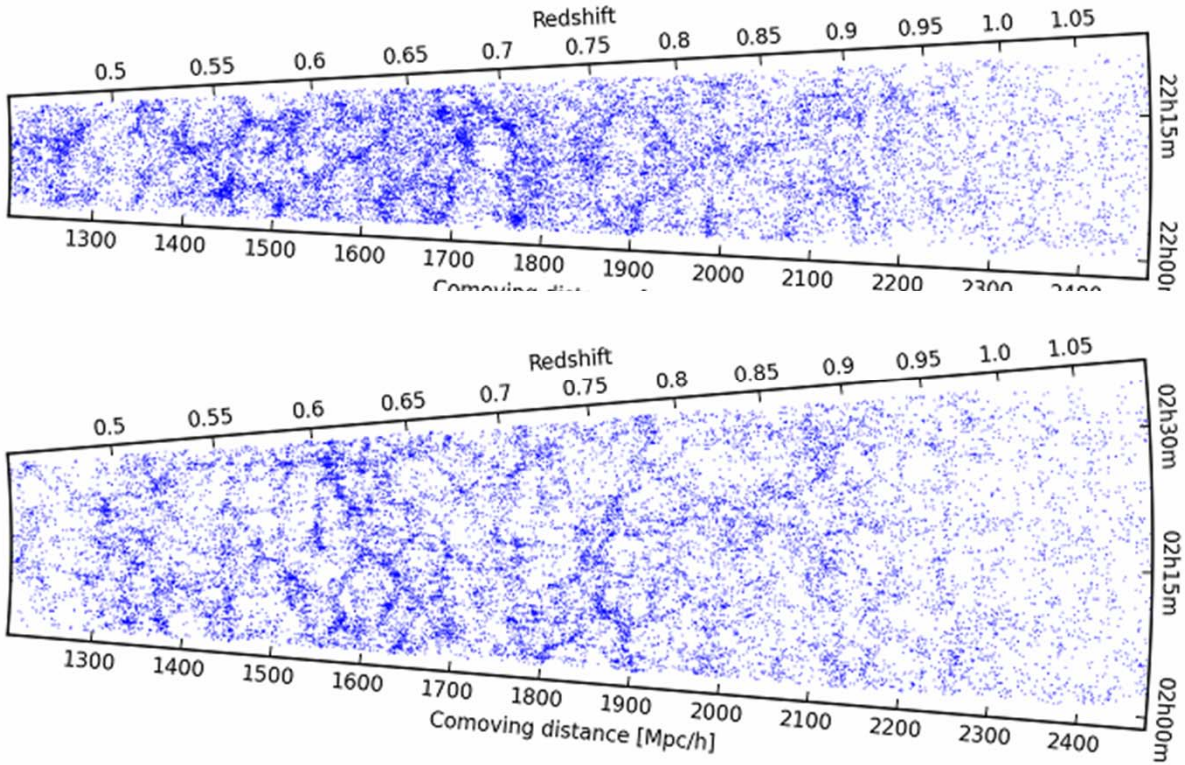
most detailed reconstruction
of the

local dark matter
Cosmic Web



Courtesy: Francisco Kitaura

VIPERS: Cosmic Web at High z



VIPERS

deep redshift survey,

z=0.4-1.2

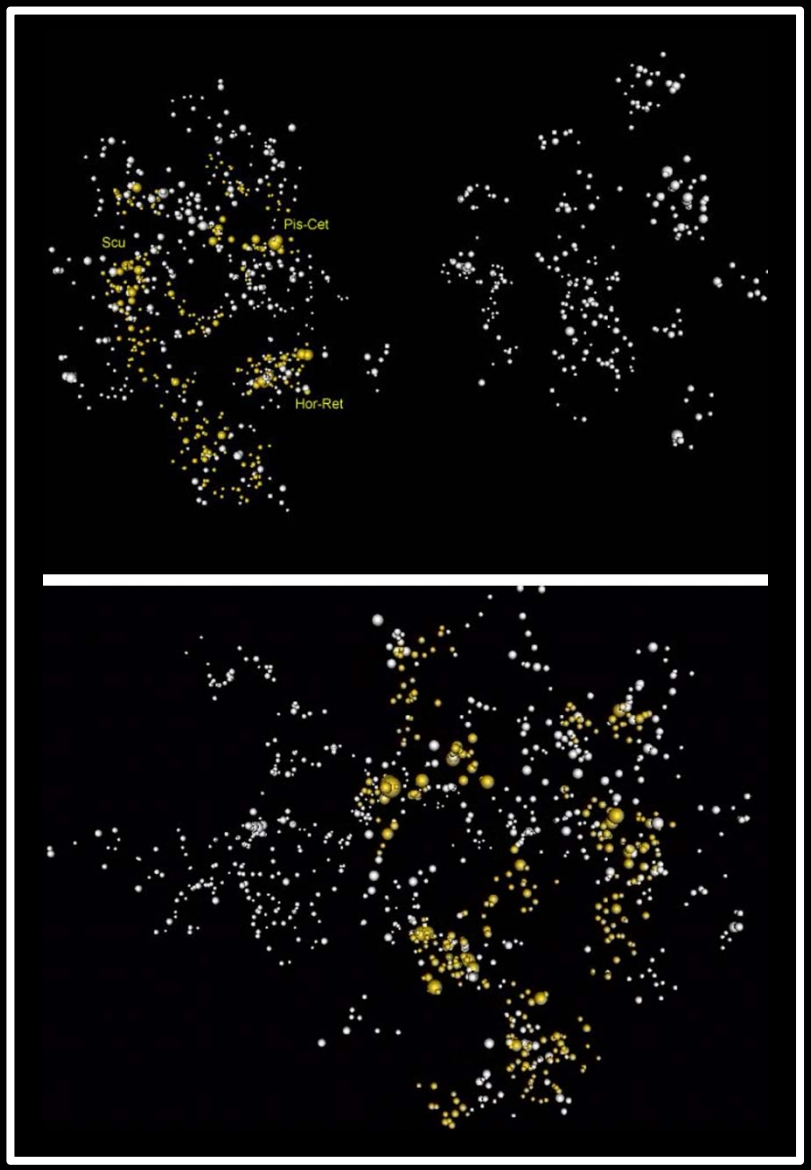
(Guzzo et al. 2014-)

recent galaxy surveys out to high cosmic depths
- eg. DEEP, VIPERS -
establish that the Cosmic Web pervades entire Universe (up to z~5 at least)

Cosmic Web::

Clusters and Voids

Voids & Clusters



Einasto, Saar et al. (1990s)

- Superclustering in Abell/APM clusters catalog

- Finding of characteristic scale ~140 Mpc, corresponding to large voids in the cluster distribution

Reflex II cluster catalogy (Bohringer et al.) reveals same population of voids in cluster distribution.

Abell 901/902 Supercluster Dark Matter Map ▪ STAGES

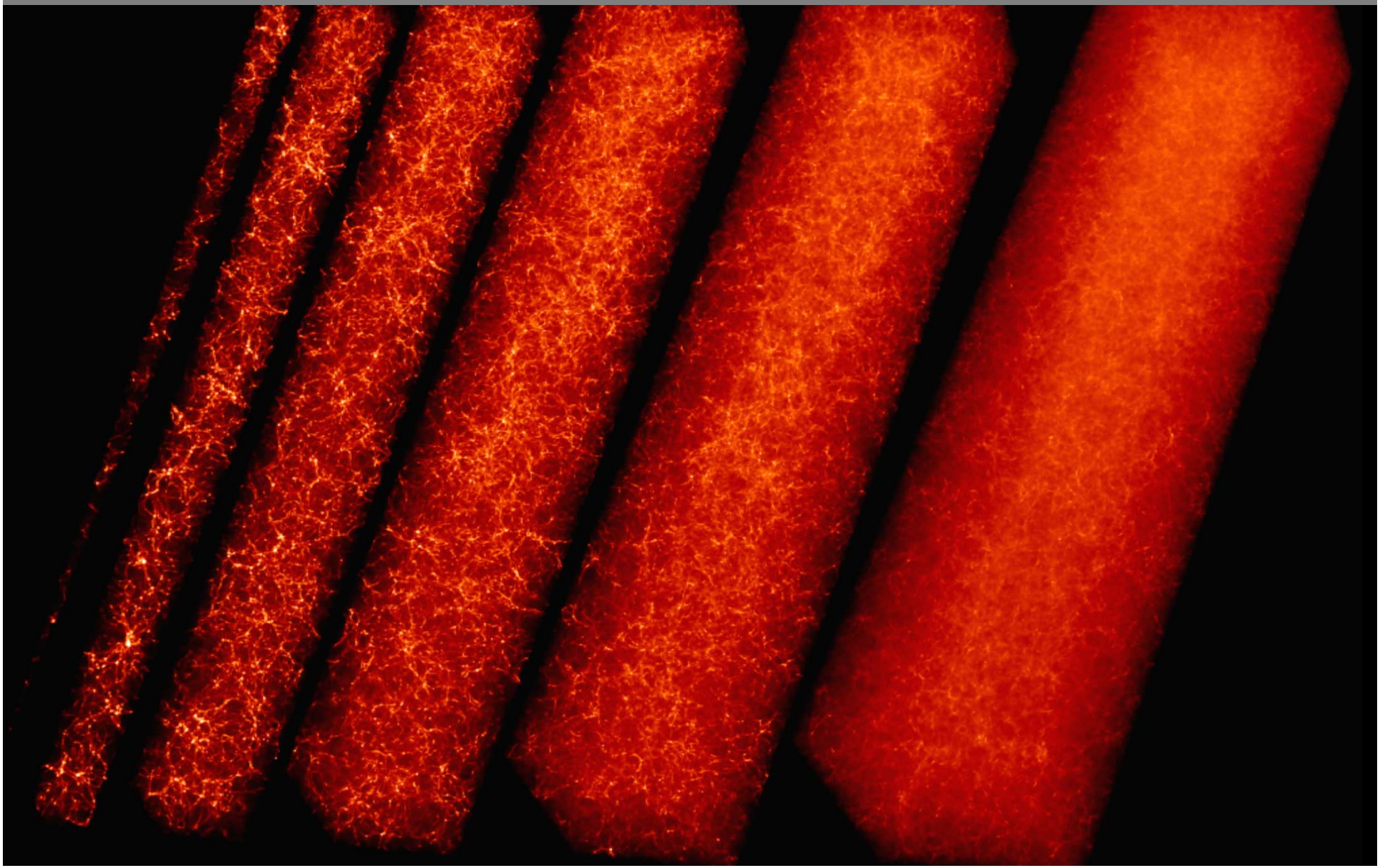
Hubble Space Telescope ▪ ACS/WFC

NASA, ESA, C. Heymans (University of British Columbia), M. Gray (University of Nottingham), and the STAGES Collaboration STScI-PRC08-03

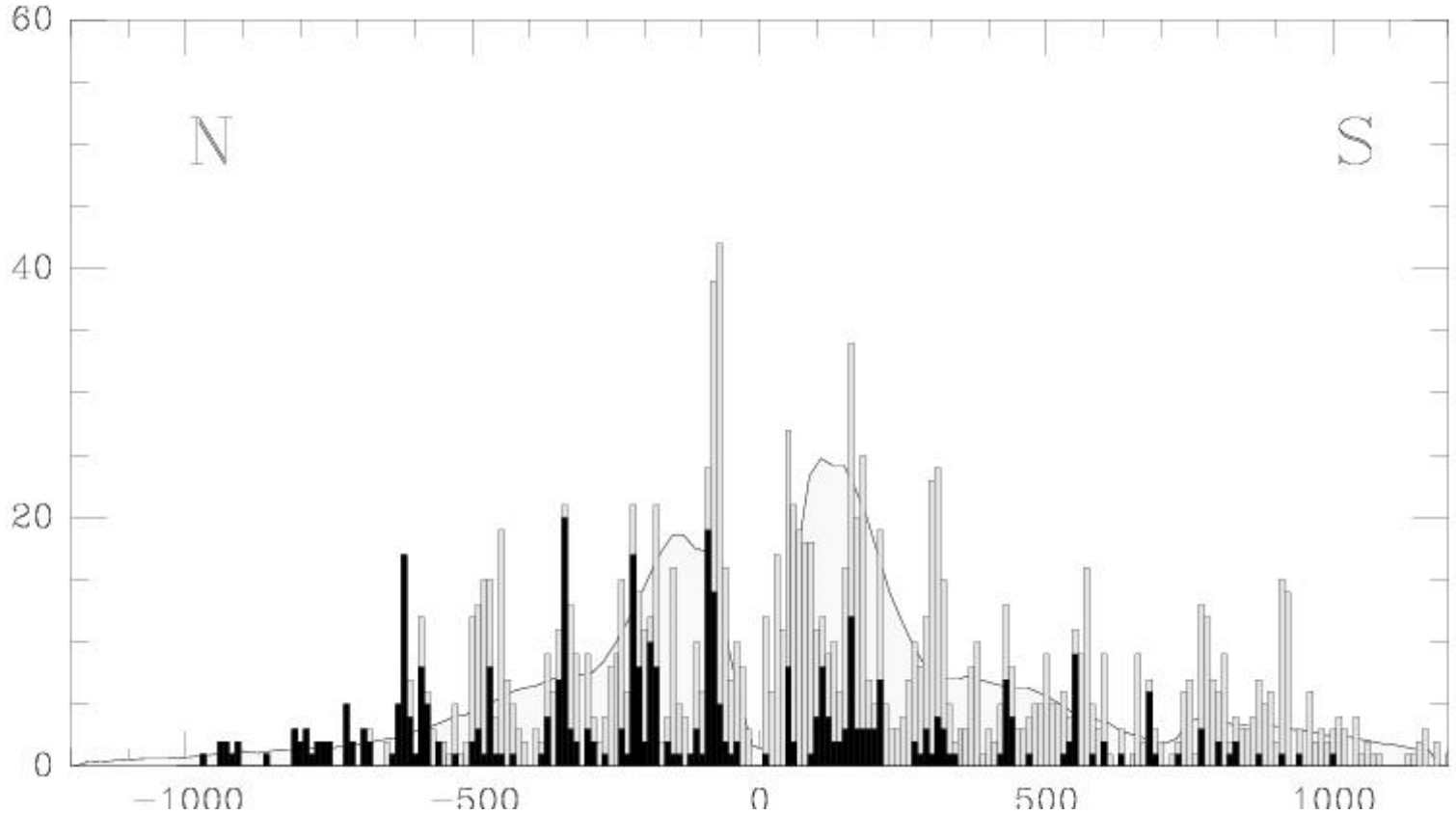
Cosmic Web::

high z

Cosmic Web at High z



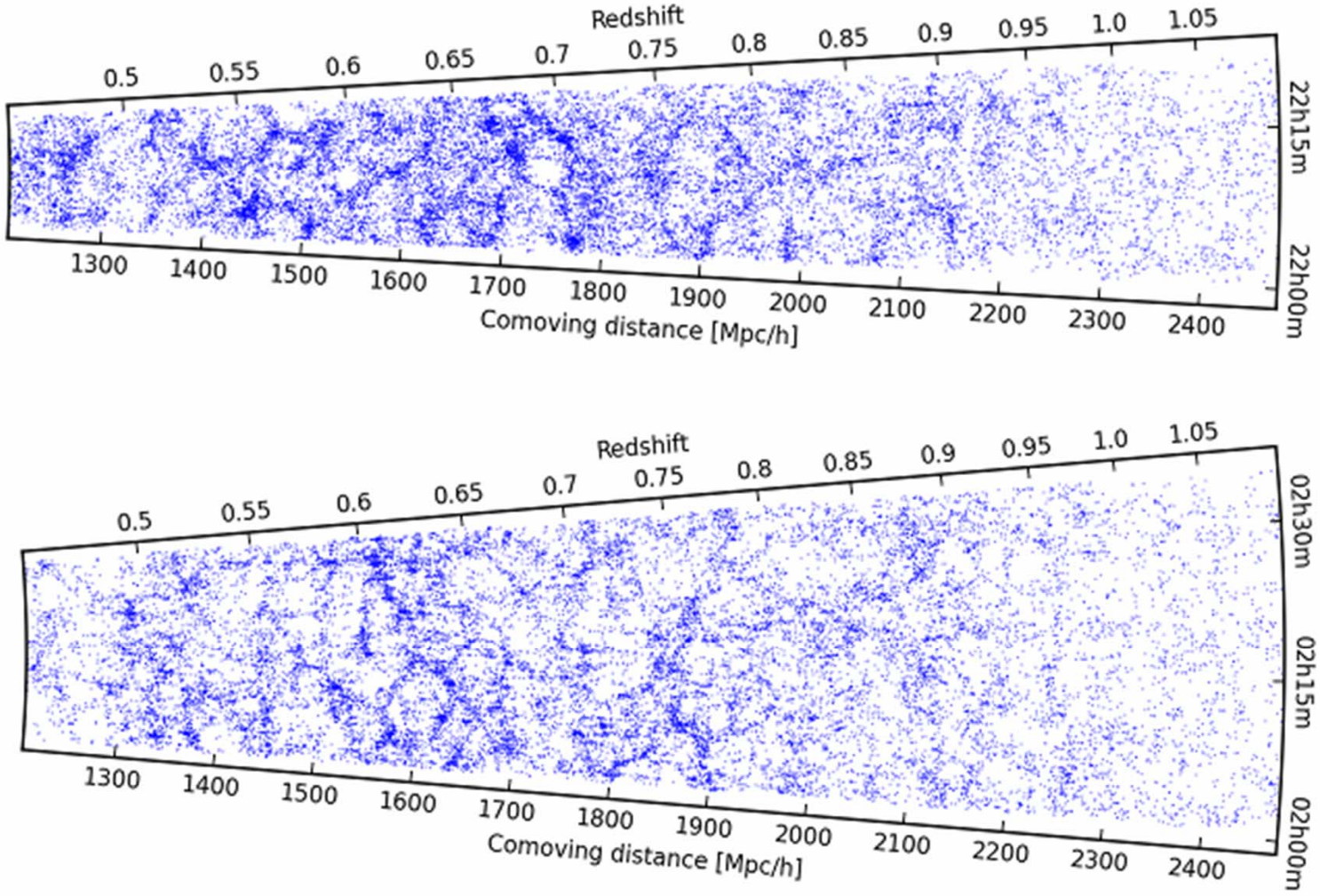
Cosmic Web at High z



Deep pencil beam survey (Broadhurst et al):

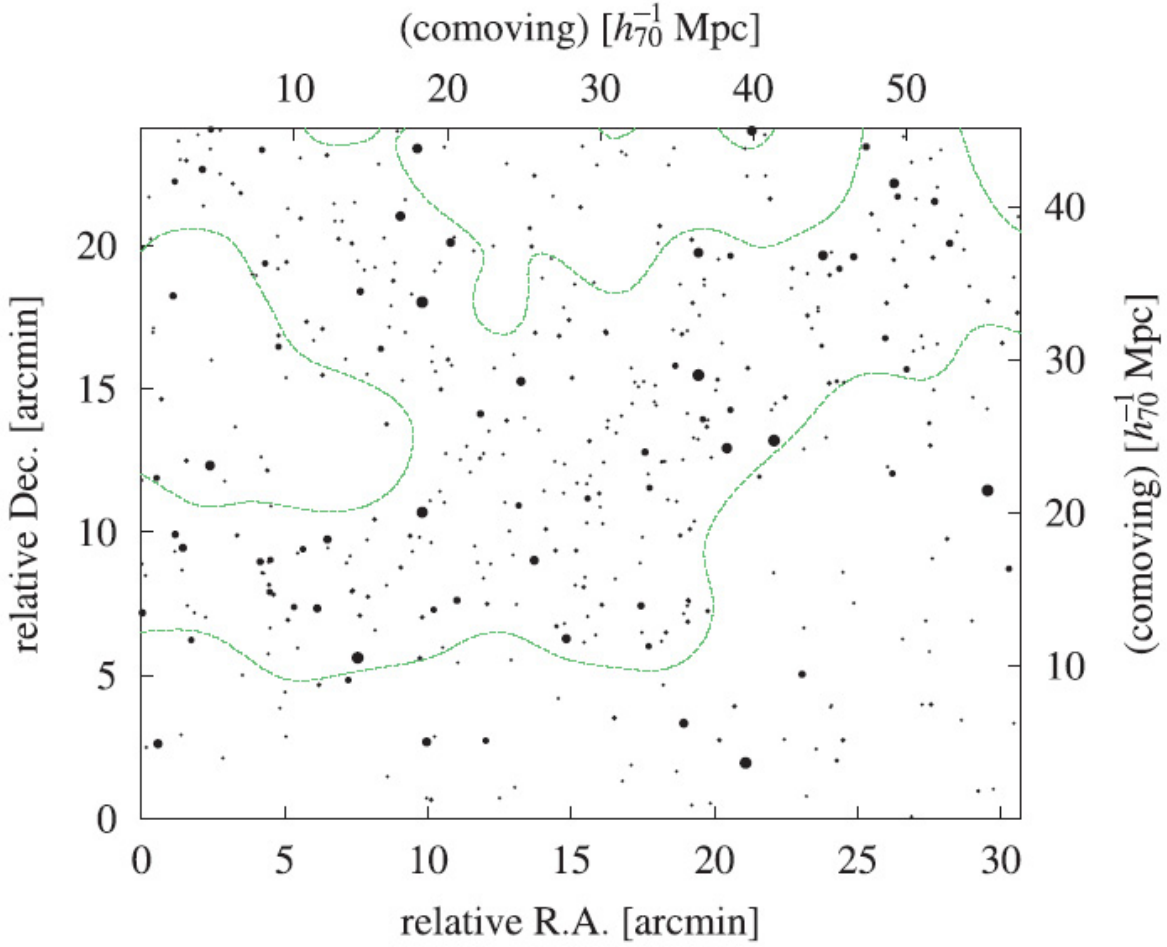
A semi-regular pattern of redshift spikes along line of sight, indicating the passage of l.o.s. through sheets, filaments and clusters. Suggestions for a characteristic scale of ~120h^{-1} Mpc should be ascribed to the 1-D character of the redshift skewer through 3-D structure.

high-z Cosmic Web: VIPERS



Guzzo et al. 2014.

Cosmic Web at High z



Subaru:

Ly emitters at z=3 (Ouchi et al. 2005)

Cosmic Web:

Cosmic Migration Flows

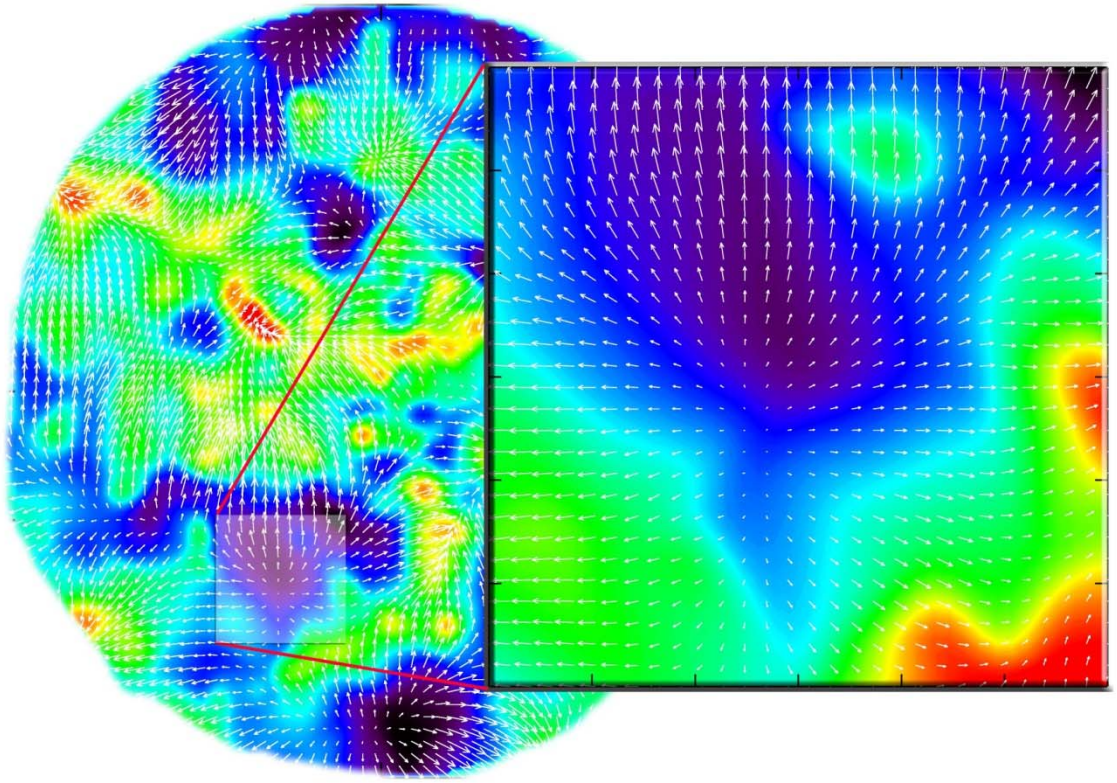
Large Scale Flows

Large-Scale Flows:

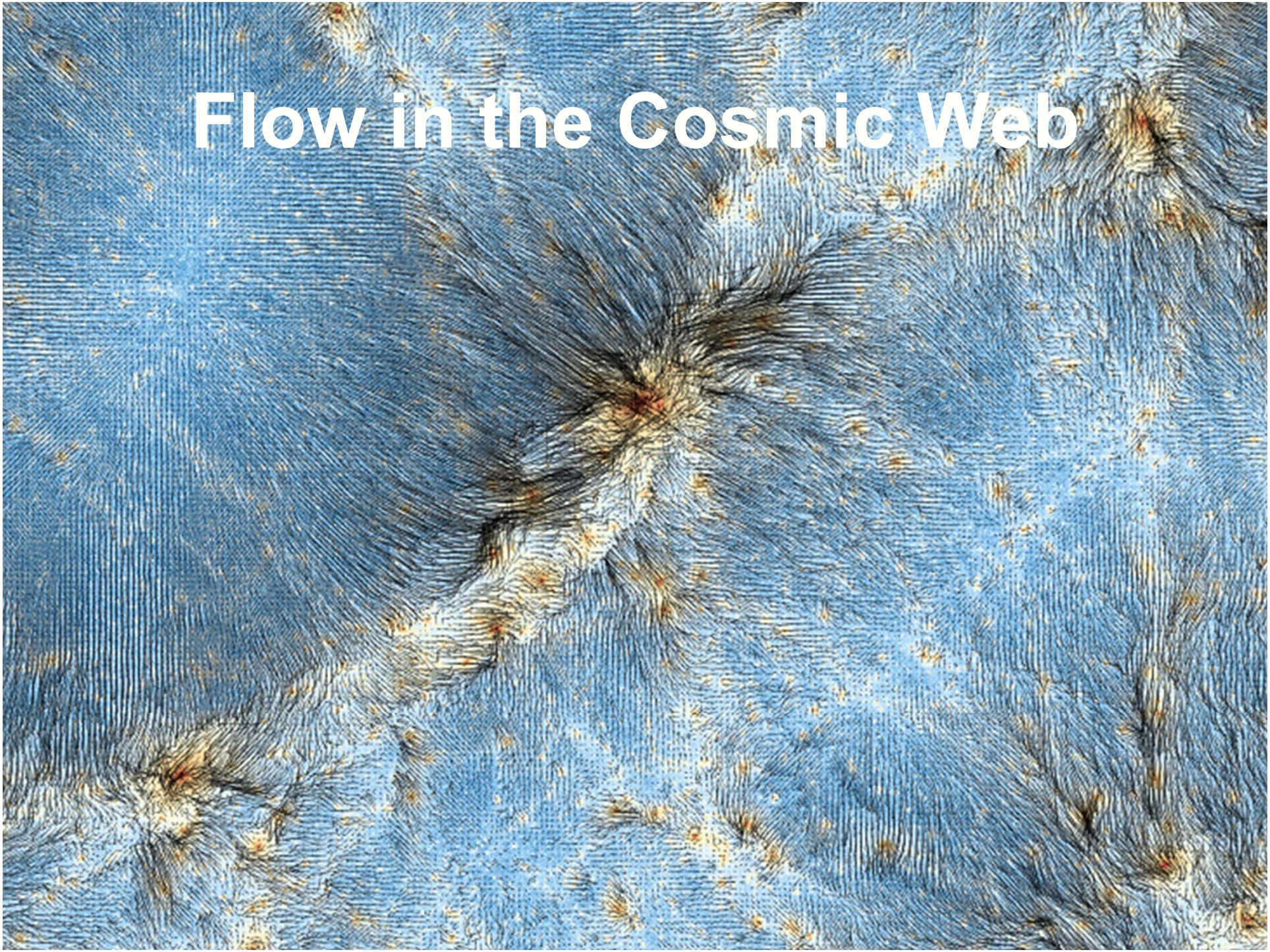
- Structure buildup accompanied by displacement of matter:
  - Cosmic flows
- On large (Mpc) scales, structure formation still in linear regime
- Directly related to cosmic matter distribution
- Note:
  redshift space distortion

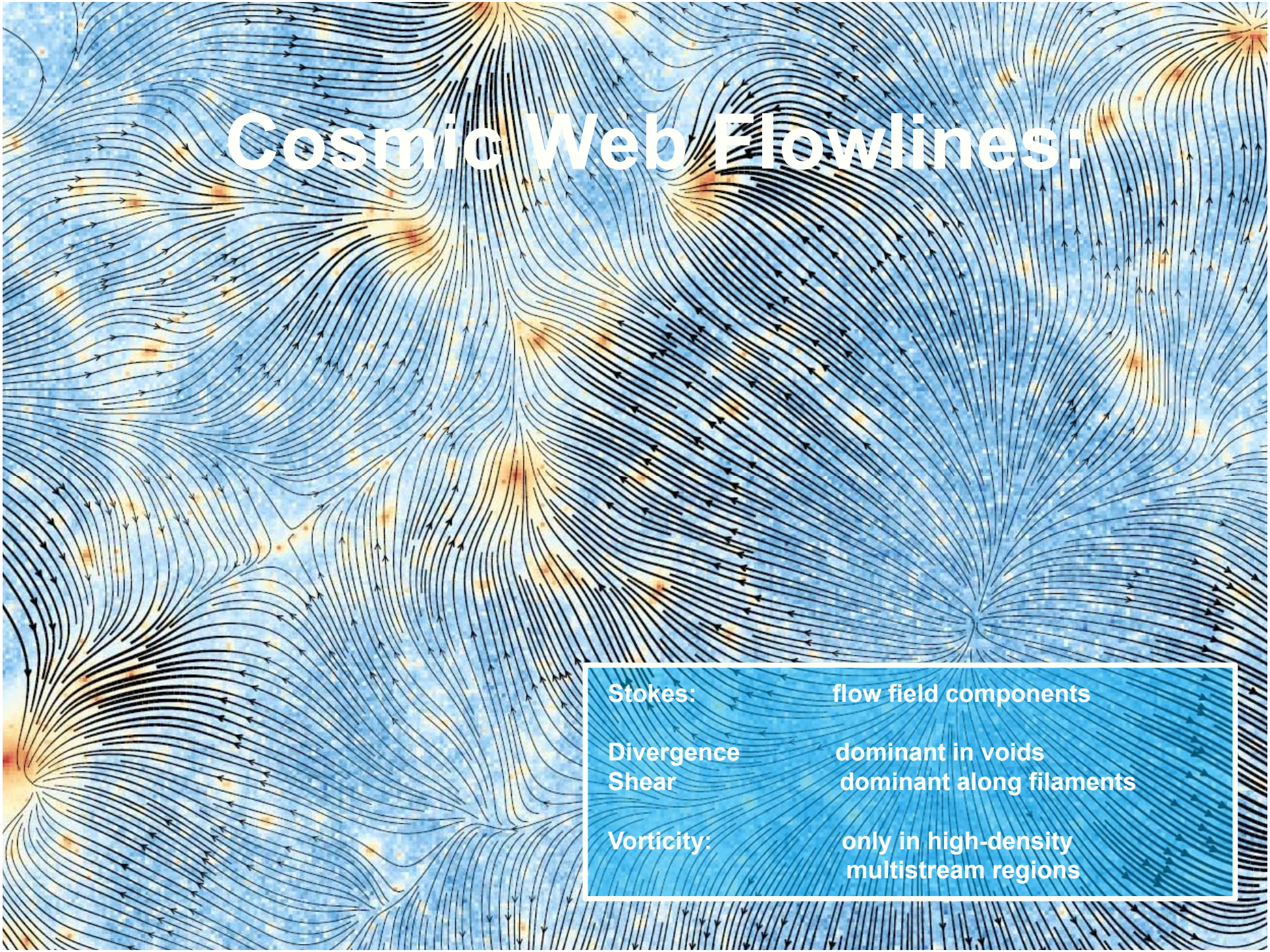
  $cz = Hr + v_{pec}$

  In principle possible to correct for this distortion, ie. to invert the mapping from real to redshift space
- Condition:
  entire mass distribution within volume should be mapped



$$\mathbf{v}(\mathbf{x},t) = \frac{H}{4\pi}\frac{f(\Omega_m)}{b}a\int d\mathbf{x}'\,\delta_{gal}(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

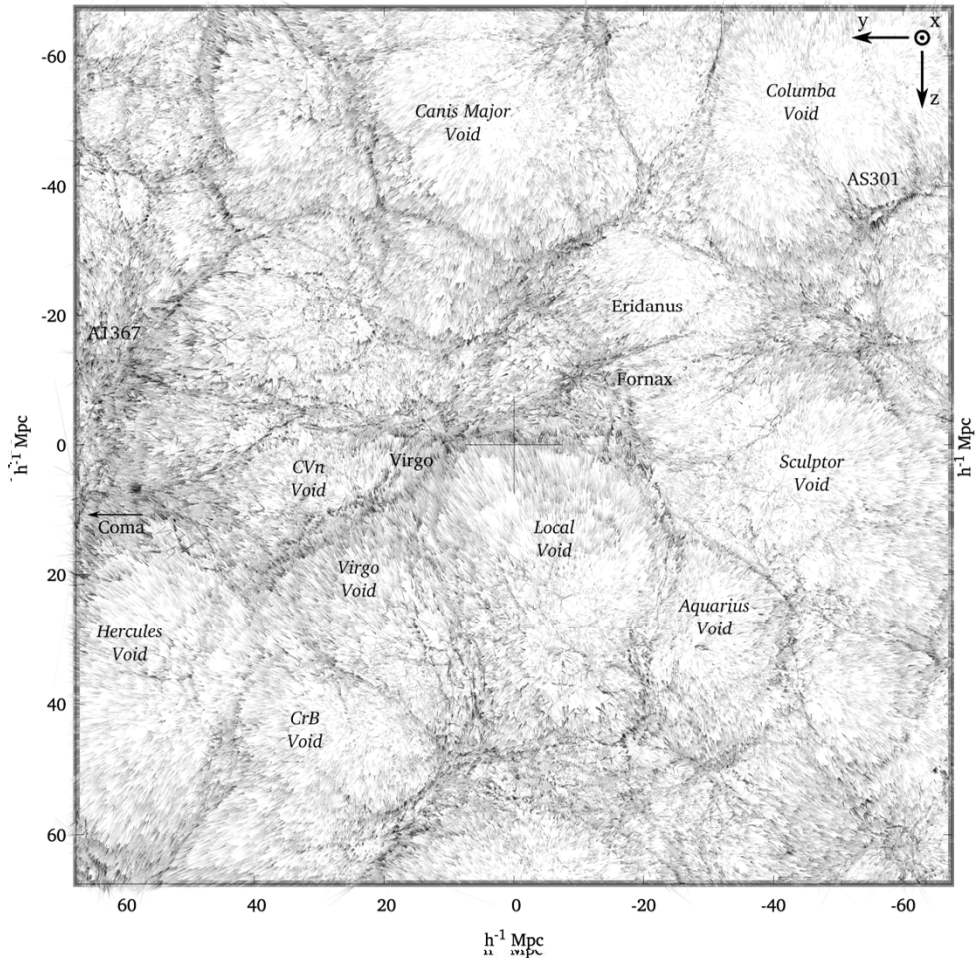

Flow in the Cosmic Web

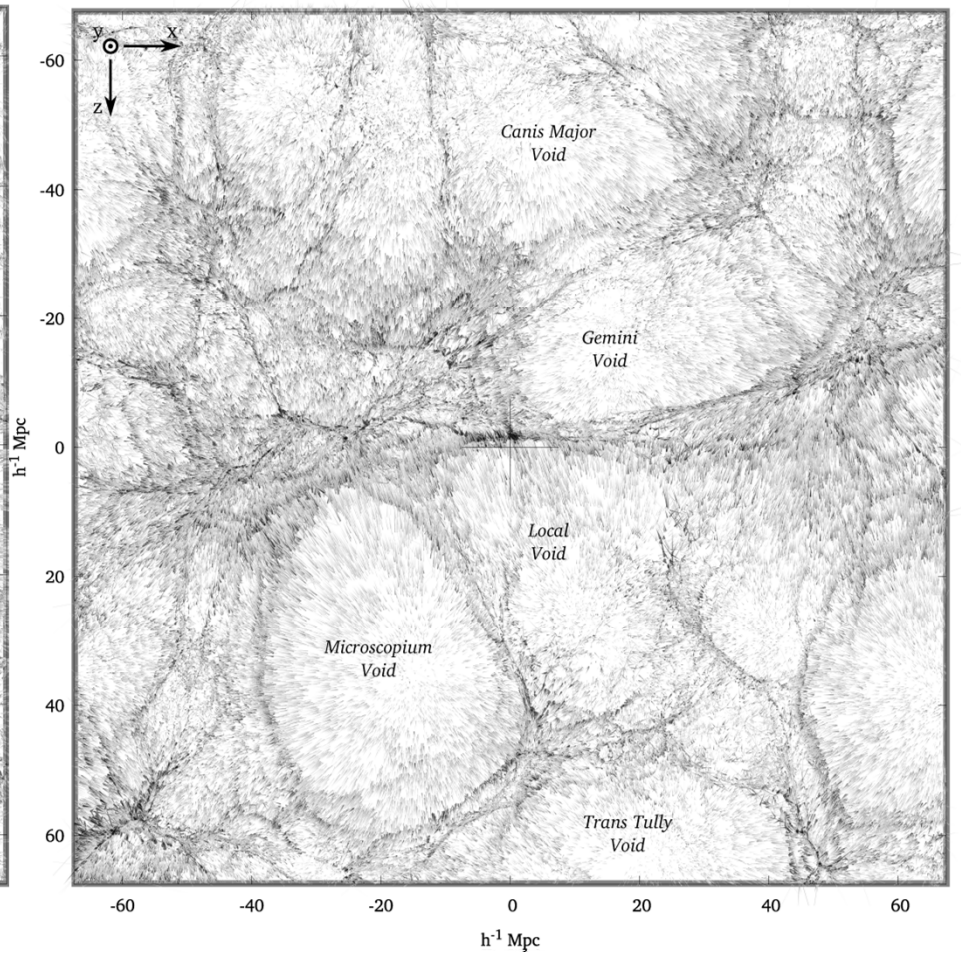

Cosmic Web Flowlines:
Stokes: flow field components
Divergence dominant in voids
Shear dominant along filaments
Vorticity: only in high-density multistream regions

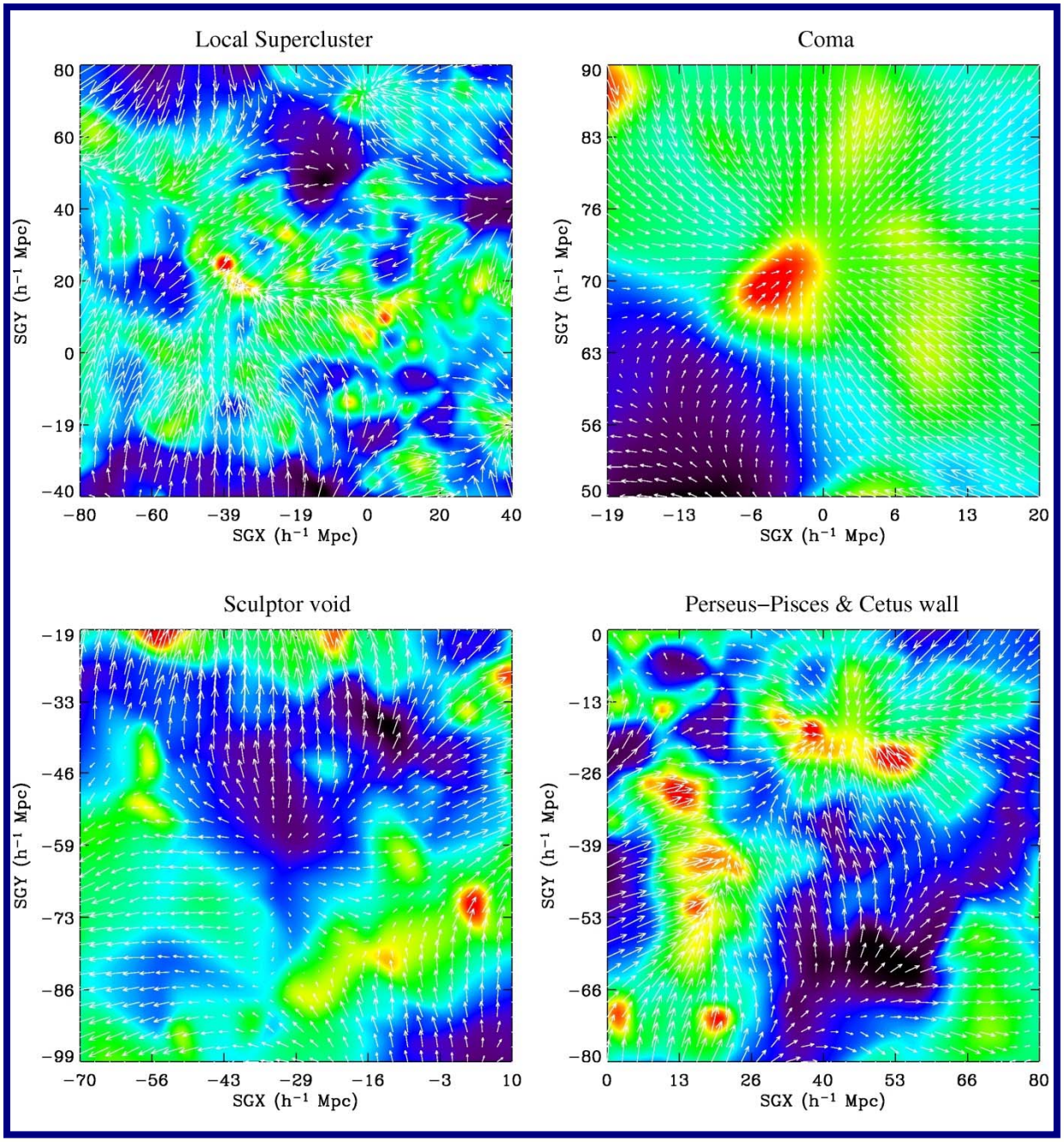
Supergalactic Plane

mean KIGEN - adhesion reconstruction

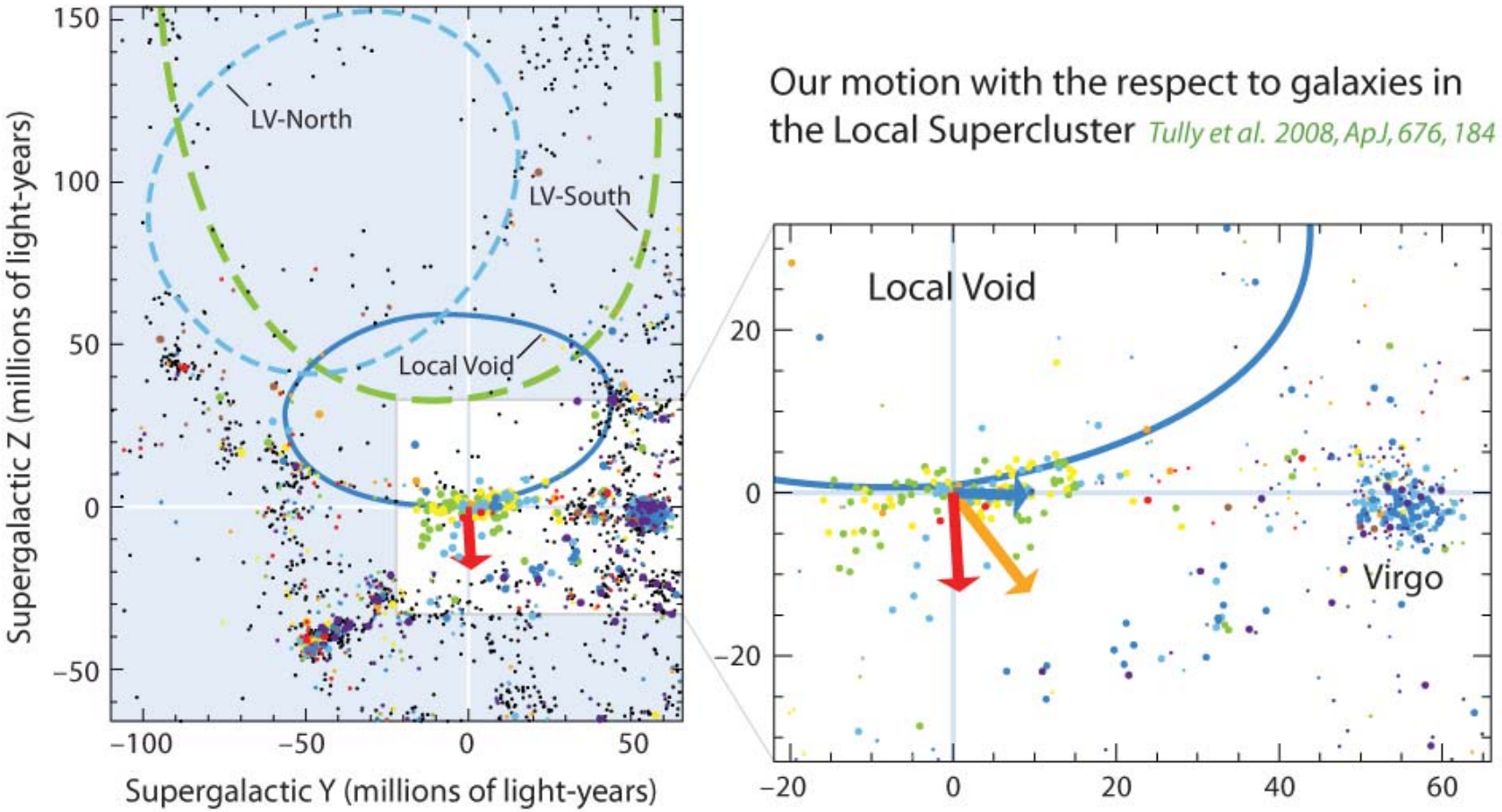
Hidding, Kitaura, vdW & Hess 2016/2017





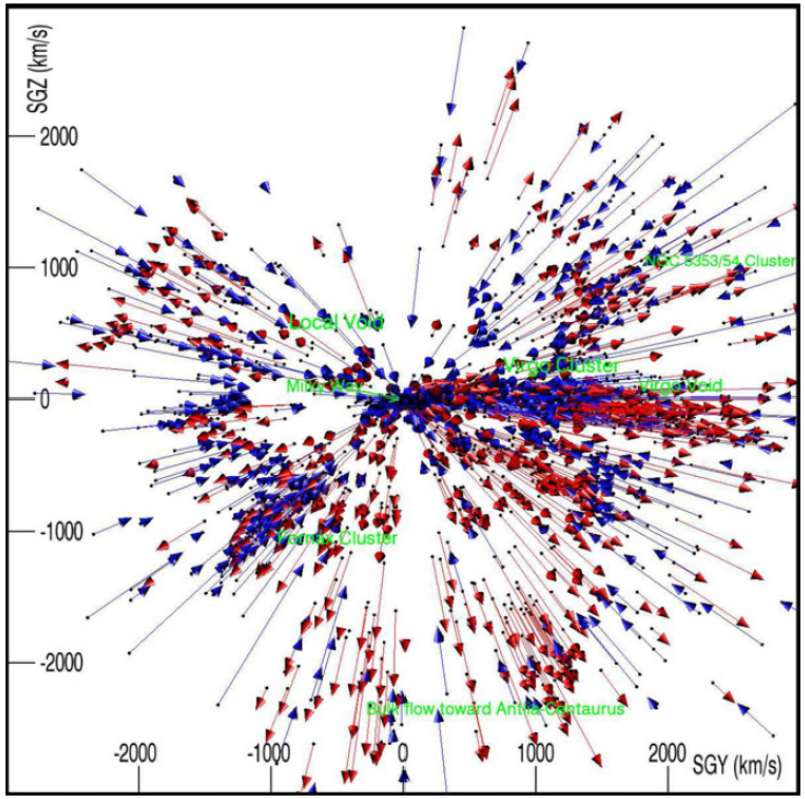

Local Supercluster
Coma
Sculptor void
Perseus–Pisces & Cetus wall
SGY (h⁻¹ Mpc)
SGX (h⁻¹ Mpc)
80
60
40
20
0
−19
−40
−80
−60
−39
−19
0
20
40
90
83
76
70
63
56
50
−19
−13
−6
0
6
13
20
−19
−33
−46
−59
−73
−86
−99
−70
−56
−43
−29
−16
−3
10
0
−13
−26
−39
−53
−66
−80
0
13
26
40
53
66
80

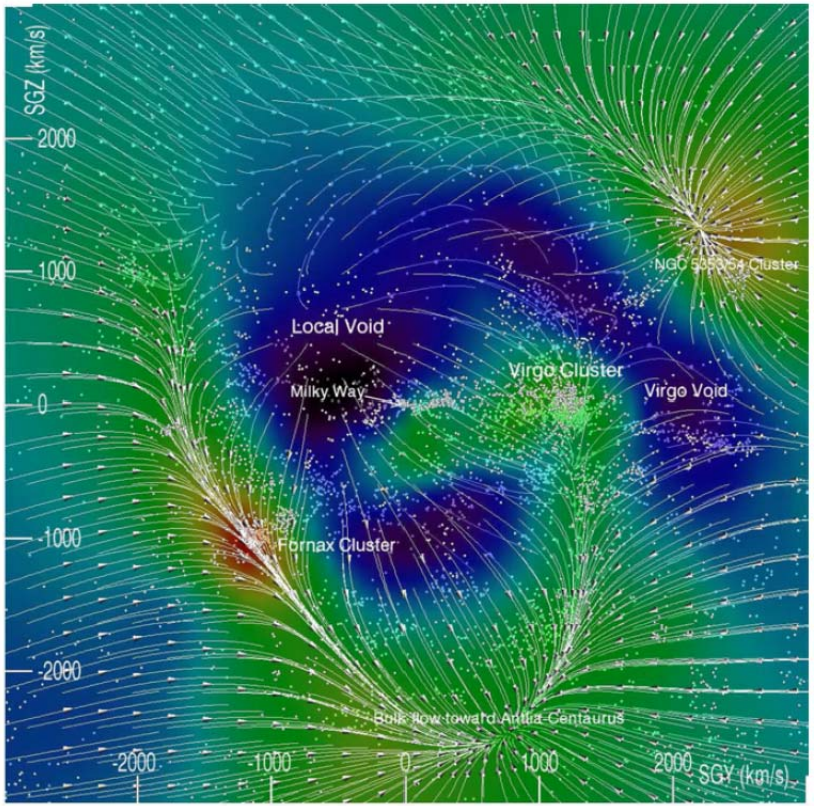
Push of the Local Void



Tully et al. 2008:
Local Void pushes with ~260 km/s against our local neighbourhood

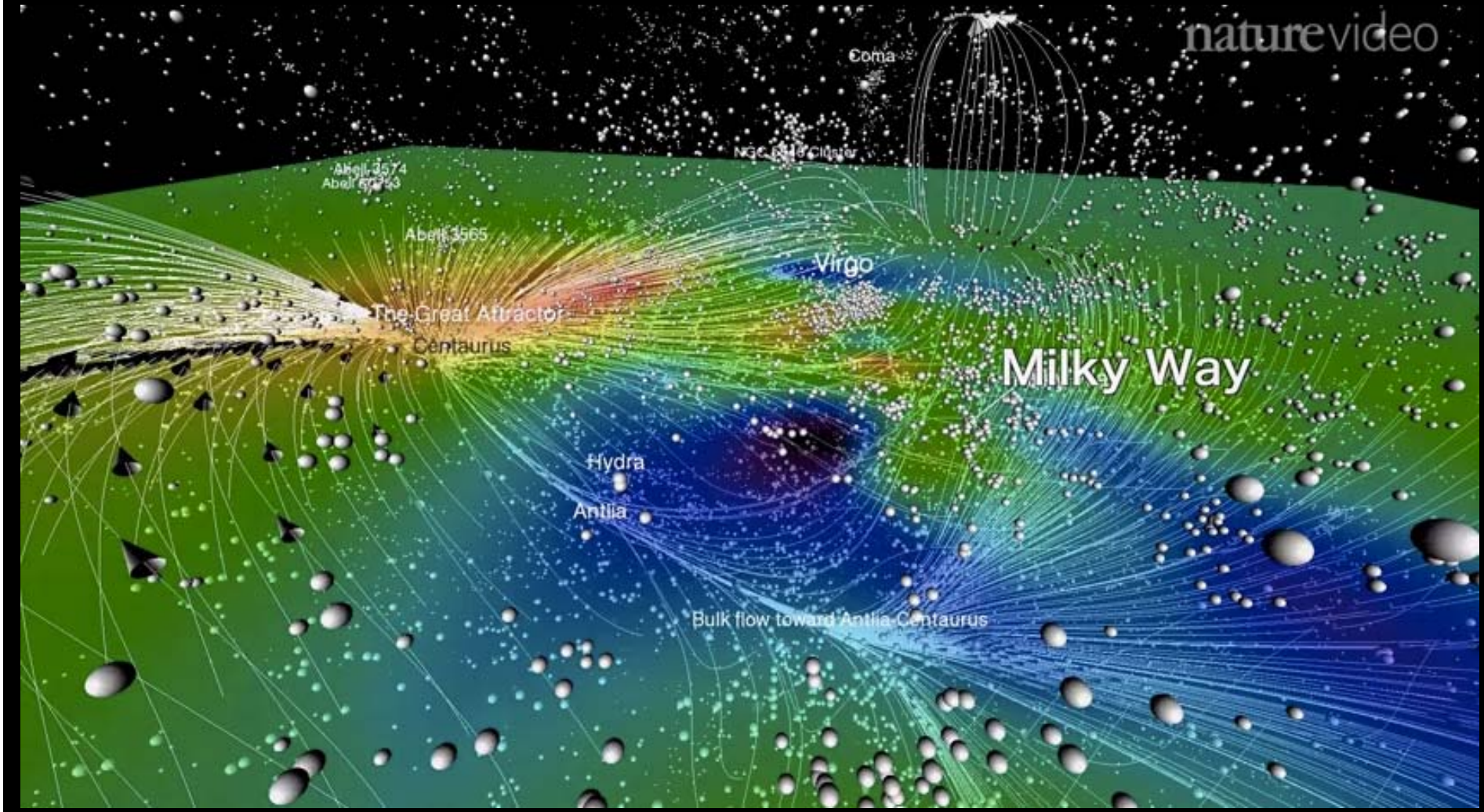
CosmicFlows-2



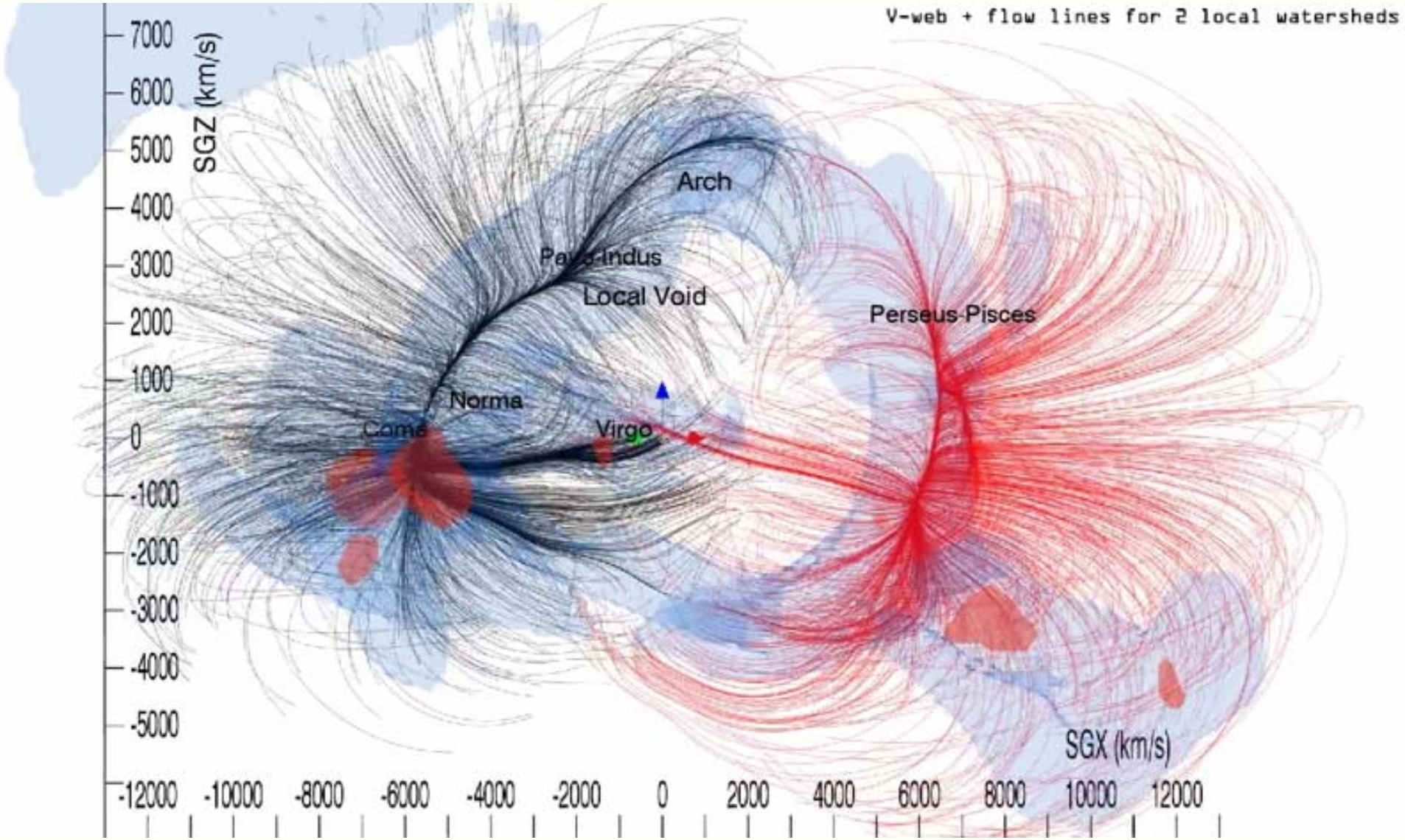


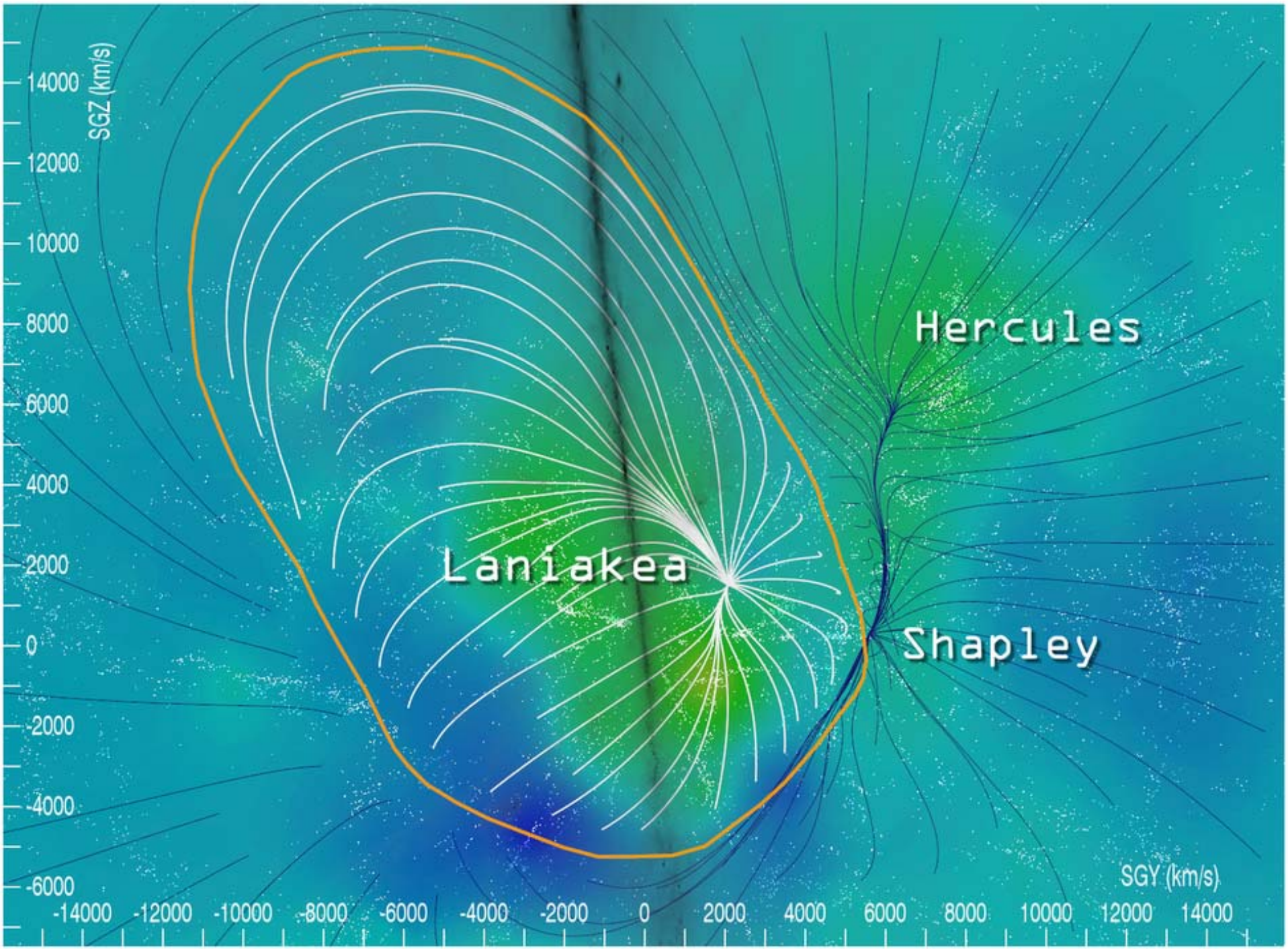
Courtois et al. 2013
Local void expansion in Cosmicflows-2

Laniakea

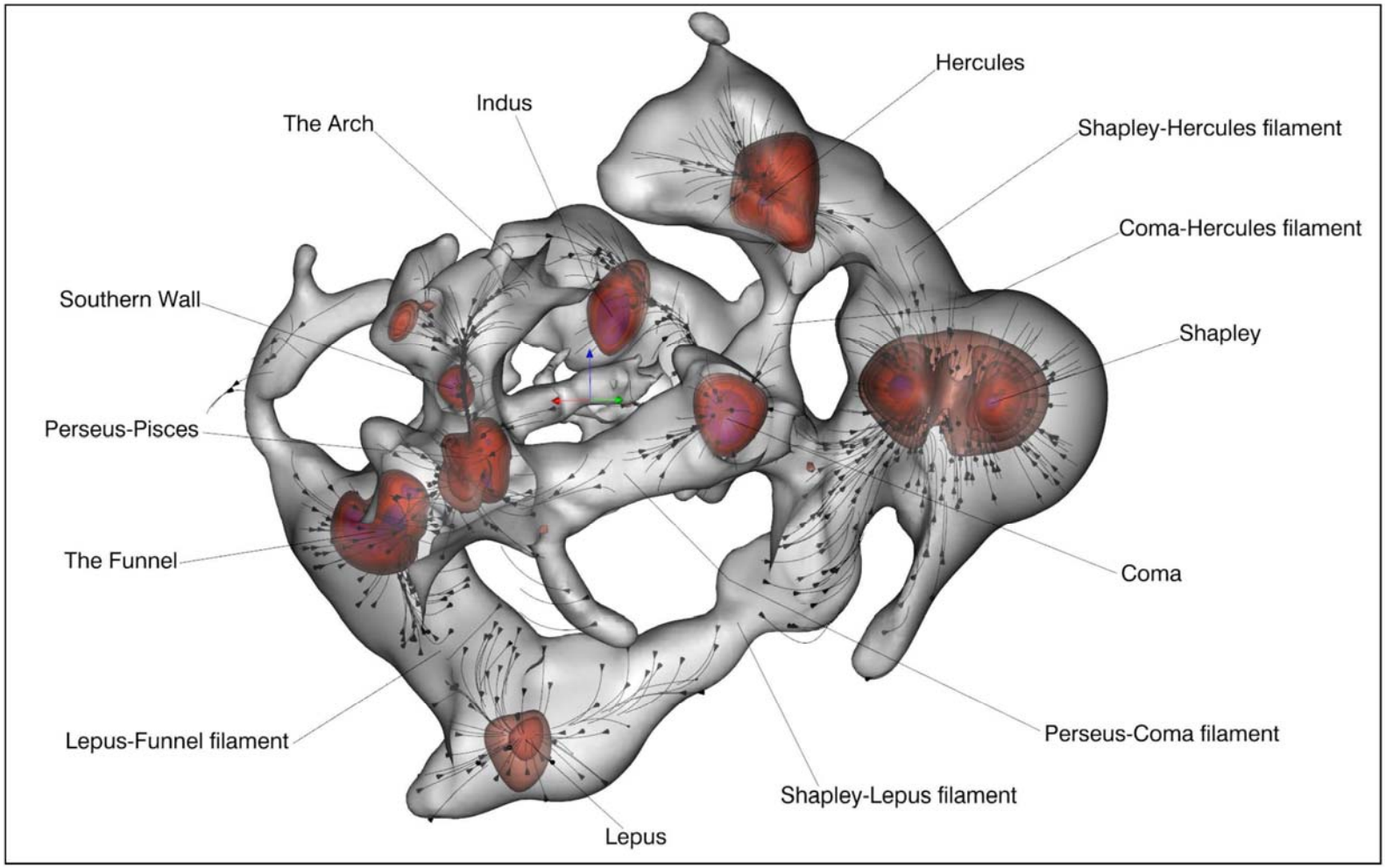

nature video
Coma
Abell 3574
Abell 3565
Virgo
The Great Attractor
Centaurus
Milky Way
Hydra
Antlia
Bulk flow toward Antlia-Centaurus

Laniakea


V-web + flow lines for 2 local watersheds
SGZ (km/s)
7000
6000
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
Arch
Local Void
Perseus-Pisces
Norma
Virgo
SGX (km/s)
-12000
-10000
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
10000
12000


Laniakea
Hercules
Shapley
SGZ (km/s)
SGY (km/s)
14000
12000
10000
8000
6000
4000
2000
0
-2000
-4000
-6000
-14000
-12000
-10000
-8000
-6000
-4000
-2000
0
2000
4000
6000
8000
10000
12000
14000

CosmicFlows-3

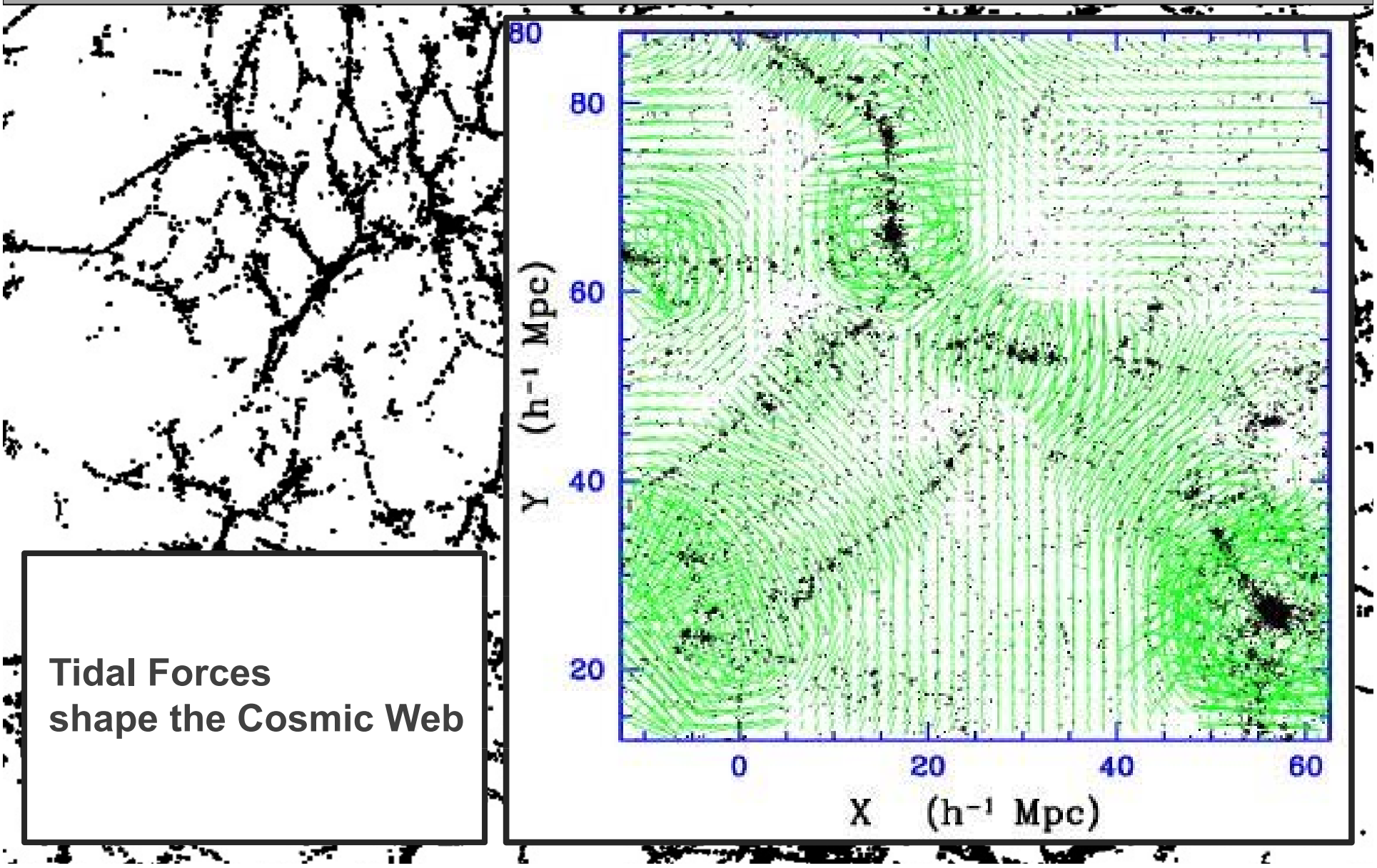


Cosmic Web morphology:
velocity shear based V-web identification flow pattern in cosmic web (Pomarede et al. 2017)

Cosmic Web:

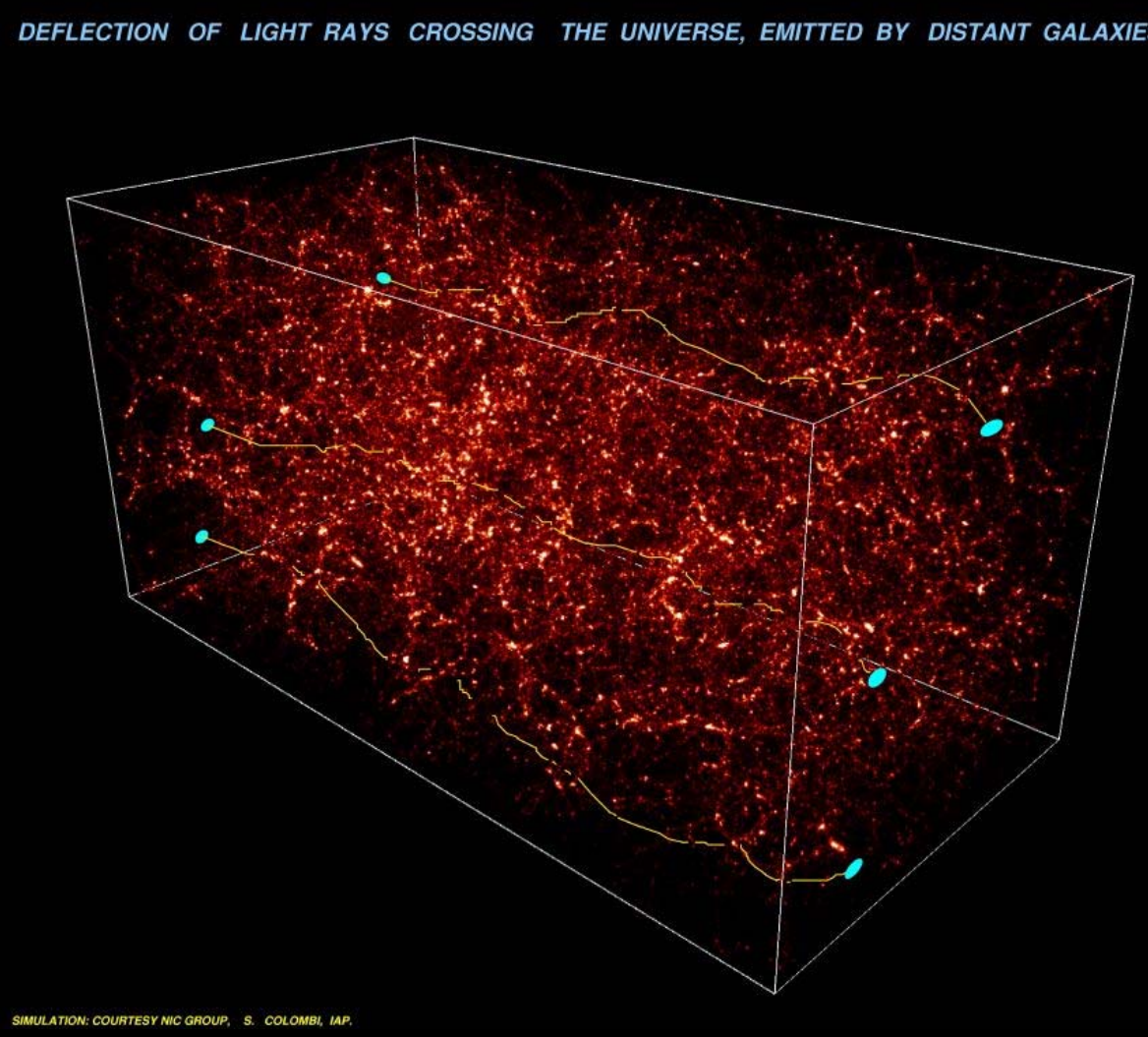
Dark Matter & Grav. Lensing

Tidal Shaping of the Cosmic Web



Tidal Forces
shape the Cosmic Web

Dark Matter Cosmic Web



Lensing of background light by dark matter distribution

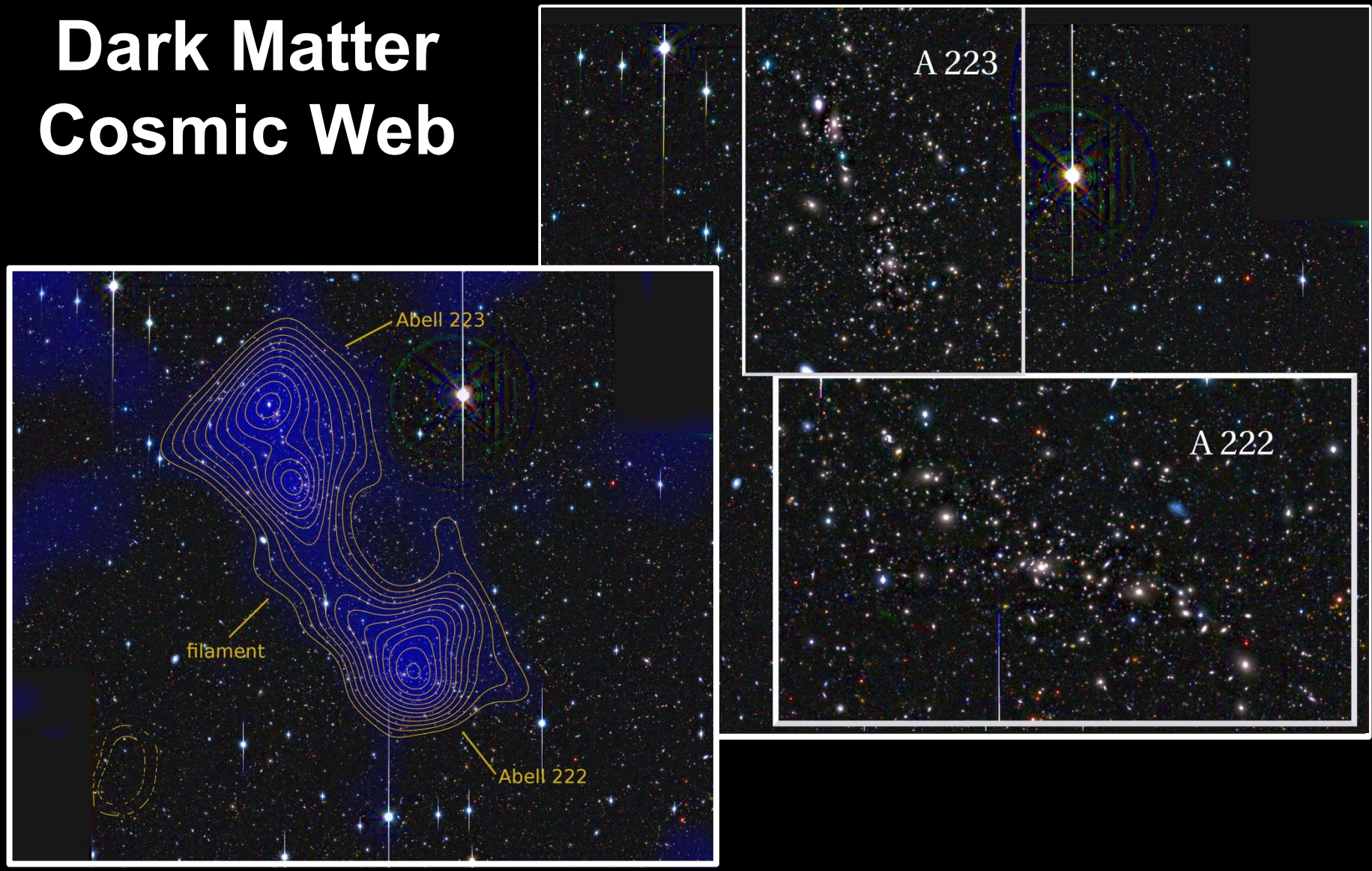
Galaxy Clusters

CL0024+17:

(Jee et al., 2007)

mapping the dark matter content of cosmic mass distribution via weak gravitational lensing

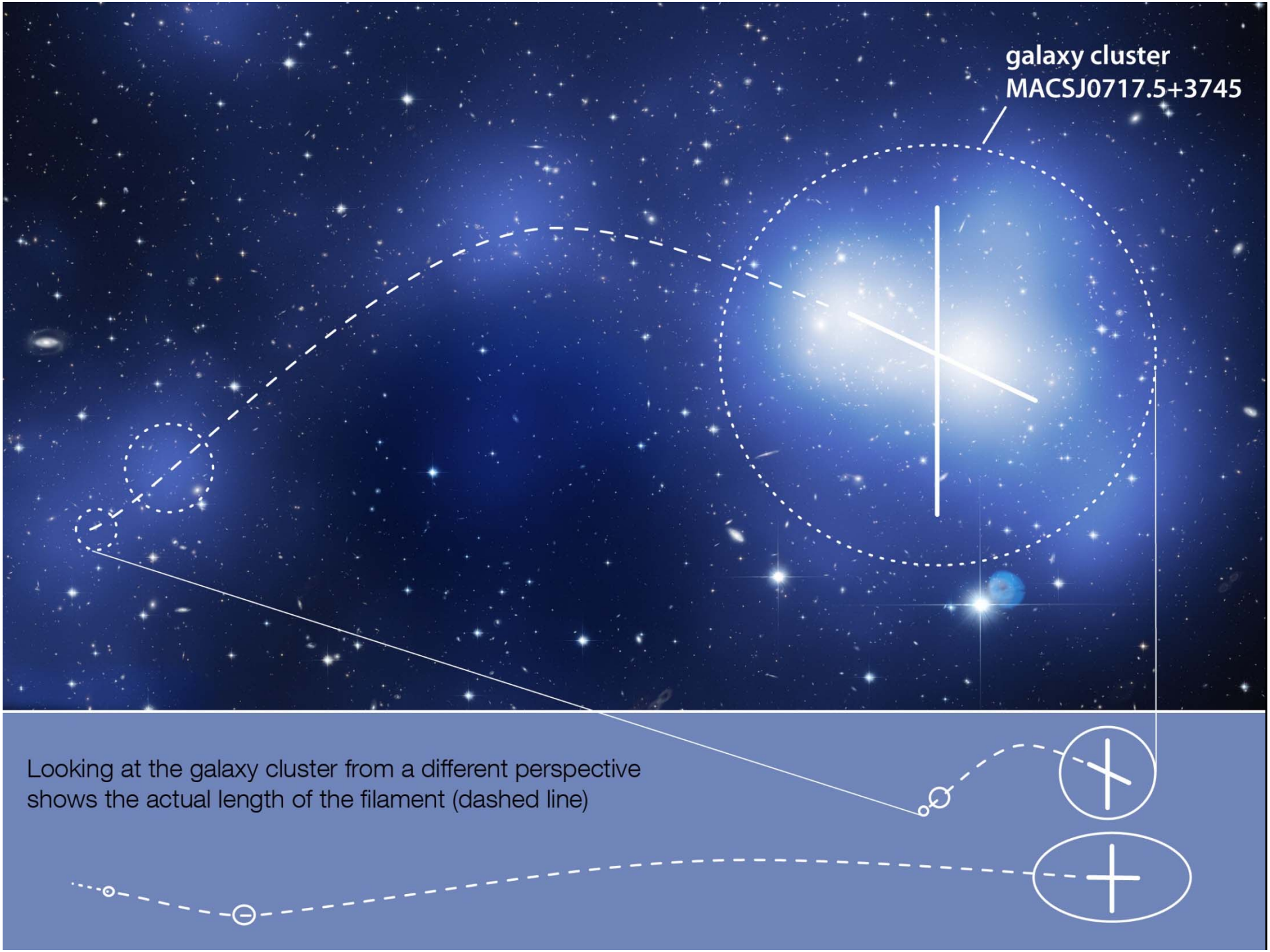
Dark Matter Cosmic Web



A222-A223
Dietrich et al. 2013

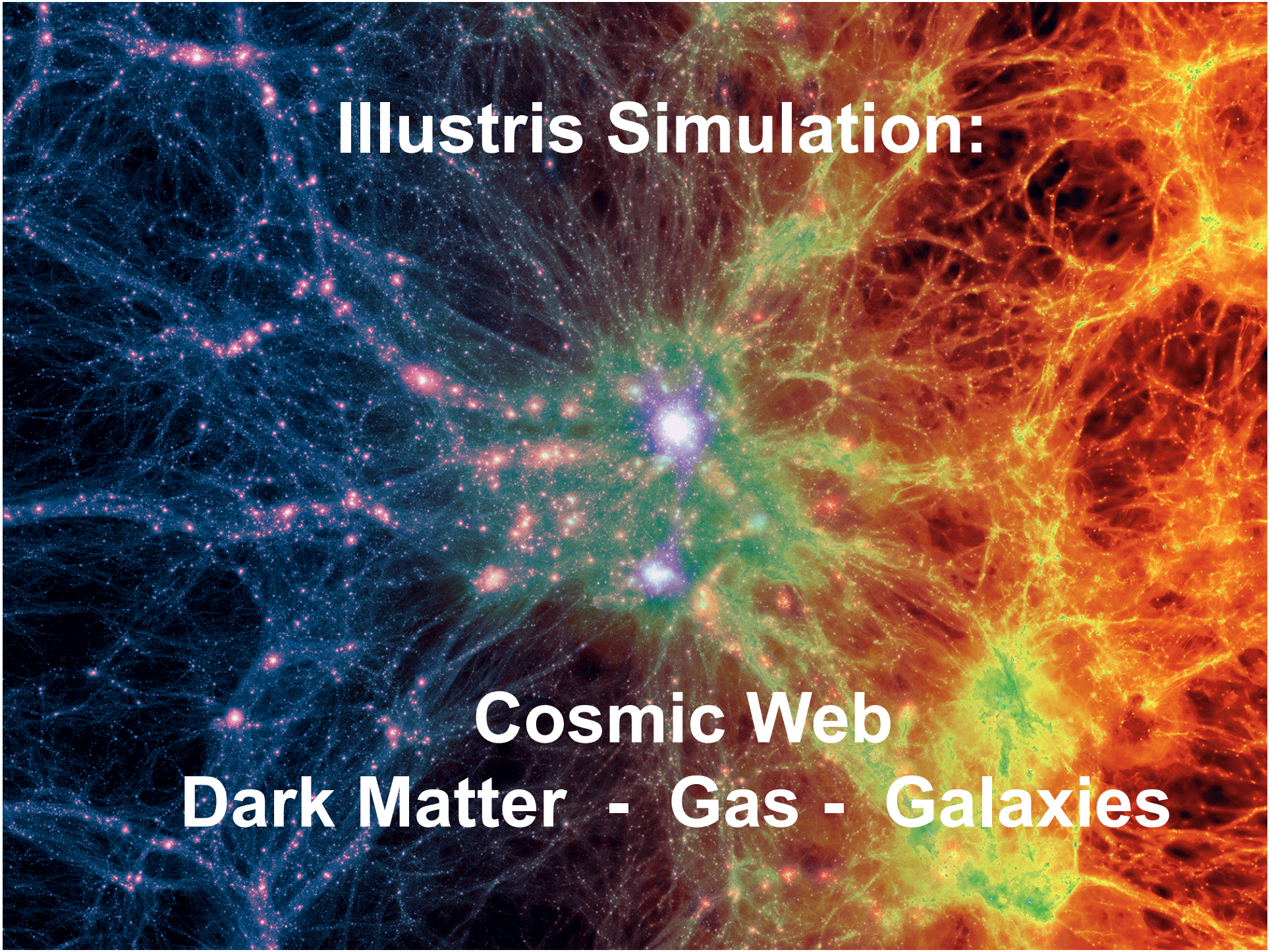
Dark Matter Cosmic Web

MACSJ0171.5+3745
Ebeling et al. 2012

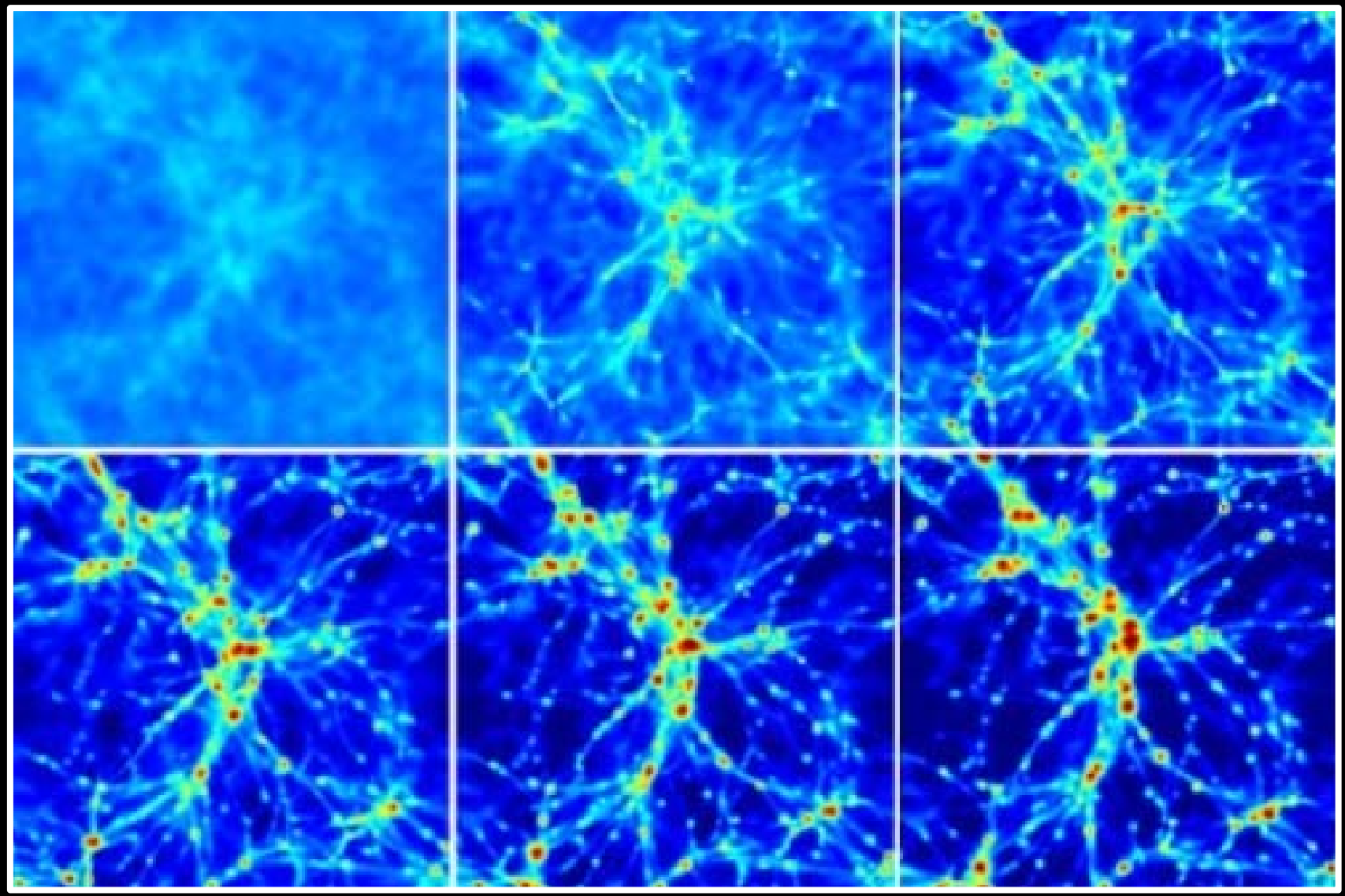

galaxy cluster
MACSJ0717.5+3745
Looking at the galaxy cluster from a different perspective
shows the actual length of the filament (dashed line)

Cosmic Web:

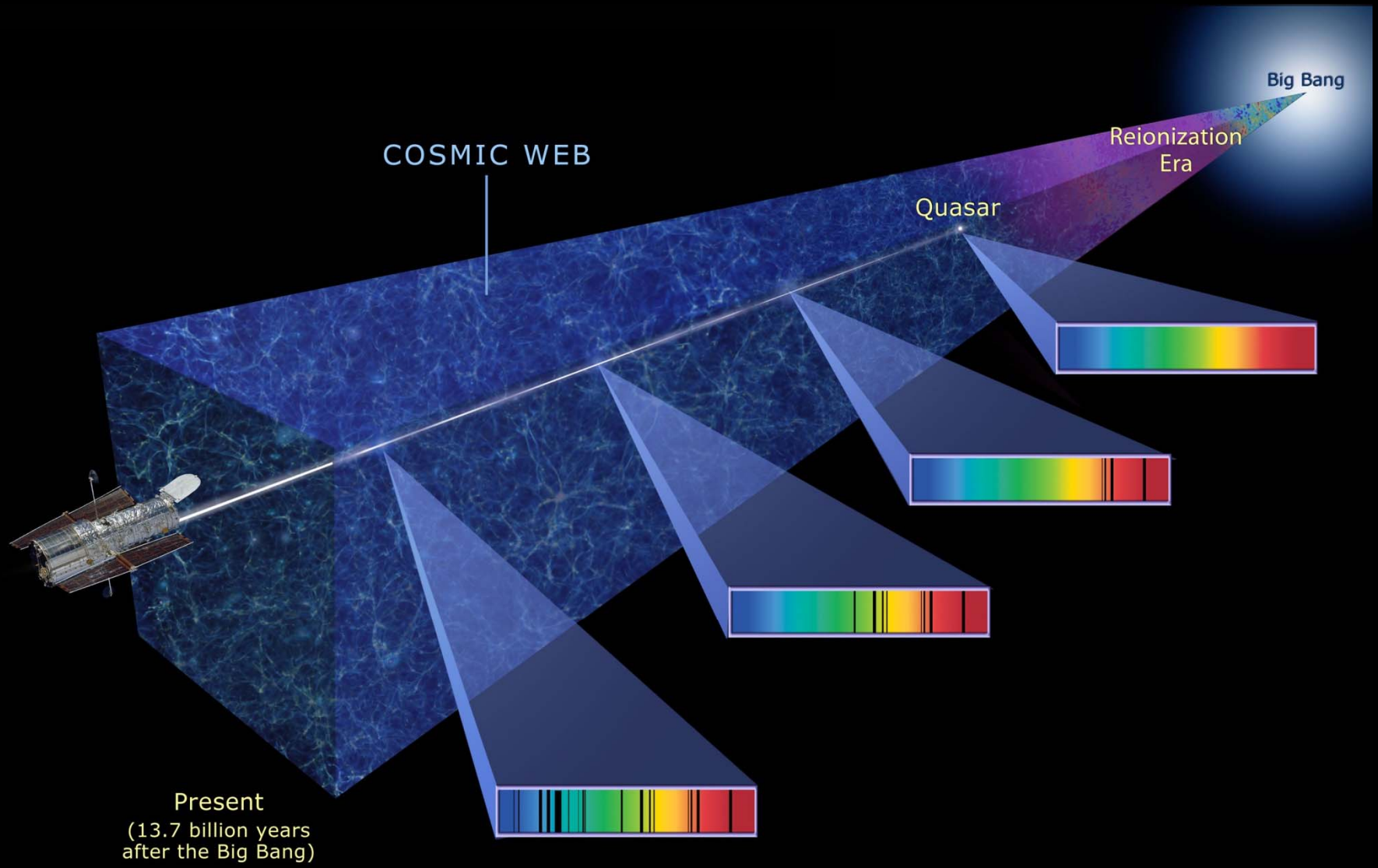
Gas


Illustris Simulation:
Cosmic Web
Dark Matter - Gas - Galaxies

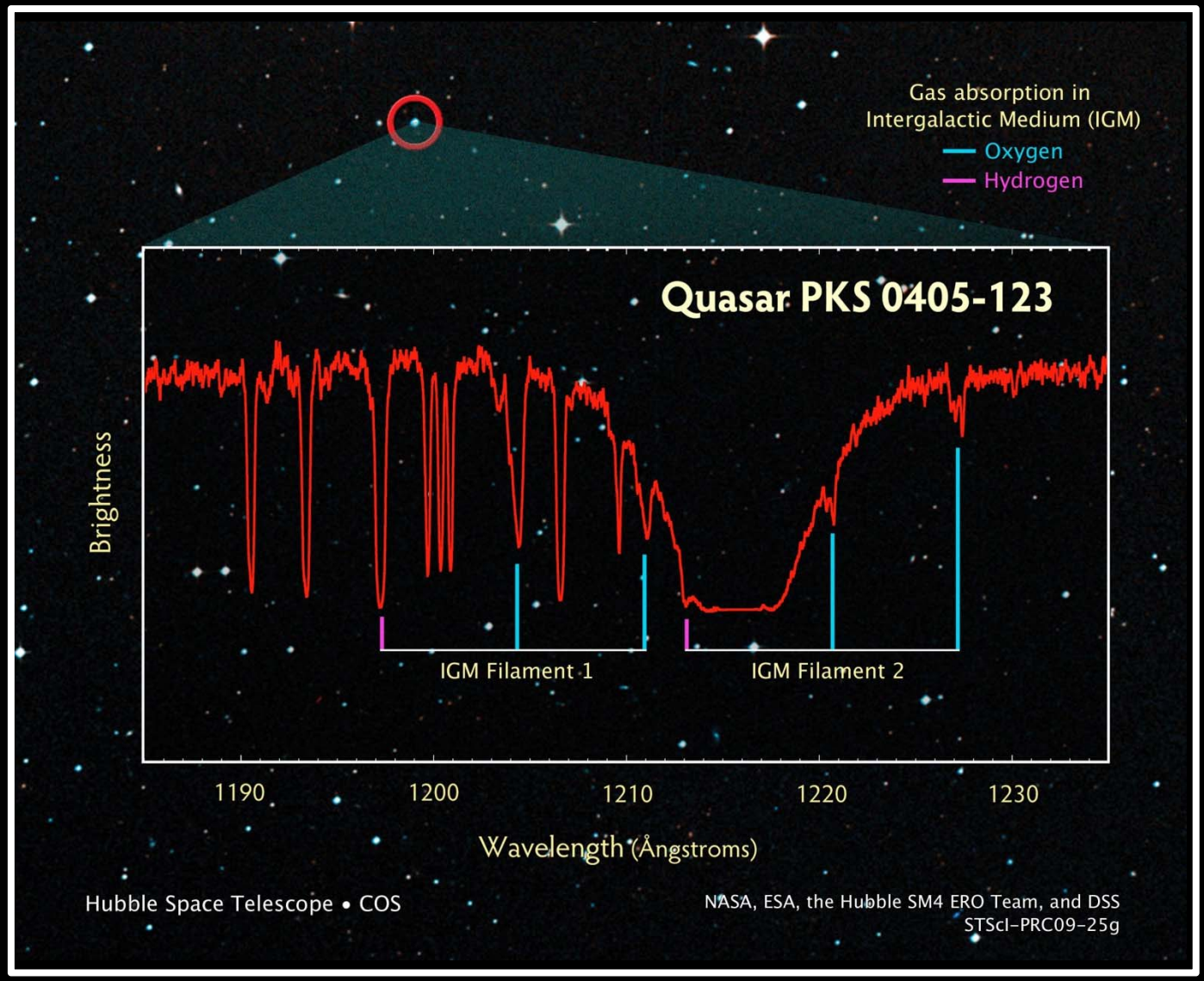
the Gaseous Cosmic Web



the Gaseous Cosmic Web



the Gaseous Cosmic Web

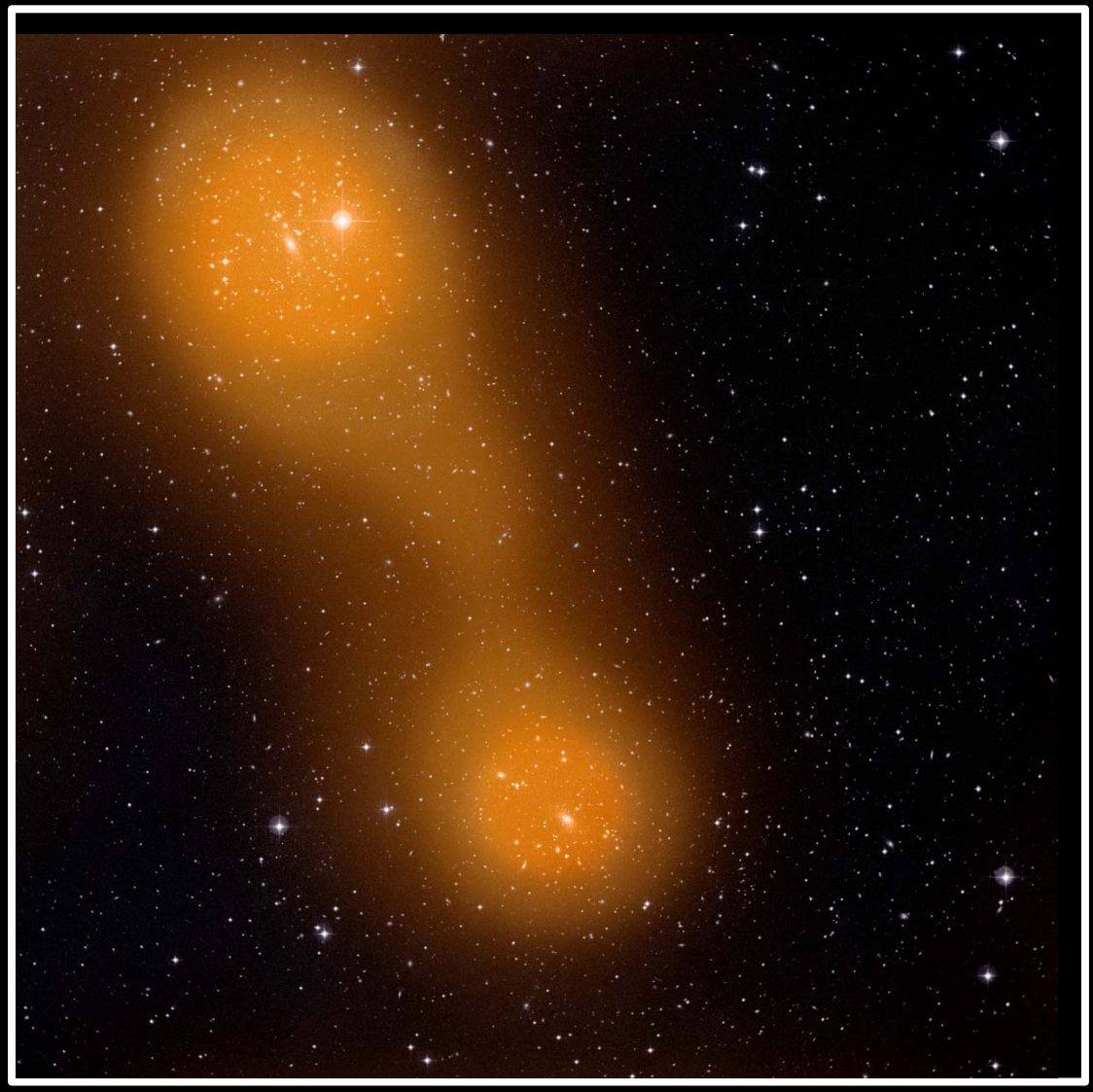


the Gaseous Cosmic Web

SZ detection of

Inter-cluster bridge/filament

in between clusters
A401 and A399



ESA/Planck collaboration