In memory of our great friend Sergei Shandarin who pioneered and drove so much of the work cosmologists are doing today.

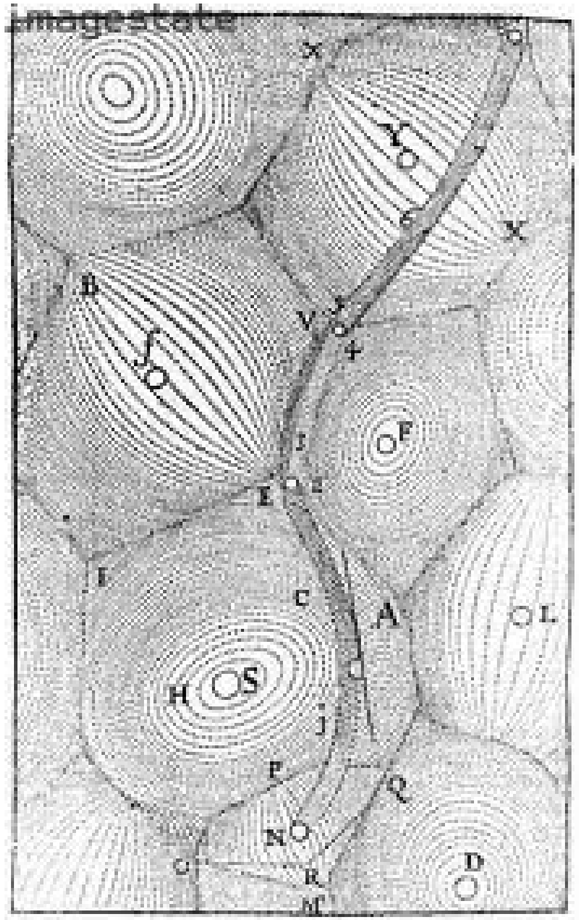
Discovering the Cosmic Web

Bernard Jones
Kapteyn Astronomical Institute
Groningen, The Netherlands

Descartes universe of swirling vortices

Principia Philosophiae, 1644.

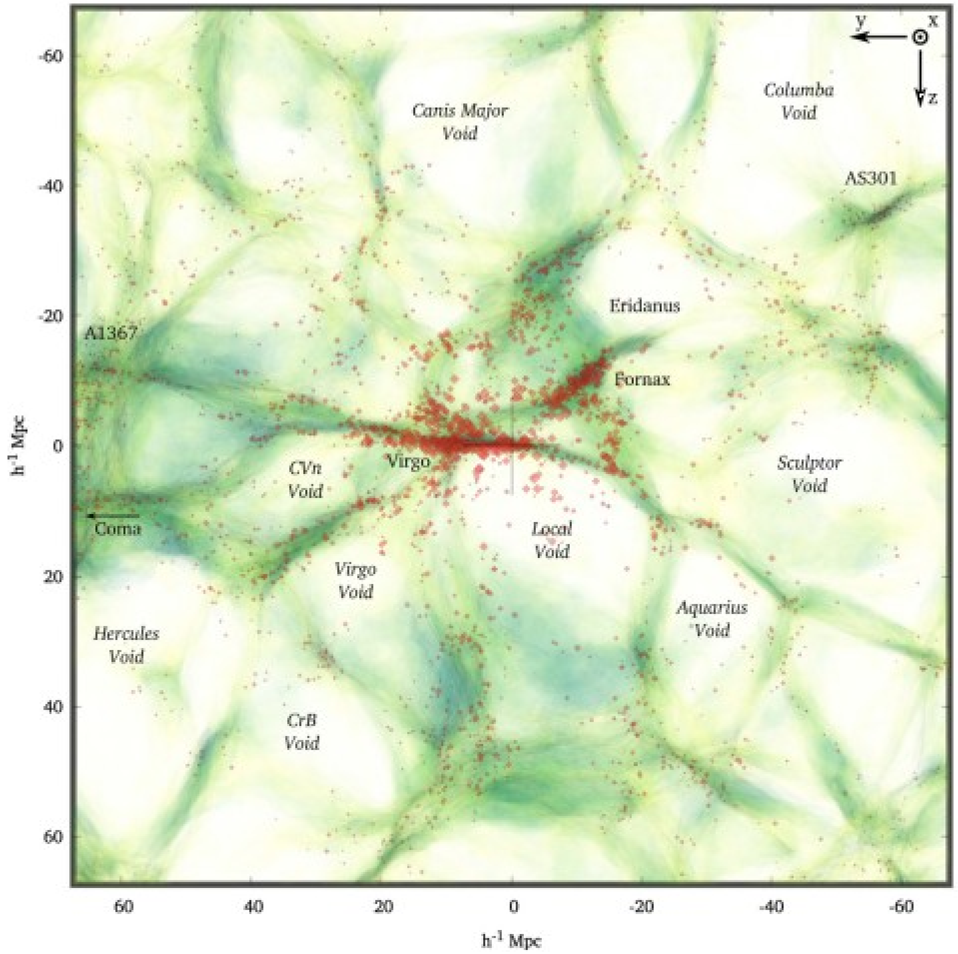
A mechanical explanation of planetary motion.

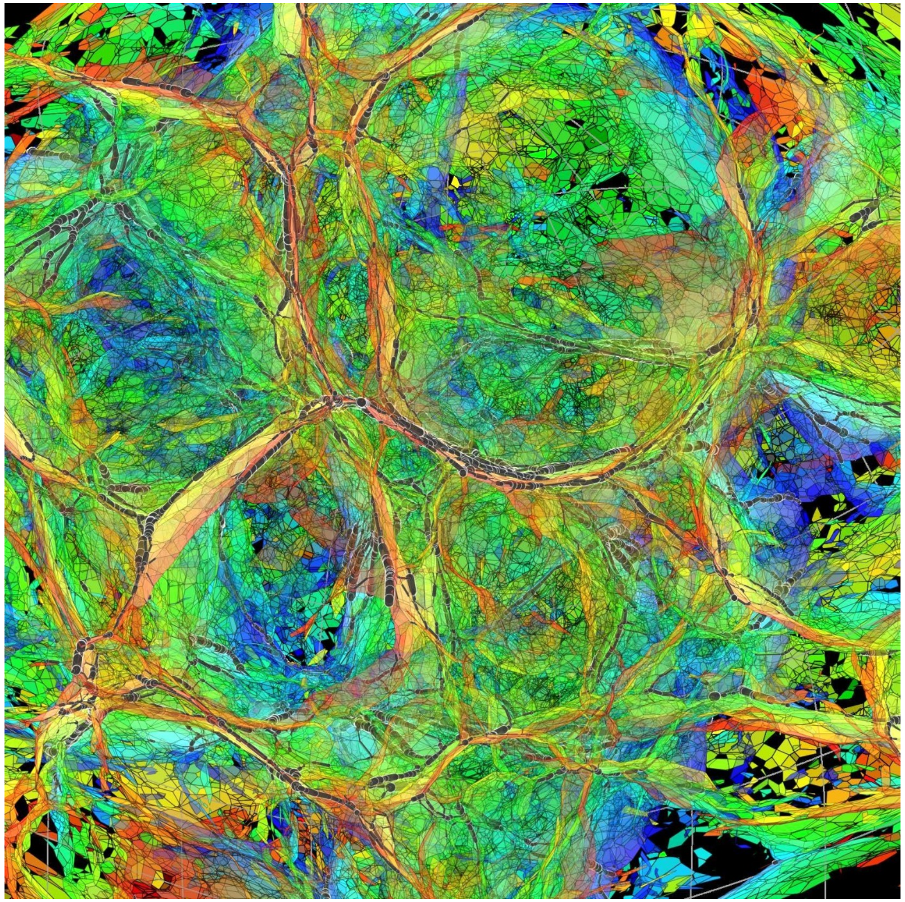


- There was no model for this with which to calculate planet orbits, so this is nothing more than his imagination of something untestable.

Two modern views of our universe on large scales

There are no vortices.

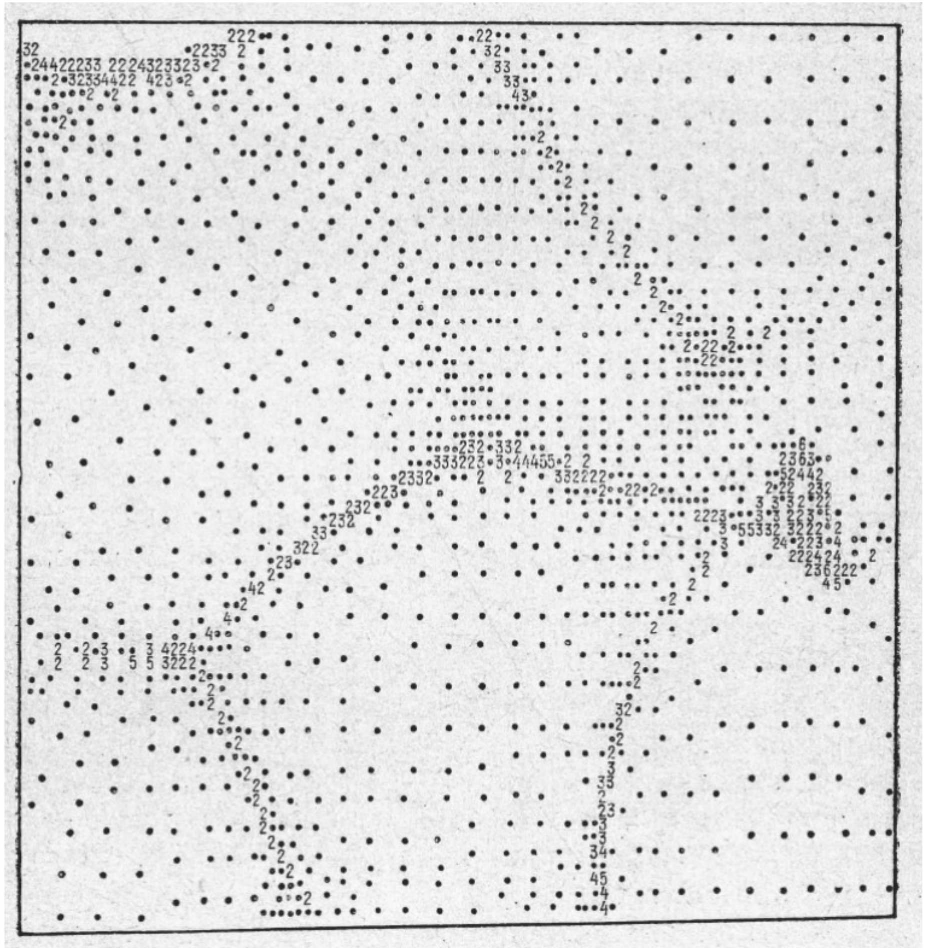




Both of these representation are from survey data (courtesy of Johan Hidding).

The “Pancake Theory” for structure formation

- 1970 Zel’dovich proposes nonlinear approximation to cosmological structure formation.
- 1973 Doroshkevich and Shandarin develop this and present, in the Russian journal *Astrofyzika,* a two dimensional numerical simulation. The paper is not available in English.
- This looks radically different from the “Western” gravitational instability point of view. Work on this in Russia develops rapidly towards the 1980’s
- **Late 1970’s: I go to Moscow to meet Sergei and his colleagues – Exciting times.**



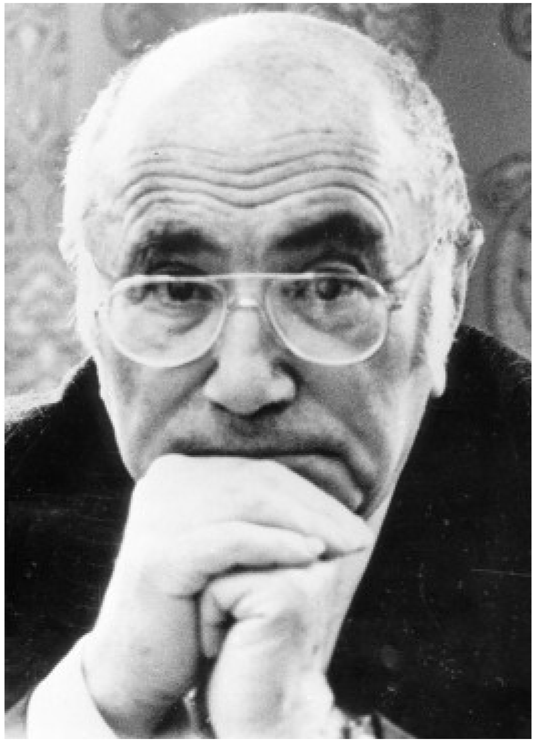
This printout is done on a line-printer. There are several different versions of thisimage, none of them published.

My first meeting Zeldovich in his office in the Landau Institute, and new friends.

Shandarin

Saar

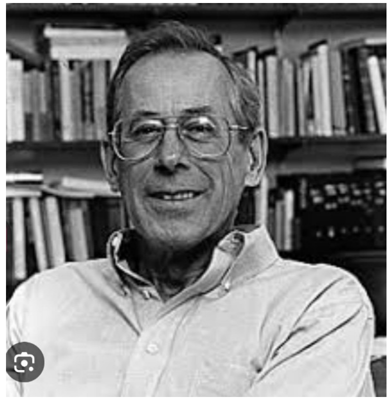
Einasto



Zel'dovich

- Others joined when we went off to Zel'dovich's apartment to discuss "science"

Peebles - the Great Paper of 1965



VOLUME 142 NOVEMBER 15, 1965 NUMBER 4

THE BLACK-BODY RADIATION CONTENT OF THE UNIVERSE AND THE FORMATION OF GALAXIES*

P. J. E. PEEBLES
Palmer Physical Laboratory, Princeton University, Princeton, N J.
Received March 8, 1965; revised June 1, 1965

ABSTRACT

A critical factor in the formation of galaxies may be the presence of a black-body radiation content of the Universe. An important property of this radiation is that it would serve to prevent the formation of gravitationally bound systems, whether galaxies or stars, until the Universe has expanded to a critical epoch. There is good reason to expect the presence of black-body radiation in an evolutionary cosmology, and it may be possible to observe such radiation directly.

Two important ideas emerged:
A mildly inhomogeneous Universe went from being totally ionised to neutral ~400,000 years ago. This was like a phase transition.

The central parameter defining what happened was the **power spectrum** of the inhomogeneities.

The quest was to determine that.

The development of this gravitational instability depends on the power spectrum of the density fluctuations at the time t_c of formation of the gas clouds. With a flat power spectrum, the total power (i.e., contribution to the variance of $\bar{\rho}$) in wavelengths greater than λ goes as λ^{-3}. However, we can find no reason to expect a characteristic random (flat) spectrum, so for the purpose of a brief discussion of the formation of bound clusters of gas clouds, we shall characterize the power spectrum d_k^2 at time t_c as

$$d_k^2 \propto \lambda^n , \qquad (20)$$

where the index n would vanish for a flat spectrum, and for boundedness $n < 3$. This is the power spectrum per increment of wavenumber k.

In the cosmological models in Table 1 the clusters of gas clouds are forming at a time when the mass density in radiation approximately may be neglected. With this assumption, we consider first a cosmologically flat Universe, such that the acceleration parameter, $q = 4\pi G\rho/(3H^2)$ is equal to $\frac{1}{2}$.

Let A be a spherical region which is expanding with the general expansion of the Universe and such that, within the volume of A, there would be a mass M of matter on the average. Then the actual mass within A at time t_c is uncertain, by the amount

$$(\delta M/M)_c \sim (M/M_c)^{-0.5+n/6} . \qquad (21)$$

The functional form of expression (21) is obtained using expression (20) by integrating the density perturbation over A and averaging the square of this integral, with the assumption of random phases of the d_k. The normalization is obtained by noting that when $M \sim M_c$, $\delta M \sim M_c$.

- First draft of this was submitted before the CMB discovery was announced

The Power Spectrum and the Correlation Function

- Peebles' realisation was that in the new cosmology we needed to be able to describe the universe that we see. For that we need **data** to guide our thoughts and **models** that purportedly describe that.
- **Science goes nowhere without well sampled data and models to describe it.** In cosmology we see a universe of galaxies and so we need great samples, which means catalogues that are complete and calibrated. Then we need inhomogeneous cosmological models, either theoretical or simulated (or both) against which to test our understanding of the data.
- Peebles led the charge.

Two-point correlation function

Everyone calculated it, but it didn't tell us very much aexcept that clustering is self-similar. Gravity is a power law – so what?

The 2-point correlation function at a distance r, ξ(r), measures the excess number of pairs of separation r over and above what would have been expected, in a random distribution of the same mean density.

There are several estimators for this, for example the simple

$$1 + \xi(r) = \frac{n_{GG}(r)}{n_{GR}(r)} \frac{N_R}{N_G},$$

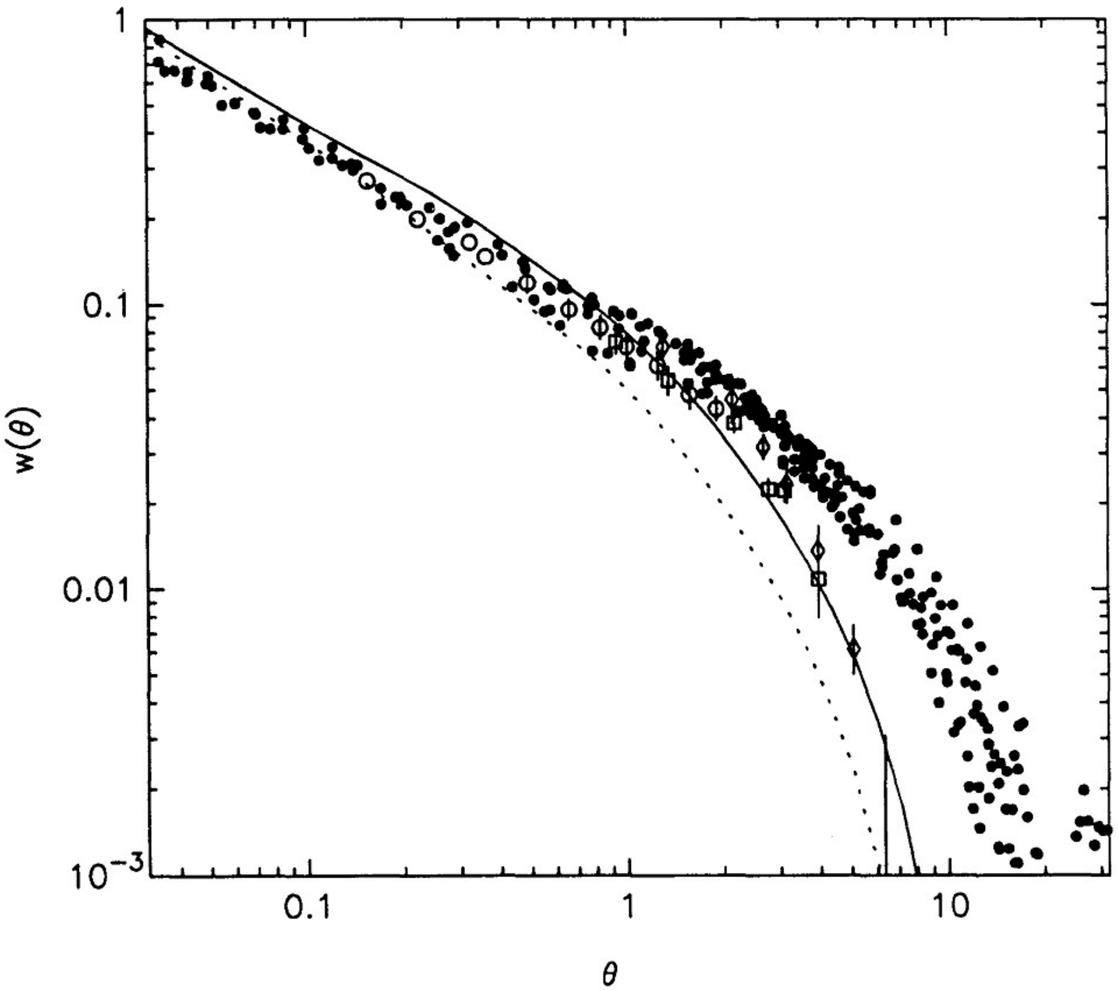
Here, N_G and N_R are the numbers of Galaxies and Randoms, N_{GG} is the numer of galaxy pairs and n_{GR} is the number of Galaxy-Random pairs.

This method is due to Marc Davis – easy to grasp. (Best is Landy and Szalay.

Perhaps the most underestimated paper

The 2-point correlation function of the APM Survey

This was the first clear statement that dark energy existed.



“The correlation function of the Cambridge APM survey”
Efstathiou,G., Sutherland, W., Maddox, S., Nature, Volume 348, Issue 6303, pp. 705-707 (1990).

Correlation functions (1990) told us that $\Lambda \neq 0$

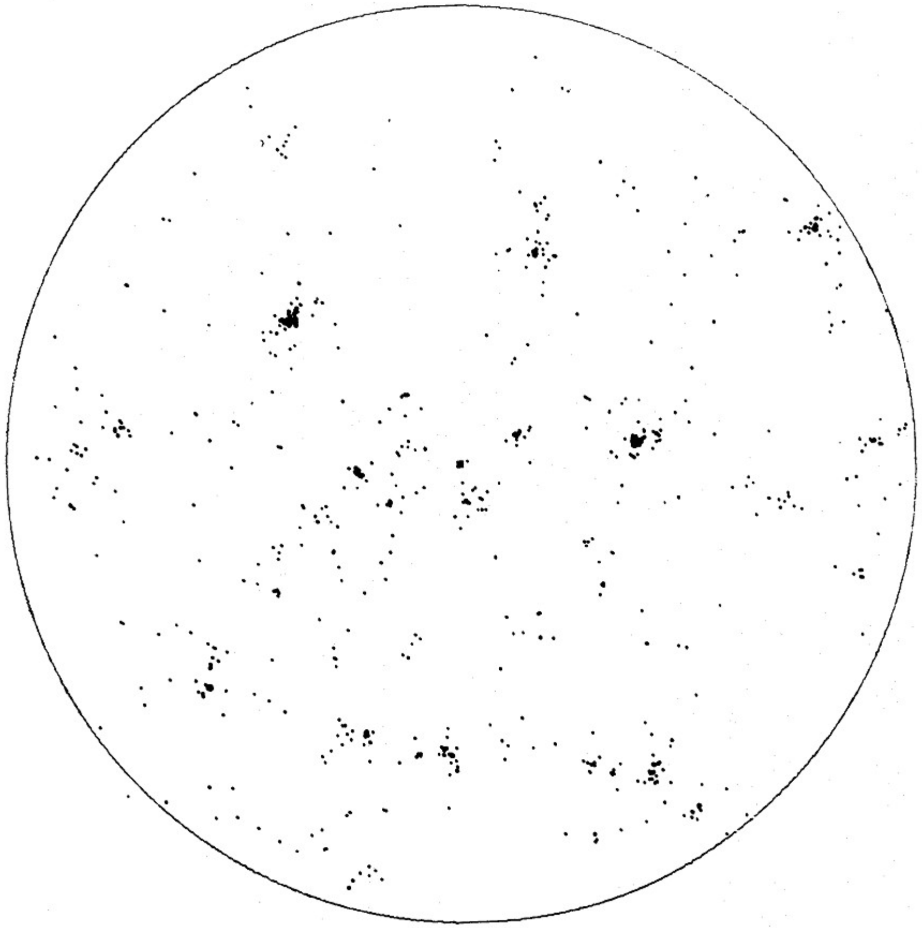
The key conclusion from that figure is that there is far too much structure on large scales for the standard model of the time (Cold Dark Matter, CDM) However, more than a simple graph is required to convince people to give up on their standard model!
From the Abstract to the Efstathiou Sutherland and Maddox paper

"We argue here that the successes of the CDM theory can be retained and the new observations accommodated in **a spatially flat cosmology in which as much as 80% of the critical density is provided by a positive cosmological constant,** which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background."

That's quite a statement!

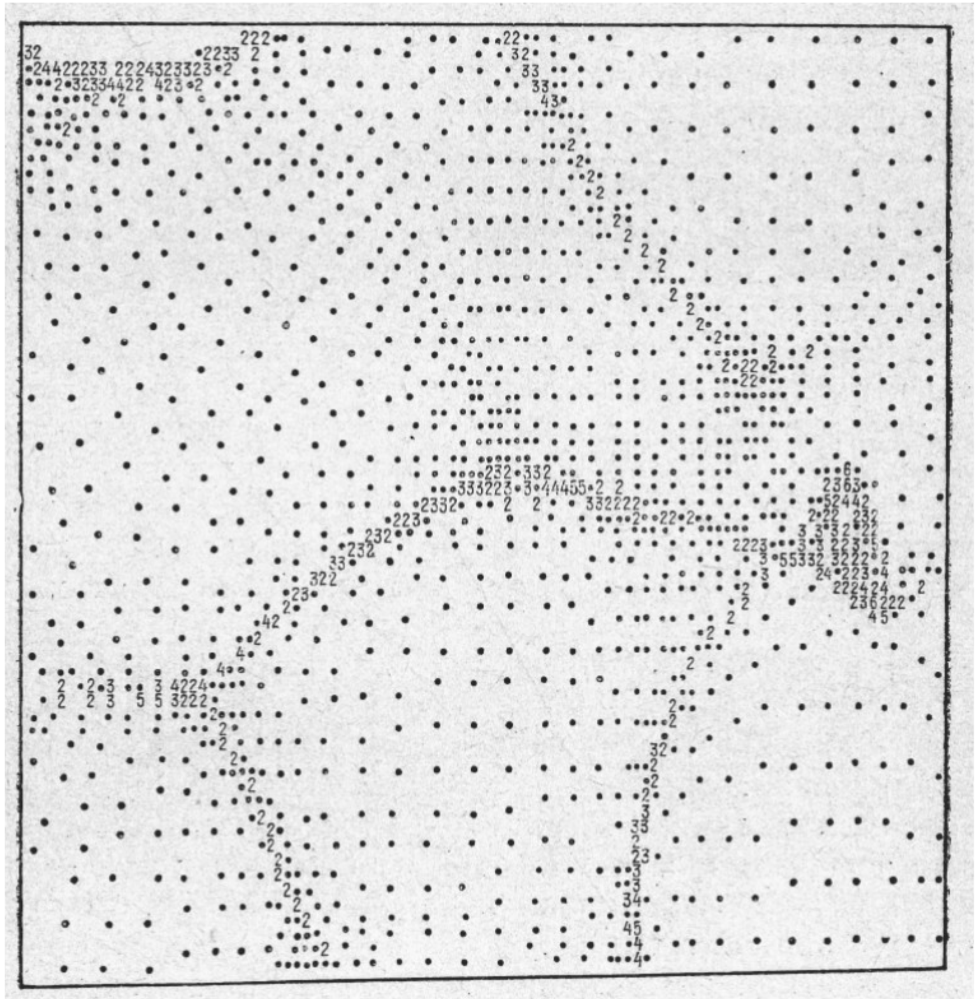
"The correlation function of the Cambridge APM survey "
Efstathiou,G., Sutherland, W., Maddox, S., Nature, Volume 348, Issue 6303, pp. 705-707 (1990).

Structure Formation - Bottom-Up versus Top-Down
This became the great schism of structure formation



- **Bottom up**

Gravitational instability



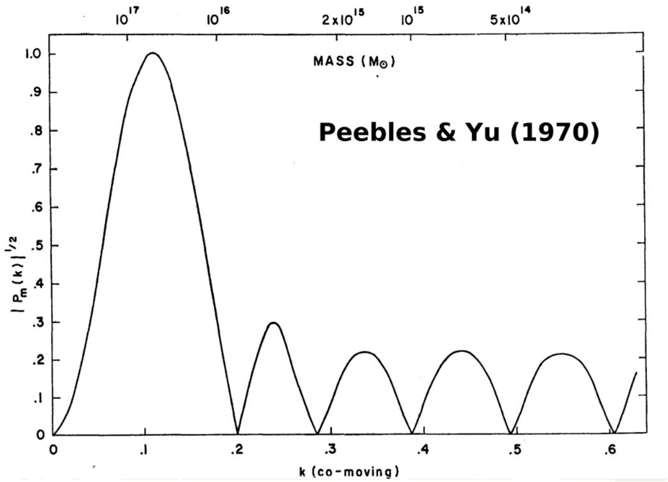
- **Top down**

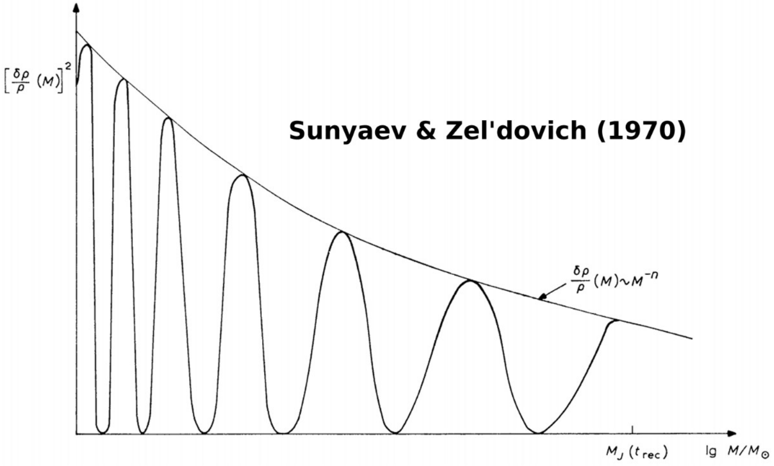
Zeldovich “pancake theory”

East meets West – post Cold War

Rashid Sunyaev

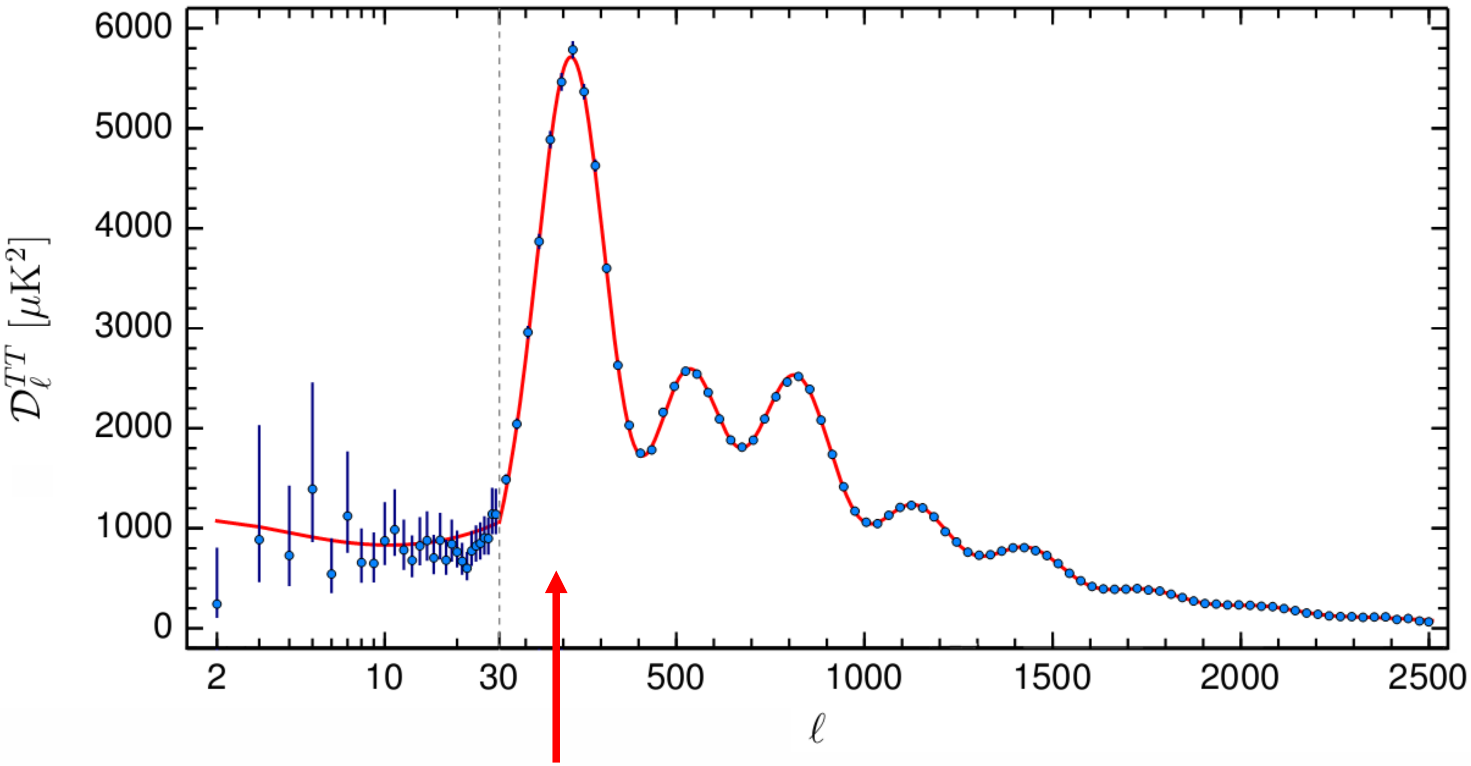
Jim Peebles





- In 1970, both independently computed the Baryon Acoustic Oscillations

What Boomerang, WMAP and Planck first revealed
The spectrum of the CosmicMicrowave Background



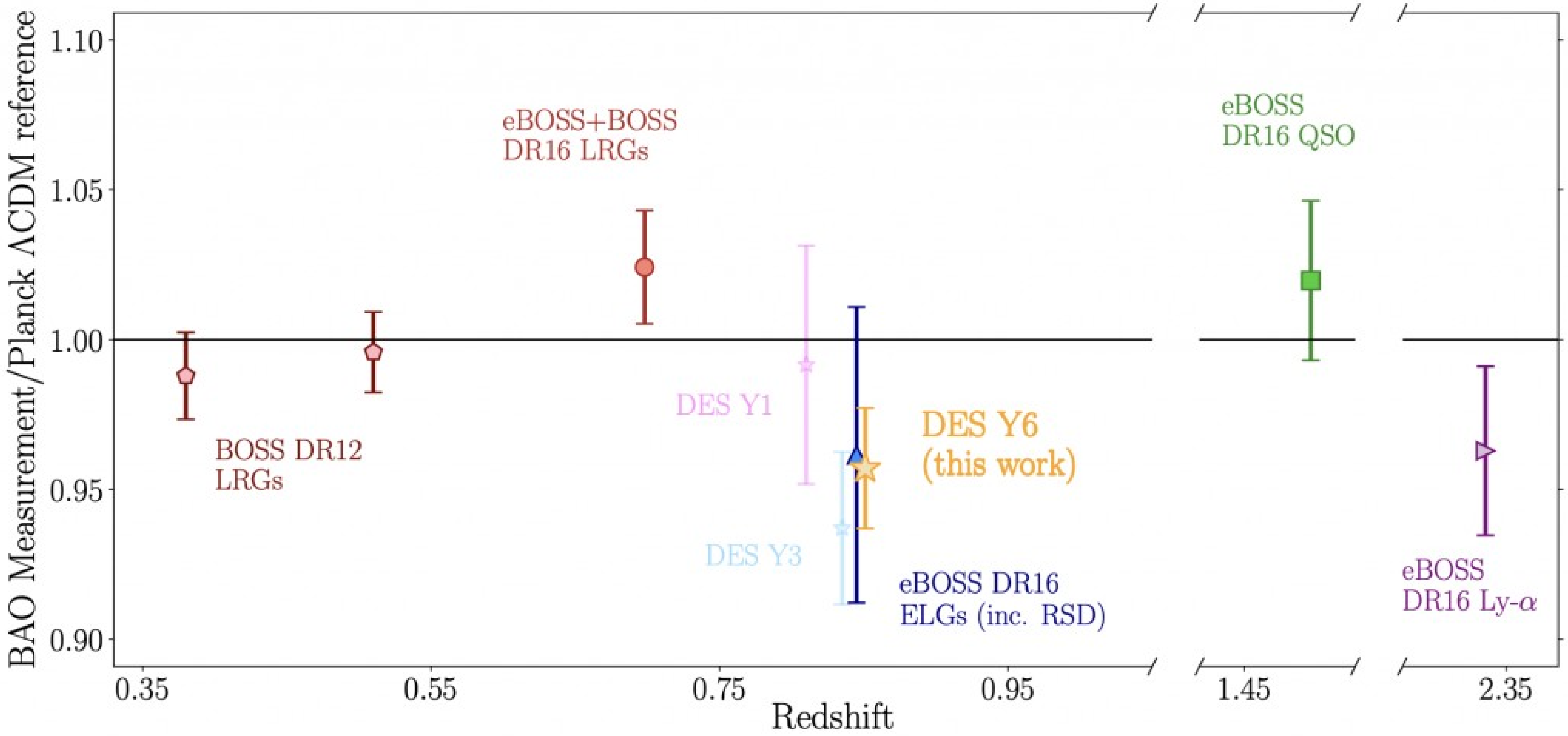
Baryonic Acoustic Oscillation (BAO) – the "**Sound Horizon**"

Scale at z=0: 147.49 h^{-1} Mpc

Scale at z=0.166 = 100.28 h^{-1} Mpc from SDSS

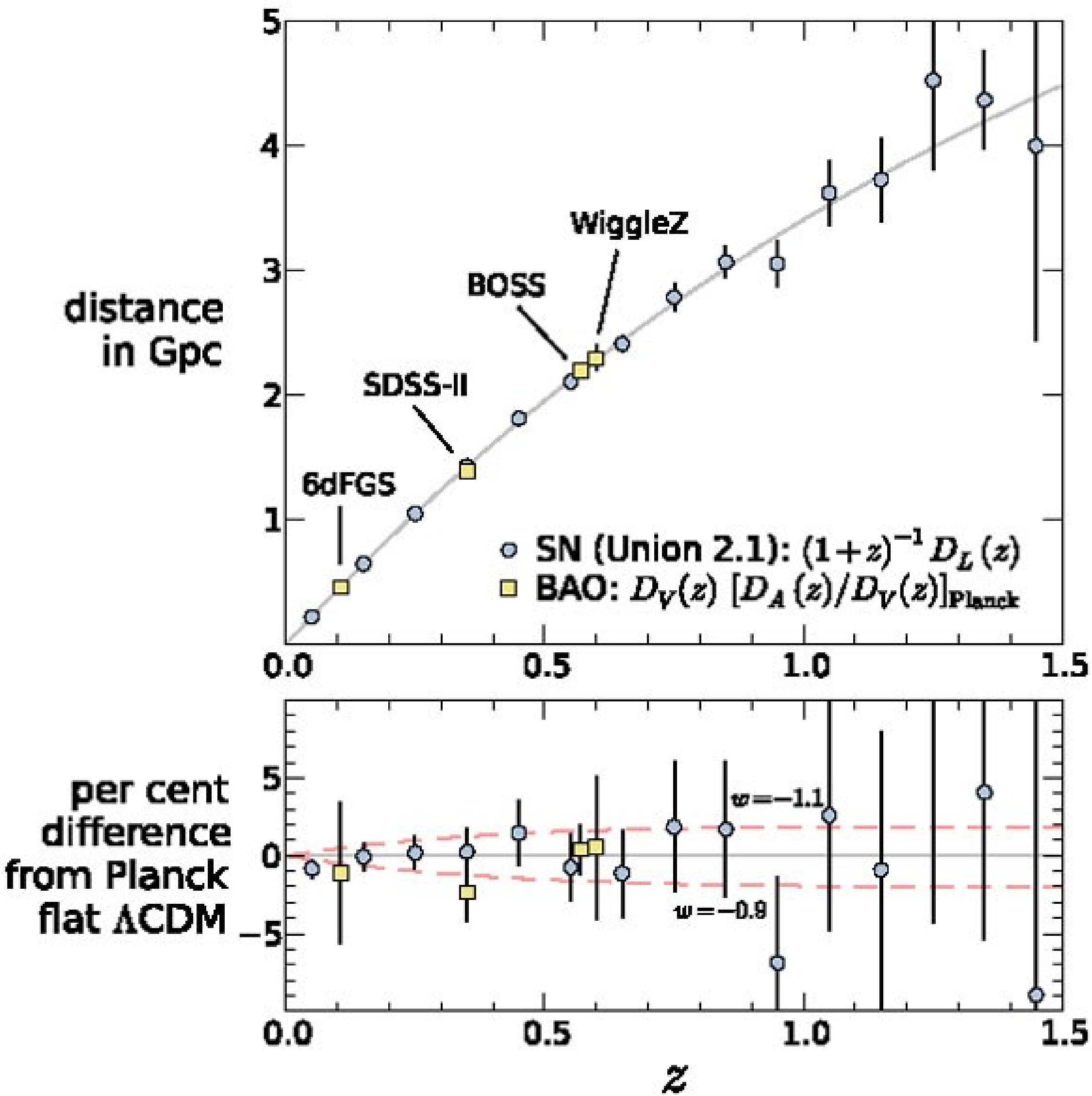
The BAO scale is a **standard ruler** and one of the most accurately in cosmology

BAOs for Cosmology: summary of experiments. Values relative to final Planck value SDSS and DESI



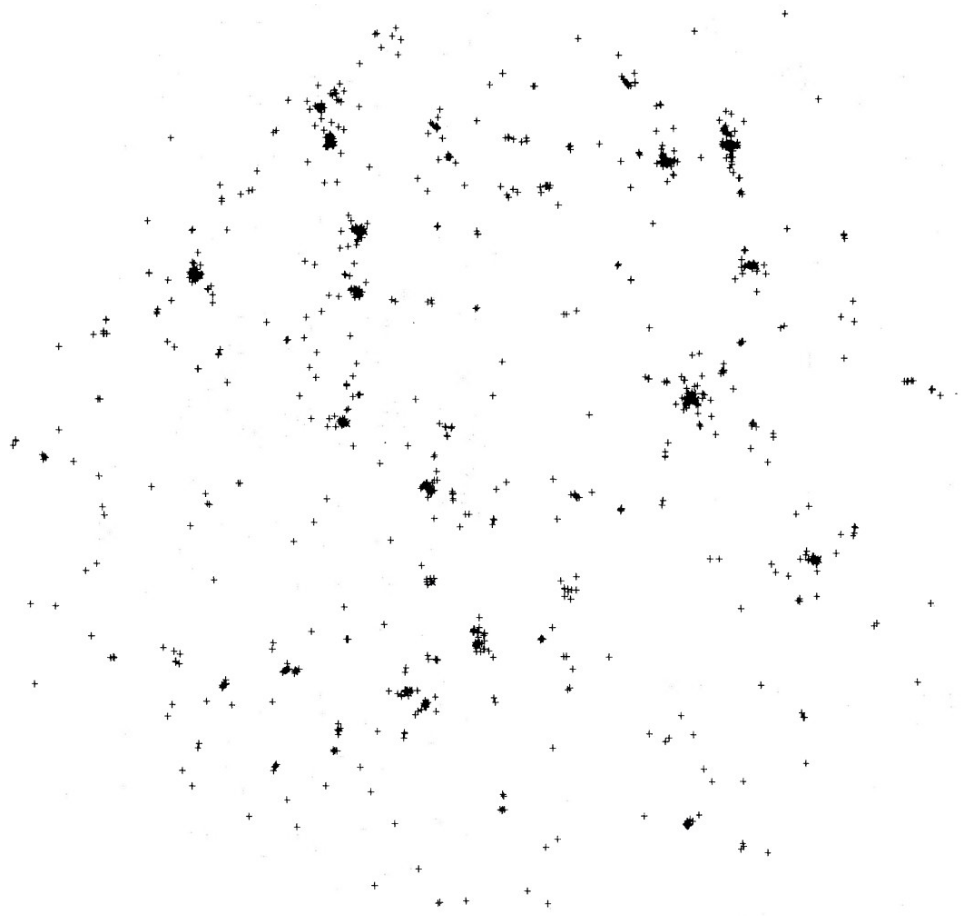
- If these differ significantly from Planck value, cosmology has a problem

BAOs check Hubble “constant” variation



Gravitational Instability – Peebles' vision

- 1965: Peebles presents a paper on the physics of galaxy formation in the context of the Hot Big Bang theory and submits it prior to the paper by Dicke, Peebles, Roll and Wilkinson announcing their discovery of the CMB radiation.
- But they are "scooped" by Penzias and Wilson.
- 1965 – 1975 Peebles continues his quest to nail the physics of the hot big bang and galaxy formation.
- 1971: Peebles publishes *"Physical Cosmology*": sets in motion a new style for cosmology. GR and Einstein take second place to physical processes.

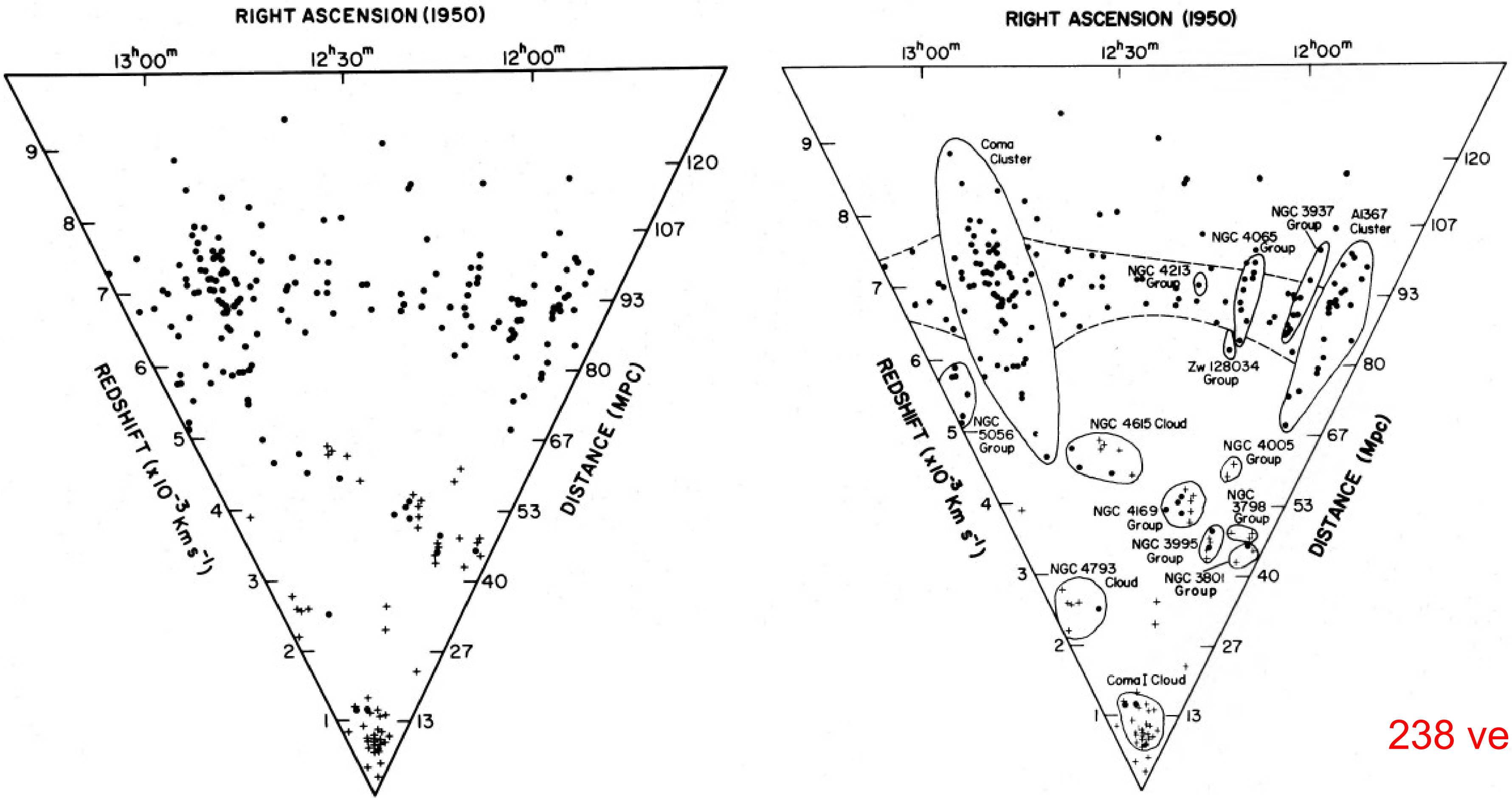


No obvious filaments
1000 body 3d siimulation verifying Peebles' tidal torque thoery for origin of galaxy spin. (Efstathiou and Jones, MN1979)

So when was this schism resolved by data?

Gregory & Thompson 1978 wedge diagram

Coma- A1367 supercluster

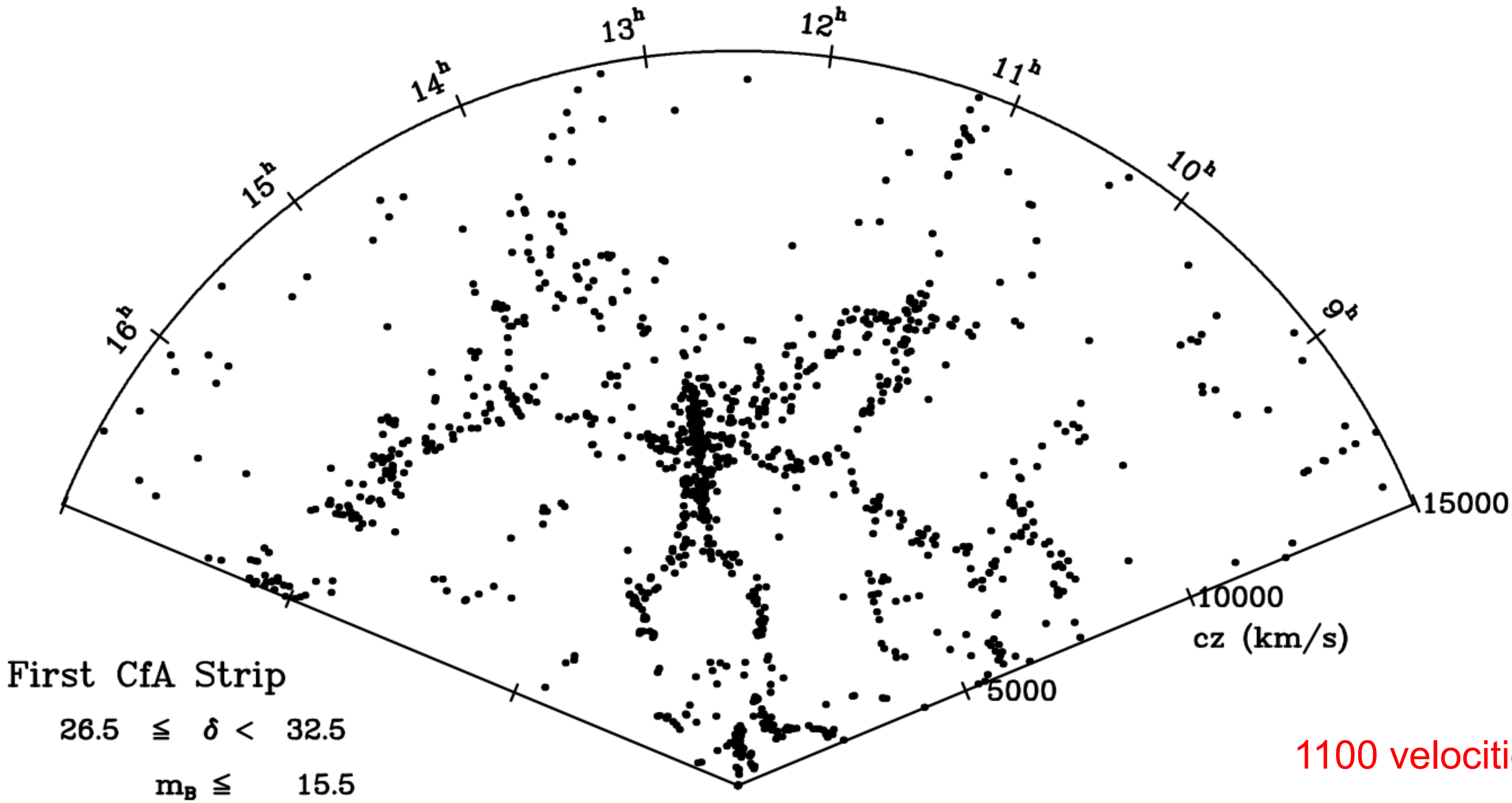


238 velocities

- S.A. Gregory & L.A. Thompson Astrohys. J. 1978, **222**, 784
  The Coma/A1367 supercluster and its environs.

Filaments,clusters and voids

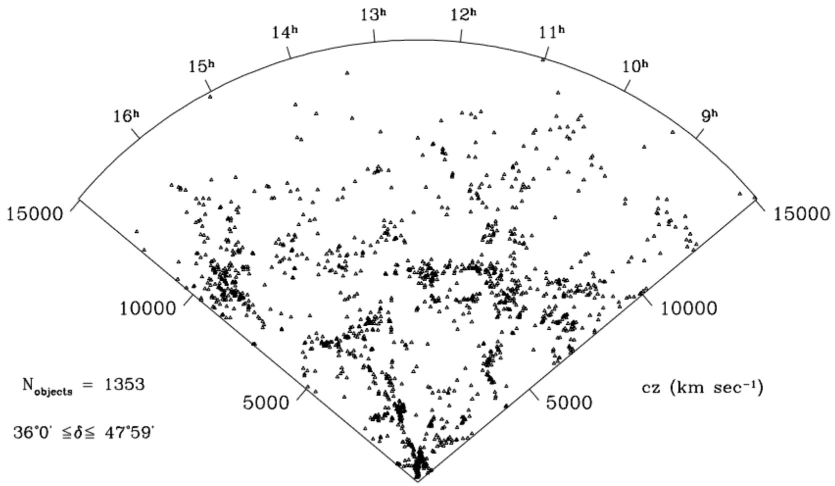
The de Lapparent Slice of the CfA Catalogue (ApJ.1986, 302,L1-L5)

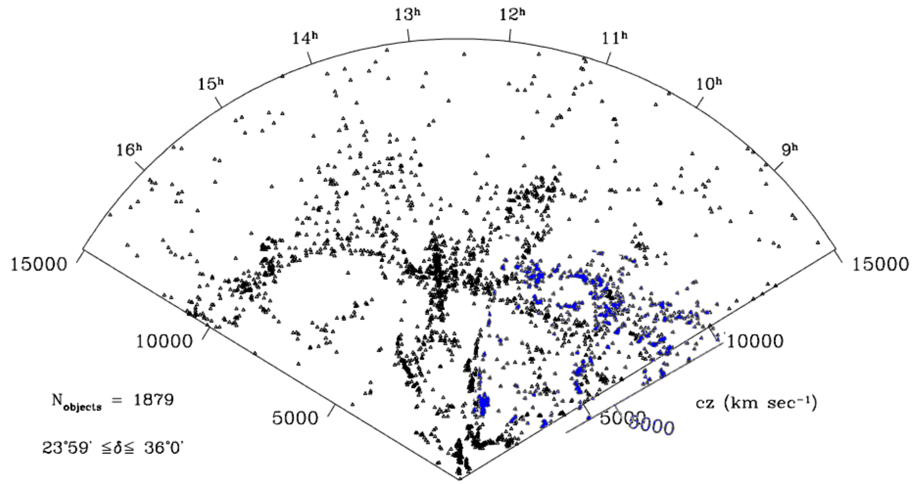


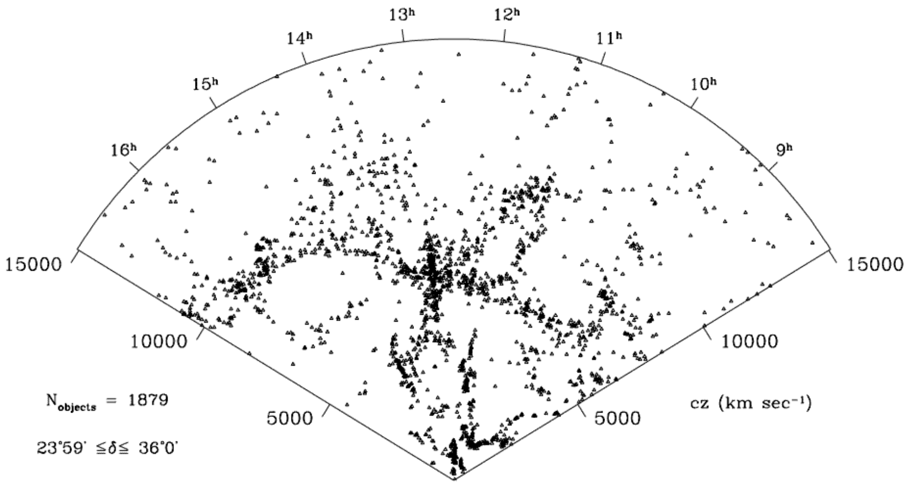
1100 velocities

- 1061 galaxies from the Zwicky Catalog of Galaxies having m<15.5
  The appearance of this map was a total surprise – it was beyond our preconceived ideas.

19000 redshifts over north Galactic Hemisphere Geller & Huchra's ZCAT







ZCAT, the final CfA Catalogue from Geller & Huchra + collaborators.
10 years of hard work by many.

Spectra of 98% of the Updated Zwicky Catalogue of Galaxies with m<15.5.
About 19000 redshifts (98% complete).

Important discoveries:
Voids and the **Great Wall**

- How do the huge voids and super-aggregates of galaxies fit in?

Beyond the CfA, CfA2, ZCAT

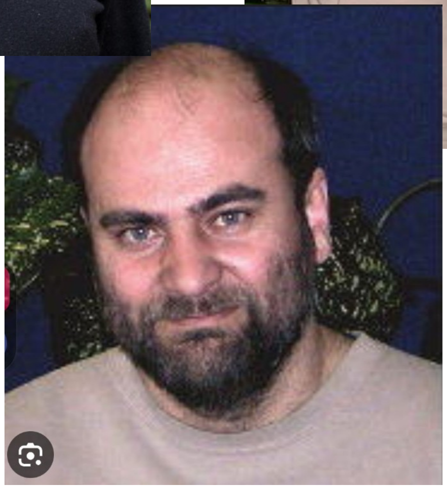
The legacy of John Huchra

- The CfA surveys had discovered the frothy nature of the local universe and the presence of giant structures (the Great Wall) that did not fall into the conventional thinking on structure origin.
- Bigger better surveys were needed – more redshifts!
- People were thinking of multi-fibre spectrographs which would surely increase the acquisition of more data: deeper and fainter galaxies.
- Sparse surveys, measuring 1 in 6 galaxies (**QDOT**) or 1 in 20 galaxies like the **Stromlo-APM survey**. These were referred to as **Diluted Surveys**.
- The last all-sky survey was the **IRAS redshift all-sky catalogue** working at a wavelength of 2 μm covering 84% of the entire sky. The redshift catalogue is referred to as the **PSCz**.
- The last great optical survey was the **Las Campanas survey** producing six parallel slices out to a redshift z=0.25 (750 h^{-1} Mpc)

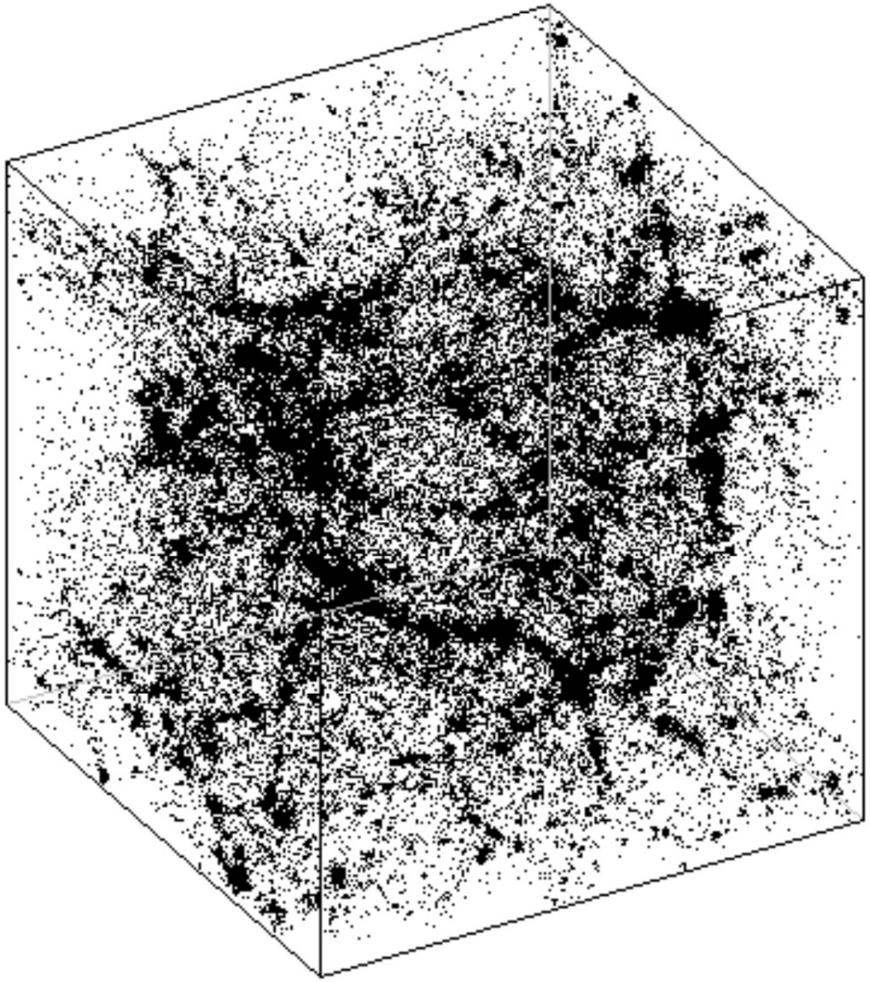
Who first referred to it as “The Cosmic Web”?

Lev Kofman

Dick Bond



Dmitry Pogosyan



Simulation from Anatoly Klypin

- How Filaments Are Woven Into The Cosmic Web Nature (1996). https://doi.org/10.1038/380603a0

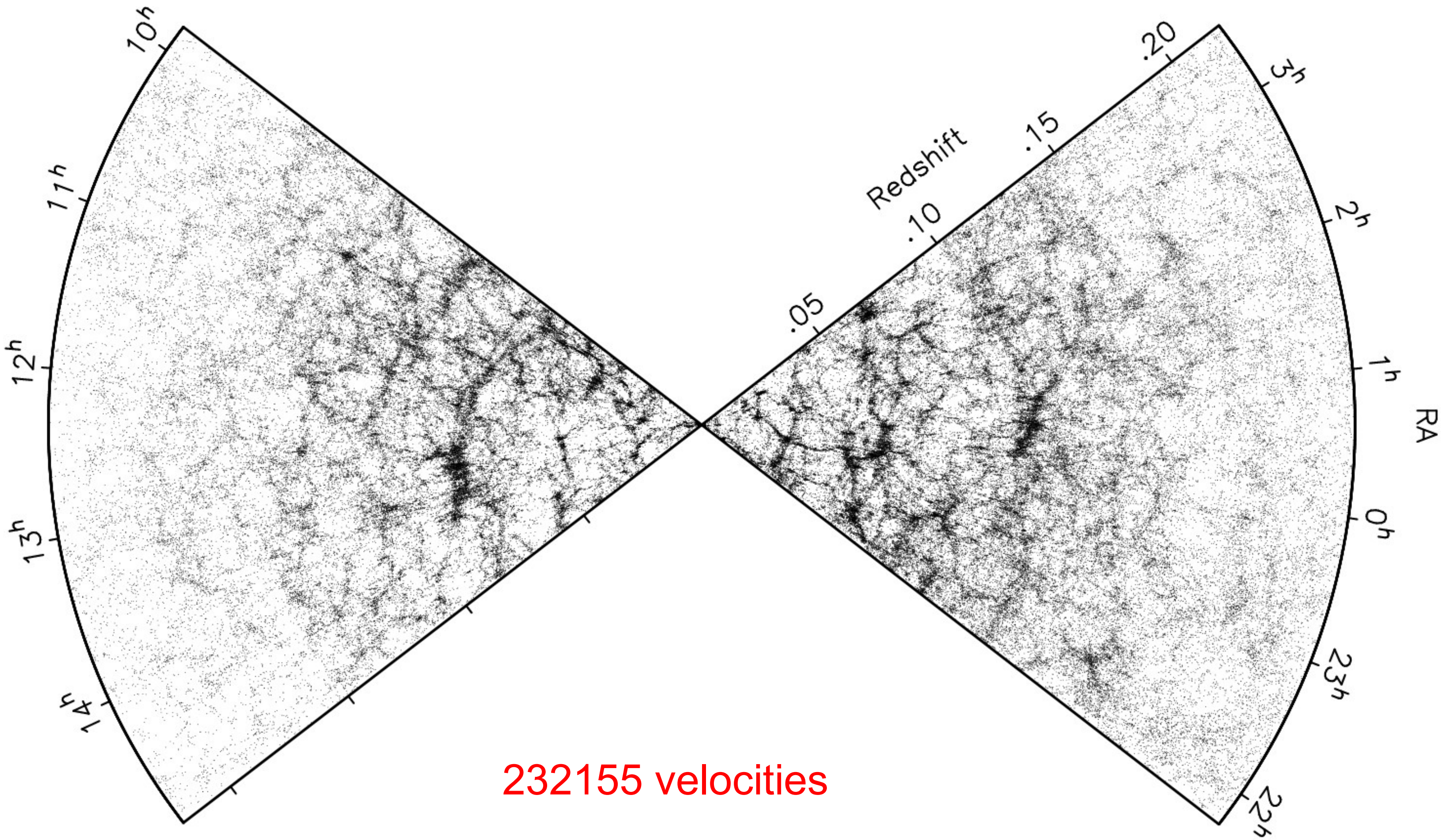
The 20th century established a basic understanding oif our universe. We now knew that $\Lambda \neq 0$ and there had been many balloon and rocket borne measurments around the peak of the CMB and making maps of small sky regions.

COBE had detected the inhomogeneity of the CMB

21st Century

We might have wondered:
Is there anything left to find?
Or are we simply refining what has already been discovered?

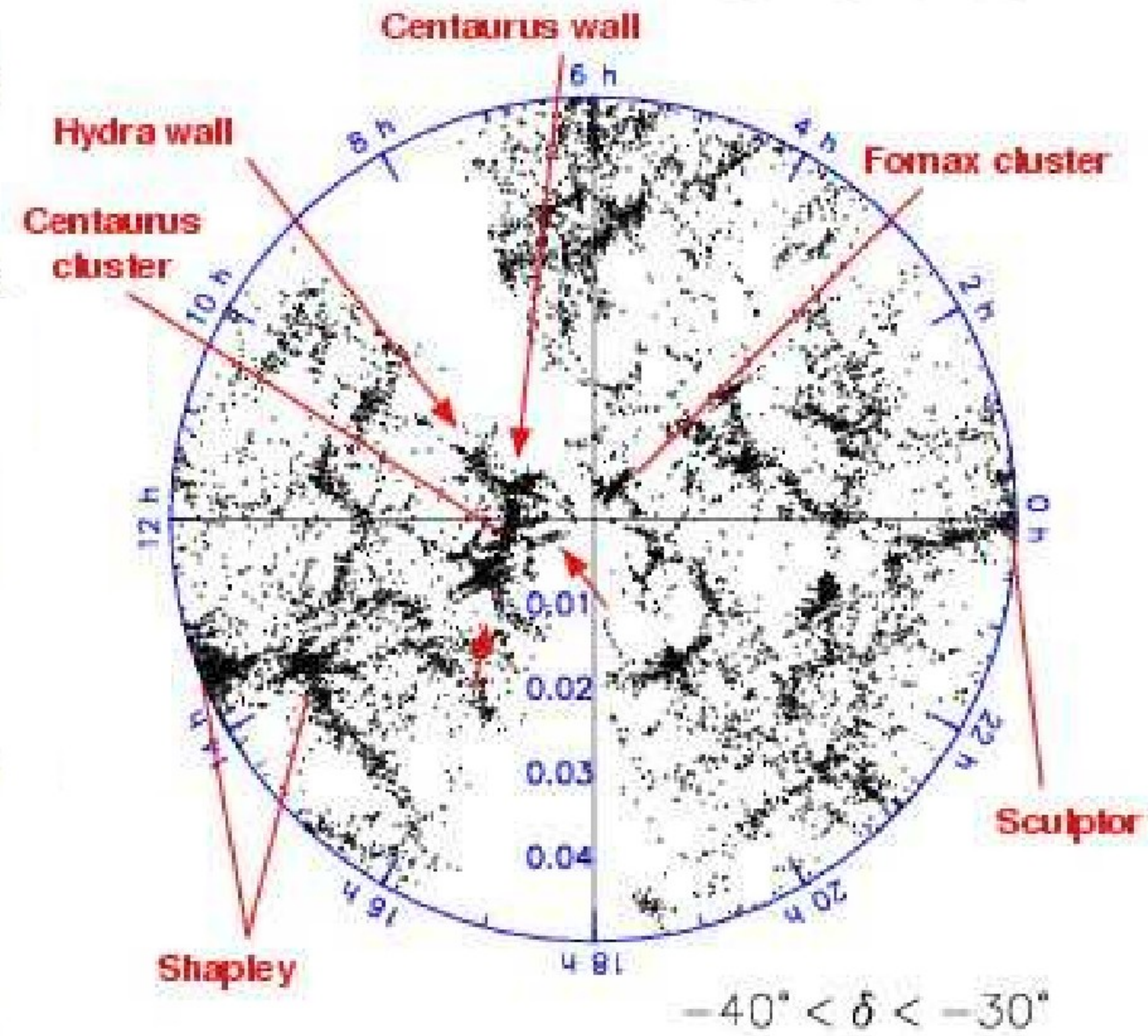
Surveys: 2dF 2001
First survey to convincingly show voids and filaments.



- Note the median redshift 0.11, beyond which voids are still seen.

Surveys: 6dF hemispheric survey, UK Schmidt.

2001-2009, 272 nights 4m AAT.

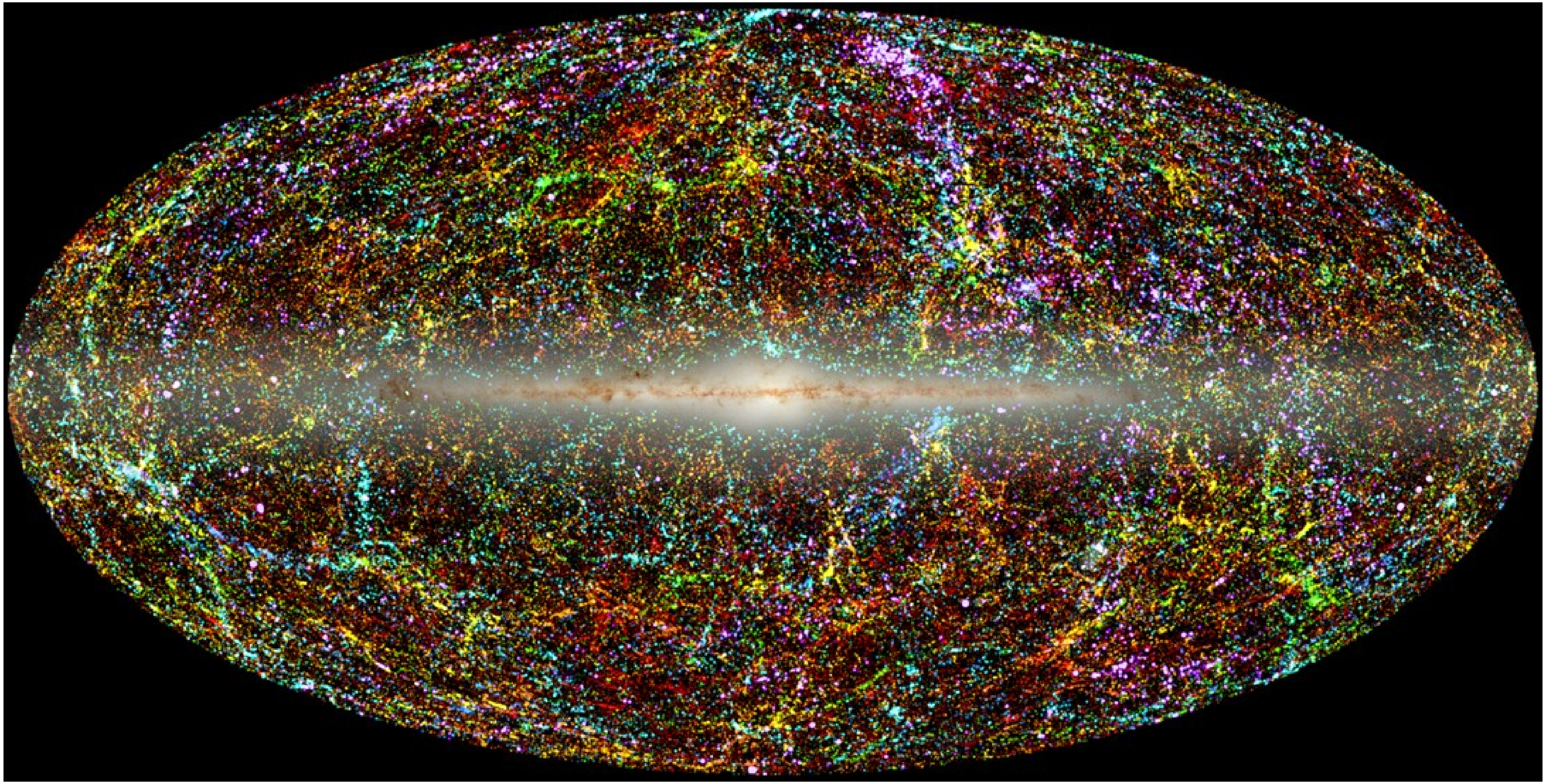


136,304 new velocities
z(median) = 0.053

- The median redshift is 0.053 reaching redshift 0.15

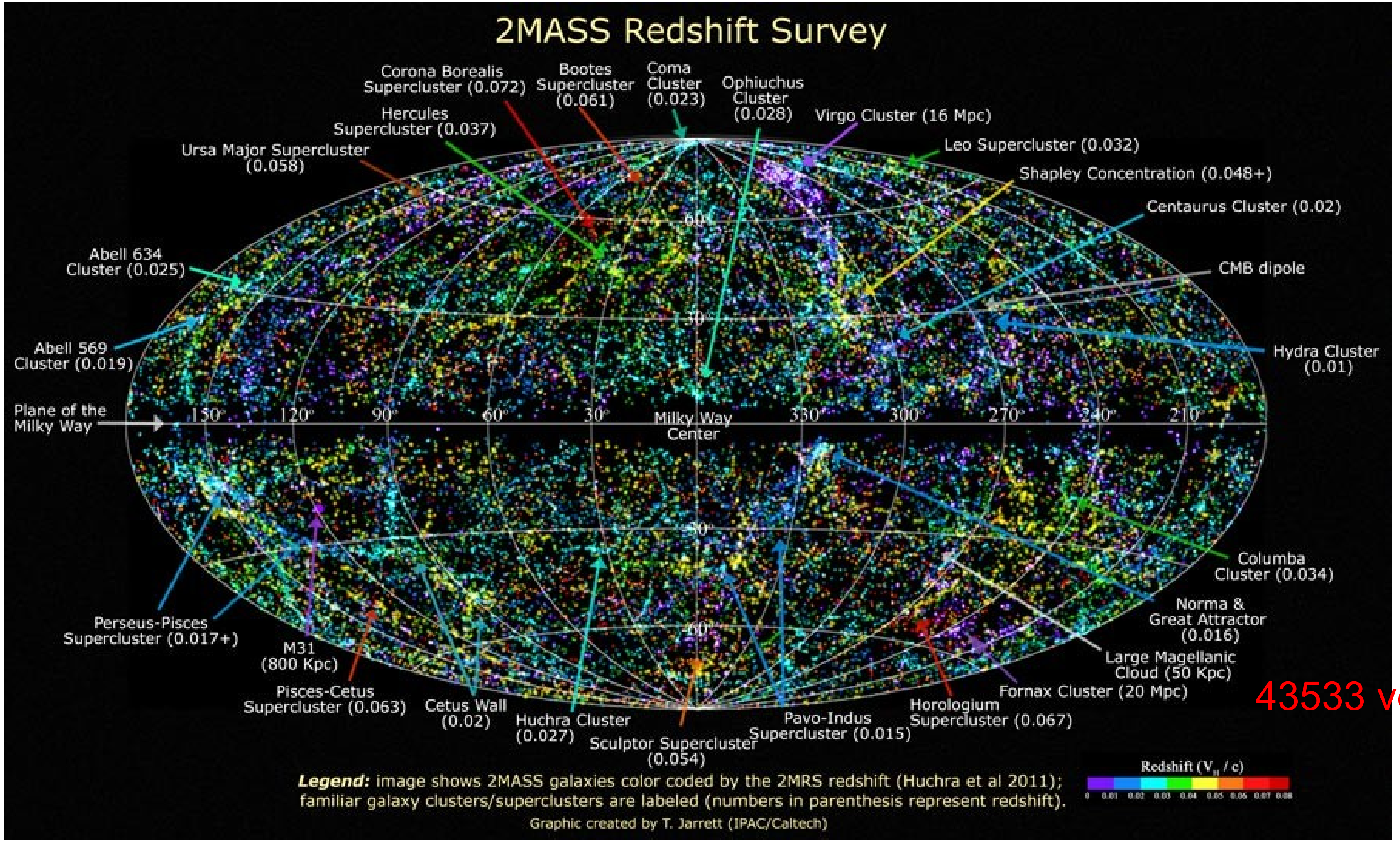
2MASS 2 micron survey of the sky (1997-2001)

Catalogued over 1 million galaxies and other stuff.



The survey took place simultaneously at two locations Mt. Hopkins and CTIO.

2MRS: 2MASS Redshift Survey (Jarrett et al 2000) Led by Huchra, ten years up to 2012.



43533 velocities

Sloan Digital Sky Survey – a series of surveys.
Currently at DR18 and other special surveys

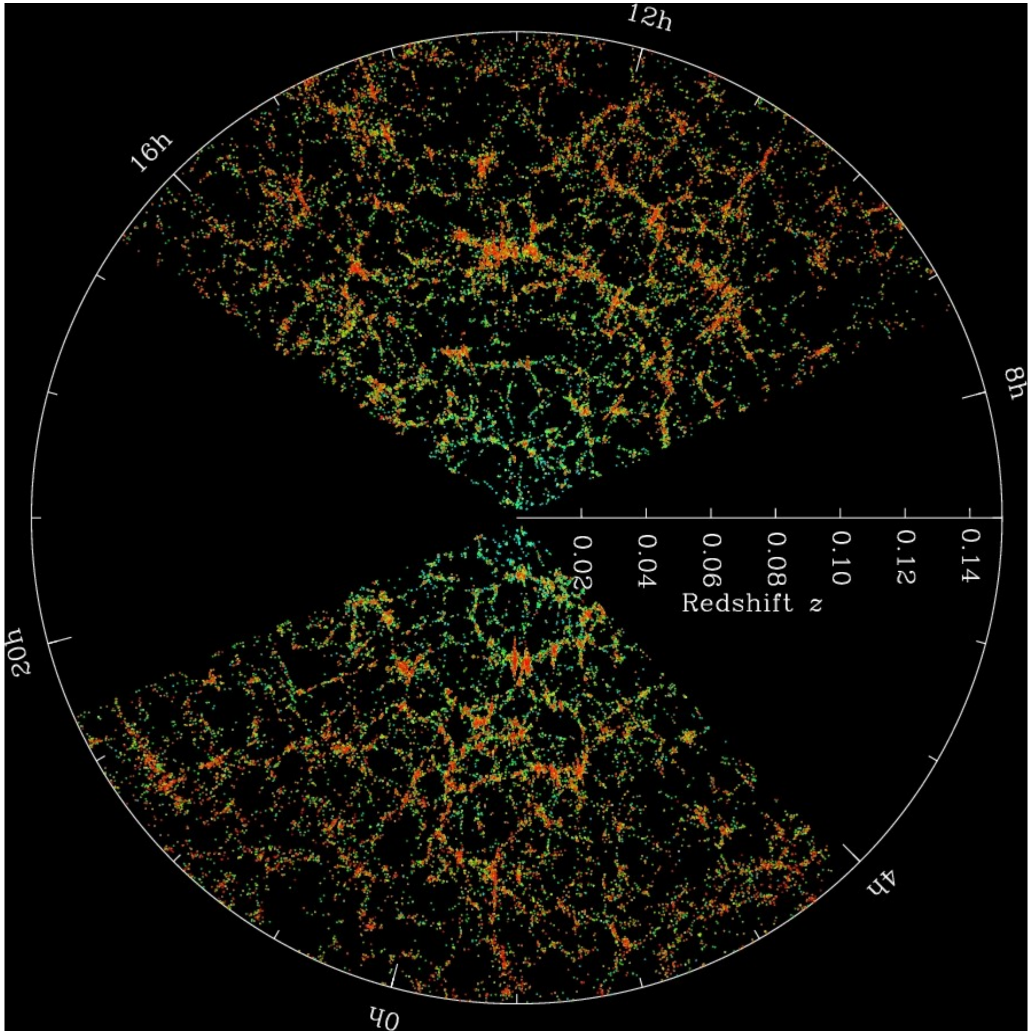
Alex Szalay
Possibly the most cited astronomer in the world.
(Must count all his publicatinos in several non-astro fields, as in his work on Chromosome 22).

Formerly Hungary's No.1 rock star with his band Pant Rei.

- SDSS started up in 1998 and is still going. Now on "Epoch V"

SDSS Telescope and Pie diagram

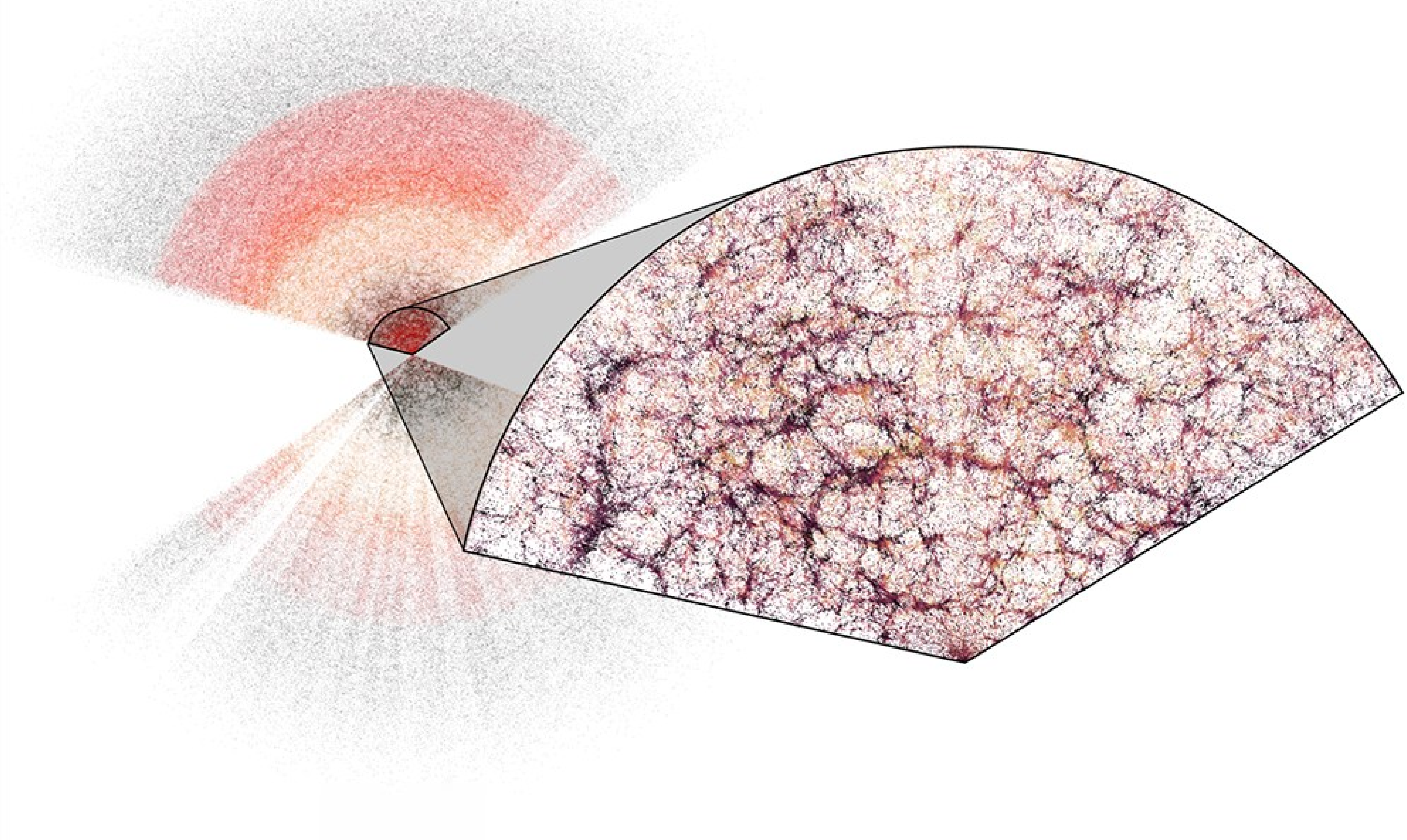
The telescope is at Apache point



- There are more detailed deeper surveys (eg. BOSS) and studies of individual objects, notably the "Galaxy Zoo" citizen science project.

DESI: Dark Energy Spectroscopic Instrument

DESI slice



6dF: baryon acoustic oscillations and the *local* Hubble constant

Florian Beutler, et al
The 6dF Galaxy Survey: baryon acoustic oscillations and the local Hubble constant
MNRAS 2011 416, 3017
From the Abstract:

We find a Hubble constant of **H_0= 67 ± 3.2 km s^{-1} Mpc^{-1}** (4.8 per cent precision) that depends only on the Wilkinson Microwave Anisotropy Probe-7 (WMAP-7) calibration of the sound horizon and on the galaxy clustering in 6dFGS. Compared to earlier BAO studies at higher redshift, our analysis is less dependent on other cosmological parameters. ... We determine that w=-0.97 ± 0.13, using only WMAP-7 and BAO data from both 6dFGS and Percival et al. (2010).

DESI, 6dF, Planck, Shoes and the Hubble constant

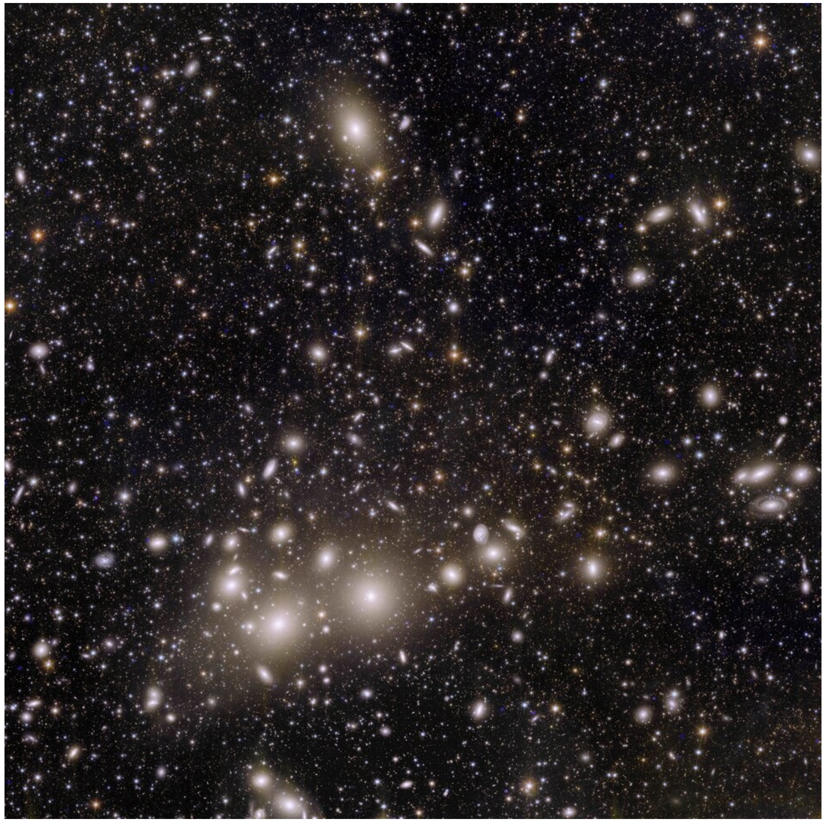
- Most recent revision of *local* H_0
- Scolnic et al: Ap. J Lett. 2025 979, L9
  The Hubble Tension in our own backyard: DESI and the nearness of the Coma Cluster
-
- DESI: $H_0 = 68.5 \pm 0.6$ km s^{-1} Mpc^{-1} (year 1 BAO)
- PLANCK: $H_0 = 67.4 \pm 0.5$ km s^{-1} Mpc^{-1}
- 6dF: $H_0 = 67 \pm 3.2$ km s^{-1} Mpc^{-1} (BAO with WMAP-7)
- SLOAN $H_0 = 68.2 \pm 2.2$ km s^{-1} Mpc^{-1} (DR7 + WMAP5)
- SHOES $H_0 = 73.2 \pm 1.3$ km s^{-1} Mpc^{-1} (SN + Cepheids)
-

DESI and 6dF use relatively nearby measurements of the BAO scale, ie: galaxies at $z << 1$. So they are local relative to Planck's z=1100

-

Euclid: launched to L2 (SpaceX Falcon) Acquire data on billions of galaxies.

- **European project with NASA participation, launched 1st July 2023.**
- 6 year survey with 1.2m telescope
- Target: A third of the sky optival + near IR, 1.5 billion galaxies
- Objective: dark matter and dark energy
- Competition: Nancy Grace Roman Space Telescope
  - (Aperture 2.4m, very wide field, 300 Megapixel camera)



First Euclid image.
1000 galaxies in Pereus Cluster (A426) plus more than 100,000 background galaxies. The principall galaxy NGC1275 has a central black hole.

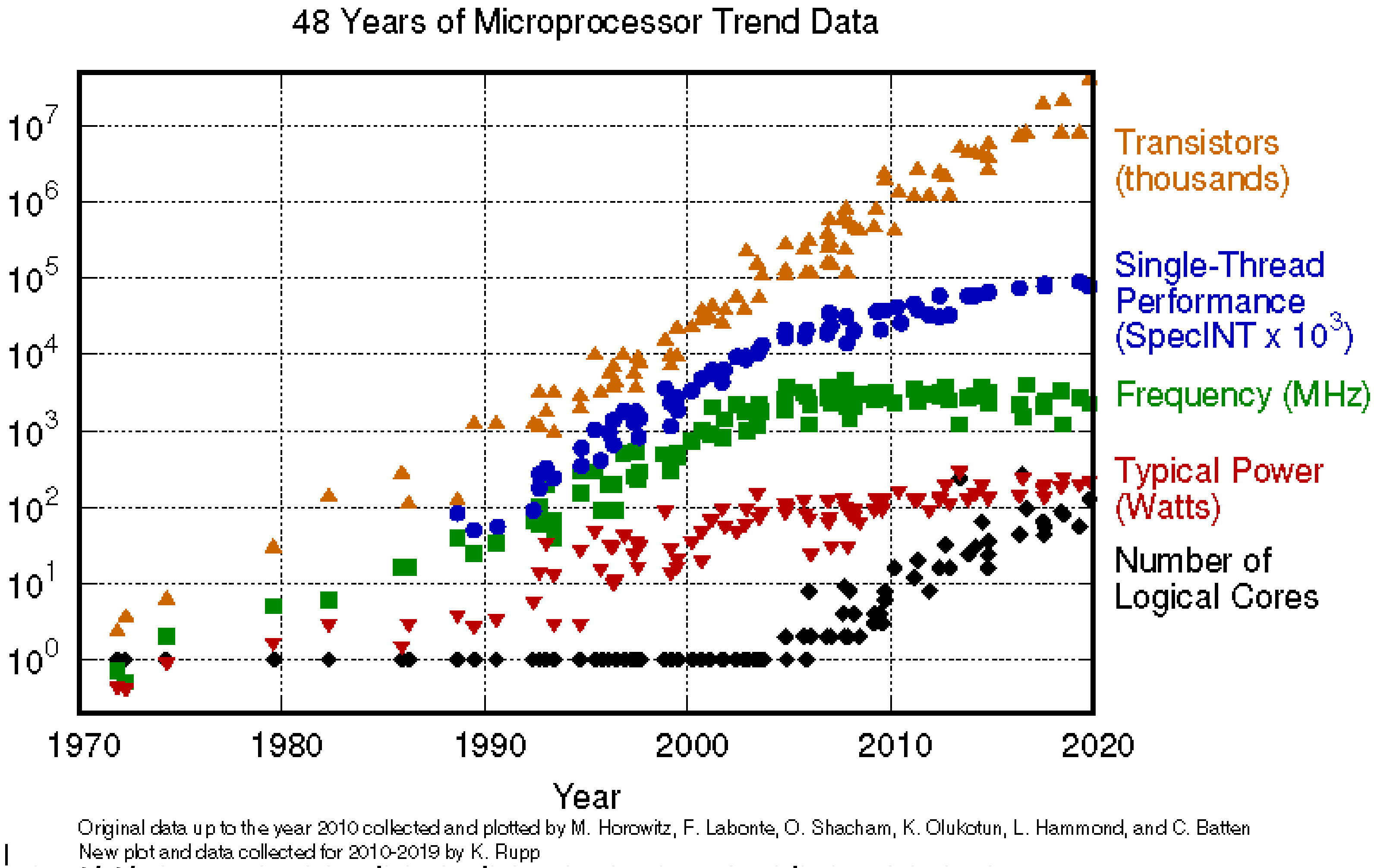
The 20th century saw 50 years of computer development at a phenomenal rate. According to **Moore's law** the power of computers, as measured by the number of transistors on a microchip, doubles every two years.

21st Century Numerical Simulations

So what happens next?

The increasing power of computers

Today's iPhone is as fast as the fastest computer in 2005.
They differ considerably in size!



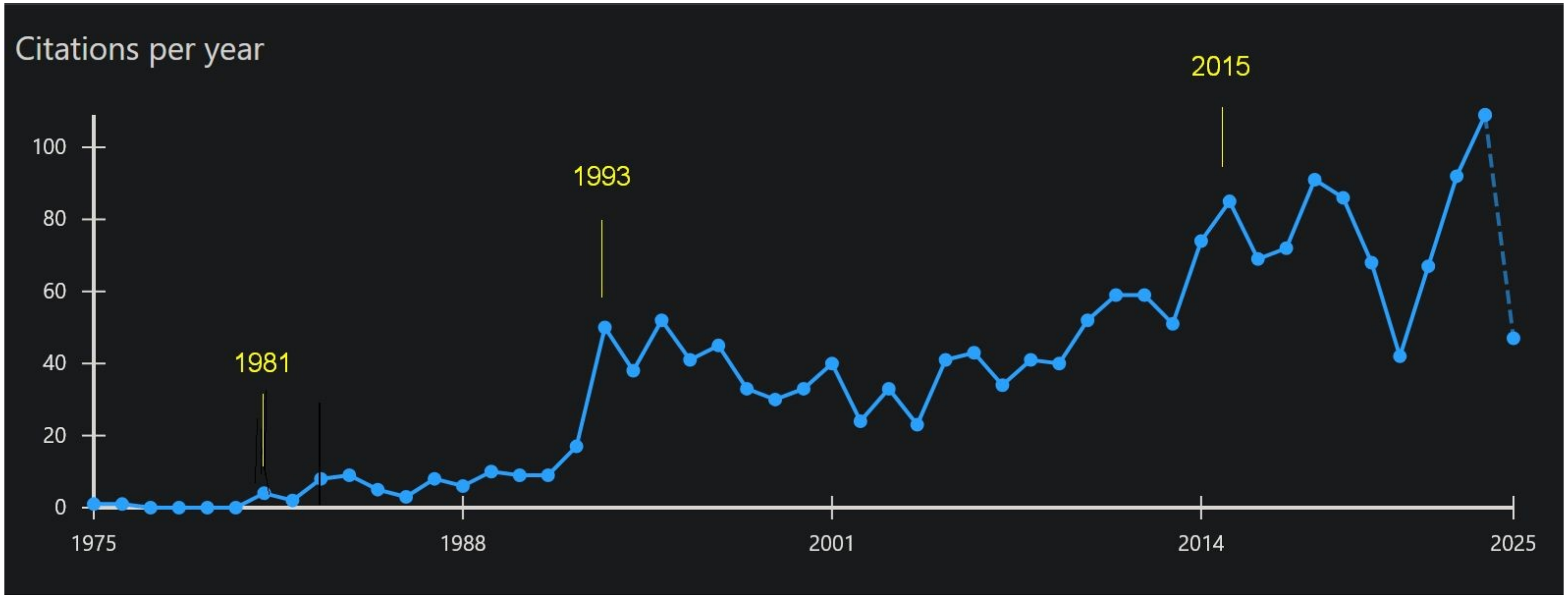
- The conti

The famous Zel’dovich approximation continues to be used, now enhanced by better 3D visualisations and techniques for analysing what is happening. There is also a deeper mathematical appreciation of the 3D topology such flows.

21st Century Zel’dovich Approximation and its variants: Skeletons, Adhesion, Burgers

So what happens next?

The Zeldovich Approximation paper
Remarks by Shandarin and Sunyaev.



- The paper appeared in a major English language journal (Astronomy and Astrophysics) in 1970, but was not cited until 1981 (except on two occasions by Russian friends). Then in 1993 it jumped to a new level of activity and since 2015 is cited more than ever before.

See a discussion of this in

S. F. Shandarin - R. A. Sunyaev
The conjecture of the cosmic web
A&A Vol. 500, Number 1, 2009

Adhesion and Burgers versions

- The **adhesion approximation** is a way of calculating the final conditions directly from the values of the density field – no integration needed. It's a purely geometric construct for which can be executed by any of a number of computer programs.
- The Burgers approach is to transform the Zel'dovich equation of motion into a partial differential equation which is a **diffusion equation** with a known analytic solution: the famous **Burgers Equation** which has played a role in the study of compressible turbulence. So, again, there is no need to integrate equations.

See

Gurbatov, Saichev and Shandarin
The Large scale structure of the universe in the frame of the model equation of nonlinear diffusion.
MNRAS (1989) 236, 385

Bernard Jones
The origin of scaling in the galaxy distribution
MNRAS (1999) 307, 376

Enhancing simulations from 20th century

- Many questions to address

Increase number of particles to gain resolution and scale
In principle easy: limitations is computer power, memory, cost.
Modern Cell phones have processors 10,000 times fast than best computer in 2000 and far more fast memory!

Need to demonstrate galaxy building
Introduce gas dynamics
Models of stellar formation and galaxy evolution

Visualisation and classification of simulations and real data.
20th century had limited computer graphics capability (no GPUs)
Automate recognition of structures
    clusters, superclusters, filaments, walls, galaxy types, etc
Need quantitative descriptors of these elements.

Characterising structure
Correlation functions, fractals, topology, persistence

- There already exists a vast collection of analysis techniques for characterising 3D distributions of a scalar, vector or tensor field.
- Not all of them are useful for astronomy, but some are and conversely some astronomy developed algorithms have other outside applications.
- The rise of AI will make a big difference: we will be able to describe things while having no idea why that is the way they are or how they came about.
  That is probably the key issue for the 21st century.

The continuing growth of computer power and the rapid rise of a huge diversity of “AI” techniques allowsfor much more computer intensive algorithms to be used. For example, simulations with gravity driving complex gas flows and processes such as star formation are now conceivable.
Our mobile phones are now more powerful than the most powerful computer running in 2000!

21st Century Algorithms

So what happens next?

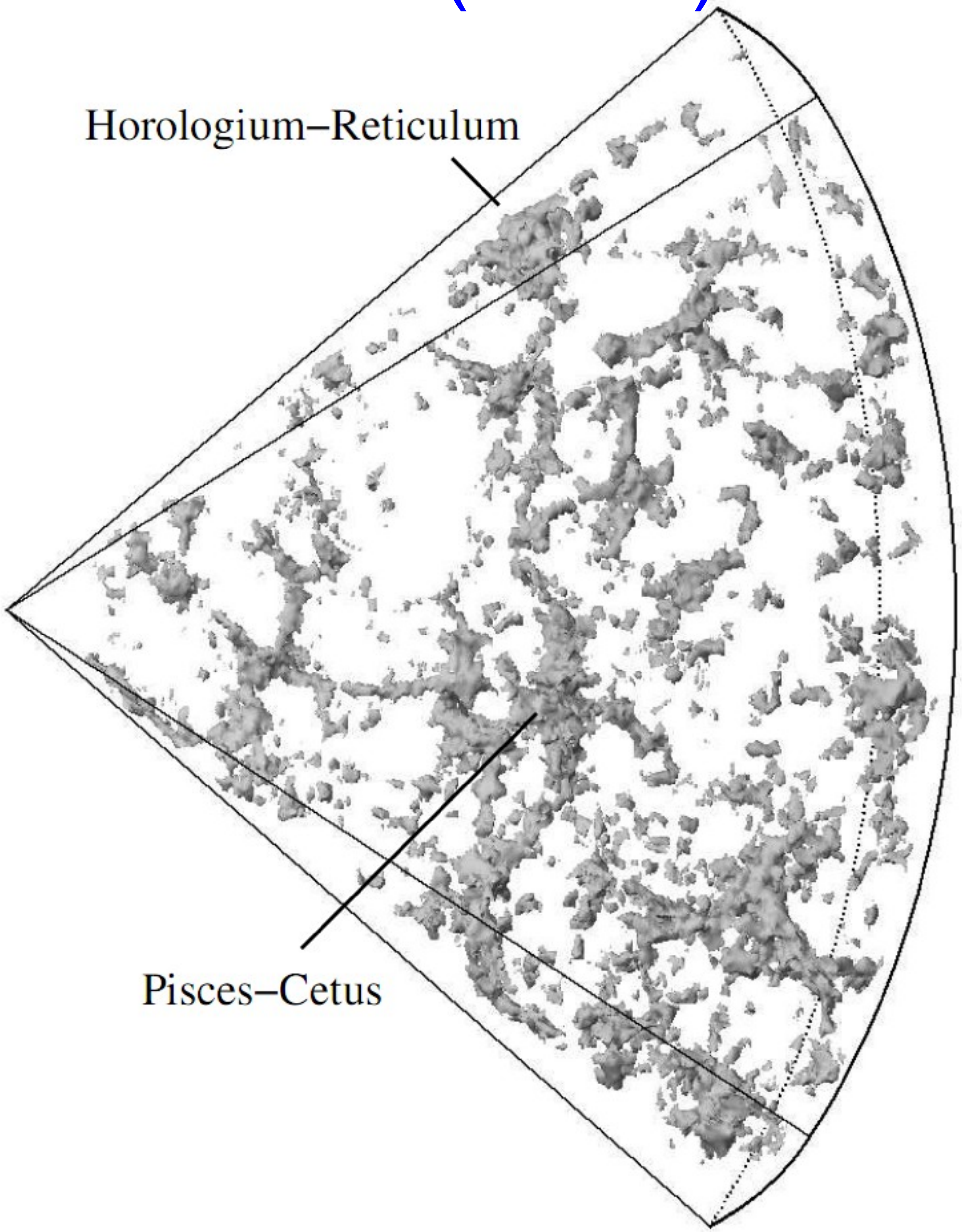
Algorithms for Data analysis

- Redshift catalogues: slices and all-sky maps
- Simulations: N-body experiments

- Density field estimation,
- feature detection,
- vector and tensor fields estimation,
- statistical data,
- Reconstruction & visualisation.

Delaunay Tesselation Field Estimator (DTFE)

- The DTFE is a self-adaptive density estimator for data sets defined on non-uniformly distributed points in a space of any number of dimensions.
- It can be used to represent the data set on a regular grid. The algorithm returns the value of the local density at each point of the set.
- It is based around the Voronoi and Delaunay tesselation of the point set.
- See W.E. Schaap and R. van de Weygaert, *Continuous fields and discrete samples: reconstruction through Delaunay tessellations Astronomy and Astrophysics*, v.363, p.L29-L32 (2000)
-



DTFE has been a key component of analyses taken point set data into an optimal reconstruction as a continuous field.

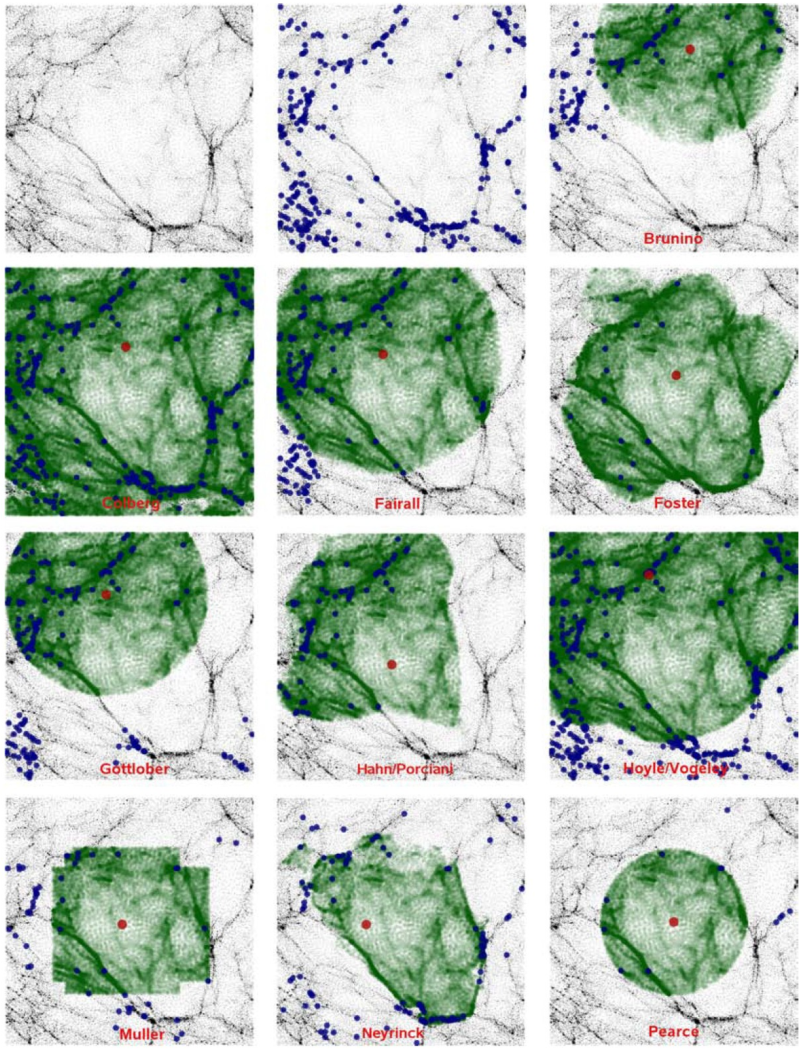
Structural analysis of the cosmic web

- Void Finders
- Filament and Wall Finders

Analysing huge data sets and simulations to isolate voids and filaments will require well understood algorithms that have been thoroughly tested. Algorithms based on AI will undoubtedly work well and can be tested, but their underlying methodology is currently generally unclear.

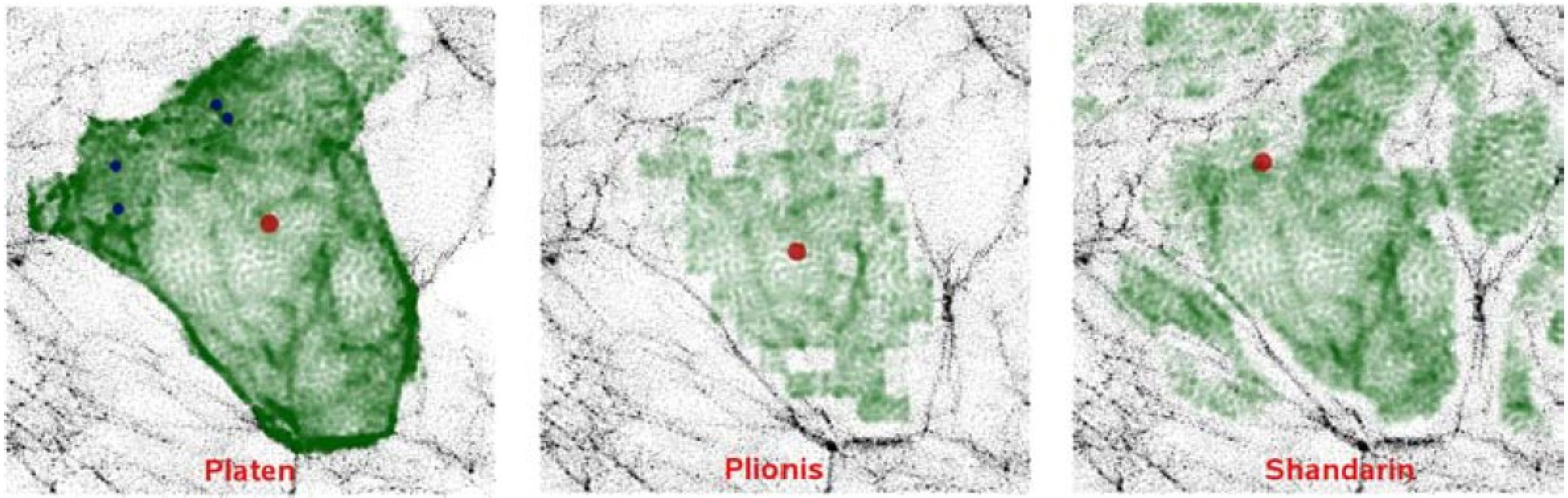
The Void Finder Comparison

A prepared configuration is presented to a number of groups.



"The Aspen–Amsterdam Void Finder Comparison Project", Colberg et al. 2008 MN **387**, 933

Void finding using **Watersheds**

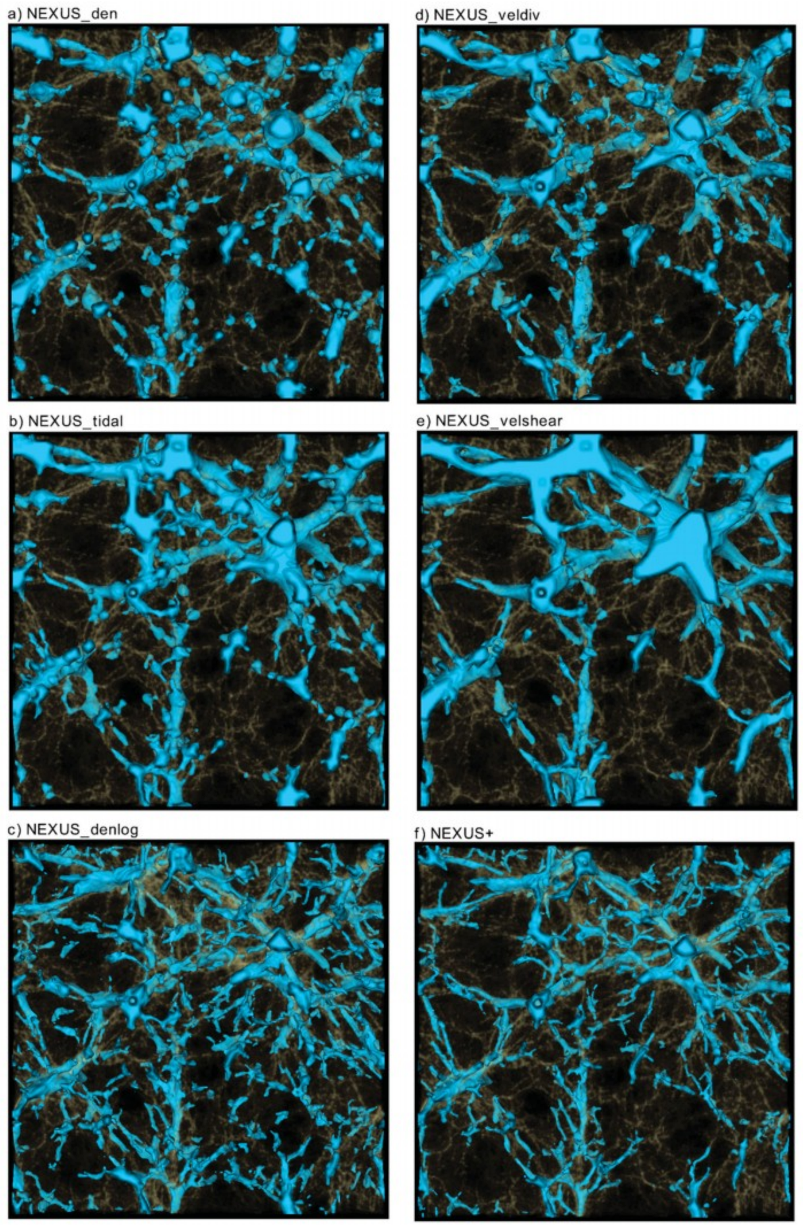


- Watersheds have long been known for finding hills and valleys in geographical applications. As the name implies it is used to show the places where flooding occurs to any given level. Also used in Climate modelling.
- Astronomy has taken this into three dimensions and optimised it for dealing with shot noise in the underlying sampling of the field. It makes a perfect void finder.

Multiscale Wall and Filament finding with MMF/Nexus

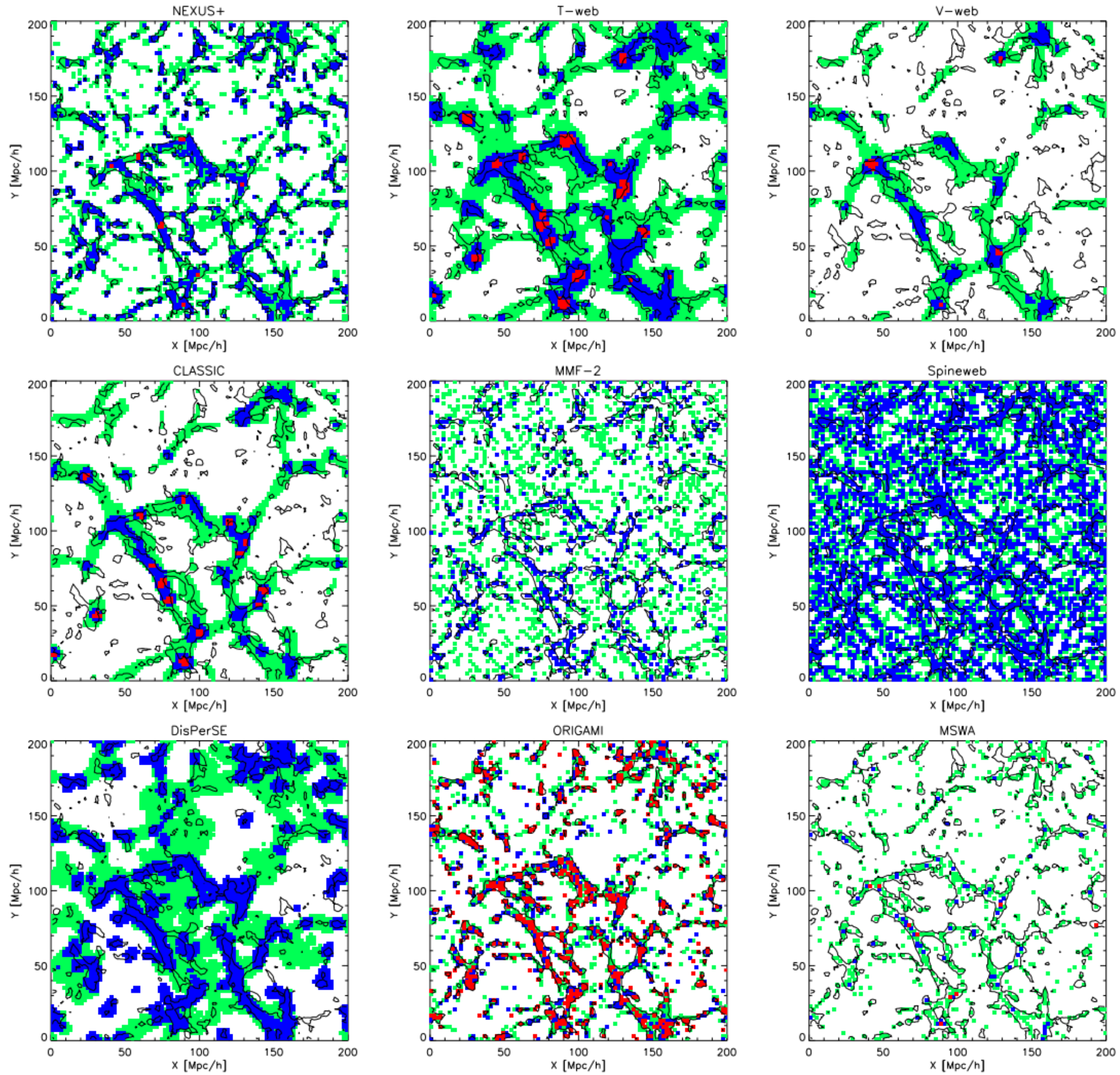
A prepared configuration is presented to a number of groups

- Slice from a simulation tht has been analysed by the NEXUS (Cautun) version of MMF (Aragon-Calvo). NEXUS handles vector and tensor fields.
- Panels show the density and velocity divergence, the tidal filed and velocity shear and the log density field with it’s NEXUS+ equivalent.
- NEXUS+ uses the logarithmic values of the field, using a log-Gaussian filter insead of a Gaussian filter. They both use the Hessian field for analysis.
- It inherits from MMF the multiscale character of the distribution.



Web Finder Comparison (Leiden 2014)

- In this comparison, only the density field from a simulation was used and the same slice showed from those partaking.
- Nexus and Nexus+ performed exceptionally (perhaps in part because they are multiscale),
- Disperse, the most popularly used by other groups, found principal structures but destroyed the fine detail revealed by others.
- Nexus and Nexus+ are now on Github nd in the public domain (perhaps MIT licensed).



Many galaxies are attended by smaller satellite systems. Two of our neighbouring large galaxies have such attendant dwarfs and they appear to lie in planes orbiting the host. This has been known for more than 75 years.
Why does this hppen?

21st Century
M31 and NGC 5128 (Cen A) planes of satellite galaxies

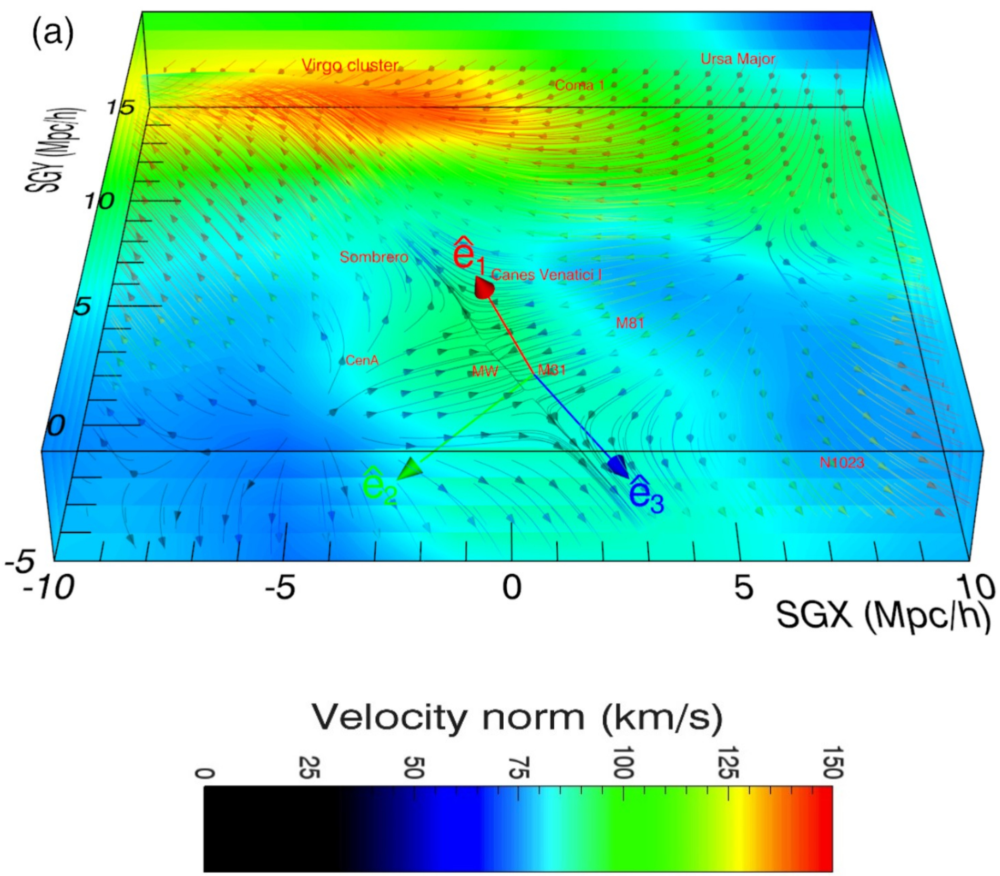
This one involved Noam Libeskind!

A simulation of the environment of the Local Group

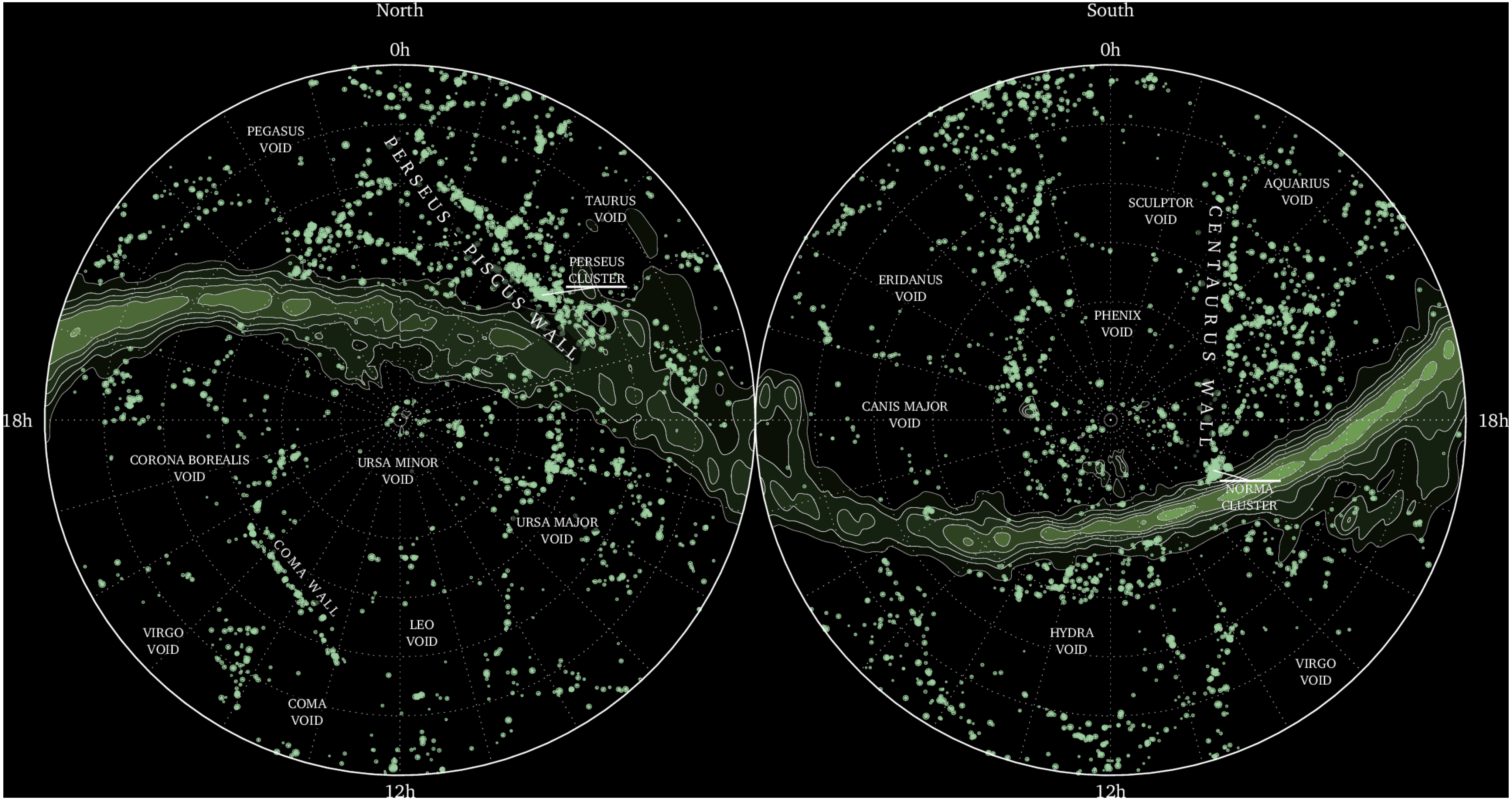
Explaining why big galaxies in the LG have satellites lying in planes

Planes of satellite galaxies and the cosmic web
Noam I Libeskind,Yehuda Hoffman, R. Brent Tully, Helene M Courtois, Daniel Pomarede, Stefan Gottlober, Matthias Steinmetz.
MNRAS 2015 462, 1052

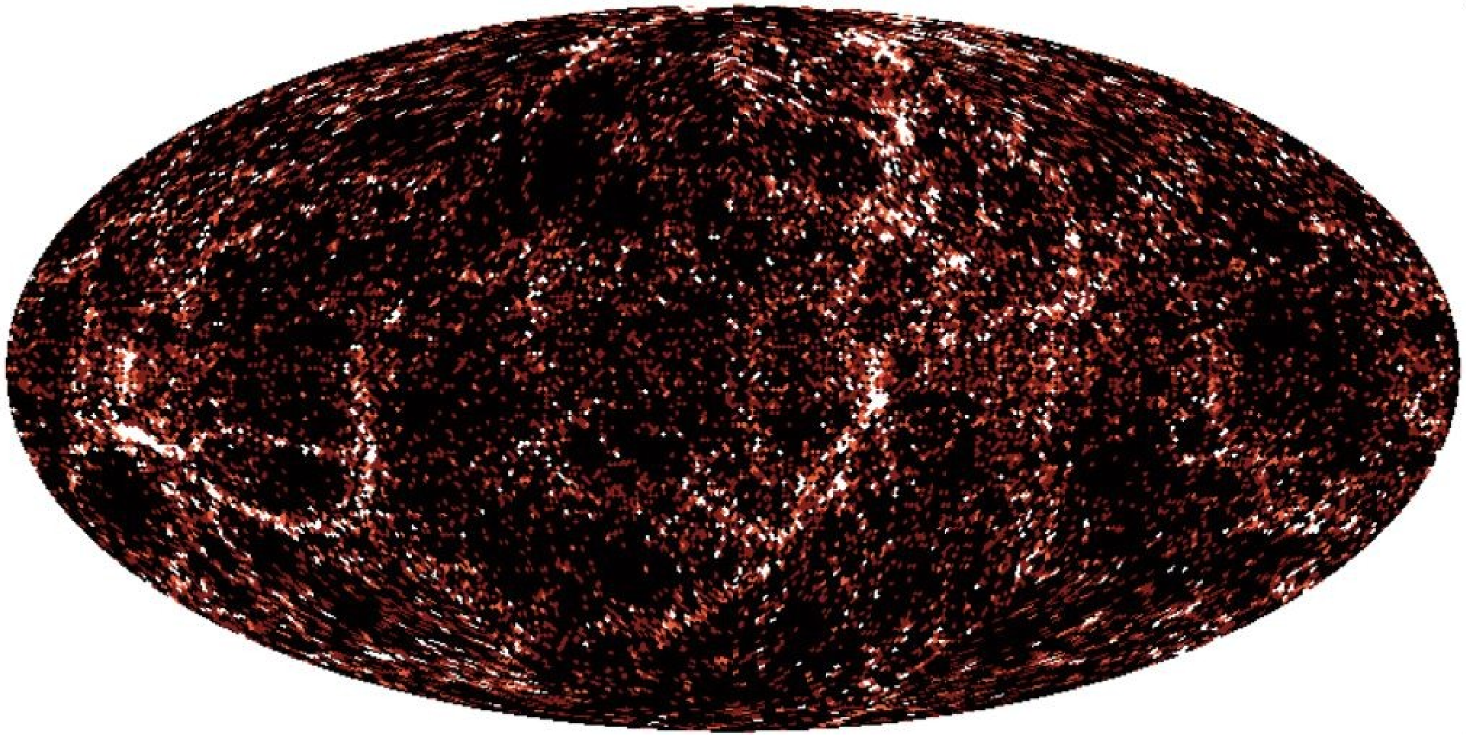
- Uses ΛCDM models and the Cosmicflows-2 dataset. The Cosmicflows-2 data acts as a constraint on the generation of the initial conditions for the N-Body calculation that reveals for formation history of the Local Volume..
- The analysis reveals that the Local Group and Centaurus A reside in a filament stretched by the Virgo cluster and compressed by the expansion of the Local Void. Four out of five thin planes of satellite galaxies are indeed closely aligned with the axis of compression induced by the Local Void.



Local voids from 2MRS survey (Johan Hidding)



A reconstruction of the galaxy distribution from inferred initial conditions Kitaura (2012) and by Frisch (2023).



- Early reconstruction of 2Mass by Kitaura.

Initial conditions that satisfy a present day constraint

- Using constrained random field theory developed in the 20th century by Bertschinger and van de Weygaert and by Hoffman and collaborators we can generate random Gaussian fields that satisfy a diversity of constraints.
- The challenge is to generate the initial condition that have led to the present configuration of galaxies determined by CosmoFlows.
- It is then possible to look at our Local Group of galaxies and evaluate the tidal stresses that act on its dynamics. This is, in essence, what Libeskind and collaborators have achieved. (See previous slide for reference).

Holmberg’s tidal interaction simulation 1941 (Lund)

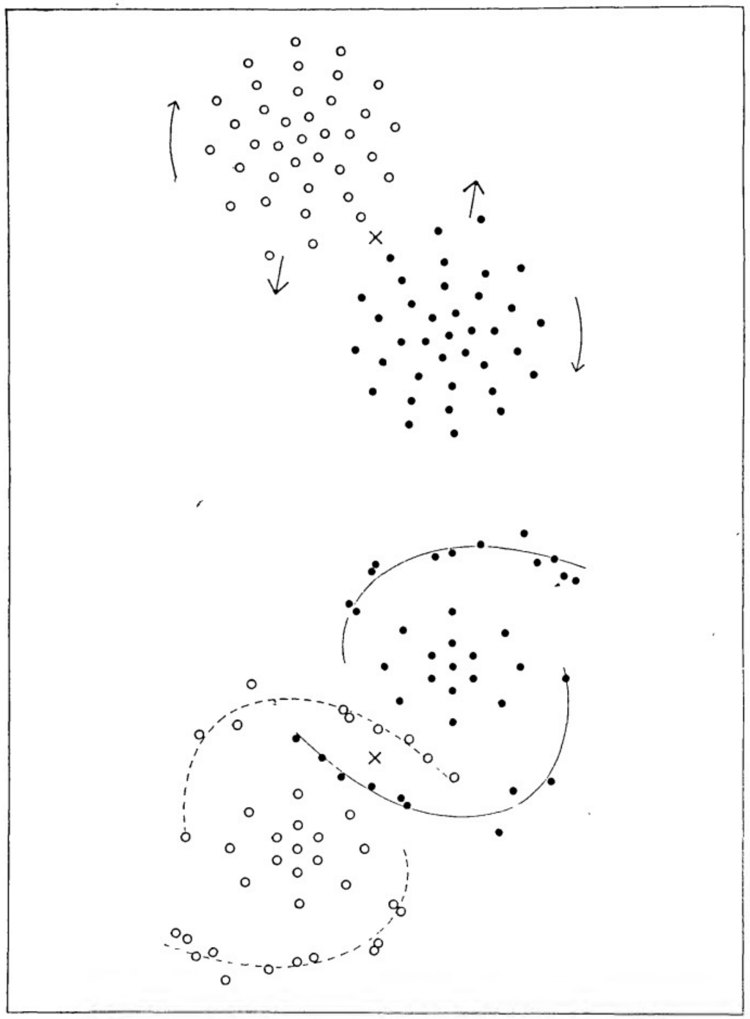


FIG. 4a

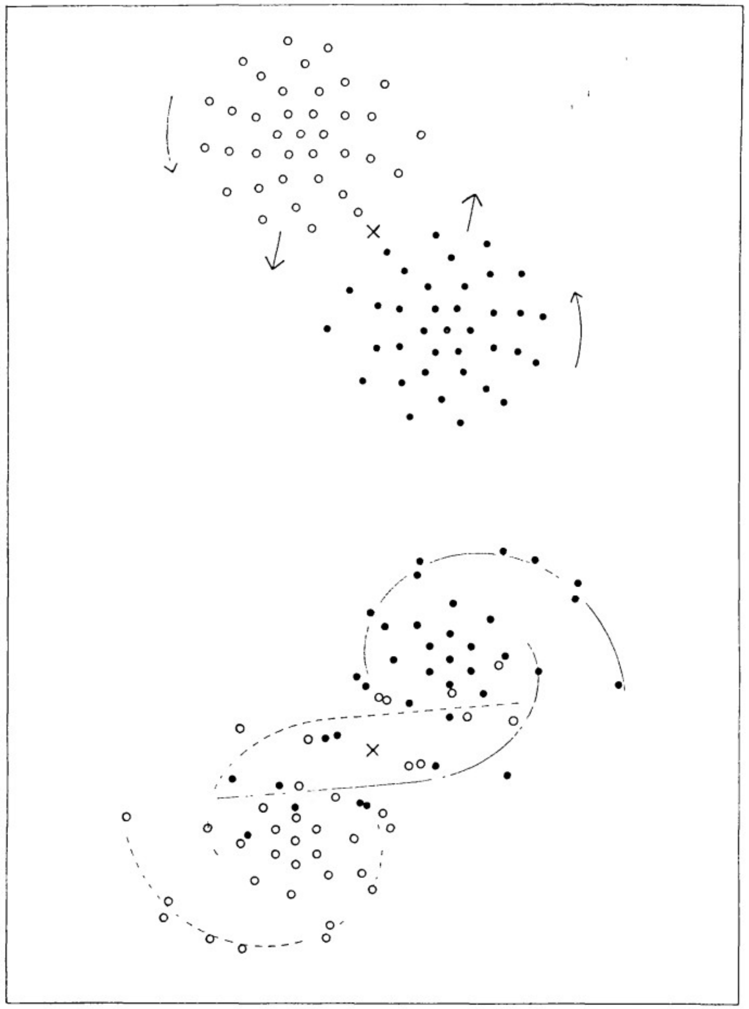


FIG. 4b

- Holmberg, E., “On the clustering tendencies among the spiral nebulae”, 1941 ApJ vol 94 p365

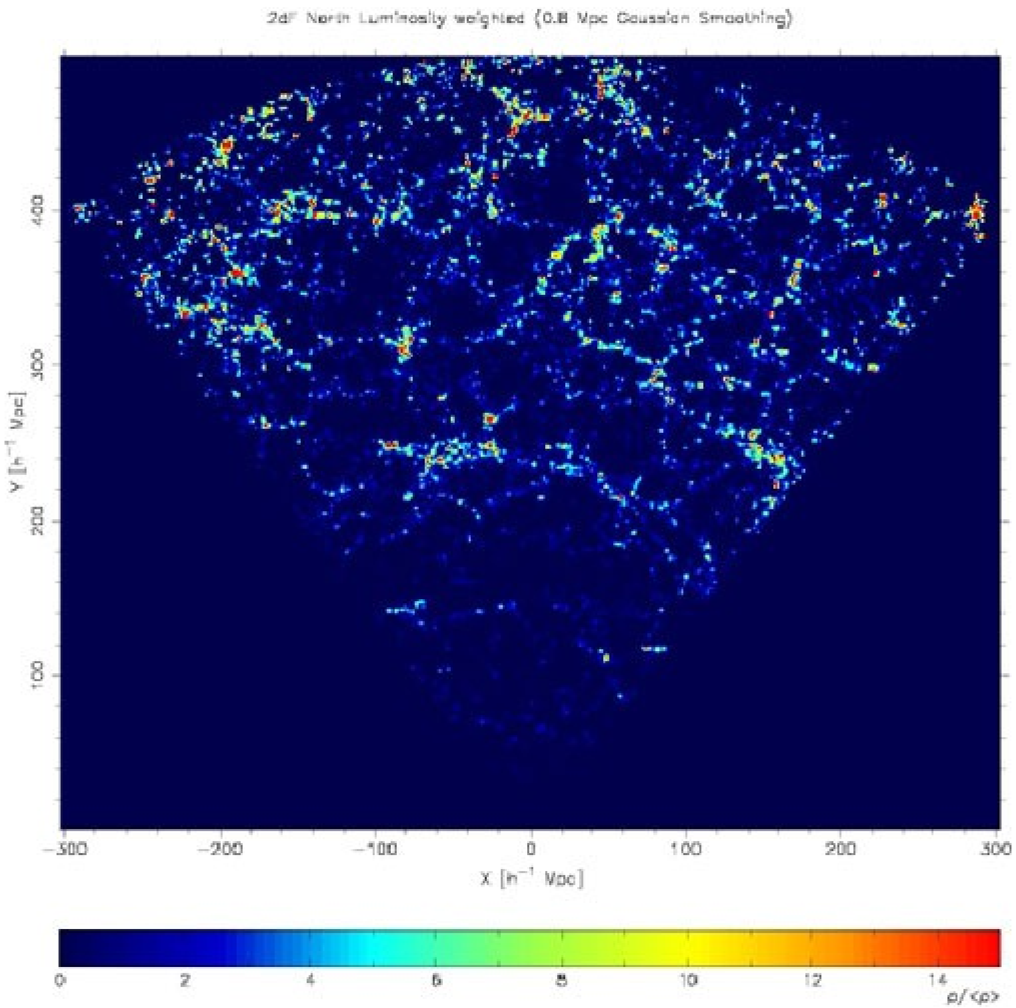
In 1961 George Abell searched for clusters of clusters, ie. superclusters in his 1958 “Abell Catalog of Rich Clusters” and was able to list 17. In 1969, Yu and Peebles (Ap.J. 1969) gave the opinion that while superclusters might exist, simply on statistical grounds. If superclusters existed then no more than 10% of clusters would be found in such superclusters.

21st Century Superclusters

So what happens next?

Deeper surveys reveal more evidence of superclusters

- In 1995 Andermach etal published an extension of the Abell, Corwin and Olowin catalog, listing redshifts for 869 of the 1304 clusters.
- This was exploited in 1997 by Einasto and collaborators to systematically look for superclusters. They catalogued 220 superclusters of galaxies having high cluster density regions.
- Maps of the superclusters revealed a manifest 120 h^{-1} Mpc regularity in their spatial distribution.

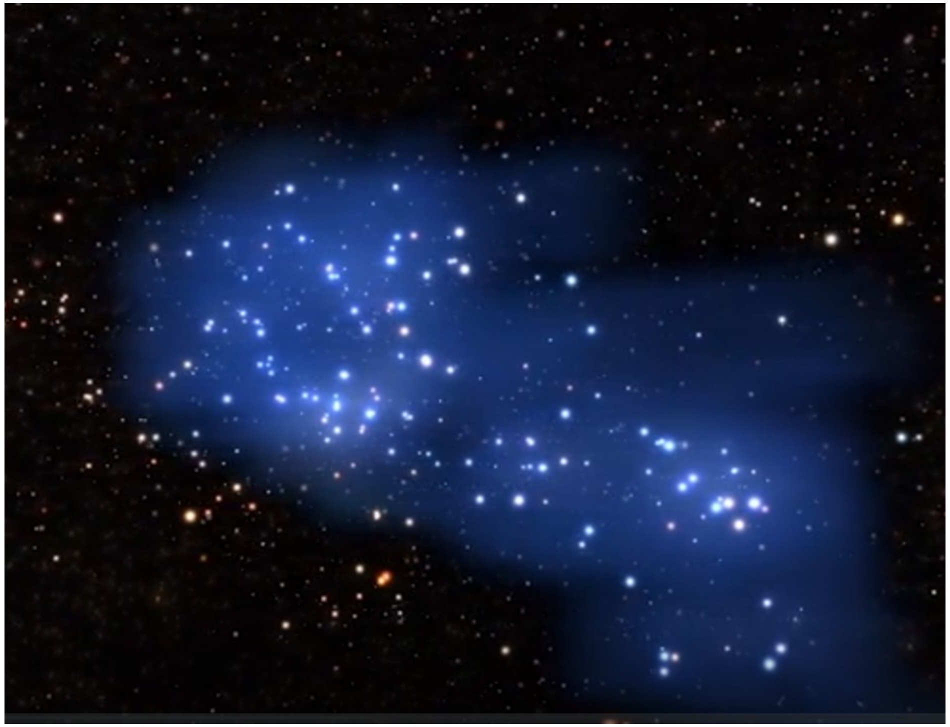


M. Einasto Galaxy Superclusters and Their Complexes in the Cosmic Web arXiv:2505.22082

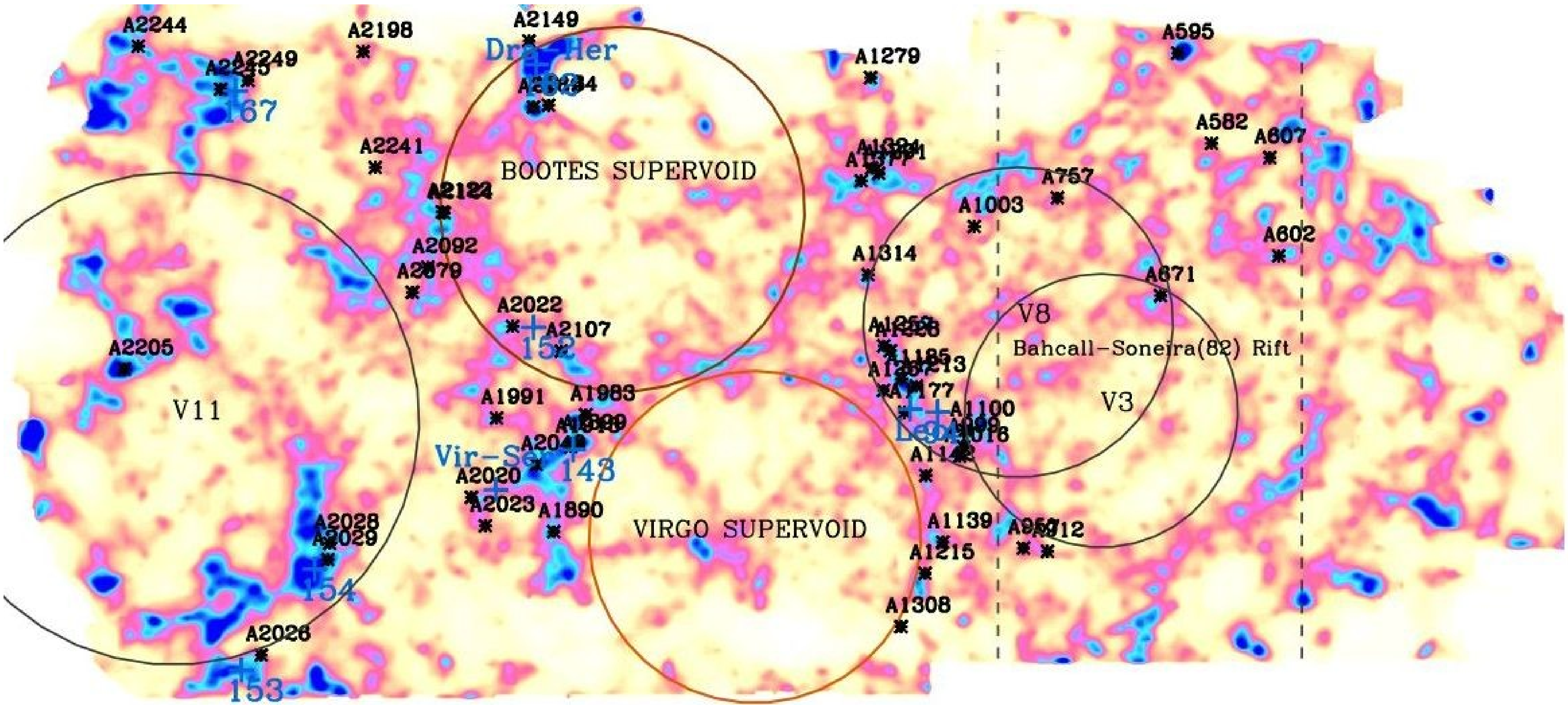
The Einasto Supercluster

- The Einasto SuperclusterIn 2023 S. Sankhyayan and collaborators published a paper, "*Identification of Superclusters and their Properties in the Sloan Digital Sky Survey Using WHL Cluster Catalog*" in which they found 662 superclusters, the most massive among which was a system with a mass of 257×10^{14} $M_{\odot}$.
- This has now been dubbed "**The Einasto Supercluster**" in honour of Jaan Einasto who has been an energetic pioneer of such studies.

It is probably the biggest and heaviest single object to have a name!



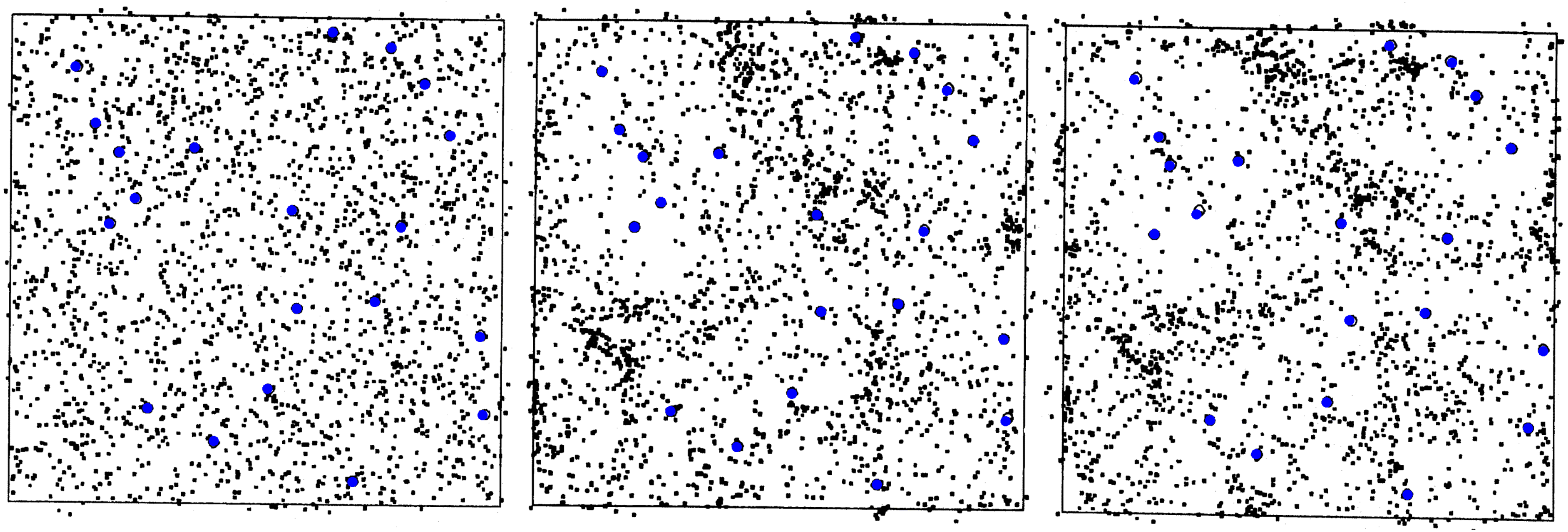
Supervoids (100-150 h^{-1}Mpc) found using Watershed
Erwin Platen, unpublished



- The place where more than 2 voids meet are often occupied by a supercluster. The structure is irregular, but more chainlike, if anything.

The van de Weygaert – Icke Voronoi Model (1989)

A 3D toy model demonstrating the influence of clusters, the vertices of the tessellation (blue dots), in moving material away from the void centres to form bridges between the clusters. The evolution procedes by a series of small Zeldovich-like approximations, moving each point away from the centre.



This serves to show, in a generic manner, how a random distribution of material might form a web-like structure instead of simply collapsing into a number of isolated spherical blobs.

- van de Weygaert & Icke
  Fragmenting the universe. II - Voronoi vertices as Abell clusters. A&A 1989, 213, 1

So what is a supercluster or supervoid? Should they exist?

- Some things are clear about superclusters and voids
  - The smaller ones involving 2-4 rich clusters are not uncommon
  - Super structures exist, some have names like Hercules and Einasto super-clusters
  - The superclusters do indeed have a higher density and the supervoids look compartively clear of luminous material.
  - There is no reason to think superclusters are gravitationally bound entities
- Some things are unclear about superclusters and voids
  - They lie in long chains like superfilaments. These appear to lie at the boundaries of supervoids.
  - The smaller (normal) voids form a void hierarchy. Are the supervoids part of that hierarchy? Likewise for superclusters
  - The primordial power spectrum after recombination does have power on very large scales (150 h-1 Mpc) , hence it might be plausible that the void-like superstructures are simply BAO’s.

P.J.E Peebles ("Jim") Nobel Prize Physics 2019

- Awarded for "**contributions to our understanding of the evolution of the universe and Earth's place in the cosmos**".

The best time for science should be now

“The greatest discoveries are yet to come”
John Archibald Wheeler