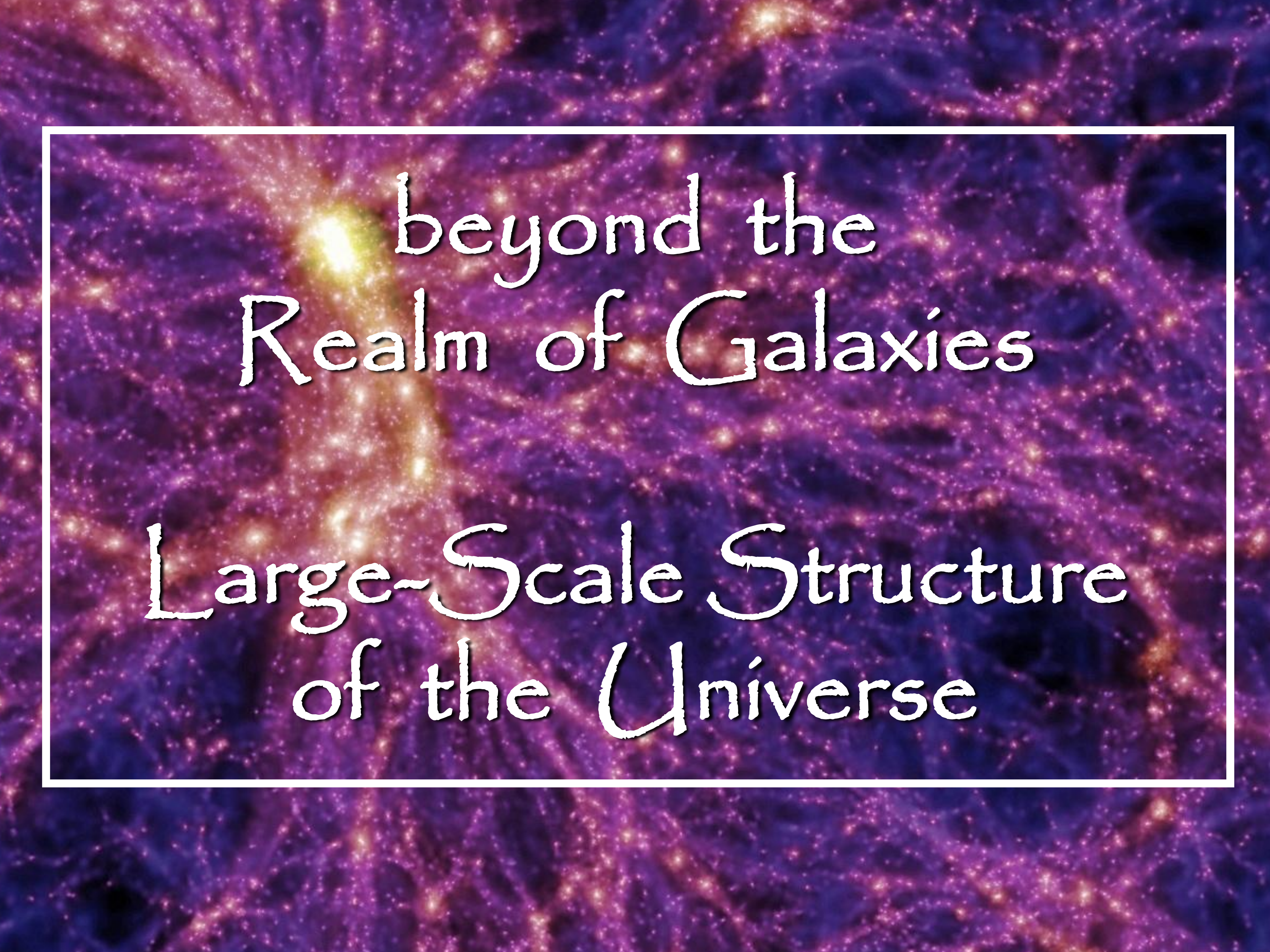
beyond the Realm of Galaxies

Large-Scale Structure of the Universe



beyond the Realm of Galaxies

Large-Scale Structure of the Universe

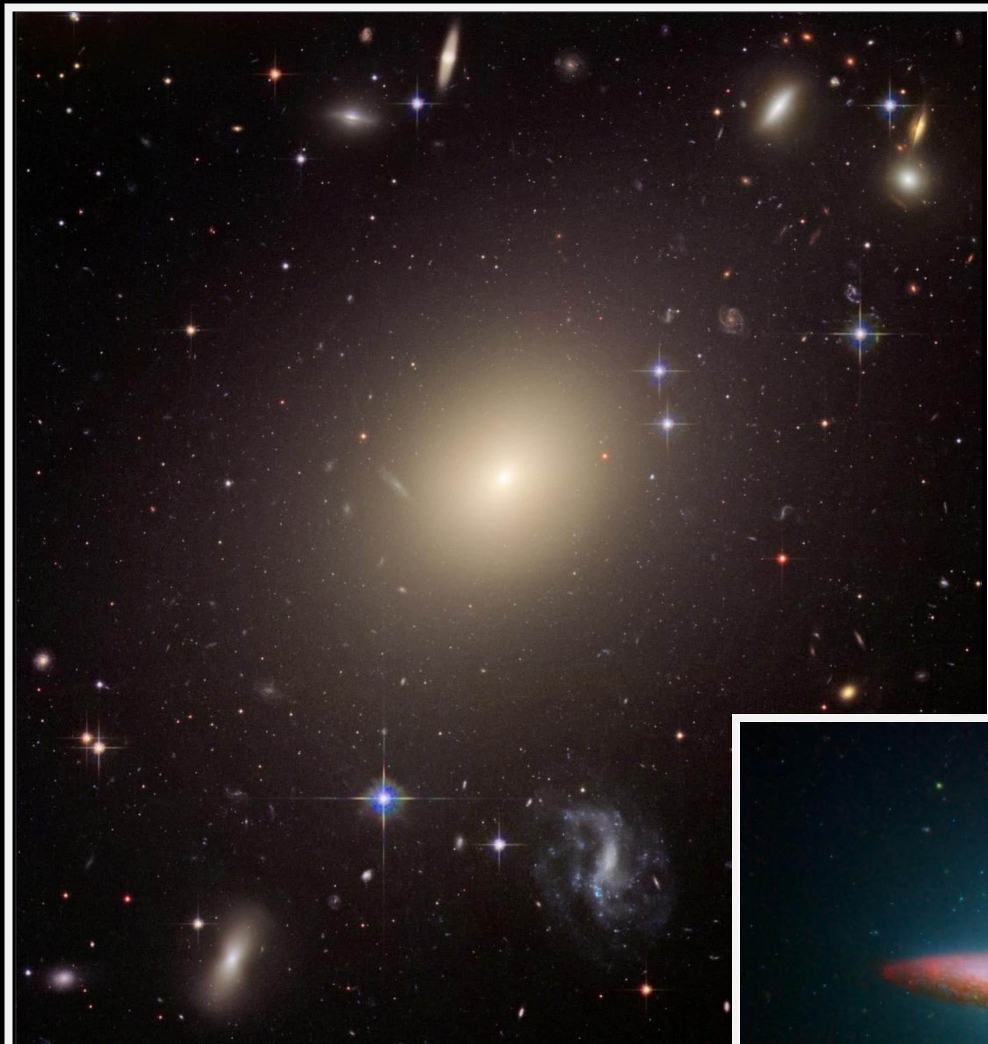
Galaxies


… Galaxies …

... Spiral

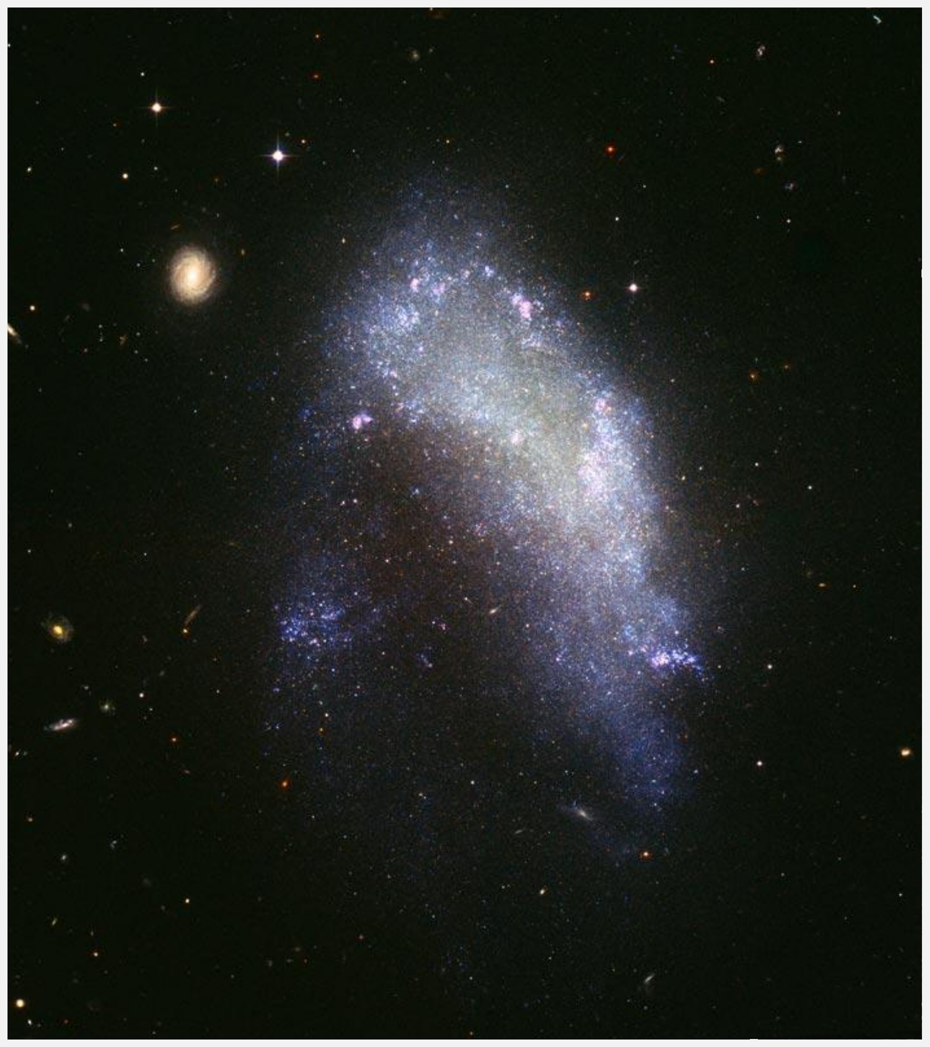
Galaxies ...

NGC 1300: a Milky Way look-alike ?



... Elliptical

... Lenticular



... Irregular

... Dwarf

Sociology

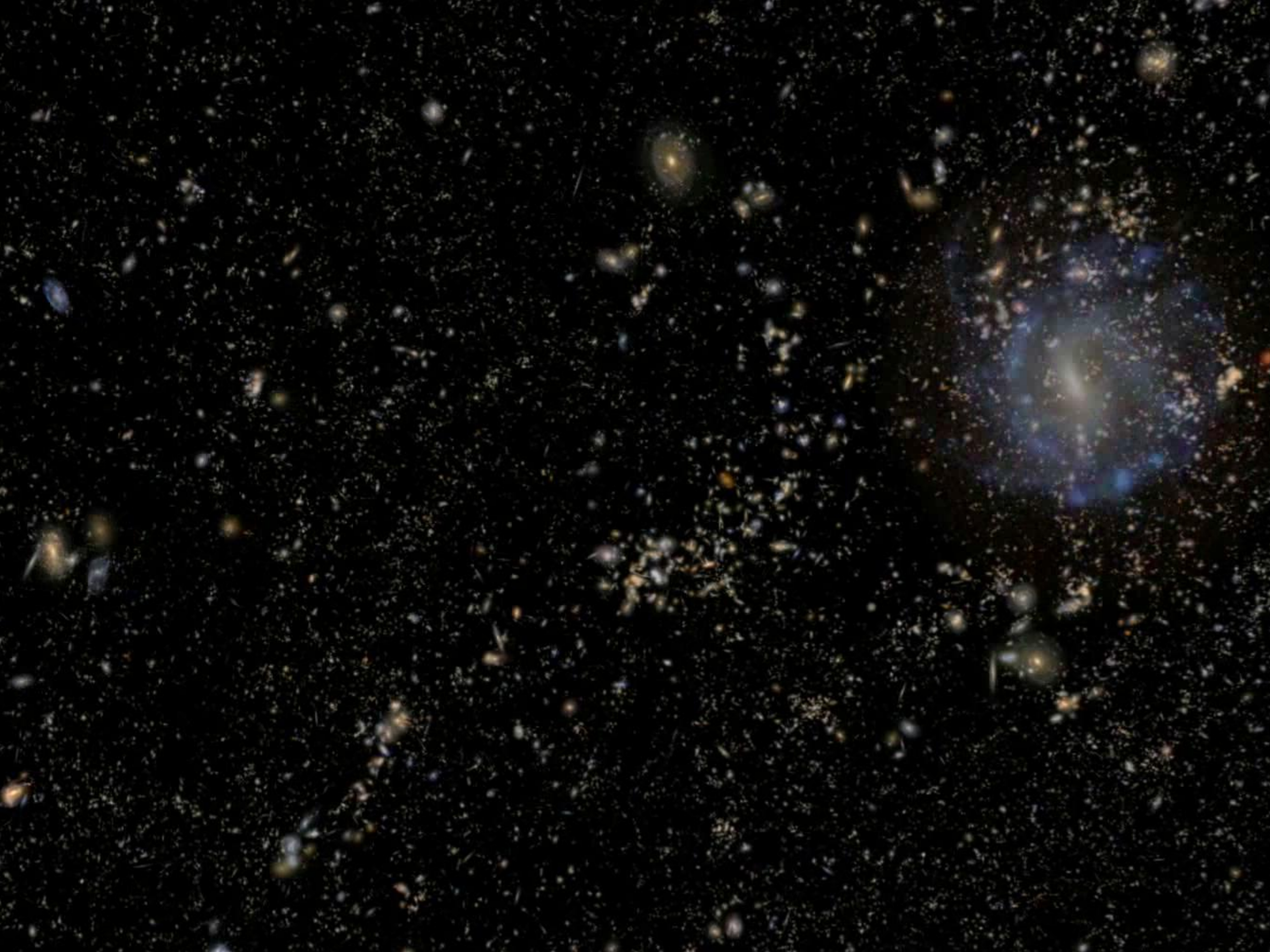
of Galaxies

Sociology of Galaxies

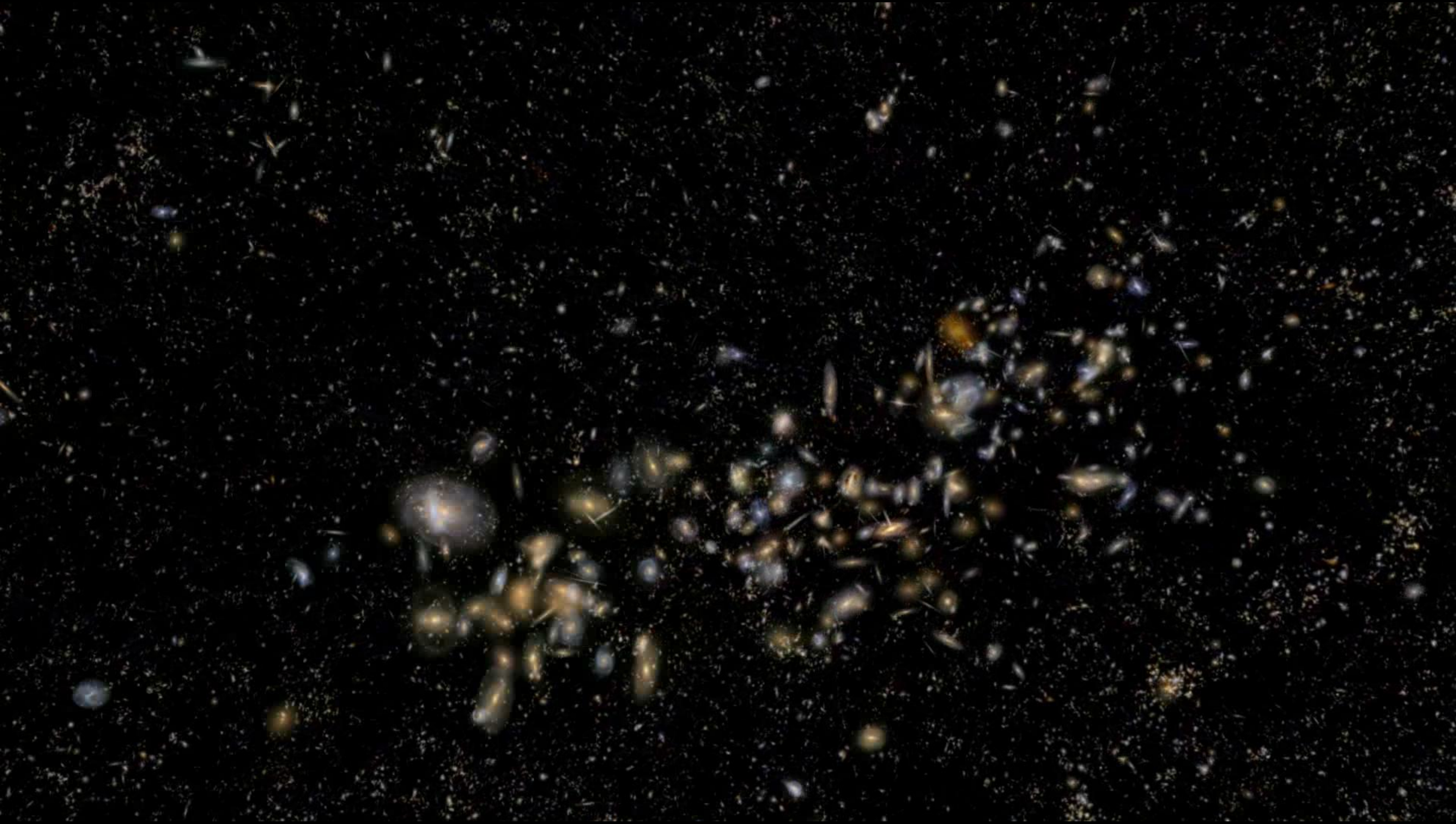
- Galaxies are not singular objects:
- they group and cluster into a hierarchy of ever larger entities.
- direct manifestation of gravitational attraction between matter: clumping of matter
- Their sociology, ie. the characteristics and patterns in which they group together, is a key to unravelling the formation of structure in the Universe.

Local Supercluster,

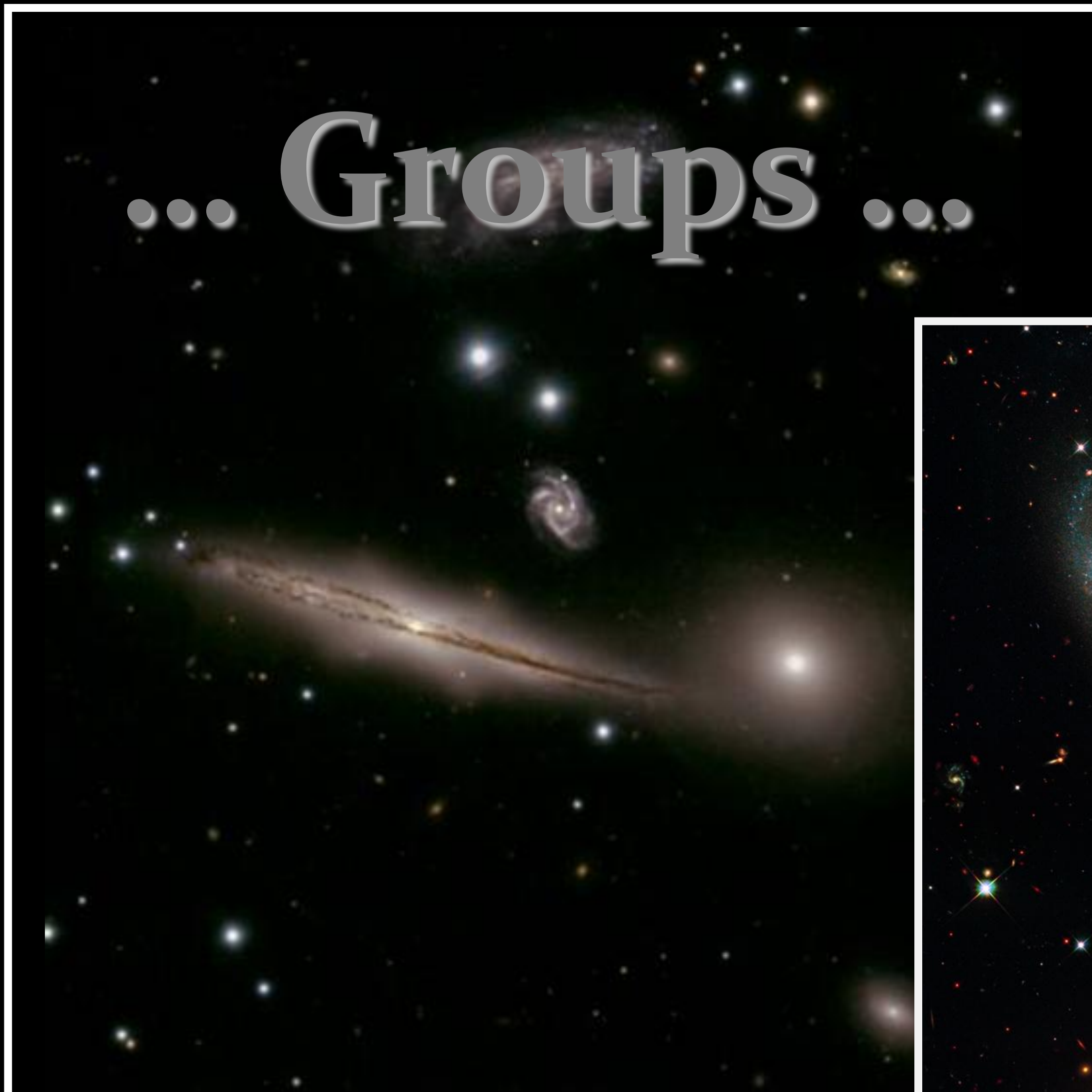
movie, Brent Tully



Interacting Galaxies

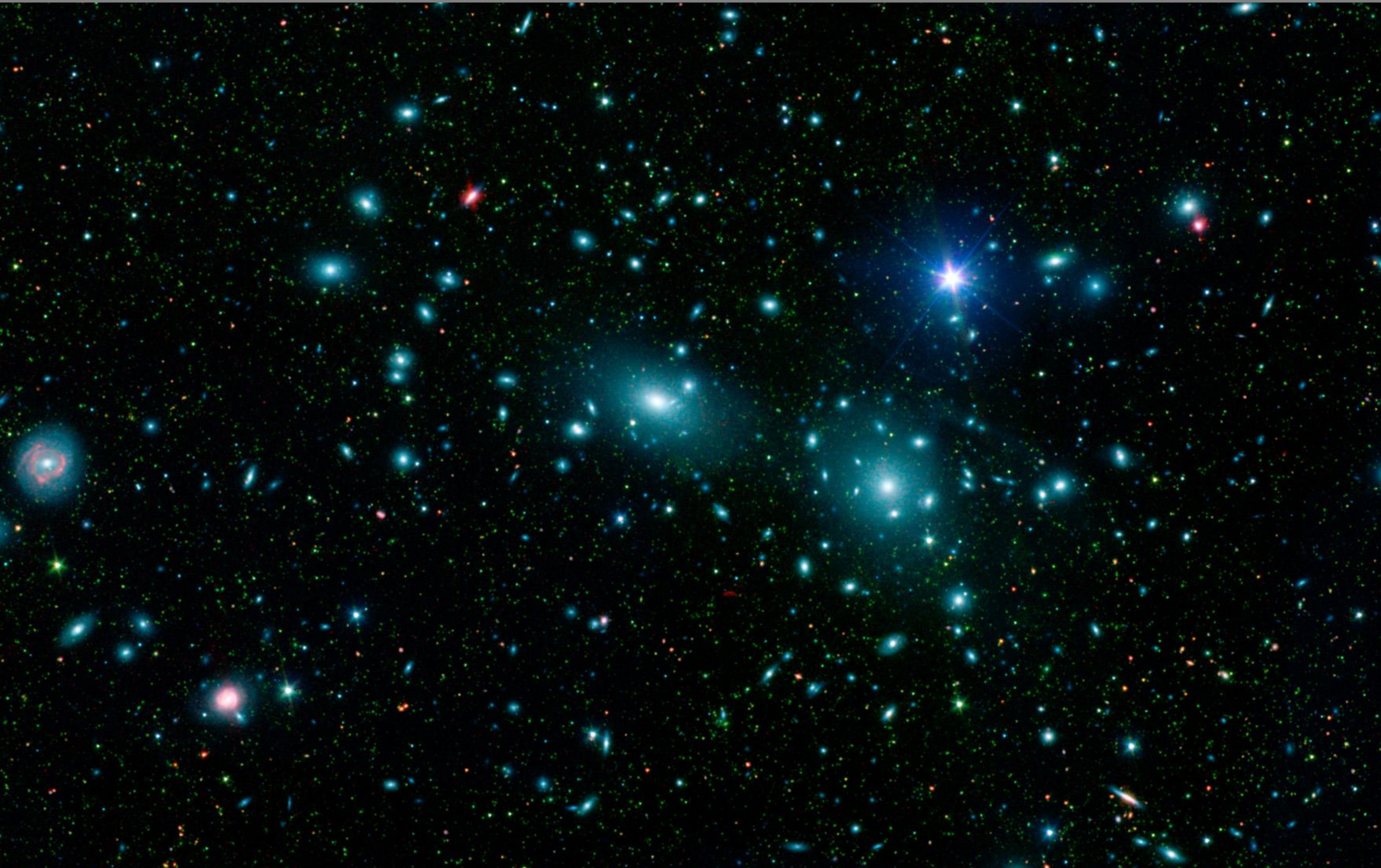


... Groups ...

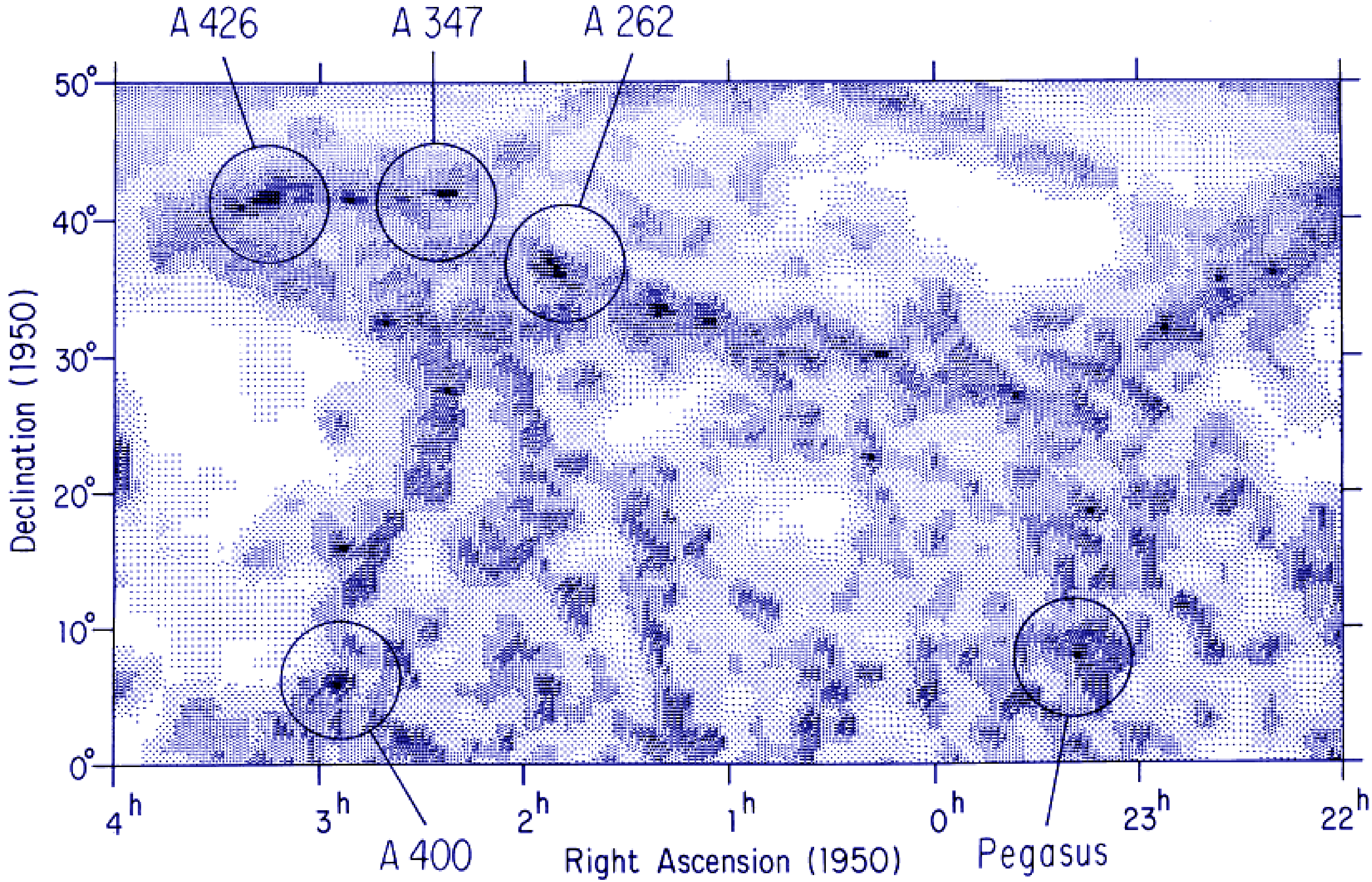


Clusters of Galaxies

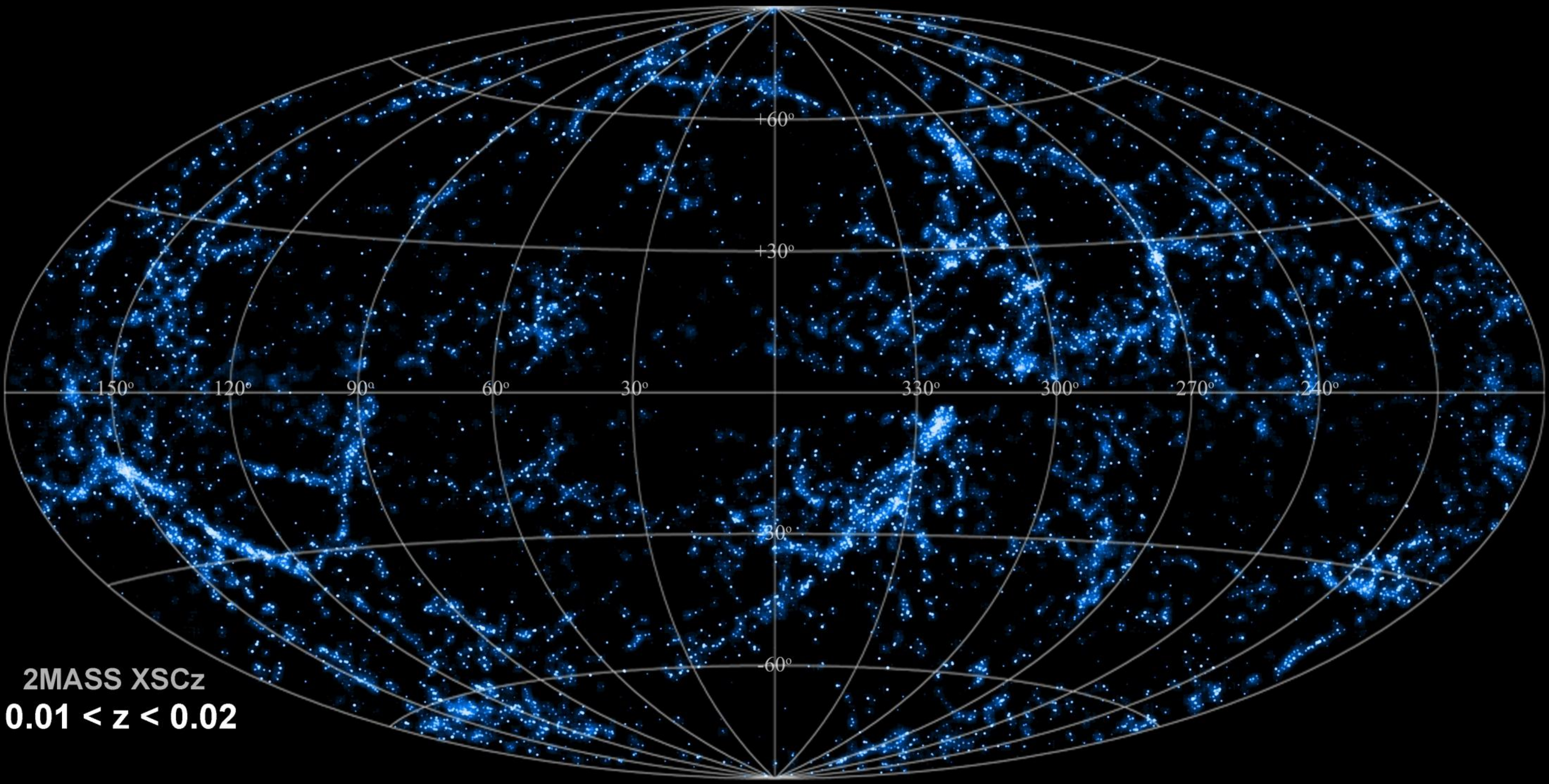
Clusters of Galaxies



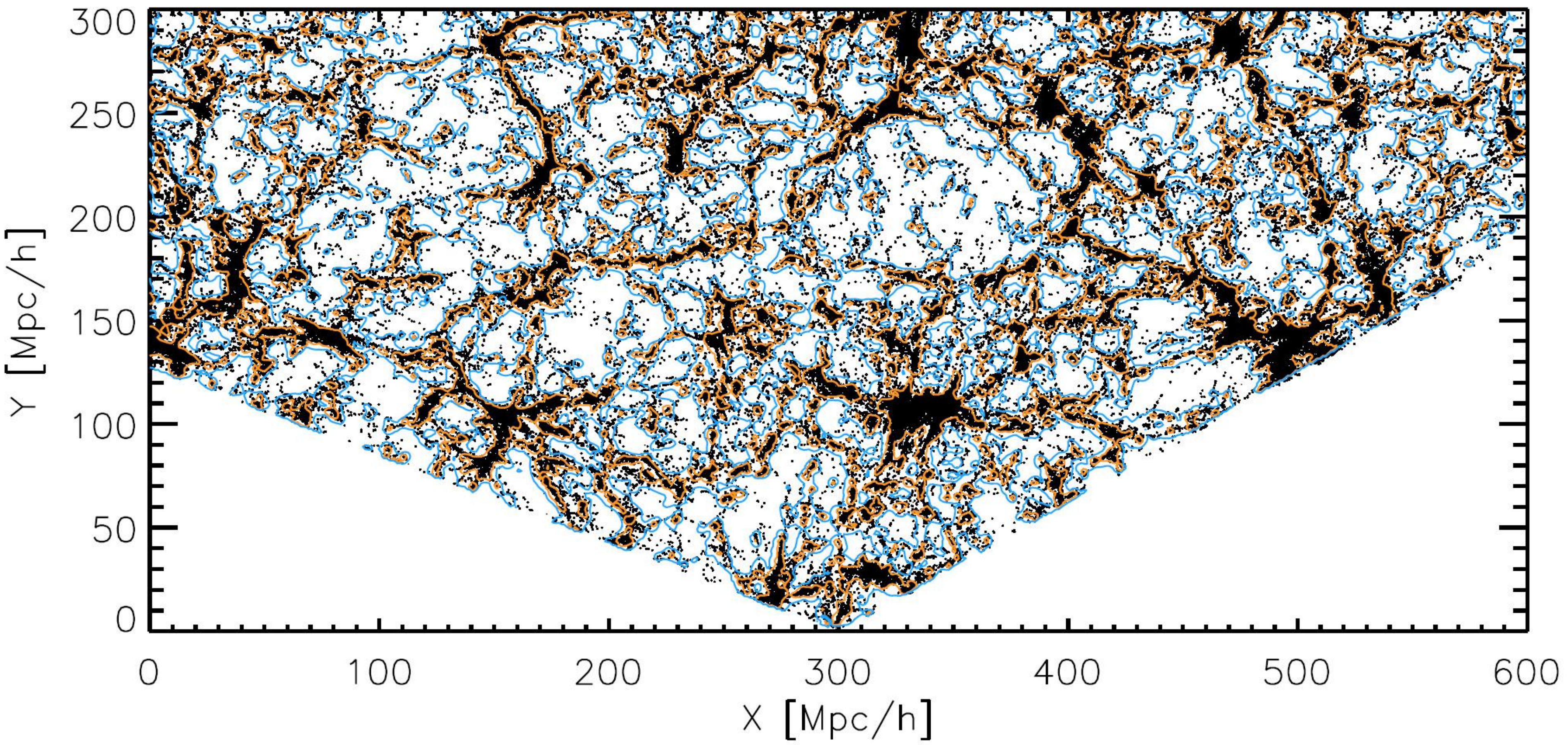
Superclusters



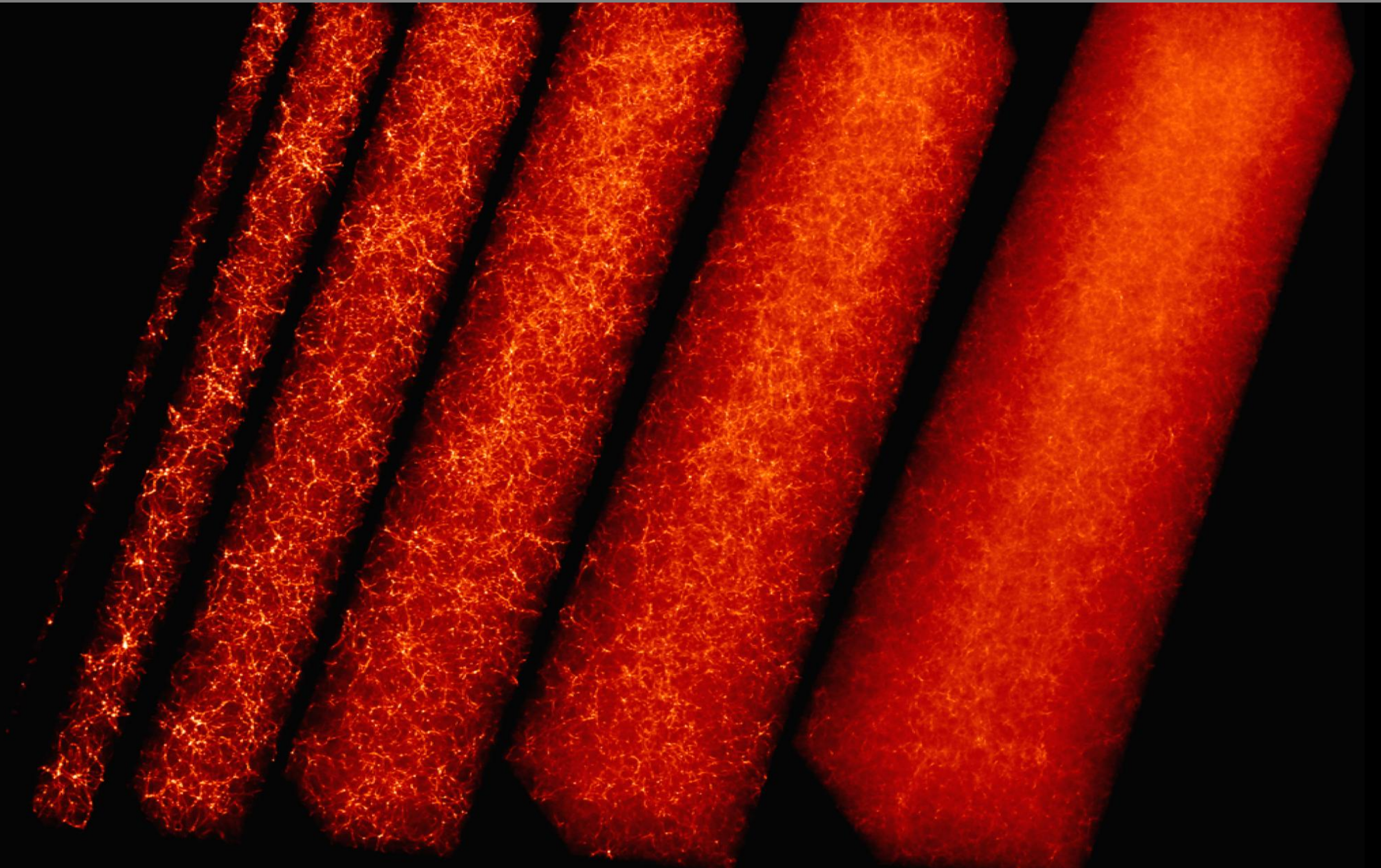
Cosmic Web



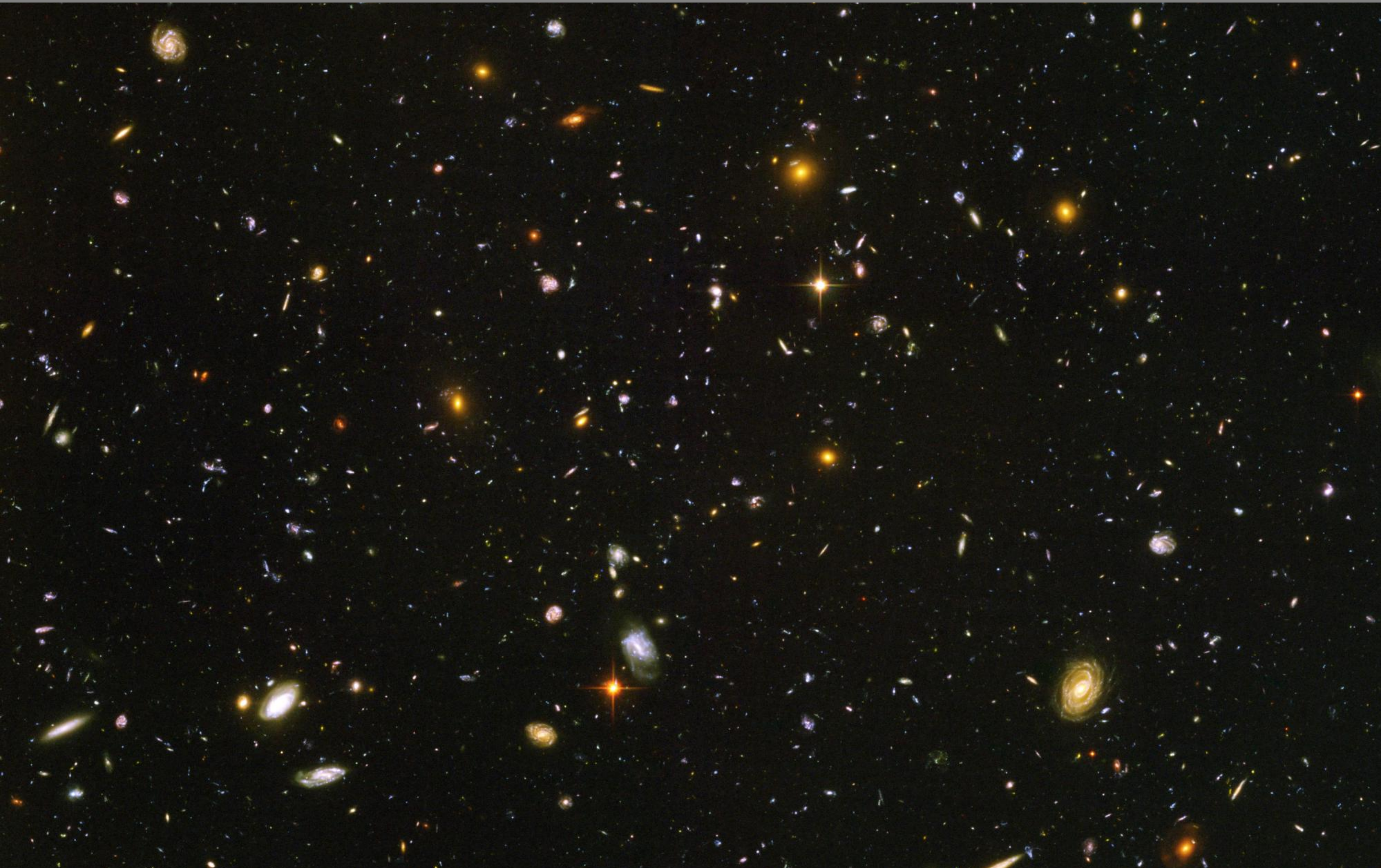
Cosmic Web



Cosmic Web



To the Depths of Universe



Megaparsec Scale Structure of the Universe

- Large Scale Structure of the Universe:

  crucial information for our understanding of
  structure formation in the Universe

- Dynamic Timescale ~ Hubble Time (age Universe):

  Megaparsec structures have evolved only mildly,
  so that one may infer their formation & evolution,
  and link to conditions primordial Universe

- Compare timescales:

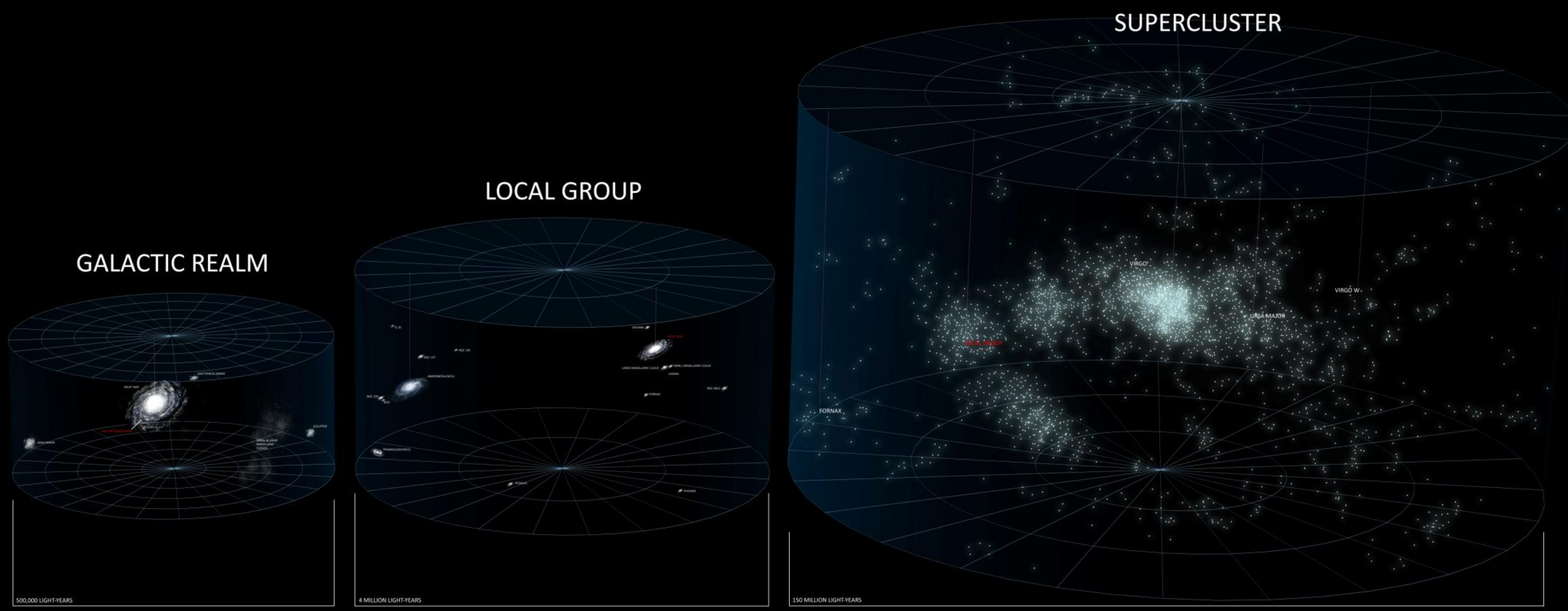
solar system	~ 1 yr
galaxy	~ 10^8 yr
clusters	~ 10^9 yr
Megaparsec structures	~ 10^{10} yr

Cosmic Fossil

Journey along the Large-Scale Universe:

Step by Step

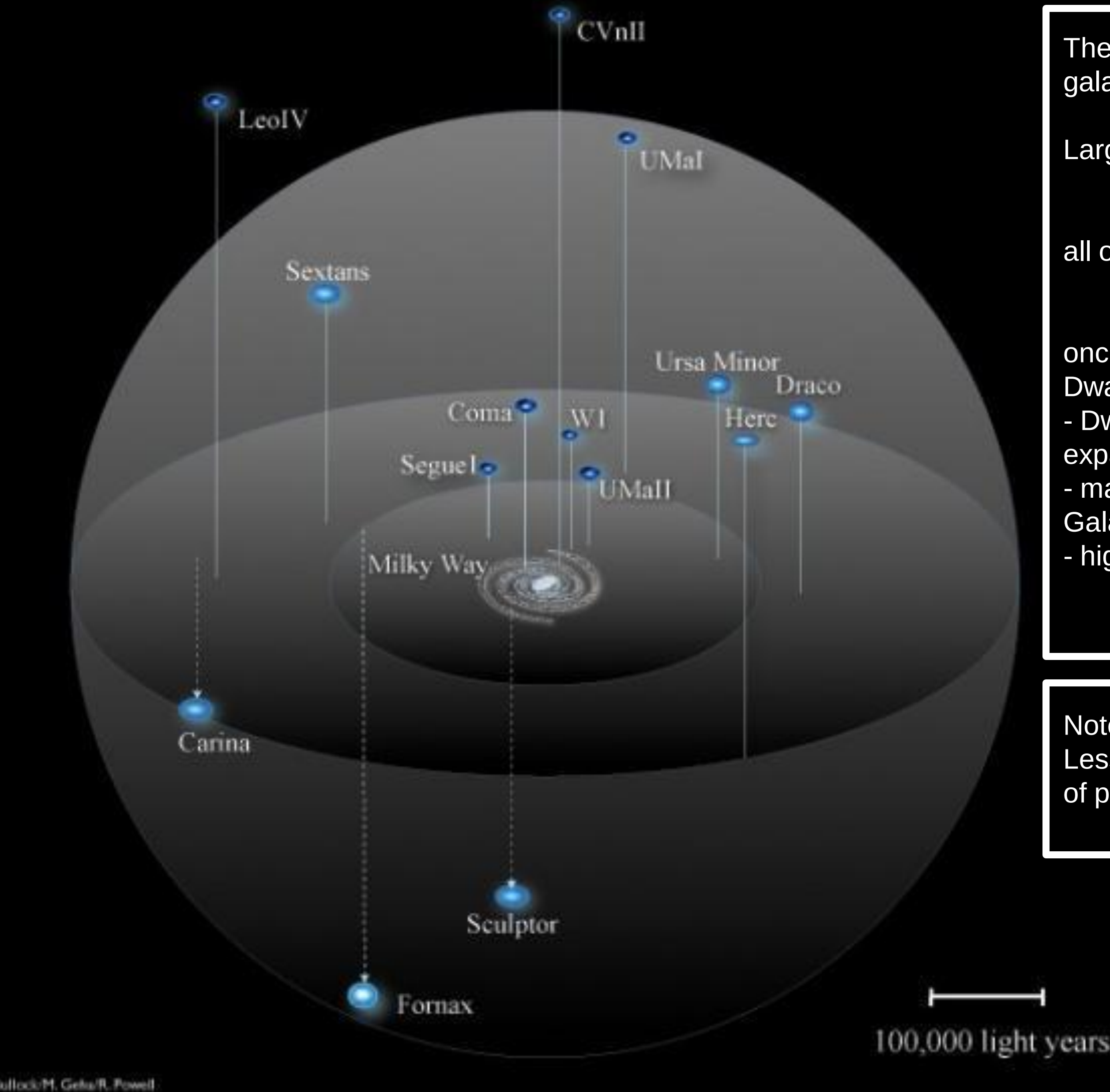
Local Universe: step by step



the Milky Way System:

the Galactic Satellites

Milky Way Satellites



The Milky Way has at least ~14 satellite galaxies.

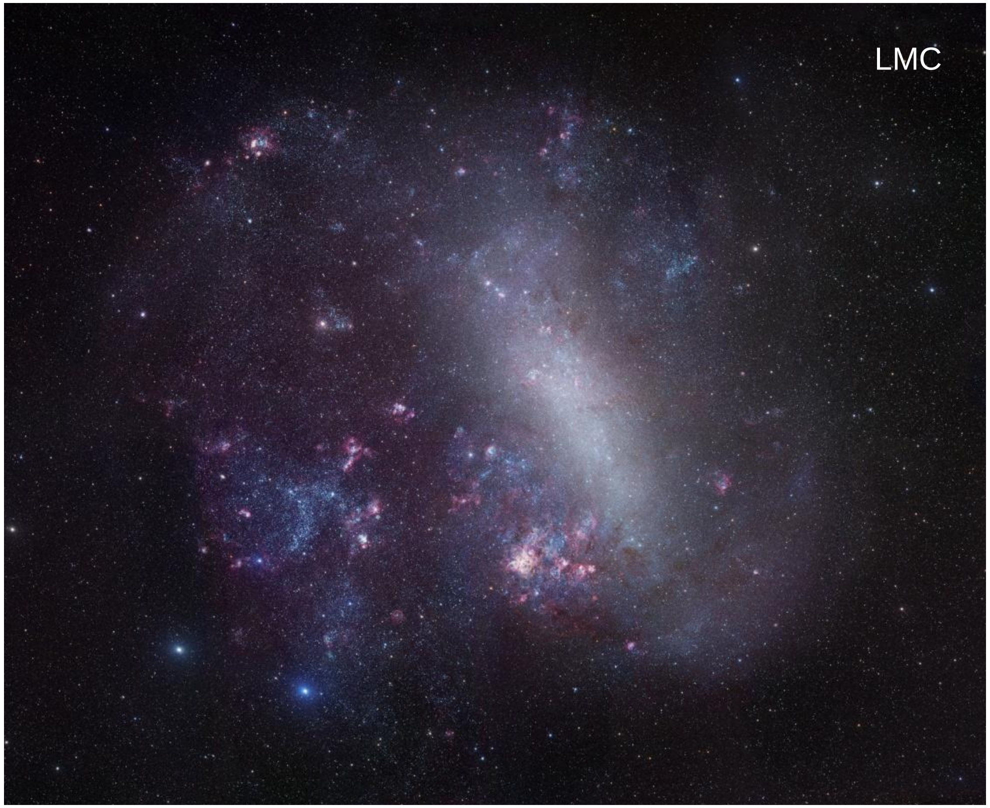
Large & Small Magellanic Clouds:
Irregular galaxies

all other satellite galaxies:
Dwarf Spheroidal

once thought of as globulars,
Dwarf spheroidals differ on 3 major aspects:
- Dwarf Galaxies contain old stars of a more expanded variety
- mass-to-light ratio much higher in Dwarf Galaxies (significant amounts of dark matter)
- higher abundance of iron than globulars

Note:
Less dwarf satellites than expected on behalf of present theories of galaxy formation

Milky Way Satellites



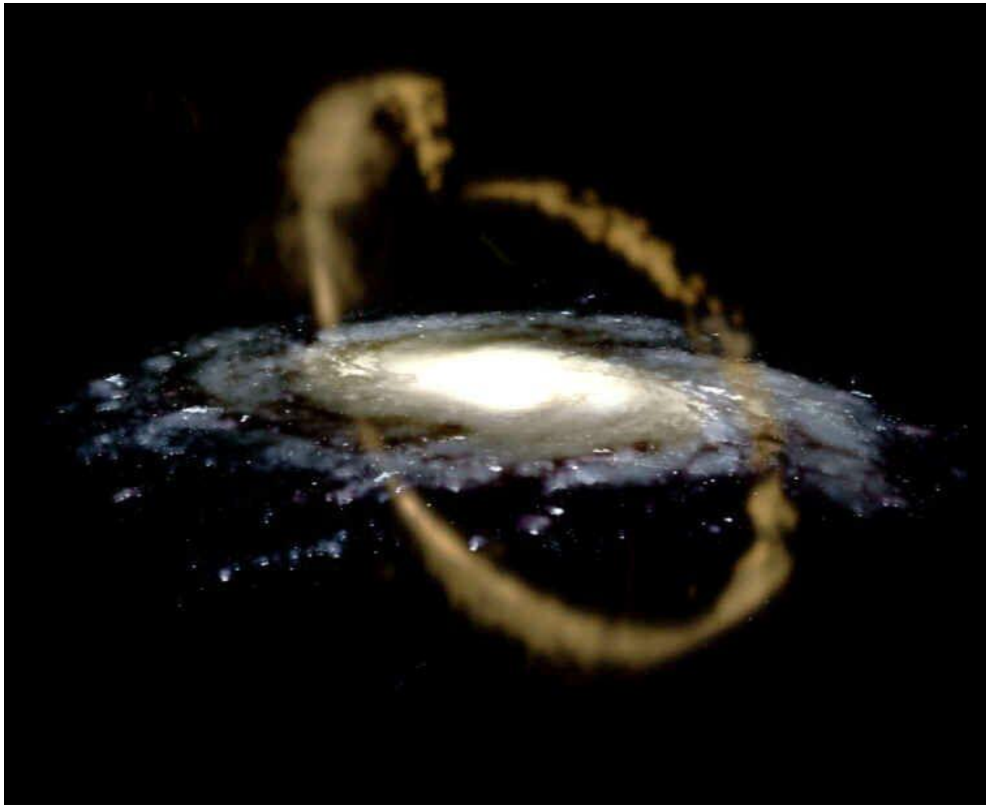
The Milky Way has at least ~14 satellite galaxies.

Large & Small Magellanic Clouds: Irregular galaxies

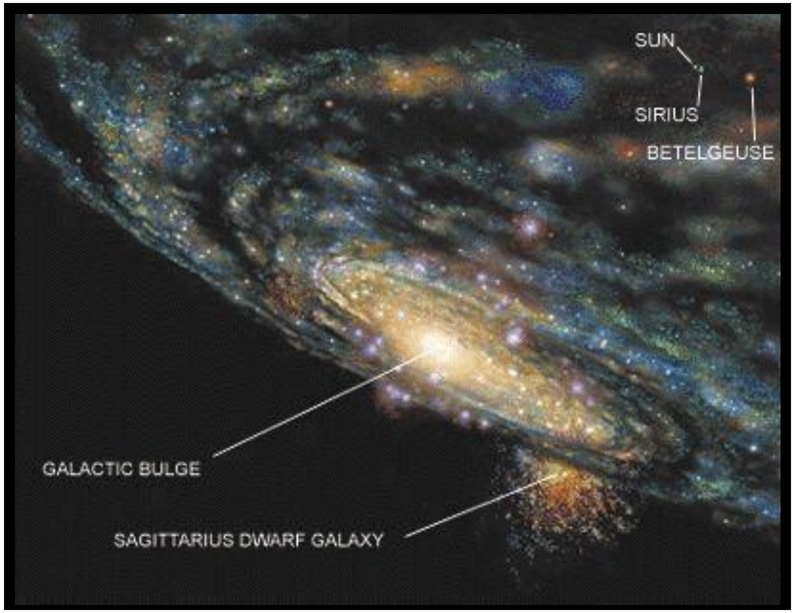
all other satellite galaxies: Dwarf Spheroidal

Sculptor Dwarf Galaxy

Sagittarius Dwarf Galaxy



Nearest known neighbour to Galaxy:
central cluster (old population II) +
loop-shaped structure wrapping around Galaxy



Based on current trajectory:

- Sag DEG main cluster is about to pass through the galactic disc of Milky Way within next 100 Myr
- extended loop-shaped ellipse already extended around and through our local space and on through the Milky Way galactic disc
  (will be slowly absorbed into Milky Way)

Globulars:
- 4 globular clusters (incl. M54)
- dynamically linked to 3 young globulars

Multiple stellar populations:
- very oldest globular cluster populations
- stars as young as ~ 100 Myr


Groups

Groups of Galaxies

- Smallest aggregates of galaxies
- Typically : <~ 50 galaxies
- Diameter: D~ 1- 2 Mpc (see 10^{22} m for distance comparisons). Their
- Mass : $M \sim 10^{13}\ M_\odot$
- Velocity Dispersion: v~ 150 km/s

- However, this definition should be used as a guide only, as larger and more massive galaxy systems are sometimes classified as galaxy groups.

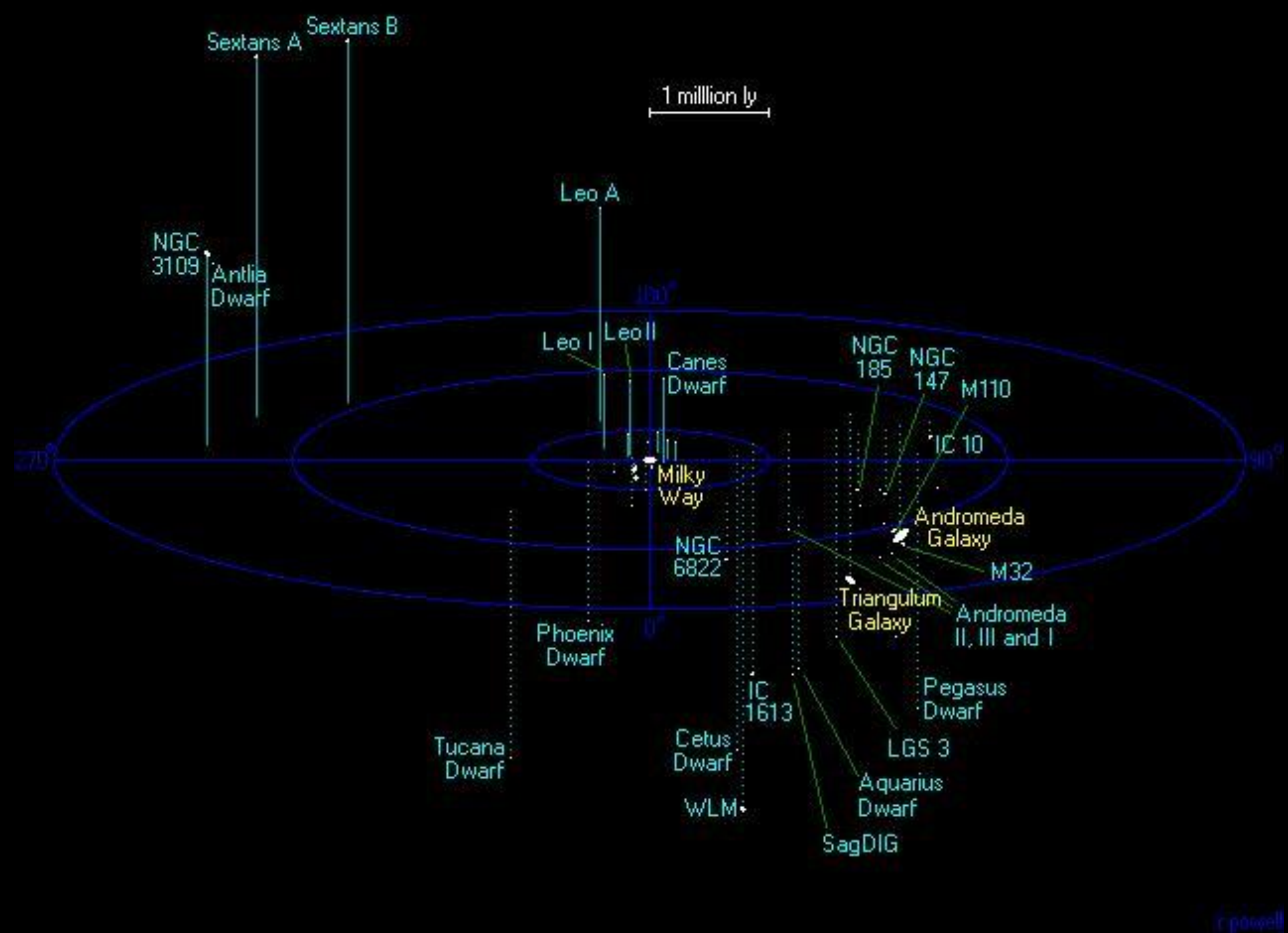
- Milky Way: member of Local Group,
  ~ 40 galaxies
- Nearby Groups: M81 group, Sculptor group, Maffei group

- Compact Groups:
  small, relatively isolated, system of typically ~4-5 galaxies
  in close proximity

Local Group

the Milky Way Family

Local Group



Sextans A
Sextans B
1 milllion ly
Leo A
NGC 3109
Antlia Dwarf
Leo I
Leo II
Canes Dwarf
NGC 185
NGC 147
M110
IC 10
270°
90°
Milky Way
Andromeda Galaxy
NGC 6822
M32
Triangulum Galaxy
Andromeda II, III and I
Phoenix Dwarf
IC 1613
Pegasus Dwarf
Tucana Dwarf
Cetus Dwarf
LGS 3
Aquarius Dwarf
WLM
SagDIG

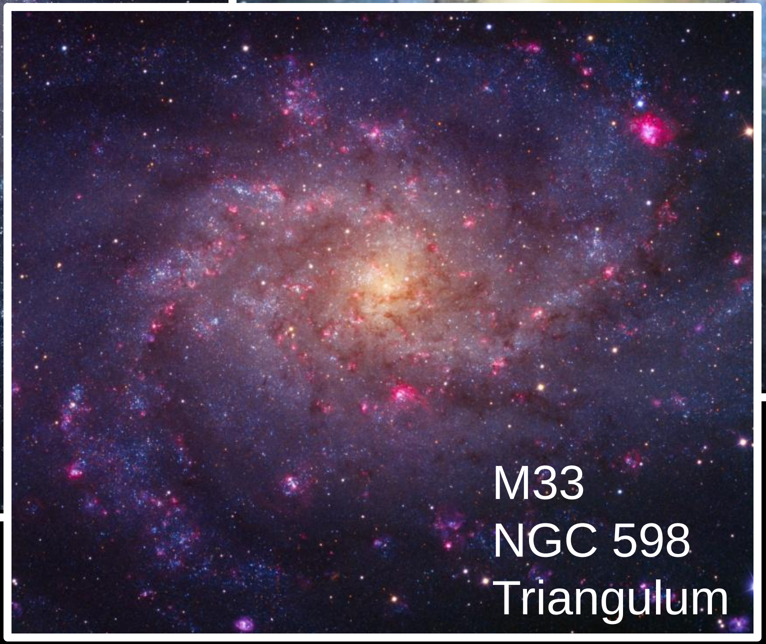
Local Group

- The **Local Group** is the group of galaxies that includes our galaxy,
  the Milky Way
- The group comprises ~ 36-40 galaxies,
  incl. dwarf galaxies
- Gravitational center located somewhere between
  the Milky Way and the Andromeda Galaxy M31
- The two most massive members of the group are
  - the Milky Way & Andromeda Galaxy M31
  - additional major galaxy is Triangulum M33
  - all these are spiral galaxies
  - Milky Way & M31 have each a system of satellite galaxies,
    M33 perhaps 1 satellite (Pisces Dwarf)
- The other members of the group are gravitationally secluded from these large subgroups:

  IC10, IC1613, Phoenix Dwarf, Leo A, Tucana Dwarf, Cetus Dwarf, Pegasus Dwarf Irregular,
  Wolf-Lundmark-Melotte, Aquarius Dwarf & Sagittarius Dwarf Irregular

Local Group

Group Portrait



Local Group

- Milky Way satellites:
  - Sagittarius Dwarf Galaxy
  - Large Magellanic Cloud (LMC)
  - Small Magellanic Cloud (SMC)
  - Canis Major Dwarf
  - Ursa Minor Dwarf
  - Draco Dwarf , Carina Dwarf,
  - Sextans Dwarf, Sculptor Dwarf,
  - Fornax Dwarf,
  - Leo I, Leo II,
  - Ursa Major Dwarf

- M31 satellites:
  - M32,
  - M110,
  - NGC 147,
  - NGC 185,
  - And I, And II, And III,
  - And IV, And V,
  - Pegasus dSph,
  - Cassiopeia Dwarf,
  - And VIII, And IX, And X.

- Diameter Local Group: $D_{LG} \sim 3$ Mpc
- Binary (dumbbell) shape
- Mass Local Group: $M_{LG} \sim 1.29 \pm 0.14 \times 10^{12} M_{\odot}$.
- The group itself is one of many density clumps within the Local Supercluster

Clusters

Clusters of Galaxies

- Assemblies of up to 1000's of galaxies within a radius of only

  $R \sim 1.5\text{-}2h^{-1}$ Mpc,
- Total masses:

  $M \sim 10^{14}\ M_{\odot}$
- Representing overdensities of $\Delta \sim 1000$
- Galaxy move around with velocities

  $v \sim 1000$ km/s
- They are the most massive, and most recently, fully collapsed structures in our Universe.

Clusters of Galaxies

Courtesy:
O. Lopez-Cruz

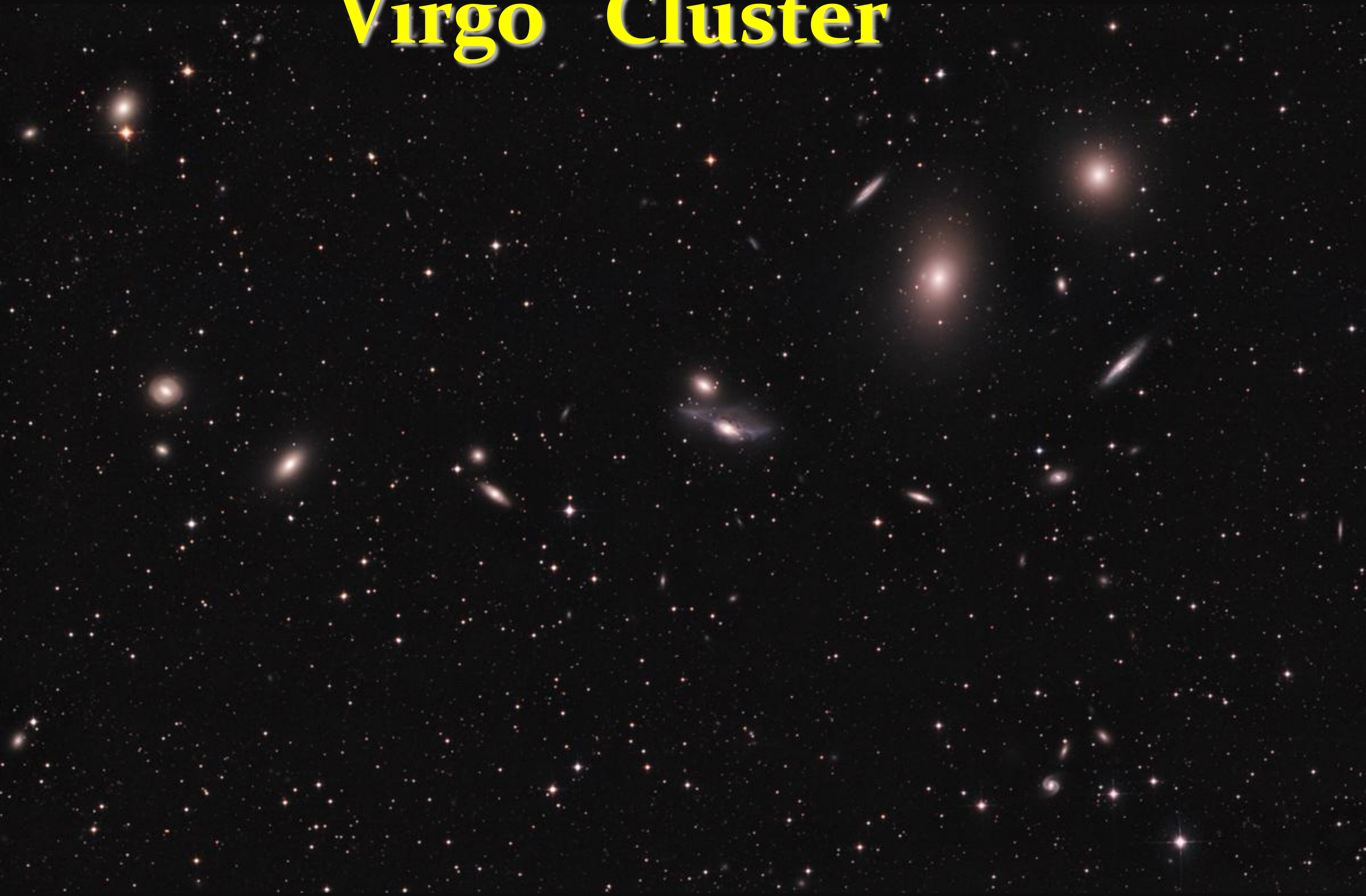
Coma Cluster

Studying Clusters

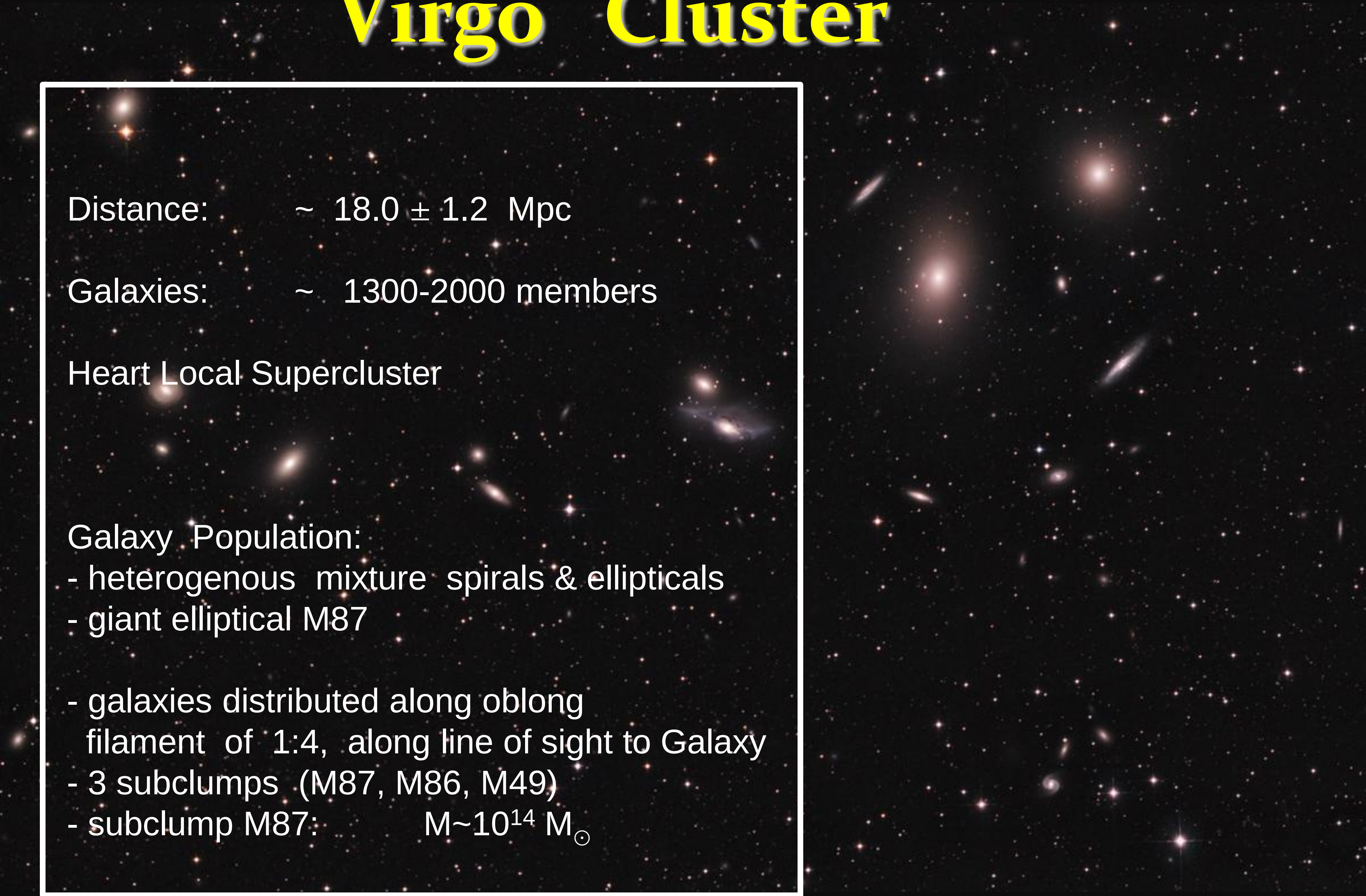
Includes many different aspects of these versatile astrophysical laboratories:

- Optical/Infrared/Ultraviolet
  - Galaxy Population:
    spatial distribution, kinematics, galaxy morphology
- X-ray observations
  - (hot, ionized) intracluster gas
  - distribution (density, temperature): cluster mass
  - abundances heavy elements (enrichment)
- Sunyaev-Zel'dovich effect:
  - "cluster shadows" in cosmic microwave background radiation
  - CMB microwave wavelength region
  - intracluster gas (pressure)
  - peculiar motion cluster (kinematic SZ)
- Gravitational Lensing
  - mainly optical, also radio, submm, …
  - strong lensing (arcs, rings), weak lensing (sheared images)
  - dark matter mass
  - dark matter distribution
- Radio wavelengths
  - radio halos, radio relics
  - synchroton radiation in shocked, hot, ionized intracluster plasma

Virgo Cluster



Virgo Cluster



Distance: ~ 18.0 ± 1.2 Mpc

Galaxies: ~ 1300-2000 members

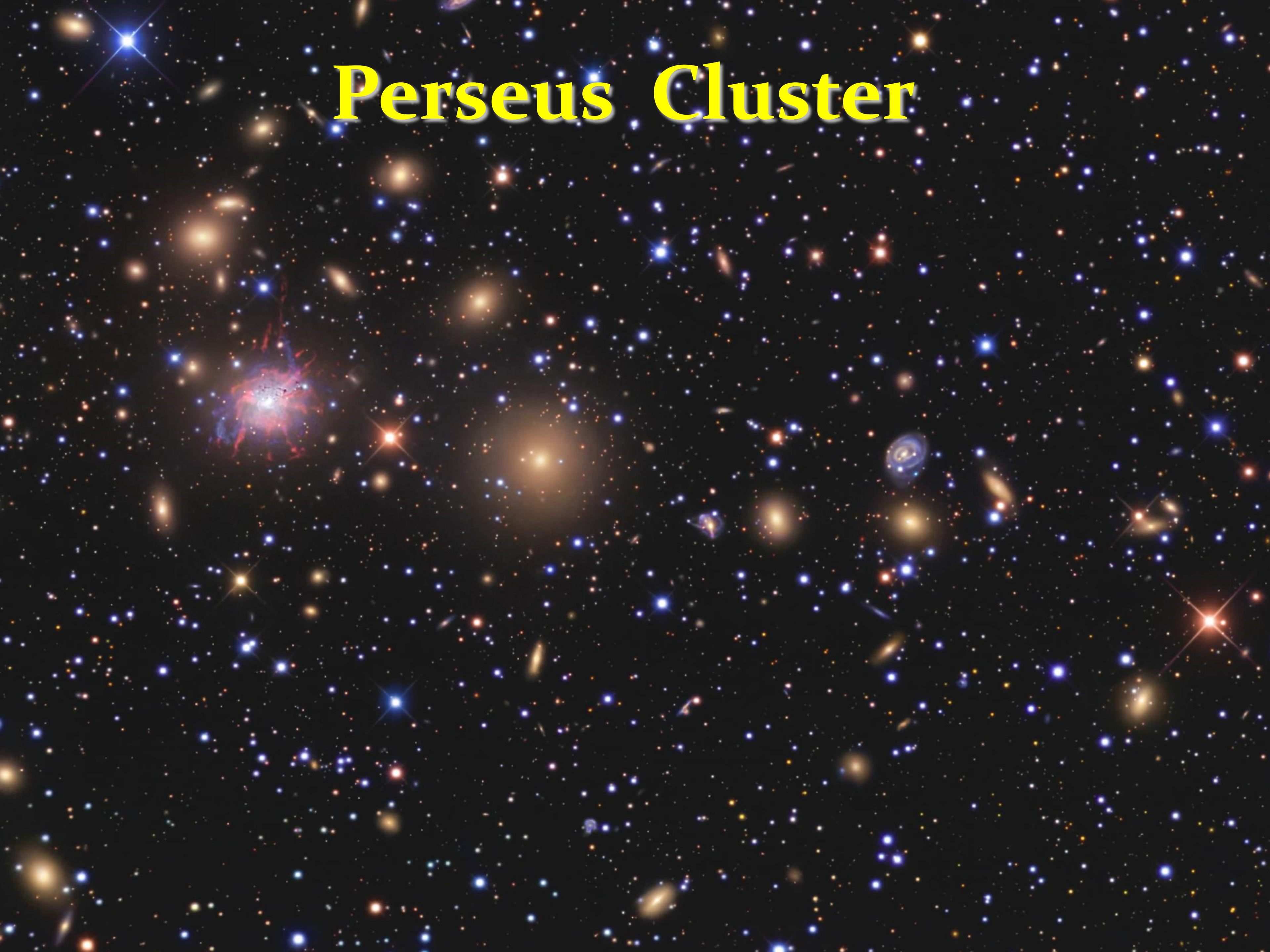
Heart Local Supercluster

Galaxy Population:
- heterogenous mixture spirals & ellipticals
- giant elliptical M87

- galaxies distributed along oblong filament of 1:4, along line of sight to Galaxy
- 3 subclumps (M87, M86, M49)
- subclump M87: $M \sim 10^{14} M_{\odot}$


Coma Cluster

Perseus Cluster



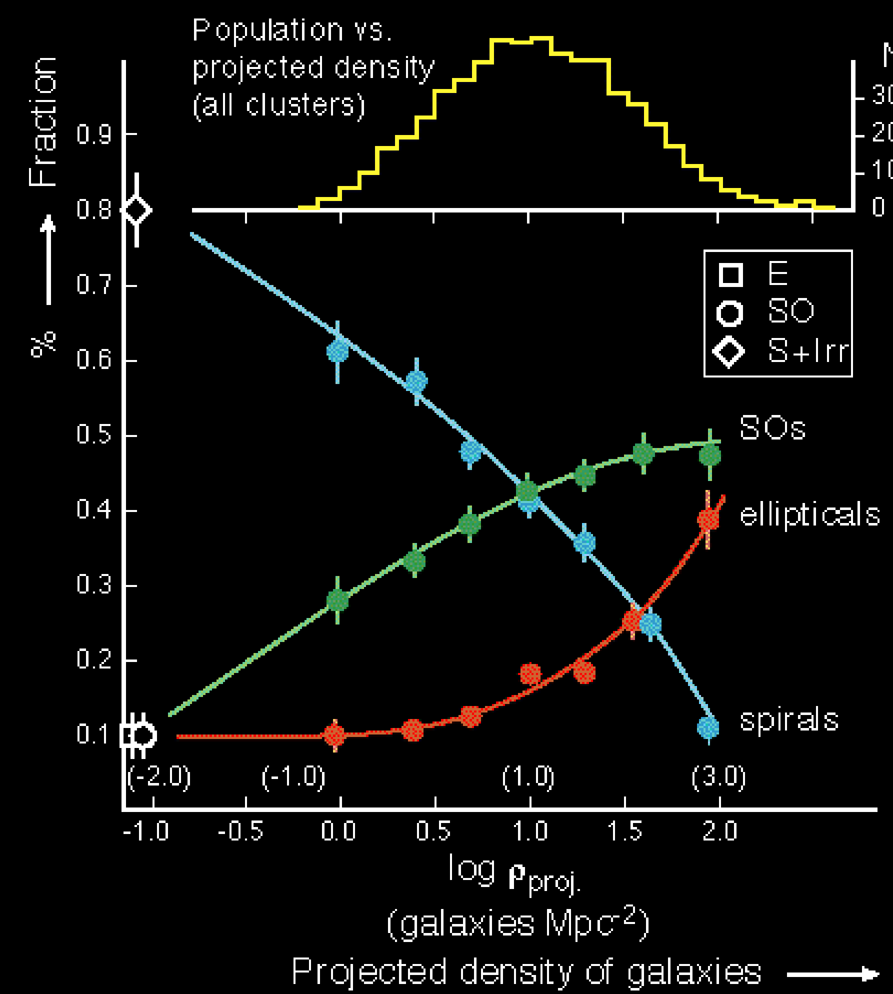
Hercules Cluster

Density-Morphology Relation

Outstanding
relation between cosmic
environment and galaxies:

- Density-Morphology Relation

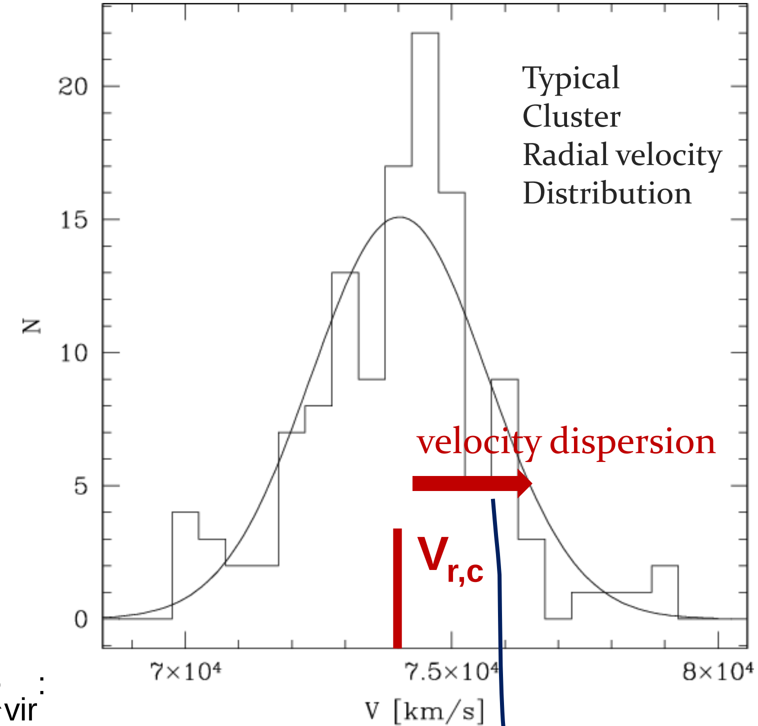
- Dense regions (clusters):
  early-type galaxies
  (ellipticals, SO,...)
- Lower Density areas:
  late-type galaxies
  (spirals, irregulars)
- From clusters to voids
- reflection of effects
  galaxy interactions
  (more frequent high
  densities)



Cluster Galaxy Motions

Clusters of galaxies:
close to virial equilibrium

$$E_{pot} = -2E_{kin}$$



Implicit assumptions:
- Cluster is in virial equilibrium
- measurements span reasonable range cluster
- all bodies same mass (or, fudge factors)
- velocity distribution isotropic

For a cluster with N galaxies within virial radius R_{vir}:

$$E_{kin} = \frac{1}{2}\sum_{i=1}^{N} m_i(\vec{v}_i - \vec{v}_c)^2 = \frac{3}{2}\sum_{i=1}^{N} m_i(v_{r,i} - v_{r,c})^2$$

$$E_{pot} = -\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{Gm_i m_j}{\left|\vec{r}_i - \vec{r}_j\right|}$$

$$E_{kin} \approx \frac{3}{2} M_{tot} \left\langle v_r - v_{r,c}{}^2 \right\rangle$$

$$M_{tot} = \sum_{i=1}^{N} m_i$$

$$E_{pot} \approx -\frac{1}{2} G \frac{M_{tot}{}^2}{R_{vir}}$$

$$\Rightarrow M_{tot}$$

Clusters of Galaxies

- Clusters not only contain galaxies:
- in fact, galaxies & stars are a minor component:

I. Clusters are Halos of Dark Matter:

$$M_{DM}/M_{total} \sim 82\%$$

II. Clusters are Hot Balls of (highly ionized) Gas

$$M_{ICM}/M_{total} \sim 16\text{-}17\ \%$$

III. Galaxies are mainly raisins in a sea of dark matter & hot gas

$$M_{stars}/M_{total} \sim 2\%$$

Clusters of Galaxies: X-ray intracluster gas

Baryonic matter in clusters is not only confined to galaxies:

~ 2 to 5 times more baryonic mass in the form of a diffuse hot X-ray emitting

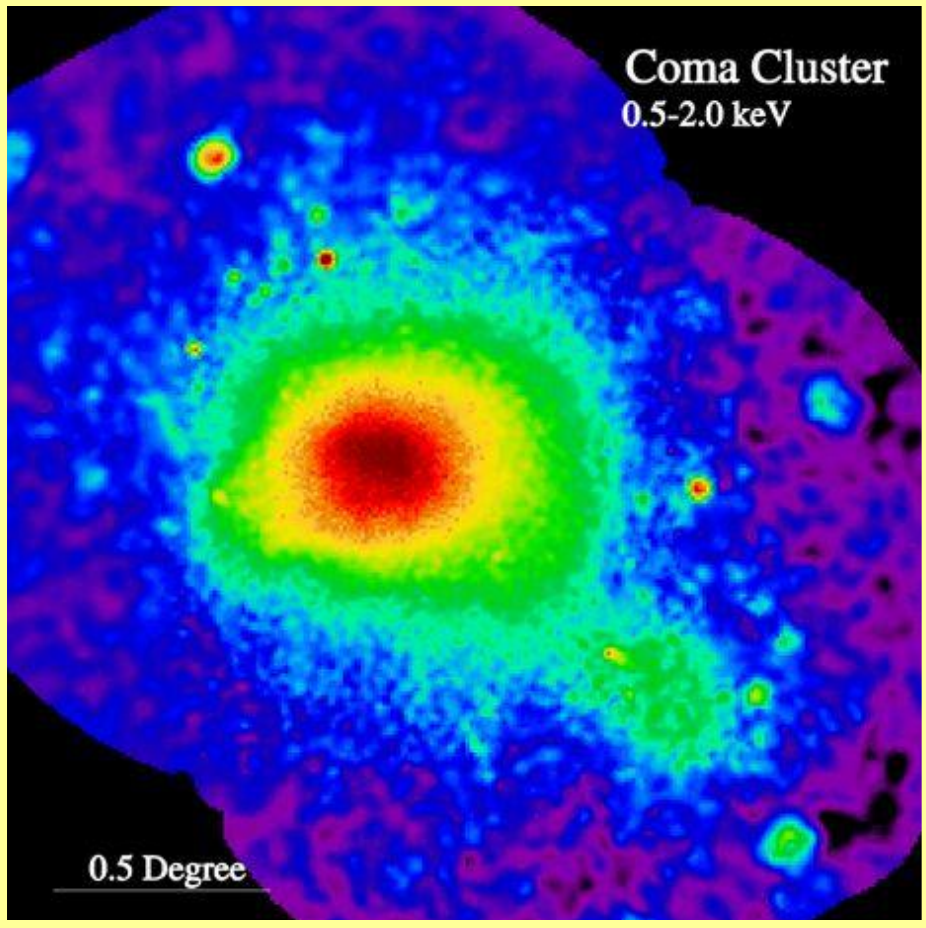
Intracluster Gas,

trapped and heated to a temperature of the order of

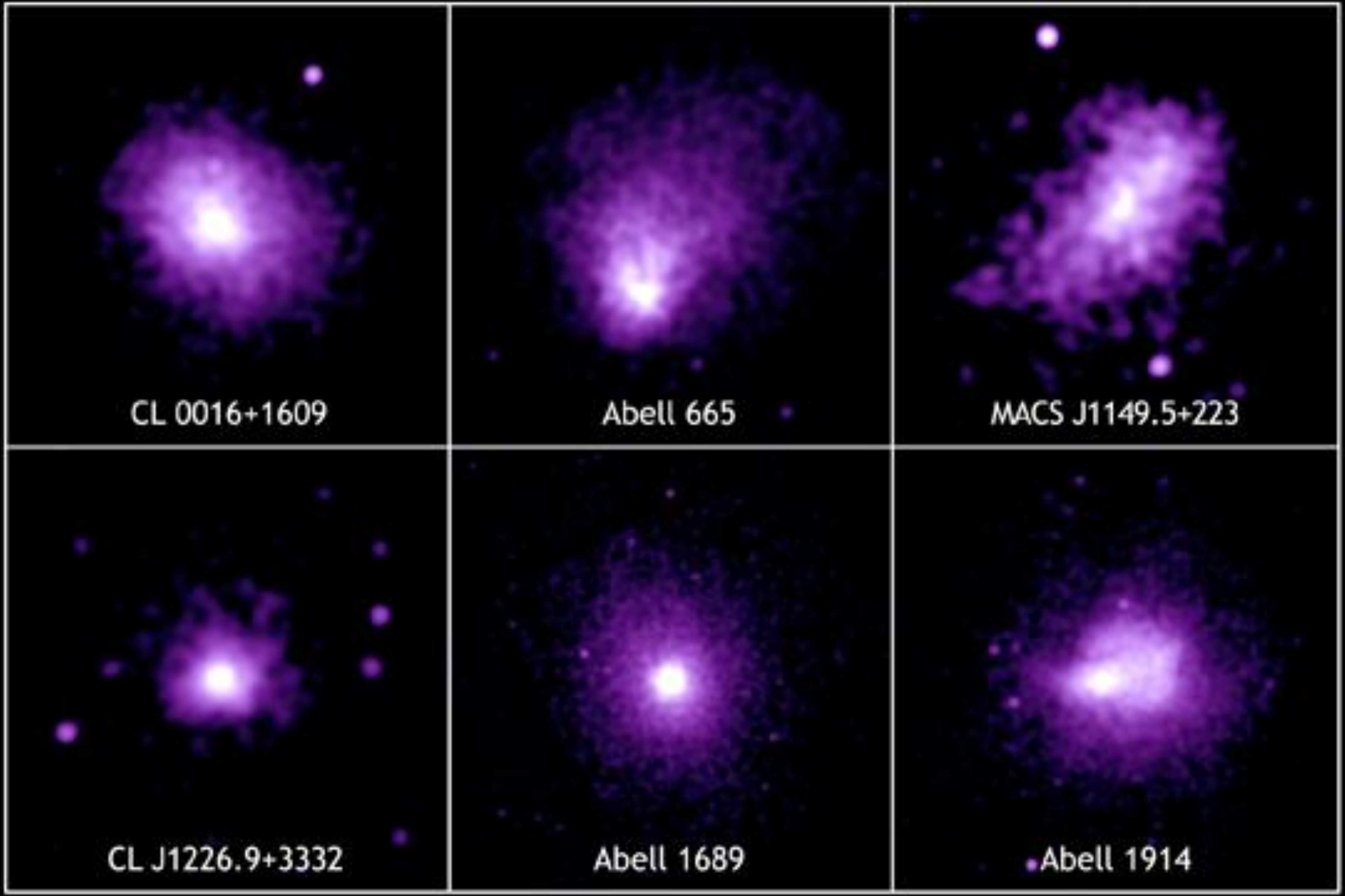
$T \sim 10^8$ K

by the gravitational potential of the cluster.

At such high temperatures, this gas is a fully ionized plasma, producing powerful X-ray emission, bremsstrahlung radiation induced by the electron-ion interactions.



ROSAT X-ray image Coma Cluster


CL 0016+1609
Abell 665
MACS J1149.5+223
CL J1226.9+3332
Abell 1689
Abell 1914

Cluster Mass: X-ray intracluster gas

Hydrostatic Equilibrium:

$$\frac{GM(r)}{r^2} = -\frac{k_B T}{\mu m_H}\left[\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right]$$

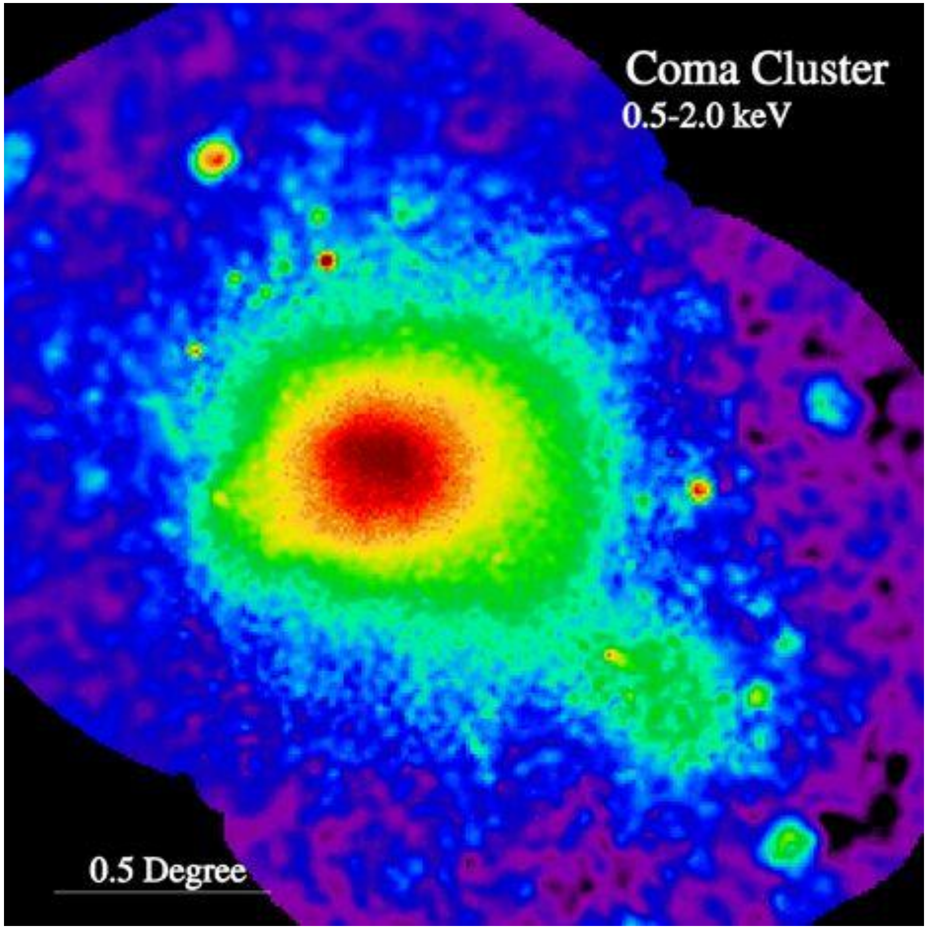
Determination Mass from X-ray observations:

-assumption:

Isothermal: $T(r)=T_o$

-density profile:

X-ray emission Bremsstrahlung: $L(r) \sim \rho(r)^2$



ROSAT X-ray image Coma Cluster

Cluster Mass: X-ray intracluster gas

Keeping in mind that X-ray emission confined to the deepest parts of the potential well

(within inner R~1.5h^{-1} Mpc)

Typical mass for clusters:

- $M_{total} \approx 5 \times 10^{14} - 5 \times 10^{15} \, M_{\odot}$
- $\frac{M_{star}}{M_{total}} \sim 1 - 2\%; \quad \frac{M_{gas}}{M_{total}} \sim 16 - 17\%; \quad \frac{M_{DM}}{M_{total}} \sim 82\%$

Dark Matter dominates the mass budget in the Universe:

Mass-light ratio for clusters,

$$\frac{M}{L_B} \approx (450 \pm 100)h$$

Considerably higher than the value for a normal galaxy, $(M/L)_{gal}$~1-2

Cluster Formation

- Clusters form around peaks in the primordial density field
- Excess Gravity counteracts the Cosmic Expansion:
  slowdown of recession velocity surrounding matter
  turning into infall
- Growing mass of cluster strengthens its gravitational attraction:
  runaway growth of cluster
- Initially expanding cluster peak comes to a halt,
  - turns around into infall
  - contraction
  - collapse
  - after collapse the cluster virializes:
    exchange of energy to reach equilibrium
- See movie: - gas density evolution
  - movie Klaus Dolag

Cluster Formation

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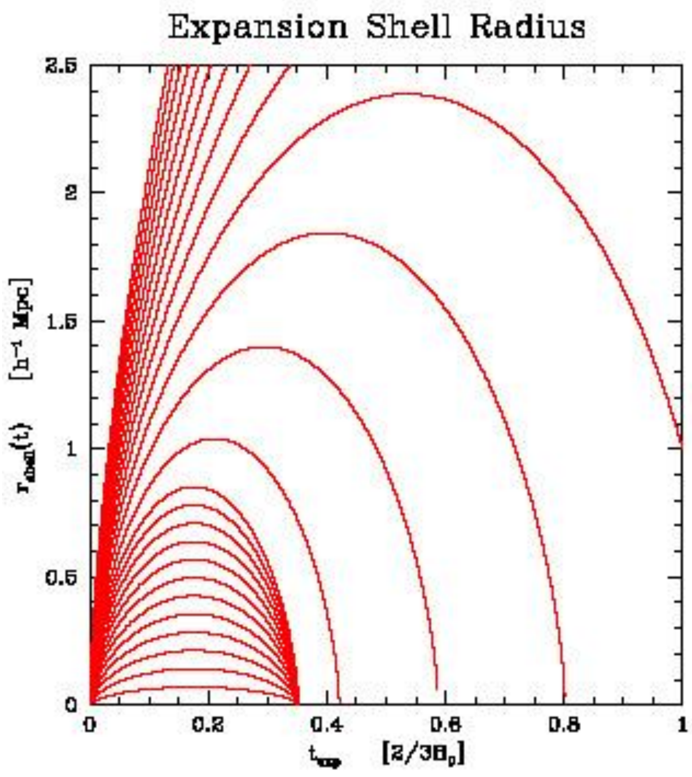
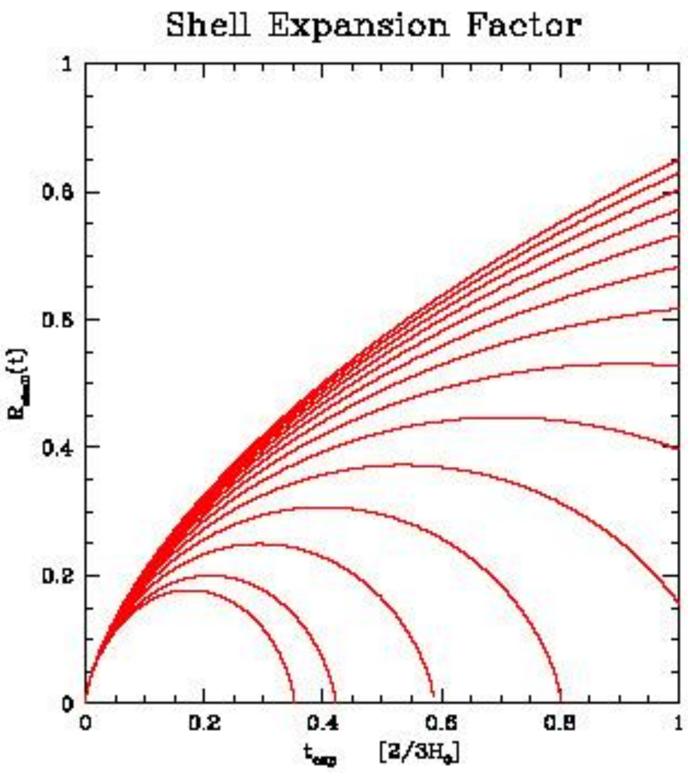




Cluster Formation, simulation,

movie, KlausDolag

Clusters of Galaxies: Gravitational Lenses

A highly promising method to determine the amount and distribution of

matter in the Universe

looks at the way it affects

the trajectories of photons

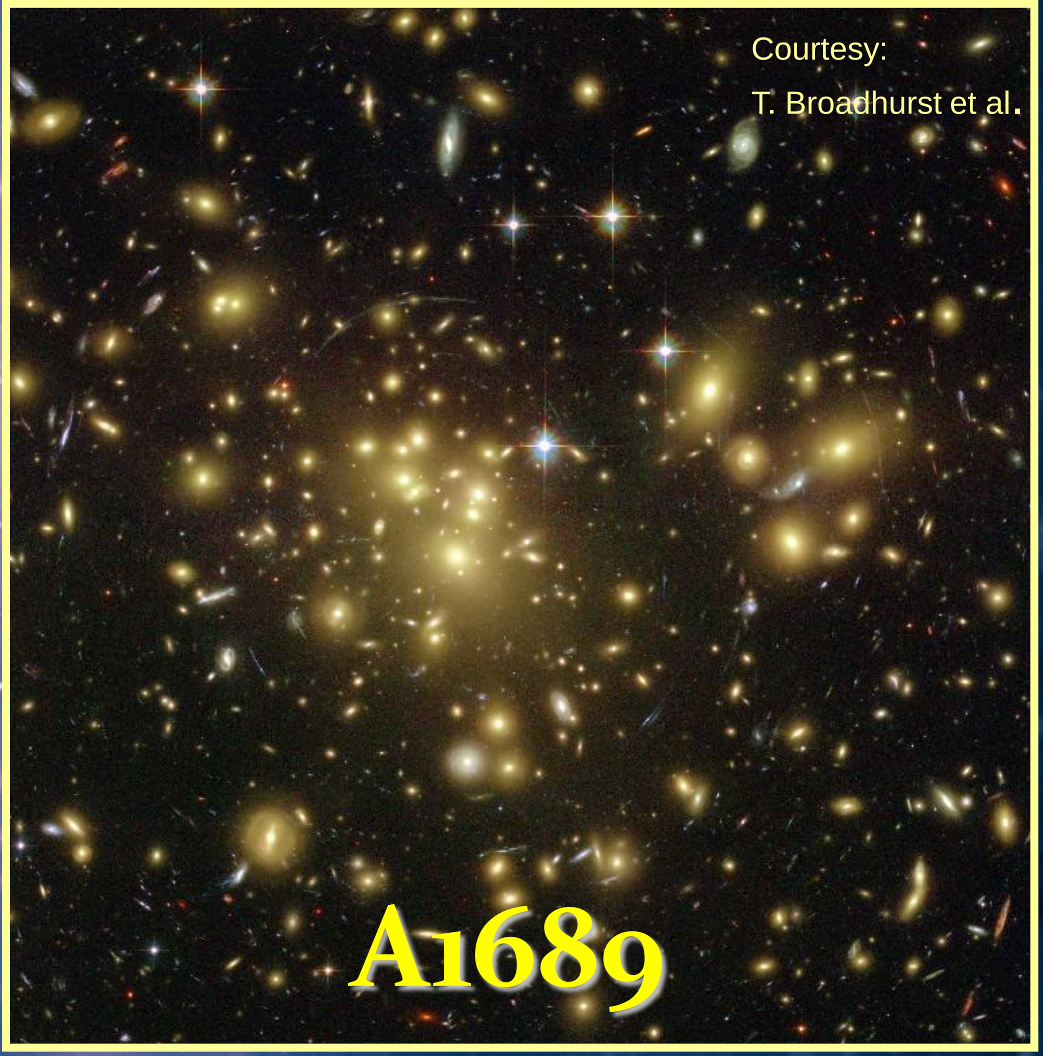
According to

Einstein's theory of

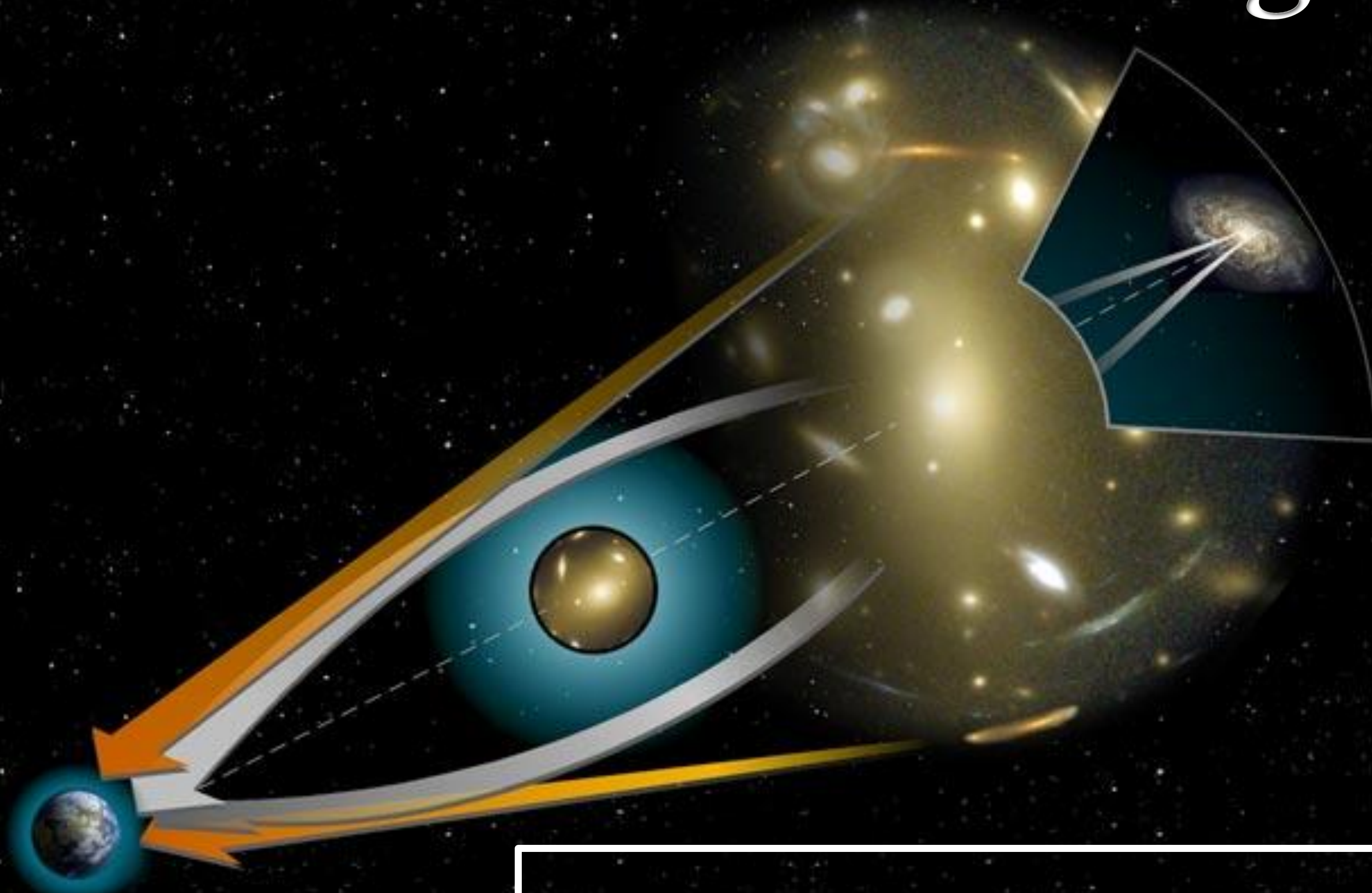
General Relativity,

gravitational potential wells will bend and focus light. Dark matter concentrations act as a

Gravitational Lens



Clusters: Gravitational Lensing



Geometry of Gravitational Lenses

Clusters: Gravitational Lensing

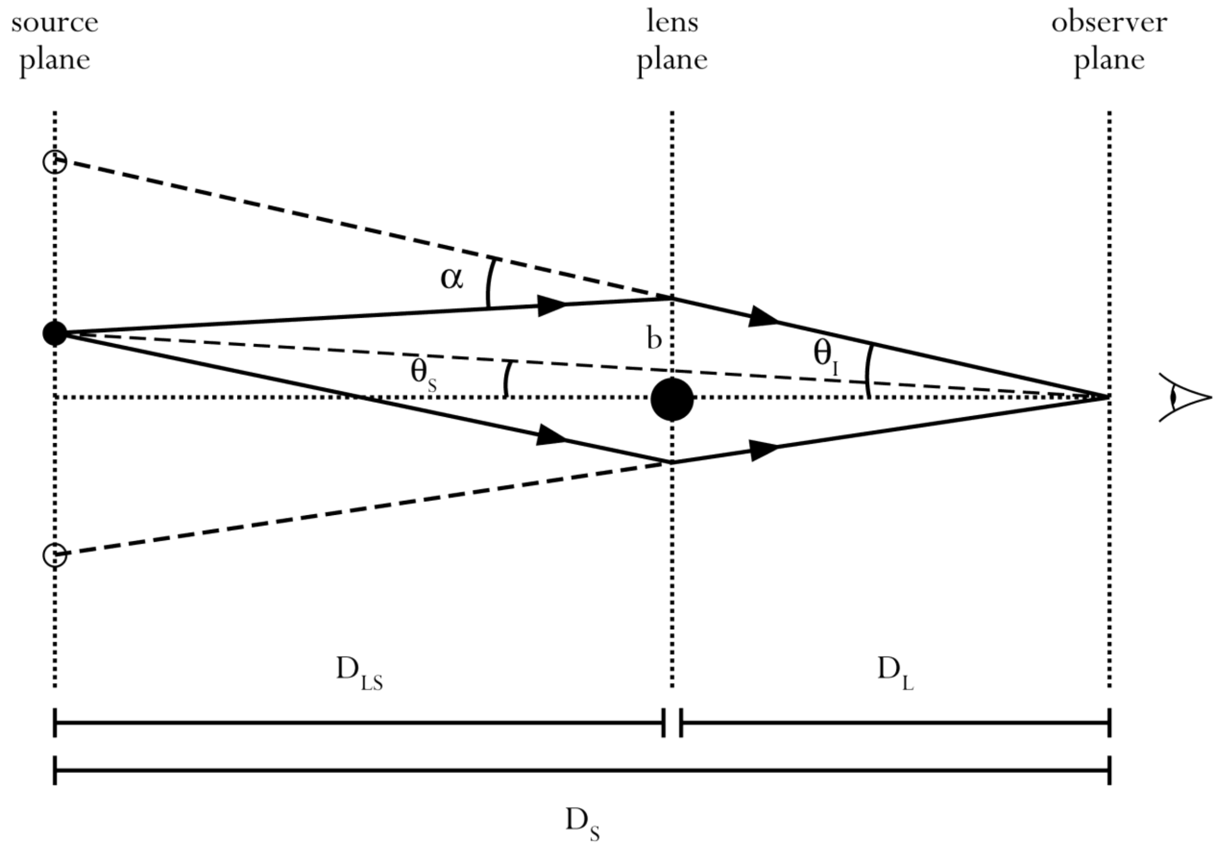
Point mass, mass M:

Gravitational deflection can be calculated from General Relativity.

For small angles α:

$$\alpha = \frac{4G}{c^2}\frac{M}{b}$$

b: impact parameter (closest distance beam to deflecting mass)



Geometry of Gravitational Lenses

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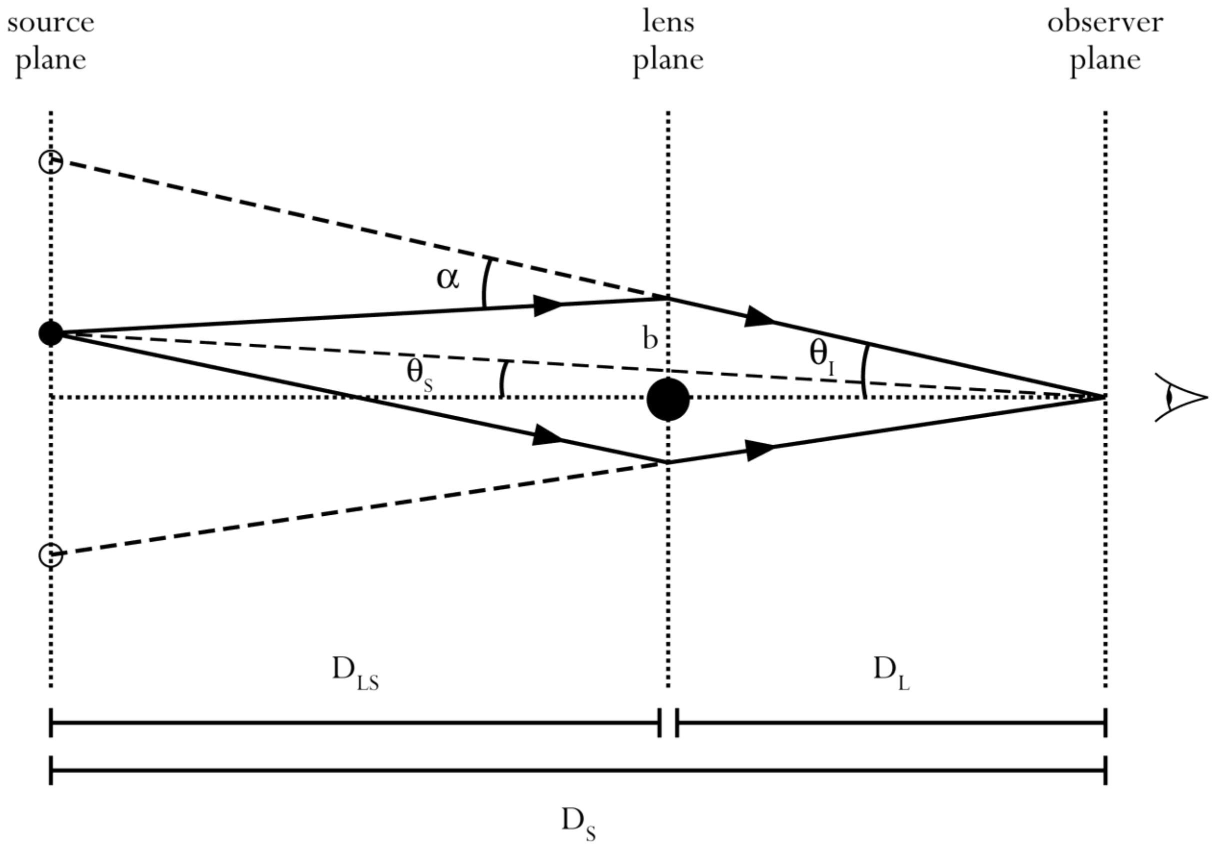
Illustration of Effect Gravitational Lens Background Galaxies

Clusters: Gravitational Lensing

Einstein Radius

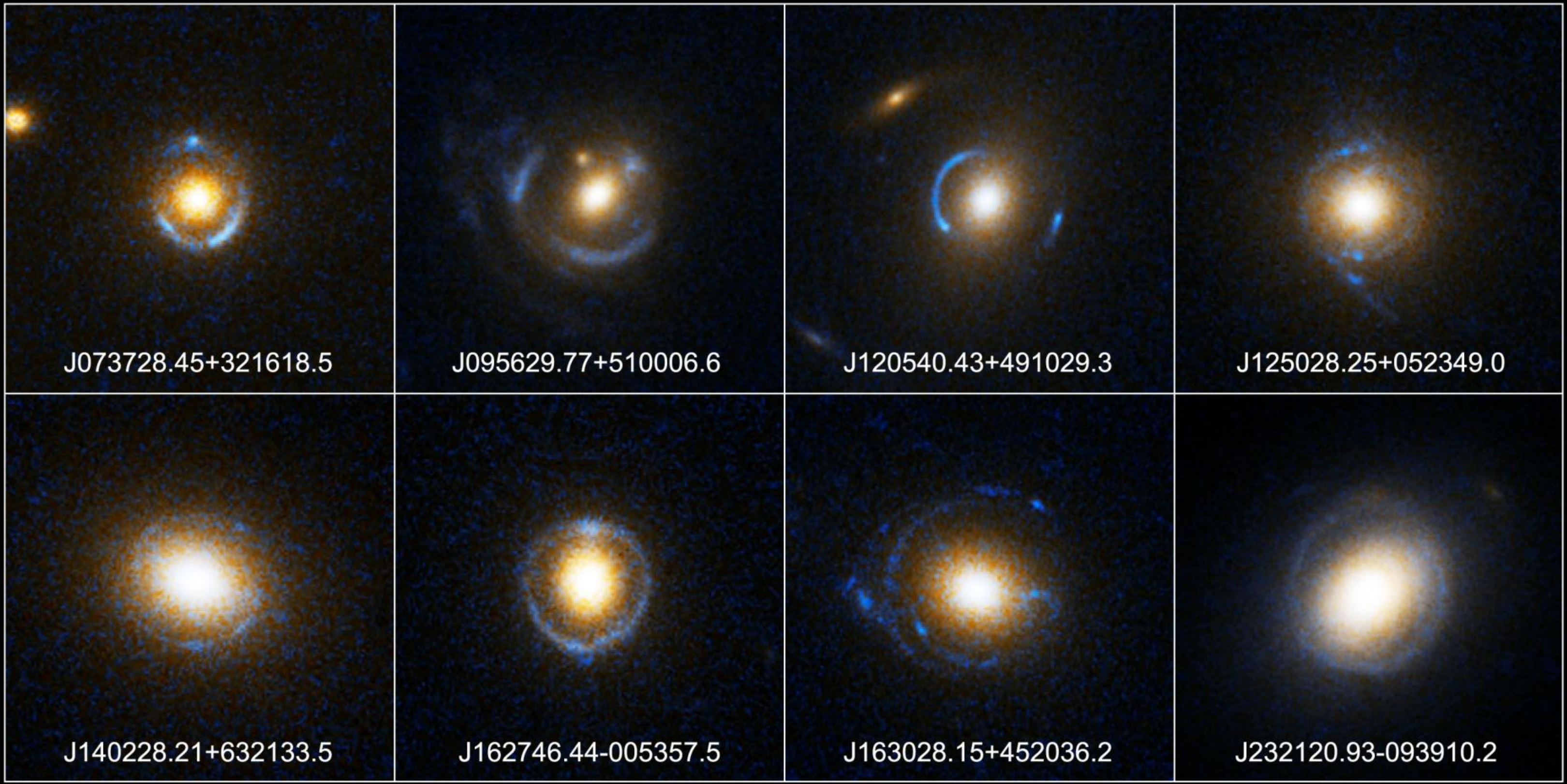
- radius of an Einstein Ring
- Einstein Ring: deformation light single source into ring as source, lens & observer aligned
- characteristic angle/radius of lensing

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_{LS}}{d_L d_S}}$$



Geometry of Gravitational Lenses

Gravitational Lensing: Einstein Ring



Einstein Ring Gravitational Lenses
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

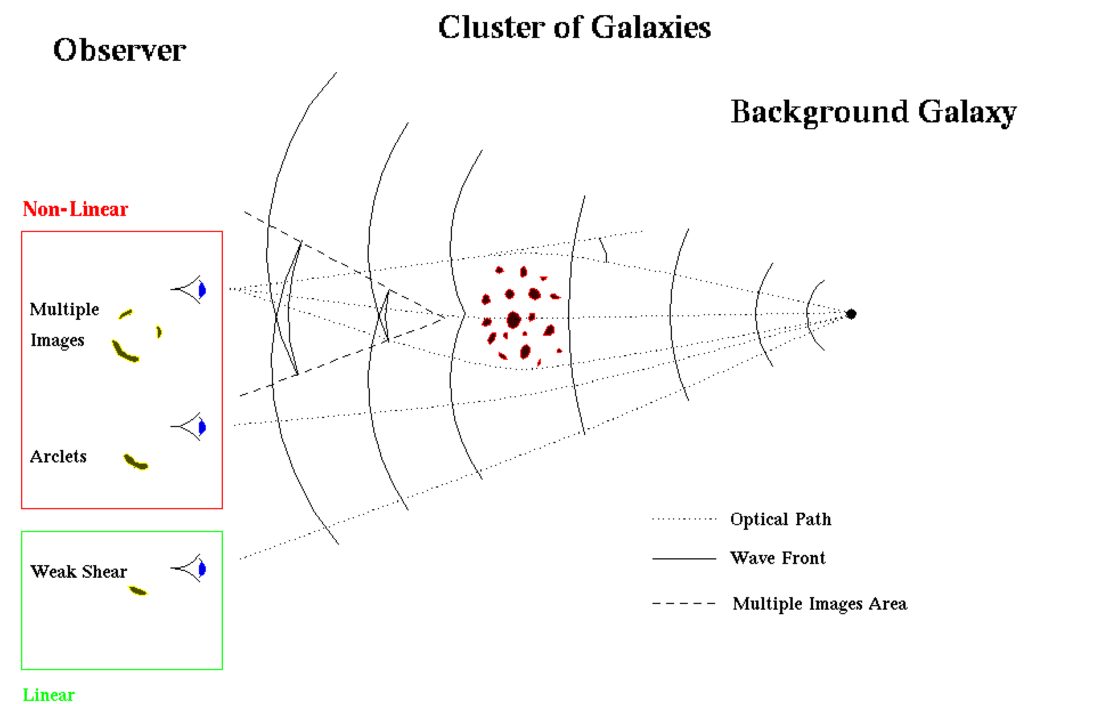
STScI-PRC05-32

Gravitational Telescopes: Weak vs. Strong Lensing

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{d_{LS}}{d_L d_S}}$$

Two kinds of lensing:

- **Strong Lensing:**
  $\theta < \theta_E$
  - nonlinear distortions
  - multiple image
- **Weak Lensing:**
  $\theta > \theta_E$
  - linear distortions
  - sheared images

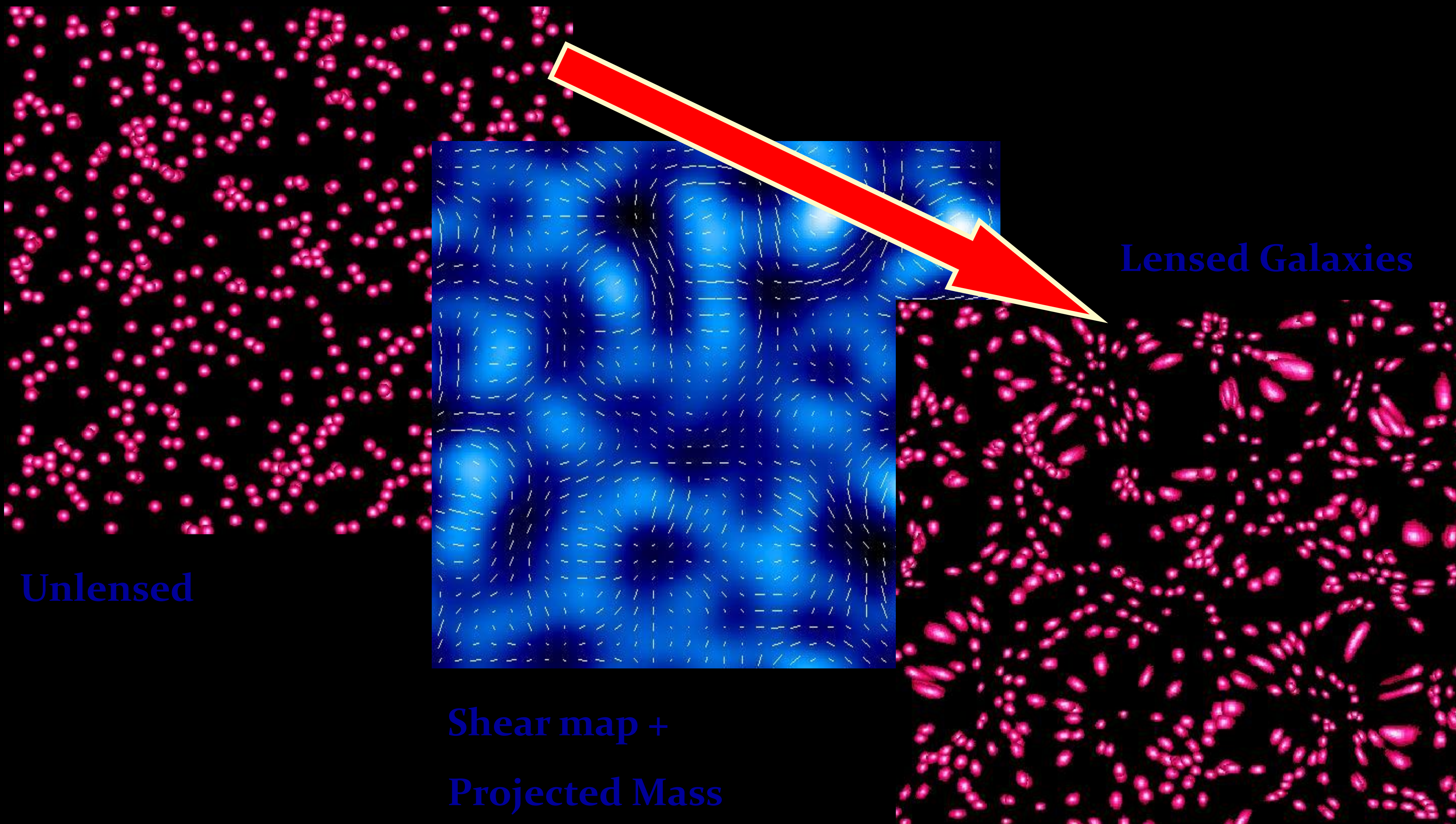


Cluster Mass determination:

Weak Lensing: Linear Inversion Distortion Field

Strong Lensing: Complex Modeling density distribution. non-trivial

Weak Gravitational Lensing



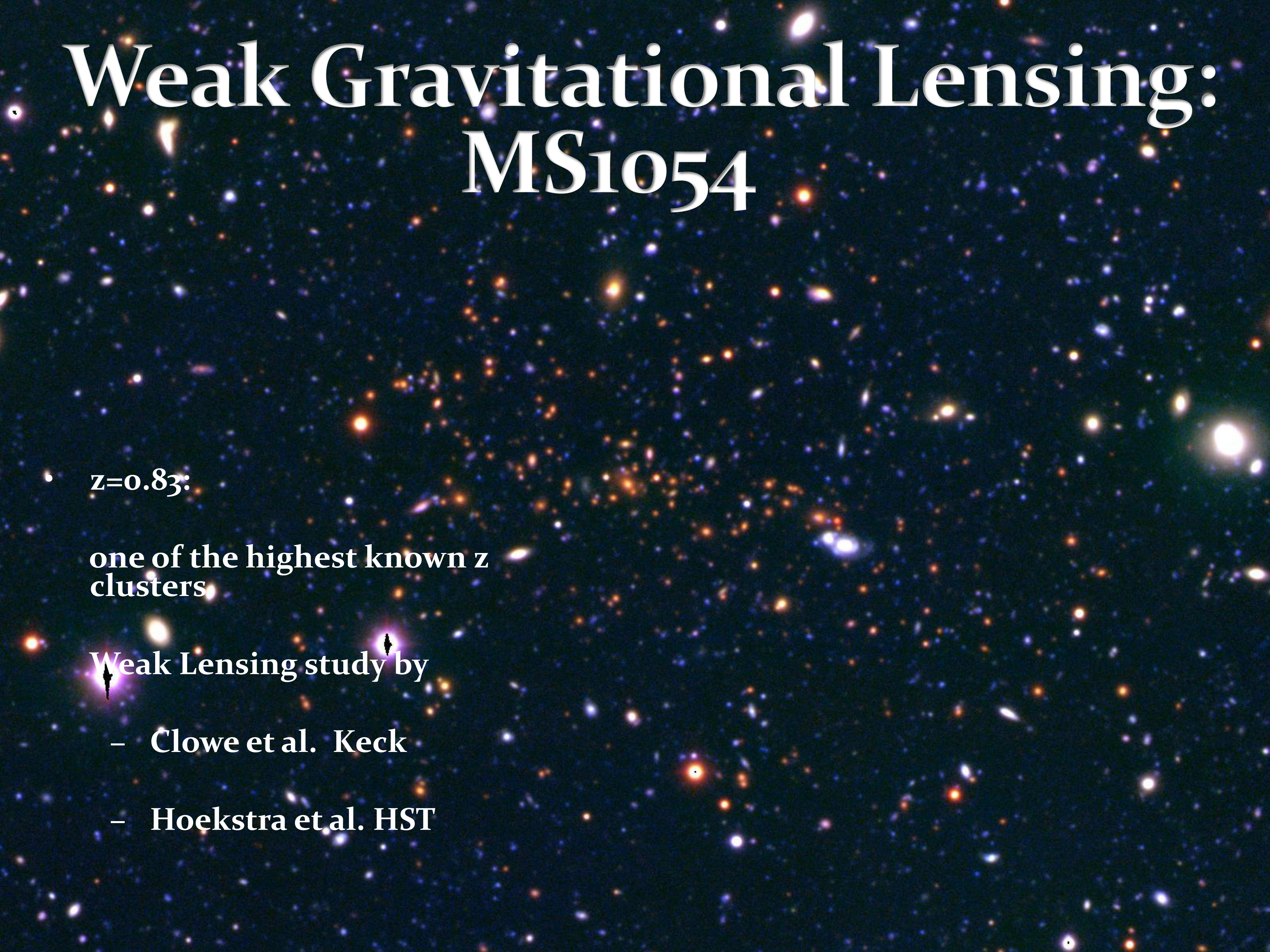
Weak Gravitational Lensing: MS1054

- z=0.83:

  one of the highest known z clusters

  Weak Lensing study by

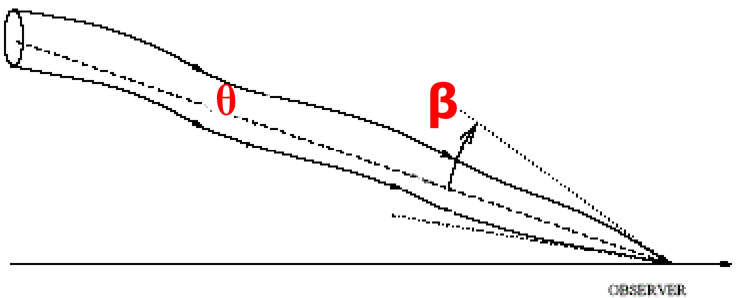
  - Clowe et al. Keck
  - Hoekstra et al. HST



Weak Gravitational Lensing

$$A_{ij} \equiv \frac{\partial \beta_i}{\partial \theta_j} = \begin{pmatrix} 1-\kappa & 0 \\ 0 & 1-\kappa \end{pmatrix} + \begin{pmatrix} -\gamma_1 & \gamma_2 \\ \gamma_2 & \gamma_1 \end{pmatrix}$$

Magnification Shear

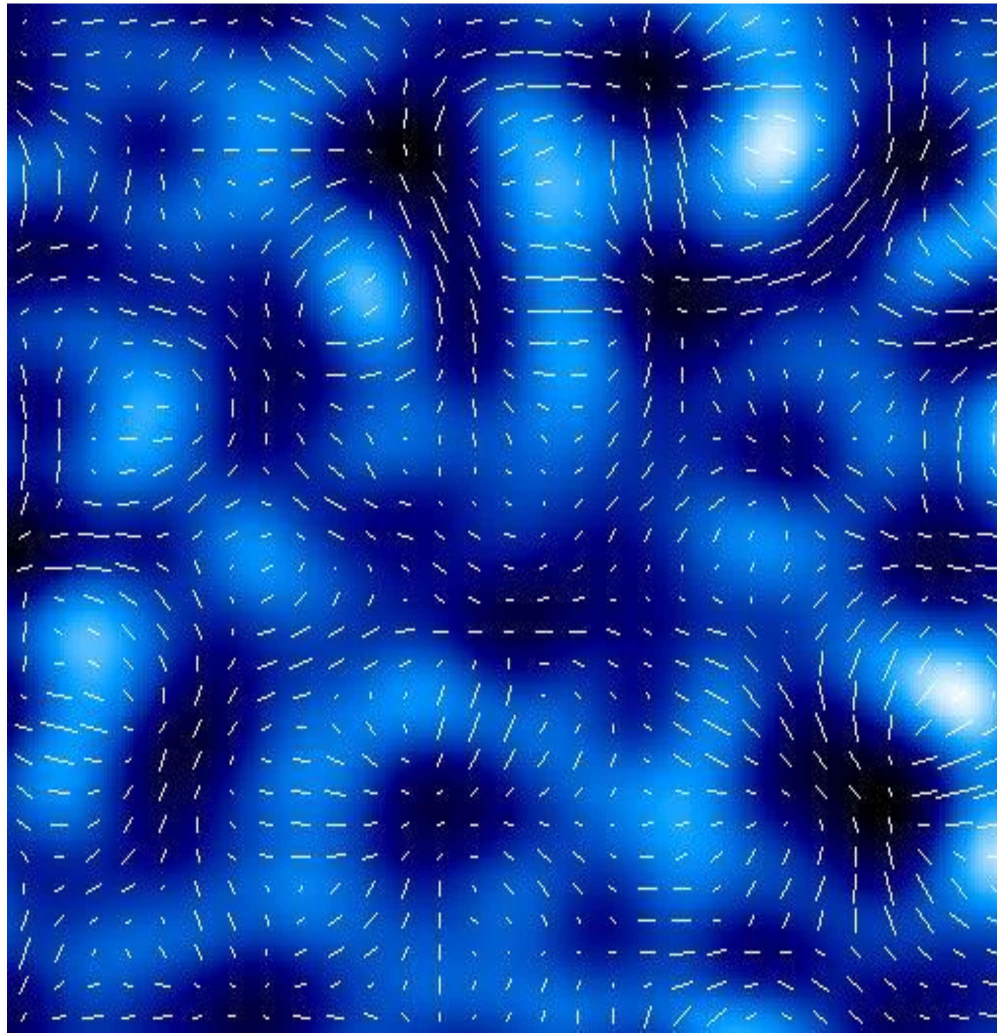


$$\kappa = \frac{1}{2}(\phi_{,11} + \phi_{,22})$$

$$\gamma_1 = \frac{1}{2}(\phi_{,11} - \phi_{,22})$$

$$\gamma_2 = \phi_{,12}$$

$$\phi_{,ij} = \frac{\partial^2 \phi}{\partial \theta_i \partial \theta_j}$$



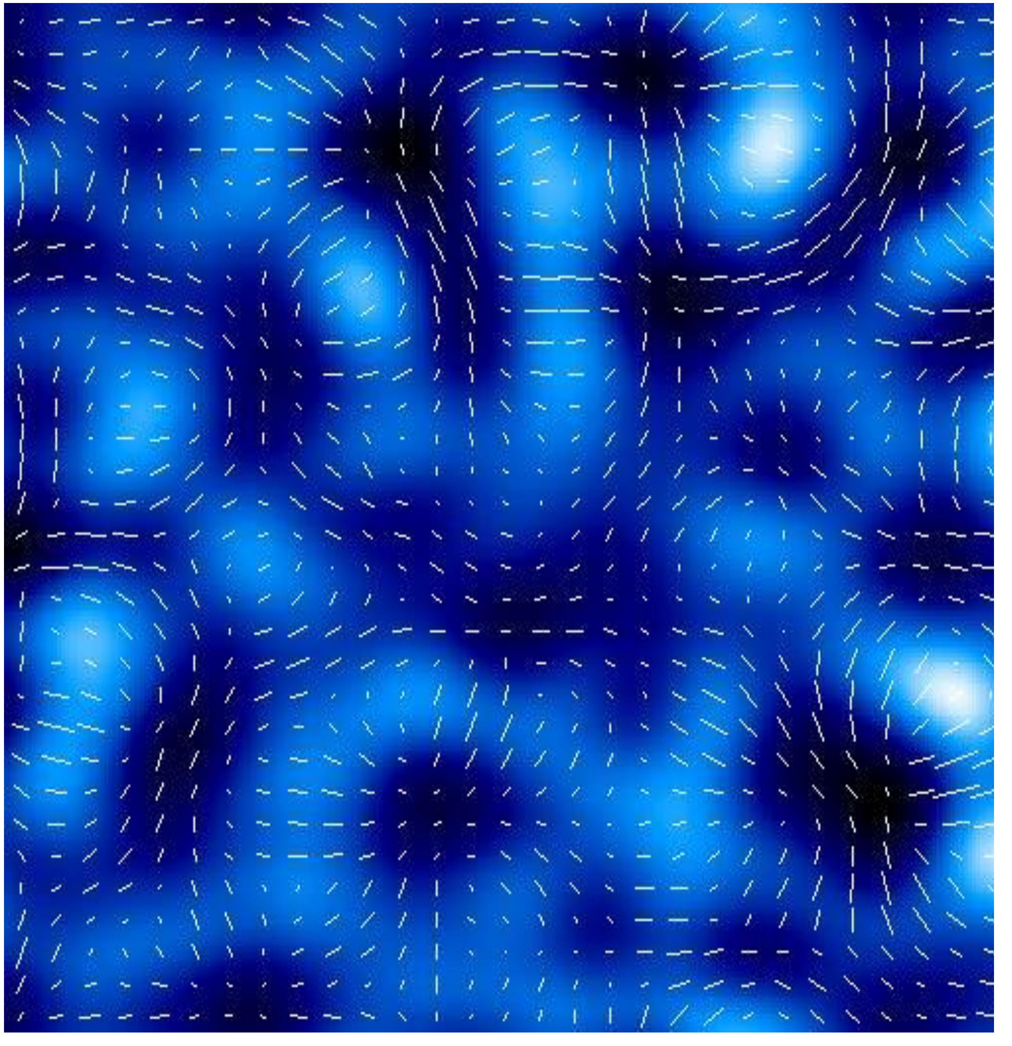
Weak Gravitational Lensing

$$\kappa = \frac{1}{2}(\phi_{,11} + \phi_{,22})$$
$$\gamma_1 = \frac{1}{2}(\phi_{,11} - \phi_{,22})$$
$$\gamma_2 = \phi_{,12}$$

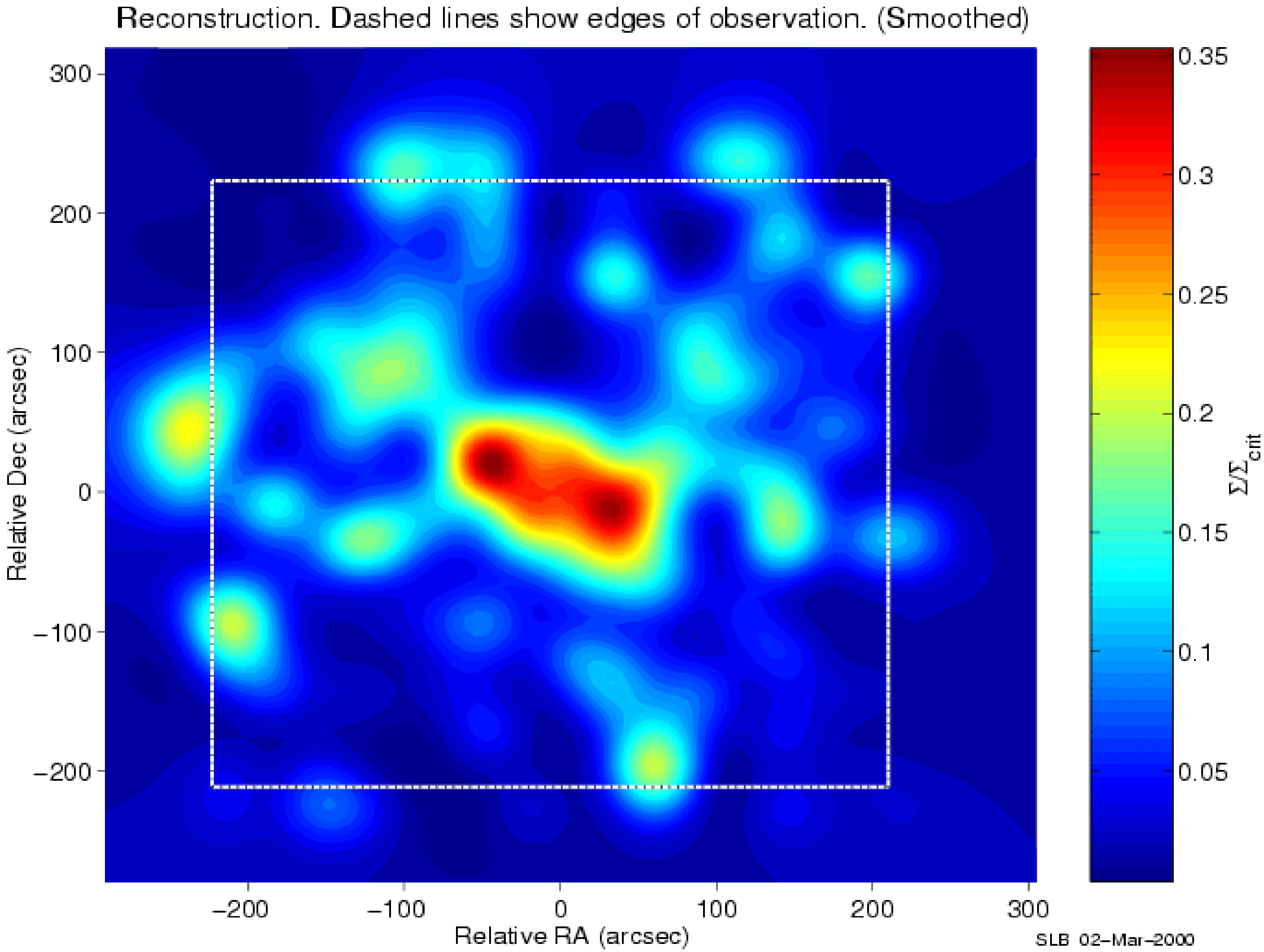
$$\phi_{,ij} = \frac{\partial^2 \phi}{\partial\theta_i \partial\theta_j}$$

Lensing Potential
related to
Peculiar Gravitational Potential

$$\phi(\mathbf{r}) = \frac{2}{c^2}\int_0^r dr' \, \Phi(\mathbf{r}') \left(\frac{1}{r} - \frac{1}{r'}\right)$$



Weak Gravitational Lensing: MS1054



Clusters of Galaxies: Dark Matter Map

A highly promising method to determine the amount and distribution of

matter in the Universe

looks at the way it affects

the trajectories of photons.

According to

Einstein's theory of

General Relativity,

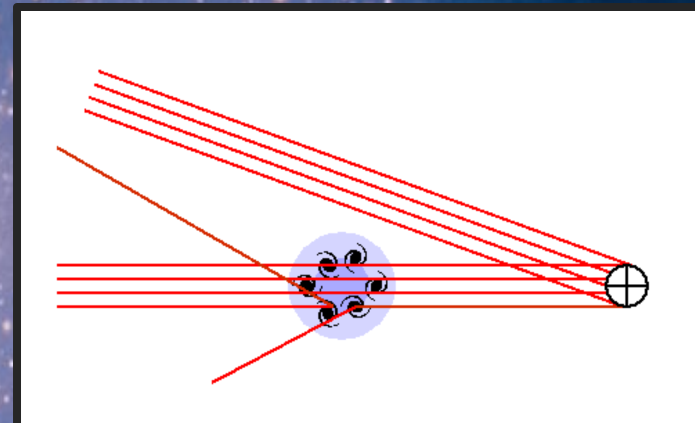
gravitational potential wells will bend and focus light. Dark matter concentrations act as a

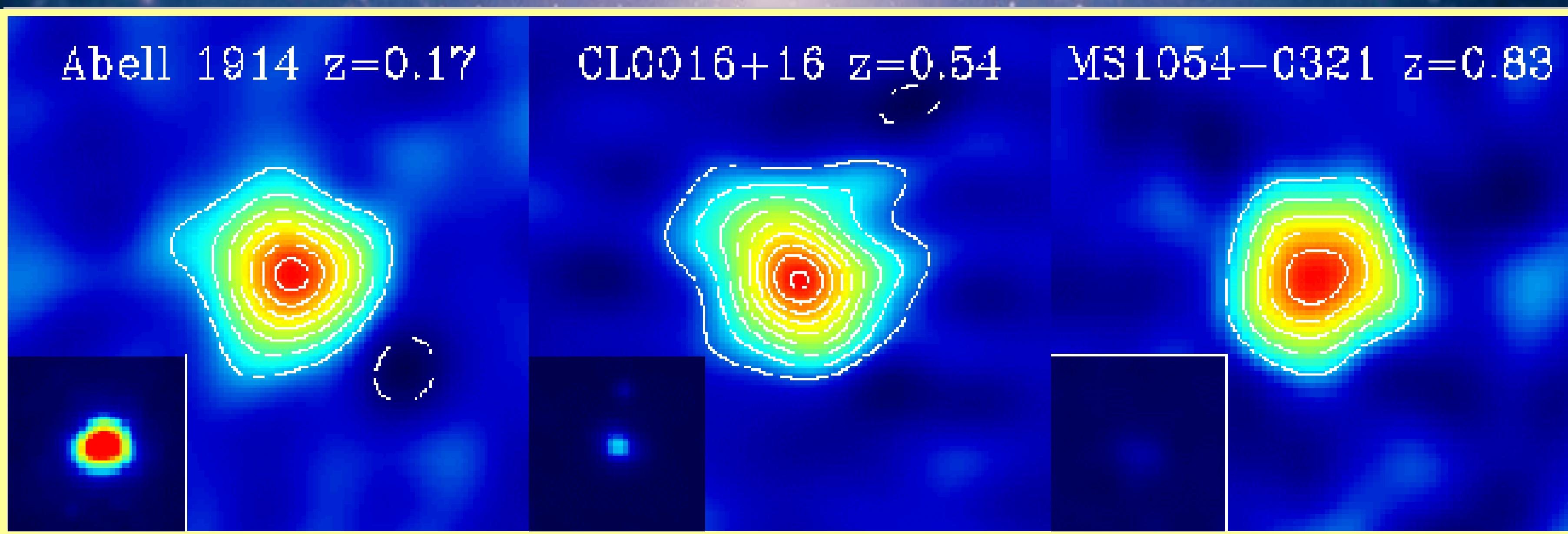
Gravitational Lens.

Clusters Shadows:
Sunyaev-Zeldovich Effect

Sunyaev-Zel'dovich effect:

- **Cluster seen as shadow against CMB**
- **scattering through inverse Compton of CMB photons by hot intracluster electrons**





Colliding Bullet Cluster

Colliding Bullet Cluster

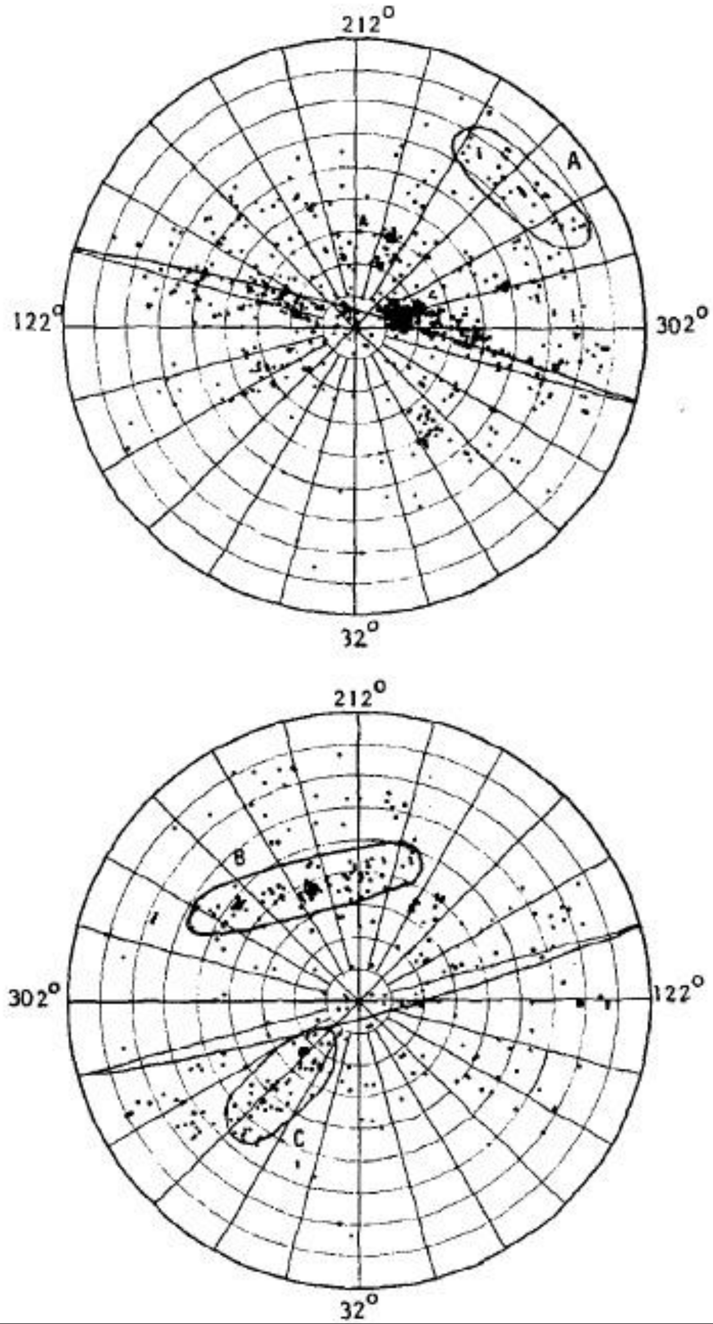
- Bullet Cluster: 2 colliding clusters
- Combination of:
  - mass distribution cluster via strong & weak lensing
  - (intracluster) gas distribution via X-ray mapping
- Center of X-ray gas does not coincide with center of mass cluster, implying that the dissipative gas lacks wrt. dynamically dominant matter distribution, which thus has to be of an "unknown" dark nature

Colliding Bullet Cluster, simulation

movie

Sky Maps:

the world all around us



Early Views

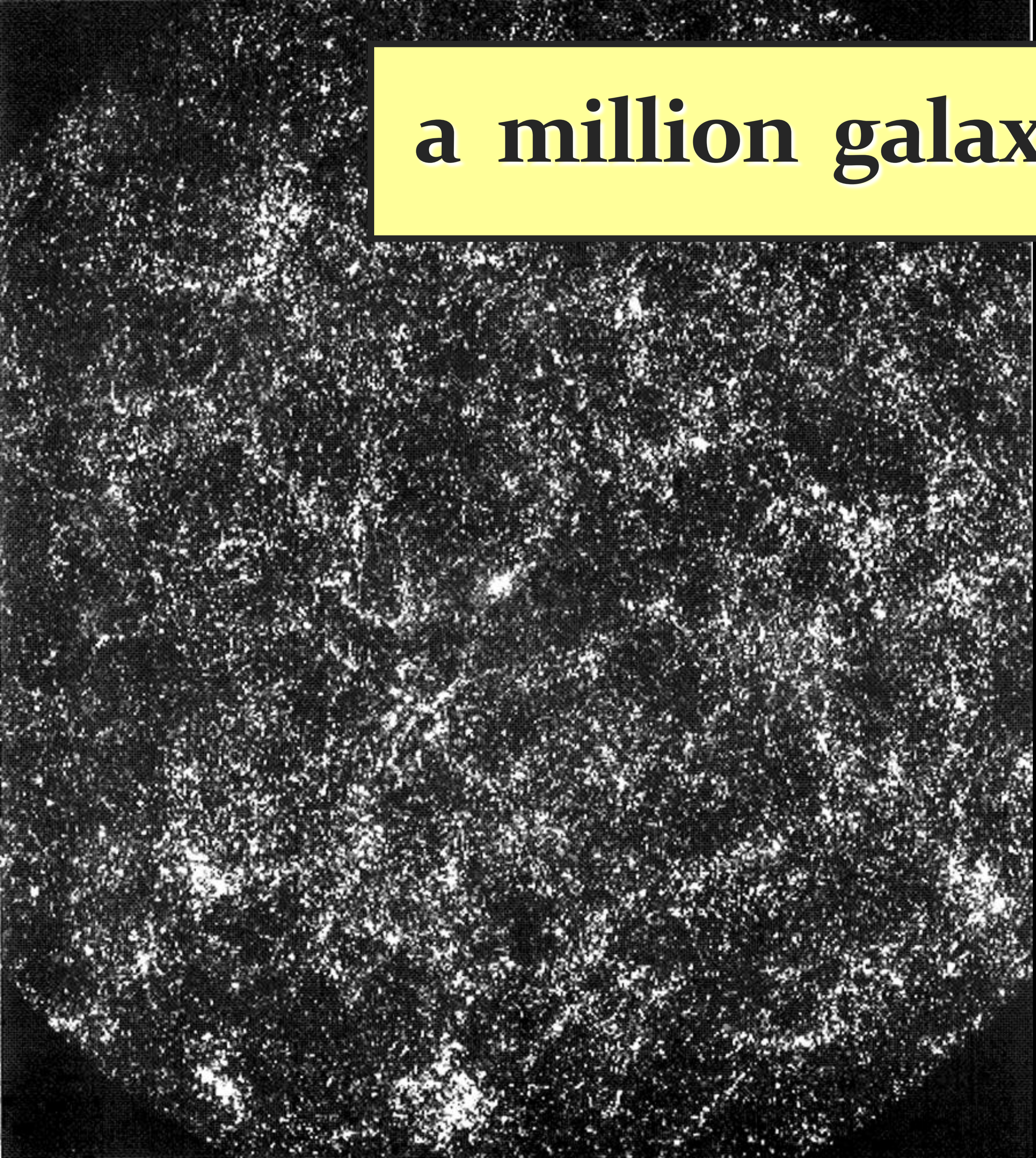
Shapley-Ames catalog (1932) of nearby galaxies:

All-sky survey of galaxies to m=18.3

$\delta > -23^o$

- numerous concentrations:
  groups and clusters (incl. Virgo cluster)
- asymmetry between north and south:
  many more galaxies on northern sky
- conspicuous concentration along a line running through richest nearby cluster, the Virgo cluster:
- The Supergalactic Plane
  (first identified by de Vaucouleurs:
  the plane of our own Local Supercluster)

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**

APM survey

- Sky map:

  2×10^6 galaxies

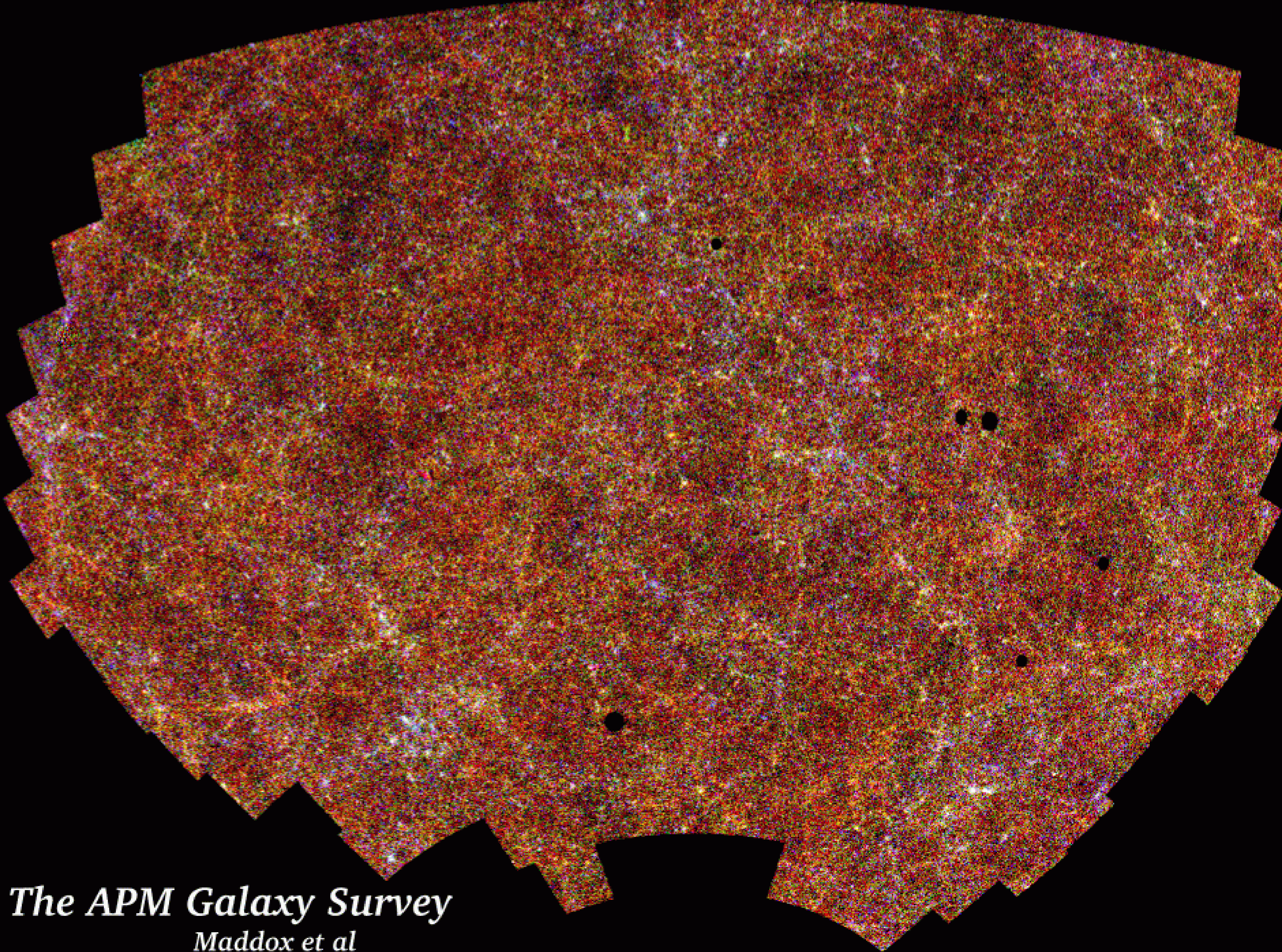
  $17 < m < 20.5$

- Uniformly defined
- Sky region: 4300 sq. deg.

  185 UK Schmidt plates, $6^o \times 6^o$

- Large inhomogeneities, hints of weblike patterns, with clusters at densest regions.

courtesy: S. Maddox, G. Efstathiou, W. Sutherland, D. Loveday



The APM Galaxy Survey

Maddox et al

the 3-D Universe

Galaxy Redshift Surveys

Galaxy Redshift Surveys

- For obtaining 3D maps of the galaxy distribution:

  measure spatial location of galaxies:
  - position on the sky (α,δ)
  - distance r

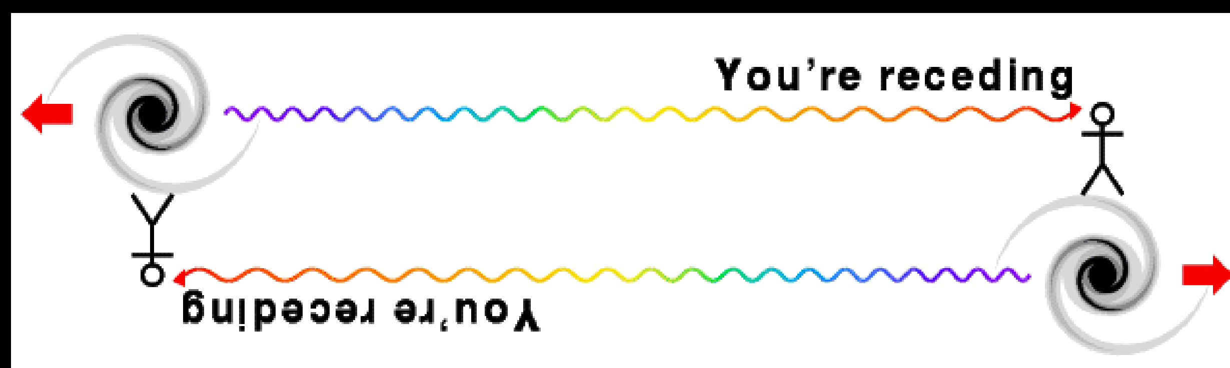
- Determination real distance r of galaxy very cumbersome, reasonably accurate estimates only for nearby gal's …

- Common approximate method:
  exploit Hubble expansion of the Universe

Galaxy Redshift Surveys

$$1 + z = \frac{1}{a} \Longleftarrow \begin{cases} \lambda_{em} = \lambda_0 \\ \lambda_{obs} = \dfrac{a(t_{obs})}{a(t_{em})}\lambda_0 \end{cases}$$

$$z \equiv \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$



Galaxy Redshift Surveys

- **Hubble Expansion:**

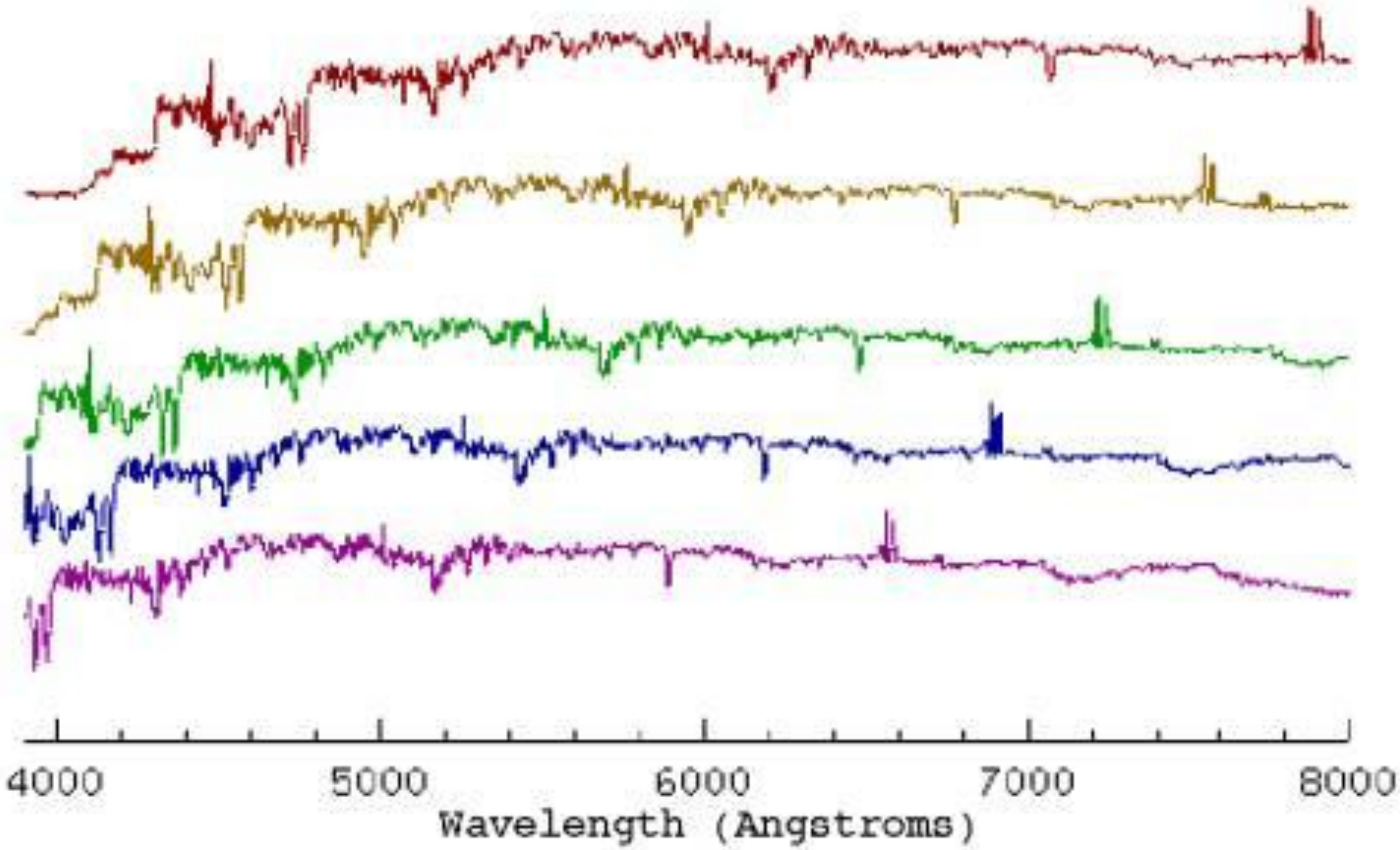
$$cz = Hr \qquad (z \ll 1)$$

galaxy at distance r
has redshift z
(c: vel. light; H: Hubble constant)

- **Redshift of galaxies can be much more easily determined than distance:**

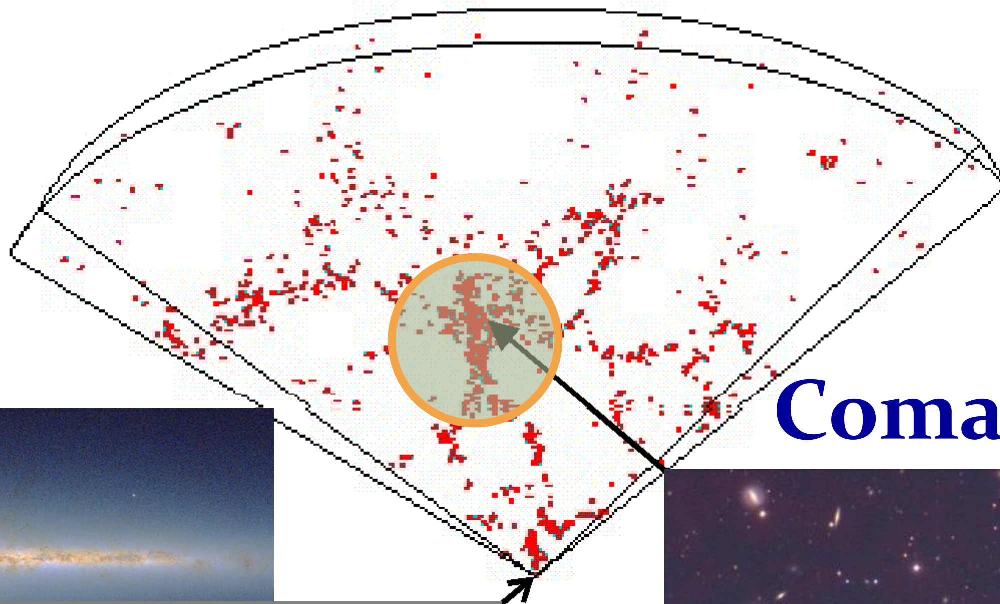
Galaxy Spectrum

Galaxy Redshift Surveys

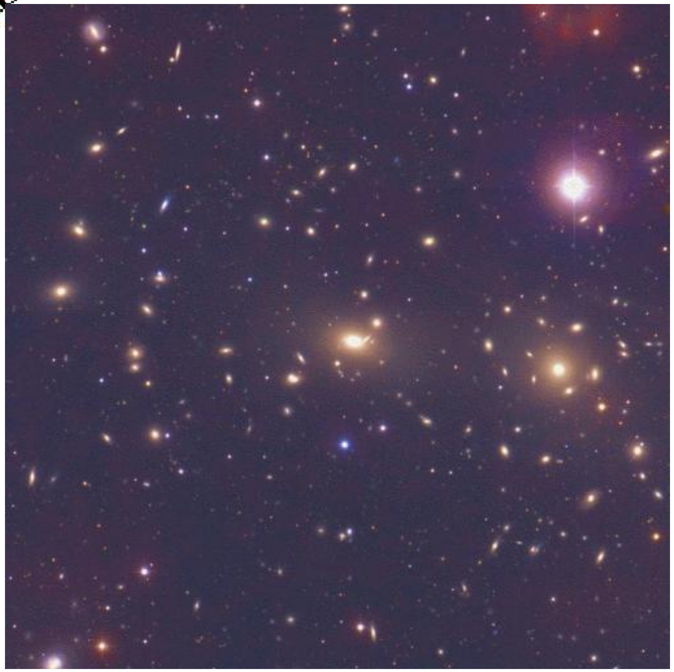


Examples of redshifted galaxy spectra

Mapping the Universe



Coma Cluster



Our own Galaxy

de Lapparent, Geller, and Huchra (1986), ApJ, 302, L1

Redshift Distortions

- In reality, galaxies do not exactly follow the Hubble flow:

  In addition to the cosmological flow, there are locally induced velocity components in a galaxy's motion:

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

  the galaxy's peculiar velocity v_{pec}

- As a result, maps on the basis of galaxy z do not reflect the galaxies' true spatial distribution

Redshift Distortions

Origin of peculiar velocities:

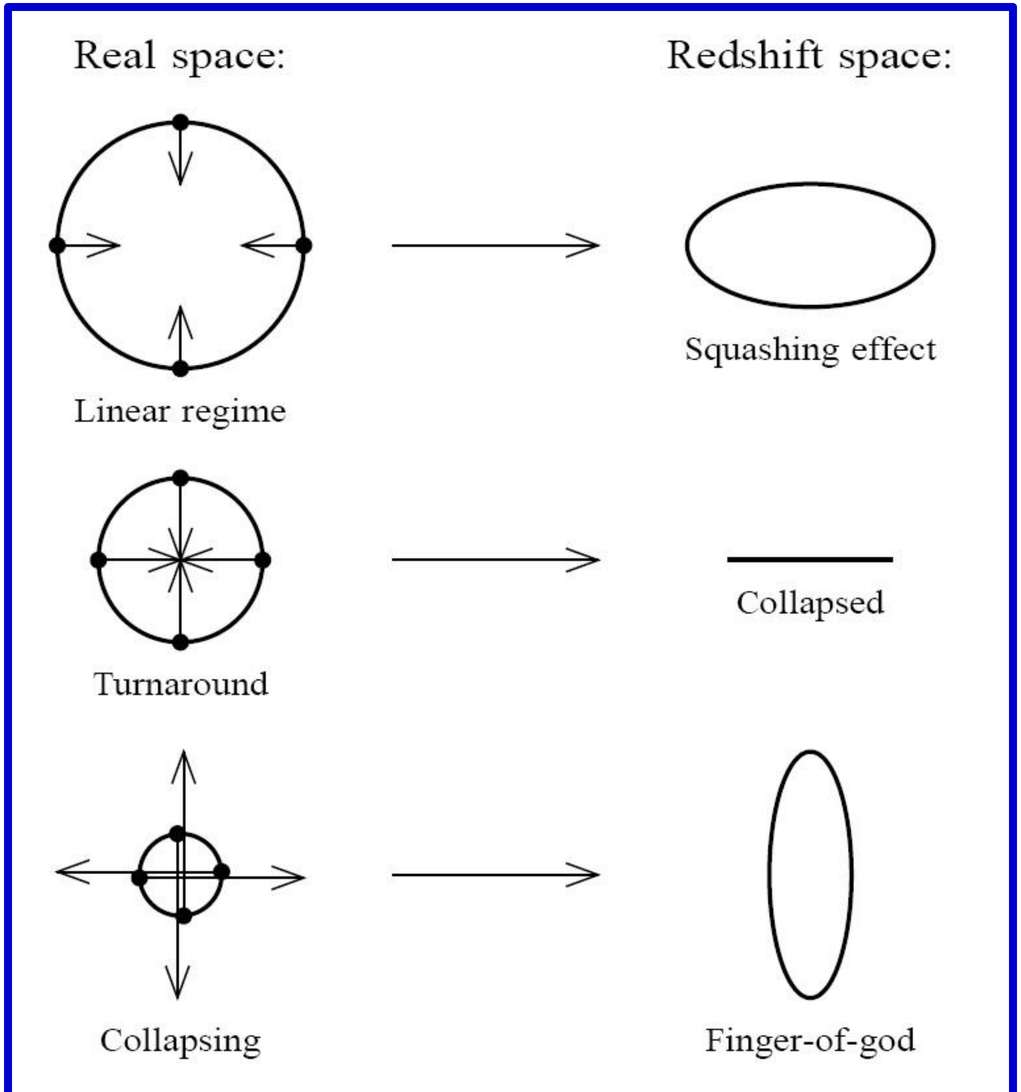
three regimes

- very high-density virialized cluster (core) regions:
  "thermal" motion in cluster,
  up to > 1000 km/s

  "Fingers of God"

- collapsing overdensity (forming cluster):
  inflow/infall velocity

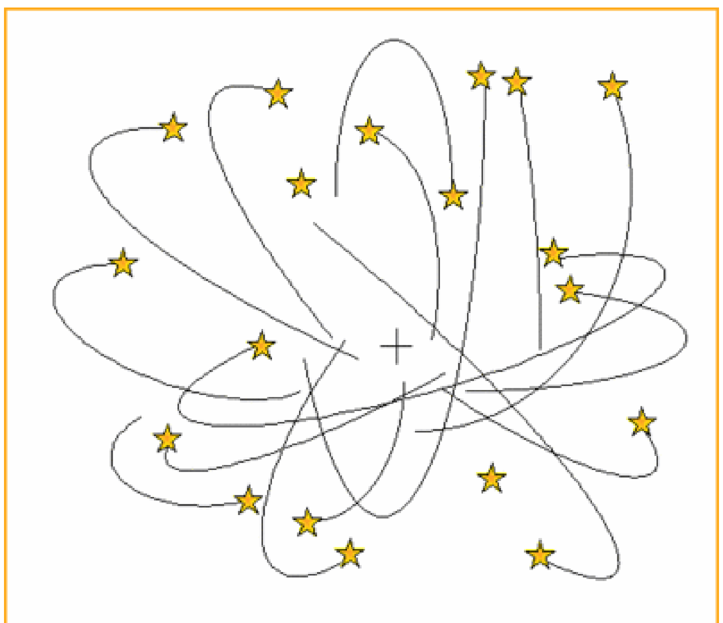
- Large scales:
  (linear, quasi-linear) cosmic flow,
  manifestation of structure growth

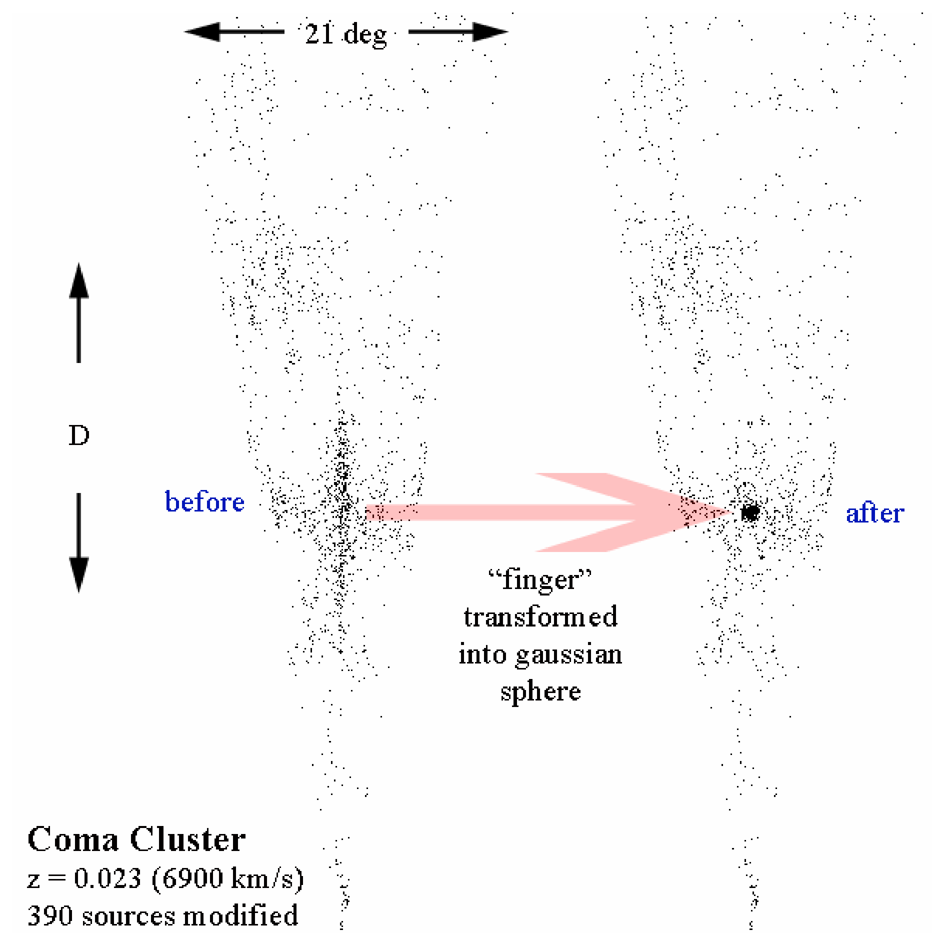


Fingers of God

$$cz = Hr_{clust} + \frac{\vec{v}_{gal} \cdot \vec{r}_{gal}}{r_{gal}}$$

Galaxy velocity component along line of sight





Fingers of God

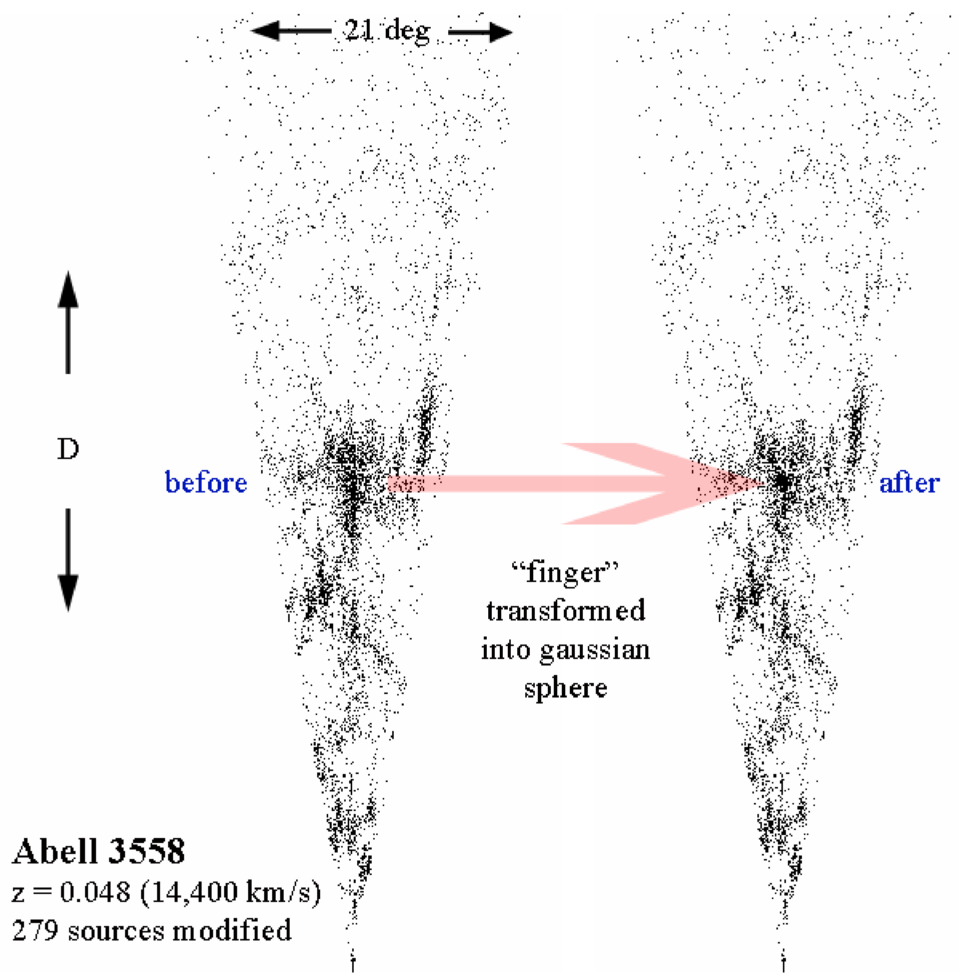
Clusters of galaxies:

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

Thermal velocity: ~ 1000 km/s

Internal cluster galaxy velocities visible in projection along line of sight

→ "Finger of God"



Magnitude vs. Volume

Limited

Survey

Magnitude vs. Volume limited Surveys

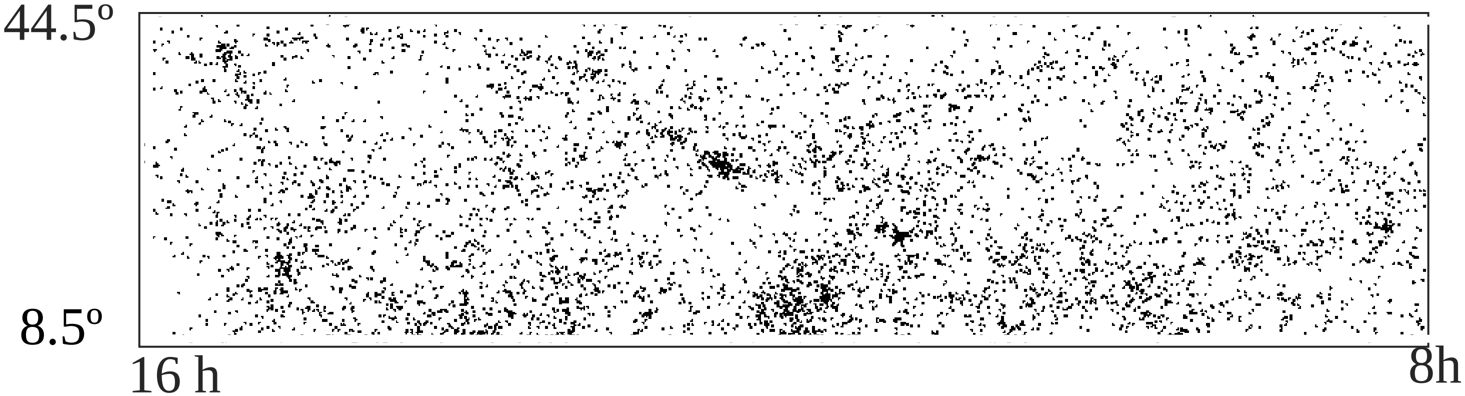
- Two different sampling approaches for analysis spatial structure from galaxy redshift catalogue:

- Volume-limited surveys:
  - uniform spatial coverage, including all galaxies within volume to depth d_s
  - all galaxies with an absolute brightness > survey limit M_s

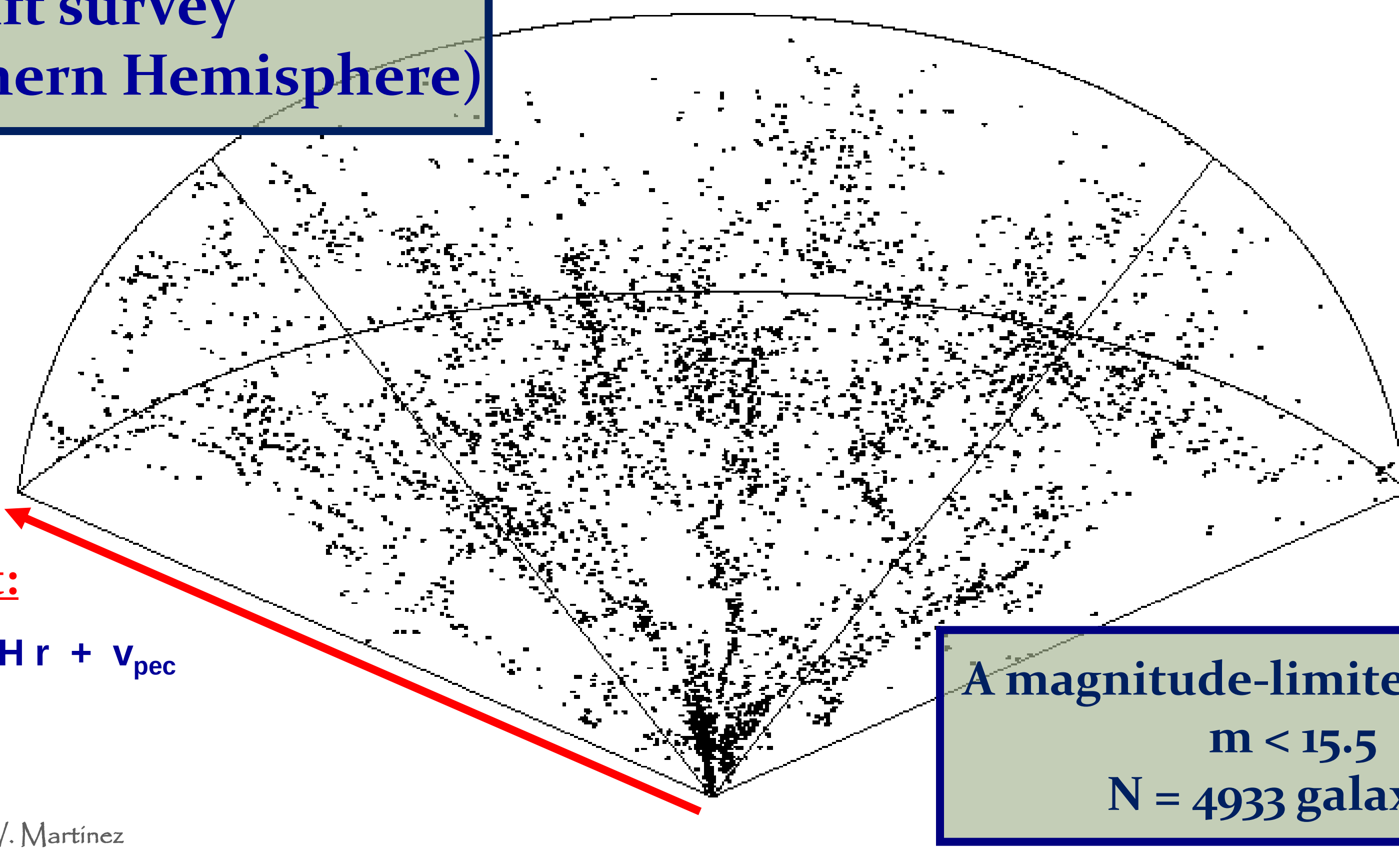
$$M_s = m_{\lim} - 5 \log d_s - 25 - k(z)$$

  - diminishing sampling density & spatial resolution as one wishes to include larger volume (excluding all galaxies $M>M_s$)

- Magnitude-limited survey
  - include all galaxies with apparent magnitude brighter than m_s
  - assures optimal use of spatial galaxy catalogue
  - at the price of an non-uniform spatial coverage & diminishing resolution towards higher depths



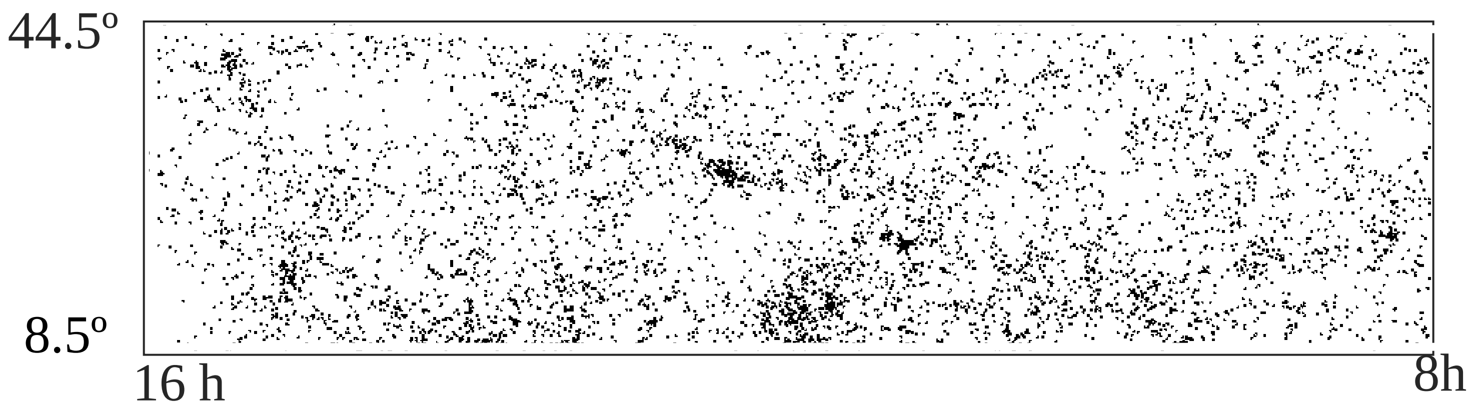
The CfA2 redshift survey (Northern Hemisphere)



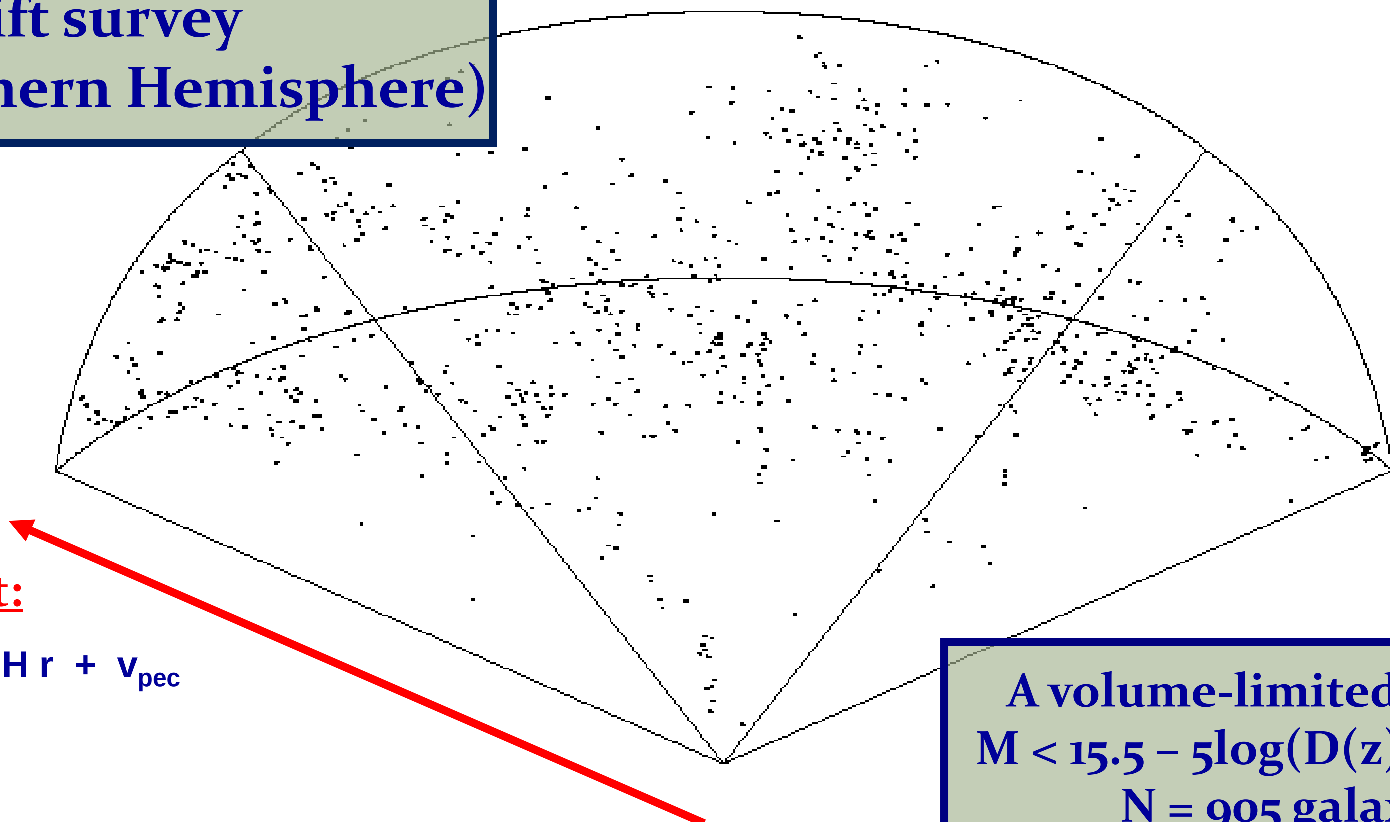
Redshift:

$v = c\,z \sim H\,r + v_{pec}$

A magnitude-limited sample,
m < 15.5
N = 4933 galaxies



The CfA2 redshift survey (Northern Hemisphere)



Redshift:

$v = c\,z \sim H\,r + v_{pec}$

A volume-limited sample,
$M < 15.5 - 5\log(D(z)) - 25 - Kz$
$N = 905$ galaxies

Figure courtesy: V. Martinez

Survey Geometry

Survey Geometry

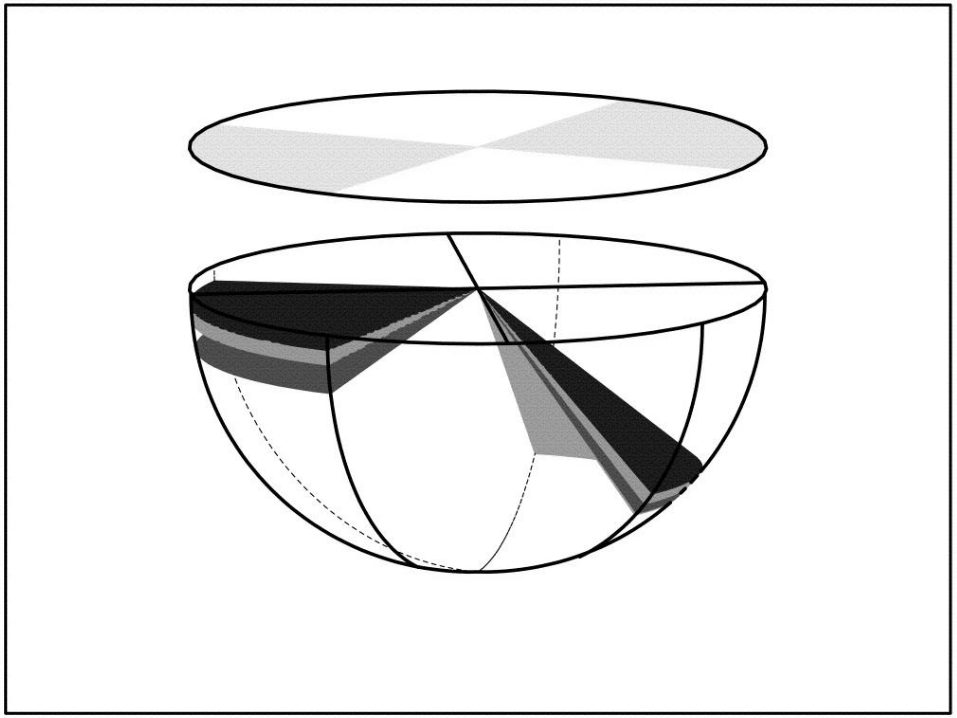
Practical Limitations

- Limited telescope time
- Limited detector sensitivity

• How to optimally sample structure in Universe ?

• Devise survey geometry that reveals optimal amount of Information on question at hand:

- Patterns galaxy distribution
- Distribution high-density peaks
- Density Field



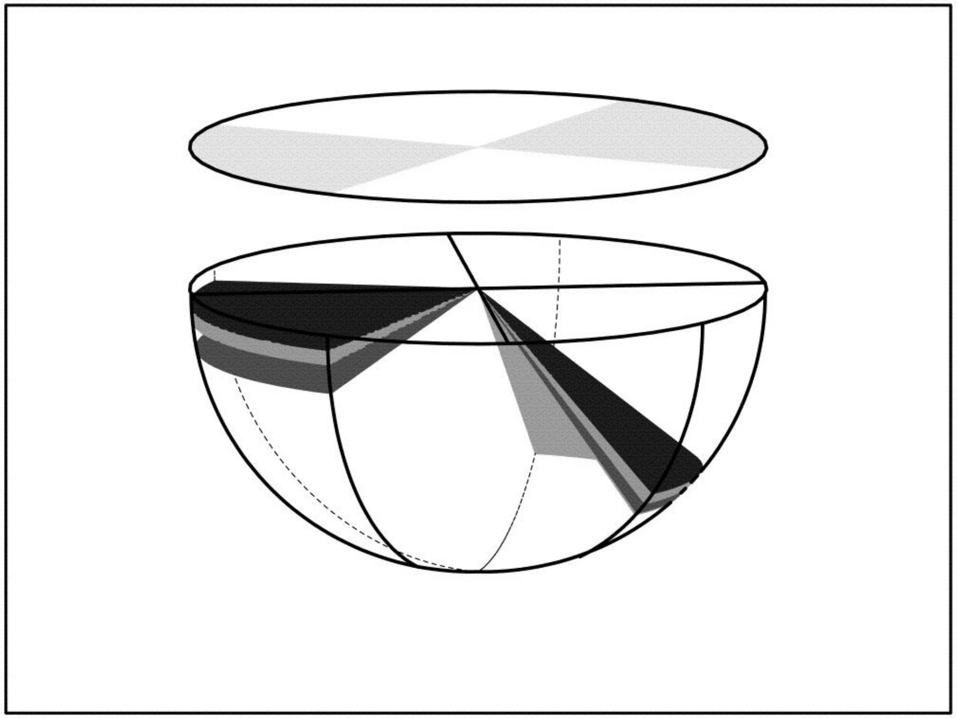
Sky Location
2-D LCRS survey slices

Survey Geometry

Survey Geometry:

- **Slice Surveys:**
  - thin stripe on sky
  - very sensitive to reveal patterns galaxy distribution

- **Pencil-beam surveys**
  - very narrow region on sky
  - very deep
  - strategy to probe largest structures
  - structure at high z (early times)



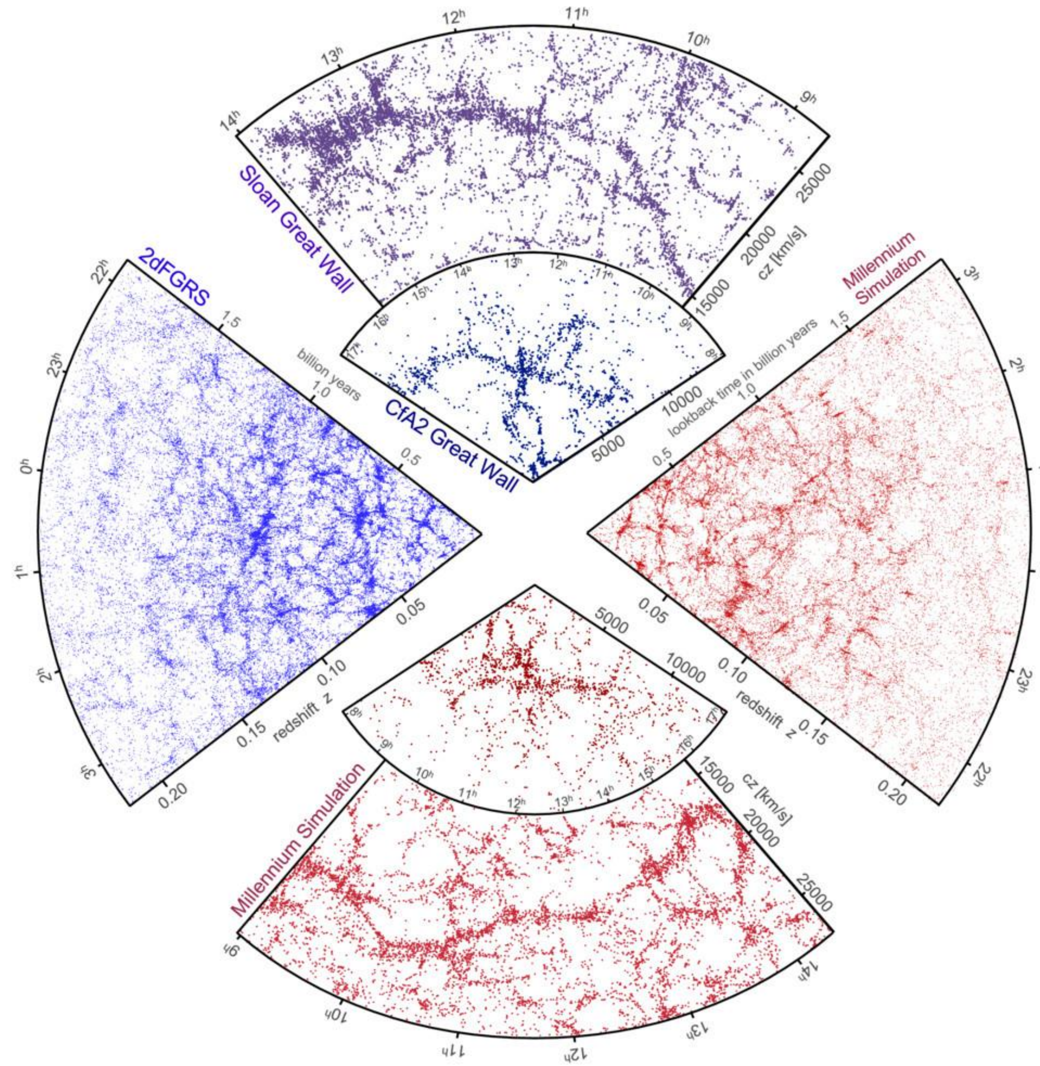
Sky Location
2-D LCRS survey slices

Survey Geometry

Examples of

Slice Redshift Surveys:

From
CfA2 -2dFGRS - SDSS

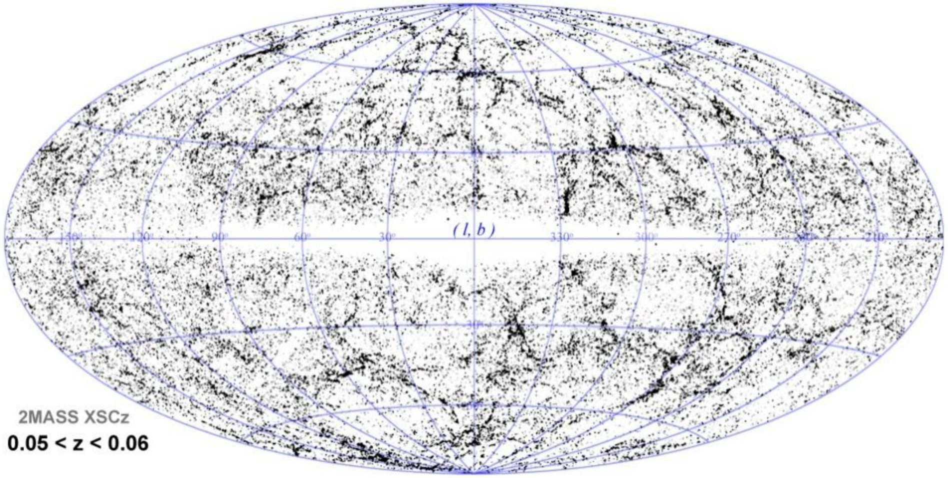


Survey Geometry

Survey Geometry:

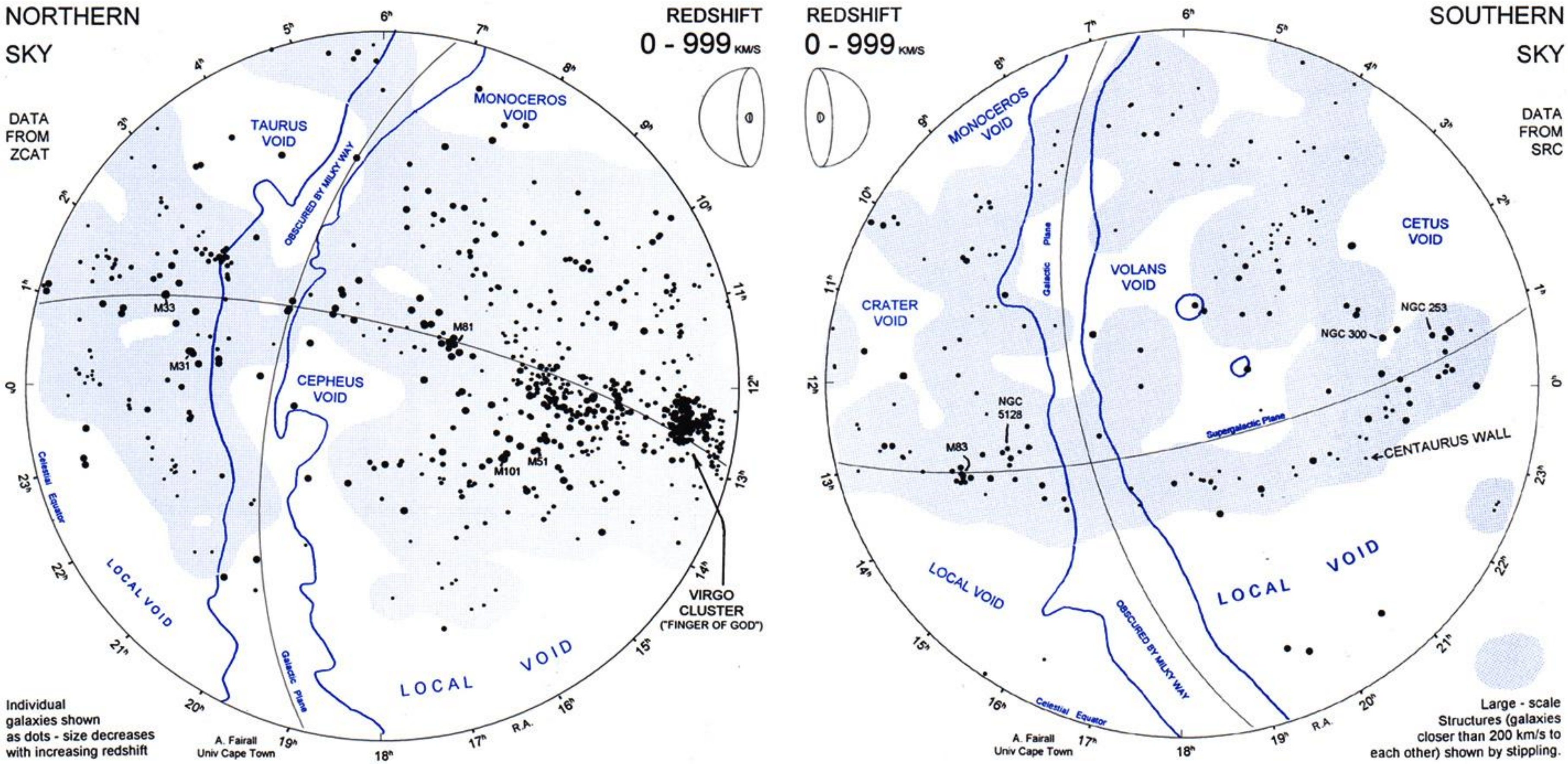
- **Sparse Sample:**
  - sampling density field
  - on scales > intergalaxy distance

- **Full-sky surveys**
  - necessary to probe dynamics cosmic regions



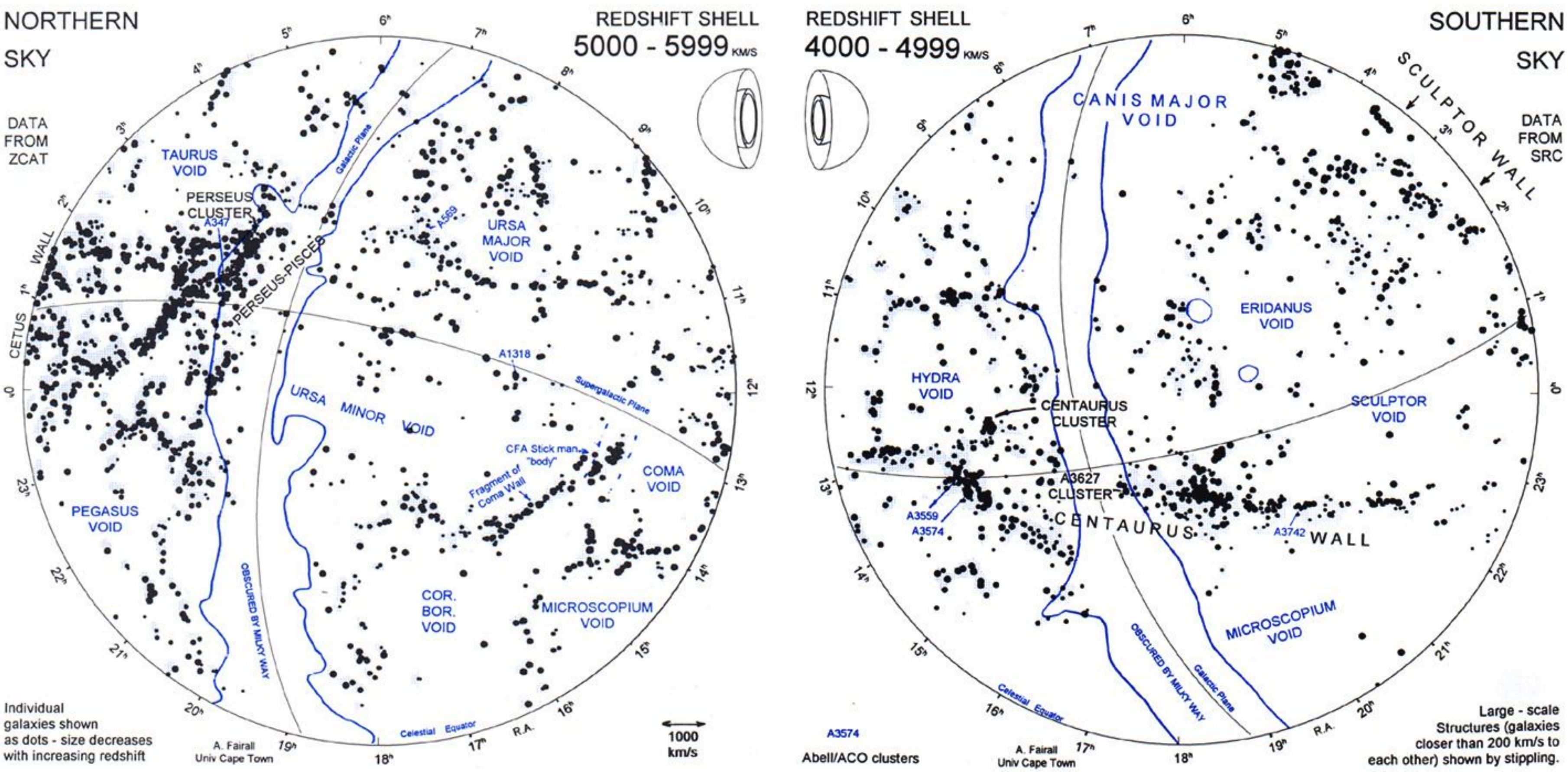
Maps of the Local Universe

Local Views



Tony Fairall's nearby LSS map: Local Supercluster clearly visible at $v < 999$ km/s

Local Views: Moving into the Web



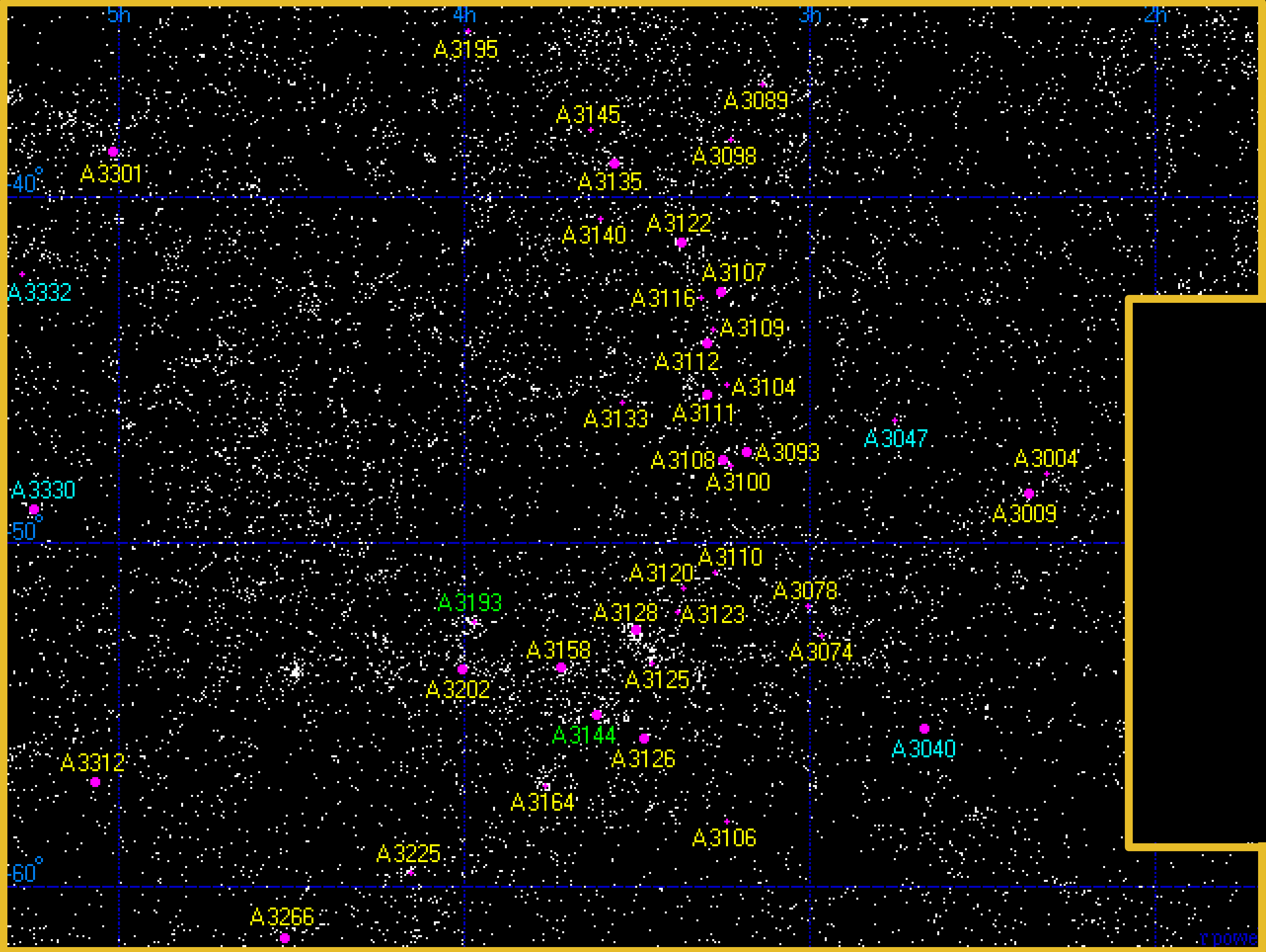
Tony Fairall's nearby LSS map:

at cz=5000-5999 km/s clear views of local cosmic web

Superclusters

Superclusters

Large groups of clusters & galaxies (1-dozens)

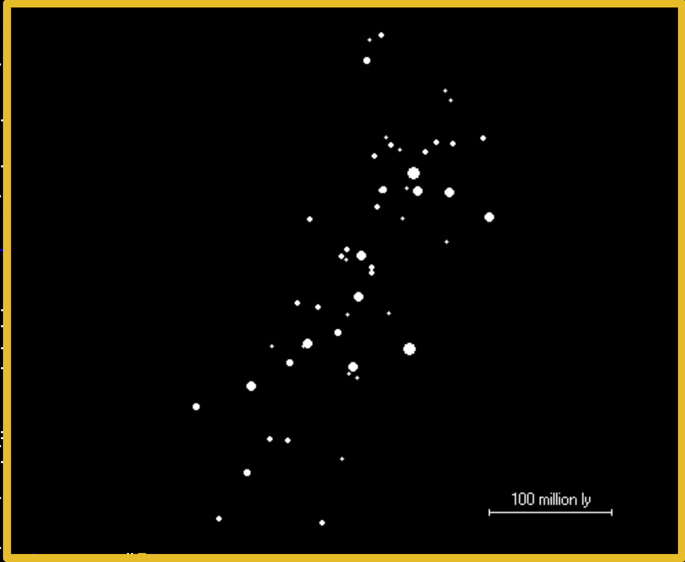


$M \sim 10^{15}$-$10^{16}\ M_\odot$

$L \sim$ few-100 Mpc

irregular shaped

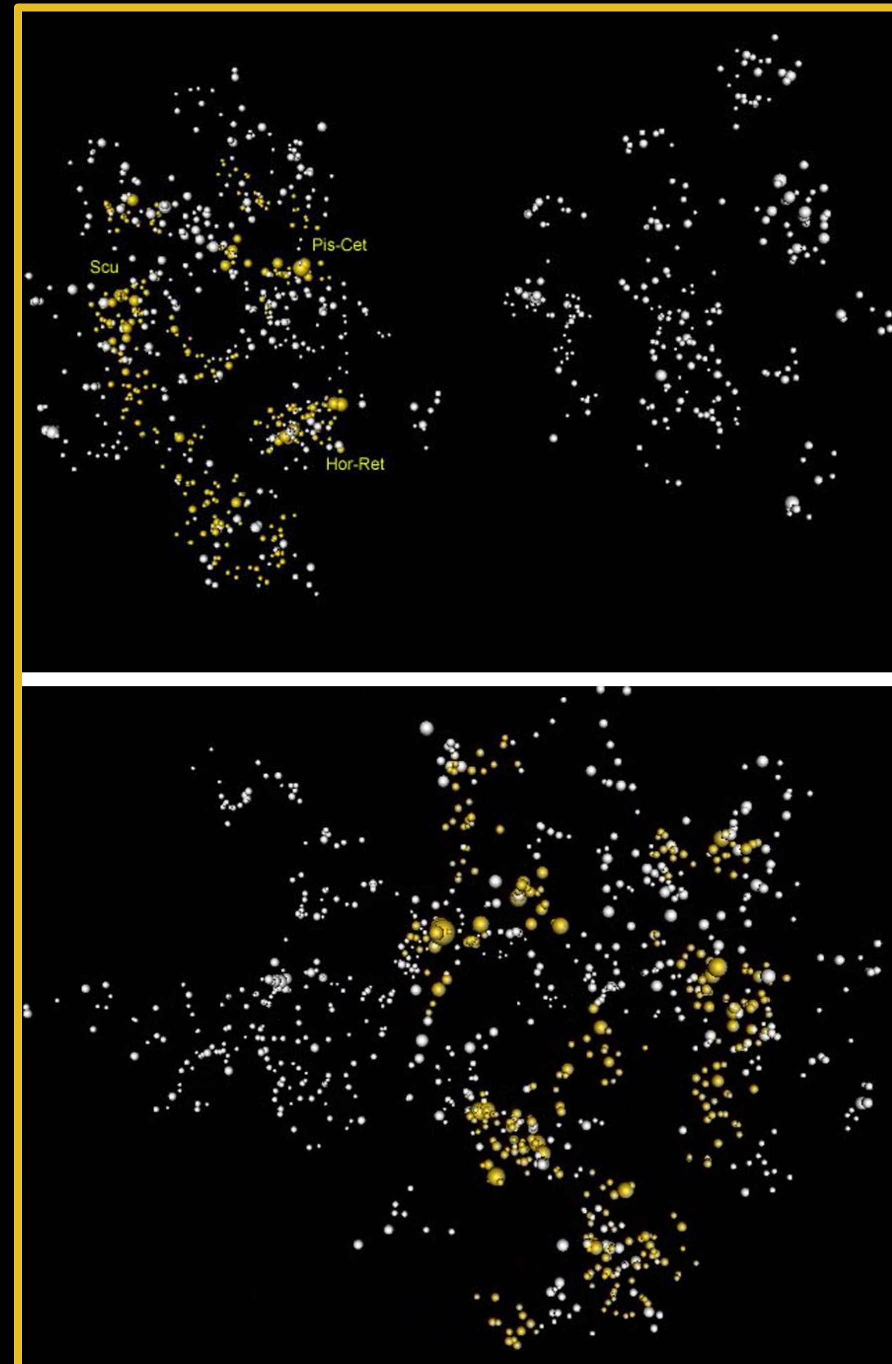
mild overdensity $\Delta \sim$ few

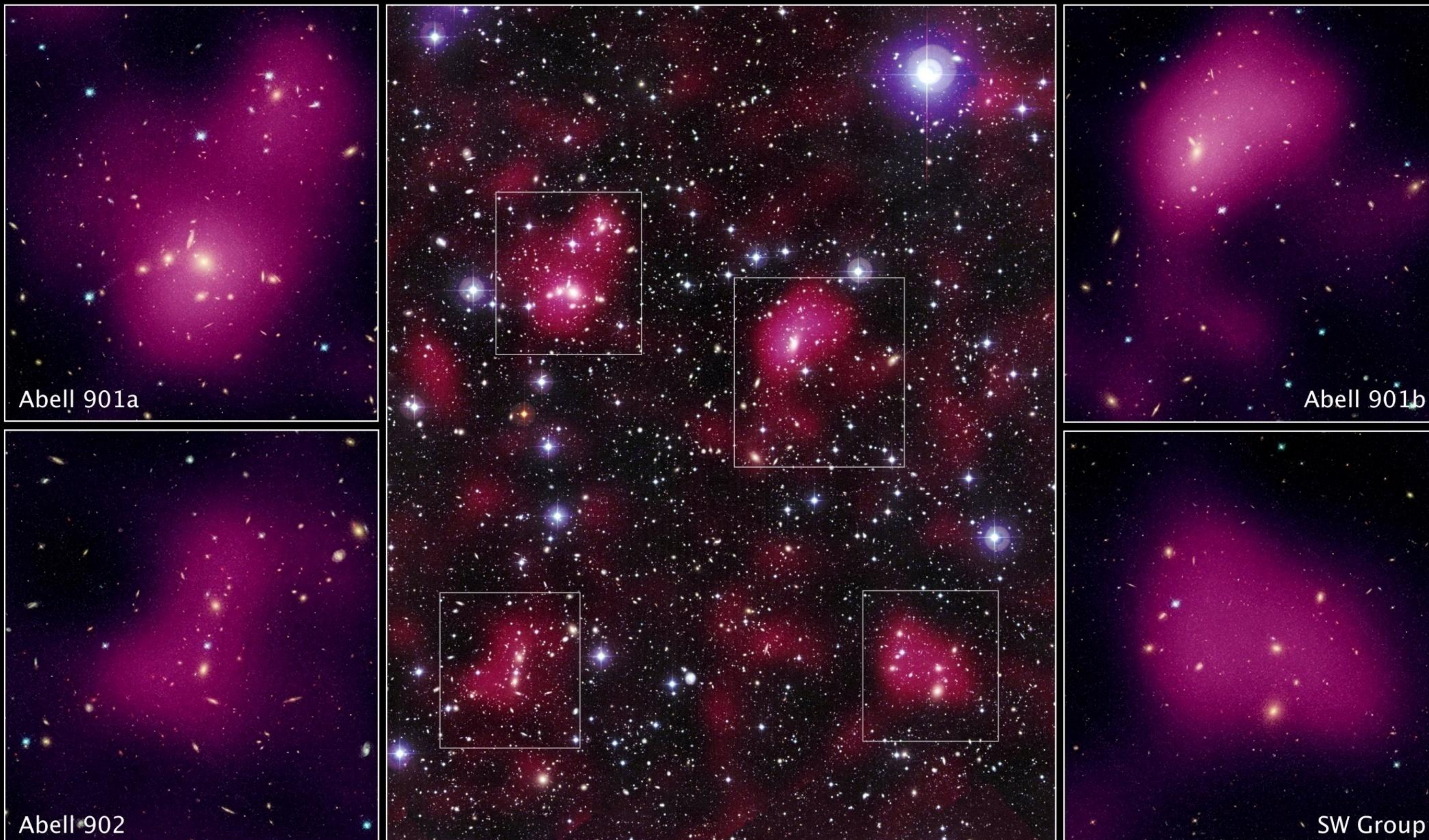


Superclusters:

Einasto et al. sample
X-ray clusters (yellow) and
Abell clusters (white)

superclusters are not isolated single objects,
but integral components in the pervasive
Cosmic Web



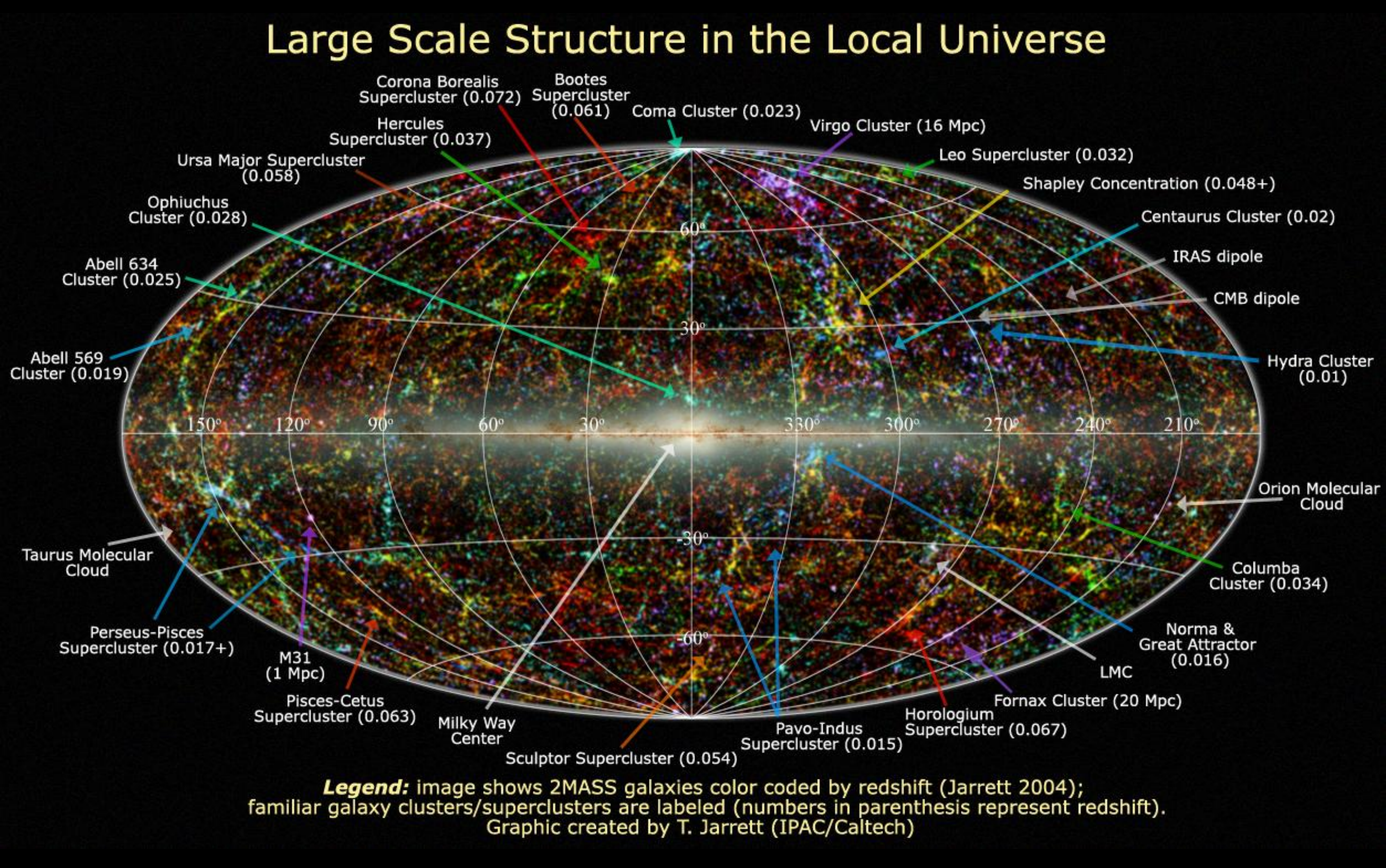


Abell 901/902 Supercluster Dark Matter Map ▪ STAGES

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

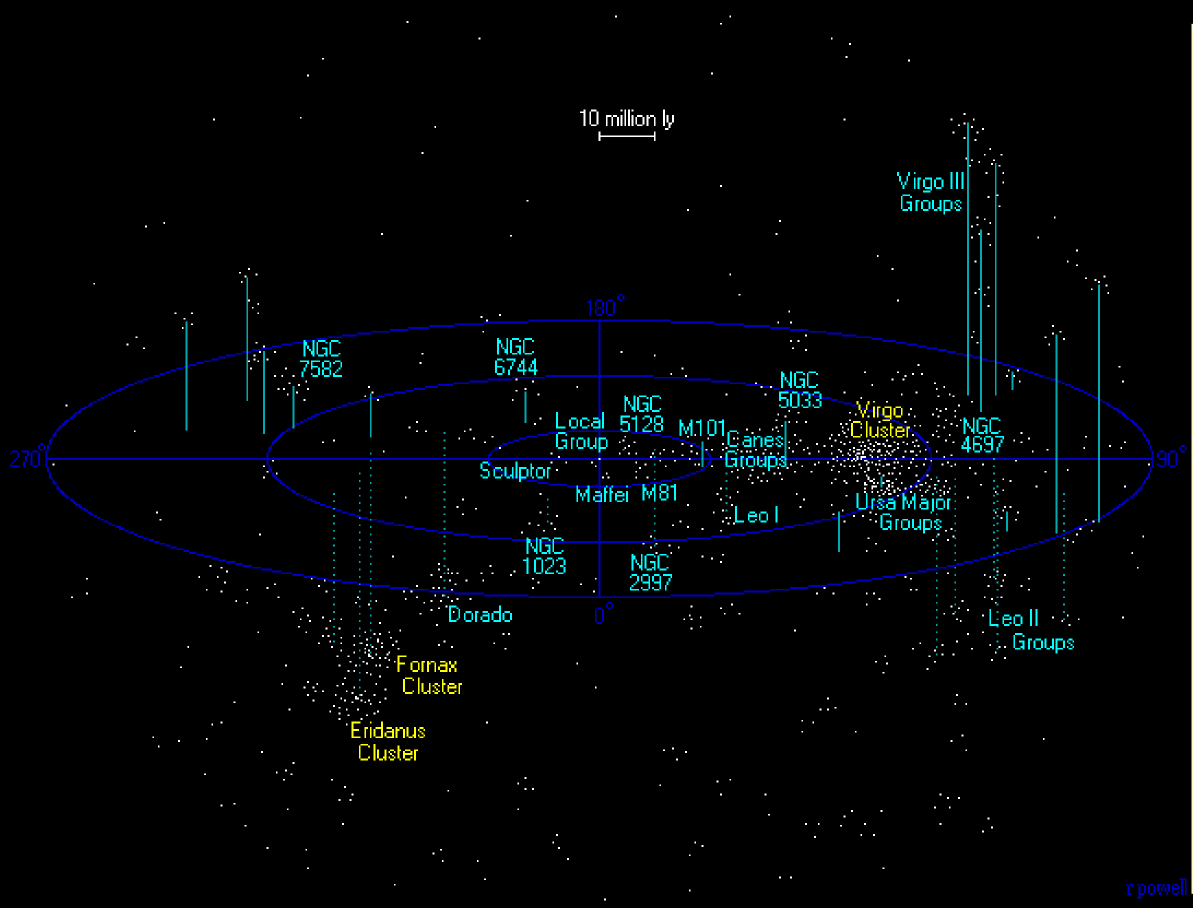
Cosmic Web


Large Scale Structure in the Local Universe
Corona Borealis Supercluster (0.072)
Bootes Supercluster (0.061)
Coma Cluster (0.023)
Virgo Cluster (16 Mpc)
Hercules Supercluster (0.037)
Leo Supercluster (0.032)
Ursa Major Supercluster (0.058)
Shapley Concentration (0.048+)
Ophiuchus Cluster (0.028)
Centaurus Cluster (0.02)
IRAS dipole
Abell 634 Cluster (0.025)
CMB dipole
60°
30°
Abell 569 Cluster (0.019)
Hydra Cluster (0.01)
150° 120° 90° 60° 30° 330° 300° 270° 240° 210°
Orion Molecular Cloud
-30°
Taurus Molecular Cloud
Columba Cluster (0.034)
-60°
Norma & Great Attractor (0.016)
Perseus-Pisces Supercluster (0.017+)
M31 (1 Mpc)
LMC
Fornax Cluster (20 Mpc)
Pisces-Cetus Supercluster (0.063)
Milky Way Center
Horologium Supercluster (0.067)
Pavo-Indus Supercluster (0.015)
Sculptor Supercluster (0.054)
Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004);
familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift).
Graphic created by T. Jarrett (IPAC/Caltech)

Local Supercluster

our cosmic province

Local Supercluster



Courtesy: B. Tully

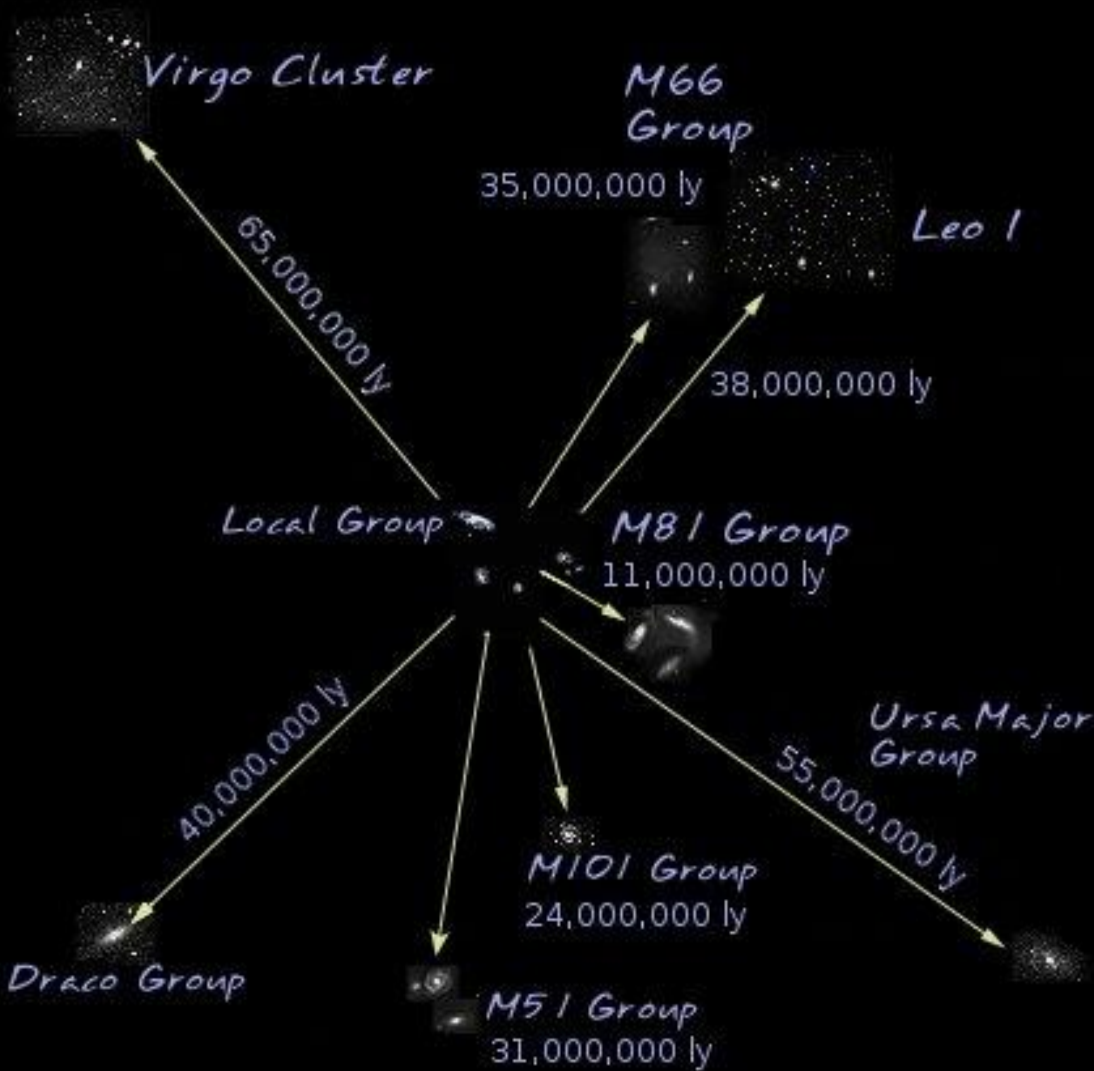
Our Local Group finds itself located at the outer region of a large supercluster region,

- the "Local Supercluster",
- centered on one rich cluster, the Virgo cluster
- ~ 33 Mpc diameter

Wrt. other superclusters:

- poor supercluster
- rather small size

Local Supercluster



Local Supercluster:

contains:

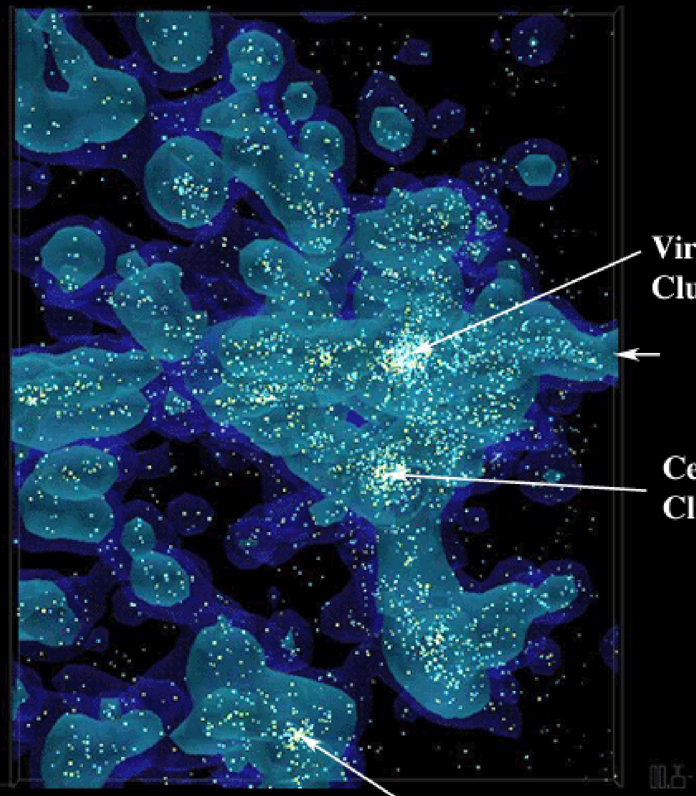
- ~ 100 galaxy groups
- 1 rich cluster - Virgo cluster

structure:

- Central Virgo cluster
- groups & galaxies connected via filamentary extensions
- Local Group:
- outskirt Local Supercluster, on filament extending from Fornax cluster – Virgo cluster

Local Supercluster

End-on View of the Local Supercluster:



150 million light years wide x 190 million light years tall

Courtesy: B. Tully

Structure Local Supercluster:

2 components:

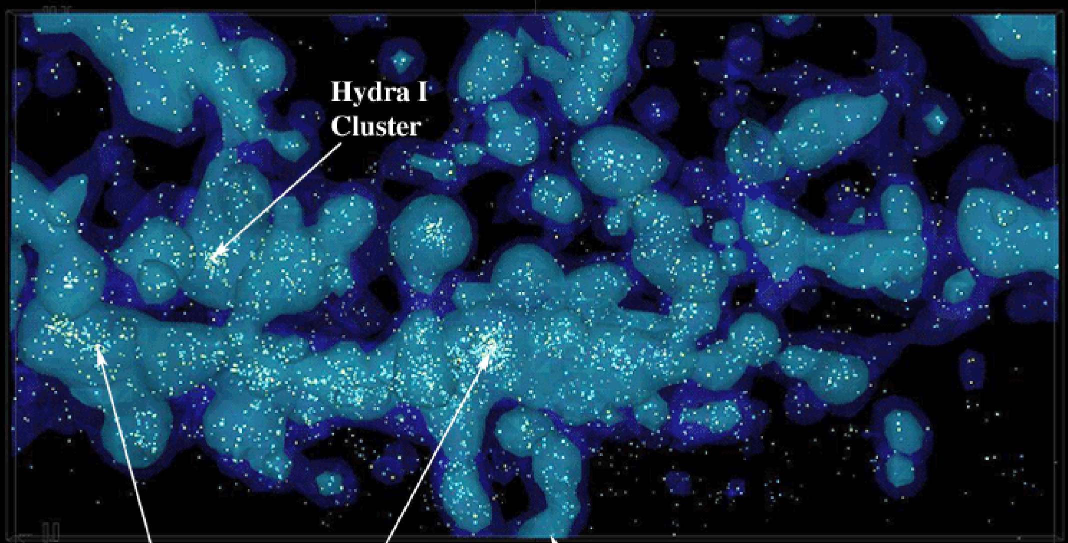
- flattened disk $2/3^{rd}$ galaxies
- spherical "halo" $1/3^{rd}$ galaxies

Disk:

- thin (~ 1 Mpc) disk,
  1:6 - 1:9 flattened

Local Supercluster

Polar View of Local Supercluster:



300 million light years wide x
150 million light years tall

Local Supercluster:

Mass (DM): $M \sim 1 \times 10^{15}\ M_\odot$

Luminosity: $L \sim 3 \times 10^{12}\ L_\odot$

M/L ~ 300

Courtesy: B. Tully

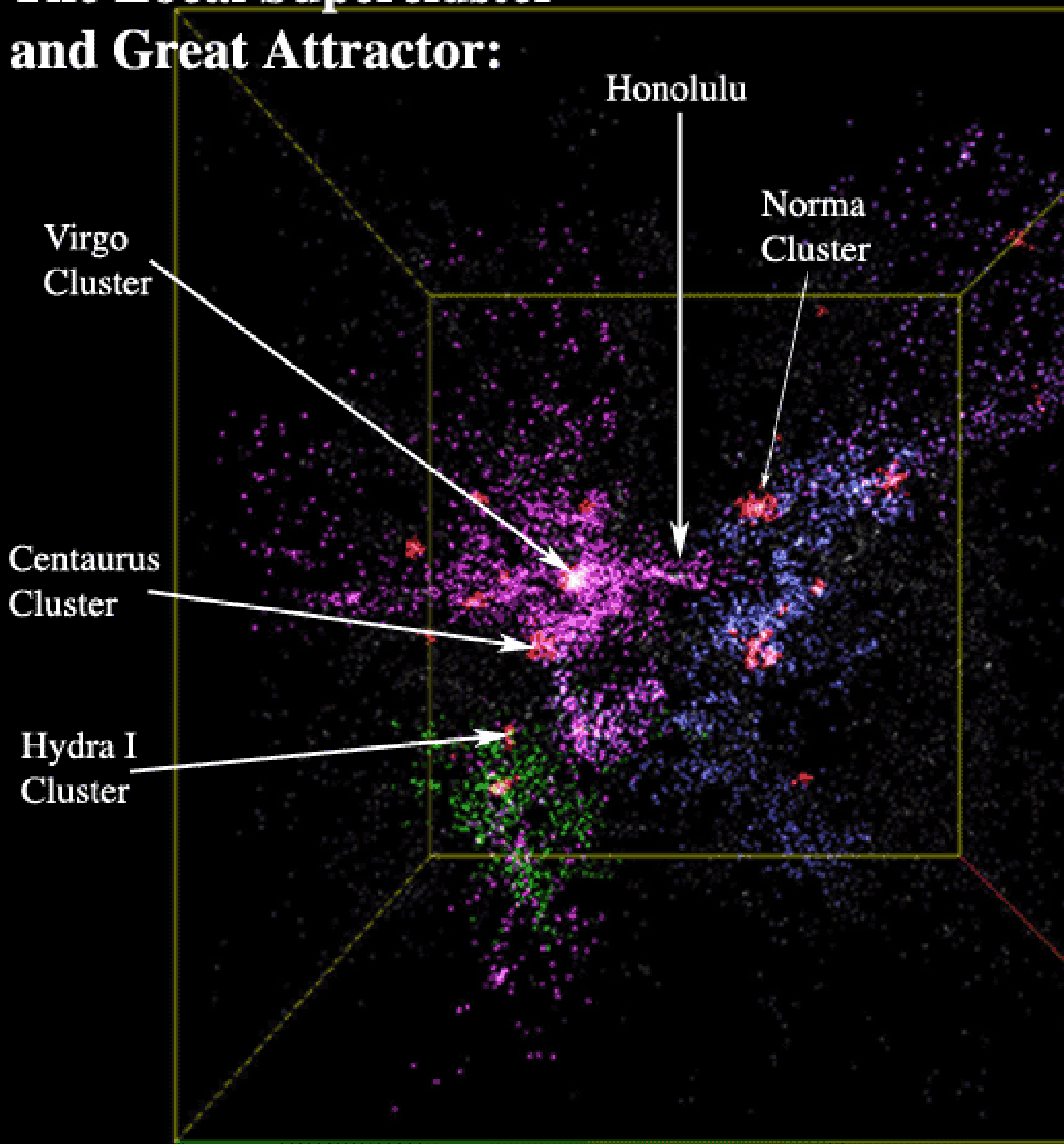
Local Supercluster
Rotating Isodensity Contours,

movie, Brent Tully

Cosmography

Local Universe

The Local Supercluster and Great Attractor:



Our Milky Way Galaxy lies in a minor filament on the outskirts of a large metropolis of many thousand galaxies. Historically this region became known as the Local Supercluster with the Virgo Cluster, 50 million light years away, at it's heart.

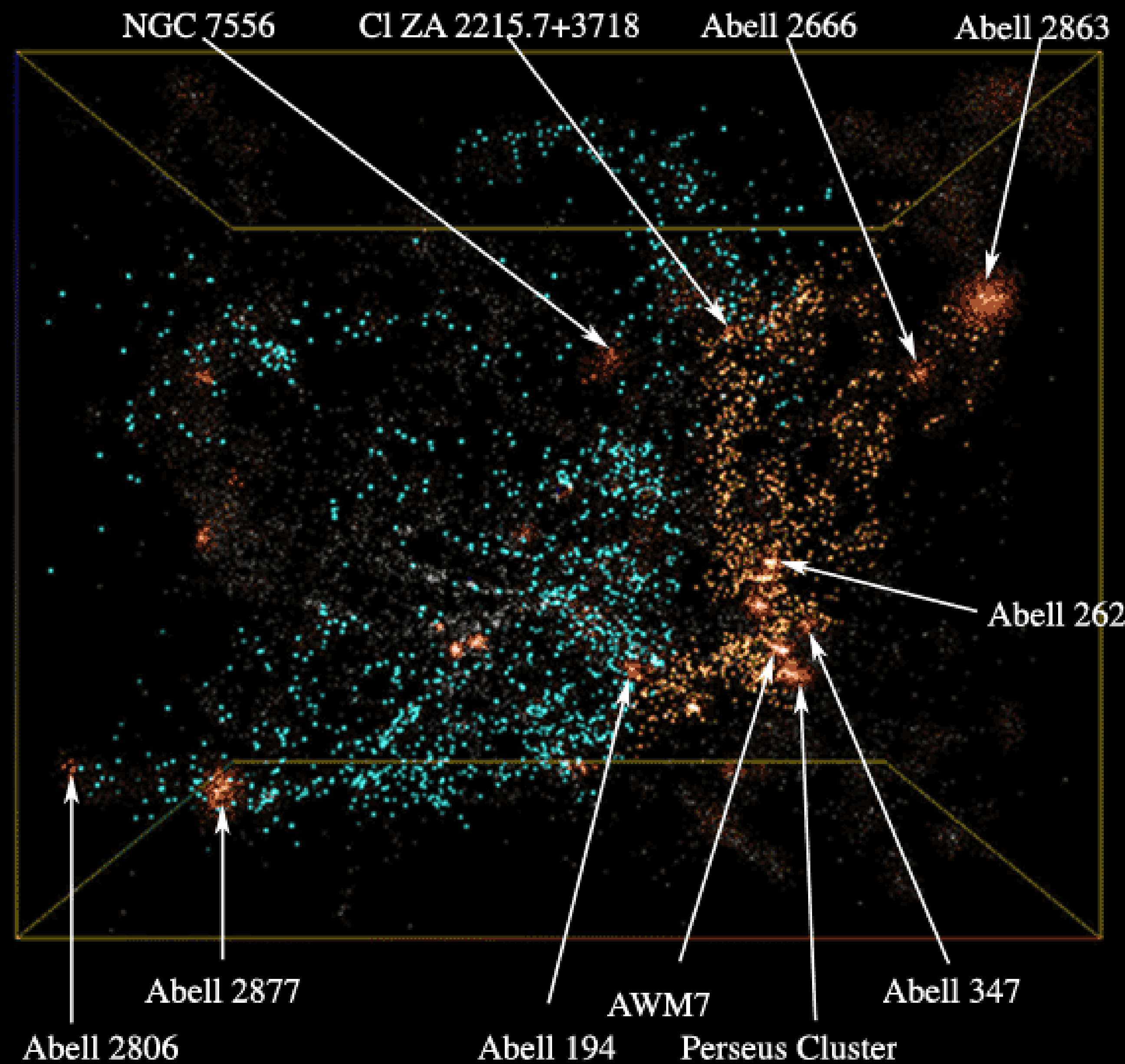
However, in recent years we have become aware that the Local Super-cluster is only part of a considerably larger structure. An early indication came from observations of galaxy streaming. We are being pulled toward a large concentration of mass now called the Great Attractor.

It has been difficult to survey the region of the Great Attractor because much of the sky in it's direction is hidden by obscuring gas clouds in the Milky Way. But now it is being mapped, with it's center in the vicinity of the Norma and Centaurus clusters, 200 million light years away.

Perseus-Pisces Arteries and the Southern Wall:

The third large concentration of galaxies within 300 million light years lies with it's densest core in the Perseus Cluster. In this case, the structure (shown in orange), resembles long twisted filaments.

One filament connects to a structure of a rather different nature: the Southern Wall. This structure (shown in cyan) is more sheet-like. It resembles the palm of a cupped hand.



The Great Wall:

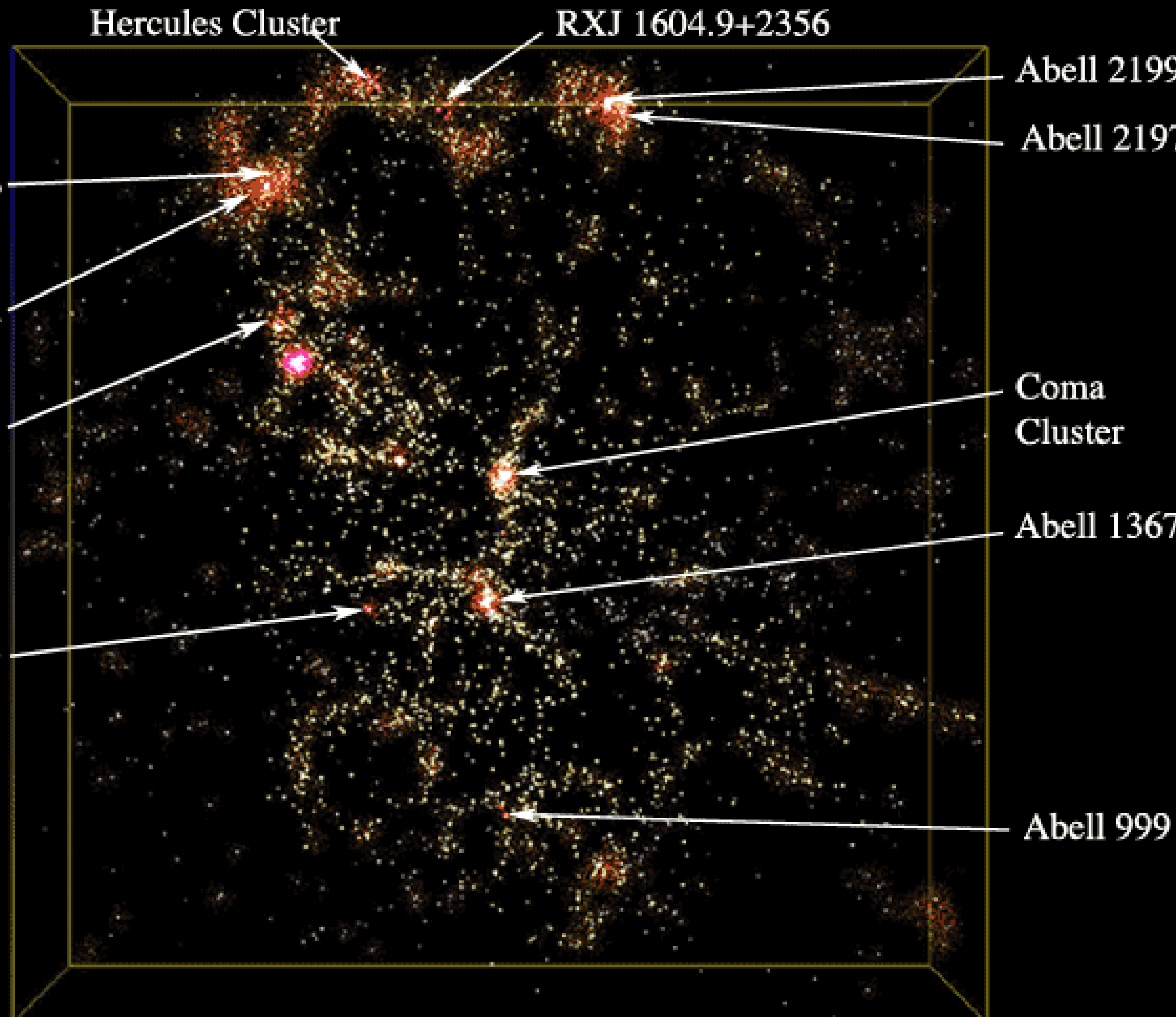
The most important structure within 350 million light years is the Great Wall.

Almost in the middle of it, is the single most dominant cluster - the Coma Cluster.

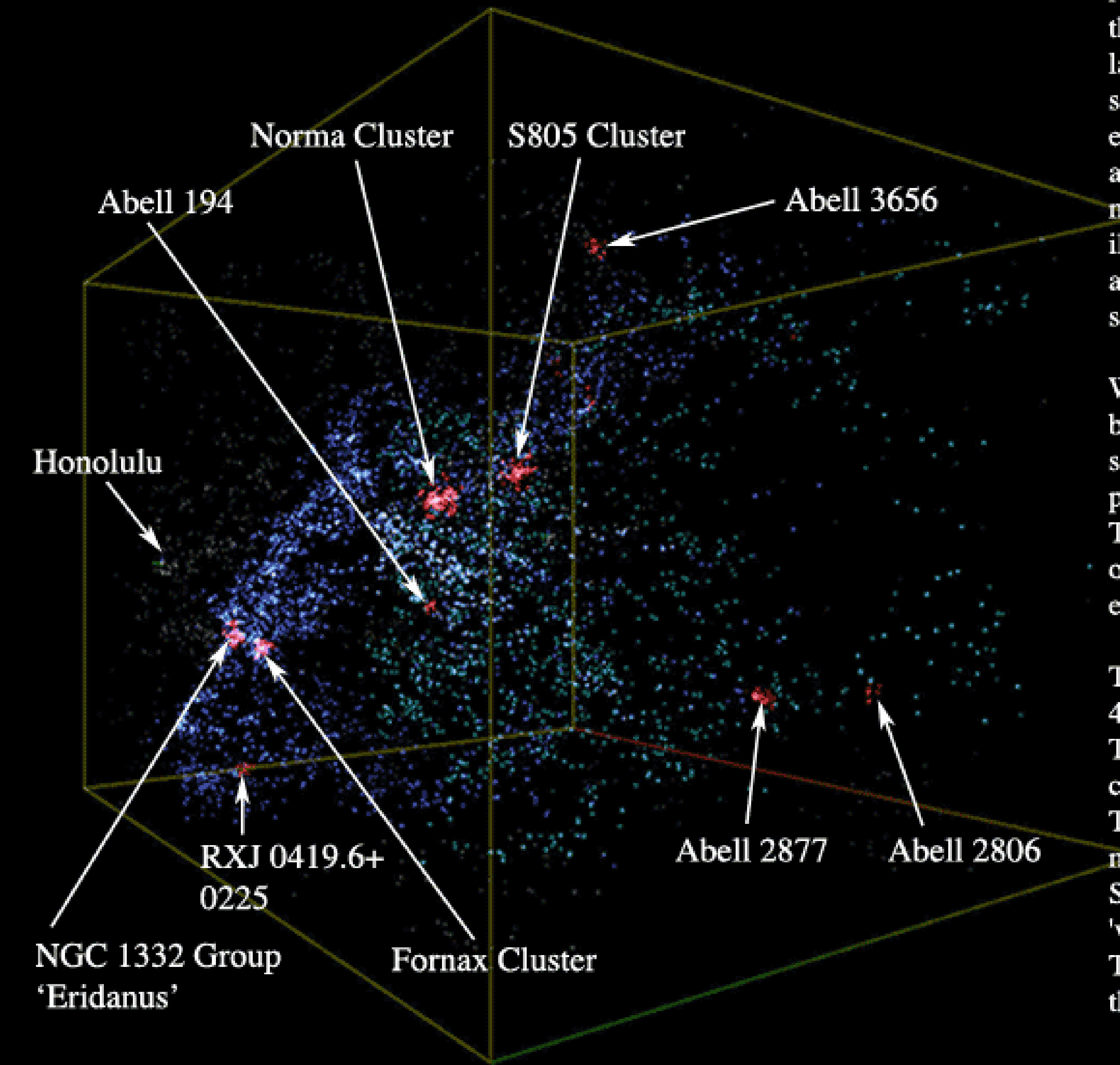
The most crowded part of the Great Wall though is in the vicinity of the Hercules Cluster.

Other knots of galaxies were identified by George Abell. Still others are clusters identified by their glow from X-Ray emitting gas.

The movie provides a circum-navigation of the Great Wall.



The South Pole Void:



Adjacent the major structures, there are big voids. Indeed, in large measure the high density structures are created by the evacuation of the voids. There are many voids within 300 million light years, but the one illustrated here deserves special attention because it is so big and so directly in our face.

We call it the South Pole Void because it occupies much of the sky directly above the southern pole of our Milky Way Galaxy. The void resembles the interior of an empty shell open at one end (though rather deformed).

The nearest wall comes within 40-50 million light years of us. This part of the structure has been called the Southern Supercluster. The far side, roughly 300 million light years away, is the Southern Wall. In fact, the 'void' is not entirely empty. There is a lacey filament that intersects it.

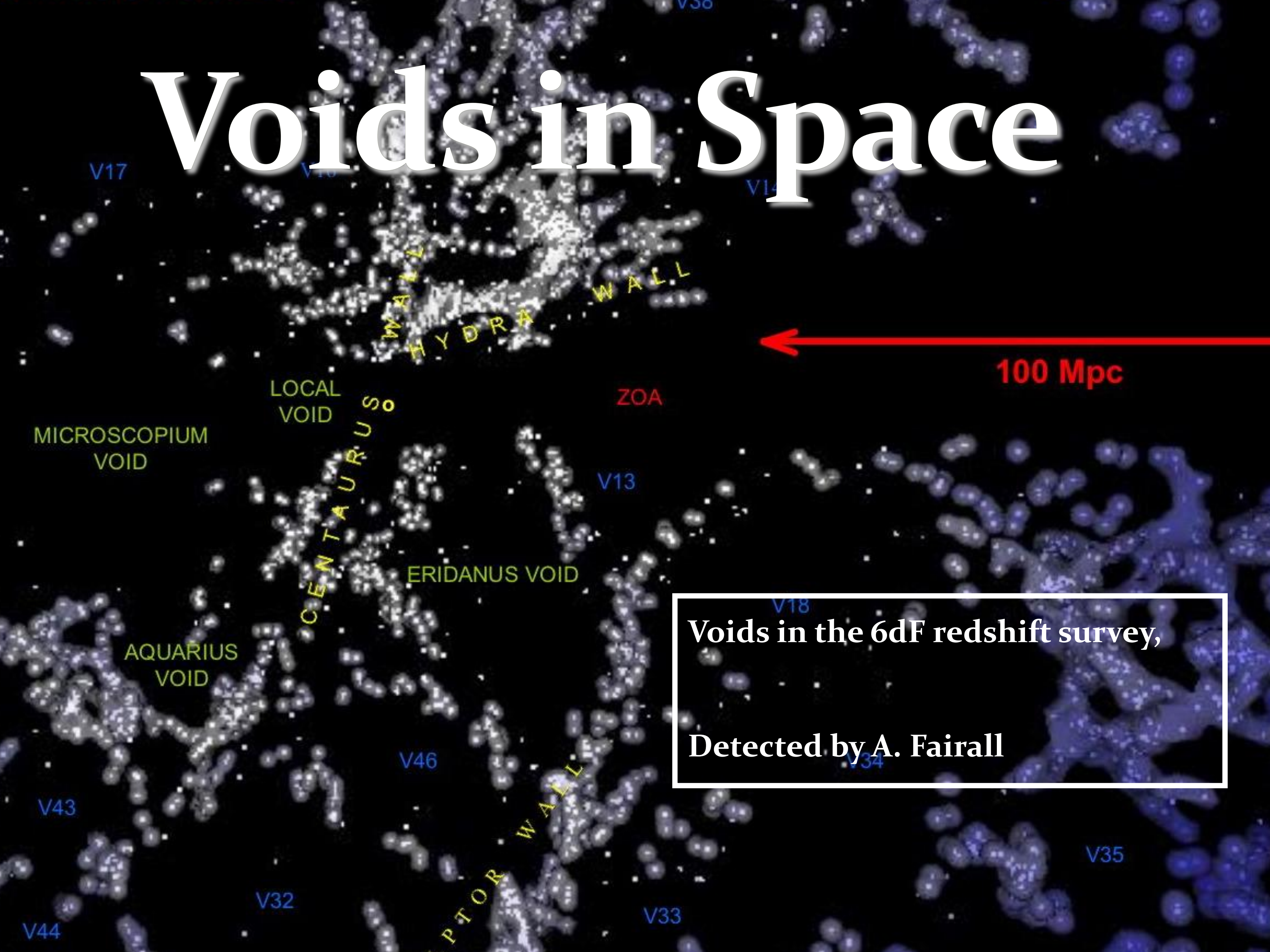
Local Universe, Constrained simulation,

movie, Klaus Dolag

Cosmic Depressions

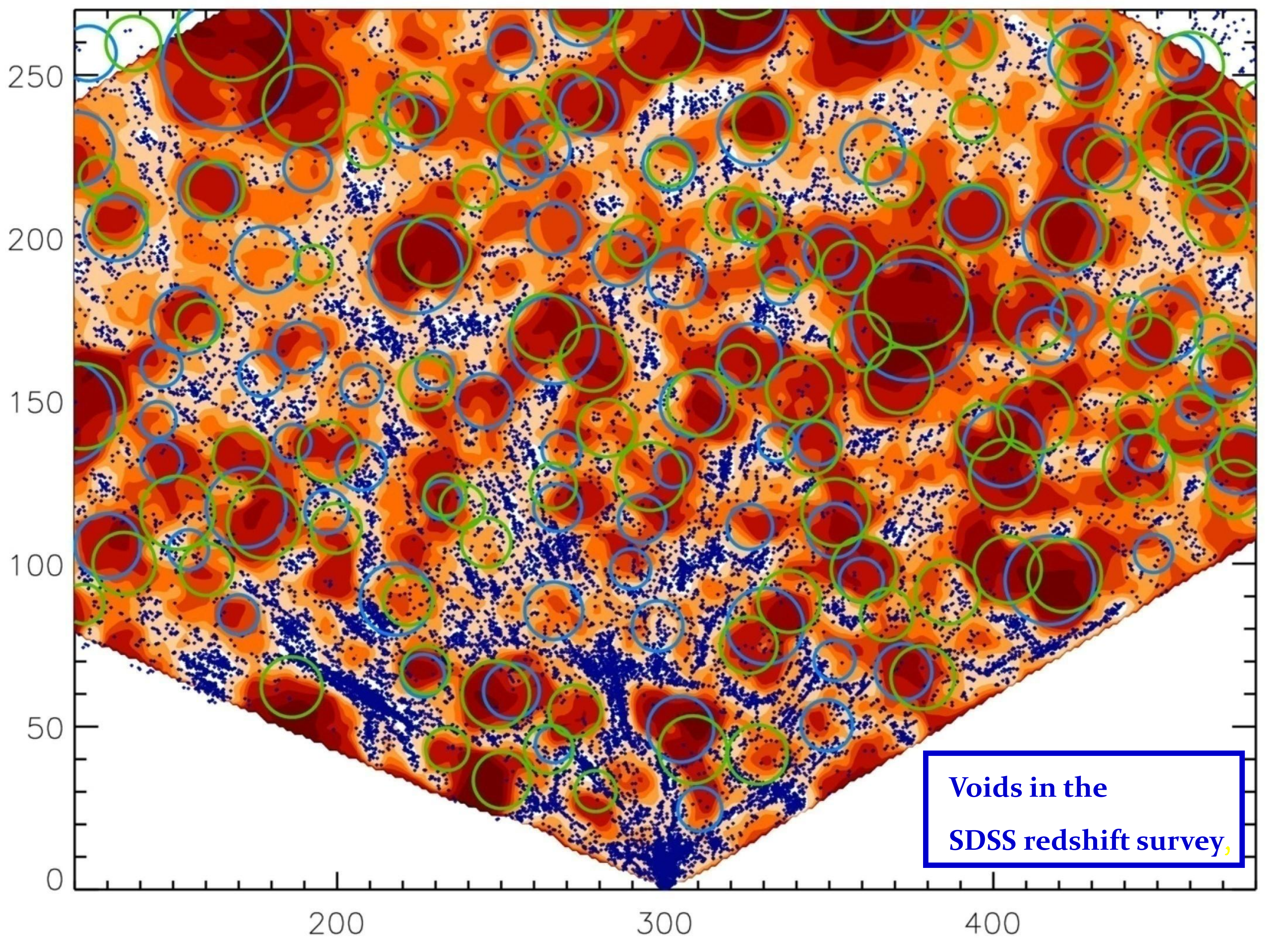
Voids in Space

Voids in Space



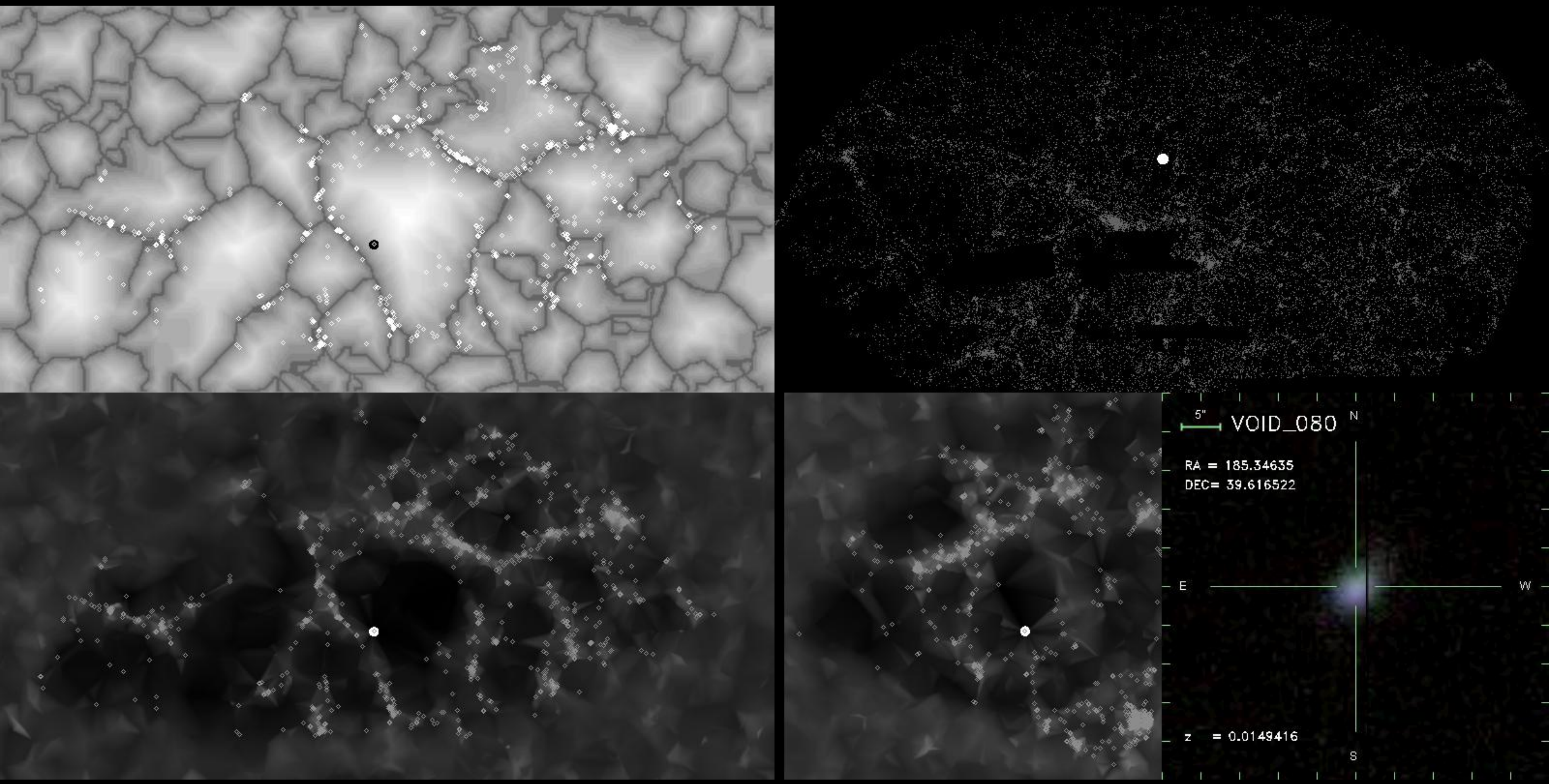
Voids in the 6dF redshift survey,

Detected by A. Fairall



250
200
150
100
50
0
200
300
400
Voids in the
SDSS redshift survey

SDSS Voids



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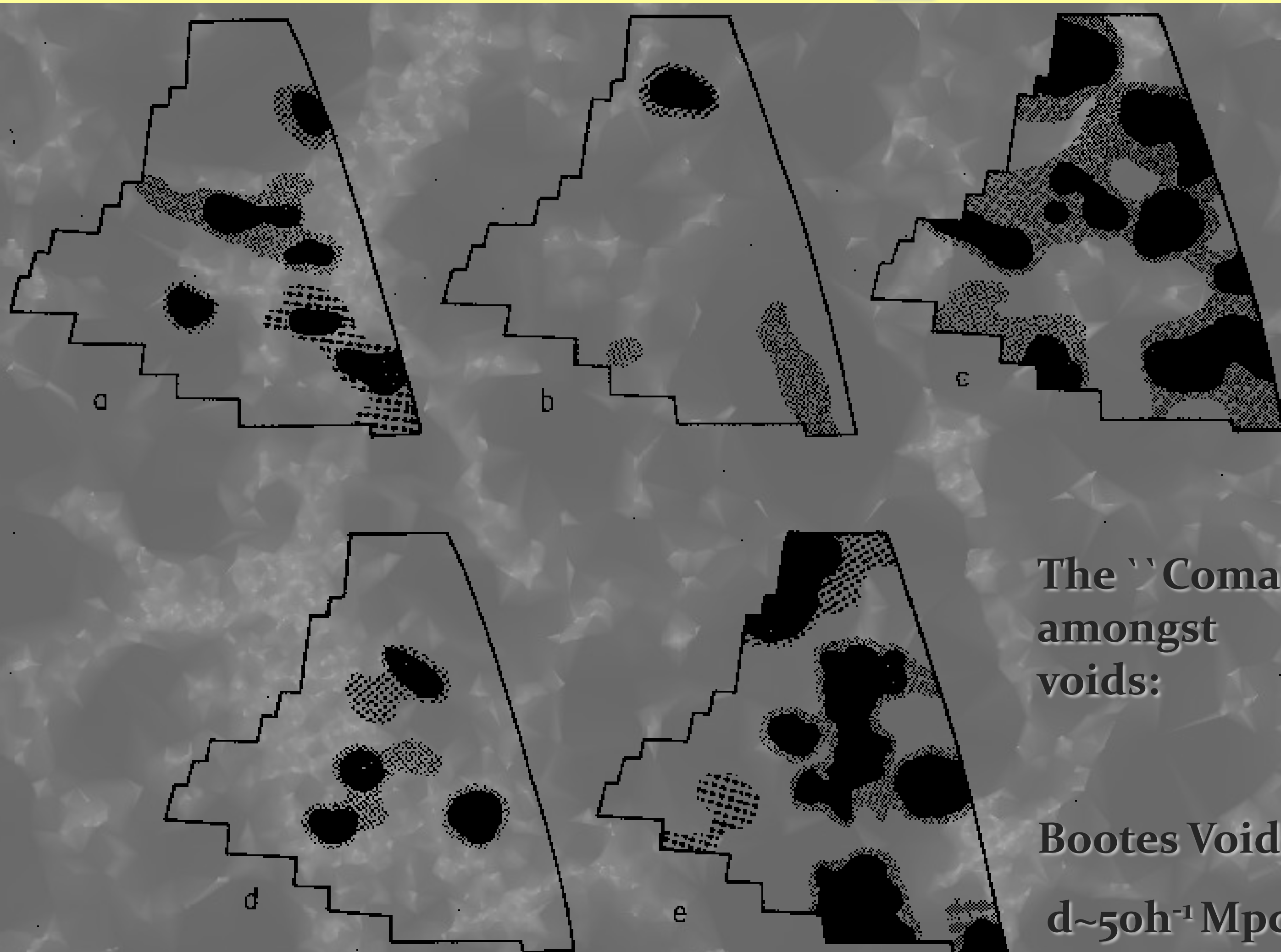
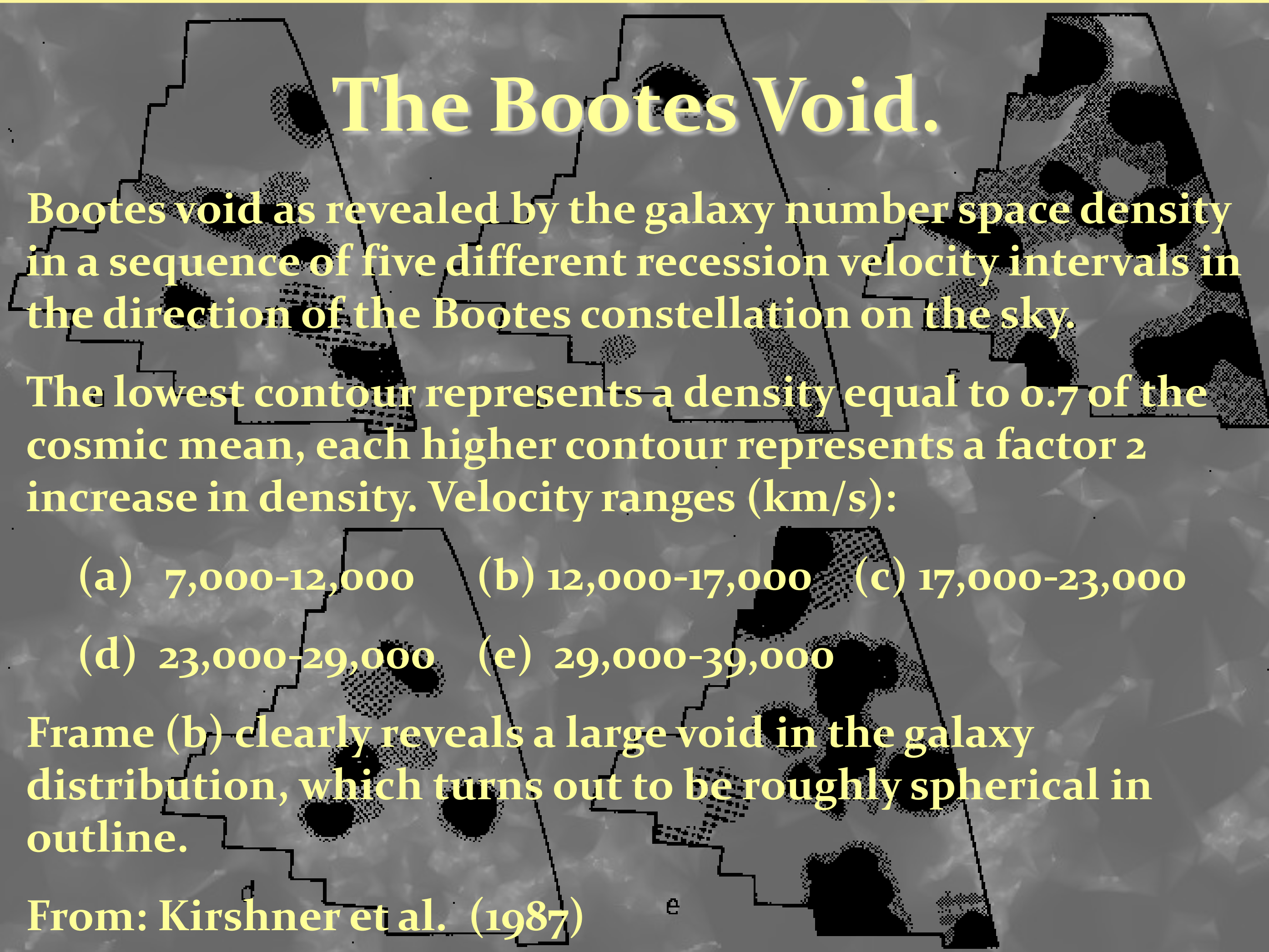


The ``Coma" amongst voids:

Bootes Void

$d \sim 50 h^{-1}$ Mpc

Voids in Space



The Bootes Void.

Bootes void as revealed by the galaxy number space density in a sequence of five different recession velocity intervals in the direction of the Bootes constellation on the sky.

The lowest contour represents a density equal to 0.7 of the cosmic mean, each higher contour represents a factor 2 increase in density. Velocity ranges (km/s):

(a) 7,000-12,000 (b) 12,000-17,000 (c) 17,000-23,000

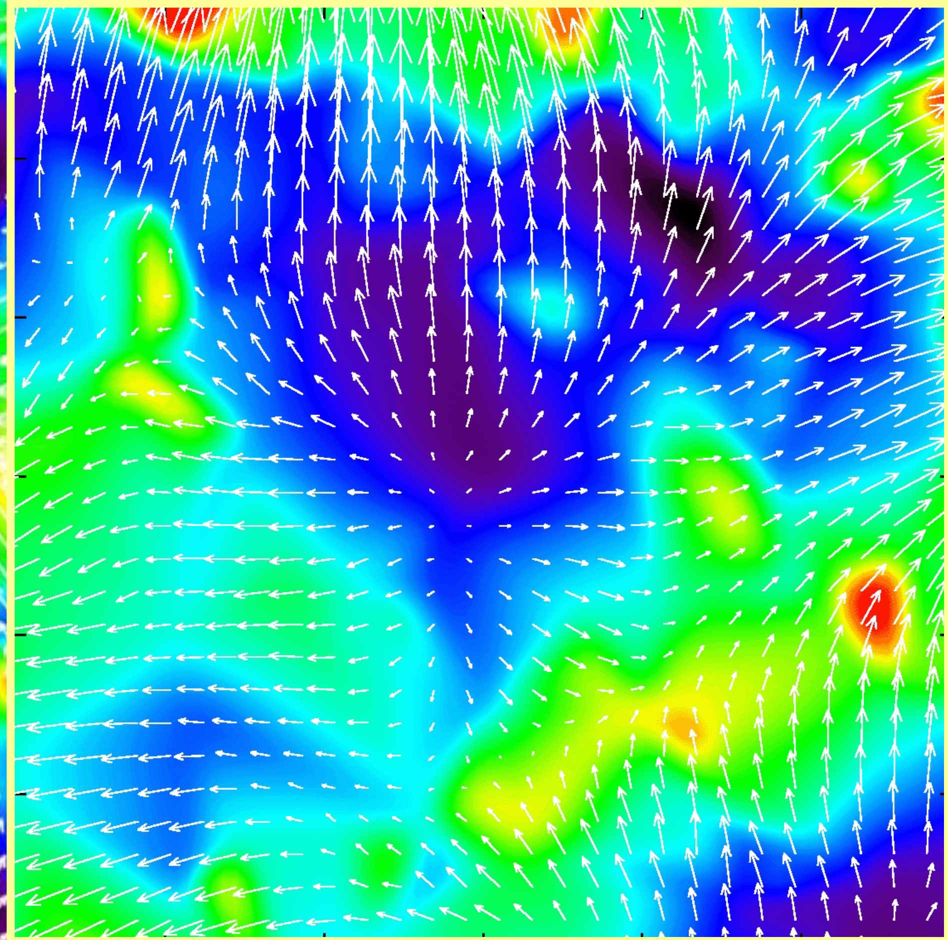
(d) 23,000-29,000 (e) 29,000-39,000

Frame (b) clearly reveals a large void in the galaxy distribution, which turns out to be roughly spherical in outline.

From: Kirshner et al. (1987)

Voids in Space

Sculptor Void



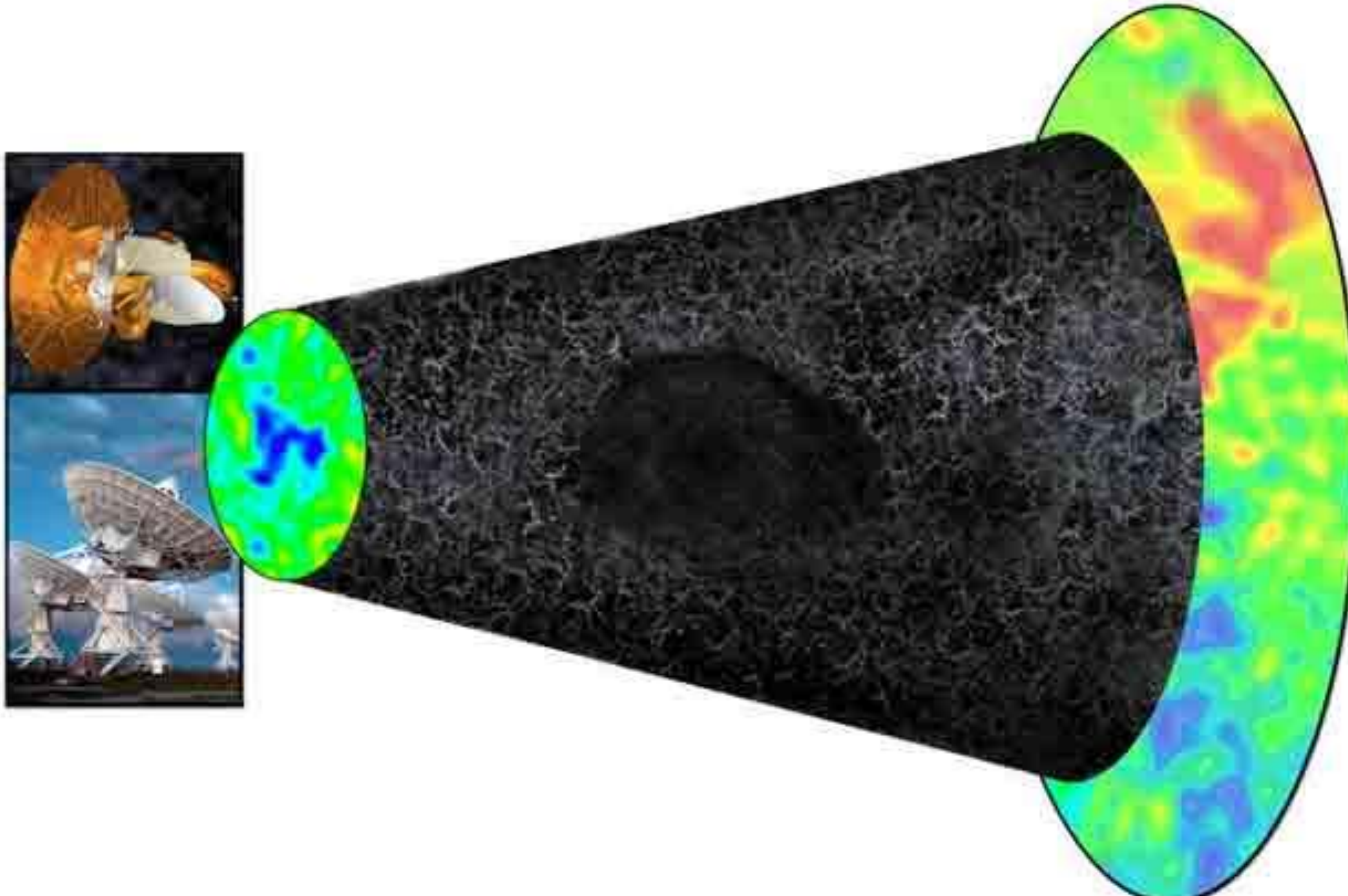
PSCz: DTFE density & velocity field

(Romano-Diaz & vdW)

Void Dynamics:

Voids exert a repulsing dynamical influence over their surroundings.

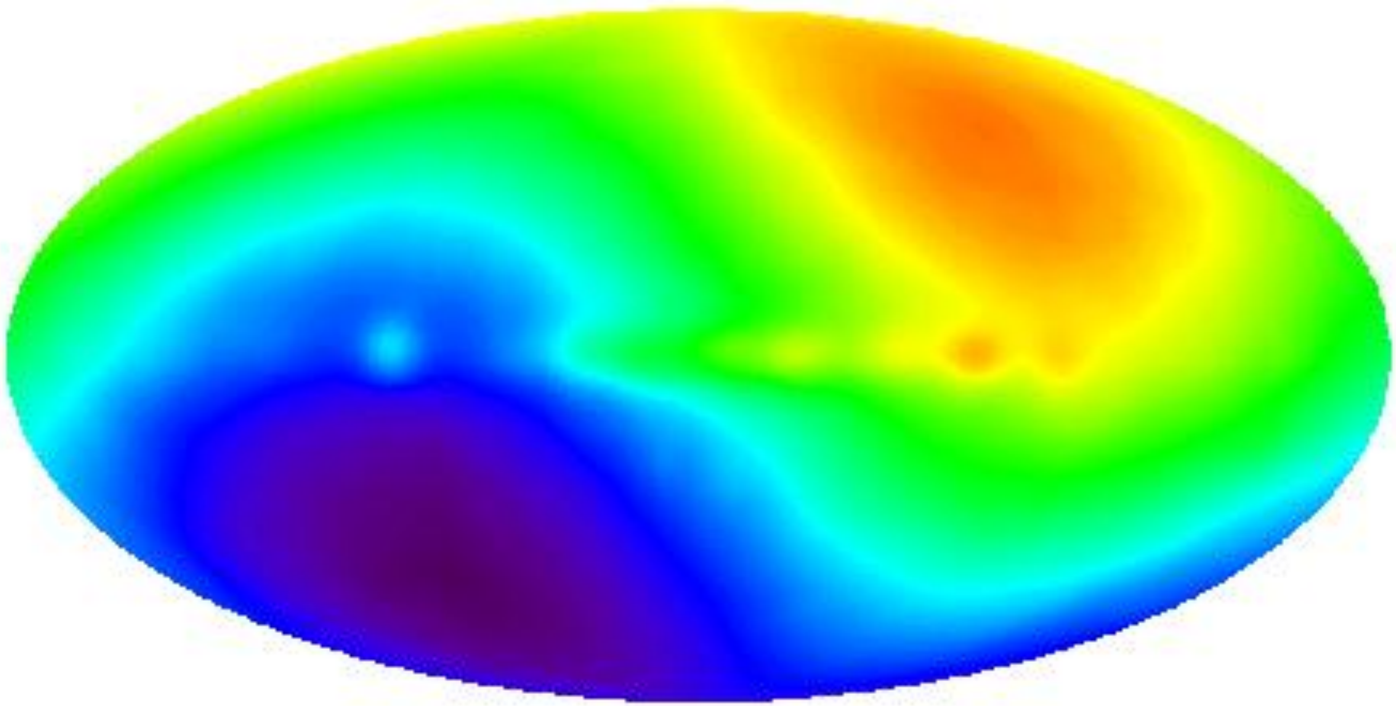
Supervoids ???



Local Universe Dynamics

Peculiar Velocities

The CMB Dipole



ΔT= 3.36 mK

(l,b)=(264.3°,48.1°)

⇒

v_{LG}= 627 +/- 22 km/s

(l,b)=(276°,30°)

We are moving with a velocity

v ~ 627 km/s

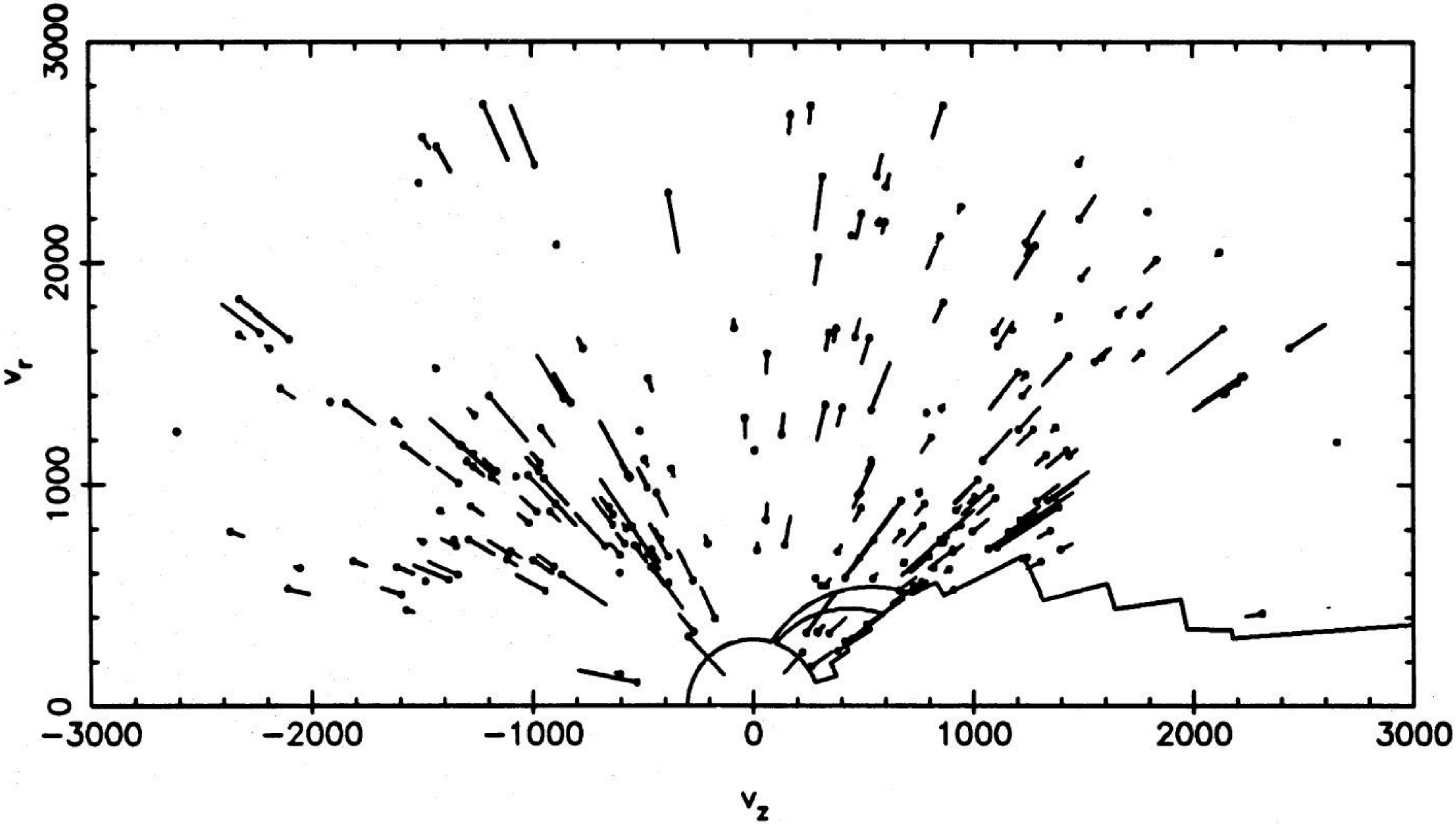
with respect to the Universe:

this motion is locally induced:

gravitational influence of surrounding mass structures

Local Supercluster flow

Lilje, Yahil & Jones 1986



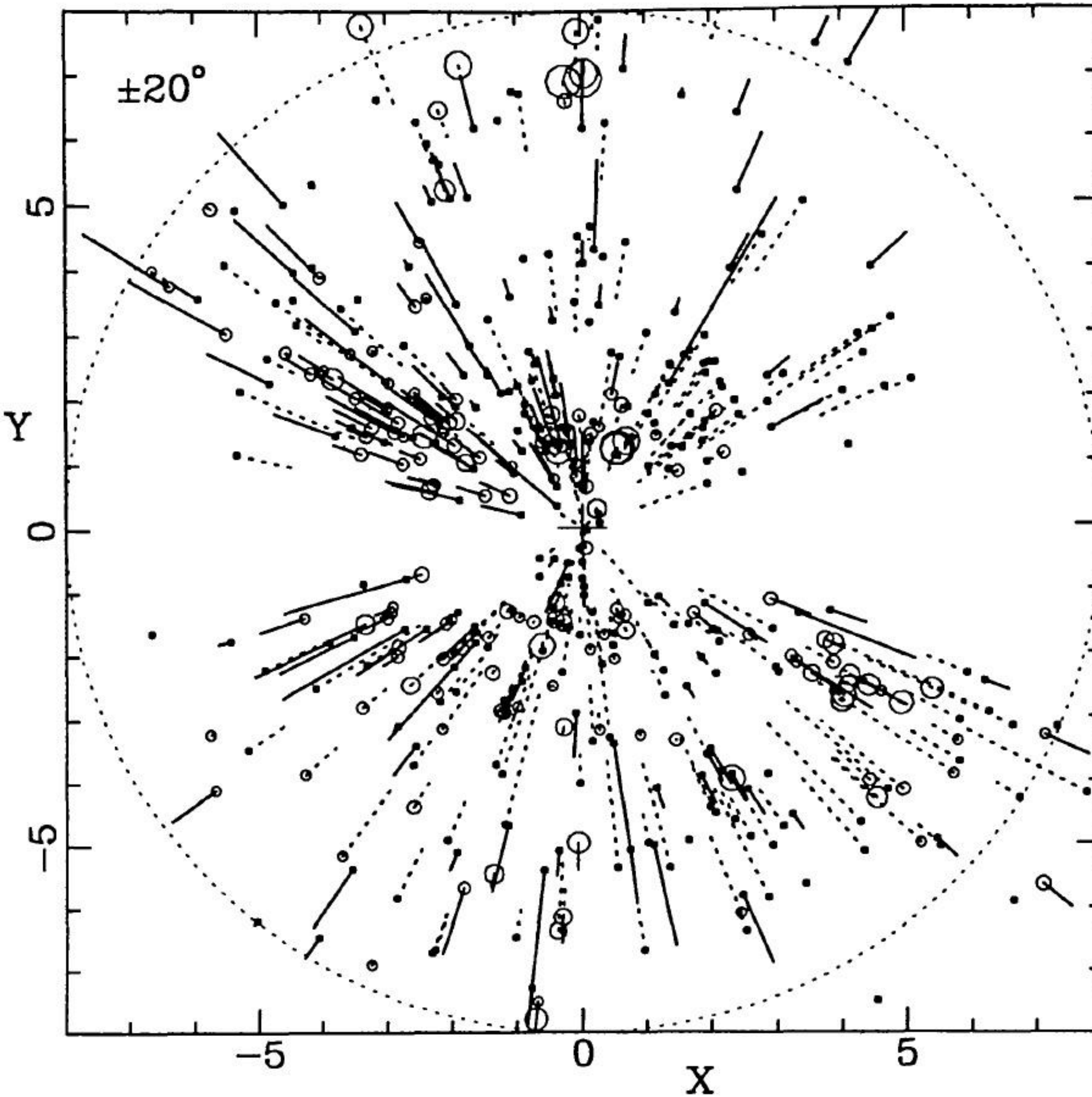
By mapping measured (radial) velocities within our Local Supercluster, one notices the (tidal) gravitational influence of external mass concentrations

Mark III

Peculiar radial velocities in Local Universe

Willick, Strauss et a

First flow maps: 7 Samurai



Velocity & Gravity

In linear regime (small density inhomogeneities)

- the velocity flow directly reflects the
  matter distribution throughout the Universe: $\delta(x)$
  (mainly a rather restricted "local" region)
- As well as the cosmic density parameter Ω
- Gravitational Acceleration (wrt. Background Universe) is
  integral over all inhomogeneities:

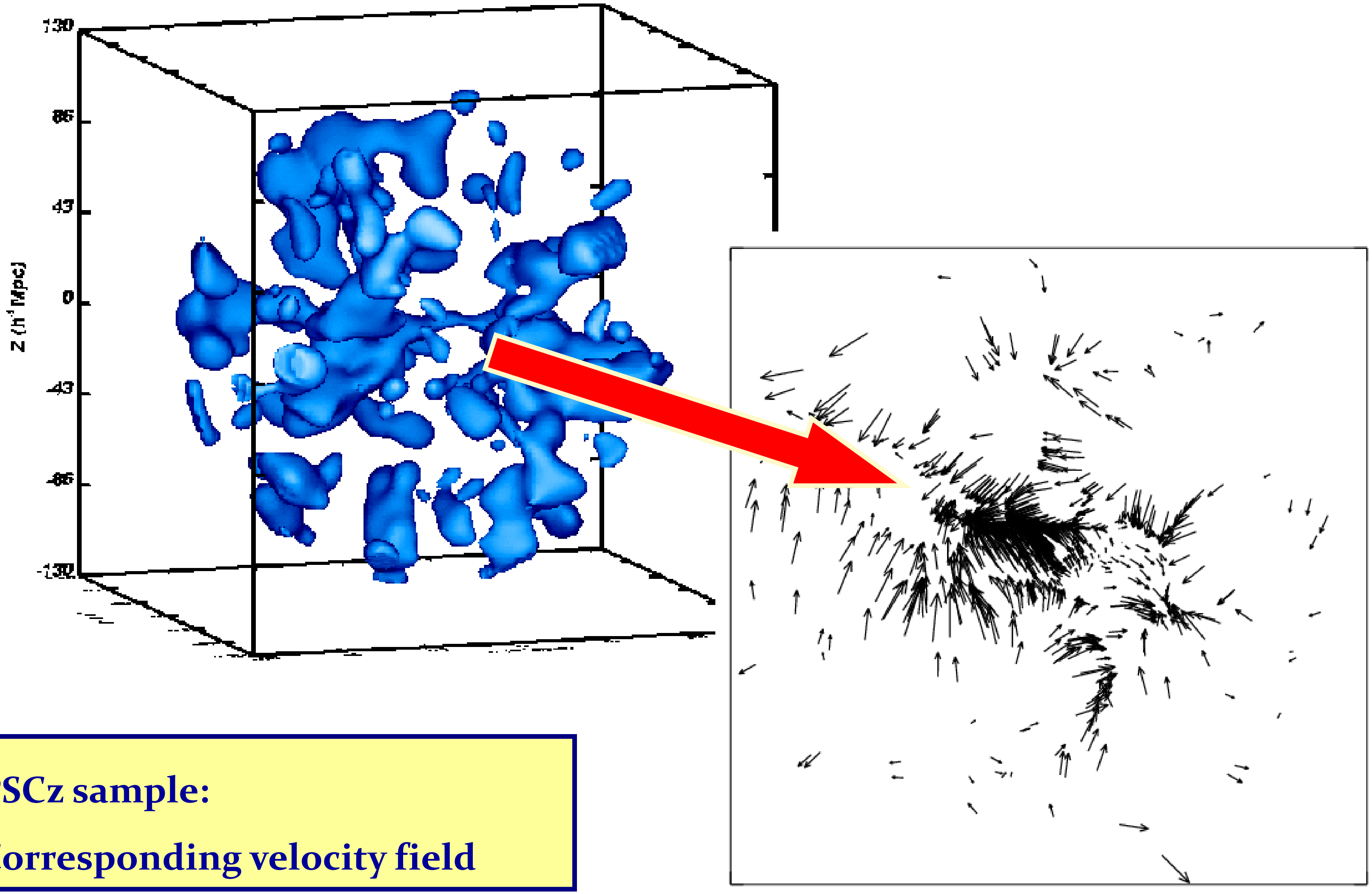
$$\mathbf{g}(\mathbf{r},t) = -\frac{1}{a}\nabla\phi = \frac{3\Omega H^2}{8\pi}\int \mathrm{d}\mathbf{x}'\,\delta(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

Cosmic Migration Flows

$$\mathbf{v} = \frac{H\,f}{4\pi G\,\rho_u}\mathbf{g} = \frac{2\,f}{3H\Omega}\mathbf{g}$$

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

Cosmic Migration Flows



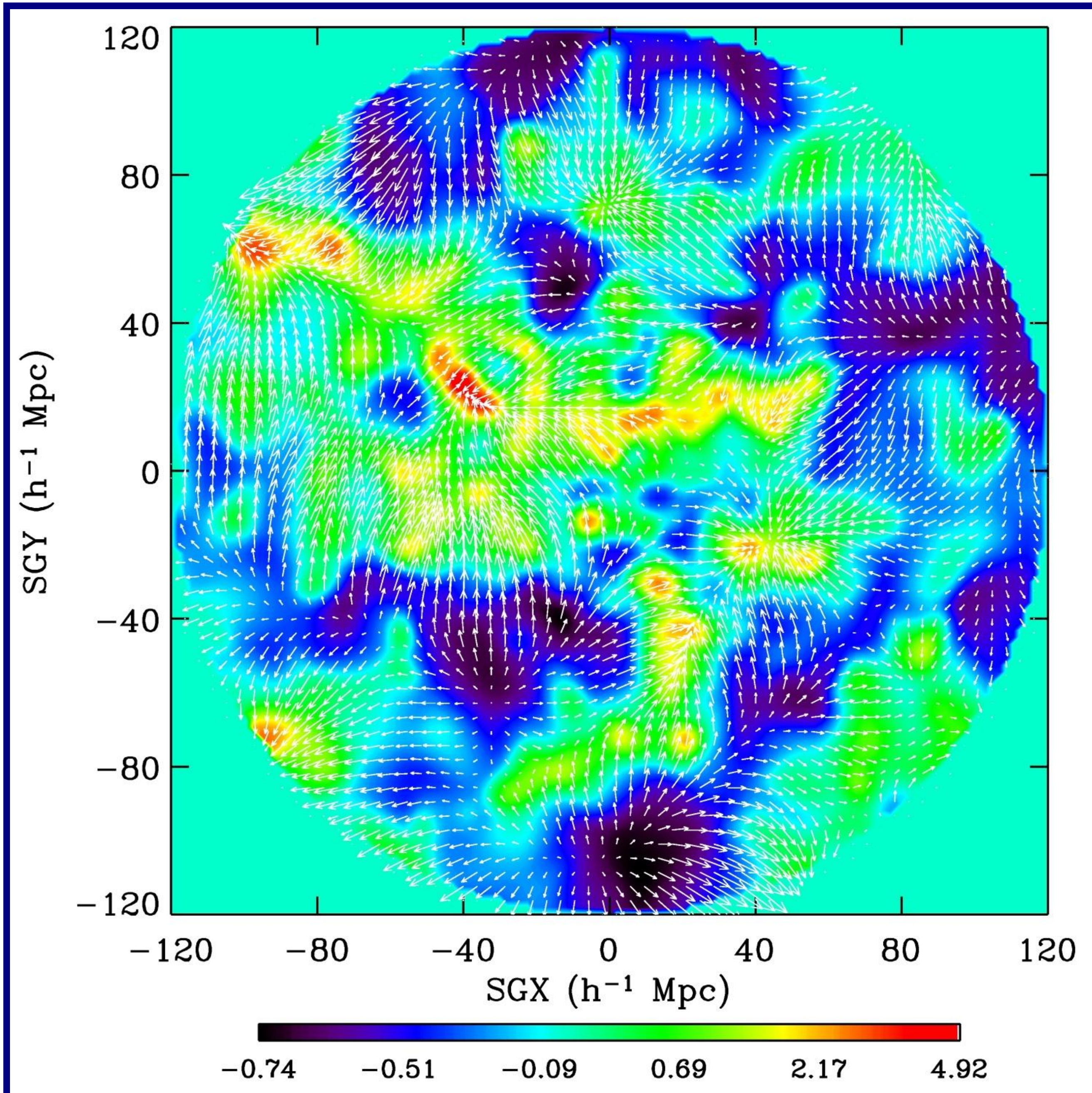
PSCz sample:

Corresponding velocity field

PSCz
flow field in
Local Universe

(centre:
Local Group)

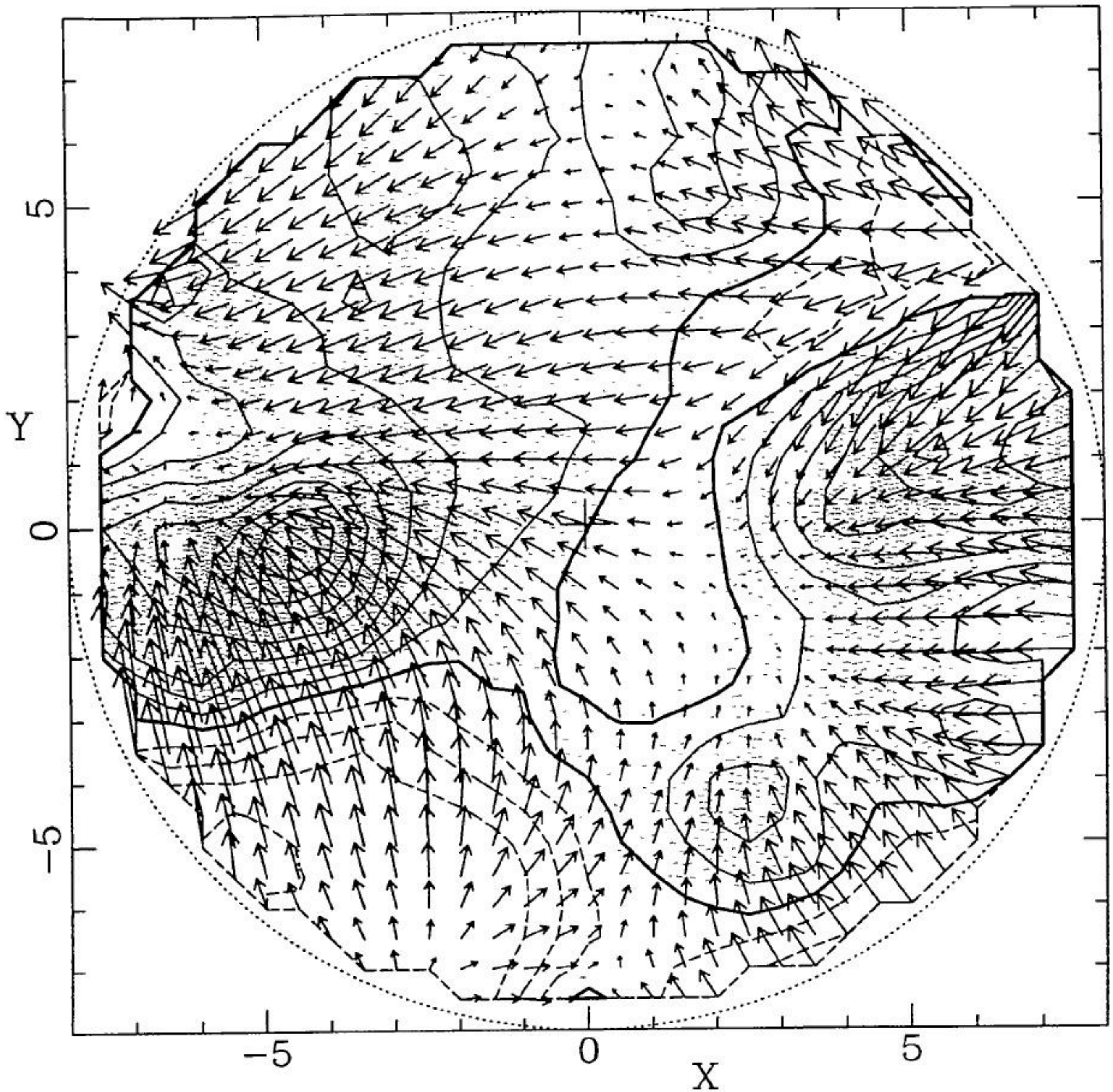
from:
Romano-Diaz & vdW



POTENT map

Mass distribution
Local Universe

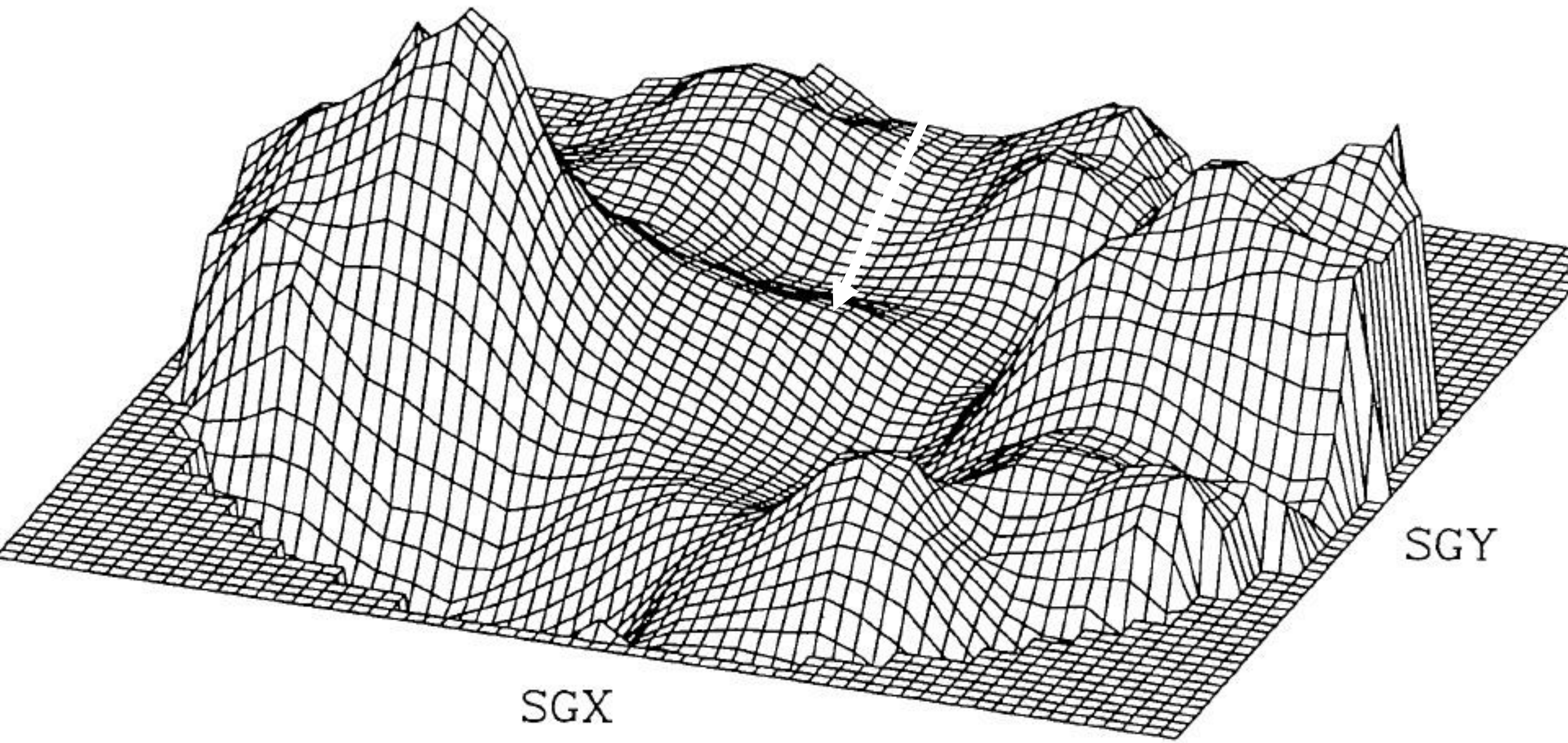
Bertschinger,
Dekel, et al.



POTENT map

Mass distribution Local Universe

Bertschinger, Dekel, et al.



Local Universe Dynamics

Great Attractor

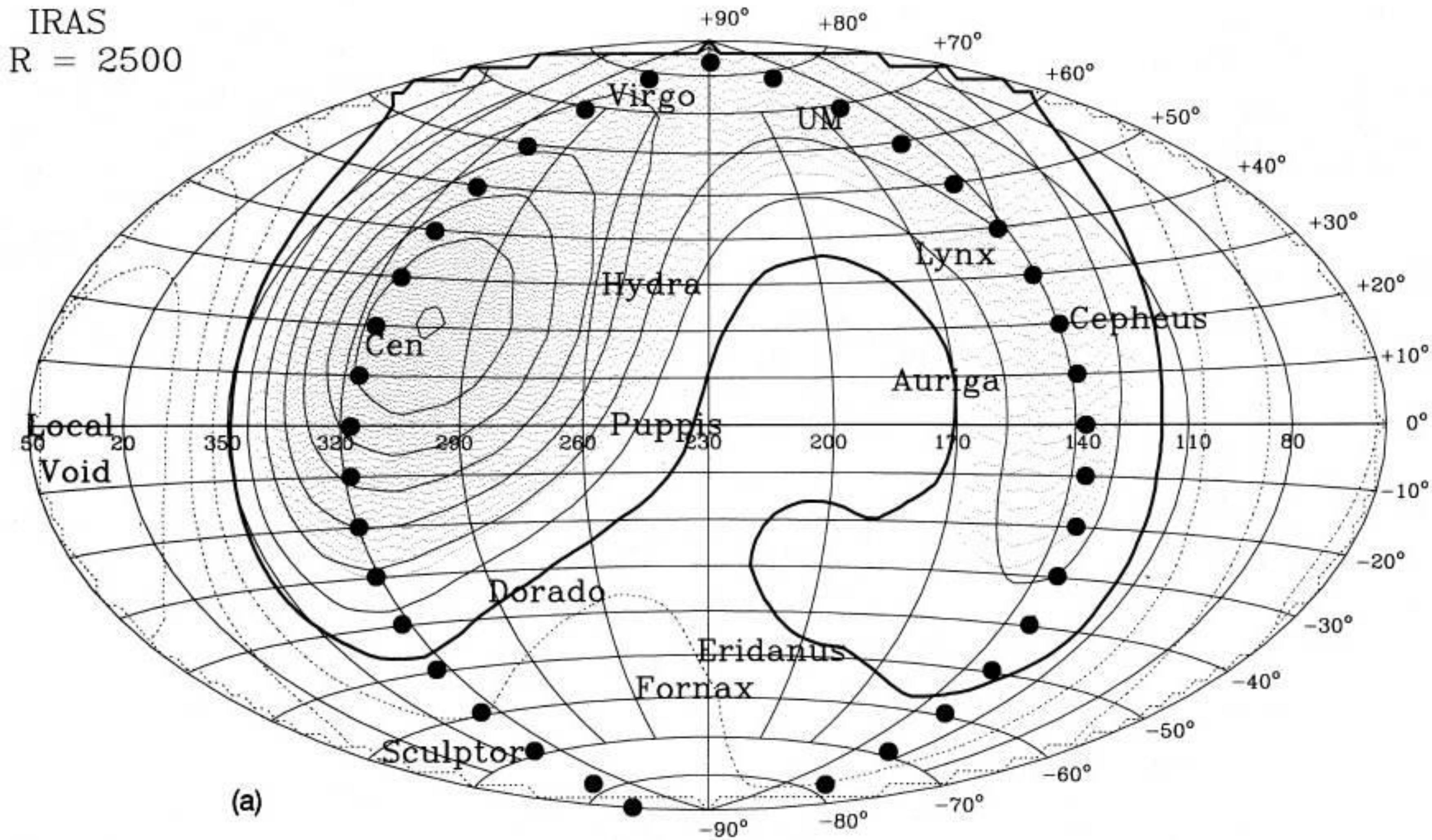


Figure 4. The galaxy density fluctuation field from the *IRAS* 1.9-Jy survey (by Yahil et al. 1991). Coordinates, smoothing, contours and shell distances are as in Fig. 3.

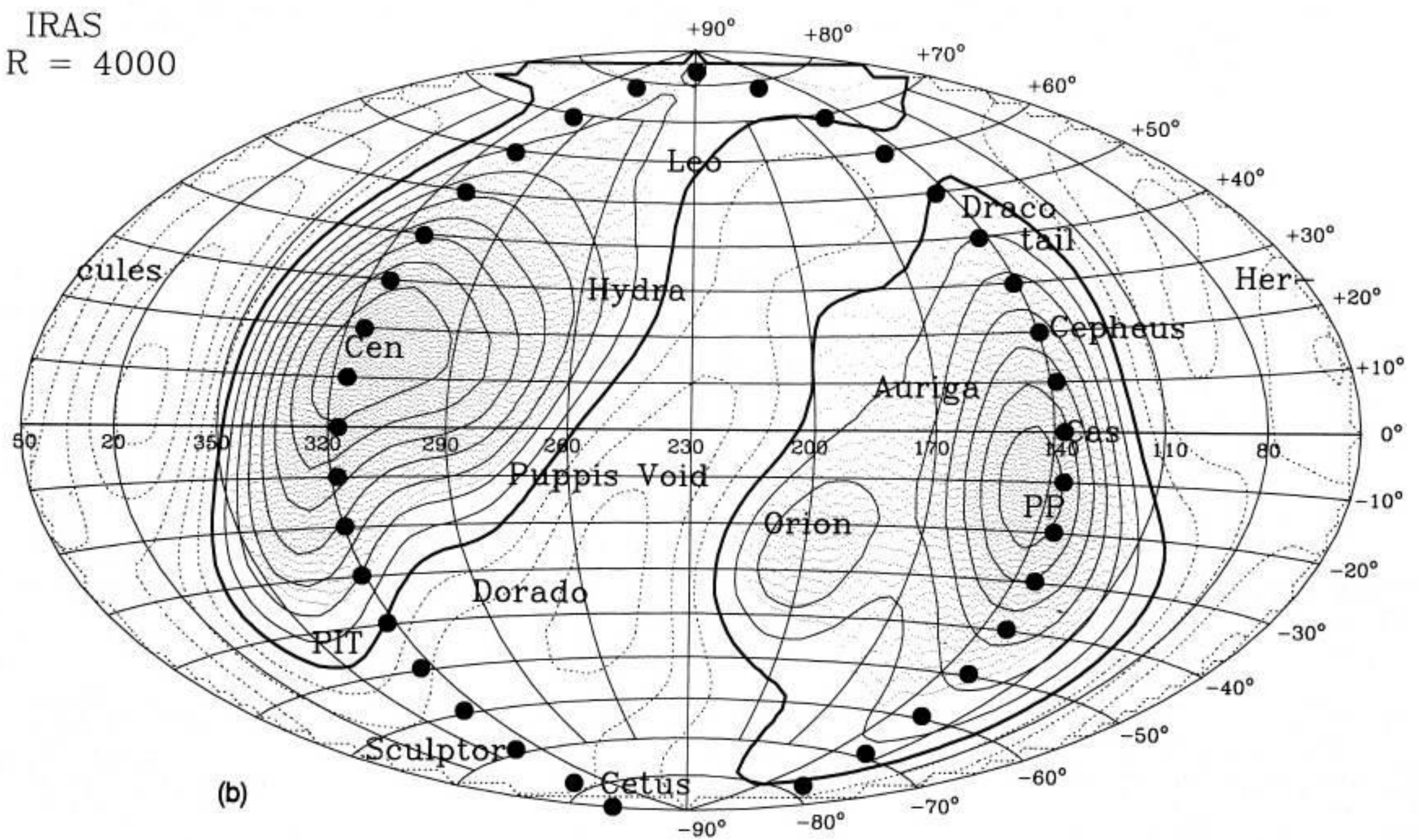
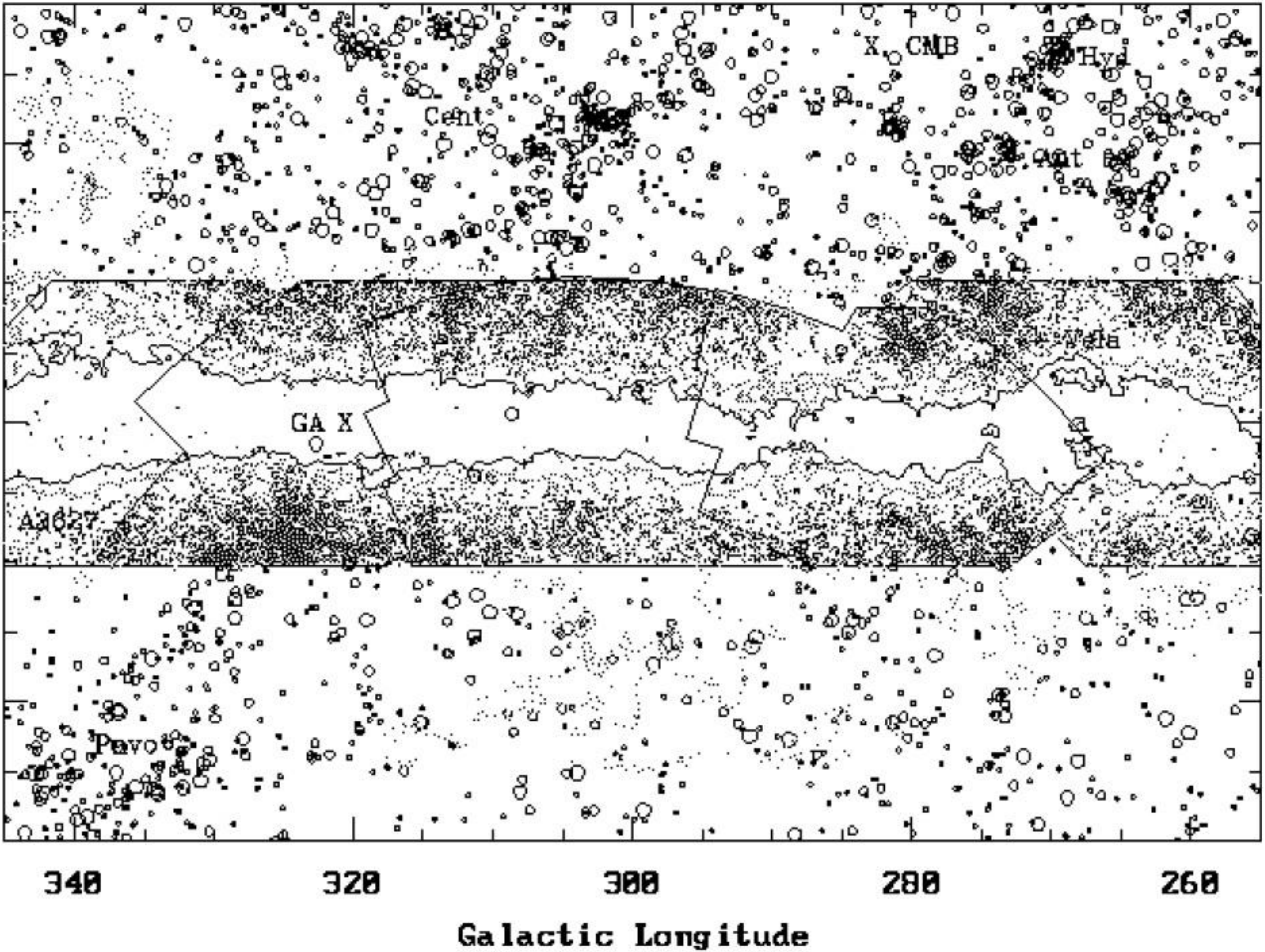


Figure 4 – *continued*



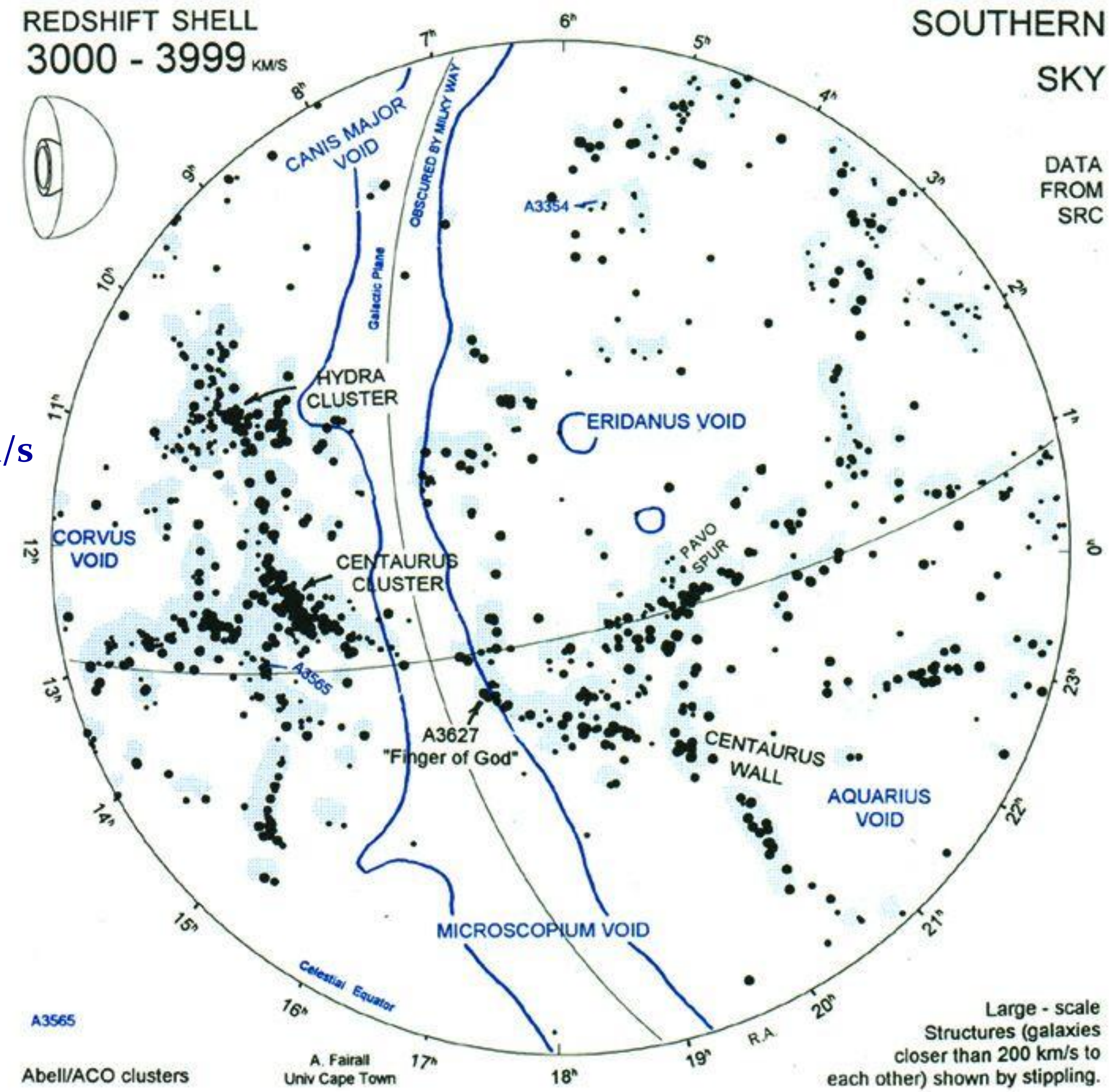
X
CMB
Hyd
Cent
Ant
Vela
GA X
A3627
Pavo
340
320
300
280
260
Galactic Longitude

Tony Fairall's nearby LSS map:

cz=3000-3999 km/s

clear views of Great Attractor:

Norma Cluster/ A3627




the Great Attractor's Heart:
Norma Cluster

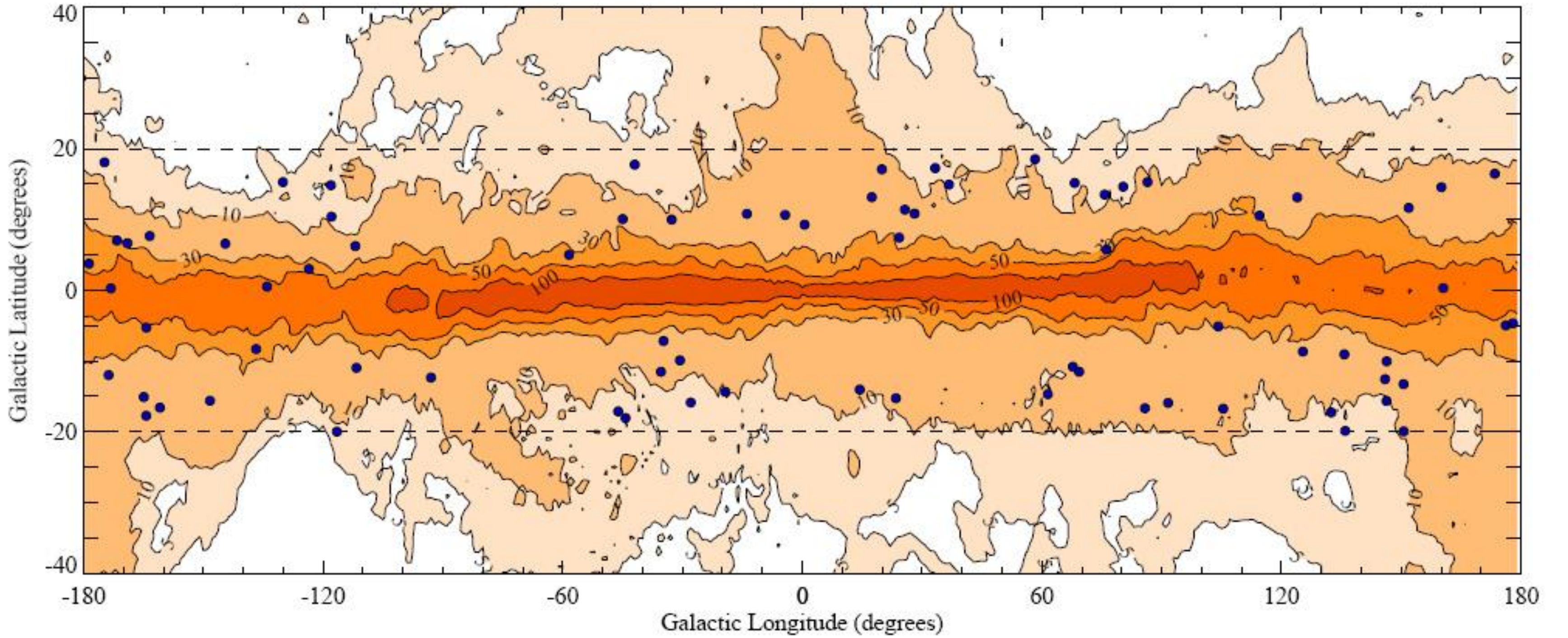
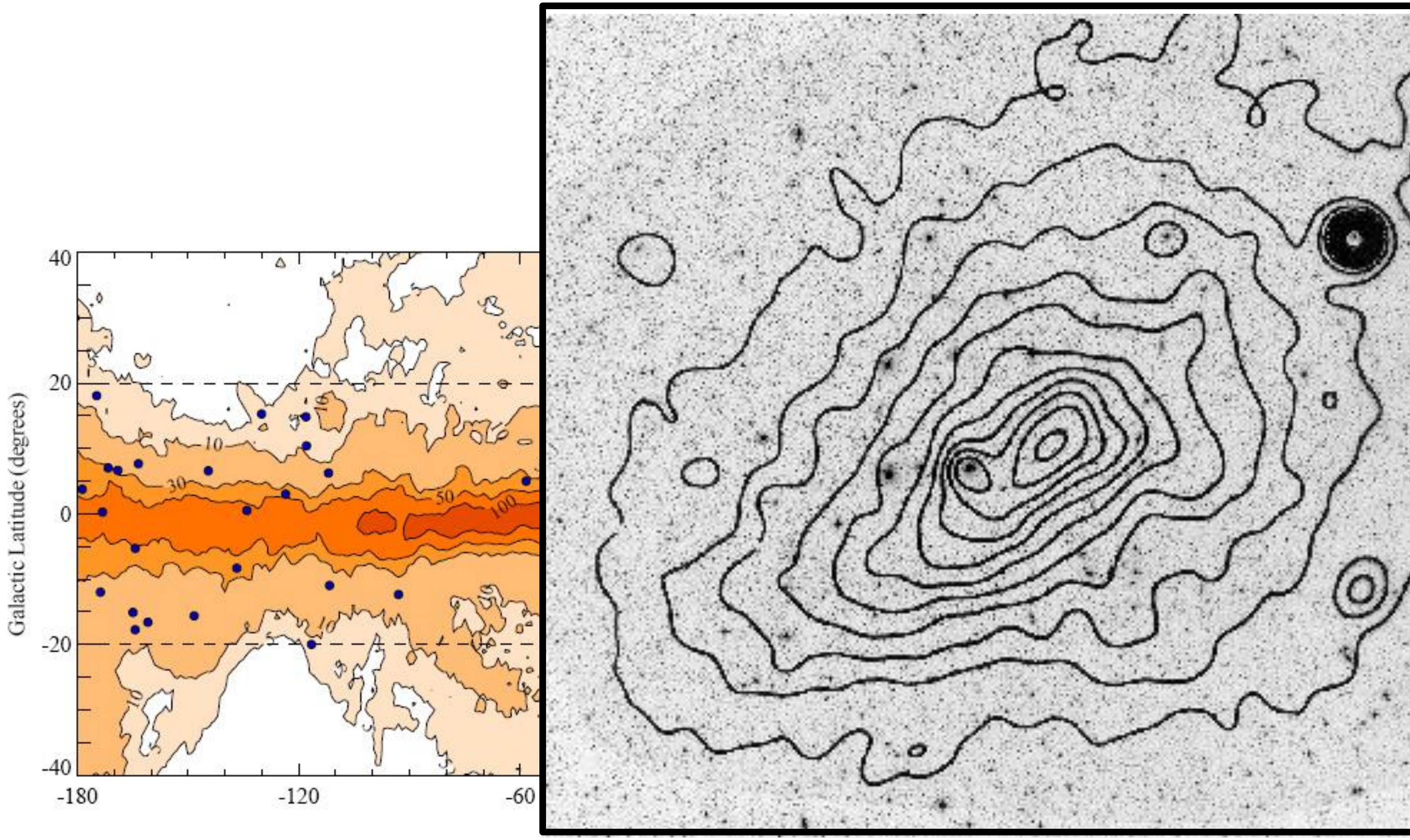


Fig. 16. Distribution in Galactic coordinates of the 76 by Ebeling et al. [129] so far spectroscopically confirmed X-ray clusters (solid dots) of which 80% were previously unknown. Superimposed are Galactic HI column densities in units of 10^{20} cm^{-2} (Dickey & Lockman 1990). Note that the region of relatively high absorption ($N_{\rm HI} > 5 \times 10^{21}$ cm^{-2}) actually is very narrow and that clusters could be identified to very low latitudes



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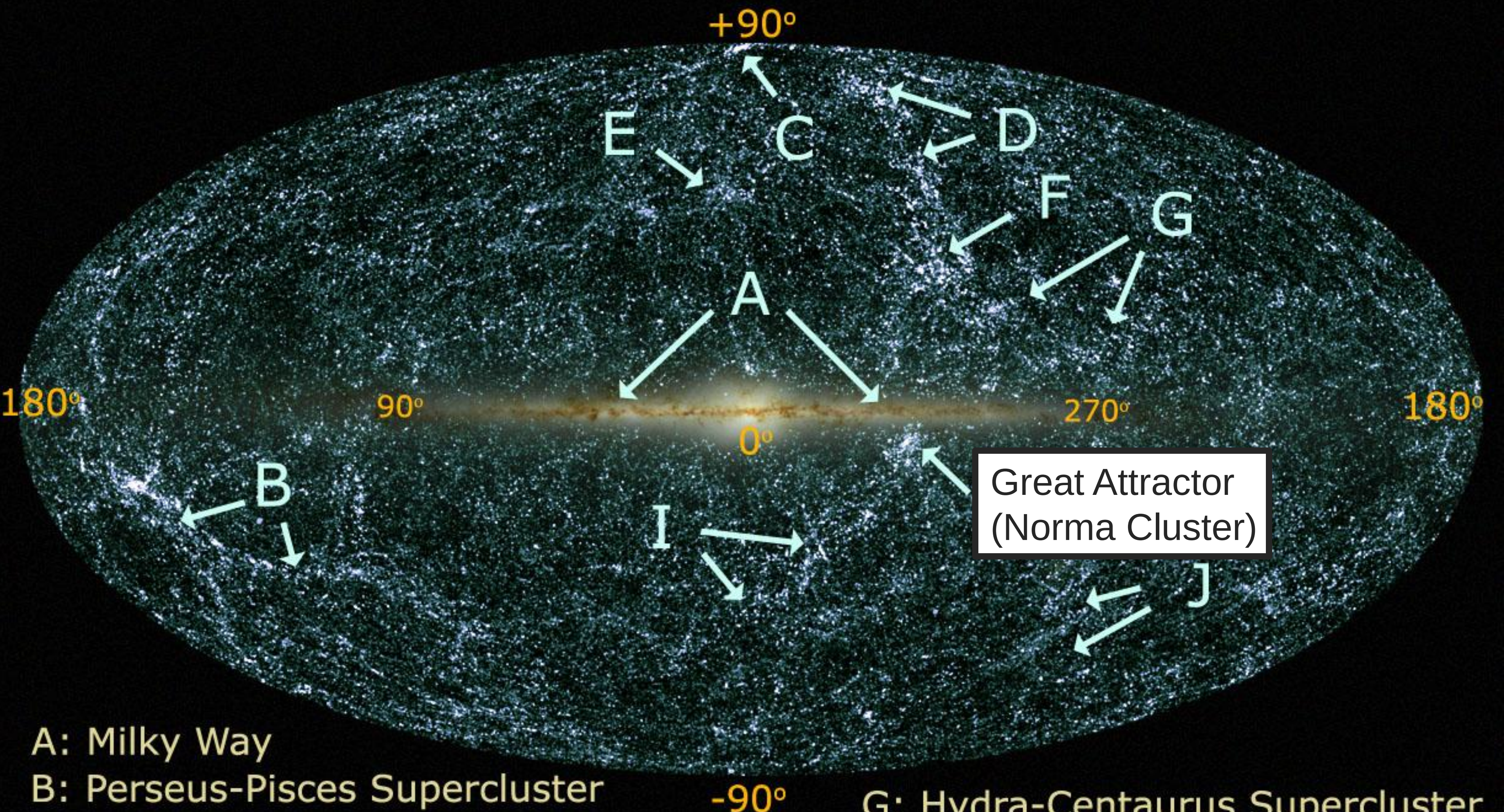


A: Milky Way
B: Perseus-Pisces Supercluster
C: Coma Cluster
D: Virgo Cluster/Local Supercluster
E: Hercules Supercluster
F: Shapley Concentration/Abell 3558
G: Hydra-Centaurus Supercluster
H: "Great Attractor"/Abell 3627
I: Pavo-Indus Supercluster
J: Horologium-Reticulum Supercluster

the

Cosmic Web

Megaparsec Scale Structure of the Universe

- a variety of structures of different
  mass, size (scale), morphology, ...:

- clusters, filaments, sheets, voids, ...

- Not distributed at random throughout cosmic volume.
  Instead,arranged within a distinct spatial pattern,

- an intricate weblike configuration, pervading the whole of
  the observable Universe.

- Filaments and Sheets delineate connected network,
  arranged by massive rich clusters in the nodes of the web,
  all surrounding huge underdense voidlike regions

the Cosmic Web

The Cosmic Web

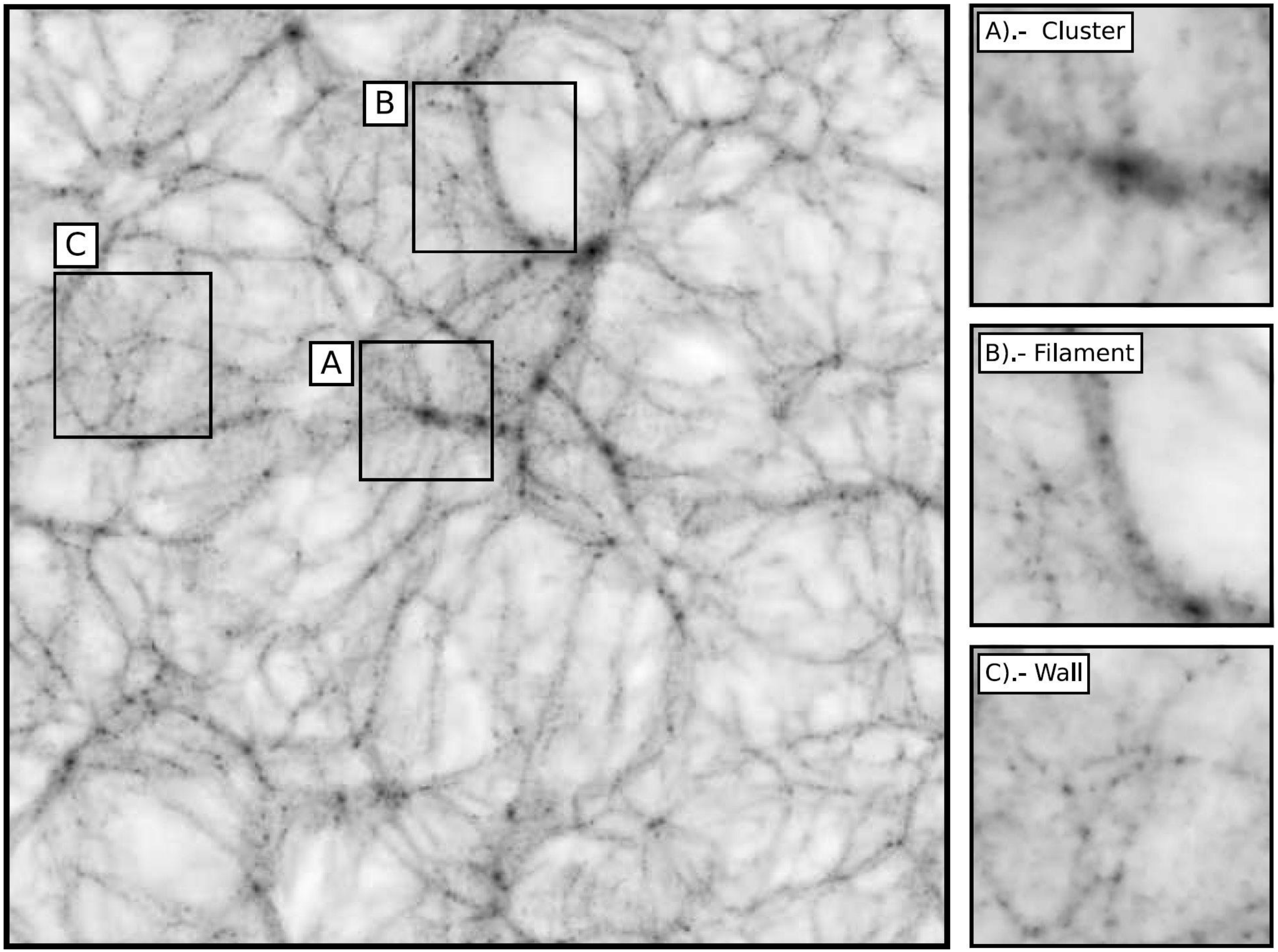
Stochastic Spatial Pattern of

- **Clusters,**
- **Filaments &**
- **Walls**

around

- **Voids**

in which matter, (DM, gas, gal's) has agglomerated



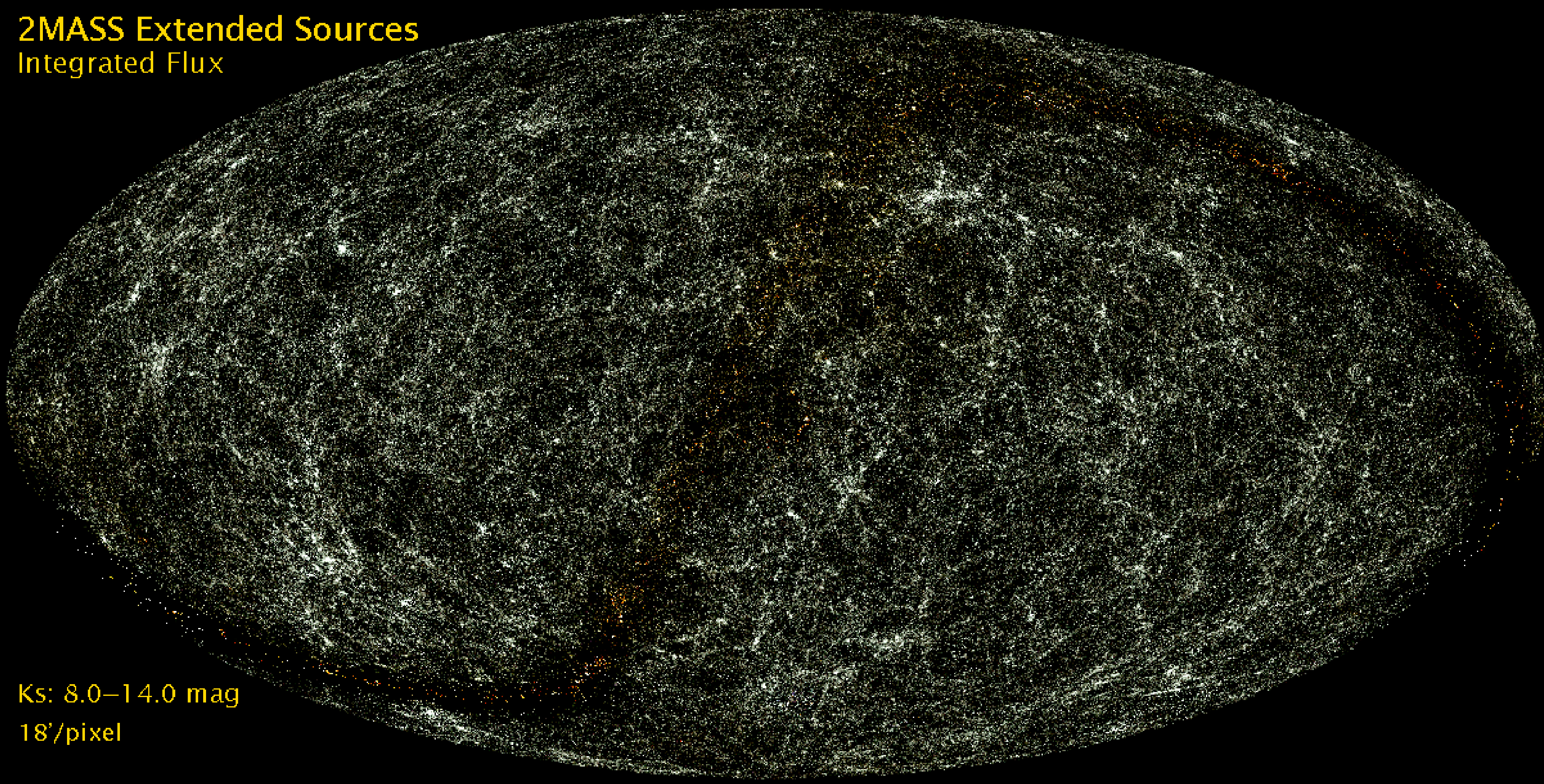
Over the past two decades we have witnessed a paradigm shift in our perception of the Megaparsec scale structure in the Universe. As increasing elaborate galaxy redshift surveys charted ever larger regions in the nearby Universe, an intriguingly complex and salient foamlike network came to unfold and establish itself as the quintessential characteristic of the cosmic matter and galaxy distribution.

In a great many physical systems, the spatial organization of matter is one of the most readily observable manifestations of the forces and processes forming and moulding them. Richly structured morphologies are usually the consequence of the complex and nonlinear collective action of basic physical processes.

The vast Megaparsec cosmic web is undoubtedly one of the most striking examples of complex geometric patterns found in nature. In its own right, the vast dimensions and intricate composition of the cosmic foam make it one of the most imposing and intriguing patterns existing in the Universe. Its wide-ranging Importance stems from its status as a cosmic fossil. On a scale of tens up to a few hundred Megaparsecs It is still relatively straightforward to relate the configuration at the present cosmic epoch to that of the primordial matter distribution from which it emerged. With the cosmic foam seemingly representing this phase, it assumes a fundamental role in the quest for understanding the origin of all structures in the Universe.

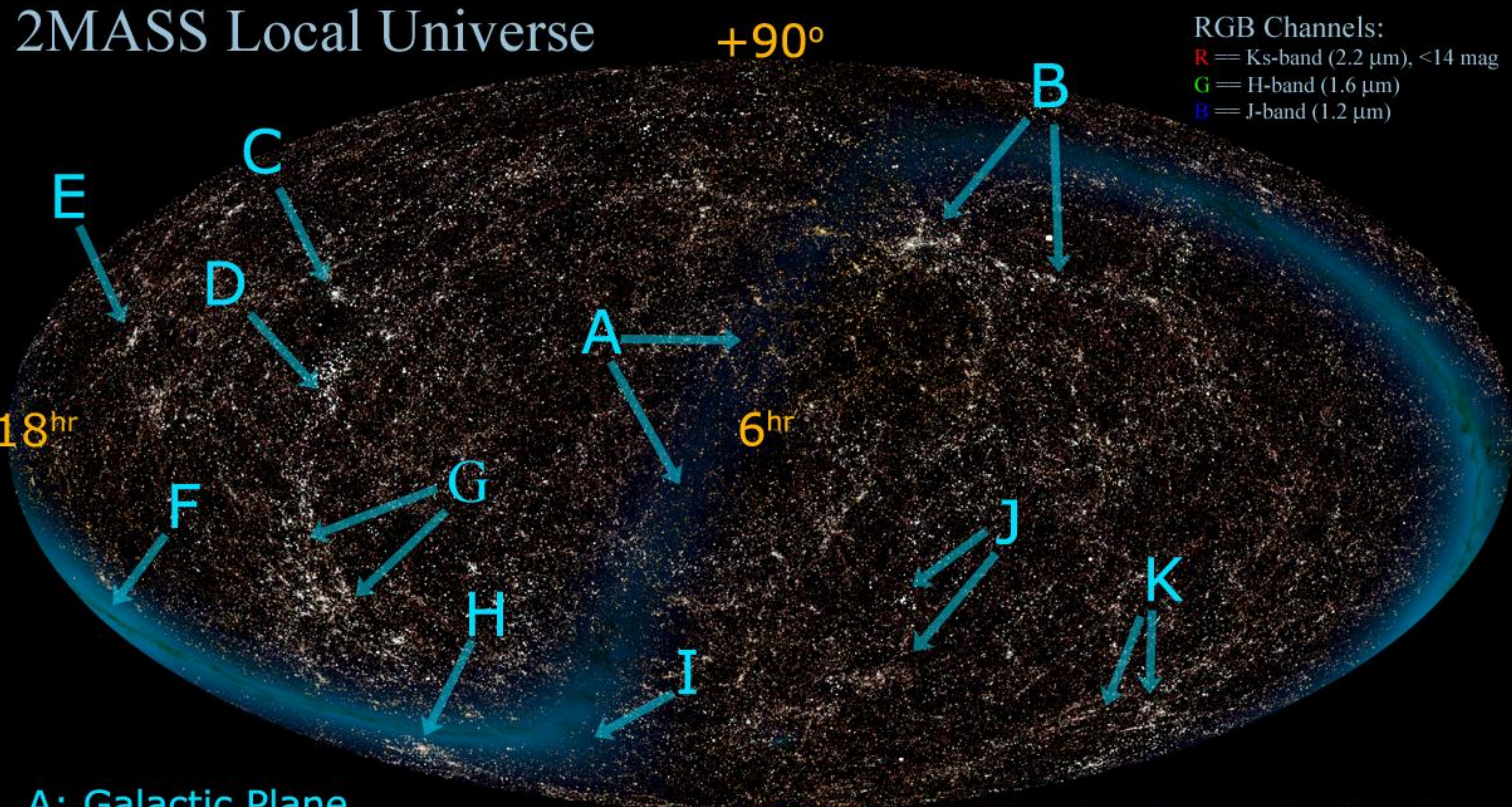
While its complex cellular morphology involves one of the most outstanding and evident aspects of the Cosmic foam, it has also remained one defying simple definitions which may be the cause of it having Remained one of the least addressed aspects. The geometry of the cosmic foam may be described as a nontrivial stochastic assembly of various anisotropic and asymmetric elements. A major deficiency in the vast majority of studies on the large scale distribution of galaxies has been the lack of suitable quantitative and statistical characterizations of the truly fundamental aspects of the comsic foam geometry.

The Cosmic Web



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

Identity of Local Structures along local Cosmic Web.



A: Galactic Plane
B: Perseus-Pisces Supercluster
C: Coma Cluster
D: Virgo Cluster/Local Supercluster
E: Hercules Supercluster
F: Galactic Center
G: Shapley Concentration/ Hydra-Centaurus Supercluster
H: "Great Attractor"/Abell 3627
I: "Local Void"
J: Eridanus/Fornax Clusters
K: Pavo-Indus Supercluster

2MASS survey

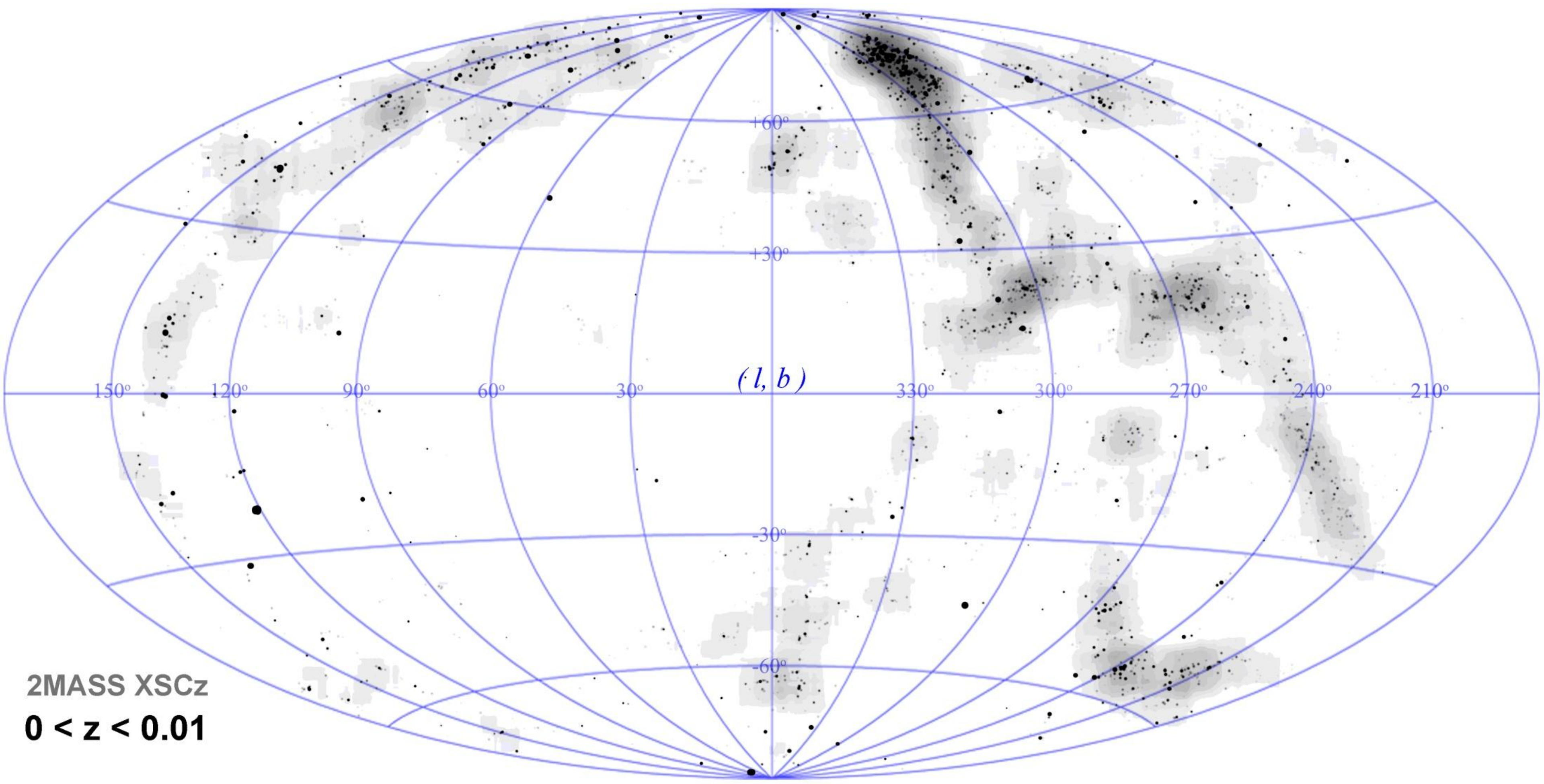
- 2MASS all-sky survey:
  ground-based near-infrared survey whole sky,
  J(1.2 μm), H(1.6 μm), K(2.2 μm)

- 2MASS extended source catalog (XSC):
  1.5 million galaxies

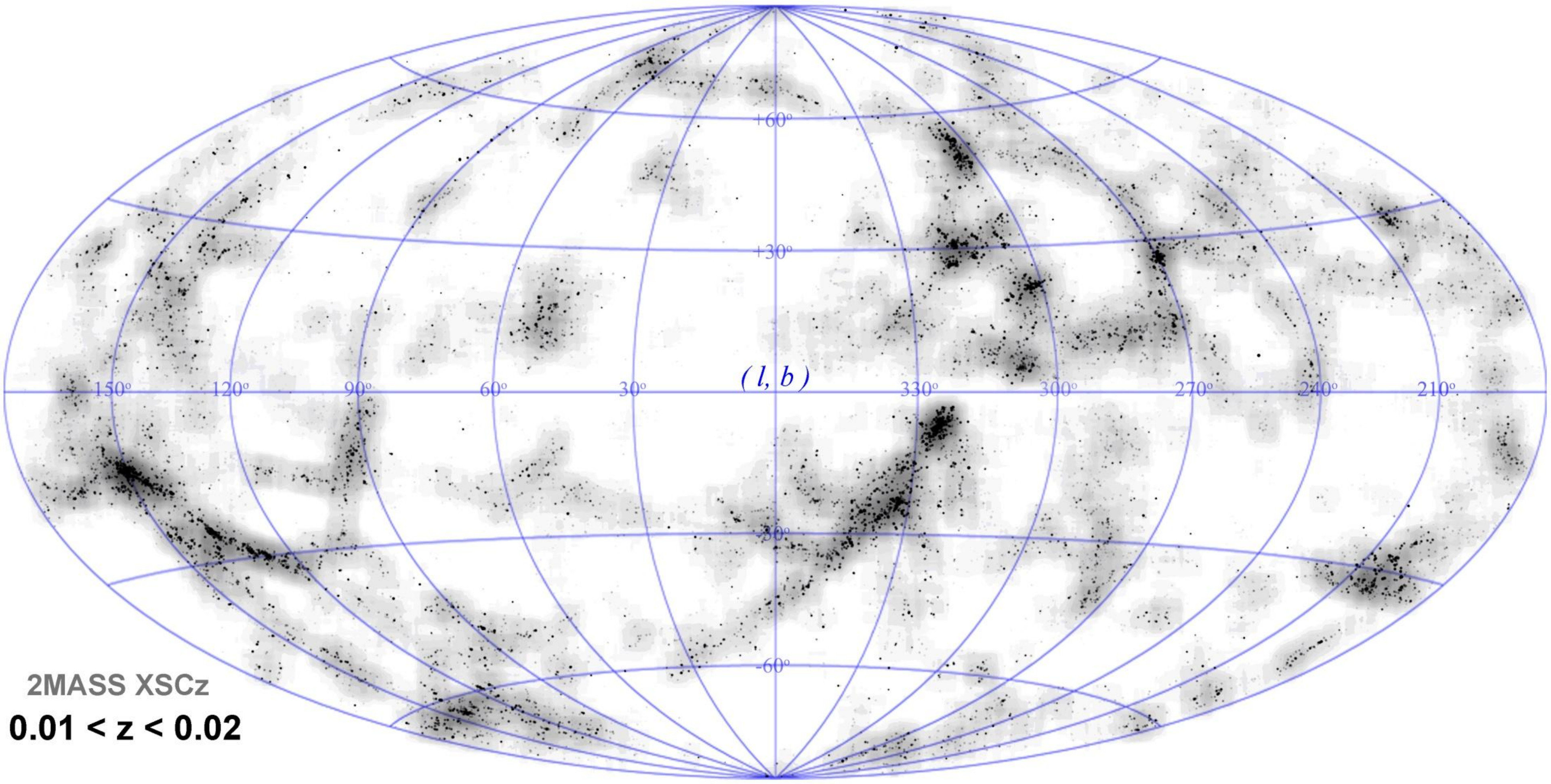
- unbiased sample nearby galaxies
- photometric redshifts:
  depth in 2MASS maps, "cosmic web" of (nearby) superclusters spanning the entire sky.

courtesy: T. Jarrett

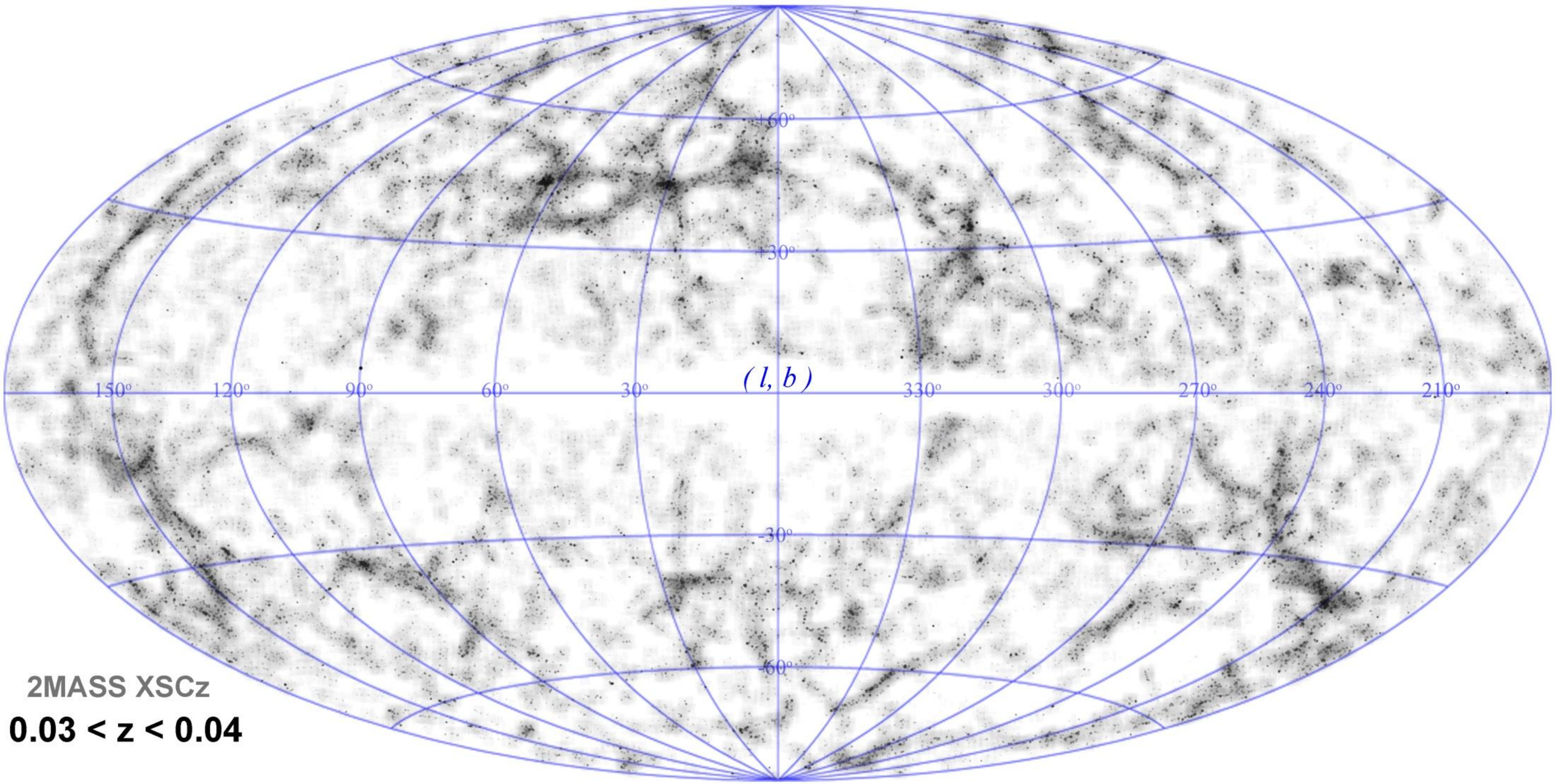
2MASS Cosmic Web



2MASS Cosmic Web



2MASS Cosmic Web



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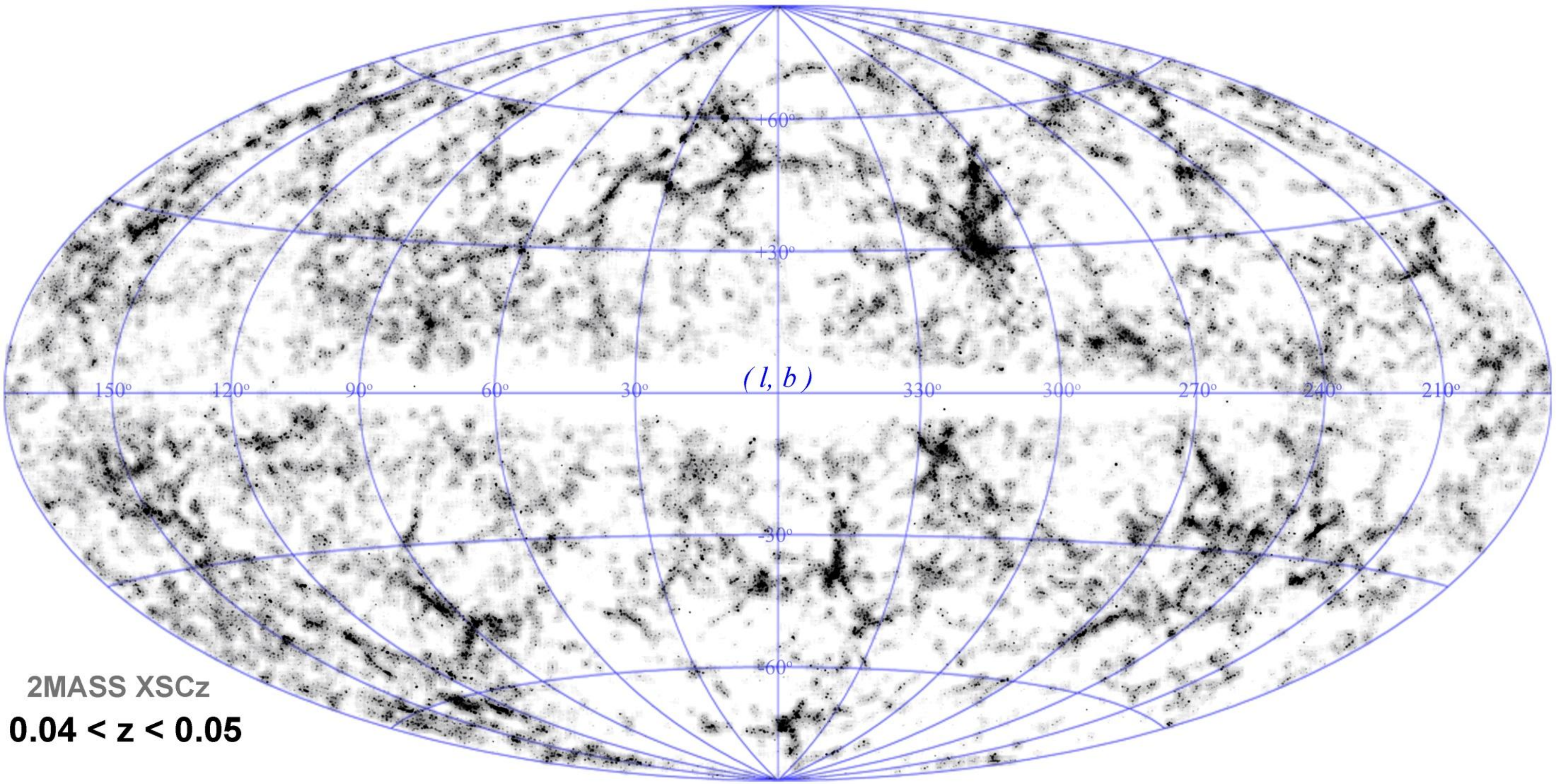
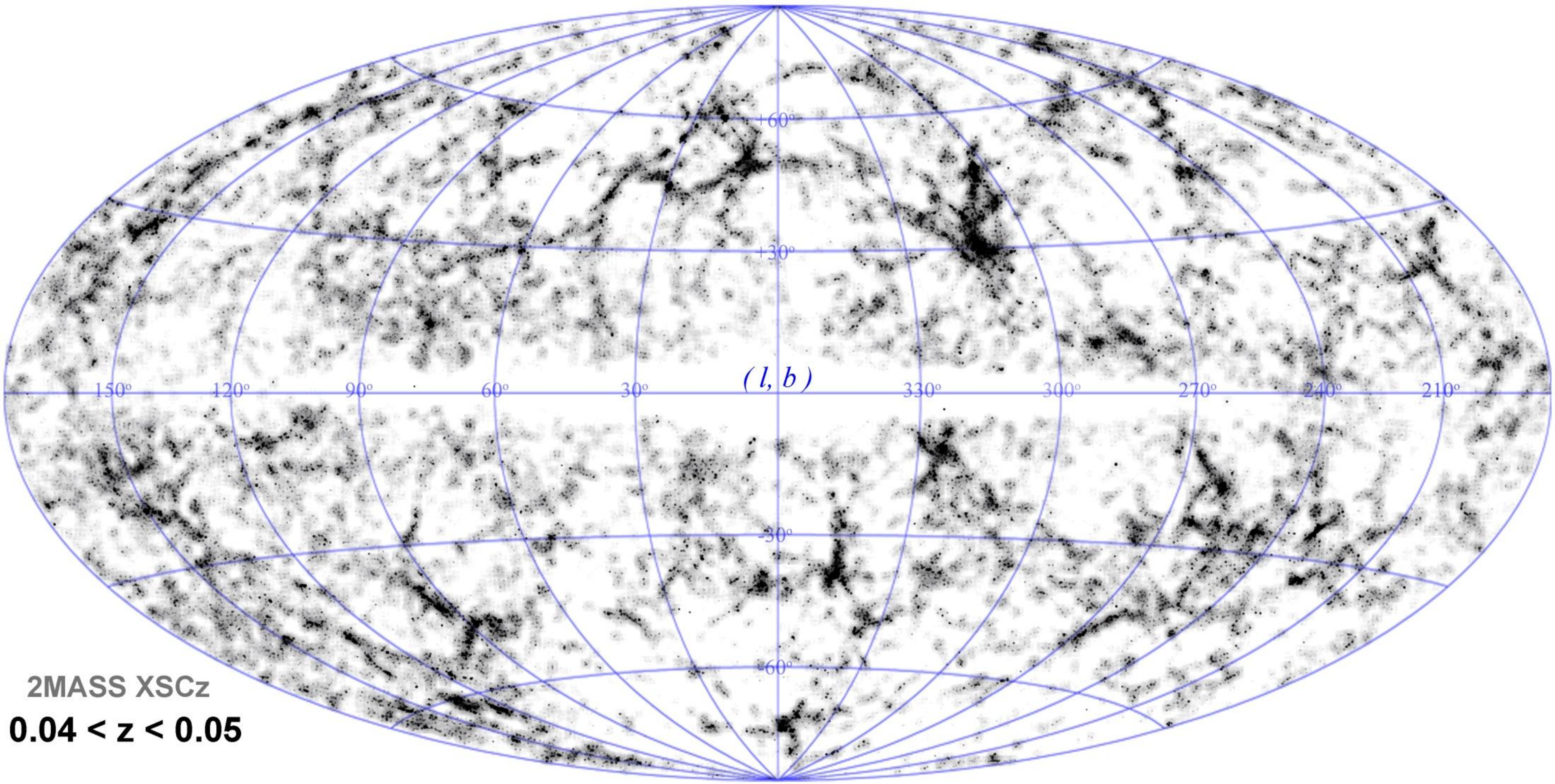
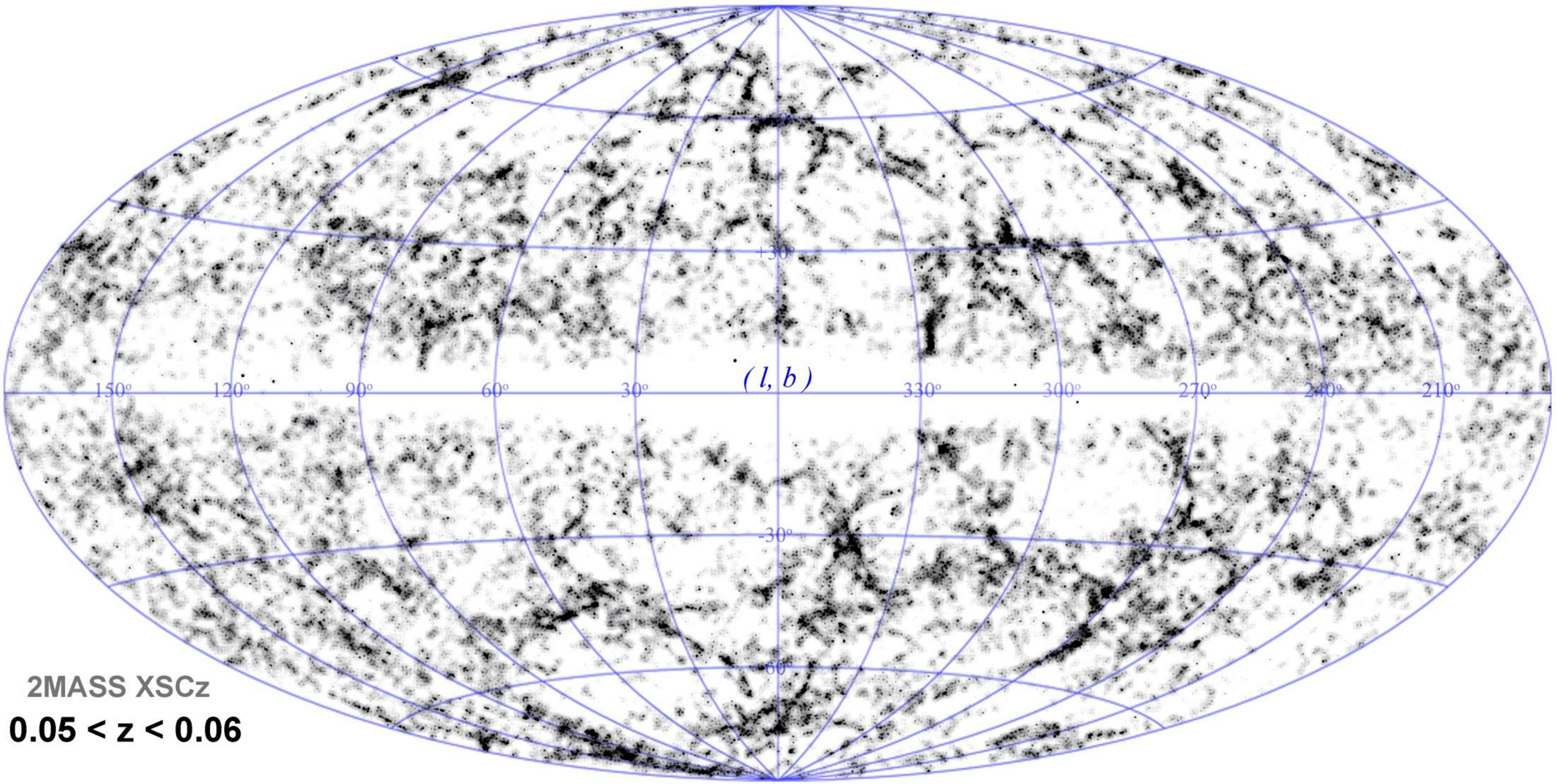


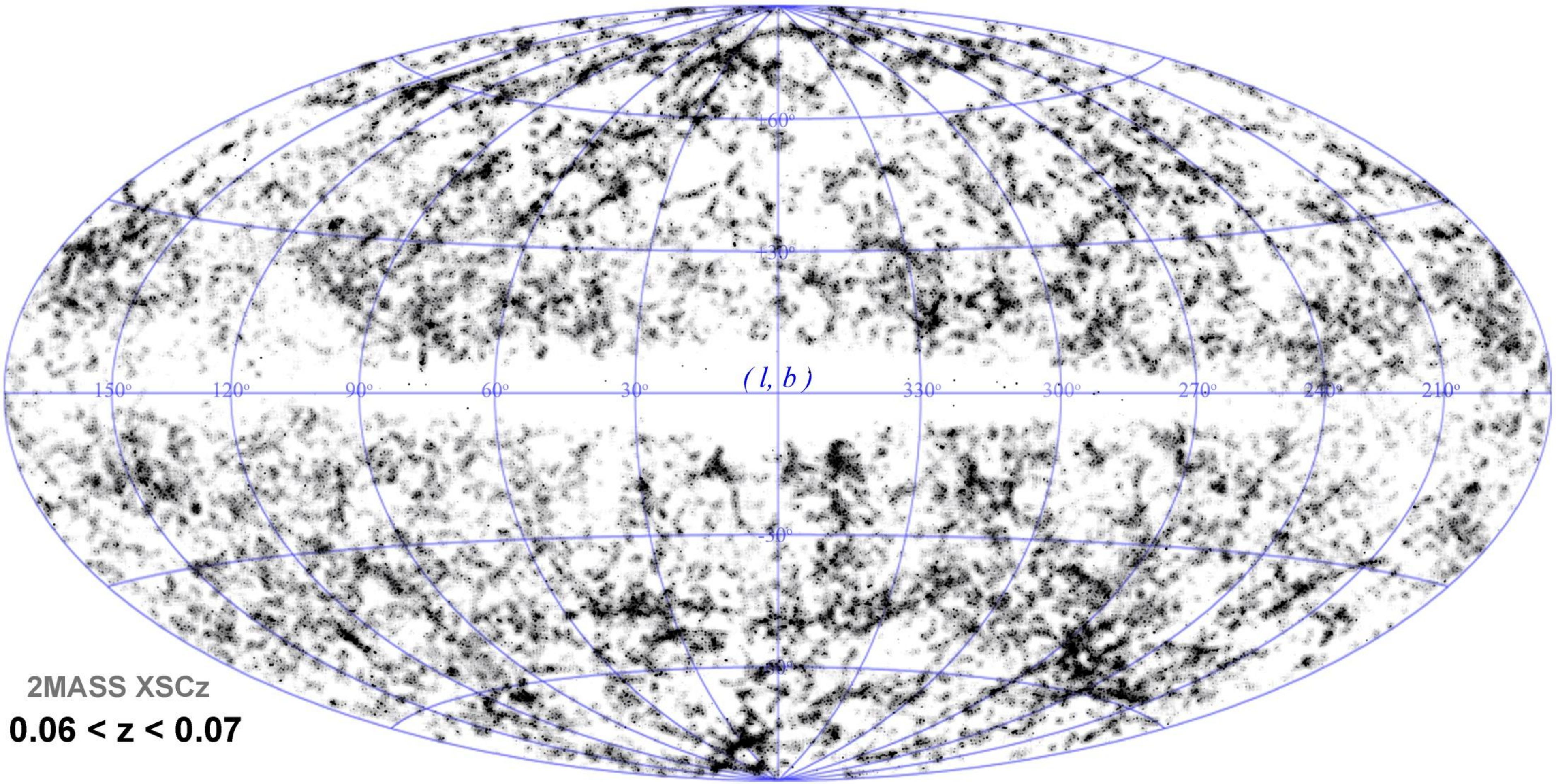
2MASS Cosmic Web



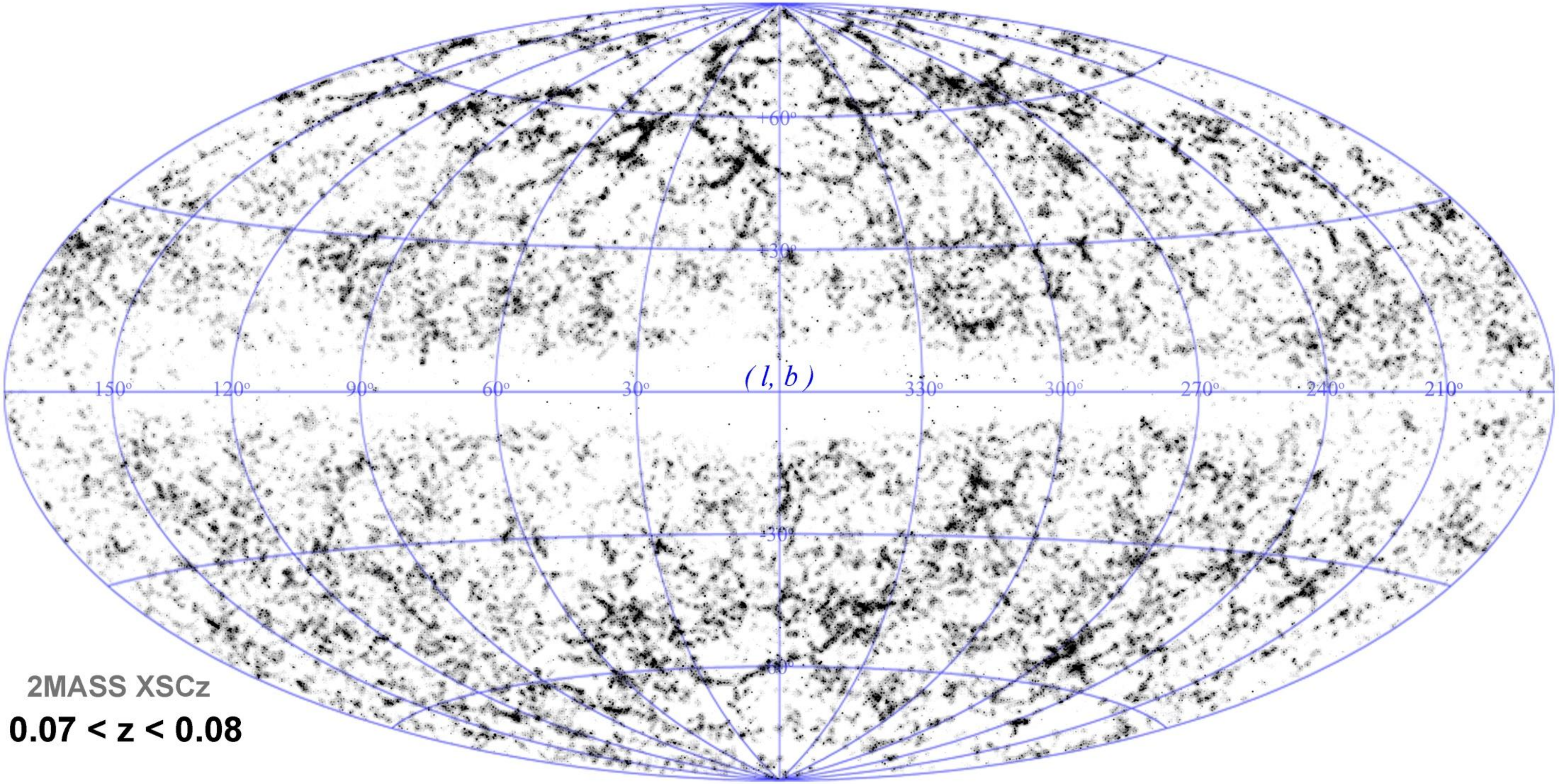
2MASS Cosmic Web



2MASS Cosmic Web



2MASS Cosmic Web



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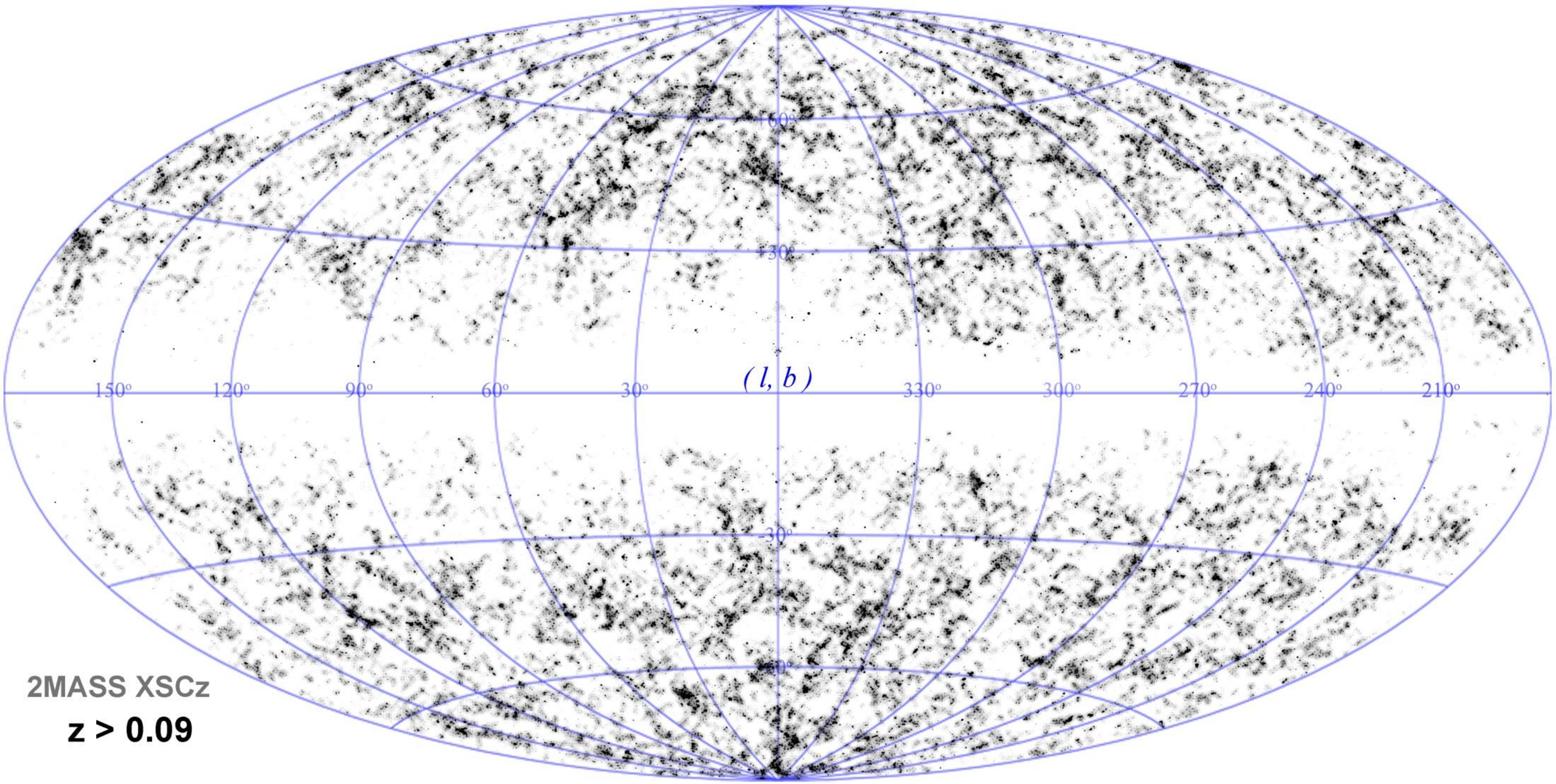

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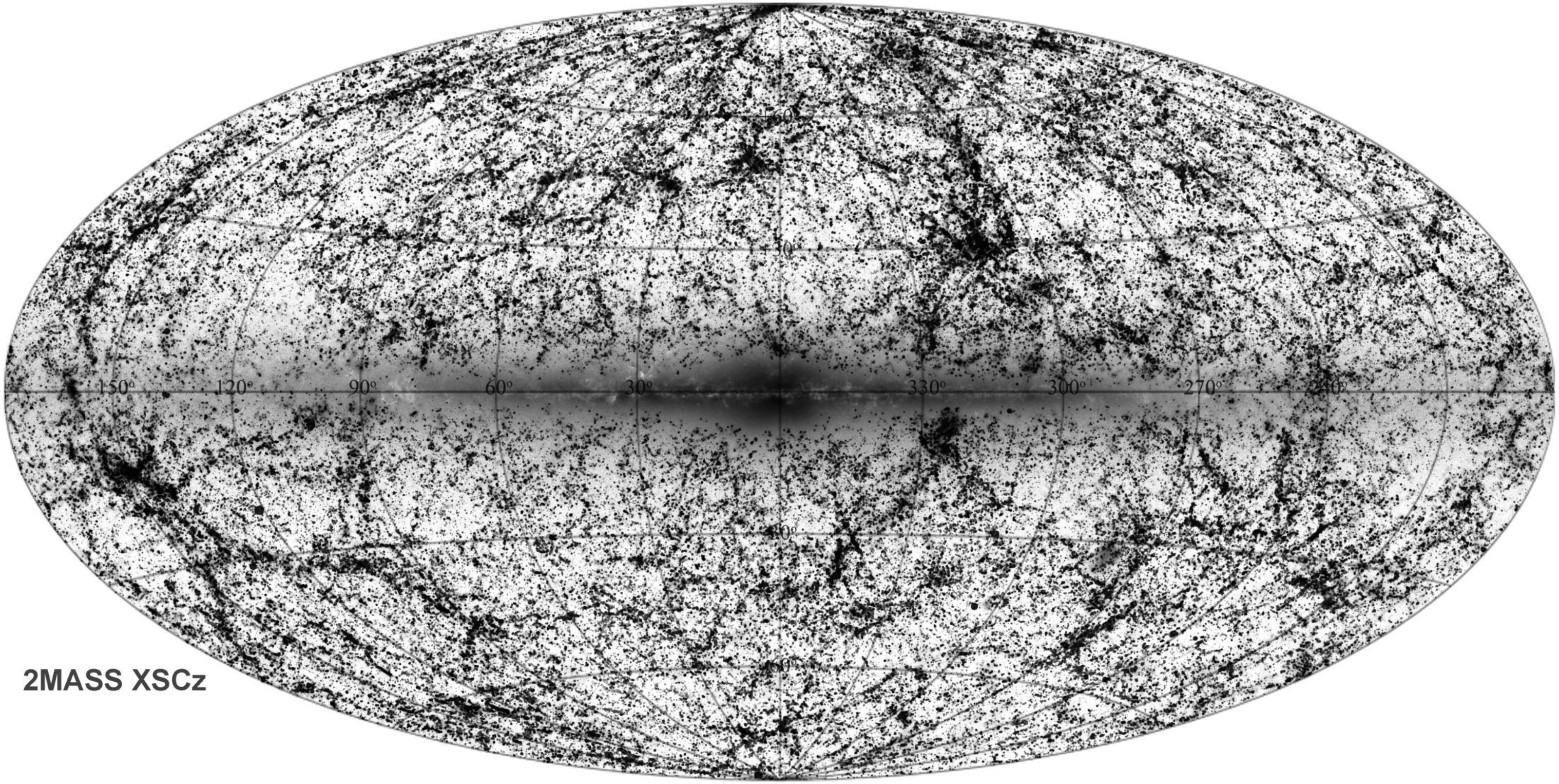


SDSS

Galaxy Redshift Survey

SDSS survey

- Largest and most systematic (digital !) sky survey in history of astronomy.
- Images sky in 5 photometric bands !!!!
  Down to apparent magnitude r~23.1
- Covers ~ 25% of the sky: 8452 sq. deg.
- With 2dFGRS, the SDSS will produce the most extensive map of the spatial structure of our cosmic neighbourhood.
- Million galaxies subsequently selected for measuring redshift z: electromagnetic spectrum

- Total:

  sky survey: 10^8 stars, 10^8 galaxies, 10^5 quasars
  spectroscopy: 10^6 galaxies, 10^5 quasars, 10^5 stars

SDSS survey

- Imaging:
  230 million objects

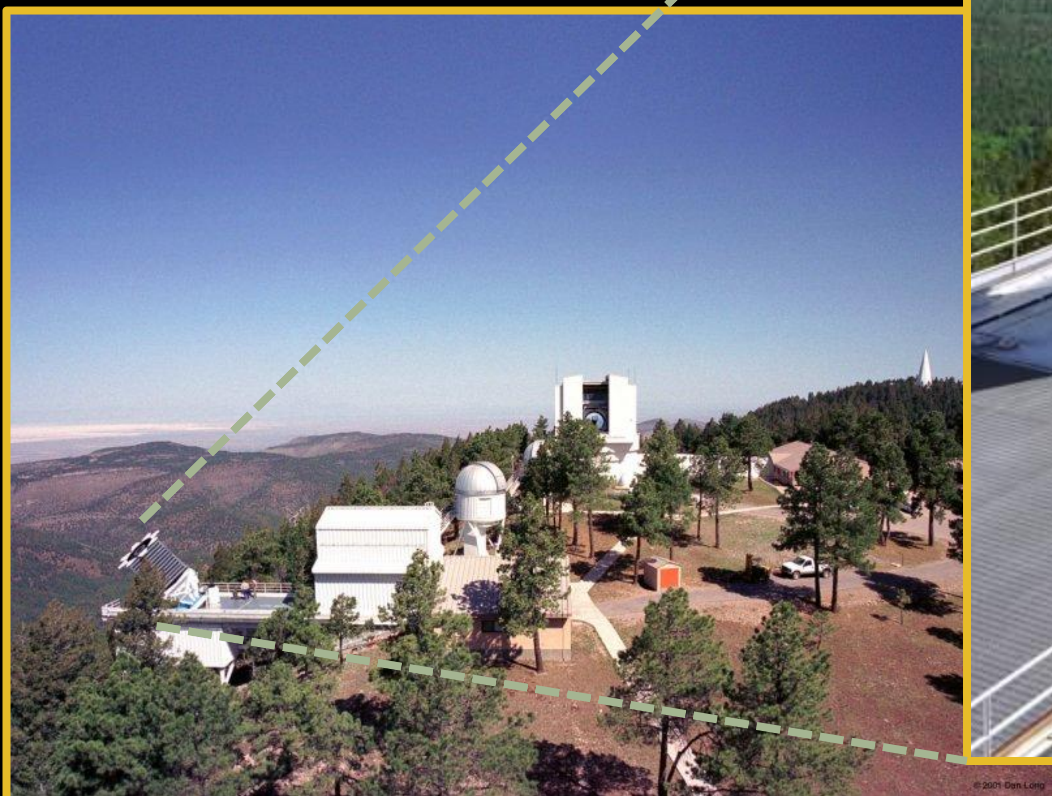
- Spectroscopic (Redshift) survey:

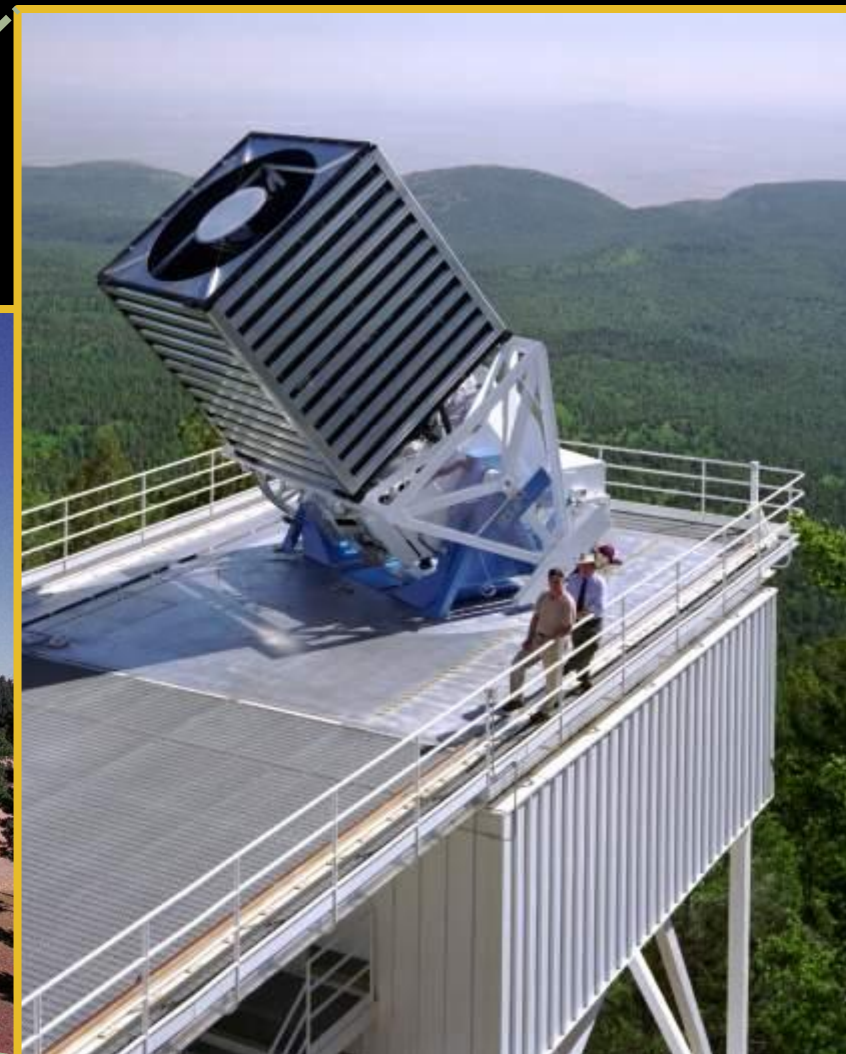
  magnitude limit:
  galaxies: (Petrosian) $r < 17.7$
  quasars $i < 19.1$ / $i < 20.2$ ($z > 2.3$)

  objects: 928,567 galaxies
  109,862 quasars $z < 2.3$
  8,802 quasars $z > 2.3$

SDSS survey

Specially dedicated
2.5m wide-angle telescope
Apache Point Observatory (New Mexico)





SDSS survey

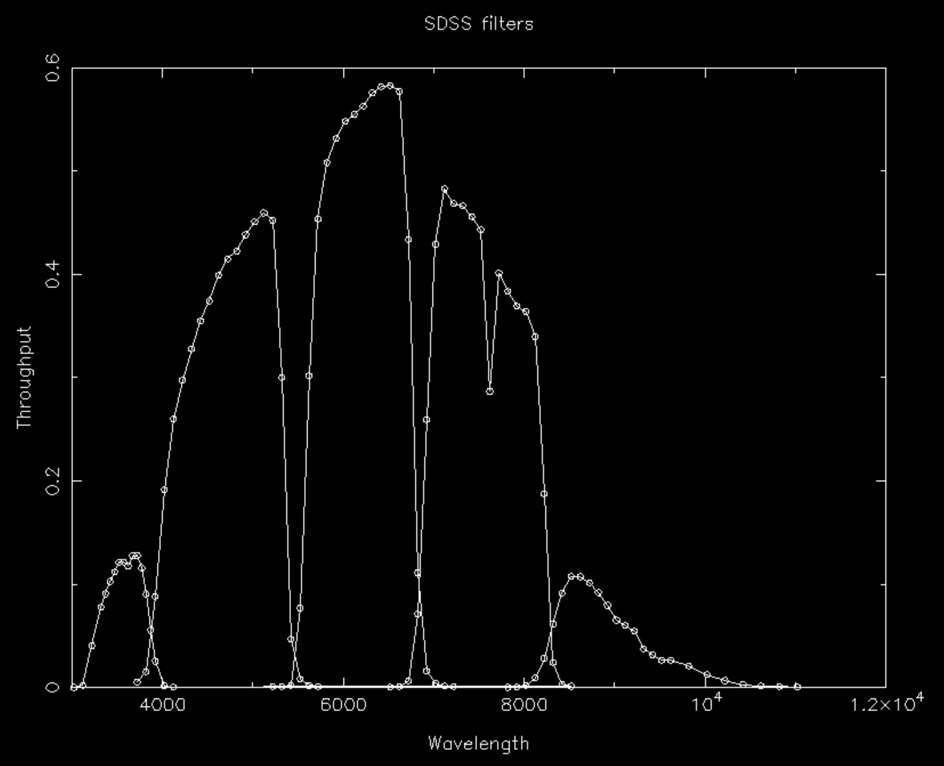
Aims to sample 25% of the sky:
DR7 - 8423 sq. deg.

Photometric system 5 filters:

	λ		m_{lim}
u	354	nm	24.4
g	476	nm	25.3
r	628	nm	25.1
i	769	nm	24.4
z	925	nm	22.9

Driftscan mode
- 5 filters:
- 30 CCD chips, 5 rows of 6
- S/N ~ 5
- CCD chip: 2048x2048 pixels
  120 Mbyte

Spectroscopy
- up to 640 (fibers) per recording
- per night 6-9 recordings



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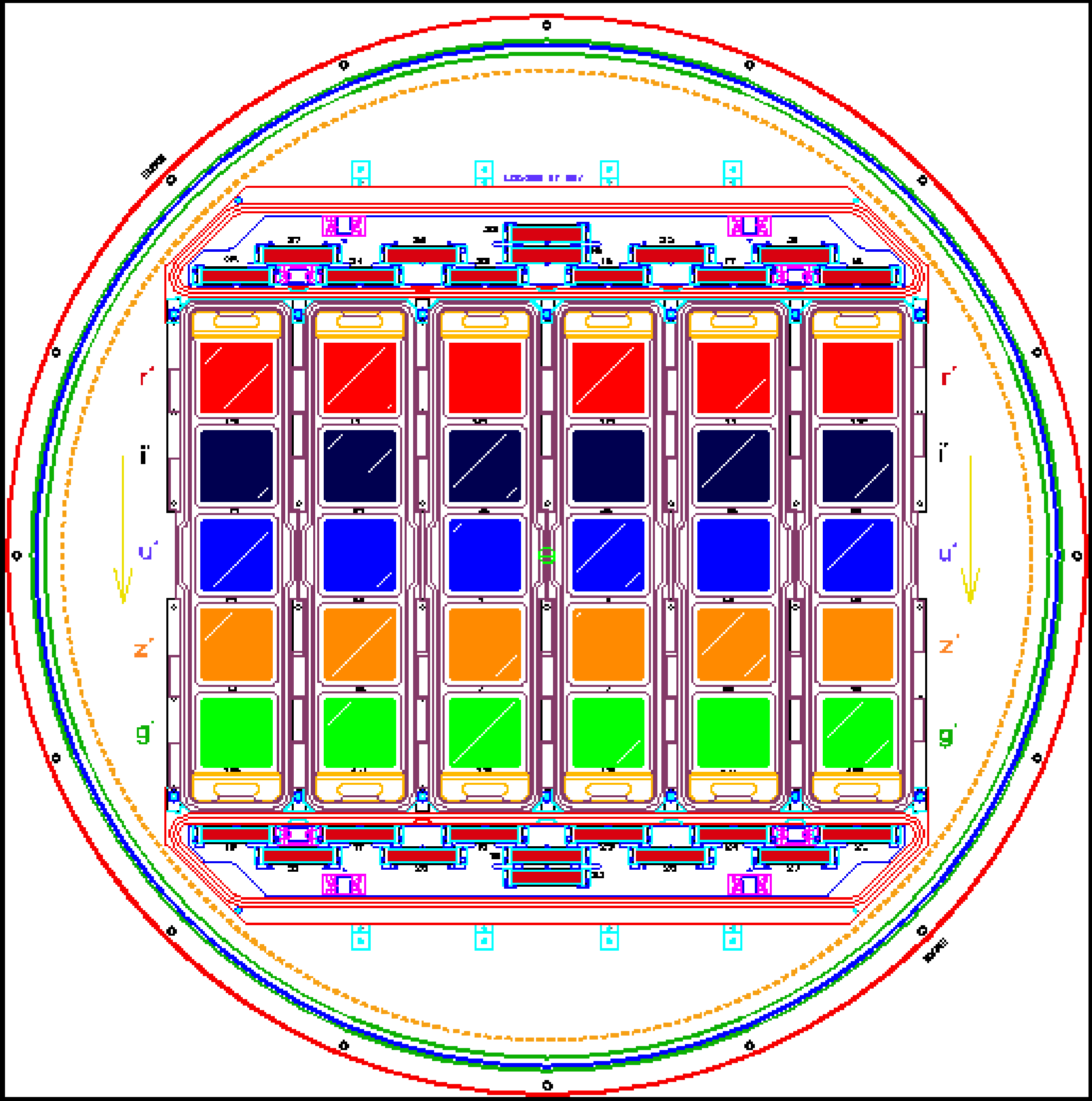
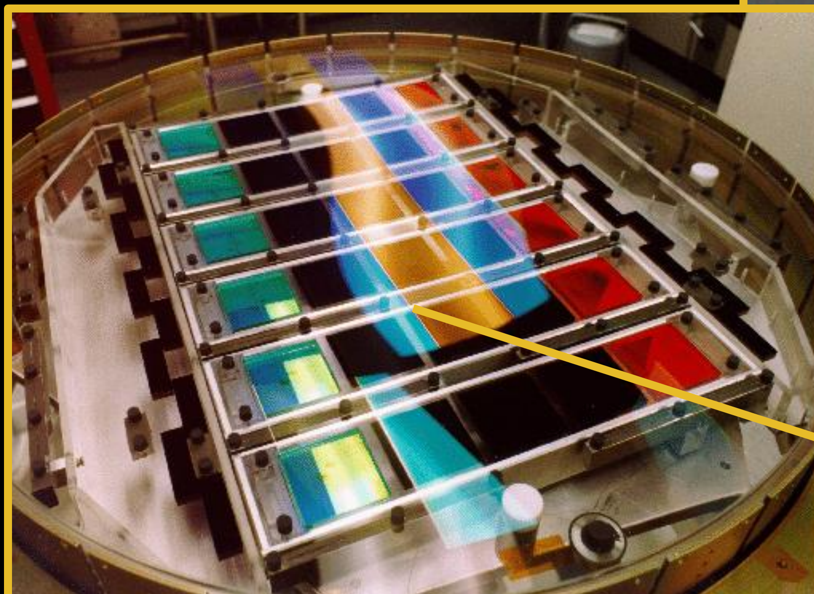


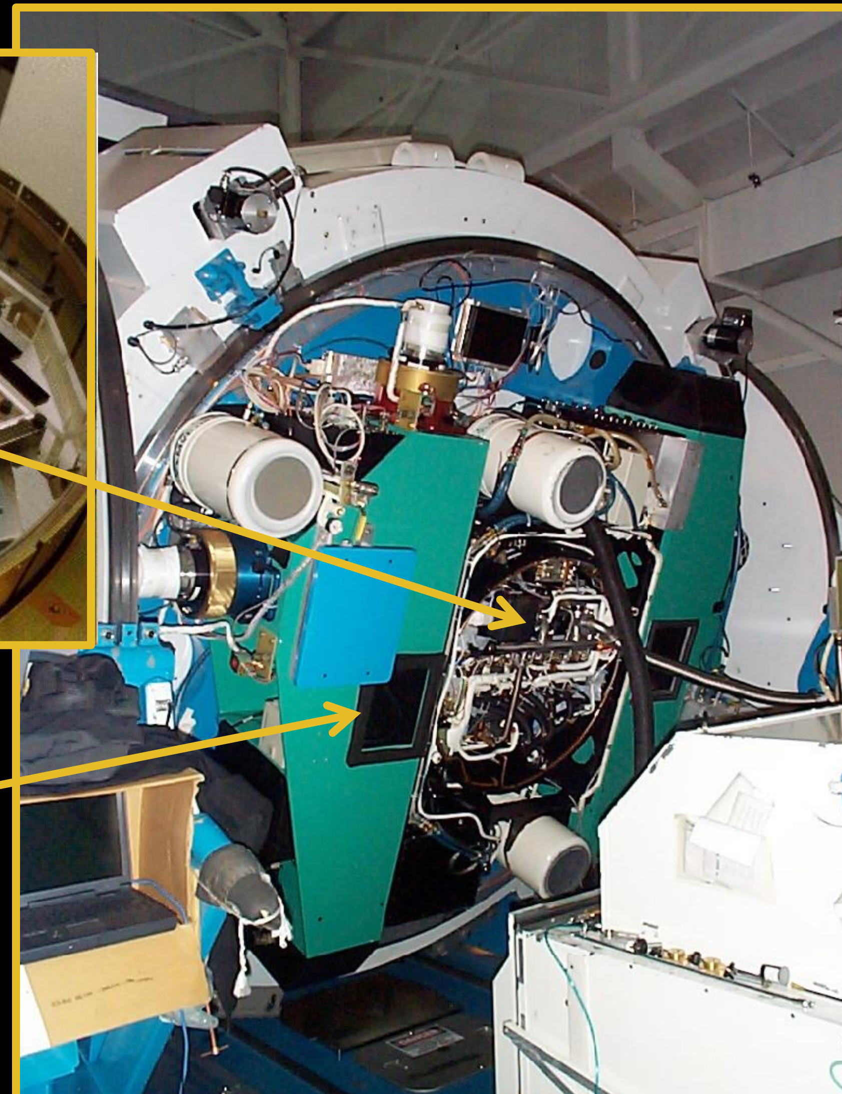
SDSS survey

5-color Camera

30 CCD chips

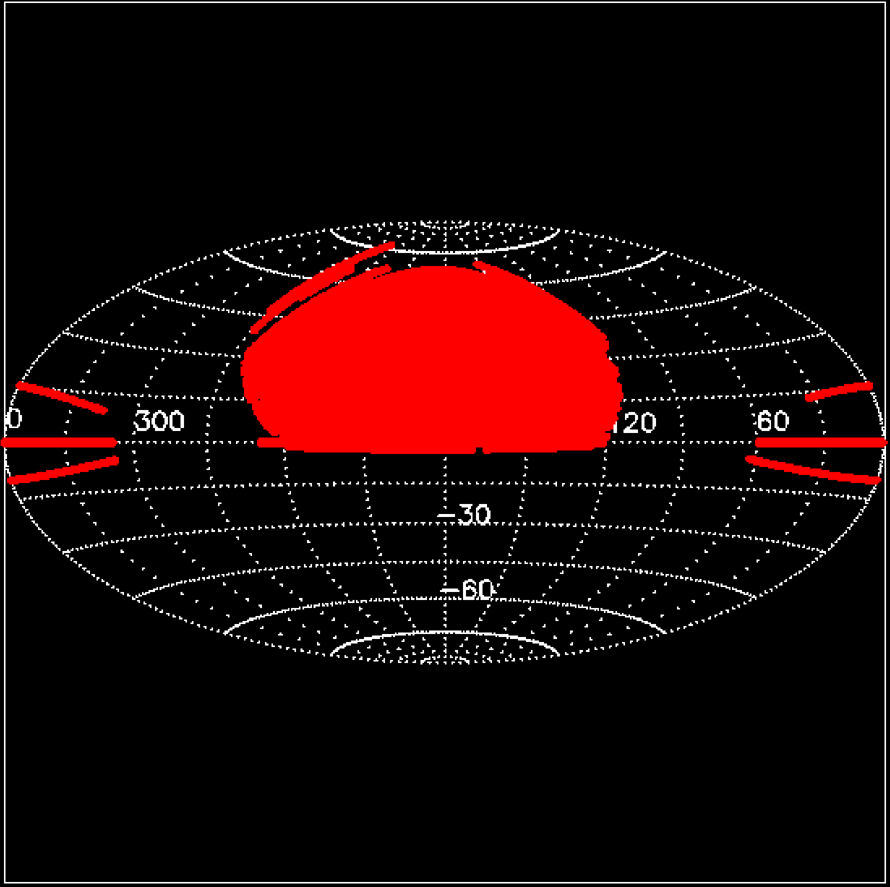


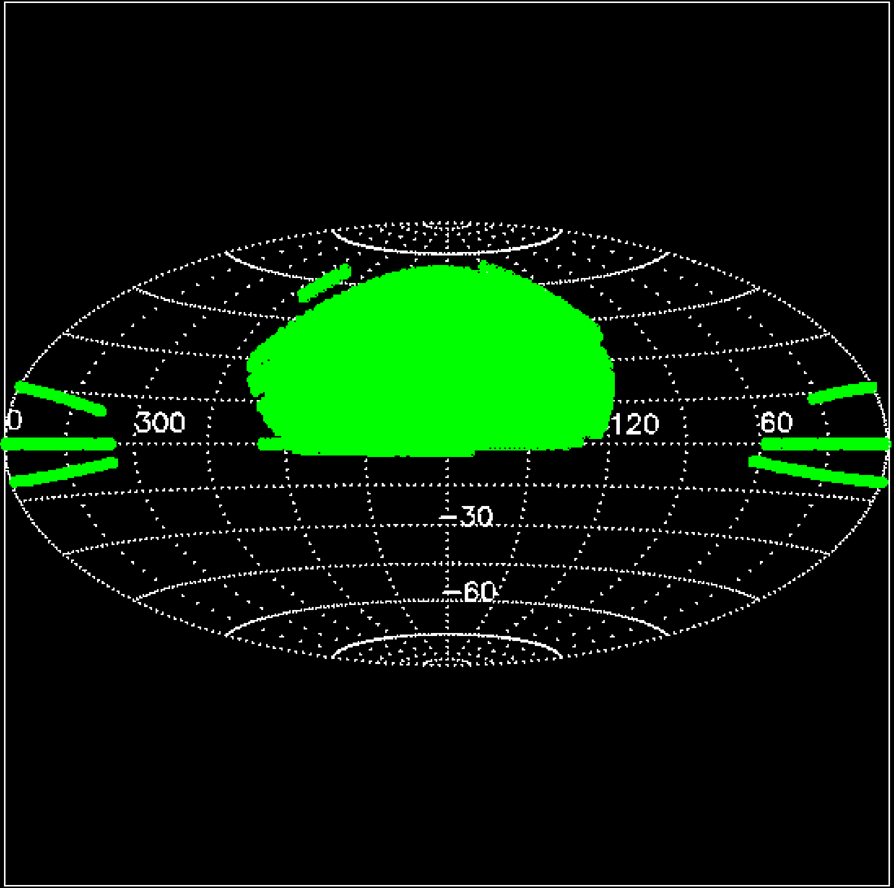
Fiber Spectrograph



SDSS survey

SDSS Data Release 7 (2008):



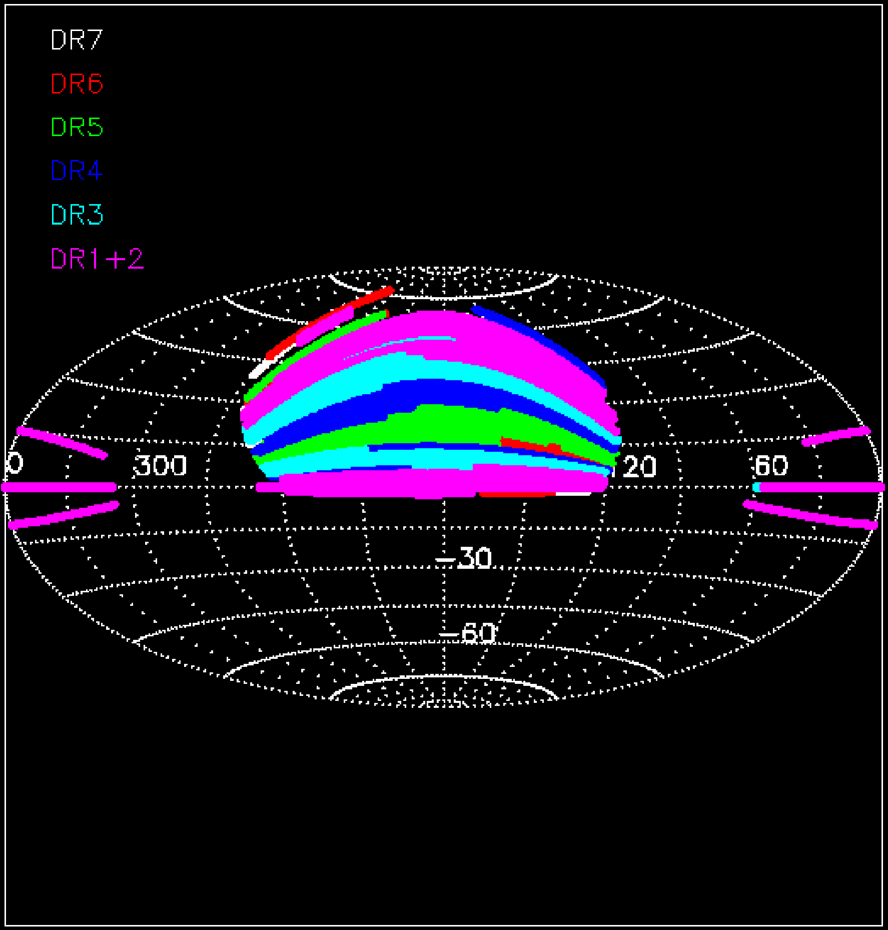


SDSS Legacy Imaging Sky Coverage:
8423 sq. deg.

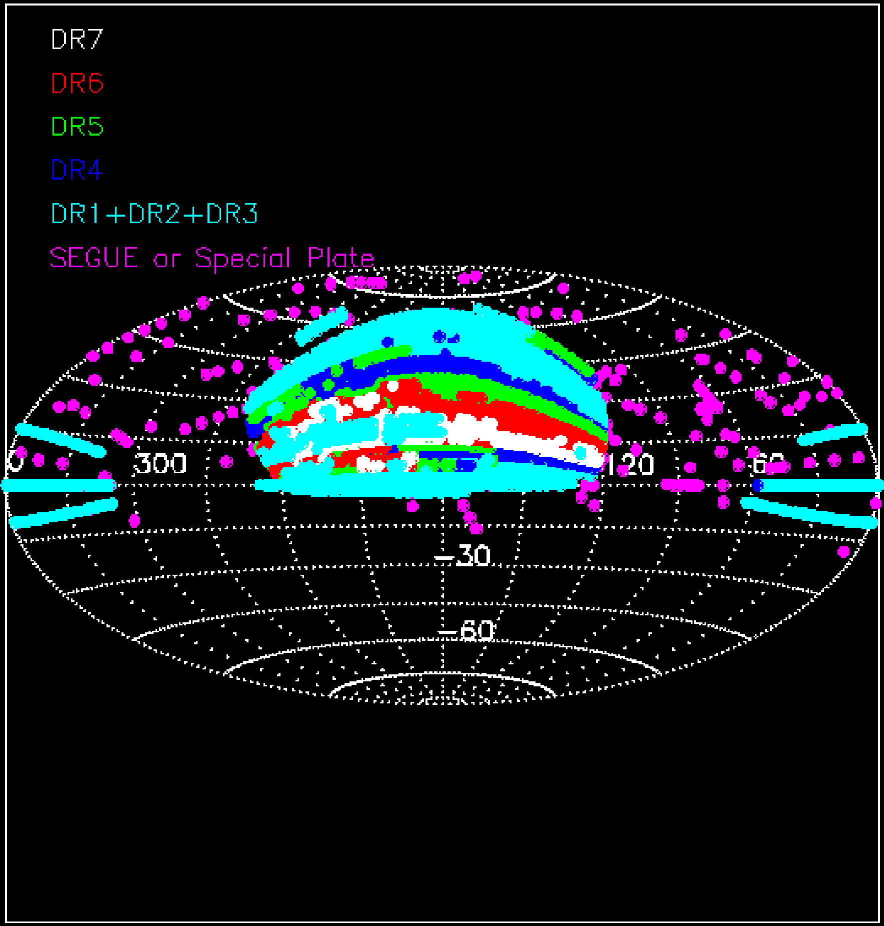
SDSS Legacy Spectral Sky Coverage:
8032 sq. deg.

SDSS survey

SDSS Data Release 1-7 (2000-2008)

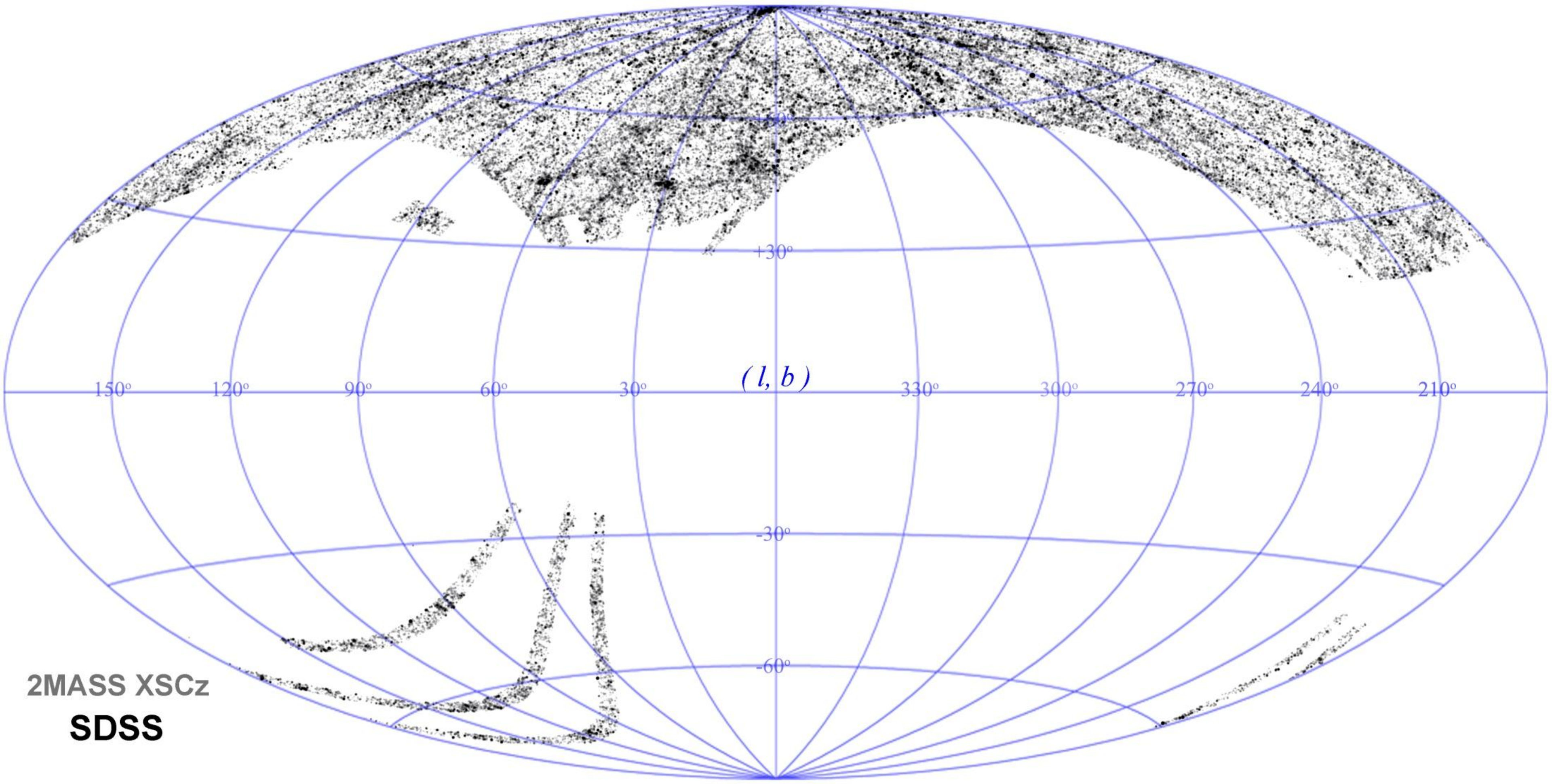


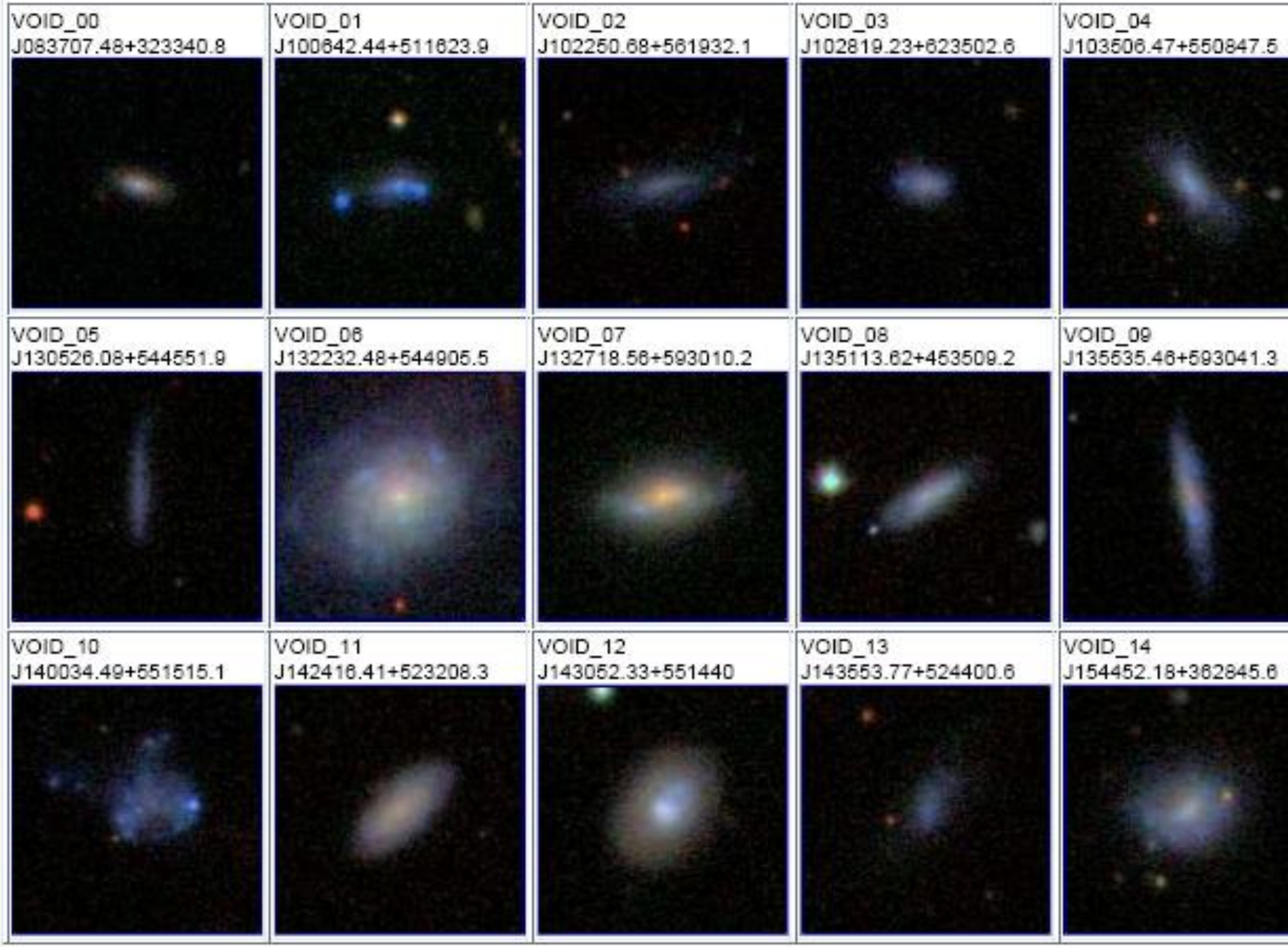
SDSS Legacy Imaging Sky Coverage:
8423 sq. deg.

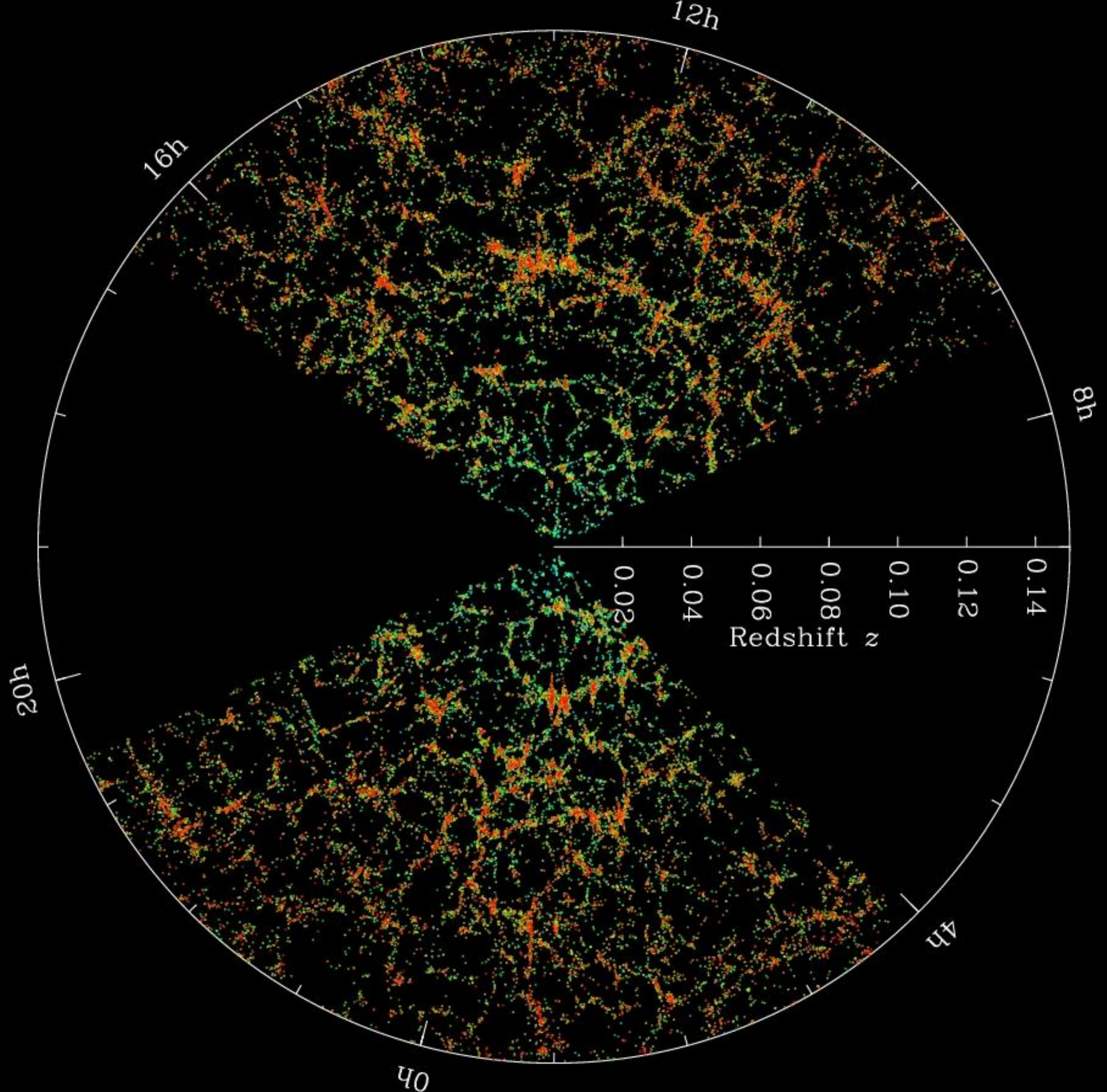


SDSS Legacy Spectral Sky Coverage:
8032 sq. deg.

SDSS Galactic region




VOID_00
J083707.48+323340.8
VOID_01
J100642.44+511623.9
VOID_02
J102250.68+561932.1
VOID_03
J102819.23+623502.6
VOID_04
J103506.47+550847.5
VOID_05
J130526.08+544551.9
VOID_06
J132232.48+544905.5
VOID_07
J132718.56+593010.2
VOID_08
J135113.62+453509.2
VOID_09
J135535.46+593041.3
VOID_10
J140034.49+551515.1
VOID_11
J142416.41+523208.3
VOID_12
J143052.33+551440
VOID_13
J143553.77+524400.6
VOID_14
J154452.18+362845.6


12h
16h
8h
20h
4h
0h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z

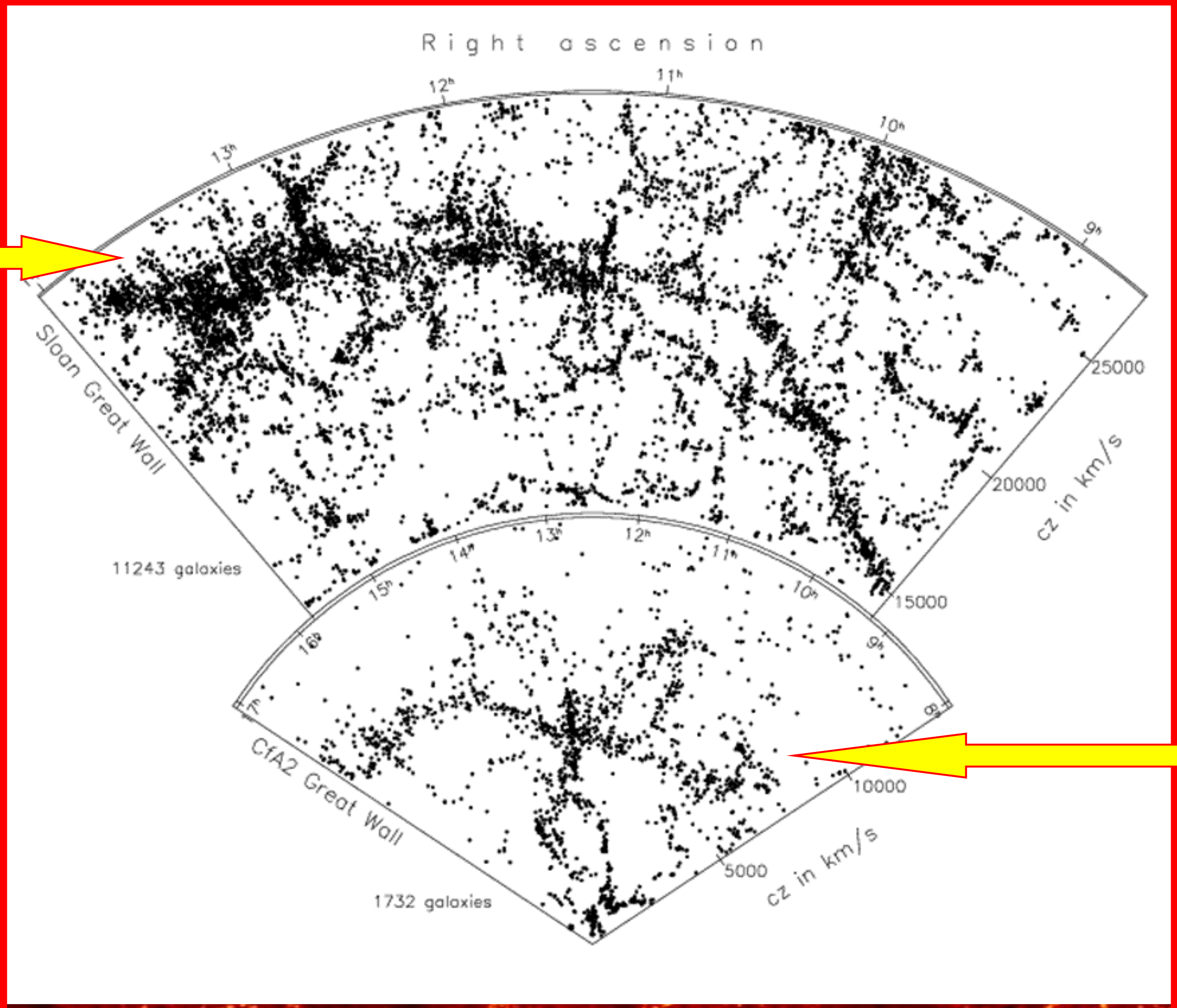
SDSS Cosmic Web Movie

the Cosmic Web:

Filaments, Walls & Cluster Nodes

Walls, Filaments & Nodes

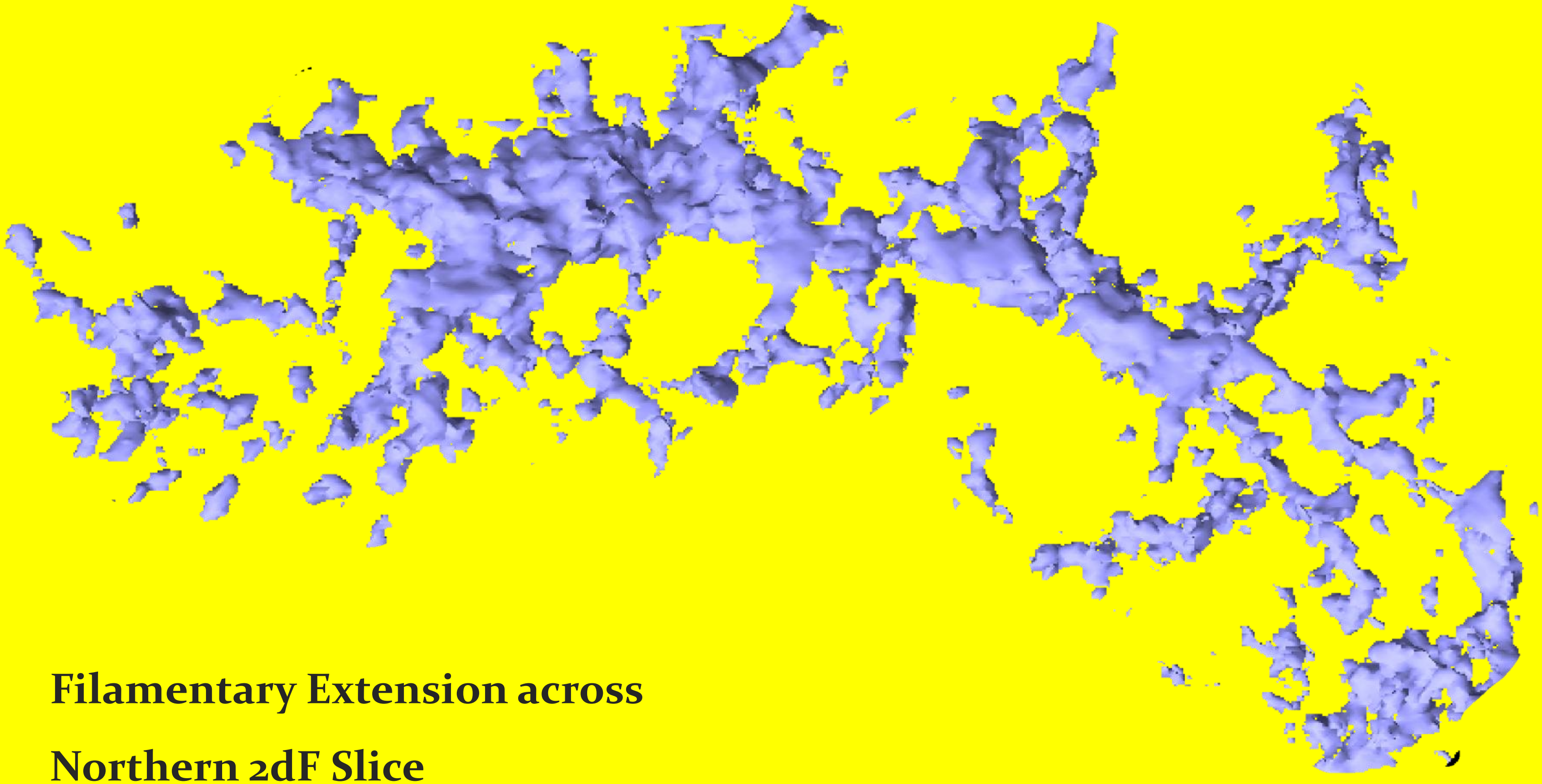
Sloan Great Wall



The ``Great Wall''

(Geller & Huchra 1989)

Walls, Filaments & Nodes

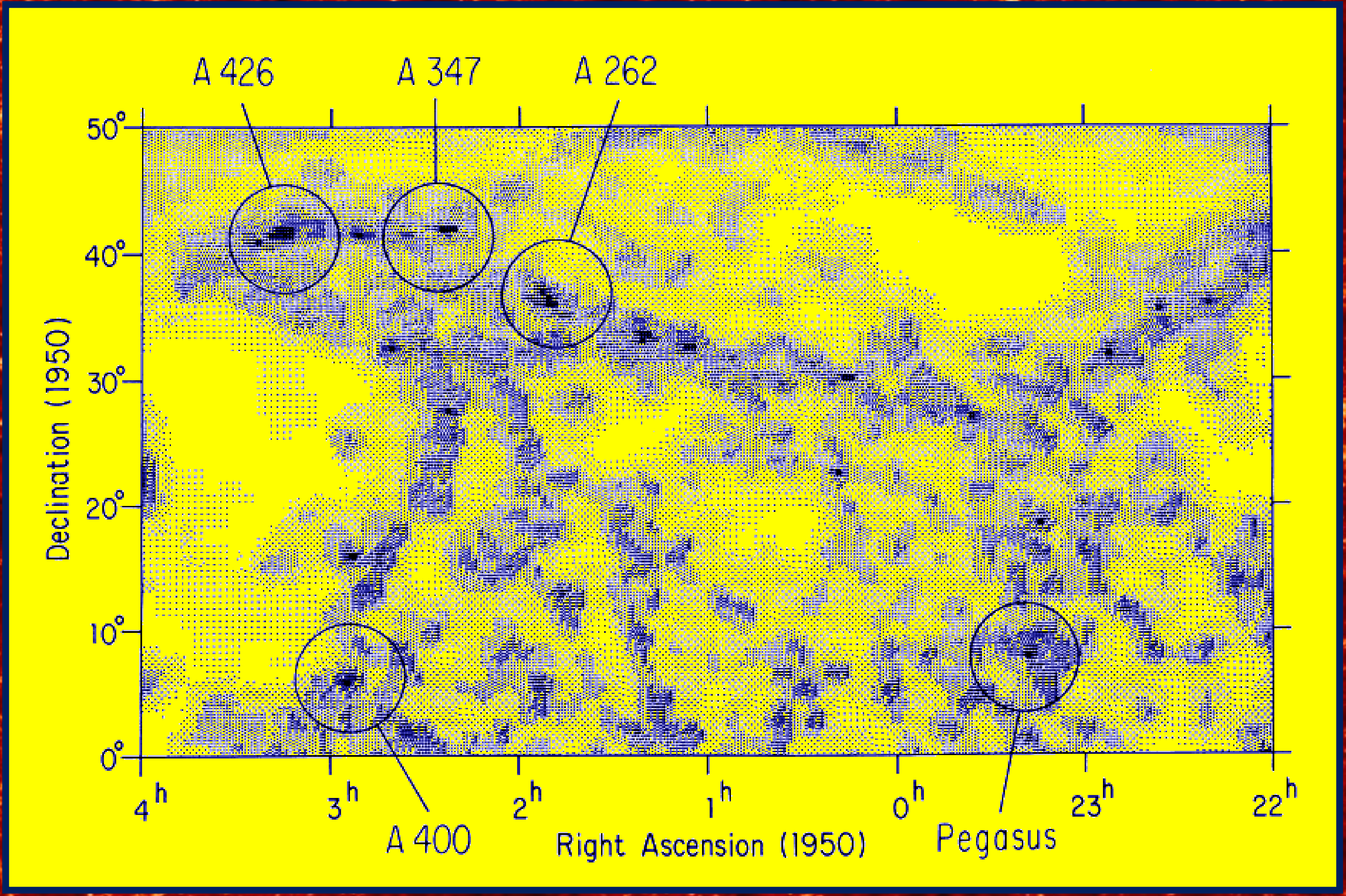


Filamentary Extension across

Northern 2dF Slice

DTFE rendering: W. Schaap

Pisces-Perseus Chain



21 cm line redshift survey,
Giovanelli & Haynes

Pisces-Perseus Chain

Canonic example of a strongly flattened supercluster consisting of

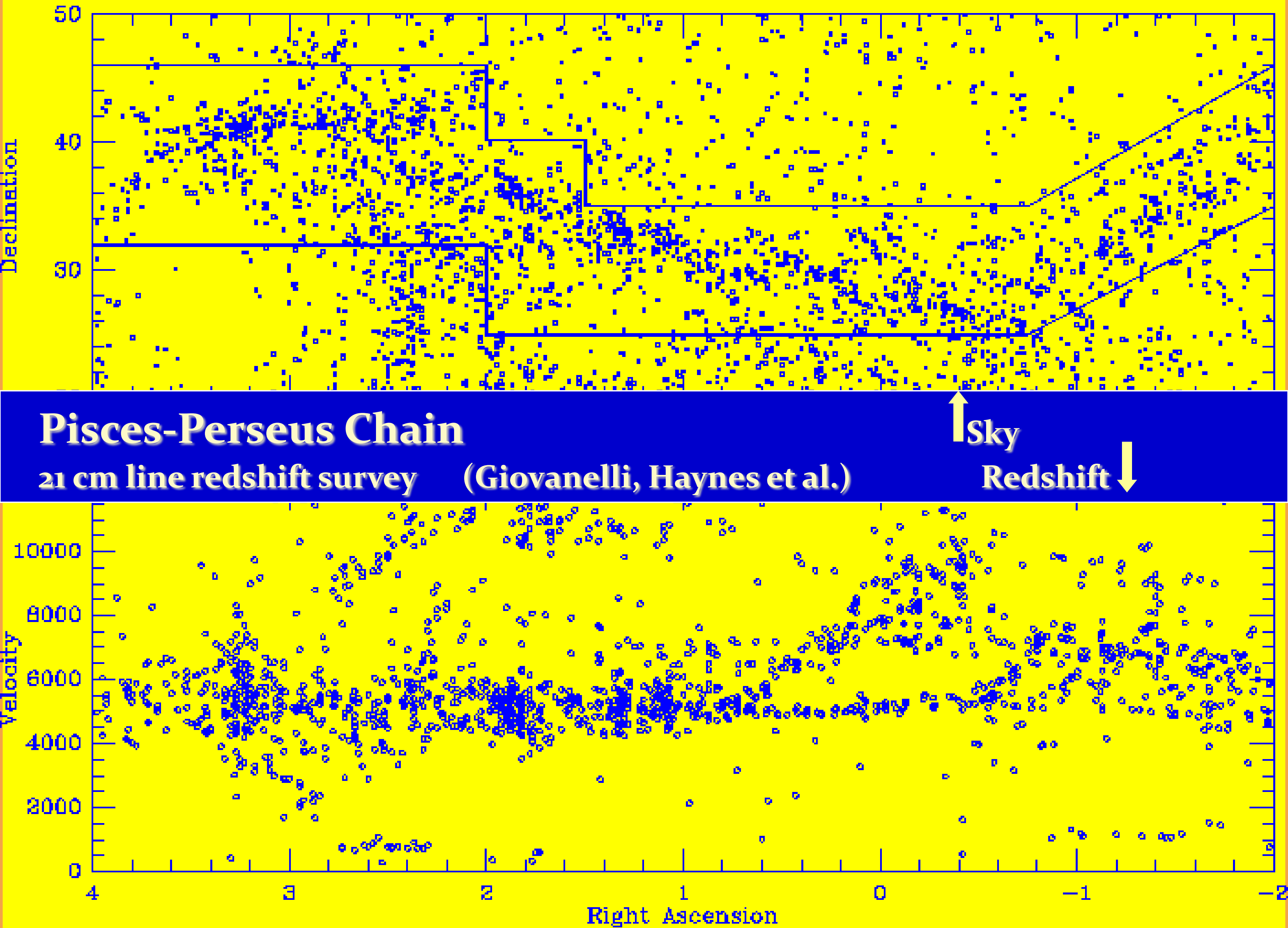
- sheet-like central region, dense filamentary boundary ridge
- Relative proximity (d ~ 55h^{-1} Mpc),
- Characteristic & salient filamentary morphology,
- Favourable orientation.

Northern boundary: ridge south-westward of Perseus cluster (A426)

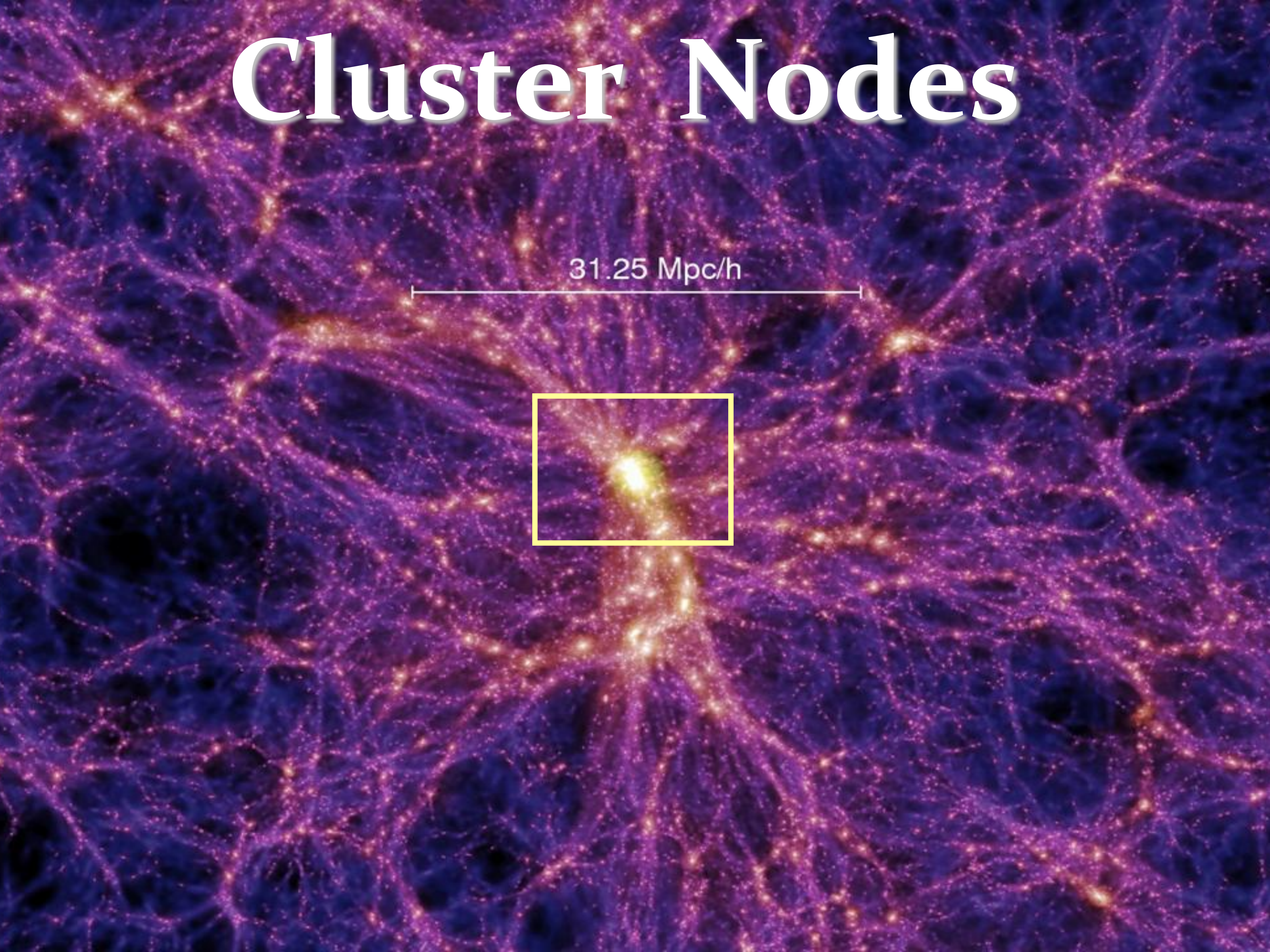
Dimensions Ridge: 5h^{-1} Mpc wide

50h^{-1} Mpc length; possible 140h^{-1} Mpc extension

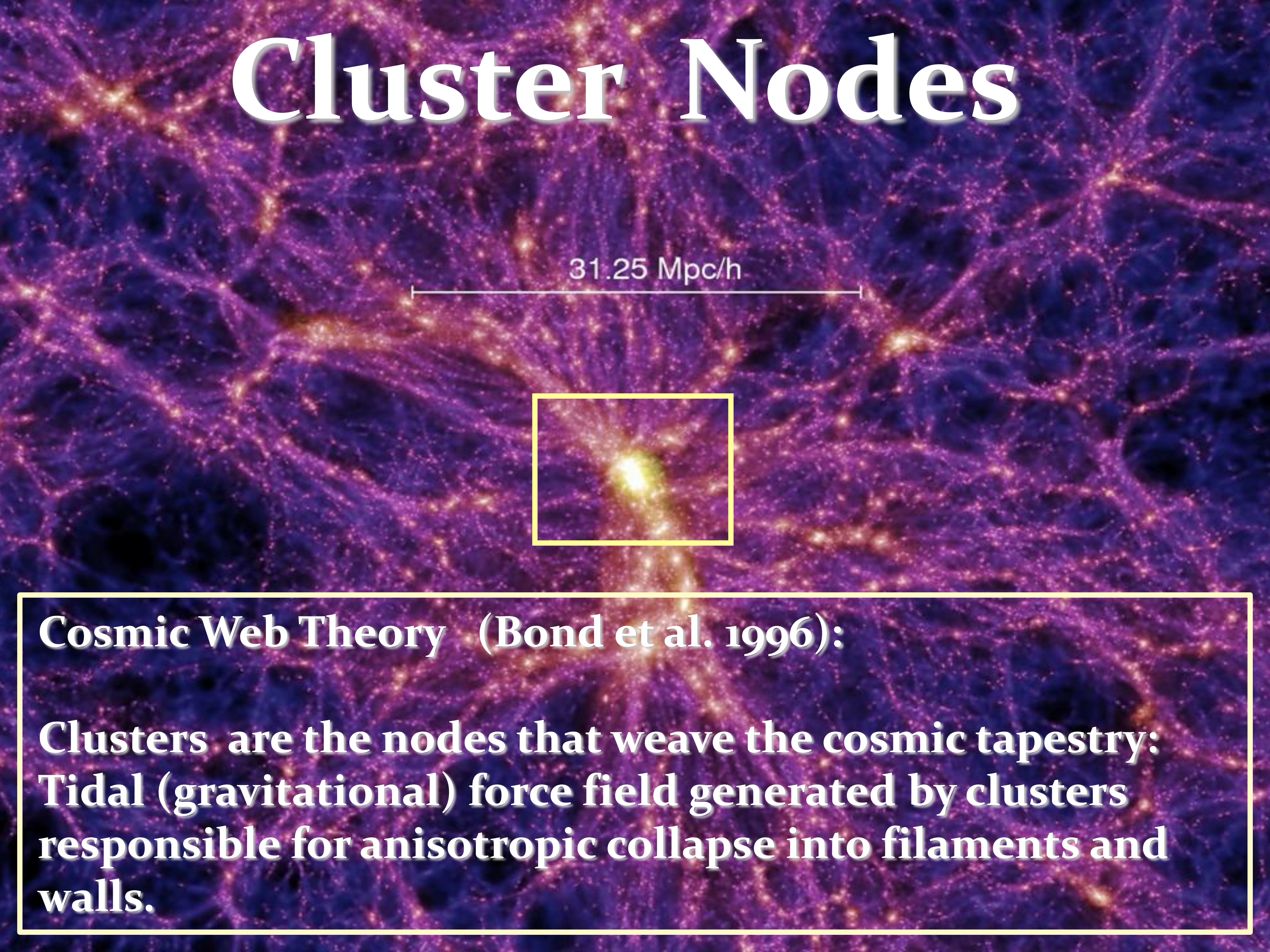
Along Ridge: high density clusters, incl. A462, A347, A262


Pisces-Perseus Chain
21 cm line redshift survey
(Giovanelli, Haynes et al.)
Sky
Redshift
Declination
50
40
30
Velocity
10000
8000
6000
4000
2000
0
4
3
2
1
0
−1
−2
Right Ascension

Cluster Nodes



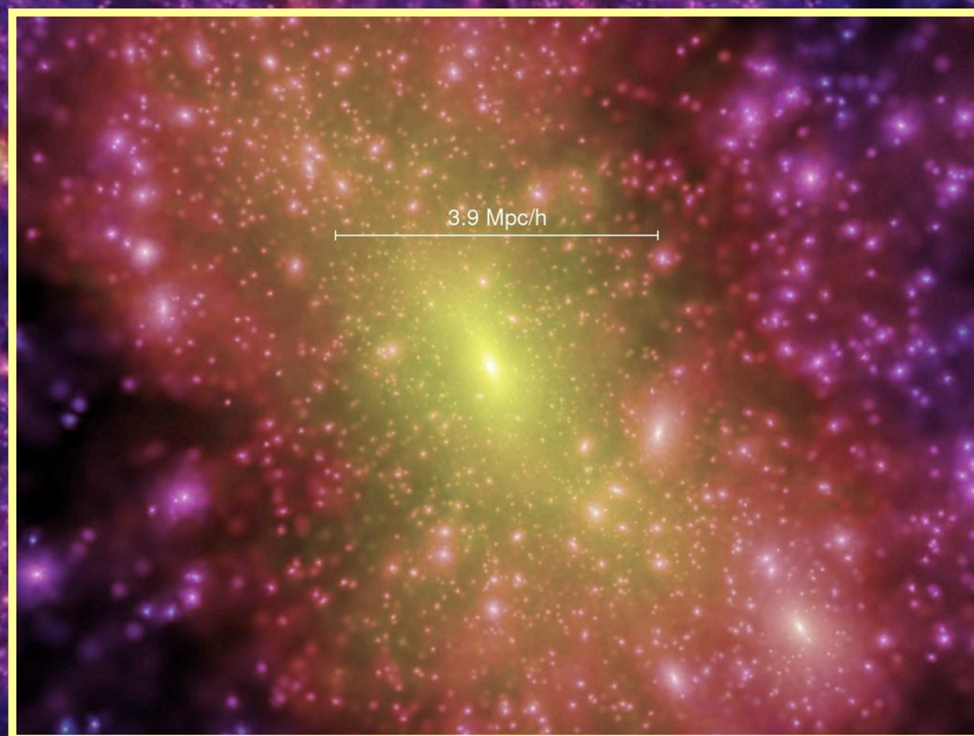
Cluster Nodes



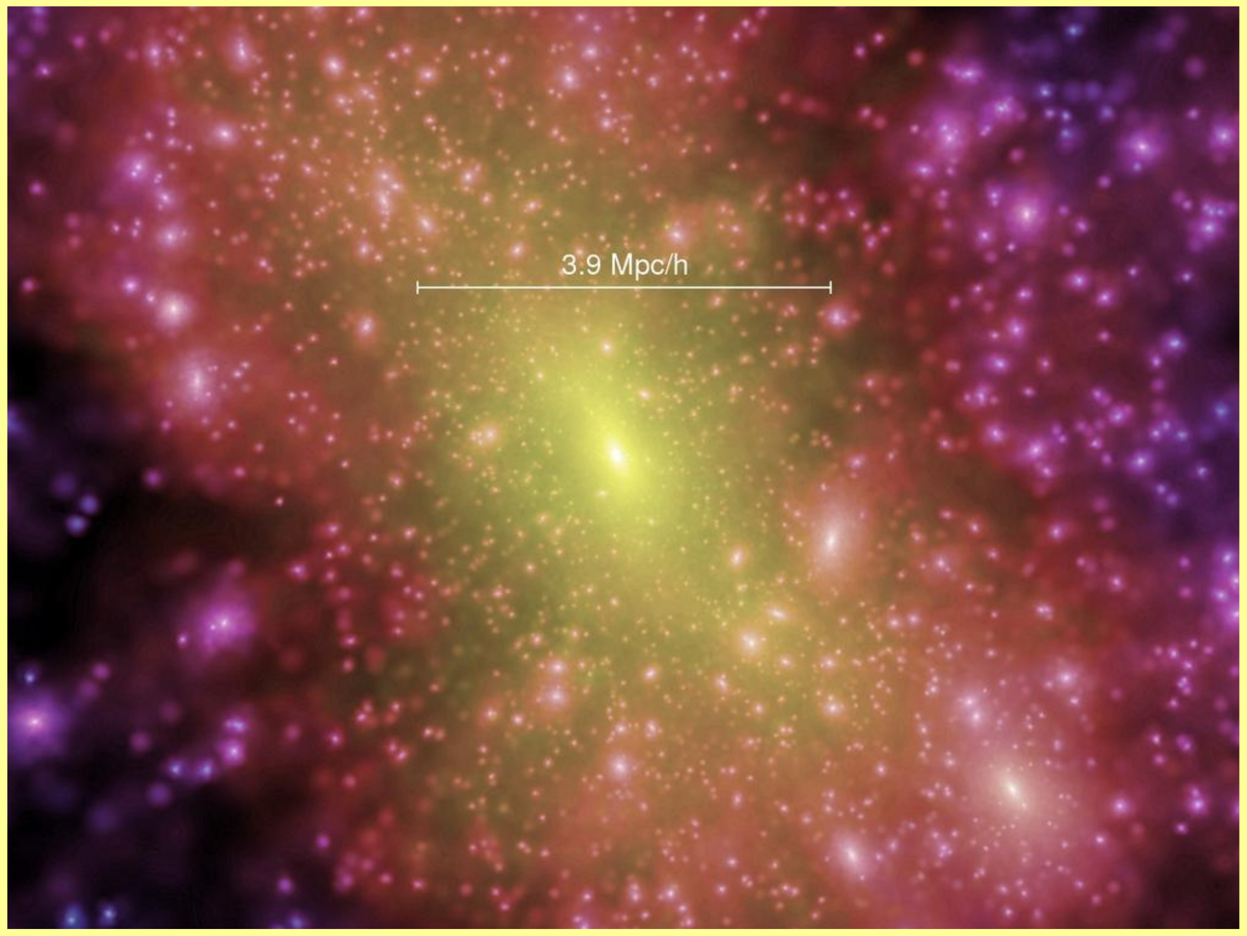
Cosmic Web Theory (Bond et al. 1996):

Clusters are the nodes that weave the cosmic tapestry:
Tidal (gravitational) force field generated by clusters responsible for anisotropic collapse into filaments and walls.

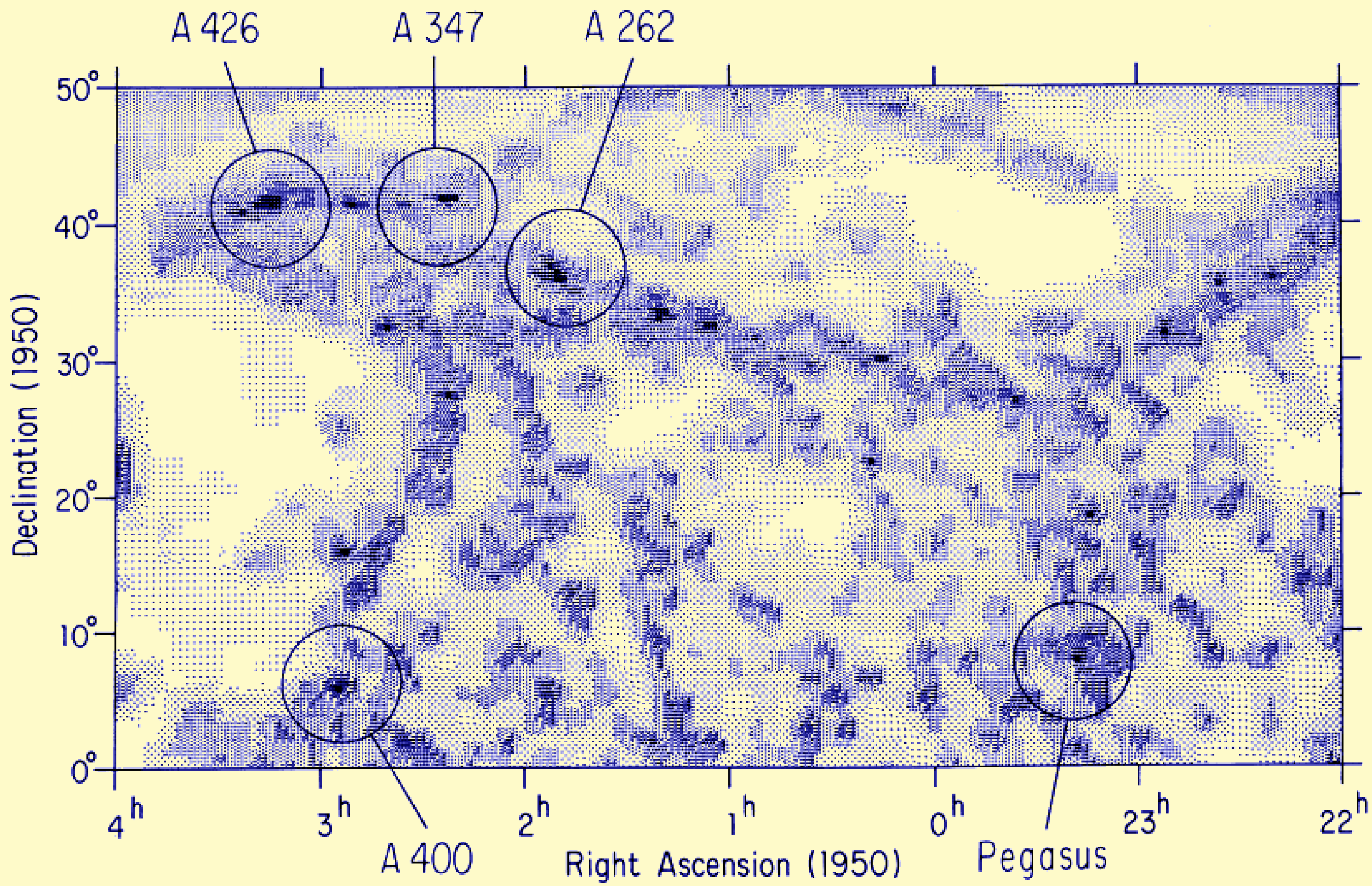
Cluster Nodes



Cluster Nodes

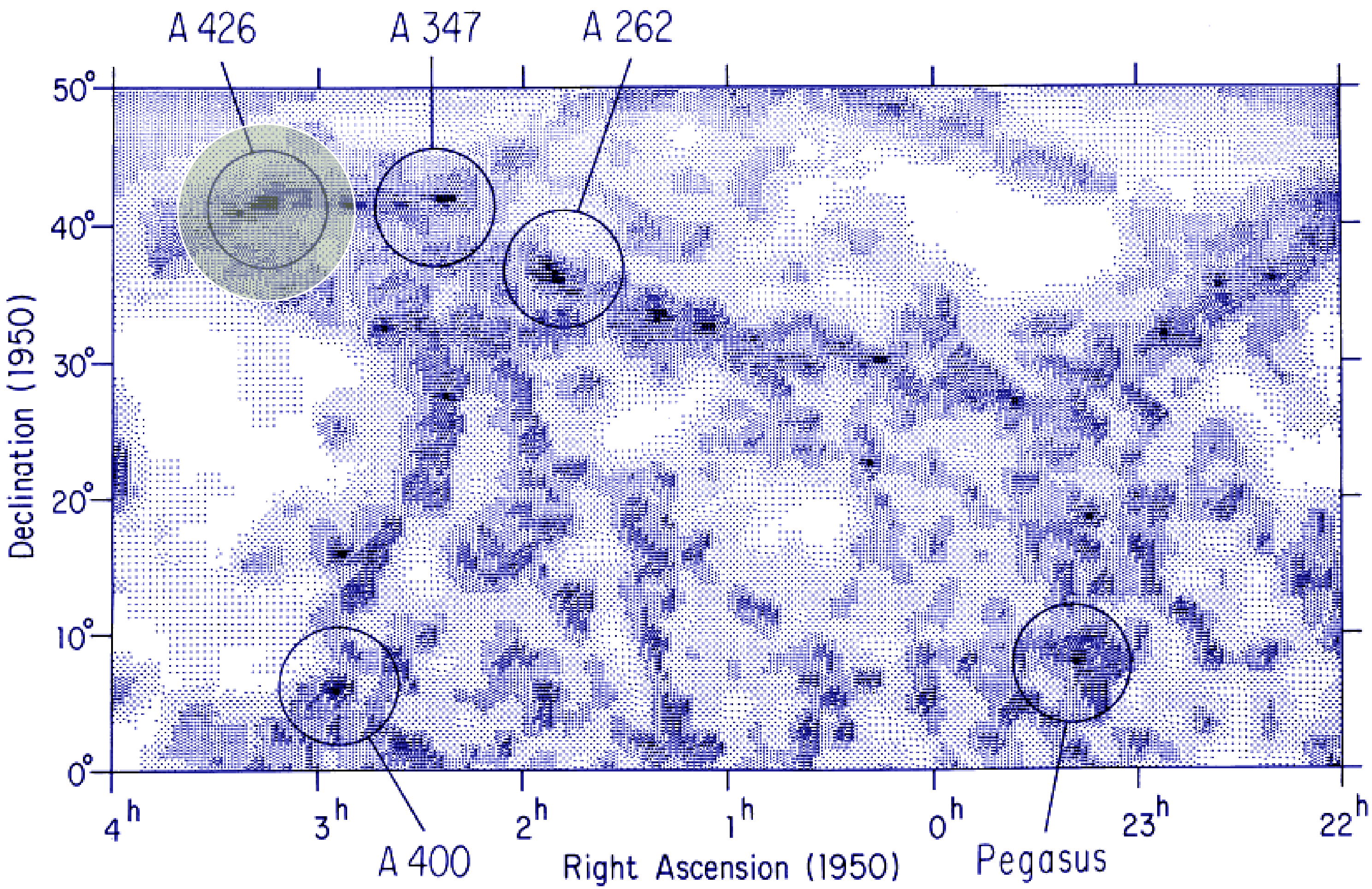


Cluster Nodes & the Web



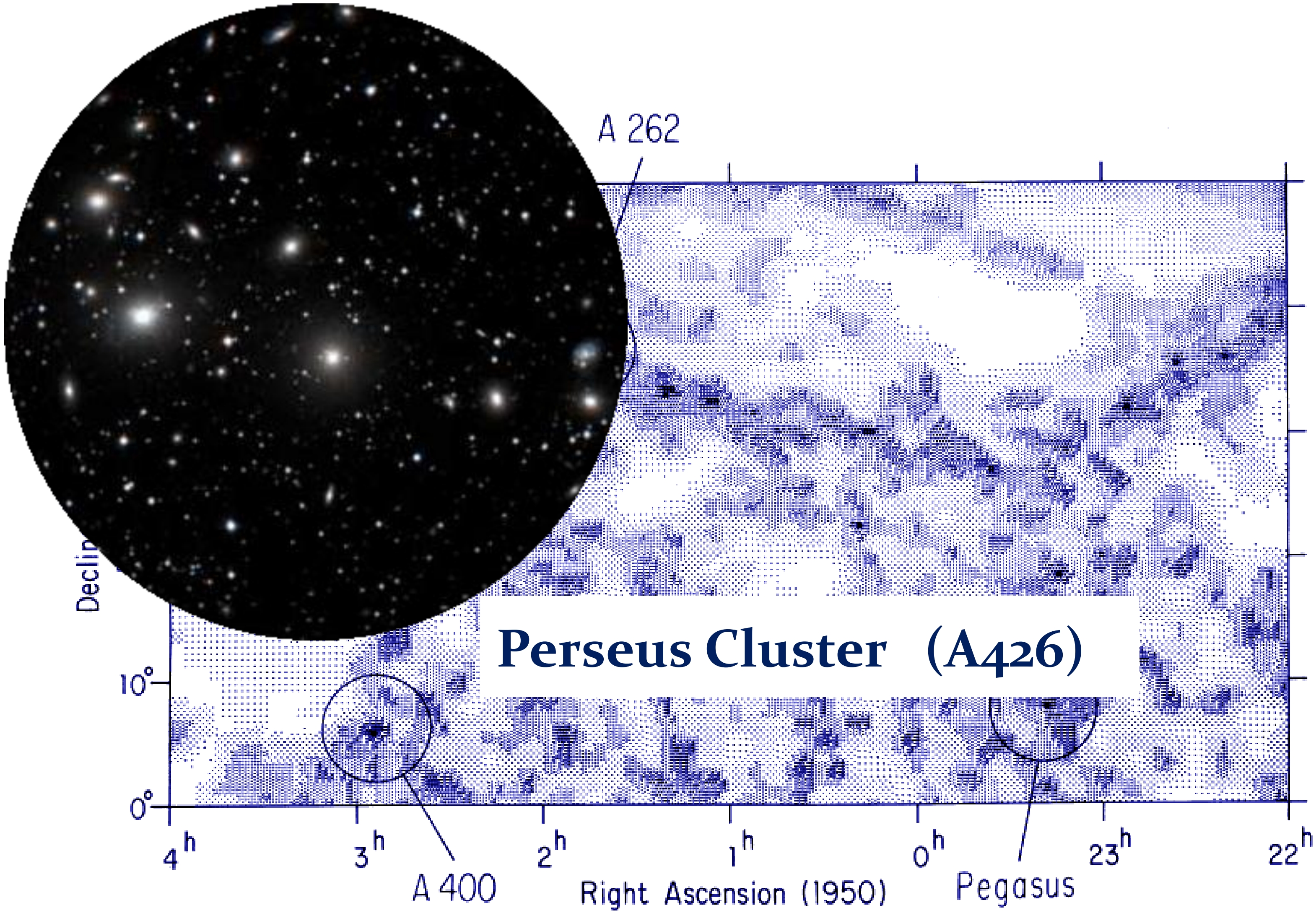
Pisces-Perseus Chain; **21 cm line redshift survey, Giovanelli & Haynes**

Cluster Nodes & the Web



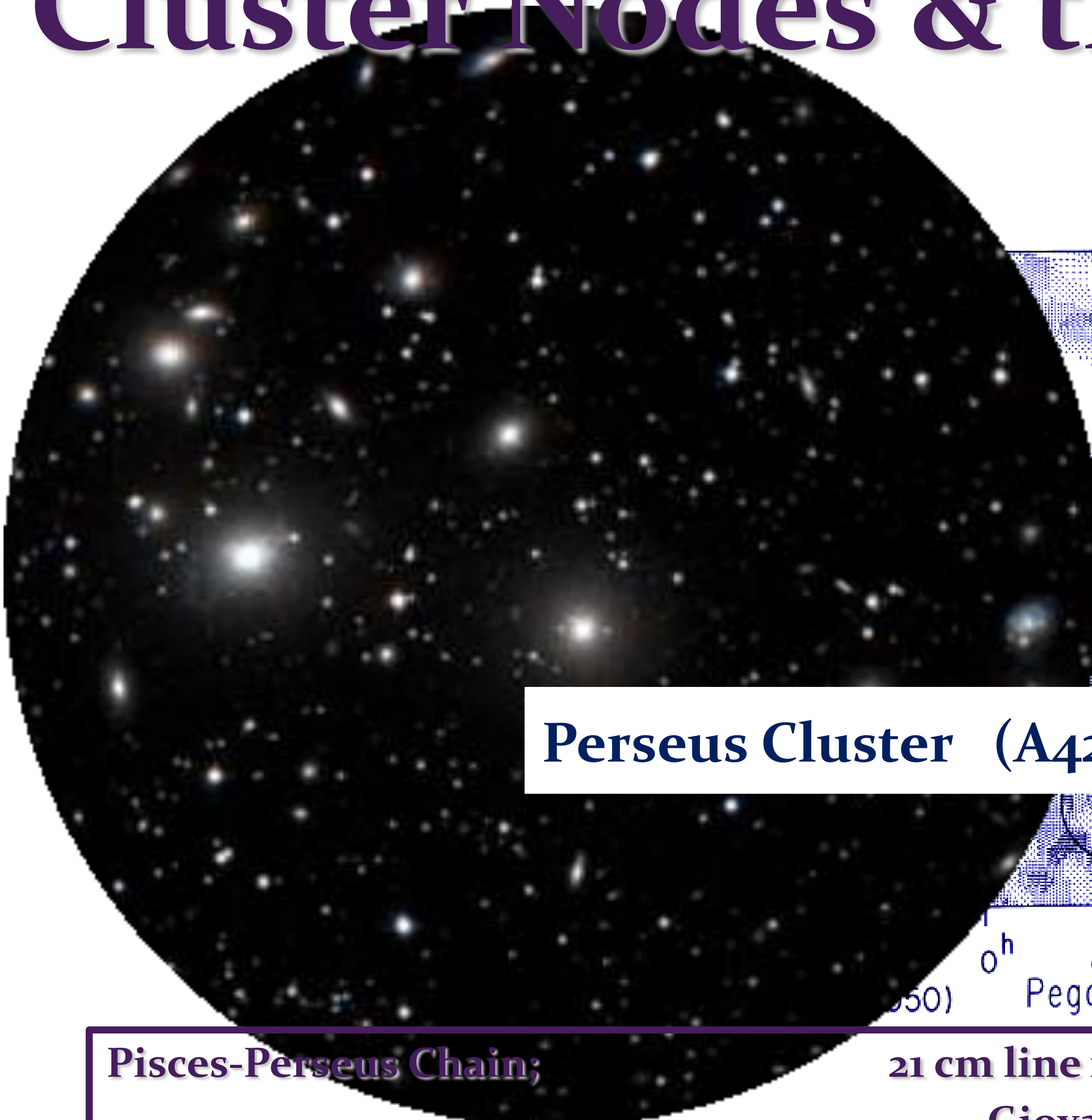
Pisces-Perseus Chain; **21 cm line redshift survey, Giovanelli & Haynes**

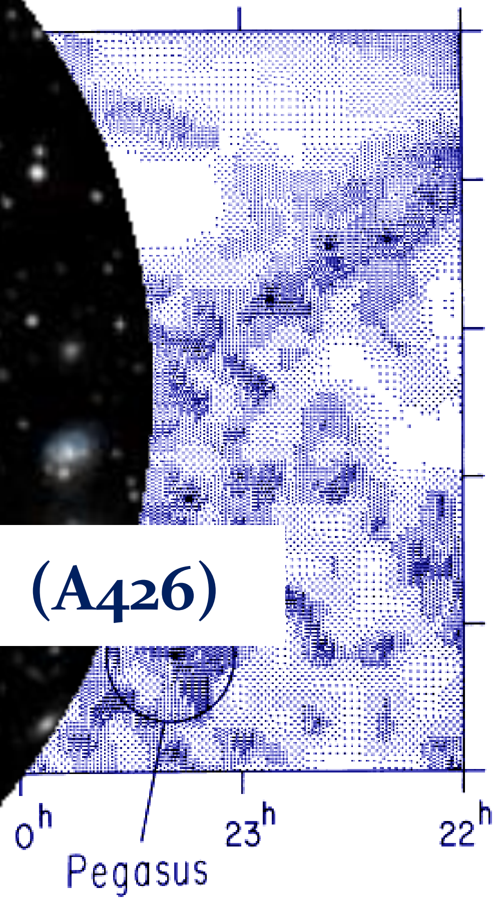
Cluster Nodes & the Web



Pisces-Perseus Chain; **21 cm line redshift survey, Giovanelli & Haynes**

Cluster Nodes & the Web



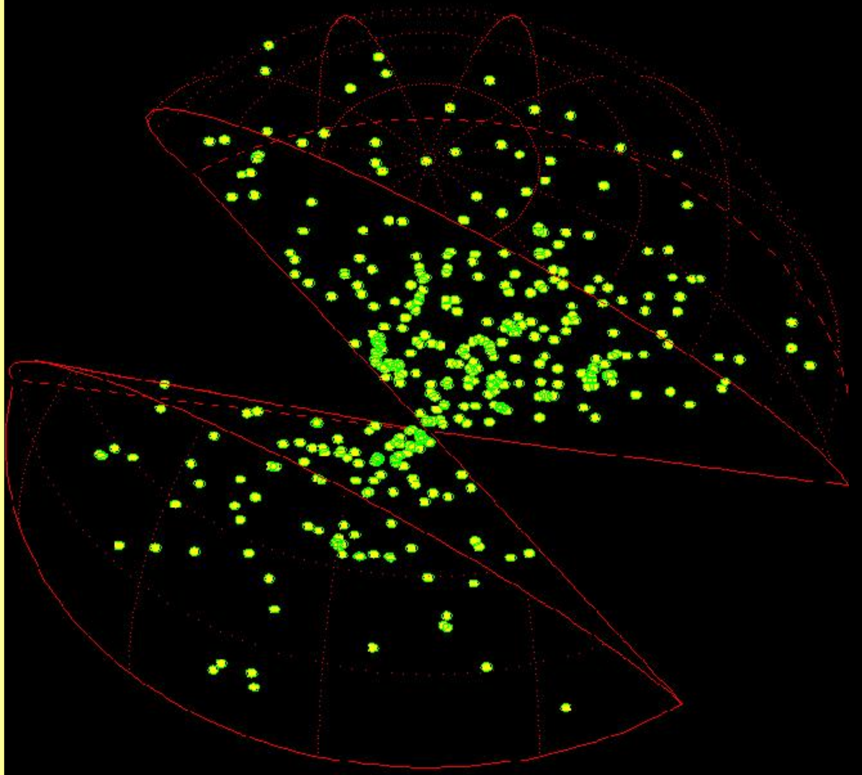


Perseus Cluster (A426)

Pisces-Perseus Chain;

21 cm line redshift survey,
Giovanelli & Haynes

Cluster Nodes & the Web



The spatial cluster distribution.

The full volume of the X-ray cluster REFLEX cluster survey within a distance of $600h^{-1}$ Mpc. The REFLEX galaxy cluster catalogue contains all clusters brighter than an X-ray flux of 3x10 ergs cm^{-2} over a large part of the in the southern sky. The missing part of hemisphere delineates the region highly obscured by the Galaxy.

REFLEX: Boehringer et al. (2001)

Courtesy: Borgani & Guzzo (2001)

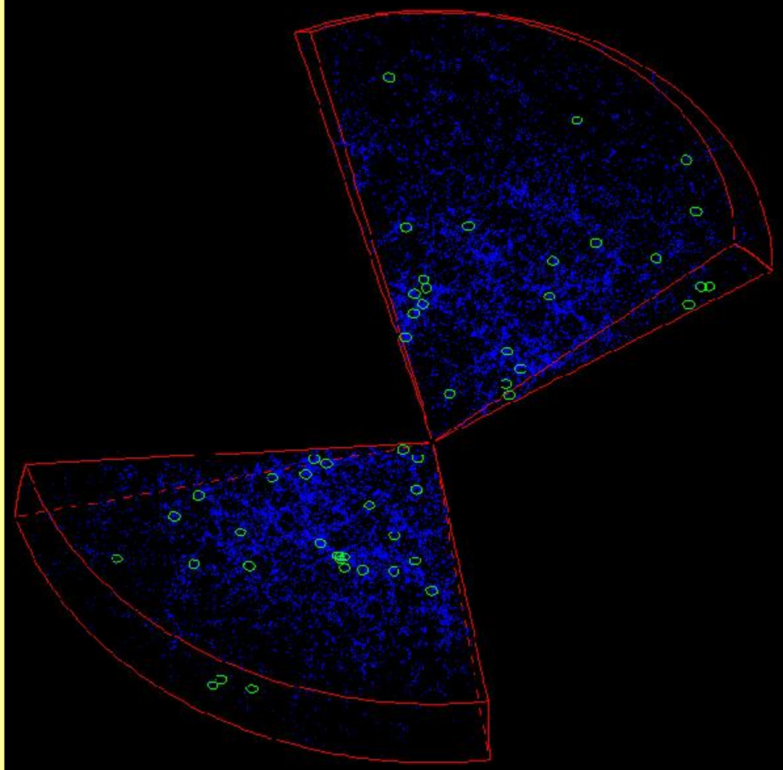
Cluster Nodes & the Web

The spatial cluster distribution and relation to Cosmic Web.

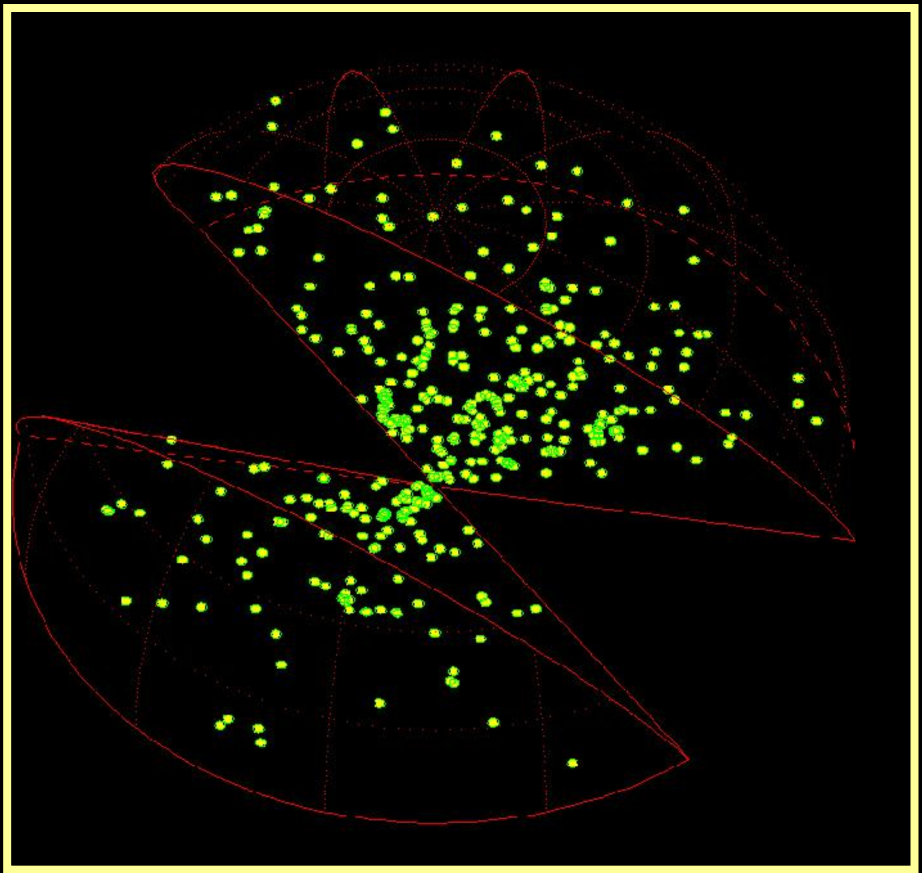
The green circles mark the positions of REFLEX X-ray clusters in the northern and southern slices of the Las Campanas redshift survey (LCRS, Shectman et al. 1996), out to a maximum distance of 600h^{-1} Mpc. Underlying, in blue, the galaxies in the LCRS delineate a foamlike distribution of filaments, walls and voids.

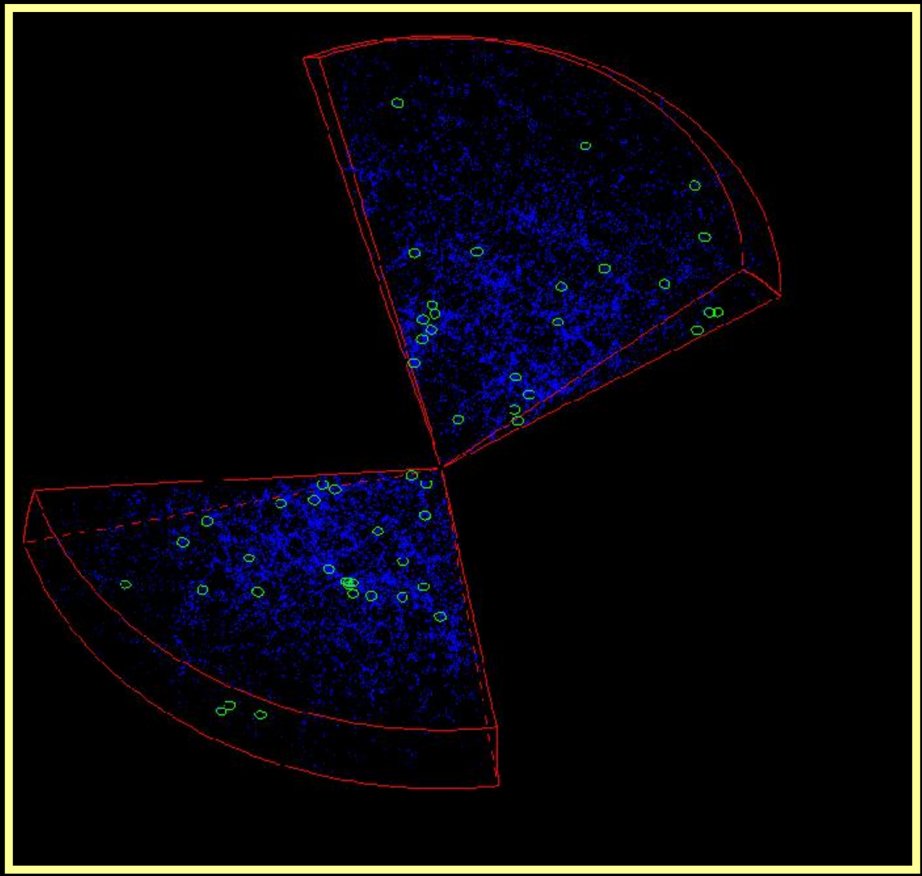
REFLEX: Boehringer et al. (2001)

Courtesy: Borgani & Guzzo (2001)



Cluster Nodes & the Web





Cosmic

Structure Formation

Early Universe

almost perfectly homogeneous and isotropic,
without any discernable structure …

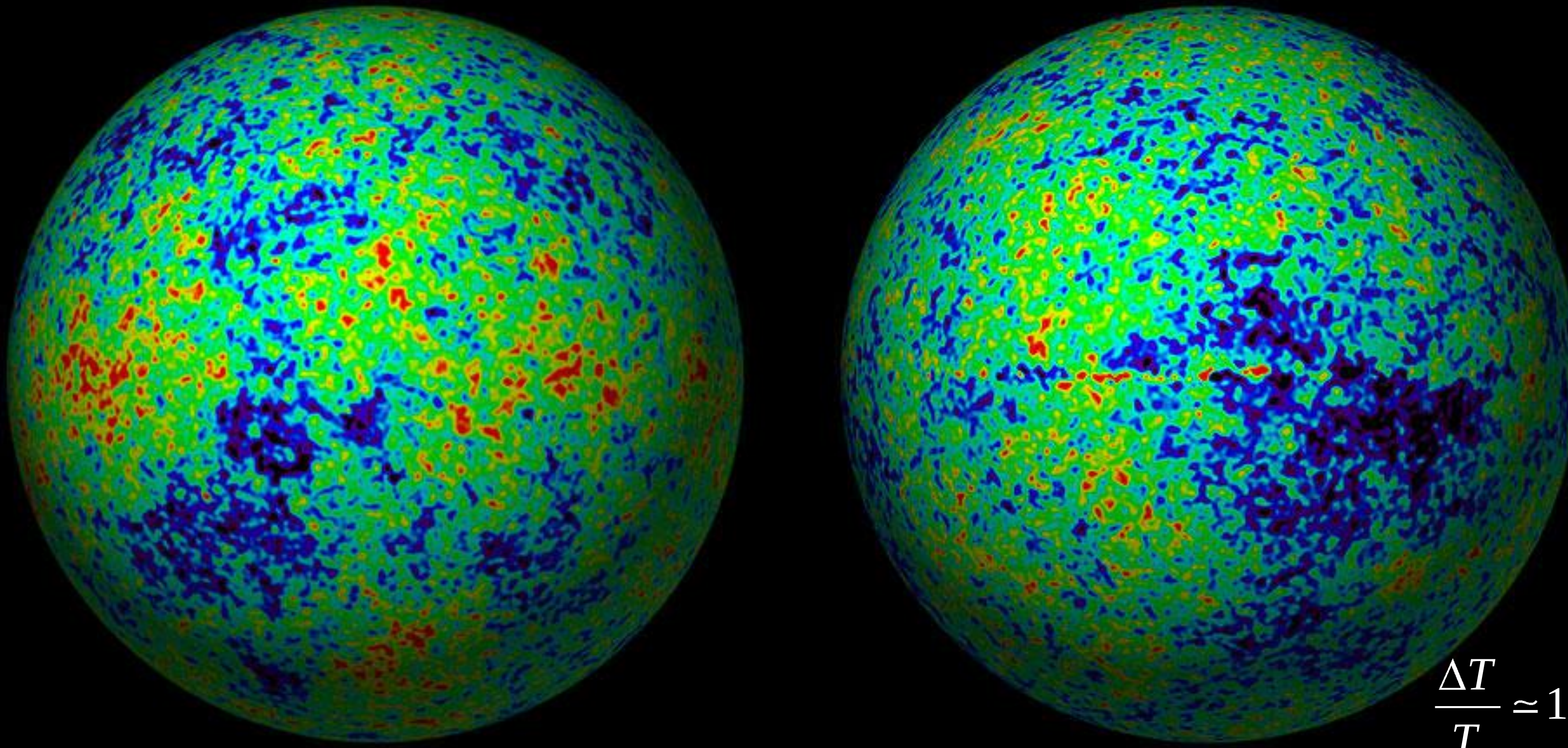
How did the present wealth and variety of
structure emerge out of
an almost featureless, pristine early Universe

?????

Cosmic Paradigm:

Gravitational Instability

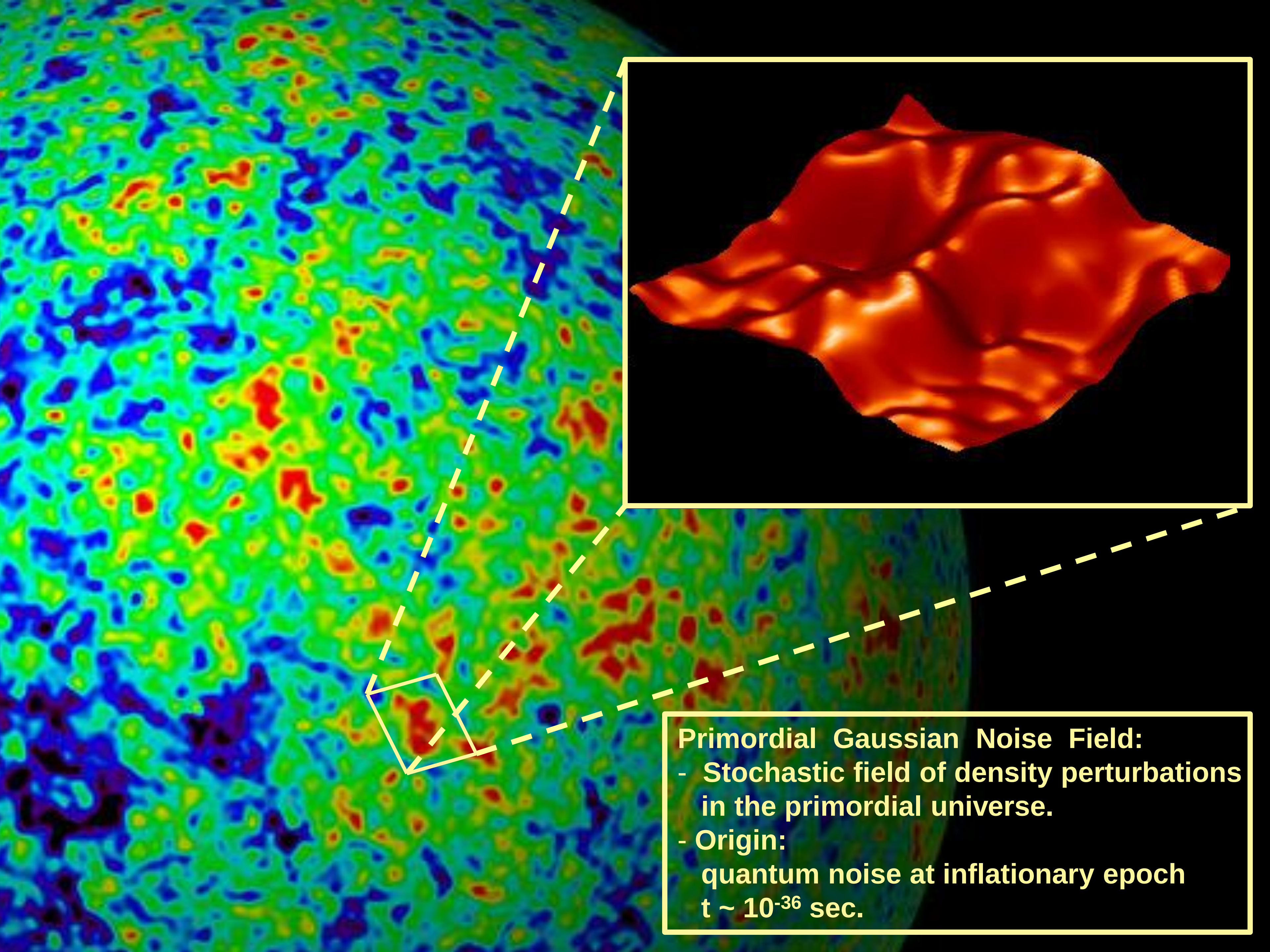
Primordial Universe



$$\frac{\Delta T}{T} \simeq 10^{-5}$$

global representation cosmic surface last scattering: the world inside out

Temperature Map CMB radiation:
Tiny variations in primordial temperature, reflecting tiny inhomogeneities in energy density of $\Delta \sim 10^{-5}$ K at recombination epoch, 379,000 yrs after Big Bang


Primordial Gaussian Noise Field:
- Stochastic field of density perturbations in the primordial universe.
- Origin:
quantum noise at inflationary epoch
t ~ 10-36 sec.

Density Perturbation Field:

$$\delta(\vec{x},t) = \frac{\rho(x,t) - \rho_u(t)}{\rho_u(t)}$$

Gravity Perturbations

Gravity Perturbations

$$\mathbf{g}(\mathbf{r},t) = -\frac{1}{a}\nabla\phi = \frac{3\Omega H^2}{8\pi}\int \mathrm{d}\mathbf{x}'\,\delta(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

Cosmic Structure Formation

(Energy) Density Perturbations

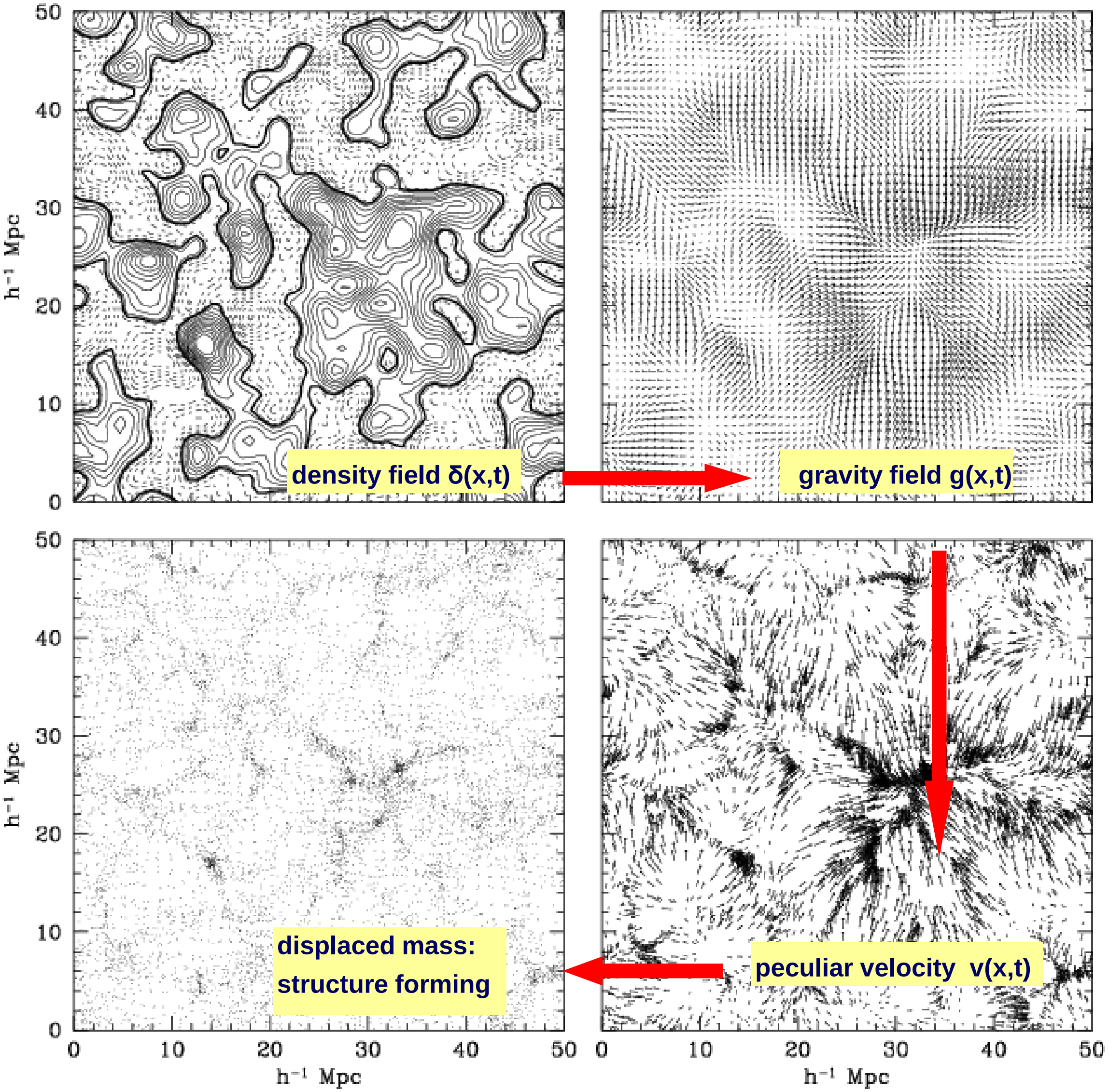
Gravity Perturbations

(Cosmic) Flows of (Energy) & Matter:

- towards high density regions:
  - assemble more and more matter
  - their expansion comes to a halt
  - turn around and collapse
- evacuating void regions
  - low-density regions expand
  - matter moves out of region
  - turn into prominent empty voids

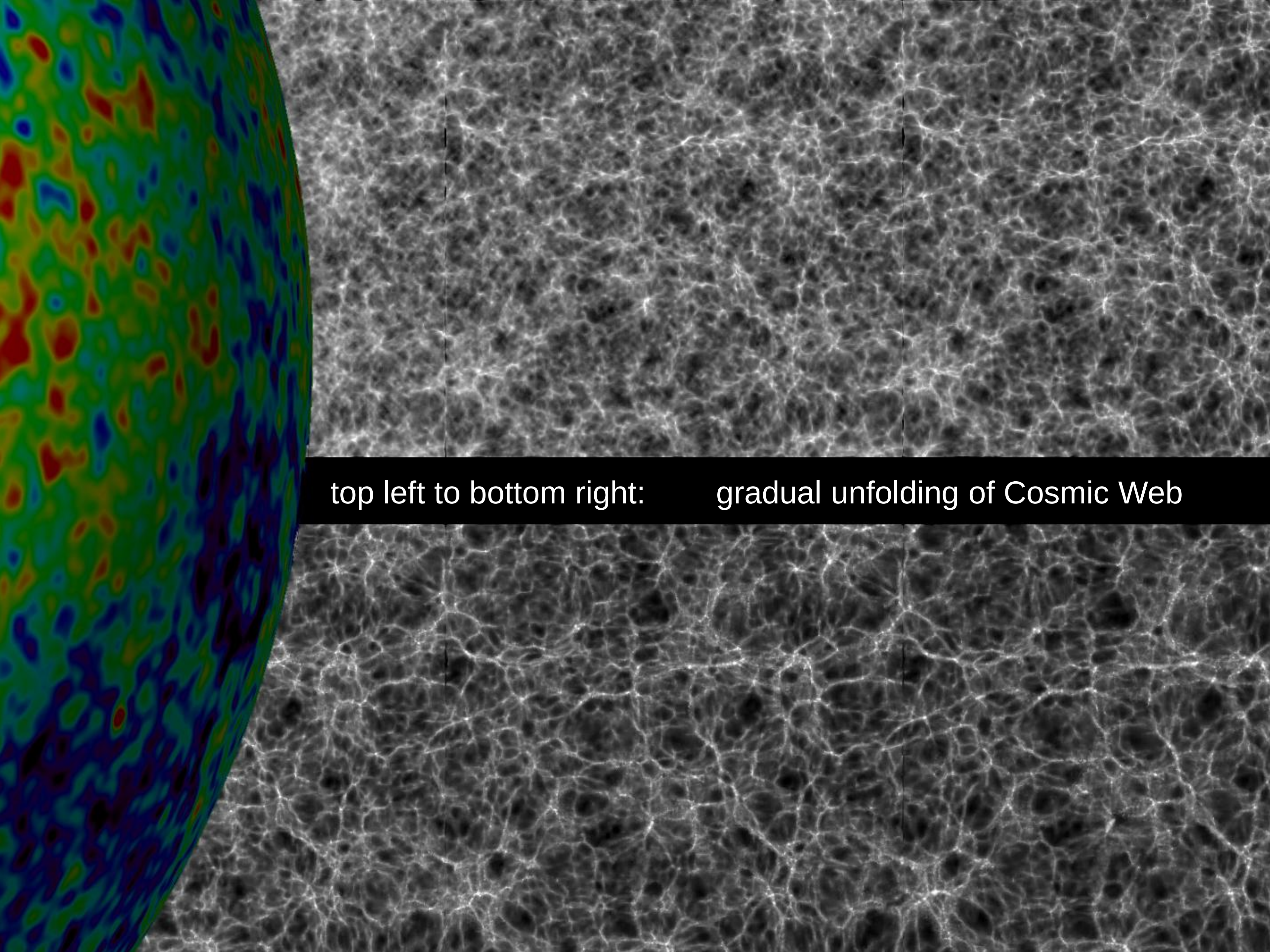
Emergence of cosmic structures

- Computer Simulations
  - succesfull confrontation with observational reality



Structure Formation GIF Simulation,

Volker Springel Movie


top left to bottom right:
gradual unfolding of Cosmic Web

following first linear phase of structure formation:

emergence of genuine cosmic structures

three generic properties nonlinear structure formation:

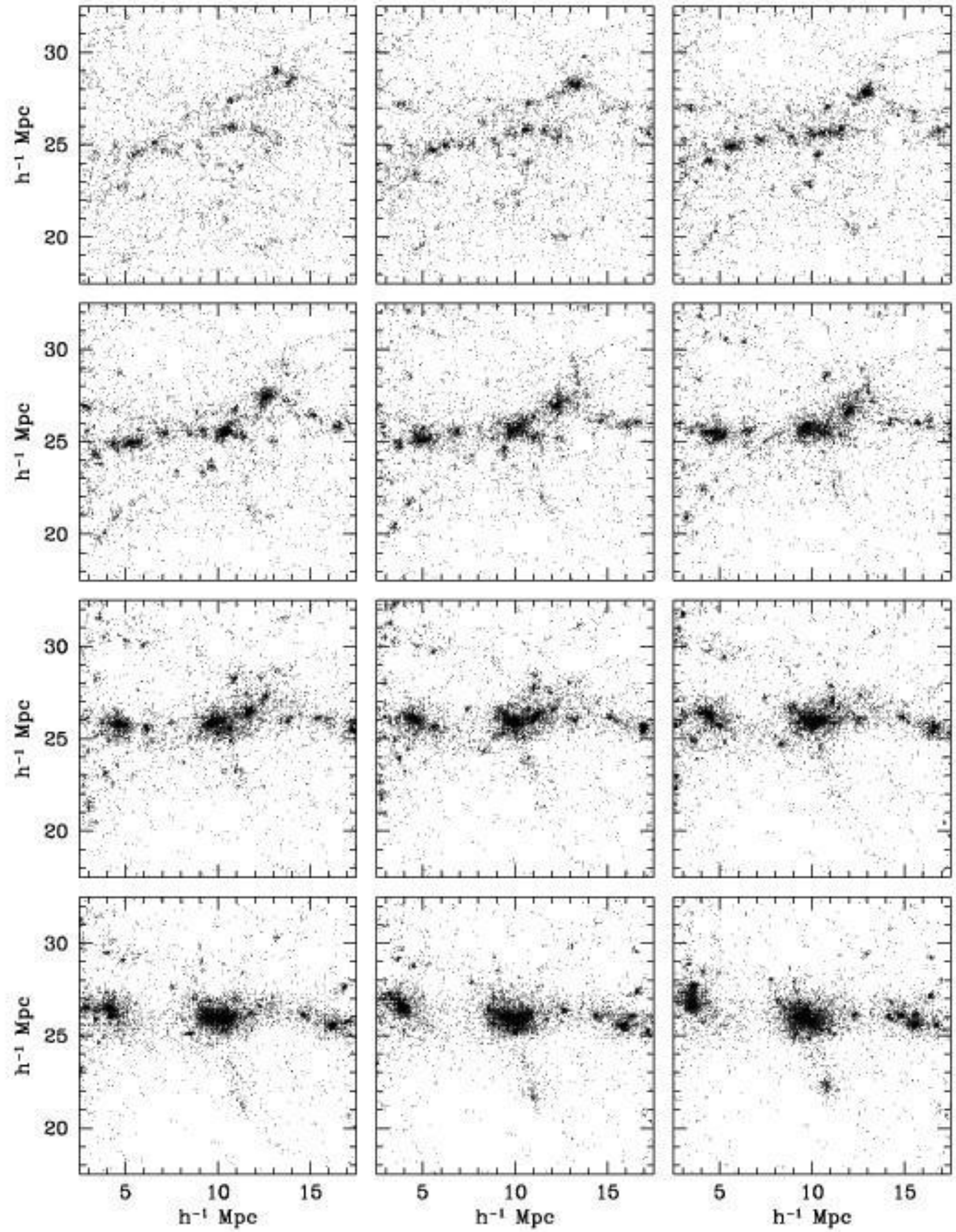
- hierarchical structure formation
- anisotropic collapse
- void formation:
  asymmetry
  overdense vs. underdense

Hierarchical Structure Formation

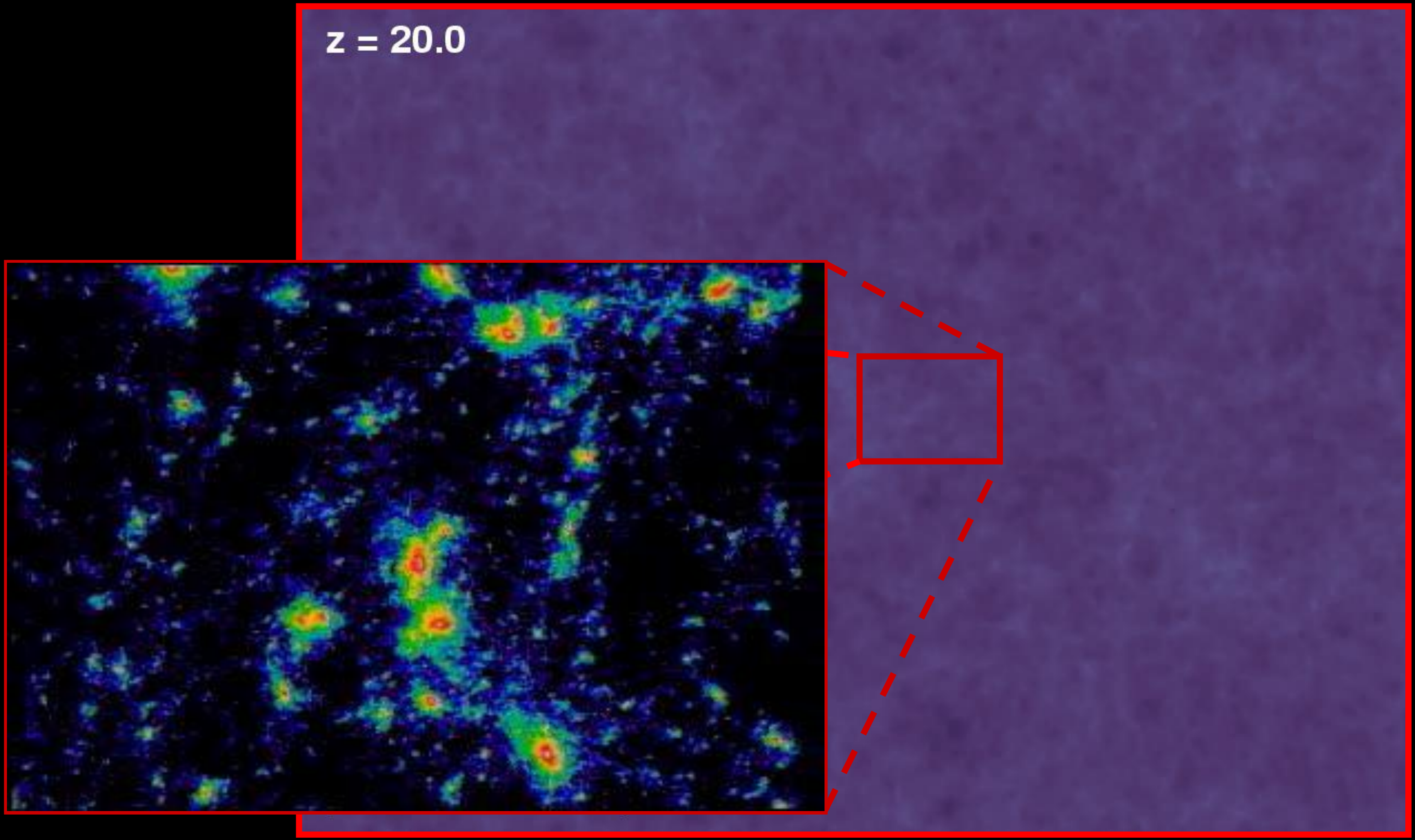
Small structures form first, then merge into larger and larger features

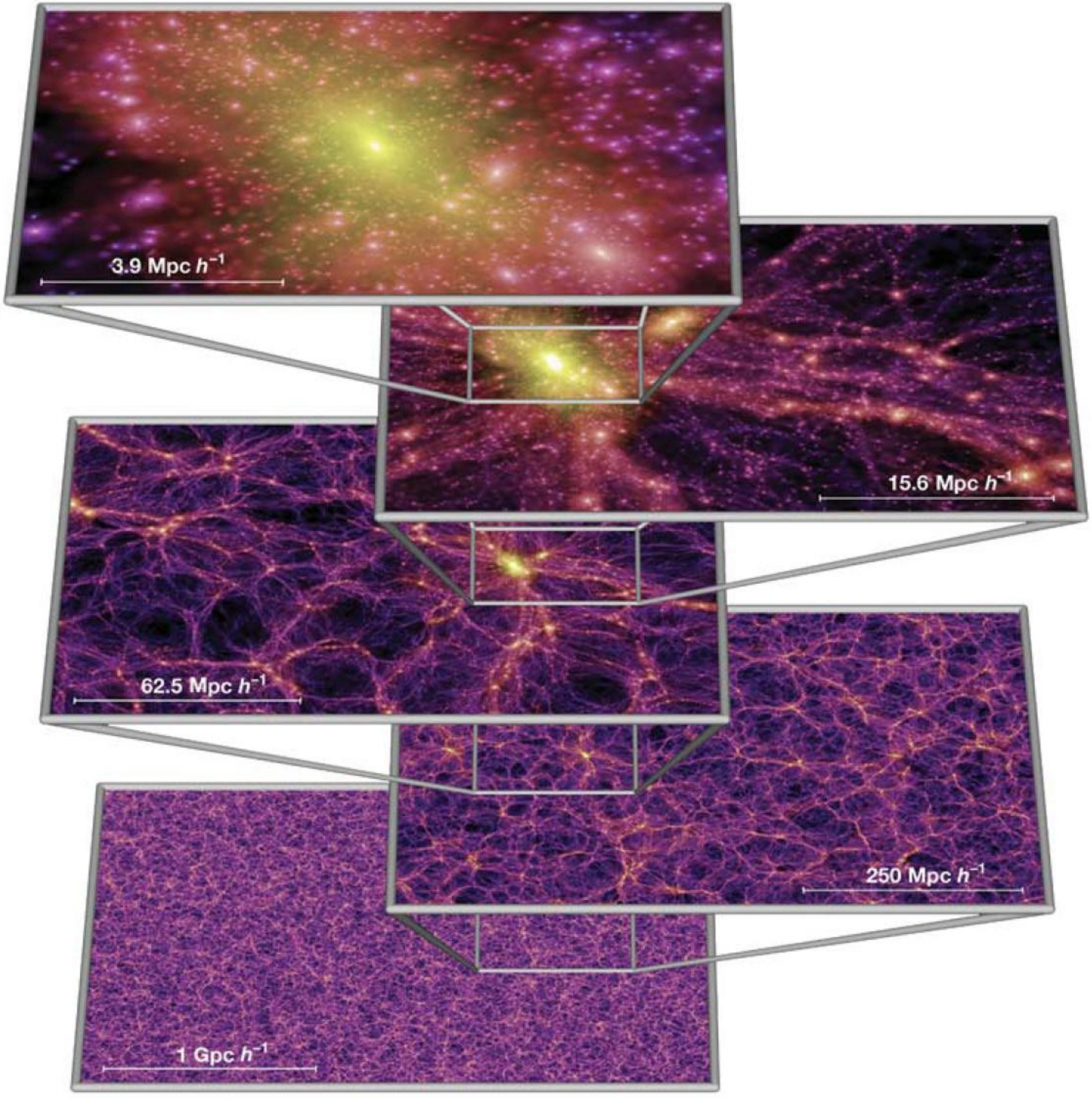
Structures in the Universe form
by
gradual hierarchical assembly:

- ❖ small objects emerge & collapse first,
- ❖ then merge with other clumps
- ❖ while forming larger objects in hierarchy



Hierarchical Structure Formation





3.9 Mpc h^{-1}
15.6 Mpc h^{-1}
62.5 Mpc h^{-1}
250 Mpc h^{-1}
1 Gpc h^{-1}

Anisotropic Structure Formation

Structures tend to collapse into

anisotropic filamentary and planar structures

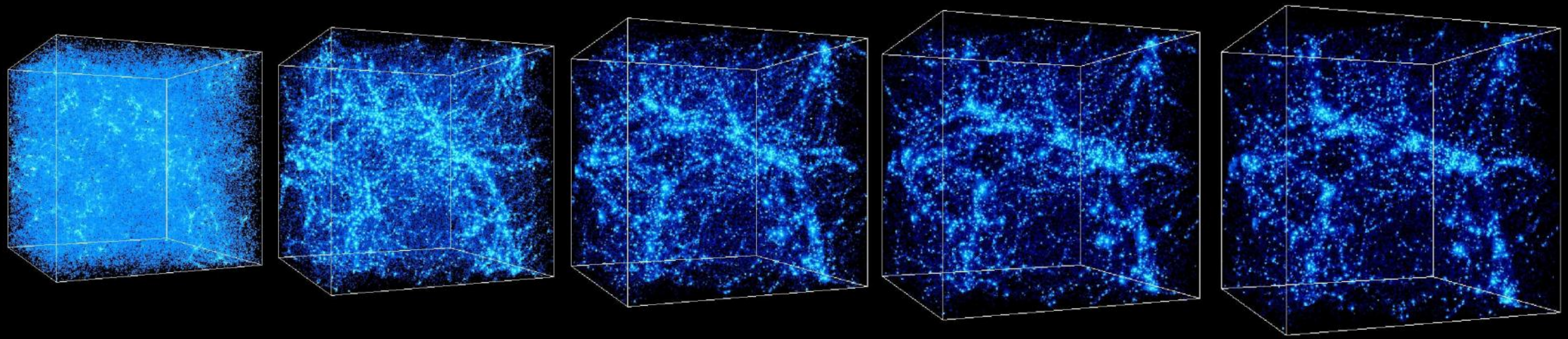
Gravitational Instability:

- any small initial deviation from sphericity of a collapsing cloud gets magnified

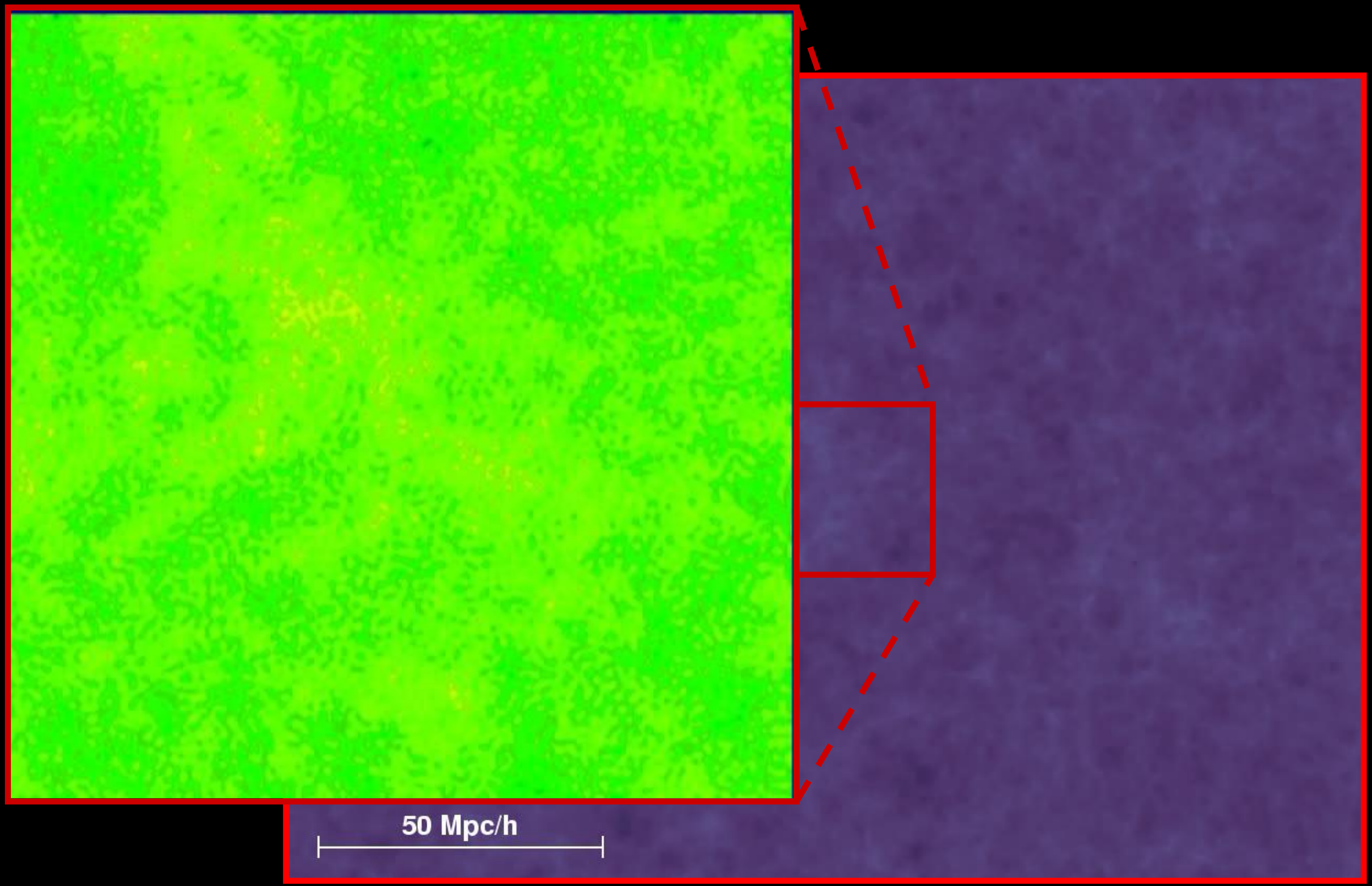
- gravitational collapse proceeds along sequence:

• collapse along smallest axis	→	planar geometry	↔	wall
• collapse medium axis	→	elongated	↔	filament
• full 3-D collapse	→	clump	↔	clump/halo

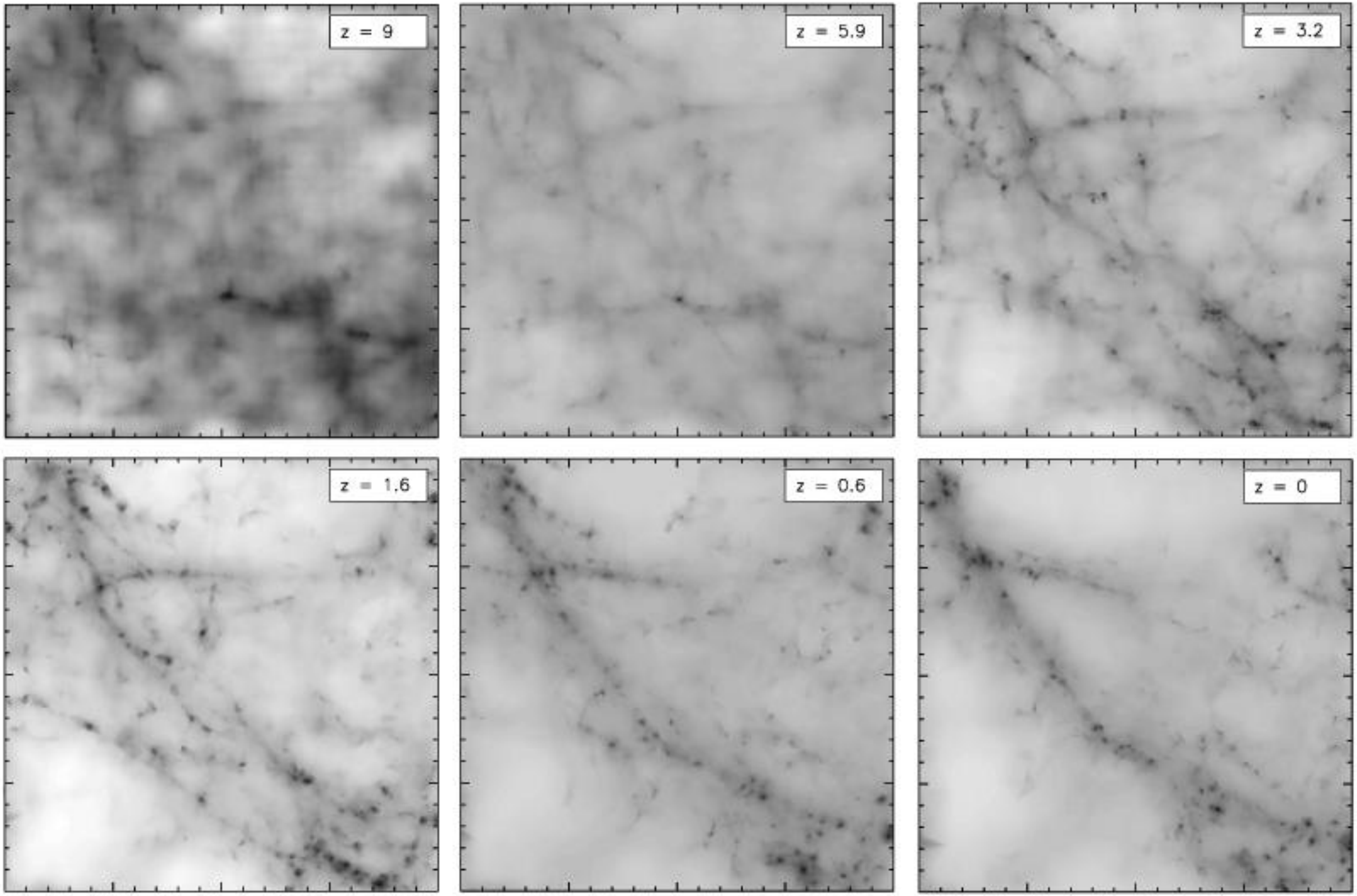
- After having collapsed into a clump, virialization and emergence cosmic object



Anisotropic Collapse



Hierarchical Filament Formation



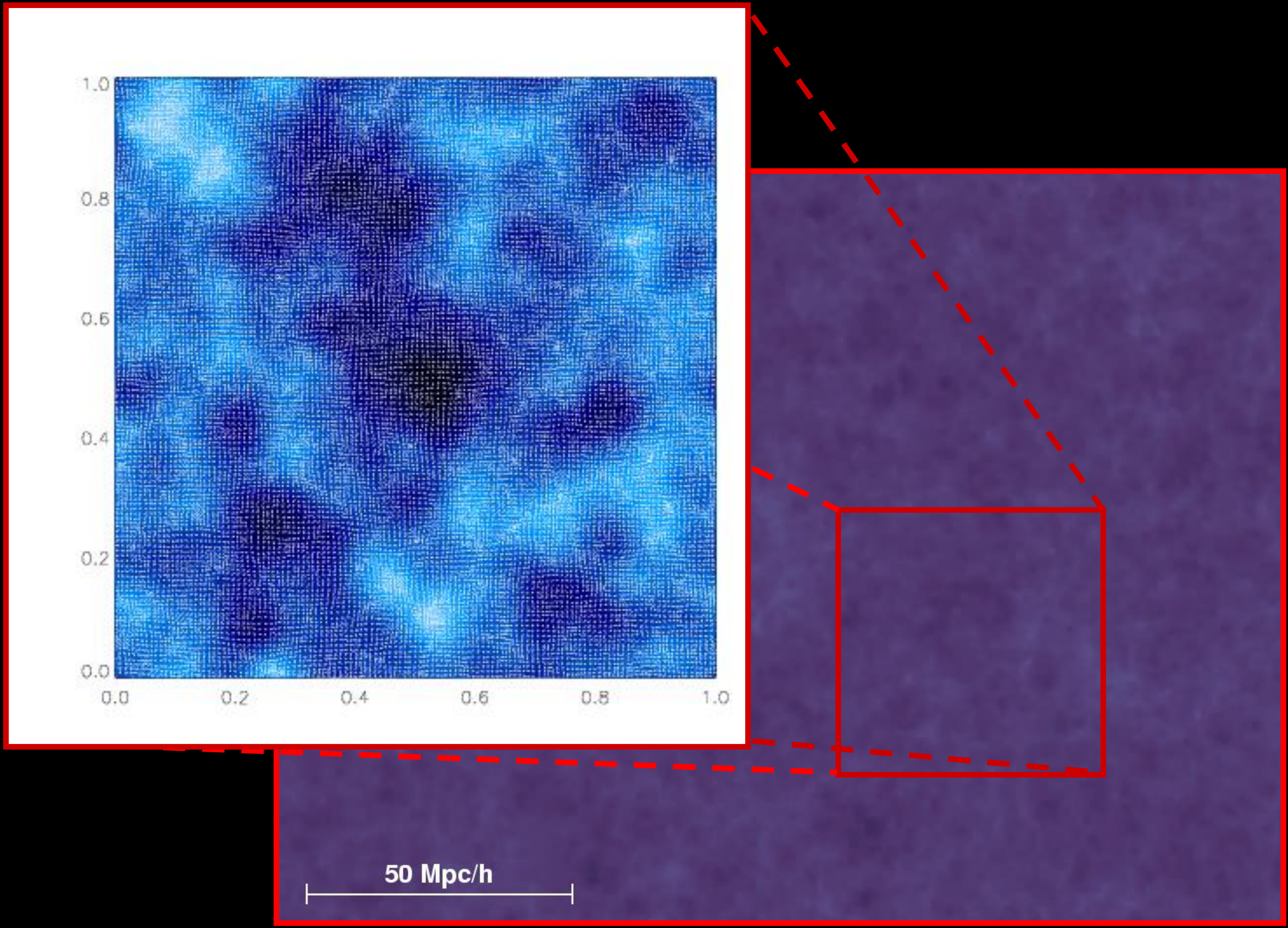
Asymmetric Structure Formation:

Void Dominance

While matter aggregates into ever denser and compacter structures, underdense void regions assume dominance in terms of occupied space.

Origin of Voids:

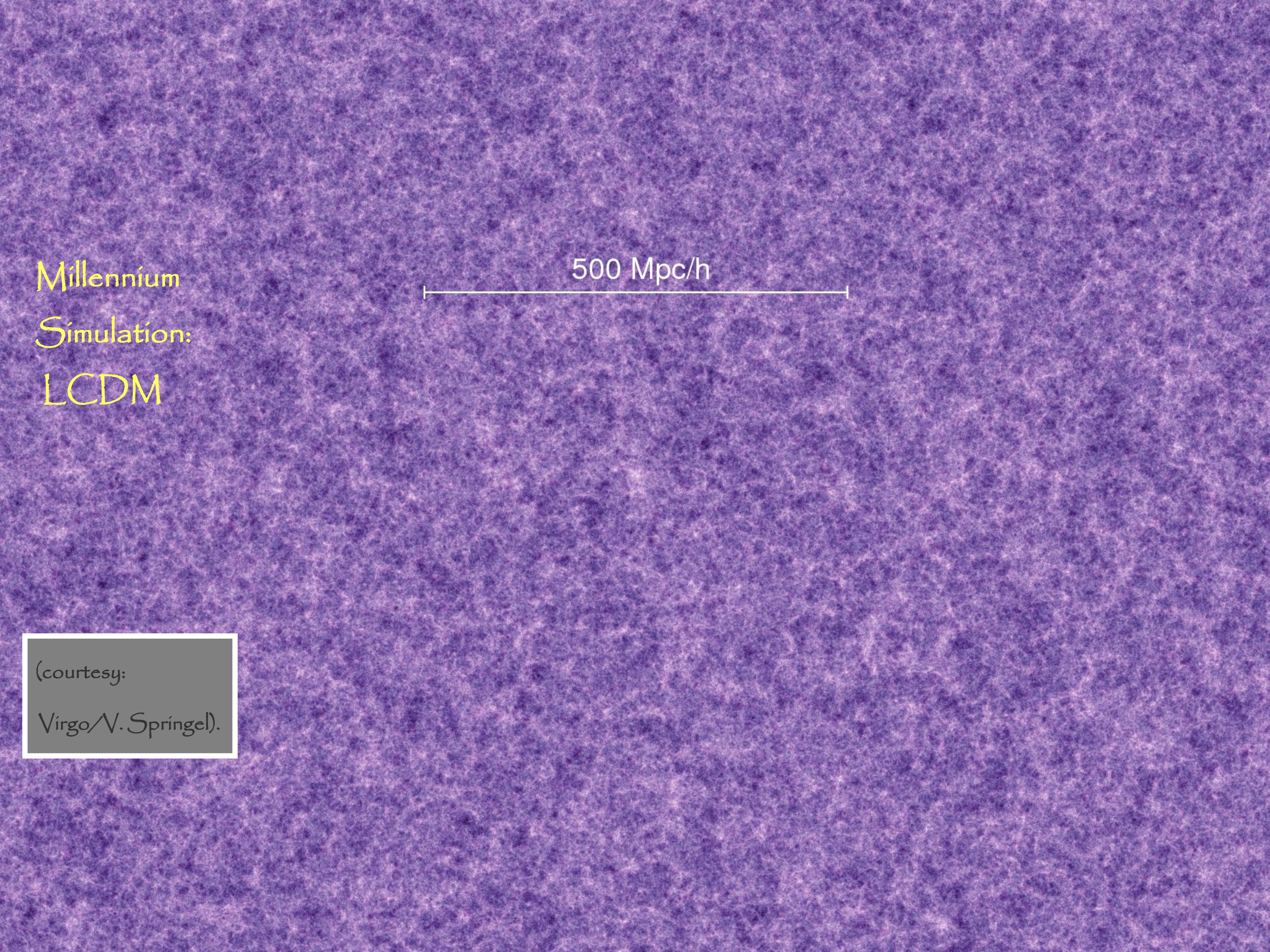
- Voids natural product gravitational instability
- Voids evolve out of primordial underdensities:
  - Underdensity ⇒
  - Gravity Deficit ⇒
  - Matter Emigration
- Primordial Density Troughs ⇒ Present-Day voids

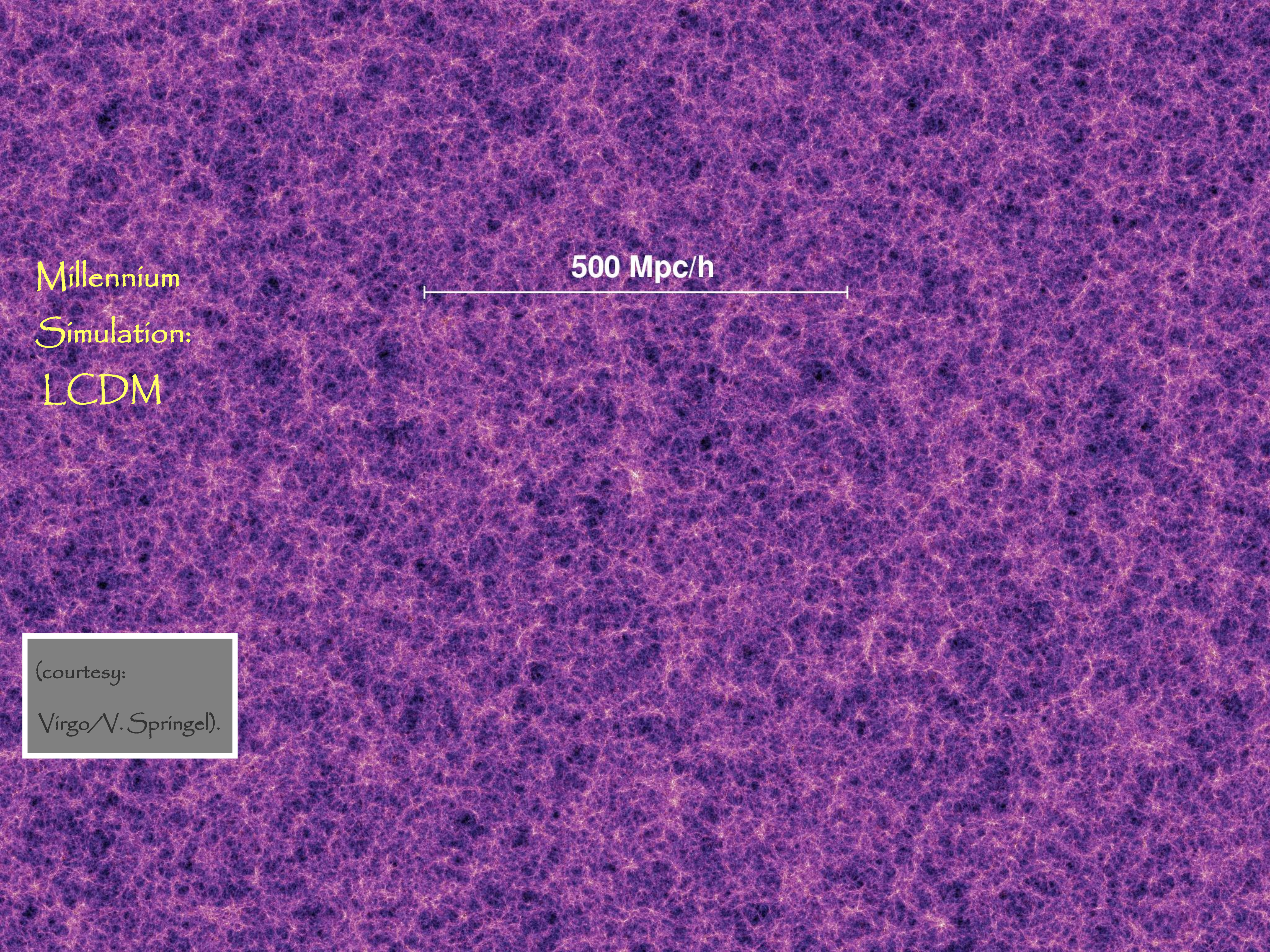


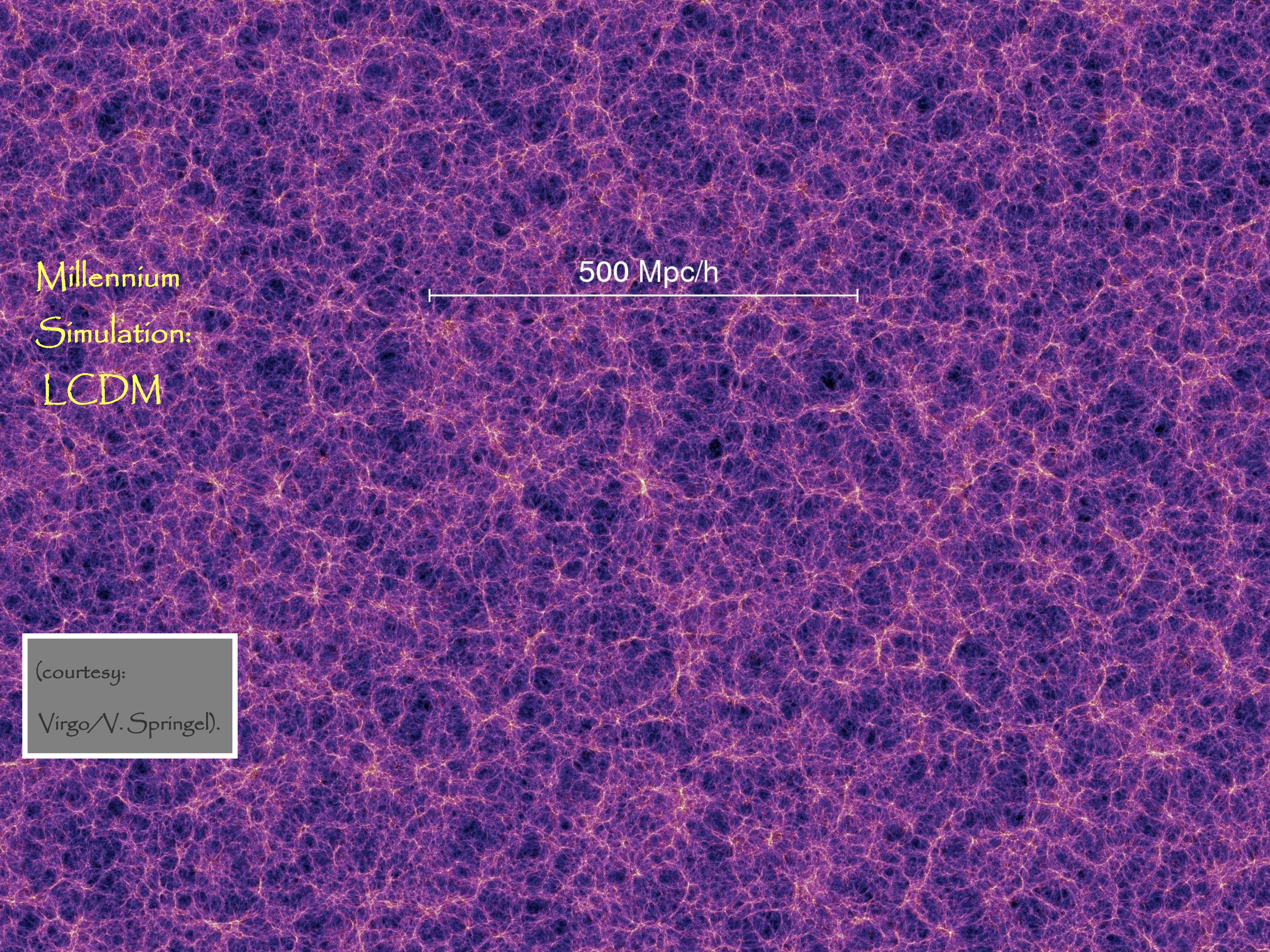
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
50 Mpc/h

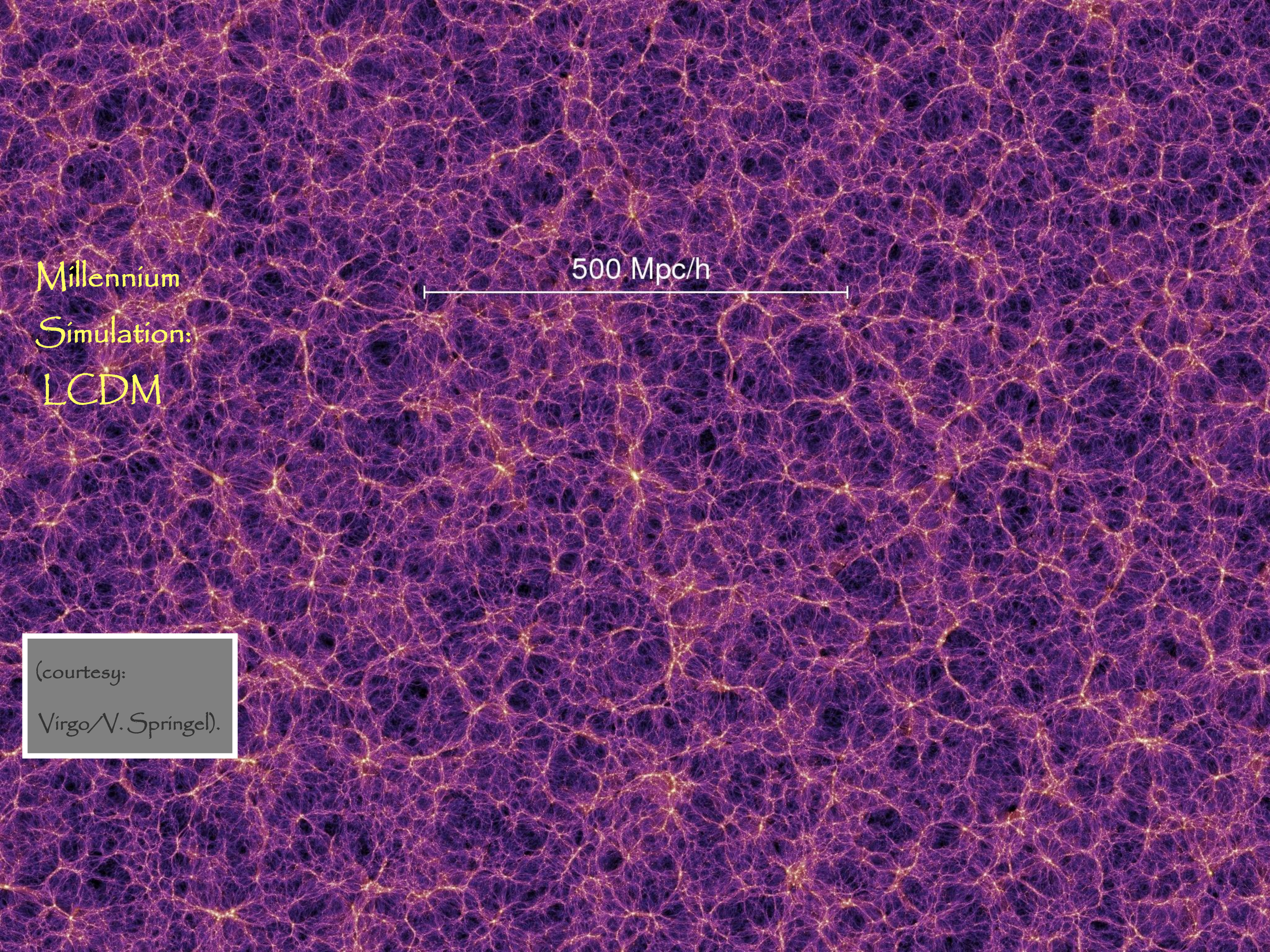
Millennium Simulation

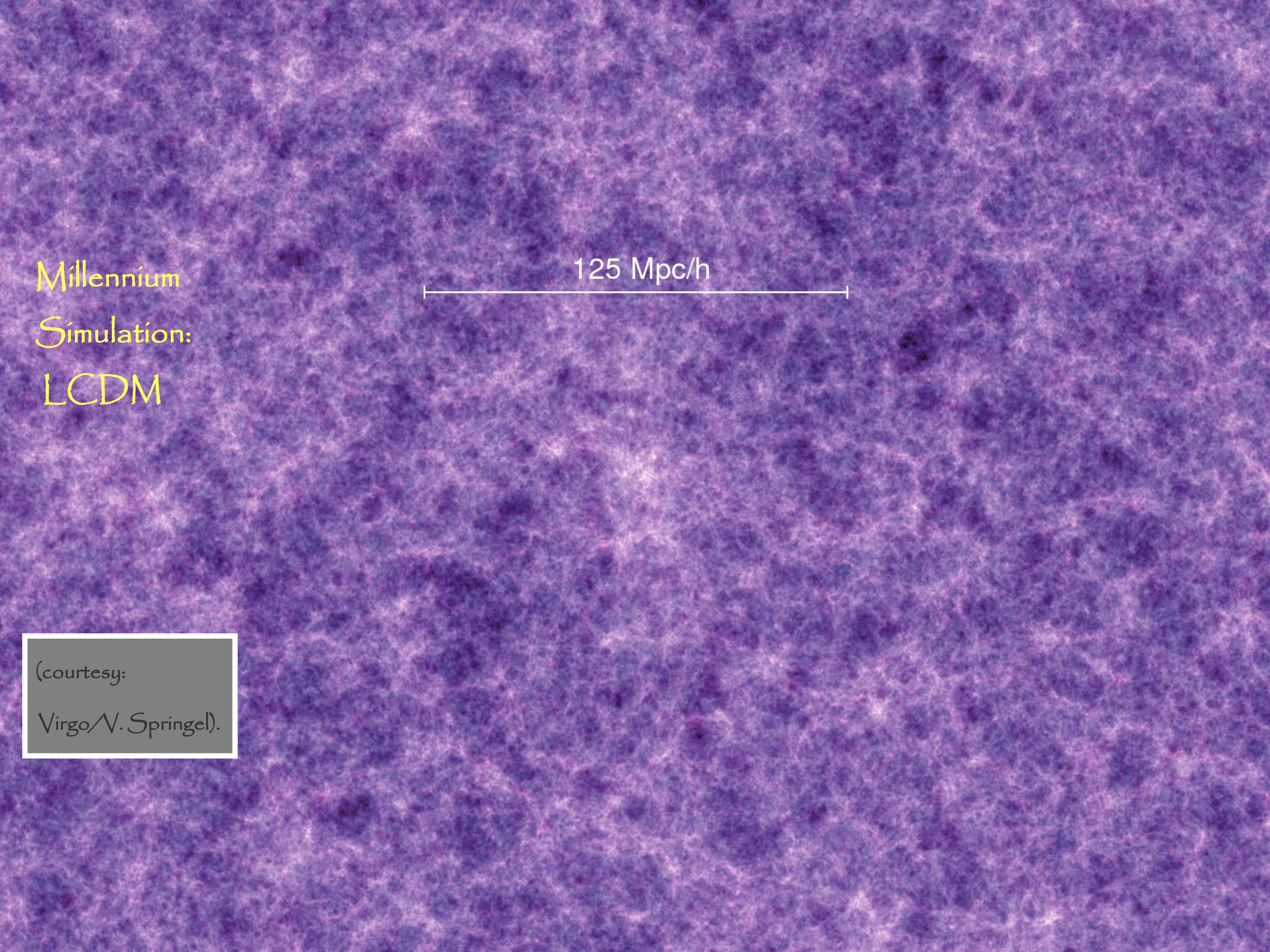
One of the largest N-body computer simulations of structure formation, illustrating the complex and intricate formation process of the "Cosmic Web"

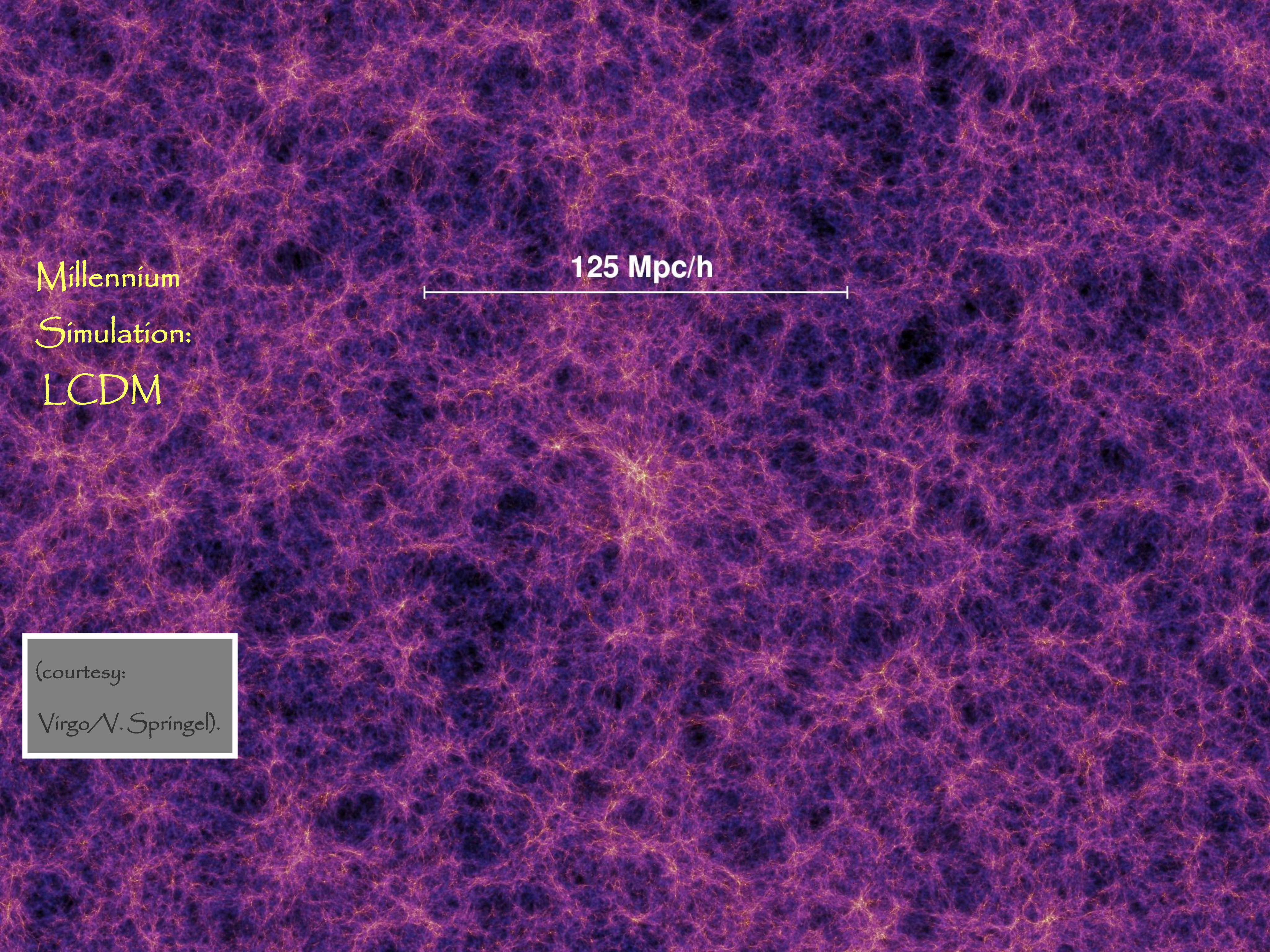

Millennium
Simulation:
LCDM
500 Mpc/h
(courtesy:
Virgo/V. Springel).

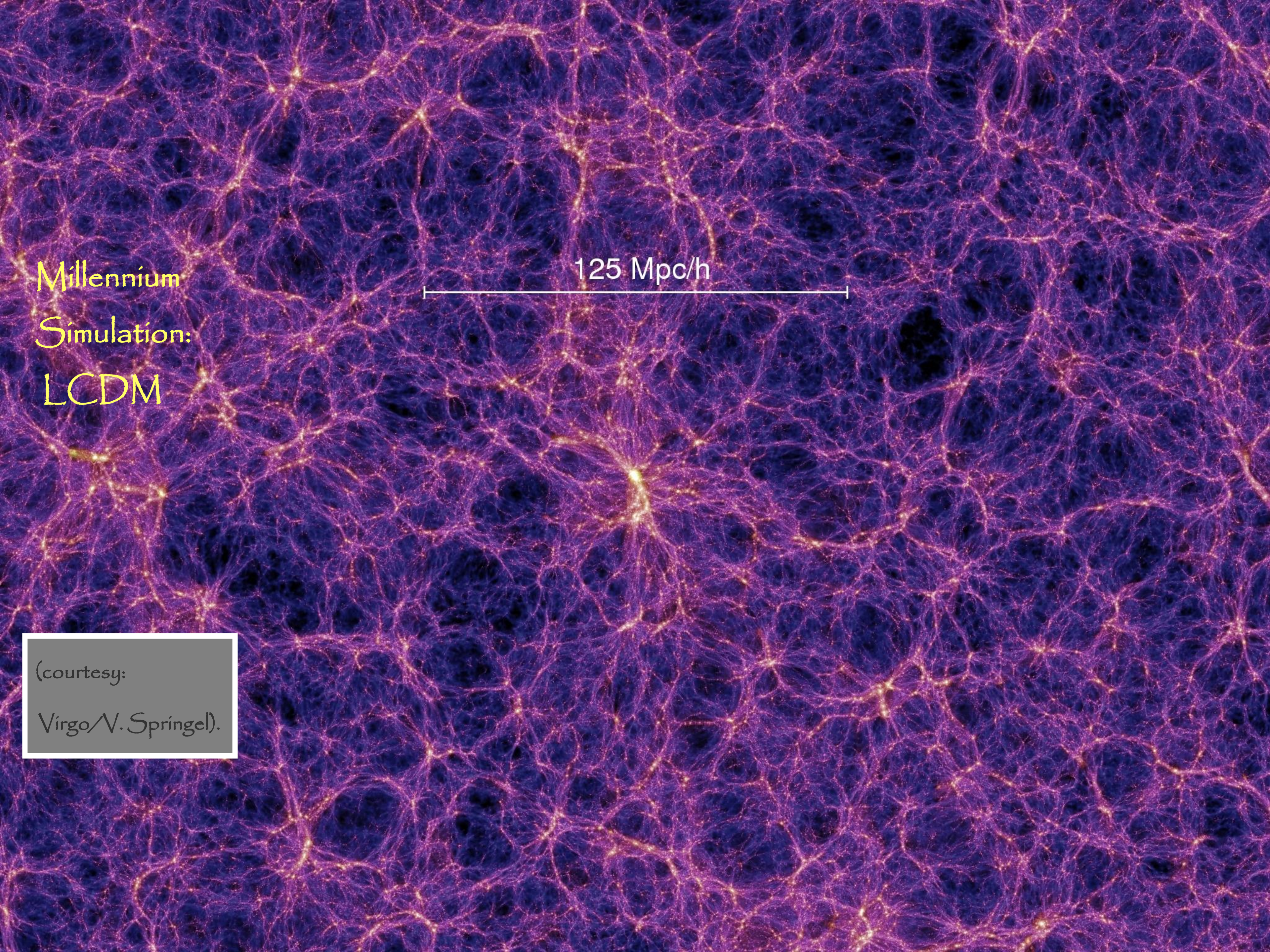

Millennium
Simulation:
LCDM
500 Mpc/h
(courtesy:
Virgo/V. Springel).

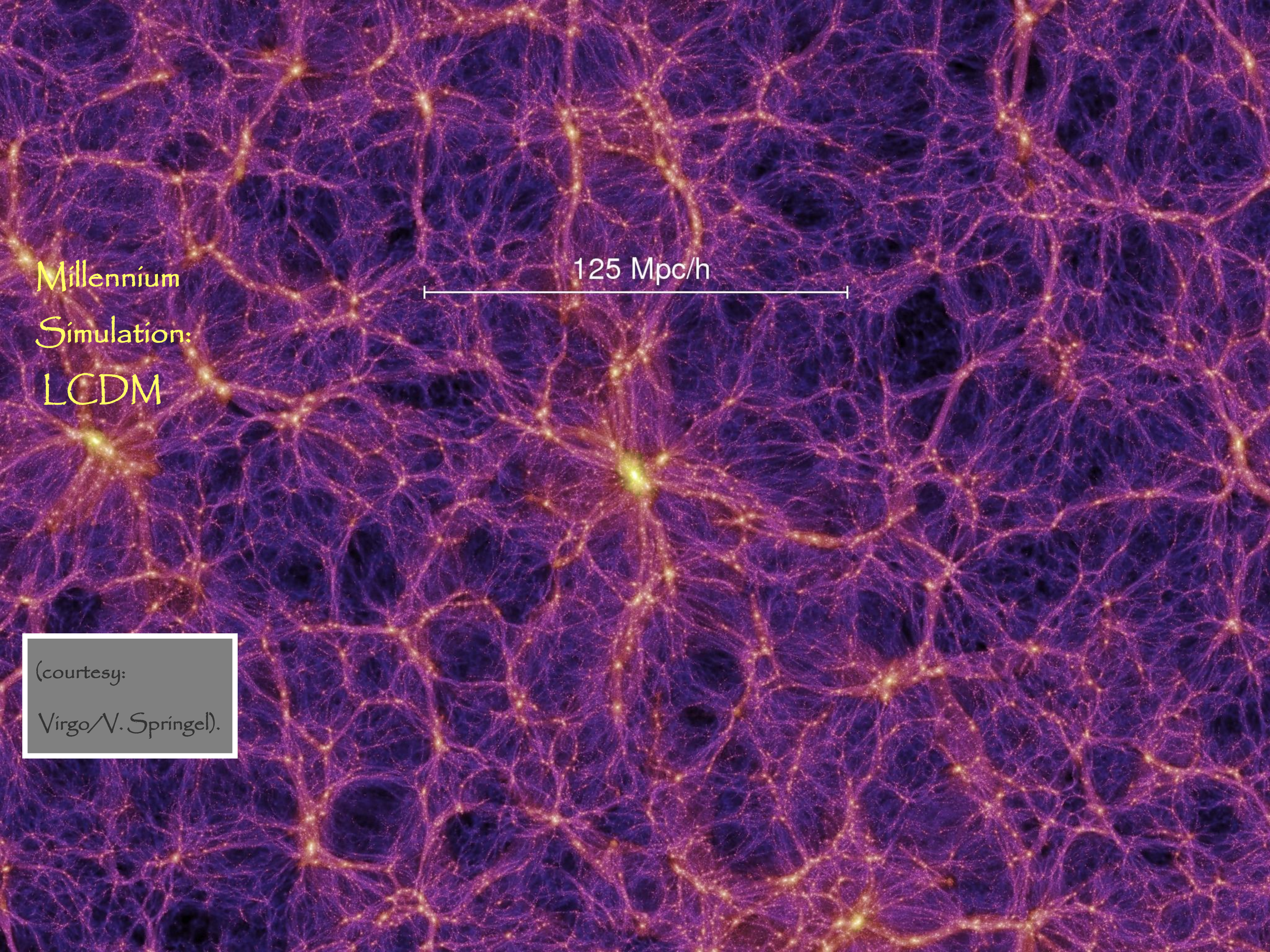

Millennium
Simulation:
LCDM
500 Mpc/h
(courtesy:
Virgo/V. Springel).

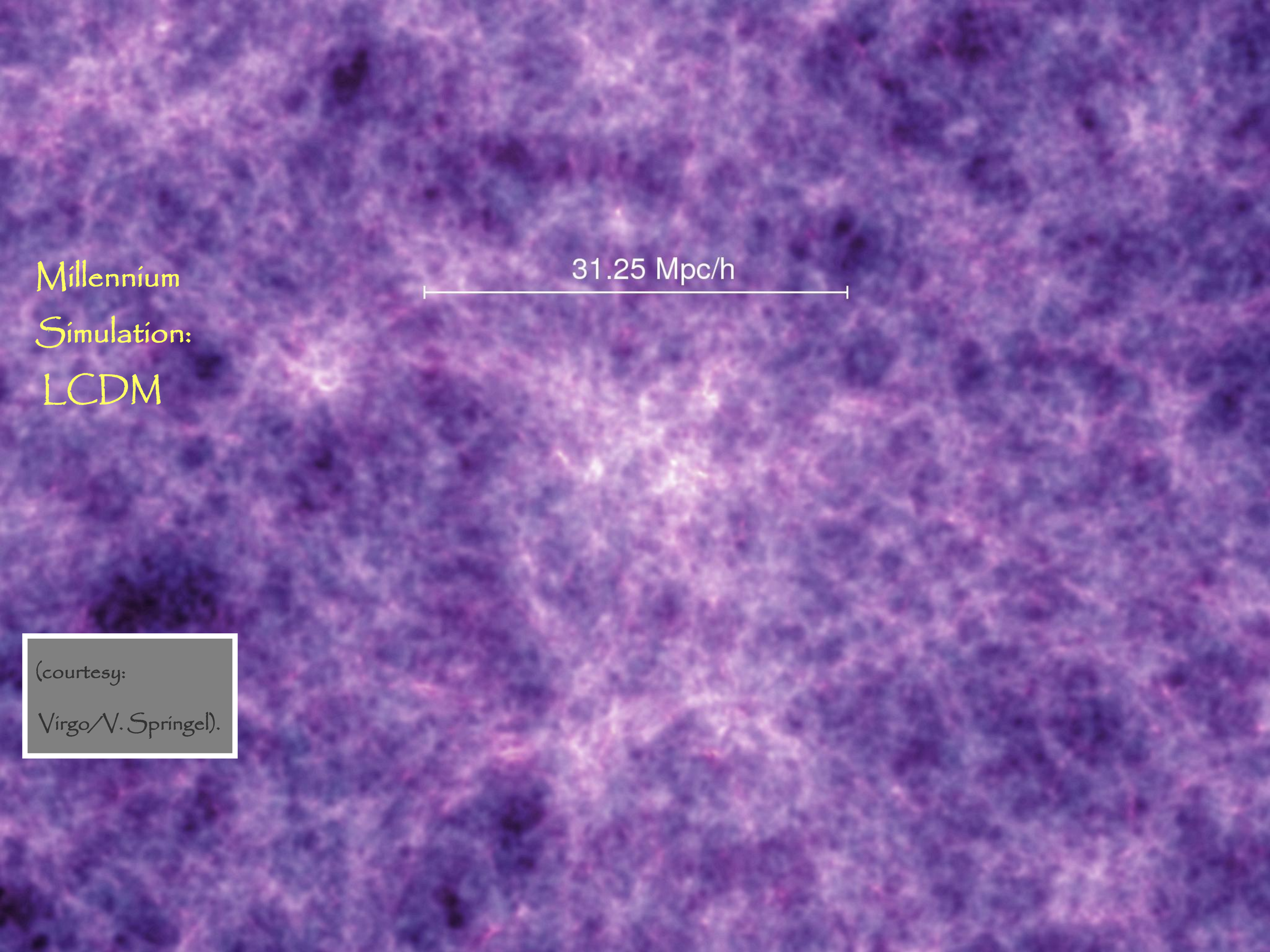

Millennium
Simulation:
LCDM
500 Mpc/h
(courtesy:
Virgo/V. Springel).

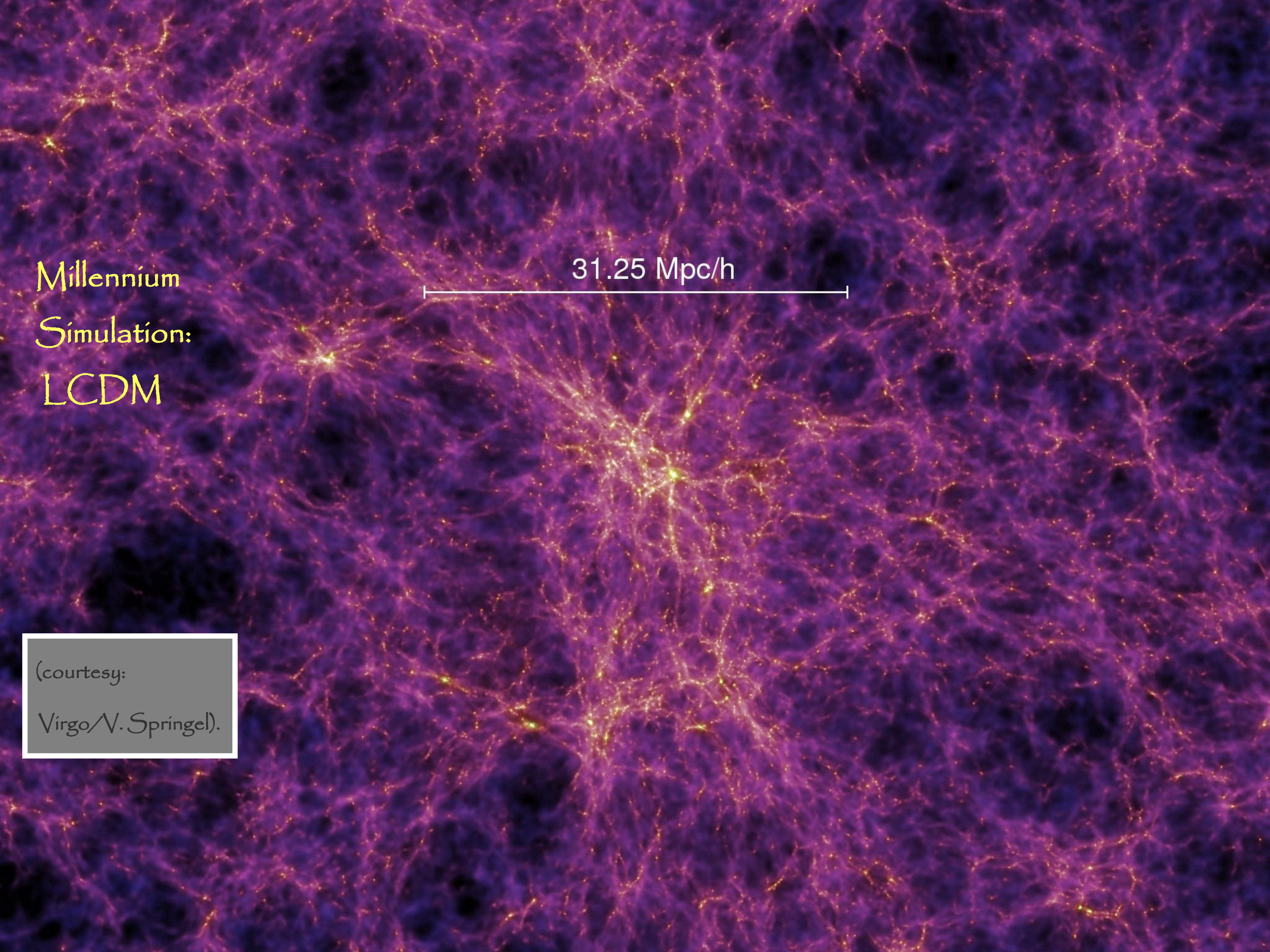

Millennium
Simulation:
LCDM
125 Mpc/h
(courtesy:
Virgo/V. Springel).

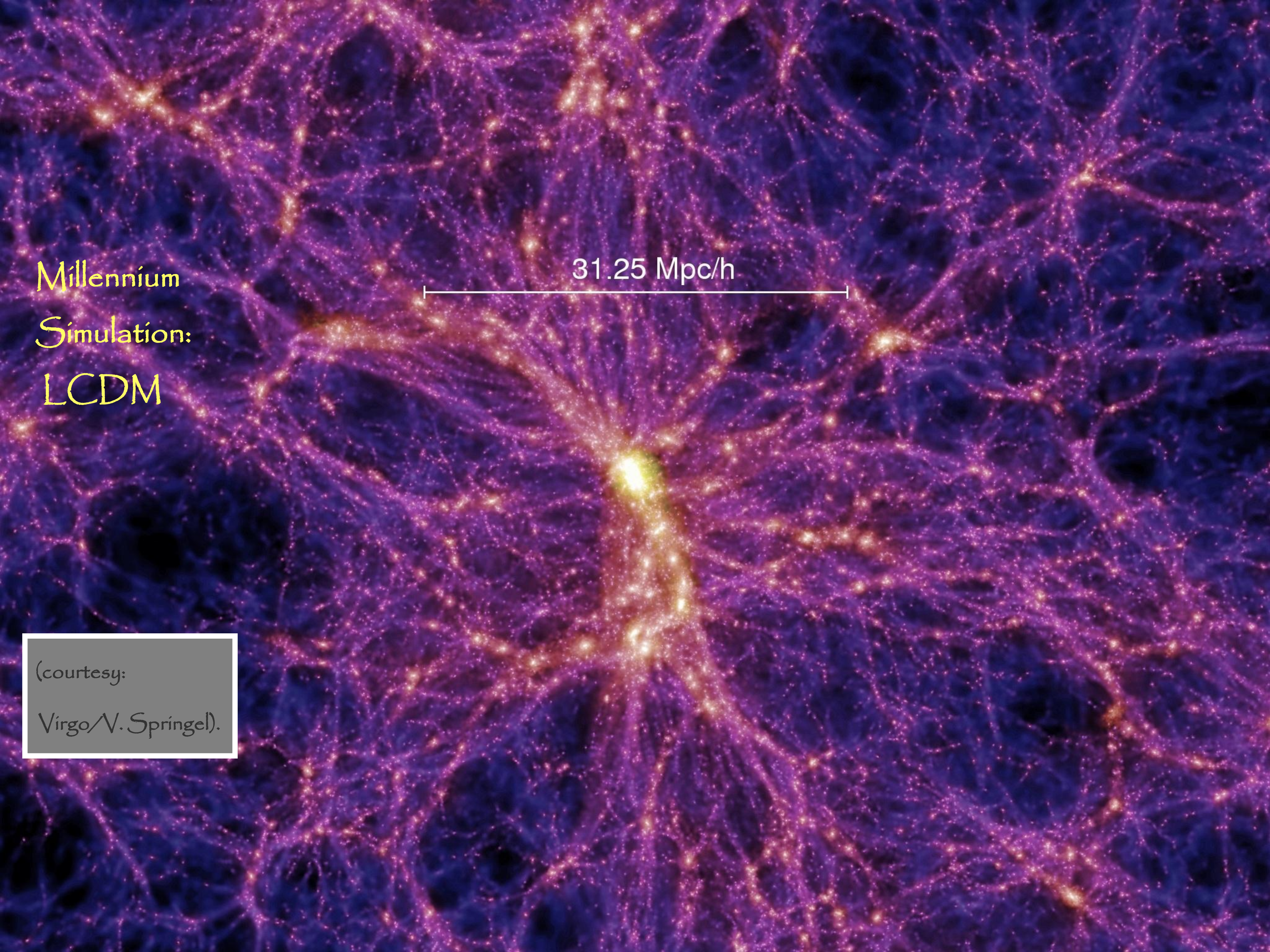

125 Mpc/h
Millennium
Simulation:
LCDM
(courtesy:
Virgo/V. Springel).


Millennium
Simulation:
LCDM
125 Mpc/h
(courtesy:
Virgo/V. Springel).

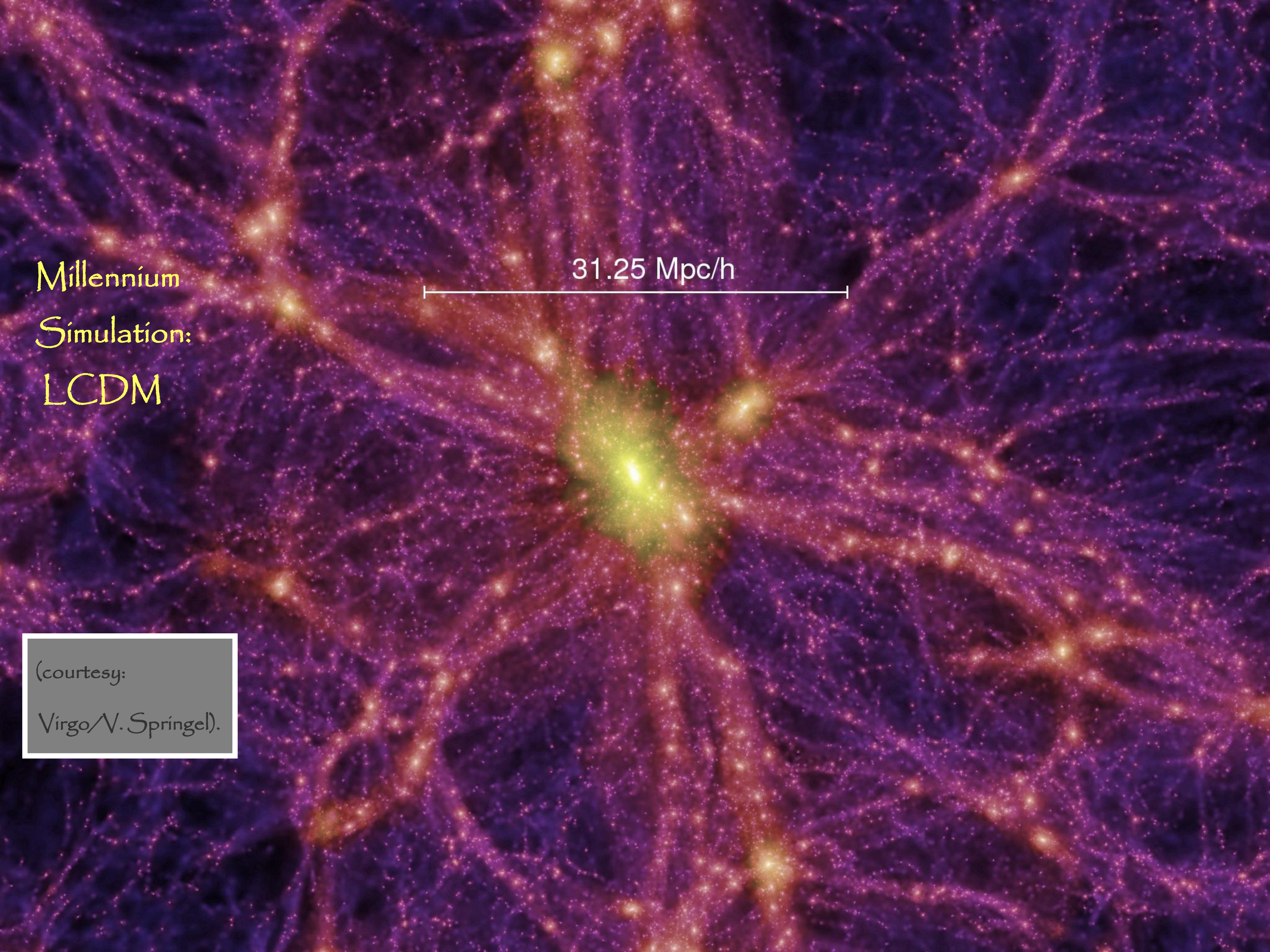

Millennium
Simulation:
LCDM
125 Mpc/h
(courtesy:
Virgo/V. Springel).


Millennium
Simulation:
LCDM
31.25 Mpc/h
(courtesy:
Virgo/V. Springel).


31.25 Mpc/h
Millennium
Simulation:
LCDM
(courtesy:
Virgo/V. Springel).



31.25 Mpc/h
Millennium
Simulation:
LCDM
(courtesy:
Virgo/V. Springel).


Millennium
Simulation:
LCDM
31.25 Mpc/h
(courtesy:
Virgo/V. Springel).

Millenium Simulation, Volker Springel,

Flythrough Movie