Cosmology,

lect. 3a

Cosmological Principle: the Evidence

Cosmological Principle

Before embarking upon an assessment of the reality of the homogeneity and isotropy of our Universe, we first should pay attention to the meaning of these two concepts:

1) Homogeneity

   The same physical circumstances prevail at any location in the Universe. In its broadest context this means:

   - physical quantities like density, temperature, pressure, ...
   - physical laws and relations

2) Isotropy

   The Universe looks the same in whatever direction you look.

Cosmological Principle

1) Homogeneity does not imply Isotropy

In principle it is perfectly possible to have an anisotropic & homogeneous medium:

- eg. more stretched in one direction than in the other, nonetheless exactly the same at every point in space:
- the local anisotropy may be the same everywhere

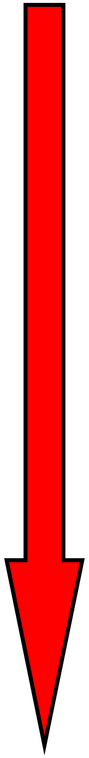
2) Isotropy does not imply Homogeneity

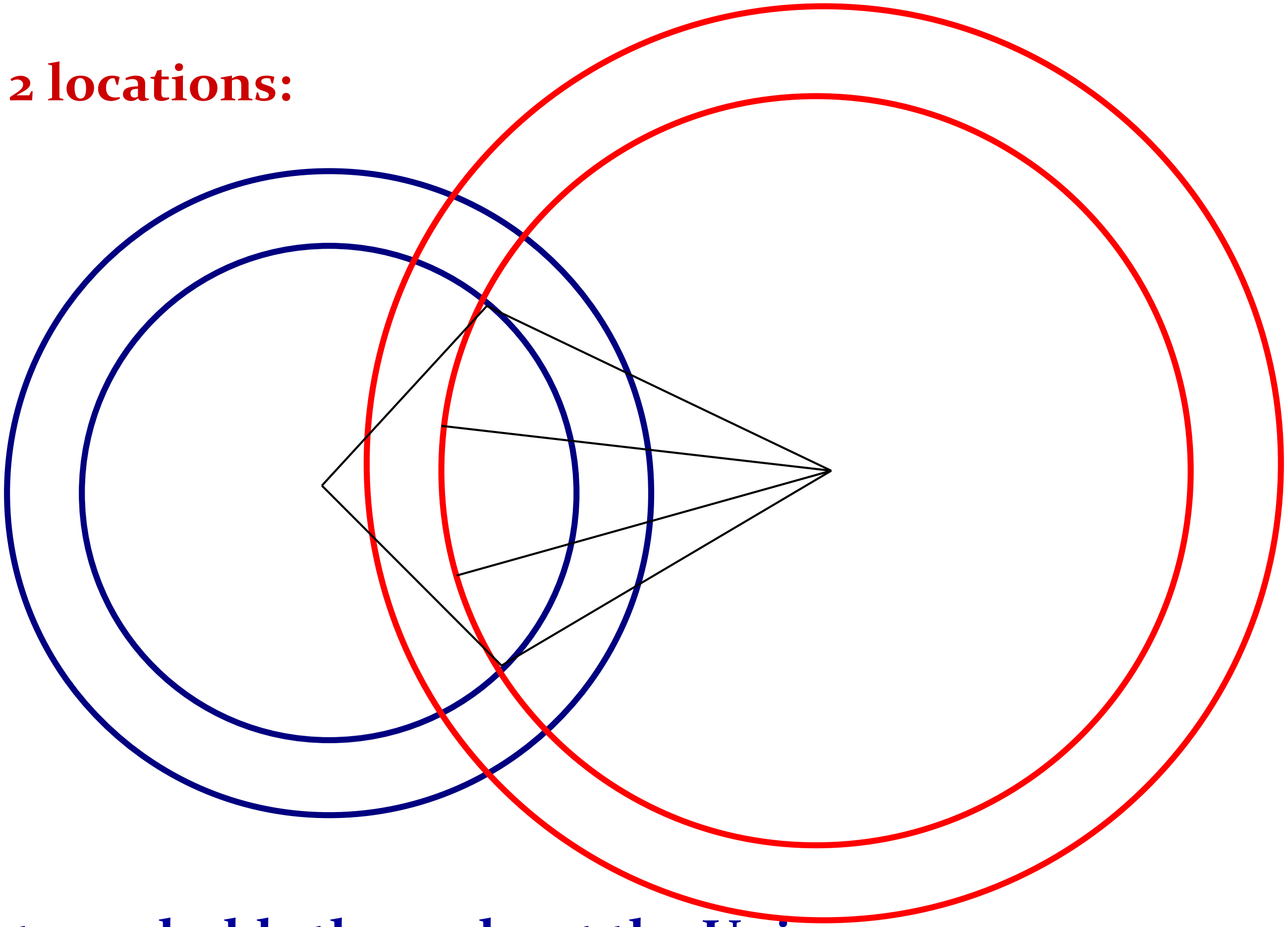
Given we know the Universe only from one vintage point, our cosmic location, we cannot be sure that our conclusion of isotropy is universilly valid:

- however, it violates our Copernican feelings
- however, if you would know isotropy to hold for 2 locations, homogeneity and isotropy holds throughout the Universe

Cosmological Principle

Knowing isotropy for 2 locations:





Homogeneity and isotropy holds throughout the Universe

Cosmological Principle

While the "homogeneity" and "isotropy" of the Universe at first sight might occur like rather crude approximations of reality, there is ample evidence that on scales exceeding a few hundred Mpc it is a reasonably accurate description of reality.

In the following we will list the observational evidence for

1) an isotropic Universe
2) a homogeneous Universe

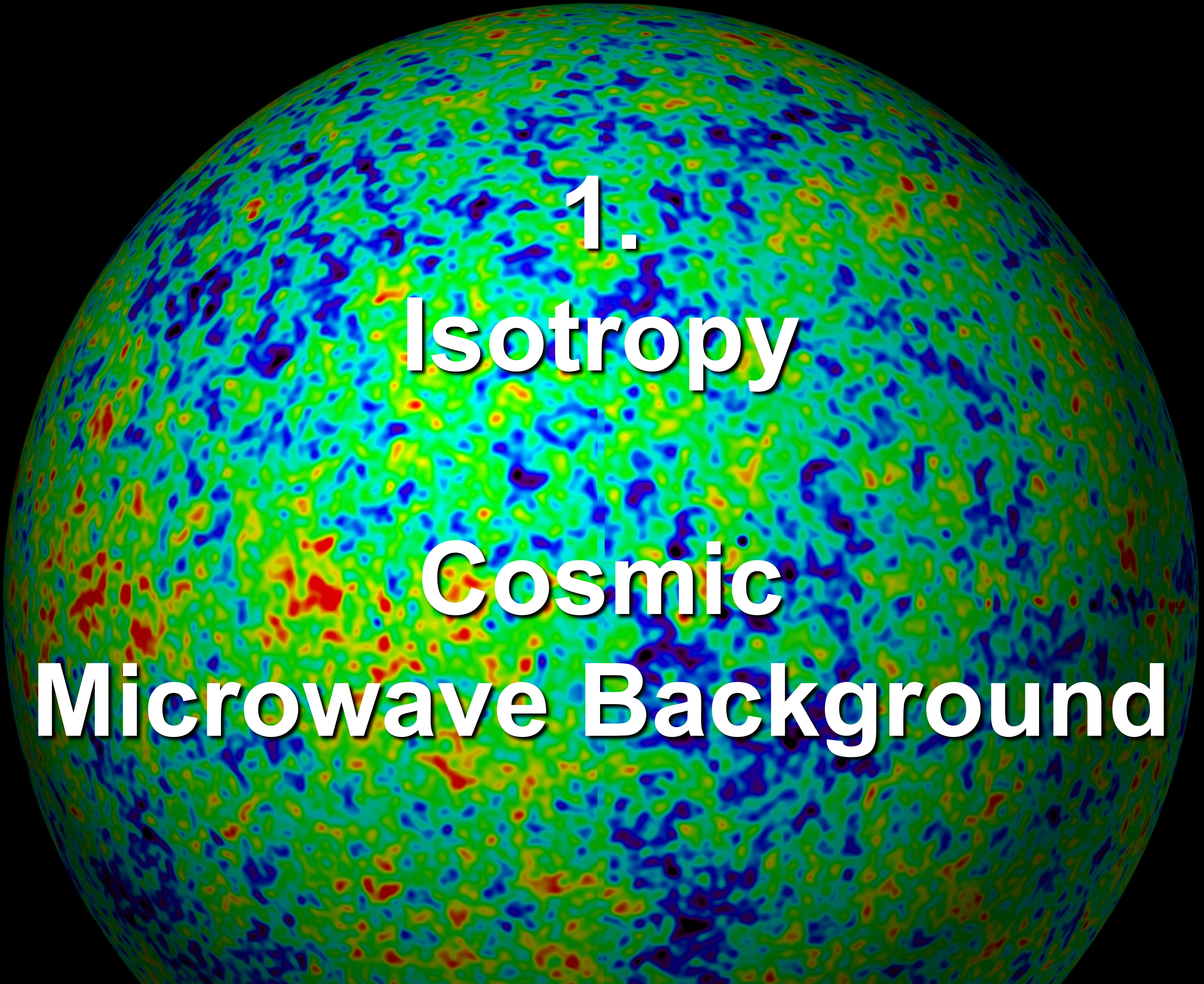
Isotropy

Prime Evidence for an Isotropic Universe:

1) **Isotropy** Cosmic Microwave Background
2) **Isotropy** X-ray Background
3) **Isotropy** Gamma Ray Bursts (GRBs)
4) **Isotropy** Galaxy Sky Distribution

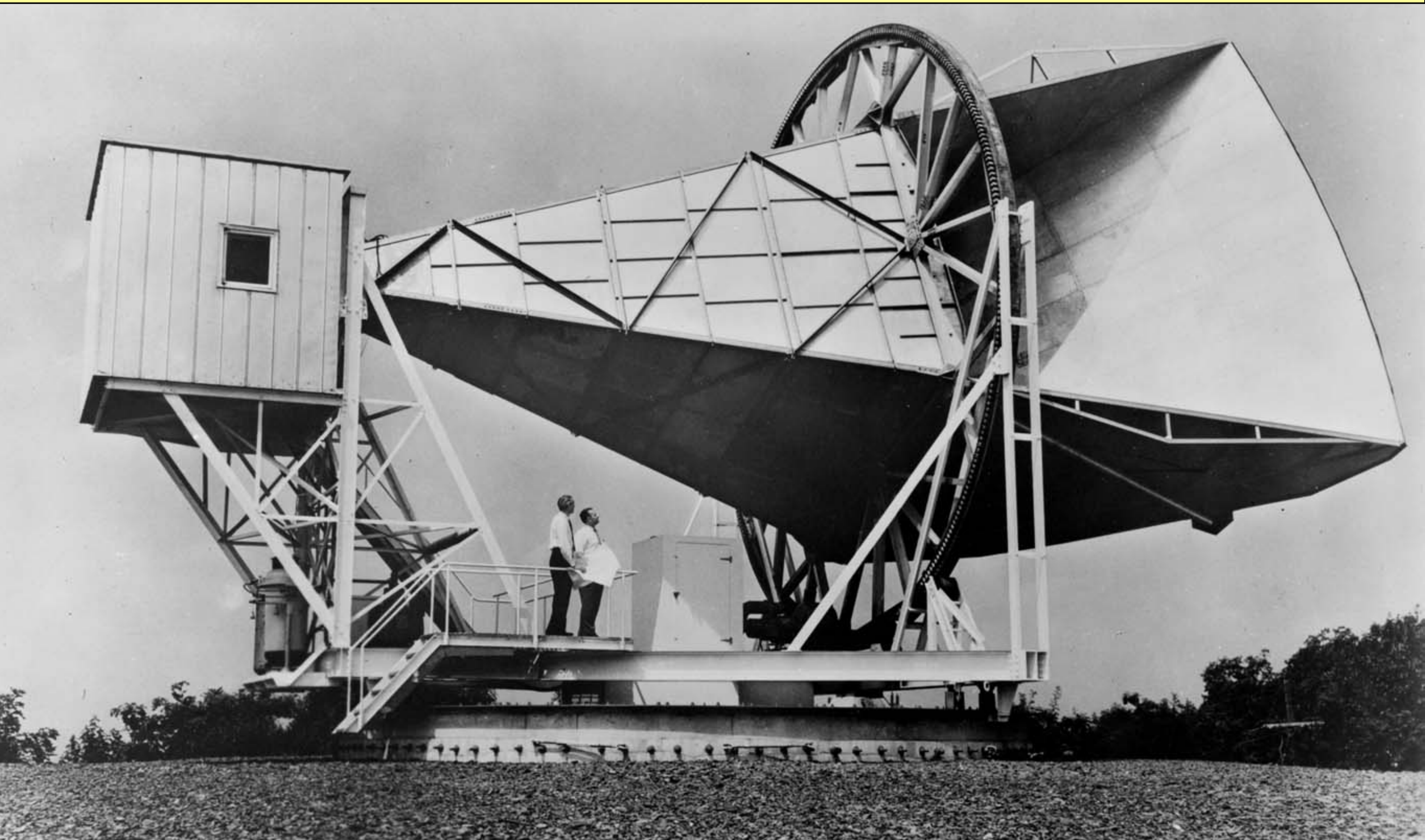
   (on cosmologically relevant scales)

5) **Isotropy** Hubble Expansion


1.
Isotropy
Cosmic
Microwave Background

Cosmic Microwave Background

discovery: 1965 (Penzias & Wilson)



Cosmic Microwave Background

Radiation Field of the Universe:

0) Discovered in 1965 (serendipitously) by Penzias & Wilson,

Nobelprize 1978 !!!!!

- Thermal radiation pervading throughout the whole Universe
- As yet it has a temperature of

$$T_\gamma = 2.725 \text{ K}$$

1) By far CMB photons represent the most abundant species in the Universe:

$$n_\gamma \sim 415 \text{ cm}^{-3}$$

- For comparison: $n\gamma/n_B \sim 1.9 \times 10^9$!!!! (second: cosmic neutrino's)
- Stellar photons: negligible !!!! (integrated over all stars at all times !)

Universe

379,000 years after Big Bang

almost perfectly smooth

Microwave Background Radiation, surface of last scattering of cosmic photons is almost perfectly isotropic, all around the same temperature:

T=2.725 K

Cosmic Microwave Background (CMB) isotropic to almost absurdly accurate levels

- The primary evidence for Isotropy Universe

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

for comparison:

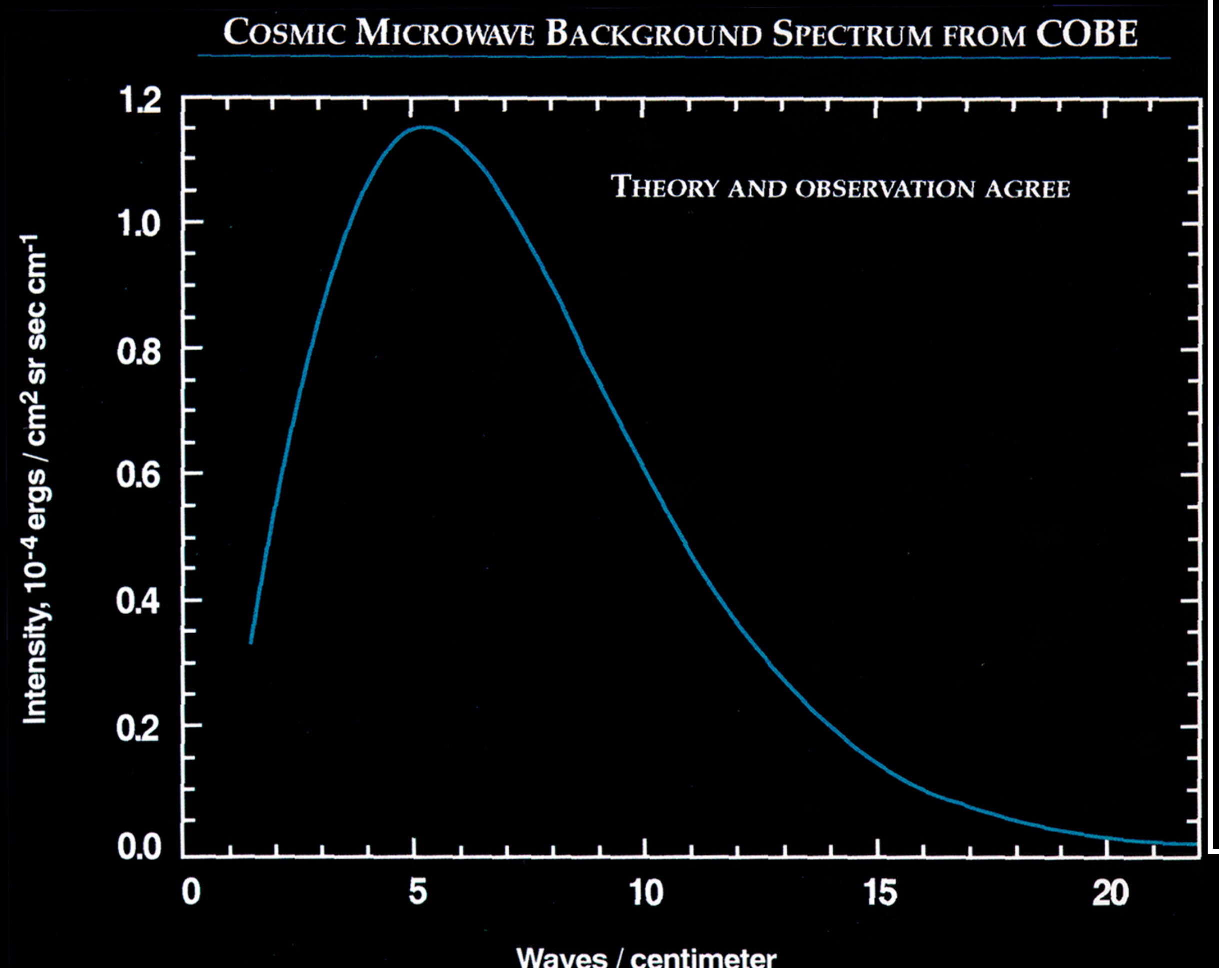
Planet Earth's

highest mountain

would be ~ 25-100 m !!!!!!!

CMB Blackbody Radiation Field:

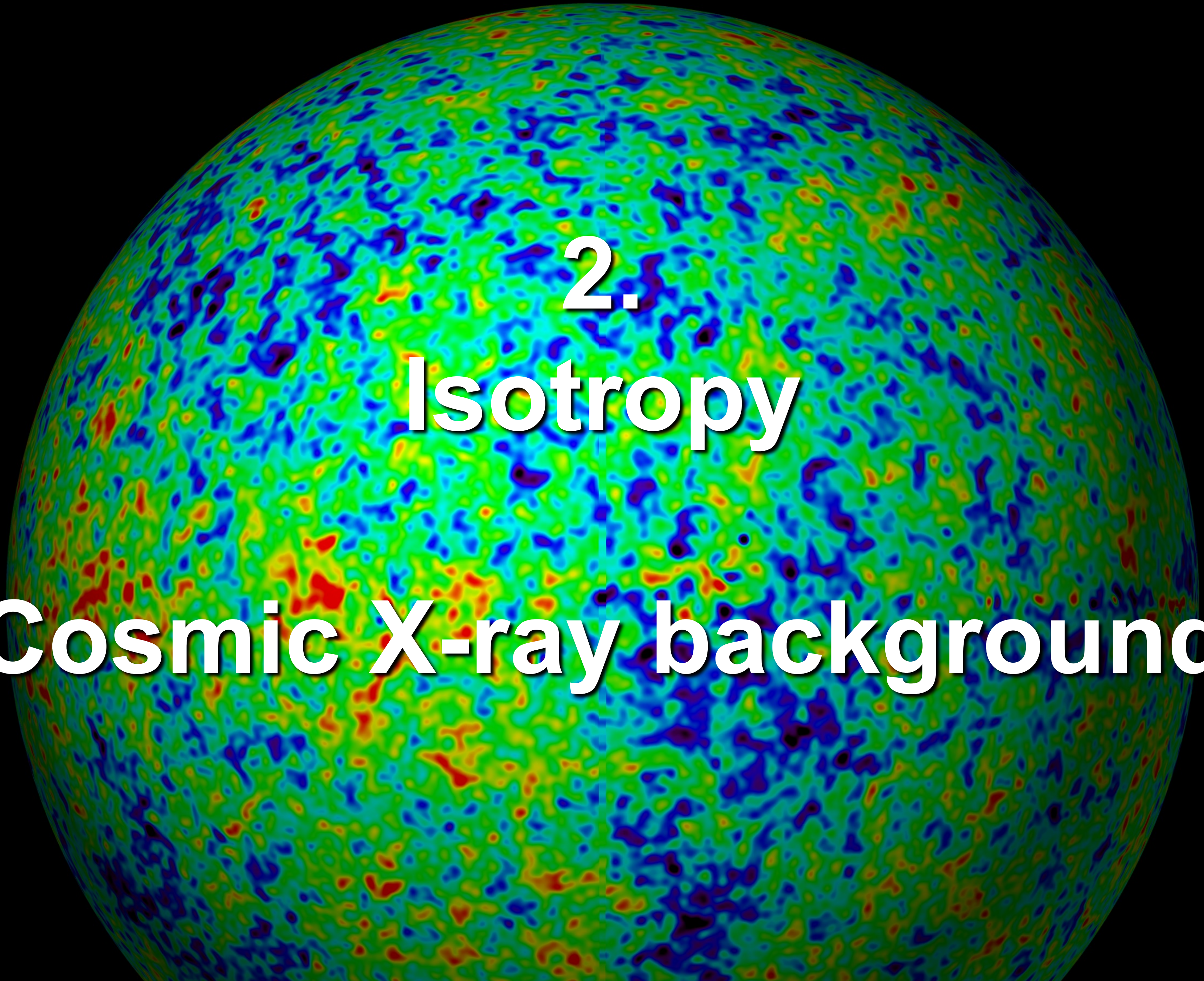
Ultimate Evidence Big Bang



- COBE-DIRBE
  (John Mather: Nobel prize 2006): perfect blackbody spectrum
- T=2.735 K

$$I_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

- most accurately known Black Body radiation field in nature

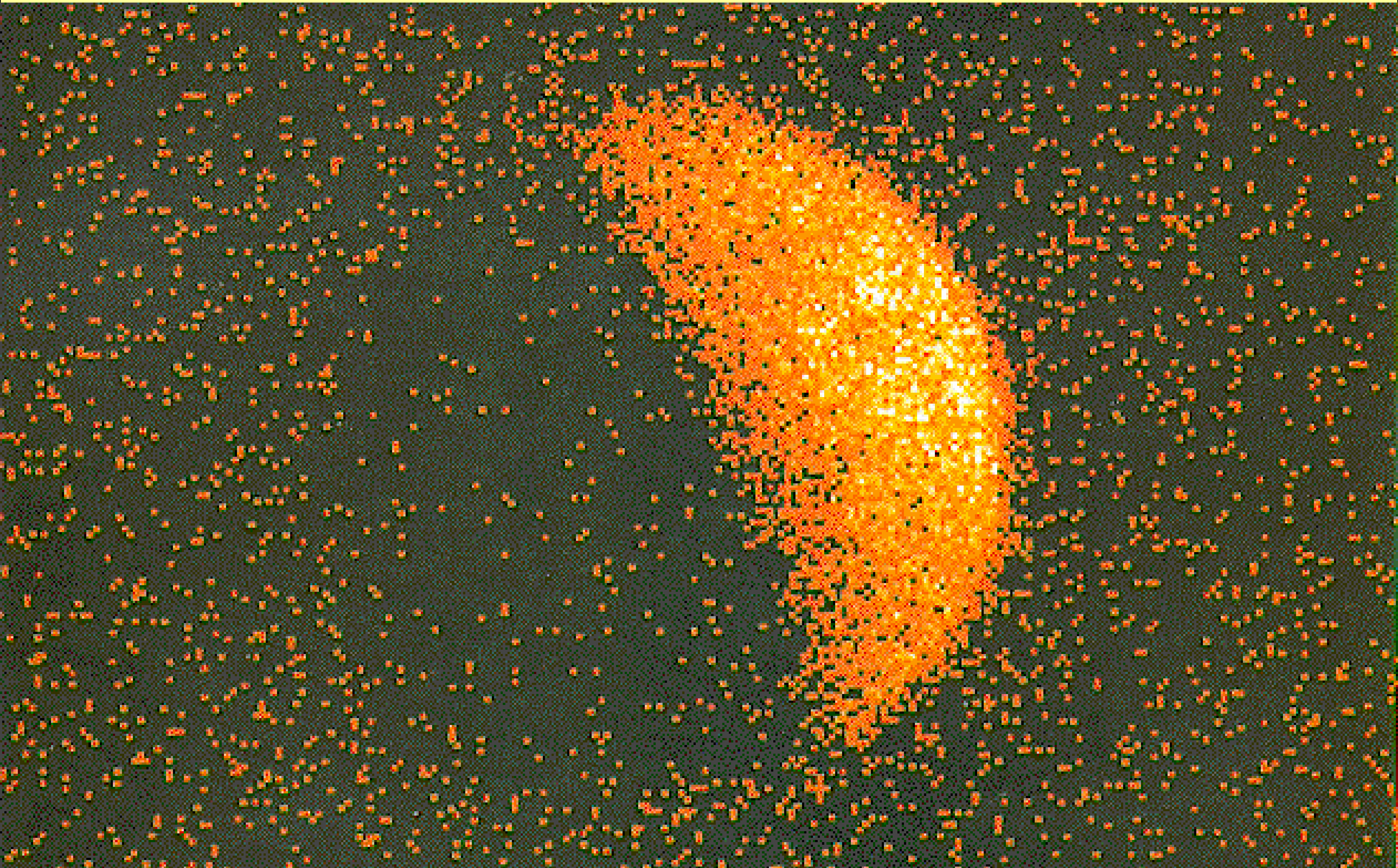

2.
Isotropy
Cosmic X-ray background

X-ray background

- The sky glows in X-rays in every direction, the X-ray Background
- discovered ~ 1962 (Giaconni), soon after launch first X-ray satellites.
- For many years its origin was not understood, possibilities were:
  - (very) hot diffuse gas (T ~ 0.2 x 10^9 K)
  - population of unresolved active centers of galaxies, AGNs, thus probably involving Massive Black Holes, most probably at z ~ 2-3
- Riddle mostly solved following launch of the Chandra & XMM X-ray observatories:
  - at least 80 percent of diffuse hard X-ray background resolved into very many very faint (and distant) sources

!!!!!!!! X-RAY BACKGROUND HIGHLY ISOTROPIC !!!!!!!

Moon & X-ray background



Moon & X-ray background

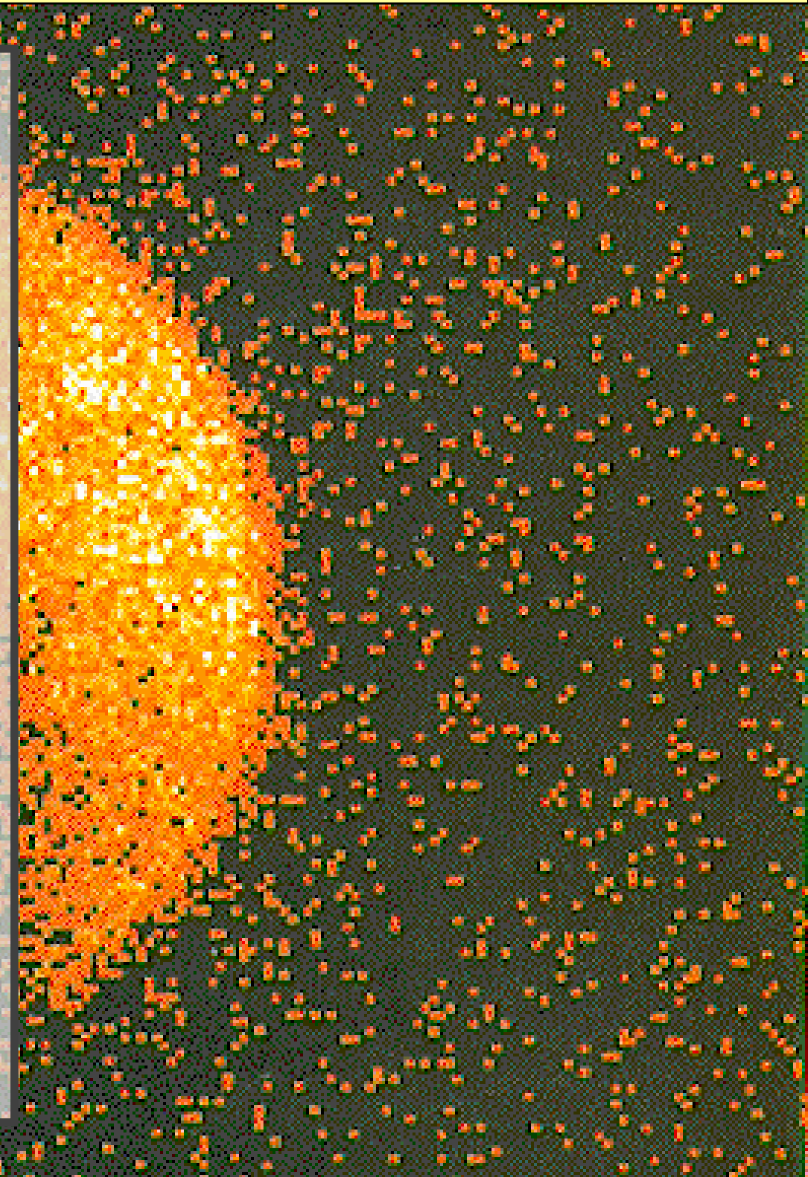
X-ray image of Moon by ROSAT (1990)

(pixel brightness: x-ray intensity)

Three different parts:

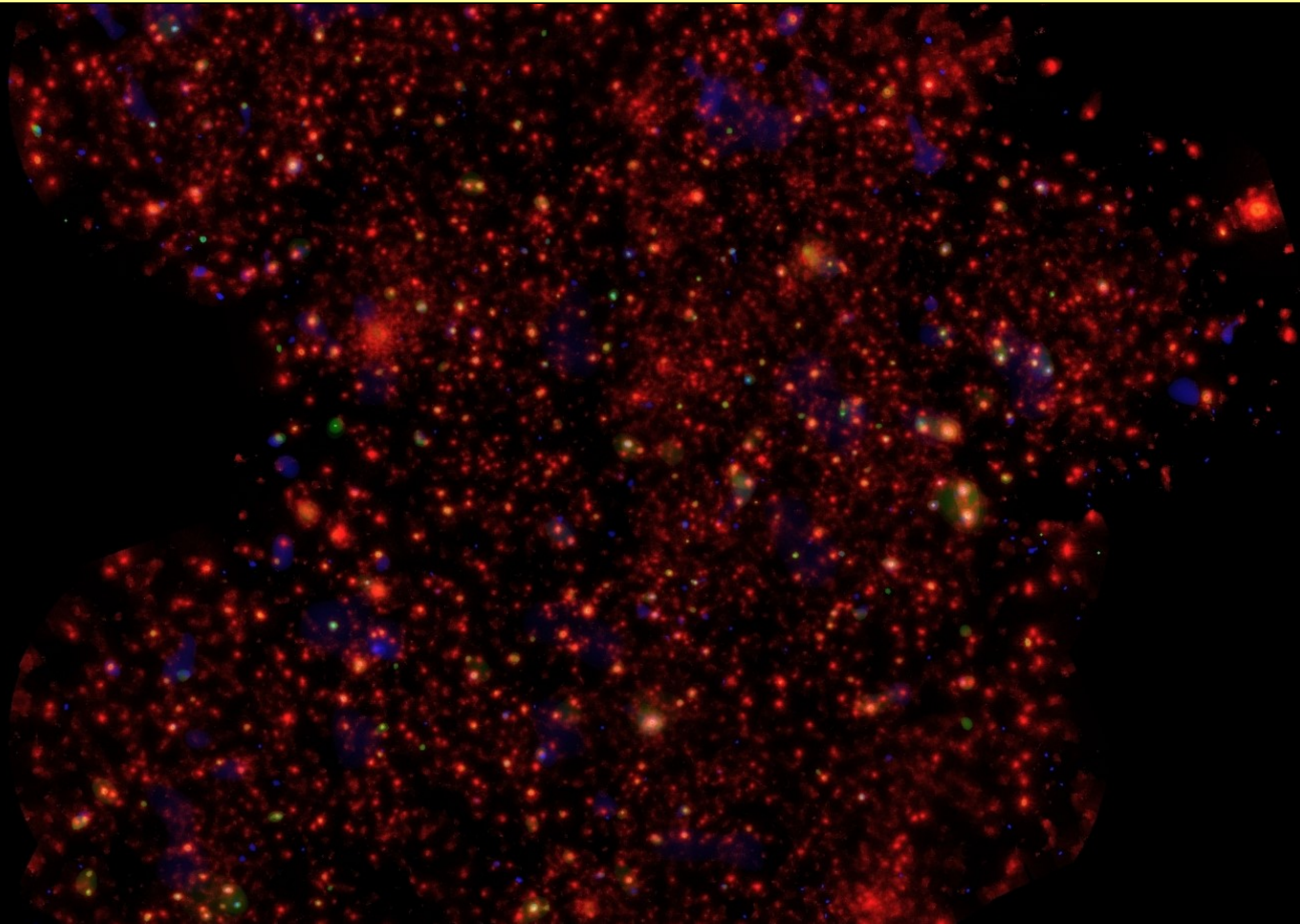
- bright part: X-ray moon
  scattered x-rays emitted by Sun
- dark half moon
  visible few photons originate in
  Earth's geocorona & extended atmosphere
- X-ray sky background
  myriad of distant, powerful active galaxies
  unresolved in ROSAT image,
  80% detected by Chandra

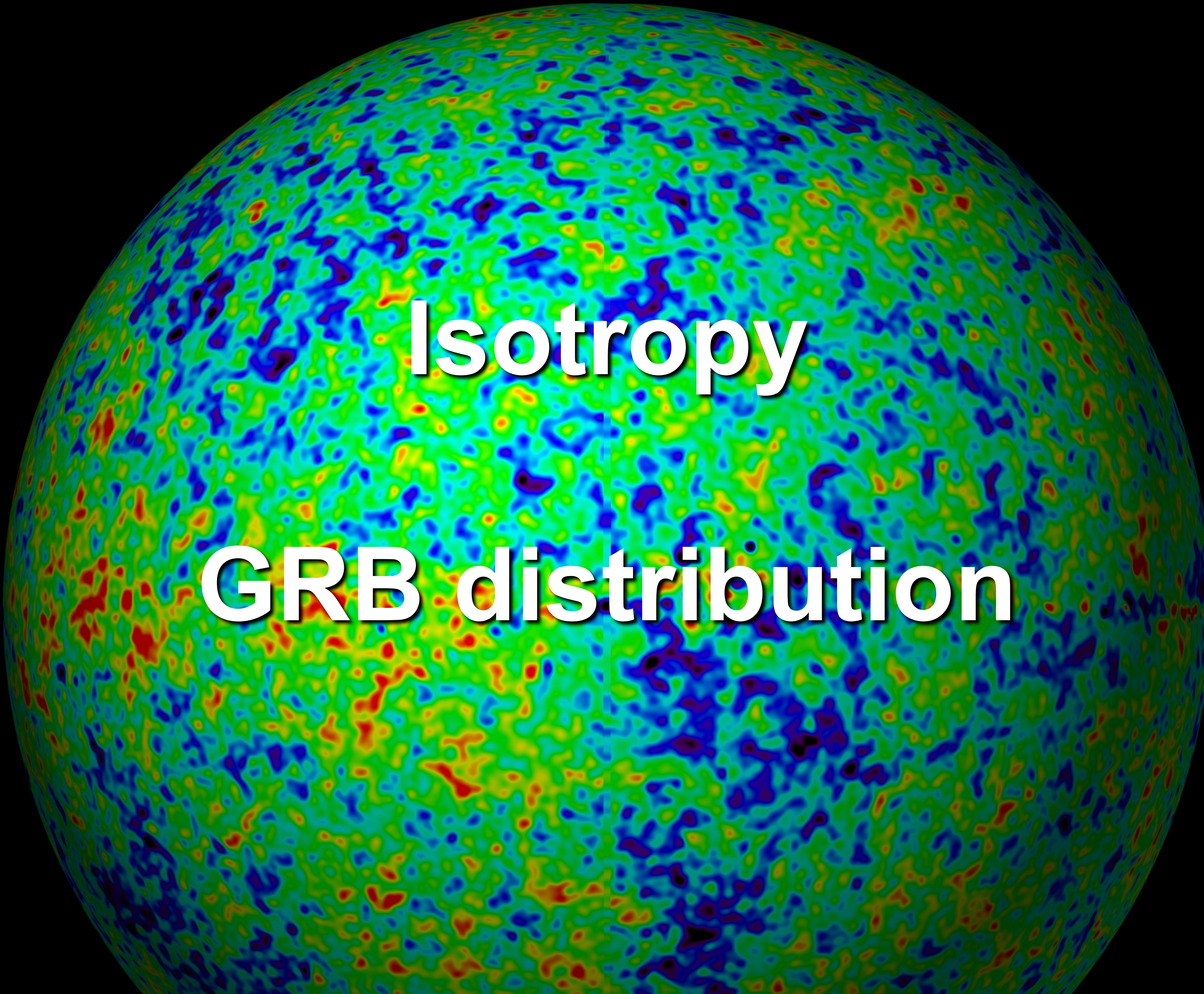
.



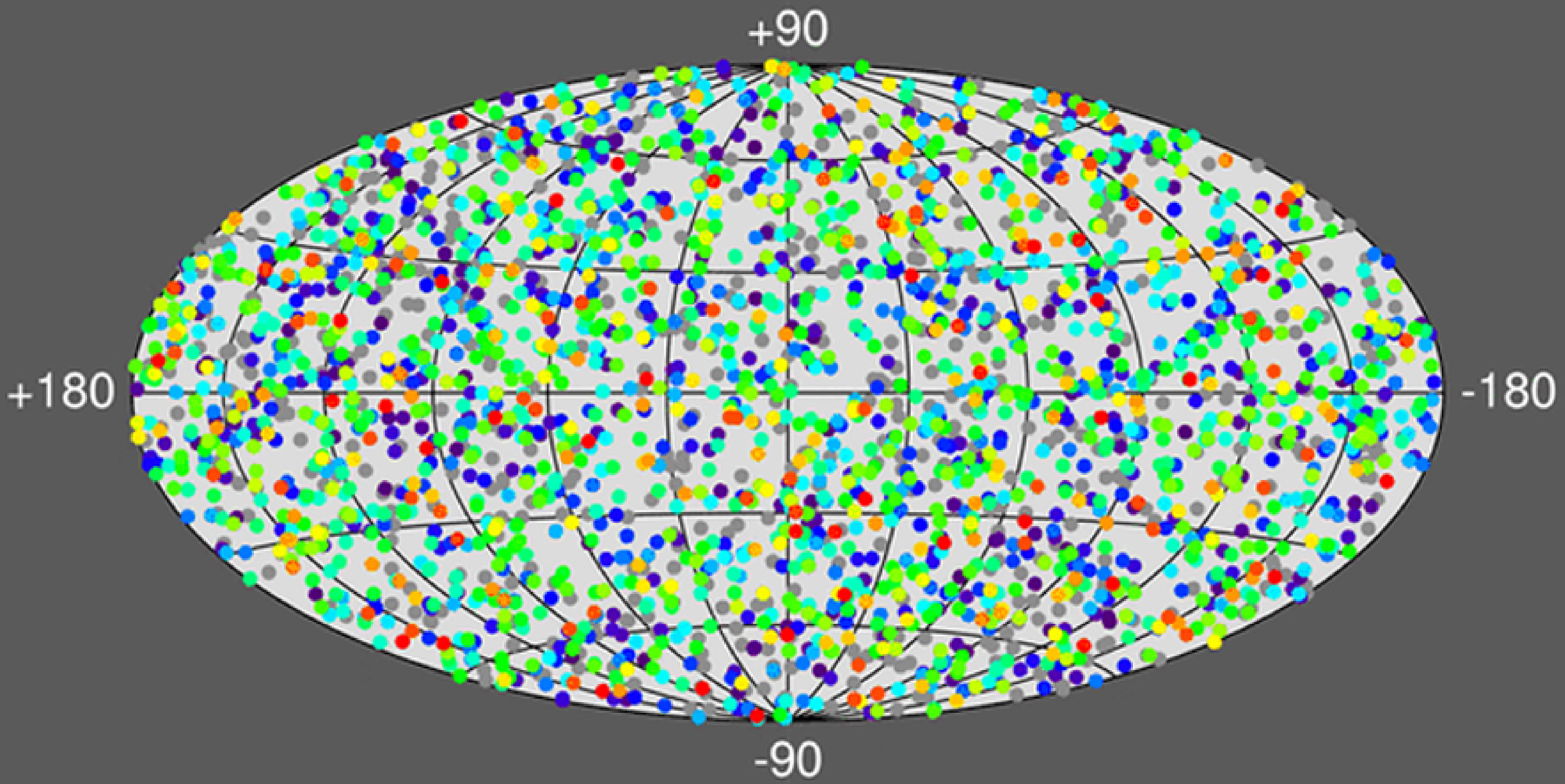
X-ray background:

high-z AGNs




Isotropy
GRB distribution

Gamma Ray Burst (GRB) sky distribution



Angular Distribution GRBs:

2704 BATSE GRB sources

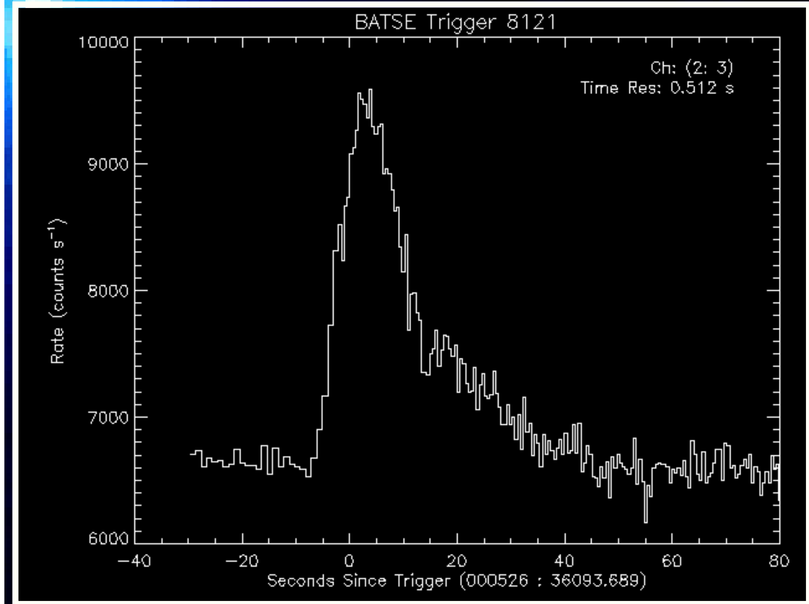
Gamma-ray Bursts

- **Brilliant flashes of γ-ray emission,**
  from ~ msec – several 10s of seconds
  followed by afterglows of X-ray, optical & radio emission
- **per day, ~ 1 GRB over entire Universe**
- **Most energetic events since Big Bang,~ 10^{54} ergs:**
  at peak emission ~ energy all galaxies in visible Universe
- **Emission most likely highly collimated: GRB jets**

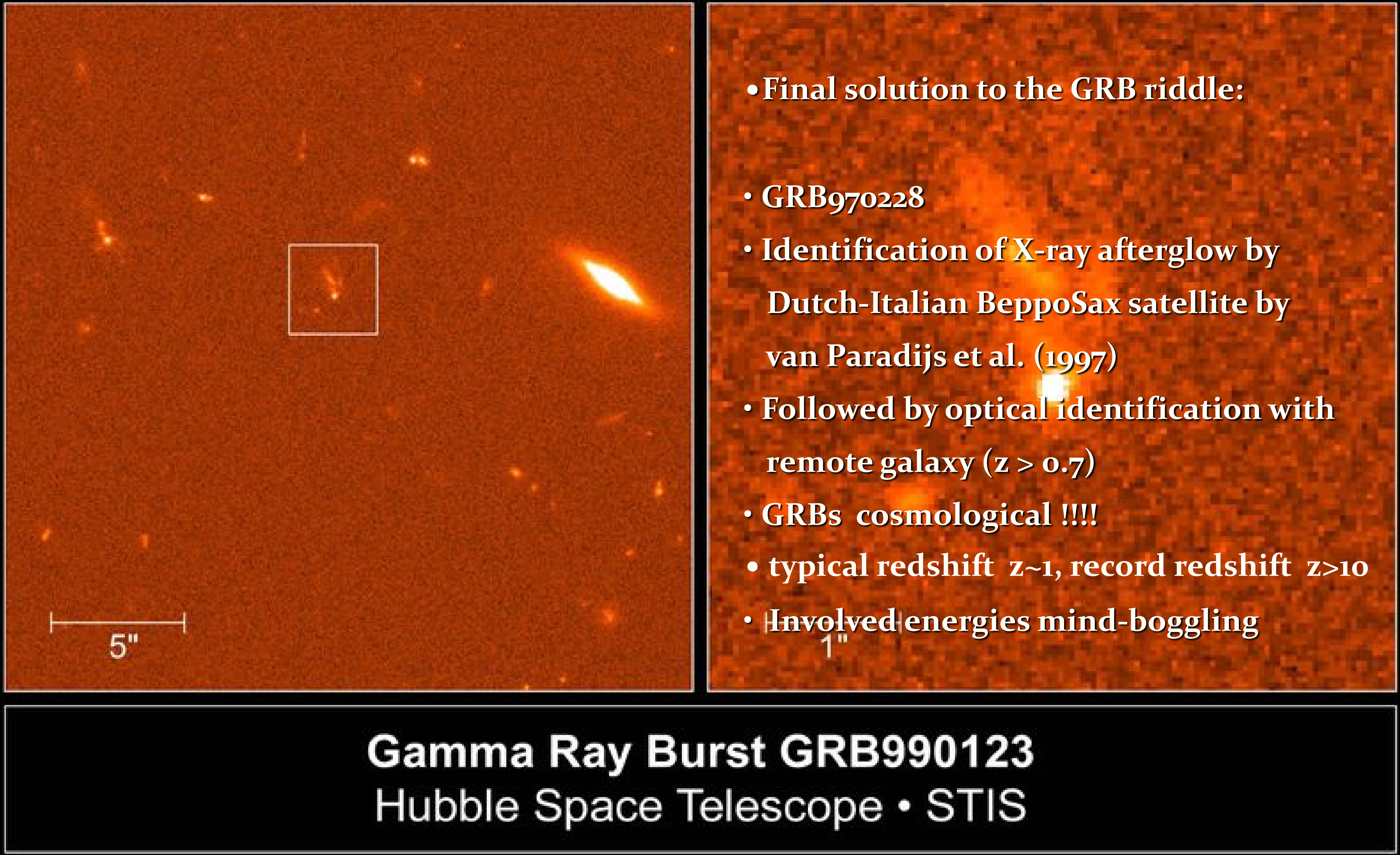
- **Discovered end of 60s by US Vela nuclear test detection satellites, testing for Soviet breaks of Nuclear Test Ban Treaty.**
  Kept classified for years, public release in 1973:
  cosmic origin

- **BATSE instrument on board of the Compton Gamma Ray Observatory (1990s):**

  2704 GRB detections



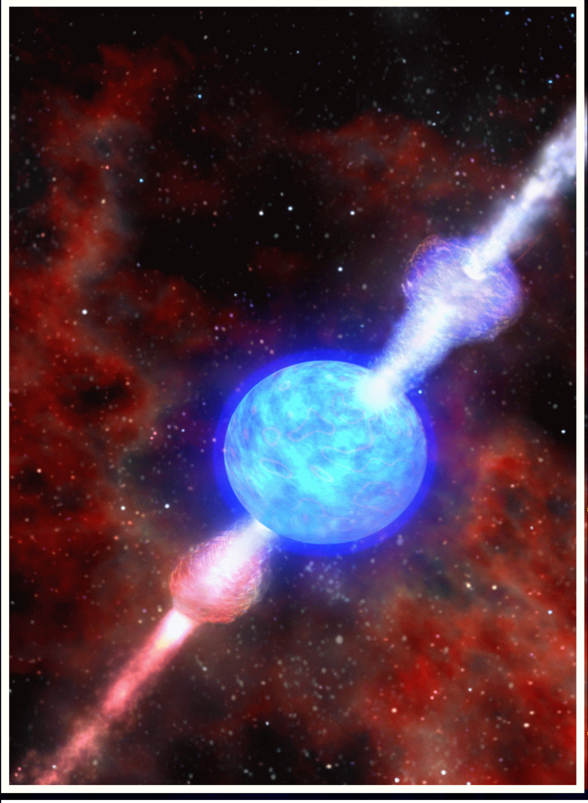
Cosmological Identity GRBs

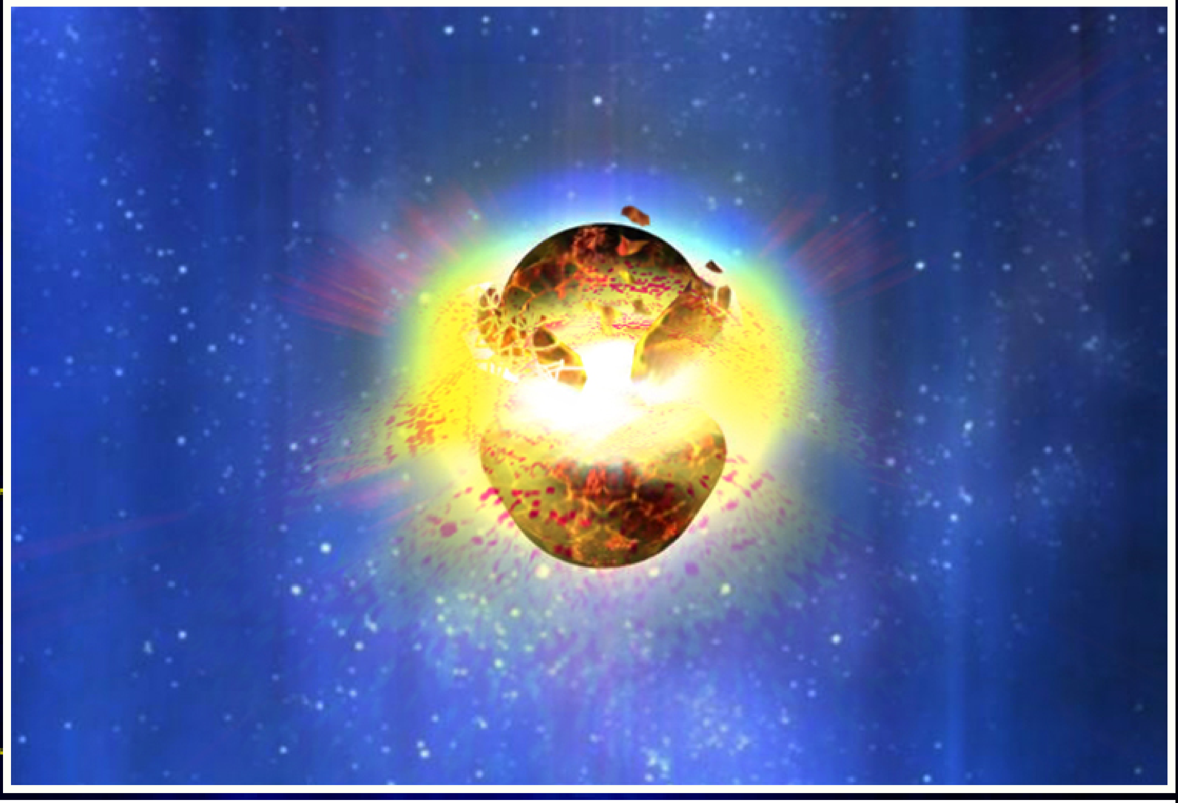


- Final solution to the GRB riddle:

- GRB970228
- Identification of X-ray afterglow by Dutch-Italian BeppoSax satellite by van Paradijs et al. (1997)
- Followed by optical identification with remote galaxy ($z > 0.7$)
- GRBs cosmological !!!!
- typical redshift $z \sim 1$, record redshift $z > 10$
- Involved energies mind-boggling

Gamma-ray Bursts



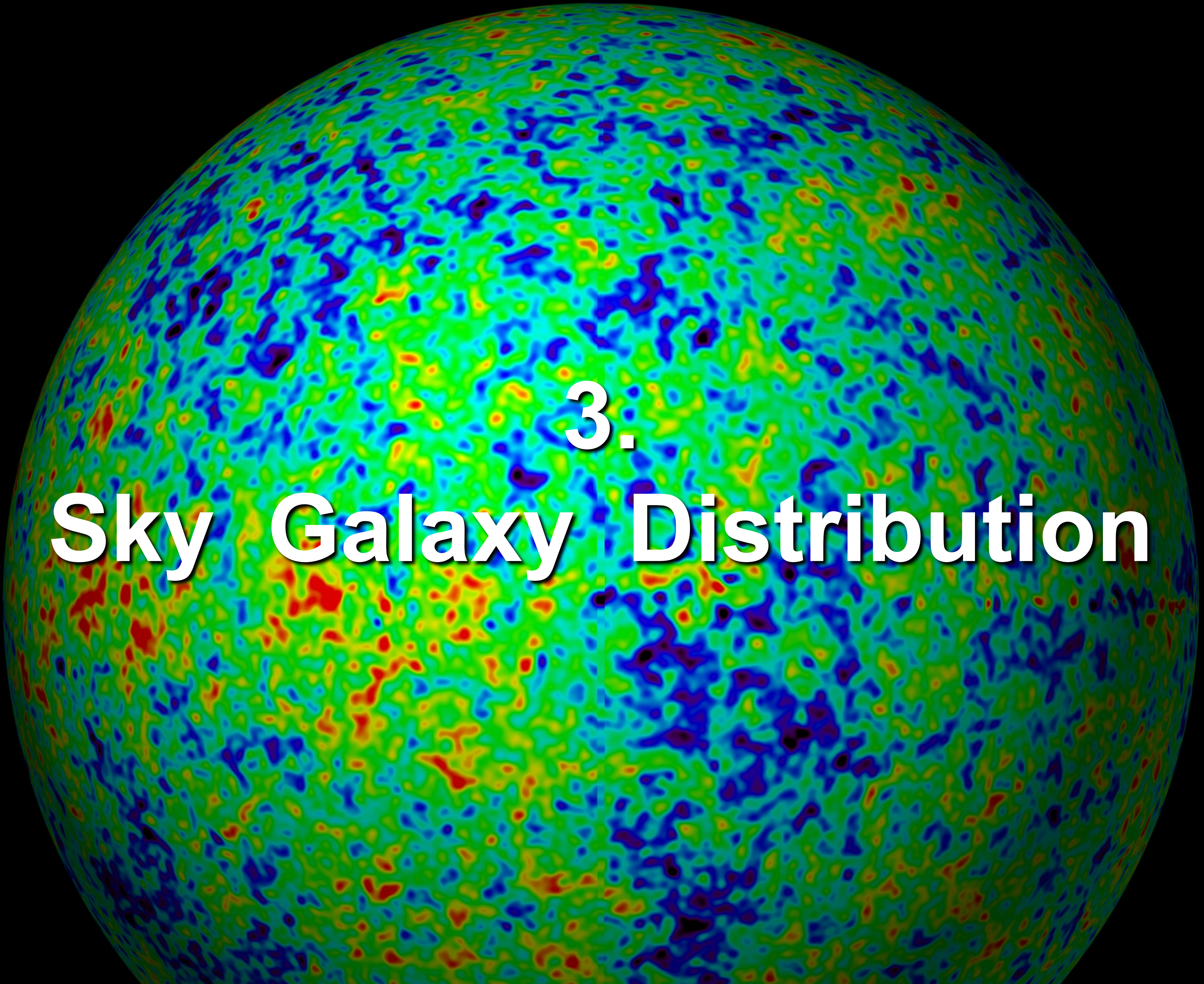


- Two classes GRBs:

long duration	> 2 sec.	collapsar/hypernovae
short duration	msec < Δt < 2 sec.	neutron star – neutron star mergers

(short duration GRBs 10 times less bright than long duration ones)

3.
Sky Galaxy Distribution



Galaxy Sky Distribution

- **Although we know that the local Universe is far from isotropic, or homogeneous,**

  when assessing the galaxy distribution to high depths:

  high level of isotropy.

- **Example of a "nearby" galaxy sample:** **2MASS survey**

  clear demonstration increasing isotropy for higher/fainter levels

- **Example of "extended nearby" galaxy sample:** **APM sky survey**
  - counting 2 million galaxies up to m=20.5
  - local "Cosmic Web" is visible as
    tenuous filamentary traces and compact dense cluster nodes
  - most of the sky marked by a uniform distribution of background galaxies
  - on scales > 100 Mpc hardly any noticeable structure

- **Even more compelling is the evidence from deep "radio galaxy" samples:** **NVVS**

  - almost perfectly isotropic

Increasing Depth

2MASS Cosmic Web

2MASS all-sky survey:

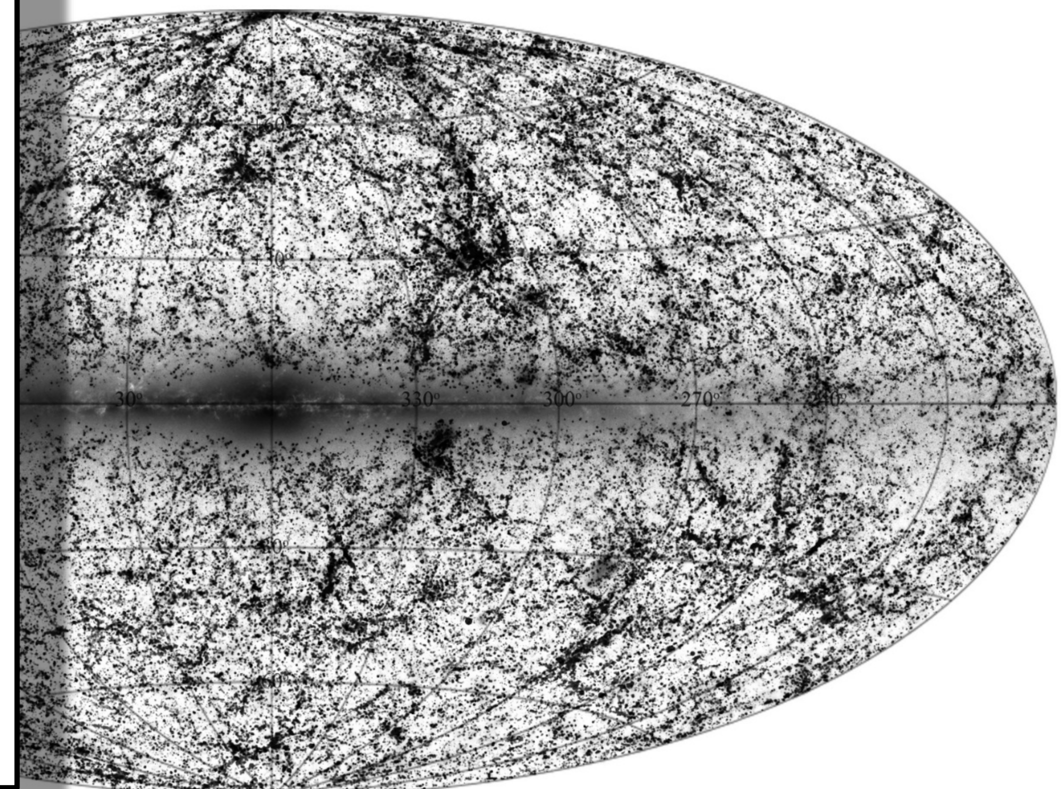
- ground-based near-infrared survey whole sky, J(1.2 μm), H(1.6 μm), K(2.2 μm)

- 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



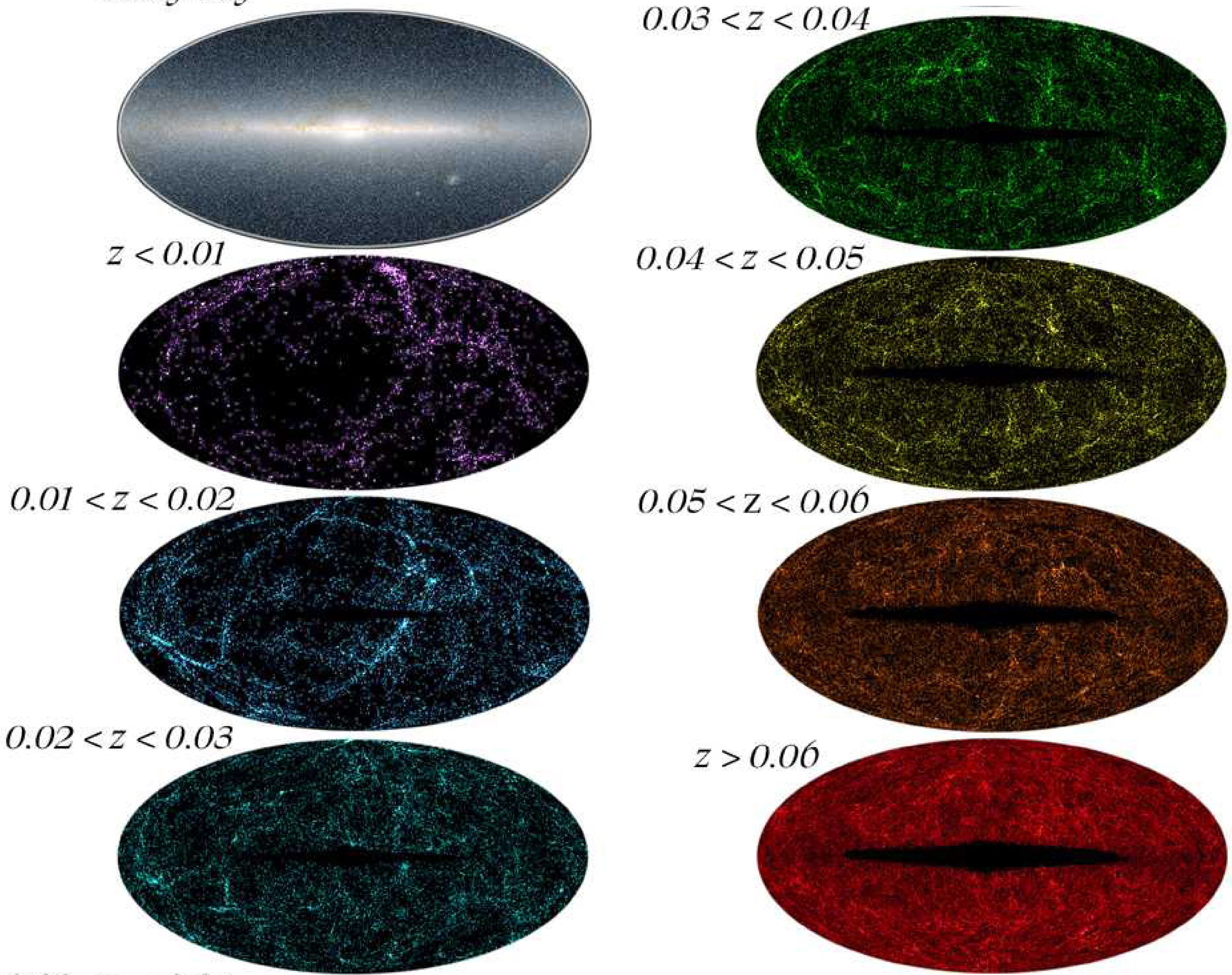
Looking around us we already see the unmistakable signatures of an intriguing weblike matter distribution in our immediate Cosmic Vicinity, together with an increasing isotropy as we go to fainter levels

The 2MASS Nearby Universe

2MASS: the integrated view

As we move outward and fainter galaxies are projected on top the sky

the galaxy sky distribution becomes more and more uniform !


0.03 < z < 0.04
z < 0.01
0.04 < z < 0.05
0.01 < z < 0.02
0.05 < z < 0.06
0.02 < z < 0.03
z > 0.06

APM Galaxy Survey

Sky map:

2 x 10^6 galaxies

17 < m < 20.5

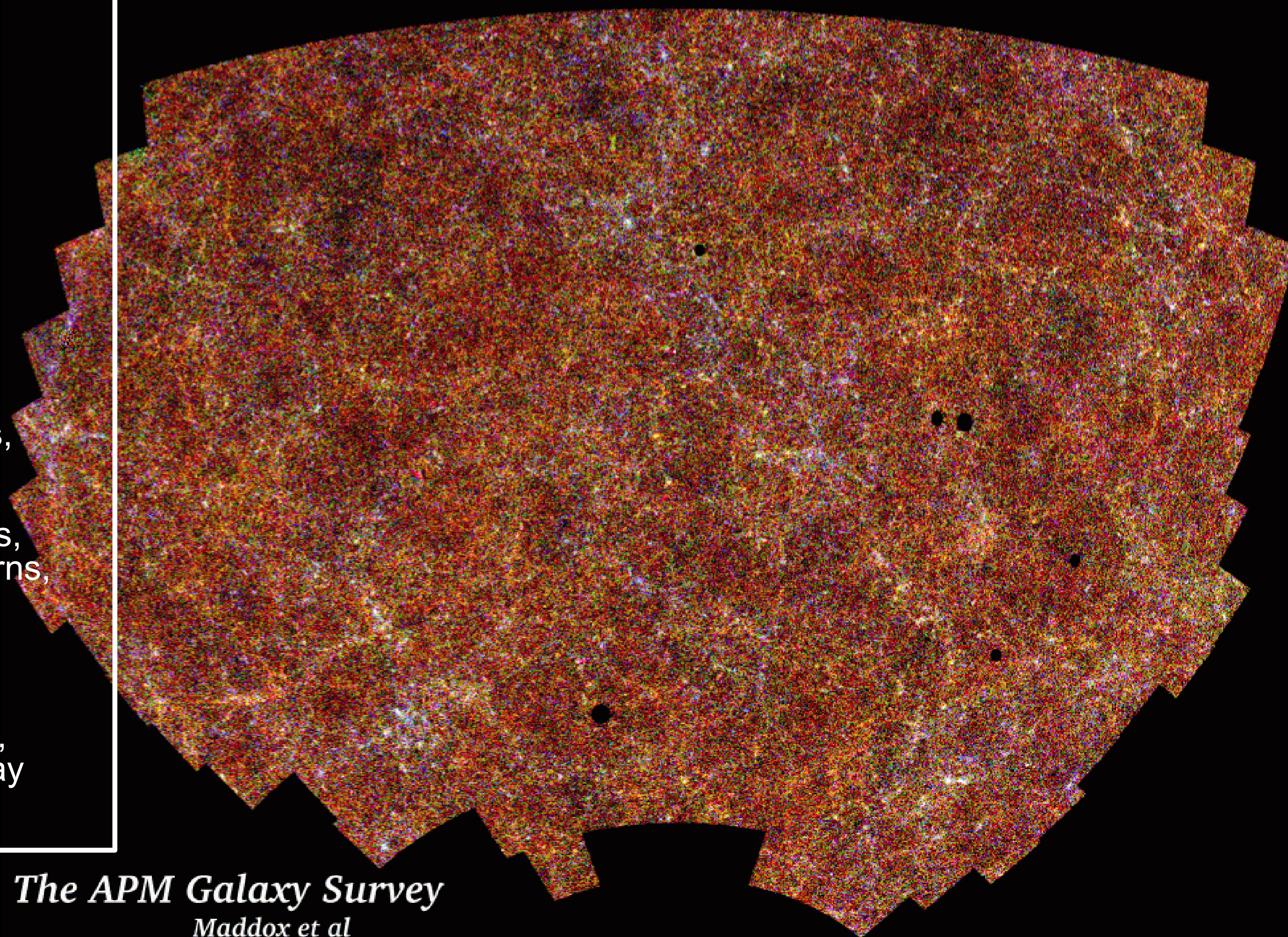
Uniformly defined

- Sky region:
  4300 sq. deg.

  185 UK Schmidt plates,
  6^o x 6^o

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

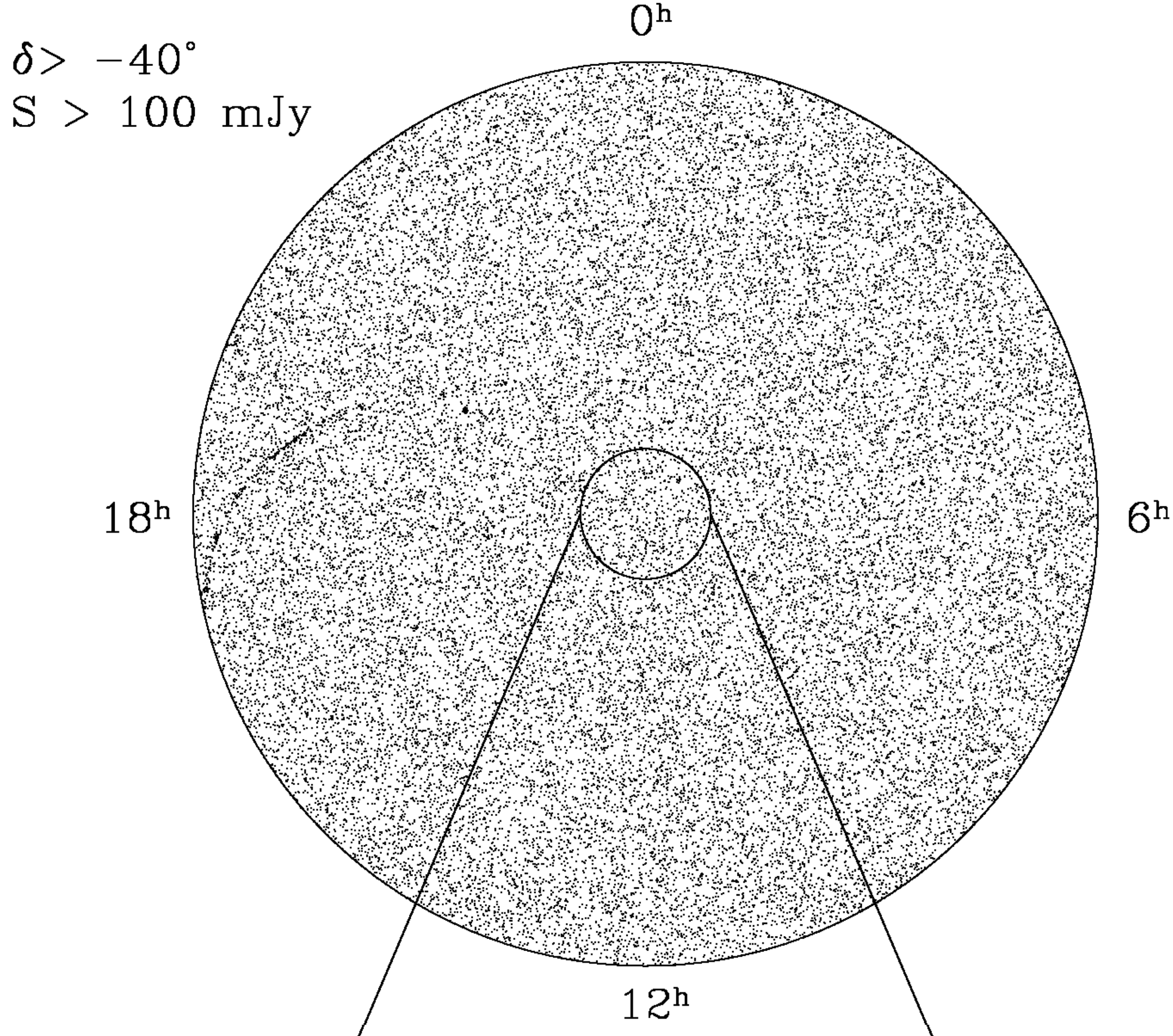
S. Maddox, G. Efstathiou,
W. Sutherland, D. Loveday



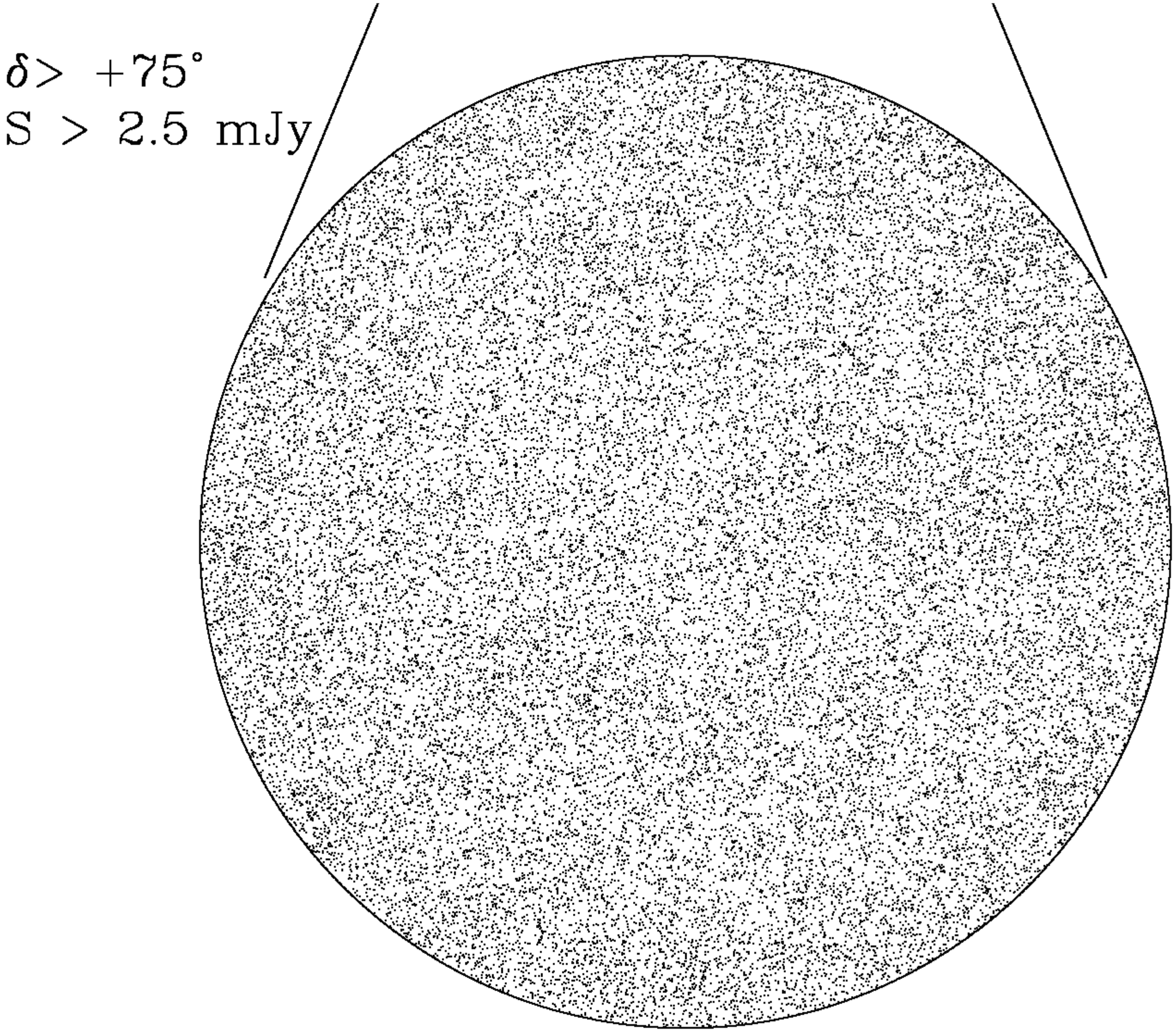
Radio Galaxies: NVVS

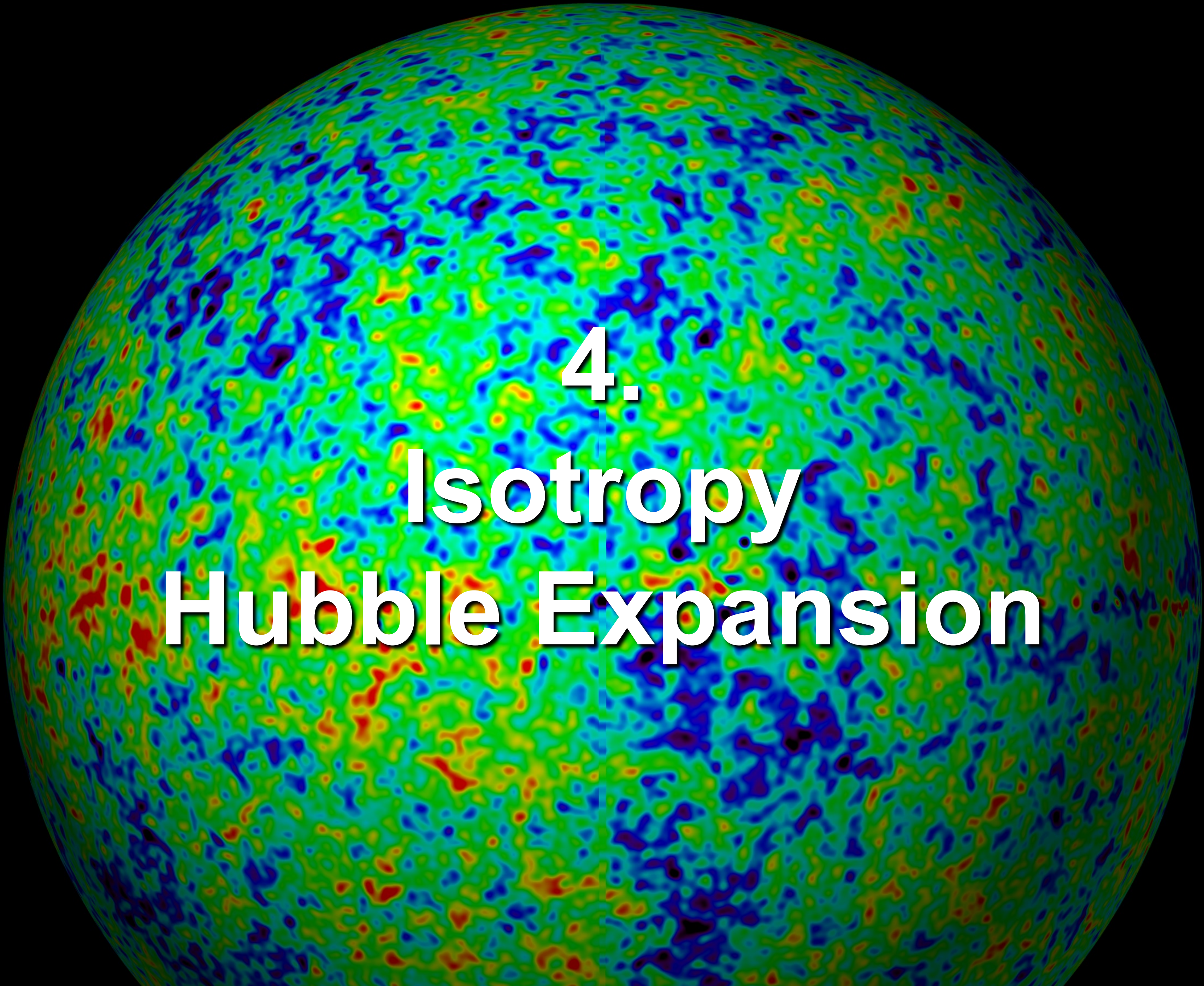
- Good tracers of the Universe on the largest scales are radio galaxies (and other AGNs)
- The most extensive sky survey of discrete radio sources is the NRAO VLA Sky Survey (NVVS)
- Covers nearly the whole of the northern sky north of $\delta=-40^o$, nearly $2x10^6$ sources stronger than S=2.5 mJy at 1.4 GHz.
- The distribution of these discrete sources on the sky is nearly perfectly isotropic

Radio Galaxies: NVVS

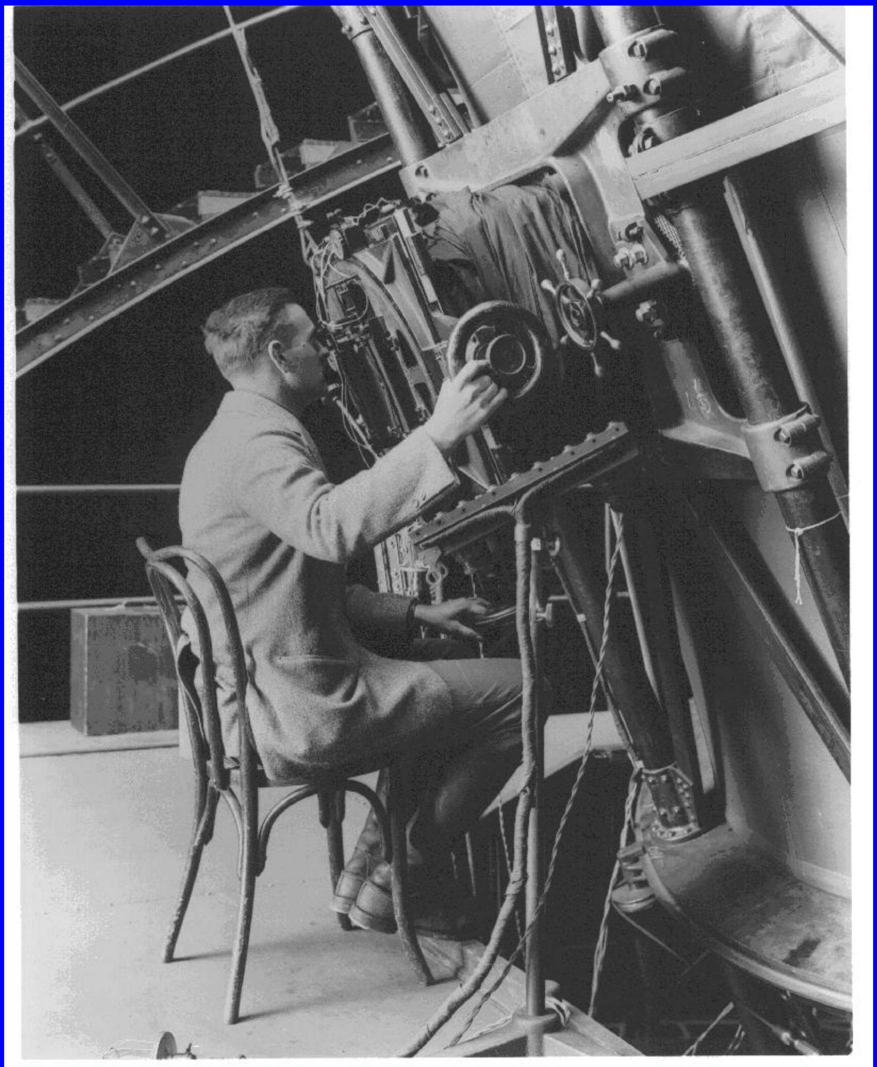


Radio Galaxies: NVVS



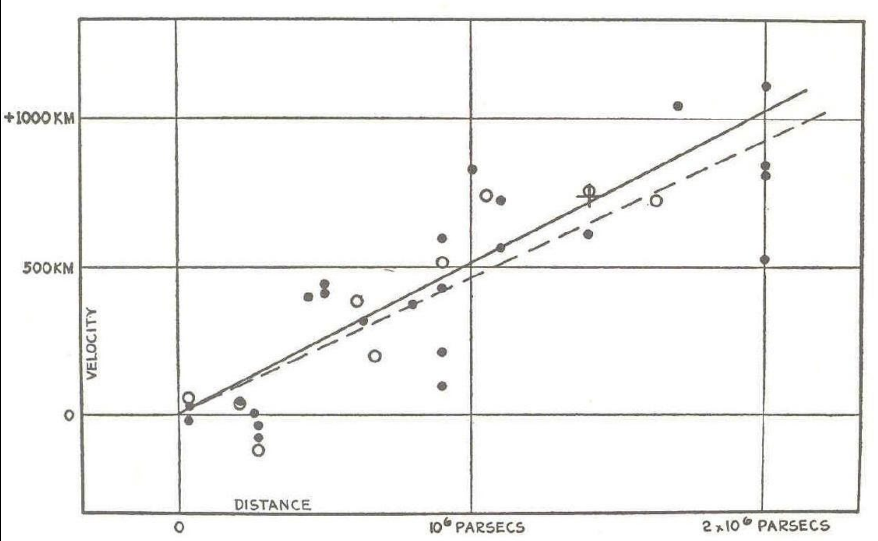

4.
Isotropy
Hubble Expansion

Hubble Expansion



Edwin Hubble

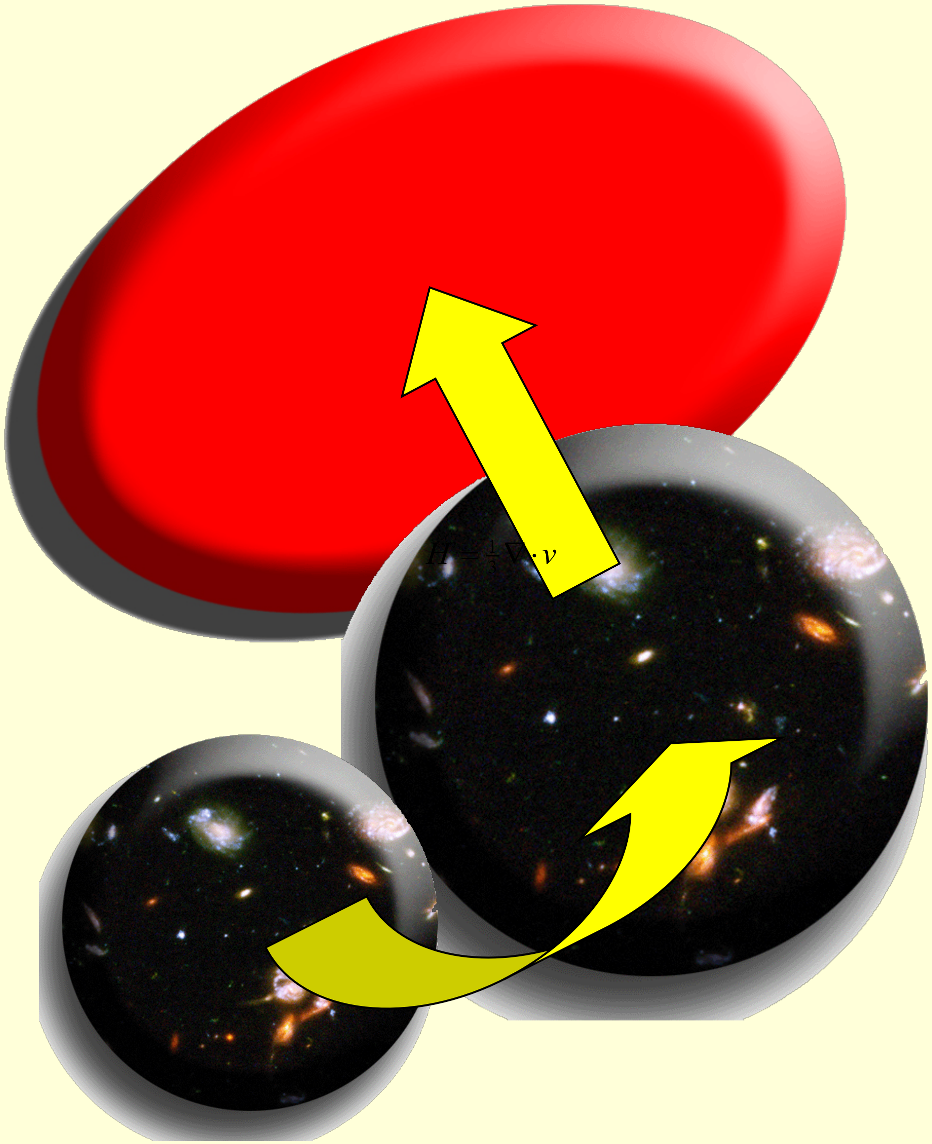
(1889-1953)



$v = H \ r$

Hubble Expansion

Deformation
Cosmic Volume Element



The evolution of a fluid element on its path through space may be specified by its velocity gradient:

$$\frac{1}{a}\frac{\partial v_i}{\partial x_j} = \frac{1}{3}\theta\,\delta_{ij} + \sigma_{ij} + \omega_{ij}$$

in which

θ: velocity divergence

→ **contraction/expansion**

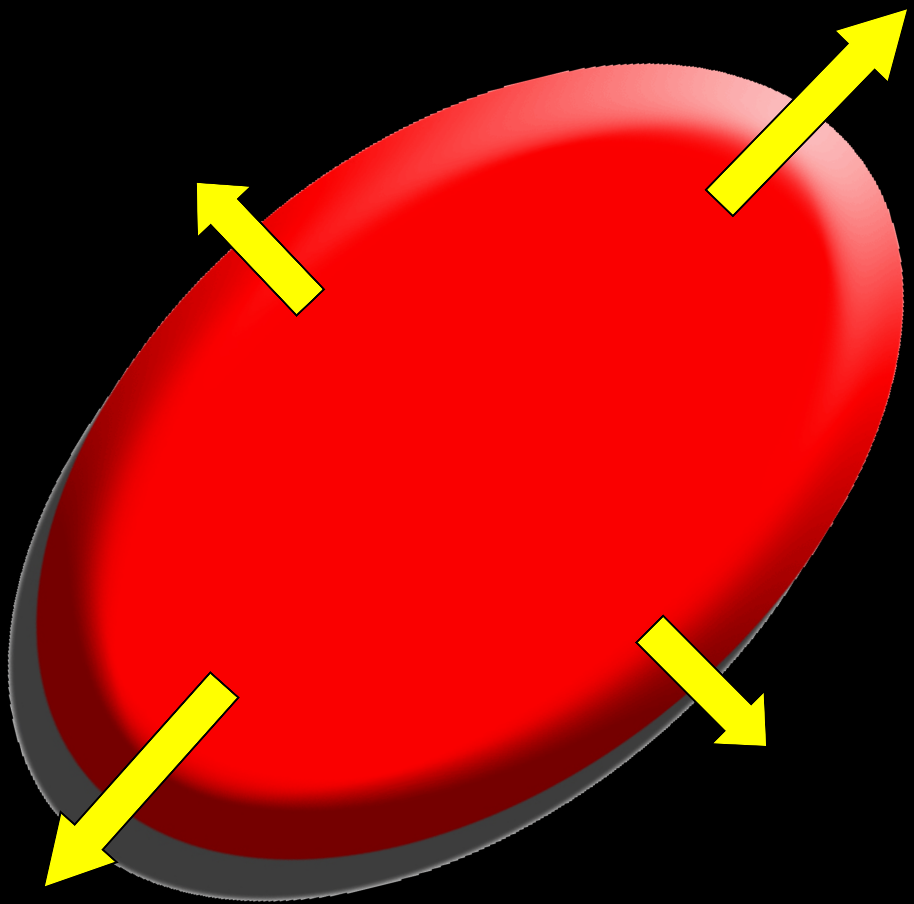
σ: velocity shear

→ **deformation**

ω: vorticity

→ **rotation of element**

Deformation
Cosmic Volume Element

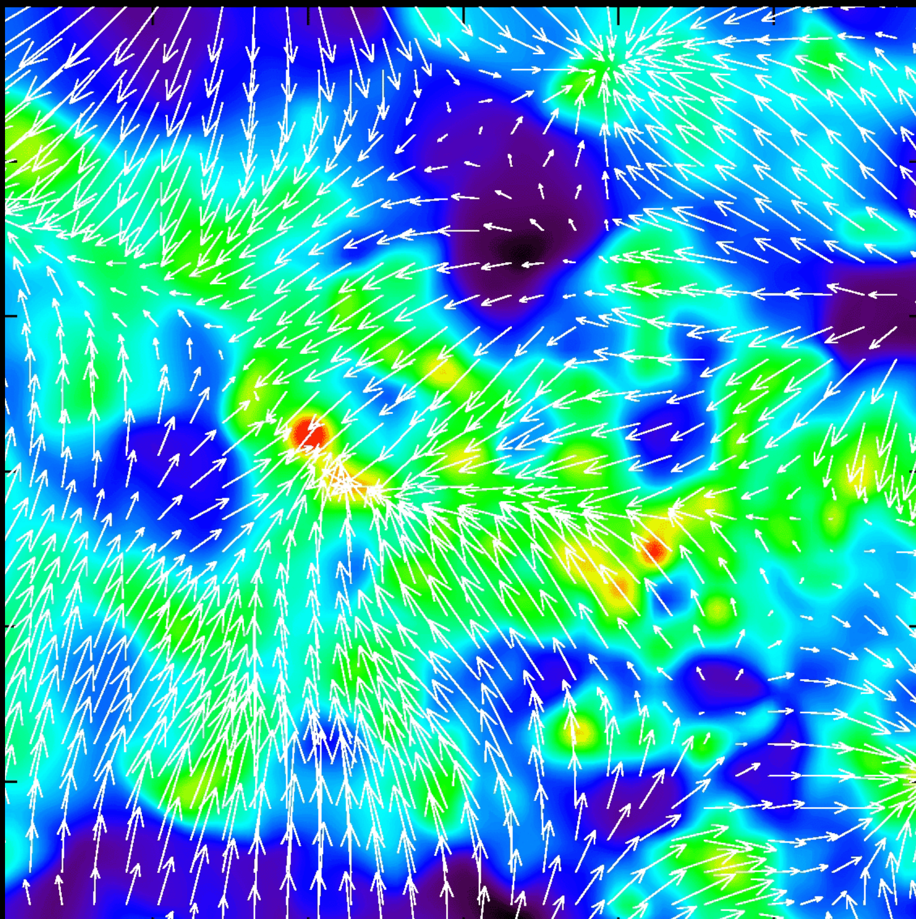


Global Anisotropic expansion/contraction

Anisotropic Relativistic Universe Models:
Bianchi I-IX Universe models

- expand anisotropically
- have to be characterized by at least 3 Hubble parameters (expansion rate different in different directions
- Only marginal claims indicate the possibility on the basis of CMB anisotropies

Deformation
Cosmic Volume Element

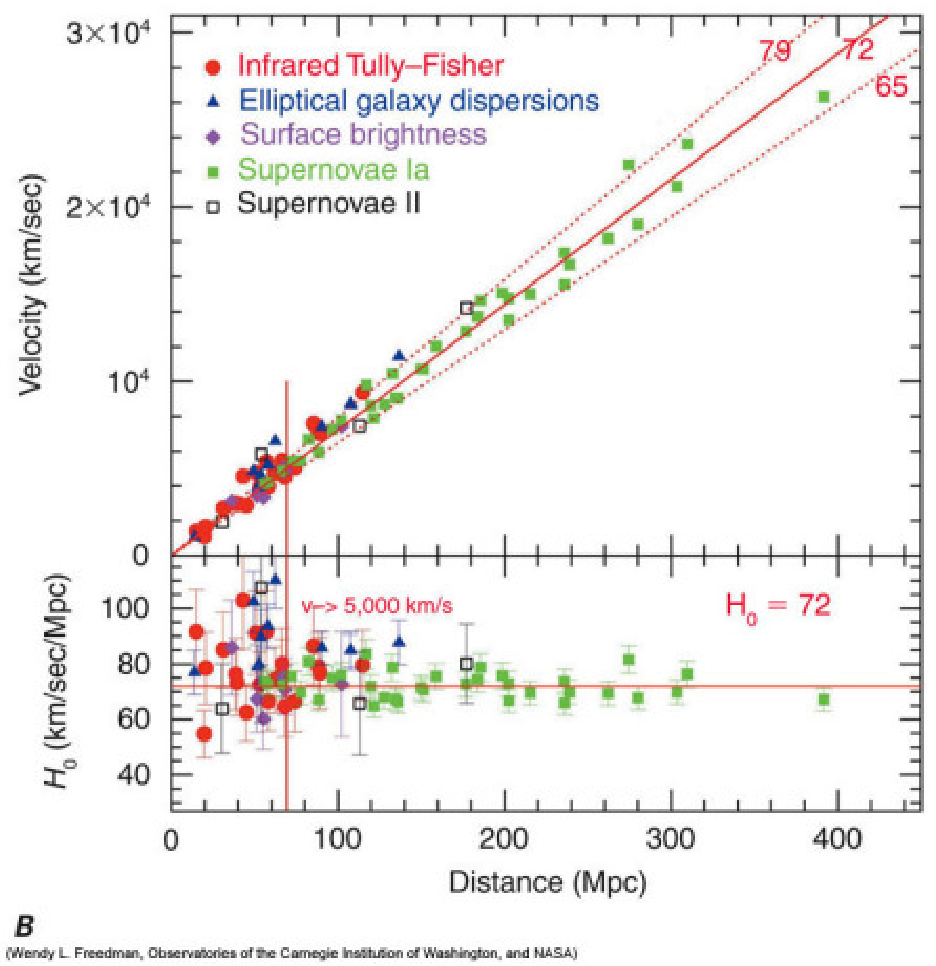


Local Anisotropic Flows:
"fatal" attractions

- **In our local neighbourhood the cosmic flow field has a significant shear**

- **This shear is a manifestation of**
  - infall of our Local Group into the Local Supercluster
  - motion towards the Great Attractor
  - possibly motion towards even larger mass entities: Shapley concentration
    Horologium supercluster

Deformation
Cosmic Volume Element



Global Hubble Expansion
Observations over large regions
of the sky, out to large cosmic depth:

- the Hubble expansion offers a very good description of the actual Universe
- the Hubble expansion is the same in whatever direction you look: isotropic

Hubble flow:

$$H = \frac{1}{3} \nabla \cdot v$$

Pure expansion/contraction

Homogeneity

Prime Evidence Homogeneous Universe:

1) The spatial galaxy distribution in galaxy redshift surveys:

   largest structures seen are ~ 100-200 Mpc

2) Galaxy number counts: $N(m) \sim 10^{0.6m}$

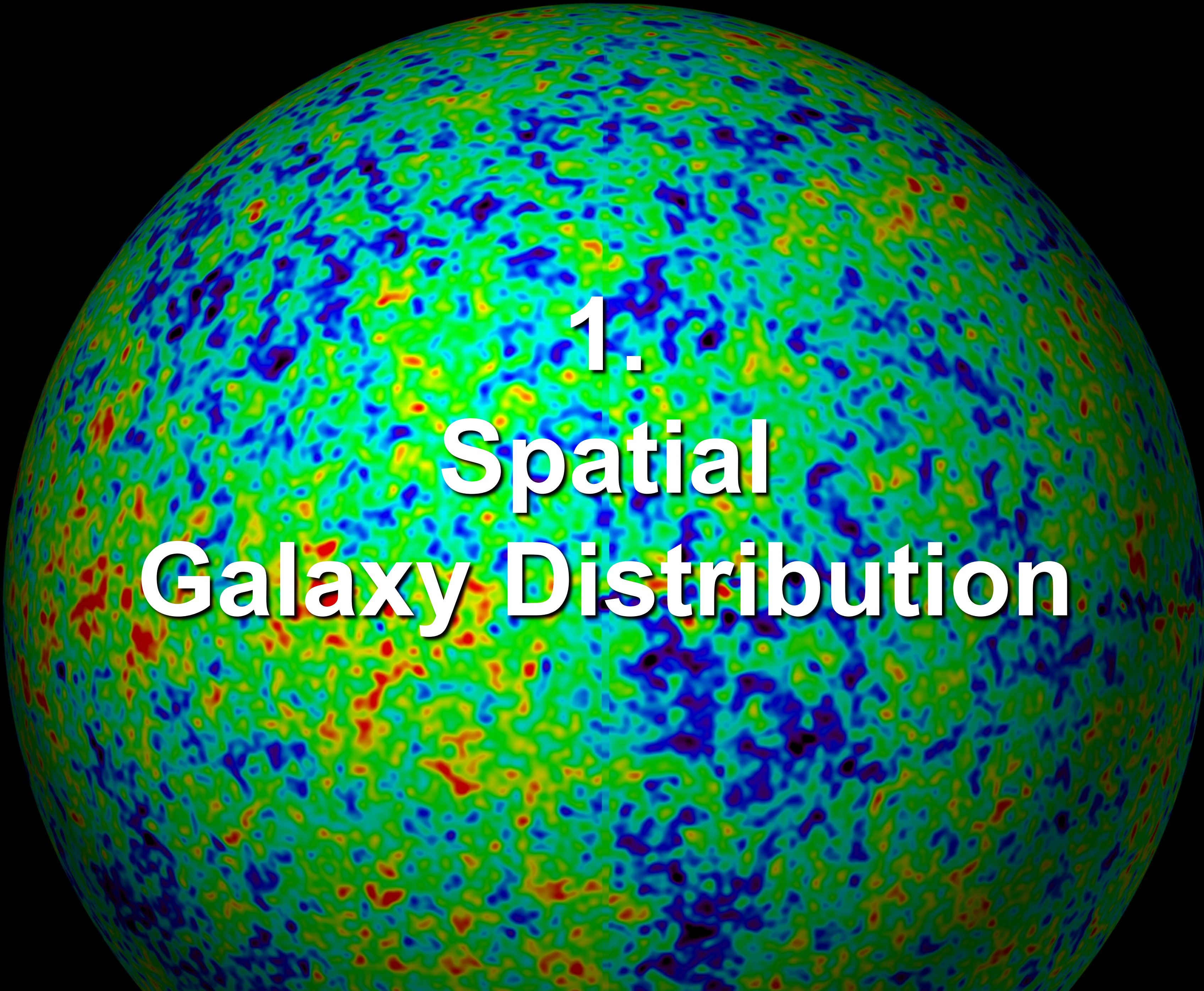
3) Scaling of the Projected galaxy distribution:

   clustering with depth galaxy sample

4) Cosmic Dipole:

   the convergence of the Local Group cosmic acceleration vector

1. Spatial Galaxy Distribution



Largest Cosmic Structures

A clear obvious test for homogeneity of the Universe is to make a map of the matter distribution in the Universe and identify

- whether there is structure:
  - yes, obvious: stars, galaxies, clusters, superclusters
- what the size is of the largest structures in the Universe, ie.
  - is there a scale beyond which the Universe tends to converge to uniformity
  - or, do you see ever larger structures as you probe deeper into the Universe

The best probe for studying the Universe is (still) the distribution of galaxies

- note: in 2007 the first map of the 3-D dark matter distribution has been produced on the basis of a meticulous gravitational (weak) lensing study

Galaxy Redshift Distribution

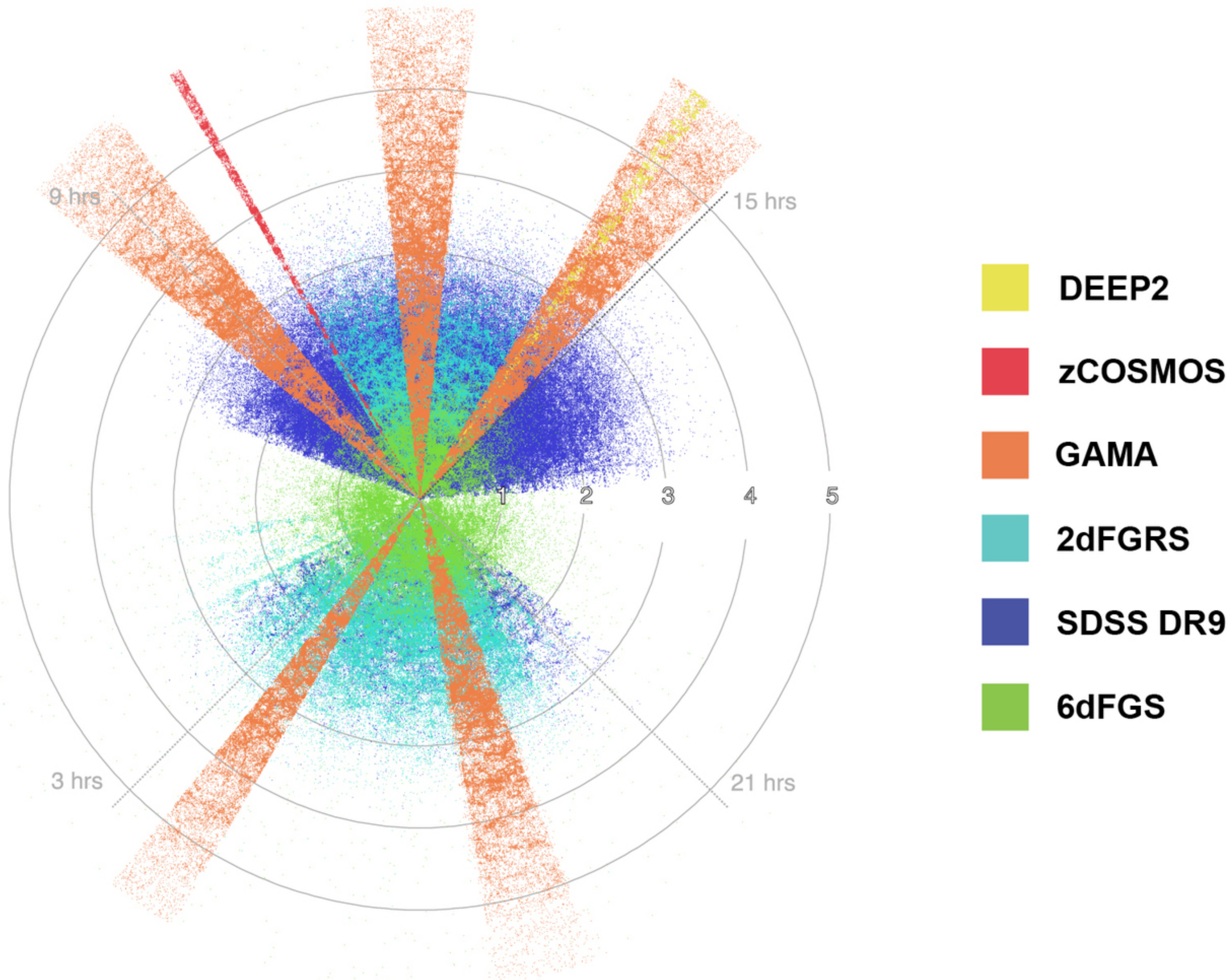
Mapping the 3-D galaxy distribution is not entirely trivial:

- We are still mostly confined to the "local" cosmic vicinity – ie. up to 500 Mpc – as galaxies quickly become too faint for a practically feasible distance estimate
- Even within our local neighbourhood it is too cumbersome to determine the real "physical" distance r of galaxies to a decent level of accuracy

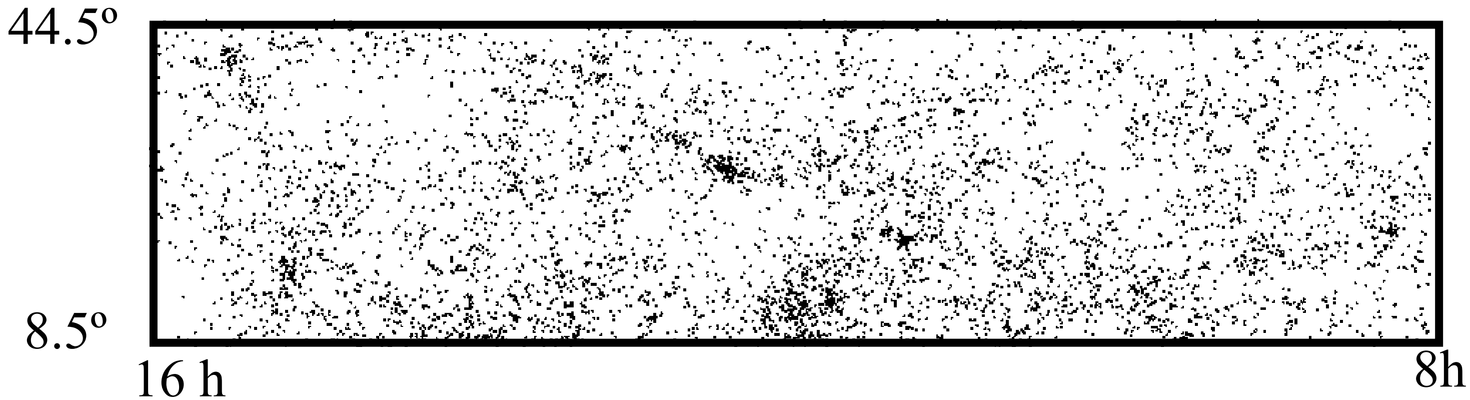
- The Hubble expansion of the Universe is of great help:

Hubble relation: $c\,z = H\,r$

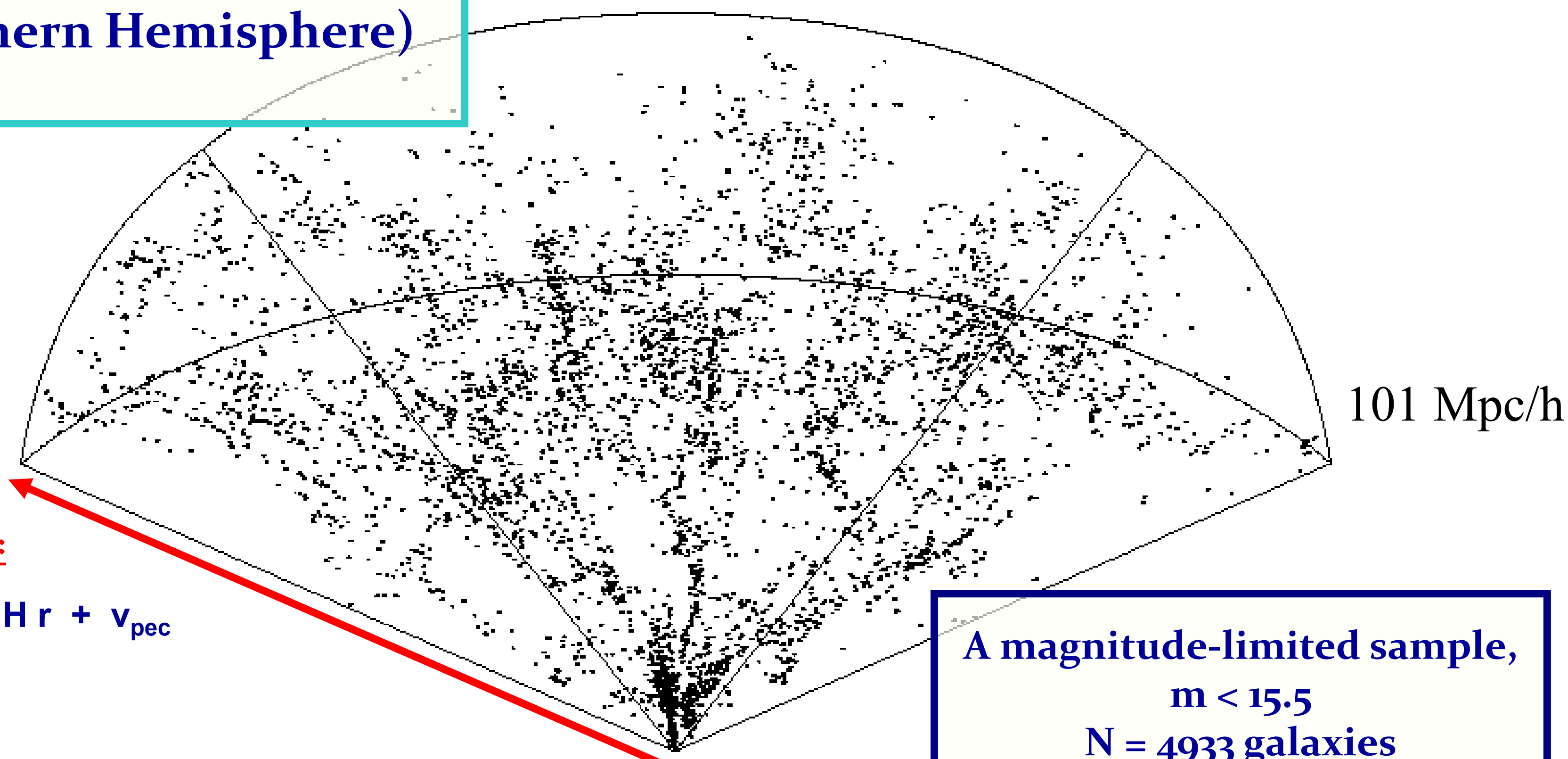
- Hubble parameter H_o: 71 km/s/Mpc
- Redshift: accurately and relatively easily determined from spectrum of galaxy
- Once good spectrographs became available towards end 1970s, major mapping campaigns got started (see next page)



9 hrs
15 hrs
3 hrs
21 hrs
1
2
3
4
5
DEEP2
zCOSMOS
GAMA
2dFGRS
SDSS DR9
6dFGS



CfA2 redshift survey (Northern Hemisphere)



Redshift:

$v = cz \sim Hr + v_{pec}$

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

Figure courtesy: V. Martinez

REDSHIFT SURVEY CAMPAIGNS

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:

THE COSMIC WEB

Galaxies are grouped into a Weblike network of galaxies:

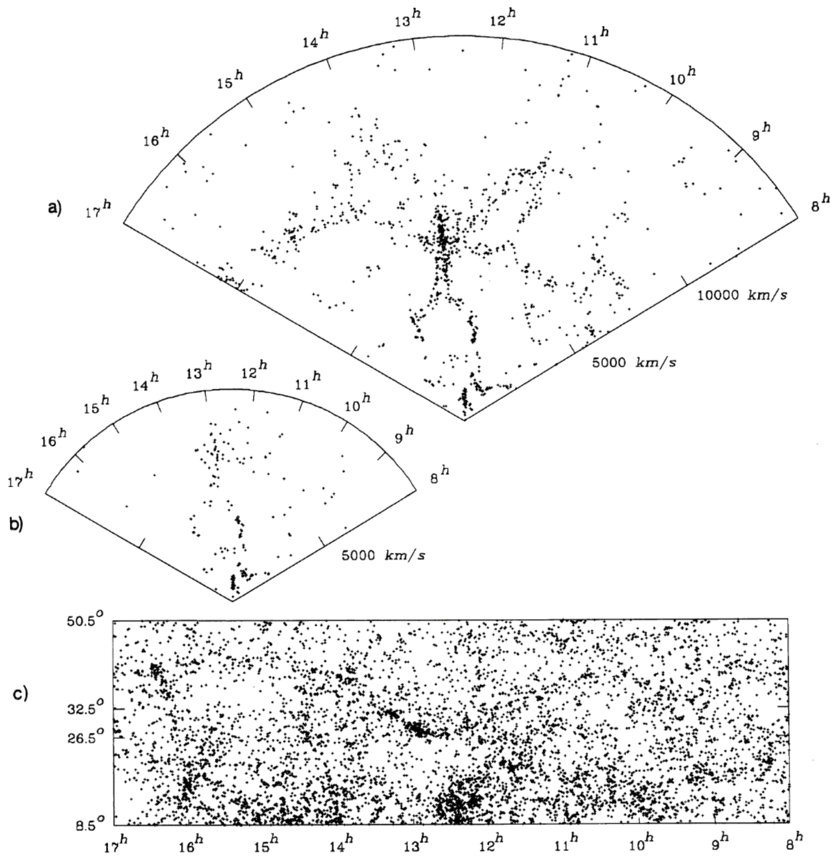
- **Sheets/Walls**
- **Filaments**
- **Clusters**
- **Voids**

These elements are spatially organized in a

- **Non-trivial stochastic pattern of filaments and walls: filaments marking the dense ridges of walls, joining up at high density junctions, sites of rich clusters**
- **Walls, filaments and clusters framed in a spatial network in which their spatial distribution is dictated by their location on the surface of roundish and near-empty voids**

Cosmic Web:

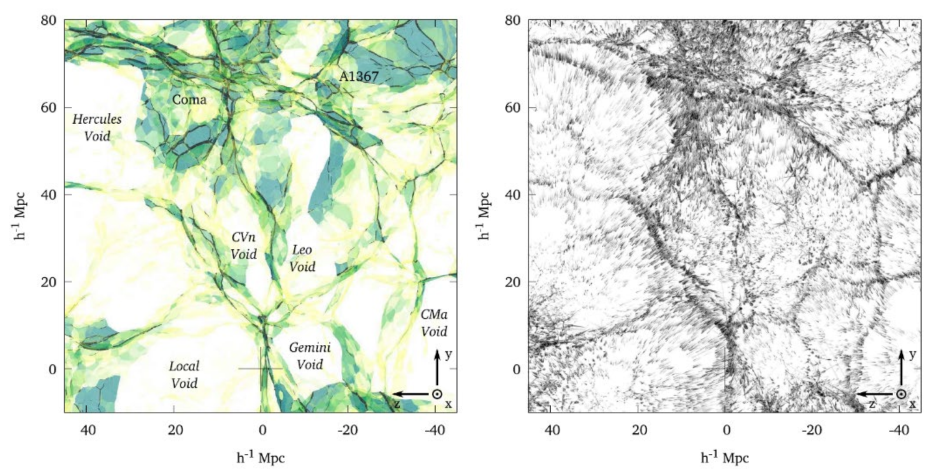
Stickman & Discovery



deLapparent, Geller & Huchra, 1986:

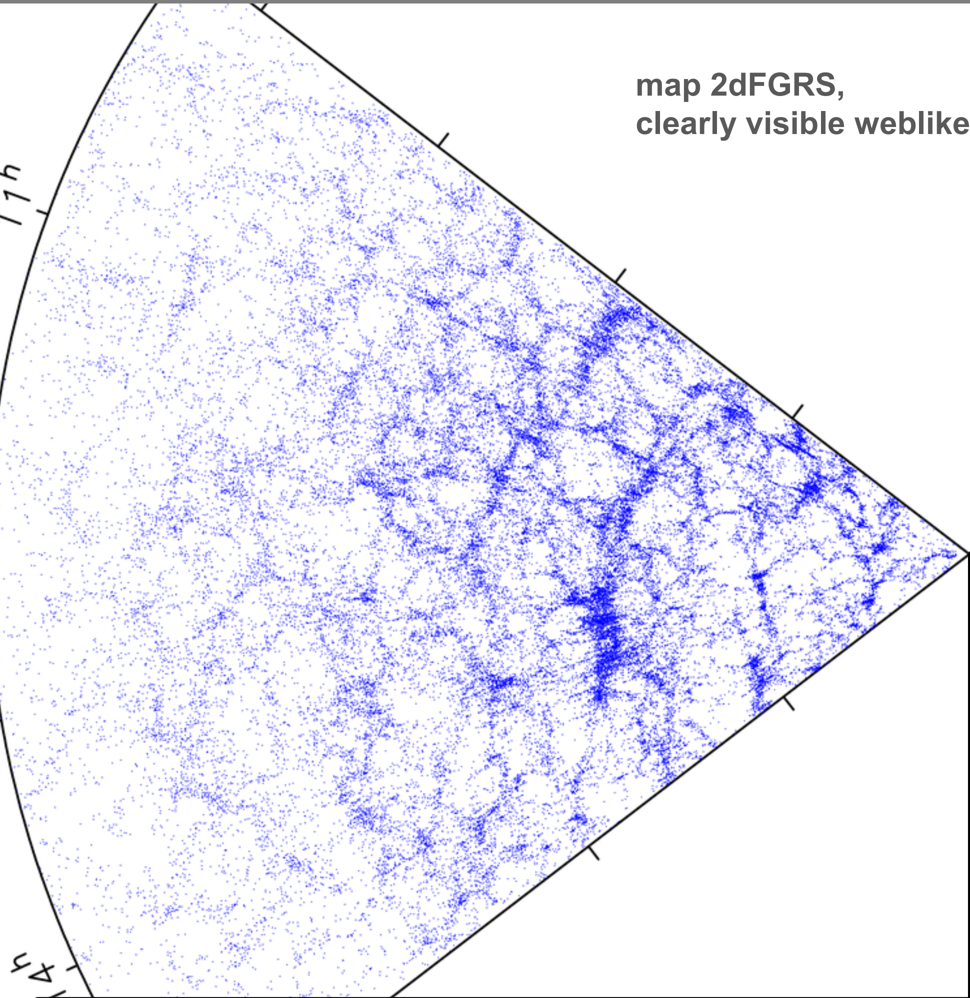
"a slice of the Universe"

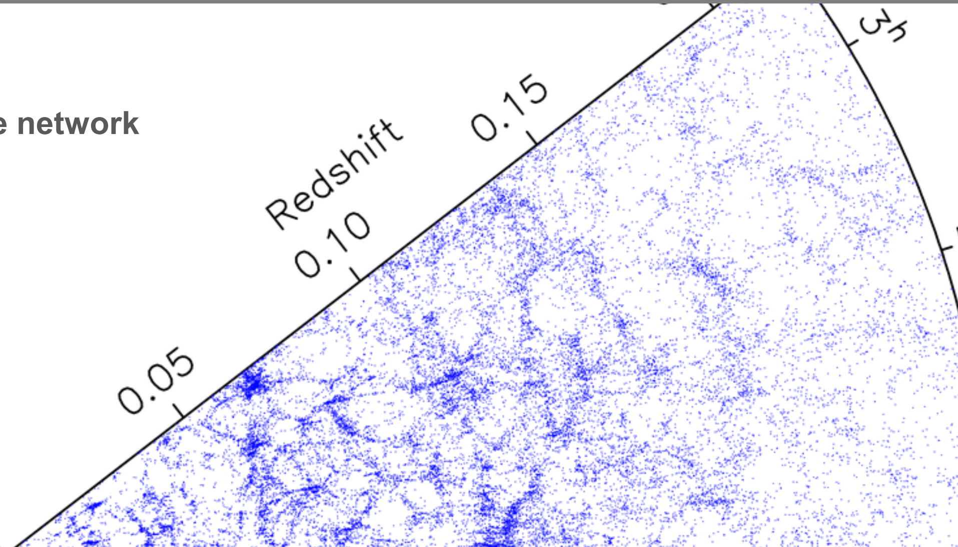
Voids appear to be an integral part of a complex weblike arrangement of galaxies

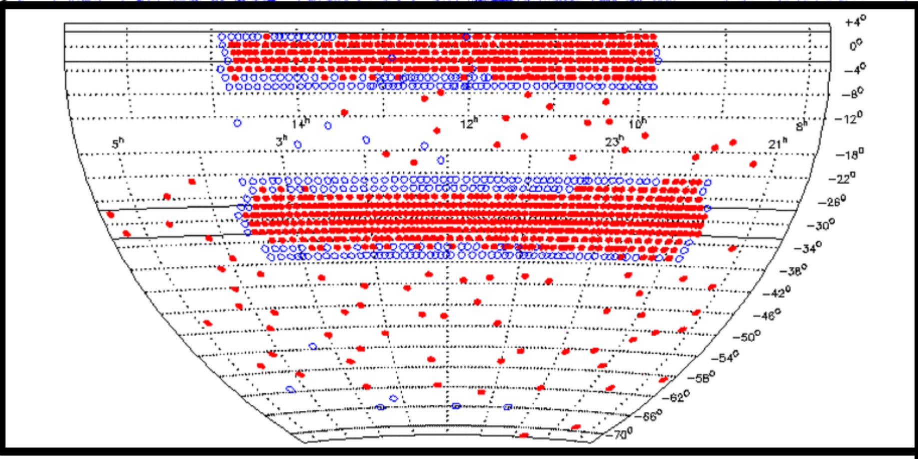


2dFGRS Galaxy Survey

map 2dFGRS,
clearly visible weblike network

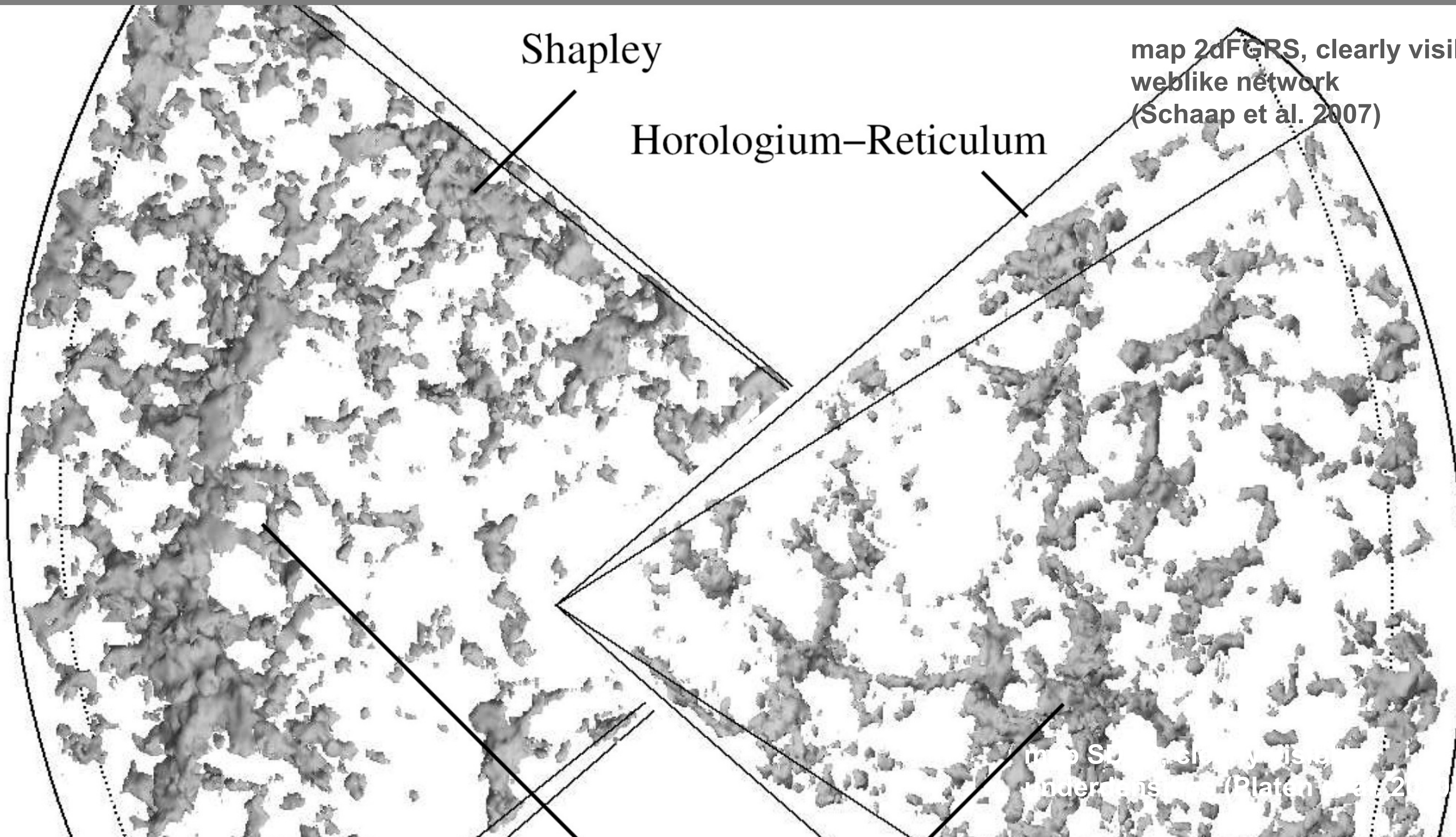






with the advent of large galaxy redshift surveys
– LCRS, 2dFGRS, SDSS, 2MRS –
voids have been recognized as one of the quintessential components of the Cosmic Web

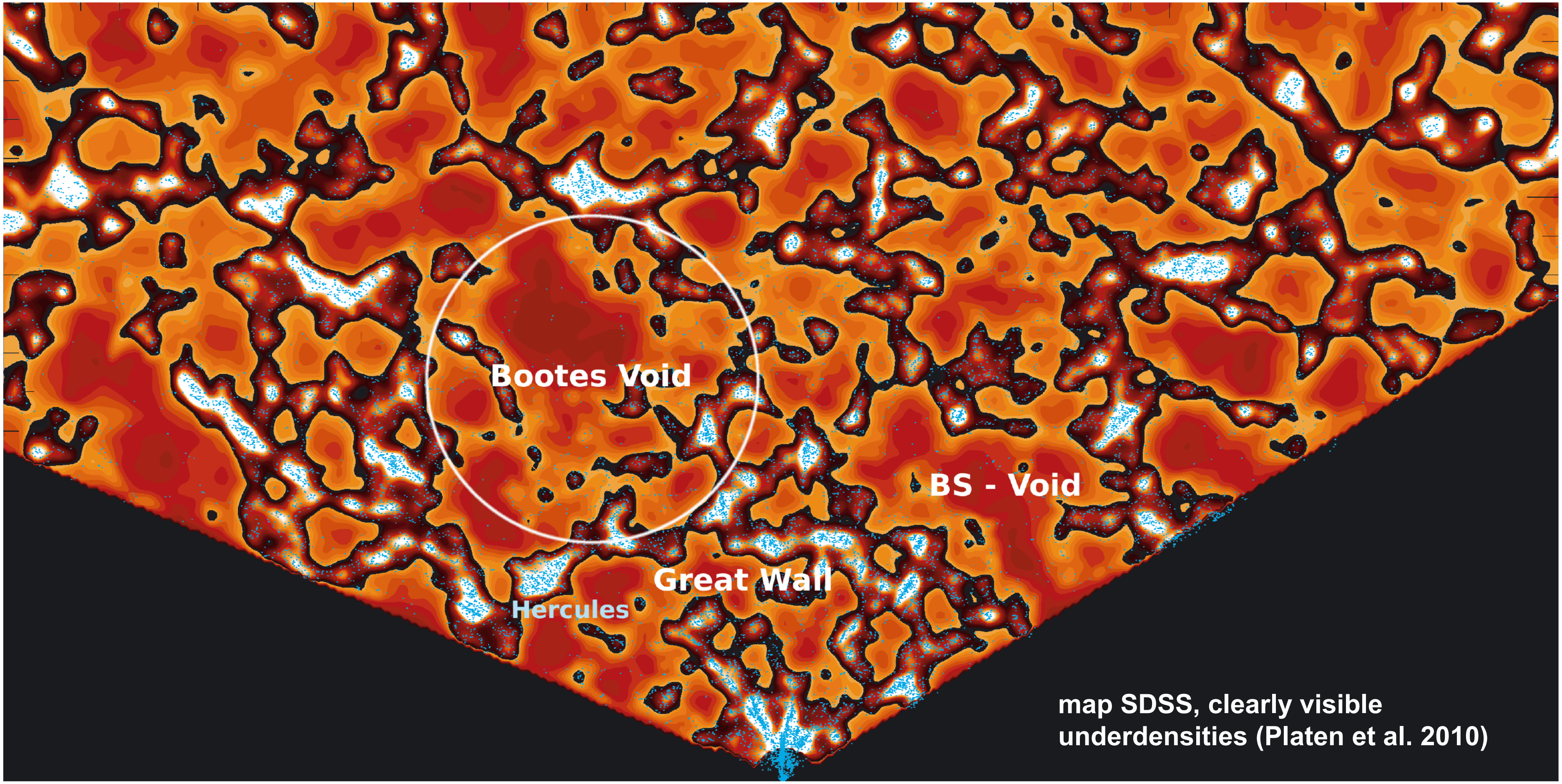
2dFGRS Galaxy Survey



map 2dFGRS, clearly visible weblike network (Schaap et al. 2007)

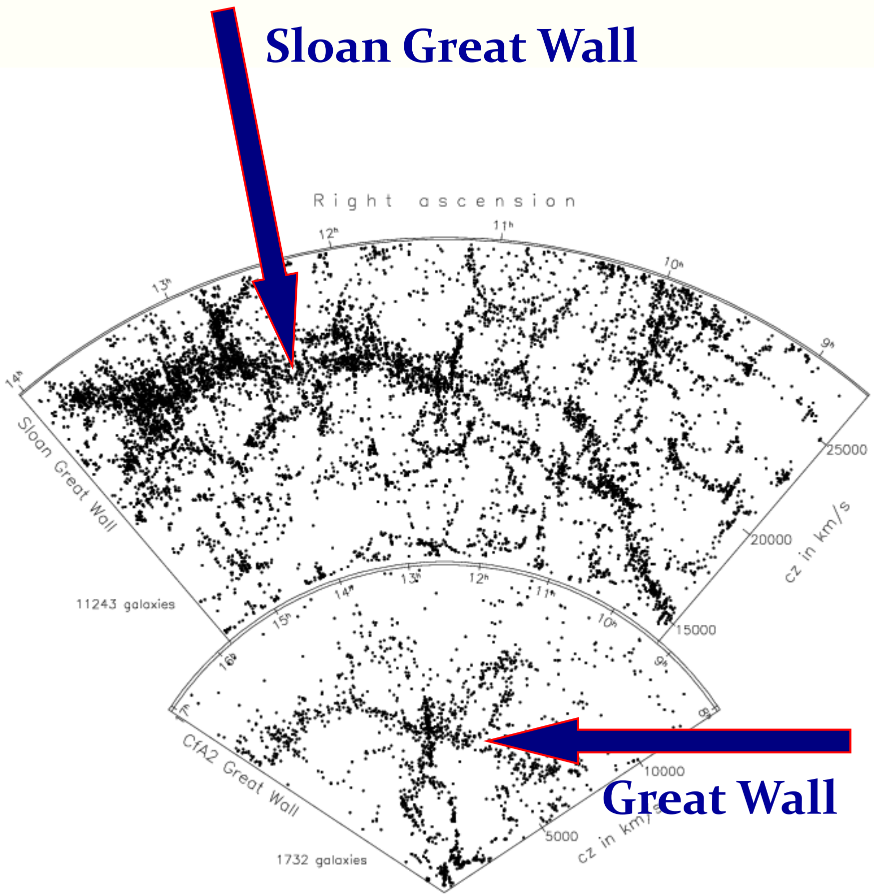
with the advent of large galaxy redshift surveys
– LCRS, 2dFGRS, SDSS, 2MRS –
voids have been recognized as one of the quintessential components of the Cosmic Web

SDSS Galaxy Survey



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

Largest Structures in the Universe

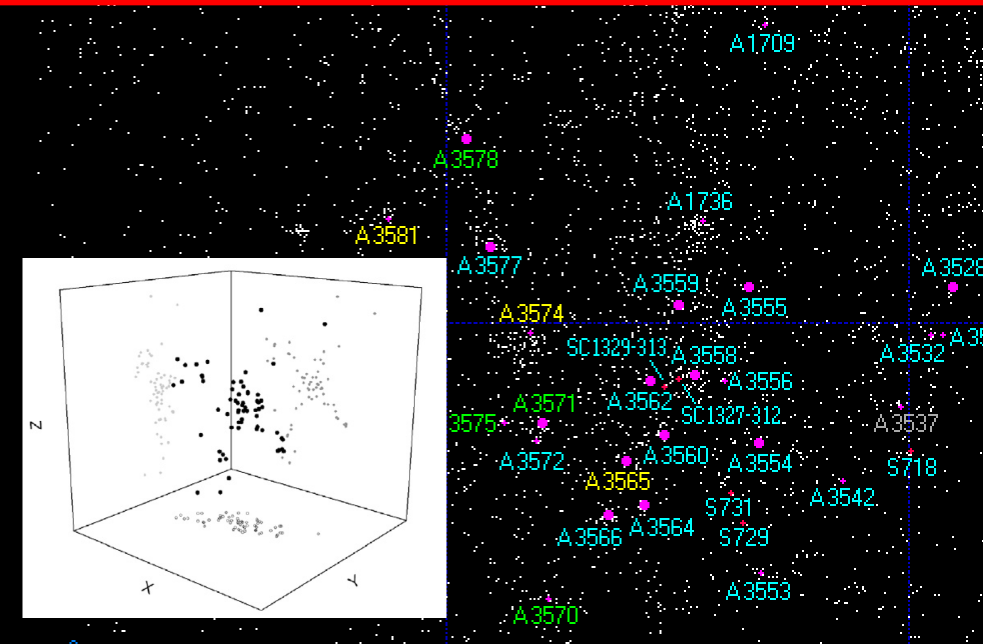


from: Gott et al. 2005

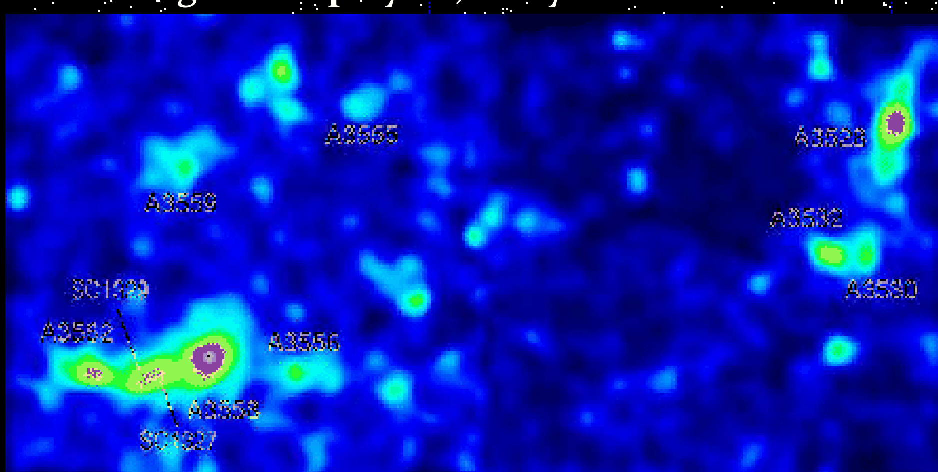
What are the largest structures that we can find in the galaxy survey maps ?

- In CfA2 a "Great Wall" of galaxies was found, dimension ~ $180h^{-1}$ Mpc
- In SDSS an even more massive and immense structure has been identified: the "Sloan Great Wall"
- However, to some extent the Great Walls are standing out as a result of:
  - proximity to peak observ. selection funct.
  - redshift distortion effect

Largest Structures in the Universe



Central region Shapley SC, X-ray: Bardelli et al.



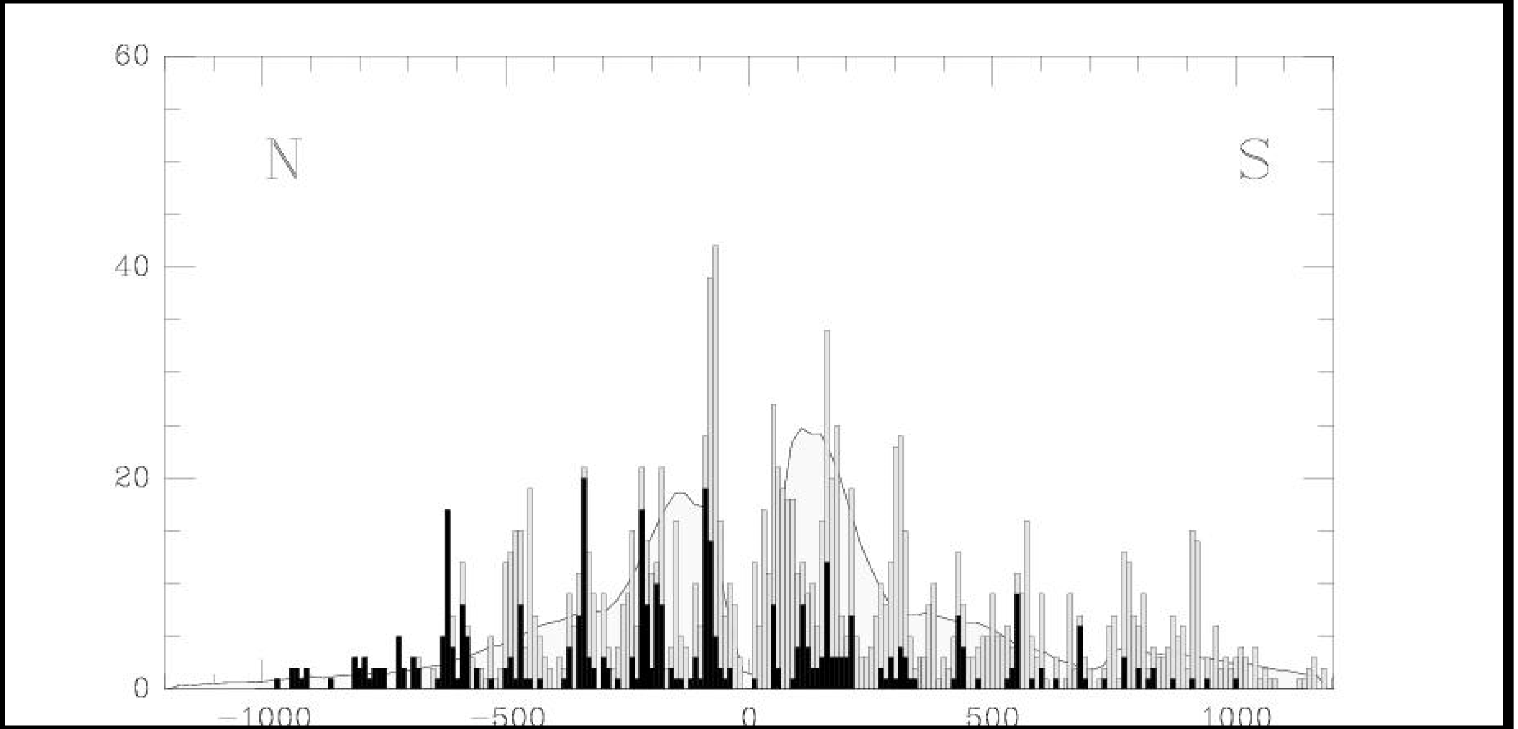
What are the largest structures that we can find in the galaxy survey maps ?

- The distribution of Clusters of Galaxies usually reveals the existence of larger scale patterns than that of galaxies.
- Clusters of galaxies tend to aggregate in superclusters, to be identified with the filaments and sheets we see in the galaxy distribution.
- The most massive superstructure in the Local Universe is the

Shapley Supercluster

- It contains 25-30 clusters of galaxies, of which at least 7 are richness I

Largest Structures in the Universe



A 1-D skewer through the Cosmos

Deep pencil beam survey (Broadhurst et al):

A semi-regular pattern of redshift spikes along line of sight, indicating the passage of l.o.s. through sheets, filaments and clusters, most of which should be identified with "Great Walls". While impressive, it also does not seem to reveal any structures larger than ~120h^{-1} Mpc.

Does this conclude the argument on the scale of homogeneity of the Universe ?

Largest Cosmic Structures

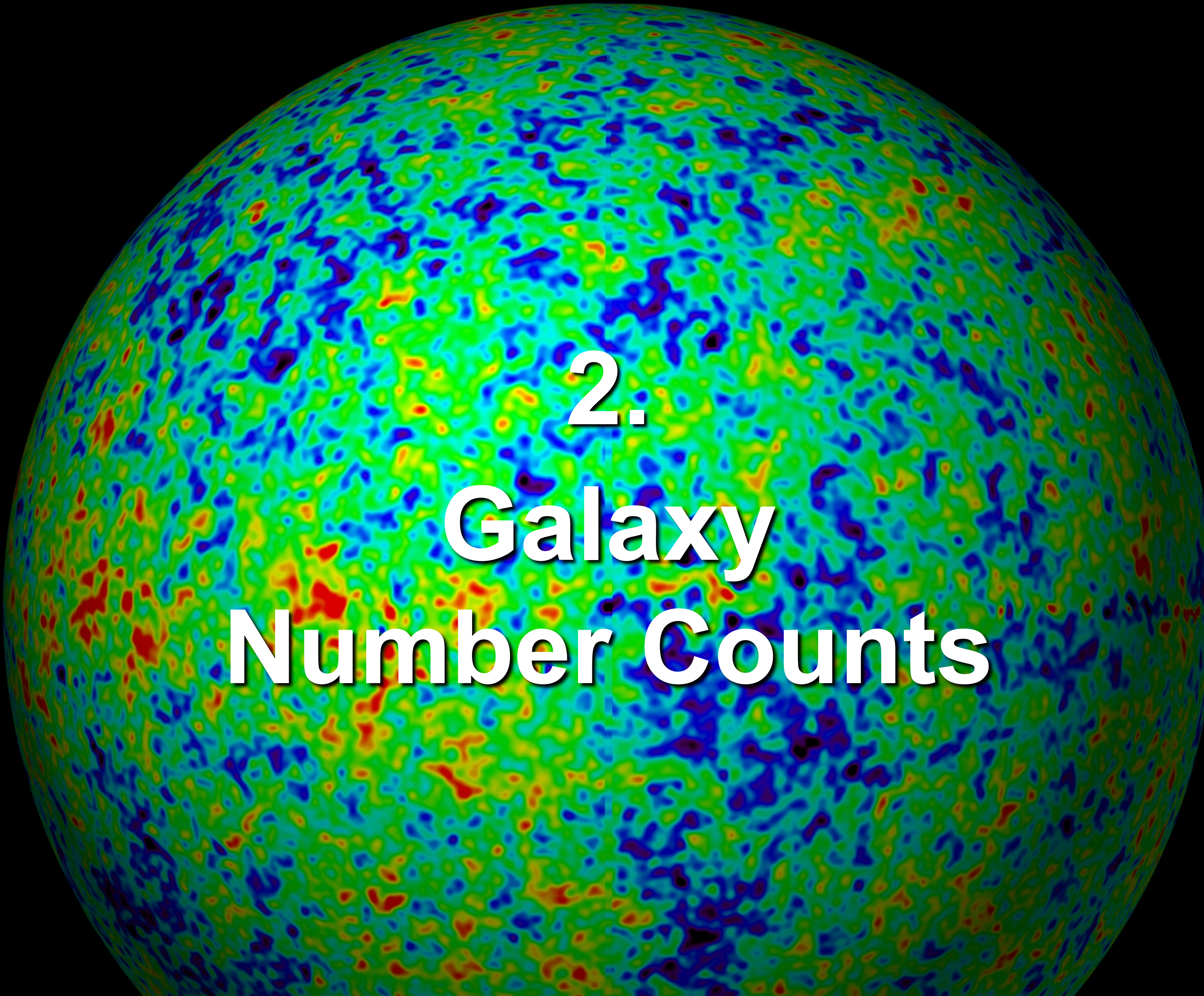
Cautious Conclusion:

While galaxy redshift surveys mapped ever larger regions of the nearby Cosmos and revealed outstanding and intriguing structures got revealed, there is

NO INDICATION

for large inhomogeneities on scales > 150-200h^{-1} Mpc (even with 2dFGRS and SDSS pressing their effective survey depth beyond this scale and therefore represent "fair samples" of the Universe).

Assumption of global cosmological homogeneity appears to be corroborated by our "cosmographic" maps.


2.
Galaxy
Number Counts

Galaxy Number Counts

Number counts of galaxies,
ie. the number of galaxies with apparent magntiude m or higher in a certain region of the sky, contain potentially a large of amount of information on the structure of the Universe.

Hubble, in "The Realm of the Nebulae" (1936)
used counts of galaxies to the limit of the Mount Wilson 100-inch telescope to demonstrate that the distribution of galaxies is

HOMOGENEOUS

on the largest cosmological scales

Galaxy Number Counts

Count the number of galaxies in a magnitude limited survey:

- **all galaxies brighter than apparent magnitude m**
- **suppose a population of objects with intrinsic luminosity function**

$$n(L)dL$$

Number density objects with $L \in [L, L+dL]$

- **At a distance r, the flux S for a source of luminosity** $L \in [L, L+dL]$

$$S = \frac{L}{4\pi r^2}$$

Galaxy Number Counts

Survey with limiting flux density S_{lim}:

- **in terms of apparent magnitude m:**

$$m = cst. - 2.5\log_{10} S$$

- **sources of luminosity L have a flux > S out to distance r_S :**

$$r_S = \left(\frac{L}{4\pi S}\right)^{1/2}$$

- **Number of sources of intrinsic luminosity L brighter than S**

→

 # sources within distance r_S and within solid angle Ω

Galaxy Number Counts

For a spatially homogeneous distribution of sources:

- **Number of sources of intrinsic luminosity L brighter than S**

→

 # sources within distance r_{S}, and within solid angle Ω:

$$N(\geq S, L)dL = \frac{\Omega}{3} r_S{}^3 N(L)dL = \frac{\Omega}{3}\left(\frac{L}{4\pi S}\right)^{3/2} n(L)dL$$

- **The total number of sources with flux higher than S is found by integration over the luminosity function of sources,**

$$N(\geq S) = \frac{\Omega}{3(4\pi)^{3/2}} S^{-3/2} \int L^{3/2} n(L)dL$$

Galaxy Number Counts

- Number of sources brighter than flux S:

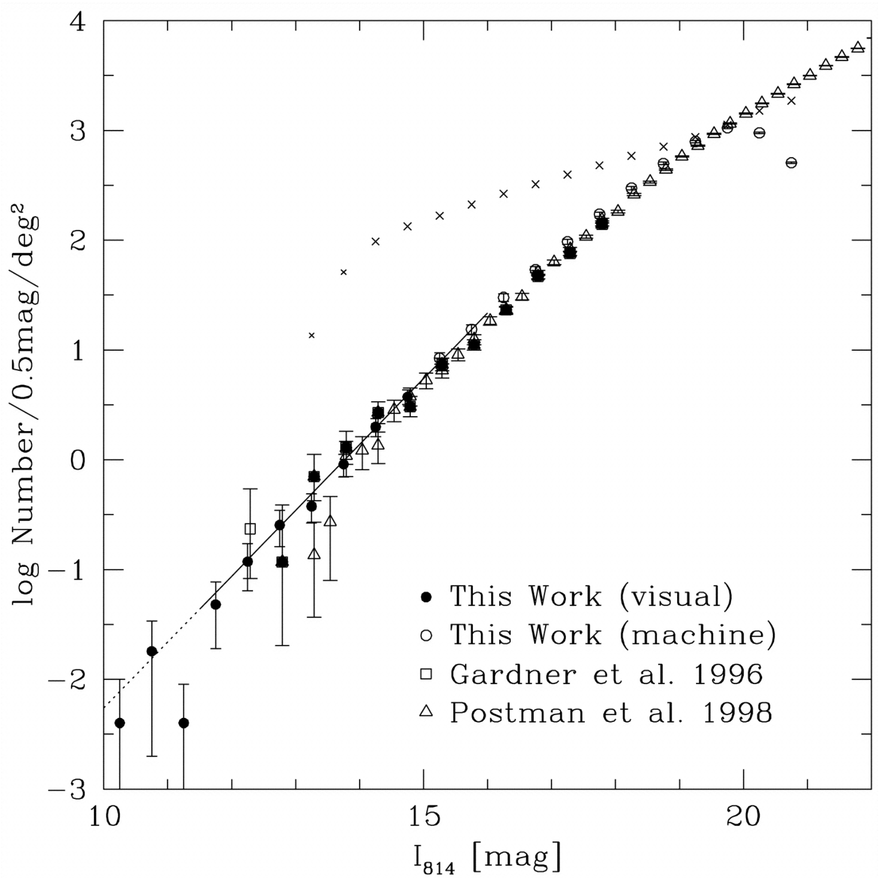
$$N(S) \approx S^{-3/2}$$

- Which in terms of magnitude m, translates into

$$N(m) \approx 10^{0.6m}$$

- Note that this is based upon the assumption of homogeneity !

Galaxy Number Counts



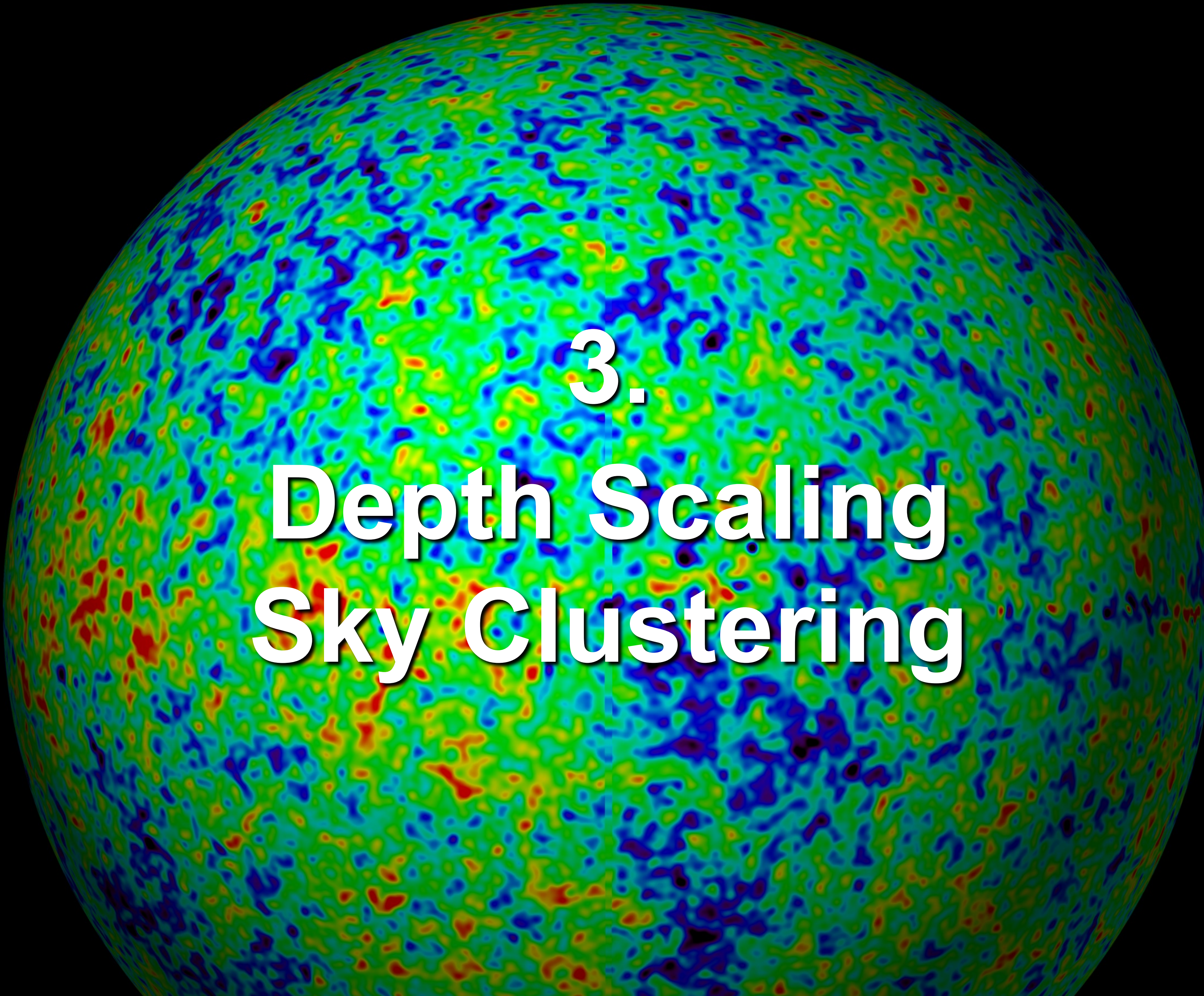
SDSS galaxy number counts:
Impressive example of the accuracy of the $10^{0.6m}$ scaling for homogeneous Univ.

- **Number counts in many galaxy surveys indeed reveal the expected scaling**

$$N(m) \approx 10^{0.6m}$$

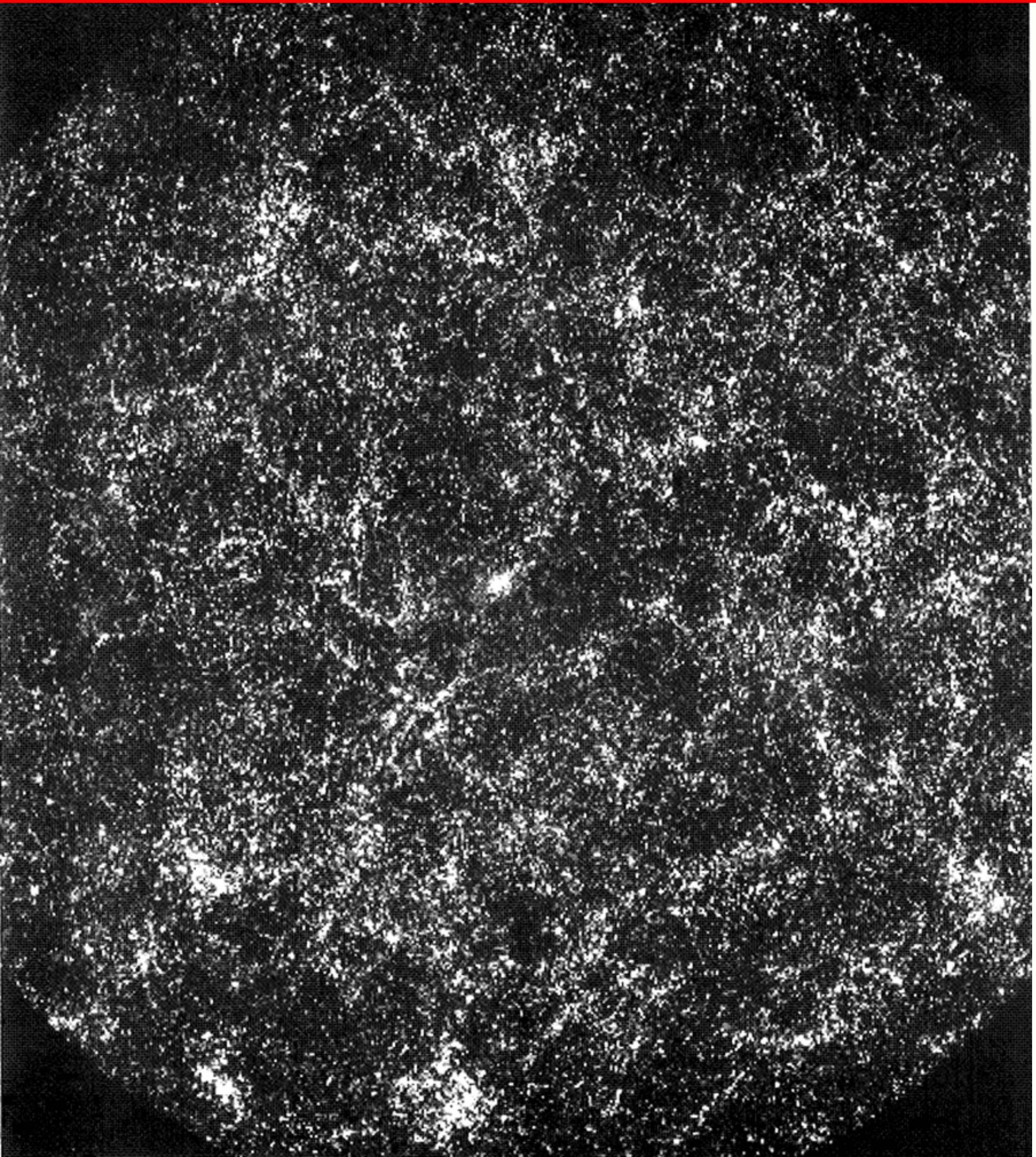
at (relatively) bright magnitudes.

- **At faint magnitudes we are looking at galaxies at high distances, over which distances the effects of the curvature and expansion of the Universe assumes a dominant role.**



3.
Depth Scaling
Sky Clustering

Angular Clustering Scaling



Galaxy sky distribution:

- Galaxies clustered, a projected expression of the true 3-D clustering

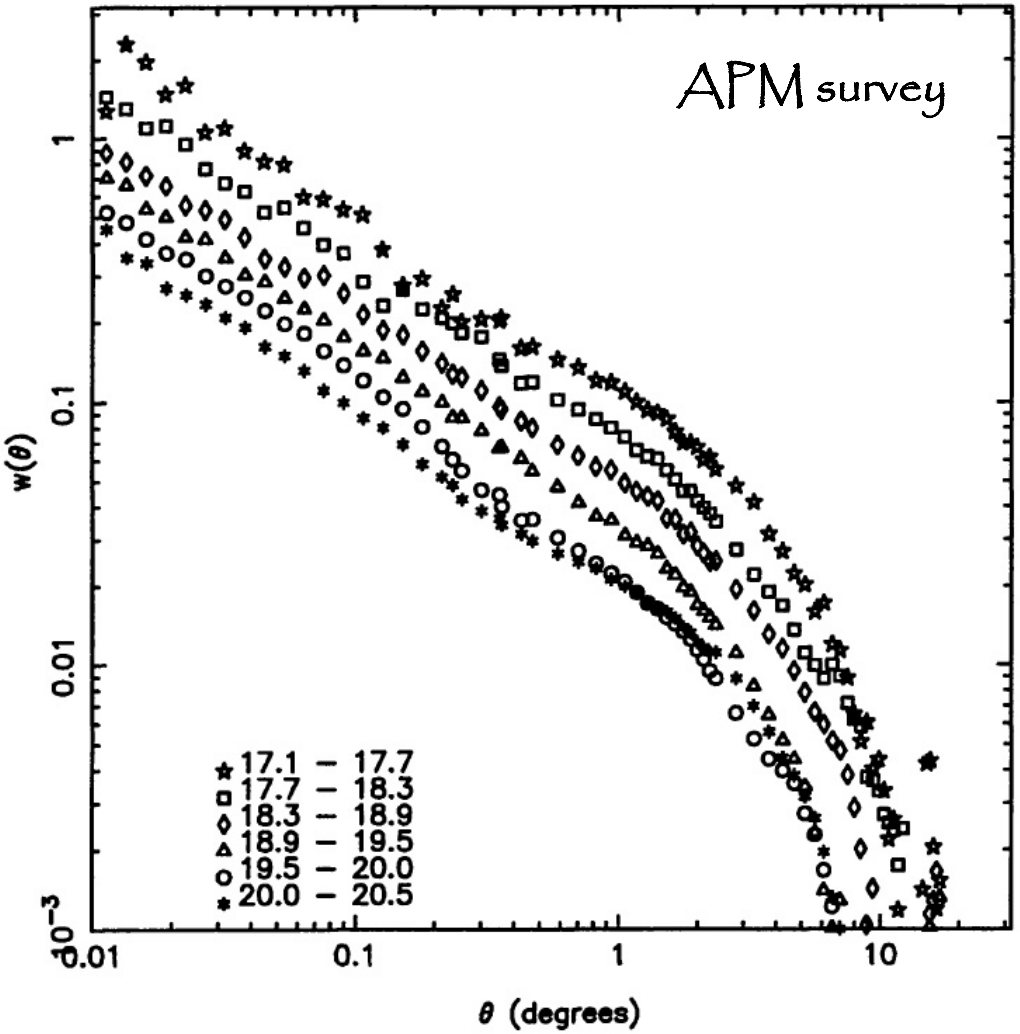
- Probability to find a galaxy near another galaxy higher than average (Poisson) probability

- Quantitatively expressed by 2-pt correlation function w(θ):

$$dP(\theta) = \overline{n}^2 \{1 + w(\theta)\} d\Omega_1 d\Omega_2$$

Excess probability of finding 2 gal's at angular distance θ

Angular Clustering Scaling



Two-point correlation function:

- **small angles: power-law**

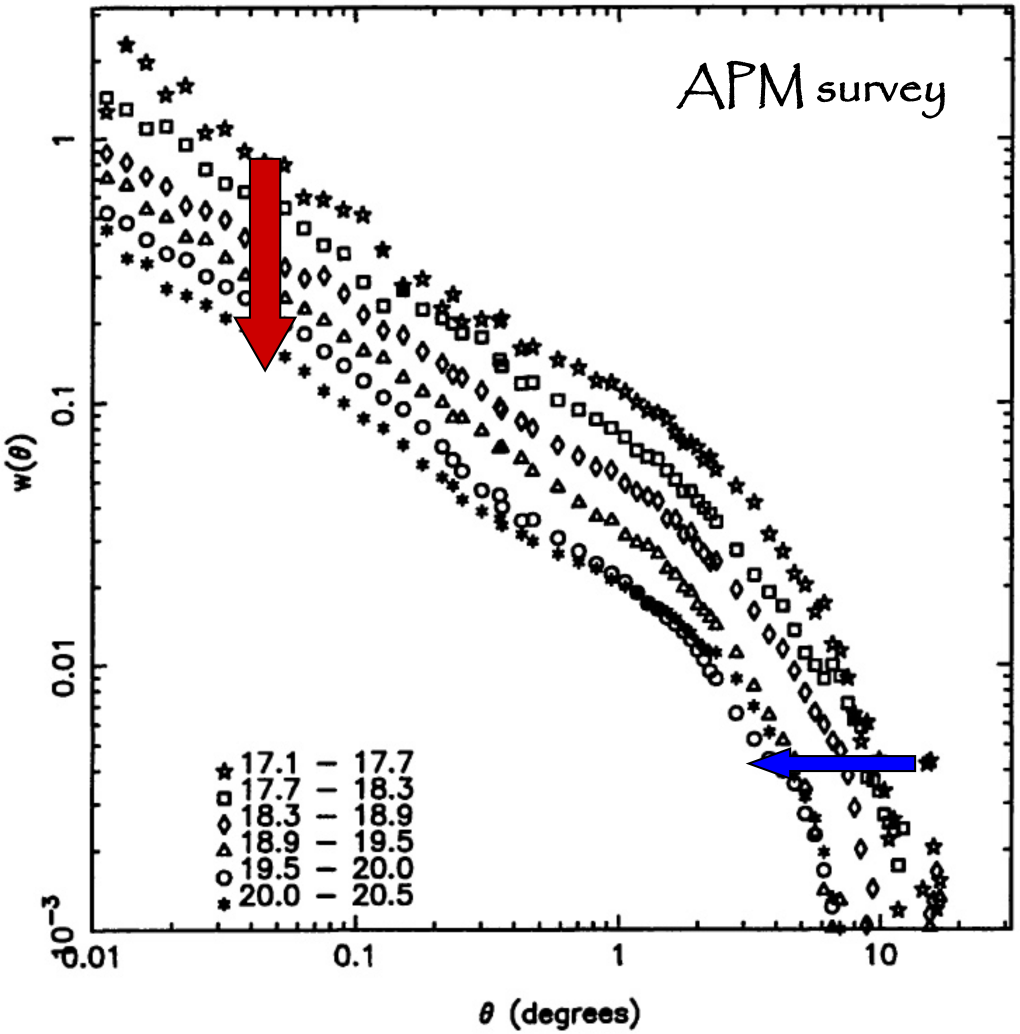
$$w(\theta) = \left(\frac{\theta}{\theta_0}\right)^{\gamma}$$

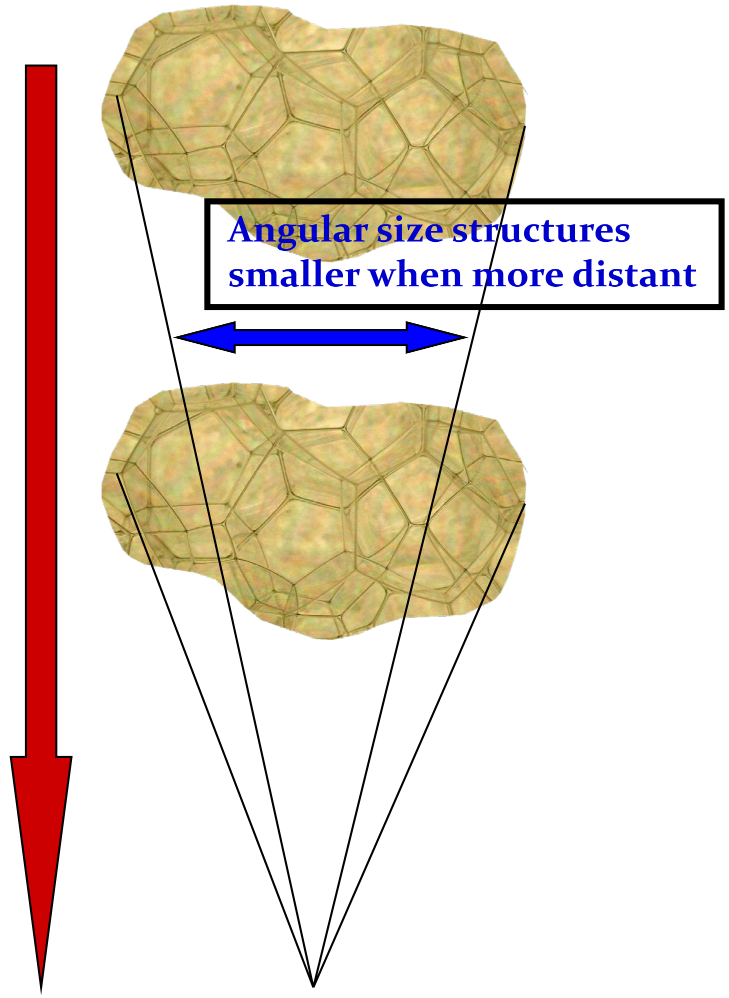
$$\gamma \approx -0.8$$

- **large angles → 0**

ie. to homogeneity

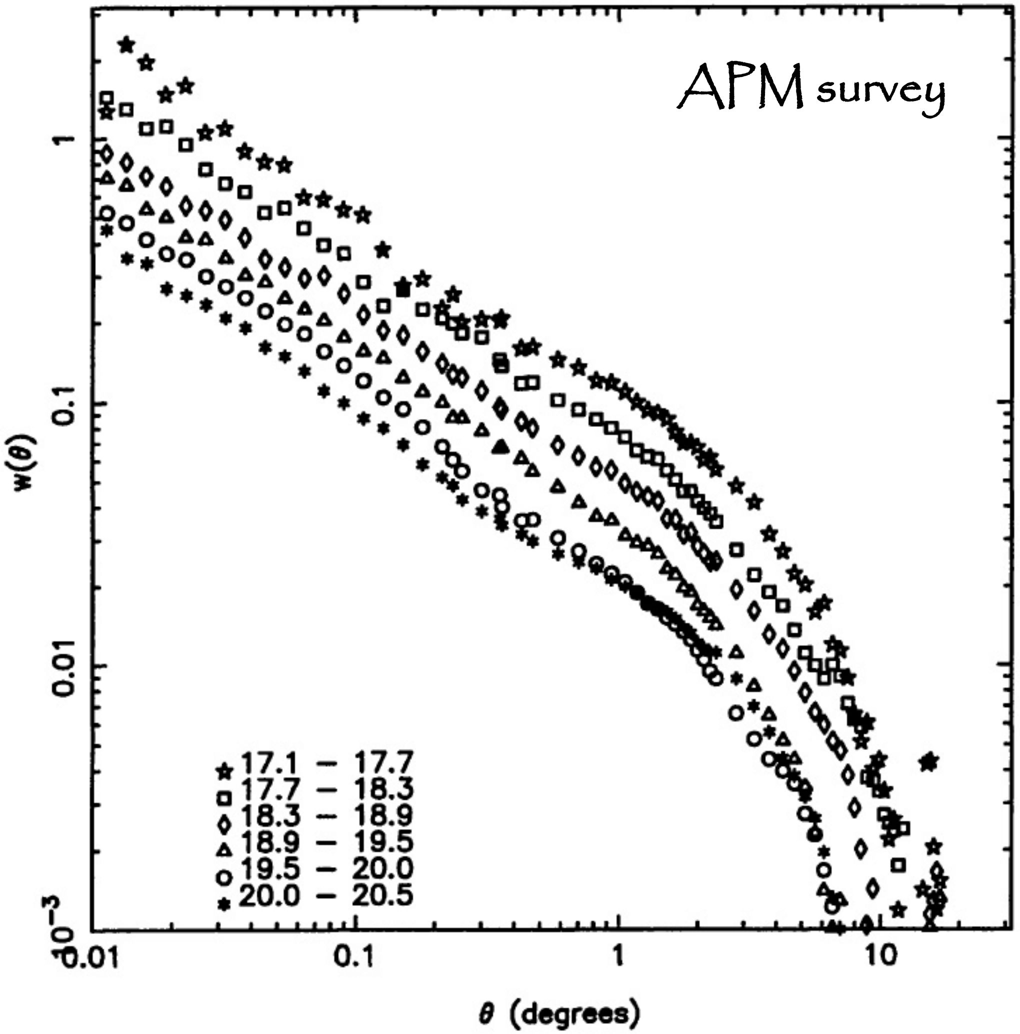
Angular Clustering Scaling





Projection of more layers leads to decreasing amplitude w(θ)

Angular Clustering Scaling

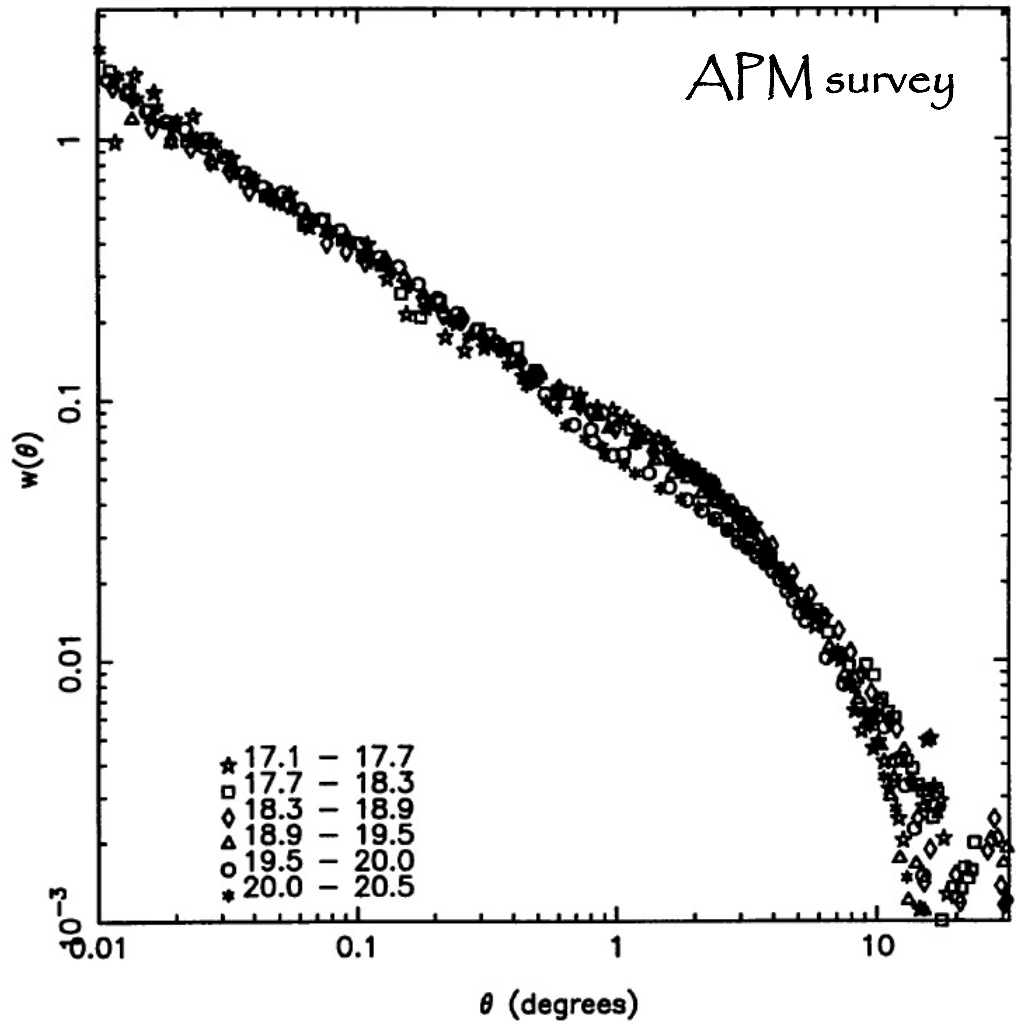


Angular size structures smaller when more distant

Projection of more layers leads to decreasing amplitude w(θ)

$$w(\theta, D_*) = \frac{1}{D_*} w(\theta D_*)$$

Angular Clustering Scaling



Angular size structures smaller when more distant

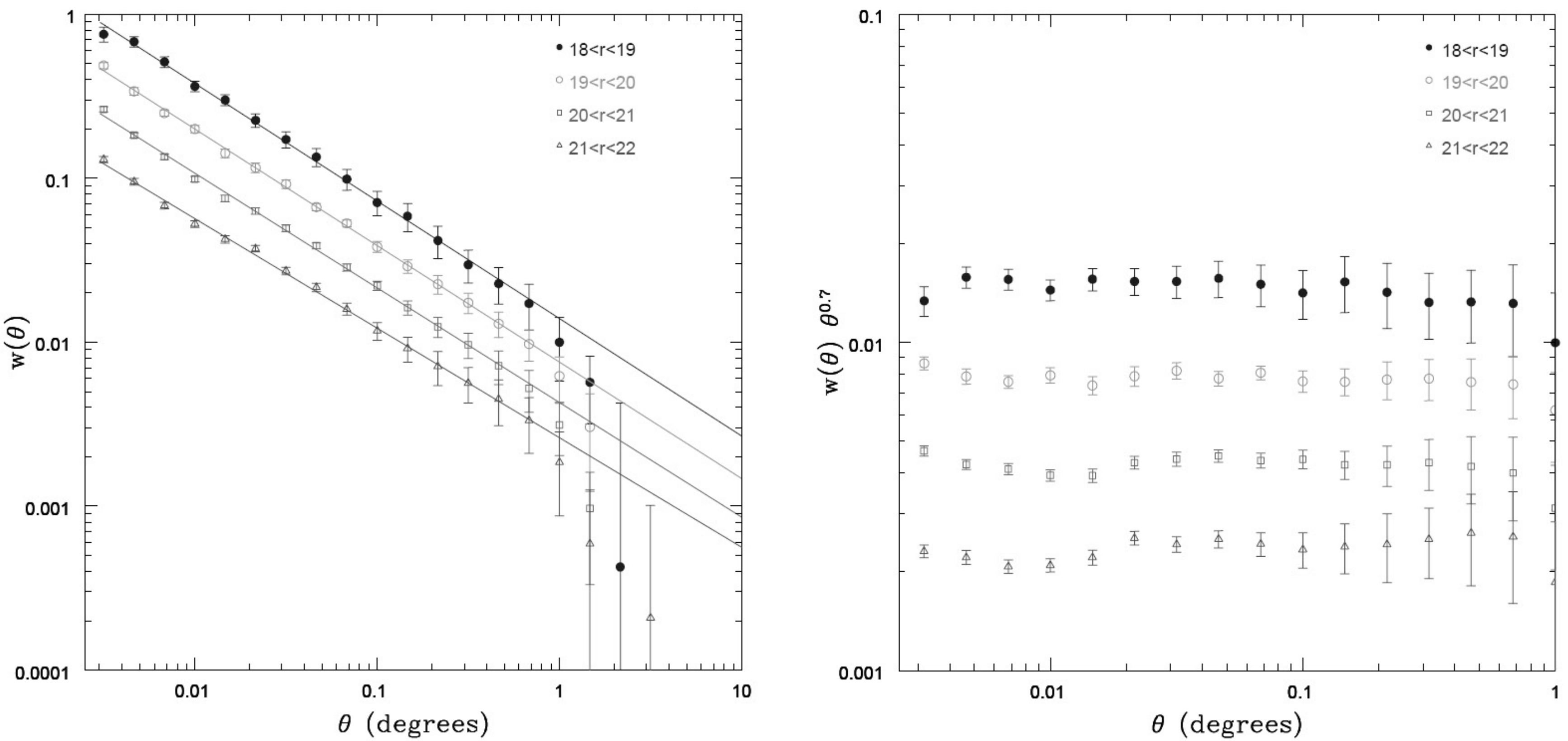
Projection of more layers leads to decreasing amplitude w(θ)

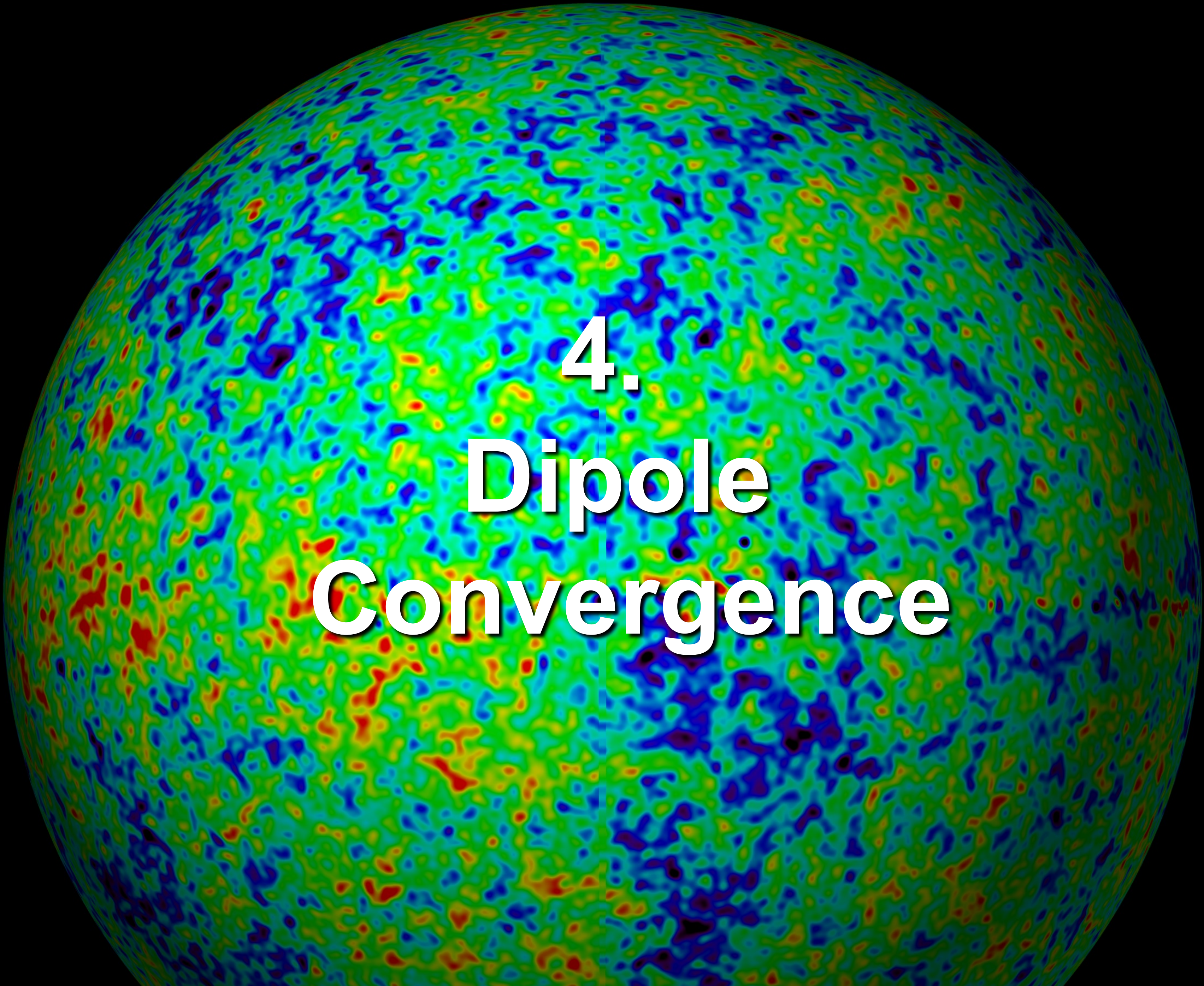
$$w(\theta, D_*) = \frac{1}{D_*} w(\theta D_*)$$

Angular Clustering Scaling

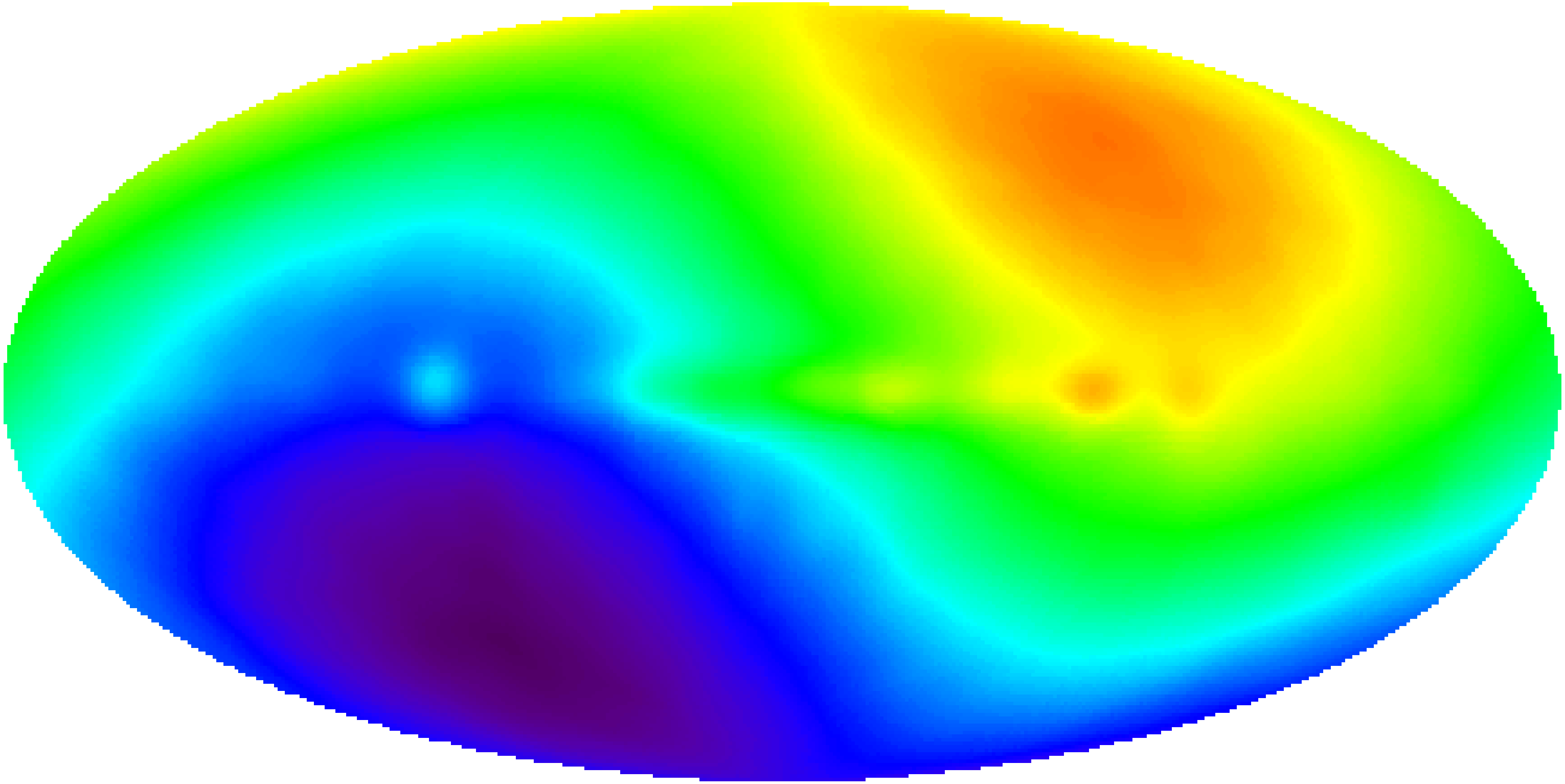
The angular scaling of w(θ) is found back to even fainter magnitudes in the SDSS survey (m=22)

Clear evidence that there are no significant large structures on scales > 100-200 Mpc



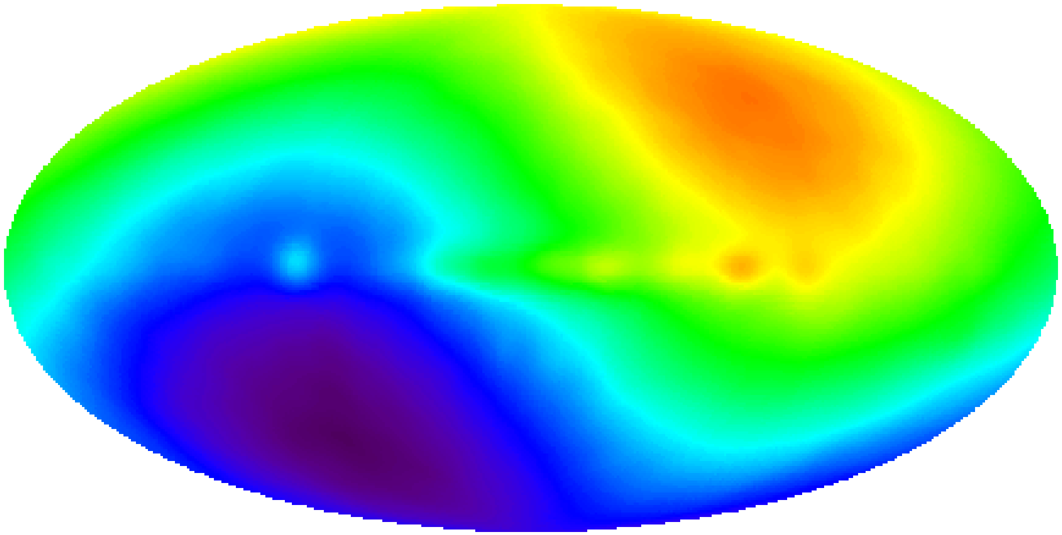

4.
Dipole
Convergence

The CMB Dipole



"Eppur si muove" (Galilei)

The CMB Dipole



The sky map of the CMB has
a clear dipole anisotropy:

- Amplitude: 3.4 mK
- Manifestation of
  Doppler shift CMB radiation:

  result our motion with respect to
  the Universe.

- It reveals a velocity of the Local Group wrt. Universe of

  v_{LG}=627±22 km/s direction: (l,b)=(276°±3,3°±2)

- Question is what and where this motion's origin is.
- It is the result of the gravitational attraction by surrounding matter concentrations.
- The dipole motion is embedded within a coherent shear flow, largely in the direction of the socalled "Great Attractor".

$$\mathbf{v}(\mathbf{x},t) = \frac{H}{4\pi}\frac{f(\Omega_m)}{b} a \int d\mathbf{x}' \, \delta_{gal}(\mathbf{x}',t) \frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3} \tag{158}$$

$$\beta \equiv \frac{f(\Omega_m)}{b} \sim \frac{\Omega_m^{0.6}}{b}$$

Velocity Field

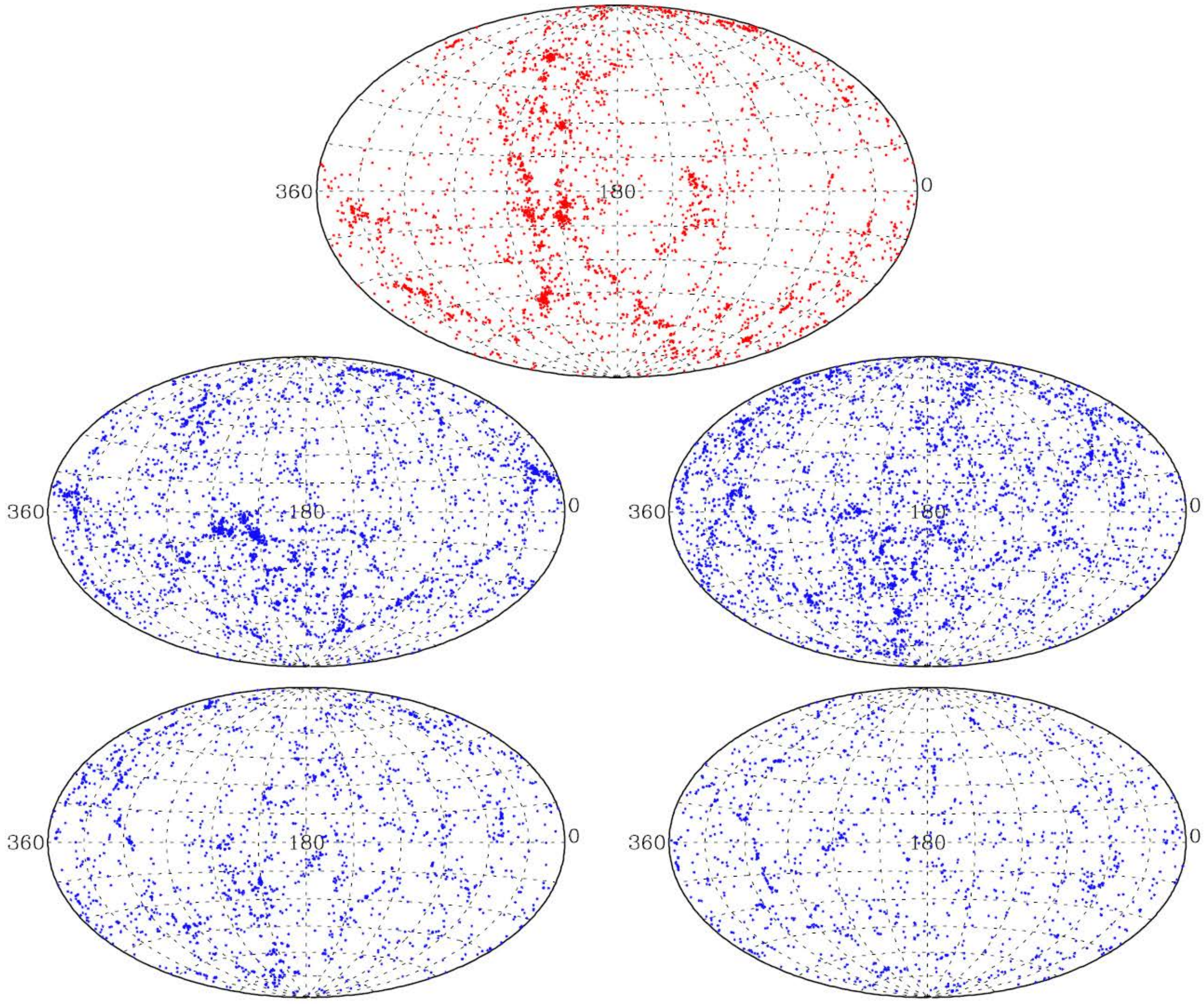
$$v_{\mathrm{LG}} = \frac{H_0 \beta}{4\pi} \int_{\boldsymbol{r}}^{\infty} \mathrm{d}^3 \boldsymbol{r}' \delta_{\mathrm{g}}(\boldsymbol{r}') \frac{\boldsymbol{r}' - \boldsymbol{r}}{|\boldsymbol{r}' - \boldsymbol{r}|^3}$$

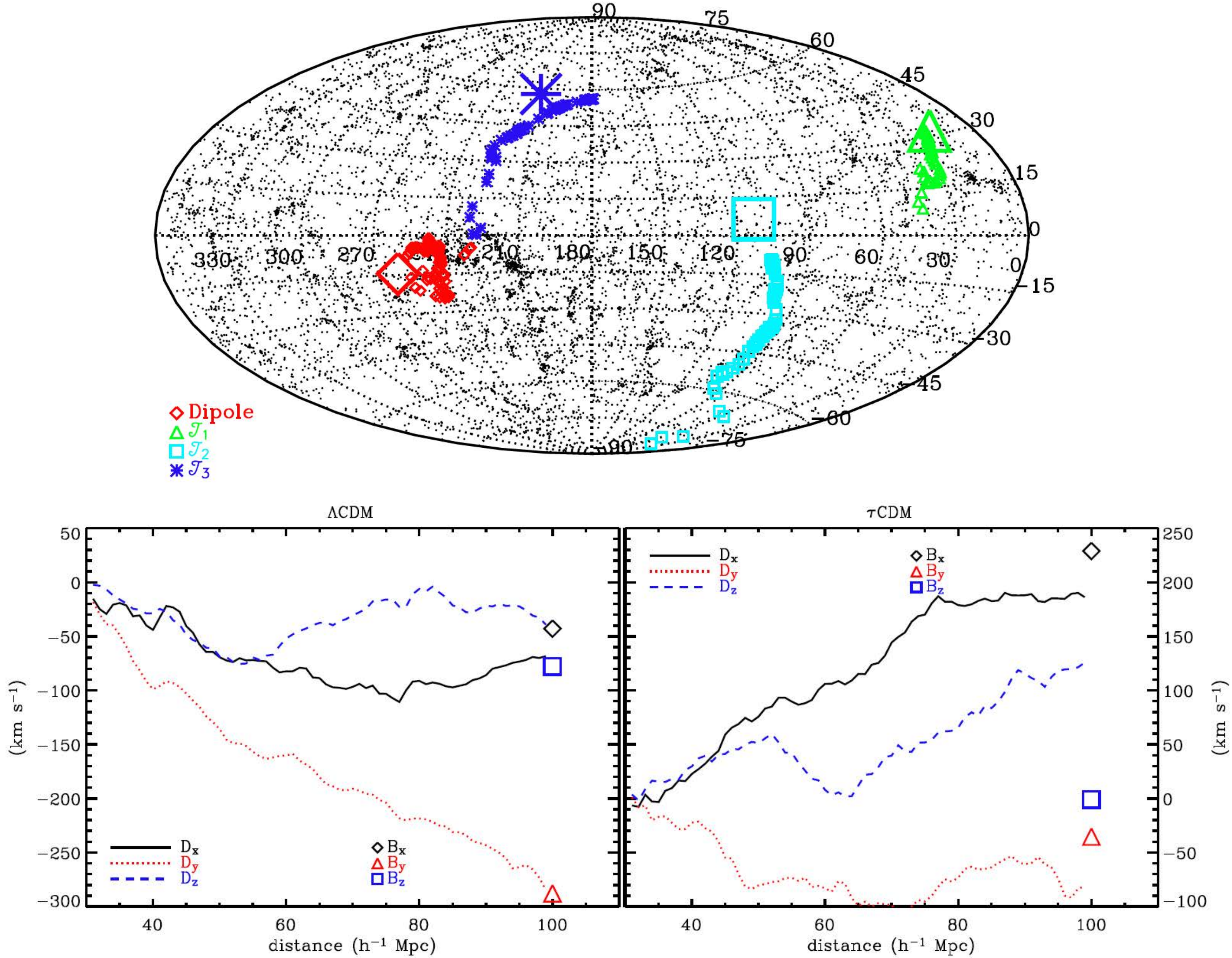
$$\Downarrow$$

$$\boldsymbol{v}(\boldsymbol{r}) = \frac{H_0 \beta}{4\pi \bar{n}} \sum_{i}^{N} \frac{w_i \hat{\boldsymbol{r}}_i}{r_i^2}$$

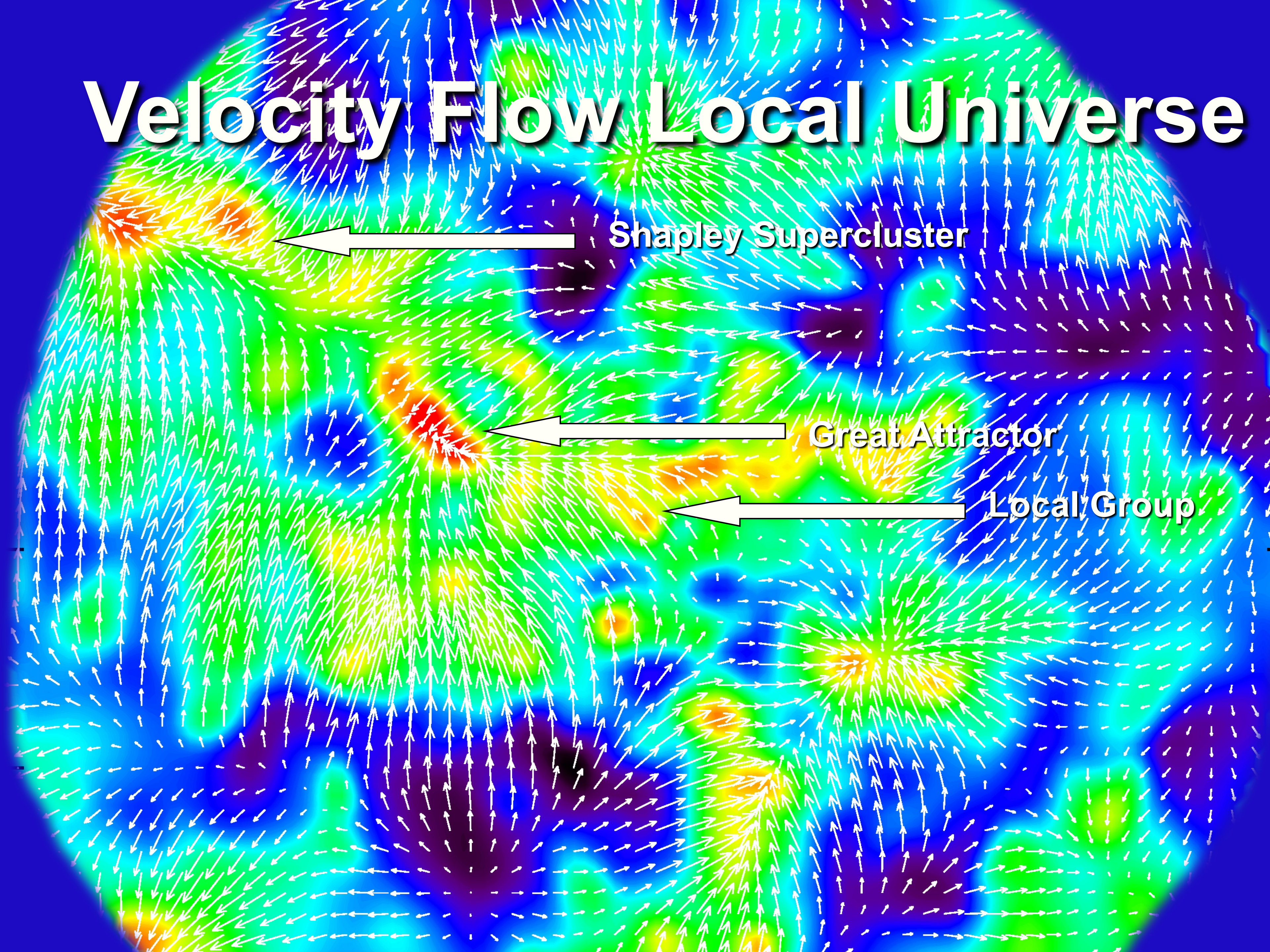
ΛCDM PSCZ+NGB mock catalog

d_{sur}: [0−30], [30−55], [55−70], [70−85], [85−100]h^{-1} Mpc

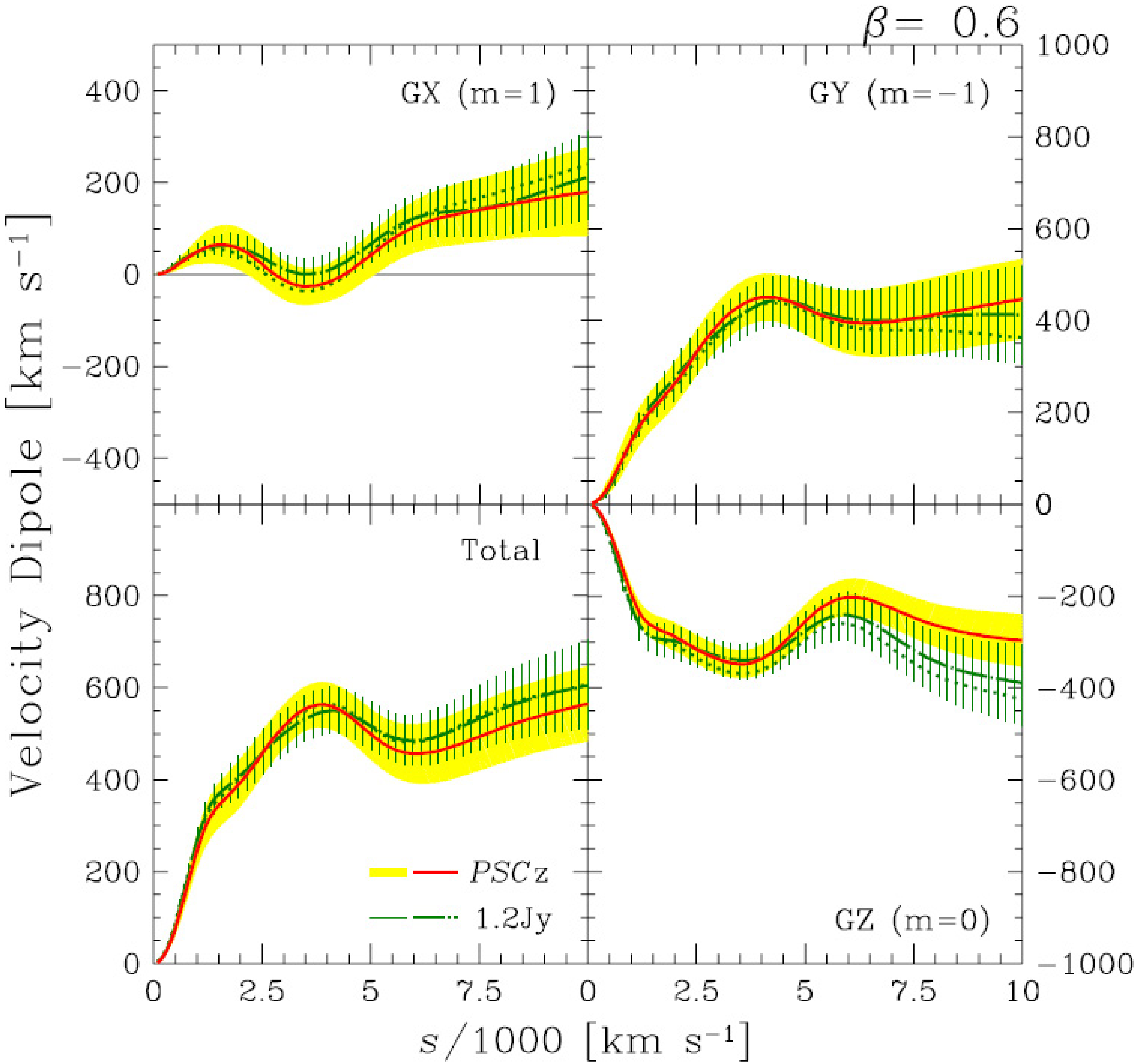




Dipole
$\mathcal{J}_1$
$\mathcal{J}_2$
$\mathcal{J}_3$
ΛCDM
τCDM
(km s^{-1})
distance (h^{-1} Mpc)
D_x
D_y
D_z
B_x
B_y
B_z


Velocity Flow Local Universe
Shapley Supercluster
Great Attractor
Local Group

PSCz dipole


β= 0.6
GX (m=1)
GY (m=−1)
Total
GZ (m=0)
PSCz
1.2Jy
Velocity Dipole [km s−1]
s/1000 [km s−1]
400
200
0
−200
−400
800
600
400
200
0
1000
800
600
400
200
0
−200
−400
−600
−800
−1000
0
2.5
5
7.5
0
2.5
5
7.5
10