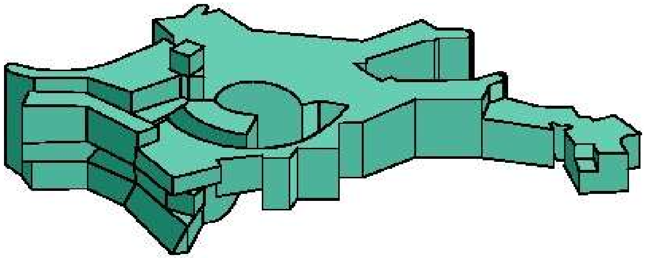


Lindau, April 2004

Formation of galaxies and other cosmic structures

Simon D.M. White
Max Planck Institute for Astrophysics

New Insights into Structure Formation

I Mapping the initial conditions

II Discovery of the accelerated expansion

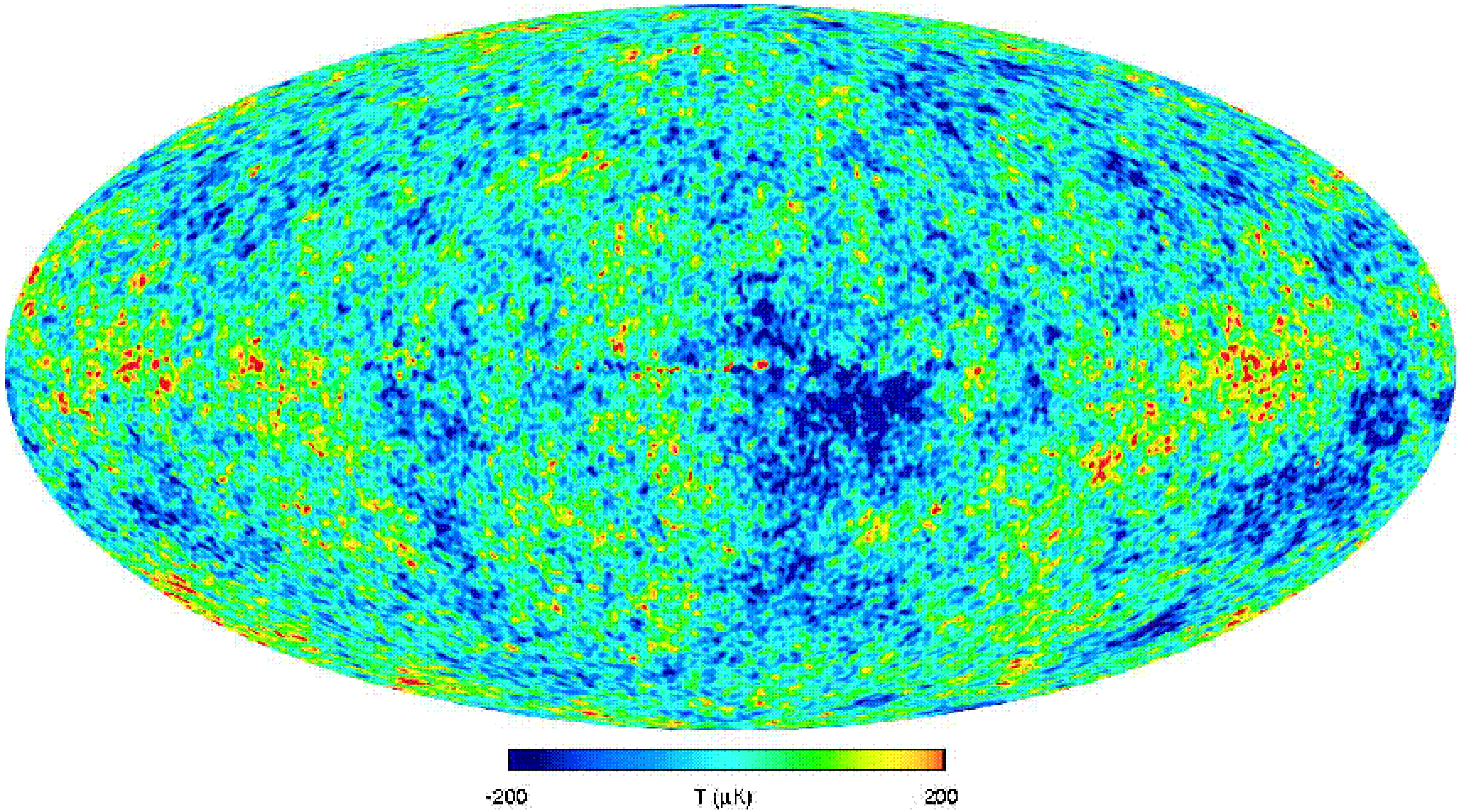
III Mapping large volumes of the present Universe

IV Seeing the dark matter

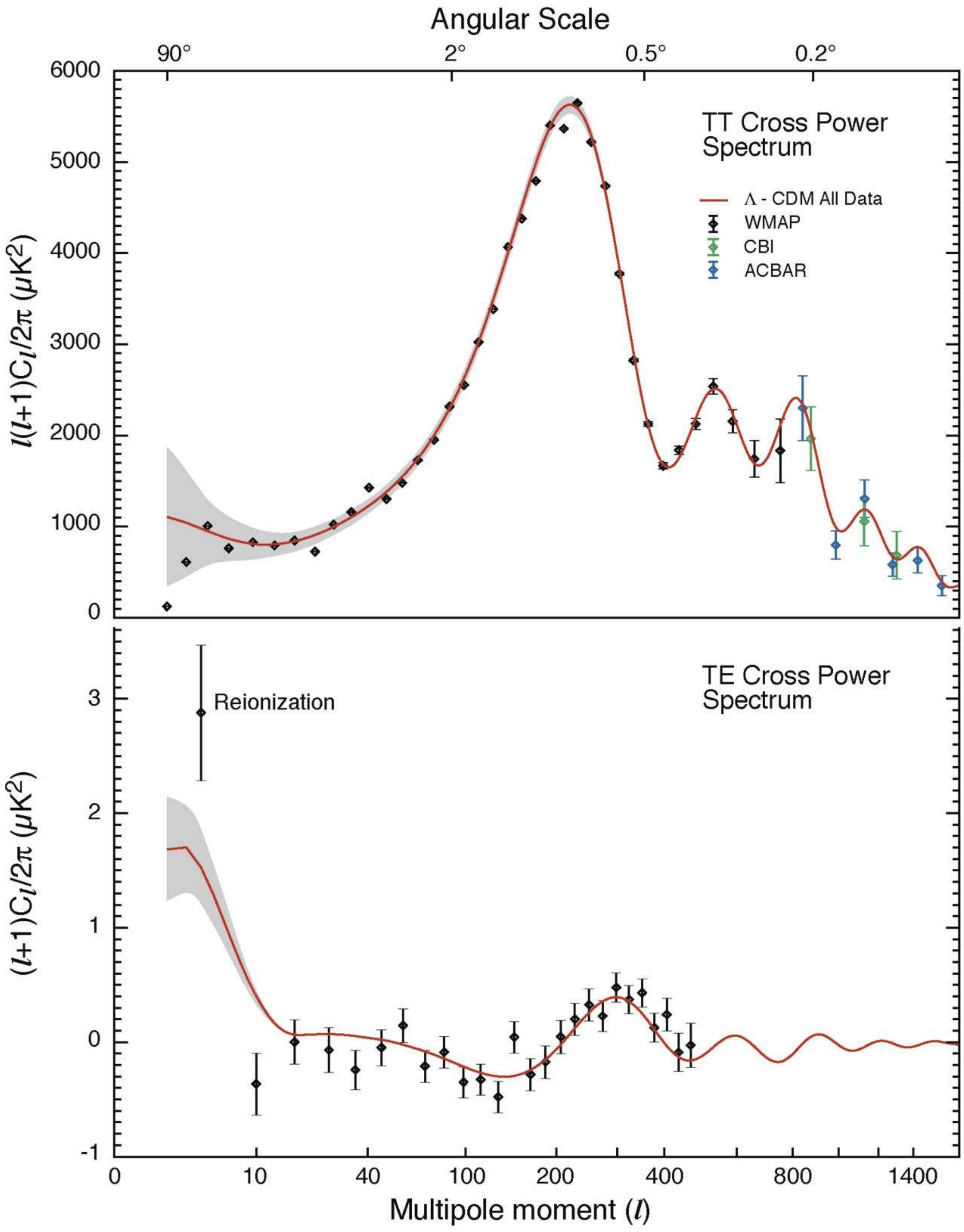
V Mapping pregalactic baryons

VI Looking back to the youth of galaxies

The *WMAP* of the whole CMB sky



Bennett et al 2003



The Emergence of the Cosmic Initial Conditions

- Temperature-temperature and temperature-E-polariz'n power spectra for *WMAP* and interferometers

- Best flat ΛCDM model has:

  (Bennett et al 2003)

  $t_o = 13.7 \pm 0.2$ Gyr

  $h = 0.71 \pm 0.03$ $\sigma_8 = 0.84 \pm 0.04$

  $\Omega_t = 1.02 \pm 0.02$ $\Omega_m = 0.27 \pm 0.04$

  $\Omega_b = 0.044 \pm 0.004$

  $\tau_e = 0.17 \pm 0.07$

- Parameters in excellent agreement with earlier data

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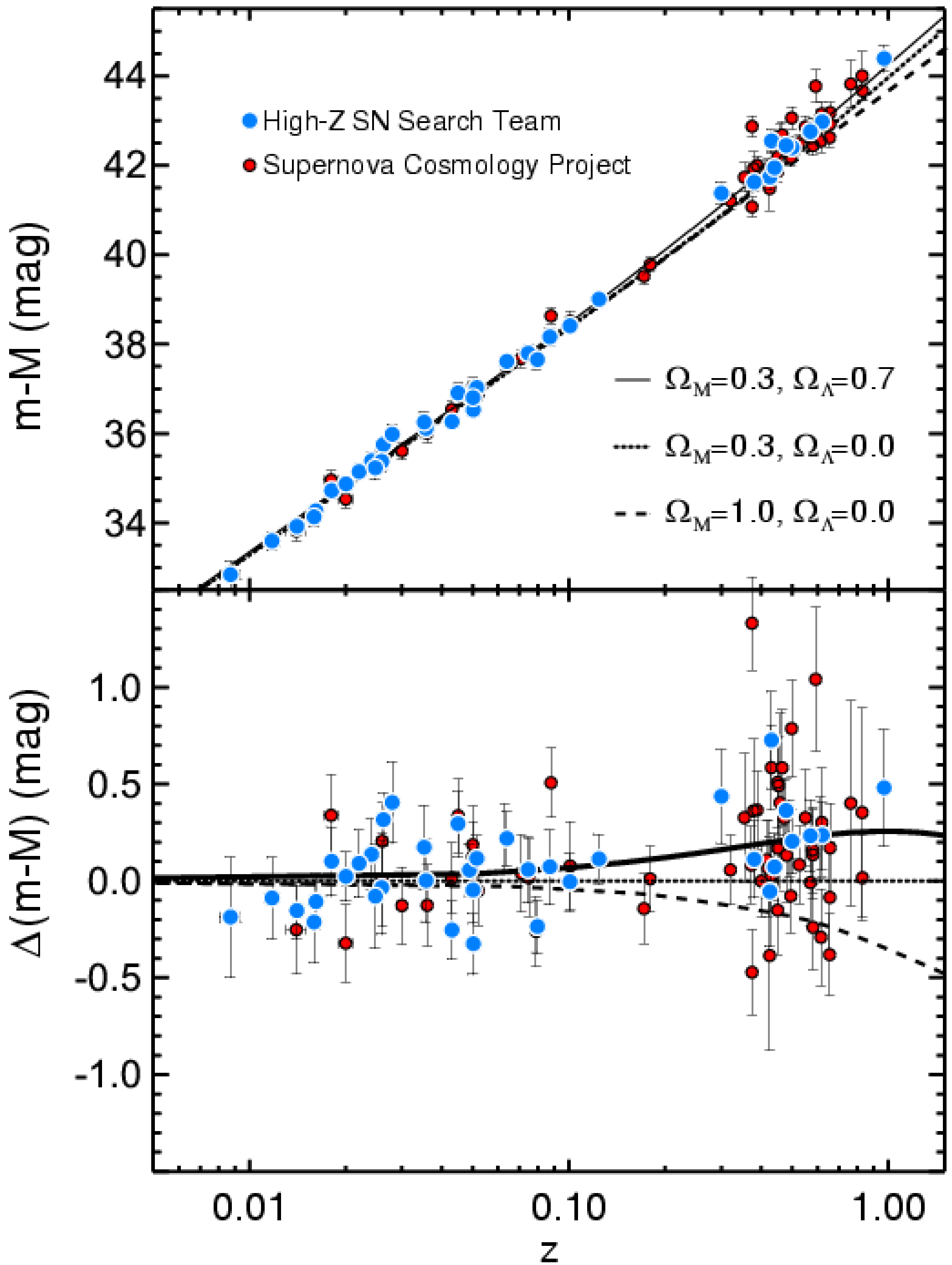

An accelerating Universe

State of the observations 2003

- Distant supernovae appear less bright than expected

↓

- Today the cosmic expansion is accelerating *not* slowing down

↓

- The dominant contribution to the cosmic mass/energy budget must have *negative* pressure

$$\ddot{R} / R = -4\pi/3\ G\ (\rho + 3\ p)$$

Dark Energy, Quintessence, a Cosmological Constant?

New Insights into Structure Formation

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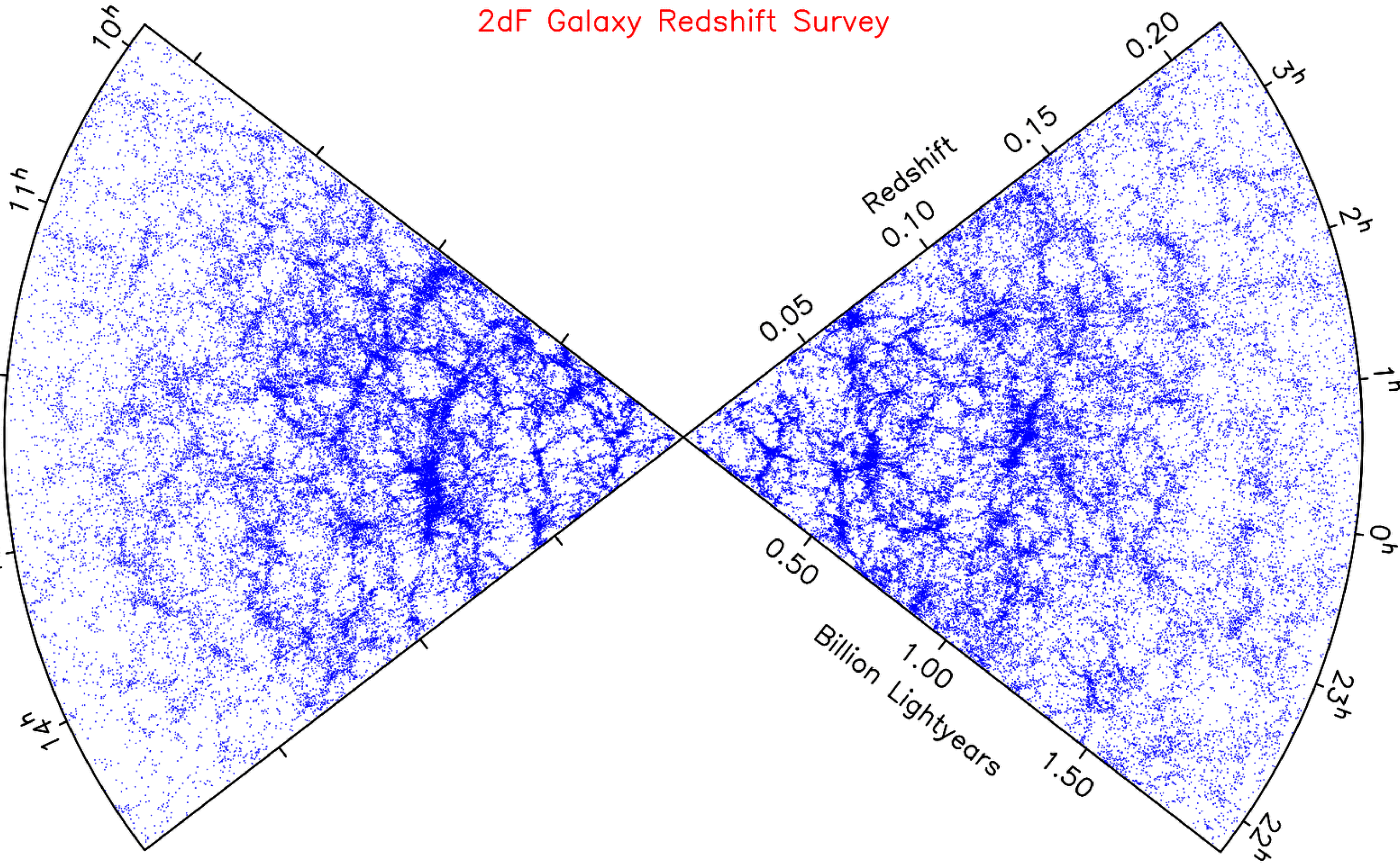
Local large-scale structure



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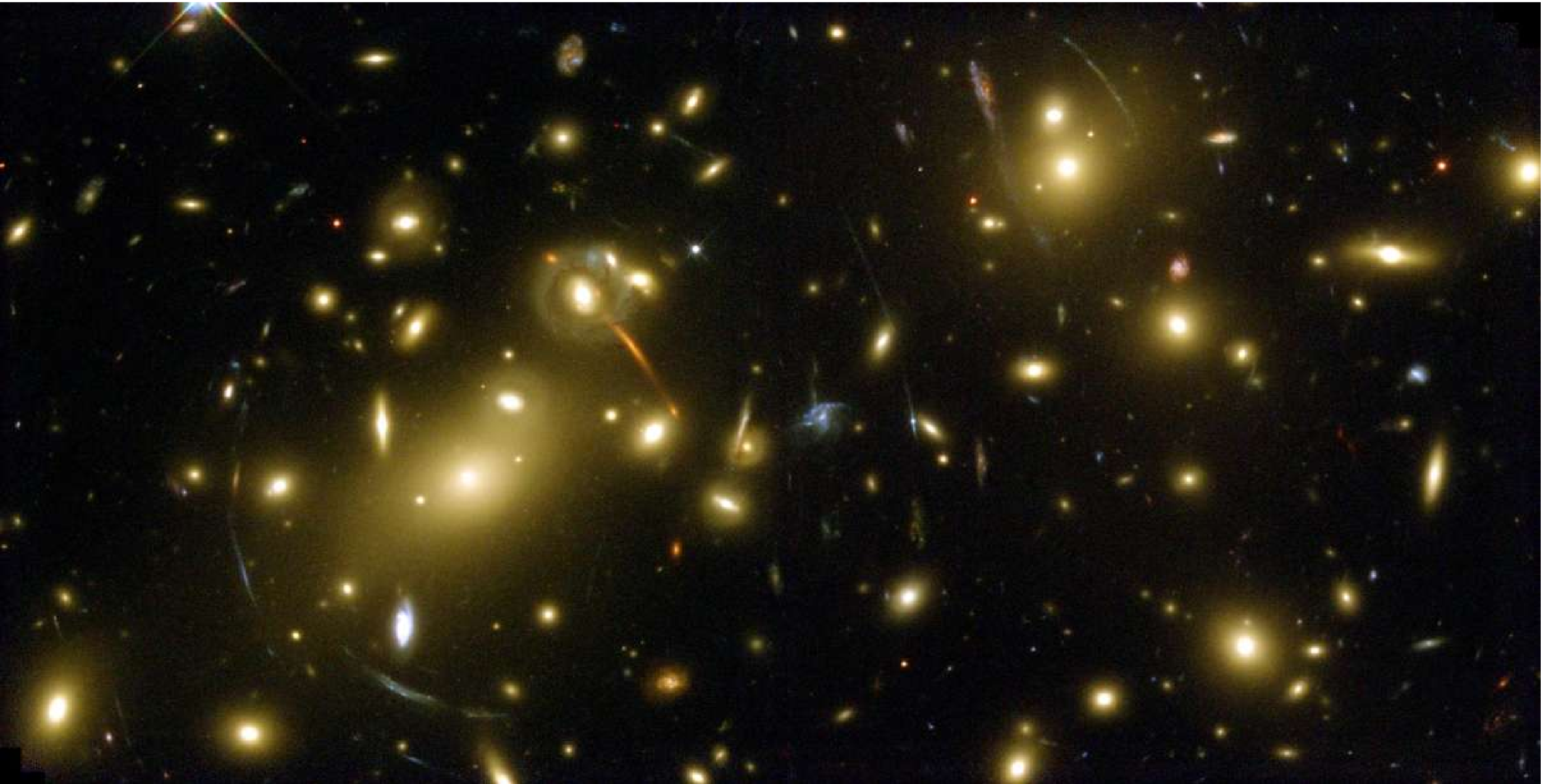
Gravitational lensing by a galaxy cluster

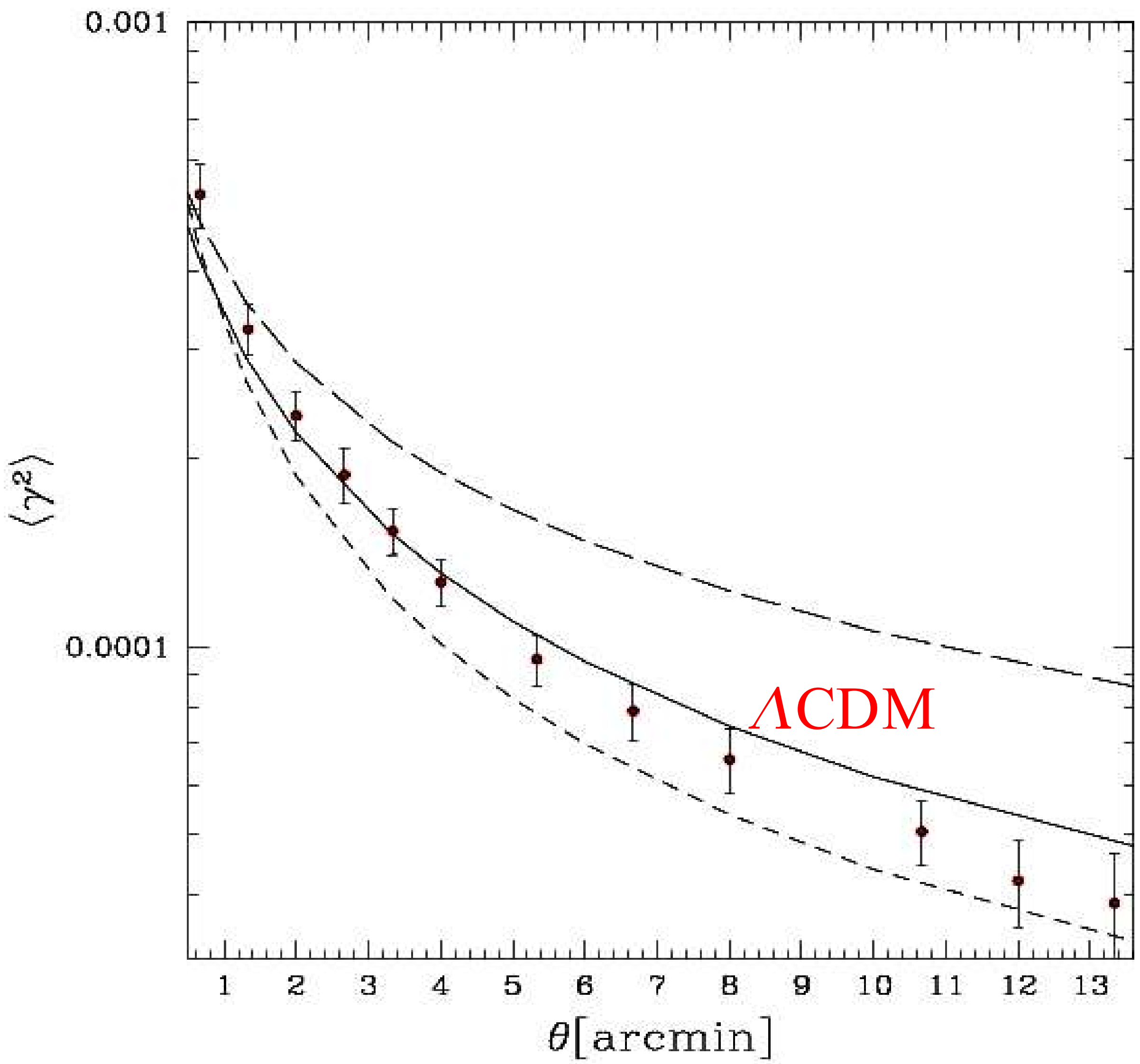
Abell 2218   z=0.17



A measurement of dark matter clustering

Van Waerbeke et al 2001

- $<\gamma^2>$ is the mean square gravitational shear of background galaxy images within circles of radius ϑ.
- It is proportional to the mean square lensing mass within these circles



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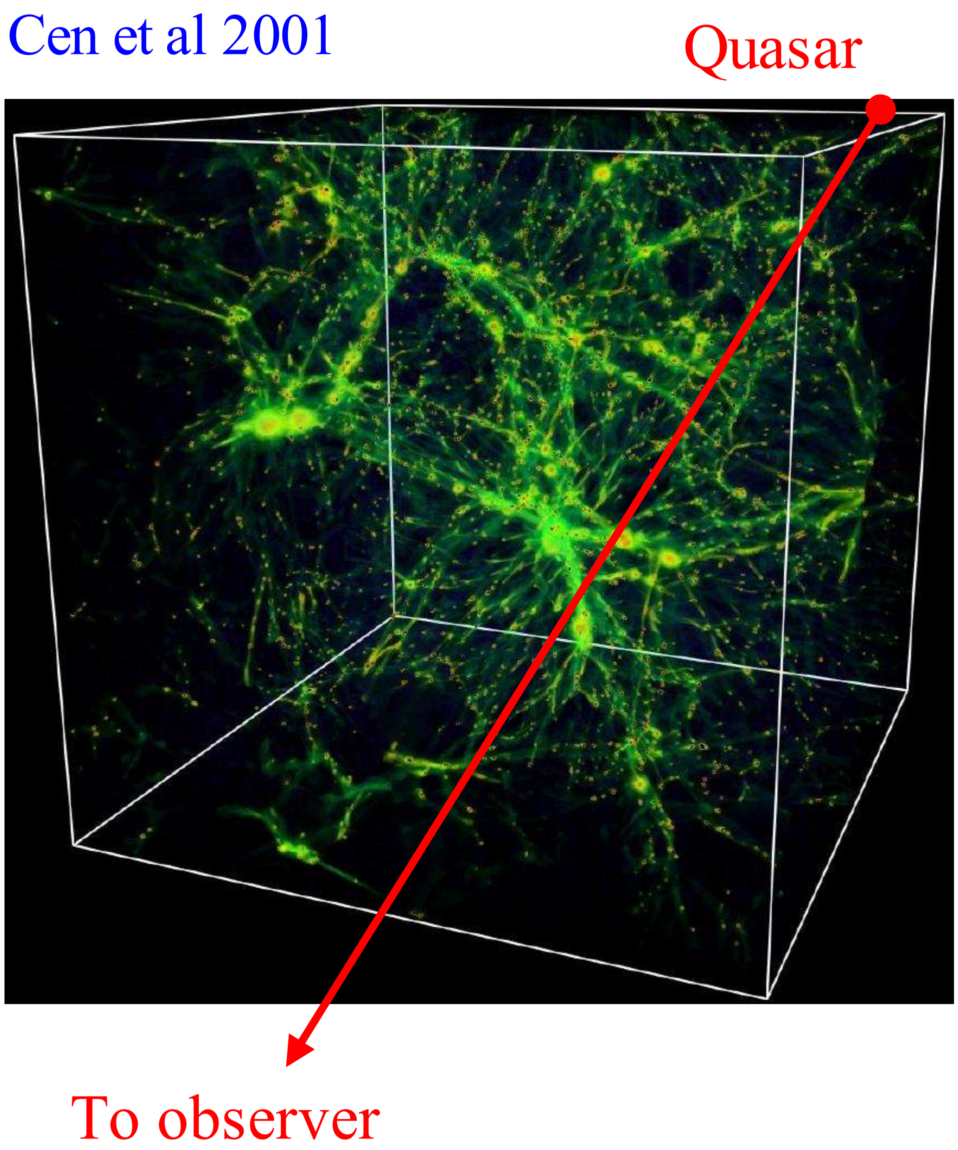
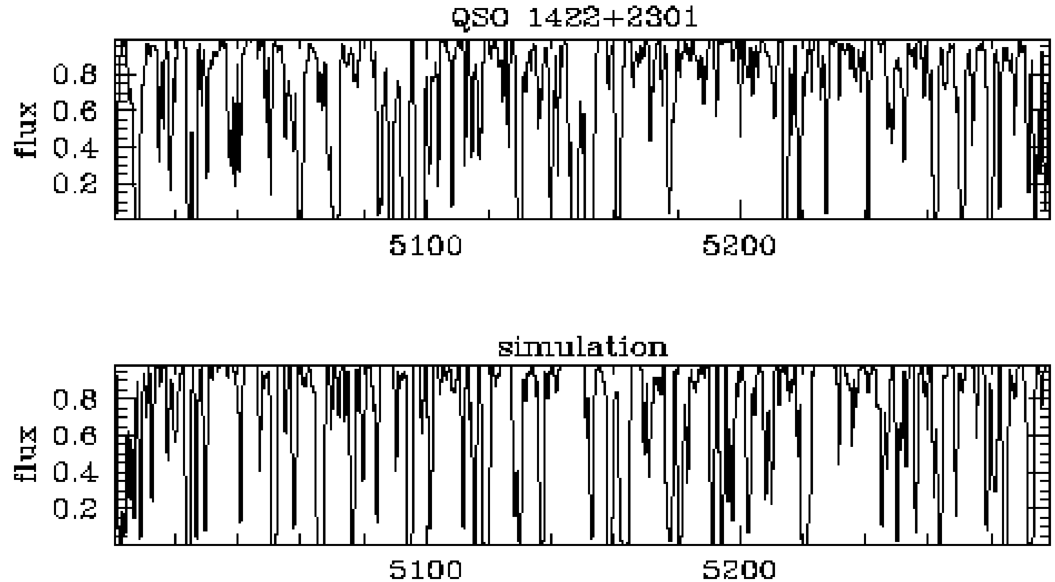
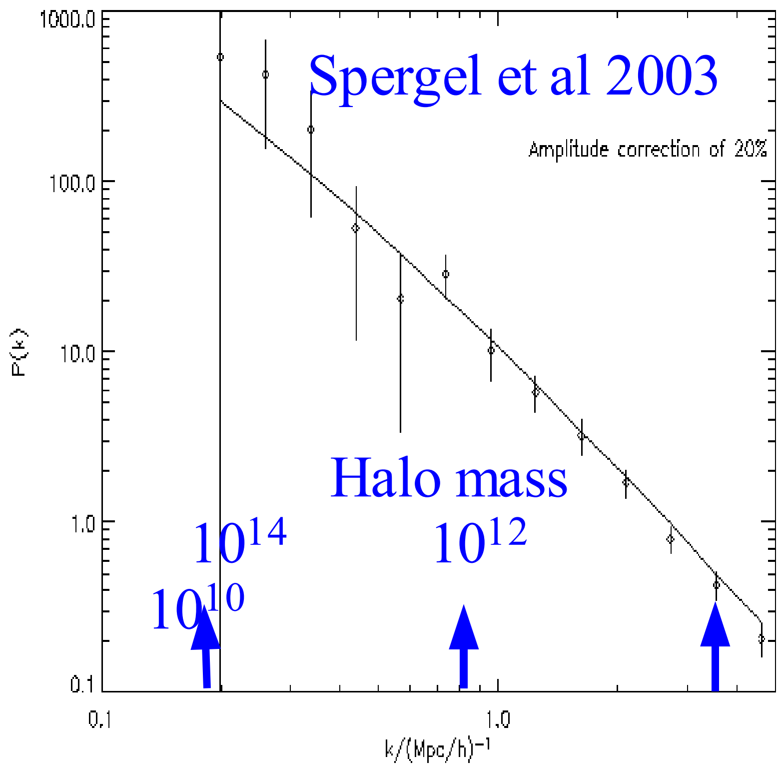
Structure in the intergalactic medium





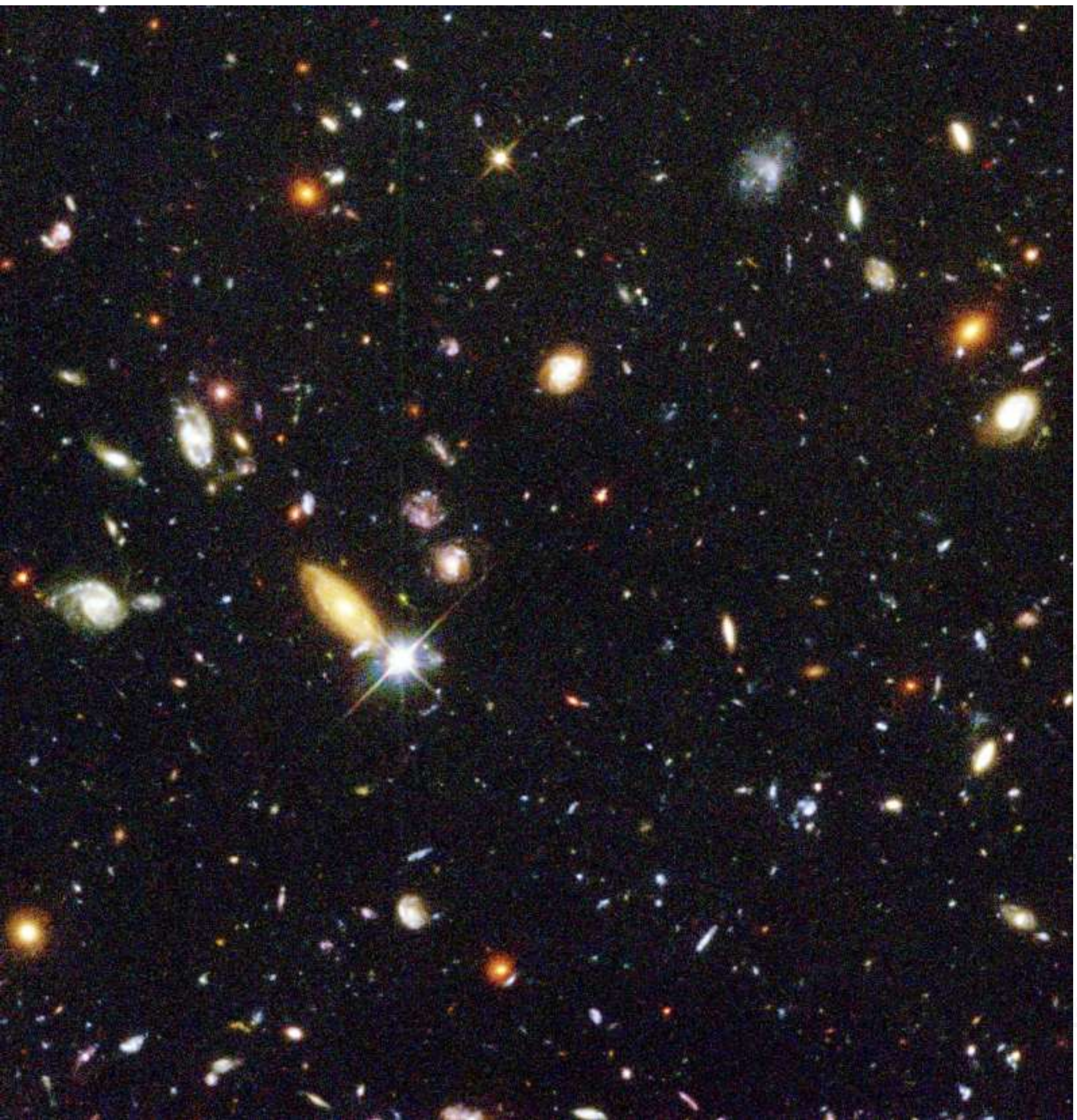


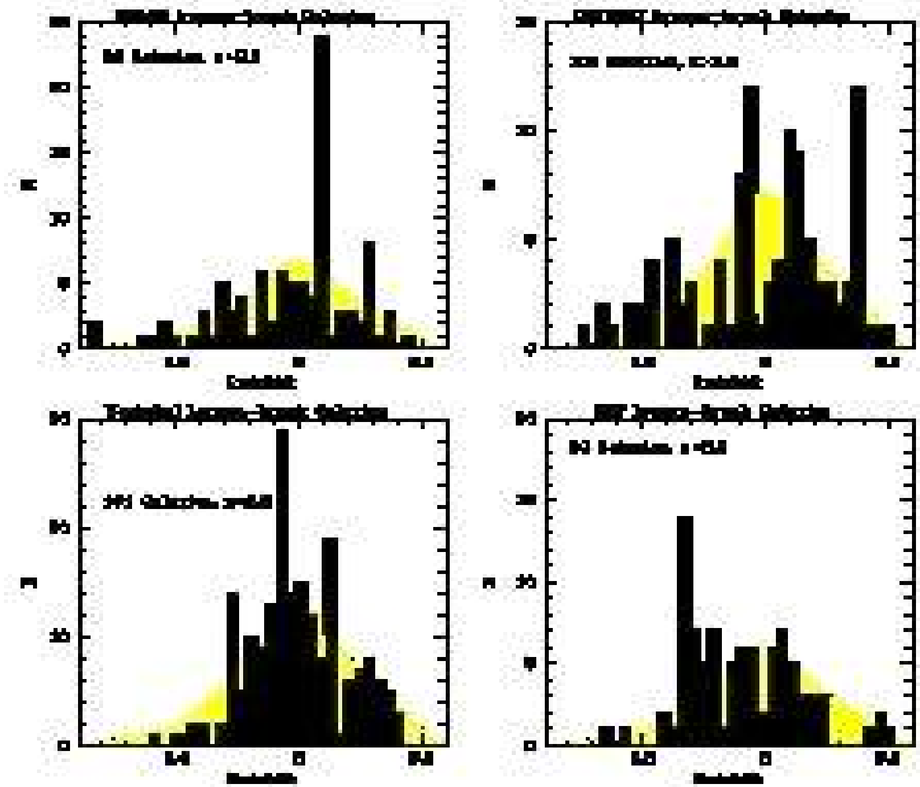
New Insights into Structure Formation

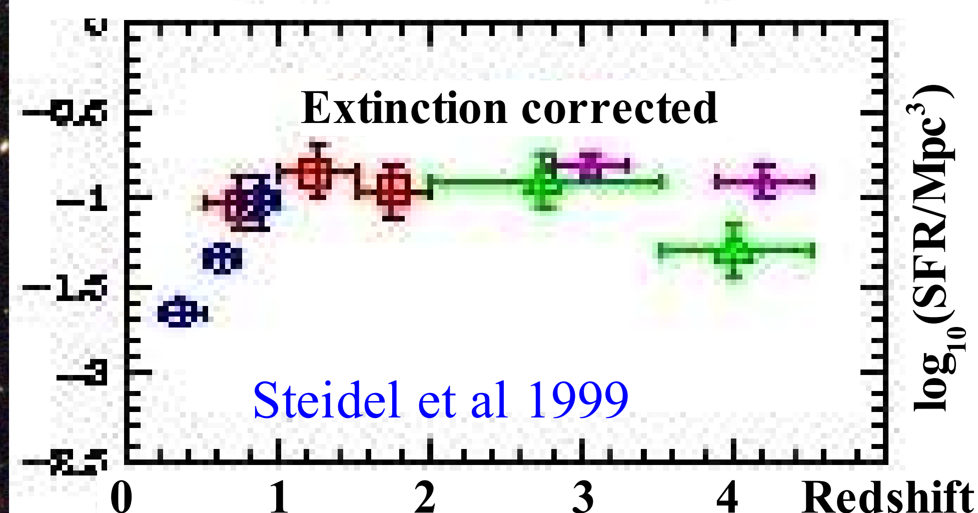
- **I** Mapping the initial conditions
- **II** Discovery of the accelerated expansion
- **III** Mapping large volumes of the present Universe
- **IV** Seeing the dark matter
- **V** Mapping pregalactic baryons
- **VI** Looking back to the youth of galaxies

Young galaxies and the cosmic star formation history

The Hubble Deep Field







New Insights into Structure Formation

I Mapping the initial conditions (z=1000, t=300,000yr)

II Discovery of the accelerated expansion (z<2)

III Mapping large volumes of the present Universe

IV Seeing the dark matter (z<1)

V Mapping pregalactic baryons (z=2 to 6)

VI Looking back to the youth of galaxies (z=1 to 5)

These diverse epochs and phenomena can be linked by simulating evolution in the standard paradigm

A standard paradigm for cosmic evolution

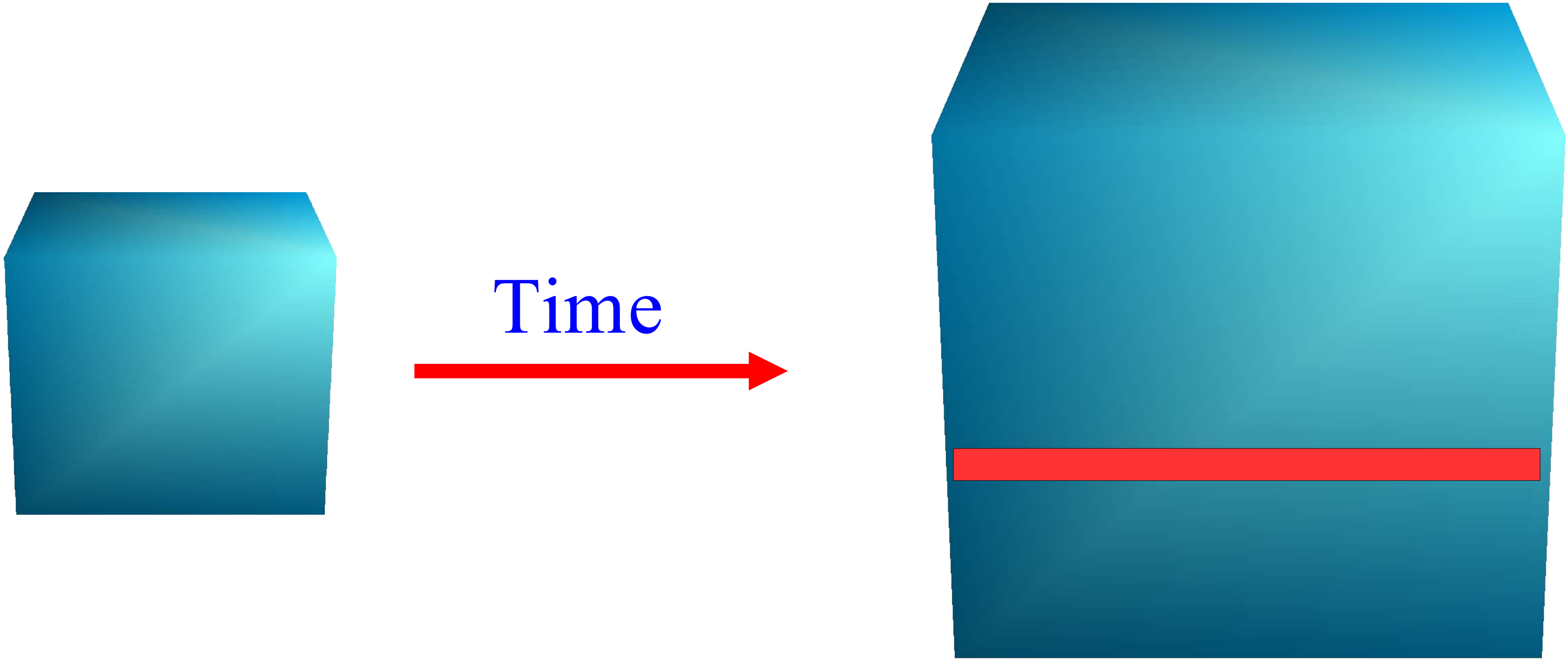
- The Universe began about 14 Gyrs ago in an almost uniform and isotropic Hot Big Bang
- All structure originated as zero-point fluctuations of a free quantum field during an early ($\sim 10^{-30}$s) period of inflation
- The current mass/energy content of the Universe is:
  - -- 70% 'dark energy' (cosmological constant or quintessence?)
  - -- 30% cold dark matter (axions, neutralinos,...?)
  - -- 4% baryonic matter (of which 1/10 lies in galaxies)
  - -- 0.1% neutrinos
  - -- 0.01% radiation (the cosmic microwave background)
- Structure growth is driven (almost) entirely by gravity
- Galaxies form when gas cools and condenses within the potential wells of dark matter 'halos'

What are simulations good for?

- To gain intuition and to make precise predictions for behaviour in the nonlinear regime
- To model observational effects
  - -- selection bias
  - -- visual appearance
  - -- effects of observational errors
  - -- "cosmic variance"
- To extrapolate into (as yet) unobserved regimes
  - -- smaller scales
  - -- higher redshifts
- To understand links between high and low z objects

Utility of results is usually limited by accuracy with which observables are modelled (M_B, B-V, r_{eff}, τ_{HI}, L_X, T_X...).

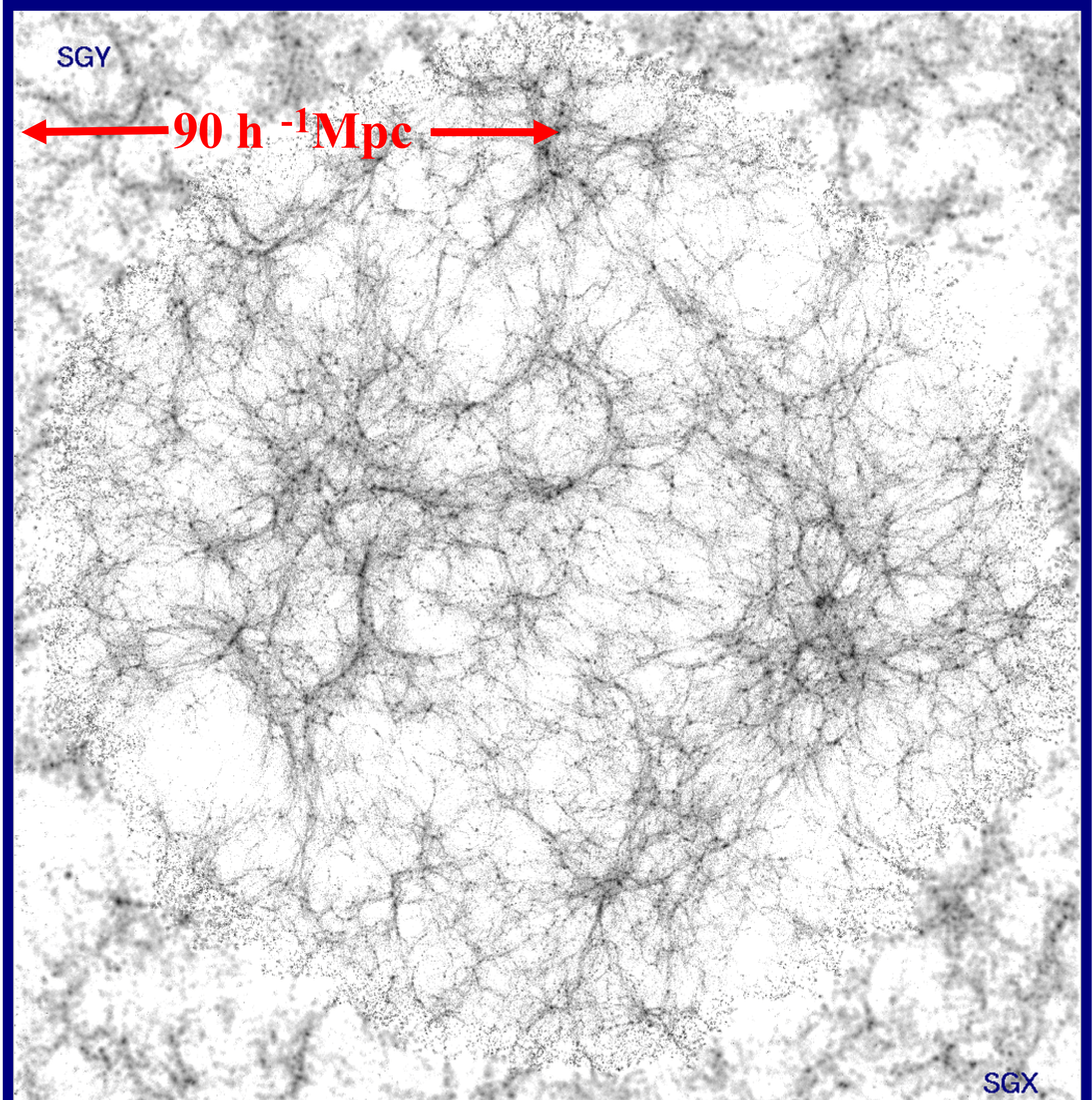
Evolving the Universe in a computer



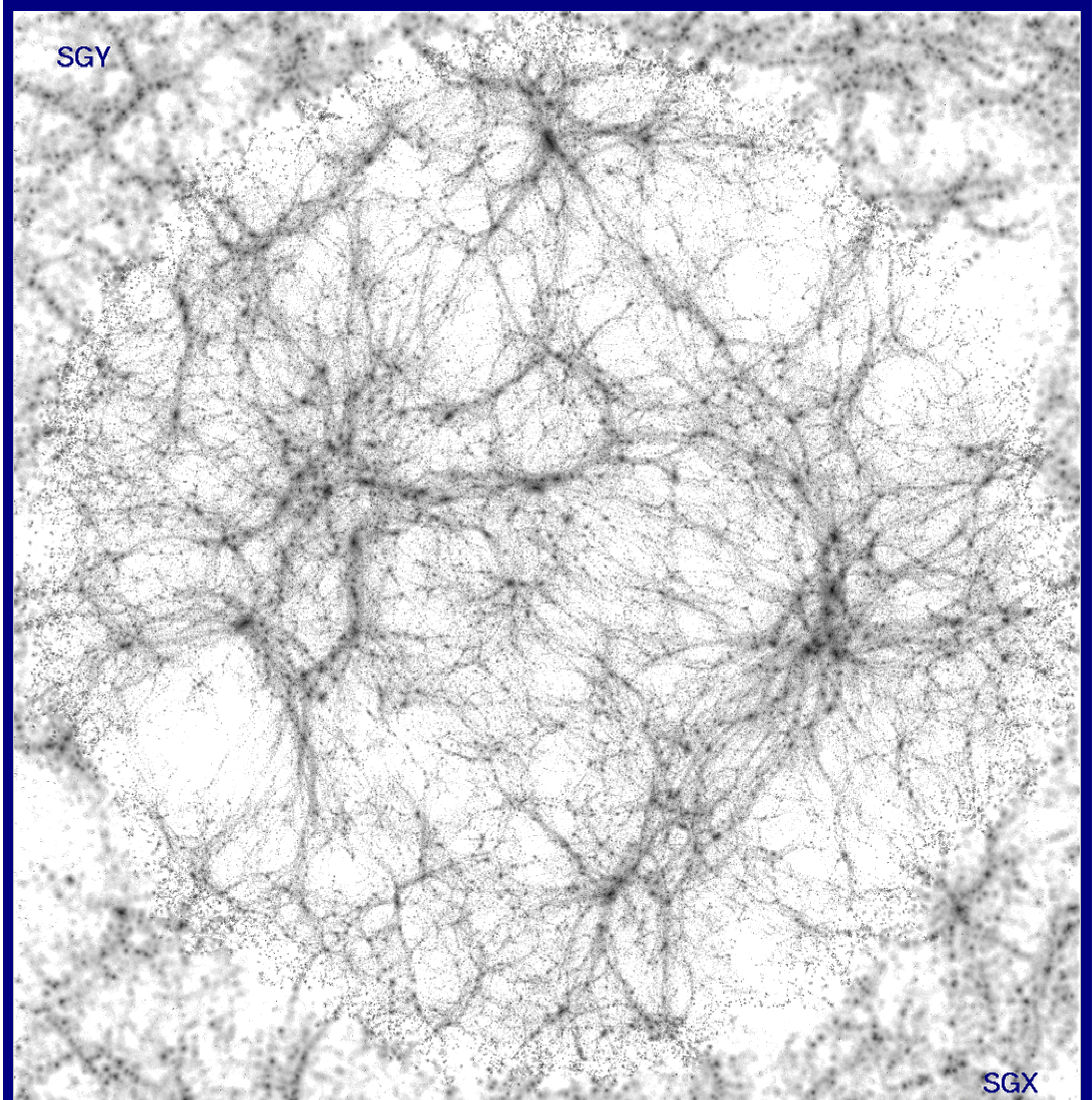
- Follow the matter in an expanding cubic region
- Start 300,000 years after the Big Bang
- Match initial conditions to the observed Microwave Background
- Calculate evolution forward to the present day

The local Universe at z = 2.4

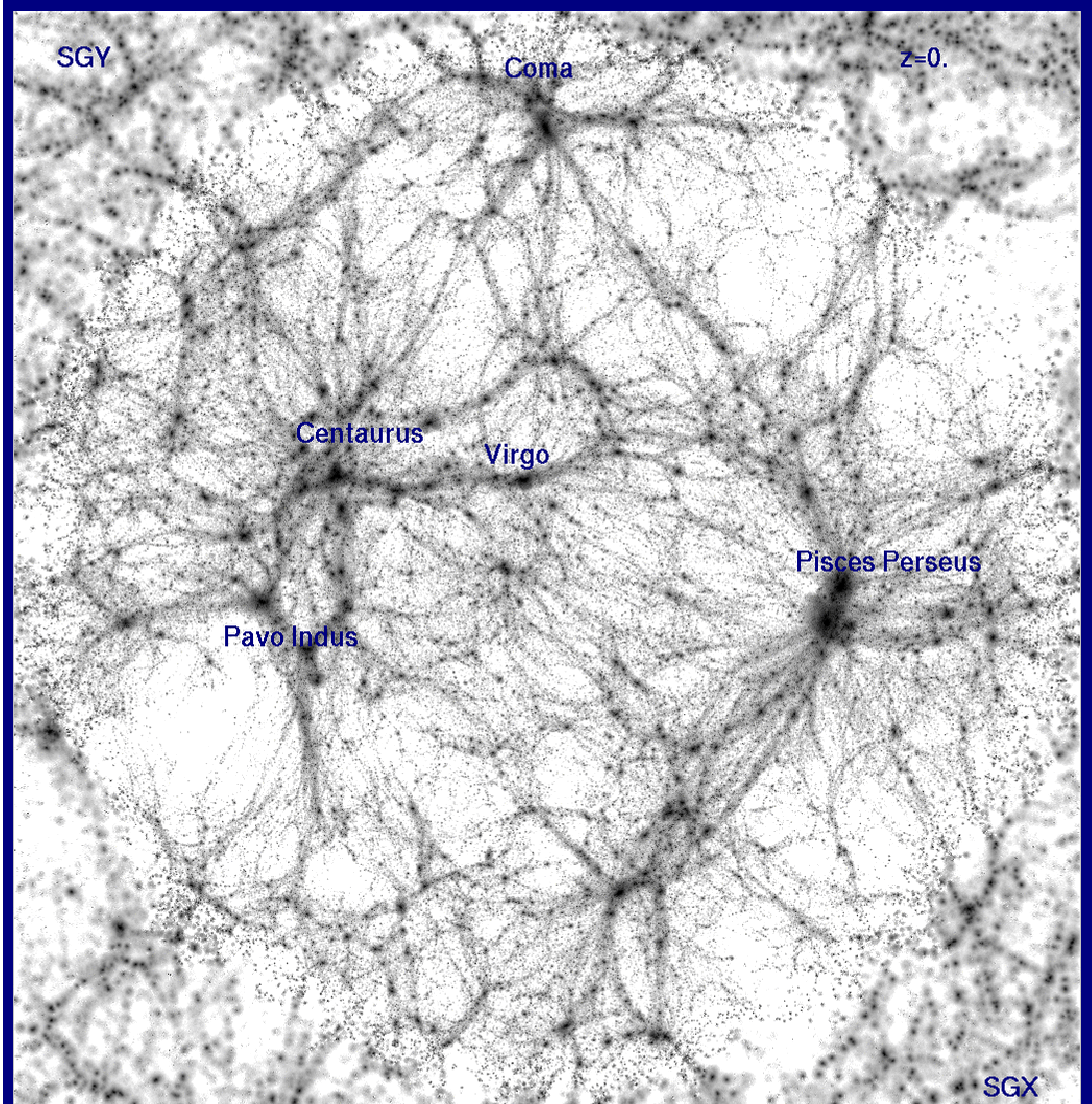
Mathis et al 2001



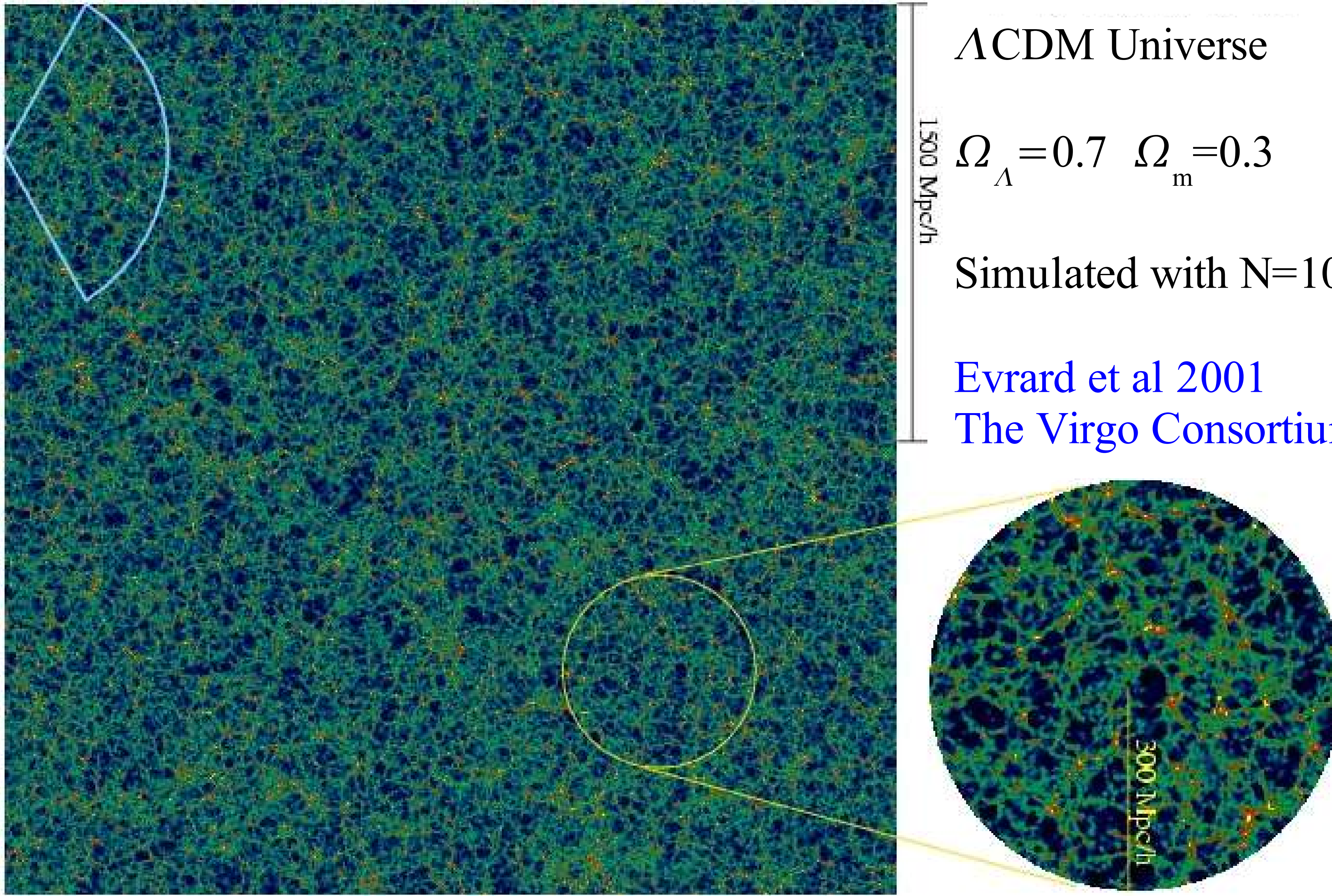
The local Universe at z=0.8



The local Universe today



Simulating the whole visible Universe



ΛCDM Universe

$\Omega_\Lambda = 0.7 \quad \Omega_m = 0.3$

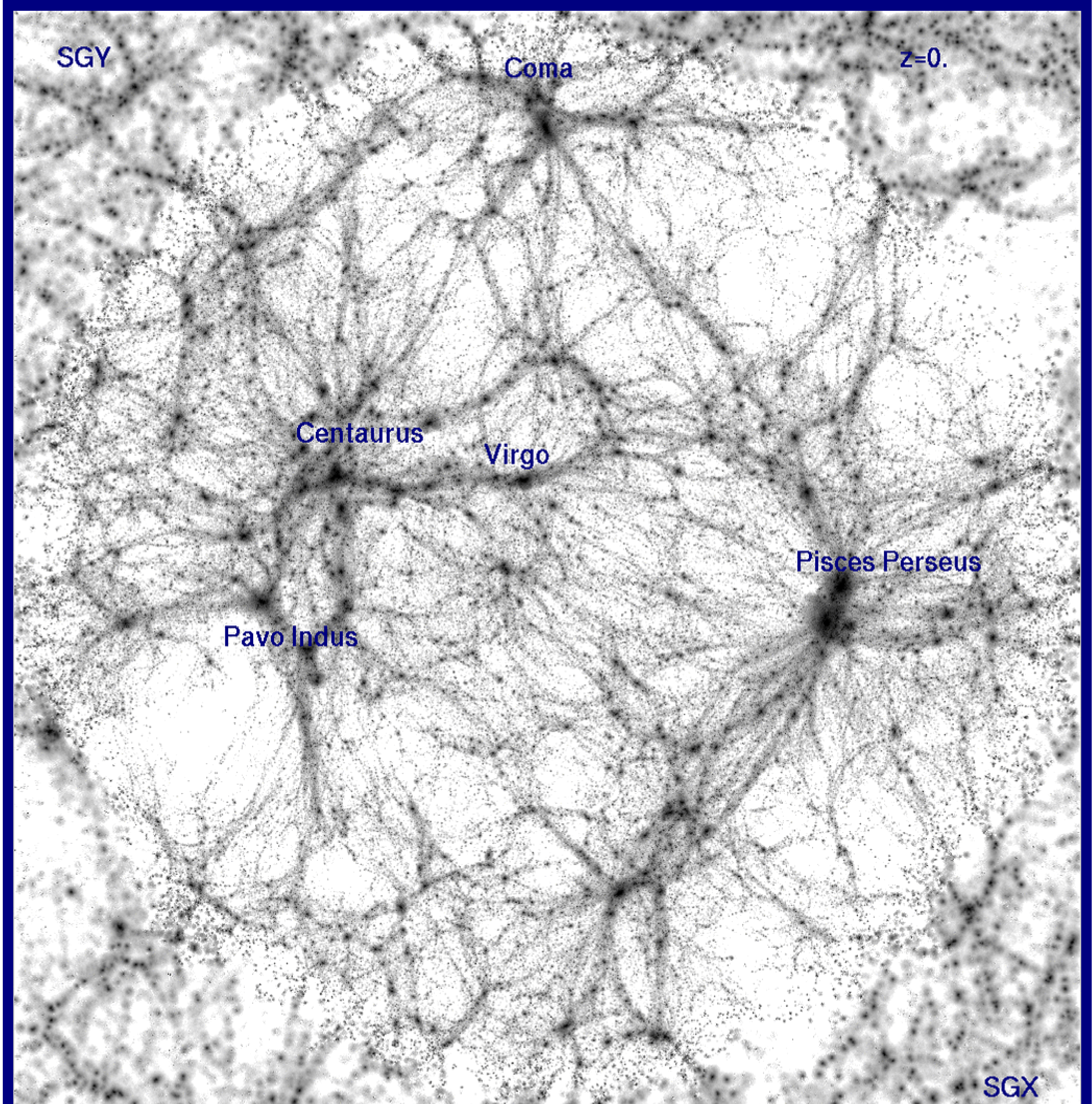
Simulated with $N = 10^9$

Evrard et al 2001
The Virgo Consortium

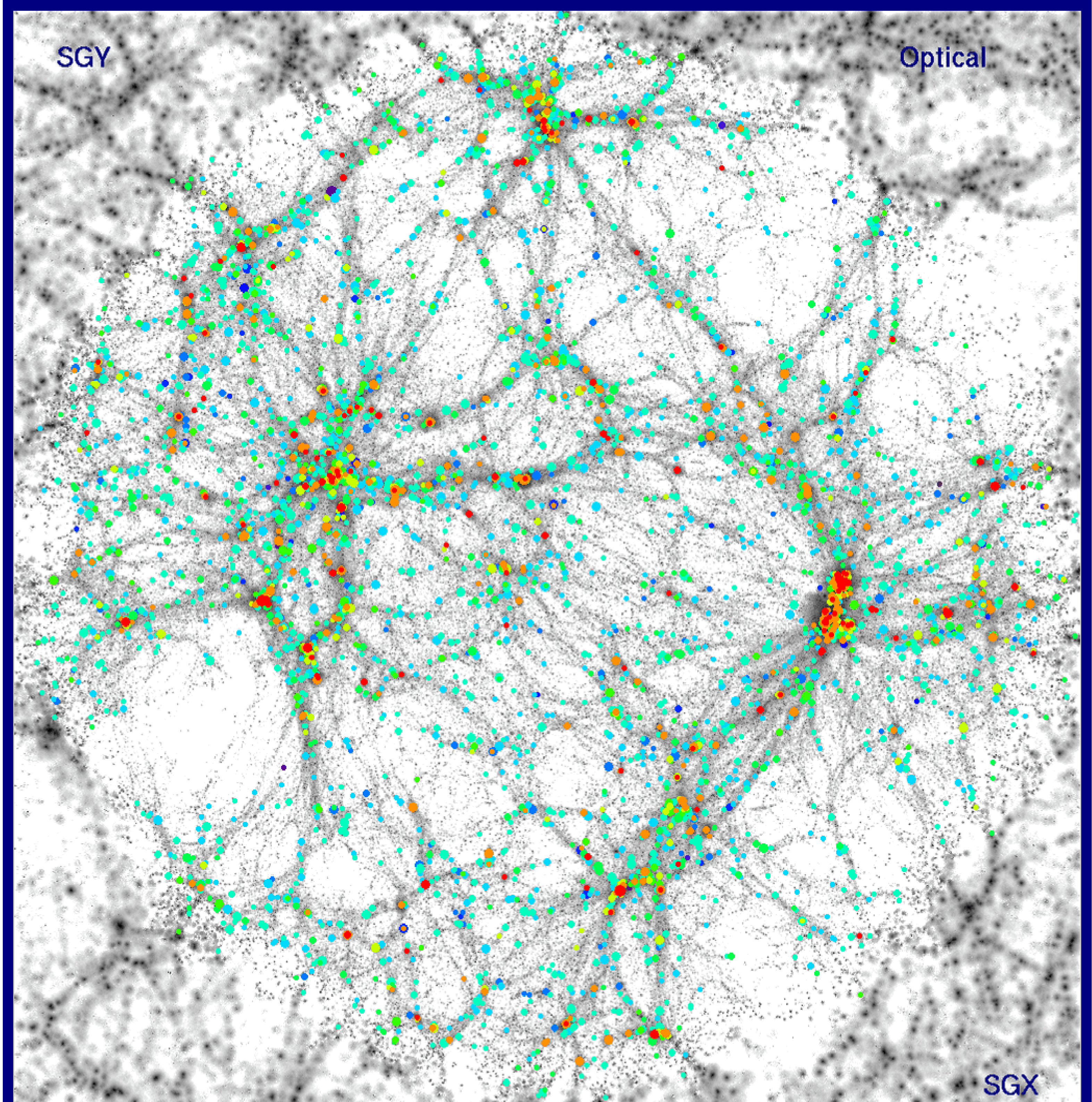
Galaxy formation in the standard paradigm

- Nonlinear dark matter clustering under gravity
  - ➡ hierarchical "dark halo" growth by accretion and merging
- Infall and shock heating of diffuse gas
  - ➡ hot gas "atmospheres" in halos (e.g. the intracluster gas)?
- Cooling and condensation of gas into "protogalaxies"
  - ➡ rotationally supported disks?
- Star formation in disks or during protogalactic collapse
  - ➡ disk galaxies or "primordial" spheroids
- Feedback from UV radiation and galactic winds
  - ➡ reionisation and enrichment of the intergalactic medium
    regulation of star formation within galaxies
- Merging of galaxies
  - ➡ starbursts
    morphological transformation : disks ➡ spheroids

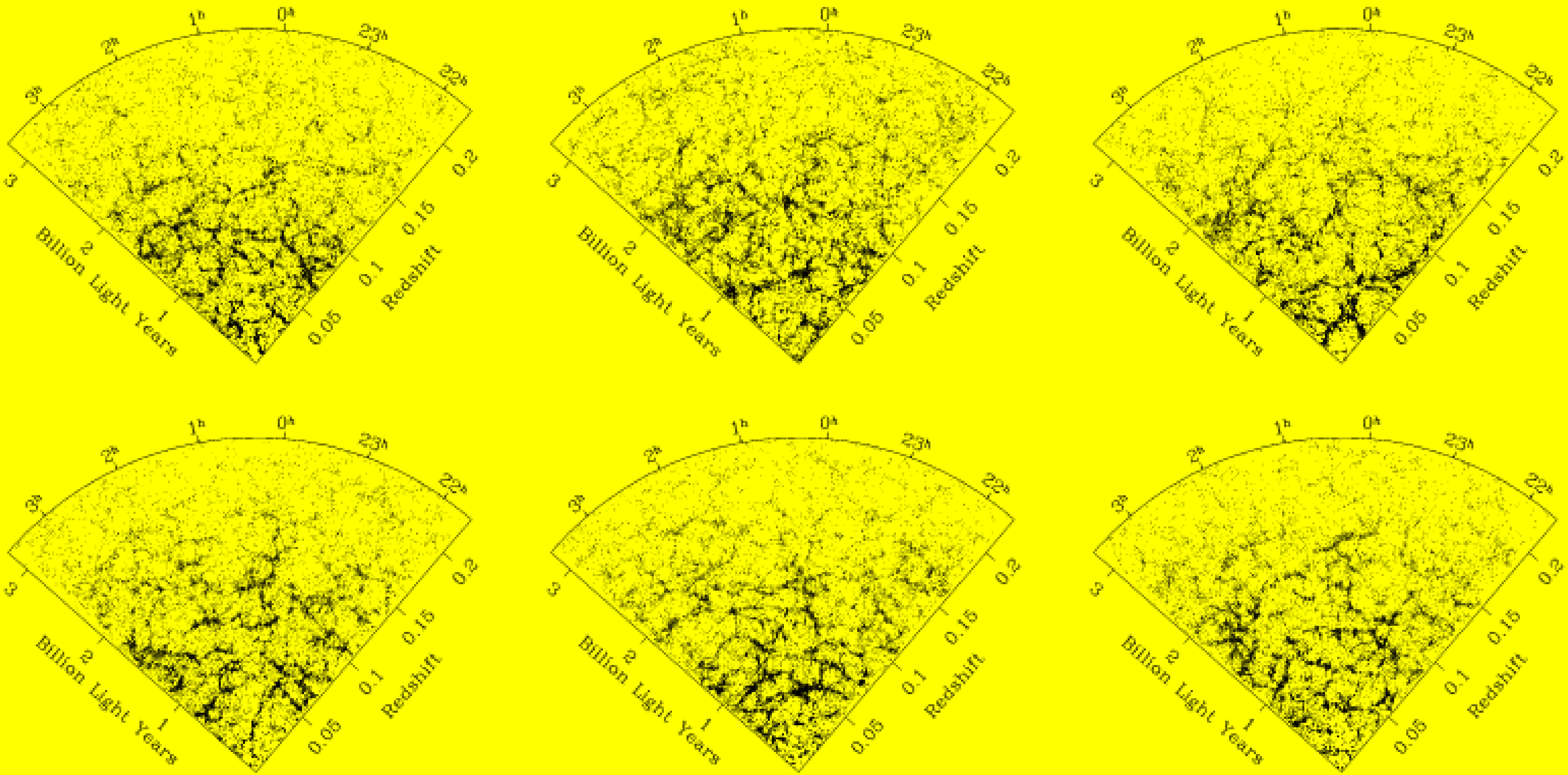
The local Universe today



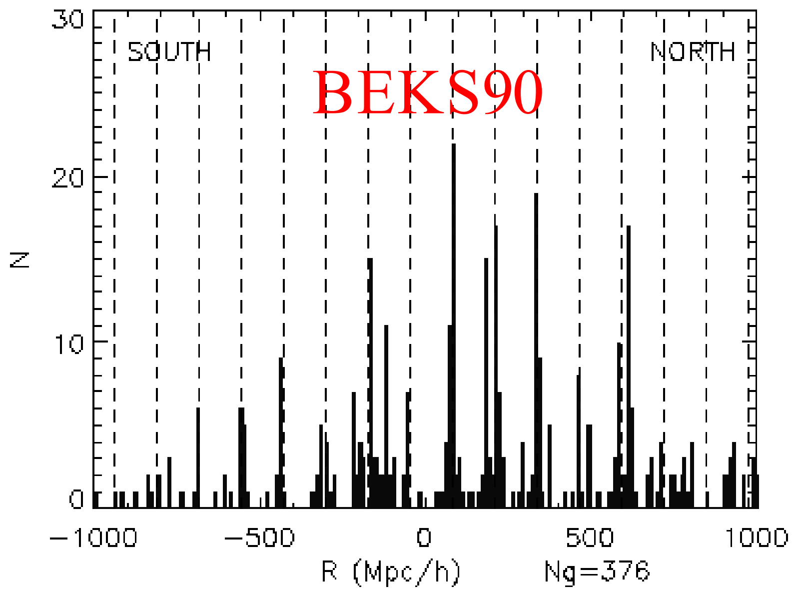
The local Universe *with* galaxies

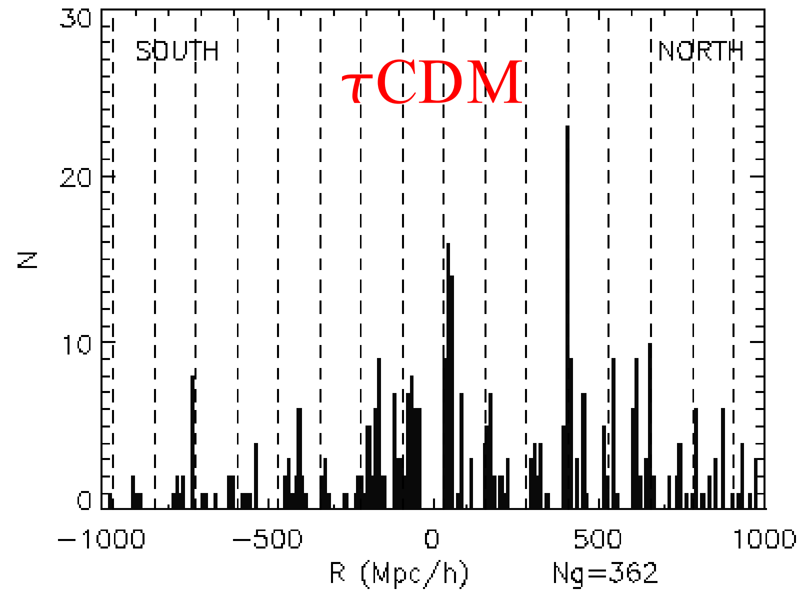


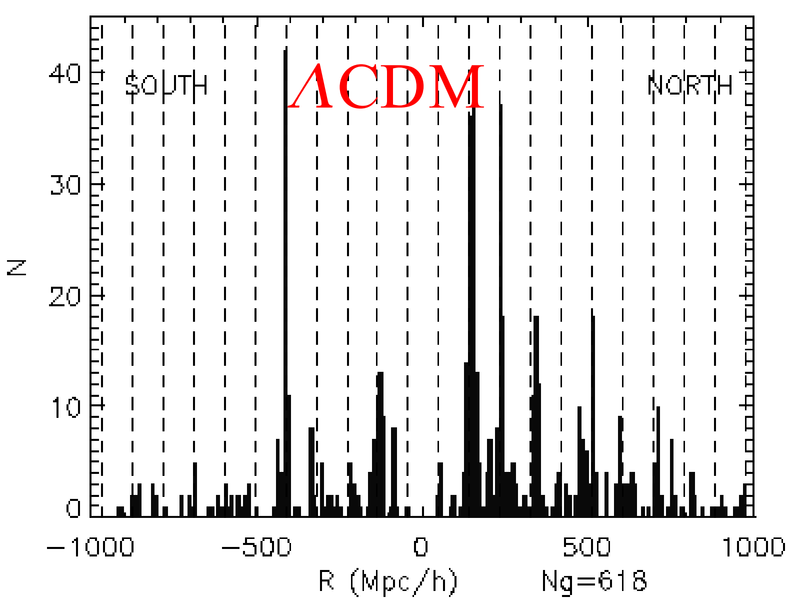
VIRTUAL vs REAL UNIVERSES II



Is the BEKS "periodicity" a cosmic fluke?



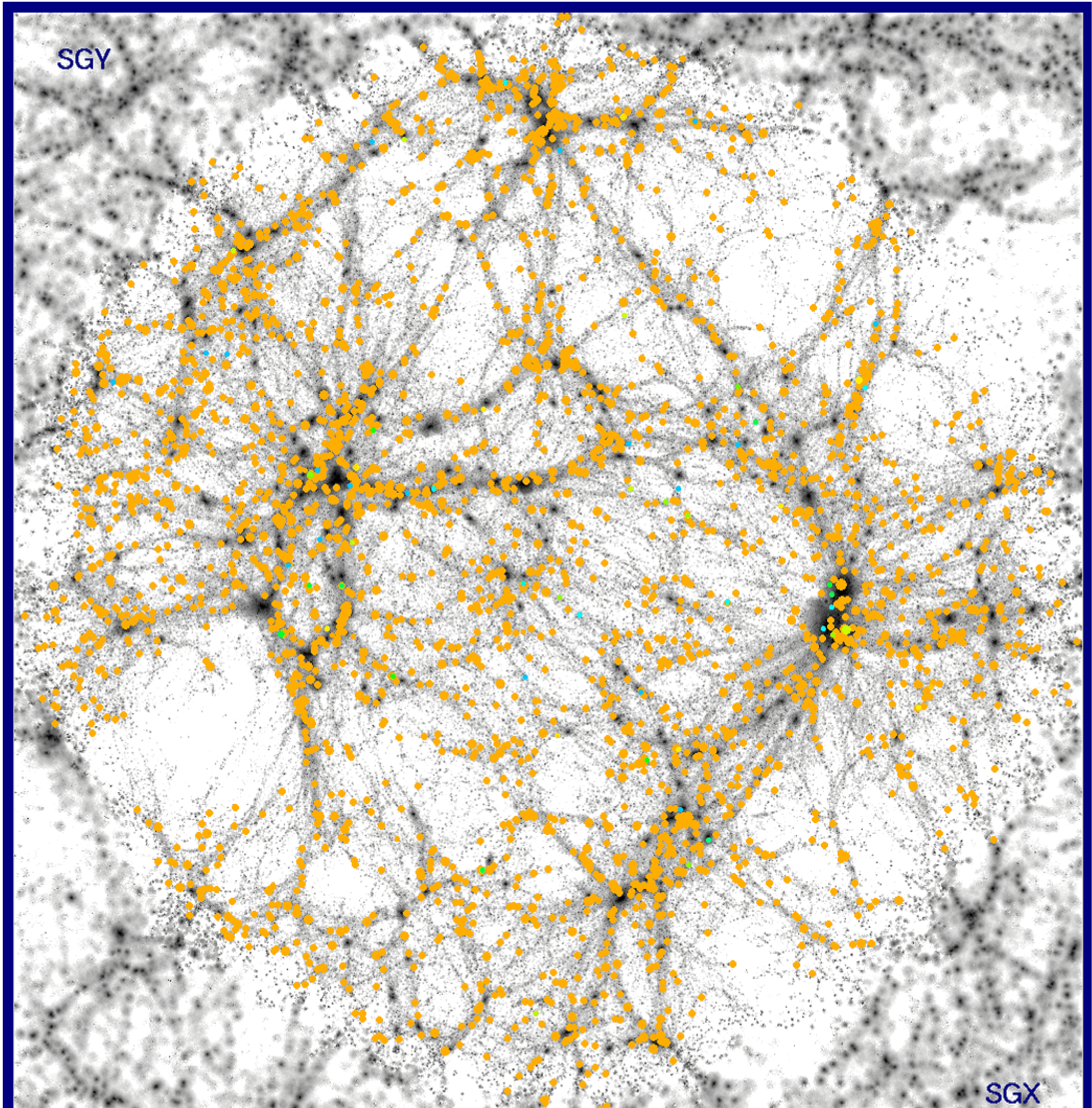




In CDM universes the kind of regularity observed by BEKS has *a priori* probability well below 10^{-3}

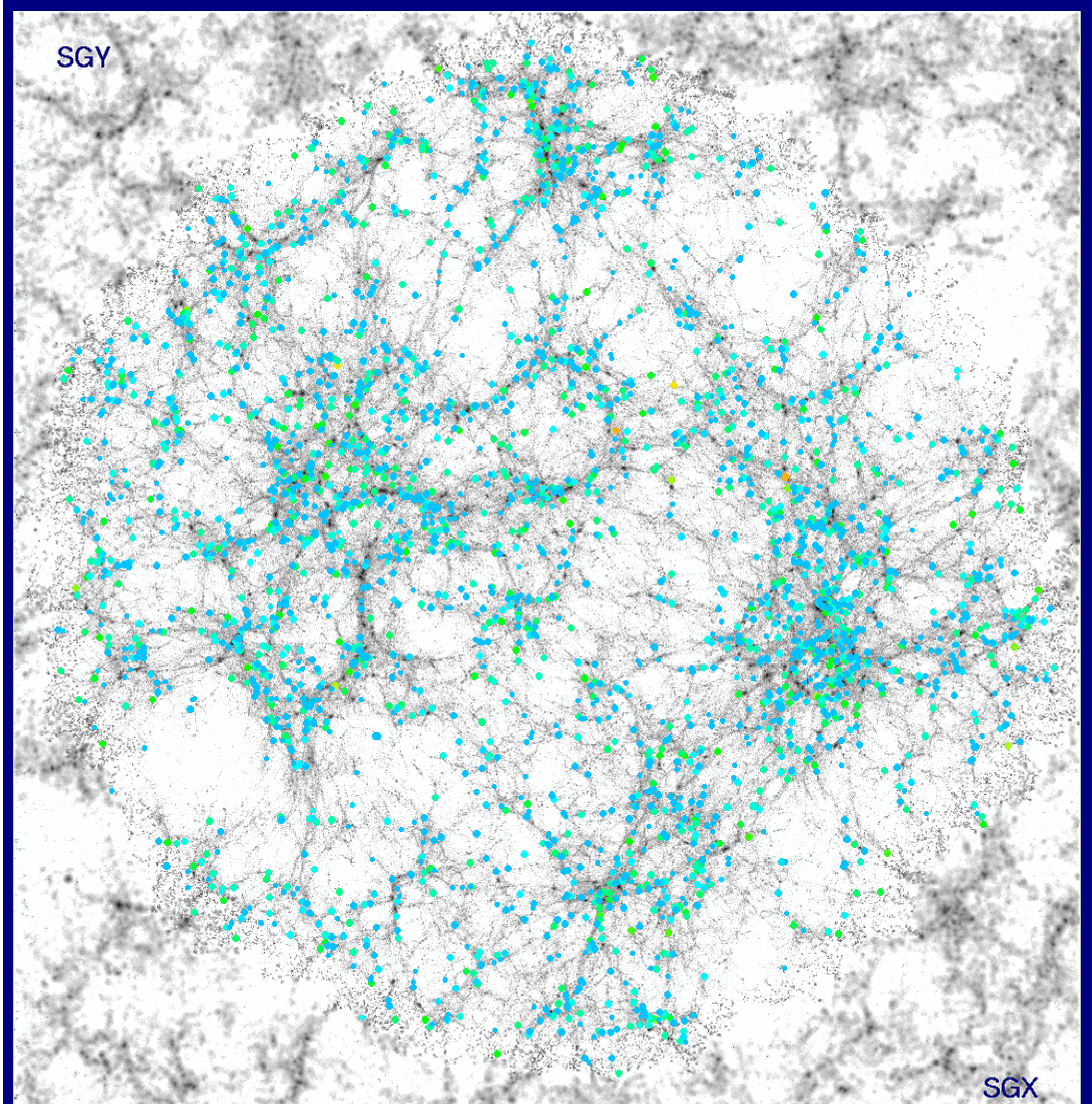
Yoshida et al (2001)

Star-forming galaxies in the local Universe: SFR>0.75

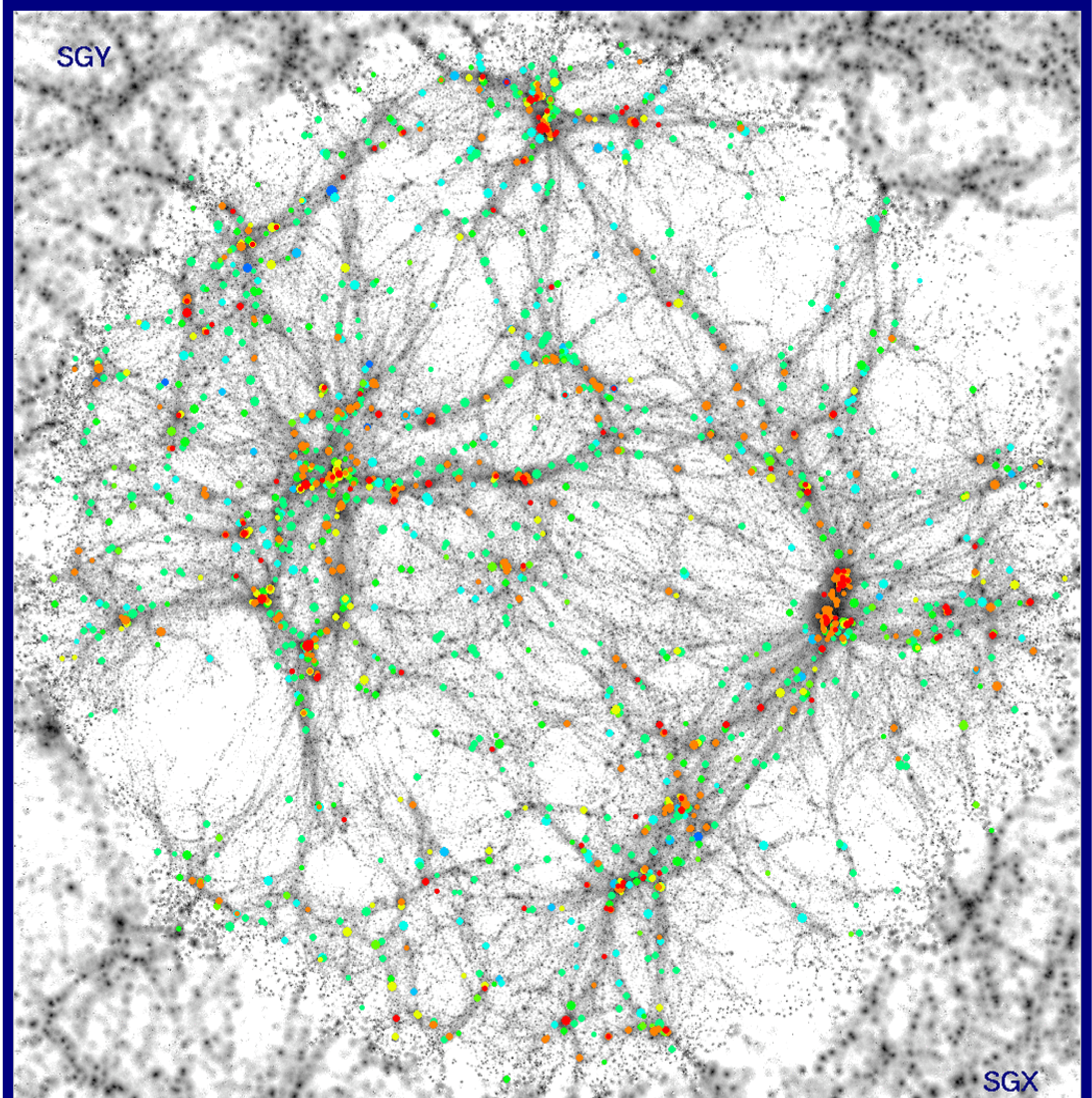


Star-forming galaxies at z=2.4

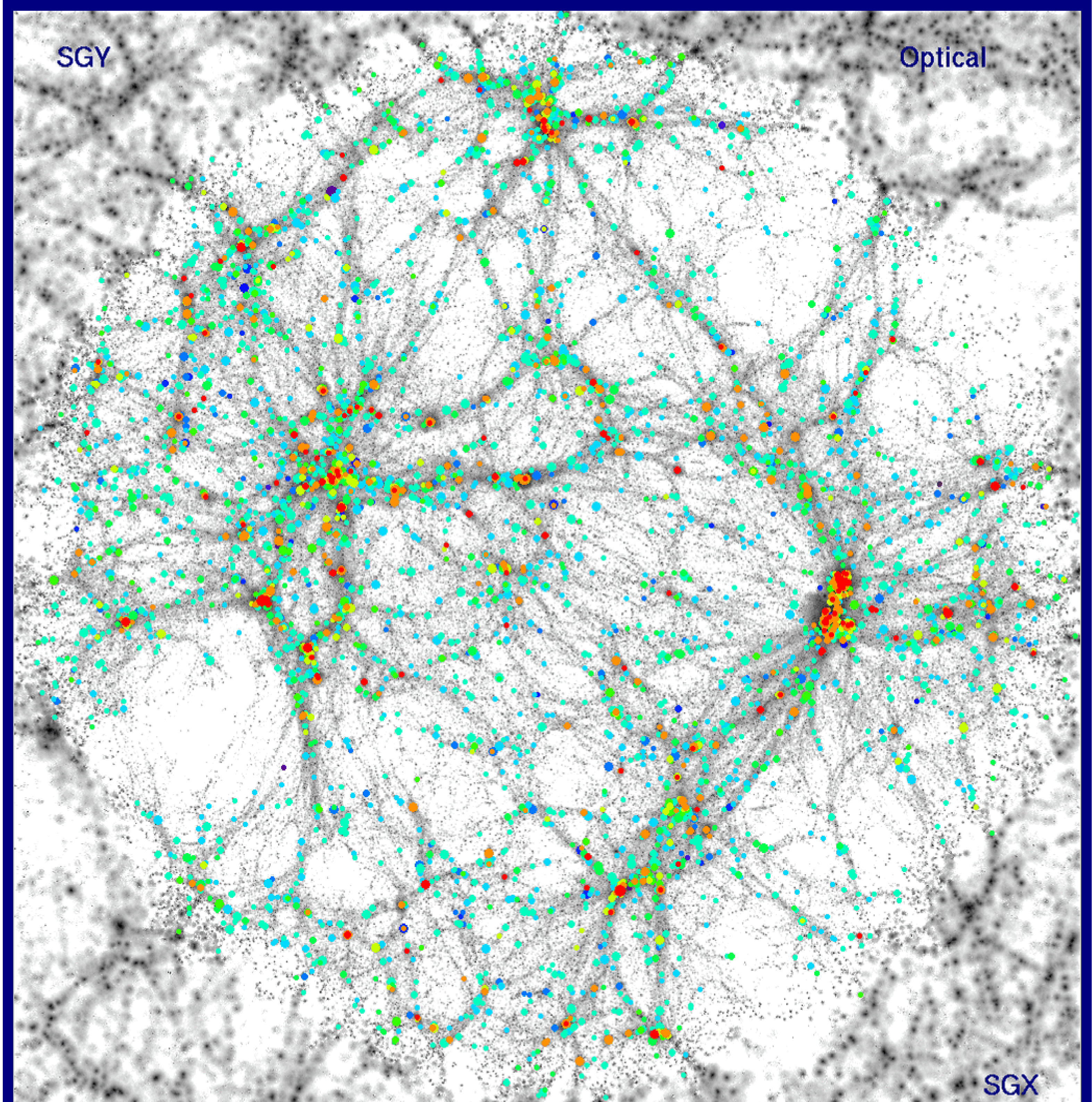
SFR>5.0



Descendents of Ly break galaxies in the local Universe



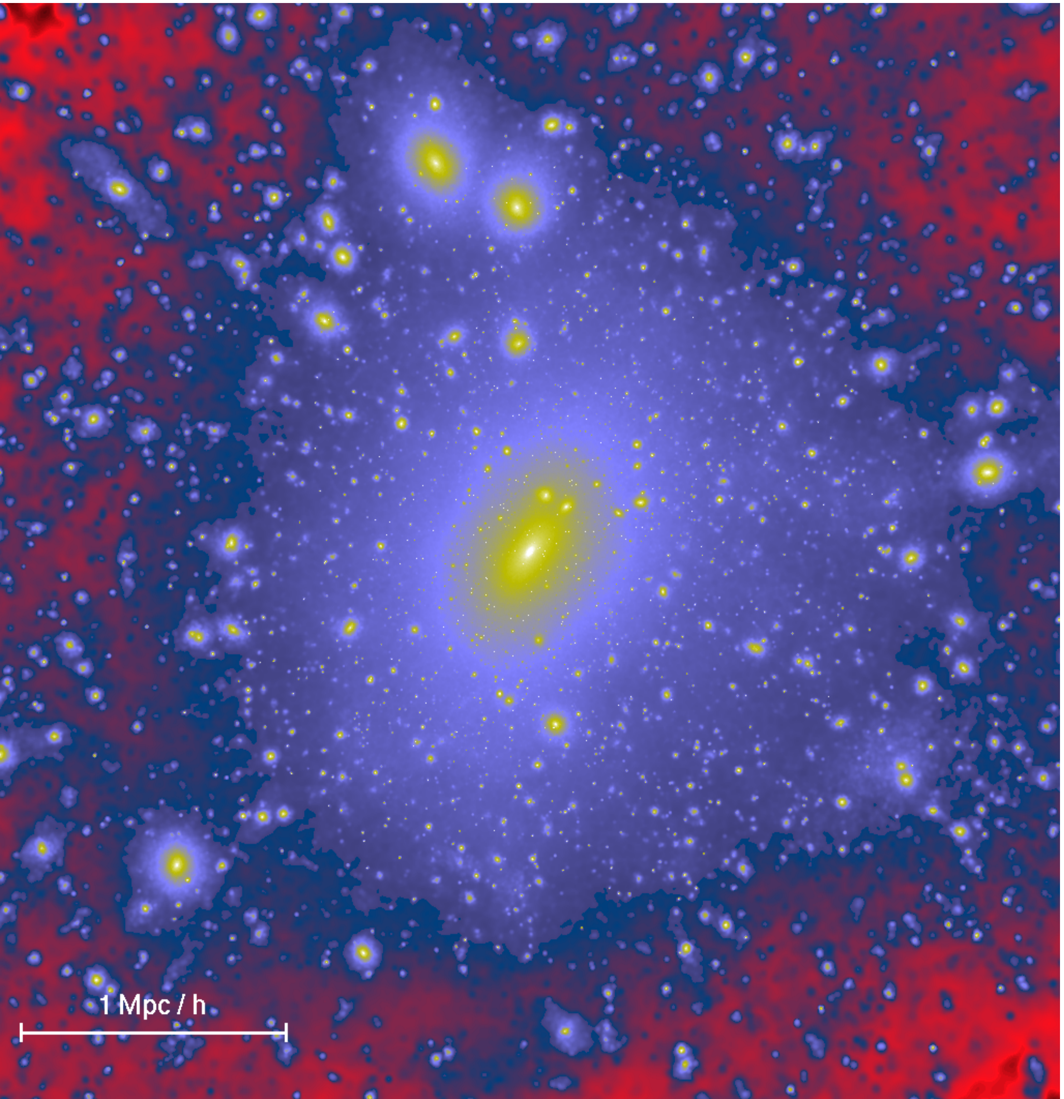
The local Universe *with* galaxies

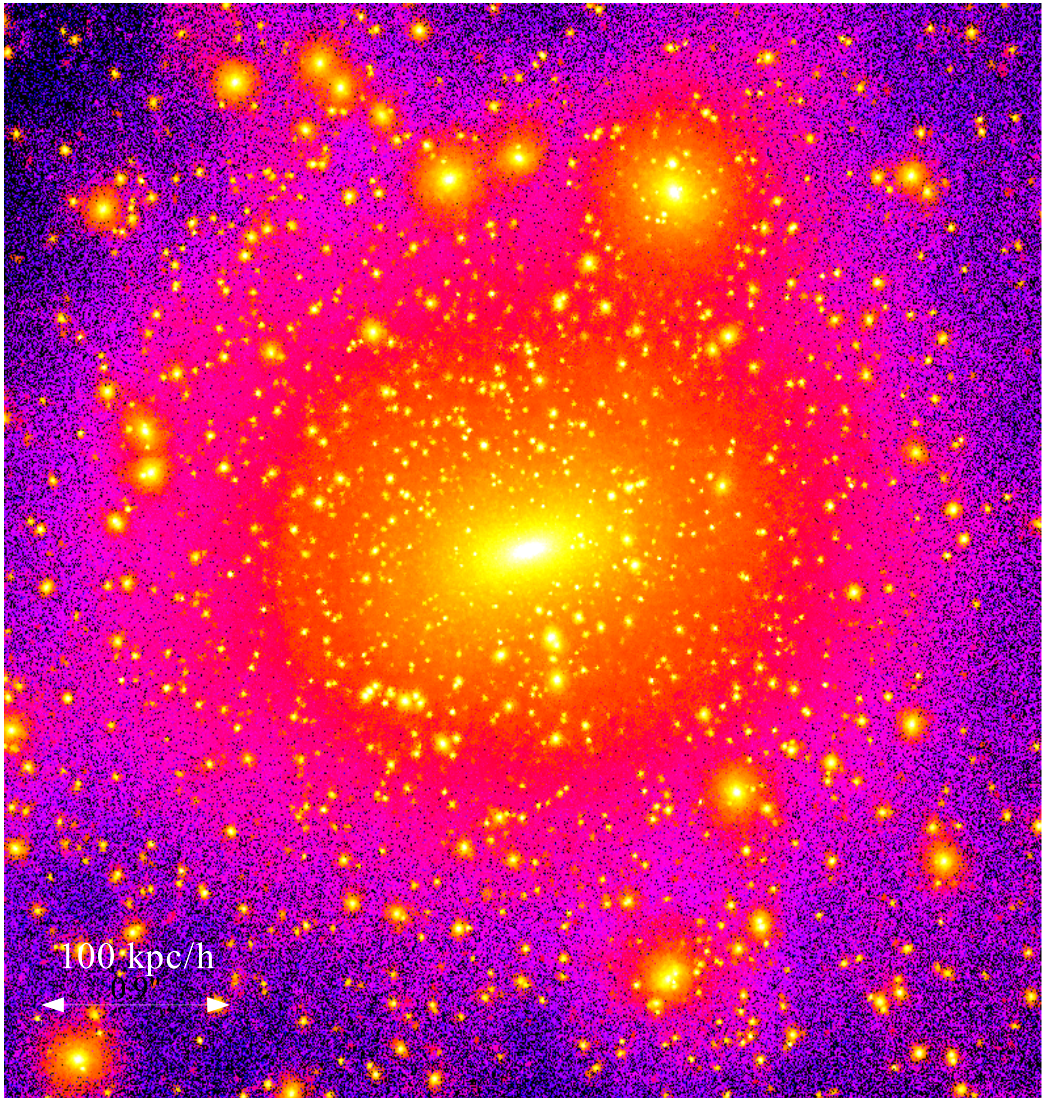


Small-scale structure in dark matter halos

A rich galaxy cluster halo
Springel et al 2001

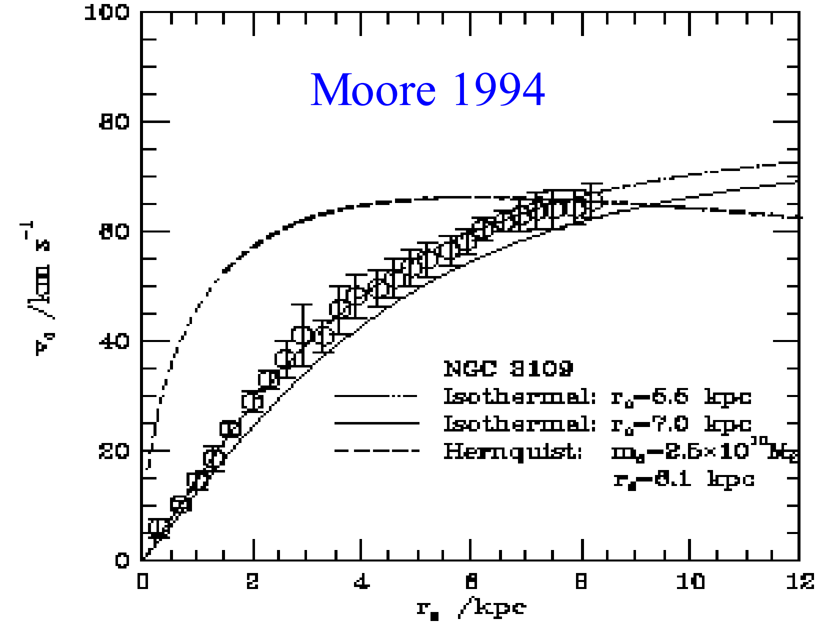
A 'Milky Way' halo
Navarro et al 2001



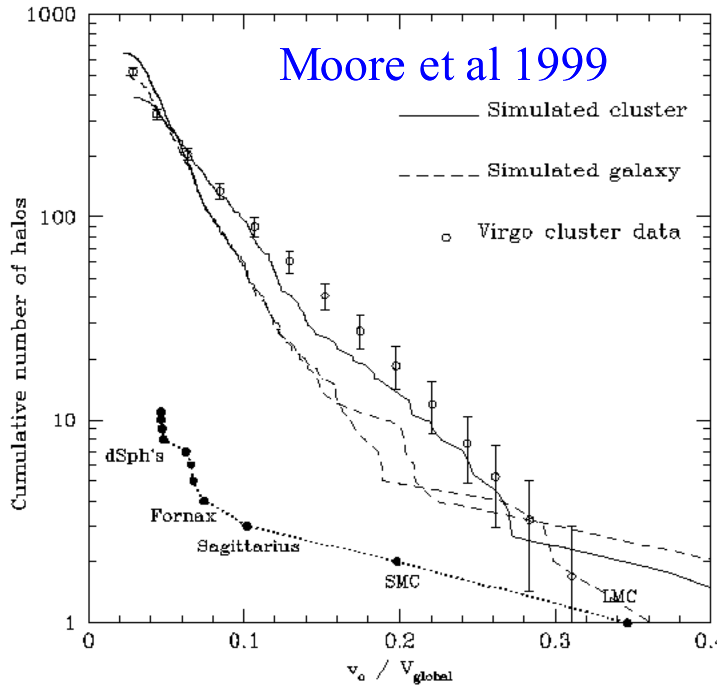


Problems for CDM on small scales?

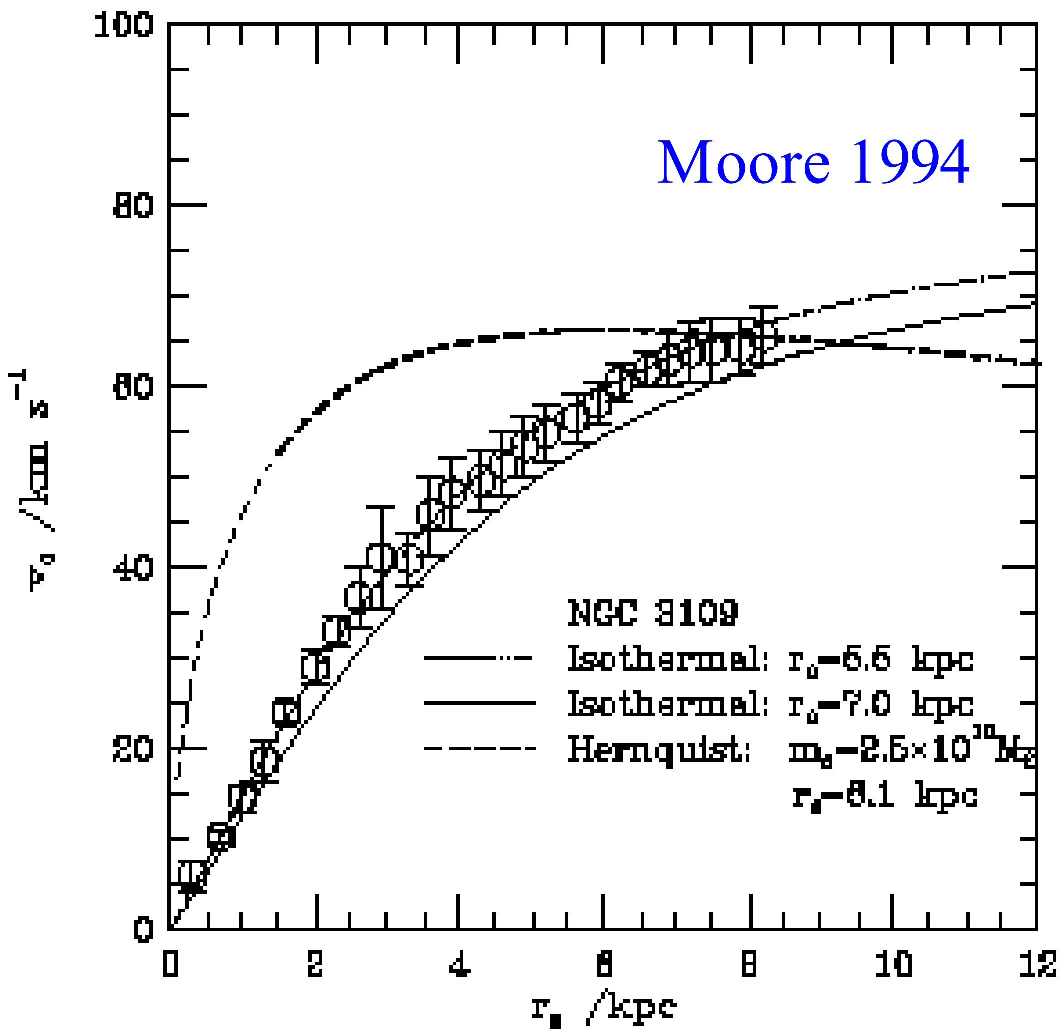
- CDM may produce dark halos which are more concentrated than those seen in dwarf galaxies



- CDM may produce more small satellites than are seen around the Milky Way



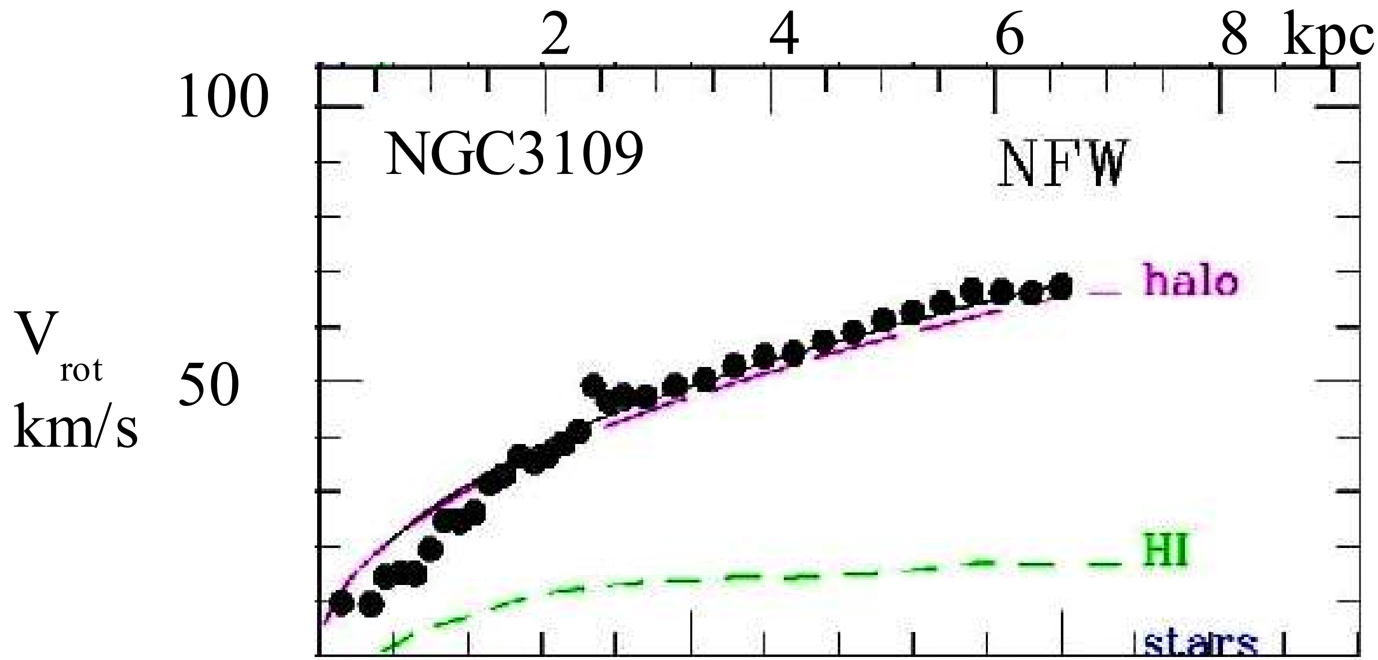
Dwarf galaxy rotation curves and CDM halos

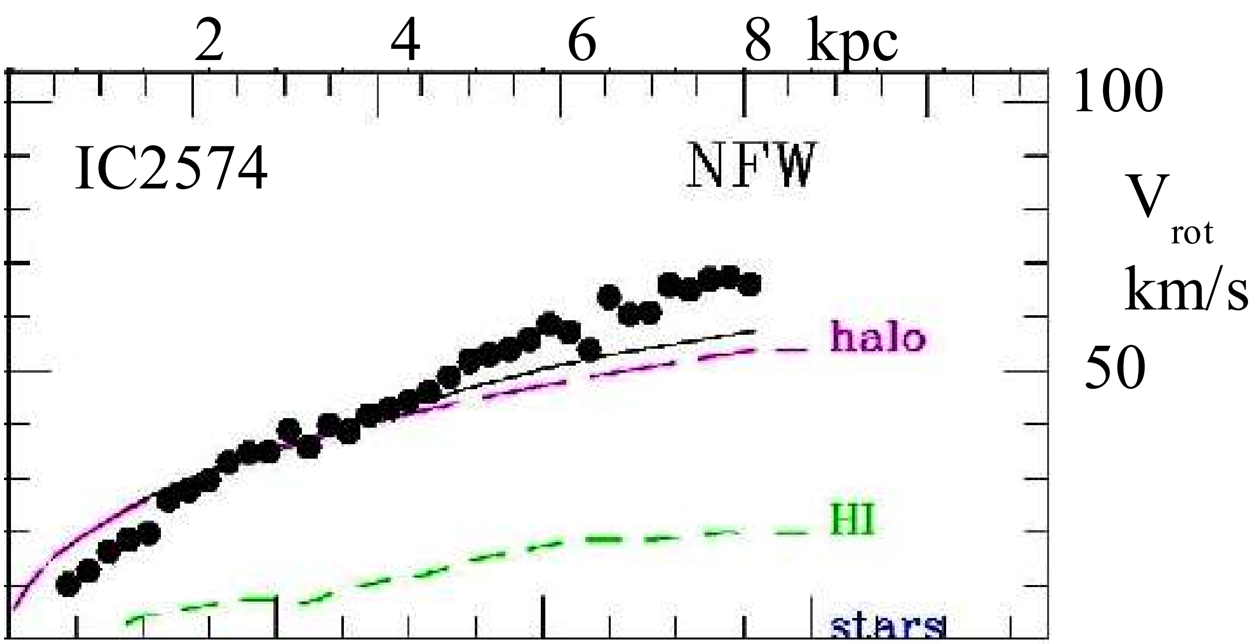


- NGC3109 is almost a solid body rotator near the centre
- It is dark matter dominated
- It is very poorly fit by a cuspy profile as scaled here
- A core gives a better fit
- The adopted profile is much too concentrated for ΛCDM

High quality rotation curves for nearby dwarfs: I

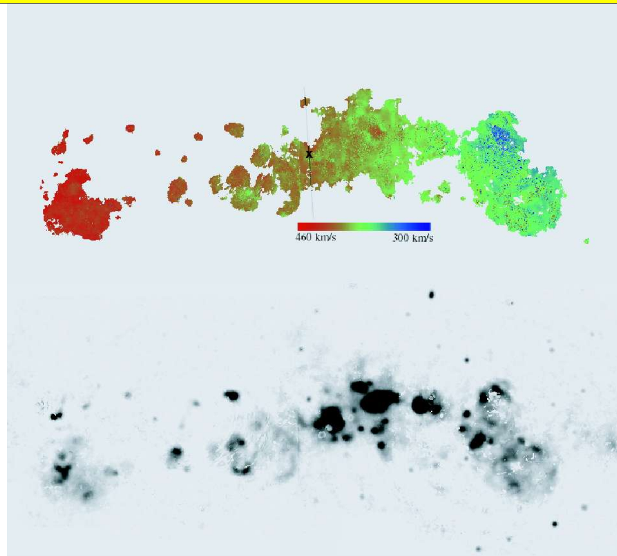
Blais-Ouellette, Amram & Carignan 2001



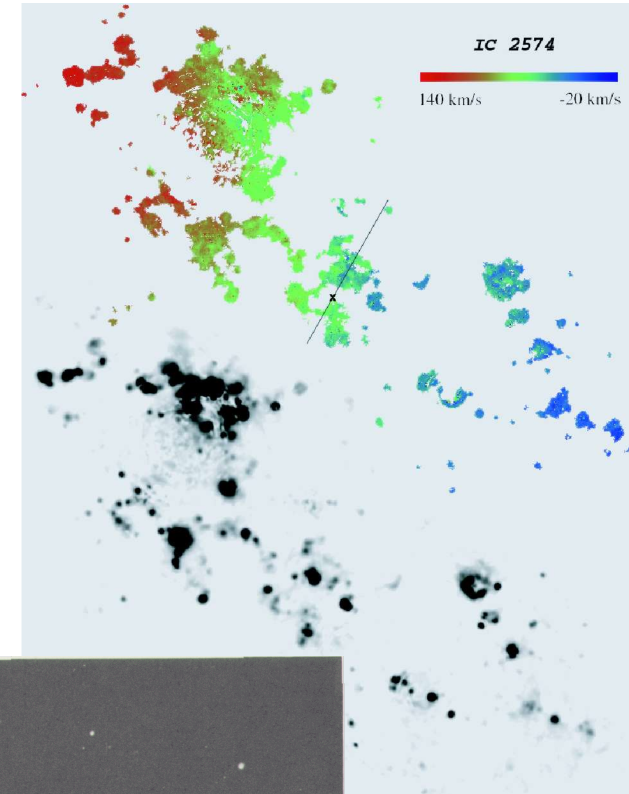


- NFW fits are not concentrated enough for a ΛCDM universe

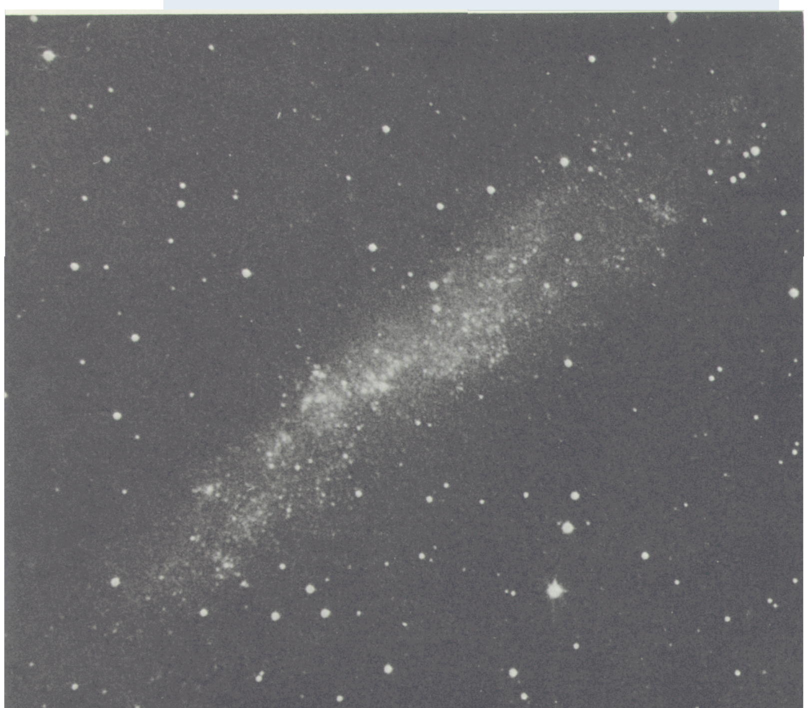
High quality rotation curves for nearby dwarfs: II

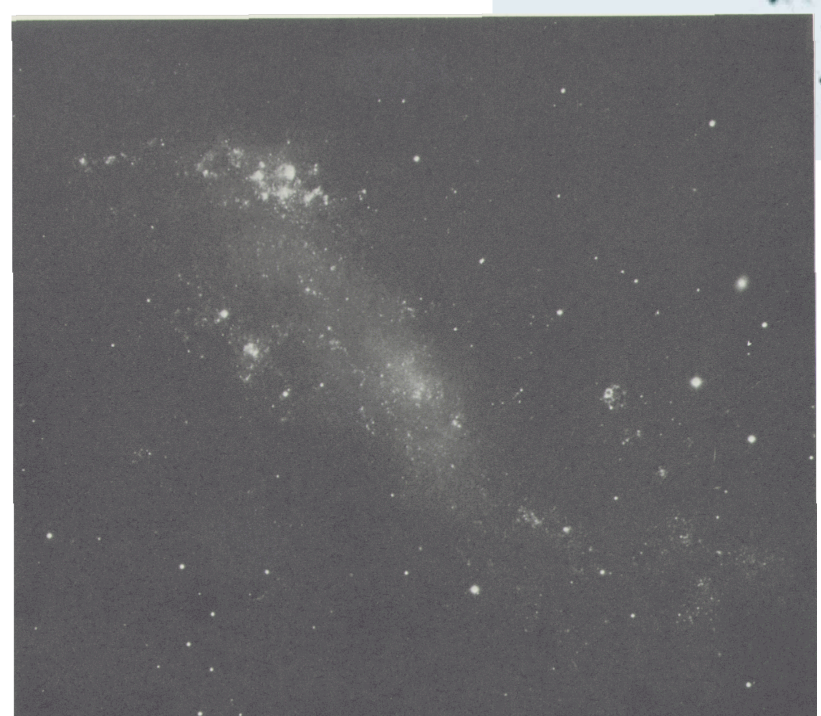


NGC3109



IC2574





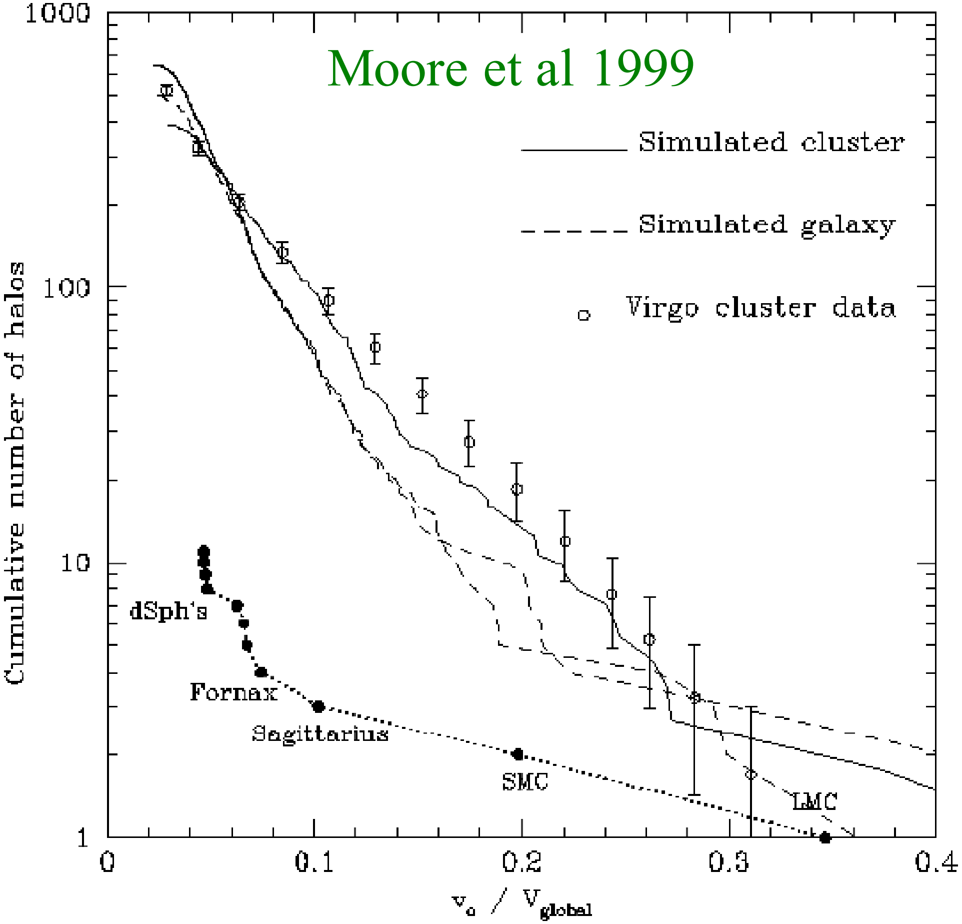
Current status of the core "problem"

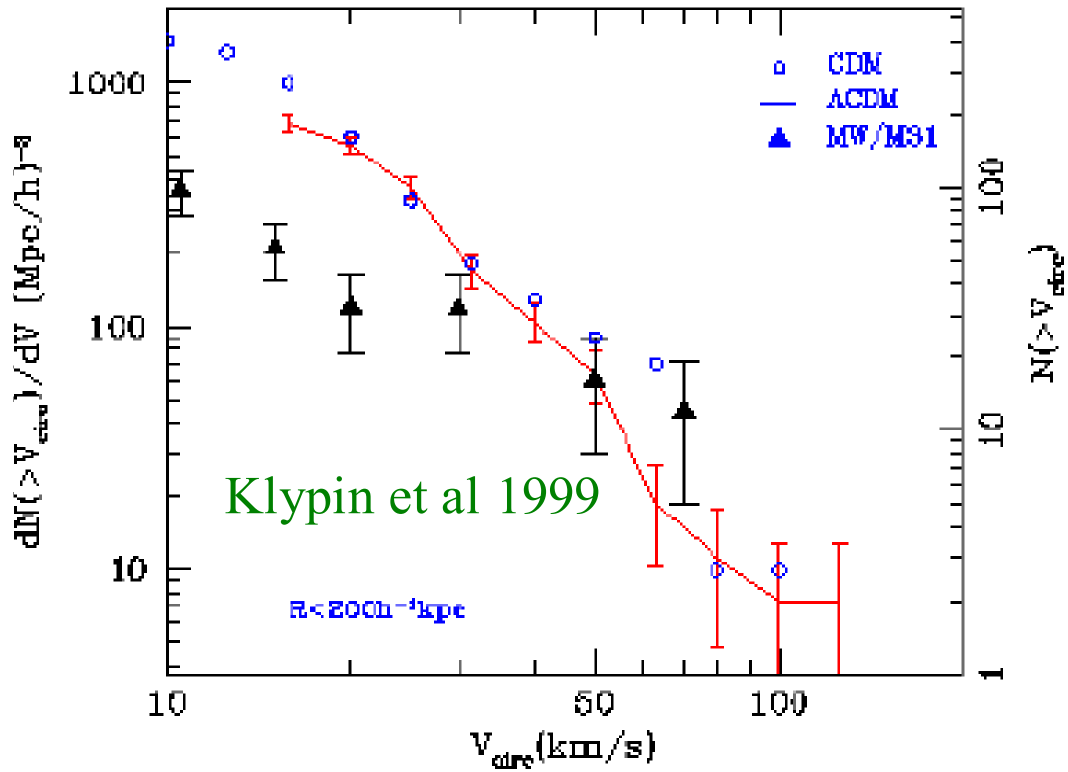
- The astronomy community working on the problem is strongly polarized
- The relevant observations are difficult to obtain and more difficult to interpret
- The discrepancy is relatively small but appears significant in *some* small and low surface brightness galaxies

Resolutions?

- The dark matter properties may need modifying
- Astrophysical processes during galaxy formation may modify the structure of the dark matter core
- Some systematics may remain in interpretation of the observations

Inconsistency with observed satellite kinematics?





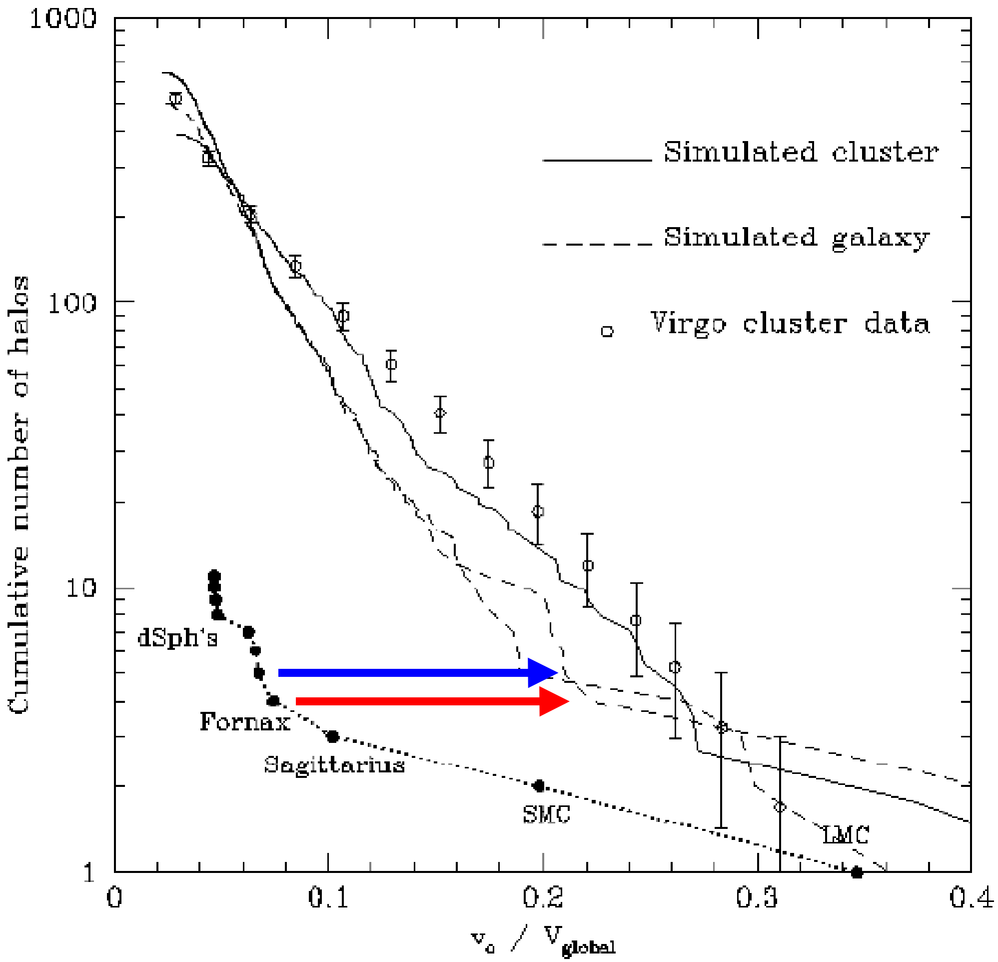
- The number of observed satellites with circular velocity $V = (GM/r)^{1/2}$ (inferred from the observed velocity dispersion) exceeding 10 km/s is at least 10 times smaller than the number expected in a ΛCDM halo

Explanations for the satellite "crisis"

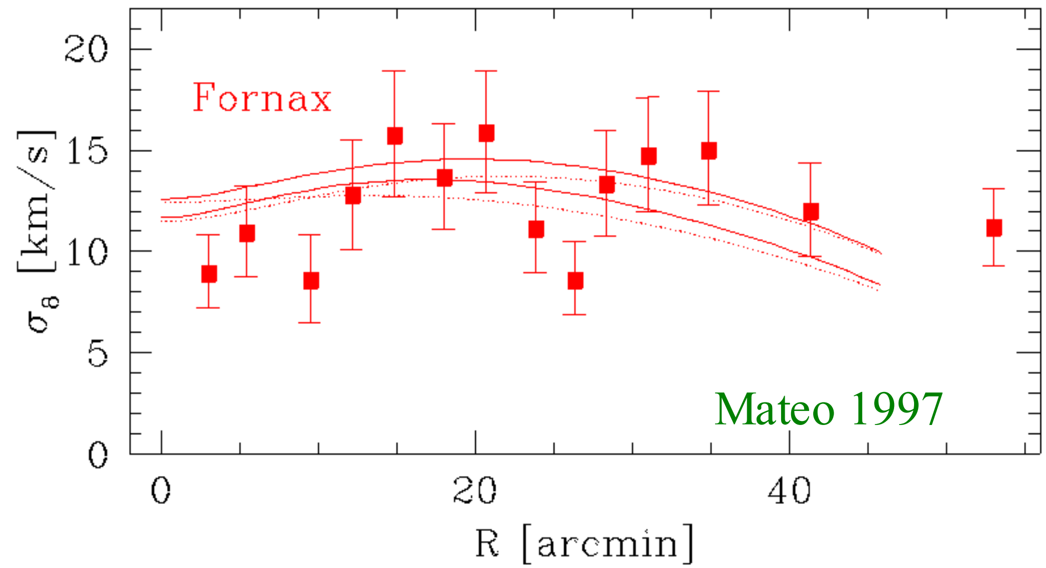
- The dark matter is warm
- The dark matter has a finite self-scattering cross-section
- The primordial density power spectrum has a break
- There is no dark matter -- gravity needs modifying
- Only 10% of sub-halos contain stars
- The comparison of models and data is incorrect

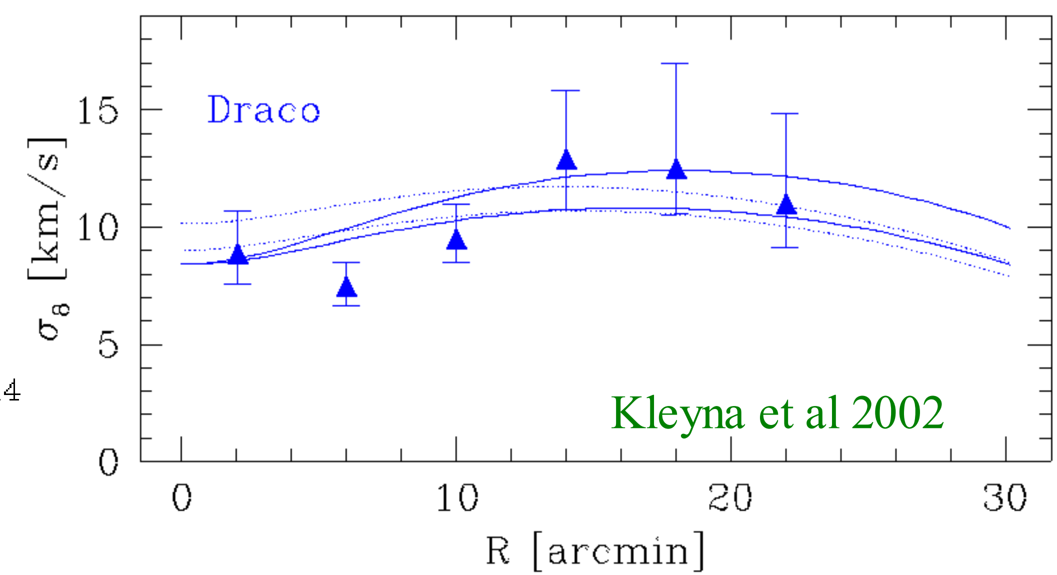
Internal velocities of Milky Way satellites

Moore et al 1999



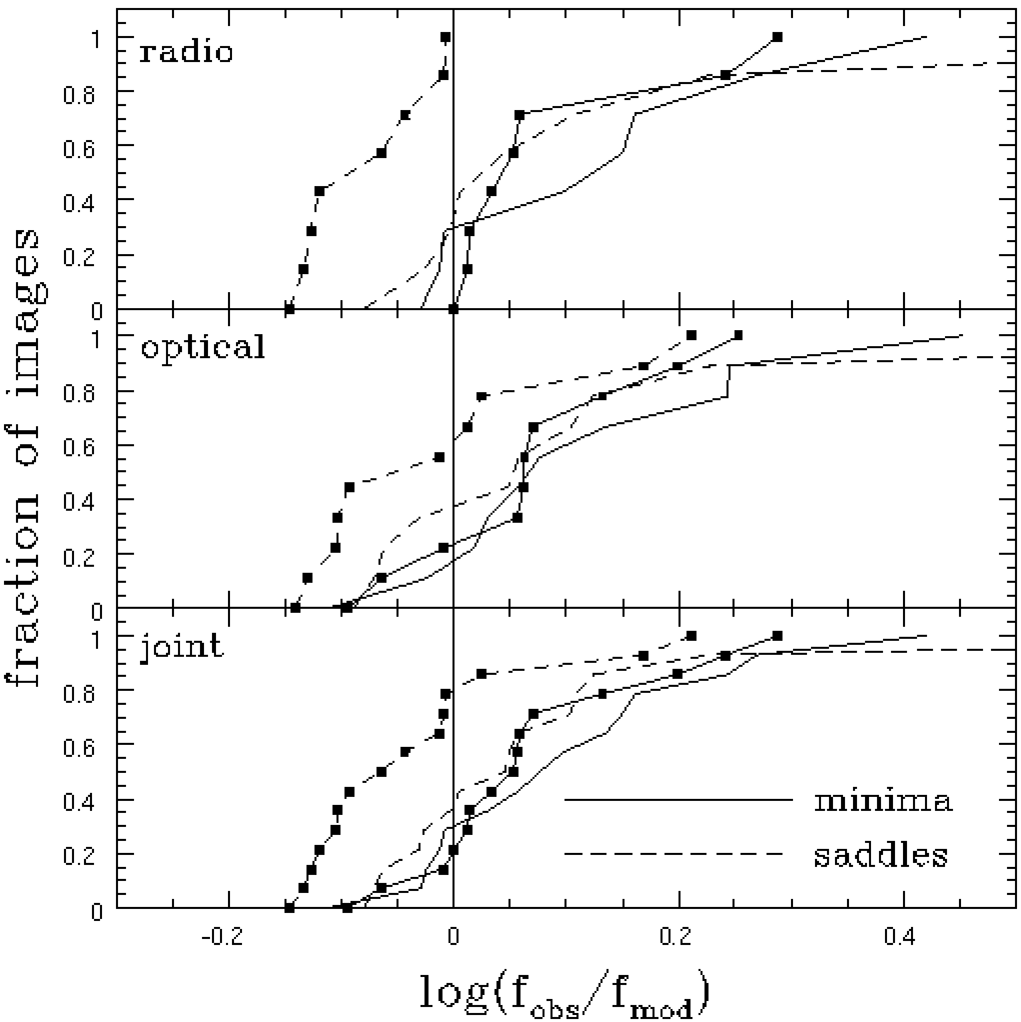
Stöhr et al 2002





Detection of ΛCDM substructure?

Dalal & Kochanek 2003



- In 4-image lensed quasars, the image *geometry* allows image classification into minima/saddles and brighter/fainter of each type
- Smooth lens models which fit the image positions usually *fail* to fit their relative brightness
- The brightest saddle image is preferentially dimmed, as expected for perturbation by fine structure
- This *cannot* be due to propagation effects, e.g. in the ISM of the lens
- It *cannot* be due to microlensing as radio images are too big
- 5 - 10% of lens mass must be in substructure

Current status of the substructure "problem"

- There is ***no*** contradiction between the structure of the most massive subhalos predicted in a ΛCDM halo and the observed structure of the Milky Way's satellites

- It is puzzling why only the most massive subhalos contain visible stars -- the explanation is probably astrophysical

- Many lower mass substructures are predicted but their effects have not yet been observed (except perhaps by their influence on multiply imaged QSO's)

Structure formation and fundamental physics

- The current "standard" ΛCDM structure formation paradigm is now tested over a wide range of length and time scales

- Qualitative agreement is good in all cases, and there are now several routes to reliable quantitative assessment

- The case is good for:
  - -- nonbaryonic dark matter
  - -- a flat low density universe → dark energy
  - -- gaussian initial fluctuations

- On small scales the structure of dwarf galaxy cores suggests a need for new DM properties, but the case is not proven

Developments to expect

- Measurement of CMB fluctuation spectrum by MAP and by polarisation-sensitive instruments

  checks of -- inflationary origin of structure
  -- presence of gravitational waves
  -- need for cosmological constant

- Precise measures of present-day structure from

  gravitational lensing -- measure of Ω_{matter}
  -- cluster core structure
  large-scale surveys -- doppler peaks?
  galaxy/satellite dynamics -- dark halo structure

- Exploration of the assembly of galaxies
- Discovery of the dark matter on Earth?