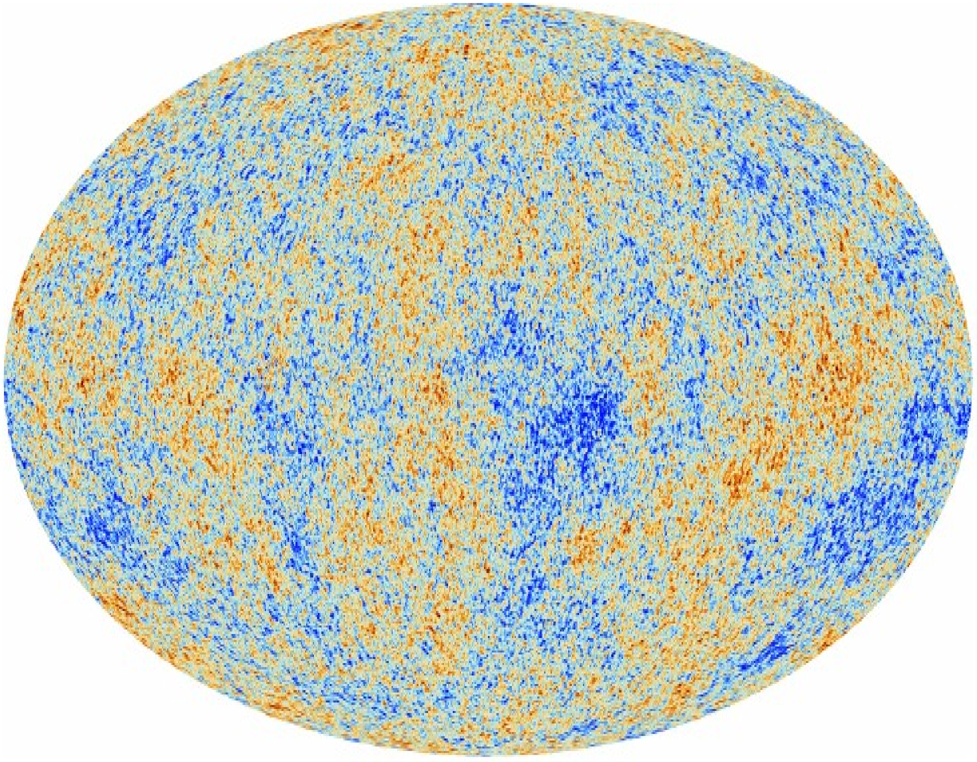


After BB: Universe is dense ("forry"), photons scatter efficiently off electrons $\Longrightarrow$ coupling of matter and radiation

Universe cools: recombination of protons and electrons to form hydrogen

$\Longrightarrow$ no free electrons

$\Longrightarrow$ no scattering

$\Longrightarrow$ photons stream freelty

Photons leaving overdense regions loose energy (gravitational red shift)

$\Longrightarrow$ visible as a temperature fluctuation (Sachs-Wolfe-Effect)

Leads to CMB fluctuations $\sim$ gravitational potential at $z \sim 1100$ (380000 yr after big bang) $\Longrightarrow$ structure

General idea of all theories of structure formation:

1. Big Bang generates initial density perturbations (=potential wells)
   density perturbations caused by Poisson statistics in the early universe, e.g., decay of inflaton or similar
2. Those density fluctuations that can grow, grow.
3. Those density fluctuations that cannot grow get smoothed out by expansion and disappear.

How fluctuations grow depends on properties of material forming structures:

Early theory (Zeldovich, 1960s): structures=baryons; large structures must form first $\Longrightarrow$ this is not what is observed.

New theory: dark matter is important:

1. DM forms initial potential wells
2. Wells develop as universe expands
3. Baryons fall into potential wells once radiation and matter decouple
4. galaxies formed first, clusters still forming

Detailed theory of structure formation uses numerical simulations, using CMB boundary conditions and assumptions on dark matter:

Hot Dark Matter: relativistic particles (e.g., neutrinos): moving with $v \sim c$. Fast particles

$\Longrightarrow$ smears out small density perturbations

$\Longrightarrow$ "top down structure formation"

Not what is observed

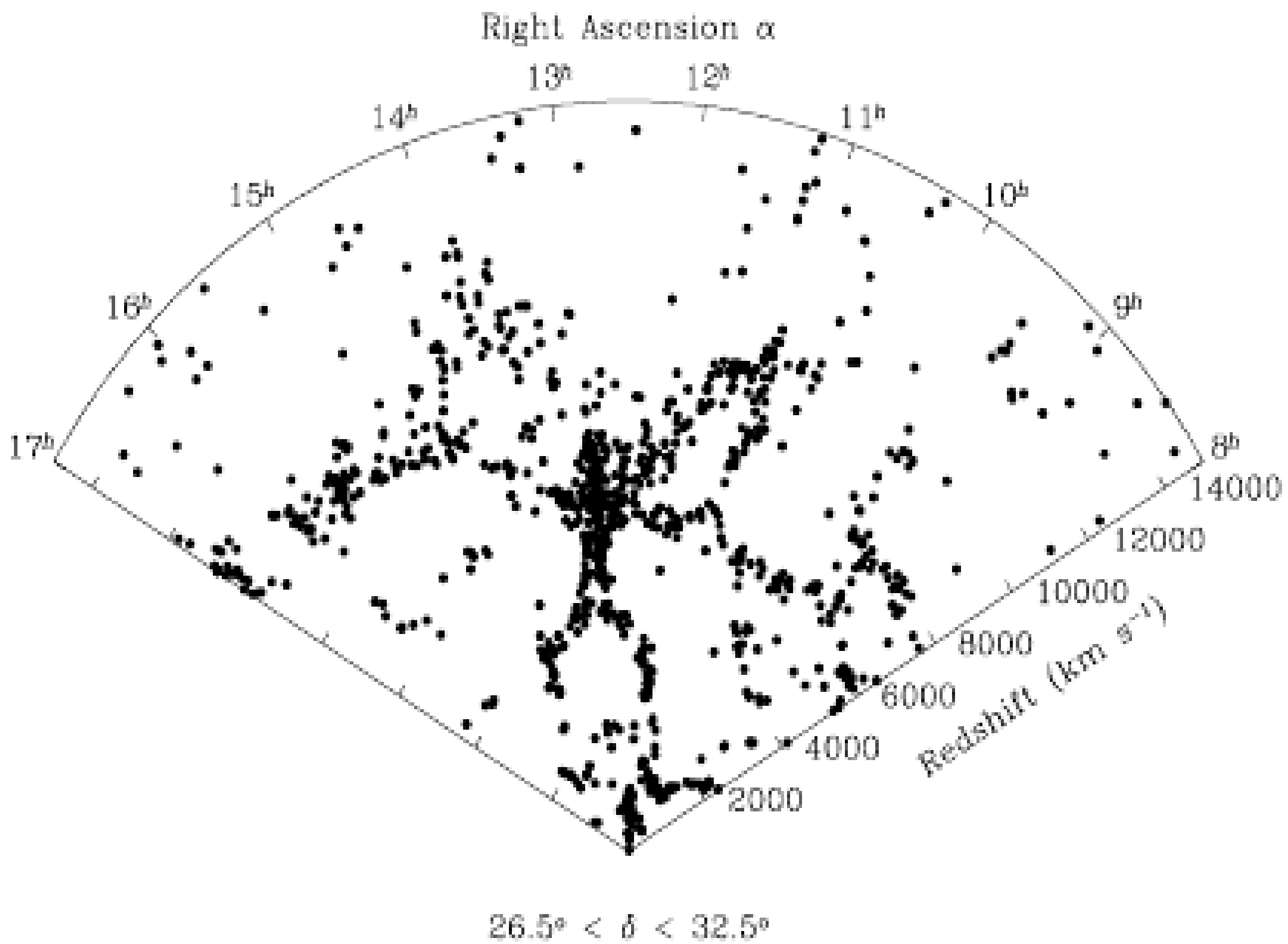
(observed: galaxies were there first, clusters are still forming)

Cold Dark Matter: slow particles, condense first, forming potential wells while baryonic matter is still coupled to radiation.

Once radiation decouples from matter (when universe is cold enough), matter falls in gravity wells.

$\Longrightarrow$ "bottom up structure formation"

Closer to what is observed



(de Lapparent et al., 1986, limiting mag $m_B = 15.6$)

Lumpy universe: spatial distribution of galaxies and greater structures.

How do we study the structure of the Universe?

$\Longrightarrow$ We need distance information for many ($10^4 \ldots 10^7$) objects

$\Longrightarrow$ Large redshift surveys

Review: Strauss & Willick (1995)

Redshift survey: Survey of (patch of) sky determining galaxy z and position to predefined magnitude or z.

First larger survey: de Lapparent et al. (1986)

Classification:

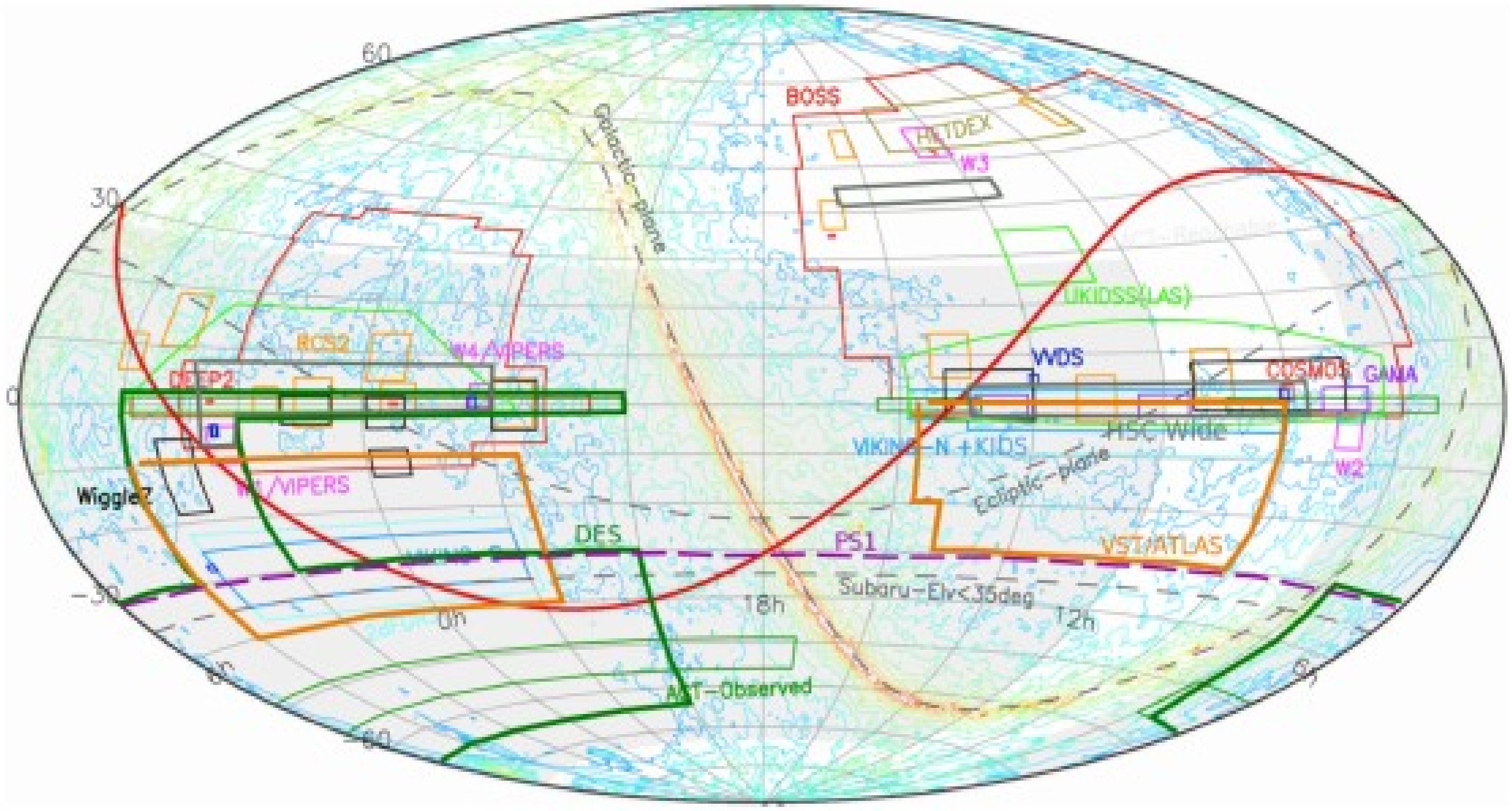
1D-surveys: very deep exposures of small patch of sky, e.g., HST Deep Field, Lockman Hole Survey, COSMOS Field, Marano Field.

2D-surveys: cover long strip of sky, e.g., CfA-Survey ($1.5 \times 100^\circ$), 2dF-Survey ("2 degree Field").

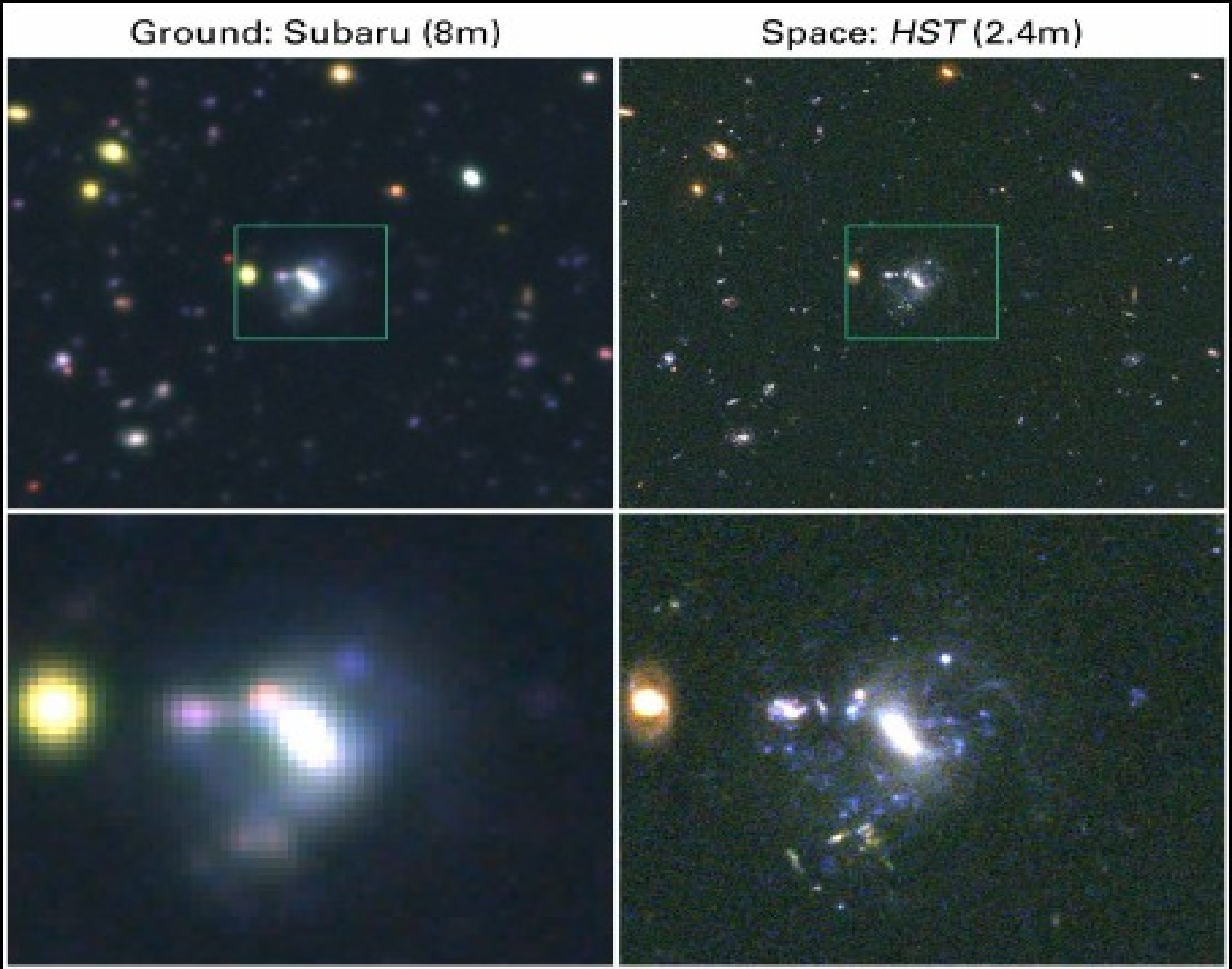
3D-surveys: cover part of the sky, e.g., Sloan Digital Sky Survey.

These surveys attempt to go to certain limit in z or m.

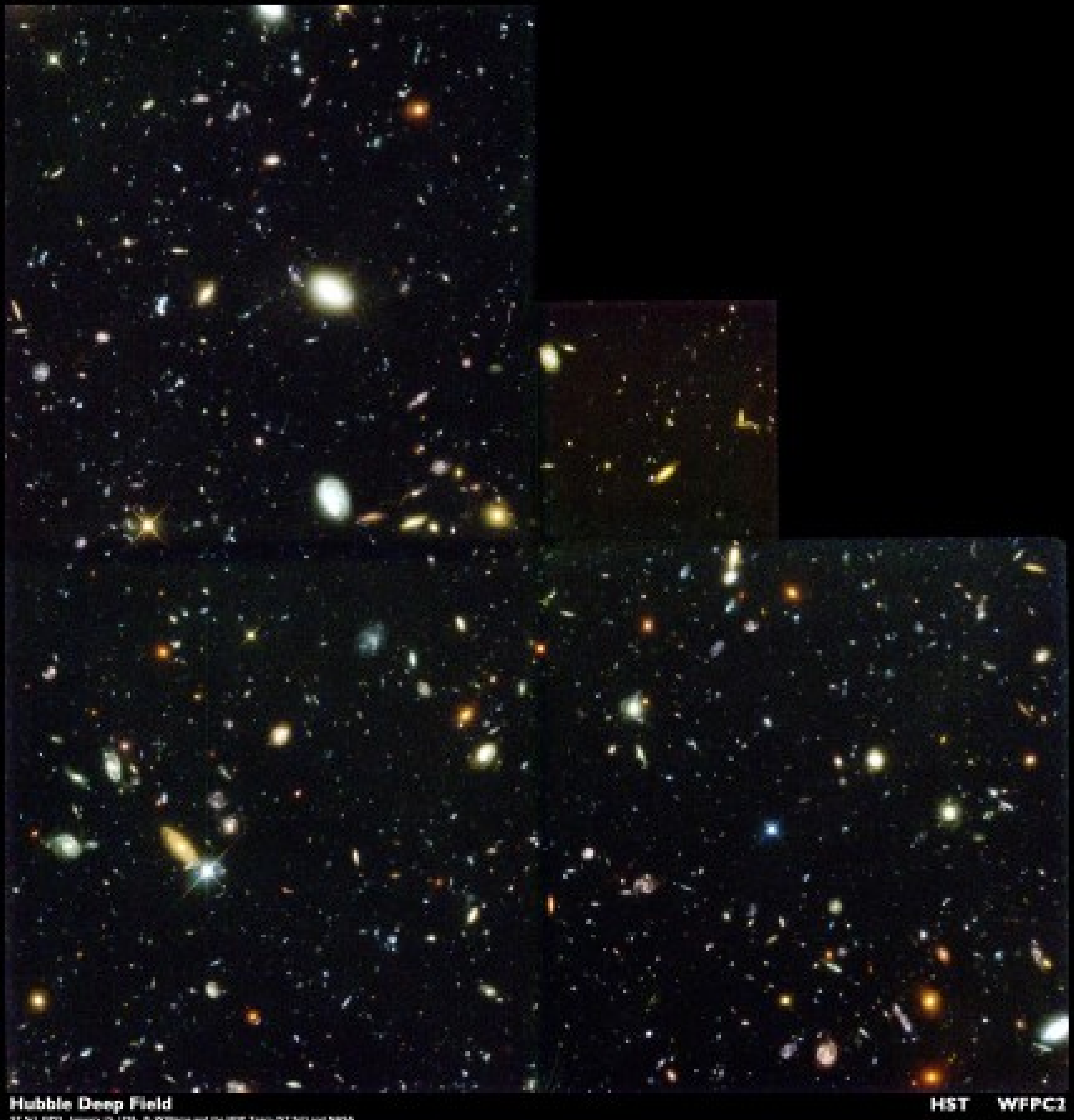
Other approaches: use pre-existing galaxy catalogues (e.g., QDOT Survey [IRAS galaxies], APM survey,...).



Merloni et al., eROSITA Science Book



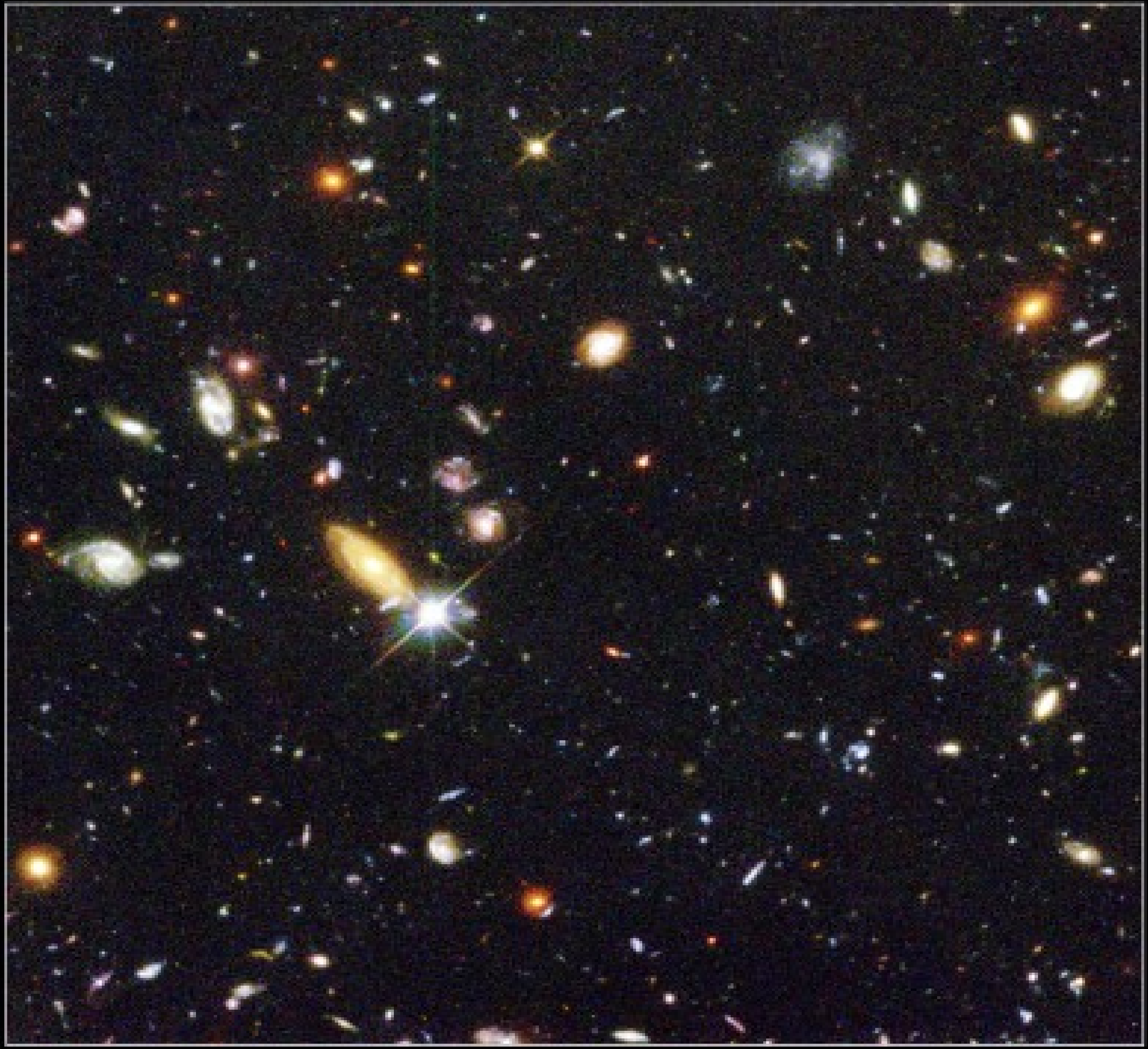
To go deep one needs to go to space



1995 December: Hubble Deep Field: $\sim$ 150 ksec/Filter for four HST Filters

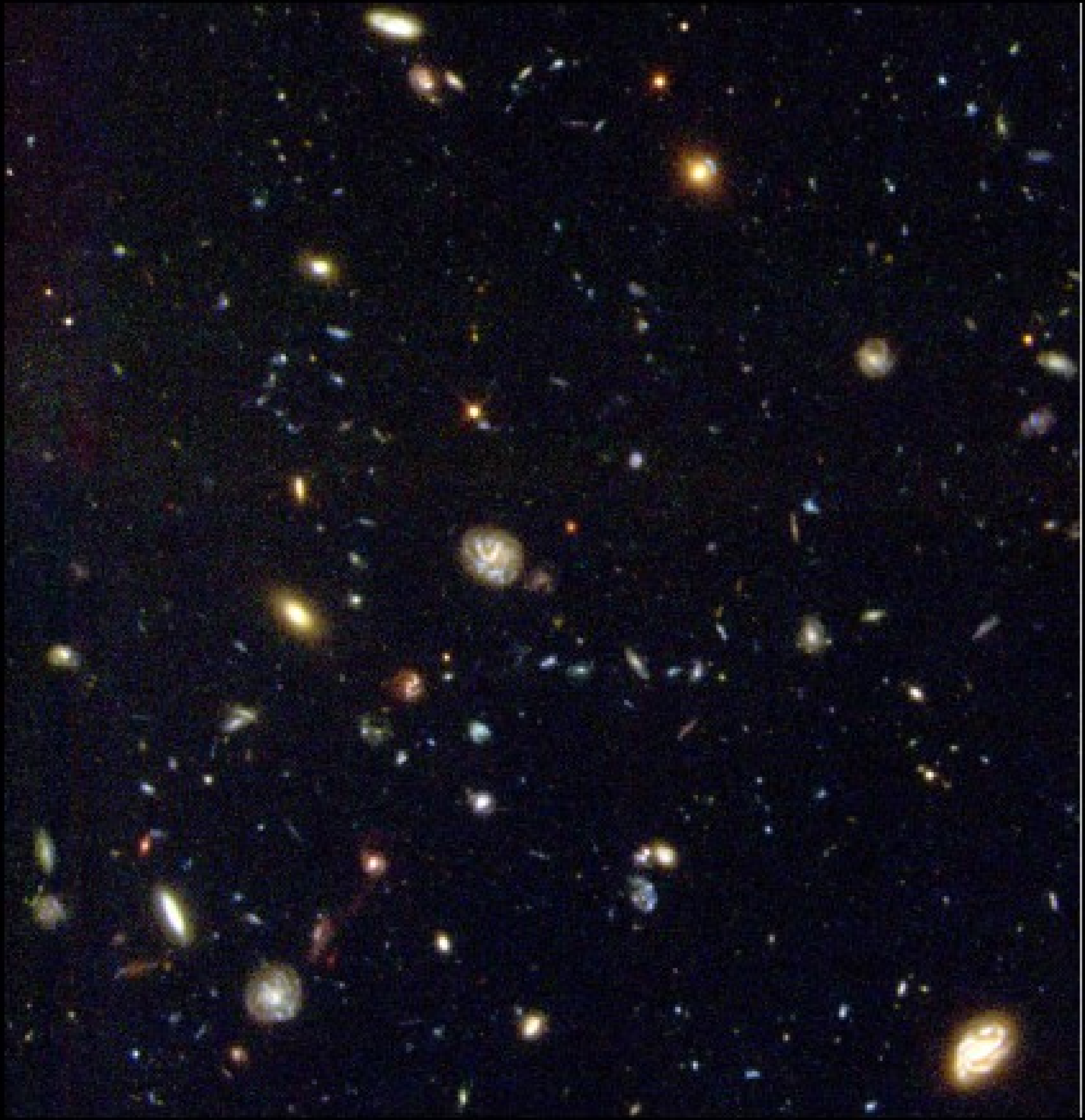
Many galaxies with weird shapes $\Longrightarrow$ protogalaxies!

Redshifts: $z \in [0.5, 5.3]$ (Fernández-Soto et al., 1999)



Hubble Deep Field

Hubble Space Telescope • WFPC2

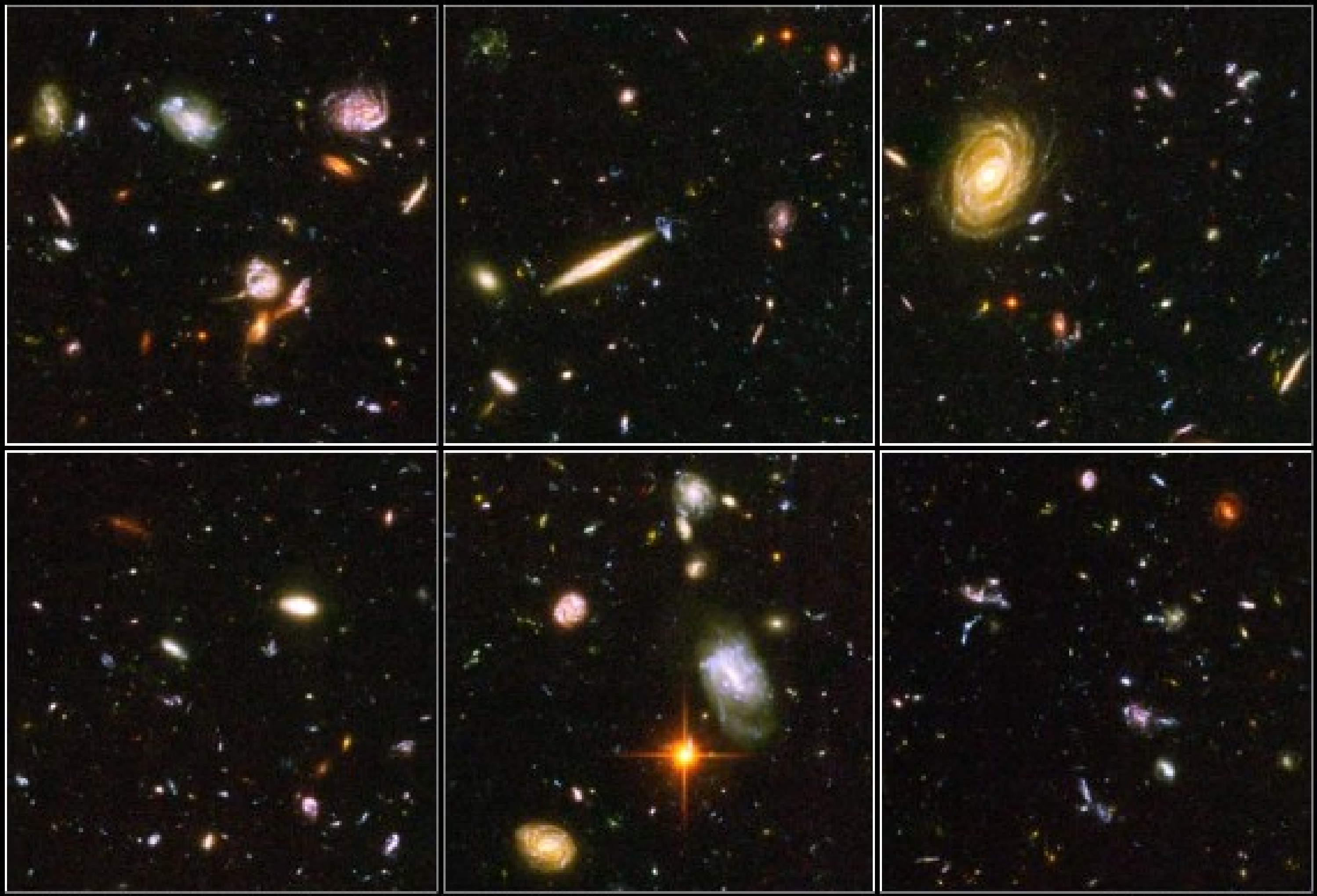


1998: Hubble Deep Field South, 10 d of total observing time!

2004: Hubble Ultra Deep Field, 1 Msec long exposure of field in Fornax. Uses updated HST with Advanced Camera for Surveys (ACS) and Near Infrared Camera and Multi-Object Spectrometer (NICMOS); diameter: $3'$ ($2\times$ HDF)
Limiting magnitude: 30 mag, $\sim$10000 galaxies visible, up to $z \gtrsim 7$
IR reveals many reddened objects

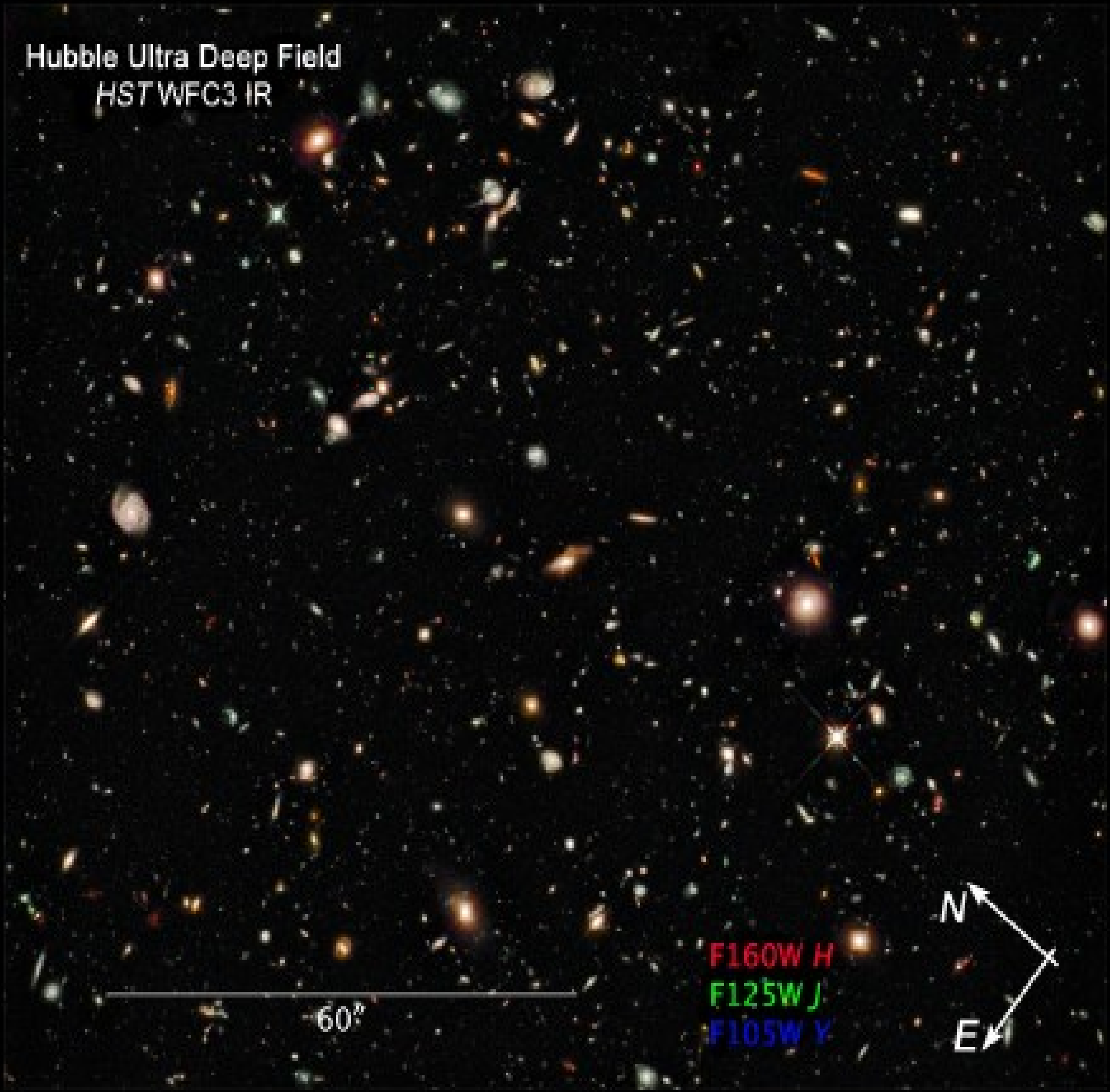
Hubble Ultra Deep Field Details

HST ▪ ACS

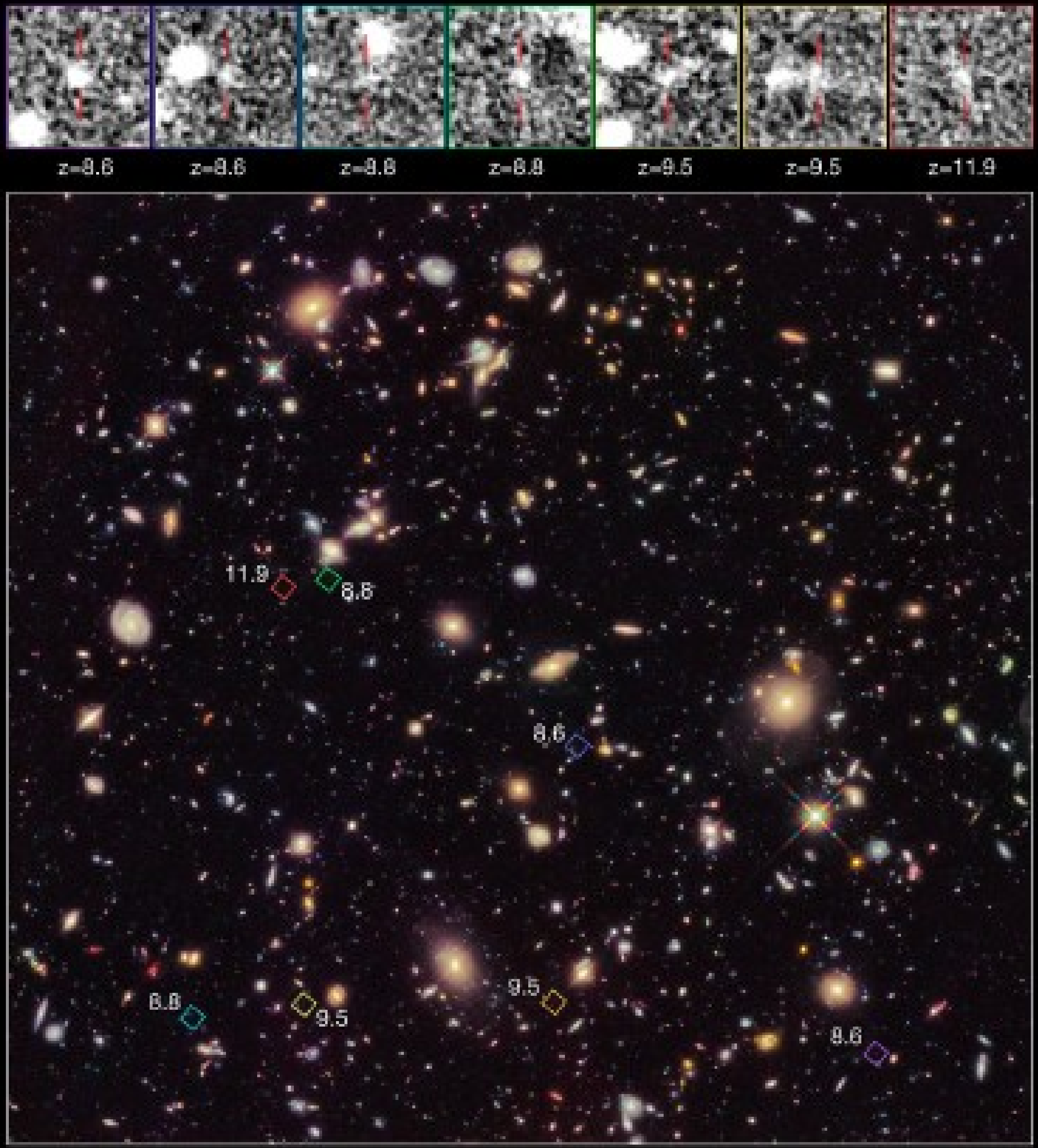


NASA, ESA, S. Beckwith (STScI) and The HUDF Team

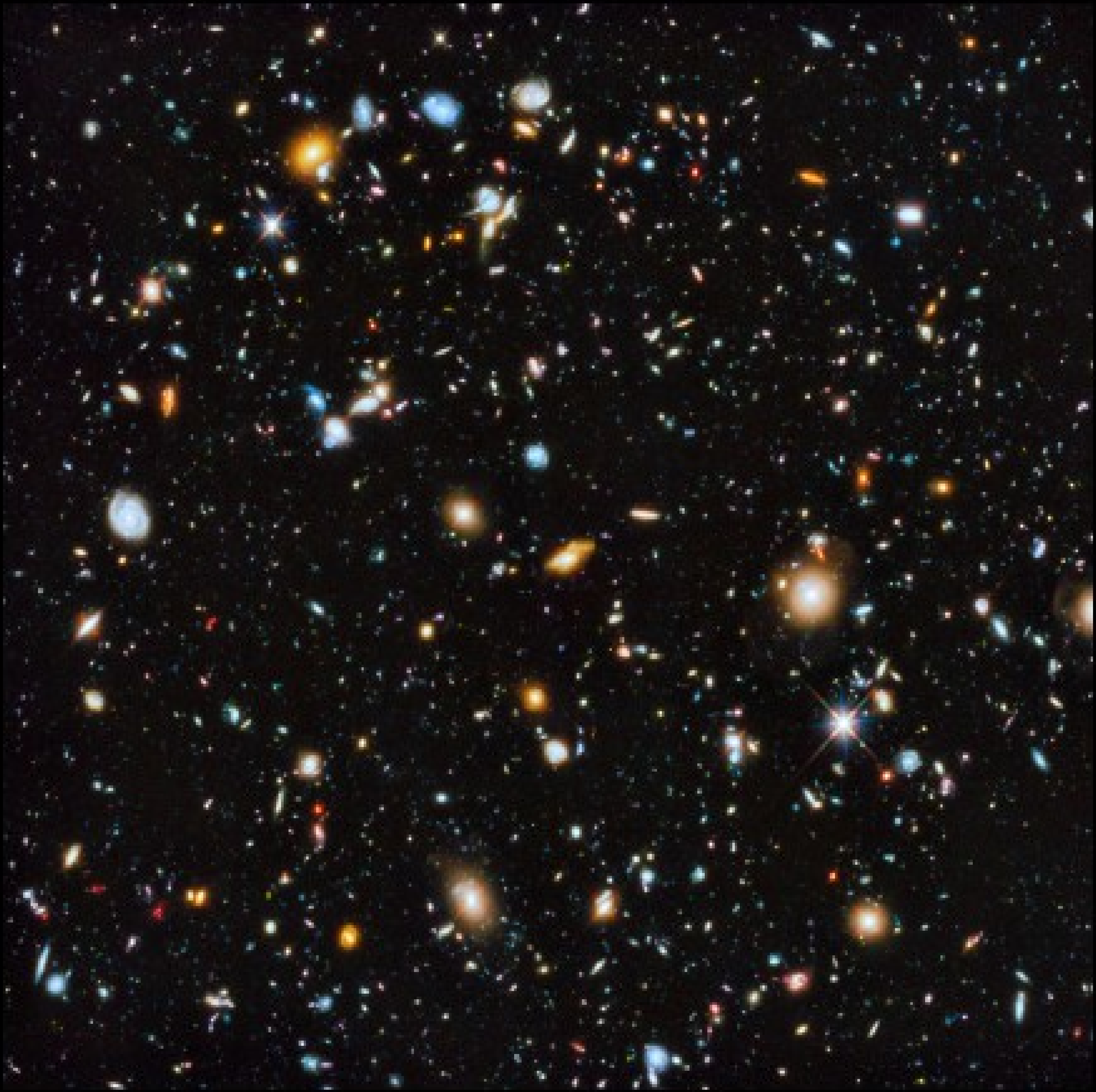
STScI-PRC04-07c



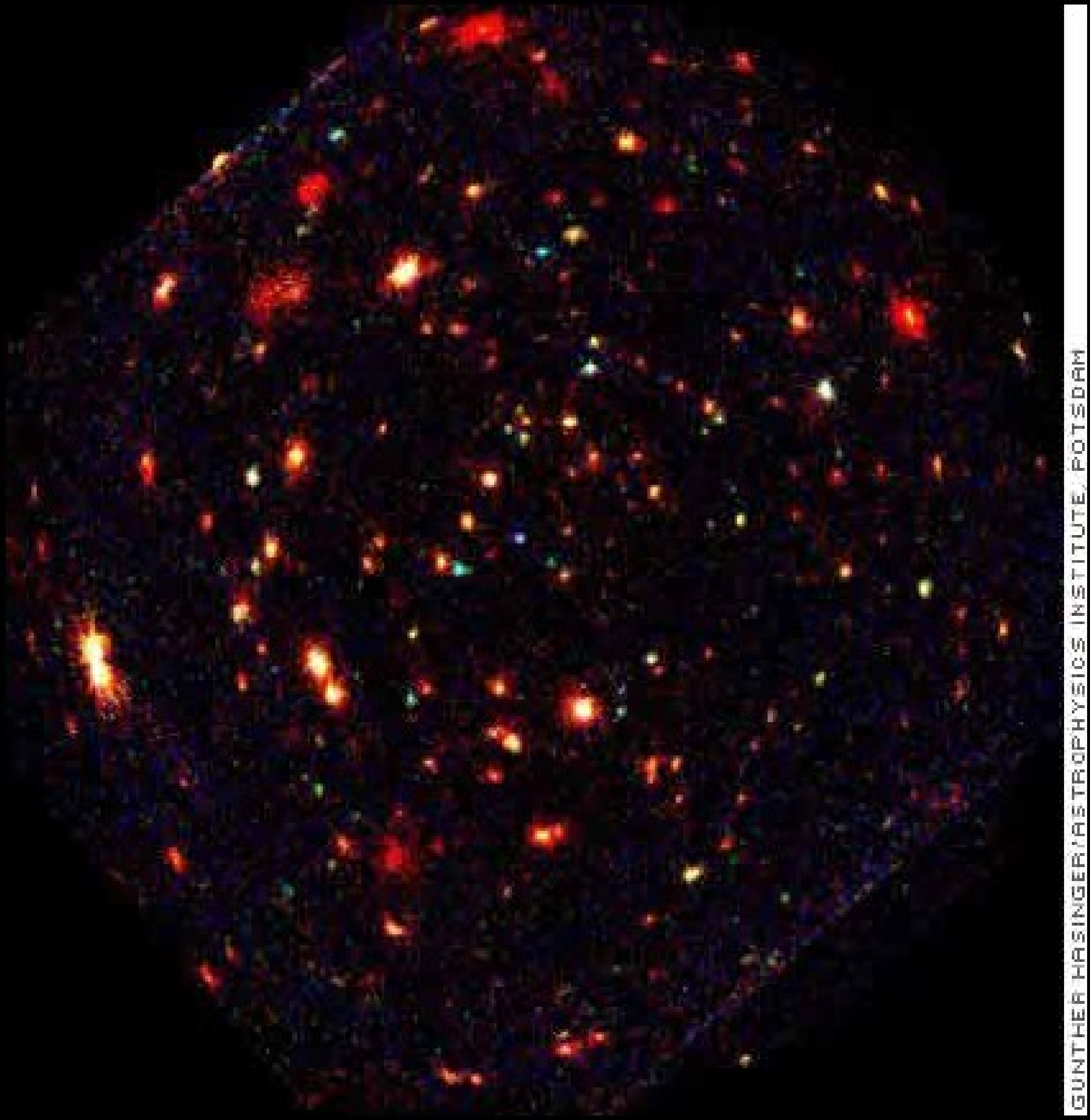
2009 August 26 – 2009 September 2009: WFC3 pushes HUDF even deeper (data taken in same region as HUDF, "Hubble Ultra Deep Field Infrared"). Exposure: 48 h



Spectroscopy finds very high redshift objects



2012: UV coverage added



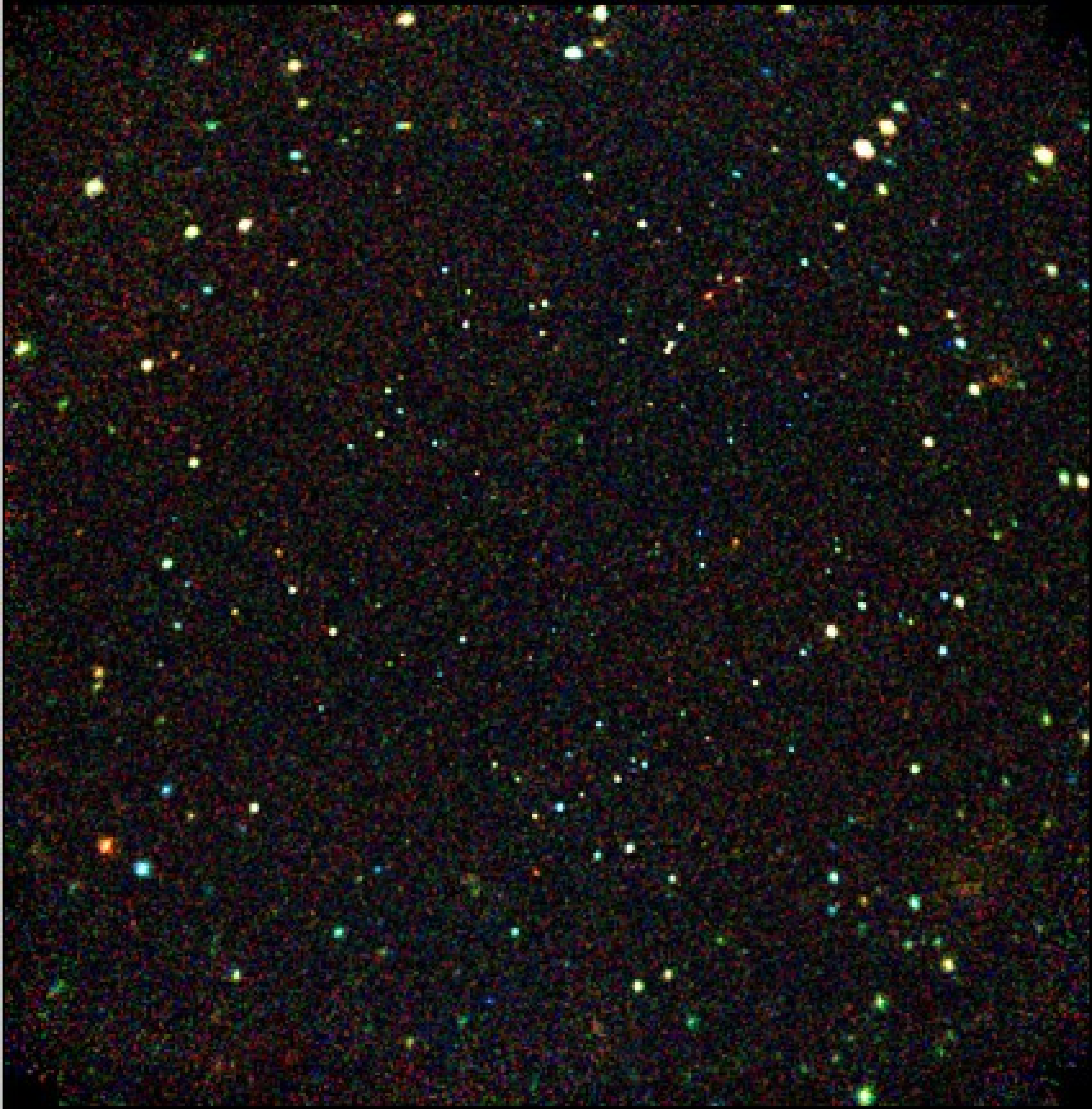
Lockman Hole: Northern Sky region with very low N_H

⟹ low interstellar absorption

⟹ "Window in the sky"

⟹ X-rays: evolution of active galaxies with z!

XMM-Newton, Hasinger et al., 2001,
blue: hard X-ray spectrum,
red: soft X-ray spectrum

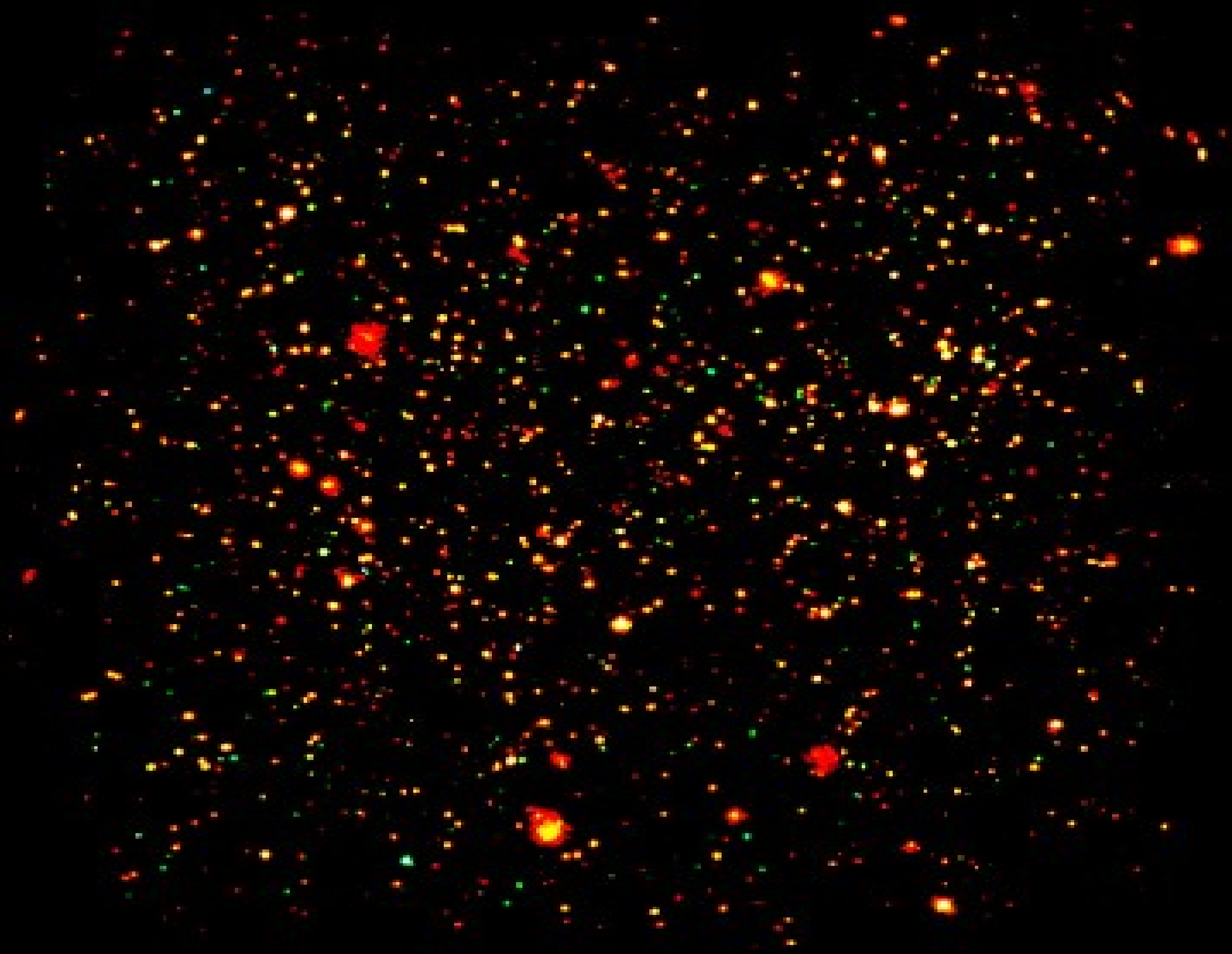


Chandra Deep Field South: 1 Msec (10.8 days) on one region in Fornax ($\alpha_{J2000.0}$ = $3^h32^m28.0^s$, $\delta_{J2000.0}$ = $-27^\circ48'30''$, coaligned with HDF-S

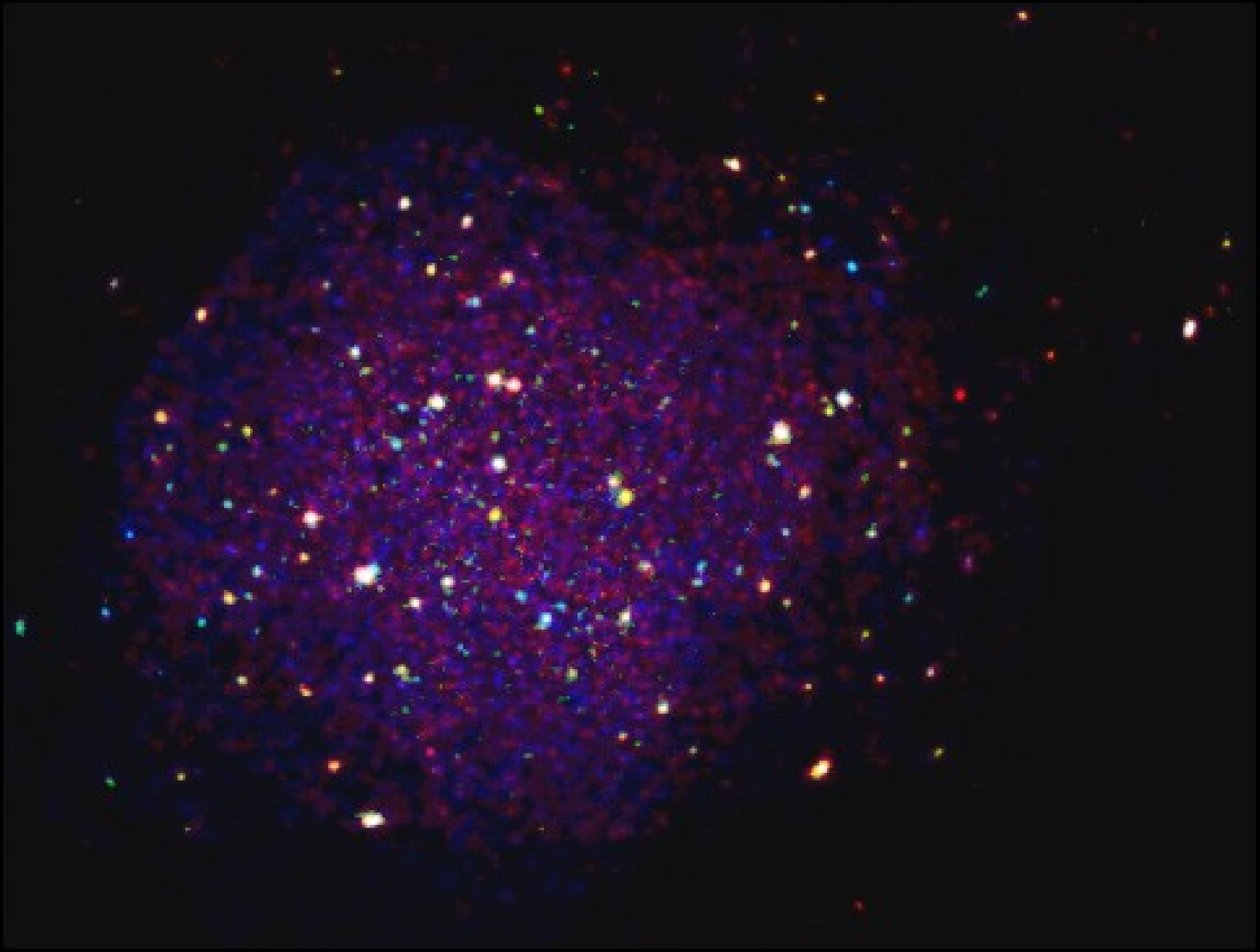
Deepest X-ray field ever

color code: spectral hardness

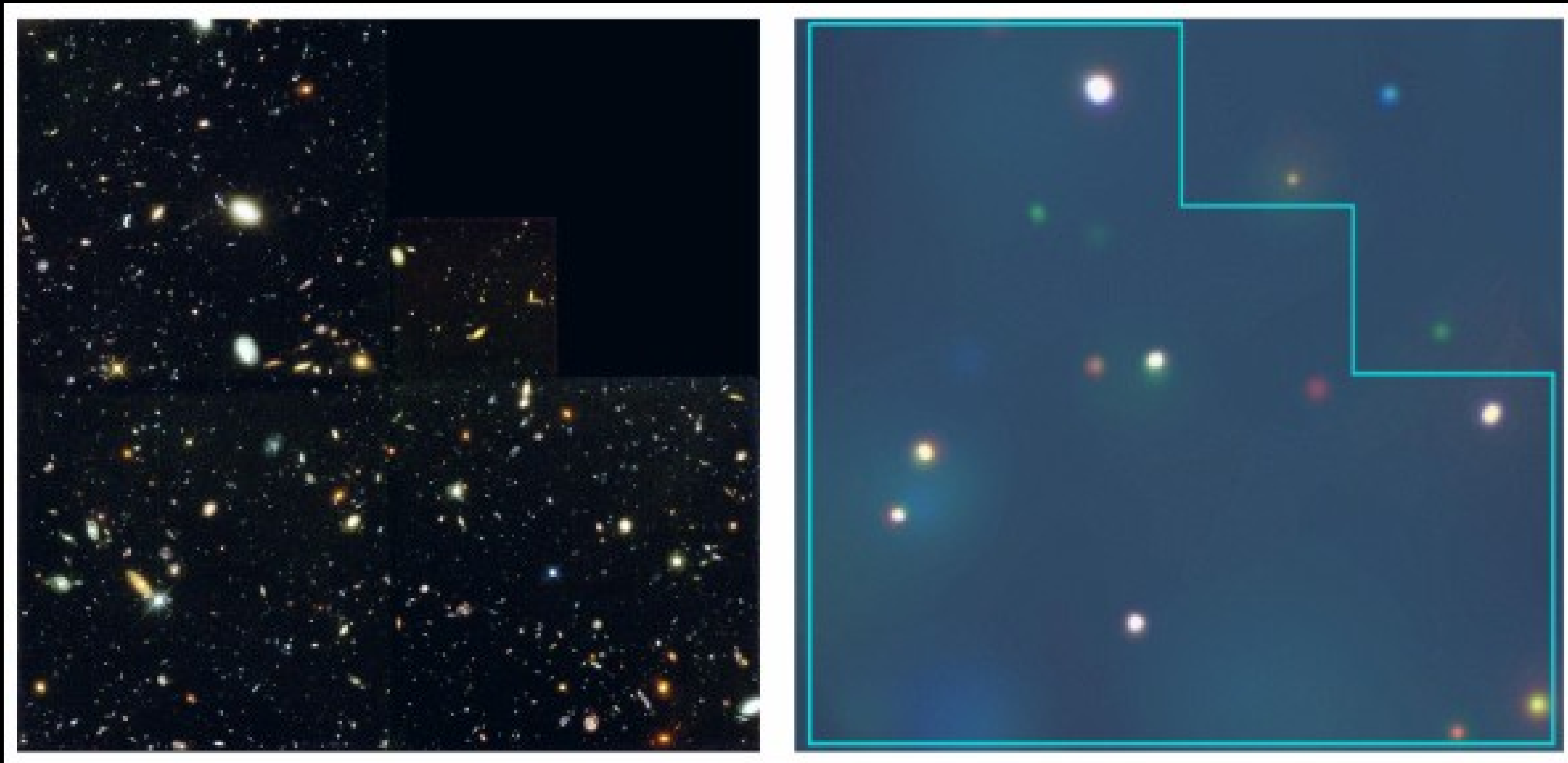
scale: $15' \times 15'$; courtesy NASA/JHU/AUI/R.Giacconi et al.



COSMOS-field: large X-ray survey for Galaxy Clusters



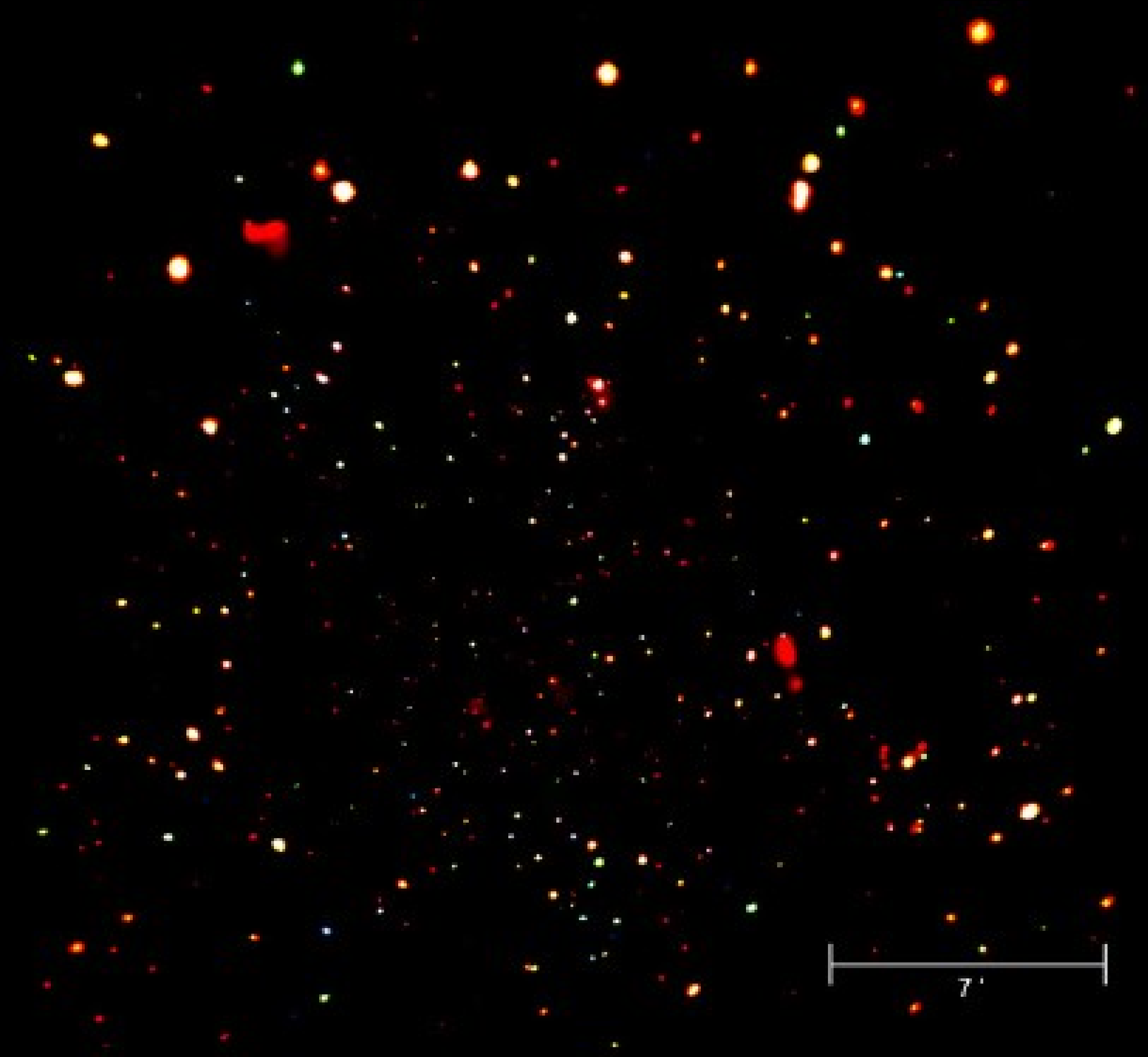
Deep *XMM-Newton* image of the Marano Field (IAAT/AIP/MPE)



HST Chandra

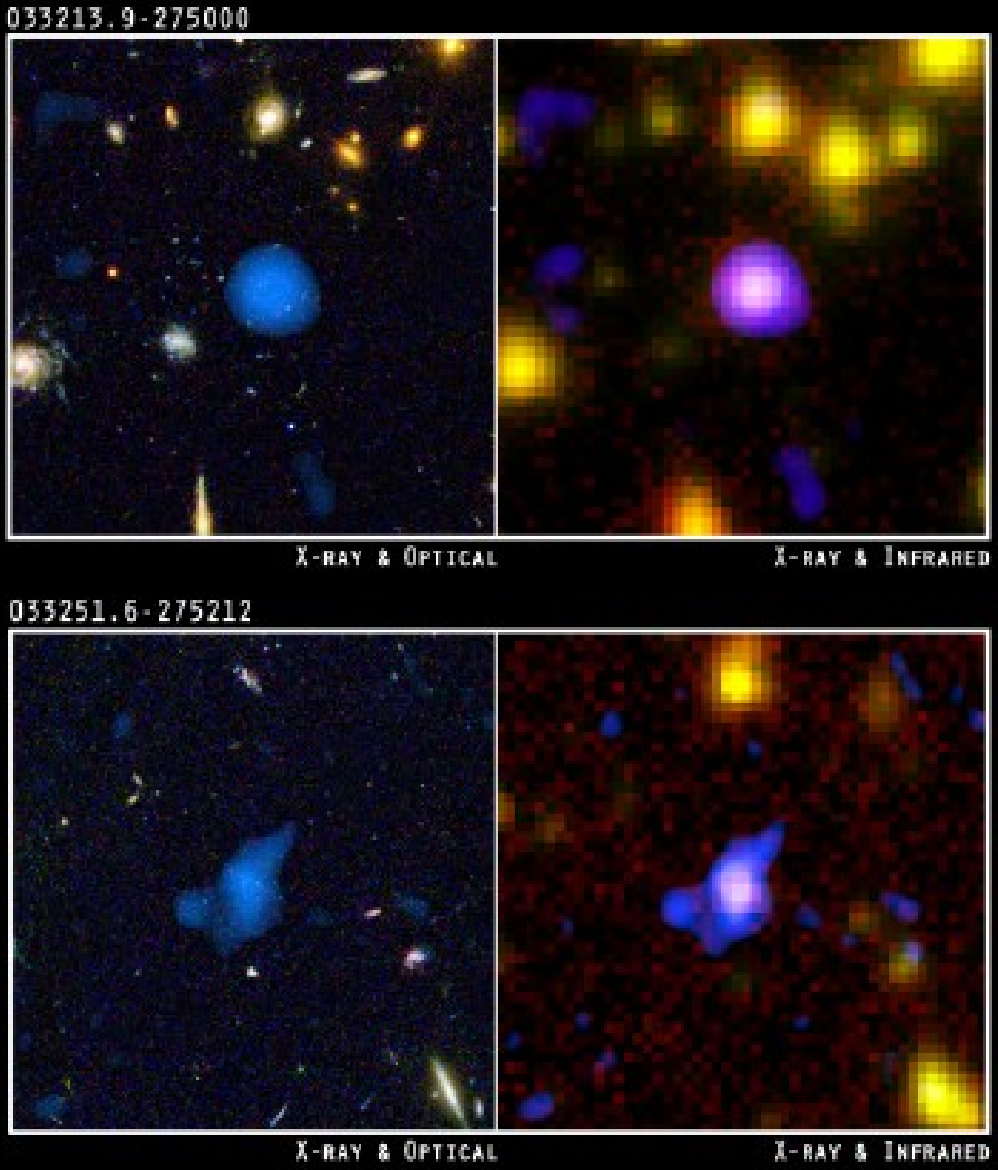
Chandra/HST Image of Hubble Deep Field North; 500 ksec

Joint multi-wavelength campaigns allow the measurement of broad-band spectra of sources in the early universe!



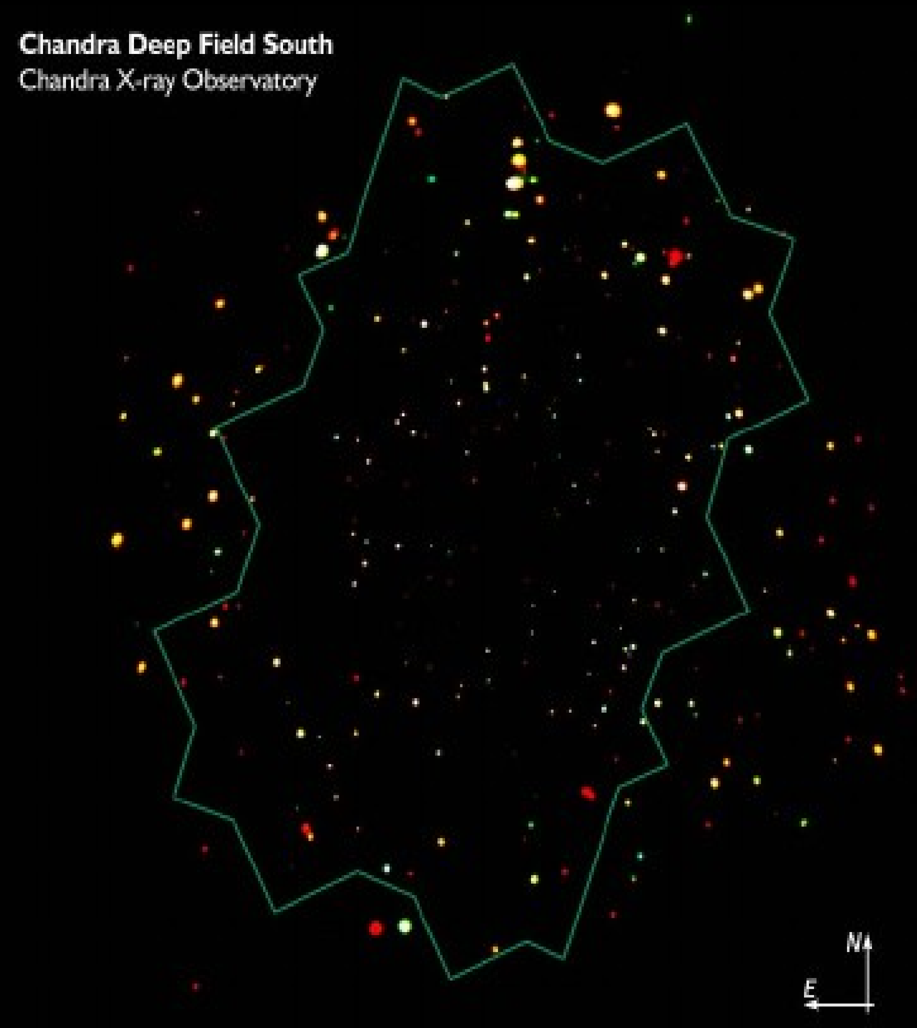
⟹ GOODS-Survey (Great Observatories Origins Deep Survey), centered on CDF-S

(same image as before, this time smoothed)



IR, optical, and X-ray image of small fraction of GOODS

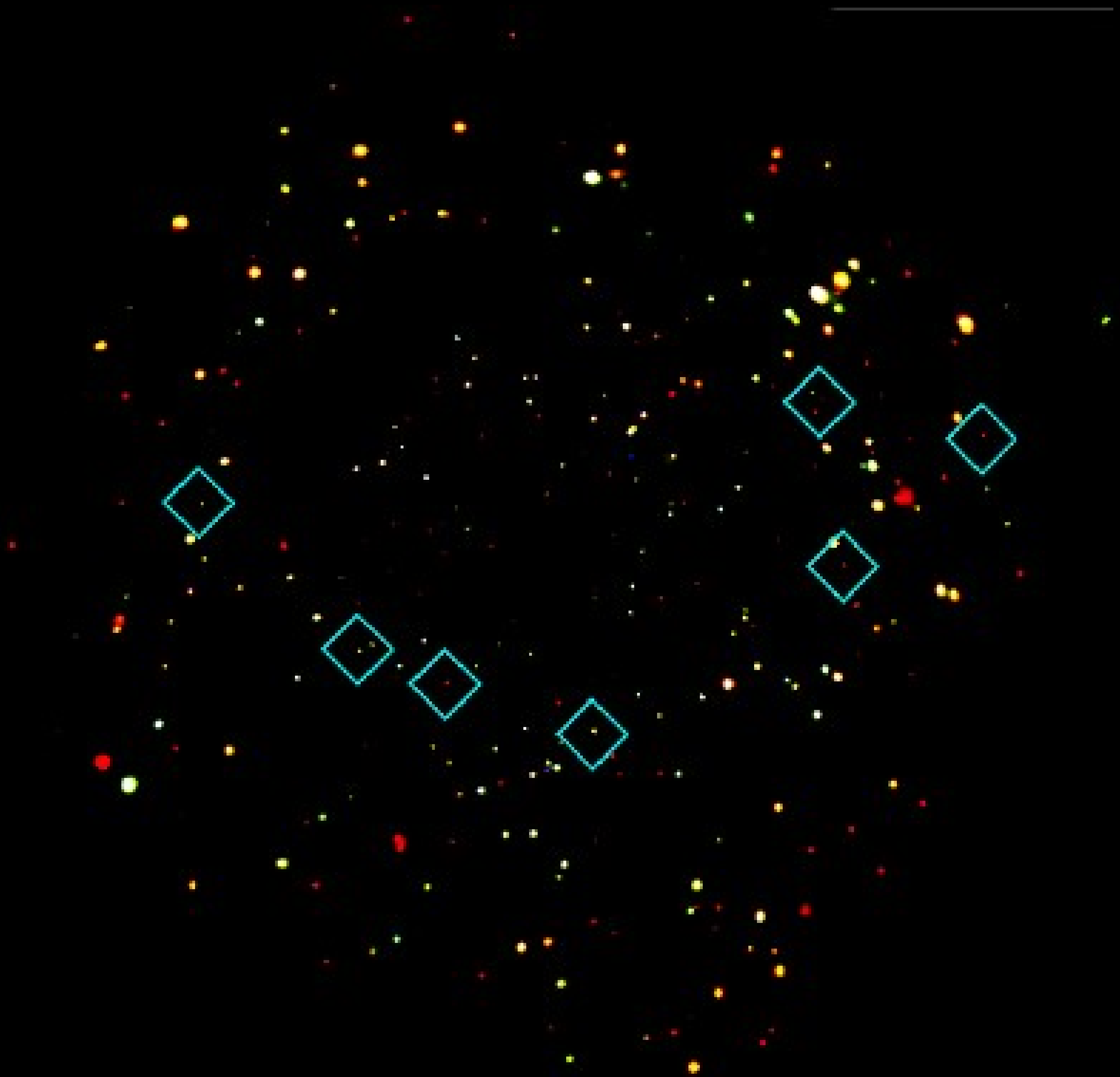
CXC/NASA



HST ACS observations of whole area of CDF-S

CXC

Chandra and HST fields aligned



CDFS: blue boxes contain objects not visible in HST

⟹ farthest black holes known

Future for Large Scale Structure: 2D and 3D Surveys observing large part of sky with dedicated instruments.

Currently largest surveys:

Las Campanas Redshift Survey (LCRS): 26418 redshifts in six $1.5 \times 80^\circ$ slices around NGP and SGP, out to $z = 0.2$.

CfA Redshift Survey: 30000 galaxies

APM: (Oxford University) $2 \sim 10^6$ galaxies, 10^7 stars around SGP, 10% of sky, through $B = 21$ mag.

2MASS: IR Survey of complete sky (Mt. Hopkins/CTIO) completed 2000 October 25), 3 bands, $\sim 2 \times 10^6$ galaxies, accompanying redshift survey (8dF, CfA)

Sloan Digital Sky Survey (SDSS): dedicated 2000 October 5, Apache Point Obs., NM, 25% of whole sky, $\sim 10^8$ objects, now in Google Earth

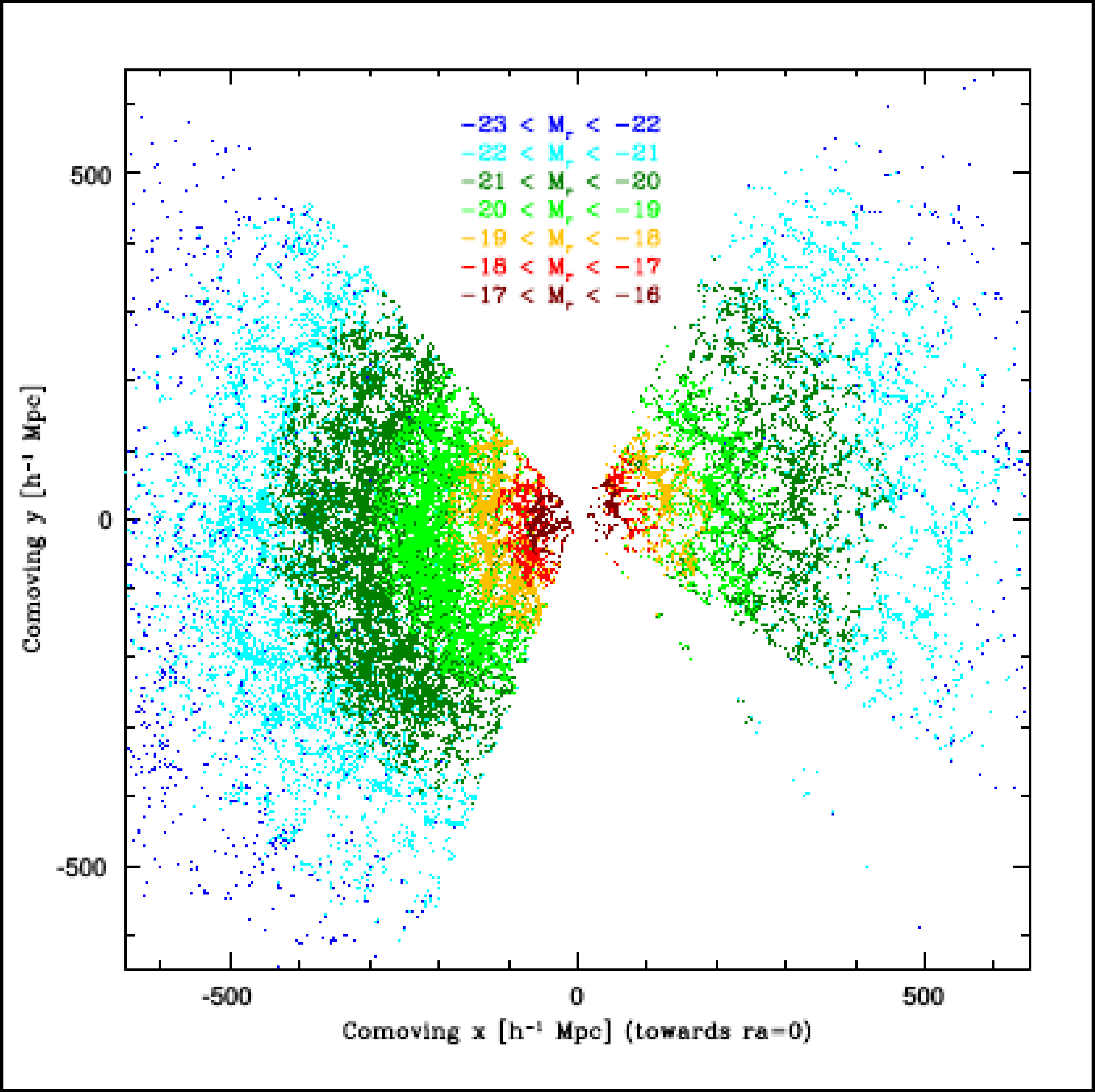
And many more (e.g., Keck, ESO, LSST,...).

SDSS 2.5 m telescope at Apache Point Observatory

courtesy SDSS

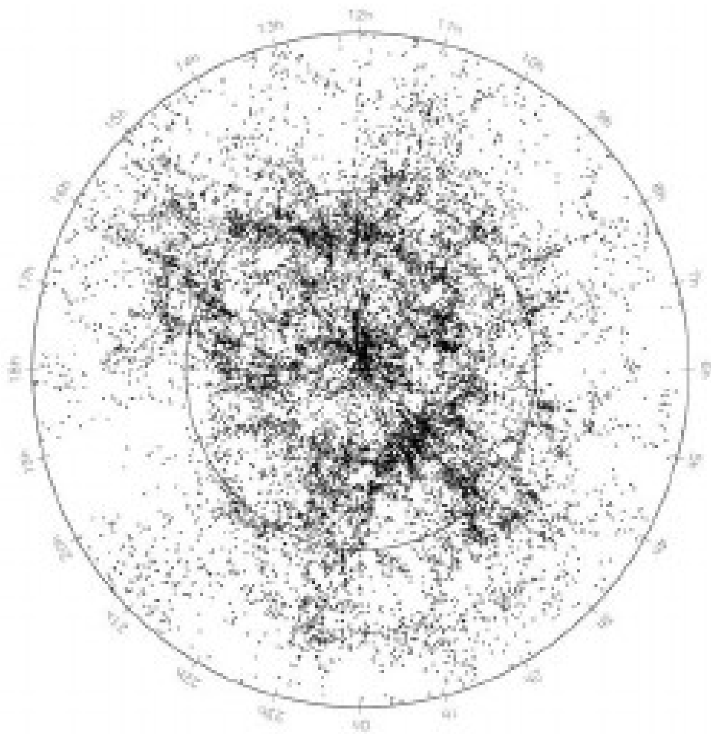
courtesy SDSS

Spectroscopy with grism (combination of prism and grating), light from objects via optical fibers and plug plate.

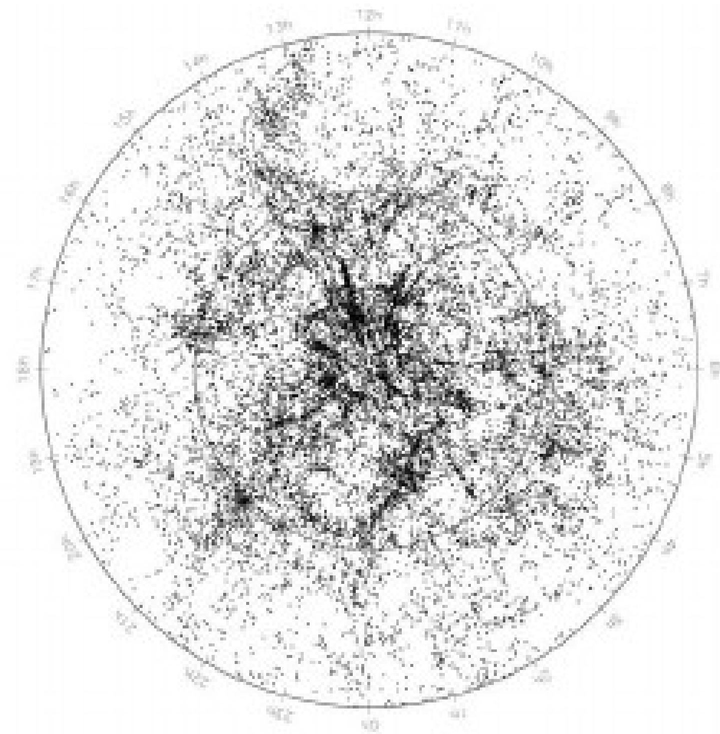


Galaxy distribution from the SDSS

(Tegmark et al., 2004, Fig. 4)



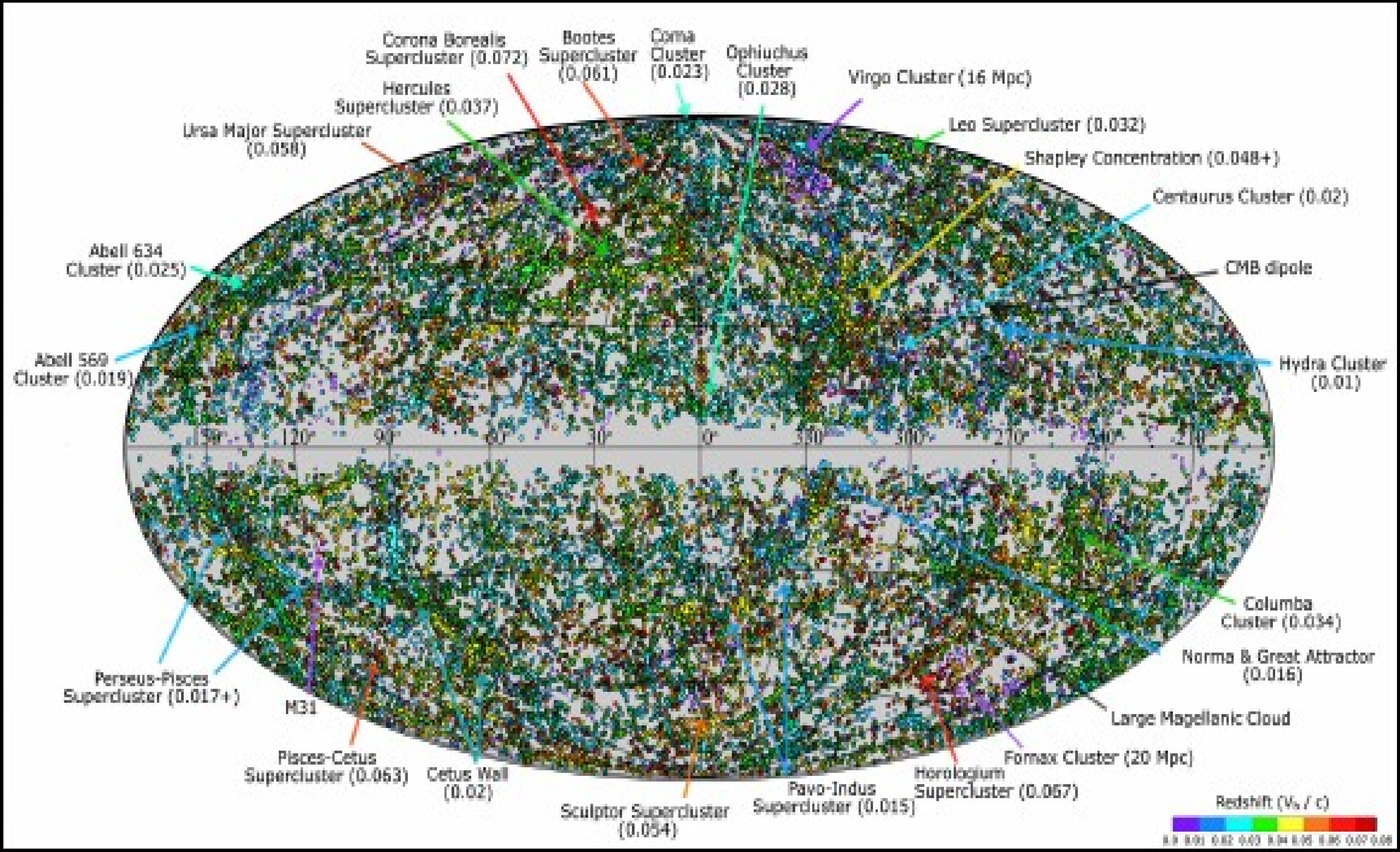
north



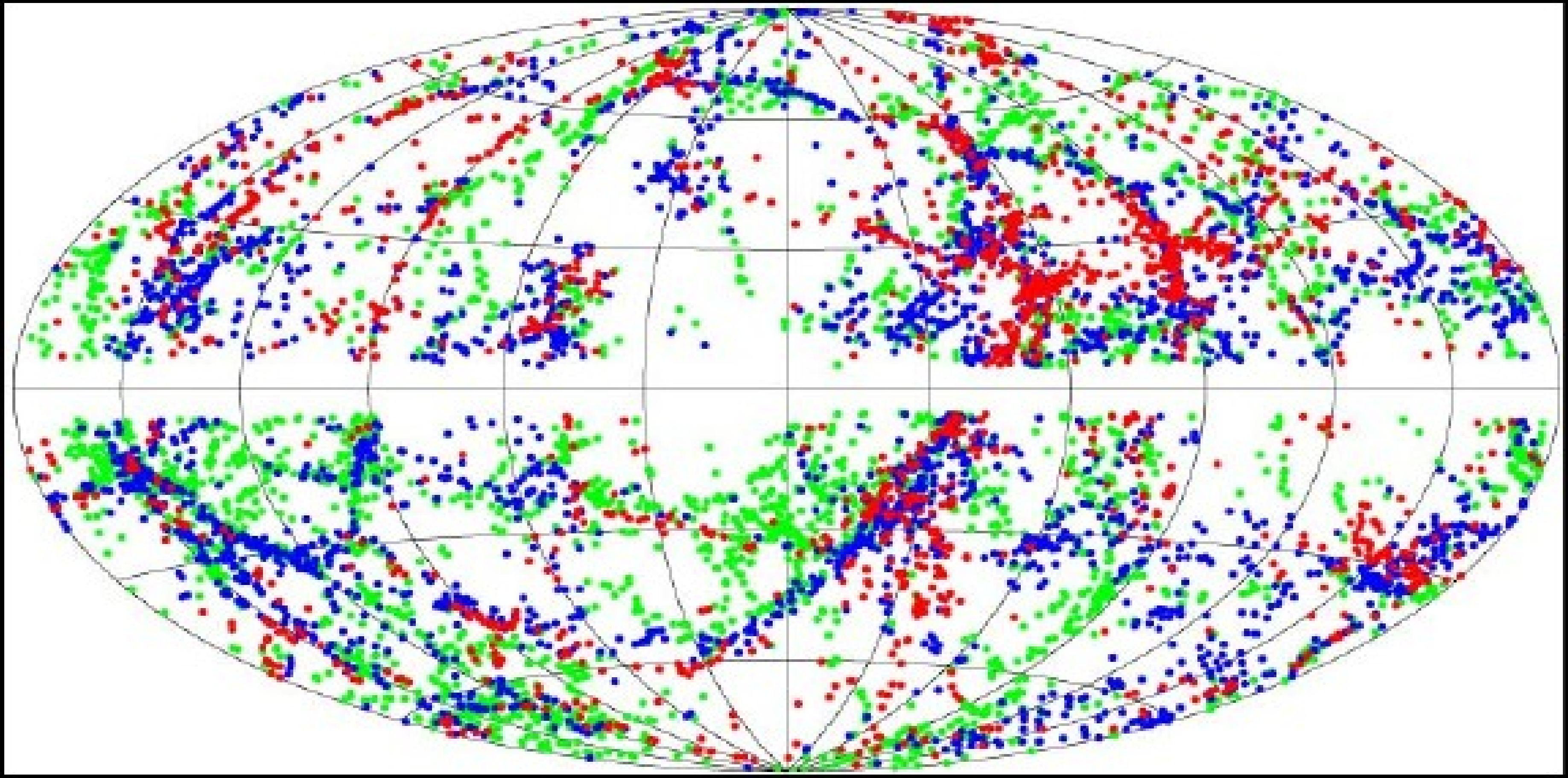
south

(Huchra et al., 2012a, Figs. 7, 8)

Two Micron All Sky Survey (2MASS): 1990–2000 in J, H, K bands;
redshifts available for ∼45000 sources

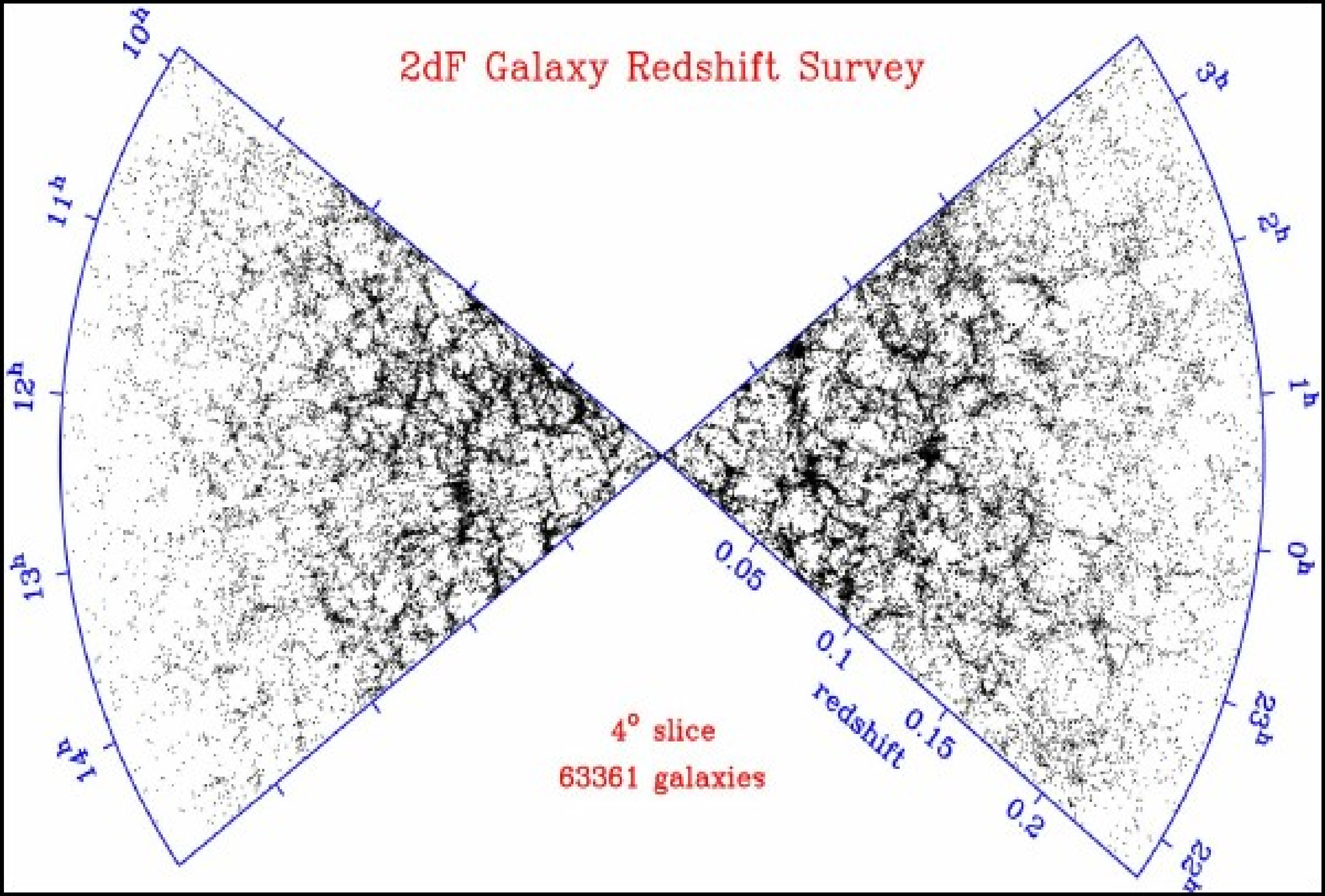


Sky distribution of the 2MASS survey (Huchra et al., 2012a, Fig. 12)



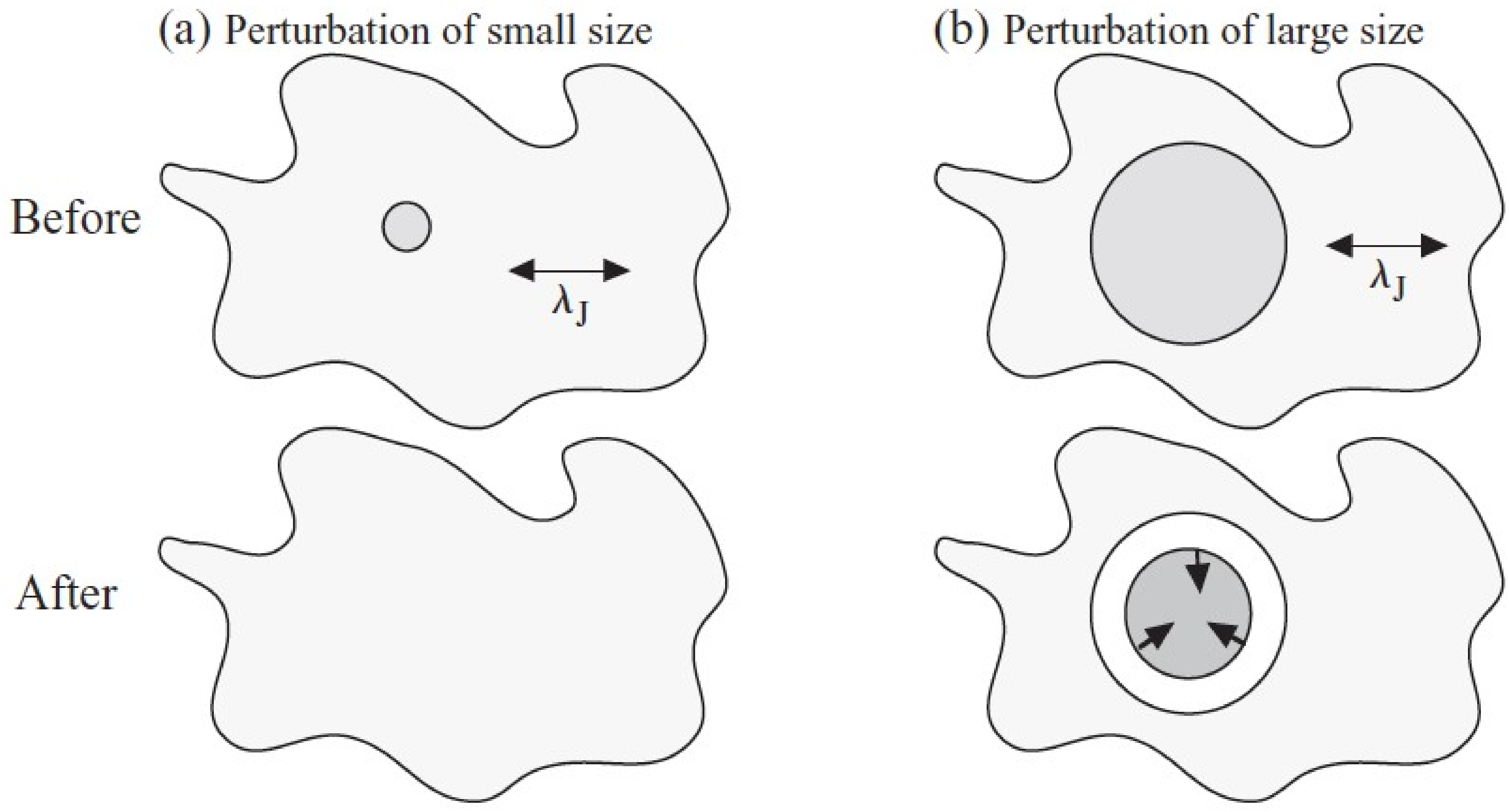
(Huchra et al., 2012a, Fig. 10)

2MASS survey:
red: $v < 1000\,\mathrm{km\,s^{-1}}$,
blue: $1000\,\mathrm{km\,s^{-1}} < v < 2000\,\mathrm{km\,s^{-1}}$,
green: $2000\,\mathrm{km\,s^{-1}} < v < 3000\,\mathrm{km\,s^{-1}}$.



courtesy 2dF collaboration

Cloud contraction



Early universe: radiation dominates:

$$c_s = c/\sqrt{3} \quad \text{and} \quad \rho_r c^2 = \sigma T^4 \tag{14.72}$$

and therefore

$$\lambda_{\mathrm{J,rad}} = c^2\sqrt{\pi/3G\sigma T^4} \propto \rho_r^{-1/2} \propto a^2 \quad \text{and} \quad M_\mathrm{J} \propto \rho_\mathrm{m}\lambda^3_{\mathrm{J,rad}} \propto a^3 \tag{14.73}$$

In the early universe, the Jeans mass grows quickly.

At time of radiation – matter equilibrium,

$$\rho_\mathrm{m} = \rho_\mathrm{rad} = \sigma T^4_\mathrm{eq}/c^2 \tag{14.74}$$

and

$$M_\mathrm{J}(t_\mathrm{eq}) = \frac{\pi^{5/2}}{18\sqrt{3}}\frac{c^4}{G^{3/2}\sigma^{1/2}}\frac{1}{T_\mathrm{eq}} \sim \frac{3.6\times 10^{16}(\Omega_0 h^2)^{-2}\,M_\odot}{(T/T_\mathrm{eq})^3} \tag{14.75}$$

assuming $1 + z_\mathrm{eq} = 24000\,\Omega_0 h^2$.

$\Longrightarrow$ much larger than mass in galaxy cluster ($\sim$ mass of $(50\,\mathrm{Mpc})^3$-cube)

Overdense regions with $m < M_{\mathrm{J,rad}}$ are smoothed out by the radiation coupling to matter.

Much larger structures also cannot grow since λ is larger than horizon radius $\Longrightarrow$ Mass spectrum of possible structures.

After t_{eq} not much happens until $T_{rec} \sim 3000\,\mathrm{K}$

$\Longrightarrow$ recombination

$\Longrightarrow$ Sound speed drops dramatically (radiation and matter decouple):

$$c_s \sim \frac{kT}{m_p} \sim 5\,\mathrm{km\,s^{-1}} \tag{14.76}$$

$\Longrightarrow$ M_J drops by 10^{11}:

$$M_{J,eq} = \frac{\pi\bar{\rho}}{6}\left(\frac{\pi k T_{rec}}{G\bar{\rho}m_p}\right)^{1/2} \sim 5\times10^5(\Omega_0 h^2)^{-1/2}\,M_\odot \tag{14.77}$$

after that, M_J drops because of expansion.

So, in a pure matter universe: huge structures (Zeldovich pancakes) form early, and then fragment at recombination. $\Longrightarrow$ "top-down model"

Problem: This is not really what has been observed (i.e., galaxy clusters are not yet fully formed, but galaxies are)

Solution: Dark matter

Structure formation with dark matter:

DM unaffected by radiation pressure $\Longrightarrow$ collapse of smaller structures possible

$\Longrightarrow$ bottom-up model

As long as DM is relativistic:

$$M_{\mathrm{J,HDM}} = \frac{\pi \rho_{\mathrm{DM}}}{6} \left(\frac{\pi c_{\mathrm{DM}}}{G \rho_{\mathrm{DM}}} \right)^{3/2} \tag{14.78}$$

Hot Dark Matter: $c_{\mathrm{HDM}} \sim c/\sqrt{3}$

Cold Dark Matter: $c_{\mathrm{CDM}} \ll c/\sqrt{3}$

Standard CDM Scenario:

- DM cools long before t_{rec}
- CDM structures form, M_{J} about galaxy mass, while baryons coupled to radiation $\Longrightarrow$ stays smooth
- t_{rec}: matter decouples, falls in DM gravity wells

CDM "seeds" structures!

Gives not exactly observed power spectrum

$\Longrightarrow$ Currently preferred: combination of CDM and ΛDM

Finally, the *real* linear theory has to be done in linearized or even full general relativity

$\Longrightarrow$ very, very complicated.

Full fledged, detailed structure formation is mainly done numerically.

N-body codes: describe particles (=galaxies) as points, compute mutual interactions in expanding universe

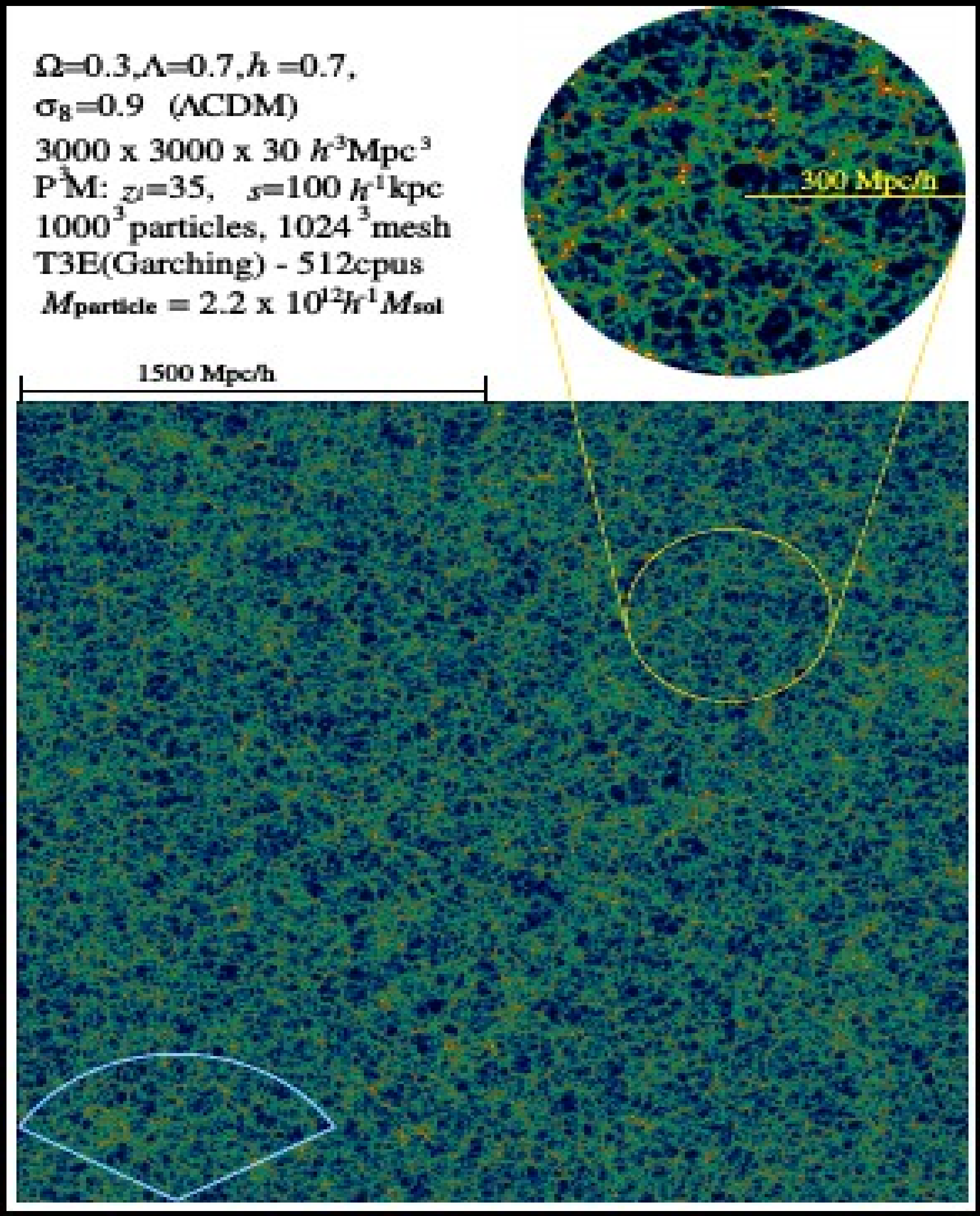
Requires massive computing power.

VIRGO consortium: USA, Canada, Germany, UK

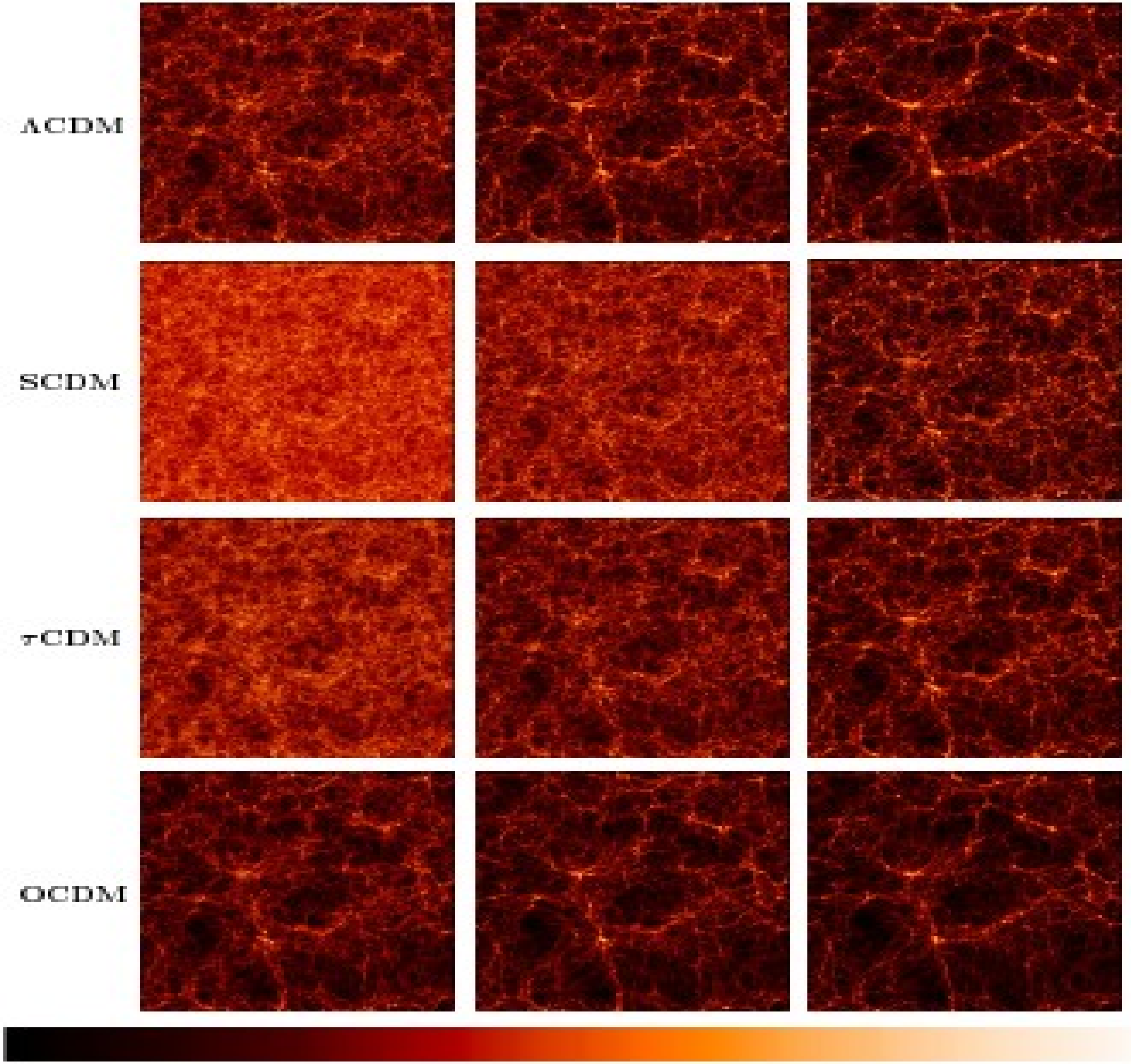
Hubble Volume Simulation: Garching T3E (512 processors), 70 h CPU time

followed by the Millenium Simulation (30 d CPU time)

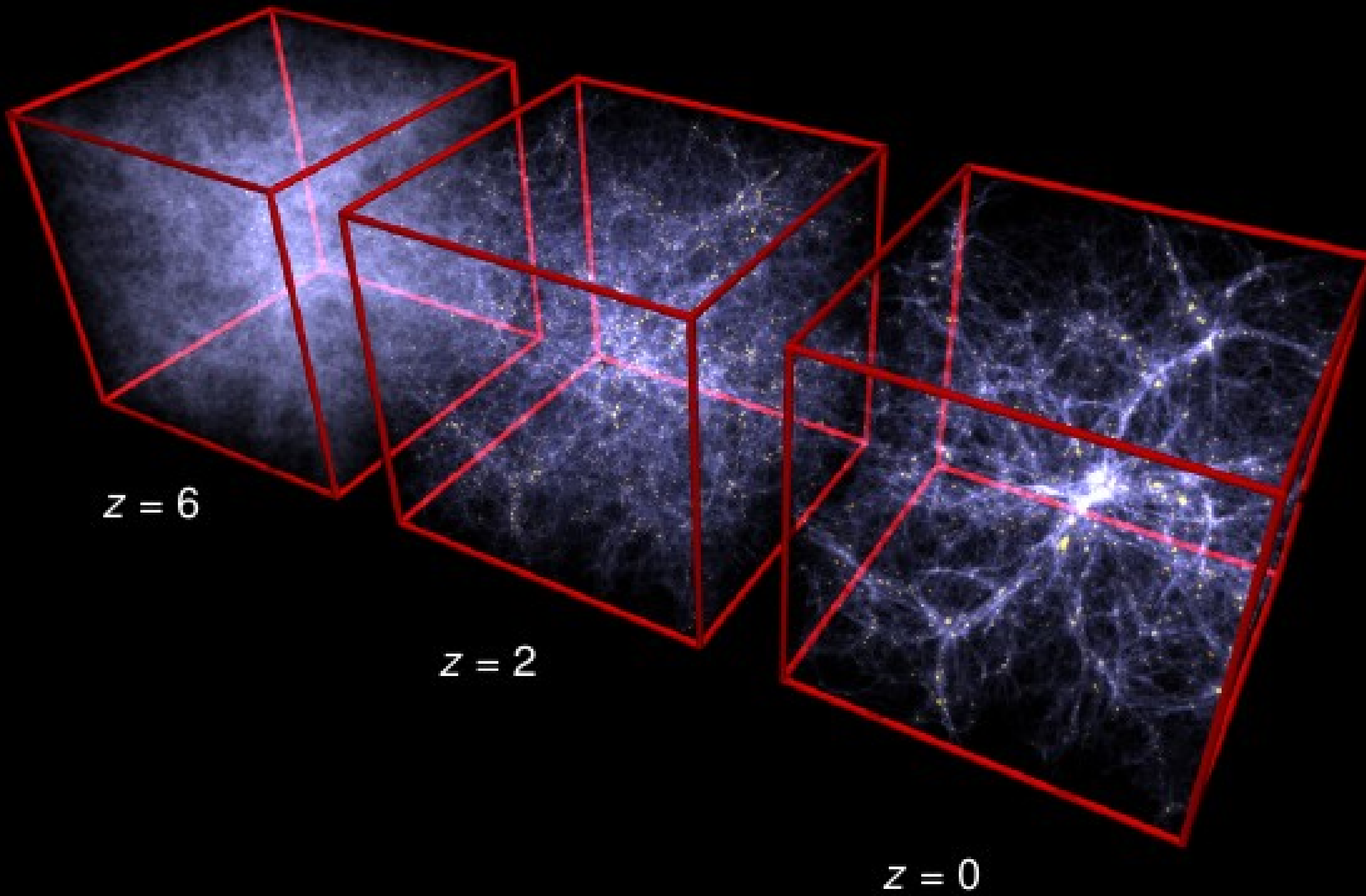
see Springel et al. (2005), Springel et al. (2006) and `http://www.mpa-garching.mpg.de/~virgo/virgo/`



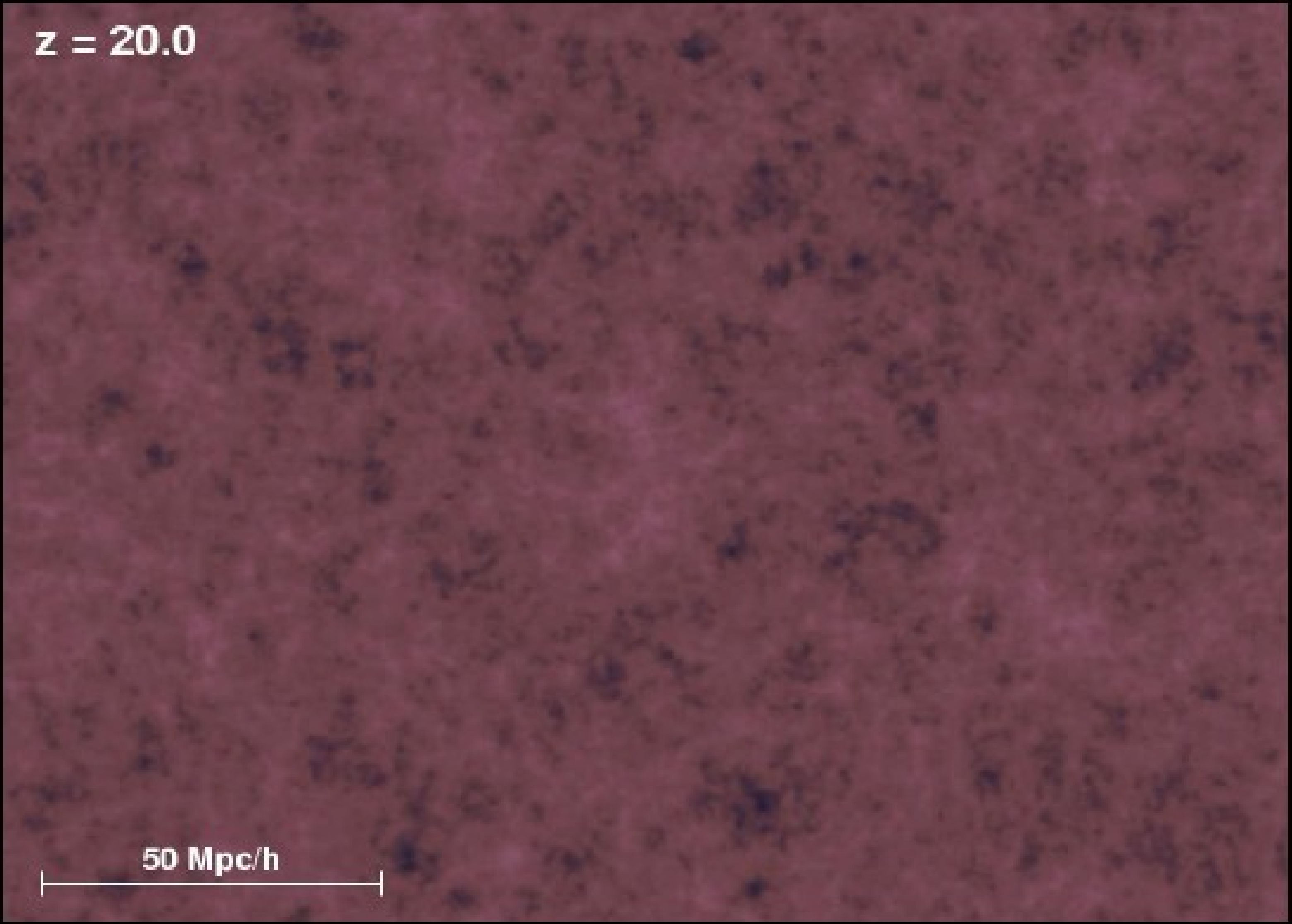
ΛDM, pie shows SDSS size



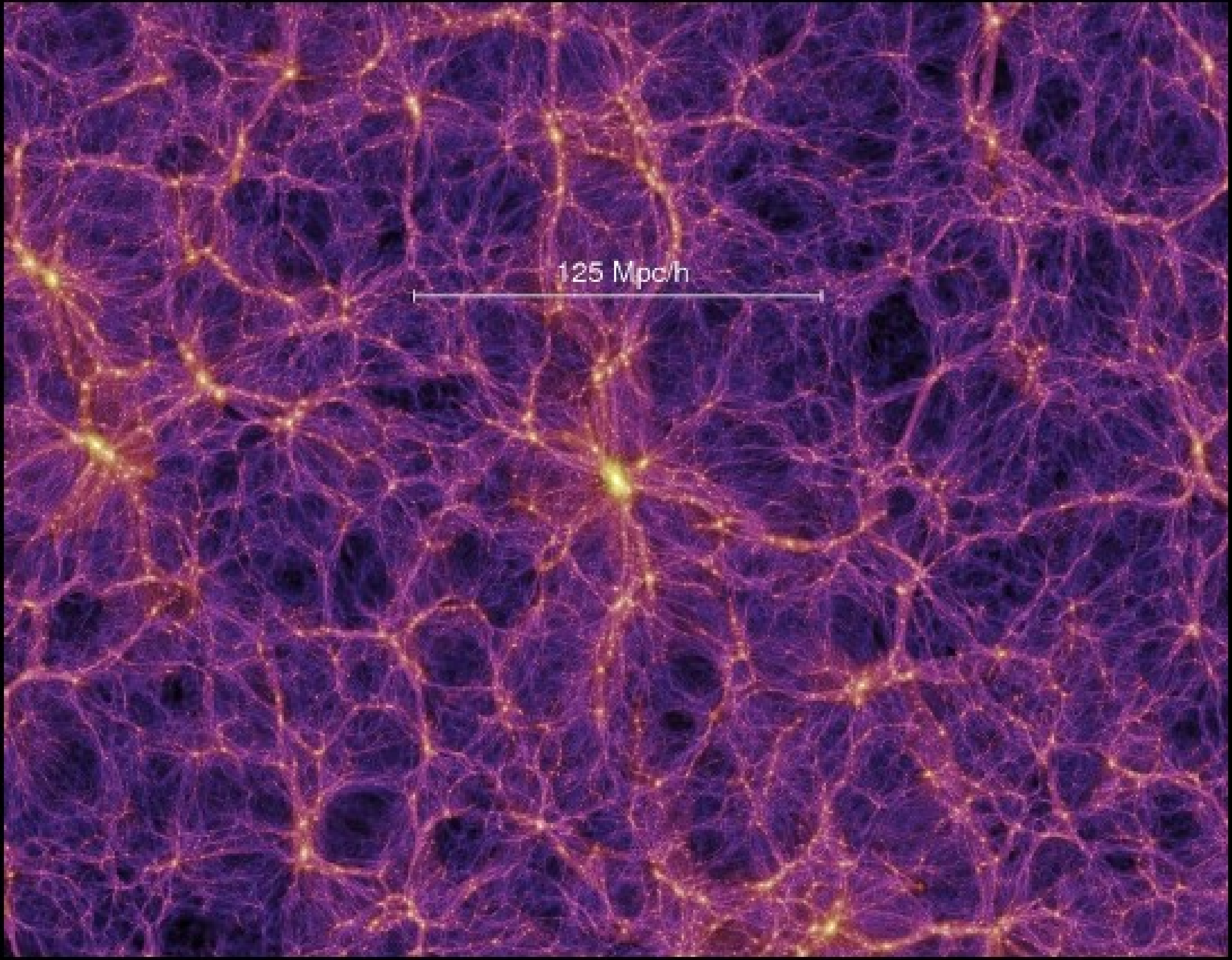
The VIRGO Collaboration 1996



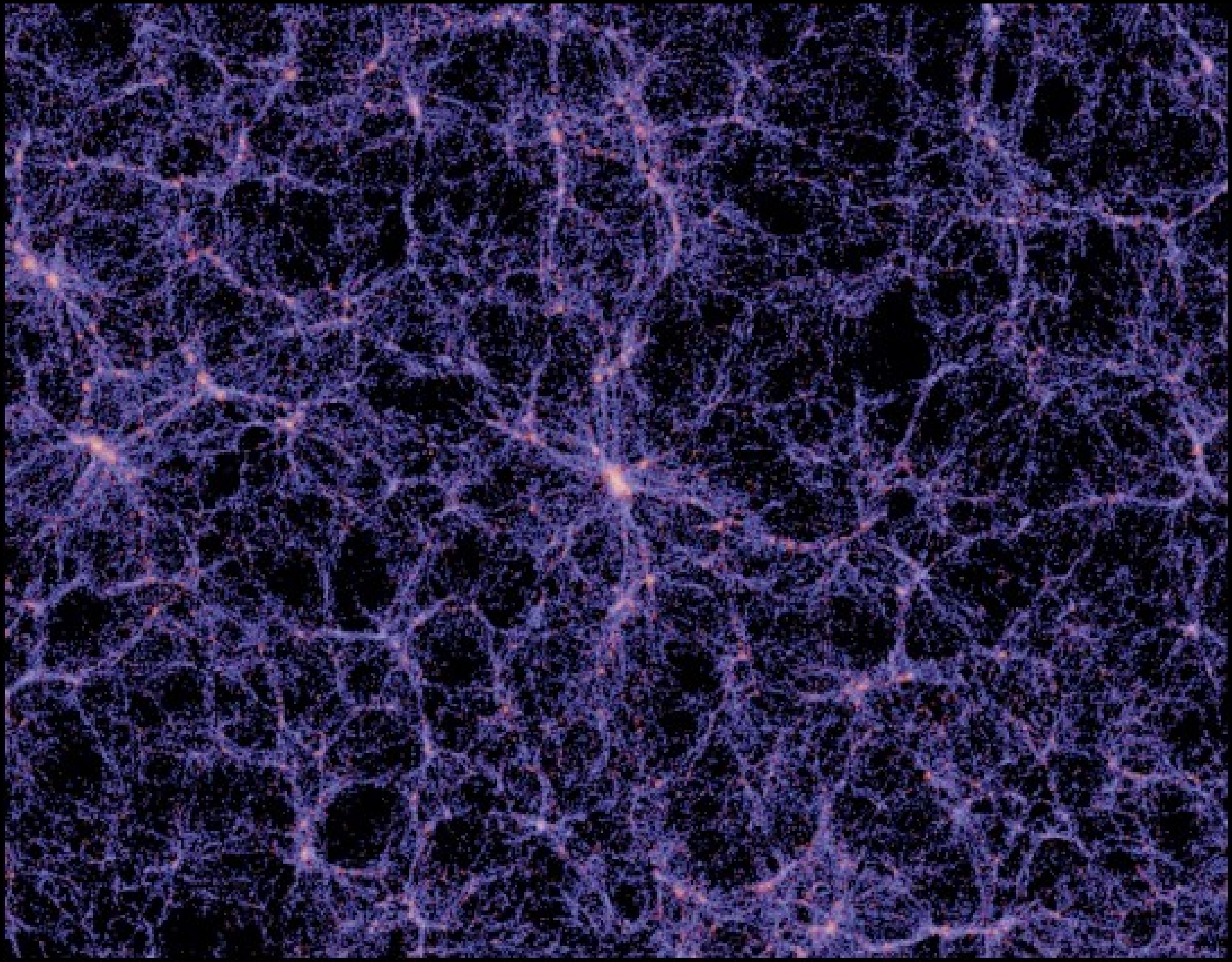
(V. Springel/MPA)



Evolution of structure in a ΛCDM Universe (MPA/V. Springel)

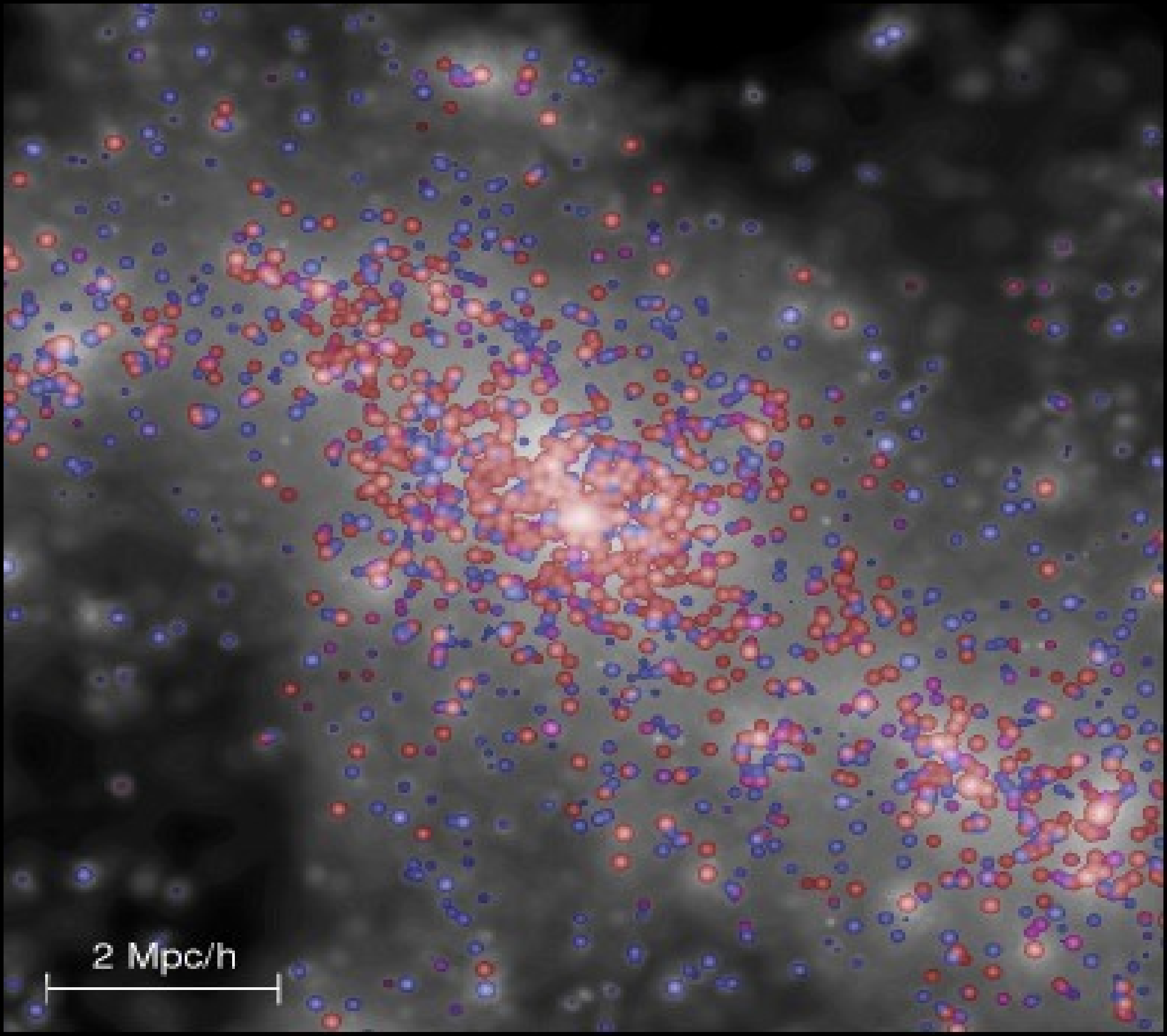


Todays dark matter distribution. . . (V. Springel/MPA)

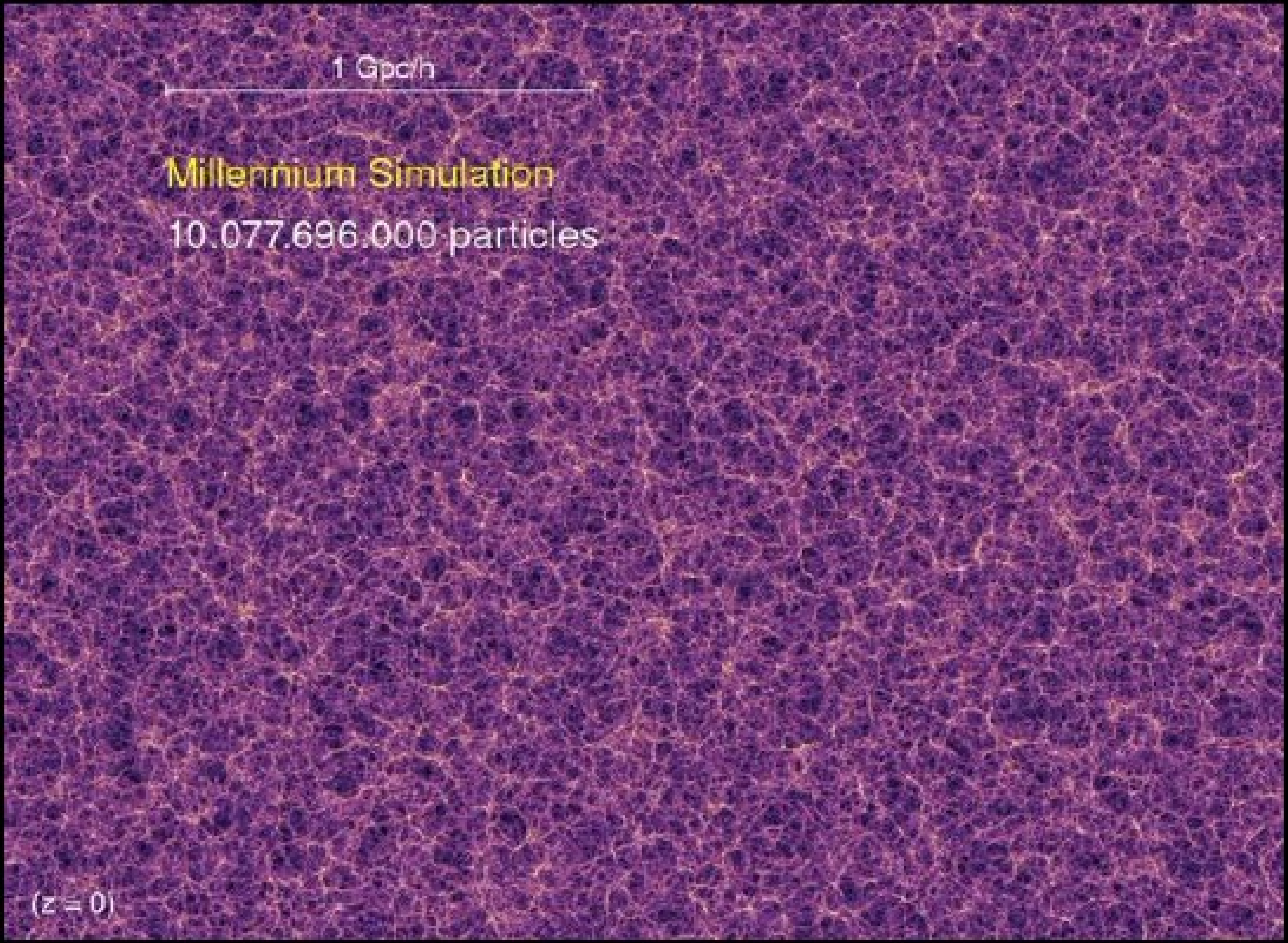


. . . and corresponding galaxy distribution (V. Springel/MPA)

Todays dark matter distribution in a cluster. . . (V. Springel/MPA)

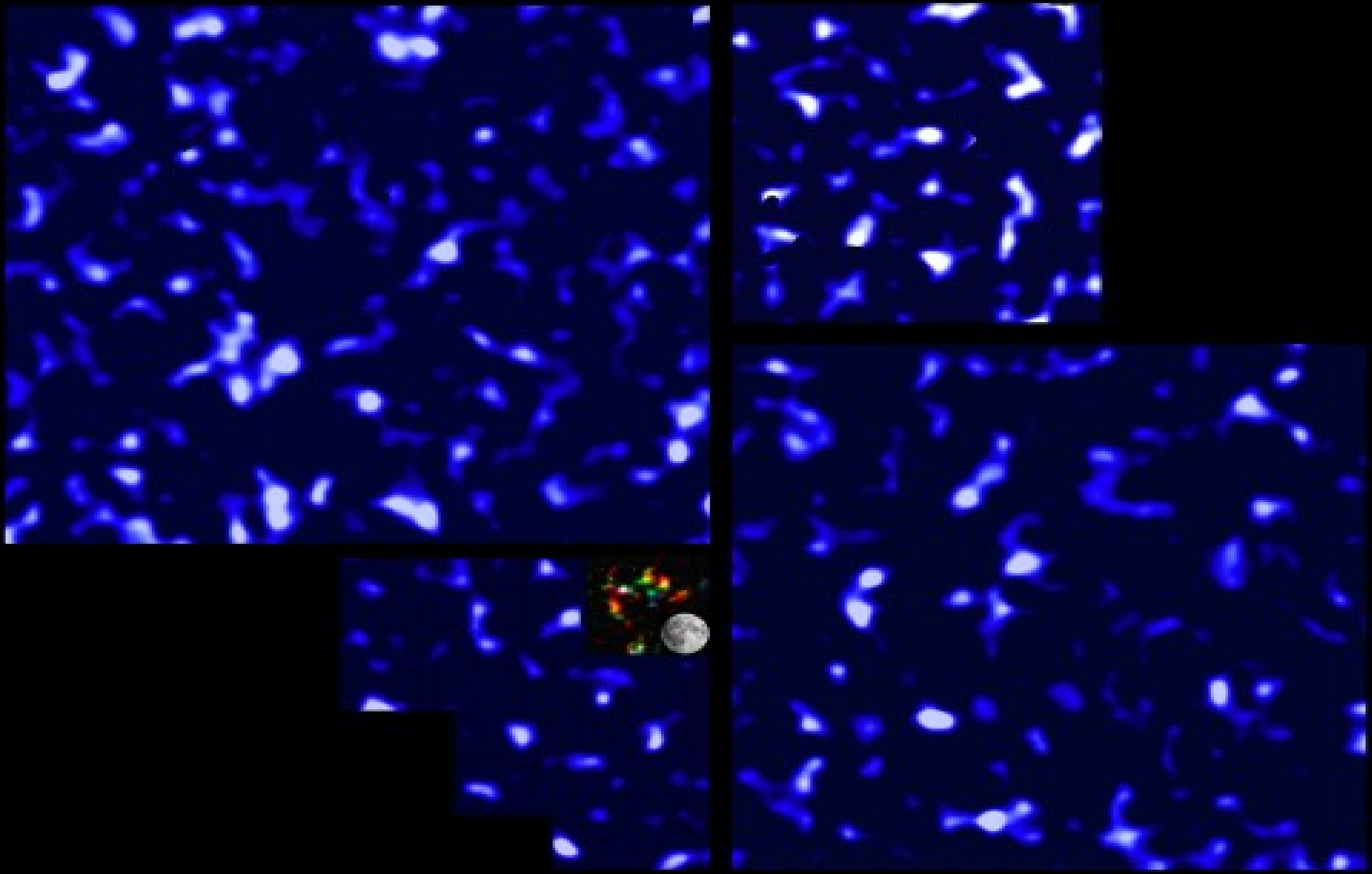


. . . and corresponding galaxy distribution (V. Springel/MPA)



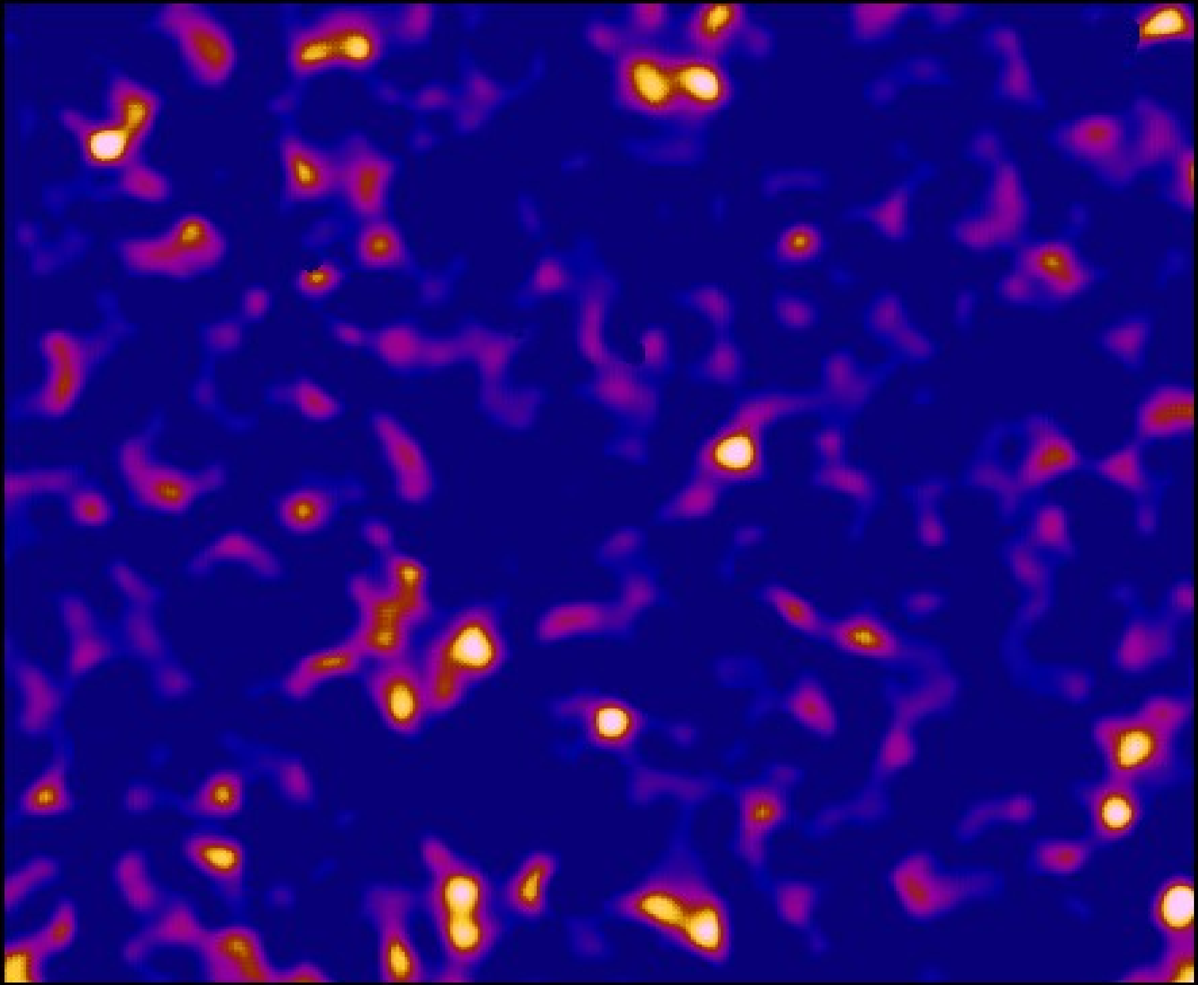
Zoom into the DM structure of the Millennium Simulation

Flight through the DM structure of the Millennium Simulation (V. Springel)



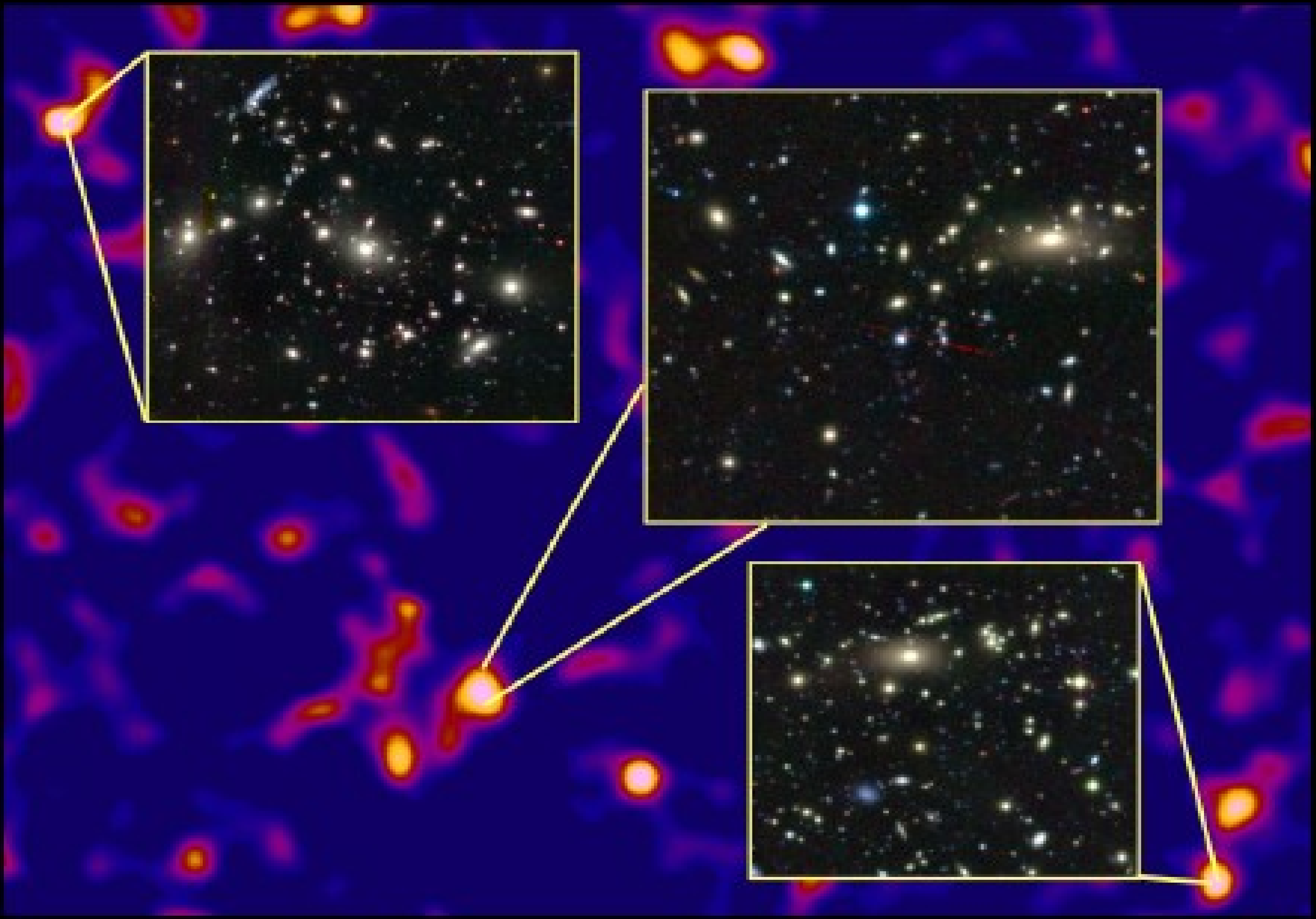
Van Waerbeke, Heymans, and CFHTLens collaboration

Jan. 2012: CFHTLens project (`http://www.cfhtlens.org/`)
First mapping of dark matter structure through microlensing



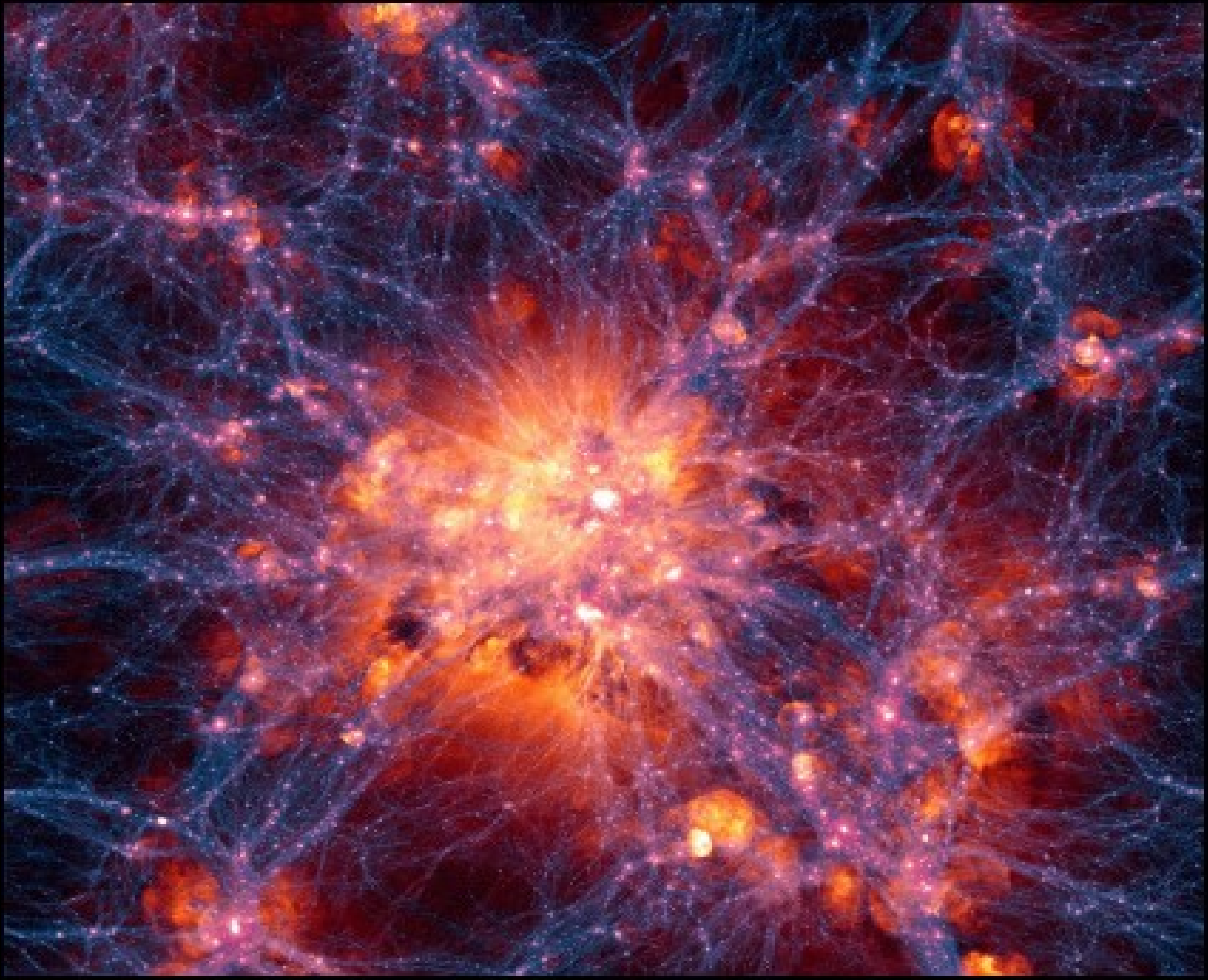
Van Waerbeke, Heymans, and CFHTLens collaboration

DM Distribution from CFHTLens project (spring 2011 region)

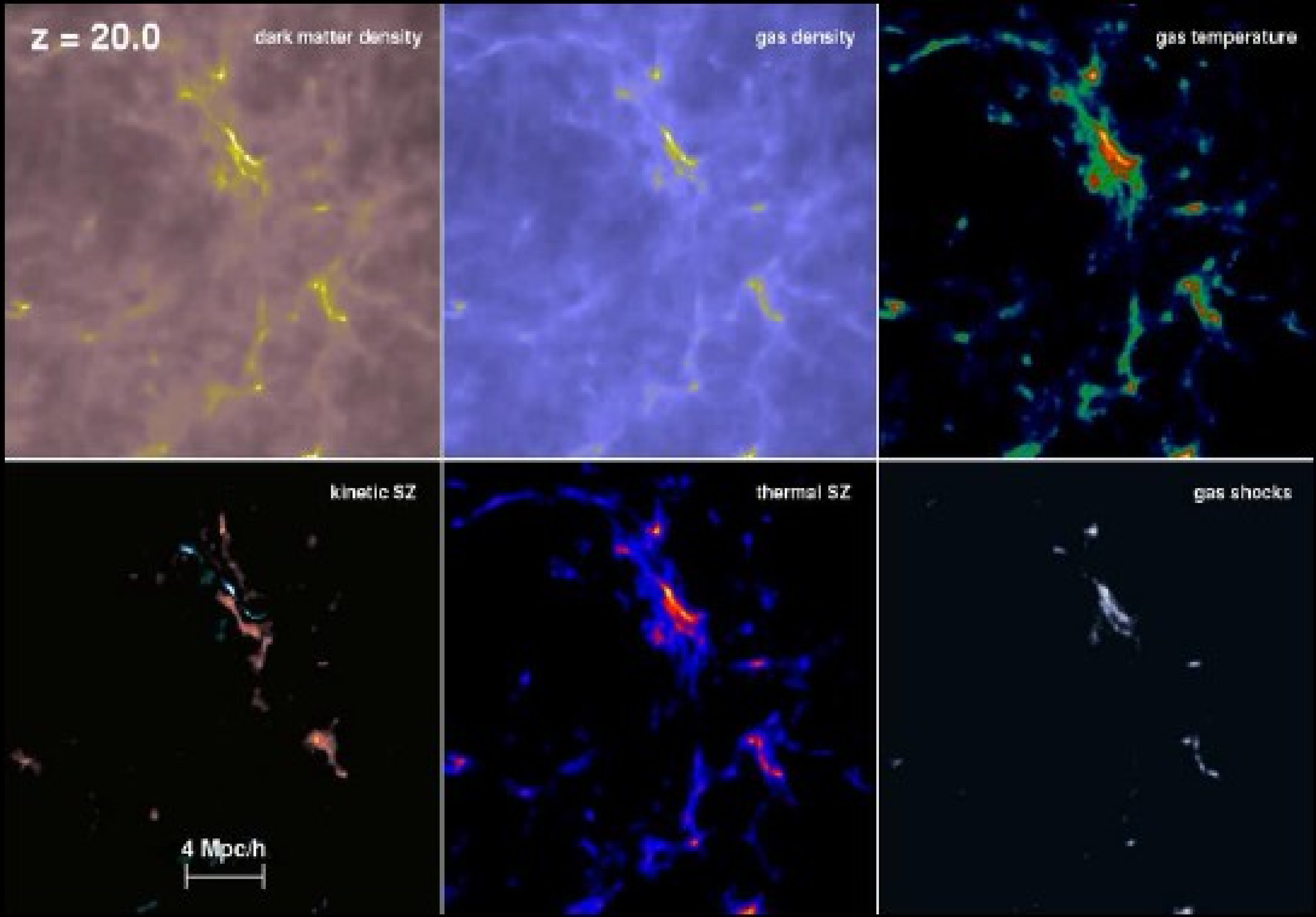


Van Waerbeke, Heymans, and CFHTLens collaboration

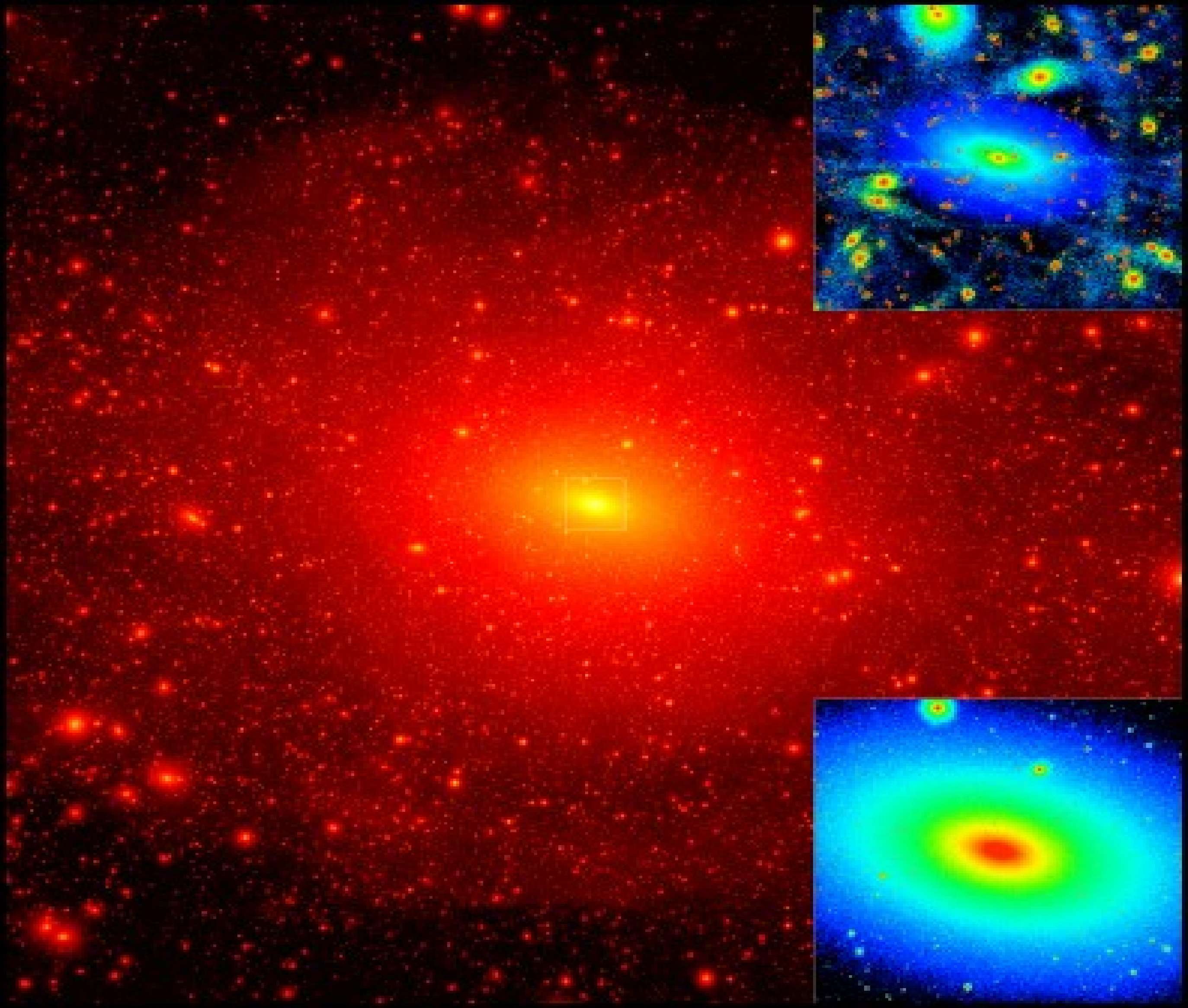
DM Distribution from CFHTLens project (spring 2011 region)



Illustris – Best computer model of the Universe

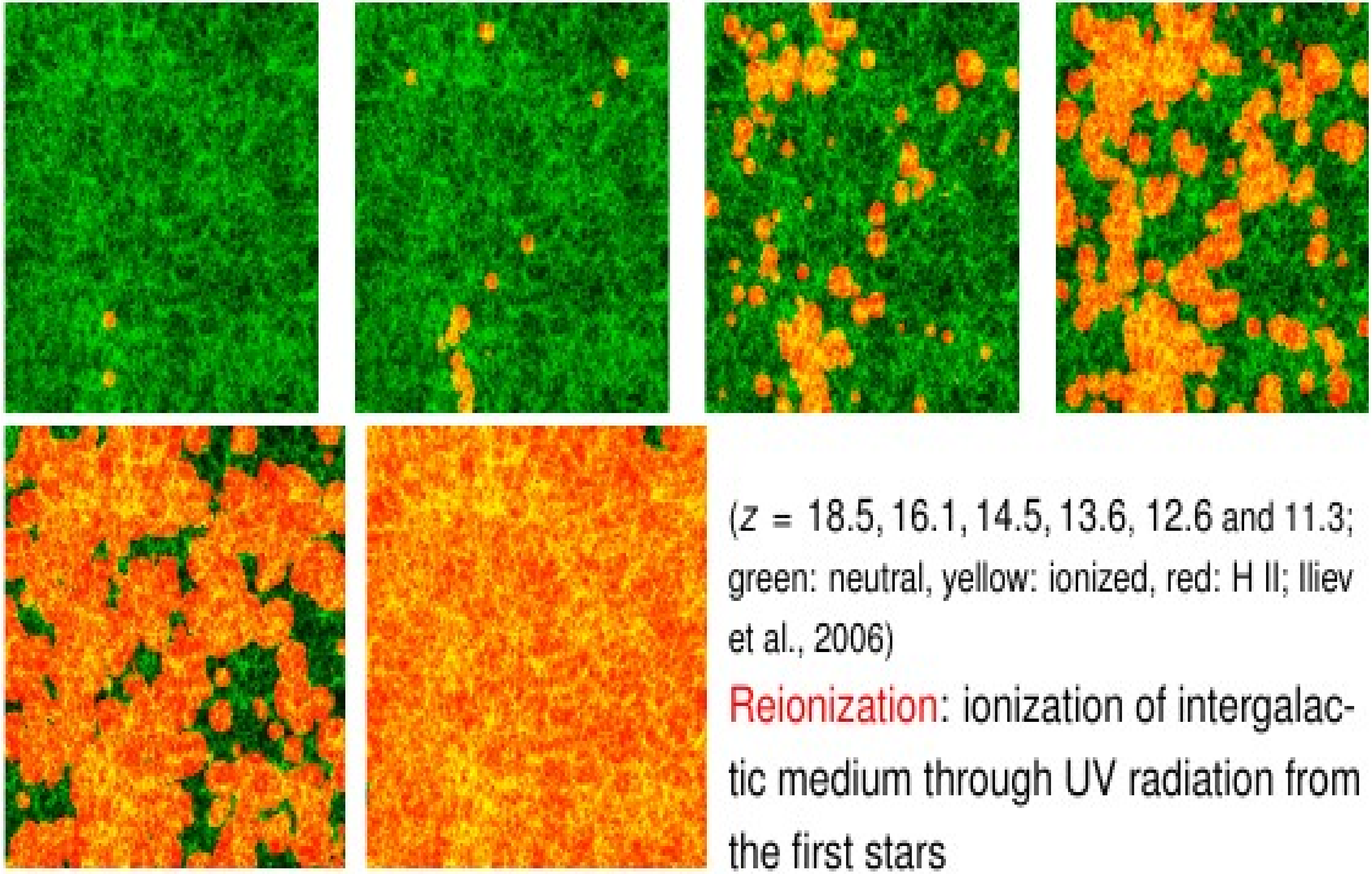


Formation of a galaxy cluster (V. Springel)



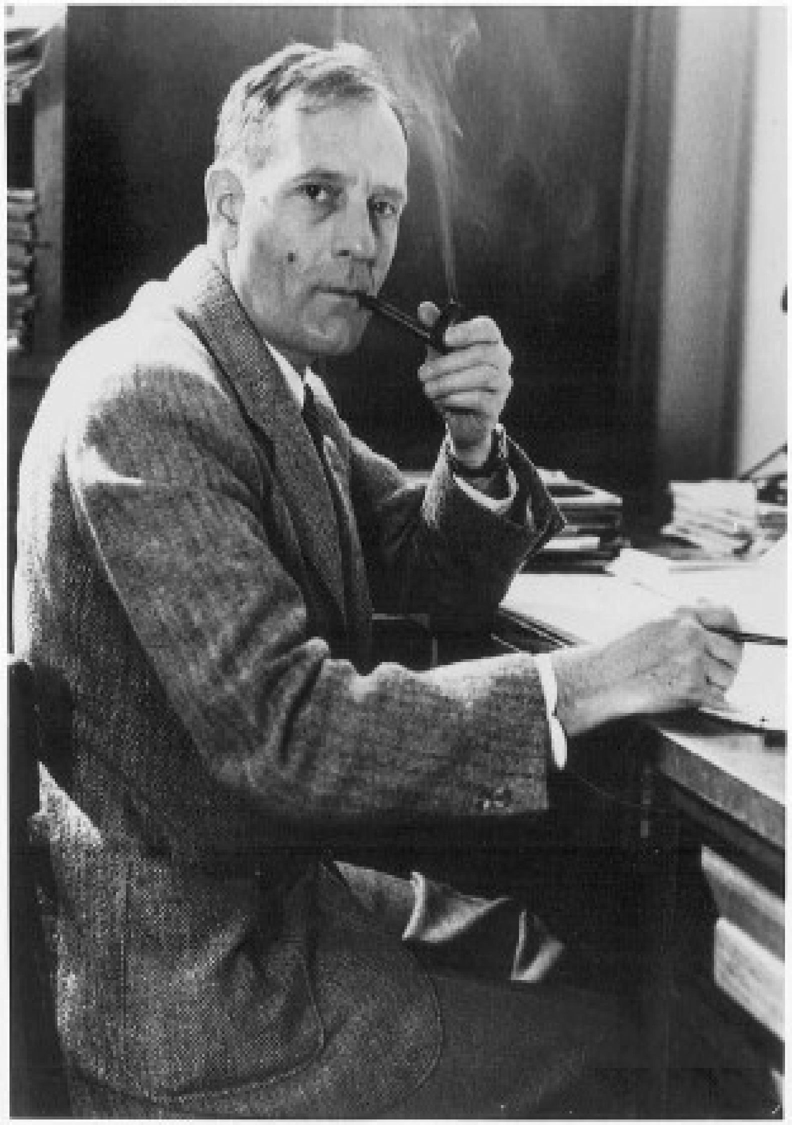
Via Lactea project: Dark Matter Halo around a galaxy

2 runs, 1 w/350000 CPU hours, 1 w/1000000 CPU hours



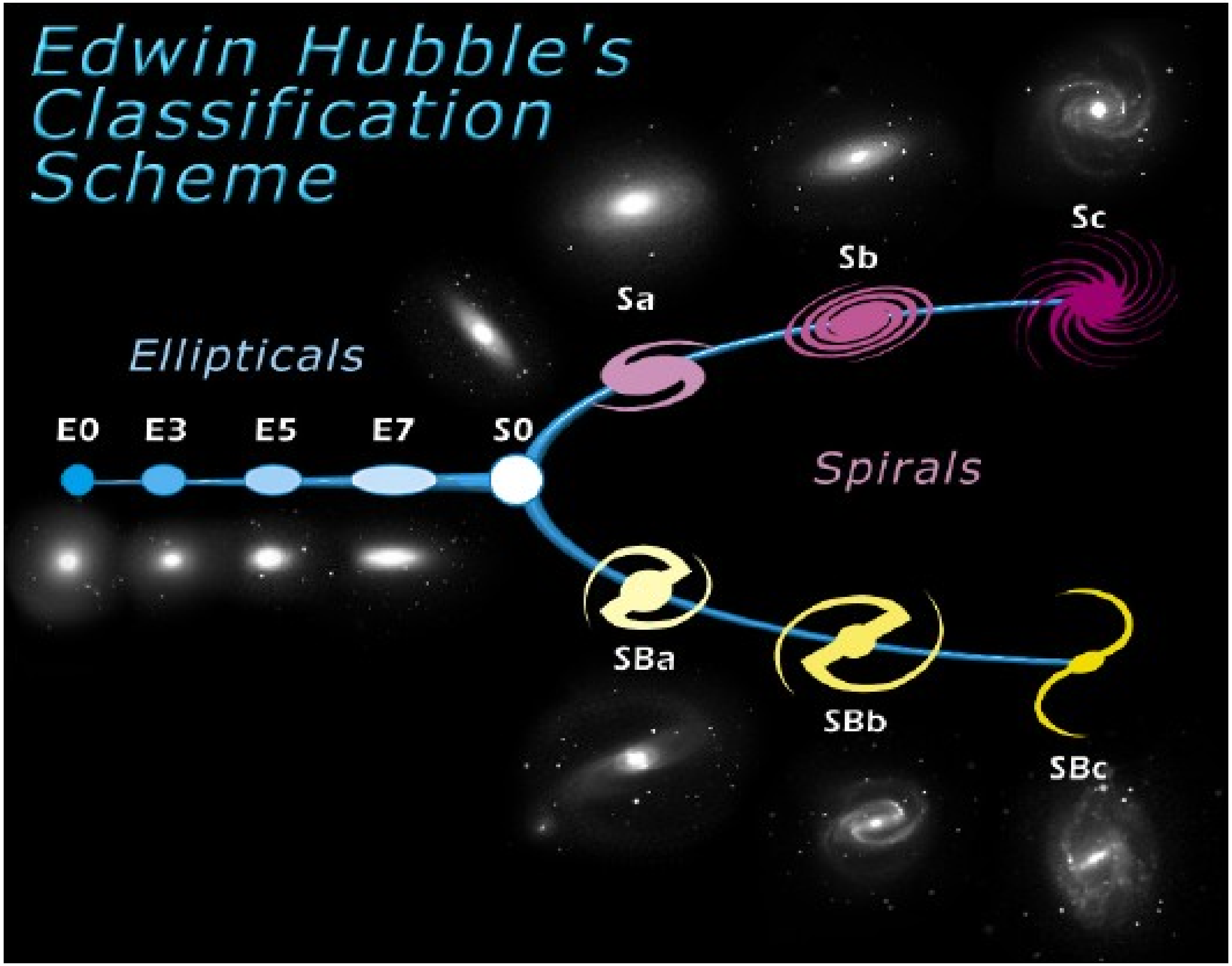
(z = 18.5, 16.1, 14.5, 13.6, 12.6 and 11.3; green: neutral, yellow: ionized, red: H II; Iliev et al., 2006)

Reionization: ionization of intergalactic medium through UV radiation from the first stars



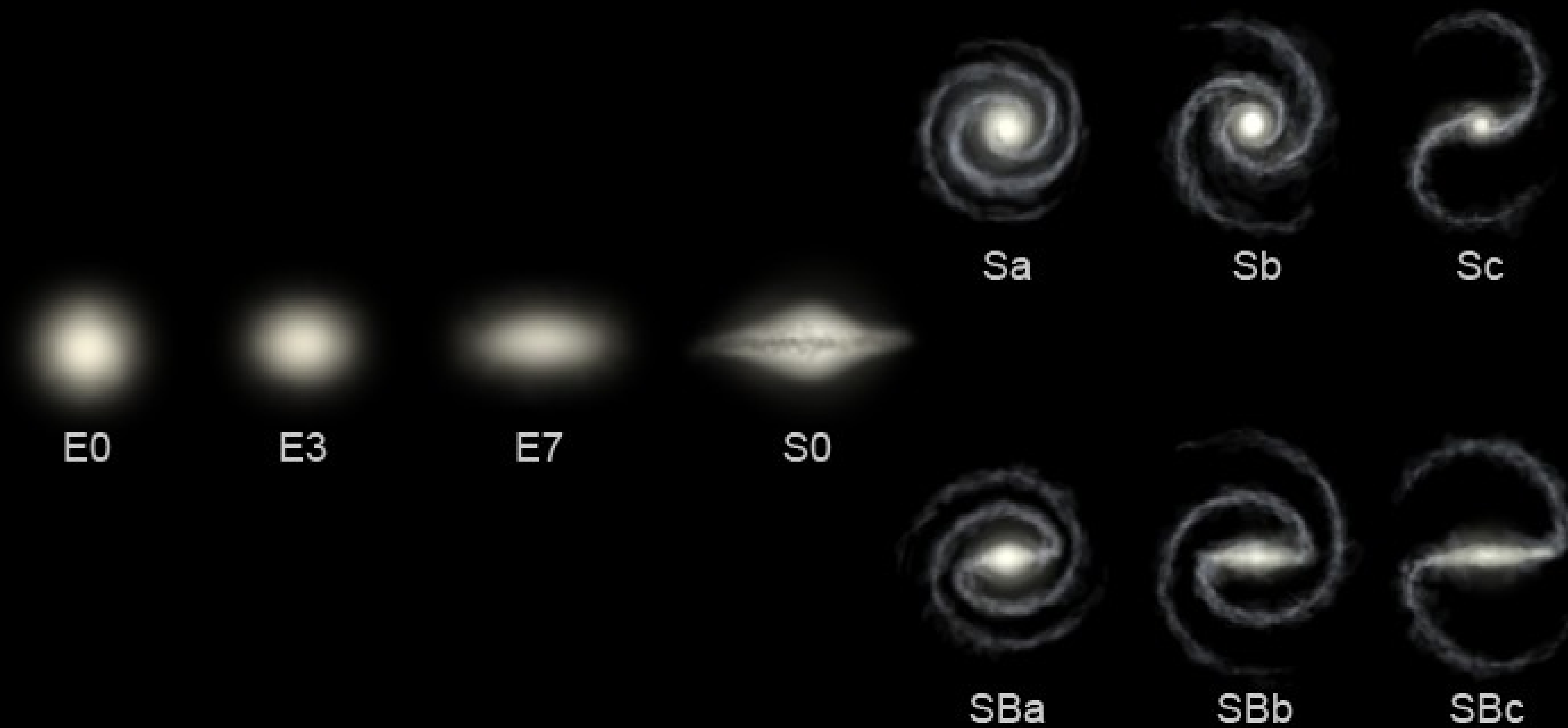
1920s: Hubble and others: classification of galaxies

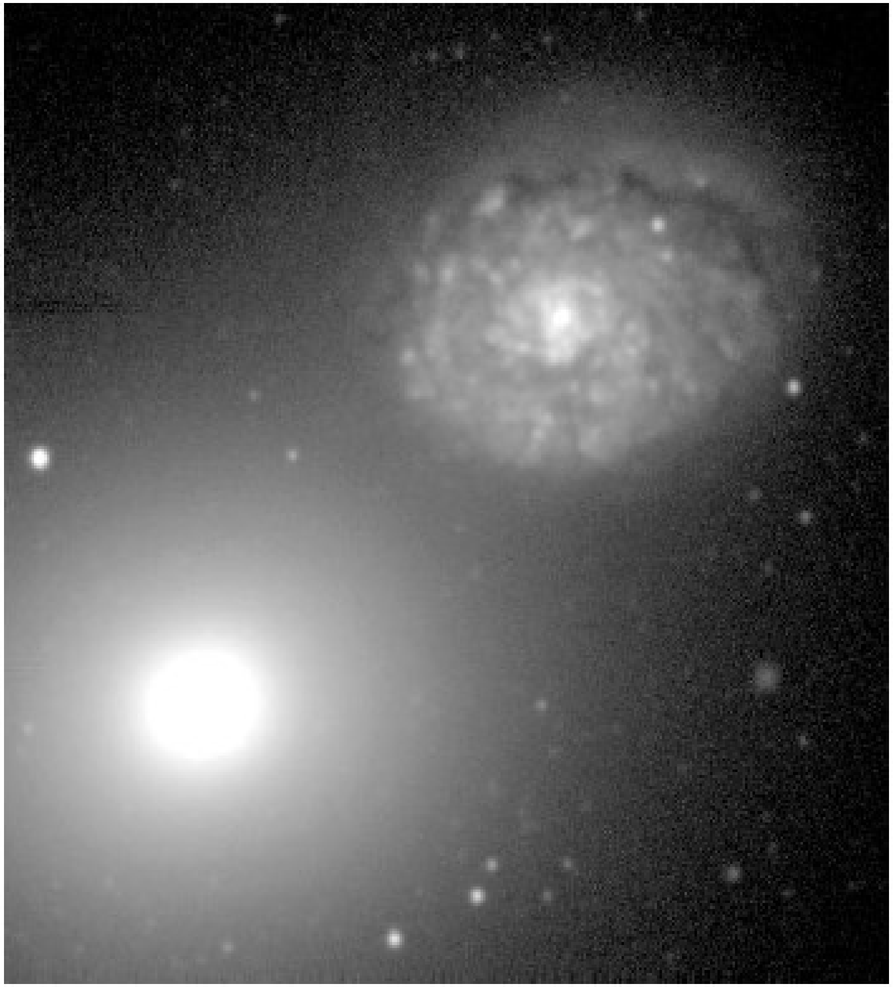
- Morphology: Appearance on photographs, photographic emulsion is blue sensitive
- *Warning:* scheme is in parts not so well defined, incomplete, and not unique
- Note: photometric (colors) and spectroscopic information are not part of the Hubble scheme.



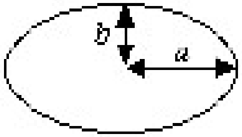
SDSS

Galaxy classification via the Hubble “tuning fork diagram”: “early types”: elliptical galaxies; “late types”: spiral galaxies, Not an evolutionary sequence!


Sa
Sb
Sc
E0
E3
E7
S0
SBa
SBb
SBc



M60 (NGC 4649), E1, U. of Alabama



Elliptical galaxies: Classification as Ex where $x = 10(a - b)/a$ (integer part; between 0 and 7)

Ellipticals are low on dust and gas, reddish color (=old stars!), typically low luminosity and low mass ($10^6\ M_\odot$)

Monsters: Also elliptical, from mergers in galaxy clusters (e.g., M87 in Virgo), M up to $10^{12}\ M_\odot$, designated cD.

Elliptical Galaxies

M51 (NGC 5194 and 5195), Sc and Irr, Kitt Peak 0.9 m

Spiral Galaxies: Elliptical nucleus ("bulge") plus disk with spiral arms, designated Sa, Sb, Sc depending on opening angle of spiral (Sa: $\sim 10^\circ$, Sc: $\sim 20^\circ$) and dominance of nucleus.

Bluer than ellipticals.

Mass content $\sim 3 \times 10^{11}\, M_\odot$, with $M/L \sim 20$,

Gas content increases from Sa to Sc from 1% to 8%.

Spiral arms probably due to density wave.

Spiral Galaxies

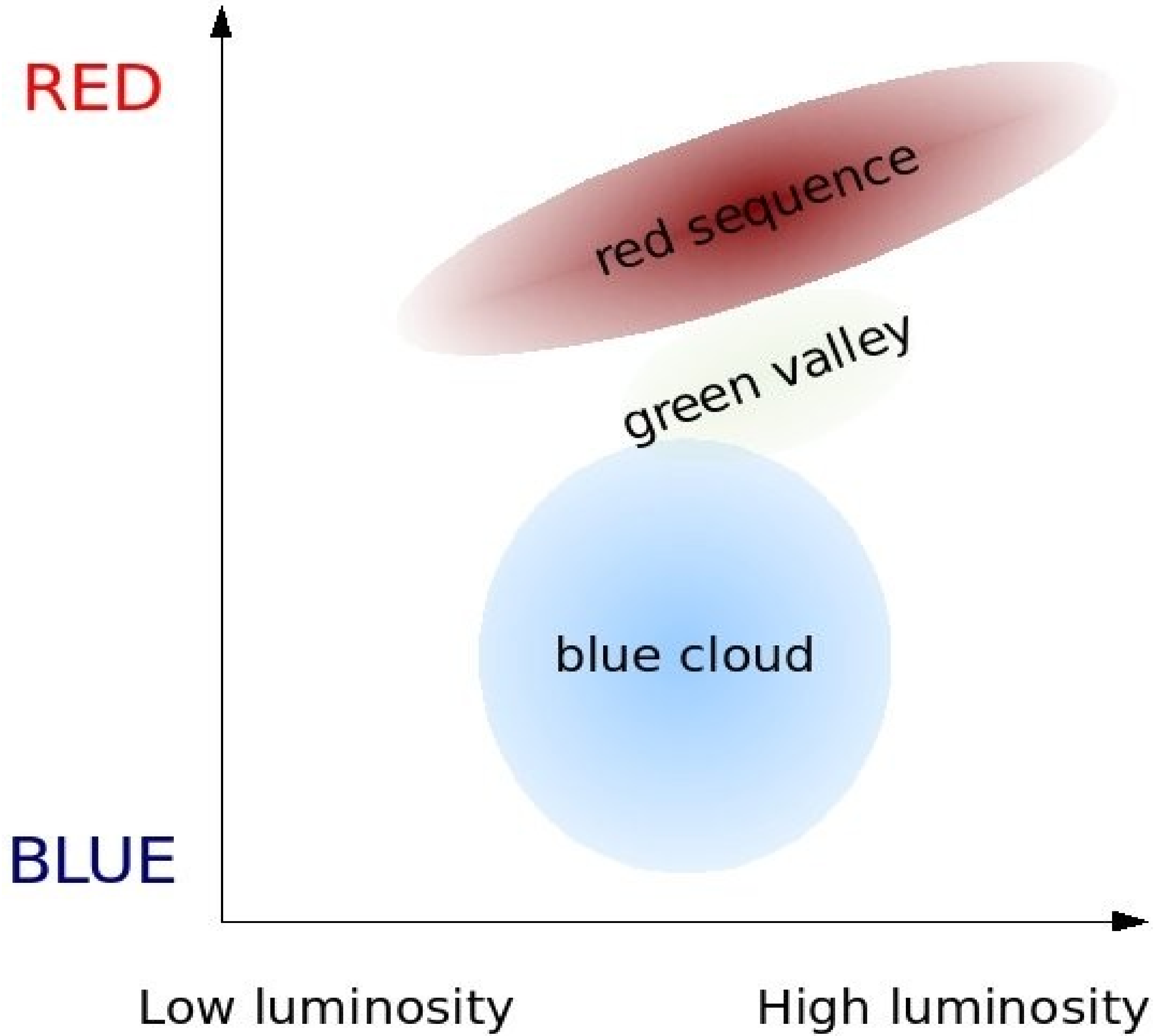
M95 (NGC 3351), SBb, INT

Barred Galaxies: Classification as SBa, SBb, SBc similar to S*x* galaxies, but additional presence of a bar (cause of bar production and stability are still debated).

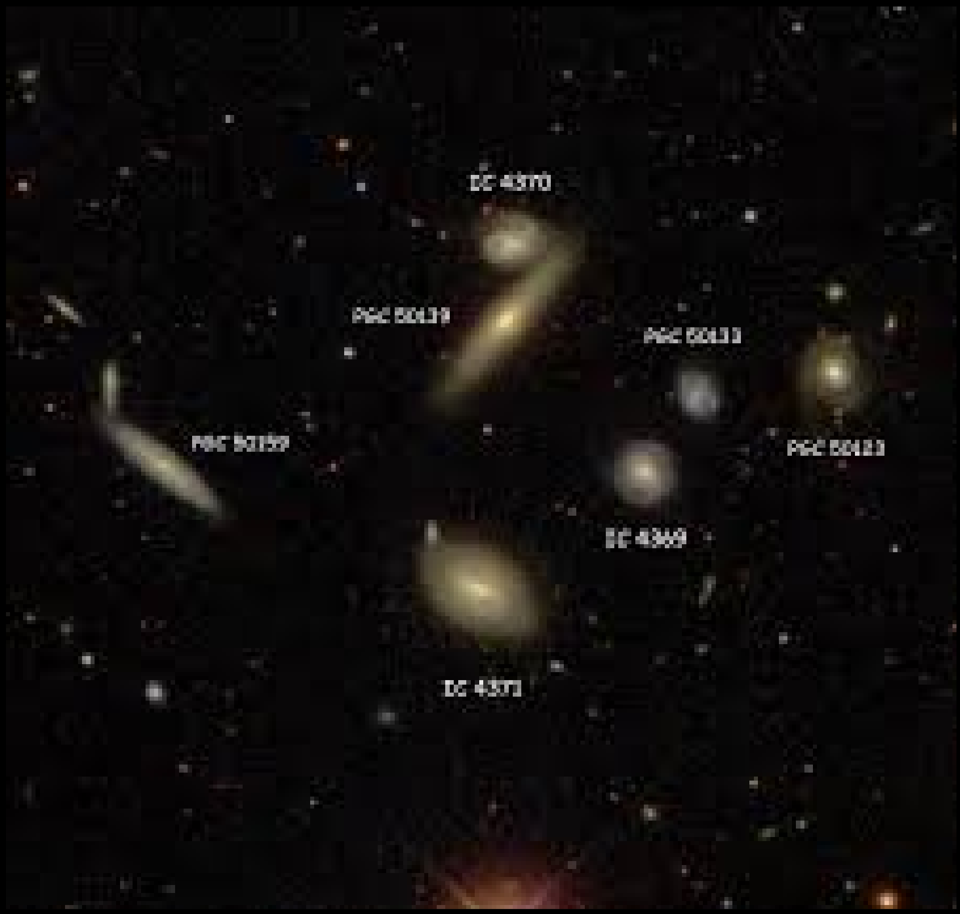
Similar masses and gas content as in normal spirals.

Milky Way is a barred spiral.

Irregular Galaxies


RED
red sequence
green valley
blue cloud
BLUE
Low luminosity
High luminosity

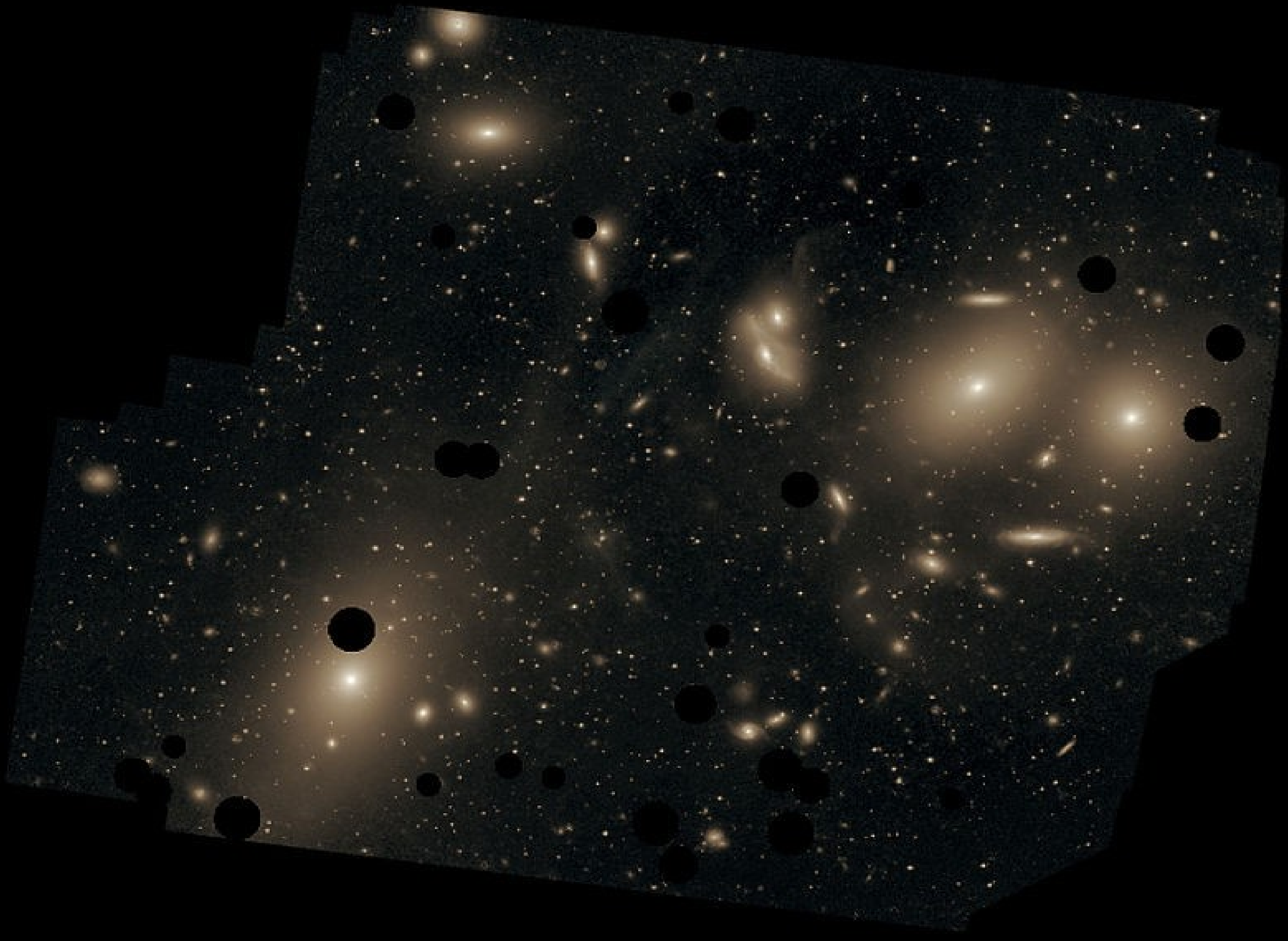
Galaxy Groups



Hickson Compact Group 70

Local Group

Virgo Cluster



M 87 - Virgo Cluster cD