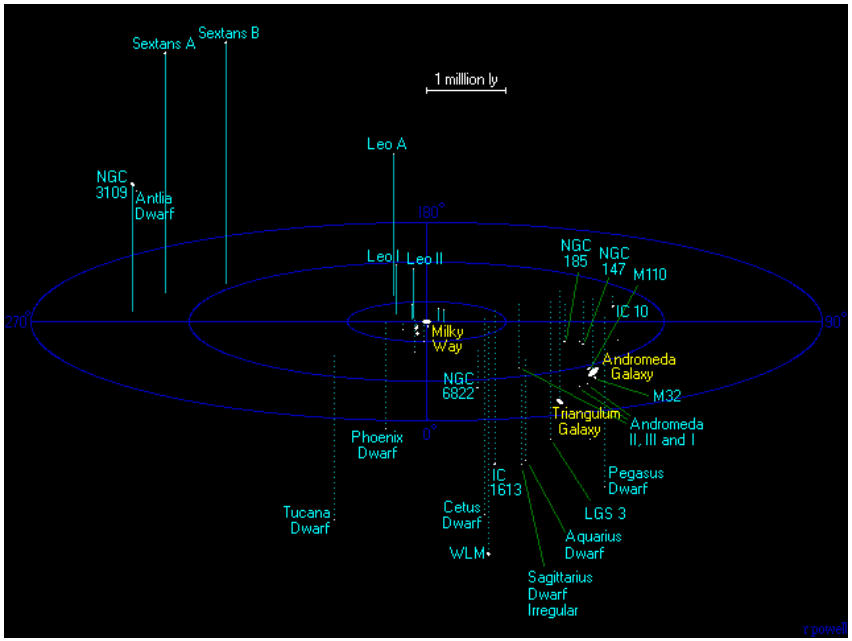
Clusters of Galaxies



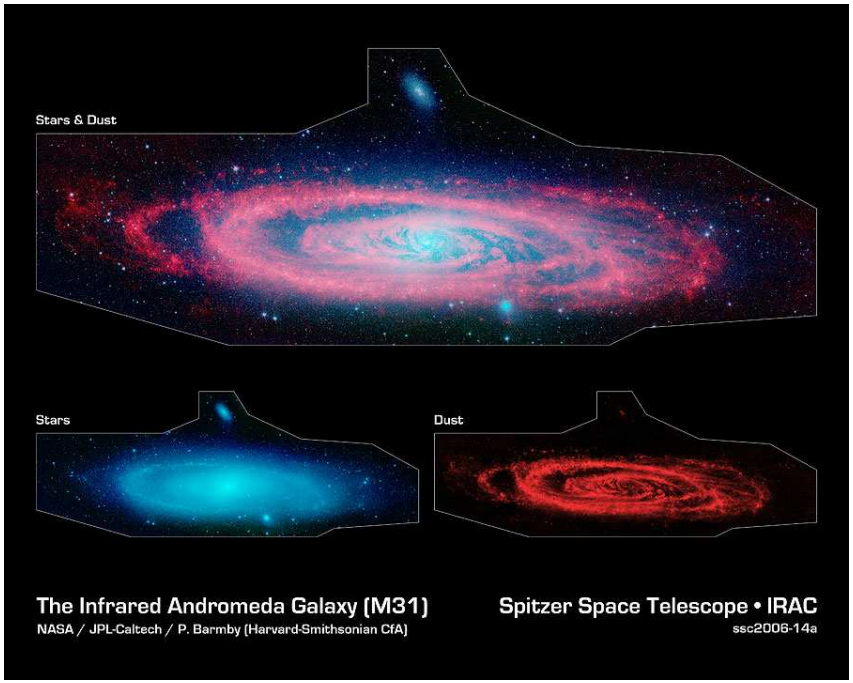
source: `http://www.anzwers.org/free/universe/localgrp.html`
The neighborhood of the Milky Way: the Local Group

Introduction

Last part of the lecture: let's get out of the cradle!

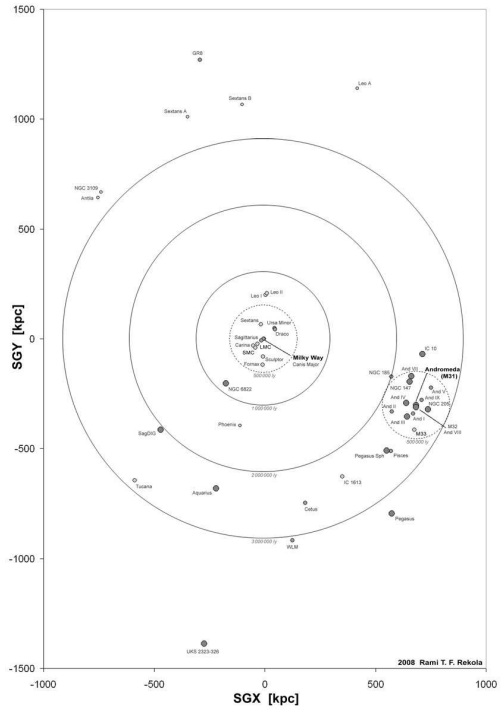
1. Local Group
2. Clusters of Galaxies and Interacting Galaxies
3. Observations of Large Scale Structure

Here mainly observational, need to look at cosmology first to understand where structure comes from (next lectures).



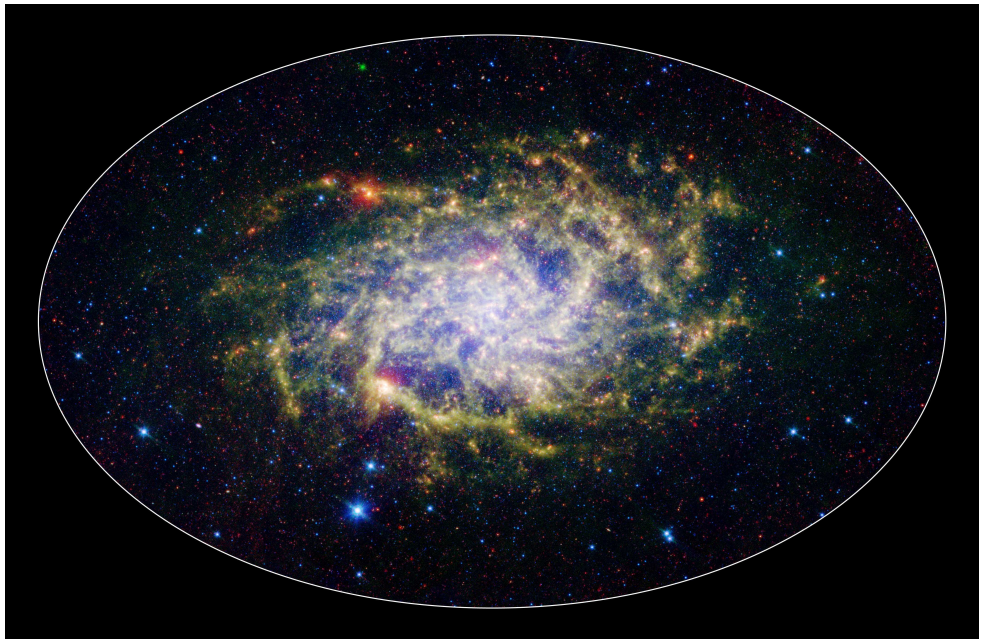
M31 (Andromeda; largest galaxy in Local Group)

M33 (Triangulum Galaxy, 3rd largest gal. in Local Group; Mortfield / Cancelli)

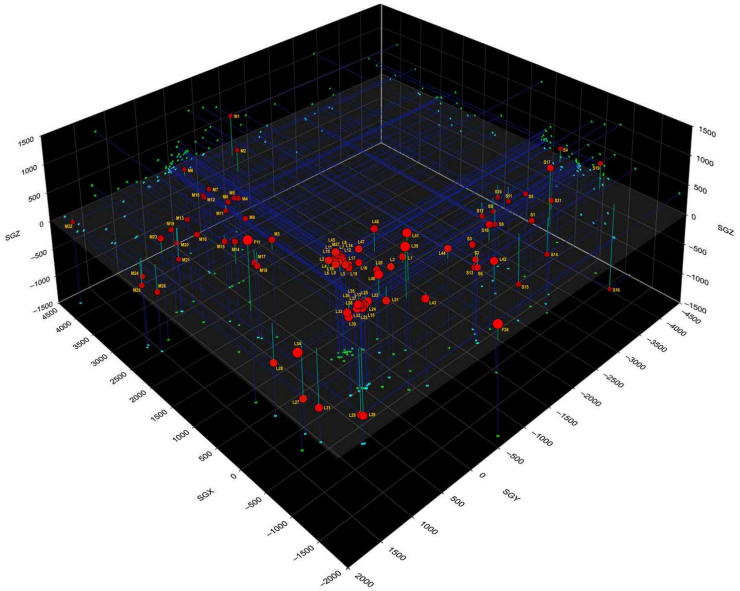


Distribution of Galaxies in Local Group

http://www.astro.utu.fi/EG/ELG/

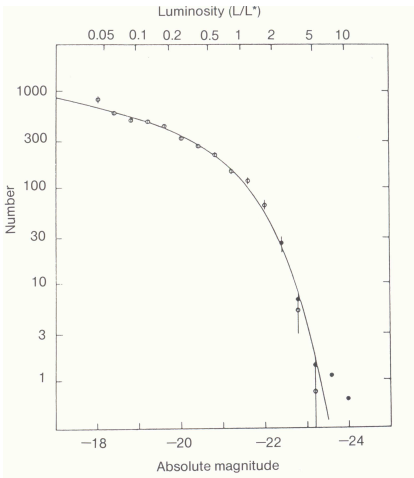


M33 (Triangulum Galaxy; Spitzer Space Telescope [Infrared])



Most galaxies in (extended) Local Group are dwarf galaxies
47 gal. in Local Group, 15 in Maffei Group, 15 in Sculptor Group

Luminosity Function

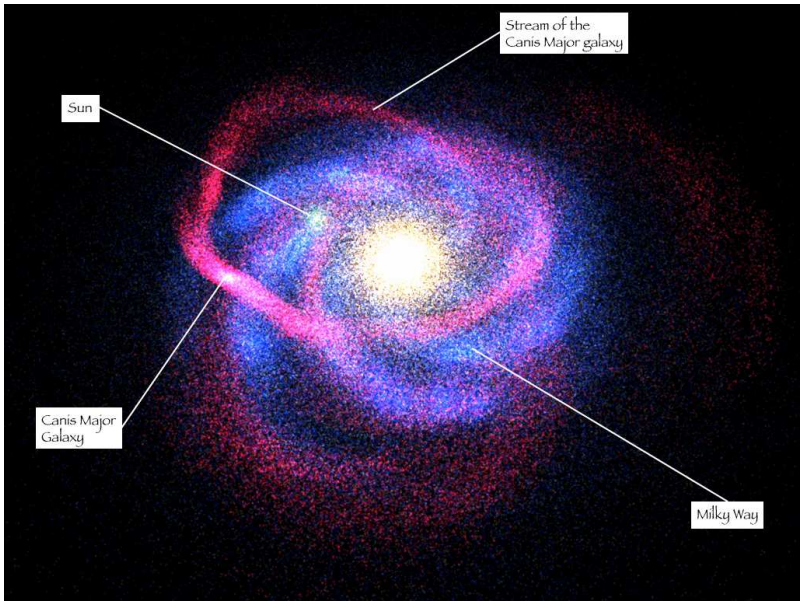


"Schechter Function" of 13 clusters (Karttunen)

Analysis of clusters finds that galaxies have wide distribution of absolute magnitudes
Generally described in terms of the luminosity function, $\Phi(L)$, where $\Phi(L)dL$ = number of galaxies per unit volume in luminosity bin $[L, L + dL]$, can be described by the Schechter function:

$$\Phi(L)dL = \Phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right)\frac{dL}{L} \quad (23.1)$$

where typically $\Phi^* \sim 4 \times 10^{-2}\,\mathrm{Mpc}^{-3}$, $\alpha \sim -1$ and where L^* is a characteristic luminosity (in magnitudes, $M^* \sim -20$ mag)

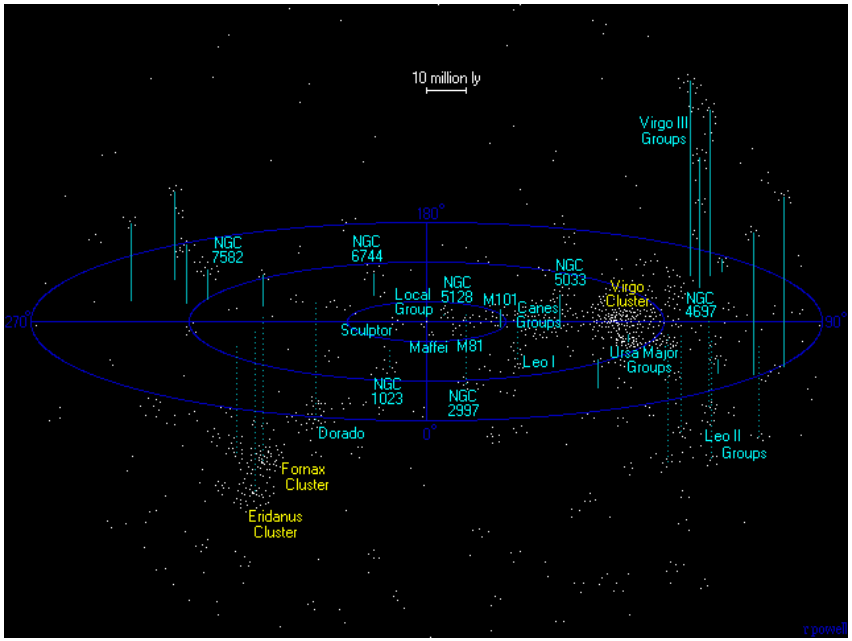


U. Strasbourg

Canis Major galaxy: overdensity of M dwarfs in direction to Canis Major; in 2003 hypothesized to be due to old, rather massive (1% milky way) galaxy being gravitationally disrupted by Milky Way (still debated)

Leo I dwarf galaxy, next to Regulus

Not much is known about the nearby dwarf galaxies, as they are difficult to find



The universe out to the Virgo Cluster

source: `http://www.anzwers.org/free/universe/virgo.html`

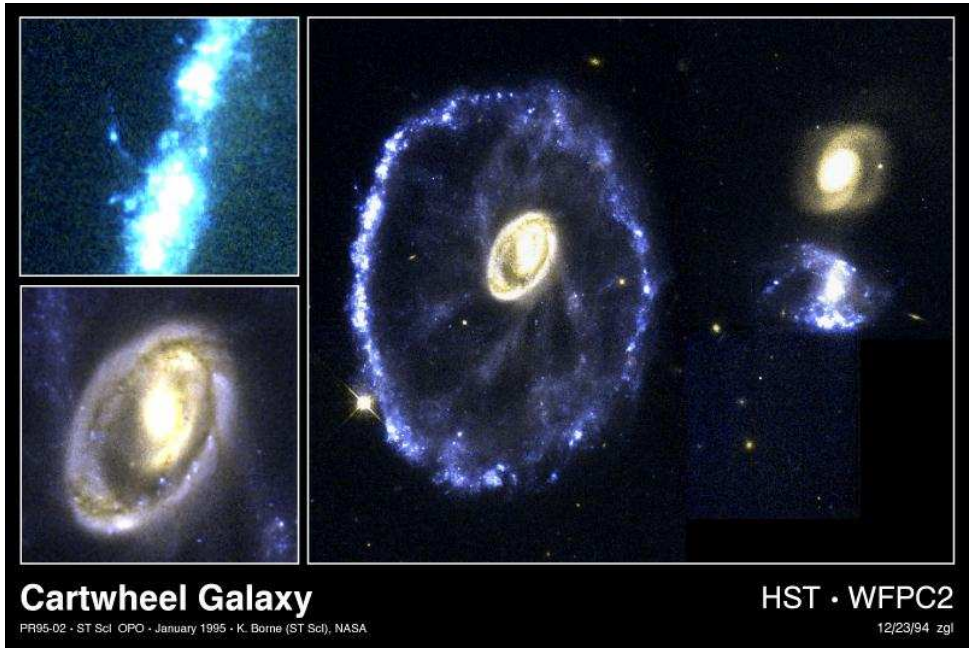
Coma cluster of galaxies (Misti/APOD)

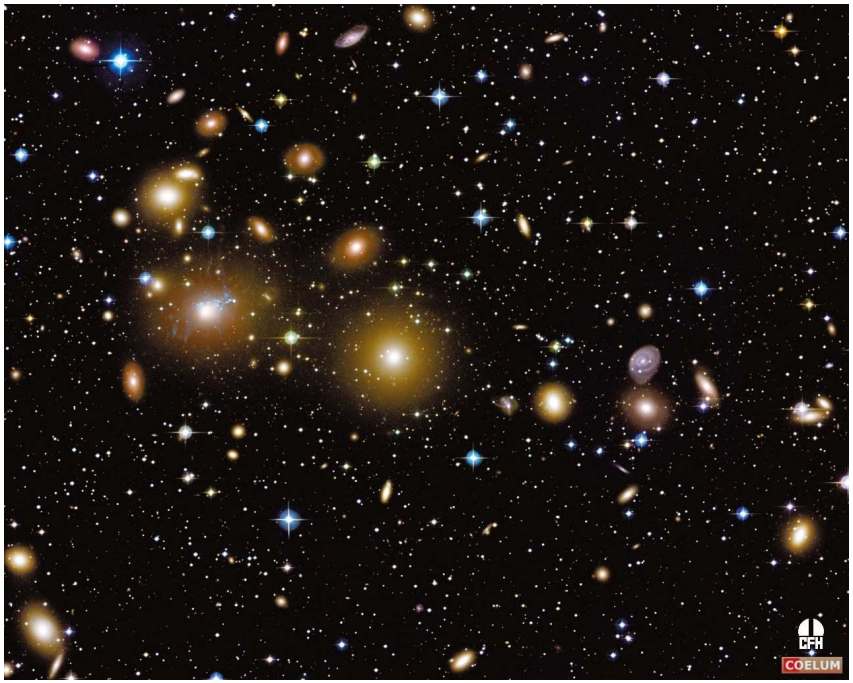
Clusters of Galaxies: largest gravitationally bound structures in the universe.

Typical numbers: up to a few 1000 galaxies, masses: 10^{14} to 10^{15} $M_\odot$

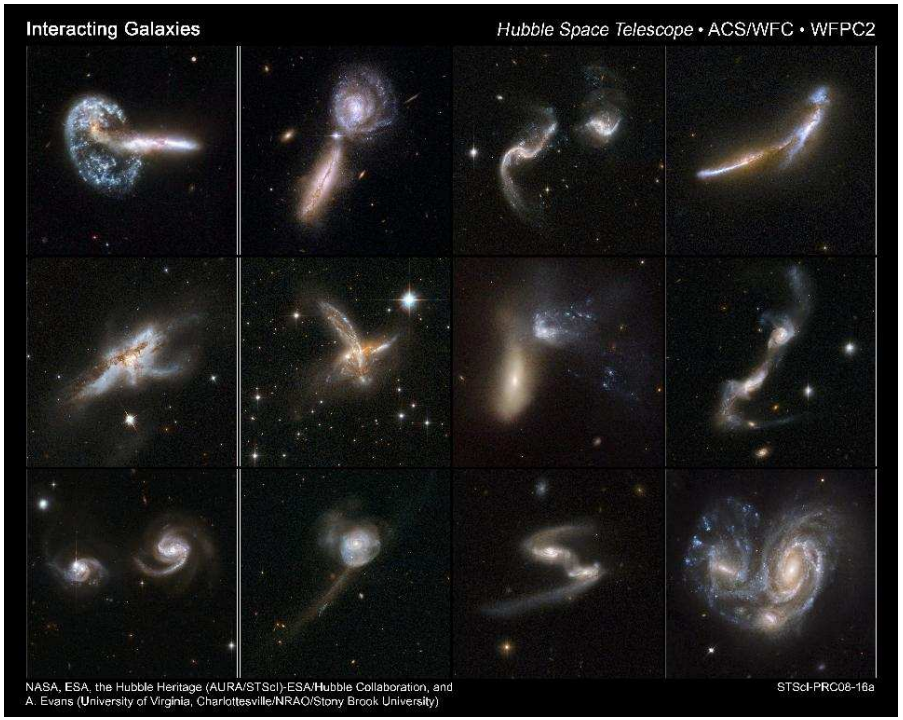
Densest clusters: visually found, “Abell clusters”

Groups of galaxies: few MPc, few 10s of galaxies





Perseus Cluster: 660 gal in field, number of spirals increases outwards

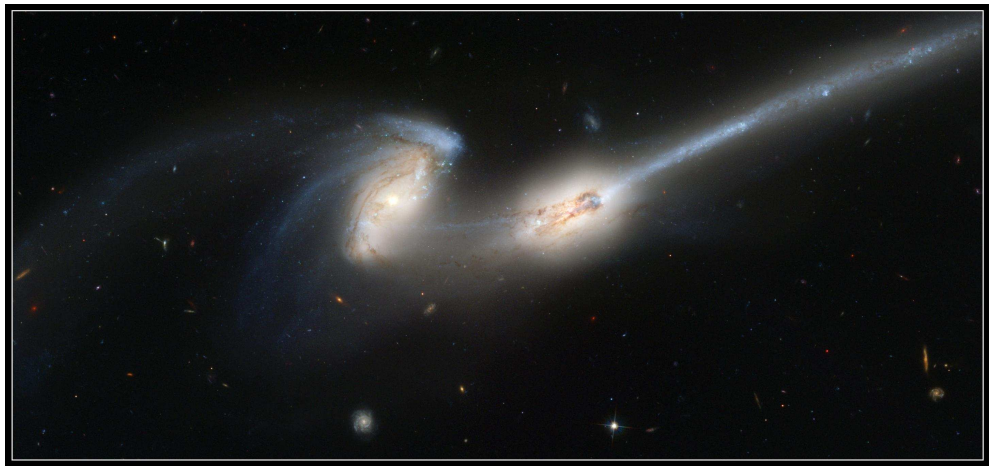


Interacting Galaxies

http://ifa.hawaii.edu/~barnes/transform.html

Numerical Merger Experiments (see movies seq1_4, seq2_4)

- two identical spiral galaxies
- bulge : disk : halo = 1 : 3 : 16
- gas: 10% of disk mass
- exponential scale length: 3.3 kpc
- rotation curve as in Milky Way
- parabolic orbit
- closest encounter: 8.8 kpc after 250 Myrs



The Mice • Interacting Galaxies NGC 4676
Hubble Space Telescope • Advanced Camera for Surveys

NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M. Clampin (STScI), G. Hartig (STScI) and the ACS Science Team • STScI-PRC02-11d

Interacting Galaxies

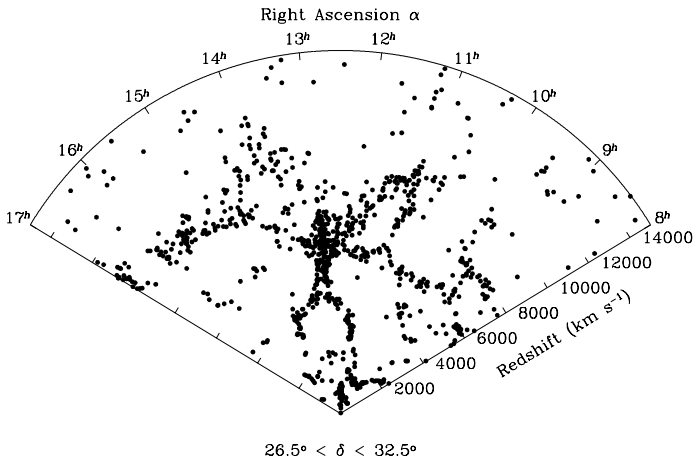
http://ifa.hawaii.edu/~barnes/transform.html

Numerical Merger Experiments: Results

- gas collapses into the central 100 pc of the merger
- tidal arms form; bridges between galaxies
- morphology of peculiar galaxies (e.g., the Mice) can be explained by two merging disk galaxies

Elliptical galaxies result from mergers of disk galaxies

Introduction



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

Lumpy universe: spatial distribution of galaxies and greater structures.

Introduction

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

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

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

Classification:

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

2D-surveys: cover long strip of sky, e.g., CfA-Survey ($1.5 \times 100^\circ$), 2dF-Survey ("2 degree Field"), 6dF-survey.

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

~~We will concentrate here on the larger surveys based on no other catalogue.~~

SDSS 2.5 m telescope at Apache Point Observatory

courtesy SDSS

2D/3D Surveys

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 $z = 0.2$.

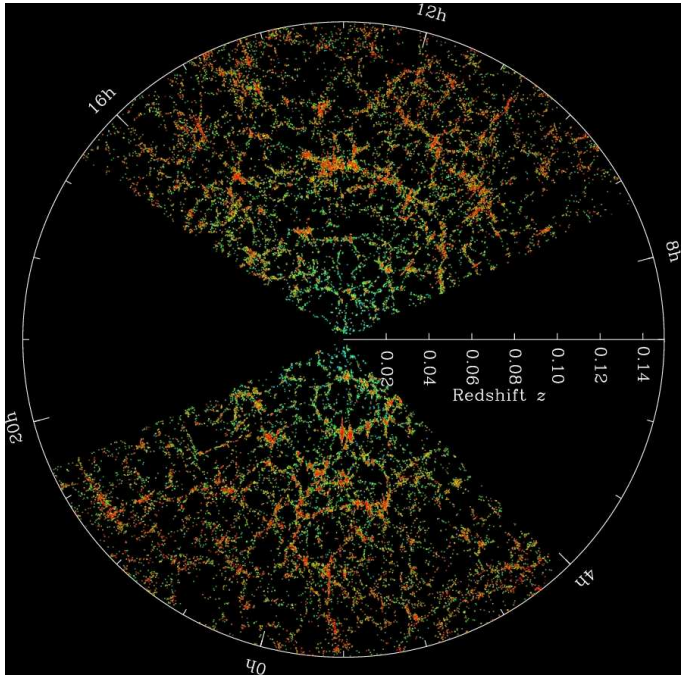
CfA Redshift Survey: 30000 galaxies

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

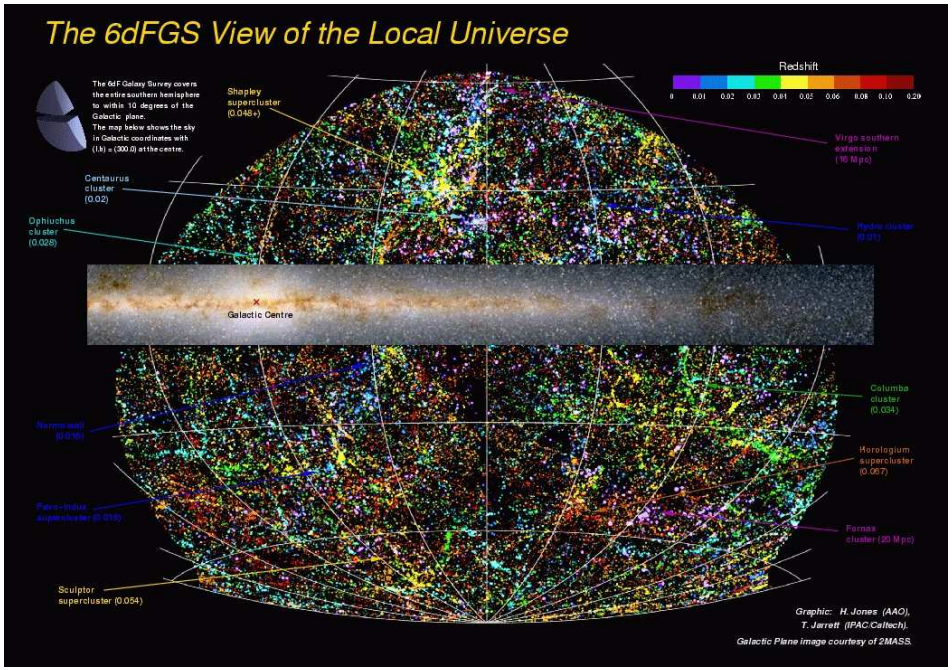
2MASS: IR Survey of complete sky (Mt. Hopkins/CTIO) completed 2000 October 25), 3 bands, $\sim 2 \times 10^6$ galaxies, accompanying redshift survey (8dF, CfA)

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,...).

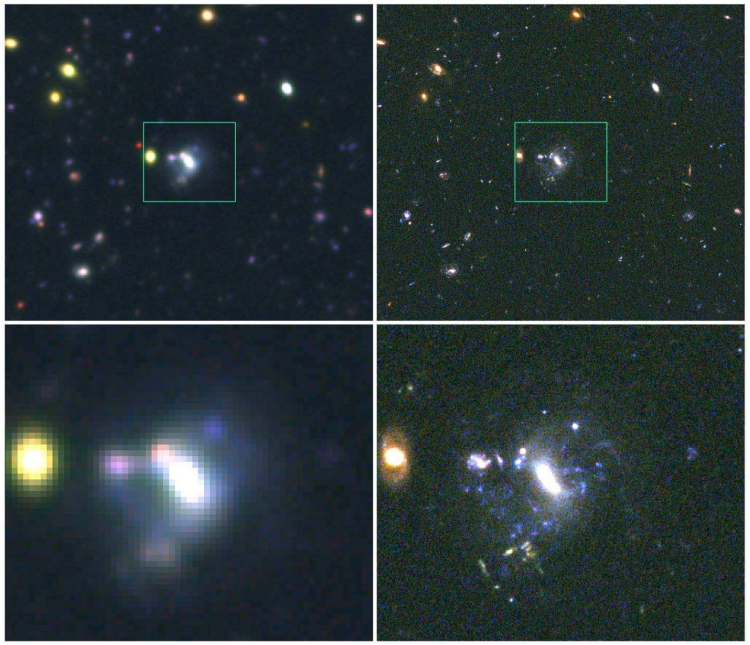


Galaxy distribution from the SDSS



STScI

Ground: Subaru (8m) Space: *HST* (2.4m)



To go deep one needs to go to space

23–28

Hubble Space Telescope

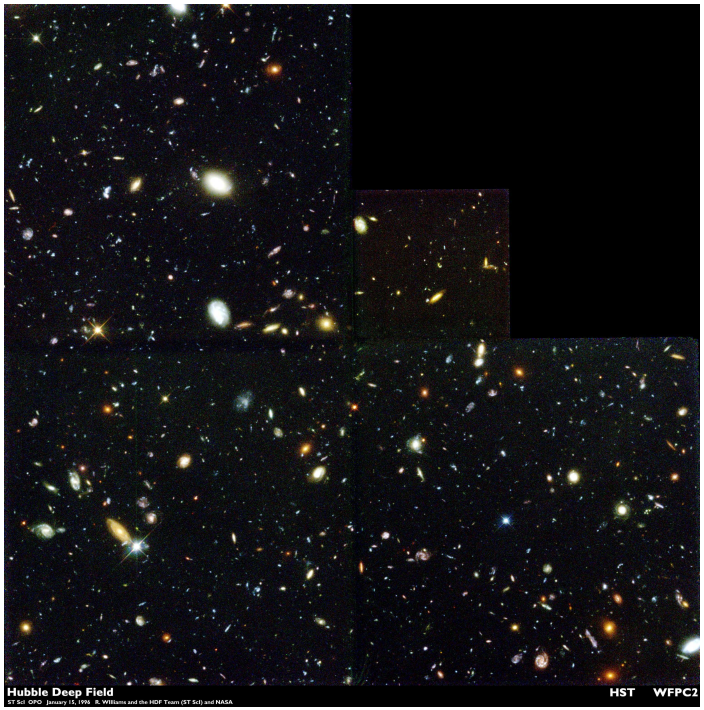
The Hubble Space Telescope has a large set of instruments well suited for cosmological observations:

Current HST Instruments :

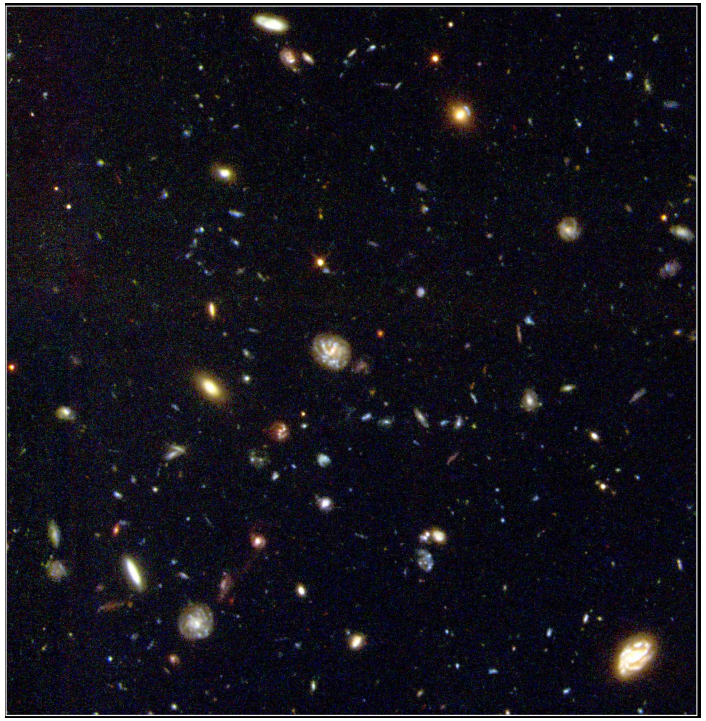
- ACS: Advanced Camera for Surveys (03.2002–)
- COS: Cosmic Origins Spectrograph (06.2009–)
- FGS: The Fine Guidance Sensors
- NICMOS: Near Infrared Camera and Multi Object Spectrometer (02.1997–)
- STIS: Space Telescope Imaging Spectrograph (02.1997–)
- WFC3: Wide Field Camera 3 (06.2009–)

Former Generation Instruments :

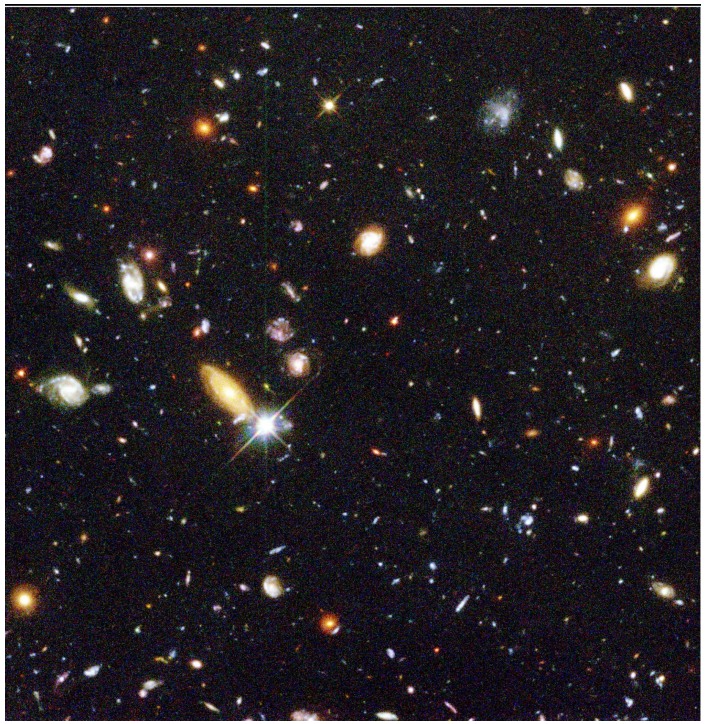
- FOC: The Faint Object Camera (04.1990–03.2002)
- FOS: The Faint Object Spectrograph (04.1990–02.1997)
- GHRS: The Goddard High Resolution Spectrograph (04.1990–02.1997)
- HSP: The High Speed Photometer (04.1990–10.1993)
- WF/PC-1: Wide Field Planetary Camera 1 (04.1990–10.1993)
- WFPC2 The Wide Field Planetary Camera 2 (12.1993–06.2009)

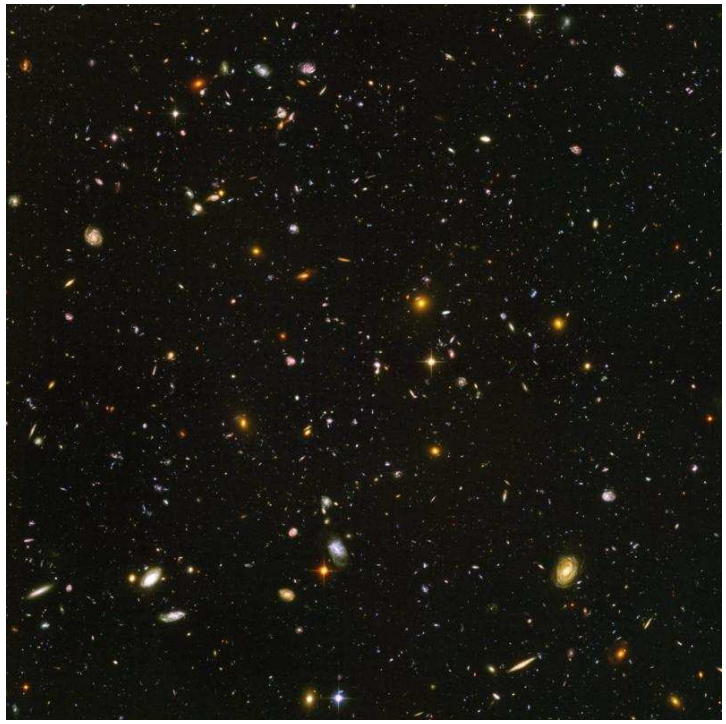


1995 December: **Hubble Deep Field**:
$\sim$ 150 ksec/Filter for four HST Filters
Many galaxies with weird shapes $\Longrightarrow$ **protogalaxies**!
Redshifts: $z \in [0.5, 5.3]$
(Fernández-Soto et al., 1999)

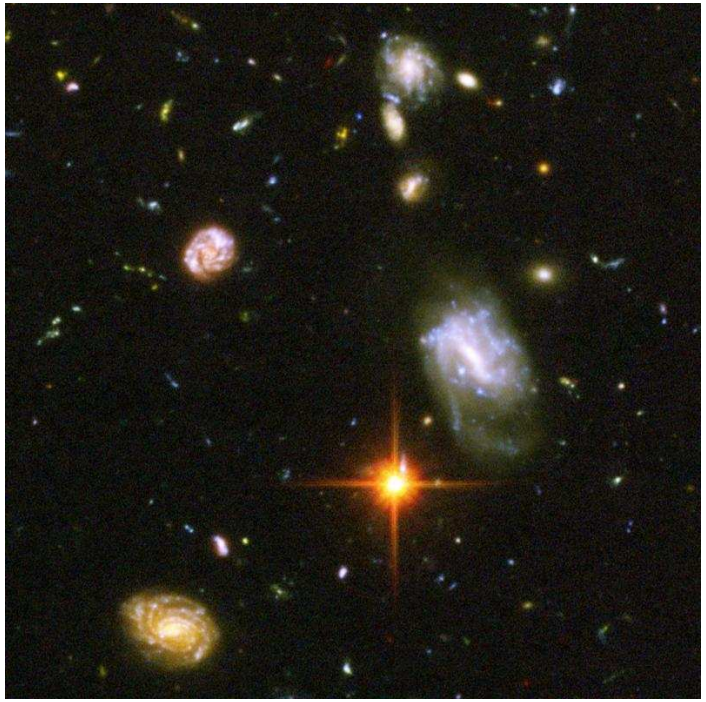


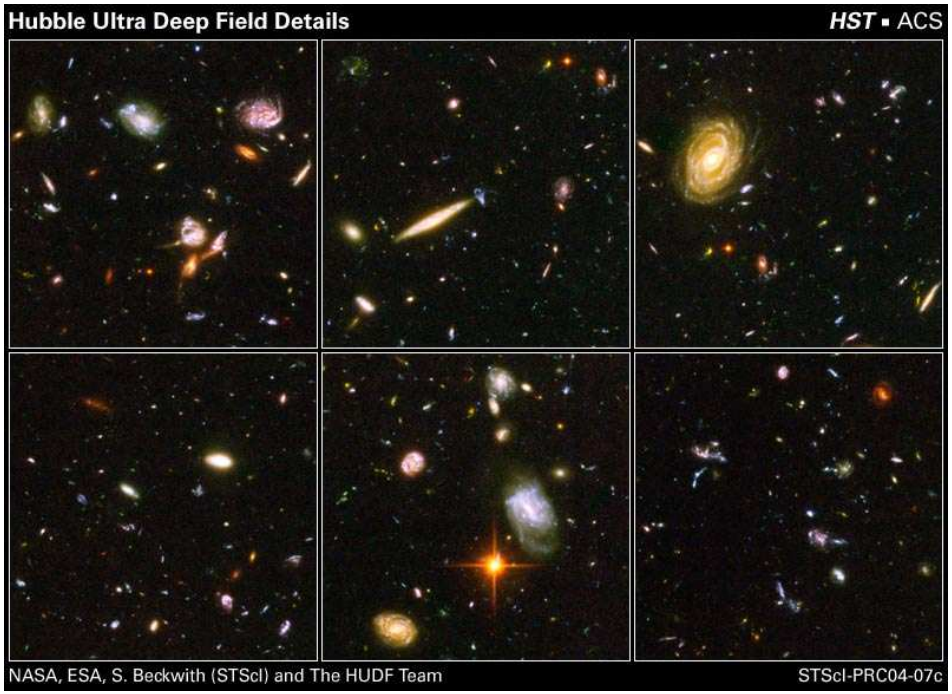
1998: **Hubble Deep Field South**, 10 d of total observing time!

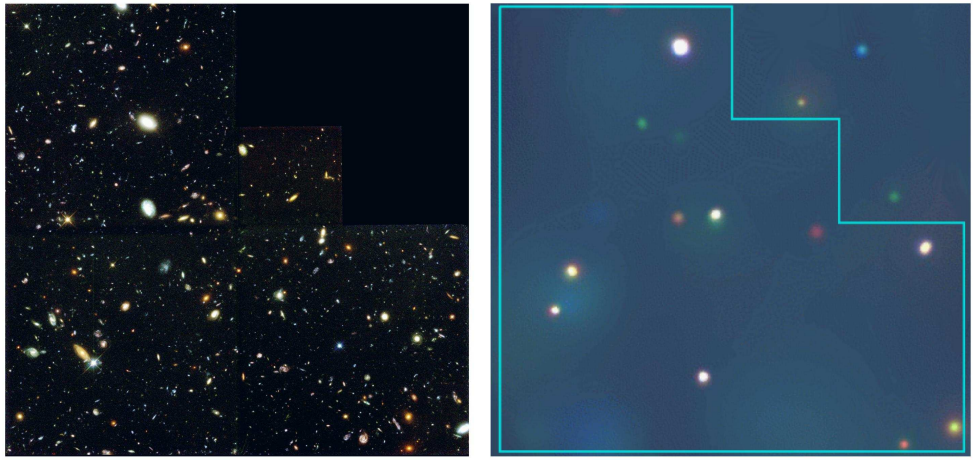




2004: **Hubble Ultra Deep Field**, 1 Msec long exposure of field in Fornax. Uses updated HST with Advanced Camera for Surveys (ACS) and Near Infrared Camera and Multi-Object Spectrometer (NICMOS); diameter: $3'$ ($2\times$ older HDF)
Limiting magnitude: 30 mag, $\sim$10000 galaxies visible, up to $z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







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!