Astronomy

- The oldest science?
- One of the most rapidly evolving fields of modern research.
- Driven by observations and instruments

Cosmology

- Intersection of **physics** (fundamental laws) and **astronomy** (contents of the universe)

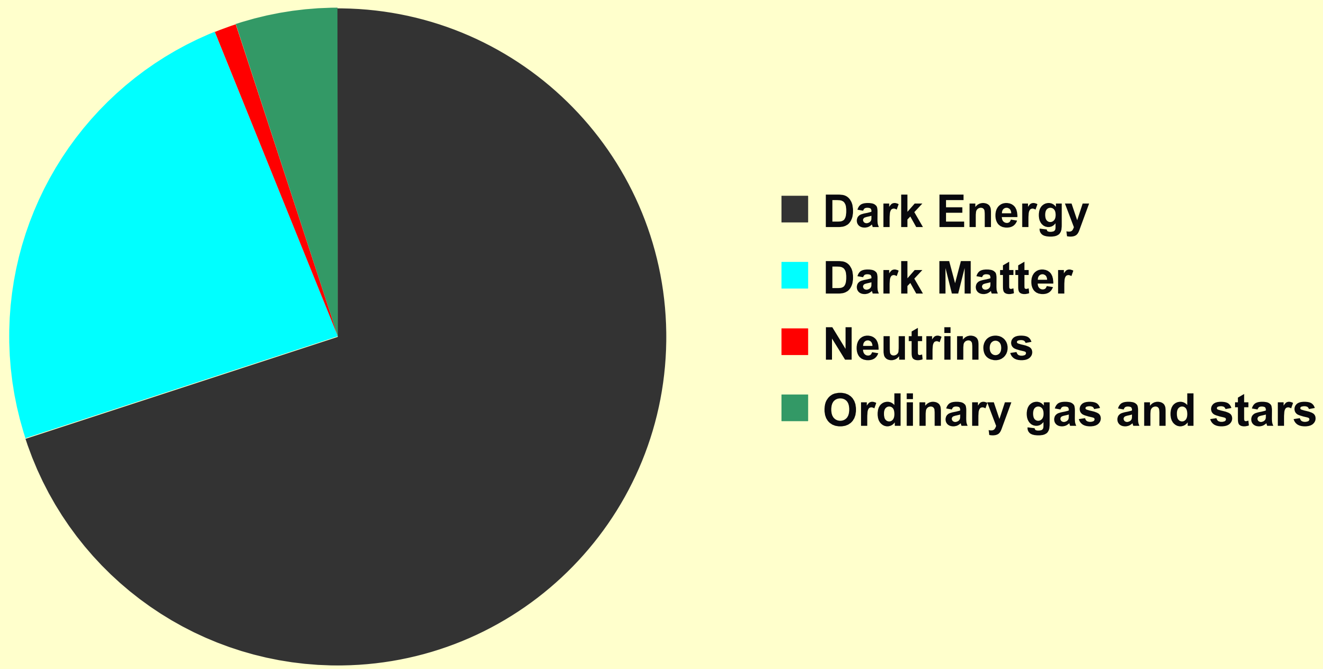
- Study of the Universe viewed as a whole
  Not a very humble field of science!
  Must coarse-grain and shove some details under the rug.

Questions in Cosmology

- **Why is the universe expanding?**
- What caused the ‘big bang’?
- What caused inflation?
- Is General Relativity a correct description?
- **What is the universe made of?**
- Why is the ‘normal matter’ mostly H + He?
- What is dark matter and dark energy?
- **How did stars and galaxies form?**
- What is the origin of initial fluctuations?
- **What is the ultimate fate of the universe?**

A Copernican-style revolution

95 % of universe is made of unidentified stuff!



A cosmologist's toolkit

- **general relativity** (back bone)
- **astronomy** (supporting data)
- **statistics** (large scale description, initial cond's)
- **plasma physics** (a system of charged particles)
- **thermodynamics** (of an expanding plasma)
- **chemistry** (late evolution; stars and galaxies)
- **nuclear physics** (evolution at earlier times)
- **particle physics** (evolution at earliest epochs)
- **mathematical physics** (initial "quantum" era)
- **… cosmetology** ("kosmos"="harmony")

The Standard Model of Cosmology

(Jim Peebles)

- **I. Cosmological Principle**
  homogeneous *and* isotropic on large scales
- **II. Expansion: kinematics**
  expanding in a way that preserves I.
- **III. Expansion: dynamics**
  obeys general relativity theory
- **IV. Hot Big Bang**
  hot dense state, dominated by thermal radiation
- **V. Inflation(*)**
  initial exponential ("superluminal") expansion
- **VI. The Dark Sector(*)**
  to account for apparent acceleration + large-scale structure

The Standard Model

- **~ 100 years old** (relativity, galaxies, expansion)
- **~ 50 yrs ago: CMB** (hot big bang, structures)
- **~ 40 yrs: Inflation** (?) **Dark Matter** (?)
- **~ 20 yrs: Dark Energy** (???)

- **cf. Particle Physics:**

  less rigorously defined

  open questions, puzzles are more numerous, and more fundamental

Census of the Extragalactic Universe

"Visible" constituents of (present-day) Universe:

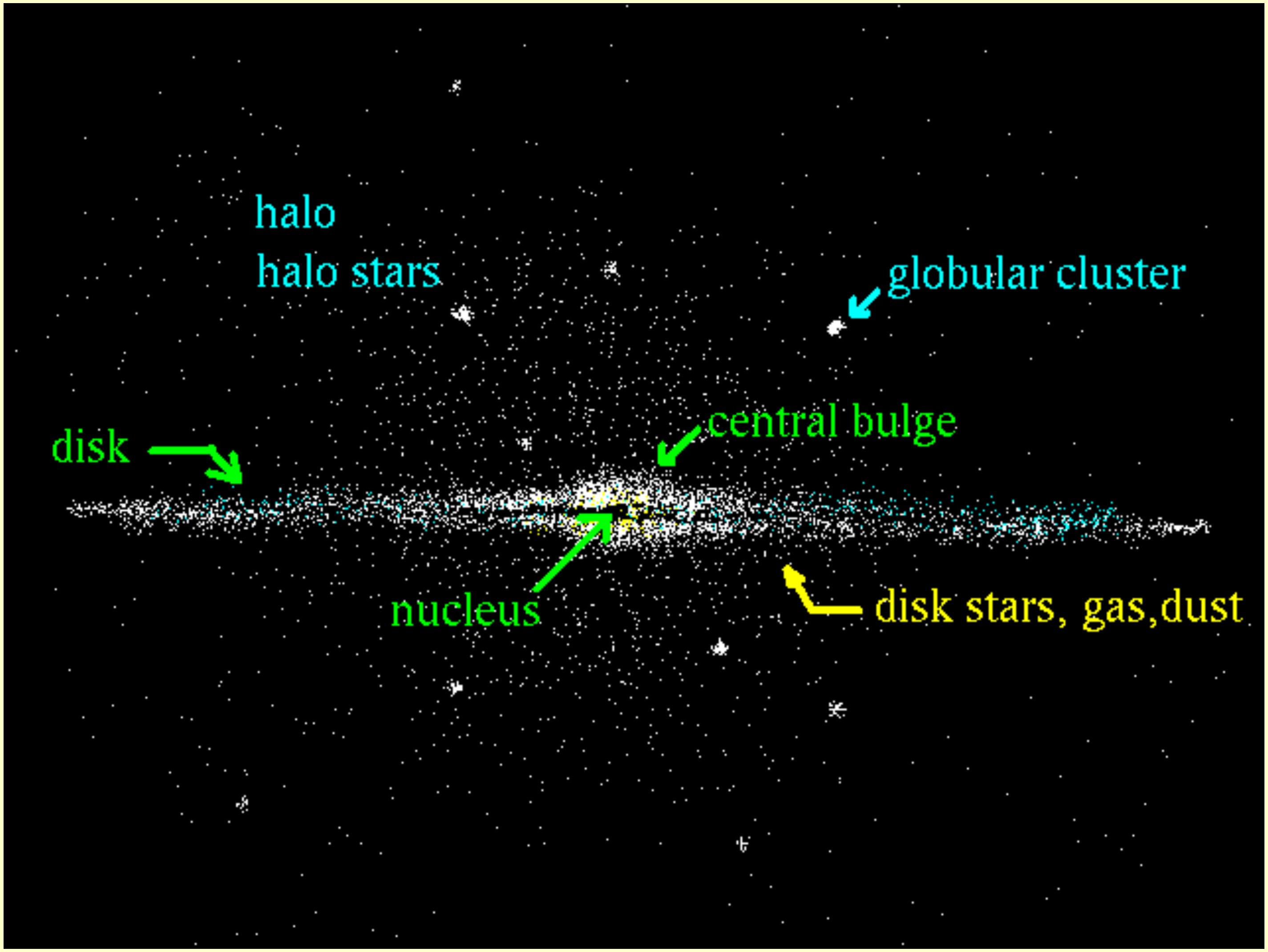
- Non-relativistic particles ("baryons"):
  - *Galaxies / Clusters / Super-clusters / Cosmic Web*
  - *Intergalactic Medium*
- Relativistic particles: radiation (+ neutrinos?)

"Invisible" constituents - a.k.a. the Dark sector:

- Dark matter: can clump and make structures
- Dark energy: smooth, only global effects

Galaxies

Individual Galaxies: Milky Way



Mass:

$2 \times 10^{11} M_\odot$

(15 kpc)

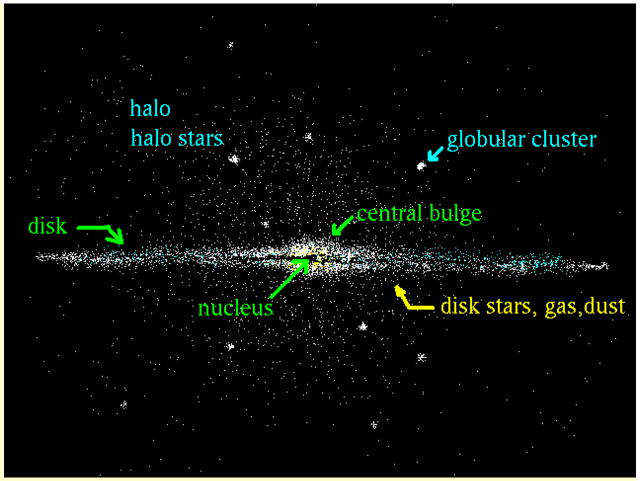
$5 \times 10^{11} M_\odot$

(100 kpc)

Age:

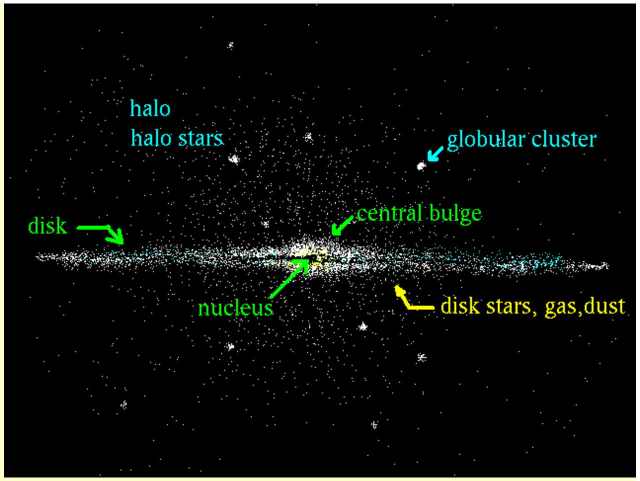
1.2×10^{10} yr

Milky Way: Halo



- Weighs ~$10^{11} M_{\odot}$ (<15 kpc)
- Extends to ~100 kpc
  - **roughly spherical distribution**
- Old stars
  - **little or no gas or dust – metal poor**
- Globular clusters
  - **$10^6 M_{\odot}$ clumps of old stars; formed first?**
- Mostly dark matter by mass
  - **MACHOs (but can make up only ~20% of mass)**

Milky Way: Disk

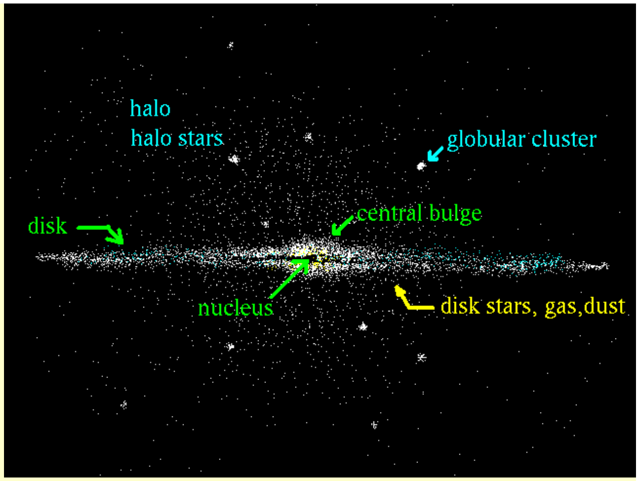


- Weighs ~5x$10^{10}M_{\odot}$

- Thin pancake of stars
  - 15 kpc radius, ~300 pc thickness (CD-Rom)
  - stars ~ 2 pc apart

- Interstellar medium
  - gas (40% by mass)
  - dust (1% of gas by mass)

Milky Way: Disk



- Spiral Arms

  - traced by young stars – triggered star formation
  - a wave phenomenon (material structure would wind up)

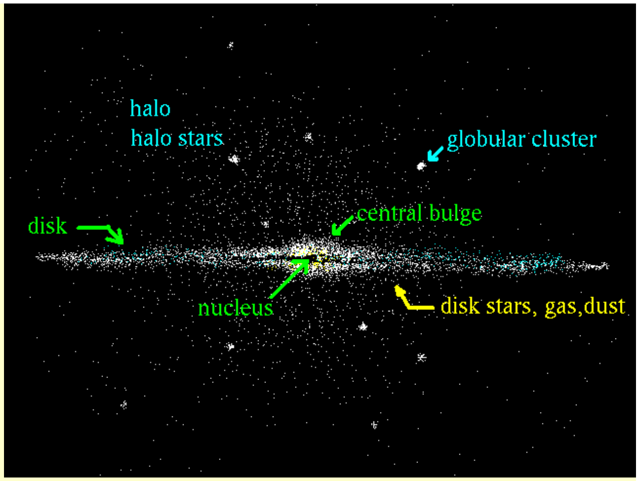
- Solar system

  - about 8 kpc from center
  - ecliptic plane nearly perpendicular to disk
  - moves around Galactic center at ~250 km/s

- Differential Rotation

  - important in generation of spiral density waves
  - "rotation curve" $v(r)$ can be used to estimate mass from $GM(<r)/r^2 = v^2/r$

Milky Way: Bulge



- Weighs ~$10^{10} M_{\odot}$
- Dense cluster of old stars
  - 1 kpc radius, core 10^5 times as dense as disk
  - almost no gas or dust
  - randomly oriented orbits
- Nucleus
  - $(4 \pm 0.2) \times 10^6 M_{\odot}$ black hole at center (Sagittarius A*)
  - inactive
- Formed before disk?

Galaxies

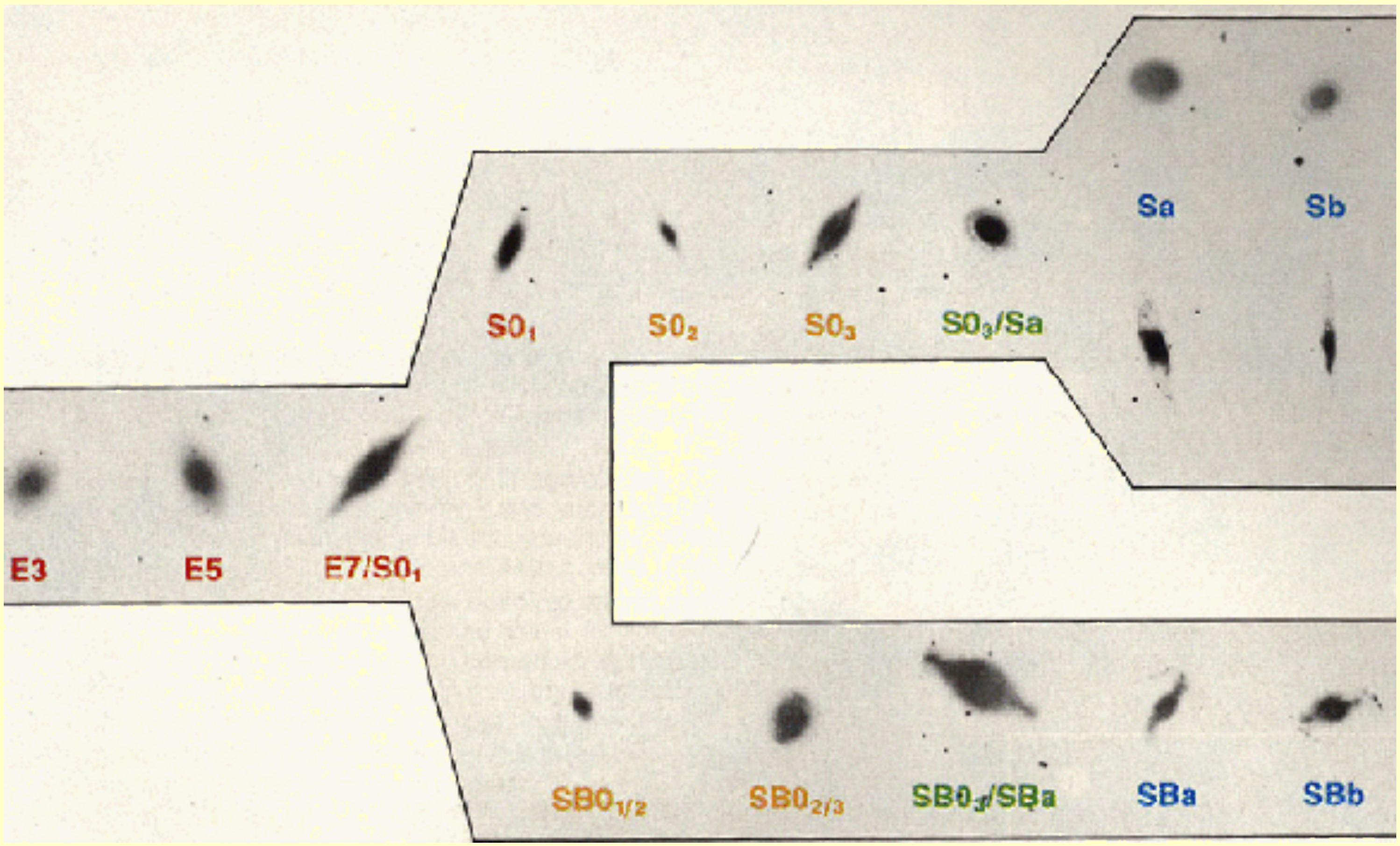
Galaxy Types: The "Hubble Sequence"

- Based on morphology
- Disks vs. Ellipticals

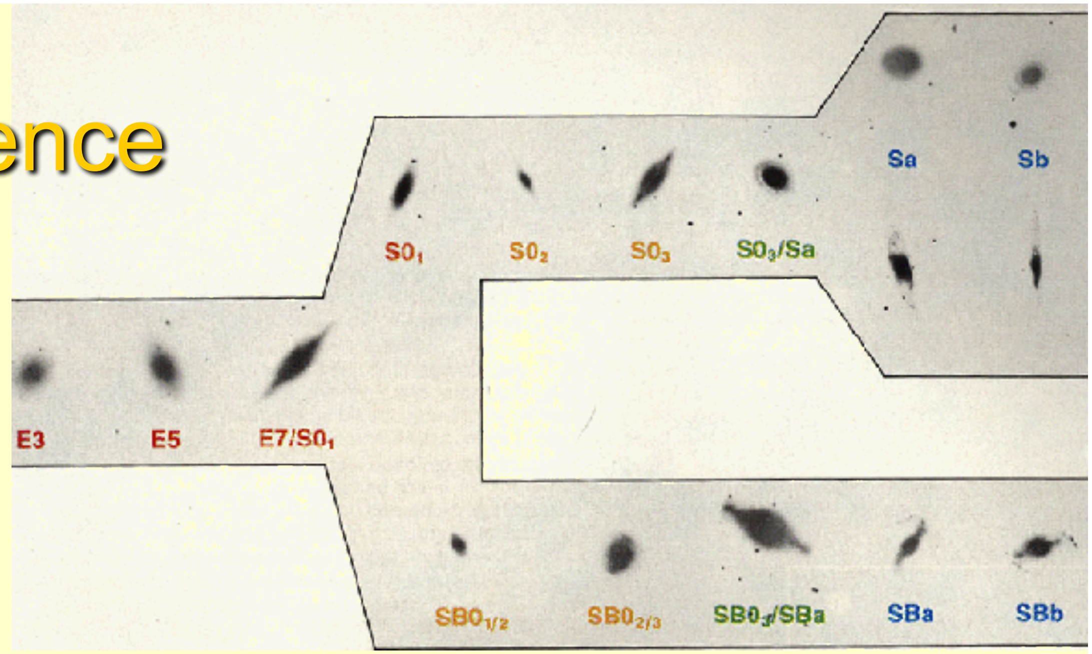
M87 in Virgo

The Hubble Sequence

Is this physics or taxonomy?

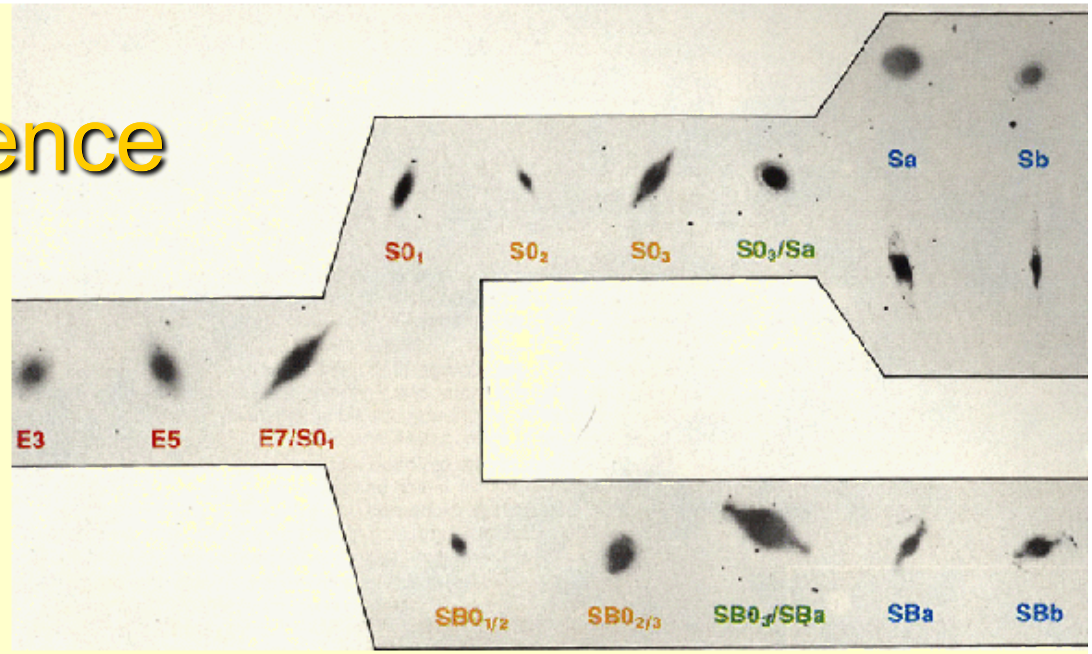


The Hubble Sequence Taxonomy



- Ellipticals (E0-E7)
  - **- by axis ratio**
- Disk galaxies with no spiral arms (S0)
  - **- rare, old, live in dense environments**
- Galaxies with spiral arms (S)
  - **- common, young – with (Sb) or without (S) a bar**
- Irregular galaxies (Irr)
  - **- no spiral arms or bulges**

The Hubble Sequence
Physics



- Evolutionary sequence

  - early types (E) vs late types (S)

  - still debated which type formed first

- Flattened vs. Puffed up Structures

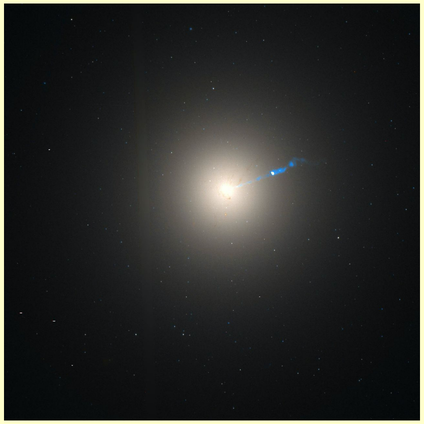
  - determined by efficiency of cooling

  - ordered vs disordered orbits of stars

- Irregulars

  - more common at earlier epochs, merger-triggered bursts?

Examples

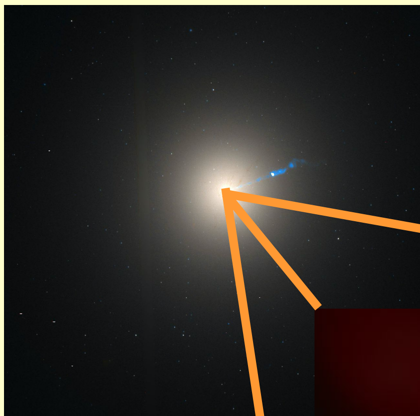
Elliptical	Spiral	Barred Spiral
		
NGC 4486 (M87)	**NGC 5194 (M51a)**	**NGC 1365**
Virgo A	Whirlpool Galaxy	The Great Barred Spiral Galaxy

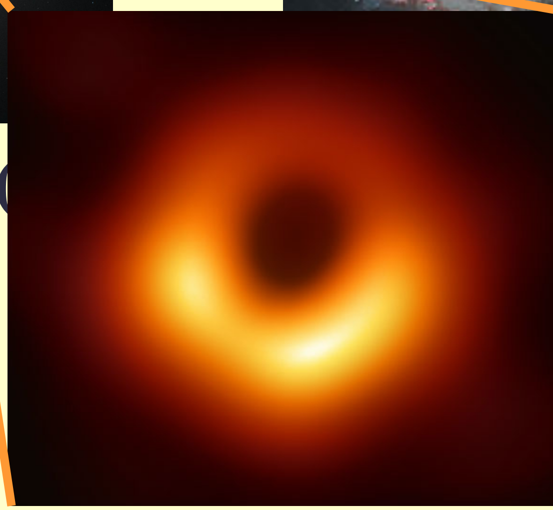
Examples

Elliptical

Spiral

Barred Spiral





NGC 4486 (

94 (M51a)

NGC 1365

Virgo A

rlpool
axy

The Great Barred
Spiral Galaxy

Galaxies

Quiet vs. Active

- Active: super-massive (10^6-10^9 $M_\odot$) black hole at the nucleus
  - accretes gas at a high rate
  - converts rest mass to light efficiently
- Quiet: no sign of active nucleus
  - either no SMBH
  - or (more likely) inefficient accretion/radiation

Galaxies

Quiet vs. Active

- The nucleus of an active galaxy normally outshines the starlight from rest of the galaxy
  - unresolved point source called “quasar” or QSO
  - discovered by Maarten Schmidt (1963)
  - host galaxies hard to image, but few examples
- Supermassive black holes
  - now thought to reside at the centers of all galaxies
  - found in all of the ~100 nearby galaxies studied

Galaxies as a Population

Scaling Laws

- Spiral Galaxies (Tully-Fisher relation)

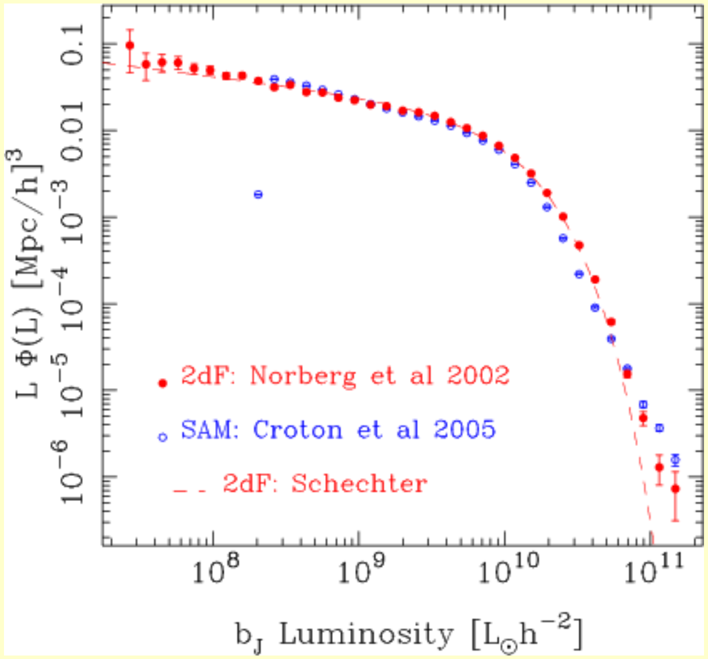
$$v_{circ} = 220\ (L/L_*)^{1/4}\ \mathrm{km/s}$$

- Elliptical Galaxies (Faber-Jackson relation)

$$\sigma = 160\ (L/L_*)^{1/4}\ \mathrm{km/s}$$

$$v_{circ} = 2^{1/2}\sigma = 220\ (L/L_*)^{1/4}\ \mathrm{km/s}$$

Galaxies as a Population



← Luminosity Function

Schechter function: $d\Phi/dL = (\Phi_*/L_*)\ (L/L_*)^{\alpha}\ \exp(-L/L_*)$

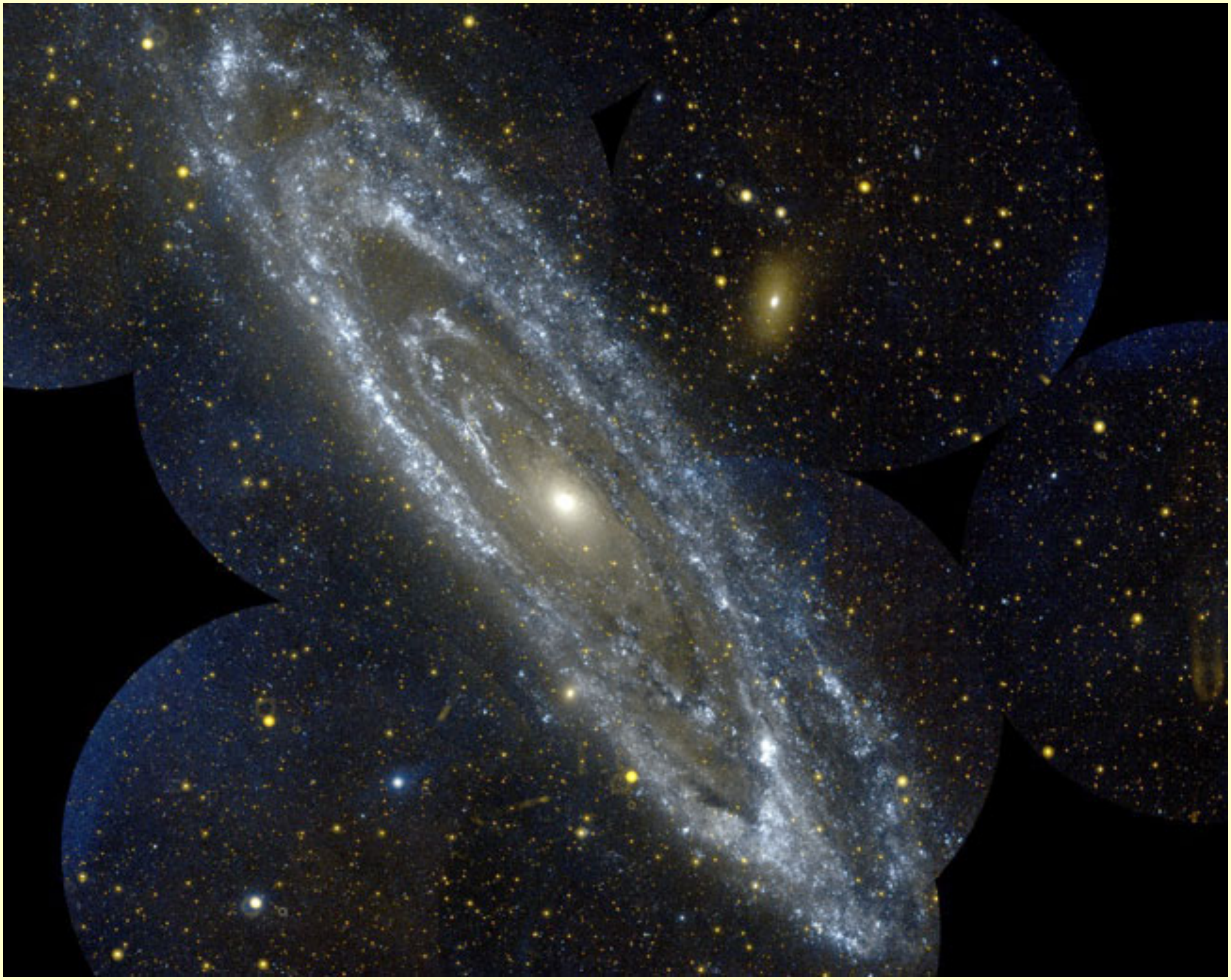
- characteristic galaxy luminosity L_* or mass M_*
- upper cutoff
- $\alpha \approx -1$: total light: $\rho_L = \Gamma(\alpha+2)\Phi_* L_*$ is finite

  total number: diverges → lower cutoff

Andromeda (M31)

- Nearest large galaxy, similar to MW
- Spectrum blue-shifted by ~120 km/s
- Distance 800 kpc ($\rightarrow v=H_0 r=60$ km/s)
- Weighs ~10^{12} $M_{\odot}$ (comparable to MW)
- Linear radius ~40 kpc twice MW
  (3 x 1 deg = 6 moons)
- Member of Local Group

Andromeda (by GALEX)



The Local Group

- dominated by MW and M31
- ~60 “satellite” galaxies (LMC/SMC, M32)
- Diameter of ~3 Mpc
- gravitational interaction and member exchange with nearby groups (Sculptor, Maffei,..)
- Moving at ~600 km/s *relative to CMB*
- Fall into Virgo Cluster, ~16 Mpc away (~200 km/s)

Galaxy Clusters

- Galaxies are not isolated entities in space

  - rather, cluster in sizes from N=2 to N~10,000

- Milky Way is in "Local Group"

  ~1 Mpc in size, ~60 galaxies

- Closest rich cluster is Virgo

  ~16 Mpc away, ~2000 galaxies (mix of spirals and E)

  ~100 Mpc away is Coma, ~1000 galaxies (mostly E)

Galaxy Clusters

Coma cluster (Abell 1656): ~ 1 Mpc in size, ~1000 galaxies

Galaxy Cluster: Properties

- Most massive *gravitationally bound* systems in nature

  Total mass up to ~10^{15} $M_{\odot}$

- Ingredients

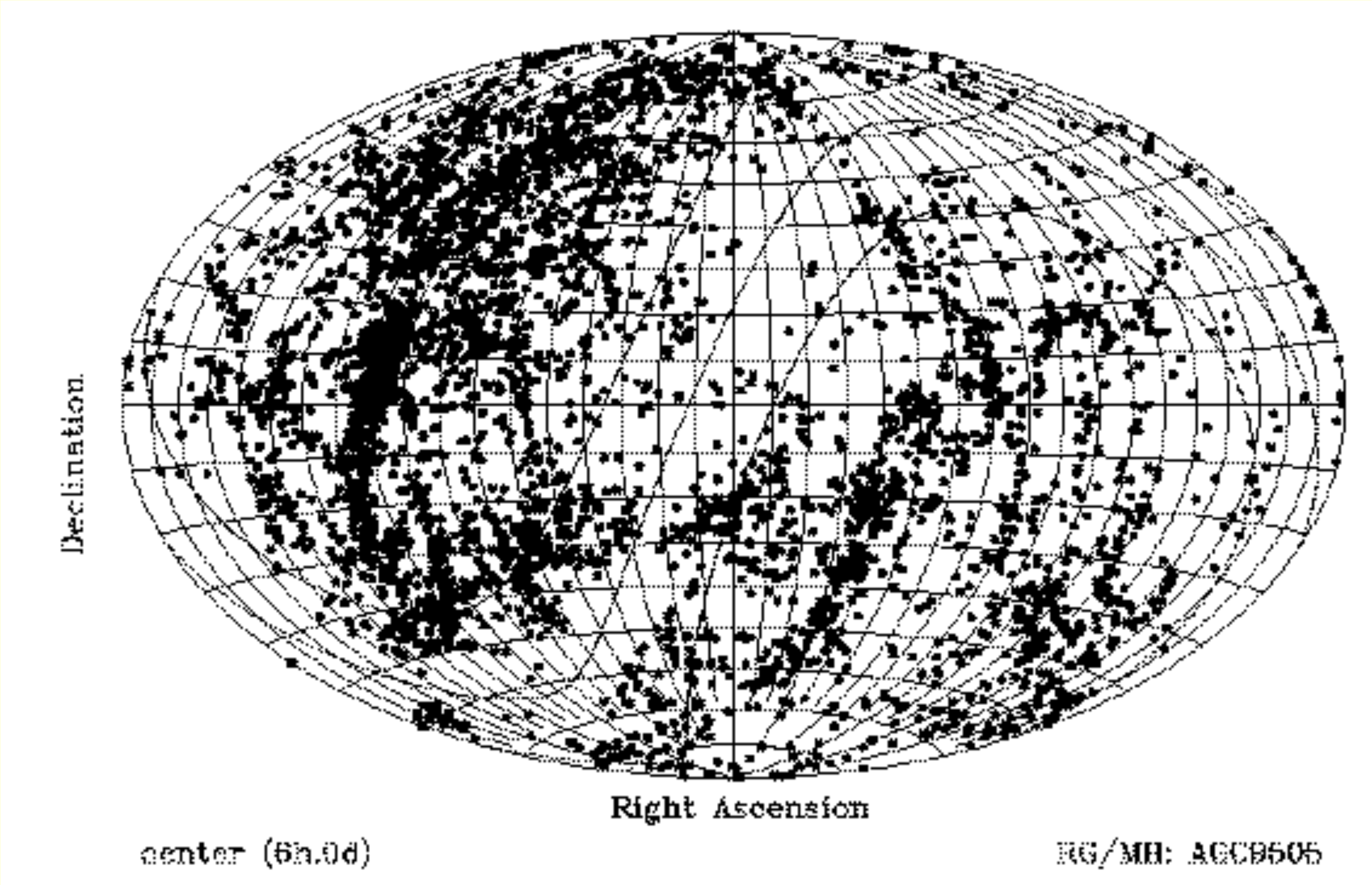
  - Dark Matter (70%) - original discovery of DM
  - Hot gas (25%) - 10-100 million K, emits X- rays
  - Galaxies (5%) - icing on the cake

- Groups contain most of the mass of the universe
- Evolve much more rapidly with time than galaxies

  - very few galaxy clusters exist beyond redshift z~1

The Local Super-cluster

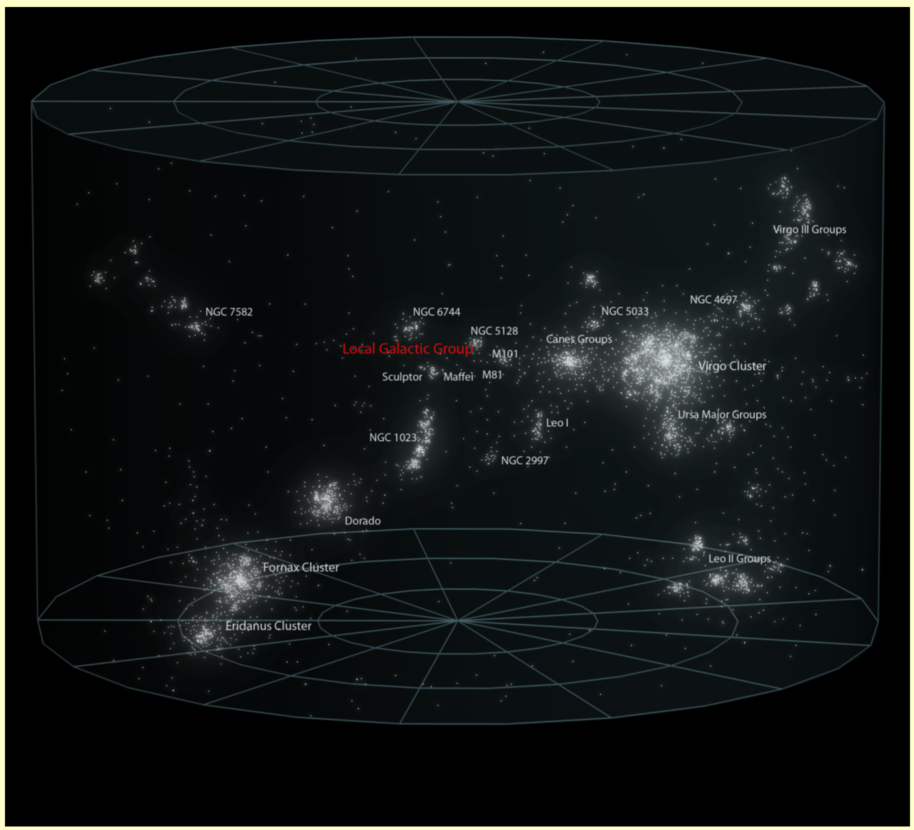
- ~10,000 galaxies, centered on Virgo cluster
- ~30 Mpc diameter, flat (pancake) structure



de Vaucouleurs
in 1950s

The Local Super-cluster

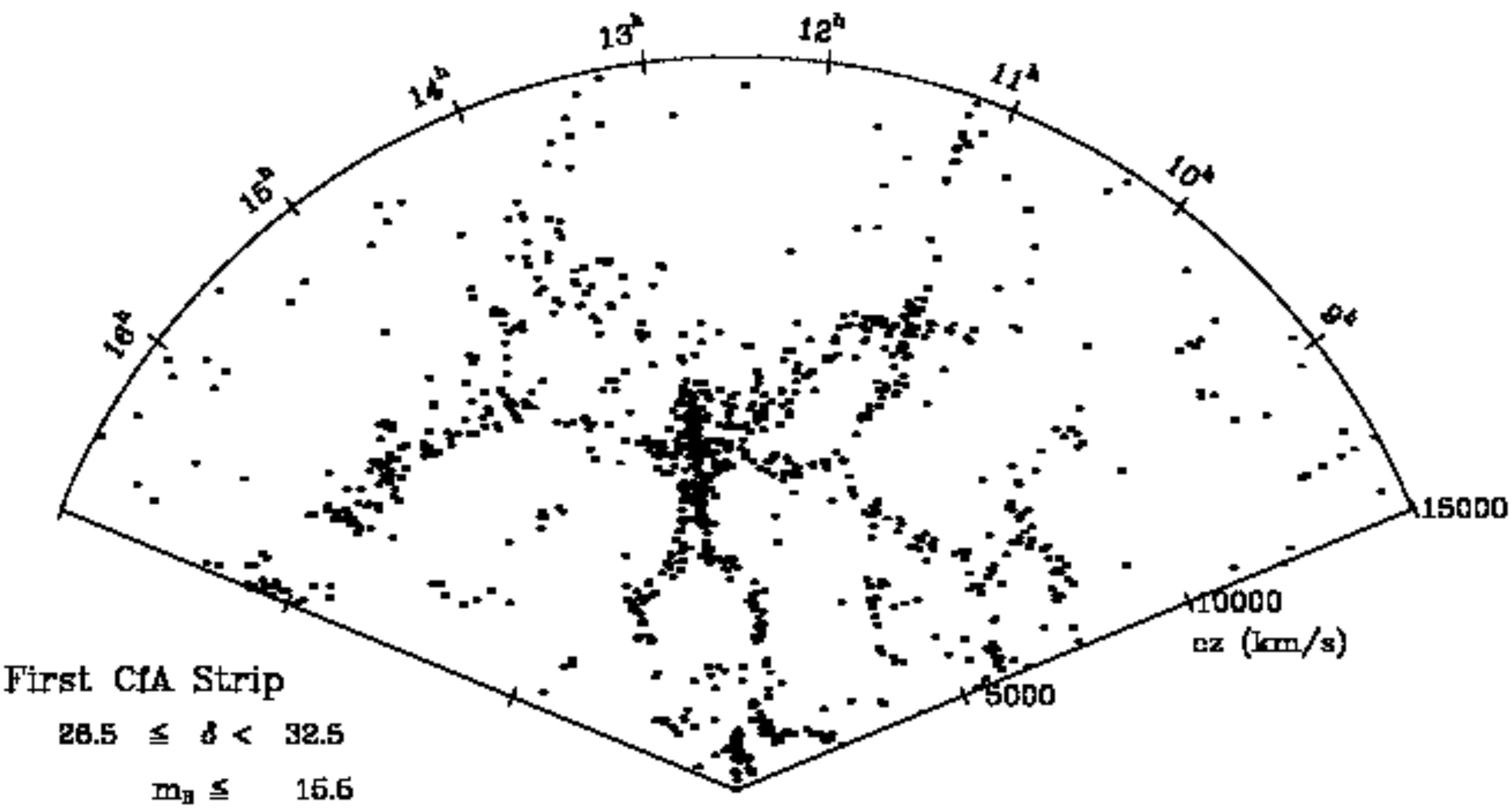
- ~100 galaxy groups and clusters
- total mass ~$10^{15} M_{\odot}$
- Moving as a whole towards “Great Attractor”



Larger Scale Structures

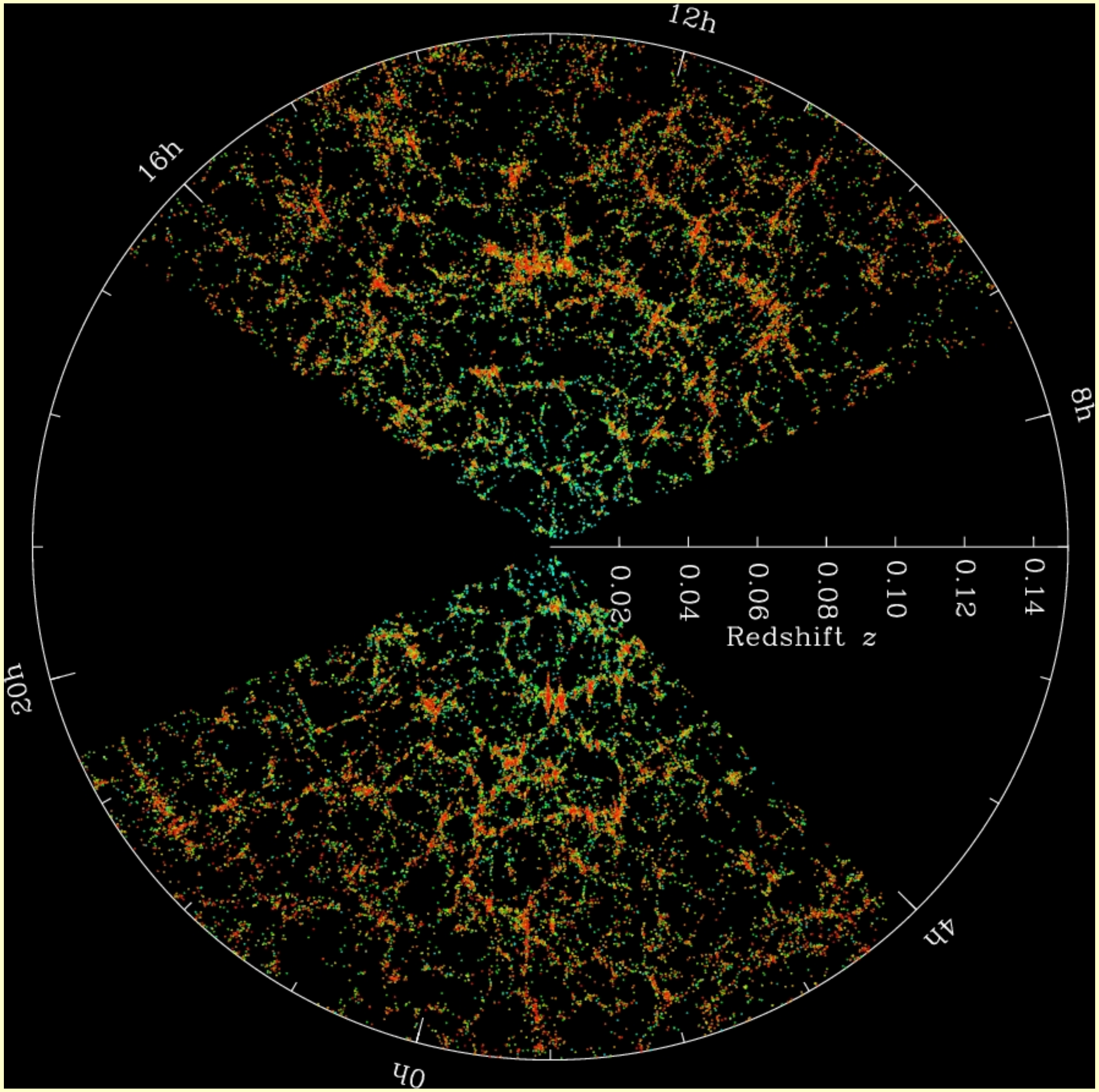
CFA redshift survey: ~200 Mpc slice with ~1000 galaxies:

- **"finger of god": artificial feature**
- **"great wall": physical structure ~100 Mpc long**



Out to the Hubble Distance

2dF, Sloan: z~0.2, v~60,000 km/s, d~1 Gpc:

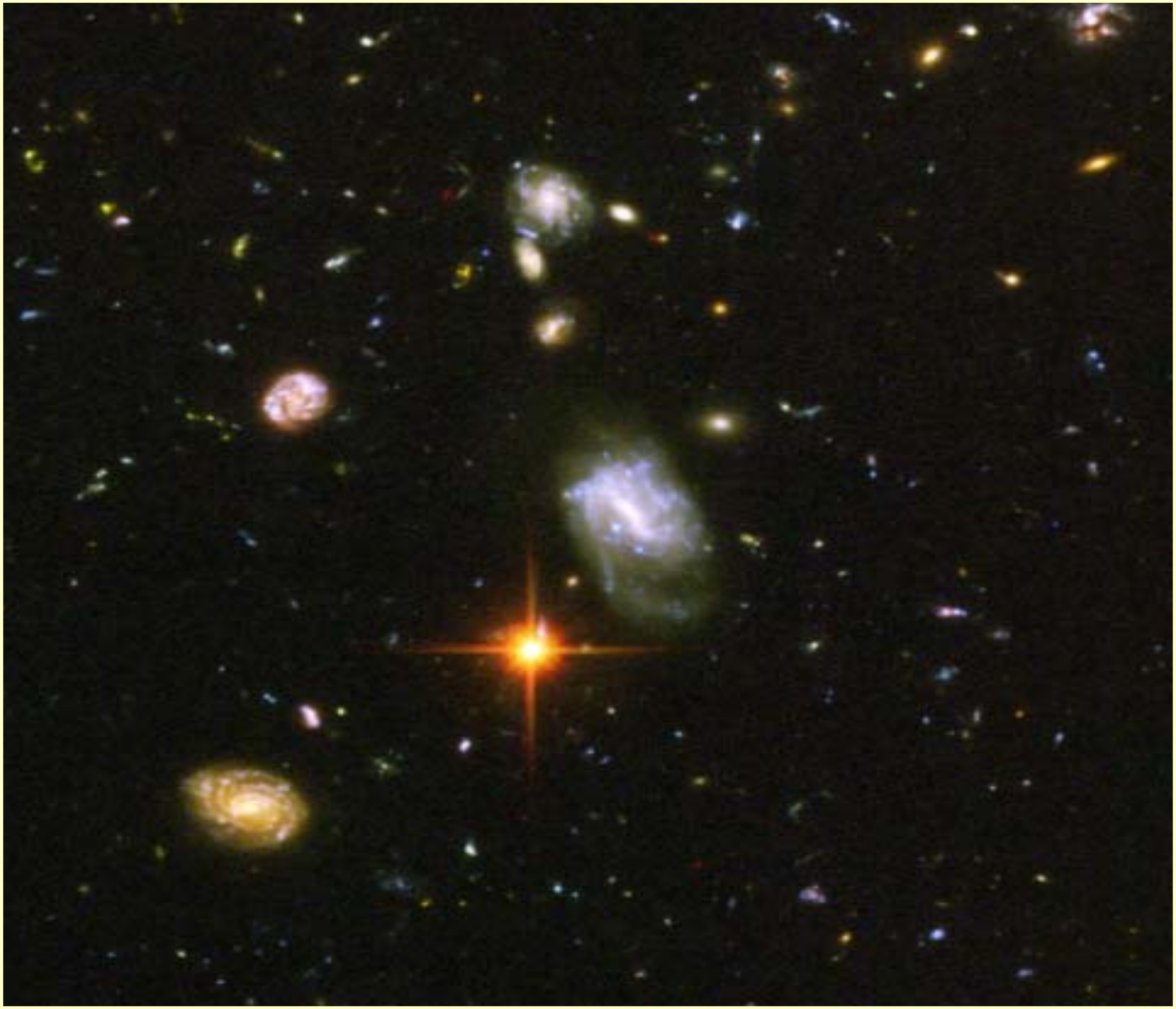


200 million galaxies
Sloan Digital Sky Survey
(Michael Blanton; NYU)

Hubble Ultra Deep Field

- Deepest view of the Universe
- Most objects are galaxies not stars
- Faintest galaxies 13 billion lyr away
- Tiny area of sky
- Record holders:
  - galaxy z~ ~~10.2~~ 11.09
  - quasar z~ ~~7.1~~ 7.54
  - gamma-ray burst z~8.2

Hubble Ultra Deep Field – Zoom

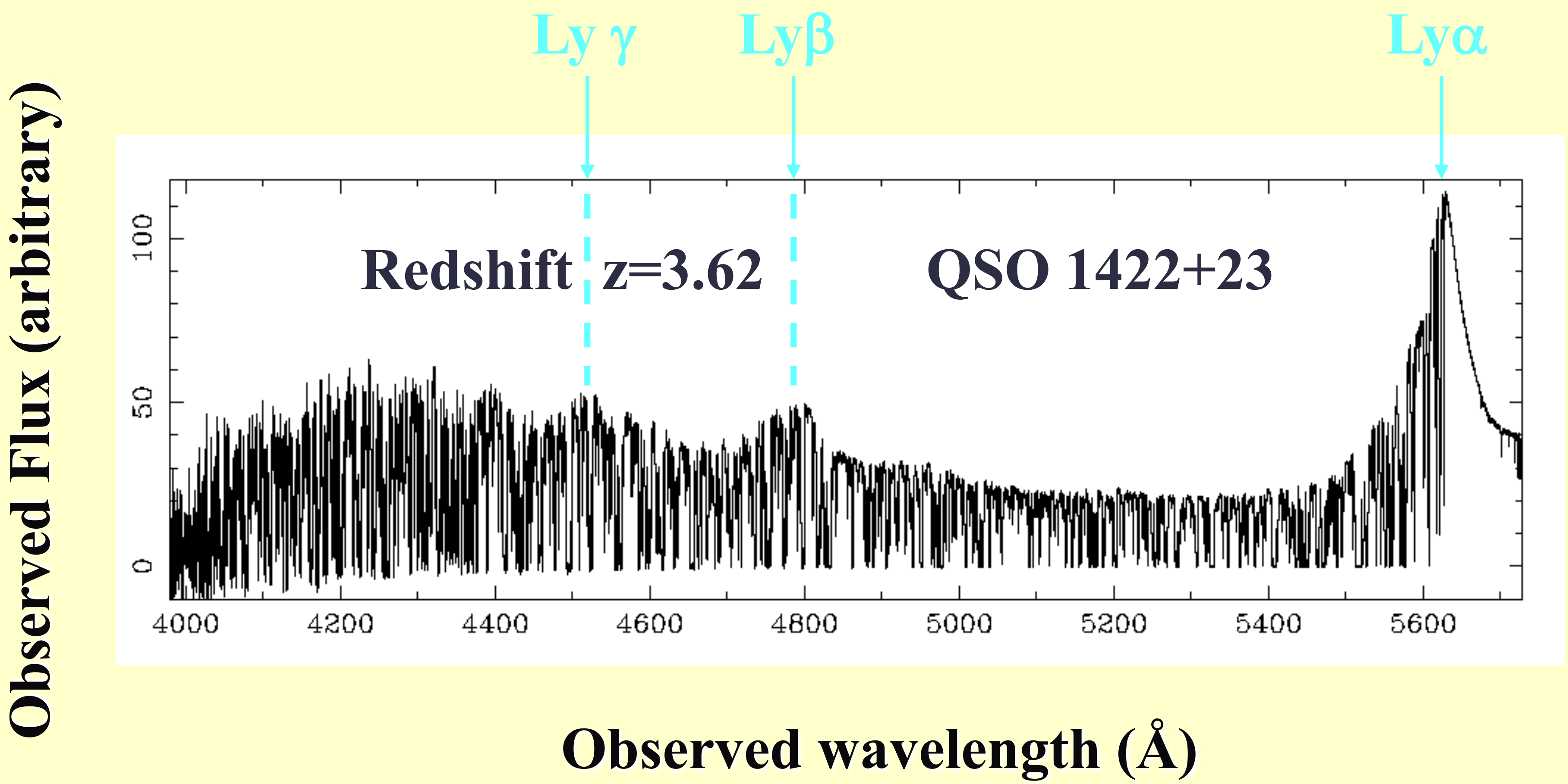


The Intergalactic Medium

What about space between galaxies and galaxy clusters?

empty ?

The Spectra of High Redshift Quasars



(Womble et al. 1996)

The Intergalactic Medium

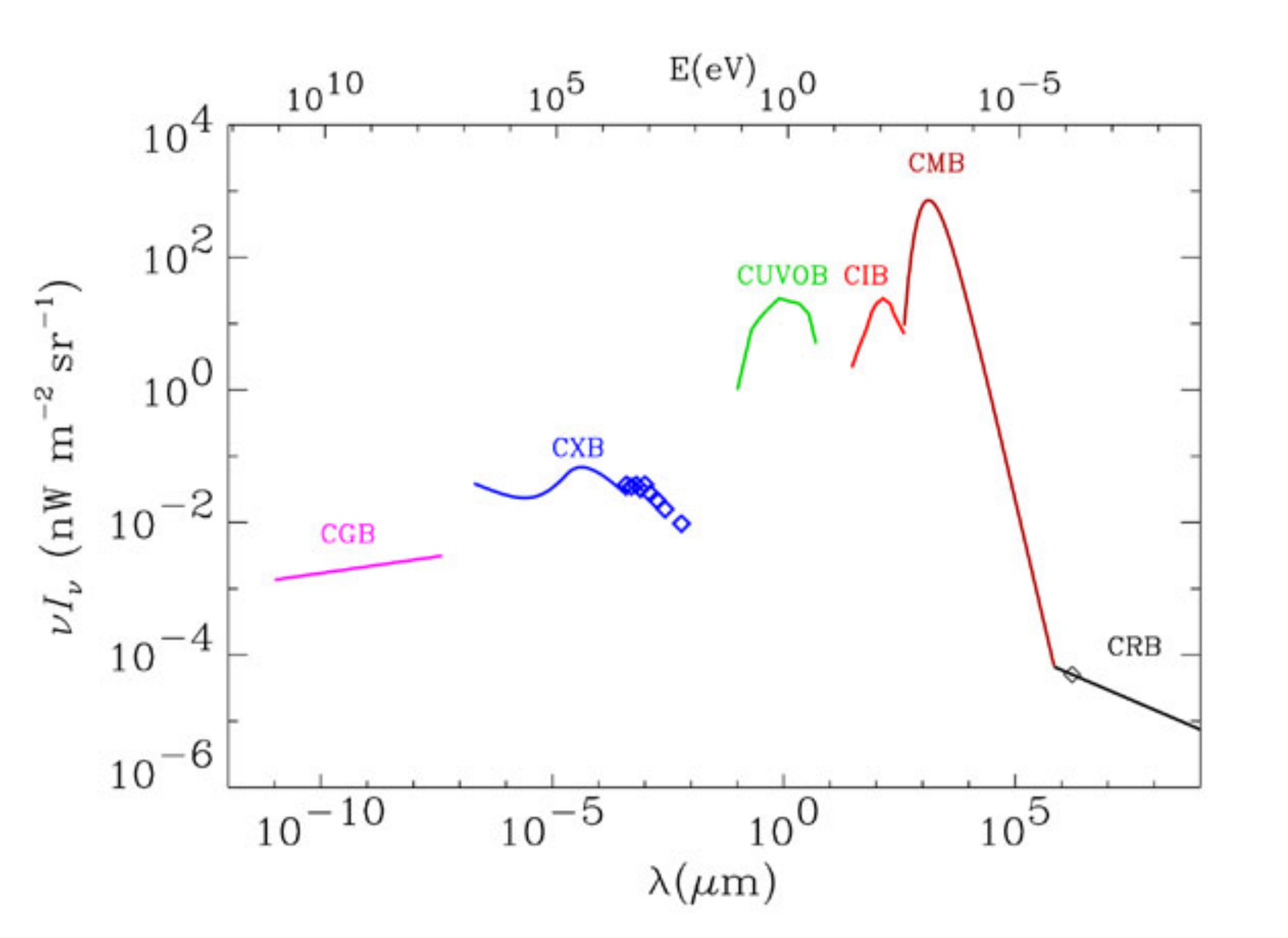
- More distant IGM (z~3) is well understood
  - can be studied in absorption against spectra of distant quasars
  - smooth H + He gas, with mild fluctuations
  - statistics of these fluctuations supports inflation theory
  - known to contain most of the baryons at z~2
  - very highly ionized (neutral H: 1 part in $\sim 10^{6}$)
  - in photo-ionization equilibrium
  - contains trace "*metals*" as far out as we can see (z~7)

The Intergalactic Medium

- Local IGM:
  - turns out much more puzzling
  - absorption lines weak and difficult to observe
    1. wrong wavelength   2. universe too dilute
  - the “missing baryons”:
    most baryons locked up in discrete objects?
    or most baryons in WHIM phase at 10^5 degrees?
  - recent searches for WHIM in OVI recombination

Photons

Extragalactic Background (Hauser & Dwek 2001)



Cosmic Microwave Background

- Mean temperature: T=2.725 ± 0.001 K
- Spectral Deviation: Compton-y parameter

$$y \equiv \int \sigma_T n_e \frac{kT}{m_e c^2} dl \leq 1.5 \times 10^{-5} \quad \text{(COBE 1992)}$$

- Energy Density:

$$u = a_B T^4 = 4.8 \times 10^{-34} g/cm^3$$

$$n_\gamma = 420 cm^{-3}$$

$$\langle h\nu \rangle = 6.3 \times 10^{-4} eV$$

$$\Omega_\gamma = 5 \times 10^{-5} \approx 10^{-3} \Omega_b$$

$$n_\gamma / n_b = 2 \times 10^9$$

Other Relativistic Particles?

Neutrinos

- Not observed directly
- Electron, muon, tau neutrinos – finite mass from oscillations: Solar ν rate (seasonal fluctuations):

  $\Delta(m_\nu^2 c^2) = 5 \times 10^{-5} eV^2$ (also from atmospheric ν' s)
- Theoretically predicted
  (from weak interactions in early universe)
- Fermi-Dirac distribution at late times (after $T \sim m_e$)
- Characterized by single parameter: temperature
- $T_\nu = (4/11)^{1/3} T_\gamma = 1.95$ K (or: $\langle E \rangle \sim 4 \times 10^{-4} eV$)
- $\Omega_\nu = 3 \times \frac{7}{8} \times \left(\frac{4}{11}\right)^{4/3} \Omega_\gamma = 0.68 \times \Omega_\gamma = 3.4 \times 10^{-5}$ (relativistic)
- $\Omega_\nu = n_\nu m_\nu = 3 \times \left(\frac{3}{11}\right) \times n_\gamma \times m_\nu = \frac{m_\nu}{46 eV}$ (present day)