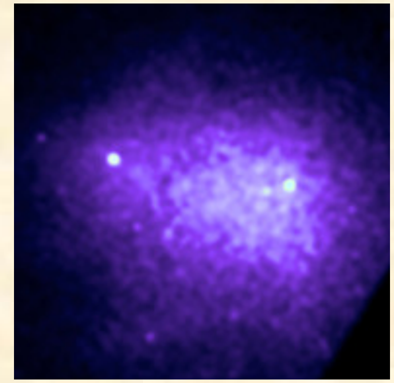
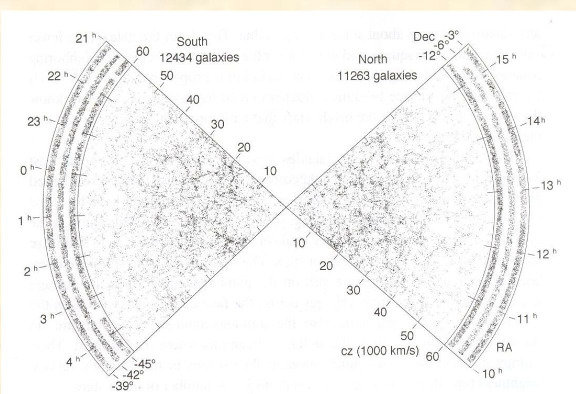
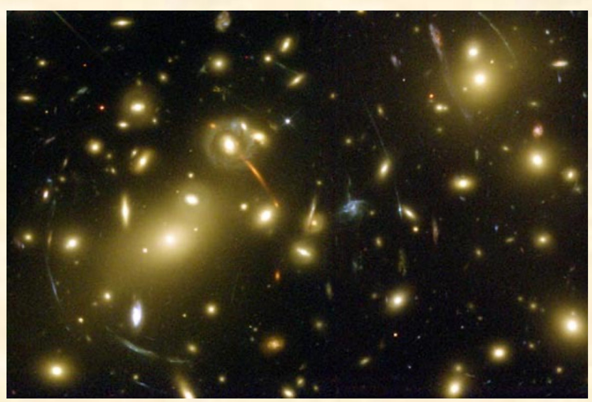
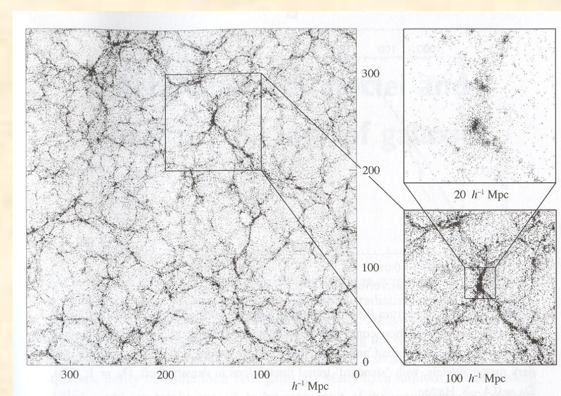
Large-Scale Structure



- Evidence for Dark Matter
- Dark Halos in Ellipticals
- Hot Gas in Ellipticals
- Clusters
- Hot Gas in Clusters
- Cluster Galaxy Velocities and Masses
- Large-Scale Distribution of Galaxies







Evidence for Dark Matter on Large Scales

- Spiral Galaxies → dark halos
  - Flat rotation curves (covered previously)
- Elliptical Galaxies → dark halos
  - Velocities of planetary nebulae in halos of giant Es
  - Rotation of embedded H I disks (in a few peculiar Es)
  - Confinement of hot ($T \approx 10^7$ K) gas
- Rich Clusters of Galaxies → large unseen mass
  - Velocities of individual galaxies, virial theorem
  - Confinement of very hot ($T > 3 \times 10^7$ K) gas
- As size scale increases, M/L increases from ~5 to ~200
  - Evidence for a large dark mass component that has a shallow density profile.
  - Hot gas may account for missing baryons, but not most of the "missing mass"

Dark Halos in Ellipticals

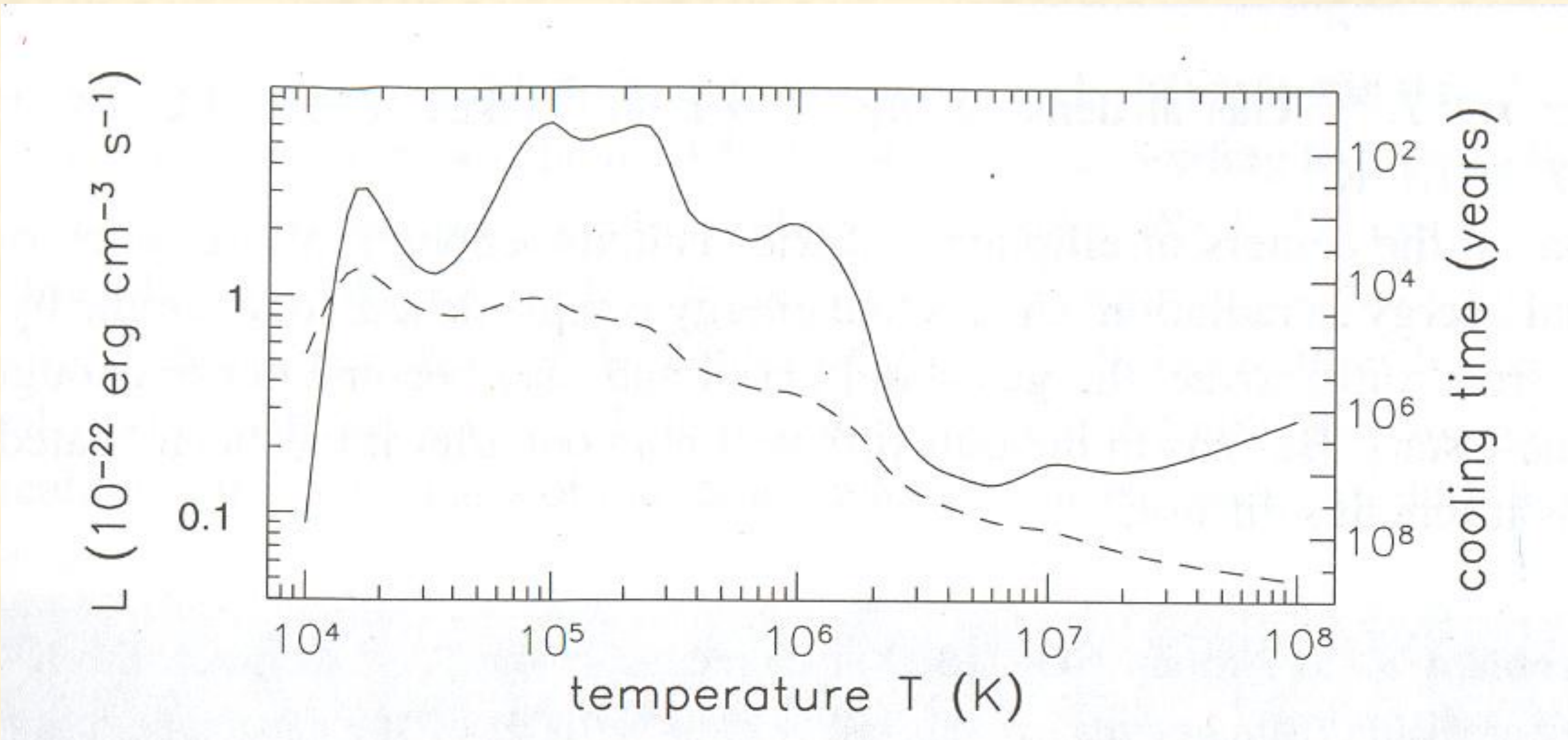
- At $R < R_{25}$ in ellipticals, $M/L_V \approx 5$
- A few peculiar Es have cold H I disks
  → H I 21-cm gives M/L = 10 – 20 at R = 25 – 50 kpc
- Planetary nebulae are bright, compact sources of emission lines (e.g., [O III] λ5007)
  - Detected at distances of 20 – 30 kpc from cores of giant Es
  - Dispersions and radial velocities flat at large distances

  → M (at $r > 30$ kpc) $\geq 10^{12}\ M_\odot$ in these ellipticals: $M/L \approx 50$

Planetary nebulae on the outskirts of NGC 1399
- [O III] filter and CCD on CTIO 4-m telescope

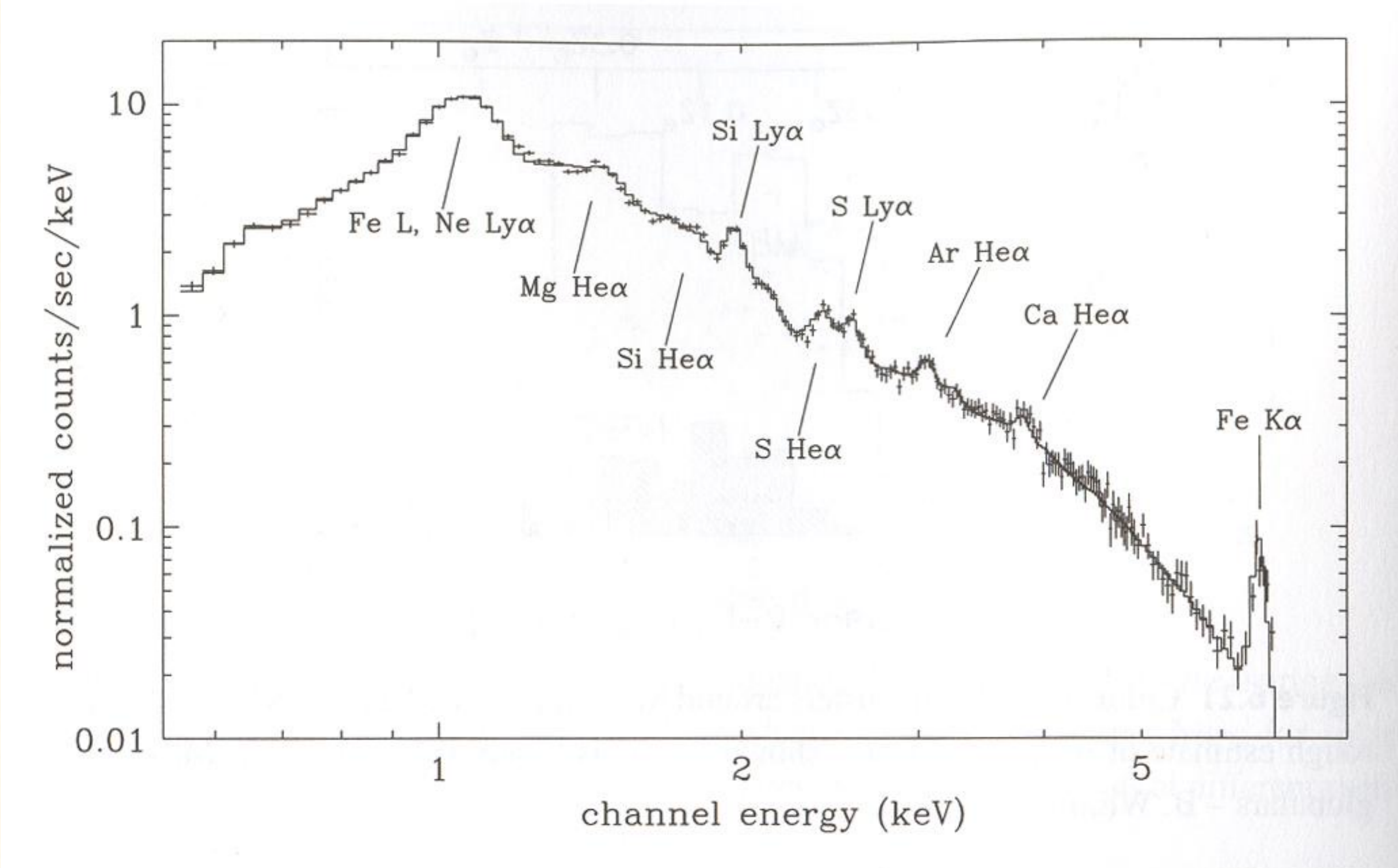
- X-ray missions (Einstein, ROSAT) discovered hot ($T \approx 10^7$ K) gas in nearby giant Es (now studied with Chandra and XMM).
- Gas is almost completely ionized – cooled by bremsstrahlung.

Cooling curve for gas with solar composition and $n_H = 1\ cm^{-3}$



solid – luminosity density, dashed – cooling time

ASCA X-ray Spectrum of Hot Gas around M87

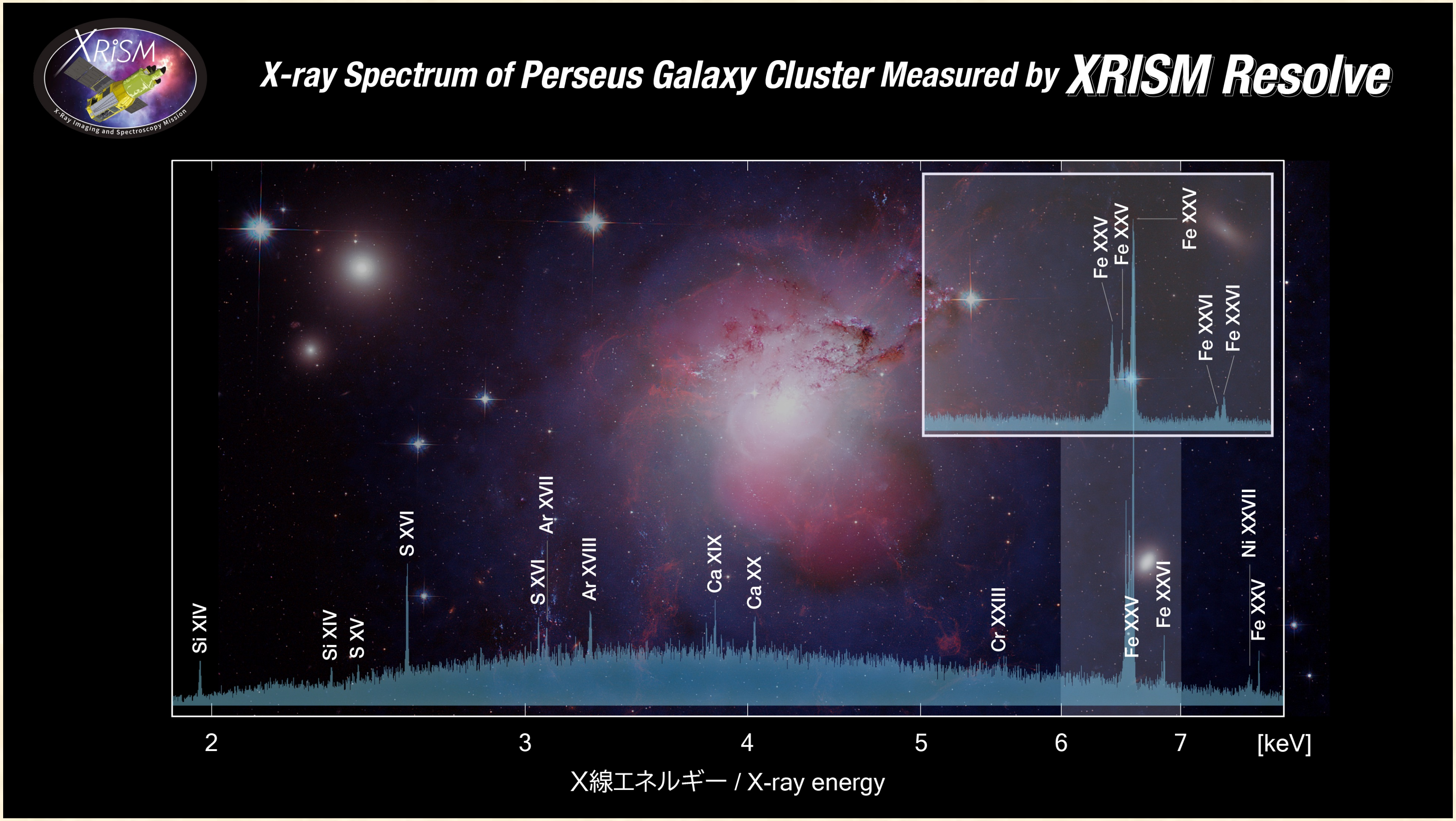


(Sparke & Gallagher, p. 272)

- H and He-like emission lines in addition to bremmstrahlung
- $Z = 0.5\ Z_\odot$ → material ejected by RG and AGB stars

($1 – 2\ M_\odot\ yr^{-1}$ per $10^{10}\ L_\odot$)

Early XRISM Observations



Why is the gas so hot?

- Gas clouds are on random orbits like their progenitor stars
- Collisions between gas clouds:

$$kT = m_p\sigma^2 \;\; \rightarrow T = 6 \text{ x } 10^6 \left(\frac{\sigma}{300 \text{ km s}^{-1}} \right)^2 \text{ K}$$

- The cooling time is: $t_{cool} \approx n_H^{-1}\, T^{1/2}$ at these high temperatures.
- At centers of giant E's, the gas may be dense ($n_H = 0.1$ cm^{-3}) enough to cool in ~ 1 Gyr → new star formation in core
- However, see the cooling flow problem for clusters
- Is the hot gas enough to provide the "missing mass"?

→ no, the mass is only $10^9 - 10^{11} M_\odot$ in giant E's

However, to keep the hot gas confined out to ~50 kpc, M/L $\approx 20 - 50$.

Rich Clusters of Galaxies

- About ½ of all galaxies are in rich clusters (others in "groups")
- Thousands of gravitationally bound galaxies within a few Mpcs
- Typically 50 to 100 galaxies with $L > L^*$ in central Mpc
- Abell (1958, 1989) catalogs: list 4073 rich clusters
- Strongly *differentiated*: core dominated by ellipticals, spirals are scarce and mostly on the outskirts

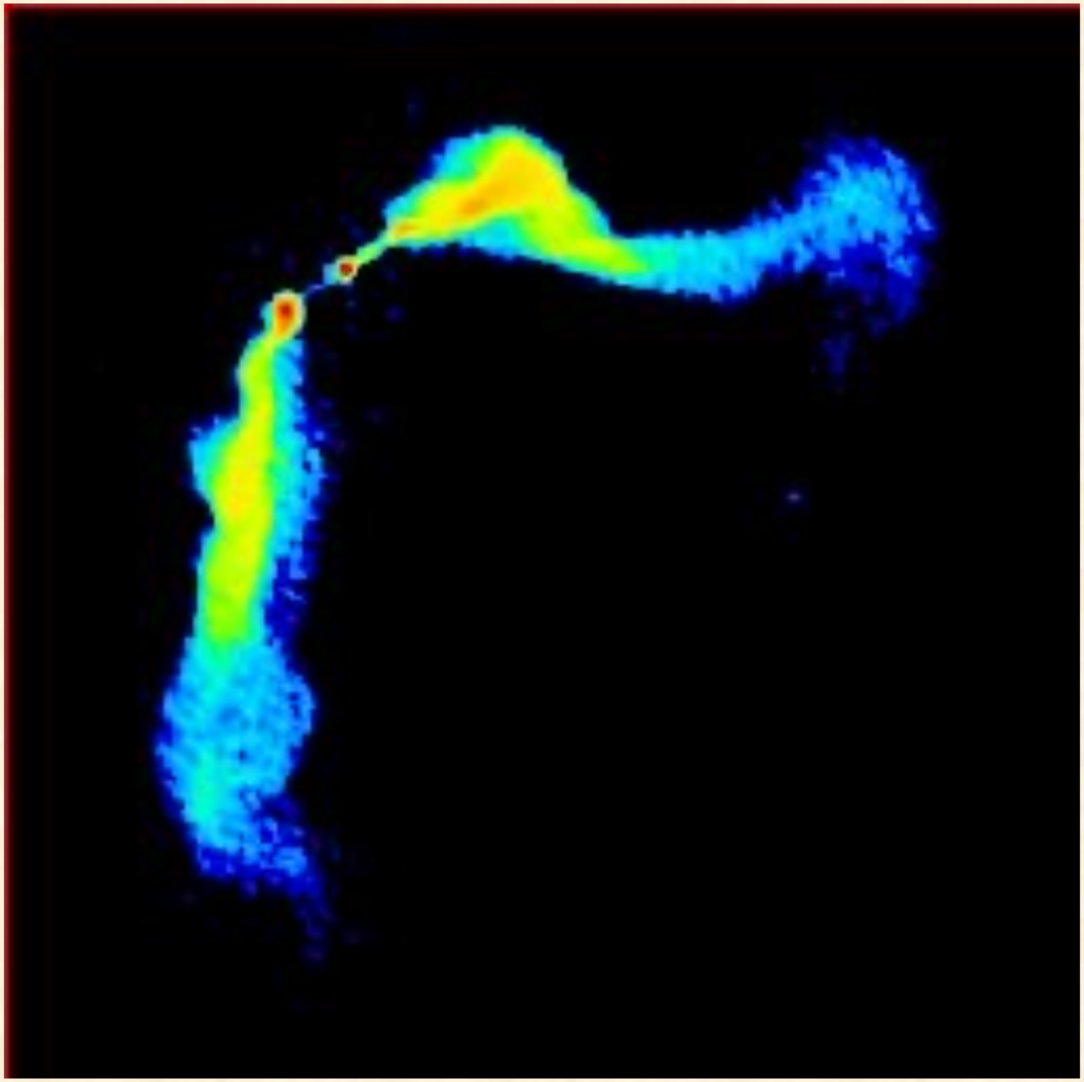
Coma Cluster

Hot Gas in Clusters

- X-ray observations: hot ($T = 3 \times 10^7$ to 10^8 K) intracluster gas
  - 3 to 6 times the stellar mass!
  - must come from intergalactic medium (IGM).

  → ongoing collapse of large-scale structure on these scales
- $Z \approx 1/3\ Z_\odot$ → enrichment of early IGM plus cluster SN
- Gas in core is dense enough to cool in Hubble time
  → *cooling flows*
- However, cooling flows are rarely observed → gas likely heated by AGN feedback.
- Ram pressure as galaxies move through cluster gas
  - Strips neutral gas in spirals, hot gas in E's; pushes back radio lobes
- Large mass needed to confine hot gas in clusters:
  $M/L \approx 200$ to 300

3C 465 in Abell 2634

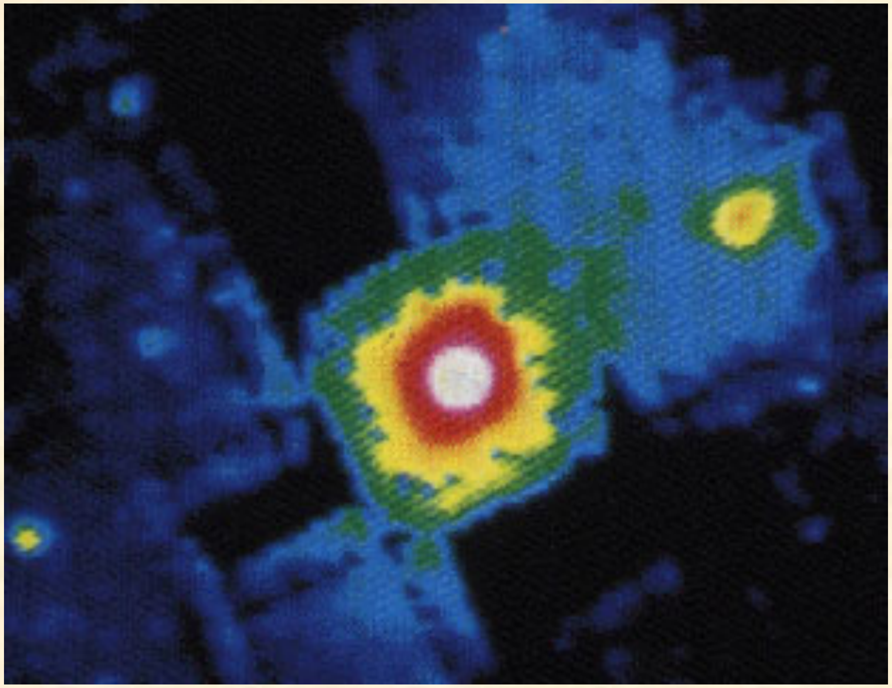


VLA 4.9 GHz image

Virgo Cluster

- Nearest rich cluster at ~ 16 Mpc
- Home of cD galaxy (and AGN) M87 in core
- Central luminosity density ~ 3 x 10^{11} $L_{\odot}$ Mpc^{-3}
- Relatively loose and irregular in shape
- Kinematics: infalling galaxies at edges – still growing

Chandra X-ray Image

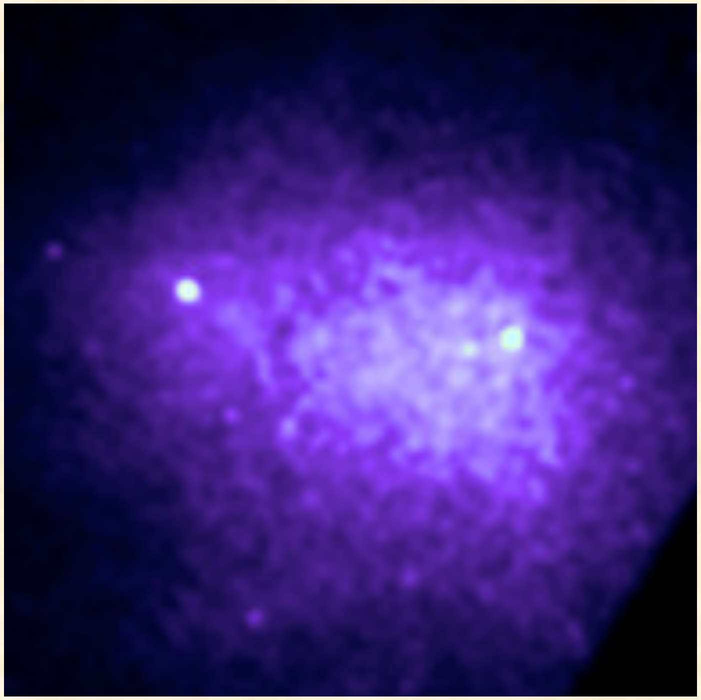


HST Visible Image

Coma Cluster

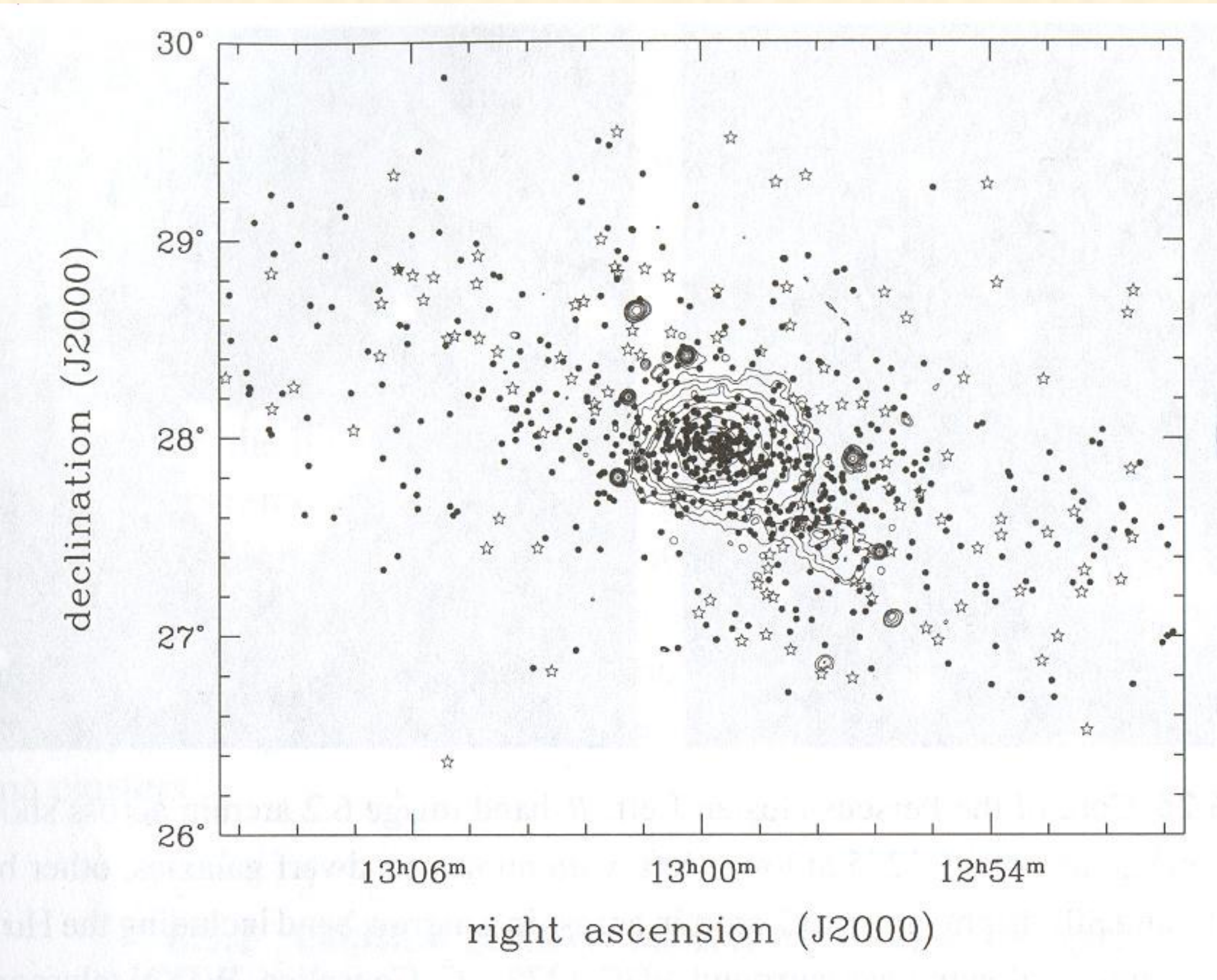
- Distance ≈ 70 h^{-1} Mpc
- 3 – 4 times more luminous than Virgo
- Core is dominated by a pair of giant E' s
- Much more spherical than Virgo

X-ray



Visible

Distribution of Galaxies in Coma Cluster



Solid dots – Ellipticals
Open stars – Spirals
Contours – Hot gas

(Sparke & Gallagher, p. 295)

Masses of Clusters from Galaxy Velocities

- Virial Theorem – assumes clusters are bound:

$$2\ \text{K.E.} = -\ \text{P.E.}$$

$$\tfrac{3}{2} M\sigma_r^2 = \frac{GM^2}{2r_c} \quad \text{(for spherical cluster)}$$

where $\sigma_r^2 = \langle v_r^2 \rangle$, r_c = core radius (Sparke & Gallagher, p. 105)

$$M = \frac{3\sigma_r^2 r_c}{G}$$

- For the Coma cluster: $r_c = 200$ kpc, $\sigma_r = 1000$ km s^{-1}
  → $M \approx 10^{15} M_\odot$, $M/L = 200\ M_\odot/L_\odot$ inside the core radius
  (note the extent of the Coma cluster is ~10 Mpc)

Gravitational Lensing (Abell 2218 Cluster)

- Gravitational lensing of distant galaxies: Cluster M/L ~200

- For galaxy core→galaxy halo→ Local Group→rich cluster:
- M/L increases: 5 → 10 → 50 → 200
- Slow drop in density from cluster cores ($\rho \sim r^{-1}$)

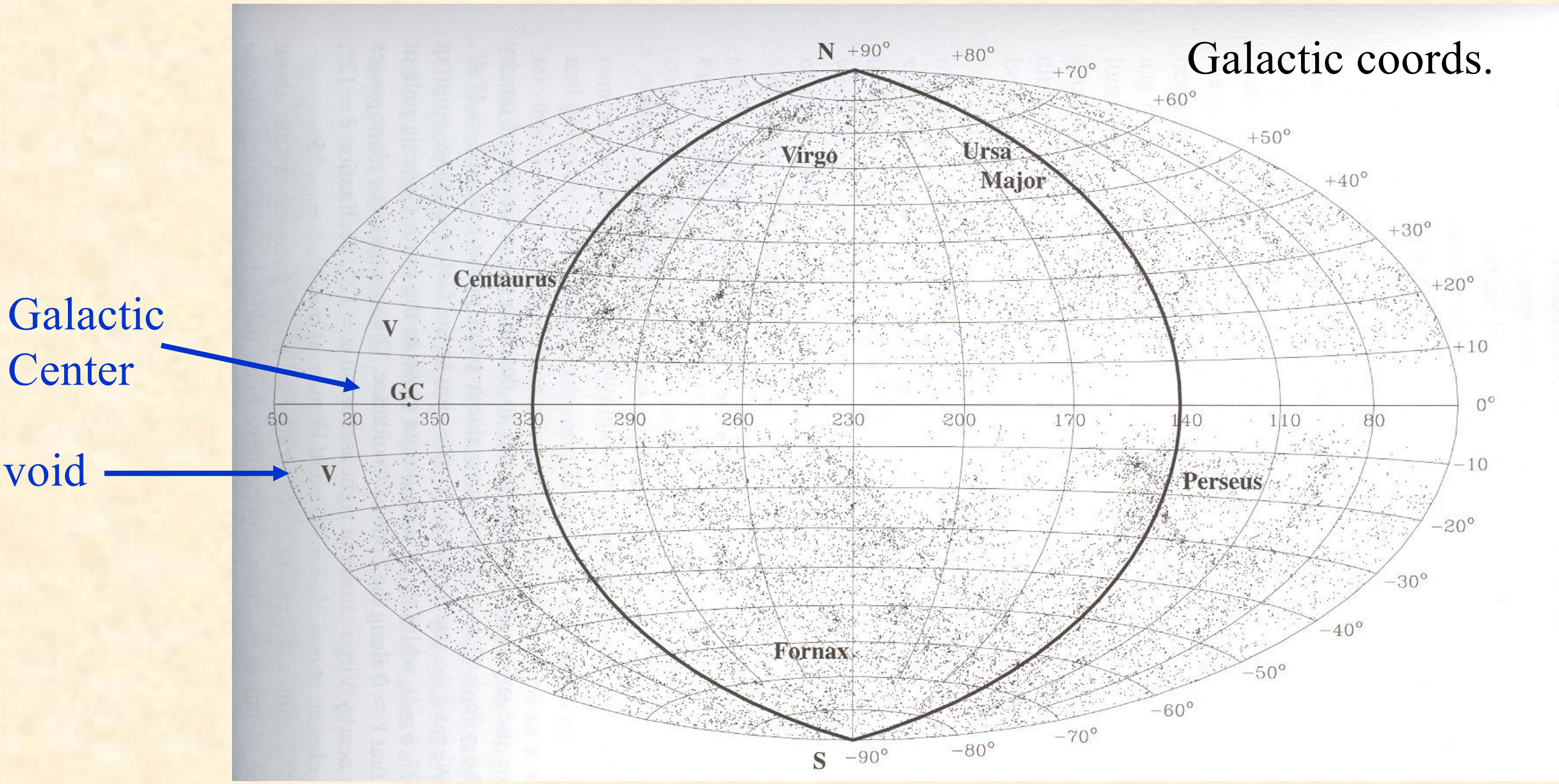
Large-Scale Distribution of Galaxies

- In the past, clusters were thought to be in superclusters
- Redshift surveys over the past decade:
  → galaxies arranged like connecting bubbles (or a sponge)
  - Clusters and superclusters are at the edges of 2 or more intersecting bubbles
- "Voids" are on the order of ~50 Mpc across
- How concentrated are the galaxies into filaments/walls?
  - Core of Virgo Cluster: $L = 3 \times 10^{11}\ L_\odot\ \mathrm{Mpc}^{-3}$
  - Average (Schechter lum. fct.): $L \approx 1.4 \times 10^{8}\ L_\odot\ \mathrm{Mpc}^{-3}$ (averaged over large volume, including voids)

  → Variation in galaxy density spans a factor of >1000
- Galaxy velocities: most clusters are still collapsing at edges

  Ex) Galaxy at edge of Coma cluster (3 Mpc): $v \approx 1000\ \mathrm{km\ s}^{-1}$
  Crossing time = 3 Gyrs! → Clusters are still coming together

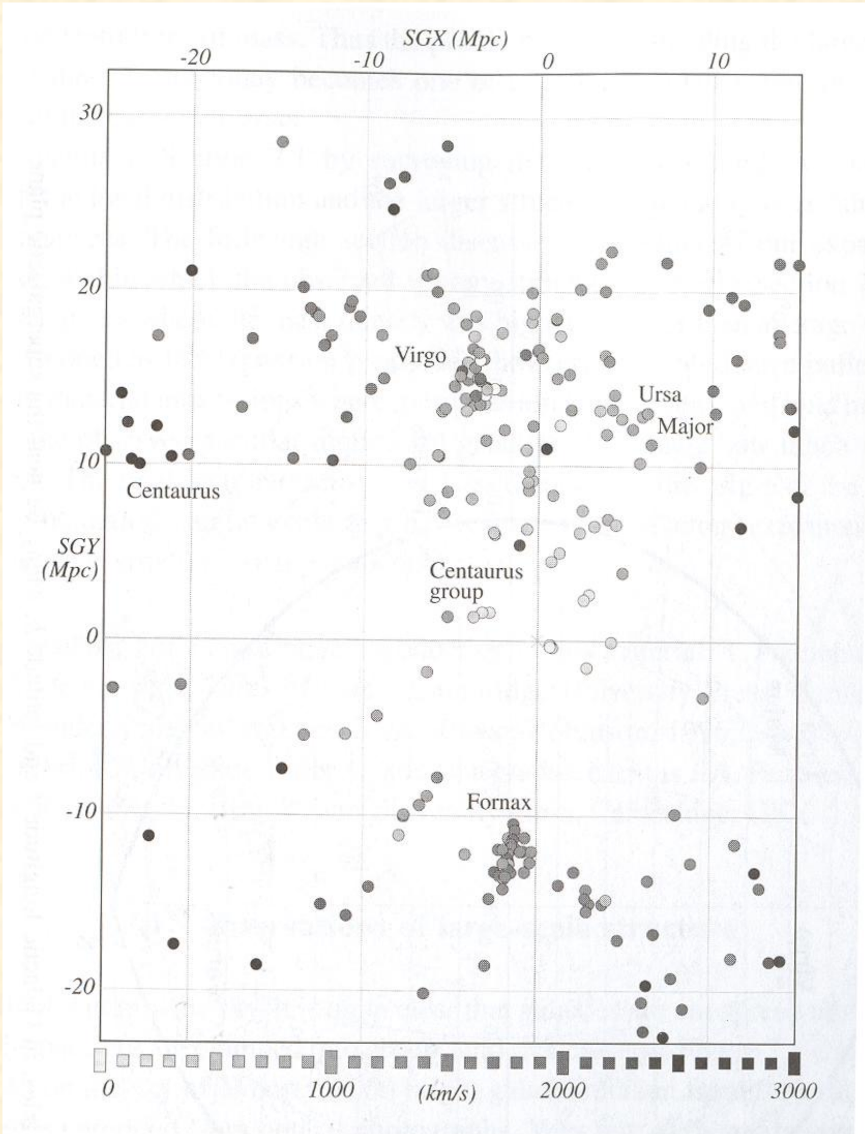
Positions of Bright Galaxies - Supergalactic Coordinates



(Sparke & Gallagher, p. 315)

- Clusters and many nearby galaxies lie close to a great circle at l = 140°, 320°
  → defines local (Virgo) supercluster and "supergalactic plane" (X,Y)
- Z axis (l = 47.4°, b = 6.3°); X (l = 137.3°, b =0°) → Y near NGP
- Supergalactic latitude = 0 in X-Y plane, longitude = 0 in X direction

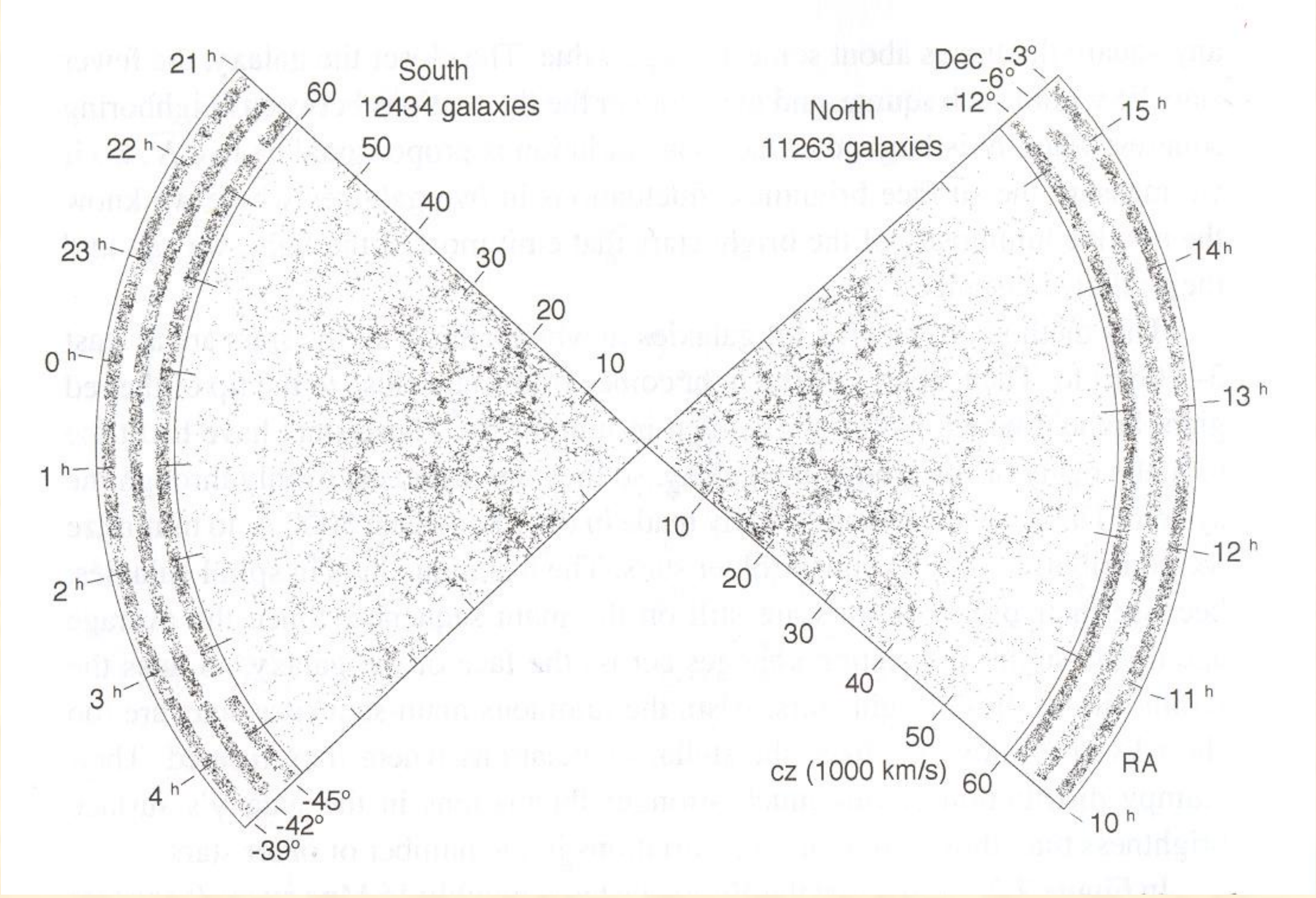
Projected Distances of Nearby Ellipticals on the Supergalactic Plane (X, Y)



clusters are not very concentrated:
→ still coming together

(Sparke & Gallagher, p. 317)

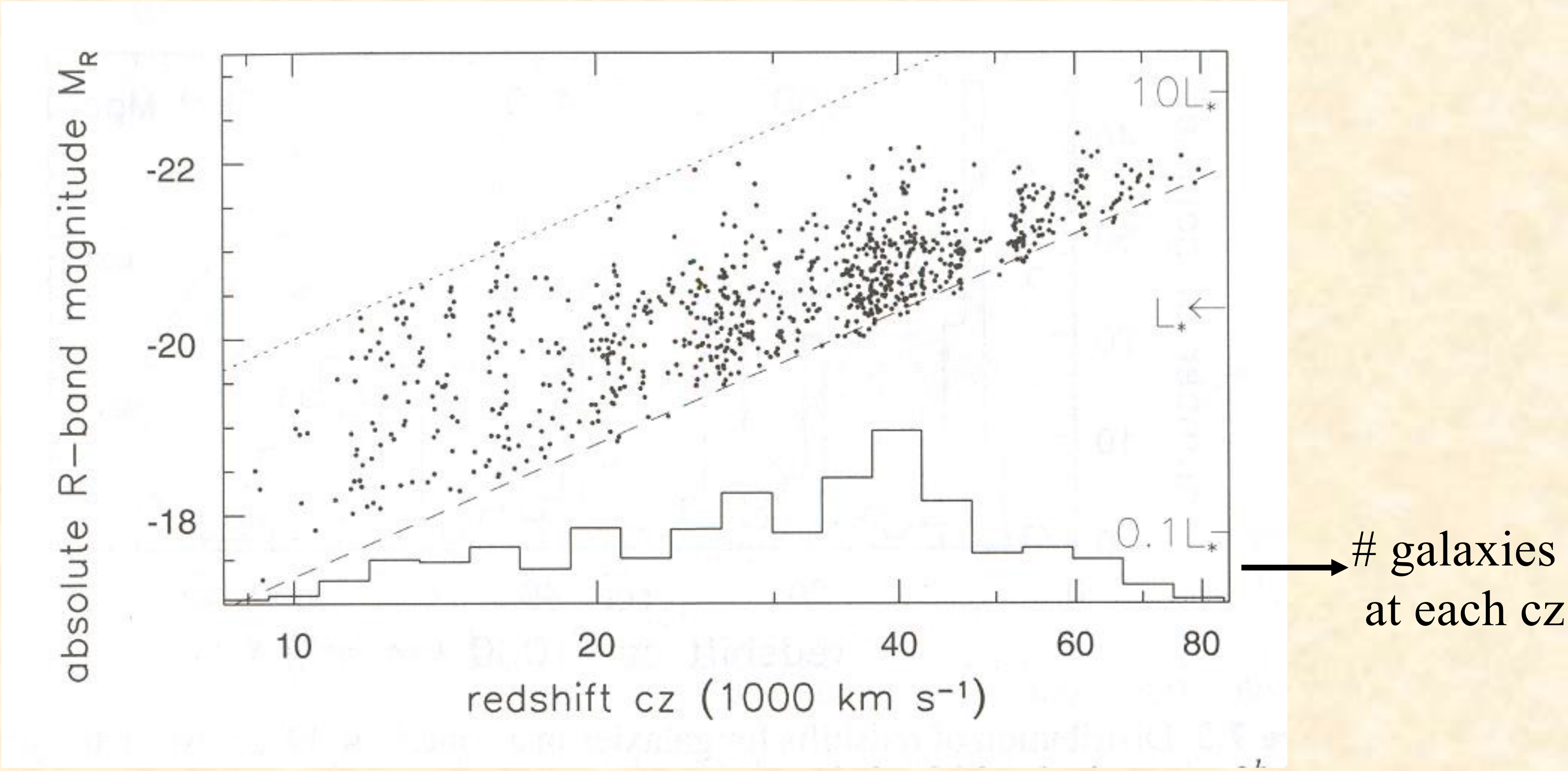
Redshift Surveys - Las Campanas



(Sparke & Gallagher 1st ed., p. 286)

- Use cz as distance indicator (approximately ~ distance at low z)
- Las Campanas survey covered 6 strips, each 1.5° wide
- number of galaxies decrease at large velocities → magnitude limit
- number of galaxies small at low velocities → small volume sampled

Luminosity Distribution for Las Campanas Survey

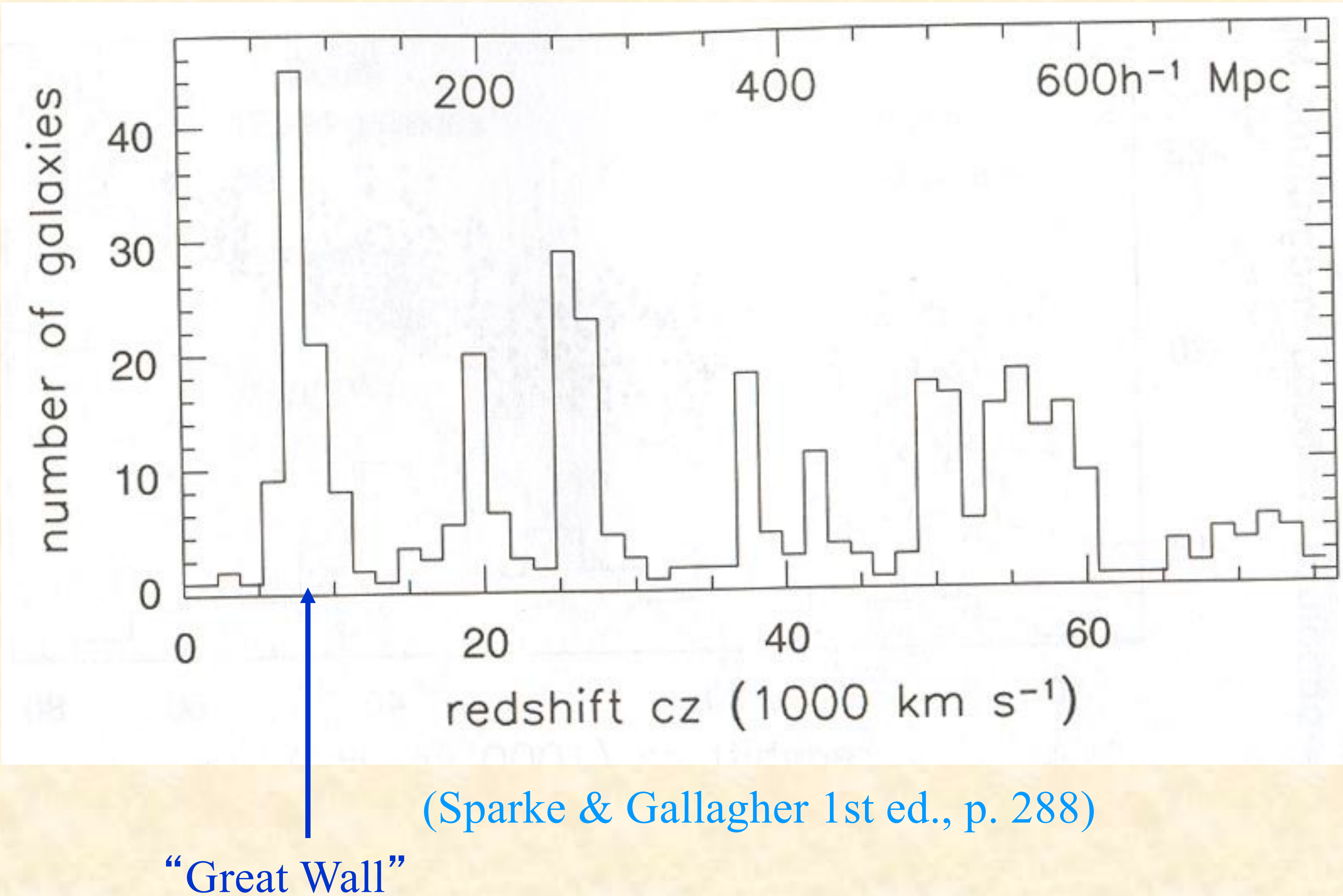


(Sparke & Gallagher 1st ed., p. 287)

Dashed line – faint magnitude limit = 17.7

Dotted line – bright magnitude limit = 15.0

Distribution of galaxies at NGP



(Sparke & Gallagher 1st ed., p. 288)

- The sharpness of the peak is exaggerated: extra mass in the wall pulls galaxies on either side toward it.

→ Peculiar velocities conspire so that cz is close to that of the Wall

Measures of Galaxy Clustering

Two-point Correlation Function (ξ):

Given an average spatial density of galaxies n $\left(\#/\mathrm{Mpc}^3\right)$

Probability of finding a galaxy in a volume ΔV_1 is $\propto n\Delta V_1$

Joint probability of finding 2 galaxies in the 2 volumes $\Delta V_1,\ \Delta V_2$:

$$\Delta P = n^2\left[1+\xi(r_{12})\right]\Delta V_1 \Delta V_2$$

If $\xi(r) > 0 \ \rightarrow$ galaxies are clustered

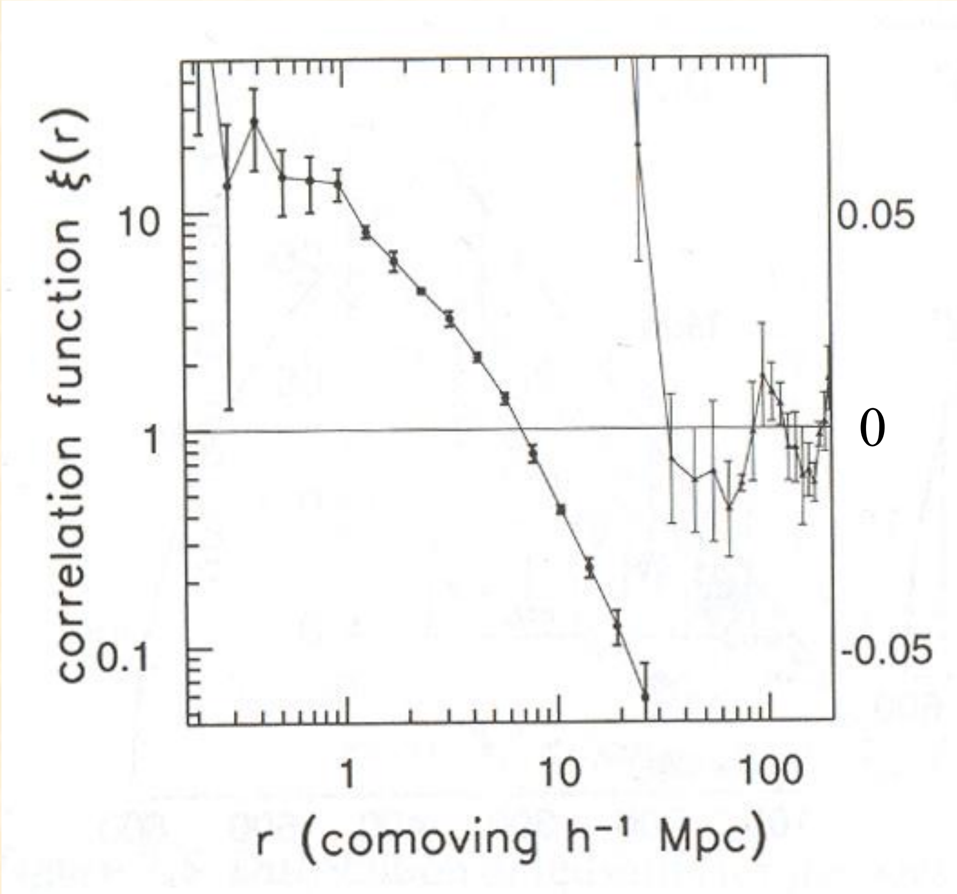
Typically, described as a power law (what else?):

$$\xi(r) = \left(r/r_0\right)^{-\gamma} \quad r_0 = \text{correlation length}$$

Can also use the Fourier transform of $\xi(r) \rightarrow$ power spectrum:

$$P(k) = 4\pi \int_0^\infty \xi(r) \frac{\sin(kr)}{kr}\, r^2 dr$$

Two-Point Correlation Function
(Las Campanas Survey)

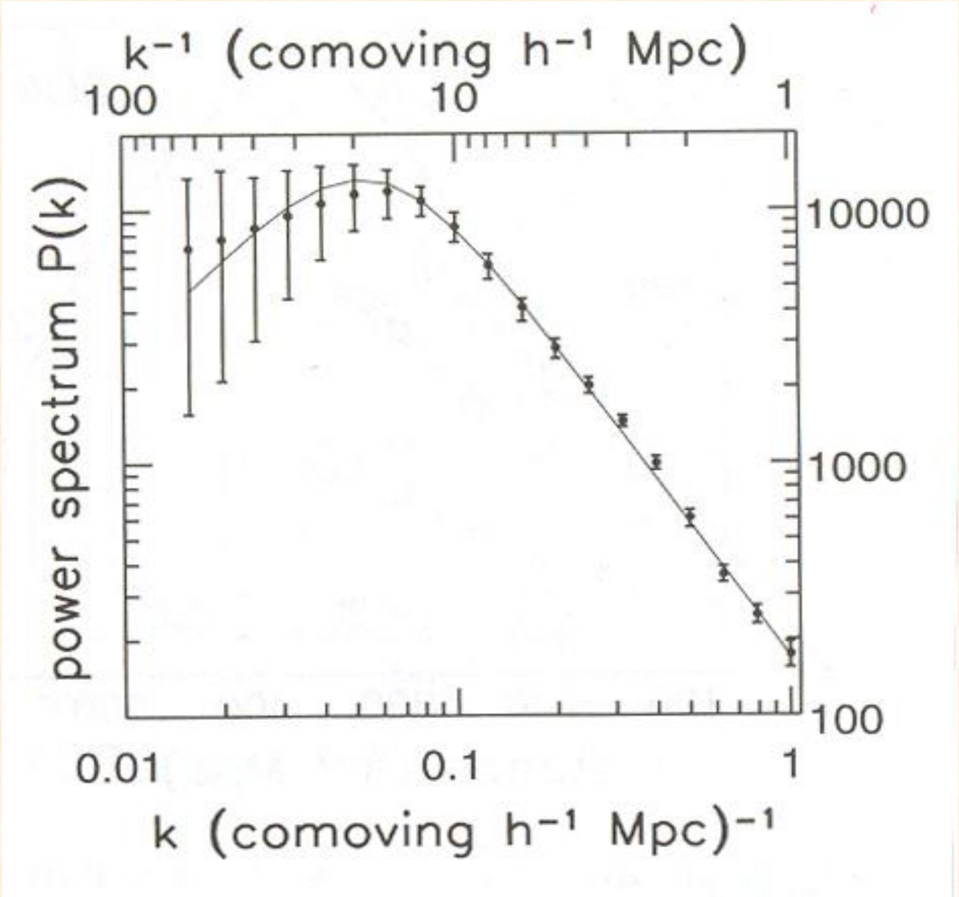


(Sparke & Gallagher 1st ed., p. 290)

$\rightarrow r_0 = 5h^{-1}\mathrm{Mpc},\ \gamma = 1.8$

Strong clustering ($\xi > 1$) at r < 20 Mpc

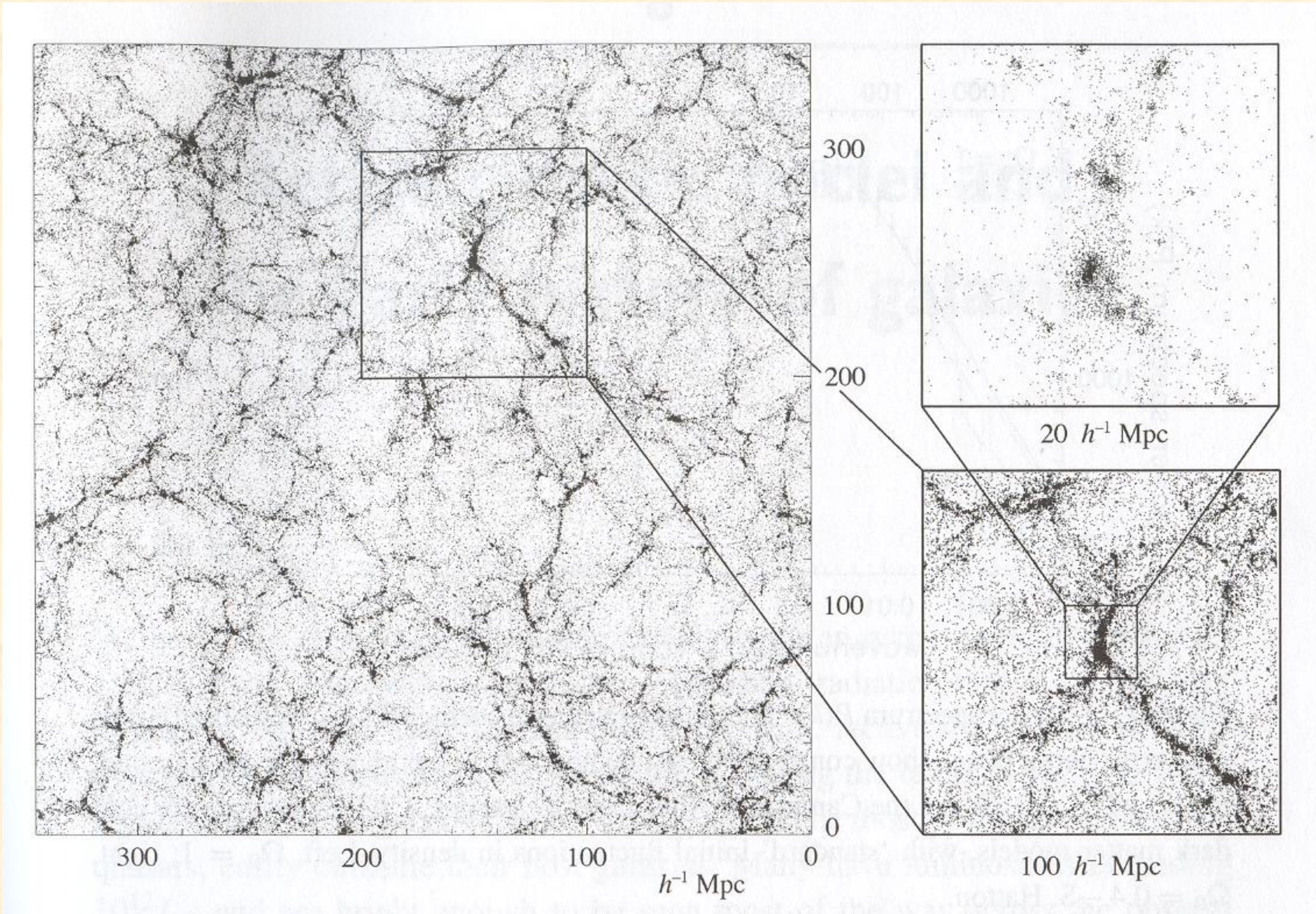
Power Spectrum (Las Campanas)



(Sparke & Gallagher 1st ed., p. 290)

- peak at ~20 h-1 Mpc
- useful for comparison with structure-formation models

CDM Model (matches COBE power spectrum)

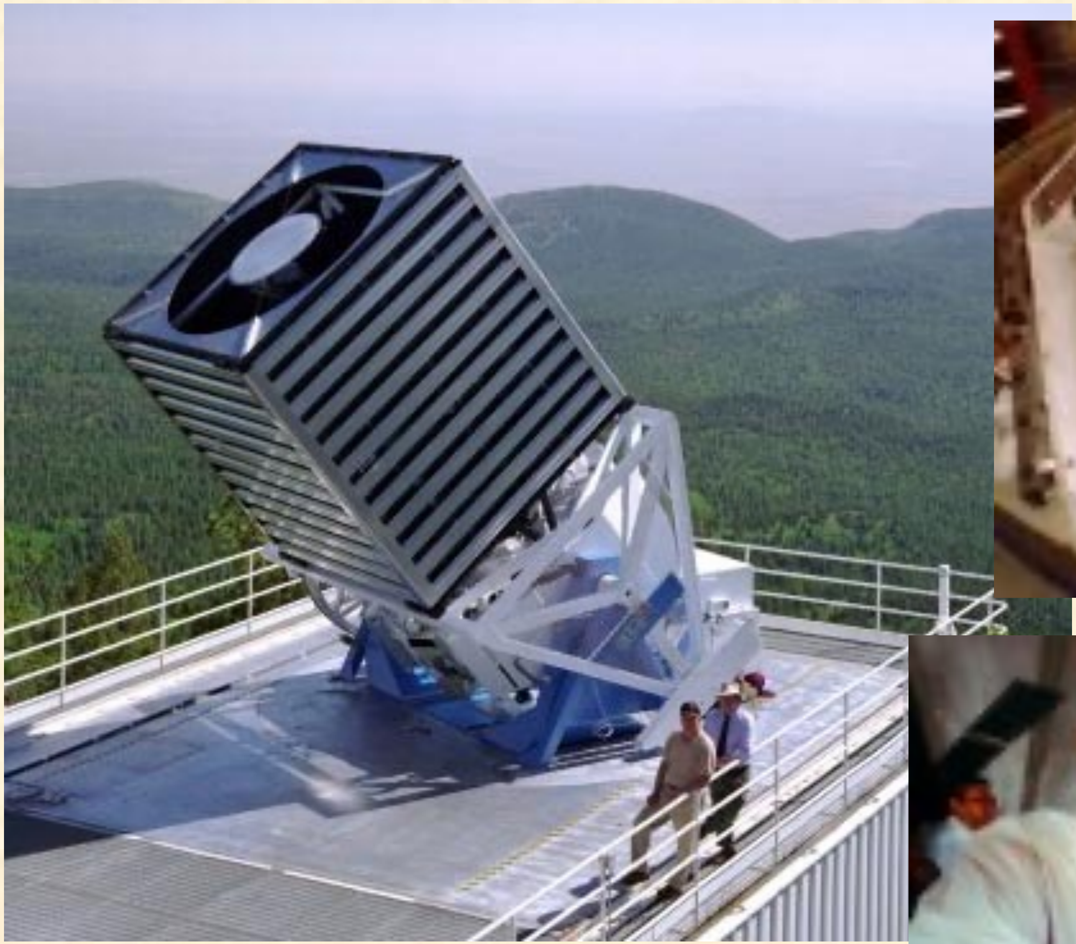


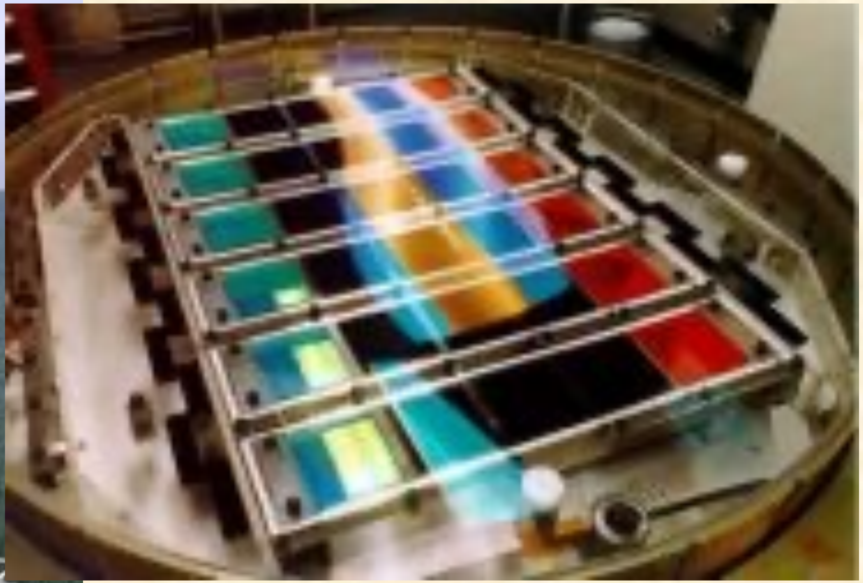
(Sparke & Gallagher, 1st ed. p. 311)

Redshift Surveys

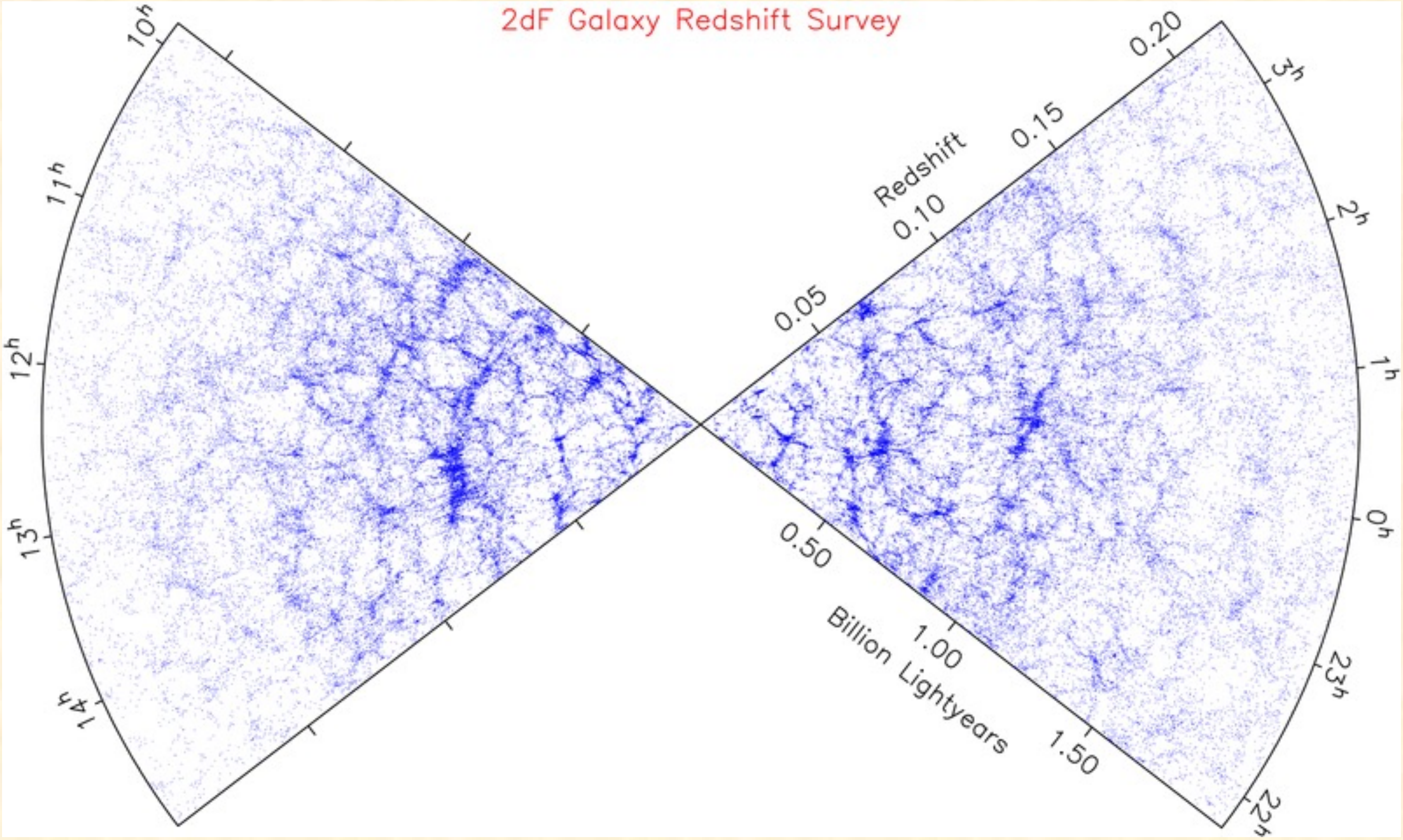
- Sloan Digital Sky Survey (http://www.sdss.org/)
  - Positions and brightnesses for 10^8 objects
  - Colors and redshifts for 10^6 galaxies, 10^5 quasars
  - Survey covers ¼ of the sky
  - 2.5-m telescope at Apache Point, NM
  - Companion 0.5-m monitors the seeing and transparency
  - 30 CCDs, 5 filters to scan the sky
  - Galaxies and quasars isolated on color-color diagrams
  - Follow-up multi-object spectroscopy at R ~ 1000
- 2DF Survey (http://www.mso.anu.edu.au/2dFGRS/)
  - Spectra of ~250,000 galaxies near the galactic poles
  - Multi-object spectrograph with the AAT (4-m)
  - Final data release in June, 2003

SDSS

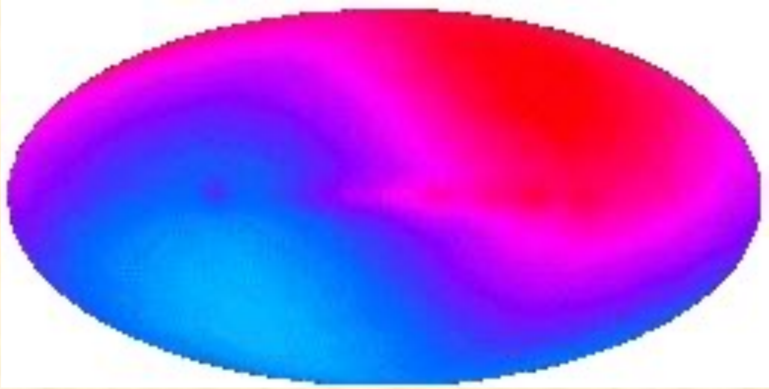




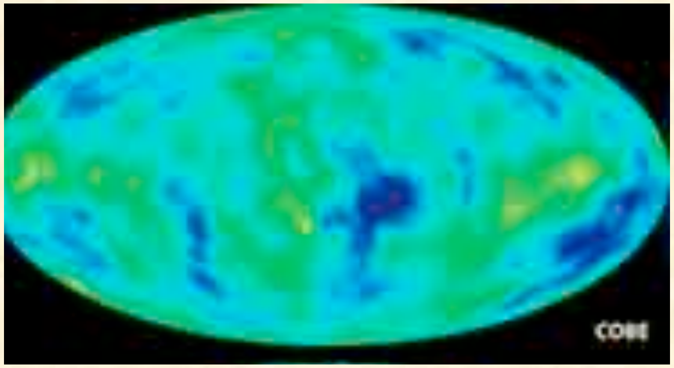
2dF "Wedge"


2dF Galaxy Redshift Survey
10h
11h
12h
13h
14h
3h
2h
1h
0h
23h
22h
Redshift
0.05
0.10
0.15
0.20
Billion Lightyears
0.50
1.00
1.50

COBE

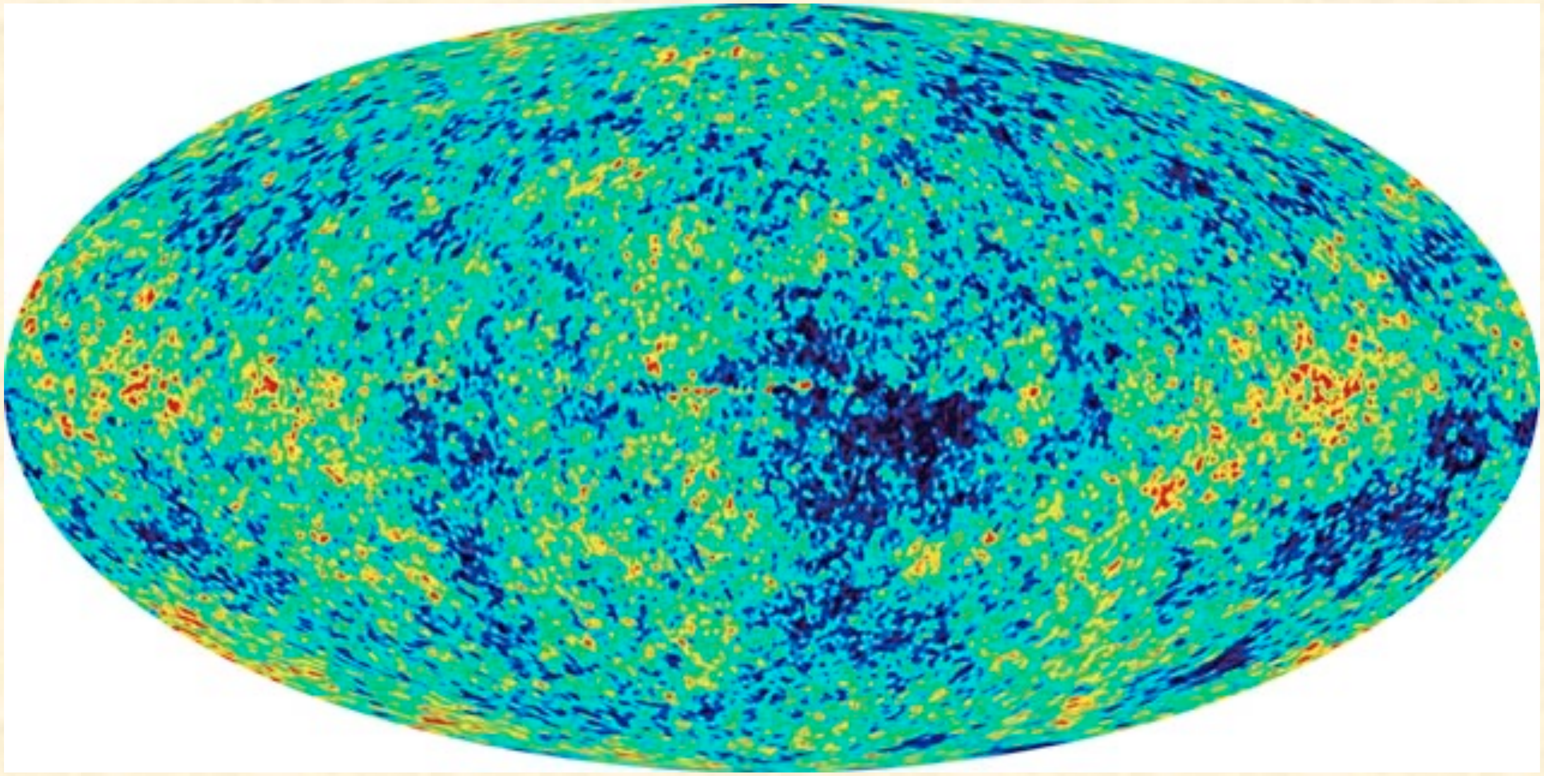


- Cosmic Microwave Background (CMB) Explorer, resolution ~7º
- "Absolute" motion of galaxy relative to CMB: strong dipole radiation ($v = 371$ km s^{-1} towards $l = 264º$, $b = +48º$)
- Due to Local Group, Virgo Infall, and "Great Attractor" (Centaurus supercluster) and Shapley supercluster motions (Mould et al. 2000, ApJ, 529, 786)



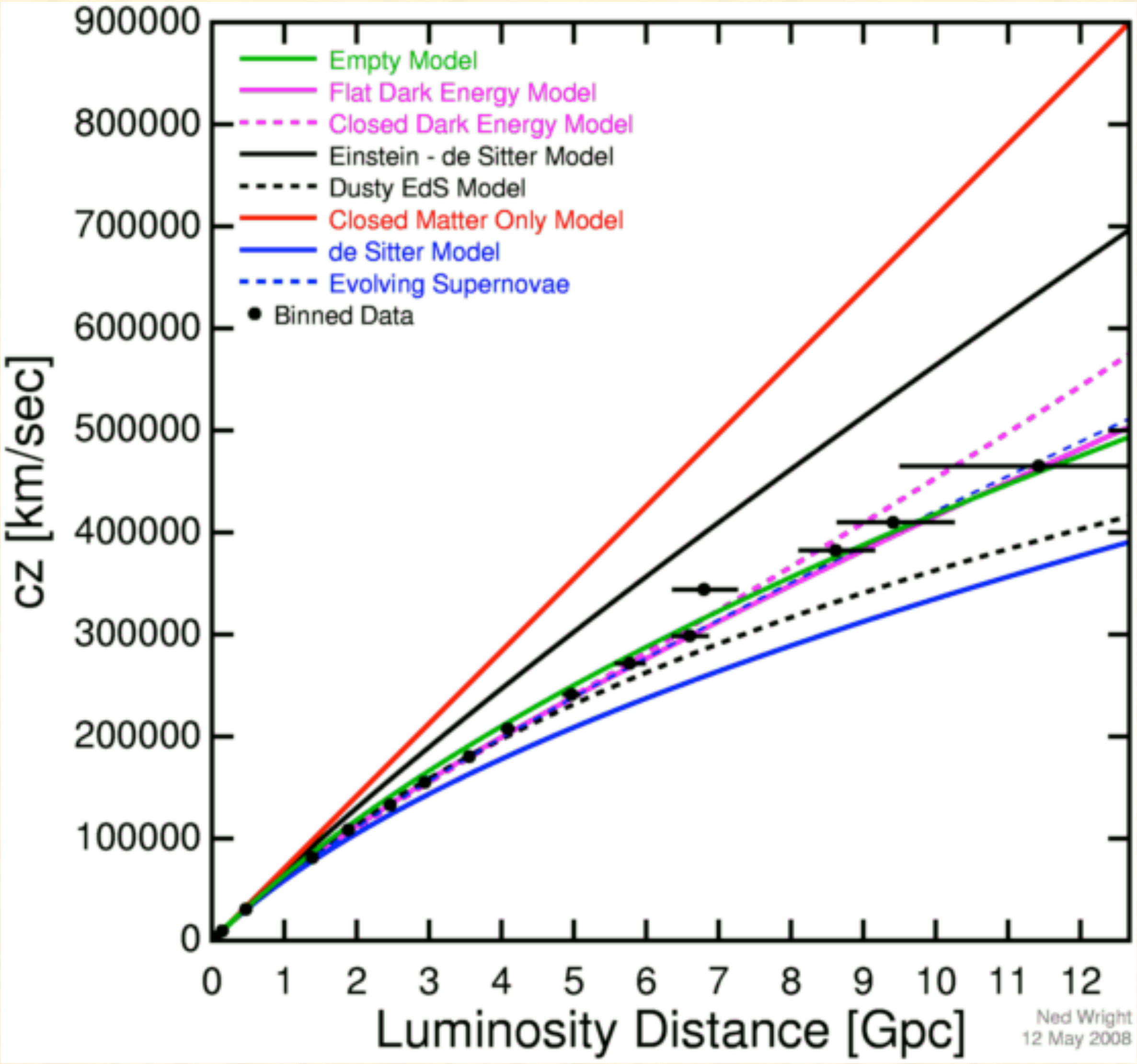
- after subraction of dipole : unresolved Temperature variations

WMAP



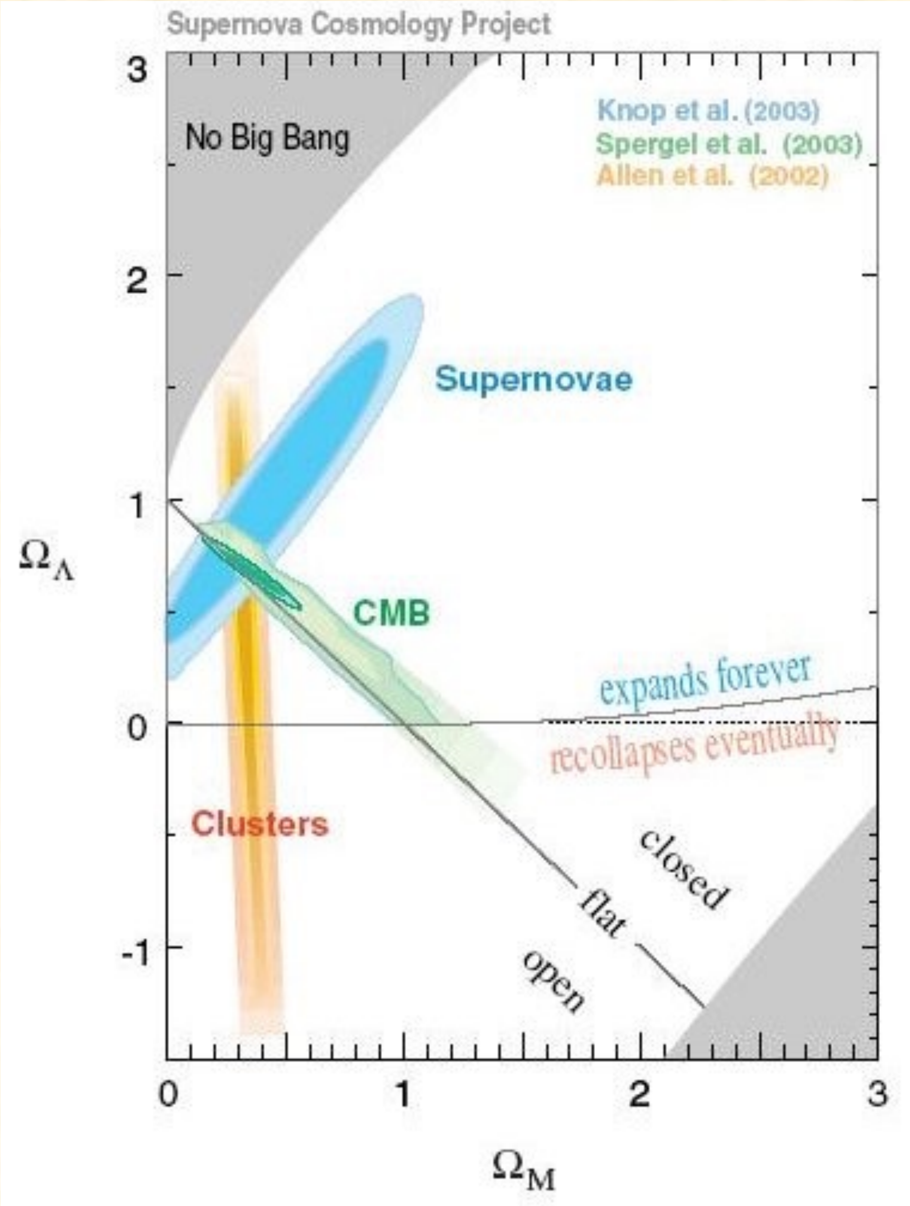
-Wilkinson Microwave Anisotropy Probe, resolution ~ 0.3º
- temperature variations of CMB: 2.73 K average, amplitude ~ 2 mK
- tiny variations in structure after Big Bang led to current large-scale structure
- agrees with inflationary theory and cold dark matter models

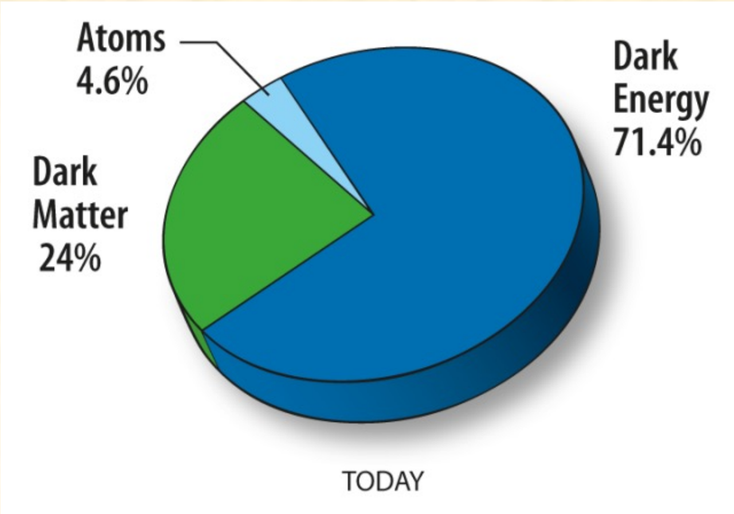
Accelerating Universe from Type Ia Supernovae

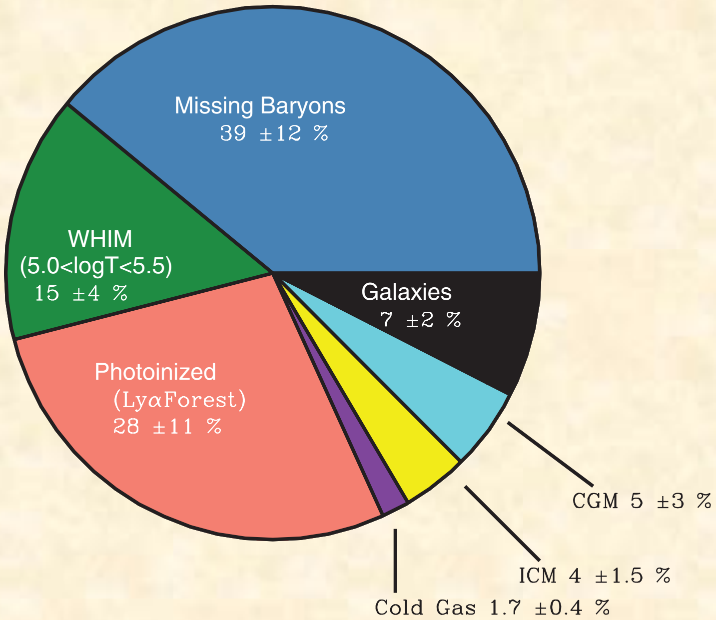


http://www.astro.ucla.edu/~wright/sne_cosmology.html

Constraints on Accelerating Universe

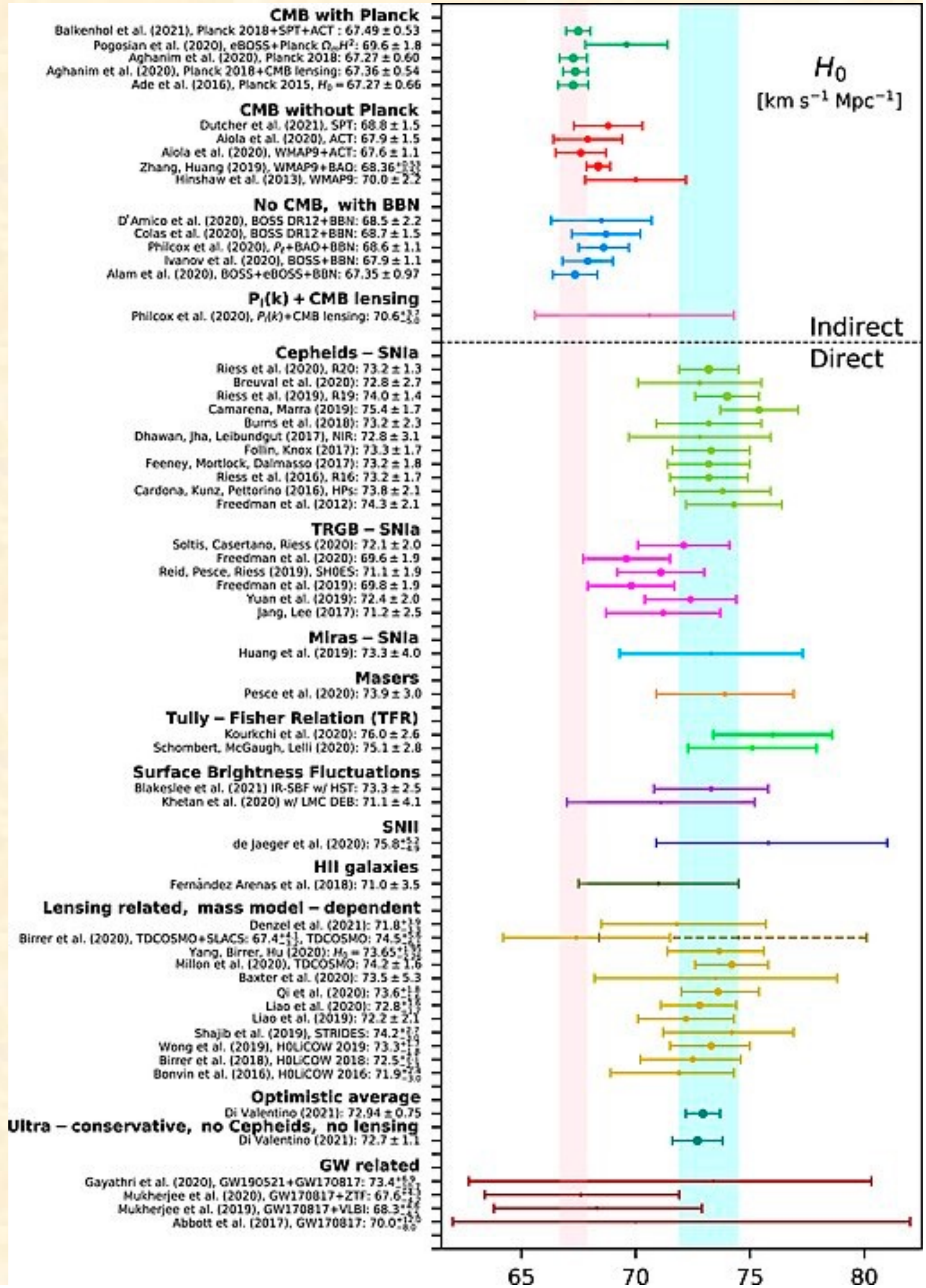






Hubble Tension
(Typical Values)

- HST (Cepheids, SNIa)
  $H_0 = 73.5 \pm 1.1$ km s^{-1} Mpc^{-1}
- CMB (Planck, λCDM)
  68.3 ± 1.5 km s^{-1} Mpc^{-1}



(Di Valentino+ 2021, CQG, 38, 153001)