Dark Matter: Observational Constraints

Does Dark Matter Exist?

Leo Blitz
UC Berkeley

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Questions I'll be addressing

- Does dark matter exist?
- Where do we know it does not exist?
- How much dark matter is there?
- What are its properties?
- Is there more than one kind of dark matter?
- What is it composed of?
- Are there alternatives to dark matter?

The First Dark Matter

Prediction of non-luminous matter from gravity alone

The First Dark Matter

Prediction of non-luminous matter from gravity alone

- Sirius and Procyon
    - Bessel (1844)
  - Detection of Sirius B
    - Clark (1862)
- Anomalous Orbit Perturbation of Uranus
    - Adams (1845)
    - Leverrier (1846)
  - Detection of Neptune
    - Galle (1846)

Does Dark Matter Exist?

- Since Dark Matter is by definition, dark, its observational constraints are generally of a dynamical nature. What this means is that there are only two equations of importance:

$$M = \alpha R V^2 / G \text{ (virial theorem)}$$

$$\frac{dP}{dr} = -\frac{GM\rho}{r^2} \text{ (hydro equlibrium)}$$

$\alpha \sim 1$ depending on the shape of the potential. In general, look for systems where M(obs) << RV^2/G, and then make sure we have all of the M.

Except on the largest scales (lensing, CMB)

Mass-to-Light Ratios

- M in solar masses ($M_\odot$)
- L in solar luminosities ($L_\odot$)
- M/L of stars in solar vicinity is 0.67 $M_\odot/L_\odot$
  - But need to include gas (atomic, molecular, ionized), dust (negligible), dead stellar remnants (white dwarfs, neutron stars, stellar black holes), very low mass stars (brown dwarfs)
- Typical value for a galactic disk is ~ 3 $M_\odot/L_\odot$ (see Oort Limit)
- Can have a value up to ~5 $M_\odot/L_\odot$ in old stellar systems
- Value also depends on wavelength

Does Dark Matter Exist?

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  - Oort (1932)
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- Stability of Cold Disks
  - Ostriker & Peebles (1973)

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Other Methods

- Weak Lensing (not discussed)
- Strong Lensing (MACHOS)
- Binary Galaxies (not discussed)

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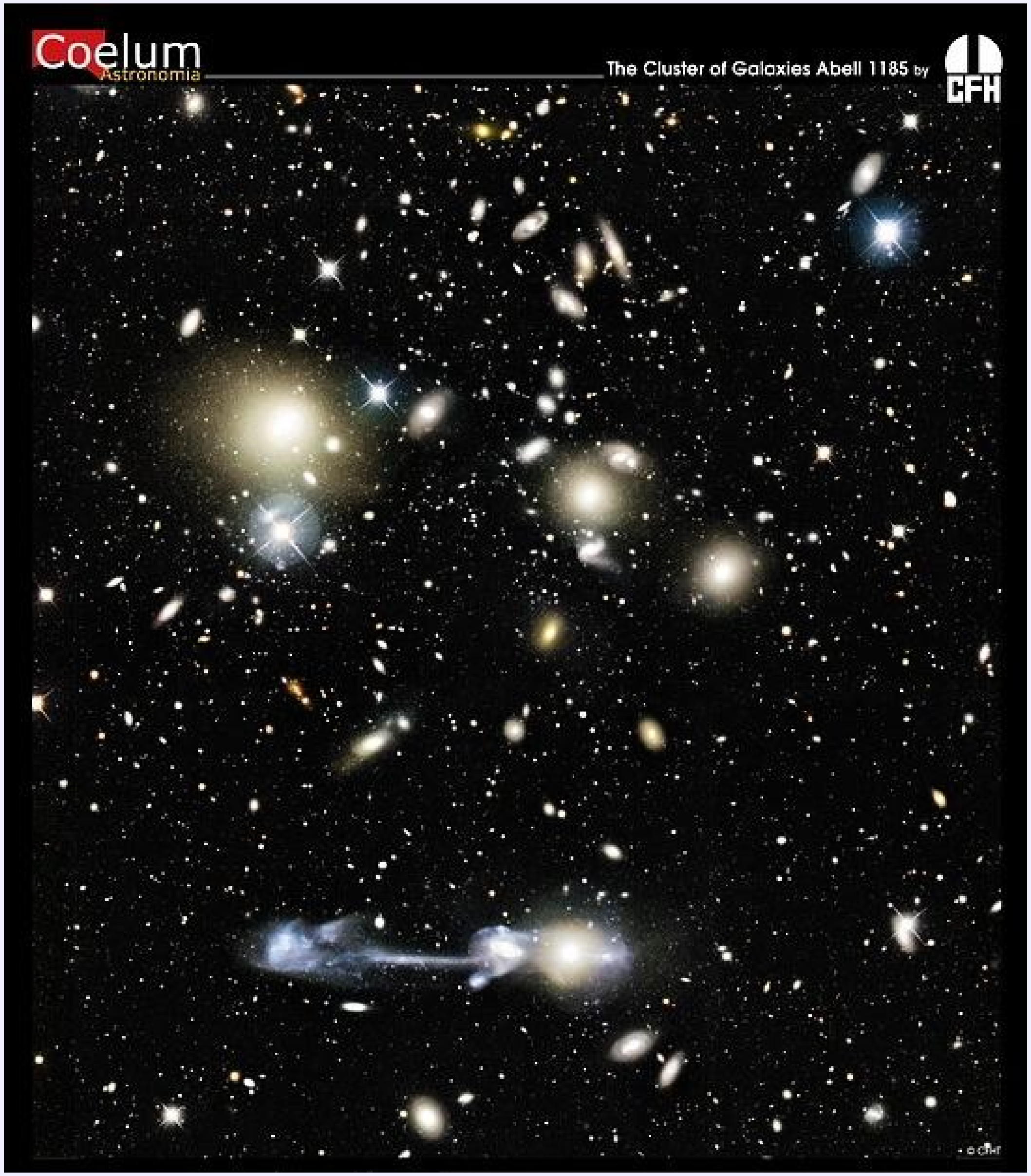
Galaxy Clusters



Does Dark Matter Exist?

- Velocity Dispersion of Galaxies in Clusters (Virial Theorem)
  - Zwicky (1933, 1937)
    - Argued that virial theorem was the most accurate way to determine the mass of relaxed galaxy clusters (Coma). $2T + V = 0$
    - Argued that traditional methods of getting nebular (galaxy) was highly biased and inaccurate (photometry, rotation).
    - Showed that for Coma cluster, virial mass ~ 400 x mass inferred from photometry (based on local calibration), therefore, there must be much non-luminous matter in galaxies.

Coma Cluster

M/L ~ 300

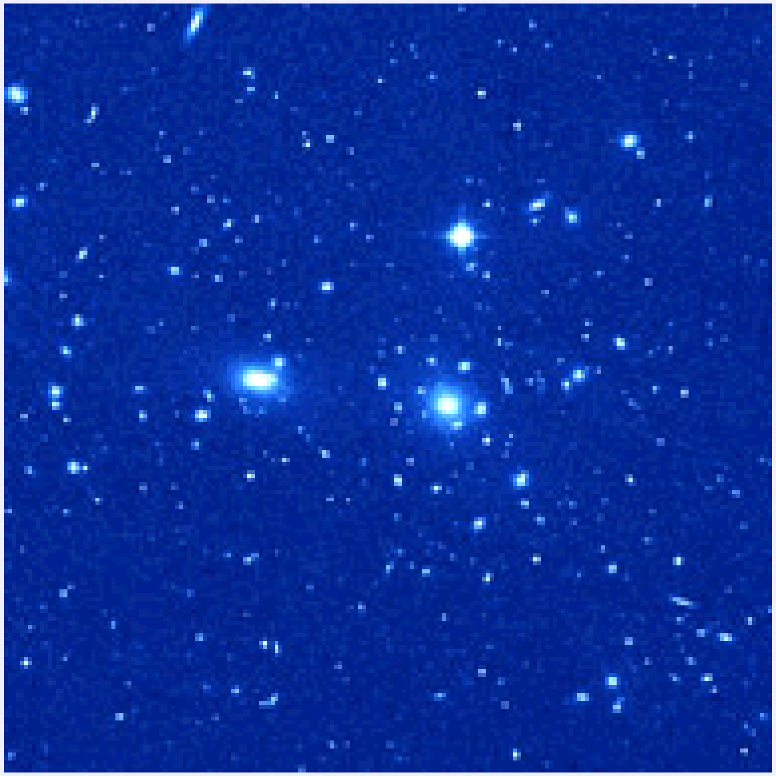
Total Mass = $1.6 \times 10^{15} M_\odot$ (Geller et al. 1999)

Total mass of galaxies ~ $7 \times 10^{13} M_\odot$

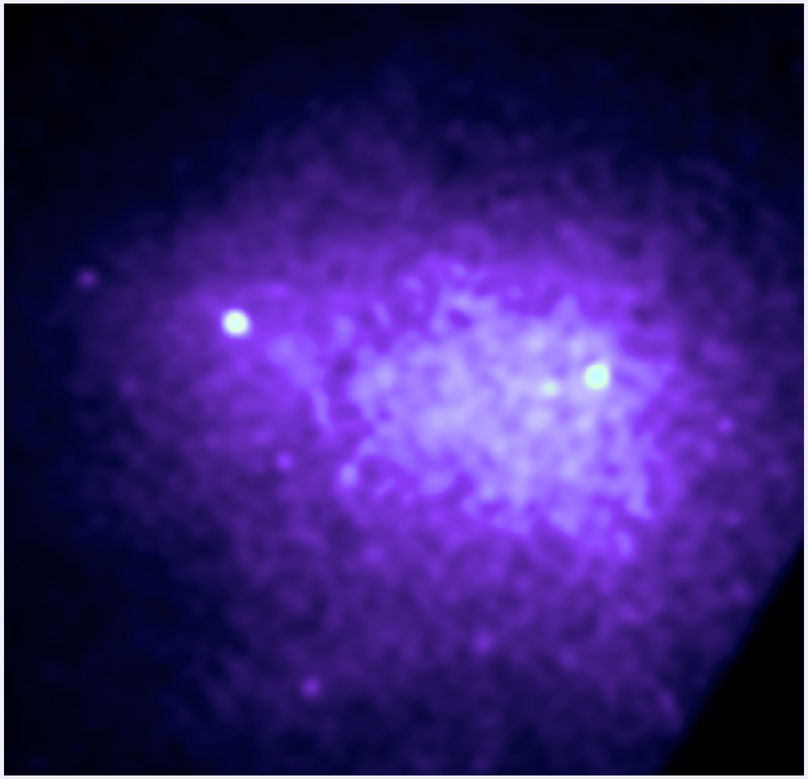
Does Dark Matter Exist?

- Velocity Dispersion of Galaxies in Clusters (Virial Theorem)
  - Zwicky (1933, 1937)
    - Used term “dark matter” perhaps for first time
    - Suggested using gravitational lensing to measure galaxy masses
    - Suggested using virial theorem to measure masses of galaxy clusters
    - But looking at the historical record, suggests that Zwicky may have made incorrect inferences about his measurements.
  - Faber & Gallagher (1979)
    - M/L in clusters of galaxies ~ 80 - 400
    - But some of this mass is in hot, x-ray emitting, and microwave absorbing gas.

Coma Cluster



Galaxies (visible)



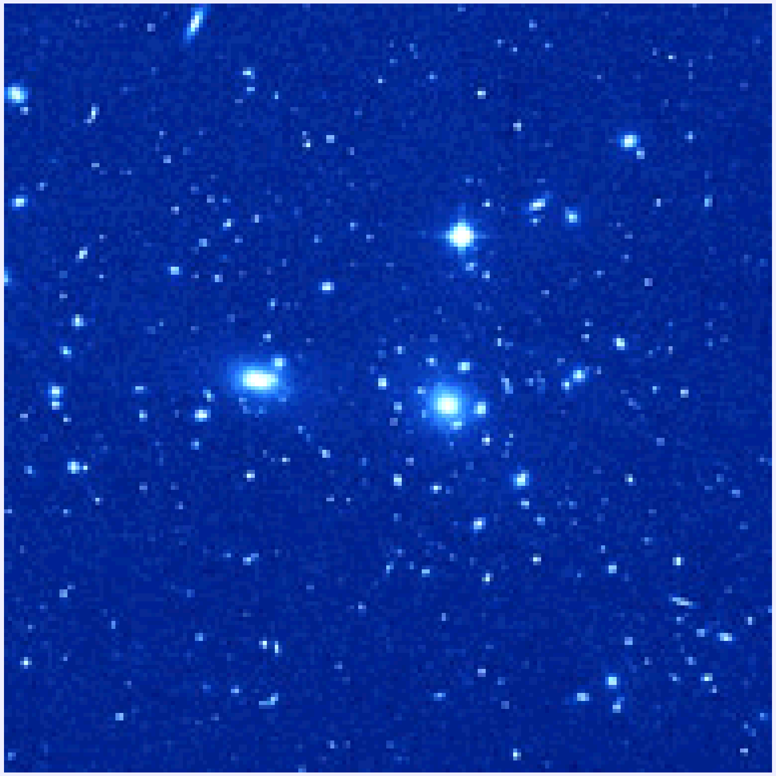
X-rays (Chandra)

M/L ~ 300

Total Mass = $1.6 \times 10^{15} M_{\odot}$ (Geller et al. 1999)

Hot X-ray mass = $0.96 \times 10^{14} M_{\odot}$ (Mohr et al. 1999)

Coma Cluster



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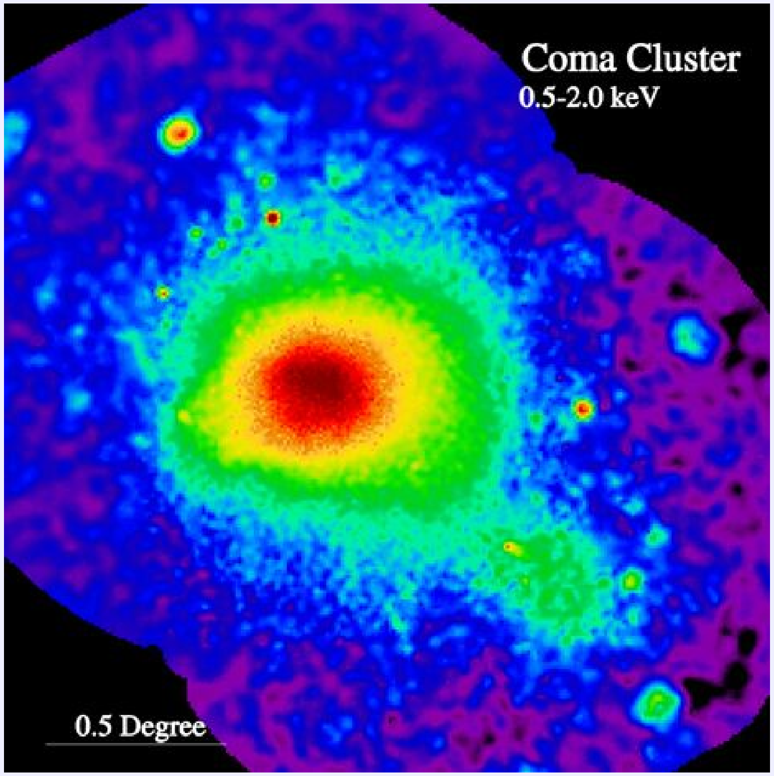

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Oort Limit

•Combining Poisson's equation with the first moment of the Boltzmann Equation in *z* for an infinite disk one obtains:

$$\frac{d}{dz}\left[\frac{1}{n(z)}\frac{d\left(n(z)\overline{v_z^2}\right)}{dz}\right] = 4\pi G\rho_0(tot)$$

$$\frac{1}{n(z)}\frac{d\left(n(z)\overline{v_z^2}\right)}{dz} = 2\pi\Sigma(z)$$

Estimates of ρ_0 and Σ

- Oort (1932)

  ρ_0(Oort Limit) ~ 0.09 $M_\odot pc^{-3}$

  ρ_0(observed) ~ 0.03 $M_\odot pc^{-3}$

- Bahcall (1984)

  ρ_0 (Oort Limit) = 0.19 $M_\odot pc^{-3}$

  ρ_0(observed, extrapolated) = 0.14 $M_\odot pc^{-3}$

This result implied that there is dark matter in the disk (density in midplane from halo DM too small), this dark matter must be dissipational!

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- Kuijken & Gilmore (1988)

  $\Sigma(z)$ (Oort Limit) = 50 $M_\odot pc^{-2}$

  $\Sigma(z)$ (observed) = 50 $M_\odot pc^{-2}$

There is no apparent need for dark matter in the disk of the Milky Way.

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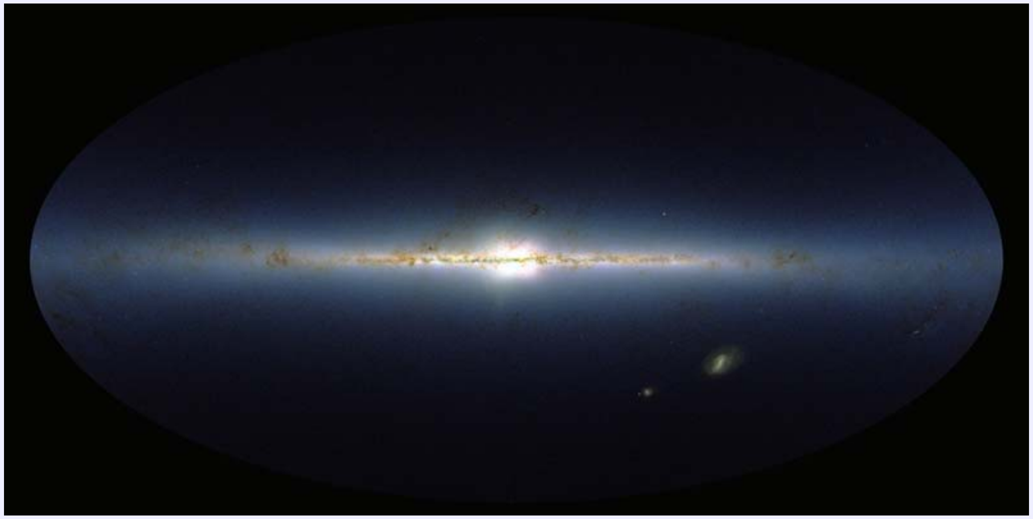
Timing Argument for M31

M31



Milky Way

Distance ~ 740 kpc

$\Delta V = -125$ km s^{-1}

Timing of M31

$$T_r = T_\psi = 2\pi\sqrt{\frac{a^3}{GM}}. \qquad (3.29)$$

The angle $\psi - \psi_0$ is known as the **true anomaly**. A useful parametric representation of the orbit is

$$r = a(1 - e\cos\eta) \quad ; \quad t = (T_r/2\pi)(\eta - e\sin\eta) + t_0, \qquad (3.30)$$

$$\tan\tfrac{1}{2}(\psi - \psi_0) = \sqrt{\frac{1+e}{1-e}}\tan\tfrac{1}{2}\eta.$$

$$\frac{\mathrm{d}\log r}{\mathrm{d}\log t} = \frac{t}{r}\frac{\mathrm{d}r}{\mathrm{d}t} = \frac{e\sin\eta(\eta - e\sin\eta)}{(1 - e\cos\eta)^2}$$

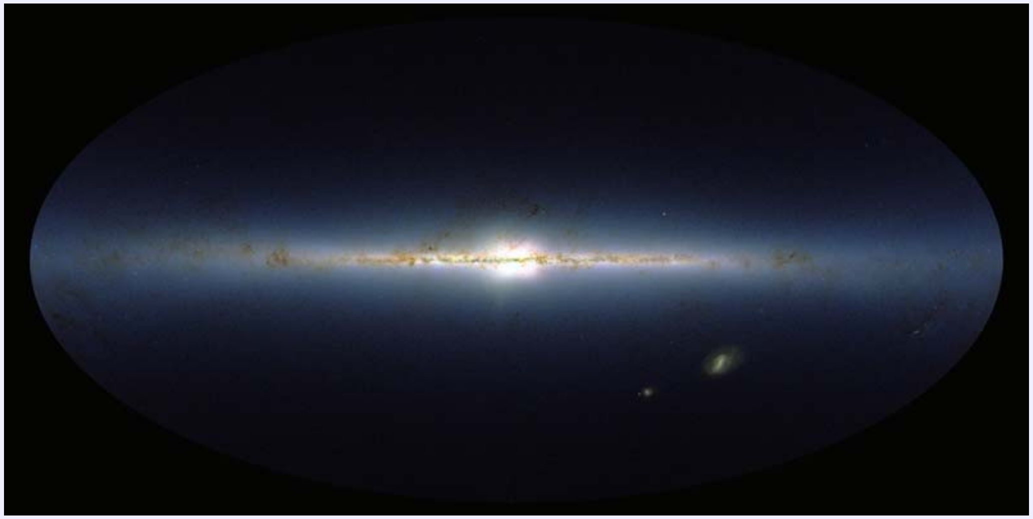
From Binney & Tremaine 2007

t = 13 Gyr; r = 740 kpc; e = 1; η = 4.26; a = 515 kpc;

Tr = 15.8 Gyr

Timing Argument for M31

M31



Milky Way

Distance ~ 740 kpc

$\Delta V = -125$ km s^{-1}

$M(tot) = 4.8 \times 10^{12}\ M_\odot$

$M_{lum}(MW) \sim 10^{11}\ M_\odot$

$M_{lum}\ (M31) \sim 1.5 \times 10^{11}\ M_\odot$

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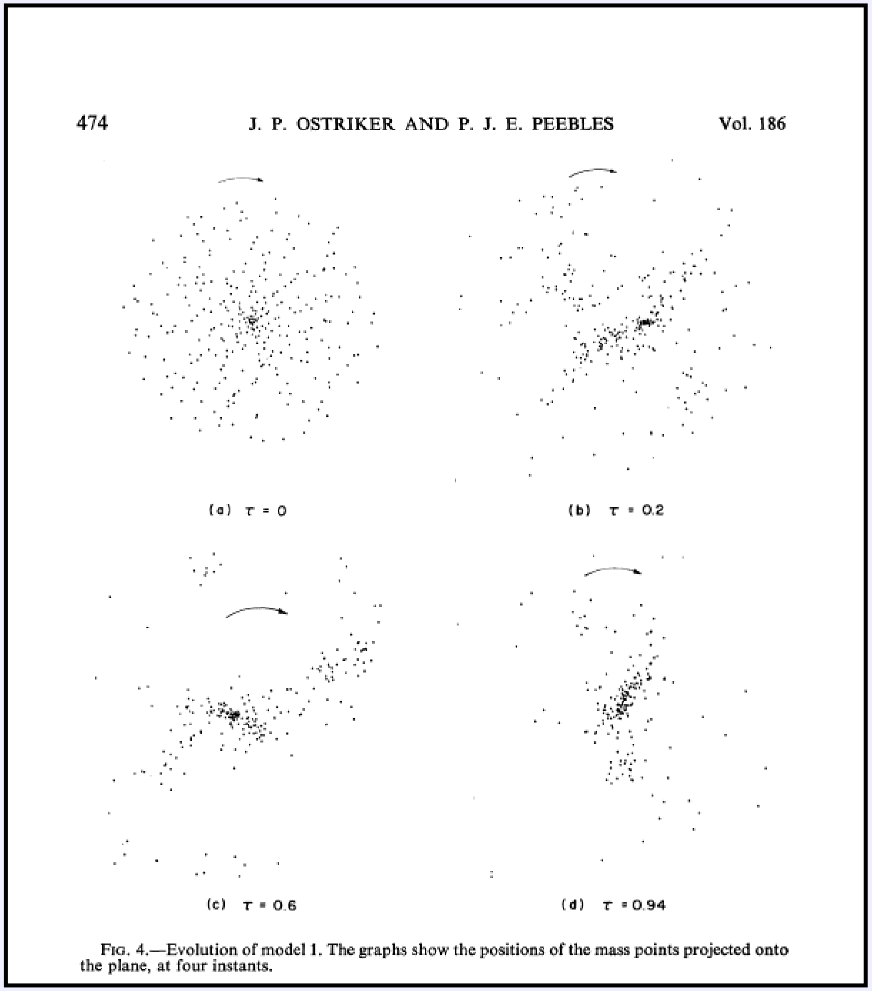
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FIG. 4.—Evolution of model 1. The graphs show the positions of the mass points projected onto the plane, at four instants.

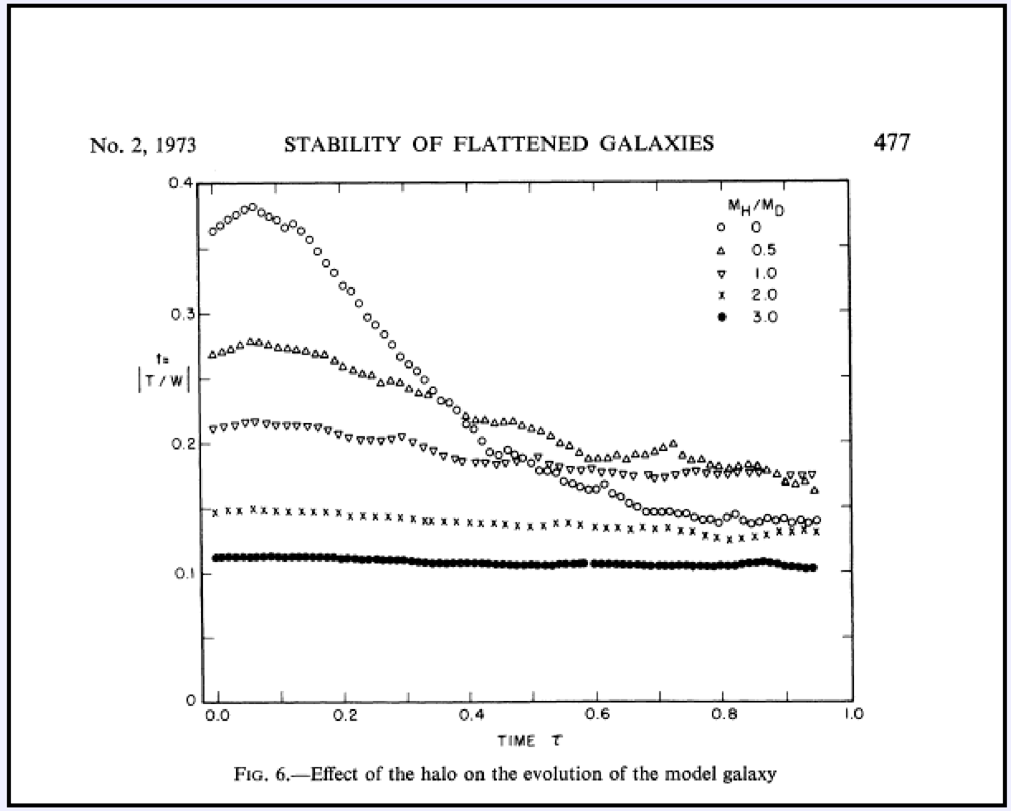
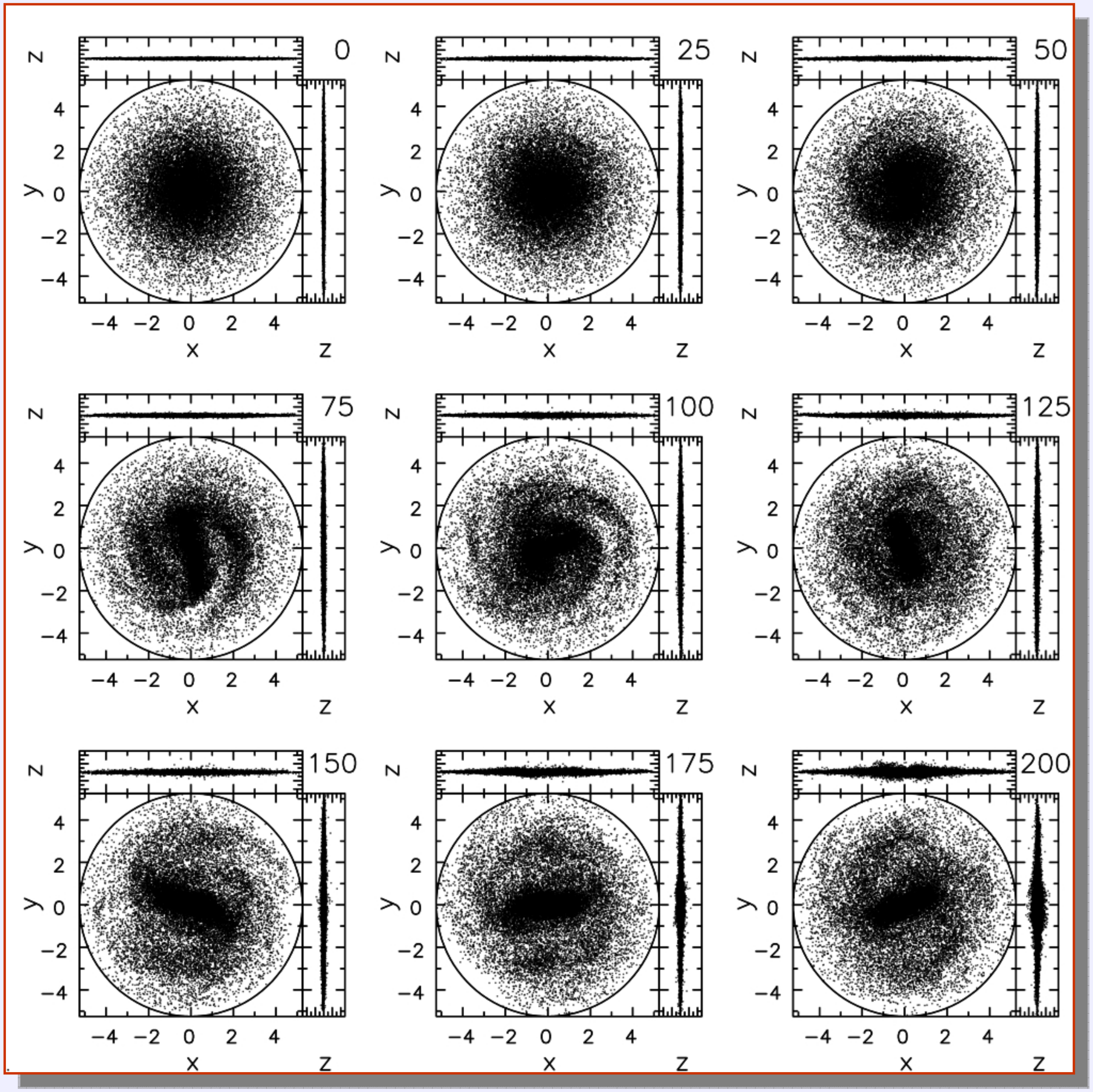

No. 2, 1973 STABILITY OF FLATTENED GALAXIES 477

FIG. 6.—Effect of the halo on the evolution of the model galaxy

Recent Calculation (Sellwood, pers. comm)



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Early suggestion

- Work of Babcock (1939) and Roberts & Whitehurst (1975) on the rotation curve of M31.

No. 2, 1975 ROTATION CURVE AND GEOMETRY OF M31 343

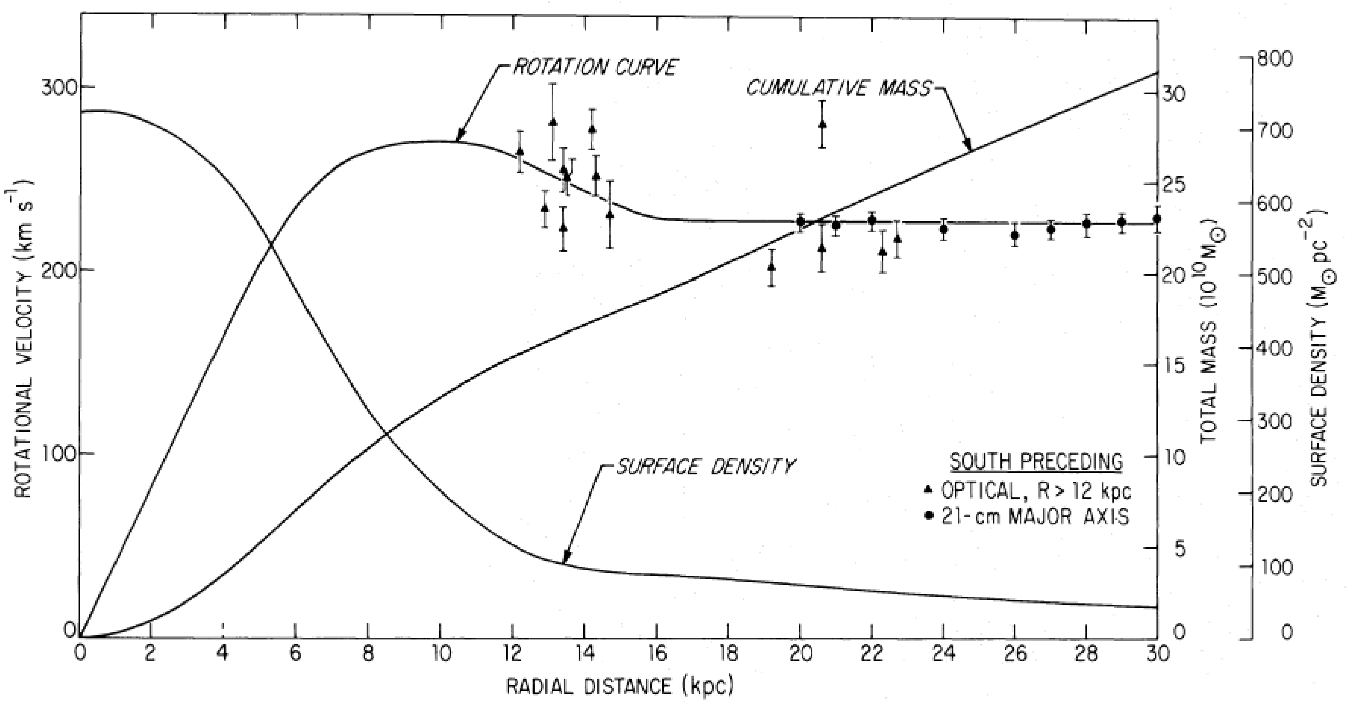


FIG. 16.—The adopted rotation curve, a composite of optical (Rubin and Ford 1970) data and 21-cm major axis measurements. The surface density and cumulative mass curves are for a highly flattened model.

21-cm (radio) rotation curve

Rubin, Thonnard & Ford (1978)

optical rotation curves

Radial scale depends on value of the Hubble constant

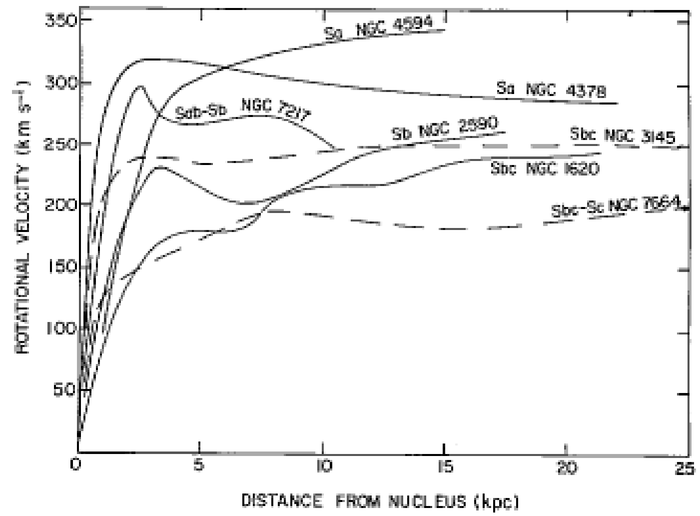


FIG. 3.—Rotational velocities for seven galaxies, as a function of distance from nucleus. Curves have been smoothed to remove velocity undulations across arms and small differences between major-axis velocities on each side of nucleus. Early-type galaxies consistently have higher peak velocities than later types.

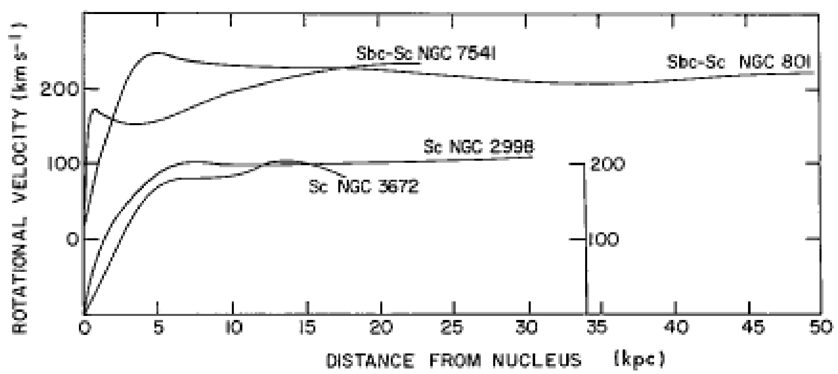
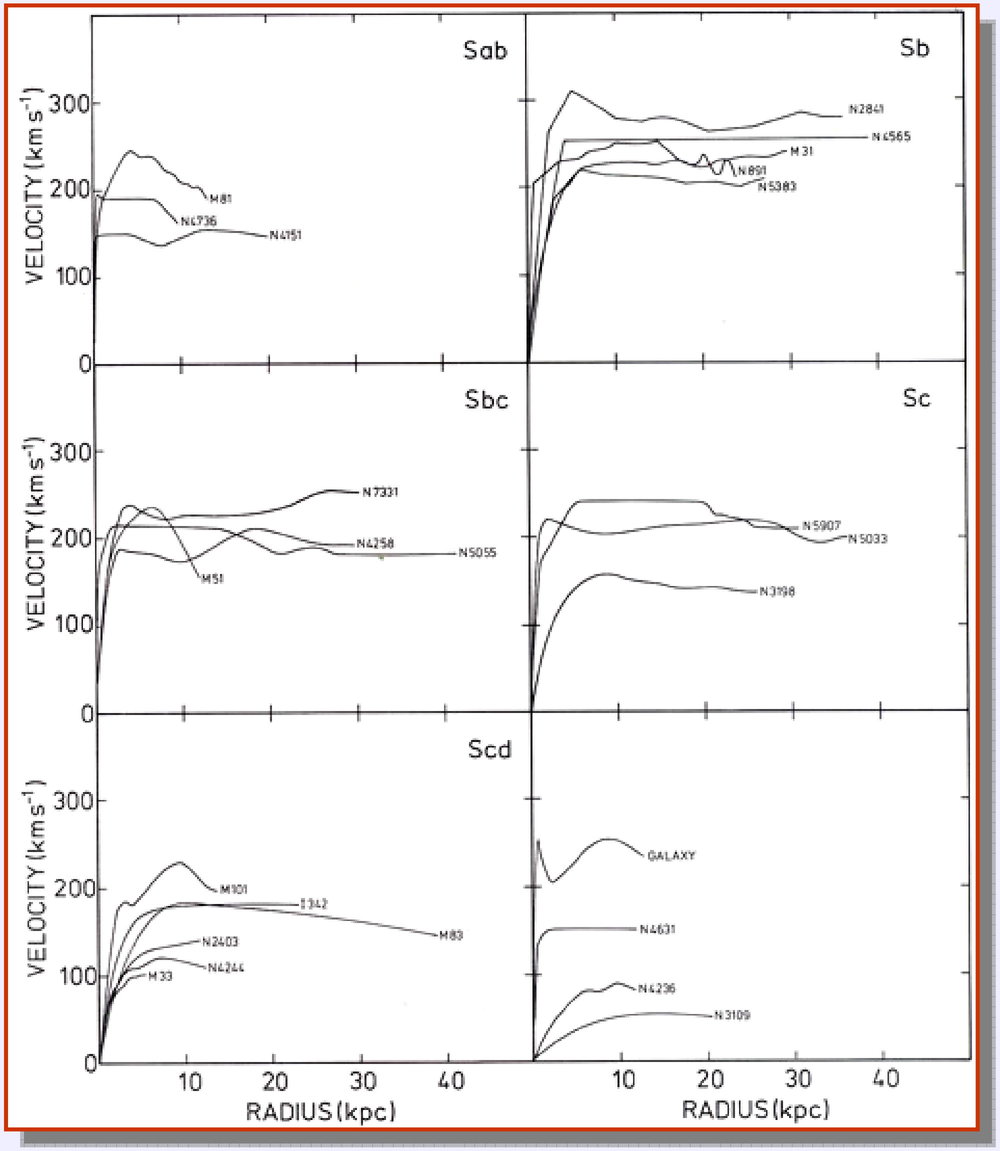


FIG. 4.—Rotation curves for two pairs of galaxies, which illustrate the lack of Tully-Fisher relation. NGC 7541 and NGC 801, both Sbc–Sc, have V_{max} values of 238 and 248 km s^{-1}. However, their luminosities (7.05 ± 0.7 and 23.8 ± 9 × 10^{10} $L_\odot$) and radii (23.2 and 49.1 kpc) differ by factors of 3 and 2. Similarly, the Sc galaxies NGC 2998 and NGC 3672 have V_{max} of 211 and 208 km s^{-1}, but luminosities 14.9 ± 1.4; 4.45 ± 0.4 × 10^{10} $L_\odot$ and radii 34.0 and 17.6 kpc.

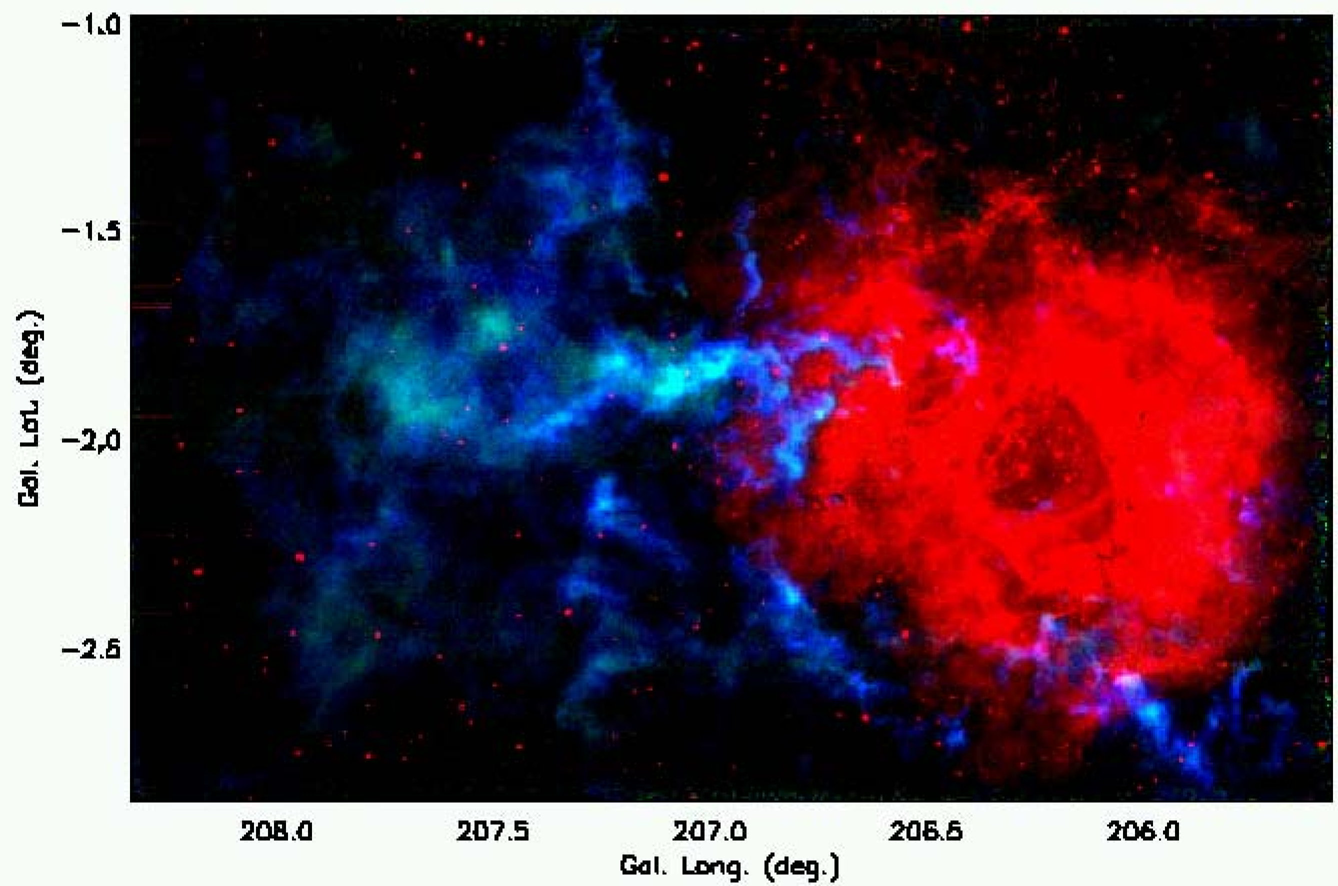
Bosma (1978)

21-cm (radio) rotation curves



Milky Way - Blitz (1979)

Rosette Nebula and Molecular Cloud



Milky Way - Blitz (1979)

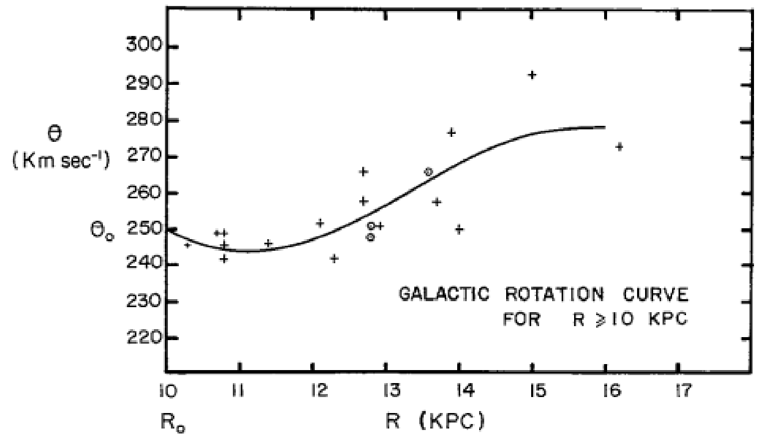


FIG. 1.—The galactic rotation curve external to the solar circle from the values in Table 2. Crosses are points for which the errors are relatively small ($\Delta R \lesssim 1.0$ kpc, $\Delta\Theta \lesssim 20$ km s^{-1}). The curve is a third-order least-squares polynomial fit to the data.

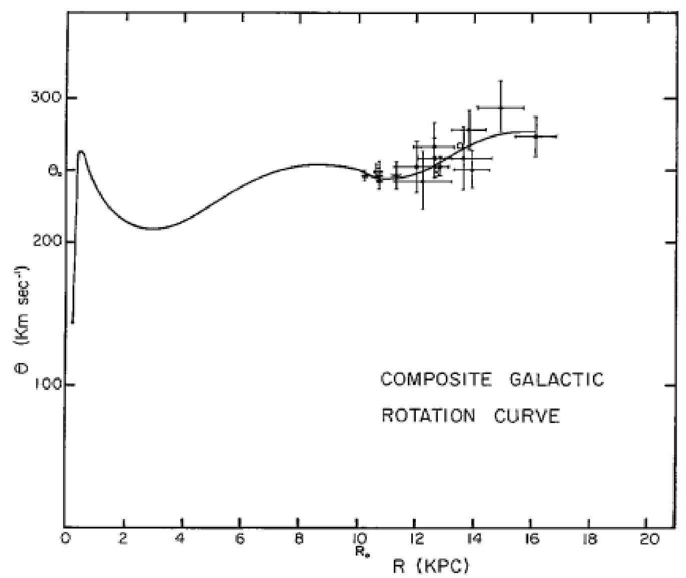
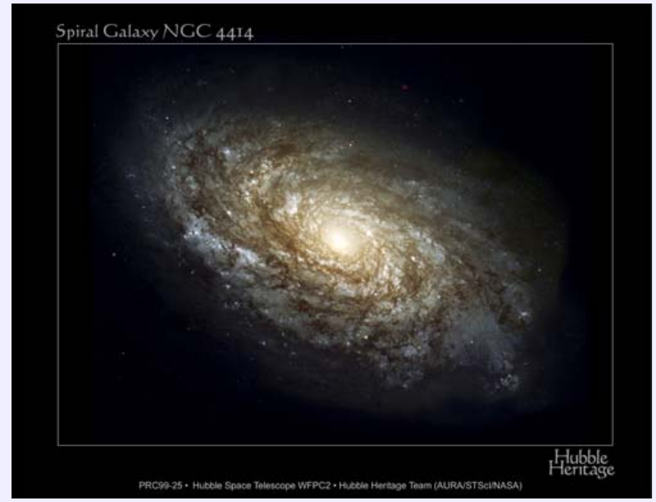


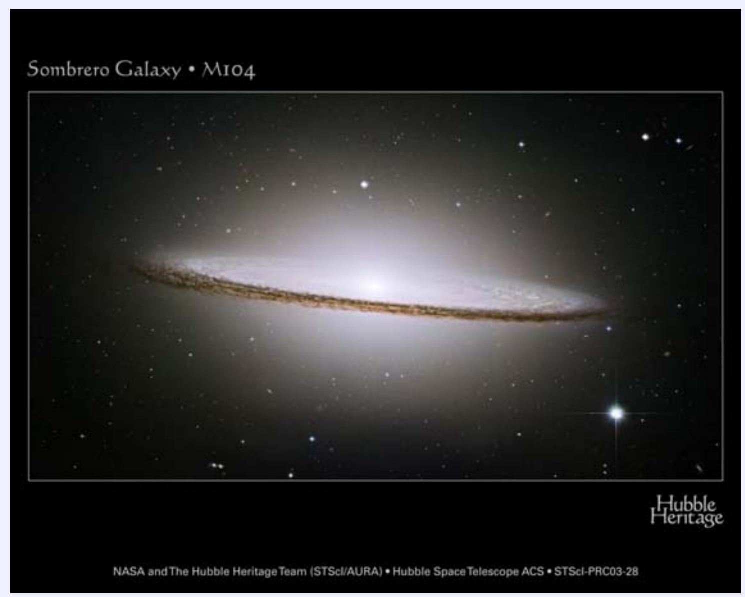
FIG. 2.—The composite rotation curve of the Galaxy, using the rotation curve from Fig. 1 matched to the 21 cm rotation curve from Burton and Gordon (1978). Error bars are shown for the points in Fig. 1 plotted as crosses.

Rotation Curve Decomposition

1. Universality of rotation curve shapes
2. Light profiles exponential
   1. If M/L in disks is constant, then mass of disk component is $M \sim R \exp\{-(R/R_0)\}$
   2. But flat rotation curves → $M(R) \sim R$
3. Oort limit + M/L suggest dark matter necessary but cannot be in disks.
4. Amount of dark matter determined by rotation curve decomposition.
   1. Led to maximum disk models

Stellar Components of Disk Galaxies





Bulge; Disk; Spheroid

Each had characteristic mass distribution

$$\boxed{\Phi_1 + \Phi_2 + \Phi_3 + \ldots = \Phi_{tot}}$$

$$v_{c1}^2 + v_{c2}^2 + v_{c3}^2 + \ldots = v_c^2$$

Athanassoula and Bosma (1988)

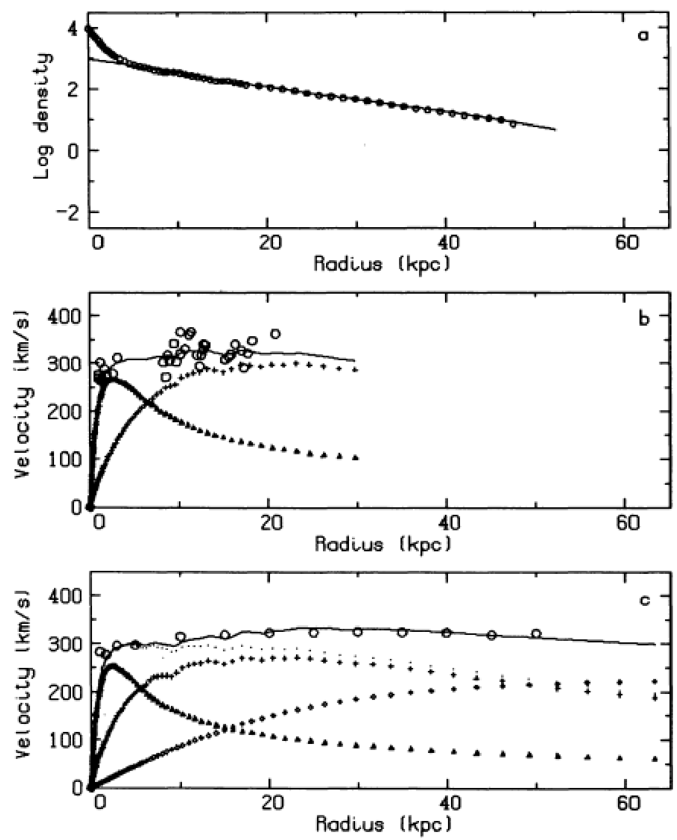
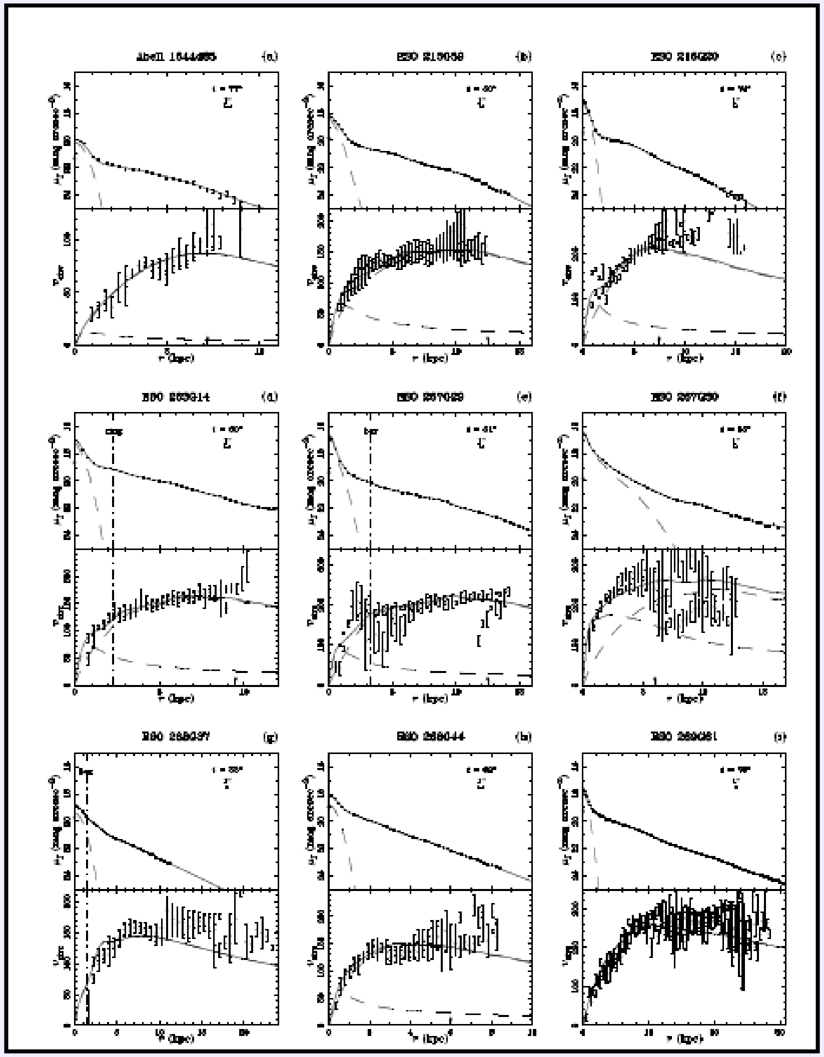


Figure 1. Mass model for NGC 488. a. Radial luminosity profile from Boroson (1981), indicating our bulge/disk decomposition. b. Maximum disk mass model derived for the optical data alone. Note that no halo appears necessary. c. Maximum disk model derived from the HI data. In order to fit the data we now have to add a halo (in this calculation assumed to be isothermal) to the bulge and disk contributions. In both panels b and c the observed data points are represented by open circles, the bulge rotation curve by triangles, the disk by plus signs, their sum by dots, the halo by diamonds, and the total by solid lines.

Rotation Curve Fits Without Dark Matter



Palunas & Williams (2000)

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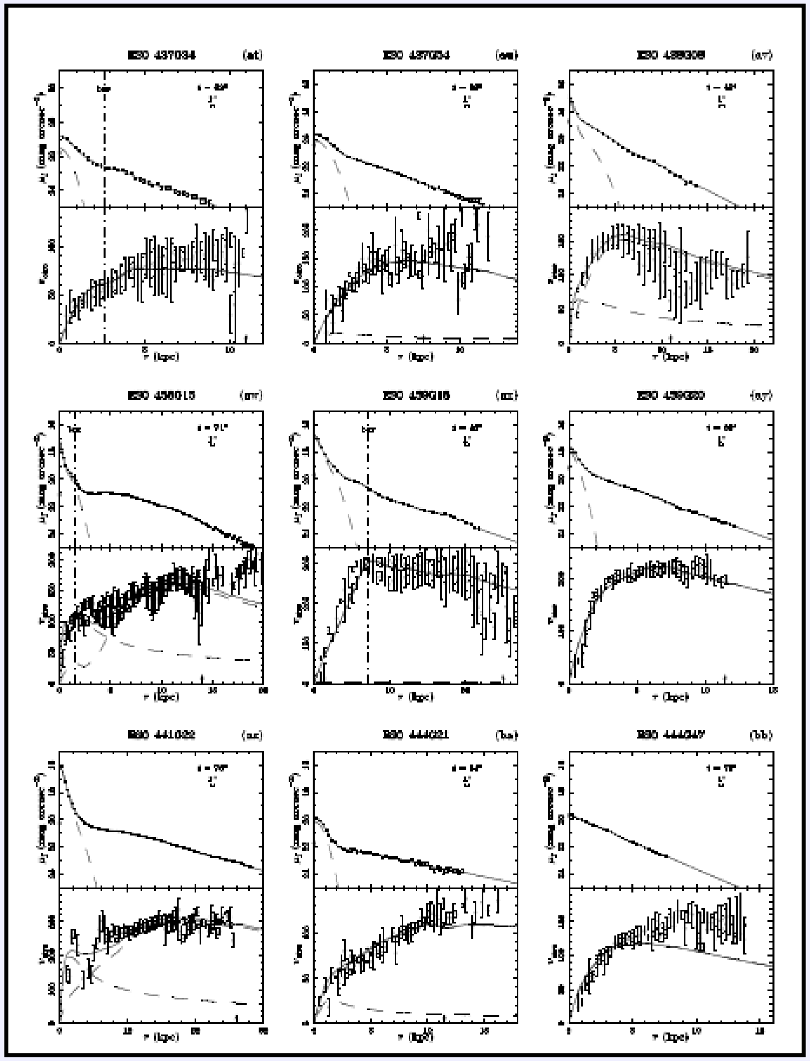

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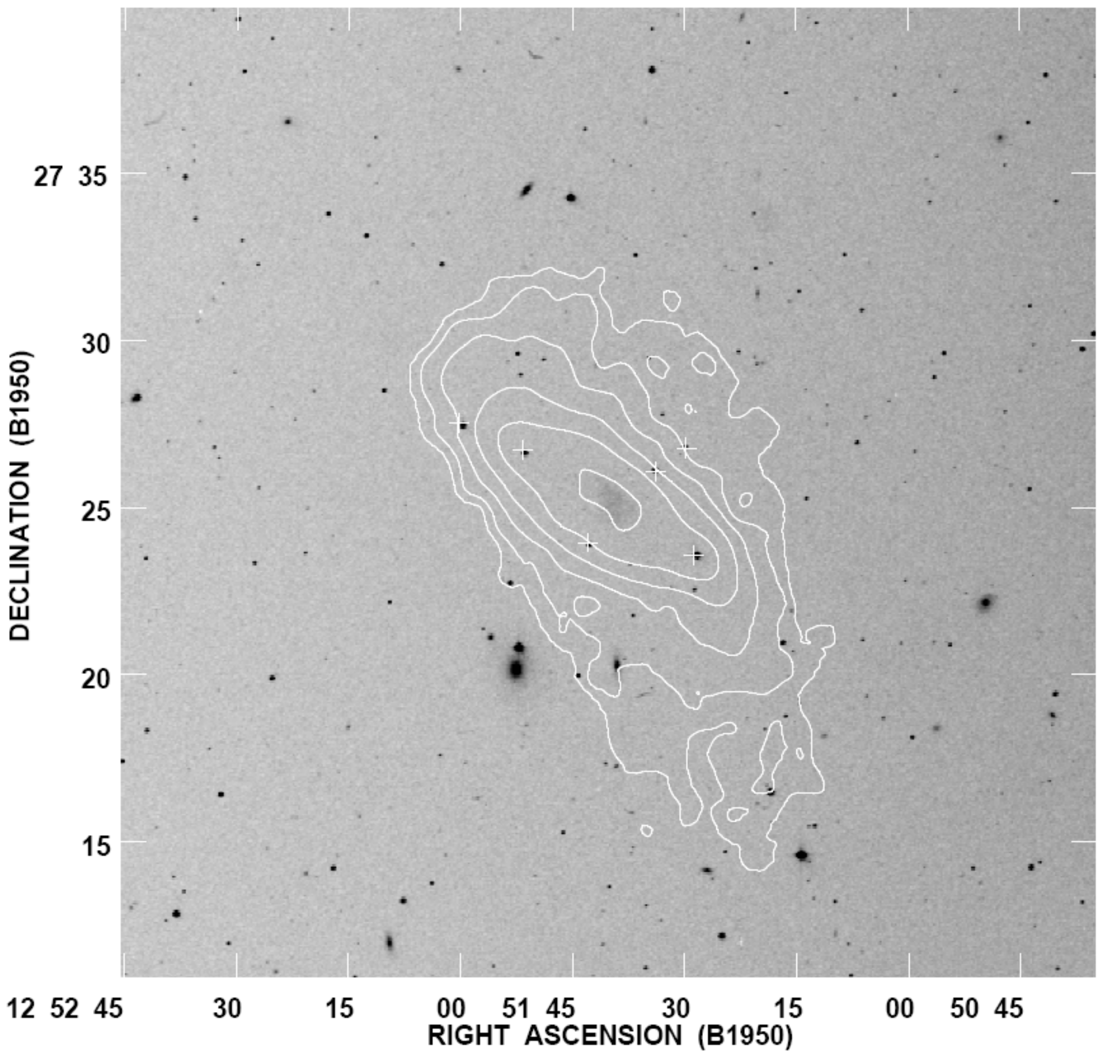

FIG. 3.—Total H I map superposed on the optical for the combined VLA + DRAO data. The contours are 0.5, 1, 2, 4, 8, and 16 × 10^{20} cm^{-2}. The circular beam size is 1′

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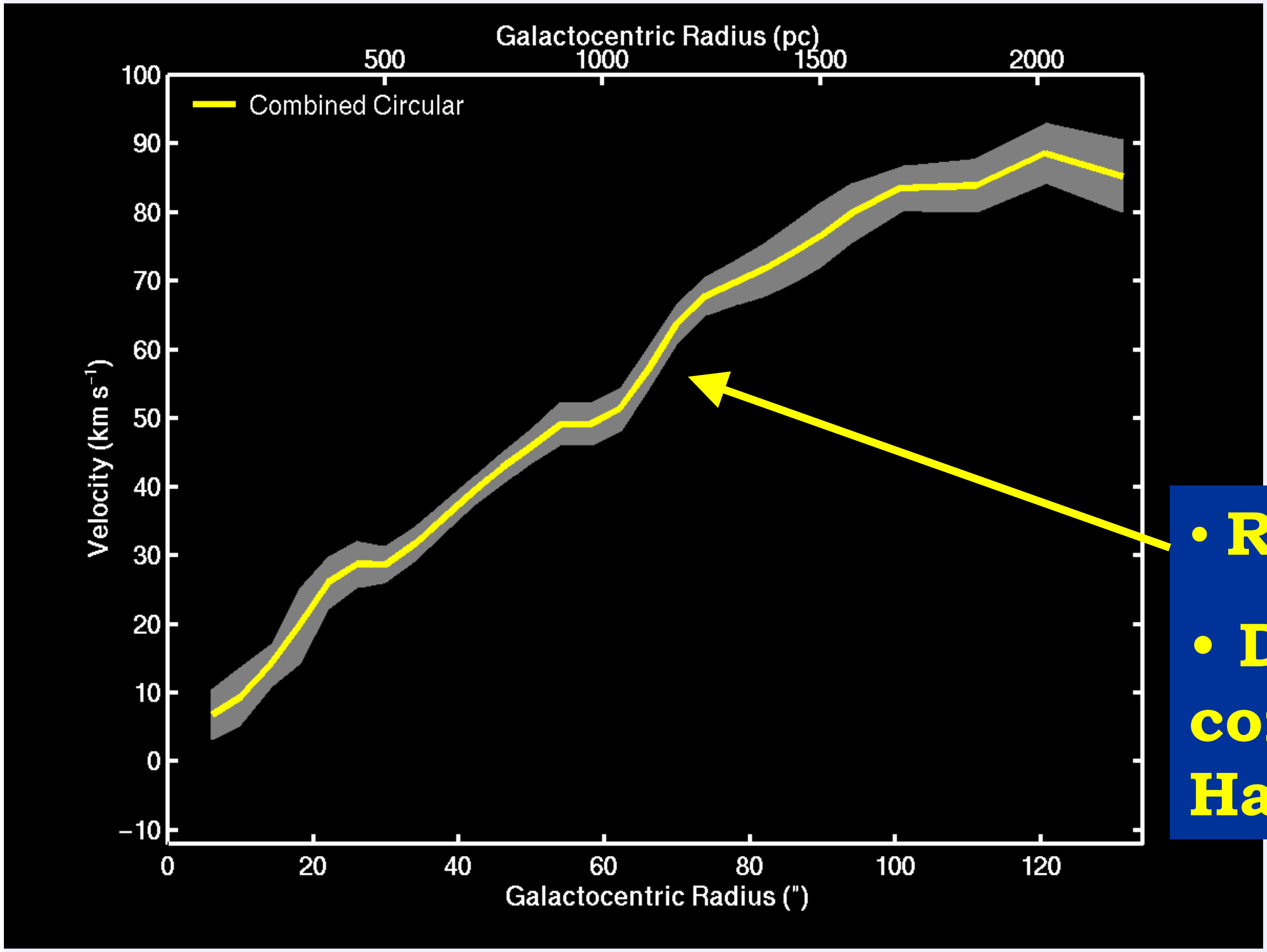
NGC 2976: B,V,R composite from Lowell 72” with CO overlay

D = 3.3 Mpc; I_{CO} = 2.2 K km s^{-1}

- •BIMA ~5” resolution (80 pc)
- • CO extends to *R* > 60” (1 kpc)
- •BVRIJHK photometry to better model stellar disk
- •2-D Hα with Densepack

NGC 2976 Rotation Curve

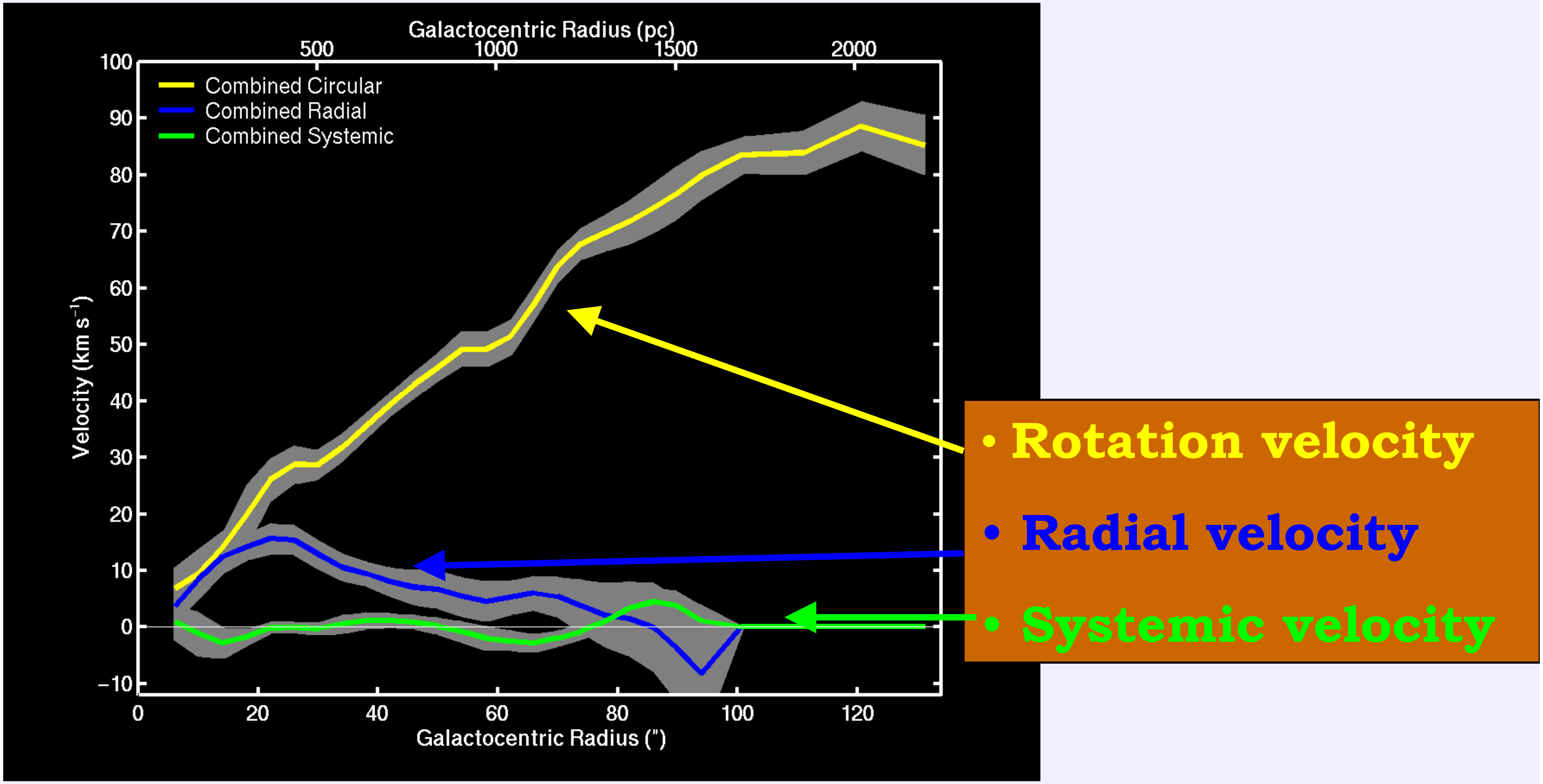
Linearly rising rotation curve implies ρ(R) ~ const;   M(R) ~ R^3



- **Rotation velocity**
- **Derived from combined CO and Ha velocity field**

NGC 2976 Rotation Curve

$$V_{obs} = V_{sys} + V_{rot} \cos\theta + V_{rad} \sin\theta$$



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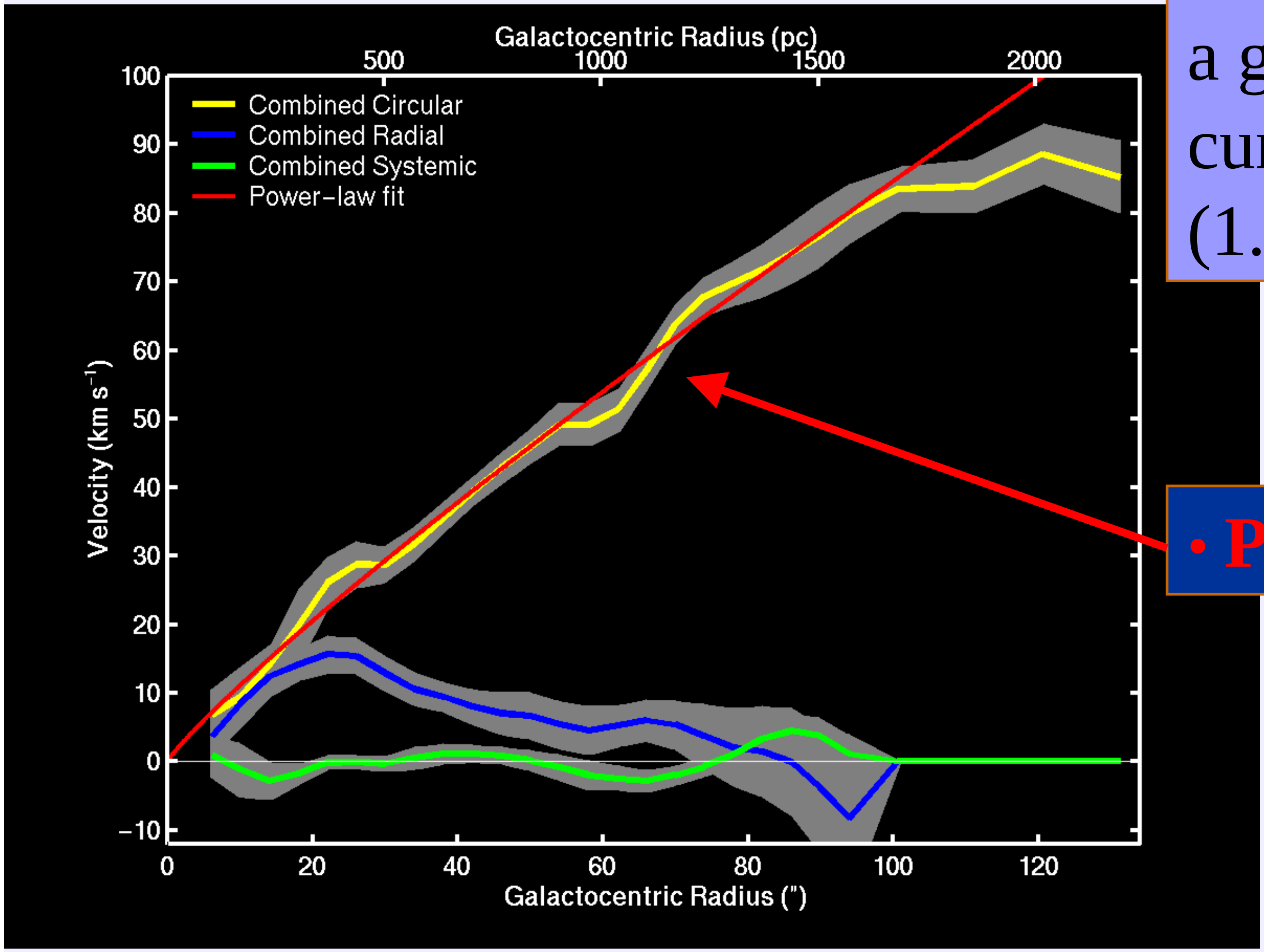
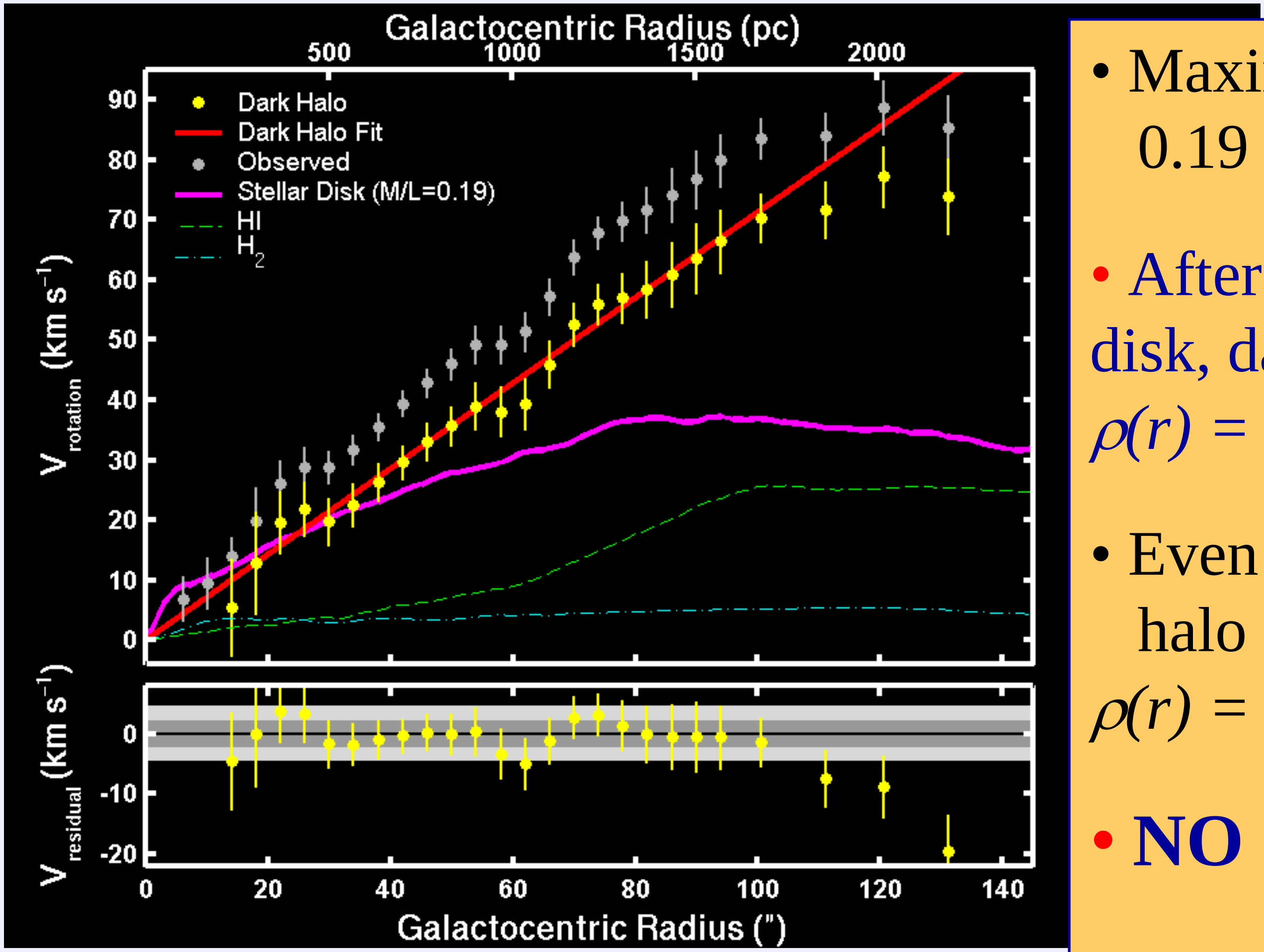


- Power law provides a good fit to rotation curve out to 100" (1.7 kpc) (red)

- **Power law fit**

Maximum Disk Fit



- Maximal disk M_*/L_K = 0.19 $M_\odot/L_{\odot,K}$
- After subtracting stellar disk, dark halo structure is $\rho(r) = 0.1\ r^{-0.01 \pm 0.12} M_\odot/pc^3$
- Even with no disk, dark halo density profile is $\rho(r) = 1.2\ r^{-0.27 \pm 0.09}\ M_\odot/pc^3$
- **NO CUSP!**

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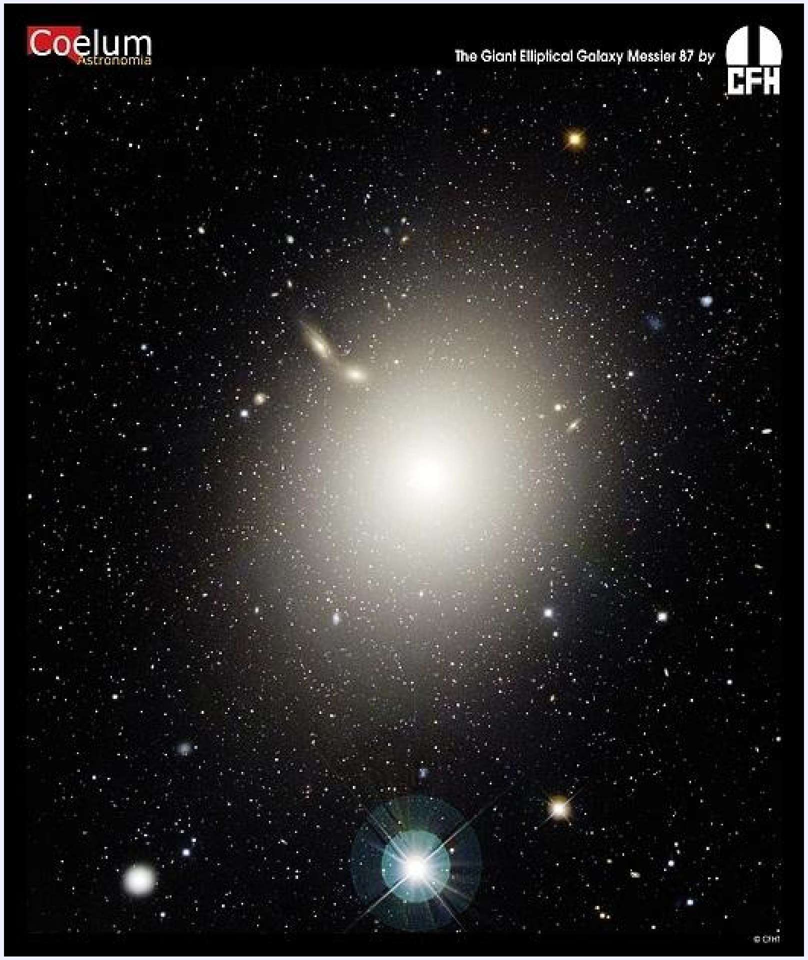
M87 (Fabricant et al. 1980)



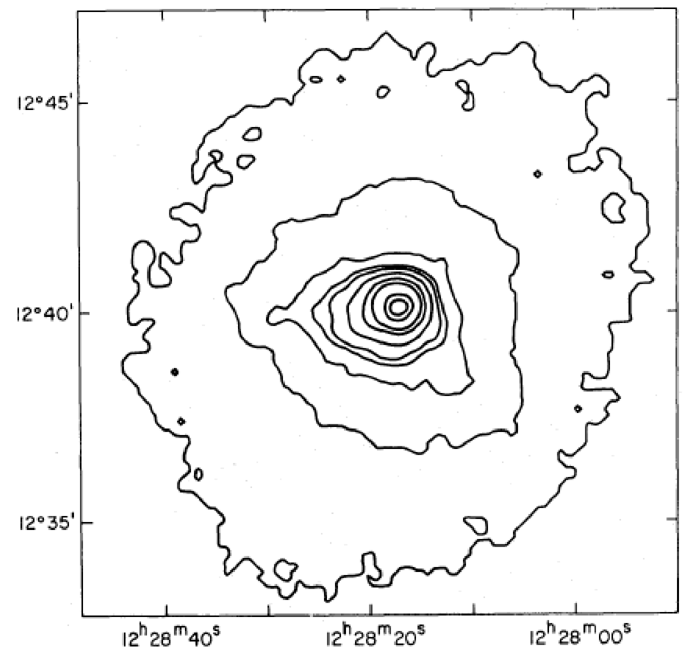


FIG. 1.—X-ray contour map of the 25′ region centered on M87, smoothed with a 10″ Gaussian function and binned at 8″ pixels. Contours represent 3%, 5%, 8%, 11%, 12%, 15%, 20%, 25%, 50%, and 75% of the peak value, which is 9.16 counts arcsec^{-2}. Note this peak value represents the average over an 8″ × 8″ resolution element (cf. legend to Fig. 2).

Schreier et al. 1982

$M_{lum} \sim 1.0 \times 10^{12}\ M_\odot$

$M_{gas} \sim 1.0 \times 10^{12}\ M_\odot$

Assuming hydro eq.

$M_{tot} \sim 1.7 - 2.4 \times 10^{13}\ M_\odot$

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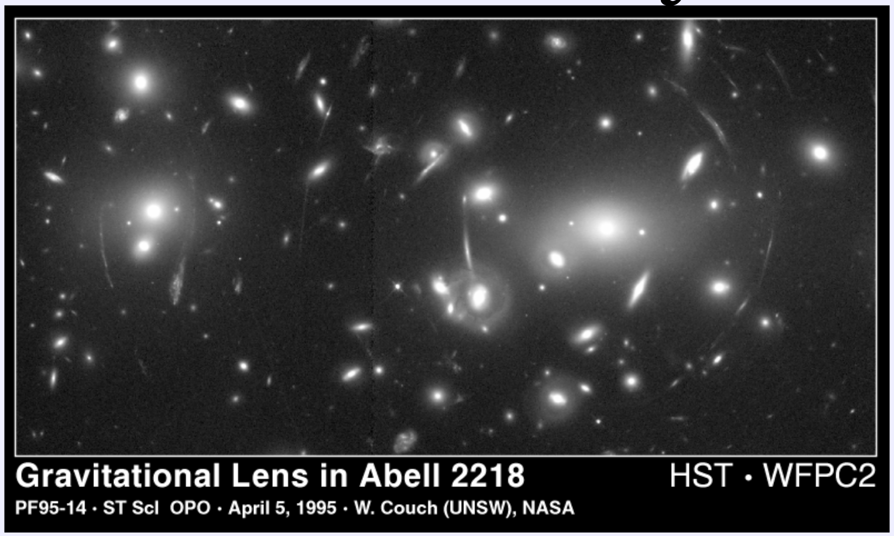
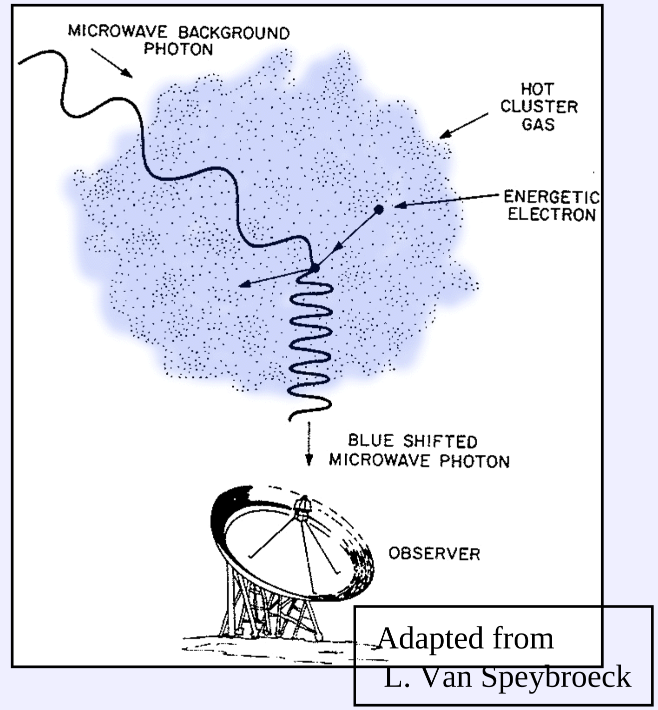
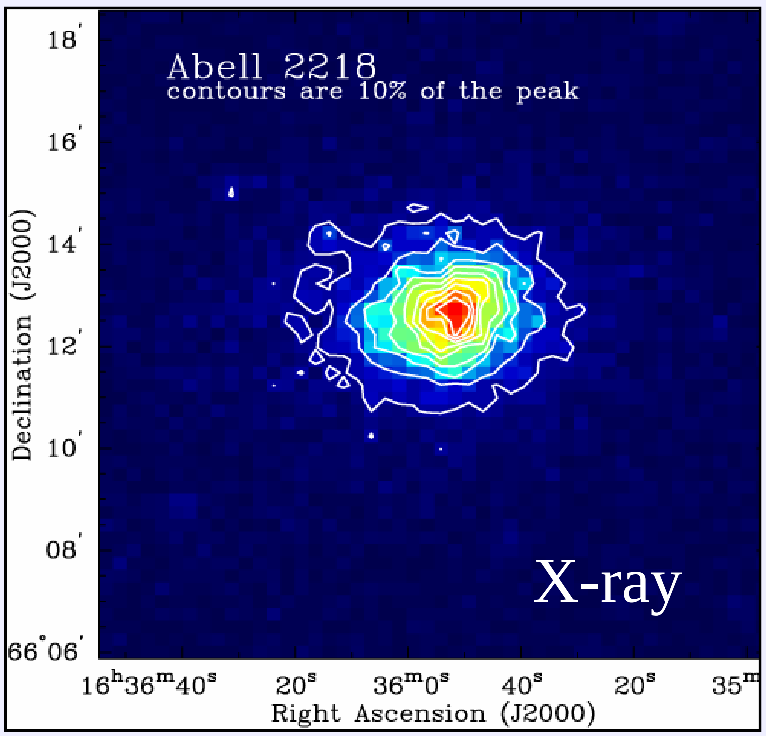
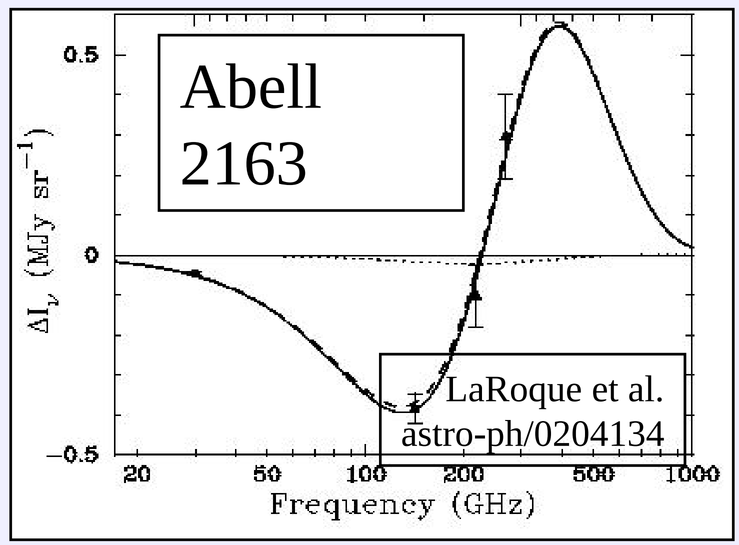
Galaxy clusters + CMB → SZE

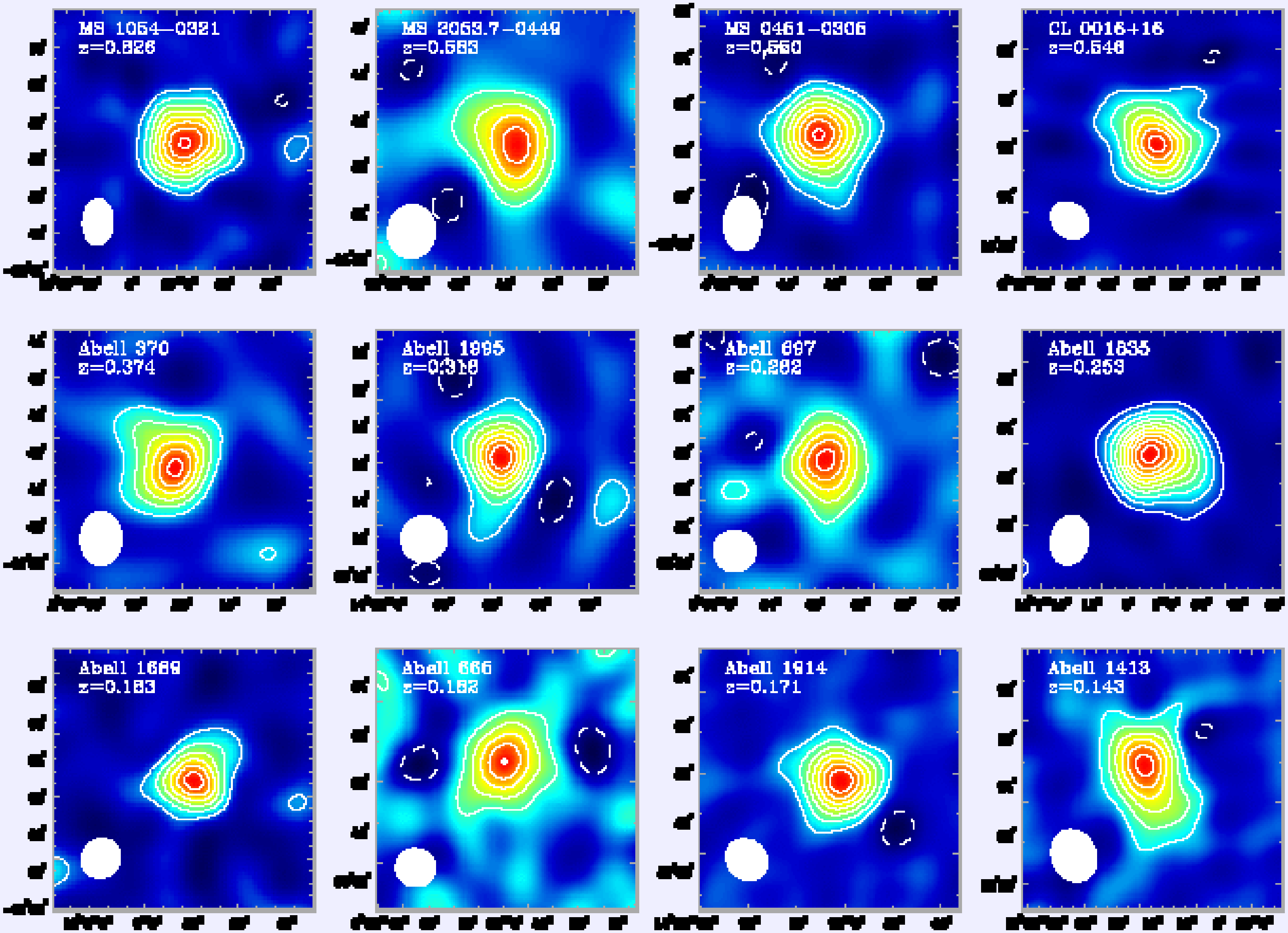






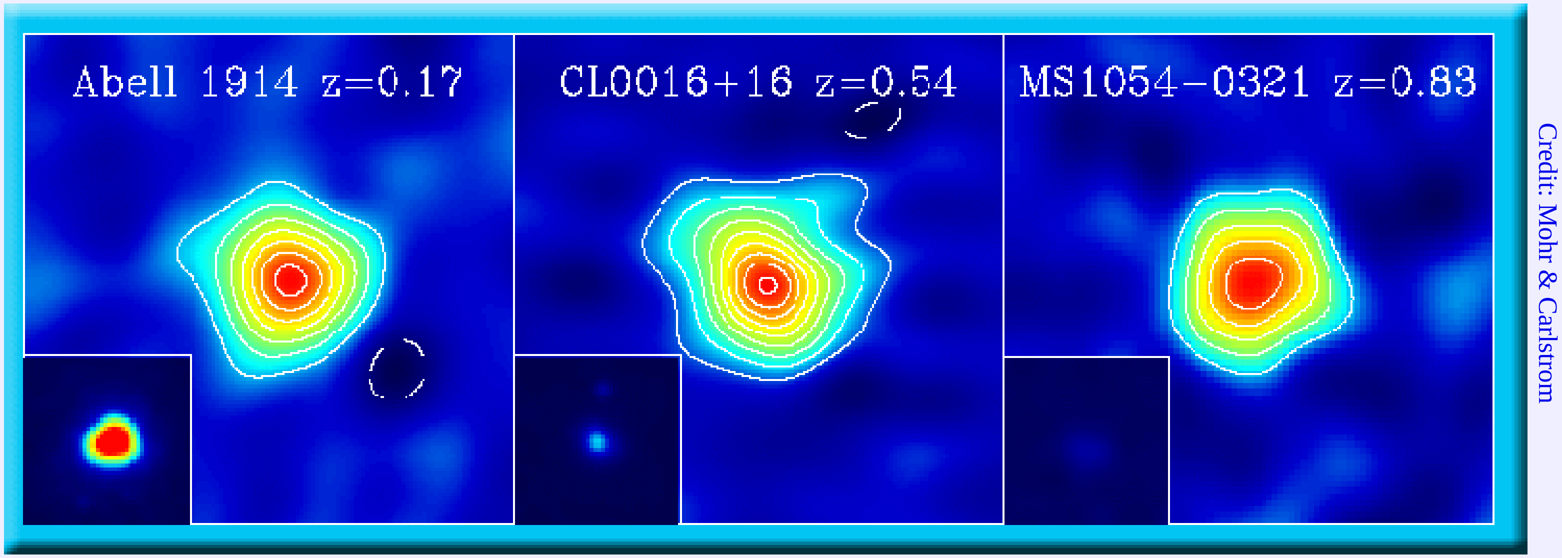


Sample from 60 OVRO/BIMA imaged clusters, 0.07 < z < 1.03



SZE Surveys – Exploit SZE redshift independence

Use SZE as a Probe of Structure Formation
and to provide nearly bias free cluster sample



SZE contours every 75μK. Same range of X-ray surface brightness in all three insets.

$$S \propto \int \Delta T \, d\Omega \propto \frac{1}{d_A(z)^2} \int n_e kT \, dV$$

- Proportional to total thermal energy of electrons
- Temperature weighted electron inventory

Results

- M_{gas}/M_{total} = 0.11 – 0.12 on average for 28 clusters (assuming ΛCDM universe) (LaRoque 2006)
- Implies ~ 18% of mass in baryons, 2/3 in hot gas and 1/3 in galaxies (stars and cold gas) (LaRoque 2006)
- M/L_B ~ 300 (from optical, infrared and weak lensing) (Diaferio 1999; Rines 2001; Kaiser 2001)
- Implies DM distributed throughout cluster outside of galaxies; M/L for individual galaxies ~ 3-5

Does Dark Matter Exist?

- Flat Rotation Curves of Galaxies (and large velocity dispersions of spheroids)
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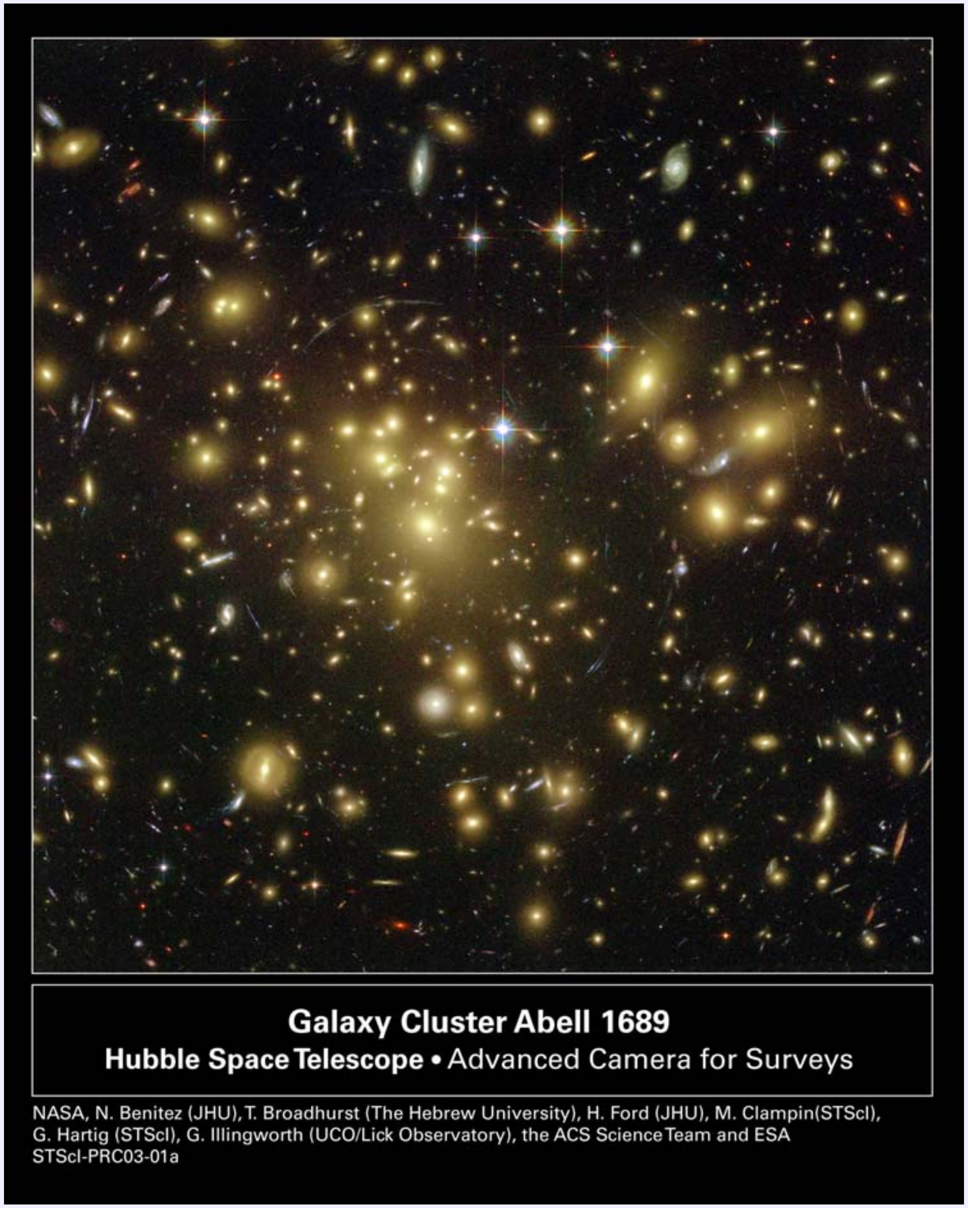
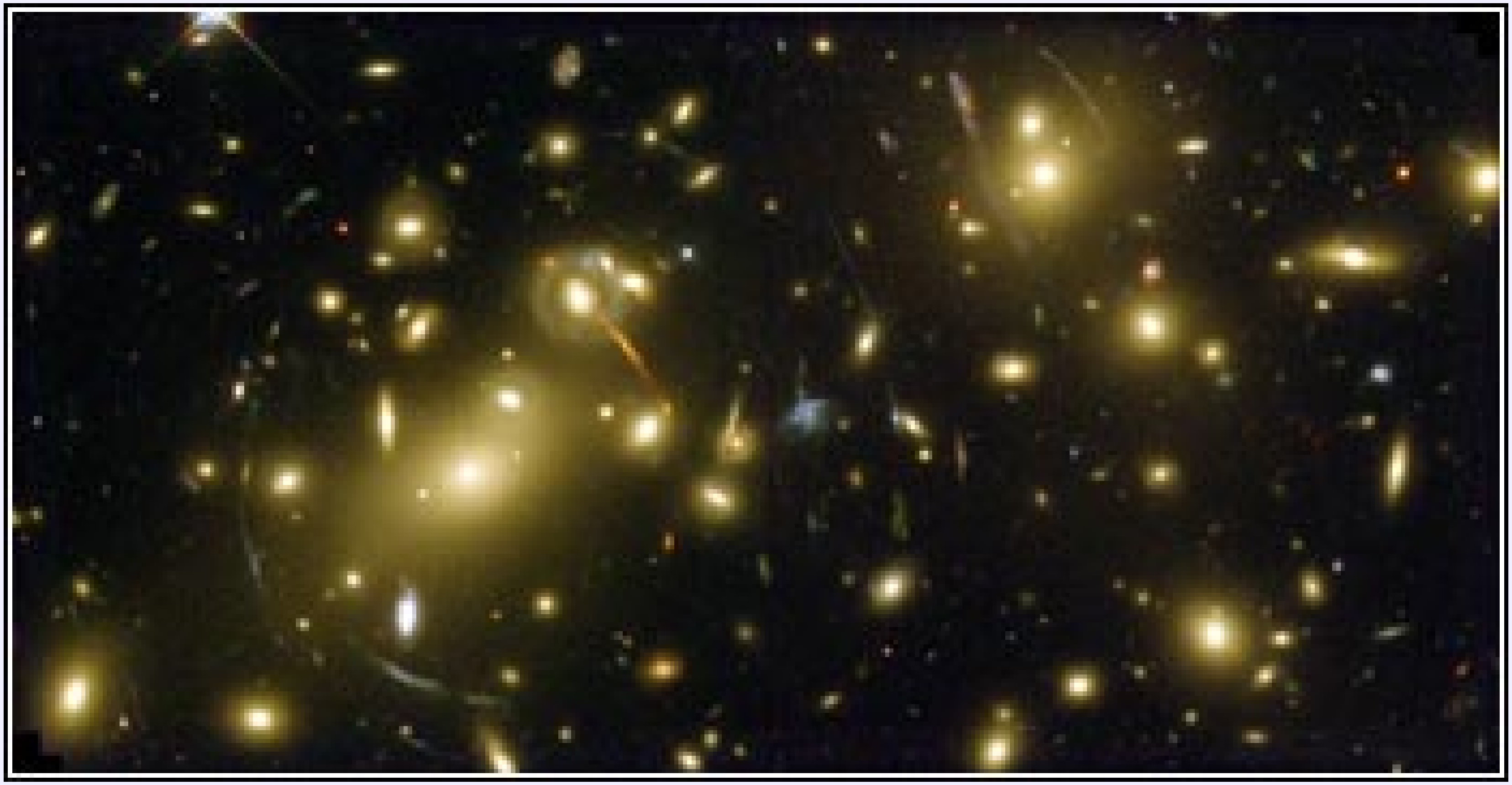
Abell 1689


Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys
NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

Abell 2261



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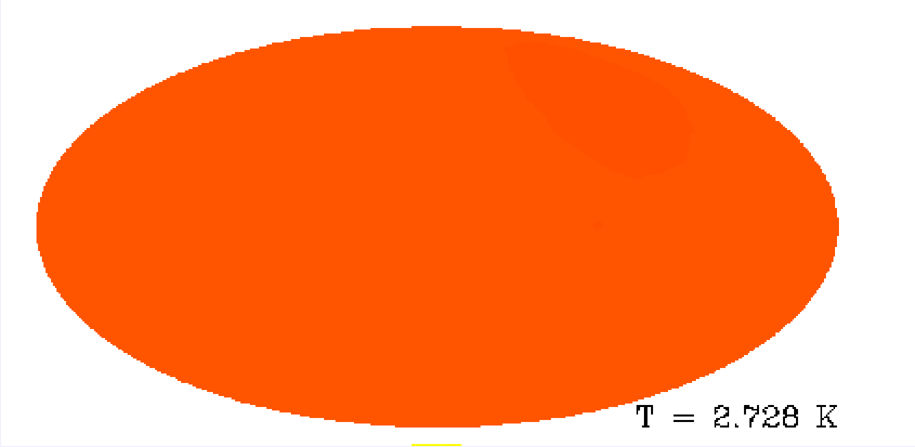


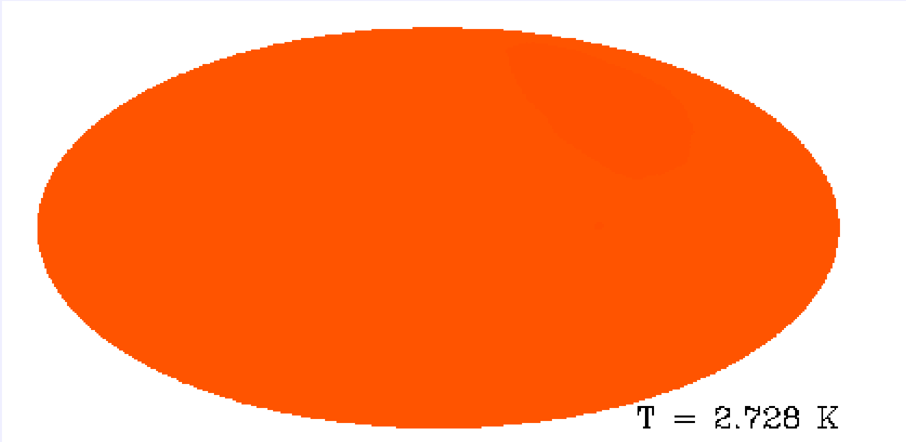
The Microwave Sky

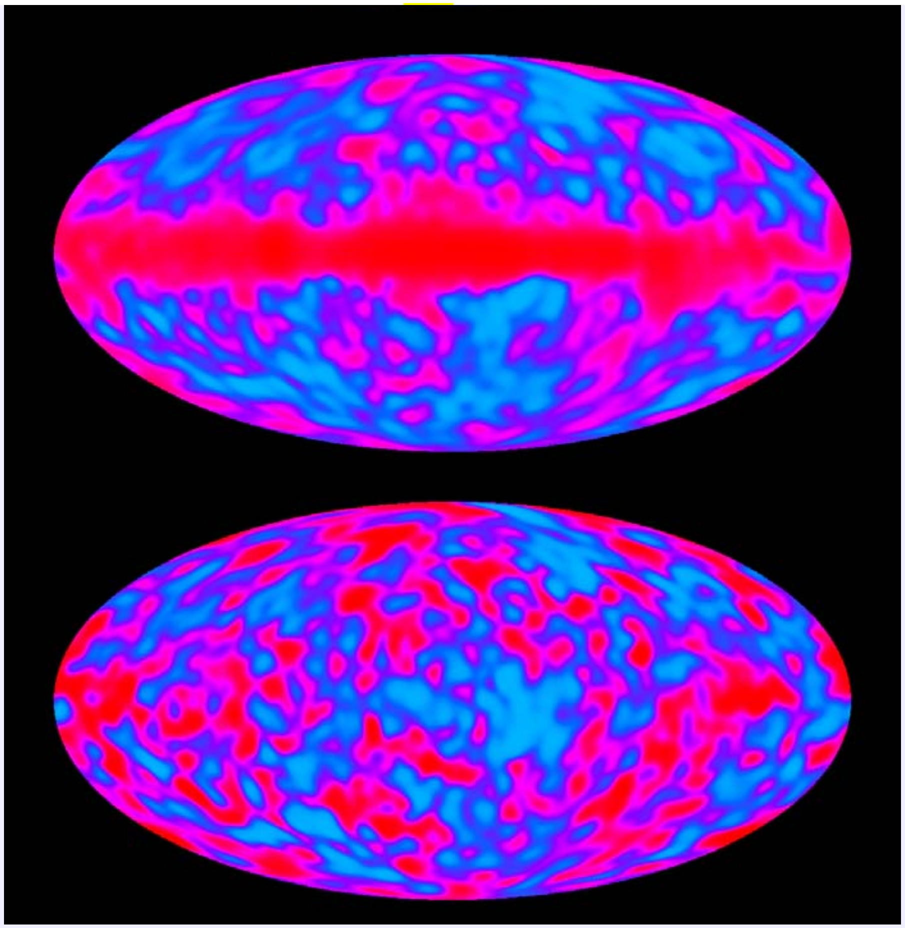
3° K Microwave Background – Radio Radiation left over from the Big Bang

Uniform and isotropic to one part in 10^5

Its distance is established by SZE

Its ubiquity from molecular excitation



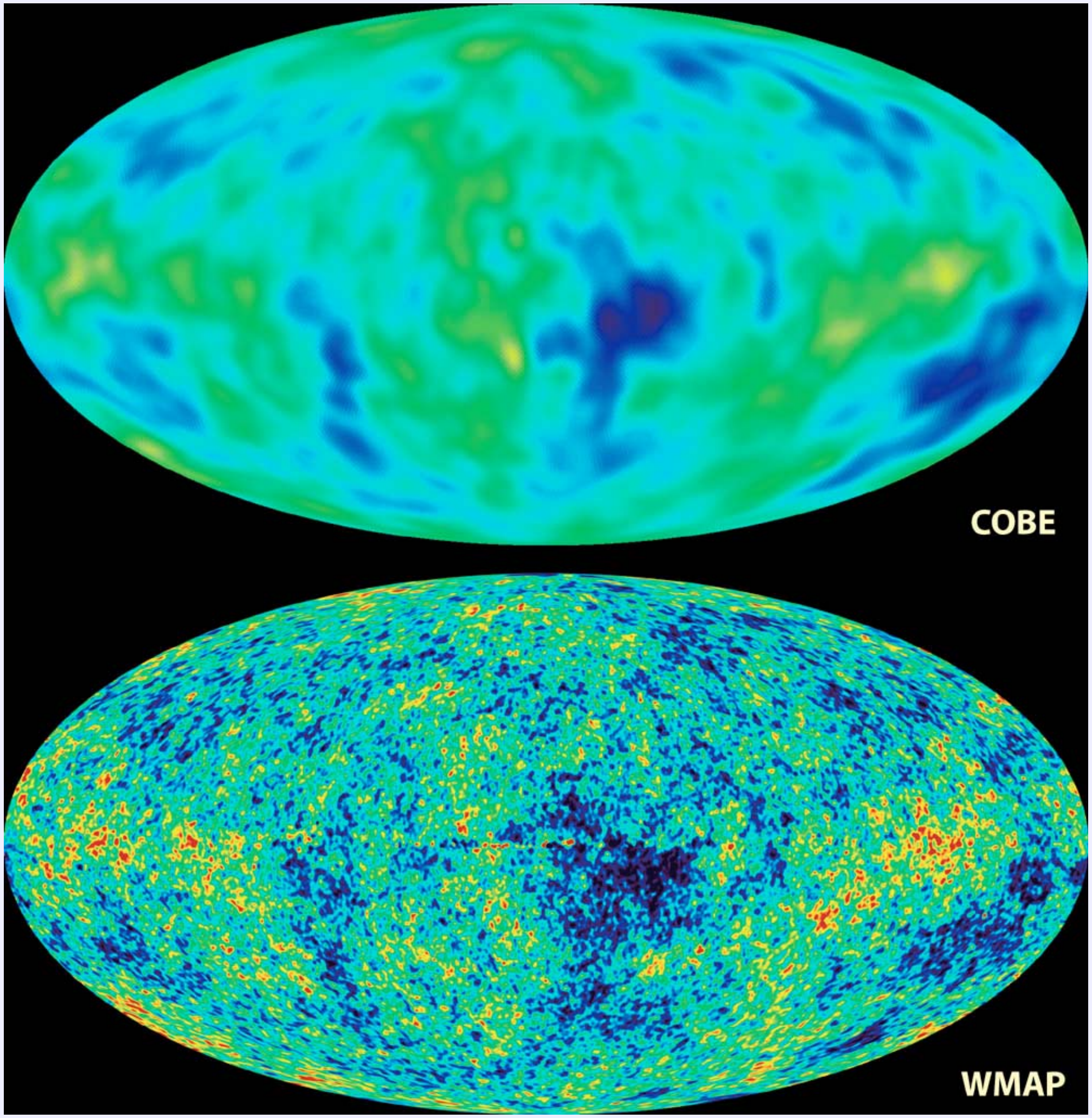


The Microwave Sky

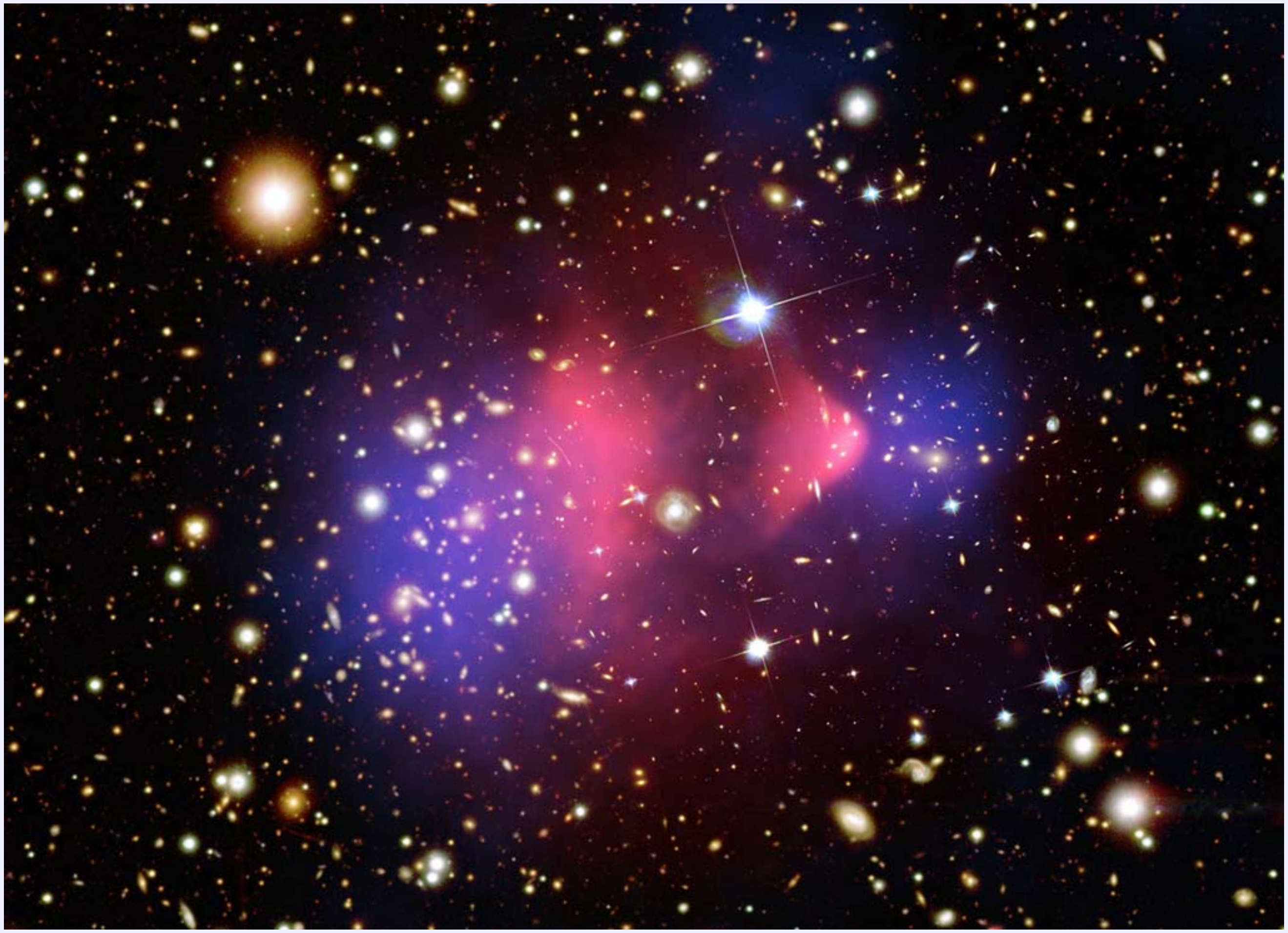
Structure from the Sachs-Wolfe Effect

3° K Background – contrast enhanced 100,000 times

WMAP



Bullet Cluster



Summary

- Existence of Dark Matter seems to be the simplest explanation for a large variety of dynamical, photometric, gravitational lensing, and microwave effects
- Occam's razor suggests that barring new physics (MOND) the existence of dark matter is quite compelling
- Determining what it is, seems to be the next step