Dark Matter: Observational Constraints

Properties of Dark Matter:

What is it? And what isn't it?

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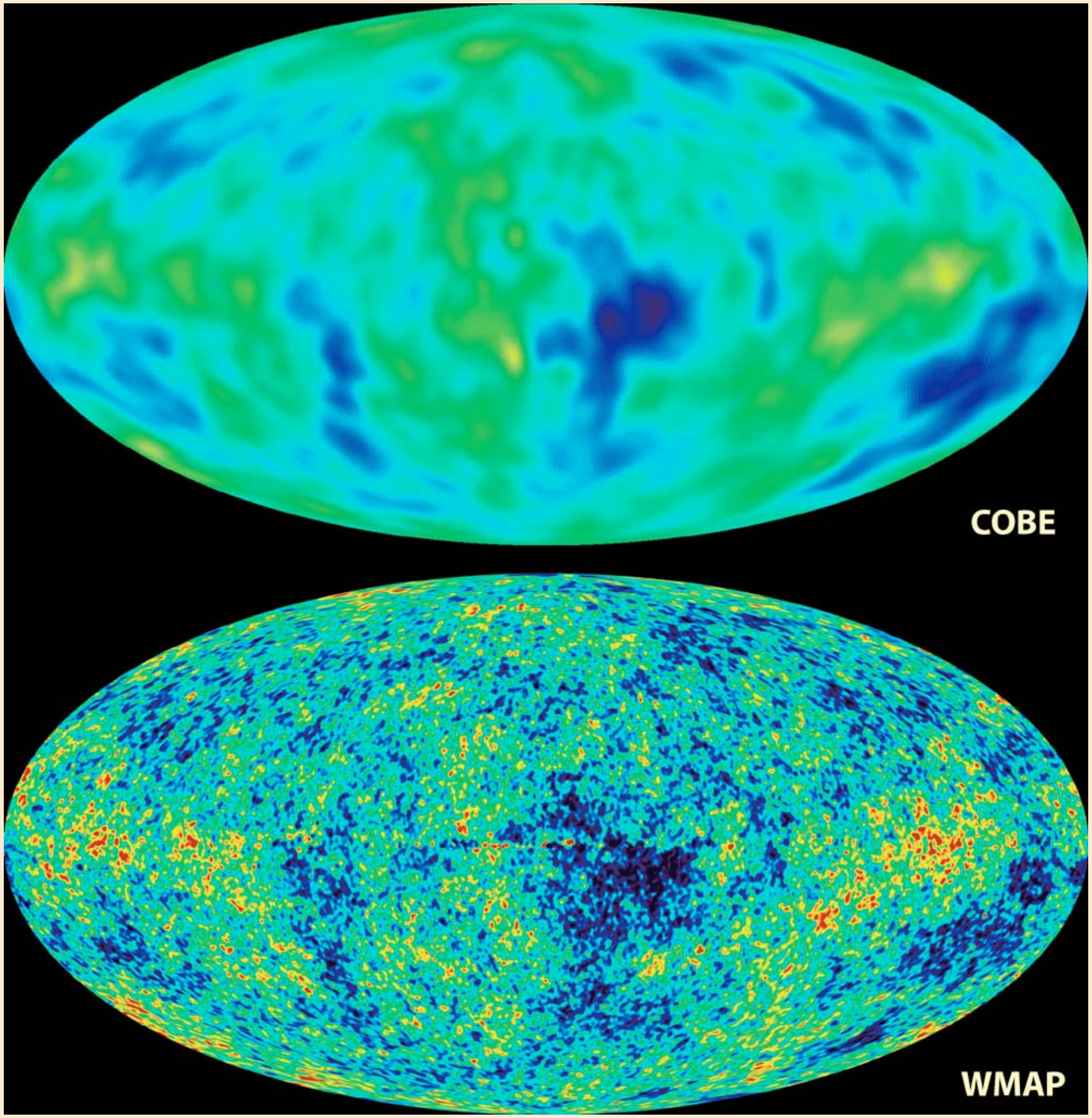
Stanford July 31, 2007

How much is there?

- WMAP results
- Rotation curves of Galaxies
- Dwarf Galaxies
- Ultrafaint Dwarf Galaxies?

WMAP



Power Law Spectrum of the CMB

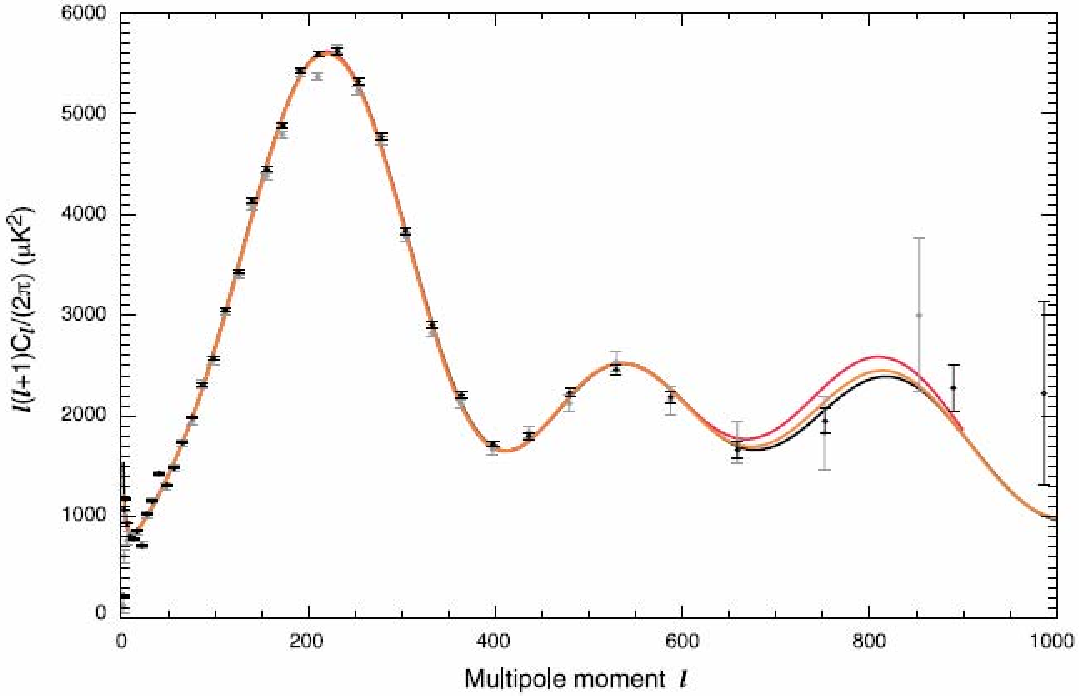


FIG. 2.—Comparison of the predictions of the different best-fit models to the data. The black line is the angular power spectrum predicted for the best-fit 3 year *WMAP* only ΛCDM model. The red line is the best fit to the 1 year *WMAP* data. The orange line is the best fit to the combination of the 1 year *WMAP* data, CBI and ACBAR (WMAPext in Spergel et al. 2003). The solid data points represent the 3 year data and the light gray data points the first-year data.

3 yr WMAP results (Spergel et al. 2007)

WMAP Results

TABLE 2

Power-Law ΛCDM Model Parameters and 68% Confidence Intervals

Parameter	First-Year Mean	WMAPext Mean	3 Year Mean (No SZ)	3 Year Mean	3 Year + ALL Mean
$100\Omega_b h^2$	$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08	2.229 ± 0.073	2.186 ± 0.068
$\Omega_m h^2$	$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009	$0.1277^{+0.0080}_{-0.0079}$	$0.1324^{+0.0042}_{-0.0041}$
H_0	72^{+5}_{-5}	73^{+3}_{-3}	73.5 ± 3.2	$73.2^{+3.1}_{-3.2}$	$70.4^{+1.5}_{-1.6}$
τ	$0.17^{+0.08}_{-0.07}$	$0.15^{+0.07}_{-0.07}$	$0.088^{+0.029}_{-0.030}$	0.089 ± 0.030	$0.073^{+0.027}_{-0.028}$
n_s	$0.99^{+0.04}_{-0.04}$	$0.98^{+0.03}_{-0.03}$	0.961 ± 0.017	0.958 ± 0.016	0.947 ± 0.015
Ω_m	$0.29^{+0.07}_{-0.07}$	$0.25^{+0.03}_{-0.03}$	0.234 ± 0.035	0.241 ± 0.034	0.268 ± 0.018
σ_8	$0.92^{+0.1}_{-0.1}$	$0.84^{+0.06}_{-0.06}$	0.76 ± 0.05	$0.761^{+0.049}_{-0.048}$	$0.776^{+0.031}_{-0.032}$

Parameter	First-Year ML	WMAPext ML	3 Year ML (No SZ)	3 Year ML	3 Year + ALL ML
$100\Omega_b h^2$	2.30	2.21	2.23	2.22	2.19
$\Omega_m h^2$	0.145	0.138	0.125	0.127	0.131
H_0	68	71	73.4	73.2	73.2
τ	0.10	0.10	0.0904	0.091	0.0867
n_s	0.97	0.96	0.95	0.954	0.949
Ω_m	0.32	0.27	0.232	0.236	0.259
σ_8	0.88	0.82	0.737	0.756	0.783

Notes.—The 3 Year fits in the columns labeled "No SZ" use the likelihood formalism of the first-year paper and assume no SZ contribution, $A_{SZ} = 0$, to allow direct comparison with the first-year results. Fits that include SZ marginalization are given in the last two columns of the upper and lower parts of the table and represent our best estimate of these parameters. The last column includes all data sets.

WMAP 3 yr results

Para	3 Year + ALL Mean
$100\Omega_b h^2$	2.186 ± 0.068
$\Omega_m h^2$	$0.1324^{+0.0042}_{-0.0041}$
H_0	$70.4^{+1.5}_{-1.6}$
τ	$0.073^{+0.027}_{-0.028}$
n_s	0.947 ± 0.015
Ω_m	0.268 ± 0.018
σ_8	$0.776^{+0.031}_{-0.032}$

Para	3 Year + ALL ML
$100\Omega_b h^2$	2.19
$\Omega_m h^2$	0.131
H_0	73.2
τ	0.0867
n_s	0.949
Ω_m	0.259
σ_8	0.783

NOTES.ıme no SZ contribution, $A_{SZ} = 0$, to columns of the upper and lower.

Spergel et al. (2007)

Ω_b = 4.46 % of $\Omega = 1$

Ω_m = 27.0 % of $\Omega = 1$

Dark Matter is 83% of total matter in the Universe. Majority of the rest is hot gas.

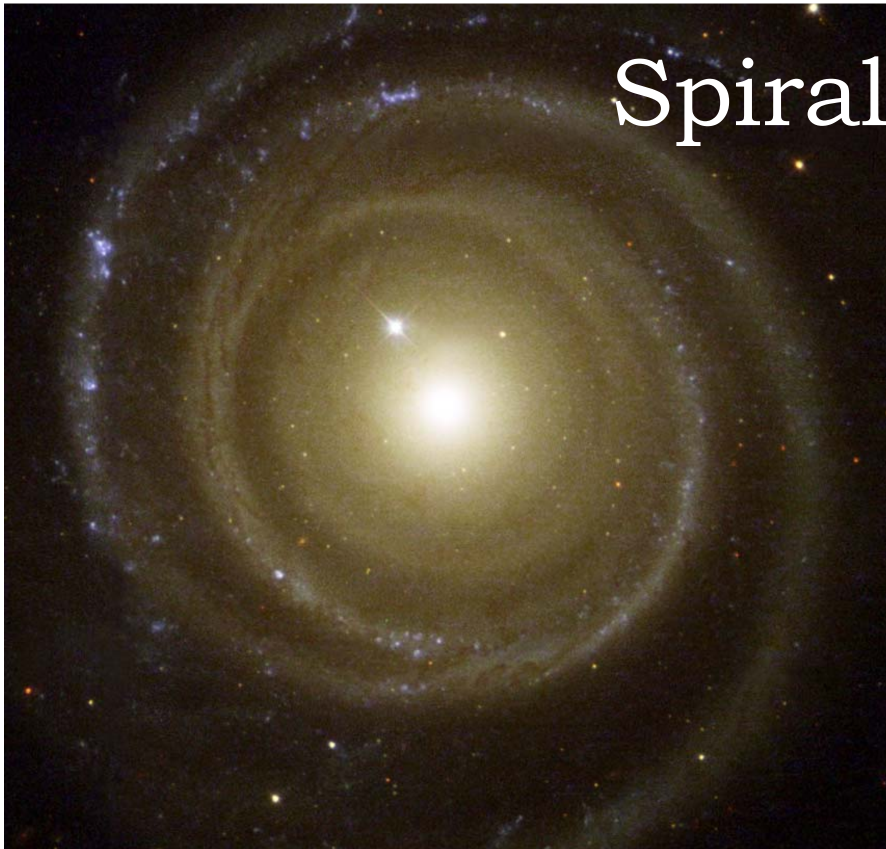
Consistent with results from SZE

How much is there?

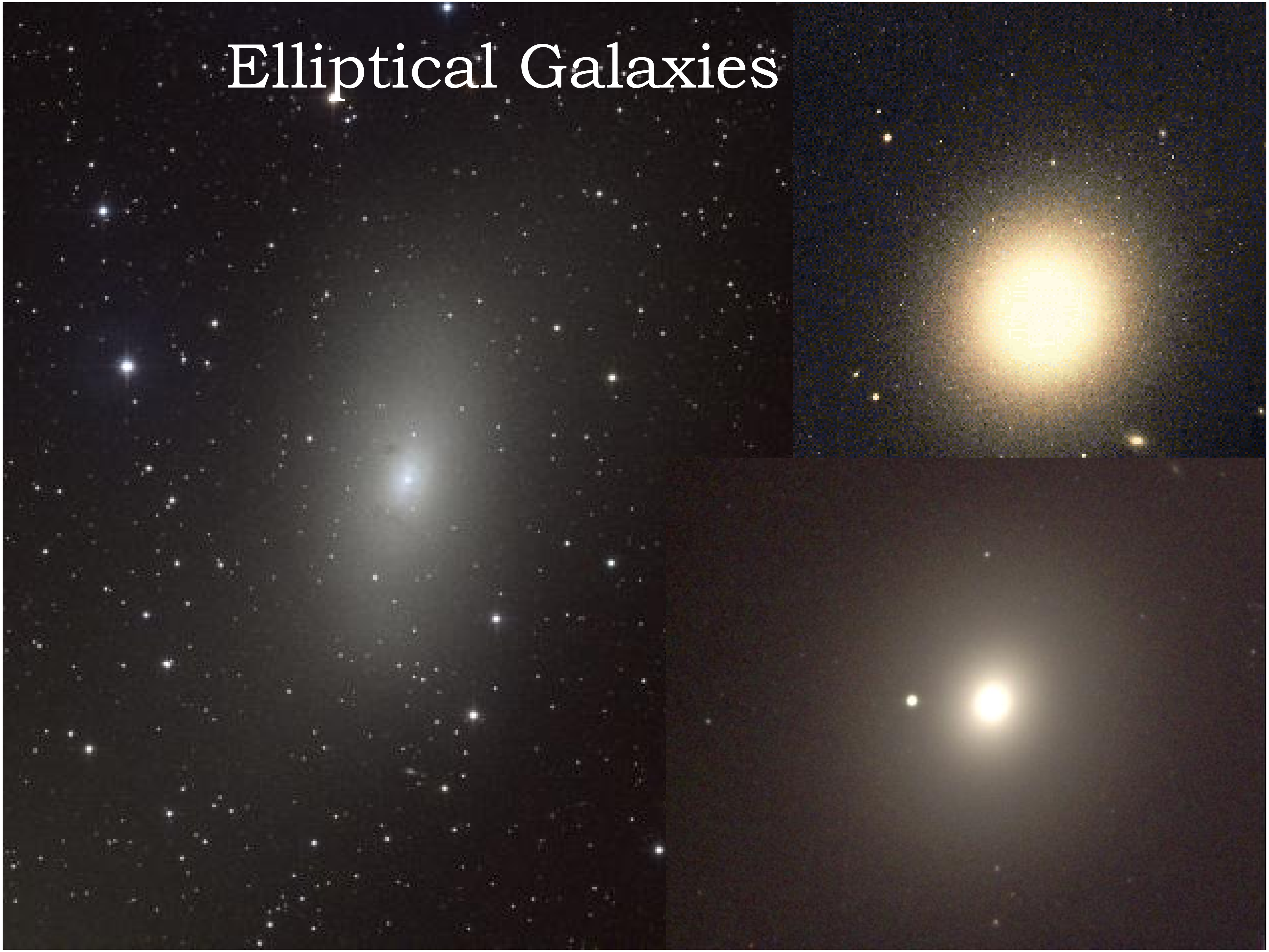
- WMAP results
- Rotation curves of Galaxies
  - Typically factor of 5 – 10 times more dark matter than luminous matter (including dead matter)
- Dwarf Galaxies
  - May have 50 – 100 times as much dark matter as luminous matter
- Ultrafaint Dwarf Galaxies?

Spiral Galaxies

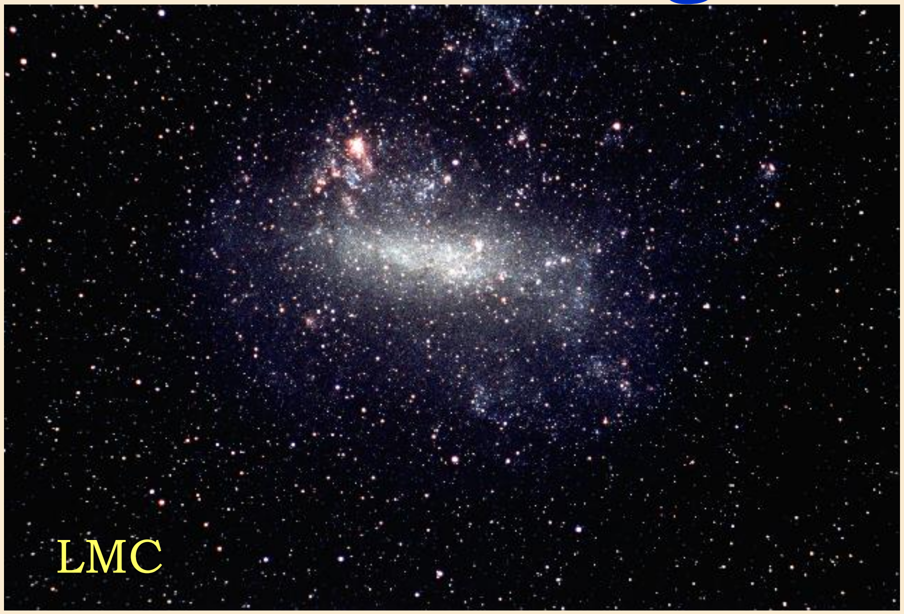
Spiral Galaxies

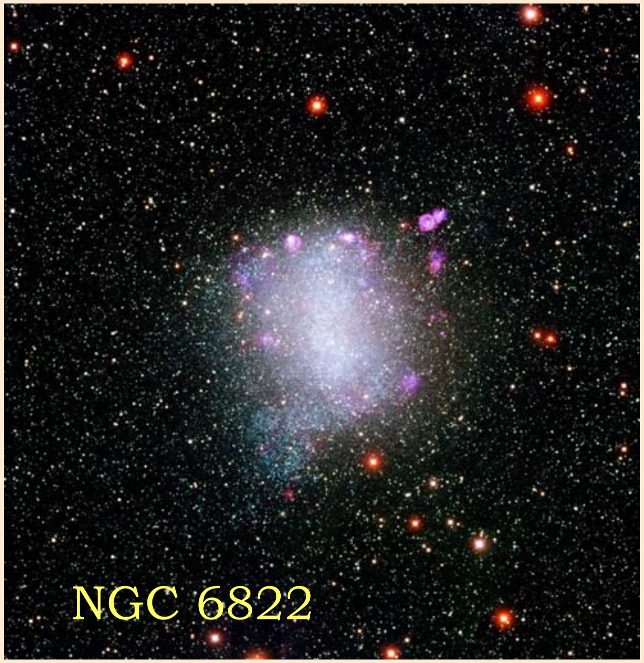


Elliptical Galaxies

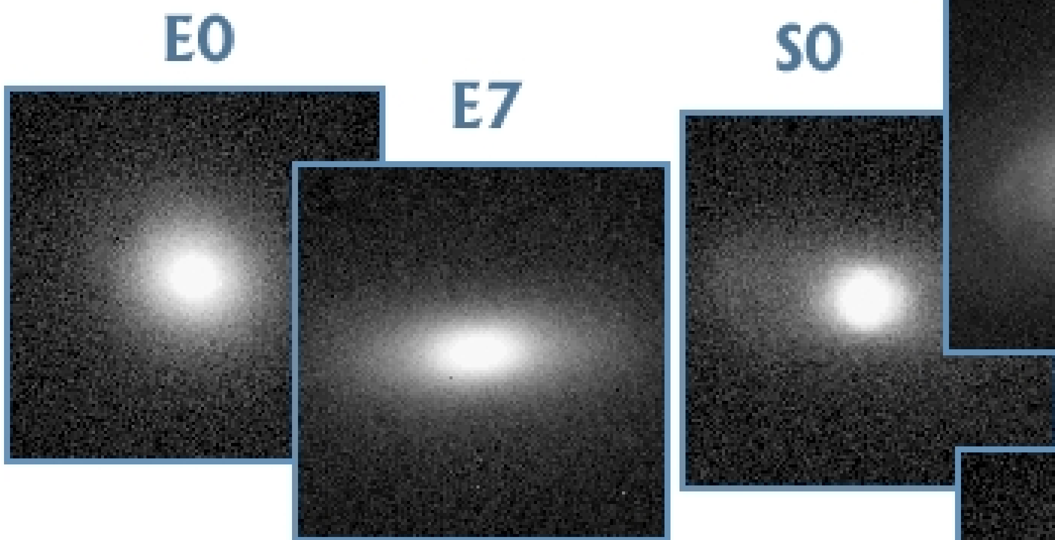


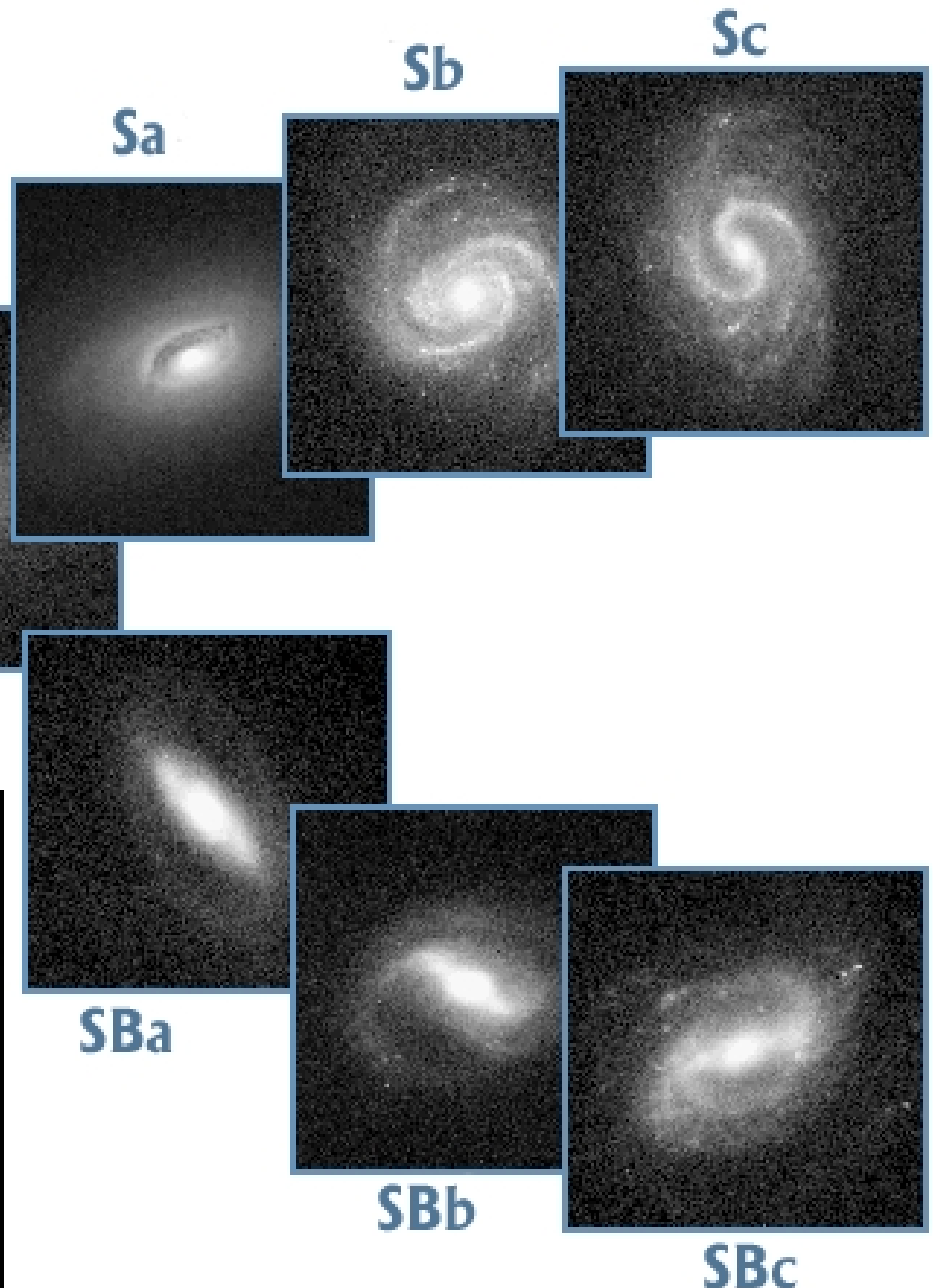
Irregular Galaxies

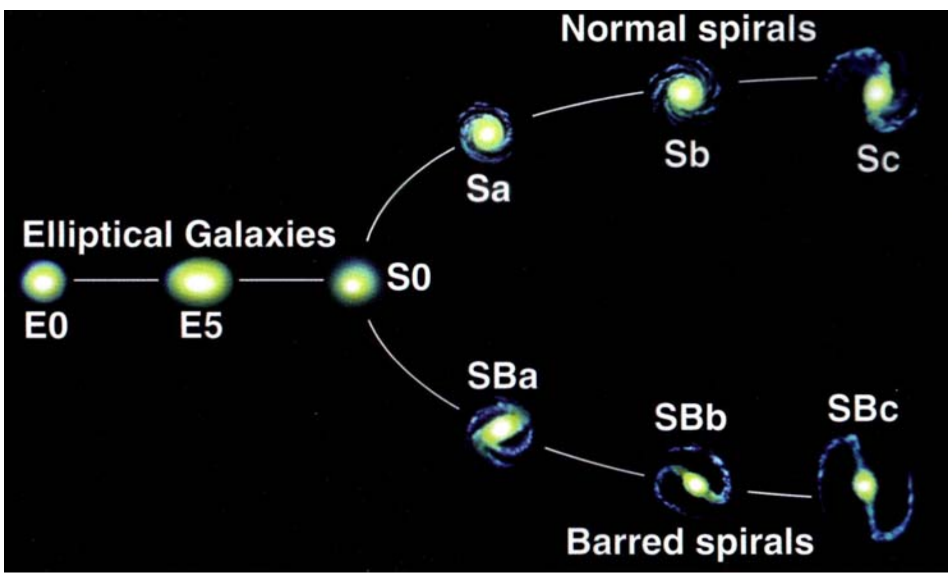




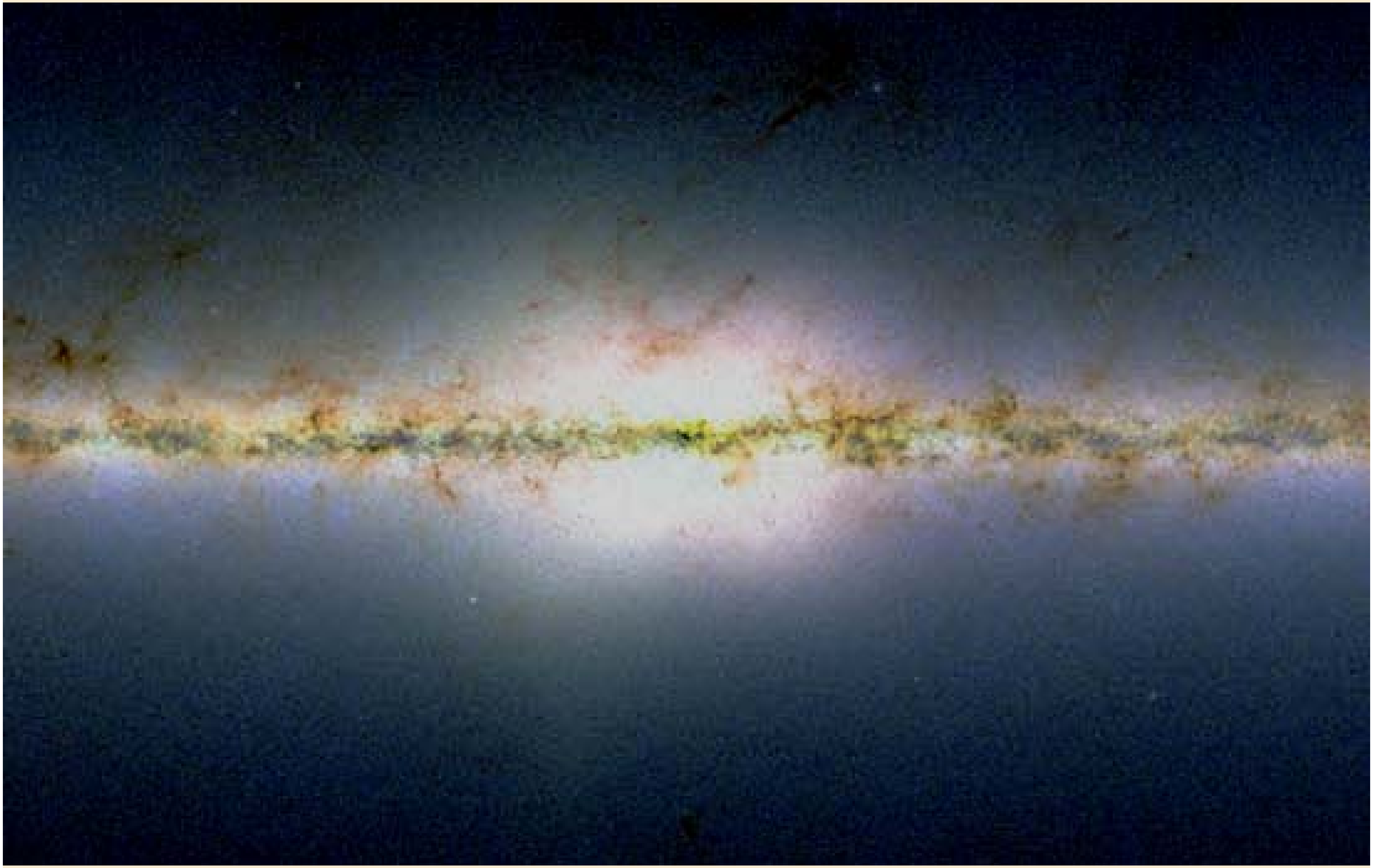
Classification of Galaxies

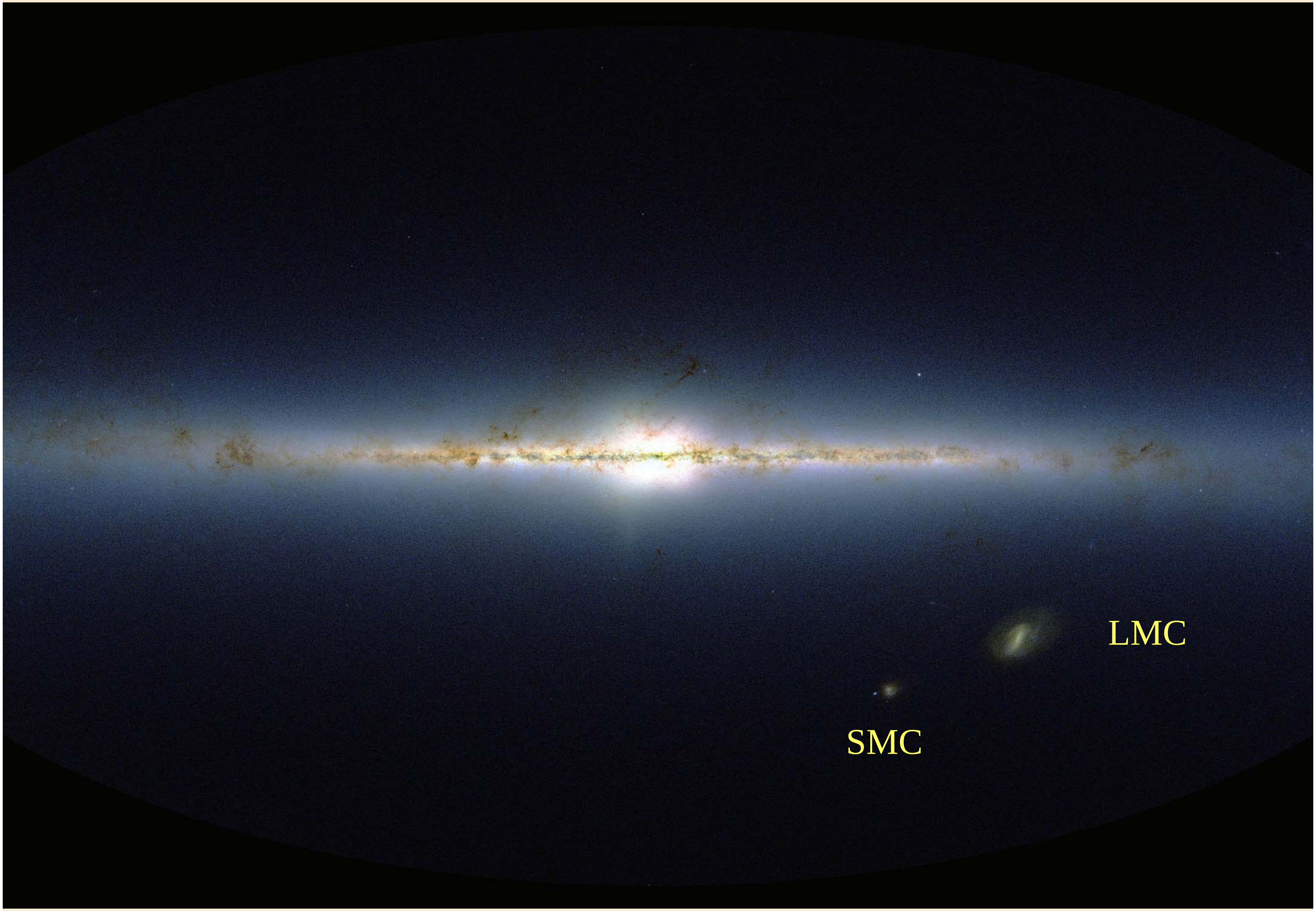






The Milky Way is a barred galaxy




LMC
SMC

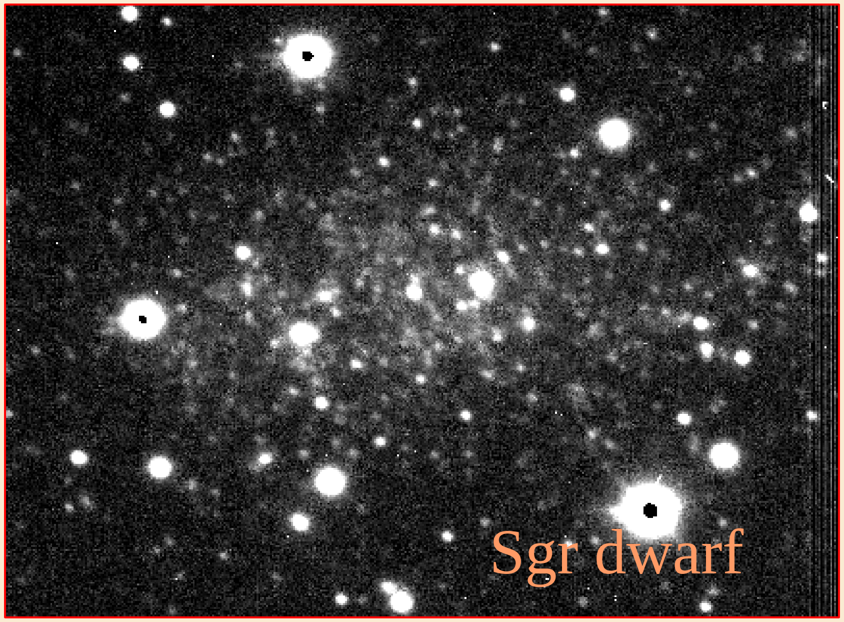

Large Magellanic Cloud
Distance = 55 kpc


UKS 17
Small Magellanic Cloud

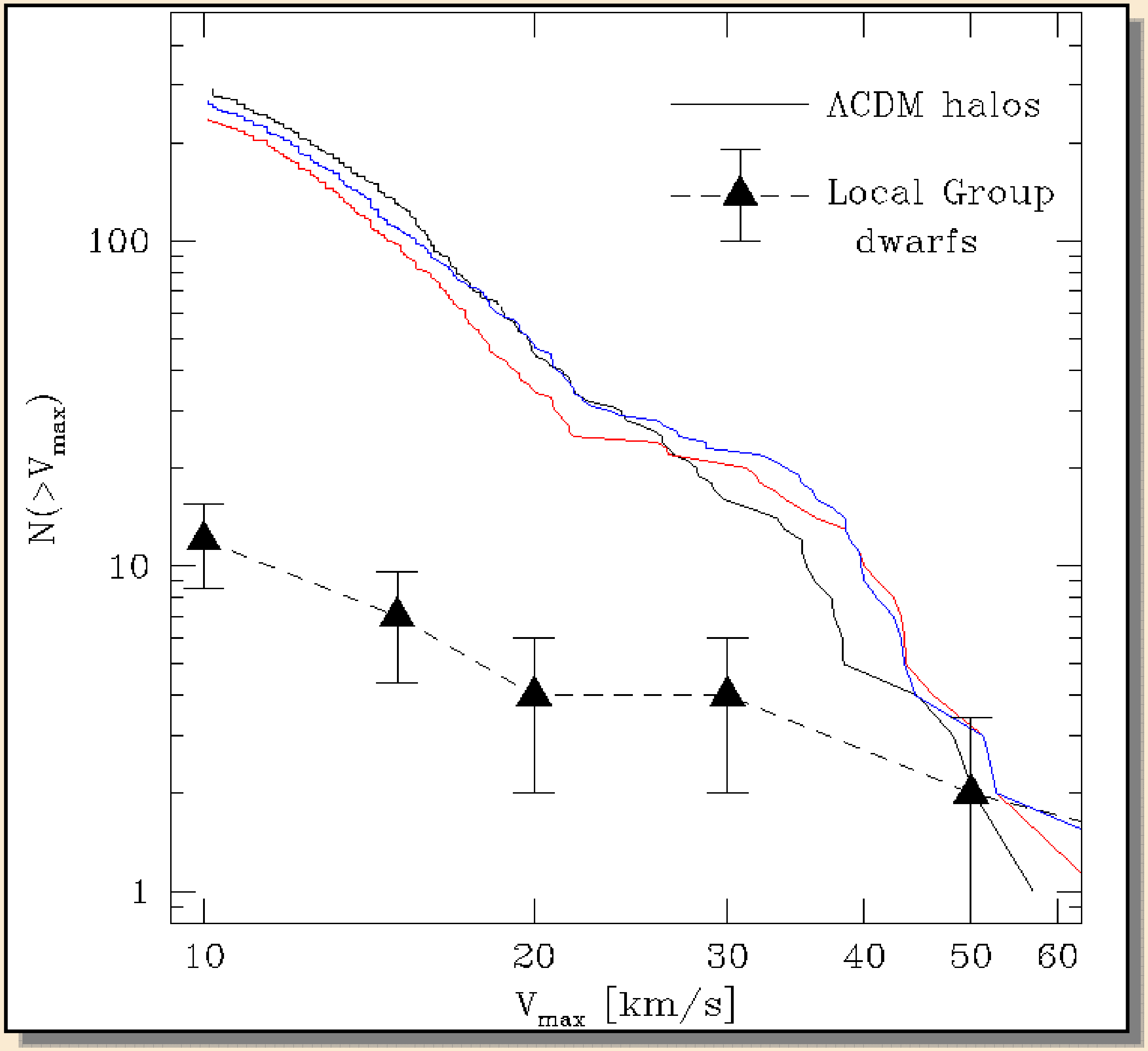

Sextans A


AAT 51
Leo I
© Anglo-Australian Observatory


Antlia

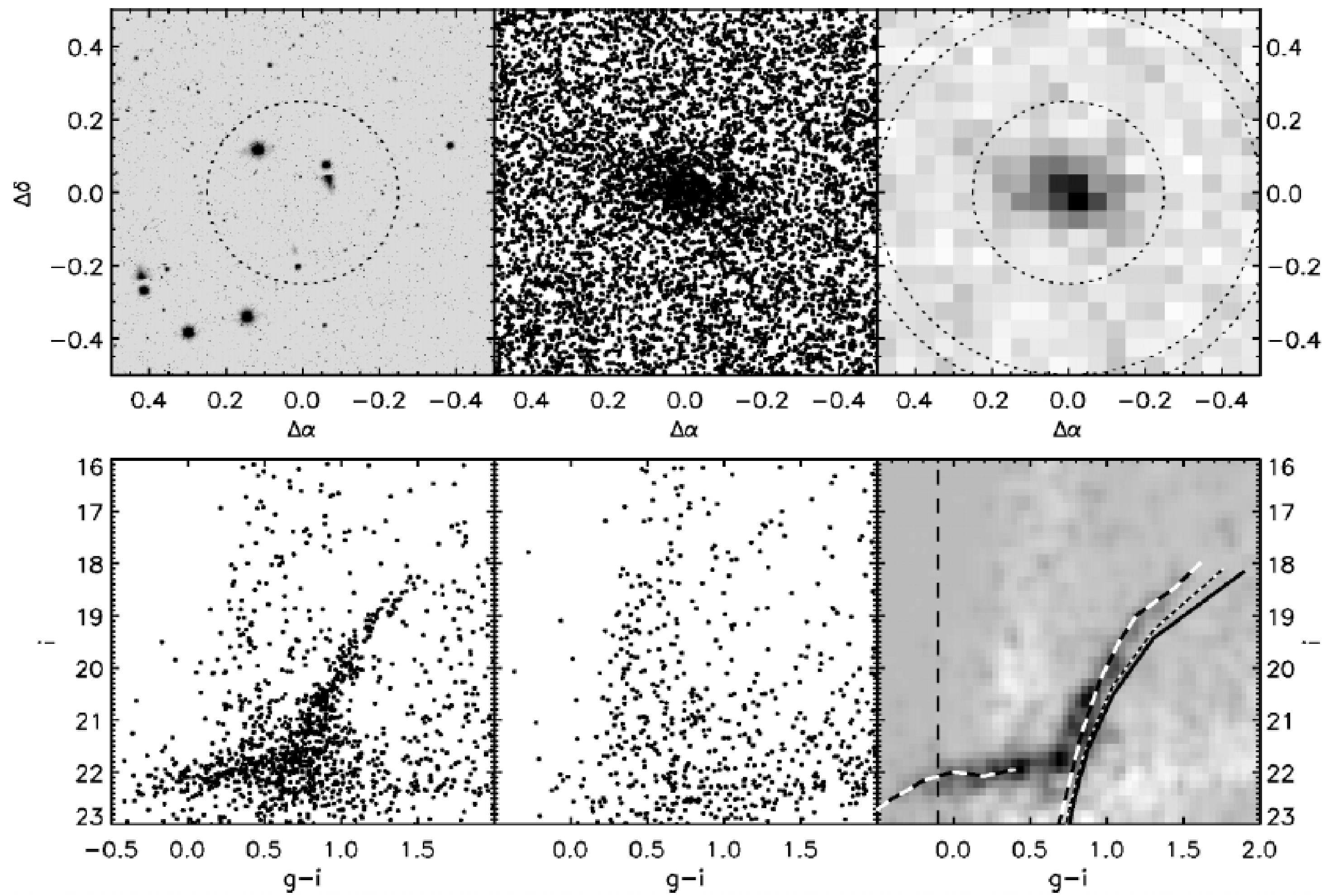

Sgr dwarf

Predicted and Observed Local Group Halos

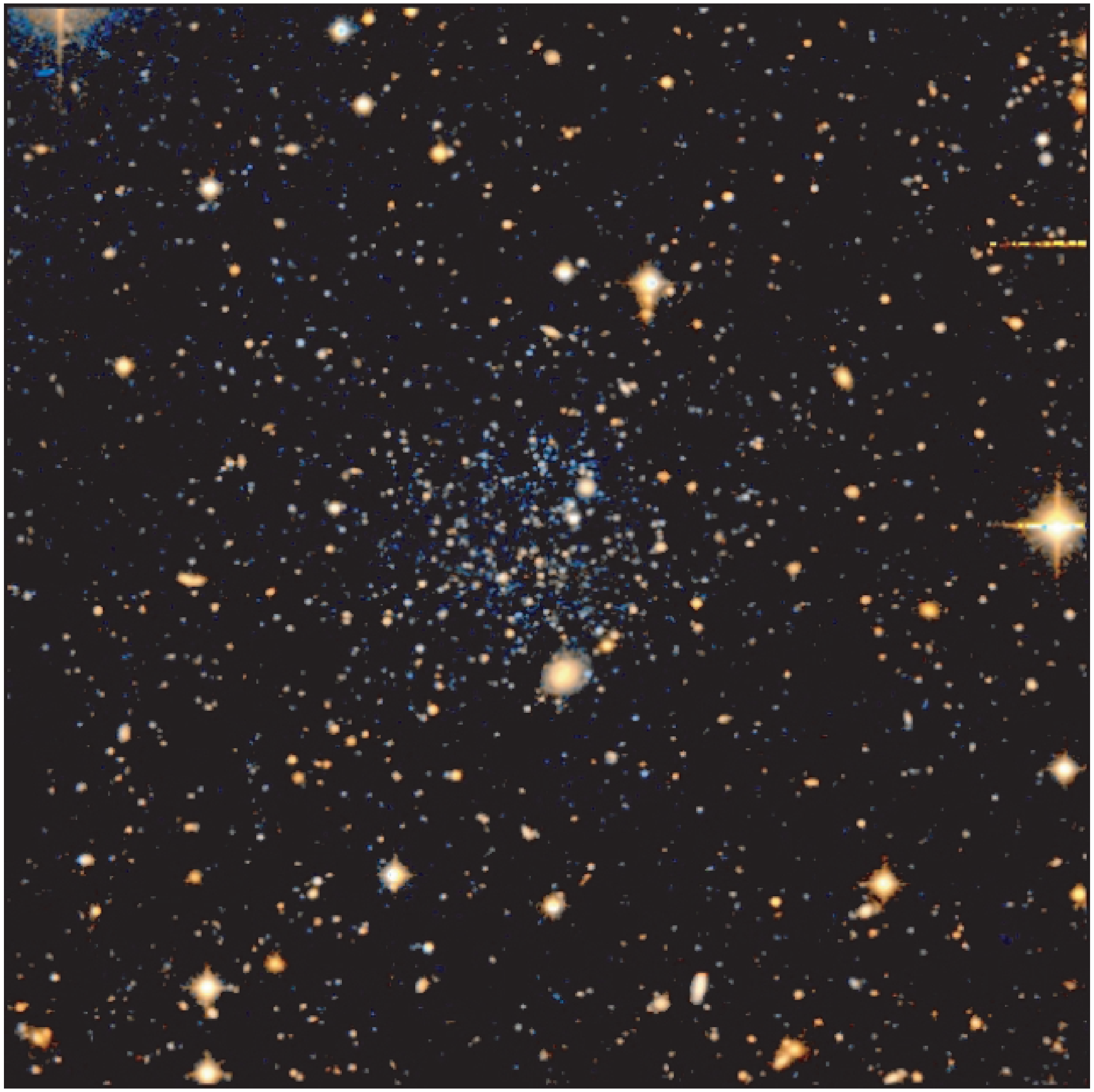


Klypin 2003

SDSS finds 20 new faint dwarf systems in the Local Group, increasing the number of LG galaxies by 20%



Leo T

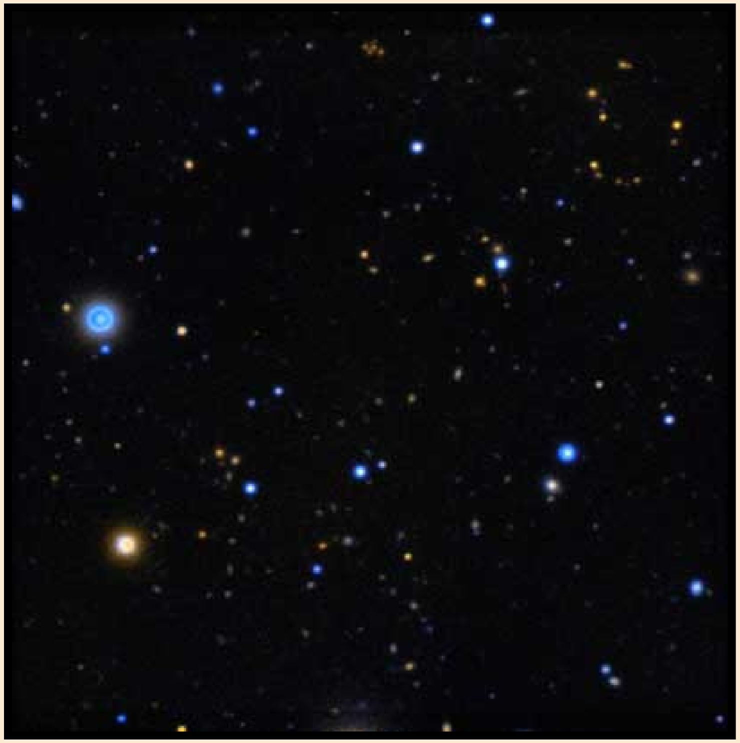


New SDSS Dwarfs

Old dwarfs (Leo II)

Palomar Sky Survey

New dwarfs (Ursa Major I)



Willman et al. (2005)

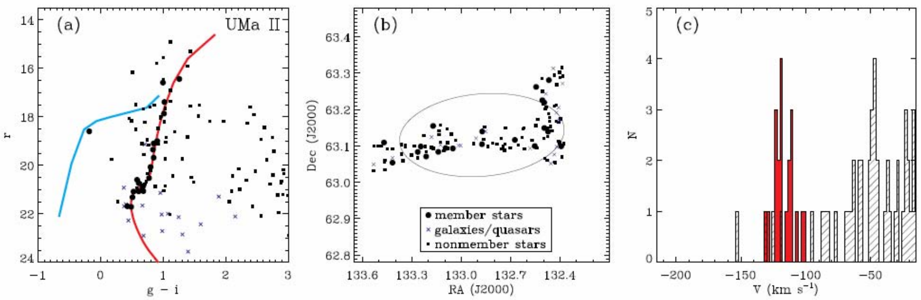


FIG. 2.— (*a*) Color-magnitude diagram of observed stars in Ursa Major II. The large black circles represent stars identified as radial velocity members of the galaxy, the small black dots represent stars identified as non-members, and the blue crosses are spectroscopically confirmed background galaxies and quasars. The red curve shows the location of the red giant branch, subgiant branch, and main sequence turnoff populations in the globular cluster M92 and the blue curve shows the location of the horizontal branch of M13, both corrected for Galactic extinction and shifted to a distance of 32 kpc (data from Clem 2005). (*b*) Spatial distribution of observed stars in Ursa Major II. Symbols are the same as in (*a*) (the figure legend applies to both panels), and the ellipse represents the half-light radius of UMa II from Zucker et al. (2006b). (*c*) Velocity histogram of observed stars in Ursa Major II. Velocities are corrected to the heliocentric rest frame. The filled red histogram represents stars classified as members, and the hatched black-and-white histogram represents non-members. The velocity bins are 2 km s^{-1} wide.

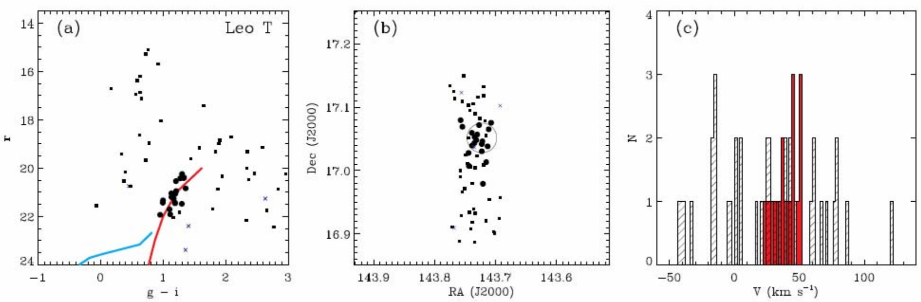


FIG. 3.— Same as Figure 2, but for Leo T.

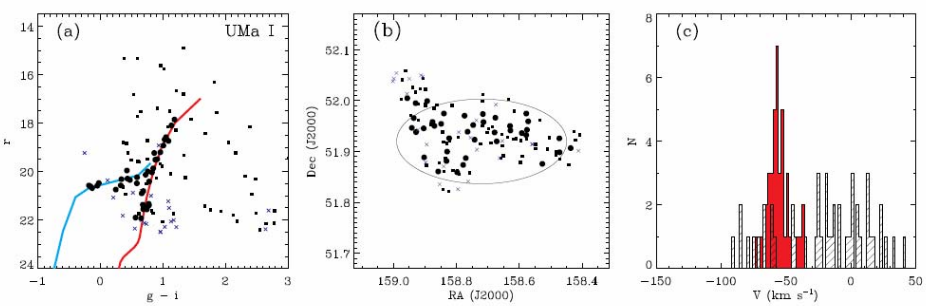


FIG. 4.— Same as Figure 2, but for Ursa Major I.

Simon & Geha (2007)

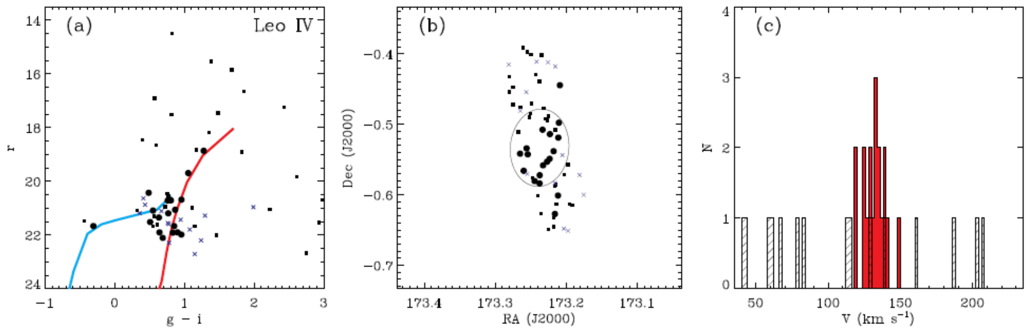


FIG. 5.— Same as Figure 2, but for Leo IV.

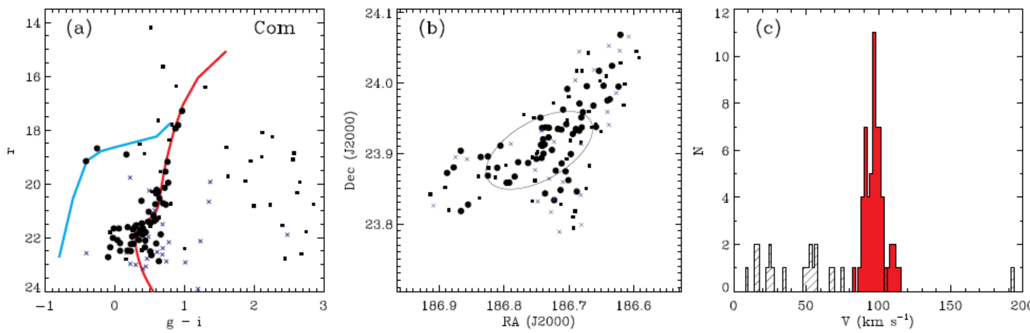


FIG. 6.— Same as Figure 2, but for Coma Berenices.

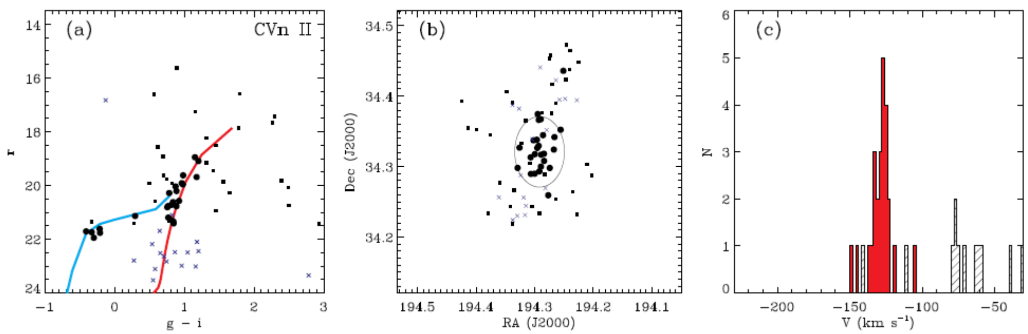


FIG. 7.— Same as Figure 2, but for Canes Venatici II.

Simon & Geha (2007)

Properties of New Milky Way Dwarfs

TABLE 6
PARAMETERS OF THE ULTRA-FAINT MILKY WAY SATELLITES

Galaxy	M_V	distance (kpc)	$r_{Plummer}$ (arcmin)	$r_{Plummer}$ (pc)	References
Ursa Major II	-3.8 ± 0.6	32^{+5}_{-4}	13.6	127 ± 21	(1),(2)
Leo T	-7.1 ± 0.3	417^{+20}_{-19}	1.4	170 ± 15	(3)
Ursa Major I	-5.6 ± 0.6	106^{+9}_{-8}	10.0	308 ± 32	(2),(4),(5)
Leo IV	-5.1 ± 0.6	158^{+15}_{-14}	3.3	152 ± 17	(6)
Coma Berenices	-3.7 ± 0.6	44 ± 4	5.0	64 ± 7	(6)
Canes Venatici II	-4.8 ± 0.6	151^{+15}_{-13}	3.0	132 ± 16	(6)
Canes Venatici I	-7.9 ± 0.5	224^{+22}_{-20}	8.5 ± 0.5	554 ± 63	(7)
Hercules	-6.0 ± 0.6	138^{+13}_{-12}	8.0	321 ± 36	(6)
Segue 1	-3.0 ± 0.6	23 ± 2	4.5	30 ± 3	(6)
Willman 1	-2.5 ± 1.0	38 ± 7	1.9 ± 0.3	21 ± 5	(8)
Boötes II	-3.1 ± 1.1	60 ± 6	4.1 ± 1.6	72 ± 28	(9)
Boötes	-5.8 ± 0.5	60 ± 6	13.0 ± 0.7	227 ± 26	(3)

REFERENCES. — (1) Zucker et al. 2006b; (2) D. Zucker & V. Belokurov 2007, private communication; (3) Irwin et al. 2007; (4) Belokurov et al. 2006b; (5) this work; (6) Belokurov et al. 2007b; (7) Zucker et al. 2006a; (8) Willman et al. 2006; (9) Walsh et al. 2007

Simon & Geha (2007)

M/L of new Milky Way UF Dwarfs

TABLE 4
MASSES, MASS-TO-LIGHT RATIOS, AND METALLICITIES

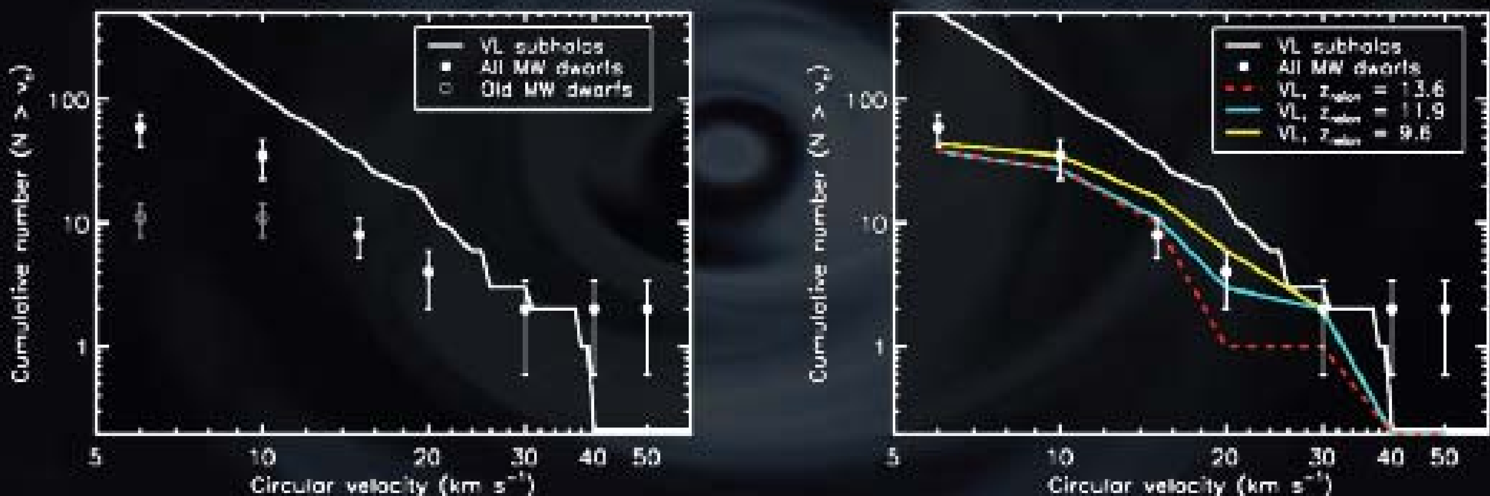
Galaxy	Mass ($M_\odot$)	M/L_V ($M_\odot/L_\odot$)	[Fe/H]	$\sigma_{[Fe/H]}$
Ursa Major II[a]	$4.9 \pm 2.2 \times 10^6$	1722 ± 1226	-1.97 ± 0.15	0.28
Leo T	$8.2 \pm 3.6 \times 10^6$	138 ± 71	-2.29 ± 0.10	0.35
Ursa Major I	$1.5 \pm 0.4 \times 10^7$	1024 ± 636	-2.06 ± 0.10	0.46
Leo IV	$1.4 \pm 1.5 \times 10^6$	151 ± 177	-2.31 ± 0.10	0.15
Coma Berenices	$1.2 \pm 0.4 \times 10^6$	448 ± 297	-2.00 ± 0.07	0.00
Canes Venatici II	$2.4 \pm 1.1 \times 10^6$	336 ± 240	-2.31 ± 0.12	0.47
Canes Venatici I	$2.7 \pm 0.4 \times 10^7$	221 ± 108	-2.09 ± 0.02	0.23
Hercules	$7.1 \pm 2.6 \times 10^6$	332 ± 221	-2.27 ± 0.07	0.31

[a] UMa II may be a tidally disrupted remnant, which would artificially inflate its mass and mass-to-light ratio.

Simon & Geha (2007)

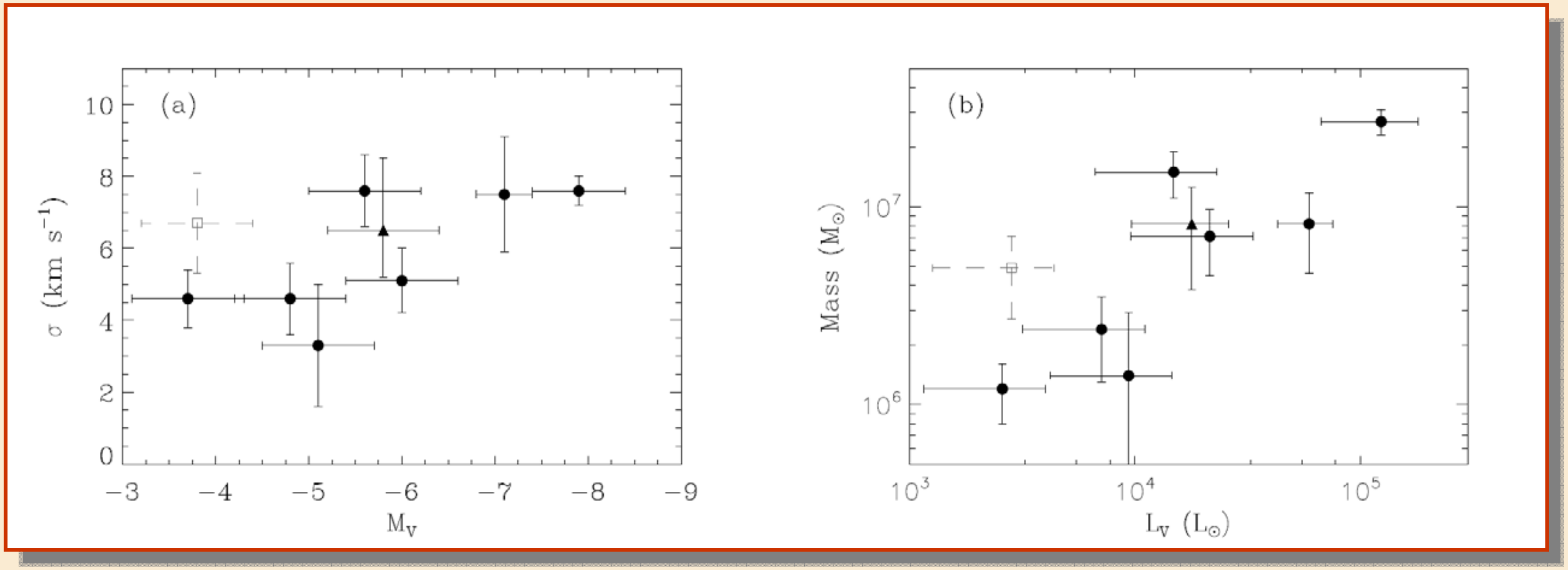
Are There Still Satellites Missing?

Comparison to Via Lactea N-body simulation (Diemand et al. 2007)



Simon & Geha (2007)

M/L of new Milky Way UF Dwarfs



Simon & Geha (2007)

Inconsistent with minimum halo mass of 3 x 10^7 $M_\odot$ (Gilmore et al. 2007)

Also inconsistent with claimed maximum dark matter density; Simon & Geha find up to about 5 Gev/c^2 or 2.1 $M_\odot$ pc^{-3}

How much is there?

- WMAP results
- Rotation curves of Galaxies
  - Typically factor of 5 – 10 times more dark matter than luminous matter (including dead matter)
- Dwarf Galaxies
  - May have 20 - 50 times as much dark matter as luminous matter
- Ultrafaint Dwarf Galaxies?
  - M/L → 1000; up to 200 – 500 times as much dark matter as luminous

Where Doesn't Dark Matter Exist?

- High Latitude Molecular Clouds
  - Blitz, Magnani, & Mundy (1984)
- Star Clusters (open and globular)
- High Velocity Clouds

Where Doesn’t Dark Matter Exist?

- High Latitude Molecular Clouds
  - Blitz, Magnani, &Mundy (1984)

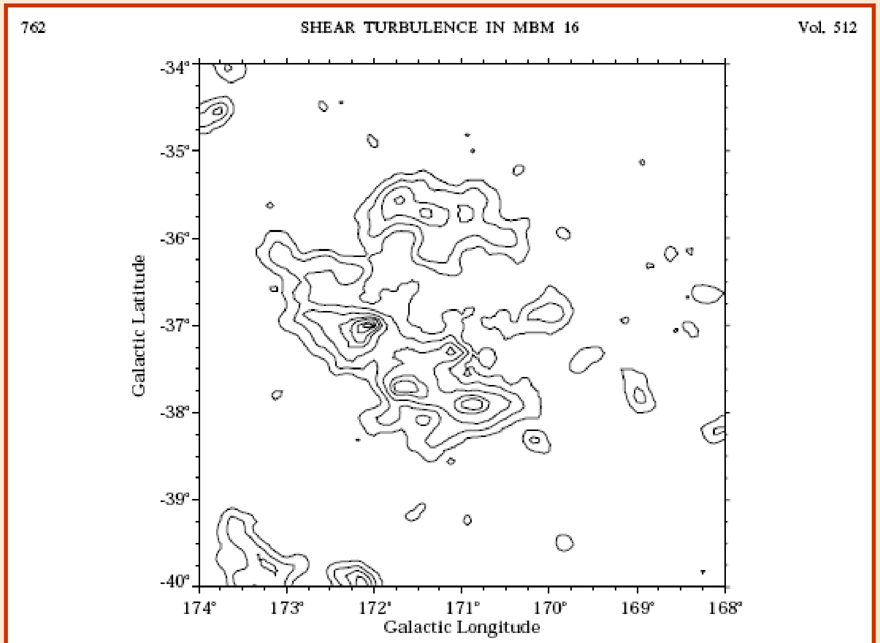


Fig. 1.—^{12}CO $J = 1$–0 contour map of a 6° × 6° region centered on MBM 16. The velocity range of the map is -10 km s^{-1} ≤ v_{LSR} ≤ 15 km s^{-1}. The contours are at [10, 30, 50, 70, 80, 90, and 95] percent of the maximum CO intensity of 7.23 K km s^{-1}. The objects to the extreme northeast and southeast of the map are probably not associated with MBM 16 (see text). The size of the 8.4 beam, the effective map resolution, is shown in the upper right-hand corner.

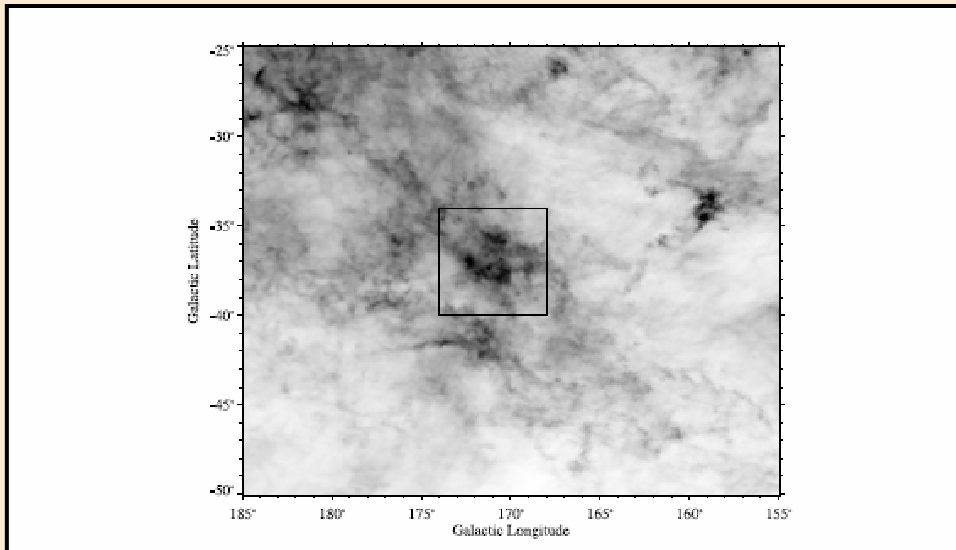


Fig. 1.—*IRAS* 100 μm map of MBM 16 and vicinity. The data are in raw form but give a good summary of the total gas and dust in the region. The translucent cloud, MBM 16, is located at 170° < l < 173°, −39° < b < −35°. At l ~ 173°, b ~ −40° is the top of a bright cirrus feature extending southward; the top of this feature also contains molecular gas (the southern extension has not been searched for CO emission) but is probably not associated with MBM 16 (see text). Similarly, the cirrus feature at l ~ 174°, b ~ −34° is also molecular but has a different velocity from the bulk of the CO emission in MBM 16.

$\sigma_v \sim$ 2-3 km s^{-1}

$M_{mol} = 100\ M_\odot$

R ~ 2 pc → M ~ 2-4x $10^3\ M_\odot$

Where Doesn't Dark Matter Exist?

- High Latitude Molecular Clouds
  - Blitz, Magnani, & Mundy (1984)

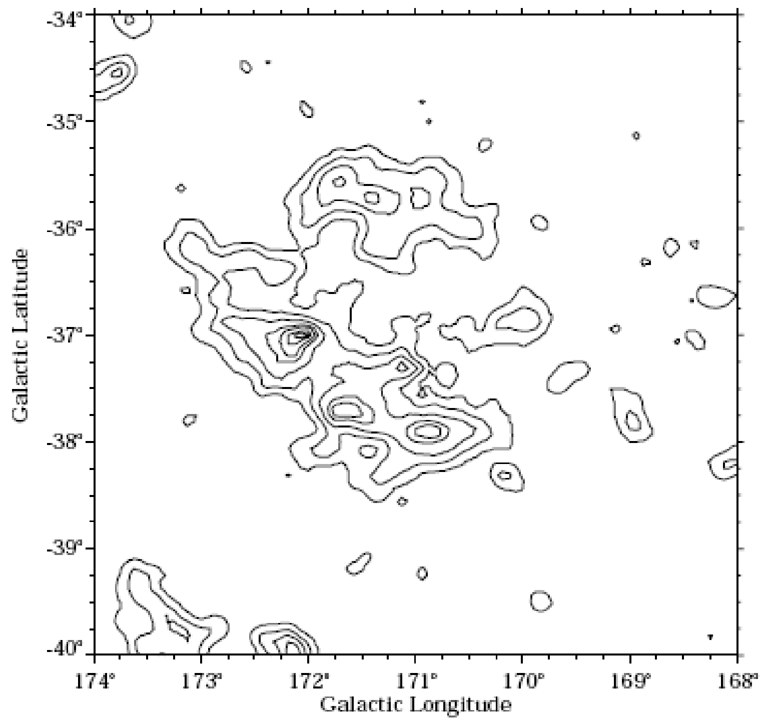


FIG. 1.—^{12}CO $J = 1$–0 contour map of a 6° × 6° region centered on MBM 16. The velocity range of the map is -10 km s^{-1} ≤ v_{LSR} ≤ 15 km s^{-1}. The contours are at [10, 30, 50, 70, 80, 90, and 95] percent of the maximum CO intensity of 7.23 K km s^{-1}. The objects to the extreme northeast and southeast of the map are probably not associated with MBM 16 (see text). The size of the 8.4 beam, the effective map resolution, is shown in the upper right-hand corner.

Where Doesn't Dark Matter Exist?

- High Latitude Molecular Clouds
  - Blitz, Magnani, & Mundy (1984)
- Star Clusters (open and globular)
- High Velocity Clouds

Where Doesn't Dark Matter Exist?

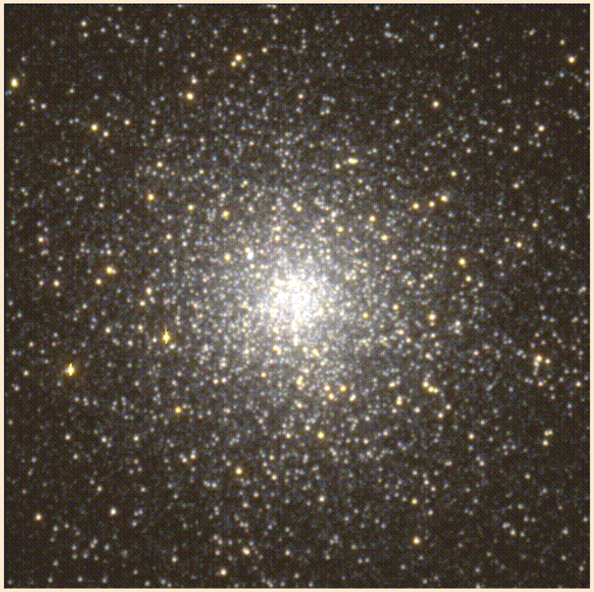
- Star Clusters (open and globular)

Pleiades

$\sigma_v \sim 0.5$ km s^{-1}

R ~ 1-2 pc → M ~ 1 x 10^2 $M_\odot$

As observed



47 Tuc

M/L ~ 1-6

But watch out for those central Black Holes!

M31 Globular clusters

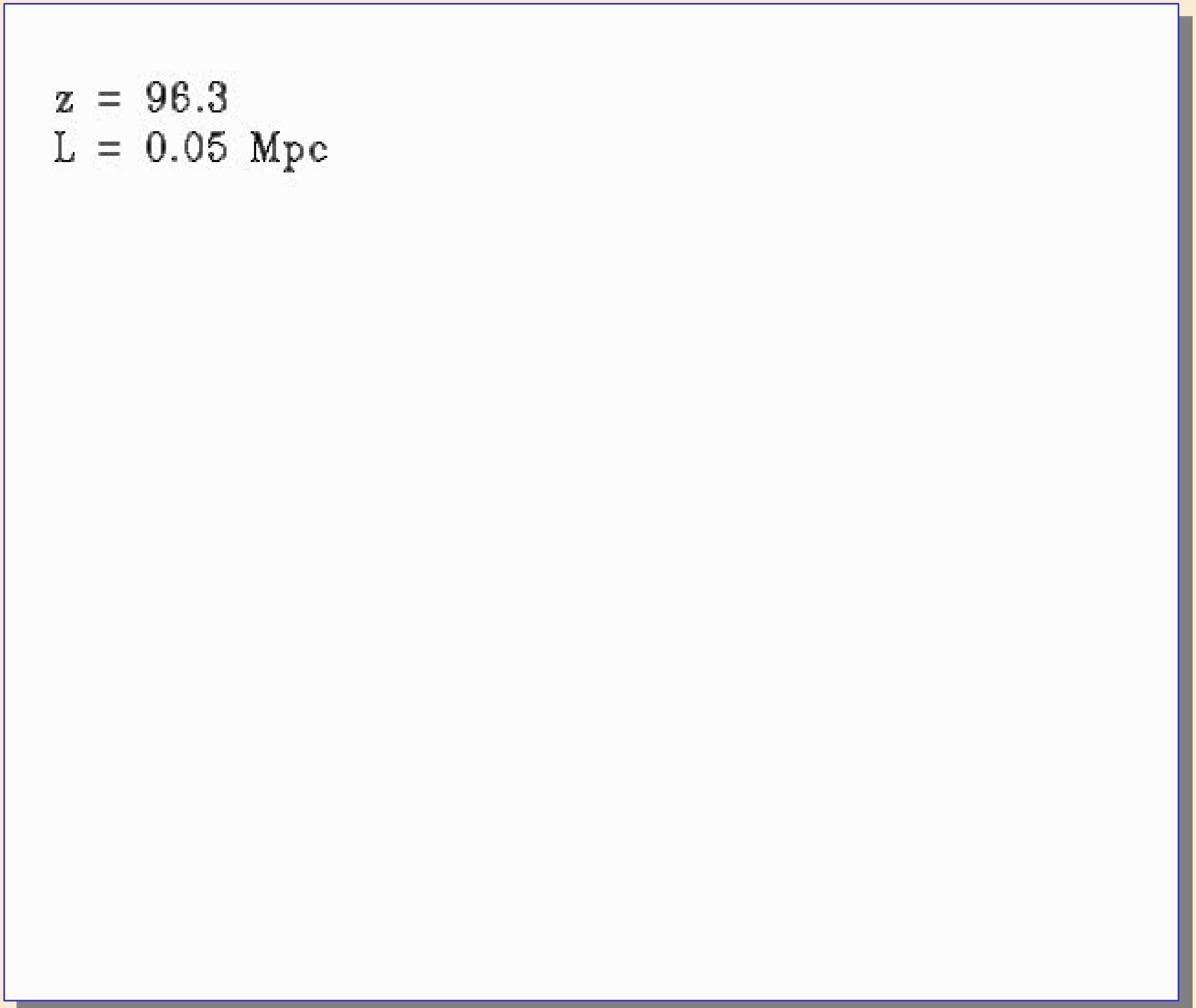
Cluster ID (1)	(2)	M_{cl} $M_\odot$ (7)	M_{cl}^{Virial} $M_\odot$ (8)	M/L_V $M_\odot/L_{\odot,V}$ (10)	M/L_V^{Virial} $M_\odot/L_{\odot,V}$ (11)
6	58	4.6×10^5	7.3×10^5	1.4	2.2
20	73	1.7×10^6	2.6×10^6	1.7	2.5
45	108	4.2×10^5	6.3×10^5	1.2	1.8
158	213	3.8×10^6	5.6×10^6	3.7	5.5
218	272	7.9×10^5	1.2×10^6	0.9	1.4
225	280	5.5×10^6	8.2×10^6	4.4	6.5
343	105	3.7×10^5	7.0×10^5	2.1	4.0
358	219	4.0×10^5	5.5×10^5	0.7	1.0
384	319	2.8×10^5	4.3×10^5	0.9	1.4

Dubath & Grillmair (1997)

Are There Dark Galaxies?

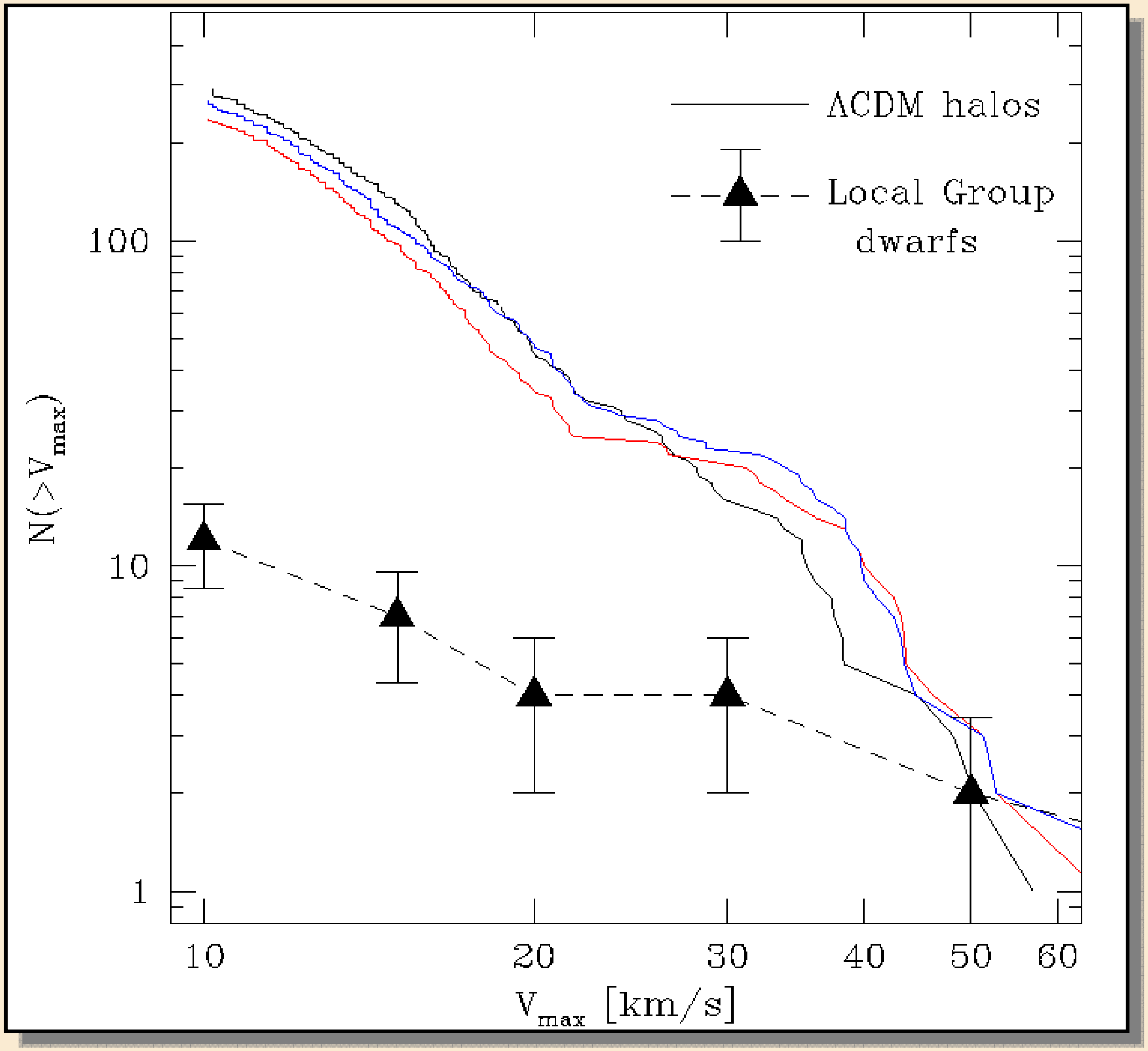
- Simulations suggest far more small DM halos than are seen as small galaxies (even with the new dwarfs).
- If $M/L > 1000$, perhaps there are some with no stars.
- Might there be some galaxies without stars, but with some gas: dark galaxies?
- Are there ways of identifying DM halos without stars and without gas?

A Simulation of the Formation of the Local Group



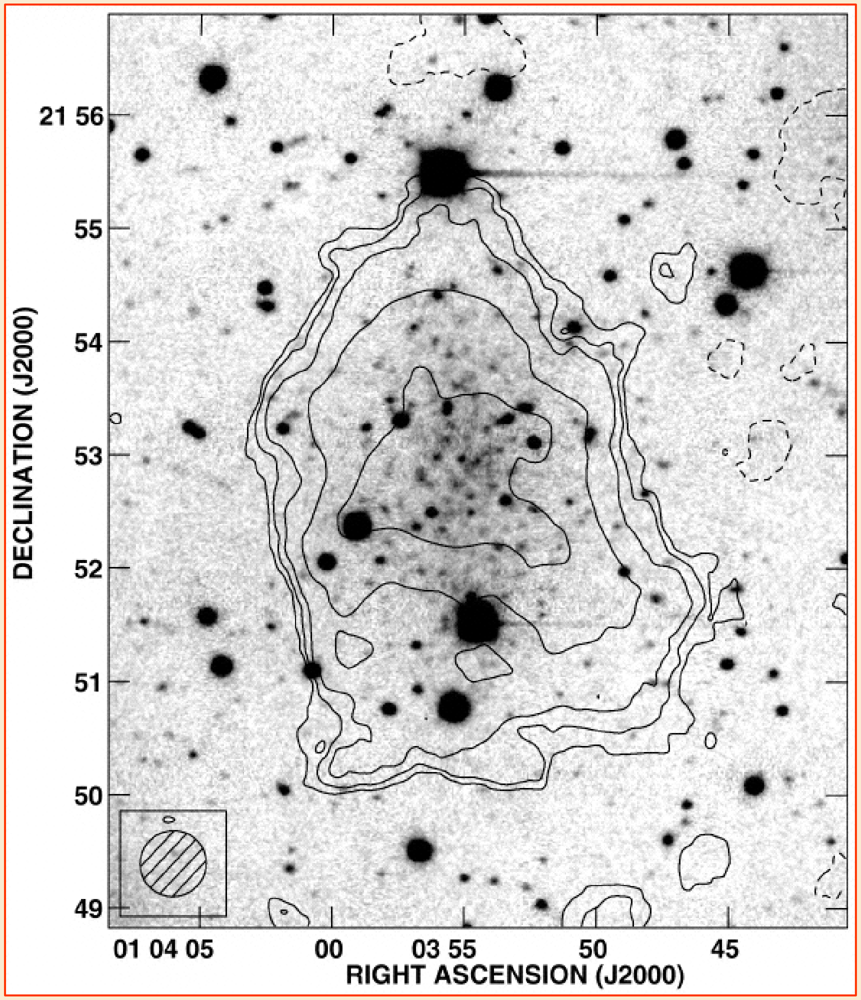
Sherfesee, Thacker & Blitz (2001)

Predicted and Observed Local Group Halos



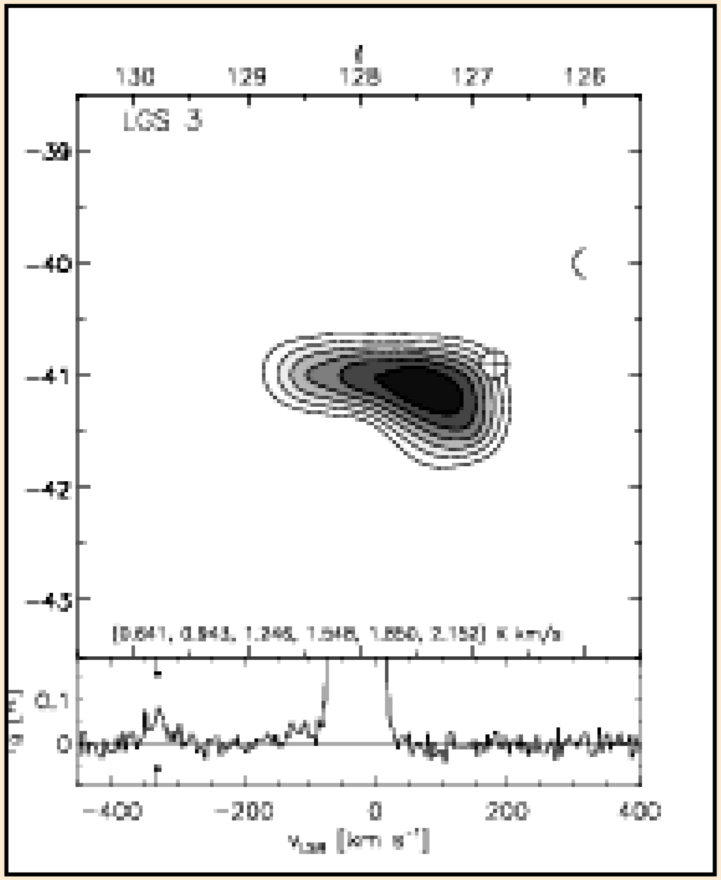
Klypin 2003

Are there halos without stars?



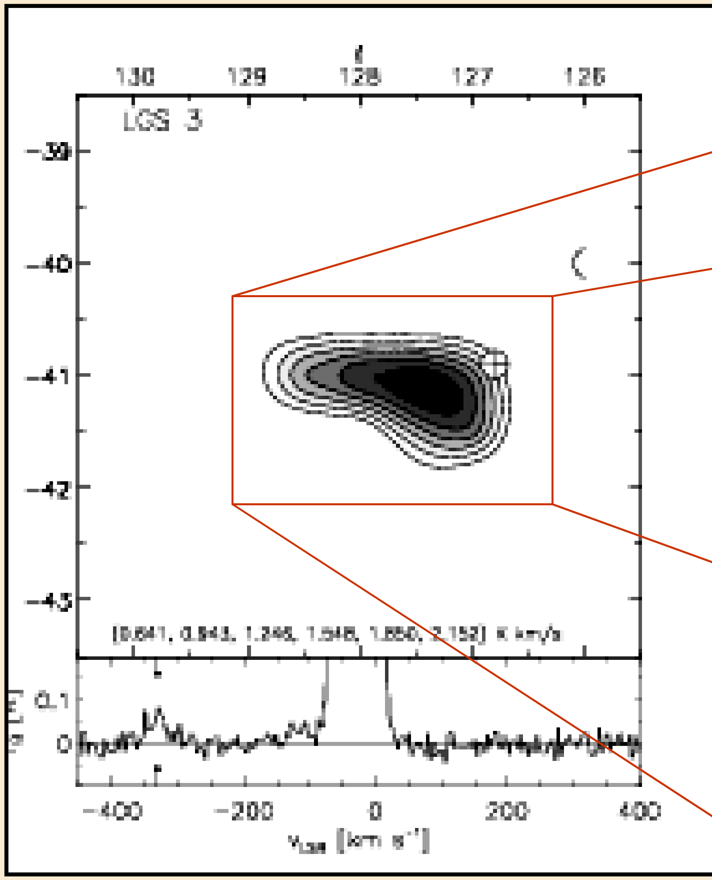
Young & Lo 1997

HVC and LGS3

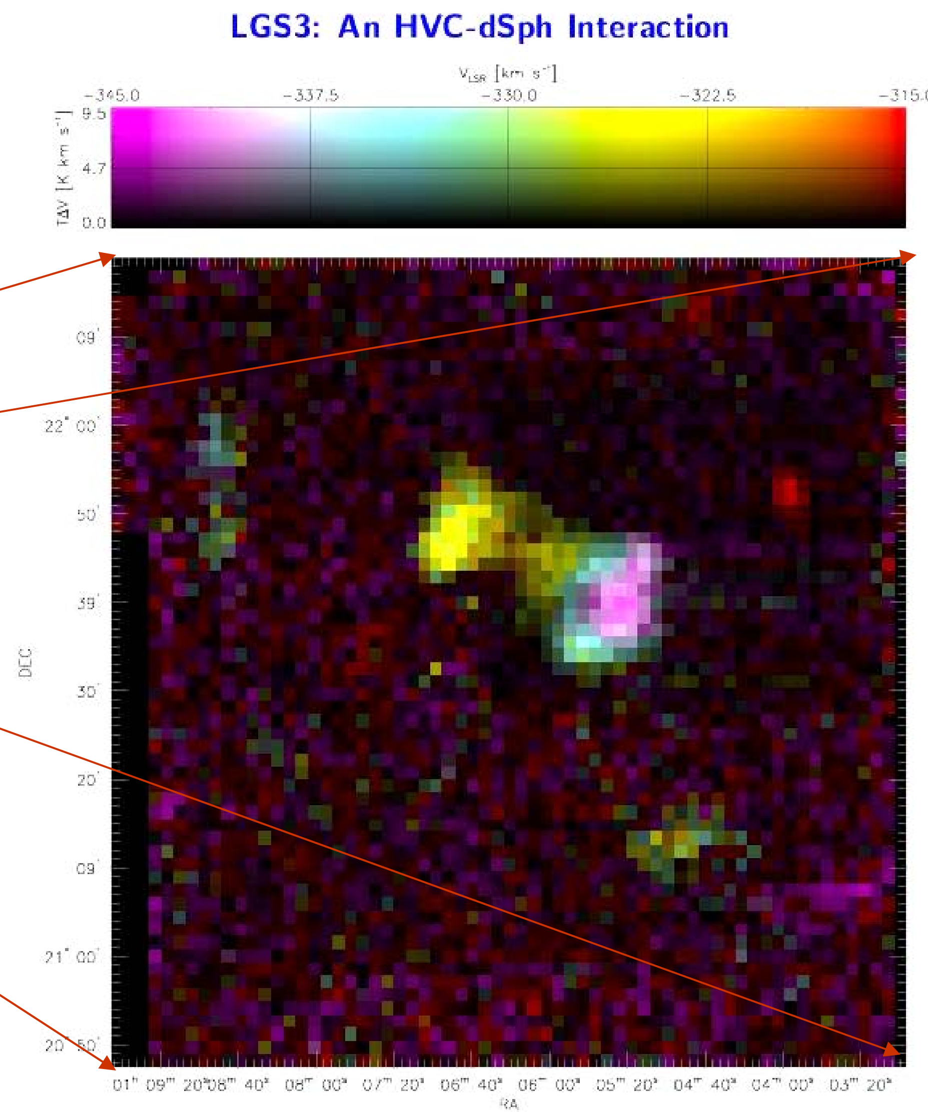


Robishaw & Blitz (2000)

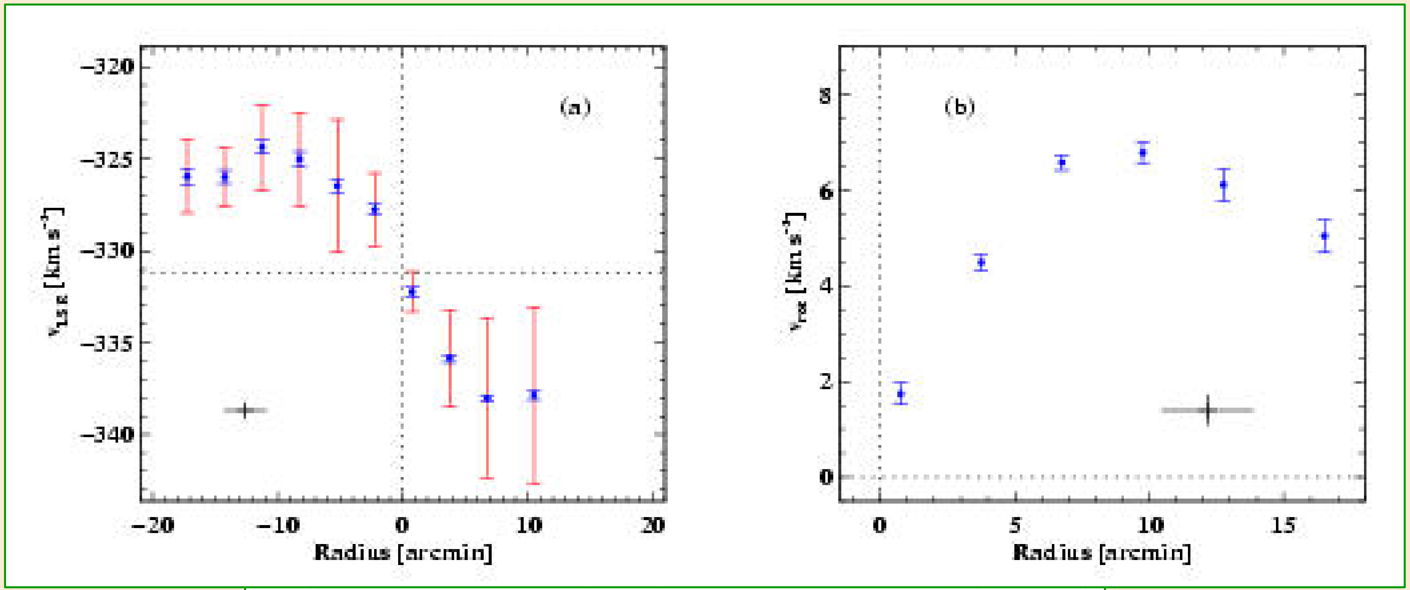
HVC and LGS3



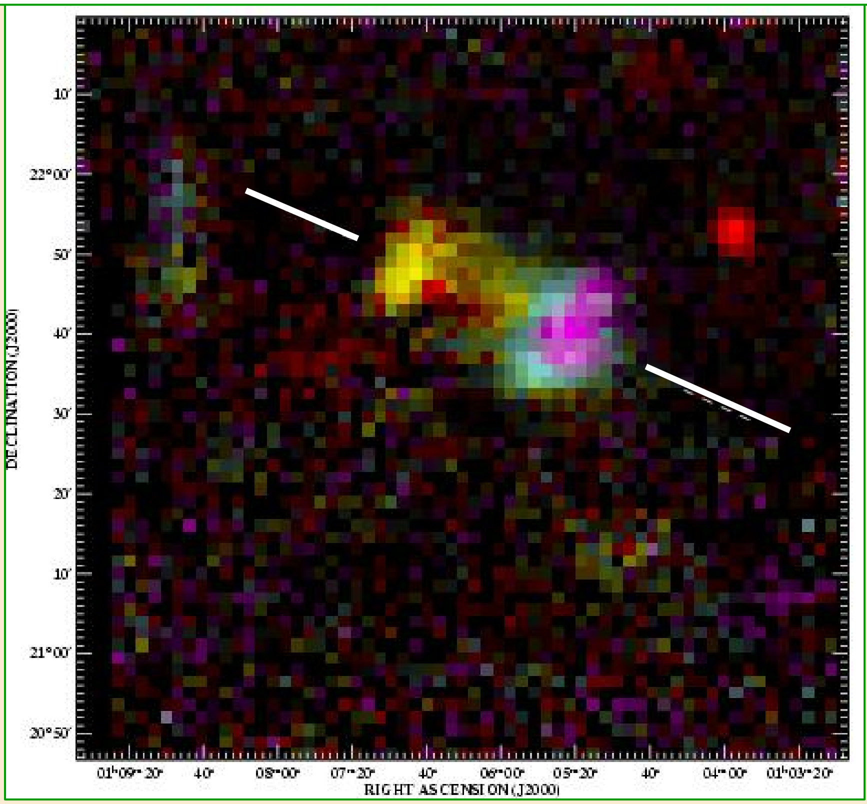
Robishaw & Blitz (2000)



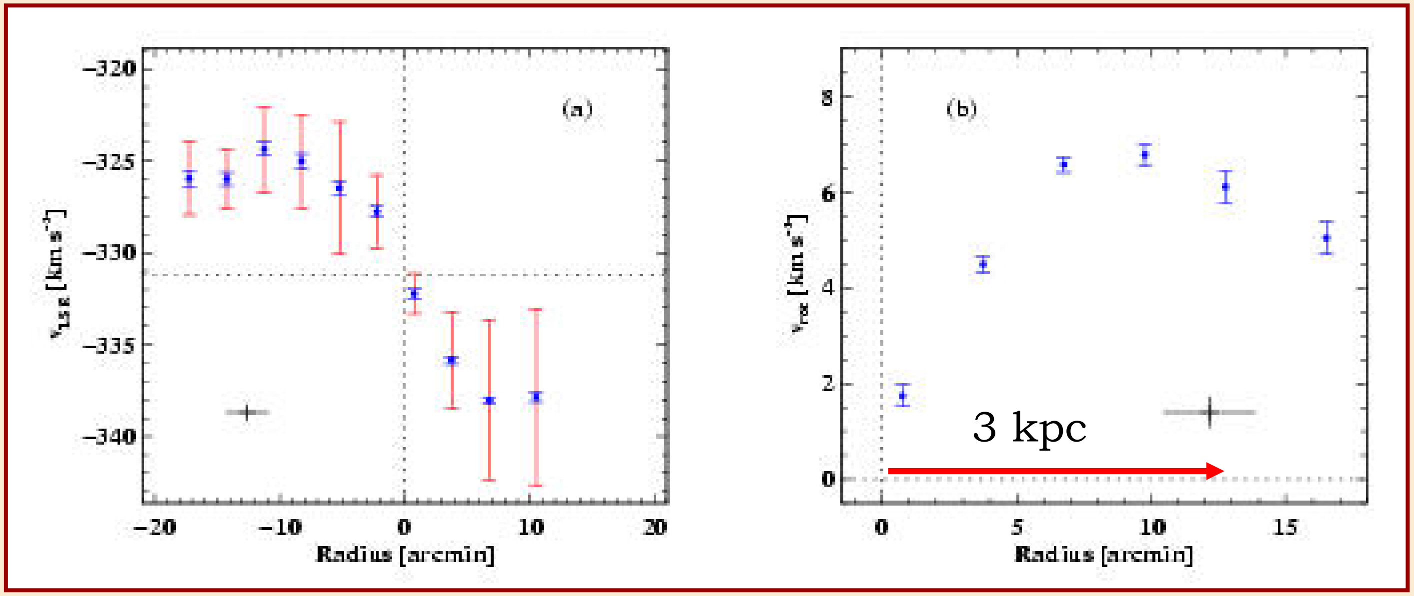
Robishaw, Simon, & Blitz (2002)

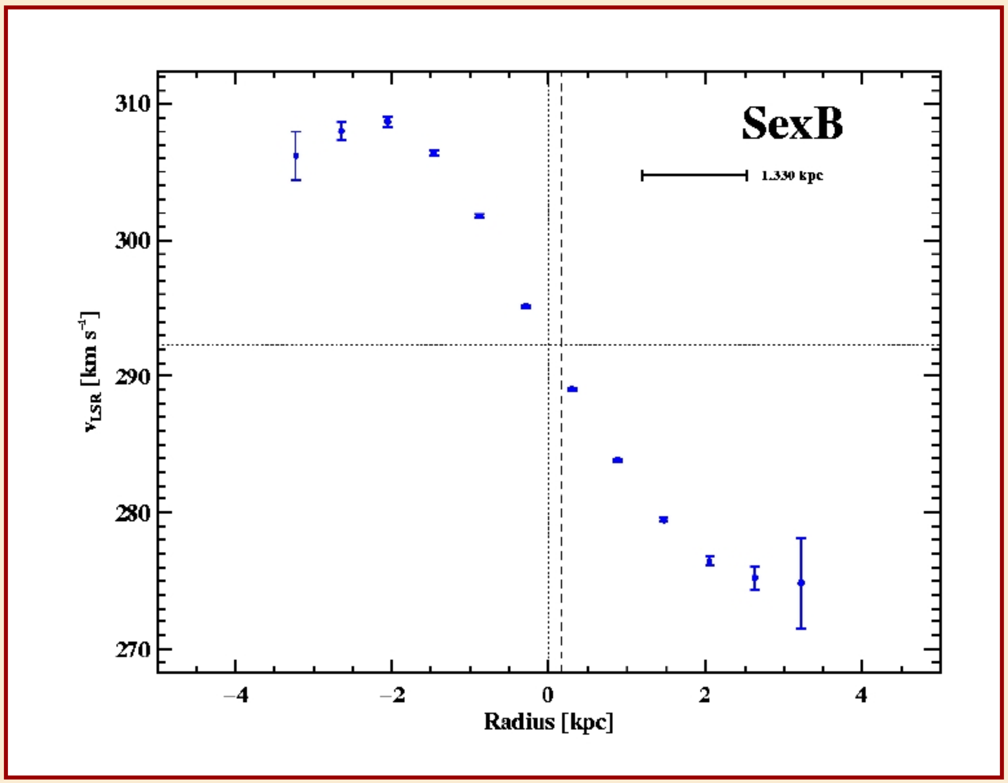


(a)
−320
−325
−330
−335
−340
v_{LSR} [km s^{-1}]
−20
−10
0
10
20
Radius [arcmin]
(b)
8
6
4
2
0
v_{rot} [km s^{-1}]
0
5
10
15
Radius [arcmin]

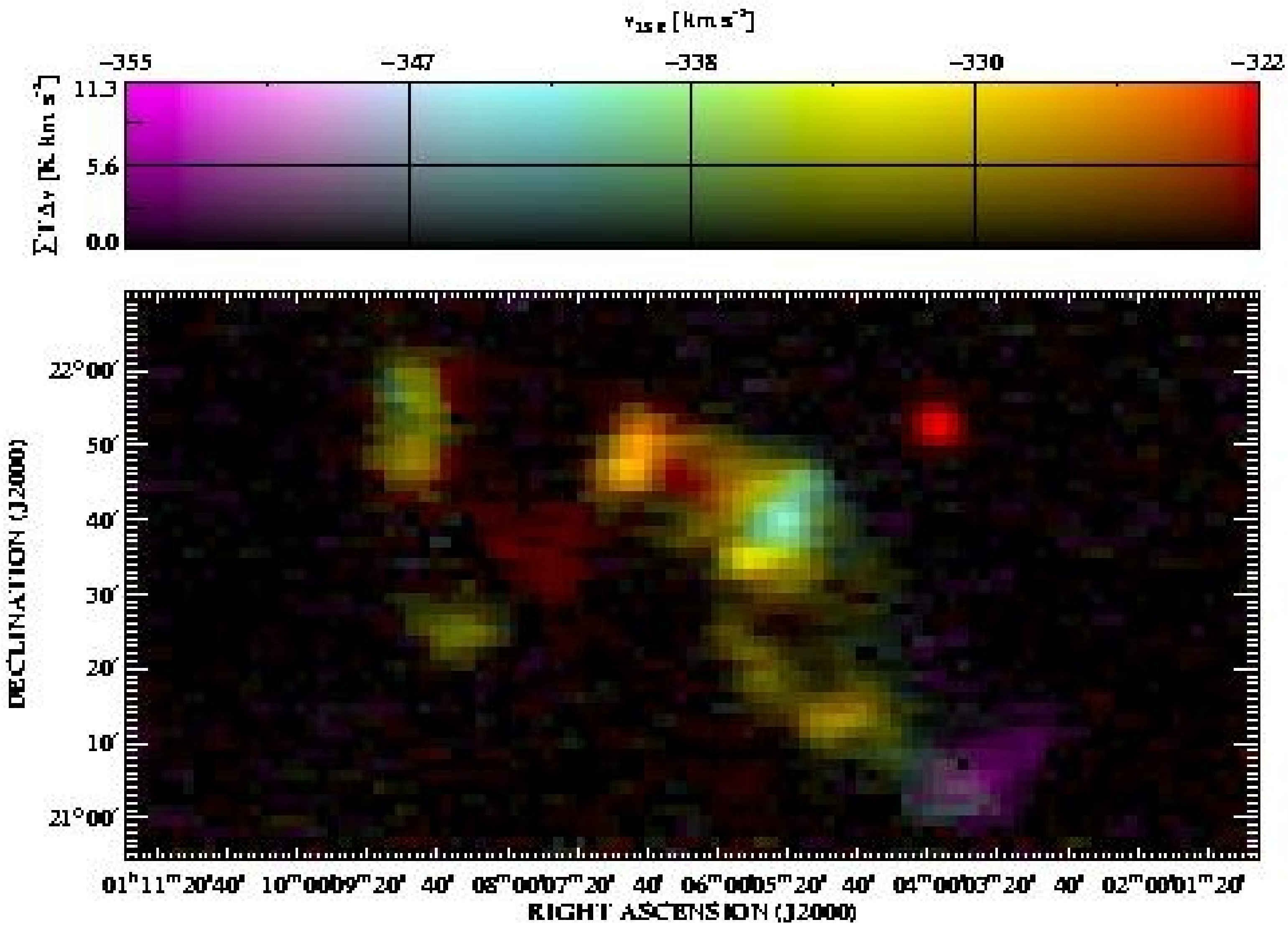


10'
22°00'
50'
40'
30'
20'
10'
21°00'
20°50'
DECLINATION (J2000)
01h09m20s
40s
08m00s
07m20s
40s
06m00s
05m20s
40s
04m00s
01h03m20s
RIGHT ASCENSION (J2000)

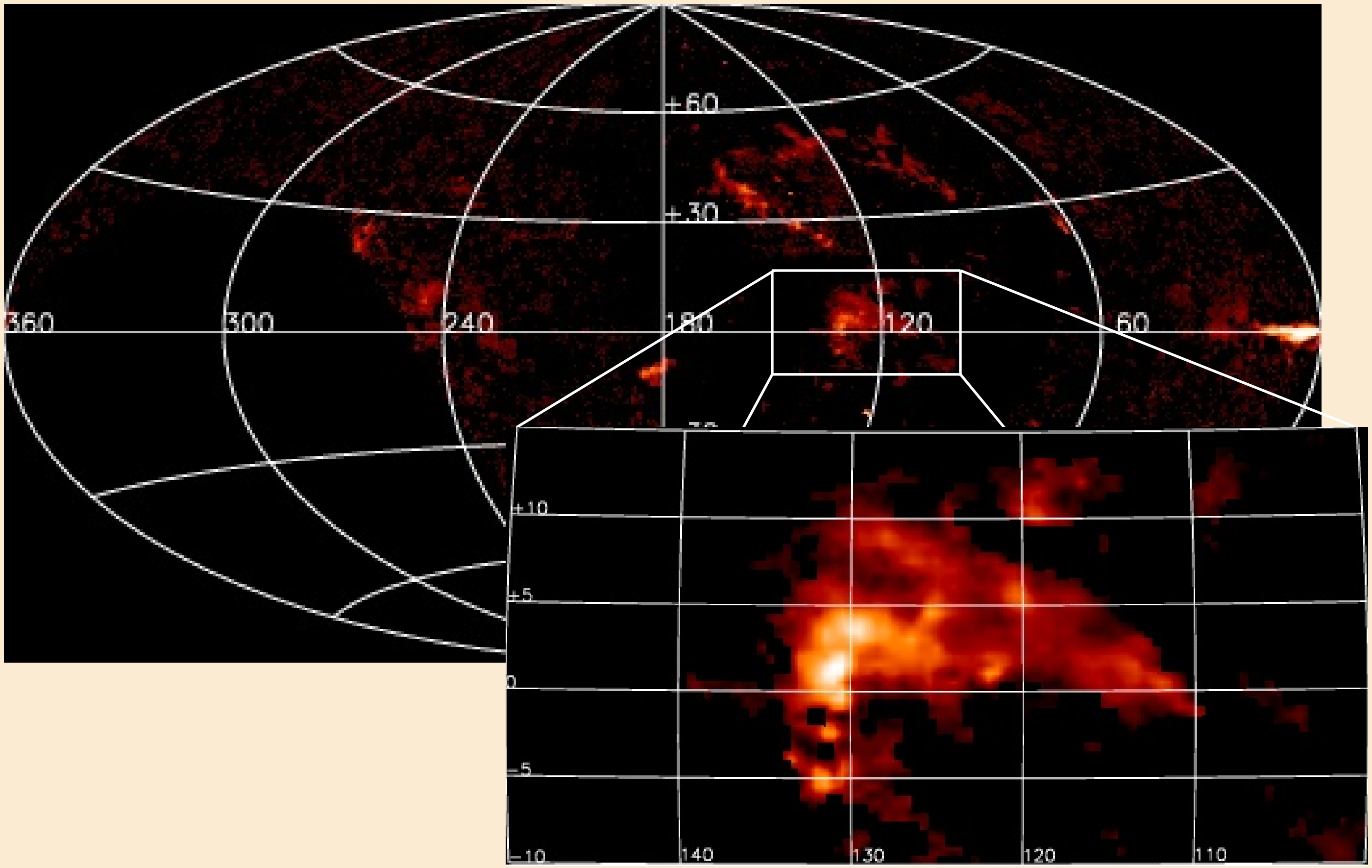

(a)
(b)
3 kpc
Radius [arcmin]


SexB
1.330 kpc
Radius [kpc]

Are there dark galaxies?



Complex H



Location in the Galactic plane makes it unique

What's it made of?

- Baryonic Matter
  - Faint main sequence stars?
  - Brown dwarfs?
  - Gas in any form?
  - Dust?
  - H_2 Snowballs?
  - MACHOS?
- Non-Baryonic Matter
- Galactic Center Black Hole
- Phase Space Arguments

What's it made of?

- Baryonic Matter (most ideas addressed best in the Milky Way)
  - Faint main sequence stars?
  - Brown dwarfs?
    - $dN(m)/dm \sim m^{-2.3}$ implies most mass is at the low mass end of the spectrum.

$$M_{tot} = \int_0^{\infty} m \times m^{-2.3} dm$$

    - Implies that there must be a turnover in the mass function, but it must occur at the hydrogen burning limit.
  - Why should stars know anything about nuclear physics?

What's it made of?

- Baryonic Matter
  - Gas in any form? (Need to hide 10^{12} $M_\odot$ of gas in a large spiral galaxy; must be hydrogen)
    - This much HI is easily observed in the 21-cm line of atomic hydrogen
    - Hot, X-ray emitting gas is observed to be insufficient
    - Warm, 10^4 K ionized gas emits by bremstrahlung. If in hydrostatic equilibrium, central regions would be dense enough to be easily observed.
    - Molecular gas must be H_2; large quantities would be ionized and observed near the galactic plane; in absorption against background quasars. If warm, would cool through quadrupole emission and be visible.
  - Dust?
    - Violates Big Bang Nucleosynthesis

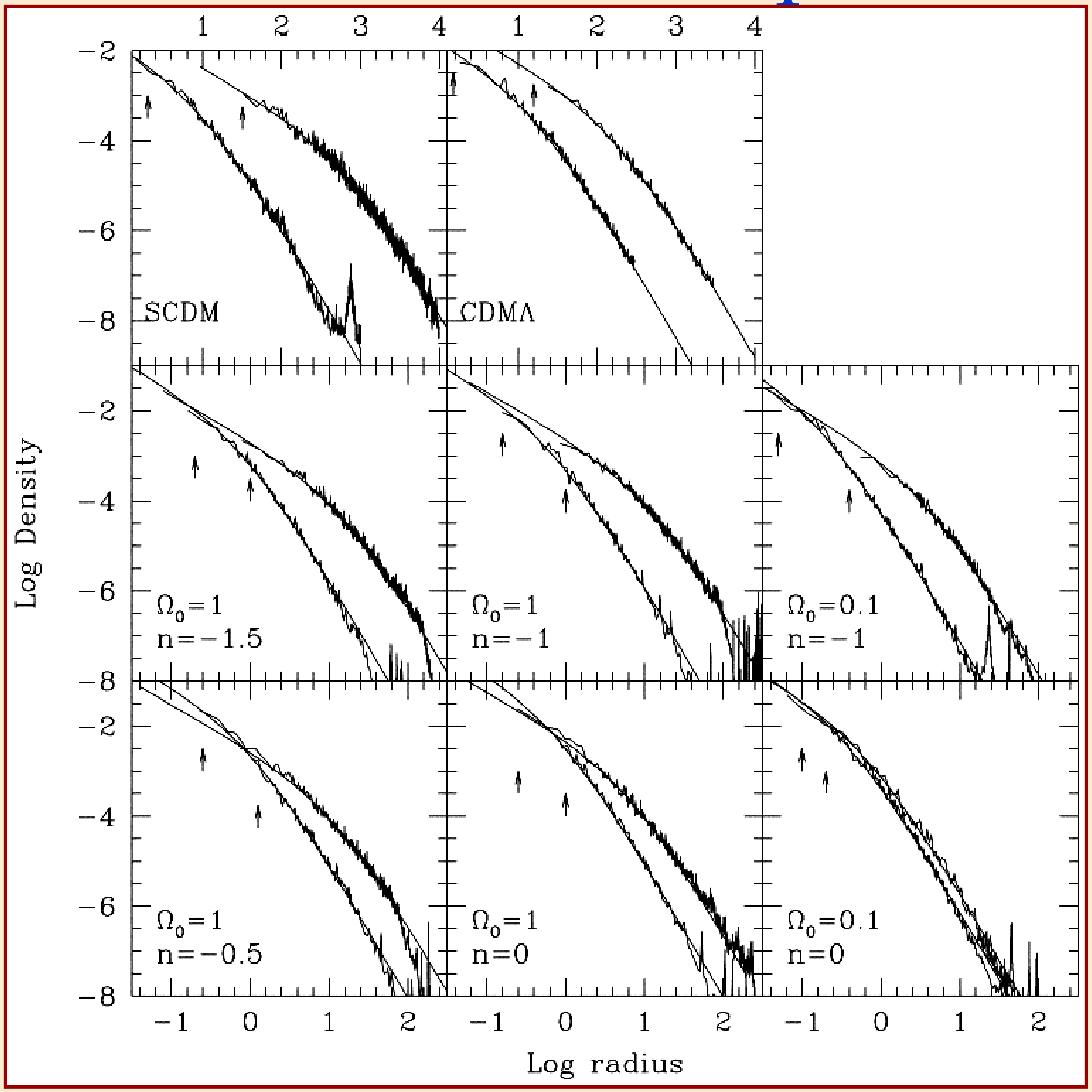
What’s it made of?

- Baryonic Matter
  - H_2 Snowballs
    - If too small, would be seen as comets with hyperbolic orbits
    - Probably could not remain frozen in the 3K bath of photons.
  - MACHOS?
    - Ruled out by microlensing observations of the Magellanic clouds
  - Primordial Black Holes?
    - Unclear how to form them prior to galaxy formation
- Non-Baryonic Matter
- Must be massive enough to condense on a scale of a dwarf galaxy.

What are its Properties?

- Cuspy?
- Interact gravitationally with baryonic matter?

NFW profiles



Least Massive Most Massive

Radius scaled to virial radius

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_s}{(r/r_s)(1+r/r_s)^2}$$

δ_s is a dimensionless density

r_s is a characteristic radius: for dwarf galaxies it is ~1 kpc

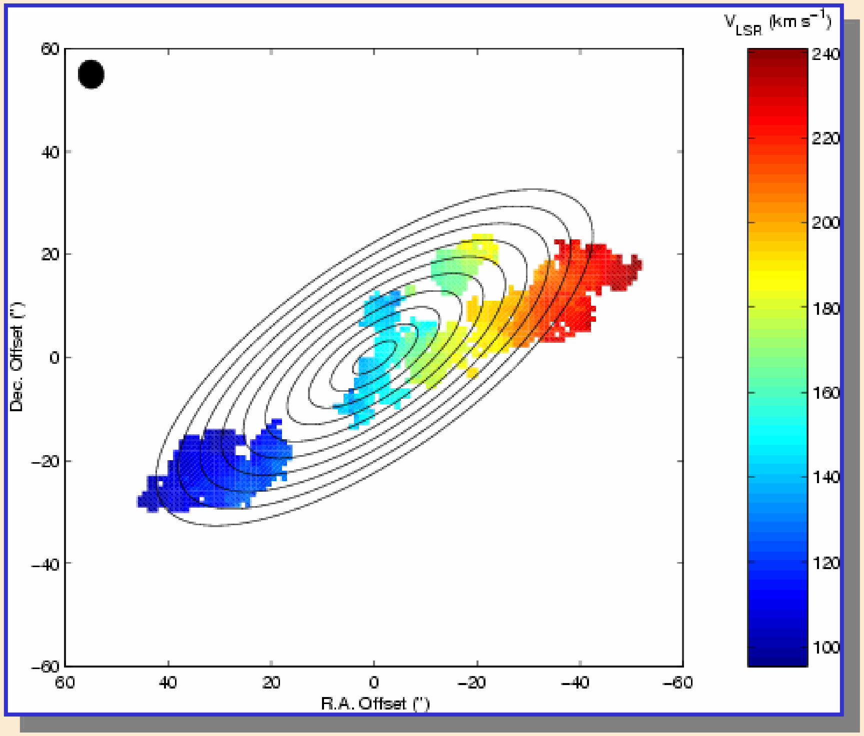
"cuspy" halos

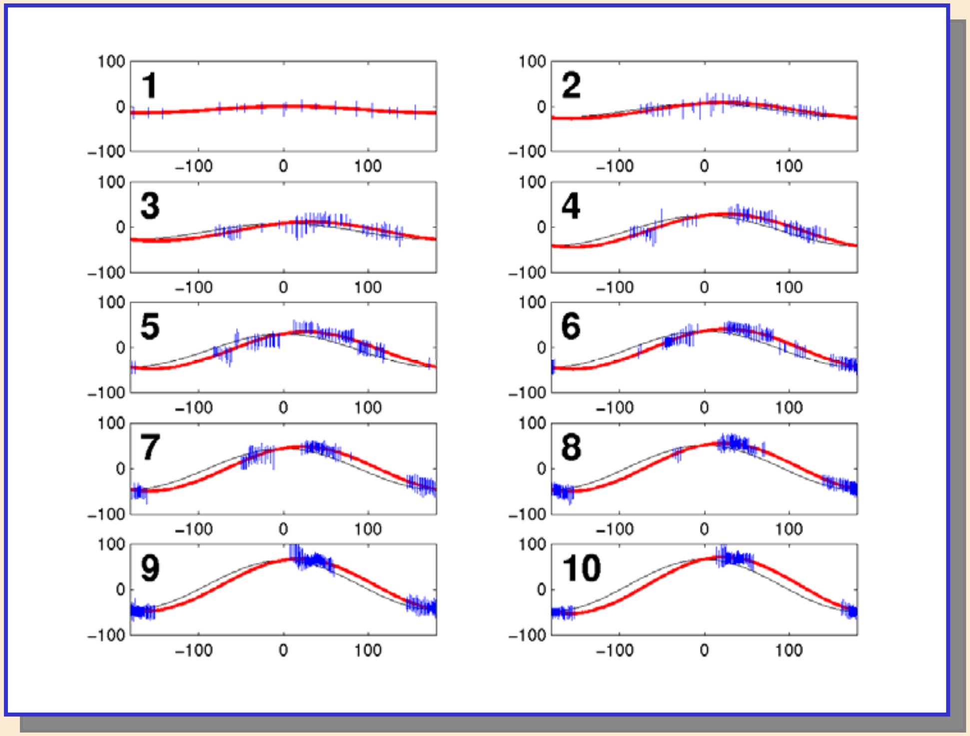
Navarro, Frenk & White 1997

The velocity field

- Fit a tilted-ring model

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

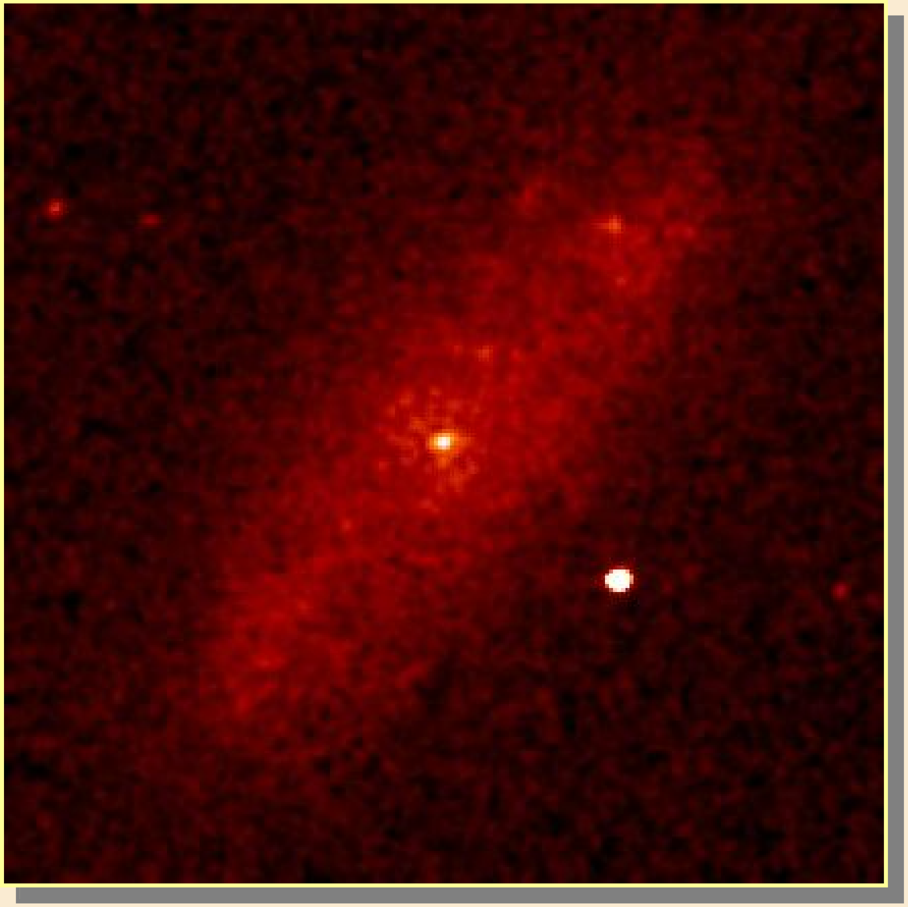




NGC 2976

B,V,R Composite

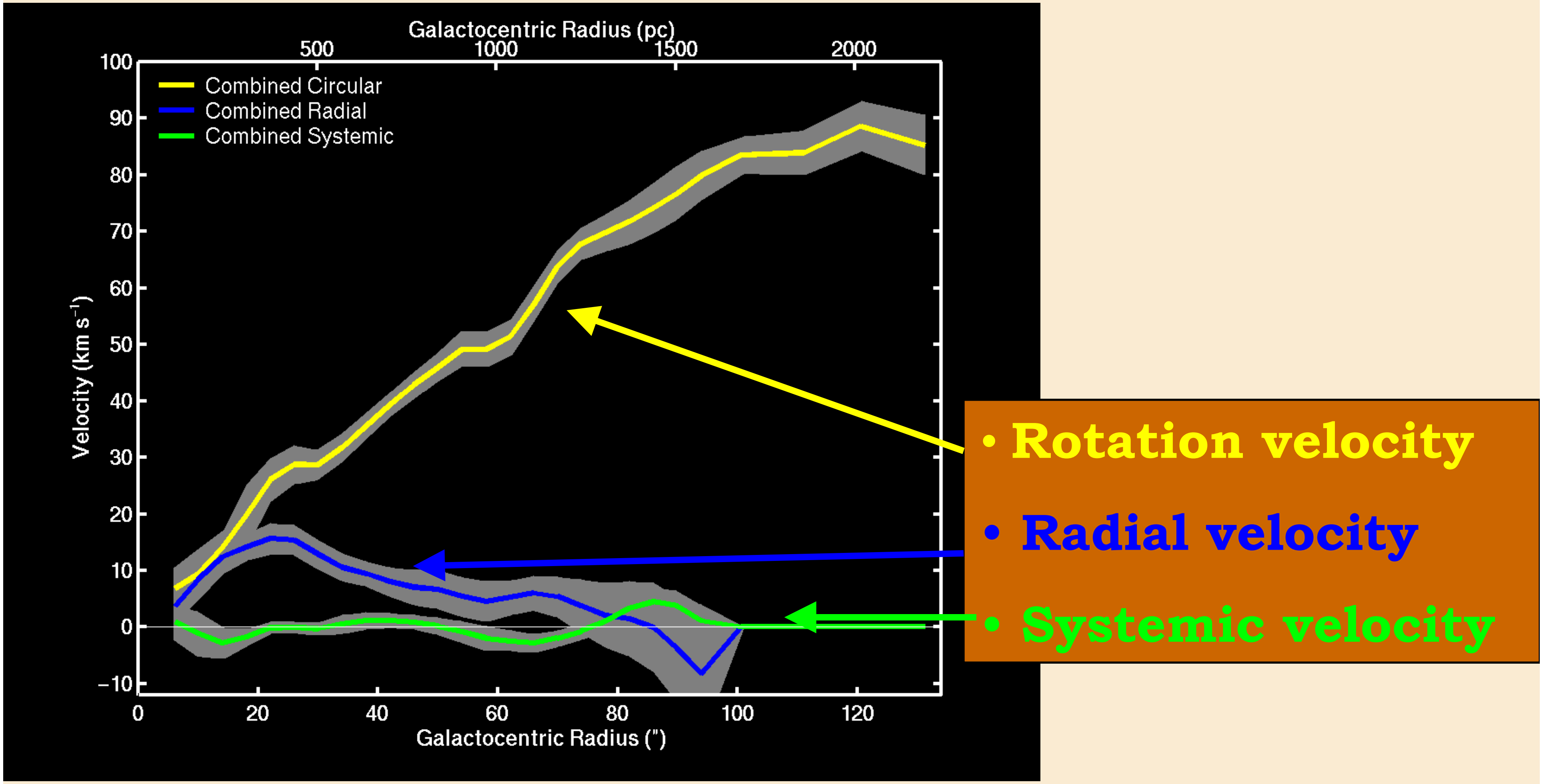
2μm (2MASS)



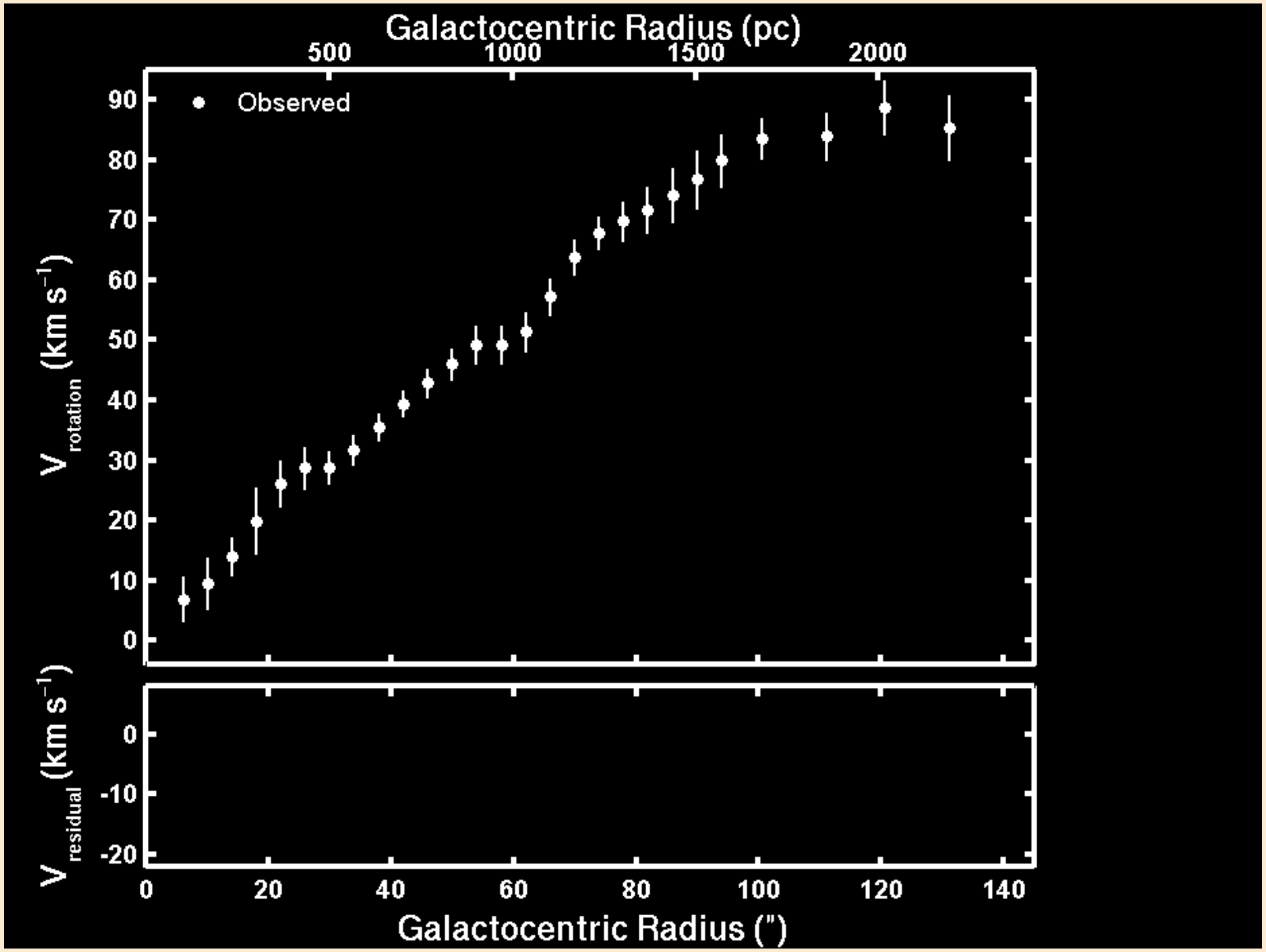
No bar, no bulge, no spiral arms

NGC 2976 Rotation Curve

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

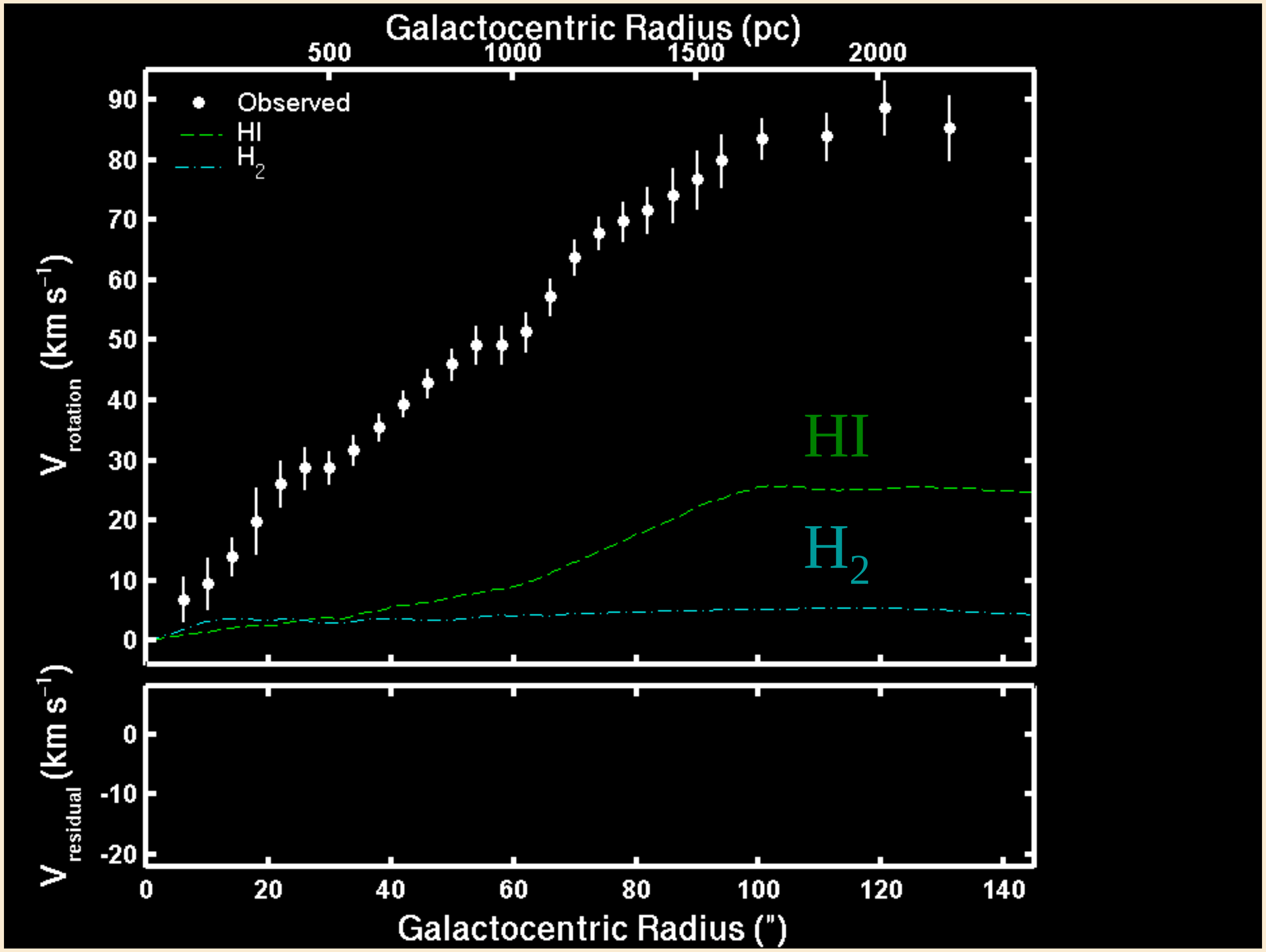


Maximum Disk Fit

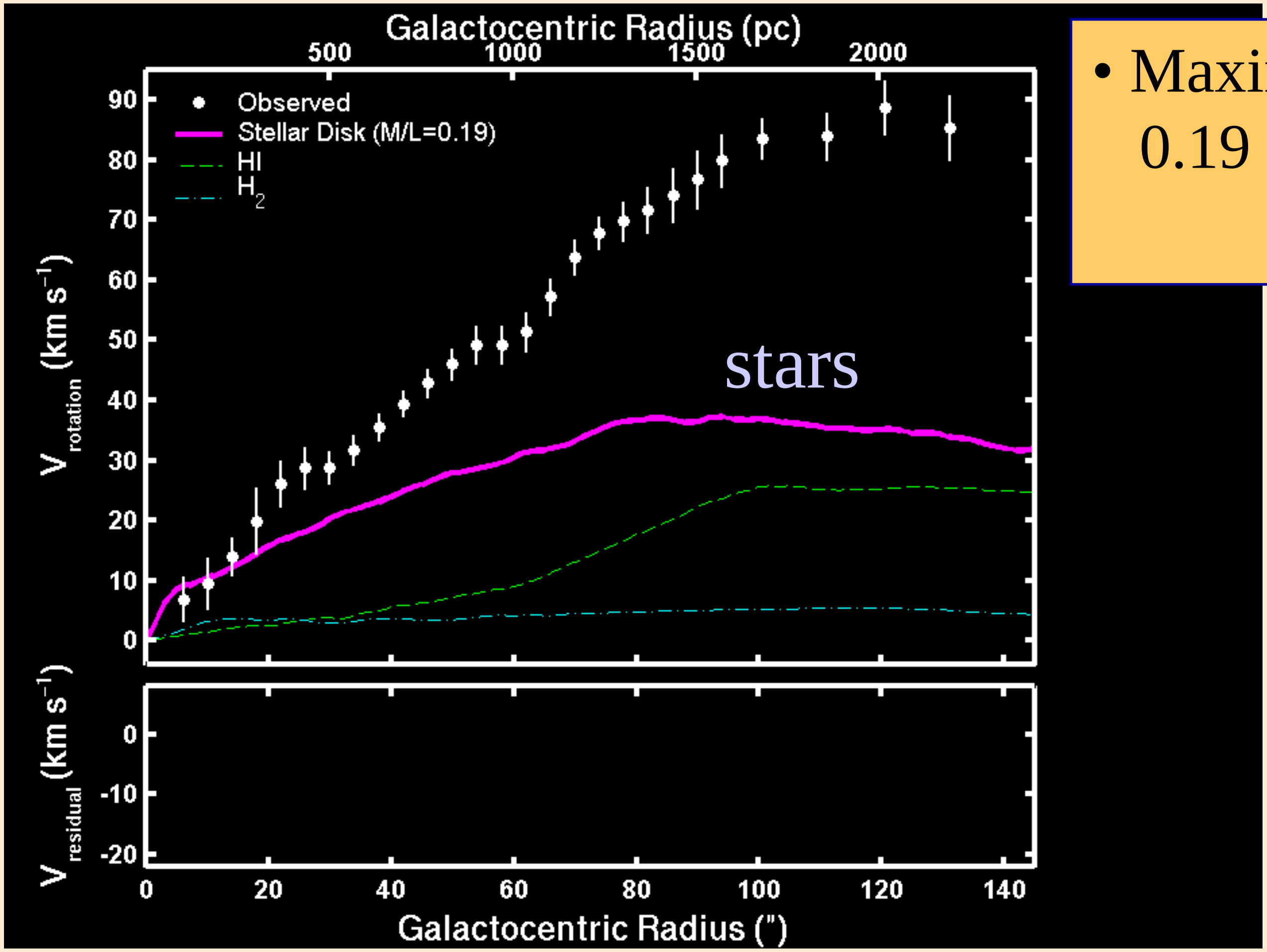


Maximum Disk Fit

How much mass does the gas add?

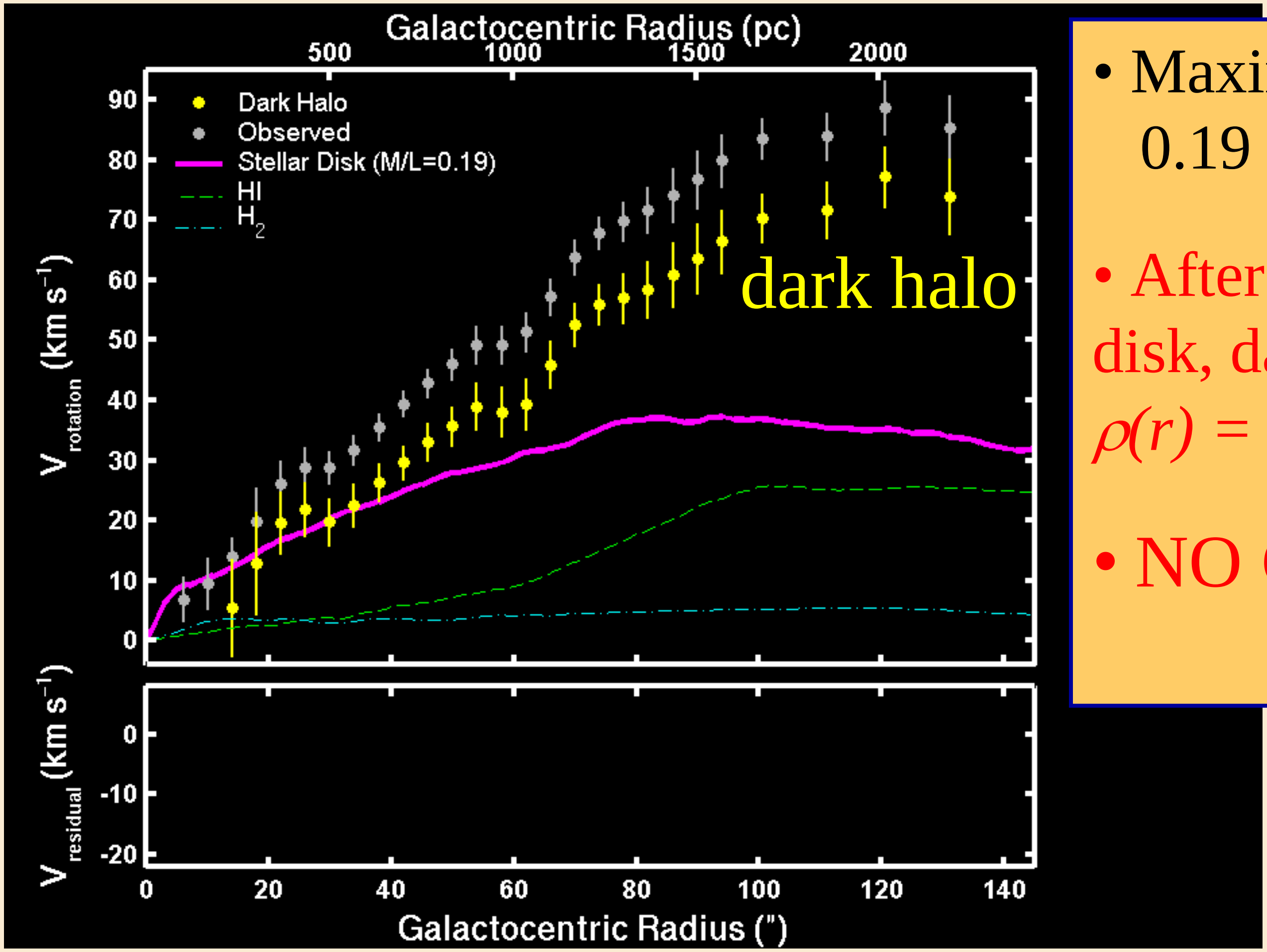


Maximum Disk Fit



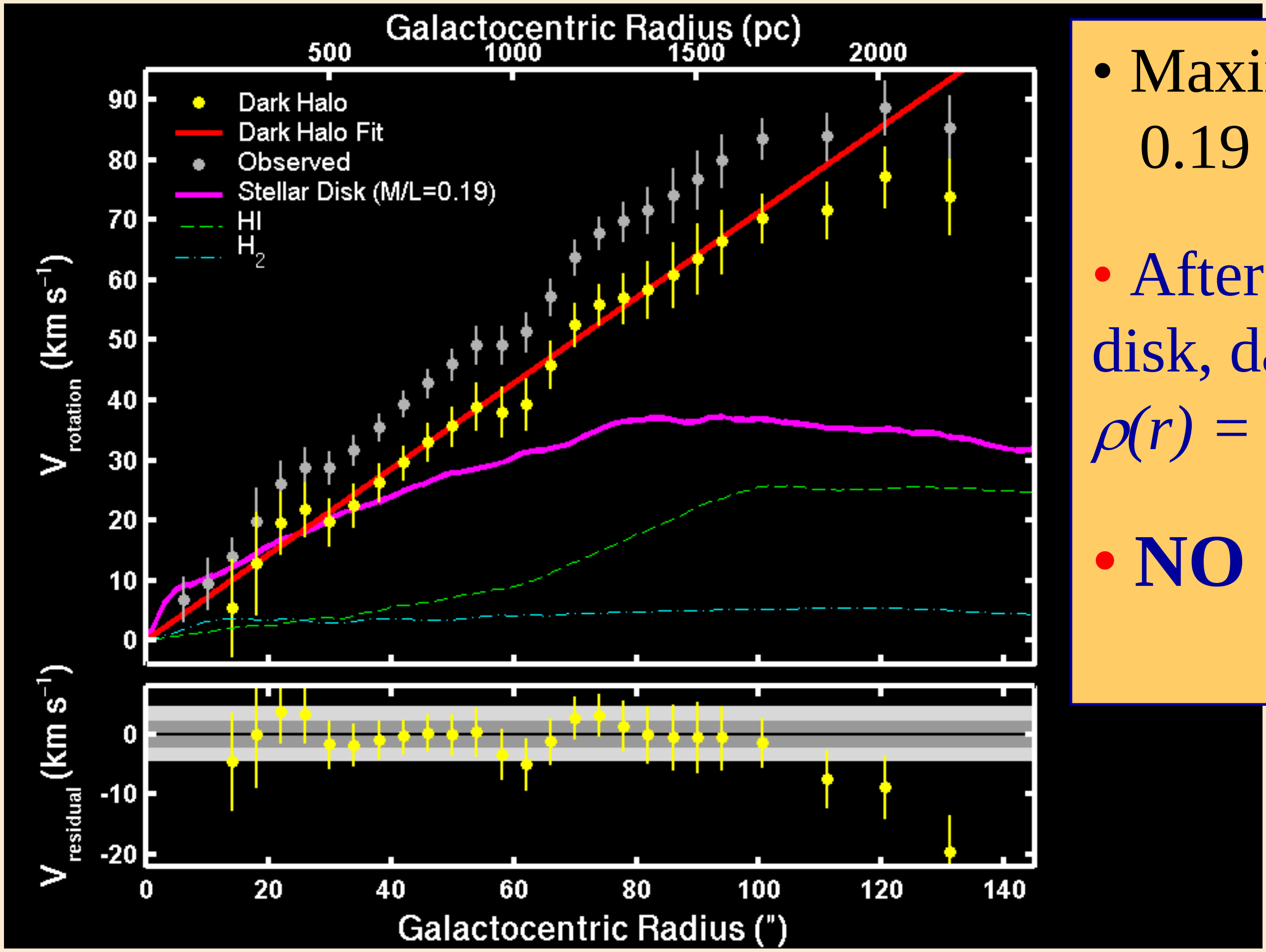
- Maximal disk M_*/L_K = 0.19 $M_\odot/L_{\odot,K}$

Maximum Disk Fit



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

Maximum Disk Fit



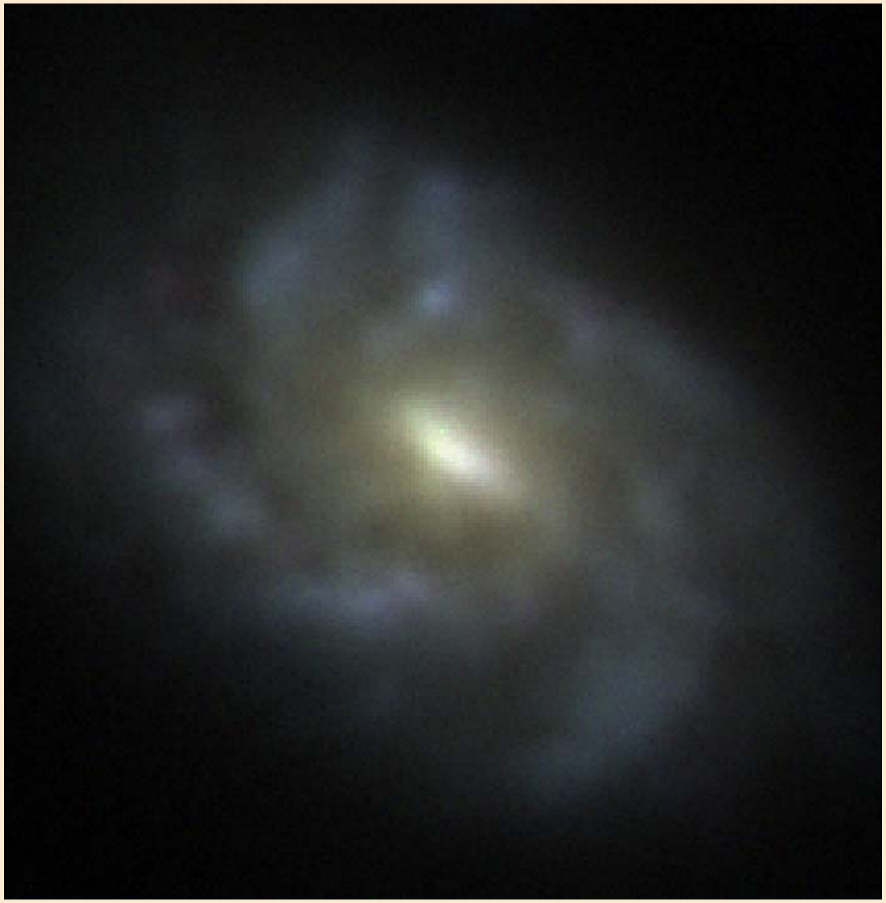
- Maximal disk M_*/L_K = 0.19 $M_\odot/L_{\odot,K}$
- After subtracting stellar disk, dark halo structure is $\rho(r) = 0.1\ r^{-0.01 \pm 0.12} M_\odot/pc^3$
- **NO CUSP!**

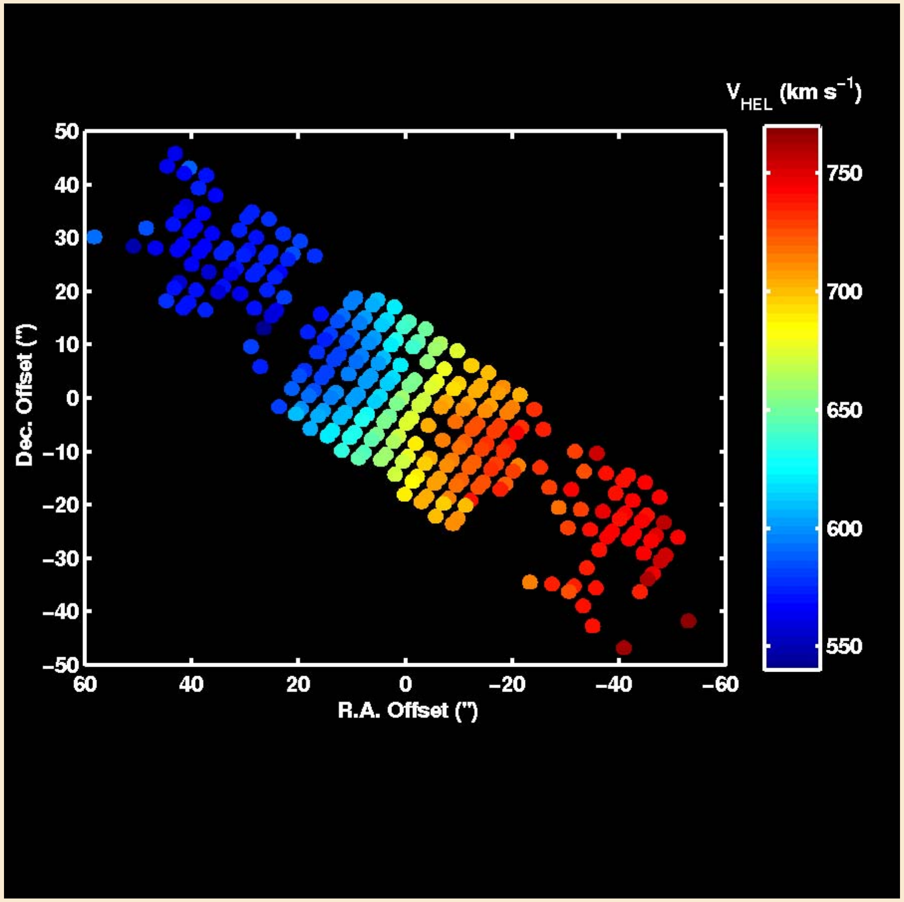
Why Are There Radial Motions???

- Possible causes:
  - Bar, triaxial dark matter halo, intrinsically elliptical disk
- Illustrates importance of 2-D velocity fields
- Not only present in NGC 2976
  - Also NGC 4605
  - And DDO 39 (Swaters et al. 2003)
  - Could have been missed in other galaxies due to longslit observations . . .

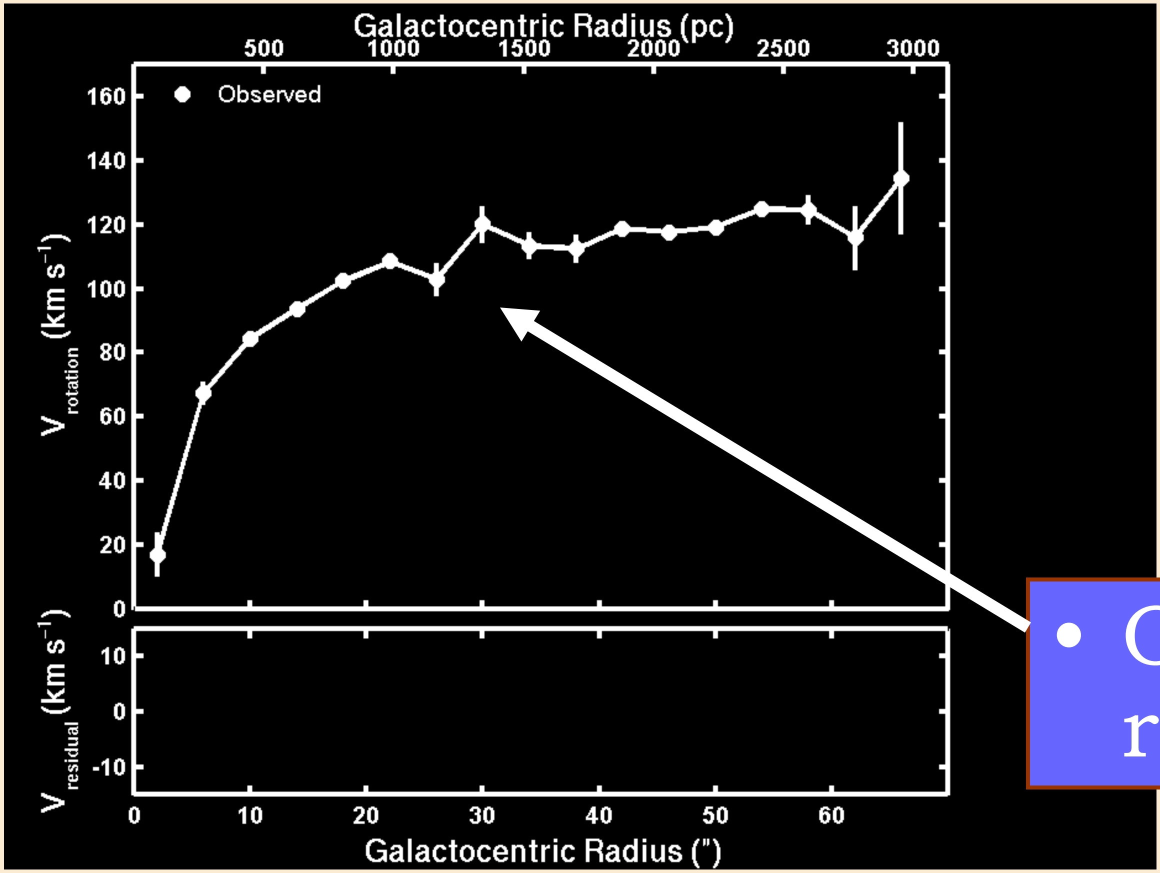
NGC 5963

- Larger and more distant galaxy (D = 10 Mpc)
- Compact inner spiral surrounded by very LSB disk



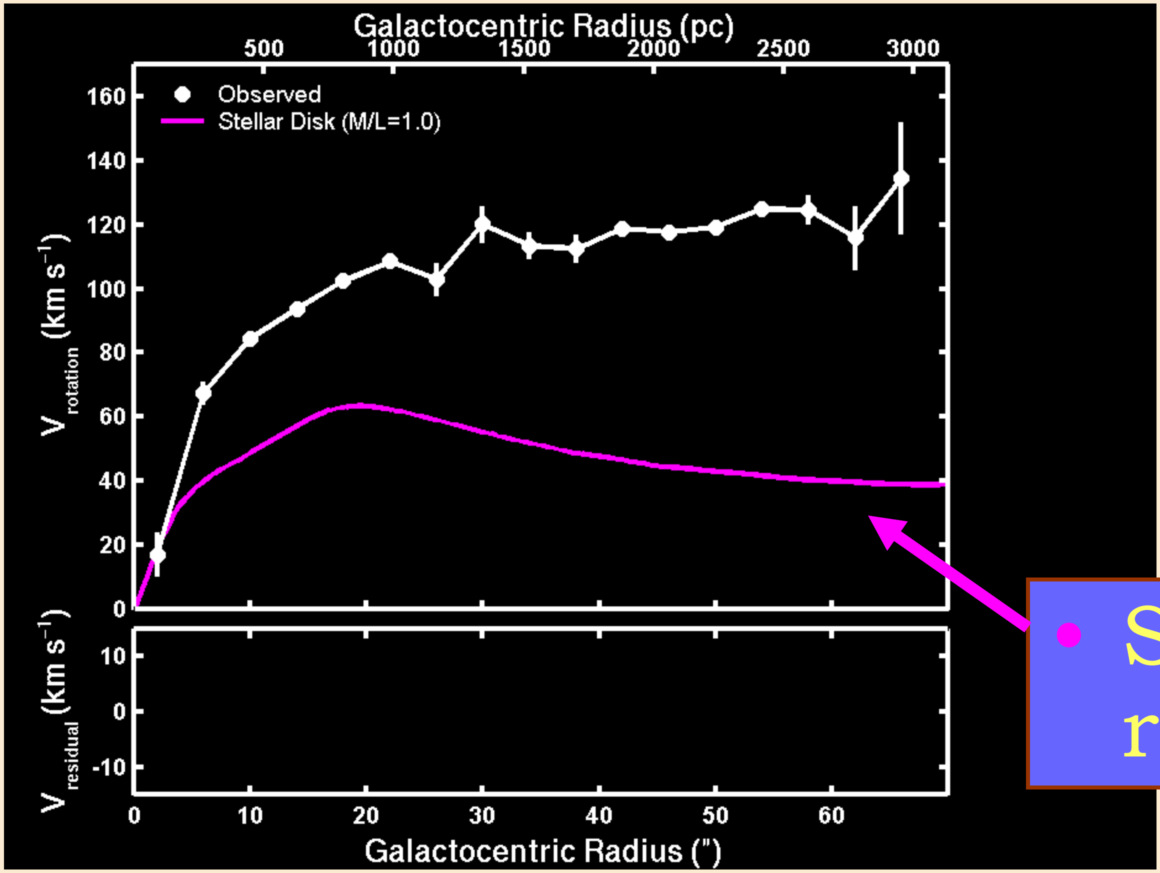


NGC 5963 Rotation Curve



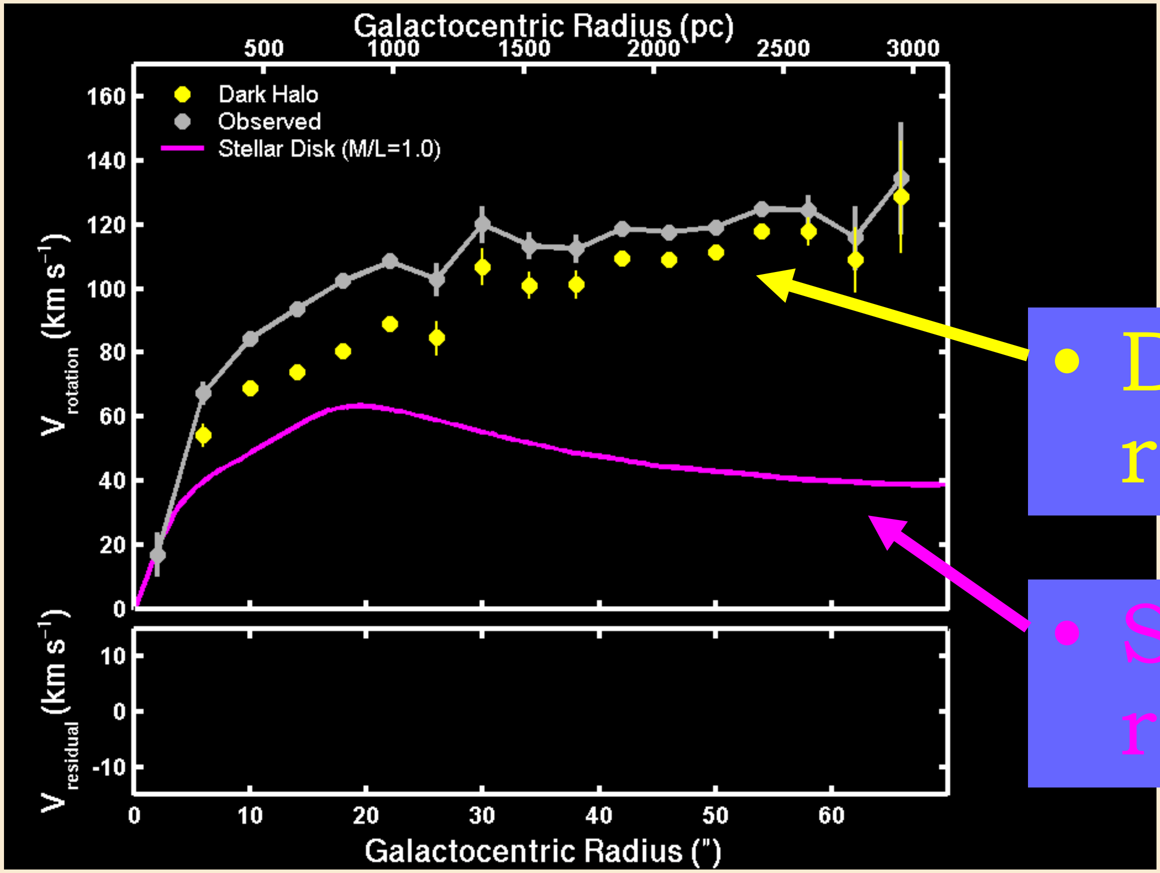
- Observed rotation curve

NGC 5963 Rotation Curve



- Stellar disk rotation curve

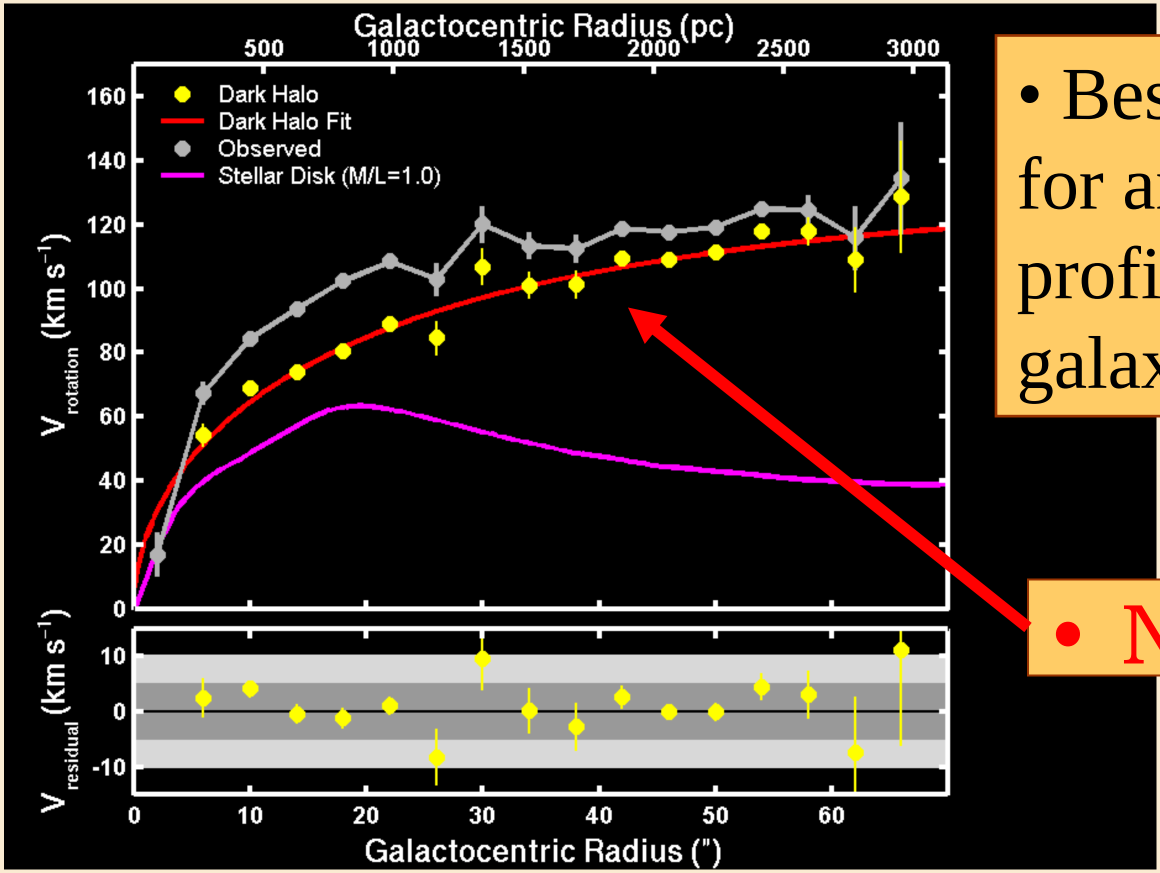
NGC 5963 Rotation Curve



- Dark halo rotation curve
- Stellar disk rotation curve

NGC 5963 Rotation Curve

- NFW rotation curve is a good fit (χ^2 = 1.2)
  - V_{200} ~ 95 km s^{-1}, R_{200} ~ 50 kpc, r_s = 3.2 kpc



- Best existing evidence for an NFW density profile in a low-mass galaxy?

- NFW fit

Summary of Galaxies to Date

Galaxy	No Disk	Max Disk
N2976	0.27	0.01
N4605	no single power law	0.65
N5963	1.49	0.93
N5949	0.83	0.63
N6689	0.97	0.43
N4625	unreliable	unreliable

General Conclusions

- There does not seem to be a universal dark matter density profile.
- Some galaxies have ~constant density cores, some are NFW.
- Something is wrong with the models.
  - Insufficient resolution?
  - DM-baryon interaction?
- Do radial motions mean triaxial dark matter halos?