Brian R. Kent
Cornell University

Ask yourself…

How do you define a galaxy?
What is the Milky Way Galaxy, and how does it compare to o
other galaxies?
What is the Local Group?
Do all galaxies have close neighbors?
What happens when galaxies collide?

Redshift

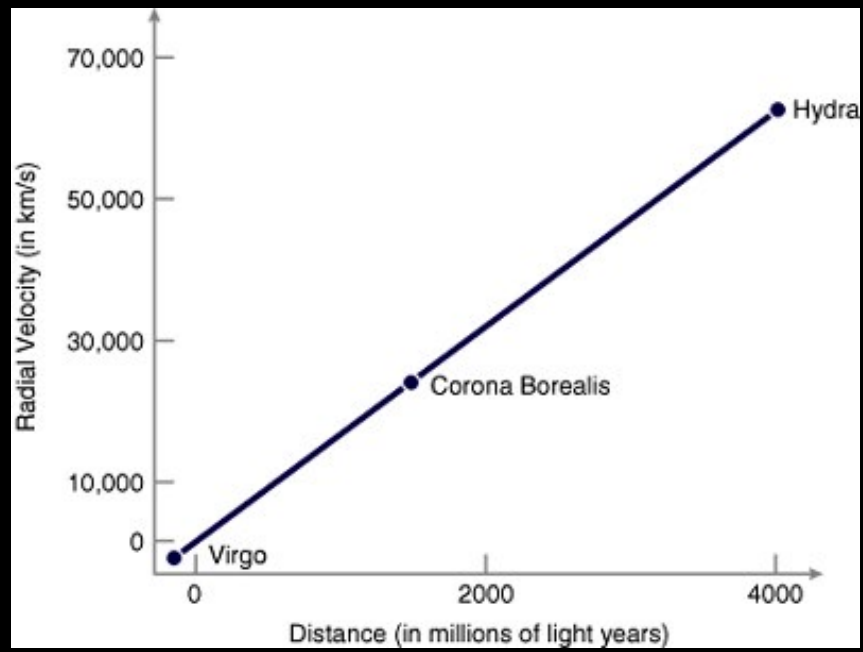
$$z = \frac{\lambda_{obs} - \lambda_0}{\lambda_0} = \frac{f_0 - f_{obs}}{f_{obs}}$$

- Measure the shift in a spectral line – f_0 is the rest frequency (λ_0 the rest wavelength)
- Extragalactic objects often identified by their *cz* measurement.
- ALFALFA will cover *cz* = –2000 to 17000 km/s
- *cz* indicator™

Expansion of the Universe

- Edwin Hubble showed the Universe was expanding!
- However, there are other factors to take into account in the local Universe – peculiar velocities! Deviations can be quite large depending on the galaxy, and whether it is part of a group or a field galaxy.

$$cz = H_0 d$$



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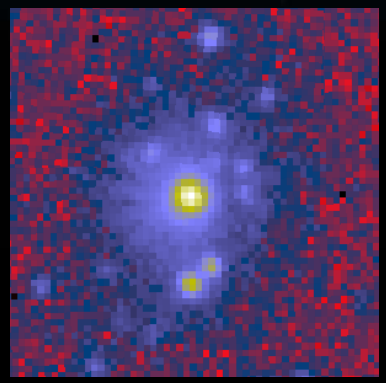
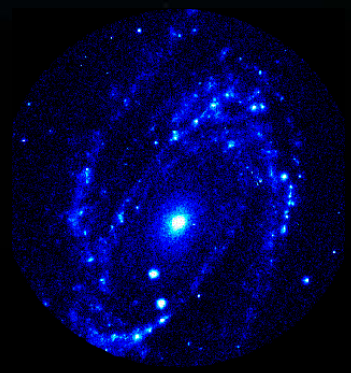
Galaxy Morphology

What do galaxies *look* like?

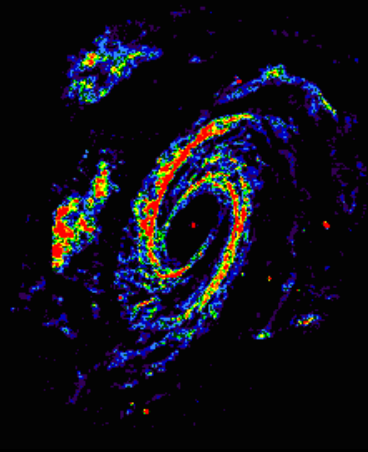
Well, it depends…

Galaxies across the spectrum

M81

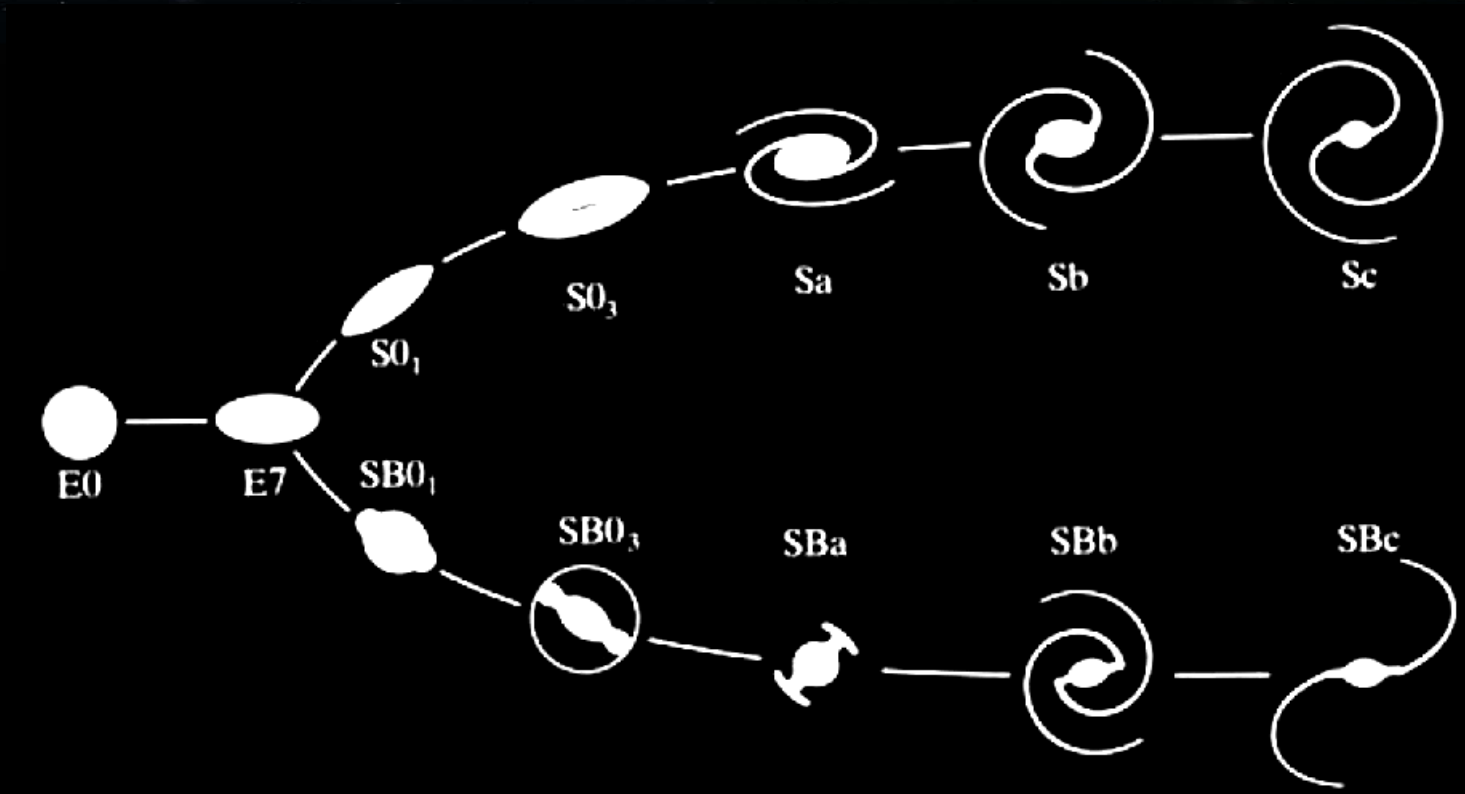


Galaxy Types

Galaxy Type	Hubble	de Vaucoulers
Spiral	S, Sa, Sb…	1 through 6
Elliptical	E	-6 through –4
Dwarf	dE, dSph	
Lenticular	S0, SB0	-3, -2, -1
Irregular	Irr	

Hubble's Tuning Fork



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Spiral Galaxies

- Thin disks
- Most have some form of a bar – arms will emanate from the ends of the bars
- Other classification:
  1. Relative importance of central luminous bulge and disk in overall light from the galaxy
  2. The tightness of the winding of the spiral arms
  3. Degree to which spiral arms are resolved into stars and individual HII regions

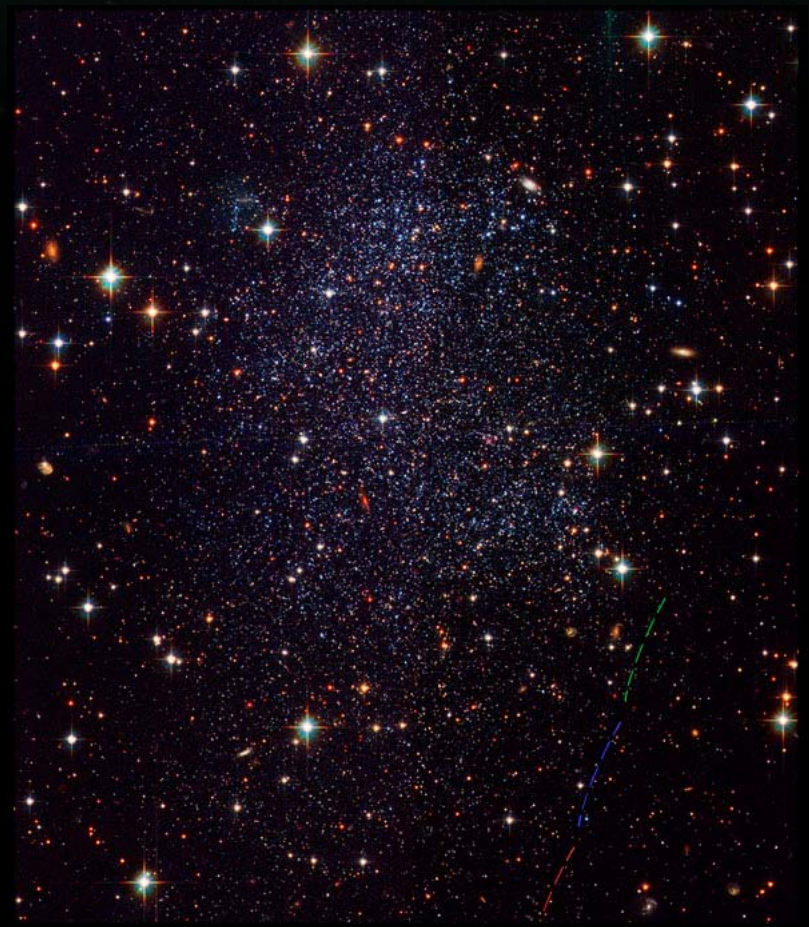
M51

M33

Dwarf Galaxies

- Smaller size than giant elliptical galaxies
- Lower surface brightness

M32



Sagittarius Dwarf

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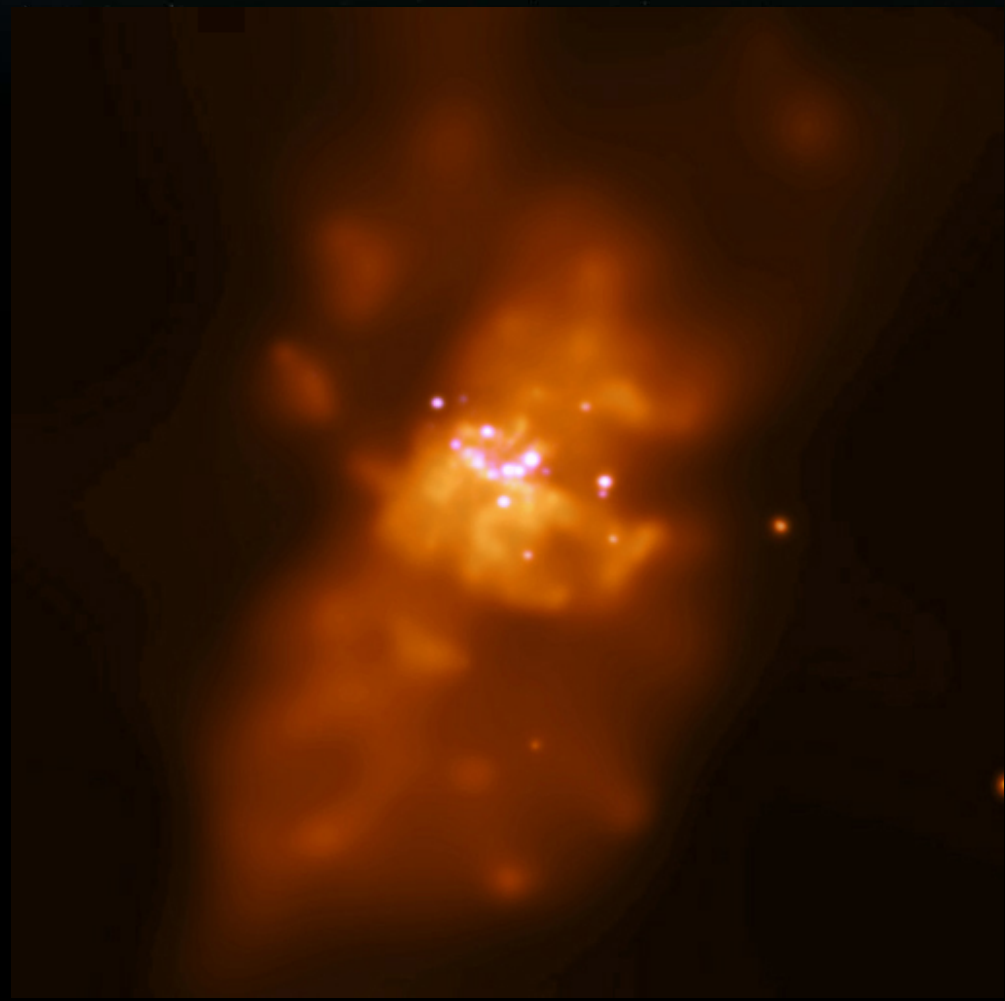
Irregular Galaxies

- LMC and SMC are satellite galaxies of our own – disrupted by gravitational interaction with the Milky Way…

LMC and SMC

Irregular Galaxies

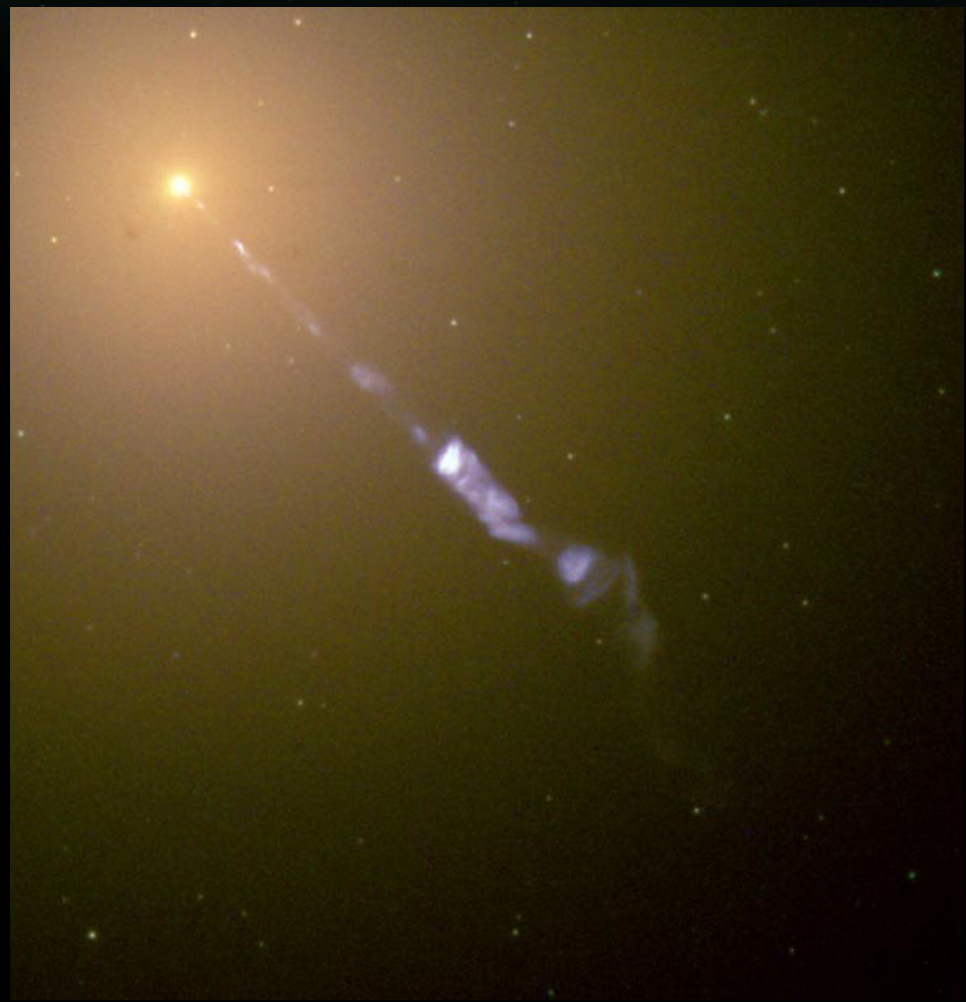
- M82 – irregular starburst galaxy
- Star formation rate at **10 times** the rate of our galaxy
- Chandra X-ray image reveals hot gas flowing out of the galaxy – hot spots indicate x-ray binary stars – some of the brightest known!



Elliptical Galaxies

- Smooth and very little structure; varying in shape
- Classified by EN where

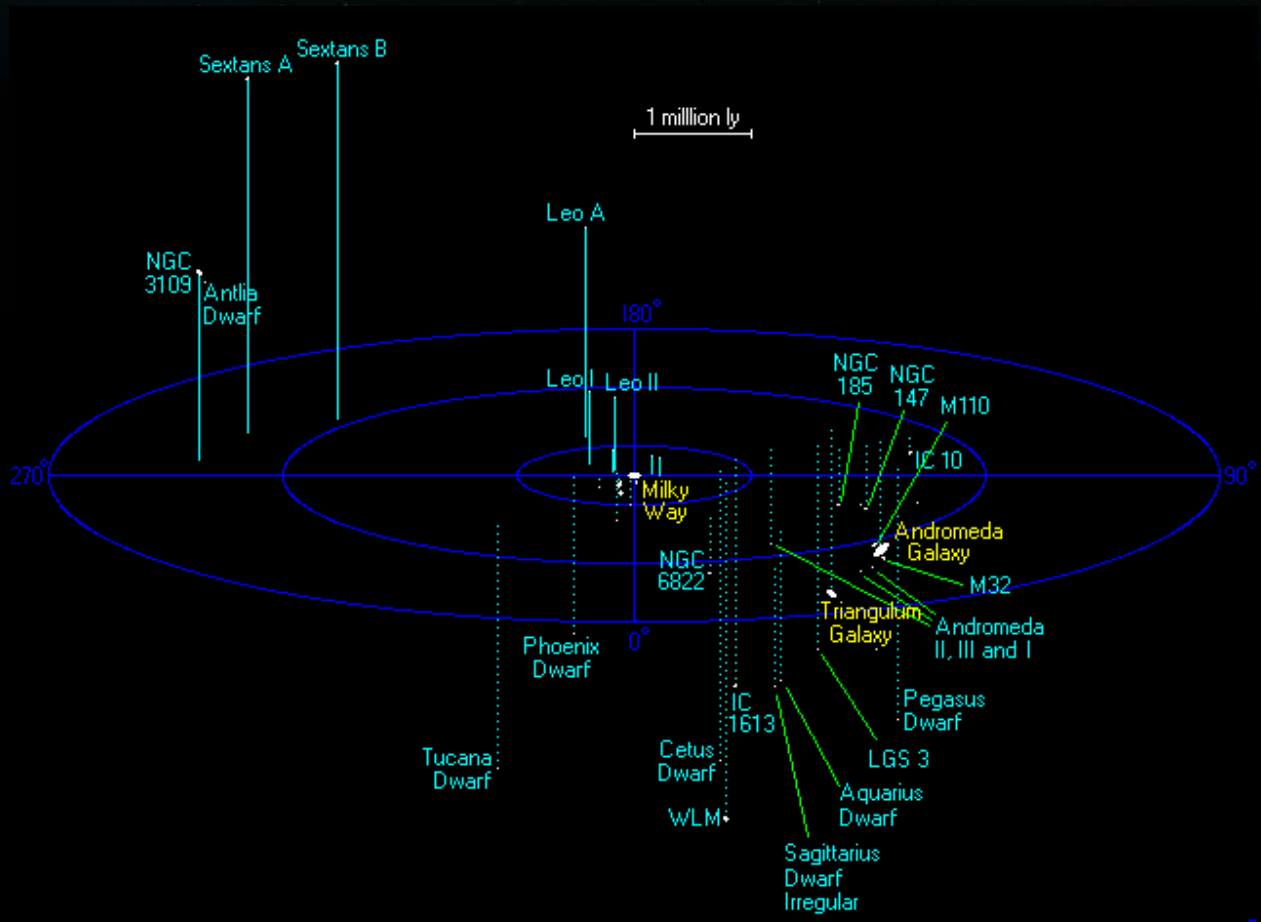
  N=10(1-b/a)
- Large populations in clusters.
- Little gas – don't see spectral HI lines



M87

The Local Group

- The Local group has 41 members, ranging from large spiral galaxies to small dwarf irregulars. Most galaxies are dwarf spheriodals…



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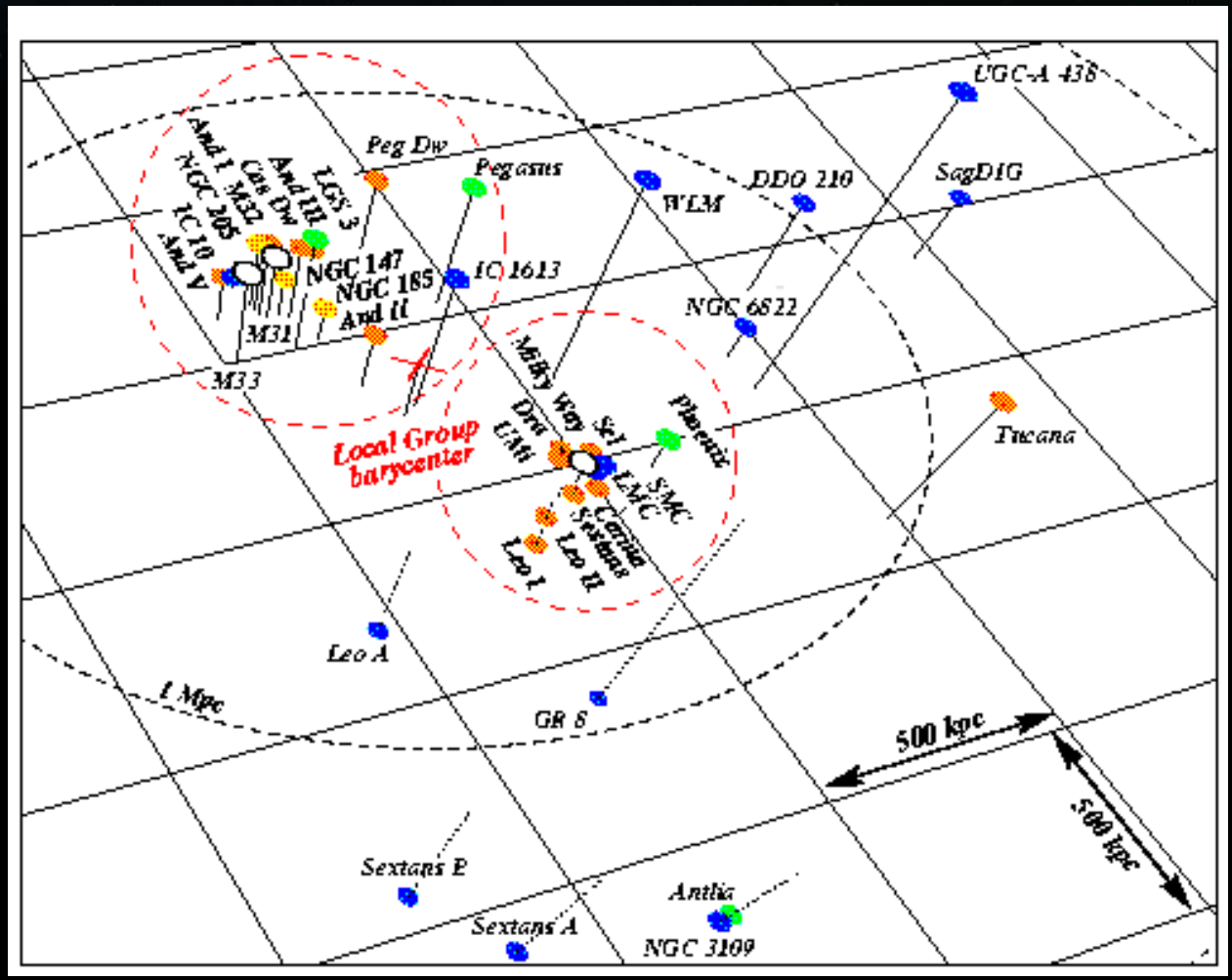
The Local Group



- Giant spirals
- dSph (+dEll)
- dIrr
- dIrr/dSph

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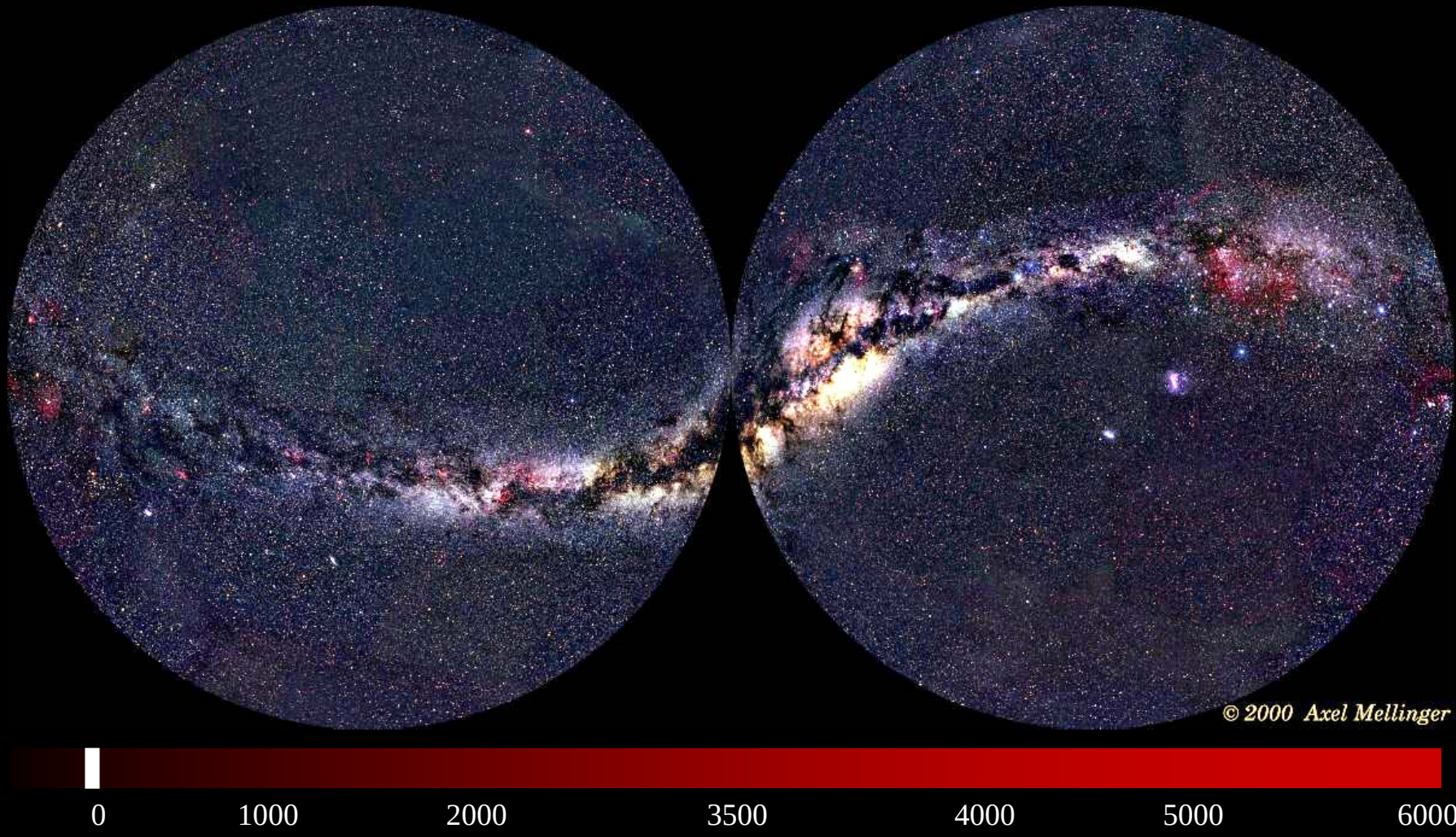
The Milky Way Galaxy

- An Sbc galaxy that is 30 kpc in diameter



Anatomy of the Milky Way

Galactic component	h_z (pc)	σ_R (km s^{-1})	σ_ϕ (km s^{-1})	σ_z (km s^{-1})	$\langle v_y \rangle$ (km s^{-1})
HI gas near the Sun	130		≈5	≈7	tiny
Local CO, H_2 gas	65		4		tiny
Disk stars: $Z > Z_\odot/4$		(Fig. 2.8)			
$\tau < 3$ Gyr	≈250	30	21	16	−11
$3 < \tau < 6$ Gyr	≈300	36	25	19	−9
$6 < \tau < 10$ Gyr	≈350	38	25	24	−16
$\tau > 10$ Gyr		62	52	37	−21
Thick disk					
[Fe/H] > −0.8	~1500	52	37	40	−35
Halo stars near Sun					
[Fe/H] < −1.6	≳1 kpc	~150	~100	~100	−210
Halo stars at $2.5R_0$	few kpc	80–100	130–150	130–150	−220

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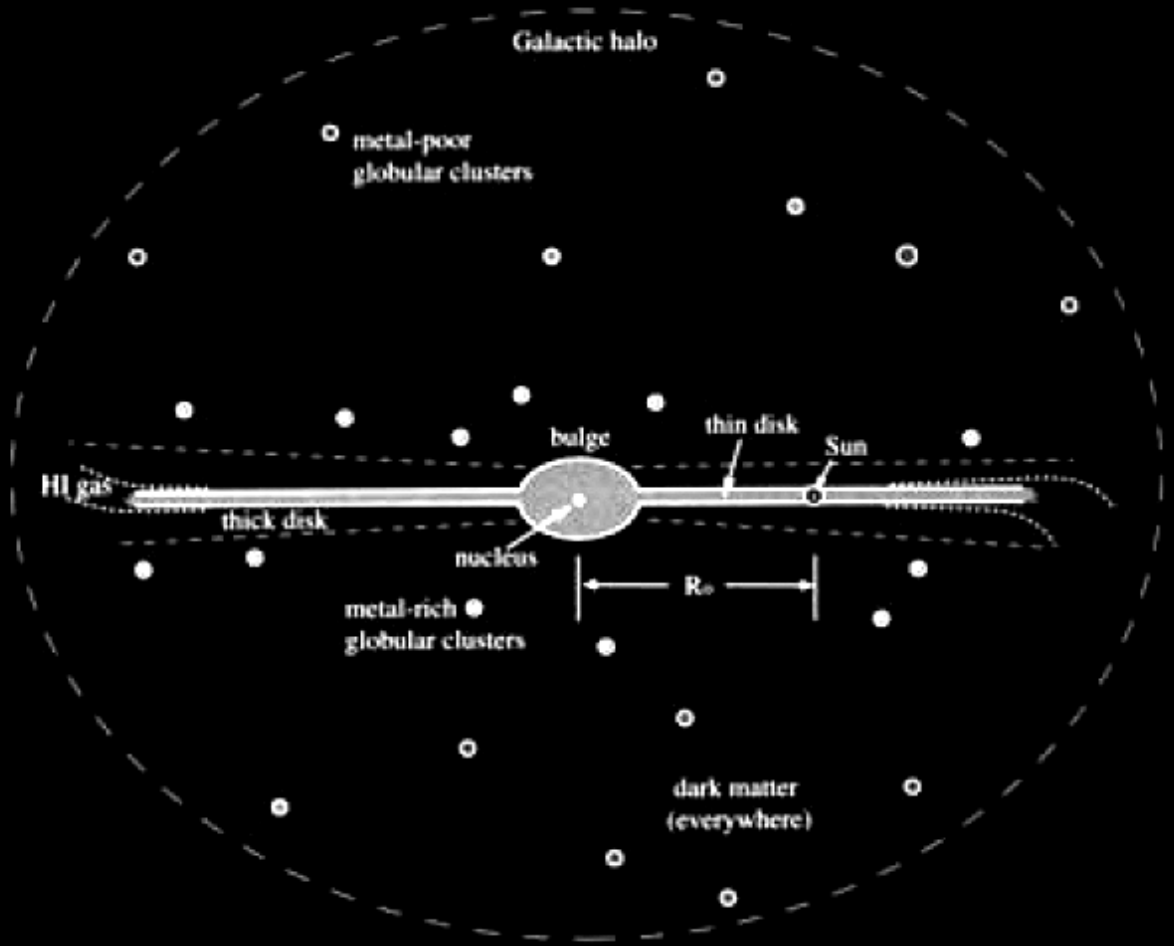
Anatomy of the Milky Way

- R_0 ~ 8 kpc
- 200 billion stars
- 5 x 10^{11} $M_\odot$
- SFR ~ 3 $M_\odot$/yr
- Bulge ~ 3 kpc in diameter



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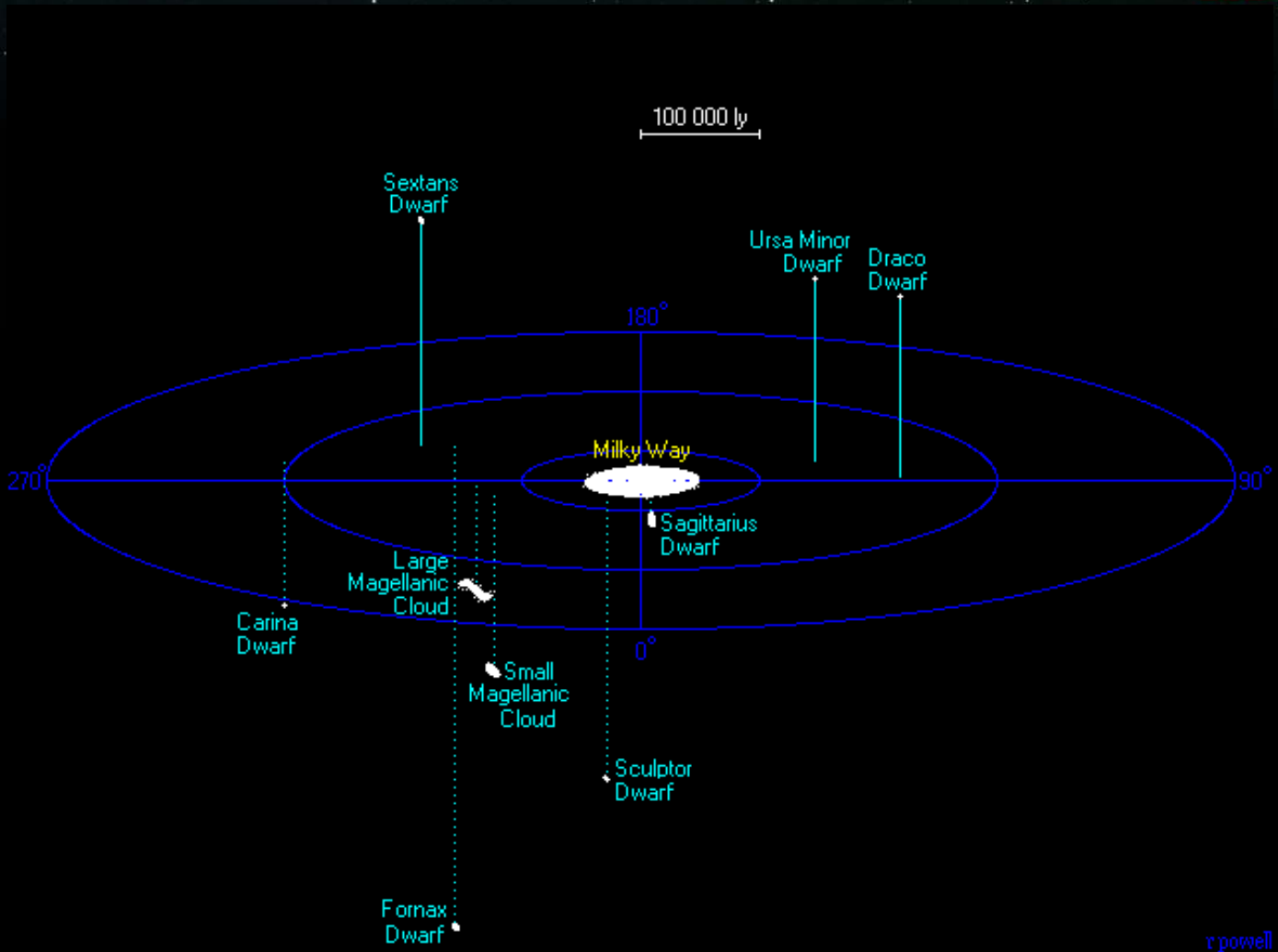
Around the Milky Way…



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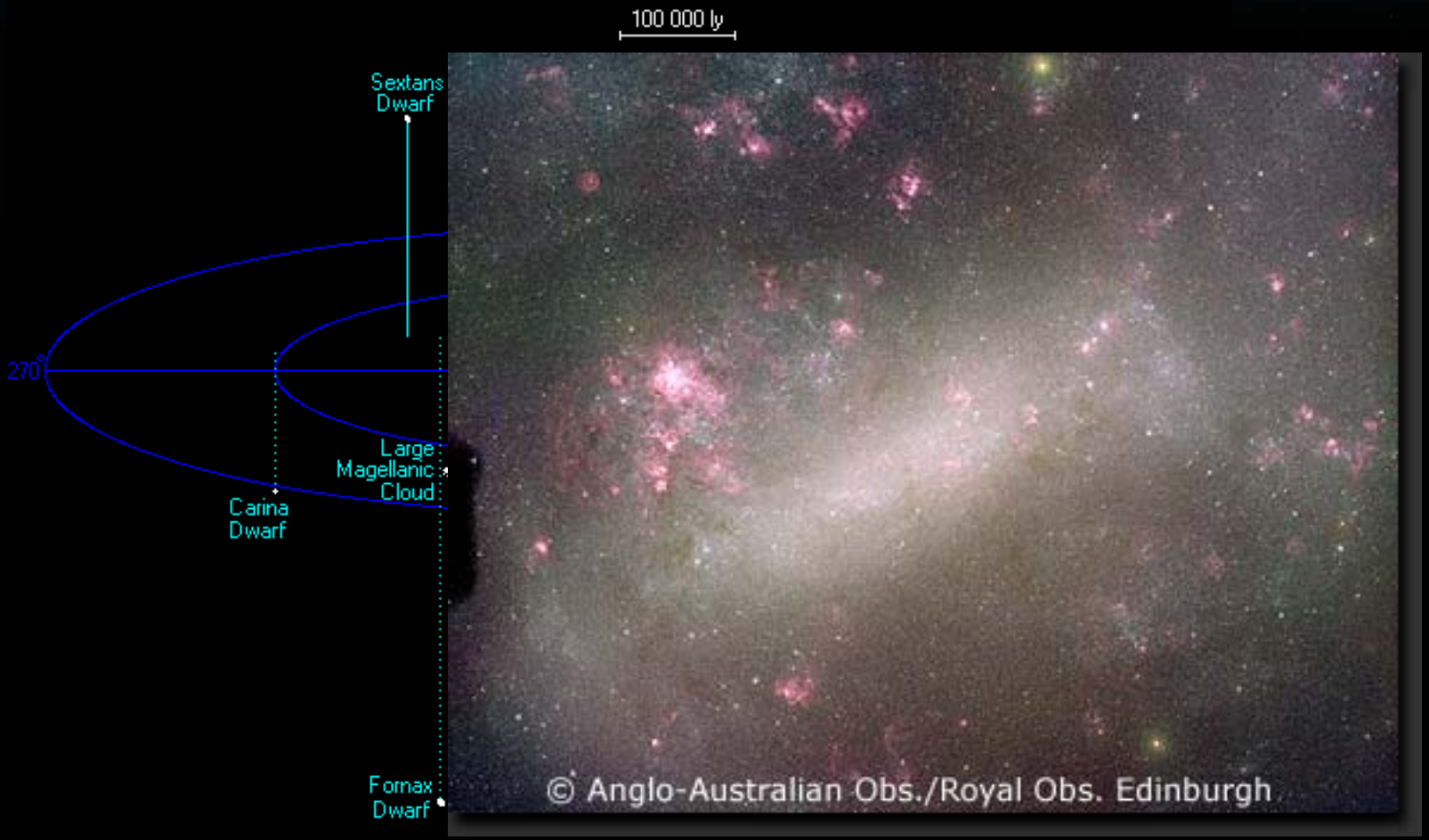
Around the Milky Way…



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Around the Milky Way...

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The Andromeda Galaxy

- Sb galaxy 770 kpc from the Milky Way.
- Larger, more luminous, with a larger disk scale length than the Milky Way – it even rotates faster at 260 km/s!
- At least 9 known satellite galaxies – dwarf elliptical and spheroidals!

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The Andromeda Galaxy

- GALEX mission mosaic in the ultraviolet

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M33

- Late-type spiral galaxy ~850 kpc from the Milky Way and ~200 kpc from Andromeda
- Disk scale length is around 1.7 kpc, rotating around 120 km/s.

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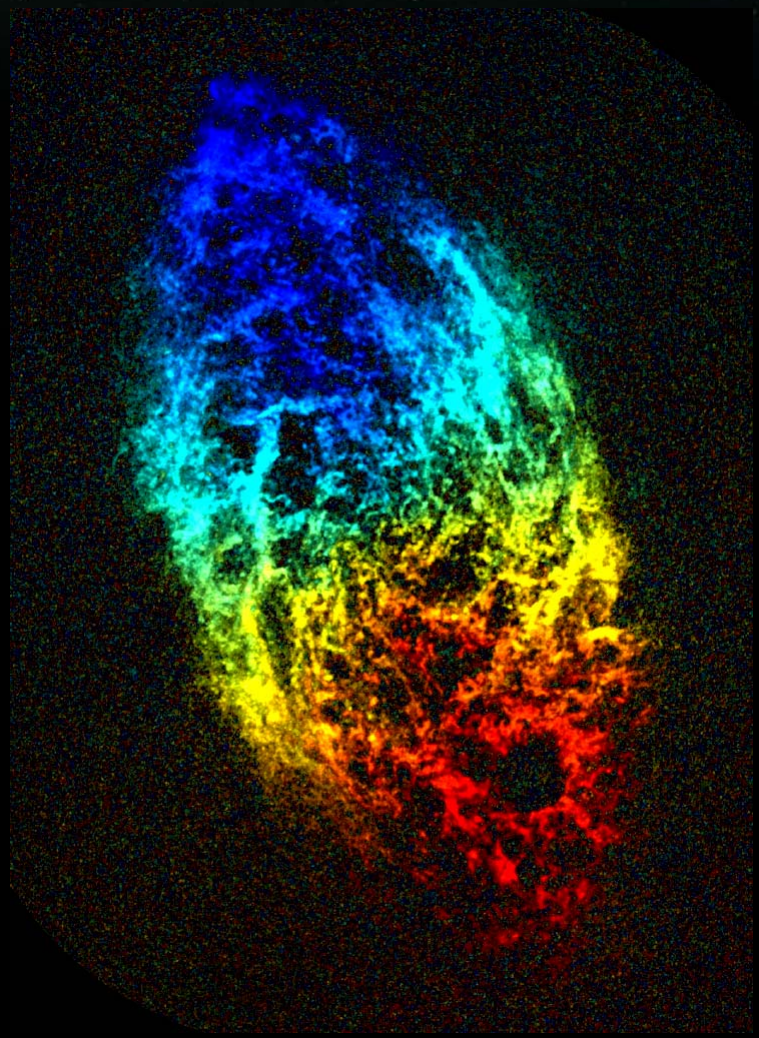
M33

- Richer in HI gas than M31 or the Milky Way – VLA doppler image show movement of the HI gas towards and away.
- The HI disk extends out to 30 kpc, enough for M31 to cause tidal effects and warp the outer disk!




Galaxy Groups

Groups of galaxies

- Galaxies can be gravitationally bound to each other, and undergo interactions and collisions.
- Separations across intergalactic distances range from 50 kpc up to 1 Mpc.
- Groups are important because one can determine a dynamical mass for the system.
- ALFALFA science goals include studying the effects within the group environment –
  - What is HI mass function?
  - How do unseen HI clouds/starless galaxies effect dynamics?
  - Are their unseen tidal remnants or debris?
  - What are sizes of HI disks?

Neighboring Galaxy Groups

Parameter	Milky Way	M31	M81	Cen A	M83	IC 342	Maffei	Sculptor[a]	CVn I[a]
D_{MW} (Mpc)	0.01	0.77	3.63	3.66	4.56	3.28	3.01:	3.94	4.09
D_{LG} (Mpc)	0.43	0.34	3.47	4.10	4.98	2.94	2.67:	3.79	4.17
SGZ[b] (Mpc)	0.00	0.07	0.04	−0.33	0.08	0.02	0.08	−0.34	0.77
N_{tot}	15	19	29	28	14	8	8:	6	9
N_{E+dSph}	10	13	11	18	4	0	1:	3	1
Type(1)	4	3	3	−2	5	5	4	5	2
M_B(1) (mag)	−20.80	−21.58	−21.06	−20.77	−20.43	−20.69	−20.15	−21.37	−19.83
V_m(1) (km s^{-1})	220	255	232	398	211	162	163	199	164
V_{LG}(1) (km s^{-1})	−88	−35	107	301	304	245	212	274	353
$\langle V_{LG} \rangle$ (km s^{-1})	−79	−16	193	312	308	229	302	279	306
σ_v (km s^{-1})	76	77	91	105	71	54	59	54	56
$\langle R_p \rangle$ (kpc)	155	254	211	290	164	322	104	359	385
L_B (10^{10} $L_\odot$)	3.28	6.83	6.11	5.55	2.31	3.21	2.69	5.58	2.00
M_{vir} (10^{10} $M_\odot$)	93	57	117	489	109	57	65	332	267
M_{orb} (10^{10} $M_\odot$)	96	111	197	288	100	95	135	153	322
M_{vir}/L ($M_\odot$ $L_\odot^{-1}$)	28	8	19	88	47	18	24	60	133
M_{orb}/L ($M_\odot$ $L_\odot^{-1}$)	29	16	32	52	43	30	50	28	161
T_{cross} (Gyr)	2.1	3.3	2.3	2.8	2.3	5.9	1.8	6.6	6.9

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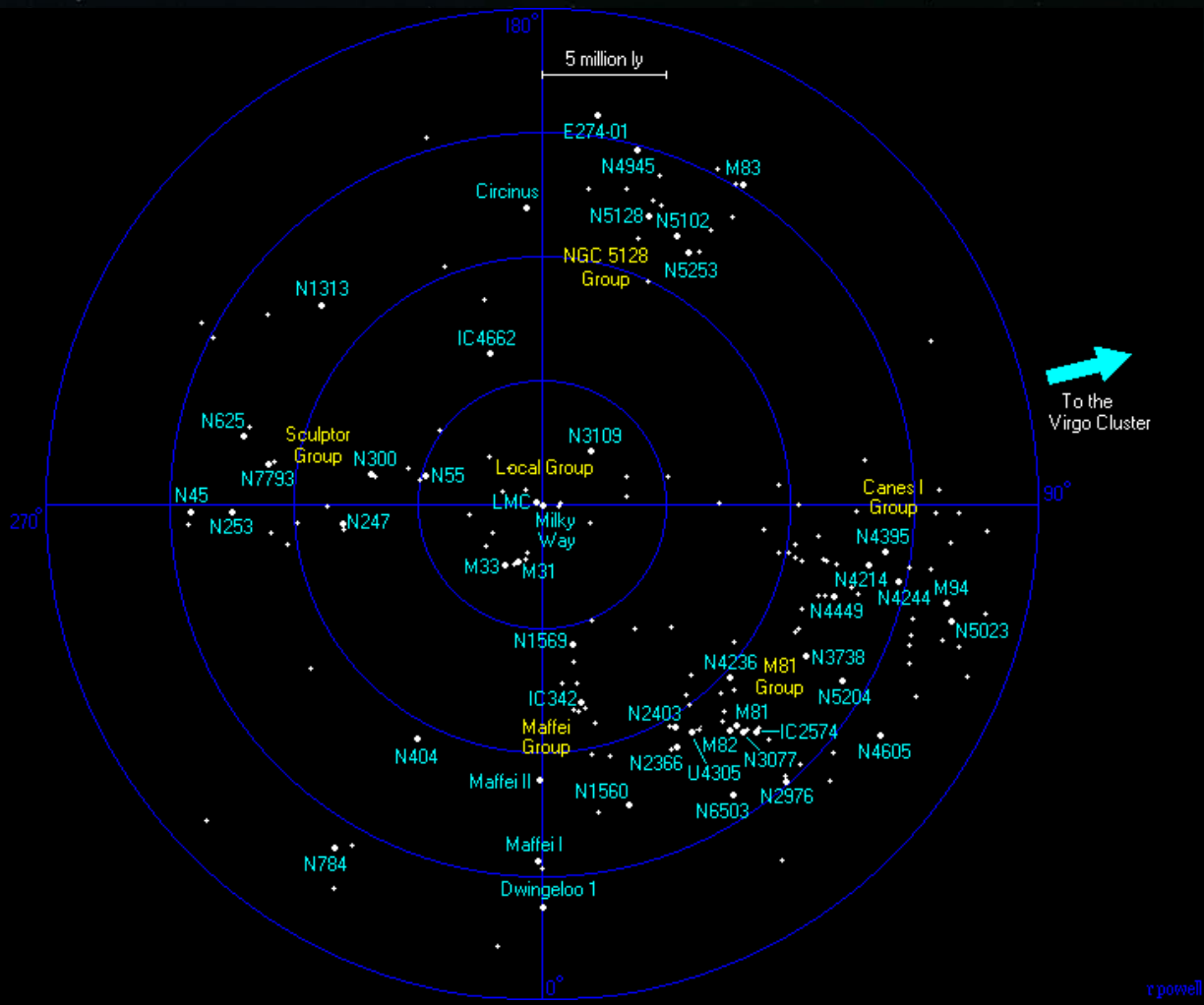
Neighboring Galaxy Groups



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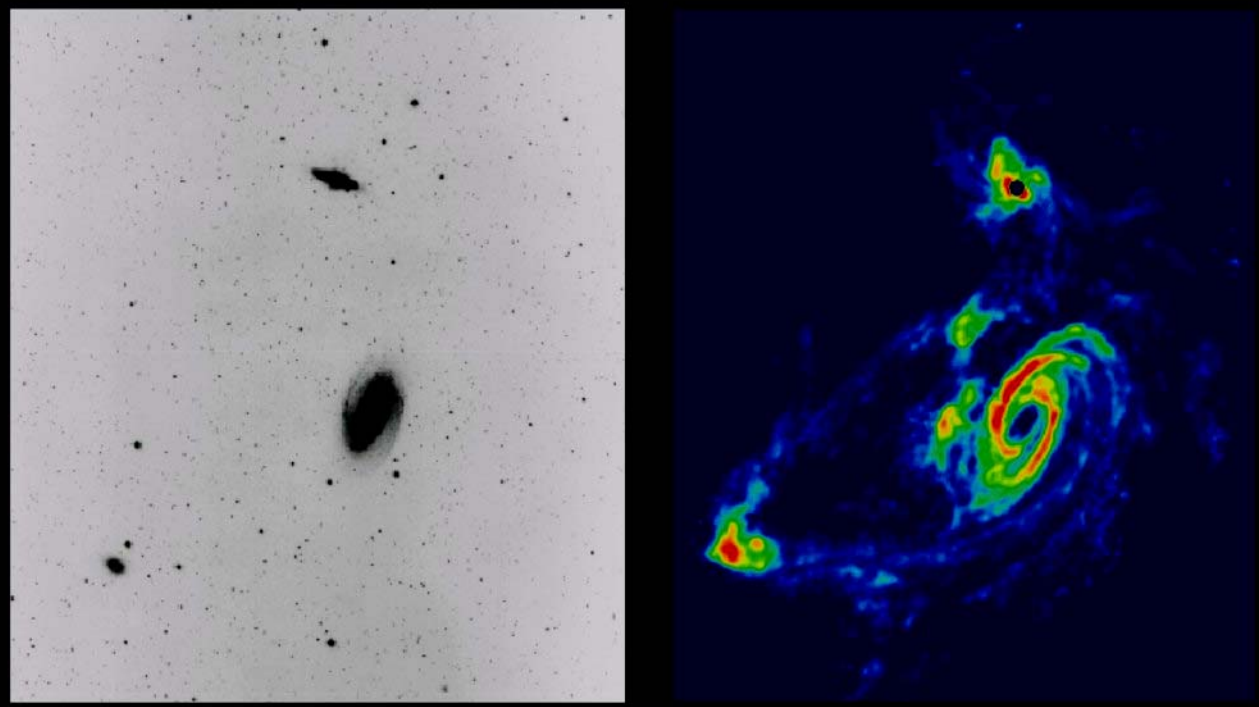
Groups of galaxies

TIDAL INTERACTIONS IN M81 GROUP

Stellar Light Distribution

21 cm HI Distribution



Cen A Group

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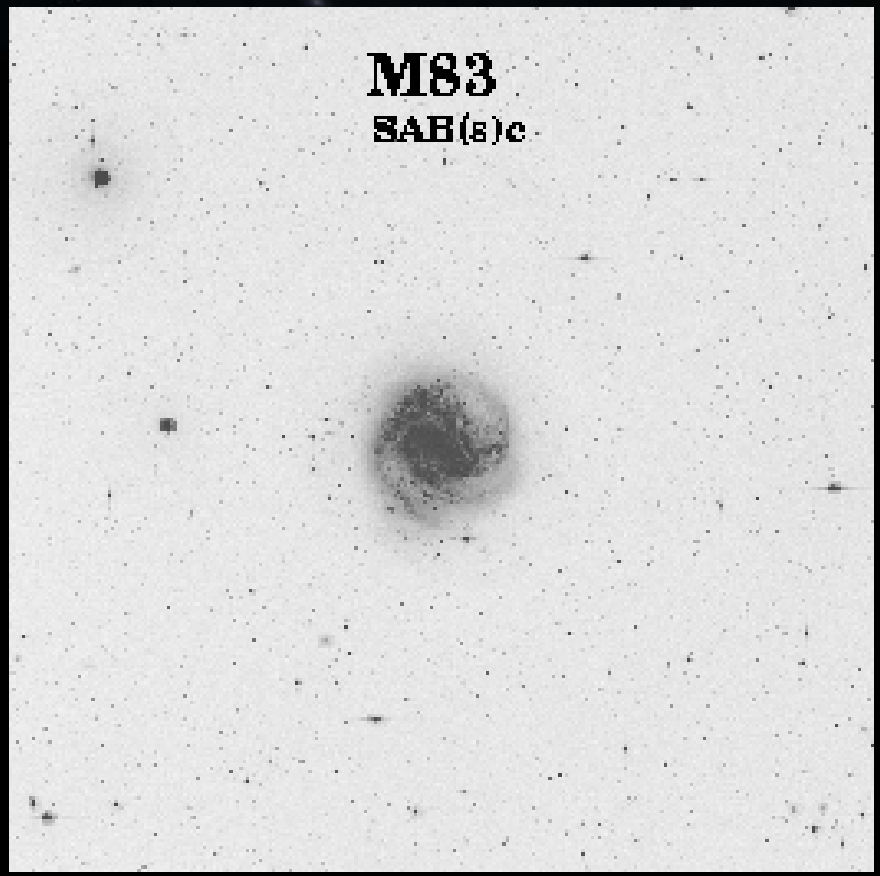
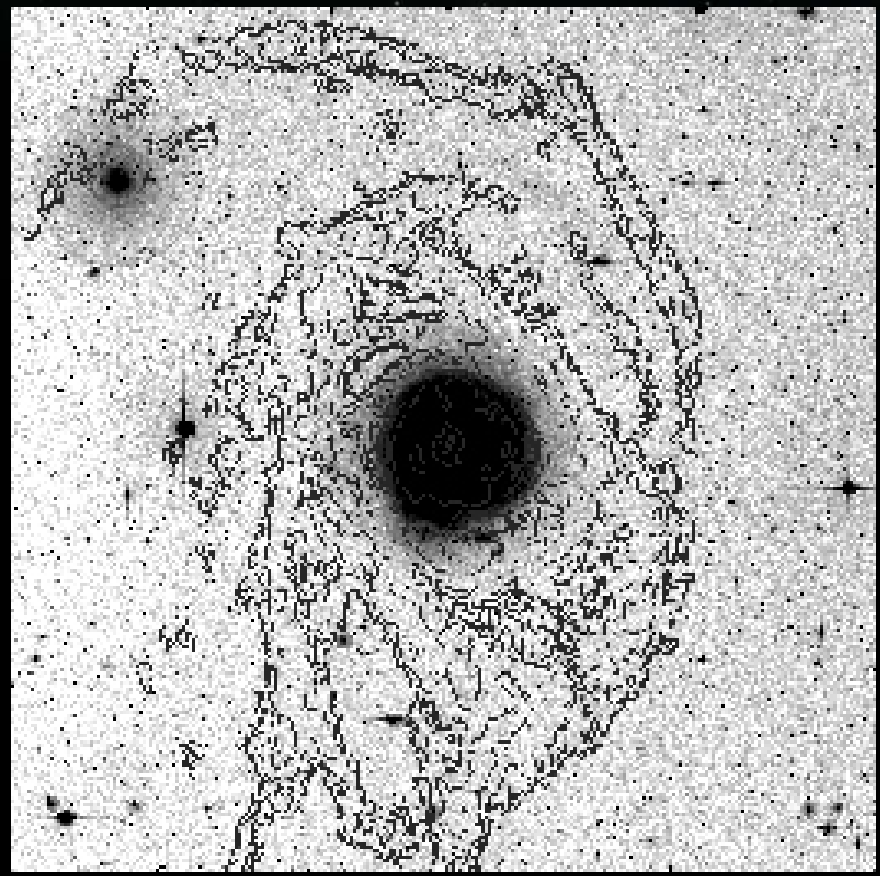
M83 Group





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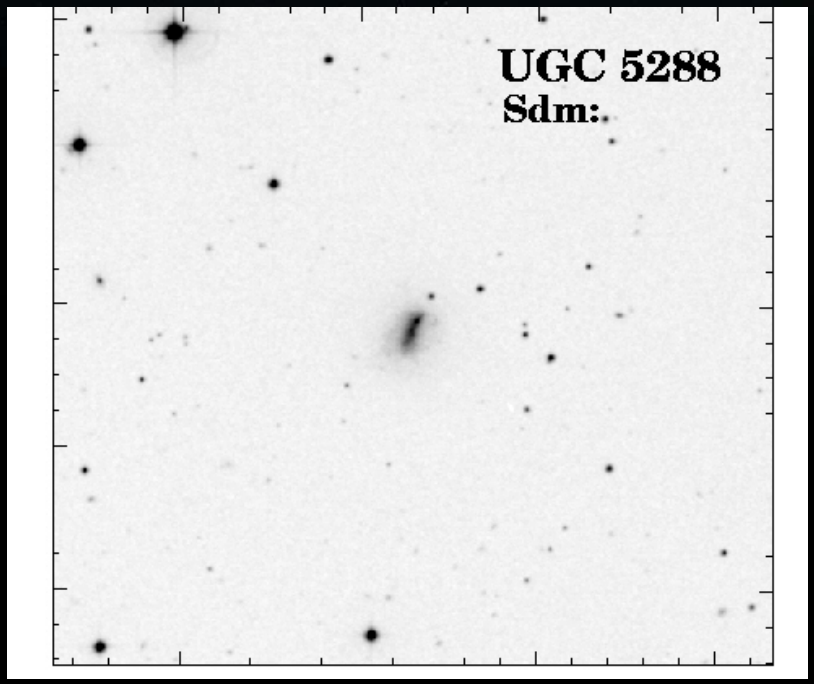
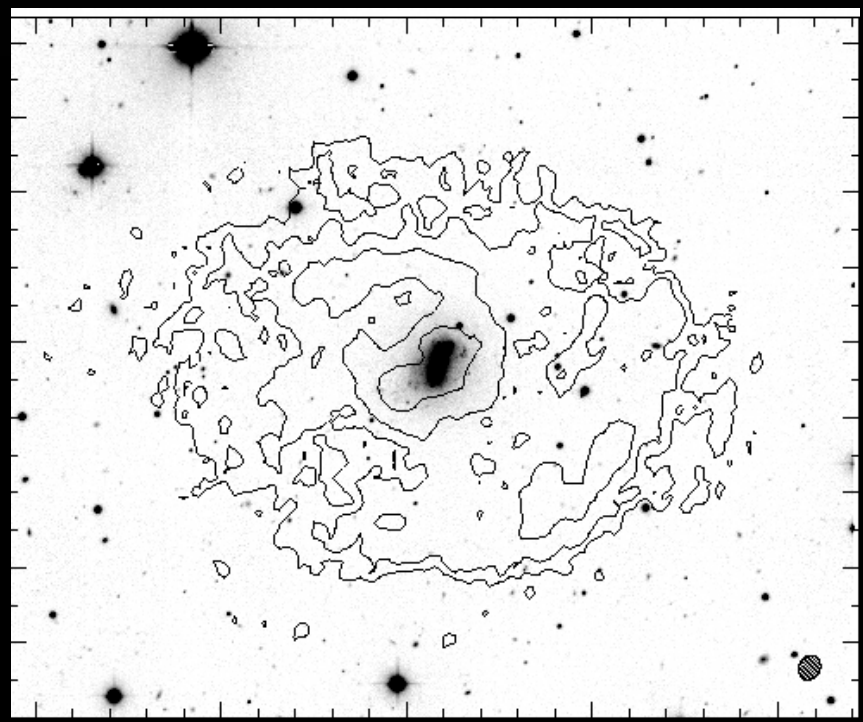
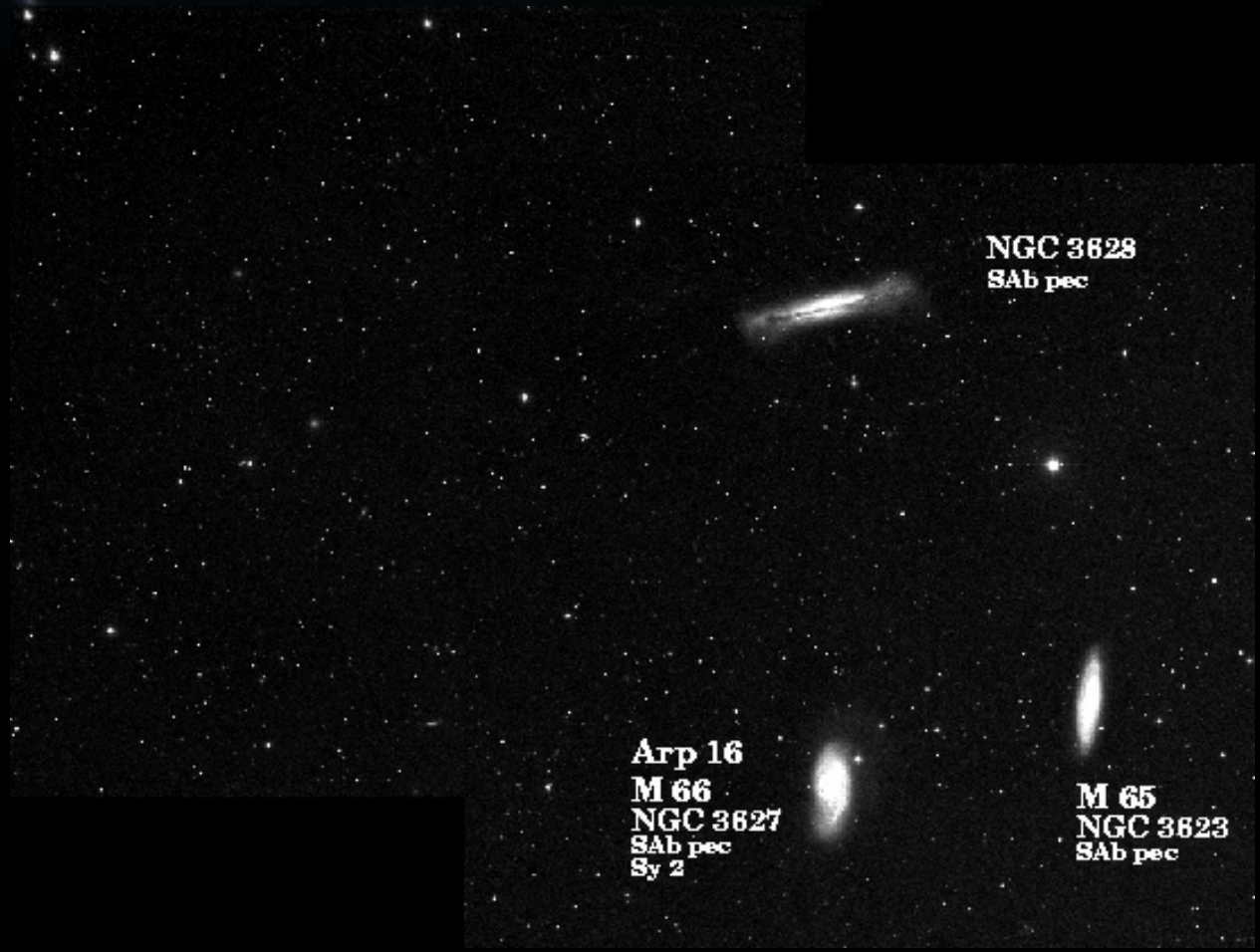
Extended HI Disk of a BCD





M66 Group



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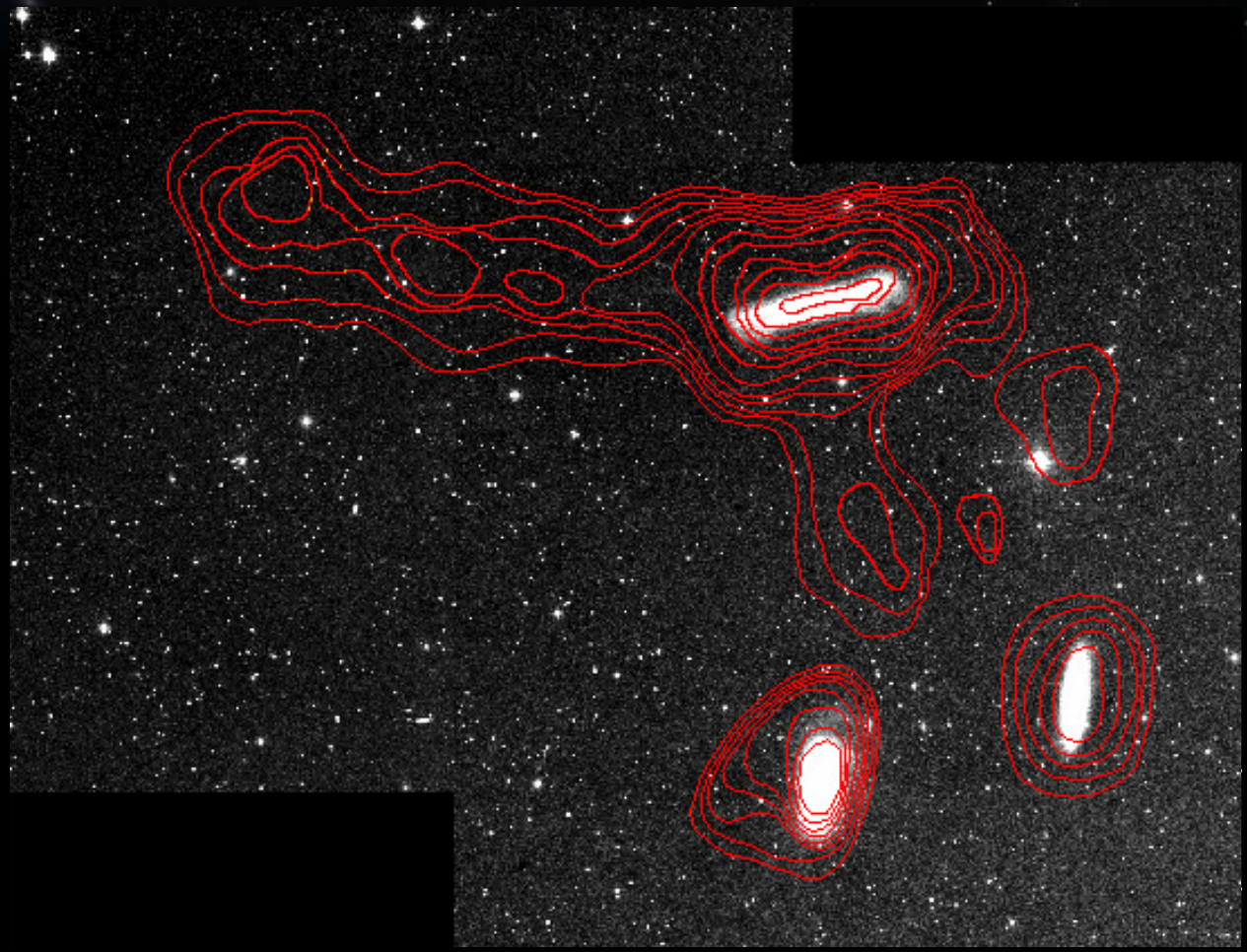
M66 Group



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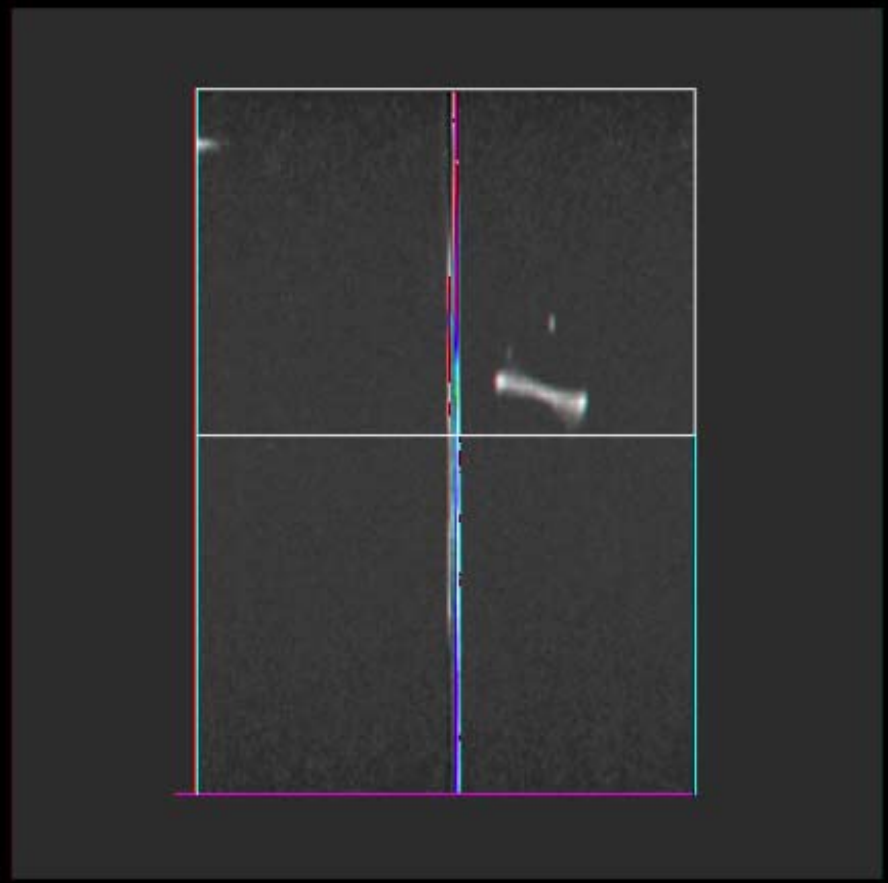
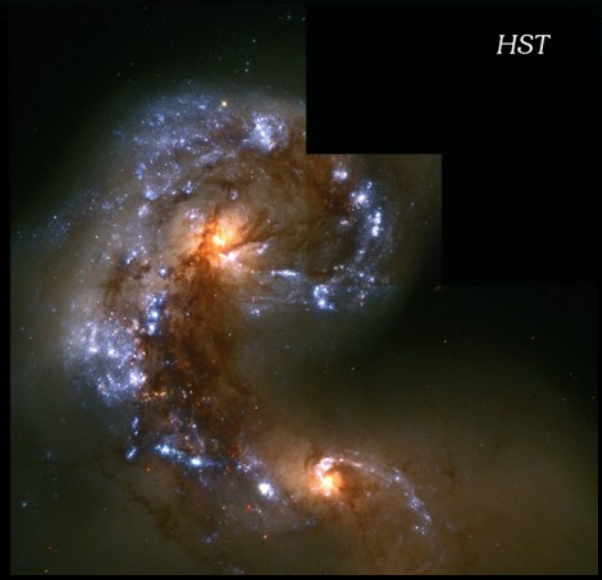
NGC 2683



Colliding Galaxies



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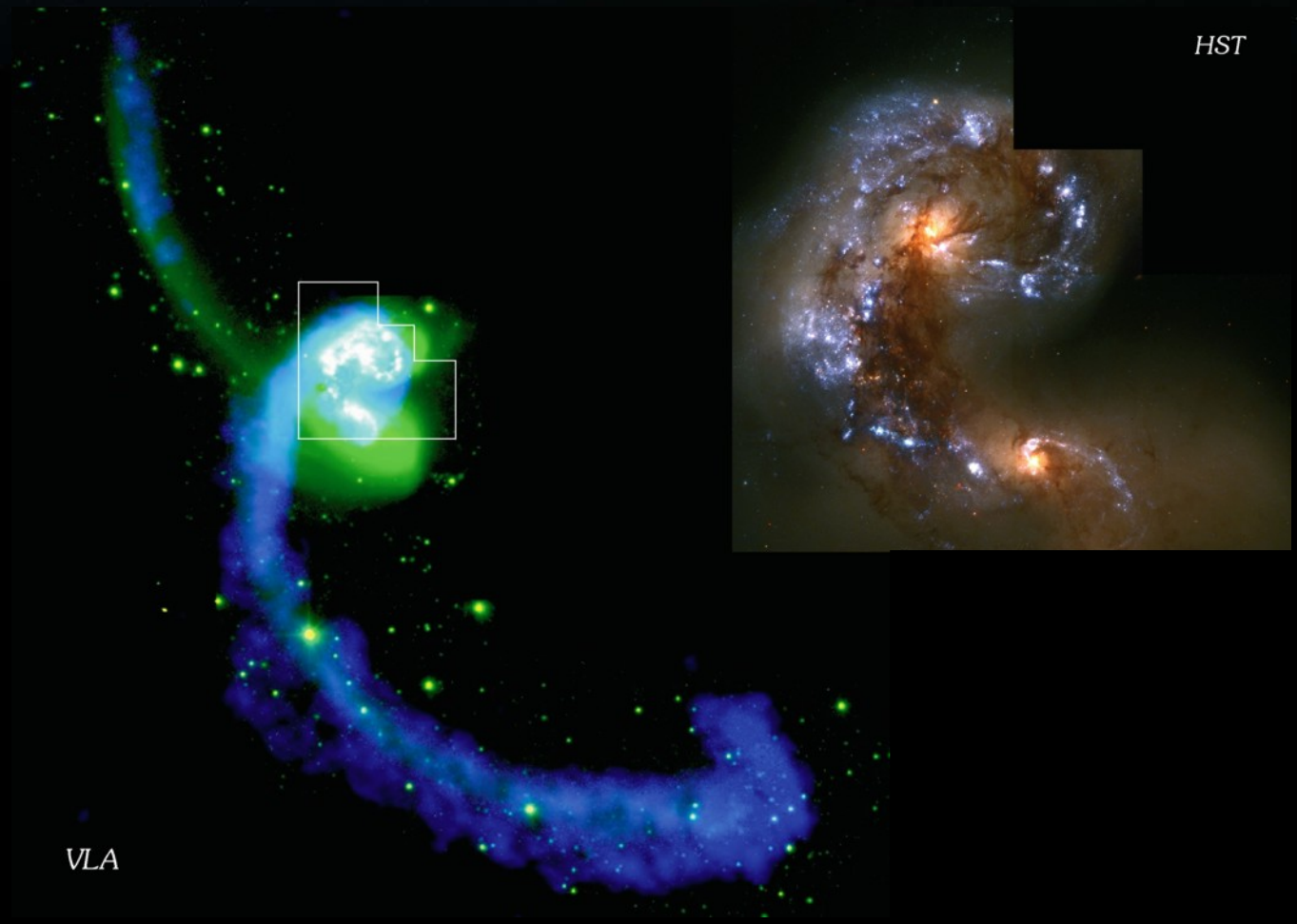
Colliding Galaxies



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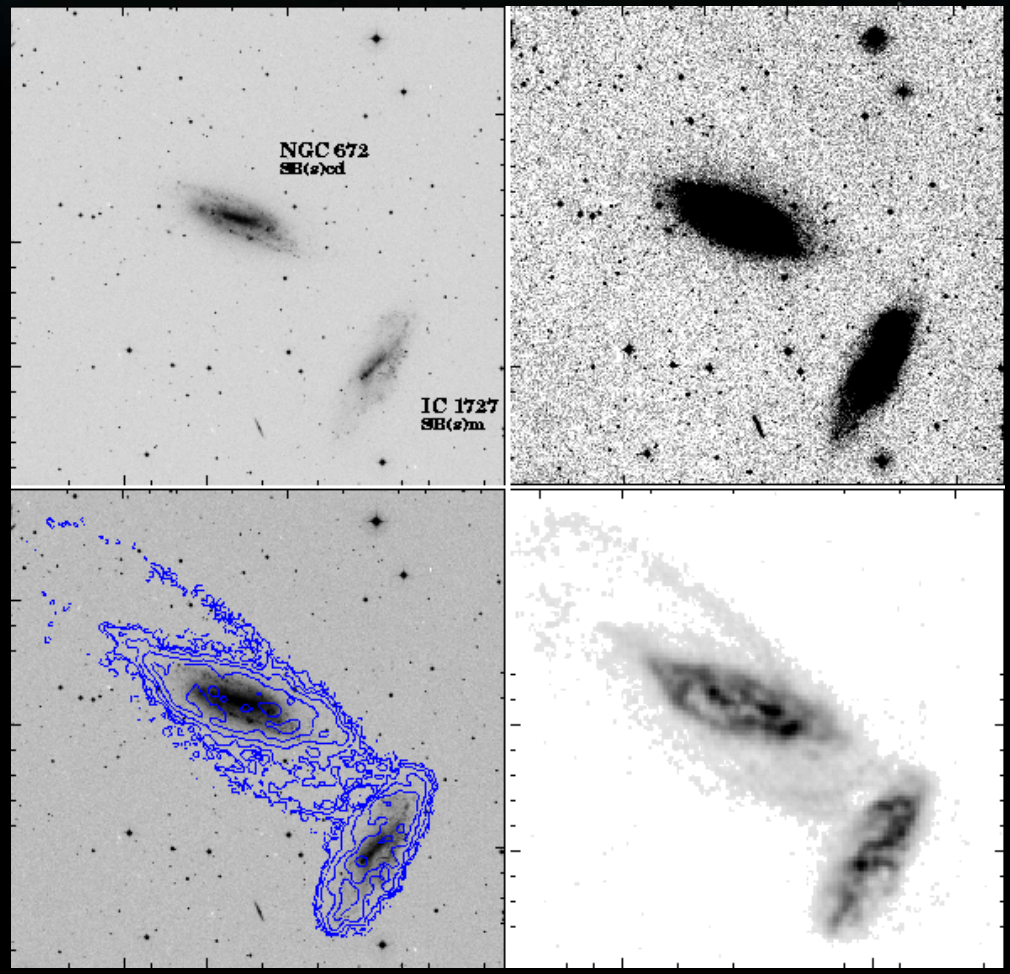
Colliding Galaxies



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Galaxy Clusters

Clusters of Galaxies

- Around half the galaxies in the Universe are found in clusters or groups.
- Cluster have a higher density than “loose” groups – brightest galaxies are S0s and ellipticals instead of spirals
- Abell Catalog contains 4073 rich clusters
- Gravity binds the members, as well as hot intracluster gas (seen in the X-ray)

Clusters of Galaxies

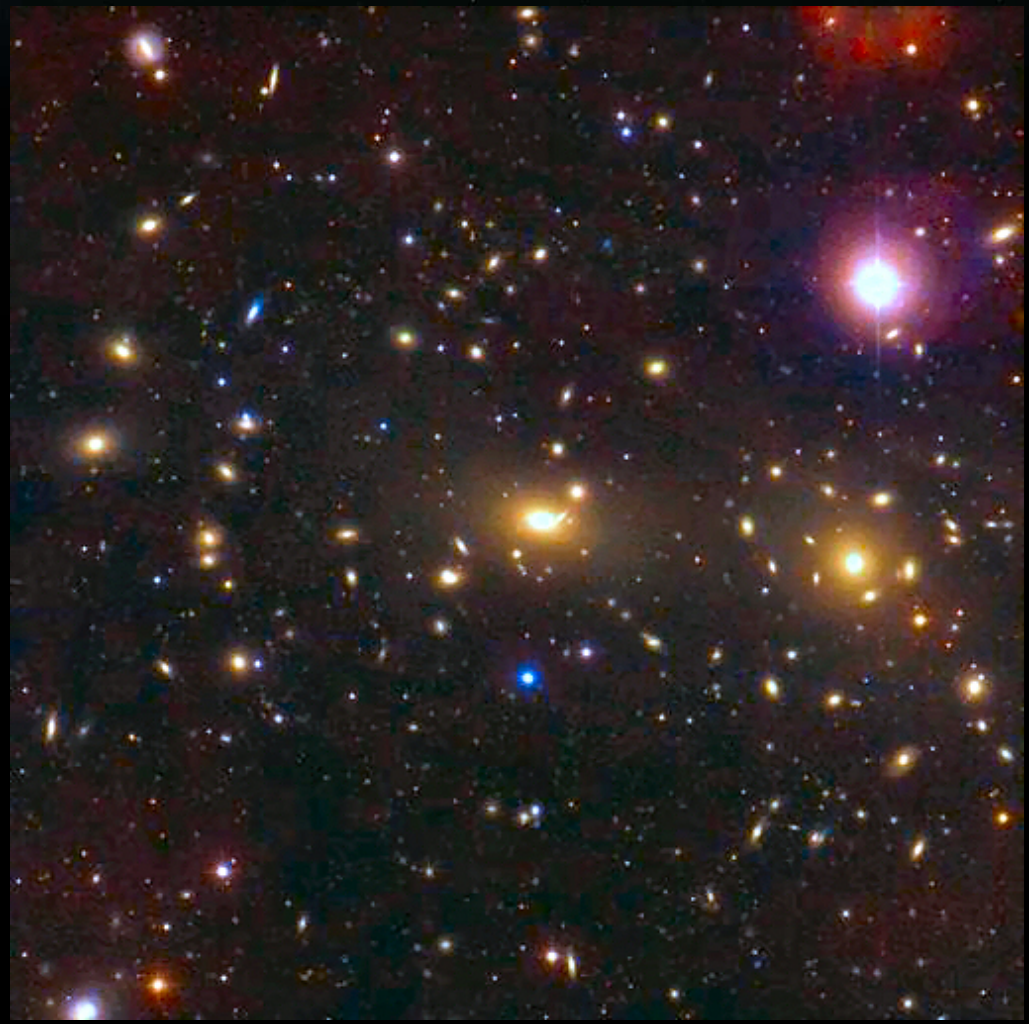
- Some well known clusters:
  - Virgo
  - Fornax
  - Eridanus
  - Coma
  - Perseus
  - Hercules
  - Leo
  - Centaurus

Virgo Cluster

- cz ~ 1050 km/s
- Δv ~ 1000 km/s !!
- 1300 catalogued members!!
- Most galaxies are dwarfs
- Core radius ~ 500 kpc

Coma Cluster

- At *cz* = 6900 km/s
- Four times the size of Virgo!!
- Core contains only ellipticals.



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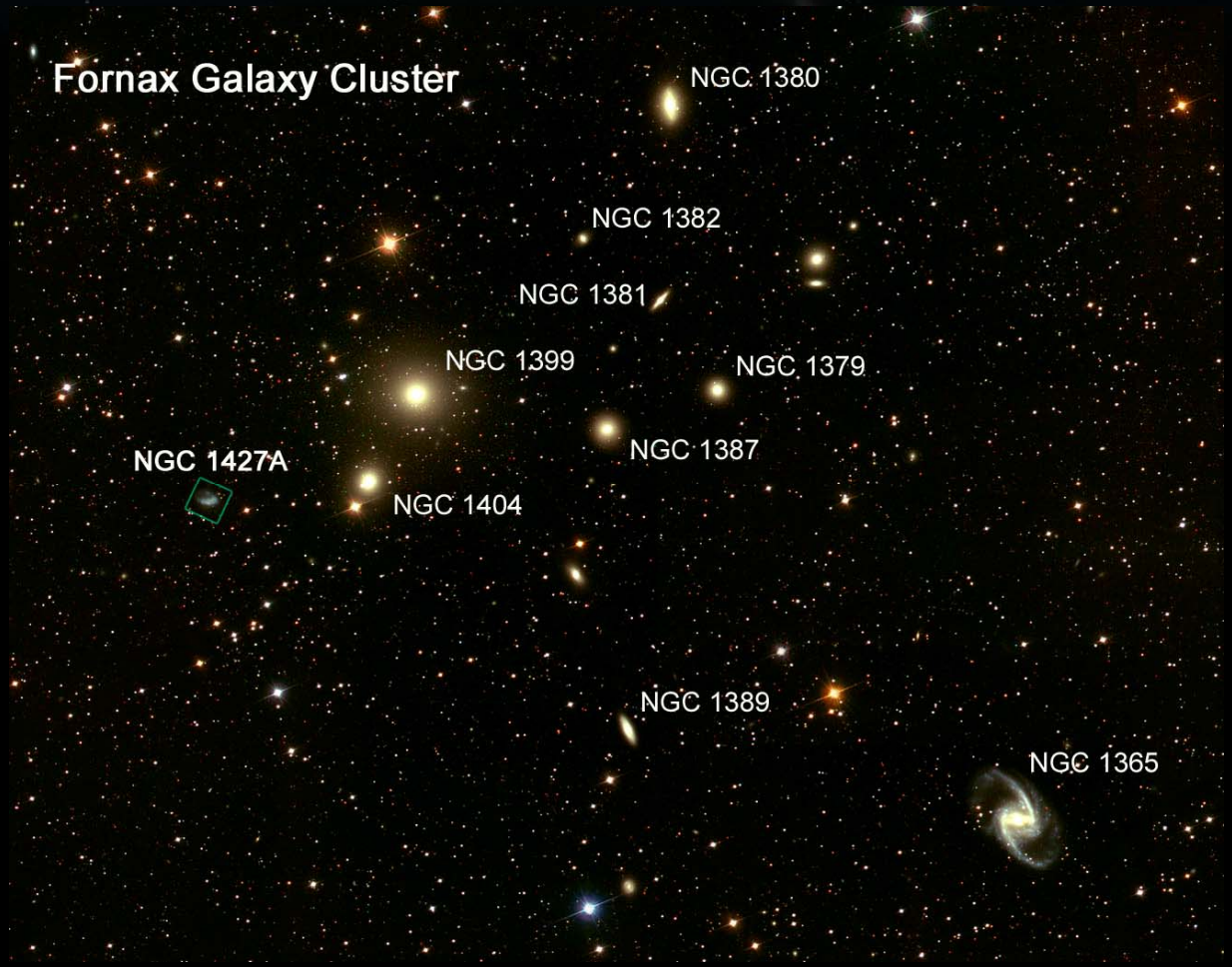
Fornax cluster

- *cz* ~ 1400 km/s



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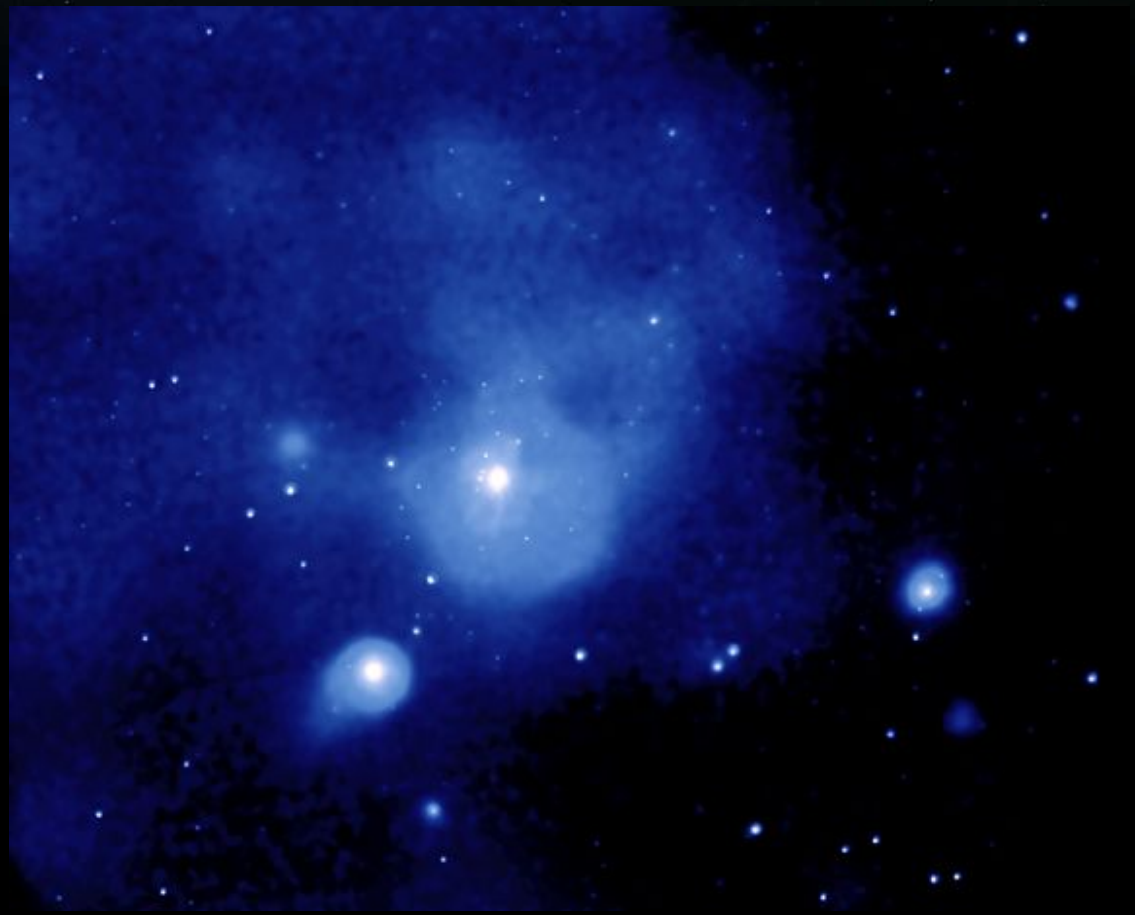
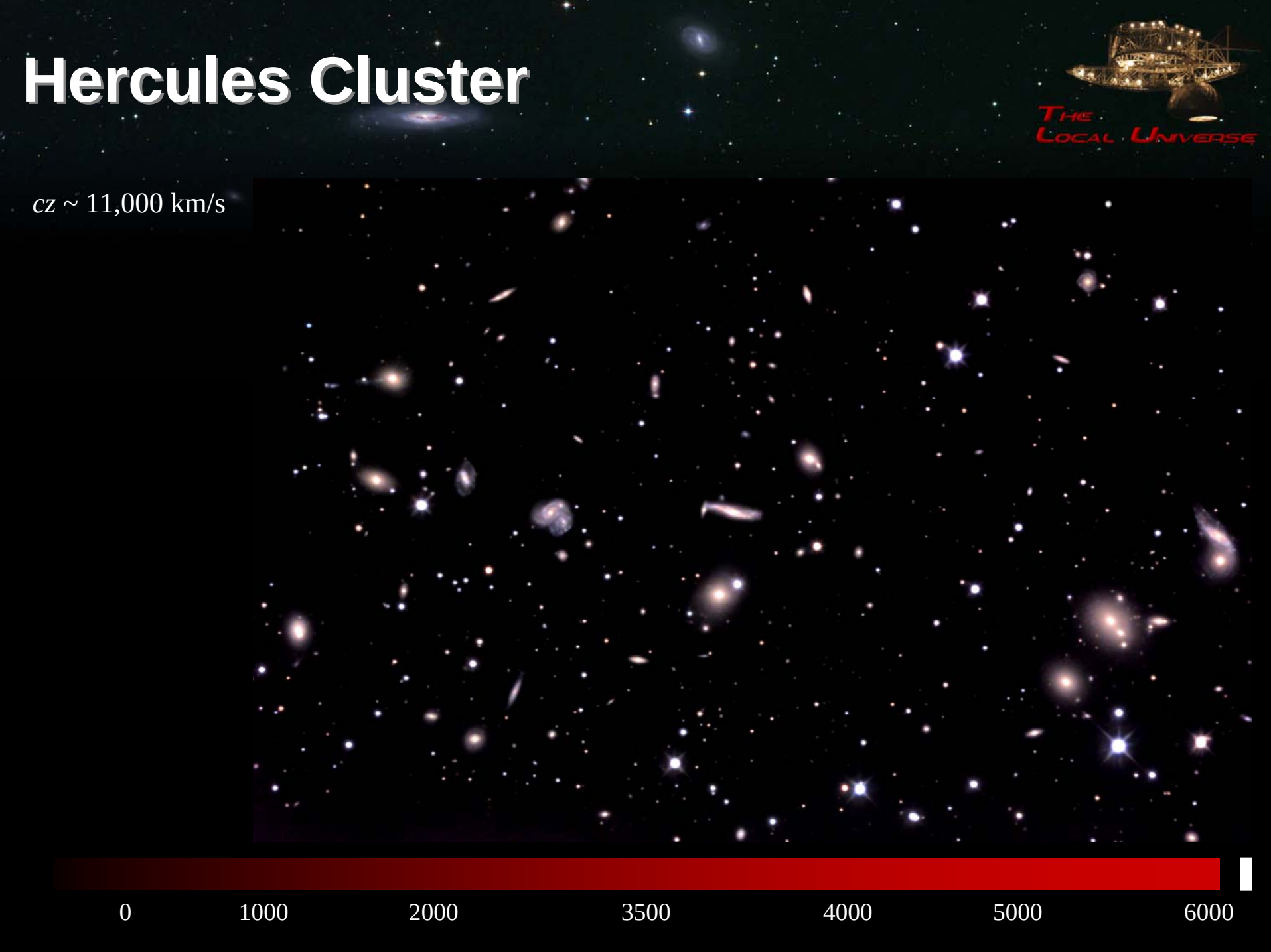
Fornax Cluster – Xray view



Fornax – optical + radio

Hercules Cluster



Perseus Cluster

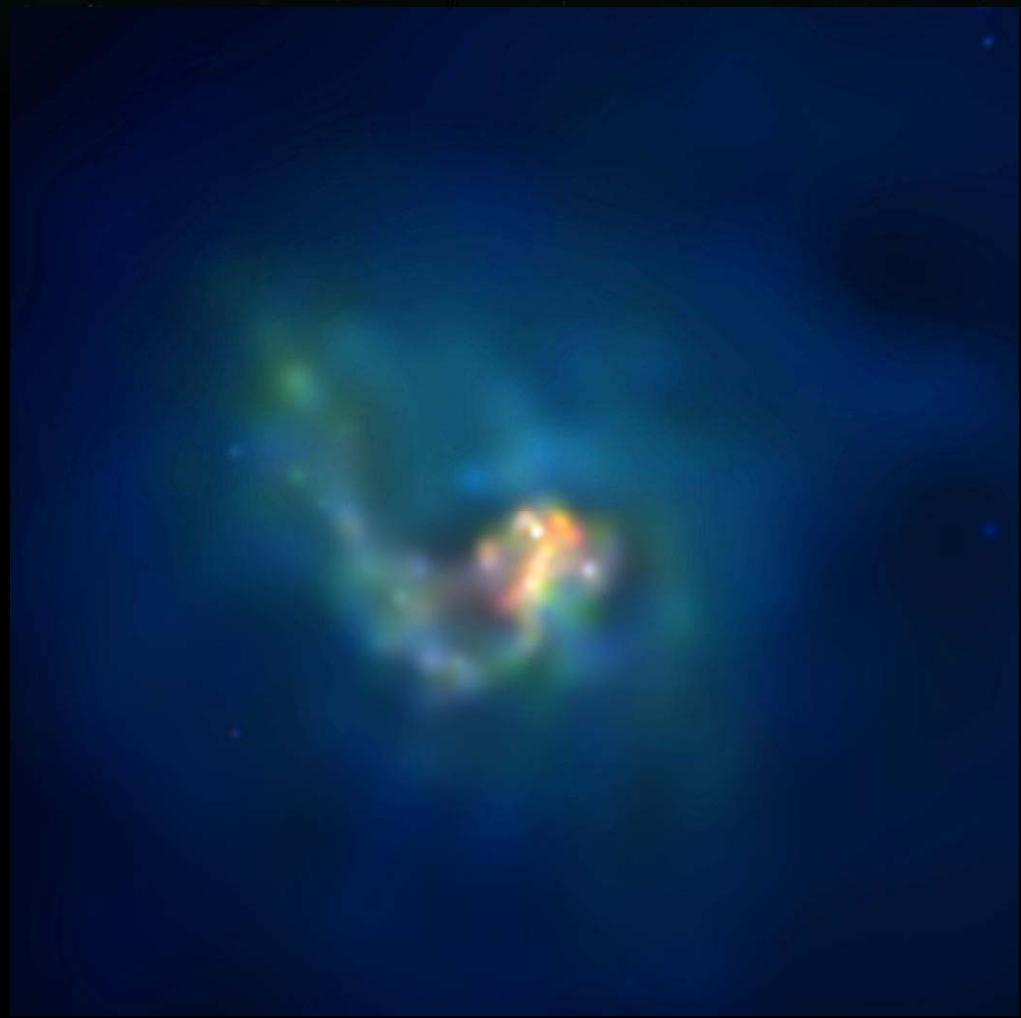
cz ~5000 km/s

Leo Cluster

- *cz* ~ 6400 km/s

Centaurus Cluster

- *cz* ~ 3000 km/s
- Xray image shows gas expelled from the central member



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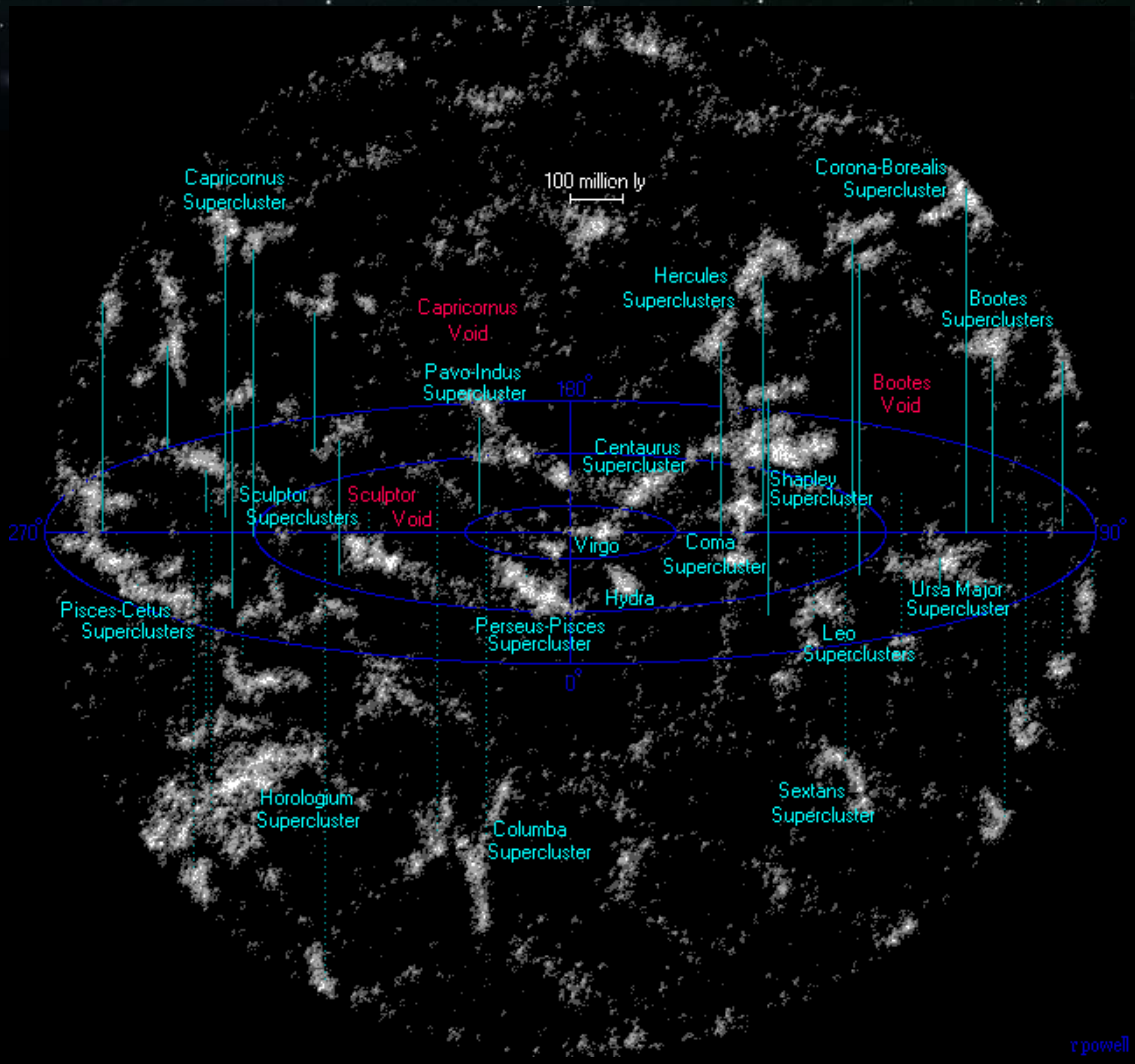
Superclusters
The largest structures
in The Universe

Superclusters in the Universe



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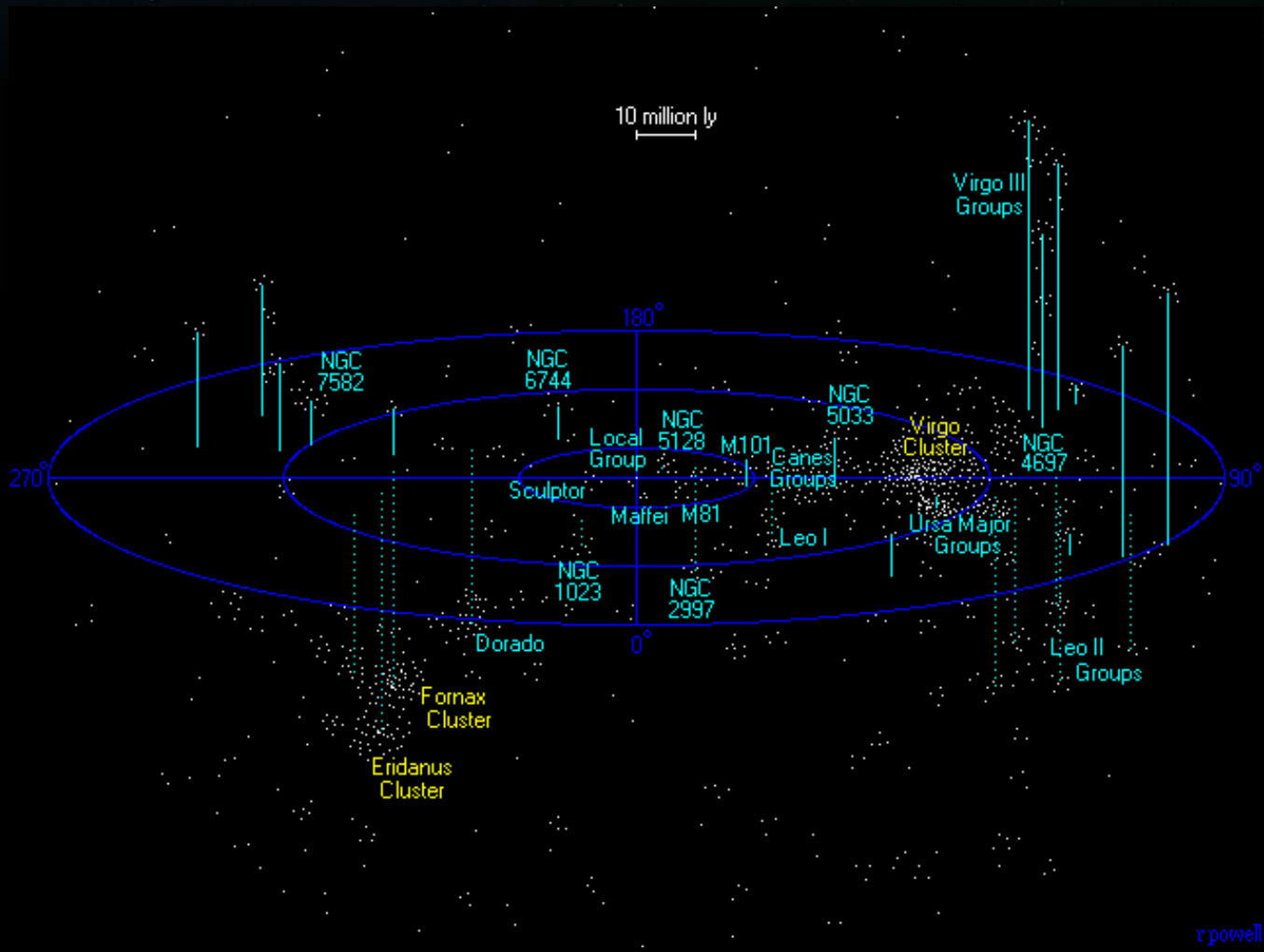
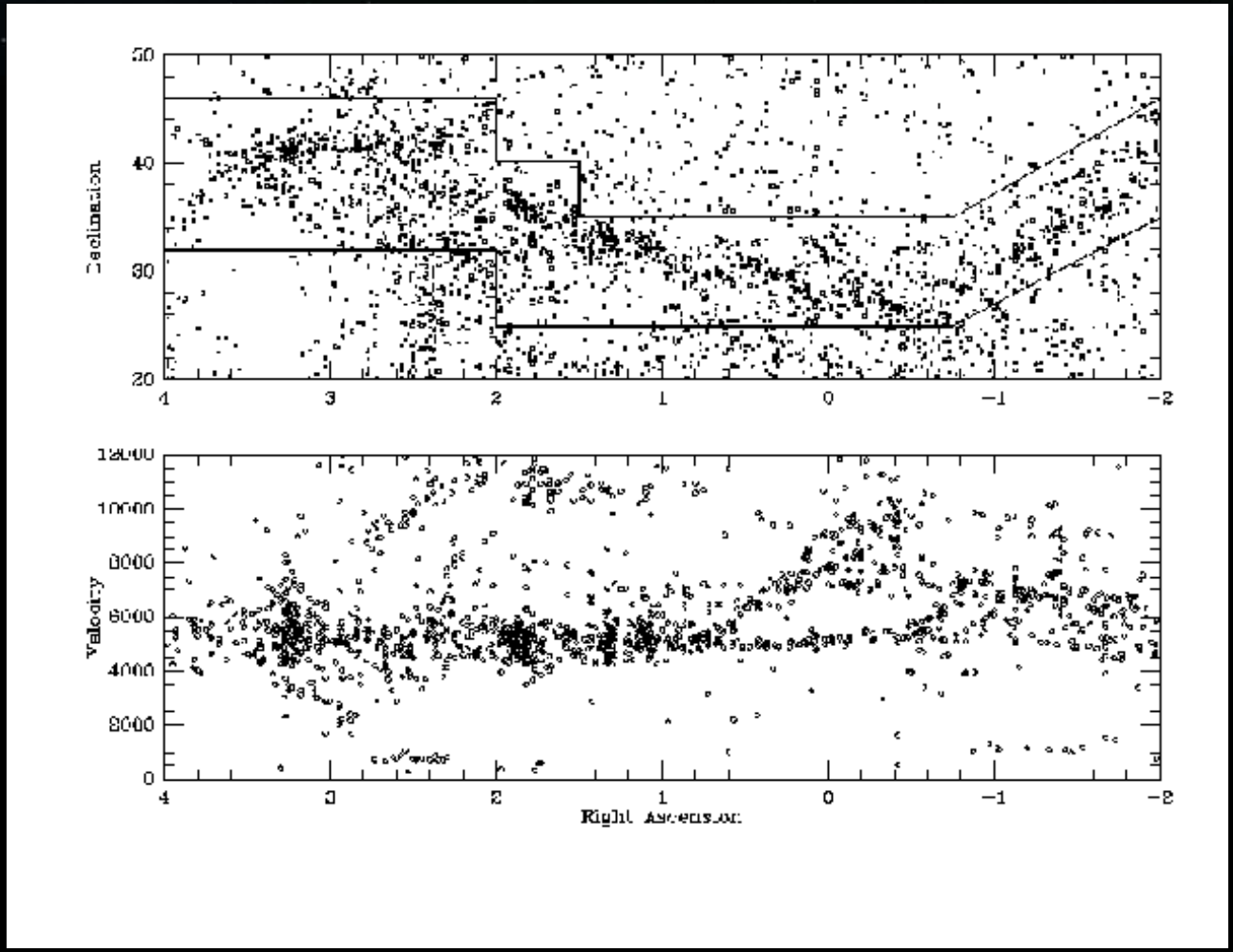
Local Supercluster



Pisces-Perseus Supercluster



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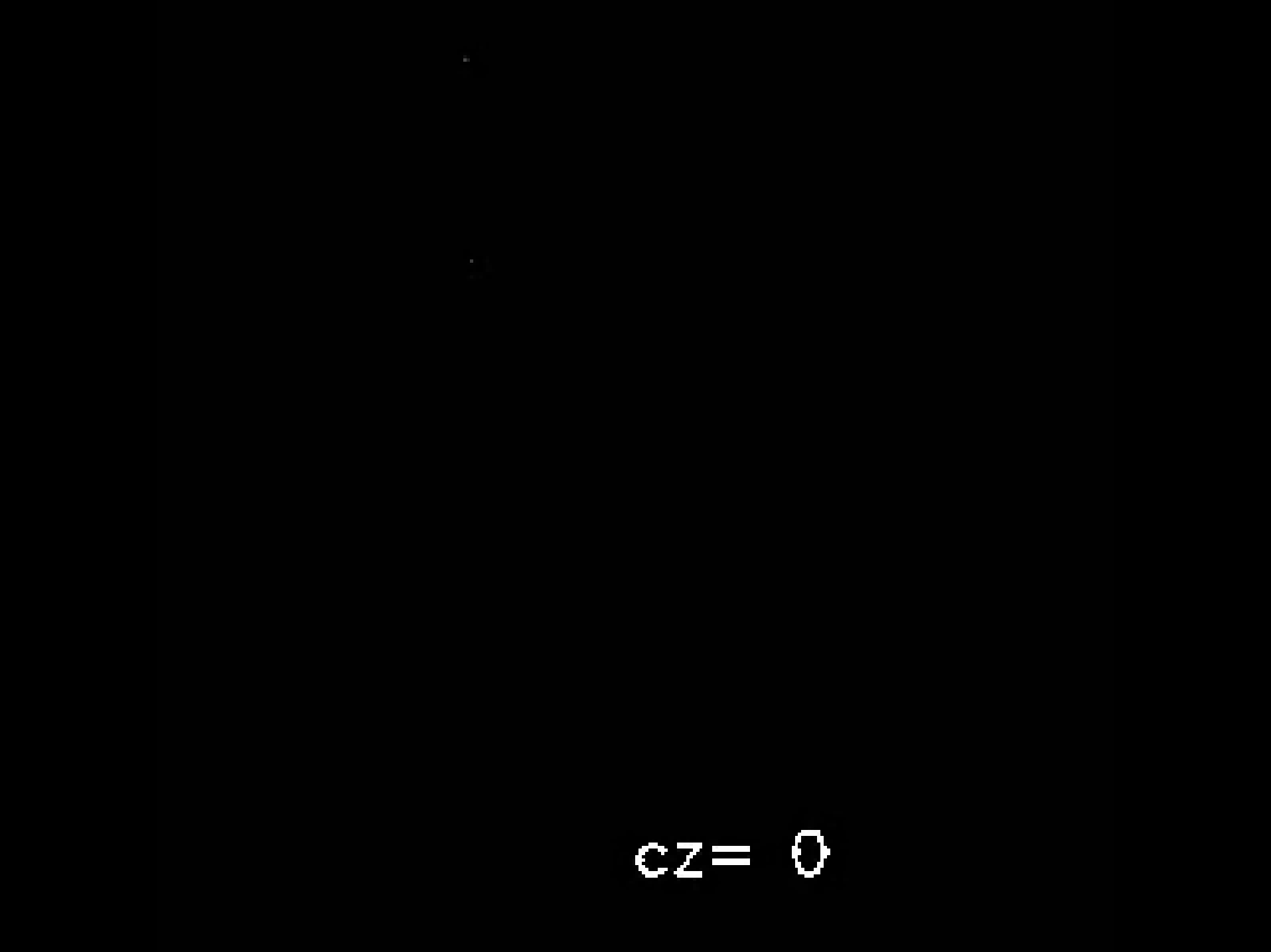
Overview of the Local Universe

Local Universe Overview

- Springob, C.M. et al. 2005, ApJS. (in press)
- ~9000 redshifts based on HI detections
- Data taken from a variety of radio telescopes…


cz= 0

References

- Hibbard's Rogue's Gallery
- Herter, T. Astro 530, Cornell University
- Malin, D. Anglo-Australiian
- Alex Mellinger
- Mateo, et. al.
- APOD
- Haynes, M. P.
- Giovanelli, R.
- J. Sanders, A. Fabian
- KPNO REU Program
- Nigel Sharp, KPNO, WIYN
- Jason Ware
- Sparke and Gallagher, Galaxies in the Universe
- Karachentsev, I.D. 2005, AJ, 129,178
- NRAO Image Gallery
- Springob, C.M.
- Spizer Multiwavelength View – M81
- Abell, et al. 1989. ApJS, 70,1
- Sarah Maddison