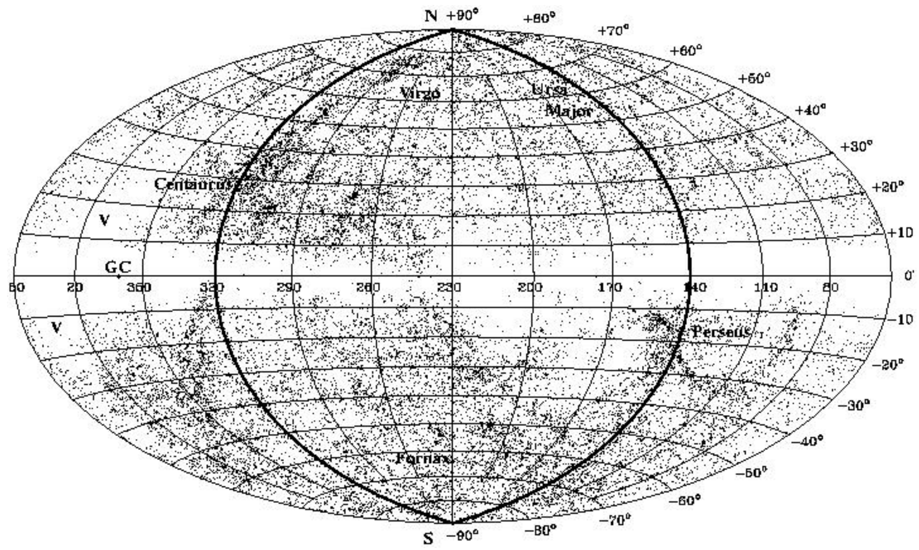
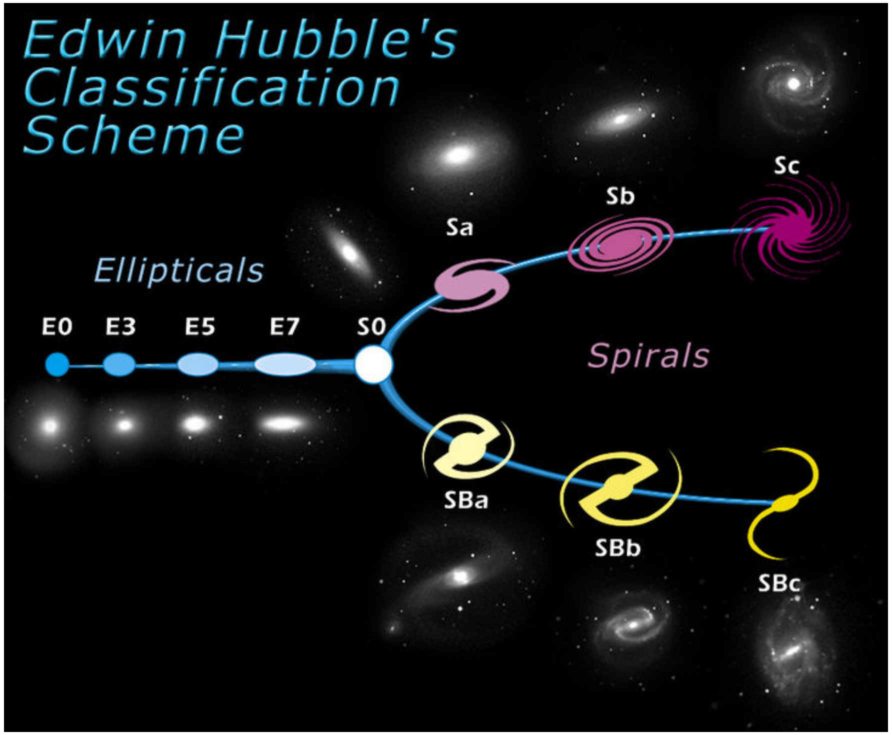
Astr 5465 Feb. 17, 2020
Distribution & Classification of Galaxies

- Distribution of Galaxies
  - Faintest galaxies are distributed ~ uniformly over the sky except for the Galactic plane (zone of avoidance)
  - Brighter galaxies show clear pattern of clustering
  - Local Supercluster includes Virgo Cluster at the center of a filament ("supergalactic plane")
  - Various bound groups located in the filament and environs
  - Note that the Local Supercluster is not gravitationally bound but contains bound groups like the Local Group.
  - In 3D (redshift as distance) structure is a flattened plane and can be quantified (Lahav et al. 2008)
  - To be continued within context of large scale structure.



Morphological Classification of Galaxies

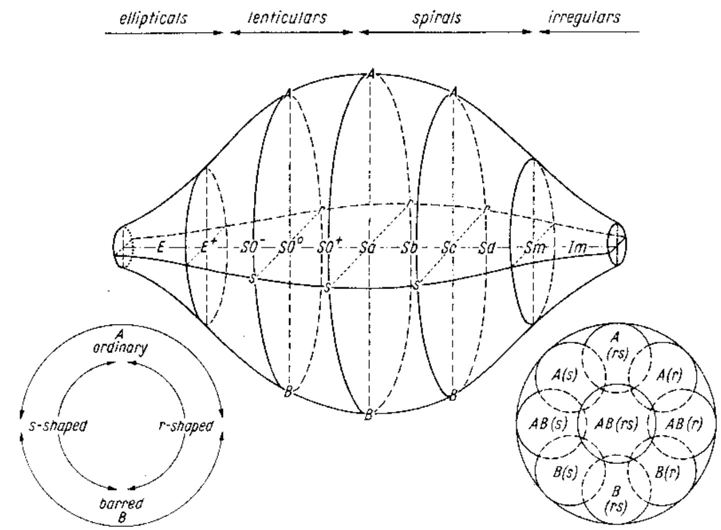
- **Hubble's Classification of Galaxies**
  - Ideal system should reproducible and relate to formation/evolutionary history. Proof is correlation of properties with morphology.
  - Most galaxies can be classified into only a few morphological (Hubble) types.
  - Broadly: Ellipticals, Spirals and Irregulars
  - Ellipticals subdivided by degree of flattening (a/b). Es are "red and dead", isotropic velocities.
  - Spirals subdivided (early-late: a-d) by opening angle of arms and sometimes by the Bulge/Disk ratio. Spirals blue & forming stars, rotationally supported.
  - S0s (Lenticulars) form transition: disk but no spiral arms, dust or star formation.
  - Spirals further classified into "barred" and "ordinary" systems
  - Peculiar galaxies that don't fit are invariably associated with tidally interacting systems and/or mergers: Arp's Atlas of Peculiar Galaxies.

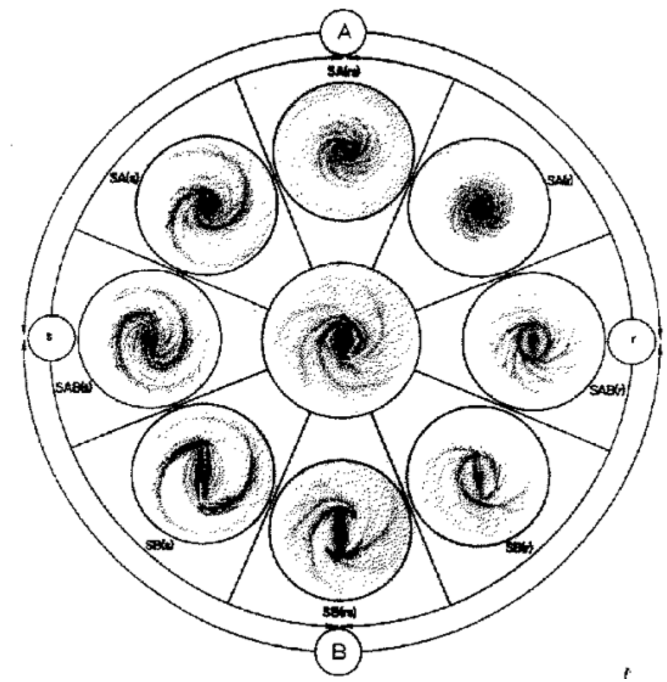


Morphological Classification of Galaxies

- **de Vaucouleurs' Classification of Galaxies**
  - **de Vaucouleurs argued that Hubble's classification scheme was incomplete.**
  - **Introduction of a third dimension of "ringed" (r) and "s-shaped"(s) spirals is more complete than just barred and ordinary.**
  - **R indicates outer ring with f and m indicating "filamentary" or "massive" spiral arms**
  - **A numerical scheme introduced for statistical purposes**

Hubble:	E	E/S0	S0	S0/Sa	Sa	Sab	Sb	Sbc	Sc	Sd	Irr
	-5	-3	-2	0	1	2	3	4	6	8	10





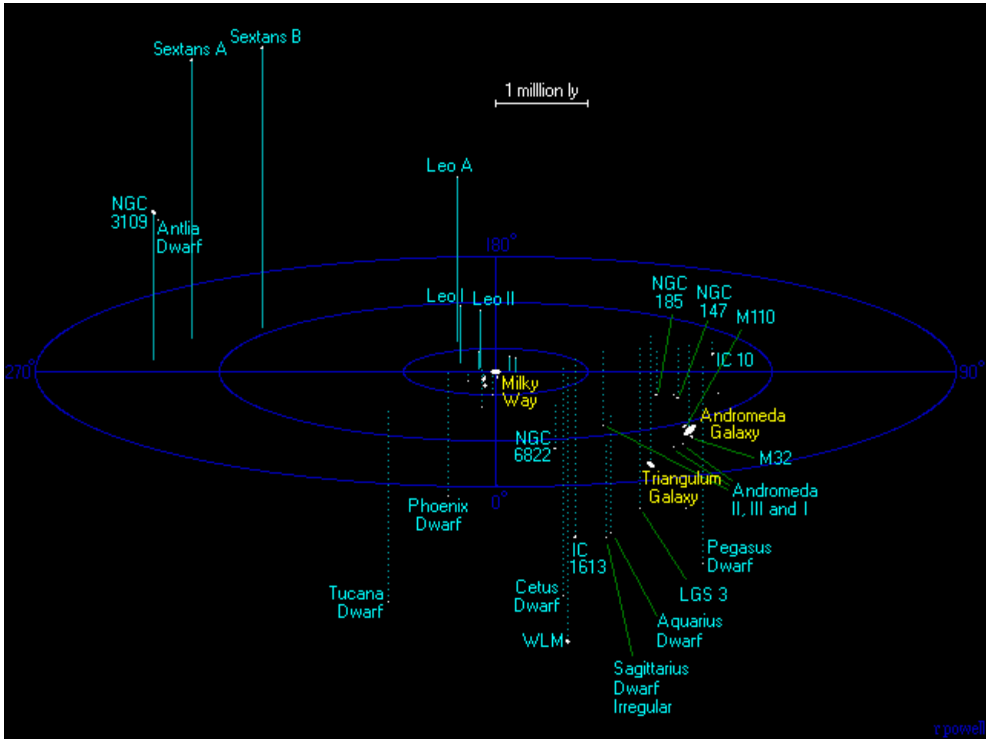
Sample of Galaxy Images

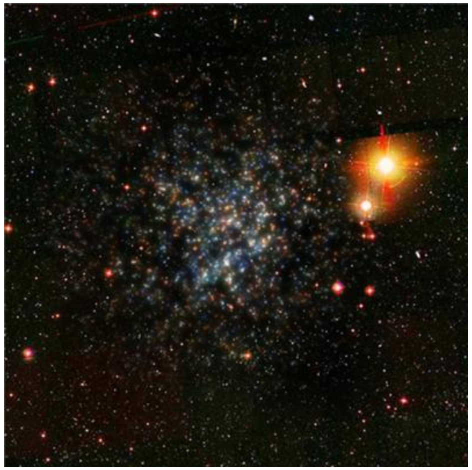




Local Group of Galaxies

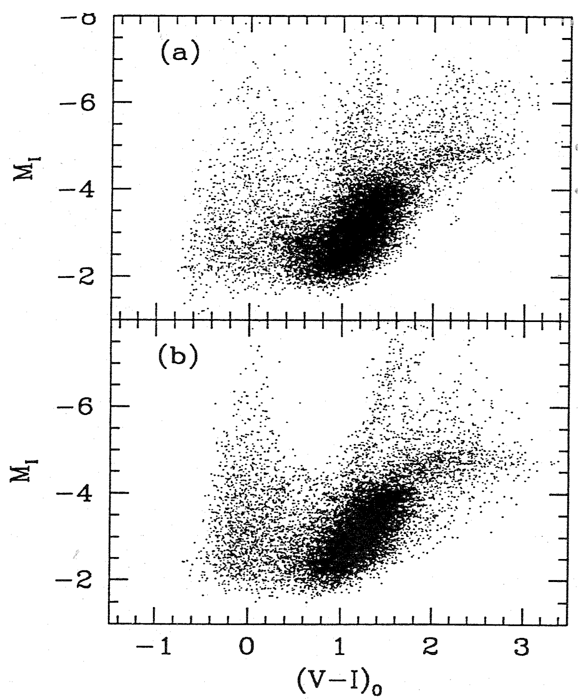
- The Local Group is Dominated by 2 Large Spirals + Satellites
  - Milky Way
  - M31
- Additional Star Forming Dwarfs
  - M33
  - NGC 3109, IC 10, WLM
  - Magellanic Clouds
- Dwarf Spheroidal Galaxies
  - M31 Companions (And I, II, III)
  - Milky Way Companions (SDG, Canes Venatici, Bootes)
  - Isolated Dwarf Spheroidals

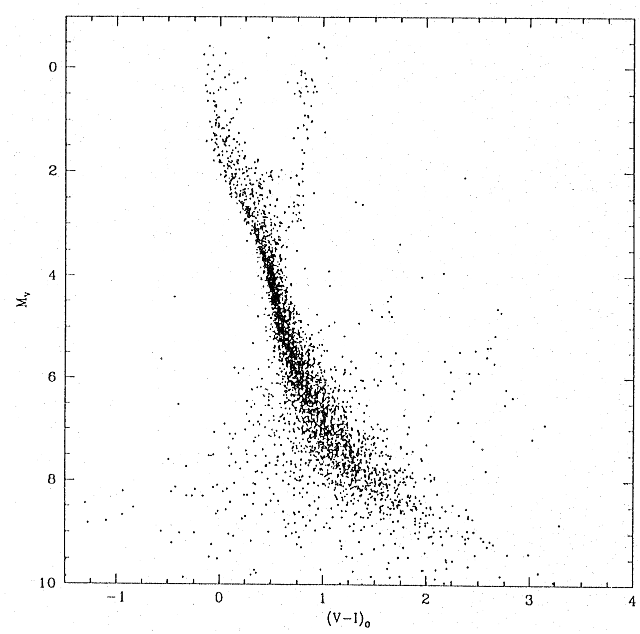




Resolved Stellar Populations Within Galaxies

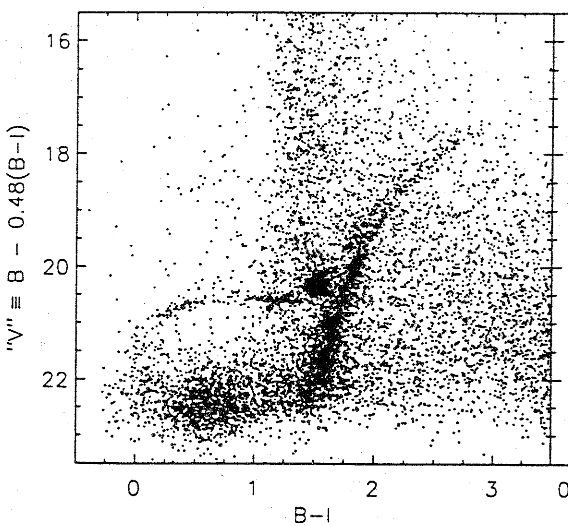
- **The LMC and Other Dwarf Irregulars**
- **HST imaging has revolutionized the study of stellar populations.**
  - **Enables photometry of individual, faint stars in Local Group galaxies**
- **CMDs reveal mix of old vs. young stars**
  - **Star formation rate over time**
- **Some CMDs reveal range of ages**
- **Some CMDs show distinct episodes of star formation.**

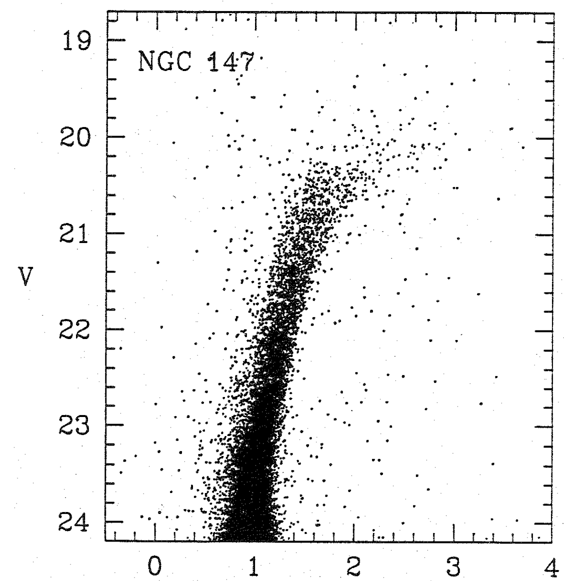


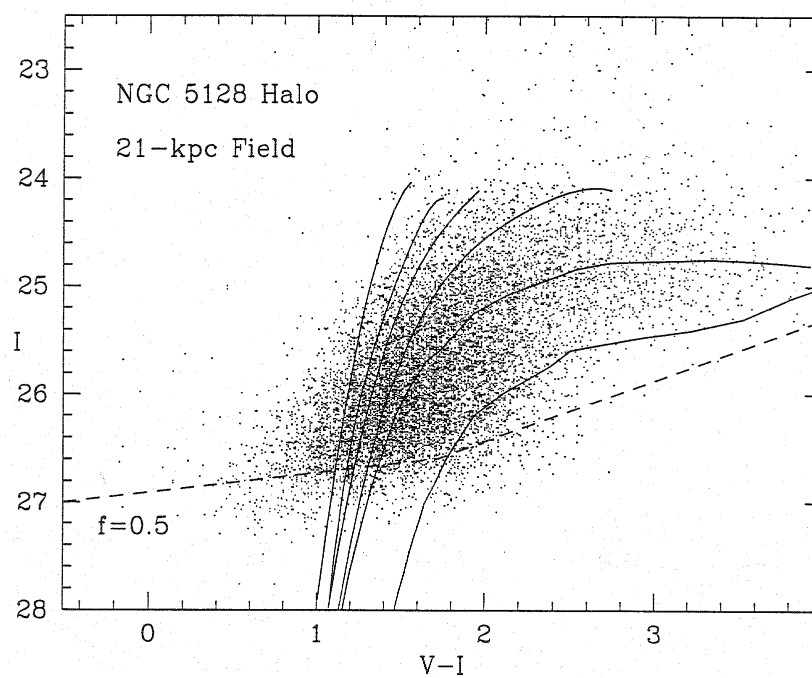


Resolved Stellar Populations Within Galaxies

- **Dwarf Elliptical (Spheroidal) Galaxies**
  - **Surprisingly complicated CMDs**
  - **Evidence for range of metallicities**
  - **Evidence for distinct episodes of star formation**

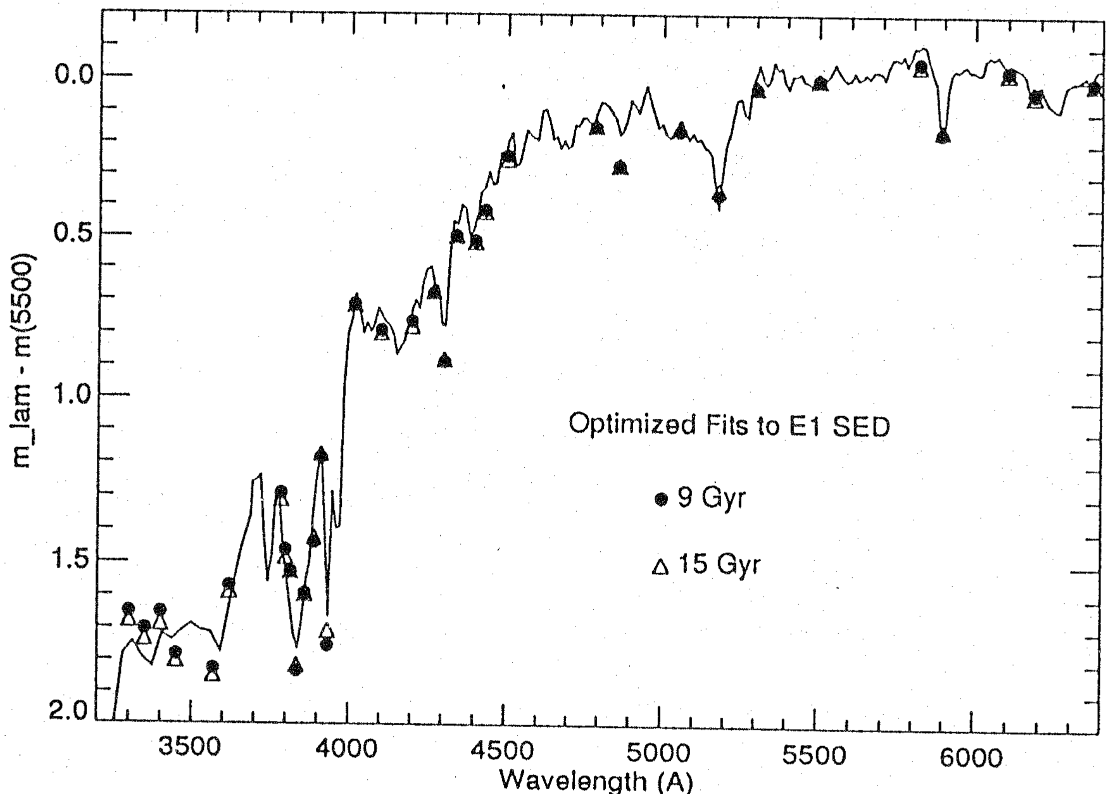


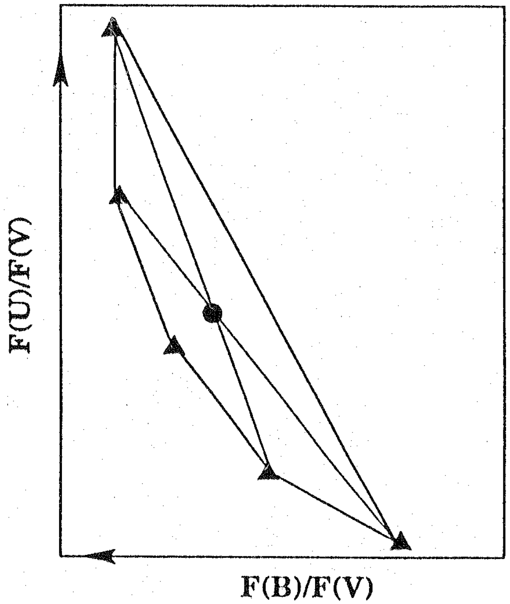




Unresolved Stellar Populations Within Galaxies

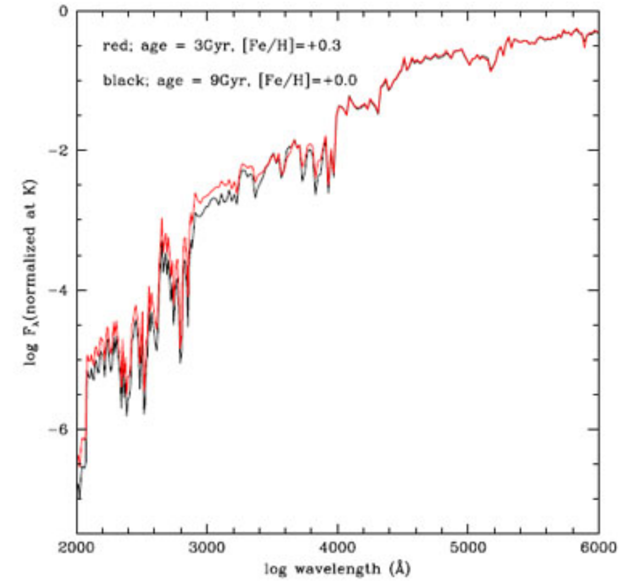
- Examples of Mixed Stellar Populations
  - Unresolved and so we only measure integrated light
- Non-unique combinations reproduce the same broad-band colors
- Spectra almost as degenerate unless range of age is high





Unresolved Stellar Populations Within Galaxies

- **Age-Metallicity Degeneracy in Stellar Populations**
- **Blue Light from HB Stars Mimics Light from Young Stars**
  - **Difficult to disentangle even with high-resolution spectroscopy**
  - **High S/N Spectra are Necessary**
- **Presence of Emission Lines or Balmer Absorption is unambiguous.**



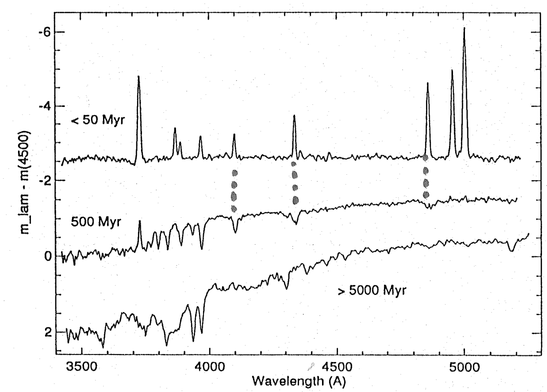
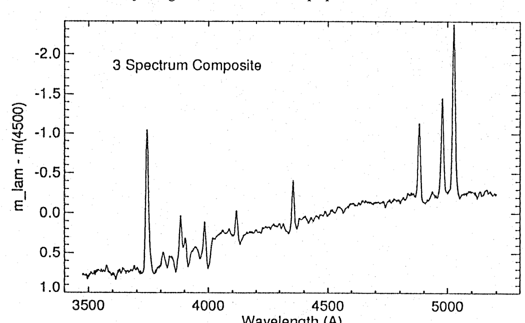
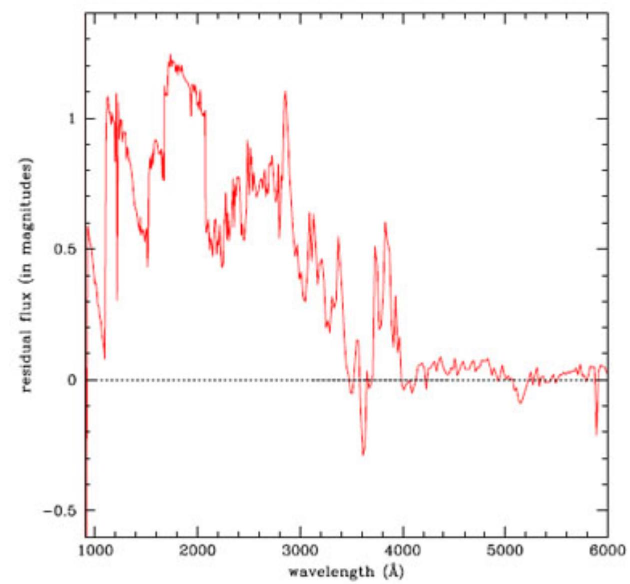


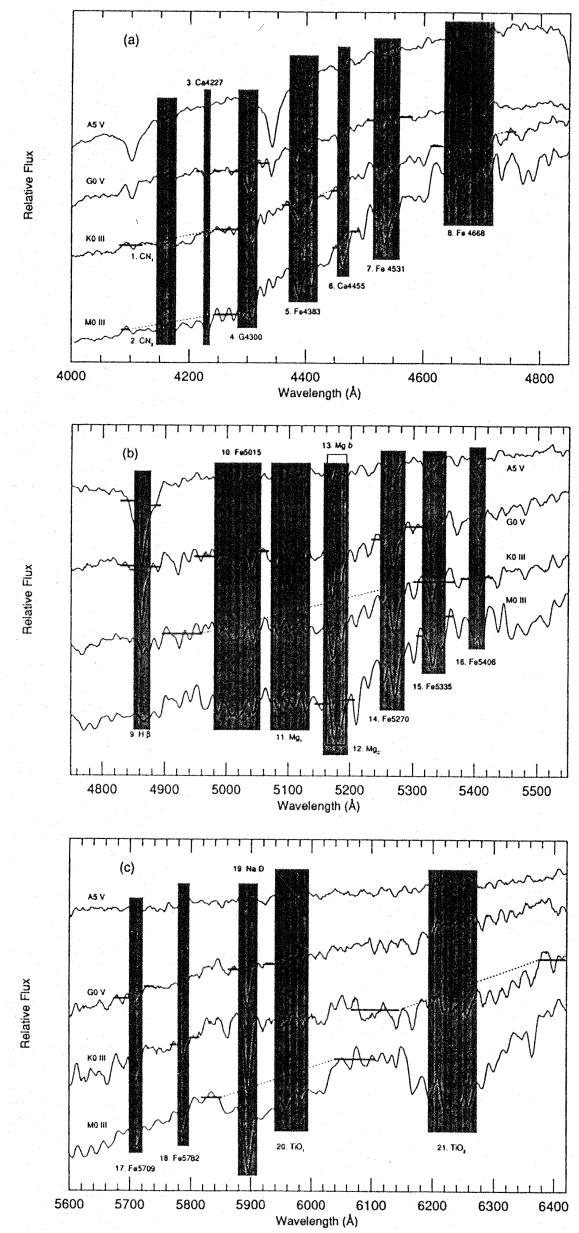
Figure 1. Nuclear spectra of three galaxies, with arbitrary offsets. Approximate light-weighted mean ages are assigned as indicated. The three are not highly composite, although the emission line in the 500 Myr spectrum demonstrates the presence of a minority component which is much younger than the mean population.



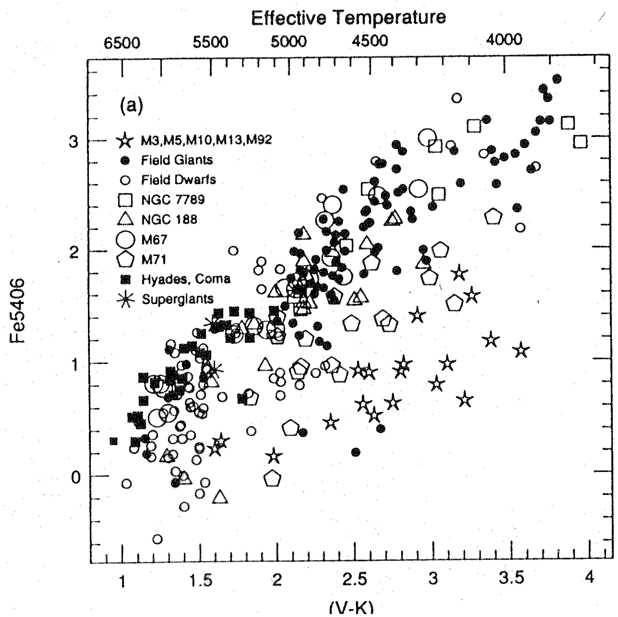


Unresolved but Simple Stellar Populations

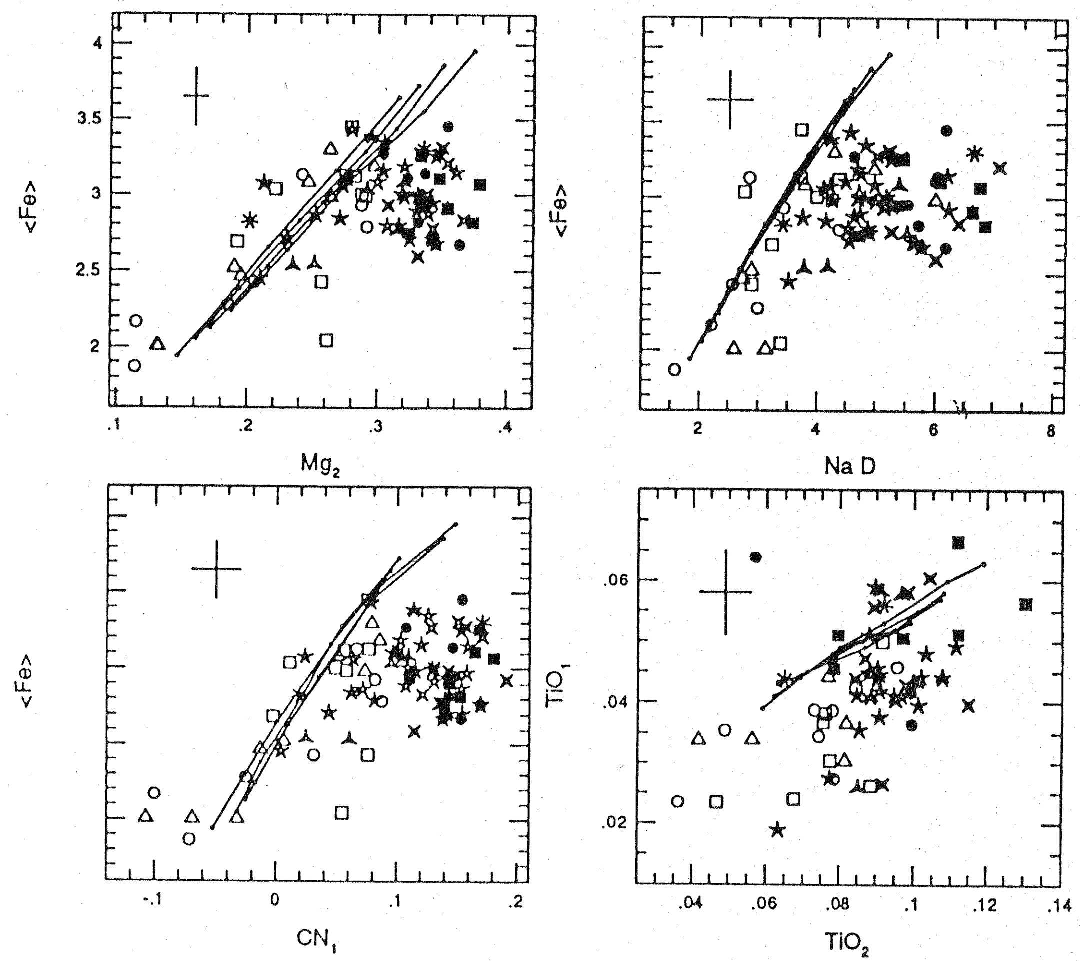
- Assume a Single Age and Metallicity
  - How can we constrain both?
- Start with Elliptical Galaxies
  - Assume Low Resolution Spectra (kinematic line broadening)
  - Assume High S/N Possible
- Lick Spectrophotometric Indices
  (Worthey et al. 1994, ApJS, 94, 687)
  - Narrow line indices computed from 1A resolution spectra
  - Sensitivity to Age and Metallicity Calibrated/Modeled



Example Lick Indices for Stars & Galaxies



Empirical Tests and Models Demonstrate Sensitivity



Data for Elliptical Galaxies Indicate Enrichment in α-elements

Lick Indices for Stars & Galaxies

Lick Index Definitions

INDEX DEFINITIONS

	Name	Index Bandpass	Pseudocontinua	Units	Measures	Error[1]	Notes
01	CN_1	4143.375-4178.375	4081.375-4118.875 4245.375-4285.375	mag	CN, Fe I	0.021	
02	CN_2	4143.375-4178.375	4085.125-4097.625 4245.375-4285.375	mag	CN, Fe I	0.023	2
03	Ca4227	4223.500-4236.000	4212.250-4221.000 4242.250-4252.250	Å	Ca I, Fe I, Fe II	0.27	2
04	G4300	4282.625-4317.625	4267.625-4283.875 4320.125-4336.375	Å	CH, Fe I	0.39	
05	Fe4383	4370.375-4421.625	4360.375-4371.625 4444.125-4456.625	Å	Fe I, Ti II	0.53	2
06	Ca4455	4453.375-4475.875	4447.125-4455.875 4478.375-4493.375	Å	Ca I, Fe I, Ni I, Ti II, Mn I, V I	0.25	2
07	Fe4531	4515.500-4560.500	4505.500-4515.500 4561.750-4580.500	Å	Fe I, Ti I, Fe II, Ti II	0.42	2
08	Fe4668	4635.250-4721.500	4612.750-4631.500 4744.000-4757.750	Å	Fe I, Ti I, Cr I, Mg I, Ni I, C_2	0.64	2
09	Hβ	4847.875-4876.625	4827.875-4847.875 4876.625-4891.625	Å	Hβ, Fe I	0.22	3
10	Fe5015	4977.750-5054.000	4946.500-4977.750 5054.000-5065.250	Å	Fe I, Ni I, Ti I	0.46	2,3
11	Mg_1	5069.125-5134.125	4895.125-4957.625 5301.125-5366.125	mag	MgH, Fe I, Ni I	0.007	3
12	Mg_2	5154.125-5196.625	4895.125-4957.625 5301.125-5366.125	mag	MgH, Mg *b*, Fe I	0.008	3
13	Mg *b*	5160.125-5192.625	5142.625-5161.375 5191.375-5206.375	Å	Mg *b*	0.23	3
14	Fe5270	5245.650-5285.650	5233.150-5248.150 5285.650-5318.150	Å	Fe I, Ca I	0.28	3
15	Fe5335	5312.125-5352.125	5304.625-5315.875 5353.375-5363.375	Å	Fe I	0.26	3
16	Fe5406	5387.500-5415.000	5376.250-5387.500 5415.000-5425.000	Å	Fe I, Cr I	0.20	2,3
17	Fe5709	5698.375-5722.125	5674.625-5698.375 5724.625-5738.375	Å	Fe I, Ni I, Mg I Cr I, V I	0.18	2
18	Fe5782	5778.375-5798.375	5767.125-5777.125 5799.625-5813.375	Å	Fe I, Cr I Cu I, Mg I	0.20	2
19	Na D	5878.625-5911.125	5862.375-5877.375 5923.875-5949.875	Å	Na I	0.24	
20	TiO_1	5938.375-5995.875	5818.375-5850.875 6040.375-6105.375	mag	TiO	0.007	
21	TiO_2	6191.375-6273.875	6068.375-6143.375 6374.375-6416.875	mag	TiO	0.006	

[1] Typical rms error per observation for stars; a factor of 1.2 larger than bright standard star errors. See text.
[2] A new index. See text.
[3] Wavelength definition has been refined. See text.

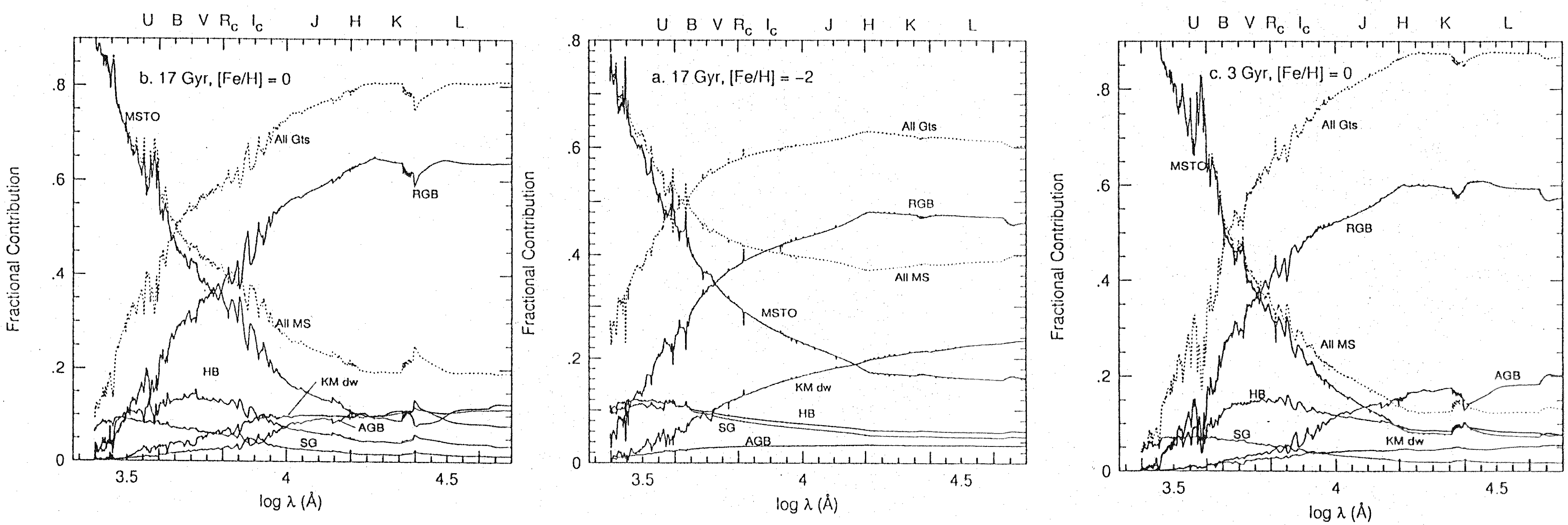
Metallicity Sensitivity

Age: < 1.0; Metallicity: > 1.0

		dom.	other species	sensitivity	
1.	CN_1	CN	C, N, (O)	1.9	
	CN_2	CN	C, N, (O)	2.1	
2.	Ca4227	Ca	(C)	1.5	weak
3.	G 4300	CH	(O)	1.0	
4.	Fe4383	Fe	C, (Si)	1.9	
	Fe5270	Fe	C, (Mg), Ca	2.3	
	Fe5335	Fe	(C), (Mg), Cr	2.8	
	Fe5406	Fe	(Mg), Cr, C	2.5	
5.	Ca4455	mix	Cr, Ca, Fe, Ni	2.0	
	Fe4531	Ti	Cr, Fe, (Si)	1.9	small range
	Fe5015	mix	Ti, (Mg), Fe	4.0	O III in sideband
	Fe5709	mix	(C), Fe, Ti, Cr	6.5	weak
	Fe5782	Cr		5.1	weak
6.	Fe4668	C_2	(O), (Si)	4.9	
7.	Mg_1	C	Mg	1.8	
	Mg_2	Mg	C	1.8	
	Mg b	Mg	(C)	1.7	
8.	Na D	Na	C	2.1	interstellar extinction
9.	TiO_1	TiO	Ti, (Fe)	1.5	
	TiO_2	TiO	V, Sc, Ti	2.5	
10.	$H\delta_A$	H		0.9	new
	$H\delta_F$	H		1.1	new
	$H\gamma_A$	H		1.0	new
	$H\gamma_F$	H		1.2	new
	Hβ	H	(Mg), (Cr), C	0.6	

Fractional Contribution to Light vs. Wavelength

- **Stellar Models Reveal Fractional Contribution to SED vs. Wavelength**
  - **Predictions Depend Strongly on Both Metallicity and Age**
    (Worthey: 1994, ApJS, 95,107



Predictions of SED vs. Age & Metallicity

- **Predicted Evolution Depends on Both Age and Metallicity**
- **Evolution (in color) Depends on Both and the Precise Isochrones Used**

(Bruzwall & Charlot 1996)