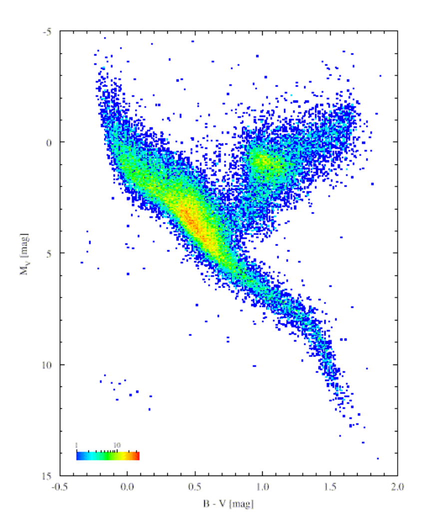
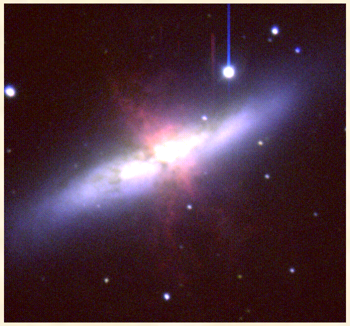
# Populations of Galaxies

- Building a Galaxy
- Stellar Luminosity Functions, Mass-Luminosity Relations
- Initial Mass Function
- Star Formation Rates
- Heavy Element Enrichment
- Evolution of a Population
- Spectral Synthesis
- Age/Metallicity Indicators
- Multiple Populations - the Milky Way
- Starburst galaxies, Ultraluminous Infrared Galaxies (ULIRGS)
- Galaxy Evolution



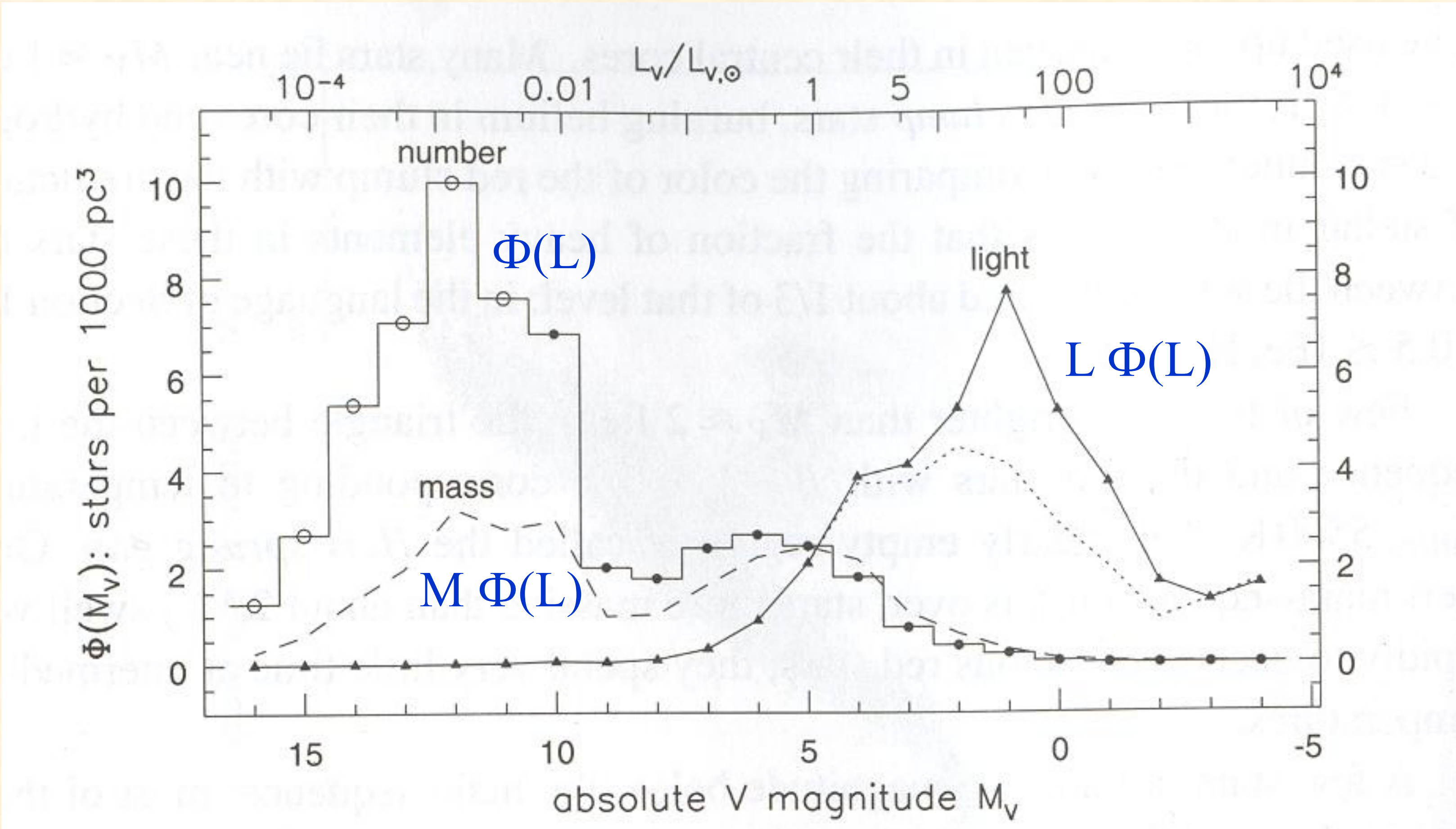
## Question: How would you build a synthetic spectrum and determine predicted colors for a population of stars?

- Start a population with an initial mass function (IMF).
  (determined from luminosity function and mass-lum. relation)
- Specify a star formation rate (SFR).
  - instantaneous? continuous? episodic?
- Add interaction with the ISM to increase metals.
- Fill in an H-R (or color-magnitude) diagram and let it evolve.
- Make a synthetic spectrum or synthetic colors .
  - Weight each spectral type by luminosity function.
  - Convolve spectrum with kinematics of the population.
- What if there is more than one population (like Milky Way)?
- Repeat the above steps for each population.
- Model populations separately if they can be resolved directly or through spectral or color gradients.

# Stellar Luminosity Functions

- $\Phi$ (L) dL: # of stars with luminosities between L and L + dL per 1000 $pc^3$
  - Need distances via parallax and secondary methods.
  - For example, use photometric distances (color gives luminosity, calibrated with parallax studies of close stars).
  - Done primarily for stars in solar neighborhood (detected via proper motion surveys) and clusters.
- Want a volume-limited sample (e.g., solar neighborhood), but must deal with magnitude limits (Malmquist bias).
  - Faint, low-mass end difficult to characterize.
- $\Phi$ for a specific class of stars is useful:
  - $\Phi_{MS}$ is needed for determining the IMF
  - Even $\Phi_{MS}$ shows dispersion due to metallicity and evolution

# General Φ




(Sparke & Gallagher, p. 63)

solid dots: Hipparcos sample
open circles: photometric sample

- ~55 stars, $35L_\odot$ per 1000 pc$^3$ in the hood

# $\Phi_{MS}$ in the Solar Neighborhood

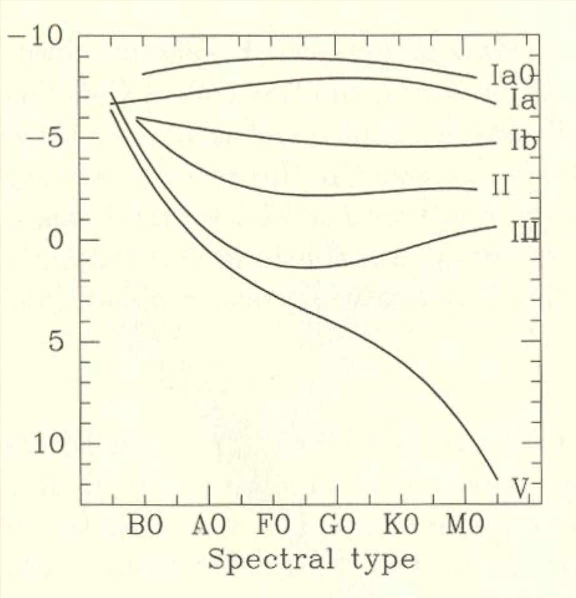
**Table 3.18** Luminosity function of MS stars

| $M_V$ | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|---|
| $S$ | B8.5 | A1.5 | A5.6 | F1.9 | F7.8 | G4.3 | K0.3 | K3.7 | K7.1 | M0.3 |
| $\Phi_{gen}(M_V)$ | 1 | 3 | 5 | 12 | 17 | 29 | 30 | 29 | 33 | 42 |
| $\Phi_{MS}$ | 0.23 | 0.74 | 1.9 | 9.6 | 19 | 24 | 24 | 33 | 17 | 20 |
| $\pm$ | 0.07 | 0.12 | 0.2 | 0.4 | 0.6 | 0.9 | 1.7 | 4 | 6 | 12 |

SOURCE: From data published in Murray *et al.* (1997)

(Binney & Merrifield, p. 129)

- Later types dominated by MS stars
- Luminosity classes squeeze together at high L




(Binney & Merrifield, p. 104)

# Mass-Luminosity Relation for M.S. Stars

- L(M) can be determined theoretically or observationally
- Theory: Combine stellar interior and atmosphere models:

$$\frac{L_{MS}}{L_\odot} = \begin{cases} 81(M/M_\odot)^{2.14} & (M > 20M_\odot) \\ 1.78(M/M_\odot)^{3.5} & (2M_\odot < M < 20M_\odot) \\ 0.75(M/M_\odot)^{4.8} & (M < 2M_\odot) \end{cases}$$

(Binney & Merrifield, p. 280)

A star evolves off the M.S. when it converts ~10% of its H to He:

$$\tau_{MS} \approx 10\left(\frac{M}{M_\odot}\right)\left(\frac{L}{L_\odot}\right)^{-1} \text{ Gyr}$$

$\rightarrow$ No star with $M \leq 0.8M_\odot$ has evolved off the M.S. ($\tau_{MS} \geq 13.8$ Gyr)

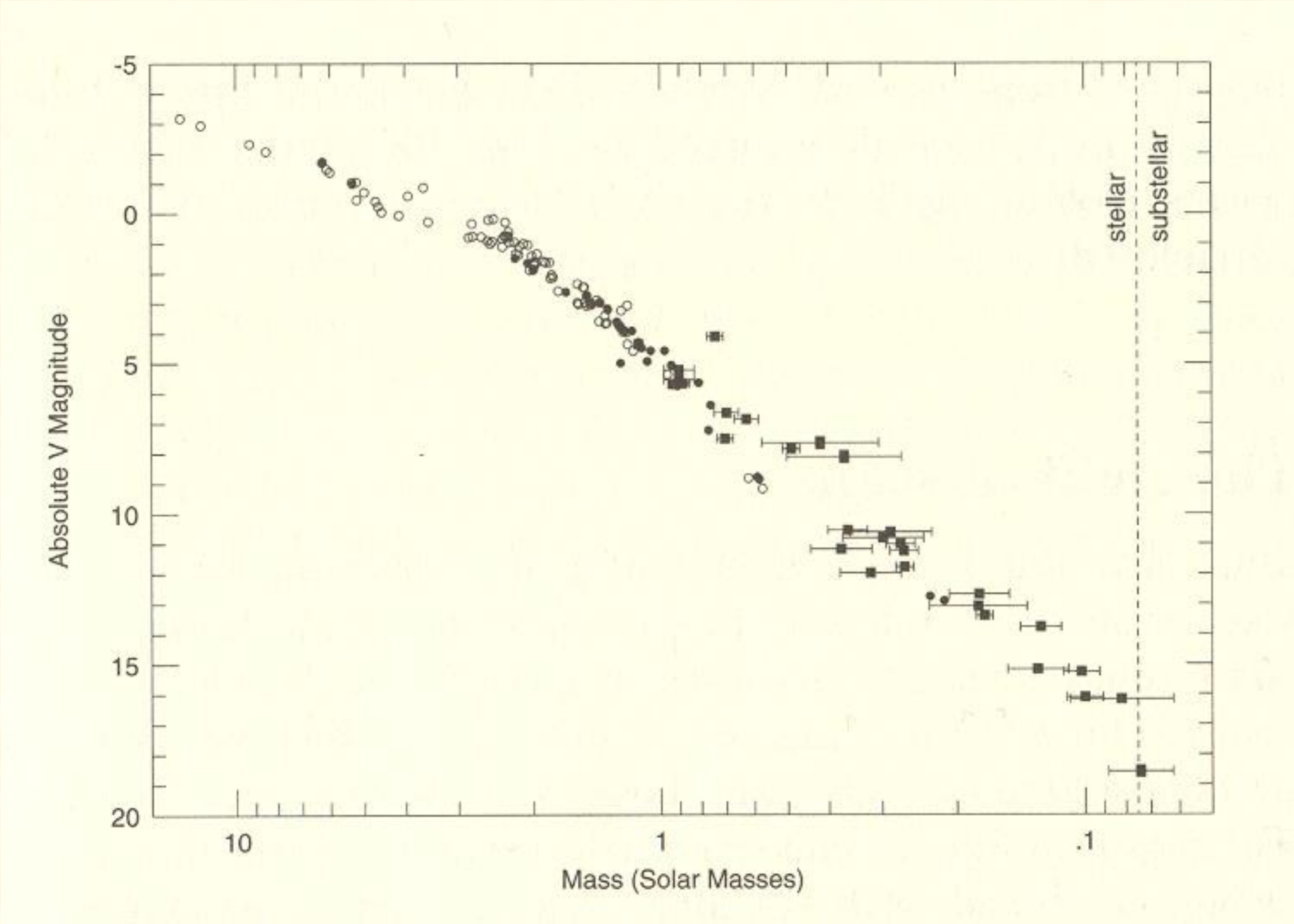
Theory Drawbacks:

1) Low mass stars may not have settled onto M.S.

2) Strong effects of molecules and abundances at $M < 0.5M_\odot$

# Observational Mass-Luminosity Relation

- Determined from binary stars (visual and eclipsing)




squares: visual
circles: eclipsing

(Binney & Merrifield, p. 81)

Problem: Large range in dL over short dM at $M < 0.2M_{\odot}$

# Initial Mass Function

- For a starburst, # new stars with masses between M and M+dM:

$$dN = N_0 \xi(M) dM, \quad \text{where } \xi(M) \text{ is the IMF}$$

$\xi(M)$ is normalized so that $\int M\xi(M)dM = 1M_\odot$

$$N_0 = \frac{\int MdN}{\int M\xi(M)dM} = \int MdN = \text{\# of solar masses in starburst}$$

- How do we get the IMF? → from $\Phi_{MS}(L)$ and Mass-Luminosity
- Need to correct $\Phi_{MS}(L)$ to cumulative value $\Phi_0(L)$

  - Starburst: correct for stellar evolution (e.g., use young clusters)
  - Constant SFR: also correct for death of massive stars early on

$$\Phi_0(L) = \Phi(L) \text{ x} \begin{cases} t/\tau_{MS}(M) & \text{for } \tau_{MS}(M) < t \\ 1 & \text{for } \tau_{MS}(M) > t \end{cases}$$

- The IMF is then: $\boxed{\xi(M) = \frac{dL}{dM}\Phi_0[L(M)]}$

# IMF Results

- Typically characterized by a power-law:

$\xi(M) \propto M^{-\alpha}$   Salpeter (1955) $\rightarrow$ $\alpha = 2.35$

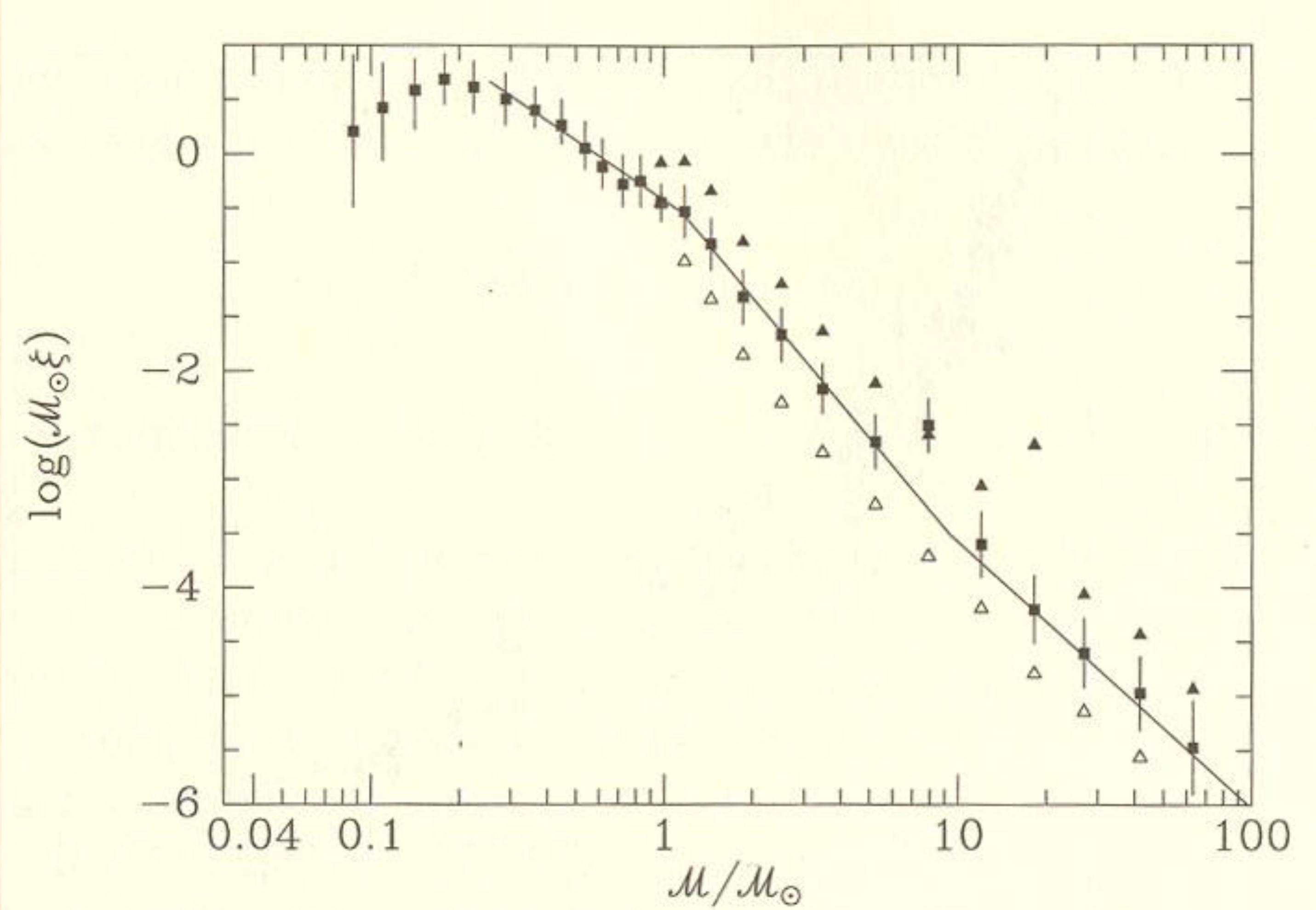
Total mass diverges at low mass if $\alpha > 2$ and at high mass if $\alpha < 2$

- More recent results – Scalo (1986) IMF:

$$\xi(M) \propto \begin{cases} M^{-2.45} & (M > 10M_\odot) \\ M^{-3.27} & (1M_\odot < M < 10M_\odot) \\ M^{-1.83} & (0.2M_\odot < M < 1M_\odot) \end{cases}$$

- IMF not well determined at $M < 0.3M_\odot$, since dL/dM is large
- Cutoffs at $M < 0.08M_\odot$ (no hydrogen fusion),
  $M > 100M_\odot$ (star's radiation pressure exceeds gravity)

# Scalo (1986) IMF




(Binney & Merrifield, p. 286)

Squares and fit: constant rate of star formation in solar neighborhood

# Star Formation Rate (SFR)

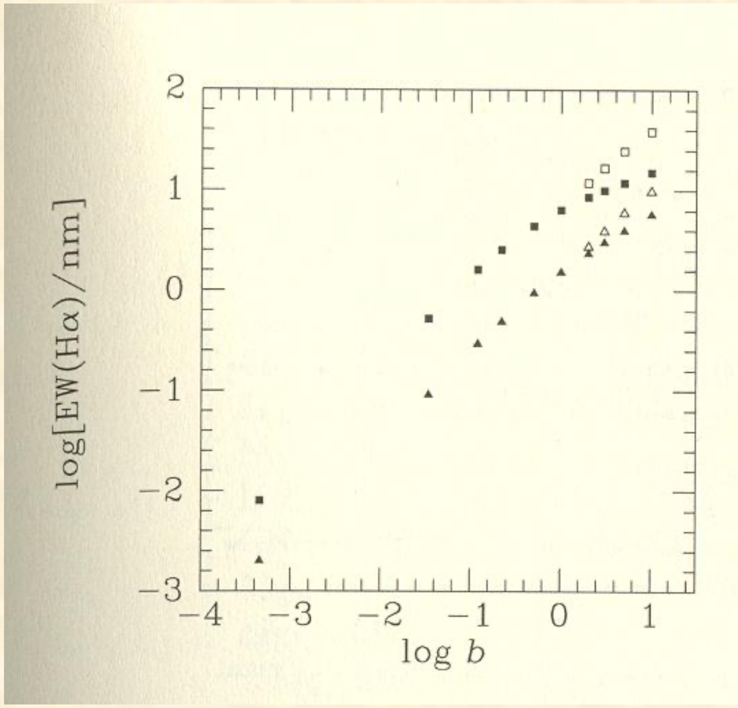
- To determine the current SFR, count the number of hot blue stars and divide by their approx. lifetime (lower limit)
- More precisely for a cluster → use H-R diagram:

  # stars above M.S.turnoff (inferred) / cluster age
- How do we count the number of hot blue stars in galaxies?
  1) UV images (GALEX): count UV photons directly
  2) Hα narrow-band images (ground-based): reprocessing of UV radiation by H II regions
  3) Dust re-radiation (IRAS): new stars enshrouded in dust
- Ideally, use a combination of the above (but note that optical and IR radiation can also heat dust grains)
- What is the SFR for the Milky Way averaged over its history?

$$\langle \mathrm{SFR} \rangle \approx \frac{10^{11}\,\mathrm{stars}}{10^{10}\,\mathrm{years}} = 10\ \mathrm{stars/year}$$

# Birth Rate

- Birth rate = b = current SFR/<SFR>
- Can be characterized by EW (Hα) ~ (# hot stars/ total # stars)
- Depends on IMF and functional form of SFR




Model predictions:
Squares: Salpeter IMF
Triangles: Scalo IMF
Filled: SFR rises exponentially
Open: Current Starburst + constant SFR

(Binney & Merrifield, p. 321)

Measured avg. b (Kennicutt et al. 1994, 435, 222):

| Sa | Sab | Sb | Sbc | Sc | Scd/Sd | Sm/Im |
|---|---|---|---|---|---|---|
| <0.07 | 0.17 | 0.33 | 0.84 | 0.99 | 0.69 | 1.67 |

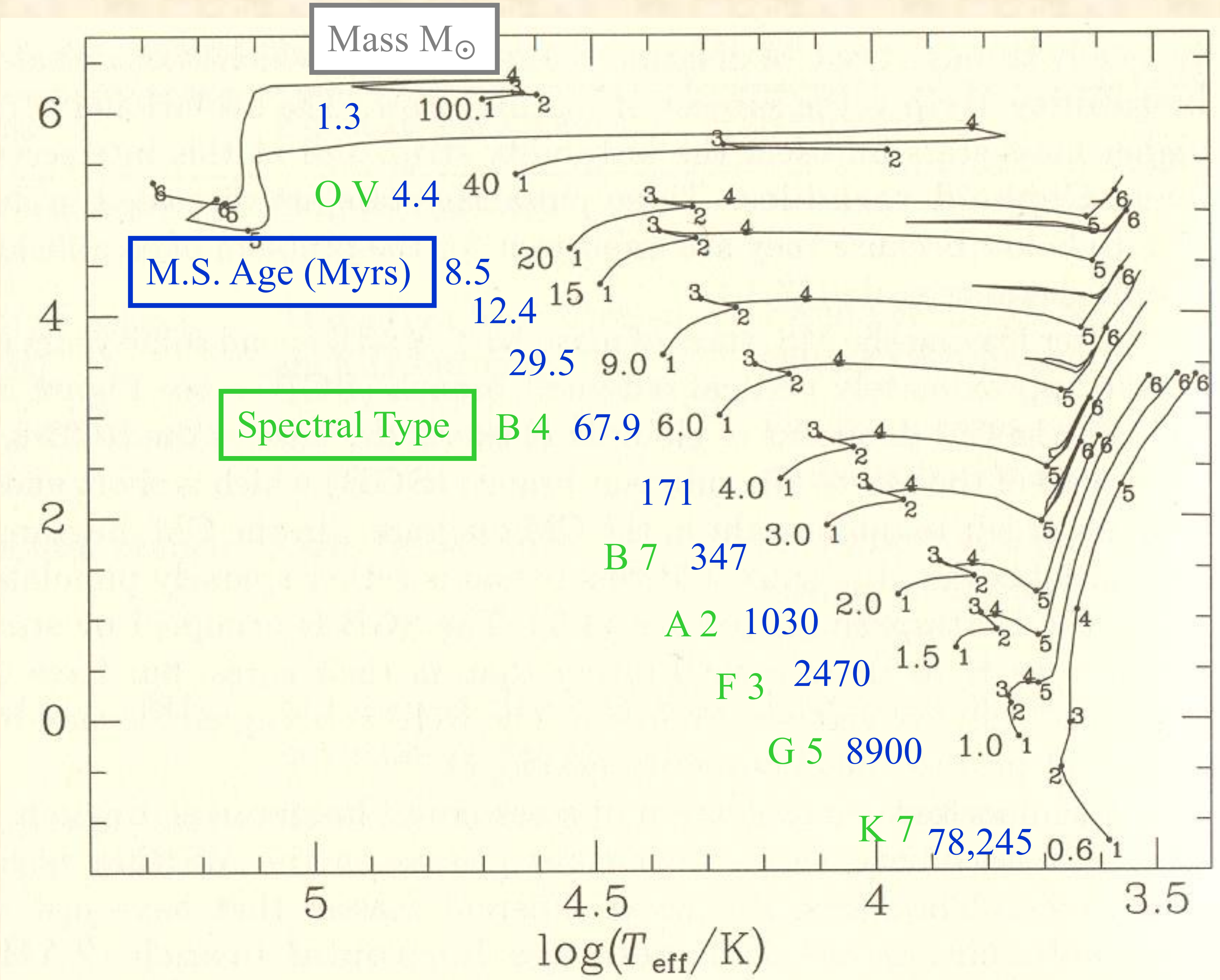
# Heavy Metal Enrichment

- A population will be enriched with metals (elements heavier than He) over time.
- Z = metallicity = mass of heavy elements/total mass ($Z_\odot = 0.02$)
- X, Y = fractional masses of H, He ($X_\odot = 0.70$, $Y_\odot = 0.28$)

# Spectral Synthesis

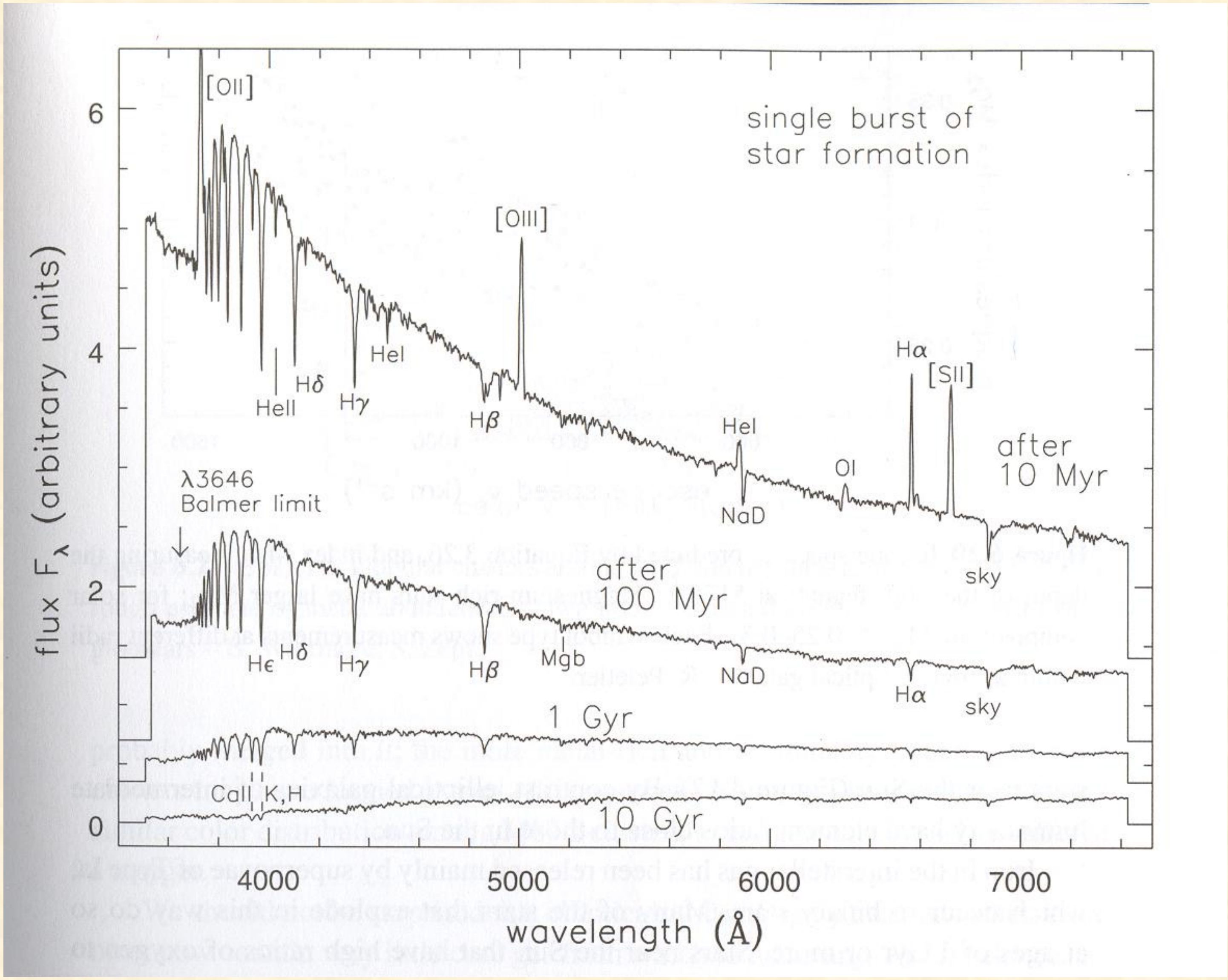
- Start with an IMF.
- Populate the H-R diagram with the proper number of stars.
- Let the population and metallicity evolve.
- Generate a synthetic spectrum (properly weighted by # stars and luminosity per star in each spectral/luminosity class).
  Ex) Bruzual & Charlot (1993, ApJ, 405, 538)
- Multiply spectrum by filter curves to get synthetic colors.

# Build an H-R Diagram and Let it Evolve




(Binney & Merrifield, p. 266)

# Spectral Synthesis and Evolution




(Sparke & Gallagher, p. 268)

# Age and Metallicity Diagnostics:

## Young Populations (≤1 Gyr)

- Age (t) - from ratio of blue or UV flux to red flux
- Metallicity (Z) – use emission lines from H II regions
  - Note: For specific elements, the "abundance" is normally given (number fraction, rather than mass fraction):

$$\text{Solar Abundance of X: } A(x) = 12.0 + \log\left(\frac{n_X}{n_H}\right)_{solar}$$

$$\text{Ex) } A(He)_{\odot} = 12.0 + \log(0.1)_{solar} = 11 \quad \rightarrow Y = 0.28$$

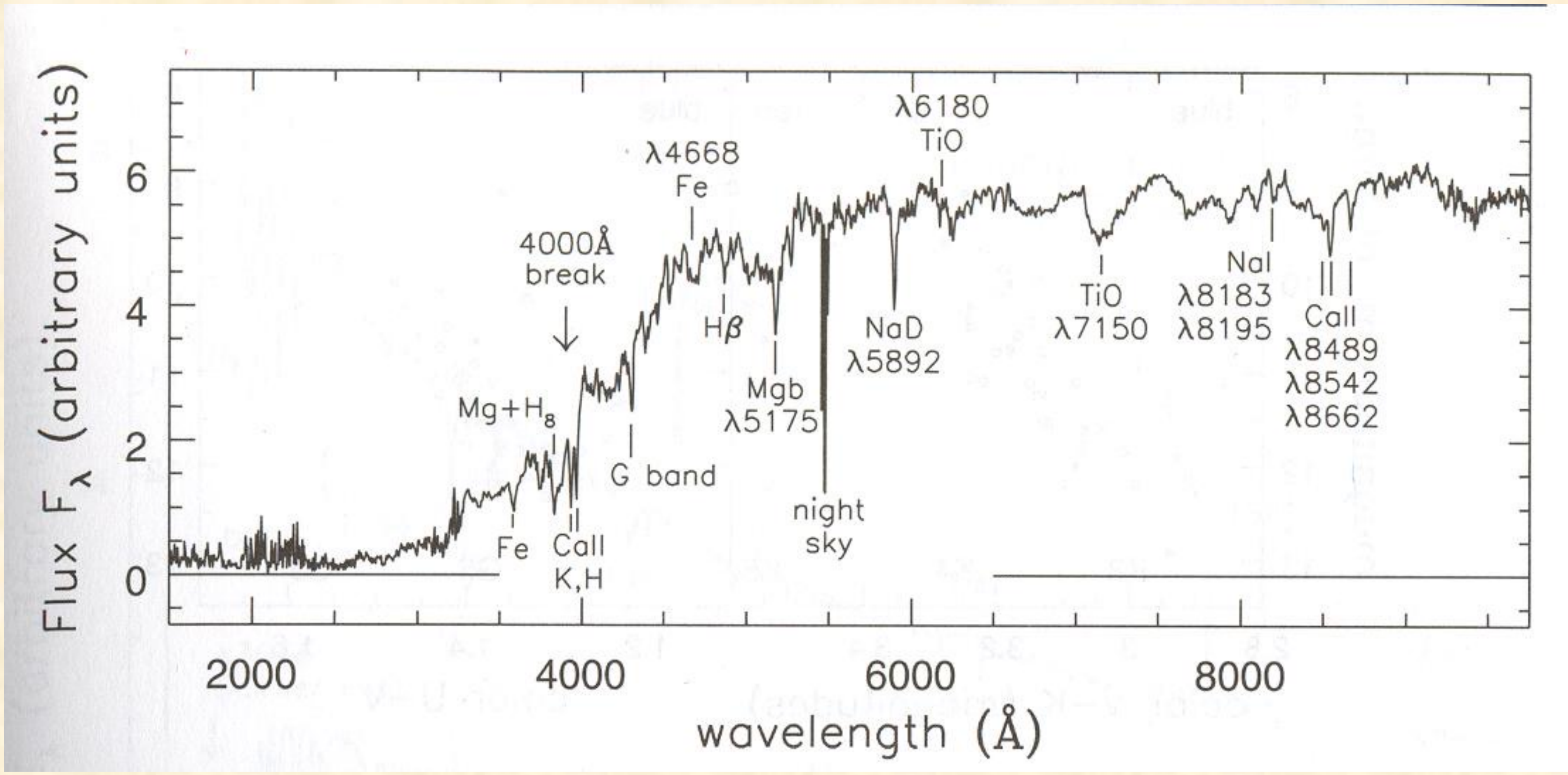
$$\text{Relative abundance of X: } [X/H] = \log\left(\frac{n_X}{n_H}\right)_{star} - \log\left(\frac{n_X}{n_H}\right)_{solar}$$

Solar (or "cosmic") abundances:

| Element | He | C | N | O | Ne | Mg | Si | S | Fe |
|---|---|---|---|---|---|---|---|---|---|
| A(x) | 11.0 | 8.6 | 8.0 | 8.8 | 7.6 | 7.5 | 7.5 | 7.2 | 7.4 |

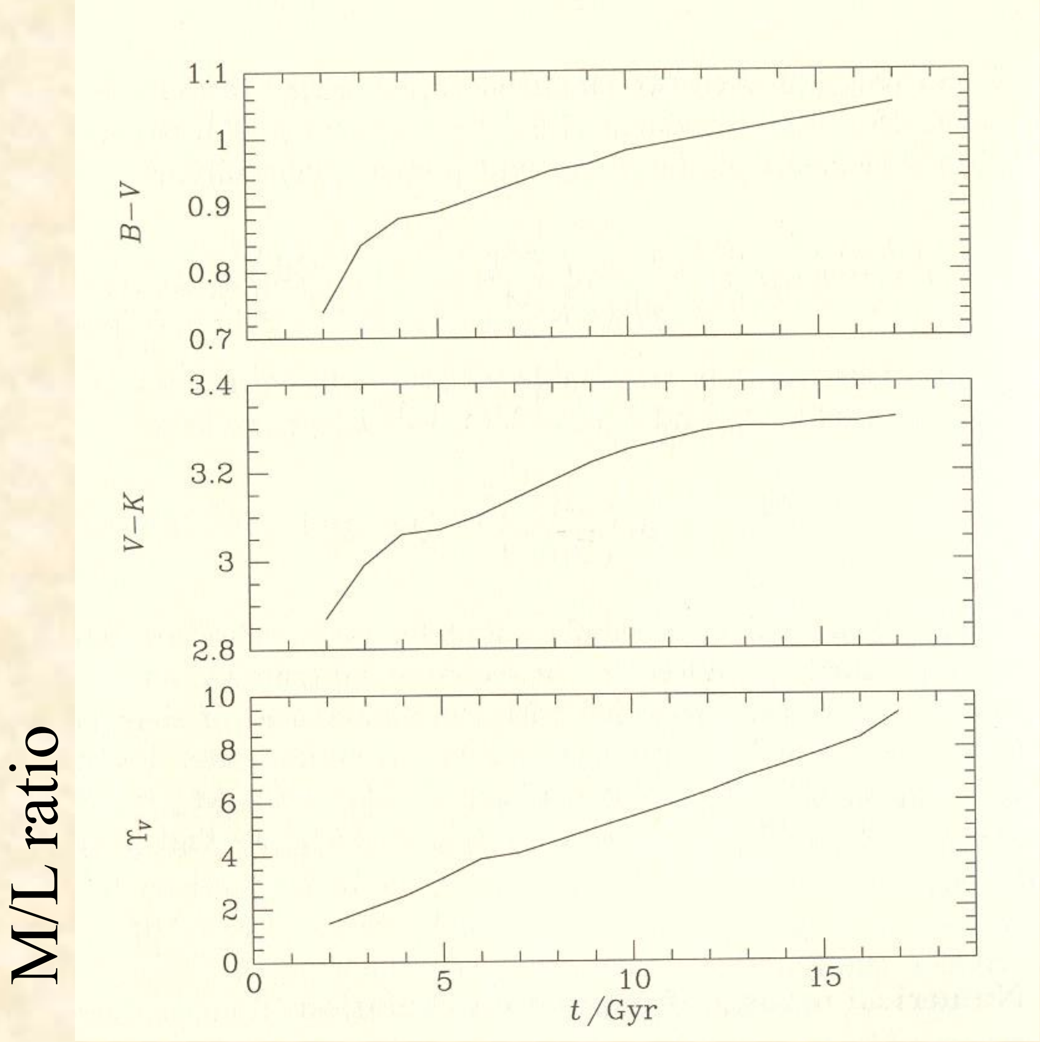
# Age and Metallicity Diagnostics:
## Older Populations (> 1 Gyr)

- Spectral features are sensitive to both t and Z




(Sparke and Gallagher, p. 267)

# Color and M/L Evolution of a Population




(Binney & Merrifield, p. 318)

- Luminosity continues to decrease with time, since it is dominated by giant stars, and later-type stars move off the M.S. at a much lower rate.

# Spectral Indices for Older Populations

Central bandpass　　Side bandpasses

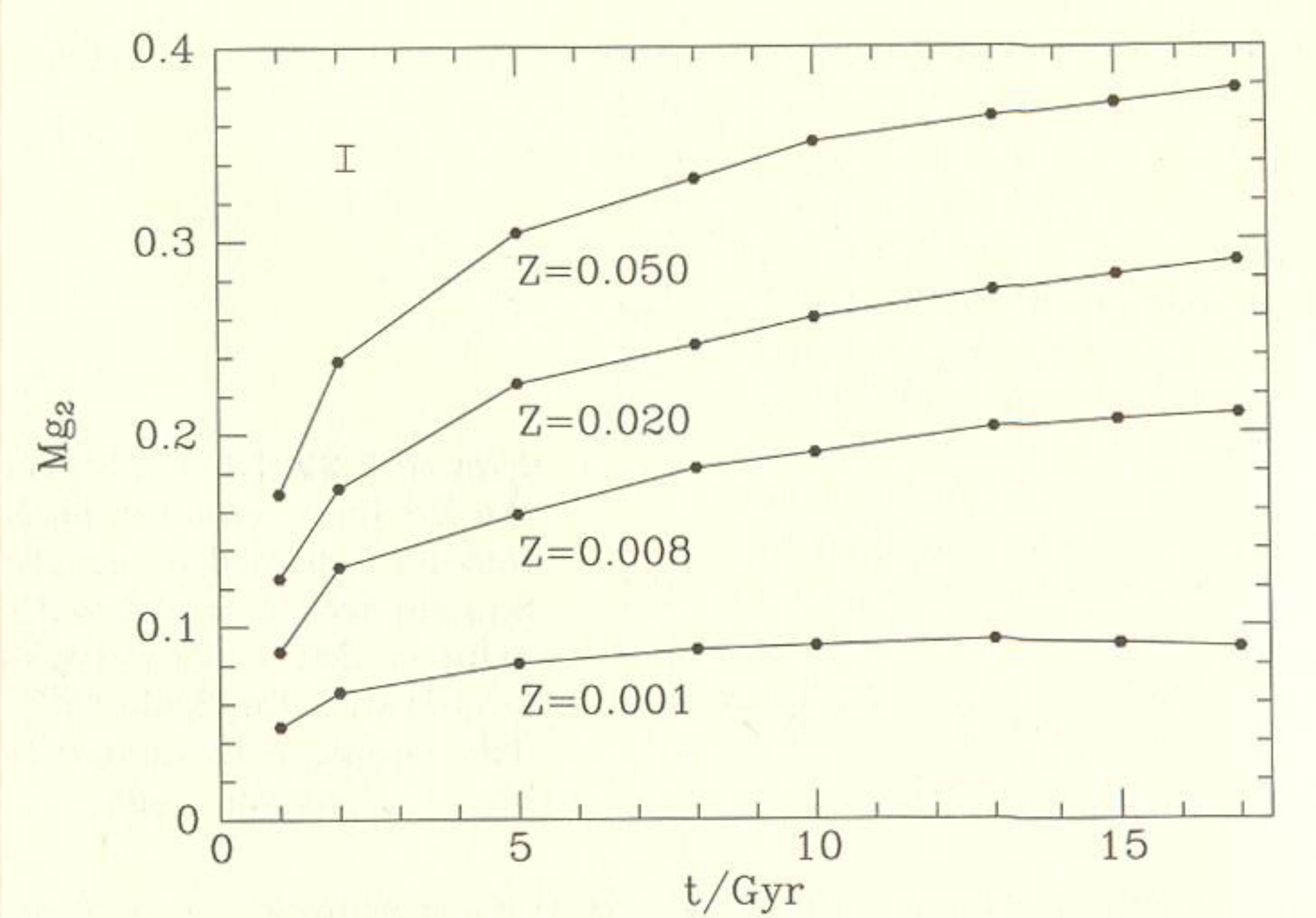
**Table 3.8** Spectral indices defined by Faber *et al.* (1985)

| Index | Feature | C. Band (nm) | S. Bands (nm) |
|---|---|---|---|
| G | CH | 428.325 – 431.700 | 426.825 – 428.325 |
| | | | 432.075 – 433.575 |
| Mg *b* | Mg *b* | 516.200 – 519.325 | 514.450 – 516.200 |
| | | | 519.325 – 520.700 |
| $Fe_1$ | $Fe^0$, $Ca^0$ | 524.800 – 528.675 | 523.550 – 524.925 |
| | | | 528.800 – 531.925 |
| $Fe_2$ | $Fe^0$, $Cr^0$, | 531.475 – 535.350 | 530.725 – 531.725 |
| | $Ca^0$, $Ti^+$ | | 535.600 – 536.475 |
| Na | Na D | 587.920 – 591.050 | 586.300 – 587.675 |
| | | | 592.450 – 594.925 |
| H$\beta$ | H$\beta$ | 484.950 – 487.700 | 482.950 – 484.825 |
| | | | 487.825 – 489.200 |
| CN | CN | 414.400 – 417.775 | 408.200 – 411.825 |
| | | | 424.600 – 428.475 |
| $Mg_1$ | MgH | 507.100 – 513.475 | 489.700 – 495.825 |
| | | | 530.300 – 536.675 |
| $Mg_2$ | MgH, Mg*b* | 515.600 – 519.750 | 489.700 – 495.825 |
| | | | 530.300 – 536.675 |
| $TiO_1$ | TiO | 593.900 – 599.525 | 581.900 – 585.025 |
| | | | 604.100 – 610.475 |
| $TiO_2$ | TiO | 619.200 – 627.325 | 606.900 – 614.275 |
| | | | 637.500 – 641.625 |

NOTES: Indices in the first group have the units of equivalent widths – see Figure 3.3. Indices in the second group are measured in magnitudes.

(Binney & Merrifield, p. 99)

# Metallicity and Age – Model Predictions




(Binney & Merrifield, p. 322)

- $Mg_2$ sensitive to both t and Z (mostly Z)

# Metallicity/Age Indicators

**Table 5.5** Sensitivities of spectral indices defined by Faber *et al.* (1985)

| Index | Dominant | Others | $(\partial \log t / \partial \log Z)_{\rm index}$ |
|---|---|---|---|
| G | CH | (O) | −1.0 |
| Mg *b* | Mg | (C) | −1.7 |
| $Fe_1$ | Fe | C, (Mg), Ca | −2.3 |
| $Fe_2$ | Fe | (C), (Mg), Cr | −2.8 |
| Na | Na | C | −2.1 |
| Hβ | H | (Mg), (Cr), C | −0.6 |
| CN | CN | C, N, (O) | −2.0 |
| $Mg_1$ | C | Mg | −1.8 |
| $Mg_2$ | Mg | C | −1.8 |
| $TiO_1$ | TiO | Ti, (Fe) | −1.5 |
| $TiO_2$ | TiO | V, Sc, Ti | −2.5 |

NOTES: Elements with brackets around them in the "others" column contribute negatively to the index.

SOURCE: Worthey (1996)

(Binney & Merrifield, p. 322)

- decrease in δlog(t) that would offset increase in δlog(Z):
- all indicators are sensitive to both Z and t →use a combination
- $Fe_2$ most sensitive to Z, Hβ most sensitive to age

# Metallicities of Galaxies – Ellipticals

- Giant ellipticals tend to be redder than dwarf ellipticals.

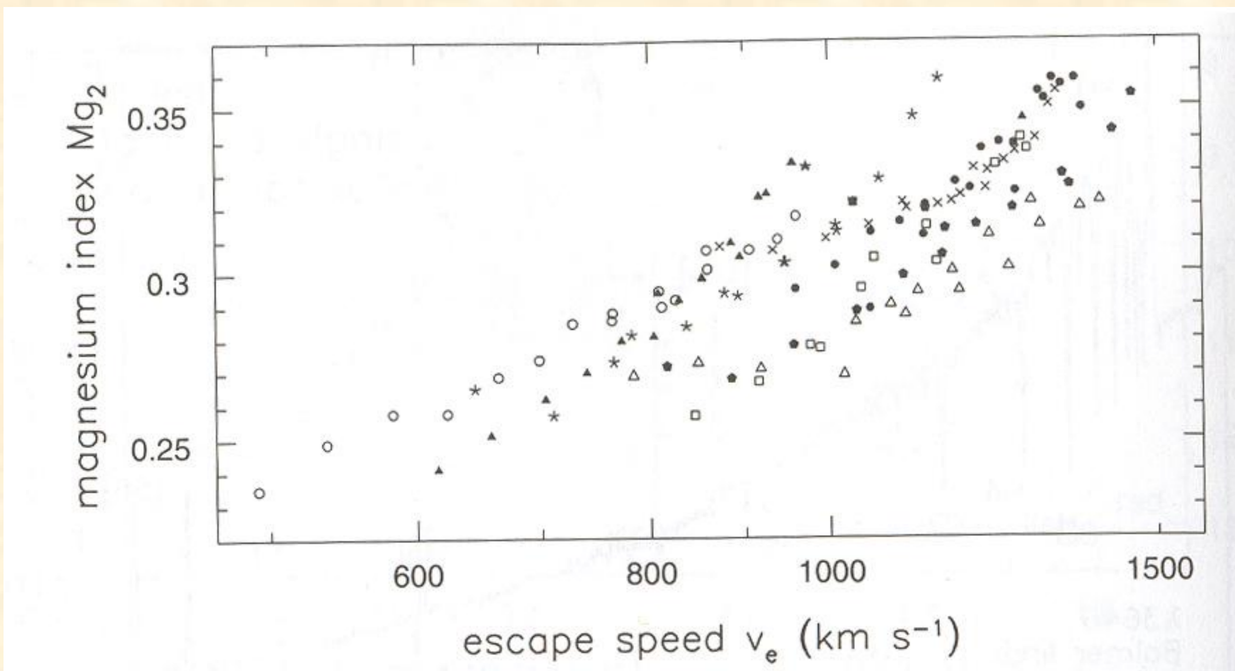
  → must be due to metallicity, since both have only old populations

- The centers of giant ellipticals are redder.

  →metallicities decrease from 1 –2 $Z_\odot$ (center) to a few times smaller (edge)

  - confirmed with spectral indices:

Increasing distance from center

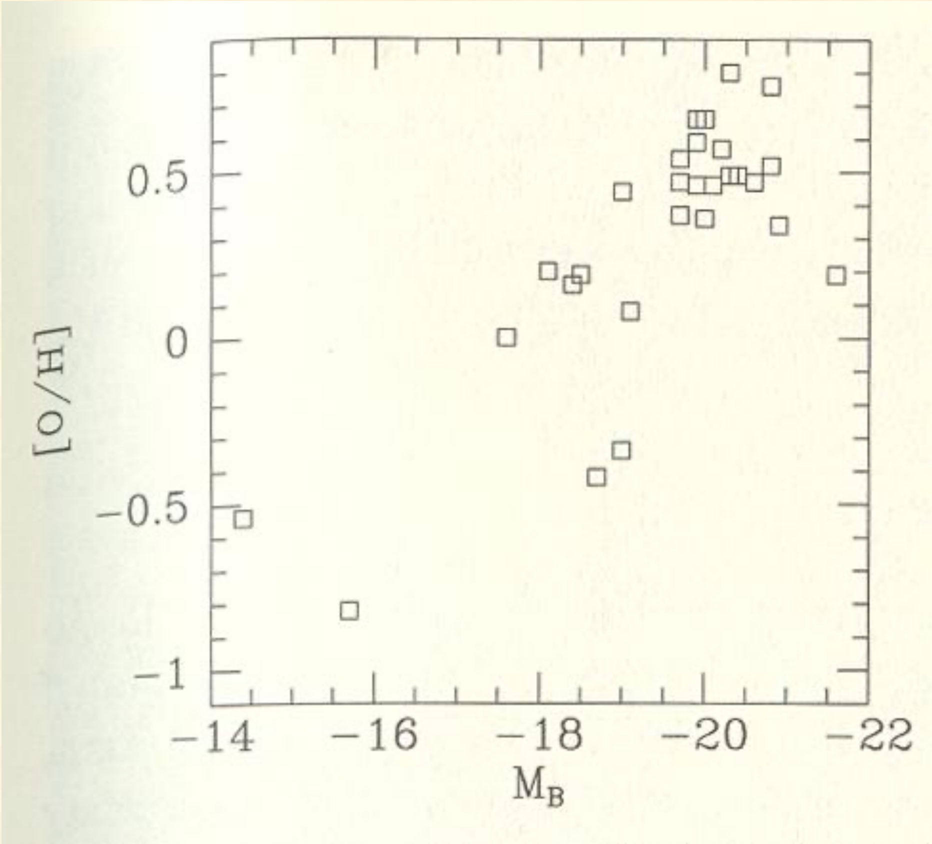



(Sparke & Gallagher, p. 260)

# Metallicities of Galaxies – Results

## Spiral Galaxies

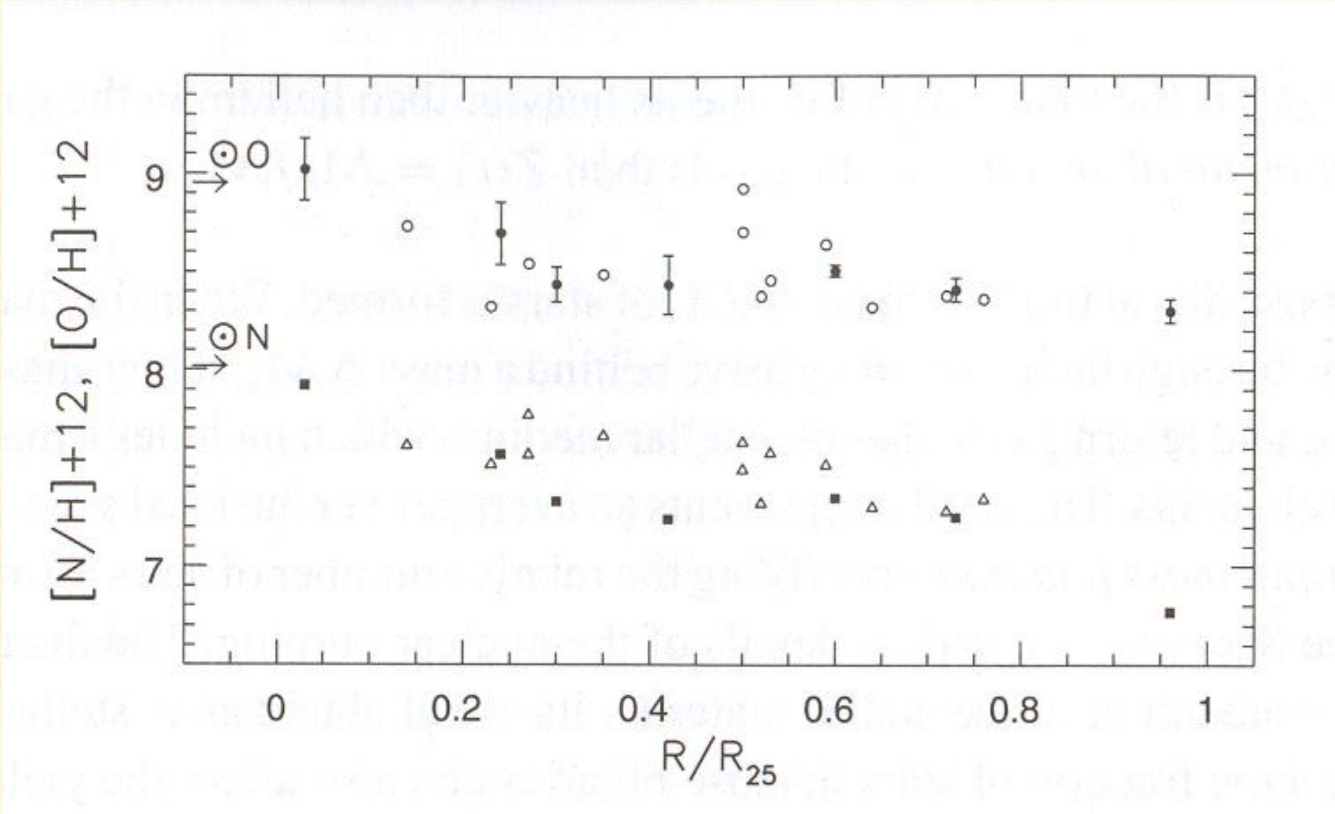
- Abundances decrease with the galaxy's absolute magnitude




(Binney & Merrifield, p. 519)

-probably due to higher gas densities (initially) and more "processing" of gas in brighter spirals (tend to be early types)

- Abundance gradients in Spirals: [O/H] and [N/H] decrease with increasing distance from center (by factor of ~10)




(Sparke & Gallagher, p. 160)

- Remember: disk colors get bluer with increasing distance (M 31),
  → partially explained by decreasing metallicity

  →also, the fraction of stars that are hot and blue increases with distance (larger fraction of mass in gas form)

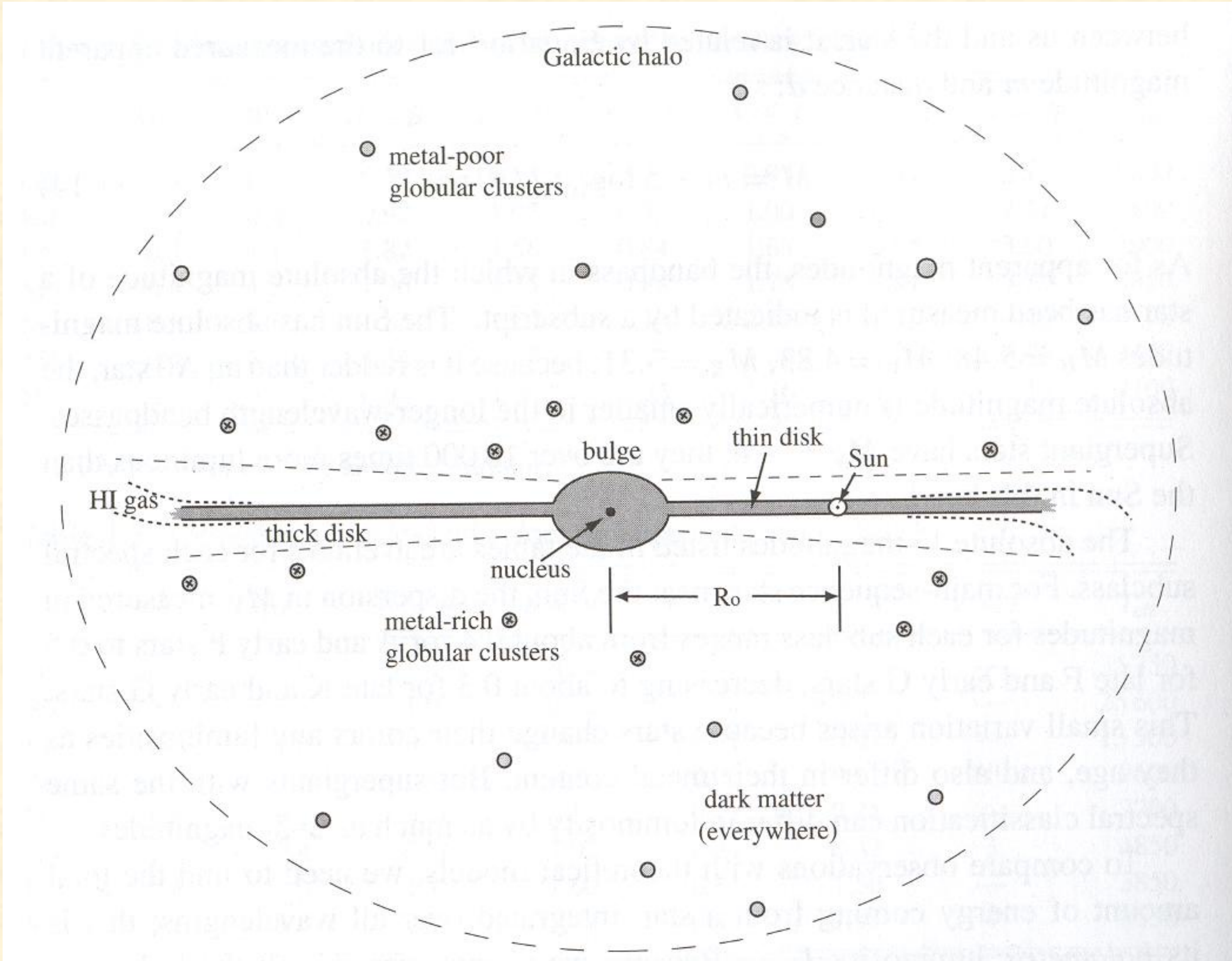
# Multiple Populations: Ellipticals

- Most giant Ellipticals are likely ≥10 Gyrs old
- Hβ absorption increases outward → younger at edges?
- There are a couple of claims that dwarf E's are a few Gyrs younger than giant E's (hard to check)
- A few have swallowed S's or Irr's and have younger populations as well → Centaurus A:

(Ground-based)

(HST)

# Multiple Populations: Spirals (like Milky Way)



# Milky Way Populations

(Allen's Astrophysical Quantities, p. 479)

| Characteristic objects and properties | Extreme Pop II "halo" | Intermediate Pop II "thick disk" | Bulge/Pop II "bulge" | Pop I "old disk" | Extreme Pop I "young disk" |
|---|---|---|---|---|---|
| | subdwarfs globular clusters with [Fe/H] < −1 RR Lyrae $\Delta S > 4$ BHB stars | globular clusters with [Fe/H] > −1 RR Lyrae, c-type LPV's, $P \sim 250^d$ RHB stars | SMR stars = "IR bulge" planetary nebulae = "optical bulge" RR Lyrae $\Delta S < 4$ tri-axial (?) | intermediate age disk stars | young stars spiral structure Cepheids |
| $\langle V_{rot} \rangle$ | 30 | 170 | 60 | 200 | 220 |
| $\sigma_U : \sigma_V : \sigma_W$ | 130:100:85 | 60:45:40 | 120:120:120 | 38:25:20 | 20:10:8 |
| $Z/Z_\odot$ | 0.03 | 0.3 | 0.1–2 | 0.9 | 1 |
| $\tau/\tau_u$ | 1.0–0.9 | 0.9–0.8 | 1.0–0.5 (?) | 0.9–0.1 | 0.1–0.0 |
| External Galaxies | dE | Sa $\rightarrow \leftarrow$ SO $\rightarrow$ gE | | $\leftarrow$ Sbcd, Irr's $\rightarrow$ | |
| Scale length (pc) | 2700 | 3000 | 500 | 3000 | 3000 |
| Scale height (pc) | 2000 | 1000 | 300 | 300 | 100 |

($\tau/\tau_u$ = age in units of Universe's age) ($\sigma_U$, $\sigma_V$, $\sigma_W$ – velocity dispersions toward the Galactic center, toward the direction of rotation, and perpendicular to the plane)

Where are the Pop III stars?
(a few halo stars have been found with $Z \sim 10^{-4} Z_\odot$)

# Irregulars - LMC

- Both old (~10 Gyr) and young (< 50 Myr) globular clusters.
- Very little star formation between 4 and 10 Gyrs ago.
- Old GCs are in a thick disk, $Z \sim 0.01\ Z_\odot$
- Young GCs are spread out and have $Z \sim 0.4\ Z_\odot$

LMC


R136a cluster in
30 Doradus nebula
(3.5 Myr old, $\sim 10^7\ L_\odot$)

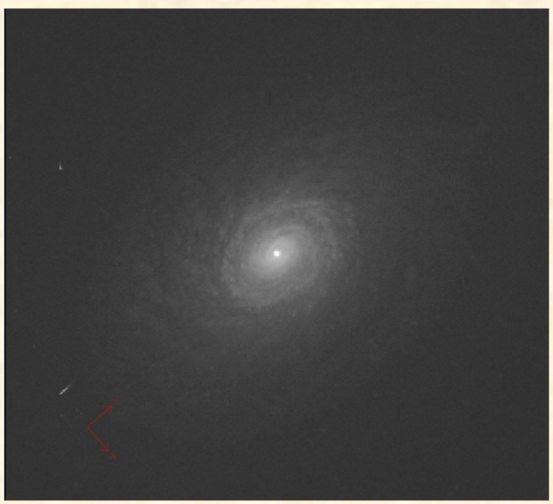
# Starburst Galaxies

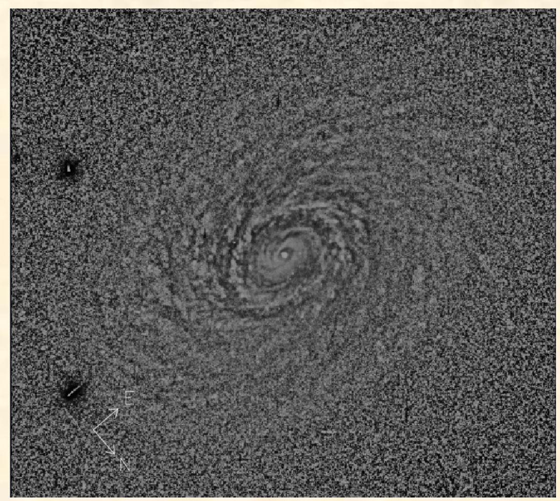
- Starbursts are found in irregulars or the centers of spirals
- Spirals with central starbursts also known as "H II" galaxies
- Gas is brought into the centers of galaxies by:

  1) Funneling of gas inward by large-scale stellar bars

  2) Mergers of galaxies → highest star formation rates (SFRs)
- Since V(R ) ~ R in the inner bulge, angular velocity is constant → no gas shear to disrupt star formation
- Gas revealed as "dust spirals" within ~1 kpc of nucleus

HST Direct Image

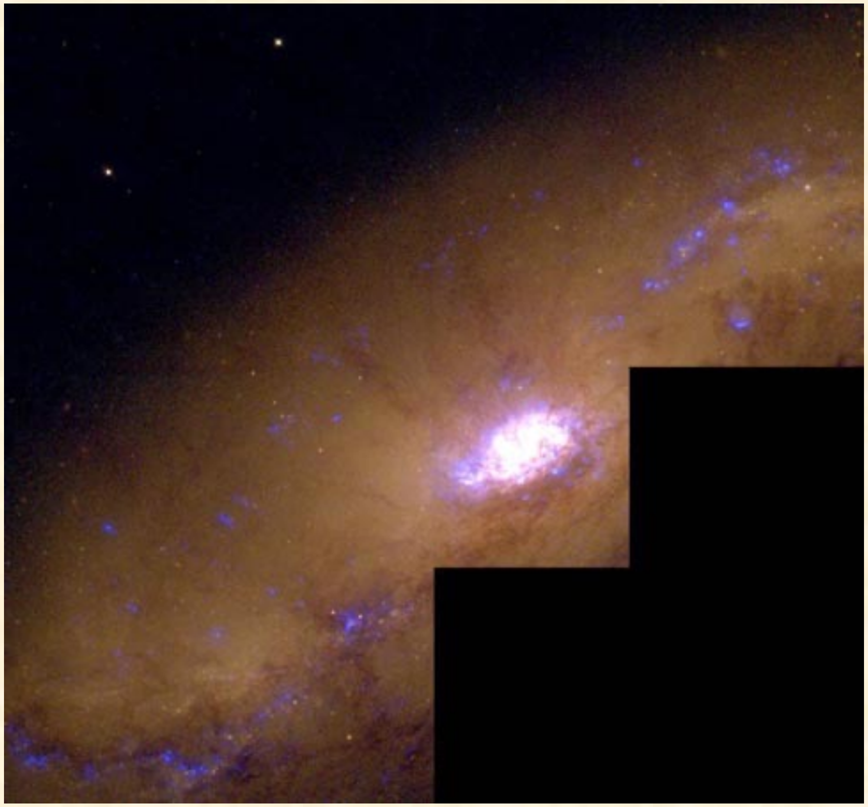




"Structure Map"

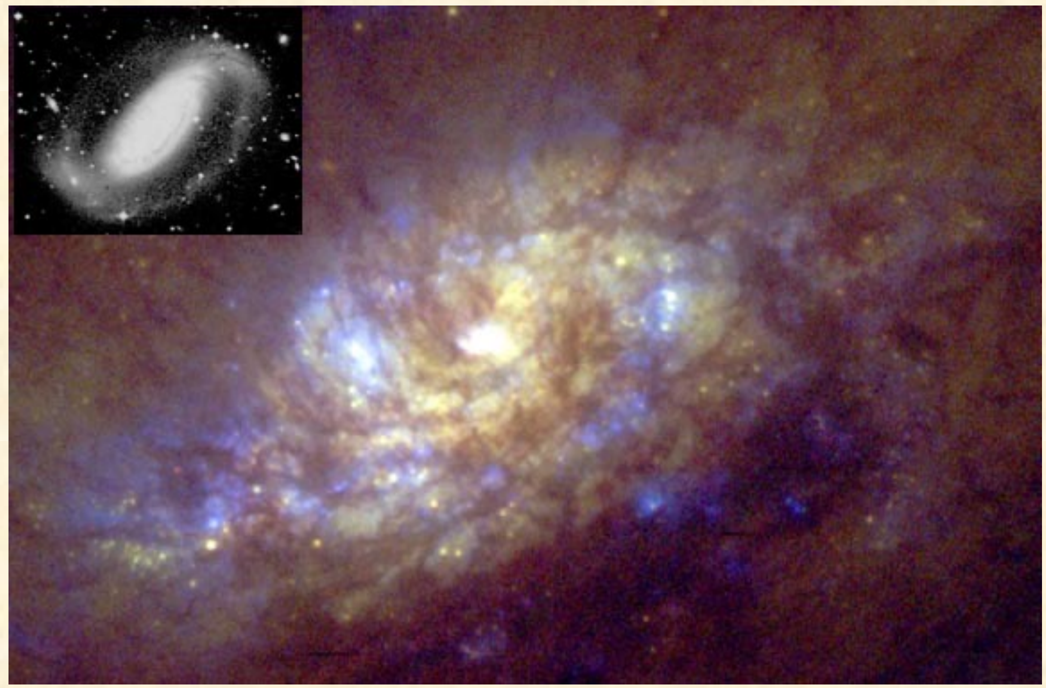
(NGC 6212, Pogge & Martini 2002, ApJ, 569, 624)

# NGC 1808 – A Nearby Starburst Galaxy



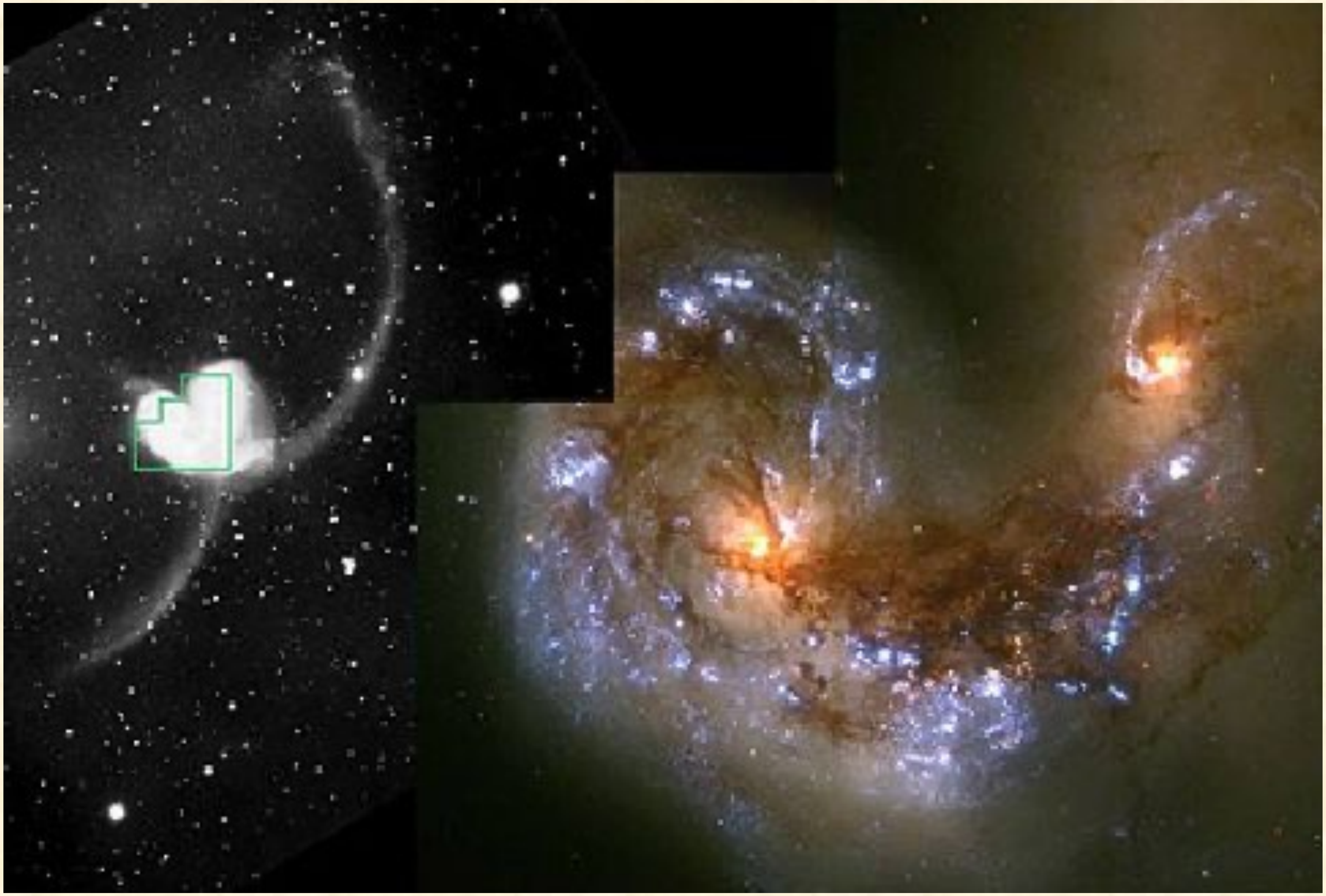
(HST)

Fed by a bar



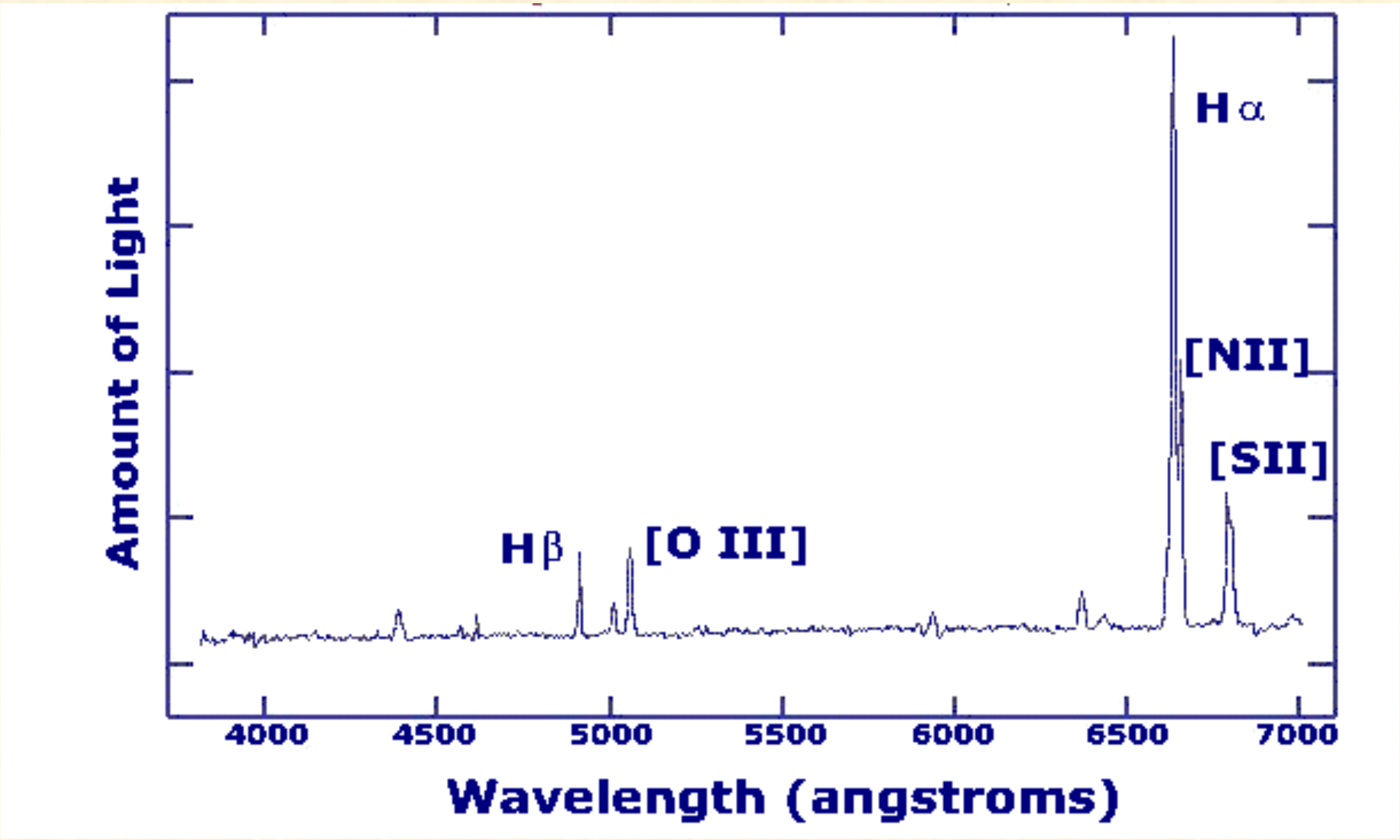
Blue – Hα emission
Red/yellow – stellar continuum

# Antennae Galaxies



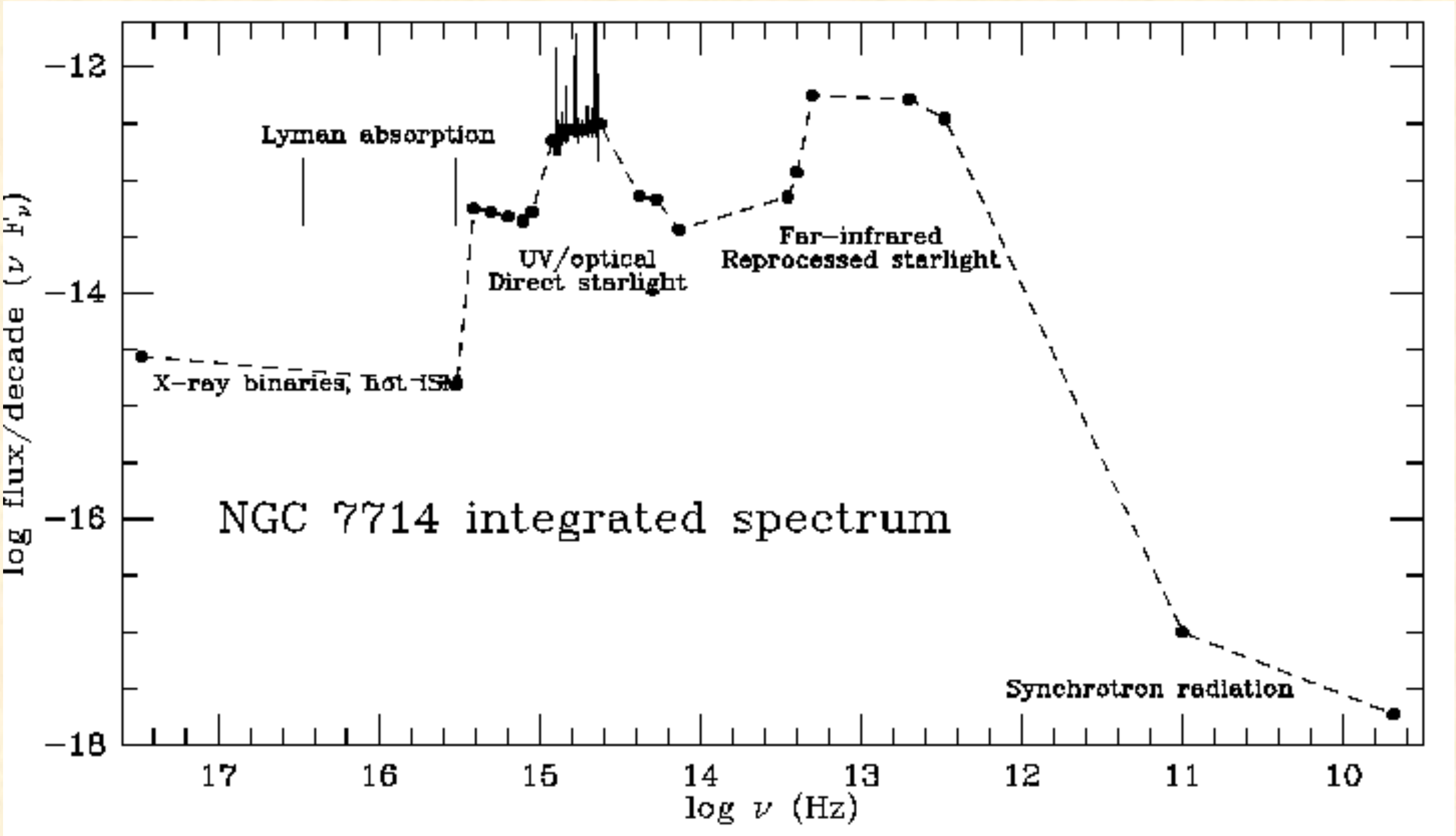
~1000 bright star clusters
- fed by a merger

# Starburst Optical Spectrum




H II region spectrum + faint stellar absorption

# Spectral Energy Distribution (SED)



# Ultraluminous Infrared Galaxies (ULIRGs)

- "Extreme" starburst galaxies with very young stars, surrounded by hot dust
- Initially detected by IRAS (12, 25, 60, 100 μm survey)
- Infrared luminosities up to $\sim 10^{13}\ L_{\odot} \approx 100 L_{MW}$!
- Some (most?) have a hidden AGN (fueled by same process)

Arp 220 – nearest ULIRG (z = 0.018)

HST NICMOS - 3 IR colors

VLA 6cm: 0.1' x 0.1'
-cores of two
colliding spirals

# Starburst Galaxy Characteristics

- High SFRs: 10 – 1000 $M_\odot$ $yr^{-1}$
- High FIR luminosities: $L_{FIR}$ (8 - 1000μ) = $10^{10}$ – $10^{13} L_\odot$
  - due to heating of dust (primarily from hot stars)
  - ULIRGs: $L_{FIR} > 10^{11} L_\odot$
- H II region-like spectra, high Balmer luminosities
- Strong radio continuum emission (from supernovae)
- Galactic superwinds (outflowing ionized gas)
- Almost always within 0.2 – 2 kpc of nucleus
- Star formation timescale (all gas is used up): 0.1 – 1.0 Gyr
- High inner gas densities: $10^2$ – $10^5$ $M_\odot$ $pc^{-2}$
- Result in a "super star cluster" at nucleus (>$10^8$ $M_\odot$ )

# Galactic Superwinds

Galactic superwind in M82 (red – Hα emission)
- outflowing ionized gas due to supernovae and hot-star winds
- also detected in X-rays, enriches IGM

For a starburst that uses 100% of its gas in a timescale $\tau_{gas}$ :

$$\mathrm{SFR} = 100\ \mathrm{M_{\odot}\,yr^{-1}} \left(\frac{\mathrm{M_{gas}}}{10^{10}\mathrm{M_{\odot}}}\right)\left(\frac{\tau_{gas}}{10^{8}\,\mathrm{yrs}}\right)^{-1}$$

(The dynamical time scale for feeding the nucleus is $\sim 10^{8}$ yrs.)

The maximum bolometric luminosity is:

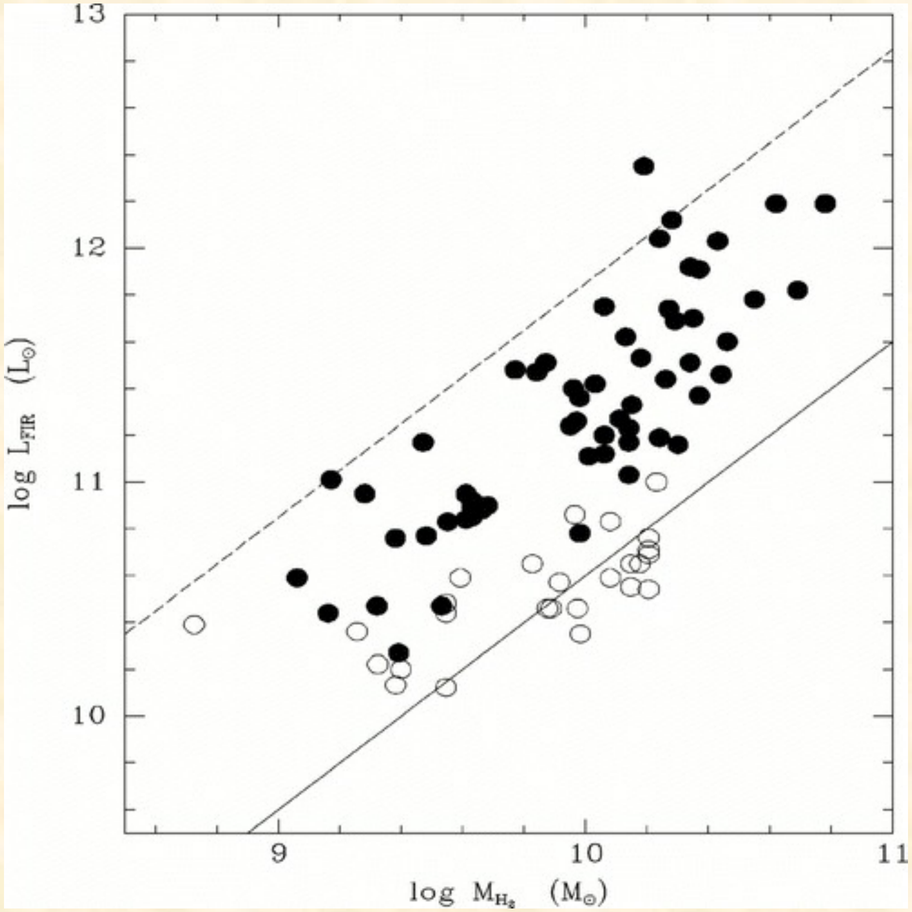
$$L_{max} \approx 0.01\, f\, \dot{M}\, c^{2} = 0.01\, f\, (\mathrm{SFR})\, c^{2}$$

where $f \approx 0.05$ for a Salpeter IMF, (fraction of stellar mass processed in $10^{8}$ yr), 0.01 is the fusion efficiency

$$L_{max} \approx 7 \times 10^{11}\ L_{\odot} \left(\frac{\mathrm{M_{gas}}}{10^{10}\mathrm{M_{\odot}}}\right)\left(\frac{f}{0.05}\right)$$

- To get $L_{FIR} \approx 10^{13}\ L_{\odot}$, you need $M_{gas} \approx 10^{11}\ M_{\odot}$
- So a ULIRG processes mass comparable to the entire ISM of a galaxy within ~ 1 kpc at 100% efficiency over $10^{8}$ years!

# Far-IR Luminosity vs. Mass ($H_2$)




Open – typical galaxies
Filled – bright IR galaxies (ULIRGs)

solid line – typical SFR
dashed – 100% efficiency

(Kennicutt, 1998, ARAA, 36, 213)

- ε is the SFR efficiency per $10^8$ yrs
- average ε ≈ 30% for ULIRGs → the gas is consumed in ~0.3 Gyrs

# Dependence on Morphological Type

- Detection of nuclear H II emission increases with later type:
  - E (0%), SO (8%), Sa (22%), Sb (51% ), Sc-Im (80%)
    (Ho et al. 1997, ApJ, 487, 579)
- However, the H II luminosities decrease with later type:
  - H II nuclei in SO-Sbc galaxies are ~10x more luminous than those in Sc galaxies

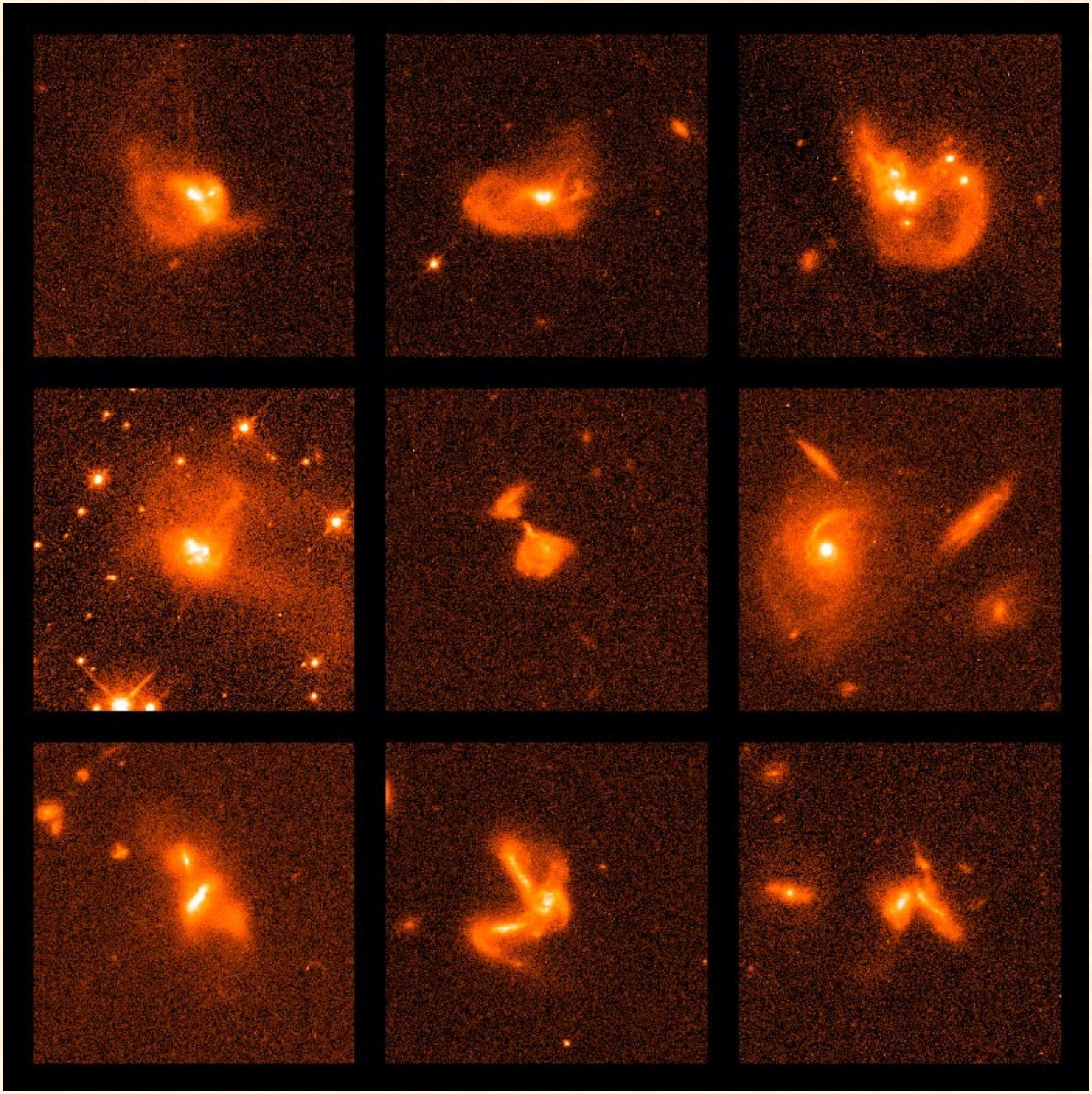
  → bars are "stronger" in early types, leading to higher fueling rates (when gas is actually available)
- Most ULRIGs are "peculiar" galaxies → mergers

  For $L_{FIR} < 10^{10}\ L_{\odot}$, 20 – 30% of IR galaxies are interacting

  For $L_{FIR} > 10^{12}\ L_{\odot}$, 70 – 95% of IR galaxies are interacting

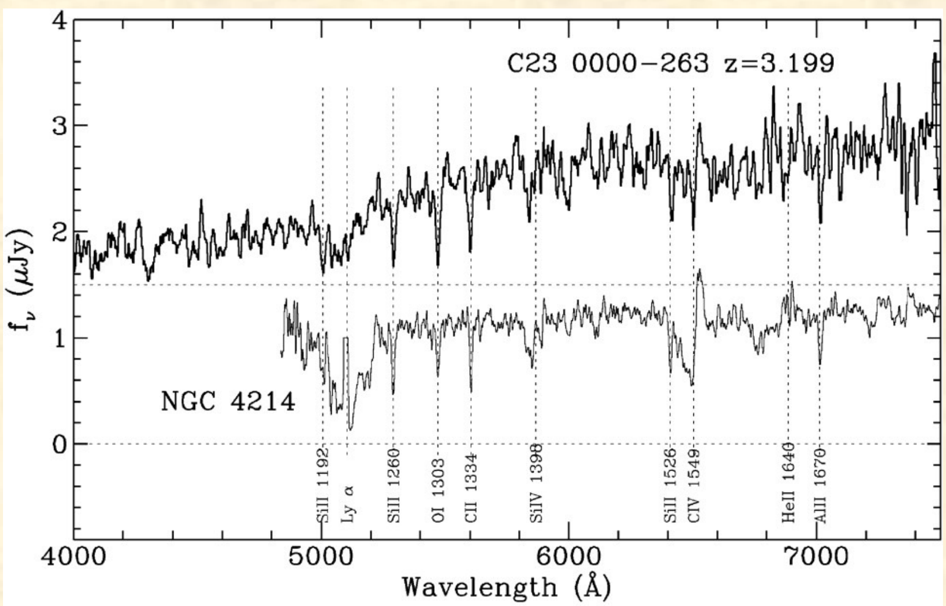
  (Sanders et al. 1988, ApJ, 325, 74)

# More ULIRGs - Major Mergers



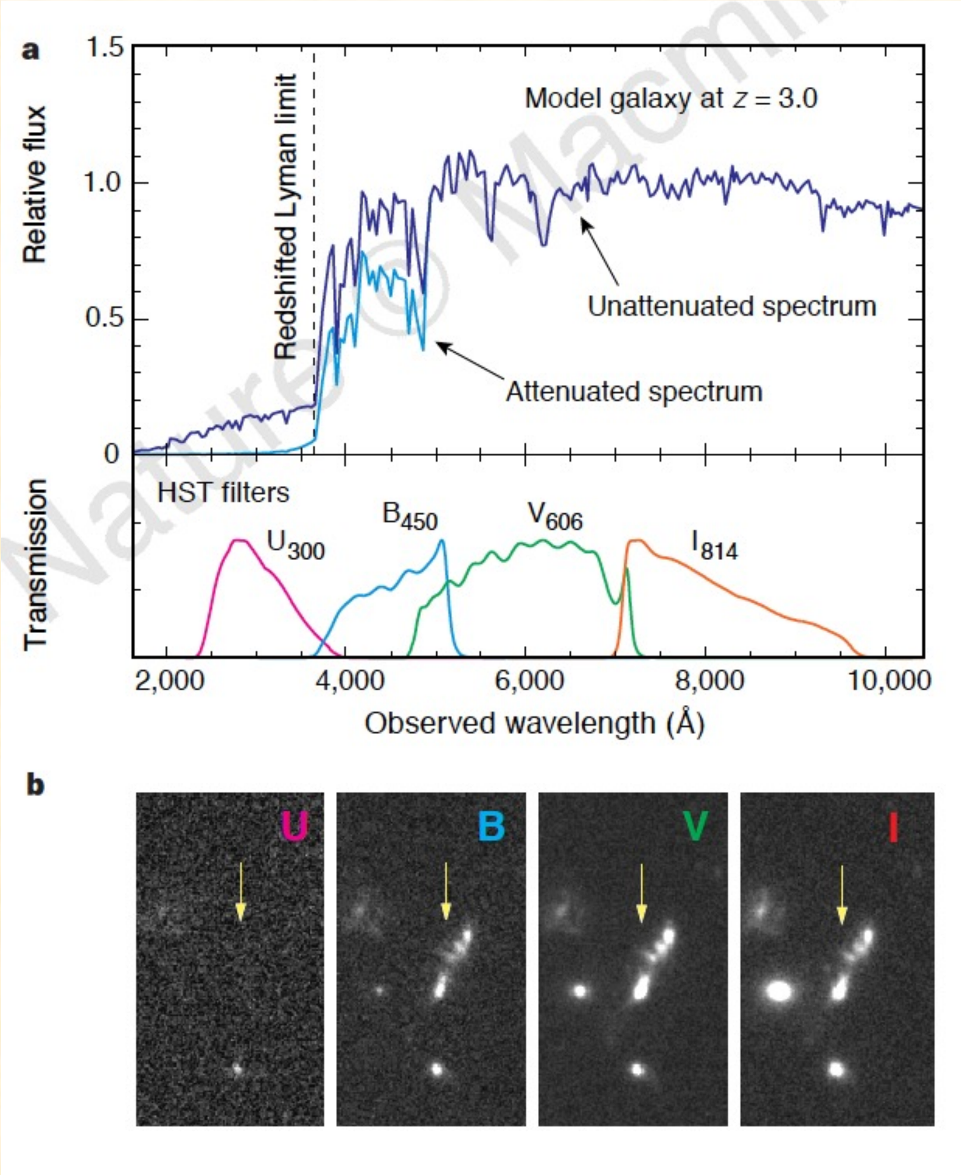
# Lyman-Break Galaxies (LBGs)

- Starburst galaxies at z = 2.5 – 5 (~10% of the Hubble time)
- Identified by their far-UV colors around the Lyman continuum break (912 Å)
  - Prominent in the atmospheres of hot stars
- Allows the photometric detection of galaxies at high z (thousands of detections so far)
  - Note: This technique identifies UV-bright starbursts at high z, but not those hidden by dust (ULIRGs)



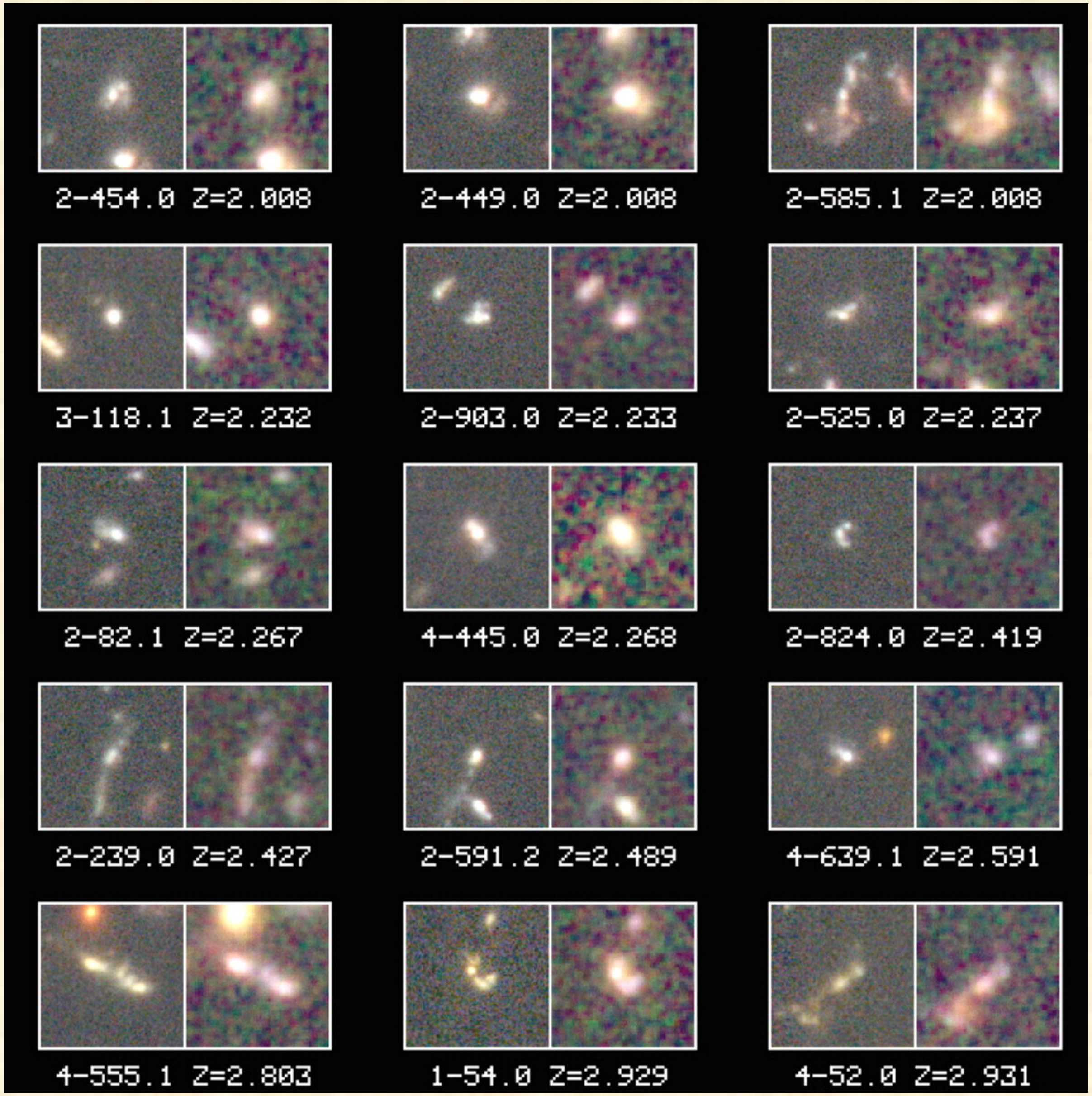

Spectra similar to low-z starburst galaxies.

# Detection of Lyman-break galaxies




(Ellis 1998)

# Galaxy Formation- HST Images




For each LBG:
Left: WFPC2 BVI
Right:NICMOS JH

Various morphologies:
(compact, diffuse, regular, irregular, fragmented)

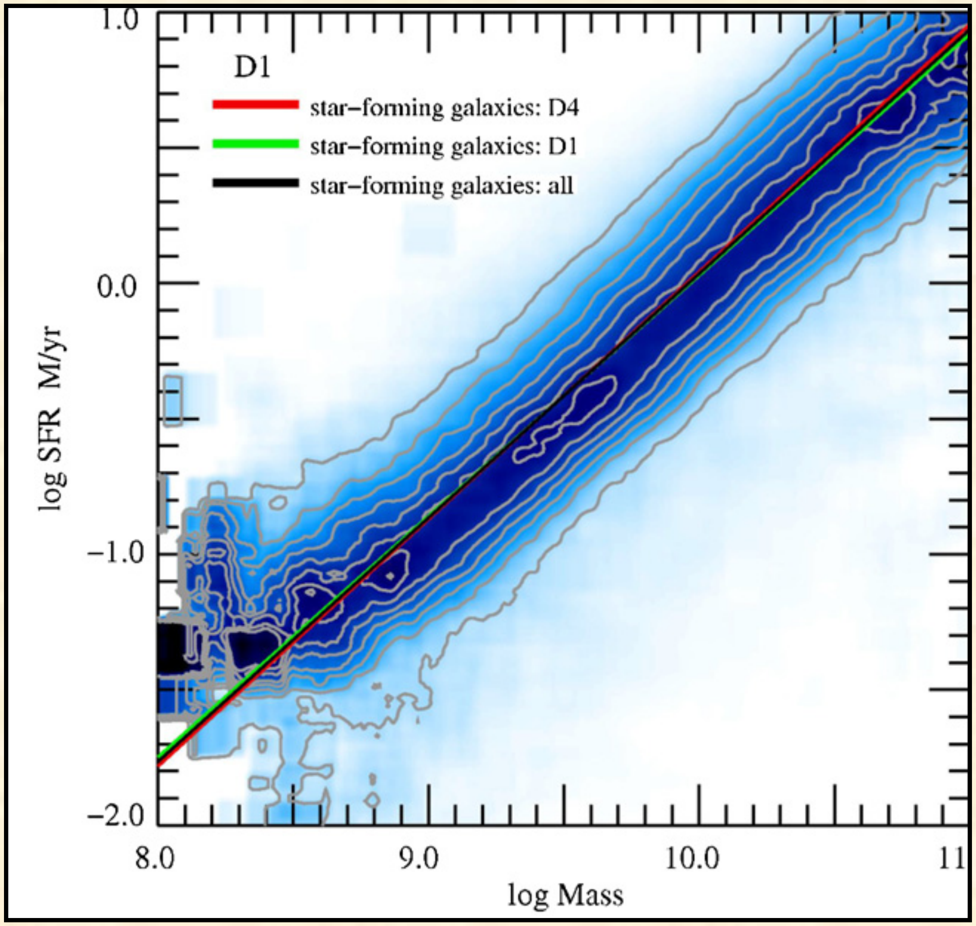
→Many similar to late-type spirals or mergers

→May not be seeing entire galaxy, just regions of high SFR.

→Note: We are seeing UV-bright starburts, but missing the ULIRGs at high z

(Giavalisco, 2002, ARAA, 40, 579)

# Galaxy Evolution: the "Main Sequence" of Star Formation




(Peng, et al. 2010, ApJ, 721, 193)

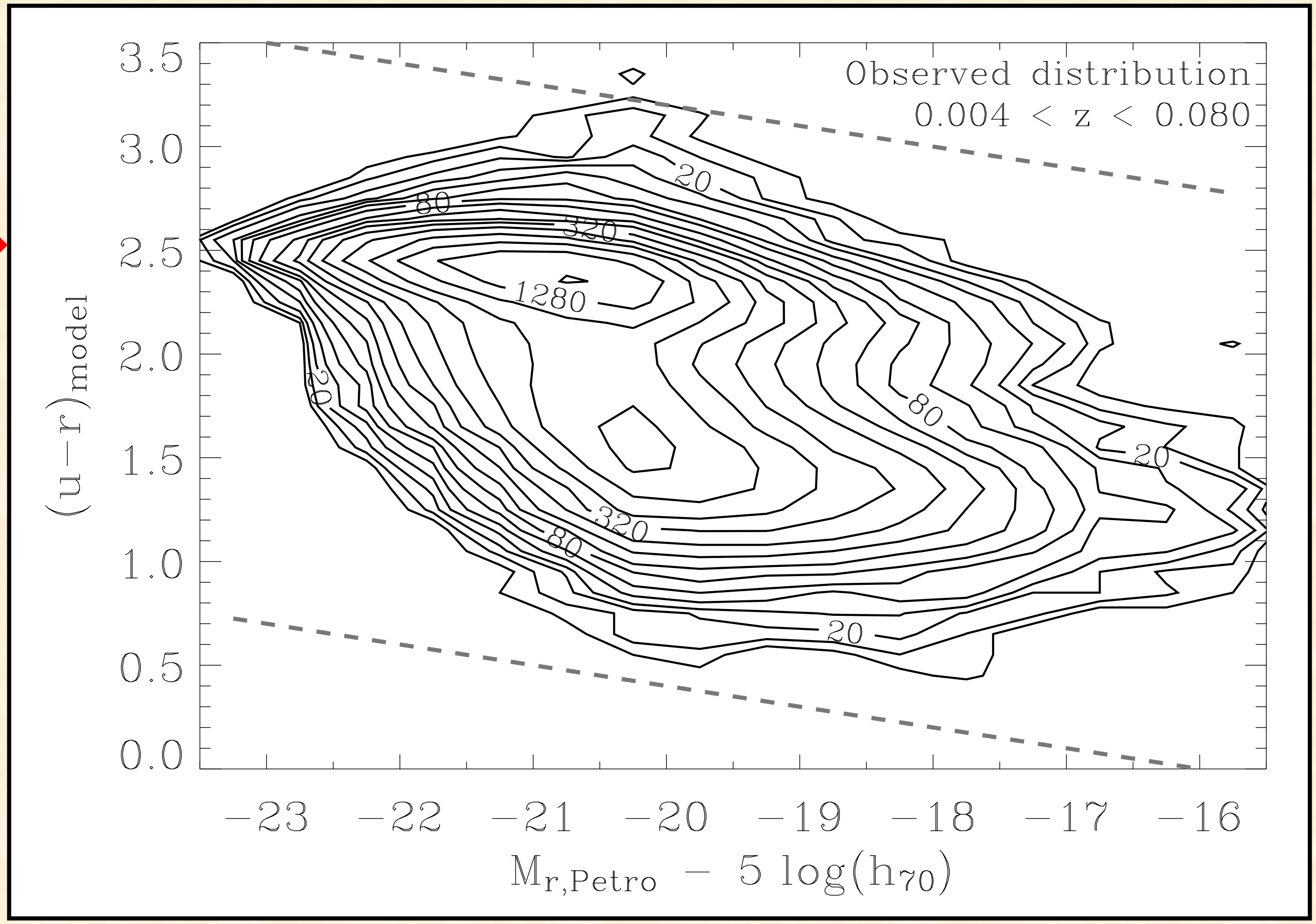
SDSS:
- Star formation rate essentially independent of low (D1) and high density (D4) environments
- Stellar mass from M/L ratio as function of color

- SFR (from Hα emission): nearly linear with stellar mass.
- Specific SFR: sSFR = SFR/M ~ $M^{-0.1}$ .
- SFR regulated by inflow and stellar feedback? (stellar winds, SNR's)
- When SF quenched, galaxy moves off the correlation (ULIRGs lie above).

# Color-Magnitude Diagram of 60,000 galaxies from SDSS

red sequence →

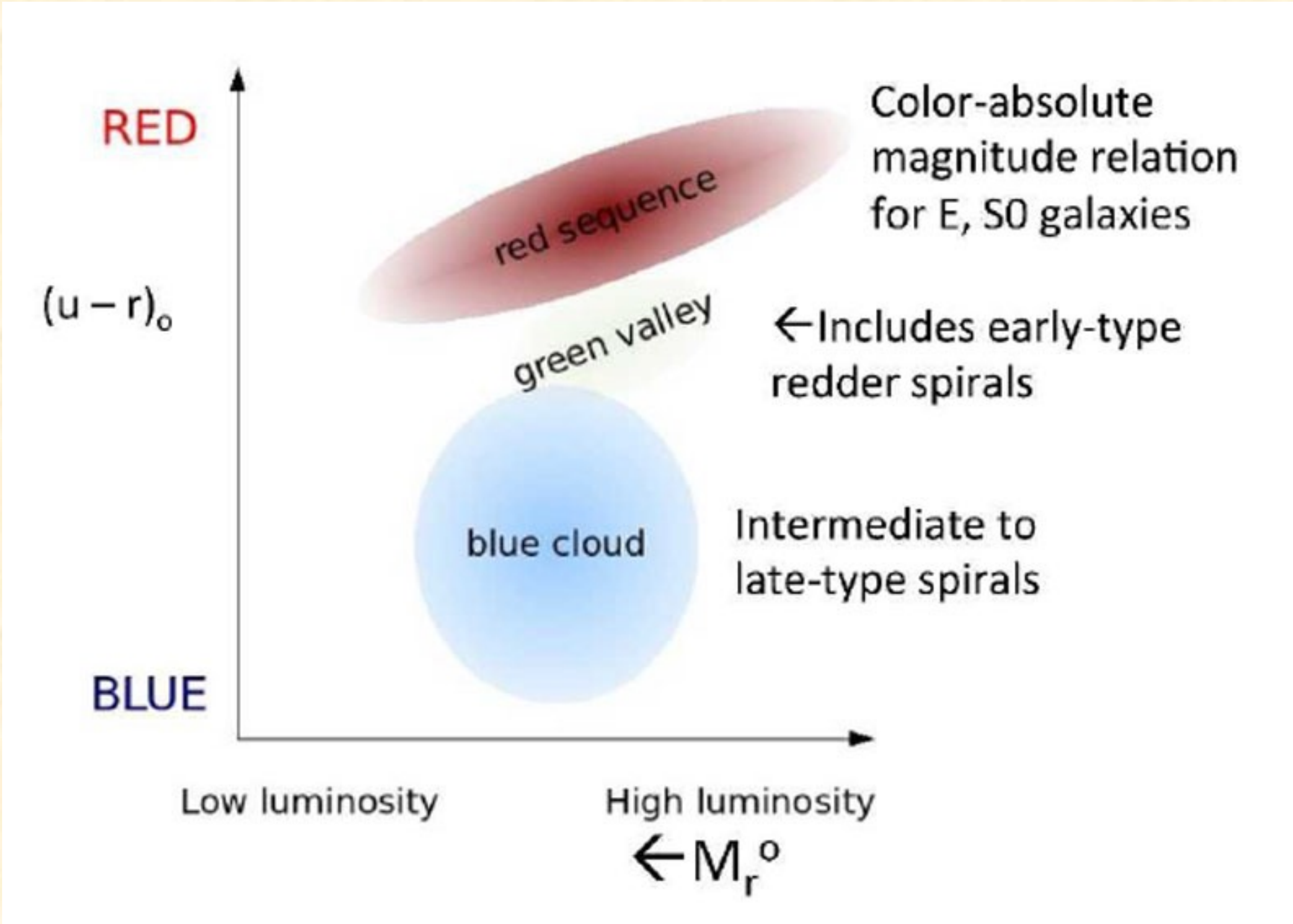
blue cloud →




(Baldry et al., 2004, ApJ, 600, 681

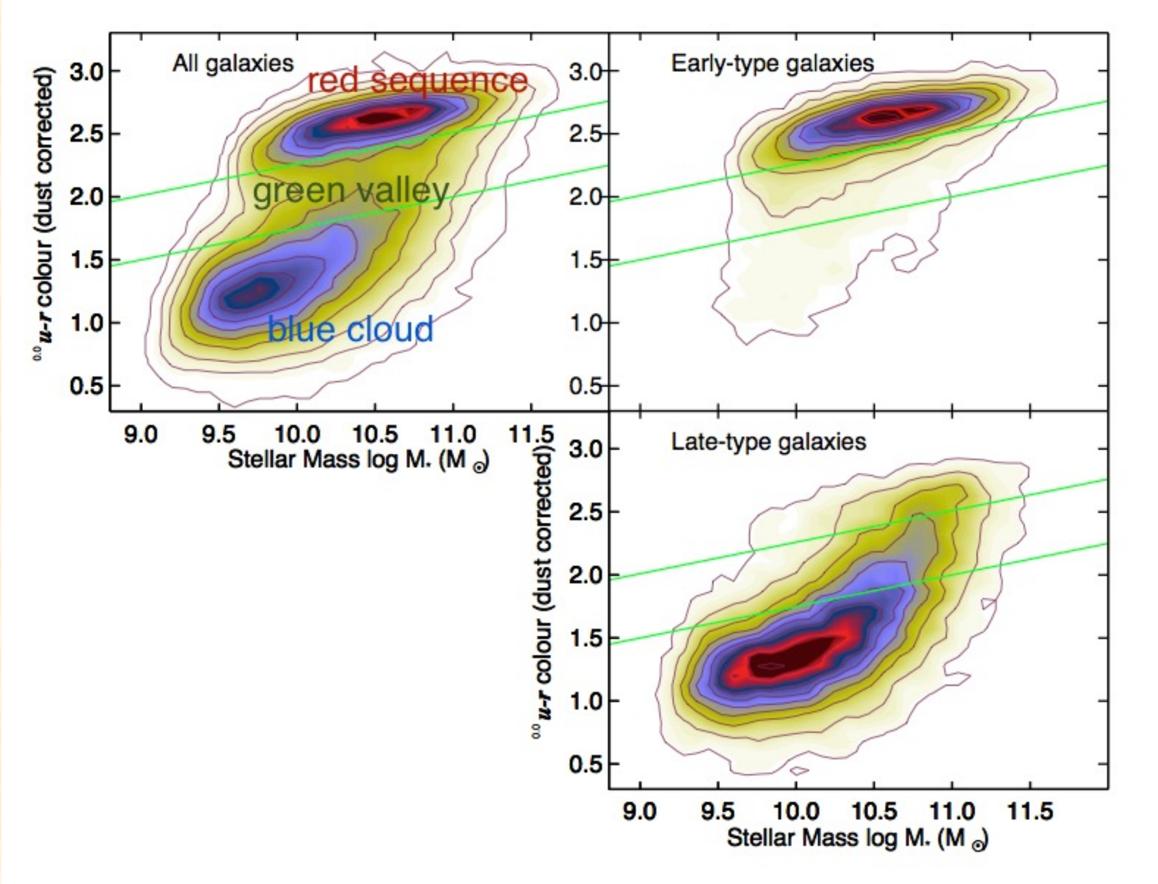
- Red sequence: primarily ellipticals; increasing (redder) color with luminosity reflects metallicity trend
- Blue cloud: primarily spirals, irregulars; increasing color with luminosity reflects increasing prominence of bulge

# C-M Diagram – Early Schematic




- Early interpretation: galaxies move from blue to red, possibly through mergers (colliding disks form ellipticals).

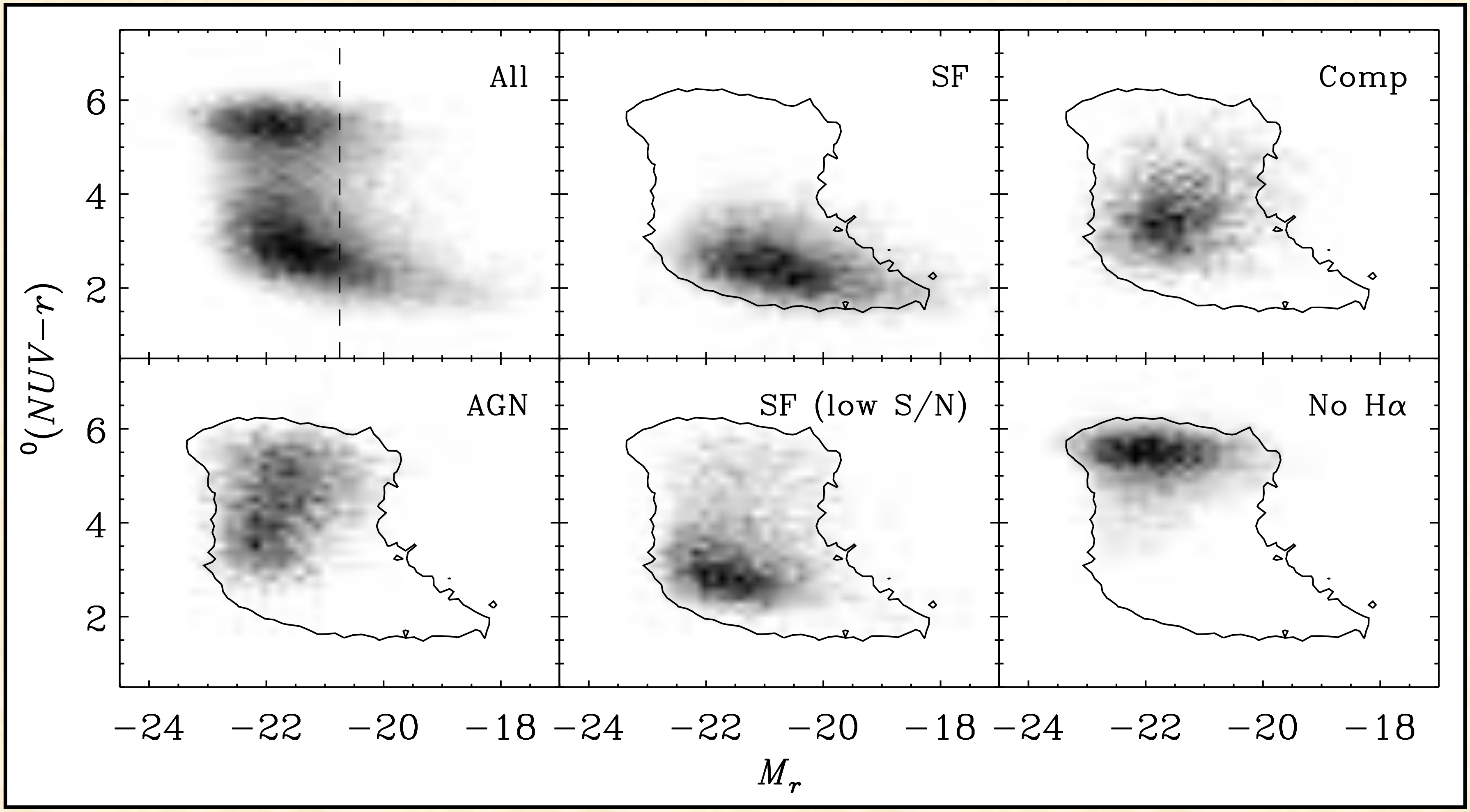
# C-M Diagrams by Morphology




Schawinski et al., 2014, MNRAS, 440, 889.

- Blue ellipticals (5%) and red spirals (7%) exist. 10% to 20% of E's and S's are in green valley.
- Possibility: SF in spirals quenches gradually, possibly through growth of hot halo. Quenching in ellipticals is result of major mergers that use up most of the gas in huge starburst (assisted by AGN feedback?)

# AGN/Star Formation Connection?




(Salim et al. 2007, ApJS, 173, 268)

- Most AGN lie in the "green valley"
- AGN activity comes toward the end of intense SF phase? (last stop for fueling?)