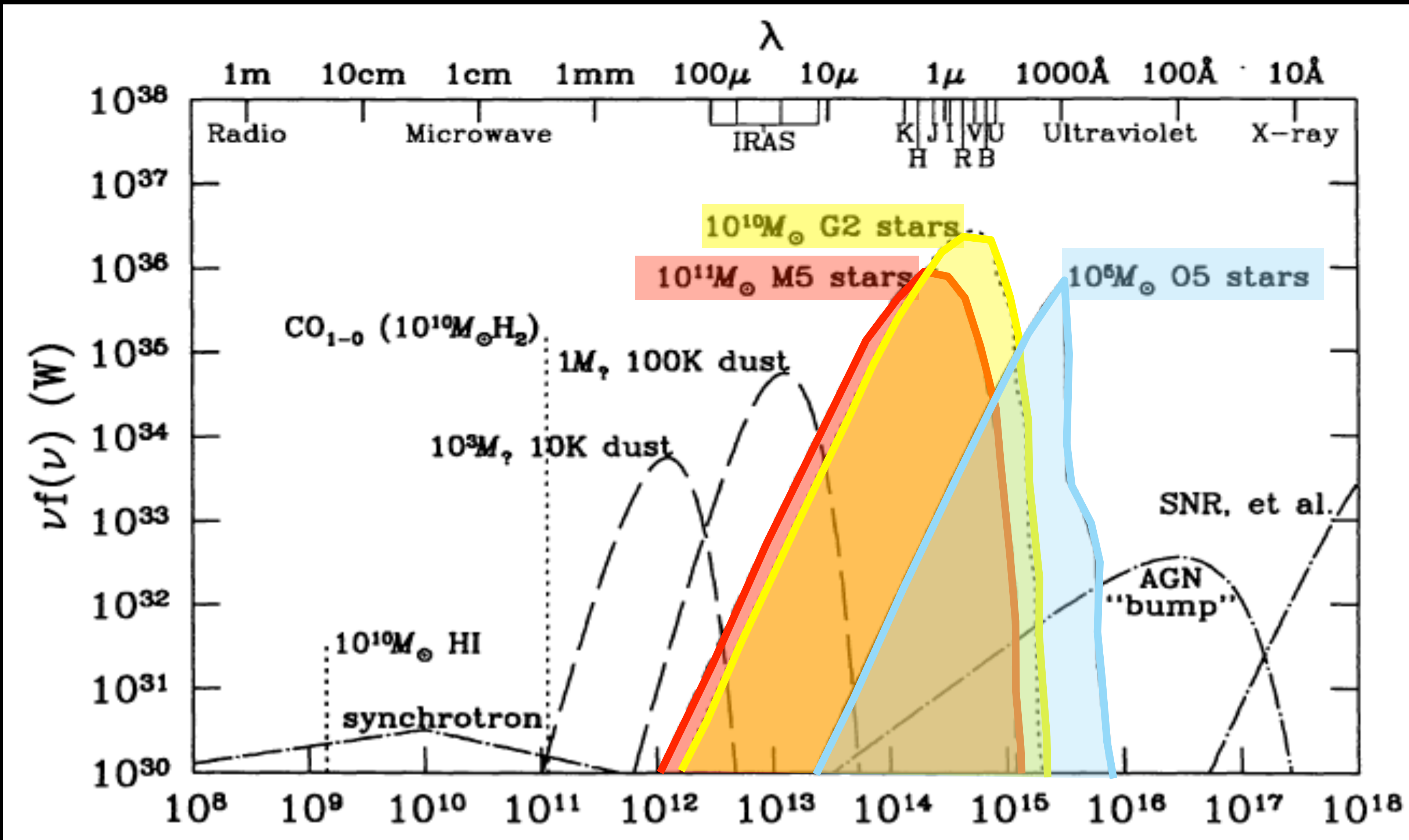
Understanding Galaxy Light: Stars

First, some context.

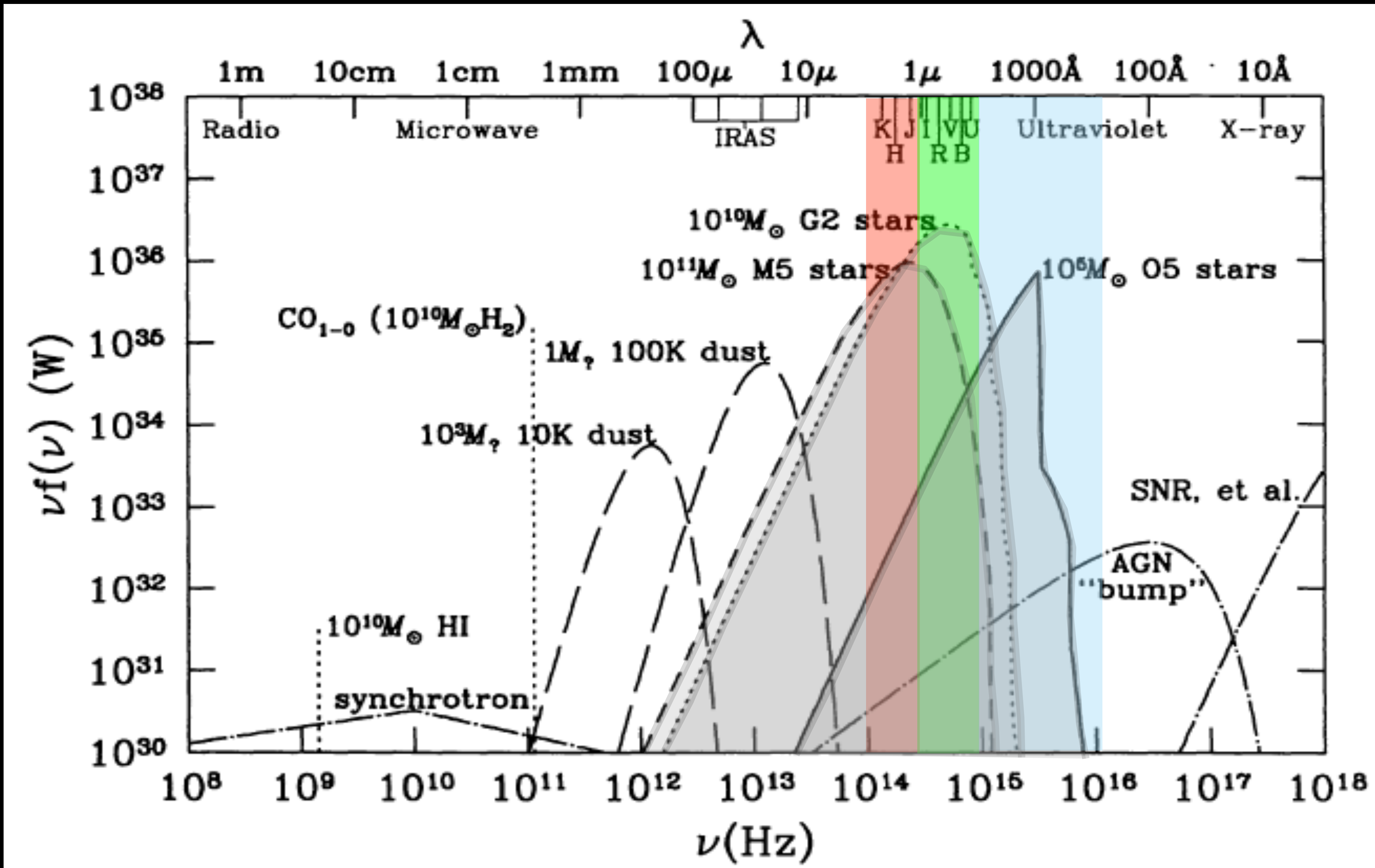
Stars are one part of a galaxy's "spectral energy distribution" (SED)



A starforming galaxy w/ an AGN

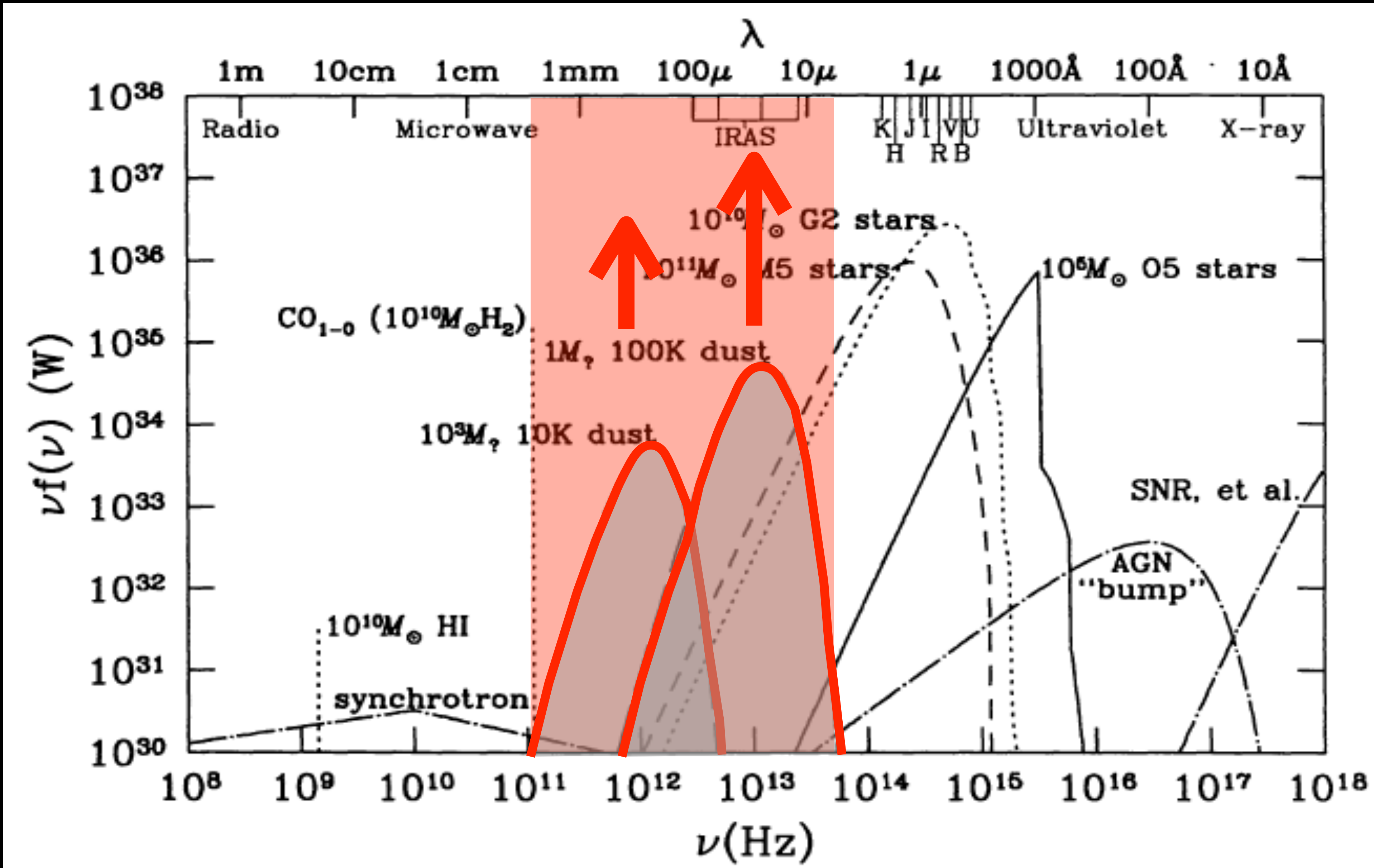
νf_ν is a better indicator of power than just flux, since it weights by photon energy…

Stars dominate in the near-IR (NIR), optical, & near UV



Radio sub-mm Far-IR Mid-IR UVOIR Far-UV X-ray

Note: Stars do not always dominate the energy budget. Dust can dominate SED for extreme star-forming galaxies

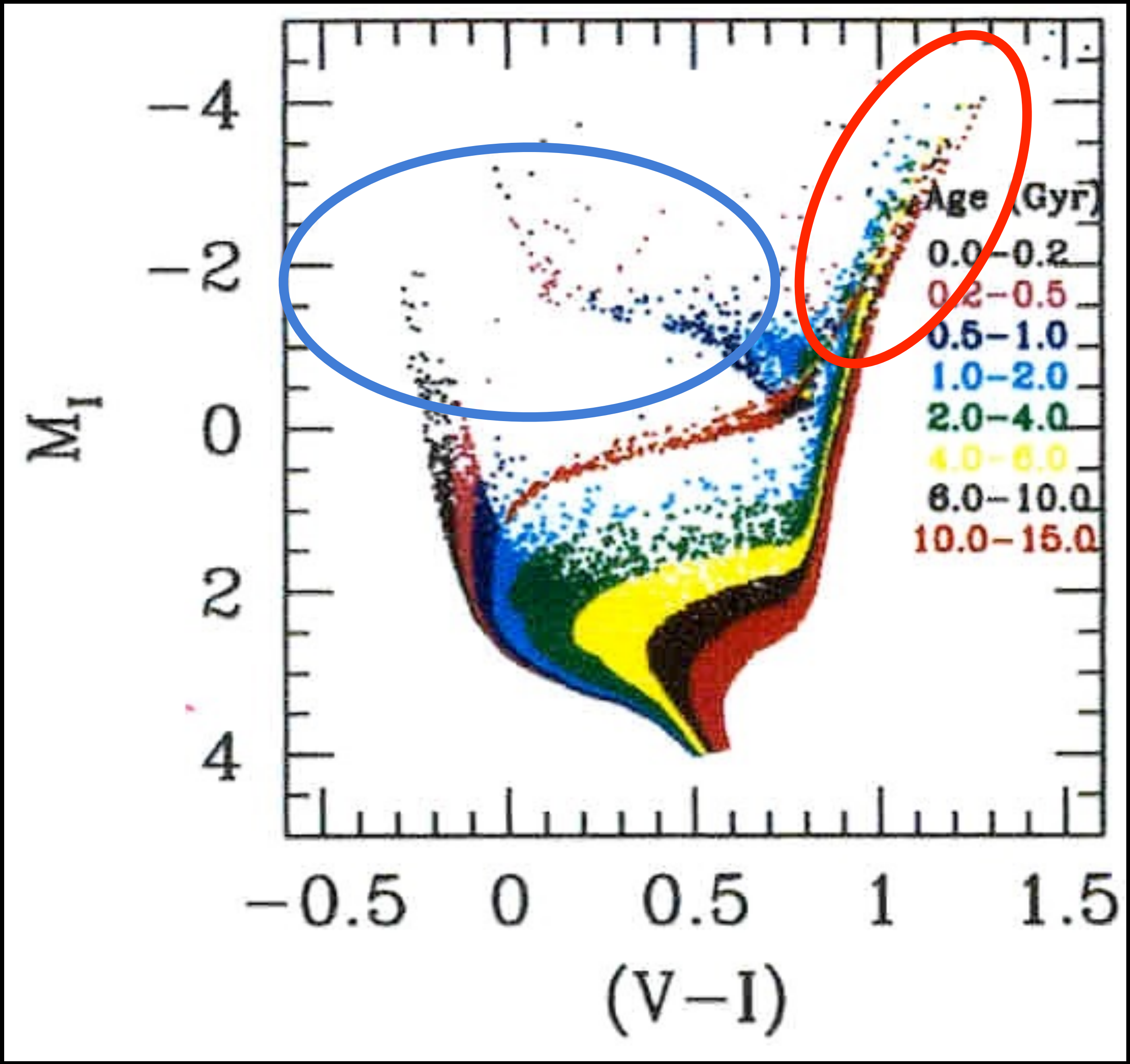


Radio sub-mm Far-IR Mid-IR Far-UV X-ray

(We'll talk about this in a subsequent lecture)

Stellar light

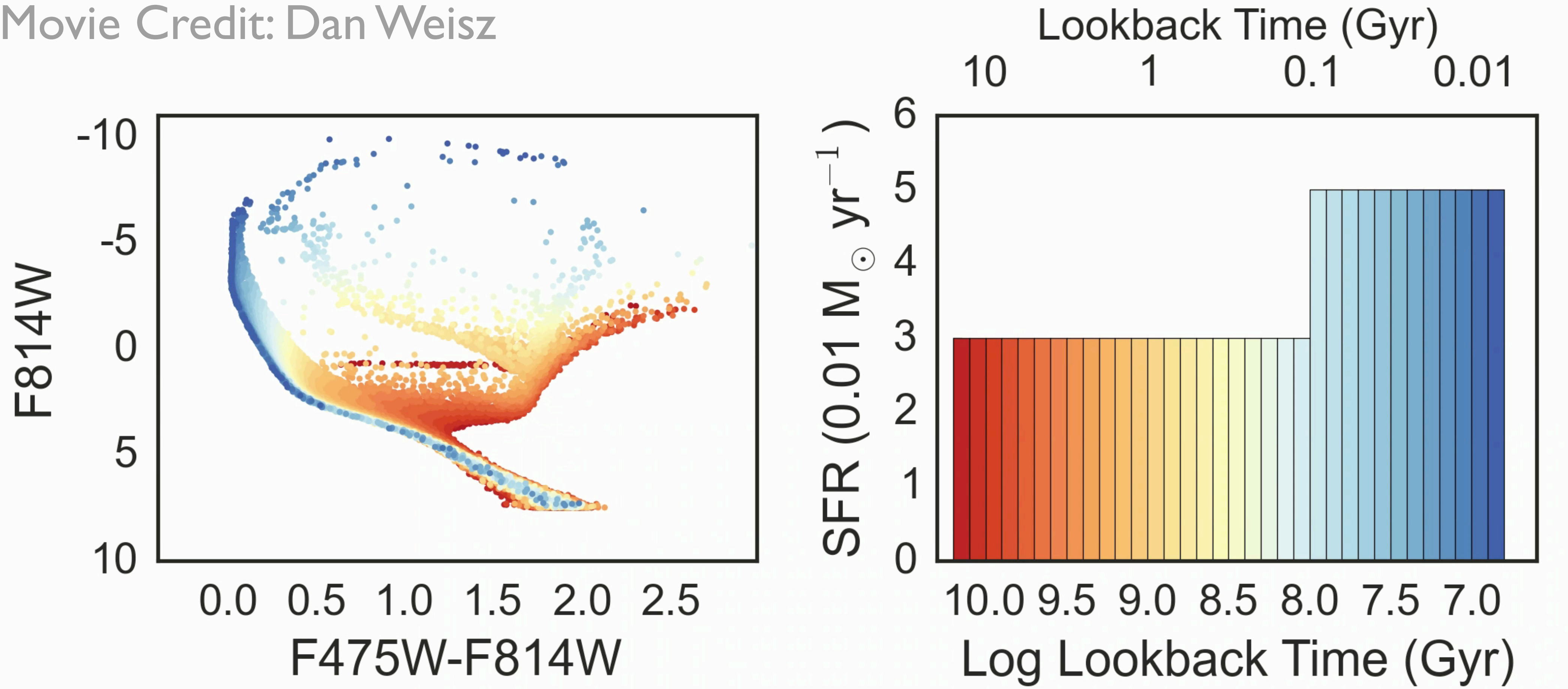
Galaxy colors/spectra are dominated by the **brightest stars** in their stellar populations



These stars are also the most massive

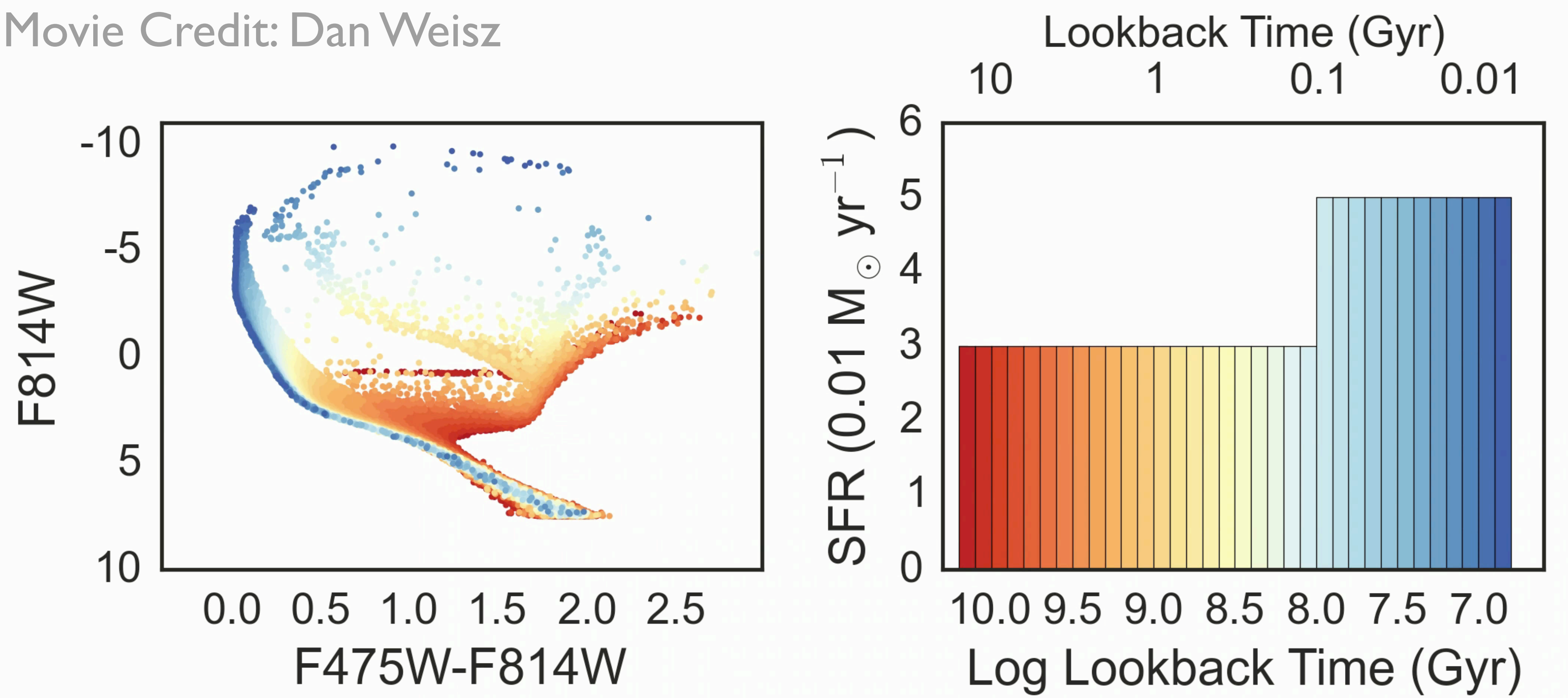
Color-Magnitude Diagrams vs Time

Movie Credit: Dan Weisz



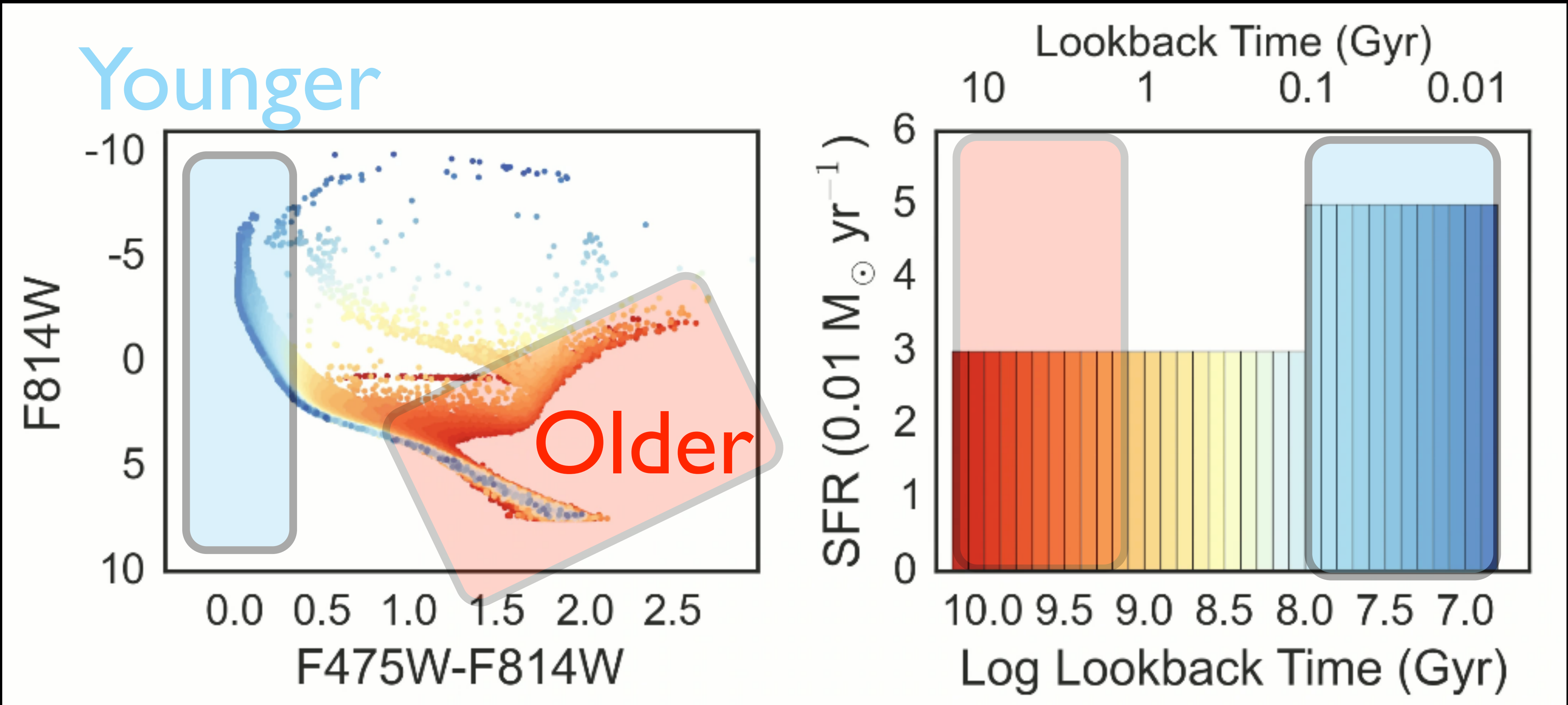
When interpreting galaxy light, its useful to understand the brightest stars at each epoch

Color-Magnitude Diagrams vs Time



Recent SF: Bright stars are blue & luminous
Ancient SF: Bright stars are red & dimmer

Age variation is ~logarithmic

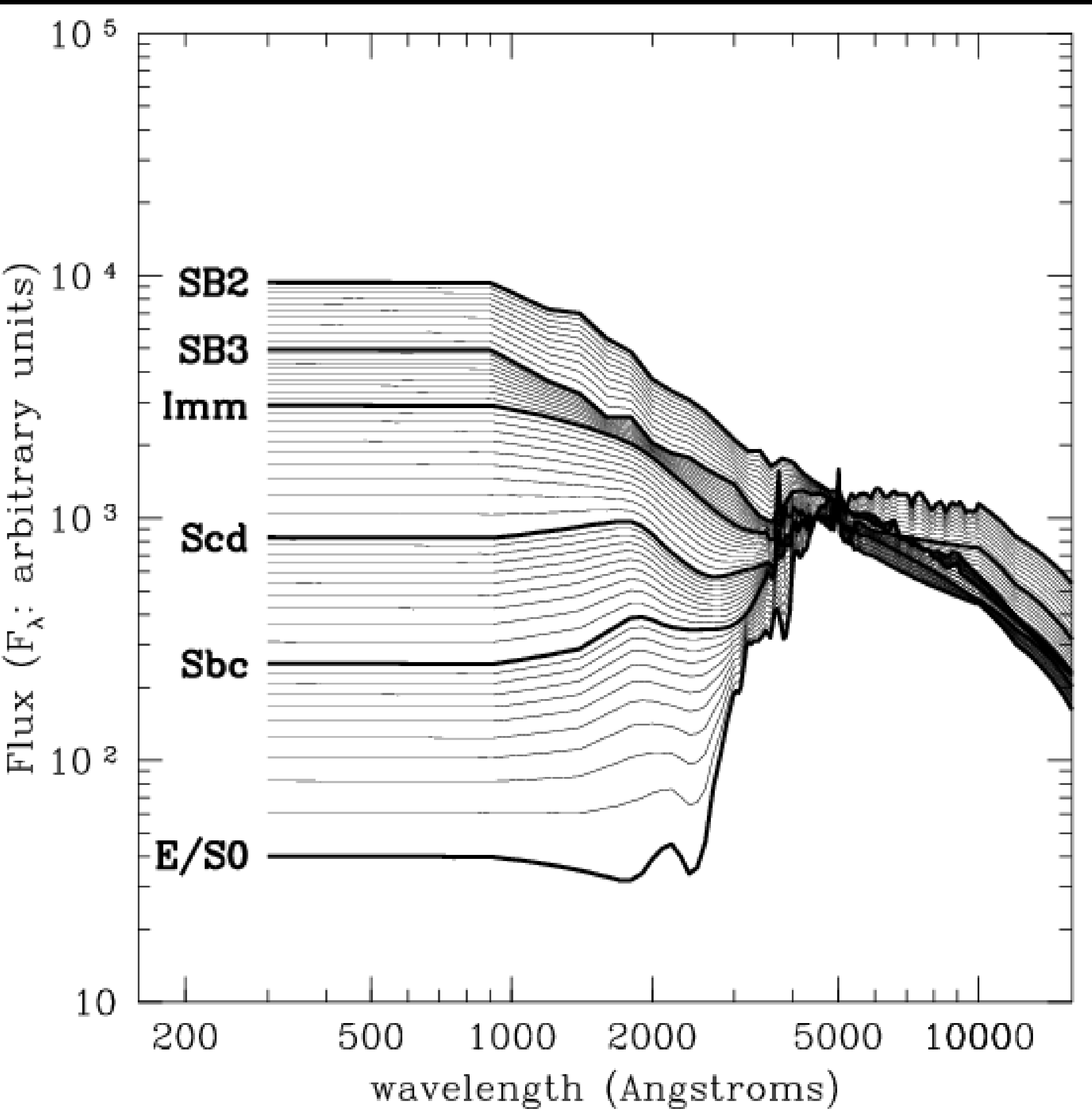


Changes in color & luminosity:

Large/rapid at <100Myr.

Small/slow changes at >2Gyr.

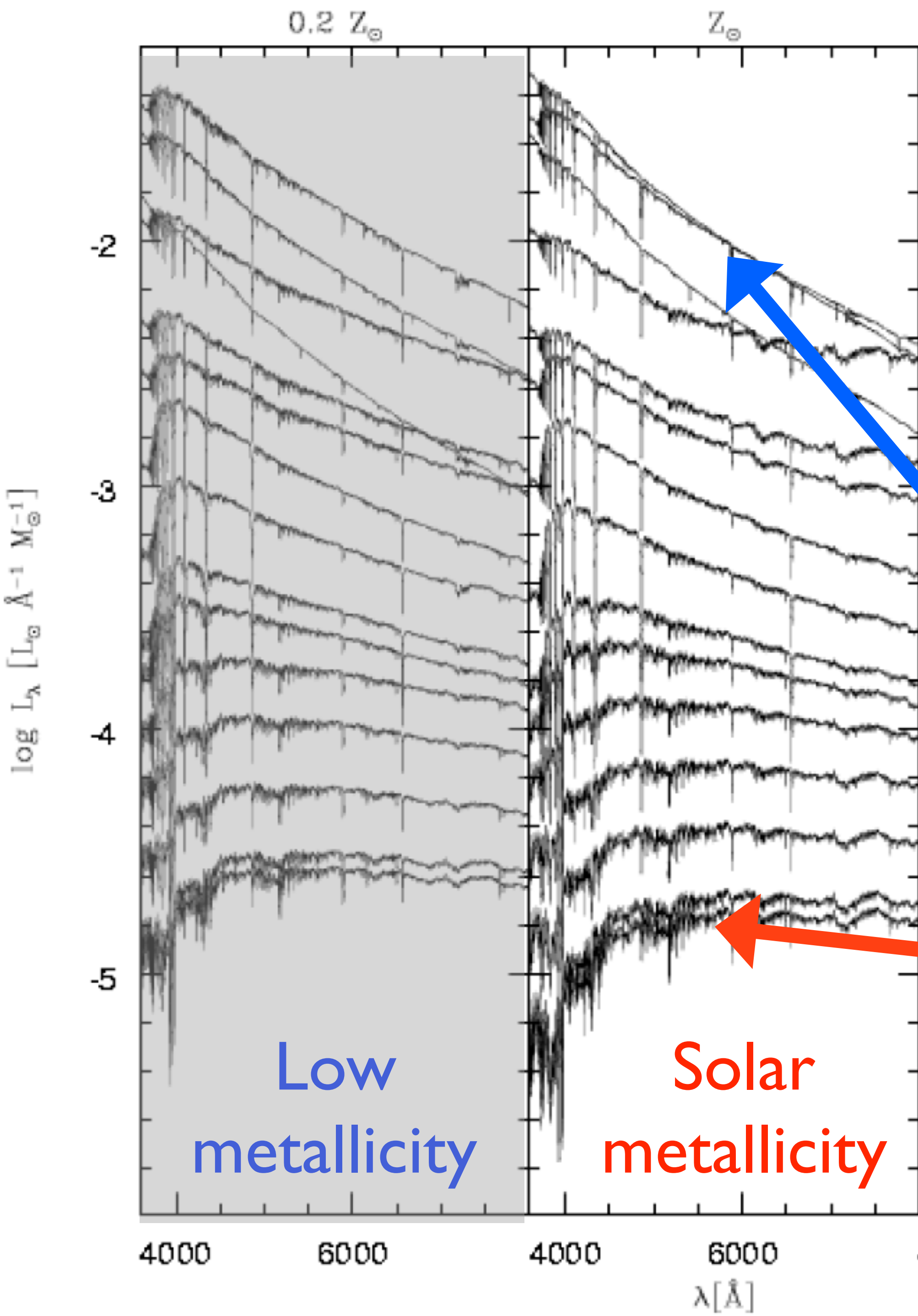
“Stellar Continuum” = sum of all stellar populations



Luminosities, *color*, and *spectra* are sensitive to the star formation history (SFH), because of the changing mix of stars

Optical

Time evolution of the optical spectra of a burst of star formation

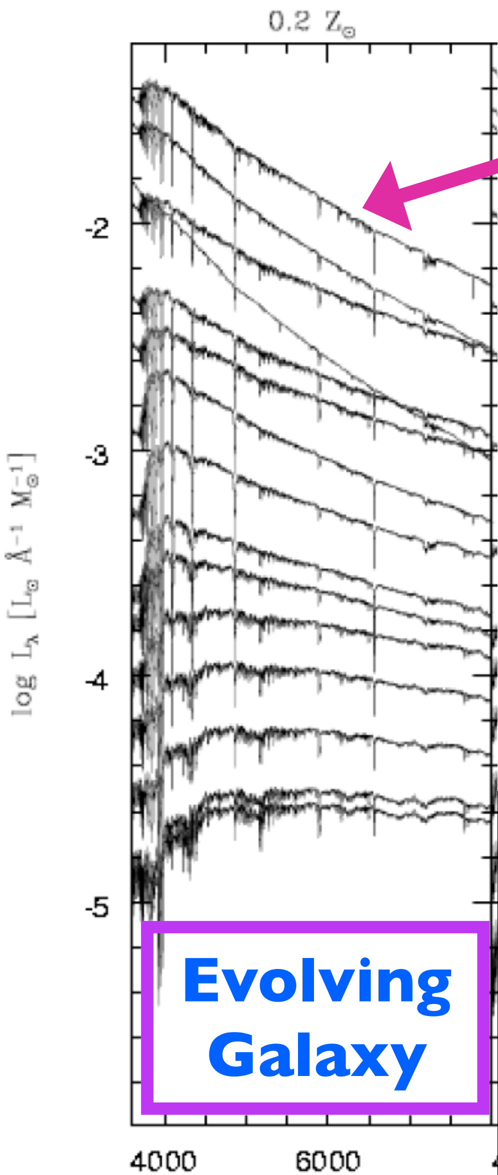


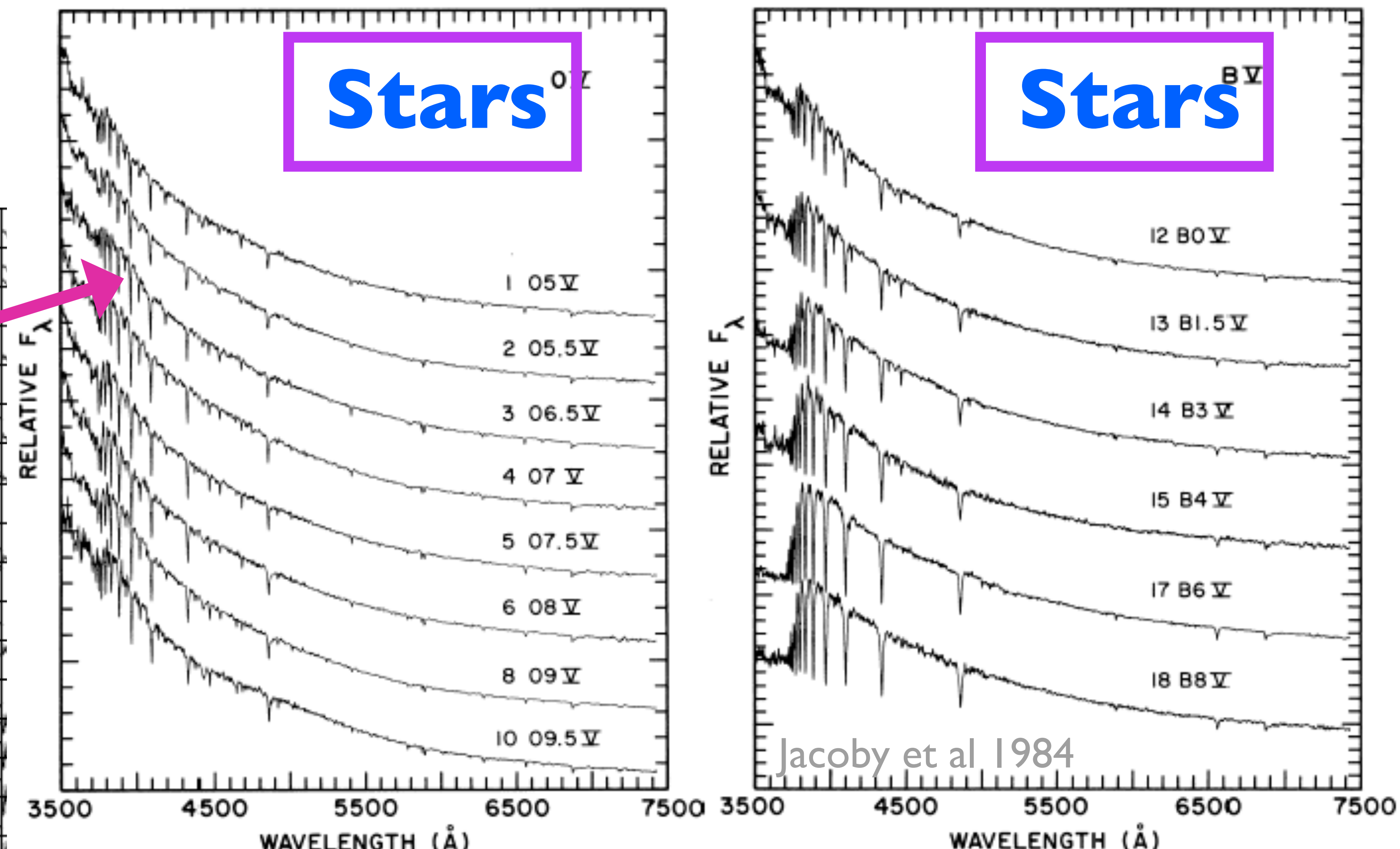
- Initially **bright** & blue, (dominated by O&B stars) w/ strong UV radiation (not shown)
- Later, "stellar population" becomes dimmer and redder (dominated by red K-giants)

Fernandes et al 2005

Figure 1. Spectra of the 45 SSPs used in the spectral synthesis (from BC03). The base comprises 3 different metallicities, $Z = 0.2$, 1 and 2.5 $Z_\odot$, and 15 ages: From top to bottom, $t = 0.001$, 0.00316, 0.00501, 0.01, 0.02512, 0.04, 0.10152, 0.28612, 0.64054, 0.90479, 1.434, 2.5, 5, 11 and 13 Gyr. All SSPs are normalized to 1 $M_\odot$ at $t = 0$.

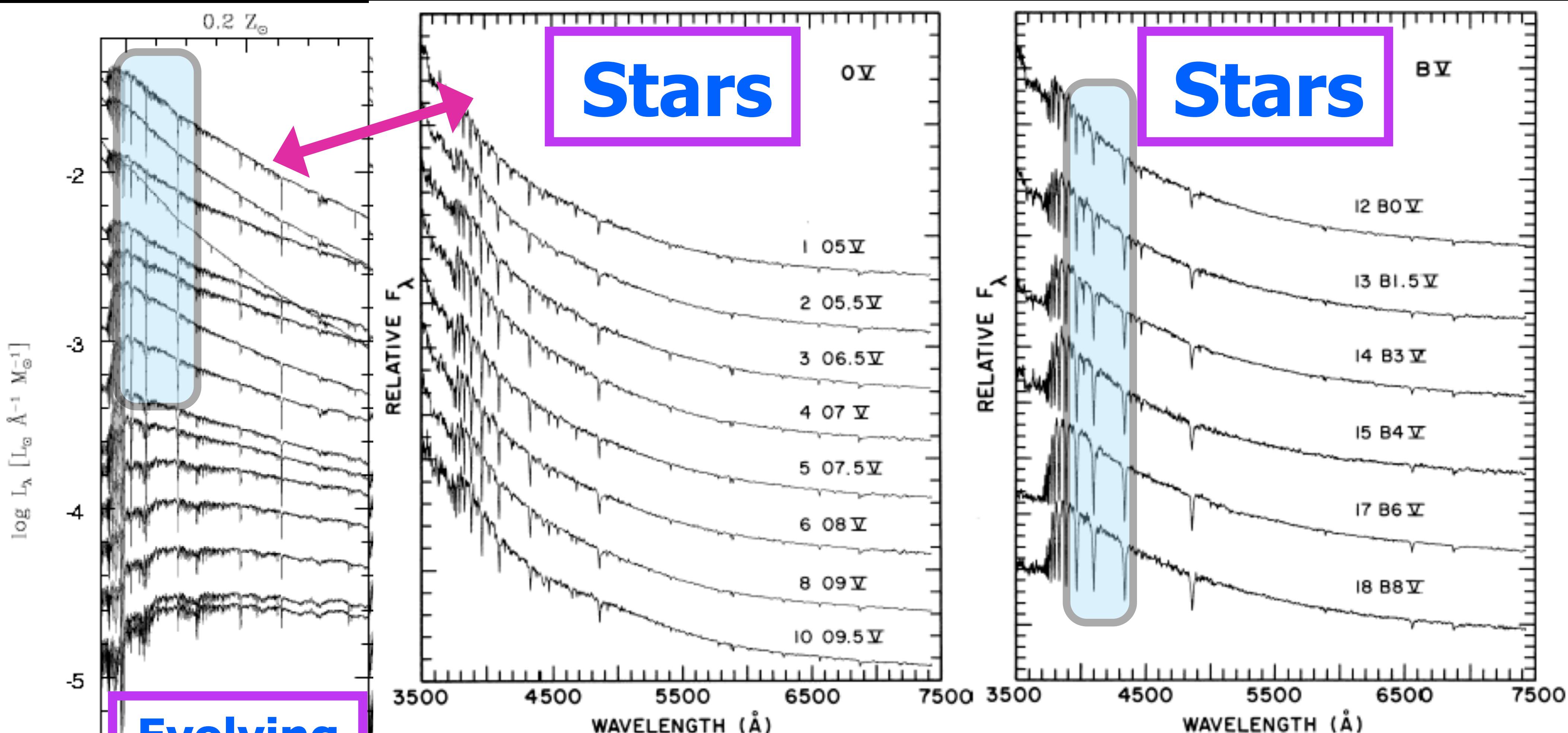
A burst of SF initially looks like O & B stars





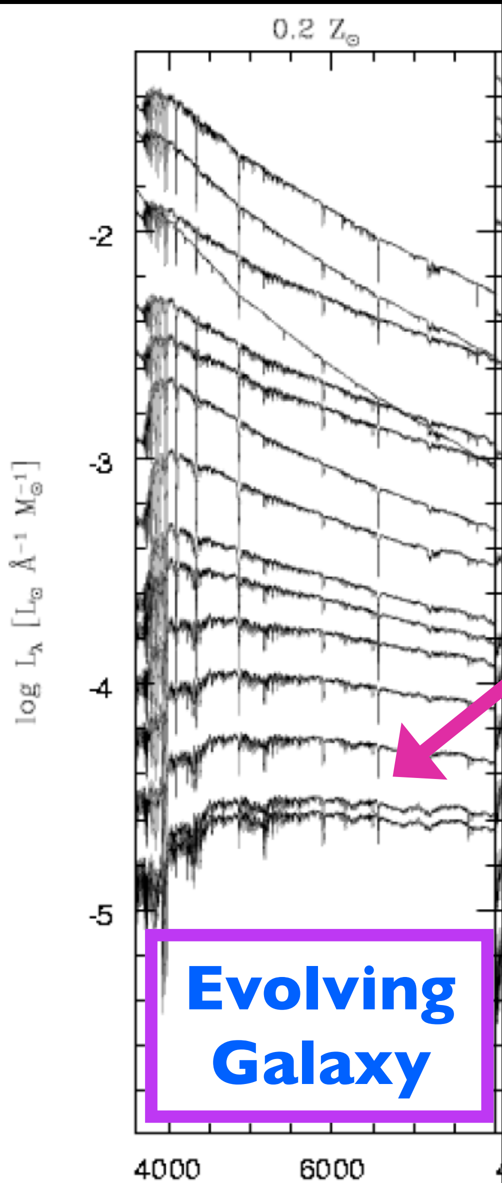
- Short-lived (>5M$_\odot$) main sequence stars dominate the spectrum
- UV parts of the spectrum are dominated by the bluest stars (>10M$_\odot$)

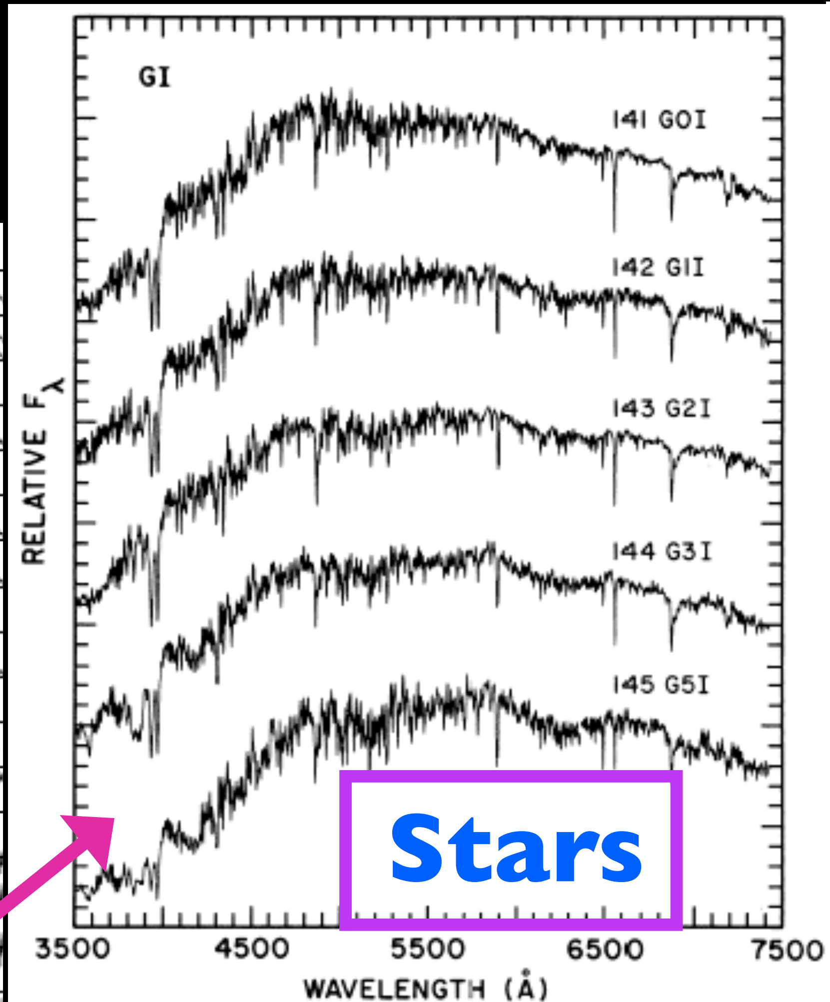
There will also be notable spectral features associated with recent star formation

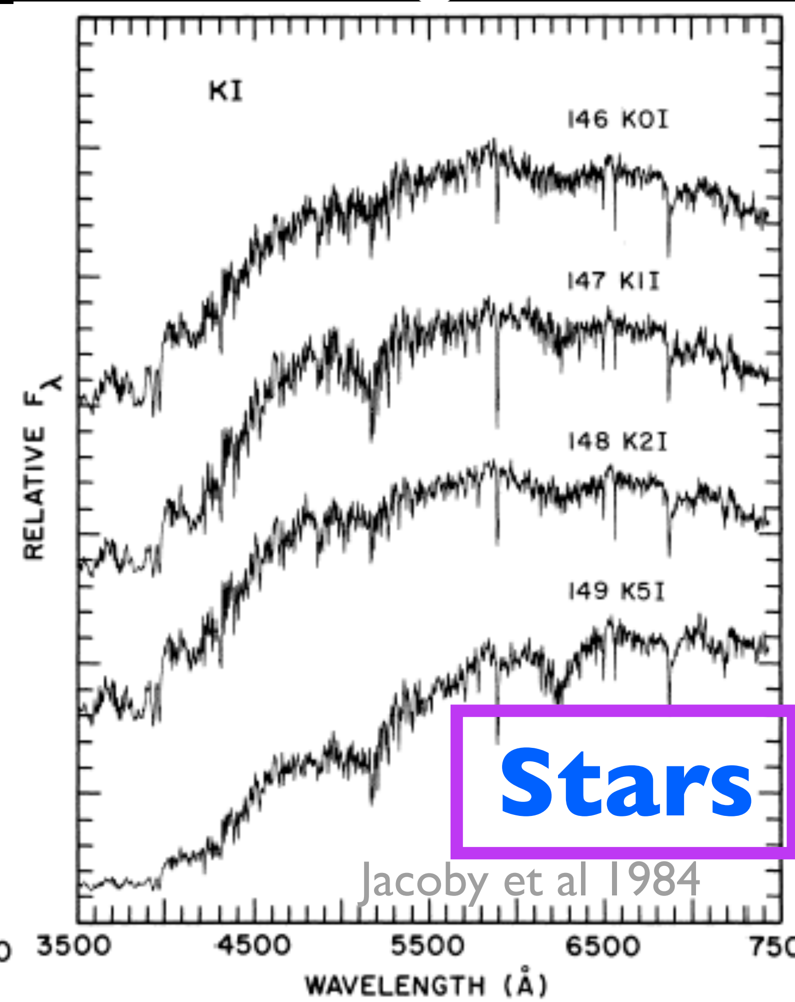


Balmer lines:
Strongest in A and B stars

Long after the burst, it looks like G/K giants

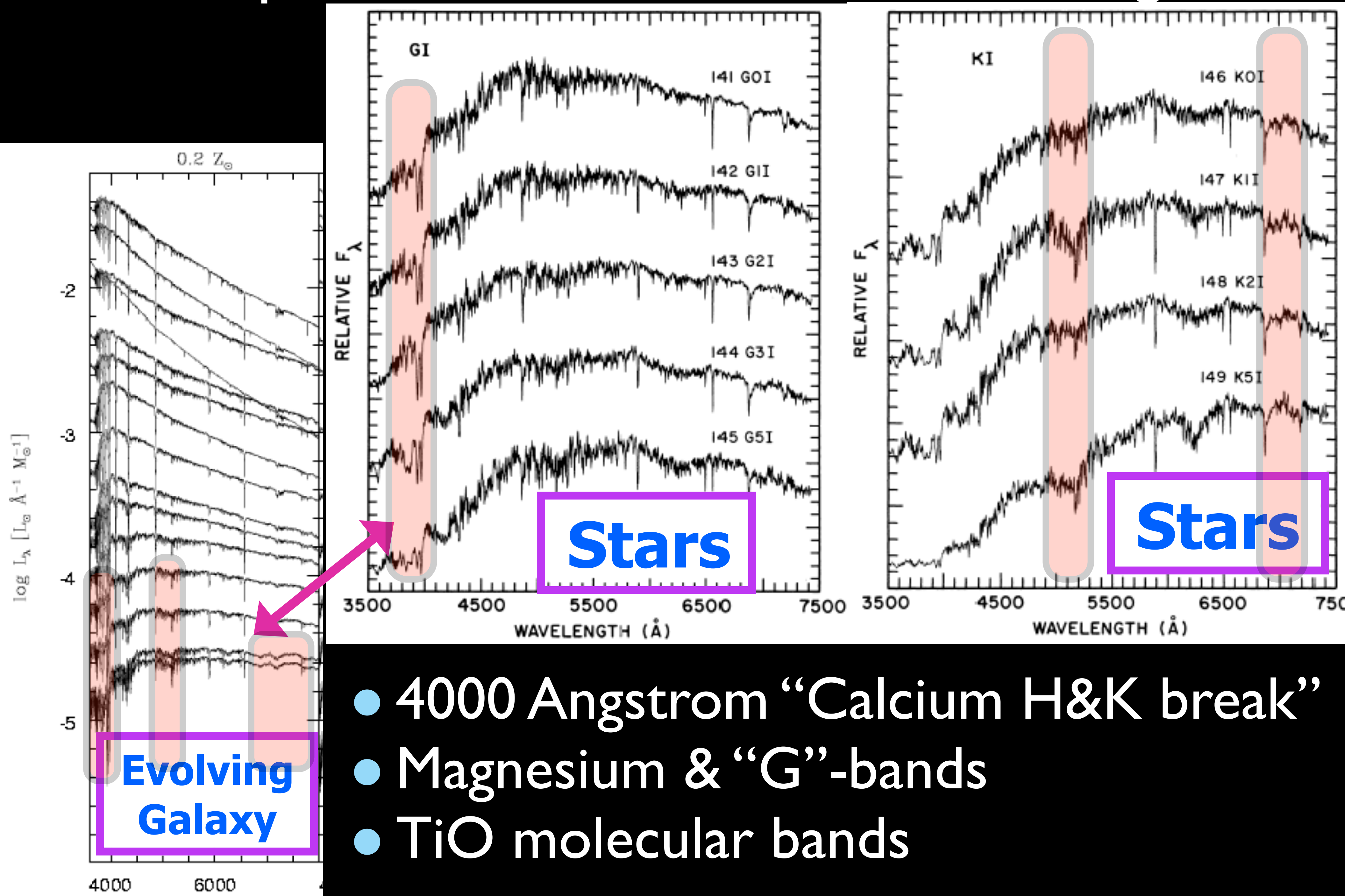






- Short-lived ($>1M_{\odot}$) main sequence stars have died off.
- Redder parts of the spectrum are dominated by redder stars

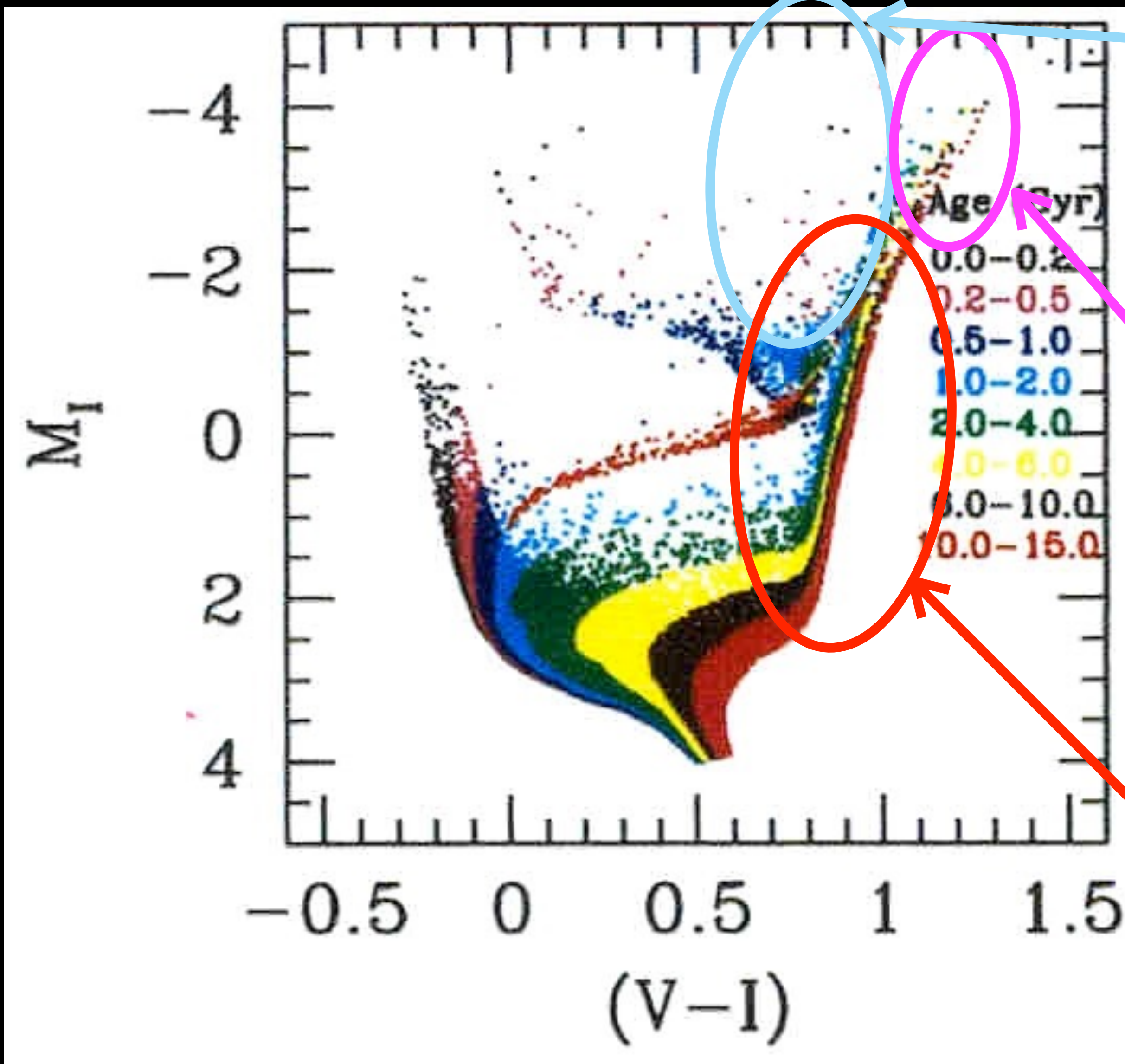
“Old” spectral features come from cool giants



- 4000 Angstrom “Calcium H&K break”
- Magnesium & “G”-bands
- TiO molecular bands

Near Infrared

NIR light is dominated by bright red stars



Massive red supergiants & red core He-burning stars

Intermediate mass asymptotic giant branch (AGB) stars

Older Red Giant Branch stars (RGB)

Near-IR Spectra: Few features, and few obvious differences among galaxy types

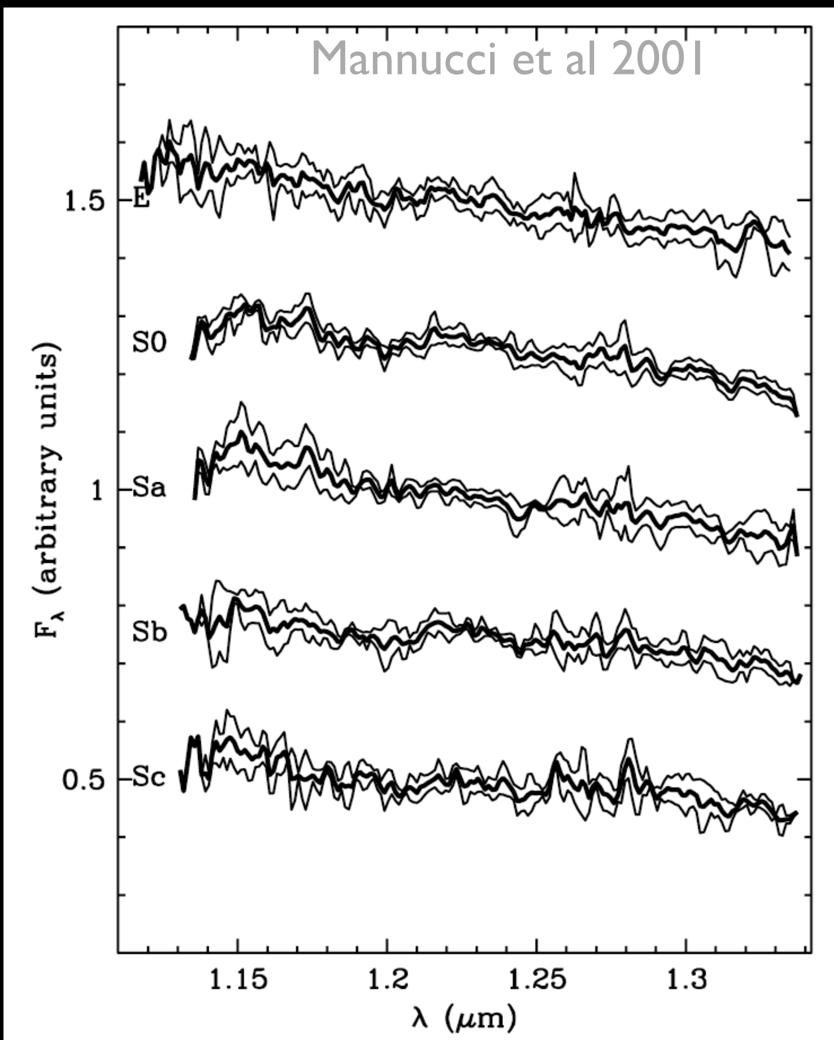


Figure 1. Rest frame average spectra of each class of galaxies in the *J* band. The thick line is the average of the observed spectra, and the thin lines show the ranges within 1 standard deviation. Arbitrary offsets were added to the spectra for clarity.

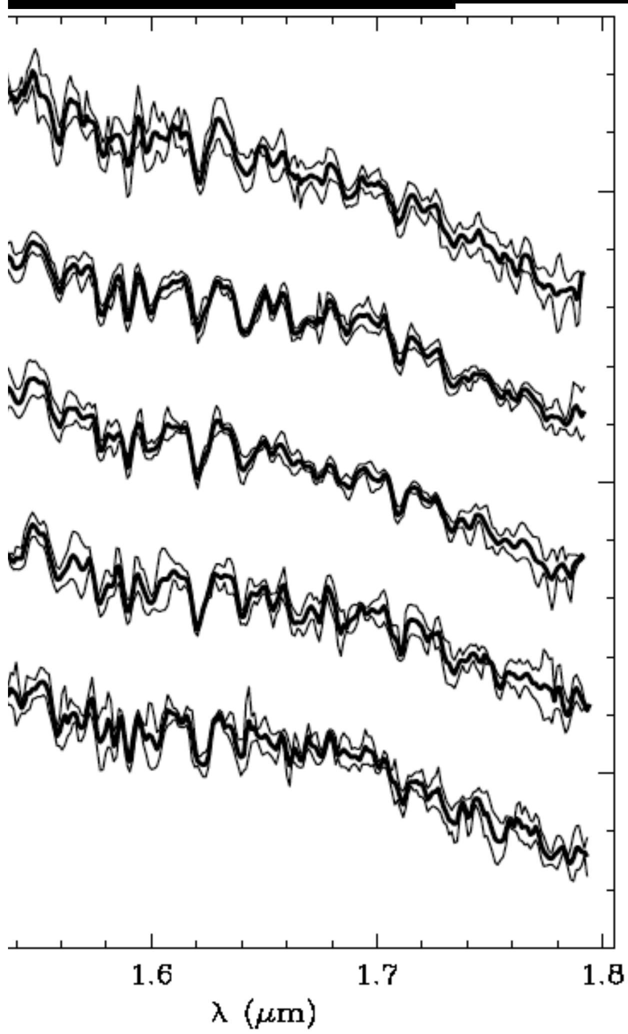


Figure 2. As Fig. 1, for the *H* band.

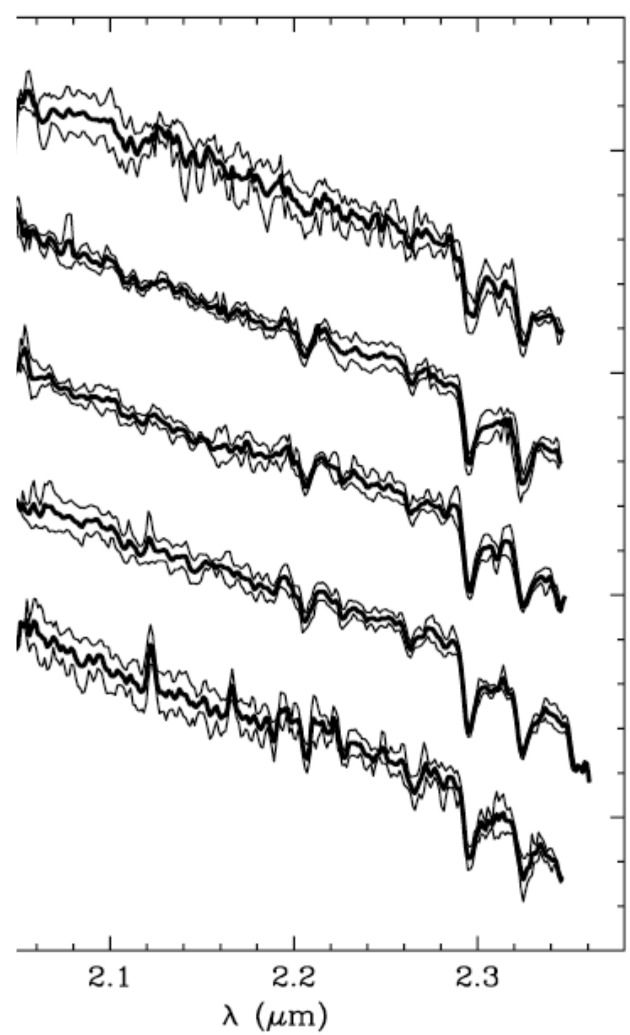
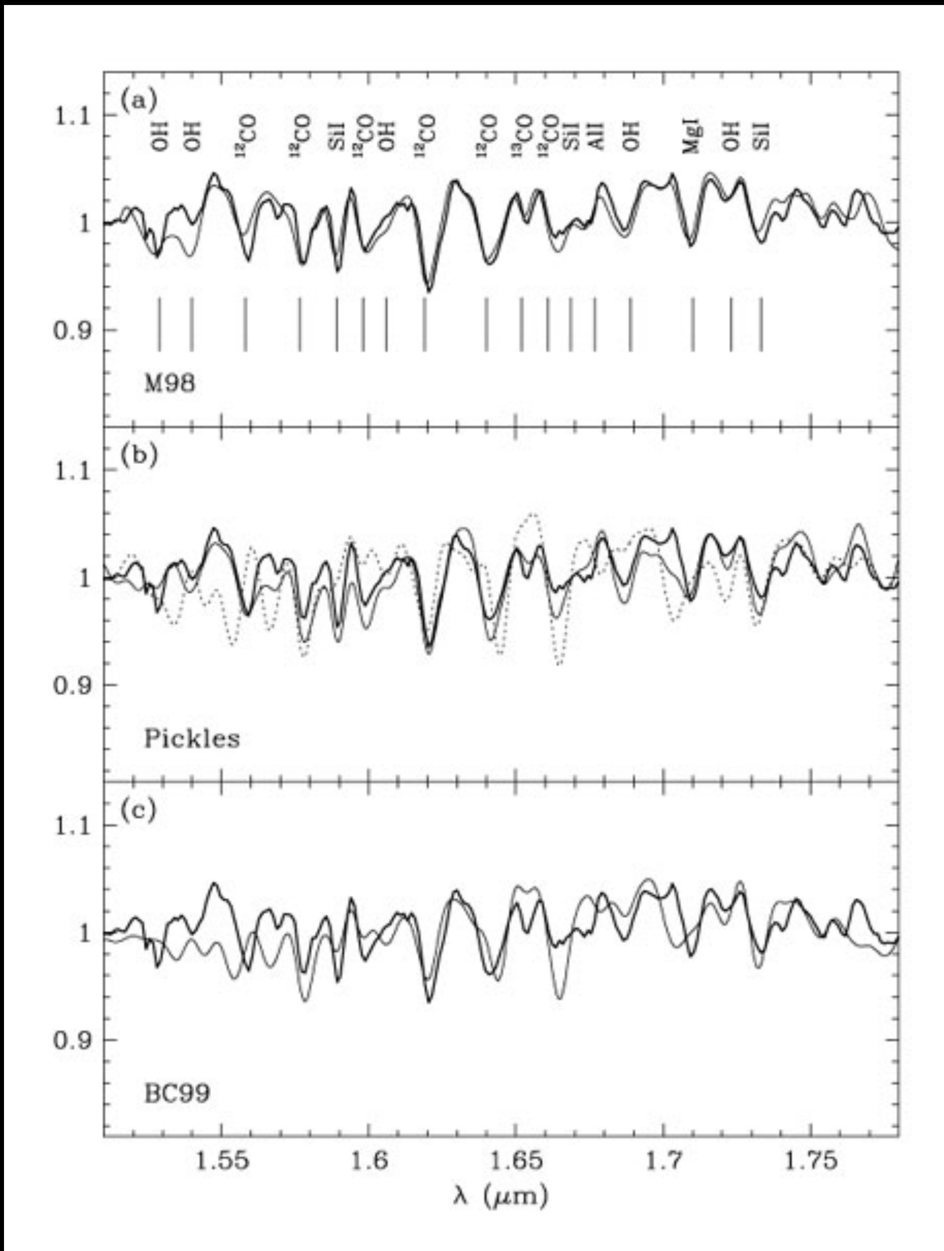


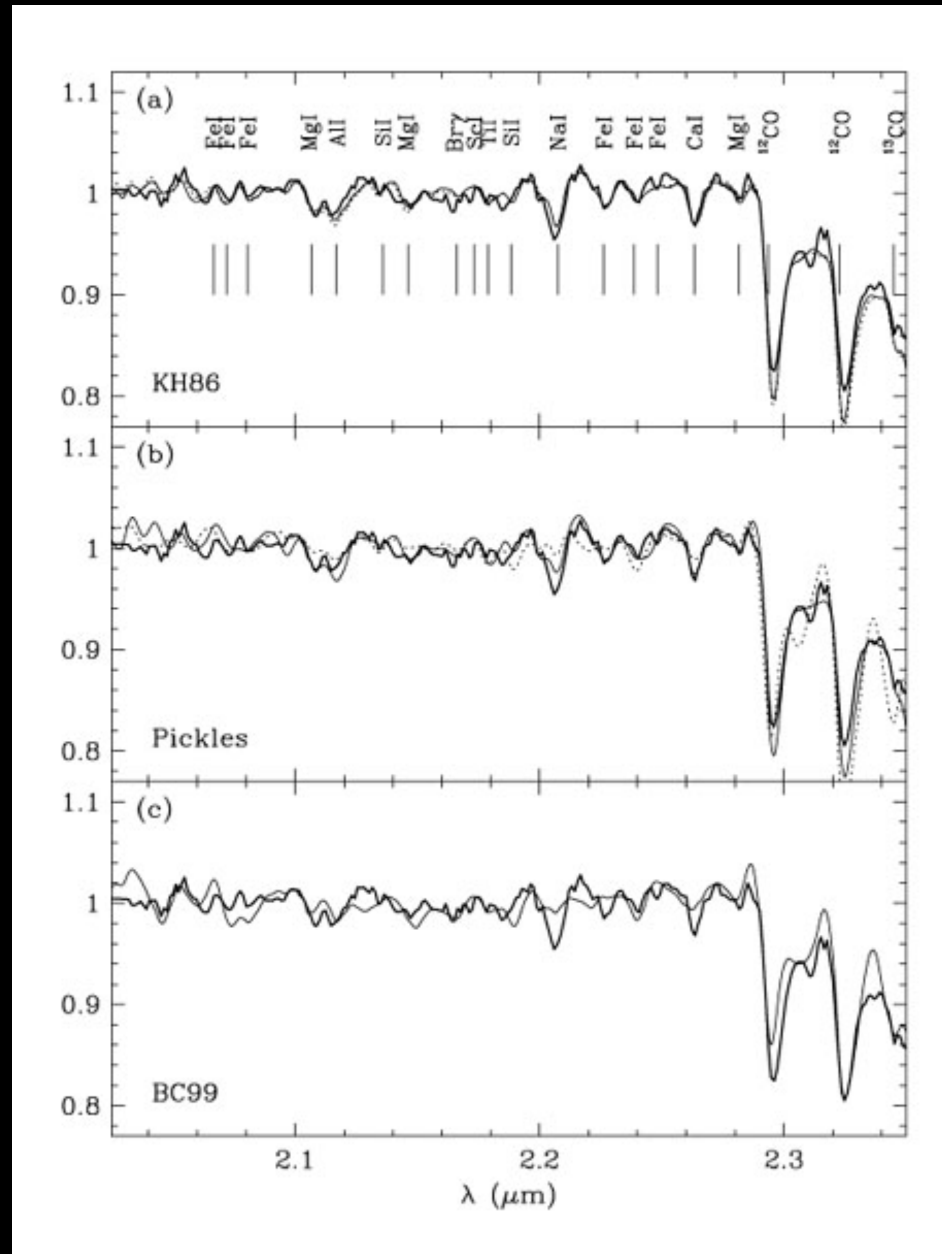
Figure 3. As Fig. 1, for the *K* band.

Pretty featureless in the UV too, except for absorption lines due to the ISM (until you get to Lyα); see Byler et al 2018

NIR absorption line IDs



H-band



K-band

Mannucci et al

Table 3. Feature identifications.

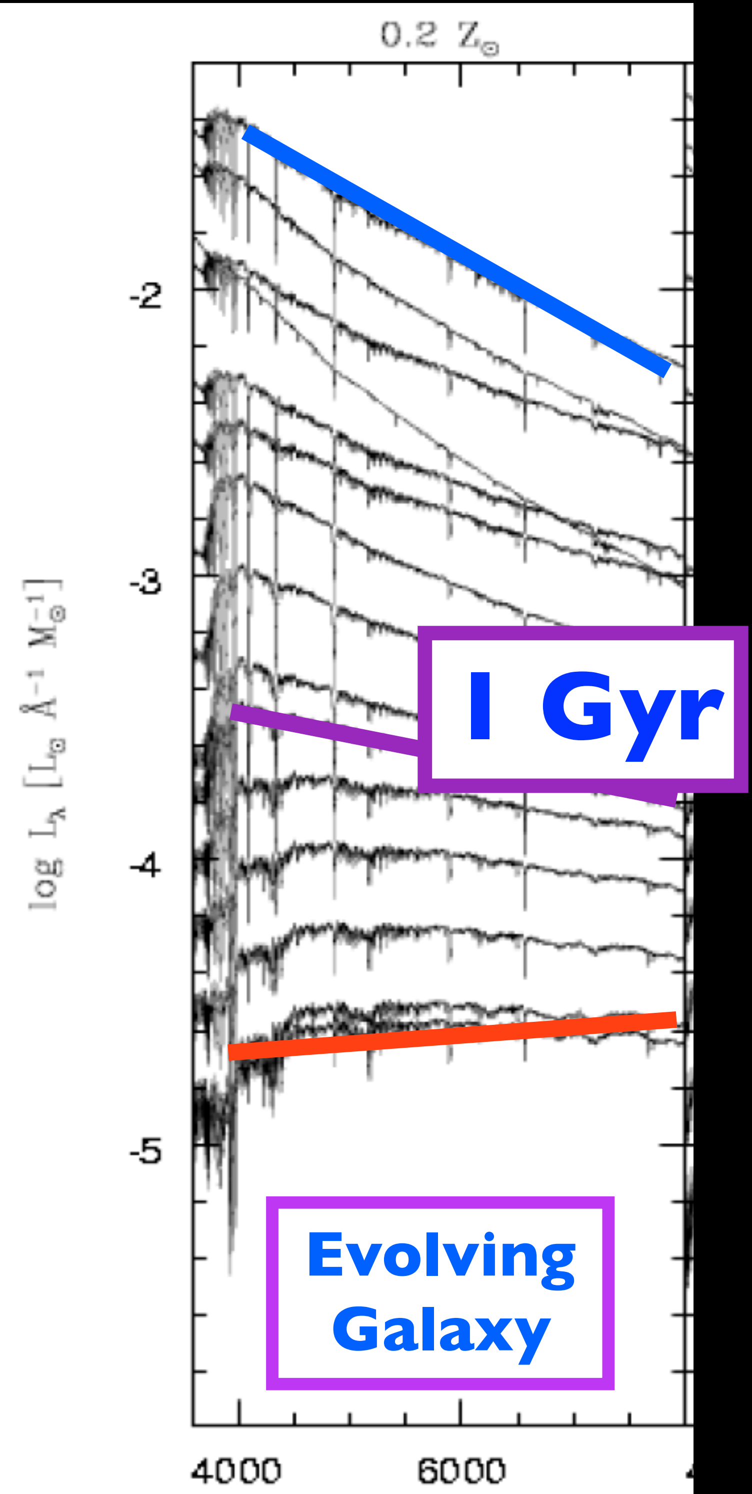
λ (μm)	Main contribution	Other species
1.529	OH	CN,TiI
1.540	OH	Si I
1.558	^{12}CO	OH
1.577	^{12}CO	Mg I,Fe I
1.589	Si I	OH
1.598	^{12}CO	Si I,^{13}CO
1.606	OH	
1.619	^{12}CO	OH,Ca I
1.640	^{12}CO	Si I,[Fe II]
1.652	^{13}CO	OH
1.661	^{12}CO	OH
1.669	Si I	OH
1.672	Al I	H I,^{12}CO
1.677	Al I	
1.689	OH	H I,CO
1.710	Mg I	CO,OH
1.723	OH	Si I
1.733	Si I	H I
2.067	Fe I	
2.072	Fe I	
2.081	Fe I	Si I
2.107	Mg I	H_2O,Si I
2.117	Al I	H_2,Mg I,Fe I
2.136	Si I	
2.146	Mg I	Na I,Si I,Ca II
2.166	Brγ	VI
2.173	ScI	Fe I
2.179	TiI	Si I,Fe I
2.189	Si I	TiI,Fe I
2.208	Na I	ScI,TiI,VI,Fe I,Si I
2.226	Fe I	ScI,TiI
2.239	Fe I	ScI
2.248	Fe I	VI,TiI
2.263	Ca I	ScI,TiI,Fe I,S I
2.281	MgI	Ca I,Fe I,S I,HF
2.294	^{12}CO	TiI
2.323	^{12}CO	
2.345	^{13}CO	

NIR absorption line IDs

- Spectrum dominated by cool stars
- Dominated by Molecules and Low Ionization Species

Ultraviolet

Basically, just O&B stars with many absorption lines from the ISM

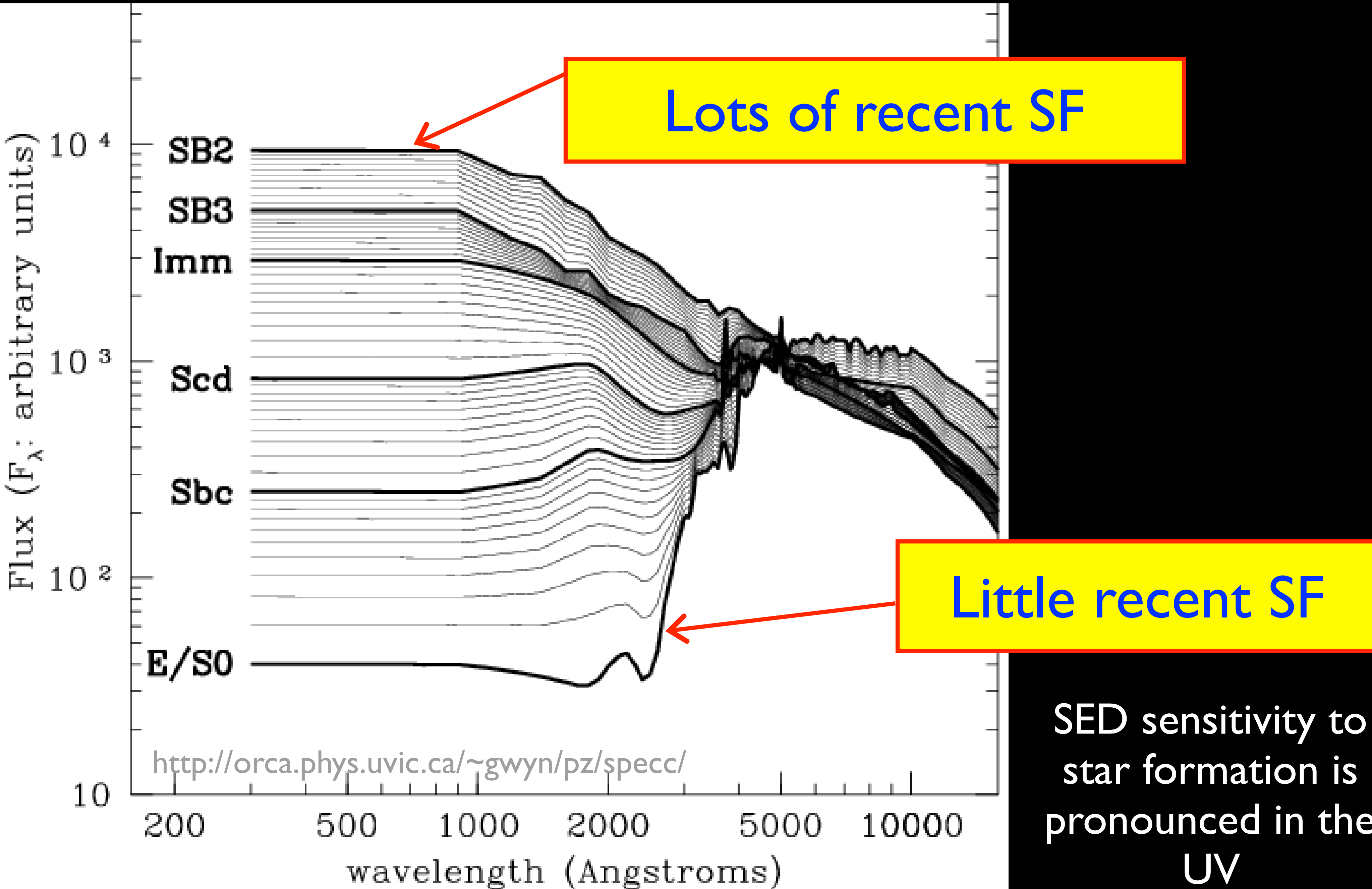


Take-away

- Bluer galaxies have a higher fraction of recent (<1Gyr) star formation
- But, "blue" does not necessarily mean "currently" forming stars
- Caution: Dust

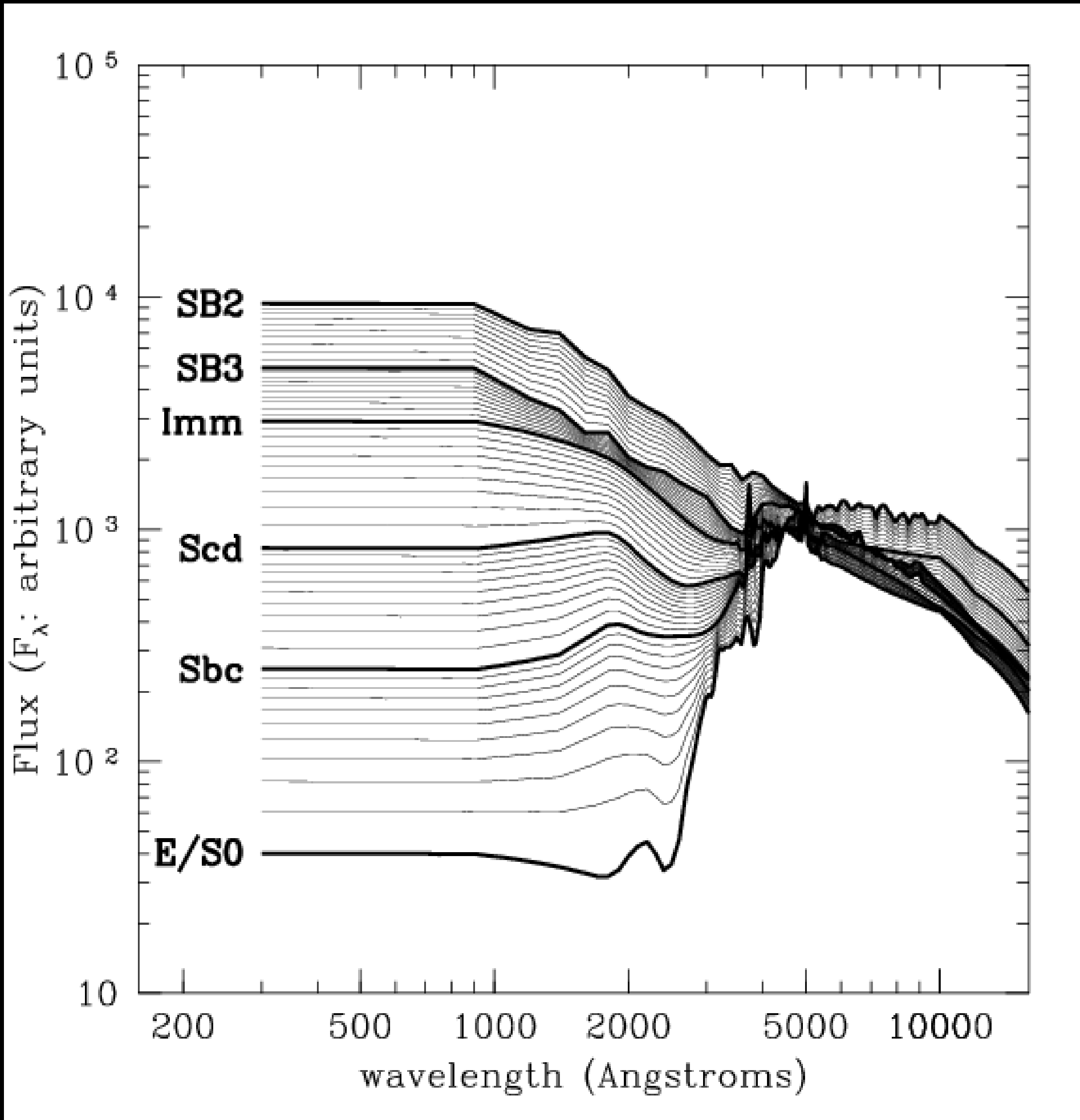
How do we model & interpret stellar light?

The overall SED is shaped by past star formation (SF)



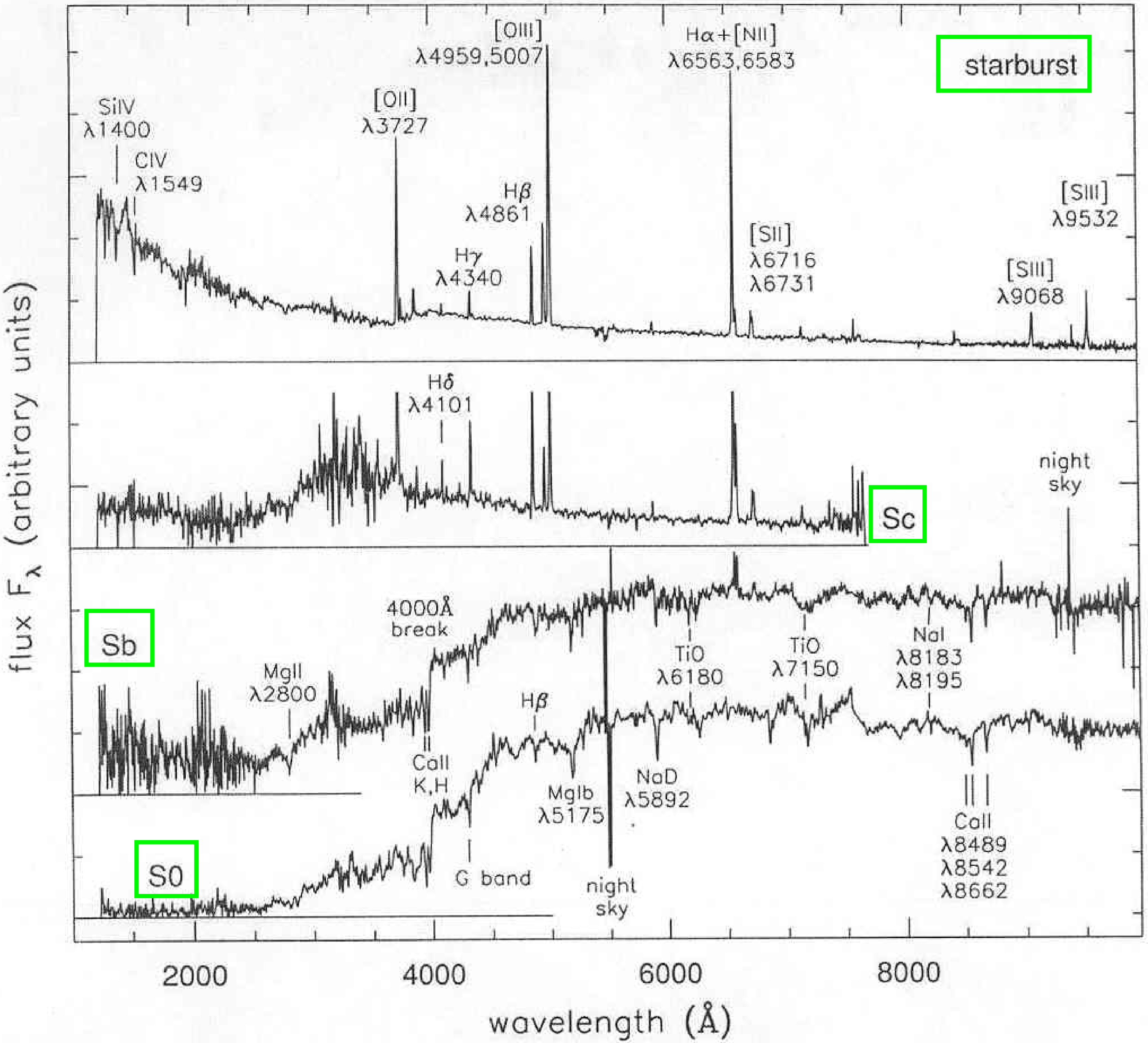
SED sensitivity to star formation is pronounced in the UV

Model the spectrum with "Stellar Population Synthesis"



Basis for essentially all estimates of extragalactic physical quantities

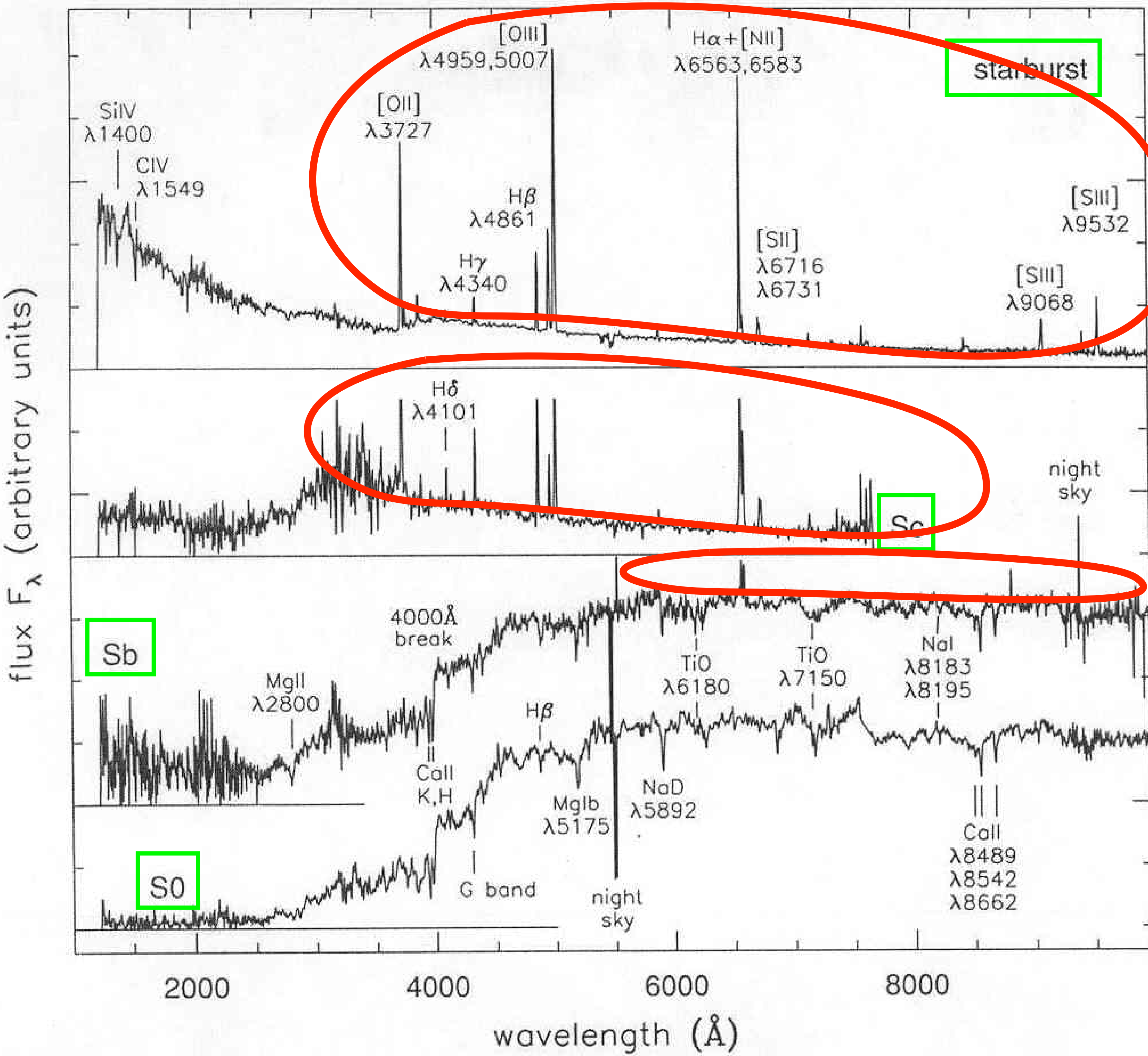
(e.g., stellar mass, age, metallicity, extinction, SFRs)



Observed Optical Galaxy Spectra

How do we make sense of this?

From Gallagher & Sparke's textbook

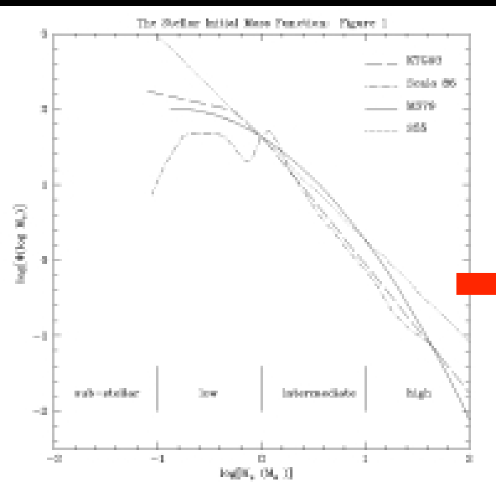


Emission lines are from HII regions, AGN, and/or shocks

For now, we're only considering the stellar contribution

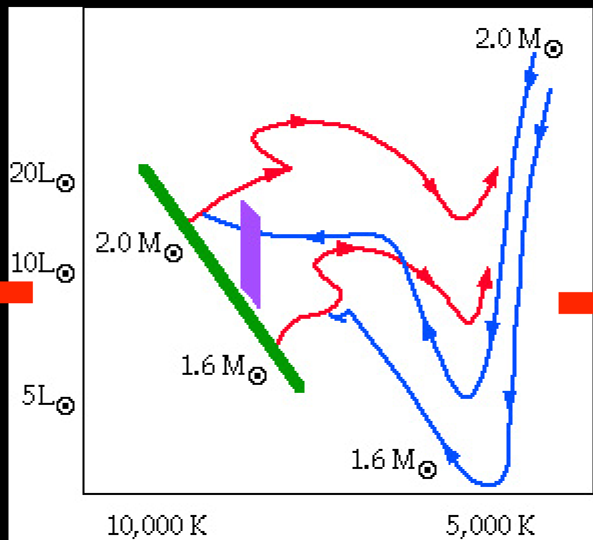
From Gallagher & Sparke's textbook

Stellar population synthesis:



"Initial Mass Function" (IMF)

+



Isochrones & Evolutionary tracks

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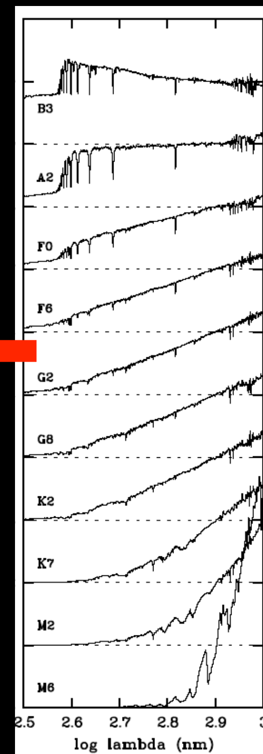

Libraries of Stellar Spectra and/or Model Atmospheres

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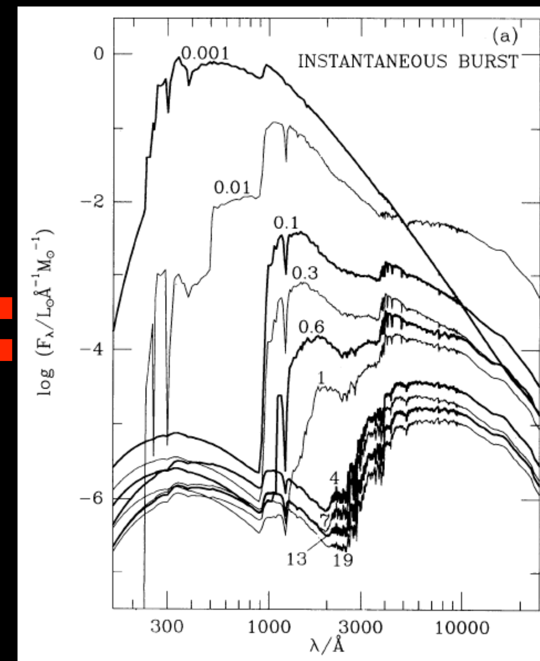
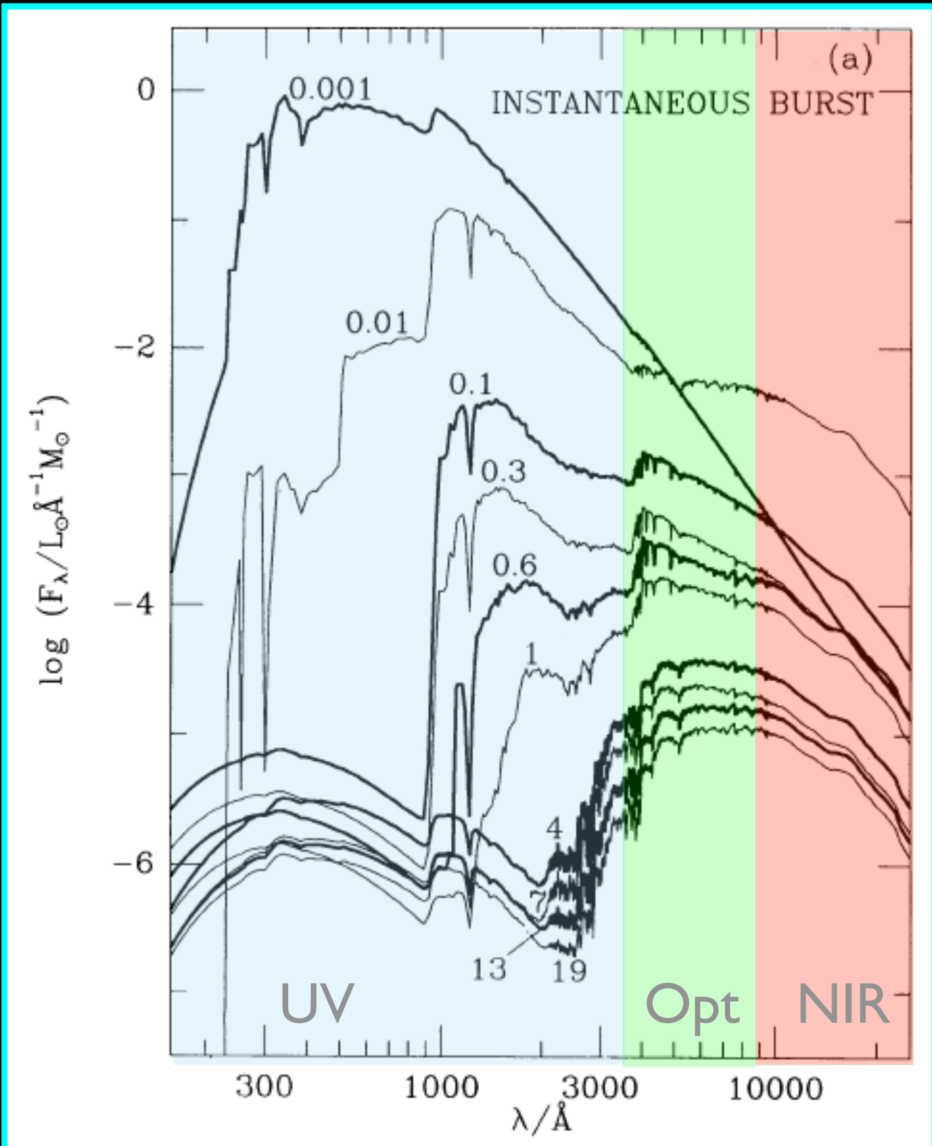


Spectral evolution of a single burst of SF

Arbitrary "star formation history" (SFH) can be built up by adding spectra for single bursts at appropriate ages

"SSP" = "single stellar population"

Instantaneous burst behavior



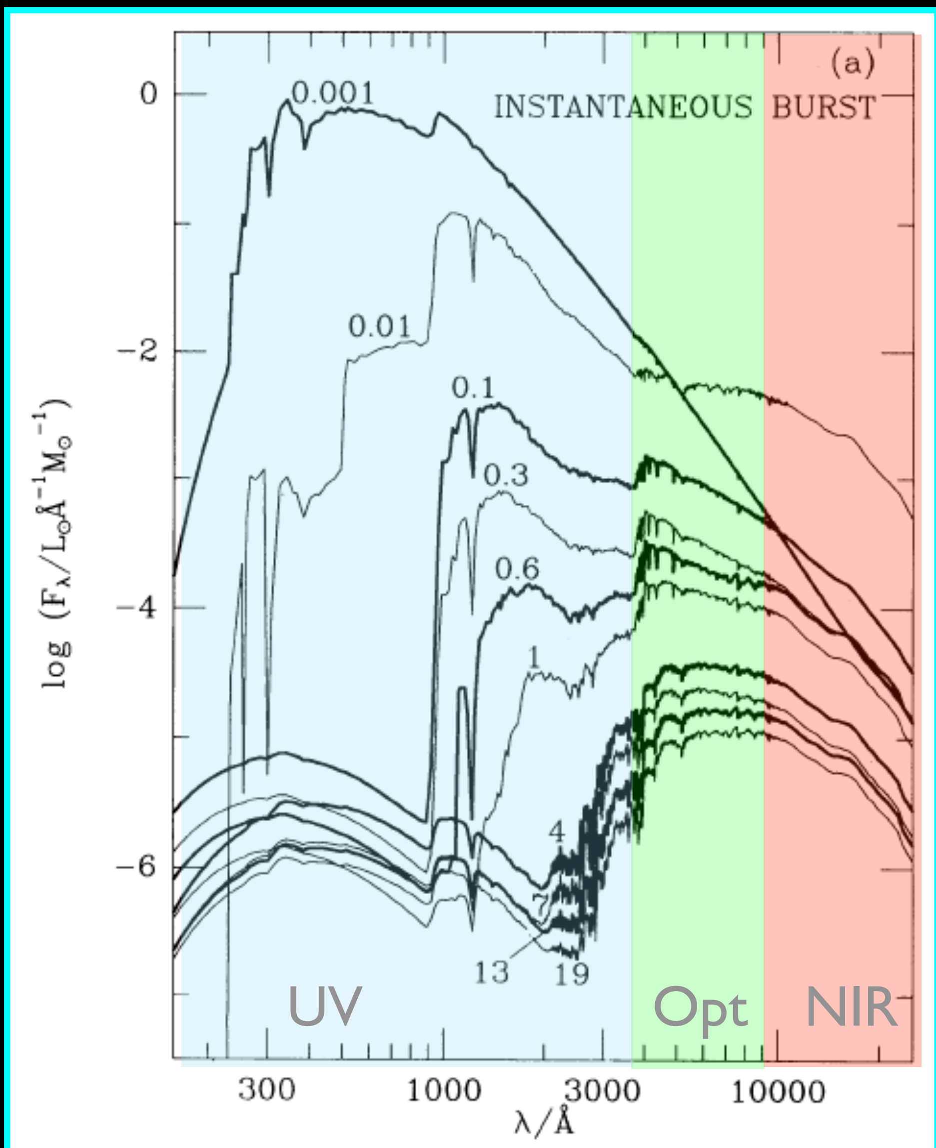
Bruzual & Charlot 1993

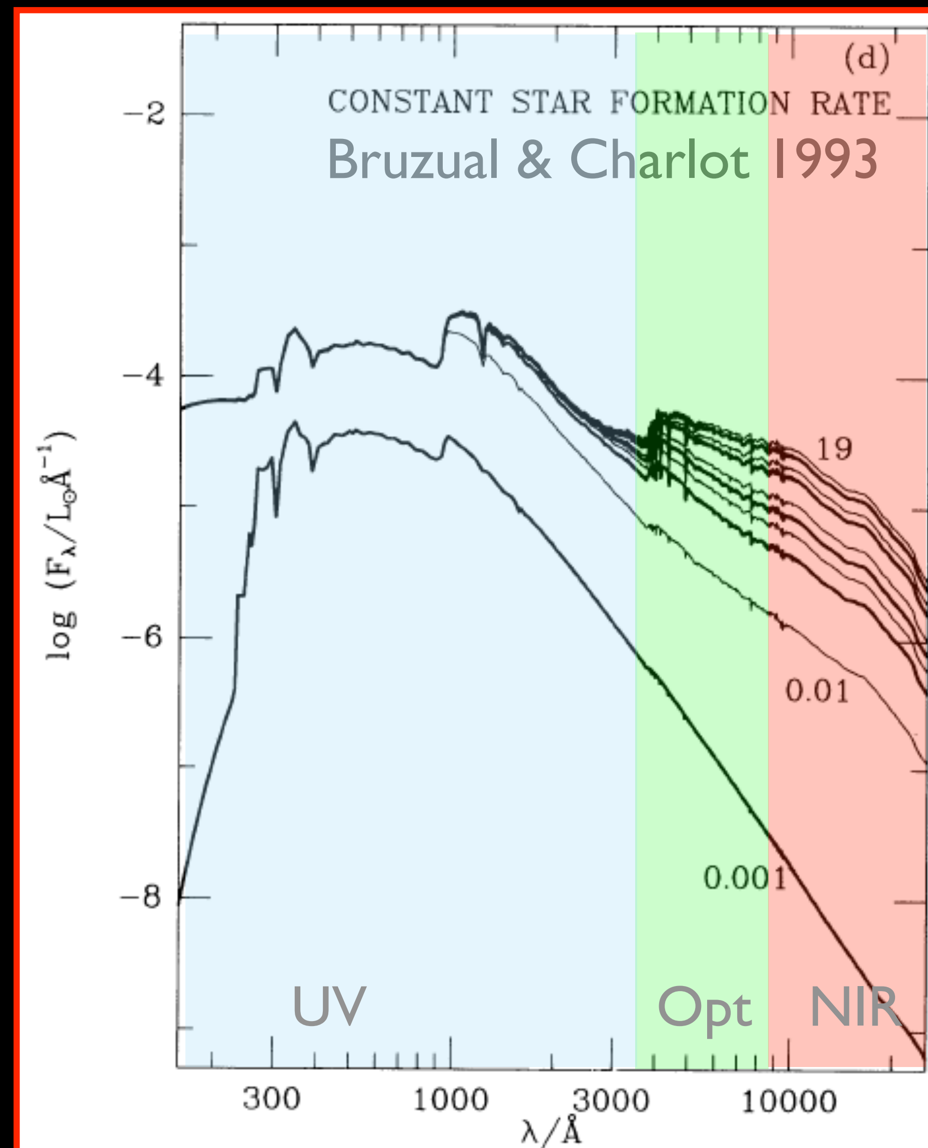
- Luminous at early times
- Fades and reddens at late times, as massive stars die
- Little spectral evolution after t>4 Gyr
- Young burst can swamp light from old stars

FIG. 4.—Spectral evolution of stellar populations with different star formation rates as predicted by the isochrone synthesis model: (*a*) instantaneous starburst; (*b*) eq. (2) with $\tau = 3$ Gyr; (*c*) eq. (2) with $\tau = 7$ Gyr; and (*d*) constant star formation. In each case, the age (in Gyr) is indicated next to the spectra. Thick lines and thin lines have been used alternatively for clarity. All models have the Salpeter IMF.

Instantaneous burst: brightens, then fades

Continuous SFR: constant UV spectra (O/B) + steady build up of red optical/NIR spectra (RGB)





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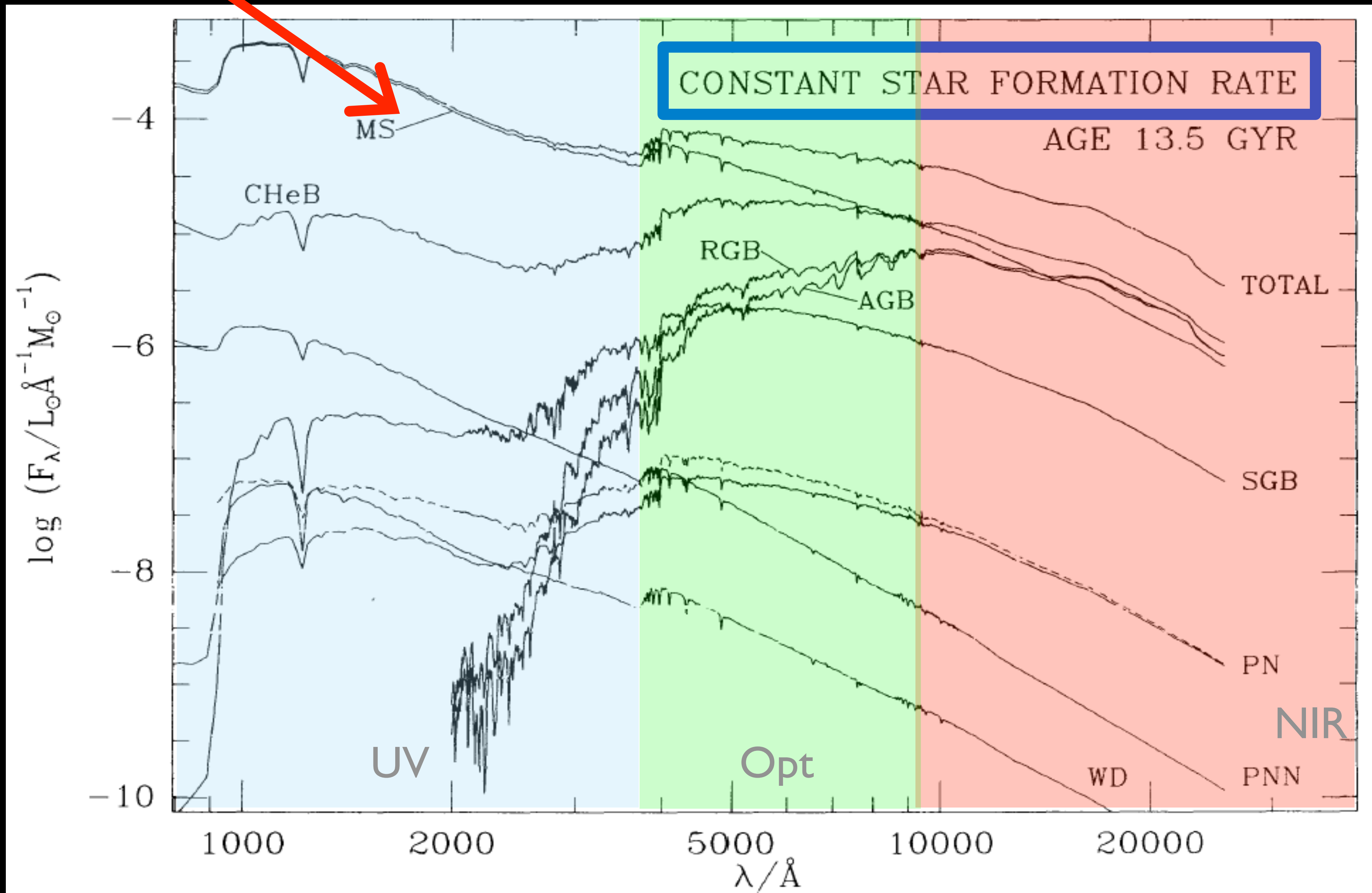
Main Sequence dominates UV/Opt



tellar population with constant star formation rate at age 13.5 Gyr

In Figure 9 we indicate the contributions to the total spectral energy distribution of the 1 Gyr burst model, at 13.5 Gyr, of stars in eight groups (the turnoff mass at 13 Gyr is about 0.85 $M_\odot$): main sequence (MS), subgiant branch (SGB), red giant branch (RGB), core He burning (CHeB), planetary nebula (PN), bare PN nucleus (PNN), and white dwarf (WD).

RGB stars dominate the NIR of old galaxies

AGB stars contribute more in NIR at younger ages (high z)

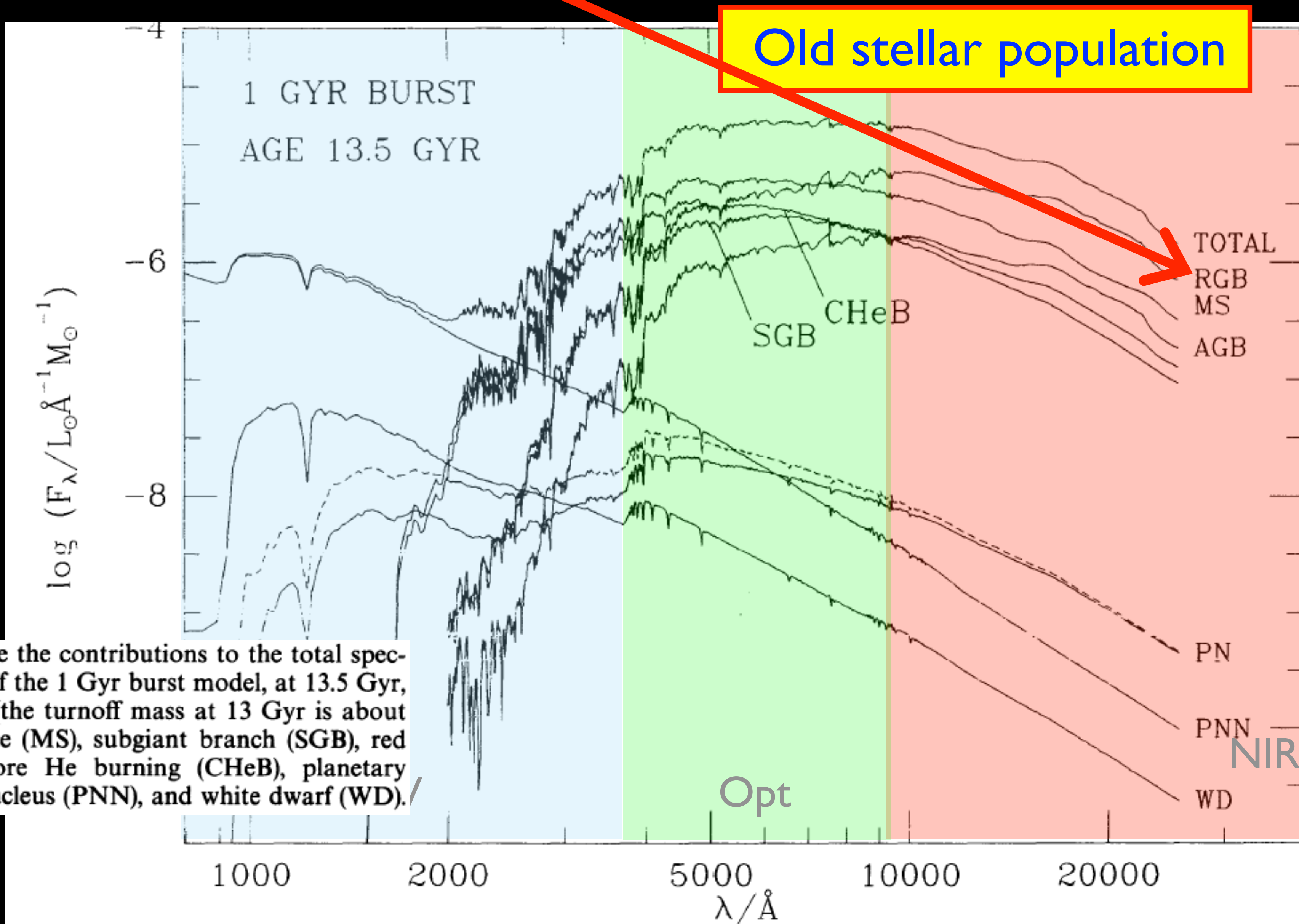


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FIG. 9.—Contribution of stars in different groups to the total spectral energy distribution of a 1 Gyr burst population with the Salpeter IMF at age 13.5 Gyr. The acronyms are defined in § 3.5. The dashed line next to the PN contribution corresponds to the case where extinction of the core radiation by the surrounding nebula is ignored. The vertical scale corresponds to a total mass in stars of 1 $M_\odot$.

SFH affects which stars dominate the spectrum

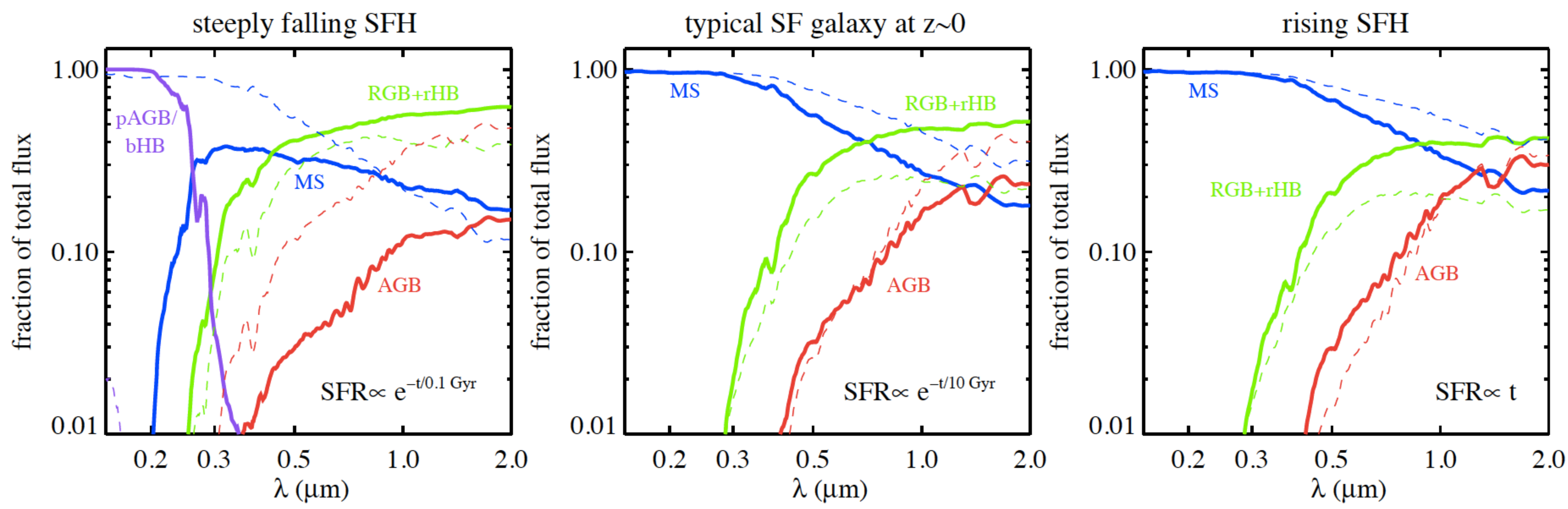
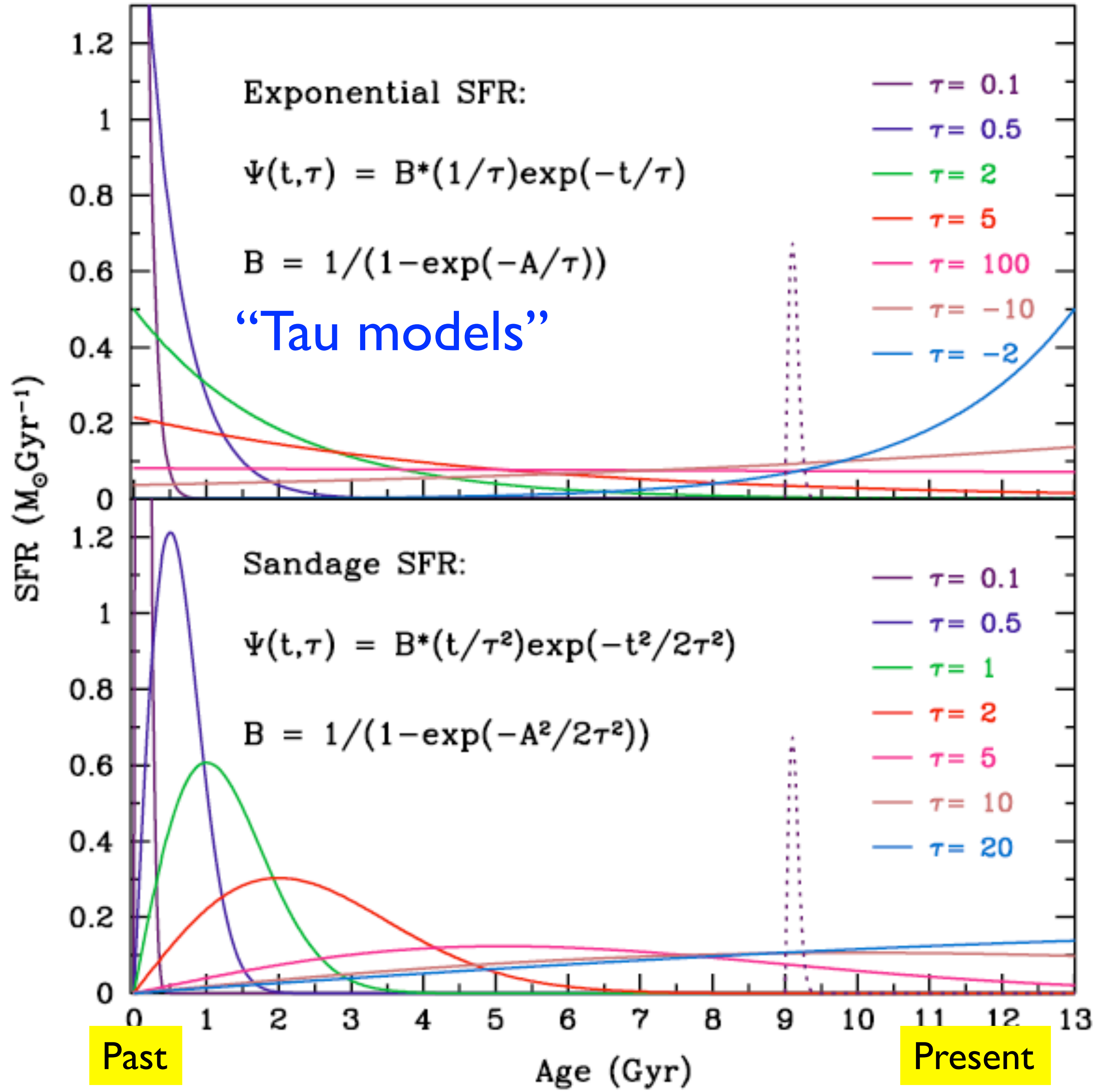


Figure 5:

Top Panels: Fractional contribution to the total flux from stars in various evolutionary phases, for three different SFHs. The left panel is representative of a galaxy that formed nearly all of its stars very rapidly at early times, the middle panel is representative of a typical star-forming galaxy at $z \sim 0$, and the right panel may be representative of the typical galaxy at high redshift. Flux contributions are at 13 Gyr (solid lines) and 1 Gyr (dashed lines) after the commencement of star formation; all models are solar metallicity, dust-free, and are from FSPS (v2.3; Conroy, Gunn & White 2009). Labeled phases include the main sequence (MS), red giant branch (RGB), asymptotic giant branch (AGB, including the TP-AGB), post-AGB (pAGB), and the blue and red horizontal branch (bHB and rHB). Bottom Left Panel: Fractional flux contributions for

Conroy et al, ARAA 2013

Typical (simplistic) SFHs assumed in stellar population synthesis models



A = age of the galaxy

MacArthur et al 2003

FIG. 4.—Time evolution for the exponential (eq. [6]) (*upper panel*) and Sandage (eq. [8]) (*lower panel*) star formation histories (*solid curves*). The dotted curve is a Sandage-style burst of star formation in which 10% of the total mass of stars are formed. See Fig. 7 for the effect of such a burst on the population model grids.

Stellar population synthesis (SPS):

Compilation: http://www.sedfitting.org/SED08/Models.html

- Many different publicly available codes:
  - *FSPS (Conroy)*
  - *GISSEL (Bruzual & Charlot)*
  - *PEGASE (Rocca-Volmerange)*
  - *STARBURST99 (Leitherer)*

If you will be doing *any* work with galaxies, it is worth learning to use one of these. FSPS is probably most python-friendly

- Various features can be added on:
  - *Metallicity evolution*
  - *Dust*
  - *Emission lines*

Stellar population synthesis limitations

- Quality of spectral libraries (not so good in NIR or extreme metallicities)
- Late-stage (post-main sequence) stellar evolution
- Cool stars

These are limitatations because they are intrinsically hard things to do.

Uncertainties in Ingredients:

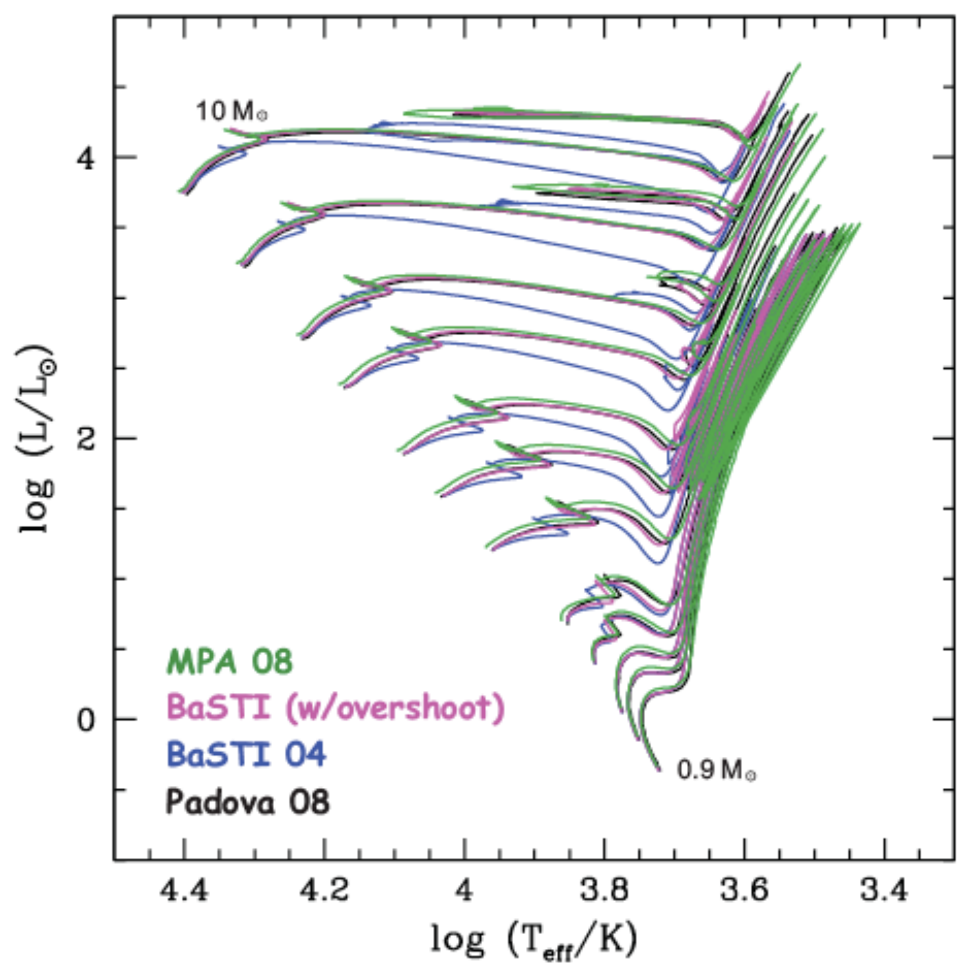


Fig. 1 Evolutionary tracks of solar composition low mass stars (0.9 - 10 $M_\odot$) demonstrating the differences between four different models (as labelled): MPA08 (Weiss and Schlattl 2008), BaSTI04 (with/without overshoot; Pietrinferni et al. 2009), and Padova08 (Marigo and Girardi 2007; Marigo et al. 2008) [Courtesy S. Charlot].

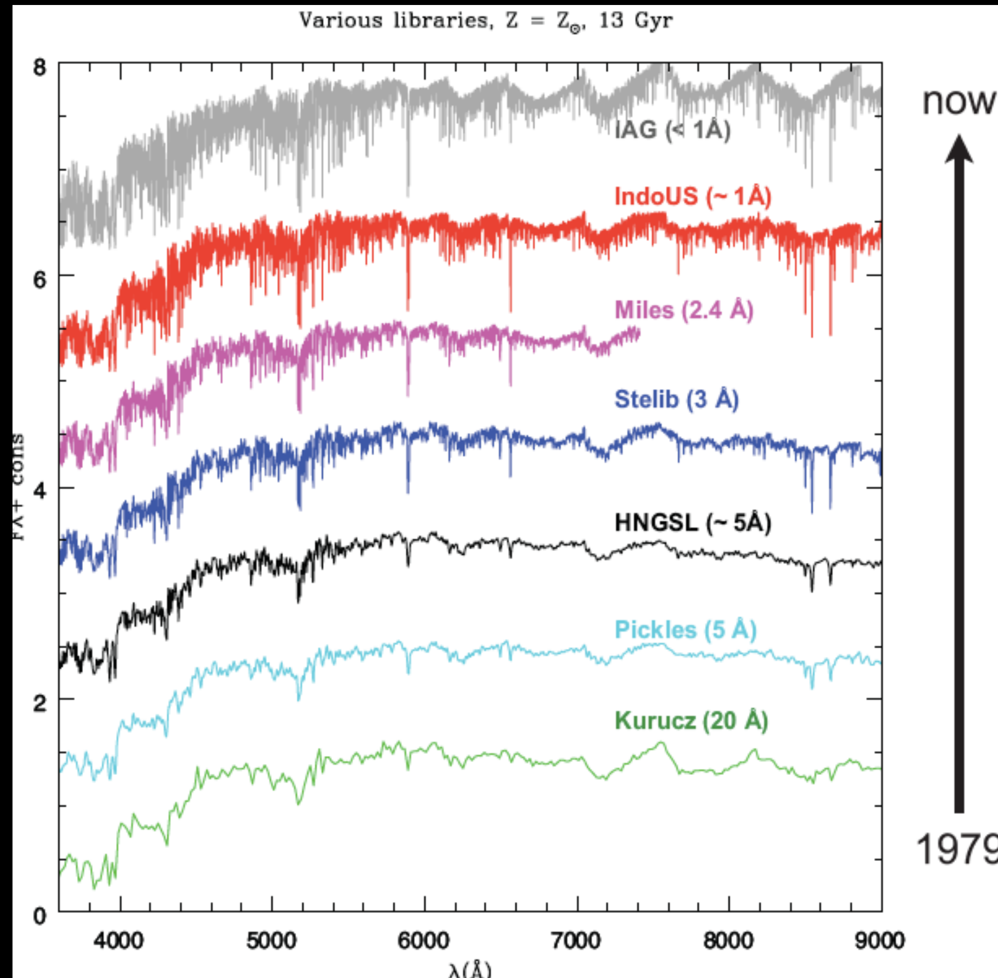


Fig. 2 Optical spectra from both theoretical and empirical stellar libraries (as labelled) demonstrating the improvement of spectral resolution over time with the associated improvement in library size [Courtesy S. Charlot].

See Conroy et al 2009, Conroy & Gunn 2010 for assessment of uncertainties

Nice Review of Synthesis Modeling: Walcher et al 2010

Two basic roles for SPS models

- Predict observable properties given star formation history, metallicity, etc.
- Infer fundamental properties (SFR, stellar mass, etc) from observed spectrum.

The latter can be highly degenerate

However, in the age of widespread spectra + multiwavelength data, using SPS for inference is unavoidable

(and better than most alternatives)

Degeneracies in SPS models

- Spectra are "light weighted", favoring young ages
- Old SSPs are faint and hard to detect
- Complex SFH's bias inference
- Higher SNR spectra, wide wavelength coverage all help
- Relative measures always better than absolute
- Summary: Be cautious if you need a factor of 2 rather than a factor of 10 level of accuracy!

Third, how do we use this knowledge for good?

1. Make Measurements of luminosity

Magnitudes are defined in "systems" *relative* to some standard which defines m=0

The apparent magnitude m_R of the source is related to its spectral density of flux $f_\nu(\nu)$ (energy per unit time per unit area per unit frequency) by

Hogg et al 2002; astro-ph/0210394

$$m_R = -2.5\,\log_{10}\left[\frac{\displaystyle\int \frac{\mathrm{d}\nu_o}{\nu_o}\,f_\nu(\nu_o)\,R(\nu_o)}{\displaystyle\int \frac{\mathrm{d}\nu_o}{\nu_o}\,g_\nu^R(\nu_o)\,R(\nu_o)}\right] \quad , \tag{4}$$

where the integrals are over the observed frequencies ν_o; $g_\nu^R(\nu)$ is the spectral density of flux for the zero-magnitude or "standard" source, which, for Vega-relative magnitudes, is Vega (or perhaps a weighted sum of a certain set of A0 stars), and, for AB magnitudes (Oke & Gunn 1983), is a hypothetical constant source with $g_\nu^{\mathrm{AB}}(\nu) = 3631$ Jy (where 1 Jy $= 10^{-26}\ \mathrm{W\,m^{-2}\,Hz^{-1}} = 10^{-23}\ \mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}}$) at all frequencies ν; and $R(\nu)$ describes the bandpass, as follows:

- Canonical standard is Vega, an A-star (m=0,*color*=0)
- Negative colors = "bluer than A-star"
- Other standards possible
  - G-stars = typical of galaxy spectra
  - Flat spectrum = "AB Magnitudes"

Definition of AB Magnitudes: Measured relative to a flat-spectrum source with a constant flux at all frequencies

We refer throughout this paper to AB magnitudes, first defined by Oke & Gunn (1983) to measure the ratio of the number of photons included in the signal of the detector relative to that number for a flat spectrum source with $g(\nu) = 3.631 \times 10^{-20}$ ergs cm^{-2} s^{-1} Hz^{-1}. For a source with a spectrum $f(\nu)$ the AB magnitude should be (for a perfectly calibrated AB system)

Blanton et al 2003

$$\begin{aligned} m_{AB} &= -2.41 - 2.5\log_{10}\left[\frac{\int_0^\infty d\lambda \lambda f(\lambda) R(\lambda)}{\int_0^\infty d\lambda \lambda^{-1} R(\lambda)}\right] \\ &= -48.60 - 2.5\log_{10}\left[\frac{\int_0^\infty d\nu \nu^{-1} f(\nu) R(\nu)}{\int_0^\infty d\nu \nu^{-1} R(\nu)}\right], \end{aligned} \quad (2)$$

where $R(\lambda)$ is the fraction of photons entering the Earth's atmosphere which are included in the signal as a function of wavelength (a unitless quantity). Note that $R(\lambda)$ can be defined even for devices which do not count photons directly (such as bolometers). This equation is written such that $f(\lambda)$ is in units of ergs cm^{-2} s^{-1} Å^{-1} and $f(\nu)$ is in units of ergs cm^{-2} s^{-1} Hz^{-1}, while λ is expressed in Å and ν is expressed in Hz. The normalizations defined here mean that an object with $f(\nu) = g(\nu) = 3631$ Jy $= 3.631 \times 10^{-20}$ ergs cm^{-2} s^{-1} Hz^{-1} has all its AB magnitudes equal to zero. The λ^{-1} appears in the integrand of the denominator of the first equation because $g(\lambda) = c/\lambda^2$ for a "flat spectrum" source with $g(\nu) = 1$. The difference in the zeropoints of the two equations simply corresponds to the factor of the speed of light c (expressed in Å s^{-1}) in that expression for $g(\lambda)$.

Skips needing to characterize Vega

Galaxy Luminosity

- More complicated than stars.
- Must define area of flux measurement
  - Fixed aperture (3", 1', etc)
  - Scaled aperture (4 scale lengths, etc)
  - Isophotal aperture (flux within $\mu_{\rm lim}$)
- Differences between these can be substantial and important.

Surface Brightness vs Luminosity:

$$L(<r) = \int_0^r \Sigma(r) 2\pi r dr$$

Total Luminosity:

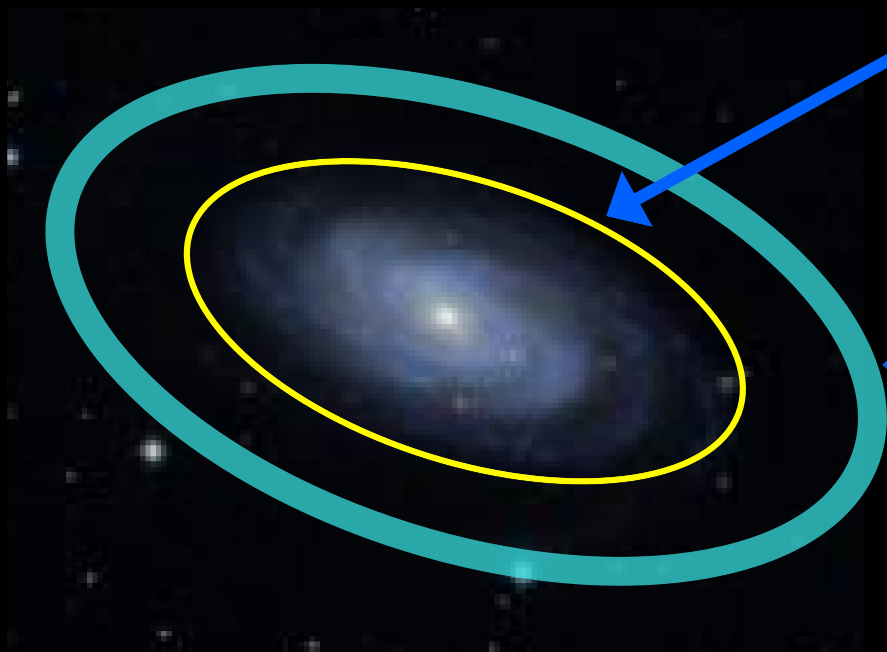
$$L_{tot} = L(<r \to \infty) = \boxed{2\pi\Sigma_0 h_r^2}$$

For an exponential disk with scale length h_r, central sb Σ_0

"Half-light radius": $r_{1/2}$ or r_e

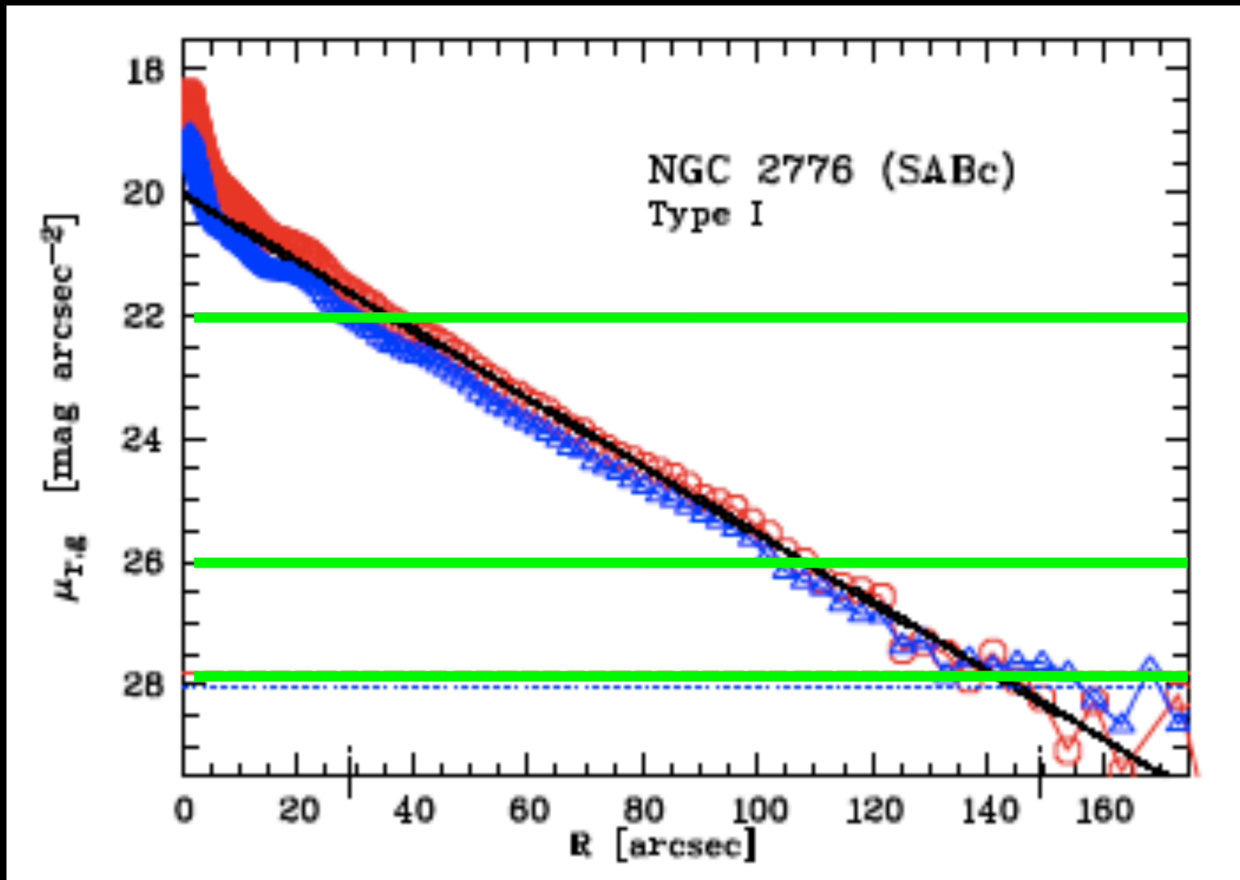
$$L(<r_{1/2}) = \int_0^{r_{1/2}} \Sigma(r) 2\pi r dr = \frac{1}{2}\int_0^{\infty} \Sigma(r) 2\pi r dr$$

Measuring fluxes of extended objects



- Pick some aperture.
- Measure the flux within the aperture
- Estimate the sky from a region outside the aperture.
- Subtract the sky from the aperture

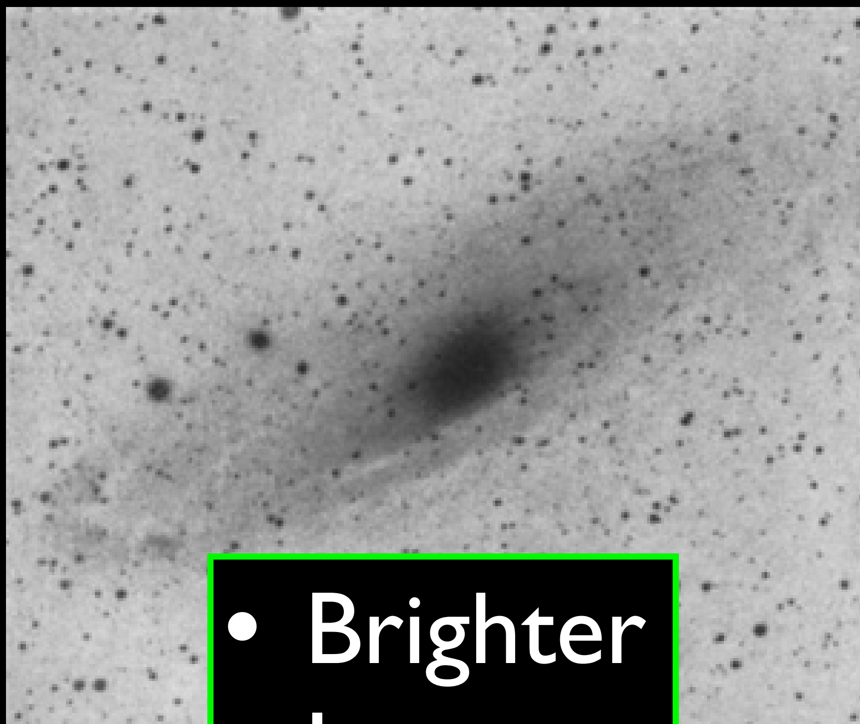
Measured Luminosity ≠ Total Luminosity!

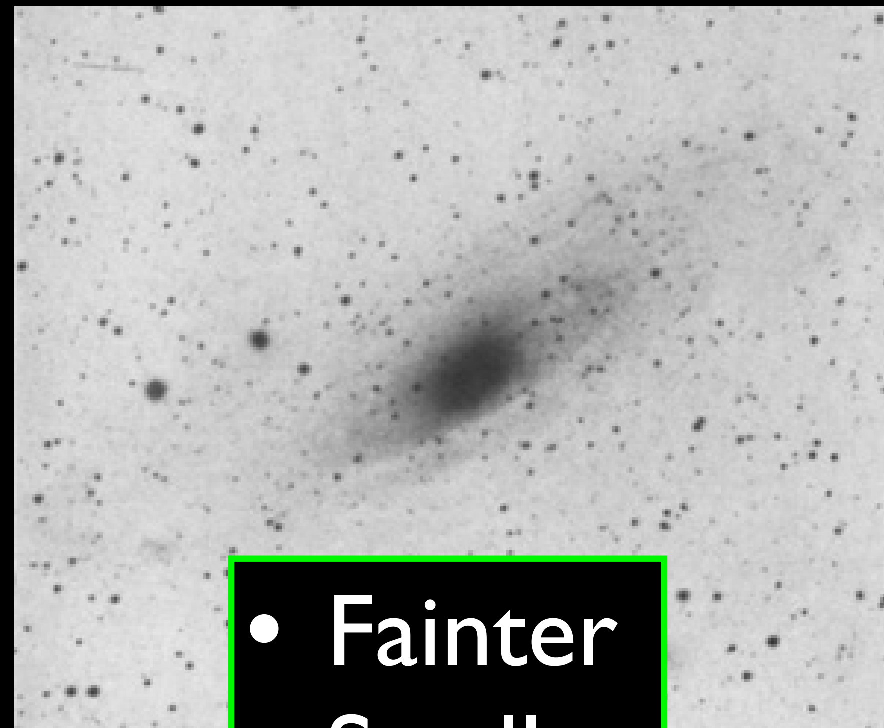


Possible limiting isophotes

Can only measure light that falls above the "limiting isophote"
(set by noise+systematics of background)

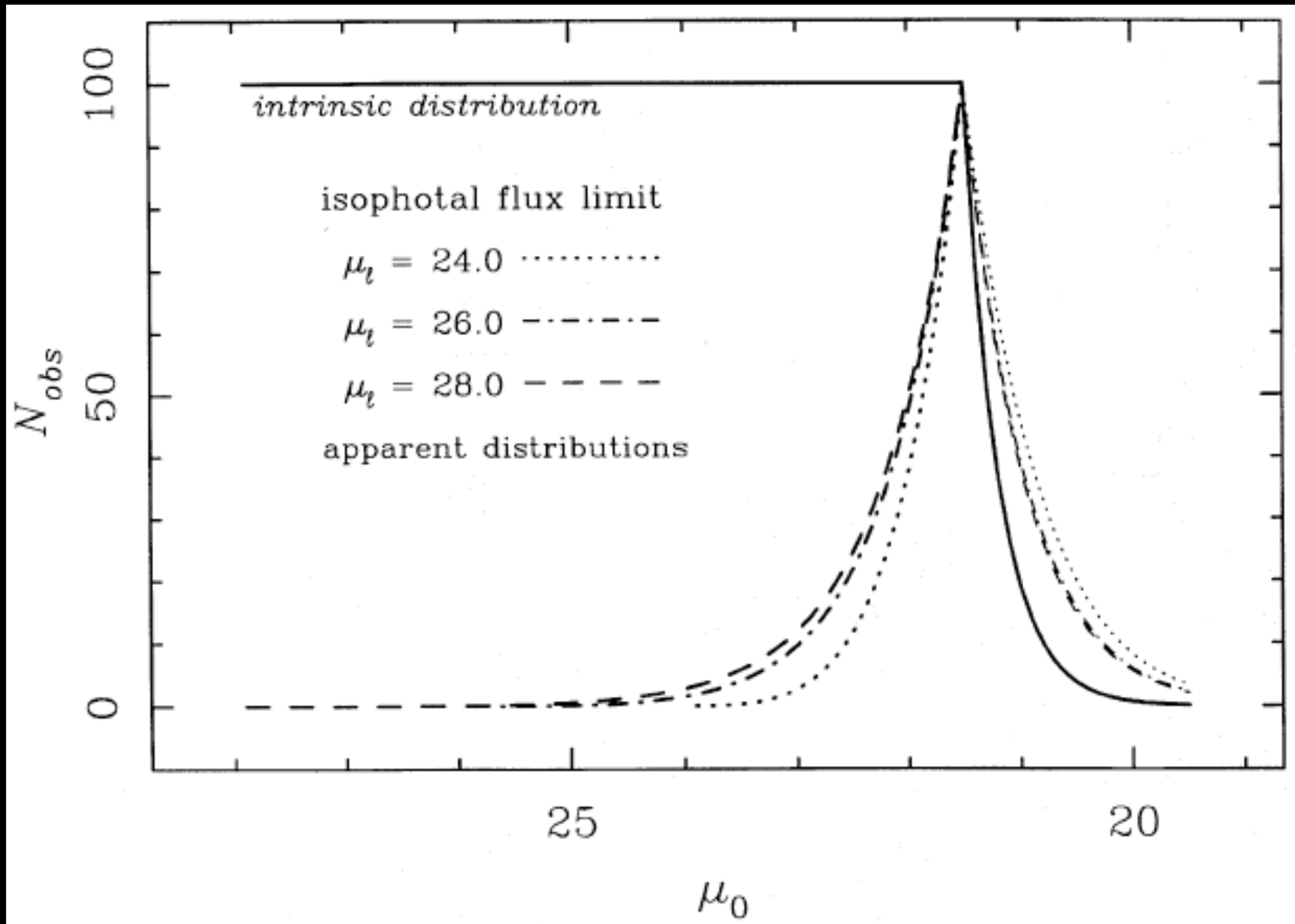
Luminosity & size affected by sky noise relative to surface brightness





"Selection Bias": lower surface brightness galaxies (LSBs) are underrepresented in catalogs of galaxies (defined as larger than or brighter than some limit).

Bias against low surface brightness disks



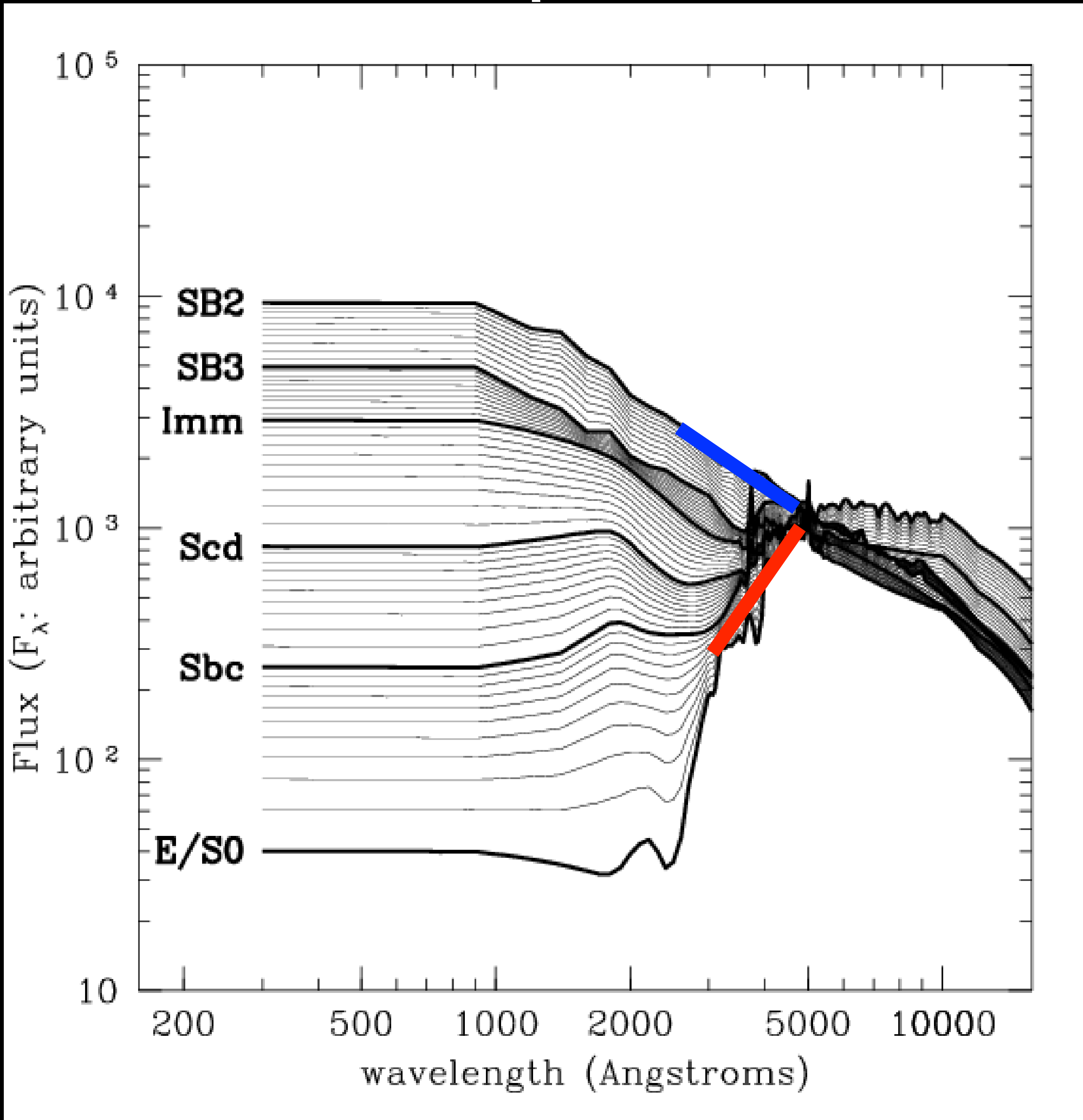
This *apparent* peak was first noted by Freeman (1970), and is known as the "Freeman Law" or "Freeman surface brightness" of 21.7 B-mag/sqr-arcsec. Disney (1976) pointed out that the apparent constancy of disk surface brightnesses could instead be a "selection effect"

Standard Photometric Apertures

- Within a fixed angular size (3” typical)
  - but, fraction of detected flux varies with distance
- Within a limiting isophotal surface brightness
  - but, fraction of detected flux varies with surface brightness
- Within a multiple of an isophotal surface brightness or 1st moment radius [e.g. “Kron (1980) magnitudes” -- “growing” the aperture]
  - better, but still surface brightness dependent
- Within a “metric” aperture [e.g. a fixed number of scale lengths, Petrosian (1976) magnitudes, etc]
  - best, but harder to measure

2. Measure colors, making smart choices about filters

"Color" = shorthand for relative flux between two bandpasses *(because difference between logs is log of a ratio)*

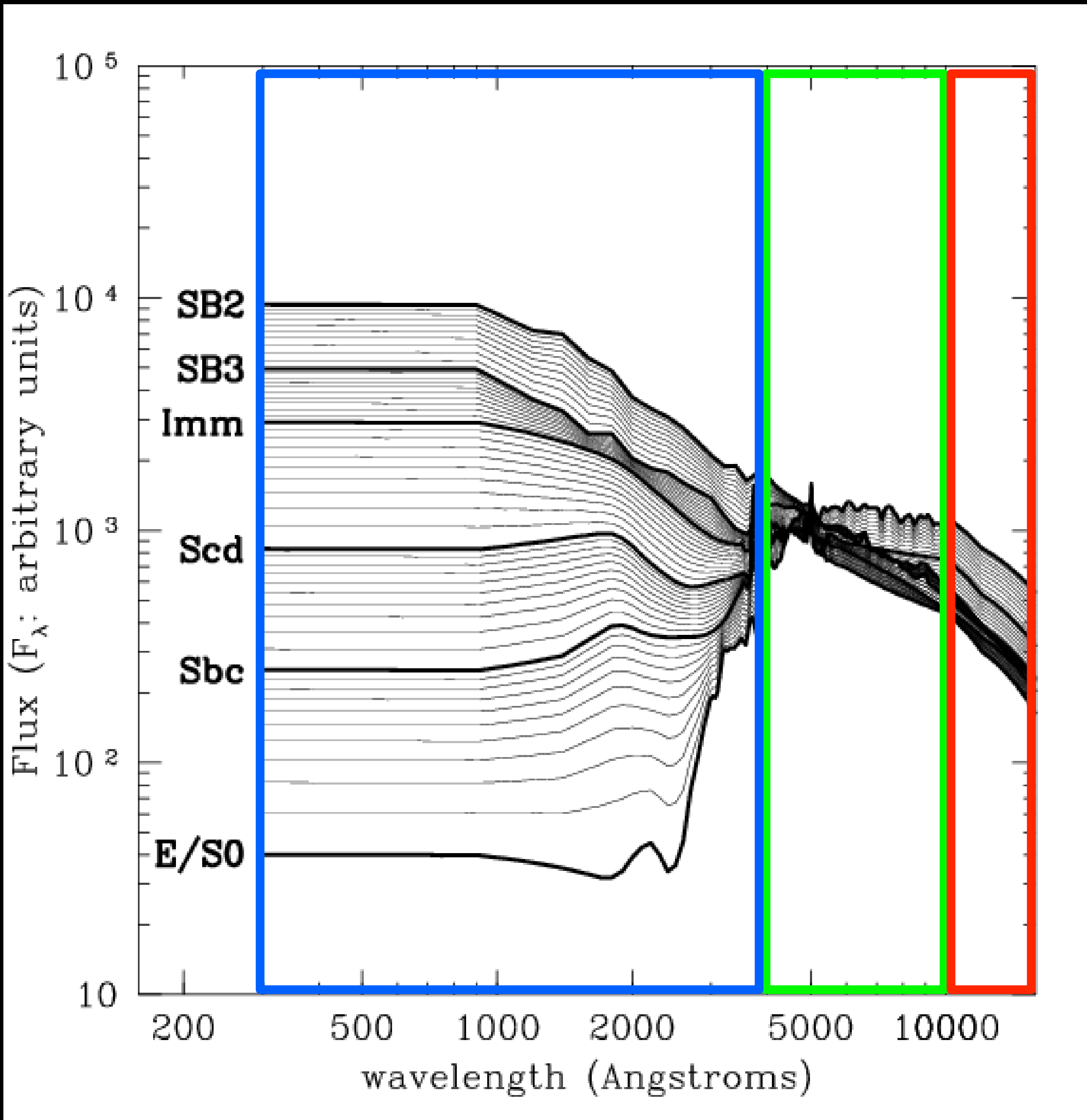


Blue: spectrum rises towards short wavelengths*

Red: Spectrum rises towards long wavelengths*

**Relative* to some reference spectrum, so colors<0 means "bluer than reference spectrum"

Colors constrain underlying spectrum



- Wider color baseline = more sensitivity
- UV, NIR add significant leverage

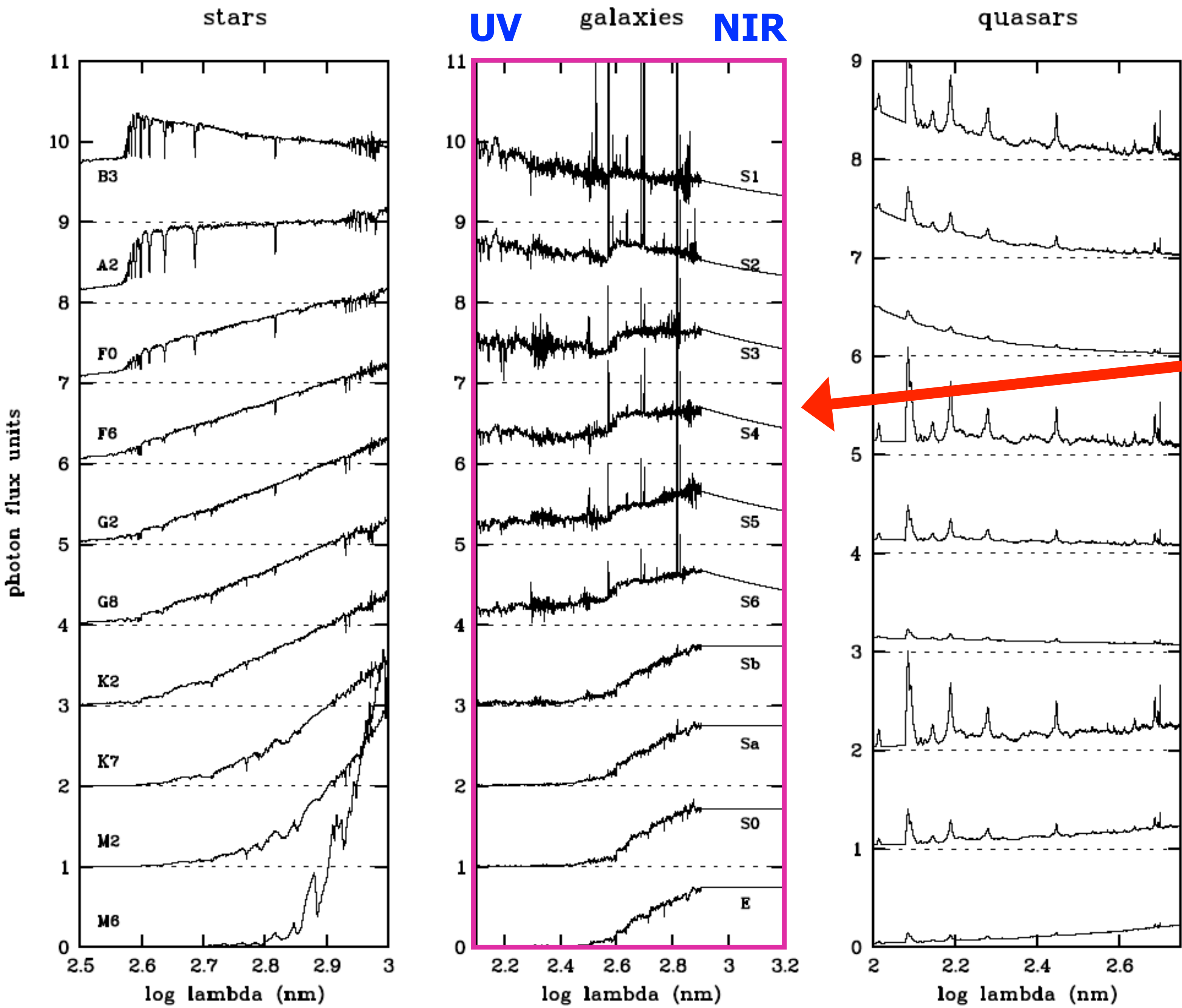
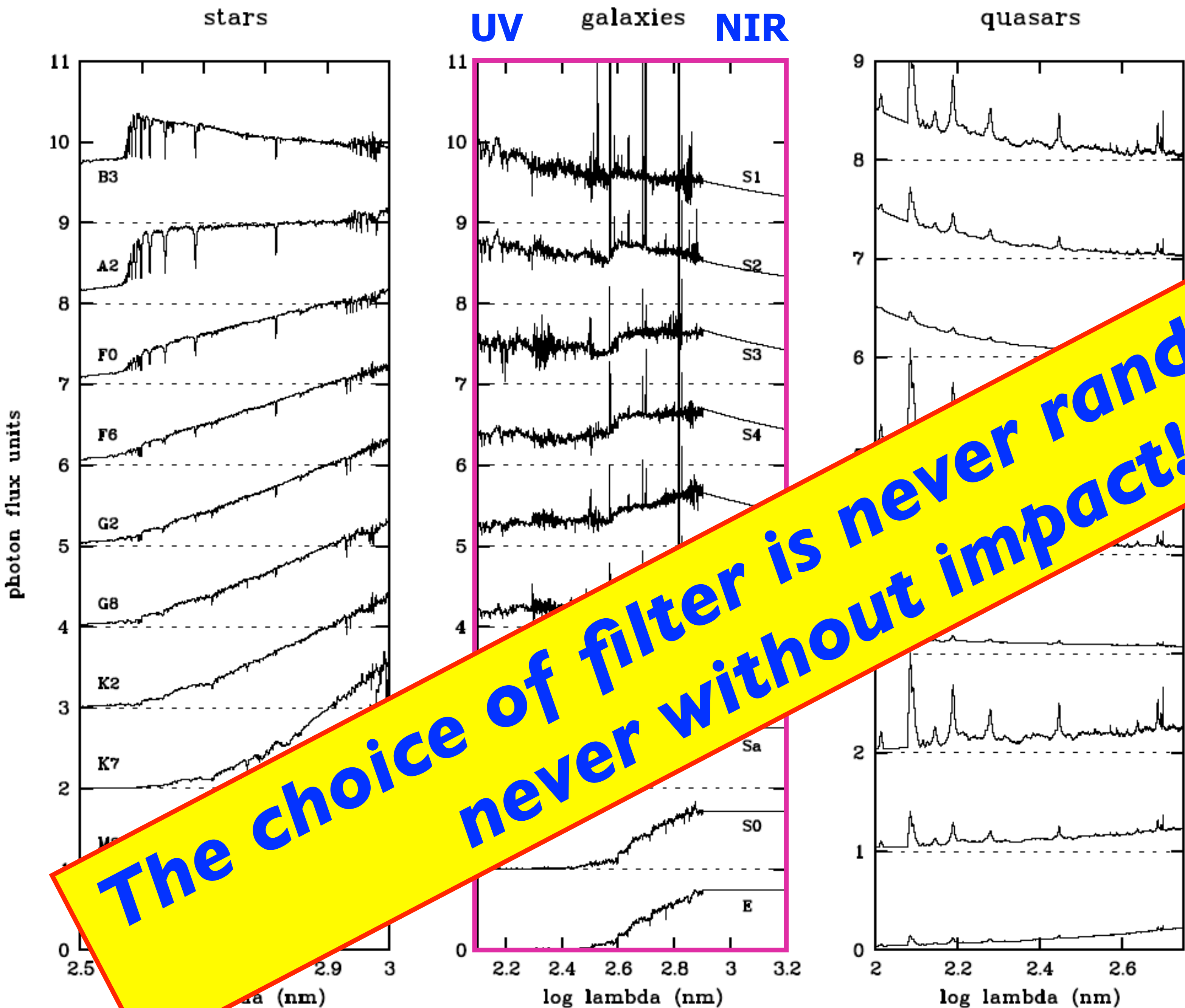


Fig. 1. This diagram shows a few selected spectra from our template libraries. The shown wavelength scale runs from 315 nm to 1000 nm for stars (left), from 125 nm to 1600 nm for galaxies (center) and from 100 nm to 550 nm for quasars (right). The flux is λf_λ in units of photons per nm, time intervall and sensitive area and offset by one unit per step within a class. The flux scale is normalised to unity at 800 nm for stars, arbitrary for galaxies, and normalised to 0.2 at 250 nm for quasars. The stellar templates are taken from Pickles (1998), the galaxy templates from Kinney et al. (1996) and quasar templates are modelled after Francis et al. (1991). The quasar diagram shows nine spectra with three different spectral indices (-2.0, -0.6, +0.8) and three different relative emission-line intensities (0.6, 2.1, 5.7).

Wolf et al 2001

Choose filters that distinguish among spectra, or isolate features you're interested in, or favor a certain type of galaxy



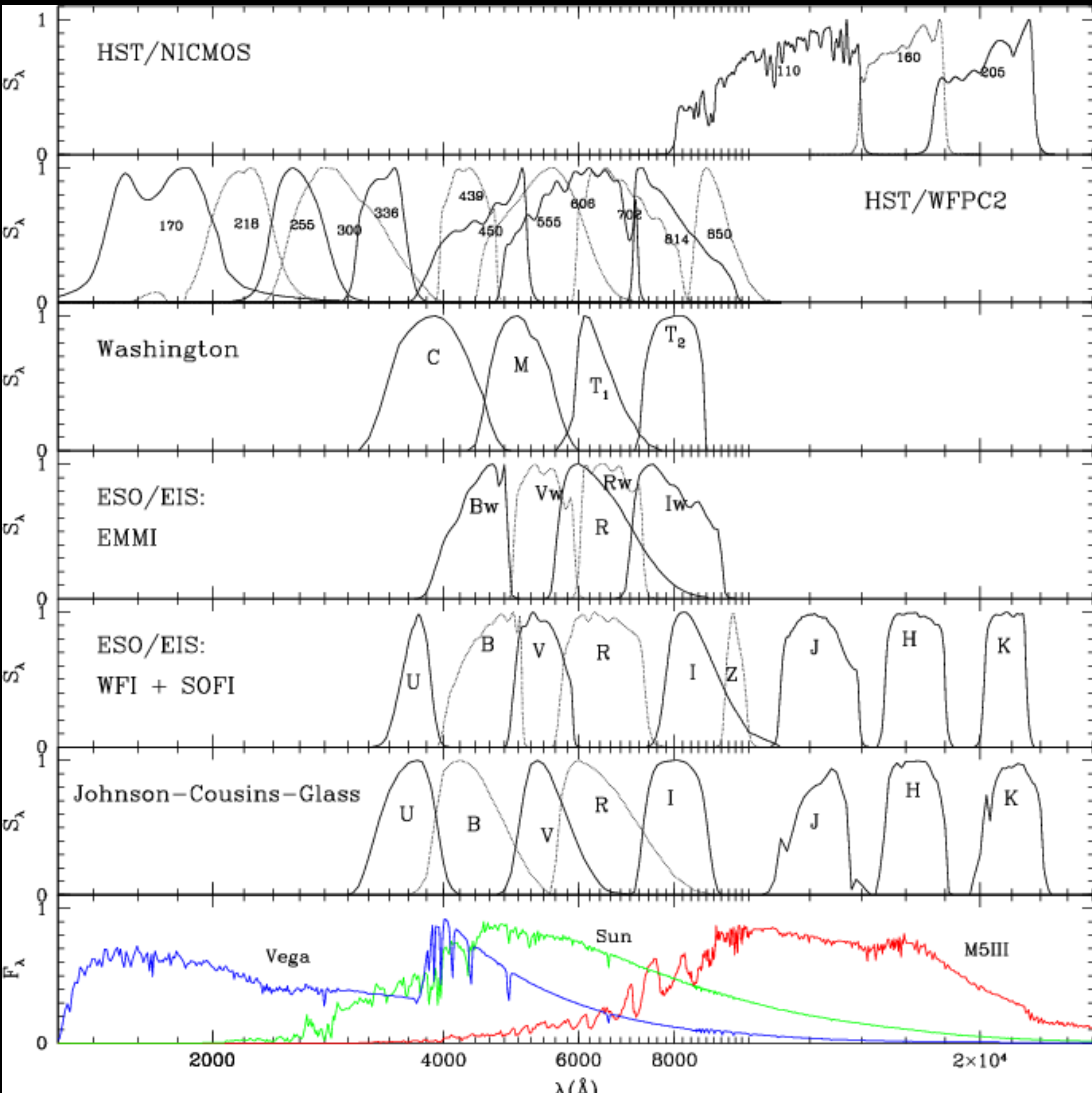
The choice of filter is never random, and never without impact!

Fig. 1. This dia shows a few selected spectra from our template libraries. The shown wavelength scale runs from 315 nm to 1000 nm for stars (left), from 125 nm to 1600 nm for galaxies (center) and from 100 nm to 550 nm for quasars (right). The flux is λf_λ in units of photons per nm, time intervall and sensitive area and offset by one unit per step within a class. The flux scale is normalised to unity at 800 nm for stars, arbitrary for galaxies, and normalised to 0.2 at 250 nm for quasars. The stellar templates are taken from Pickles (1998), the galaxy templates from Kinney et al. (1996) and quasar templates are modelled after Francis et al. (1991). The quasar diagram shows nine spectra with three different spectral indices (-2.0, -0.6, +0.8) and three different relative emission-line intensities (0.6, 2.1, 5.7).

Wolf et al 2001

Choose filters that dis sh tra, or isolate features you're interested in, or favor a certain type of galaxy

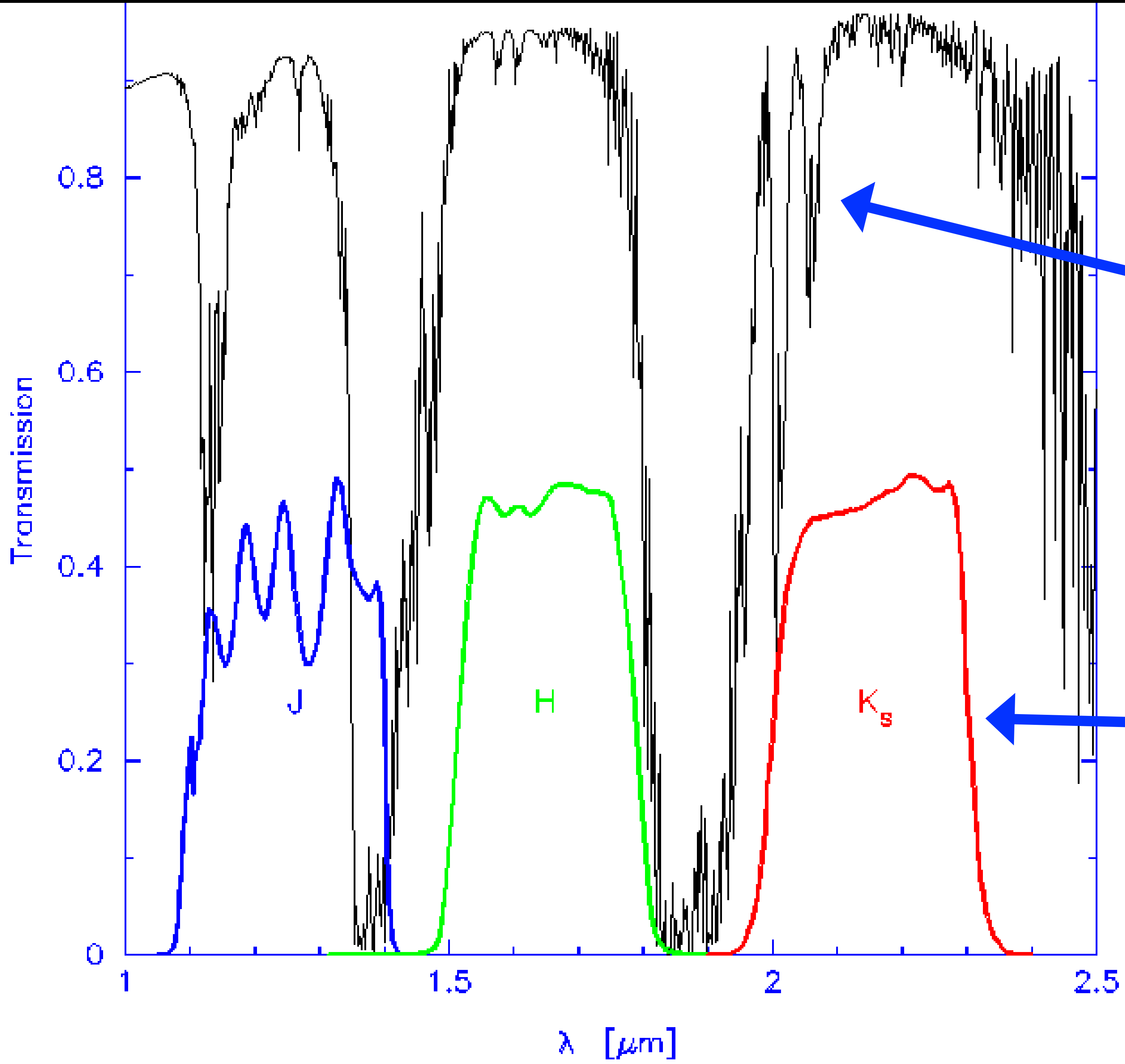
Filters highlight different spectral features



- Very low resolution spectroscopy!
- Different filter systems can share same filter names
- Must specify name + system

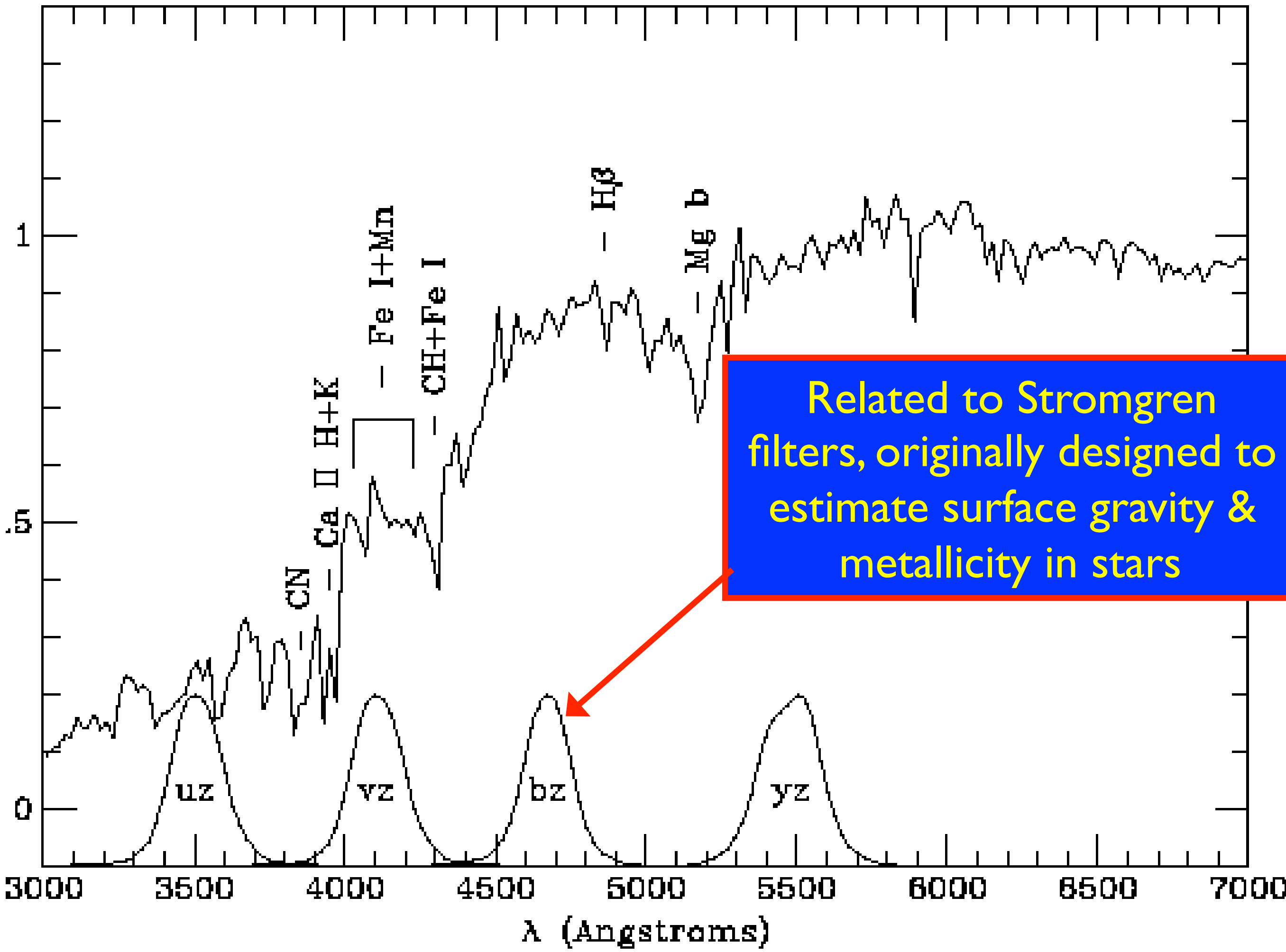
(Girardi, Bertelli, Bressan et al, 2002, A&A, 391, 195; see also Fukagita et al 1995) http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6_4b.html

NIR Filters



Atmospheric transmission

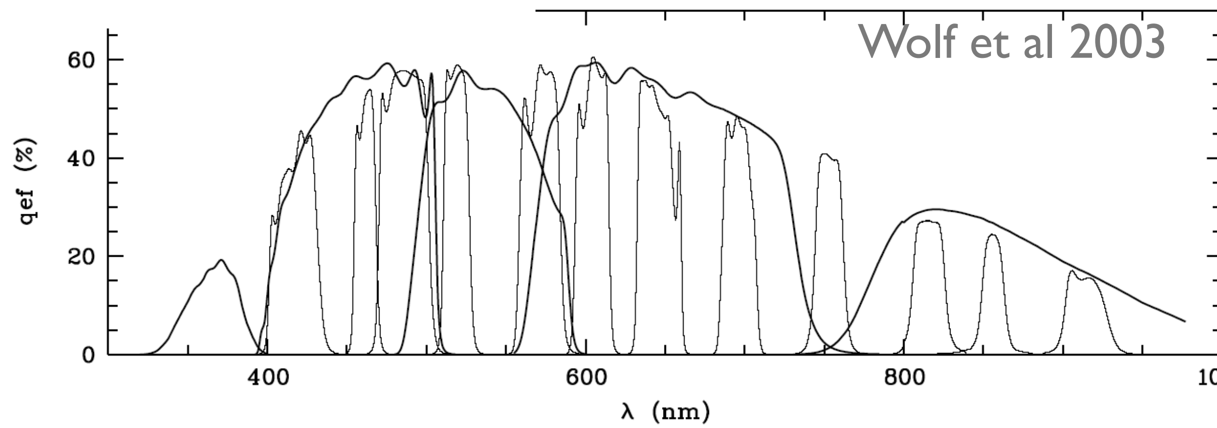
2MASS filters



Related to Stromgren filters, originally designed to estimate surface gravity & metallicity in stars

Non-standard "intermediate band" (rather than standard "broad band") filters

Isolates "interesting" stellar features



Wolf et al 2003

Fig. 1. COMBO-17 filter set: Total system efficiencies are shown in the COMBO-17 passbands, including two telecope mirrors, WFI instrument, CCD detector and average La Silla atmosphere. Combining all observations provides a low-resolution spectrum for all objects in the field. Photometric calibrations of such "multi"-colour datasets are best achieved with spectrophotometric standards inside the target fields.

For reference: Average galaxy colors measured for different Hubble types

Table 2. Average effective colours of galaxies with $M_V < -21$. For each colour the standard deviation and the number of used objects are also reported.

	$U-B$	$B-V$	$V-R$	$V-I$	$V-K$	$J-H^a$	$H-K^a$
E	0.50	0.99	0.59	1.22	3.30	0.66	0.21
	(0.08)	(0.05)	(0.05)	(0.07)	(0.09)	(0.05)	(0.02)
	323	418	314	221	32	225	225
S0	0.47	0.97	0.58	1.20	3.25	0.66	0.22
	(0.11)	(0.08)	(0.05)	(0.08)	(0.14)	(0.05)	(0.02)
	287	344	227	158	13	235	235
Sa	0.36	0.90	0.58	1.17	3.24	0.67	0.25
	(0.19)	(0.11)	(0.08)	(0.11)	(0.18)	(0.06)	(0.03)
	138	185	73	82	17	105	105
Sb	0.22	0.82	0.57	1.16	3.21	0.66	0.25
	(0.20)	(0.12)	(0.09)	(0.11)	(0.28)	(0.06)	(0.03)
	321	541	156	315	16	93	93
Sc	0.06	0.70	0.52	1.15	3.03	0.66	0.25
	(0.18)	(0.13)	(0.10)	(0.15)	(0.24)	(0.07)	(0.04)
	294	536	133	287	23	46	46
Sd[b]	−0.12	0.62	0.47	1.09	2.95	0.65	0.23
	(0.16)	(0.18)	(0.13)	(0.19)	(0.32)	(0.08)	(0.05)
	53	99	25	58	12	26	24
I[c]	−0.15	0.51	0.40	1.08	2.35	0.51	0.21
	(0.20)	(0.17)	(0.20)	(0.30)	(0.35)	(0.10)	(0.06)
	102	117	28	35	5	22	20

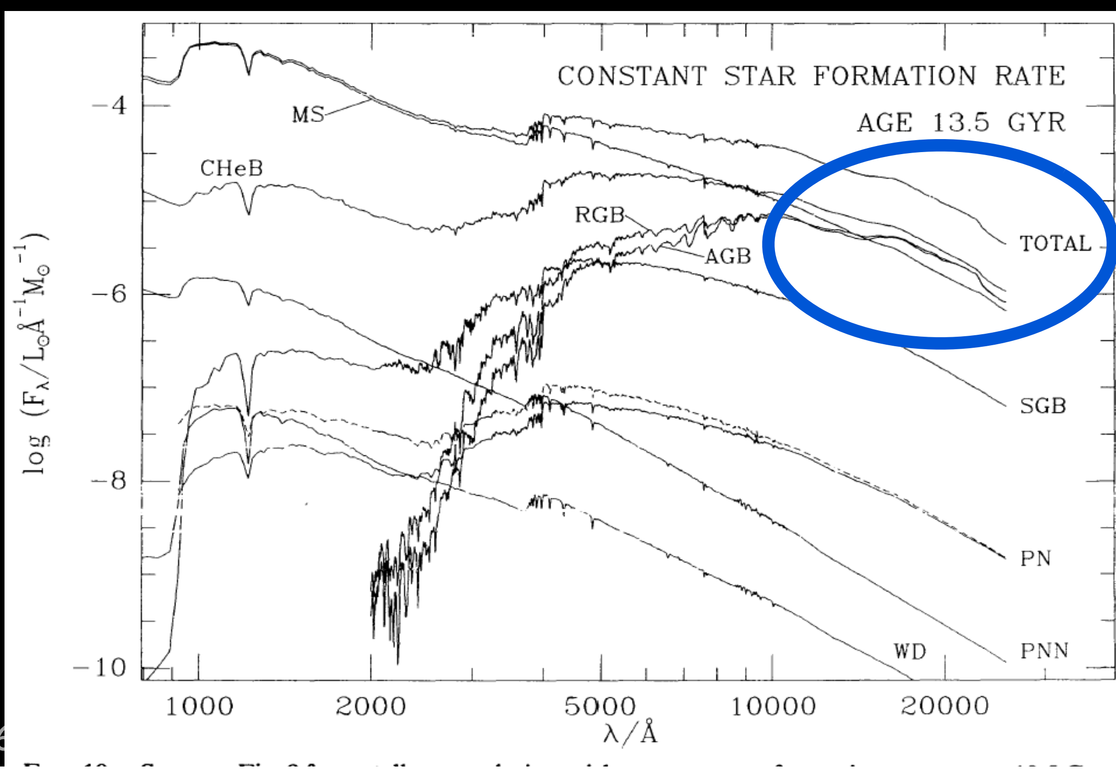
[a]: The $J-H$ and $H-K$ colours are based also on the results in Fioc & Rocca-Volmerange (1999), where only average quantities are given. In these cases the scatter is not measured but estimated.
[b]: $M_V < -20$.
[c]: No magnitude selection.

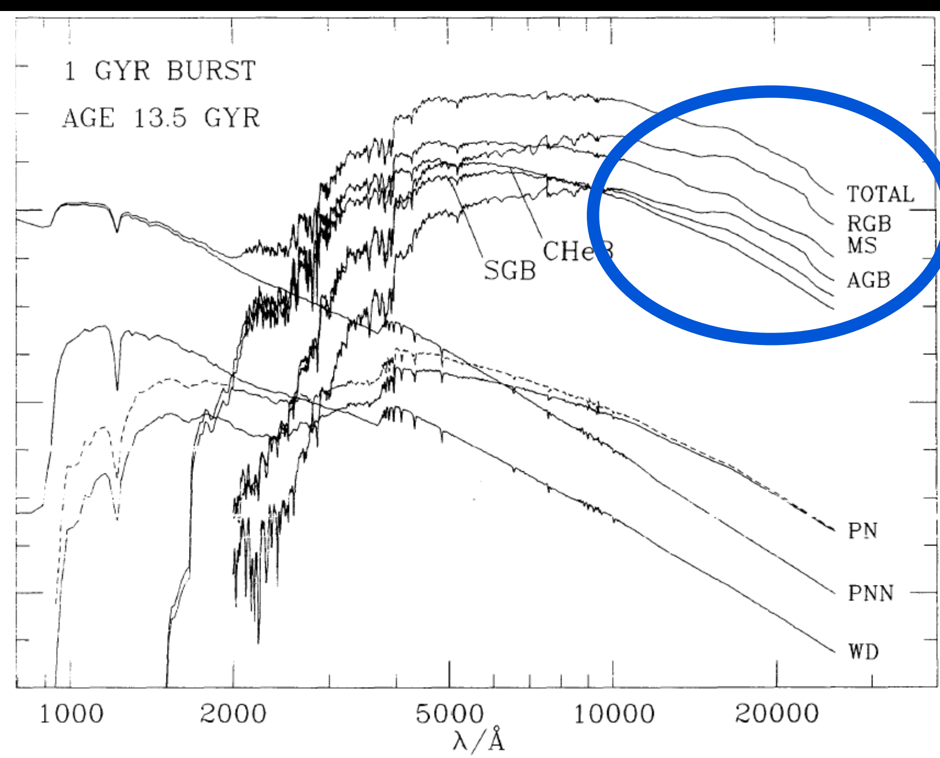
Mannucci et al 2001

3. Some Applications: Using models to interpret broad-band fluxes and colors

Stellar Mass indicators

- Luminosity
- Luminosity in redder, NIR filters
- Luminosity + color (i.e. correct for young vs old)
- Spectral fitting (either multiple broad-band colors, or detailed fitting of spectra)





Application: Stellar mass-to-light ratios as a function of SF history & metallicity

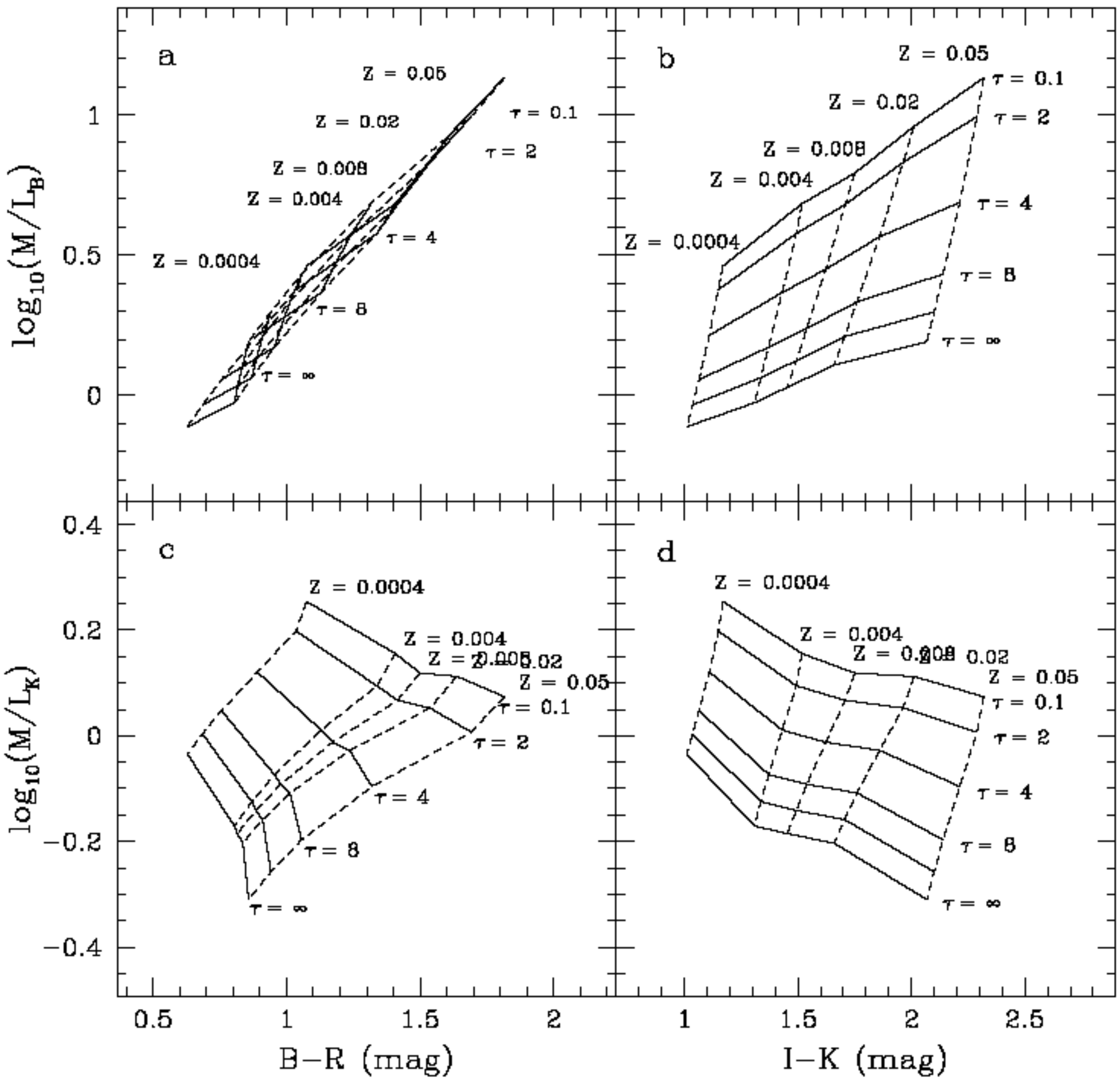


FIG. 2.—Trends in simple exponential SFH model stellar M/L ratios with color. Stellar M/L ratios for a Salpeter IMF in B (panels [*a*] and [*b*]) and K band (panels [*c*] and [*d*]) of single-metallicity exponentially declining star formation rate models from A. G. Bruzual & S. Charlot (2001, in preparation) are shown against the model $B-R$ (panels [*a*] and [*c*]) and $I-K$ (panels [*b*] and [*d*]) broadband colors. Models of the same *e*-folding timescale τ have been connected by solid lines, while models of the same metallicity Z are connected by dashed lines.

- varies with color
- little variation in K

Bell & de Jong 2001

Mass-to-light ratio vs color, for models constrained to fit the Tully-Fisher relation

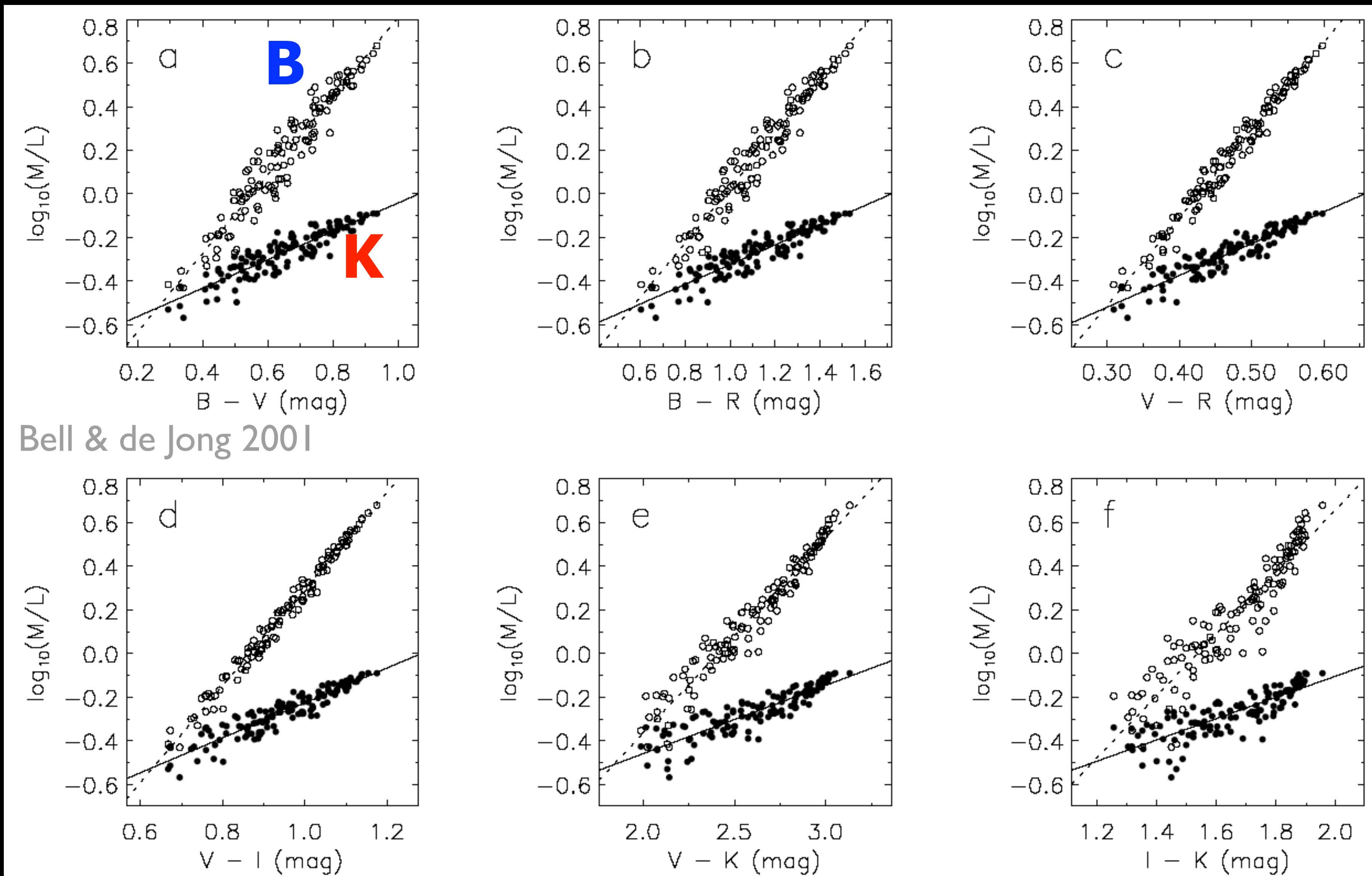


FIG. 9.—Trends in stellar M/L for the formation epoch model with bursts in K (*filled circles*) and B band (*open circles*) with (*a*) $B-V$, (*b*) $B-R$, (*c*) $V-R$, (*d*) $V-I$, (*e*) $V-K$, and (*f*) $I-K$ color. We also show the least-squares fit to the variations of stellar M/L ratio with color for the B-band (*dotted line*) and K-band (*solid line*) stellar M/L ratio.

Handy look-up tables…

STELLAR M/L RATIO AS A FUNCTION OF COLOR FOR THE FORMATION EPOCH MODEL WITH BURSTS, ADOPTING A SCALED SALPETER IMF

Color	a_B	b_B	a_V	b_V	a_R	b_R	a_I	b_I	a_J	b_J	a_H	b_H	a_K	b_K
$B-V$	−0.994	1.804	−0.734	1.404	−0.660	1.222	−0.627	1.075	−0.621	0.794	−0.663	0.704	−0.692	0.652
$B-R$	−1.224	1.251	−0.916	0.976	−0.820	0.851	−0.768	0.748	−0.724	0.552	−0.754	0.489	−0.776	0.452
$V-I$	−1.919	2.214	−1.476	1.747	−1.314	1.528	−1.204	1.347	−1.040	0.987	−1.030	0.870	−1.027	0.800
$V-J$	−1.903	1.138	−1.477	0.905	−1.319	0.794	−1.209	0.700	−1.029	0.505	−1.014	0.442	−1.005	0.402
$V-H$	−2.181	0.978	−1.700	0.779	−1.515	0.684	−1.383	0.603	−1.151	0.434	−1.120	0.379	−1.100	0.345
$V-K$	−2.156	0.895	−1.683	0.714	−1.501	0.627	−1.370	0.553	−1.139	0.396	−1.108	0.346	−1.087	0.314

NOTE.—$\log_{10}(M/L) = a_\lambda + b_\lambda$Color. Note that the stellar M/L values can be estimated for any combination of the above colors by a simple linear combination of the above fits. Note also that if *all* (even very high surface brightness) disks are submaximal, the above zero points should be modified by subtracting a constant from the above relations.

Bell & de Jong 2001

STELLAR M/L RATIO AS A FUNCTION OF COLOR

Color	a_g	b_g	a_r	b_r	a_i	b_i	a_z	b_z	a_J	b_J	a_H	b_H	a_K	b_K
$u-g$	–0.221	0.485	–0.099	0.345	–0.053	0.268	–0.105	0.226	–0.128	0.169	–0.209	0.133	–0.260	0.123
$u-r$	–0.390	0.417	–0.223	0.299	–0.151	0.233	–0.178	0.192	–0.172	0.138	–0.237	0.104	–0.273	0.091
$u-i$	–0.375	0.359	–0.212	0.257	–0.144	0.201	–0.171	0.165	–0.169	0.119	–0.233	0.090	–0.267	0.077
$u-z$	–0.400	0.332	–0.232	0.239	–0.161	0.187	–0.179	0.151	–0.163	0.105	–0.205	0.071	–0.232	0.056
$g-r$	–0.499	1.519	–0.306	1.097	–0.222	0.864	–0.223	0.689	–0.172	0.444	–0.189	0.266	–0.209	0.197
$g-i$	–0.379	0.914	–0.220	0.661	–0.152	0.518	–0.175	0.421	–0.153	0.283	–0.186	0.179	–0.211	0.137
$g-z$	–0.367	0.698	–0.215	0.508	–0.153	0.402	–0.171	0.322	–0.097	0.175	–0.117	0.083	–0.138	0.047
$r-i$	–0.106	1.982	–0.022	1.431	0.006	1.114	–0.052	0.923	–0.079	0.650	–0.148	0.437	–0.186	0.349
$r-z$	–0.124	1.067	–0.041	0.780	–0.018	0.623	–0.041	0.463	–0.011	0.224	–0.059	0.076	–0.092	0.019
Color	a_B	b_B	a_V	b_V	a_R	b_R	a_I	b_I	a_J	b_J	a_H	b_H	a_K	b_K
$B-V$	–0.942	1.737	–0.628	1.305	–0.520	1.094	–0.399	0.824	–0.261	0.433	–0.209	0.210	–0.206	0.135
$B-R$	–0.976	1.111	–0.633	0.816	–0.523	0.683	–0.405	0.518	–0.289	0.297	–0.262	0.180	–0.264	0.138

Note. — Stellar M/L ratios are given by $\log_{10}(\mathrm{M/L}) = a_\lambda + (b_\lambda \times \mathrm{Color})$ where the M/L ratio is in solar units. If *all* galaxies are sub-maximal then the above zero points (a_λ) should be modified by subtracting an IMF dependent constant as follows: 0.15 dex for a Kennicutt or Kroupa IMF, and 0.4 dex for a Bottema IMF. Scatter in the above correlations is ~ 0.1 dex for all optical M/L ratios, and 0.1–0.2 dex for NIR M/L ratios (larger for galaxies with blue optical colors). SDSS filters are in AB magnitudes; Johnson BVR and JHK are in Vega magnitudes.

Bell et al 2003

However, uncertainty among models:

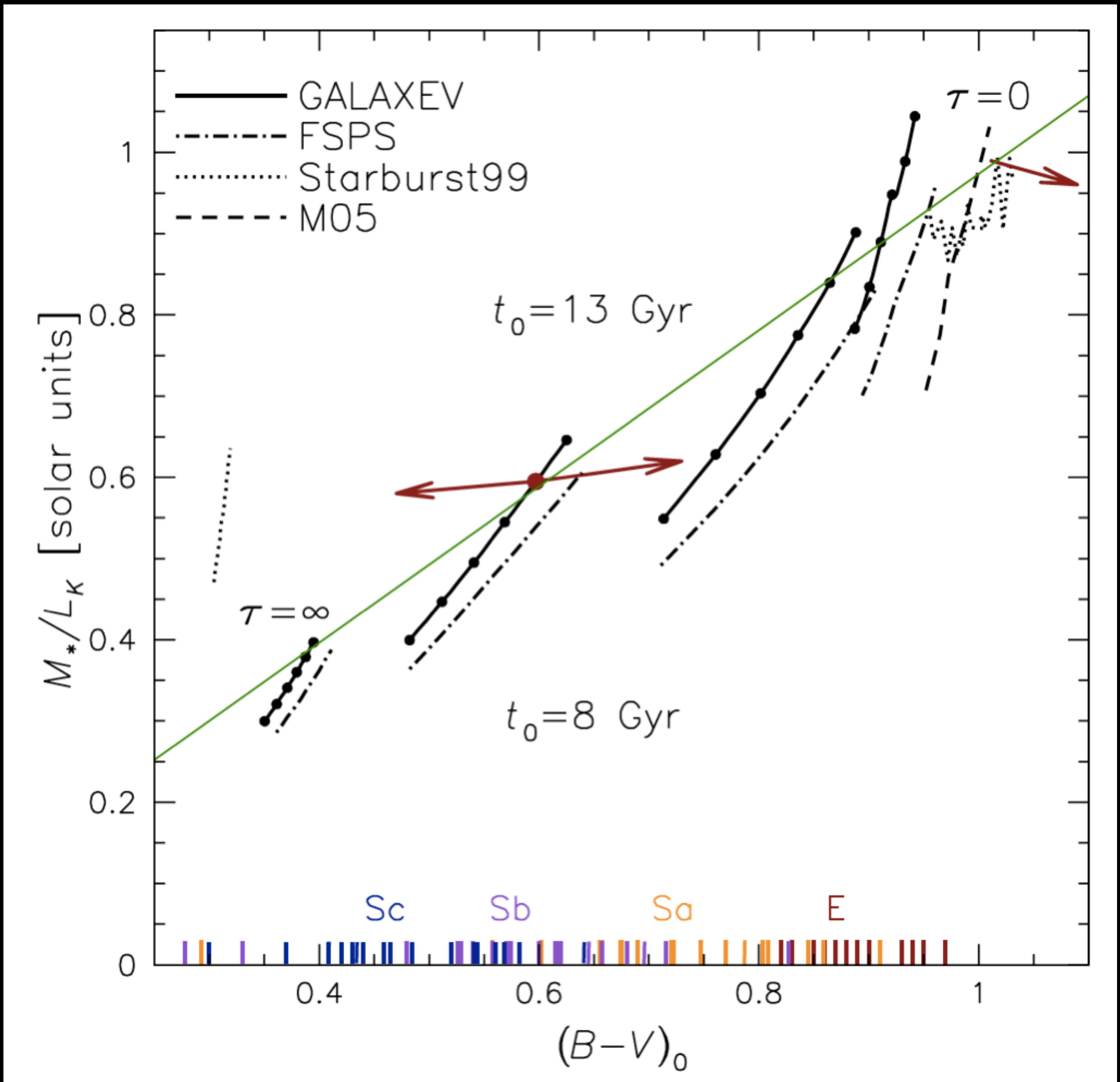
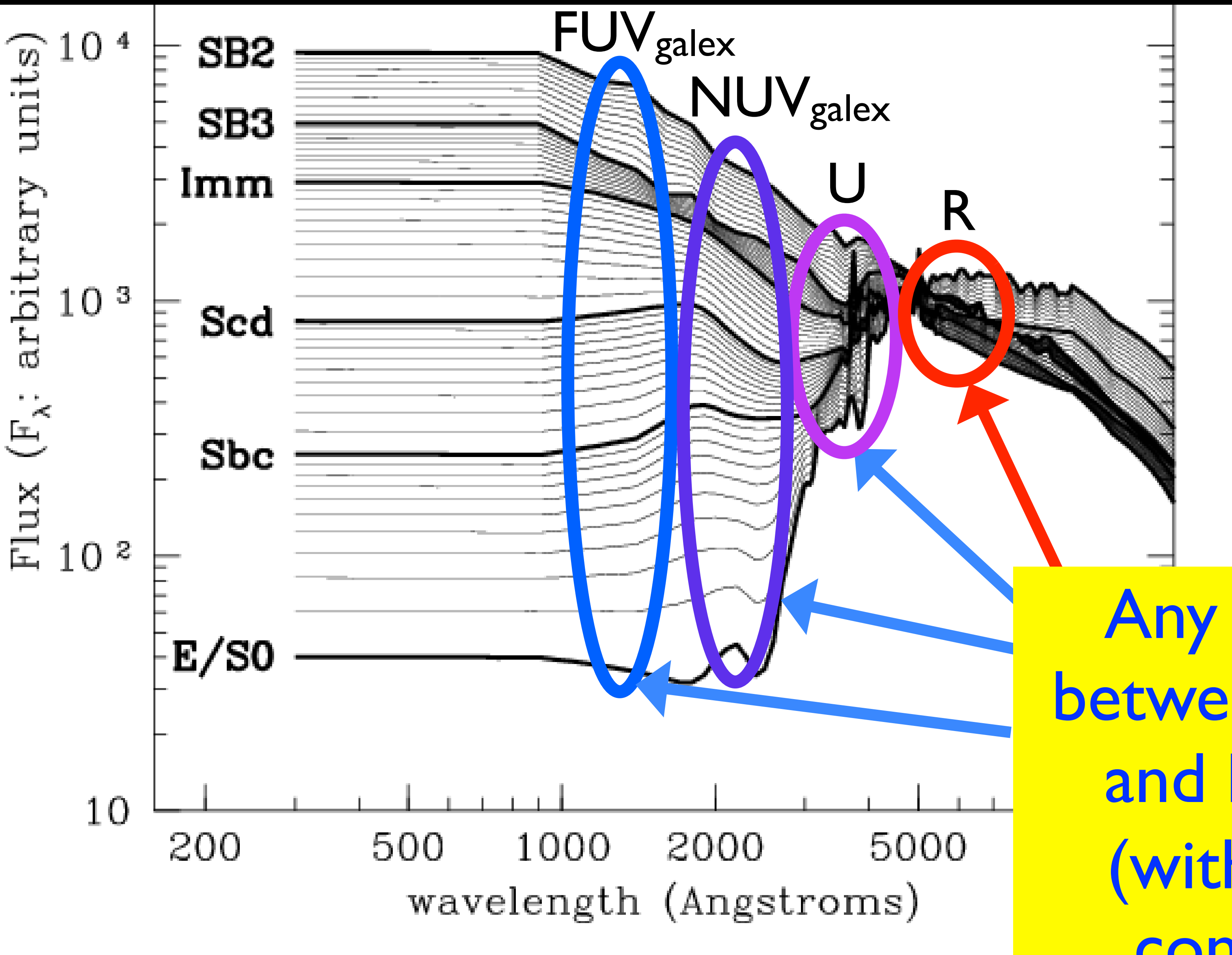


Figure 1. K-band mass-to-light ratio plotted against extinction-free $B-V$ color for stellar population models with exponential SFRs, several decay times τ, and initial ages that vary continuously from $t_0 = 8$ Gyr to $t_0 = 13$ Gyr. The models are: GALAXEV and FSPS with $\tau = 0$, 2 Gyr, 5 Gyr, ∞; Starburst99 with $\tau = 0, \infty$; and M05 with $\tau = 0$. The arrows show the effects of ± 0.6 mag of extinction in the B band (two-headed arrow) and an increase in the metallicity from $Z_\odot$ to $2.2Z_\odot$ (one-headed arrow). The diagonal green line represents our adopted correlation between $M_\star/L_K$ and $(B-V)_0$ (Equation (1)). The tick marks at the bottom of the figure indicate the extinction-corrected $B-V$ colors of the galaxies in our sample.

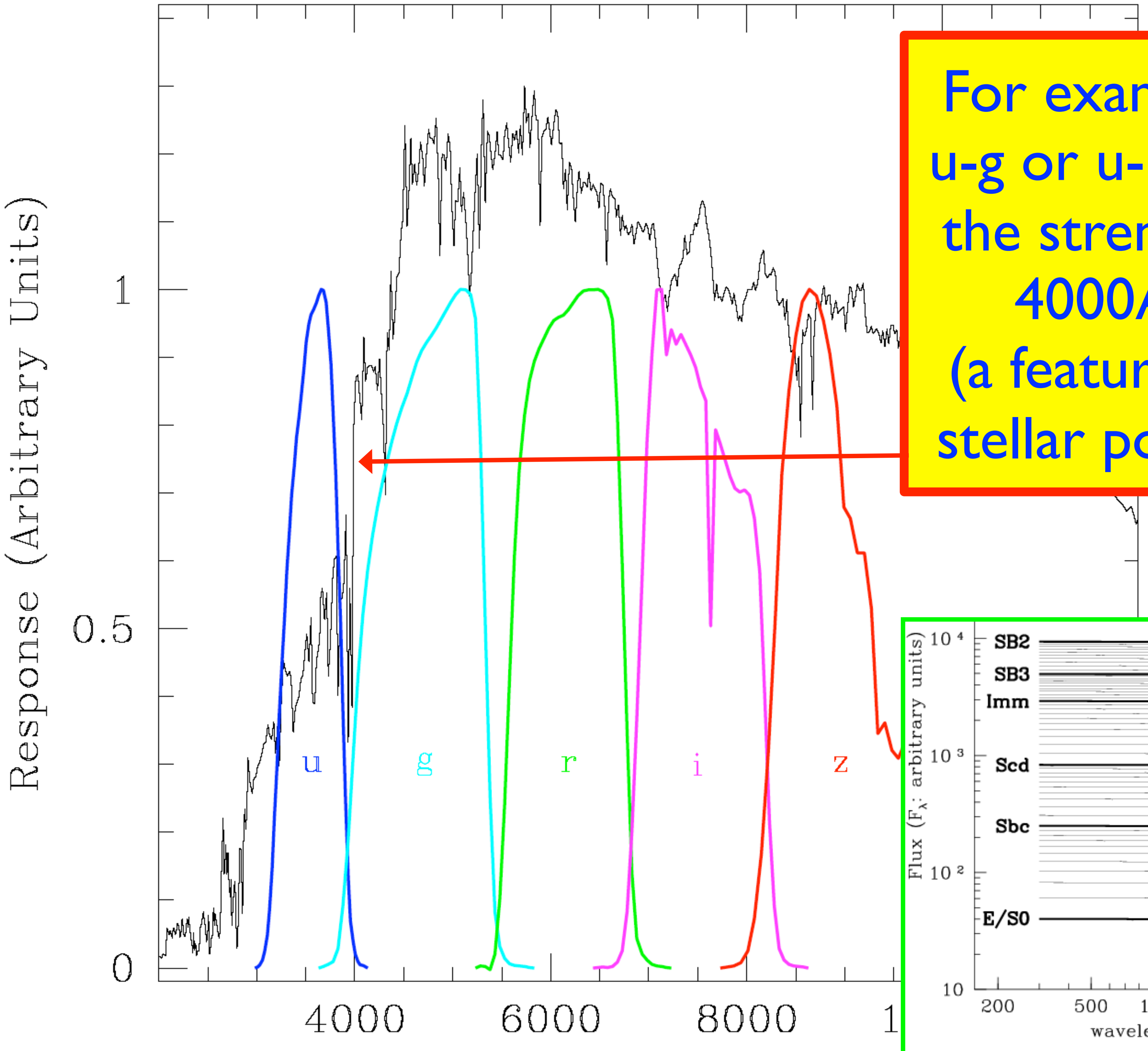
Fall & Romanowsky 2013

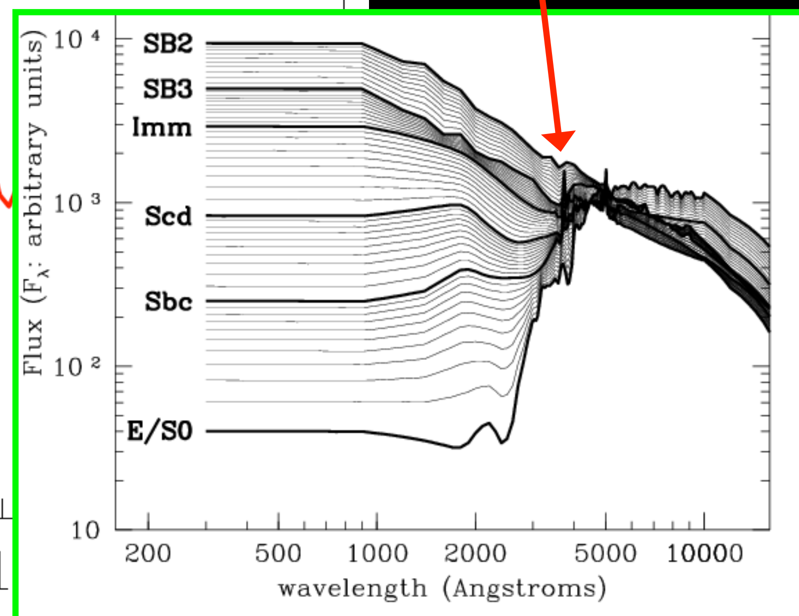
Application: Color as an age indicator



Any comparison between a red filter and **bluer** filter (with λ<4000A) constrains age

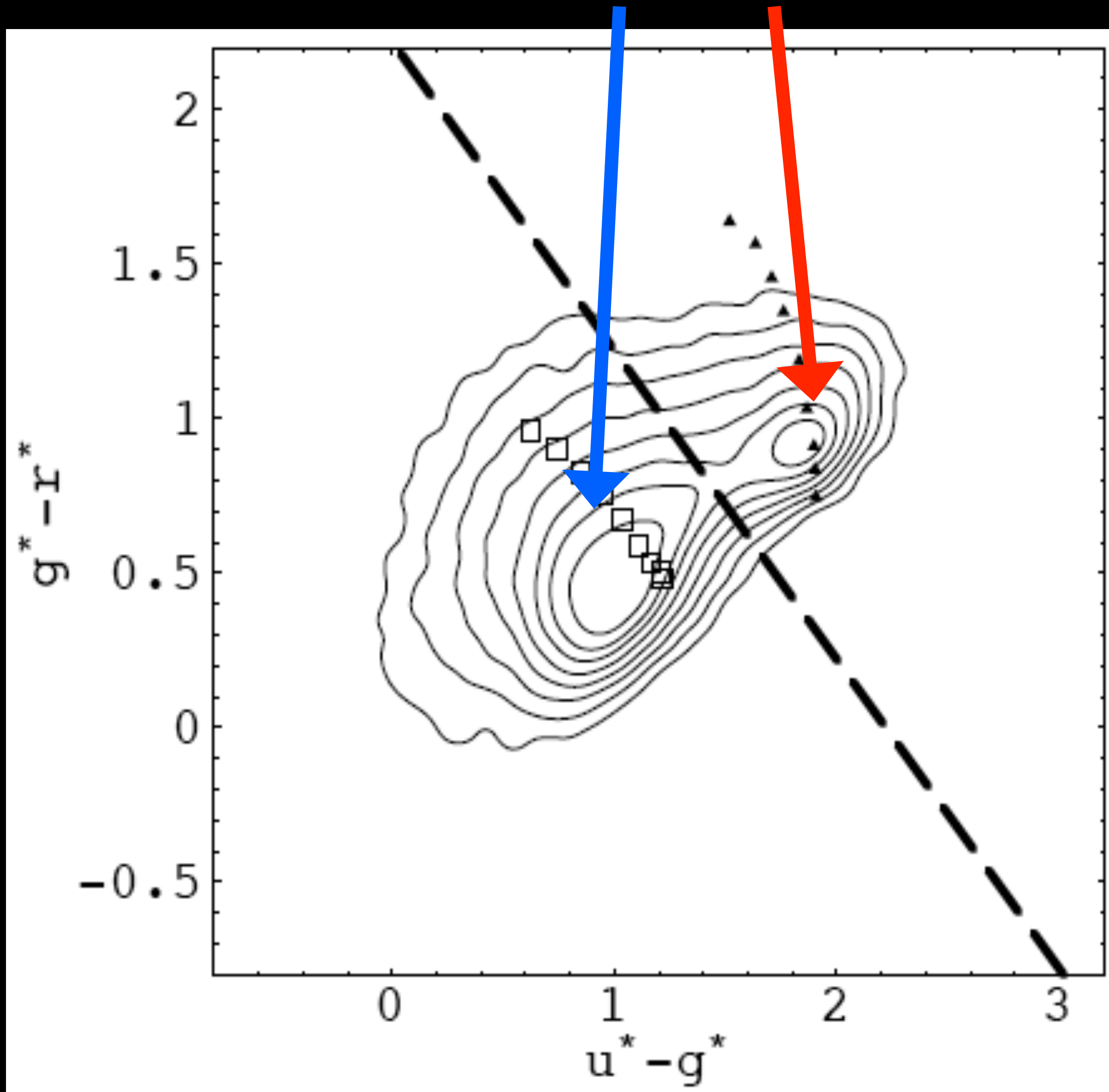
For example, SDSS u-g or u-r measures the strength of the 4000Å break (a feature of older stellar populations)





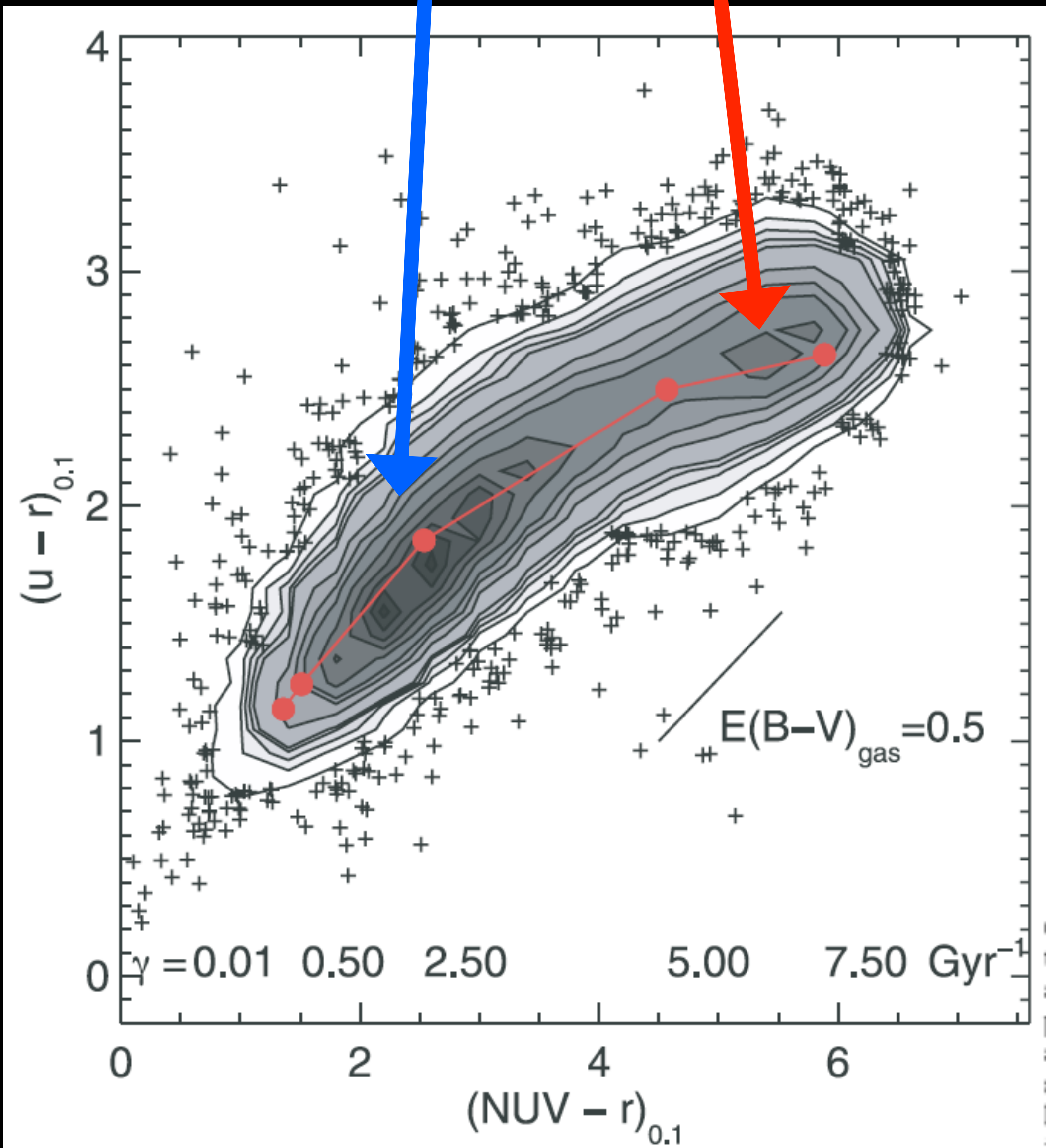
Blanton et al 2003

Galaxies show bimodality in blue SFR-sensitive colors



 SDSS: Stavetska et al 2001

Bimodality more extreme when using shorter wavelengths



Color varies by > 3 mag!

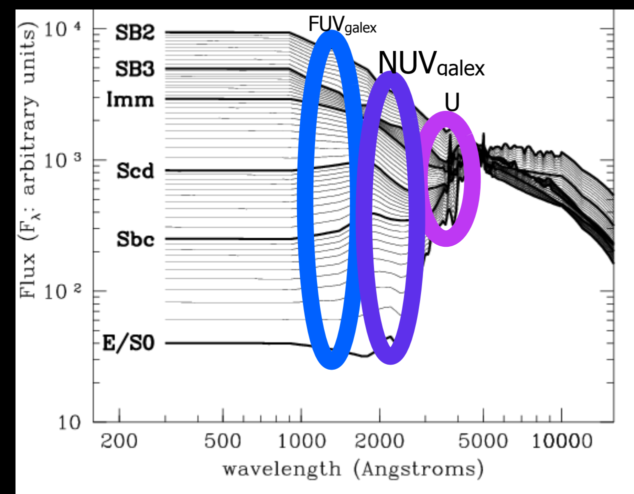


Fig. 22.—Number of galaxies (not weighted by $1/V_{max}$) as a function of $(u-r)_{0.1}$ and $(NUV-r)_{0.1}$. These are the same galaxies plotted in Fig. 7, except that galaxies with u-band errors greater than 0.3 mag were excluded. The data are plotted as contours where the density of galaxies is high and as individual points where it is low. The solid red circles are Bruzual & Charlot (2003) models at an age of 13 Gyr with no dust, solar metallicity, and exponentially declining star formation histories. The time constant in units of Gyr^{-1} in the star formation history for each model is indicated at the bottom of the figure. The black line indicates the reddening vector in this diagram for $E(B-V)_{gas}=0.5$ and assuming the Calzetti et al. (2000) attenuation law.

 Galex: Wyder et al 2007

The bluer galaxies tend to be fainter

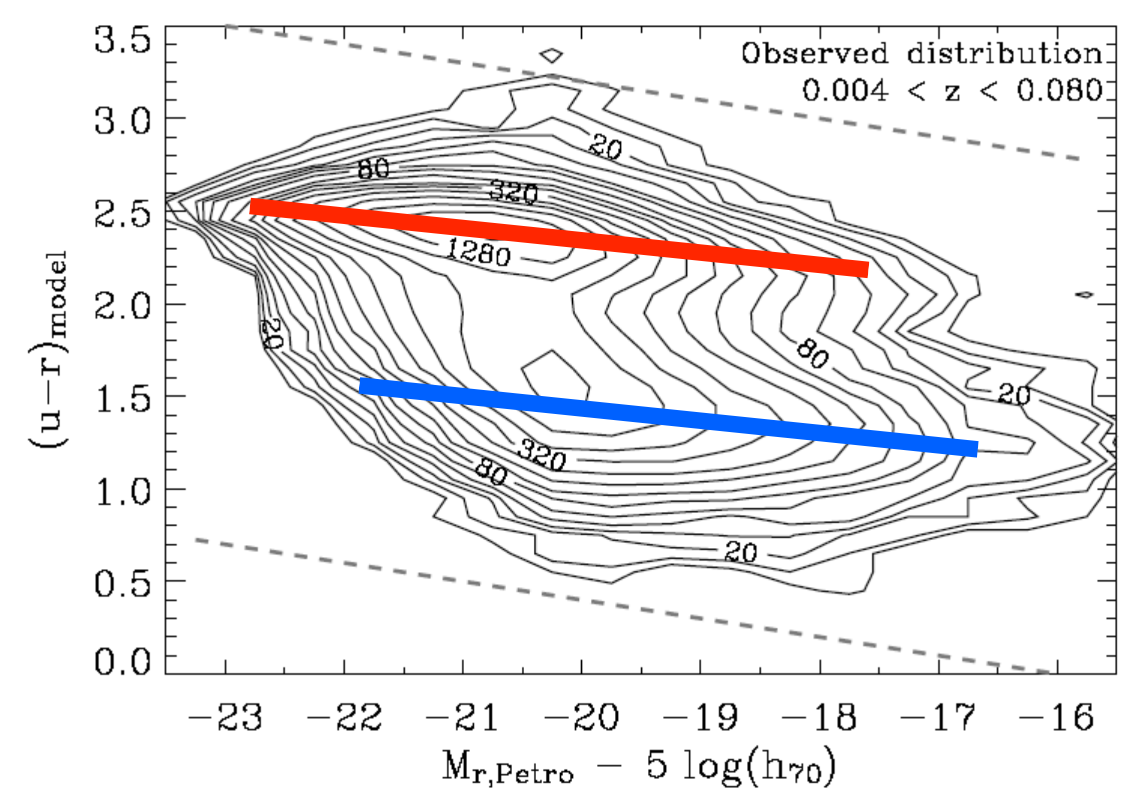


FIG. 1.—Observed bivariate distribution of the sample in rest-frame color vs. absolute magnitude. The contours are determined for galaxy number counts in 0.1 color × 0.5 mag bins (with a total of 66,846 galaxies). The contour levels are on a logarithmic scale, starting at 10 and doubling every two contours. The dashed lines represent the limits used in the double-Gaussian fitting described in § 4.

SDSS: Baldry et al 2004

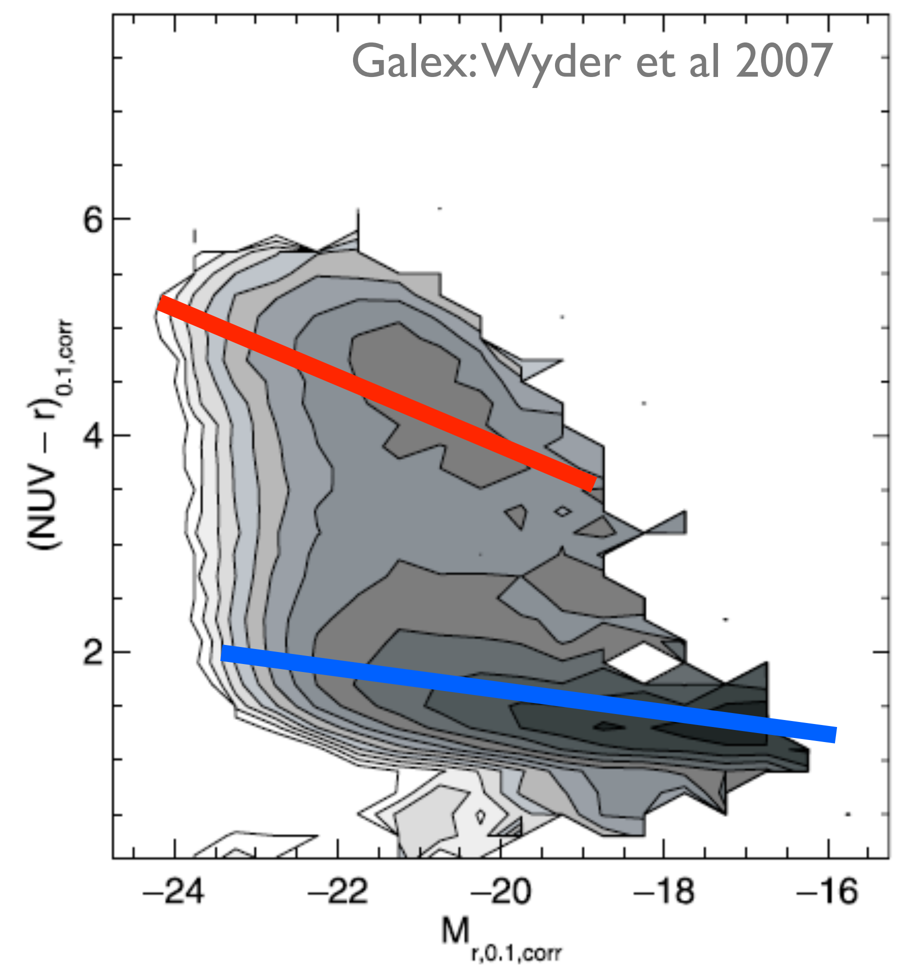
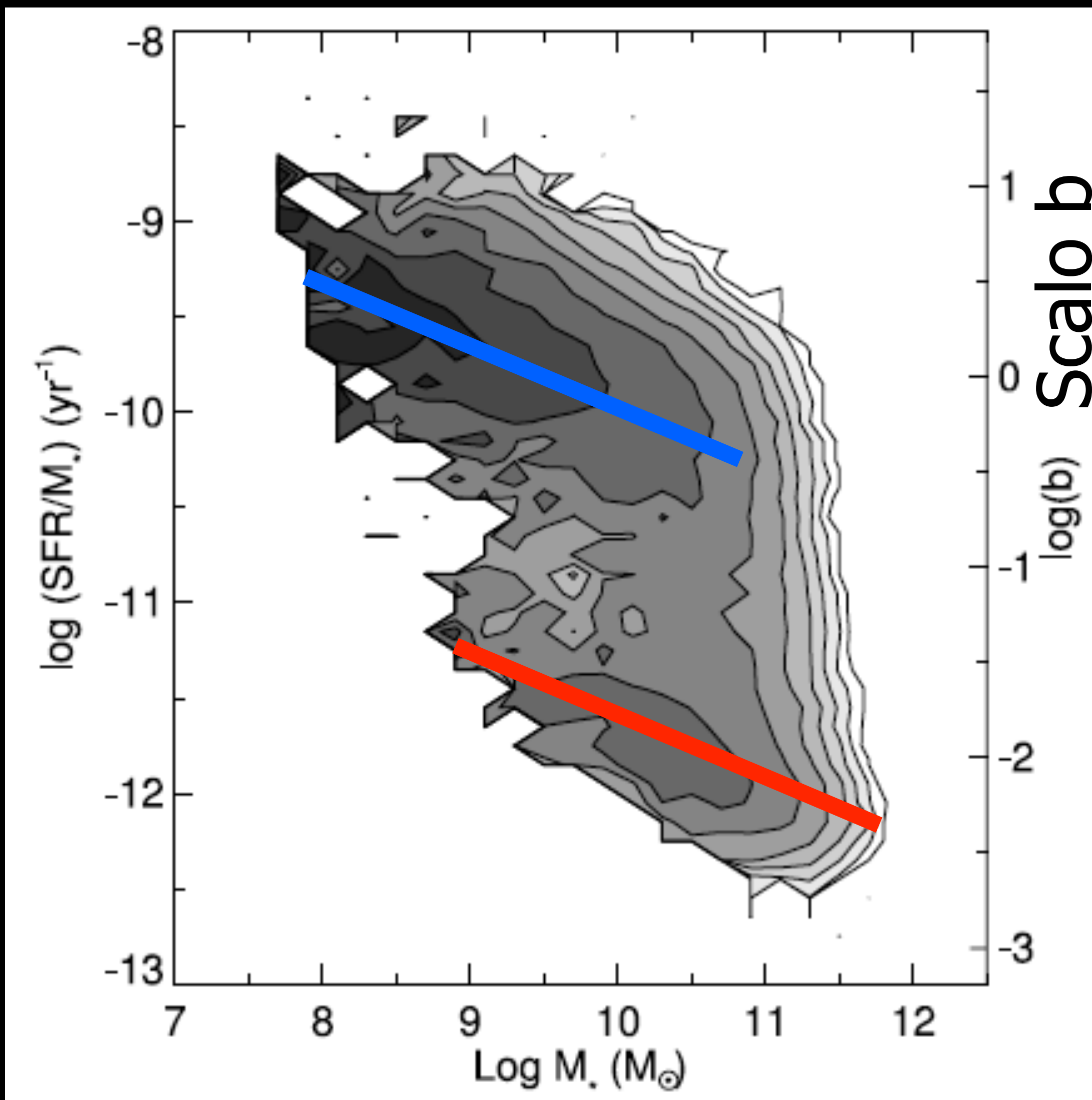


FIG. 25.—Volume density of galaxies as a function of dust-corrected $(NUV - r)_{0.1,\mathrm{corr}}$ and $M_{r,0.1,\mathrm{corr}}$. The FUV attenuation was derived using eq. (10) in the text based on the analysis of Johnson et al. (2006). The corresponding values of A_{NUV} and A_r were calculated using $A_{\mathrm{NUV}} = 0.81A_{\mathrm{FUV}}$ and $A_r = 0.35A_{\mathrm{FUV}}$ from the Calzetti et al. (2000) attenuation law. The contours are spaced logarithmically from $10^{-5.5}$ to $10^{-2.0}$ Mpc^{-3} mag^{-2}.

Note: Always good to show measured quantities in addition to derived age, mass…

Colors & Luminosities Translated to "Specific SFR" and Stellar Mass



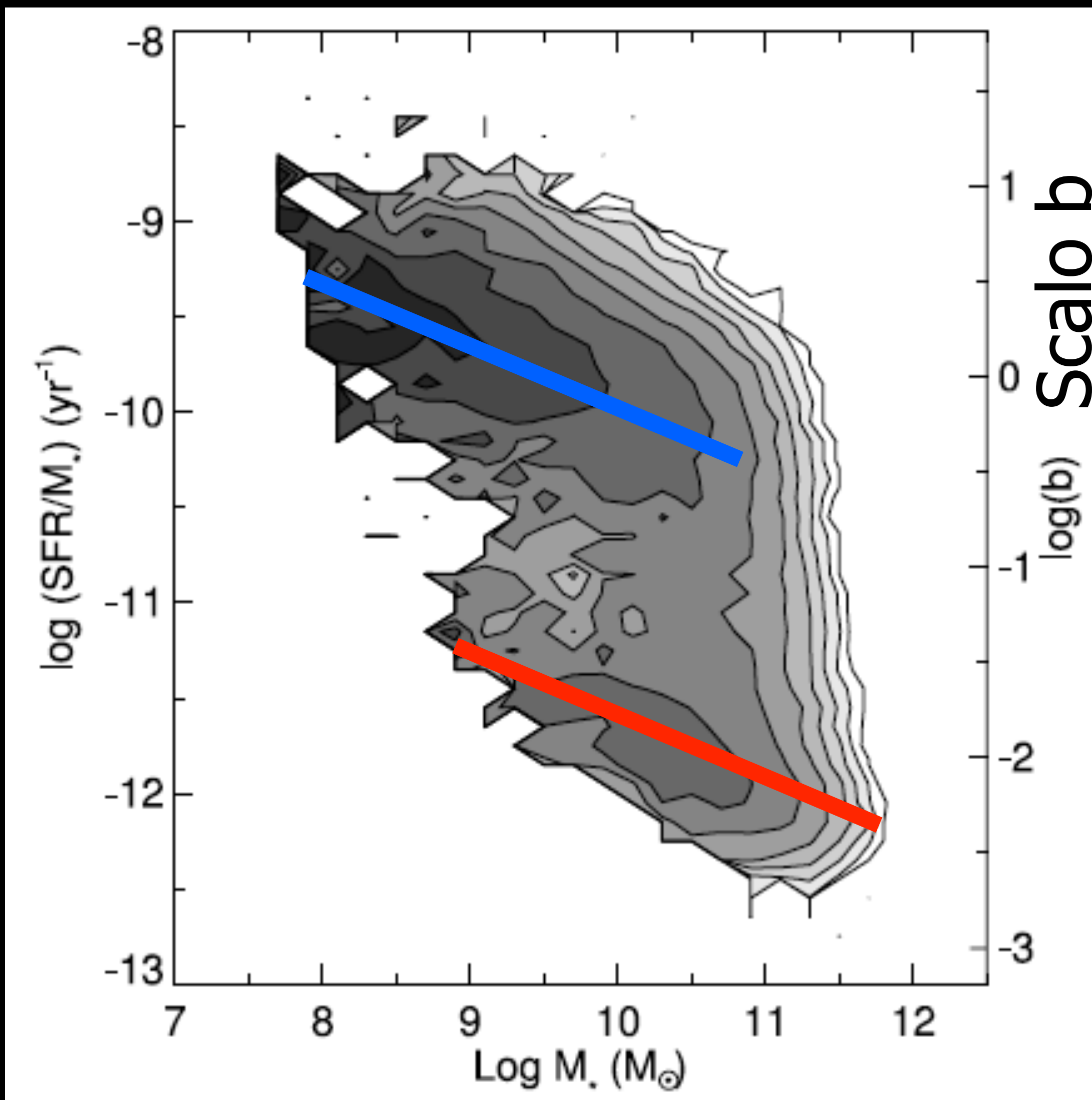
Transformation uses stellar population synthesis models

"Specific SFR" = SFR per unit of current stellar mass. Large values indicate SFR is high compared to historical past average. Inverse is how long it would take to produce exisiting stars, given current SFR.

FIG. 26.—Volume density of galaxies as a function of specific SFR and stellar mass M^*. The SFR has been calculated from the NUV luminosity, corrected for dust using the Balmer lines measured from the SDSS fiber spectra as described in the text. The density was calculated in bins 0.2 dex wide in mass and 0.1 dex wide in specific star formation rate. The contours are spaced logarithmically from 10^{-5} to $10^{-1.9}$ Mpc^{-3} dex^{-2}. We converted the NUV luminosities to SFRs using the conversion factor given in Kennicutt (1998) after applying a correction factor to convert to the Kroupa (2001) IMF used to calculate the stellar masses. The axis on the right-hand side gives the value of the logarithm of the ratio of current to past averaged SFR, log b, calculated as described in the text.

Galex: Wyder et al 2007

“Blue and Red Sequence” galaxies



Galex: Wyder et al 2007

Or “Star forming main sequence”

Which is an abomination of nomenclature