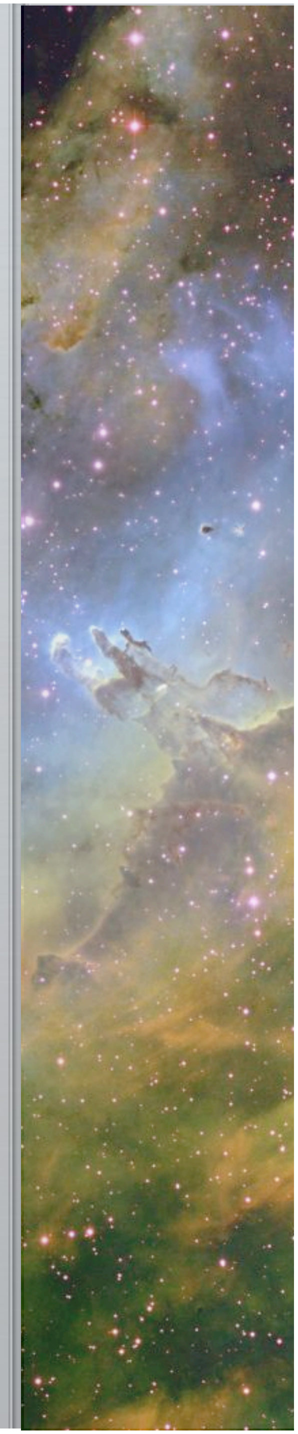
Measuring Star-Formation Rates

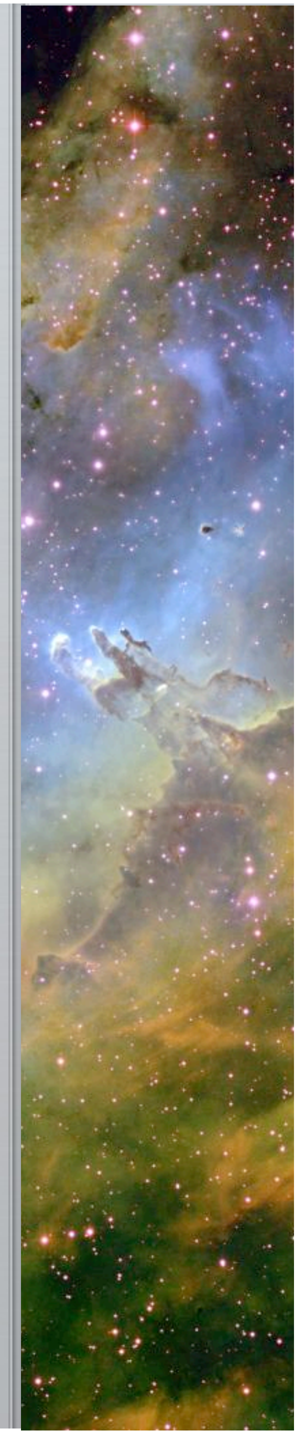
Rose Finn
Siena College

ALFALFA Undergraduate Workshop
Jan. 2011



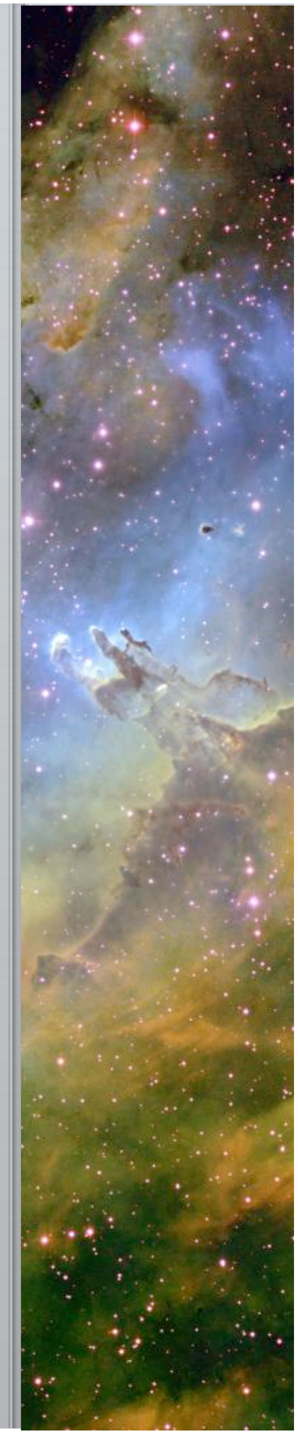
Acknowledgements

- This presentation is based in large-part on
  - the ARAA article by Rob Kennicutt (1998, ARAA)
    - This is the most-cited ARAA article and well worth reading!
  - Calzetti, “Star Formation Rate Determinations”, arXiv:0707.0467



Star-Formation Rates

- Quantifies how quickly a galaxy is converting gas into new stars
- Why should we care?
    - Star-forming regions make for great pictures!



Pillar and Jets HH 901/902

Hubble Space Telescope ▪ WFC3/UVIS

NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI)

STScI-PRC10-13c

Star-Forming Region NGC 3603

NASA, ESA, R. O'Connell (University of Virginia), the WFC3 Science Oversight Committee,
and the Hubble Heritage Team (STScI/AURA) • *HST* WFC3 • STScI-PRC10-22

Star-Forming Region 30 Doradus

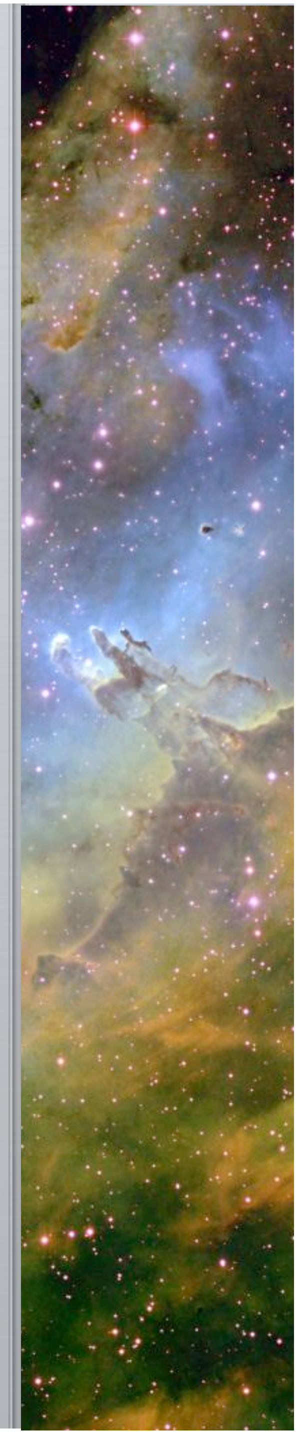
HST • WFC3/UVIS

NASA, ESA, F. Paresce (INAF–IASF, Italy), and the WFC3 Science Oversight Committee

STScI-PRC09-32a

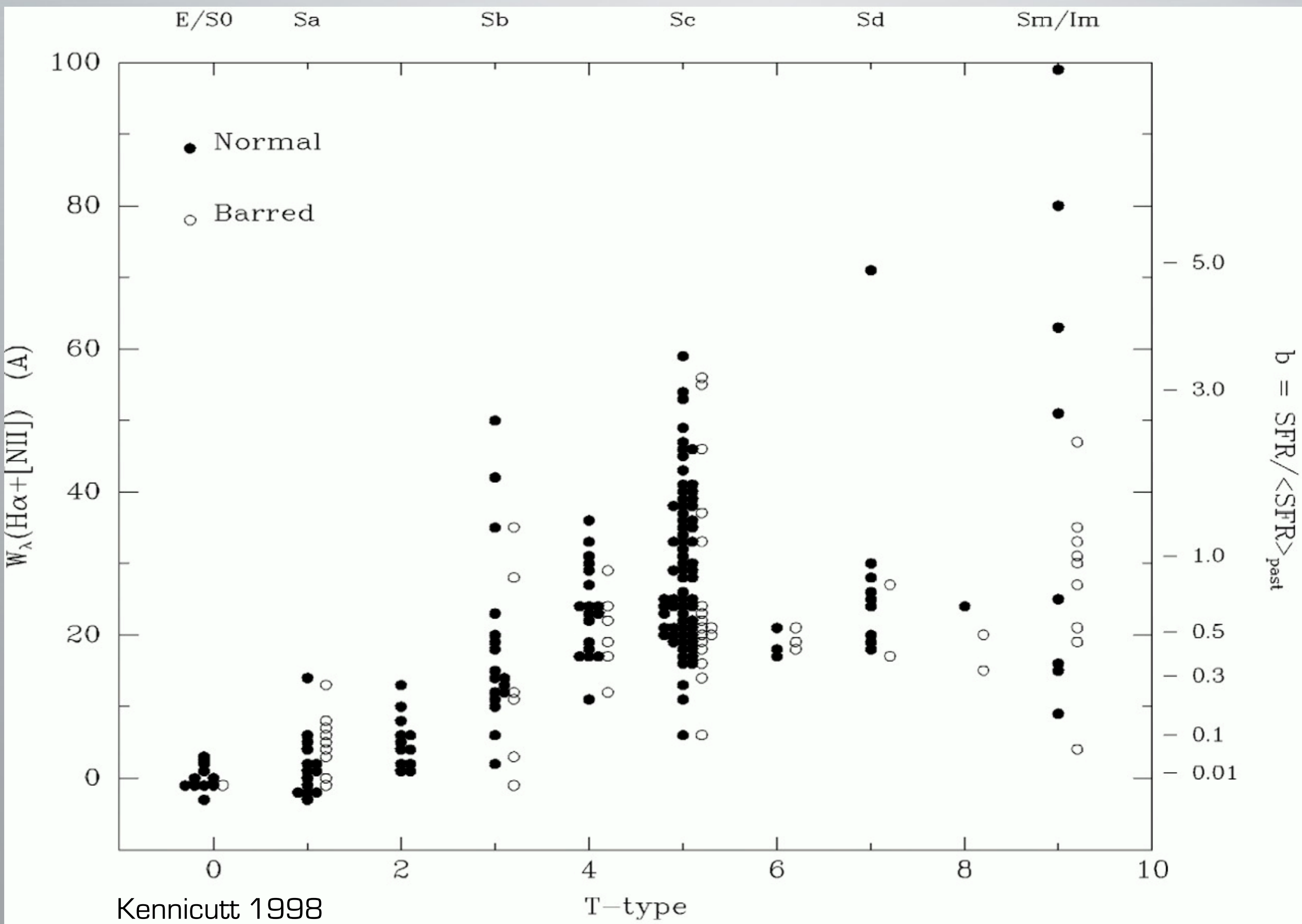
Star-Formation Rates

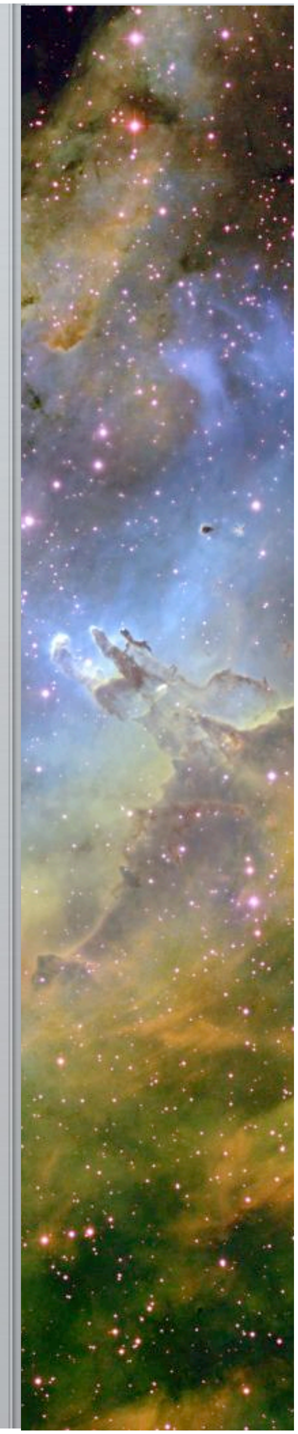
- Quantifies how quickly a galaxy is converting gas into new stars
- Why should we care?
  - Star-forming regions make for great pictures!
  - **Helps drive galaxy evolution**
    - Depletes gas
    - Leads to metal enrichment of ISM and IGM
  - A global property that we can measure
    - We can study individual star-forming regions in the Milky Way and other nearby galaxies.
    - I will focus on global star-formation rates (SFRs) – what we can measure for more distant galaxies.



Some Observational Results

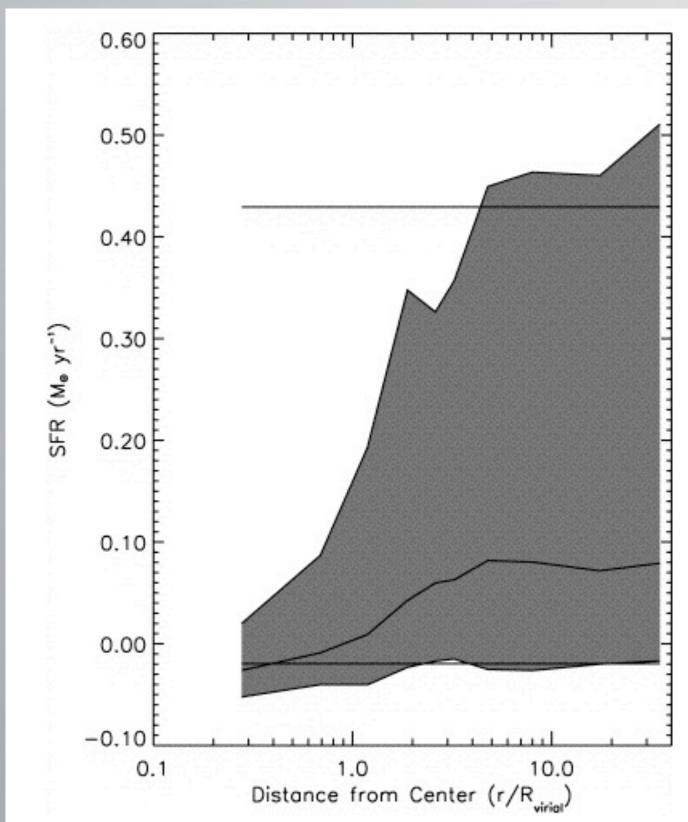
SFRs vary widely among galaxies

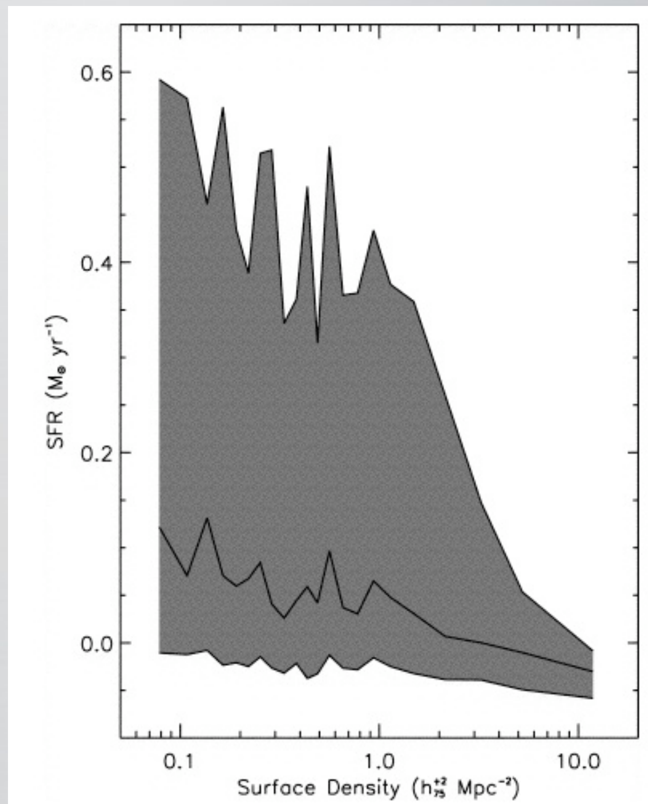




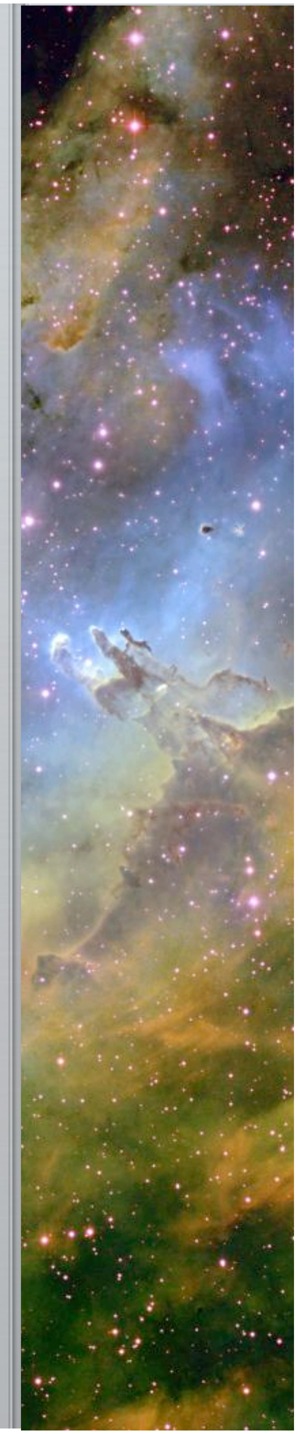
SFRs vary with Environment

- Observations of local universe show that SFRs are lower in dense environments.



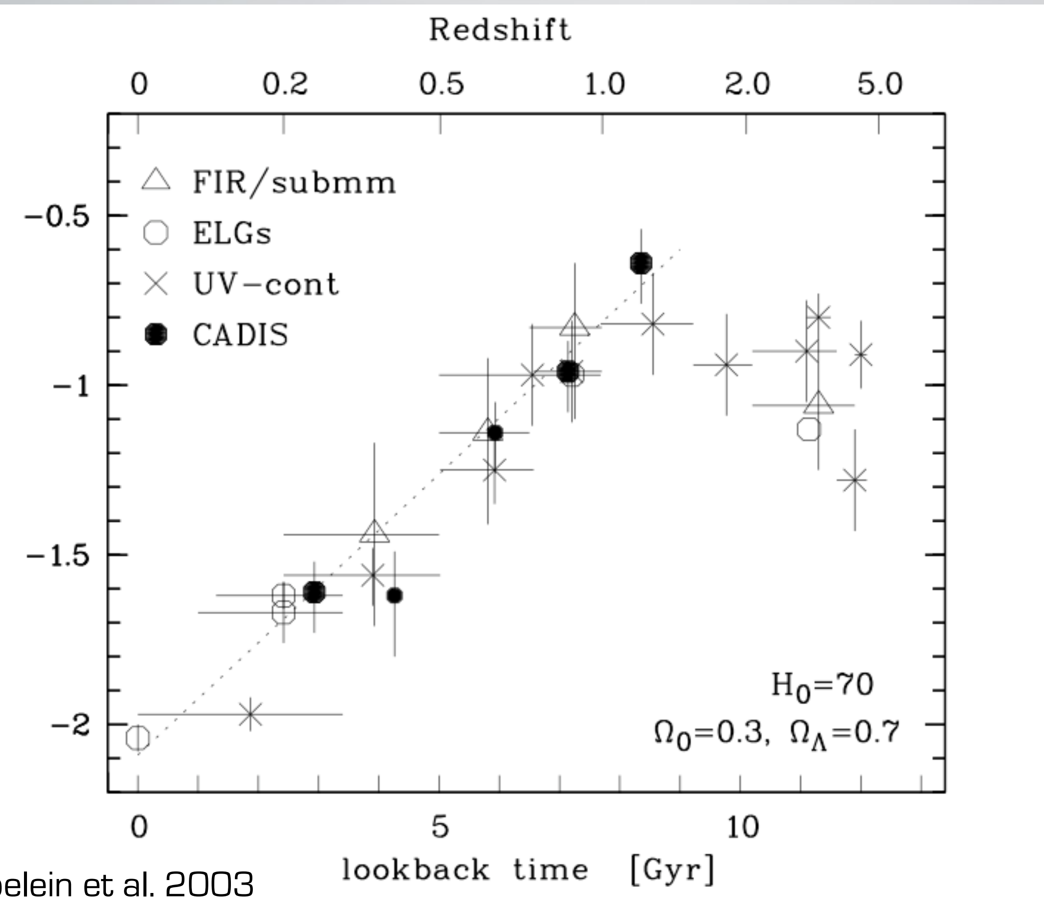


Results from Sloan Digital Sky Survey (Gomez et al. 2003)

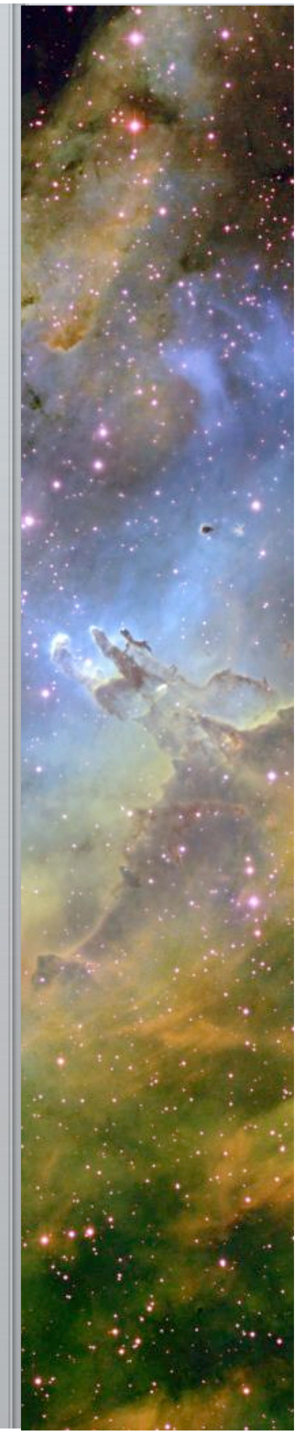


SFRs vary with redshift

- Observation of high-redshift universe show that SFRs were higher in the past.

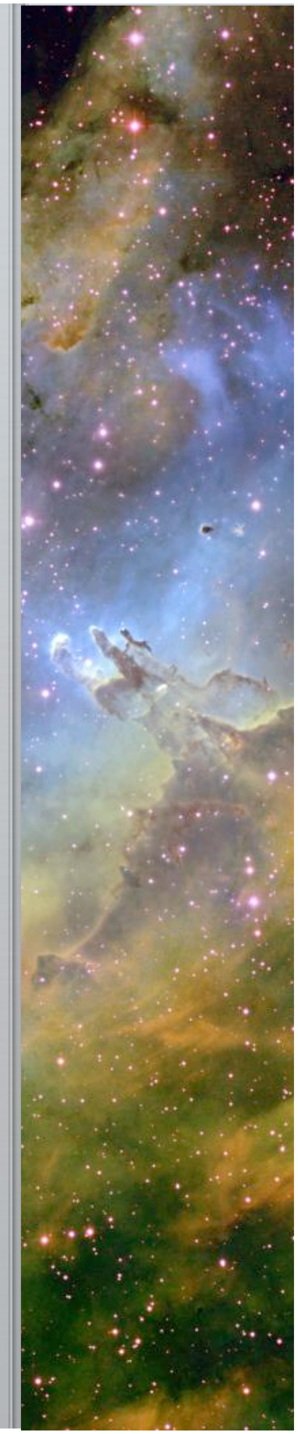


Hippelein et al. 2003

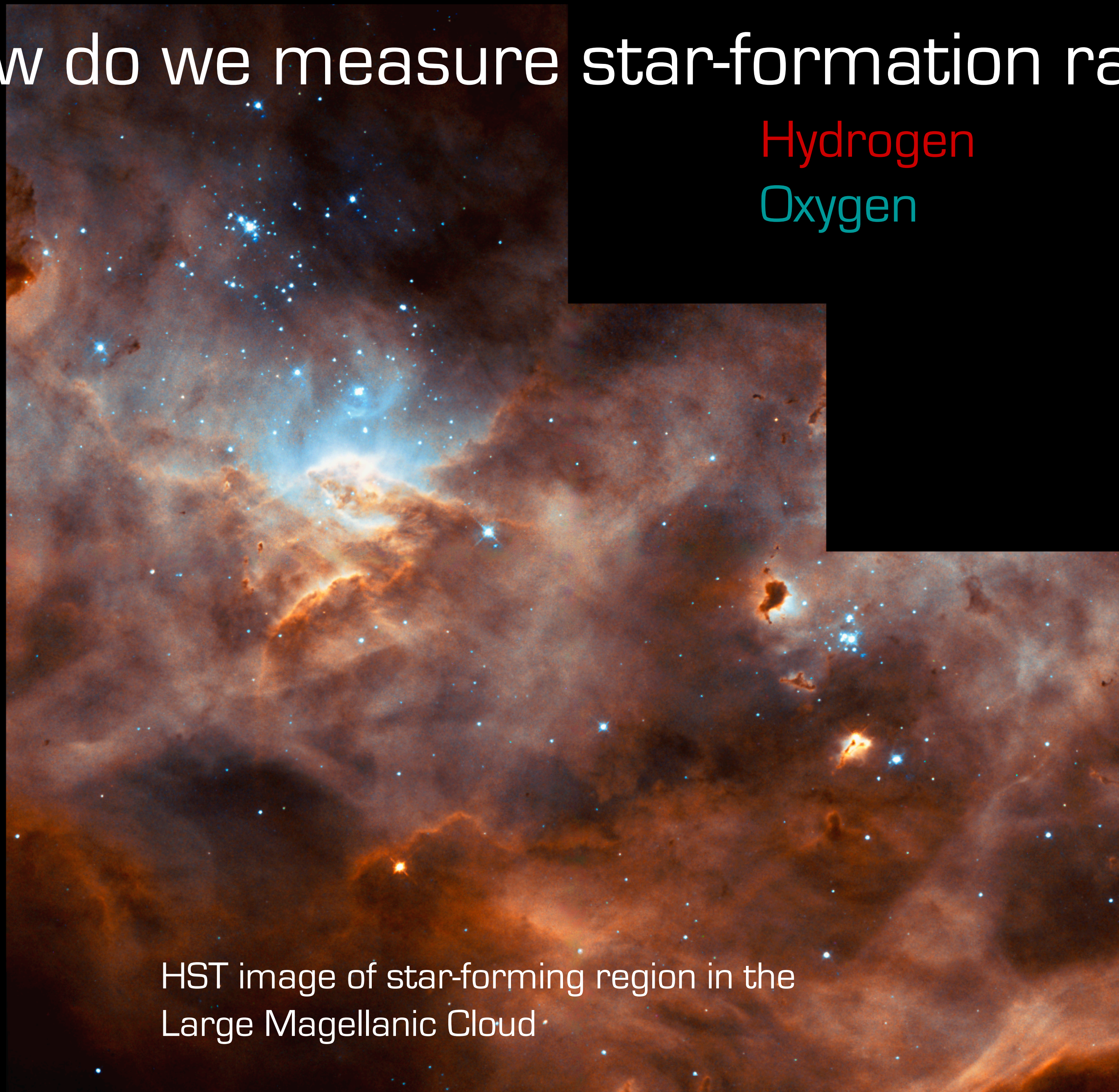


SFRs: Why do we care?

- Lots of questions:
  - Why do SFRs vary so widely among galaxies?
  - What determines a galaxy's SFR?
  - Why do SFRs vary with galaxy environment?
  - Why were SFRs higher in the past?
- Need to find answers if we are to understand galaxy evolution
  - Linked to NASA's origins theme
  - Decadal survey: Astro 2010



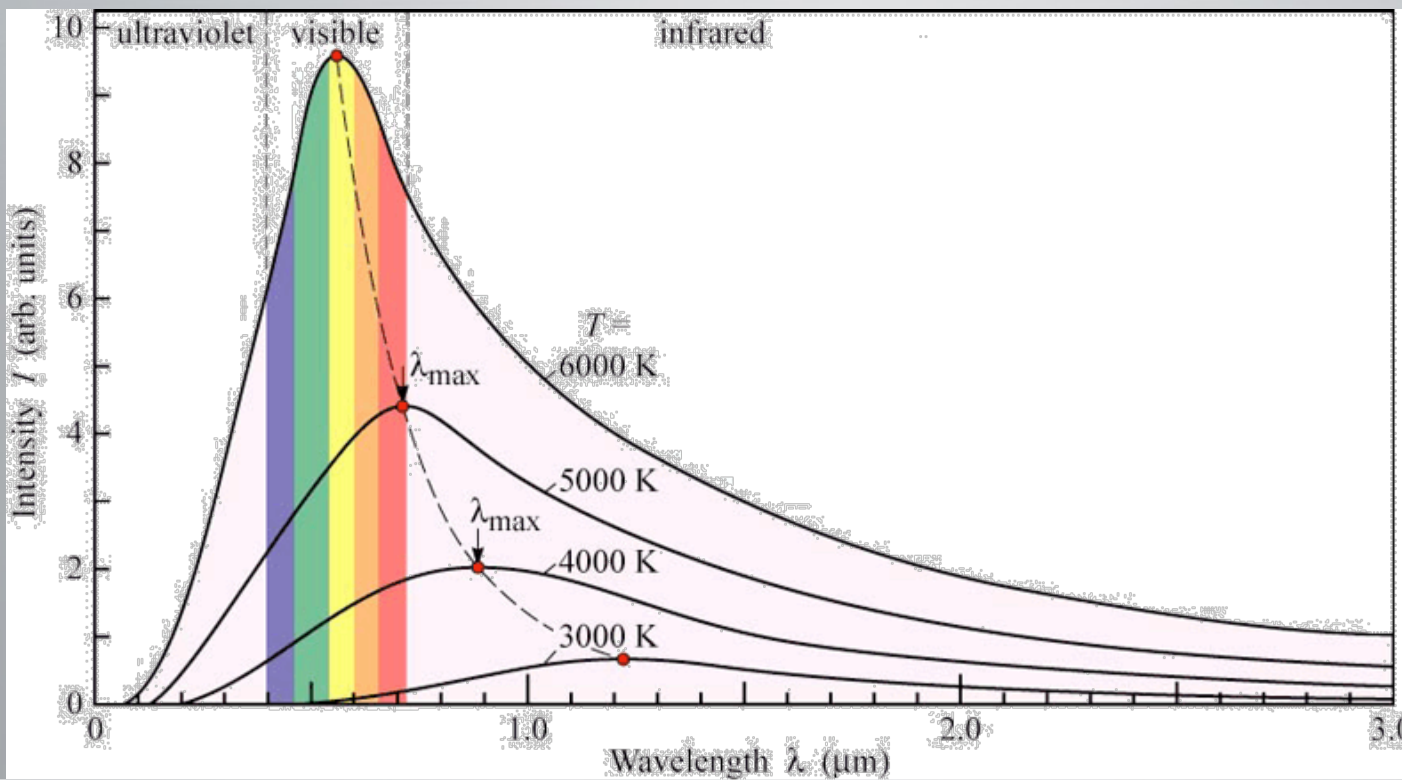
How do we measure star-formation rates?

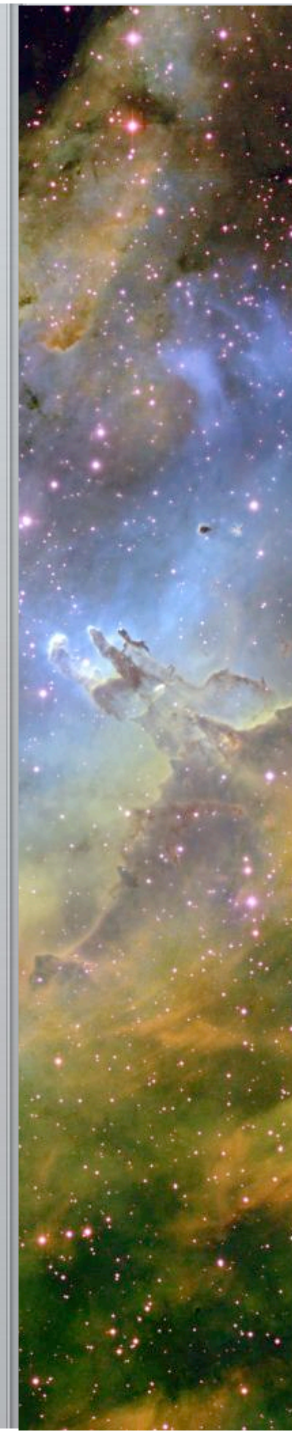


HST image of star-forming region in the Large Magellanic Cloud

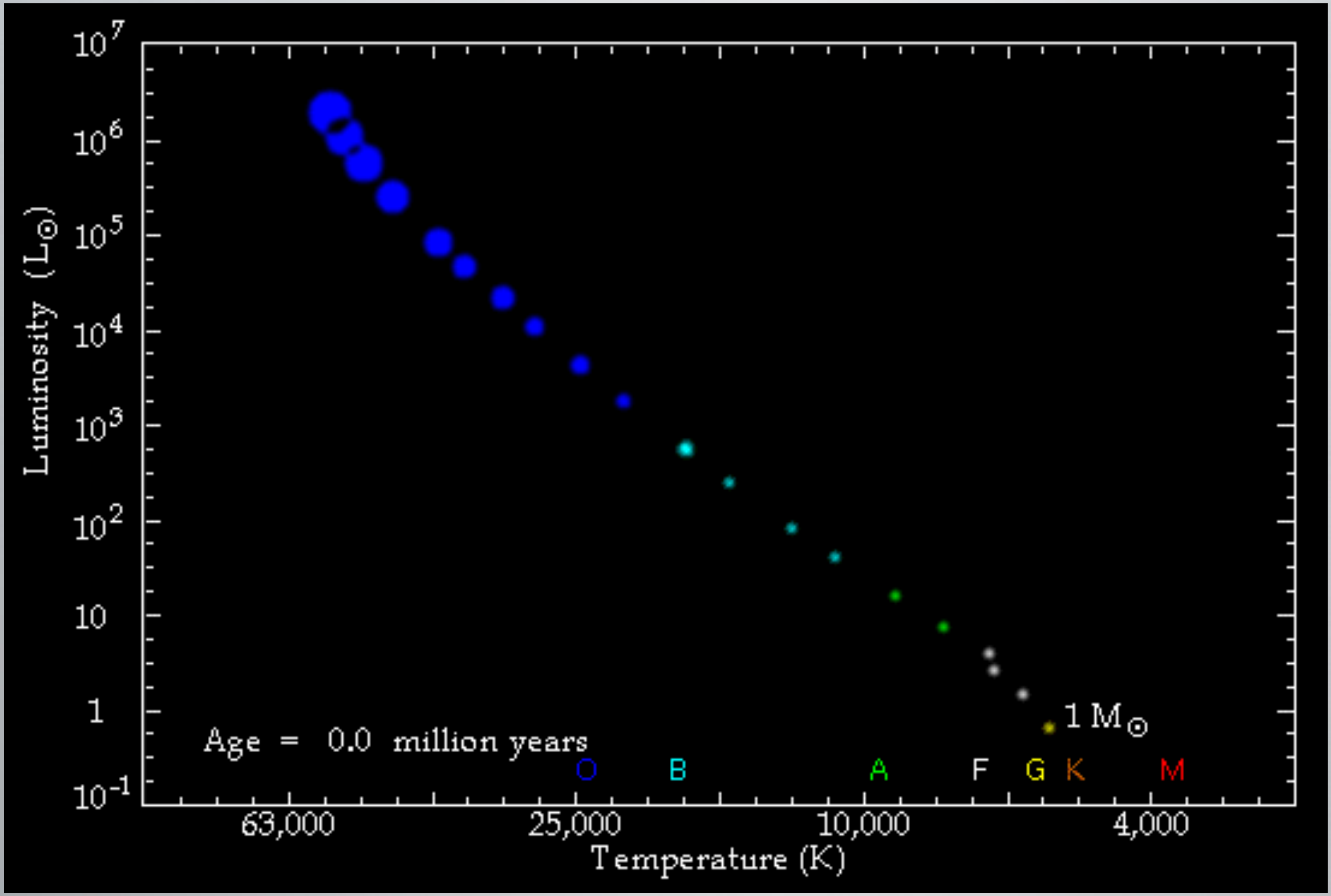
Integrated Colors of Galaxies

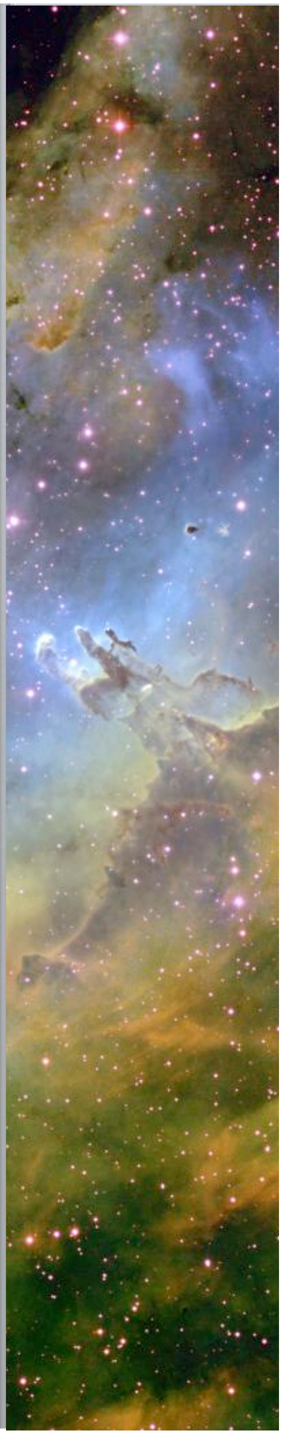
- First method used to determine SFRs
- UV and blue light is dominated by hot stars.
  - These must be young because they don't live long





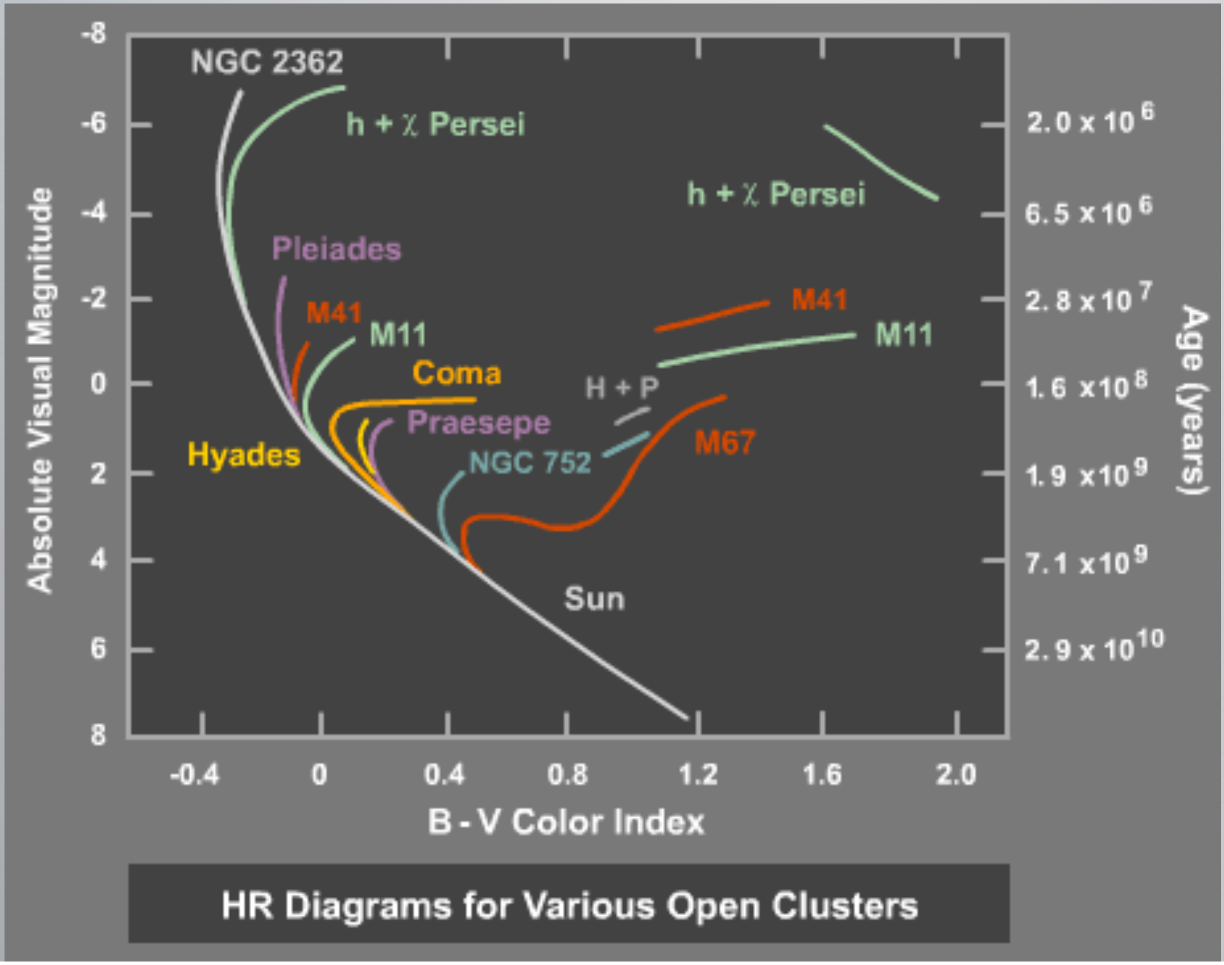
Stellar Evolution

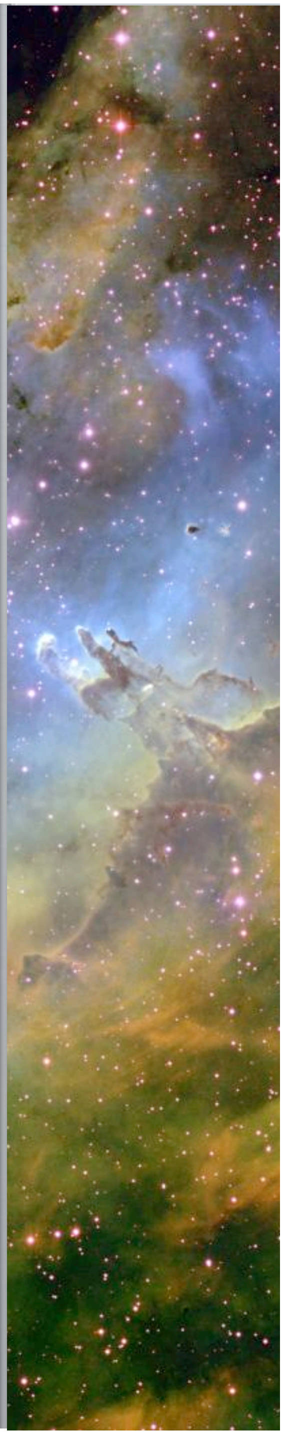




Color-Age Connection

- O-B stars burn out quickly and leave main sequence in 10 Myr





Synthesis Models

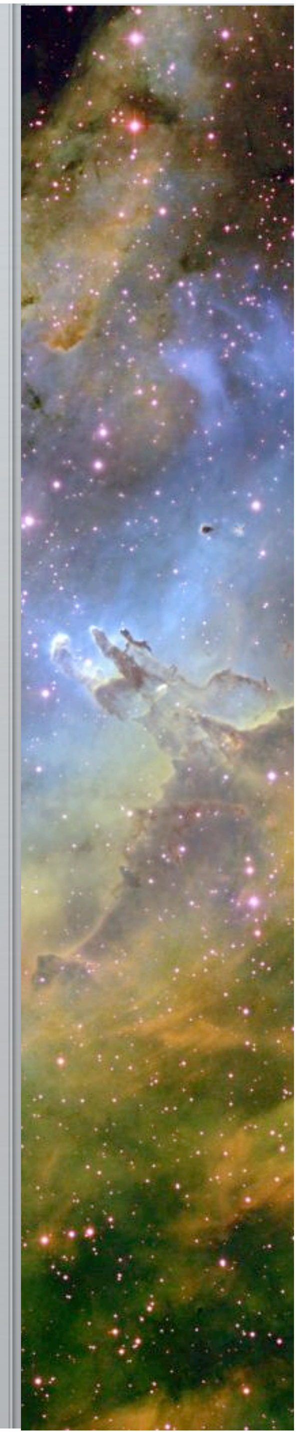
- **Use stellar evolution tracks to derive the temperature and luminosity of stars as a function of time.**
- Use an initial mass function to determine how many stars of a given stellar mass to use when constructing properties of a galaxy versus time.
- You can combine these single-age populations and let them evolve to mimic many different star-formation histories.

Synthesis Models

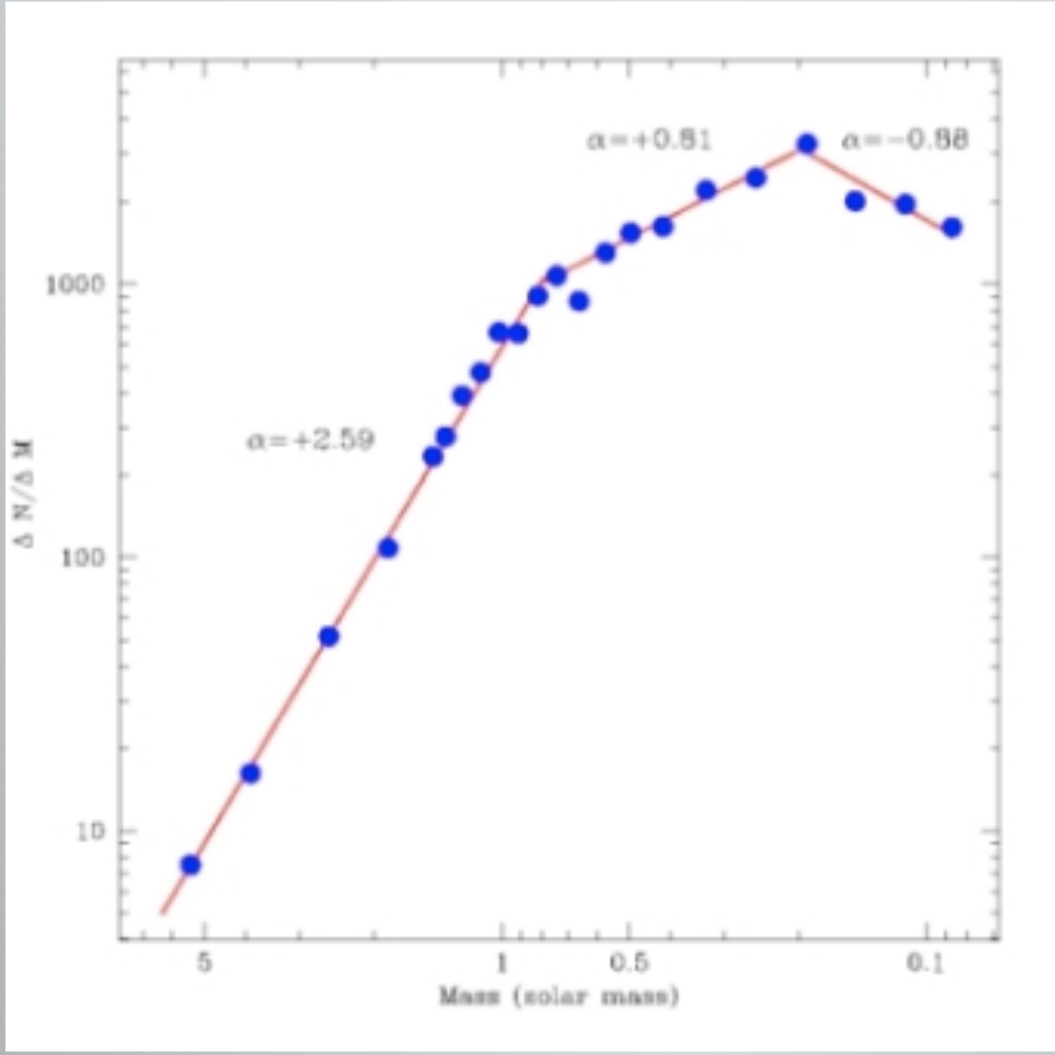
- Use stellar evolution tracks to derive the temperature and luminosity of stars as a function of time.

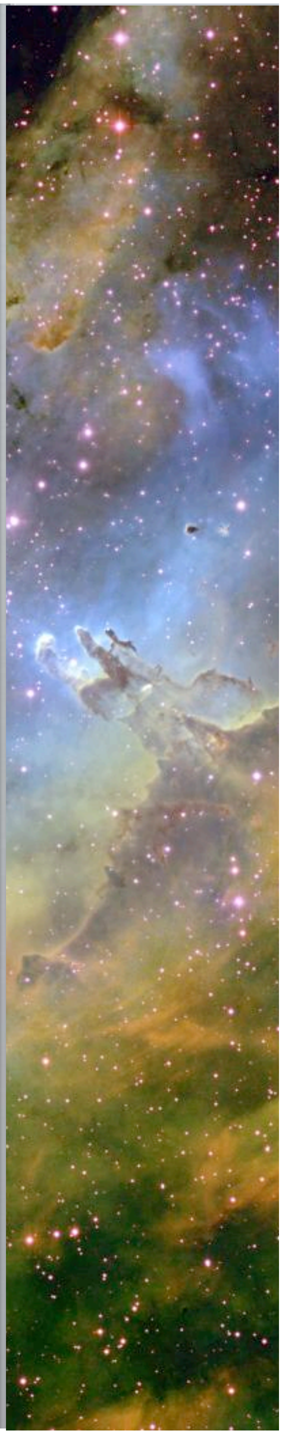
- **Use an initial mass function to determine how many stars of a given stellar mass to use when constructing properties of a galaxy versus time.**

- You can combine these single-age populations and let them evolve to mimic many different star-formation histories.



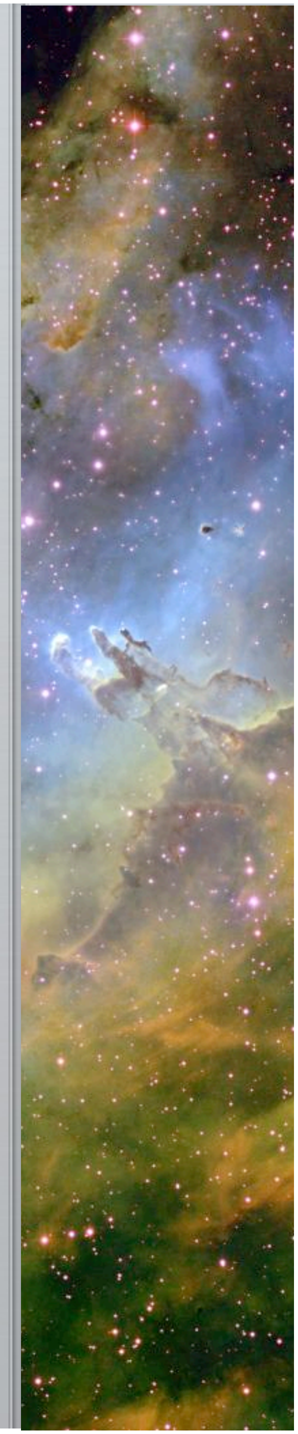
Initial Mass Function





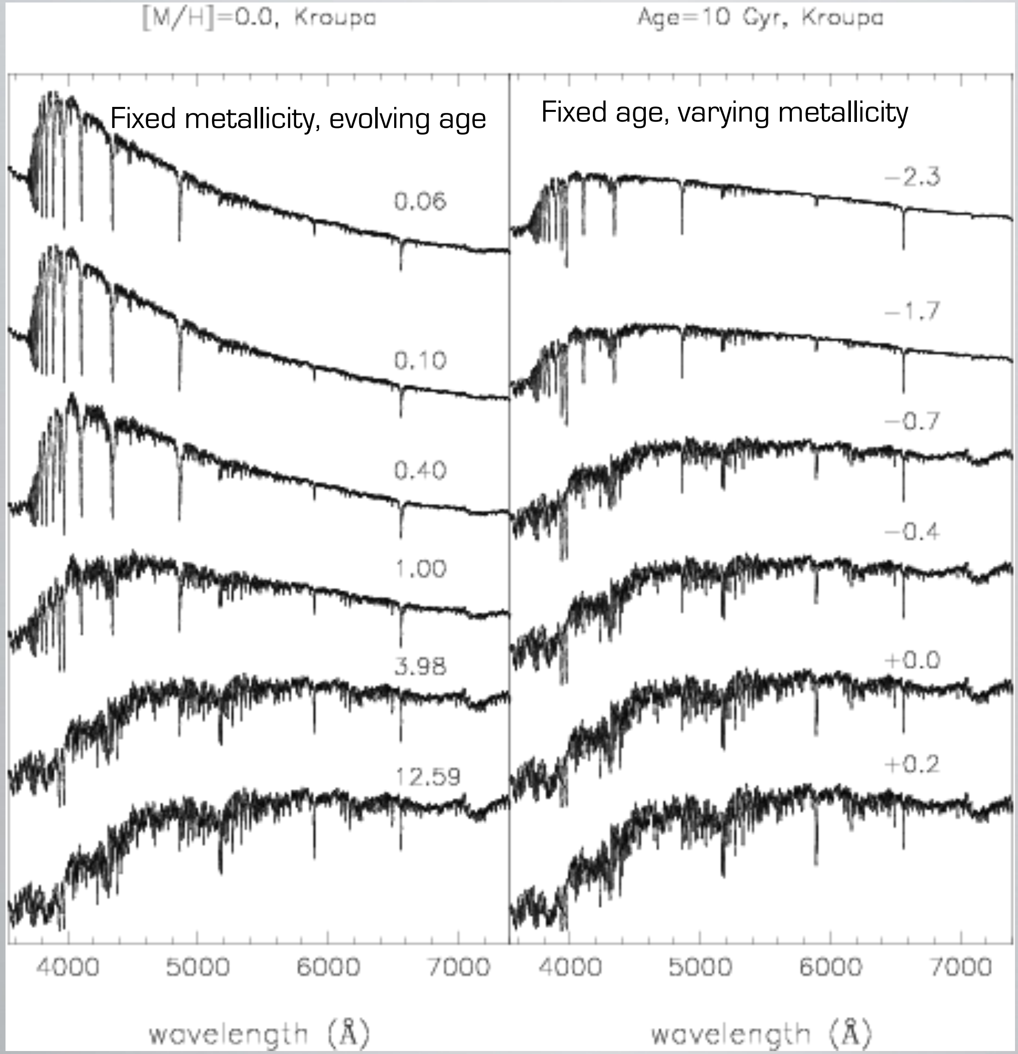
Synthesis Models

- Use stellar evolution tracks to derive the temperature and luminosity of stars as a function of time.
- Use an initial mass function to determine how many stars of a given stellar mass to use when constructing properties of a galaxy versus time.
- **You can combine these single-age populations and let them evolve to mimic many different star-formation histories.**



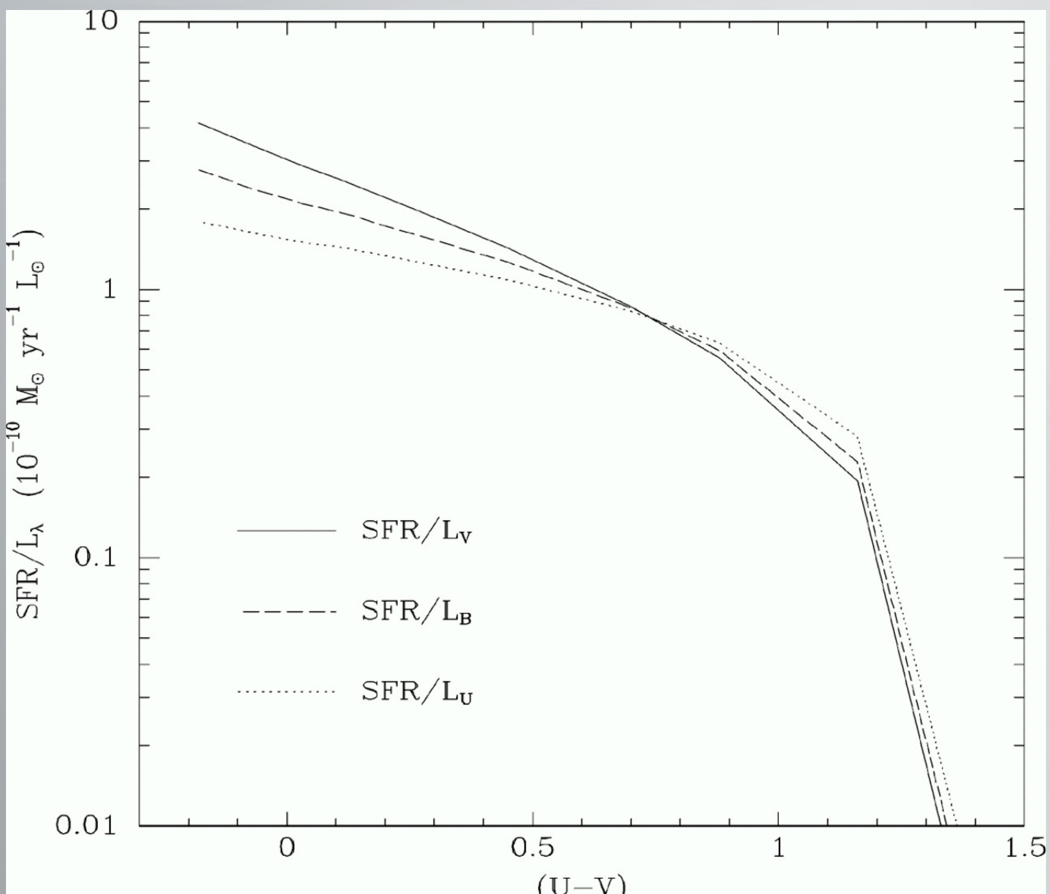
Example:


MILES
Population Synthesis
for the 21st Century
Overview
Team
Single-Stellar Population models SEDs

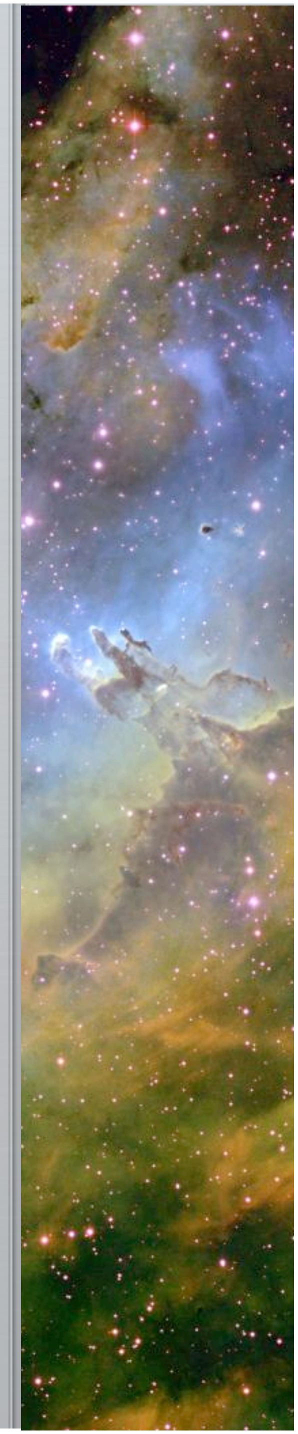

[M/H]=0.0, Kroupa
Age=10 Gyr, Kroupa
Fixed metallicity, evolving age
Fixed age, varying metallicity
0.06
0.10
0.40
1.00
3.98
12.59
-2.3
-1.7
-0.7
-0.4
+0.0
+0.2
4000
5000
6000
7000
wavelength (Å)

Synthesis Models

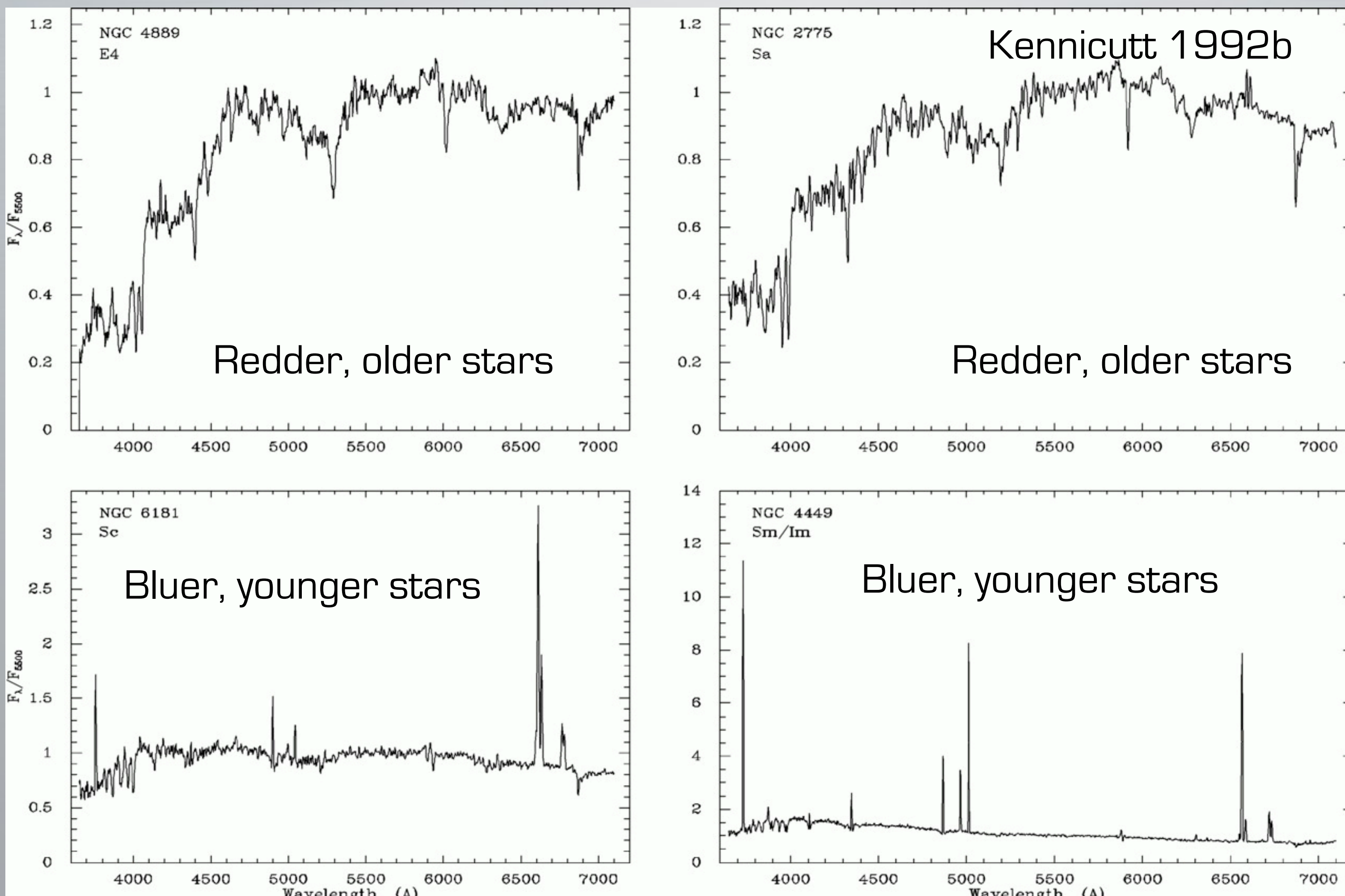
- Synthesis models can then provide the link between broad-band color and SFR.

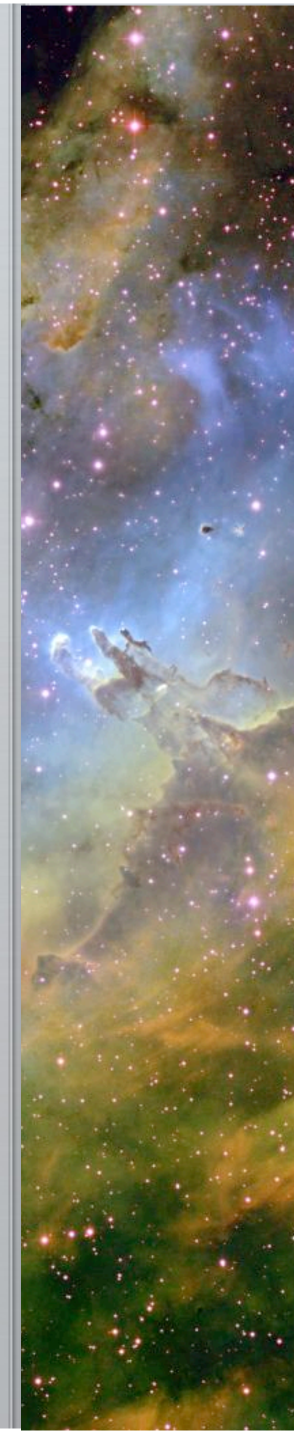


Example from Kennicutt et al (1994) linking SFR and broadband luminosities



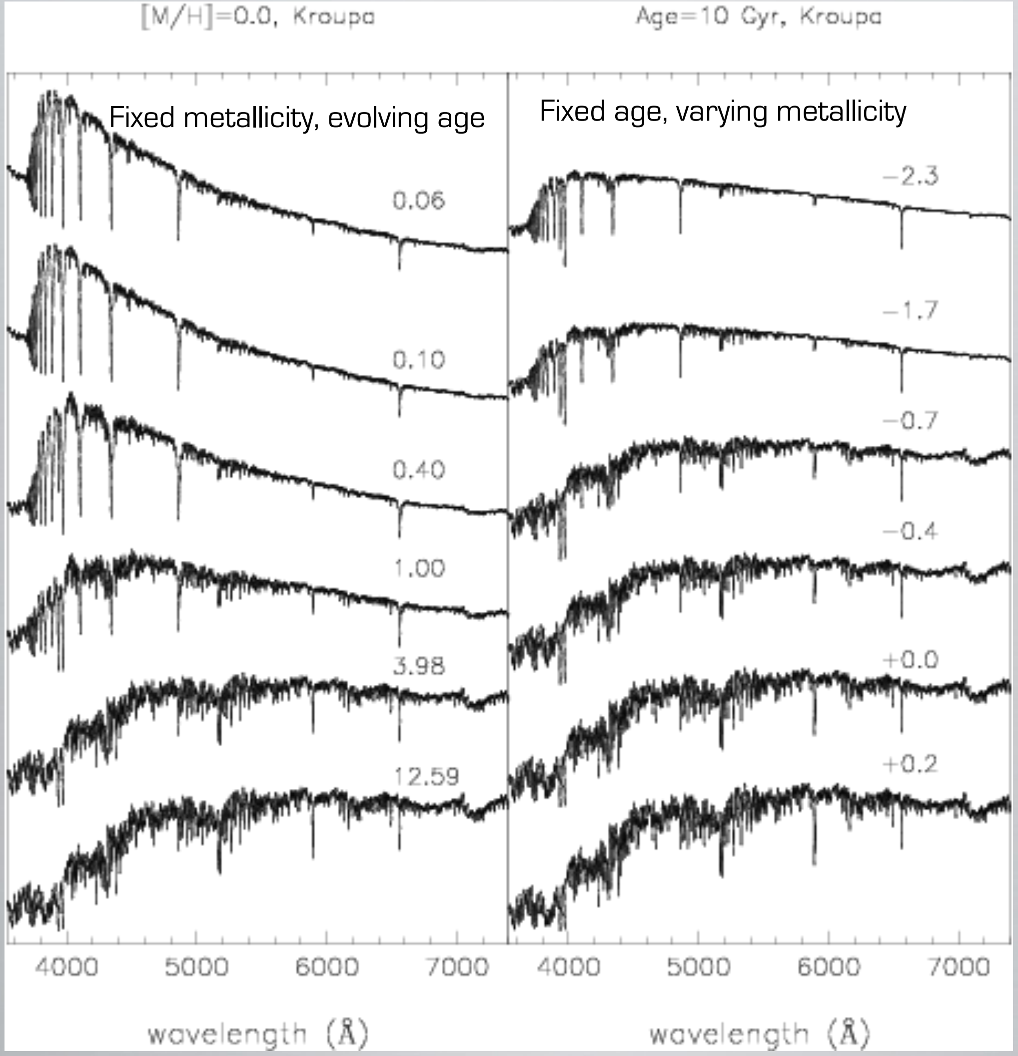
Integrated Spectra of Galaxies

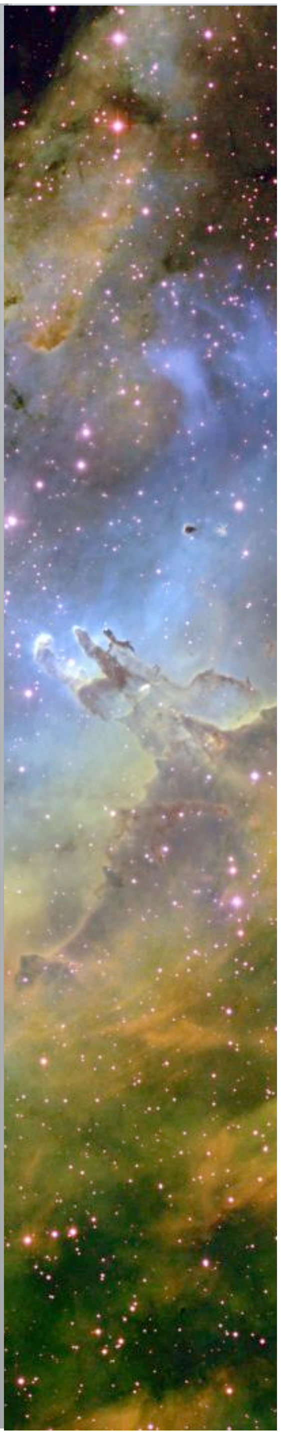




Example:


MILES
Population Synthesis
for the 21st Century
Overview
Team
Single-Stellar Population models SEDs


[M/H]=0.0, Kroupa
Age=10 Gyr, Kroupa
Fixed metallicity, evolving age
Fixed age, varying metallicity
0.06
0.10
0.40
1.00
3.98
12.59
−2.3
−1.7
−0.7
−0.4
+0.0
+0.2
4000
5000
6000
7000
wavelength (Å)

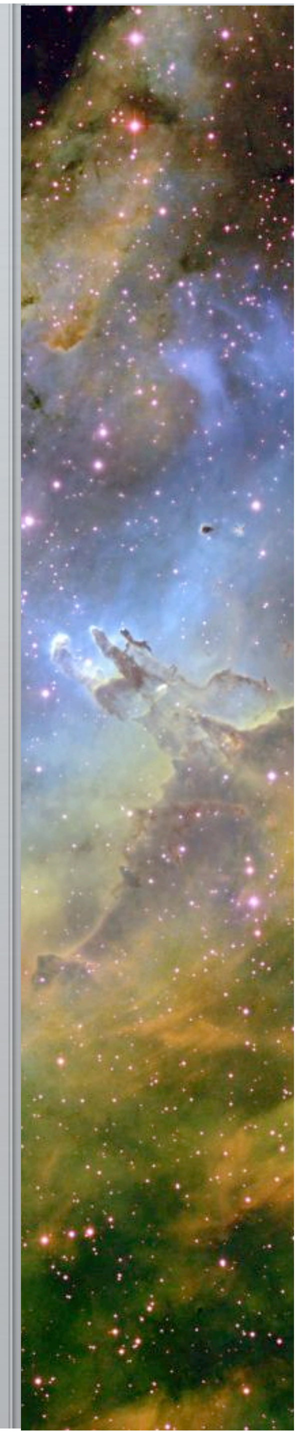


Ultraviolet Continuum

- In UV, spectrum is dominated by young stars
  - λ ~900-3000 Å (Calzetti 2007)
- Amount of UV radiation scales linearly with the SFR:

$$SFR(M_{\odot}\ yr^{-1}) = 1.4 \times 10^{-28} L_{\nu}(ergs\ s^{-1}\ Hz^{-1})$$

- Probes stars with ages < 100 Myr.
  - Recent star formation



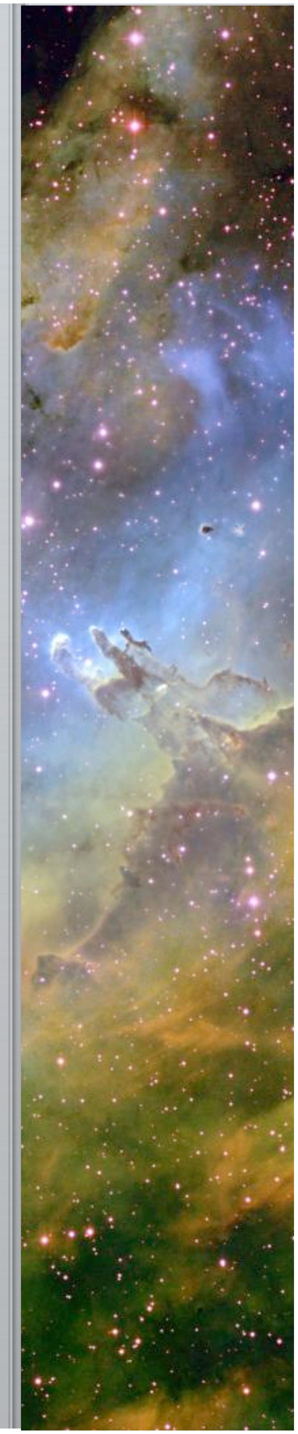
Ultraviolet Continuum

Advantages

- Tied directly to emission from young stars
- Wavelength range is observable for distant galaxies
  - Good for quantifying evolution
- Lots of data from GALEX

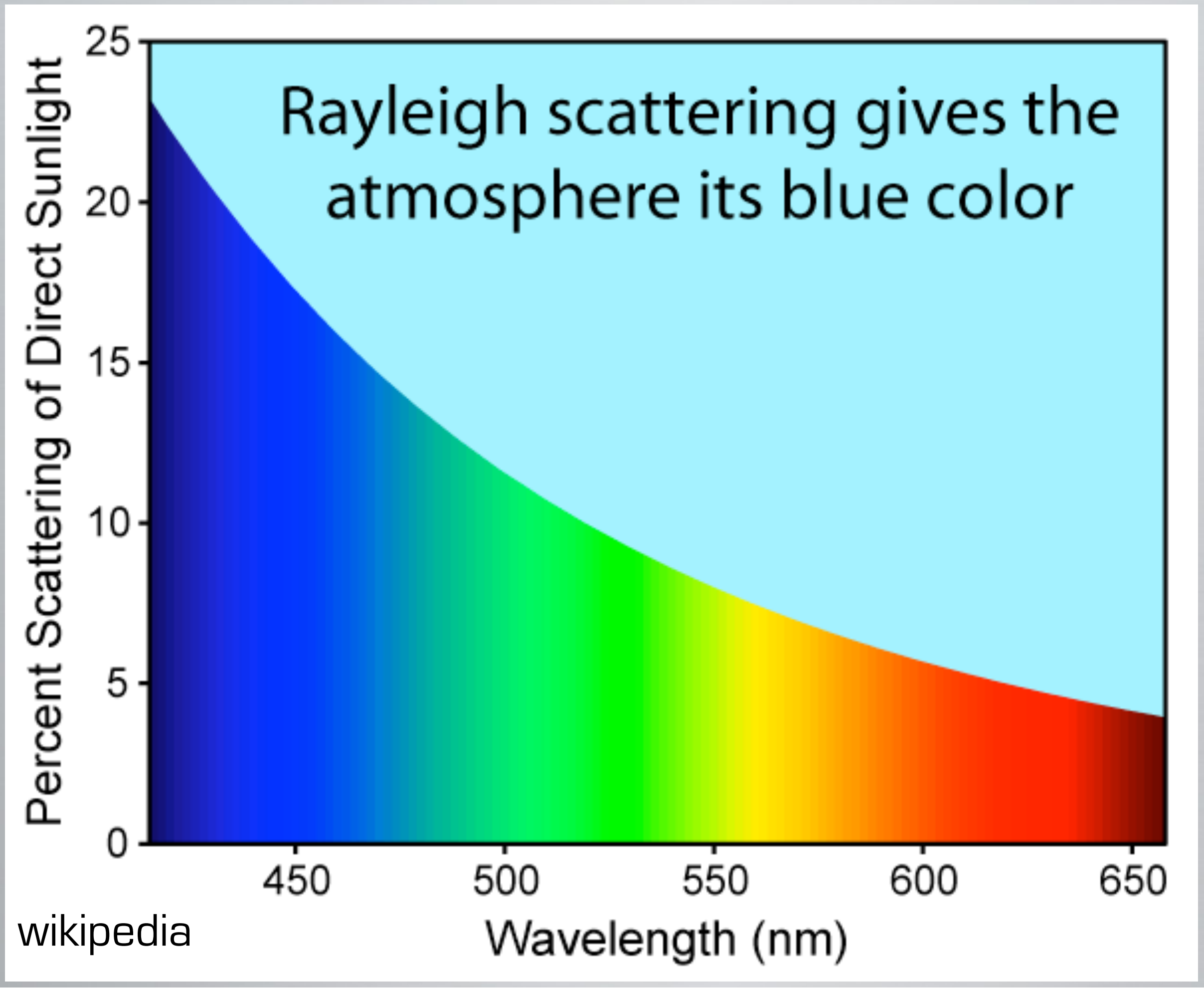
Disadvantages

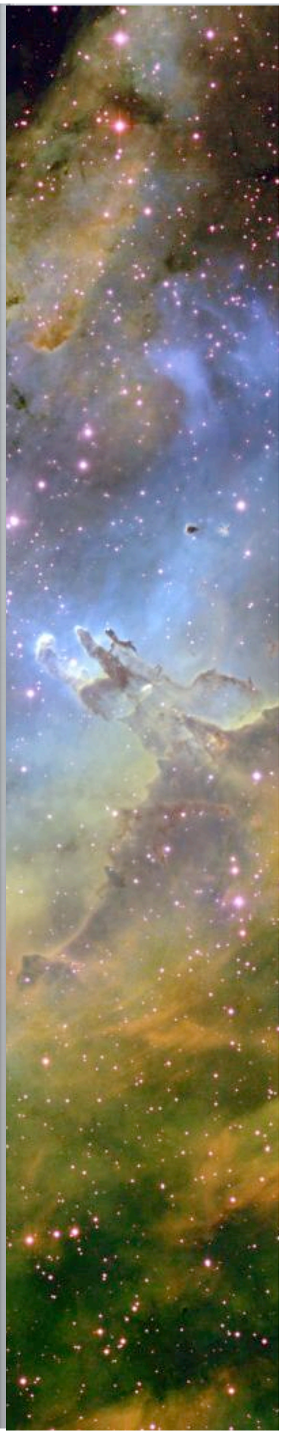
- UV light is attenuated by dust
- Dust (and therefore extinction) is patchy
- Depends on the IMF that you use
  - This is true for most SFR indicators



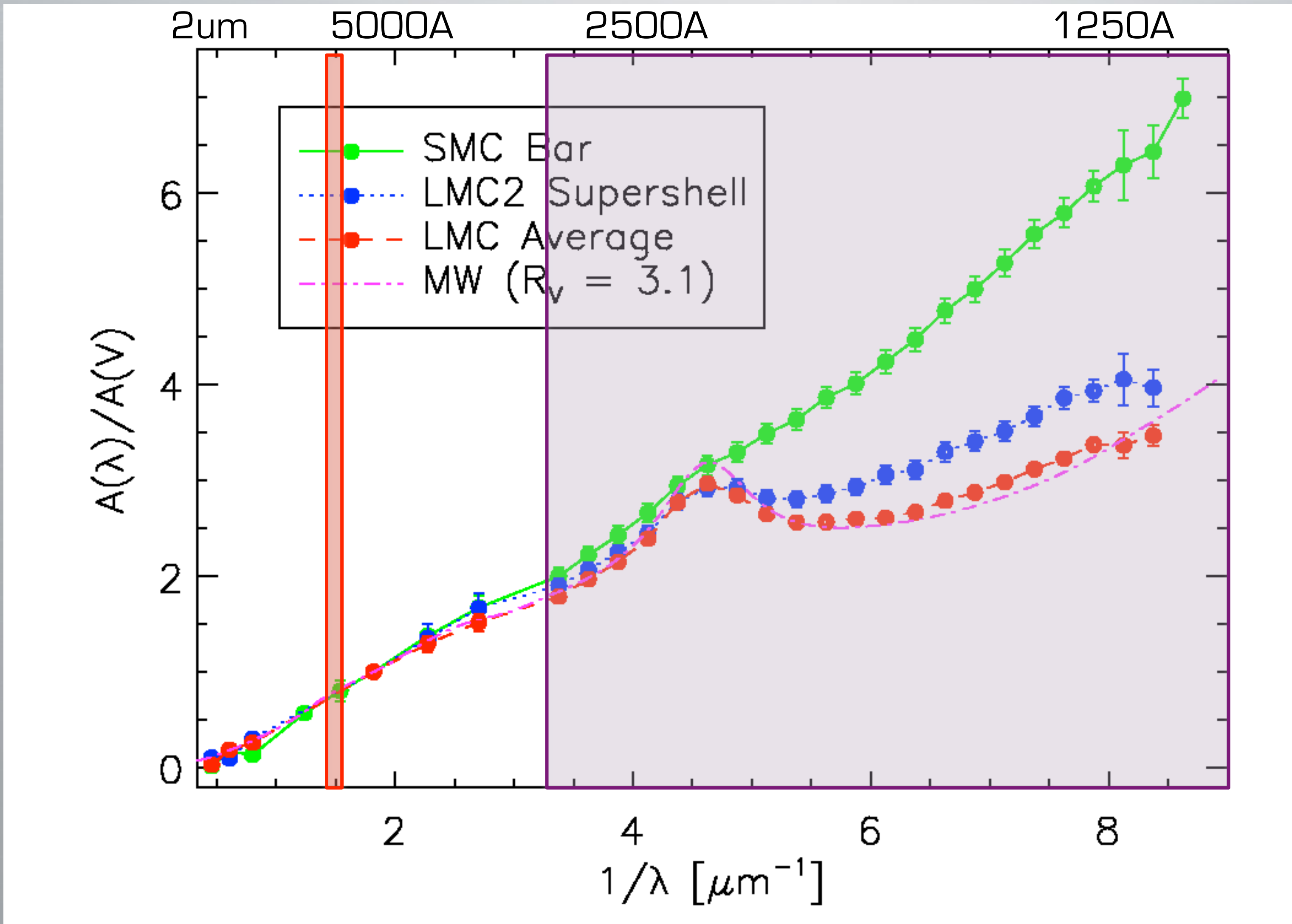
Extinction of Starlight

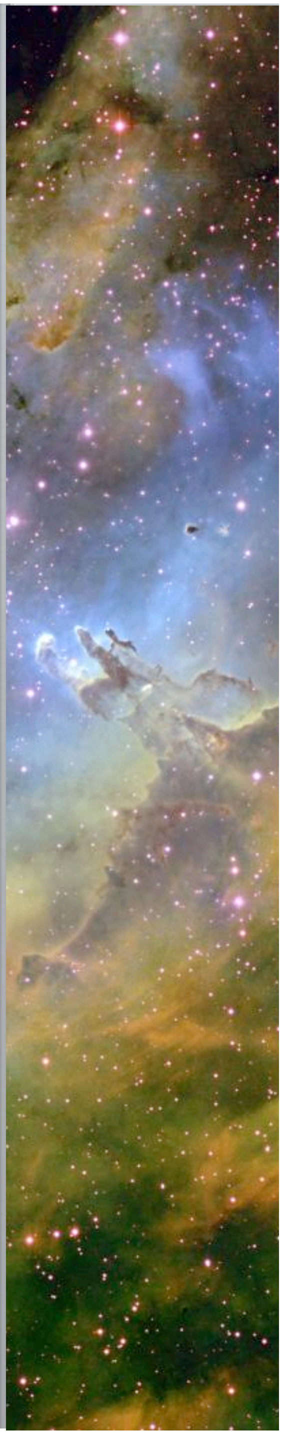
$$scattering \propto \frac{1}{\lambda^4}$$





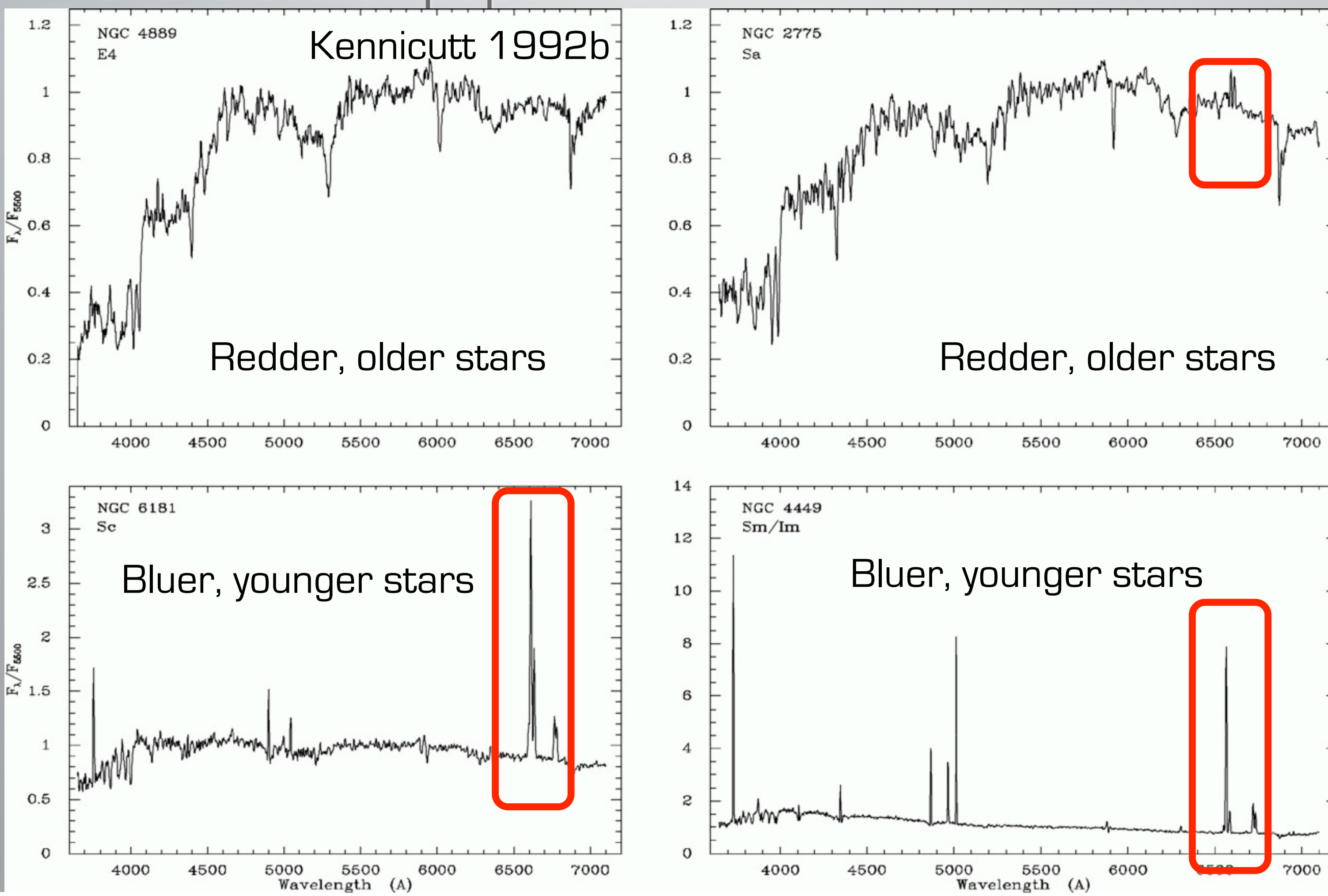
Extinction of Starlight

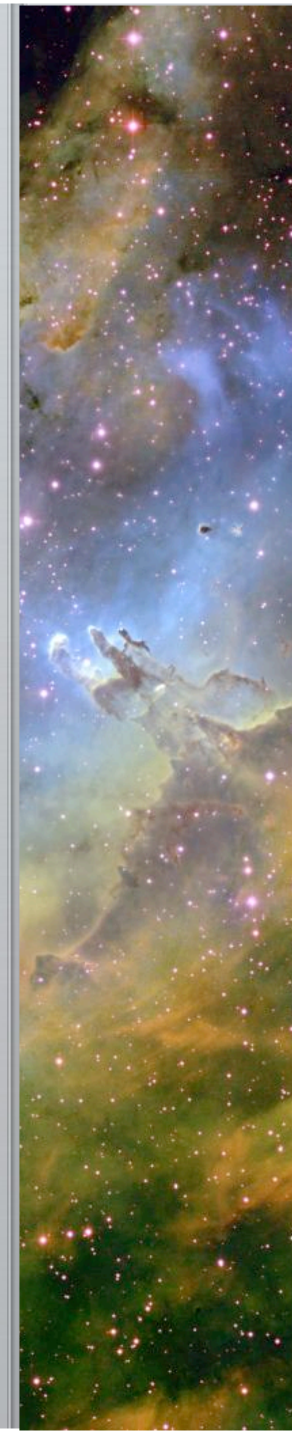




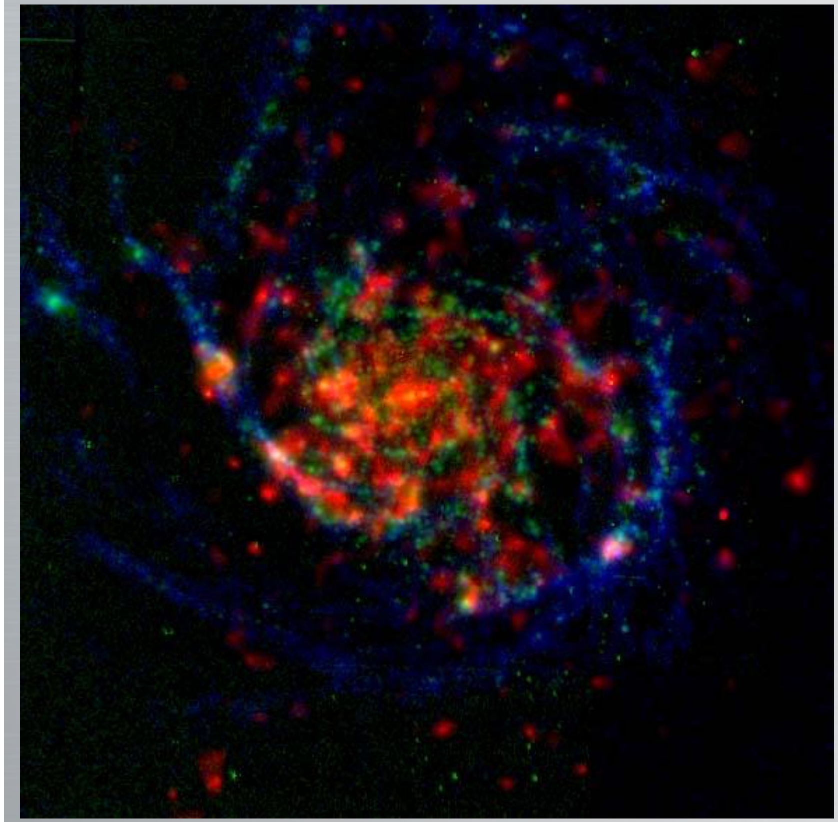
Recombination Lines

- Strength of H emission lines varies with the age of the stellar population





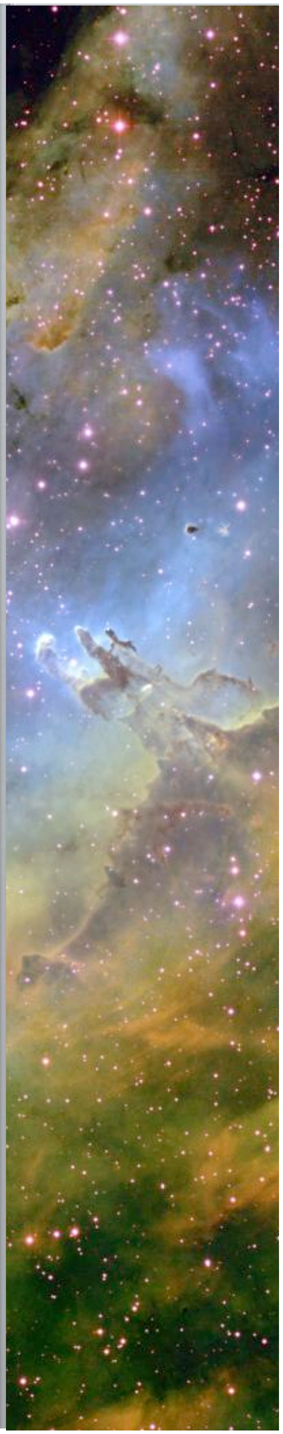
Measuring Star Formation Rates from H α



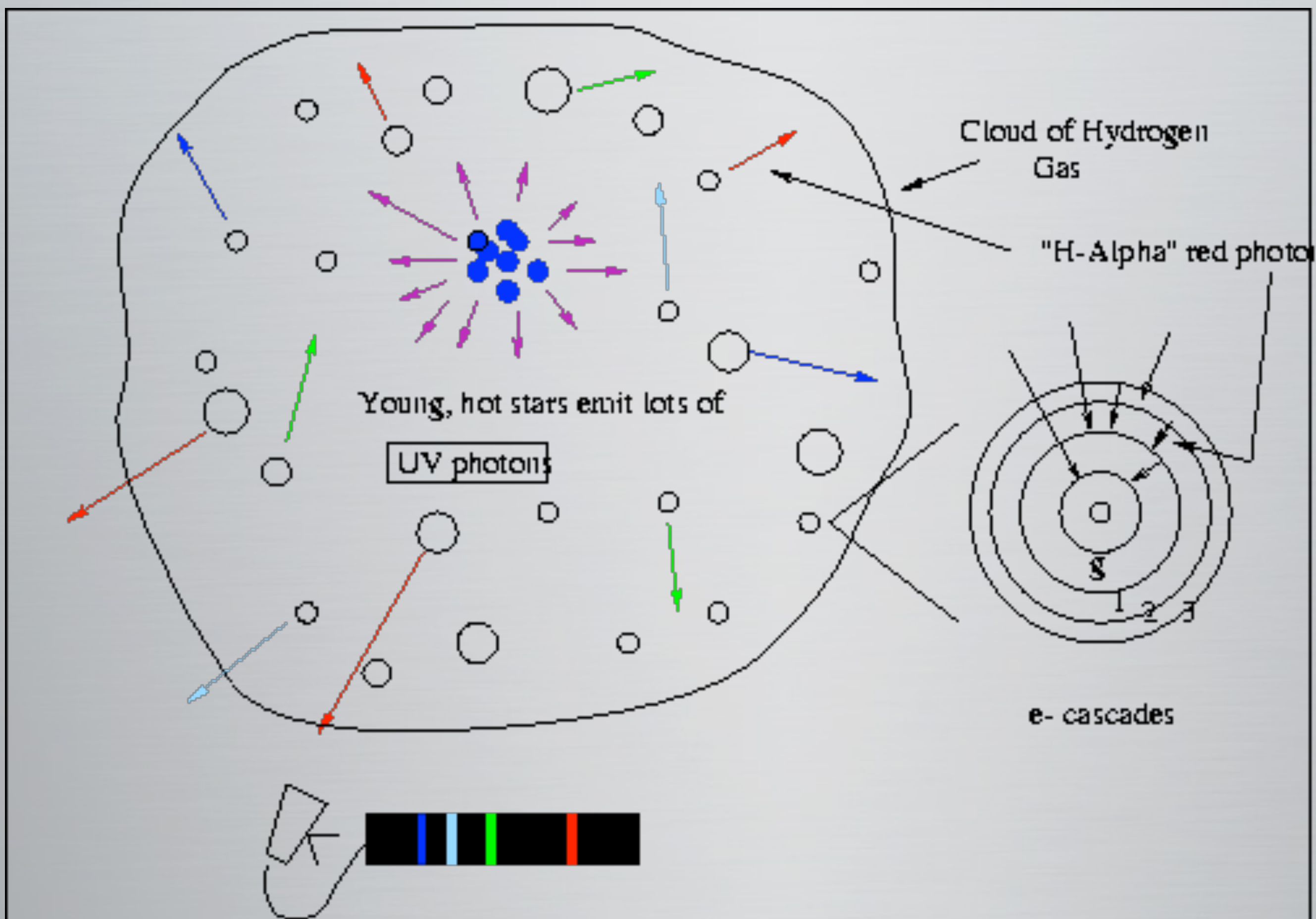
M101: X-ray, HI 21-cm, H α
(D. Wang et al.)

- Hydrogen is ionized by massive stars (ages < 10 Myr)
- Hydrogen recombines
- As electron transitions from 3 to 2 orbital, the atom releases a photon at 6563 Å.
- This is the H α line.

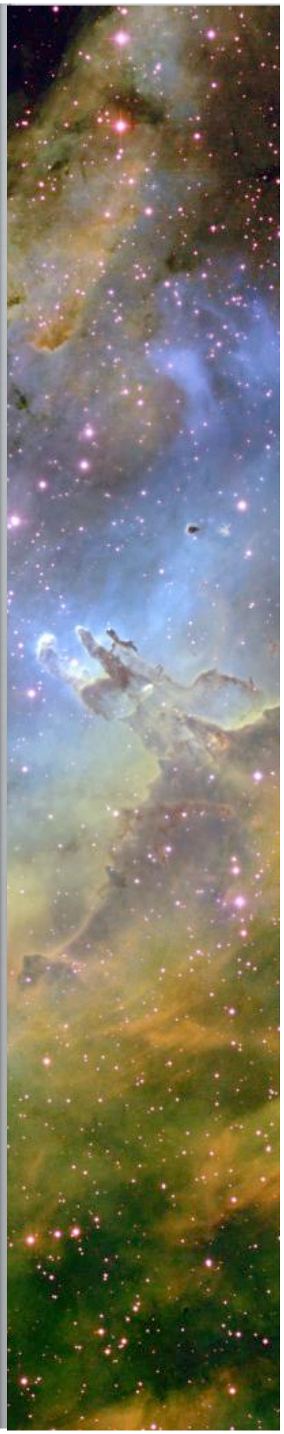
Bonus: Use the Bohr model of the atom to predict the wavelength of H-alpha



H-alpha Emission from HII Regions



http://www.ucolick.org/~bolte/AY4_00/week3/HII_region.gif

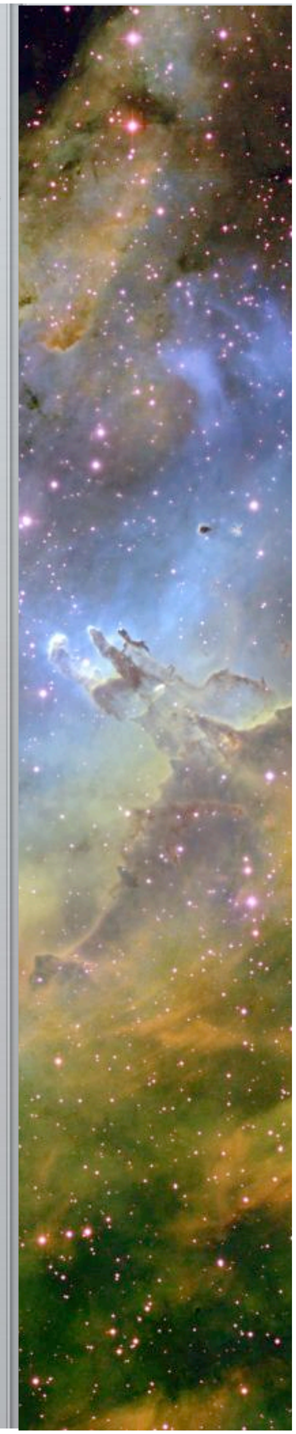


Measuring Star Formation Rates from Hα

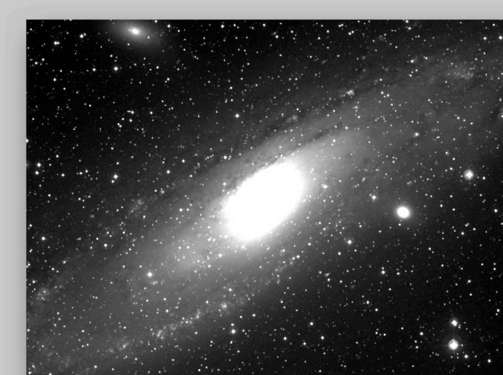
- Relate Hα flux to amount of ionizing radiation
- Convert to total star formation rate using stellar initial mass function (e.g. Kennicutt 1998)

$$SFR(M_\odot\ yr^{-1}) = 7.9 \times 10^{-42} L(H\alpha)(ergs\ s^{-1})$$

- Hα is used most commonly, but you can use other H lines too (Hβ, Paβ, Paα, Brγ)

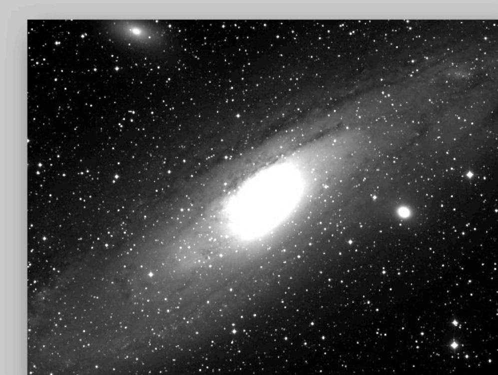


H-alpha Image of M31



Hα

-



Red

=

Hα pure

http://www.manalokos.com/emission/Continuum_subtraction_tutorial

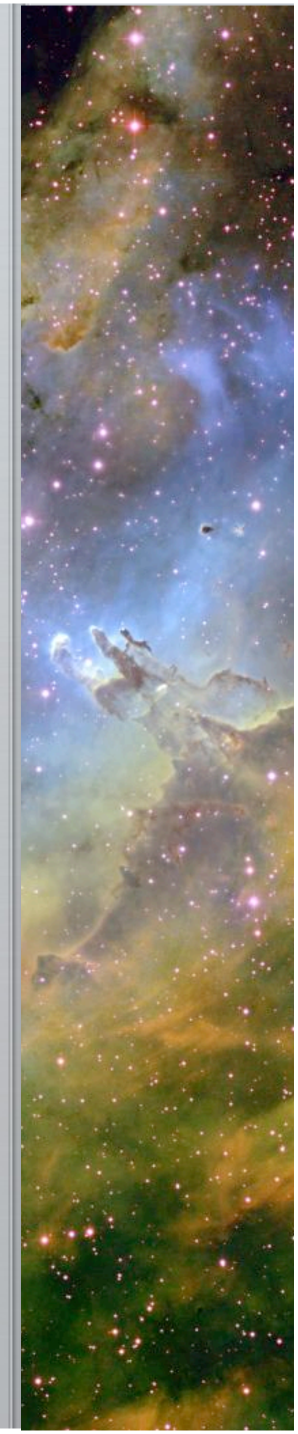
Hα Emission

Advantages

- Direct link between nebular emission and massive star-formation
  - Traces “current” SF
- Used widely at low redshift
- Can obtain resolved images from modest ground-based telescopes
- Accessible at higher-redshift

Disadvantages

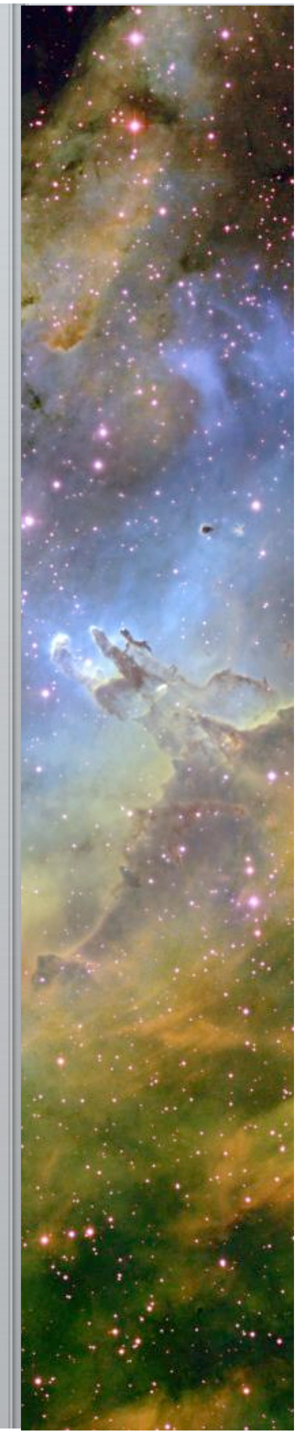
- Sensitive to extinction by dust
- Shifts out of optical window at $z>0.4$, so observations become more difficult
- Depends on IMF, particularly upper mass limit



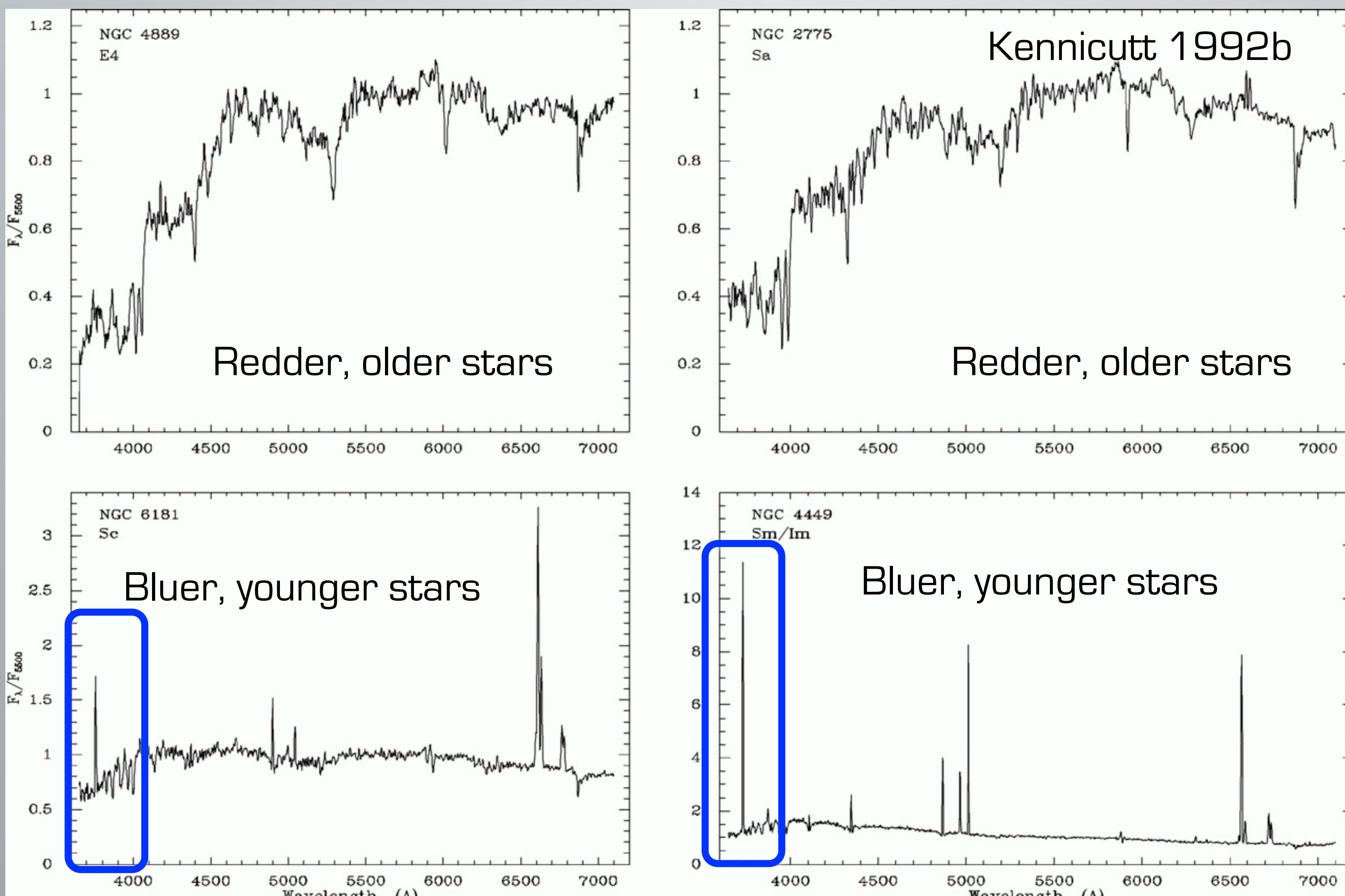
Forbidden Lines

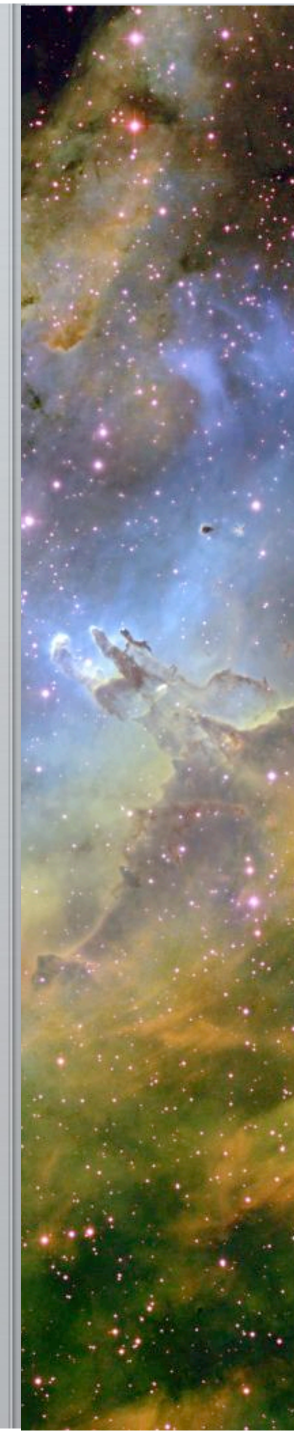
- A bluer line would allow access in optical window to higher redshift
- Blue Hydrogen lines are weaker and are affected by stellar absorption
- Lots of effort to calibrate [O II] (3727 Å) emission line as a star-formation indicator
    - Empirical calibration based on Hα

$$SFR(M_\odot \ yr^{-1}) = 1.4 \pm 0.4 \times 10^{-41} L([O \ II])(ergs \ s^{-1})$$



[O II] Emission





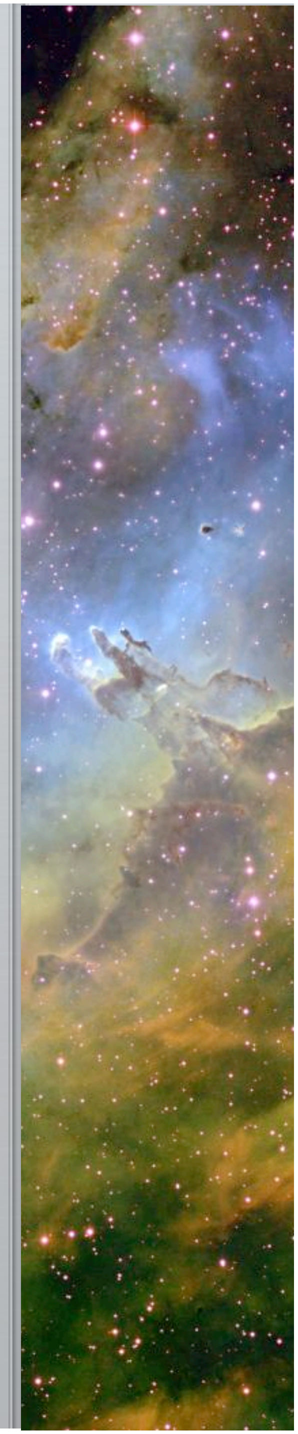
[O II] Emission

Advantages

- Strong emission line
- Blue, so line is accessible in optical window out to $z \sim 1.5$

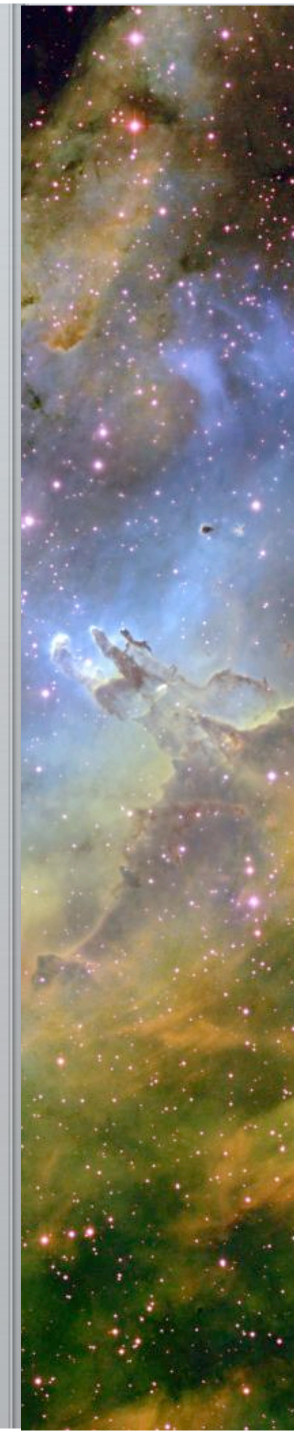
Disadvantages

- Line strength varies with metallicity
- More affected by extinction than Hα



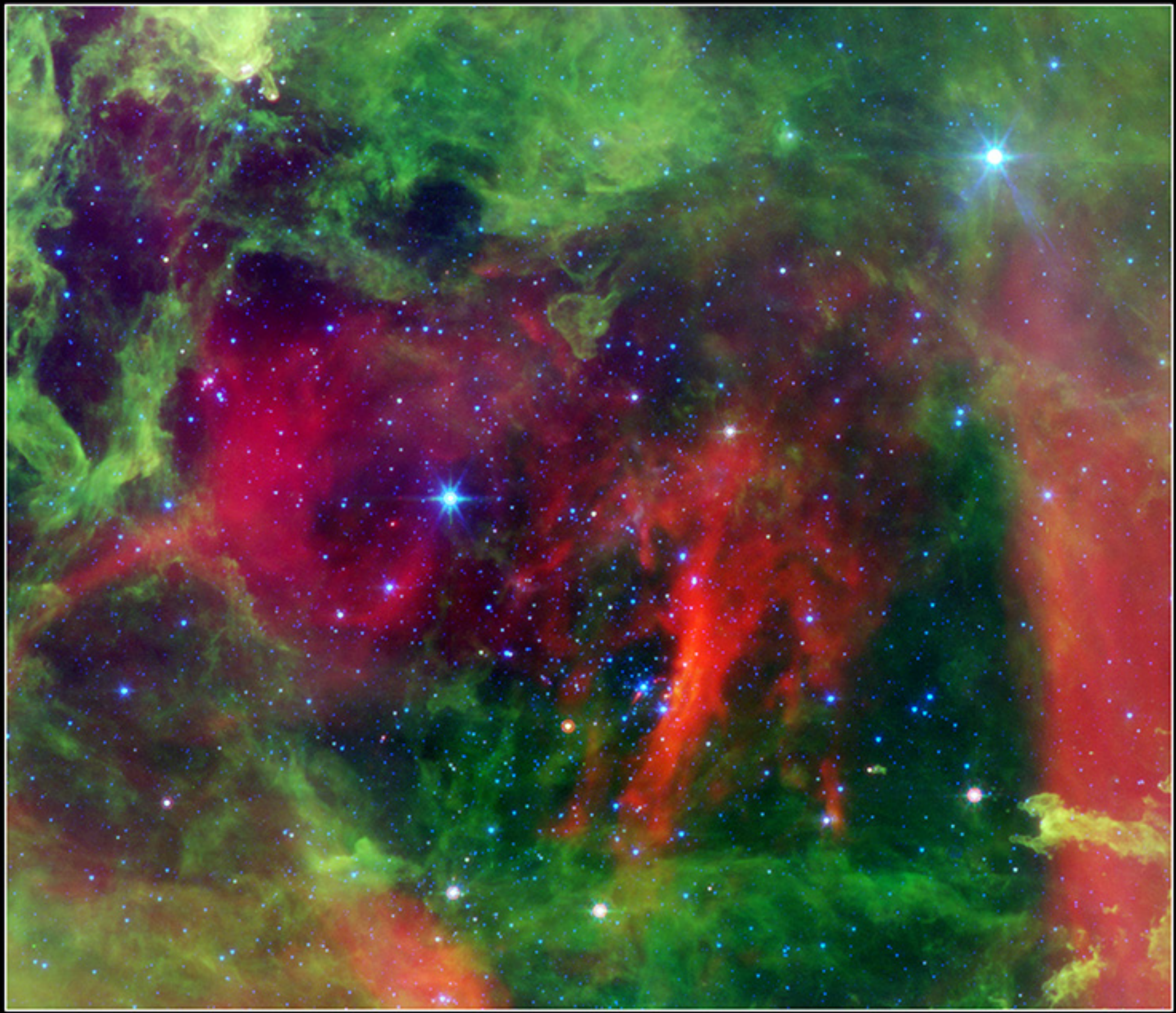
Far-Infrared Continuum

- A significant fraction of a galaxy’s light is absorbed by dust and re-rediated in the infrared



Star Formation Rates from the Thermal IR

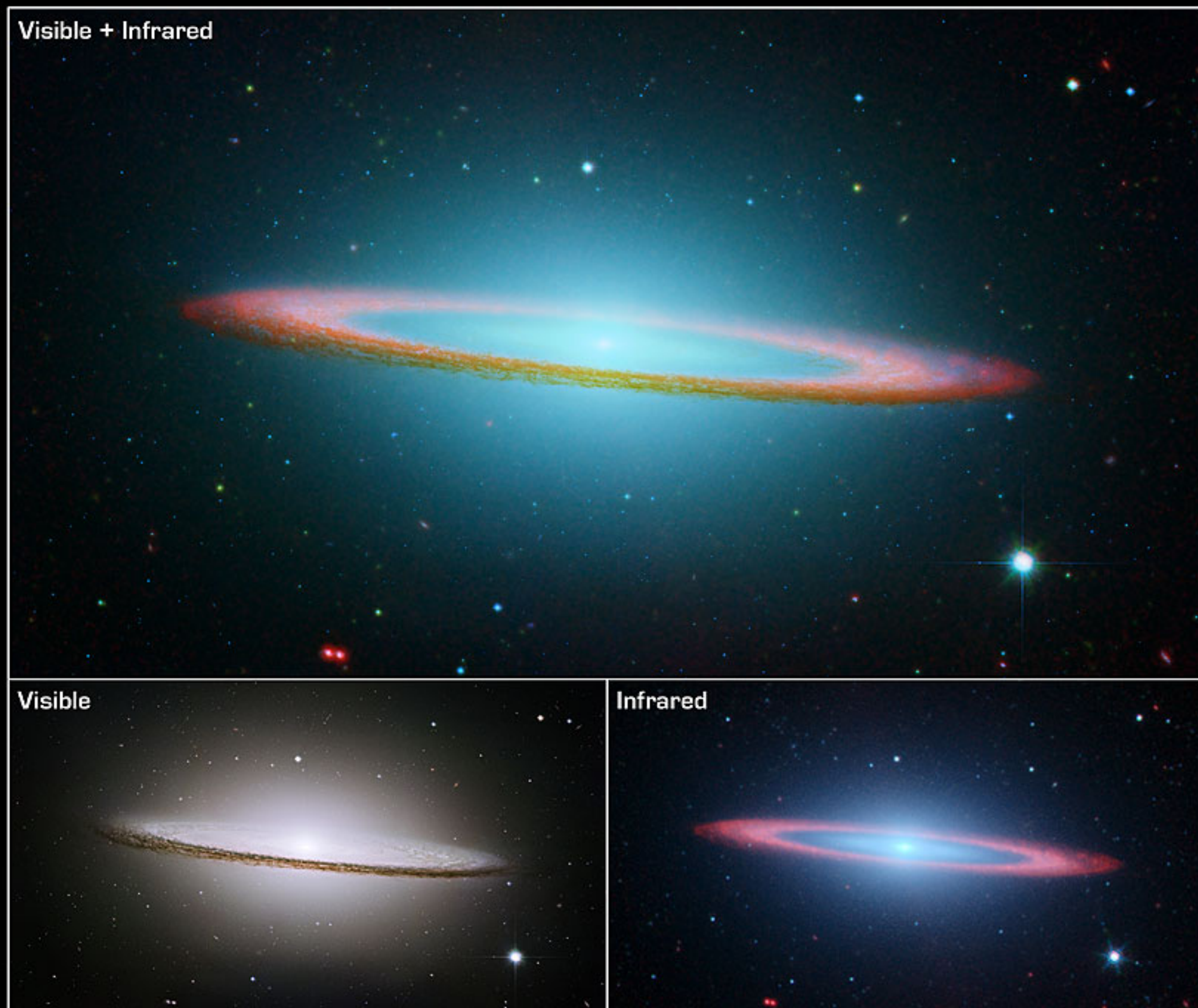
4.5 um
8.0 um
24 um



Star-Forming Rosette Nebula (NGC 2244) Spitzer Space Telescope • IRAC • MIPS
NASA / JPL-Caltech / Z. Balog (Univ. of Ariz./Univ. of Szeged) ssc2007-08a

Star Formation Rates from the Thermal IR

3.6 um
4.5 um
8.0 um



Sombrero Galaxy/Messier 104

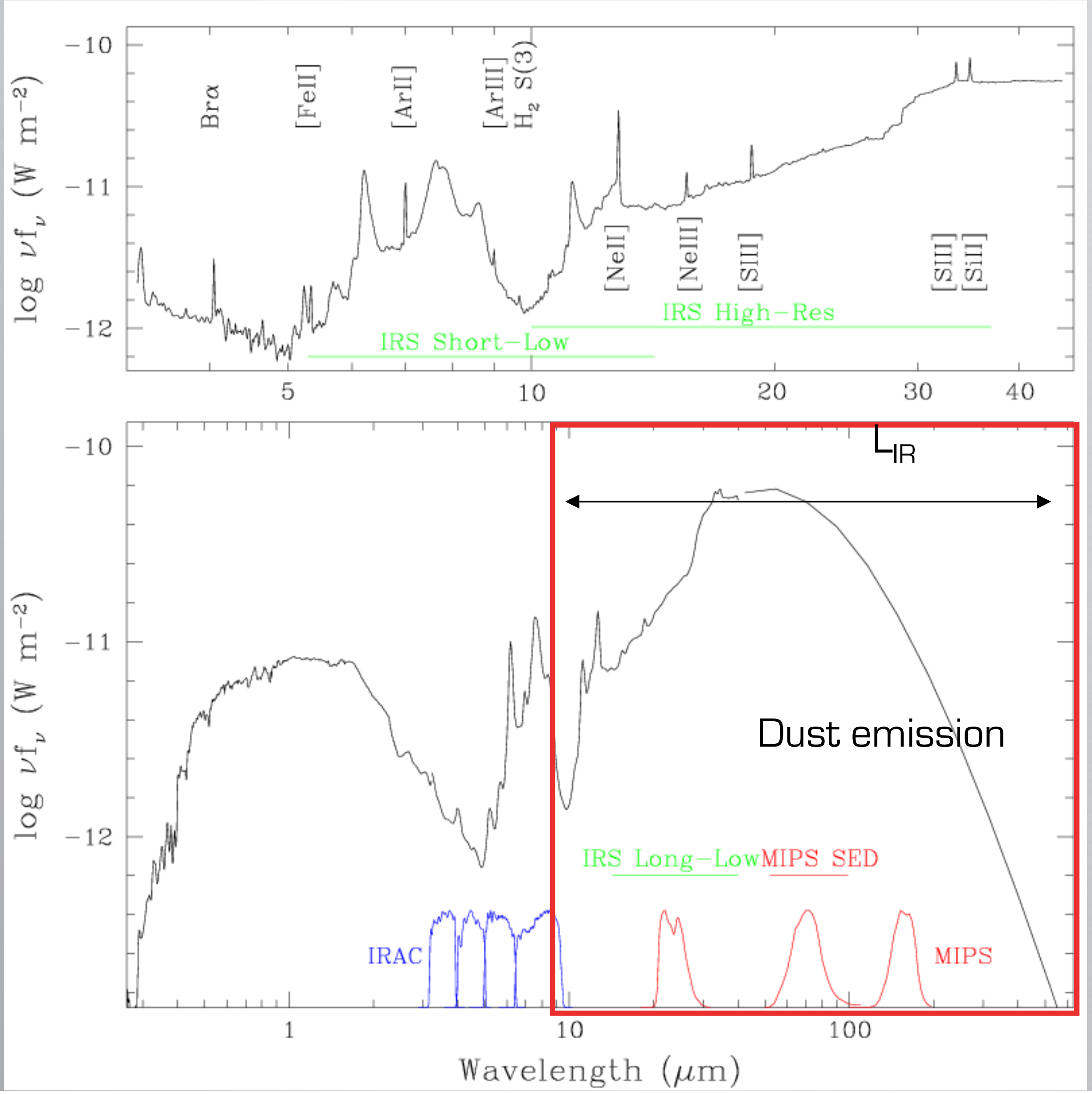
Spitzer Space Telescope • IRAC

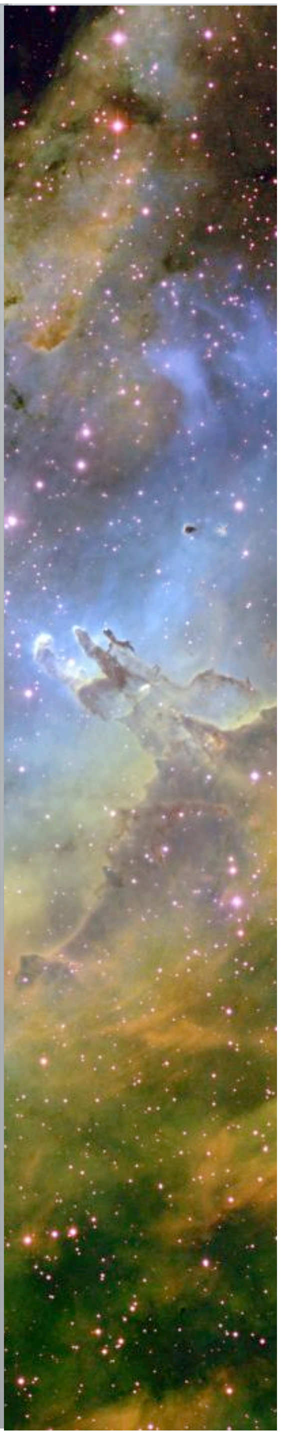
Visible: Hubble Space Telescope/Hubble Heritage Team

NASA / JPL-Caltech / R. Kennicutt (University of Arizona), and the SINGS Team

ssc2005-11a

Star Formation Rates from the Thermal IR



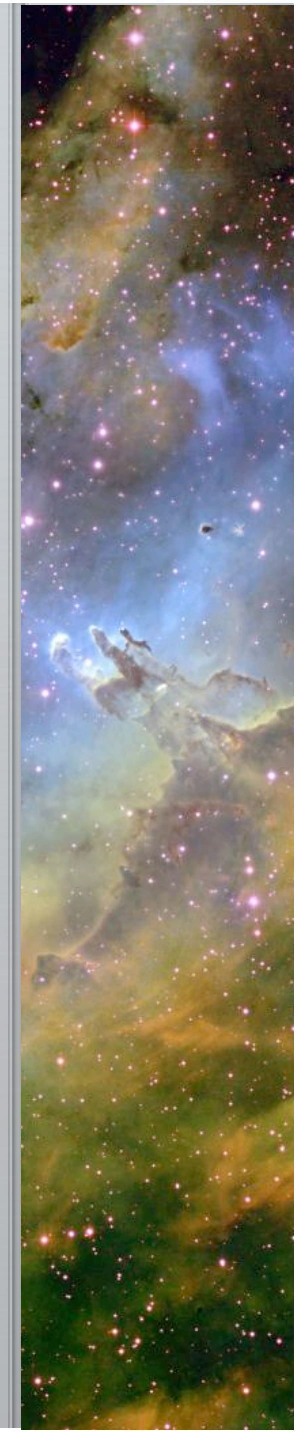


Far-Infrared Continuum

- A significant fraction of a galaxy's light is absorbed by dust and re-rediated in the infrared
- The conversion is derived using synthesis models

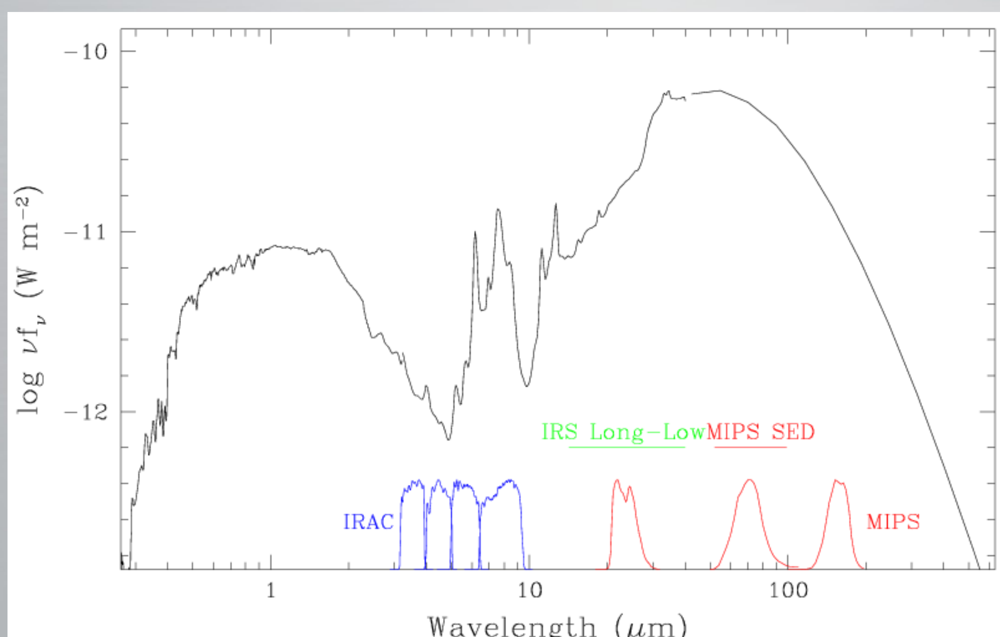
$$SFR(M_\odot \; yr^{-1}) = 4.5 \times 10^{-44} L(FIR)(ergs \; s^{-1})$$

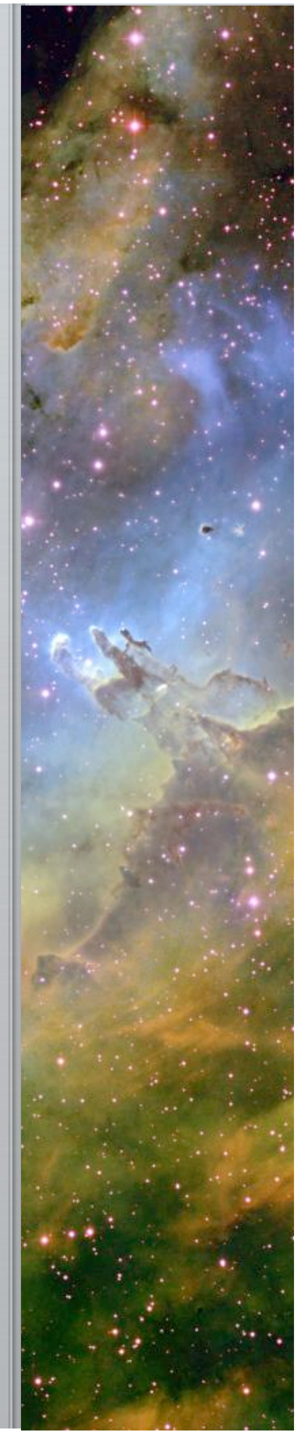
applies to starbursts with ages less than 10^8 yrs



Far-Infrared Emission

- SFR calibration is based on emission between 8 and 1000 μm.
- Need to use model spectra (e.g. Dale & Helou 2002) to relate observed fluxes to total IR luminosity





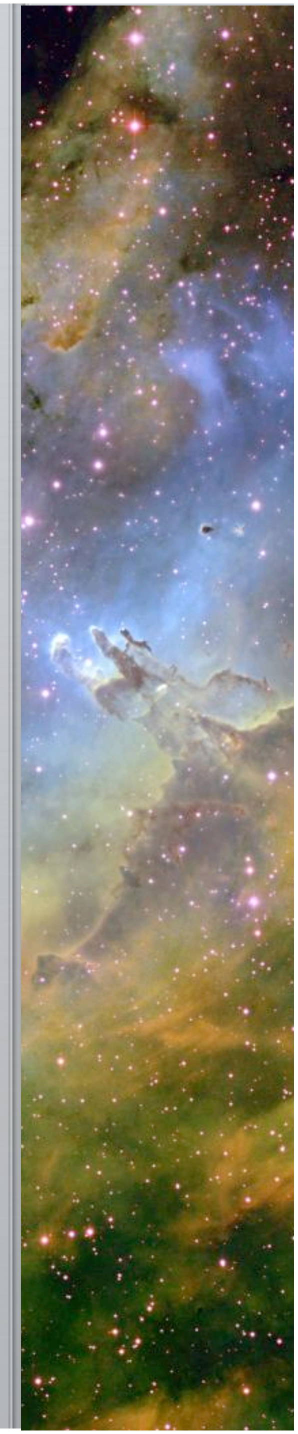
Far-Infrared Emission

Advantages

- Extinction is not an issue
- Complementary to optical/near-IR indicators which result from unabsorbed light
- Lots of data from *Spitzer* and *Herschel*

Disadvantages

- Dust can be heated by older stellar populations and AGN
- Missing light that escapes at UV wavelengths
- Need to extrapolate total IR luminosity from broad-band observations
  - Calibrations exist for monochromatic IR idicators (e.g. 24um; Calzetti 2007)



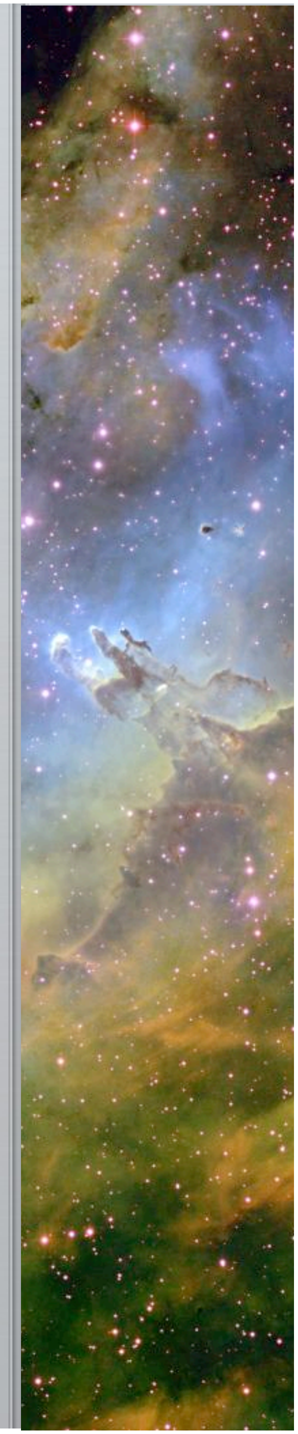
Current State-of-the-art

- Combination of multiple SFR indicators yield the most reliable SFRs

- Example:

$$\mathrm{SFR}(M_\odot\,\mathrm{yr}^{-1}) = 5.3 \times 10^{-42}[L(\mathrm{H}\alpha)_{\mathrm{obs}} + (0.031 \pm 0.006)L(24\,\mu\mathrm{m})].$$

- Others use UV + IR (e.g. Bell et al. 2005)



Other SFR indicators

- I have focused on UV – IR indicators
- Other methods exist
  - X-ray emission
  - Radio Continuum