Measuring Star-Formation Rates

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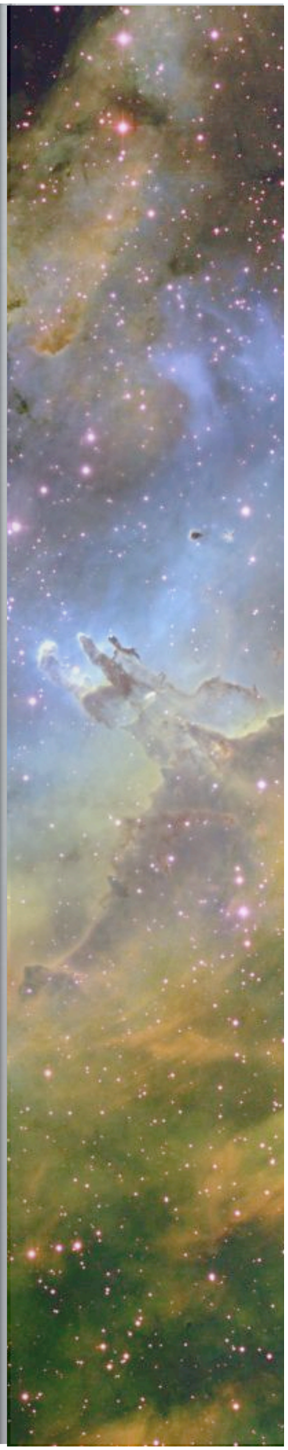
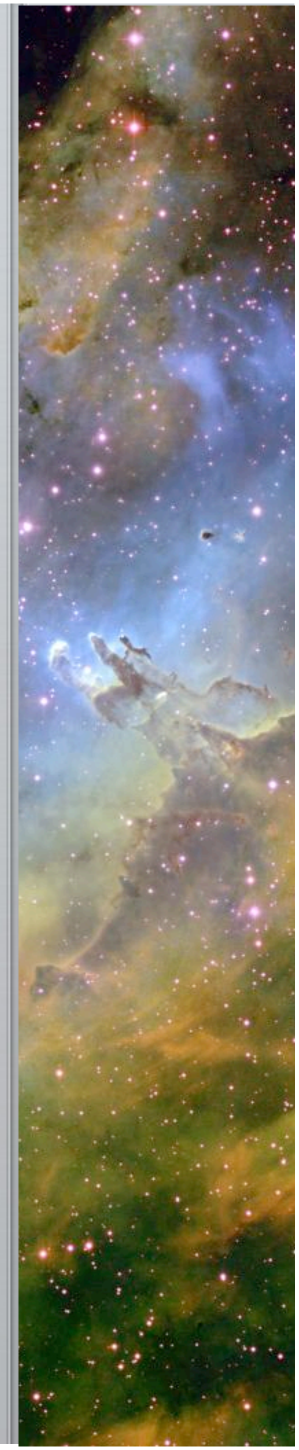
Siena College

ALFALFA Undergraduate Workshop
Jan. 2013



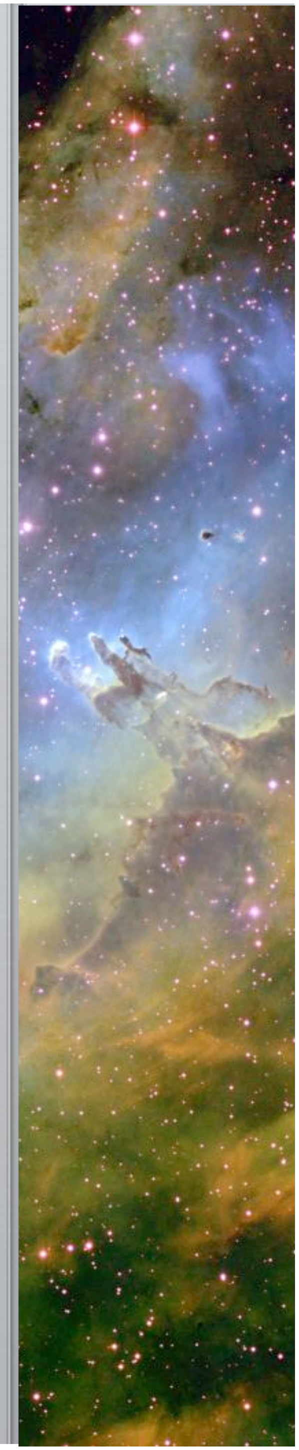
Acknowledgements

- 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



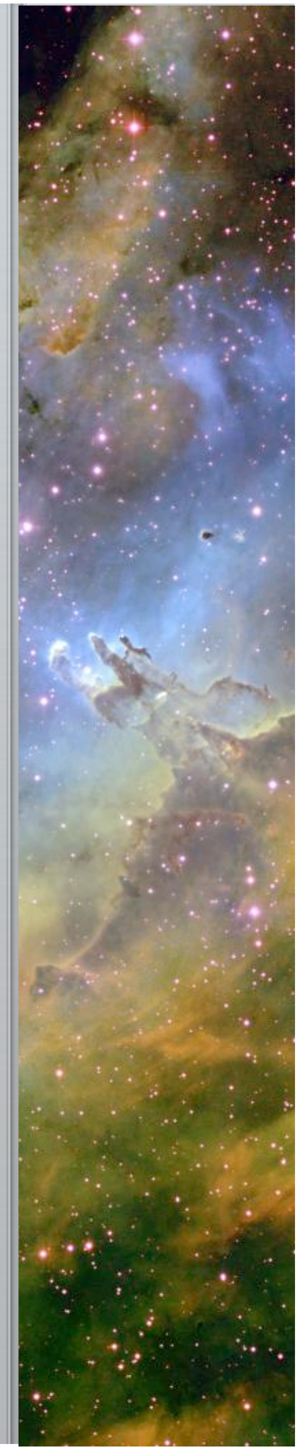
Disclaimer

- I will focus on UV – IR indicators
- Other methods exist
  - X-ray emission
  - Radio Continuum



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

Hubble Heritage

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

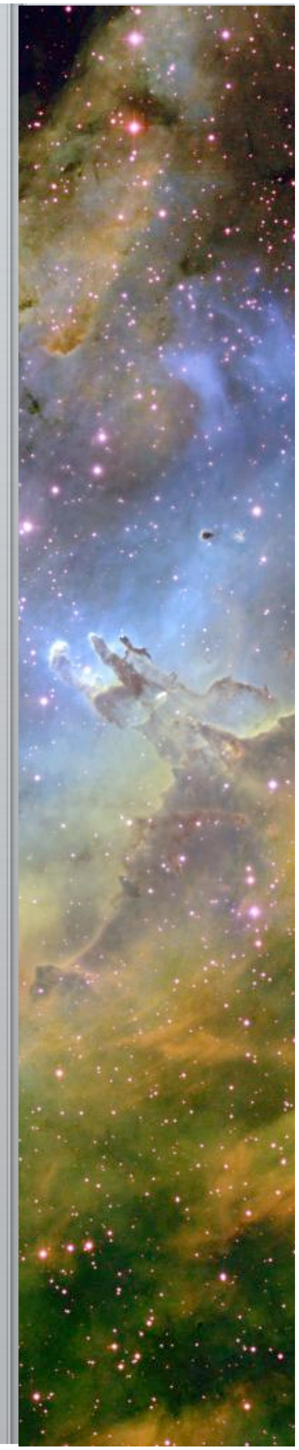
HST • WFC3/UVIS

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

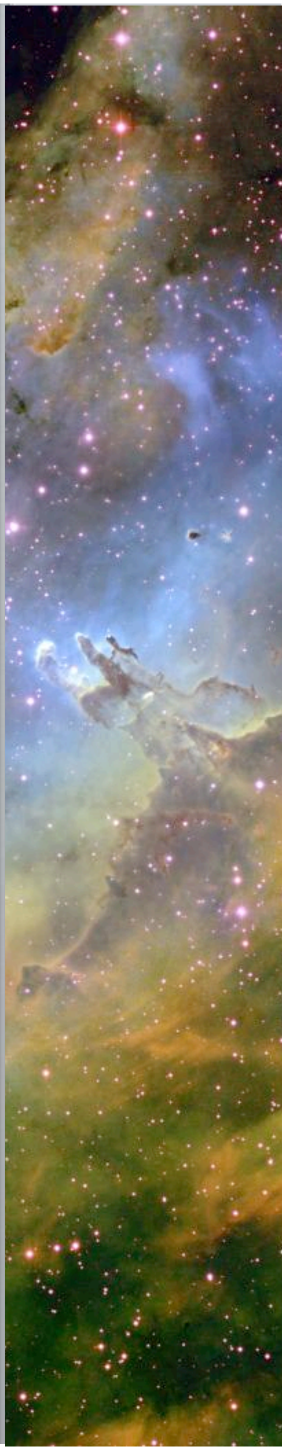
STScI-PRC09-32a

Star-Formation Rates

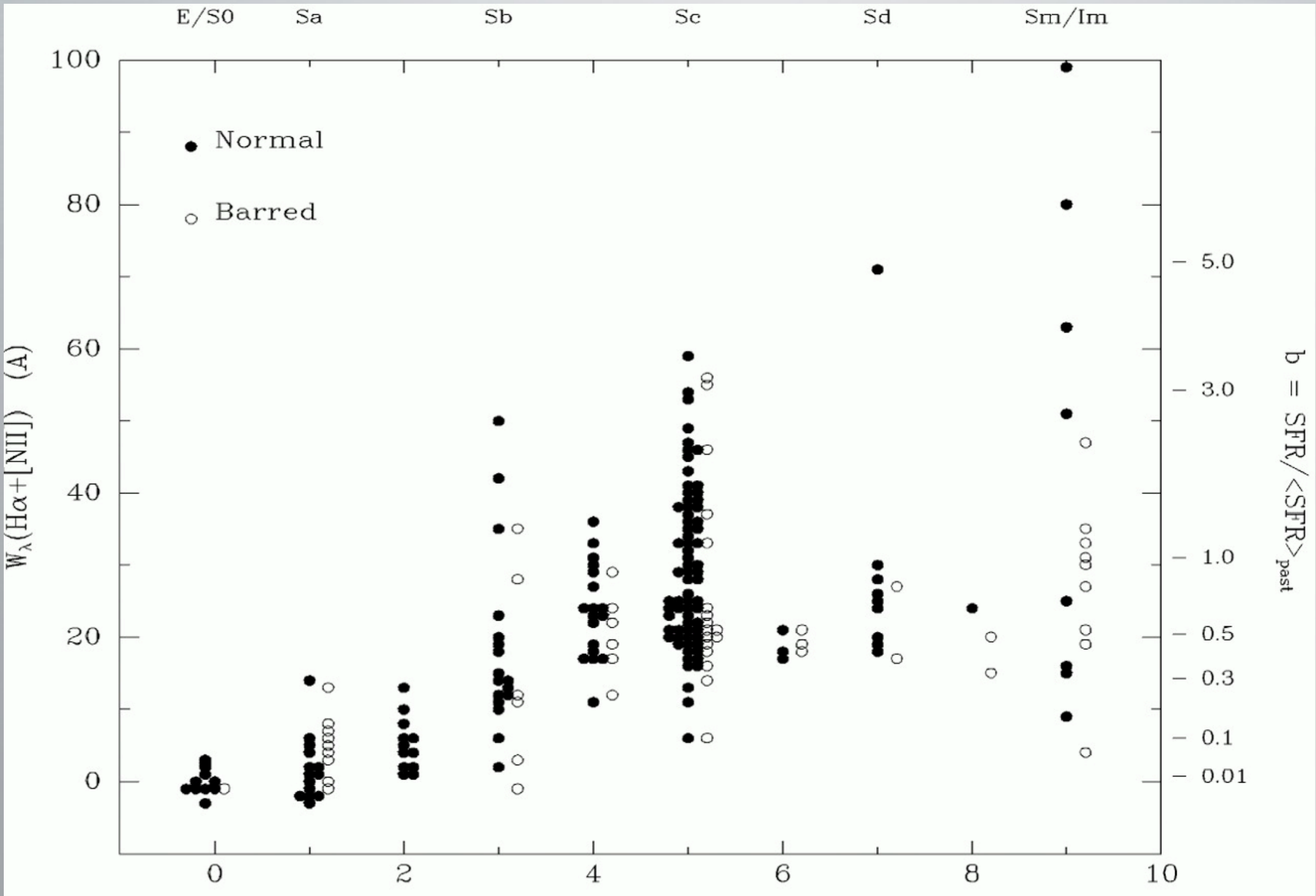
- Quantifies how quickly a galaxy is converting gas into new stars
- Why should we care?
  - Star-forming regions make for great pictures!
  - **Helps drive galaxy evolution**
    - Depletes gas
    - Leads to metal enrichment of ISM and IGM
  - A global property that we can measure
    - We can study 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



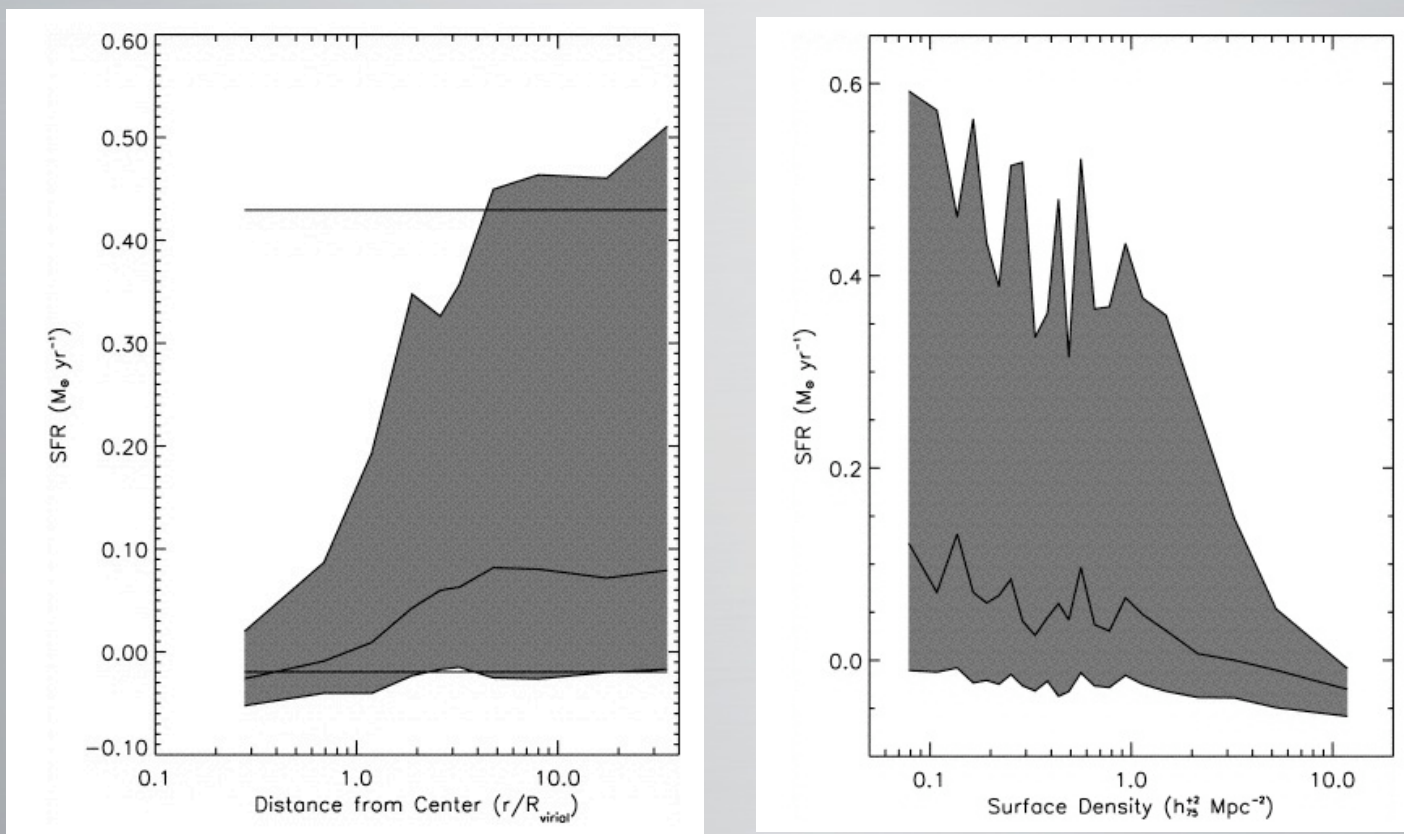
SFRs vary widely among galaxies



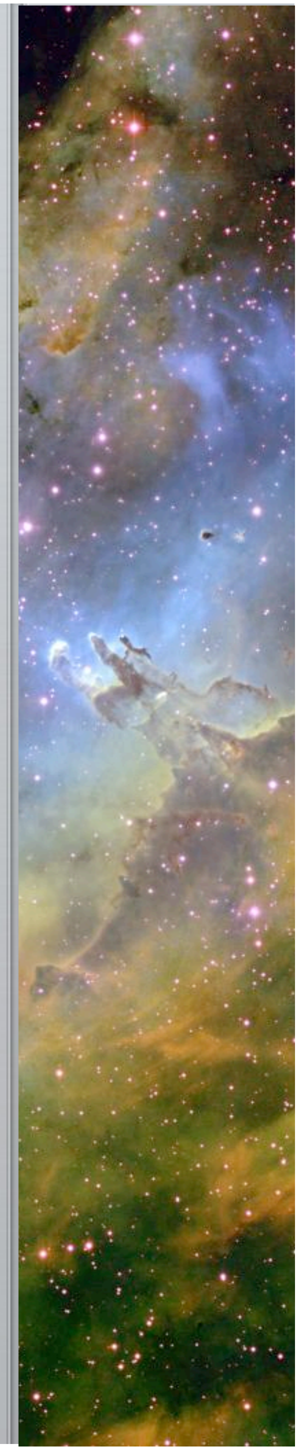
Kennicutt 1998

SFRs vary with Environment

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

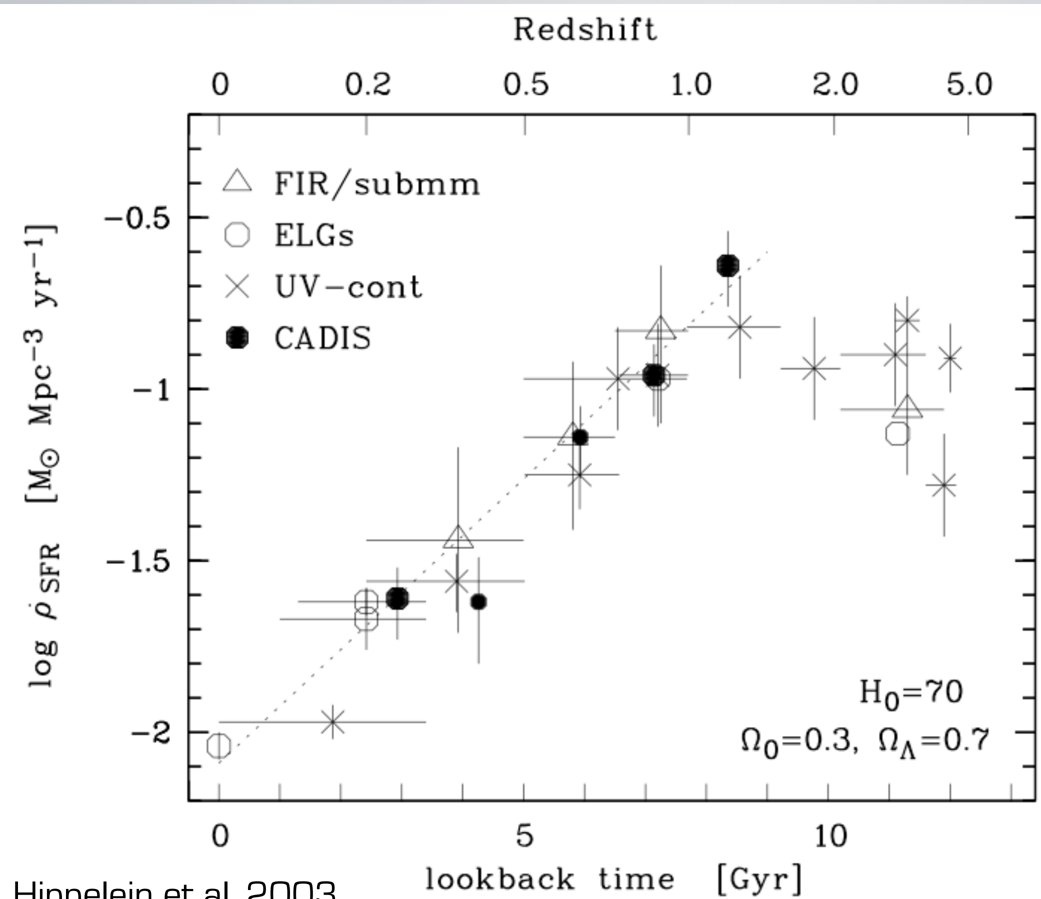


Results from Sloan Digital Sky Survey (Gomez et al. 2003)

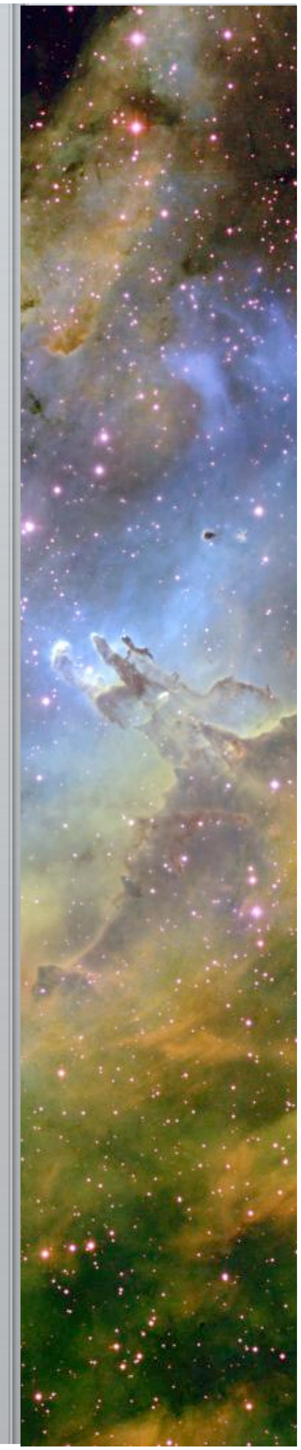


SFRs vary with redshift

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

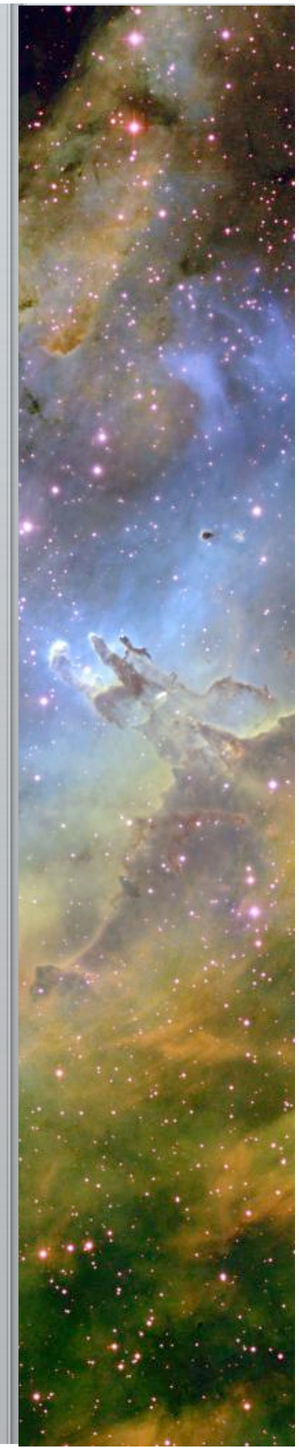


Hippelein et al. 2003



SFRs: Why do we care?

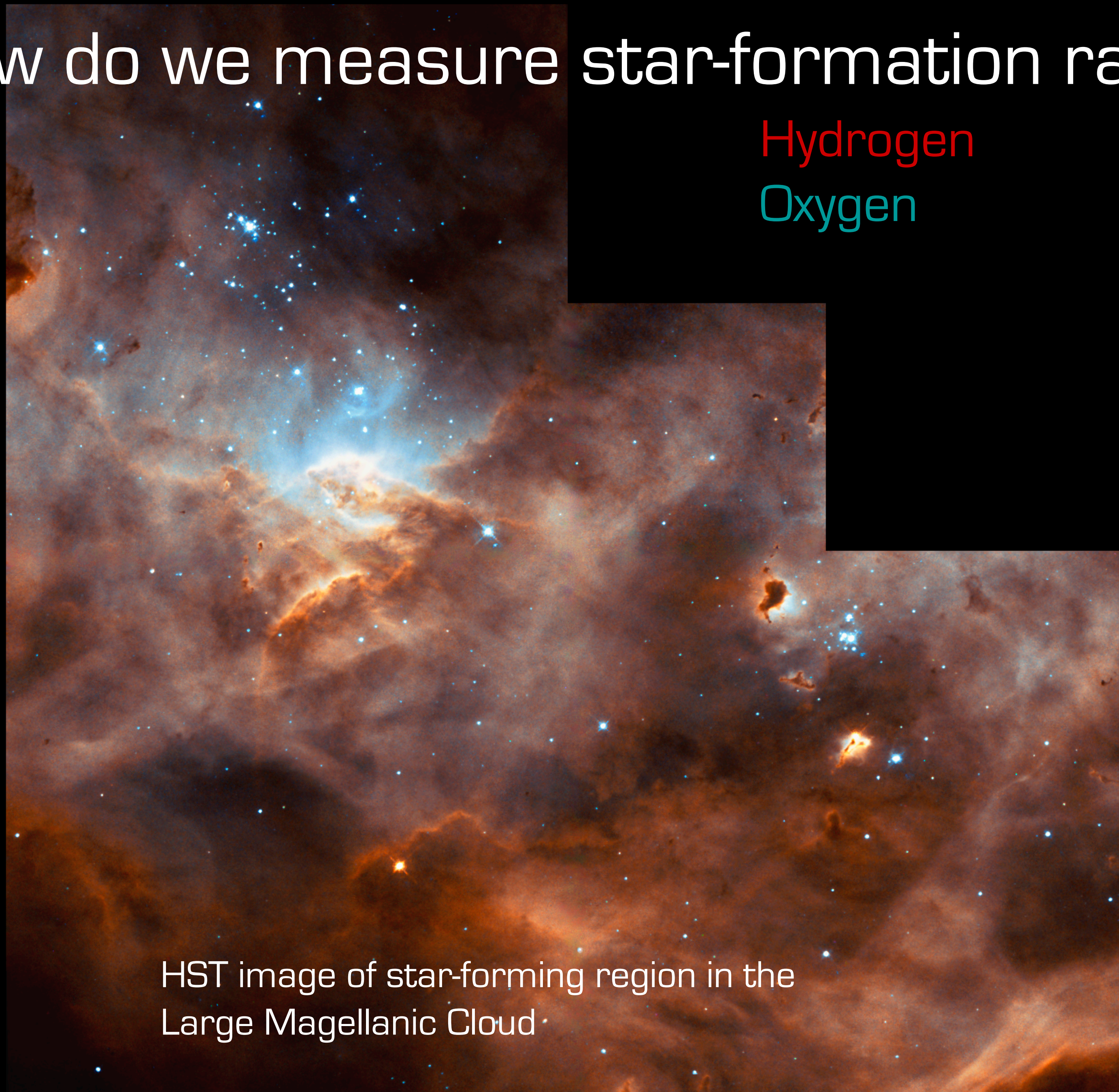
- Lots of questions:
  - Why do SFRs vary so widely among galaxies?
  - What determines a galaxy's SFR?
  - Why do SFRs vary with galaxy environment?
  - Why were SFRs higher in the past?
- Need to find answers if we are to understand galaxy evolution
  - Linked to NASA's origins theme
  - Decadal survey: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



How do we measure star-formation rates?

Hydrogen

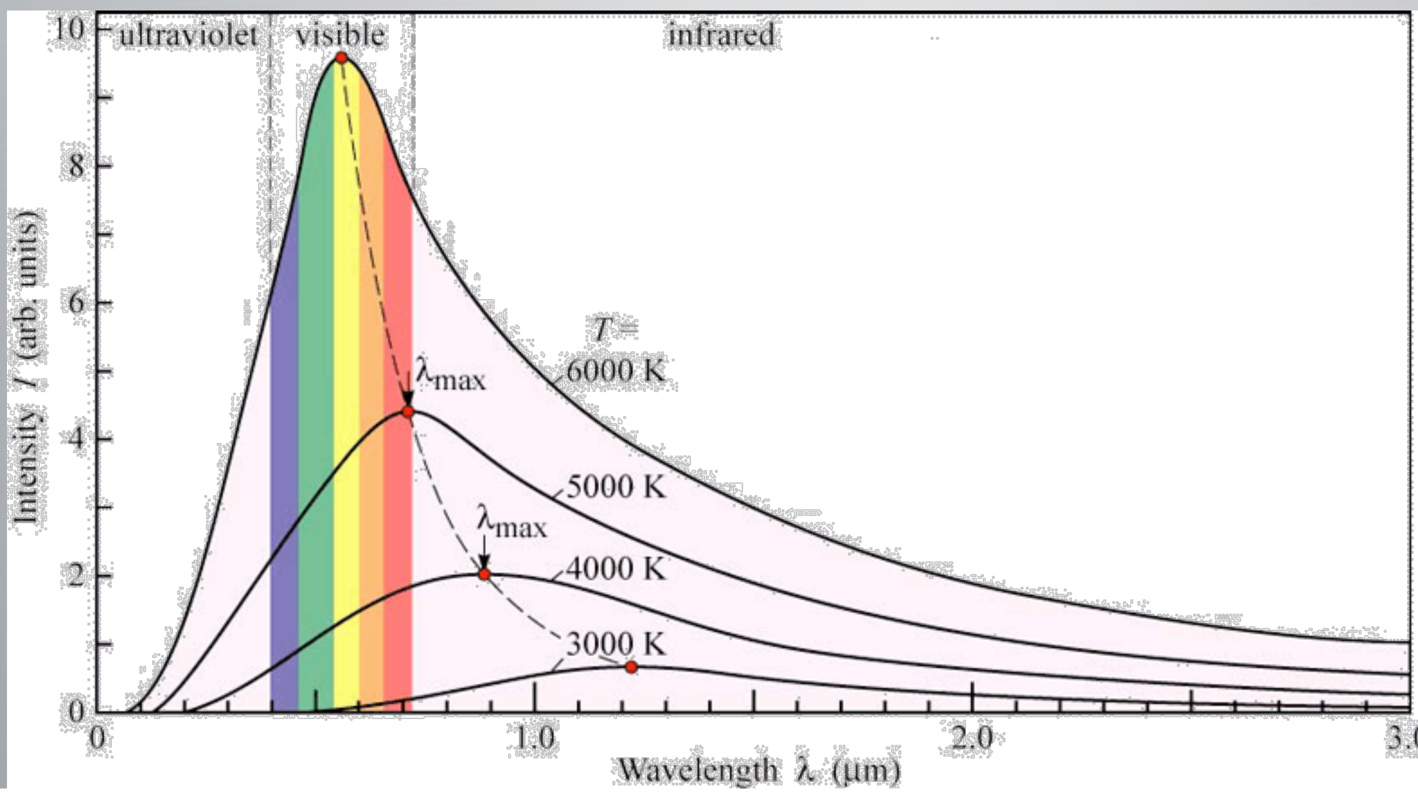
Oxygen

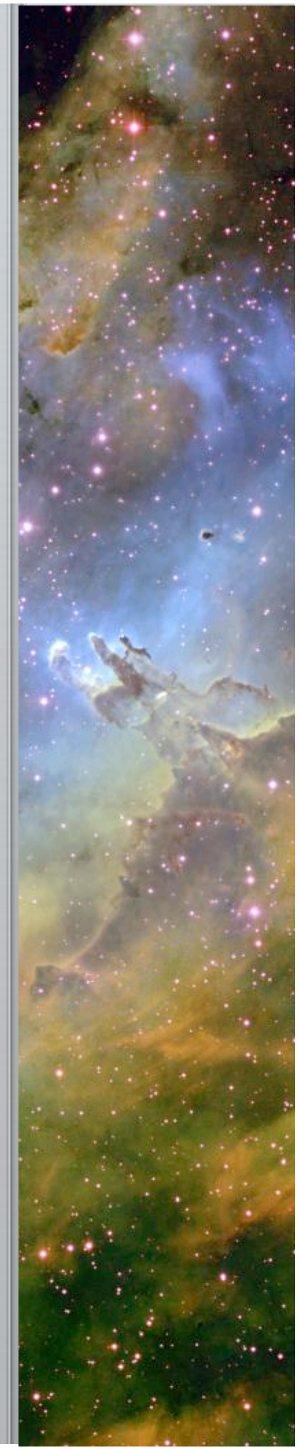


HST image of star-forming region in the Large Magellanic Cloud

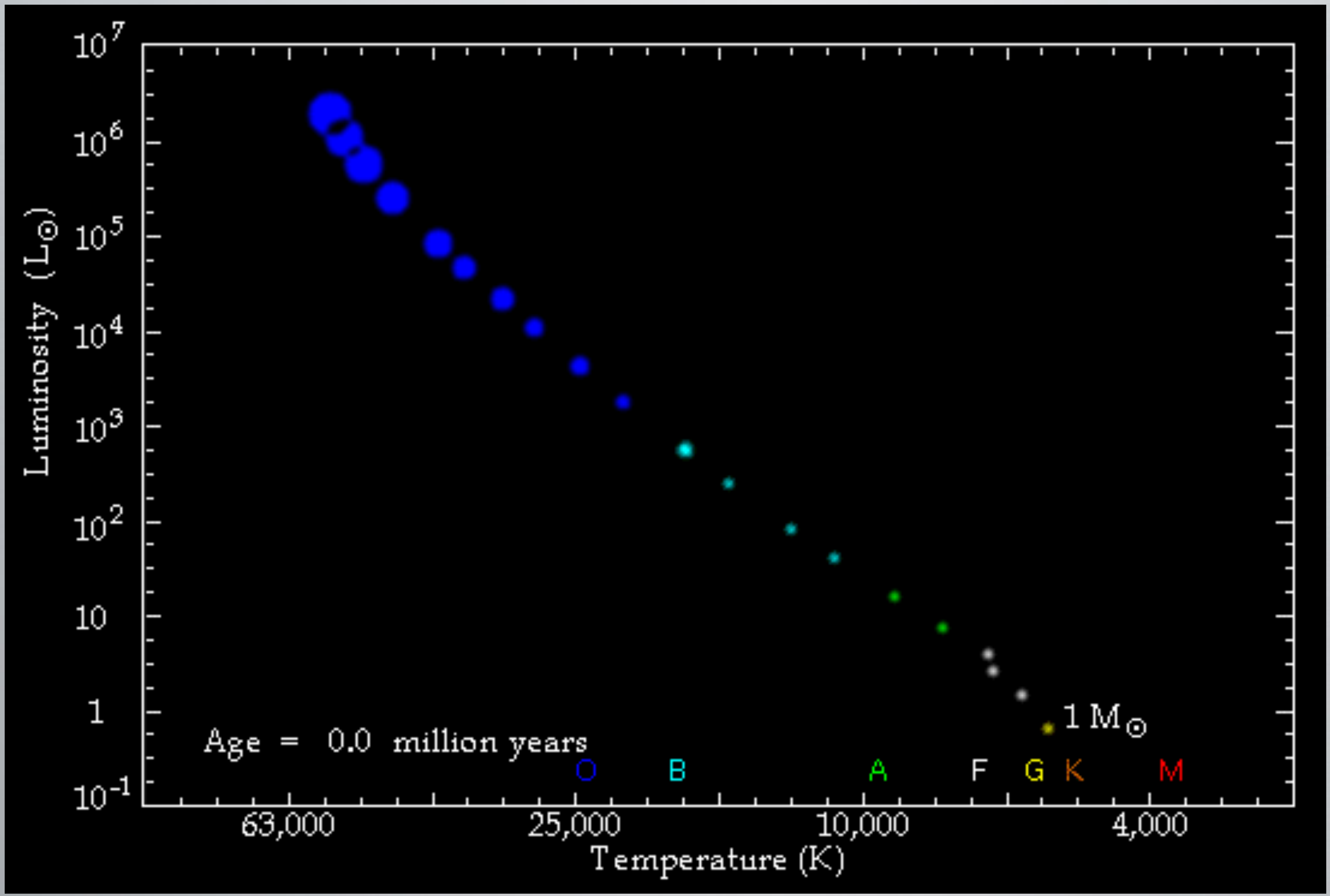
Integrated Colors of Galaxies

- 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



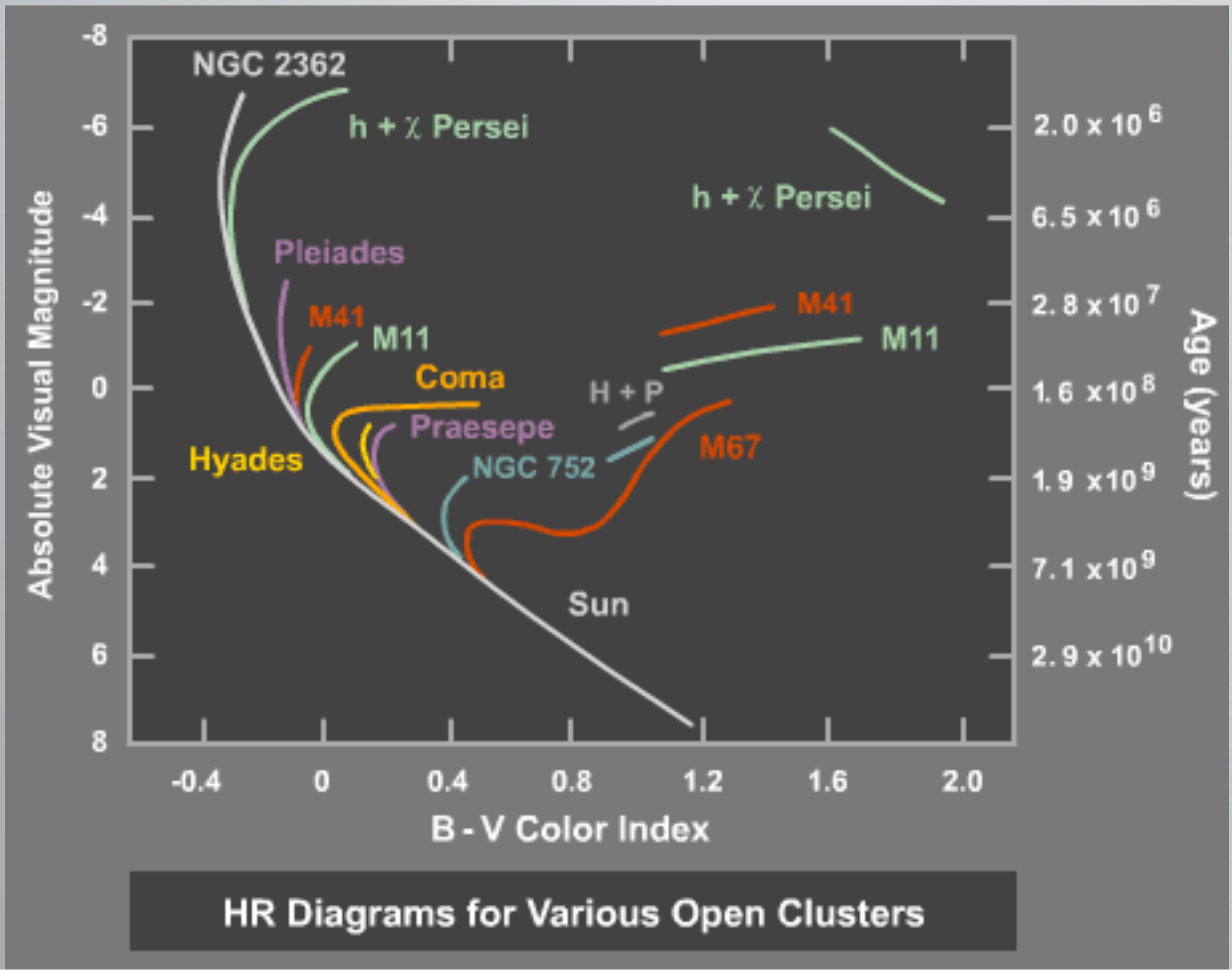


Stellar Evolution



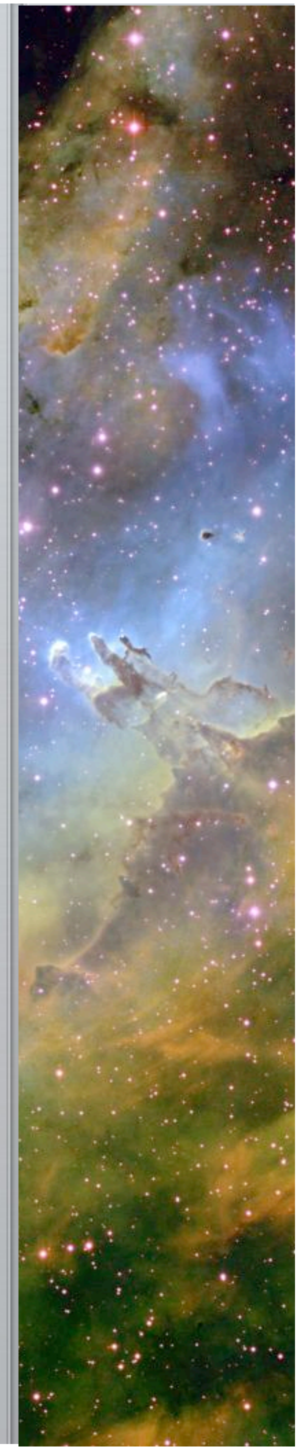
Color-Age Connection

- 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.



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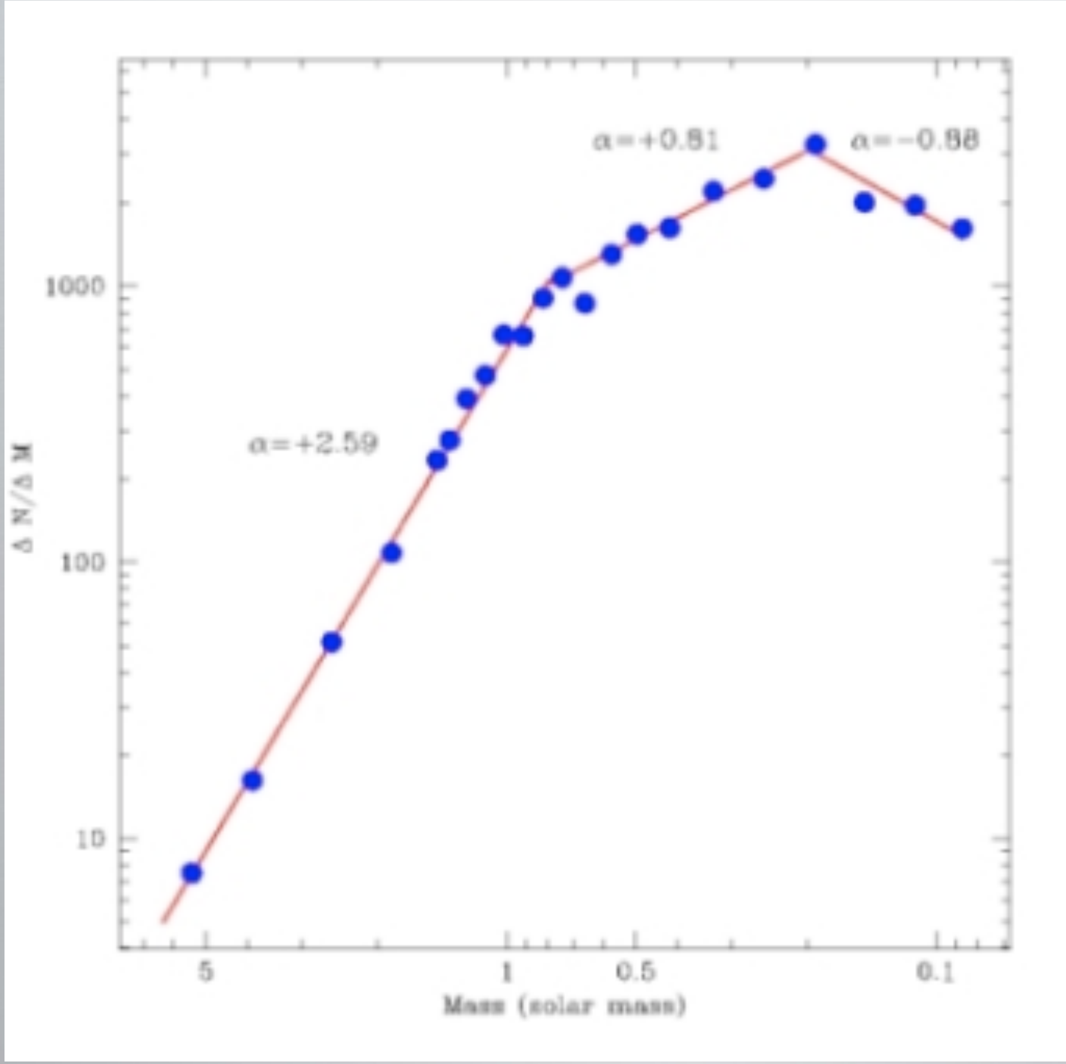
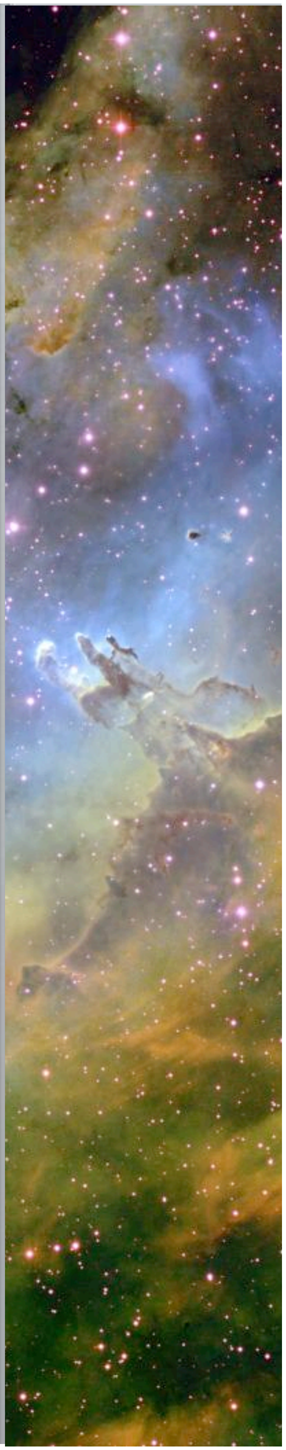
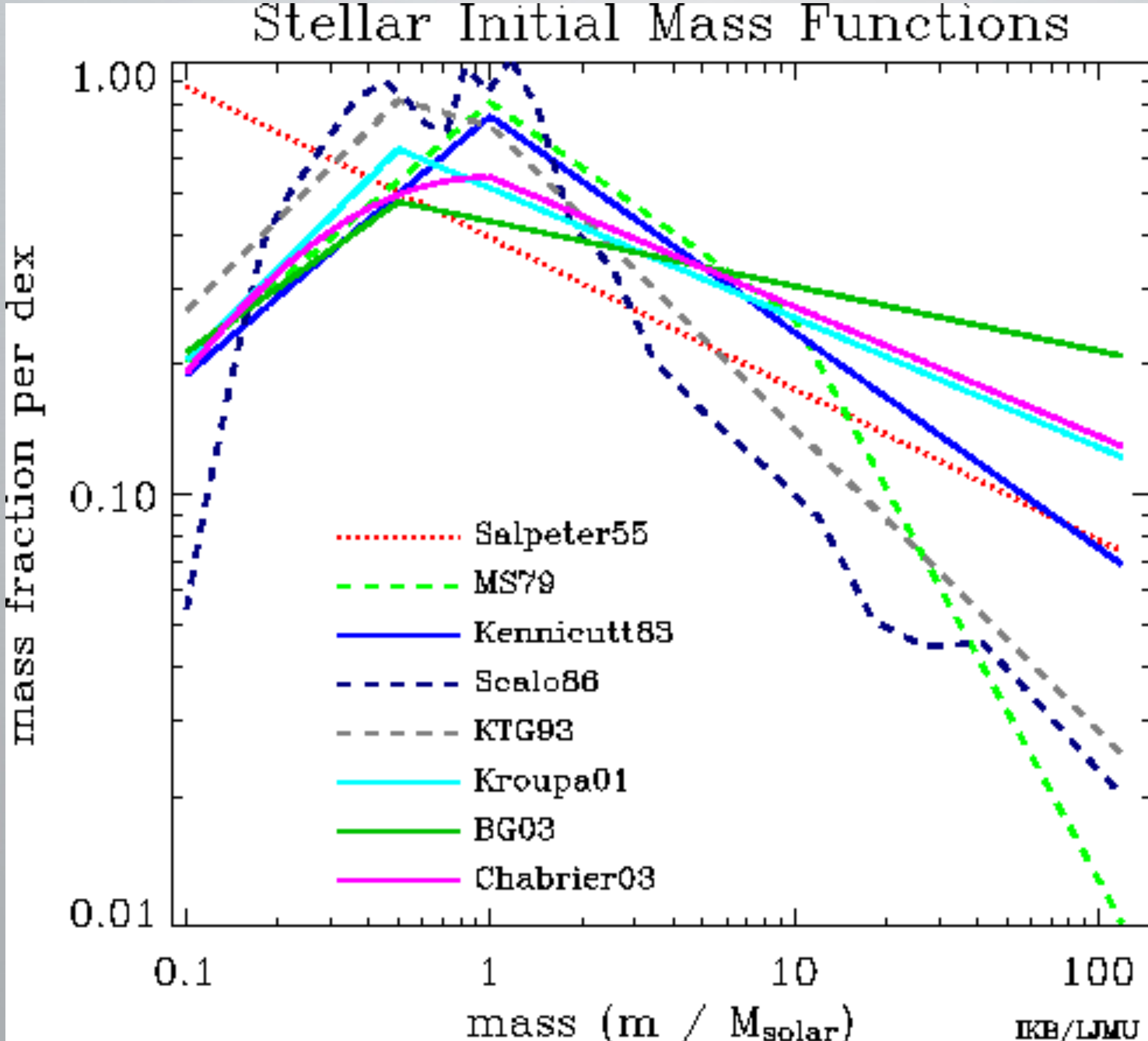
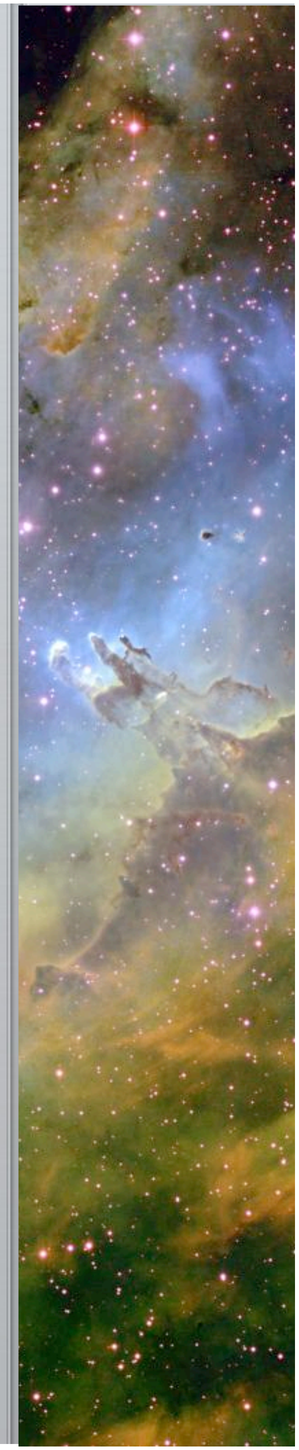
Initial Mass Function





Initial Mass Function





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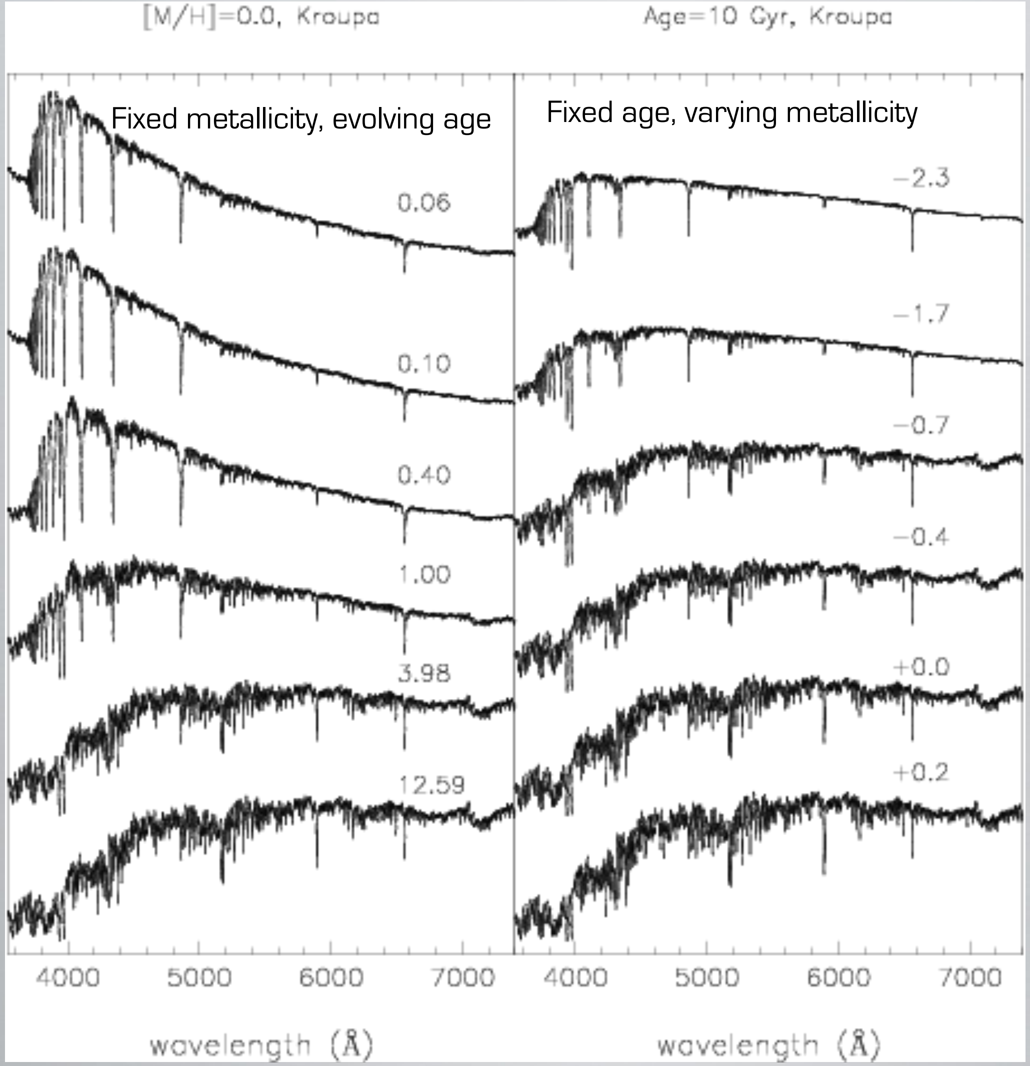
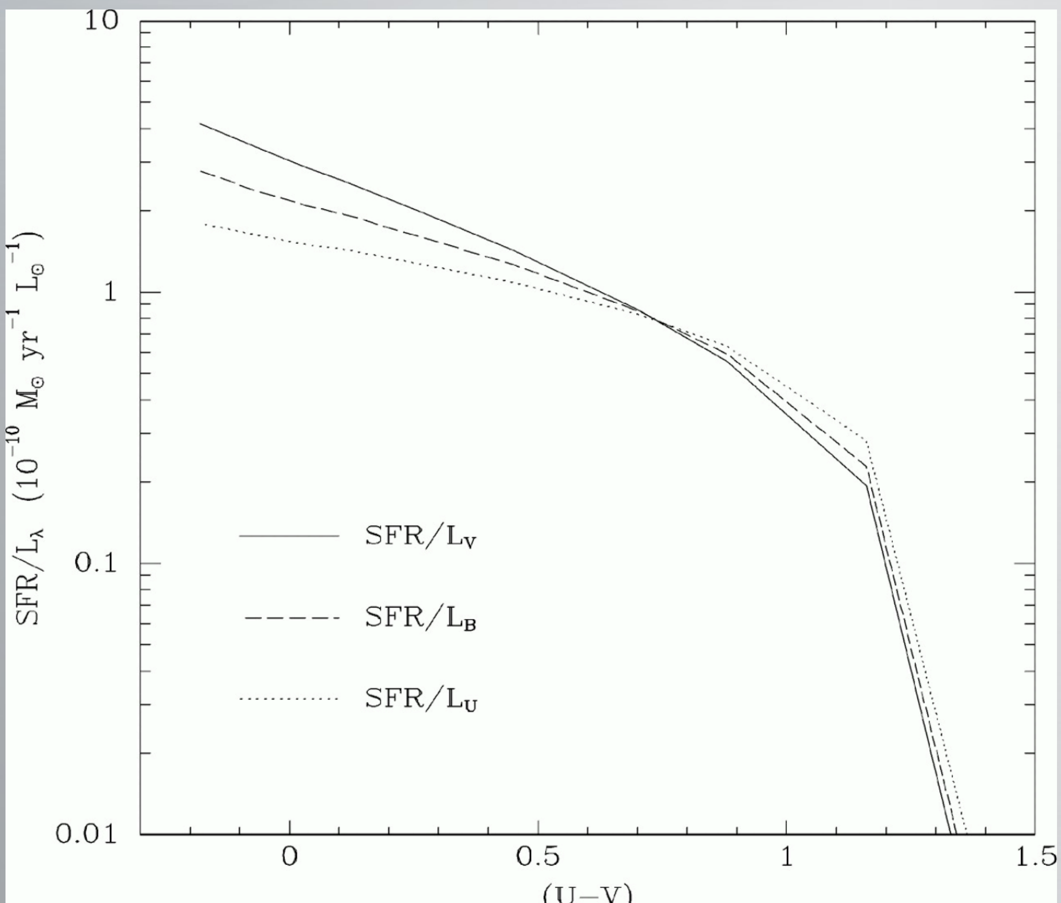
Example:


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)

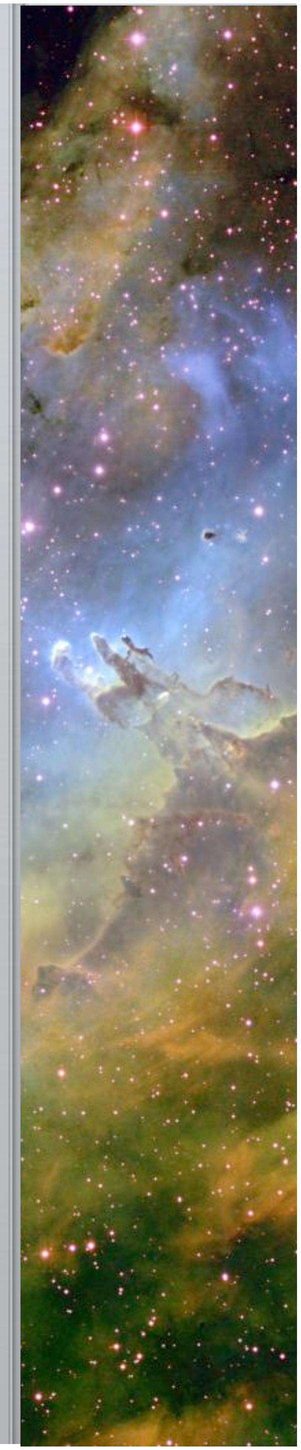
Synthesis Models

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

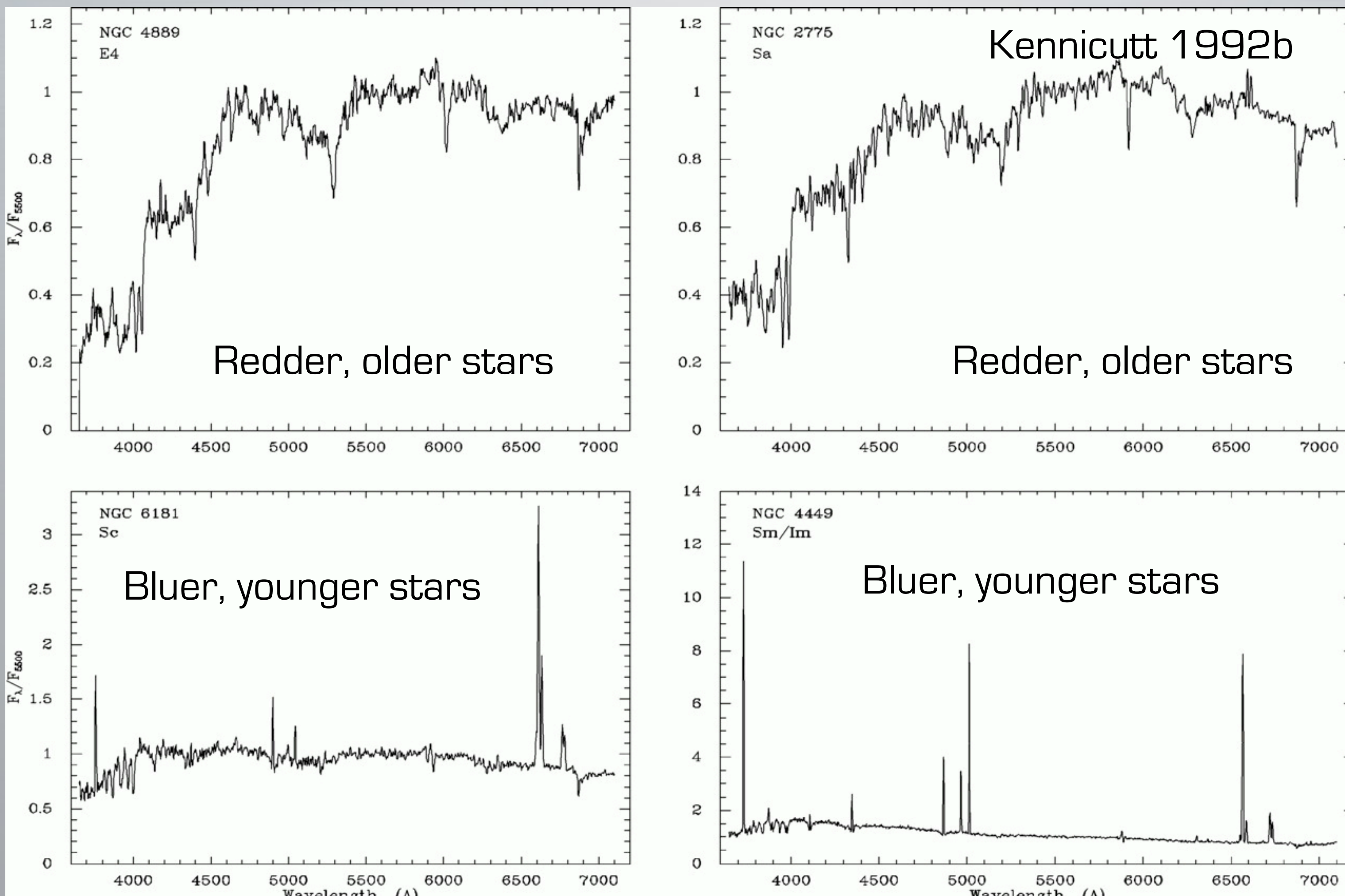


Example from Kennicutt et al (1994) linking SFR and broadband luminosities

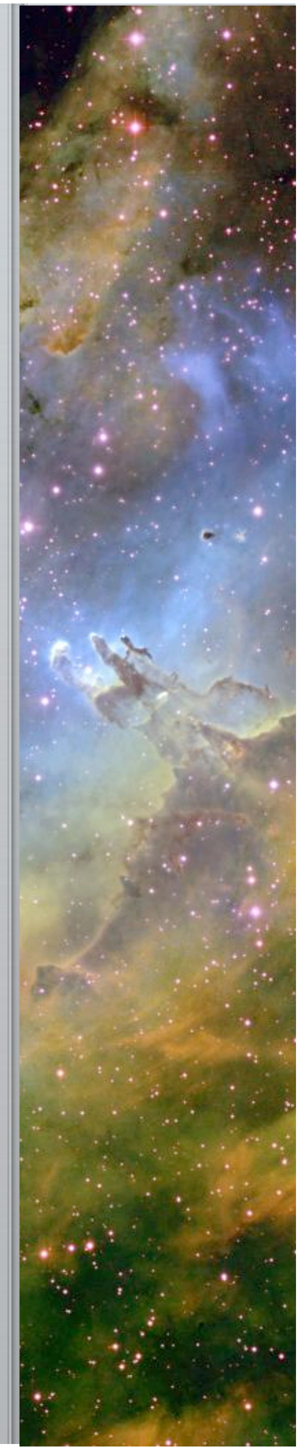
Gives fraction of stars formed in the last 10^8 – 10^9 years



Integrated Spectra of Galaxies



More info than broad-band colors.
Can model these with stellar population models.



Example: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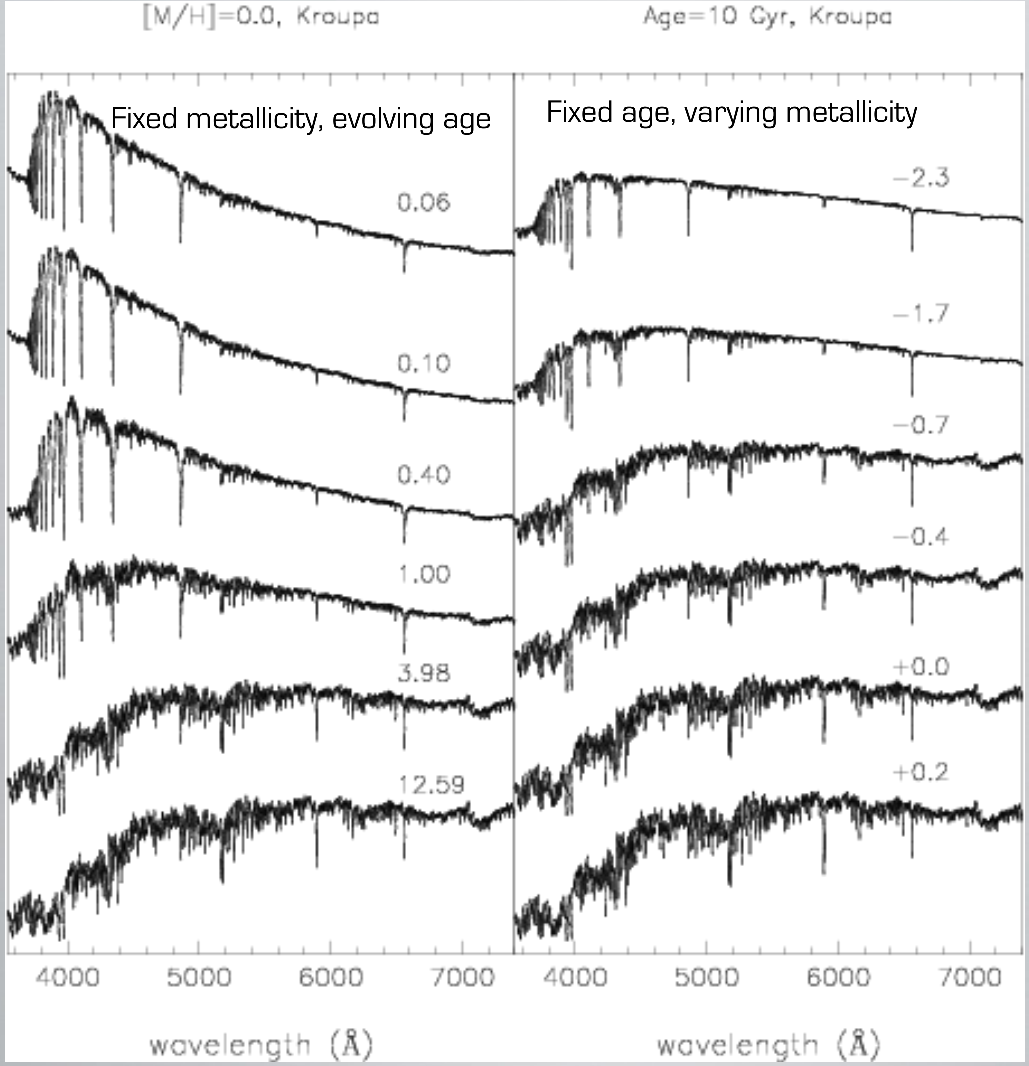

[M/H]=0.0, Kroupa
Age=10 Gyr, Kroupa
Fixed metallicity, evolving age
Fixed age, varying metallicity
0.06
0.10
0.40
1.00
3.98
12.59
−2.3
−1.7
−0.7
−0.4
+0.0
+0.2
4000
5000
6000
7000
wavelength (Å)

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

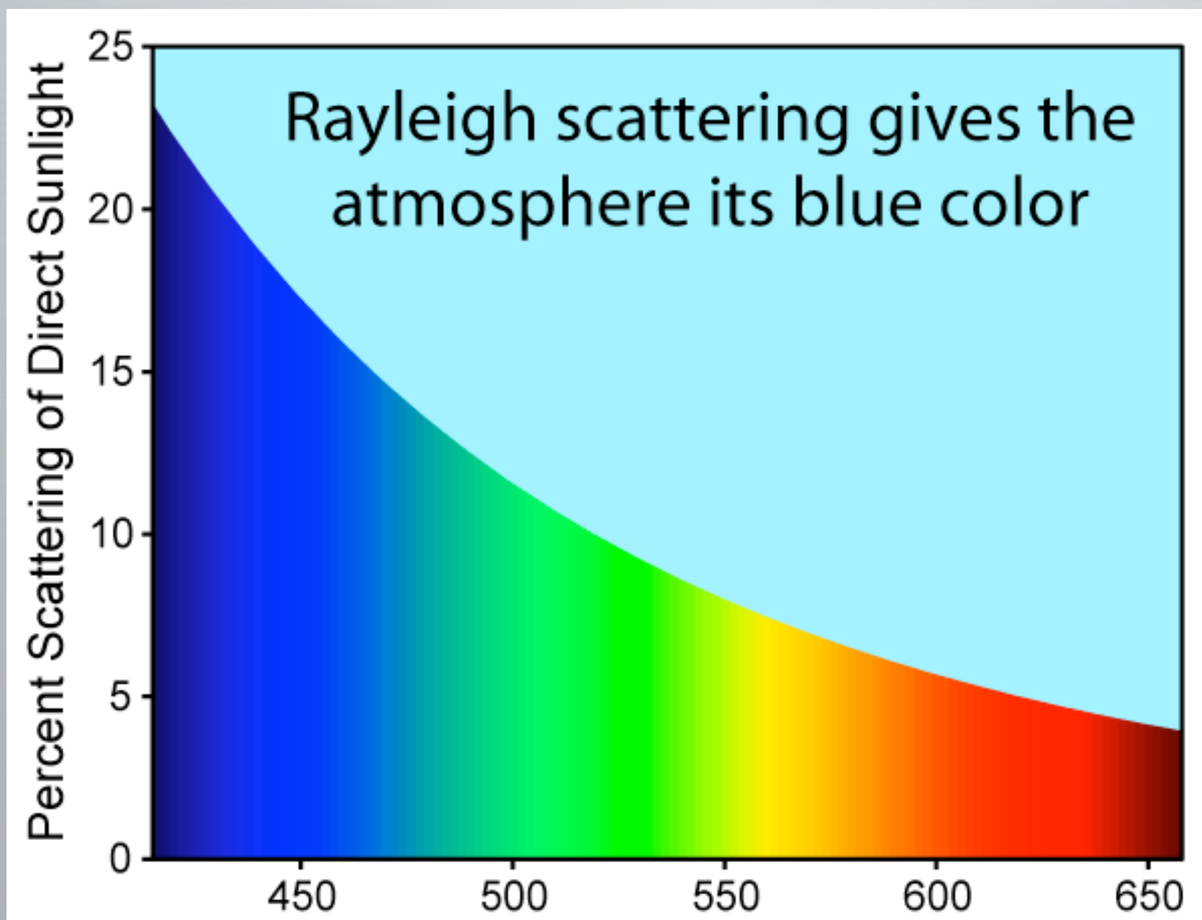
- Tied directly to emission from young stars
- Wavelength range is observable for distant galaxies
  - Good for quantifying evolution
- Lots of data from GALEX

Disadvantages

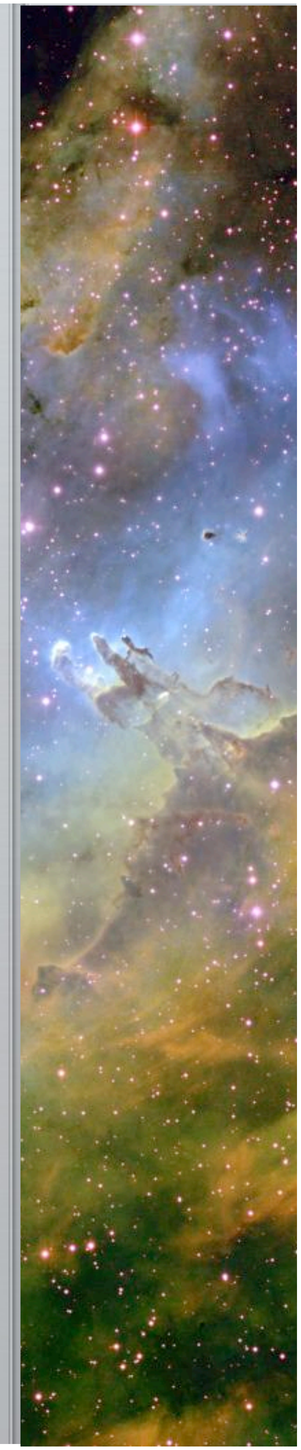
- UV light is attenuated by dust
- Dust (and therefore extinction) is patchy
- Depends on the IMF that you use
  - This is true for most SFR indicators

Extinction of Starlight

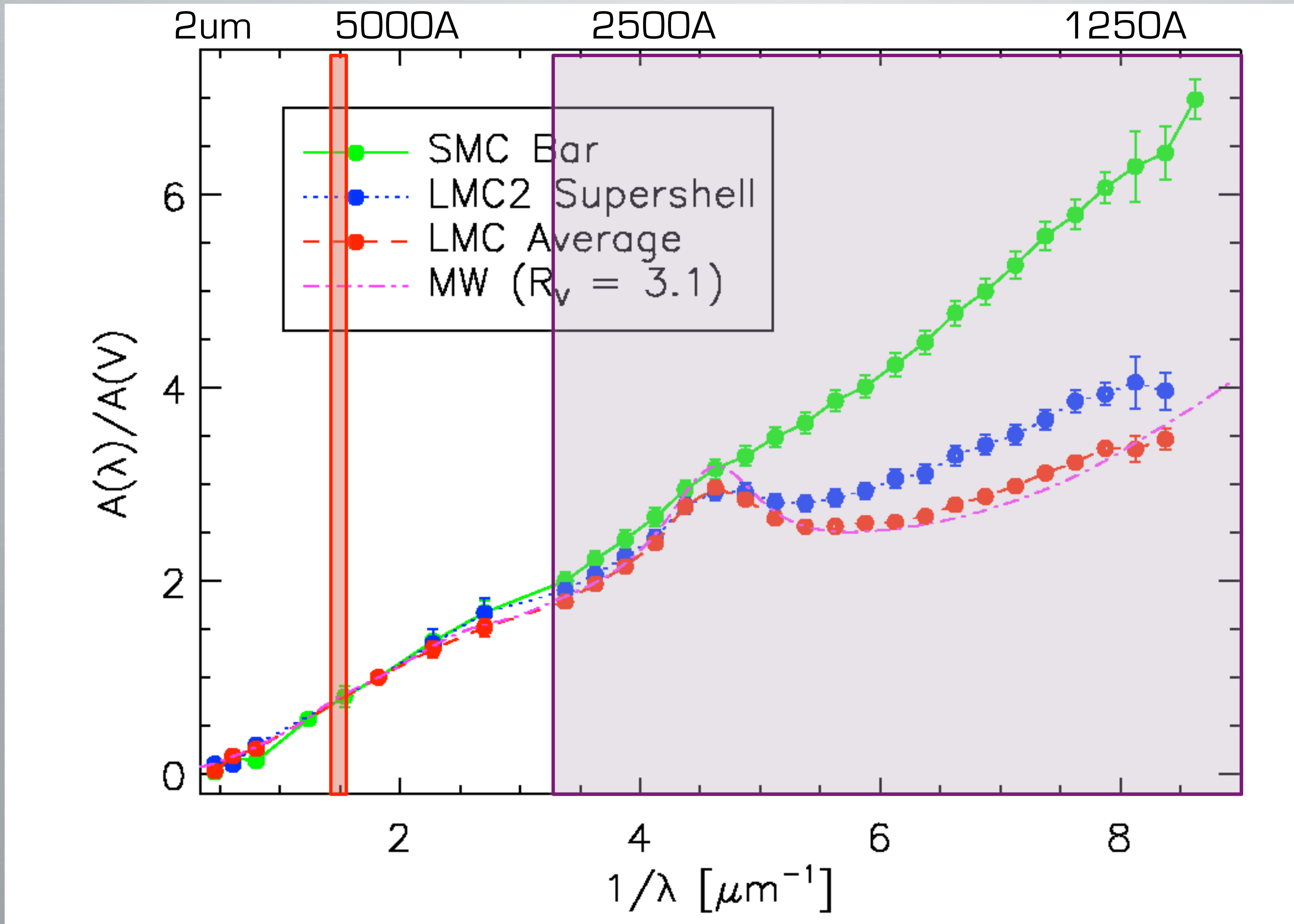
$$scattering \propto \frac{1}{\lambda^4}$$

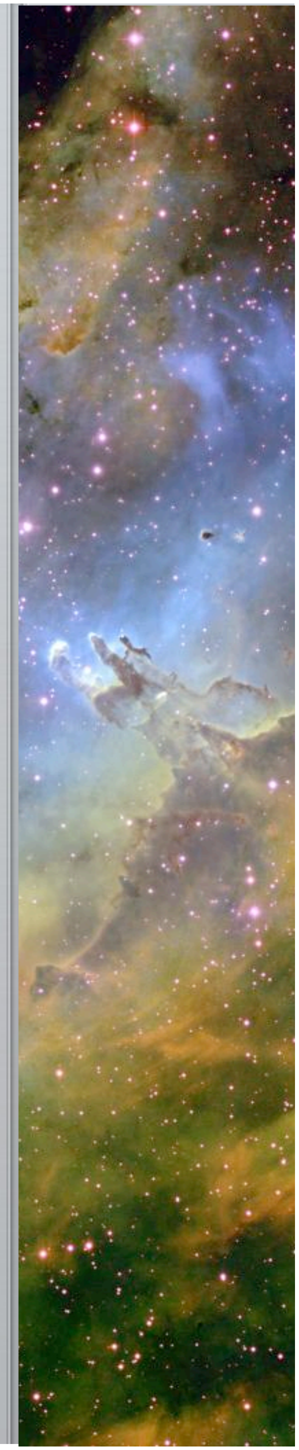


wikipedia



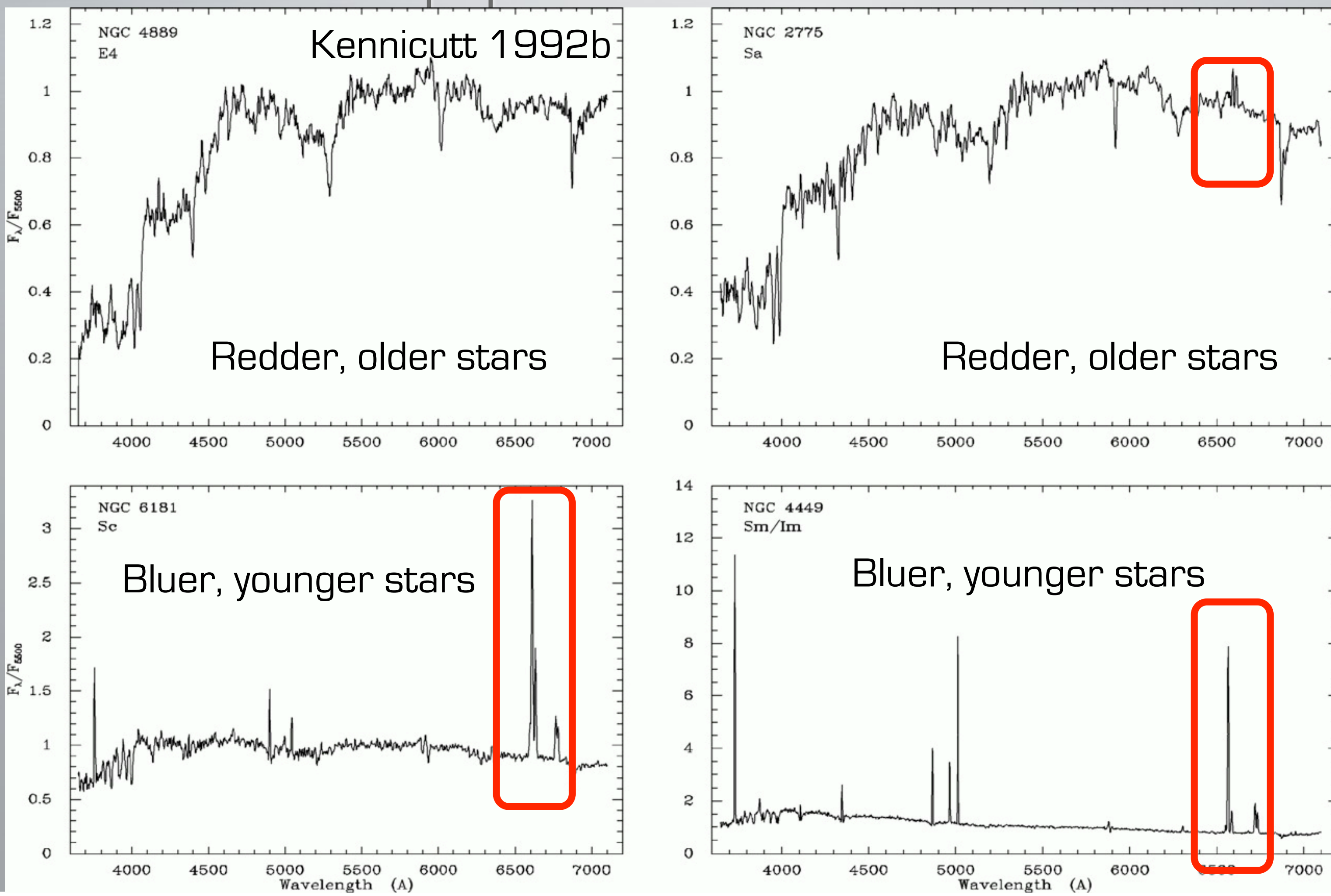
Extinction of Starlight

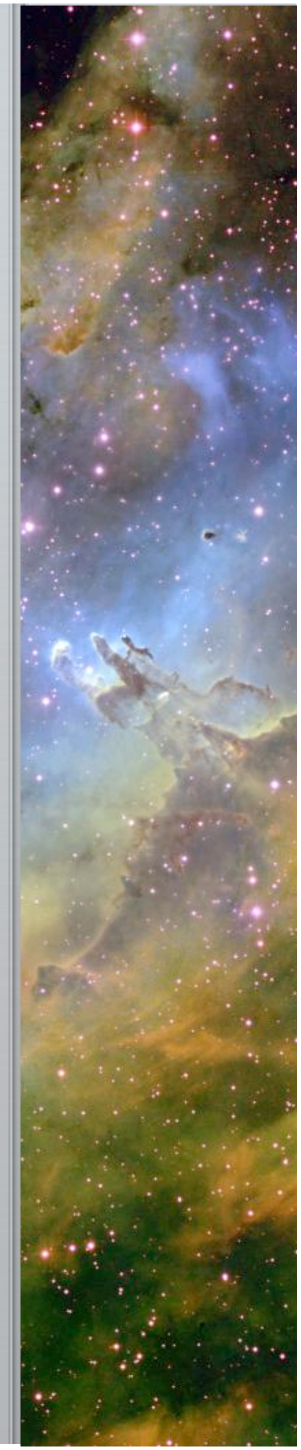




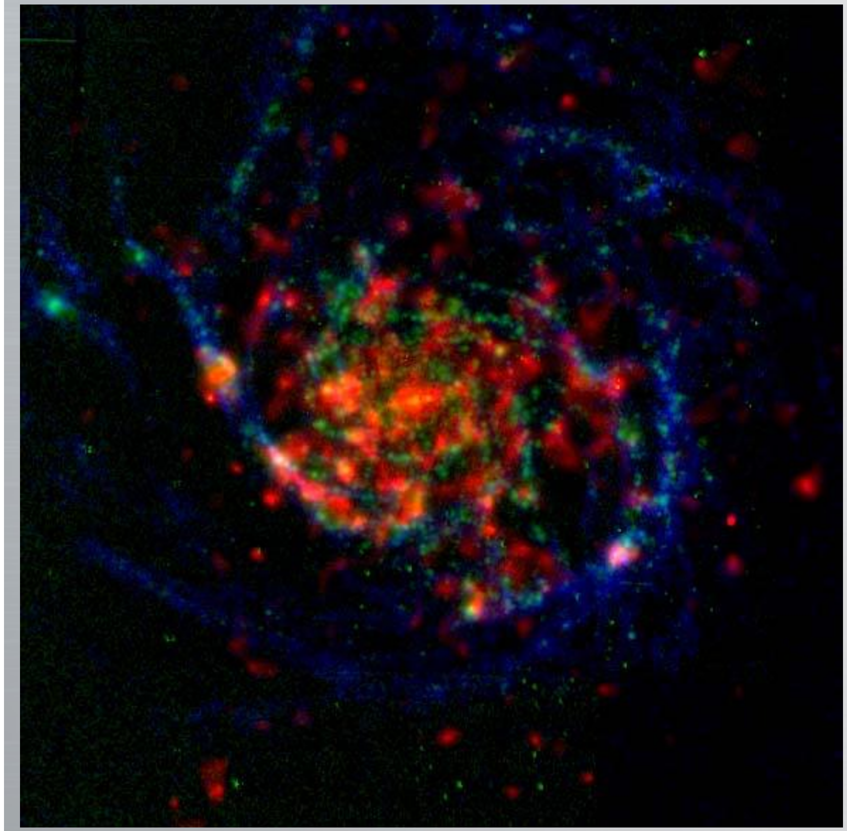
Recombination Lines

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





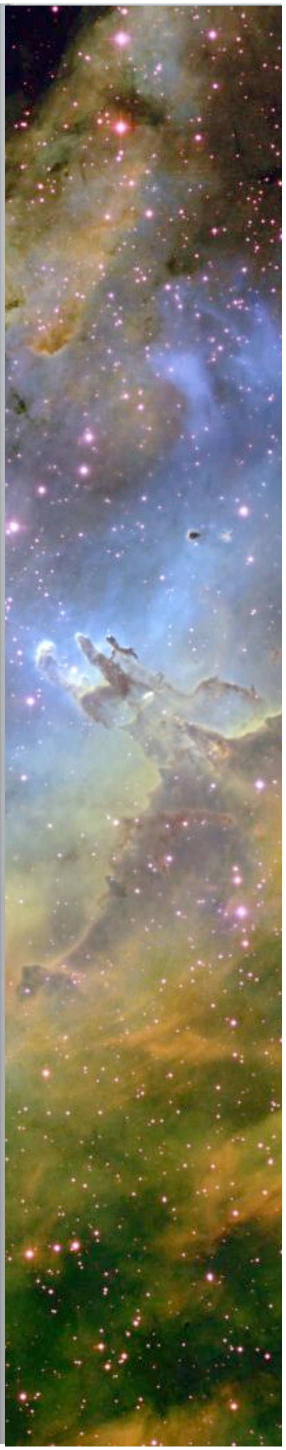
Measuring Star Formation Rates from H α



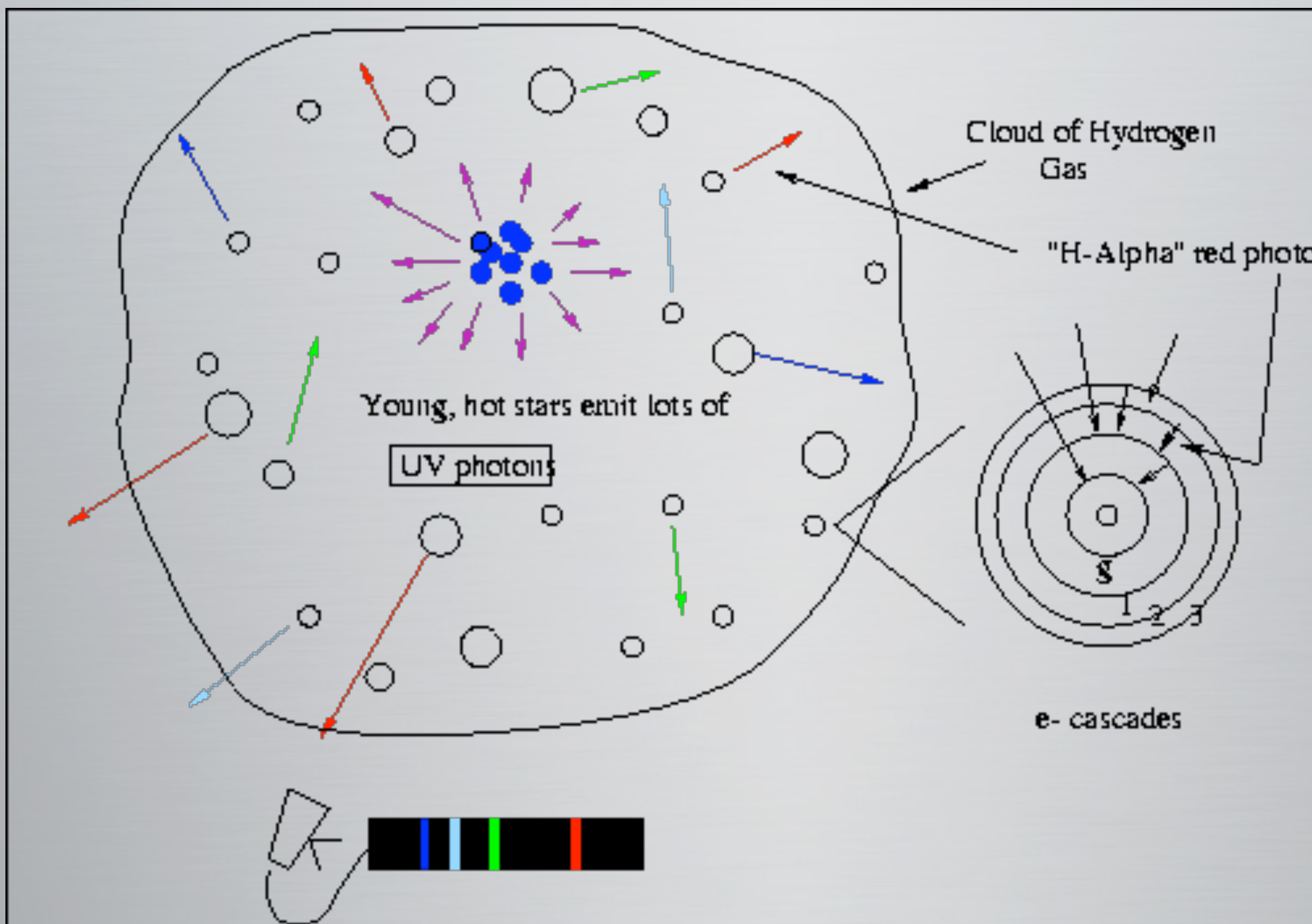
M101: X-ray, HI 21-cm, H α
(D. Wang et al.)

- 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

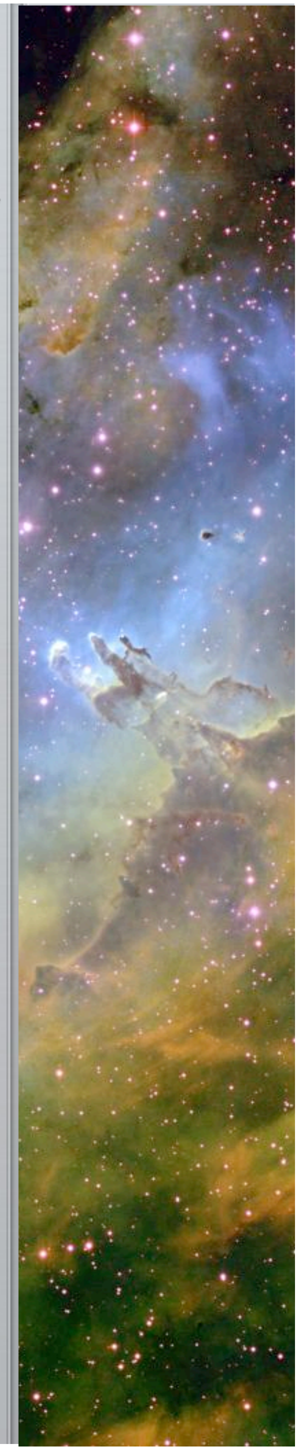
Measuring Star Formation Rates from Hα

- Relate Hα flux to amount of ionizing radiation
  - Only stars wit M >10 $M_\odot$ and lifetimes <20 Myr contribute significantly to the integrated ionizing flux

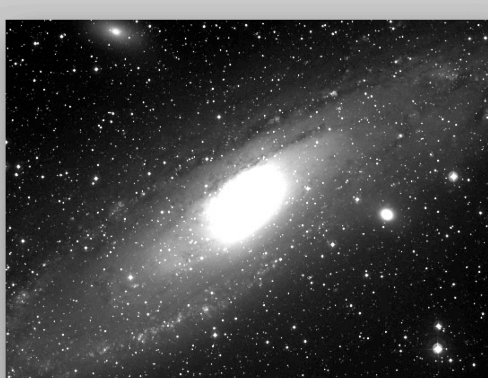
- Convert to total star formation rate using stellar initial mass function (e.g. Kennicutt 1998)

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

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

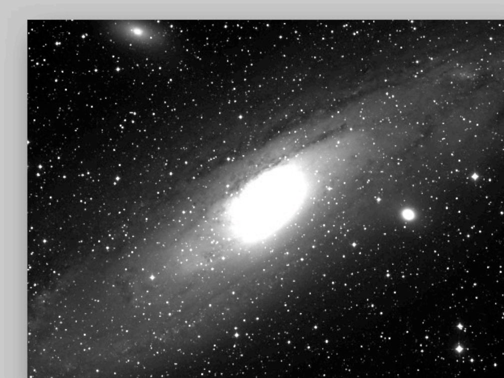


H-alpha Image of M31



Hα

\-



Red

=

$H\alpha_{pure}$

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

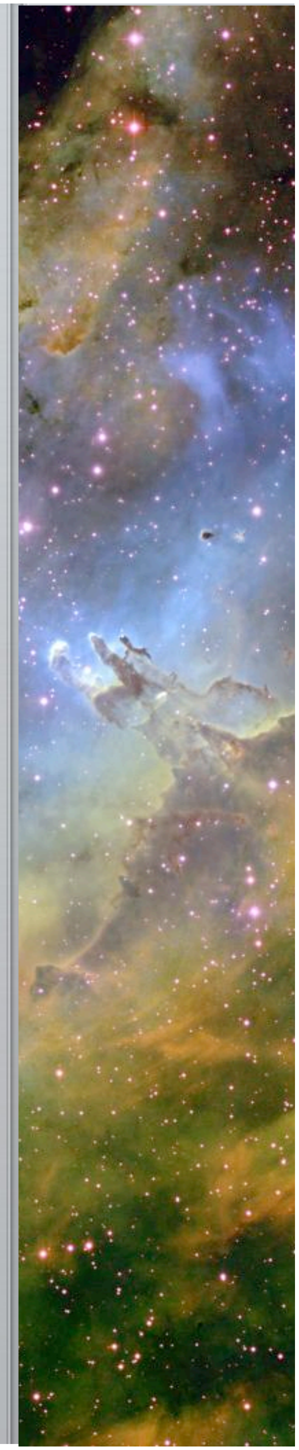
Hα Emission

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

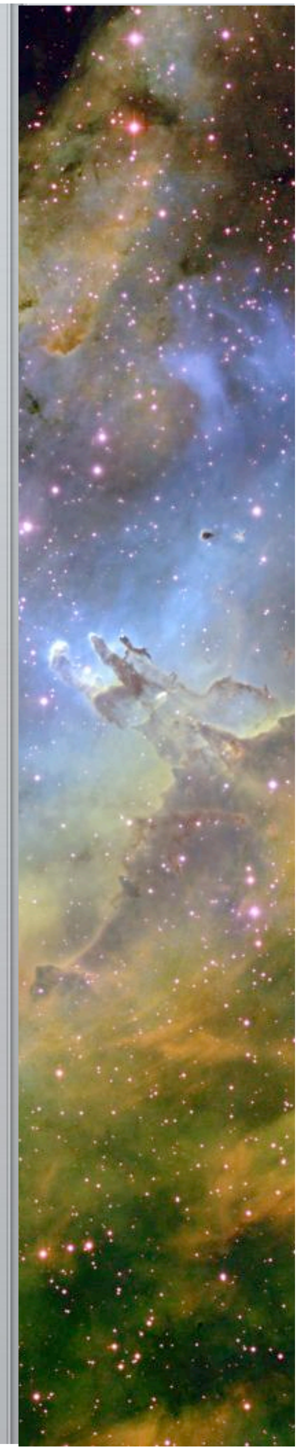
- Sensitive to extinction by dust
- Shifts out of optical window at $z>0.4$, so observations become more difficult
- Depends on IMF, particularly upper mass limit



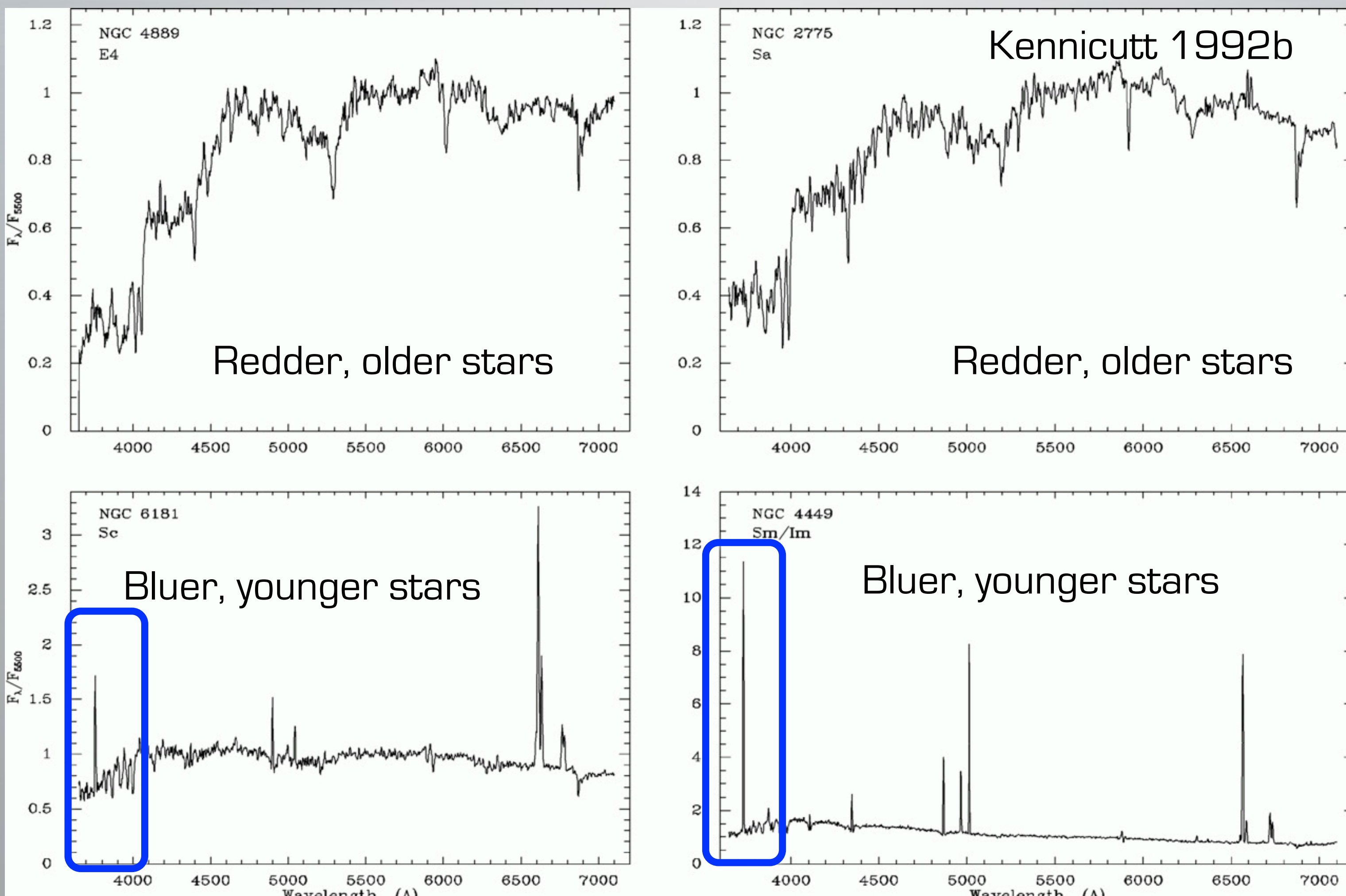
Forbidden Lines

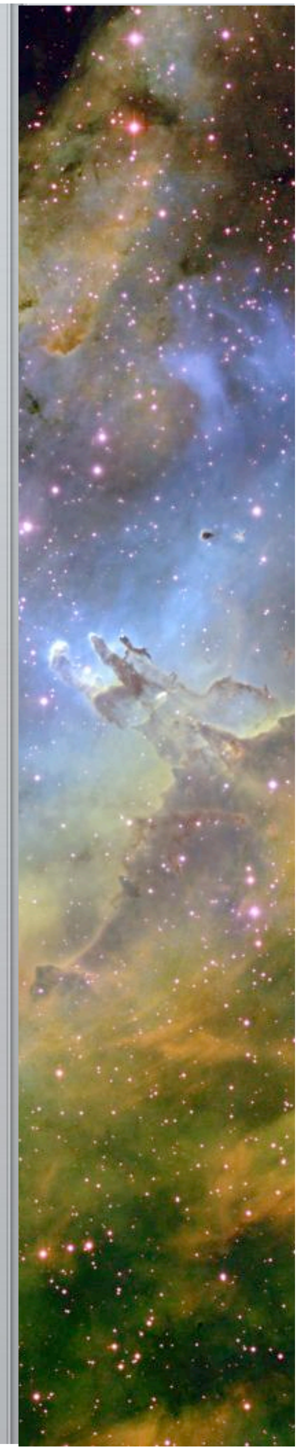
- A bluer line would allow access in optical window to higher redshift
- Blue Hydrogen lines are weaker and are affected by stellar absorption
- Lots of effort to calibrate [O II] (3727 Å) emission line as a star-formation indicator
  - Empirical calibration based on Hα

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



[O II] Emission





[O II] Emission

Advantages

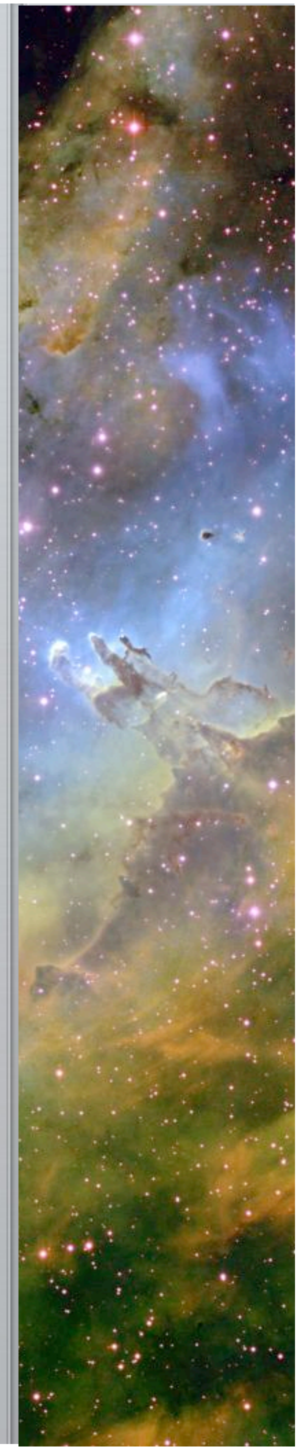
- Strong emission line
- Blue, so line is accessible in optical window out to $z \sim 1.5$

Disadvantages

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

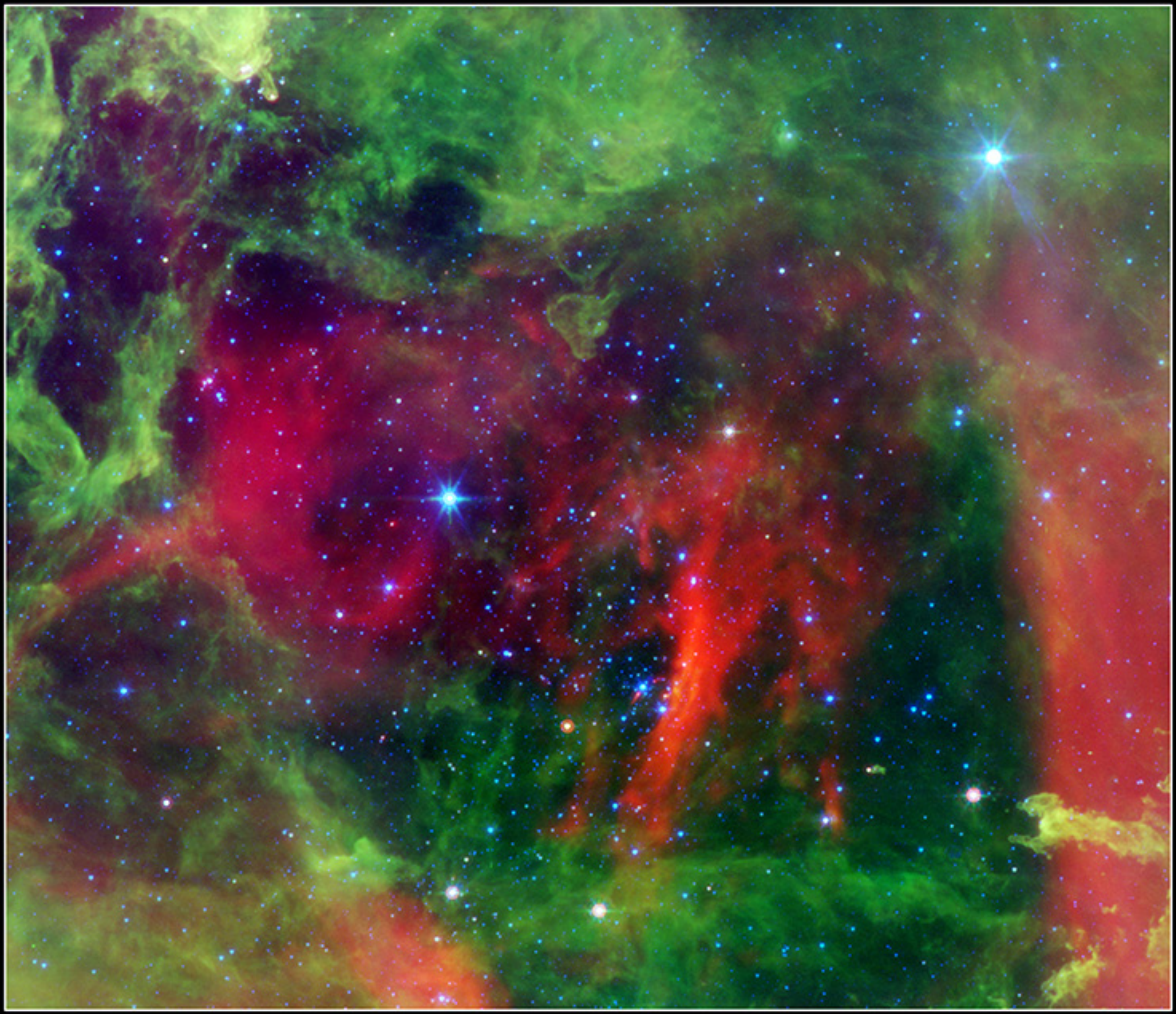
Far-Infrared Continuum

- 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

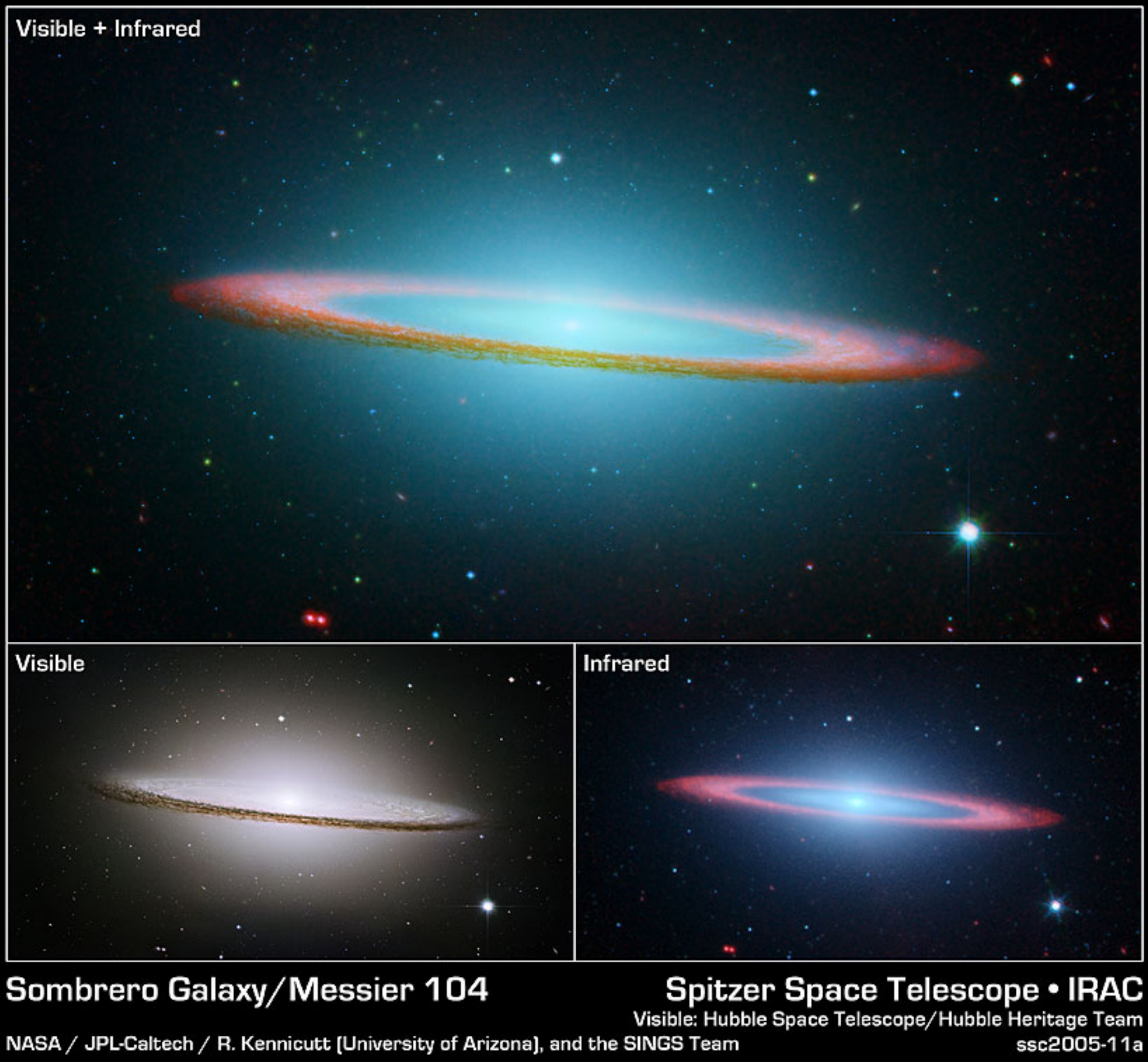
4.5 um
8.0 um
24 um



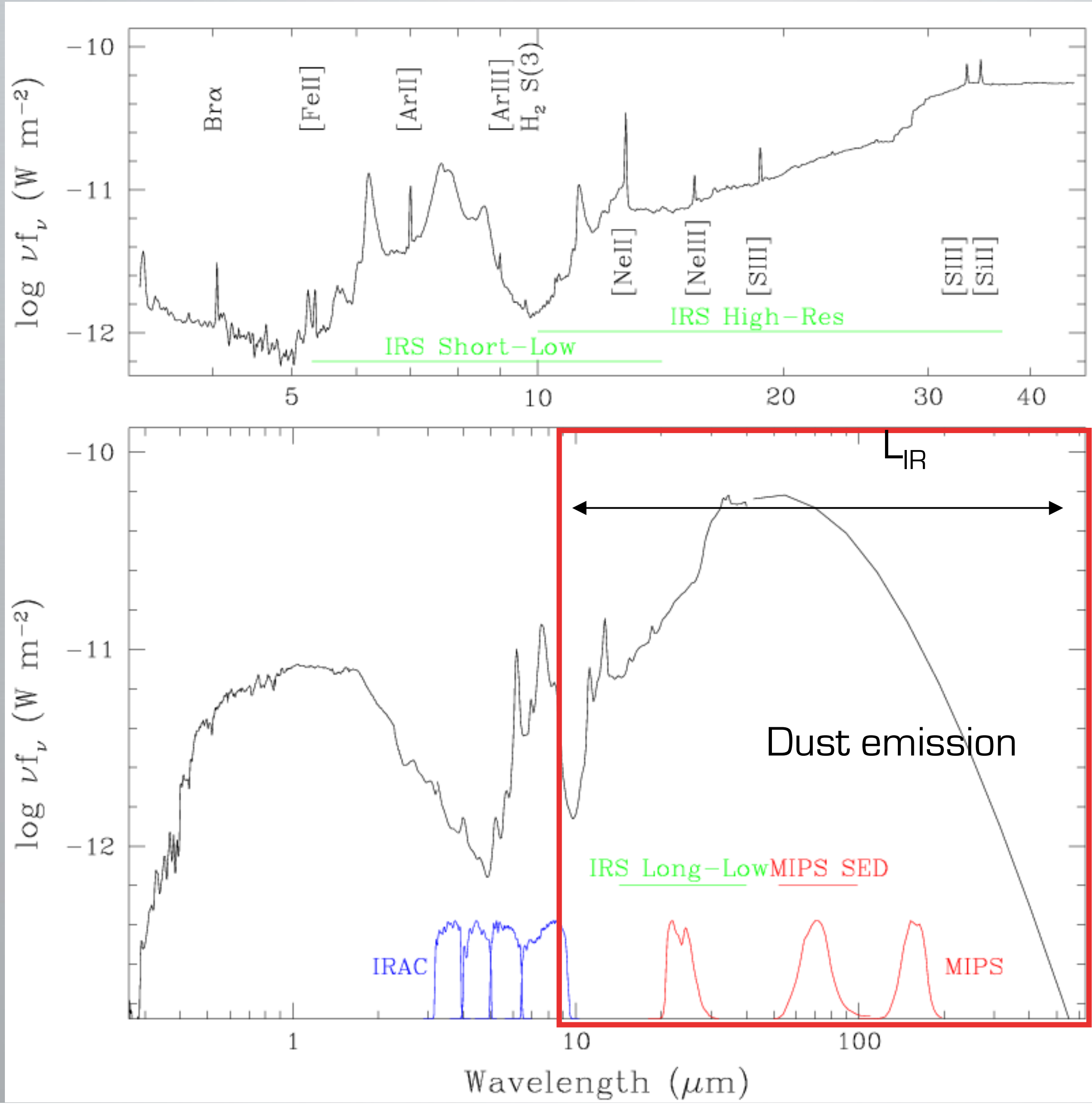
Star-Forming Rosette Nebula (NGC 2244) Spitzer Space Telescope • IRAC • MIPS
NASA / JPL-Caltech / Z. Balog (Univ. of Ariz./Univ. of Szeged) ssc2007-08a

Star Formation Rates from the Thermal IR

3.6 um
4.5 um
8.0 um



Star Formation Rates from the Thermal IR

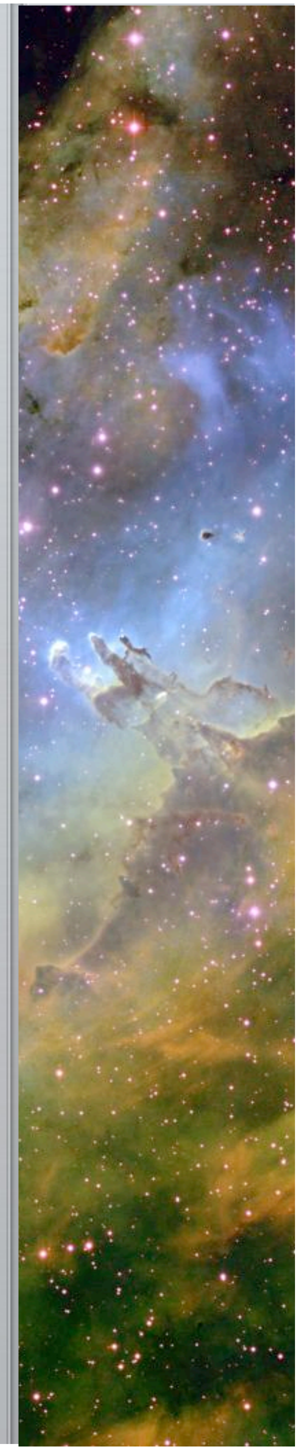


Far-Infrared Continuum

- 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

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

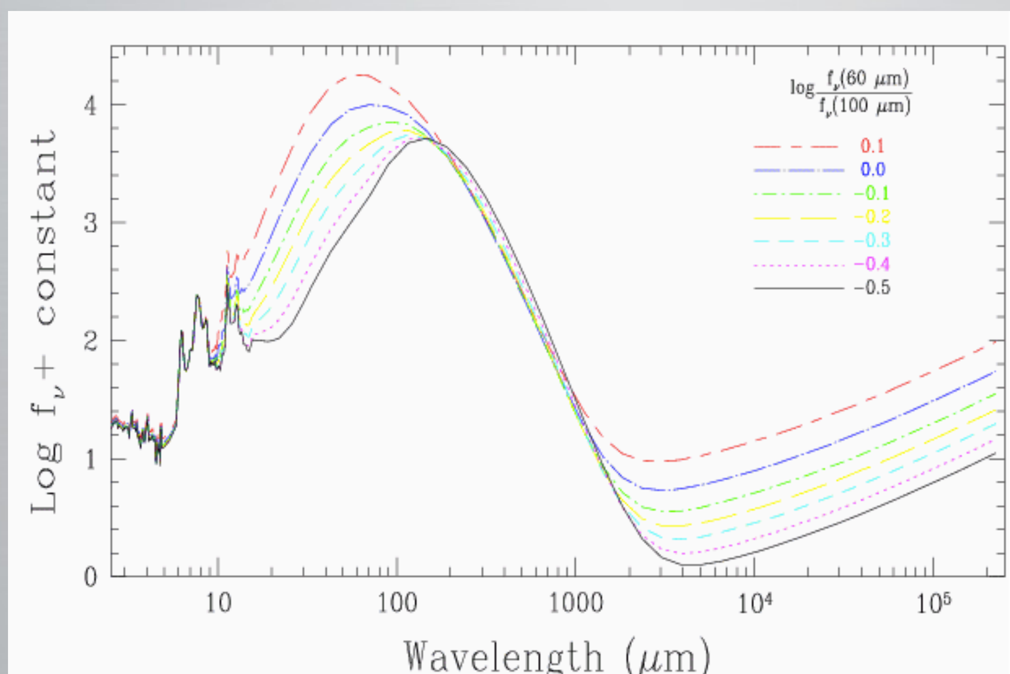
applies to starbursts with ages less than 10^8 yrs



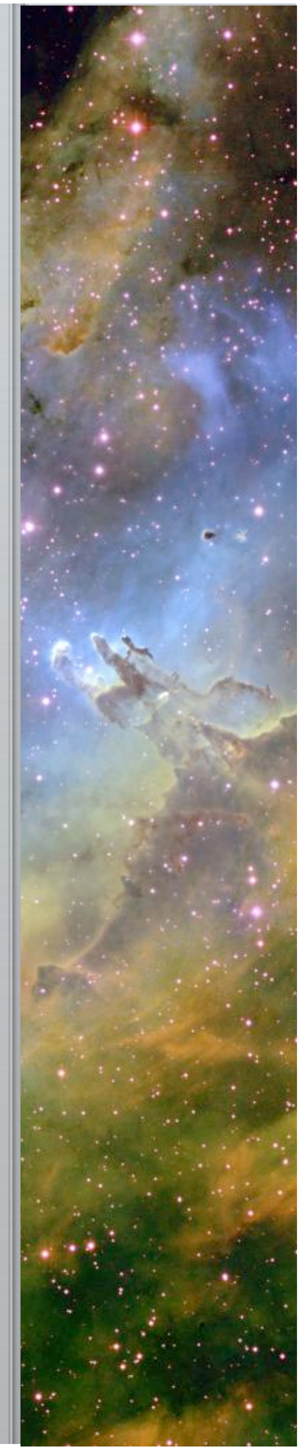
Far-Infrared Emission

- SFR calibration is based on emission between 8 and 1000 μm.

- Need to use model spectra to relate observed fluxes to total IR luminosity
  (Dale & Helou 2002; Chary & Elbaz 2001; Rieke et al 2909)



http://physics.uwyo.edu/~ddale/research/seds/seds.html



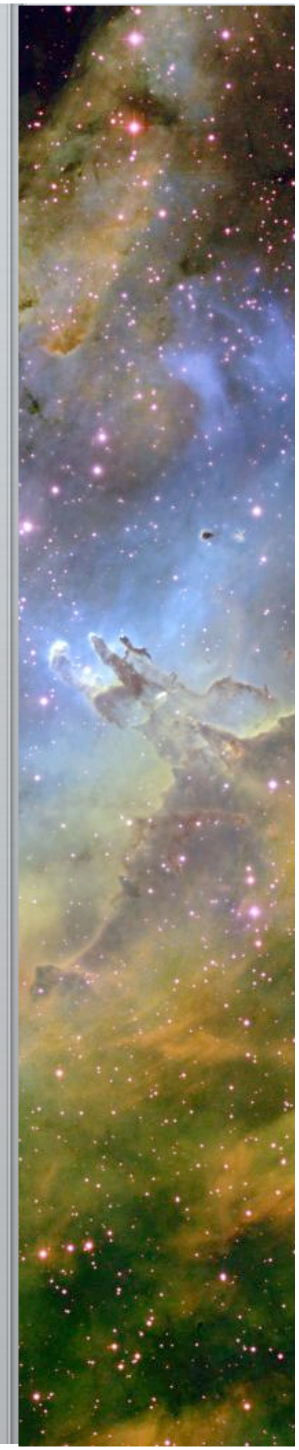
Far-Infrared Emission

Advantages

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

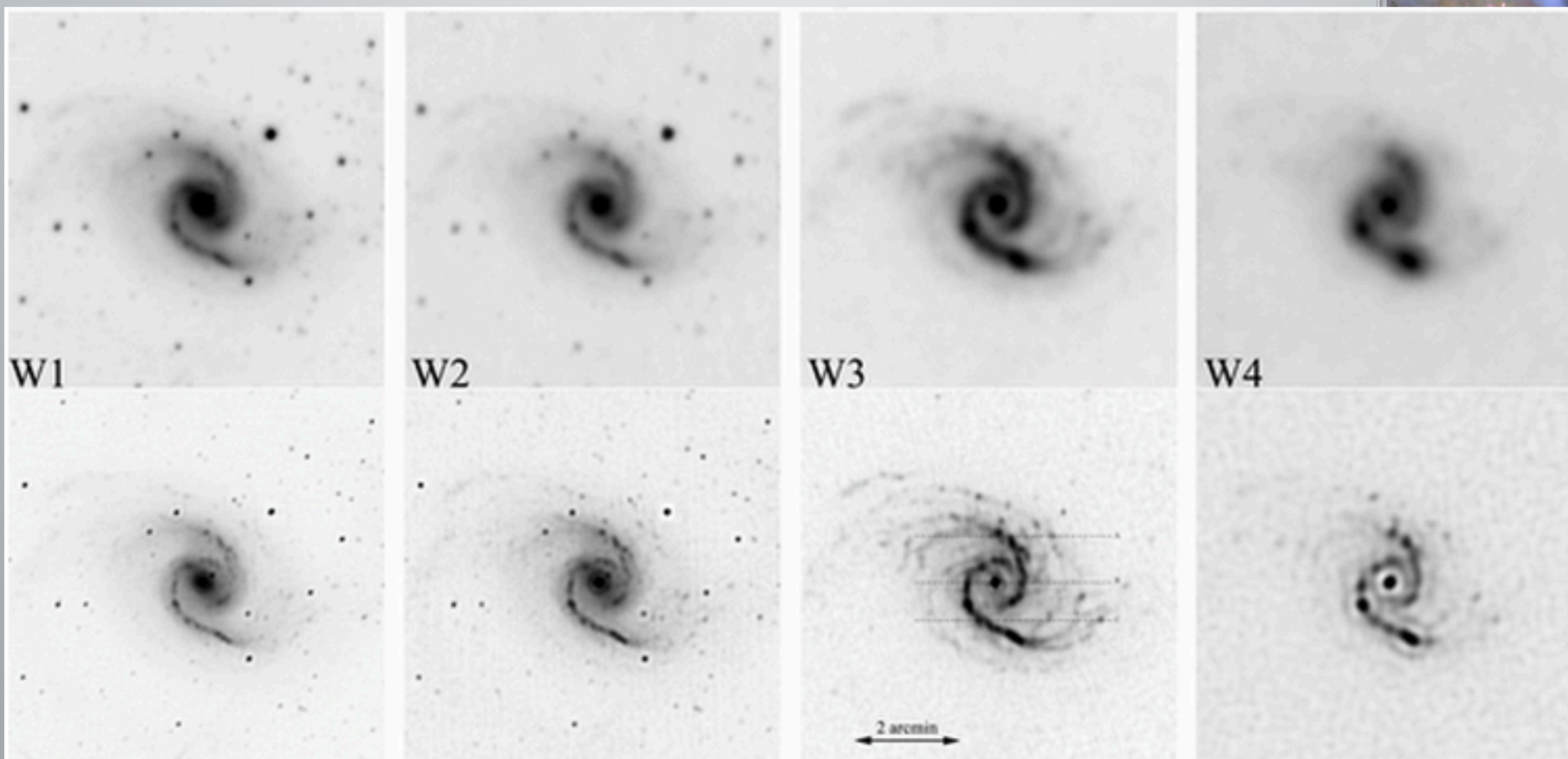
Disadvantages

- 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)



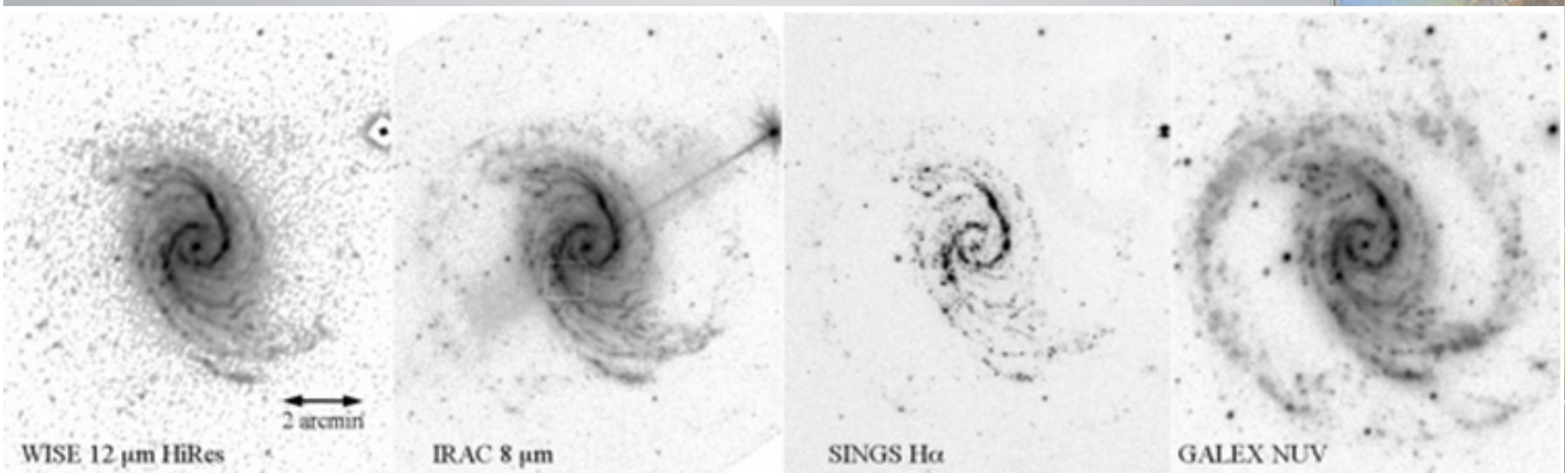
Estimating SFR_{IR} using WISE

Band	wavelength (μ)
W1	3.4
W2	4.6
W3	12
W4	22



Jarrett et al 2012

Estimating SFR_{IR} using WISE



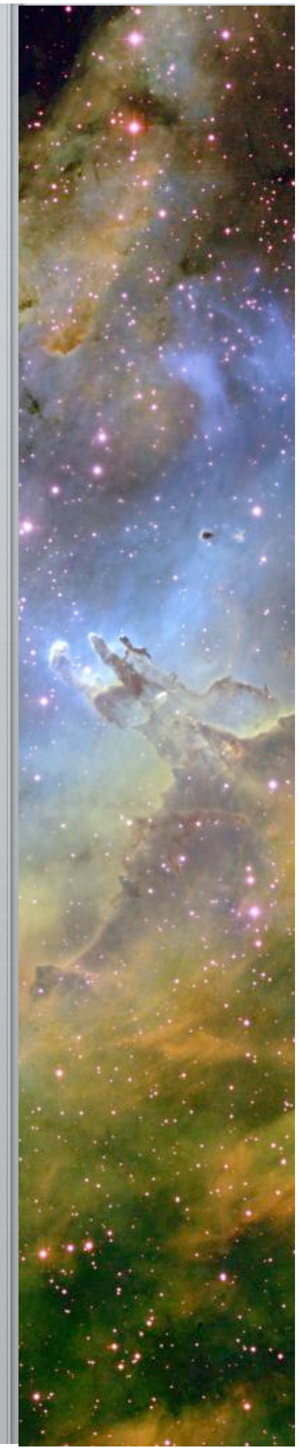
Jarrett et al 2012

WISE 22um vs Spitzer 24um

Table 5 Broadband Spectral Luminosities

Name	K_s 2.2 μm	*W1* 3.4 μm	*W2* 4.6 μm	*W3* 12 μm	*W4* 22 μm	MIPS 24 μm
	log $(\nu L_\nu/L_\odot)$	log $(\nu L_\nu/L_\odot)$	log $(\nu L_\nu/L_\odot)$	log $(\nu L_\nu/L_\odot)$	log $(\nu L_\nu/L_\odot)$	log $(\nu L_\nu/L_\odot)$
NGC 584	10.101	9.586	9.183	8.178	7.513	7.440
NGC 628	9.559	9.225	8.887	9.220	8.911	8.883
NGC 777	10.594	10.176	9.794	8.834	8.039	7.988
NGC 1398	10.498	10.027	9.650	9.477	8.846	...
NGC 1566	9.677	9.273	8.922	9.161	9.048	9.004
NGC 2403	9.110	8.791	8.462	8.693	8.505	8.442
NGC 3031	10.099	9.652	9.262	8.925	8.457	8.454
NGC 4486	10.585	10.236	9.845	8.861	8.412	8.309
NGC 5194	10.116	9.685	9.353	9.808	9.566	9.550
NGC 5195	9.814	9.359	8.983	8.702	8.574	8.601
NGC 5236	9.963	9.587	9.248	9.613	9.578	9.558
NGC 5457	9.969	9.567	9.233	9.542	9.251	9.226
NGC 5907	10.264	9.815	9.472	9.619	9.281	9.264

Jarrett et al 2013



Getting Position-matched WISE Catalogs

http://irsa.ipac.caltech.edu/applications/Gator/

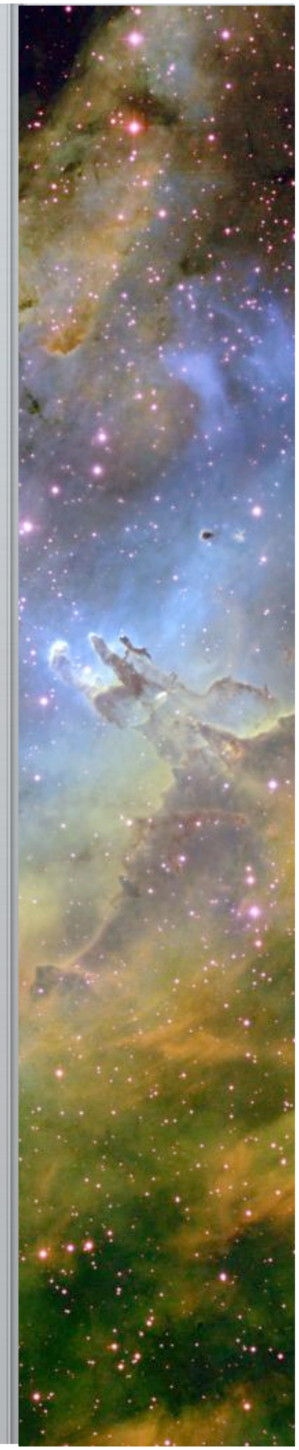
- select WISE, and then the select button
- select WISE All-Sky Source Catalog, then the red Select button
- near the bottom, select 'Long Form' button under Table Selection
- 'Select All Columns'
- back near top of page, click 'Multi-Object Search' button
- upload a file that contains an RA and Dec list
- set the cone search radius = 2 arcsec
- selet the 'Run Query' button
- download table
- open it using topcat
    - select ipac table in open file dialog
    - save table as a fits file
- then you can open table in python using atpy

```
import atpy
t1=atpy.Table('full-filename')
t1.describe()
```

WISE data columns are described here http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec2_2a.html

wise gives magnitudes. Our mips catalogs give fluxes in Janskys (micro-Jy). To convert, read instructions here http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec4_4h.html

make sure the colors of our sources (W1-W2, W2-W3, W3-W4) are consistent with fc ~= 1



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)