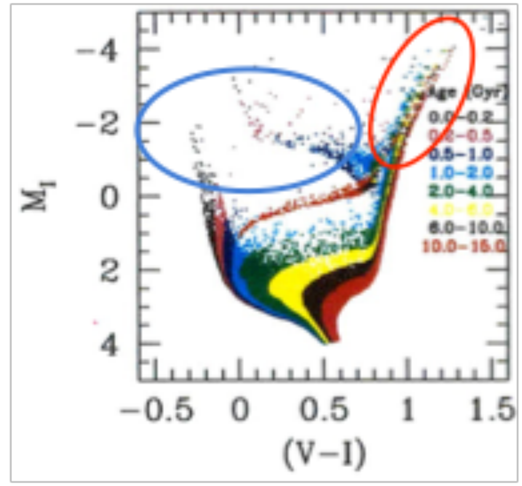
How do we infer galaxy ages?

Closely coupled to concept of "stellar populations*"

*previously discussed in the context of colors

1

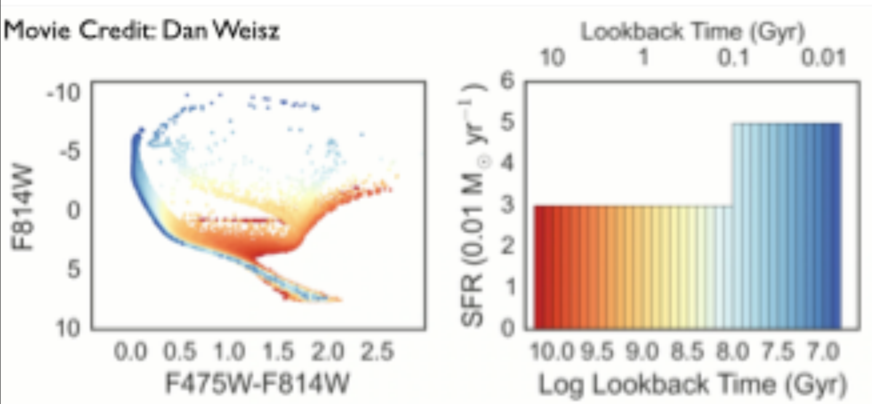
Galaxy colors/spectra are dominated by the brightest stars in their stellar populations



These stars are also the most massive

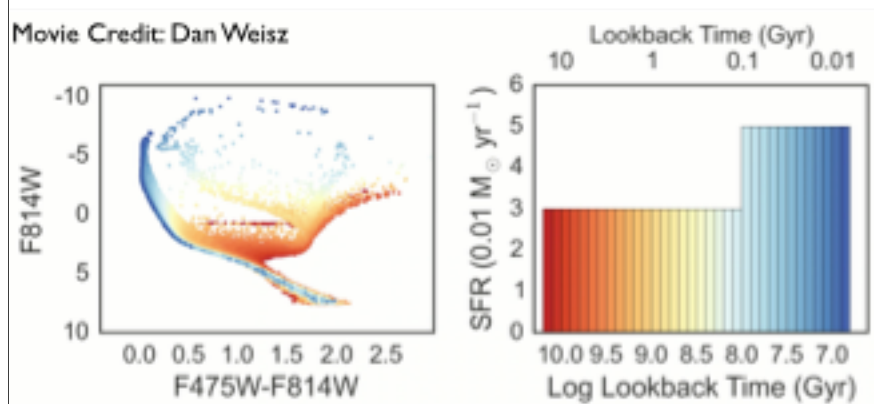
2

Color-Magnitude Diagrams vs Time



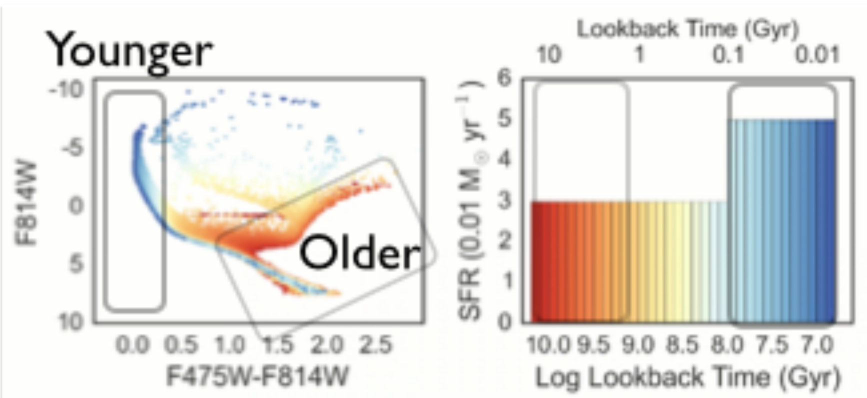
What are the brightest stars at each epoch?

Color-Magnitude Diagrams vs Time



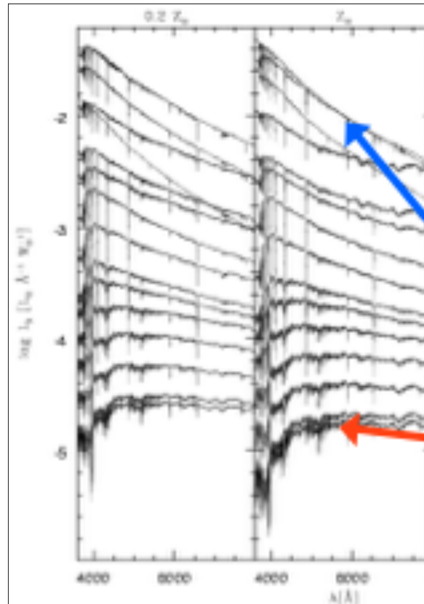
Recent SF: Bright stars are blue & luminous
Ancient SF: Bright stars are red & dimmer

Age resolution is ~logarithmic



Changes in color & luminosity:
Large/rapid at <100Myr.
Small/slow changes at >2Gyr.

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

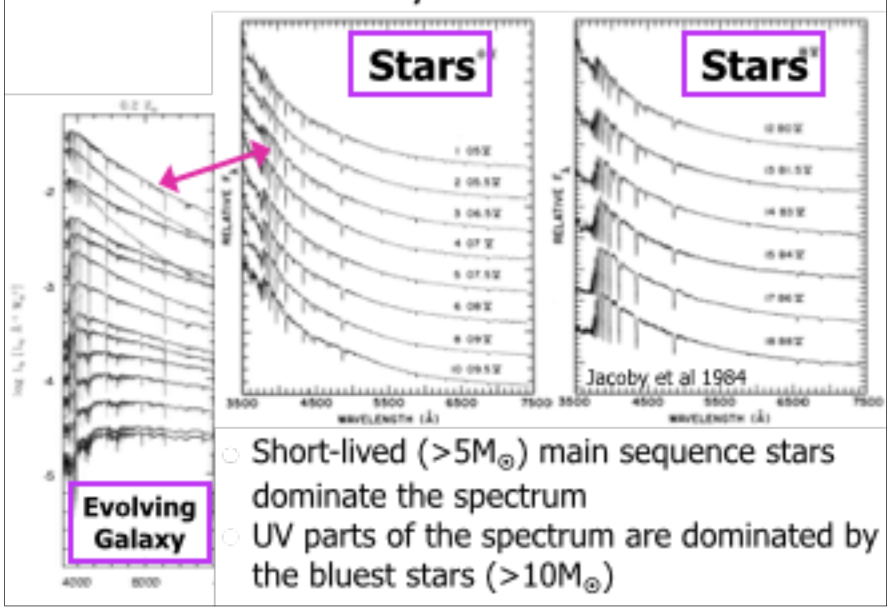


- Initially **bright** & blue, (dominated by O&B stars) w/ strong UV radiation (not shown)
- Later, "stellar population" becomes dimmer and redder (dominated by red K-giants)

Fernandes et al 2005

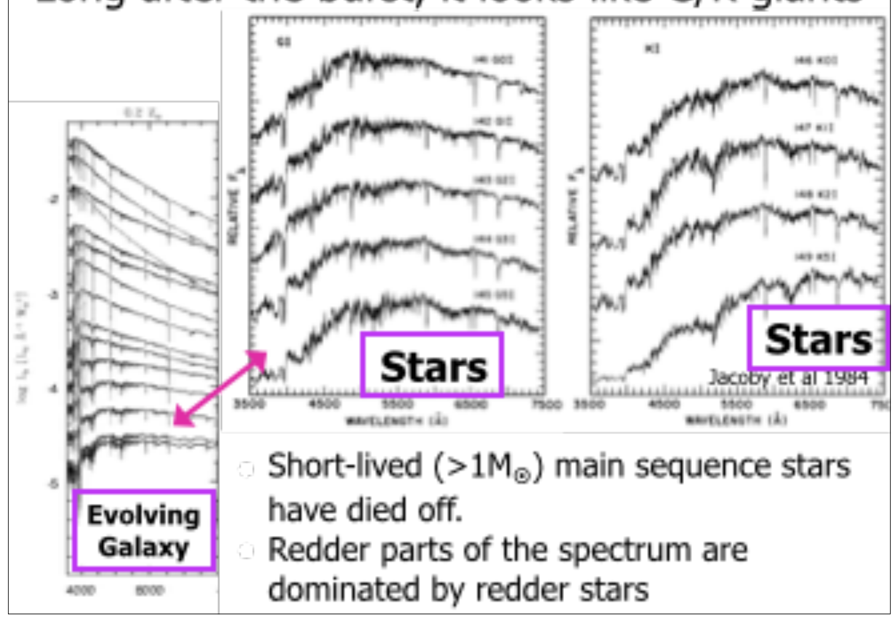
Figure 1. Spectra of the 45 SSPs used in the spectral synthesis (from BC03). The base comprises 3 different metallicities, $Z = 0.2$, 1 and 2.5 $Z_\odot$, and 15 ages: From top to bottom, $t = 0.001$, 0.00316, 0.00501, 0.01, 0.02512, 0.04, 0.10152, 0.28612, 0.64054, 0.90479, 1.434, 2.5, 5, 11 and 13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

A burst of SF initially looks like O & B stars

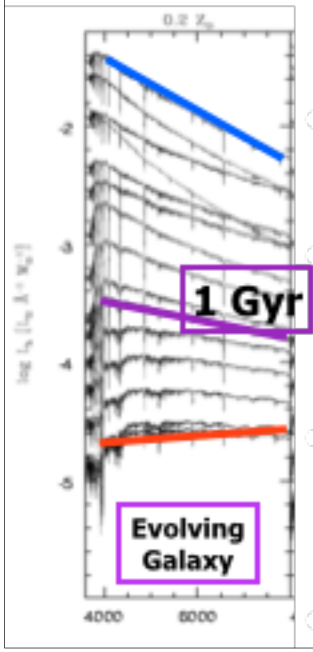


- Short-lived (>5$M_\odot$) main sequence stars dominate the spectrum
- UV parts of the spectrum are dominated by the bluest stars (>10$M_\odot$)

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



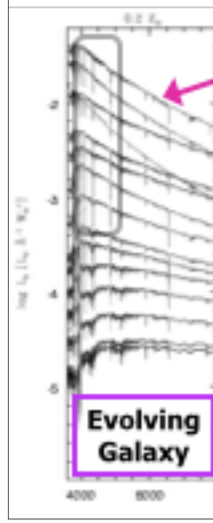
- Short-lived (>1$M_\odot$) main sequence stars have died off.
- Redder parts of the spectrum are dominated by redder stars

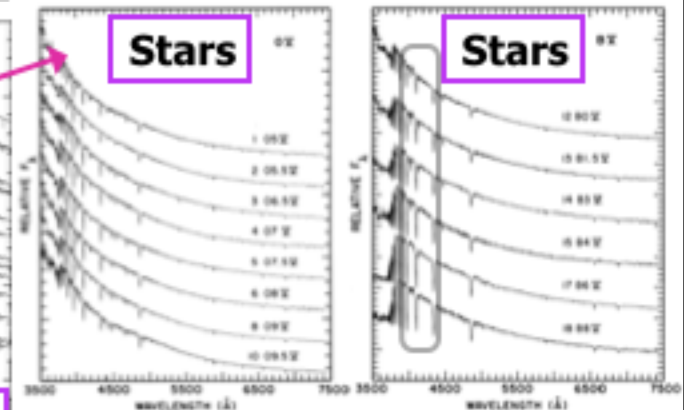


Take-away

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

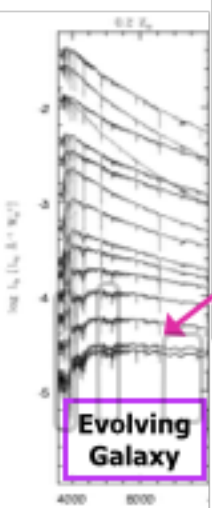
Beyond colors, use spectral features for age-dating, based on features in dominant stellar type

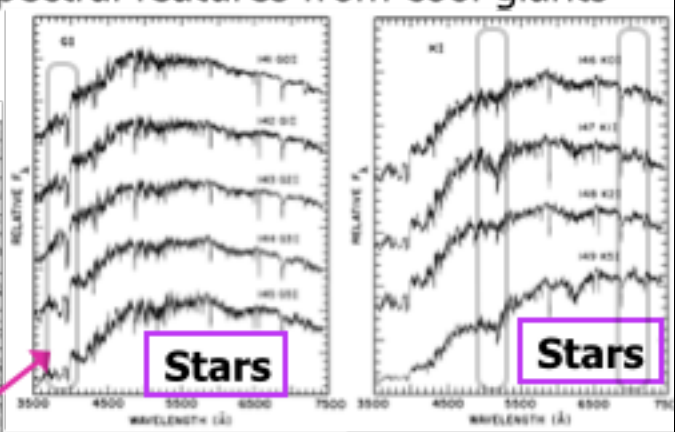




Balmer lines:
Strongest in A and B stars

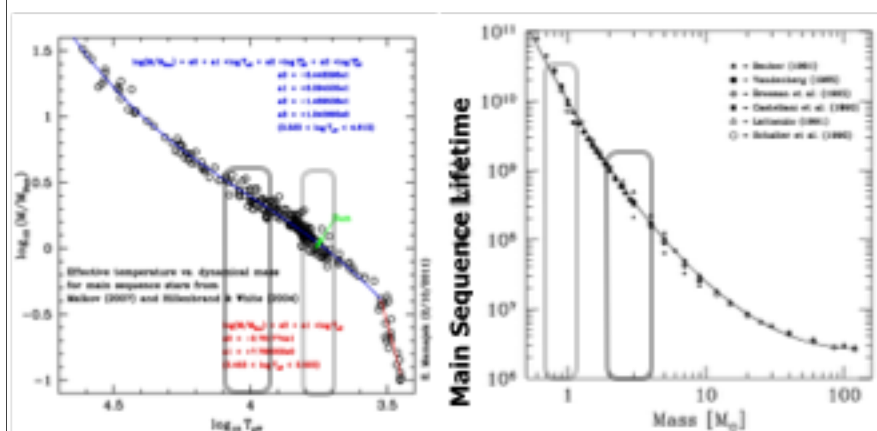
"Old" Spectral features from cool giants



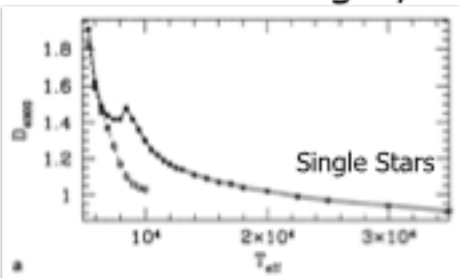


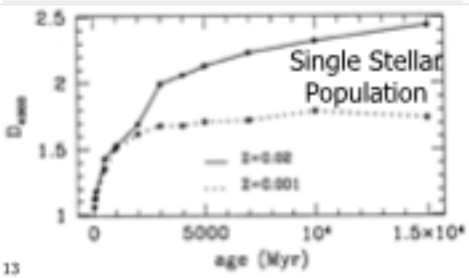
- 4000 Angstrom Calcium H&K break
- Magnesium & "G"-bands
- TiO molecular bands

Age sensitivity comes from "what mass star is dominating spectrum"

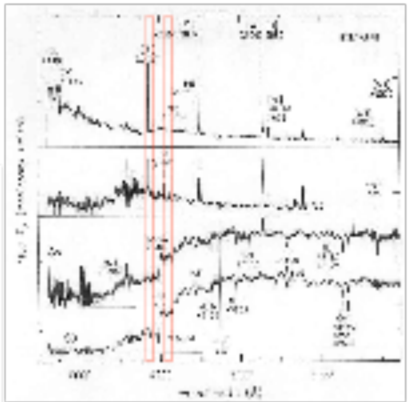


Ages from D4000: 4000 Angstrom Break
Works to old ages, but metallicity issues



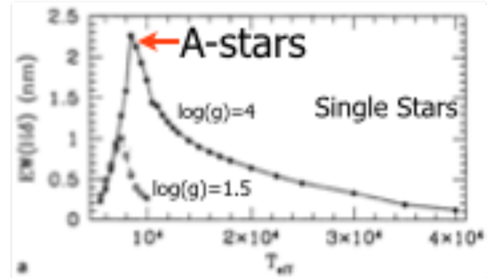


D_{4000} is largely used to determine the star formation characteristics of distant field and cluster galaxies. Hereafter the 4000 Å break is defined as the ratio between the average flux density in ergs s^{-1}cm^{-2}Hz^{-1} between 4050 and 4250 Å and that between 3750 and 3950 Å (Bruzual 1983).



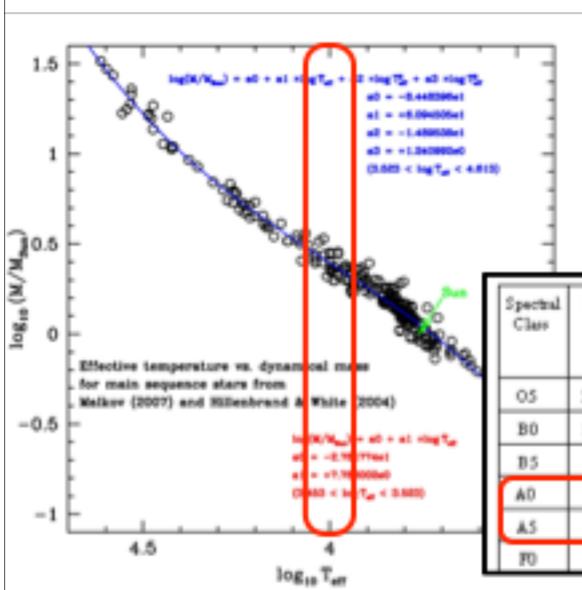
Poggianti & Barbaro 97

Ages from Balmer Absorption Lines: Hδ



Strongest Balmer absorption lines are from A-stars with moderately high masses, and short (0.5-1 Gyr) lifetimes

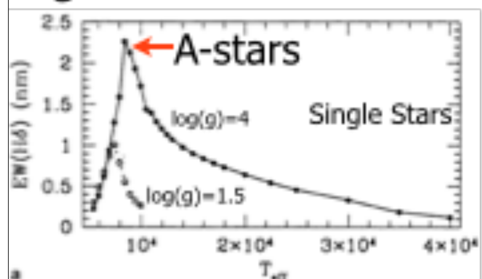
Ages from Balmer Absorption Lines: Hδ



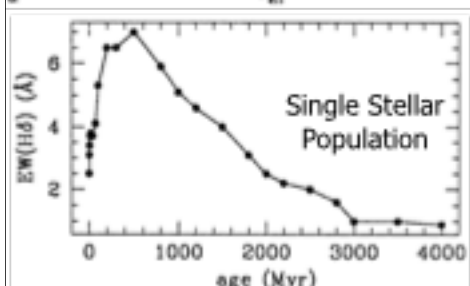
Peak Balmer line strength for 2-3 $M_\odot$ stars

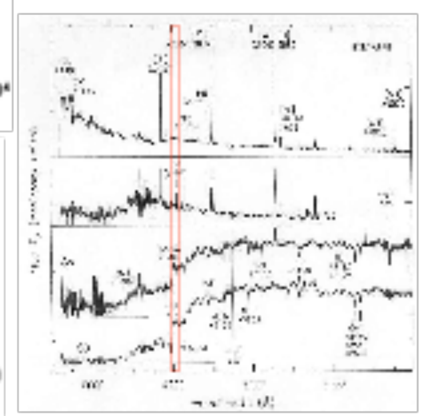
Spectral Class	Mass [$M_\odot$]	time to form [million years]	MS lifetime [million years]	time till He-flash [million years]
O5	32	0.01	1	
B0	16	0.1	10	2
B5	6		100	5
A0	3	1	500	30
A5	2		1,000	
F0	1.75		2,000	300

Ages from Balmer Absorption Lines: Hδ

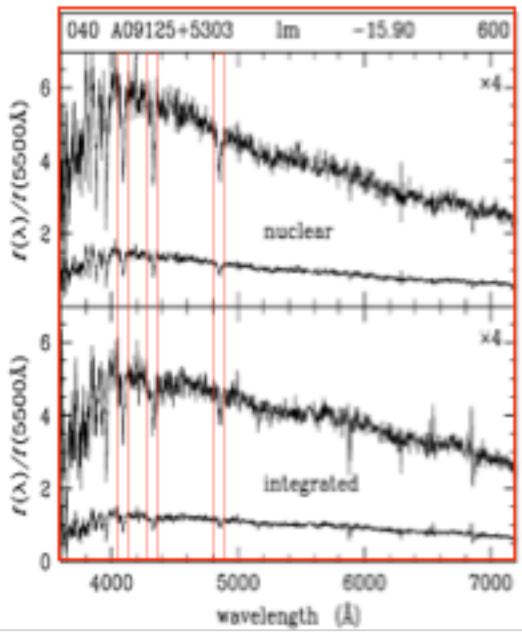


Note: Not sensitivity past a few Gyrs





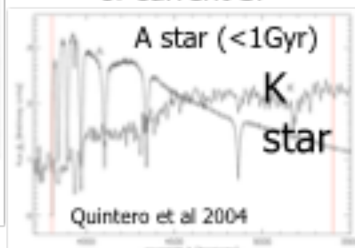
Poggianti & Barbaro 97



Example: Post-Starburst Spectrum

Blue stellar spectra, but no emission lines

strong Balmer absorption lines indicative of short lived A stars, but no sign of current SF



How do we infer star formation rates?

Similar principles apply to inferring presence of "recent" star formation

Overview: Star formation in Galaxies

- Initial focus will be on global properties
  - Not concerned w/ details of how individual gas blobs turn into stars
- Measuring the "instantaneous" star formation rate (in $M_{\odot}$/yr)
- Variation in SFR within the galaxy population
- Correlation between physical properties & galaxy's global star formation rate (SFR)
- SFR variation with time

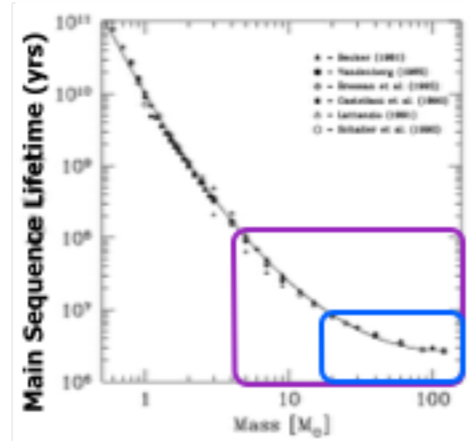
Measuring Star Formation (SF)

- Galaxy spectra in the presence of young stars
- The IMF
- Observable consequences of SF
  - UV emission
  - Recombination lines
  - Free-Free emission
  - Dust emission
- Wrinkles -- Obscured vs UnObscured, IMF variations
- SF rates
  - Typical galaxies
  - ULIRGS
  - Dwarfs

Why is measuring SFR important?

- Converting gas into stars is a major evolutionary pathway
- SFR affects SN feedback, production of metals, state of the ISM, galaxy luminosity and color...basically everything!
- Should evolve with redshift
  - Need many indicators that work in different redshift regimes, and that can be checked against each other

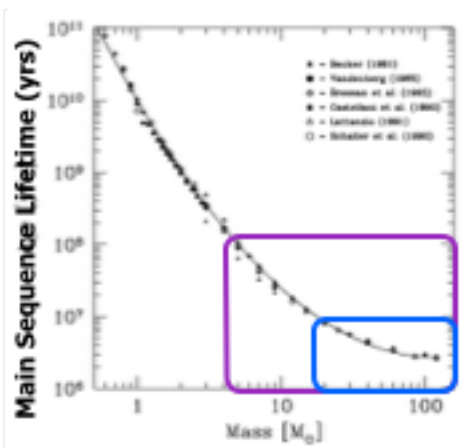
Measuring the “instantaneous” SFR



Define “instantaneous” to be <10-100 Myr

 http://www.bo.astro.it/~eps/buz10201/ajf03.jpg

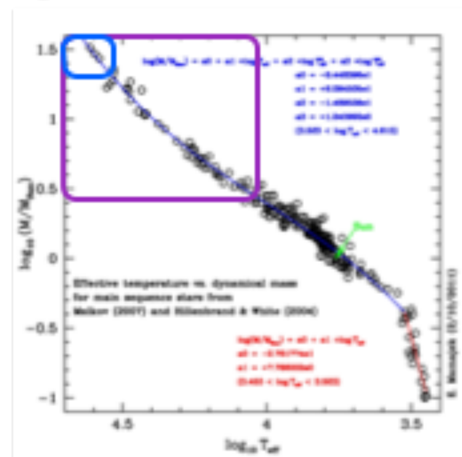
Measuring the “instantaneous” SFR



Find tracers of >4-20 M⊙ (B & O) stars

 http://www.bo.astro.it/~eps/buz10201/ajf03.jpg

Measuring the “instantaneous” SFR



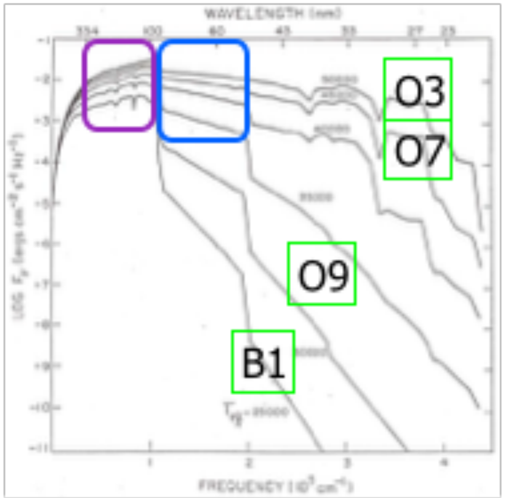
http://www.pas.rochester.edu/~emamajek/coolplots.html

10-100Myr ⇨ 4-20 M⊙ ⇨ $T_{\rm eff}$ >11,000-35,000K

Signatures of >10,000-35,000K stars:

near- & far-UV flux

<100Myr



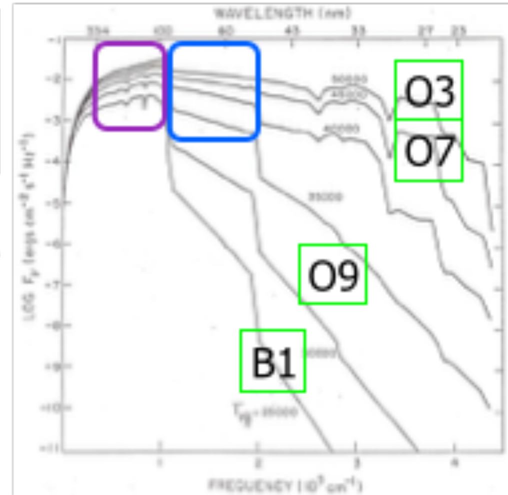
Ionizing radiation

<10 Myr

Current SFR Tracers:

near- & far-UV flux

<100Myr



Ionizing radiation

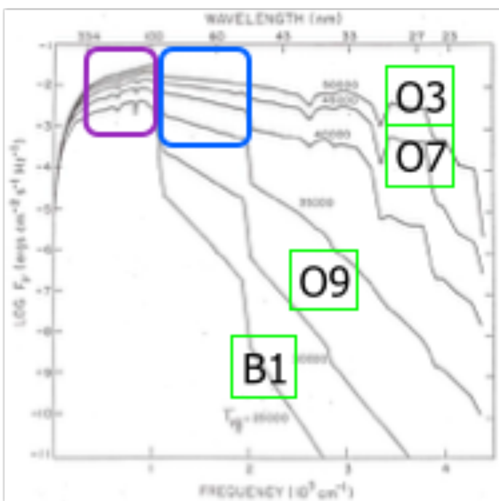
<10 Myr

All amount to looking for UV flux or signs of ionized gas

Current SFR Tracers:

near- & far-UV flux

<100Myr

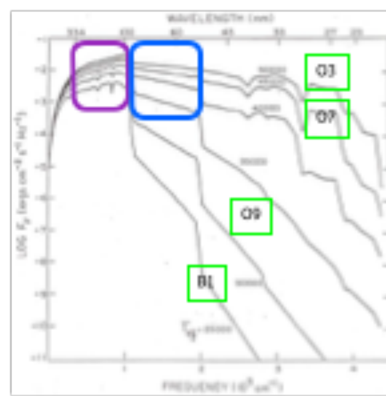


Ionizing radiation

<10 Myr

But!!! Must translate measurements of flux to quantitative SFR ($M_\odot$/yr)

Total UV & Ionizing Flux depends on exact numbers of very hot stars

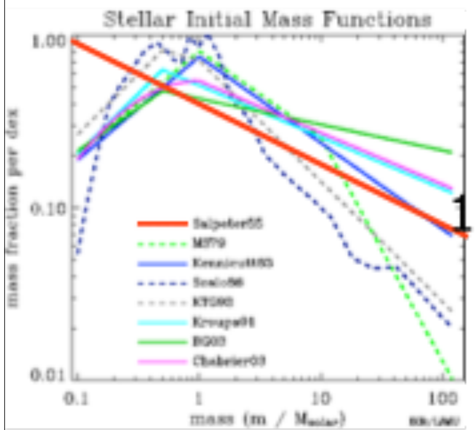


Converting to SFR ($M_\odot$/yr) requires **extrapolating** to the total stellar mass associated with the detected O & B stars

Both depend sensitively on the "Initial Mass Function"

The Initial Mass Function (IMF):

stars with M → M + dM $= N_0 \xi(M) dM$

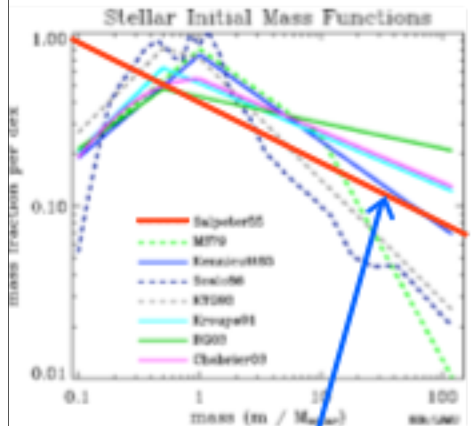


where N_0 sets the size of the burst, and the IMF ξ(M) is normalized such that

$$1 M_\odot = \int M \xi(M) dM$$

KTG93=Kroupa et al 1993
MS79=Miller & Scalo 1979
BG03=Baldry & Glazebrook 2003

http://www.astro.ljmu.ac.uk/~ikb/research/imf-use-in-

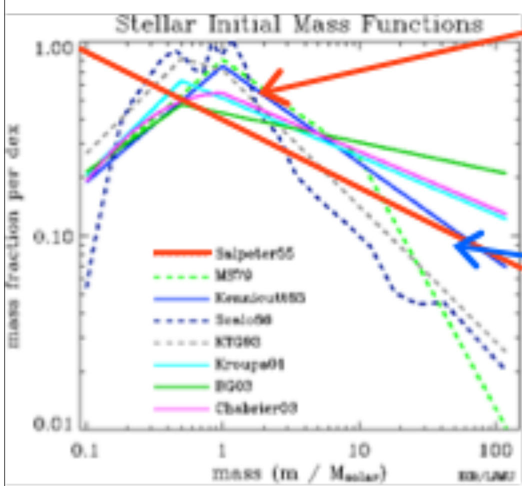


IMF is frequently approximated as a power law

$$\xi(M) \propto M^{-(1+x)}$$

If x=1.35, you get the "Salpeter IMF"

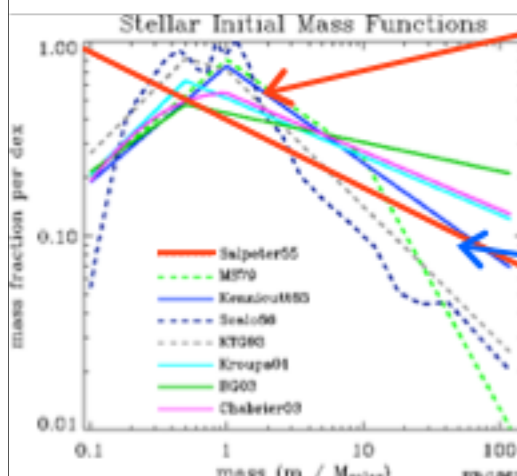
The Initial Mass Function (IMF):



Lots of long-lived low mass stars

Few short-lived high mass stars

The Initial Mass Function (IMF):



Dominates the stellar mass

$M\xi(M) \propto M^{-1.35}$

Dominates the luminosity, UV, & ionizing output

$L_{MS} \propto M^{+3.5}$

$L\xi(M) \propto M^{+1.15}$

IMF variations for low mass stars

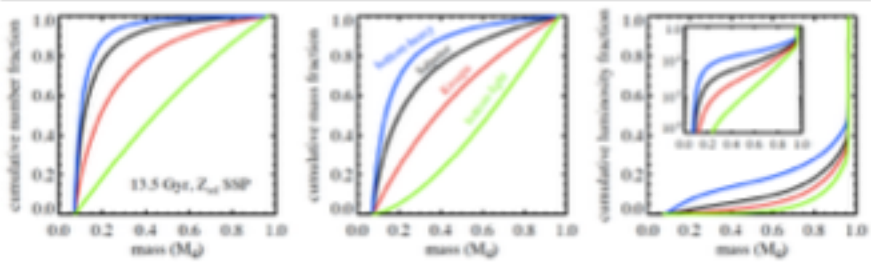
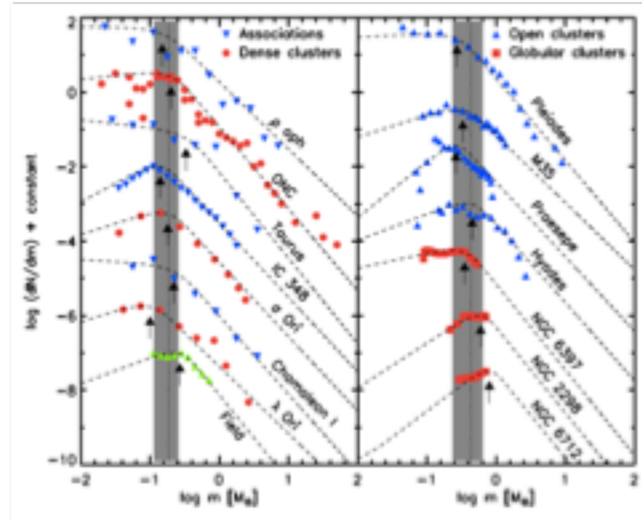


Figure 4:

Fractional contribution to the total number, mass, and bolometric luminosity as a function of stellar mass for a 13.5 Gyr solar metallicity model. Lines correspond to different IMFs: a bottom-heavy with logarithmic slope $x = 3.0$ (blue line); Salpeter ($x = 2.35$; black line); MW IMF (specifically a Kroupa IMF; red line); a bottom-light IMF (specifically of the form advocated by van Dokkum (2008); green line). The inset in the right panel shows the cumulative luminosity fraction in logarithmic units. Low mass stars dominate the total number and mass in stars, but contribute a tiny fraction of the luminosity of old stellar populations.

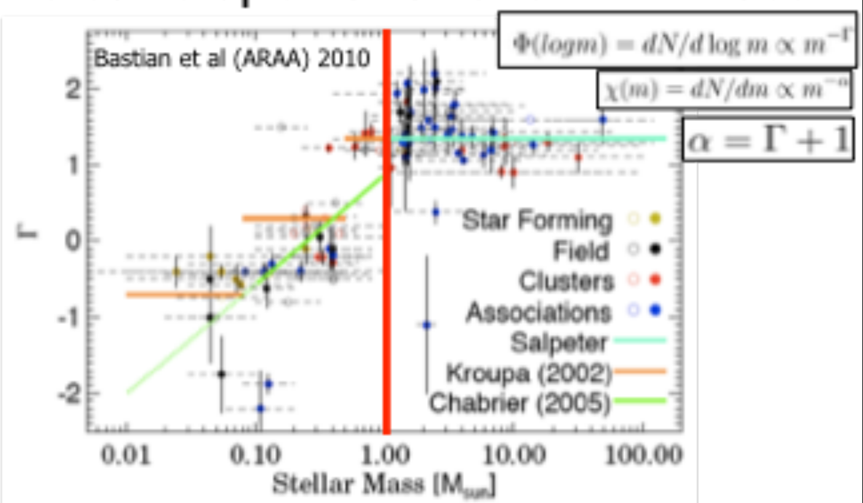
33 Conroy et al (ARAA) 2013

Derived typically from stellar clusters



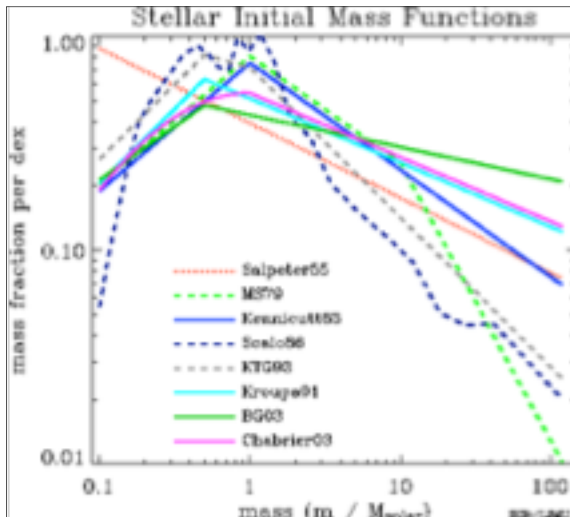
34 Bastian et al (ARAA) 2010

Clear slope variations with mass



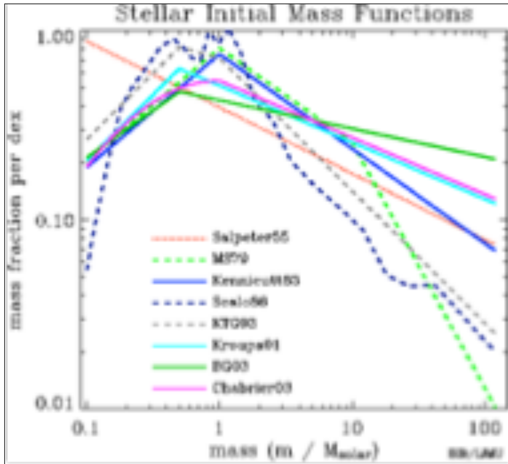
MW high-mass slope (>1 M☉) relatively constant

35



IMF propagates into nearly every aspect of extragalactic astronomy

36 http://www.astro.ljmu.ac.uk/~ikb/research/imf-use-in-cosmolog

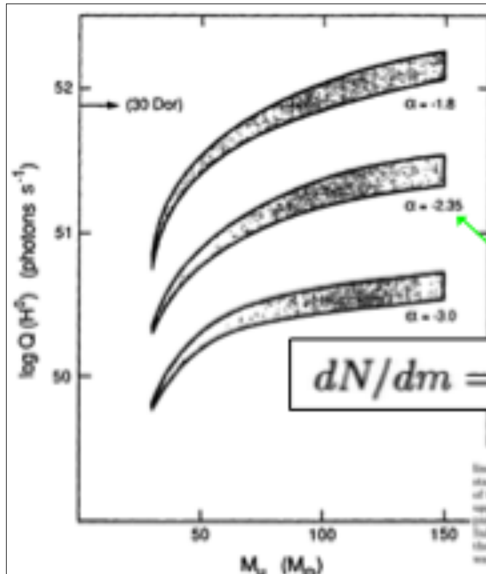


The high-mass IMF slope has particularly large effects

- Metal production
- SN rates
- SN feedback
- Ionizing flux

http://www.astro.ljmu.ac.uk/~ikb/research/imf-use-in-cosmolog

Ionizing UV flux vs slope of high-mass IMF



Salpeter IMF

$$dN/dm = a\, m^{-\gamma}$$ $$\gamma = 2.35$$

Figure 1. Initial ionizing luminosity for a star cluster with fixed mass (luminosity $M_V = -9$ at age 100 Myr), as functions of the IMF slope α and upper mass limit M_u, from Kennicutt & Chu (1988).

Kennicutt IMF Review 1998

Back to calculating SFRs...

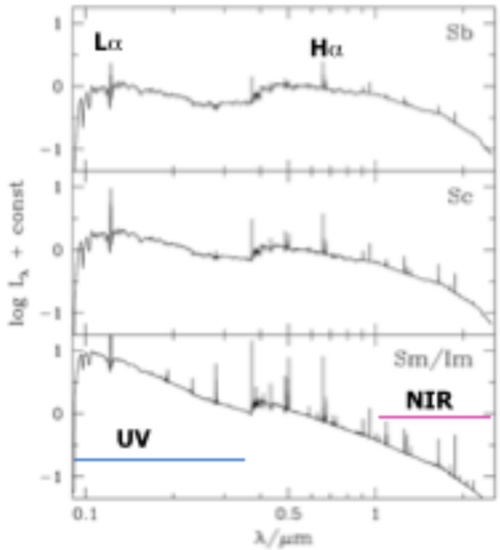
Convert tracers of >4-20 $M_\odot$ (B & O) stars to quantitative values for the SFR

- Use "stellar population synthesis models" w/ adopted IMF to calculate mapping from SFR to observables
  - Usually assumes constant SFR for >100 Myr
- Use SFRs derived from older/reliable measurement to calibrate newer/less-reliable method

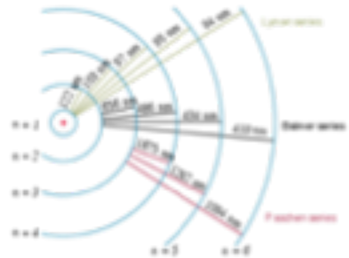
Most direct constraint on ionizing flux

- Recombination lines of Hydrogen
  - Directly traces the numbers of ionizing photons
  - Effectively "counts" emission from O-stars
  - Lya may have issues with being resonance line...
  - May not be photoionized by O-stars. Can have contributions from other sources of ionization (i.e., AGN, shocks)

Recombination lines appear in the UV, IR, and even radio

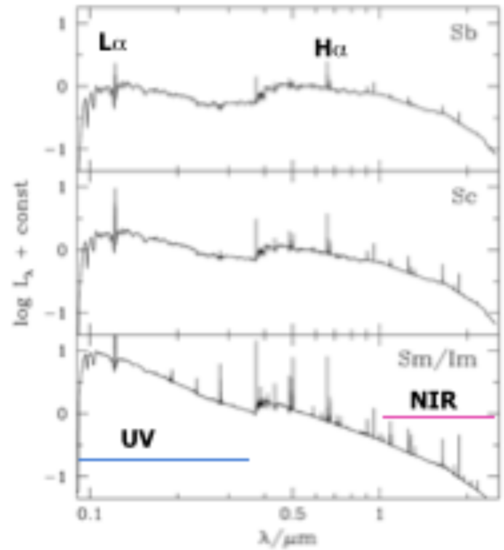


UV: Lyα
NIR: Paschen series



Charlot & Longhetti 2001

Recombination lines appear in the UV, IR, and even radio

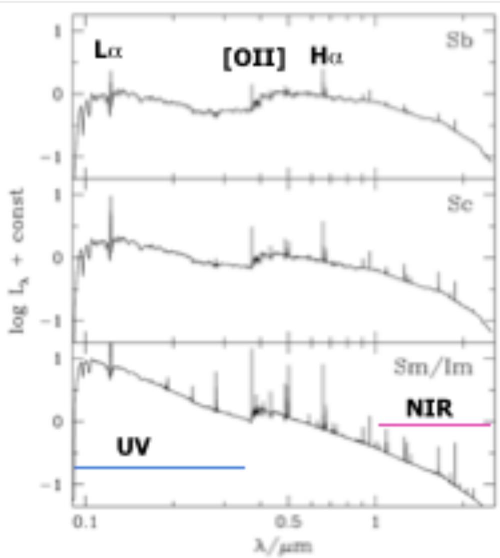


UV: Lyα
NIR: Paschen series

- UV lines are good for higher redshift
- NIR lines are good for avoiding dust attenuation uncertainties

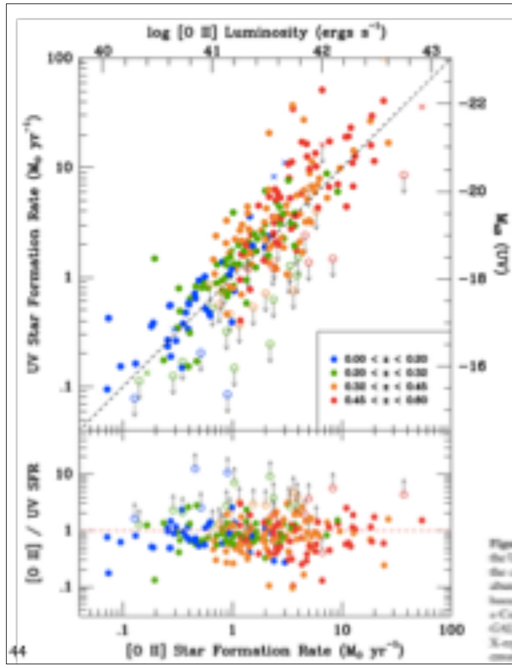
Charlot & Longhetti 2001

Forbidden lines are used as well, but:



- Less direct tracer of ionization
- Depends on metallicity, ionization parameter
- But, only lines accessible at some redshifts (e.g., [OII] doublet at 3727A appears between La and Ha)

Charlot & Longhetti 2001



Example of calibrating [OII] forbidden line as SFR indicator

Ciardullo et al 2013

For references: Wavelengths of emission lines

Table I. Computed lines: Hydrogen recombination lines (upper pannel), Elium and metal lines (lower pannel)

Lyα 1216	Lyβ 1025	Lyγ 972	Lyδ 949	Ly 937	Ly 930
Ly 926	Ly 922	Hα6563	Hβ 4861	Hγ 4340	Hδ 4102
H 3970	H 3889	H 3835	H 3798	Paα 18752	Paβ 12819
Paγ 10939	Paδ 10050	Pa 9546	Pa 9229	Pa 9015	Pa 8863
Brα 40515	Brβ 26254	Brγ 21657	Brδ 19447	Br 18175	Br 17363
Br 16808	Br 16408	Pfα 74585	Pfβ 46529	Pfγ 37398	Pfδ 32964
Pf 30386	Pf 28724	Pf 27577	Pf 26746	Huα 123690	Huβ 75011
Huγ 59071	Huδ 51277	Hu 46716	Hu 43756	Hu 41700	Hu 40201
HeII 1640	HeII 1217	HeII 1085	HeII 4686	HeII 3203	HeII 2733
HeII 2511	HeI 4471	HeI 5876	HeI 6678	HeI 10830	HeI 3889
HeI 7065	[CI]9850	[CI]8727	[CI]4621	[CI]609μm	[CI]369μm
[CII]157.7μm	CII]2326	CIII]1908	[NI]5199	[NI]3466	[NI]10400
[NII]6584	[NII]6548	[NII]5755	[NII]122μm	[NII]205μm	NII]2141
[NIII]57μm	[OI]6300	[OI]6363	[OI]5577	[OI]63μm	[OI]145μm
[OII]3727	[OII]7325	[OII]2471	OIII]1663	[OIII]5007	[OIII]4959
[OIII]4363	[OIII]2321	[OIII]88μm	[OIII]52μm	[OIV]26μm	[NeII]13μm
[NeIII]15.5μm	[NeIII]36μm	[NeIII]3869	[NeIII]3967	[NeIII]3343	[NeIII]1815
[NeIV]2424	[NeIV]4720	MgII2800	[SiII]35μm	[SII]10330	[SII]6731
[SII]6717	[SII]4070	[SII]4078	[SIII]19	[SIII]33.5	[SIII]9532
[SIII]9069	[SIII]6312	[SIII]3722	[SIV]10.4μm	[ArII]69850	[ArIII]7135
[ArIII]7751	[ArIII]5192	[ArIII]3109	[ArIII]3005	[ArIII]22μm	[ArIII]9μm

Second constraint on ionizing flux

- Free-free bremsstrahlung emission from electrons
  - Easy to measure from the ground (1.4 GHz, 4.3 GHz widely used)
  - Unaffected by dust

VLA map at 20cm

On Hα | On optical

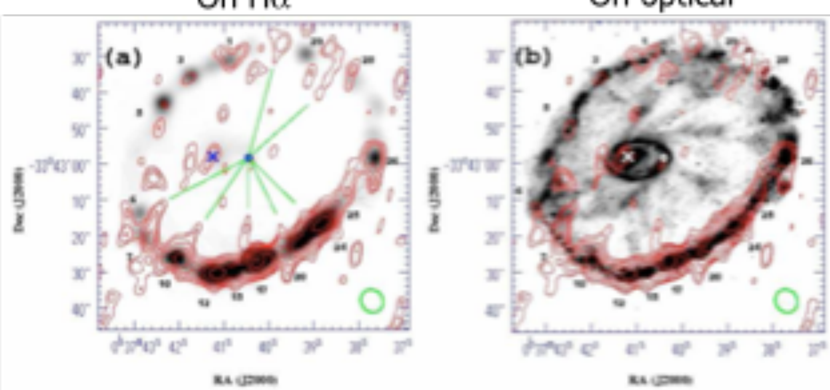
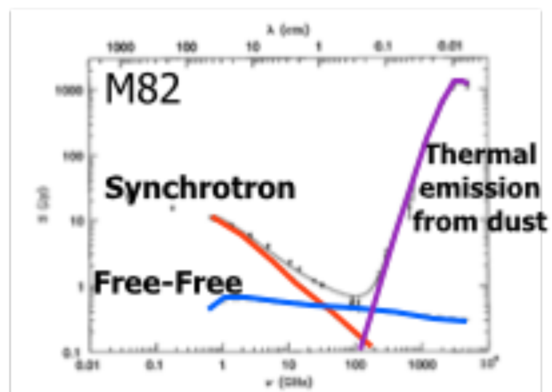


FIG. 1.— 20 cm RC intensity contours of the Cartwheel superimposed on (a) an Hα image (gray scale), which has been smoothed to the resolution of the 20 cm RC image, and (b) the HST B-band image. The lowest contour level corresponds to 60 μJy beam^{-1} (≈ 2σ), and the subsequent contour levels increase by a factor of $\sqrt{2}$. The ellipse at the bottom-right corner indicates the RC beam size. In (a) note the excellent positional correspondence between radio peaks and Hα complexes, which have been labeled by their H95 numbers. Straight lines are drawn connecting the filamentary structures or spokes to the geometrical center of the ring. Unlike the optical spokes (features connecting the inner ring to the outer ring in (b)), the RC spokes are straight and short. The position of the nucleus is marked by a cross.

 Mayya et al 2005

Free-Free emission caveat

- Contaminated by non-thermal emission (synchrotron), which also depends on SFR, but in an unpredictable way.

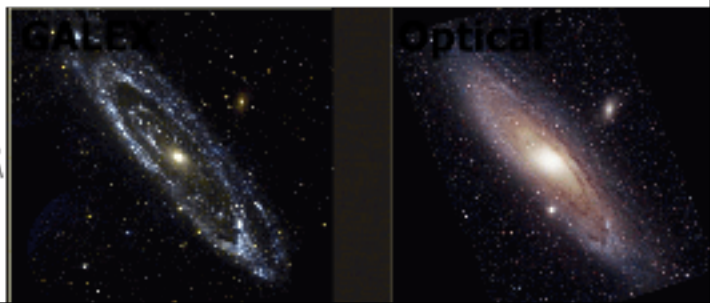


M82

Direct constraints on UV flux

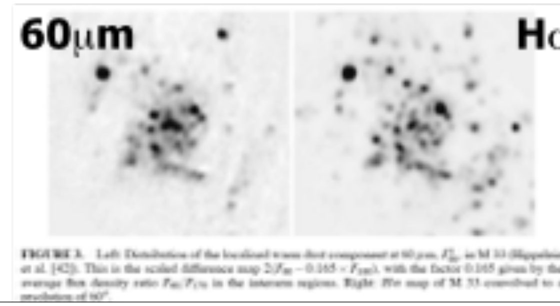
- Measure the UV flux directly
  - Shorter wavelengths more sensitive to recent SF (higher mass stars), but requires space
  - Strongly affected by dust

GALEX
FUV: 1400-1700A
NUV: 1800-2750A



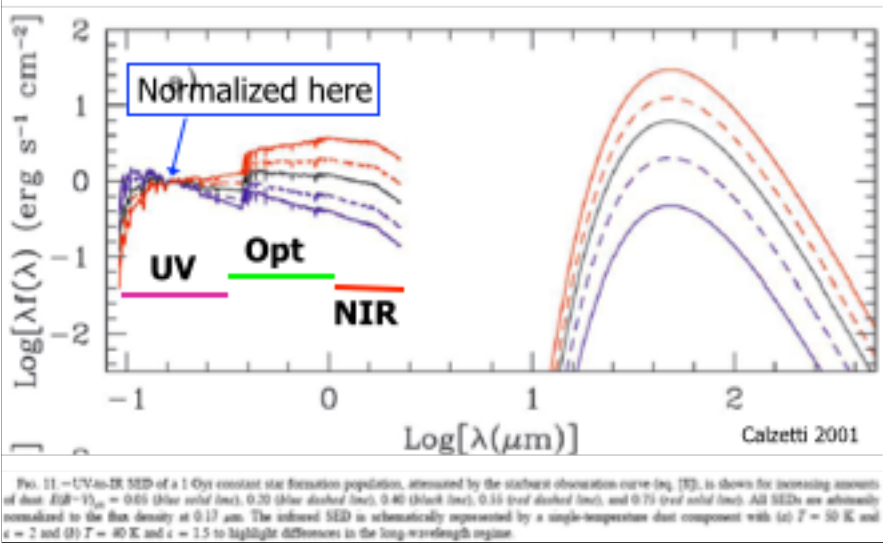
Indirect constraints on UV flux

- Measure mid- and far-IR (FIR) emission from dust to track reprocessed UV flux
  - depends on metallicity, dust optical depth
  - must avoid contamination from cold dust



Tuffs & Popescu 2005

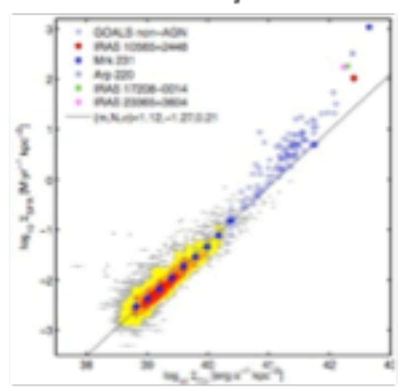
At fixed SFR, FIR emission varies with amount of dust, so 24μm not perfect SFR indicator on its own



Calzetti 2001

Indirect constraints on UV flux

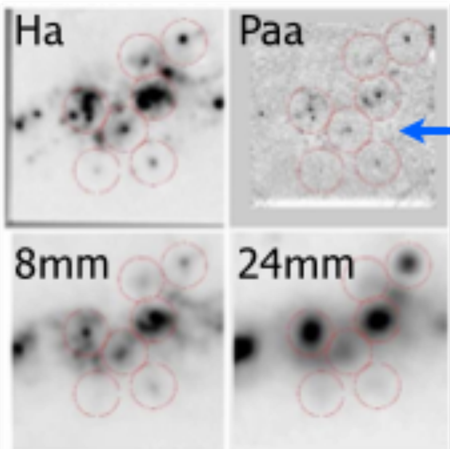
- Measure FIR [CII] cooling line
  - If cooling = heating, should constrain UV
  - Potential method w/ ALMA



Calibrate w/ KINGFISH Herschel survey of nearby galaxies

Herrera-Camus et al

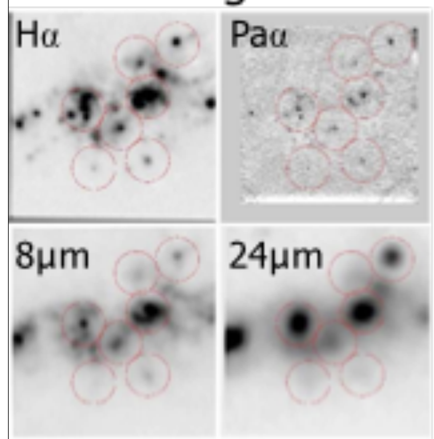
Turning IR obs into Star Formation Rates

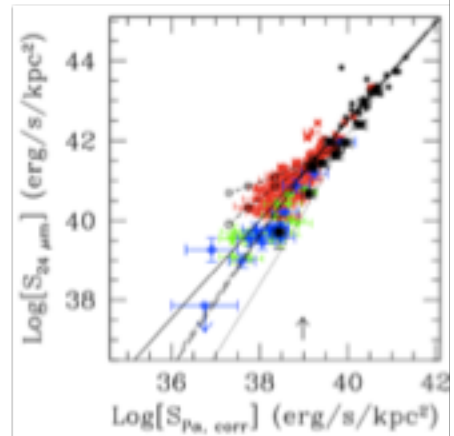


Assume Paα is "ground truth" (NIR, so little extinction)

53 Calzetti et al 2007

Calibrating IR Star Formation Indicators





Verify relationship is linear, and compare to models

Note: 8micron does not look nearly as linear.

54 Calzetti et al 2007

SFR's ($M_\odot$/yr) from measured luminosities:

Kennicutt & Evans 2012

$$\boxed{\log \dot{M}_*(\mathrm{M_\odot\ year^{-1}}) = \log L_x - \log C_x}$$

Table 1 Star-formation-rate calibrations

Band	Age range (Myr)[a]	L_x units	log C_x[b]	$\dot{M}_*/\dot{M}_*$(K98)[c]	Reference(s)
FUV	0–10–100	ergs s^{-1} (νL_ν)	43.35	0.63	Hao et al. (2011), Murphy et al. (2011)
NUV	0–10–200	ergs s^{-1} (νL_ν)	43.17	0.64	Hao et al. (2011), Murphy et al. (2011)
Hα	0–3–10	ergs s^{-1}	41.27	0.68	Hao et al. (2011), Murphy et al. (2011)
TIR	0–5–100[d]	ergs s^{-1} (3–1100 μm)	43.41	0.86	Hao et al. (2011), Murphy et al. (2011)
24 μm	0–5–100[d]	ergs s^{-1} (νL_ν)	42.69		Rieke et al. (2009)
70 μm	0–5–100[d]	ergs s^{-1} (νL_ν)	43.23		Calzetti et al. (2010b)
1.4 GHz	0–100	ergs s^{-1} Hz^{-1}	28.20		Murphy et al. (2011)
2–10 keV	0–100	ergs s^{-1}	39.77	0.86	Ranalli et al. (2003)

[a]Second number gives mean age of stellar population contributing to emission; third number gives age below which 90% of emission is contributed.
[b]Conversion factor between SFR and the relevant luminosity, as defined by Equation 12 in Section 3.8.
[c]Ratio of star formation rate (SFR) derived using the new calibration to that derived using the relations in Kennicutt (1998a). The lower SFRs now mainly result from the different initial mass function and from updated stellar population models.
[d]Numbers are sensitive to star-formation history; those given are for continuous star formation over 0–100 Myr. For more quiescent regions (e.g., disks of normal galaxies), the maximum age will be considerably longer.
Abbreviations: FUV, far ultraviolet; NUV, near ultraviolet; TIR, total infrared.

Typically calculated from models of stellar populations where the SFR is constant over the lifetime of O/B stars (~10^8yrs). Sensitive to the assumed IMF and upper mass cutoff.

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Obscured vs Unobscured SF

UV emission

Recombination Lines (Lyα, Hα, Pα)

Thermal emission from warm dust

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Obscured vs Unobscured SF

Total SF requires "counting" all photons from O-stars.

Need to sum up SF inferred from both obscured and unobscured UV photons.

$$L_{\mathrm{UV}}(\mathrm{corr}) = L_{\mathrm{UV}}(\mathrm{observed}) + \eta\, L_{\mathrm{IR}}$$

Summary of corrections:

Table 2 Multiwavelength dust corrections for normal galaxies

Composite tracer	Reference
$L(\mathrm{FUV})_{\mathrm{corr}} = L(\mathrm{FUV})_{\mathrm{obs}} + 0.46\, L(\mathrm{TIR})$	Hao et al. (2011)
$L(\mathrm{FUV})_{\mathrm{corr}} = L(\mathrm{FUV})_{\mathrm{obs}} + 3.89\, L(25\ \mu\mathrm{m})$	Hao et al. (2011)
$L(\mathrm{FUV})_{\mathrm{corr}} = L(\mathrm{FUV})_{\mathrm{obs}} + 7.2 \times 10^{14}\, L(1.4\ \mathrm{GHz})^{a}$	Hao et al. (2011)
$L(\mathrm{NUV})_{\mathrm{corr}} = L(\mathrm{NUV})_{\mathrm{obs}} + 0.27\, L(\mathrm{TIR})$	Hao et al. (2011)
$L(\mathrm{NUV})_{\mathrm{corr}} = L(\mathrm{NUV})_{\mathrm{obs}} + 2.26\, L(25\ \mu\mathrm{m})$	Hao et al. (2011)
$L(\mathrm{NUV})_{\mathrm{corr}} = L(\mathrm{NUV})_{\mathrm{obs}} + 4.2 \times 10^{14}\, L(1.4\ \mathrm{GHz})^{a}$	Hao et al. (2011)
$L(\mathrm{H}\alpha)_{\mathrm{corr}} = L(\mathrm{H}\alpha)_{\mathrm{obs}} + 0.0024\, L(\mathrm{TIR})$	Kennicutt et al. (2009)
$L(\mathrm{H}\alpha)_{\mathrm{corr}} = L(\mathrm{H}\alpha)_{\mathrm{obs}} + 0.020\, L(25\ \mu\mathrm{m})$	Kennicutt et al. (2009)
$L(\mathrm{H}\alpha)_{\mathrm{corr}} = L(\mathrm{H}\alpha)_{\mathrm{obs}} + 0.011\, L(8\ \mu\mathrm{m})$	Kennicutt et al. (2009)
$L(\mathrm{H}\alpha)_{\mathrm{corr}} = L(\mathrm{H}\alpha)_{\mathrm{obs}} + 0.39 \times 10^{13}\, L(1.4\ \mathrm{GHz})^{a}$	Kennicutt et al. (2009)

[a]Radio luminosity in units of ergs s^{-1} Hz^{-1}.
Abbreviations: FUV, far ultraviolet; NUV, near ultraviolet; TIR, total infrared.

Kennicutt & Evans 2012

What fraction of star formation is obscured?

Can characterize with $\mathrm{IRX} = \log\left(\frac{\mathrm{L(TIR)}}{\mathrm{L(FUV)_{obs}}}\right)$

Where the total IR luminosity is defined from Spitzer (SIRTF)

fluxes. A simple combination of *SIRTF* Multiband Imaging Photometer fluxes recovers the total 3–1100 μm flux (TIR) for the full range of normal galaxy infrared SED shapes,

$$L_{\mathrm{TIR}} = \zeta_1 \nu L_\nu(24\ \mu\mathrm{m}) + \zeta_2 \nu L_\nu(70\ \mu\mathrm{m}) + \zeta_3 \nu L_\nu(160\ \mu\mathrm{m}),$$

where $[\zeta_1, \zeta_2, \zeta_3] = [1.559,\ 0.7686,\ 1.347]$ for $z = 0$. (4)

Def'n from Dale & Helou 2002

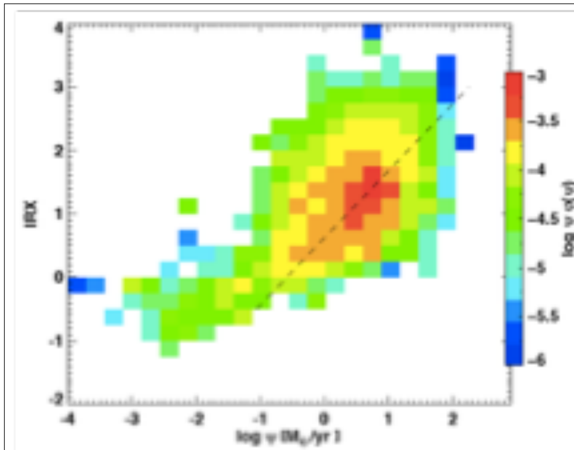

Figure 10. The star formation rate volume density function as a function of SFR (Fig. 5), further expanded in a second dimension (along the ordinate) to show the breakdown with IRX. The 'z' axis represents $\psi\,\Phi(\psi)$. The dotted line shows the IRX-SFR relationship derived from the L_{IR} vs. E(B − V) relationship given by Hopkins et al. (2001). E(B − V) was converted into A_{FUV} using the Cardelli (1989) extinction law with $R_V = 3.1$, which gives $A_{\mathrm{FUV}} = 8.0$ E(B − V). IRX and ψ were obtained from A_{FUV} and L_{IR} as above.

Bothwell et al 2011

IRX is correlated with SFR: More obscuration when SFR is high

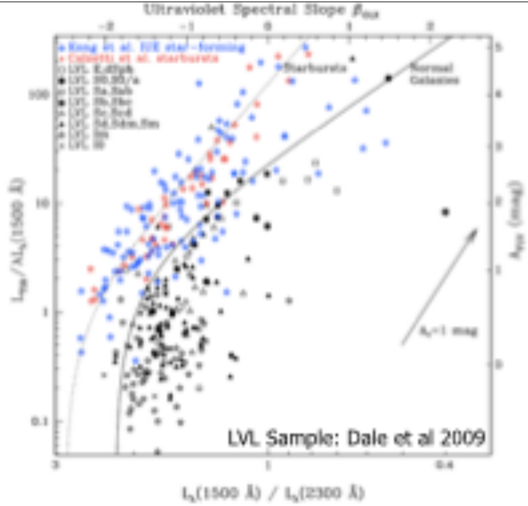

Figure 13. Infrared-to-far-ultraviolet ratio as a function of ultraviolet spectral slope. Normal star-forming and starburst galaxies from Kong et al. (2004) and Calzetti et al. (1995) are plotted in addition to the LVL data points. The dotted curve is that for starburst galaxies from Kong et al. (2004) and the solid curve is applicable to normal star-forming galaxies (Dale et al. 2007). The reddening vector assumes the reddening curve of Li & Draine (2001) and the far-ultraviolet extinction prescription used for the right-hand-side axis is from Buat et al. (2005).

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IRX also correlates with UV spectral slope

- Tight correlation for high SFR galaxies
- Way worse if normal galaxies are included

See Munoz-Mateos et al 2009b for modelling...

Global Measures of Star Formation

- Star formation rates (SFR)
- Specific star formation rates (sSFR)
- Star Formation intensity (S_{SFR})
- Star Formation efficiency

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1. Total Star Formation Rates

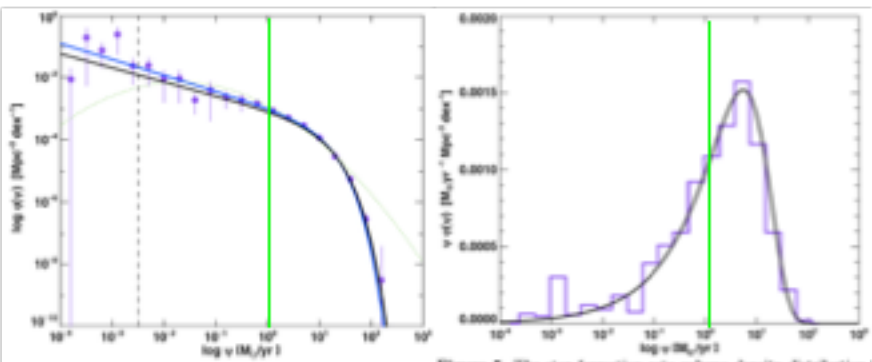

Figure 4. The star formation rate distribution function for the resultant combined sample, as described in §3.3. The black line is a least squares Schechter function fit to these points, the blue line is the maximum likelihood Schechter function fit. The vertical dashed line is drawn at log SFR = −2.5 $M_\odot\ yr^{-1}$, the level at which incompleteness becomes significant. The green log-normal function indicates the SFR function given by Martin et al. (2005). Errors (1σ) were calculated using Monte Carlo bootstrapping.

Figure 5. The star formation rate volume density distribution function, for the resultant combined sample as in Fig. 4. The purple histogram shows the V_{max}-derived data as above, and the black fit to the data is the convolved Schechter function $\psi\Phi(\psi)$, with the maximum-likelihood fit parameters as above.

Bothwell et al 2011

Most galaxies have low SFRs (<1 M☉/yr), but integrated SFR dominated by galaxies with ~10 M☉/yr

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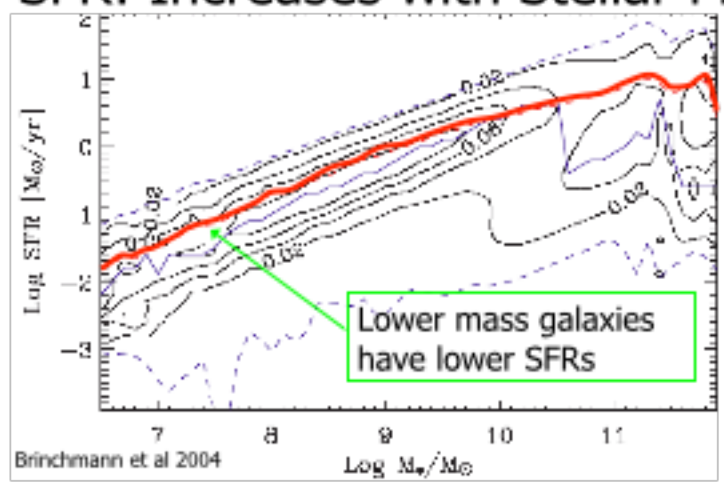
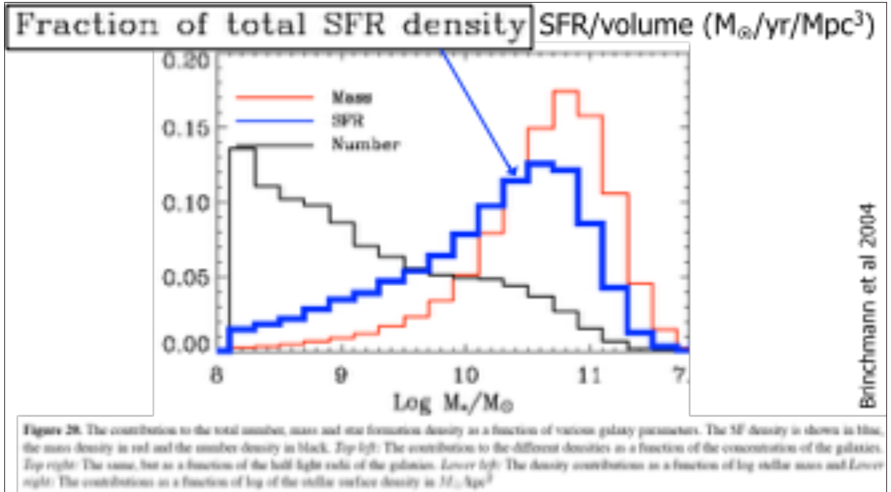
1. SFR: Increases with Stellar Mass



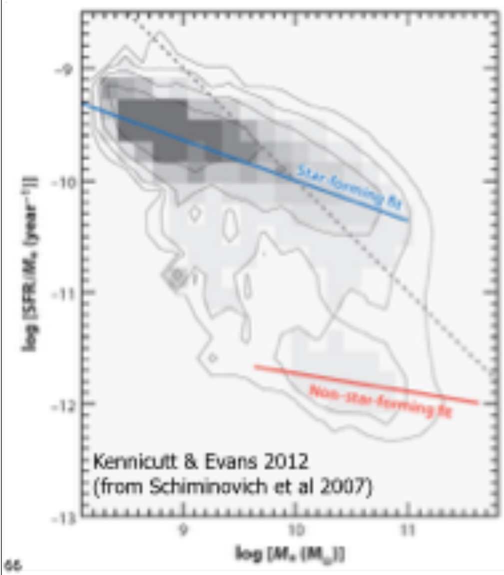
But, bigger things are bigger, so not profound...

(calculated within SDSS fibers)



Massive galaxies dominate the current production of stars, since they own most of the baryons

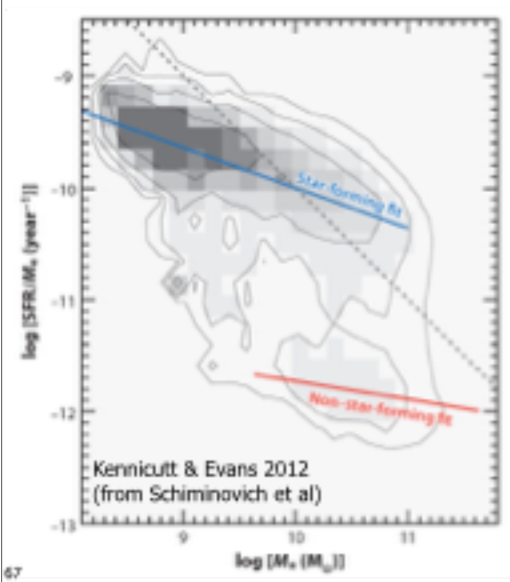
2. Specific SFR = SFR / stellar mass



Relative importance of current to past SF

Units of inverse time (i.e., How long would it take to make the current stellar mass, at the current SFR)

2. sSFR shows two sequences



"Red" and "Blue"

Blue SF sequence

"Green Valley"

Red SF sequence

2. Related def'n of sSFR Scalo Birthrate Parameter: Ratio of Current to Past SFR

$b = SFR_{now} / \langle SFR \rangle$

$b < 1$: SFR greater in the past
b = 1: SFR ~ constant
b > 1: SFR higher today than in past
b > 2-3: Classified as Starburst

Note: b alone does not distinguish between a steady increase in SF to the present day, or an episodic burst

Measuring the Birthrate Parameter

$$b = SFR_{now} / \langle SFR \rangle$$

Use any SF indicator

Proportional to the total mass in stars ($\sim M_{star}/t_{universe}$)

Will Correlate with lots of measures, like:

- L_{FIR}/L_{NIR}
- SFR/M_{star}
- Hα Equivalent Width

2. Specific SFR: Lower mass galaxies have systematically higher sSFR's

Bimodal

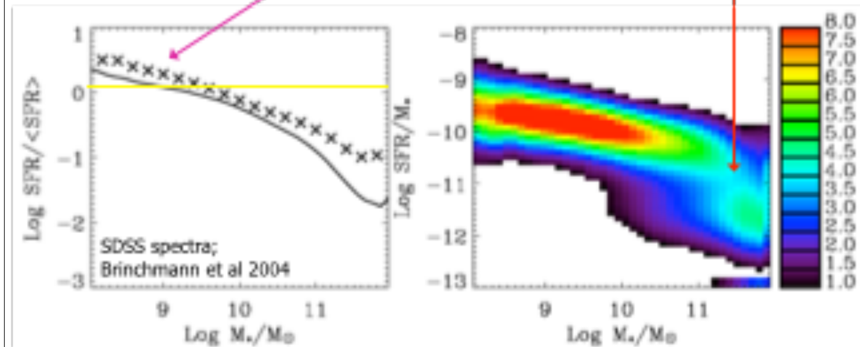
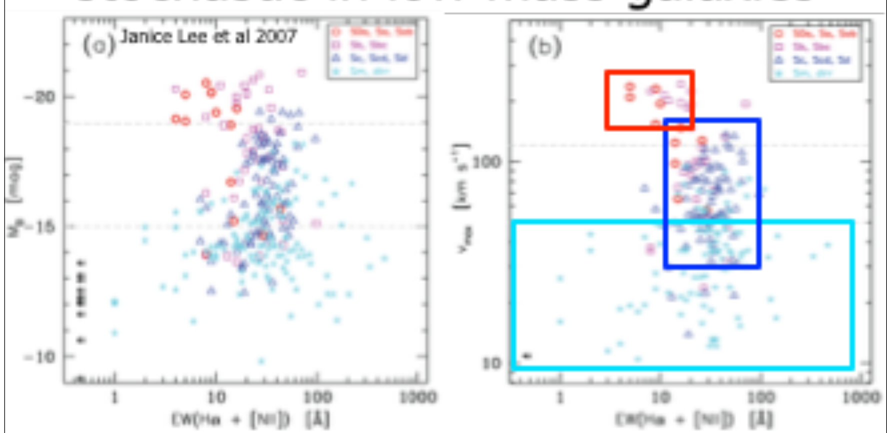


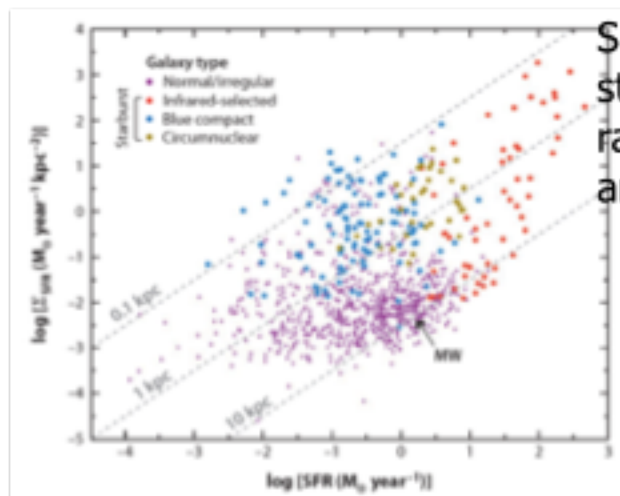
Figure 24. Similar to Figure 23 but this time showing b as a function of the stellar mass.

2. Specfic SFR: Warning. Hα can be stochastic in low mass galaxies



 Hα equivalent widths ($\propto b$). FUV will be better

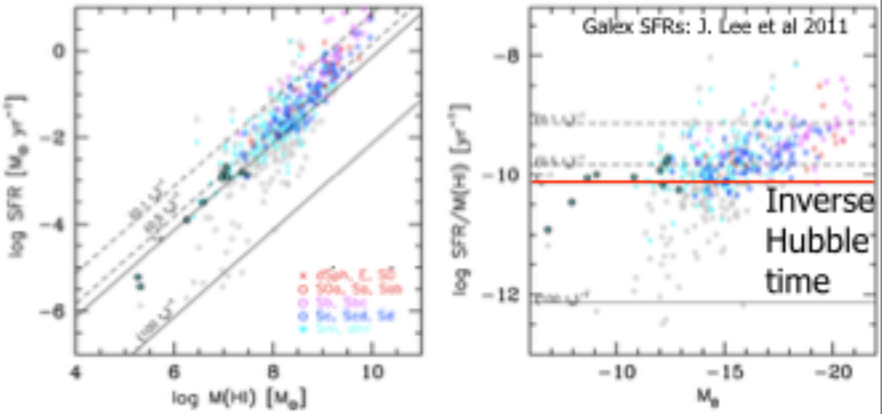
3. Star formation rate intensity (S_{SFR})



SFR Intensity: star formation rate per unit area

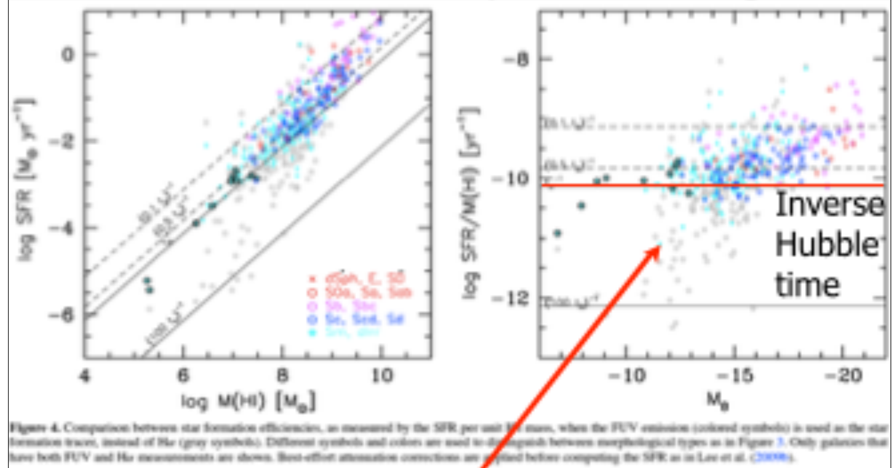
Best proxy for local physical conditions, particularly in disks

4: SFR Efficiency: SFR / M_{gas}



Measure of timescale to consume all gas
(Inverse = "gas consumption timescale")

4. SFR Efficiency: SFR / M_{gas}



- dIrrs would take close to a Hubble time to consume their gas
- Higher mass galaxies close to finished, if not resupplied

Galex SFRs: J. Lee et al 2011

4. SFR Efficiency: Milky Way

First Order:
$M_{stars,spiral} = 10^{10}\ M_{\odot}$
$t_{universe} = 10^{10}$ yrs

So, average:
$\langle SFR \rangle \sim 1\ M_{\odot}/yr$

How long can this go on?

First Order:
$M_{gas} = 10^{9}\ M_{\odot}$
$SFR \sim 1\ M_{\odot}/yr$

So, average:
$t_{gasconsumption} \sim 10^{9}$ yrs

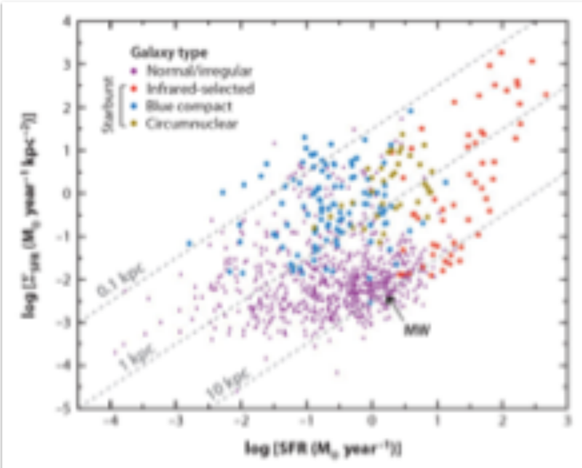
So either we live in a special time where the MW is about to run out of gas, or there is on-going gas accretion to fuel continuing SF

Systems with High Star Formation

- High Star formation rates (SFR)
- High Star Formation intensity (S_{SFR})
- High Specific star formation rates (sSFR)

1. Useful as probes of extreme conditions
2. Important phases in build-up of stars

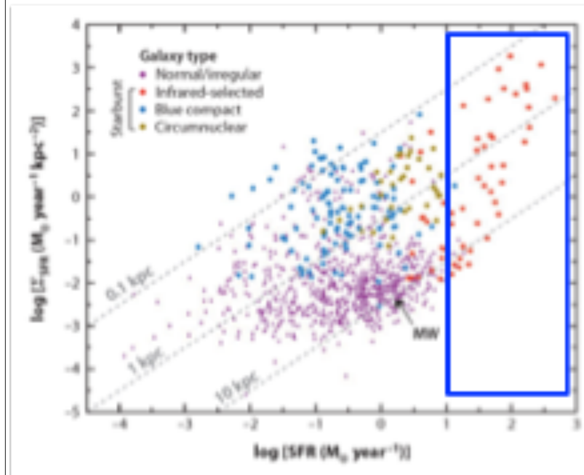
The High SFR End



Possible Definitions of "High"

- High absolute SFRs
- High SFR intensities
- High SFRs compared to past average

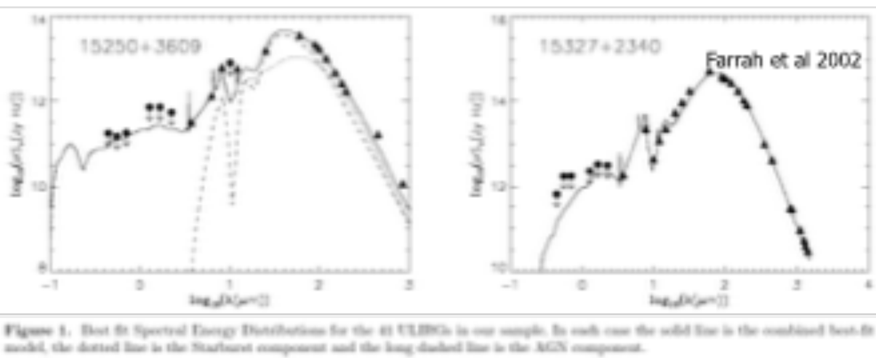
The High SFR End



Possible Definitions of "High"

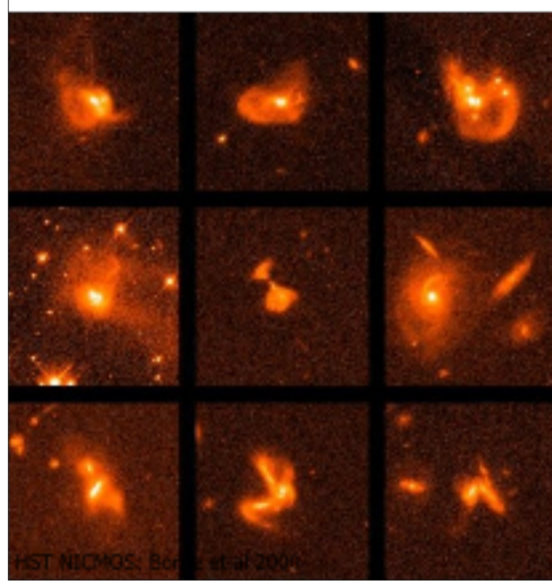
- High absolute SFRs
- High SFR intensities
- High SFRs compared to past average

"ULIRGS" (ultraluminous infrared galaxies)Highest SFRs (10-1000 M_0/yr)



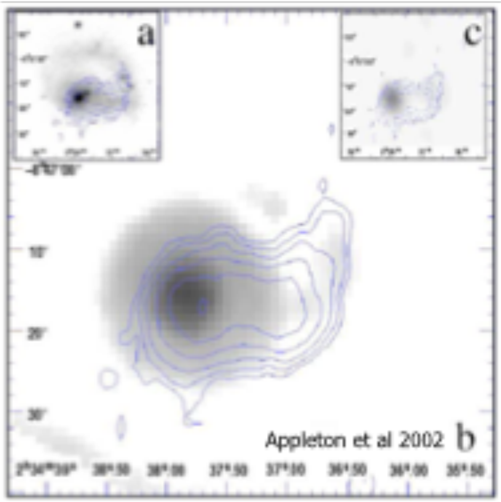
- Majority of their enormous luminosity is reprocessed to FIR.
- Inconspicuous in optical because highly obscured.

ULIRGS are almost universally massive major mergers

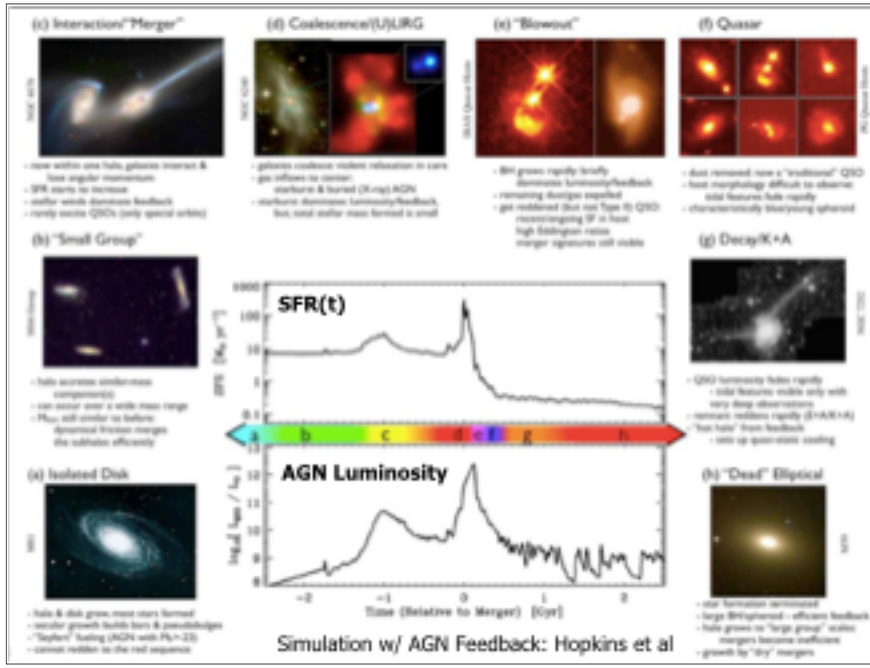


- Probably good local analogs of the formation of ellipticals at high redshift.
- These rare systems may actually dominate the star formation rate locally (1 galaxy w/ $10^3 M_\odot$/yr = 10^3 galaxies w $1 M_\odot$/yr)

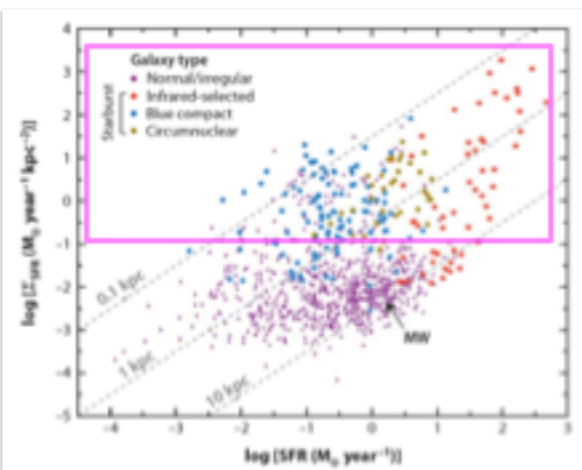
ULIRGs have extremely high gas surface densities (10^2-10^5 $M_\odot/pc^2$ within R<0.1-1kpc)



- Equivalent to a galaxy's whole ISM funnelled into the center.
- Possibly associated with AGN activity (lots of gas dumping onto central BH)
- SFR is near maximum possible ($SFR_{max} \sim M_{gas}/t_{dyn}$)



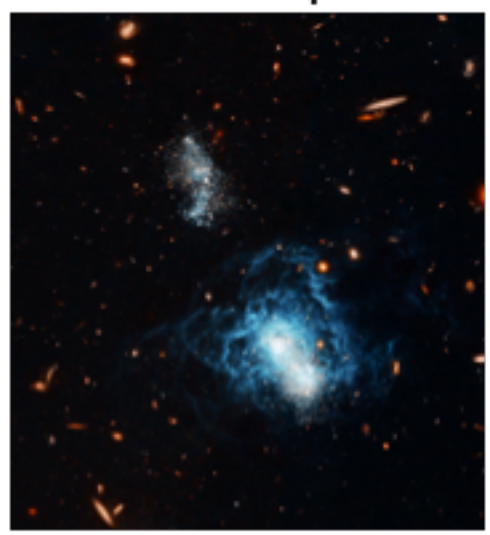
The High SFR End



Possible Definitions of "High"

- High absolute SFRs
- High SFR intensities
- High SFRs compared to past average

Blue Compact Dwarfs (BCDs)

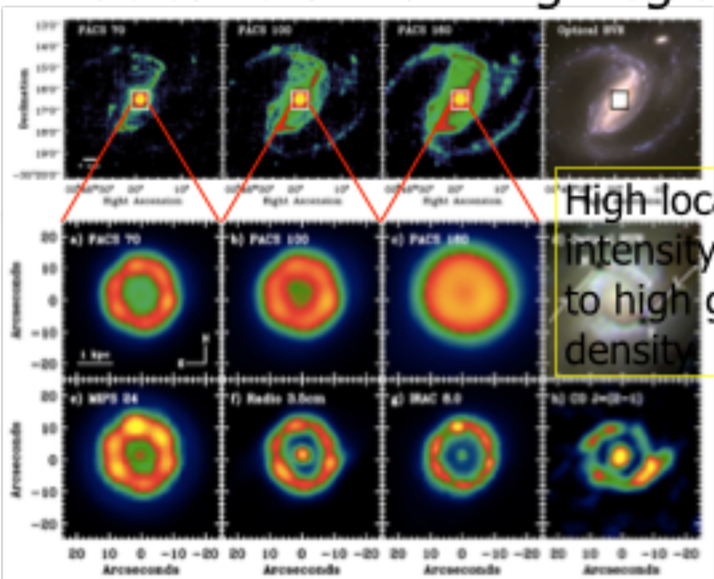


I Zw 18

- Very high SFR intensity
- Very low mass
- Among lowest metallicity galaxies known

Well represented in Zwicky catalog, Markarian catalog

Nuclear Star Forming Regions



High local SFR intensity, due to high gas density

Sandstrom et al 2010

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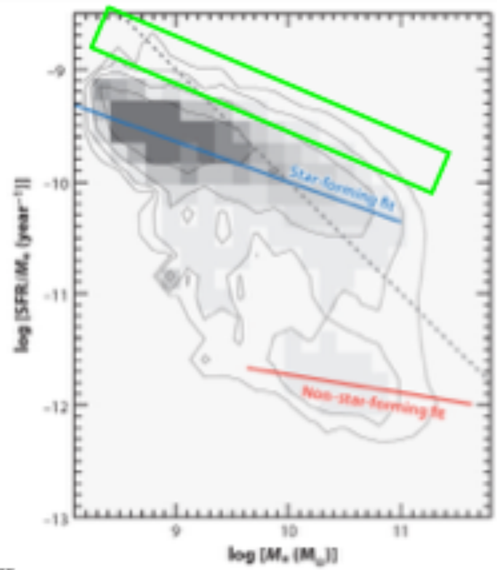
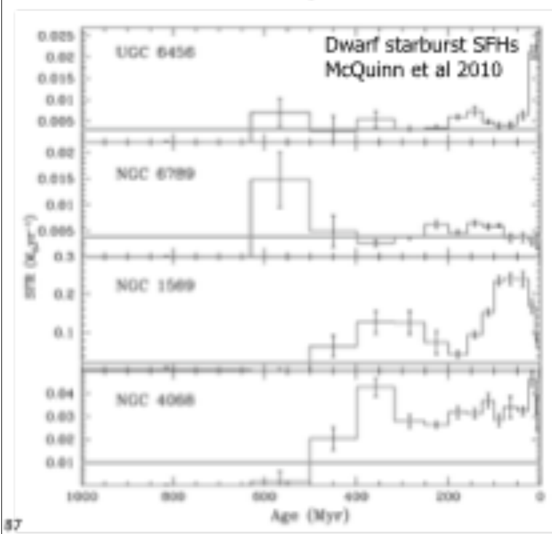
The High SFR End



Possible Definitions of "High"

- High absolute SFRs
- High SFR intensities
- High SFRs compared to past average

Starbursts: Usually defined as >2-3 times past average SFR



Possible Triggers?

- Interactions?
- Gas accretion?

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