# NEW TOPIC- Star Formation MBW ch 9

- One of the most important processes for galaxy formation and evolution
- Big questions
  - When and how does star formation occur ?
  - How is it related to the evolution of galaxy properties?
  - What are the physical processes that drive star formation ?
    - **star formation occurs (at least in spirals at low z) almost exclusively associated with molecular clouds**
      - what is the rate at which stars form in this cloud
      - what mass fraction of the cloud forms stars
      - what controls the IMF?

- for a review see

**THE CURRENT STATUS OF GALAXY FORMATION**

**Joseph Silk, Gary A. Mamon**

https://ned.ipac.caltech.edu/level5/March12/Silk/Silk_contents.html

# Star Formation in Spirals

- This is an enormous subject- lots of recent work (see Kennicutt 1989 and Kennicutt and Evans 2012 for reviews)

- Broadly.. Observations of nearby galaxies have shown, over a broad range of galactic environments and metallicities, **that star formation occurs only in the molecular phase of the interstellar medium (ISM).**
  - Star formation is inextricably linked to the molecular clouds
  - Theoretical models show that this association results from the correlation between chemical phase, shielding, and temperature.
  - See MWB sec 9.1.-9.3 for a discussion

- Interstellar gas converts from atomic to molecular only in regions that are well shielded from interstellar ultraviolet (UV) photons, and since UV photons are also the dominant source of interstellar heating, only in these shielded regions does the gas become cold enough to be subject to *Jeans instability* (Krumholz 2012)

## At Low Z Star Formation Occurs Primarily in Spirals

- star-forming galaxies at all redshifts are *dominated* by disks, while passive (non-starforming or non-active) galaxies have spheroidal structures
  - (Eales et al 2015)- estimate that ≃83% of the stellar mass-density formed over the history of the Universe occurred in LTGs (jargon, late type galaxies, aka spirals)
- However since ~50% of all stellar mass lies in passive galaxies- need either to transform spirals into E's or merge them

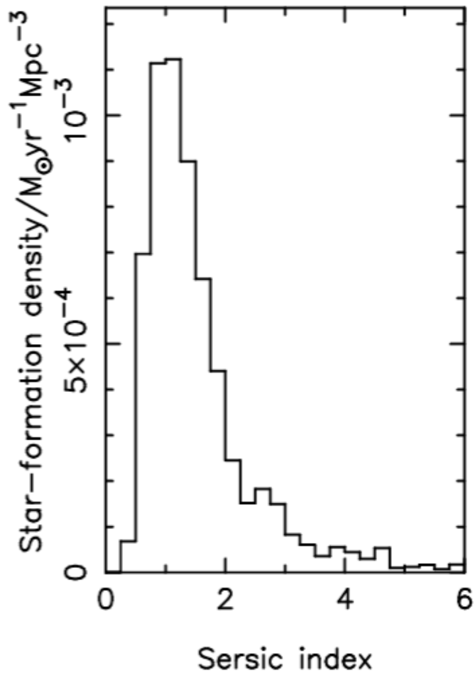



**Figure 1.** Star-formation rate per unit comoving volume in the Universe today as a function of Sérsic index.

## Star Formation- How to Measure It- 5 Ways

Current SF can be estimated from a variety of techniques

- Hα observations, which gives the number of ionizing photons if one assumes that all ionizing photons are used and eventually re-emitted - ionizing photons are almost exclusively emitted by massive (hot) stars which have short lifetimes; so the effects of dust can be large
- far-IR flux - this assumes that a constant fraction of the emitted stellar energy is absorbed by dust
- radio continuum emission - this statistically correlated very well with the IR radiation- physics is complex since radio emission comes from synchrotron radiation from relativistic electrons+ thermal bremmstrahlung from hot gas
- far-UV flux - which is primarily emitted by young (hot) stars- but older /less massive than those responsible for Hα
- X-ray emission- produced by 'high mass' x-ray binaries (a Neutron star or black hole with a massive companion ) +hot gas

# How to Normalize SFR

- Since essentially all techniques measure the total (or ionizing) luminosity of massive stars we need to transform to ALL the stars
- Use the IMF (Initial mass function)
  - For Kroupa IMF
    - $\Psi(M) \sim M^{-1.4}$ $0.1 < M_{\odot} < 1$
    - $\Psi(M) \sim M^{2.5}$ $1 < M_{\odot} < 100$
- Integrate $\Psi$ from $10\text{-}100 M_{\odot}$ get 0.16 of all the mass (correction factor)- these are the stars which have short lifetimes and are hot and thus produce the signatures of star formation.
  - Formation of low mass stars can only be detected in MW and Magellanic clouds

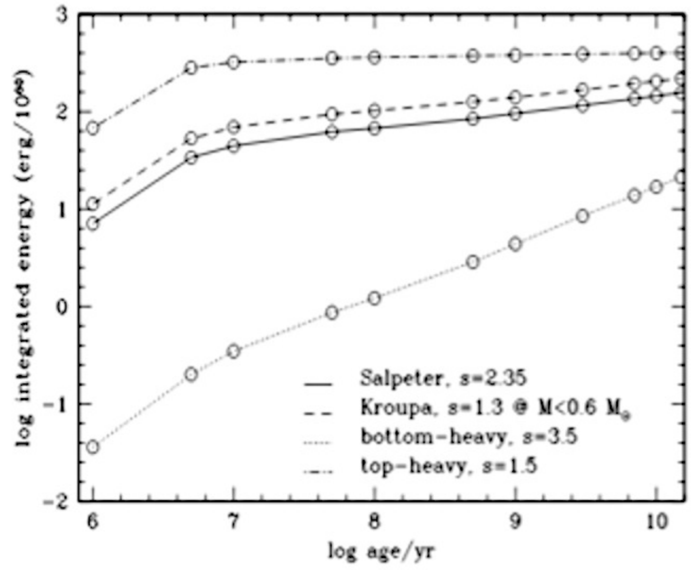
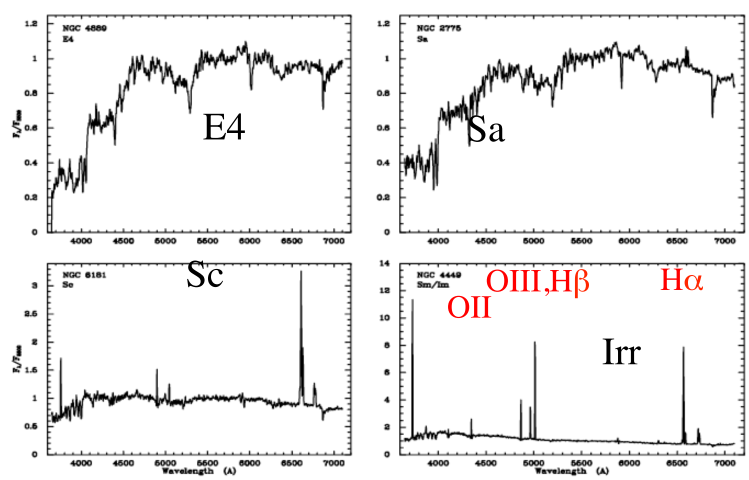



**Figure 3.** The total energy that has been emitted by a
age for a single stellar population with a mass of $10^{11}$ $M_{\odot}$

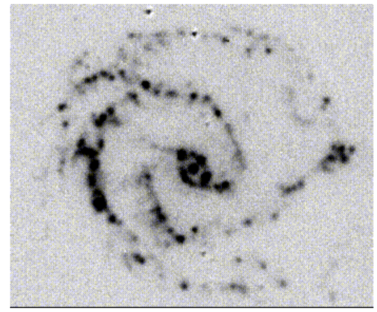
# Reminder from last time-Importance of Emission Lines

- As one moves on the Hubble sequence the galaxy spectra get more and more emission line dominates and relative prominence of lines changes
- Hα or OII are SFR indicators
  - these strong optical lines are produced by gas ionized by hot stars (OIII is also produced by active galaxies and so it is often difficult to separate AGN from star formation)




Kennicutt 1998

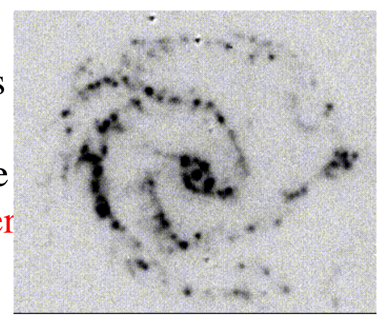
## How to Determine SFR from Observables-Hα or Hβ see 10.3.7,10.3.8



Hα image of a star forming galaxy

- The strength of the emission lines is the convolution of the number of ionizing photons, the fraction of them that are absorbed and the physical conditions of the gas.
- Using stellar models and the IMF one ends up with $SFR(M_\odot/yr)=L(H\alpha)/7\times10^{41}$ ergs/sec for $M>10M_\odot$ stars or for all stars
- **$SFR(M_\odot/yr)=L(H\alpha)/1.1\times10^{41}$ ergs/sec**

## How to Determine SFR from Observables-Hα or Hβ



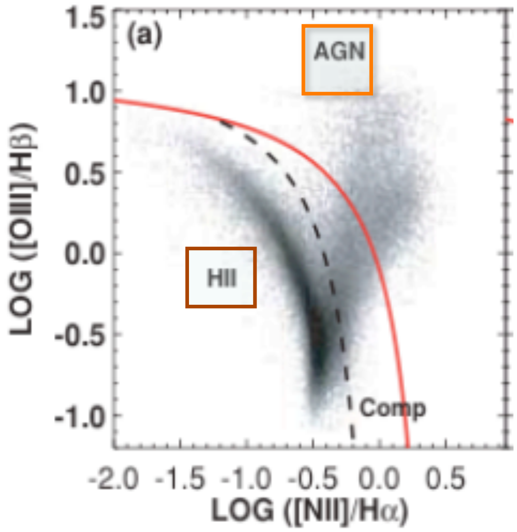
Hα image of a star forming galaxy

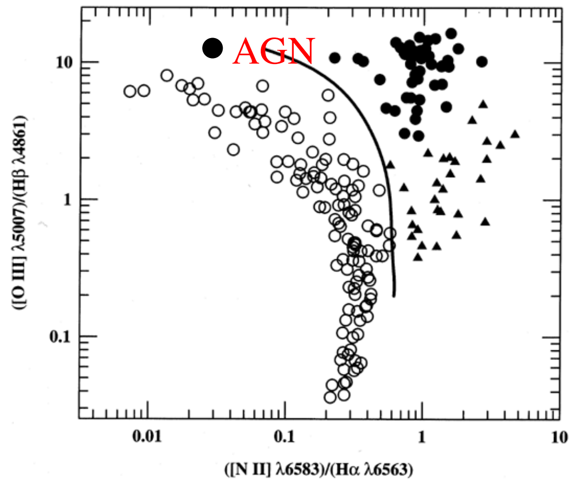
- Young, massive stars produce copious amounts of ionizing photons that ionize the surrounding gas. Hydrogen recombination cascades produce line emission, including the well-known Balmer series lines of Hα(6563Å) and Hβ (4861Å), which are strong.
  - Only stars more massive than $20M_\odot$ produce an ionizing photon flux.
- In a stellar population formed through an instantaneous burst the ionizing photon flux decreases by two orders of magnitude between 5Myr and 10Myr after the burst.
- So Hα measures the '**instantaneous**' star formation rate

•http://www.astr.ua.edu/keel/galaxies/sfr.html

Digression-From spectroscopy how does one classify a galaxy as star forming or an AGN??

Observe strong lines to make life easier- but these are not necessarily to most diagnostic.




Different lines have different dependences on temperature excitation mechanism (collisions, photoionization)

Ratios of certain lines (chosen to be close in wavelength do dust is not an issue)

AGN have 'harder' radiation field (higher UV/optical) and collisional excitation less important than in star forming regions.

# UV

- The youngest stellar populations emit the bulk of their energy in the rest frame UV (<0.3μ); in the absence of dust attenuation, this is the wavelength range 'par excellence' to investigate star formation in galaxies over timescales of ≈10–300Myr,
  - the lifetime of an O6 star is ~6Myr, and that of a B8 star is ~350Myr.

The luminosity ratio of a O6 to B8 star at 0.16 μ is ~90, but for every O6 star formed, 150 B8 stars are formed.

Thus, at age zero, the UV emission from the collective contribution of B8 stars is comparable to that of O6 stars. And since B8 stars live a lot longer they dominate the UV flux on longer timescales.

(Calzetti 2012)

# UV Continuum

- in principle great- direct measure of total luminosity of young massive stars.
- Three big problems
  - DUST- UV extinction is much larger than in optical - light that is absorbed is re-emitted in the IR -the most active and luminous systems are also richer in dust, implying that they require more substantial corrections for the effects of dust attenuation; (MBW-10.3.8(b))
    - effects of dust are BIG- $A_V$ =0.9 produces a factor ten reduction in the UV continuum at 1300Å (remember: S+G pg 33-34 for discussion of reddening)
  - at low redshift must observe from space – e.g. UV does not get thru the atmosphere
  - VERY sensitive to IMF- at best can only constrain 15% of all the stars forming
  - For a Kroupa IMF with with constant star formation

$$SFR(UV) M_\odot/yr = 3.0\times10^{-47} L_{UV}(ergs/sec)(912\text{-}3000Å)$$

# IR Continuum

- Wavelength at which emission peaks is related to temperature of dust

8μ ~360k, 24μ ~121k, 70μ ~40k, 160μ ~20k  based on Black Body Formula

**$\lambda_{peak} \sim 29\mu/T_{100}$  $\lambda_{peak}$ in units of microns and T in units of 100k**

(these are the common wavelengths for IR space borne instruments IRAS, Spitzer, WISE, Herschel)

$T \sim \lambda^{-1}$ but $L \sim AT^4$ so to get a lot of luminosity at long wavelengths needs a large emitting area, A

Temperature is set primarily by equilibrium; energy absorbed=energy emitted and physics of dust grains.

Most galaxies are dominated by T~20-40K dust, rapid star forming galaxies up T ~100k.

Need wide range of temperatures to produce observed IR spectra.

*Roughly* SFR ($M_\odot$/yr)=$L_{total\ IR} \times 4.5\times10^{-44}$ ergs/sec (integrating IR from 8-1000μ)

Advantages- relatively free from extinction, can do at high z with Herschel

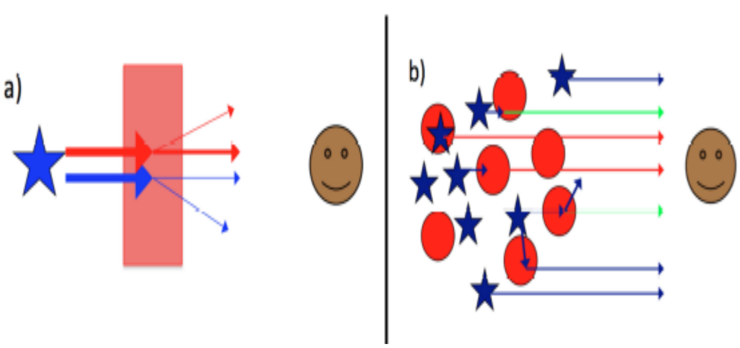
Problems- requires lots of assumptions and scaling. Need to assume SF rate law

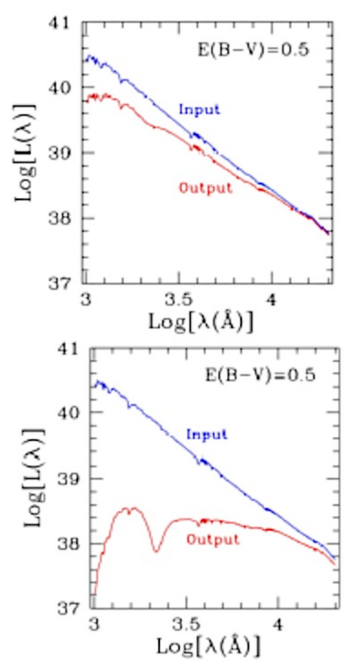
# IR Continuum

- Ideal for starburst galaxies because:
- Young stars dominate total UV-optical radiation, $\tau > 1$, $L_{IR} \sim L_{SB}$

and cross-section of the dust grains for stellar light is higher in the UV than in the optical

Geometry is a serious issue- the same amount of dust has different effects depending on the relative position of the stars and the dust

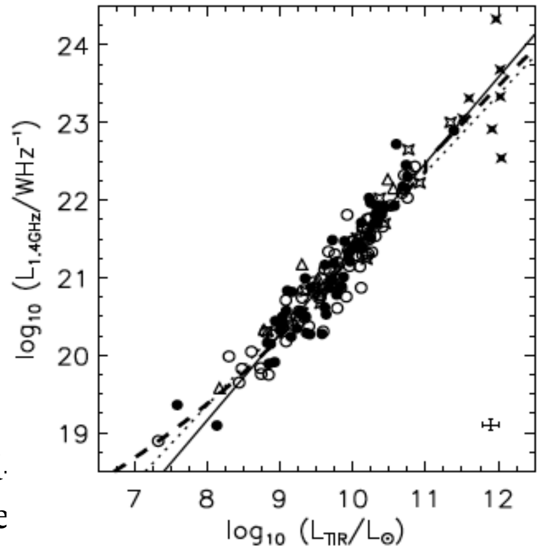


# Star Formation- Radio View

- Radio continuum emission from star-forming galaxies has two components: thermal bremsstrahlung from ionized Hydrogen and non-thermal synchrotron emission from cosmic ray electrons spiraling in the magnetic field of the galaxy
- This method does not depend on how one handles dust or ionizing continuum,
- But physics is not fully understood- why cosmic rays/magnetic field are so finely tuned so that radio synchrotron traces star formation

Relation of radio to IR luminosity



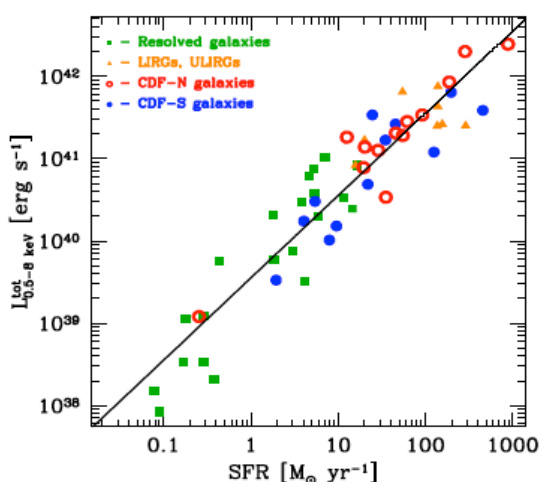

Bell 2002

# Star Formation X-rays

Mineo et al 2012

- In a rapidly star forming galaxies x-rays are produced by

1) high mass x-ray binaries with a lifetime $\tau \sim 2 \times 10^7$yrs
   surprisingly the luminosity function of these sources is very similar from galaxy to galaxy with only the normalization~SFR changing
2) hot gas from Supernova- results imply that only 5% of SN energy is needed to produce the observed "diffuse" x-rays




major advantage of x-rays: do not need to be concerned about dust, can do this at high redshift

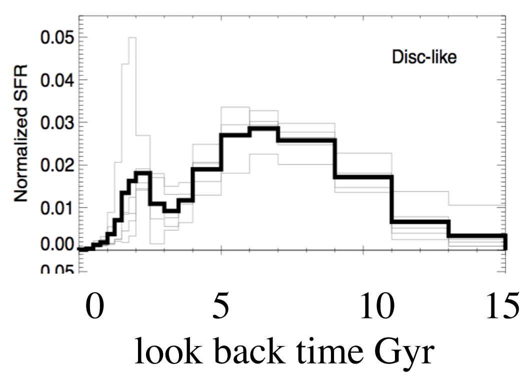
# Summary of the various indicator

- Hα: emitted by gas ionized by stars with $T_{eff}$>~20,000k ($M>10M_\odot$) which emit photons that can ionized Hydrogen ($E_{ioniz}$=13.6eV) - t<20Myrs
- IR Continuum- UV light absorbed by dust
- UV continuum- direct signature of massive, young stars
- X-ray 'high mass' binaries are the result of SN explosions+ a massive star
- Radio continuum – emission from relativistic particles produced in supernova remnants and emission from hot gas

# SF History

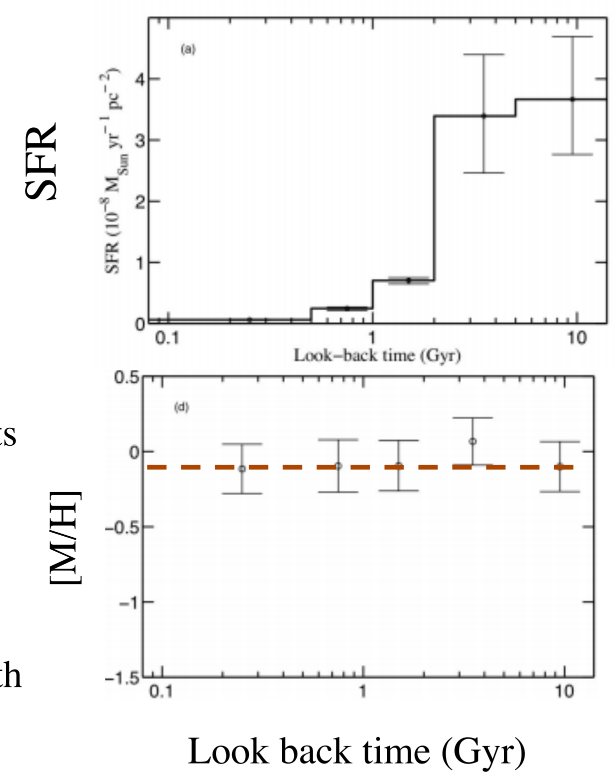
- M31 has some of the best data
- In general
- The disc formed most of its mass (~65 percent) since z~1

  giving a median age of 7 Gyr,
- with one quarter of the stellar mass formed since 5 Gyr .



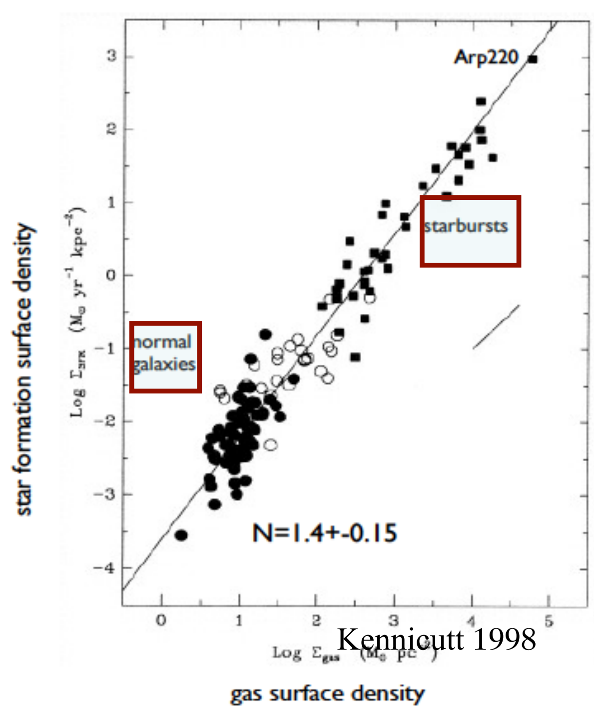
# Star Formation History of an Elliptical

- M32- a dwarf elliptical companion of M31 is close enough to have a CMD for resolved stars-
- very different history than the LMC or M31
- ~95% of its mass formed 5-14 Gyr ago. 2 dominant populations; ~30% ± 7.5% of its mass 5-8 Gyr old population, ~65% ± 9% of the mass in a 8-14 Gyr old population (Monachisi et al 2012)
- Metallicity does not change with time (!)- where do the created metals go ?




# Kennicutt Schmidt Law (MBW sec 9.5)

- Simplest idea-assume that SFR rate is proportional to total amount of gas
  - $SFR \sim \rho_{gas} \sim d\rho_{gas}/dt$; sol't $\rho_{gas} \sim \rho(0)_{gas} e^{-t/\tau}$
- Empirically one finds that the SFR surface density is proportional to the gas surface density to the 1.4 power (the surface density is directly observable)




Kennicutt 1998

## Kennicutt Schmidt Law (MBW sec 9.5)

$\Sigma_{SFR}=A\Sigma^{n}_{gas}$ n~1.4 can be explained by

- Kennicutt–Schmidt law interpreted as indicating that the starformation

rate is controlled by the self-gravity of the gas. If so, the rate of star formation

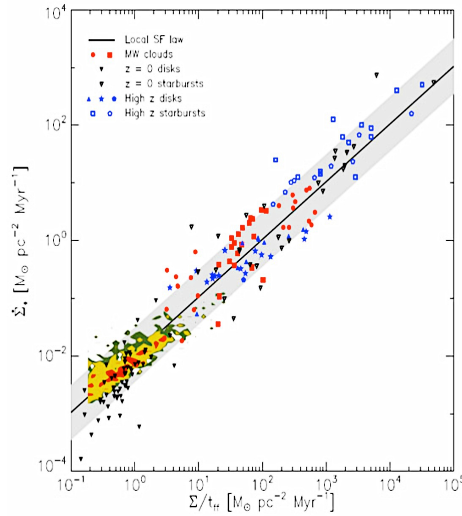
will be proportional to the gas mass divided by the time scale for gravitational collapse.

For a gas cloud with mean density ϱ, the free-fall time $\tau_{ff} \propto 1/ sqrt(G\varrho)$ so that

$d\varrho/dt = \varepsilon_{SF}\, \varrho_{gas} / \tau_{ff} \propto \varrho_{gas}1.5$

$\varepsilon_S$ is the efficiency of star formation

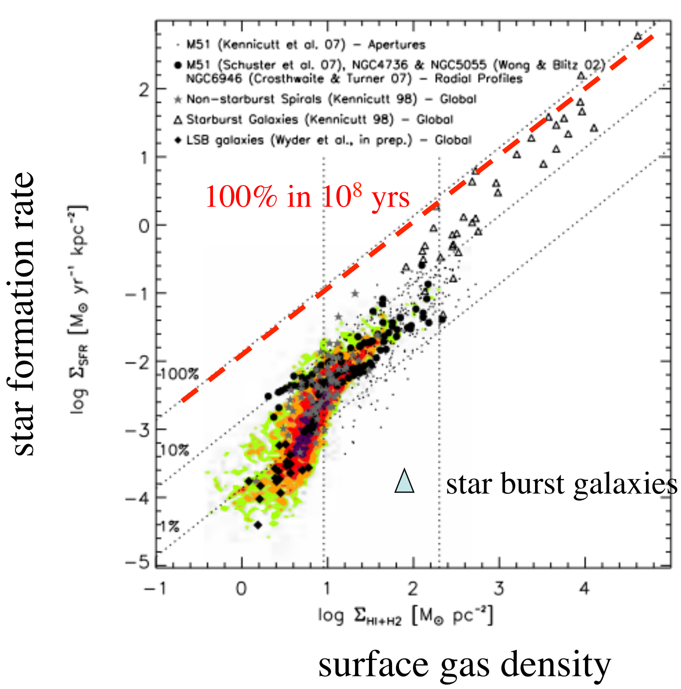
gas consumption efficiency is low; takes ~1.5x$10^9$yrs to convert the gas into stars




Not only for whole galaxies but also for parts of them (Krumholz et al. 2012).

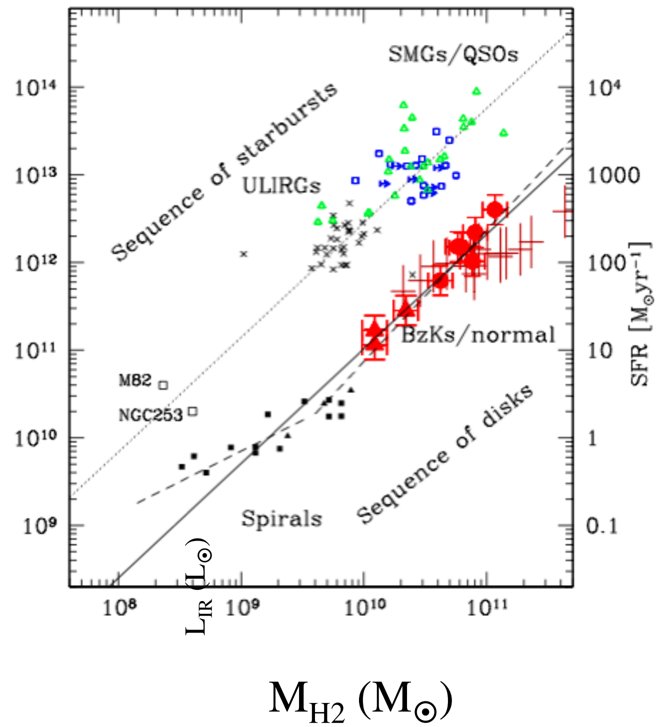
## Kennicutt Law with Starbursts

- Newer data show starburst galaxies- the highest star forming rate galaxies obey a different law
- They seem to convert the gas into stars 'as fast as possible'-e.g on freefall timescale.
- This produces a wind as a large amount of energy is injected by star formation in a short time.



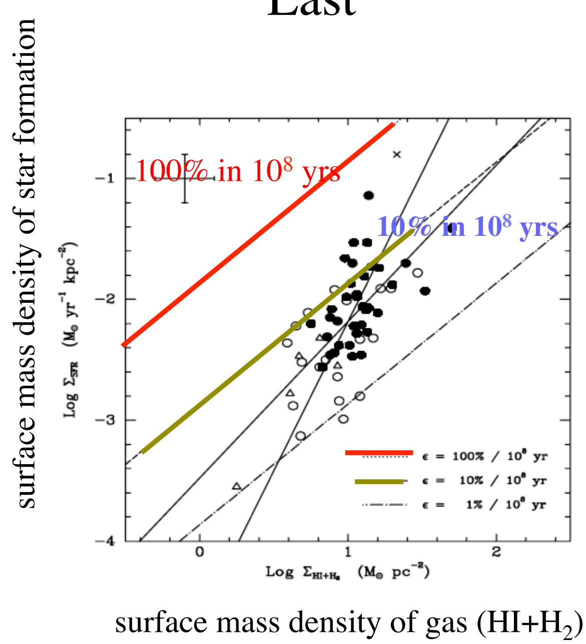
## Starbursts- Higher Redshifts

- In the low redshift universe there are very few, very high SFR objects- these are much more important in the high z universe
- It appears that the relations for very rapid SF galaxies are different




- SF in normal galaxies use about 5% of available gas every $10^8$ yrs !
  - But this does not include 'recycling'- e.g. when stars die they recycle gas back into the ISM
- Since the typical gas mass fraction in disks ~ 20% of baryonic mass implies that stellar mass of the disk grows by about 1% per $10^8$ years, i.e. the time scale for building the disk (at the present rate) is ~ Hubble time.
- The average gas depletion timescale, ~ 2.1 Gyr.
  - Recycling of interstellar gas from stars extends the actual time scale for gas depletion by factors of 2–3

## How Long Does the Gas Last




Relationship for 'normal' star formation
Kennicutt 1998

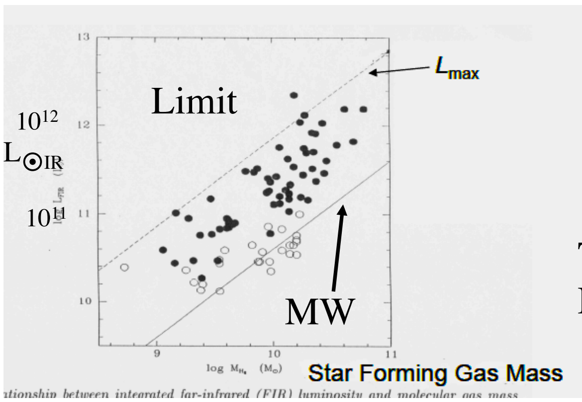
# How Long Does the Gas Last- Star Bursts

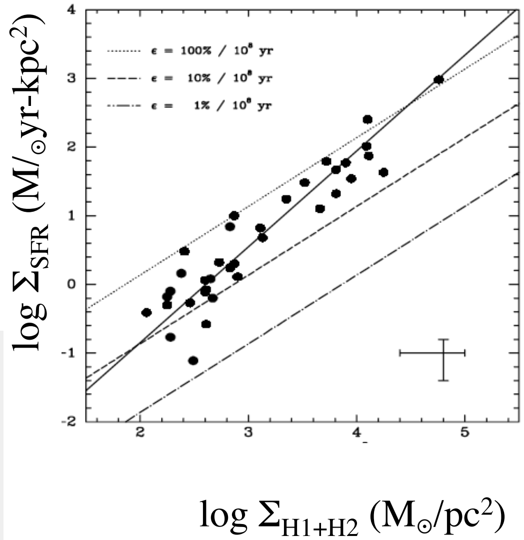
- Starburst use up their gas much faster
- <30%> of gas used every $10^8$ yr
- Depletion timescale≈ 0.3 Gyr
- How luminous are these objects?

$SFR_{max}$~100M/yr(Mgas/$10^{10}M_\odot$)($10^8$yrs/ $\Delta t_{dyn}$)

nuclear fusion is ~0.7% efficient

the fraction of rest mass converted to energy for a Saltpeter IMF is ε~0.05 during $10^8$yrs $10^{11}$-$10^{12}$ $L_\odot$ !!




This gives $L_{max}$~0.07ε(dM/dt)$c^2$

$L_{max}$~$10^{11}L_\odot(M_{gas}/10^{10}M_\odot)(\varepsilon/0.05)$

# Jeans Criterion for collapse of spherical cloud

MBW pg 167, sec 8.2.3, 9.1.2

- Gravitational instability sets in if the free-fall time is less than the sound crossing time
- $t^2_{ff}=1/G\rho<(R/c_s)^2\sim10^8 n^{-1/2}_H$ yrs;
  - free fall time from $d^2r/dt^2=-GM/r^2$ ; $n_H$ is the number density of gas
  - hydrodynamical timescale from $d^2r/dt^2=(-1/\rho(r))dP/dr$= $R/c_s$

**Characteristic mass for system to collapse is Jeans Mass**

**Jeans mass $M_J= 4/3\pi\lambda^3{}_J\rho=4/3\pi c^3{}_s\rho^{-1/2}$**

# Jeans Criterion for collapse of spherical cloud

**Jeans mass $M_J = 4/3\pi\lambda^3{}_J\rho = 4/3\pi c^3{}_s\rho^{-1/2}$**

**Jeans length $\lambda_J = \text{sqrt}(\pi c_s^2/G\rho)$ − distance a sound wave travels in a grav free-fall time**

For typical values

- $M_J = [\pi^{5/2}/6][c^3{}_s/(G3\varrho)^{1/2}] \sim 40M_\odot[\,c_s/0.2\text{kms}^{-1}]^3\,[\,n_{H2}/100\text{cm}^{-3}]^{-1/2}$

$M_{J\ \text{SOLAR UNITS}} = (T/10k)^{3/2}(n_H/10^5\text{cm}^{-3})^{-1/2}$

in units of surface mass density $\lambda_J = c_s^2/G\Sigma$

$c_s$= sound speed=sqrt($dP/d\rho$)=sqrt($k_BT/\mu m_H$) for hydrogen ($k_B$= Boltzmann's constant, $m_H$= mass of hydrogen atom, $\mu$ = mean molecular weight)

- For typical values $c_s$=0.3km/sec$(T/10k)^{1/2}$

However the gas cannot collapse unless it can radiate away the heat from conversion of potential energy so need $t_{cool} < t_{ff}$ the rate at which gas cools depends on a strong function of temperature and the density squared.

# Gravitational Instability

- Another derivation of Jeans length/mass
- Balance pressure and gravity (pg 355 of S+G)
- Potential energy= $-1/2 \int \rho(x)\phi(x)d^3x \sim G\rho^2r^5$
- if gas moves at sound speed $KE = c_s^2M$
- $M = 4/3\pi\rho r^3$

- **In equilibrium viral theorm says KE=PE/2 so define a length $\lambda_j$ where that is true and get $\lambda_j = c_s\text{sqrt}(\pi/G\rho)$**

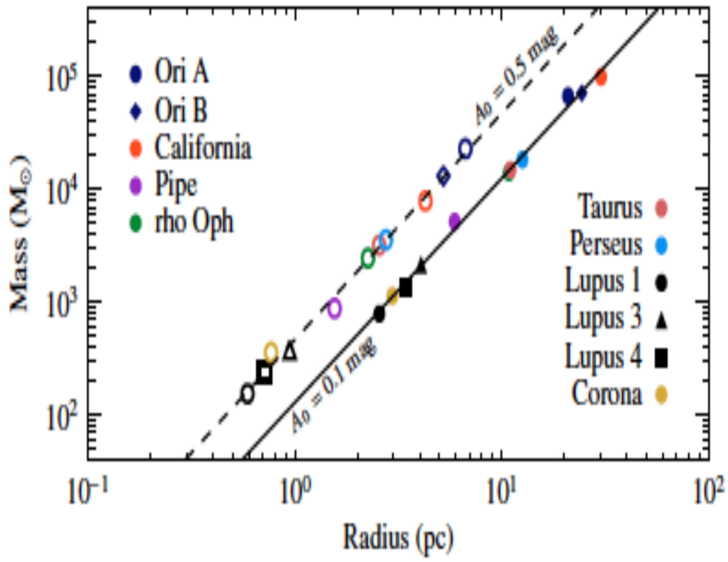
The cloud's radius is the Jeans' Length and its mass ($4/3\pi\rho\lambda^3{}_j$) is the Jeans mass -when thermal energy per particle equals gravitational work per particle. At this critical length the cloud neither expands nor contracts. Dimensionally this is $kT=GM/r$

# Molecular Clouds MWB sec 9.2

If self gravitating, isothermal spheres collapse if mass exceeds the Jeans mass $M_j \sim 40 M_\odot (c_s/0.2\text{km/sec})^3 (n_{H2}/100)^{-1/2}$

which they do by a lot~!

collapse on free fall time $t_{ff}=(3\pi/32G\rho)^{1/2}$ $\sim 3.6\times10^6 (n_{H2}/100)^{-1/2}$yrs

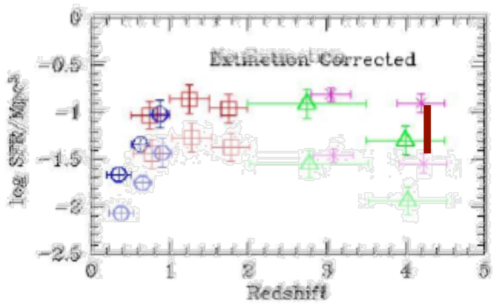



# Star formation Occurs in Giant Molecular Clouds

- Cooling to $10^4$ K is not sufficient to form stars.
- The gas has to cool well below 100K and must be shielded from UV radiation by dust.
- Star formation occurs in giant molecular clouds with masses of $10^3$-$10^7$ M and radii of 1-100pc.
- These clouds can become gravitationally unstable and collapse and form stars .

# Dust

- As we discussed before the effects of dust and how one treats is can be a very large effect.
- As an example take the star formation history of the universe as revealed by deep 'optical' studies- it shows that 'correcting for dust' introduces a factor of 3 change!
- Correcting for dust is not easy to do




For those interested in more details on starbursts see Peter Barthels course notes
http://www.astro.rug.nl/~pdb/starbursts.htm

# Low Z SFR-Summary

Kennicutt 1998

| Property | Spiral Disks | Star Bursts |
|---|---|---|
| Radius | 1 – 30 kpc | 0.2 – 2 kpc |
| SFR | 0 – 20 $M_\odot$ $yr^{-1}$ | 0 – 1000 $M_\odot$ $yr^{-1}$ |
| Bolometric Luminosity | $10^6 - 10^{11}$ $L_\odot$ | ~~$10^6 - 10^{13}$~~ $L_\odot$ |
| Gas Mass | $10^8 - 10^{11}$ $M_\odot$ | $10^6 - 10^{11}$ $M_\odot$ |
| Star Formation Timescale | 1 – 50 Gyr | 0.1 – 1 Gyr |
| Gas Density | 1 – 100 $M_\odot$ $pc^{-2}$ | $10^2 - 10^5$ $M_\odot$ $pc^{-2}$ |
| Optical Depth (0.5 $\mu$m) | 0 – 2 | ~~1 – 1000~~ |
| SFR Density | 0 – 0.1 $M_\odot$ $yr^{-1}$ $kpc^{-2}$ | 1 – 1000 $M_\odot$ $yr^{-1}$ $kpc^{-2}$ |
| Dominant Mode | steady state | steady state + burst |

- $t_{freefall}=(R/G\Sigma)^{1/2}$
- $t_{cross}=(R/\sigma)$
- the fastest things can happen is when this are equal and - $R_{Jeans}$ the Jeans length

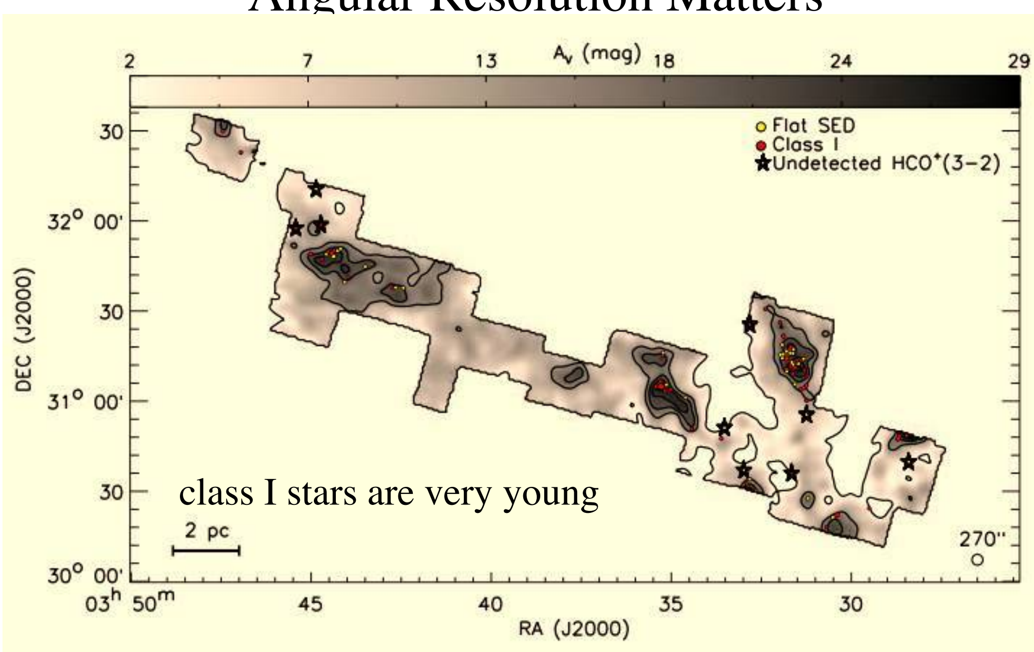
$R_{Jeans} \sim \sigma^2/G\Sigma$

# Summary of Situation

- Large scale SFR is determined by a hierarchy of physical processes spanning a vast range of physical scales:
  - the accretion of gas onto disks from satellite objects and the intergalactic medium(Mpc)
  - the cooling of this gas to form a cool neutral phase (kpc)
  - the formation of molecular clouds (10-100 pc);
  - the fragmentation and accretion of this molecular gas to form progressively denser structures such as clumps (~ 1 pc) and cores (~ 0.1 pc)
- The first and last of these processes operate on galactic (or extragalactic) and local cloud scales, respectively, but the others occur at the boundaries between these scales and the coupling between processes is not yet well understood.
- the challenge of explaining the low efficiency of star formation remains.
- Similarly, an understanding of the full IMF, remains elusive.

**Kennicutt and Evans 2012**

# Angular Resolution Matters




— Example of the strong concentration of star formation in regions of high extinction, or mass surface density in

In Perseus molecular cloud all the young stars lie in very dusty regions

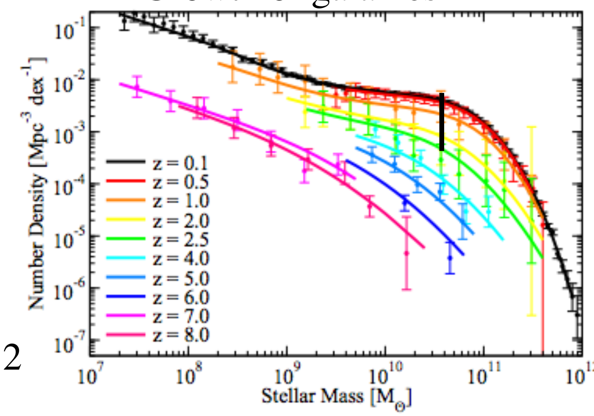
## Cosmic History of Star Formation

### General Results

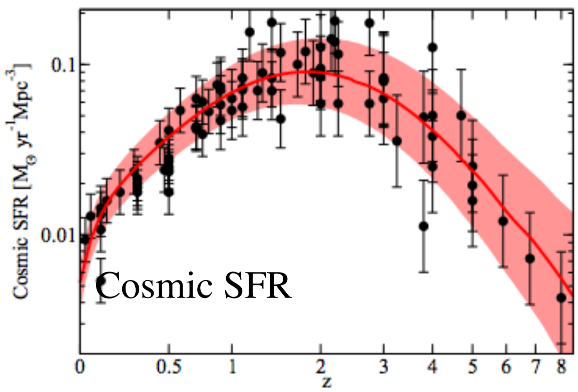
- 90% of all stars formed since z~3
- SFR has dropped by ~10x sin z~1.

Behroozi et al 2012

Growth of galaxies

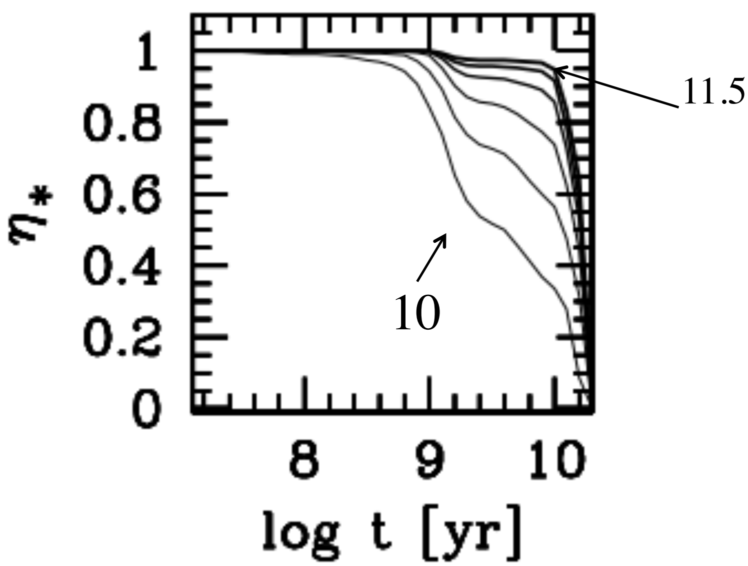



- **•The most massive galaxies** grow 50:50 by merging z<1
- Form stars vigorously at z>2
- Also at earlier epochs: most stars lived in the most massiv galaxies at the time
- Effects of dust are dominant a z>3 *and results are uncertain*




## Results from Stellar Paleontology

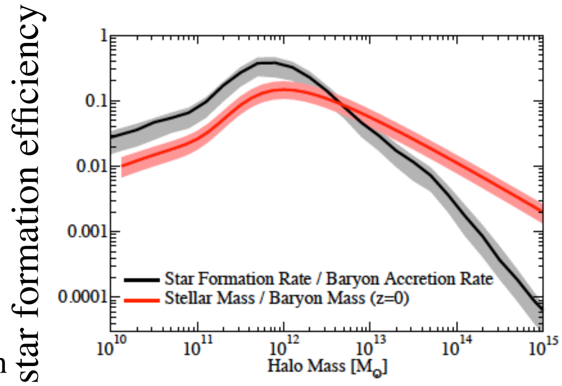
- History of stellar growth in **6 mass bins 10, 10.3, 10.6, 10.9, 11.2, 11.5 vs time** - *big objects form first, evolve rapidly and then remain the same for long times* (Vale Asari et al 2009) and metallicity $Z_*$



# Theoretical ideas About Galaxy Wide Star Formation

- Theoretical predictions are that galaxy formation is most efficient near a mass of $10^{12}$ $M_\odot$ based on analyses of supernova feedback and gas cooling times

- Hydrodynamical simulations indicate that the host dark matter halo mass strongly influences gas accretion onto galaxies
- For low halo masses, simulations predict that gas accretes in cold filaments ("cold mode accretion") directly to the galaxy disk, efficiently forming stars.
- Above a transition halo mass of ~$10^{11}M_\odot$ a shock develops at the virial radius which heats accreting gas ("hot mode accretion") and rapidly quenches instantaneous star formation

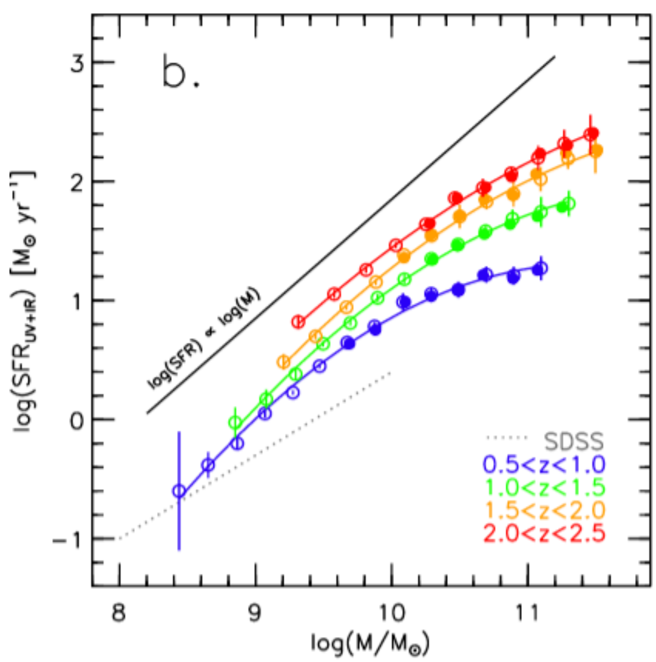



# 'Main Sequence' of Star Formation

- Galaxy surveys out to z~4

show that the majority of star-forming galaxies follow a relatively tight relation between star formation rate (SFR≡Ψ) and stellar mass ($M_\star$)

  – this is called the main sequence of star formation




Whitaker et al 2015

# Star Formation Summary

- Next: Elliptical Galaxies