Summary of Last Lecture - Local Group

- Discussion of detailed properties of M31, M33 comparison to MW; differences in how they formed; MW very few 'major mergers' M31 more; not all galaxies **even those close to each other do not have the same history.**
- Dynamics of local group allow prediction that M31 and MW (and presumably the Magellanic clouds) will merge in ~6 gyr
- A supermassive black hole exists in the centers of 'all' massive galaxies- properties of BH are related to the bulge and not the disk of the galaxy
- Use 'timing argument' to estimate the mass of the local group (idea is that this is the first time MW and M31 are approaching each other and the orbit is radial) use 'simple' mechanics to get mass
- Local group is part of a larger set of structures- the 'cosmic web' galaxies do not exist in isolation

NEW TOPIC- Star Formation
All over the place in S&G

- 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.

- 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- see later* (Krumholz 2012)

Star Formation Occurs Primarily in Disks (Spirals)

- star-forming galaxies at all redshifts are *dominated* by disks, while passive (non-starforming or non-active) galaxies have 'spheroida'l structure
  - (Eales et al 2015)- estimate that ≈85% 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 today lies in passive galaxies- need either to transform spirals into E's or merge them

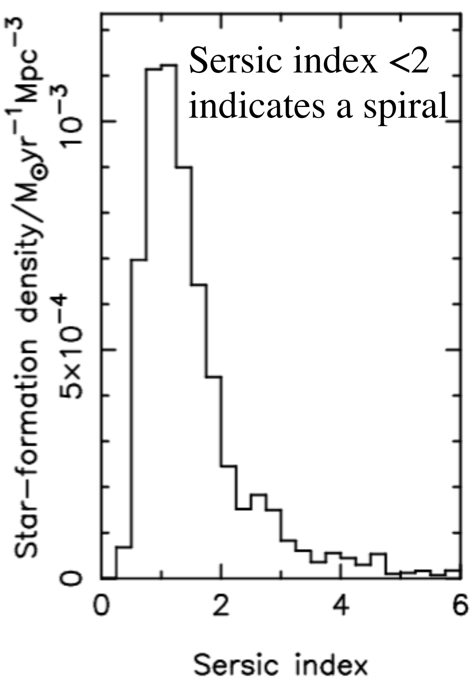


Figure 1. Star-formation rate per unit comoving volume in the Universe today as a function of Sérsic index.

Star Formation- How to Measure It- 5 Ways see https://ned.ipac.caltech.edu/level5/Sept12/Calzetti/Calzetti1_2.html

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 correlates 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 due to supernova

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 Ψ from 10-100$M_\odot$ 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 directly detected in MW and Magellanic clouds

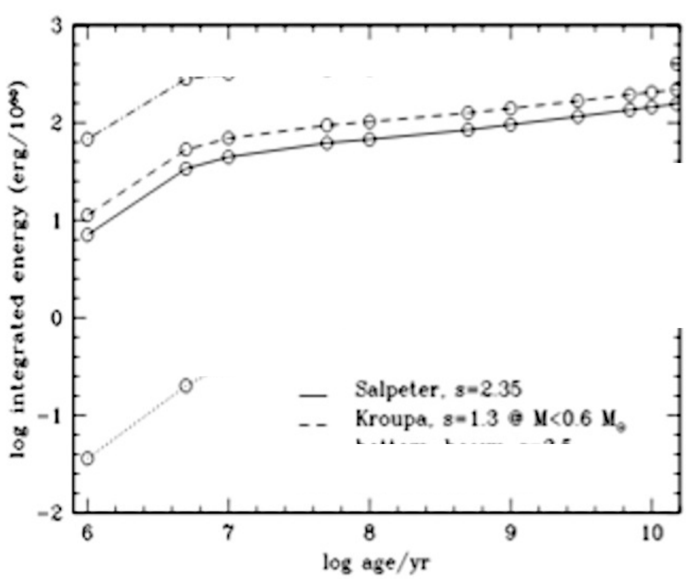
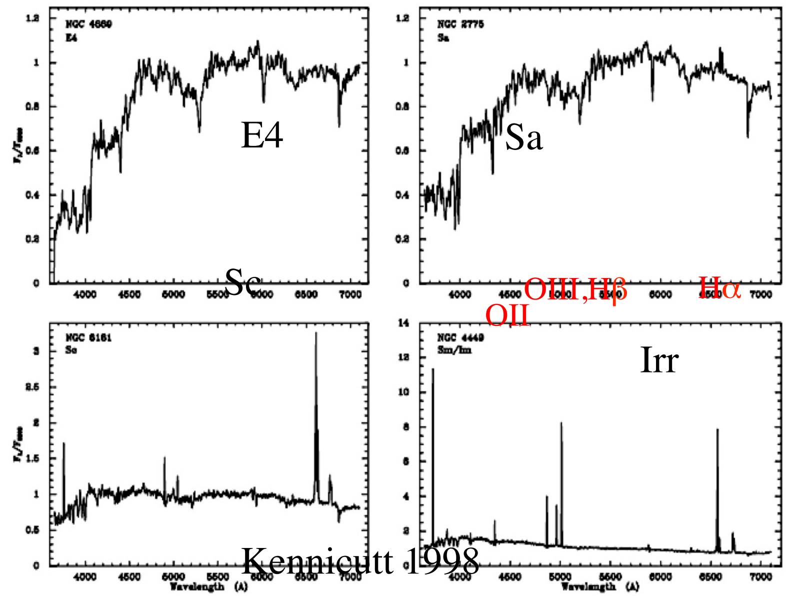


Figure 3. The total energy that has been emitted by a ... age for a single stellar population with a mass of 10^{11} $M_\odot$

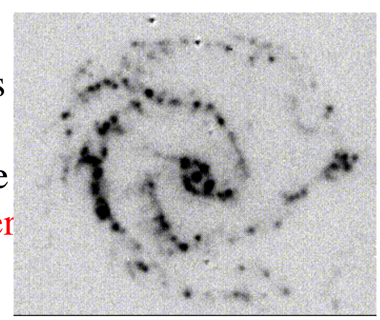
Reminder -Importance of Emission Lines

- 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)



How to Determine SFR from Observables-Hα or Hβ

- 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 ~10-20$M_\odot$ 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- short life of massive stars.
- So Hα measures the '**instantaneous**' star formation rate

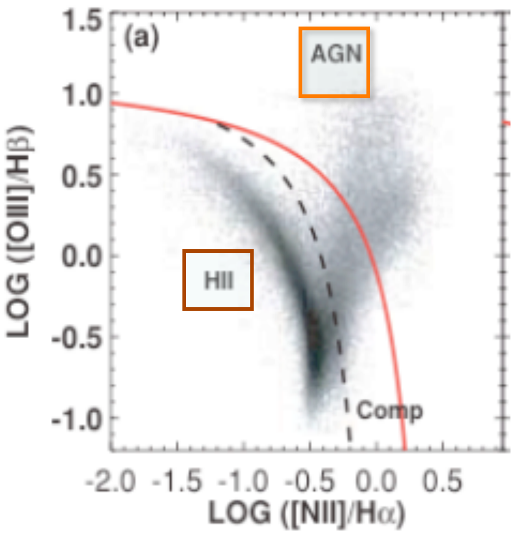


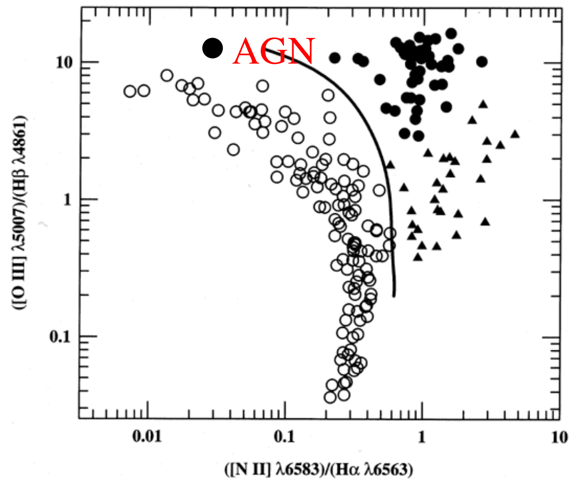
Hα image of a star forming galaxy

•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 the 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.

How to Determine SFR from Observables-Hα or Hβ

- 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(Hα)/7x10^{41} ergs/sec for M>10$M_\odot$ stars or for all stars
- **SFR($M_\odot$/yr)~L(Hα)/1.1x10^{41} ergs/sec**

SFRs derived from this method are especially sensitive to the form of the IMF. Adopting the Scalo (1986) IMF, for example, yields SFRs that are ~3 times higher than derived with a Salpeter IMF.

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,

- Which stars dominate the UV from a star forming galaxy ??
  - both O and B stars are brighter in the UV than at longer wavelengths.
  - 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, weighting by a Saltpeter IMF SSP 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 12)

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 can be BIG- A_V =0.9 produces a factor ten reduction in the UV continuum at 1300Å (see MBW pg 479, S+G pg 33-34 for discussion of reddening- more later in lectures on dust)
  - Observations show that at 'low' SFR dust is not a big effect, at high values critical
- 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

$$SFR(UV) M_{\odot}/yr = 3.0 \times 10^{-47} L_{UV}(ergs/sec)(912\text{-}3000\text{Å})$$

IR Continuum

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 to T ~100k.

Need wide range of temperatures to produce observed IR spectra.

Roughly SFR ($M_\odot$/yr)~$L_{\text{total IR}}$ x4.5x10^{-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

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

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

λ_{peak}~29μ/T_{100} λ_{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)

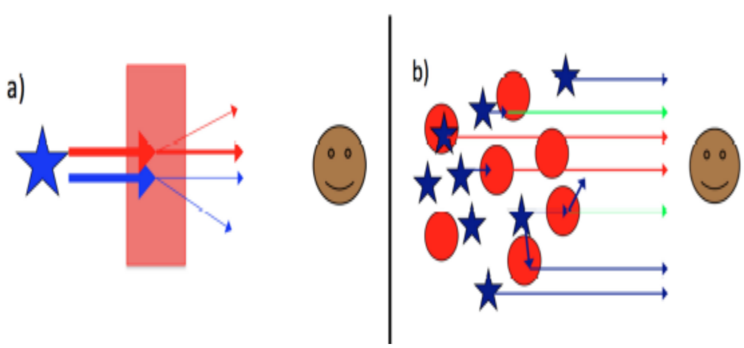
T~λ^{-1} but L~AT^4 so to get a lot of luminosity at long wavelengths needs a large emitting area, A

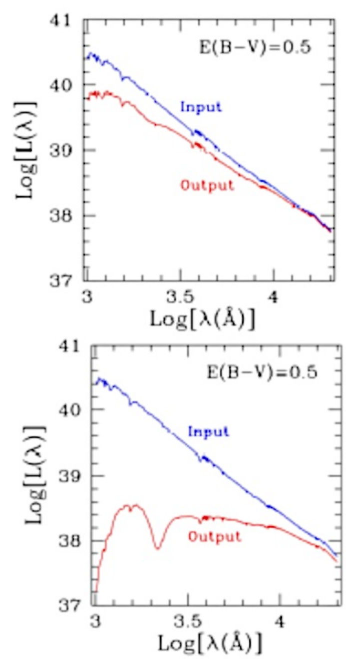
IR Continuum

- 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

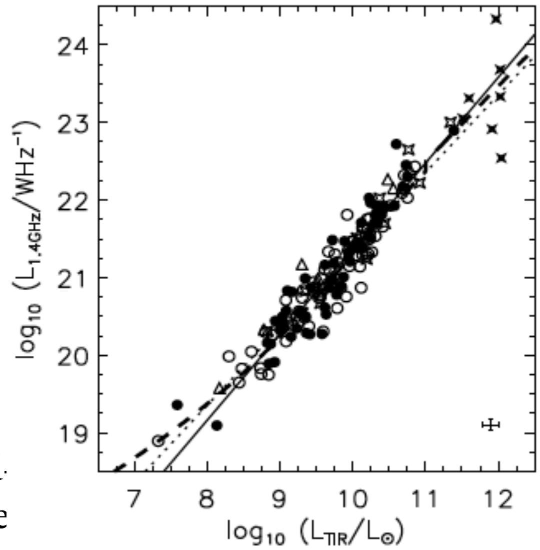




Star Formation- Radio View

- 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

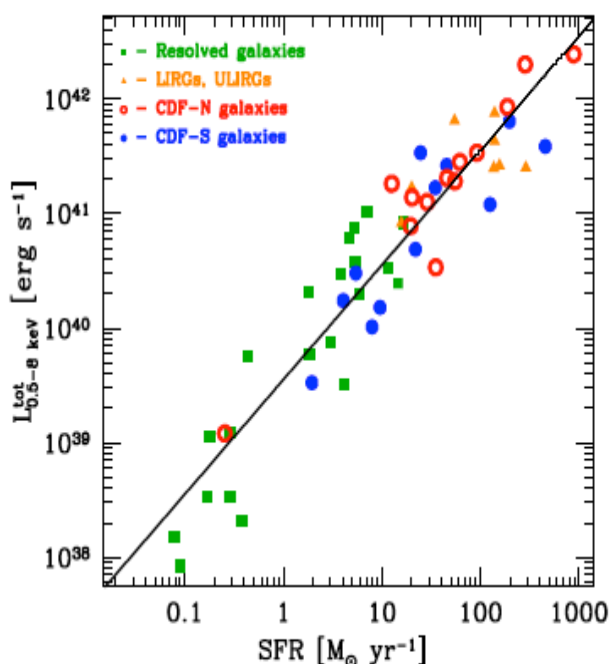


Bell 2002

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 $\tau \sim 2\times10^7$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

How to Infer SFR from Optical Continuum Data

- Construct stellar evolutionary tracks containing parameters such as T_{eff}, L_{bol},
- Construct IMFs containing parameters such as Luminosity, Color, Spectra of Single Age Population
- Add together IMFs from step 2 to get spectra & colors of a galaxy with an arbitrary star formation history
- Lots of parameters to determine (see http://arxiv.org/pdf/1208.5229.pdf) for a detailed discussion of the steps and uncertainties

1) Star Formation History

2) Galaxy Age

3) Metal Abundance

4) IMF

One iterates by comparing the actual galactic emission to the output of a set of galactic stellar population models. The models that best fit the observed data are then used to estimate the galactic properties of interest (e.g. stellar mass, present star formation rate, internal extinction etc.);

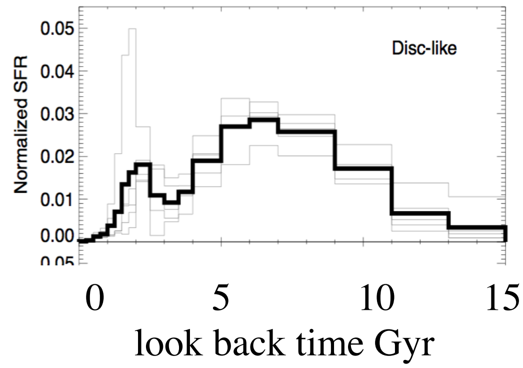
How to handle dust??

Summary of the various indicators

- 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
- Optical continuum- model SED to reproduce observed colors and intensity − can infer star formation history...

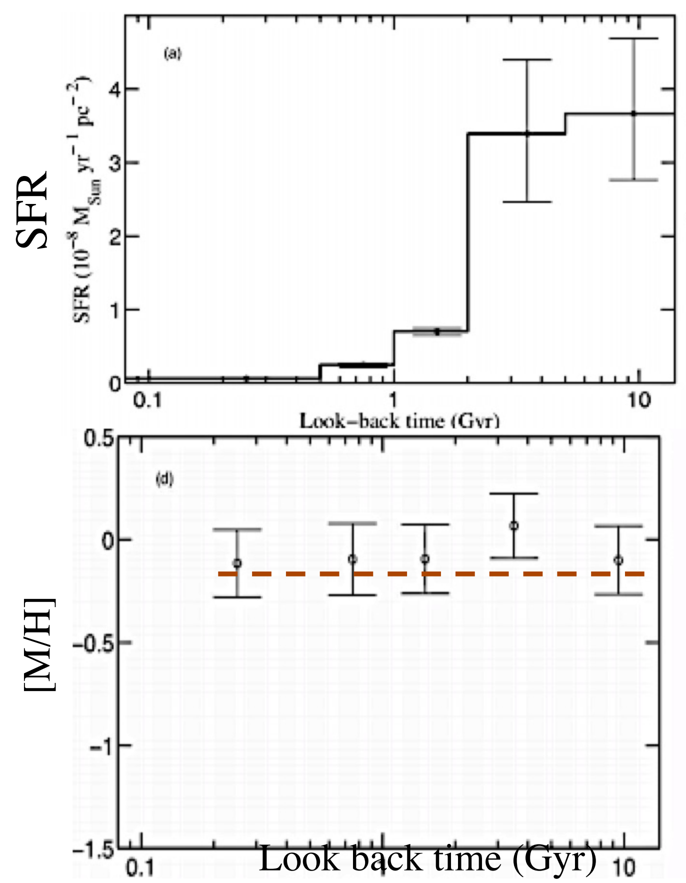
SF History

- M31 has some of the best data
- 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.
- Metallicity does not change with time (!)- where do the created metals go ?



SFR indicators

- SFR indicators are derived across the full electromagnetic spectrum, from the X-ray, through the ultraviolet (UV), via the optical and infrared (IR), radio, and using both continuum and line emission

(review Kennicutt 1998, Kennicutt & Evans (2012).

- The importance of these indicators change over cosmic time due to observational issues.

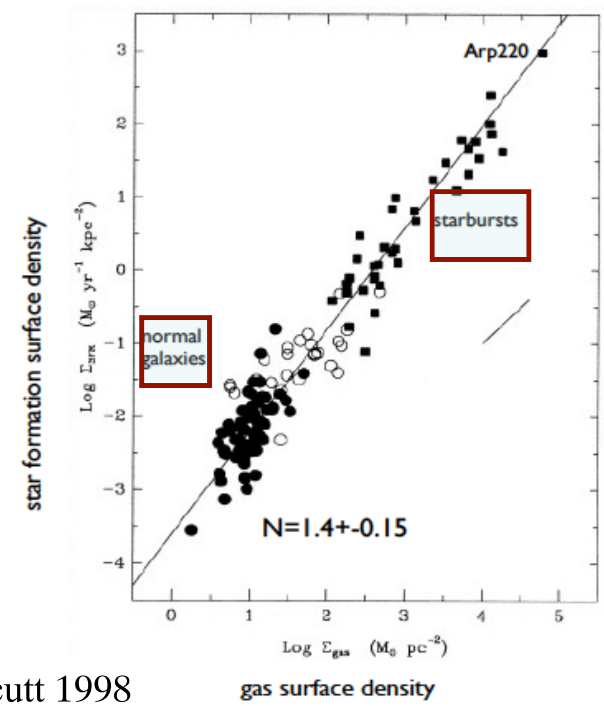
What is Star Formation Related To?

- Observations of star formation rates (SFRs) in galaxies provide vital clues to the physical nature of the Hubble sequence, and are key probes of the evolutionary histories of galaxies.

Kennicutt Schmidt Law

- 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)

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

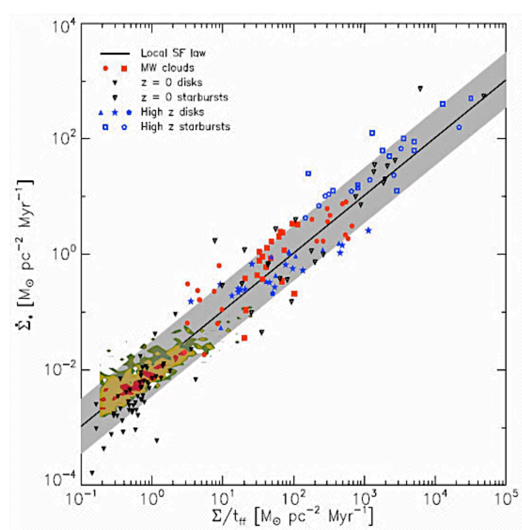
- interpreted as indicating that the star formation rate is controlled by the self-gravity of the gas. If so, the rate of star formation will be proportional to the gas mass divided by the time scale for gravitational collapse.

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

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

ε_{SF} is the efficiency of star formation

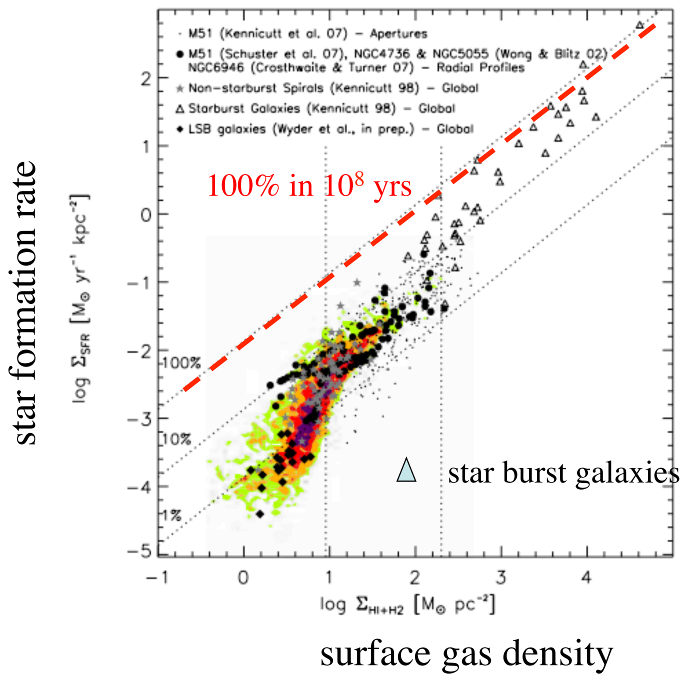
gas consumption efficiency is low; takes ~1.5×10^9yrs to convert the gas into stars



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

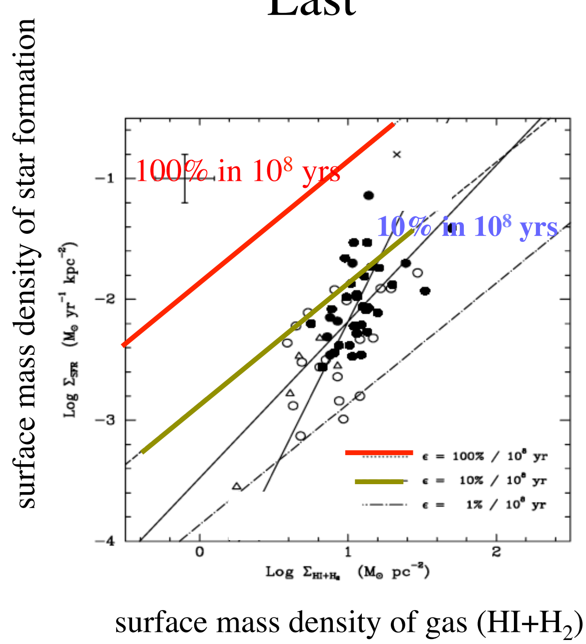
Kennicutt Law with Starbursts

- 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 free fall timescale.
- This produces a wind in the galaxy as a large amount of energy is injected by star formation in a short time.



- 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
- 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

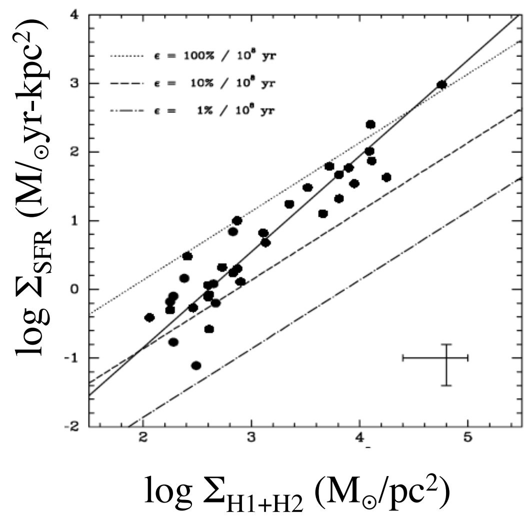
- Starburst use up their gas much faster
- <30%> of gas used every 10^8 yr
- Depletion timescale≈ 0.3 Gyr
- How luminous are these objects?

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

nuclear fusion is ~0.7% efficient

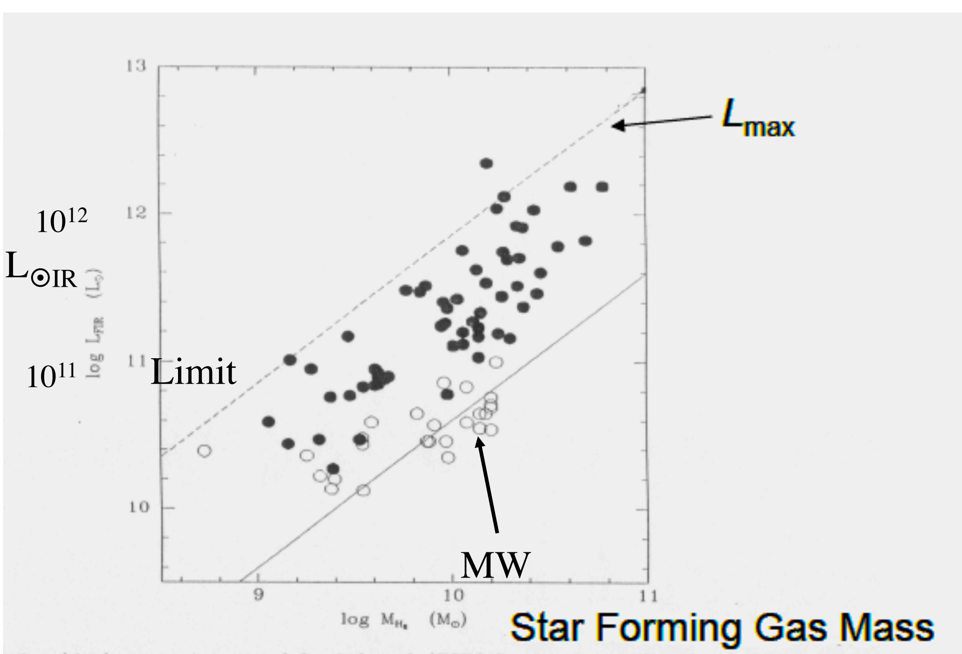
the fraction of rest mass converted to energy for a Saltpeter IMF is ε~0.05 during 10^8yrs

$L \sim 10^{11}$-10^{12} $L_\odot$!!



How Long Does the Gas Last-Star Bursts

This gives $L_{max} \sim 0.07\varepsilon(dM/dt)c^2$
$L_{max} \sim 10^{11}L_\odot(M_{gas}/10^{10}M_\odot)(\varepsilon/0.05)$



Jeans Criterion for collapse of spherical cloud

see S&G 8.5.1 Pressure battles gravity: the Jeans mass

- Gravitational instability sets in if the free-fall time is less than the sound crossing time (c_s = sound speed)
- $t^2_{ff}=1/G\rho<(R/c_s)^2\sim10^8 n^{-1/2}_H$ 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 $M_J= 4/3\pi\lambda^3{}_J\rho=4/3\pi c^3{}_s\rho^{-1/2}$

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 λ_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 $kT=GM/r$

Jeans Criterion from Sparke and Gallagher

- if the kinetic energy is less than the thermal energy (remember the Virial theorem!) the cloud will collapse until it reaches 'virial' equilibrium
- If we assume that the relevant velocities are the thermal (sound) velocities
- the potential energy of a uniform sphere of radius r and density ϱ is
- $PE \equiv -1/2\int \rho(x)(x)d^3x \approx -(16\pi^2/15)G\rho^2 r^5$, and the is
- $KE \approx (3c_s^2/2)(4\pi r^3\rho/3)$ eqs 8.70

- Applying the virial theorem
- $2r > \mathrm{sqrt}(15\pi c_s^2/G\rho) \approx \lambda_J$, where $\lambda_J \equiv c_s \mathrm{sqrt}(\pi/G\rho)$.
- λ_J is called the Jeans length.
- Jeans mass M_J is the amount of matter in a sphere of diameter λ_J:
- $M_J \equiv \pi/6\lambda^3_J\varrho_m$,notice this differs from the previous value

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 $\lambda_J=\mathrm{sqrt}(\pi c_s^2/G\rho)-$ distance a sound wave travels in a grav free-fall time **(see http://christopherlovell.co.uk/blog/2016/04/26/jeans-mass.html for a nice derivation which shows the 2 values of Jeans mass or http://icc.dur.ac.uk/~tt/Lectures/Galaxies/TeX/lec/node37.html)**

For typical values

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

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

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

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

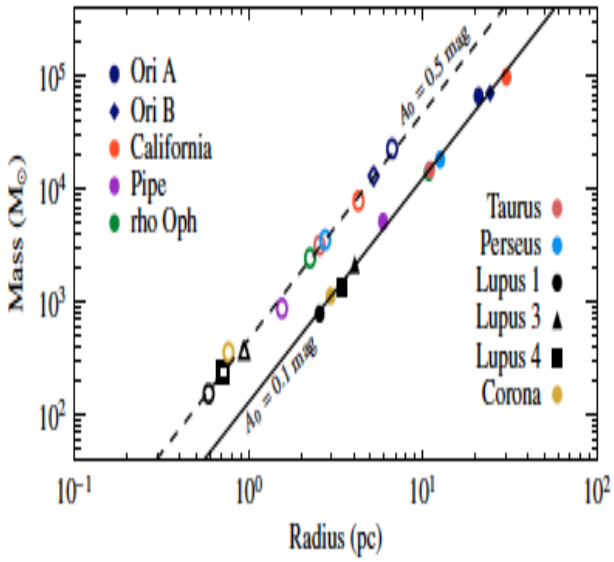
- For typical values c_s=0.3km/sec$(T/10k)^{1/2}$

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.

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
$t_{ff}=(3\pi/32G\rho)^{1/2}$
$\sim 3.6\text{x}10^6(n_{H2}/100)^{-1/2}$yrs

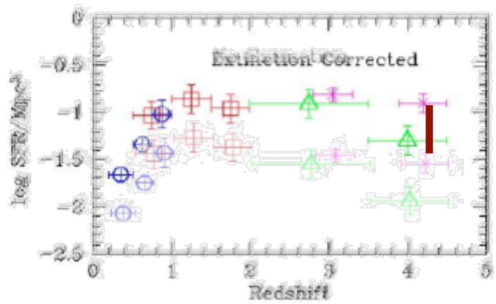
If work directly with temperature T
$M_J=(-5k_bTGm)^{3/2}(3/4\,\pi\,\rho)^{1/2}$

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	$10^6 - 10^{11}\ L_\odot$	$\cancel{10^6 - 10^{13}}\ L_\odot$
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 μm)	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 these are equal and - R_{Jeans} the Jeans length

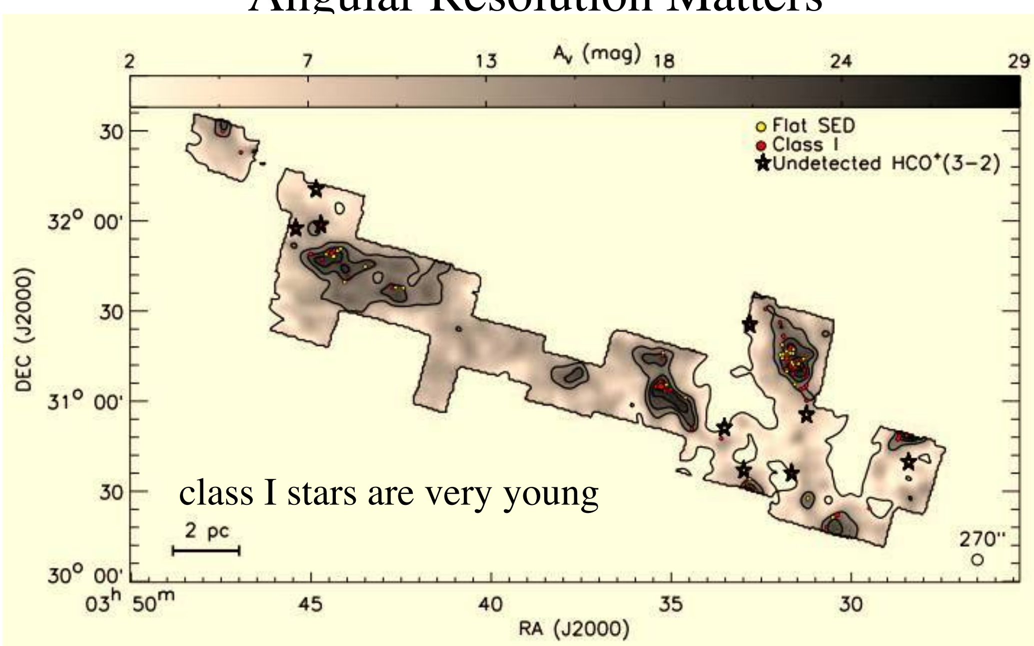
  $R_{Jeans} \sim \sigma^2/G\Sigma$

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

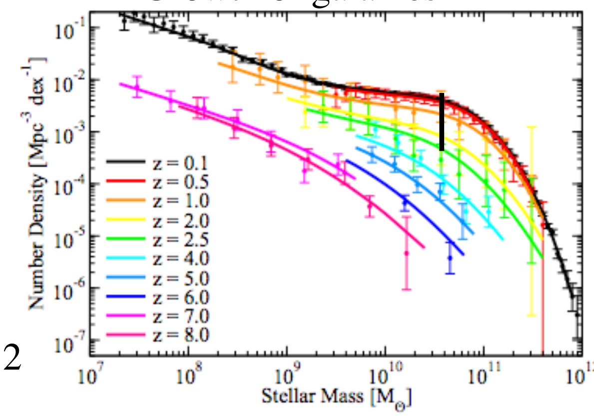
General Results

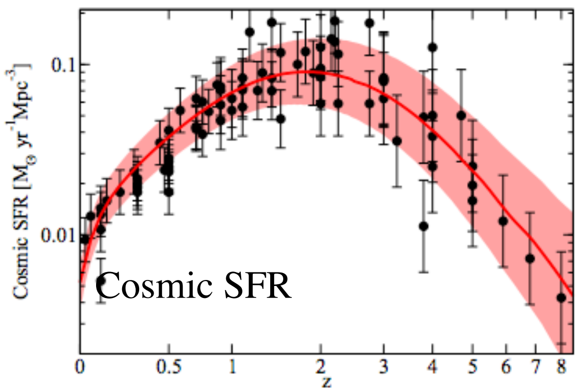
- 90% of all stars formed since z~3
- SFR has dropped by ~10x sin z~1.

Behroozi et al 2012

- **•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*

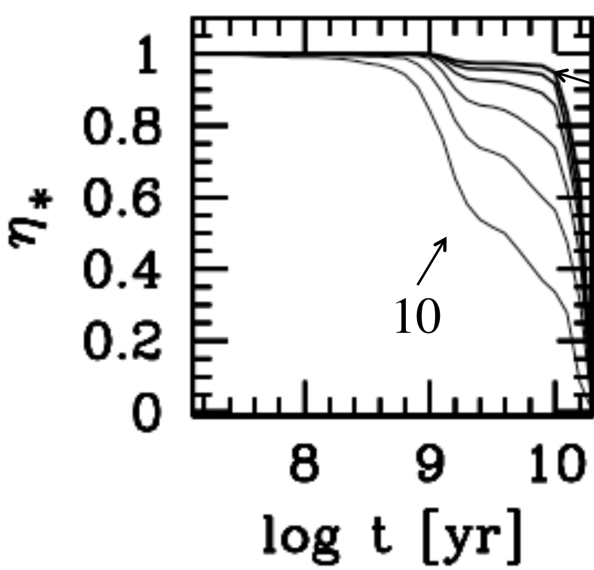
Growth of galaxies





Results from Stellar Paleontology

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



11.5

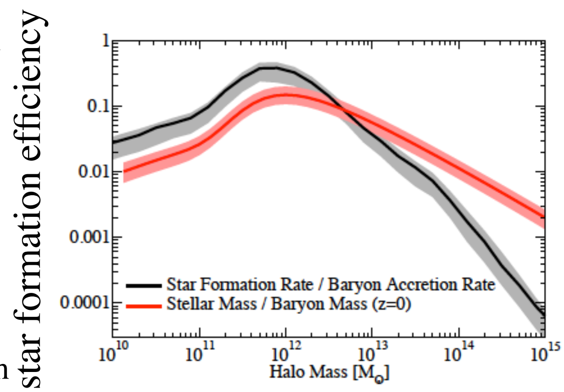
less massive galaxies grow slower and are still growing today

notice time scale is log

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 $\sim 10^{11} M_\odot$ a shock develops at the virial radius which heats accreting gas ("hot mode accretion") and rapidly quenches instantaneous star formation

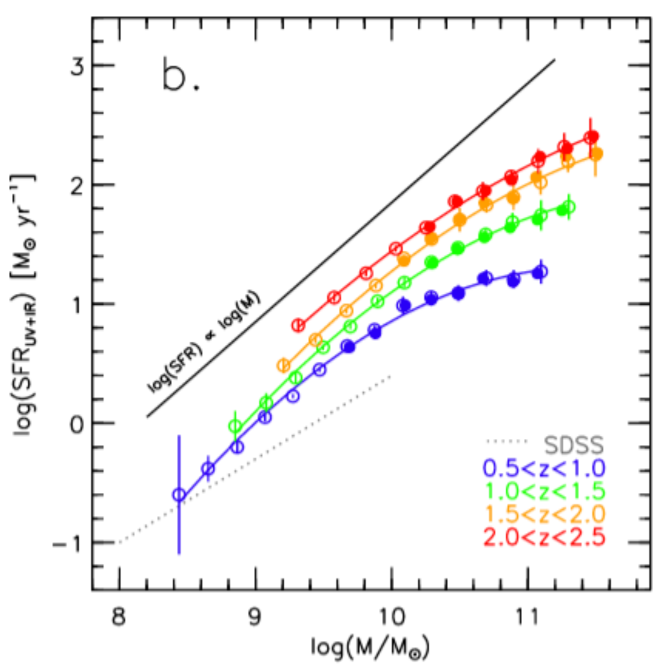


'Main Sequence' of Star Formation

- Galaxy surveys out to z~4

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

  – this is called the main sequence of star formation



Whitaker et al 2015

- Next: Spiral Galaxies
- Read Ch 5 of S&G