NEW TOPIC- Star Formation- Ch 9 MBW Please read 9.1-9.4 for background

- 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?
    - is high redshift star formation the same sort of process as at low z?

Star Formation in Spirals

- This is an enormous subject- lots of recent work (see Star Formation in the Milky Way and Nearby Galaxies Kennicutt, Jr. and Evans ARA&A Vol. 50 (2012): 531)
- Observations of nearby galaxies
  - over a broad range of galactic environments and metallicities, star formation occurs only in the molecular phase of the interstellar medium (ISM). e.g. Star formation is strongly linked to the molecular clouds
  - Theoretical models show that this is due to the relationship 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** (Krumholz 2012)
- In the MW and other well studied nearby galaxies SF occurs mostly in

  (Giant molecular clouds (GMCs, which are predominantly molecular, gravitationally bound clouds with typical masses ~ $10^5 - 10^6\ M_\odot$)- but GMC formation is a local, not a global process
- Observationally one uses CO as a tracer for H_2 (not perfect but the best we have right now). This is time consuming but lots of work has been done (Leroy et al 2008)

top level

The physics of star formation (what processes produce stars) and the astrophysics (where and when were the stars produced) are two of the dominant issues in astrophysics at present.

- Stars form from dense, cold gas either in disks or in gas that is violently shock compressed (in mergers)
- We do not have time to go into the details of the microphysics -the formation of individual stars in dense molecular clouds nor into macrophysics- the details of how molecular clouds form and evolve.

Star Formation Estimators

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; 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)

Jeans Criterion for collapse of spherical cloud

- Gravitational instability sets in if the free-fall time is less than the sound crossing time
- $t^2_{ff}=(3\pi/32)/G\rho^{*}<(R/c_s)^2=10^8 n^{-1/2}_H$ yrs; free fall time from $d^2r/dt^2=-GM/r^2$;n_H is the number density of gas, **c_s is the sound speed** ; 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 length λ_J=sqrt($\pi c_s{}^2/G\rho$)

B&T prob 3.4: a homogeneous sphere of a pressureless fluid with density ρ will collapse to a point in time t_{ff} = 1/4 sqrt*($3\pi/2G\rho$); the free-fall time in an isothermal potential $t_{ff} \sim R^{3/2}$

$t_{ff} \sim 3.6\text{x}10^6$ yr ($n/100\text{cm}^{-3})^{1/2}$

Jeans Criterion for collapse of spherical cloud

For typical values

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

units of surface mass density Jeans length is $\lambda_J=c_s{}^2/G\Sigma$

c_s= sound speed=sqrt($dP/d\rho$)=sqrt($\gamma k_B T/\mu m_H$) for hydrogen (k_B= Boltzmann's constant, m_H= mass of hydrogen atom, μ = mean molecular weight) γ- polytropic index of gas (perfect gas $\gamma=5/3$)

- 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. (see MWB sec 8.5 for details)

remember that cooling time ~1/n

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
- For Kroupa IMF $\Psi(M)$
  - $\Psi(M) \sim M^{-1.4}$ $0.1<M<1$
  - $\Psi(M) \sim M^{2.5}$ $1<M<100$
- Integrate Ψ from 10-100M get .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

- How to correct various indicators
- Hα: emitted by gas ionized by stars with $T_{eff}>\sim 20{,}000$k ($M>10M_\odot$) which emit photons that can ionized Hydrogen ($E_{ioniz}=13.6$eV) -t<20Myrs
- IR Continuum- UV light absorbed by dust
- UV continuum- direct signature of massive, young stars

- The star formation rates is determined using many different indicators.
- The most important of are
  - far infrared emission tracing deeply embedded star formation
  - Hα emission tracing H II regions;
  - and far ultraviolet emission tracing young, massive stars that have dispersed their natal gas and dust.
  - Radio emission tracing relativisitic particles created by SF processes (e.g. supernova)
- Molecular hydrogen surface density correlates linearly with star formation rate -HI seems not to matter-

Star Formation

- One of the most important processes for galaxy formation and evolution
- What are the general conditions for star formation?
  - in the low z universe star formation in spirals occurs mostly in molecular clouds
  - in ellipticals it is not understood; but is it clear that in some ellipticals stars are forming now.
  - special class of star forming galaxies- star bursts
- General scenario gas cloud collapses, fragments, stars form (somehow).

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: it seems that most of the star formation at redshift z~1–3 was enshrouded in dust but at z>3 dust was much less important.

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 ≈100–300Myr,
- both O and B stars are brighter in the UV than at longer wavelengths good signature of SF.
- The lifetime of an O6 star is~6Myr, and that of a B8 star is ~350Myr.

The luminosity ratio of these 2 stars at 0.16 μ is ~90, but, weighting by the 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 2012)

UV Continuum

Ultraviolet stellar continuum: key advantages

- direct photospheric measure of young massive stars
- primary groundbased SFR tracer for galaxies at z>2

- 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;
    - effects of dust are BIG- A_V =0.9 produces a factor ten reduction in the UV continuum at 1300A.
    - Observations show that at 'low' SFR dust is not a big effect, at high values critical
  - at low redshift must observe from space -
  - VERY sensitive to IMF- at best can only constrain 15% of all the stars forming
    - For a Kroupa IMF with with constant star formation

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

IR Continuum

- Direct observations show that **~1/2 of total galaxy light in spirals appears in IR**
- This is thermal emission emitted by dust as a grey body
- Wavelength at which emission peaks is related to temperature of dust

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

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

(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 spectra.

Roughly SFR (M/yr)=$L_{\text{total IR}} \times 4.5\times10^{-44}$ 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 continuous SF

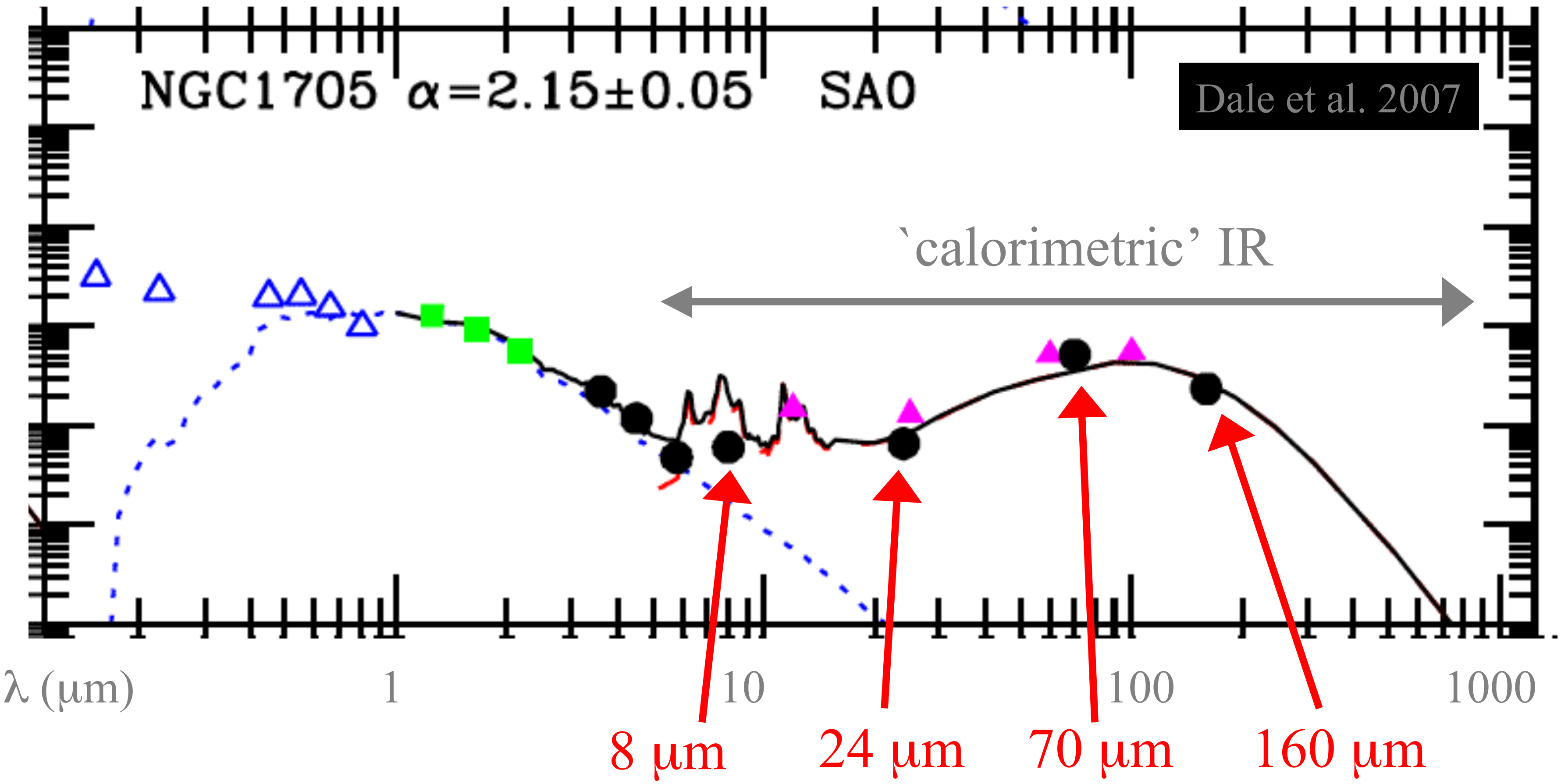
IR Continuum

- Ideal for starburst galaxies because:
- Young stars dominate 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

- Not ideal for SF in disks of normal galaxies because:a fair fraction of the IR luminosity is produced by dust re-radiation of emission from 'old' stars e.g. cirrus in the MW. - that is the calibration between SFR and L_{IR} depends on the age of the system

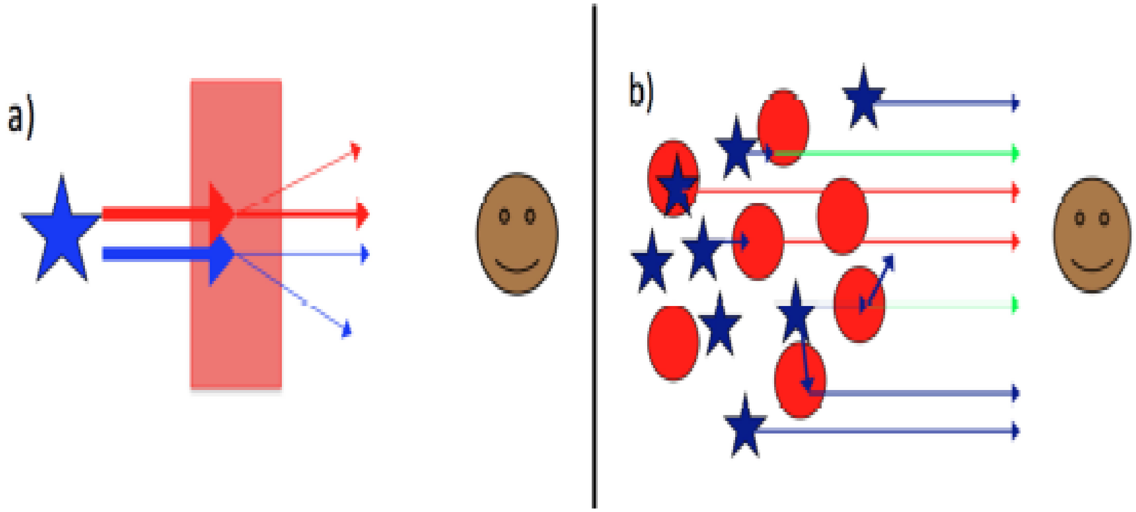
FIR to SFR?- Kennicutt

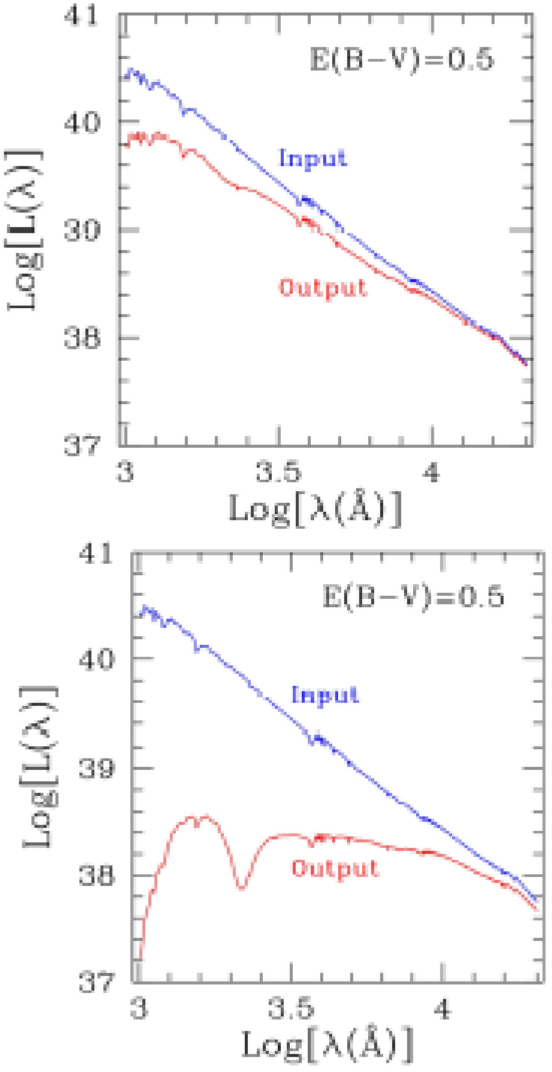


Dale et al. 2007

FIR - can be sensitive to heating from old stellar populations as well as hot young stars
8 µm - mostly single photon heating (PAH emission)
24 µm - both thermal and single photon heating
70 µm and 160 µm - mostly thermal, also from old stars

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

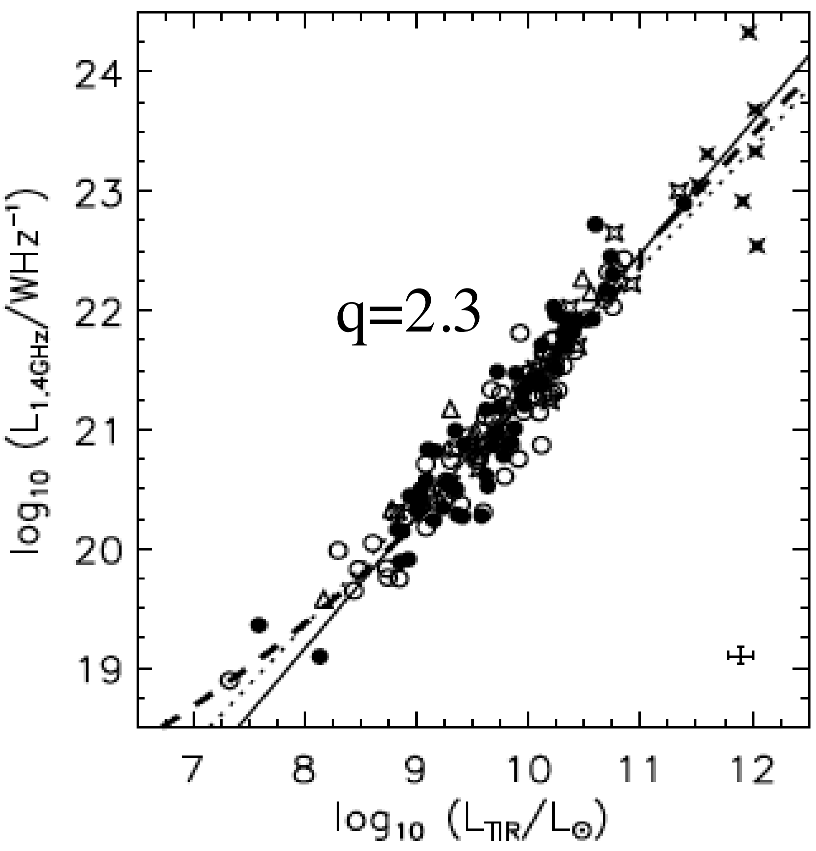




Star Formation- Radio View

$$q = log\left(\frac{FIR}{3.75 \times 10^{12}\mathrm{W\ m^{-2}}}\right) - log\left(\frac{S_{1.4\mathrm{GHz}}}{\mathrm{W\ m^{-2}\ Hz^{-1}}}\right)$$

- 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
- The relative ratio is frequency dependent because of the different spectral slopes of the 2 processes ($F_\nu \sim \nu^\alpha$, α=-0.7 for synch, -0.1 for TB)
- 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



Bell 2002

Star Formation X-rays

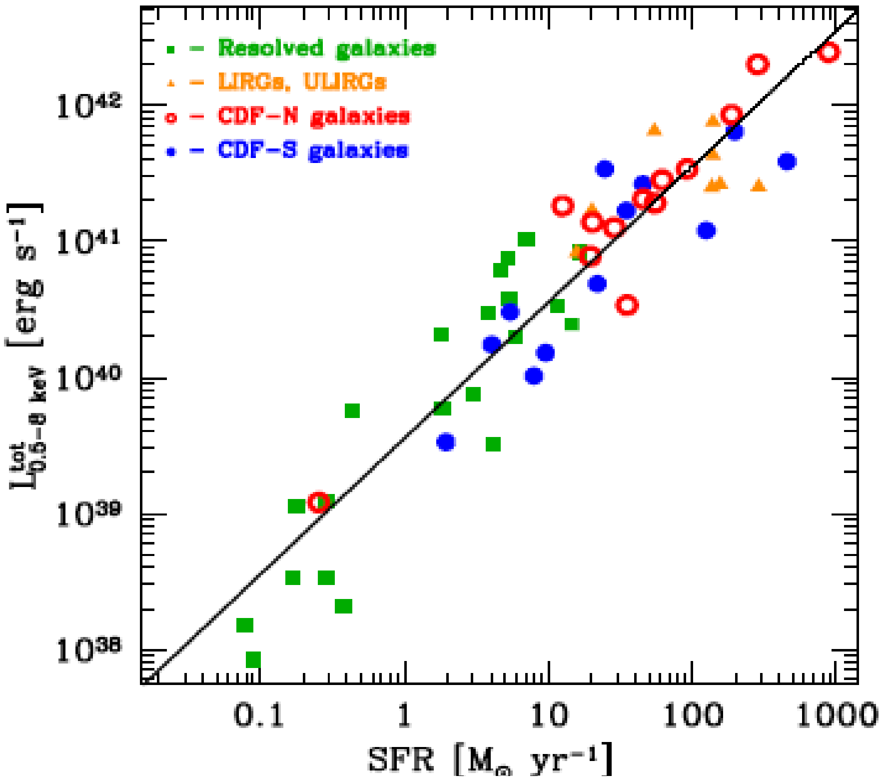
Mineo et al 2012

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

1) high mass x-ray binaries with a lifetime τ~2x10^7yrs

   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 "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 Data

- Construct stellar evolutionary tracks containing parameters such as T_{eff}, L_{bol},
- These are typically obtained via atmospheric models & spectral libraries

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

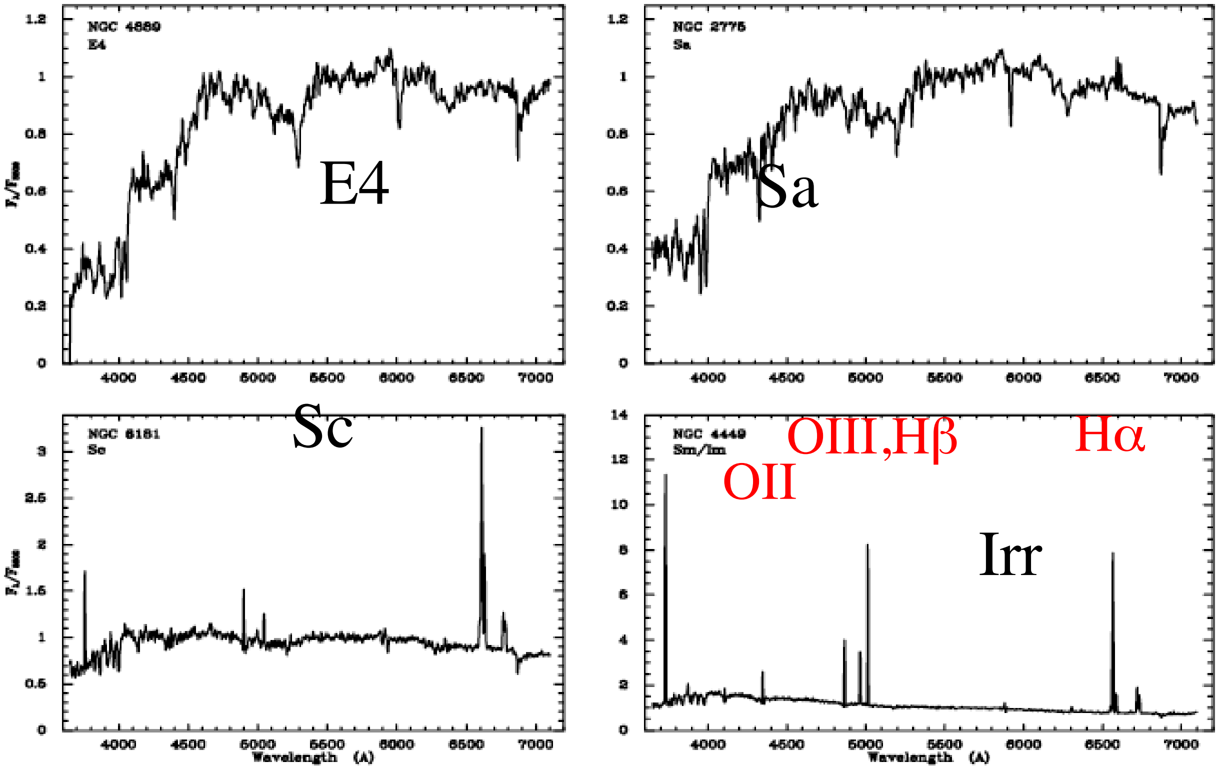
4) IMF

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??

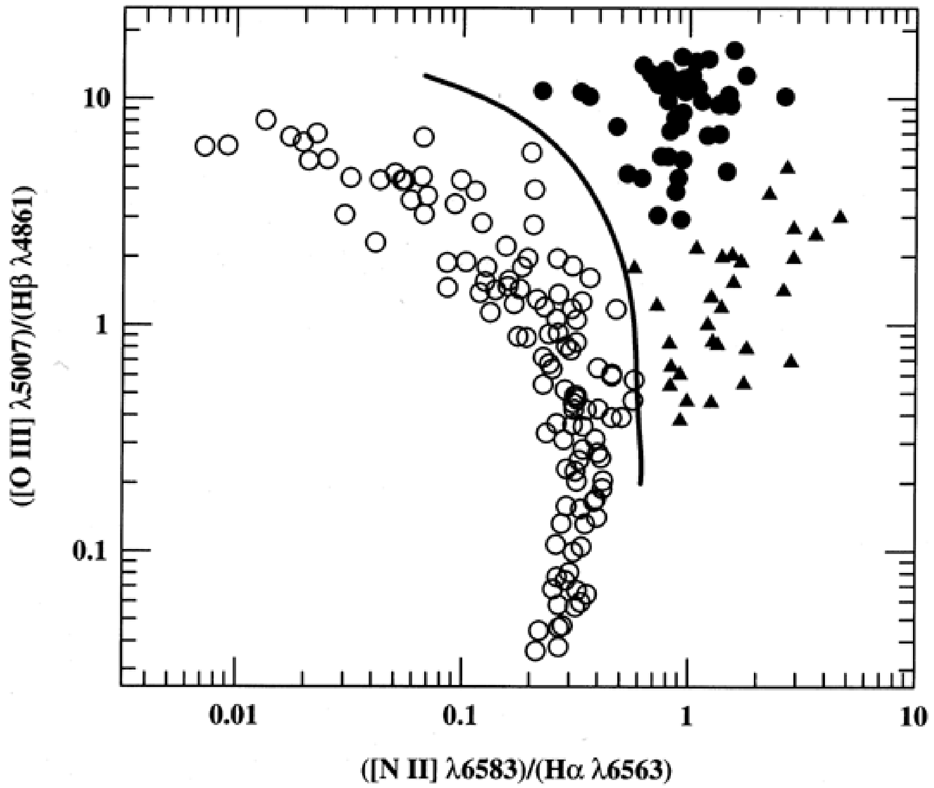
Importance of Emission Lines

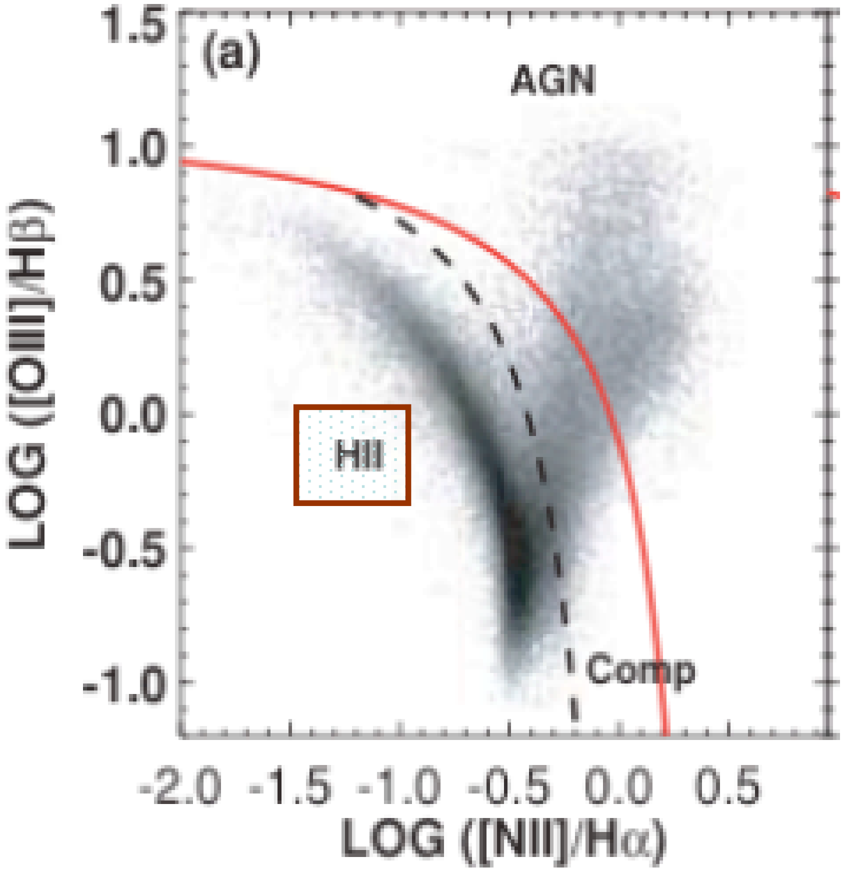
- As one moves on the Hubble sequence the galaxy spectra get more and more emission line dominates and relative prominence of lines changes
- Thus many authors use Hα or OII as SFR indicators (OIII is also produced by active galaxies and so it is often difficult to separate AGN from star formation)



Kennicutt 1998

- 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.



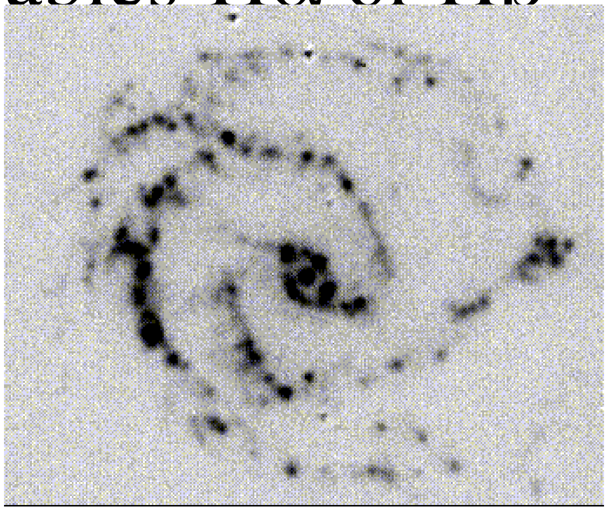


Different lines have different dependences on temperature excitation mechanism (collisions, photoionization)

Ratios of certain lines (chosen to be close in wavelength so 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 Hß

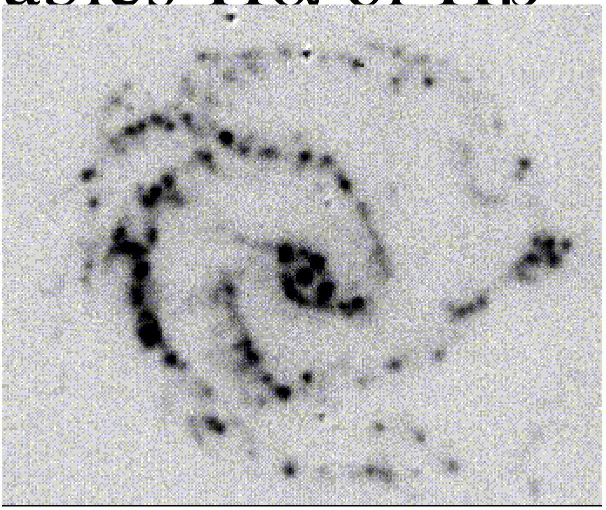


Hα image of a star forming galaxy

- 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.
- Simplifying assumptions: gas of constant temperature, given IMF, gas is internally dust free, Case B (optically thick to ionizing continuum)(Hα/Hβ=2.9)
  - Hα only comes from ionized gas (HII regions)- very non-uniform images (pearls on a string)

- Using stellar models and the Saltpeter IMF one ends up with SFR($M_\odot$/yr)=L(Hα)/7x10^{41} ergs/sec for M>10$M_\odot$ stars or
- SFR($M_\odot$/yr)=L(Ha)/1.1x10^{41} ergs/sec for all stars
- while this seems great, have to worry about dust, the age of the population- the equation assumes a zero age IMF. The older the population is, the less Hα there is- harder to see how much star formation occurred if it has turned off and the system is more than 20Myrs old.

How to Determine SFR from Observables-Hα or Hß



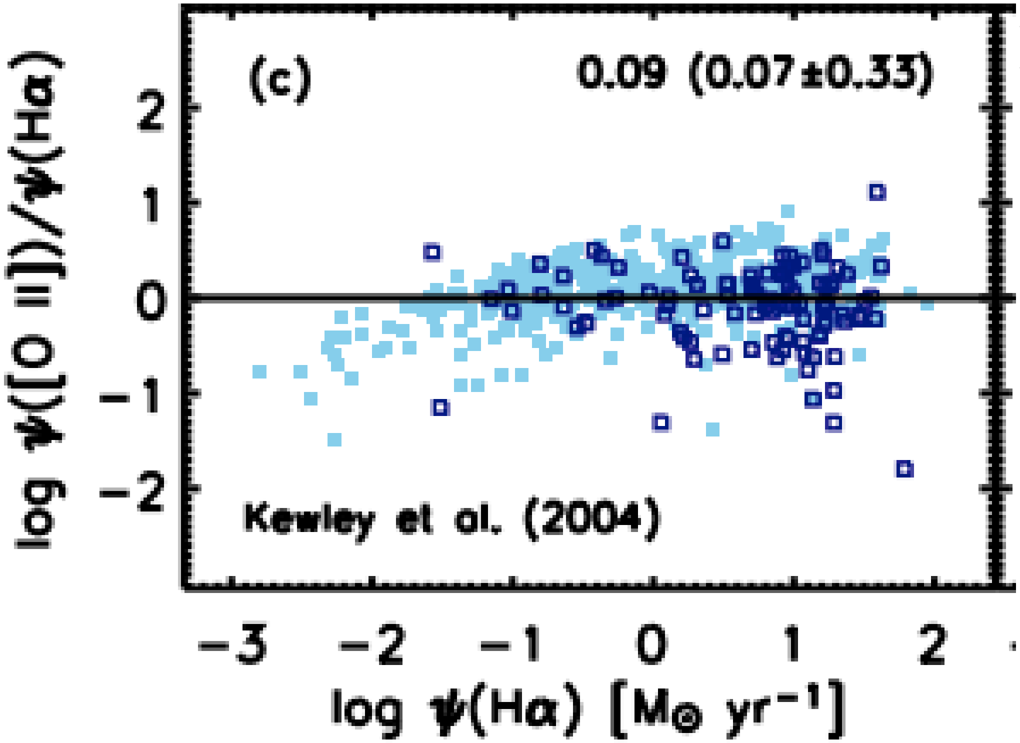
Hα image of a star forming galaxy

- 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 (6563A) and Hβ (4861A), which are strong.
- Only stars more massive than $20M_\odot$ produce an ionizing photon flux.
- In a stellar population formed through an instantaneous burst with a Kroupa IMF 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

How to Determine SFR from Observables-[OII]

- [OII] (a forbidden line, collisionally de-excited in dense gas) is the next most prominent line and is visible until z~1.4 from the ground (Hα is only visible to z~0.4)
- Calibrate it empirically using Hα since its luminosity is not directly coupled to the ionizing continuum (it is collisionally excited, not a cascade from photoionization) - but fairly wide variation in Hα /O[II]makes it noisier.



Ratio of SFR from [OII] to Hα rate vs Hα rate (Moustakas 2006)

Cookbook- Kennicutt

Extinction-Free Limit (Salpeter IMF, $Z=Z_{Sun}$)

SFR (M_o yr^{-1}) = 1.4×10^{-28} L_ν (1500) ergs/s/Hz

SFR (M_o yr^{-1}) = 7.9×10^{-42} L (Hα) (ergs/s)

Extinction-Dominated Limit; SF Dominated

SFR (M_o yr^{-1}) = 4.5×10^{-44} L (FIR) (ergs/s)

SFR (M_o yr^{-1}) = 5.5×10^{-29} L (1.4 GHz) (ergs/Hz)

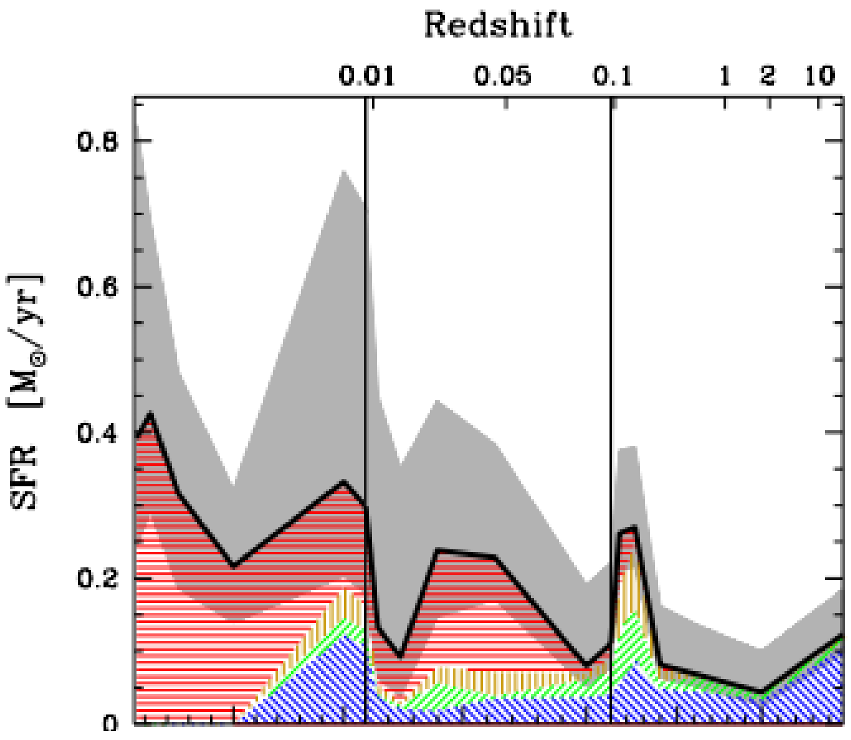
Composite: SF Dominated Limit

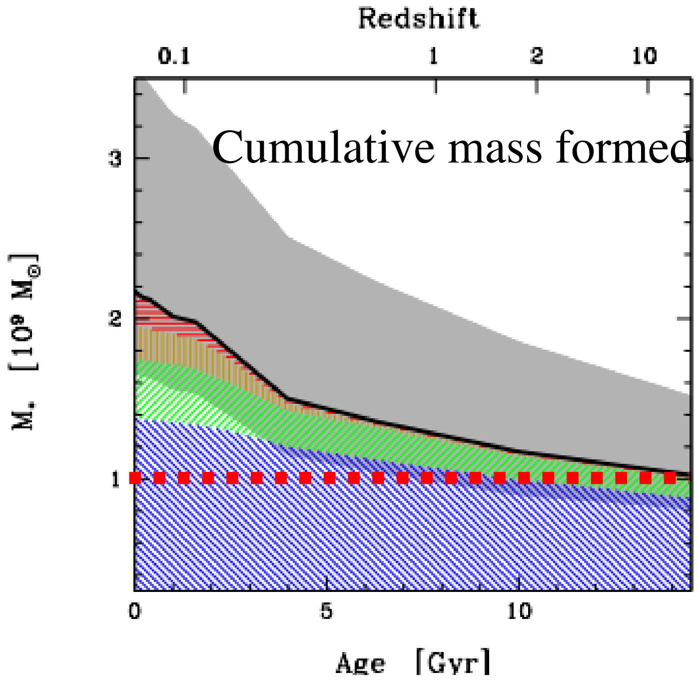
SFR (M_o yr^{-1}) = 7.9×10^{-42} $[L_{H\alpha,\,obs} + a\,L_{24\mu m}]$ (erg s^{-1})
[a = 0.15 – 0.31]

SFR (M_o yr^{-1}) = 4.5×10^{-44} [L(UV) + L (FIR)] (ergs/s)

Uncertainties in Estimating Stellar Masses

- Star formation history- only in a few nearby galaxies can the star formation history be determined
    - e.g. LMC an initial burst of star formation(1/2 mass formed), then a quiescent epoch from ~12 to 5 Gyr ago. Star formation then resumed and continues at an average rate of roughly 0.2 $M_{\odot}$/yr, with variations at the factor-of-two level (Harris and Zaritsky 2010)
- IMF uncertainty: fundamental, factor of 2 in transformation of light to mass (also how many binaries!)
- Metalliticity: less important (30% effect)
- Different stellar evolution codes- can be very important at different ages (factor of 2)
- Spatial variation in SF history/rate

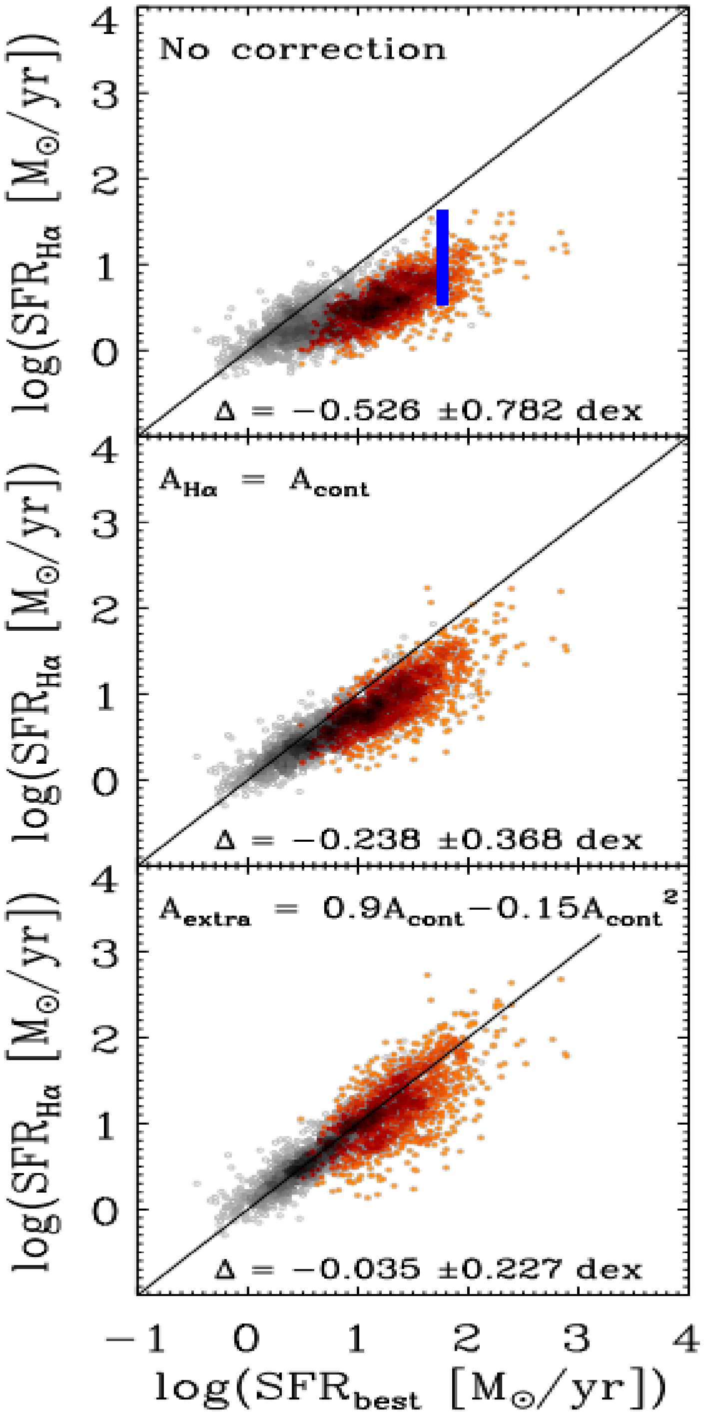




Importance of Dust

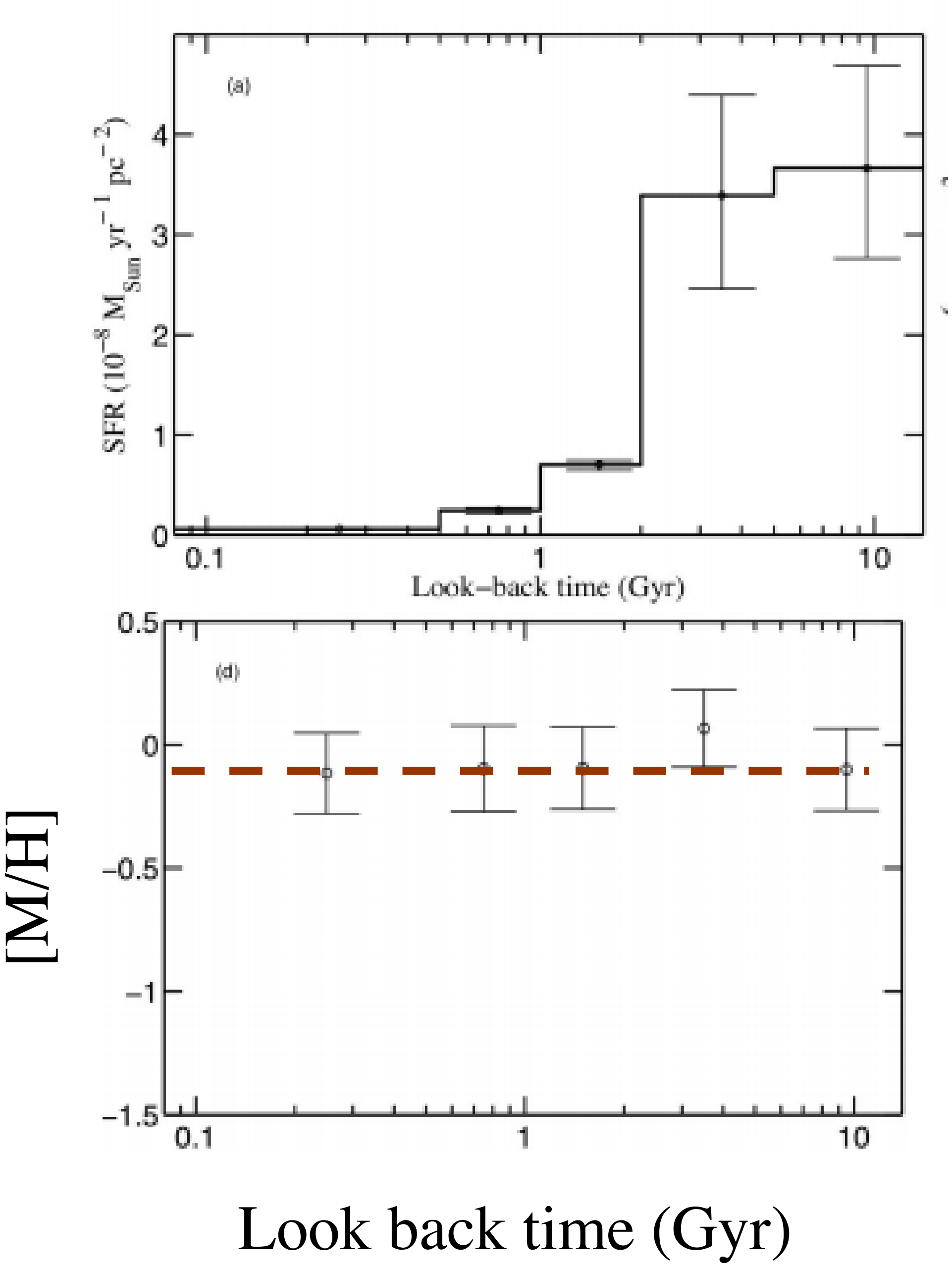
- Correction for effects of dust is crucial in interpreting UV or optical SF indicators (Wuyts et al arxiv 1310.5702)

- Top panel shows inferred SFR from Ha vs those from multi-wavelength fits (including IR, optical, UV)-solid line is equality
  - at high SFR rates errors can be a factor of 10
  - using a simple A_v correction from the continuum reddening still leaves a systematic error (homework problem !- e.g. the connection between reddening and extinction is geometry dependent)
  - an empirical extinction correction can work... how to justify it?



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
- ~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 (another lecture)
- M31 has yet another history the stellar populations of the inner regions of the disk and spheroidal components of M31 are older and more metal-poor than M32



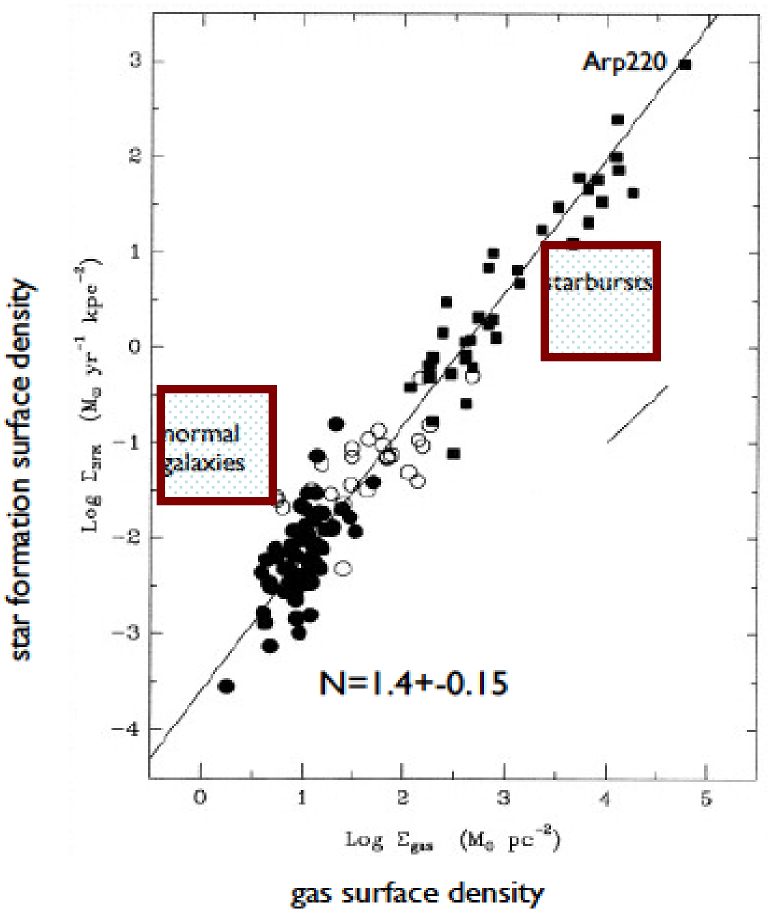
Kennicutt Schmidt Law

- Assume that SFR rate is proportional to total amount of gas
- SFR~ρ_{gas}~$d\rho_{gas}/dt$; sol't ρ_{gas} ~$\rho(0)_{ga}e^{-t/\tau}$

- More generally assume SFR~ρ^{n}_{gas-}
- e.g. as gas compresses stars form more easily or there maybe another timescale in the process such as the free-fall time of the gas SFR~$\rho_{ga}/t_{freefall}$
- **Frequently this expressed in terms of surface density (an observable)**
- $\Sigma_{SFR}=A\Sigma^{n}_{gas}$ n~1.4 can be explained by

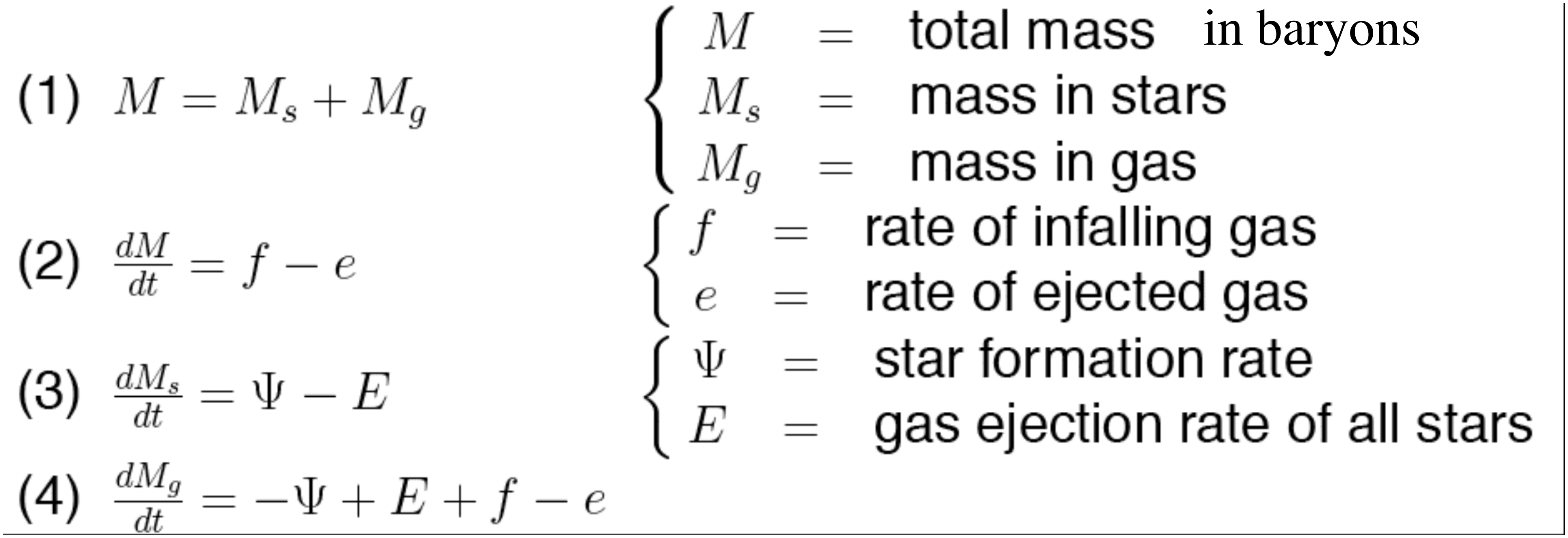
stars form with a characteristic timescale equal to the free–fall time in the gas disk, which in turn depends inversely on the square root of the gas volume density, τ_{ff} ~$\rho^{-1/2}_{gas}$ **for a fixed scale height** ρ_{gas} ~Σ_{gas}

gas consumption efficiency is low ~$1.5x10^{9}$yrs to convert the gas into stars



Kennicutt 1998

Basic Equations of Star Formation- see S+G 4.3.2



(1) $M = M_s + M_g$

(2) $\frac{dM}{dt} = f - e$

(3) $\frac{dM_s}{dt} = \Psi - E$

(4) $\frac{dM_g}{dt} = -\Psi + E + f - e$

M = total mass in baryons
M_s = mass in stars
M_g = mass in gas

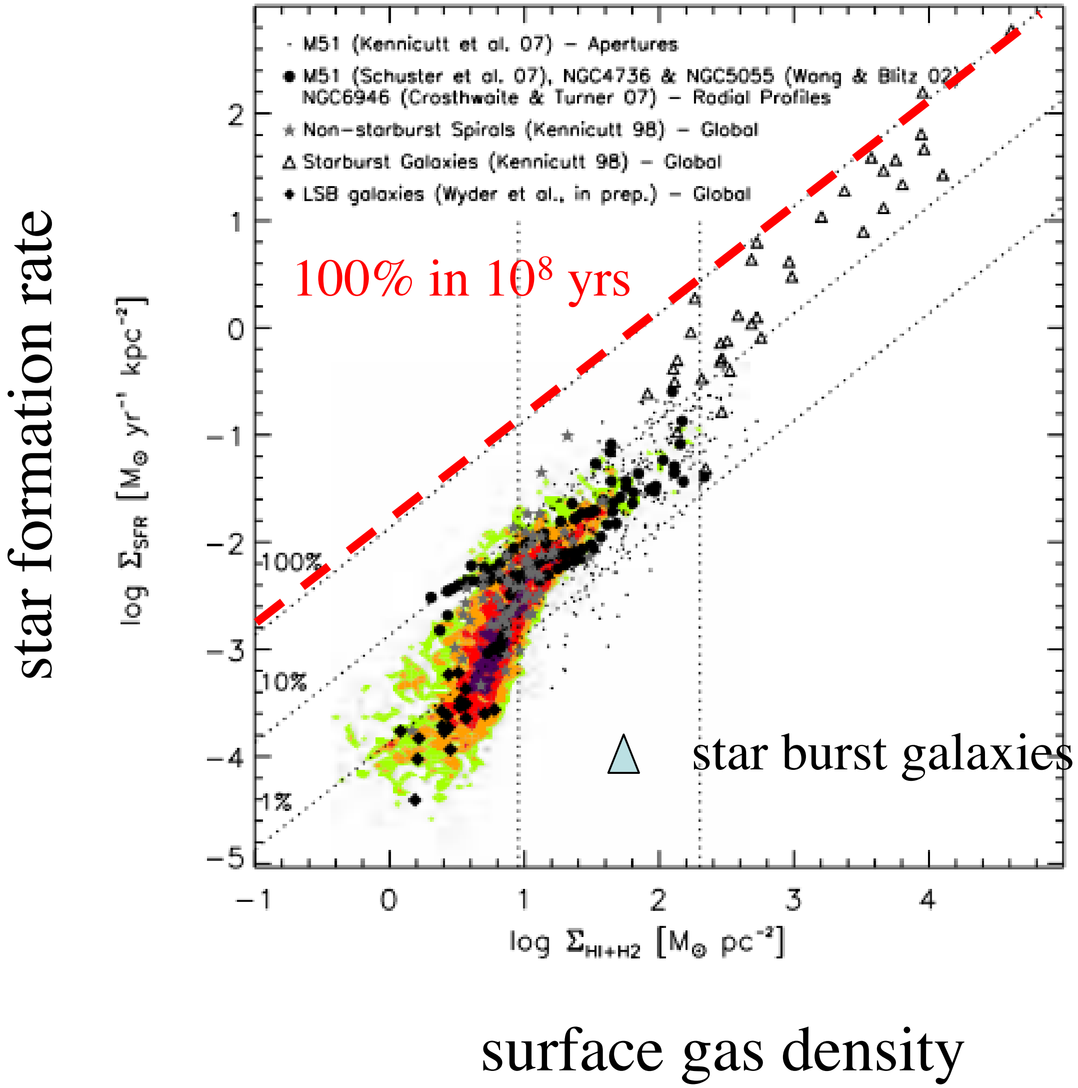
f = rate of infalling gas
e = rate of ejected gas

Ψ = star formation rate
E = gas ejection rate of all stars

- D. Elbaz; based on Tinsley 1980, Tinsley 1980, Fund. Of Cosmic Physics, 5, 287-388; Maeder 1982

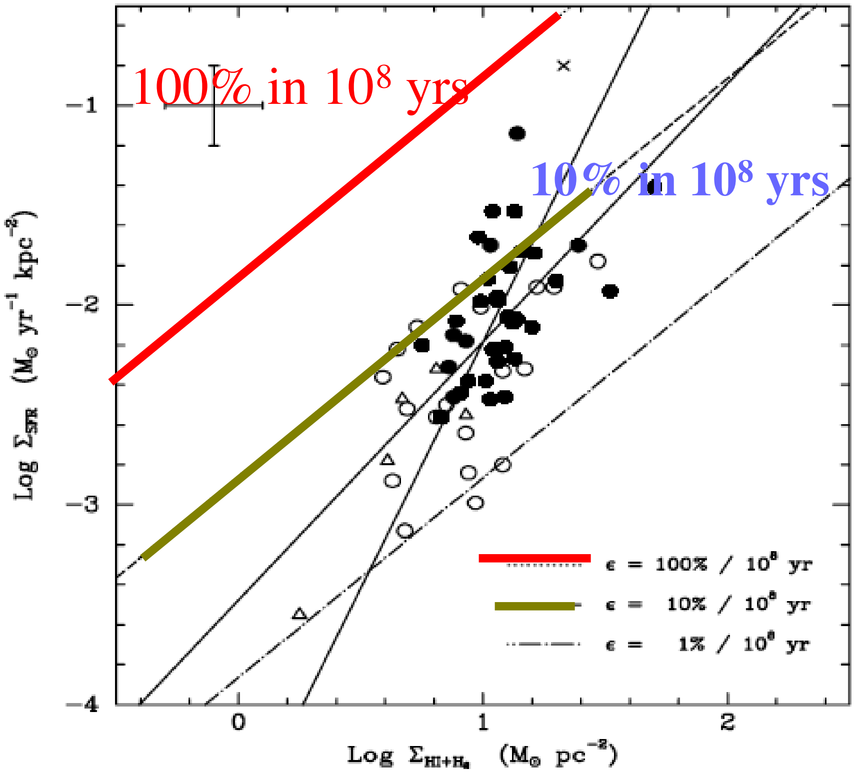
Kennicutt Law with Starbursts

- 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.



How Long Does the Gas Last

- SF in normal galaxies uses 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% (but changes a lot as a function of 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.
- In terms of the average gas depletion timescale, ~ is 2.1 Gyr.
- Recycling of interstellar gas from stars extends the actual time scale for gas depletion by factors of 2–3



surface mass density of star formation

surface mass density of gas ($HI+H_2$)

Relationship for 'normal' star formatio

Kennicutt 1998

How Long Does the Gas Last- Star Bursts

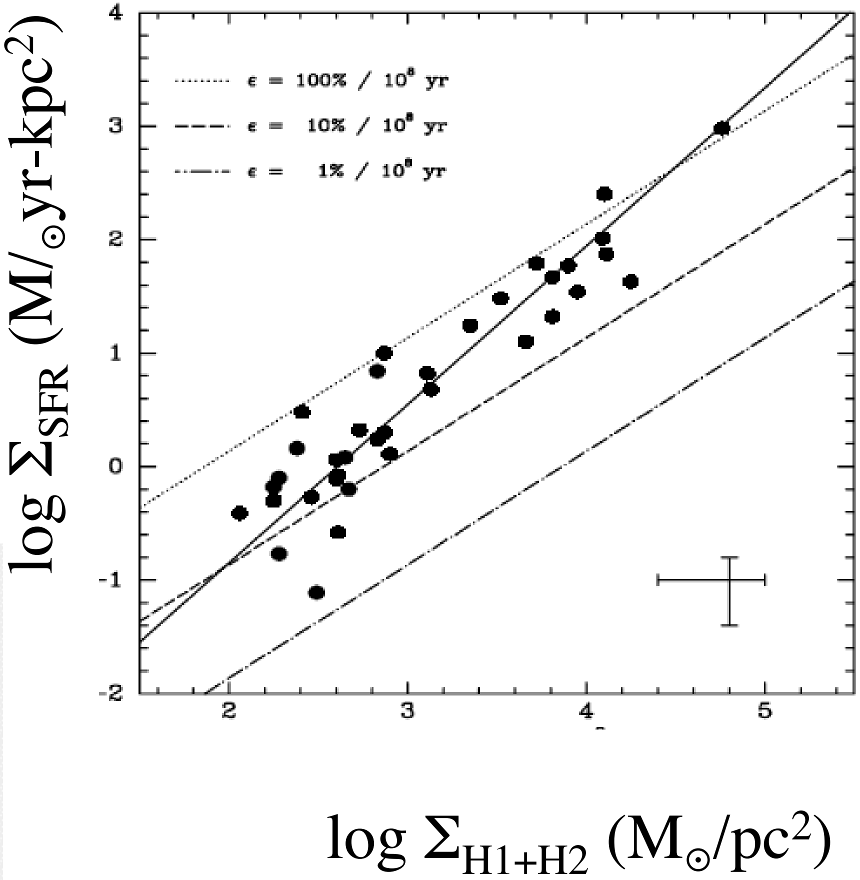
- Starbursts use up their gas much faster
- <30%> of gas used every 10^8 yr
- Depletion timescale≈ 0.3 Gyr
- How luminous are these objects?

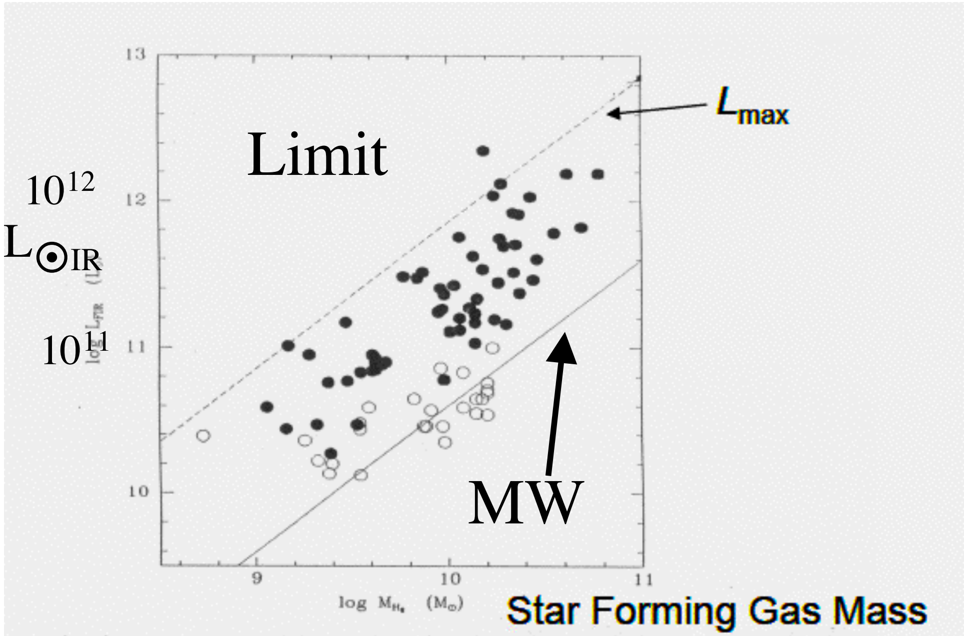
SFR_{max}~100M/yr(Mgas/$10^{10}M_\odot$)(10^8yrs/Δt_{dyn})

Now nuclear fusion is ~0.7% efficient the fraction of rest mass convert to energy for a Saltpeter IMF is ε~0.05 during 10^8yrs

This gives L_{max}~0.07ε(dM/dt)c^2

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





Possible Star Formation 'Laws'

- Define star formation efficiency $SFE=\Sigma_{SFR}/\Sigma_{gas}$
- to form stars in in spirals need
  - cold phase ($n \sim 4–80$ cm^{-3}, $T \sim 50–200$ K)
  - and gravitationally bound clouds
- A star formation law *should* predict the SFE from local conditions (physics)

1) Kennicutt-Schmidt law $\Sigma_{SFR} \sim \Sigma_{gas}{}^{1.5}$

- stars form on a characteristic timescale equal to the free-fall time in the gas disk, $\sim\rho^{-1/2}$
- since $\rho_{gas} \sim \Sigma_{gas}$ and $\Sigma_{SFR} \sim \Sigma_{gas}{}^{1.5}$
- expect $SFE \sim \Sigma_{gas}{}^{0.5}$

Disk free-fall time : if scale height of disk set by hydrostatic equilbrium then $t_{ff} \sim G\rho^{-1/2}$ related to the velocity field and density of stars and gas

or some other timescale such as orbital timescale such as orbital timescale $t_{orb}=\Omega/2\pi=2v(r)/2\pi r$

or perhaps gravitational instability - gas unstable against collapse when Toomre $Q=\sigma_g\kappa/\pi G\Sigma_{gas}<1$;κ is the epicyclic frequency; velocity dispersion of the gas σ_g

Is Q Important?

- SFR and Q are anti-correlated

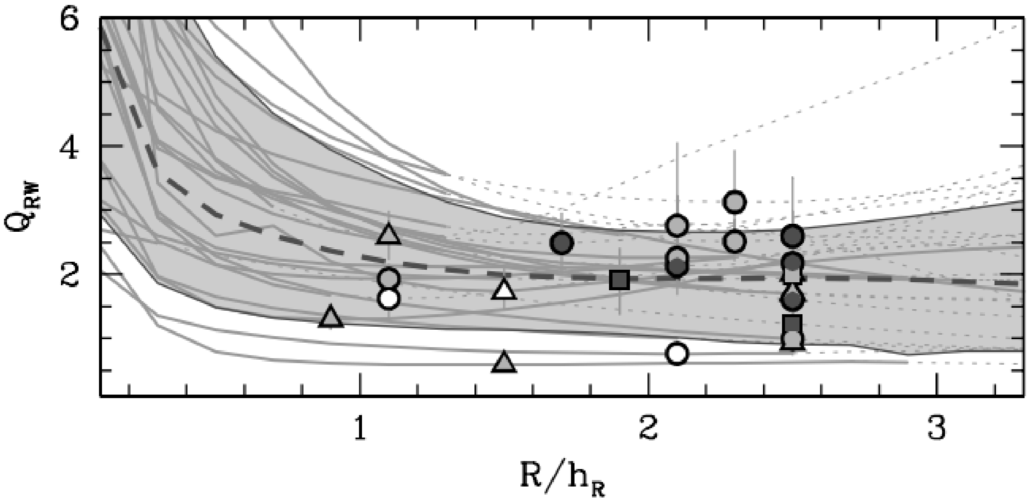
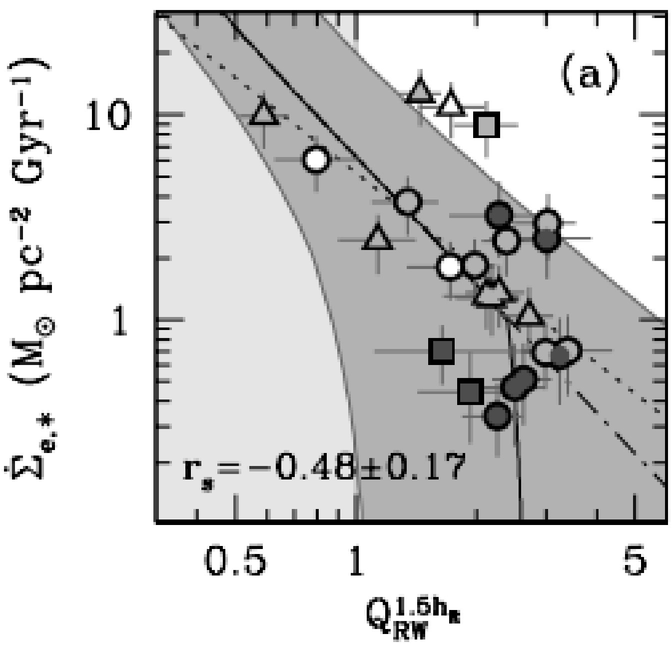


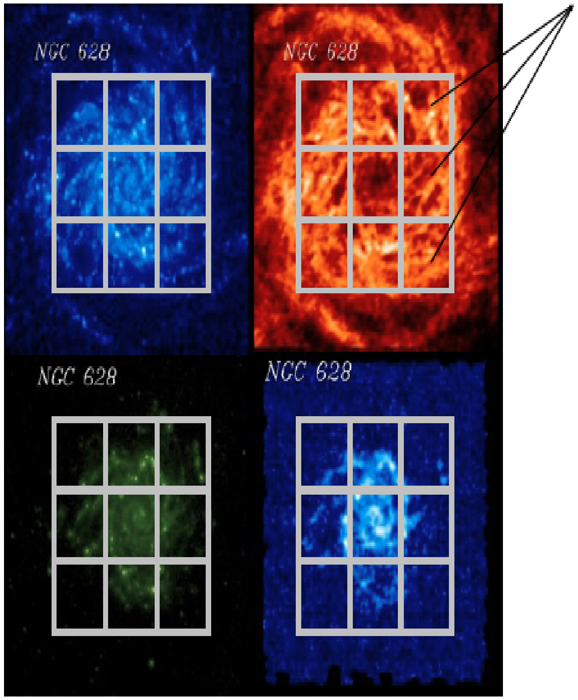
Figure 1. The two-component disk stability, Q_{RW}, as a function of R/h_R from the dynamical model of each galaxy. The profile for each galaxy transitions from the solid- to dotted-gray lines at the radius when the model is no longer directly constrained by our LOS stellar velocity dispersions, only by the rotation curves. m Q_{RW} within 2.5 h_R, Q_{RW}^{min}, is marked for each galaxy: light-gray is ” and “c” type spirals; white and dark-gray are used for earlier and types, respectively. Circles, triangles, and squares are for unbarred (S), d (SAB), and barred (SB) galaxies, respectively. The dark-gray dashed edian Q_{RW} from the marginalized distributions at each R/h_R, and the gion is the 68% confidence interval.



The Stability of Galaxy Disks
arxiv 1310.4980
Westfall,1 et al

Kennicutt-Schmidt Updated

- SFR depends on surface density of molecular gas
- (red points are averages, **gray points are individual samples in galaxies)**



Local...

HI Surface Density

H_2 Surface Density

Stellar Surface Density

Star Formation Rate

Rotation Velocity

Gas Velocity Dispersion

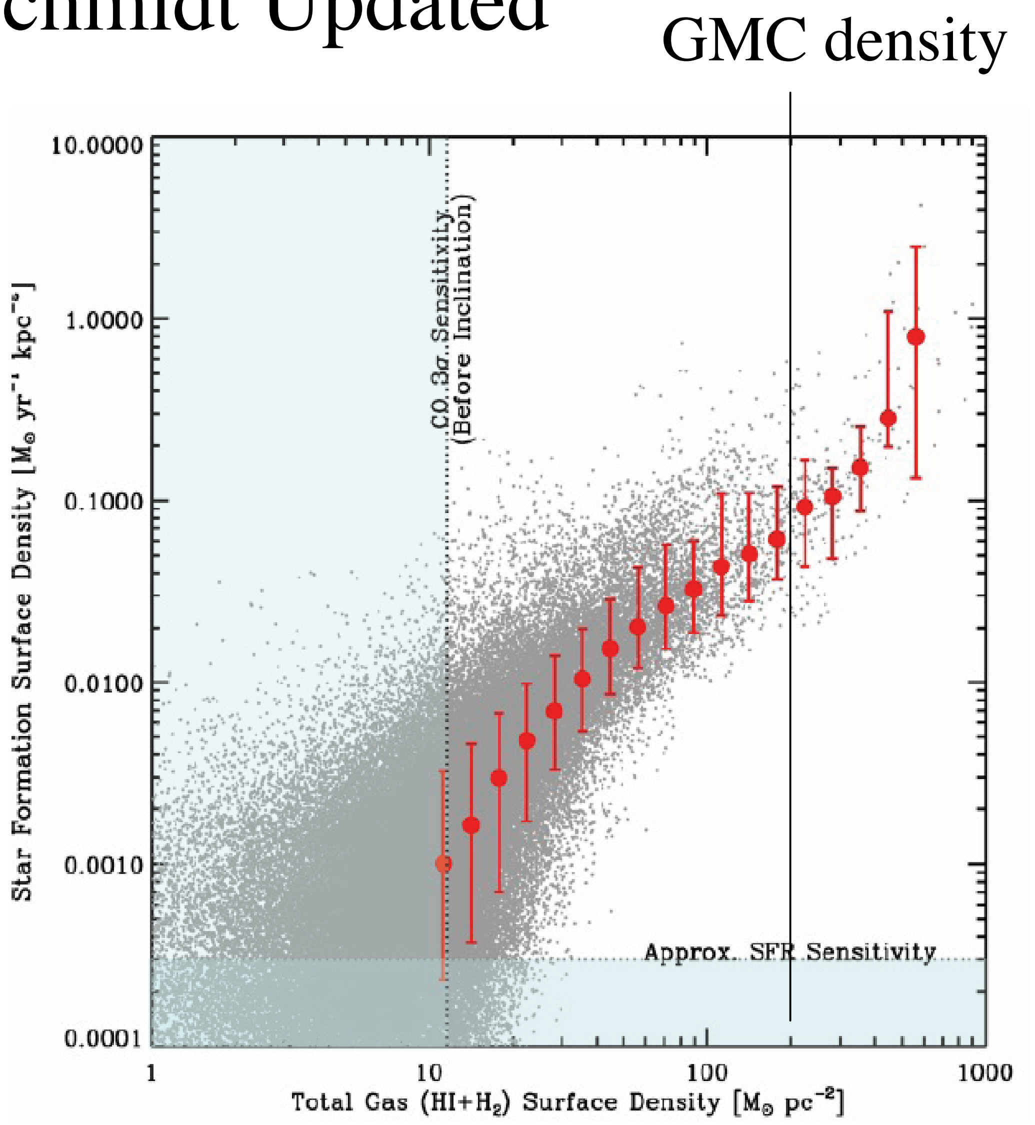
Stellar Velocity Dispersion

Dust-to-Gas Ratio

Radiation Field

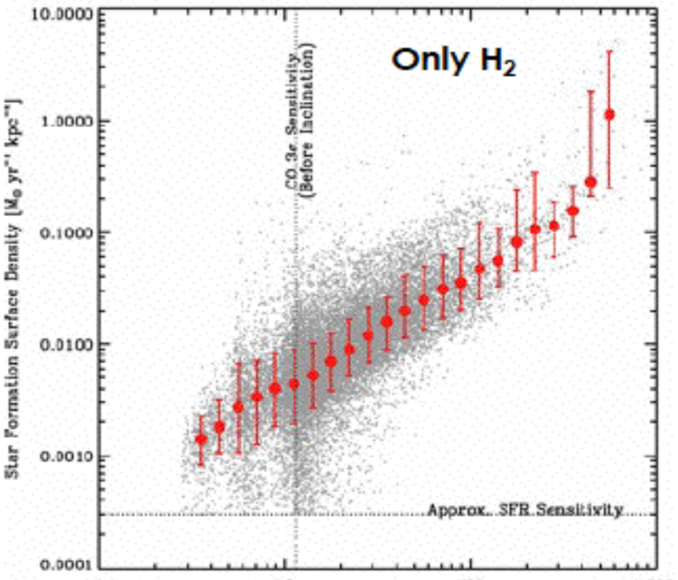
Midplane Pressure

F. Walter

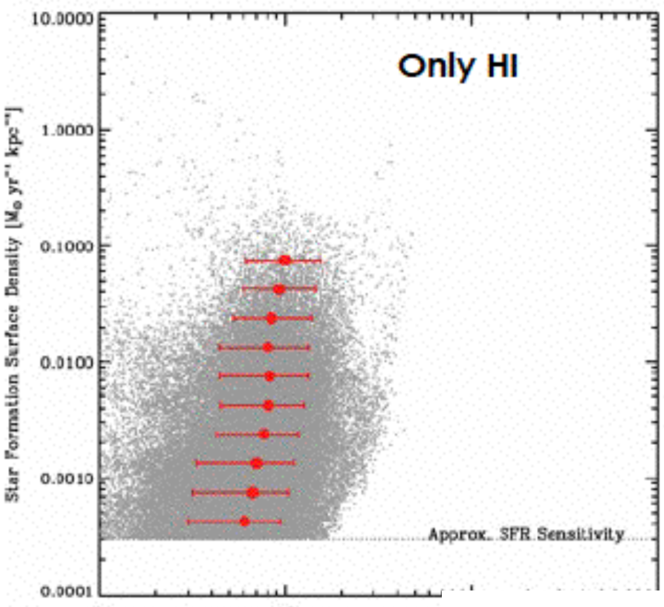


Only H_2 Counts

Bigiel et al. 2008/10, Leroy et al. 2008/11



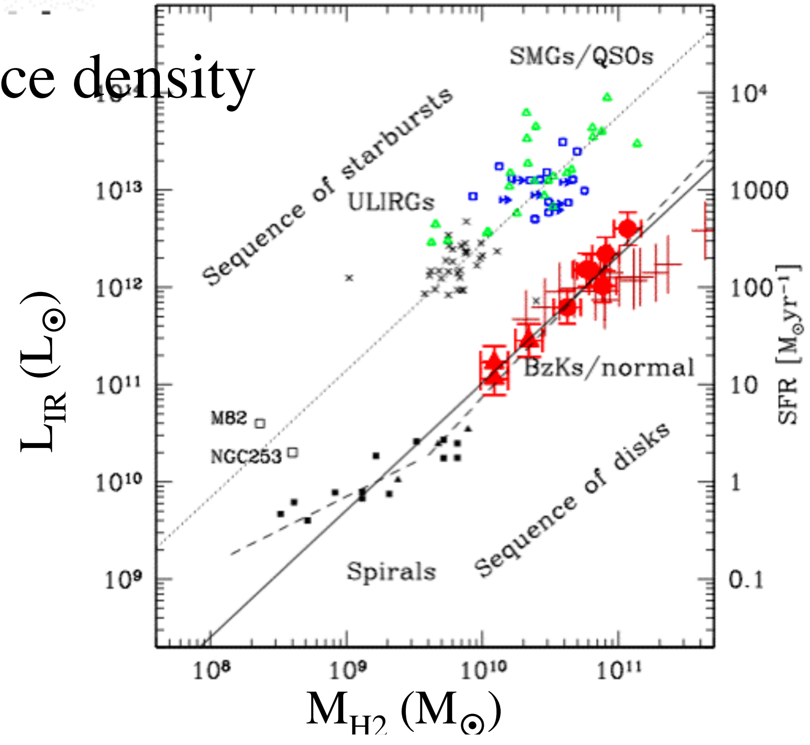
H_2 Surface density



HI Surface density

stars seem to form only in dense molecular gas...

- 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

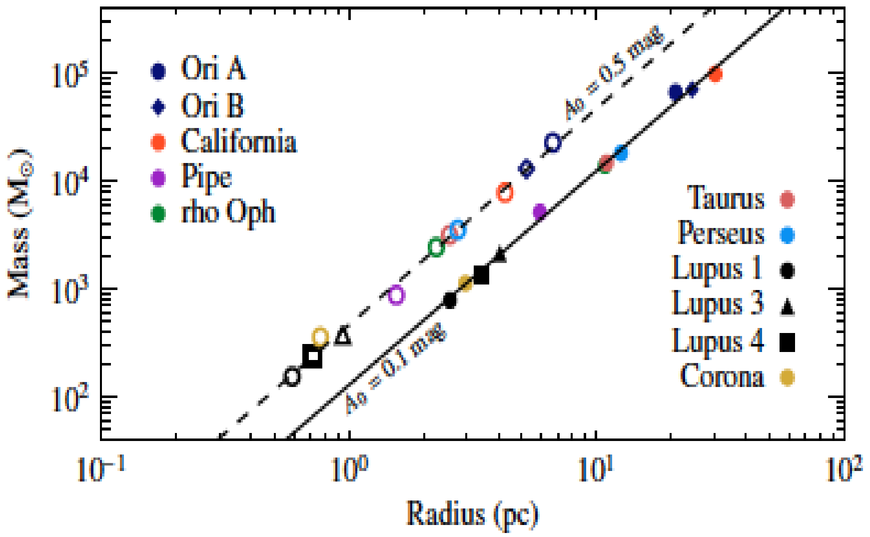


Star formation Occurs in Giant Molecular Clouds

- 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 .
- The effects of feedback (e.g. stellar winds and SNR) are not at all clear

Molecular Clouds

- this is a vast subject with lots of details- see MBW sec 9.1-9.2
- As the gas density increases the fraction that is molecular increases rapidly (a sharp transition)- H_2 forms on dust grains when it is cold
- These clouds are in rough virial equilibrium $2GM/\sigma^2=R$, $M\sim R^2$, $\delta V\sim R^{1/2}\sim\rho^{-1/2}$
- $M\sim10^5\text{-}5\times10^6 M_\odot$, r ~10's pc $n_{H2}\sim100\text{-}500\text{cm}^{-3}$ but there is a lot of structure, in protostellar cores density much higher
- Cold T~10k in MW) - UV light cannot penetrate- heating by Cosmic rays (?)- quite turbulent
- Strongly associated with young star clusters- short lived (?) $t\sim10^7$ yrs



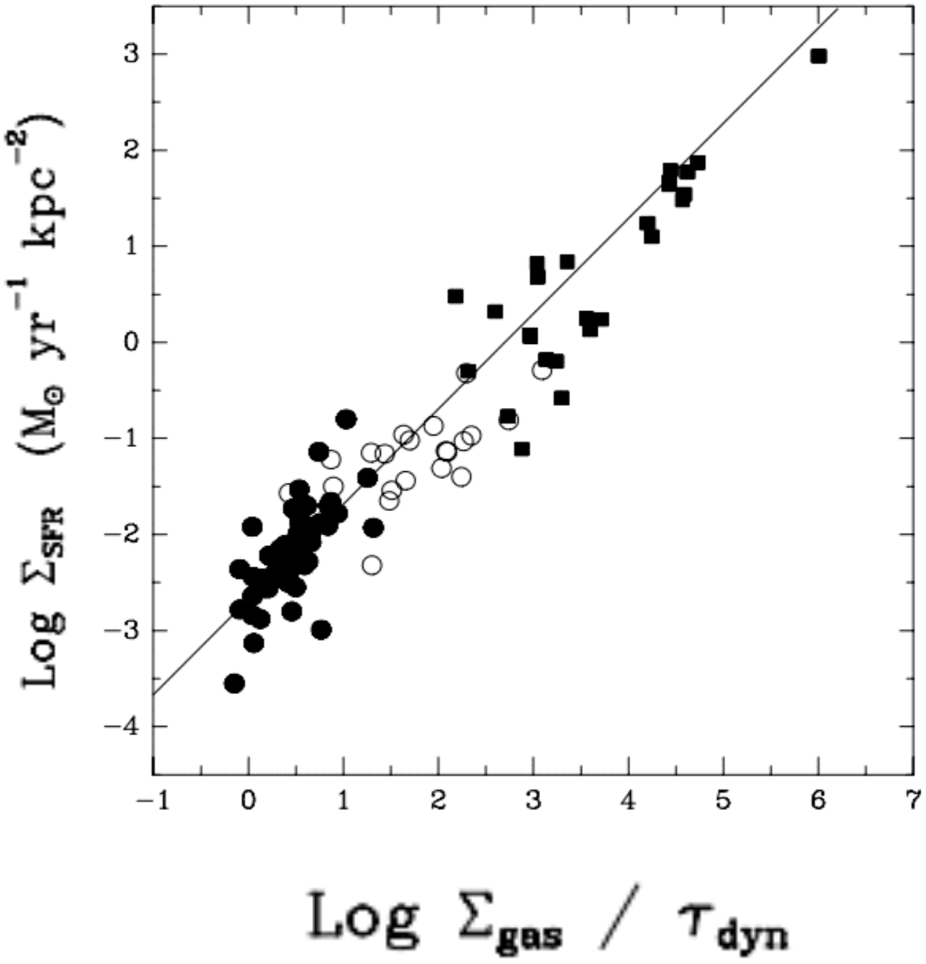
If self gravitating isothermal spheres collapse if mass exceeds the Jeans mass

$M_j\sim40M_\odot(c_s/0.2\text{km/sec})^3\,(n_{H2}/100)^{-1/2}$

which they do by a lot~!
collapse on free fall time
$t_{ff}=(3\pi/32G\rho)^{1/2}\sim3.6\times10^6\,(n_{H2}/100)^{-1/2}\text{yrs}$

Kennicutt Schmidt Continued

- What other scaling relations seem to hold?
- Kennicutt shows that Σ_{SFR} is also correlated with $\Sigma_{gas}/\tau_{dynamical}$ in a galaxy sample (but not inside a galaxy!)
- where $\tau_{dynamical}$ is the orbital time at the radius of the star forming region $2\pi R/V_{rot}(R)$
- In a disk galaxy there is another restoring force (other than pressure) which is important for the Jeans criterion- conservation of angular momentum (Coriolis force)
- Perturbations are unstable to gravitational collapse if
- $Q=c_s\kappa/pG\Sigma_{mass}<1$ where κ is the epicyclic freq (MBW 9.10)
- The K-S $\tau_{dynamical}$ law follows if Q<1 (Silk)



Criteria for Collapse

- Jeans Criterion for collapse of spherical cloud
- Gravitational instability sets in if the free-fall time is less than the sound crossing time
- $t^2_{ff}=1/G\rho<(R/c_s)^2=10^8 n^{-1/2}_H$ yrs; free fall time from $d^2r/dt^2=-GM/r^2$;n_H is the number density of gas, c_s is the sound speed ; 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 length $\lambda_J=\mathrm{sqrt}(\pi c_s{}^2/G\rho)$

For typical values

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

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

c_s= sound speed=$\mathrm{sqrt}(dP/d\rho)=\mathrm{sqrt}(\gamma k_B T/\mu m_H)$ 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.

Gravitational Instability

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

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

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

Forming Molecular Clouds-MBW sec 9.2

- The Jeans criterion :a perturbation will grow if its self-gravity overpowers the internal pressure.
- However, in a disk galaxy, pressure is not the only restoring force.
- Unless the galaxy's circular velocity scales as $V_{cirular} \sim R^{-1}$, conservation of angular momentum forces a perturbation to rotate.

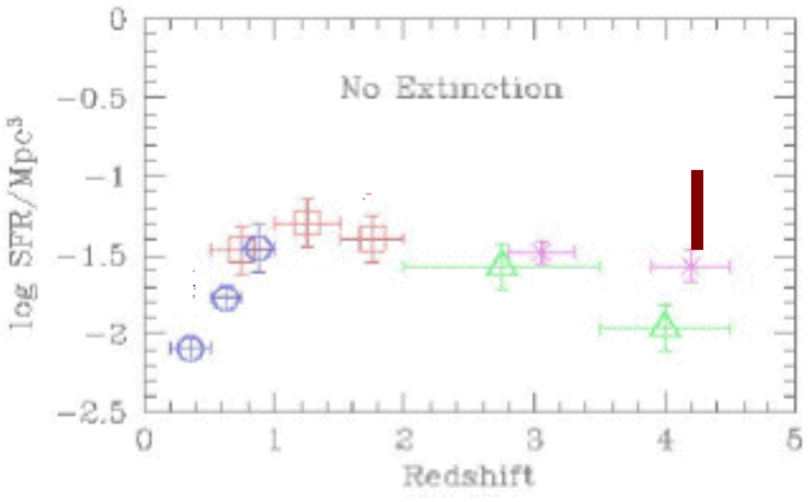
The resulting Coriolis force provides support against collapse.

MBW sec 11.5.2 shows that a rotationally supported disk is unstable against gravitational collapse if the Toomre parameter

- $Q=c_s\kappa/\pi G\Sigma < 1$, c_s is the sound speed and κ is the epicycle freq, Σ is the surface density of the disk (remember that $\kappa=\sqrt{2}$ sqrt $[(V^2_{cirular}/R^2)+(V_{cirular}/R)dV/dR]$
- near sun $\kappa^2 \sim 36$ km/s/Kpc
- If Q<1 only perturbations of critical wavelength
  $\lambda_{crit}<2\pi^2 G\Sigma/\kappa^2$ will collapse (~1kpc)
  which have a mass $M \sim \pi\Sigma(\lambda^2_{cri}/2)^2 \sim 2.4\times10^7 M_\odot(\Sigma/30M_\odot pc^{-2})$- this is much larger than the mass of molecular clouds

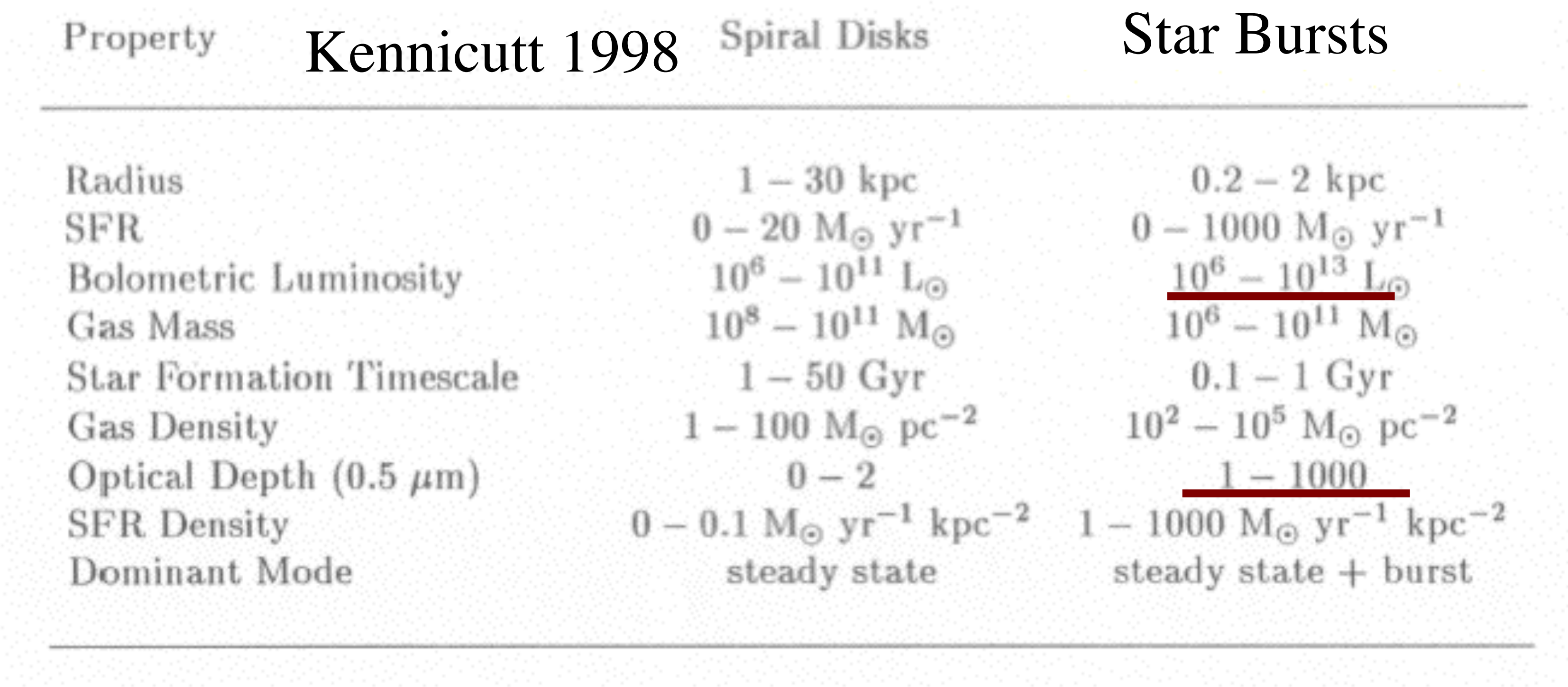
Dust

- 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	$10^6 - 10^{11}$ $L_\odot$	$\underline{10^6 - 10^{13}\ L_\odot}$
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	$\underline{1 - 1000}$
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

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

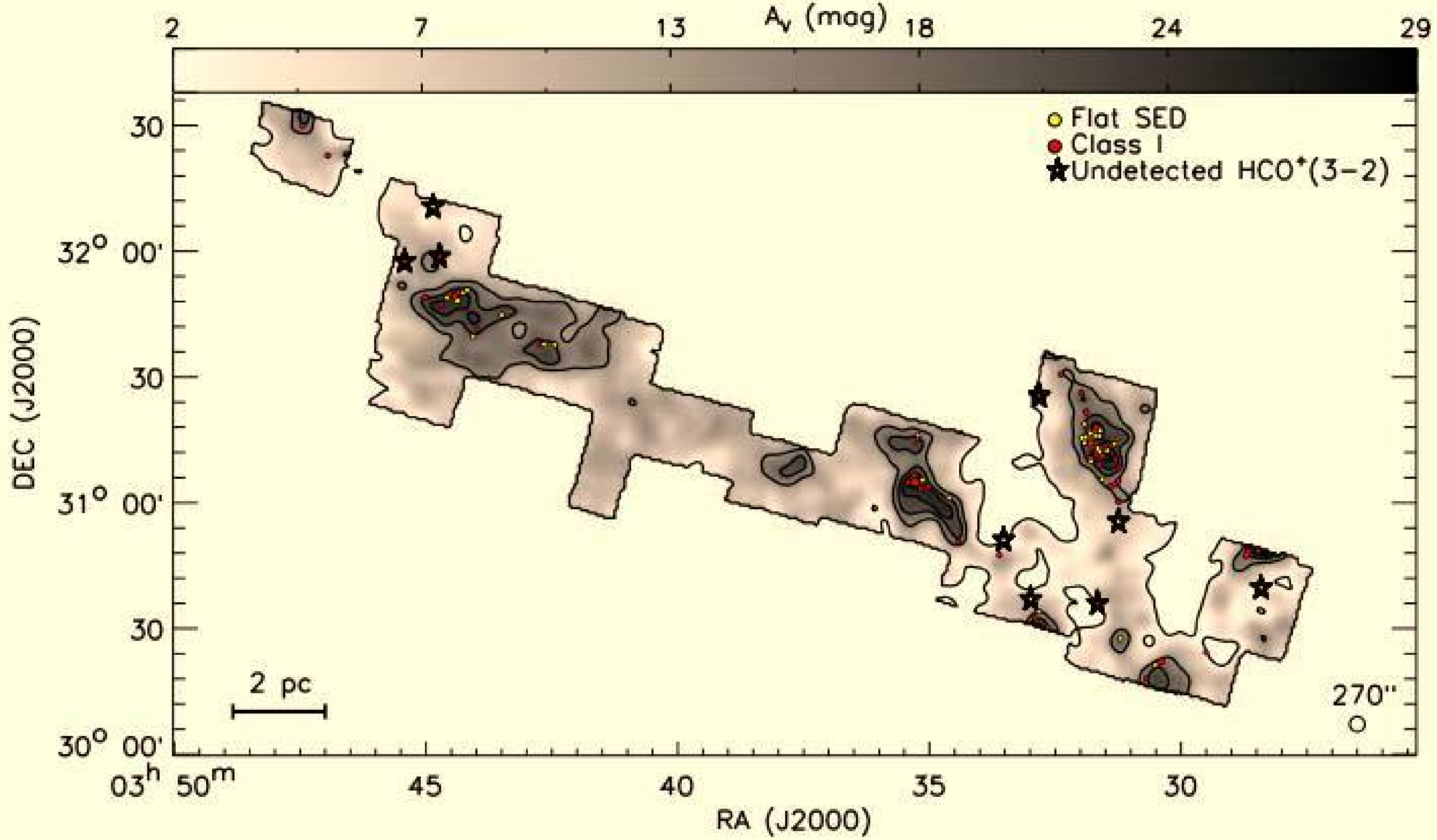
  $R_{\mathrm{Jeans}} \sim \sigma^2/G\Sigma$

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

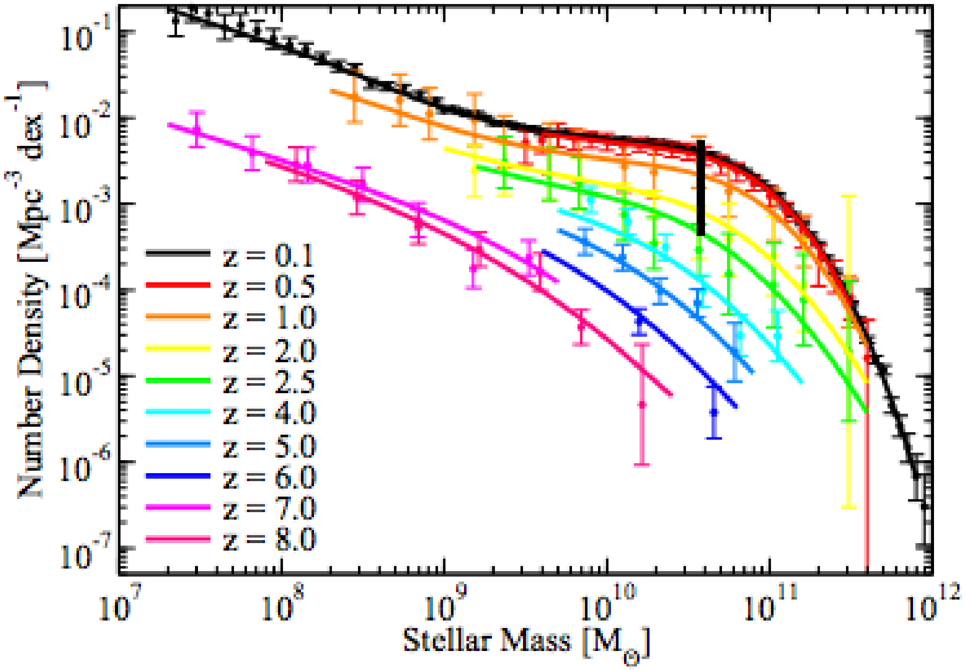
In Perseus molecular cloud all the young stars lie in very dusty regions

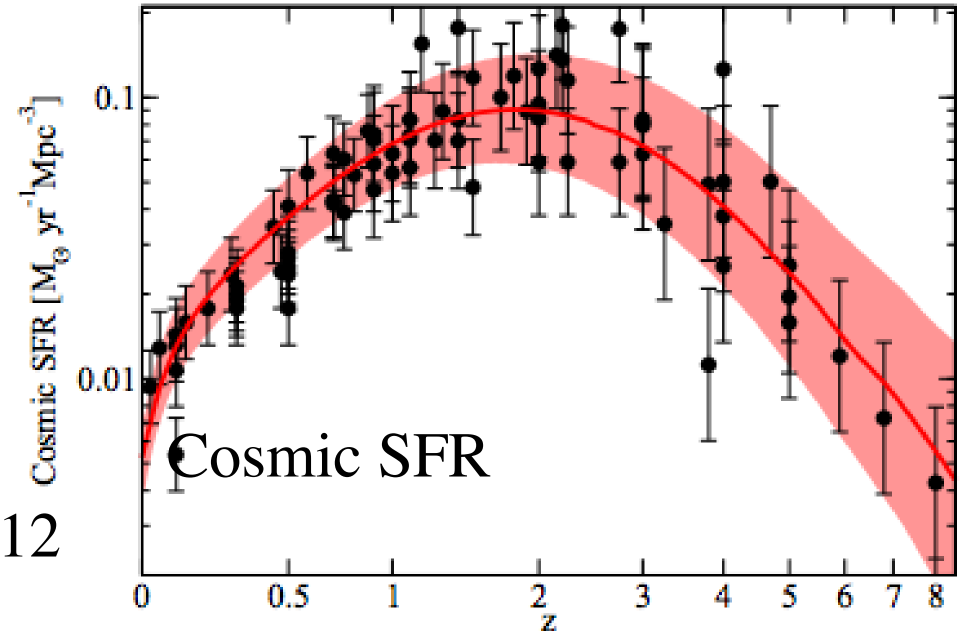
Cosmic History of Star Formation
General Results

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

- •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 massive galaxies at the time
- Effects of dust are dominant at z>3 *and results are uncertain…*

Growth of galaxies



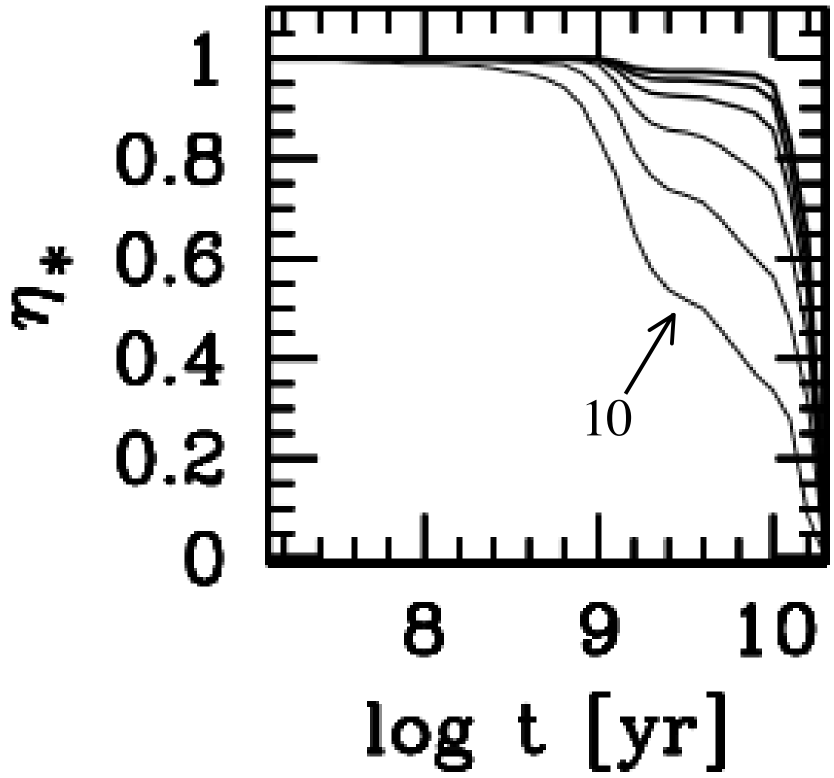


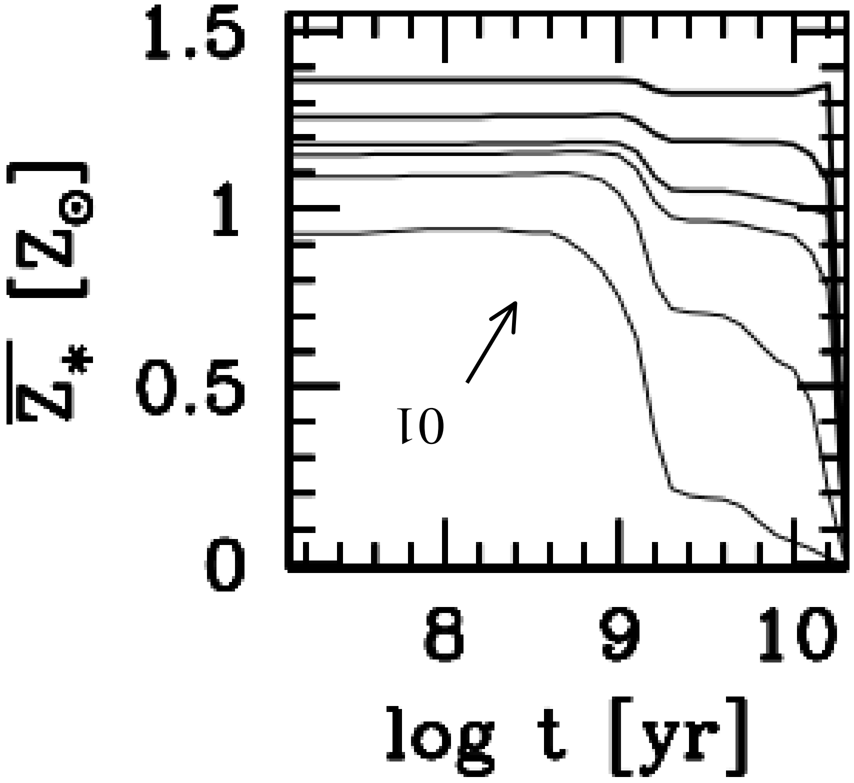
Cosmic SFR

Behroozi et al 2012

Results from Stellar Paleontology

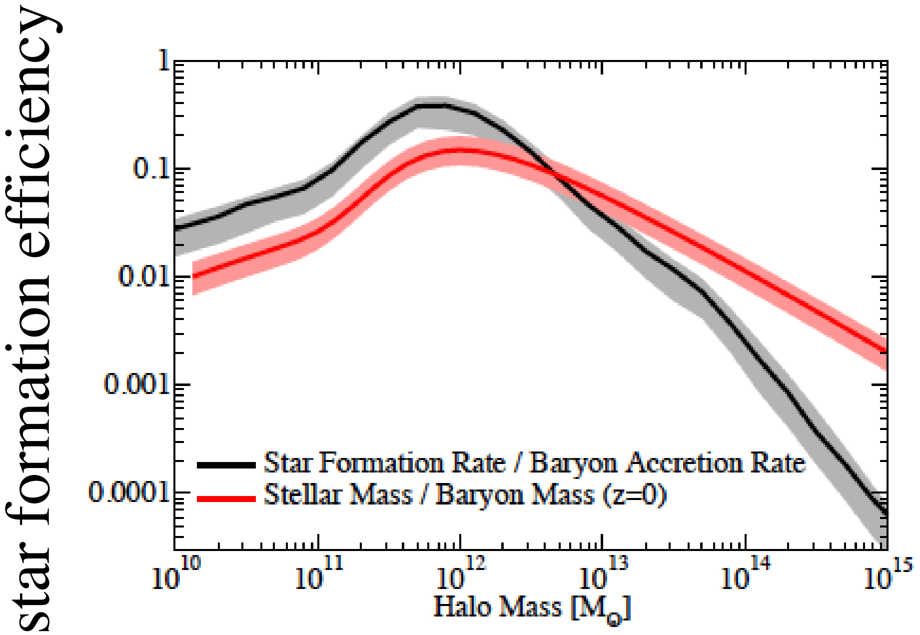
- History of stellar growth in **6 mass bins 10, 10.3, 10.6, 10.9, 11.2, 11.5 vs time** - *big objects form first, evolve rapidly and then remain the same for long times* (Vale Asari et al 2009) and metallicity Z_*





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 (Silk 1977; Rees & Ostriker 1977; Dekel & Silk 1986; White& Rees 1978; Blumenthal et al. 1984).
- 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



Star Formation Efficiency Vs Galactocentric Radius

- Where H_2 dominates HI SFE is roughly constant and declines exponentially at larger radii.
- where the ISM is mostly H2 in

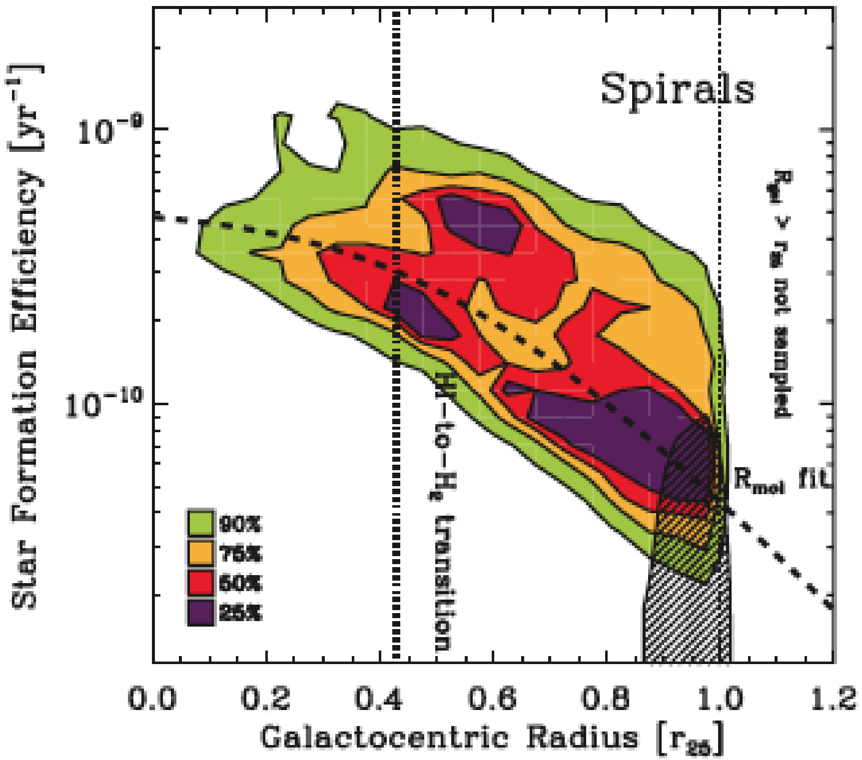
spiral galaxies, the SFE does not vary strongly with any of the obvious

quantities : including radius, Σ_{ga}, Σ_*, Ph, Ωorb,

Summary of results

- Molecular gas, star formation, and stellar surface density all decline with nearly equal exponential scale lengths, ~$0.2r_{25}$, giving the appearance of a long-lived star-forming disk embedded in a sea of HI.
- The ISM is mostly H_2 within ~$0.5r_{25}$ and

where Σ_* >80 M



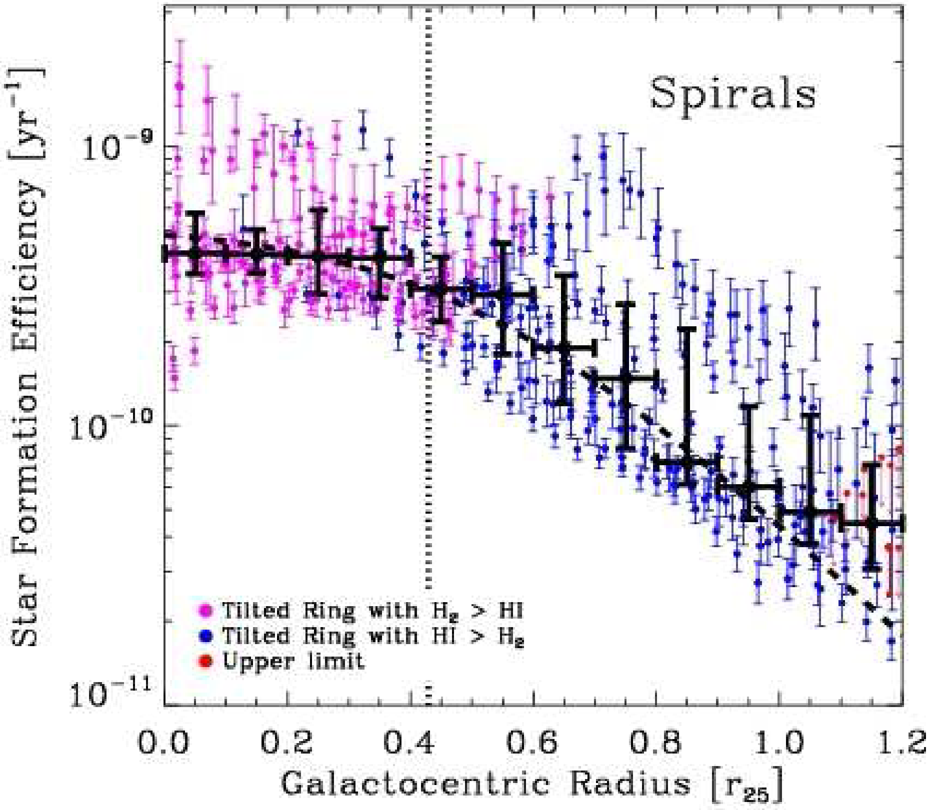
What Does Not Work-Leroy et al 2008

- the disk freefall time for a fixed scale height disk
- orbital timescale
- Rotation curve dependences (e.g. orbital timescales)
- Q_{gas}
- BUT
- SFE (H2) is constant as a function of a range of environmental parameters for disks of spiral galaxies, and **not** starbursts or low metallicity dwarf galaxies.

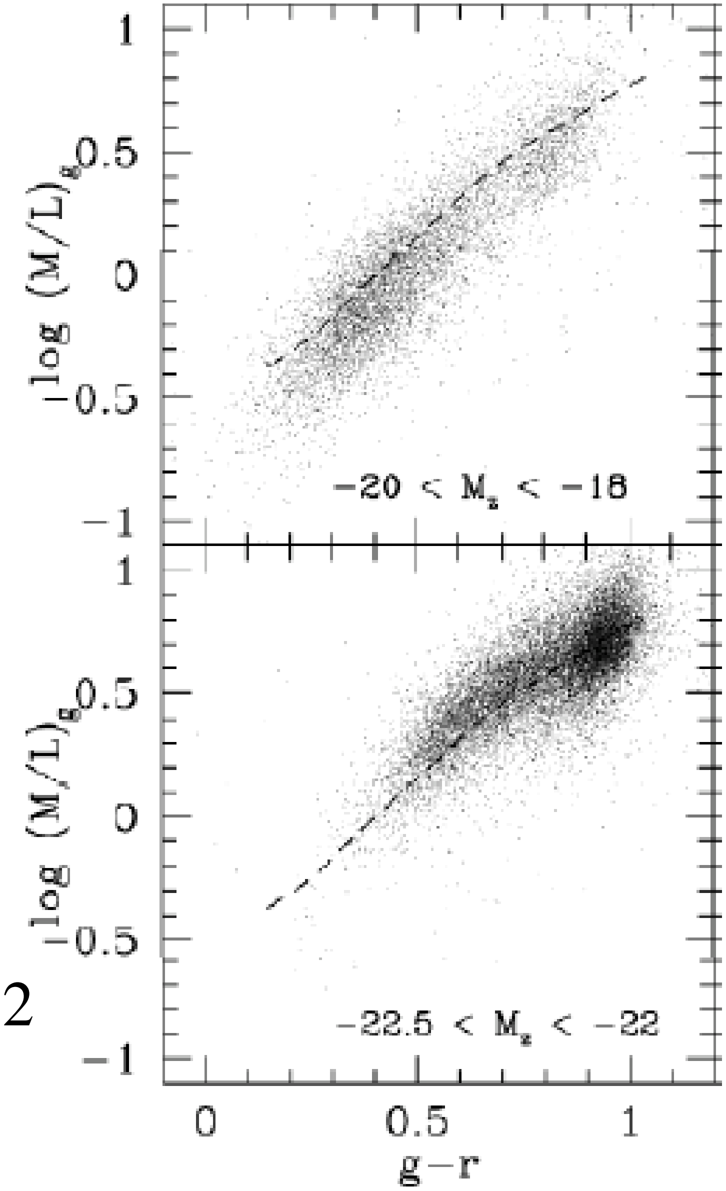
- Despite enormous amount of work at a resolution of 800pc NO unique driver for the SFE, but perhaps
- ISM physics —balance between warm and cold Hi phases, H2 formation, and perhaps shocks and turbulent fluctuations driven by stellar feedback—govern the ability of the ISM to form GMCs out of marginally stable galaxy disk

Star Formation Efficiency Vs Radius and H2/HI

- Leroy et al (2008) show that star formation efficiency (how long it would take to convert all the gas into stars) changes with galactic radius and the relative fraction of gas in H2 and HI.
- Where H_2 is dominant the SFE is constant at about $5x10^{-10}$ or it takes ~$2x10^9$ yrs to convert ALL the local gas into stars.



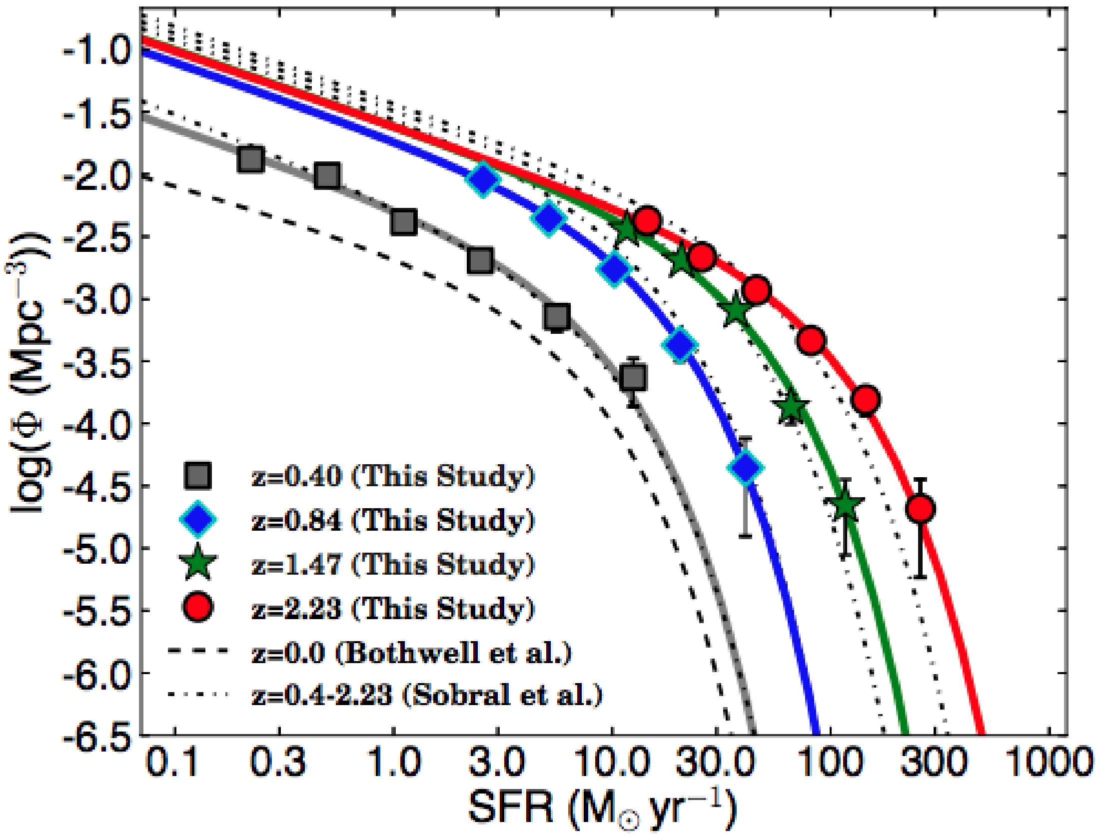
- Integrated colors or spectra
  - – Cannot be robustly inverted to yield f(t_{age},[Fe/H])
  - – (M/L)* can be robustly (better than x2) determined, for assumed IMF
  - – Star formation rates (to ~ x2) can be determined, from Hα, UV, thermal IR



Bell and DeJong 2002

Output From All this Analysis

- Sobral et al 2013(1311.1503.pdf) - which galaxies have which star formation rate as a function of redshift.
- The fraction of stellar mass density contained in star-forming galaxies has been continuously declining from ~100% at z ~ 2.2 to only ~ 20% at z= 0.4, a consequence of the build-up of the passive/quenched population over time.



Closed Box Model

- One-Zone, Closed Box
- – Galaxy’s gas is well-mixed
- – No infall, no outflow

  – $M_{tot} = M_{gas} + M_{star} = M_g + M_s = M_{baryons}$ = constant

  – M_H mass of heavy elements in gas = $Z_g M_g = Z M_g$
- Instantaneous recycling approximation:
- – The (high-mass) stars return their nucleosynthetic products rapidly (much faster than the time to form a significant fraction of the stars)
- – dMs' = total mass made into stars
- – dMs'' = amount of mass instantaneously returned to ISM …………from SNe, etc; enriched with metals)
- – $dM_s = dM_s' - dM_s''$ = net matter turned into stars
- – y =yield of heavy elements (made instantaneously)
- – So $y dM_s$ = mass of heavy elements returned to ISM

Closed Box Model

- Stellar evolution theory says
- Only stars more massive than ~ 8 M_{sun} make heavies (SNe)
- $dM_s'' / dM_s \sim 0.20$ = fraction of mass returned to ISM
- y ~ 0.01 (depends on stellar evolution and Initial Mass Function -IMF)
- Z(shed gas) = (heavies shed) / (mass shed) = $y \, dM_s/dM_s'' = 0.01/0.2 = 0.05$

(compared with Zsun ~ 0.02)

- Mass conservation implies: $dM_g + dM_s = 0$ (1)

  Net change in metal content of the gas:

  – $dM_h = y \, dM_s - Z \, dM_s$

  – $dMh = (y - Z) \, dMs$ (2)
- Change in Z

  – Since $dM_g = - dM_s$ and $Z = M_h / M_g$

  – $dZ = dM_h / M_g - M_h \, dM_g / M_g^2$

  $= (y - Z)dMs / Mg + (Mh/Mg) (dMs/Mg) = y \, dMs / Mg$

  – $dZ/dt = - y \, (dM_g/dt) / M_g$

Closed Box- continued

- Assuming y = constant (i.e. independent of time and Z):
- $Z(t) = Z(0) – y \ln [M_g(t)/M_g(0)] = Z(0) – y \ln \mu(t)$
- where μ= gas (mass) fraction = $M_g (t) / M_g (0) = M_g (t) / M_t$
- The metallicity of the gas grows with time, as new stars are formed and the gas is consumed

- Metallicity Distribution of the Stars
- The mass of the stars that have a metallicity less than Z(t) is
- $M_s [< Z(t)] = M_s(t) = M_g(0) – M_g(t)$
- or $M_s [< Z(t)] = M_g(0) * [1 – \exp (–(Z(t)-Z(0))/y)]$
- When all the gas has been consumed, the mass of stars with metallicity Z, Z + dZ is

$dMs(Z)\ \mu\ \exp (– (Z-Z(0))/y)\ dZ$

Yield Derived From Observations

- $Z(\text{today}) \sim Z(0) - y \ln [M_g(\text{today}) / M_g(0)]$
- The average metal content of the gas in the disk near the Sun is Z ~ 0.7 Zsun
- The initial mass of gas $M_g(0) = M_s(\text{today}) + M_g(\text{today})$ where
- $M_s(\text{today}) \sim 40\ M_{sun}/pc^2$ and $M_g(\text{today}) \sim 10\ M_{sun}/pc^2$
- Assuming that Z(0) = 0, we derive $y \sim 0.43\ Z_{sun}$