NEW TOPIC- Star Formation

- 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?

Status of JWST

- YEARLY THEMES

2013: Instrument Integration: The Science instruments are finished and begin their testing as an integrated science payload

2014: Manufacturing the Spacecraft: Construction will commence on the spacecraft that carries the science instruments and the telescope

2015: Assembling the Mirror: The mirror segments, secondary mirror and aft optics will be assembled into the telescope

2016: Observatory Assembly: The three main components of the observatory will be completed (instruments, telescope, spacecraft)

2017: Observatory Testing: The instruments, telescope and spacecraft will be tested and readied for assembly into a single unit

2018: Kourou Countdown: All parts of the observatory will be brought together, tested and readied for launch in Kourou, French Guiana

Star Formation in Spirals

- This is an enormous subject- lots of recent work (see Kennicutt 1989 for a review)
- 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 form stars (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).
-

Star Formation

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- *unfortunately they are not covered by the text*.

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- short lifetime systems)

How to Normalize SFR

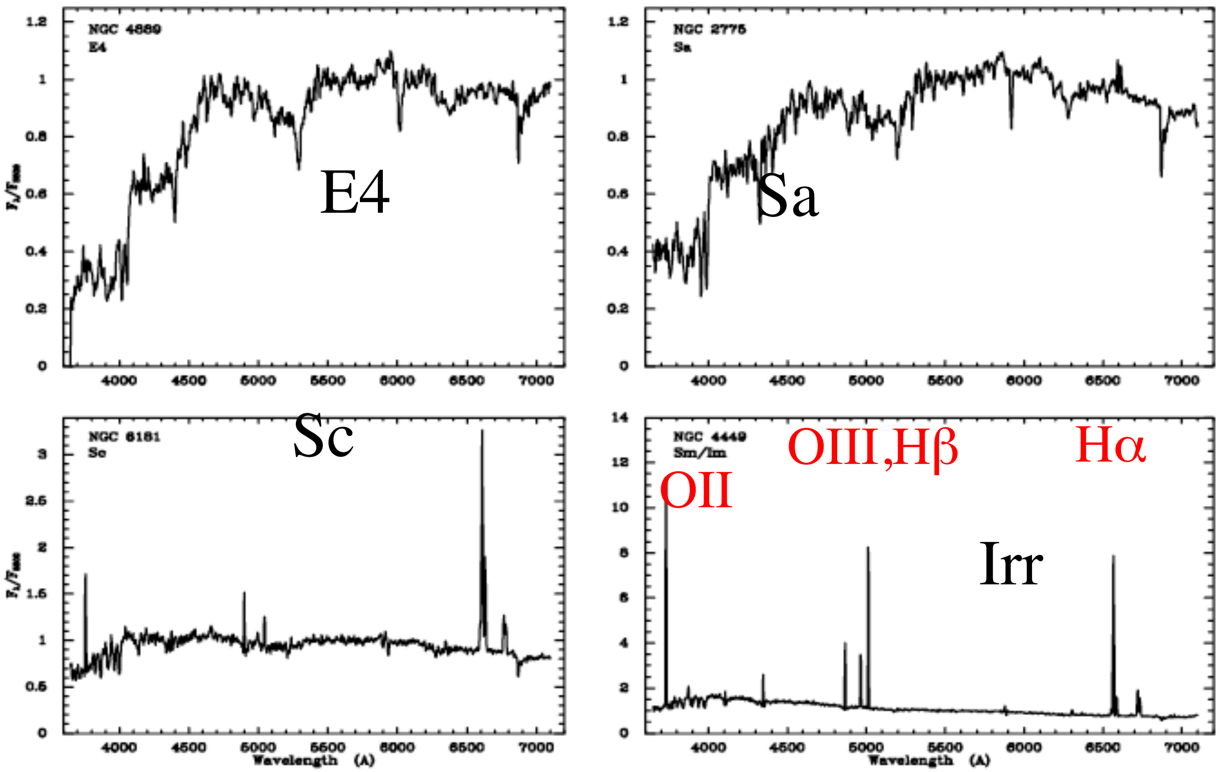
- Since essentially all techniques measure the total (or ionizing) luminosity of massive stars we need to transform to ALL the stars
- Use the IMF
- For Kroupa IMF
  - $\Psi(M) \sim M^{-1.4}$ $0.1M_{\odot} < M < 1M_{\odot}$
  - $\Psi(M) \sim M^{-2.5}$ $1M_{\odot} < M < 100M_{\odot}$
- Integrate Ψ from 10-100M 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

How to connect the various indicators

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

Importance of Emission Lines

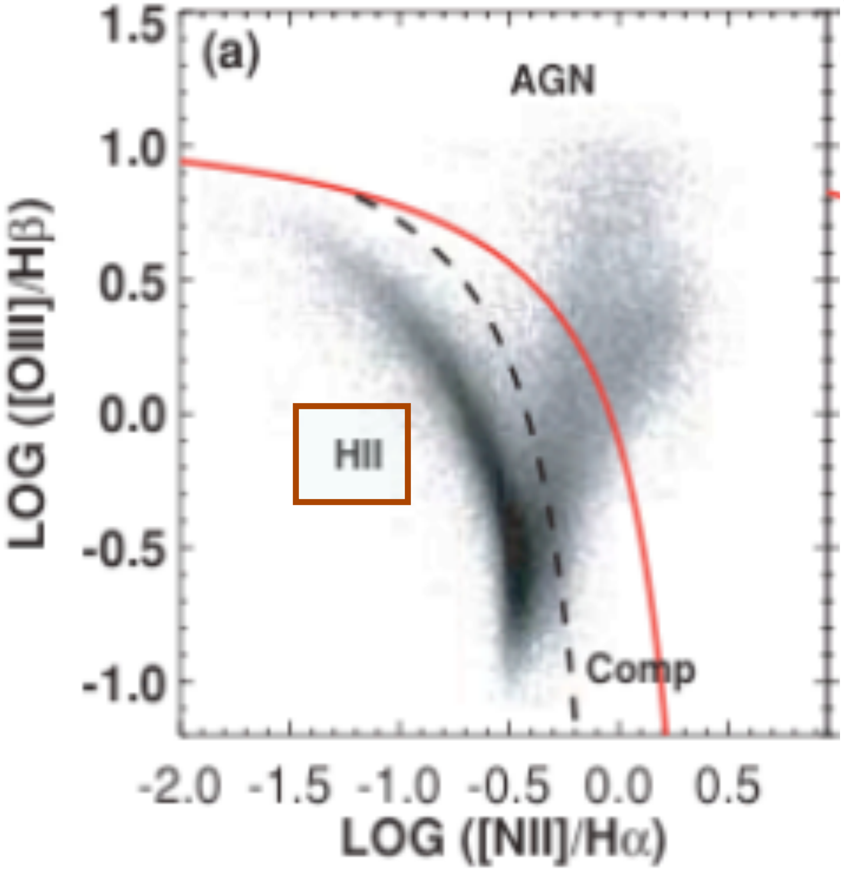
- As one moves on the Hubble sequence the galaxy spectra get more and more emission line dominates and relative prominence of lines changes
- Thus many authors use $H\alpha$ or OII as SFR indicators (OIII is also produced by active galaxies and so it is often difficult to separate AGN from star formation)

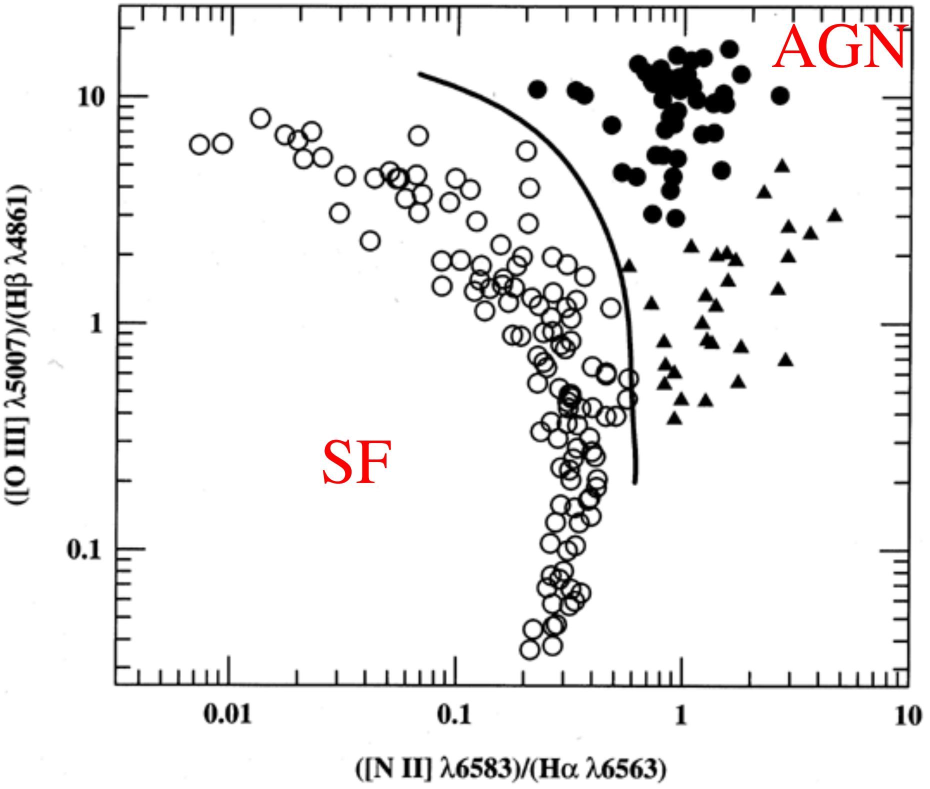


Kennicutt 1998

Separating AGN from SF Galaxies

- AGN also have strong lines-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 best diagnostics





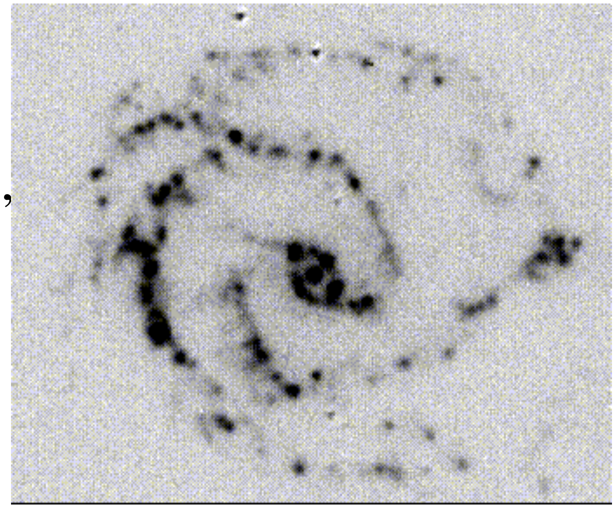
Different lines have different dependences on temperature excitation mechanism (collisions, photoionization)

Ratios of certain lines (chosen to be close in wavelength so dust is not an issue) separate AGN from SF galaxies

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

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 (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

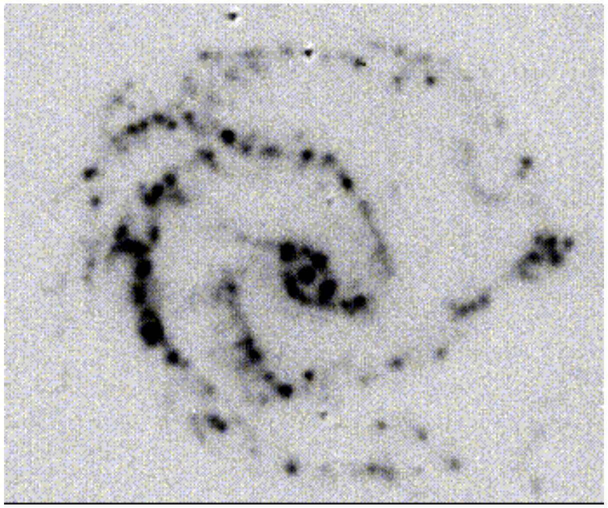


Hα image of a star forming galaxy

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

How to Determine SFR from Observables-Hα or Hβ

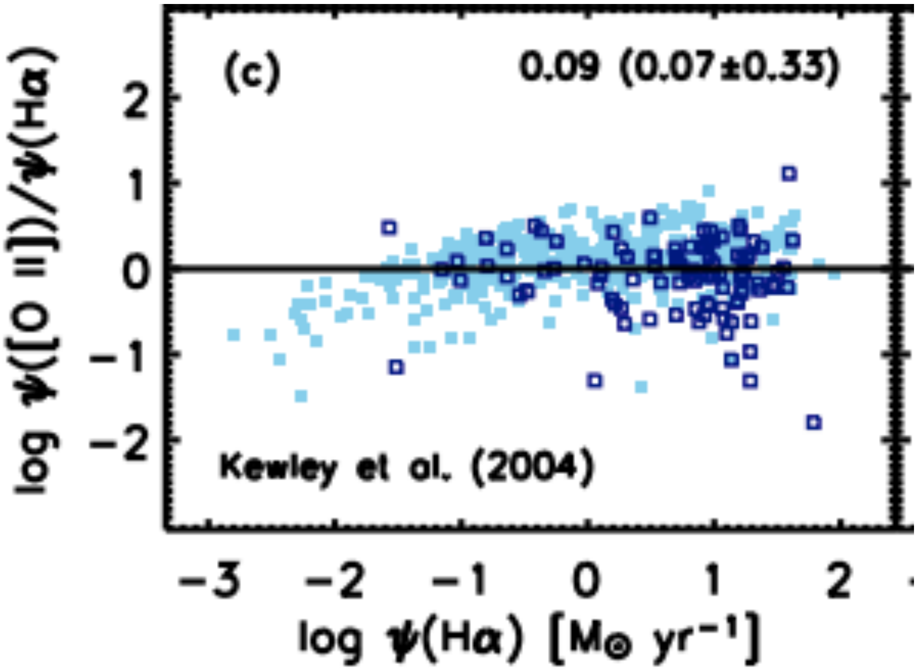
- The strength of the emission lines is the convolution of the number of ionizing photons, the fraction of them that are absorbed and the physical conditions of the gas.
- Simplifying assumptions: gas of constant temperature, given IMF, gas is *internally* dust free, Case B (optically thick to ionizing continuum)(Hα/Hβ=2.9)
  - Hα only comes from ionized gas (HII regions)- very non-uniform images (pearls on a string)
- For each type of star one can calculate the number of Hα photons, for (O7) star it is 10^{38}ph/sec
- 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
- **$SFR(M_\odot/yr)=L(H\alpha)/1.1\times10^{41}$ 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.



Hα image of a star forming galaxy

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)

Summary and Look Forward

- The star formation rates is determined using many different indicators- so far just discussed Hα emission which traces H II regions;

- The most important other tracers are
  - far infrared emission tracing deeply embedded star formation
  - and far ultraviolet emission tracing young, massive stars that have dispersed their natal gas and dust.
  - Radio emission tracing relativistic 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 so Far

- 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 ≈1–300Myr,
- since 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 (O6 to B8 star) 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

- 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 - turns out that the most active and luminous systems are also richer in dust, requiring 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

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

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

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)

$T \sim \lambda^{-1}$ but $L \sim AT^{4}$; so to get a lot of luminosity at *long wavelengths* need 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.

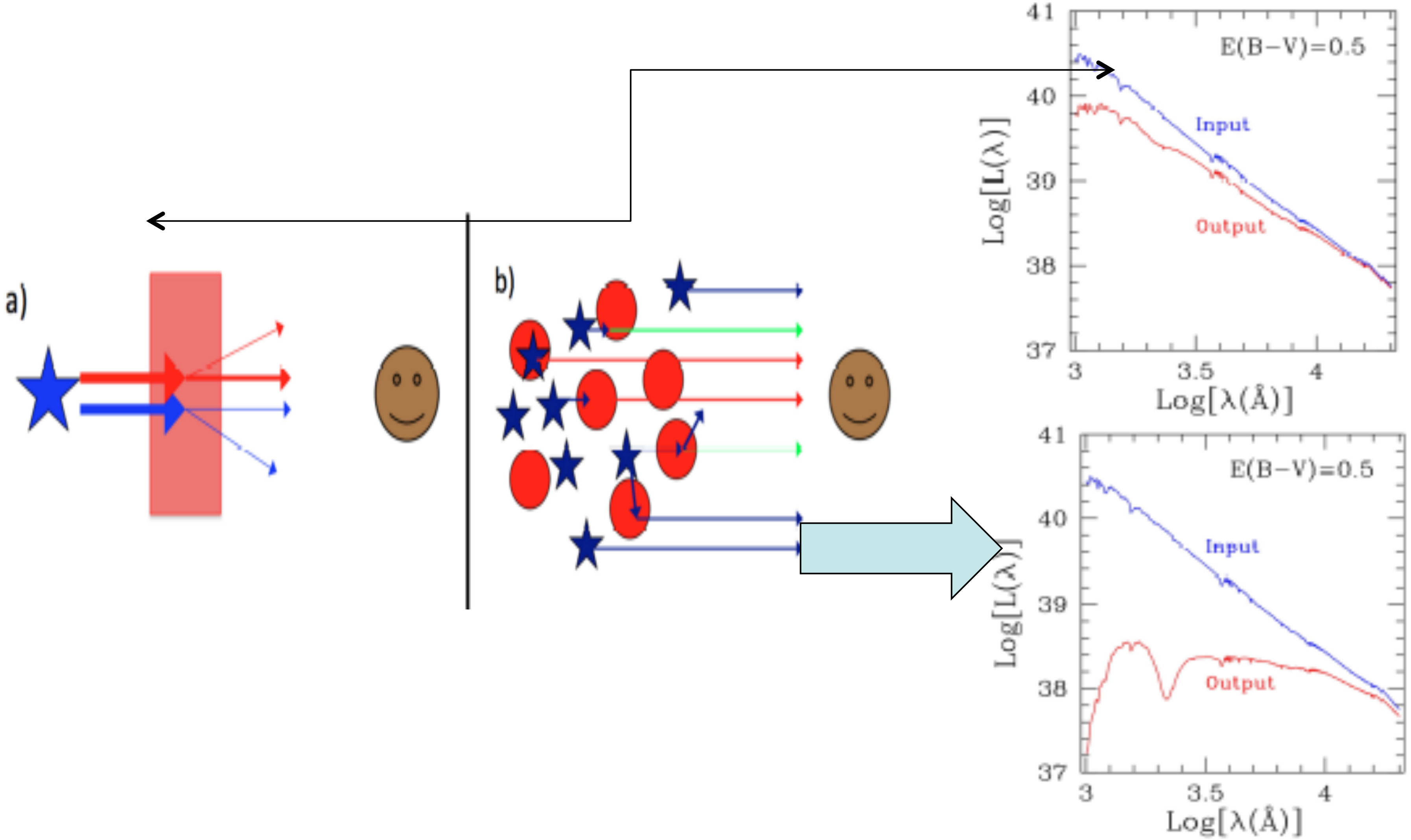
Need wide range of temperatures to produce observed spectra.

Roughly SFR (M/r)=$L_{\text{total IR}}$ x4.5×10^{-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

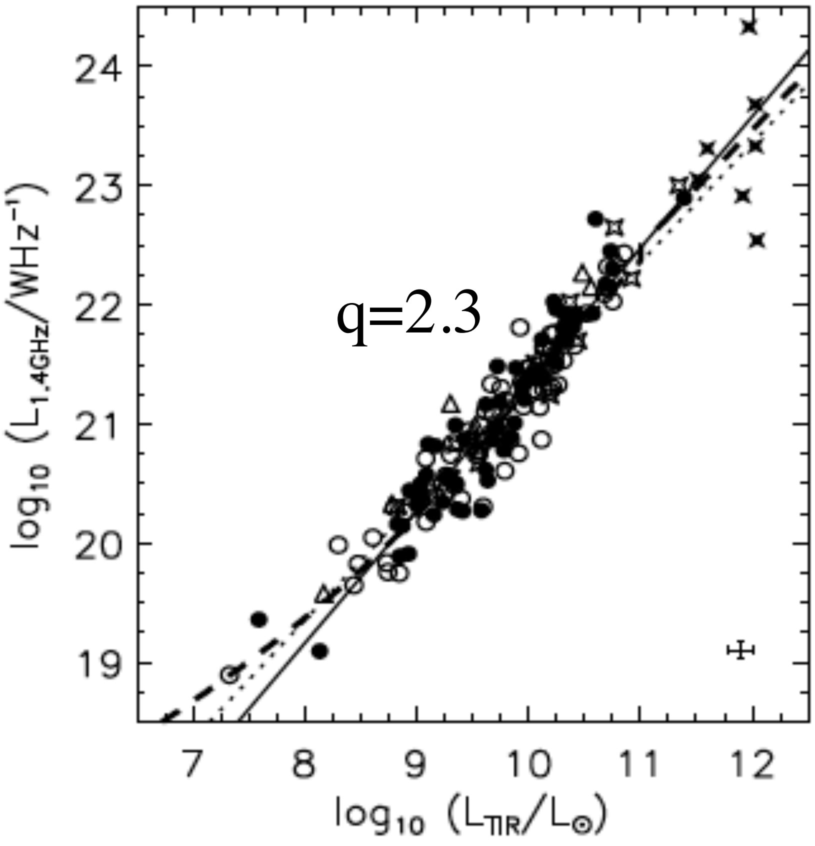
Geometry is a serious issue- the same amount of dust has different effects depending on the relative position of the stars and the dust



Star Formation- Radio View

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

- 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

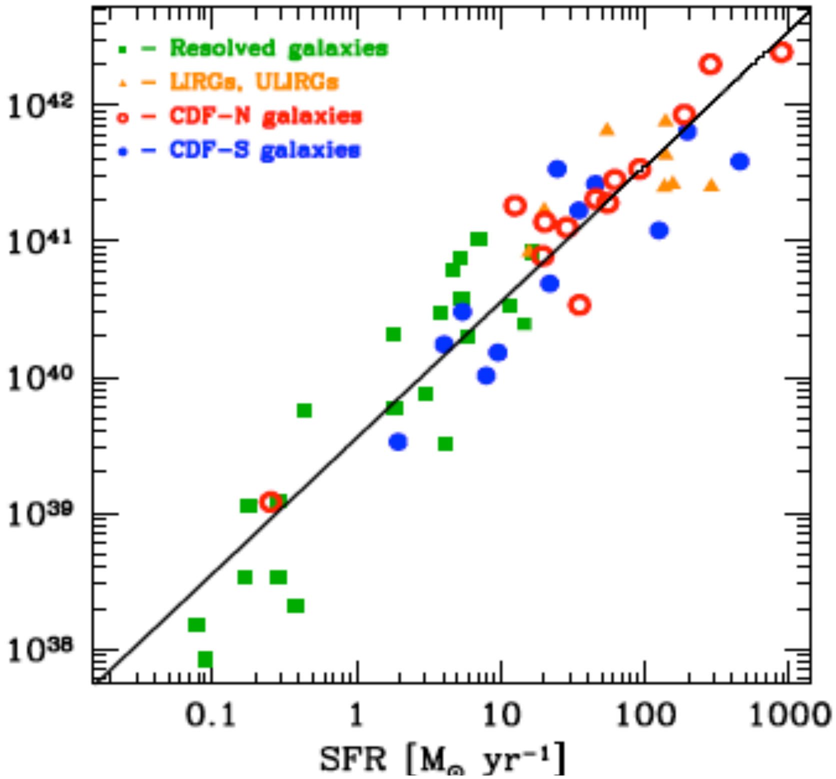
1) high mass x-ray binaries with a lifetime τ~2x10^{7}yrs

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 "diffuse" x-rays

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

X-ray Luminosity



Star formation rate

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.);

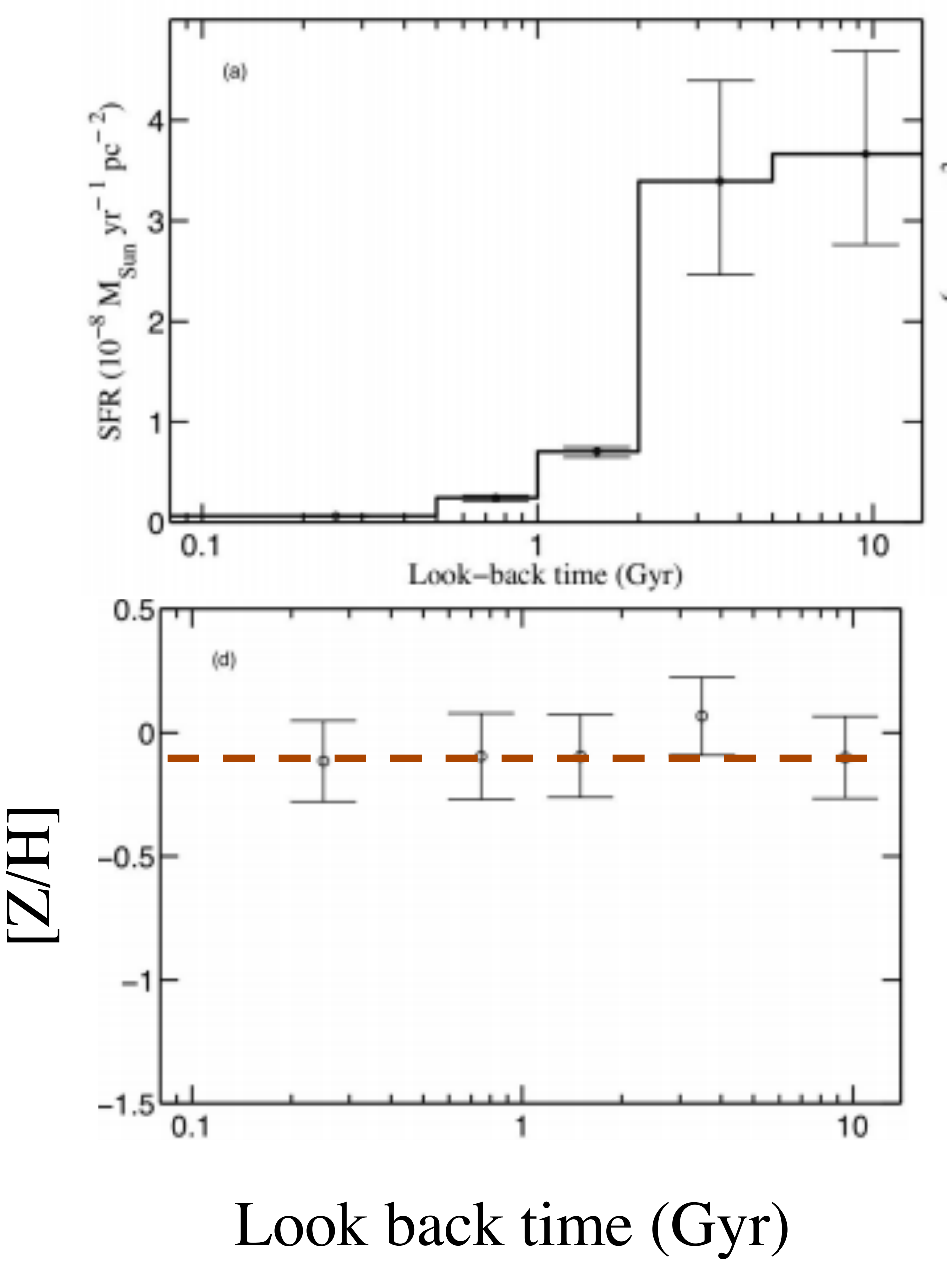
How to handle dust??

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)

Star Formation History of an Elliptical

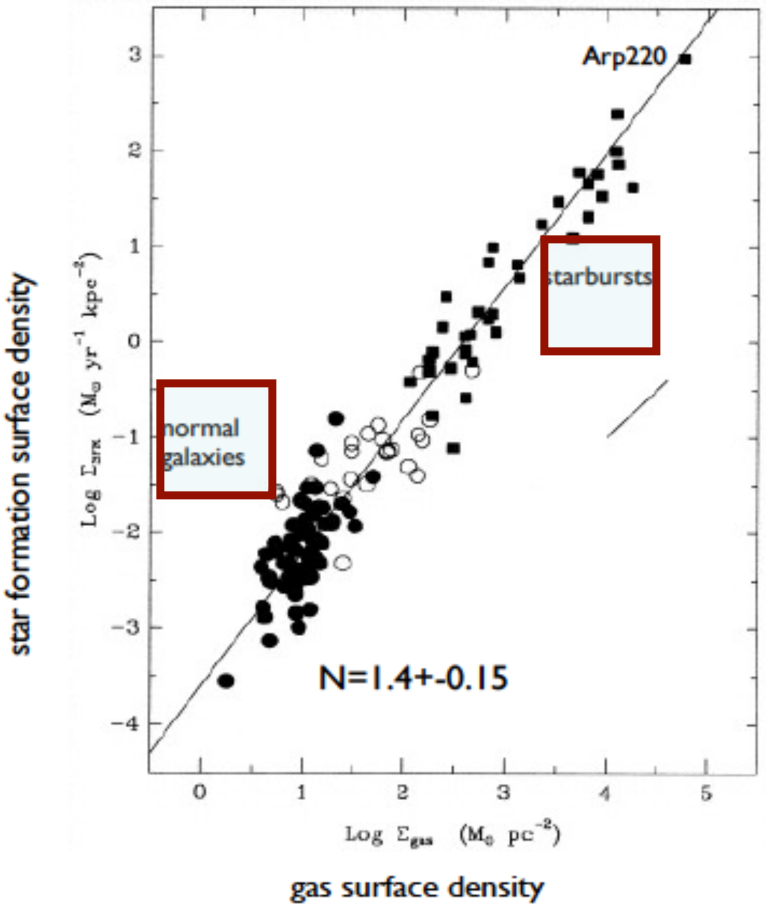
- M32- a dwarf elliptical companion of M31 is close enough to have a CMD for resolved stars-
- very different history than the LMC
- ~95% of its mass formed 5-14 Gyr ago. 2 dominant populations; ~30% of its mass 5-8 Gyr old population, ~65% of the mass in a 8-14 Gyr old population (Monachisi et al 2012)
- 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

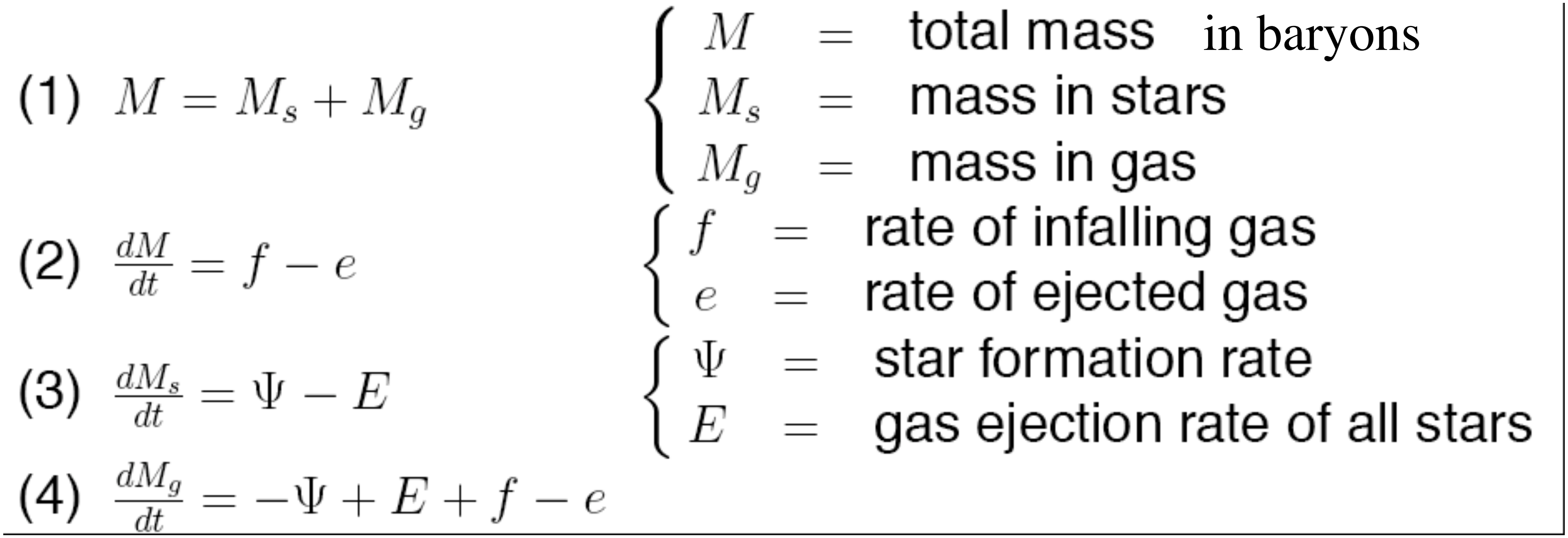
- Assume that SFR rate is proportional to total amount of gas
- $\mathrm{SFR} \sim \rho_{gas} \sim d\rho_{gas}/dt$; sol't $\rho_{gas}(t) \sim \rho(0)_{gas} e^{-t/\tau}$
- More generally assume $\mathrm{SFR} \sim \rho^{n}{}_{gas-}$
- e.g. as gas compresses stars form more easily or there maybe another timescale in the process such as the free-fall time of the gas $\mathrm{SFR} \sim \boldsymbol{\rho_{ga}/t_{freefall}}$
- **Frequently this expressed in terms of surface density (an observable)**
- Observe $\Sigma_{SFR} = A\Sigma^{n}{}_{gas}$ n~1.4
- can be explained by assuming 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, $\tau_{ff} \sim \boldsymbol{\rho^{-1/2}{}_{gas}}$ **for a fixed scale height** $\boldsymbol{\rho_{gas} \sim} \Sigma_{gas}$

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



Kennicutt 1998

Basic Equations of Star Formation- see S+G 4.3.2



(1) $M = M_s + M_g$

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

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

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

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

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

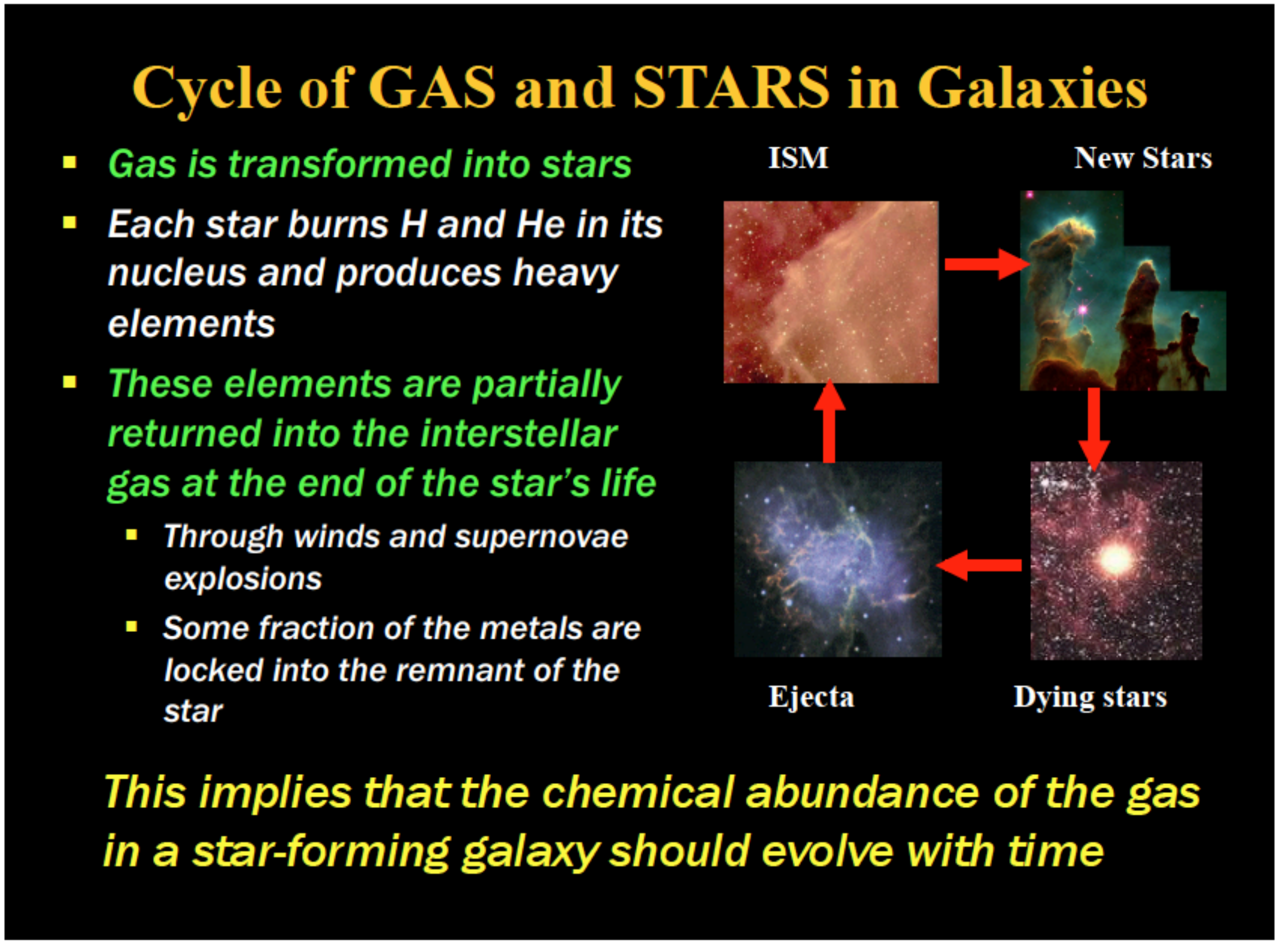
(4) $\frac{dM_g}{dt} = -\Psi + E + f - e$

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

Basics of Chemical Evolution

- H and He were present very early on in the Universe, while all metals (except for a very small fraction of Li) were produced through nucleosynthesis in stars
- The fraction by mass of heavy elements is denoted by Z

–



Cycle of GAS and STARS in Galaxies

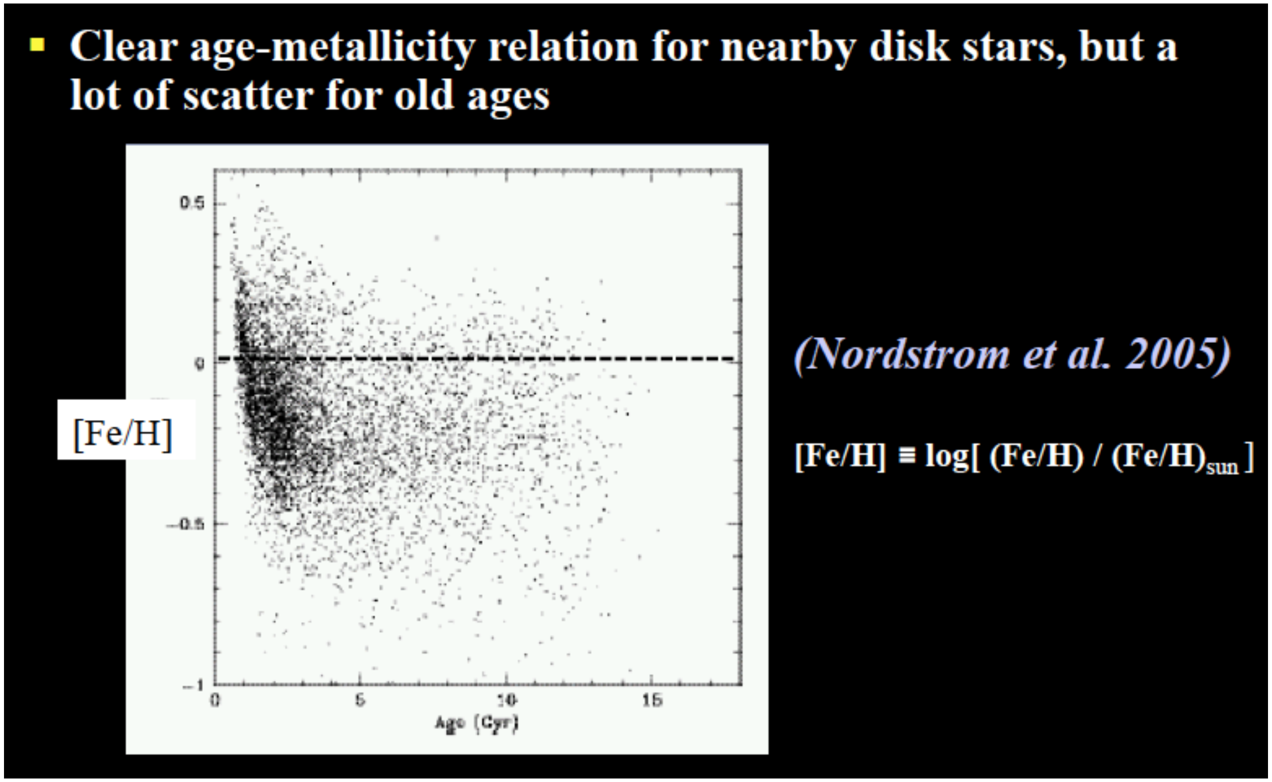
- *Gas is transformed into stars*
- *Each star burns H and He in its nucleus and produces heavy elements*
- *These elements are partially returned into the interstellar gas at the end of the star's life*
  - *Through winds and supernovae explosions*
  - *Some fraction of the metals are locked into the remnant of the star*

This implies that the chemical abundance of the gas in a star-forming galaxy should evolve with time

The Sun's metal abundance $Z_{sun} \sim 0.02$

– The most metal-poor stars in the Milky Way have $Z \sim 10^{-5}$ -- $10^{-4}\ Z_{sun}$

Generic Predictions



- **Clear age-metallicity relation for nearby disk stars, but a lot of scatter for old ages**

(Nordstrom et al. 2005)

[Fe/H] ≡ log[(Fe/H) / $(\mathrm{Fe/H})_{\mathrm{sun}}$]

- If a galaxy is a closed box predict increase of metallicity with time
- Since alpha elements produced by SnII (from massive short lived stars) while Fe from type Is (longer lived white dwarf binaries) change in chemical composition with age

Repeat Eq's of 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 ydM_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
- $y \sim 0.01$ (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

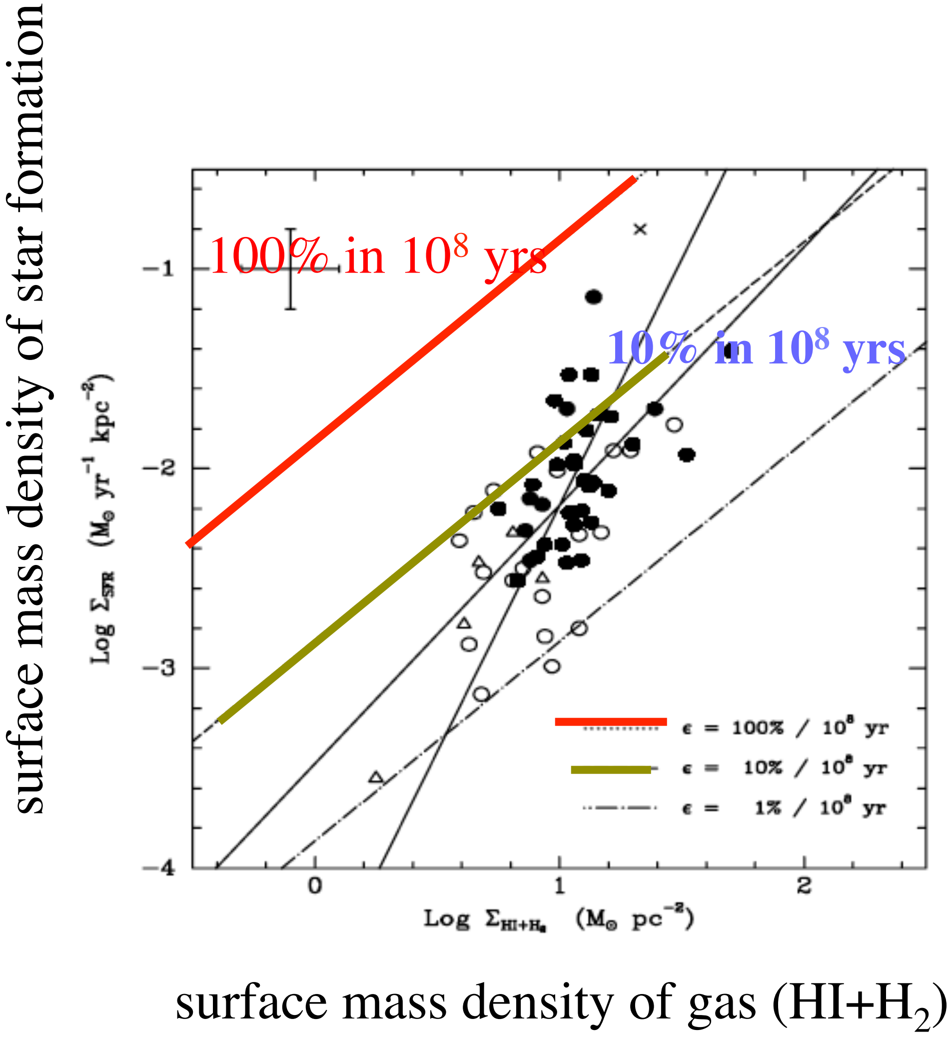
- Metallicity Distribution of the Stars
- The mass of the stars that have a metallicity less than Z(t) is
- $M_s [< Z(t)] = M_s(t) = M_g(0) – M_g(t)$
- or $M_s [< Z(t)] = M_g(0) * [1 – \exp (–(Z(t)-Z(0))/y)]$
- When all the gas has been consumed, the mass of stars with metallicity Z, Z + dZ is $dM_s(Z)\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

Yield Derived From Observations

- Z(today) ~ Z(0) – y ln [M_g(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(today) + M_g(today) where
- M_s(today) ~ 40 M_{sun}/pc^2 and M_g(today) ~ 10 M_{sun}/pc^2
- Assuming that Z(0) = 0, we derive y ~ 0.43 Z_{sun}

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 stellarmass 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



Relationship for 'normal' star formatio

Kennicutt 1998

Possible Star Formation 'Laws'

- Define star formation efficiency SFE=$\Sigma_{SFR}/\Sigma_{gas}$
- to form stars in in spirals need
  - cold phase (n ~ 4–80 cm^{-3}, T ~ 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

$t_{ff} \sim \rho^{-1/2}$ related to the velocity field and density of stars and gas

or some other timescale such as orbital timescale - 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

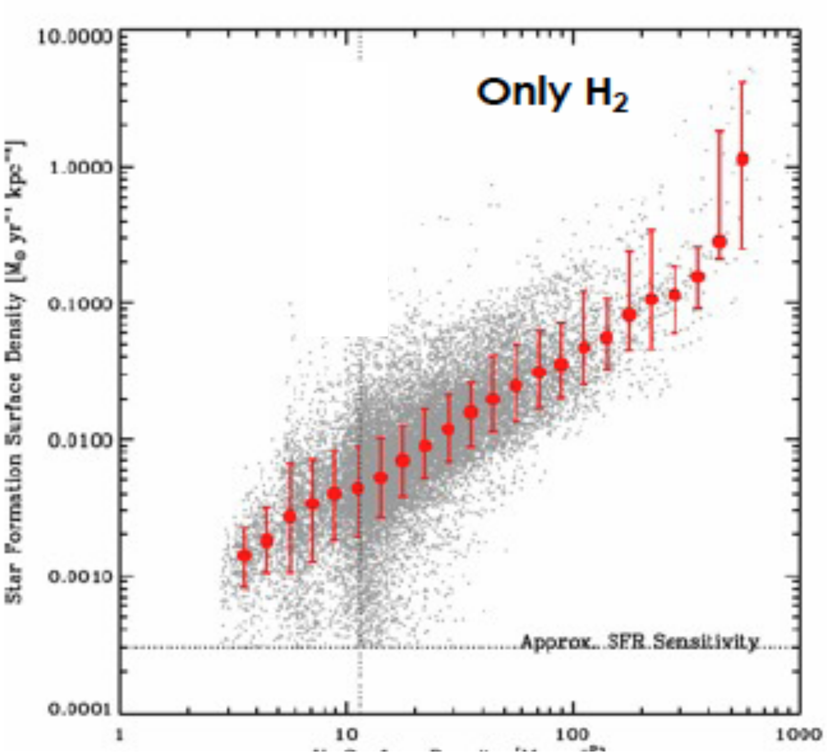
Star formation Occurs in Giant Molecular Clouds

- 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

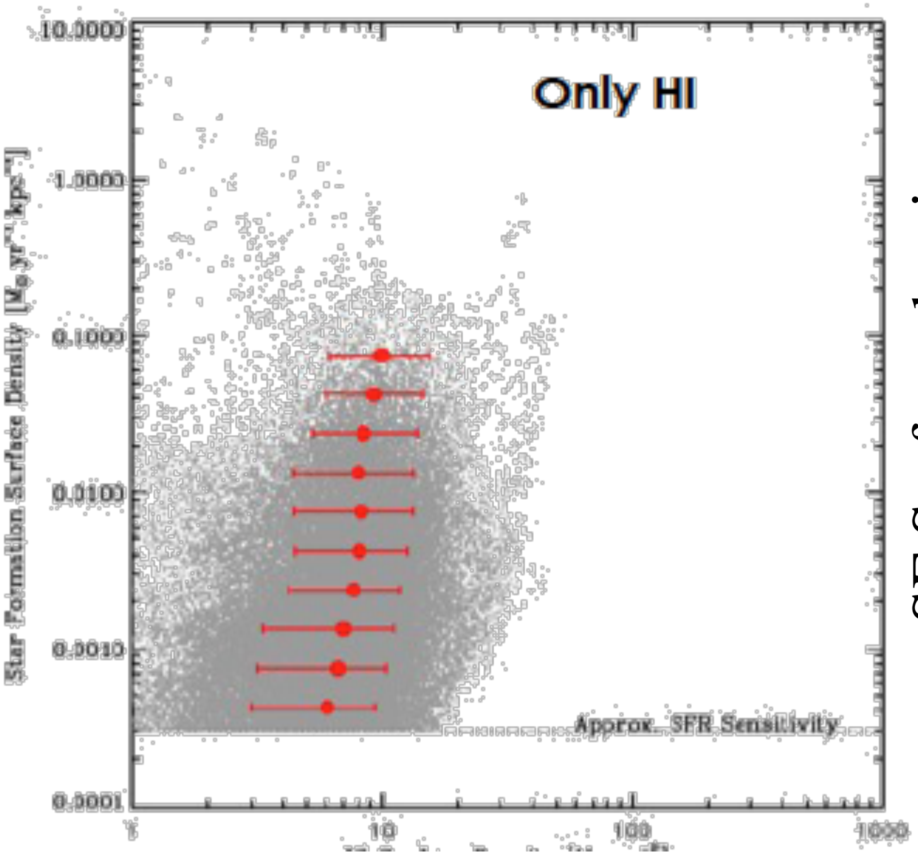
Only H_2 Counts

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

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



H_2 Surface density

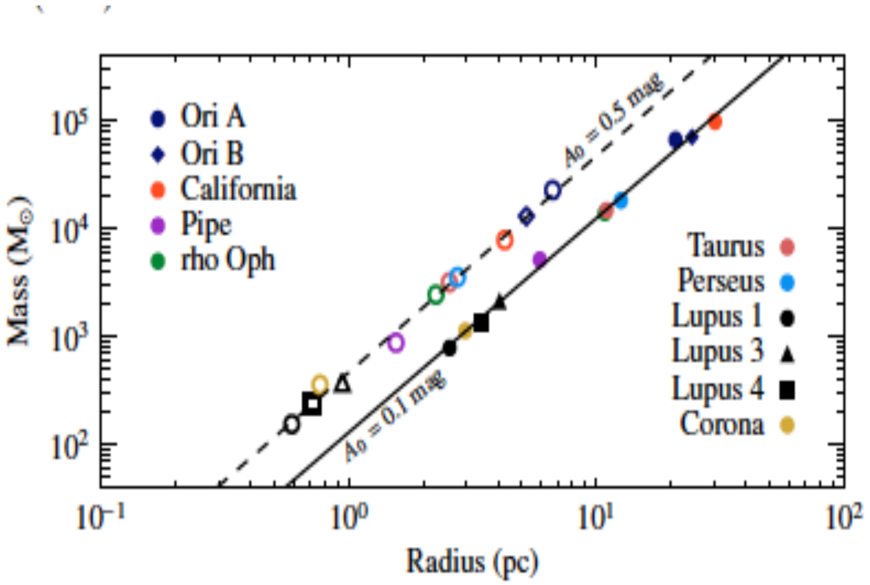


SF Surface density

HI Surface density

Molecular Clouds

- this is a vast subject with lots of details- not discussed in text
- 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 $2GM/\sigma^2=R$, $M\sim R^2$, $\delta V\sim R^{1/2}\sim\rho^{-1/2}$
- $M\sim10^5$-$5\times10^6 M_\odot$, r ~10's pc $n_{H2}\sim100$-$500\,\mathrm{cm}^{-3}$ 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~10^7 yrs



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

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

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

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
- $t^2_{ff}=1/G\rho<(R/c_s)^2=10^8n^{-1/2}_H$ 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 length $\lambda_J=\mathrm{sqrt}(\pi c_s{}^2/G\rho)$

For typical values

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

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

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

Gravitational Instability

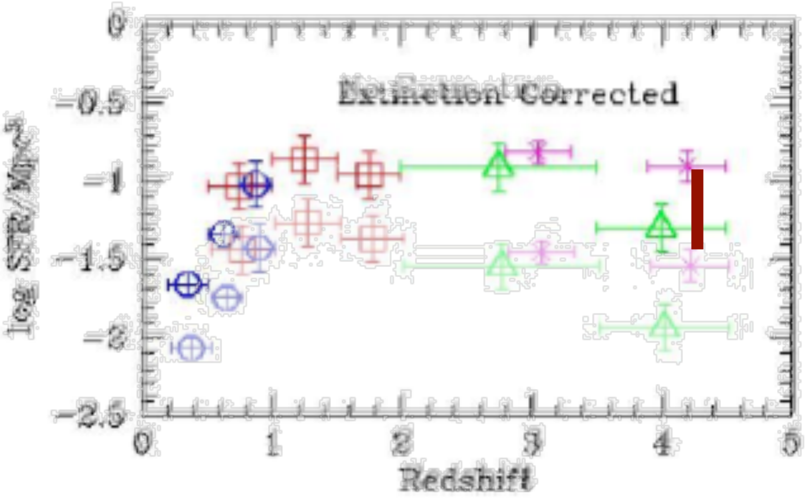
- Another derivation of Jeans length/mass
- Balance pressure and gravity (pg 355 of S+G)
- Potential energy= $-1/2 \int \rho(x)\phi(x)d^3x \sim G\rho^2 r^5$
- if gas moves as sound speed KE=$c_s^2 M$
- $M=4/3\pi\rho r^3$

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

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

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

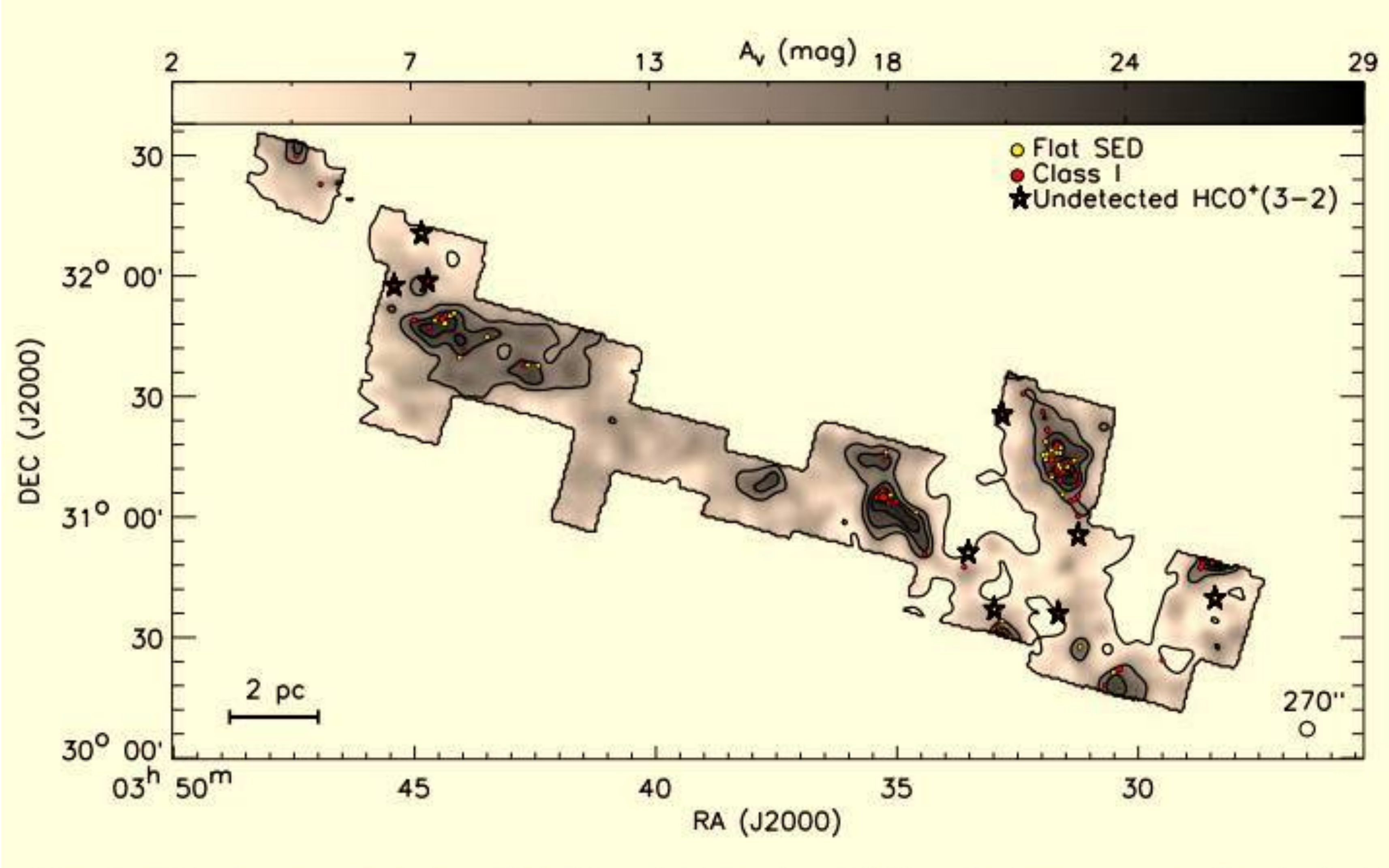


Summary of Situation

- 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

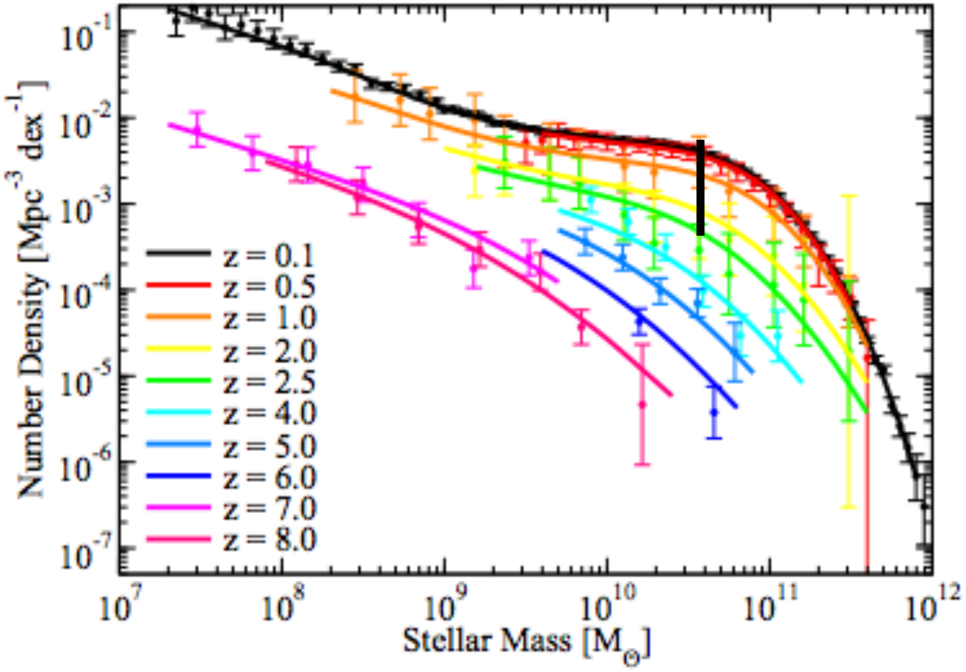
Cosmic History of Star Formation

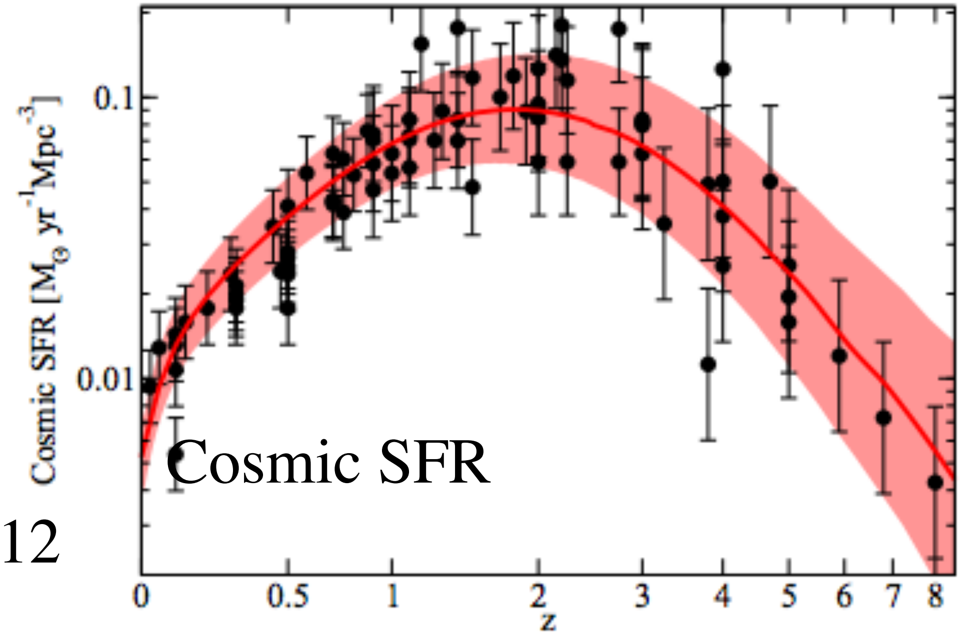
General Results

- 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



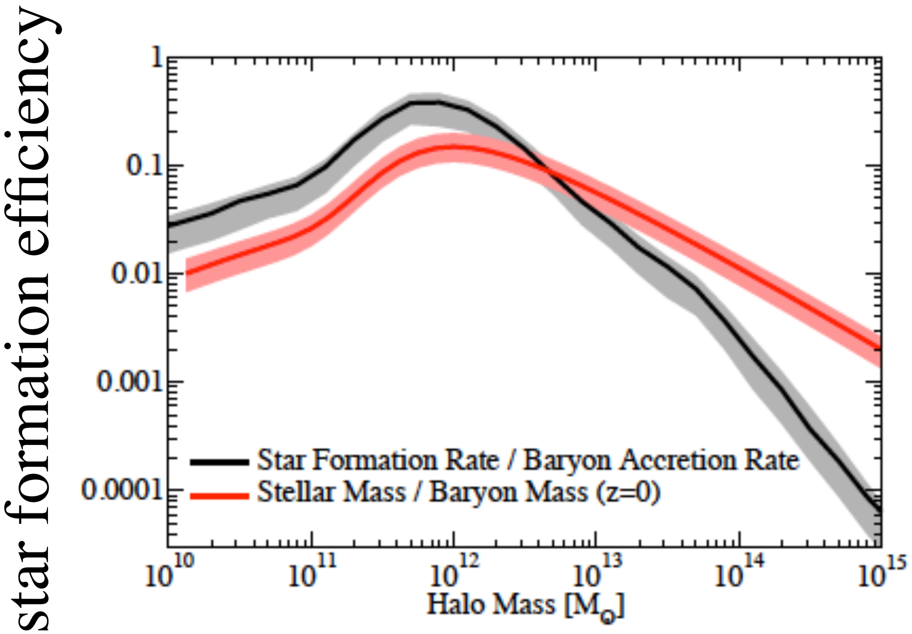


Cosmic SFR

Behroozi et al 2012

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



Theories of SF That Do 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