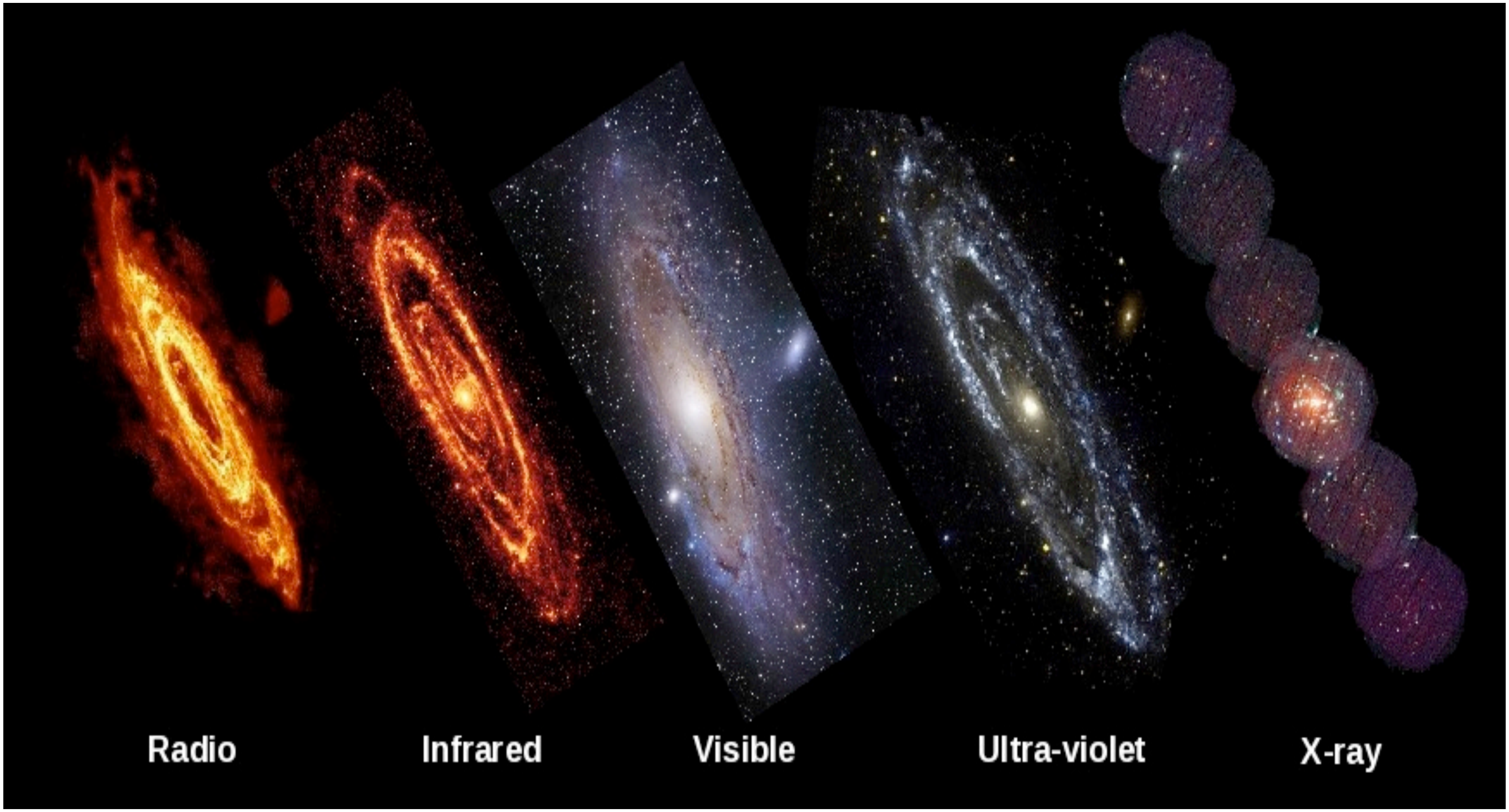
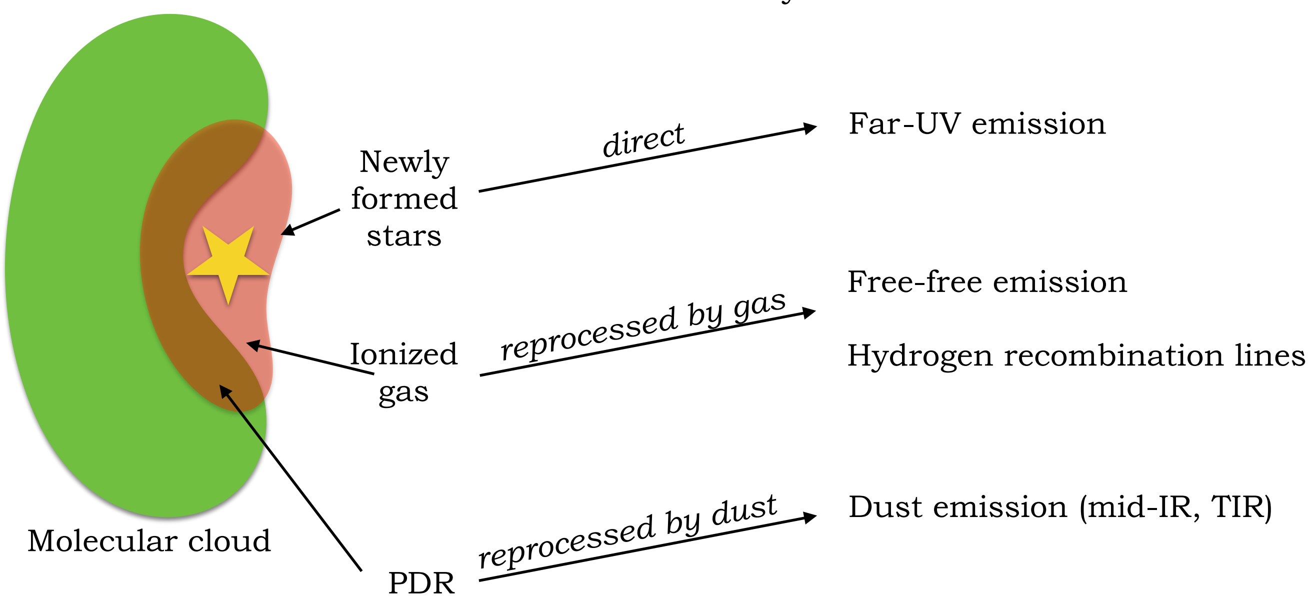
Star Formation Rates in Galaxies



Radio
Infrared
Visible
Ultra-violet
X-ray

Making the measurements…

SFR Surface Density



Generally: either FUV or Hα plus IR to correct for extinction (e.g. Calzetti et al. 2007)

Slides: Karin Sandstrom

Measuring Star Formation Rates: Linear relations between luminosity and SFR. (old)

- L_{IR}

$$\frac{\mathbf{SFR}}{1\ M_\odot\ \mathrm{yr}^{-1}} = \frac{L_{\mathrm{FIR}}}{2.2 \times 10^{43}\ \mathrm{ergs\ s}^{-1}} = \frac{L_{\mathrm{FIR}}}{5.8 \times 10^{9}\ L_\odot}\ .$$

- L_{UV}

$$\mathrm{SFR}(M_\odot\ \mathrm{yr}^{-1}) = 1.4 \times 10^{-28}\ L_\nu(\mathrm{UV})\ (\mathrm{erg\ s^{-1}\ Hz^{-1}}).$$

- L_{halpha}

$$\mathrm{SFR}(M_\odot\ \mathrm{yr}^{-1}) = 7.9 \times 10^{-42}\ L(\mathrm{H}\alpha)\ (\mathrm{erg\ s^{-1}})$$

Kennicutt 1998: Assumes a Salpeter IMF, with mass limits from 0.1 to 100 Msun and Solar metal abundances. SFR is assumed to be constant over the past 10 Myr (for UV) and 100 Myr (for Halpha). L(UV) must be corrected for dust extinction.

K98 **UPDATED** !!

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

Kennicutt & Evans 2012 eqn 12. Kroupa IMF

Table 1 Star-formation-rate calibrations

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

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

Note: Assumes solar metallicity

Recall :
Initial Mass Function

$$\xi(M)dM = \xi_0(M/M_\odot)^{-\alpha}\frac{dM}{M_\odot}$$

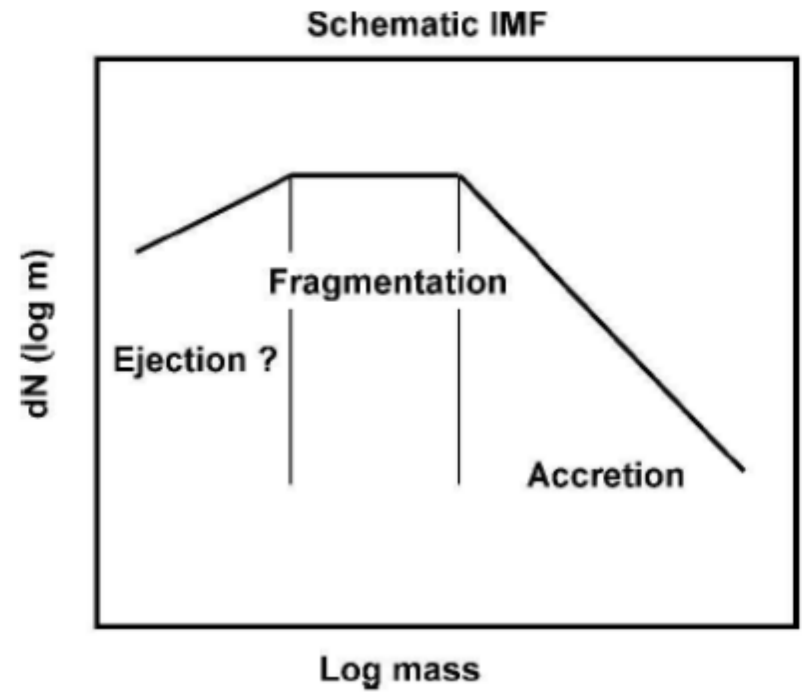
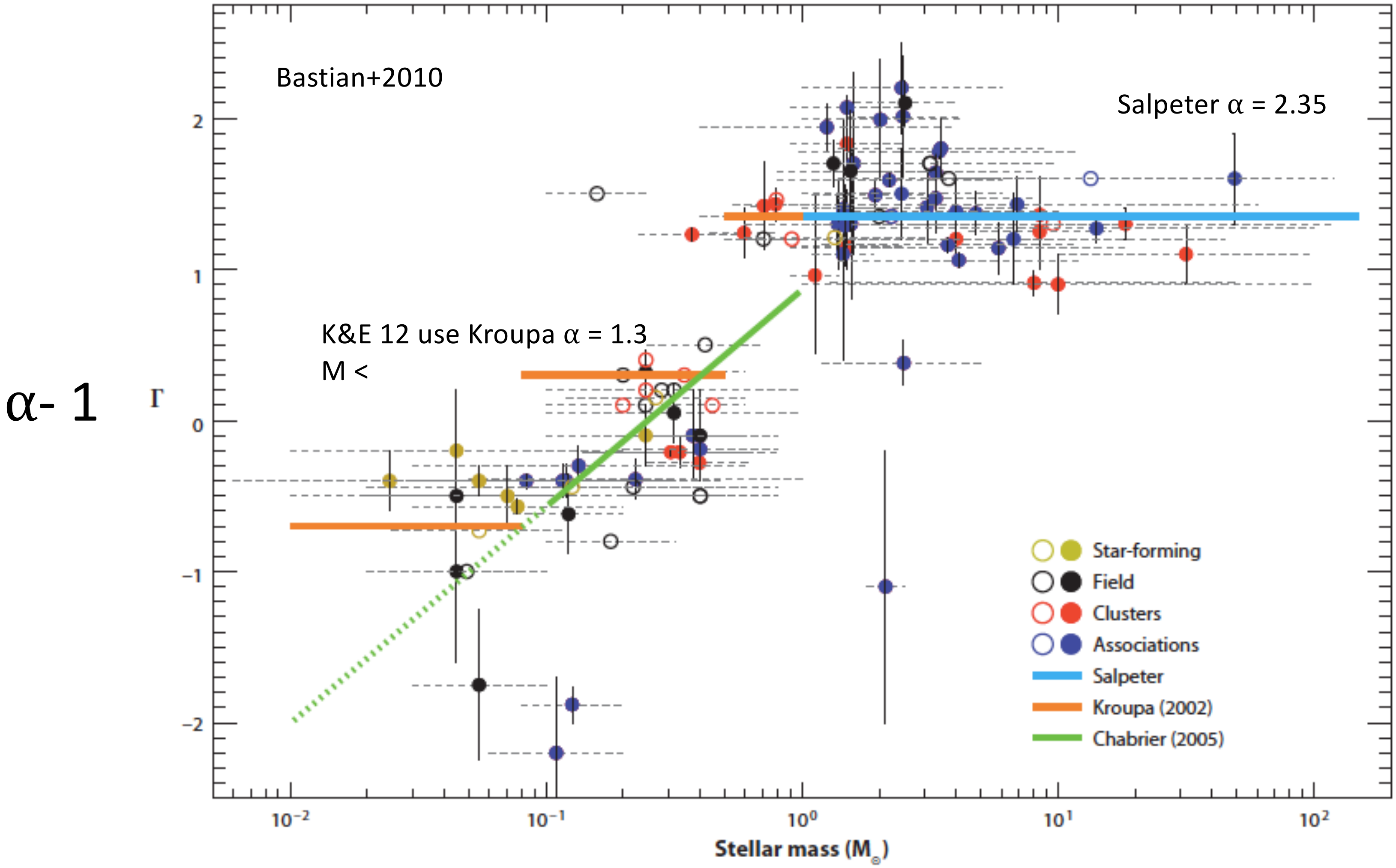


Fig. 11.— A schematic IMF showing the regions that are expected to be due to the individual processes. The peak of the IMF and the characteristic stellar mass are believed to be due to gravitational fragmentation, while lower mass stars are best understood as being due to fragmentation plus ejection or truncated accretion while higher-mass stars are understood as being due to accretion.



α- 1
Γ
Bastian+2010
Salpeter α = 2.35
K&E 12 use Kroupa α = 1.3
M <
2
1
0
−1
−2
10⁻²
10⁻¹
10⁰
10¹
10²
Stellar mass (M☉)
Star-forming
Field
Clusters
Associations
Salpeter
Kroupa (2002)
Chabrier (2005)

Kennicutt & Evans 2012

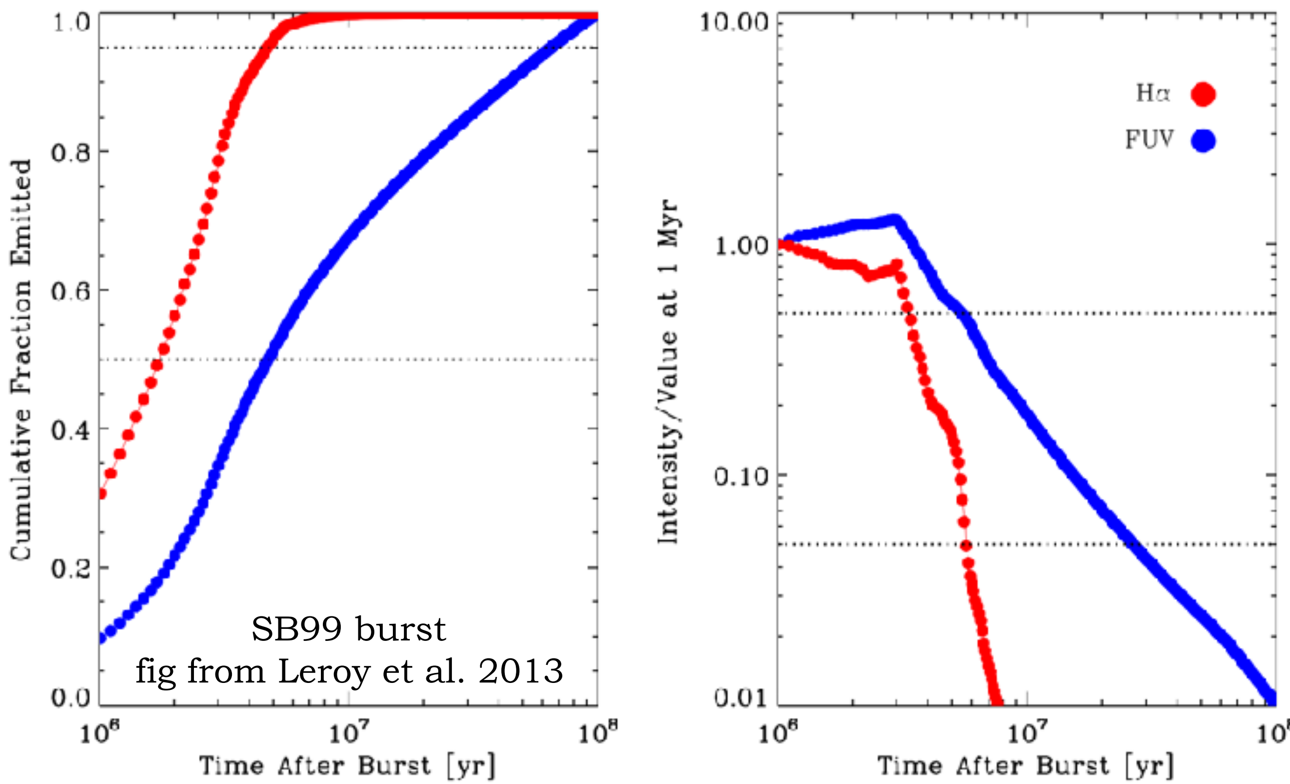
Table 2 Multiwavelength dust corrections for normal galaxies

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

[a] Radio luminosity in units of ergs s^{-1} Hz^{-1}.

Abbreviations: FUV, far ultraviolet; NUV, near ultraviolet; TIR, total infrared.

Observational challenges:
Differing timescales for SFR tracers (i.e. FUV, Hα and IR)



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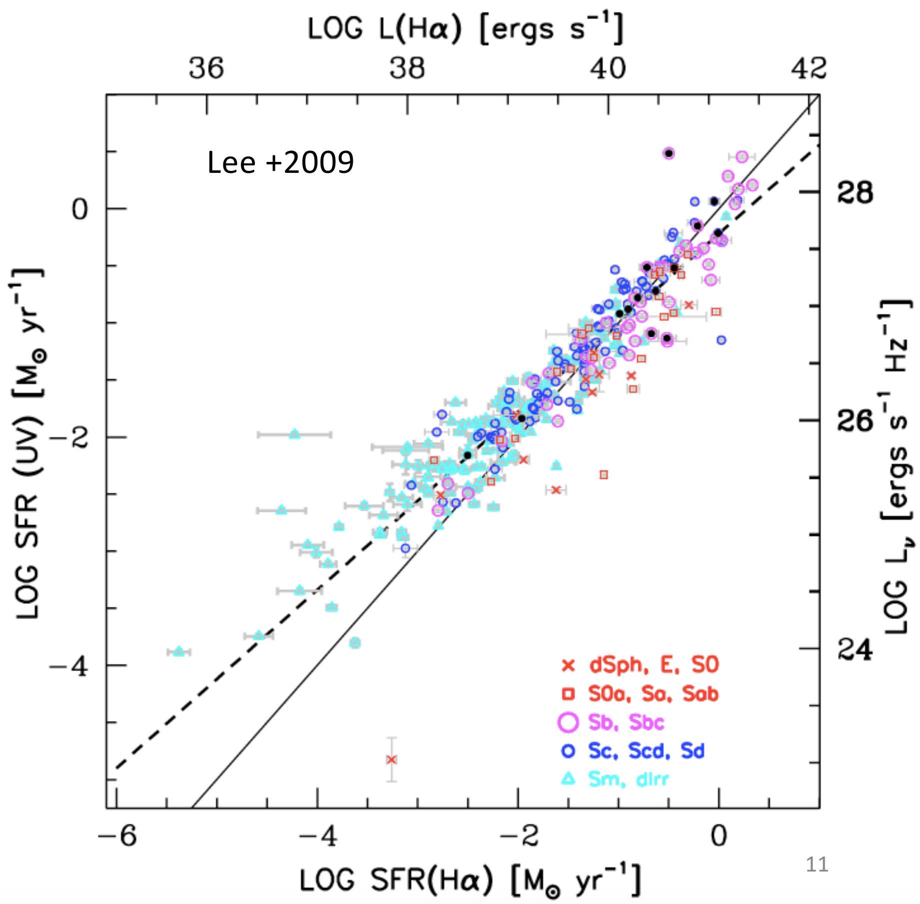
Star Formation Rates: UV vs. Halpha

EXCEPTION:

At low luminosities (less than SMC), Halpha tends to under predict the SFR relative to UV.

May be an issue with:
- IMF assumptions.
- Spatial distribution (Halpha tends to be more clumpy).
- Metallicity

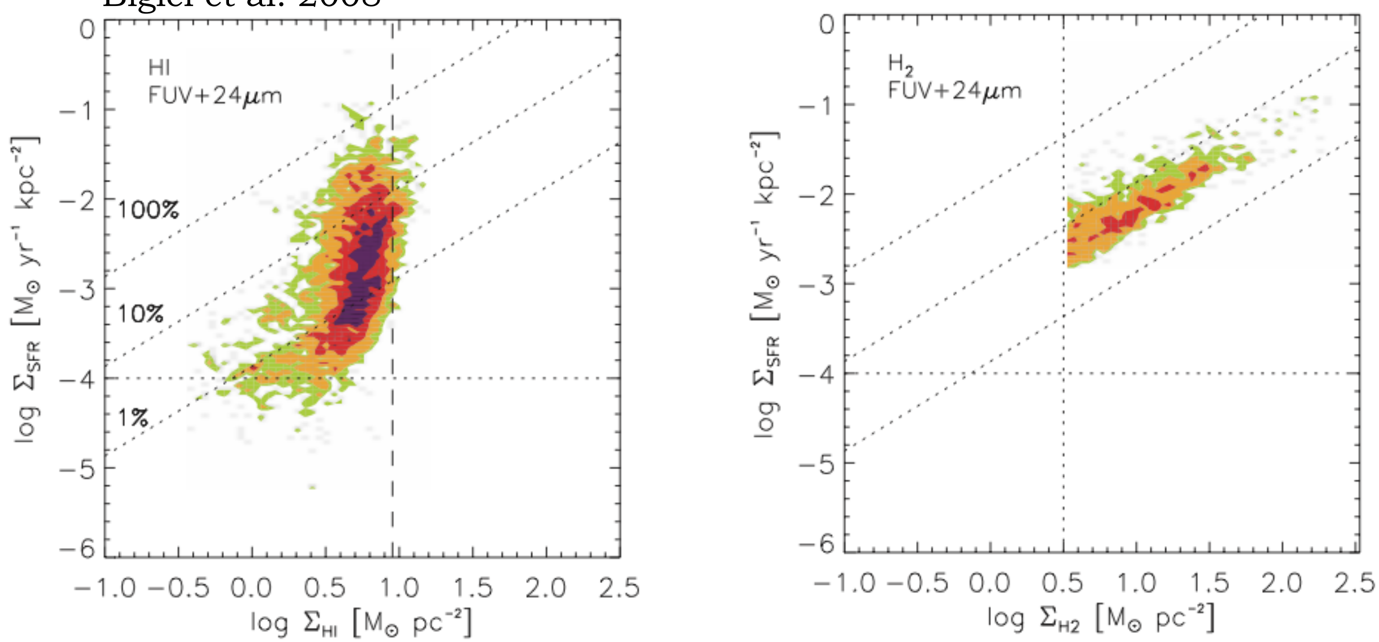


The Roles of HI and H_2

Kiloparsec scale

On kpc scales, SFR correlates best with H_2.

Bigiel et al. 2008



Rownd & Young 1999, Wong & Blitz 2002, Heyer et al. 2004,
Kennicutt et al. 2007, Bigiel et al. 2008, Leroy et al. 2008, others

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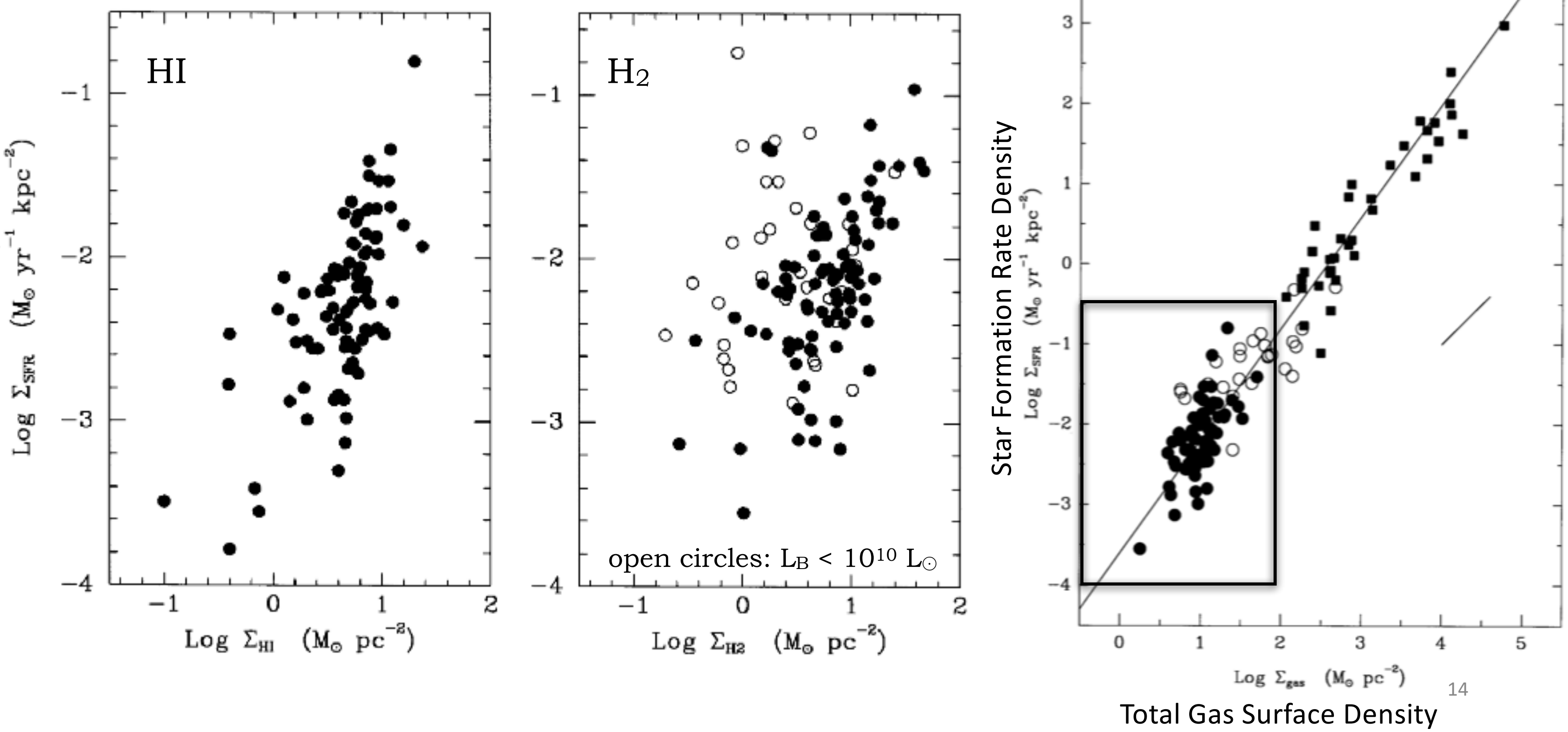
On Galaxy Scales

SFR best correlated with total gas - better than HI or H_2 alone.

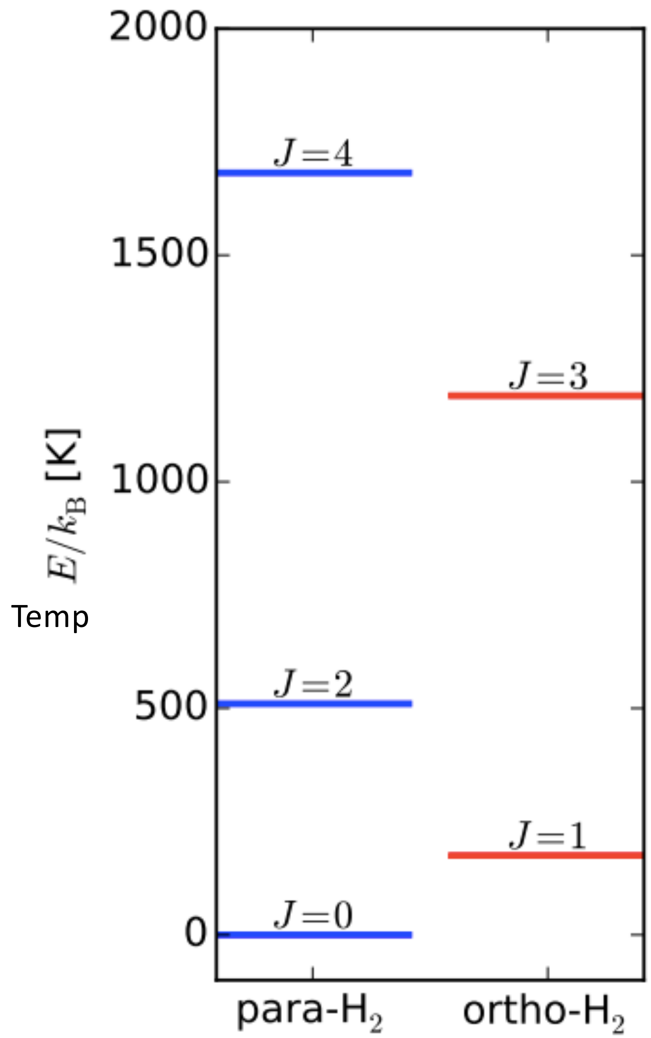
Scatter not explained by observational uncertainties.

Kennicutt 1998



H2

Level diagram for the rotational levels of para- and ortho-H2, showing the energy of each level.



175 K vs GMC temp of 10 K

Column density of H2 Conversion factor Intensity of CO emission

$$N(H_2) = X(CO)I(CO).$$

$$X(CO) = 2.8 \times 10^{20}\ \mathrm{cm}^{-2}\ (\mathrm{K\ km\ s}^{-1})^{-1}$$ Kennicutt 1998b

$$X(CO) = 2.0 \times 10^{20}\ \mathrm{cm}^{-2}\ (\mathrm{K\ km\ s}^{-1})^{-1}$$ Pineda + 2010b MW Value

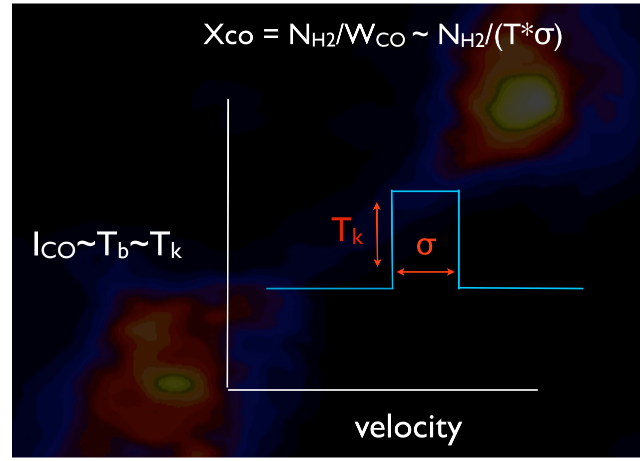
Why this works …

$$M(r) \propto \sigma^2 r$$

Virial Theorem

$$\sigma = C\, R^{0.5}$$ Larson 1981

$$M_{vir} \propto \sigma^4$$



$$L_{\rm CO} = \sqrt{2\pi^3} T_B\, \sigma\, R^2$$

Surface brightness x area

$$L_{\rm CO} \propto T_B \sigma^5$$

$$M_{vir} \approx M_{mol} \approx 200 \left(\frac{C^{1.5}\, L_{\rm CO}}{T_B} \right)^{0.8}$$

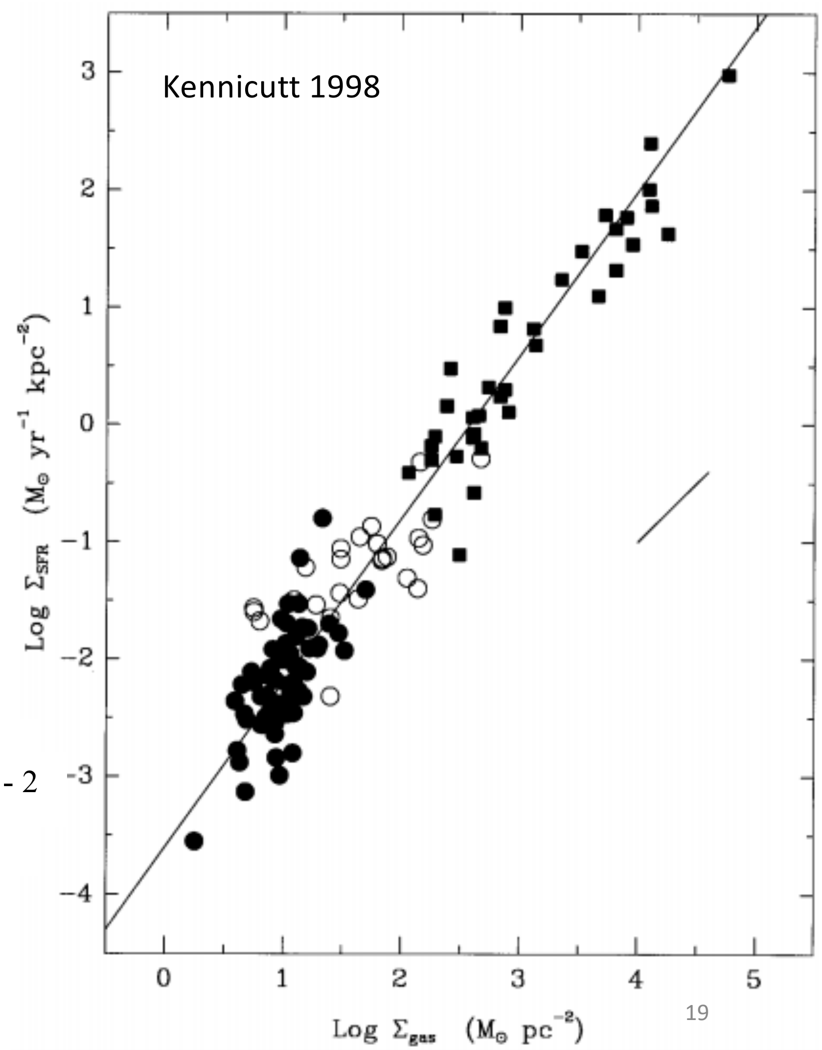
Bolatto+2013 Review

SFRs: Kennicutt-Schmidt Relation

$$\Sigma_{\mathrm{SFR}} \propto \Sigma_{\mathrm{gas}}^{1.4}$$

Higher surface densities represent more dense gas.

$$\Sigma_{\mathrm{SFR}} = 2.5 10^{-4} \left(\frac{\Sigma_{\mathrm{gas}}}{1 M_{\odot} \mathrm{pc}^{-2}} \right)^{1.4} M_{\odot}\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$$



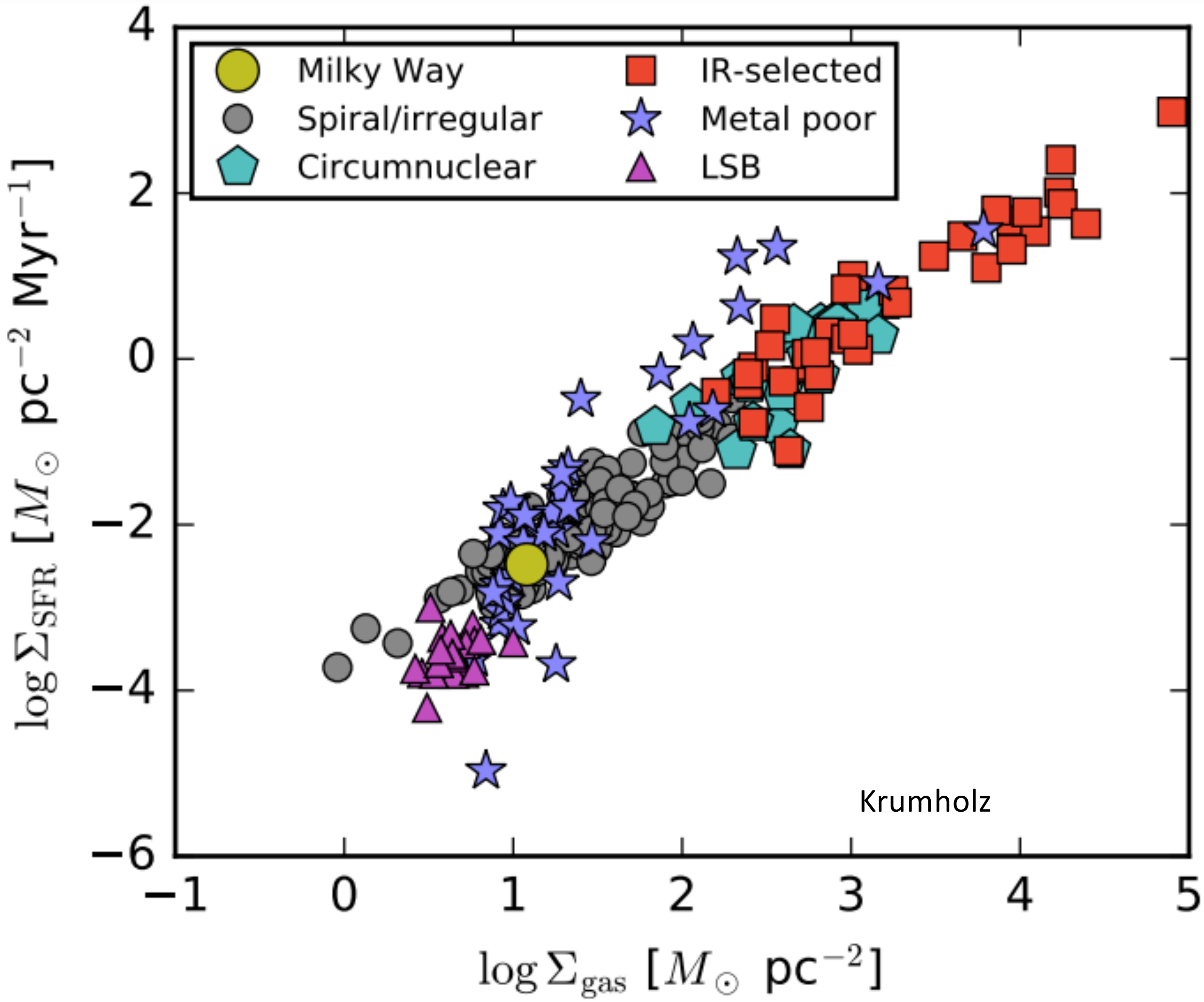
Understanding the Kennicutt – Schmidt relation

$$\mathrm{SFR} \propto \rho_{\mathrm{gaz}}/\tau_{\mathrm{ff}} \propto \rho^{1.5}$$

where $$t_{\mathrm{ff}} = (3\pi/(32\ \mathrm{G}\ \rho))^{0.5}$$ Cloud free-fall time,

Kennicutt-Schmidt

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{1.4}$$

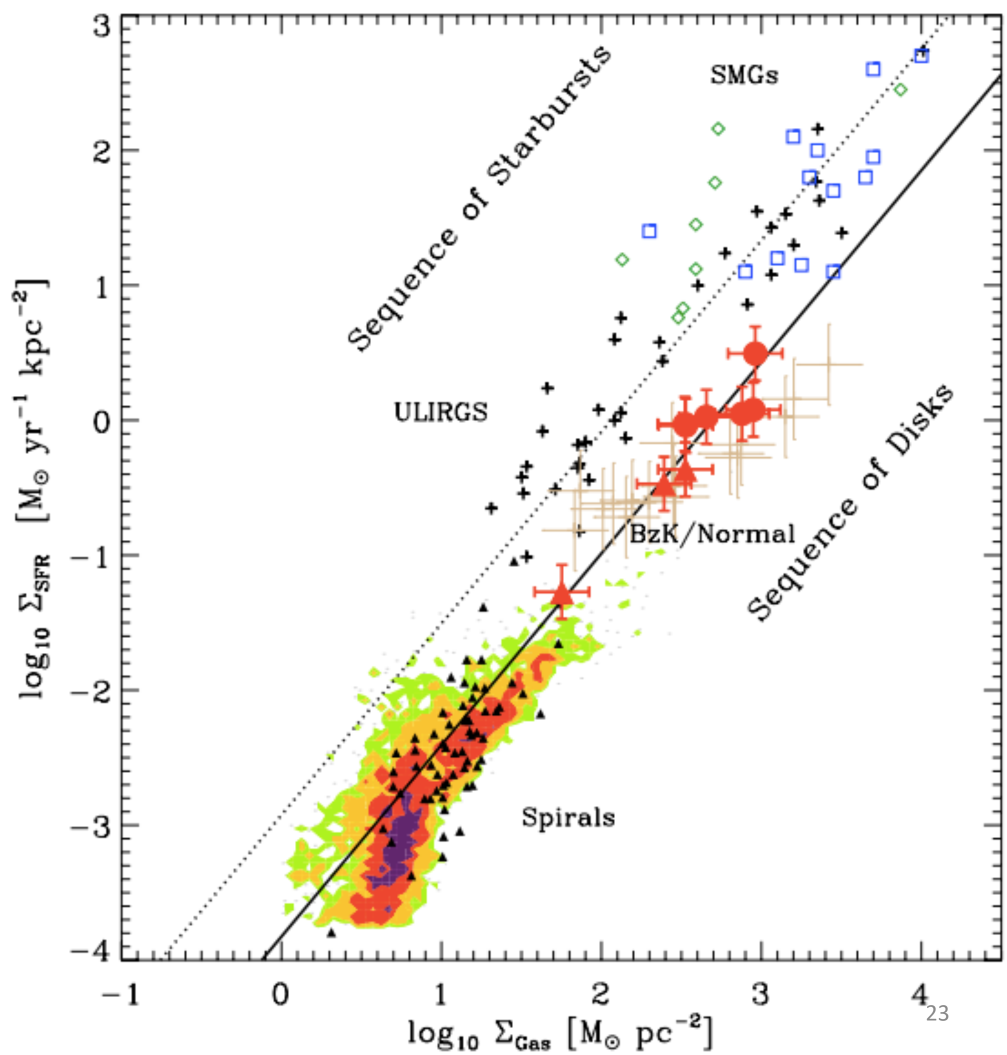


LSB = low surface brightness galaxy

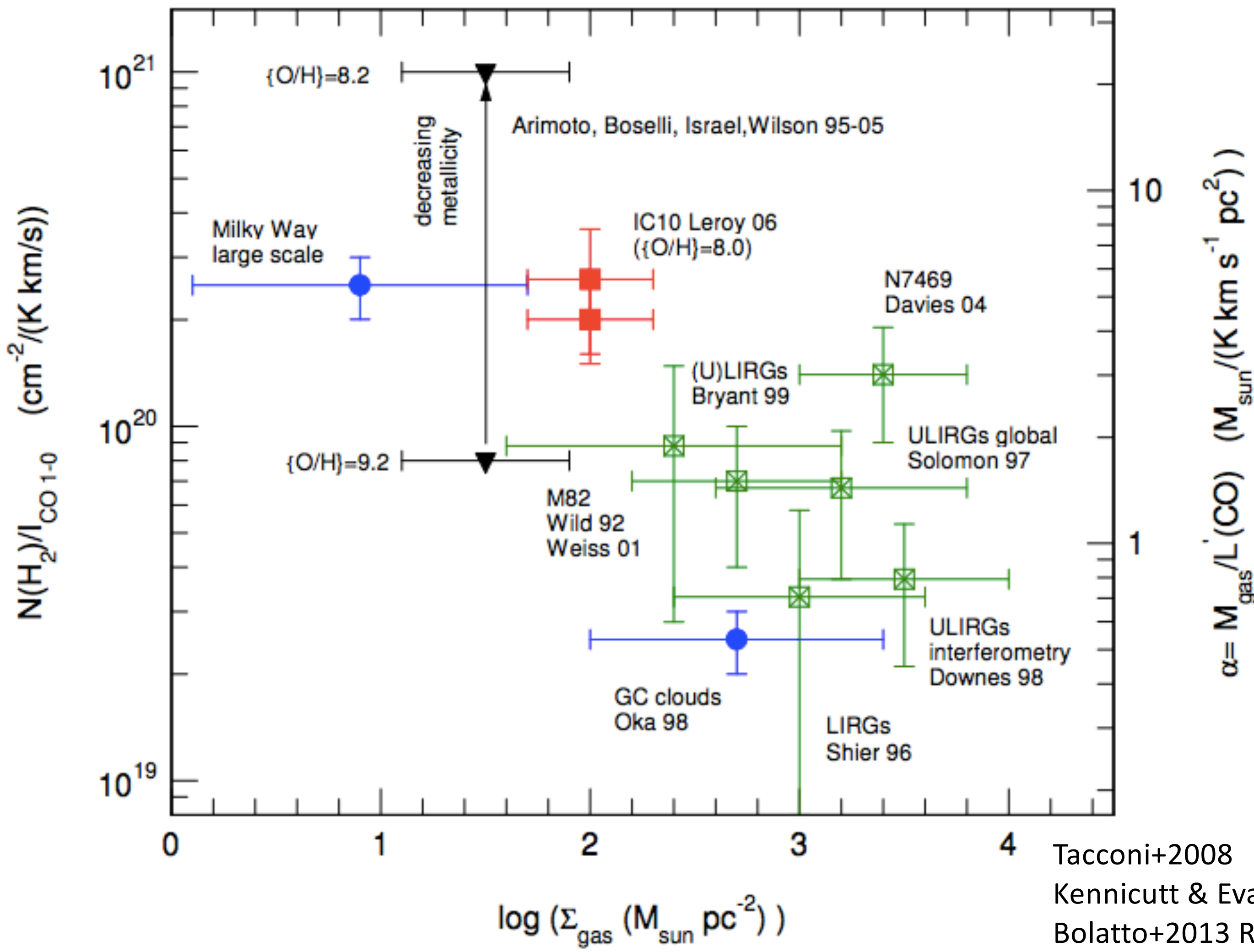
High Redshift K-S

Two different sequences?

Or an artificial X(CO) issue?



X(CO)



Tacconi+2008
Kennicutt & Evans 2012 Review
Bolatto+2013 Review

This results in a relation between $X_{\rm CO}$, Z', and $\langle W_{\rm CO}\rangle$:

$$X_{\rm CO} = \frac{6.75 \times 10^{20} \langle W_{\rm CO}\rangle^{-0.32}}{Z'^{0.65}}$$

Surface Brightness (K-km/s)

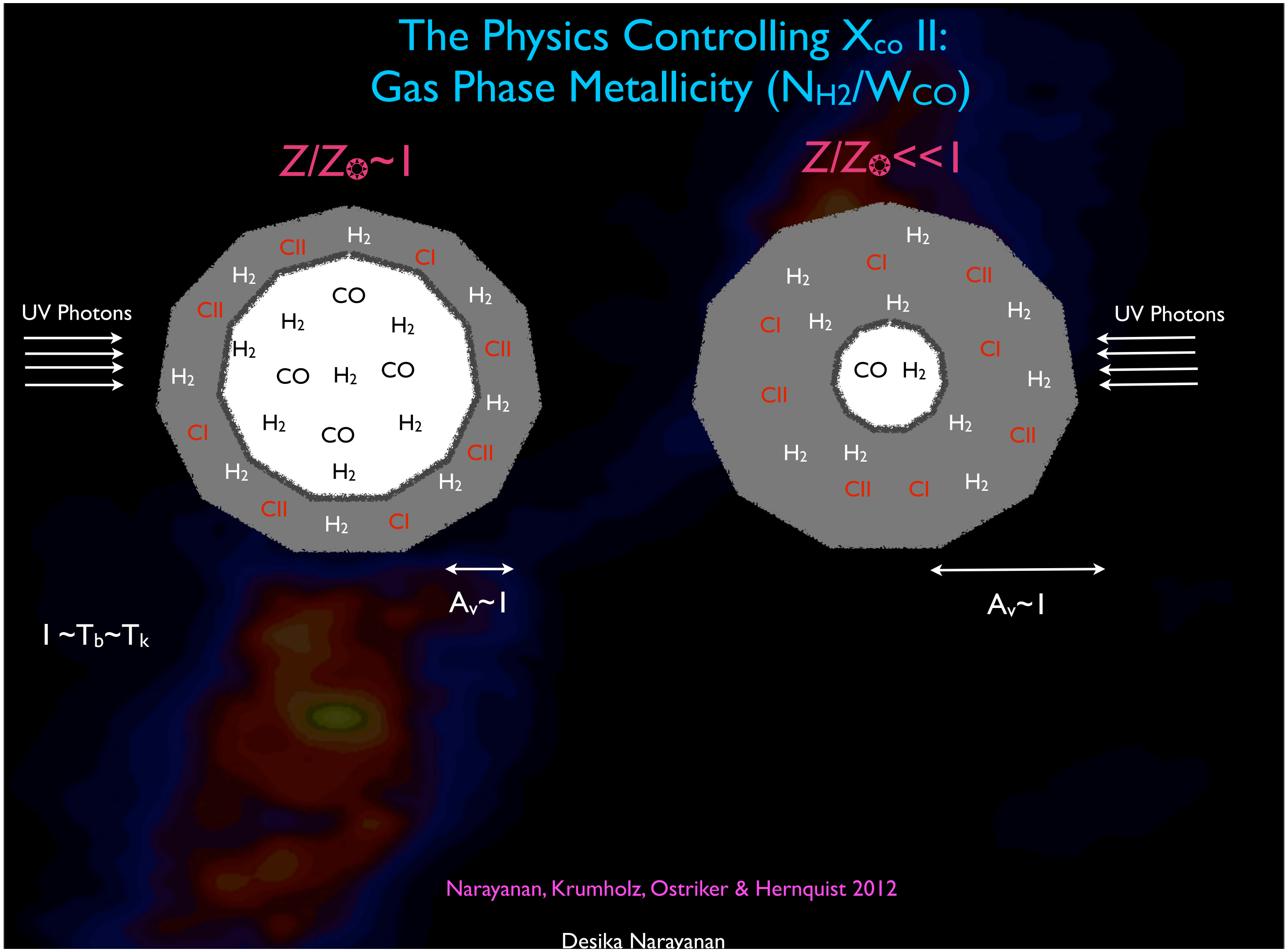
(units of $Z_\odot$)

Xco depends on galactic environment:

I. In high surface-density environments, $X_{\rm CO}$ is lower than the MW "constant" value due to high T and σ

II. In low metallicity gas, CO cannot easily survive and $X_{\rm CO}$ rises rapidly - can have $X_{\rm CO}$ a factor of 100 larger than MW

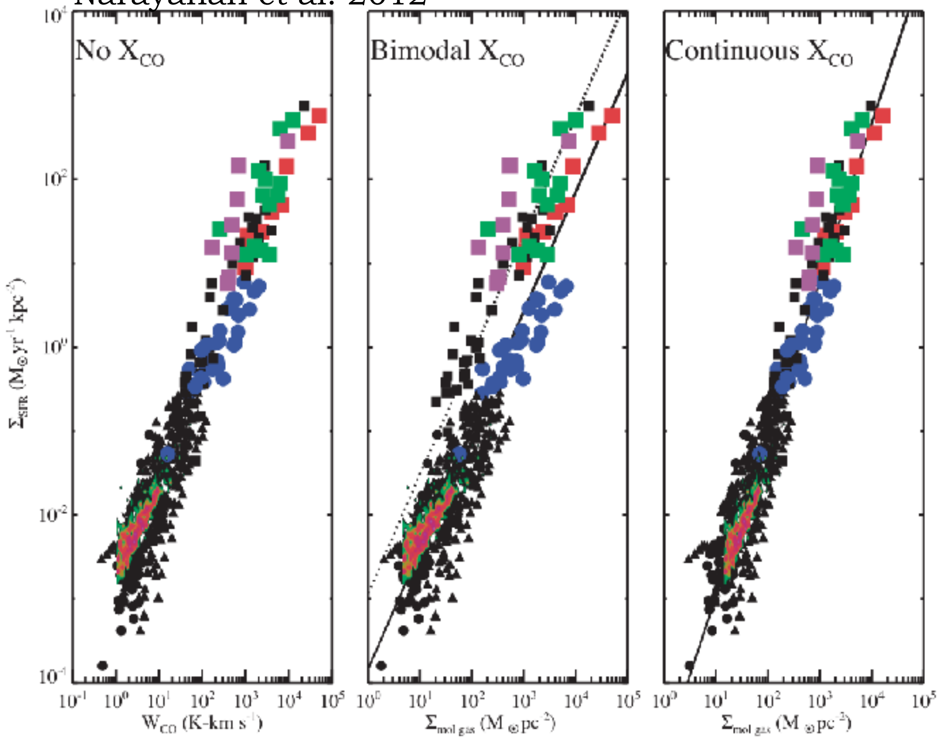
Narayanan, Krumholz, Ostriker, Hernquist 2012


The Physics Controlling X_{co} II:
Gas Phase Metallicity (N_{H2}/W_{CO})
$Z/Z_\odot \sim 1$
$Z/Z_\odot << 1$
UV Photons
UV Photons
CII
H_2
CI
CO
H_2
$A_v \sim 1$
$A_v \sim 1$
$I \sim T_b \sim T_k$
Narayanan, Krumholz, Ostriker & Hernquist 2012
Desika Narayanan

Bimodality in the SF Law?

Depending on the assumption of X_{CO} - 2 parallel sequences or one steeper sequence.

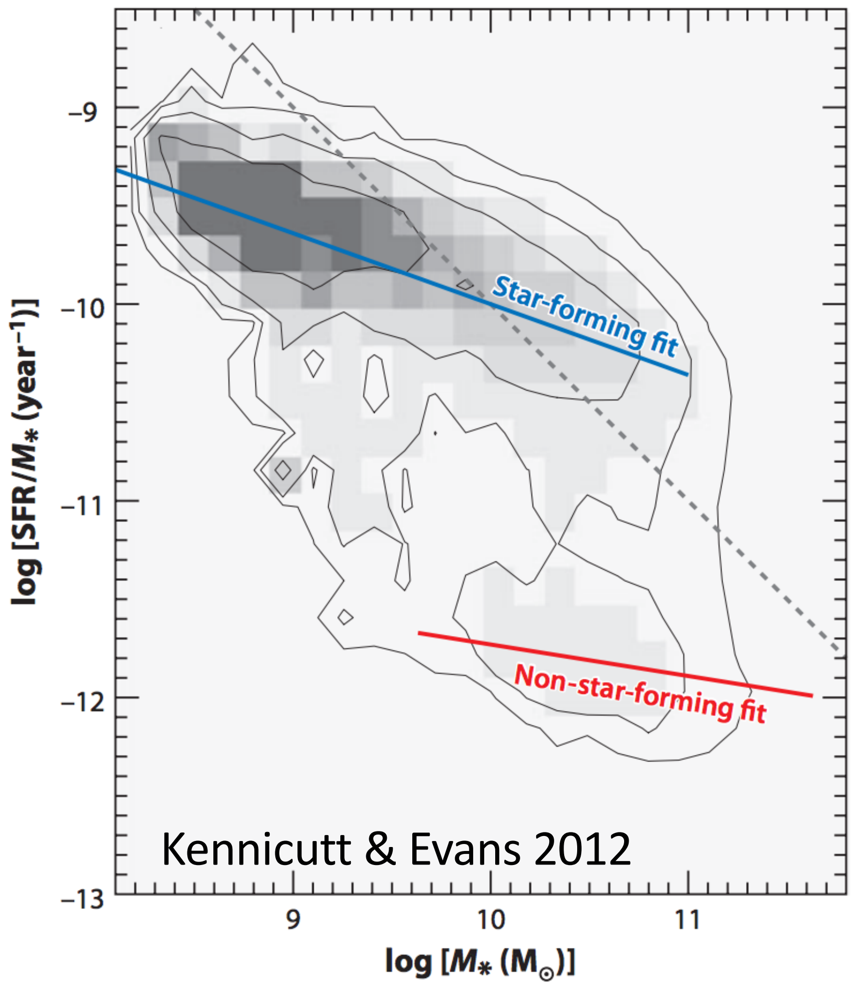
Narayanan et al. 2012



Star Formation Main Sequence

There is a tight relation between star formation rate and galaxy stellar mass

Brinchmann et al. 2004;Noeske et al. 2007; Elbaz et al. 2007, Whitake+2015



Star Formation Main Sequence

Whitaker+2012

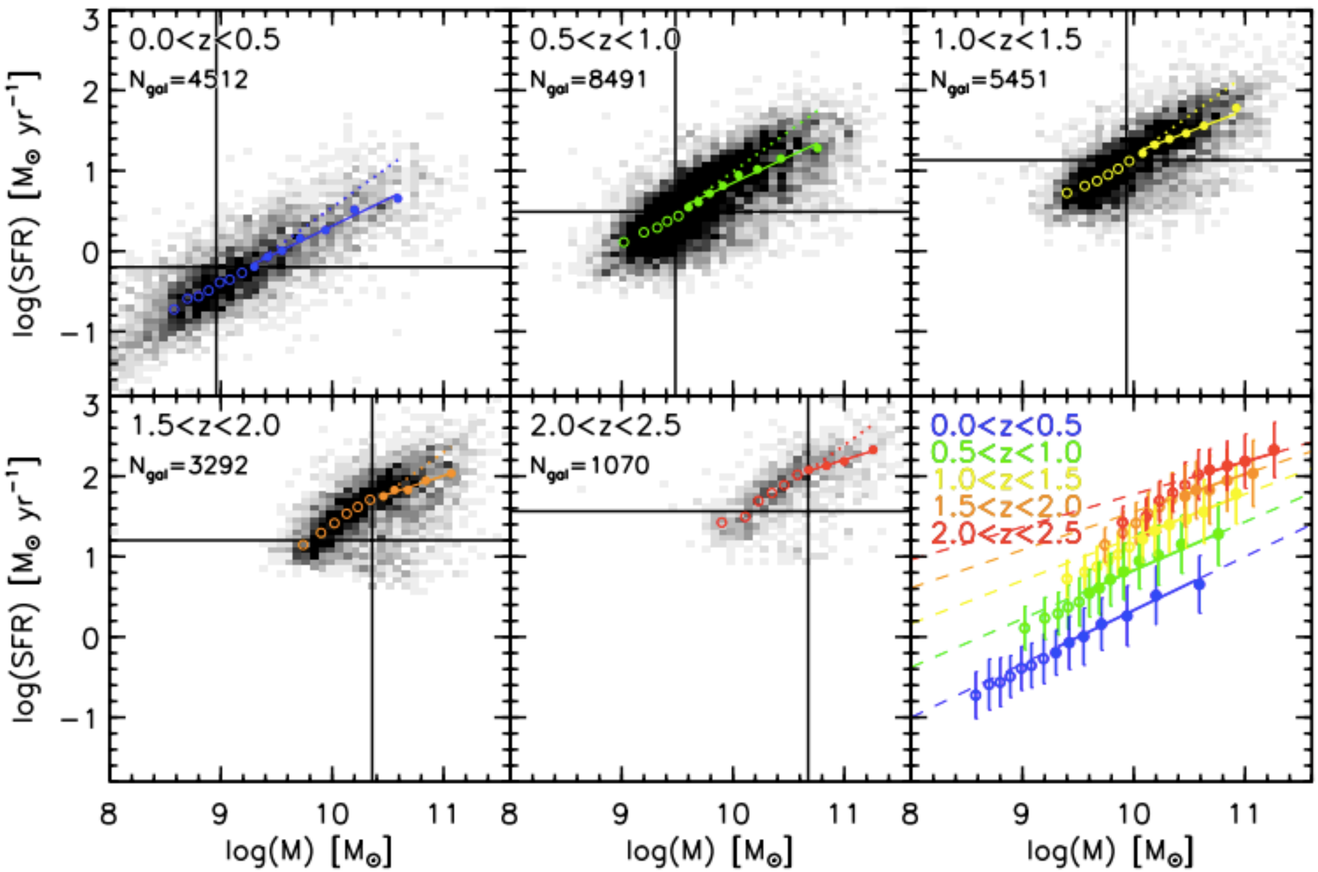


Figure 1. SFR mass sequence for star-forming galaxies has a nonlinear slope at $0 < z < 2.5$ (dotted line is linear). The running medians and scatter are color-coded by redshift, with a power law fit above the mass and SFR completeness limits (solid lines in bottom–right panel).

Cosmic downsizing: star formation is dominated by lower mass galaxies over time

SF Main Sequence Evolution

Whitaker+2012

$$\log(\mathrm{SFR}) = \alpha(z)(\log M_\star - 10.5) + \beta(z).$$

$$\alpha(z) = 0.70 - 0.13z$$

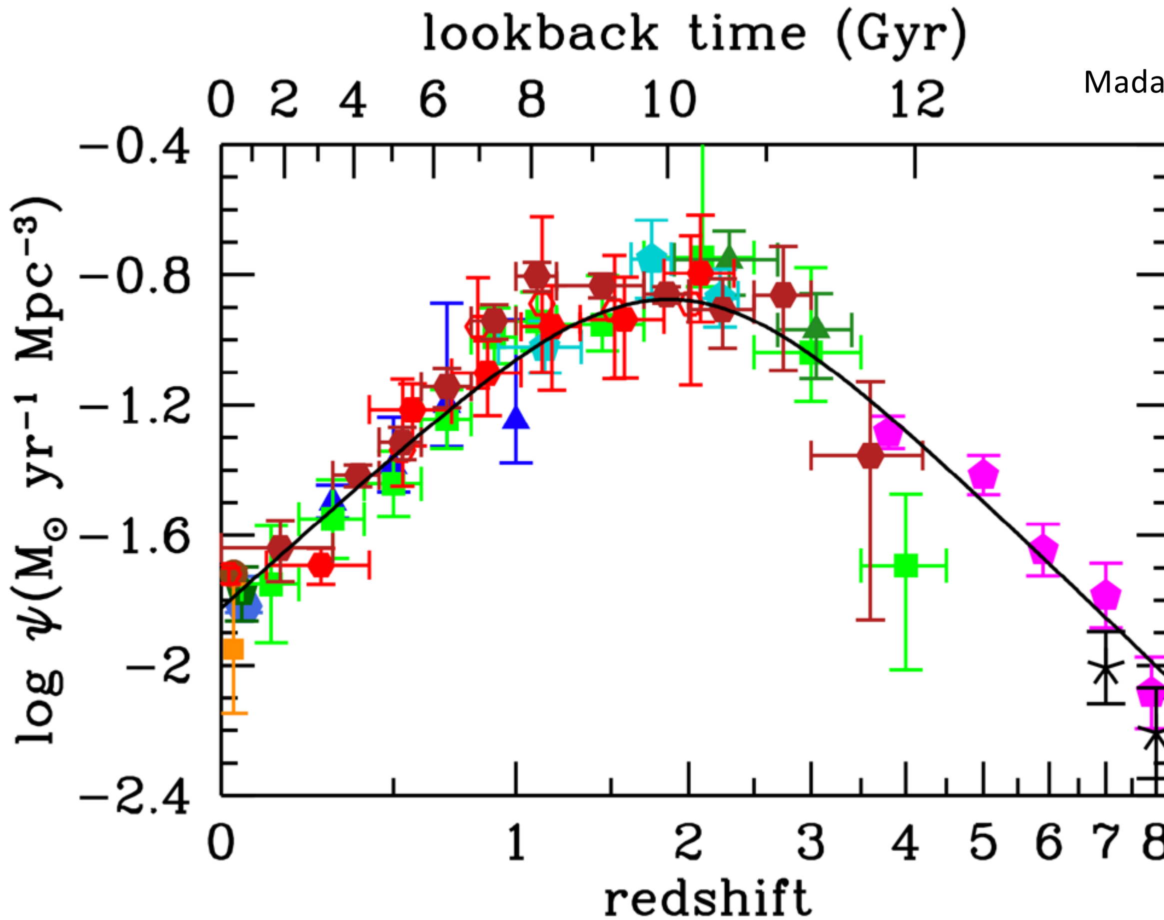
$$\beta(z) = 0.38 + 1.14z - 0.19z^2.$$

The slope of this relation is the specific star formation rate
sSFR = SFR / M*

z ~ 1 – 3: Peak Epoch of Cosmic Star Formation Activity

z ~ 2 :
Cosmic Noon:

Suggests this should also be the peak of merger activity



Madau & Dickinson (2014)