The Scaling of Star Formation: from Molecular Clouds to Galaxies

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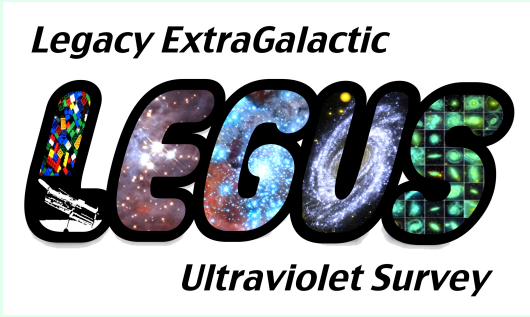
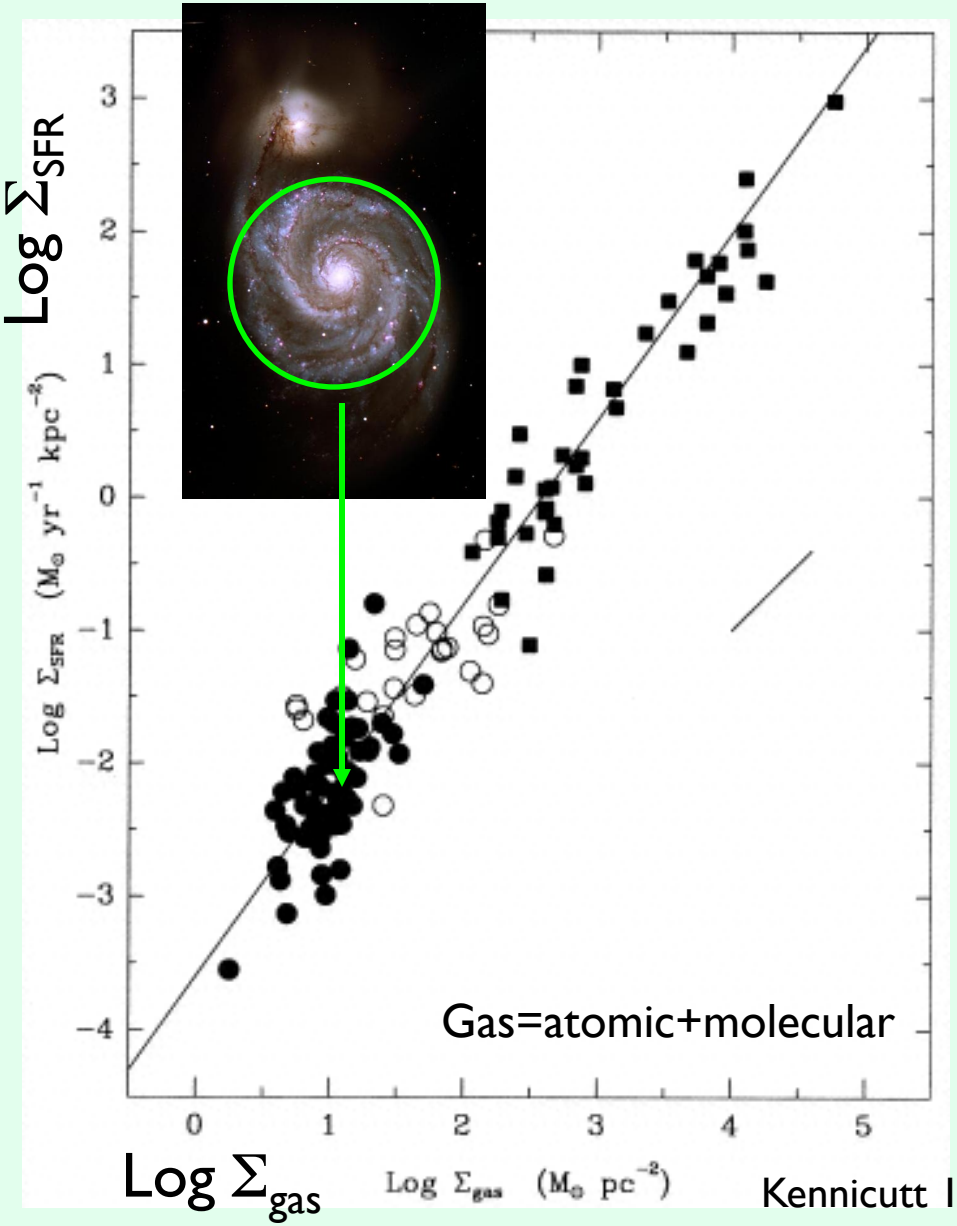


IAU Symposium 309, Galaxies in 3D across the Universe,
Vienna, Austria, July 7-11, 2014

Disclaimer

- A daunting task, that involves an incredible amount of literature *(the most recent review on the topic, Kennicutt & Evans, 2012, ARAA, 50, 531 contains in excess of 500 references)*, impossible to fit in the confines of a talk.
- Will need to be incomplete, and many excellent results will not be mentioned.

Some Historical Perspective



A fundamental question in galaxy evolution is how/when/where gas converts into stars.

This can be broken into a number of sub-questions:

- Is the gas reservoir of a galaxy connected to its SFR?

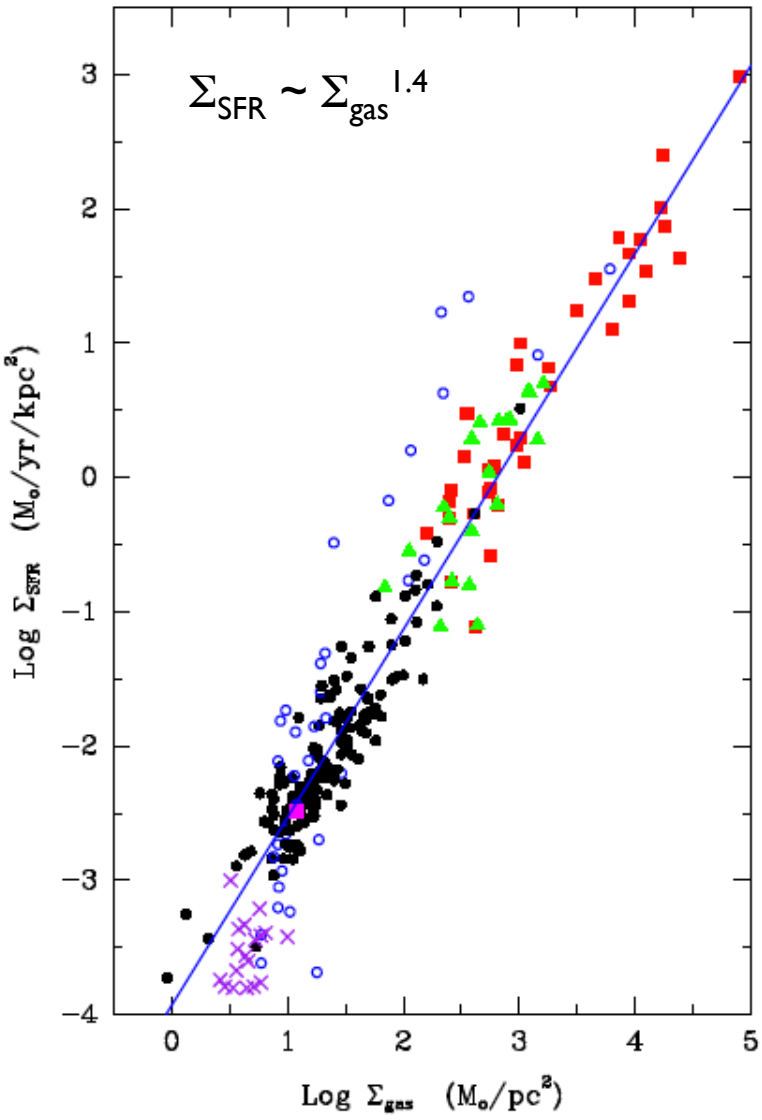
The existence of a relation between SFR and **total** gas mass (or their densities and/or projected surface densities) = YES!

$$\Sigma_{SFR} \sim \Sigma_{gas}^{1.4}$$

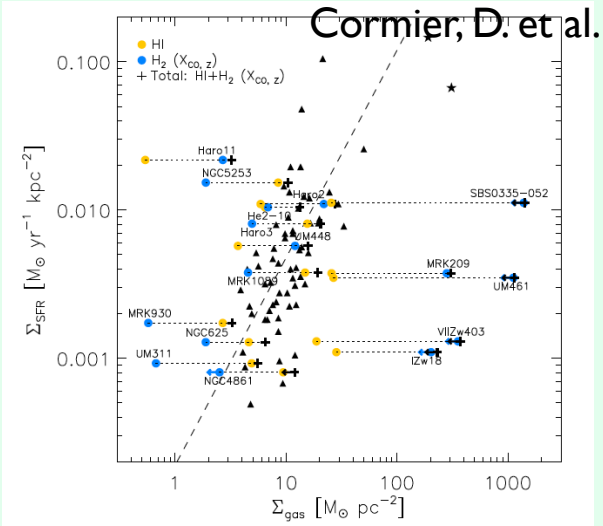
This sub-question remains, still today, a fundamental one.

Kennicutt 1998, ApJ, 498, 541

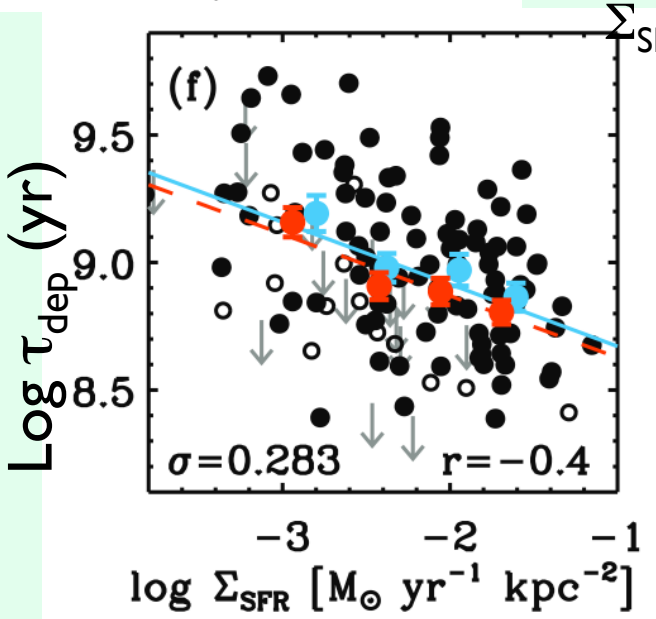
Fast Forward ~15 Years Later



Kennicutt & Evans 2012, ARAA



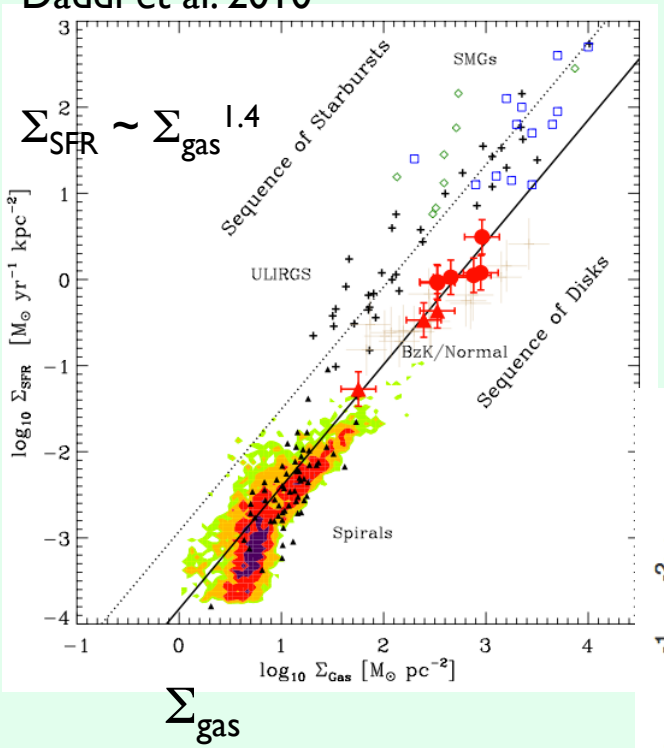
Cormier, D. et al. 2014 – DGS sample (dwarfs)



Saintonge et al. 2011 – massive galaxies

Breaking the Redshift Barrier

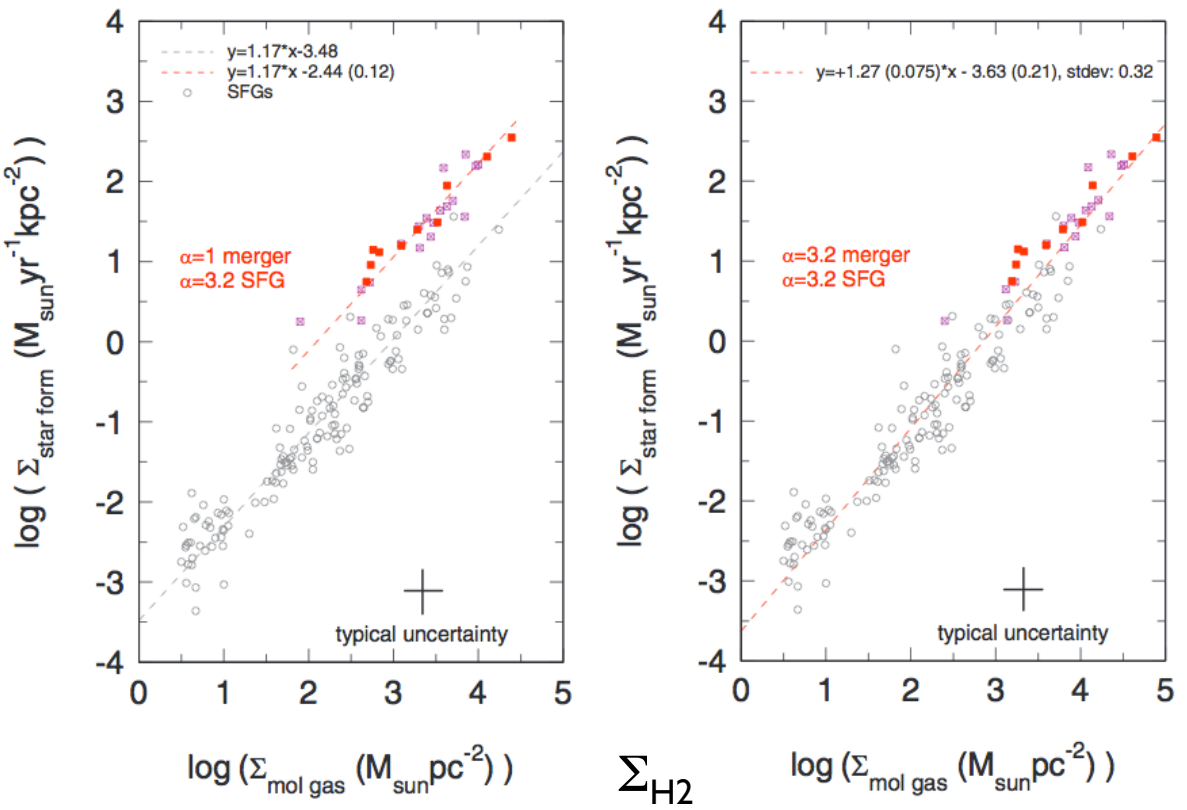
Daddi et al. 2010



The high redshift measurements suggest the need for two tracks: `starburst' and `disk' or `normal' galaxies.

Double track mainly driven by the choice of the CO-to-H2 conversion factor

$\Sigma_{SFR} \sim \Sigma_{H2}^{1.2\text{-}1.3}$ Genzel et al. 2010



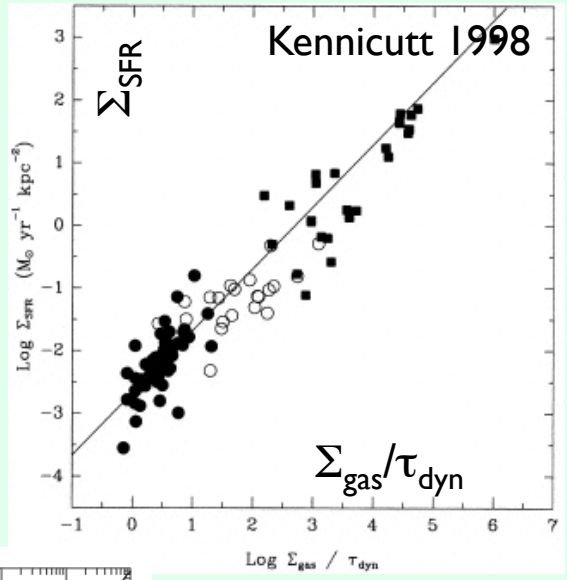
The issue is still open.
Include the possibility that the CO-to-H2 conversion factor may not be dichotomic, but may have a continuous trend (Narayanan et al. 2011)

The Role of Dynamical Timescales

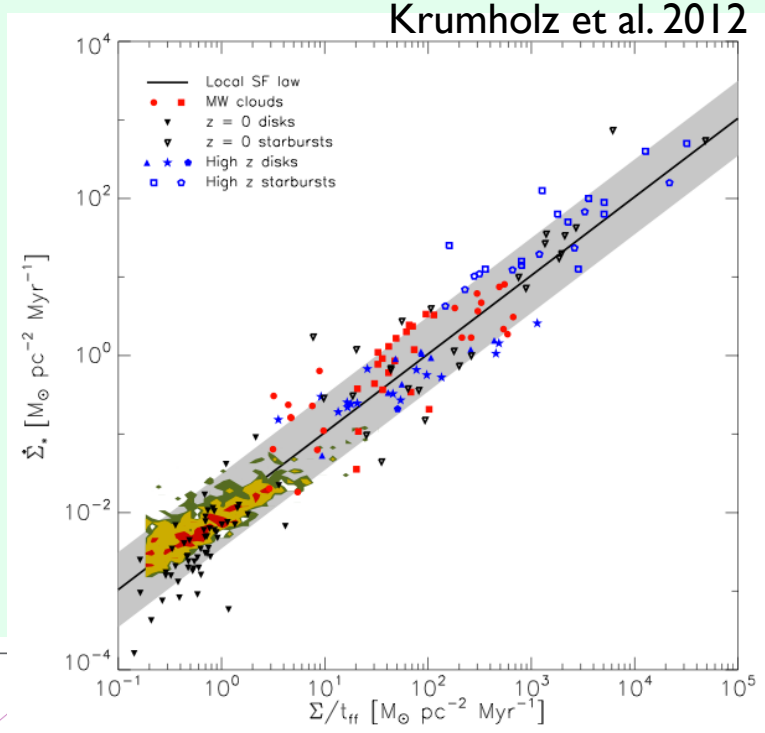
$\Sigma_{SFR} = \varepsilon_{ff} \Sigma_{gas}/\tau_{dyn}$

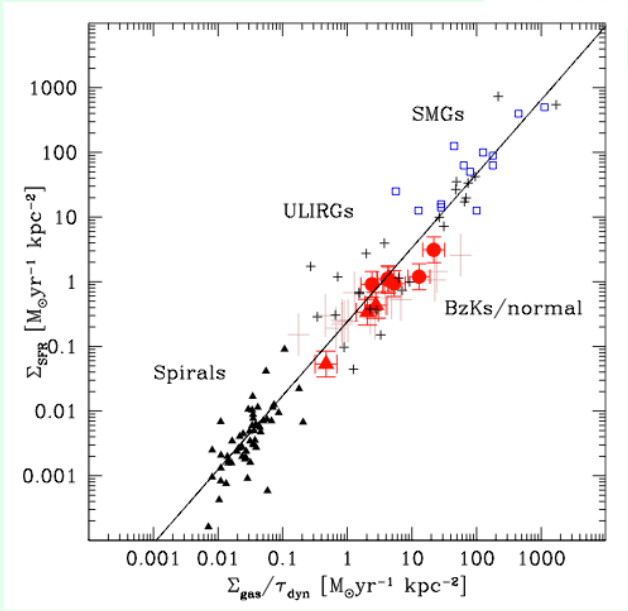
$\tau_{dep} \sim \tau_{dyn}/\varepsilon_{ff}$

$M_* = \varepsilon(M_* + M_{gas})$

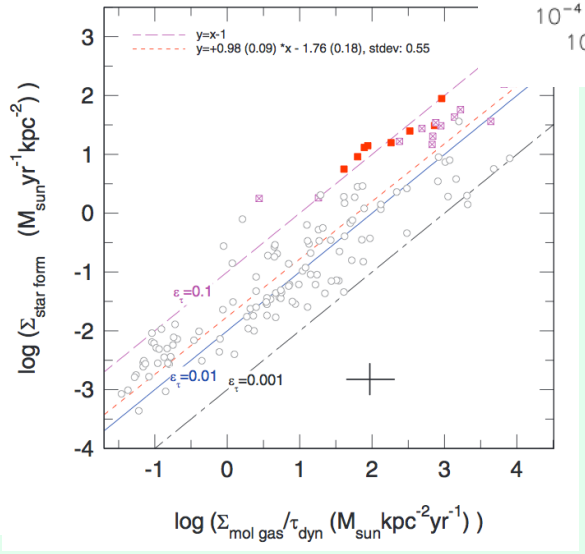


Krumholz et al. 2012





Daddi et al. 2010



Genzel et al. 2010

Still open:

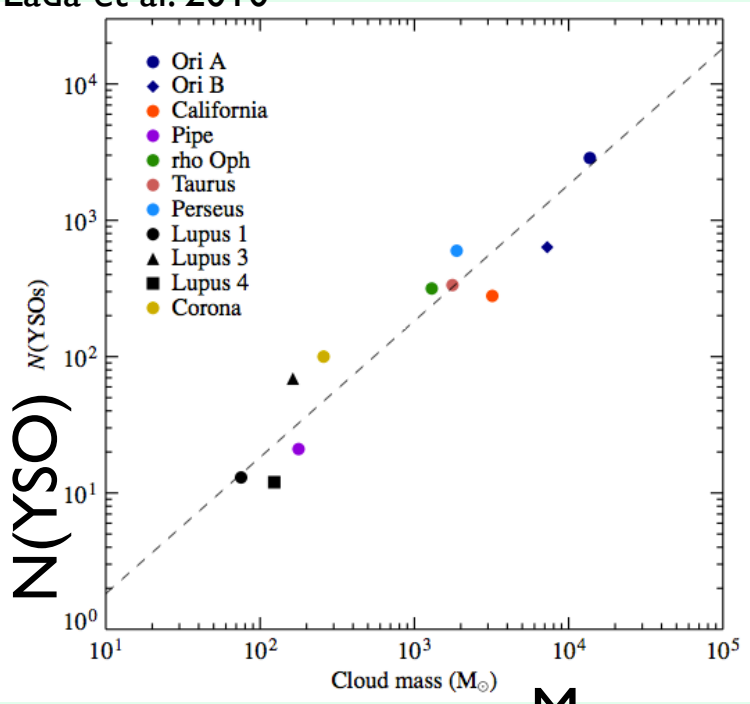
- Agree/physically justify the choice of τ_{dyn}
- Physically justify ε_{ff}

Linking Galaxies to Clouds and Clumps

The open issues from the previous slide are the basis for the second sub-question:
- How do we progress from the gas reservoir to the formation of stars?

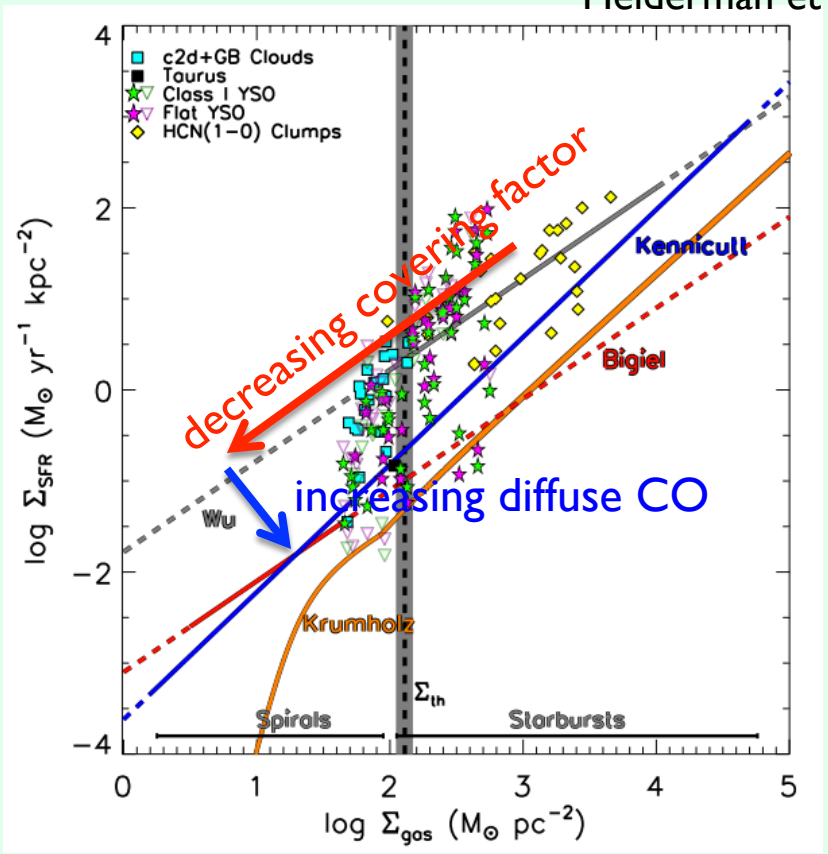
1. Within galaxies, molecular clouds are more closely related to SF than total gas.
2. Dense gas within clouds is more closely related to SF than the whole cloud.
3. ….

Lada et al. 2010



N(YSO) / M_{dense}

Heiderman et al. 2010



Tracing Gas

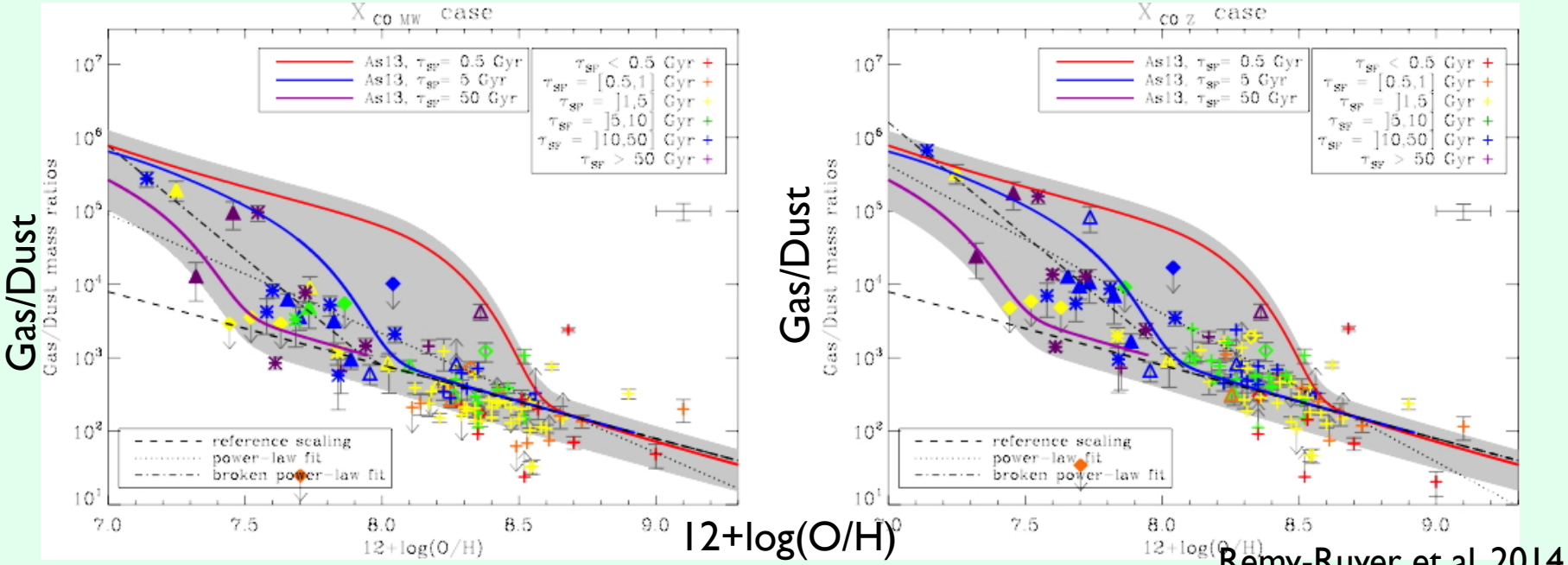
(a.k.a.: the covering factor and diffuse CO are not your only worry…)

1. $M_{dust} = D/G\ [M(HI) + M(H_2)]$

- FIR SED modeling uncertainties ~2X (Galametz et al. 2012)
- submm/mm excess (e.g., Galametz et al. 2009, 2013, Kirkpatrick et al 2013)
- D/G may be not linearly dependent on metallicity:

2. $M(H_2) = \alpha_{CO}\ L(CO)$

- $\alpha_{CO} = \alpha_{CO}(Z, T, \sigma_{disp})$ (Bolatto et al 2013)
- Systematic variation of CO(2-1)/CO(1-0) ratio (~2X, Koda et al. 2012, Narayanan et al. 2008, Juneau et al. 2009)
- Higher CO transitions trace warm gas (e.g., Kamenetsky et al. 2012, Rigopoulou et al. 2013, Rosenberg et al. 2014)

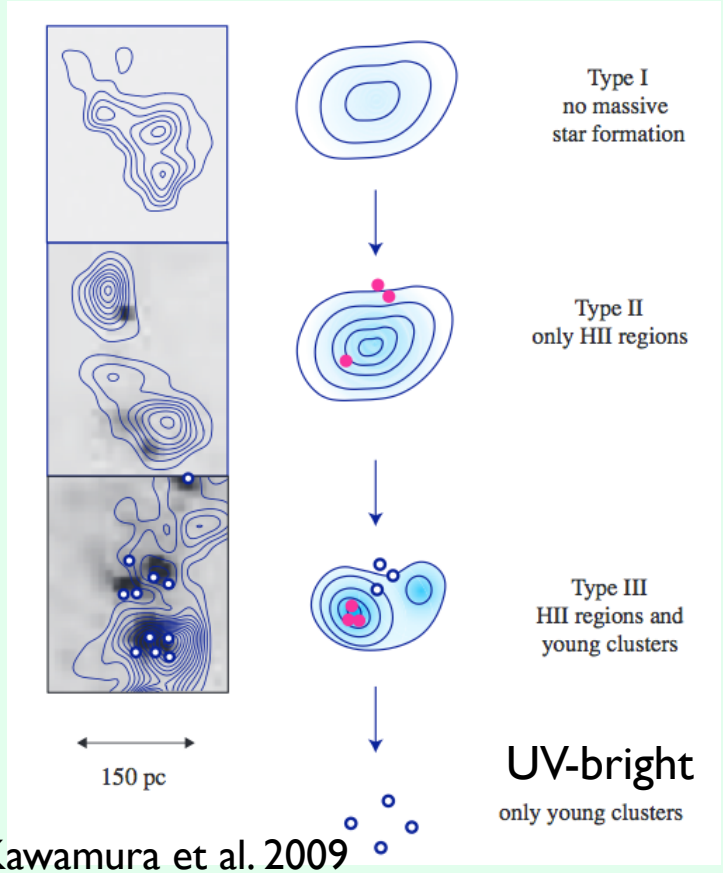


Remy-Ruyer et al. 2014

Tracing Star Formation

Whichever tracer is being used (FIR, UV, Hα, etc., or combinations thereof), its fidelity is often non-transferable from one system to another.
Zooming in from whole galaxies (~isolated systems) to regions within galaxies (interconnected systems) implies:

1. Timescale of gas-SF association



Kawamura et al. 2009

2. Timescale of tracer (stellar population diffusion)

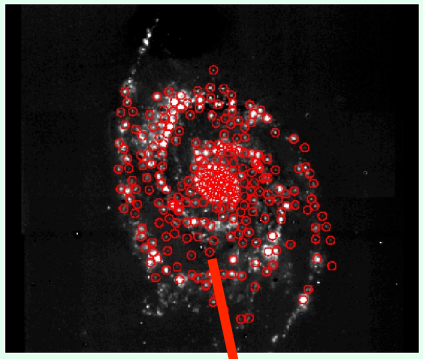
GALEX FUV+NUV
NGC628, 7.5 Mpc

~30%-50% of observed FUV not associated with current SF

~30%-60% of observed Hα not associated with current SF (DIG)
~20%-60% of observed L(24) not associated with current SF. Fractions increase for longer wave IR.

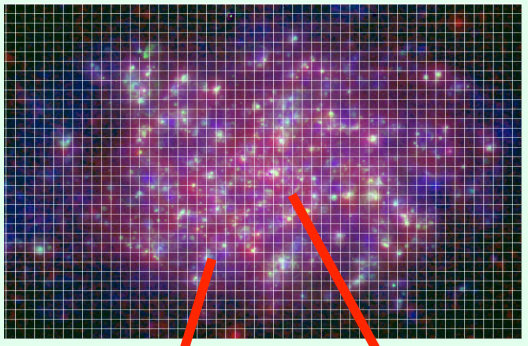
(Liu et al. 2011, Li et al. 2010, 2013, 2014, Johnson et al. 2013, C. 2013, Calapa et al 2014)

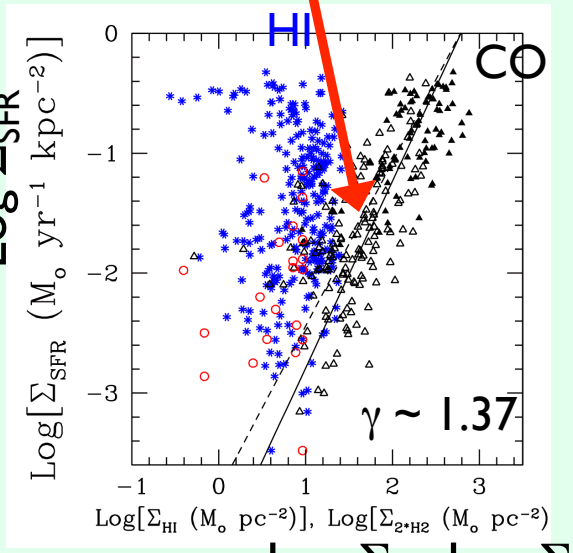
In-Between GMCs and Galaxies



Two main ways to analyze regions within external galaxies.

$\Sigma_{SFR} \sim \Sigma_{H2}^{\gamma}$

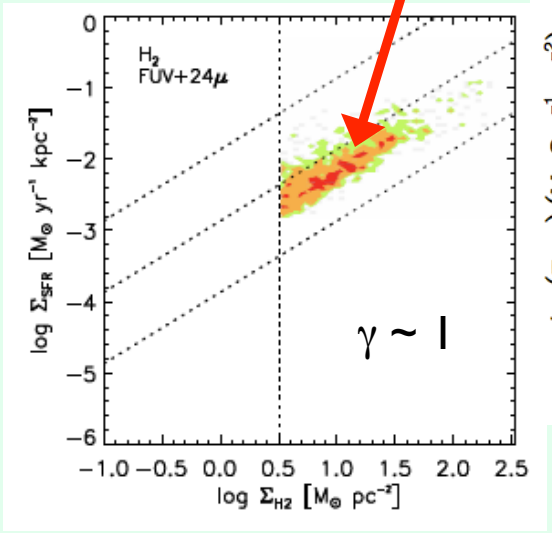




Log Σ_{SFR}

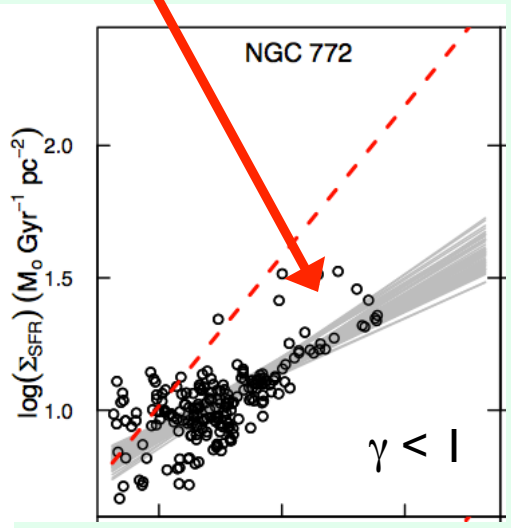
Log Σ_{HI}, Log Σ_{H2}

Kennicutt et al. 2007, Liu et al. 2011, Momose et al. 2012, …



Log Σ_{H2}

Bigiel et al. 2008, Blanc et al. 2009, Rahman et al. 2011, …



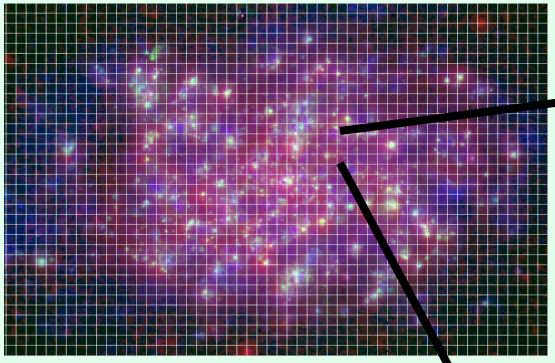
Log Σ_{H2}

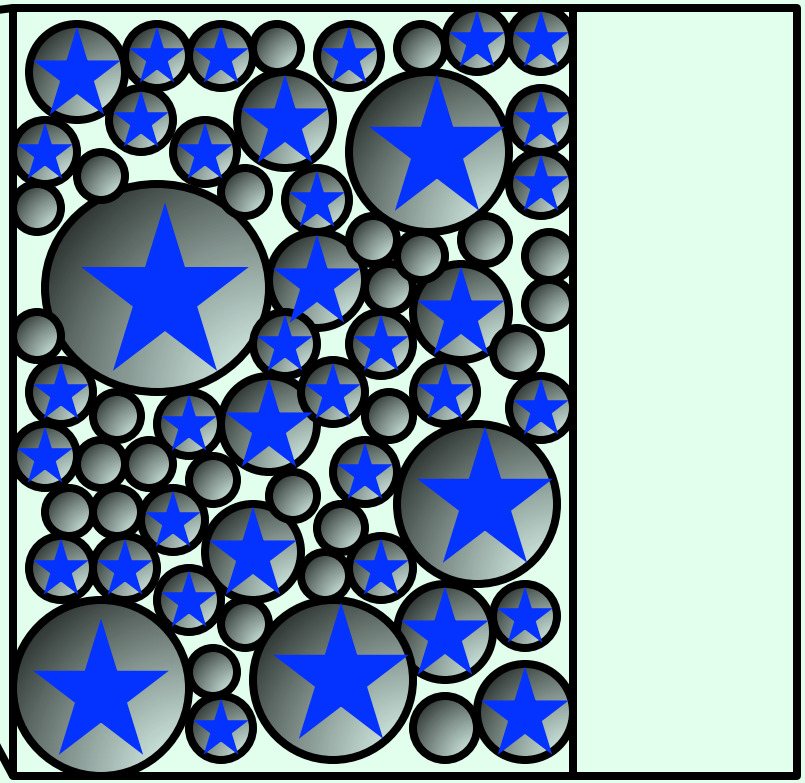
Shetty et al. 2013

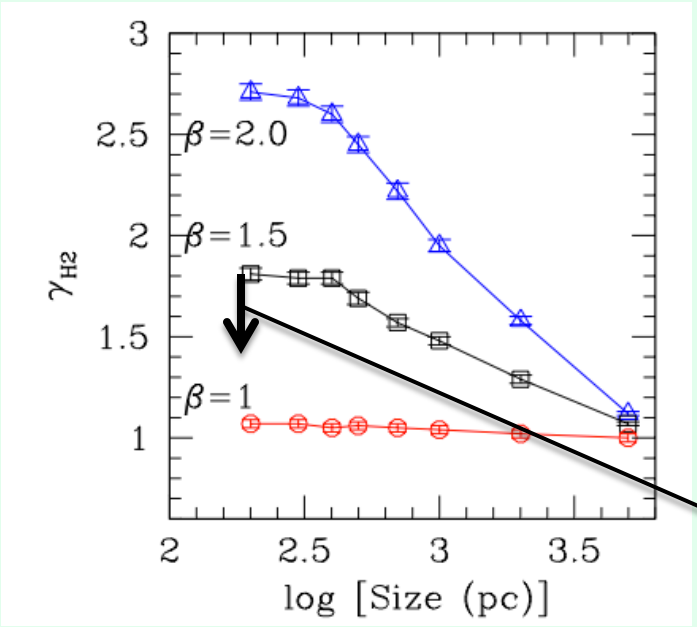
The Effects of Cloud Sampling and Covering

C+2012

Bisector fitting
β = input slope
γ = recovered slope







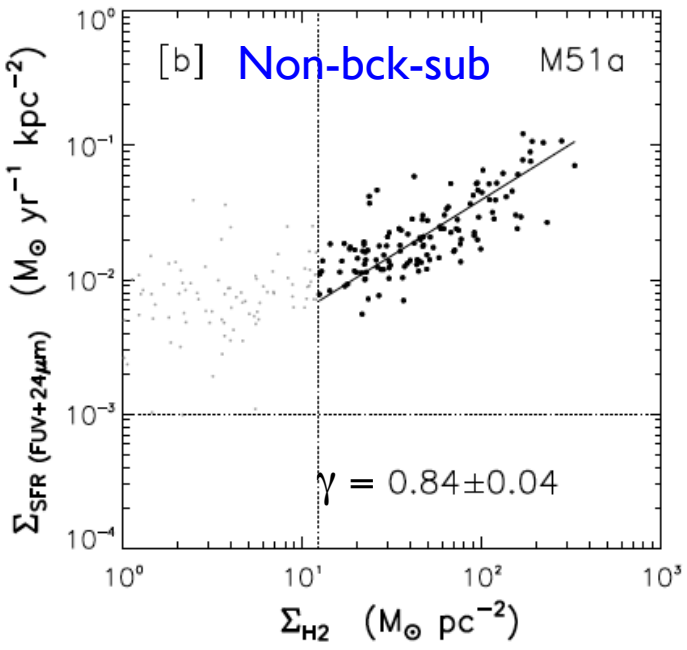
Decreasing $R(cloud)_{max}$

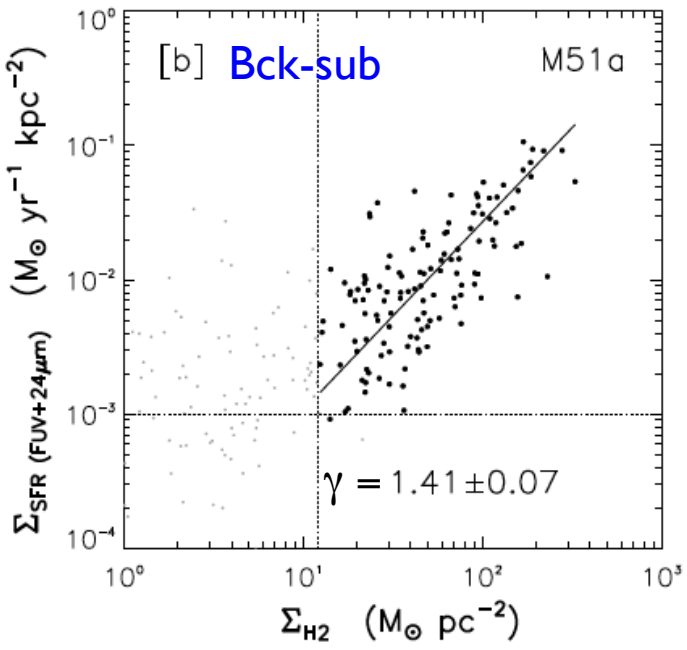
Monte Carlo simulations:

- Distribution of covering factors
- Range of cloud mass functions
- R(cloud) ~ 1 - 300 pc

Decreasing γ for increasing region size
(trends are more extreme for $R(cloud)_{max}$<300 pc)

Effects of SFR Tracer Contamination

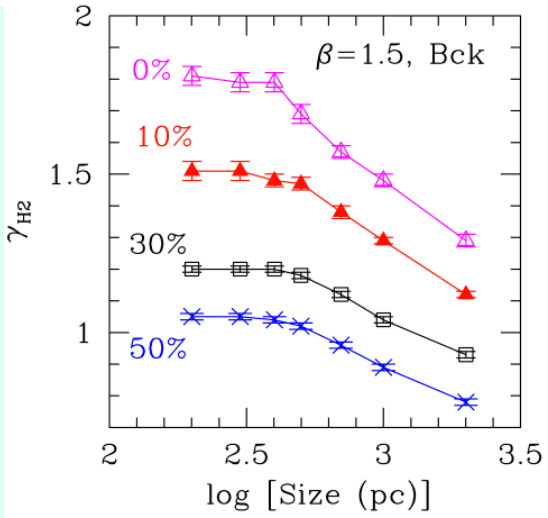




Liu et al. 2011

← Data

Simulations →

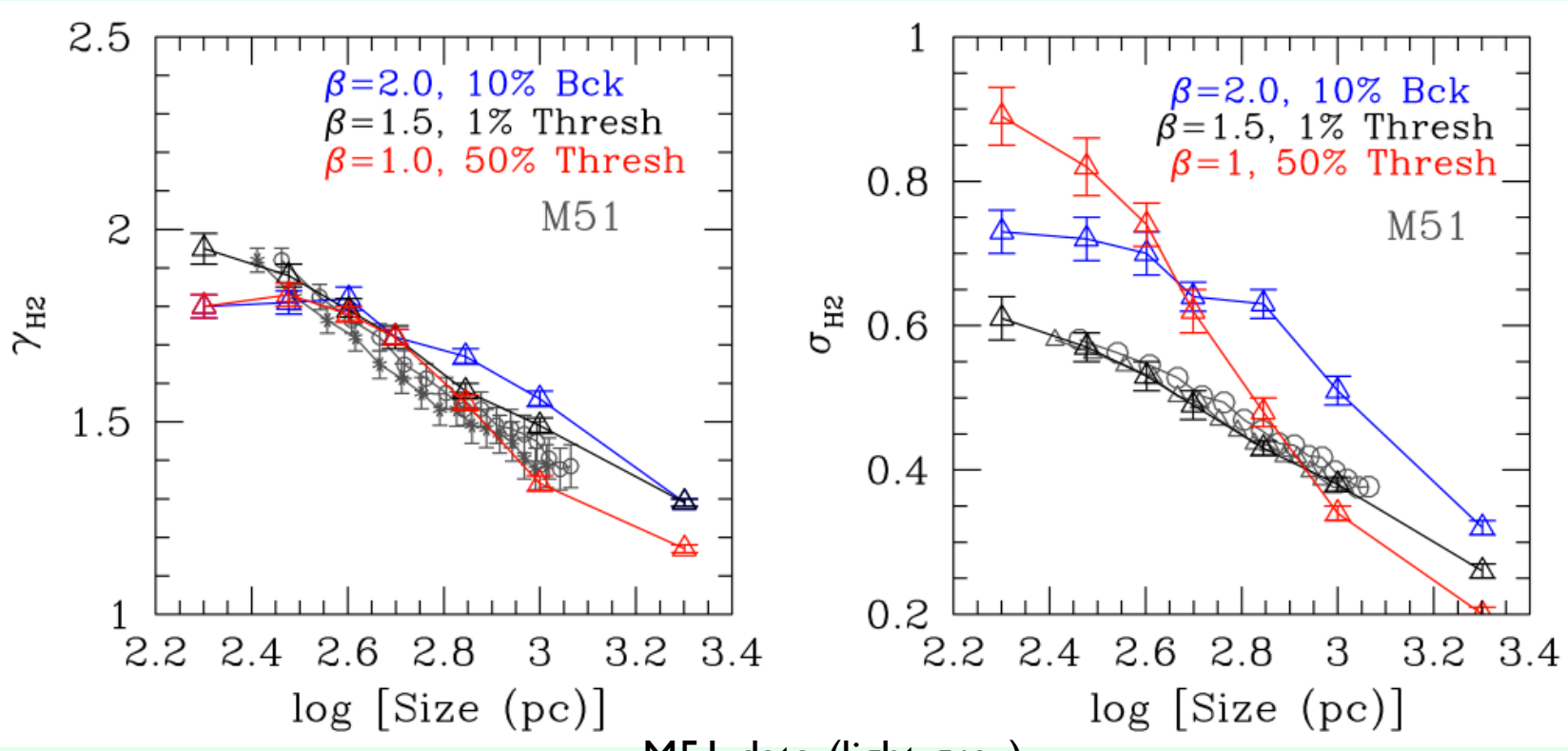


C+2012

Inclusion of non-SF background stellar light to the SFR tracer flattens the recovered slope

A ~50% contamination gives γ<1 at 1 kpc (smaller region sizes for $R(cloud)_{max}$ < 300 pc)

Not Only Slope, but also Scatter…



M51 data (light grey)

Decreasing slope for increasing region size is found in the data when removing contamination from SFR tracers (Liu et al. 2011)

Expected for increasing cloud sampling.

To explain both slope and scatter, about 1% of `diffuse' CO is required in M51 (would go up for $R(\text{cloud})_{max} < 300$ pc).

In Summary

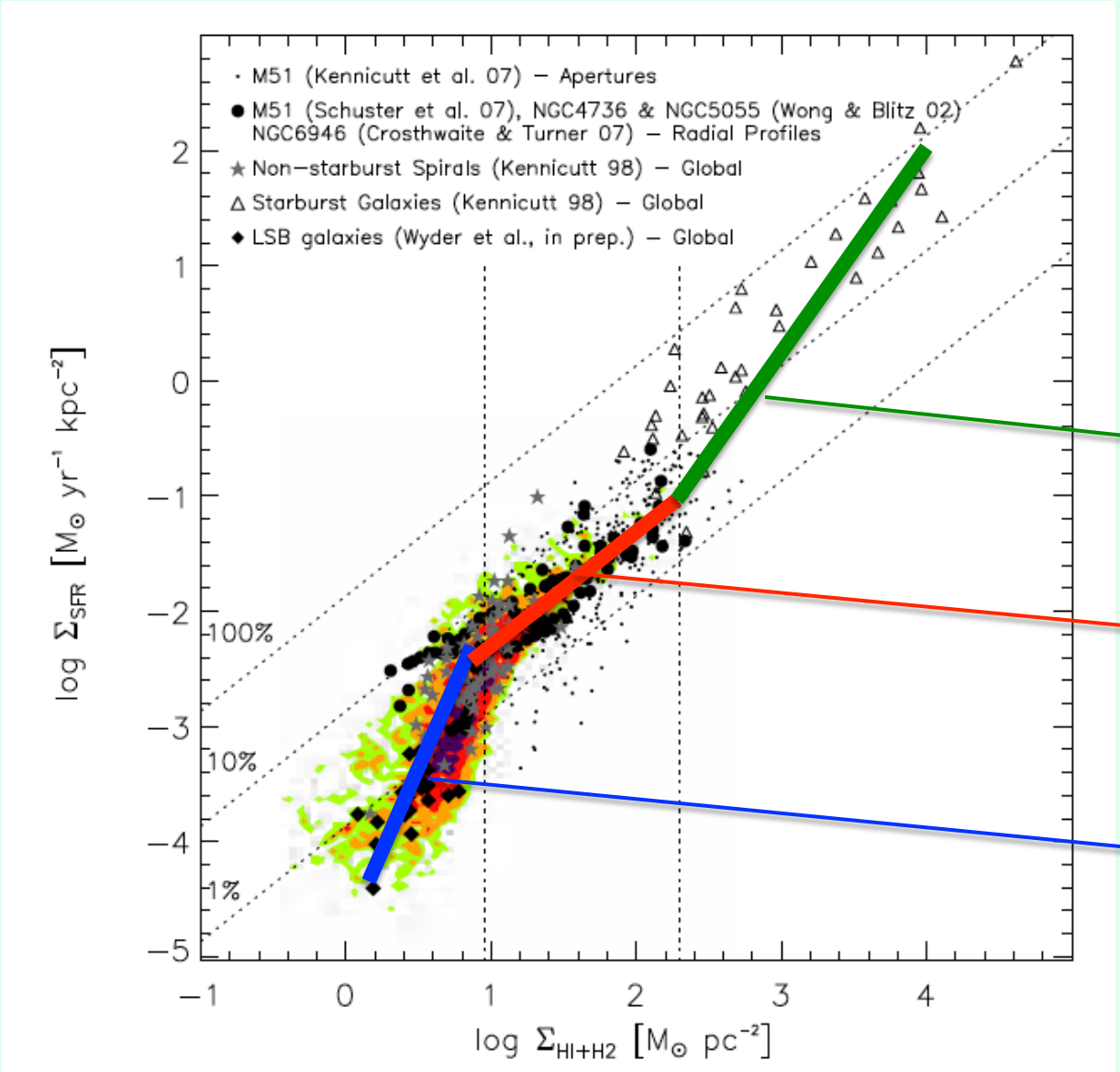


Figure from Bigiel et al. 2008

Merging of clouds, physical relation between gas and SF

Cloud sampling and covering factors dominate; geometry rather than physics

Stochastic regime of cloud and star formation (similar to a threshold)

Conclusions

- Much progress both on the observational and theoretical fronts has been accomplished over the past ~15 years, but connection between the large scale (whole galaxy) and small scale (clumps, cores) SF is still elusive (Kennicutt & Evans 2012, ARAA)

- On the observational front:
  - Investigate and understand how tracers of SF work on intermediate (~kpc) scales
  - Investigate and understand how the various phases of the cold gas link to each other at different scales
  - For external galaxies, best accomplished with high-angular resolution facilities (HST+JWST to trace SF; ALMA+EVLA to trace gas)

- Important to connect SF and gas on the intermediate scales, while trying to control for contaminating/diluting factors.
  - One option is to avoid `blind' region selections.