Connecting Star Formation and Gas in Galaxies

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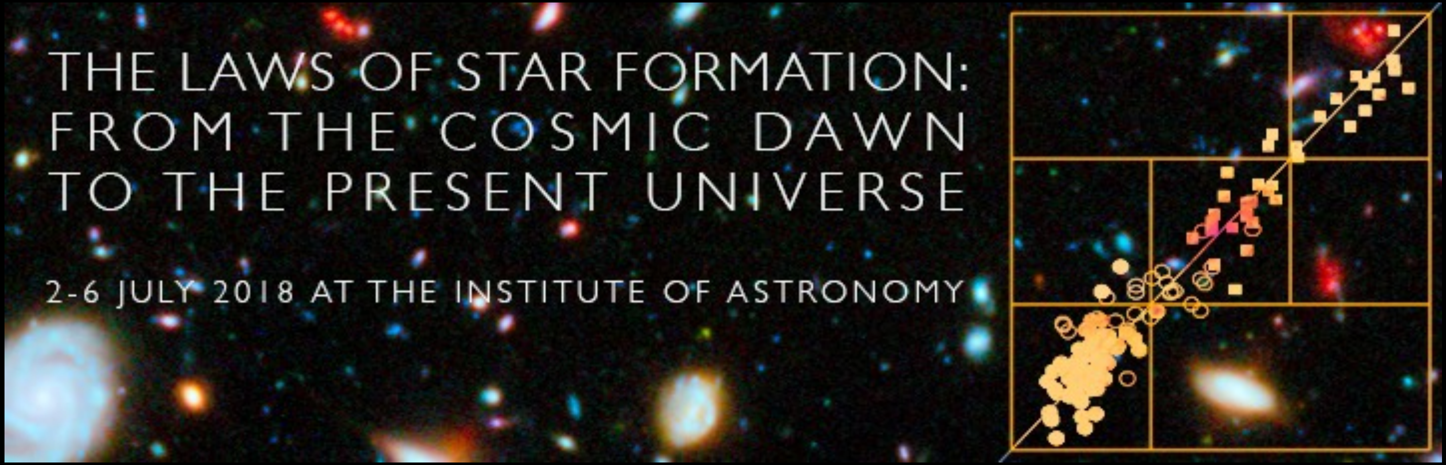
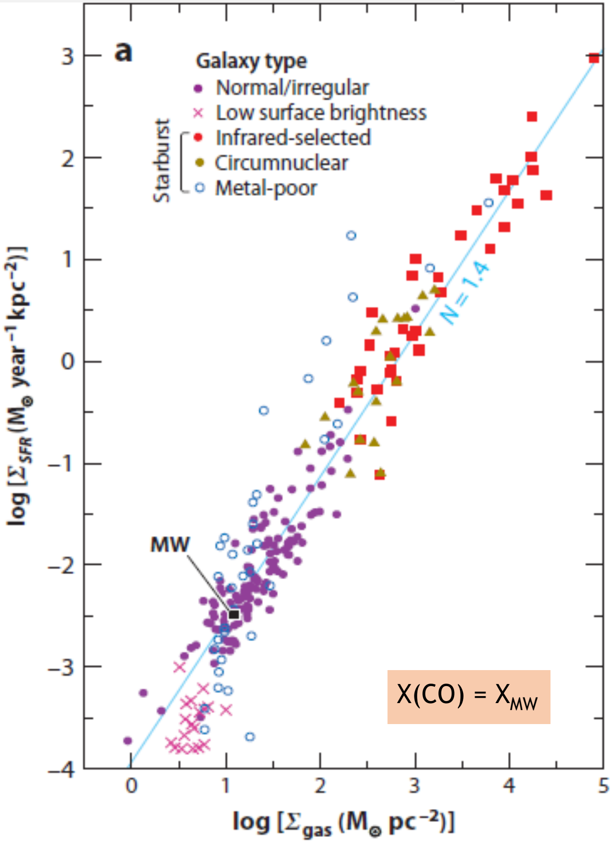


The Challenge: Identify the key physical drivers and regulators of star formation, and their defining physical (and algorithmic) relationships.

Why Should We Care?

- As remarkable scaling laws of nature that beg to be understood
- As key sub-grid inputs ("recipes") for models and simulations of galaxy formation and evolution
- As vital boundary conditions and clues to the physics of star formation generally



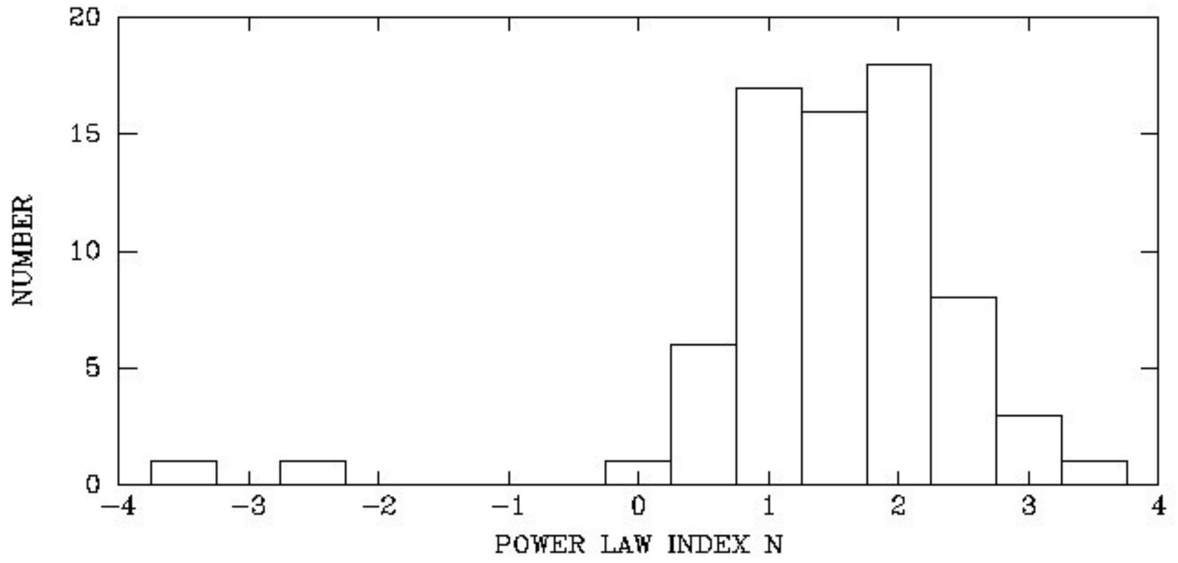
Kennicutt & Evans 2012

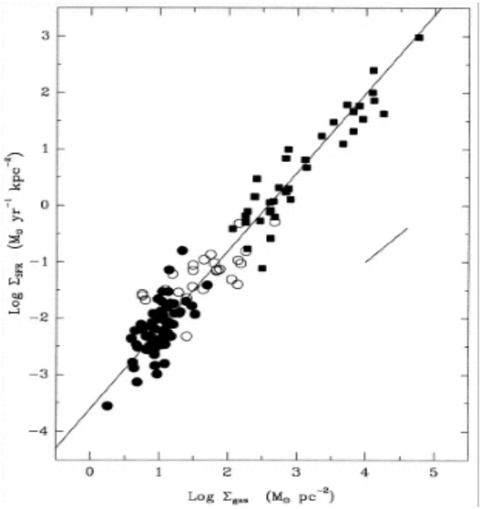
Unraveling the critical path to star formation is complicated!

- accretion from the IGM
  - may ultimately regulate the global SFR
- formation of a neutral ISM (cooling, thermal instabilities)
  - easy for disks, difficult for massive spheroids
  - dictated by gas density and ambient UV radiation field
- formation of bound interstellar clouds (Jeans/gravitational instabilities)
  - dictated by gas density and galactic shear, tidal field, shocks
- formation of a cool neutral phase (thermal/pressure instabilities)
  - dictated by ISM pressure and temperature
- formation of molecular gas (phase instability)
  - dictated by cloud opacity (to photodissociating UV) and ambient UV field
- formation of bound molecular cloud clumps, cores
  - dictated by Jeans, fragmentation, turbulence, competitive accretion…
- formation of stars, planets
  - complicated(!), but appears to be deterministic(?) once cores are formed
- re-injection of energy to ISM from feedback processes
- *All above are necessary conditions, but which are critical drivers is subject to debate. The critical path may change in different interstellar environments, galactic environments, cosmic epochs, etc.*

- 1959: Maarten Schmidt introduces concept of power law scaling between volume densities of cold gas and stars: Schmidt law: $\rho_{SFR} = a\, \rho_{gas}^{n}$

- 1963: Schmidt introduces scaling relation in terms of surface densities of gas and stars: $\Sigma_{SFR} = A\, \Sigma_{gas}^{N}$

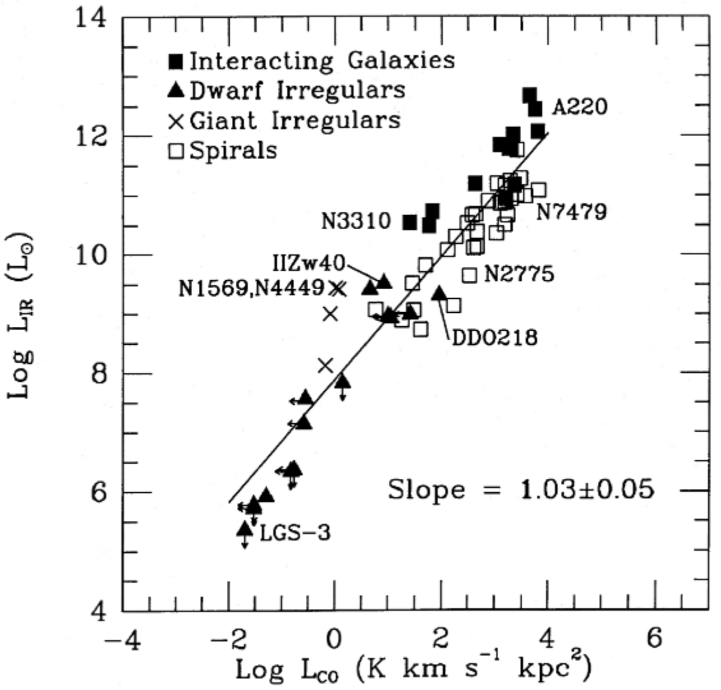




Kennicutt 1997, in The Interstellar Medium in Galaxies, ed. J.M. van der Hulst (Springer)

1980s – 1990's

- Key enablers
  - surveys of resolved HI in nearby galaxies (mostly WSRT)
  - surveys of resolved CO emission in nearby galaxies (mostly FCRAO)
  - quantitative diagnostics, surveys of SFRs (mostly KPNO, Steward!)
- Go beyond correlations of integrated masses/ luminosities to analyze surface densities
  - avoid meaningless "cloud counting" linear relations
  - low spatial resolution of CO data limited study to global and radially-averaged SF vs gas density correlations



Tacconi & Young 1987

21-CM LINE STUDIES OF SPIRAL GALAXIES. II. THE DISTRIBUTION AND KINEMATICS OF NEUTRAL HYDROGEN IN SPIRAL GALAXIES OF VARIOUS MORPHOLOGICAL TYPES

A. BOSMA [a)]

The Palomar-Westerbork survey of northern spiral galaxies

B. M. H. R. Wevers, P. C. van der Kruit and R. J. Allen (*)

The HI properties of spiral galaxies in the Virgo Cluster. III. The HI surface density distribution in 36 galaxies

R. H. Warmels (*)

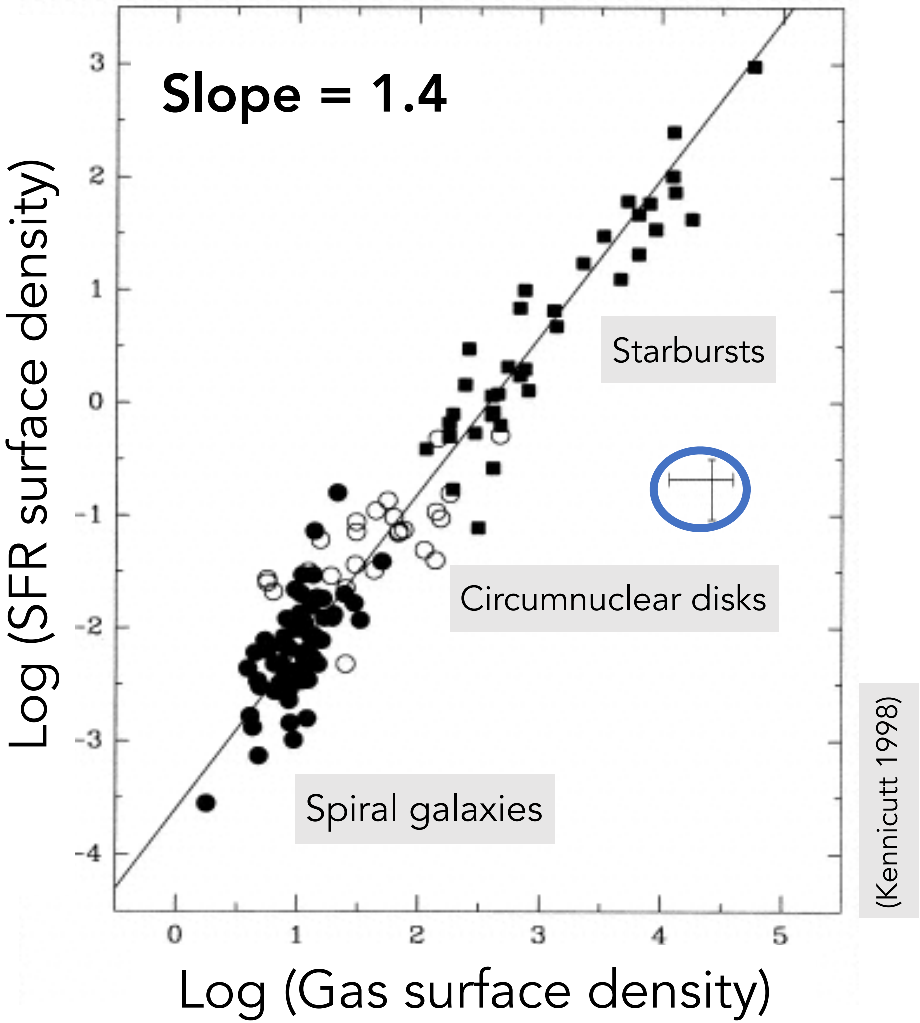
Distribution and motions of atomic hydrogen in lenticular galaxies

XI. A summary of H I observations and evolutionary scenarios

W. van Driel [1,2,3] and H. van Woerden [1]

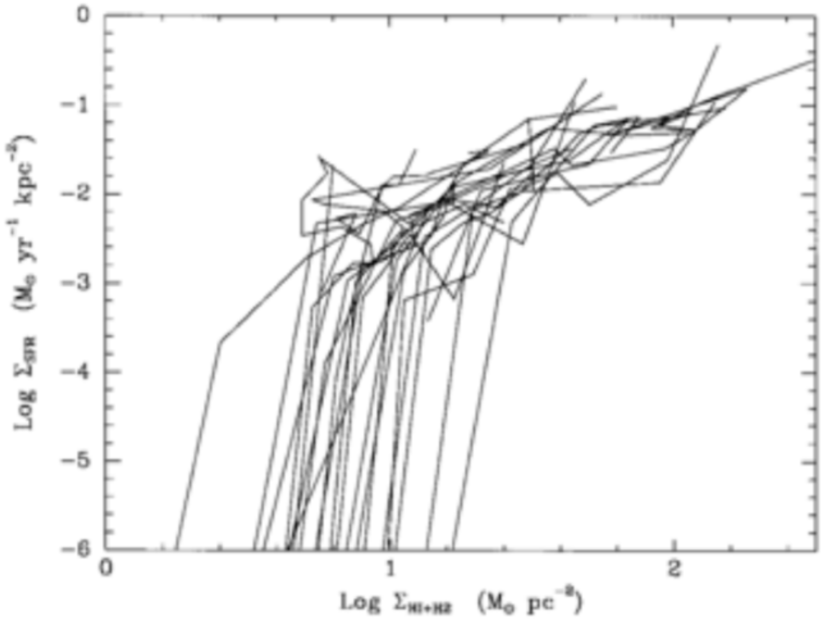
WHISP

Westerbork observations of neutral Hydrogen in Irregular and SPiral galaxies



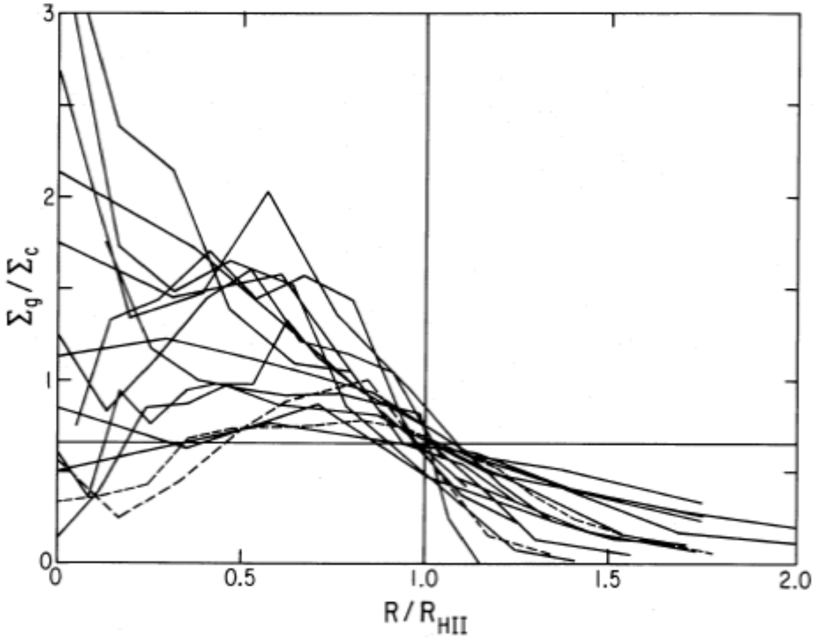
NB: slope N~1.5 is expected if SF timescale is driven by self-gravity

Kennicutt 1989, Martin & Kennicutt 2001

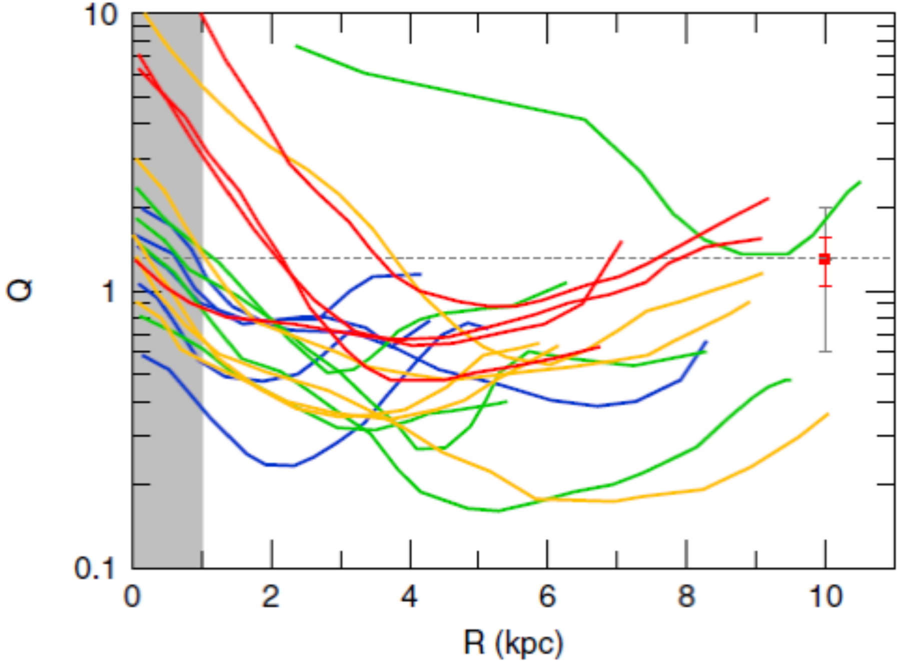


SF disks are gravitationally meta-stable

Toomre $Q = \kappa c / \pi G \Sigma_{gas} = \Sigma_{crit} / \Sigma_{gas}$

z=0
Kennicutt 1989

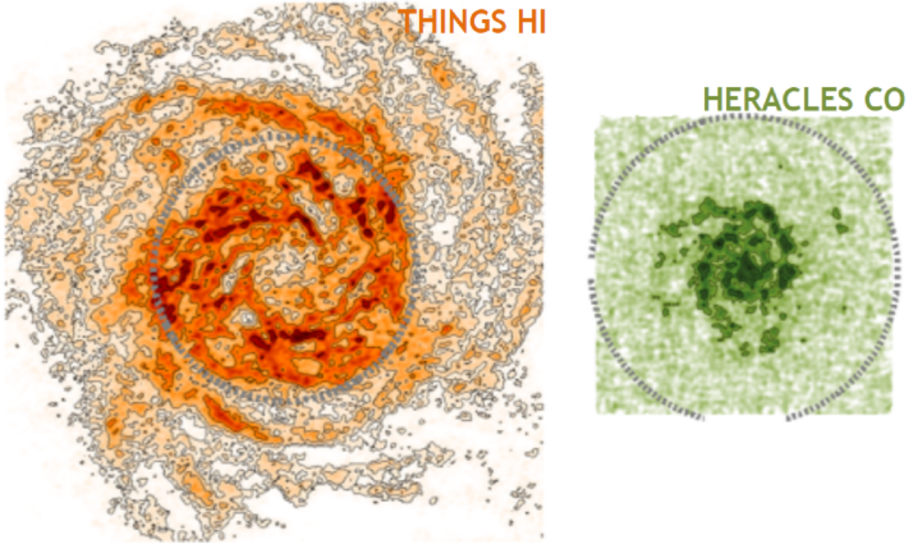


z~2 SINS/PHIBBS
Genzel+ 2014

2008 – 2018: Spatially-resolved measurements

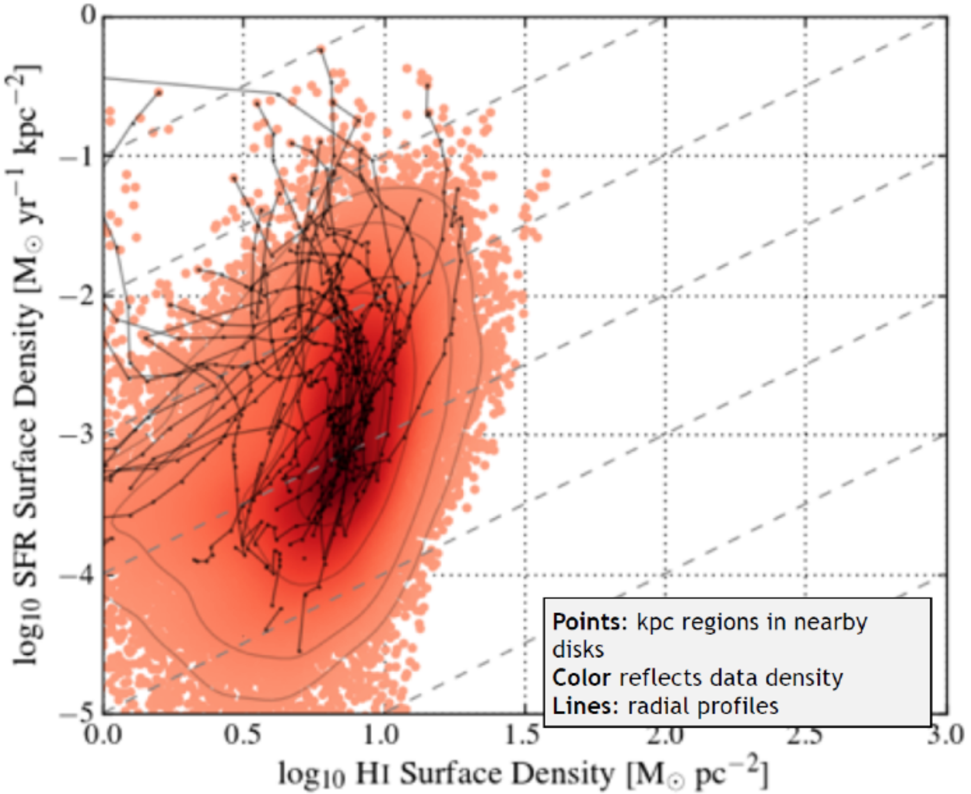
I will show a mixture of plots from Rob's papers, plots from other papers, and plots made using data from series of papers by the HERACLES and THINGS collaborations drawing heavily on SINGS.

For 30 galaxies H_2 from CO 2-1 from HERACLES, HI from THINGS, stellar surface densities from SINGS 3.6μm, and SFR from Hα+24μm.



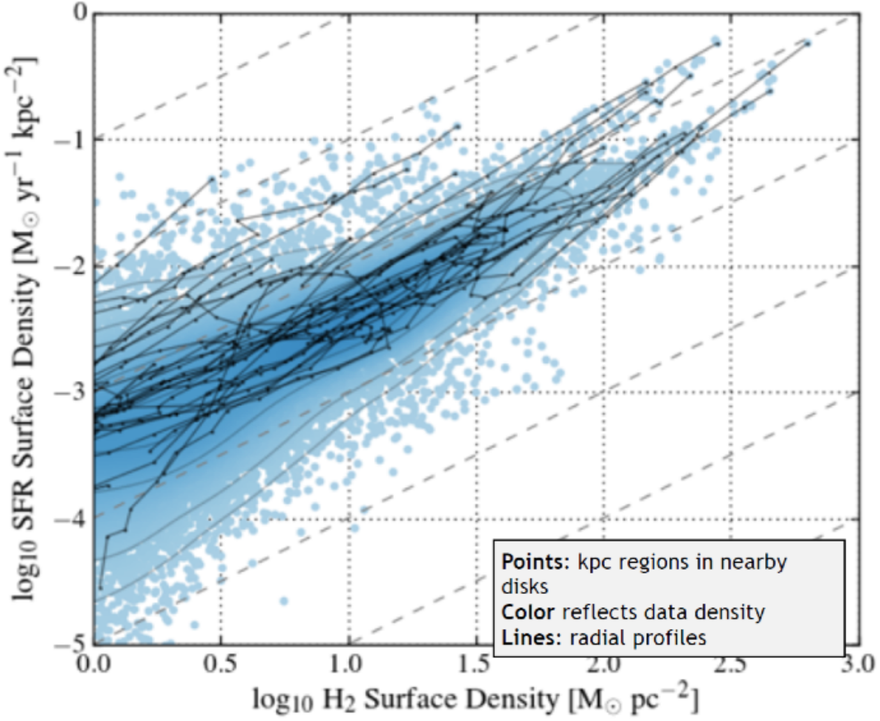
BIGIEL ET AL. (2008), LEROY ET AL. (2008), WALTER ET AL. (2008), LEROY ET AL. (2009), BIGIEL ET AL. (2010), BIGIEL ET AL. (2011), SCHRUBA ET AL. (2011), LEROY ET AL. (2012), SCHRUBA ET AL. (2012), LEROY ET AL. (2013), SANDSTROM ET AL. (2013)

HI shows a steep and scattered correlation with star formation. The same surface density of HI forms stars at many rates depending on other factors. H_2 traced by CO shows a much tighter relation. SFR/H_2 varies less than SFR/HI.



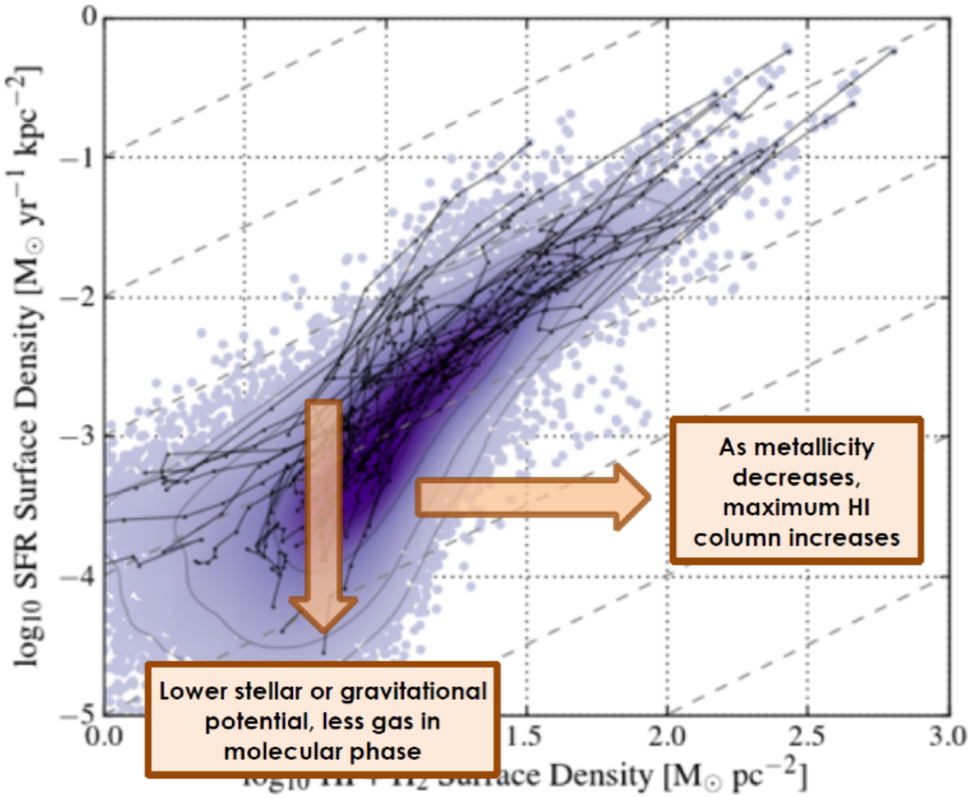
THINGS & HERACLES, C.F. WONG & BLITZ 2002, BOISSIER ET AL. 2003

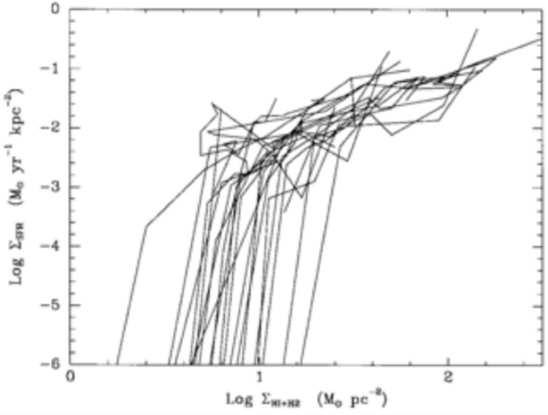
HI shows a steep and scattered correlation with star formation. The same surface density of HI forms stars at many rates depending on other factors. **H_2 traced by CO shows a much tighter relation. SFR/H_2 varies less than SFR/HI.**



see Schaye 04, Glover & Clark 11, Krumholz et al 11 regarding causality vs. correlation

Both metallicity and the local mass surface density (stars, but also gas in the far outskirts) appear to be drivers for this threshold behavior.



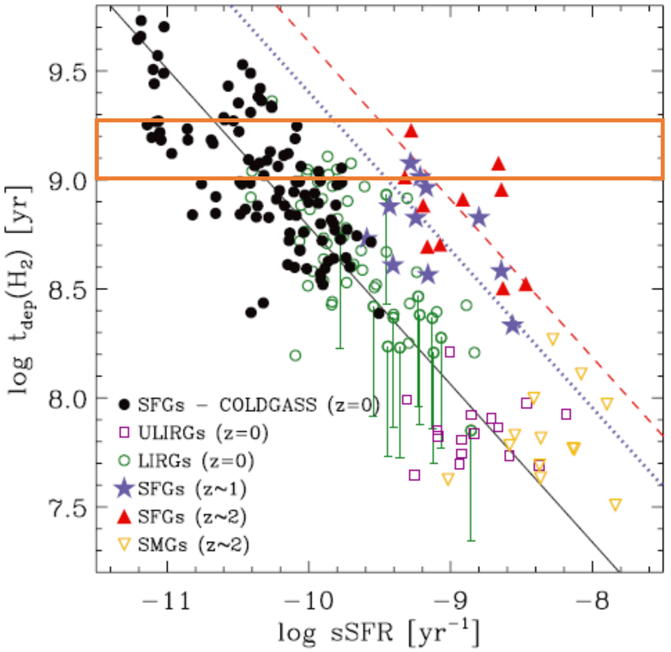


In short, one can interpret the observed properties of the large-scale star formation law in terms of two completely different (simplistic) pictures:

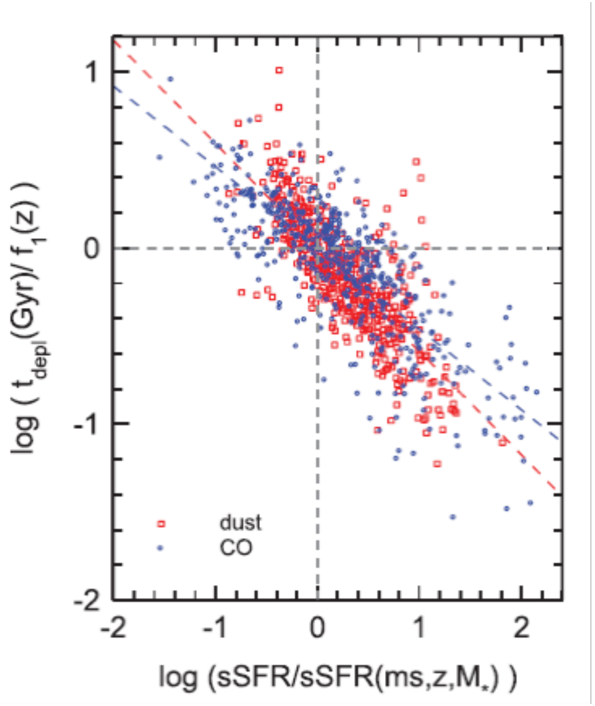
- Top down: in which cloud and star formation are primarily driven by gravitational processes (free-fall time, disk instabilities), largely independent of ISM phase or temperature. In this picture the slope of the Schmidt law is driven by dynamics. Causation is driven by gravity and apparent correlations with molecular properties are merely secondary consequences.

- Bottom up: in which cloud and star formation are primarily driven by the formation of molecular gas and a (near-constant) star formation efficiency per unit molecular gas. In this picture the slope of the Schmidt law is the consequence of a combination of a linear molecular SF law with a (molecular-driven) threshold at low densities. Causation is driven by ISM phase and apparent correlations with bound vs diffuse gas are secondary consequences.

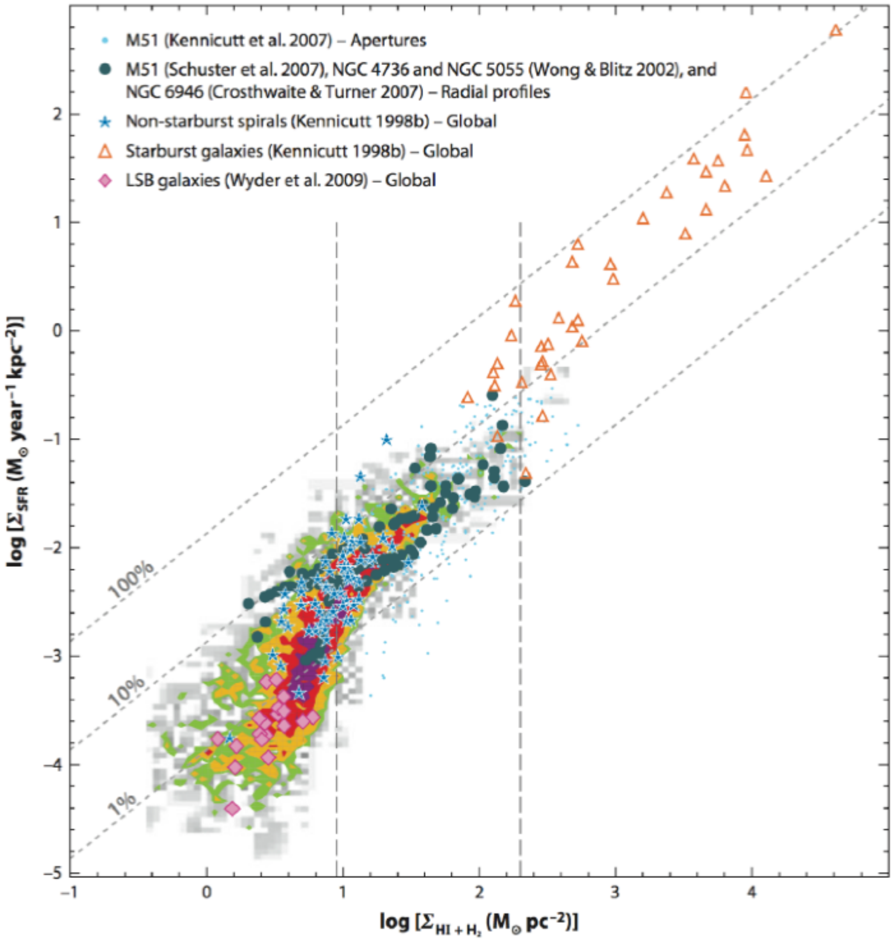
But the entire story is not so simple…



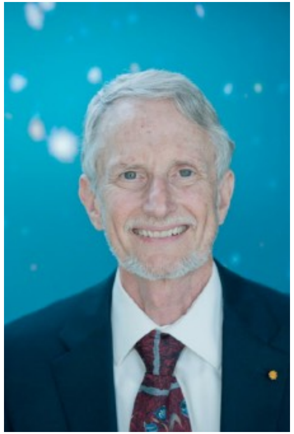
Saintonge+ 2011



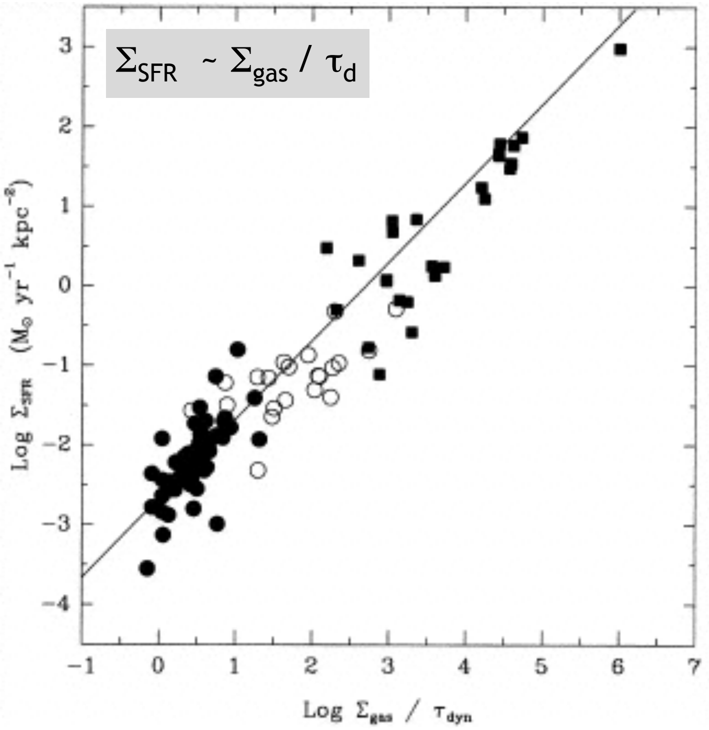
Genzel+ 2014, 2015



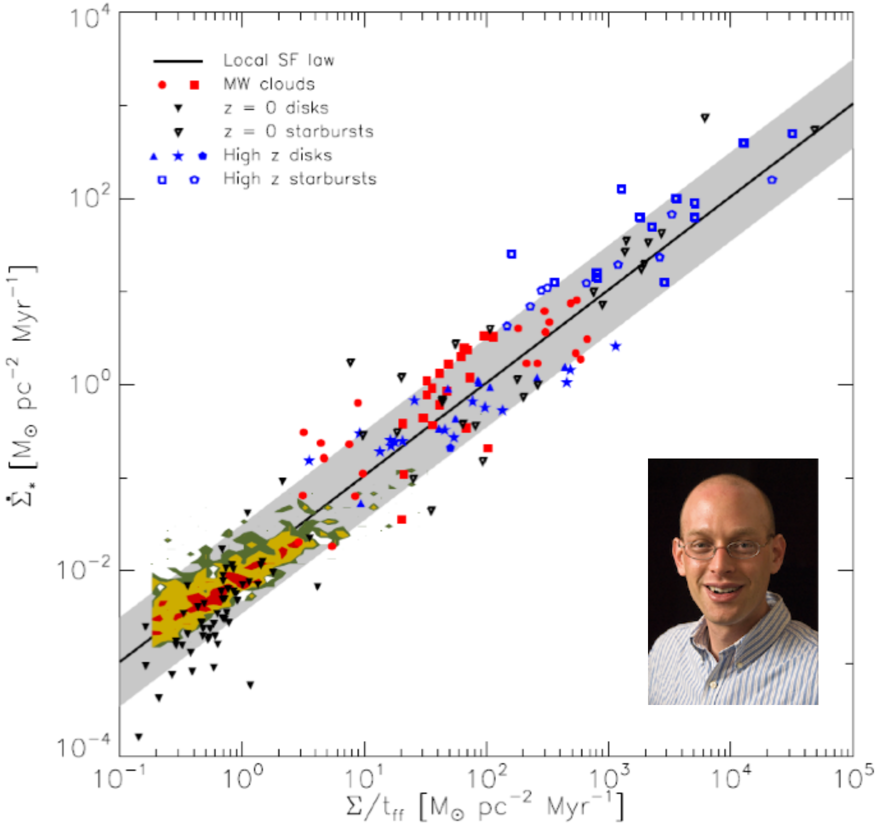
Kennicutt & Evans 2012



Silk-Elmegreen Law



Kennicutt 1998



Krumholz+ 2012

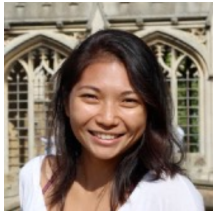
Looking ahead: 2018+

Updating the Global Star Formation Law

Mia de los Reyes – Caltech
Rob Kennicutt – U. Arizona

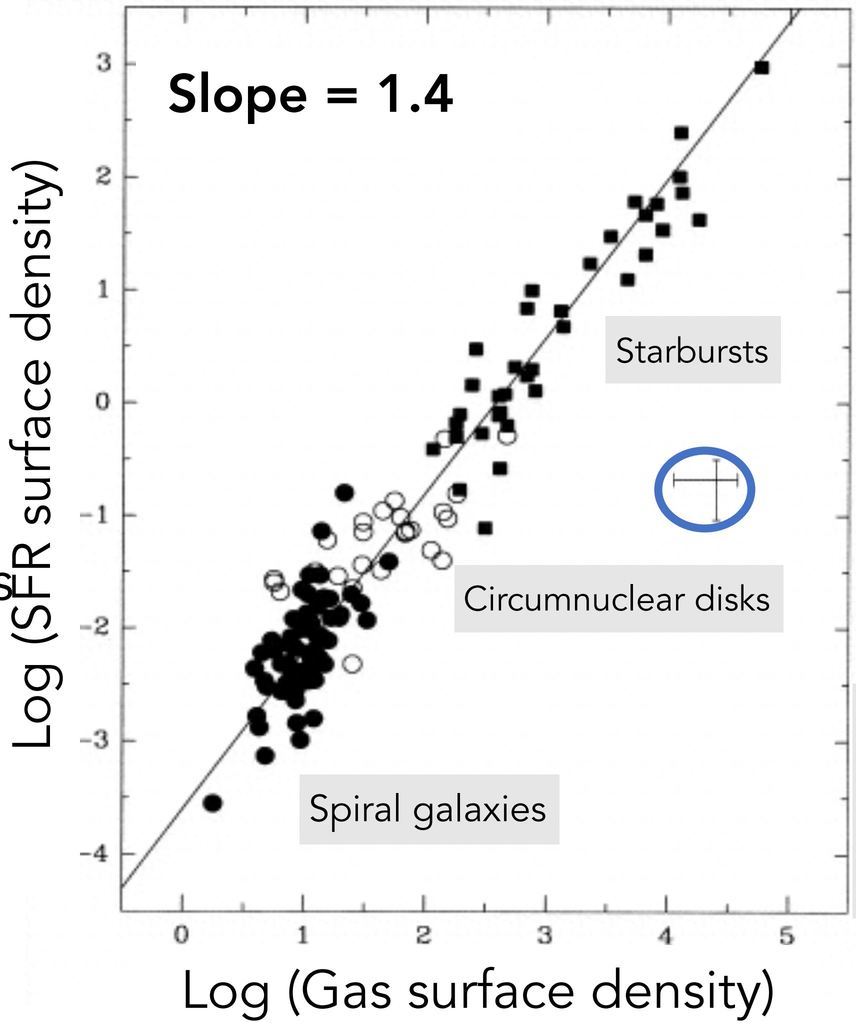
The Laws of Star Formation

2 July 2018



Problems with K98

- Small sample
  - N = 61 spiral galaxies
  - N = 36 circumnuclear starbursts
- Large uncertainties
  - Measurement uncertainties ≈ factor of 2-3
  - Can't tell if scatter is intrinsic



(Kennicutt 1998)

Now: improved multi-wavelength observations

SFR densities

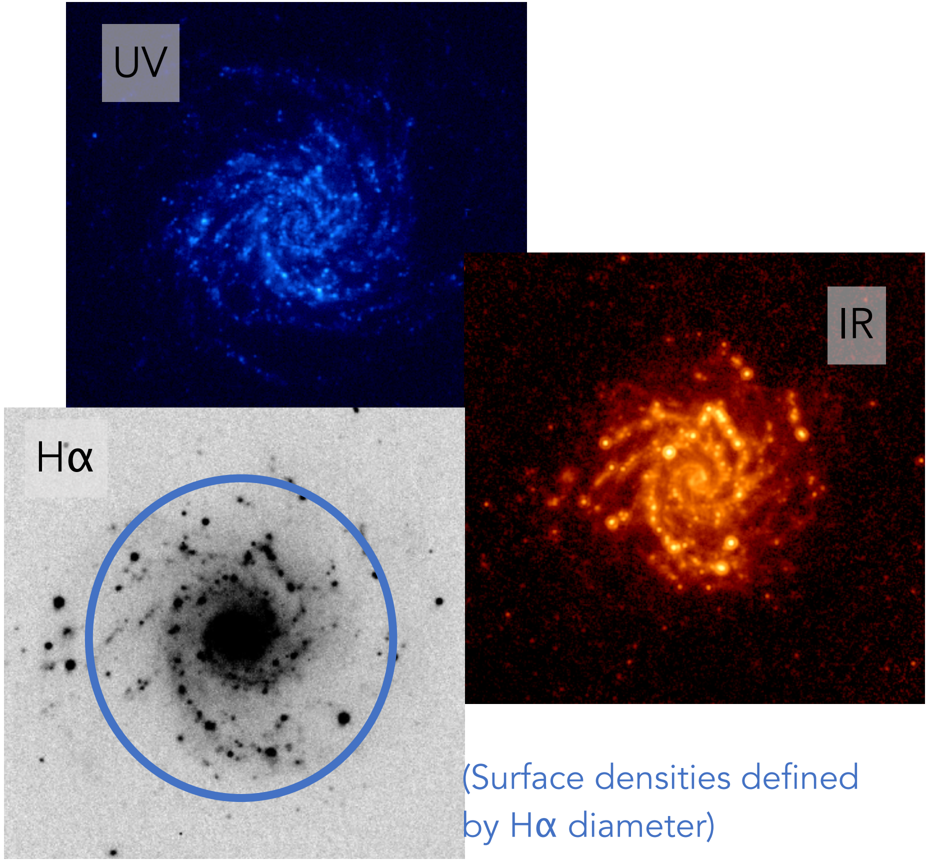
- FUV (GALEX)
- Dust: ~24μm IR (Spitzer, WISE)

Gas densities

- Atomic (**HI**): 21-cm line
- Molecular (**H_2**): CO(J = 1→0)

Final sample

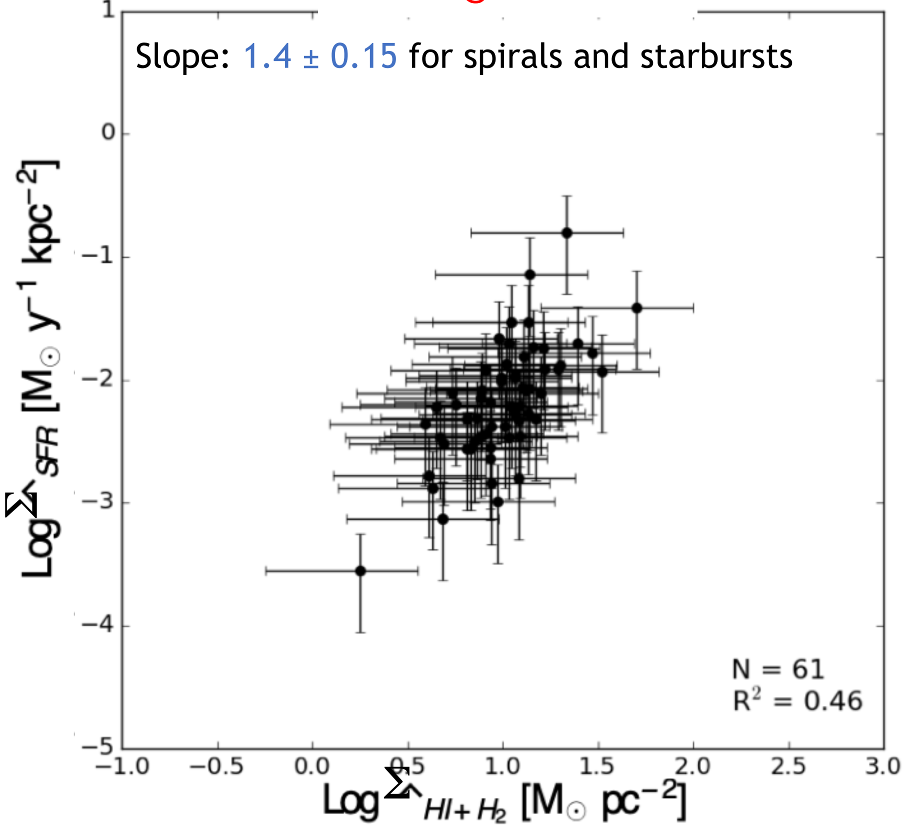
- N = 154 spiral galaxies
- N = 90 dwarf galaxies
- N = 126 circumnuclear starbursts



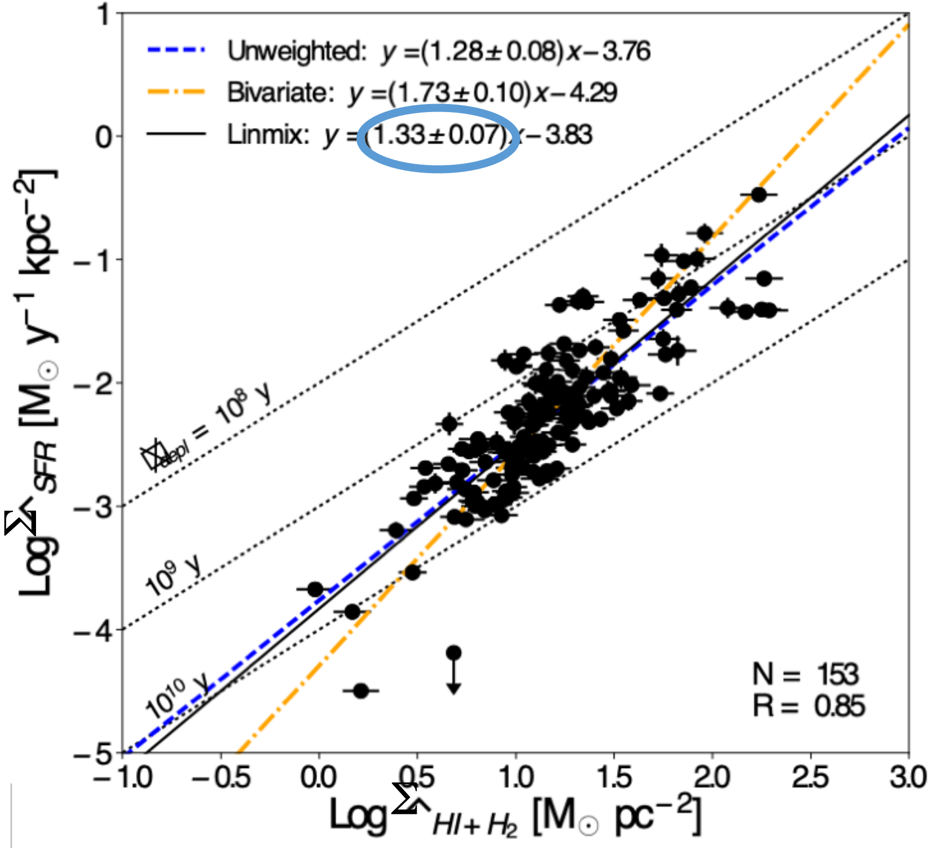
(Surface densities defined by Hα diameter)

1. Redo K98 analysis for spiral galaxies

K98 original data

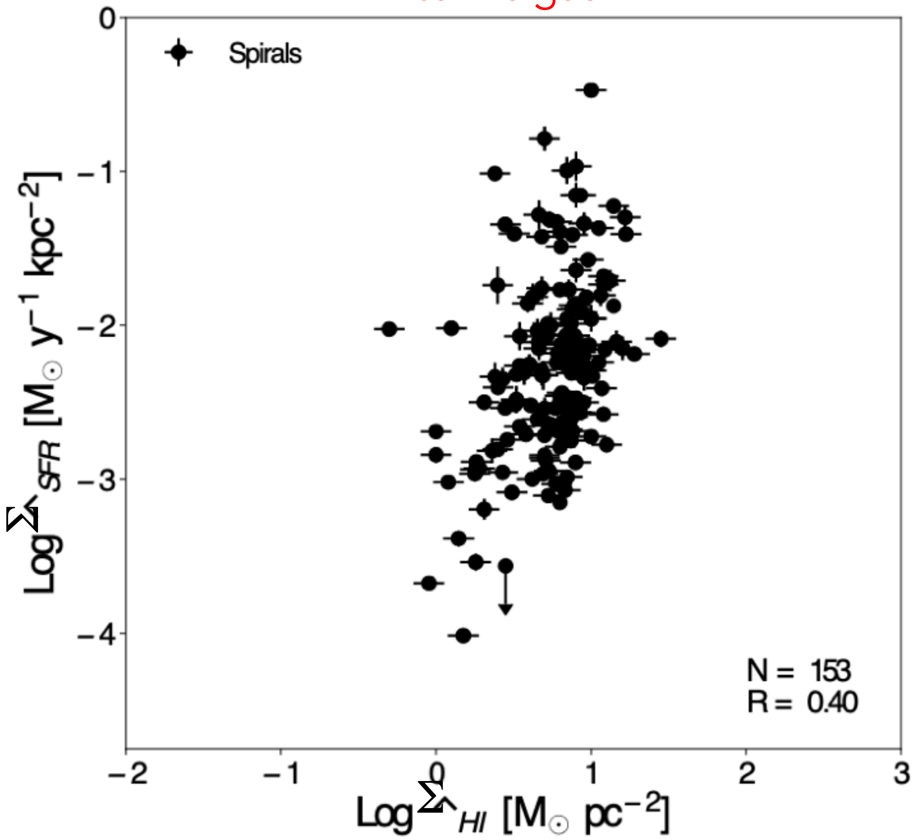


New data

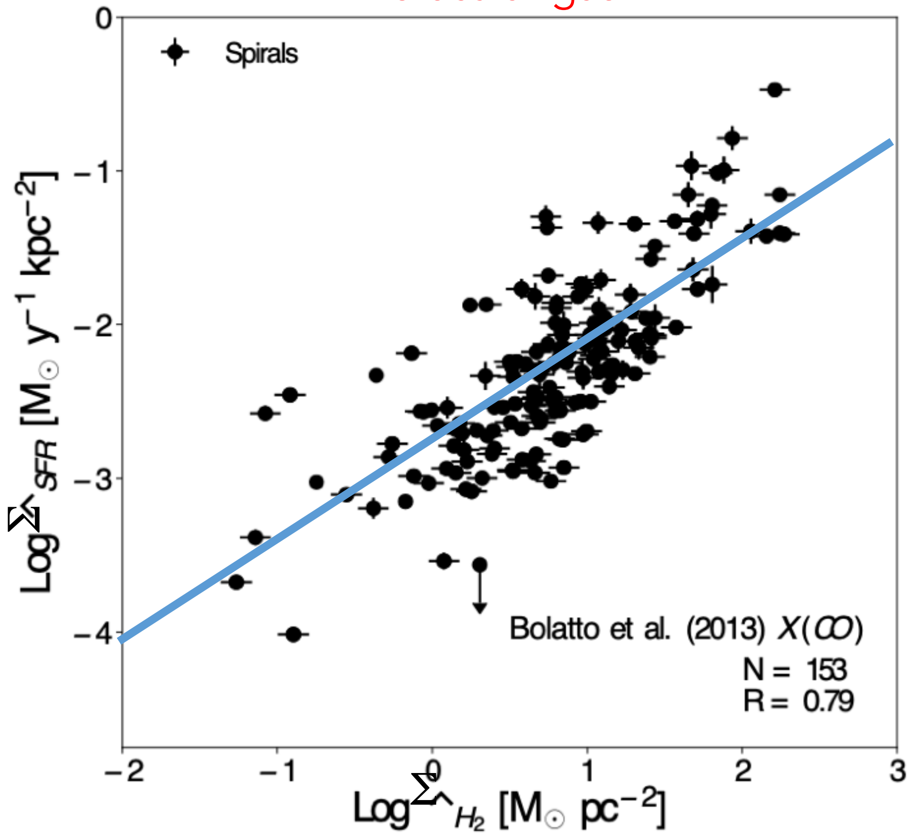


1. Redo K98 analysis for spiral galaxies

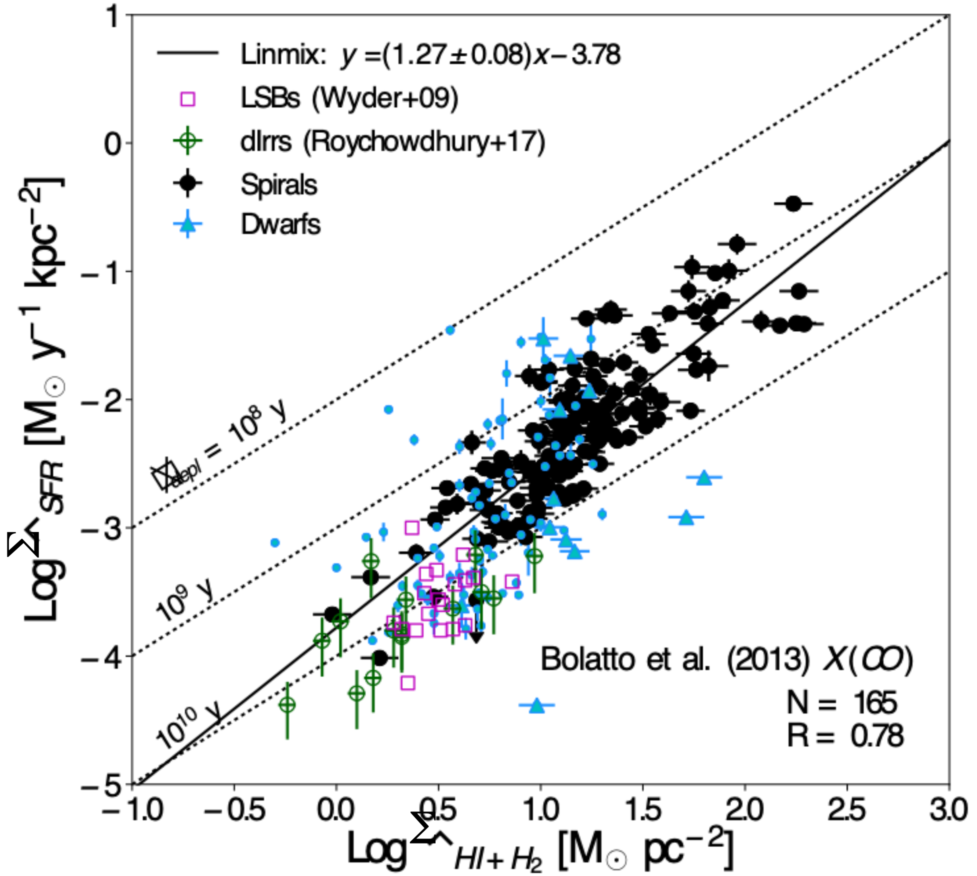
Atomic gas



Molecular gas



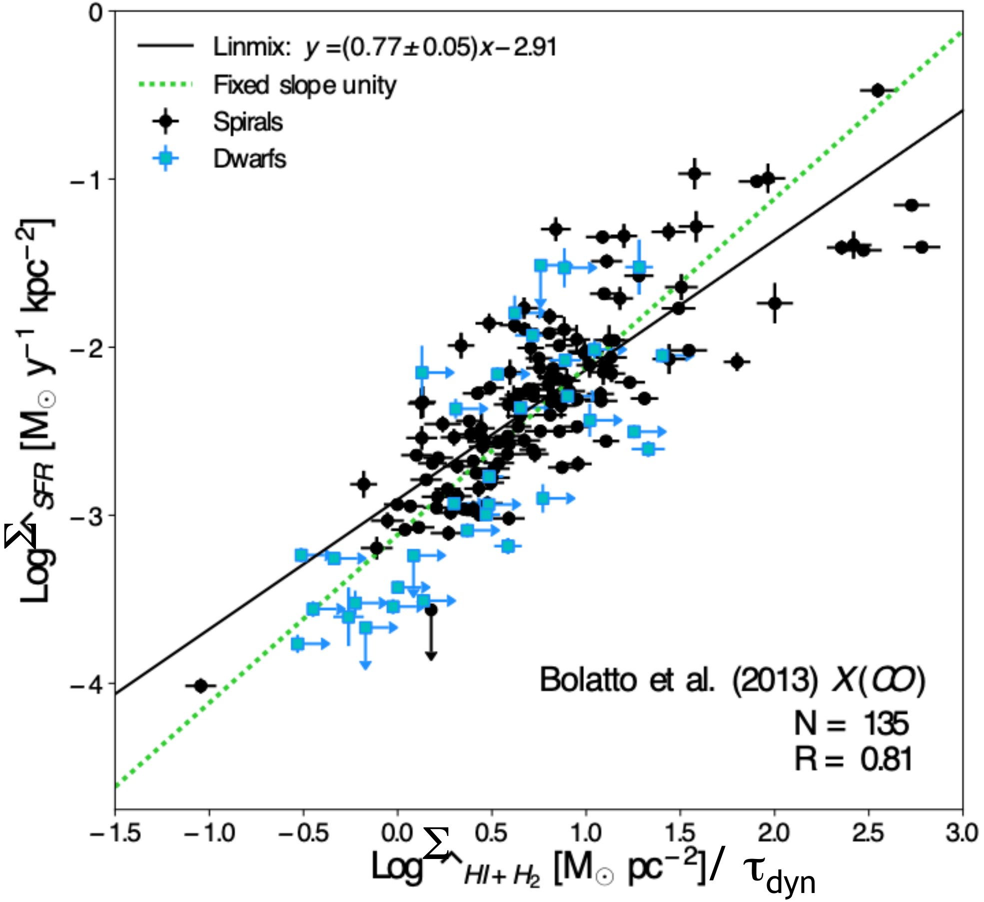
2. Dwarf galaxies: compare to spirals



- Dwarfs with CO detections seem to fall below spirals
  - Also low surface brightness galaxies (LSBs) and dIrrs
- Threshold in star formation law?

(e.g., Bigiel 2008)

Silk-Elmegreen law

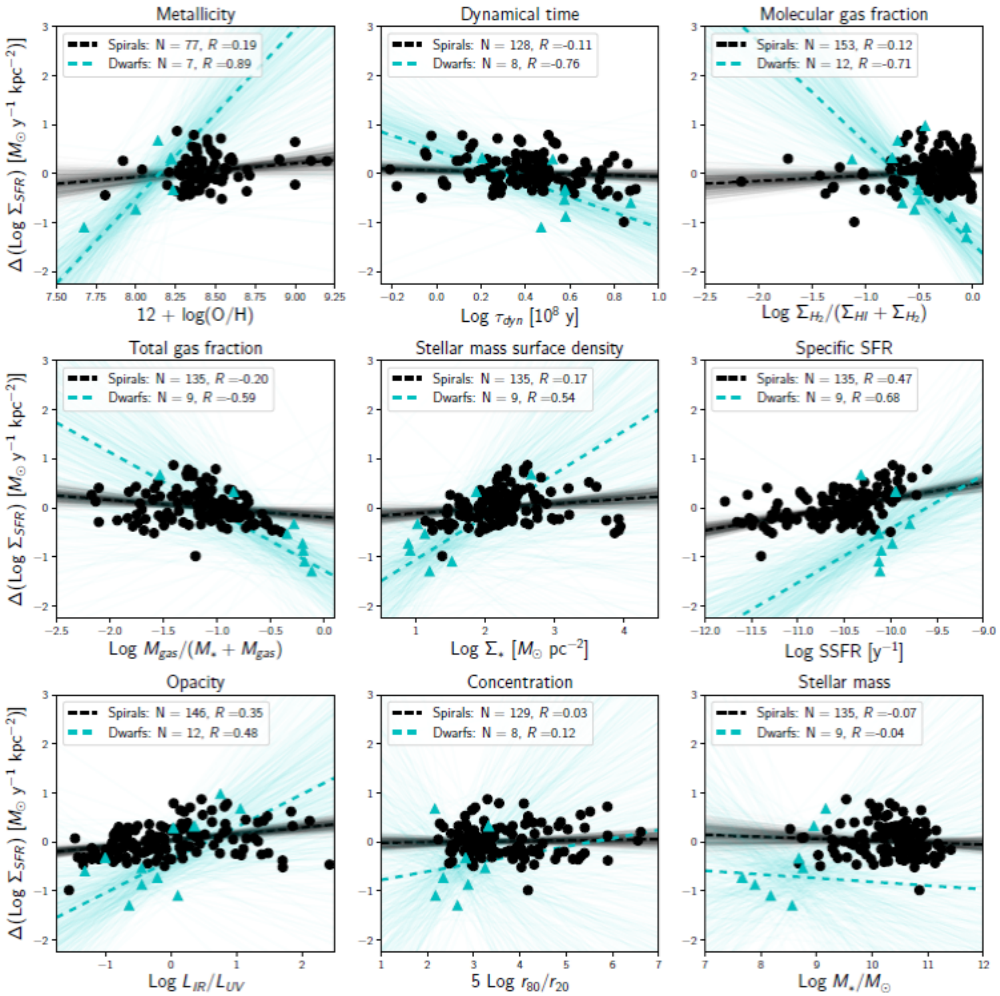


3. Second-order correlations

- Metallicity
- Stellar mass
- Mass density
- H_2/HI ratio
- Opacity
- Gas/stars ratio
- Concentration
- Diameter of star-forming region
- Specific star formation rate

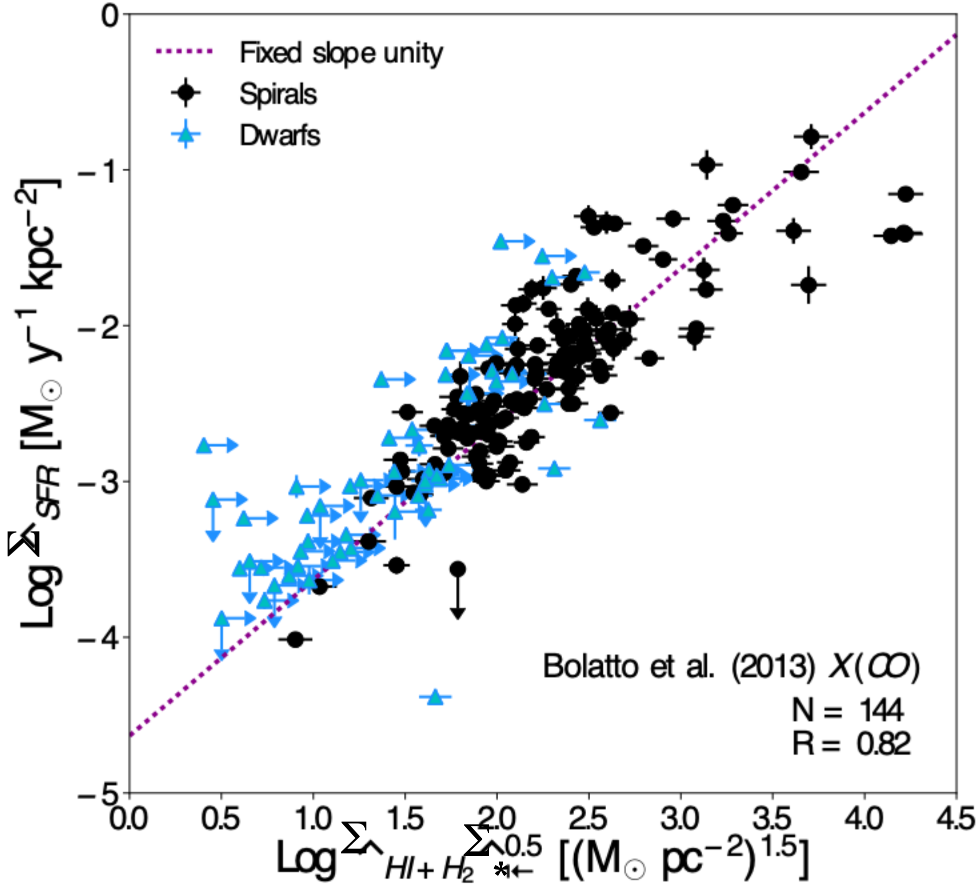
How to find correlations?

- Plot against residuals
- Correlation matrices
- PCA



Metallicity
Spirals: N = 77, R =0.19
Dwarfs: N = 7, R =0.89
12 + log(O/H)
Dynamical time
Spirals: N = 128, R =-0.11
Dwarfs: N = 8, R =-0.76
Log τ_{dyn} [10^8 y]
Molecular gas fraction
Spirals: N = 153, R =0.12
Dwarfs: N = 12, R =-0.71
Log $\Sigma_{H_2}/(\Sigma_{HI} + \Sigma_{H_2})$
Total gas fraction
Spirals: N = 135, R =-0.20
Dwarfs: N = 9, R =-0.59
Log $M_{gas}/(M_* + M_{gas})$
Stellar mass surface density
Spirals: N = 135, R =0.17
Dwarfs: N = 9, R =0.54
Log Σ_* [$M_\odot$ pc^{-2}]
Specific SFR
Spirals: N = 135, R =0.47
Dwarfs: N = 9, R =0.68
Log SSFR [y^{-1}]
Opacity
Spirals: N = 146, R =0.35
Dwarfs: N = 12, R =0.48
Log L_{IR}/L_{UV}
Concentration
Spirals: N = 129, R =0.03
Dwarfs: N = 8, R =0.12
5 Log r_{80}/r_{20}
Stellar mass
Spirals: N = 135, R =-0.07
Dwarfs: N = 9, R =-0.04
Log $M_*/M_\odot$
Δ(Log Σ_{SFR}) [$M_\odot$ y^{-1} kpc^{-2}]

2. Dwarf galaxies: alternative scaling laws



- An alternative version:

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}(\Sigma_*)^{0.5}$$

Stellar density

"extended Schmidt law"
(Dopita 1985, Shi+2011)

- No threshold!
  - **Tighter** than Kennicutt-Schmidt (rms smaller by ~0.1 dex)

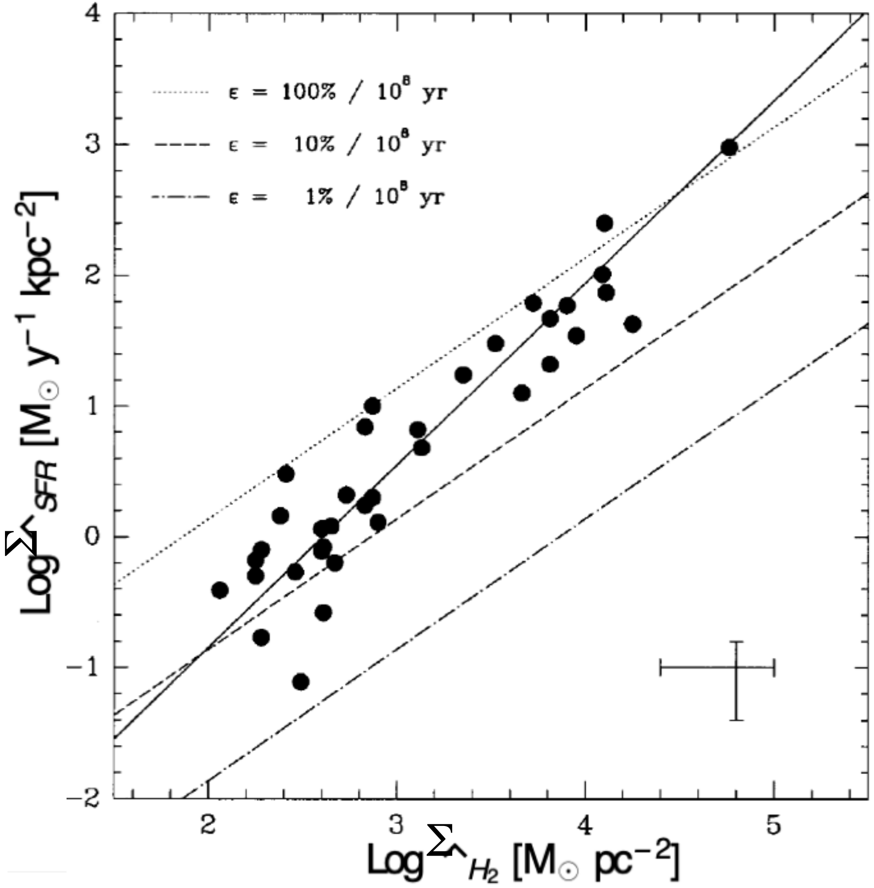
- Feedback regulation?

(e.g., Kim & Ostriker 2015)

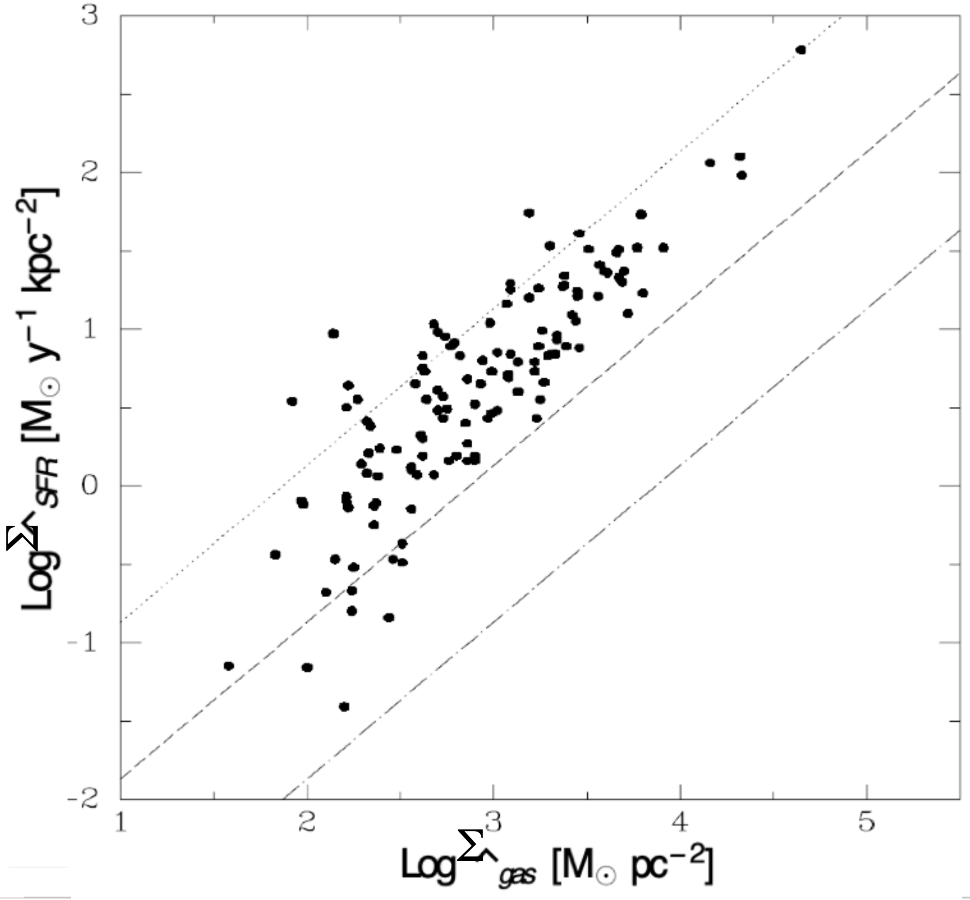
4. Starburst Galaxies

- Sample a mix of LIRGs/ULIRGs and circumnuclear disks of nearby (mostly barred) galaxies (N=126 vs 36 in K98)
- Gas masses from CO(1-0) or CO(2-1) observations
- SFRs from total IR luminosities
- SF region sizes from CO maps, IR maps, and/or Paα images

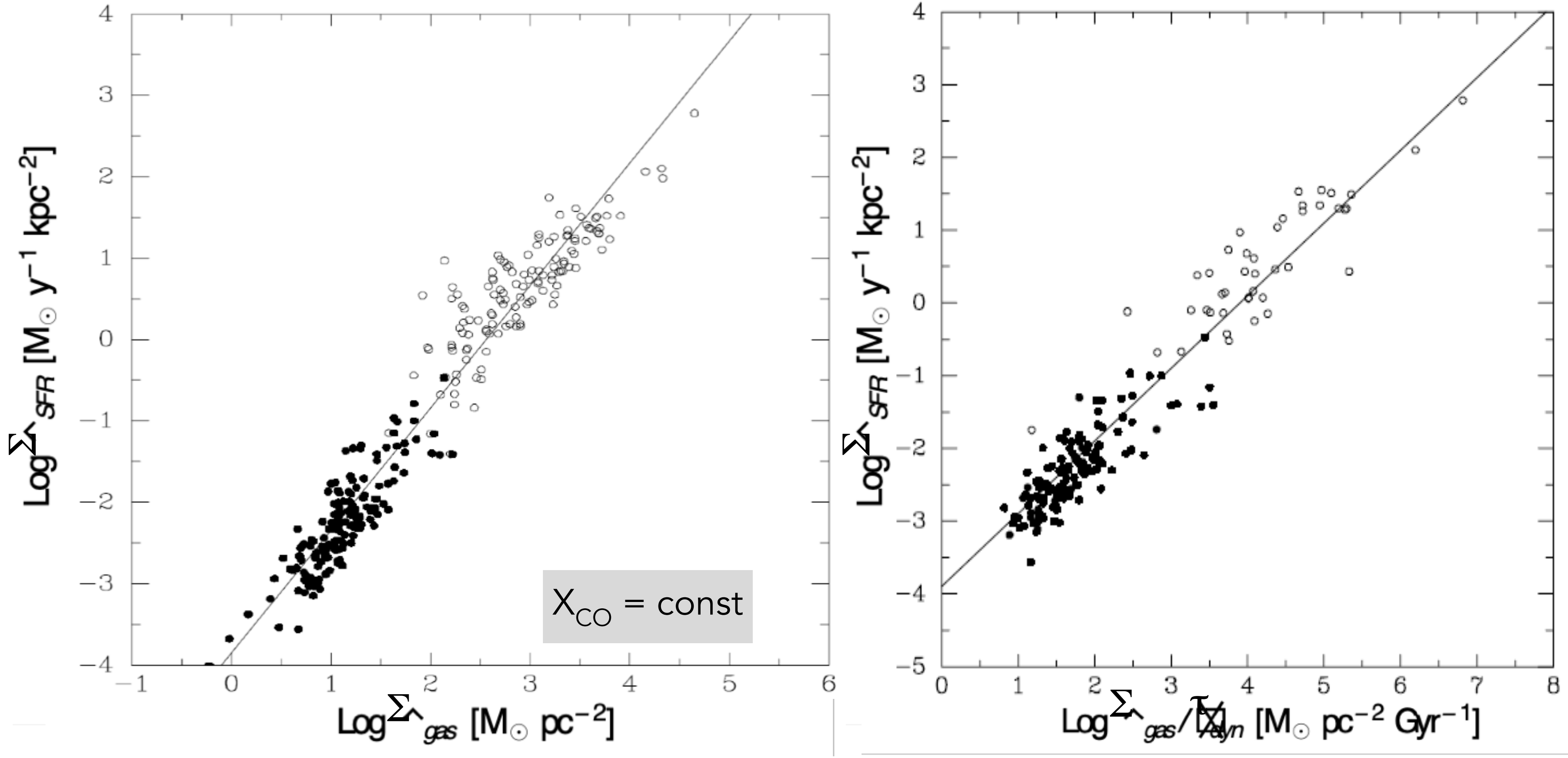
K98


ε = 100% / 10⁸ yr
ε = 10% / 10⁸ yr
ε = 1% / 10⁸ yr
Log Σ_SFR [M⊙ y⁻¹ kpc⁻²]
Log Σ_H2 [M⊙ pc⁻²]
4
3
2
1
0
−1
−2
2
3
4
5

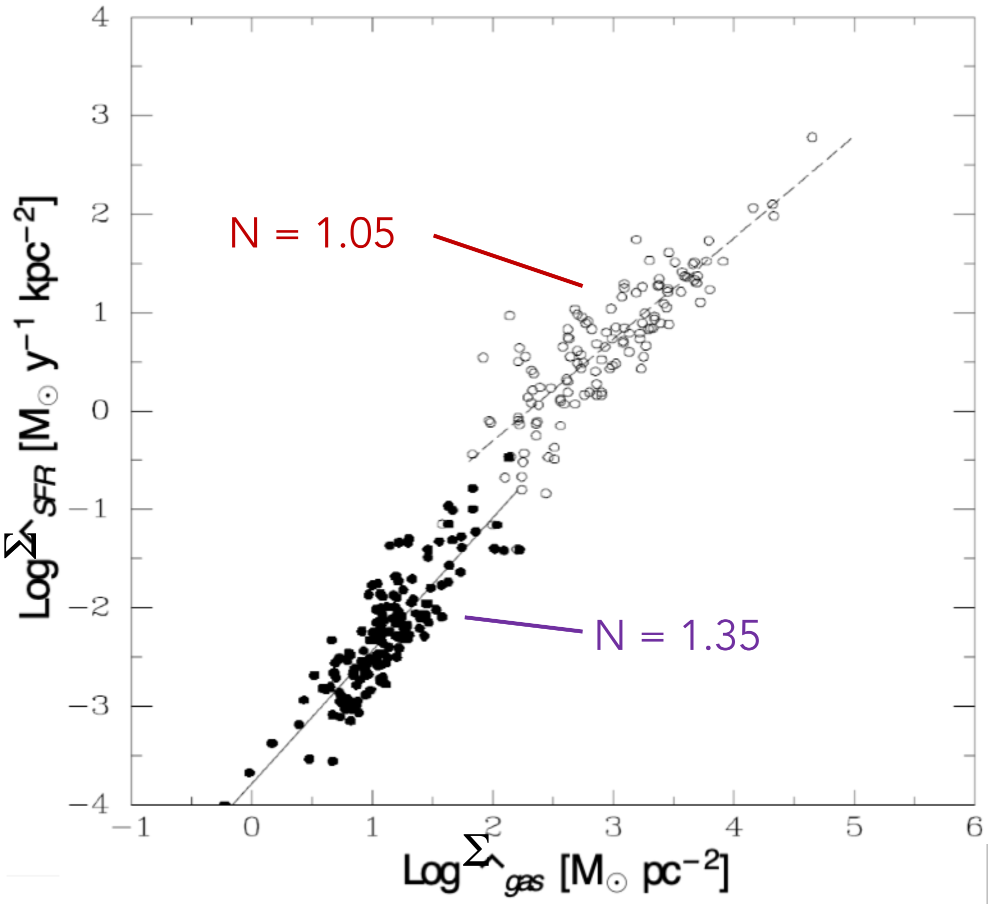
New Data


Log Σ_SFR [M⊙ y⁻¹ kpc⁻²]
Log Σ_gas [M⊙ pc⁻²]
3
2
1
0
−1
−2
1
2
3
4
5

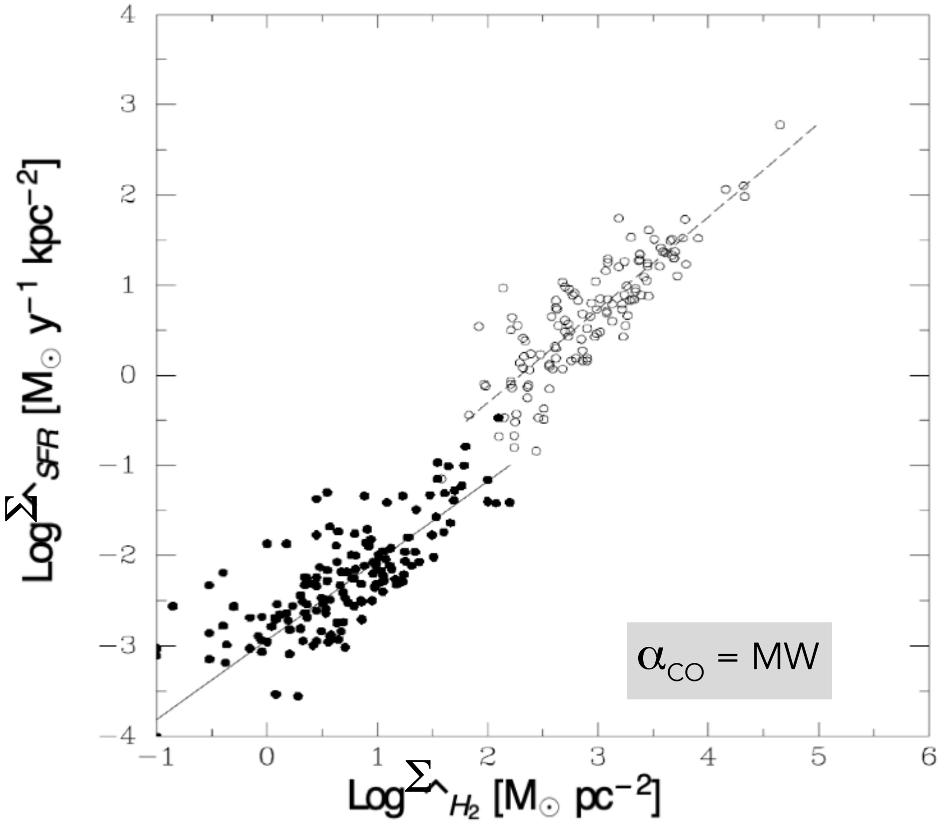
At first glance, data are well fitted by a common power law with N =1.50

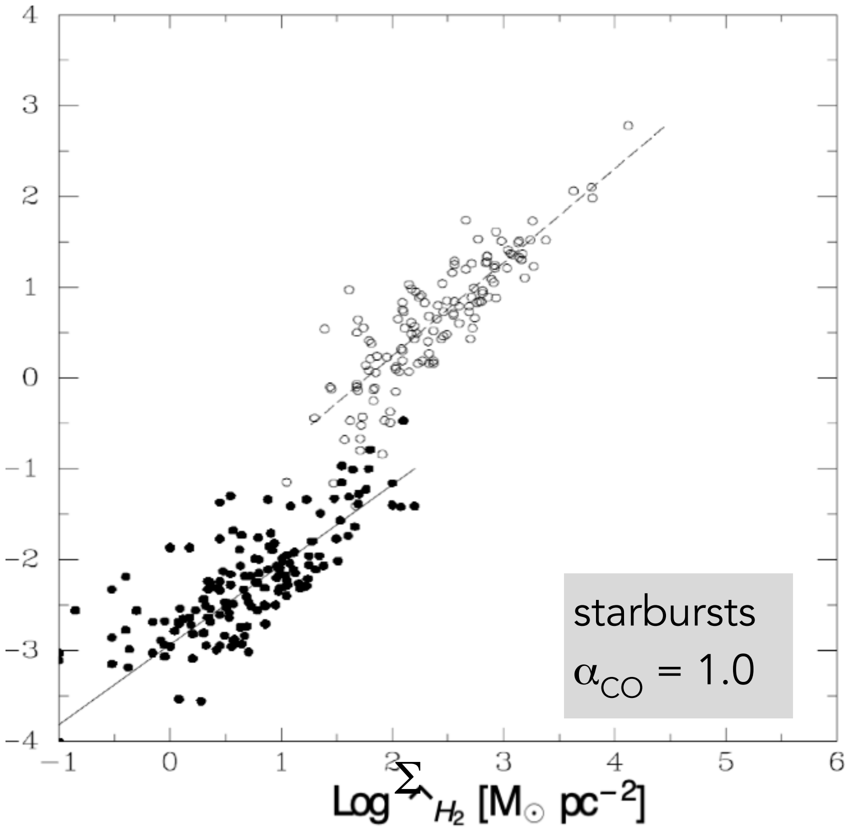


Interpretation somewhat different if you fit normal and starburst galaxies separately

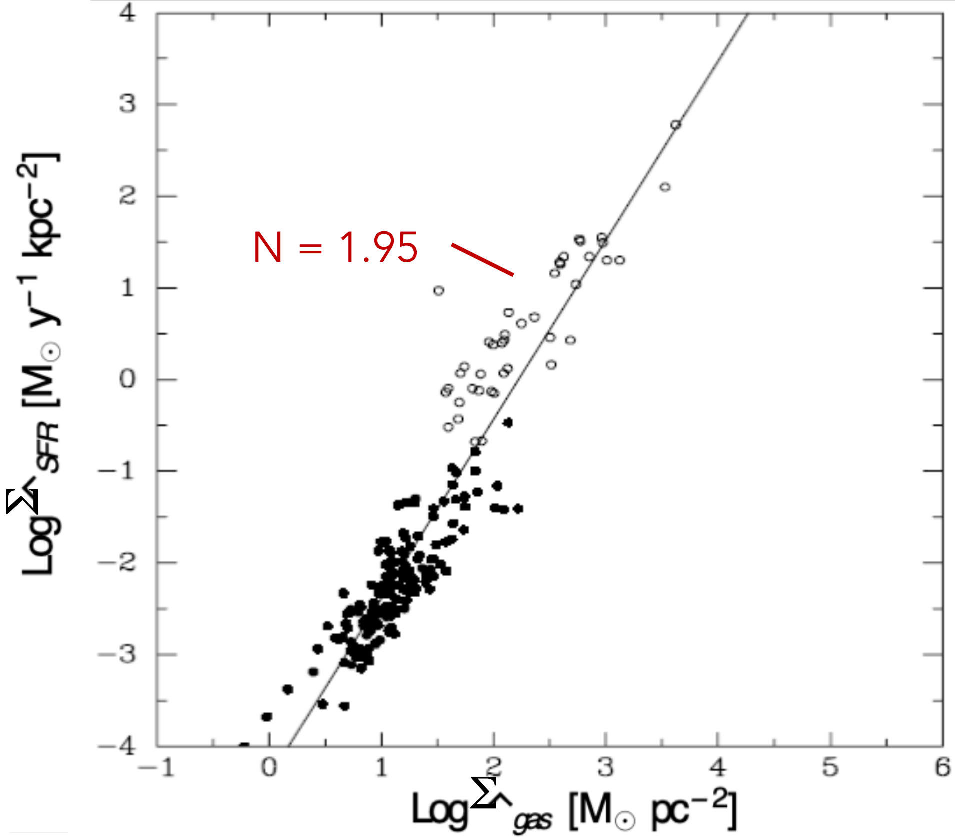


Considering the molecular gas SF law alone does not change matters…





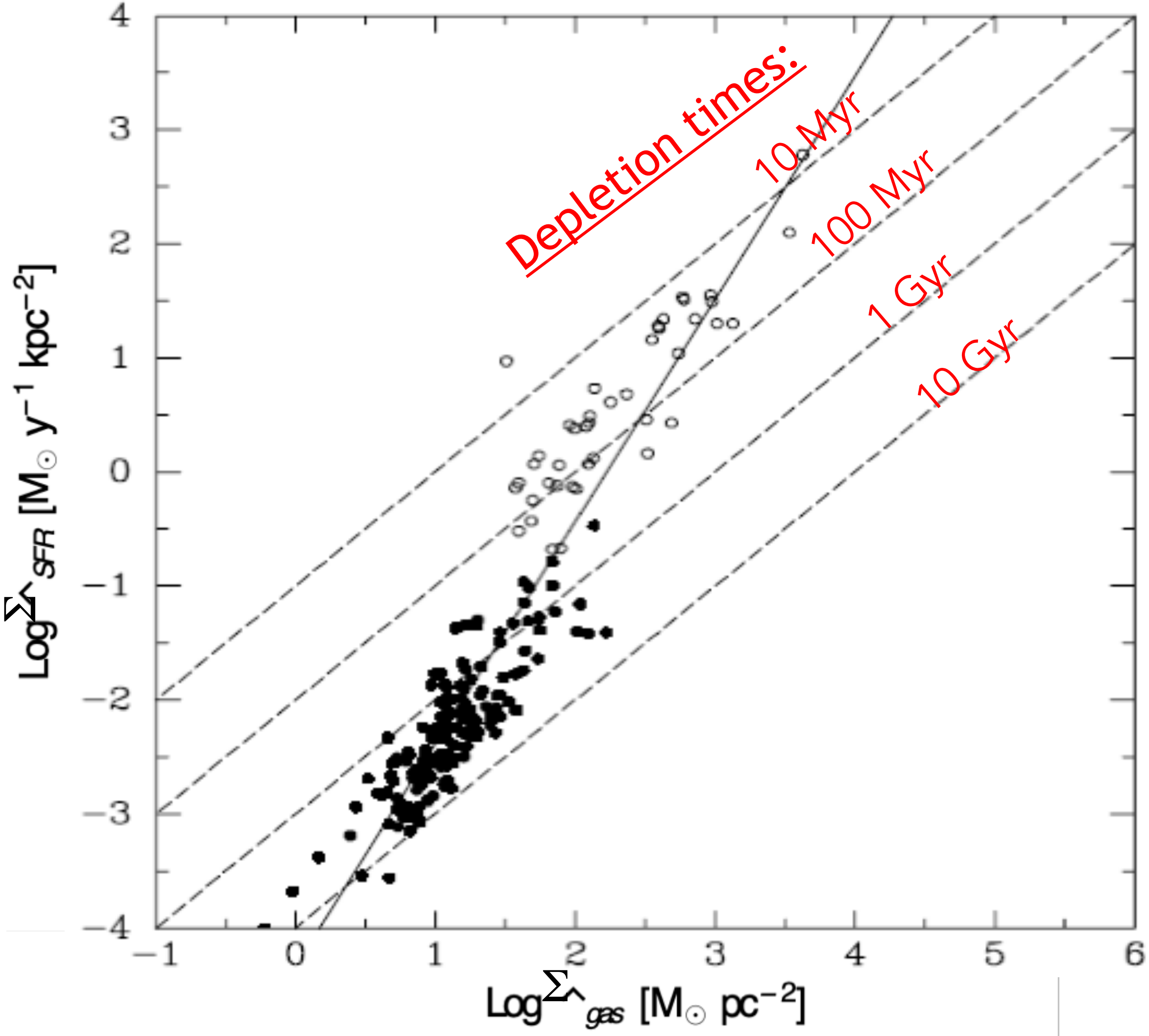
Adopting a density-dependent α_{CO} conversion factor reduces bimodality, but also produces a very steep Schmidt law



$$\alpha_{CO} \approx 2.9 \exp\left(\frac{+0.4}{Z' \, \Sigma_{GMC}^{100}}\right)\left(\frac{\Sigma_{total}}{100\,M_\odot\,pc^{-2}}\right)^{-\gamma} M_\odot\,(K\,km\,s^{-1}pc^2)^{-1},$$

Bolatto+ 2013

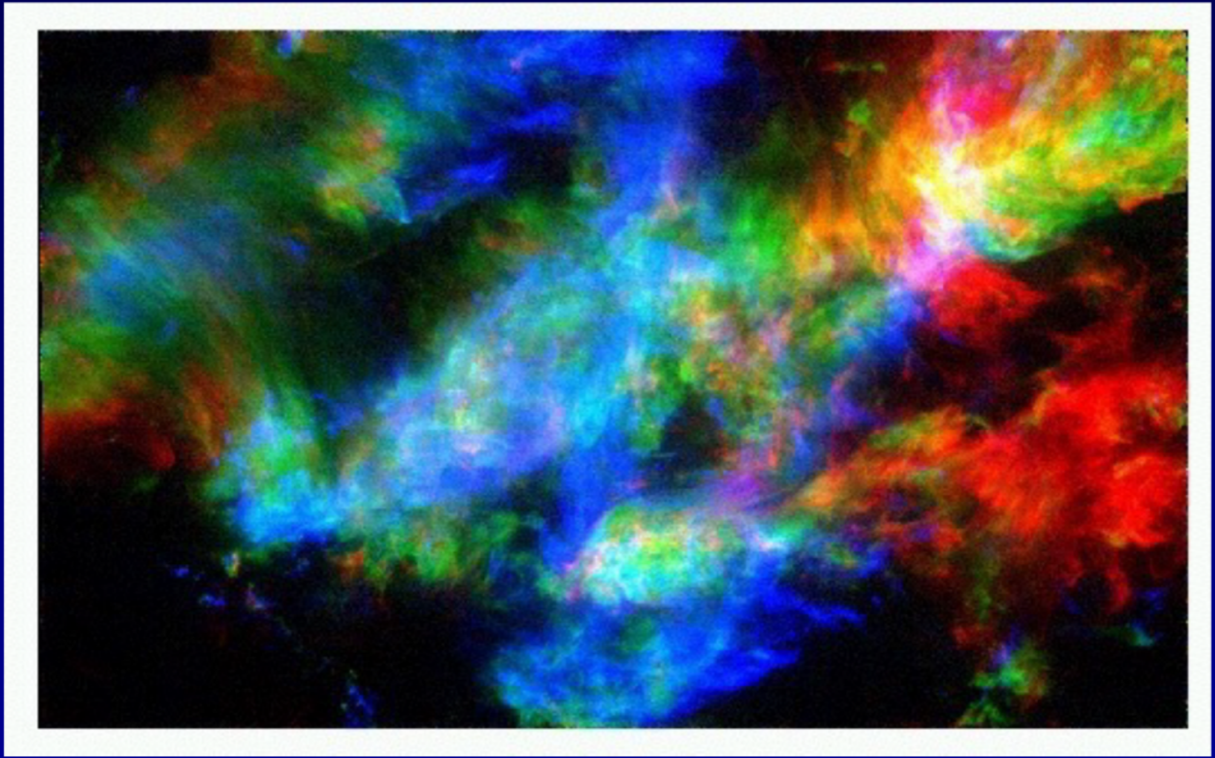
cf. Naryayanan+ 2012



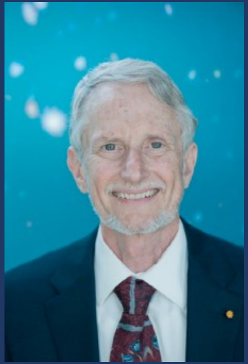
A concern with very low CO conversion factors is that gas depletion times fall to <<100 Myr

Far lower than the dynamical assembly times for the mergers/disks and implying very brief starbursts (or strong selection effects in current LIRG/ULIRG samples)

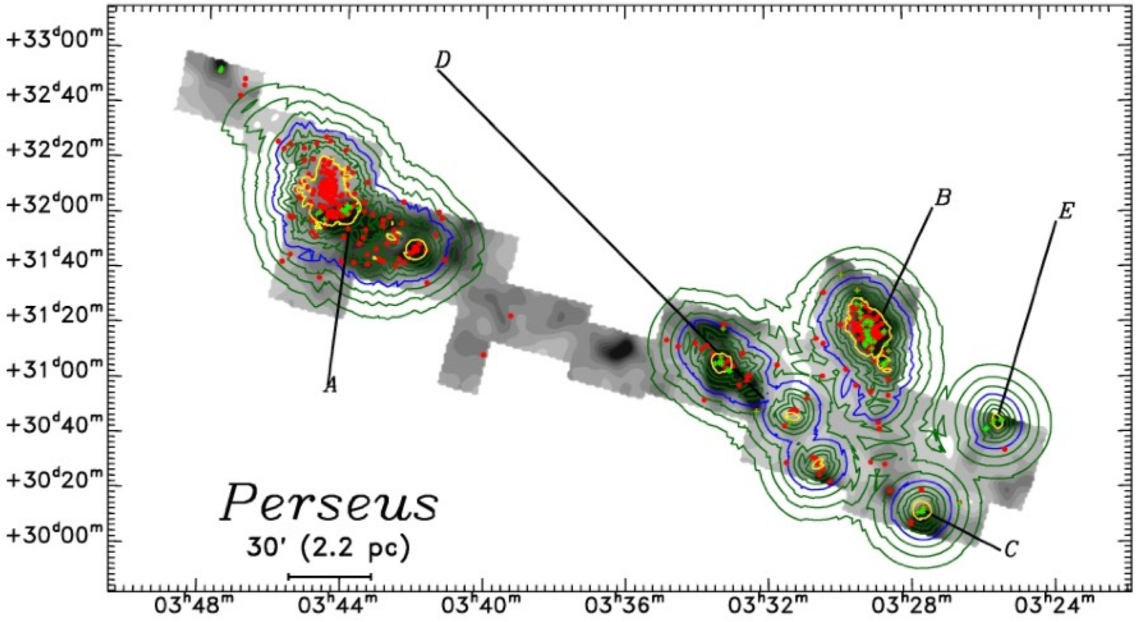
Does this look bound?

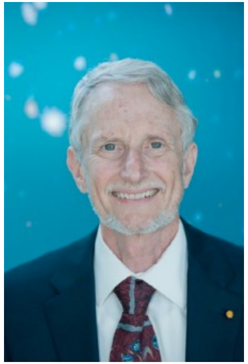


The Taurus Cloud : three colors for velocity components (Heyer & Dame, ARAA)



Within GMCs star formation is localized to the dense clumps

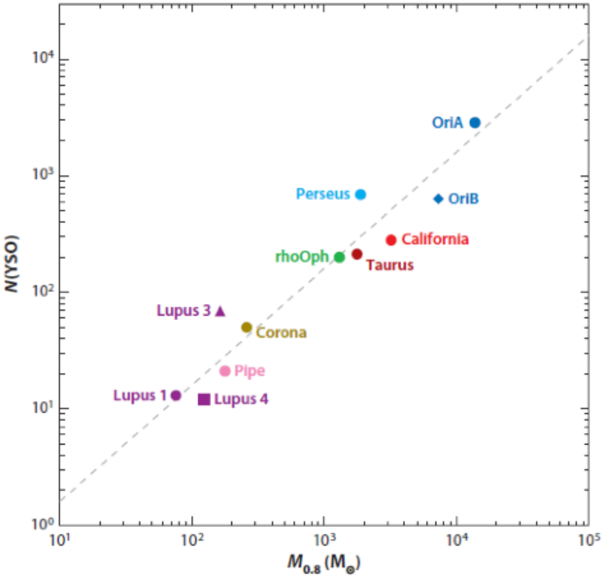


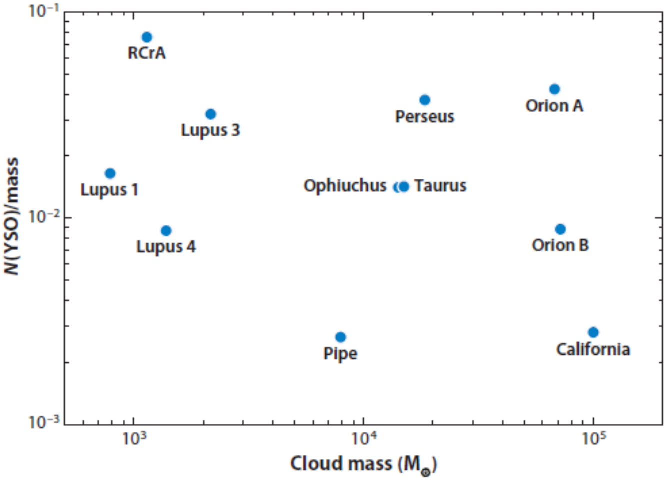


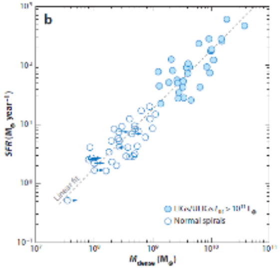
Gray is extinction, red dots are YSOs, contours of volume density (blue is 1.0 M_{sun} pc^{-3}; yellow is 25 M_{sun} pc^{-3})

Heiderman et al. 2010

SF efficiency in molecular clouds varies by factor of 50, but within dense clumps (above Σ_{gas} ~ 200 M_o/pc^2) is nearly constant







Lada et al 2011

Phangs-ALMA CO Survey – Pilot Sample

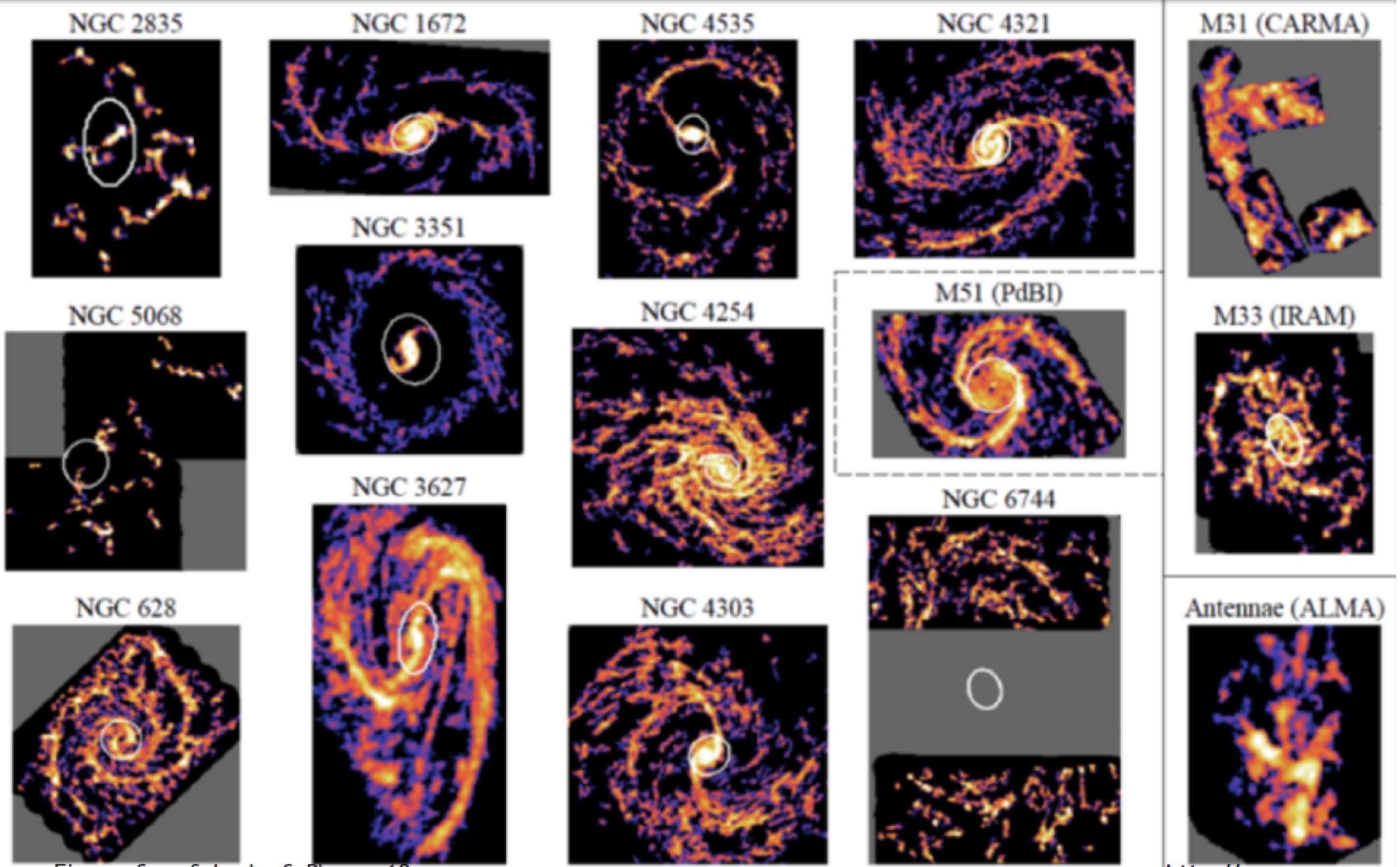
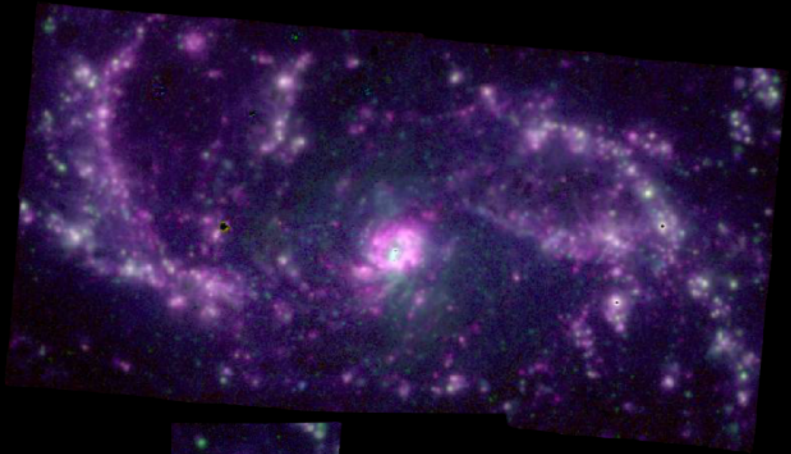


Figure: Sun, Schruba & Phangs 18

http://
phangs.org

PHANGS

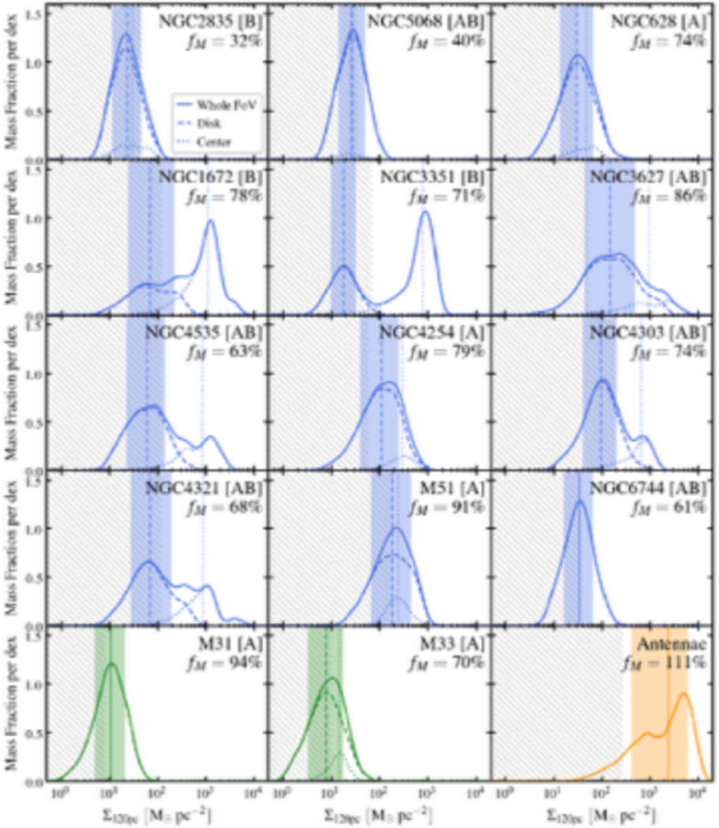


Hα
[OIII]
[SII]

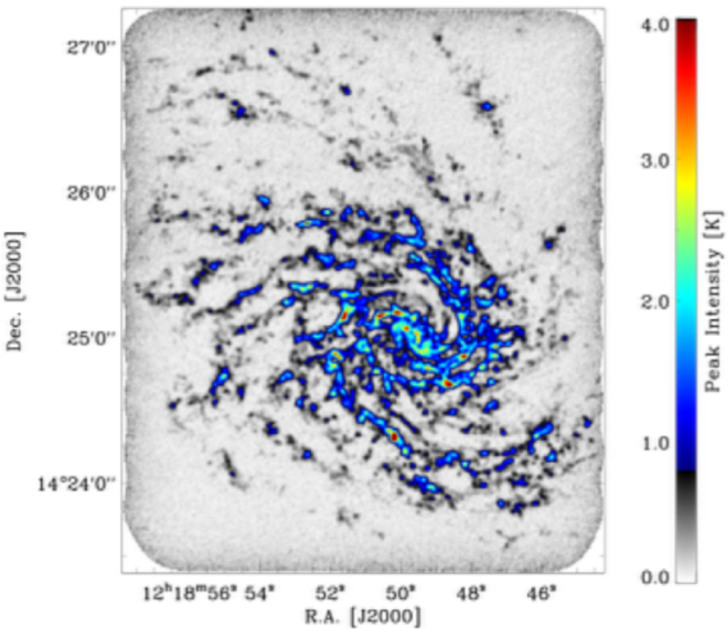
MUSE@VLT (optical IFU)

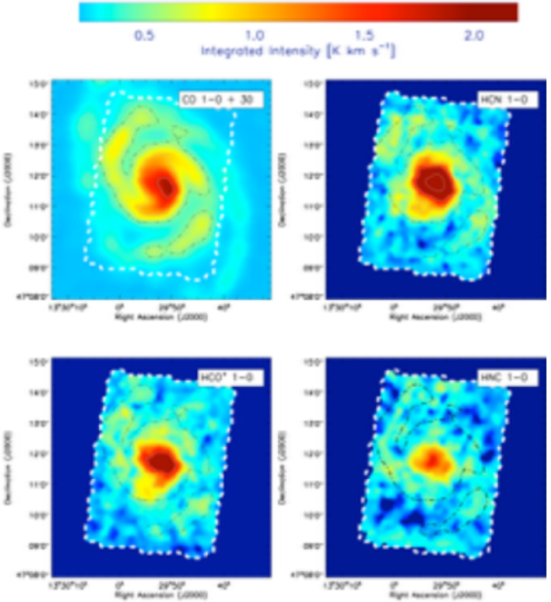
(172h for 18 PHANGS galaxies, PI Schinnerer)

Distribution of mass (CO flux) as a function of cloud-scale (here 120 pc) surface density in 15 galaxies. The small-scale surface density varies from galaxy to galaxy and as a function of dynamical environment.



Jiayi Sun et PHANGS (2018)





Cloud Scale Gas Mapping

PHANGS-ALMA: Leroy, Schinnerer (PI), Blanc, Hughes, Rosolowsky, Schruba,, Pety, Herrera et al. (in prep.)

Time Axis: Kruijssen, Chevance, Schinnerer

Dense Gas Mapping

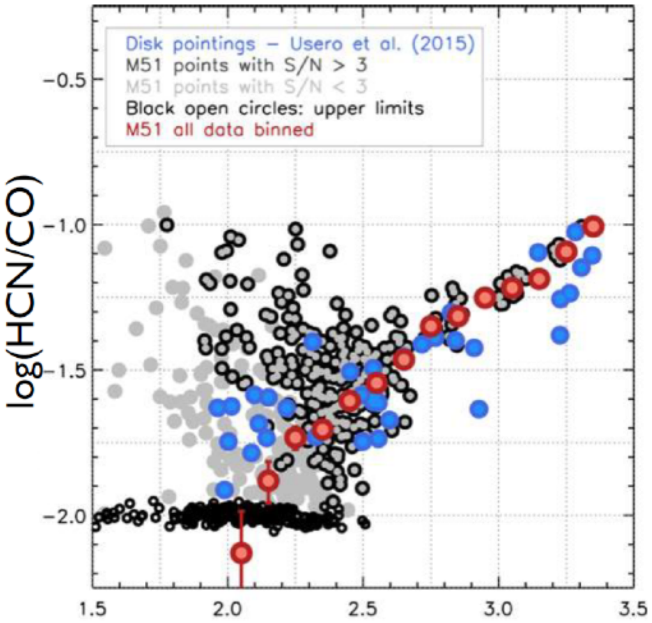
EMPIRE (PI Bigiel): Jimenez Donaire talk, Puschnig poster
DEGAS (PI Kepley): Kepley poster
Wilson talk, Bemis poster

Dense gas fraction

Bigiel et al. (2016)

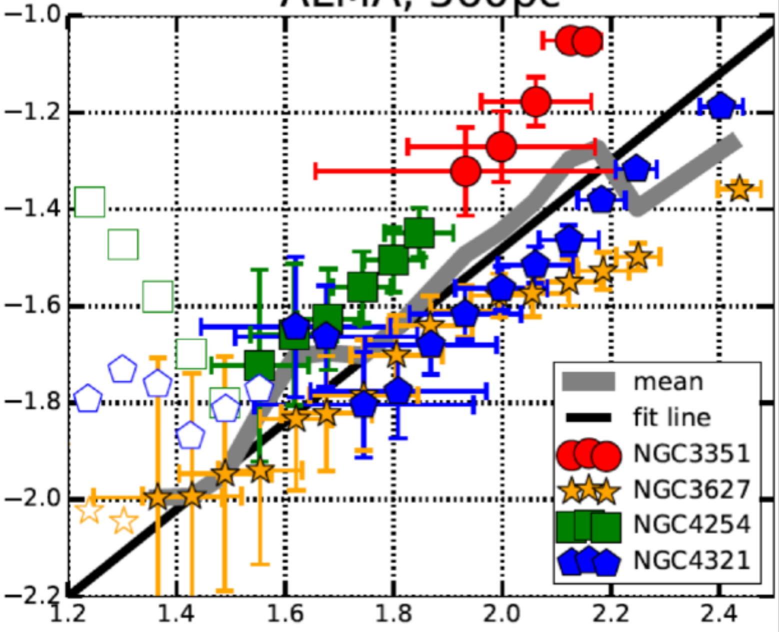
Gallagher et al. (in prep.)

28" single dish (IRAM 30m)



log(stellar surface density)

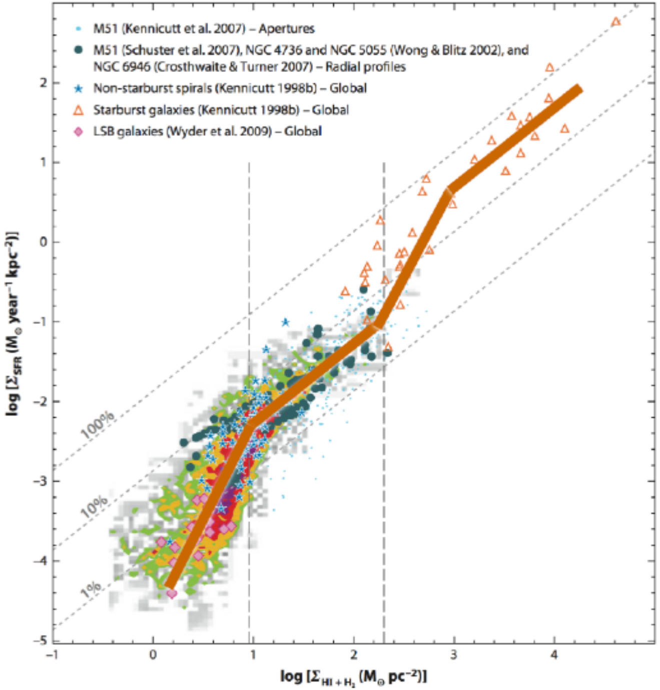
ALMA, 560pc



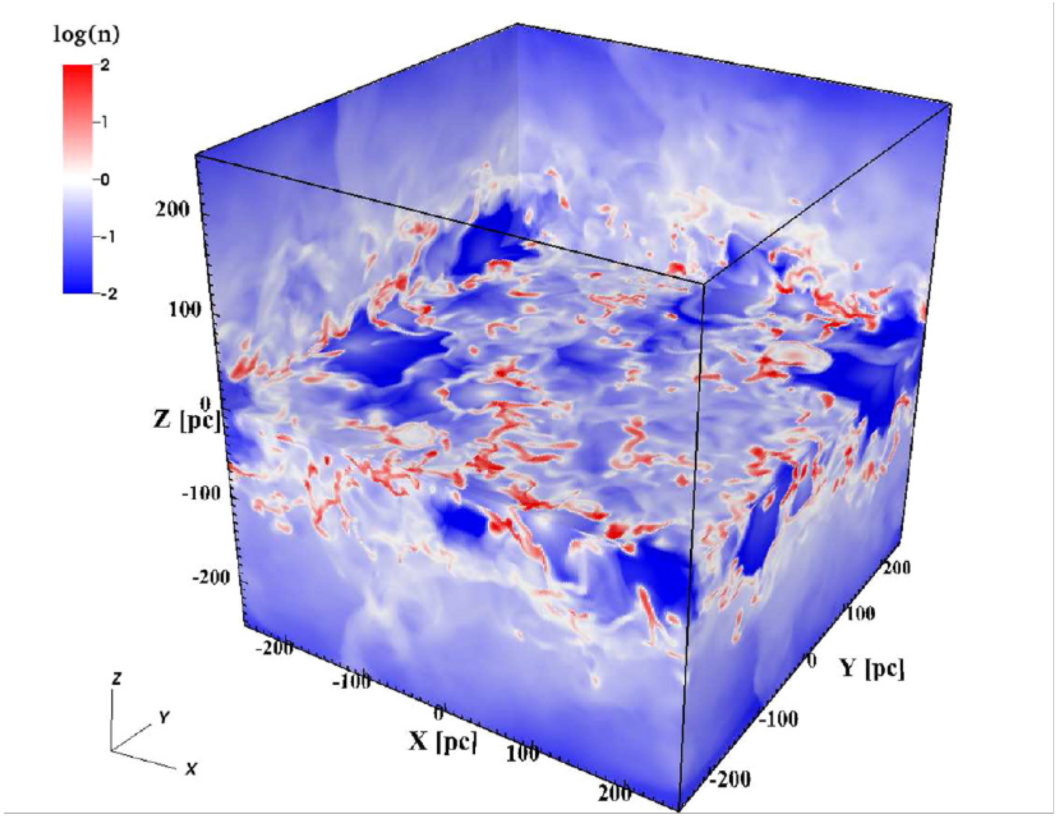
log(cloud gas surface density)

Predicts multiple physical regimes; efficiency & timescale degenerate again

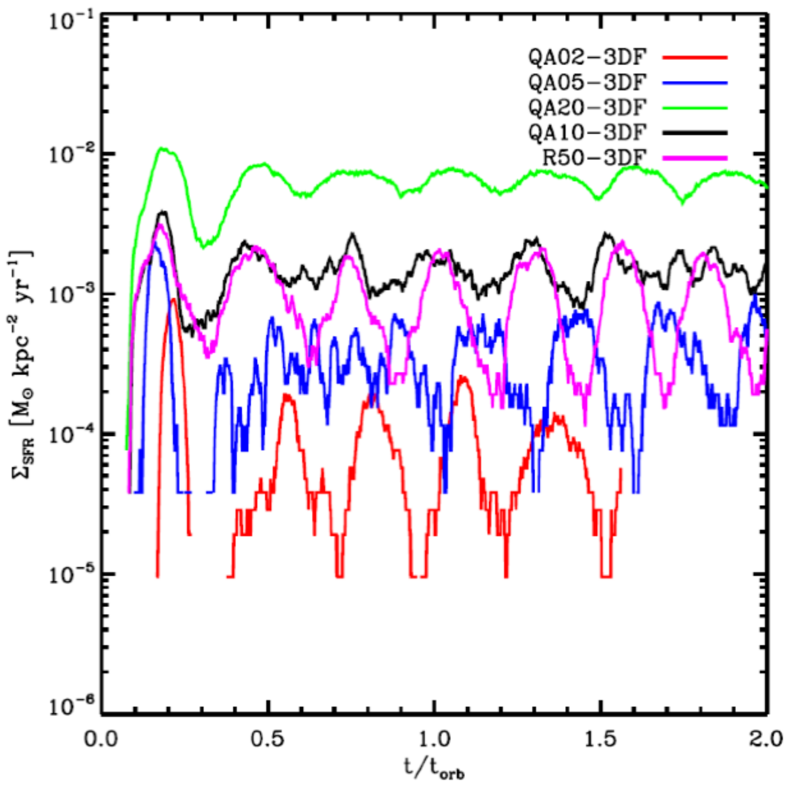
$$\Sigma_{\rm SFR} = \frac{\epsilon}{t_{\rm SF}}\Sigma_{\rm gas}$$

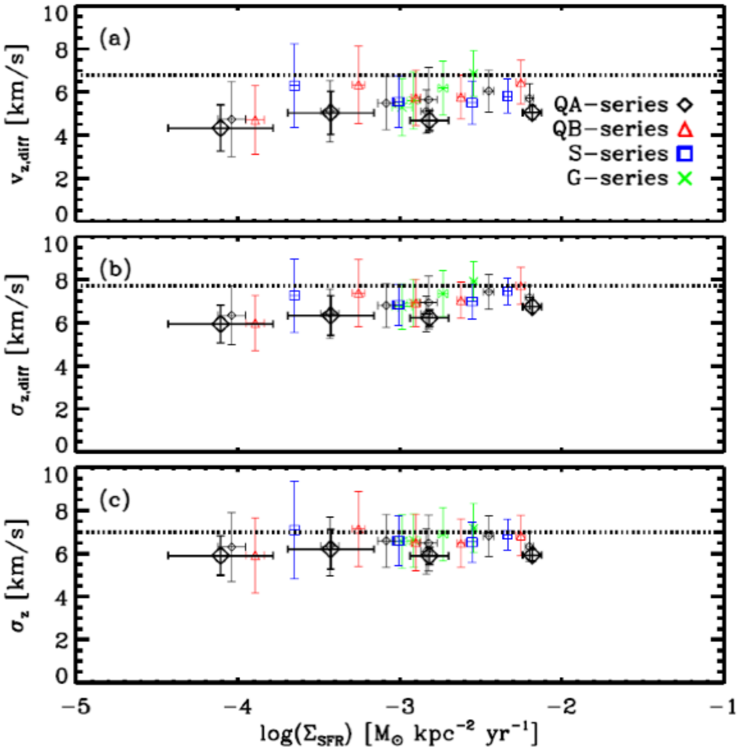


Kennicutt & Evans 2012

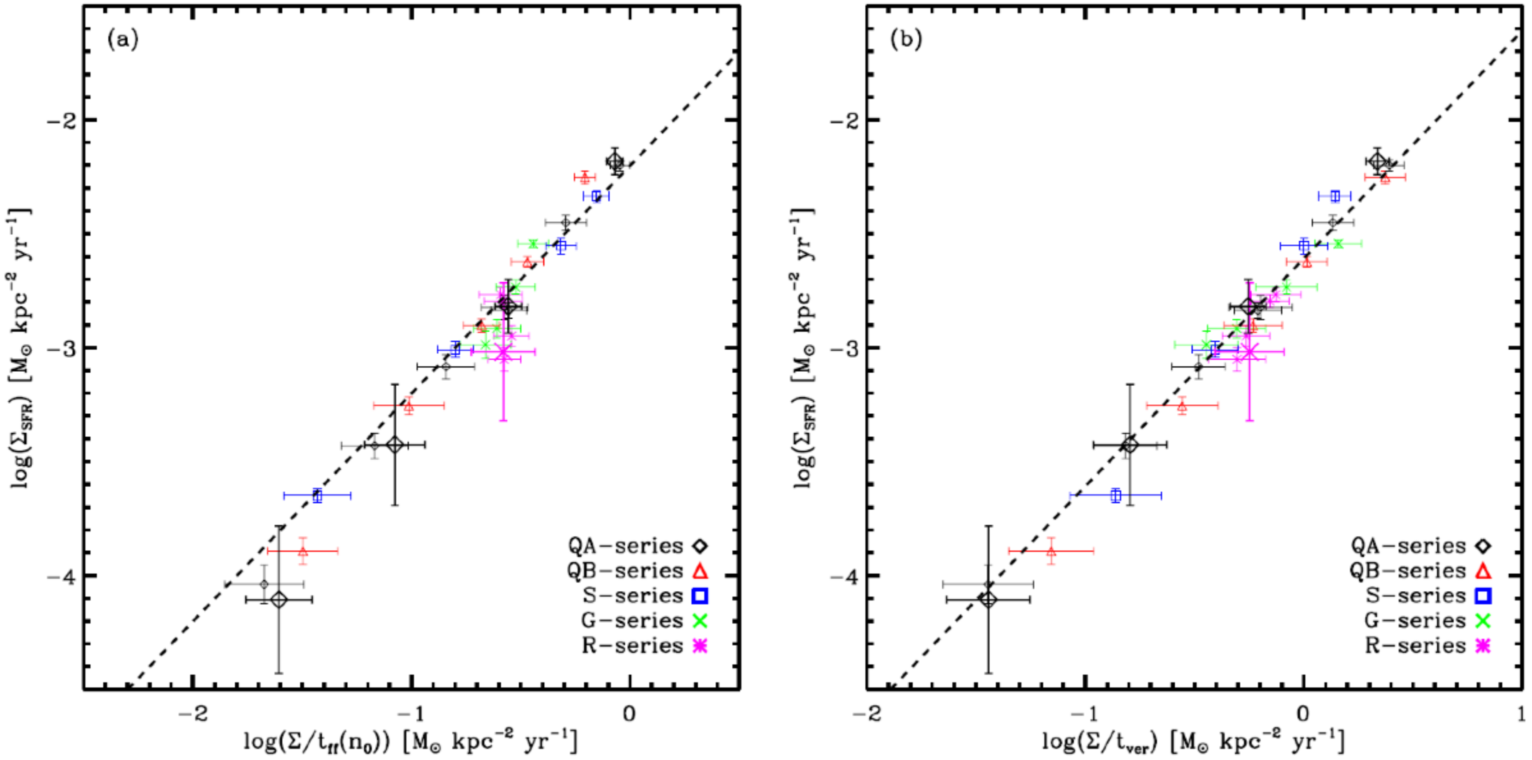


Kim, Ostriker, Kim 2013


QA02−3DF
QA05−3DF
QA20−3DF
QA10−3DF
R50−3DF
Σ_{SFR} [$M_\odot$ kpc^{-2} yr^{-1}]
t/t$_{orb}$


(a)
(b)
(c)
$v_{z,diff}$ [km/s]
$\sigma_{z,diff}$ [km/s]
σ_z [km/s]
QA−series
QB−series
S−series
G−series
log(Σ_{SFR}) [$M_\odot$ kpc^{-2} yr^{-1}]

Kim+ 2013


(a)
(b)
log(Σ_SFR) [M⊙ kpc⁻² yr⁻¹]
log(Σ/t_ff(n_0)) [M⊙ kpc⁻² yr⁻¹]
log(Σ/t_ver) [M⊙ kpc⁻² yr⁻¹]
QA−series
QB−series
S−series
G−series
R−series
−2
−3
−4
−1
0
1

Kim+ 2013

Key Takeaway Points: Observations

- A simplistic monotonic Schmidt power law with N ~ 1.5 remains as a useful “recipe” for modelling and simulating large-scale star formation over a wide range of physical conditions
- Complexity lurks beneath the surface of the global Schmidt law. There is strong evidence for phase transitions:
    - a threshold at low densities,near the transitions between the atomic/molecular, diffuse/bound, and warm/cool ISM phases. These thresholds are virtually coincident in the solar neighborhood but become distinct in regions of much higher or lower surface density and P_{ISM}
    - another apparent transition near the surface density for the formation of bound molecular clumps within clouds. This may be associated with the onset of a high-efficiency SF mode in starburst regions. Whether this transition is discreet or continuous remains to be established

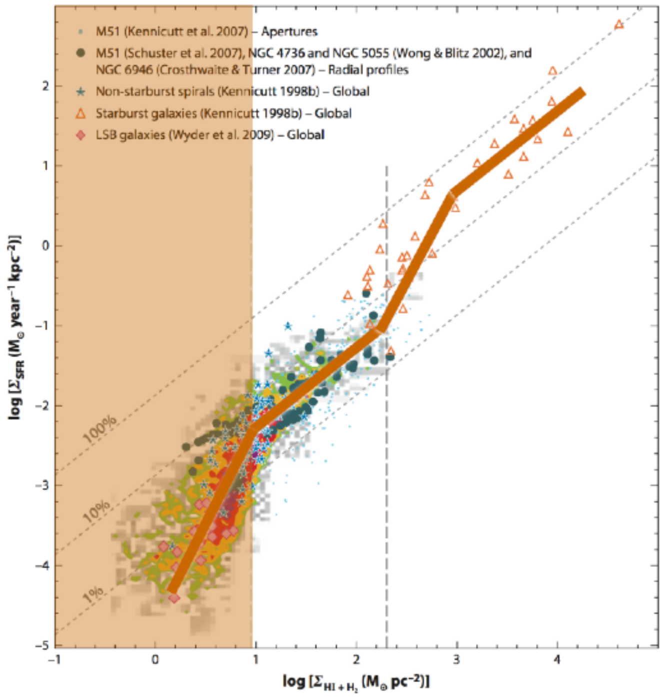
Key Takeaway Points: Interpretation

- Understanding the physics underlying the observed scaling laws and the key regulators and triggers of star formation requires a multi-scale approach, both observationally and theoretically (1 – 100,000 pc!)
  - much of the key physics appears to lie at the interfaces between key SF scales: between galaxies and the CGM/IGM, at the interfaces between clouds and the diffuse ISM, HI and H2, warm and cool gas, between bound and unbound structures within clouds, and between molecular clumps and cores. No theoretical picture can be complete without understanding the transitions at <u>all</u> of these interfaces
  - observations and theory increasingly point to the importance of feedback and self-regulation as key drivers of the SFR. We are dealing with complex ecosystems, in which physical processes on all scales are relevant

Atomic regime: heating / cooling balance sets molecular gas fraction

heating rate → $\Sigma_{SFR} \propto \Sigma_{gas}^2$ ← cooling rate

(also linear dependence on metallicity)

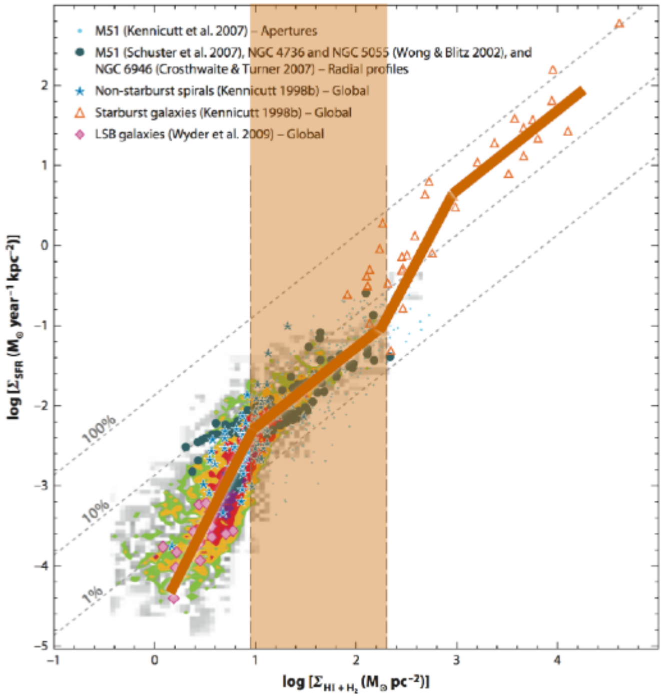


Kennicutt & Evans 2012

Schaye 2004
Krumholz+ 2009
Ostriker+ 2010
Hayward & Hopkins 2015
Orr+ 2018
…and many others

Intermediate Σ regime: momentum injection / turbulent dissipation balance

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}(\Sigma_{\rm gas} + \Sigma_{\rm star}) \propto \Sigma_{\rm gas}$$ (also linear dependence on Toomre *Q*)

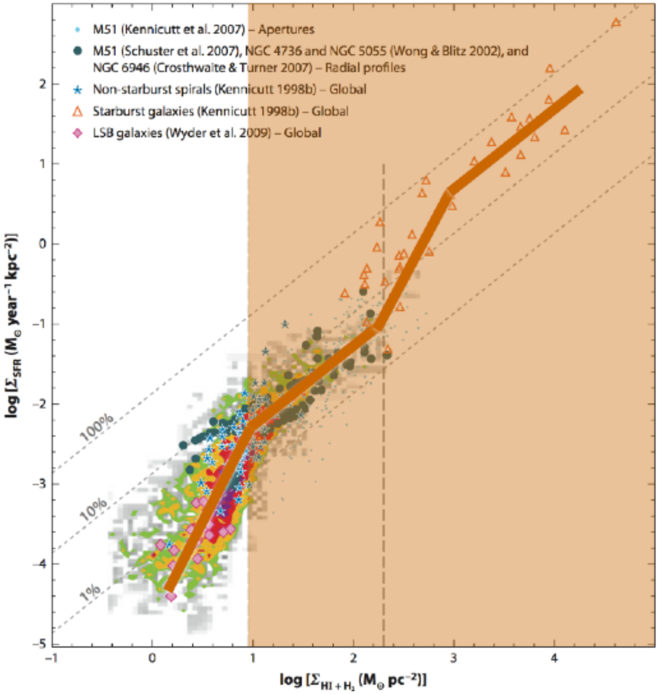


Kennicutt & Evans 2012

Ostriker & Shetty 2011
Faucher-Giguere+ 2013
Kim & Ostriker 2015
Orr+ 2018

Molecular regime: momentum injection / turbulent dissipation balance

momentum injection rate → $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}(\Sigma_{\rm gas} + \Sigma_{\rm star}) \propto \Sigma_{\rm gas}$ ← turbulent dissipation rate (also linear dependence on Toomre Q)

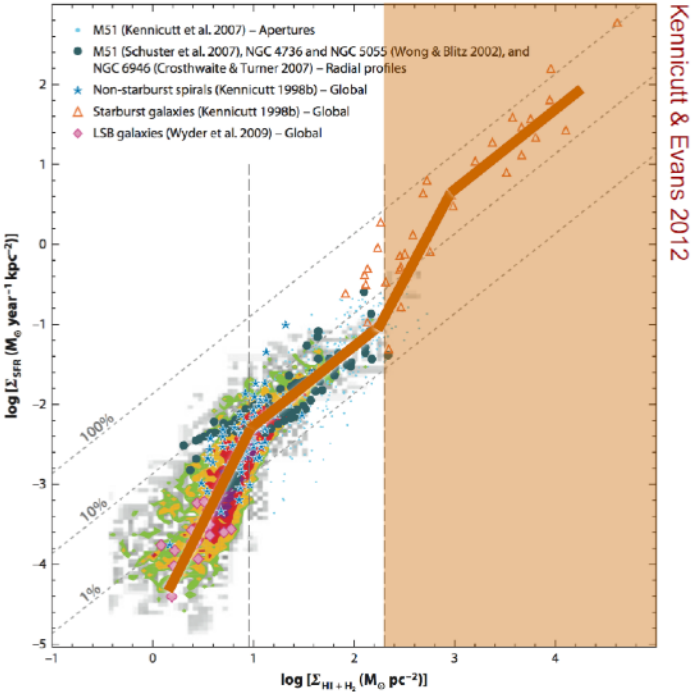


Kennicutt & Evans 2012

Ostriker & Shetty 2011
Faucher-Giguere+ 2013
Kim & Ostriker 2015
Orr+ 2018

High Σ regime: momentum injection / turbulent dissipation balance

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}(\Sigma_{\rm gas} + \Sigma_{\rm star}) \propto \Sigma_{\rm gas}^2$$ (also linear dependence on Toomre *Q*)



Ostriker & Shetty 2011
Faucher-Giguere+ 2013
Kim & Ostriker 2015
Orr+ 2018