National Research Foundation | SAAO South African Astronomical Observatory

Local Star Formation : The Molecular View

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Feast Fest 2017

Photo Credit: M100, Judy Schmidt

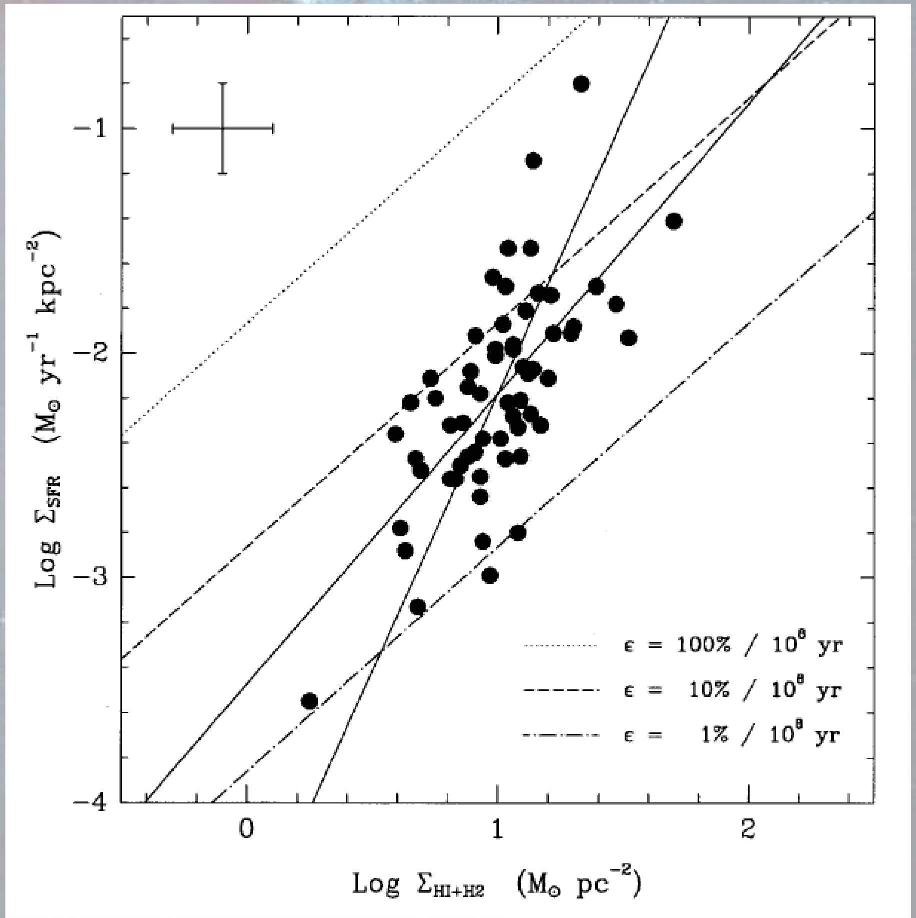
Spitzer and the Dust!

- Spitzer 1941
- Two dust particles absorb radiation.
- Decrease in Energy density
- Radiation Pressure causes attraction between particles

Photo Credit: M100, Judy Schmidt

Higher Gas Density > More Stars

- Schmidt (1959)
  - SFR ∝ (Density of Gas)^n
- Kennicutt (1989)
  - $\Sigma_{SFR} \propto (\Sigma_{Gas})^n$

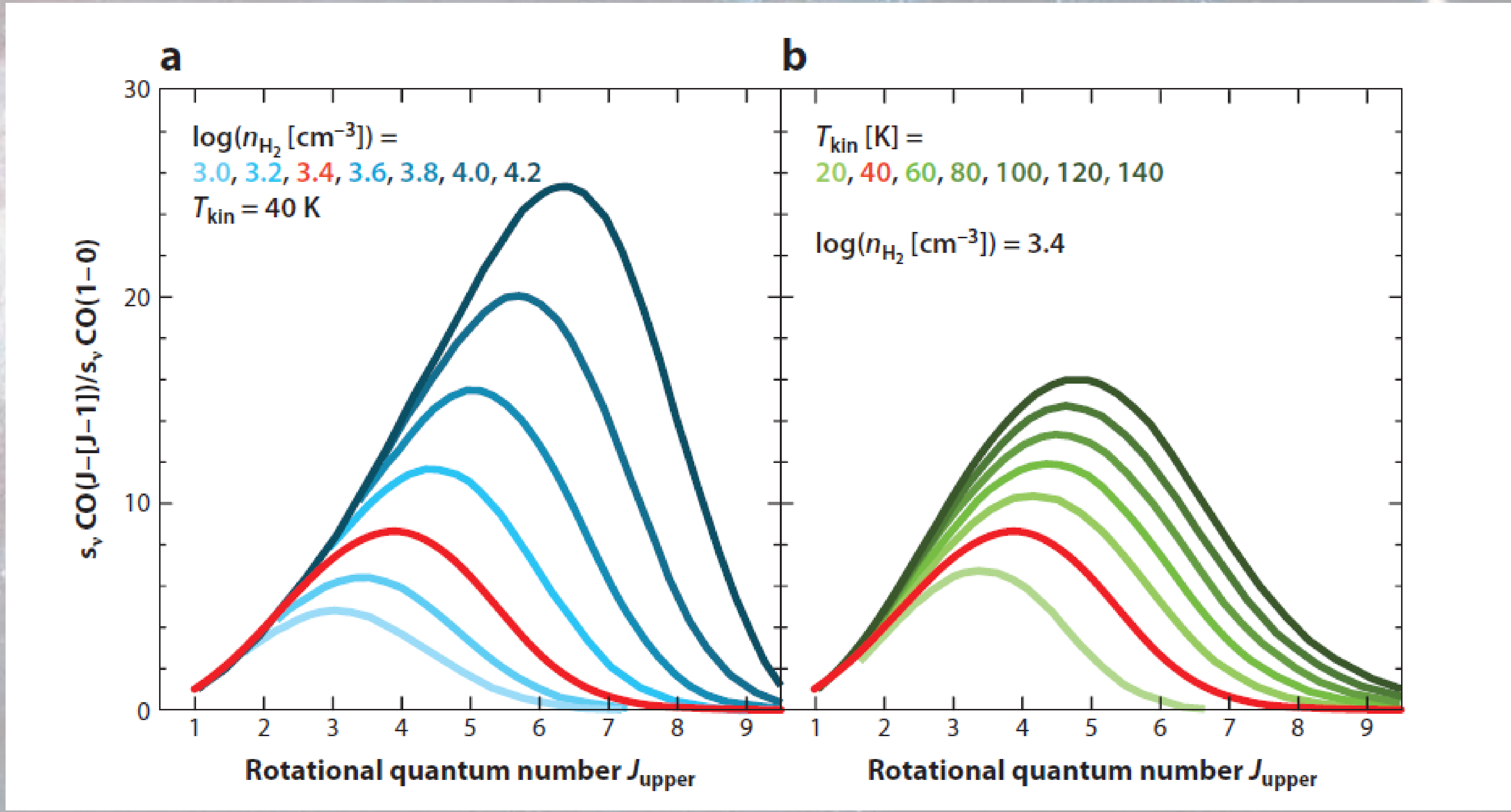


Star Formation Surface Density

Gas Surface Density

Tracing the Molecular Gas

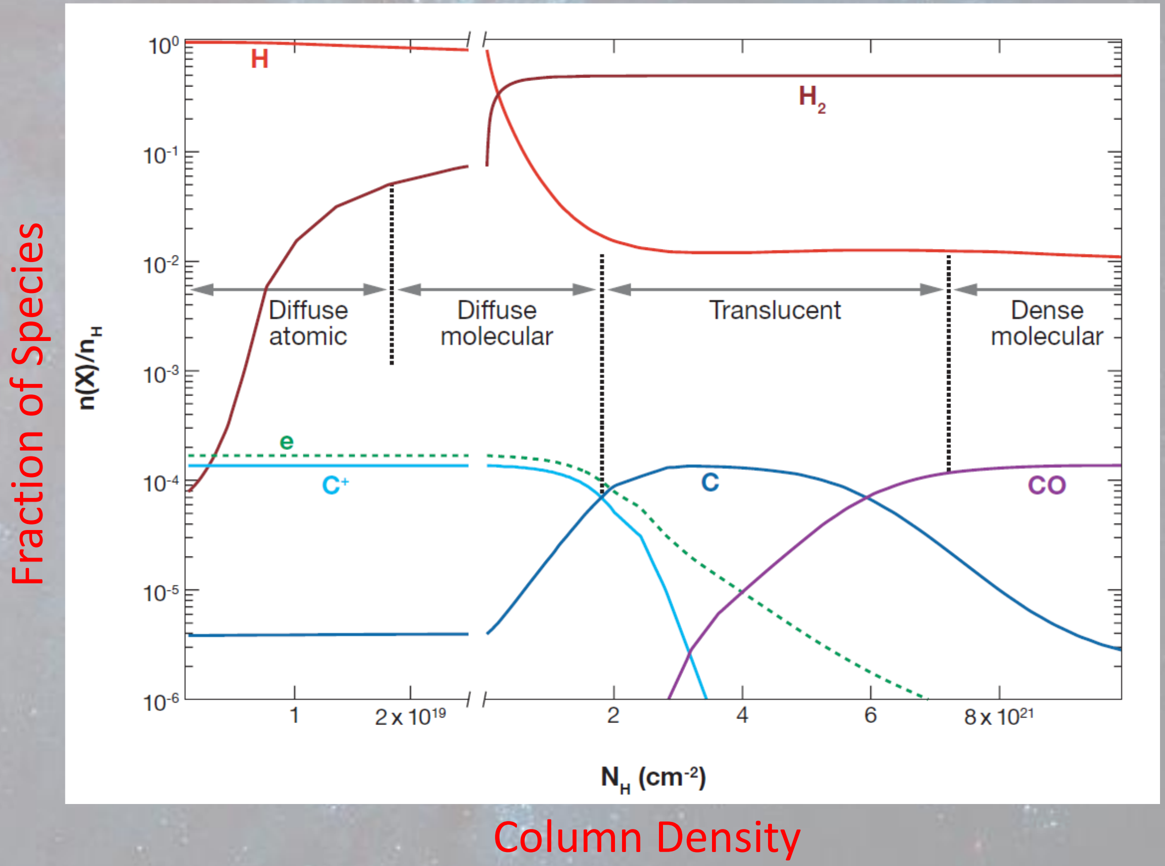
- CO
- Rotational Transition
- J=1-0, J=2-1, J=3-2



Carilli & Walter (2013)

Higher Density Gas… More Molecules

- Above ~10 M_{sol}/pc^2 – HI is saturated (i.e. the density of gas increases while HI density remains constant)
- At high densities molecular gas densities increase and HI converted to H_2 .



Neufeld et al. (2005), Snow & McCall (2006)

Higher Density Gas... More Molecules

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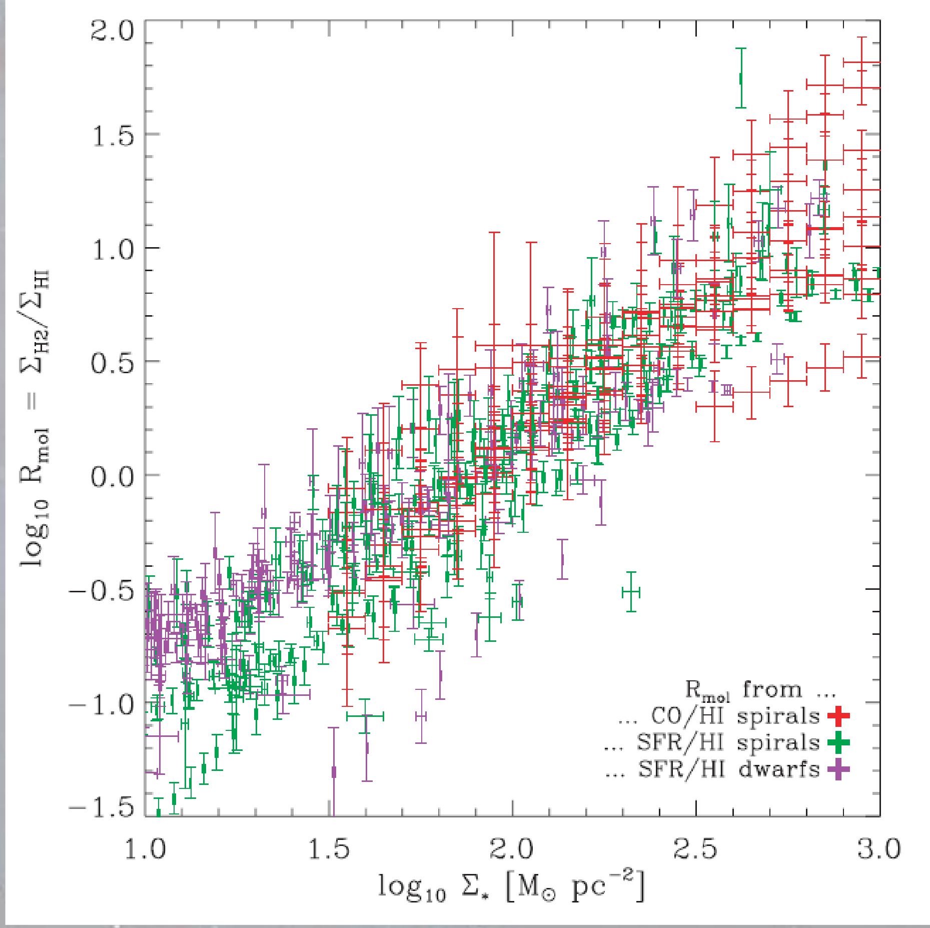
- At high densities molecular gas densities increase and HI converted to H_2 .

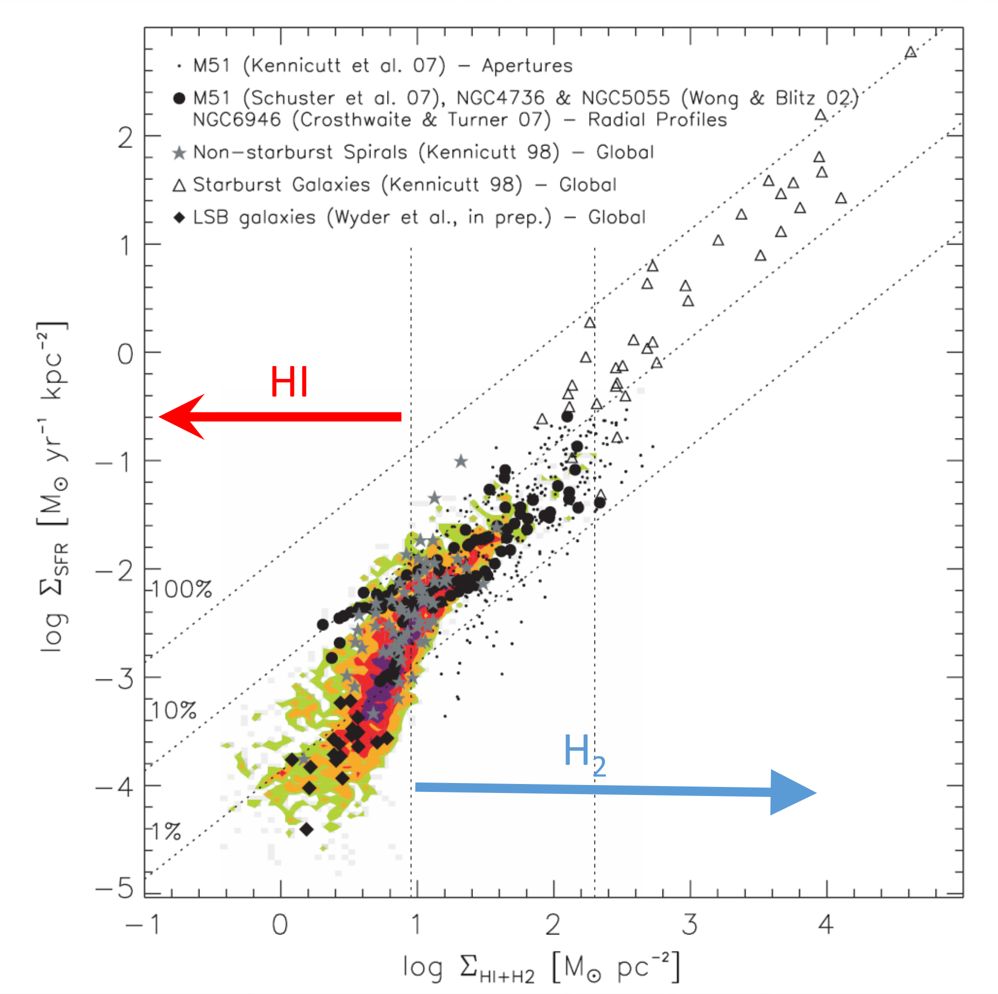
Molecular Gas Fraction



Stellar Surface Density

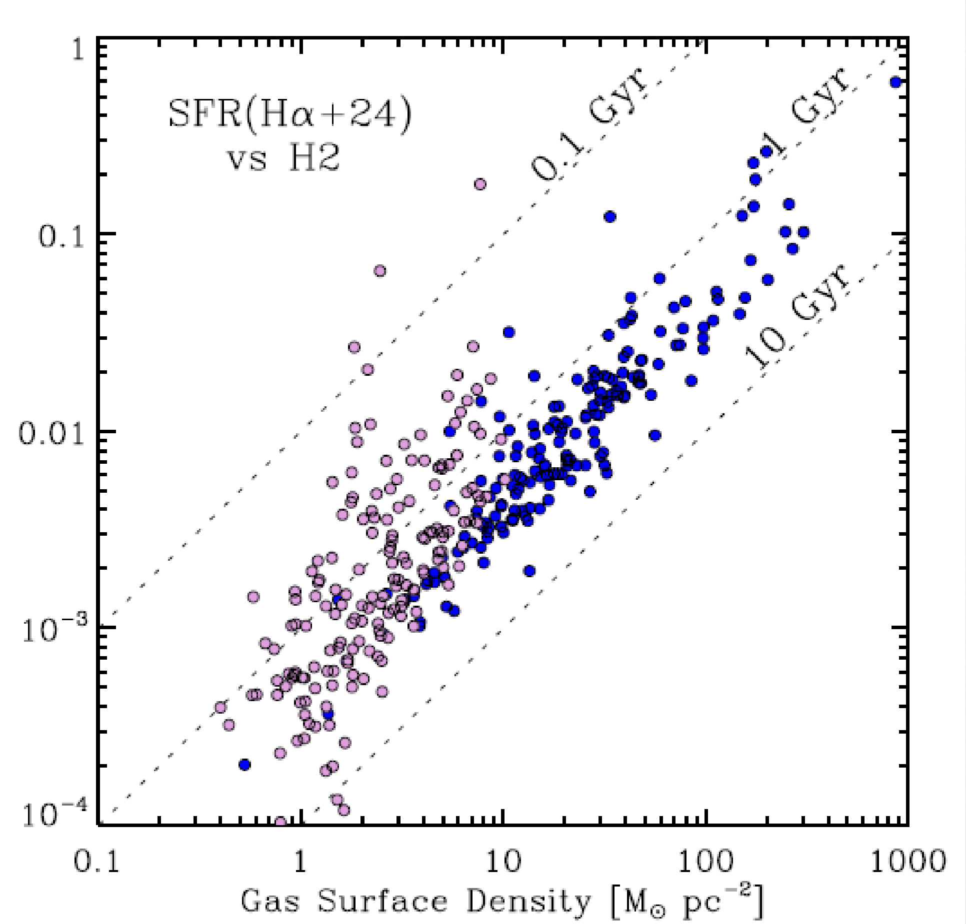
Leroy et al. (2008)

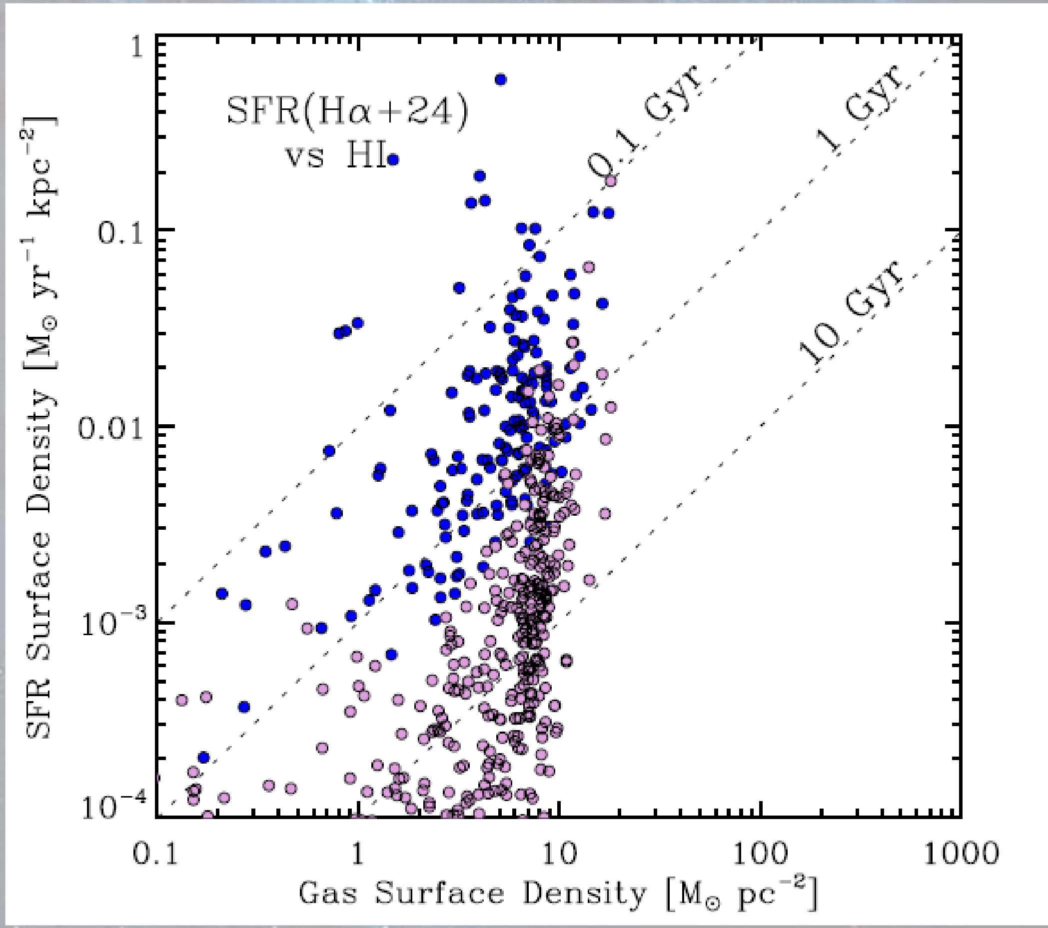
Molecular Star Formation Law?



Bigiel et al. (2008)

Molecular Star Formation Law



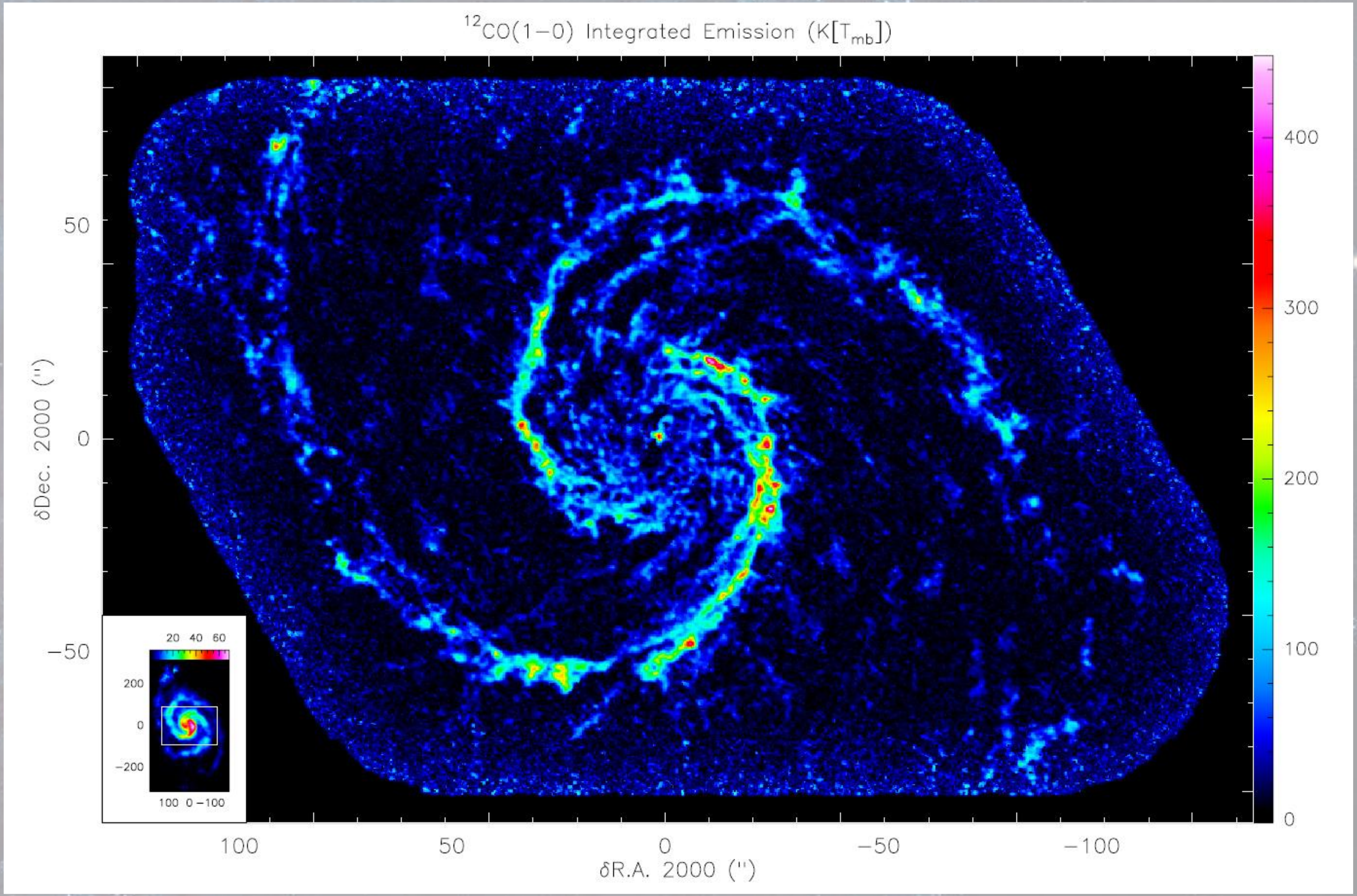


Blue : CO Dominant
Other : HI Dominant

Schruba et al. (2011)

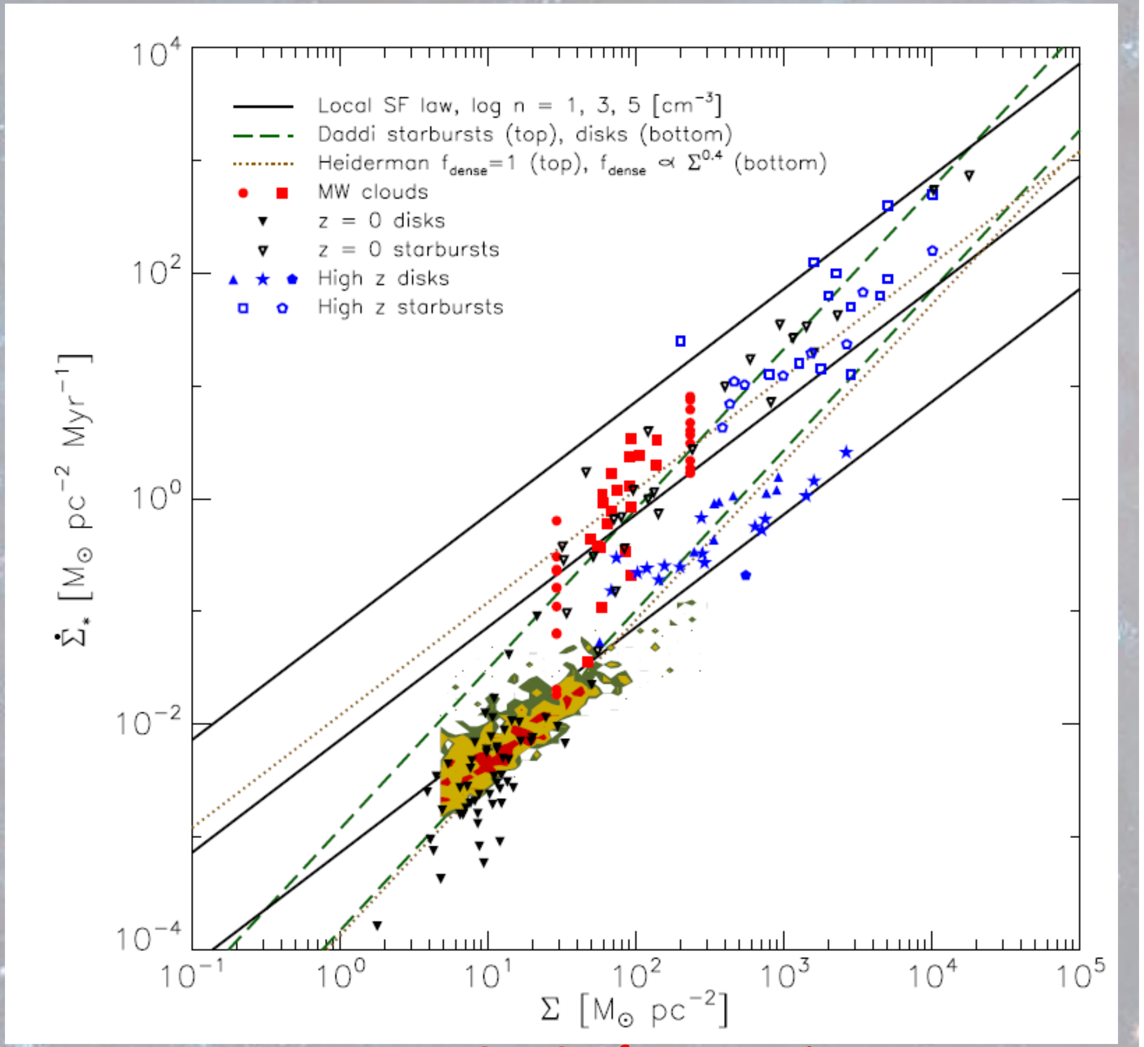
Scales

- 100s pc
  - Arms
- 40pc
  - GMCs



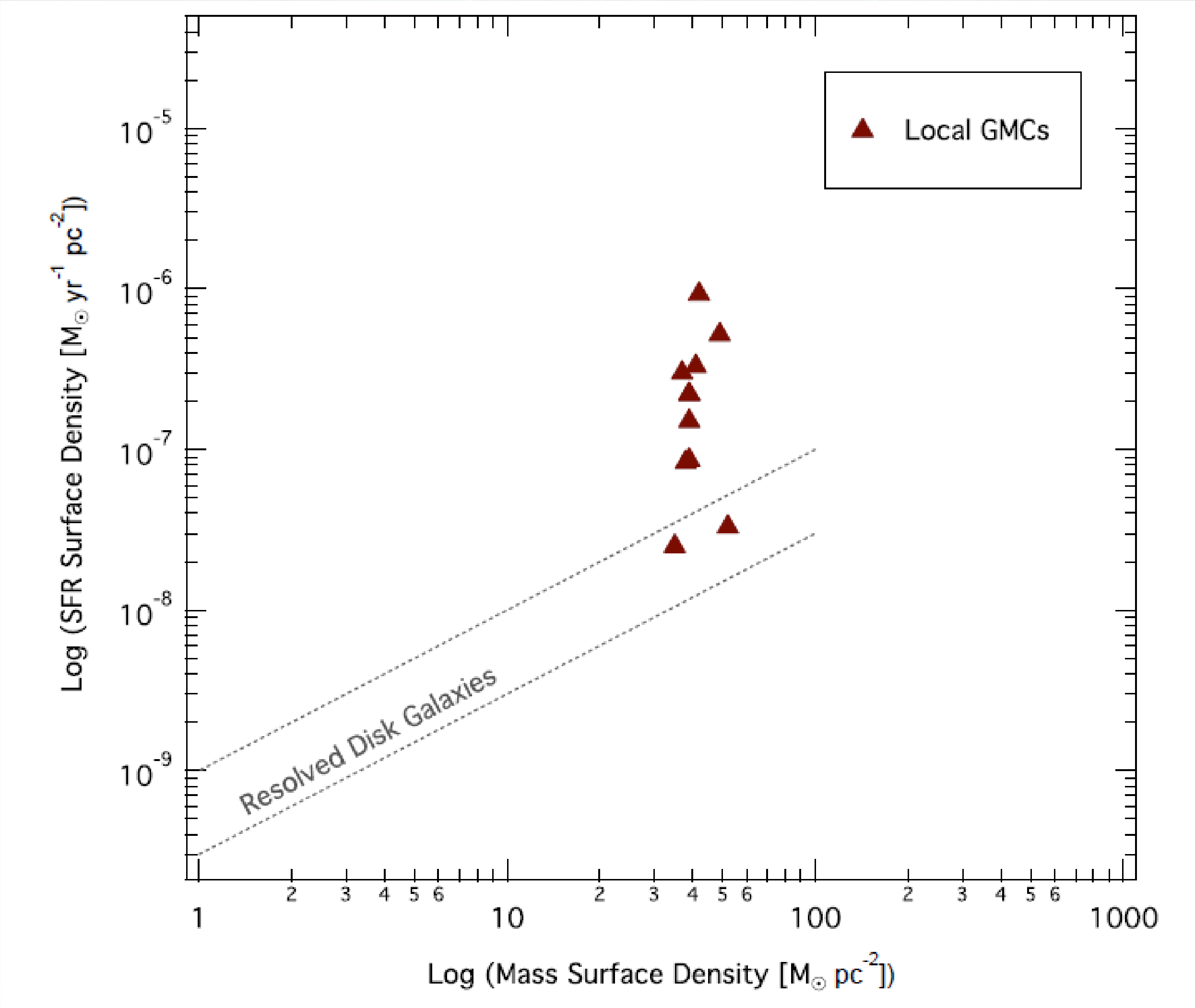
Pety et al. (2013) & PAWS

Scales



Gas Surface Density

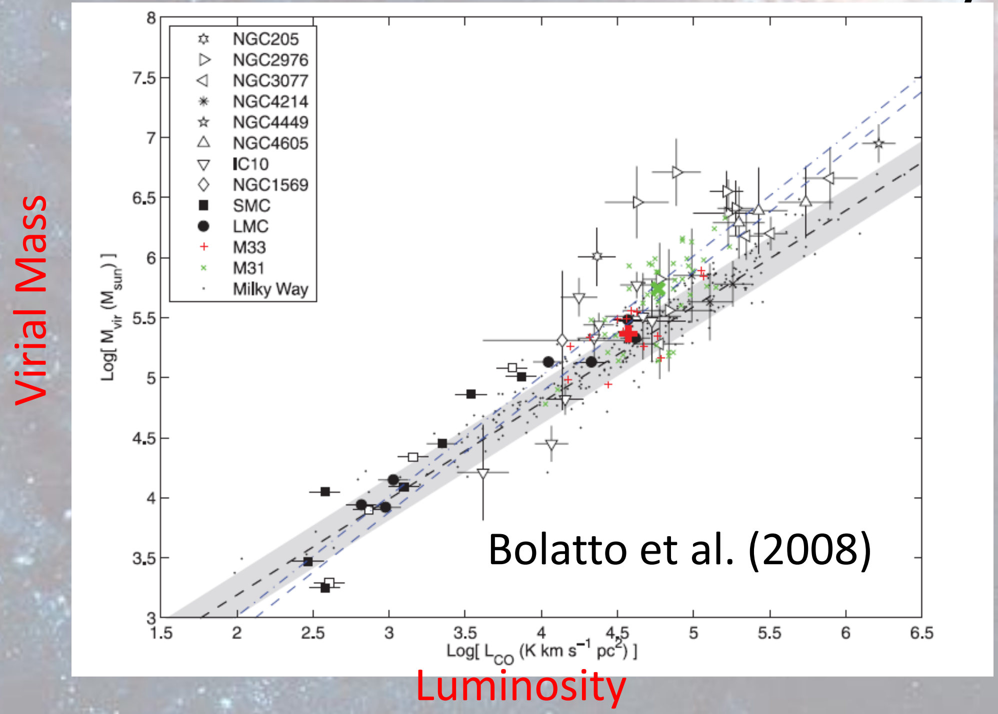
Krumholz et al. (2013)

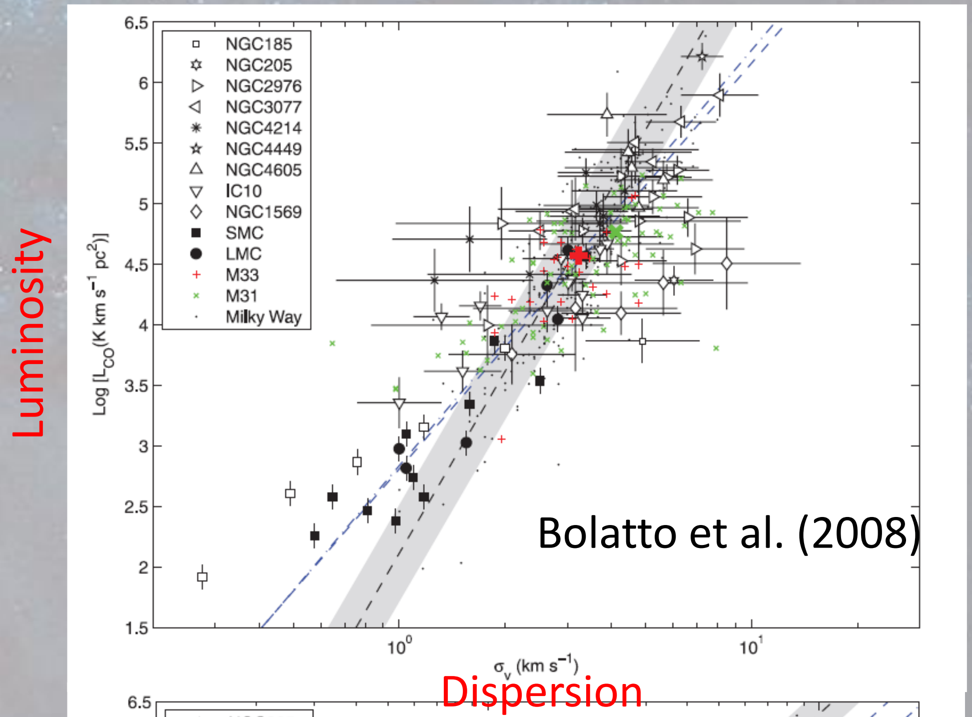


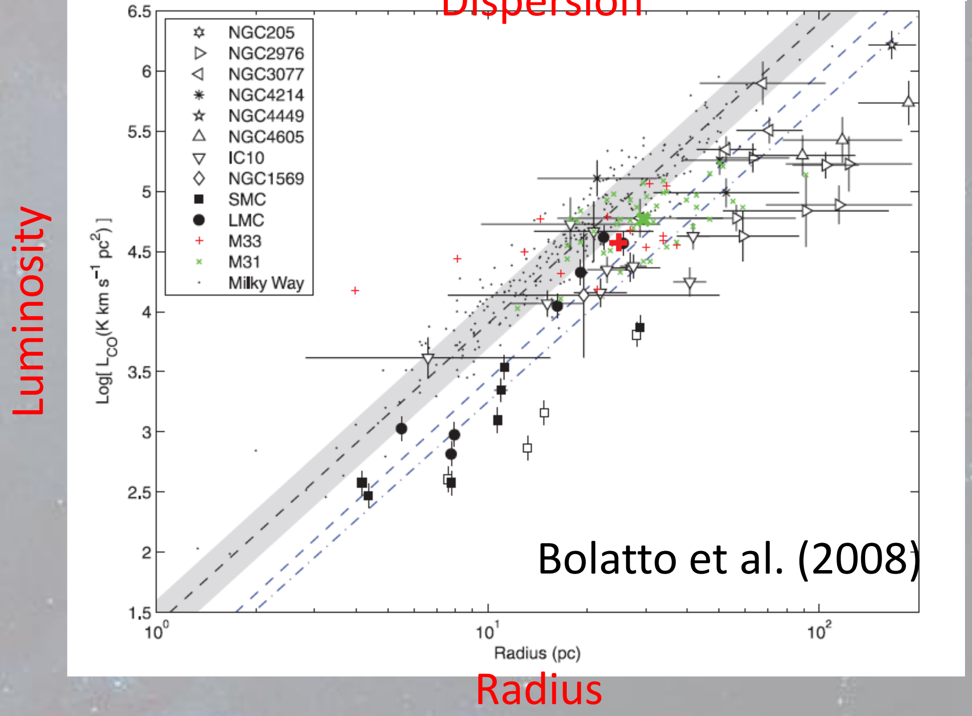
Lada et al. (2013)

Molecular Clouds

- Larson Scaling Relations :
  - Size – Line width
  - Luminosity – Line width
  - Luminosity – Size
  - Larson (1981), Solomon et al. (1987)
- Virialized Mass – Luminosity

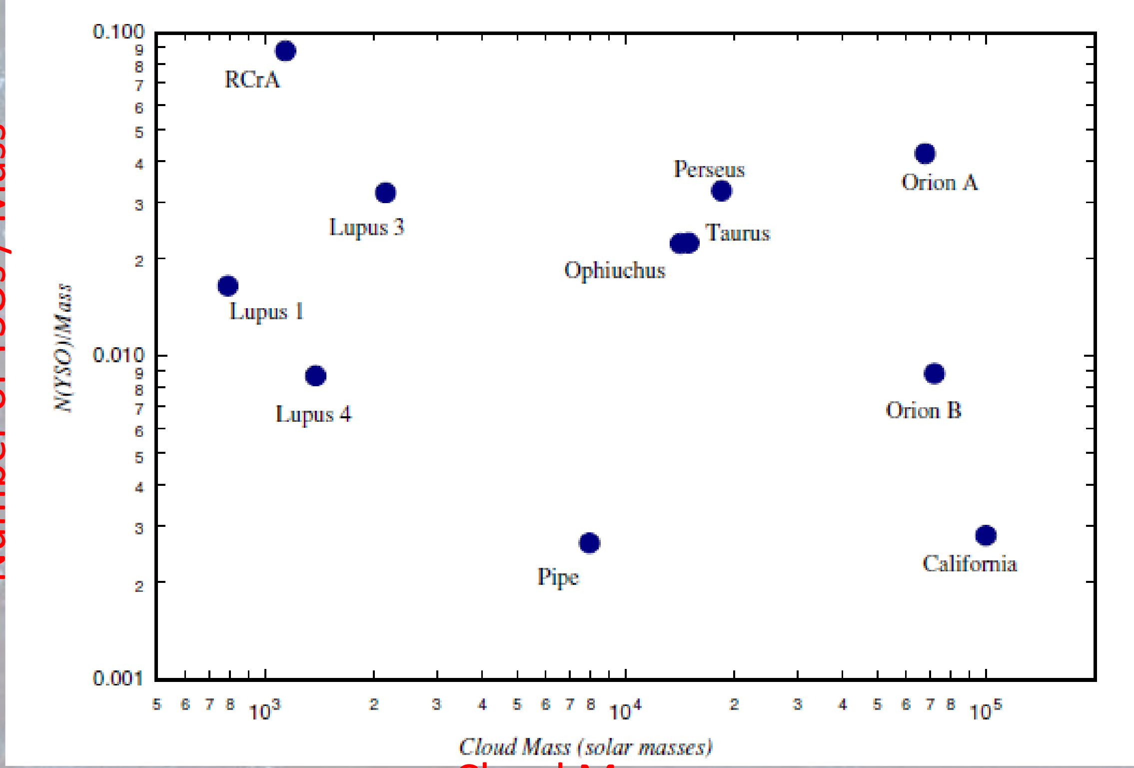






Molecular Clouds

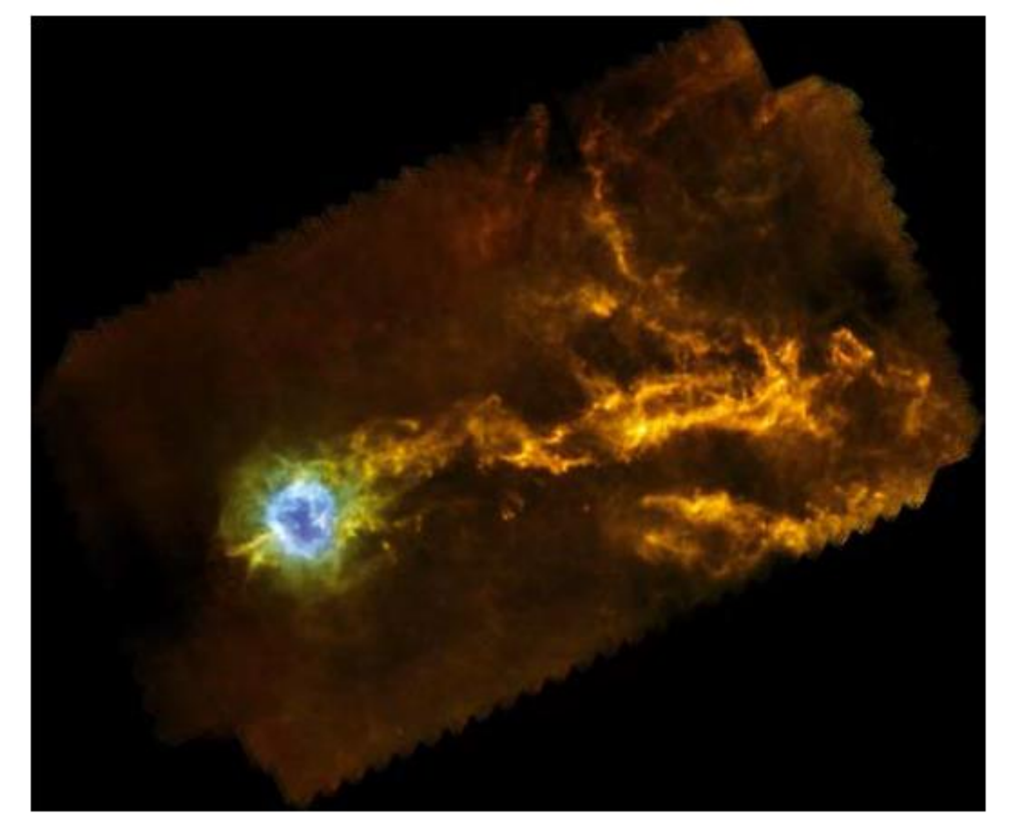
- Clouds are complex structures
- Down to <1pc scales



Number of YSOs / Mass

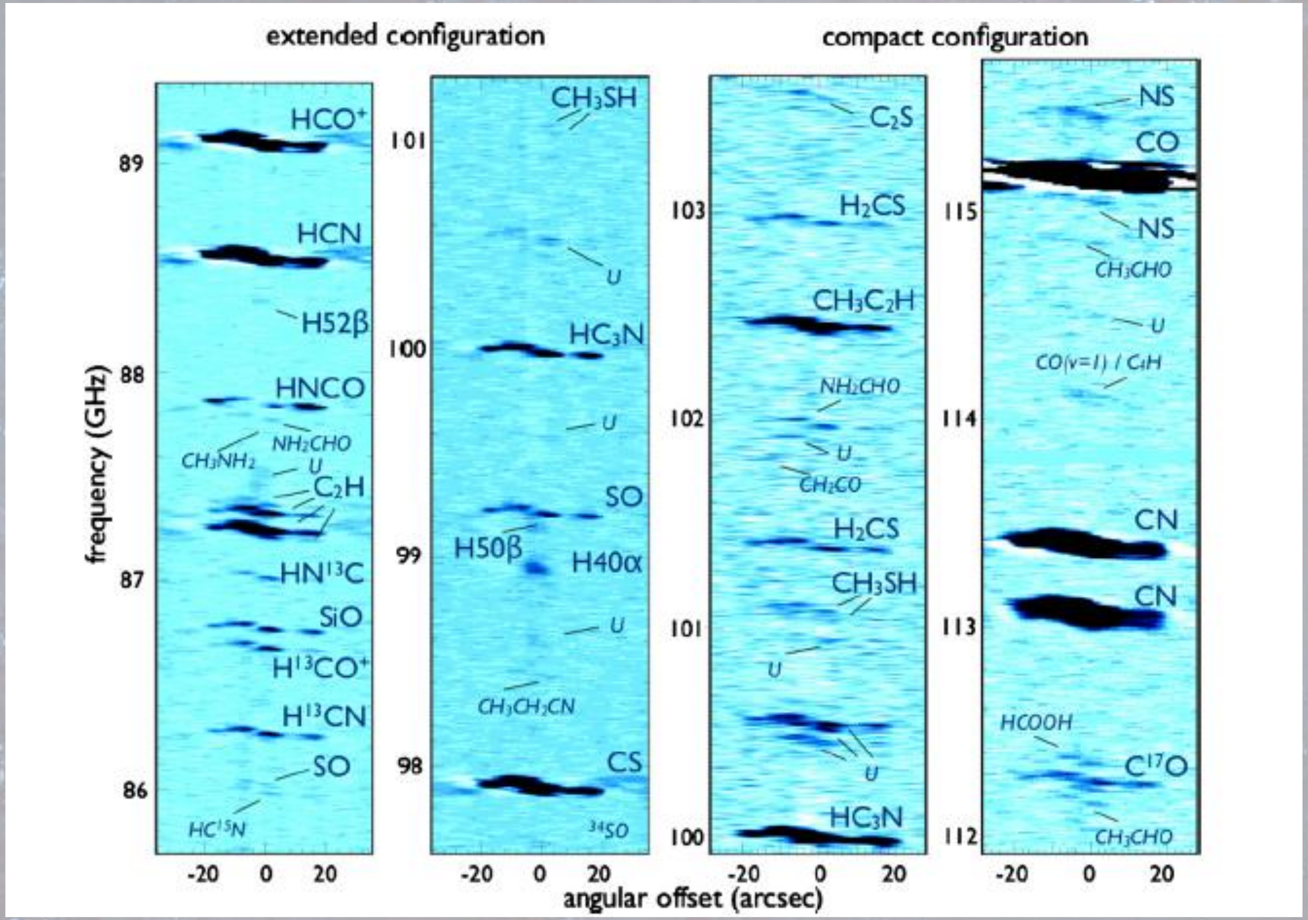
Cloud Mass

Lada et al. (2010)

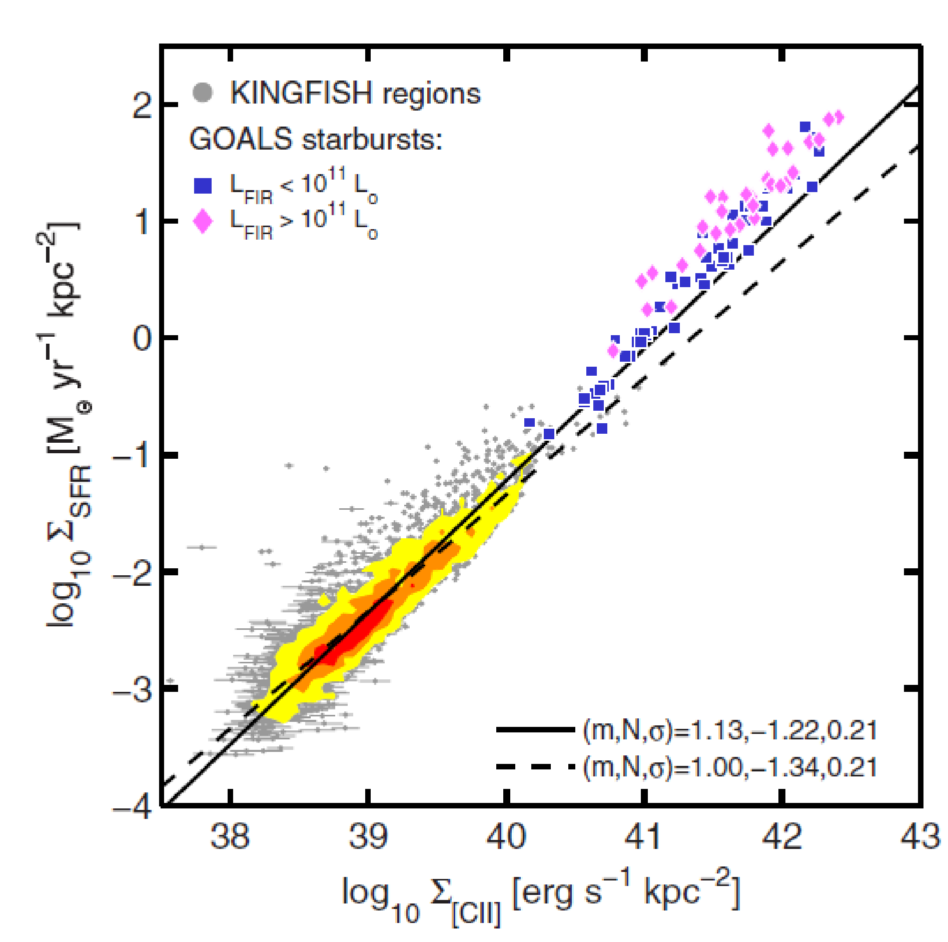


HERSCHEL Composite Arzoumanian et al. (2011)

Tracers



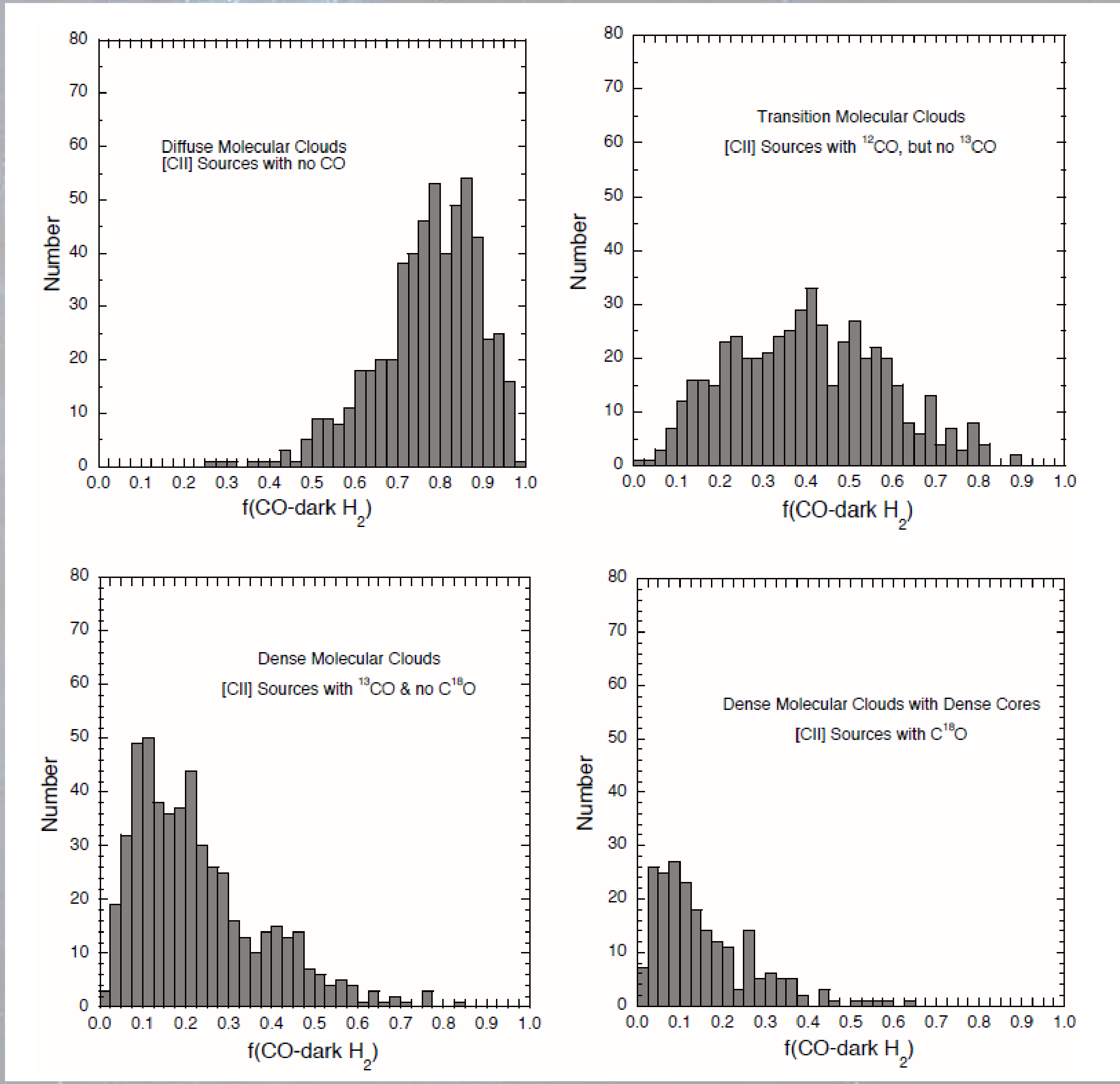
Meier et al. (2015)



Herrera-Camus et al. (2015)

Tracers

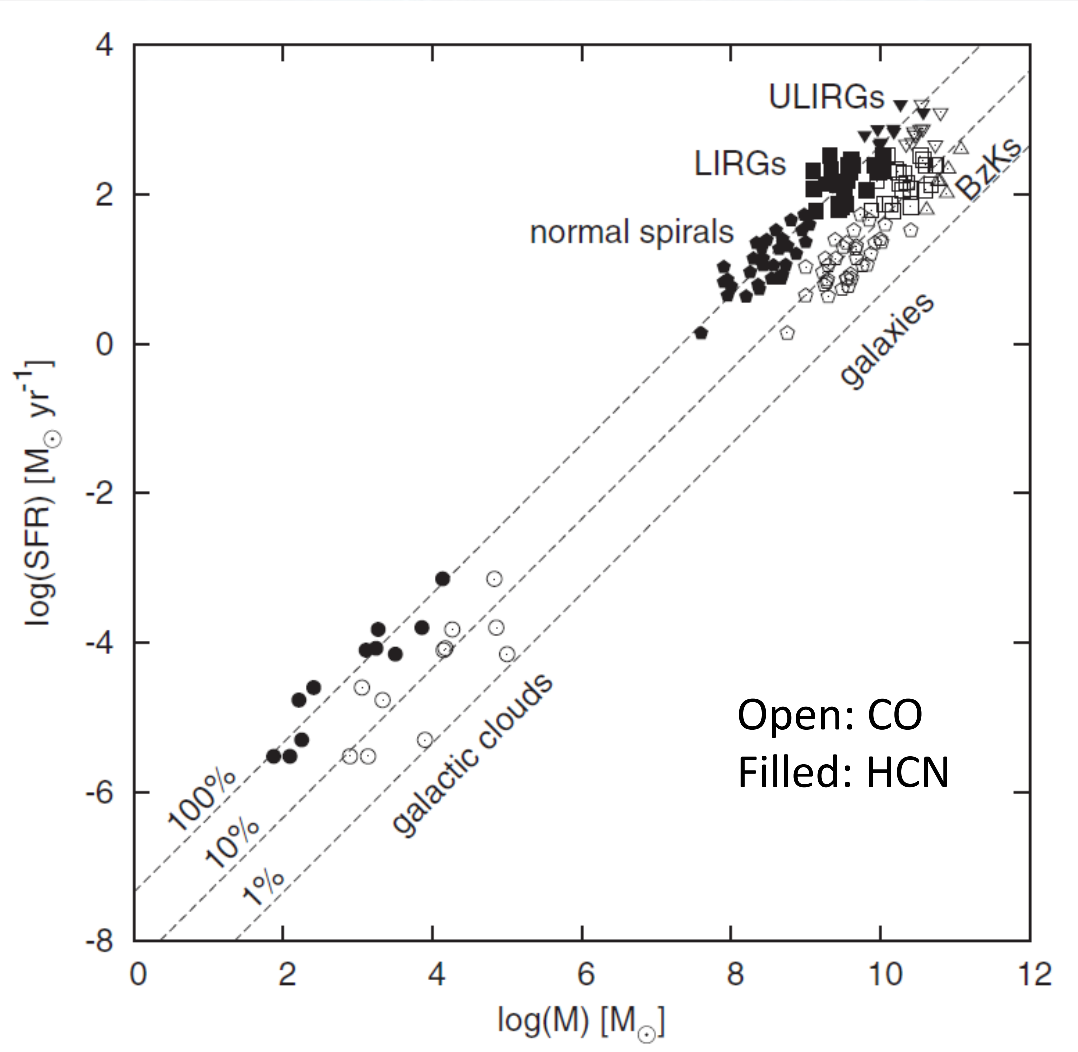
- $^{12}C^{16}O$ (J=1-0,J=2-1,J=3-2) Do not trace all the H_2
- Other CO isotopes and other molecules (eg. HCN) trace denser H_2
- CII traces more diffuse H_2



Langer et al. (2014)

Scales and Tracers

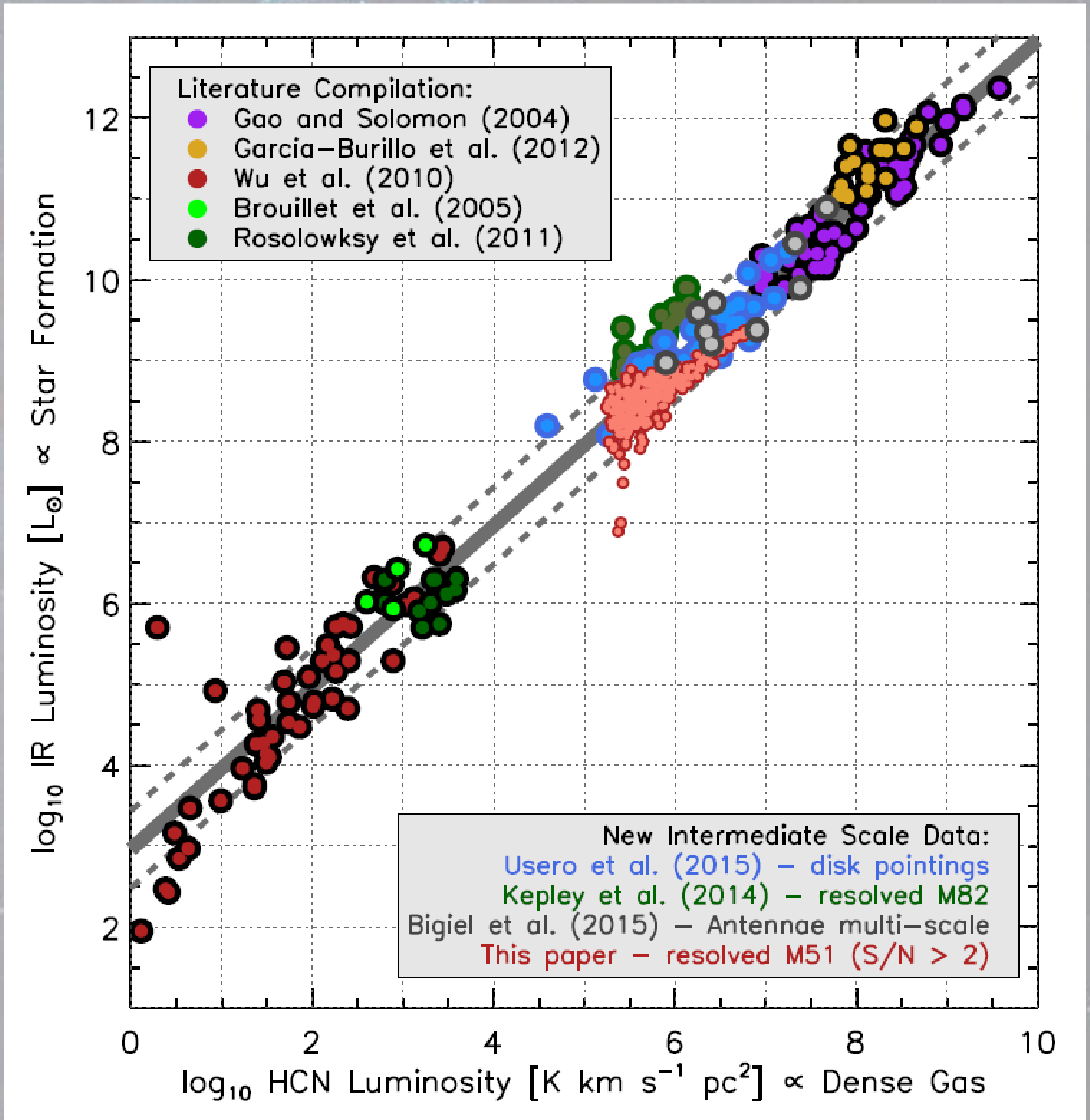
- Turbulence dominated Clouds
- CO does not trace the densest H_2 well
- Clouds have complex 3D structures



Lada et al. (2012)

Scales and Tracers

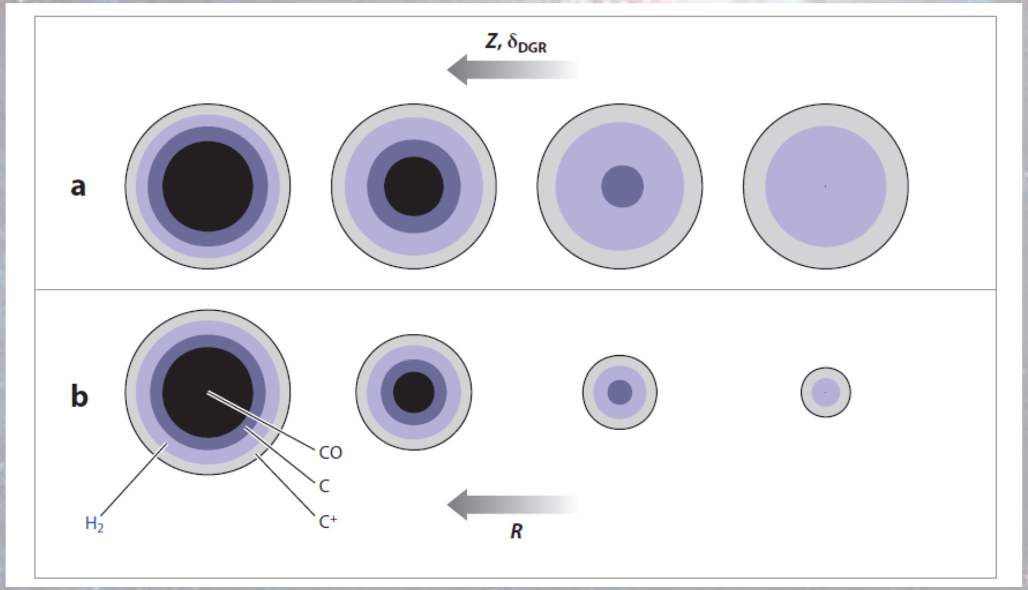
- Using Dense Gas tracers instead of CO improving SFR relations across different scales
- Tightest Relationship is between dense gas and SFR
- IRAM & ALMA Revolutionizing dense molecular gas studies



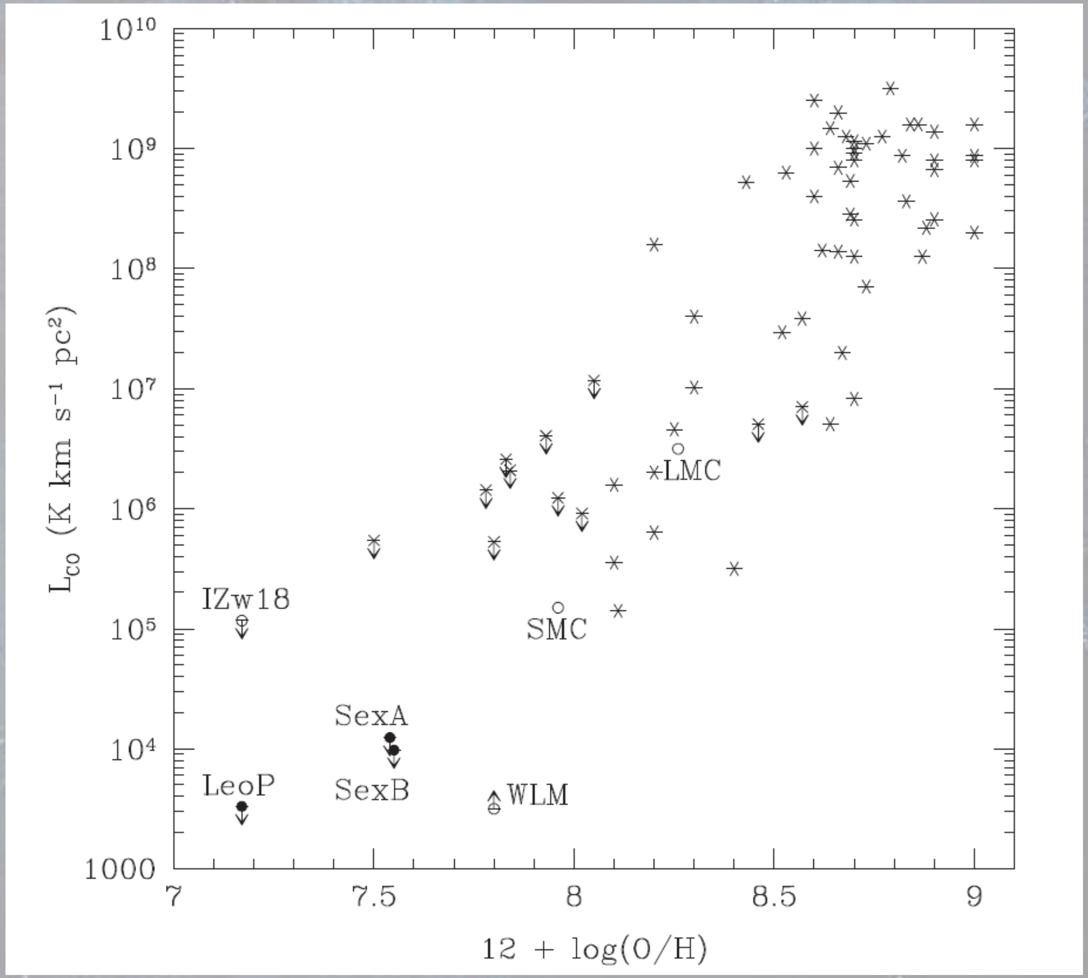
Bigiel et al. (2016)

Environmental Effects : Low Metallicity

- HI dominated environments
- CO is a poor tracer for H_2
  - Higher: α_{CO} conversion



Bolatto et al. (2013)



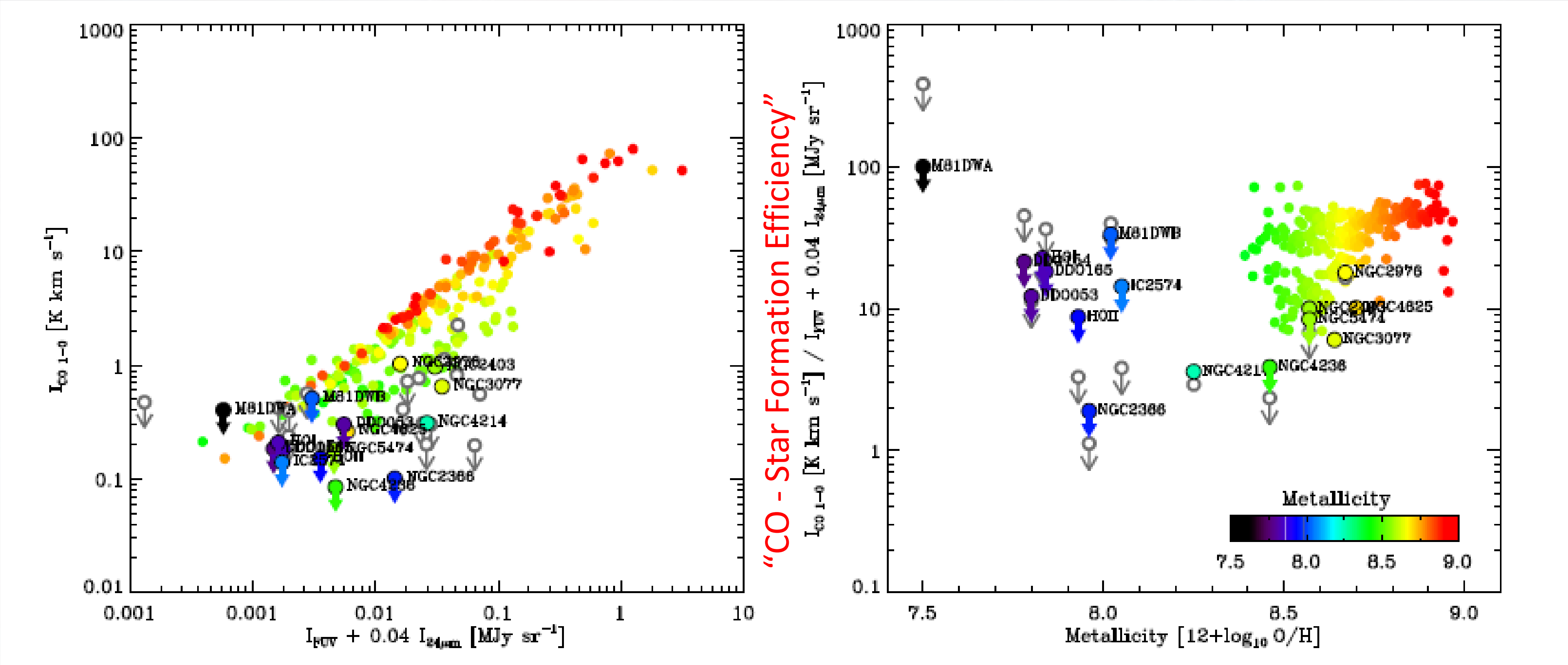
Warren et al. (2015)

Environmental Effects : Low Metallicity

- Variations affect SFR Relations
- Variations affect measured SFE

“CO Molecular Gas Surface Density”

“CO - Star Formation Efficiency”



“Star Formation Surface Density”

Schruba et al. (2012)

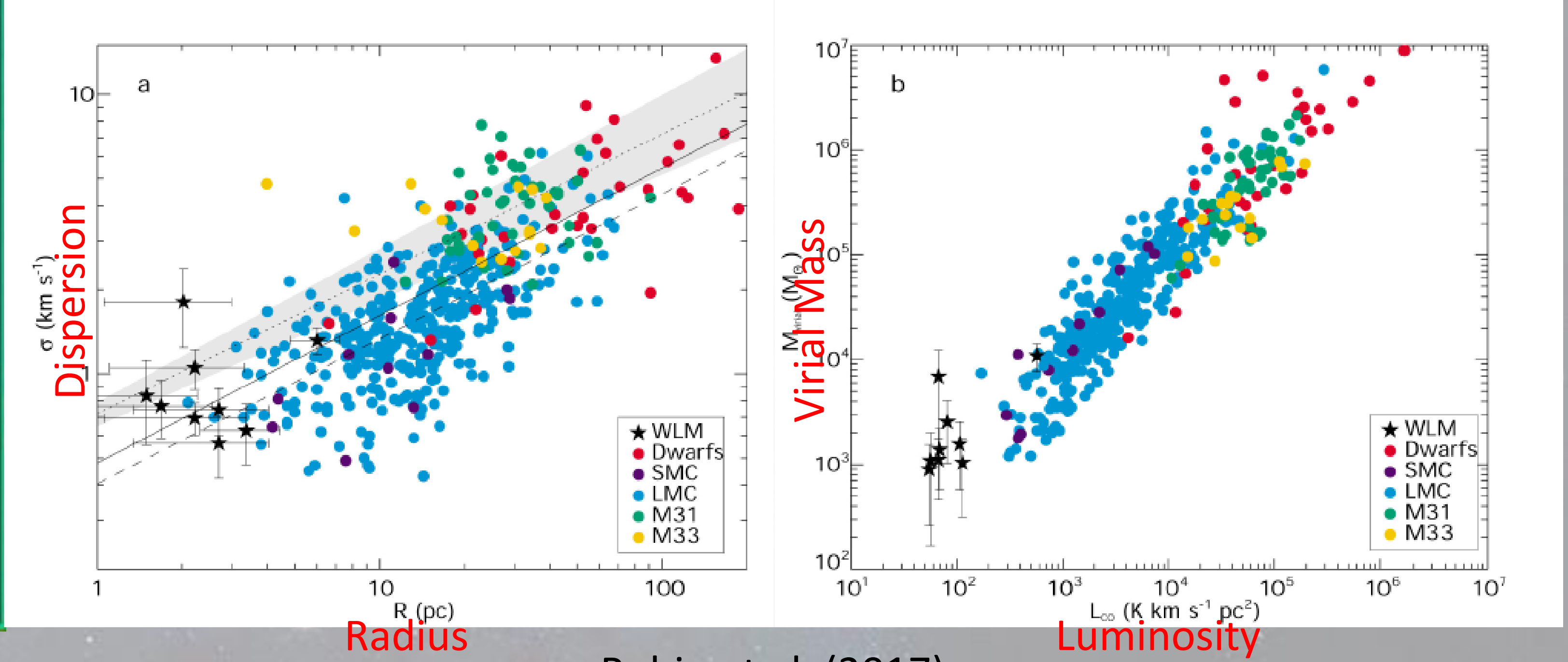
Metallicity

Environmental Effects : Low Metallicity

- WLM: 13% solar Z (metallicity)

Rubio et al. (2017)

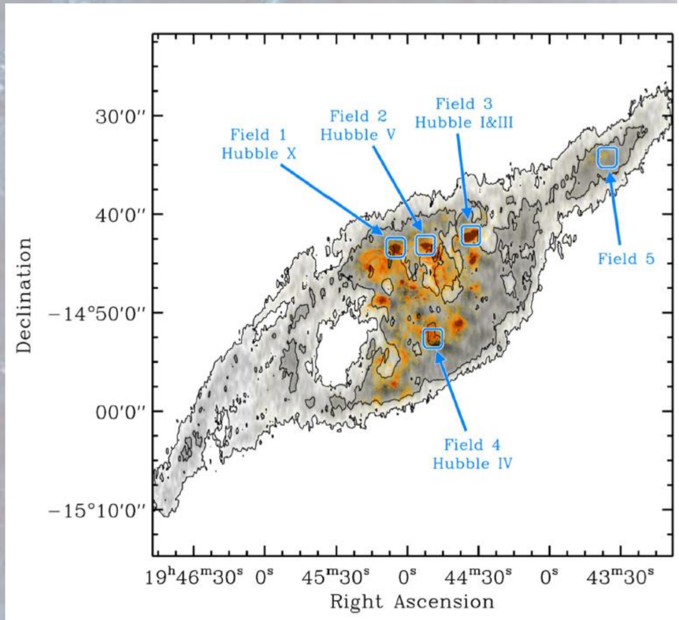
- ALMA CO
- Smaller Molecular Clouds
- Normal Densities



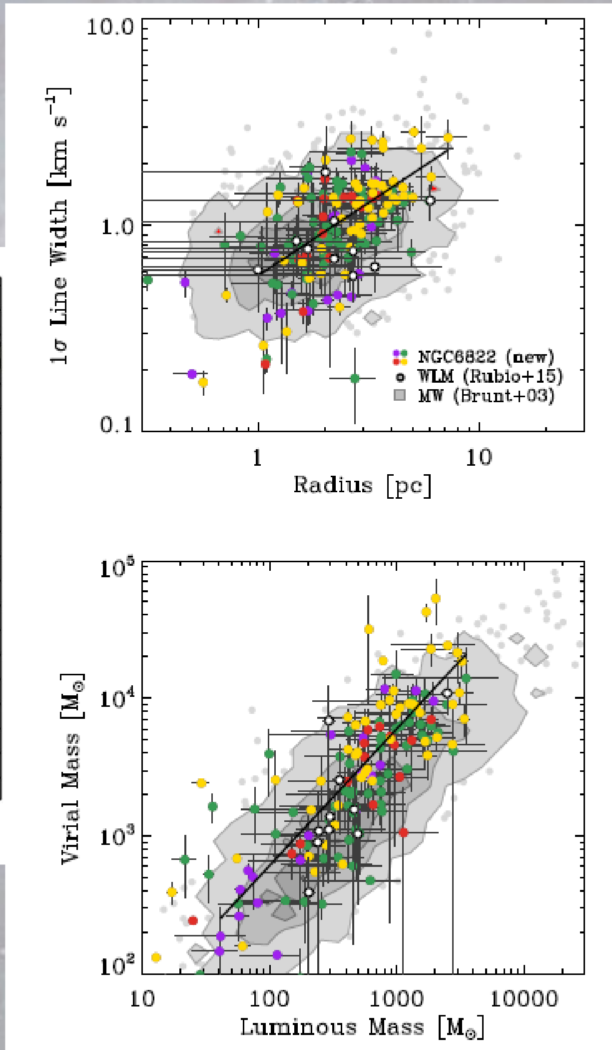
Rubio et al. (2017)

Environmental Effects : Low Metallicity

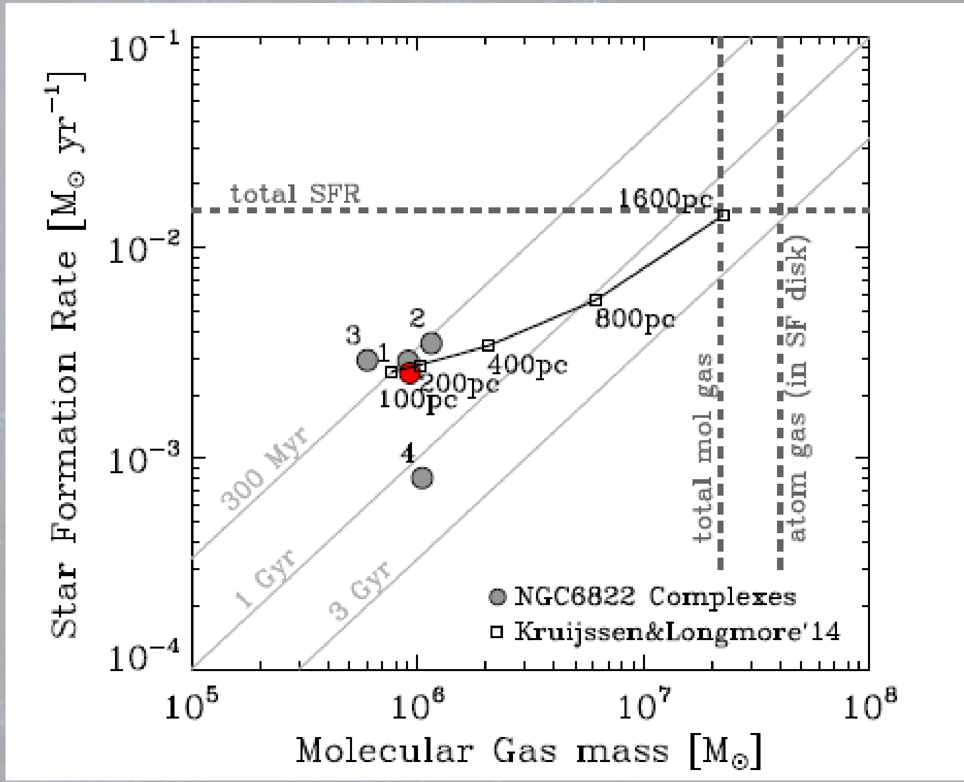
- NGC 6822
- 20% solar Z



Schruba et al. (2017)



- Consistent with WLM & outer MW
- SFE Consistent with lower resolution Large High metallicity disks



Stability of Disks?

- Stability of galaxy disks against gravitational collapse
  - Toomre (1964), Goldreich & Lynden-Bell (1965), Elmegreen (1979)…
- Toomre parameter:

$$Q = \frac{\sigma_g \kappa}{\pi G \Sigma}$$

Toomre (1964)

Pressure, Shear

vs

Gravity

Stability of Disks?

- Infinitesimally thin gas-only disk
- σ: velocity dispersion
- κ: epicyclic frequency
- Σ: density

$$Q = \frac{\sigma_g \kappa}{\pi G \Sigma}$$

Toomre (1964)

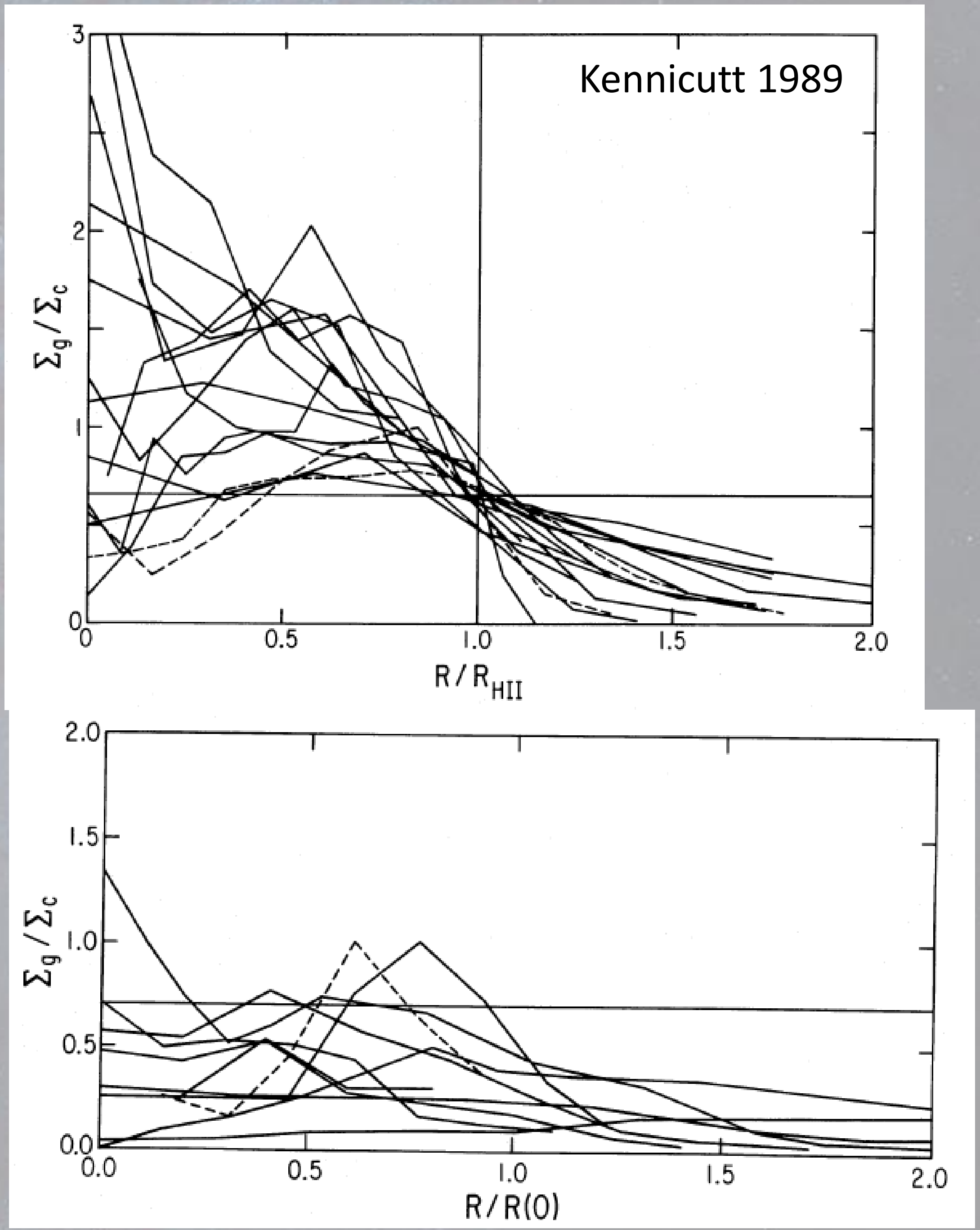
Pressure, Shear

vs

Gravity

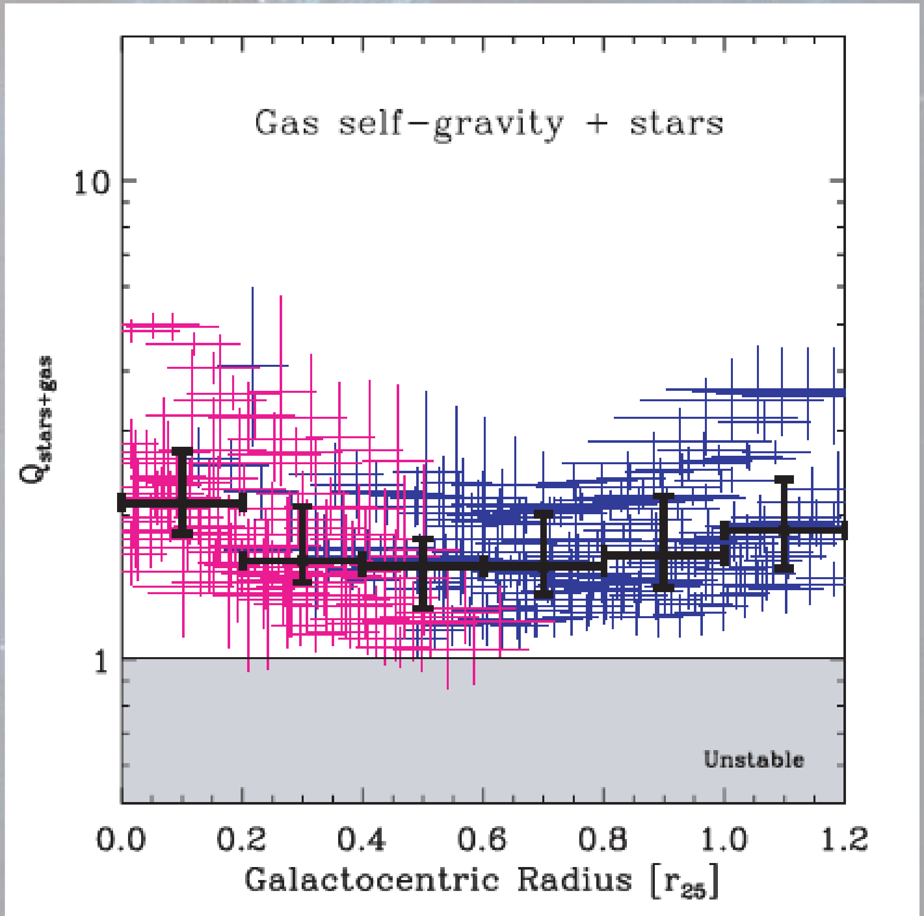
Stability of Disks

- Gas Parameters:
  - σ: HI profiles (outer disk, constant)
  - κ: HI rotation curve
  - Σ: HI + Molecular Gas



Toomre Criterion… complications

- Non-axisymmetric perturbations
- Stars
- Thick disks
- Realistic shear on molecular clouds
- Turbulence



Leroy et al. 2008

Stability of Disks

- Romeo & Falstad (2013)
  - Multi-component disks
  - Finite disk thickness
  - Simple formulation

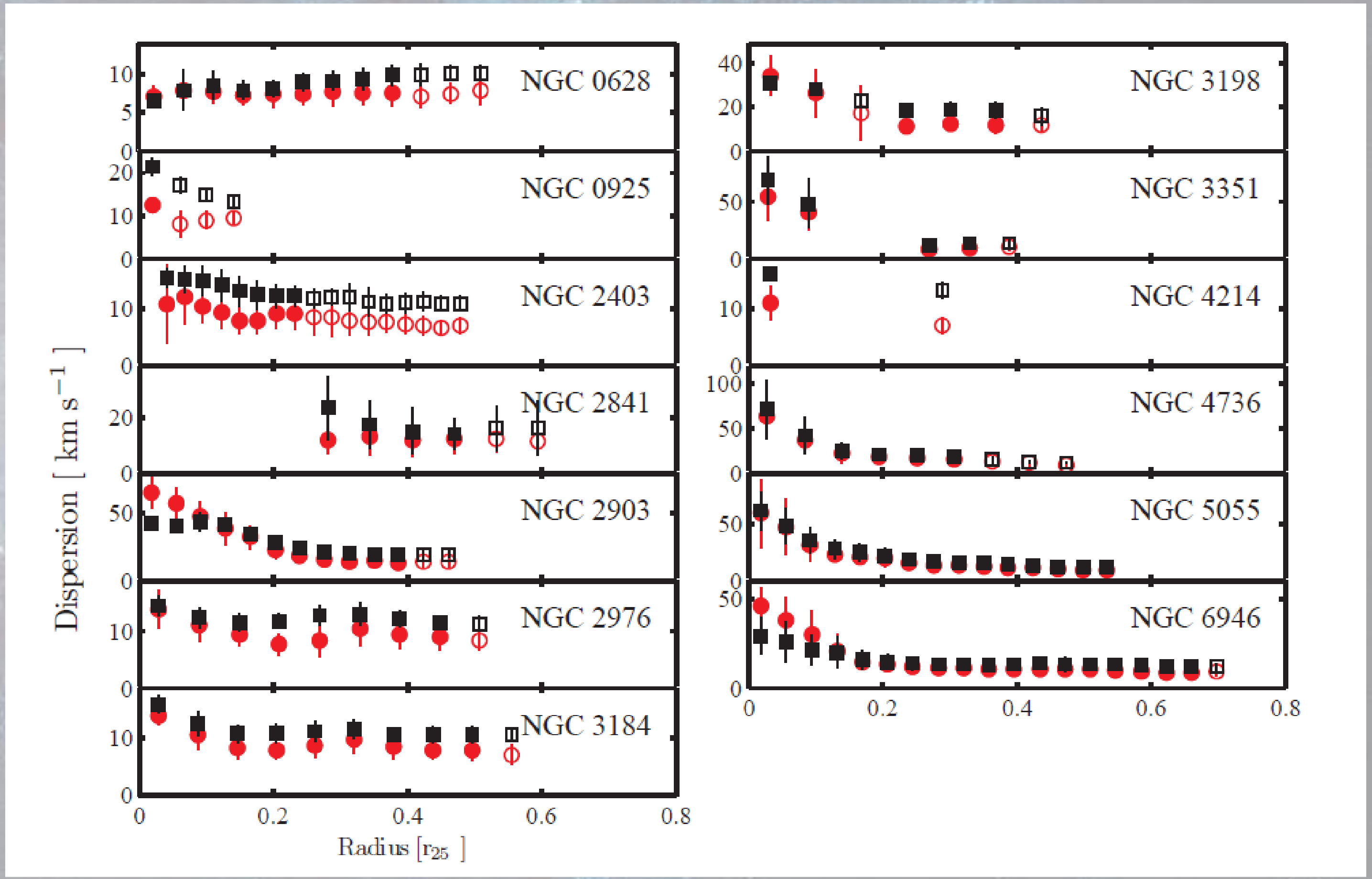
$$\frac{1}{Q_N} = \sum_{i=1}^{N} \frac{W_i}{Q_i}$$

Dependent on relative dispersions of components

Toomre Parameter of each component

Dispersions

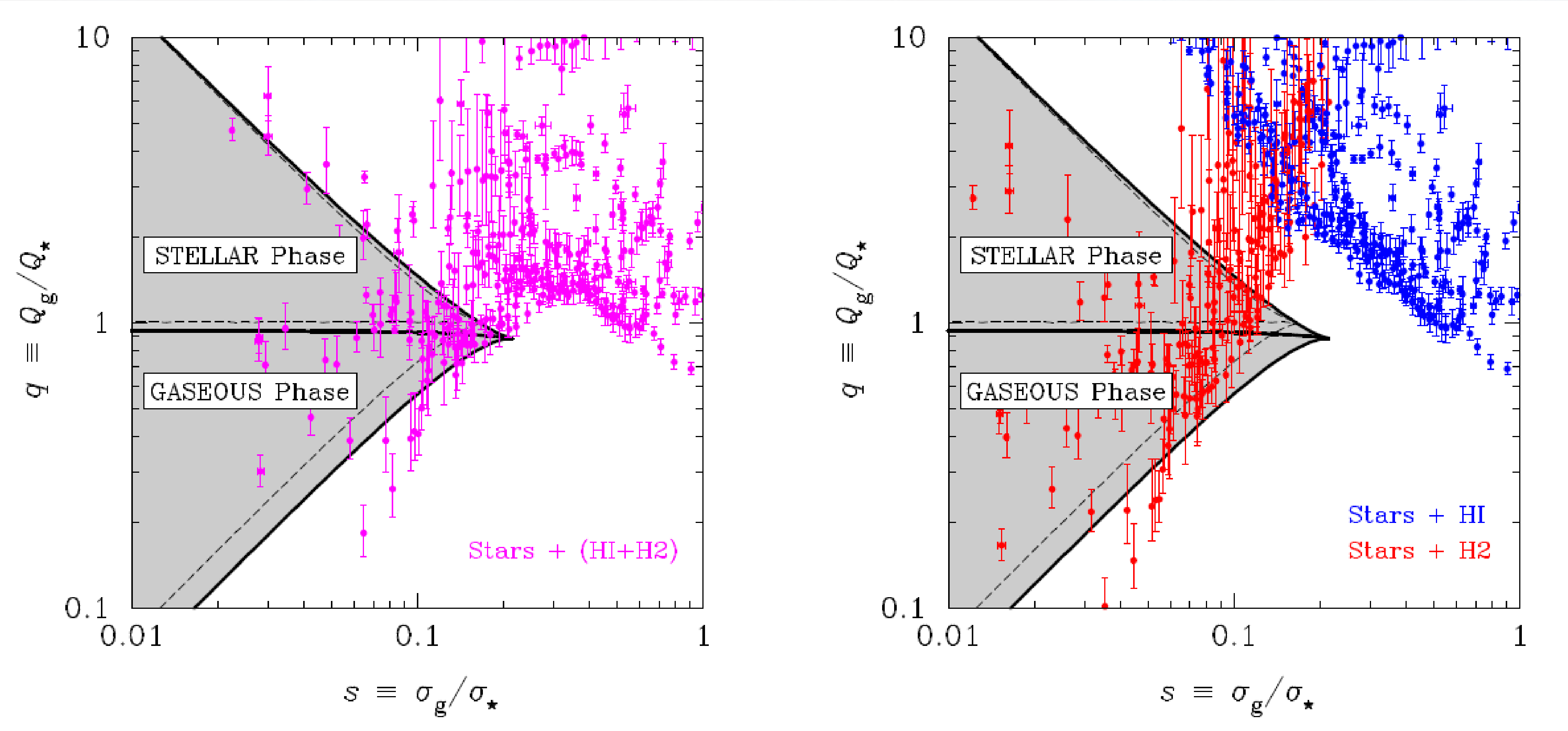
- Gas dispersions decline with radius
- CO dispersions lower than HI but difference is not as large as expected.
- Stacking experiments (Pety et al. 2013, Caldu Primo et al. 2013) show CO dispersions larger than expected with low intensity broad component.



Mogotsi et al. (2016)

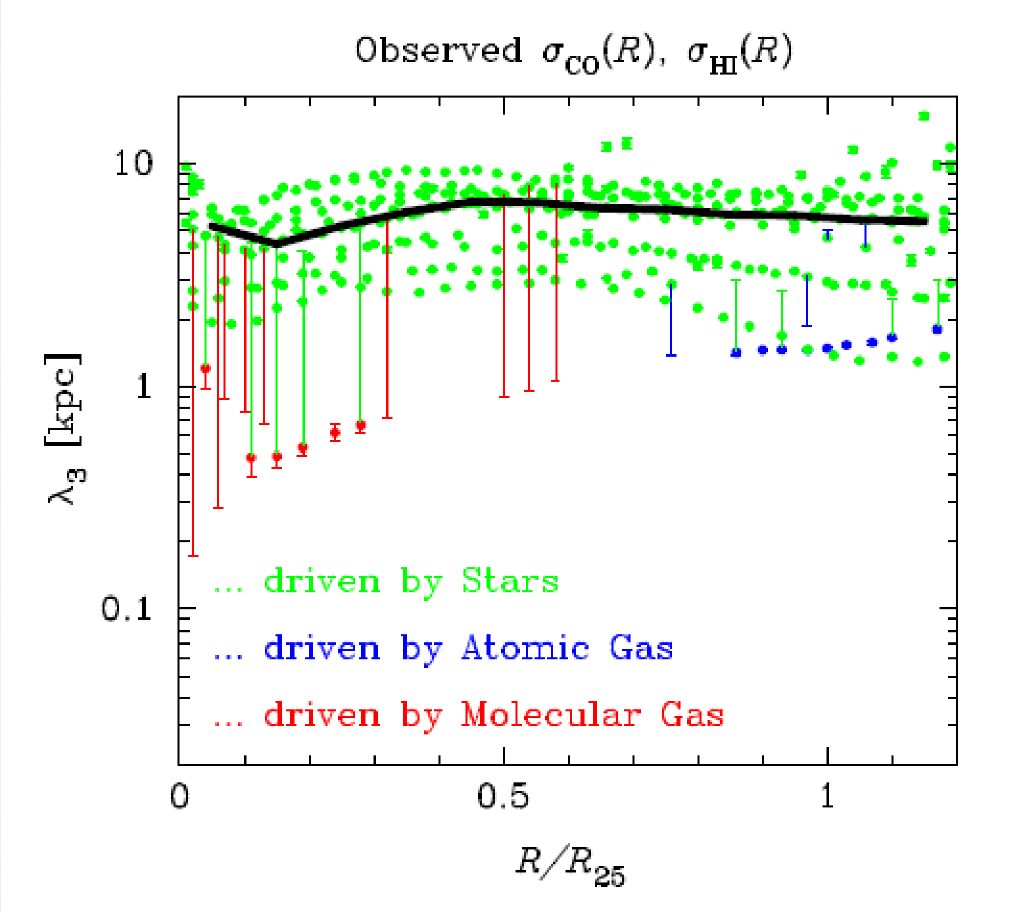
Photo Credit: M100, Judy Schmidt

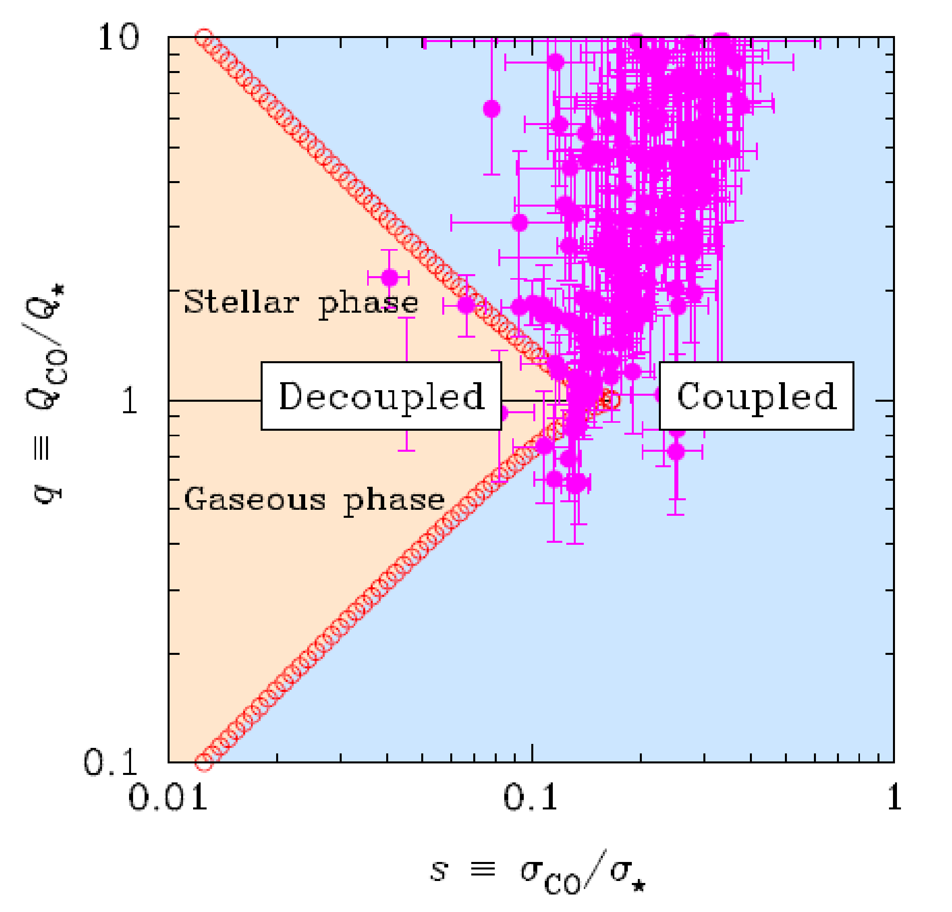
Multi-component stability



Romeo & Falstad (2013)

Stability using observed Dispersions

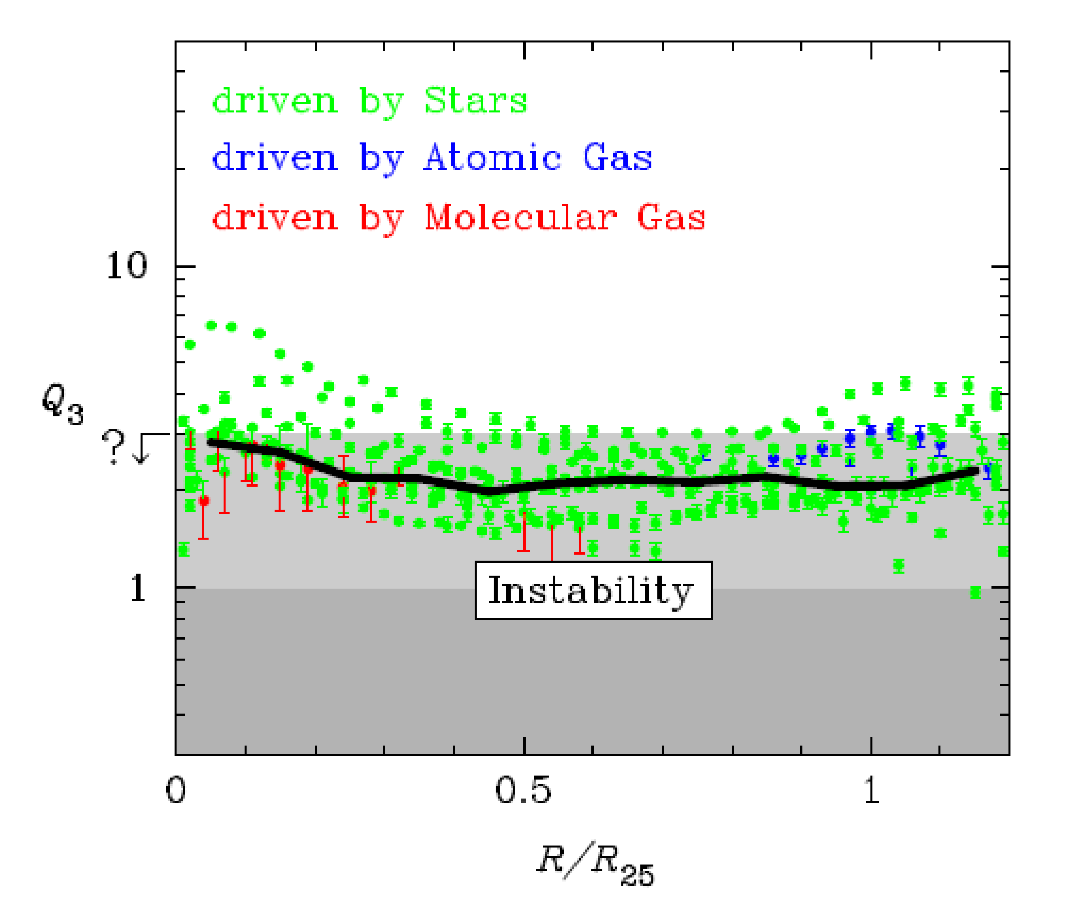




Romeo & Mogotsi (2017)

Stability using observed Dispersions

- When stars, HI and molecular gas are treated as individual components of the disks:
  - Instabilities are primarily driven by stars
  - Molecular gas drives instabilities at short radii
  - Small scale instabilities are driven by the gas (molecular)
  - Q ~ 2.2 i.e. stable against axi-symmetric instabilities



Romeo & Mogotsi (2017)

Molecular meets Atomic

- Cold HI closer to CO than overall HI
  - (e.g. Ianjamasimana et al. 2013, 2015; Mogotsi et al. 2016)

- Low metallicity, outer disk regions dominated by HI
- Feedback and Fuelling of galaxy gas reservoirs

Photo Credit: M100,
Judy Schmidt

Molecular Universe…

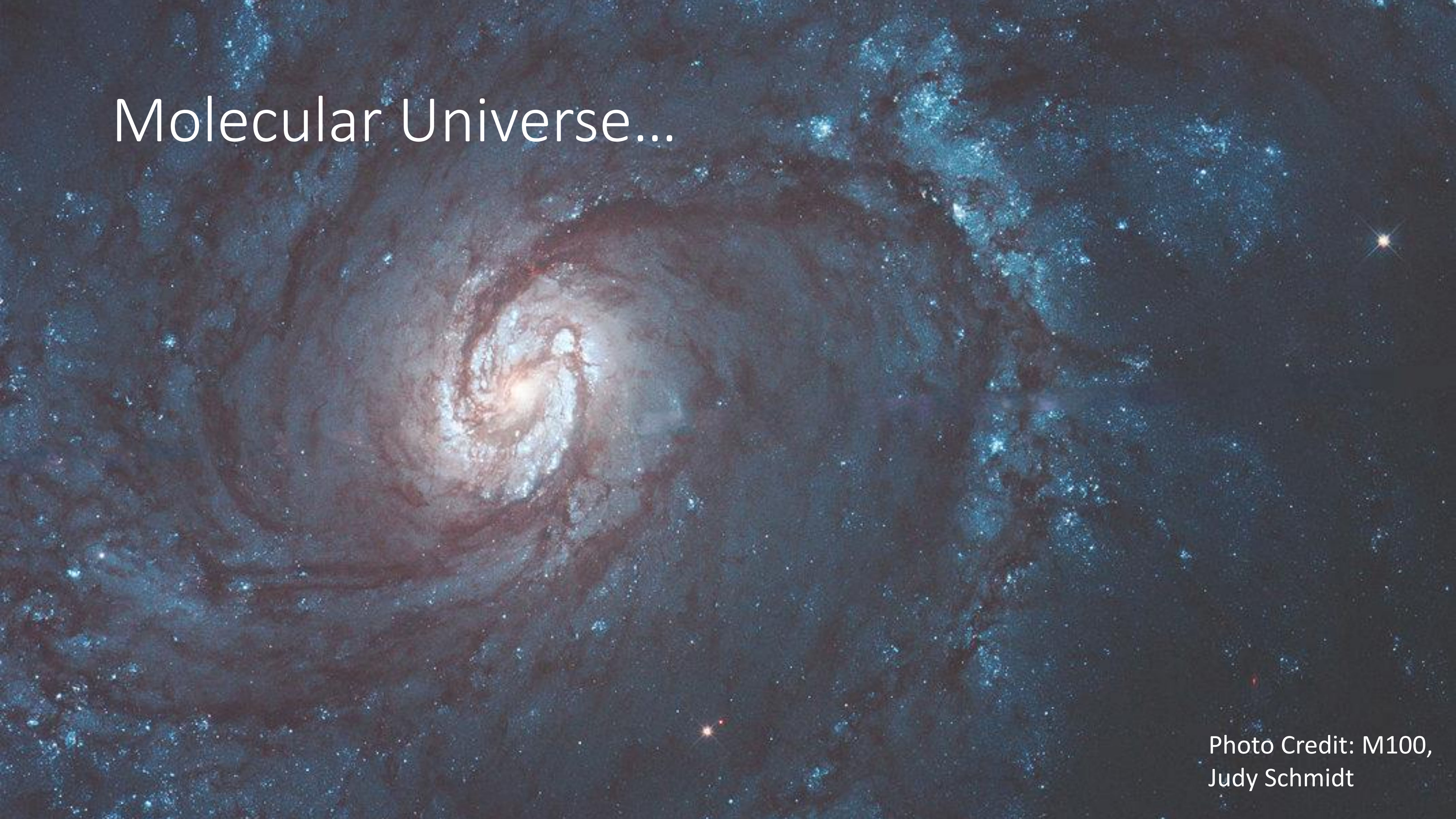
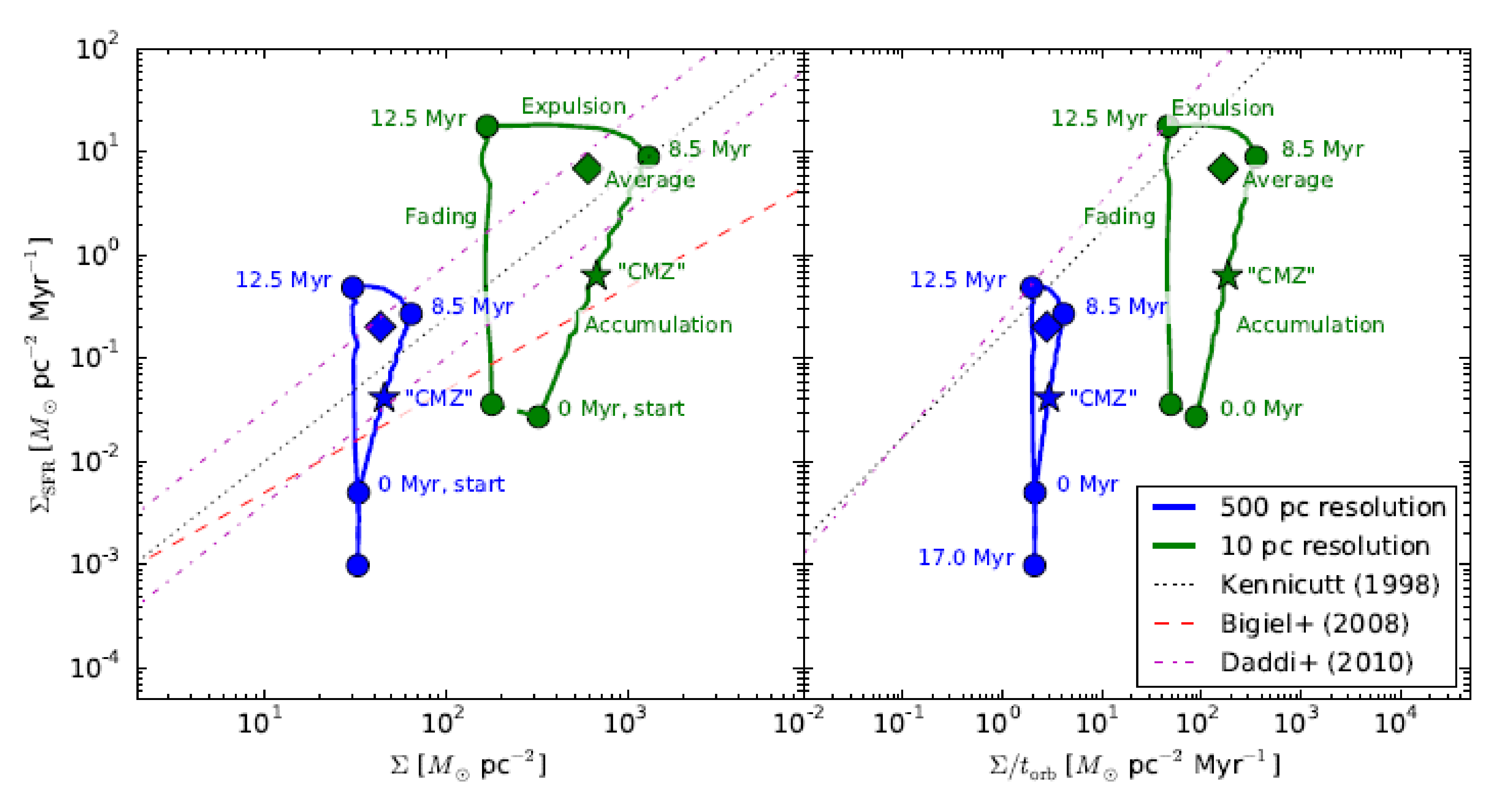


Photo Credit: M100,
Judy Schmidt

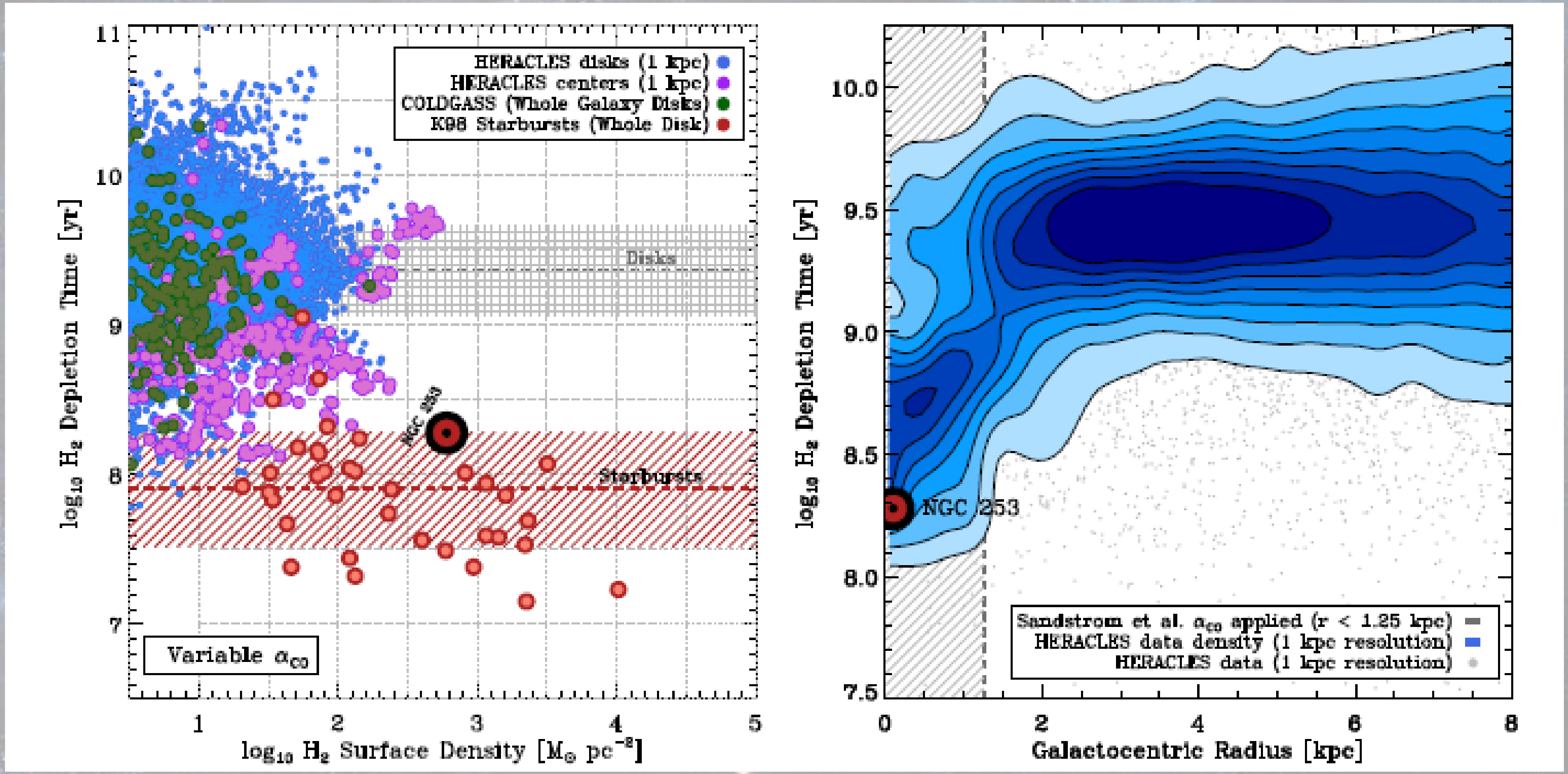
Too Far…

Time evolution of Star Formation



Krumholz et al. (2015)

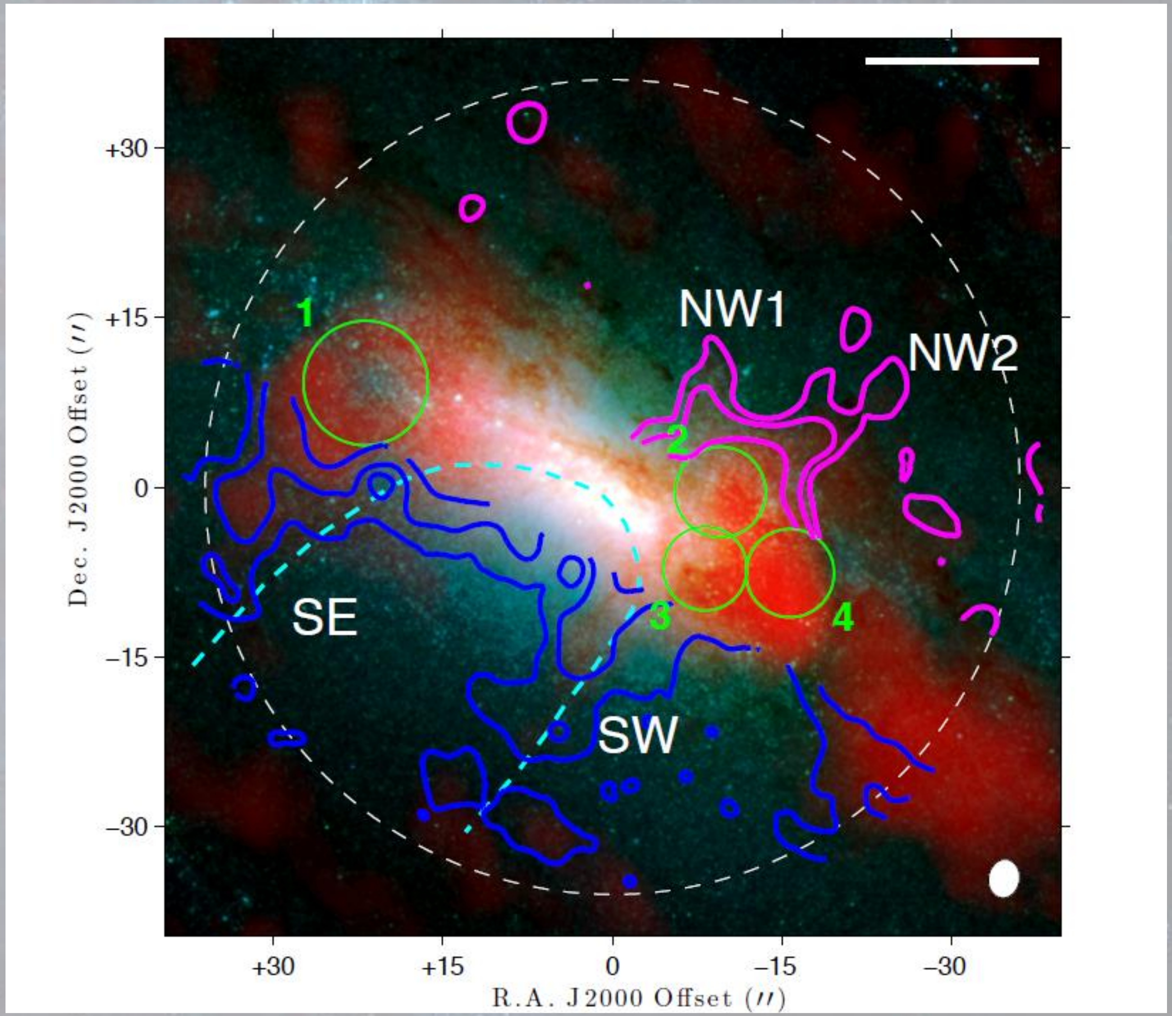
Environmental Effects : Starbursts



Leroy et al. (2015)

Baryonic Cycle

- Winds, Outflows
- Feedback
- Stability, kinematics and lifecycles of GMCs



ALMA + HST , Bolatto et al. 2013