Connecting Gas to Star Formation

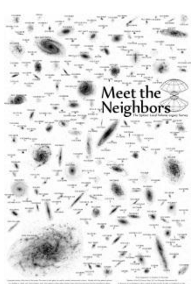
Robert Kennicutt

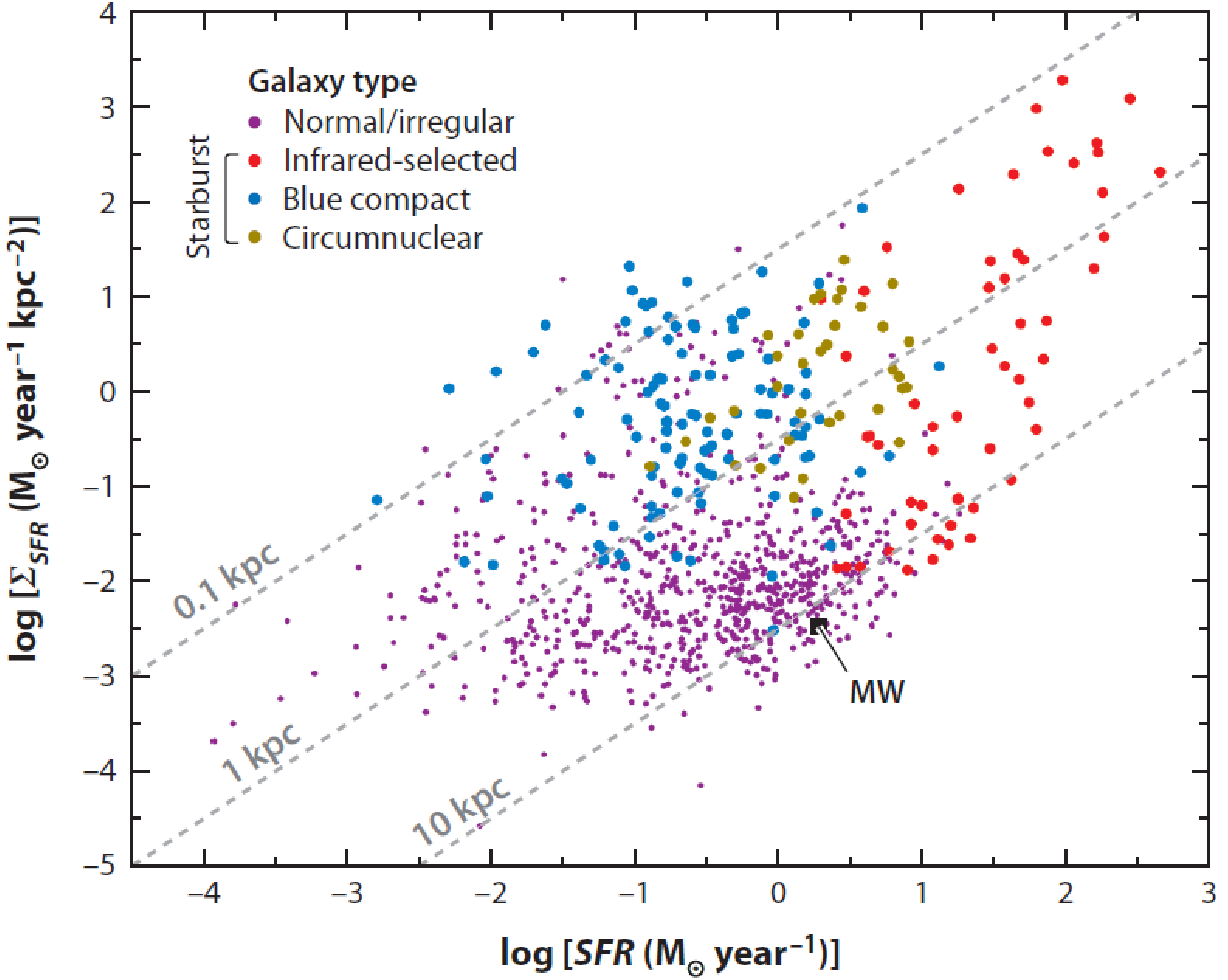
University of Cambridge

with

Neal Evans

UT Austin





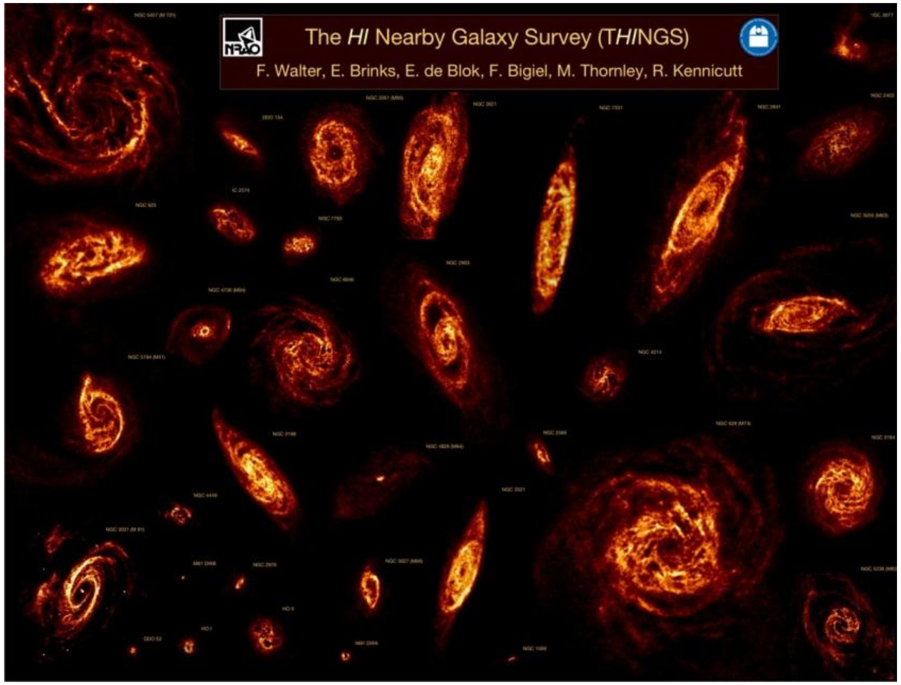
Galaxy type
Normal/irregular
Infrared-selected
Blue compact
Circumnuclear
Starburst
0.1 kpc
1 kpc
10 kpc
MW
4
3
2
1
0
−1
−2
−3
−4
−5
−4
−3
−2
−1
0
1
2
3
log [Σ_SFR (M⊙ year⁻¹ kpc⁻²)]
log [SFR (M⊙ year⁻¹)]

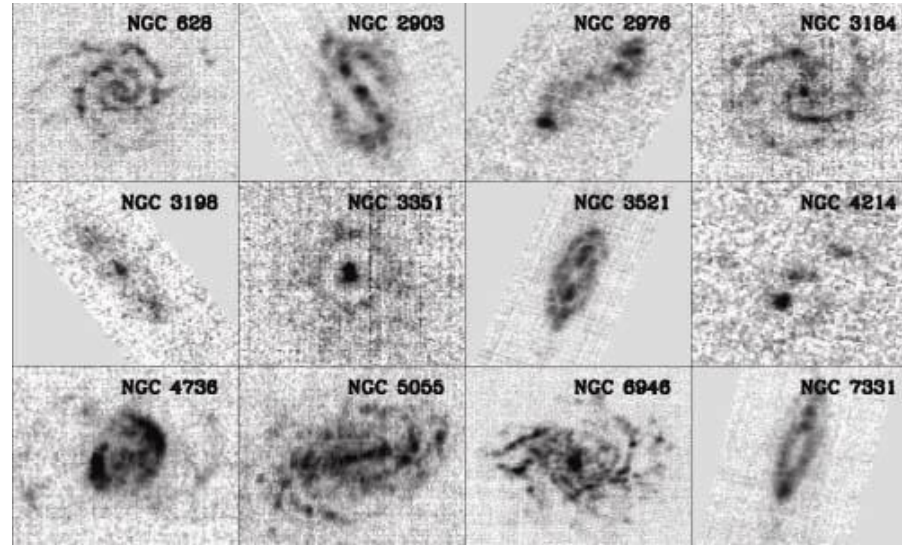
"I still don't understand the interplay between HI, H_2 (as traced by CO), and star formation." *M. Haynes*

- The path from accretion to star formation involves several steps, with "critical path" dictated by the most difficult physical hurdle.
  - formation of a neutral ISM (cooling, thermal instabilities)
    - easy for disks, difficult for massive spheroids
    - dictated by gas density and ambient UV radiation field (internal and external)
  - formation of bound interstellar clouds (Jeans/gravitational instabilities)
    - dictated by gas density and galactic shear, tidal field
  - 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 (photodissociating UV) and ambient UV field
  - formation of bound molecular cloud cores
    - dictated by Jeans, fragmentation, turbulence, competitive accretion…
  - formation of stars, planets
    - complicated(!)
- Of all of these processes only the latter appear to be deterministic in present-day galaxies. Which of the other processes is "critical" is a subject of debate, and this may change in different environments, cosmic epochs

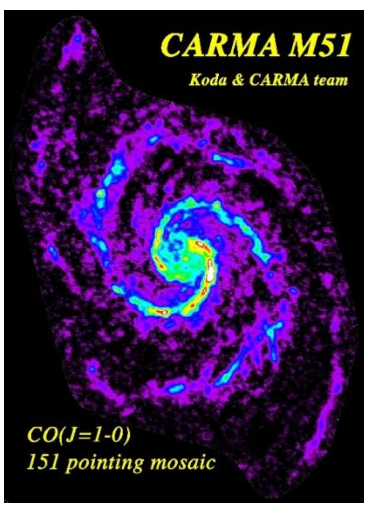
Outline

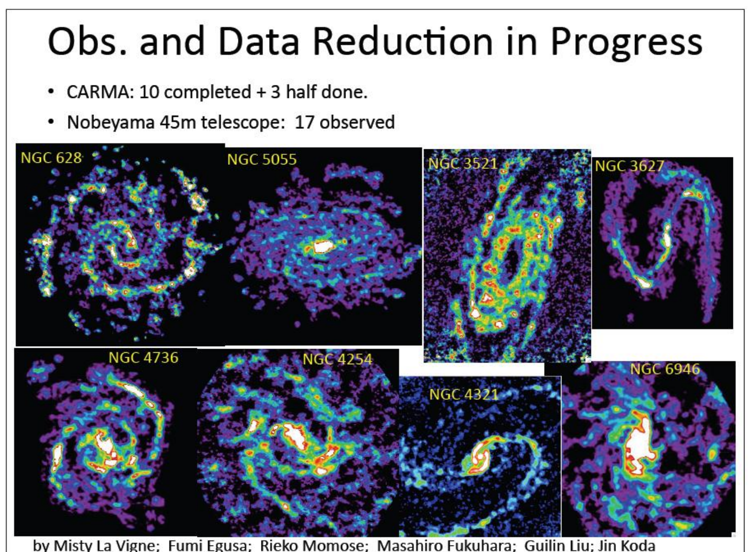
- Current state of knowledge of star formation law
  - integrated star formation law in galaxies
  - spatially-resolved SF law in galaxies
  - clues from SF in the Milky Way
- Insights, Questions, and challenges

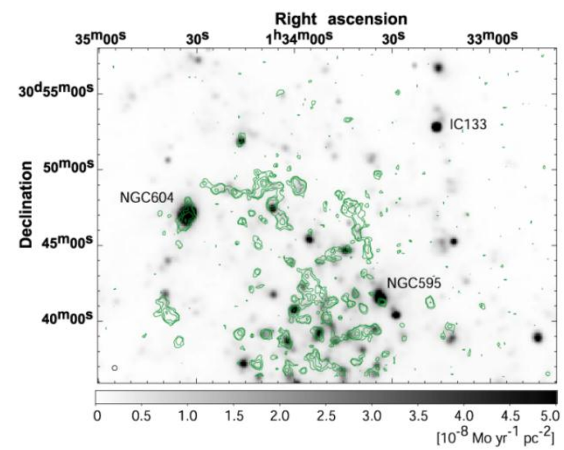




HERACLES CO 2-1 survey (IRAM)

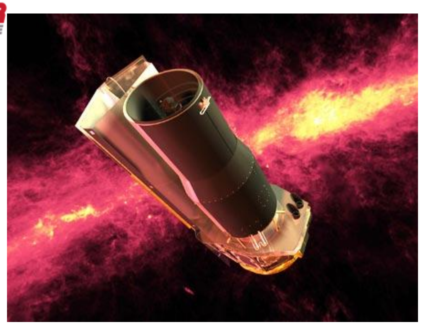


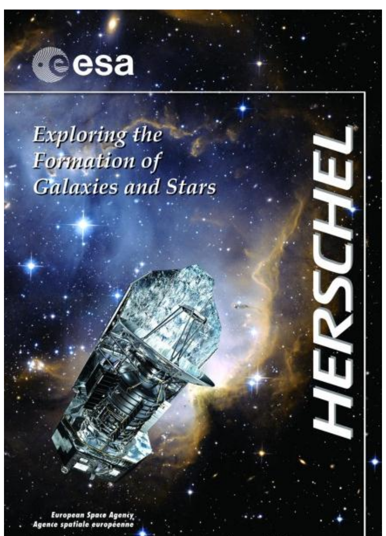


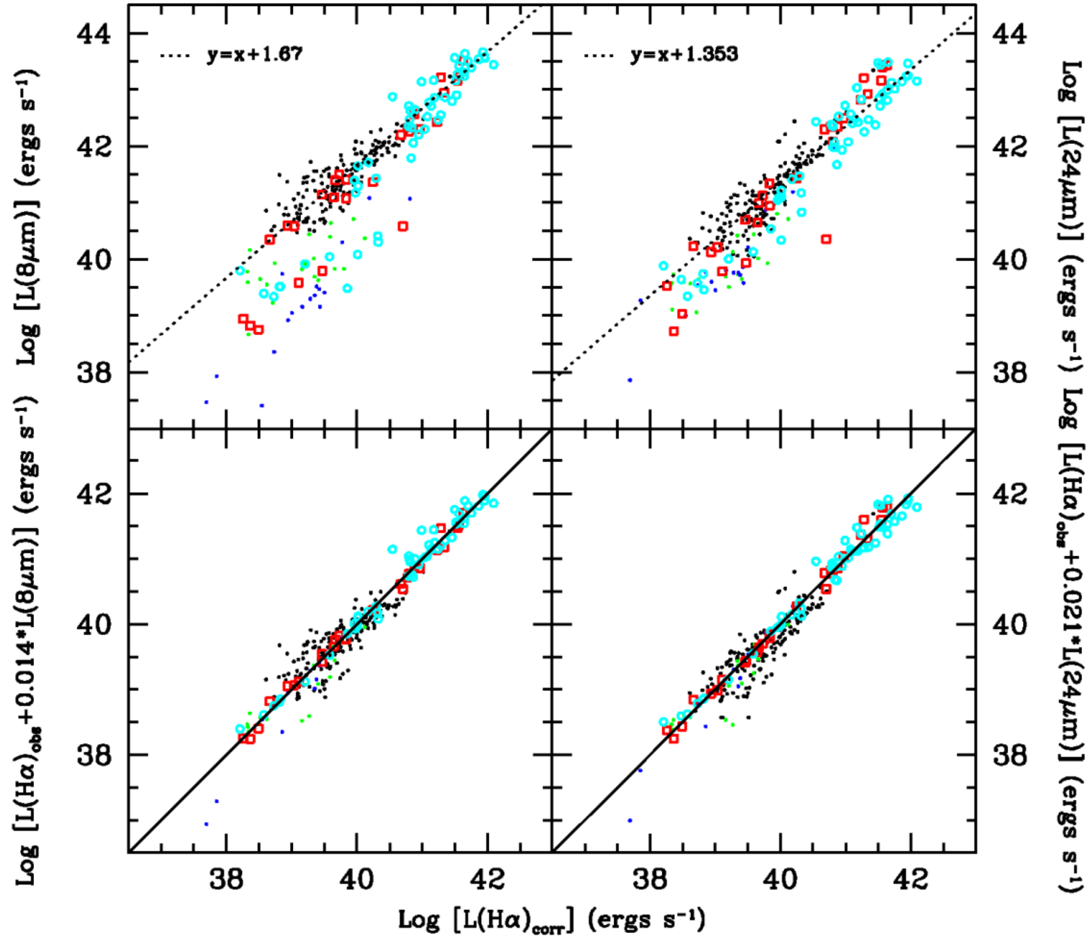


Nobeyama CO survey of M33

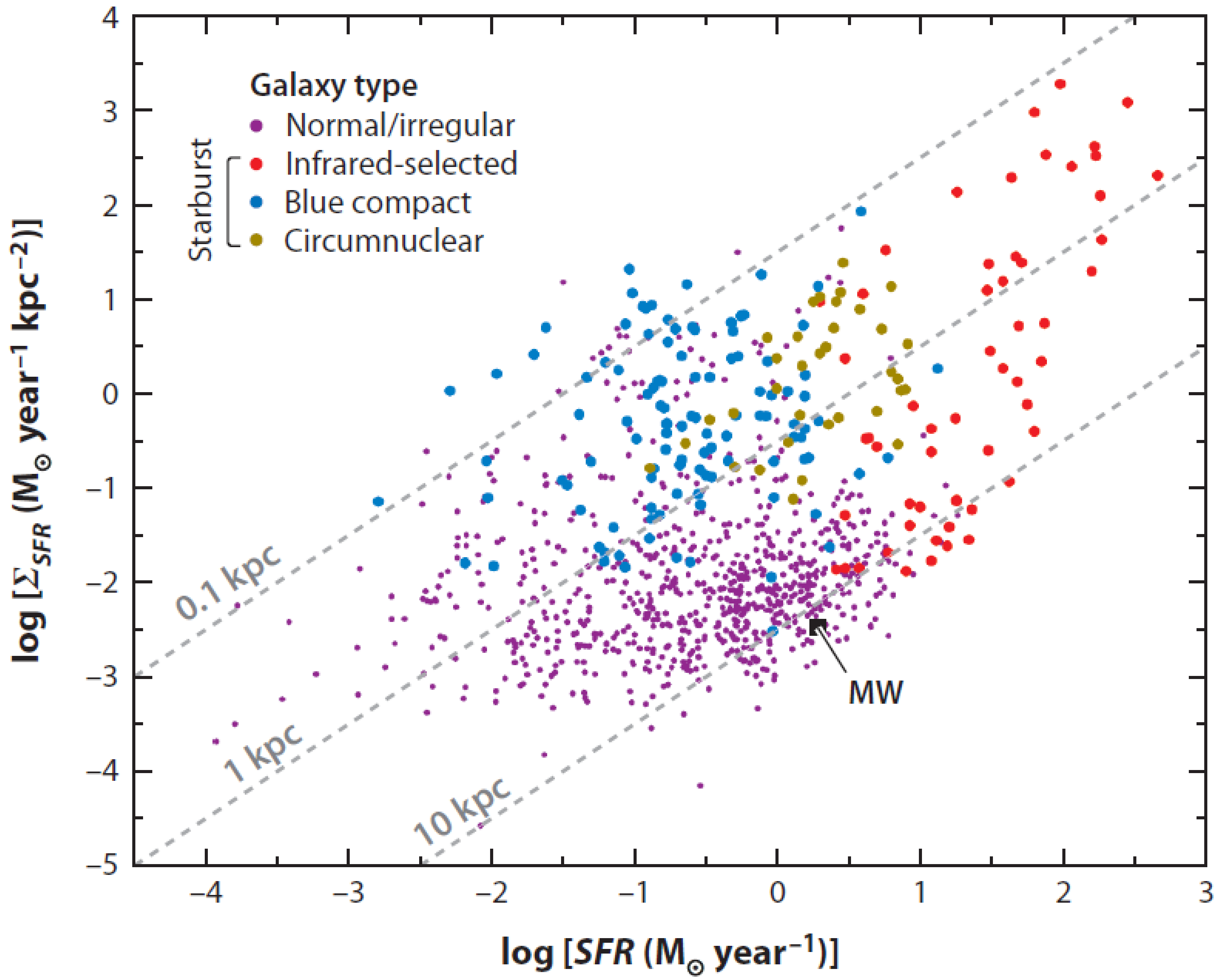
Multiwavelength observations provide dust-free SFR tracers







Kennicutt et al. 2009


Galaxy type
Normal/irregular
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Blue compact
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Starburst
0.1 kpc
1 kpc
10 kpc
MW
log [Σ_{SFR} ($M_\odot$ year^{-1} kpc^{-2})]
log [SFR ($M_\odot$ year^{-1})]
4
3
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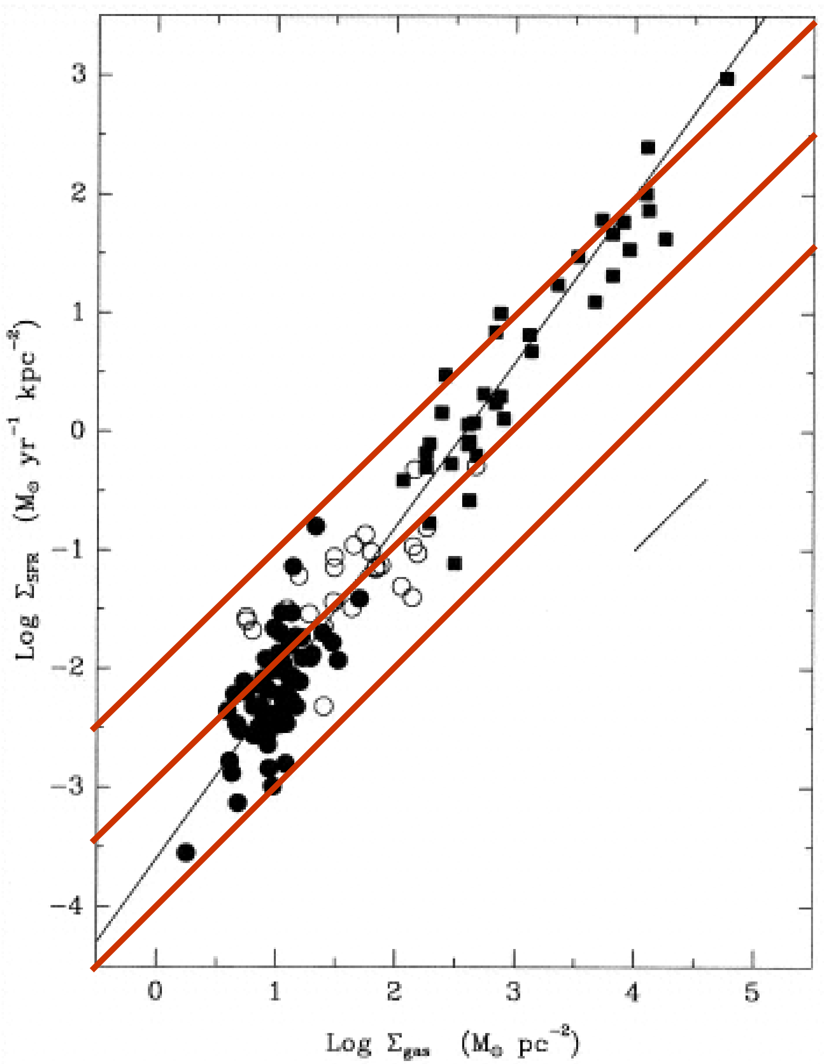
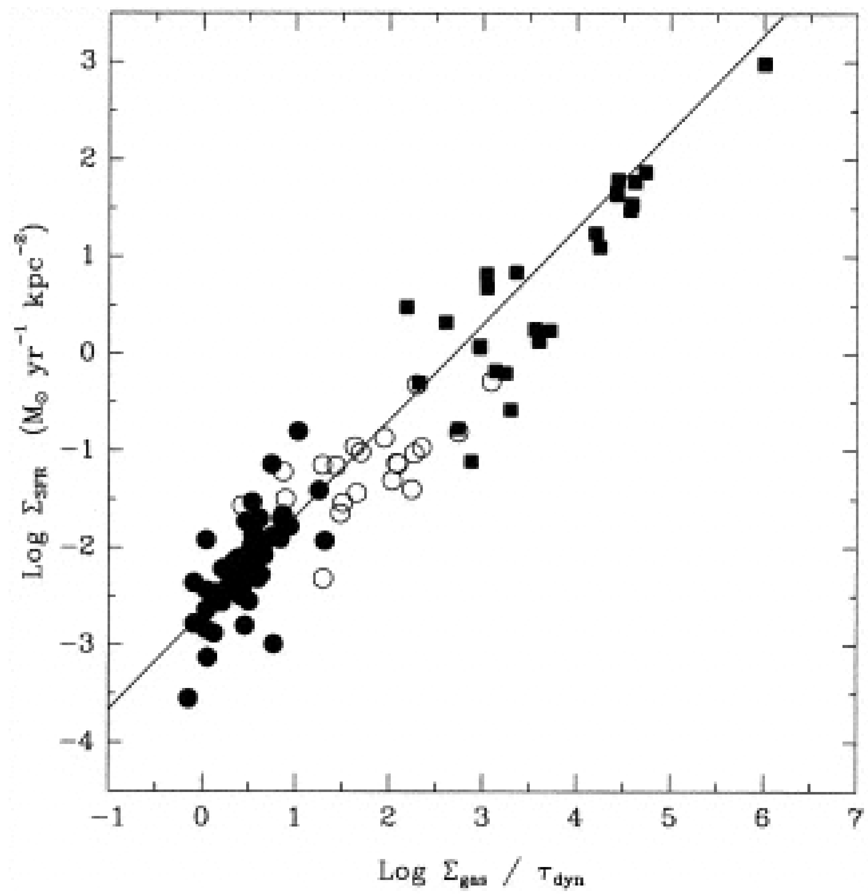
−2
−3
−4
−5
−4
−3
−2
−1
0
1
2
3

Integrated scaling laws circa 1998 – 2006

$\Sigma_{SFR}/\Sigma_{gas} \sim \Sigma_{gas}^{0.5}$



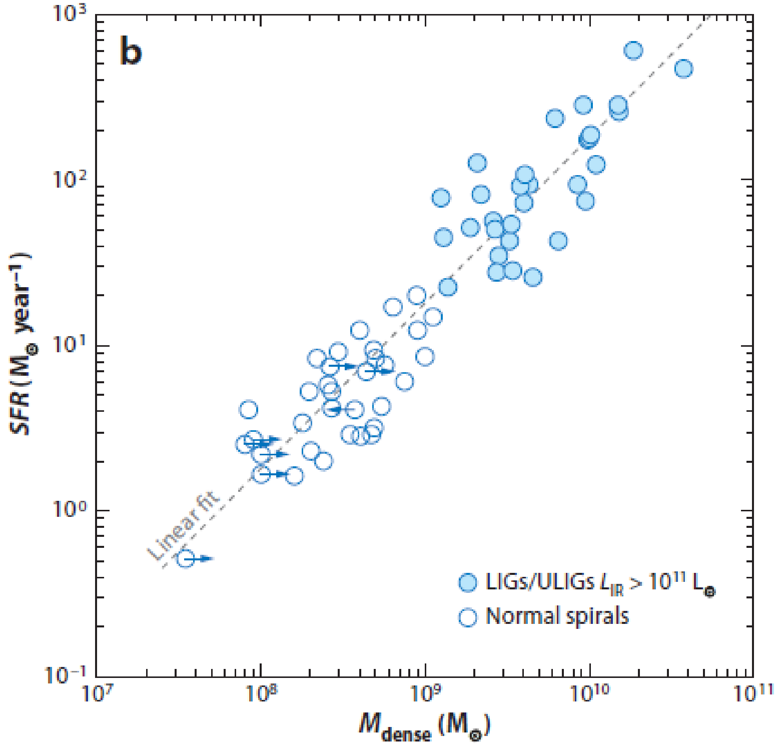
$\Sigma_{SFR} \sim \Sigma_{gas} / \tau_d$

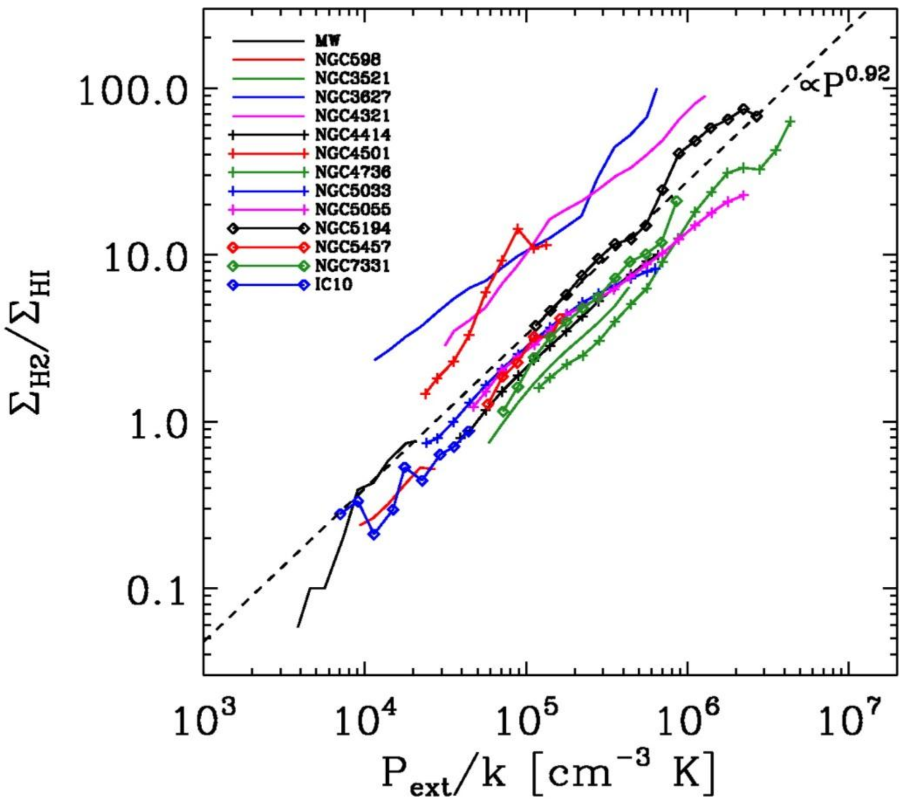


Kennicutt 1998

SFR/M_{HCN} ~ const

Σ_{H_2}/Σ_{HI} ~ Pressure



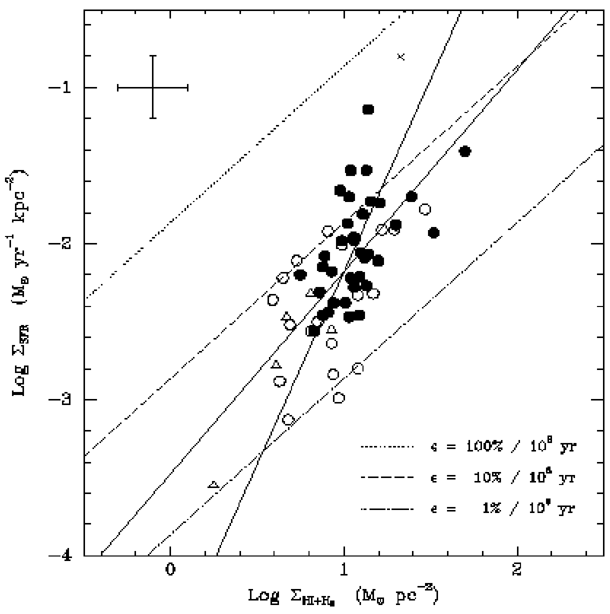


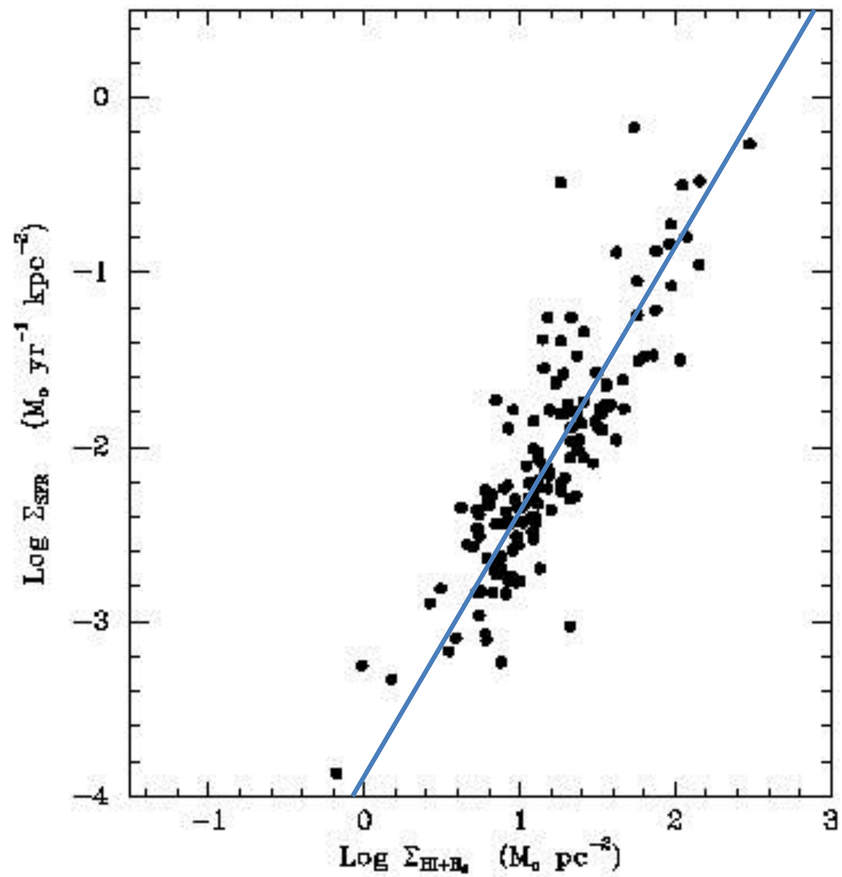
Gao, Solomon 2004

Blitz, Rosolowsky 2006

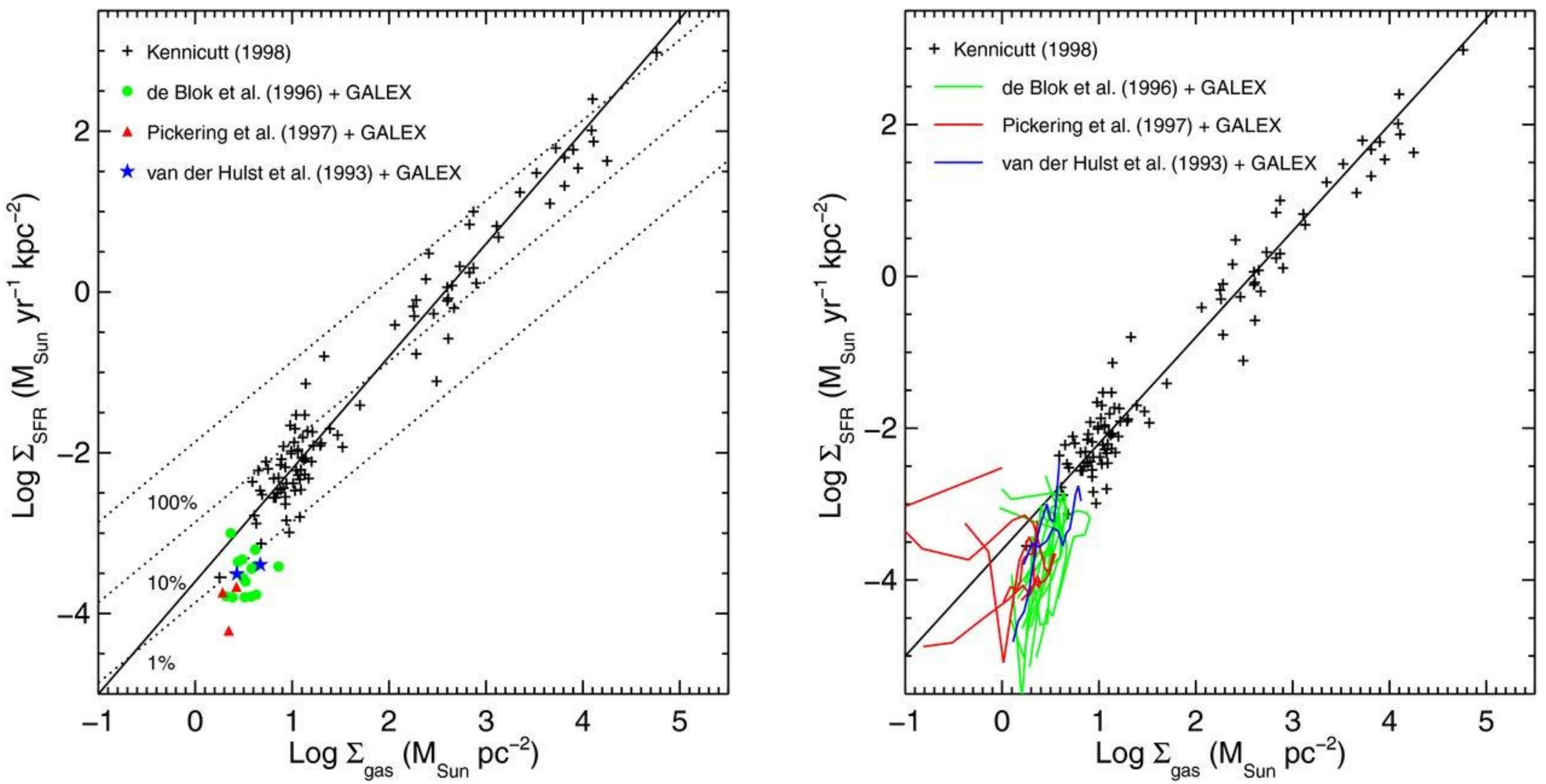
Integrated Schmidt Law - Normal Spirals

- larger sample, higher dynamic range
- individual dust corrections
- individual [NII] corrections
- Hα-defined disk radii

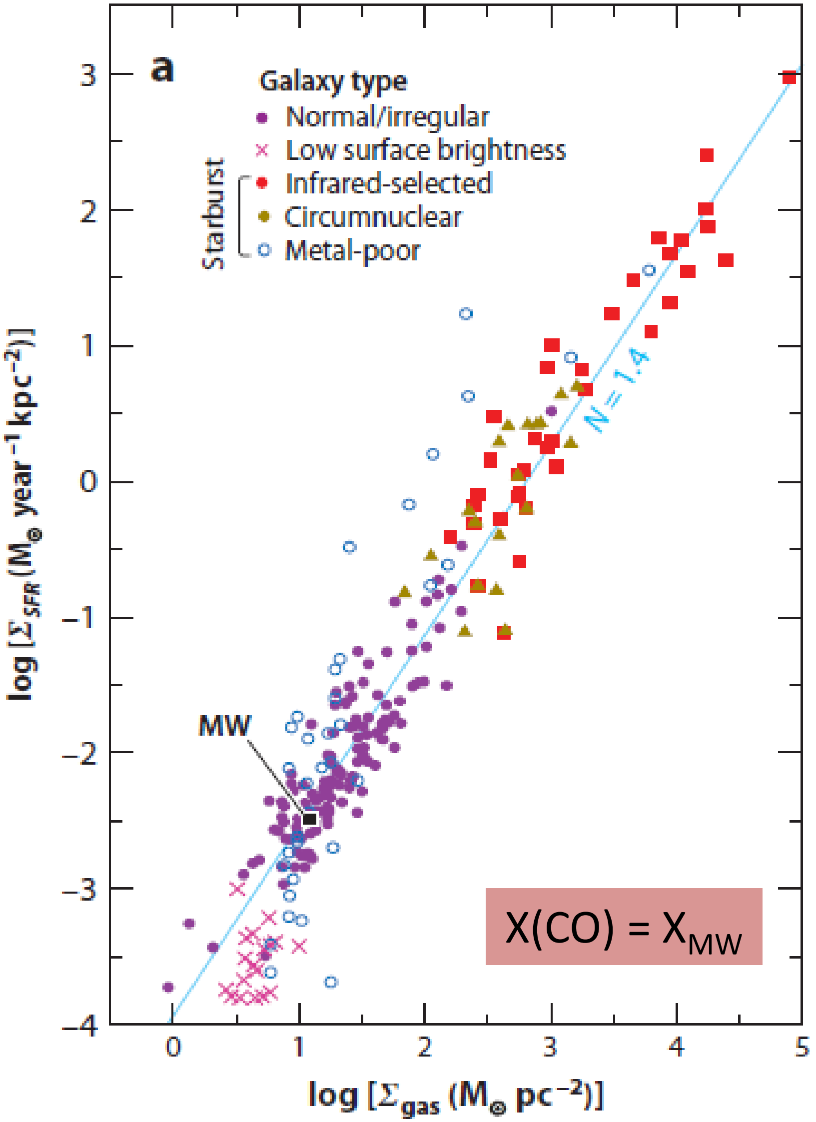


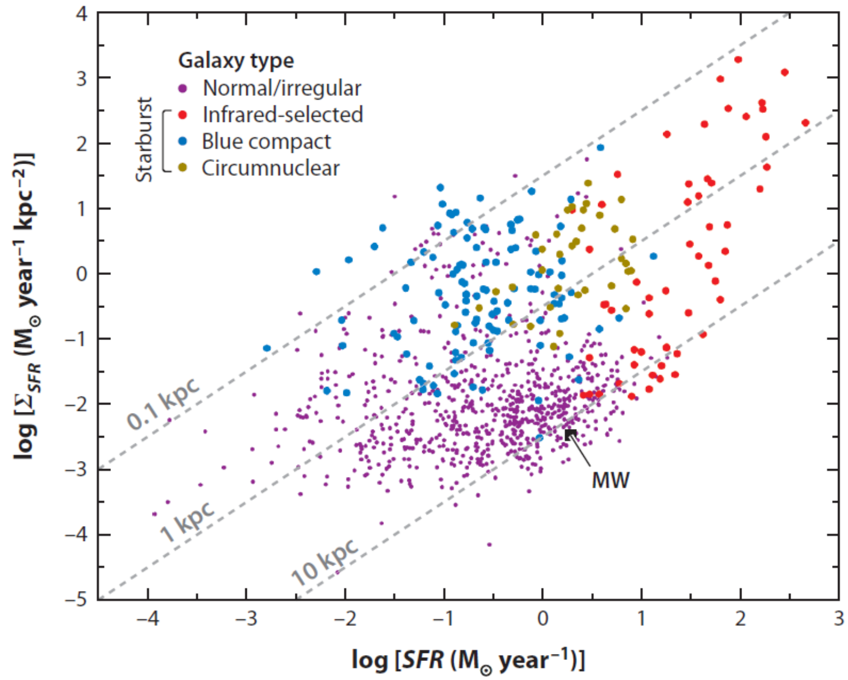


Extension to Low Surface Brightness Galaxies

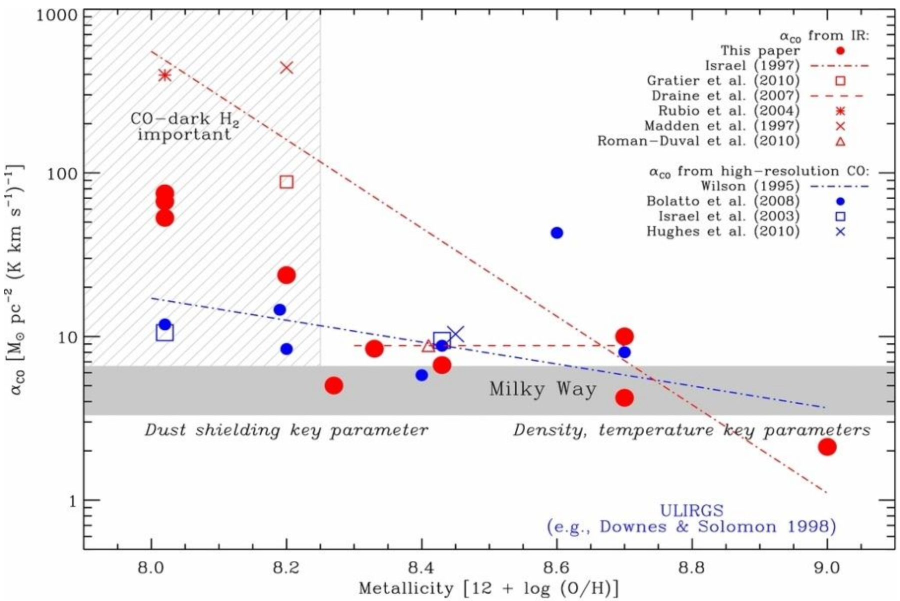


Wyder et al. 2009, ApJ, 696, 1834

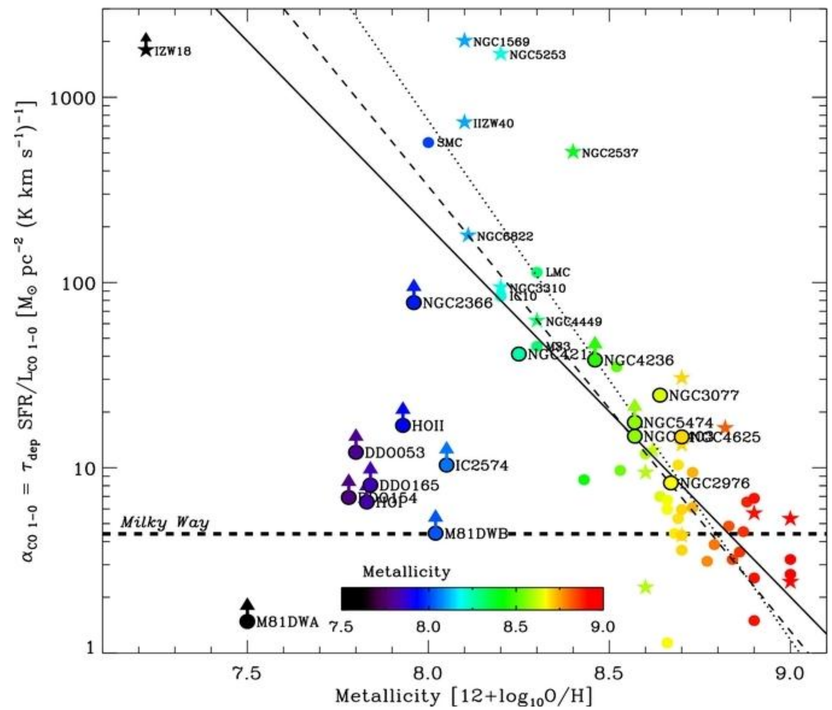

a
Galaxy type
Normal/irregular
Low surface brightness
Infrared-selected
Circumnuclear
Metal-poor
Starburst
N = 1.4
MW
X(CO) = X_MW
log [Σ_SFR (M_⊙ year⁻¹ kpc⁻²)]
log [Σ_gas (M_⊙ pc⁻²)]


Galaxy type
Normal/irregular
Infrared-selected
Blue compact
Circumnuclear
Starburst
0.1 kpc
1 kpc
10 kpc
MW
log [Σ_SFR (M_⊙ year⁻¹ kpc⁻²)]
log [SFR (M_⊙ year⁻¹)]

Corrections to X(CO) in dwarfs removes most of discrepant behaviour in SFR/M_{gas}, but not in SFR/M_{H_2}

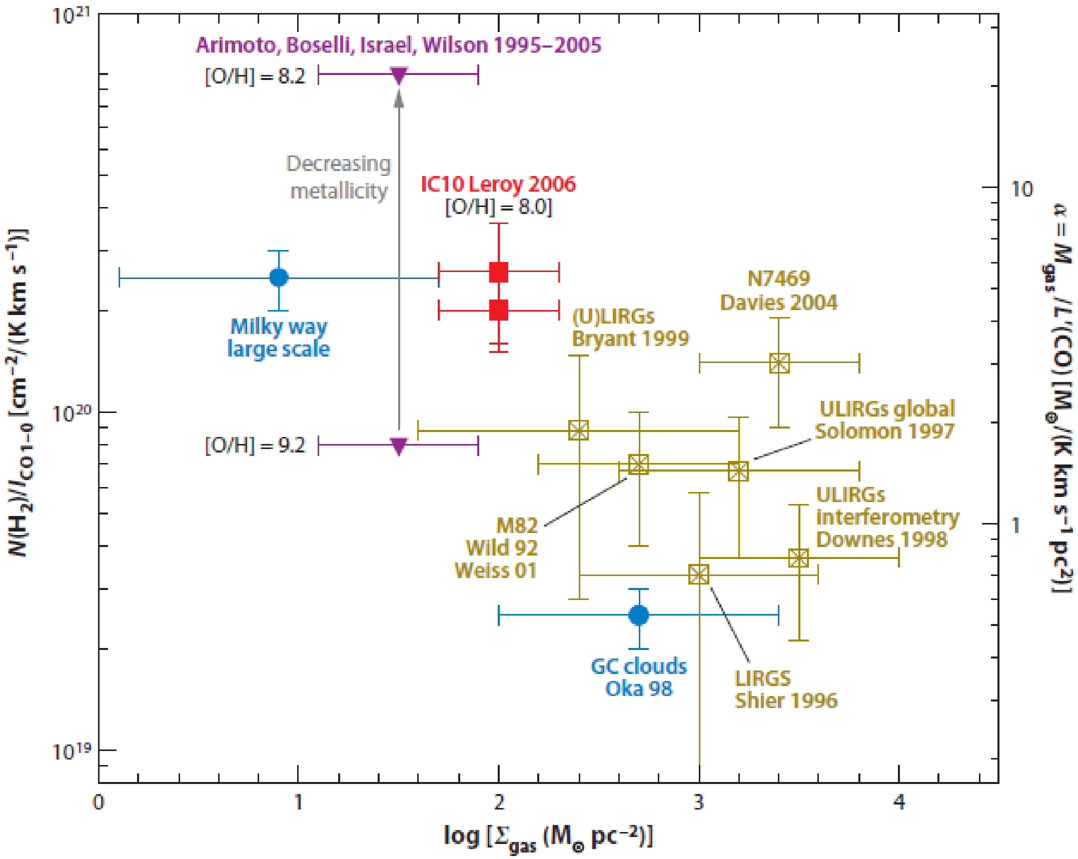


Leroy et al 2011
- *also see* Genzel et al 2012



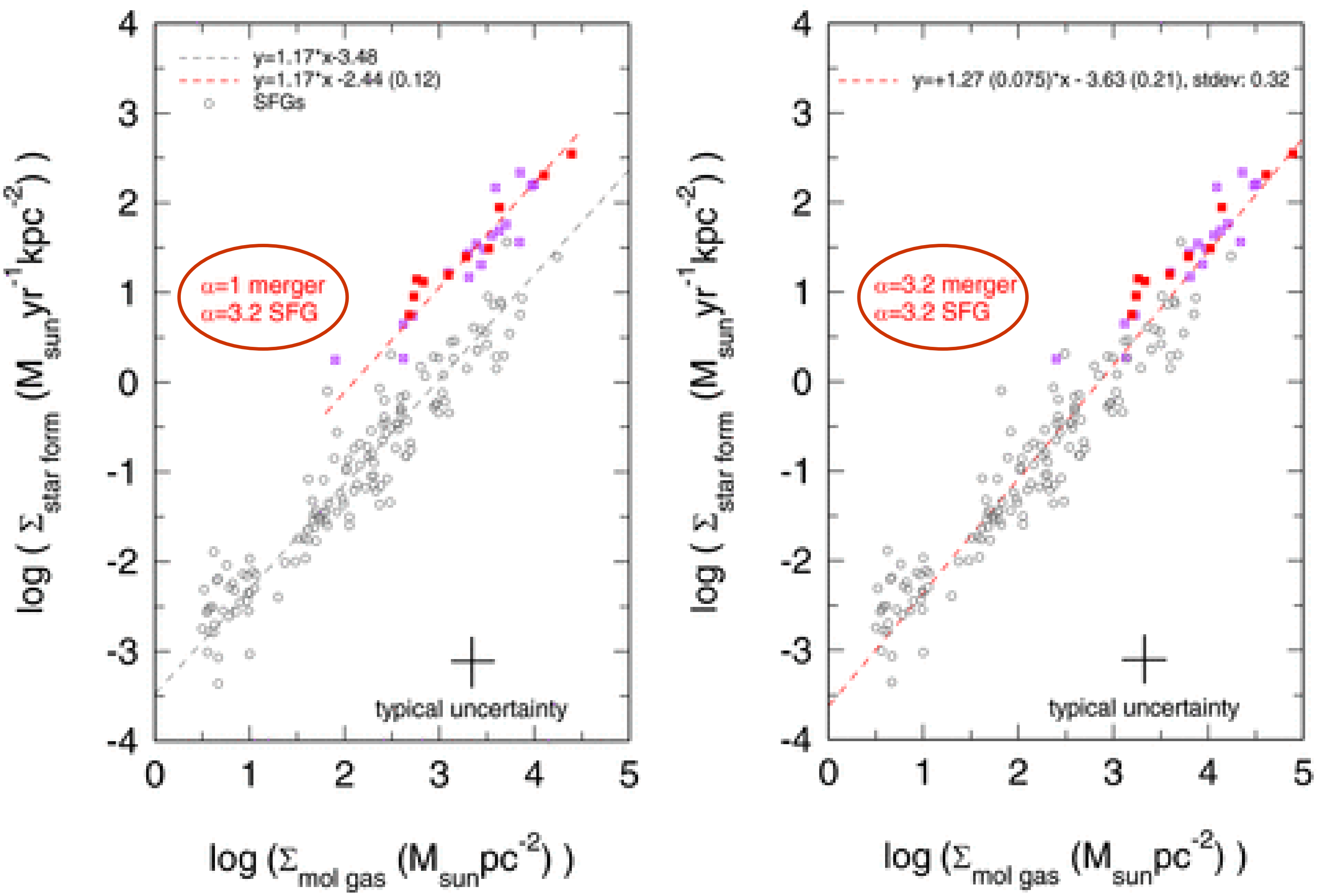
Schruba et al 2012

Evidence for low X(CO) in ULIRGs, dense starbursts



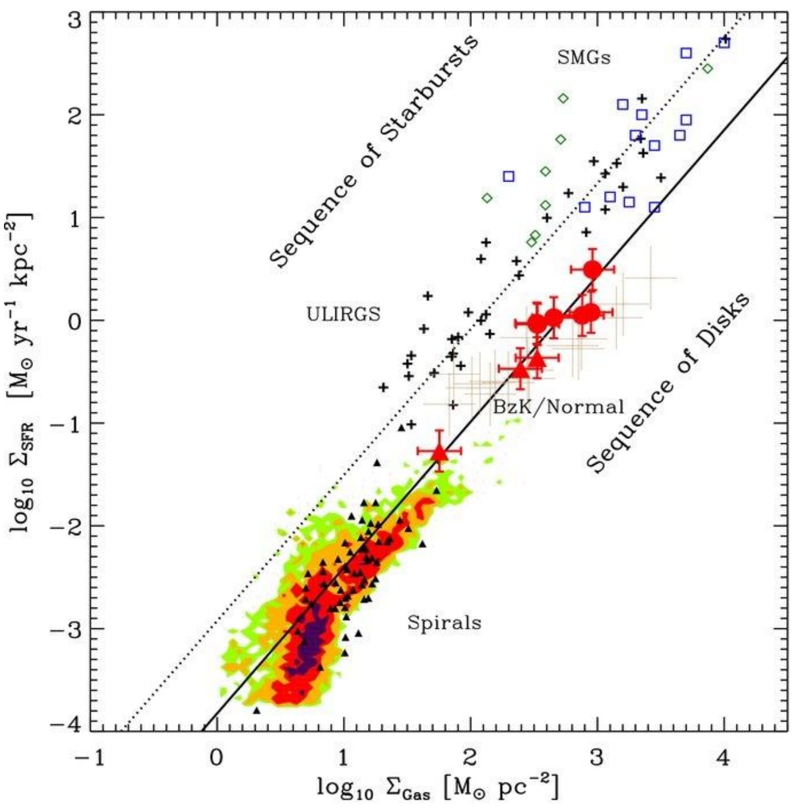
Tacconi et al 2008

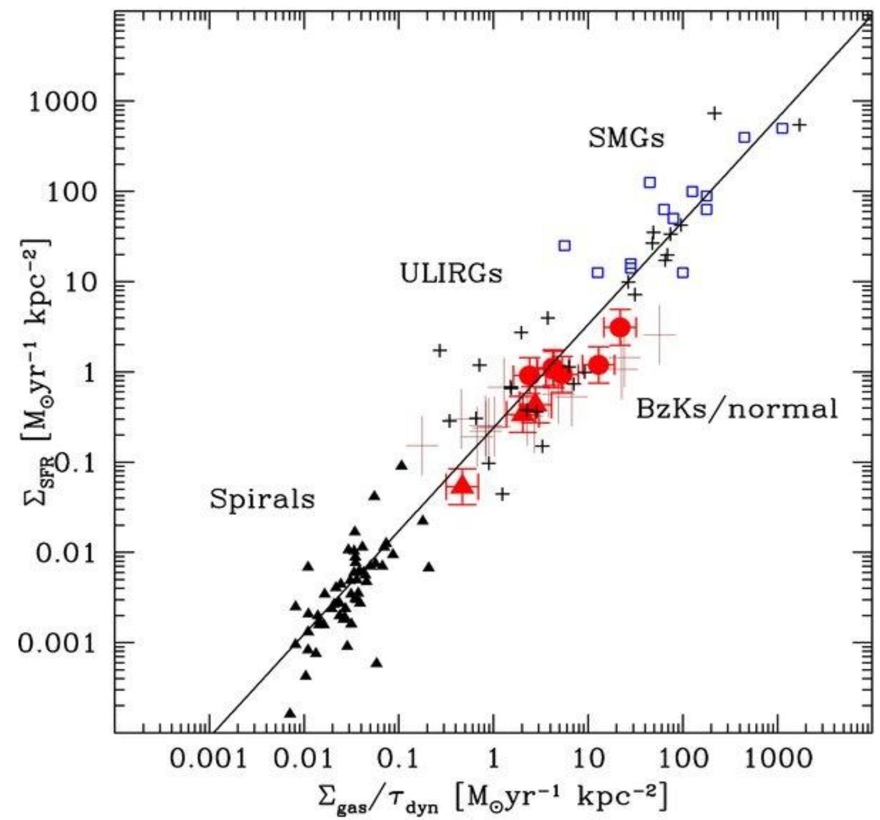
Is the Schmidt law bimodal?



Genzel et al. 2010

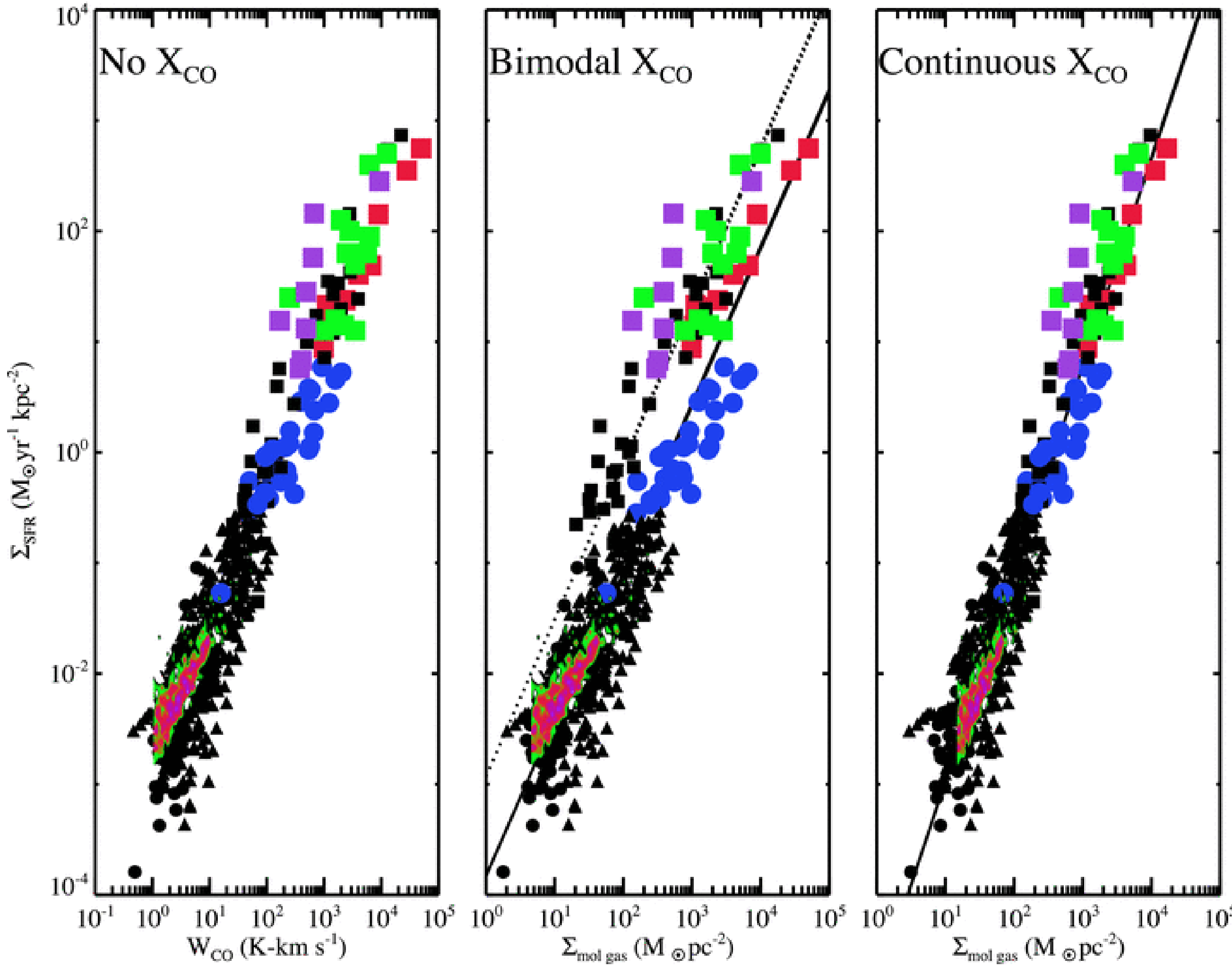
The bimodal branches of the Schmidt law merge in the "Silk law" relation





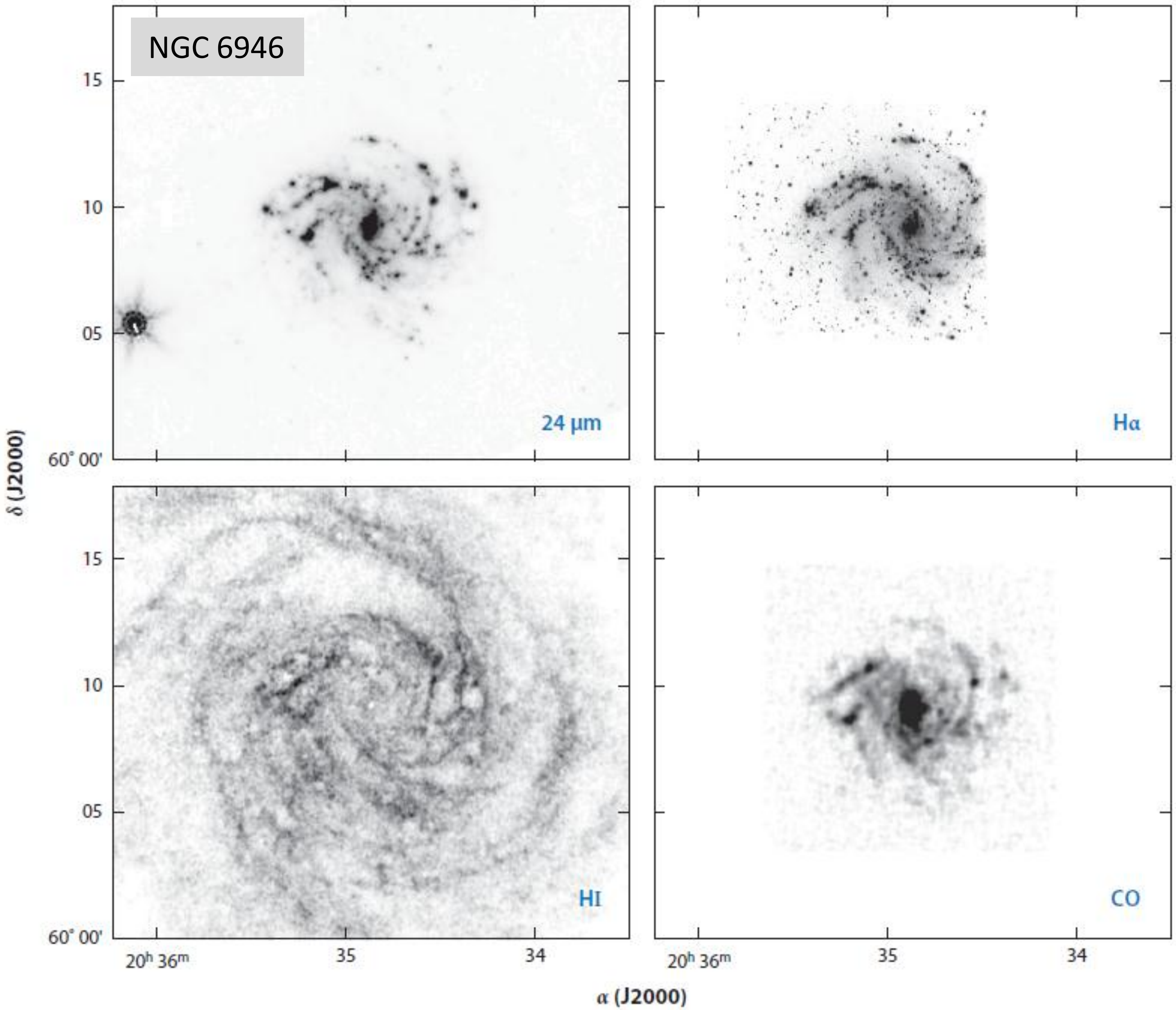
Daddi et al 2010

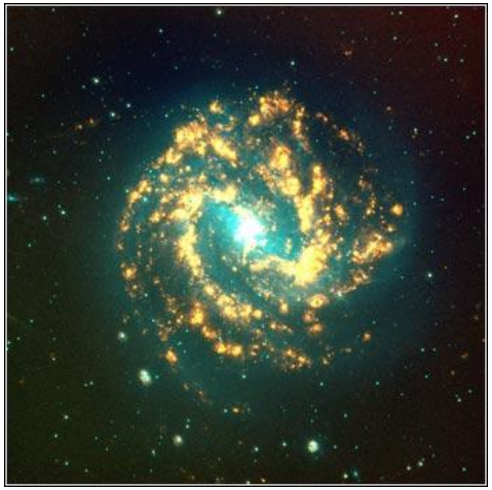
A continuously varying X(CO) produces a steeper Schmidt law

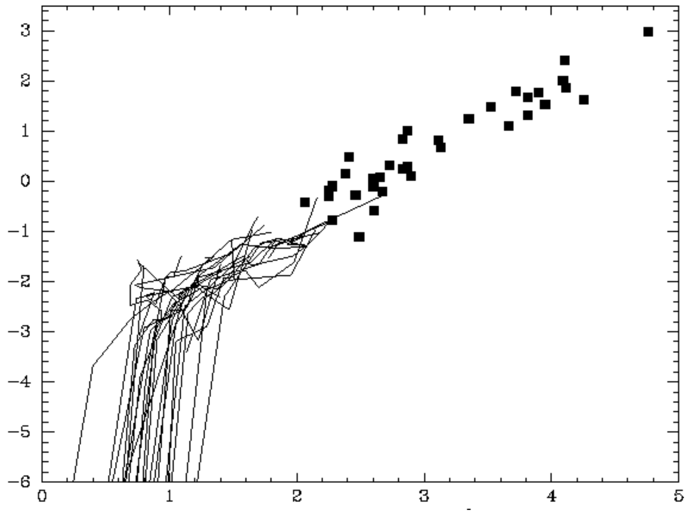


Narayanan et al 2012

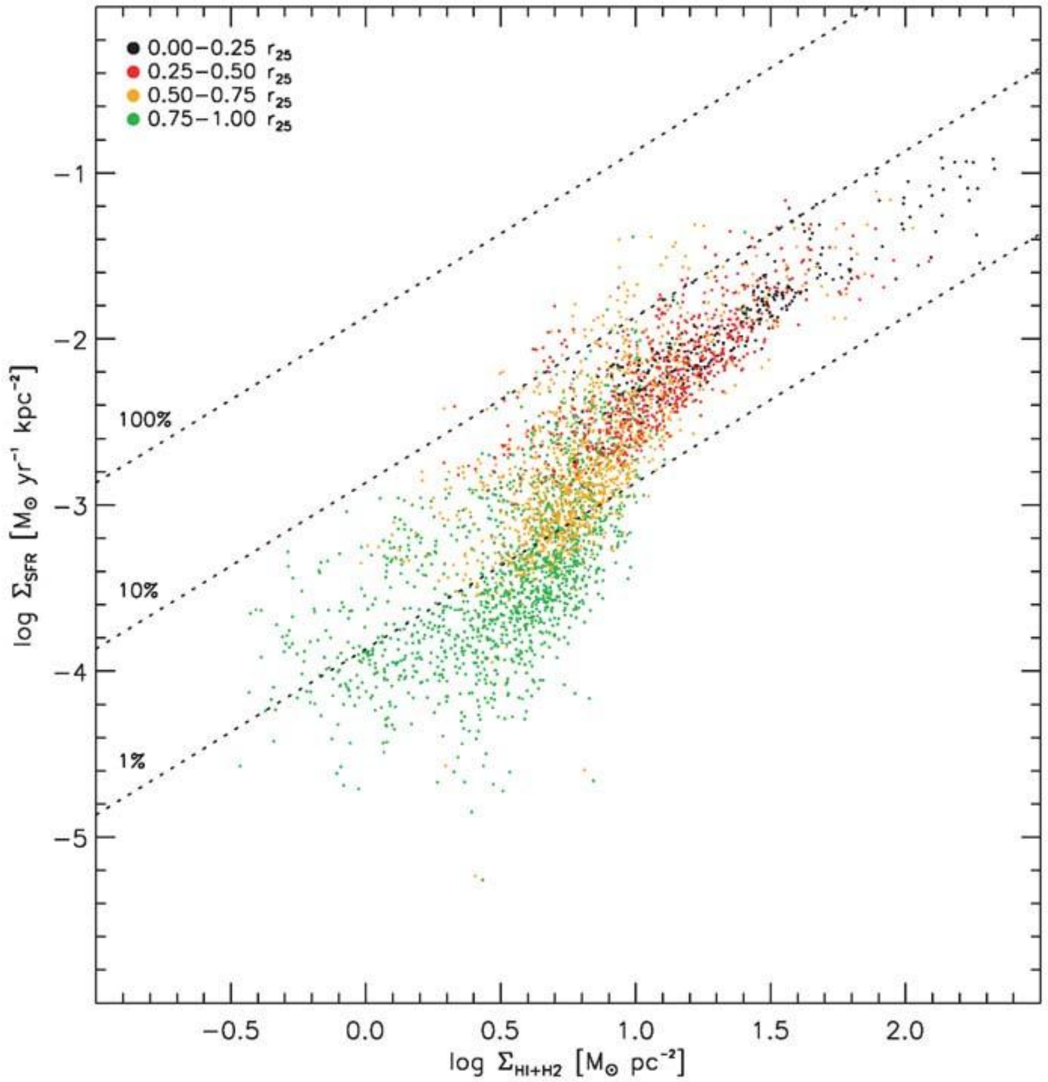
Spatially-Resolved Measurements of the SF Law





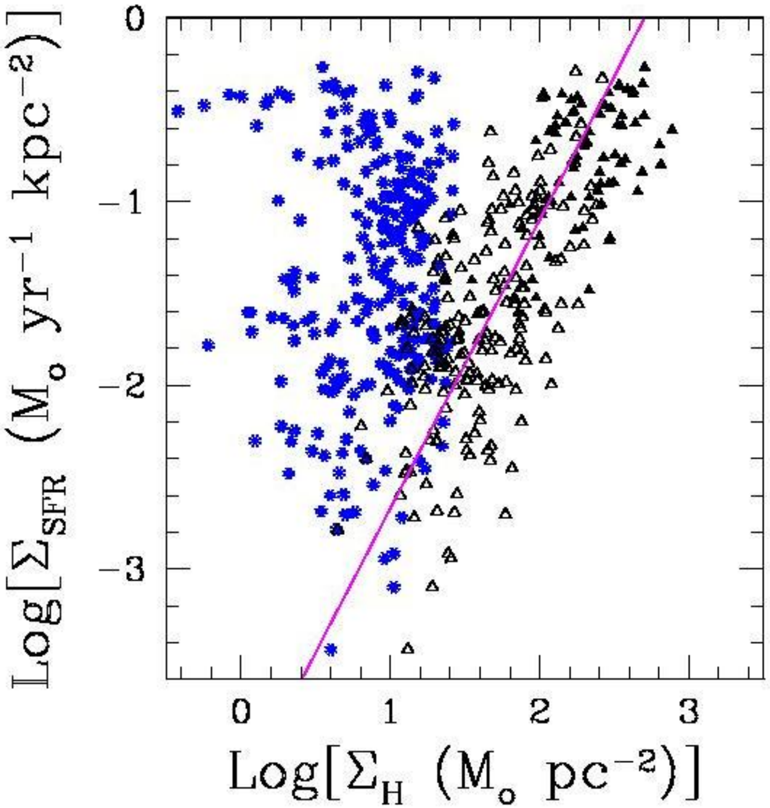


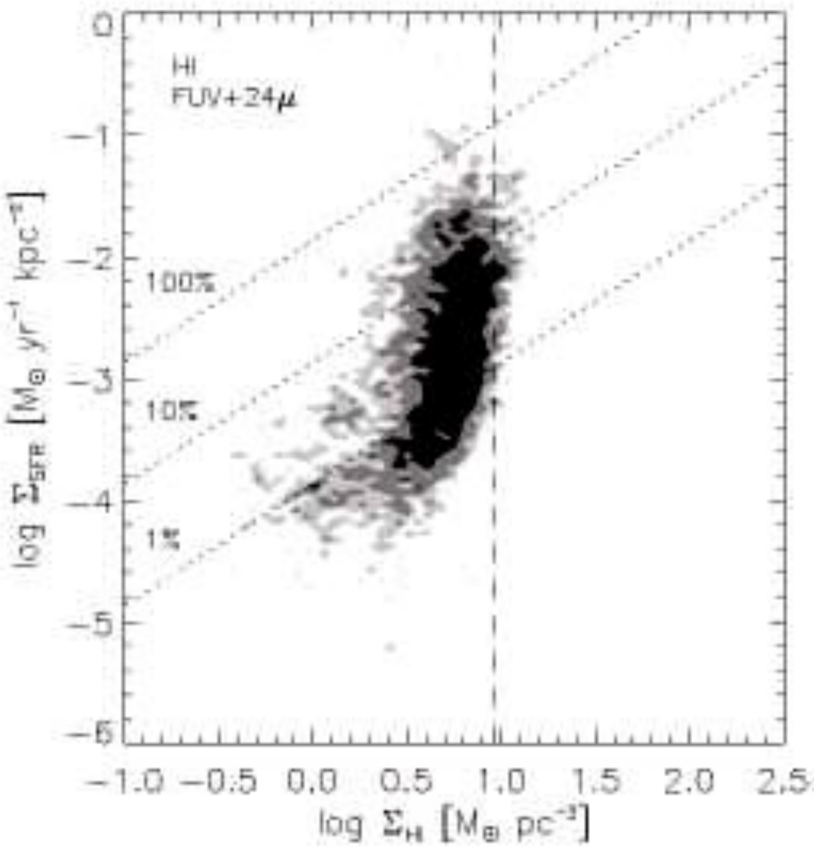
Martin & Kennicutt 2001



Bigiel et al 2008 (THINGS)

HI component uncorrelated with local SFR
(defines low-density threshold regime)

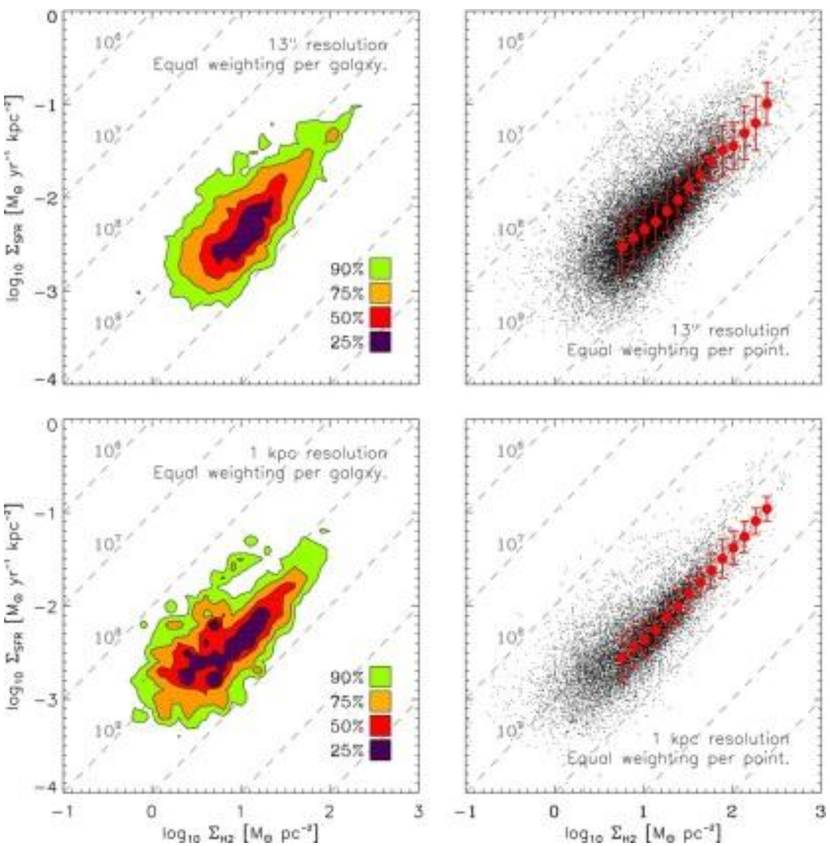


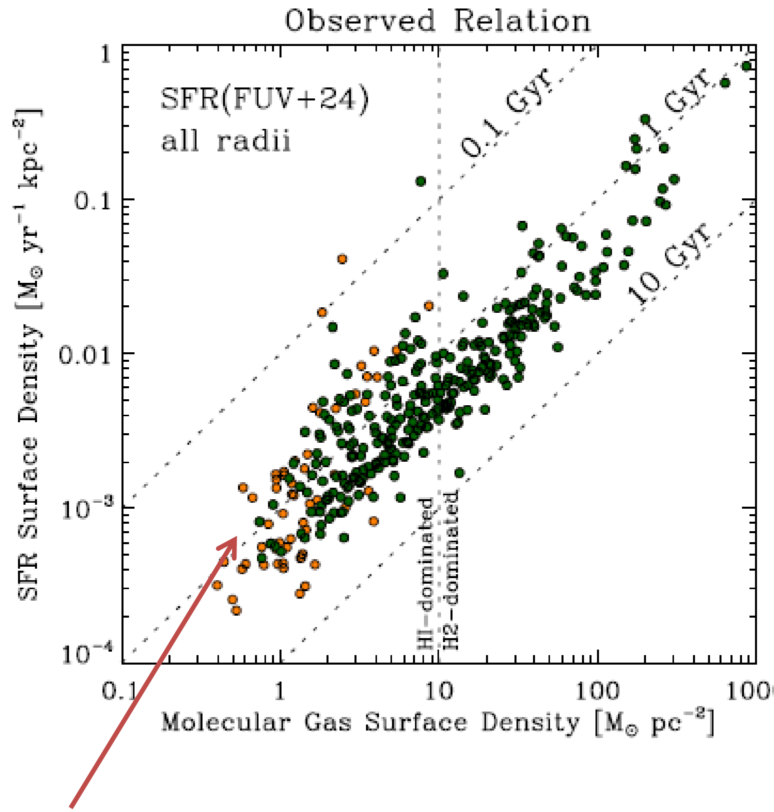


Kennicutt et al. 2007 (M51)

Bigiel et al. 2008 (THINGS)

Schmidt law regime dominated by molecular gas





even in HI-dominated regime!

Bigiel et al. 2011

Schruba et al 2011

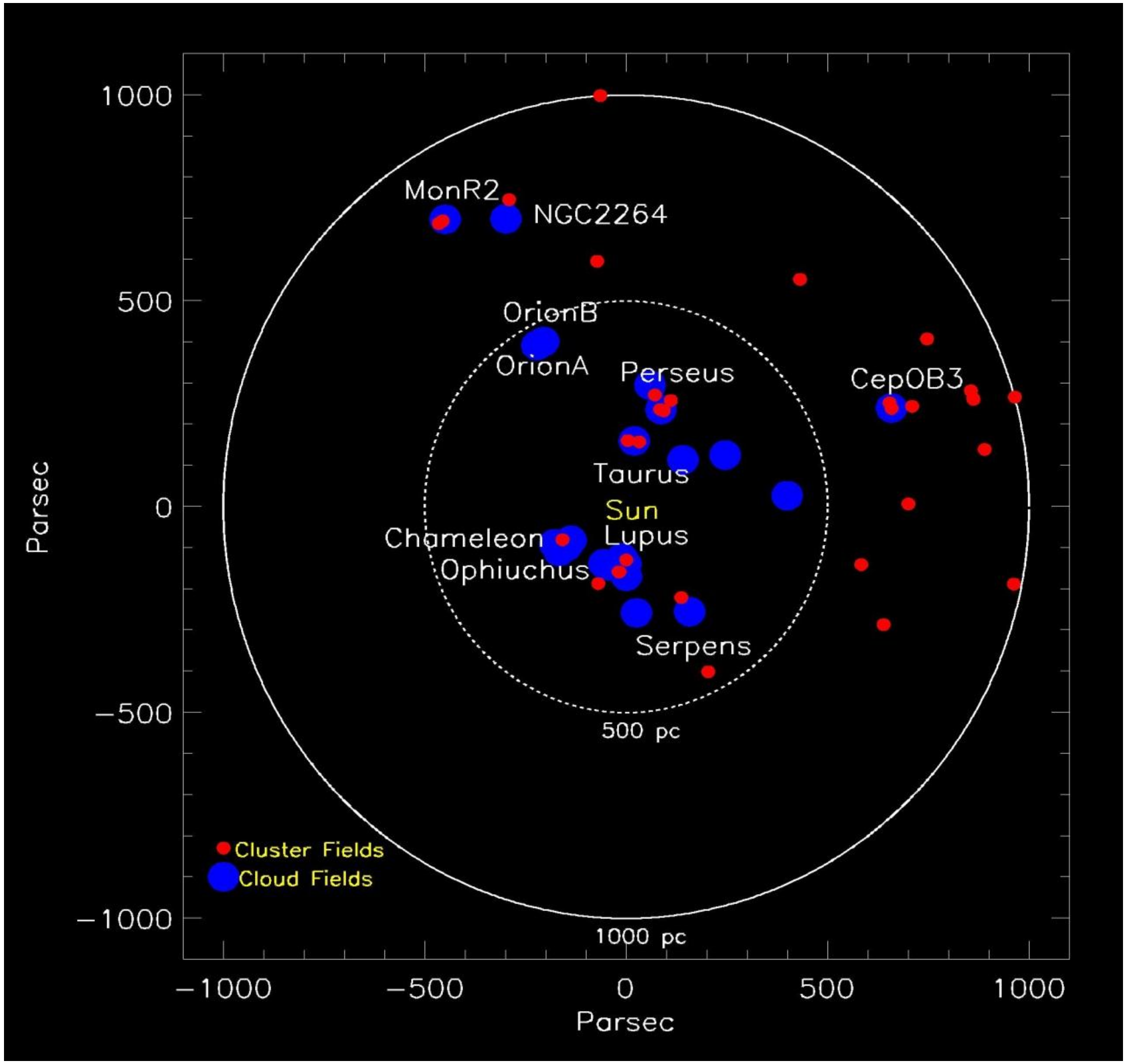
Very Near: Clouds in Solar Neighborhood

Spitzer Programs

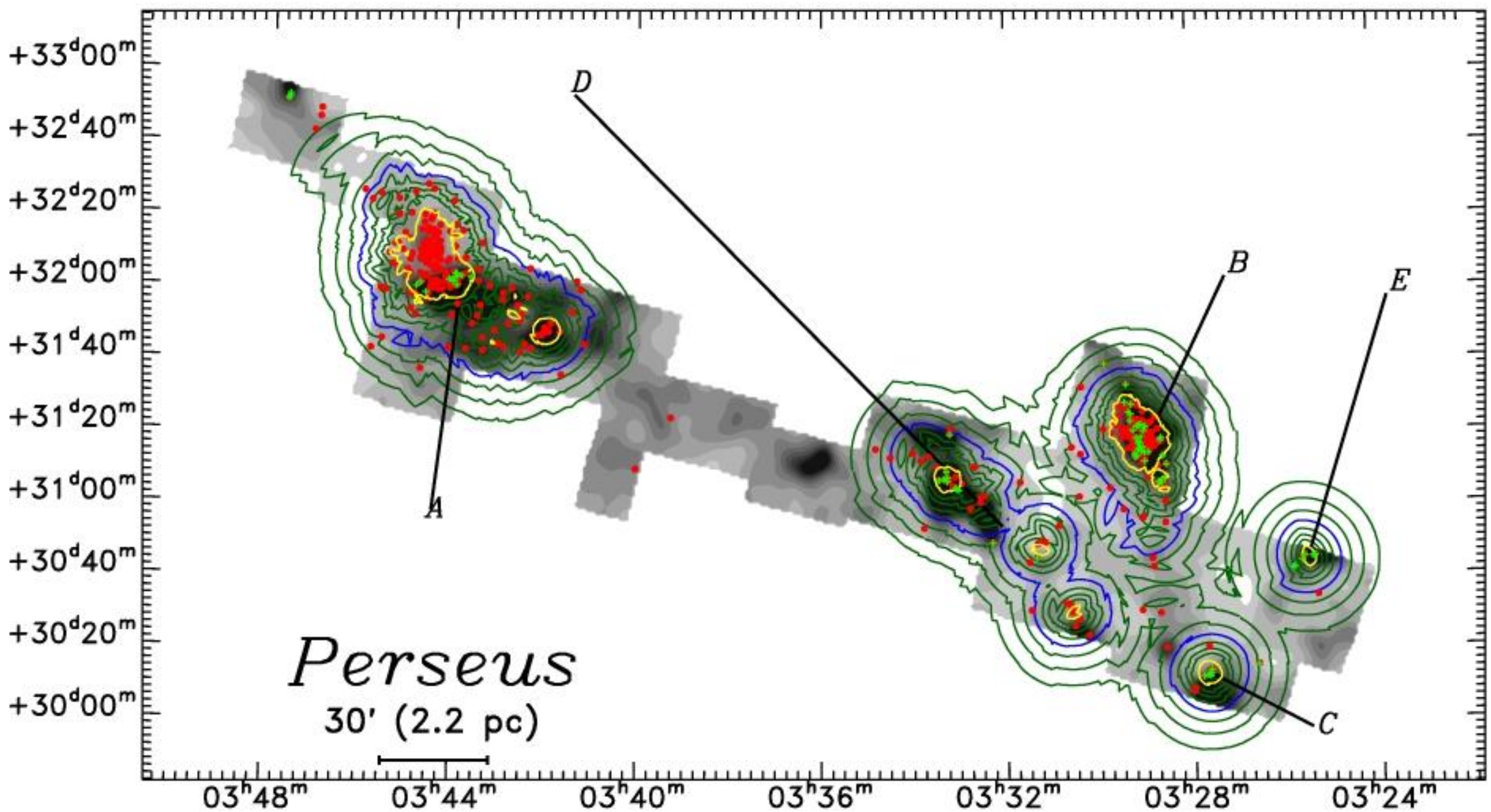
c2d + Gould Belt:
20 nearby molecular clouds
(blue circles)

Cluster Project:
35 young stellar clusters
(red circles)

90% of known stellar groups
and clusters *within 1 kpc*
(complete to ~ 0.1 M_{Sun})



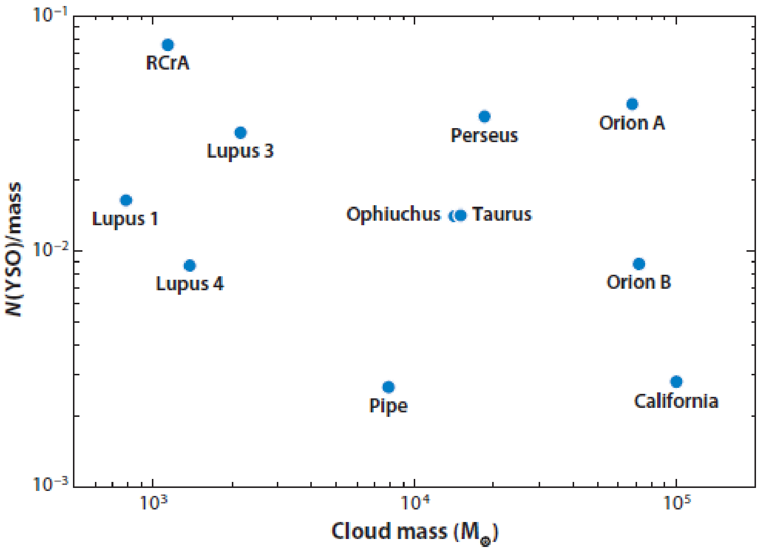
Star Formation is Very Localized

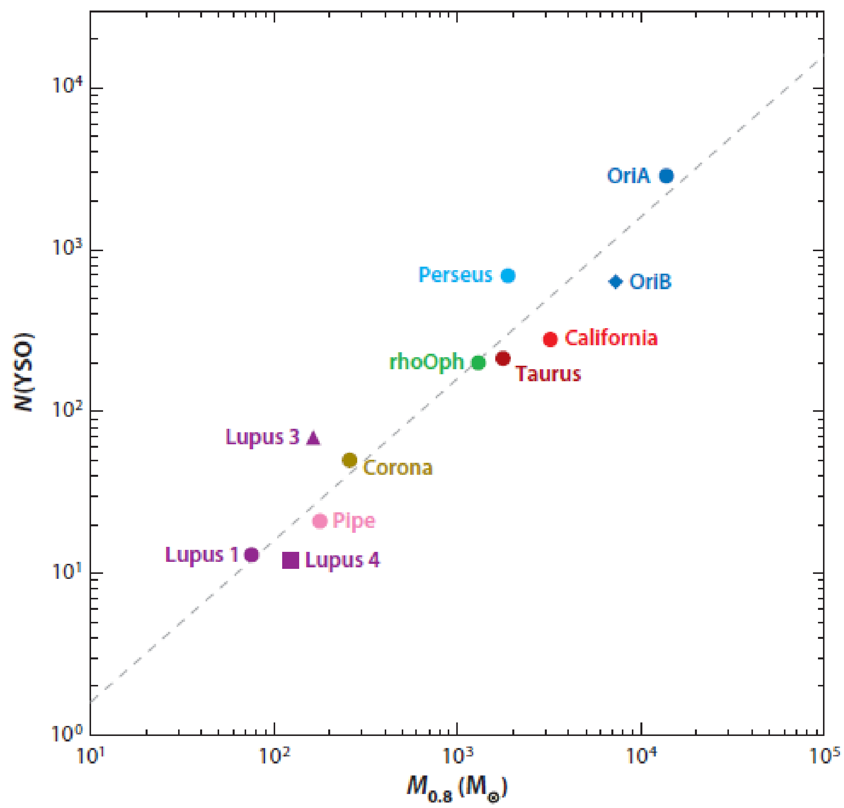


Gray is extinction, red dots are YSOs, contours of volume density (blue is 1.0 M_{sun} pc^{-3}; yellow is 25 M_{sun} pc^{-3})

Heiderman et al. 2010

SF efficiency in clouds varies over orders of magnitude, but within dense clumps is nearly constant





Lada et al 2011

- Combined evidence <u>suggests</u> a simple picture:
  - the fundamental star-forming unit is the dense molecular clump, with a near-universal SFE within clumps everywhere
  - key regulators of SFR are formation rate of molecular clouds (pressure?)
    - <u>and</u> the fraction of molecular mass in dense cores
- Main features in SF law on kpc scales driven by
  - first threshold for forming molecular gas
  - second threshold where global Σ_{gas} approaches critical density for forming molecular clumps

But it can't be that simple…

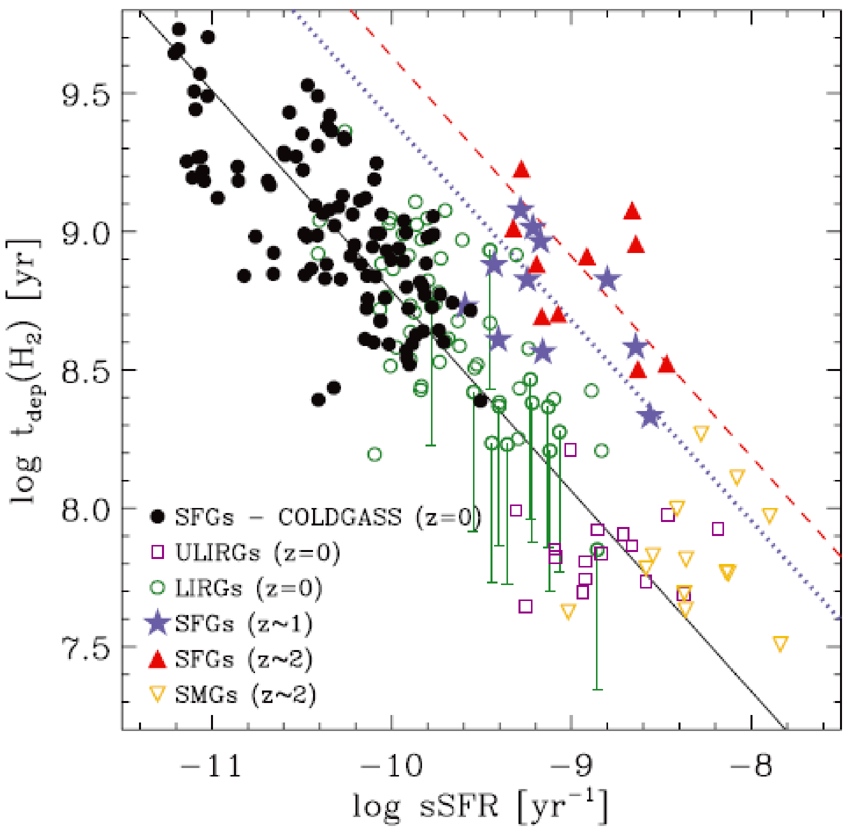
- the starburst phenomenon itself implies a highly non-linear SF regime
- global molecular "SF efficiencies" vary over 100x in galaxies

Example: Milky Way vs Arp 220

MW: M_{mol} = 1.75e9 M_o
SFR = 1.9 M_o/yr
τ_{mol} = 0.9 Gyr

Arp 220 ($X_{CO} = X_{MW}$)
M_{mol} = 3e10 M_o
SFR ~ 250 M_o/yr
τ_{mol} ~ 120 Myr

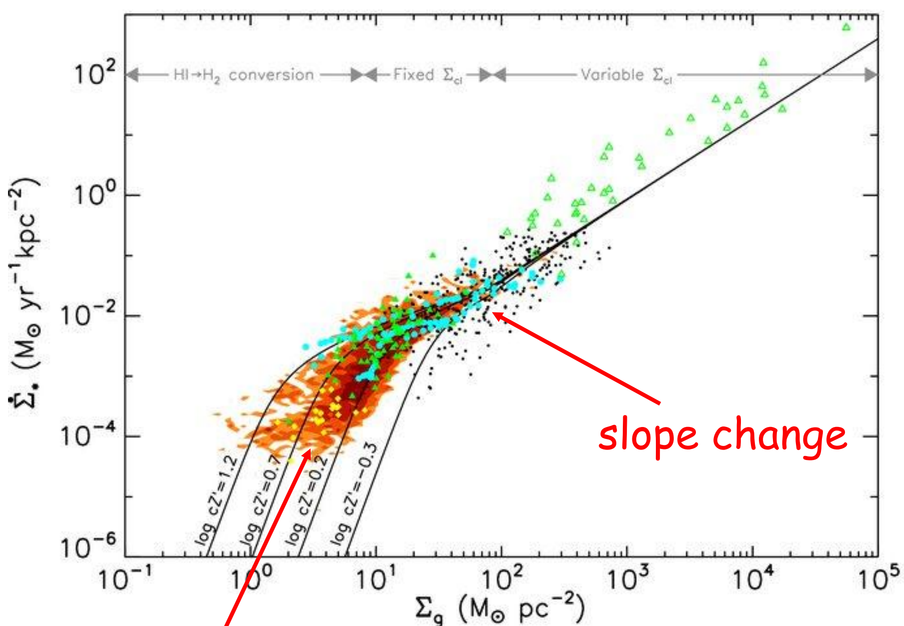
Arp 220 ($X_{CO} = 0.2\ X_{MW}$)
M_{mol} = 6e9 M_o
τ_{mol} ~ 24 Myr



Saintonge et al 2011

Two Possible Ways to Reconcile

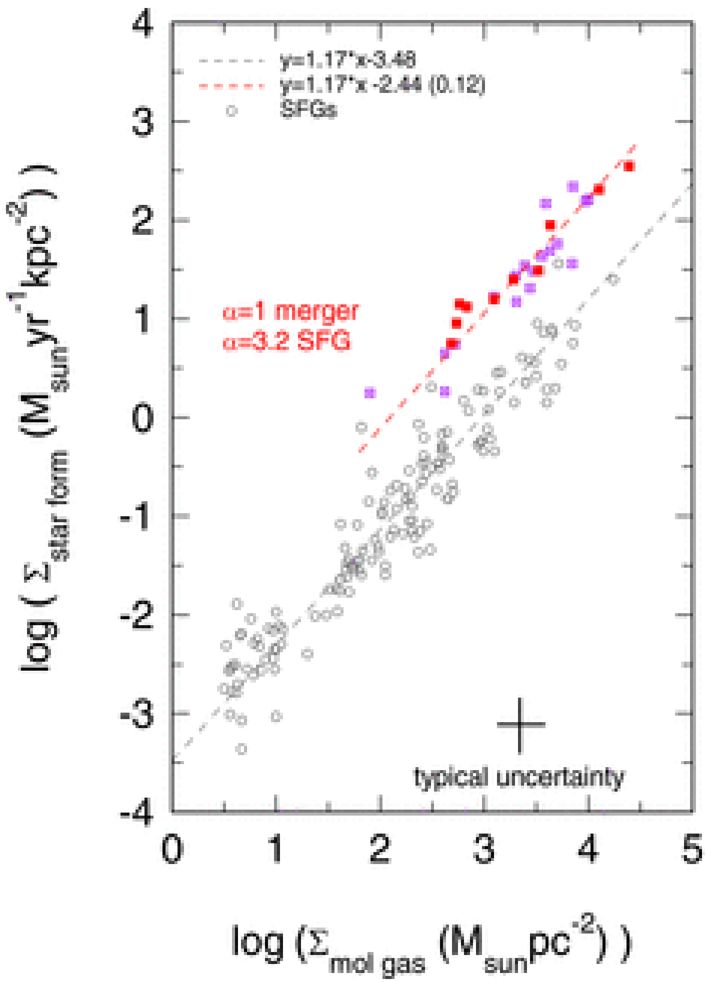
invoke a third SF regime…



slope change

thresholds from UV shielding, not gravity

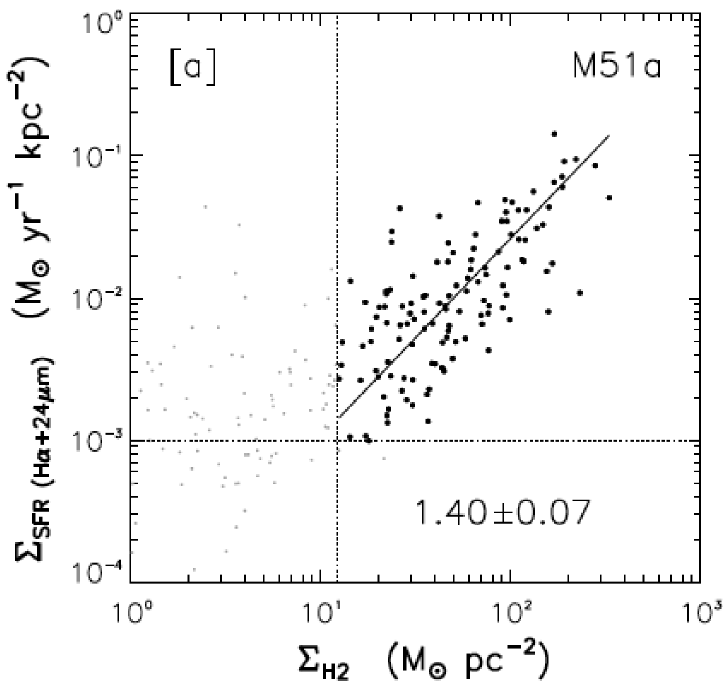
…or invoke bimodality



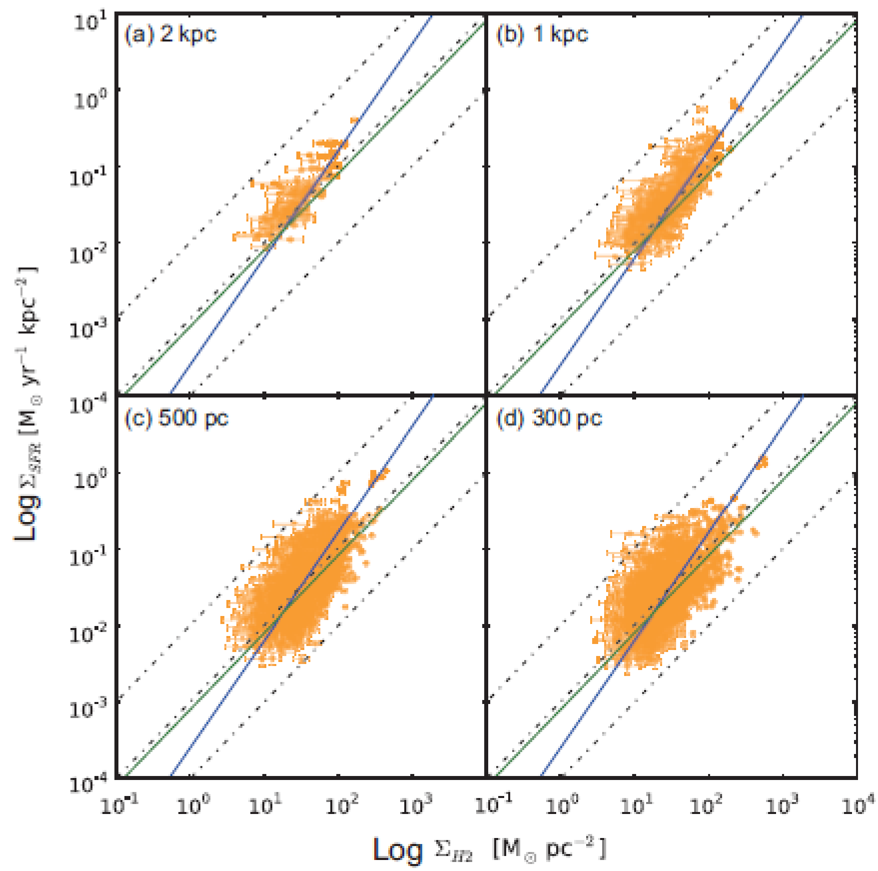
Krumholz et al. 2009

Or maybe we need to look again at the observations: Is the molecular SFE constant?

- some studies report a non-linear molecular Schmidt law



Liu et al 2010



Momose 2012, PhD thesis, U Tokyo

Why so difficult?

- the path from observed emissivities to SFR

- observed L(Hα) → dust-corrected L(Hα)
  - assume dust radiative transfer model
- corrected L(Hα) → ionisation rate
  - assume ionisation bounded nebulae/galaxy, dust absorption
- ionisation rate → L_{bol} of OB stars
  - assume well populated IMF, M_{upper}, trustworthy stellar models
- L_{bol} of OB stars → mass of massive stars
  - trust stellar models some more, including ages
- mass of massive stars → total mass of stars
  - assume IMF
- mass of young stars at this moment → SFR
  - assume smooth SF history

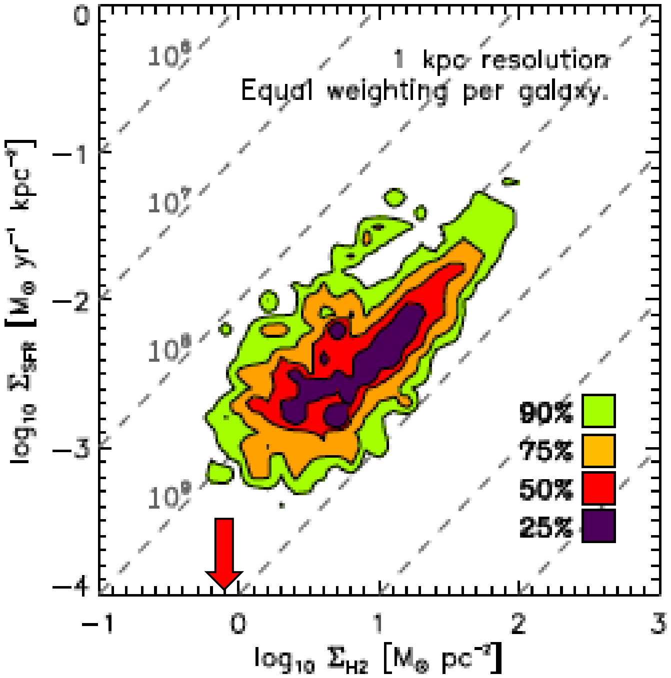
Most of these assumptions are (relatively!) secure for galaxies with SFR > 0.01 M_o/yr, uncertainties larger (~2x) for luminous starbursts

The Challenge: Spatially-Resolved SFRs

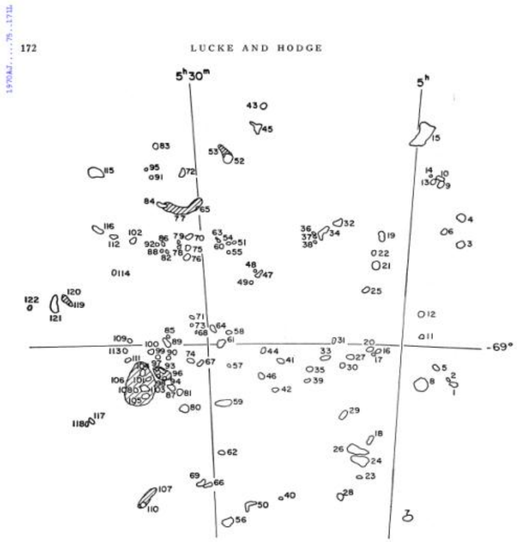
- the robustness of galaxy-wide SFRs rests several approximations:
  - averaged over full range of region ages
  - IMF is fully populated, well represented
  - dust geometry effects average out
  - SFR averaged over a galaxy roughly steady with time, so age sensitivity of tracers (Hα, UV, IR) can be ignored
- extending this approach to a "SFR map" uncovers several systematic effects:
  - local emission dependent on small number statistics of individual stars, "cosmic variance" (especially for Hα, other ionised gas tracers)
  - variations in dust geometry add scatter to "SFRs"
  - age of stellar population varies locally, altering Hα/UV/IR emission per unit SFR
  - Hα and dust emission trace gas, not stars
  - diffuse emission produces false "star formation" signal far away from any young stars
  - meaning of "SFR" itself ill defined on local scales

A Case Study in "Cosmic Variance": Orion

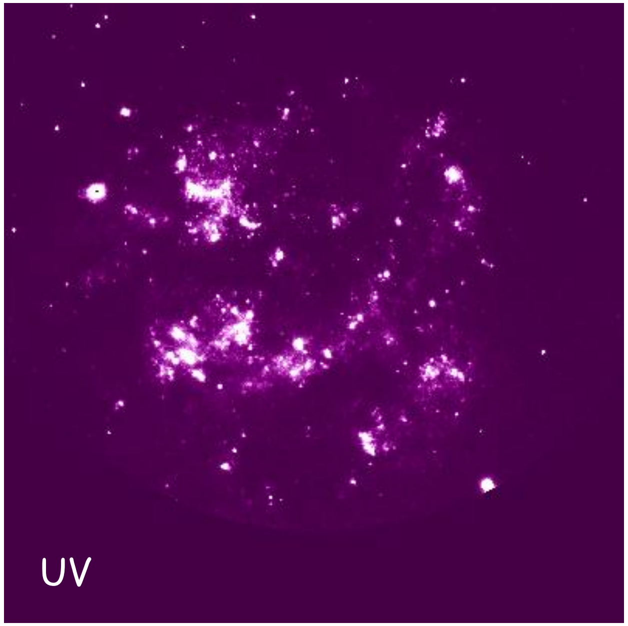
- L(Hα) underestimates SFR of Orion complex by 20x
- L(IR) underestimates SFR by 8x



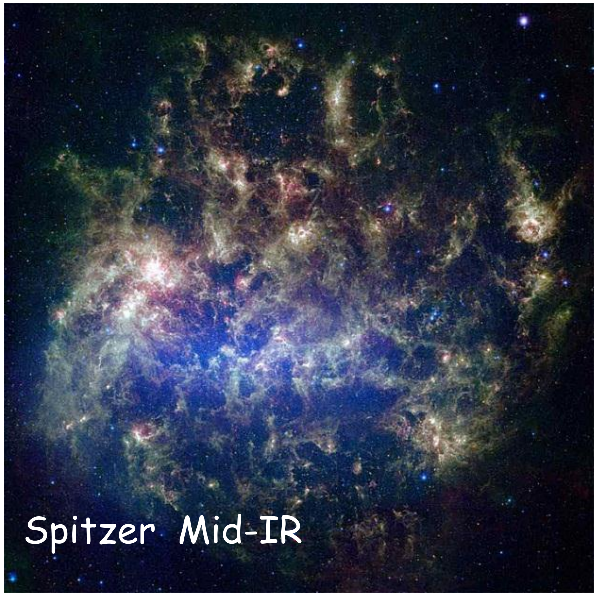
How faithfully do tracers follow distribution of young stars?



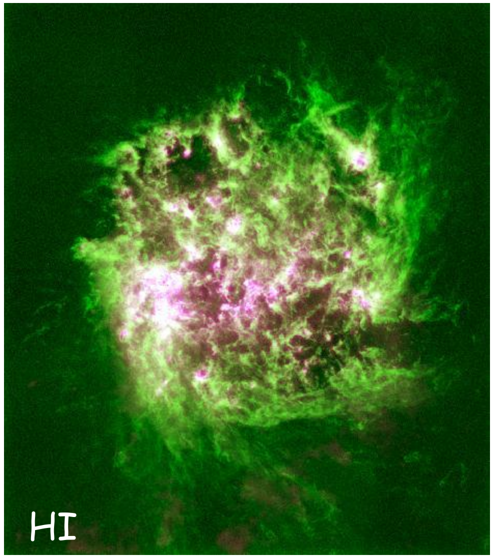
Lucke-Hodge OB associations


UV

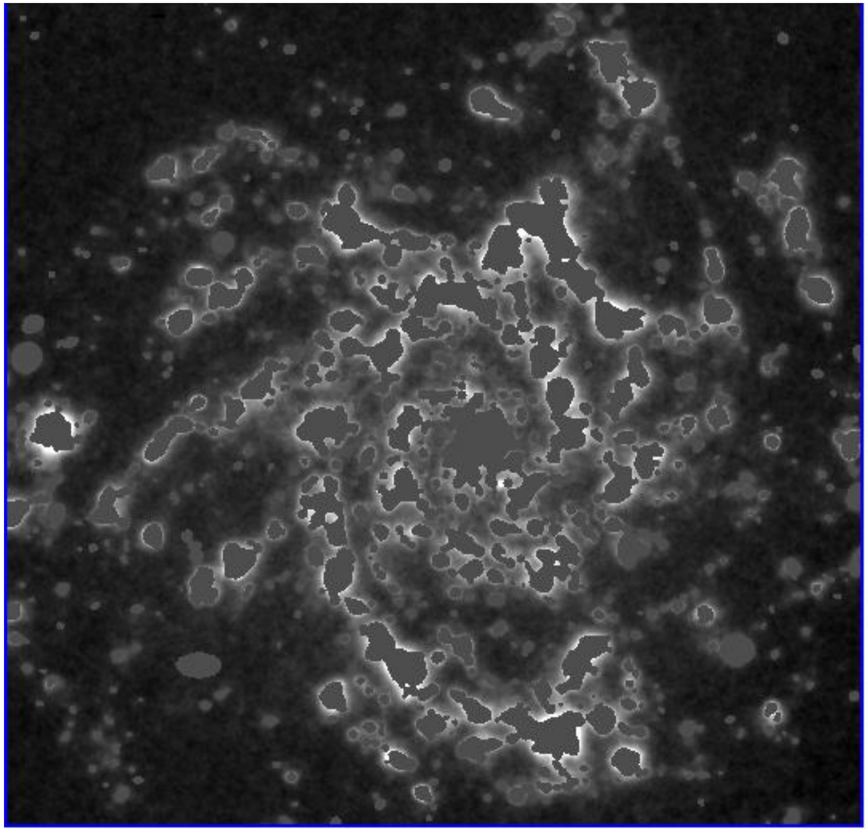

Hα

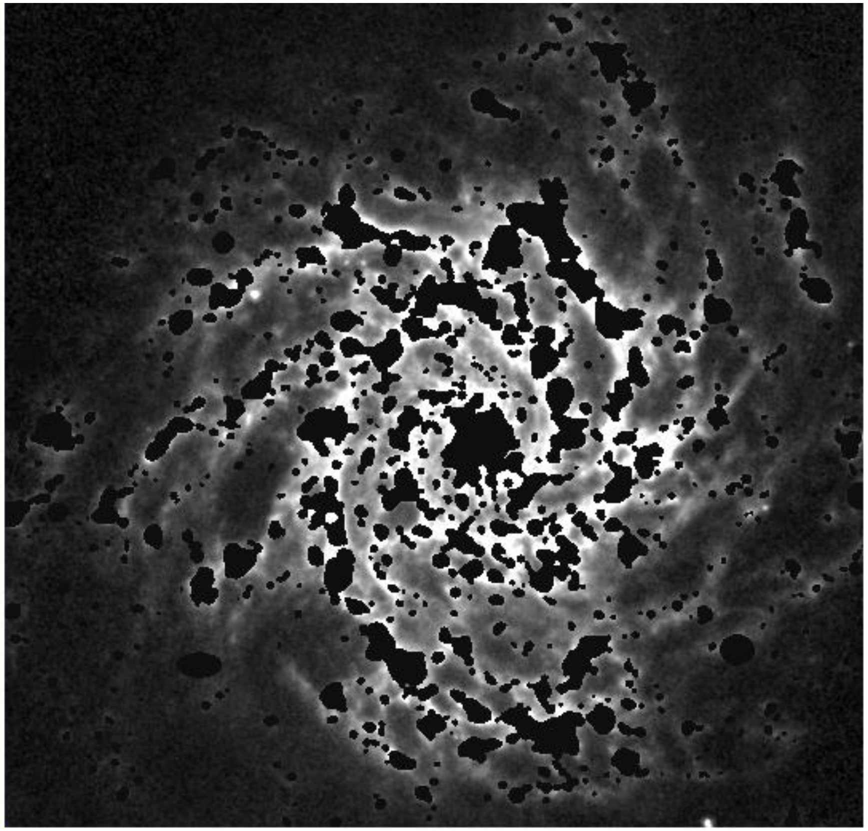

Spitzer Mid-IR


Herschel Far-IR/Submm


HI

Contamination by diffuse emission

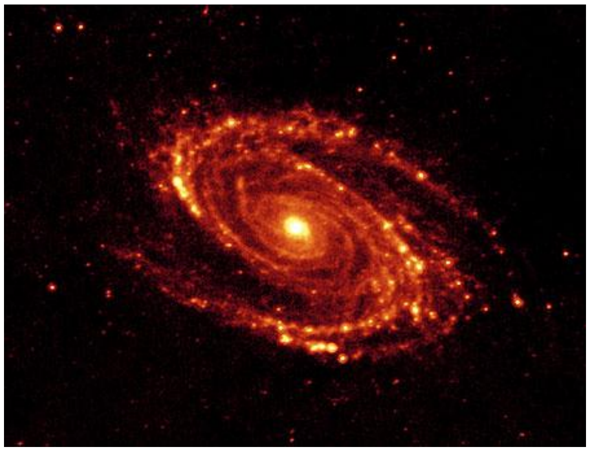


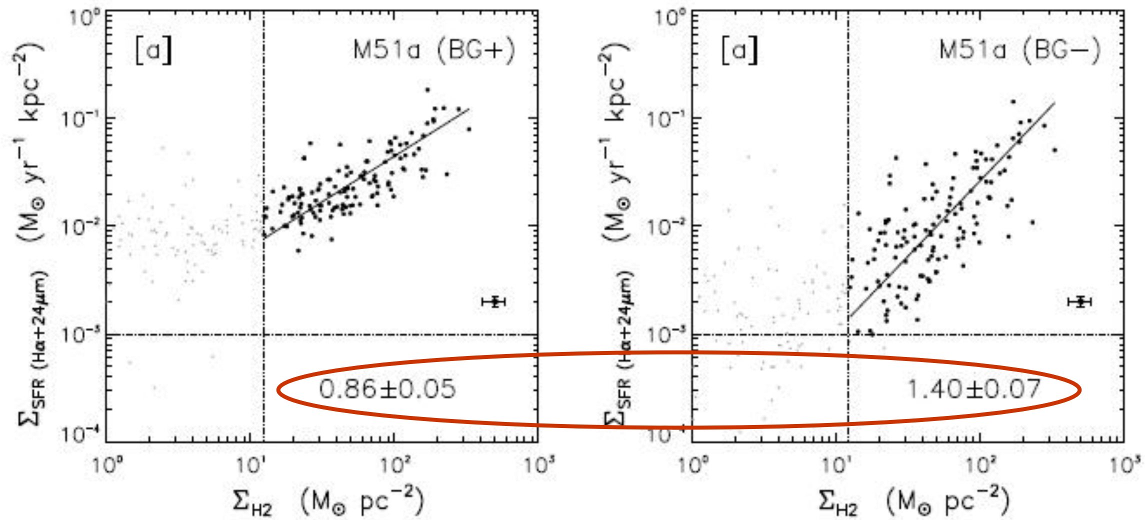


❖ Difficult problem that requires masking out of clustered regions of star formation (HII regions/clusters) and separate diffuse SF-associated PAH emission associated from non-SF diffuse PAH emission (Crocker et al 2012, Leroy et al 2012)

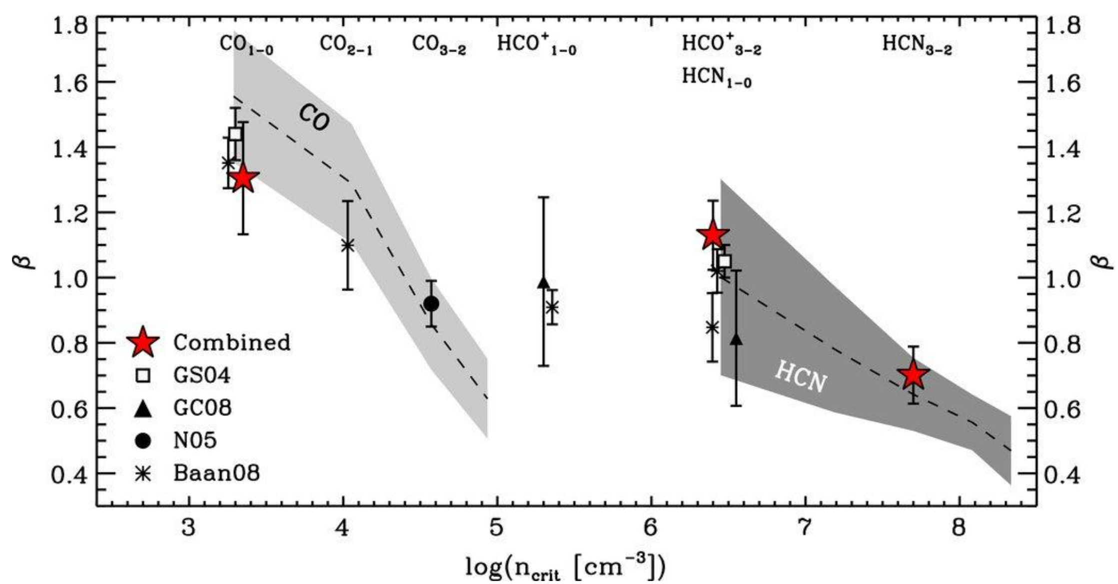
Contribution of diffuse emission can bias slope of derived Schmidt law

Liu et al. 2010





Results may also depend on CO transition used



Juneau et al. 2009
Koda et al 2012

Lessons Learned and Challenges Ahead

- Key astrophysical questions
  - constancy of $\Sigma_{sfr}/\Sigma_{mol}$: is there a second threshold in the starburst regime?
  - bimodality in the SF law?
  - roles of molecular/atomic vs cold phase, gravitational thresholds?
  - is the molecular clump/core as a fundamental SF unit?
    - is there a universal SF efficiency in clumps?
- Uncertainties in key diagnostics are (still) a limiting factor
  - X(CO), especially at extremes of metallicity, SFR, and P_{ISM}
  - SFRs on a spatially-resolved basis and in the low-density regime
    - these problems are tractable with ALMA, IFUs, multi-λ data
    - don't forget the IMF…
- Much key physics lies at the interface between galactic-scale and local (intra-cloud) scales
  - Relevant scales extend from 1 pc (clumps) to >1 kpc (pressure, gravitational/hydrodynamical disturbances…)
  - fertile ground for observations, theory, simulations