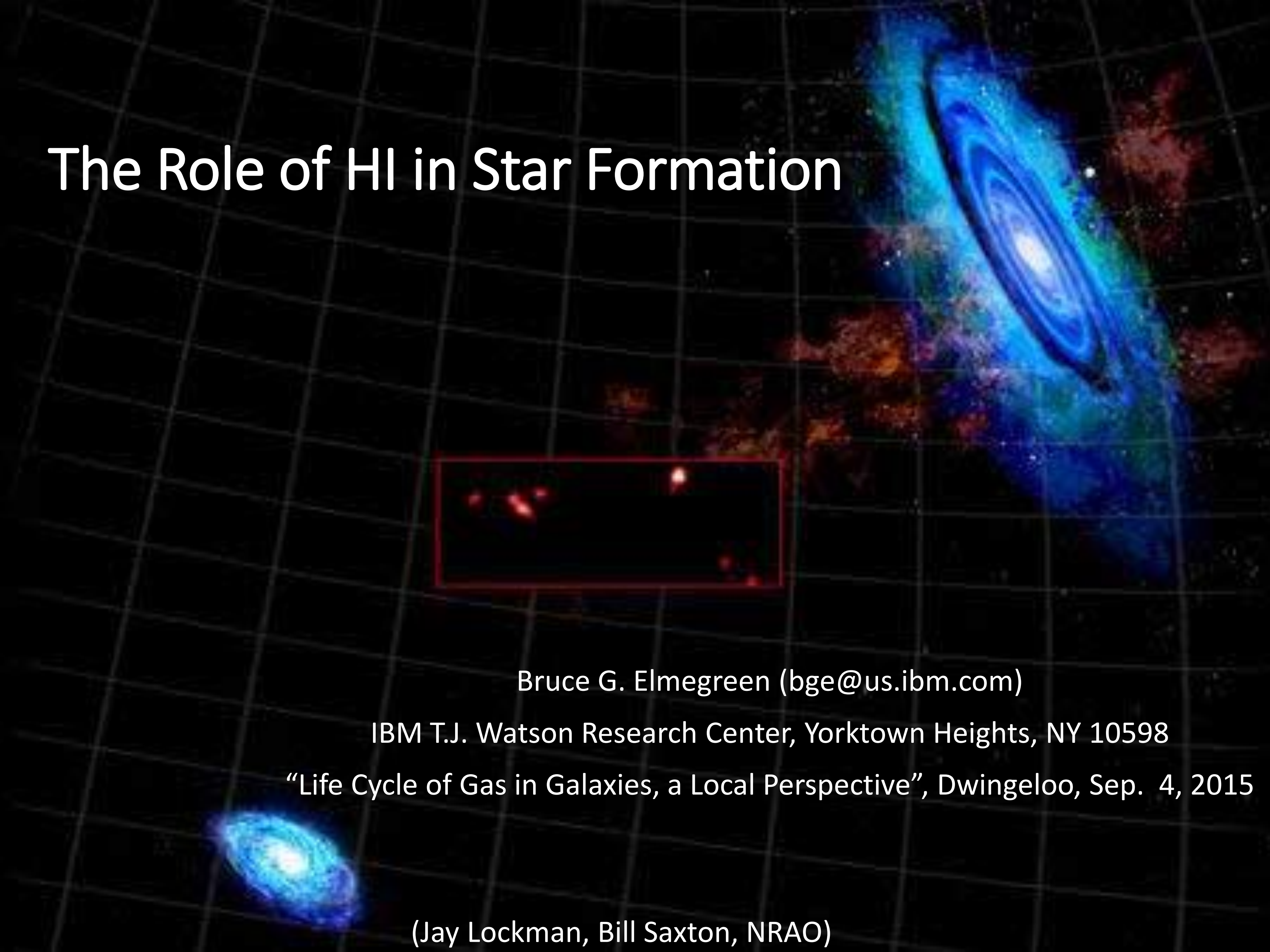
The Role of HI in Star Formation



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“Life Cycle of Gas in Galaxies, a Local Perspective”, Dwingeloo, Sep. 4, 2015

(Jay Lockman, Bill Saxton, NRAO)

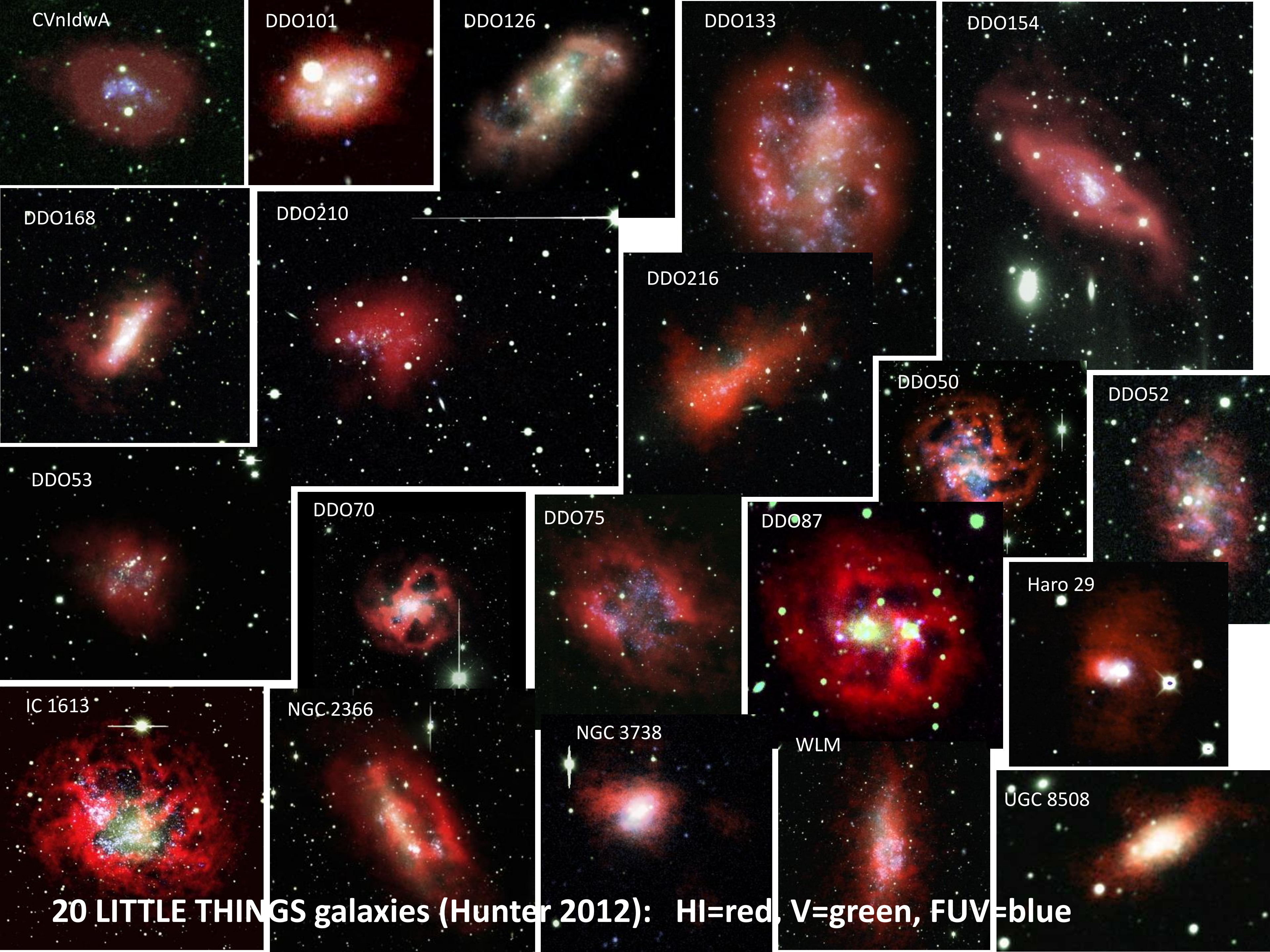
The essentials:

1. $f(H_2)$ decreases outward in galaxies, which means:

   Inner disks build big GMCs from small GMCs, and FB breaks them up
   - processes: random collisions, GIs, and compressions from turbulence, SN, spiral shocks
   - SF likely triggered by the same cloud-building processes (since they all increase self-gravity)

   Outer disks & dwarfs build medium-size GMCs from the CNM
   - we don’t know how: outer disks have weak or no GIs, weak turbulence, few SNs
   - maybe outward-moving gas spirals collect the CNM
   - maybe it is gravitationally unstable in a different way

   This is the puzzle of SF in HI-dominant gas



20 LITTLE THINGS galaxies (Hunter 2012): HI=red, V=green, FUV=blue

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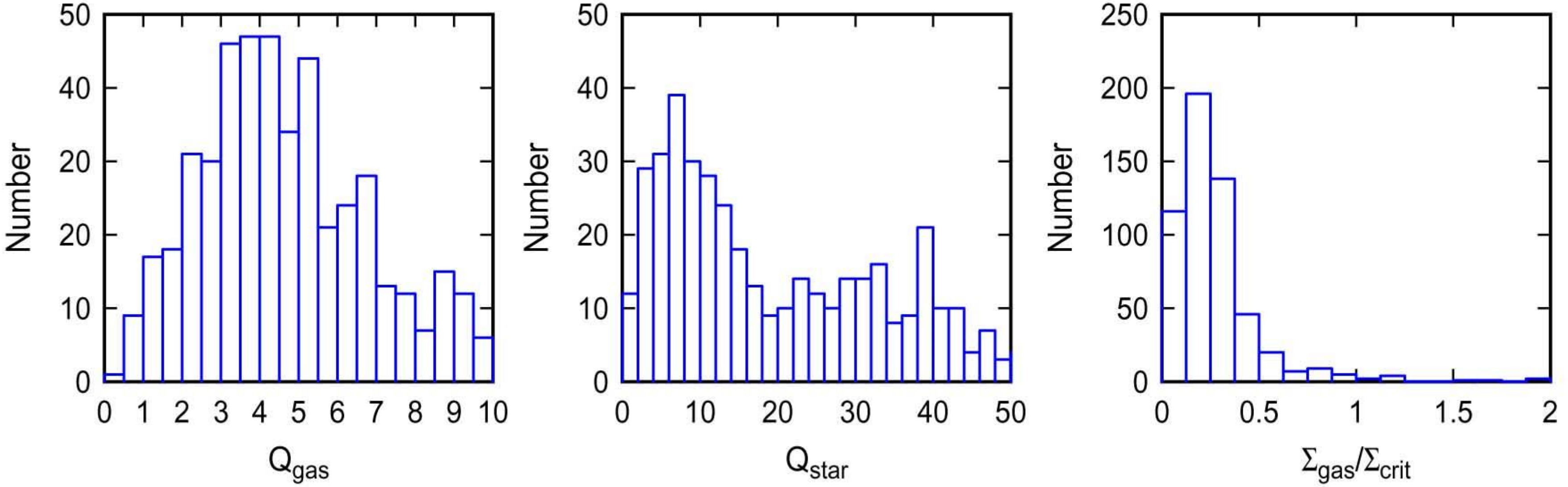

Using V_{rot} for κ, Σ_{gas}, σ_{gas}, Σ_{star}, σ_{star} for radial annuli in 20 galaxies:

Q_{gas} and $Q_{star} >> 1$

Two fluid effective $Q = 1/\,(\,1/Q_{gas} + 1/Q_{star}\,) >> 1$

$\Sigma_{gas} / \Sigma_{crit} << 1$

→ SF pervasive and normal-looking without Q ~ 1-2 as in spirals.
→ SF & Q do not self-regulate to make Q ~ 1-2 <u>everywhere</u>

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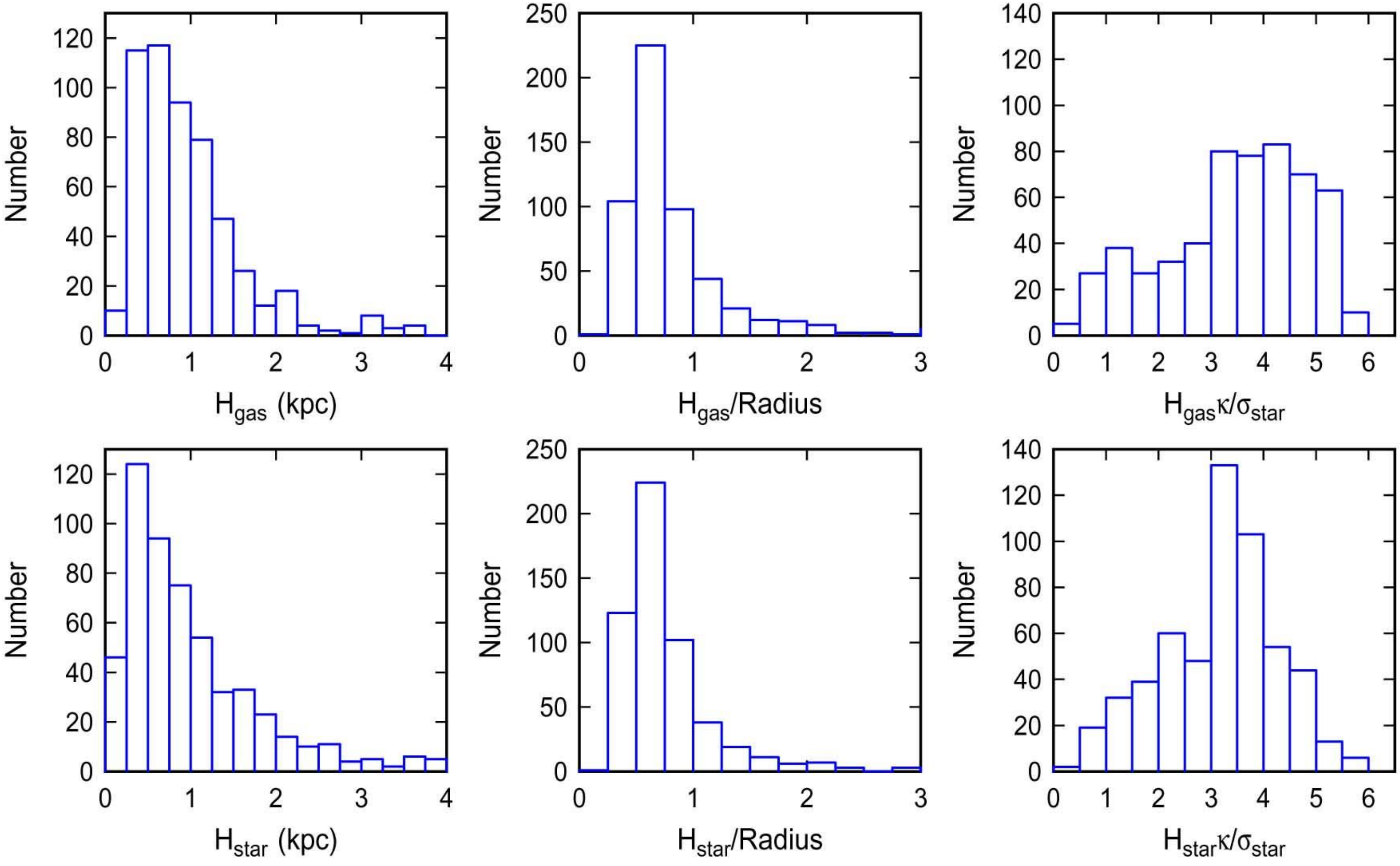
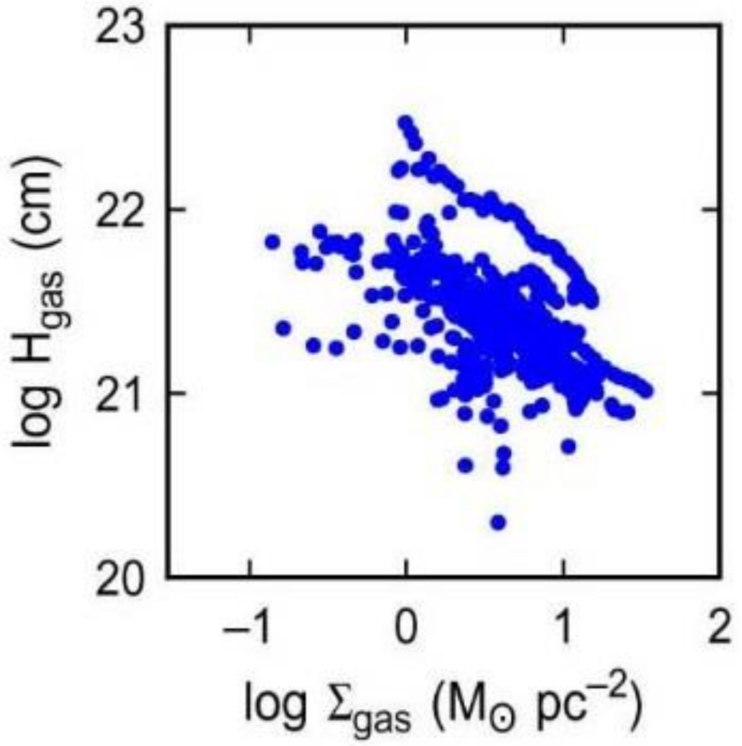


Scale height H: vertical equilibrium with gas, stars & disk DM (Narayan & Jog 02)

Thick disks: H/Radius ~ 0.6; H/$R_{epicycle}$ ~ 4, make dIrrs even more stable.

→ dIrrs have thick disks



All of the dwarfs have increasing H with radius (and decreasing Σ_{gas})

Consistent with $H = \sigma^2 / \pi G \Sigma_{gas}$ for $\Sigma_{gas} >> \Sigma_{star}$ and constant σ

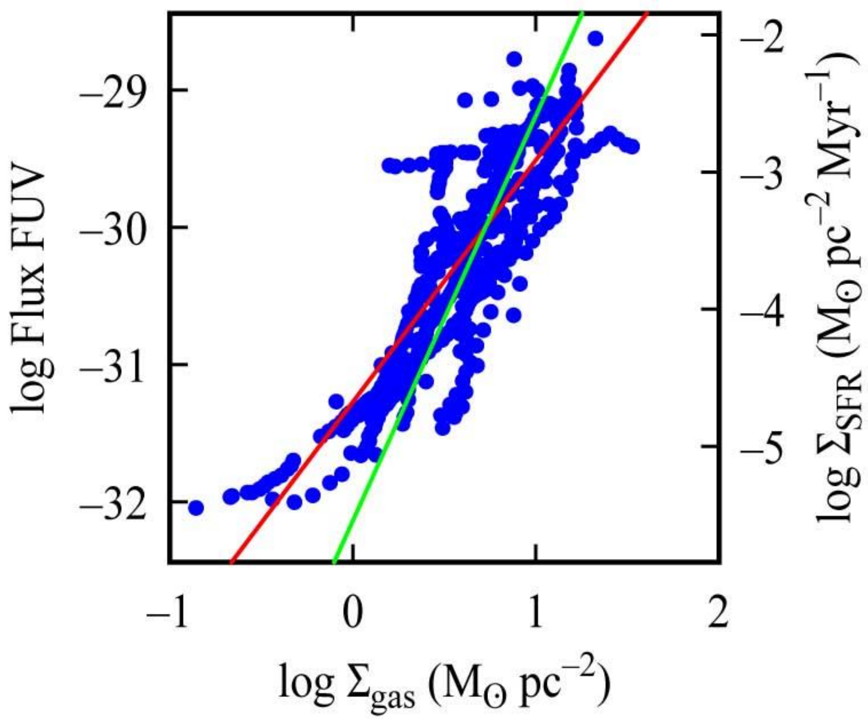
The outer parts of spirals are gas dominant with a flare too.

Inner spiral disks vs outer spiral disks & dIrr

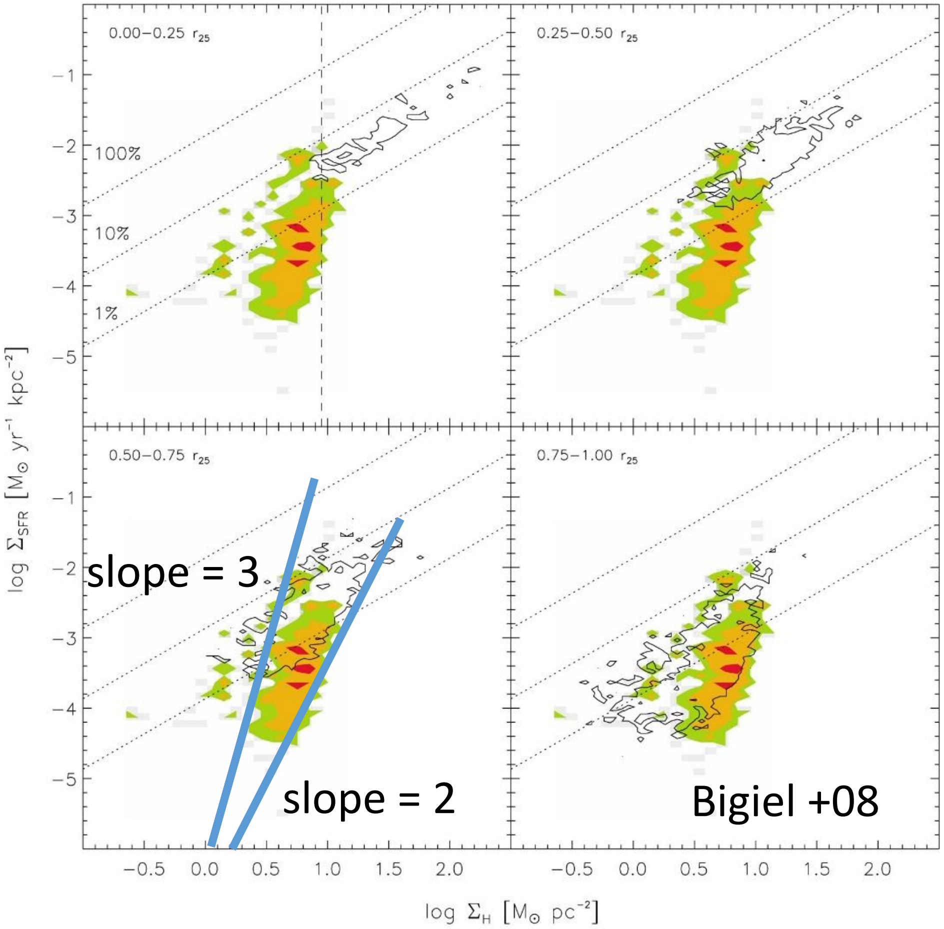
Inner	**Outer & dIrr**
• small, constant H	• big, increasing H (flare)
• decreasing σ	• constant σ
• driven SDW	• no SDWs & outside OLR
• $f(H_2) > 0.1$	• $f(H_2) < 0.1$
• $\Sigma_{gas} < \Sigma_{stars}$	• $\Sigma_{gas} > \Sigma_{stars}$

Exponential light profiles throughout, with no obvious correlation between the break radius in type II exponentials and the transition to an HI-dominant disk

The KS relation slope ~ 2 - 3



Red slope (all pt avg.) = 1.76pm0.08
Green slope (avg. of gal. slopes)
= 2.95pm2.09



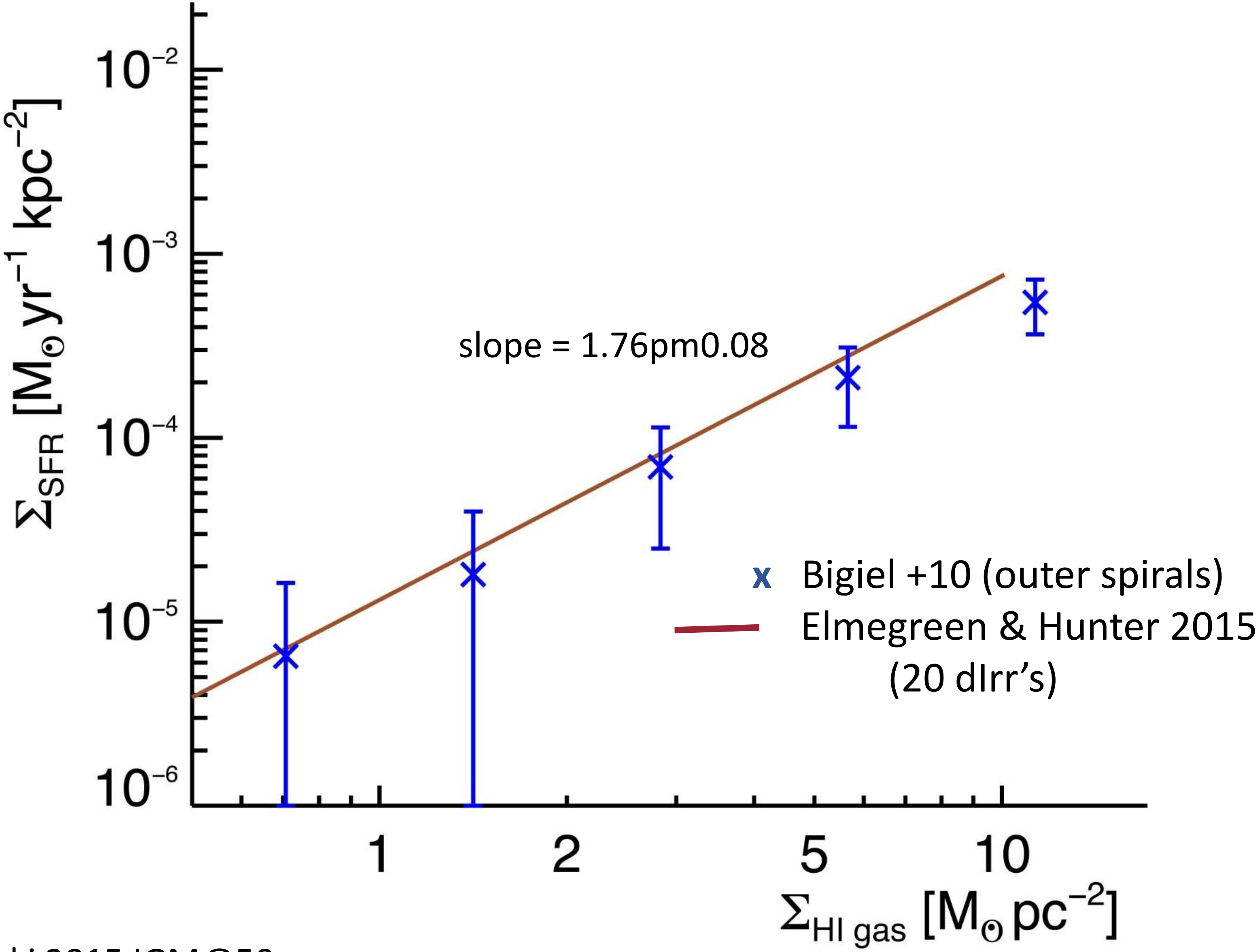
slope = 3

slope = 2

Bigiel +08

KS in dwarfs like outer parts of spirals.

The dIrr KS relation exactly matches the outer disks of spirals



slope = 1.76pm0.08

x Bigiel +10 (outer spirals)

Elmegreen & Hunter 2015
(20 dIrr’s)

Rafelski 2015 IGM@50

What do we expect in HI-dominated gas? For a Gravitational Instability:

$\Sigma_{SFR} = \varepsilon_{ff}\, \Sigma_{HI} / t_{ff}$ for midplane $t_{ff} = (3\pi/[\, 32\, G\, \rho\,])^{1/2}$ and $\varepsilon_{ff} \sim 1\%$

where the midplane $\rho = \Sigma_{HI} / [2H]$ and $H = \sigma^2 / [\, \pi\, G\, \Sigma_{HI}\,]$

giving $\Sigma_{SFR} = \varepsilon_{ff}\ (\, 4/3^{1/2}\,)\ (\, G / \sigma\,)\ \Sigma_{HI}{}^2$

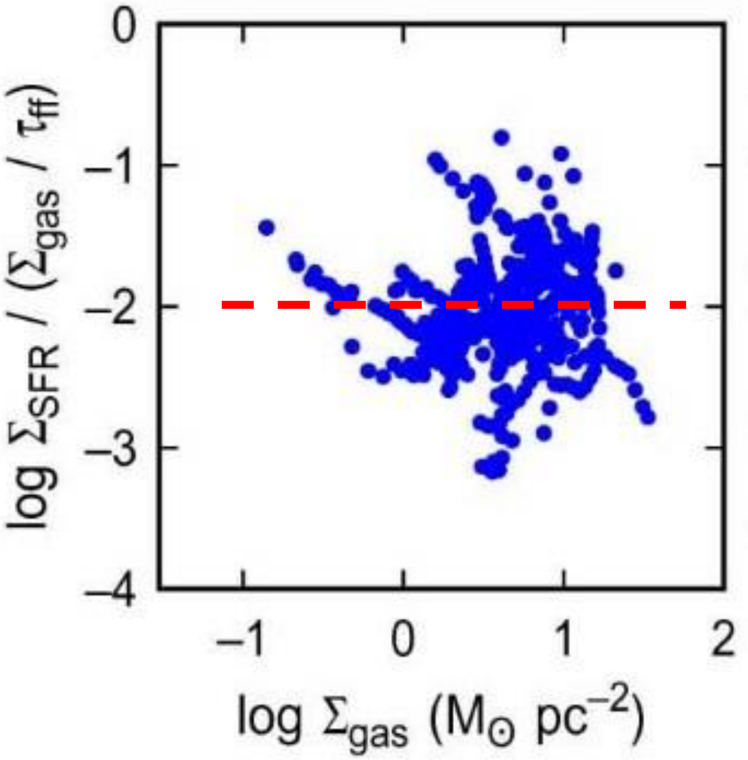
$$= 1.7 \times 10^{-5}\, (\Sigma_{HI}/1\ M_O/pc^2)^2\, (\sigma/6\ km\ s^{-1})^{-1}$$

And the observation is

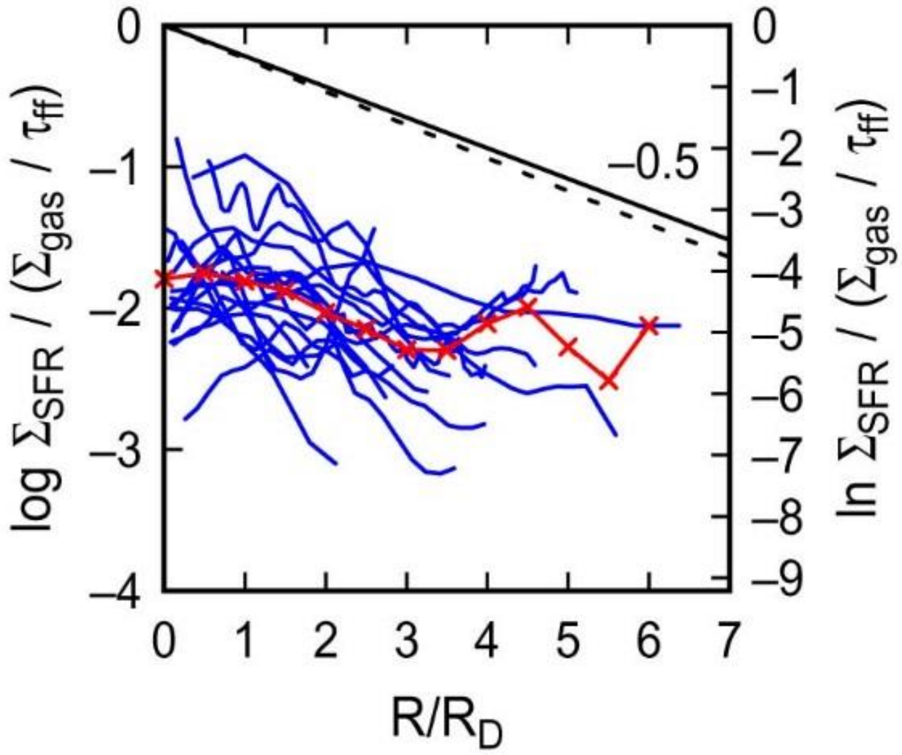
$$\Sigma_{SFR} = 2.1 \times 10^{-5}\, (\Sigma_{HI}/1\ M_O/pc^2)^{1.8}$$

<u>These are the same!</u>

Look at $\varepsilon_{ff} = \Sigma_{SFR} / (\Sigma_{gas}/\tau_{ff})$: It is 1% with a radial dependence



$\Sigma_{SFR}/(\Sigma_{gas}/\tau_{ff}) = \varepsilon_{ff}$ ~1% on average for all regions



In detail, ε_{ff} (R) follows an exponential:

$\varepsilon_{ff}(R) \sim \exp(-0.5R/R_D)$

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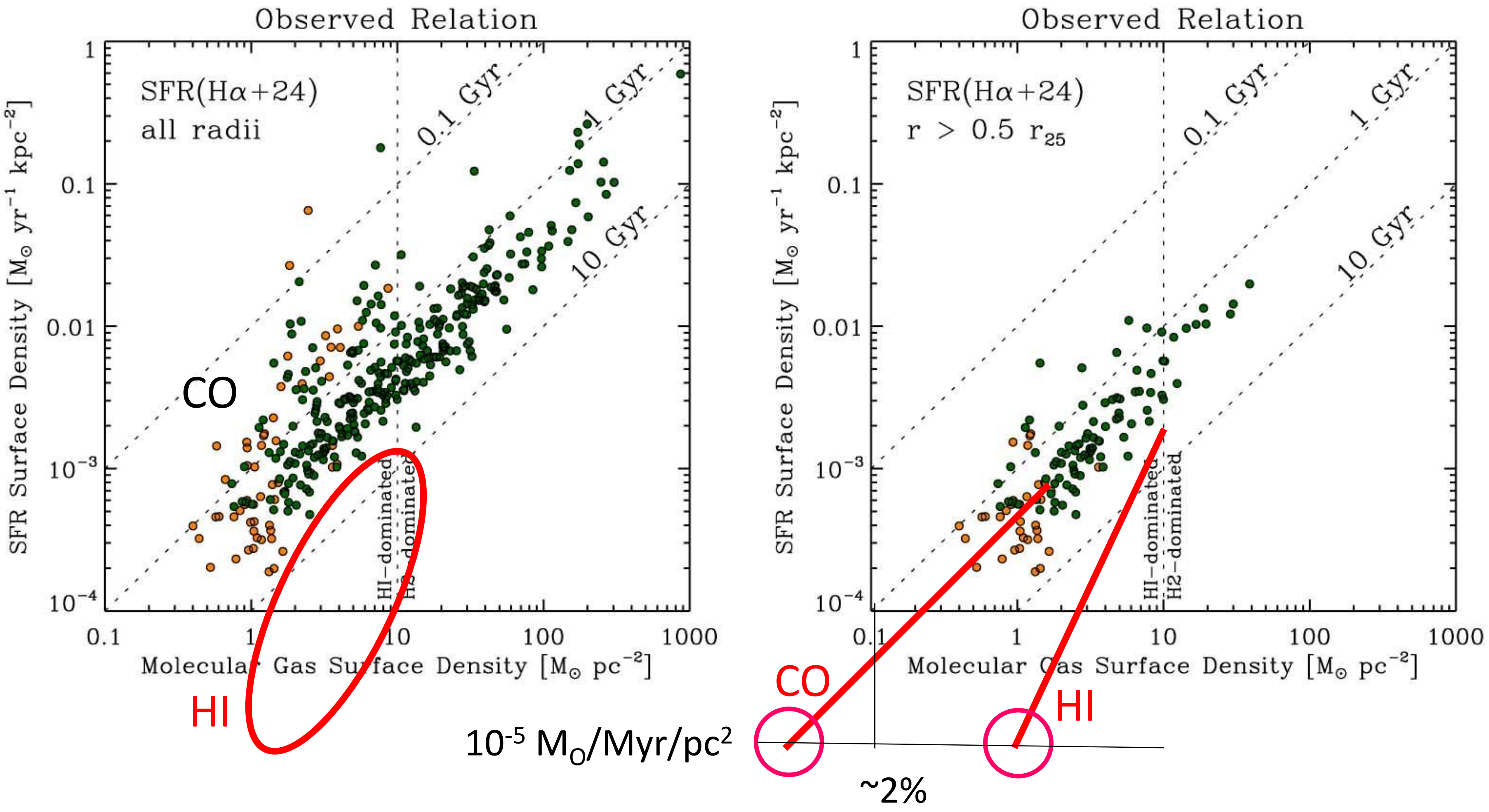
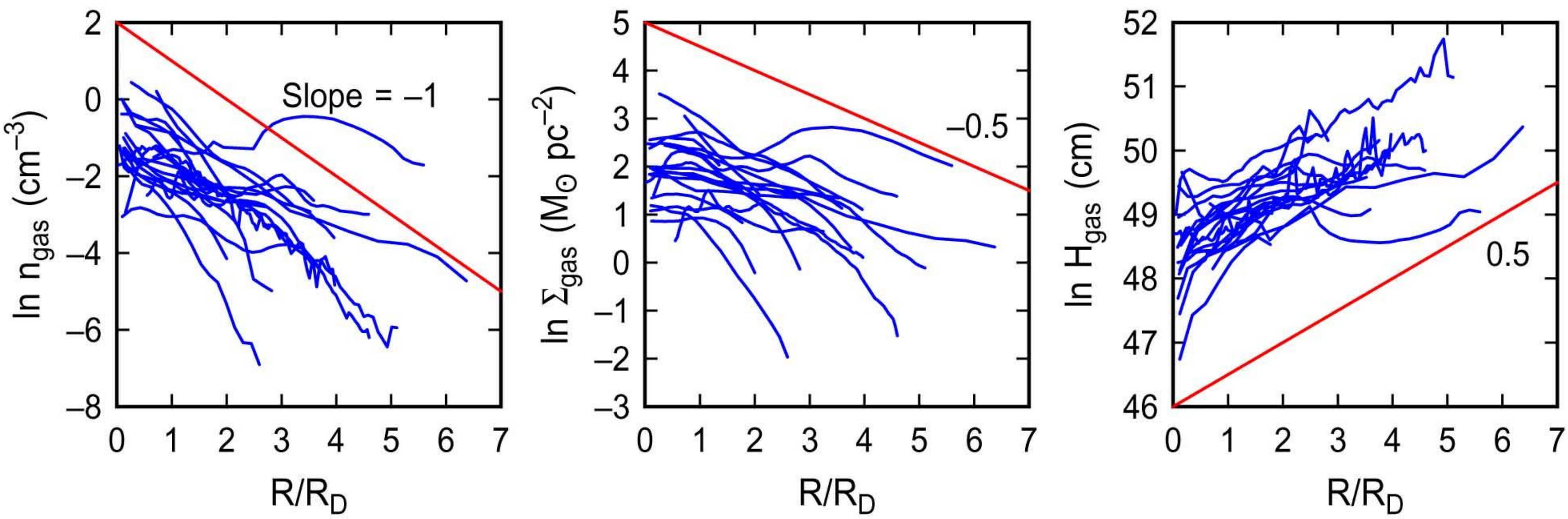


Schruba +11: CO observed in the far-outer regions by stacking.

$$\Sigma_{SFR} \sim \Sigma_{CO}^{1}\ ;\ \ \Sigma_{SFR} \sim \Sigma_{HI}^{2}$$

→ Molecular fraction, $f(H_2) \sim \Sigma_{CO}/\Sigma_{HI} \sim \Sigma_{SFR}^{1/2} \sim \Sigma_{HI}$

(same for LMC – see Bolatto et al. 2011)



n_{gas} ~ exp(-R/R_D) Σ_{gas} ~ exp(-0.5R/R_D) H_{gas} ~ exp(0.5R/R_D)

ε_{ff}(R) and Σ_{gas} both follow exp(-0.5R/R_D) for the 20 dIrr

So ε_{ff} (R) follows Σ_{gas} (R) like CO/HI in Schruba +11, Bolatto +11

→ ε_{ff} may be related to the molecular fraction

Summary for the 20 dIrr:

1. Q not regulated by SF feedback; high Q does not stop SF.

2. $\Sigma_{SFR} \sim \Sigma_{gas}^2$ because gas (HI) dominates mass and the disk flares

3. $\Sigma_{SFR} = \varepsilon_{ff}(R)\Sigma_{gas}/\tau_{ff}$ where ε_{ff} may scale with the H_2/HI fraction

……

1 implies 2D GI (Q, spirals) are irrelevant
3 implies disk gravity is important, but in the midplane, and 3D
3 very low density and low CO/HI imply SF starts in the diffuse phase

and:
4. The average metallicity of these 20 dwarfs is 13%. What is CO like at this metallicity?

CO at low-metallicity

WLM galaxy is 1 Mpc away in the Local Group

Z ~ 13% solar (comp. 20% in SMC)

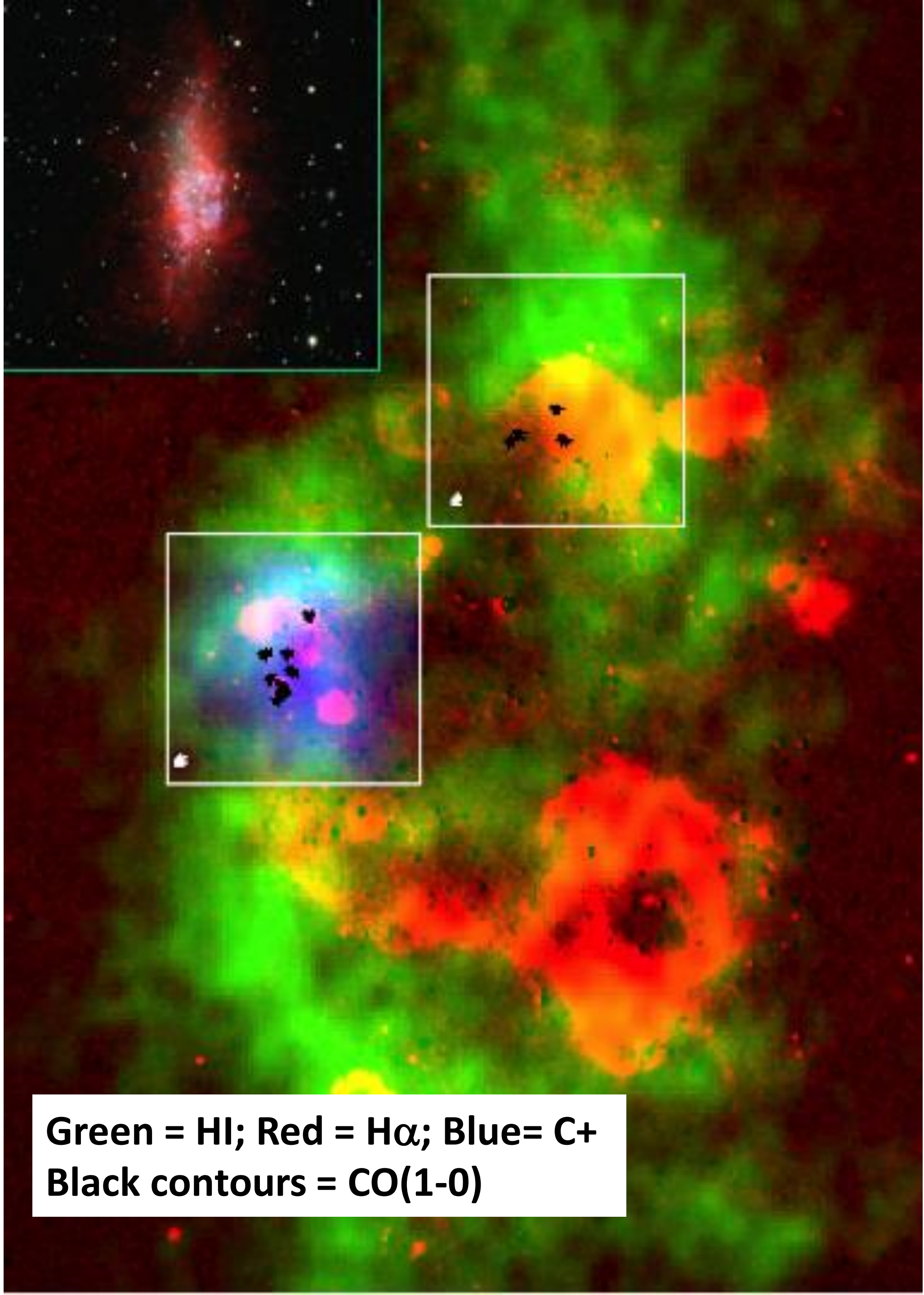
ALMA shows CO clouds (contours)

Green = HI, Red = Hα, Blue = CII

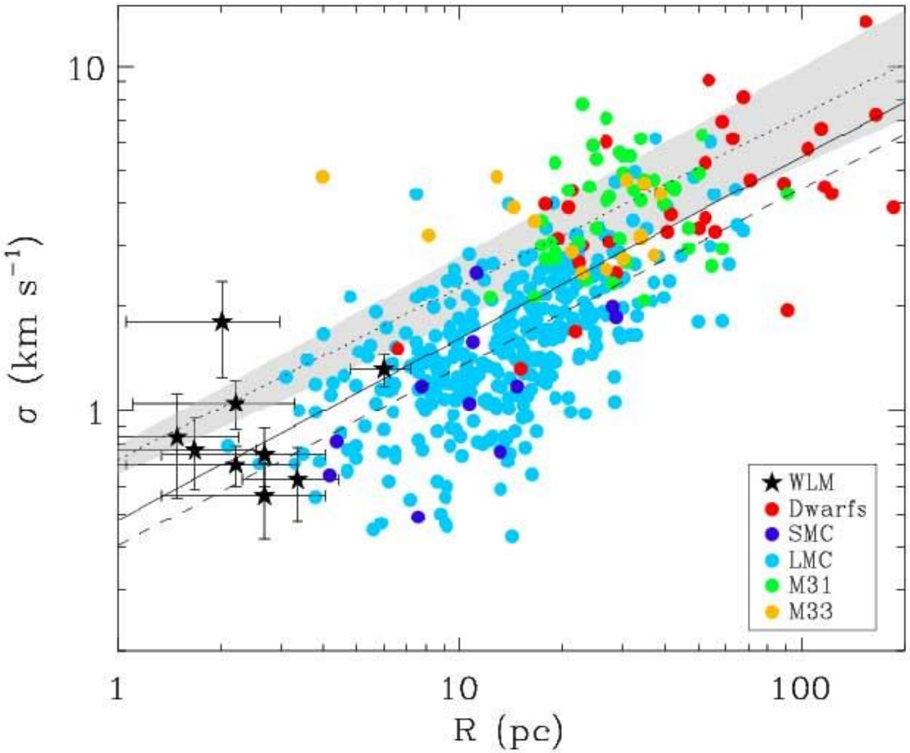
→ CO clouds are tiny cores inside giant H_2 envelopes

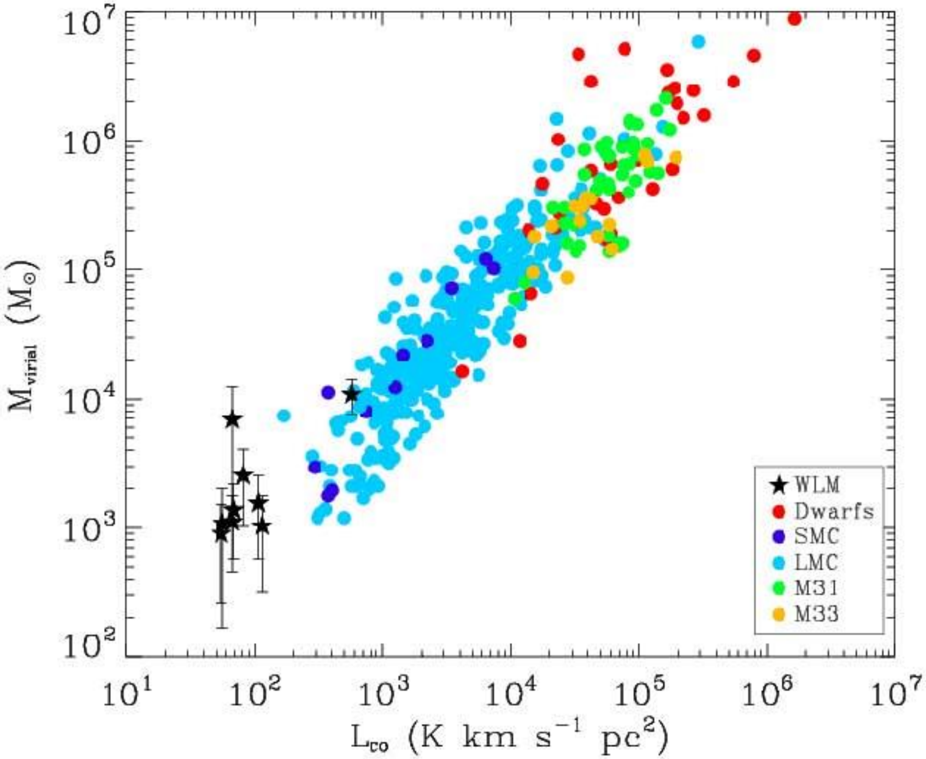
α_{CO} ~ 124+-60 M_O/K km s^{-1} pc^{-2}

Rubio, Elmegreen, Hunter, Brinks, Cortes, Cigan 2015, Nature, in press



Green = HI; Red = Hα; Blue= C+
Black contours = CO(1-0)





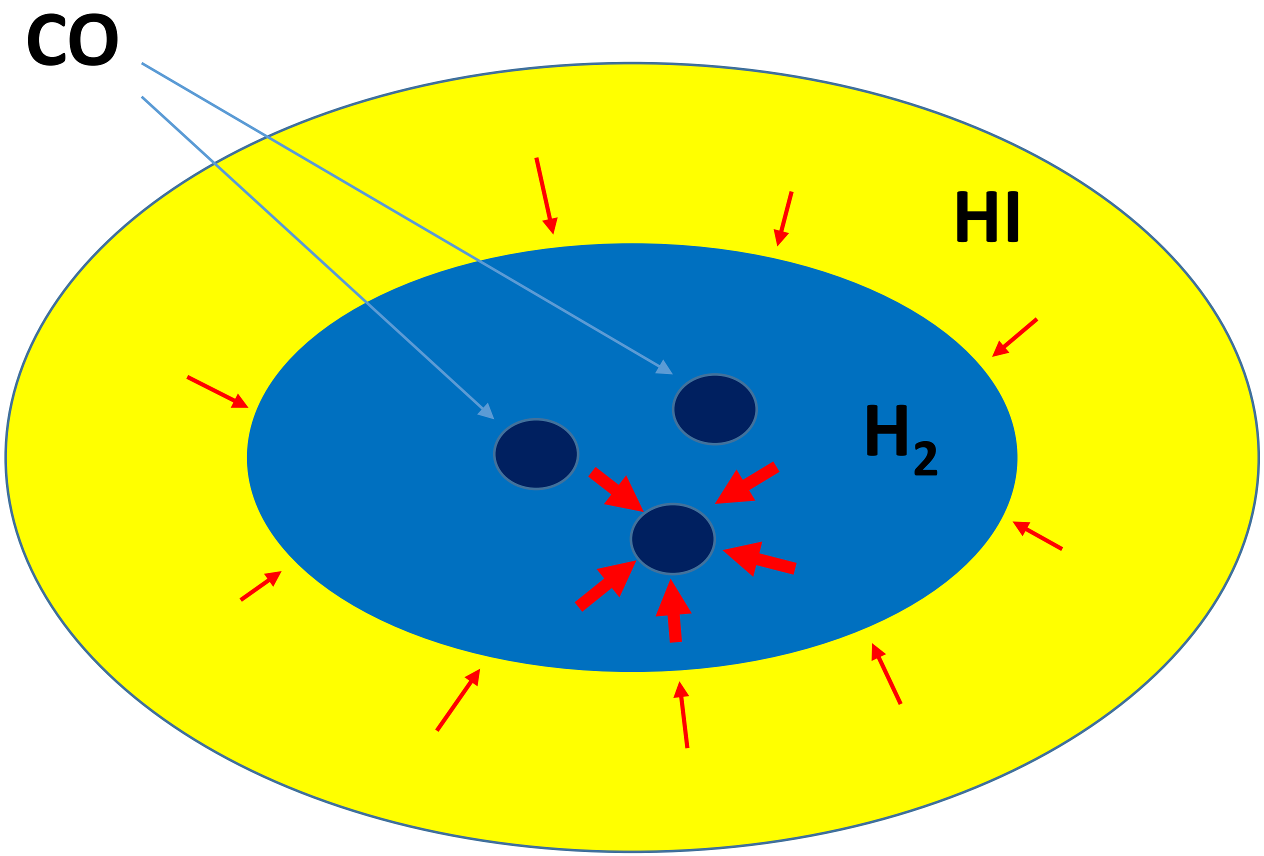
CO clouds in WLM satisfy the usual R-σ and M-L_{CO} relations for dwarfs.

For R ~ 2 pc, M_{virial} ~ $2\text{x}10^3$ M_O, the virial density is 10^3 H_2 / cm^3
With σ=0.9 km/s, the pressure is $\rho\sigma^2 = 2.4\text{x}10^5$ k_B, like MCs in the MW

→ This pressure equals the <u>Weight/Area</u> of the H_2(dust)+HI layer

$$P = (\pi/2)G(\Sigma_{H2}+\Sigma_{HI})^2 = (\pi/2)G(31+27\ M_O/pc^2)^2 = 1.1\text{x}10^5\ k_B$$

The extinction for the H_2+HI part is 0.4 mag; for the CO part is 1.4 mag



HI bears down on the H_2, and both bear down on the CO to give the CO region a high P, ρ, Av

Summary

- SF in HI dominated regime (outer spiral disks and all of dIrr's) is normal-looking
    - exponential disks, clusters and associations, etc.
- BUT compared to inner spiral disks:
    - KS relation is steeper, Q is high, H is high and flaring, metallicity is low, no stellar spirals (beyond all spiral wave CR resonances), $f(H_2) << 0.5$, stars unimportant dynamically ($\Sigma_{stars} << \Sigma_{gas}$)
- SF is possibly related to 3D gravitational instabilities with an efficiency per free fall time related to the molecular fraction (which is very small).
- CO in tiny cores of H_2 and HI clouds

Discussion

Questions from you (via Betsey)…

How do we recognize gas accretion when we see it?

Do high-resolution observations of the atomic and molecular gas provide evidence if the star formation process is ultimately govern by gravitational instability or related to the formation of a molecular gas phase?

Is all star formation restricted to massive GMCs or do we have evidence or how can we test for star formation in low-mass (potentially atomic) clouds?

What is/are the most likely infall channel/s and how to observe it/them?

The problem of the angular momentum transport: How gas is taken to galactic centers?

What is the difference between cold accretion and minor mergers?

Physical processes determining the segregation of HI gas in different galactic environments.

The scale dependence of the relation between gas and star formation

A discussion about the self-regulation of star formation?

Neutral and ionized gas clouds in the Fermi Bubble

The role of cold gas in galaxy clusters, especially the similarities and differences to field galaxies.

Physics of disk-halo transition region in Milky Way and nearby galaxies.
i) The central region of Starburst galaxies (Dominant central objects).
ii) Escape fraction from starburst galaxies & AGN: implication on reionization.
iii) Superbubbles, supershells, galactic winds
iv) High velocity clouds (HVCs)
v) Different gaseous phases (ionized, atomic, molecular) of ouflows: the physics behind them.