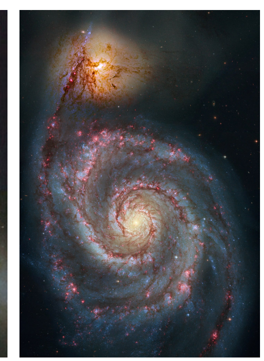
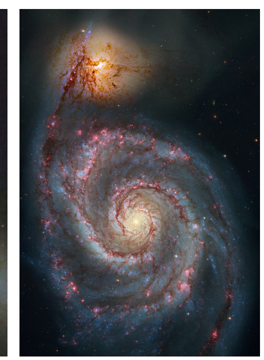
"Star Formation on Galactic Scales"

“Star Formation on Galactic Scales”



An Incomplete Look at Star Formation on Galactic Scales

Terminology / Framework

Scales

HI-SF Balance

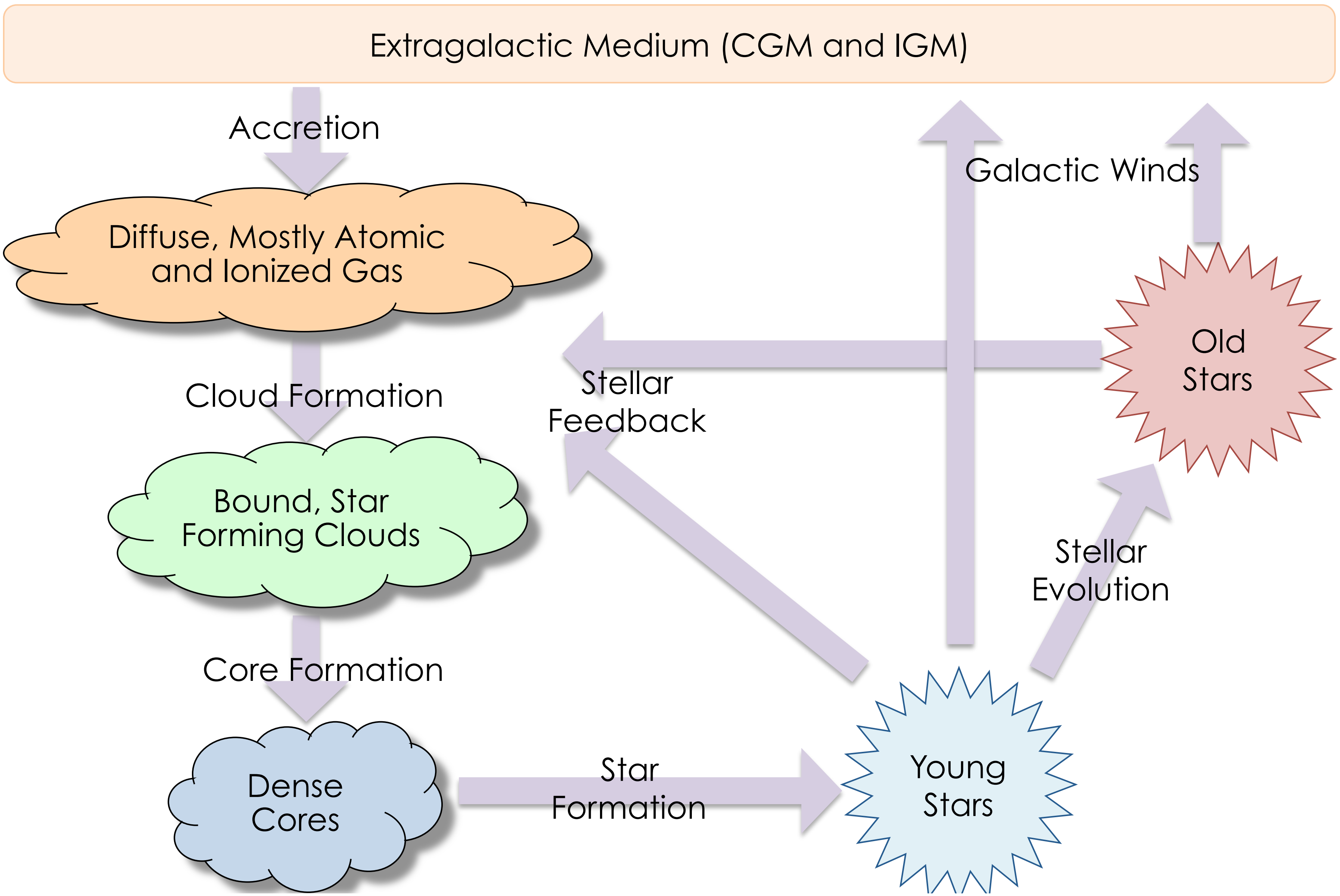
H_2-SF Balance

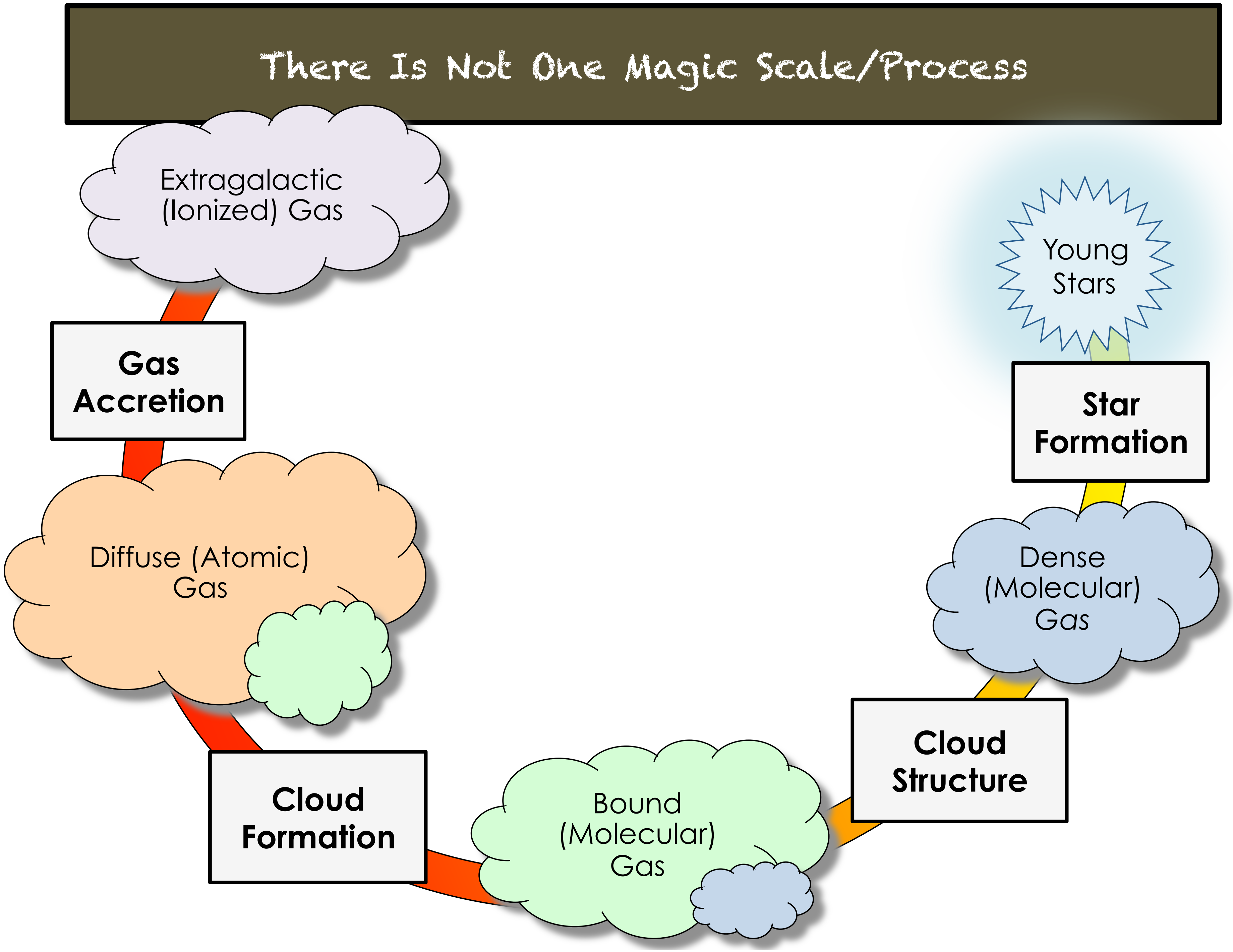
H_2-HI Balance

Cloud Structure / Dense Gas Fraction

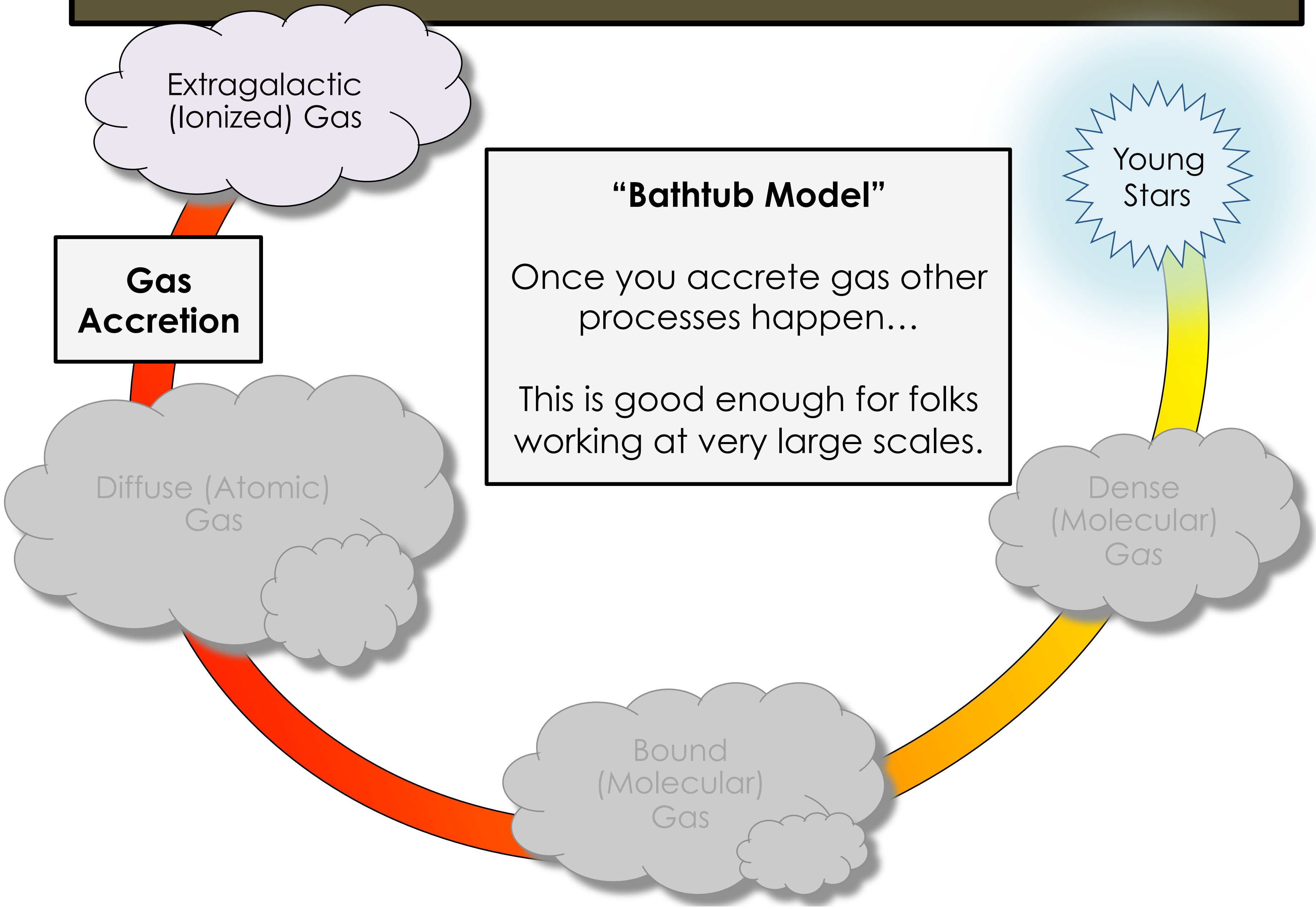
Please Speak Up!

Multi-Process and Multi-Scale

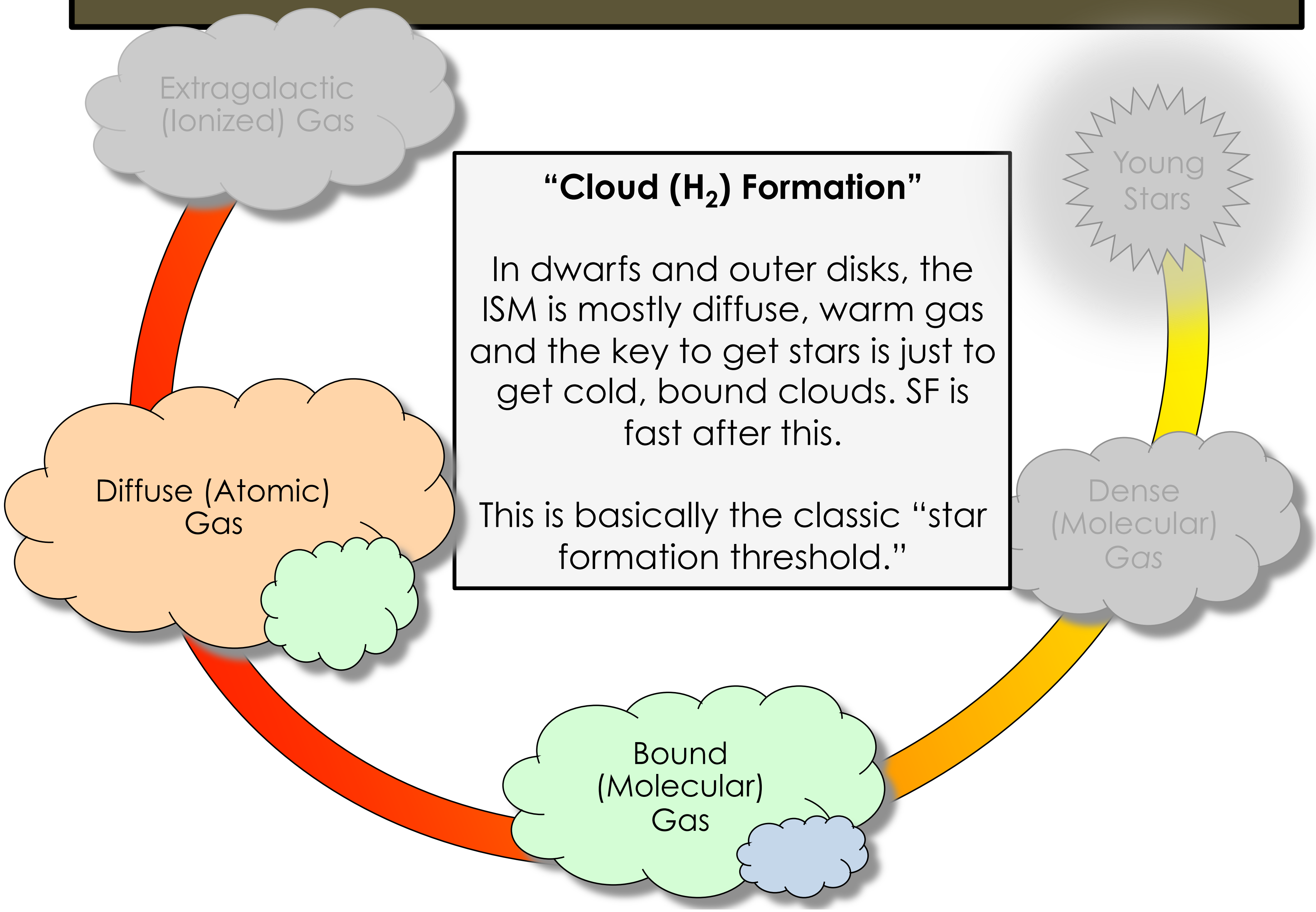



There Is Not One Magic Scale/Process
Extragalactic (Ionized) Gas
Gas Accretion
Diffuse (Atomic) Gas
Cloud Formation
Bound (Molecular) Gas
Cloud Structure
Dense (Molecular) Gas
Star Formation
Young Stars

If you zoom out enough



A Molecular Bathtub

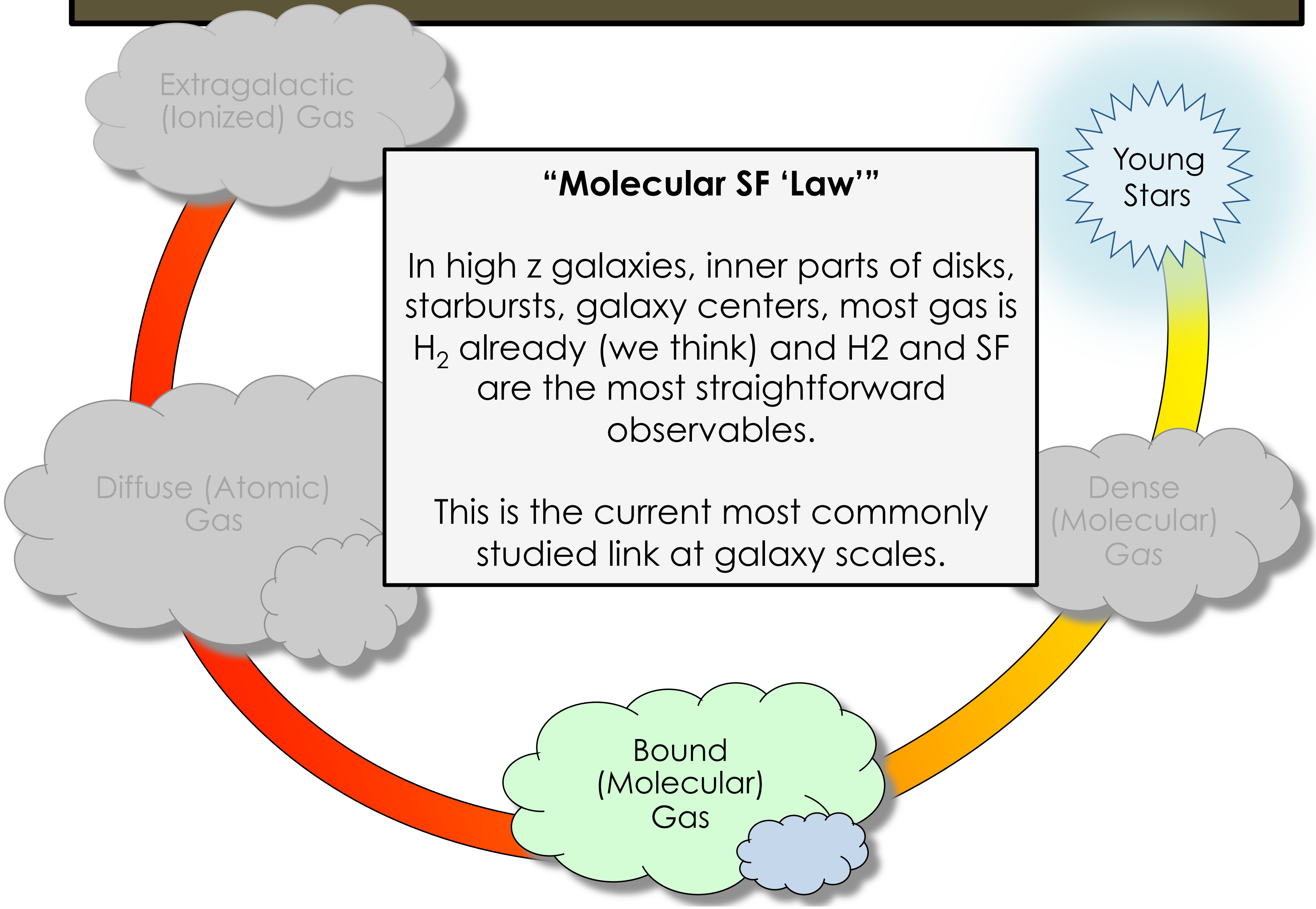


"Cloud (H_2) Formation"

In dwarfs and outer disks, the ISM is mostly diffuse, warm gas and the key to get stars is just to get cold, bound clouds. SF is fast after this.

This is basically the classic "star formation threshold."

From Cold (Bound?) Gas to Stars



“Molecular SF ‘Law’”

In high z galaxies, inner parts of disks, starbursts, galaxy centers, most gas is H_2 already (we think) and H2 and SF are the most straightforward observables.

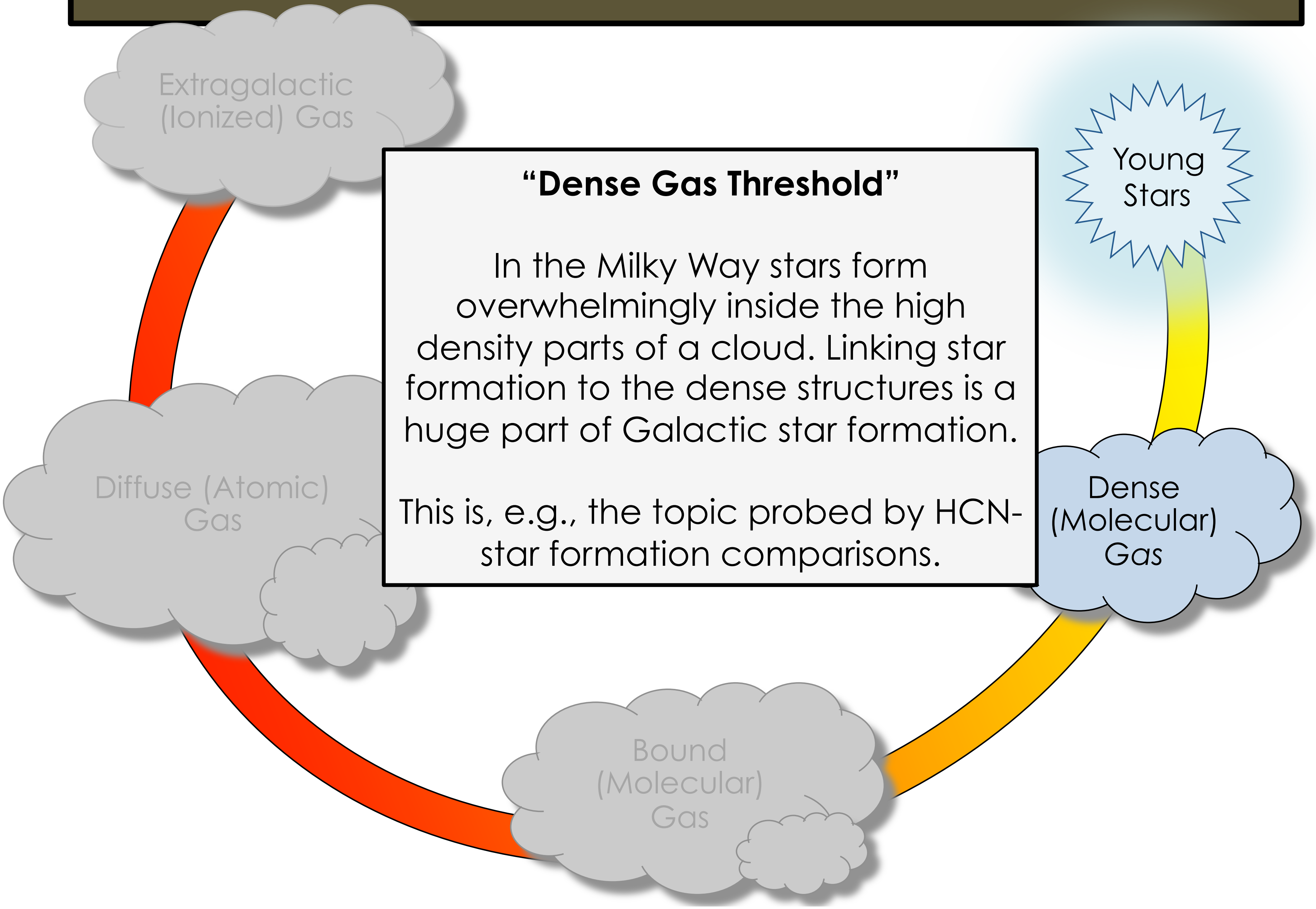
This is the current most commonly studied link at galaxy scales.

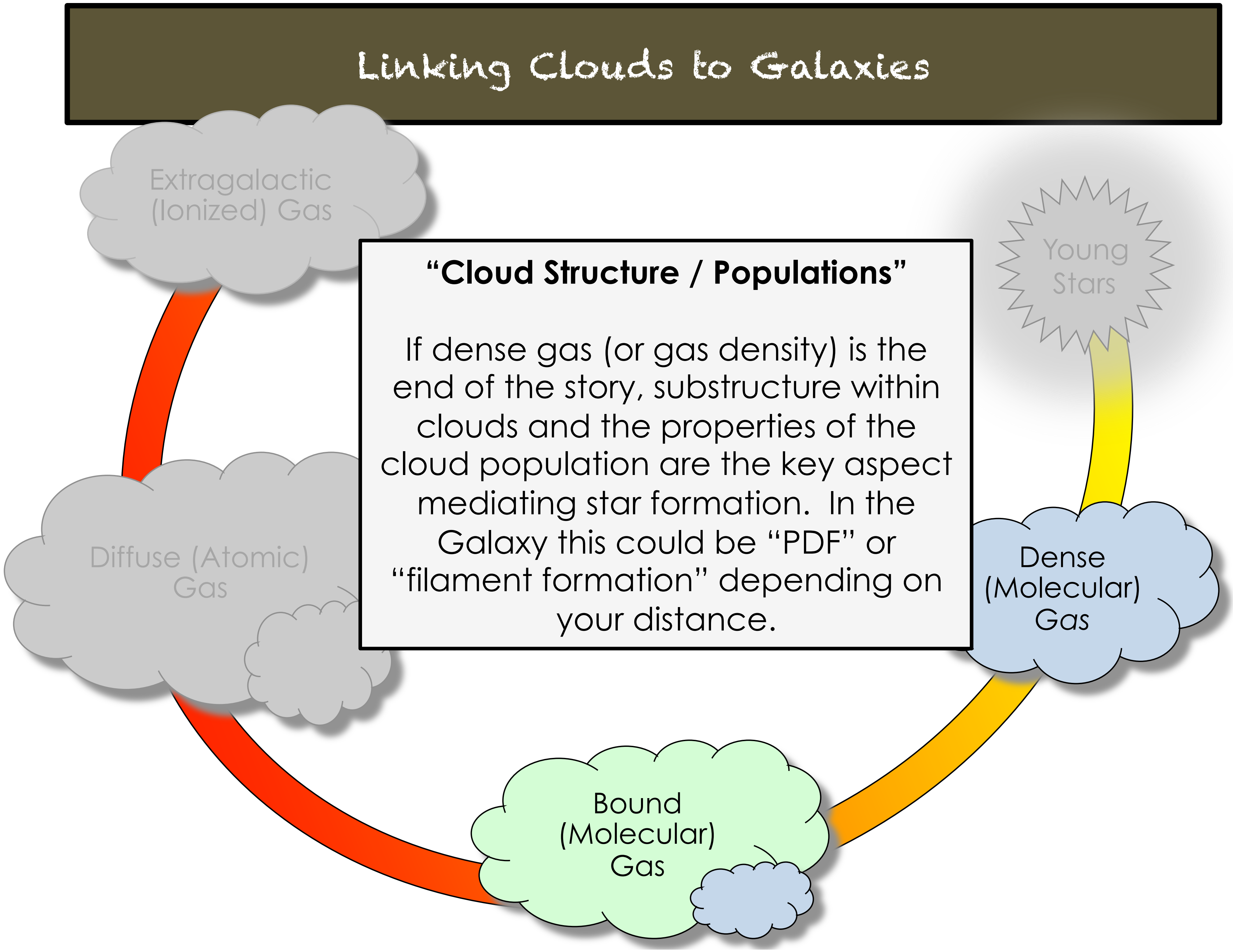
But Only Dense Gas Forms Stars

“Dense Gas Threshold”

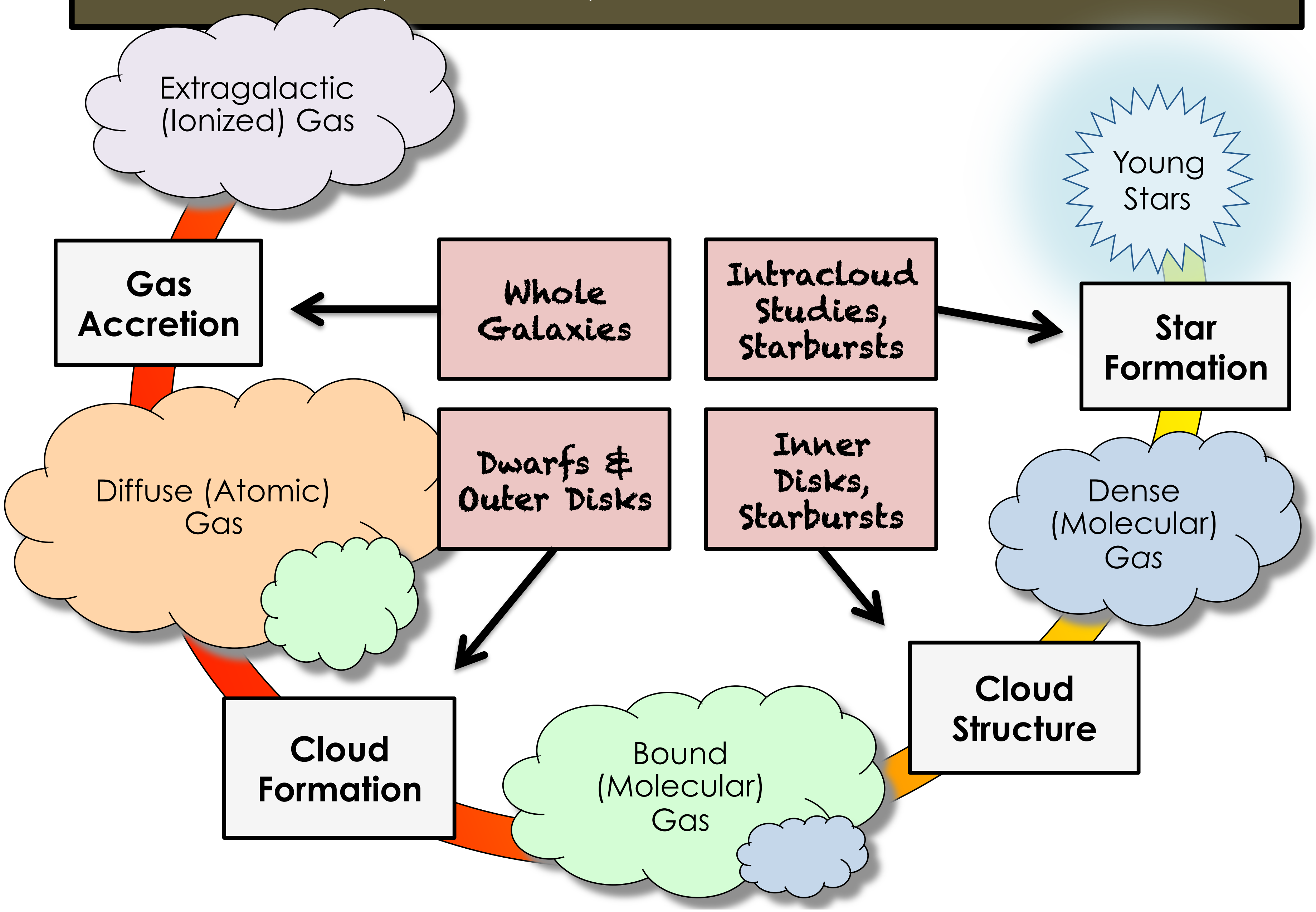
In the Milky Way stars form overwhelmingly inside the high density parts of a cloud. Linking star formation to the dense structures is a huge part of Galactic star formation.

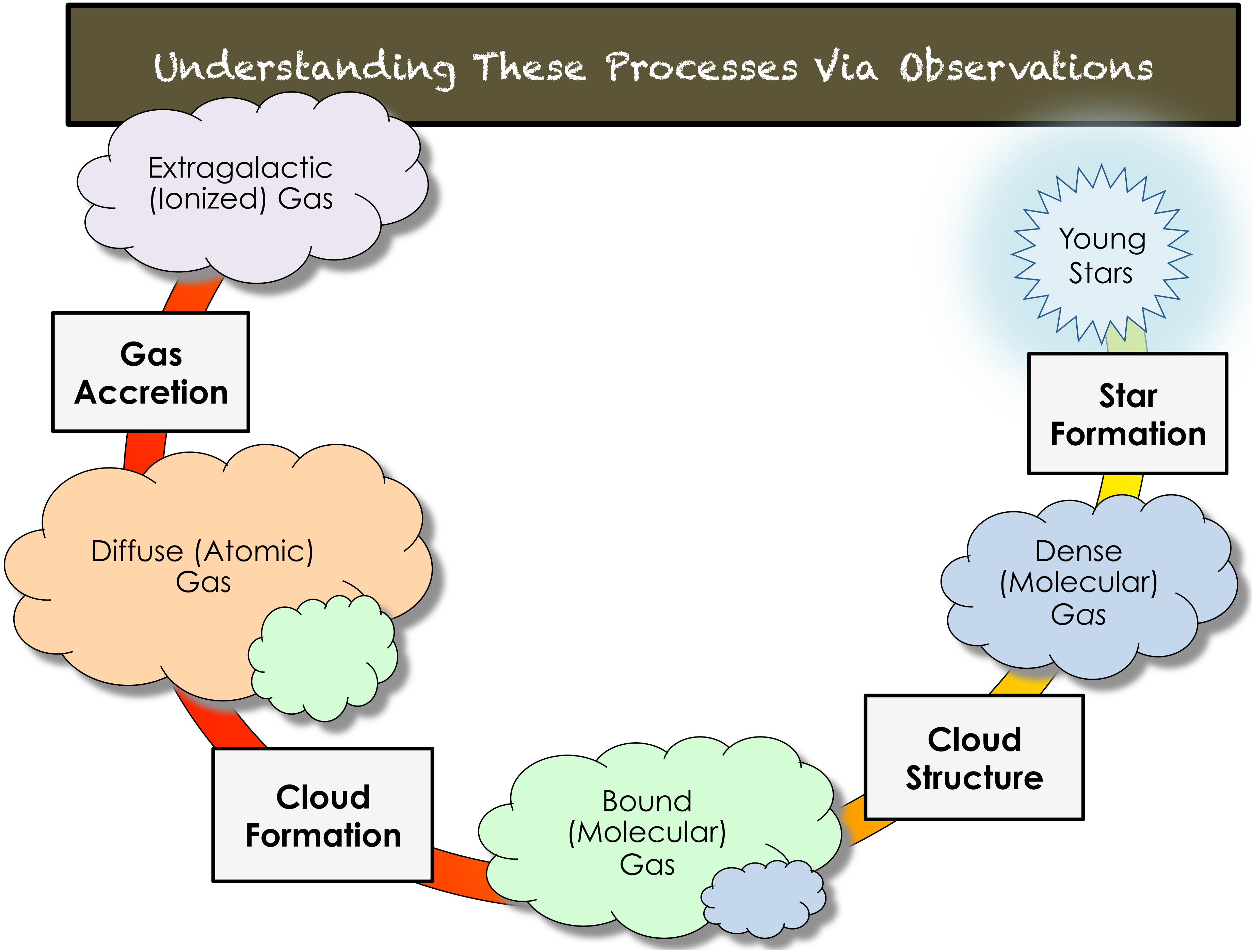
This is, e.g., the topic probed by HCN-star formation comparisons.




Linking Clouds to Galaxies
Extragalactic (Ionized) Gas
Young Stars
"Cloud Structure / Populations"
If dense gas (or gas density) is the end of the story, substructure within clouds and the properties of the cloud population are the key aspect mediating star formation. In the Galaxy this could be "PDF" or "filament formation" depending on your distance.
Diffuse (Atomic) Gas
Dense (Molecular) Gas
Bound (Molecular) Gas

A Vastly Oversimplified Sketch of Regimes




Understanding These Processes Via Observations
Extragalactic (Ionized) Gas
Gas Accretion
Diffuse (Atomic) Gas
Cloud Formation
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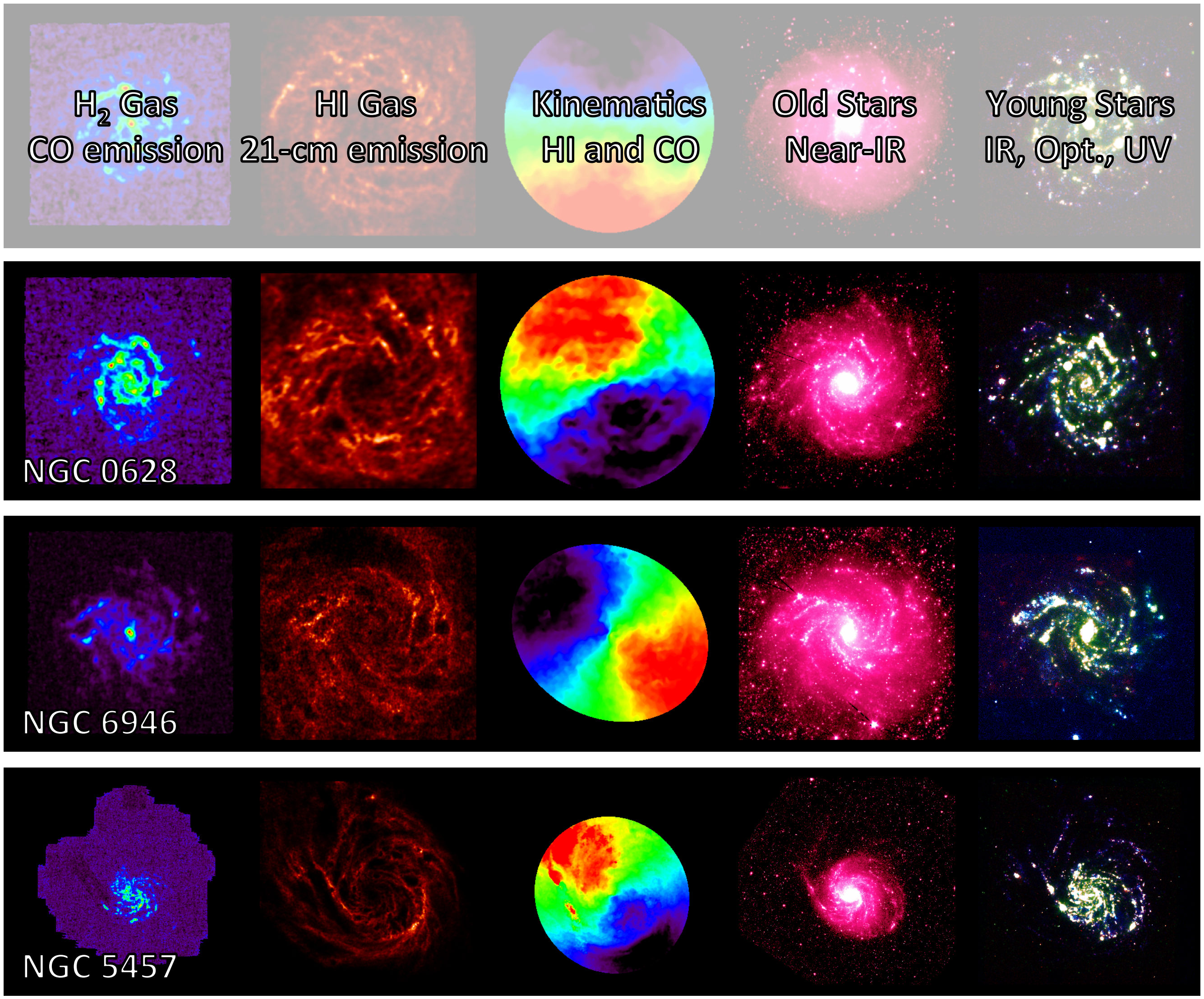
Cloud Structure
Dense (Molecular) Gas
Star Formation
Young Stars

Understanding These Processes Via Observations



H_2 (CO)

HI (21-cm)

SFR (IR, Hα, UV)

Dust (IR)

Metallicity (spec)

UV field (IR)

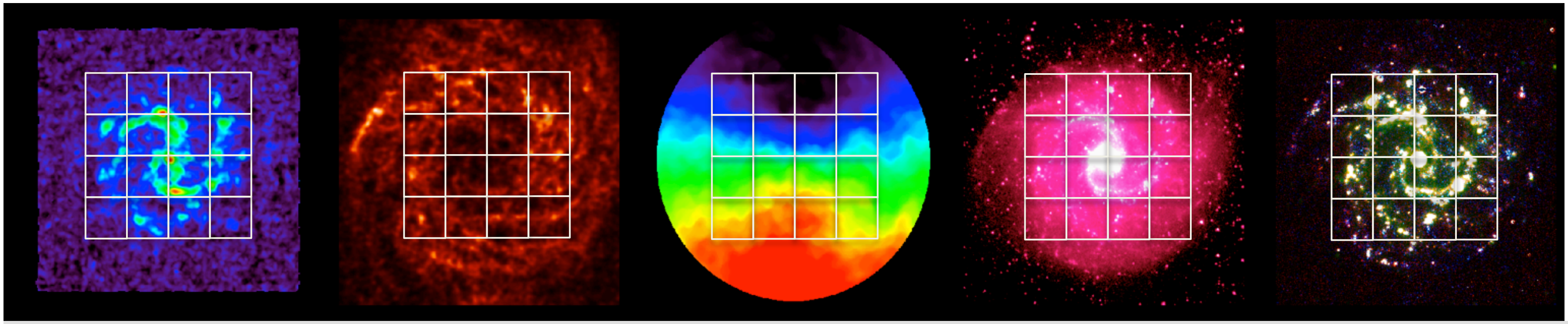
Stars (optical/NIR)

Rotation (HI/CO)

Dynamics (HI/CO)

Cloud Properties

Understanding These Processes Via Observations



$$\tau_{\text{Dep}}^{\text{H2}} = \frac{M_{H2}}{M_{SFR}}$$

"gas depletion time."
Timescale x efficiency. Specific SFR per M_{H2}.

*Observable, **normalized**, natural theoretical prediction, **scale independent***.*

These types of quantities should reflect equilibrium in long lived systems.

*That is, they encode **formation** & destruction (and so depend on **feedback**).*

$$\frac{\text{SFR}}{M_{gas}} \quad \frac{\text{SFR}}{M_{\text{HI}}} \quad \frac{\text{SFR}}{M_{\text{H2}}} \quad \frac{\text{SFR}}{M_{\text{Dense}}} \quad \frac{M_{\text{H2}}}{M_{\text{HI}}} \quad \frac{M_{dense}}{M_{\text{H2}}}$$

Natural Way to Talk About These Processes

$$\tau^{\mathrm{H2}}_{\mathrm{Dep}} = \frac{\Sigma_{\mathrm{H2}}}{\Sigma_{\mathrm{SFR}}}$$

"gas depletion time."
Timescale x efficiency. Specific SFR per M_{H2}.

*Observable, **normalized**, natural theoretical prediction, **scale independent***.*

These types of quantities should reflect equilibrium in long lived systems.

*That is, they encode **formation** & destruction (and so depend on **feedback**).*

$$R_{mol} = \frac{\Sigma_{\mathrm{H2}}}{\Sigma_{\mathrm{HI}}}$$

"Molecular-to-atomic ratio. "
How molecular is the cold ISM?

$$f_{dense} = \frac{\Sigma_{\mathrm{H2}}\ (n > 10^5\,\mathrm{cm}^{-3})}{\Sigma_{\mathrm{H2}}} \propto \frac{I_{HCN}}{I_{CO}}$$

"Dense gas fraction."
How much of an average cloud's mass is dense?

* Once you zoom out enough. This is an important caveat!

Some examples of ideas expressed this way:

SFR/M_{gas} depends on disk-averaged Σ_{gas}
Kennicutt '98 and many following

Physics: largely observational, but free fall in a fixed-h disk works

SFR/M_{gas} depends on disk-averaged orbital time Ω
Silk '97, Tan '00, Daddi+'10, Genzel+ '10, Garcia-Burillo+ '12

Physics: disk self-regulation

SFR/M_{H2} depends on M_{dense}/M_{H2}
Gao & Solomon '04ab, Heiderman+ '10, Lada+ '10, 12, Evans+ '14

Physics: universal processes (efficiency in self-gravitating dense gas), i.e., a "dense gas threshold"

Some examples of ideas expressed this way:

M_{H2}/M_{HI} depends surface density of individual clouds and D/G ratio
Krumholz+ 09, 10, McKee+ '10, Sternberg+ '14

Physics: PDR-type modeling of HI-to-H_2 transition in clouds.

M_{H2}/M_{HI} depends on disk surface density (stars) and scale height
Elmegreen+ '89, '94, Wong, Blitz, Rosolowsky '04, '06, Ostriker+ '10,11

Physics: vertical hydrostatic equilibrium self-regulation

SFR/M_{gas} (or M_{H2}/M_{HI}) depends on radial stability (Q in one form or another)
Kennicutt '89, Boissier+ '03, Schaye '04, Li+ '05, '06, Krumholz+ '12

Physics: radial disk stability self-regulation

Some examples of ideas expressed this way:

SFR/M_{gas} depends on the free-fall time (density) across many scales
Elmegreen 00, Krumholz & Tan ‘07, Krumholz+ ’12

Physics: Regulated gravitational instability still uses collapse time

SFR/M_{H2} depends positively on shear / cloud collision rate
Tan ‘00, ‘10, Tasker ‘09, Fukui+ ’14; Koda+ ‘09, Wada similar (w/ arms)

Physics: compression of clouds from collision needed for high mass SF

SFR/M_{H2} anti-correlates with Bernoulli-style pressure
Meidt+ ’13, but bar-suppression similar

Physics: radial disk stability self-regulation

Framework & Approach

1. Building stars on a galactic scales occurs over multiple scales and processes. The limiting process varies by regime.

2. Intensive quantities that capture a balance of formative processes and feedback offer a useful, scale independent way to study these processes in multiwavelength data sets.

3. Many current theories can be readily expresses this way.

4. The same approach applies to, e.g., cloud properties, HI phases, internal conditions in the gas, dynamical features like arms & bars, etc.

An Incomplete Look at Star Formation on Galactic Scales

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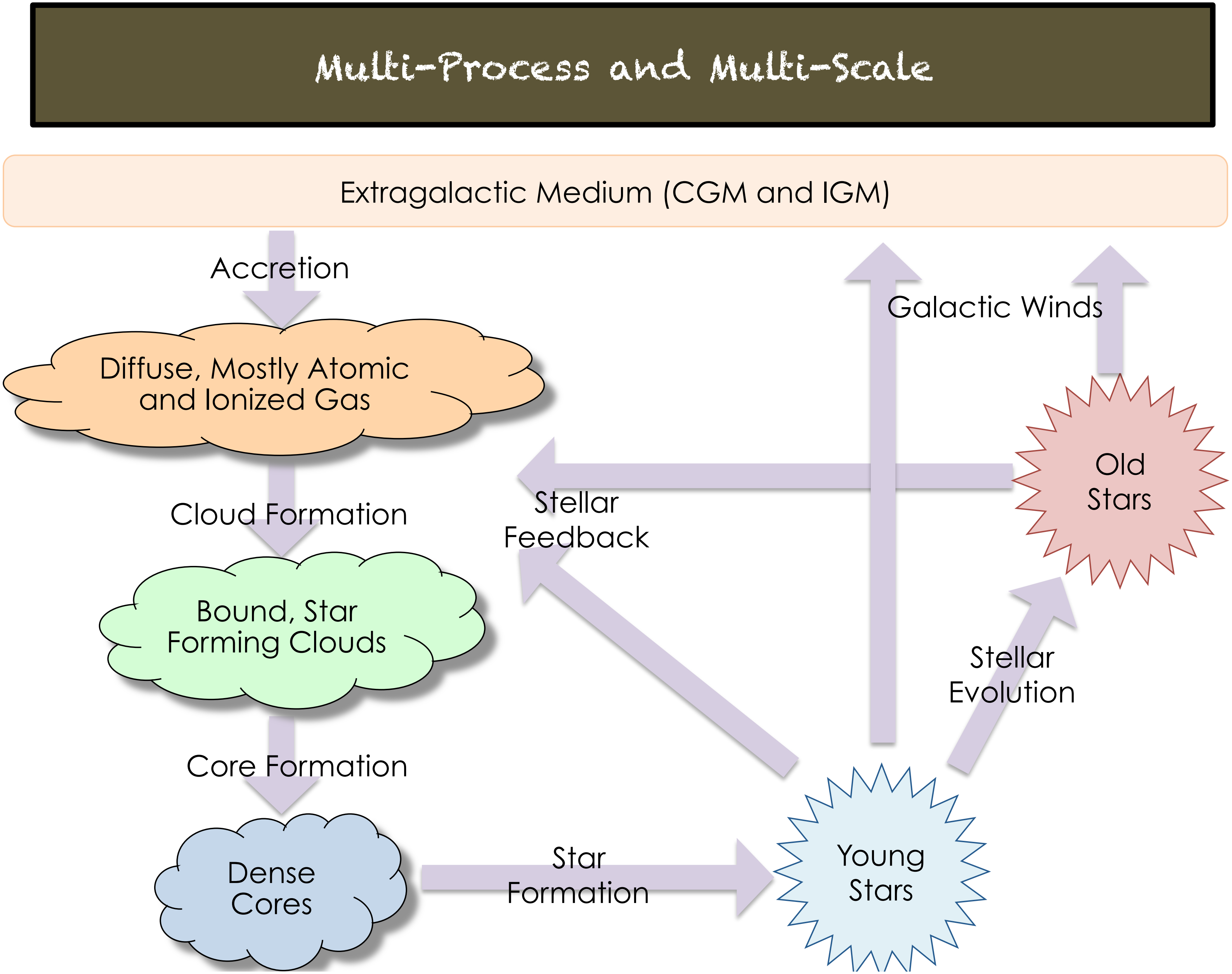
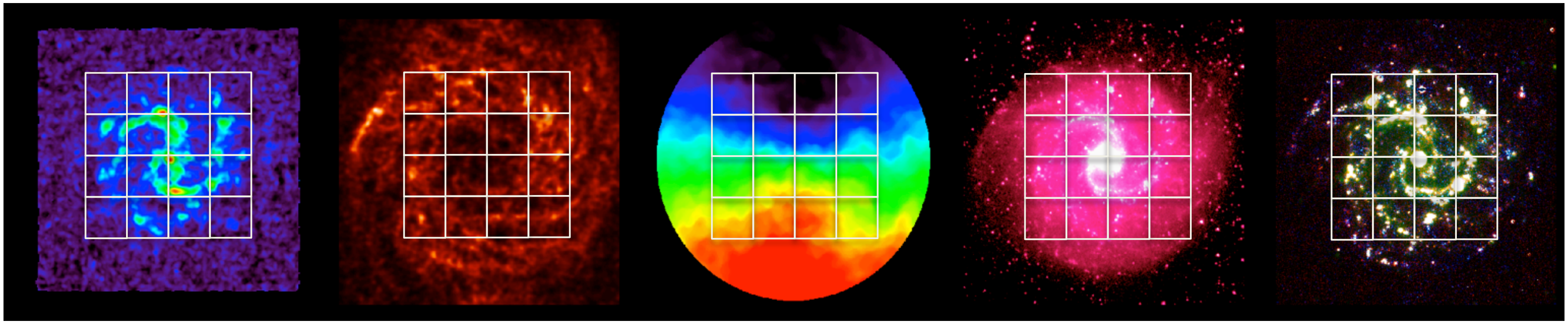
H_2-HI Balance

Cloud Structure / Dense Gas Fraction

Please Speak Up!


Multi-Process and Multi-Scale
Extragalactic Medium (CGM and IGM)
Accretion
Galactic Winds
Diffuse, Mostly Atomic and Ionized Gas
Cloud Formation
Stellar Feedback
Old Stars
Bound, Star Forming Clouds
Stellar Evolution
Core Formation
Dense Cores
Star Formation
Young Stars

Time Averaged Processes and Individual Regions



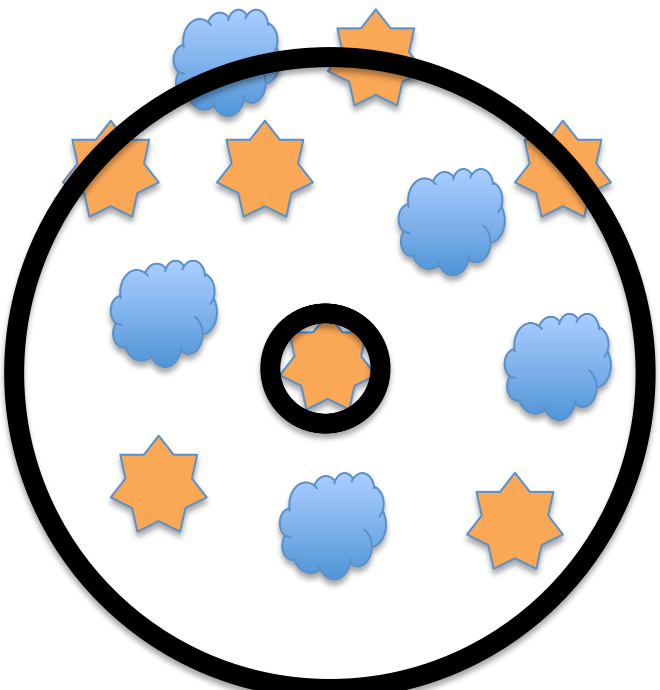
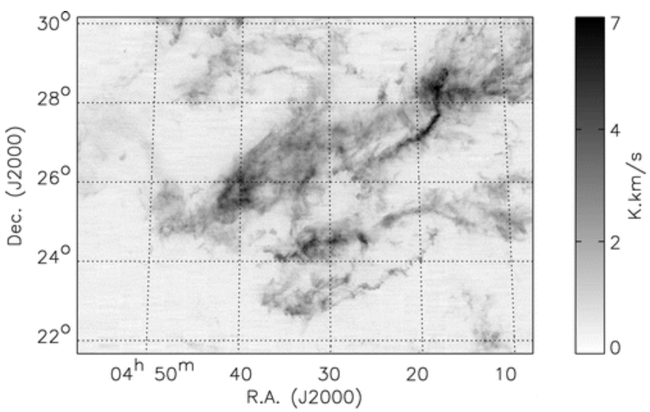
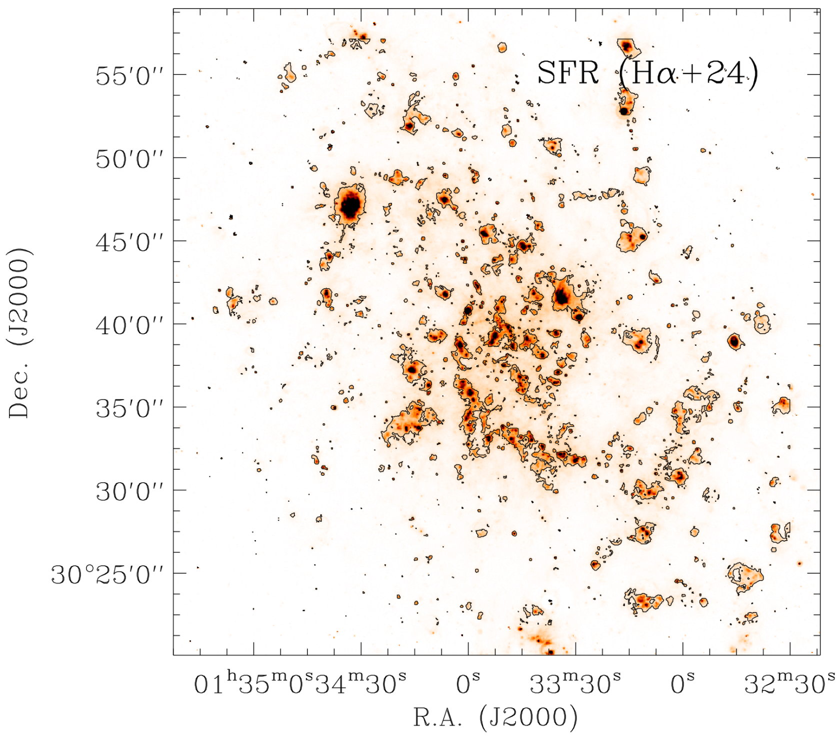


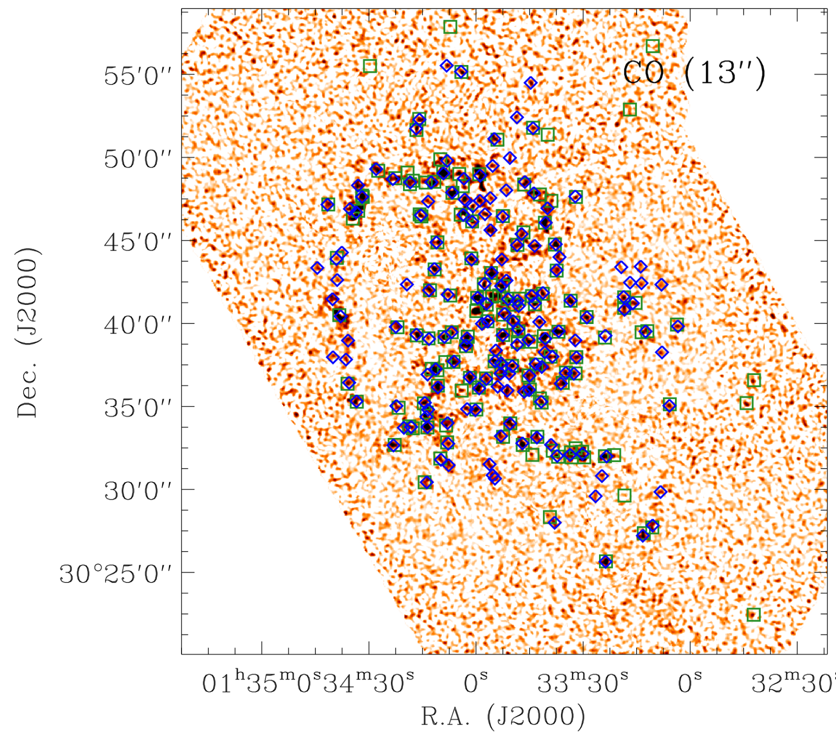
Photo credit: R. Gendler



Goldsmith+ '08

The Complications of High Resolution

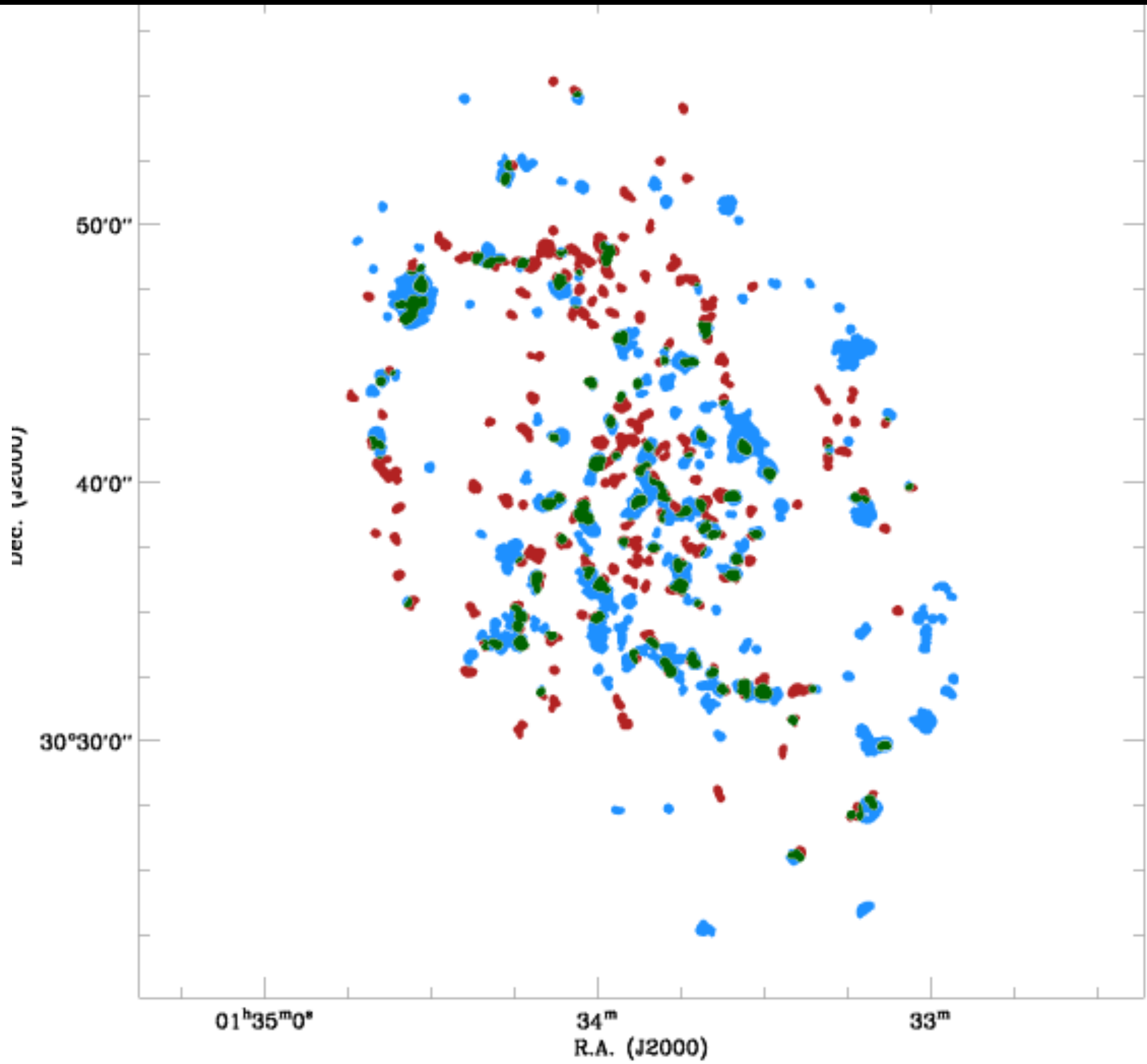




SCHRUBA+ '10

ROSOLOWSKY+ '07, HODGE+ '02

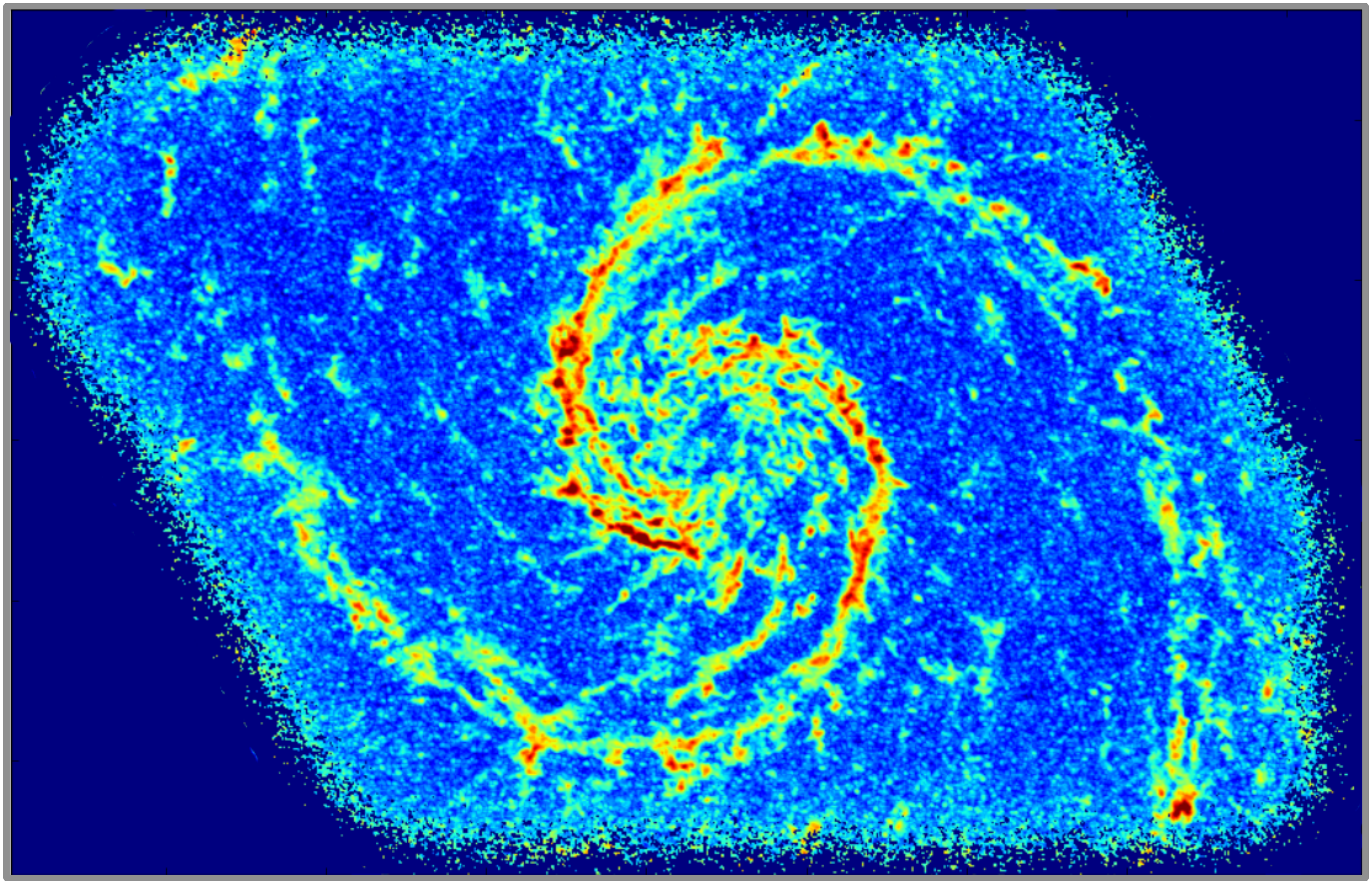
At High Enough Resolution, Evolution is Visible



SCHRUBA+ '10

ROSOLOWSKY+ '07, HODGE+ '02

The Complications of High Resolution



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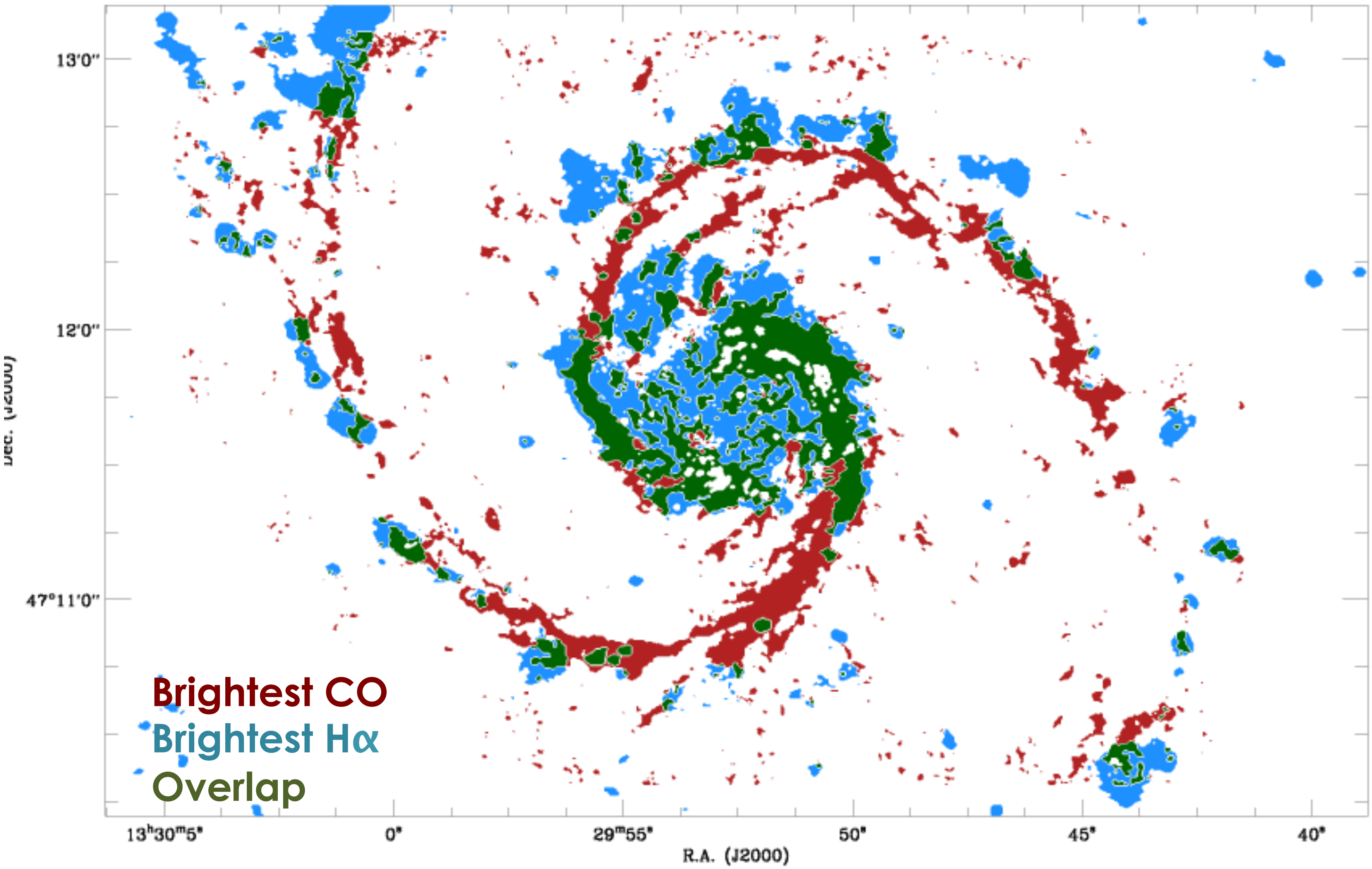
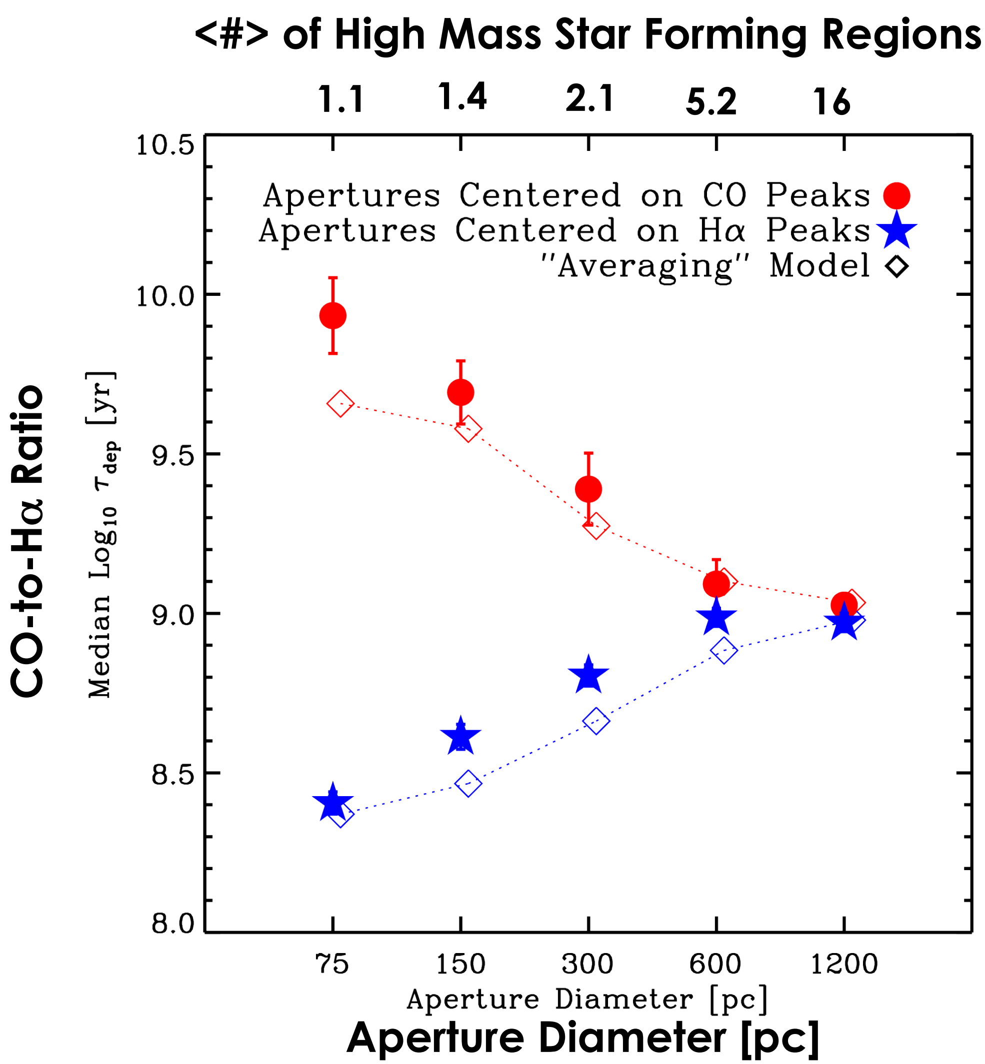


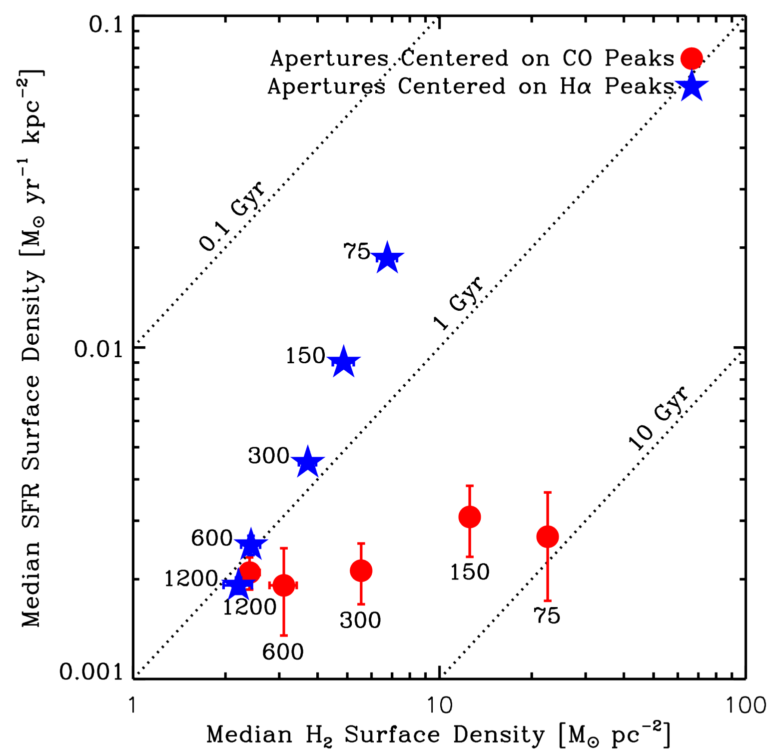
SCHINNERER ET AL. (2013), PETY ET AL. (2013) – ASK **S. MEIDT**, HUGHES, LEROY ET PAWS IN PREP.

Effect of Resolution & Targeting on CO-to-Hα



SCHRUBA+ '10

Evolution as "Scatter" in SFR-to-Gas Ratios



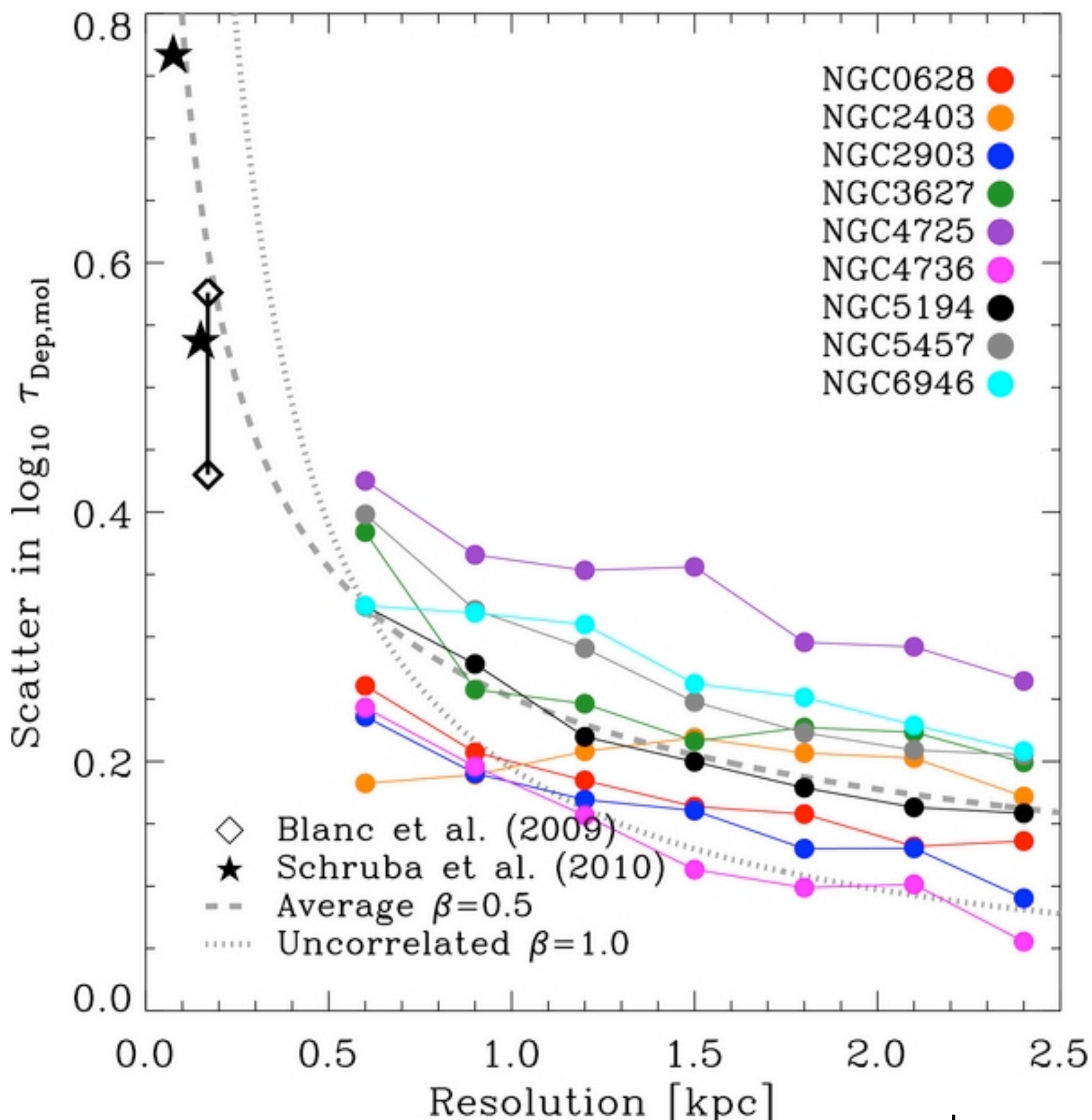
SFR Surface Density

H_2 Surface Density

SCHRUBA+ '10; MILKY WAY: MURRAY '10; LMC: KAWAMURA+ '09

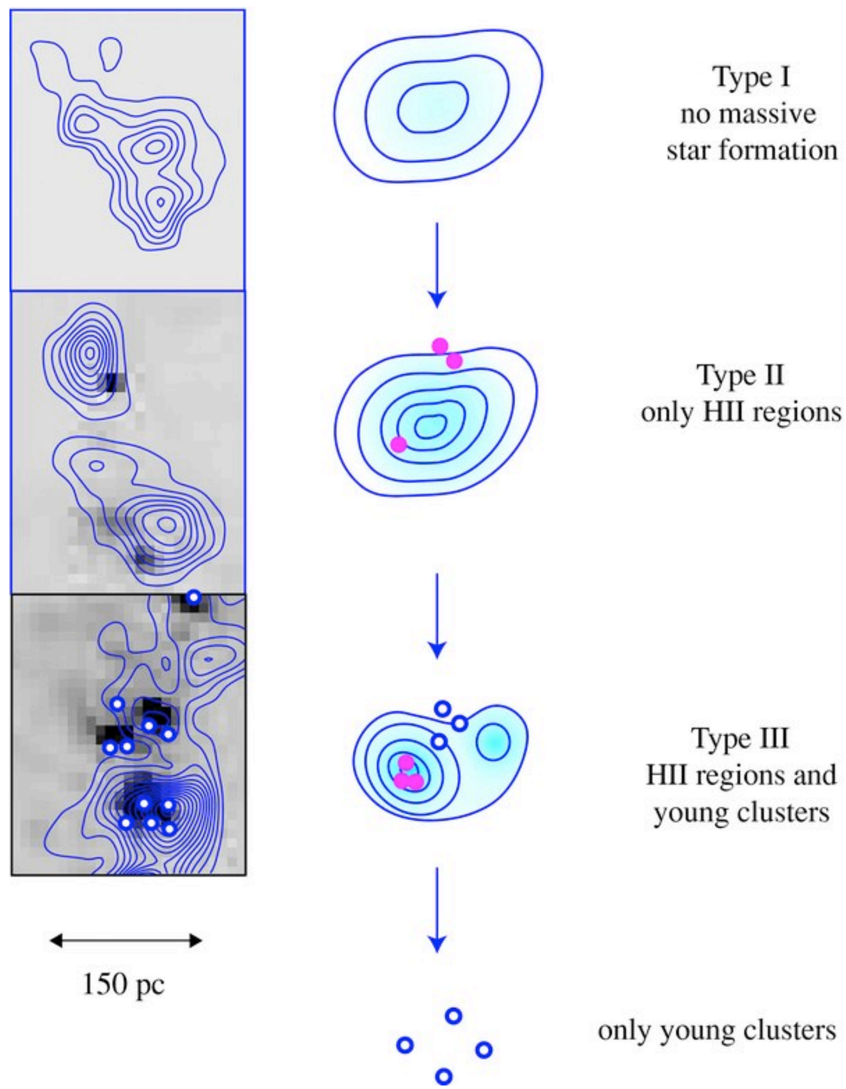
THEORY: FELDMAN+ '10, FELDMAN+ '12, HOPKINS+ '12, KRUIJSSEN '14, KRUIJSSEN IN PREP.

Scale-Dependence of Scatter in H_2/SFR



LEROY+ '13, BLANC+ '09

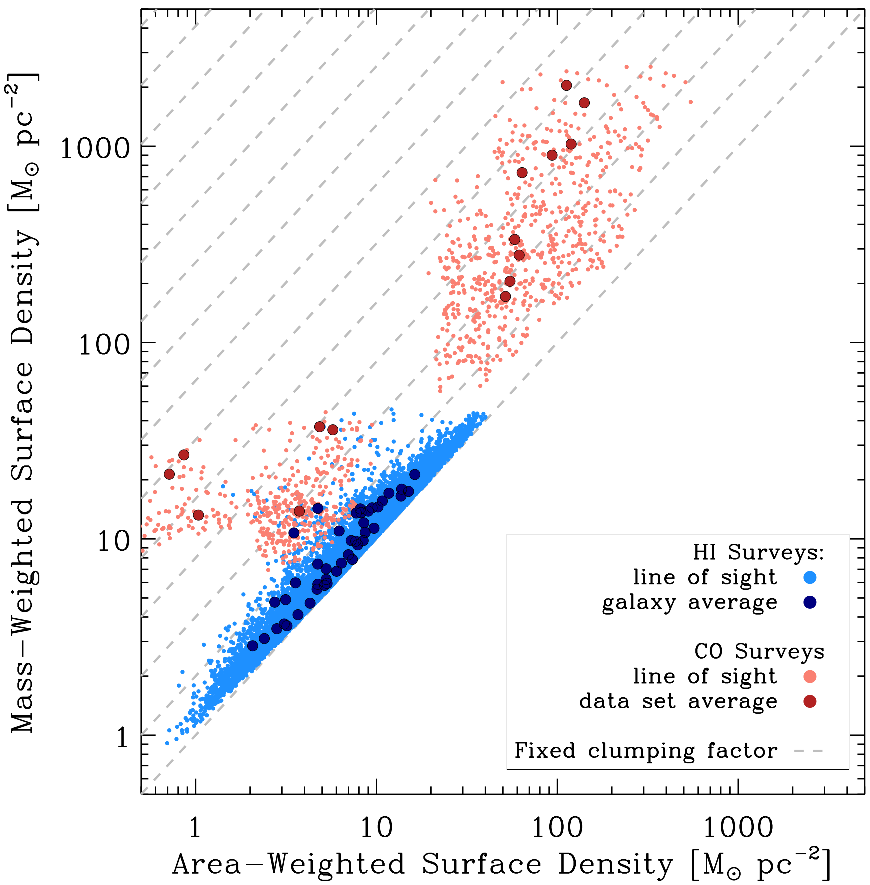
Resolving Evolution in Individual Regions

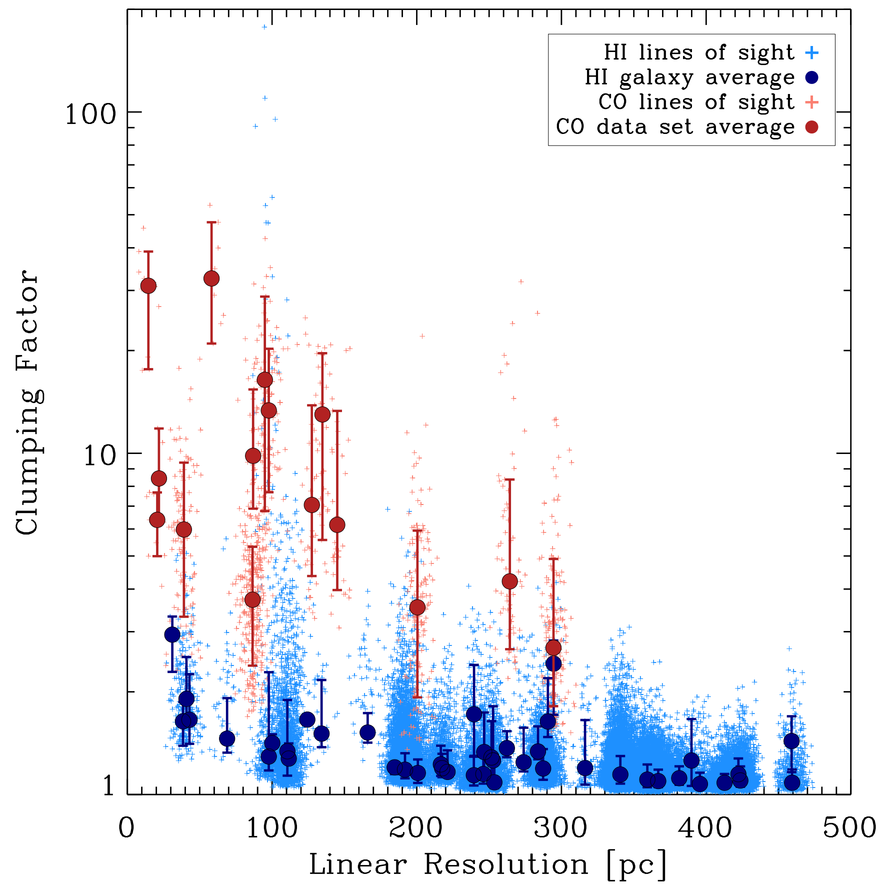


LMC - Kawamura+ '09, Fukui & Kawamura '10

Surface Density and Scale

Surface density is not scale independent - especially for CO





LEROY, LEE, SCHRUBA ET AL. '13

Scale and Studying SF in Galaxies

1. Galaxy scale observations allow study of time-averaged processes by blending regions in many evolutionary states.

2. The increasing resolution of extragalactic data sets allows one to distinguish individual regions.

3. Capturing these regions in a specific state (HII region, molecular cloud, exposed cluster) introduces scatter into attempts to measure time-averaged equilibria.

4. The same scatter allows access to the life cycle of star forming regions. (c.f. NANTEN surveys, PAWS, Milky Way)

5. There is almost certainly not a key <u>scale</u> but a key degree of averaging (e.g., integrated SFR or mass)

An Incomplete Look at Star Formation on Galactic Scales

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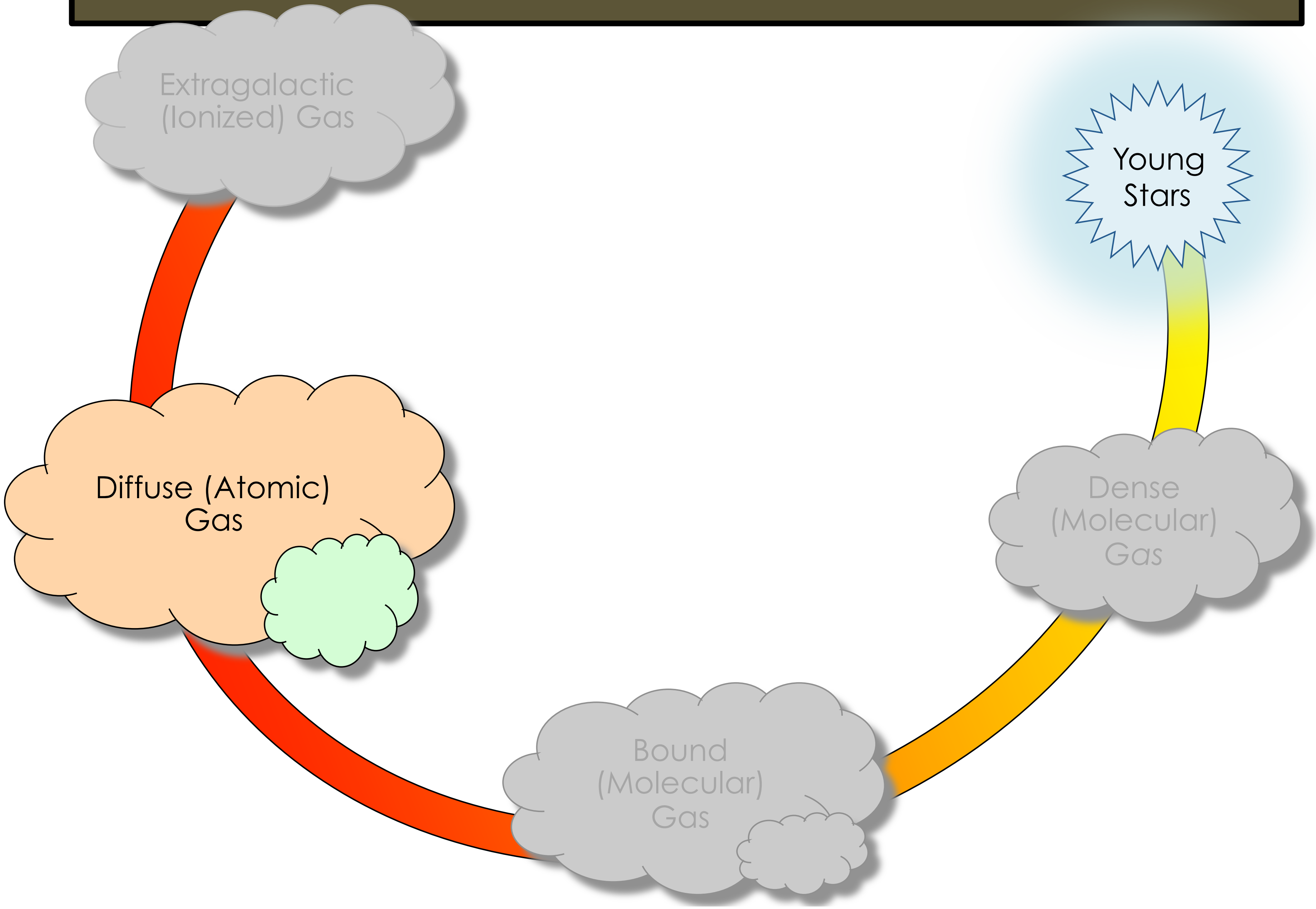
H_2-HI Balance

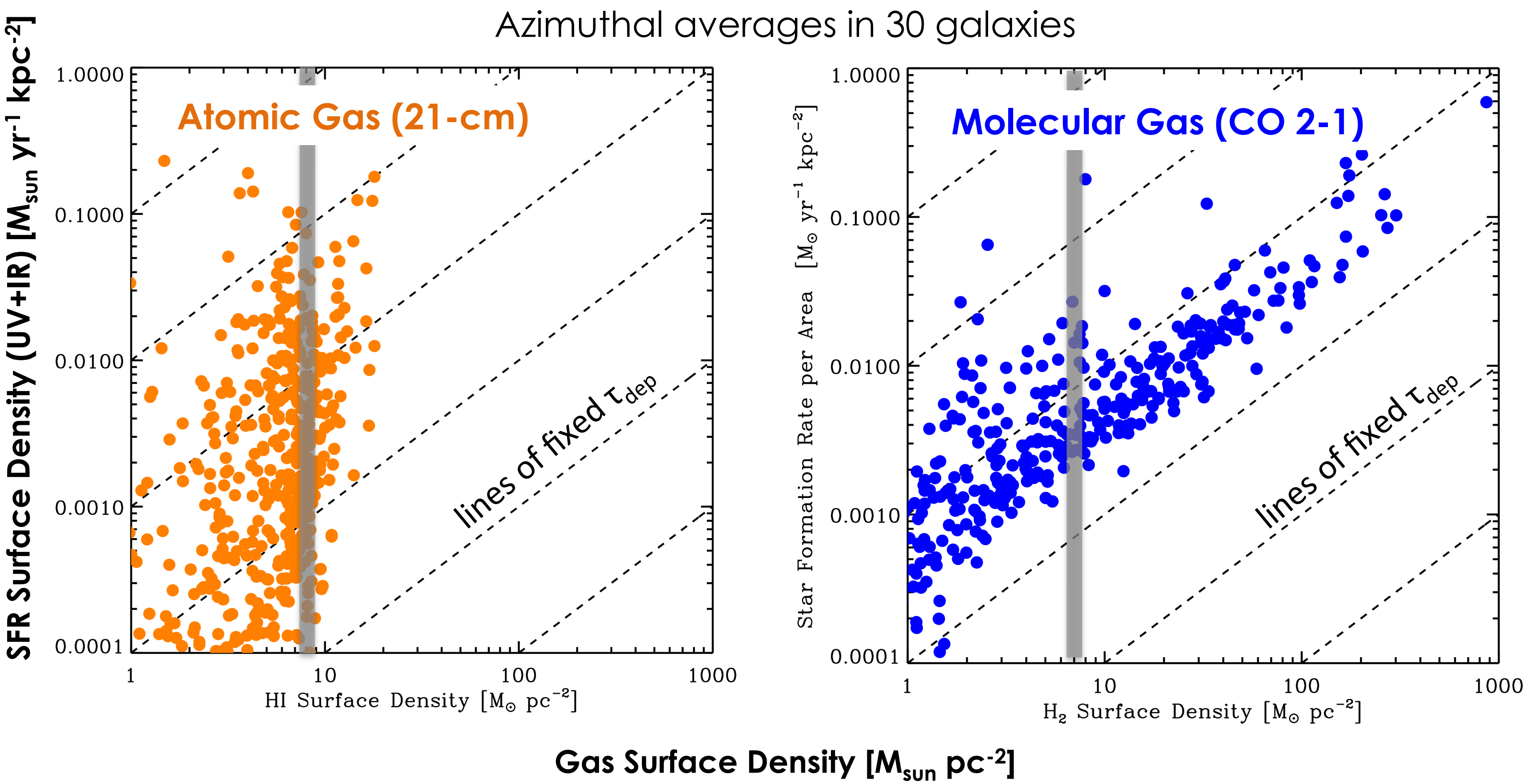
Cloud Structure / Dense Gas Fraction

Please Speak Up!

HI/SFR: cloud+star formation in dwarfs/outer disks



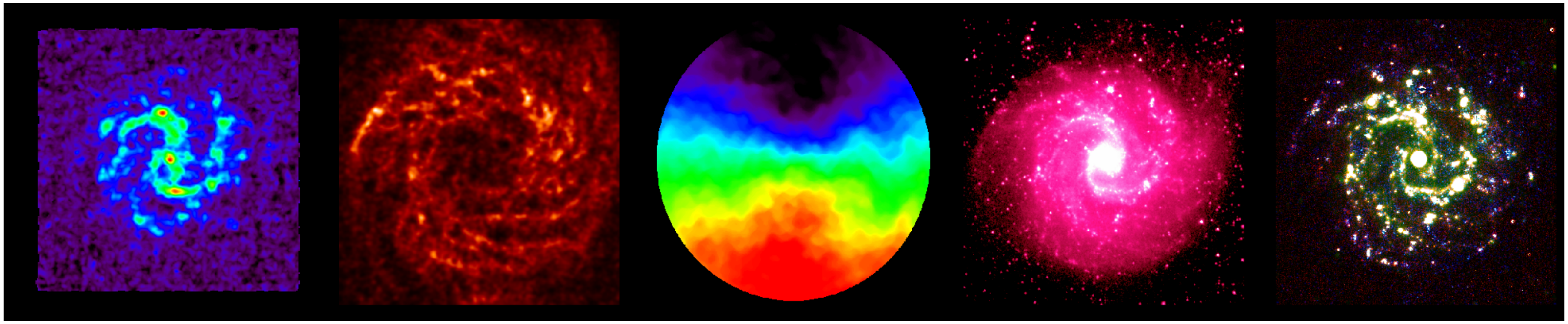
Star Formation Occurs in Molecular Gas



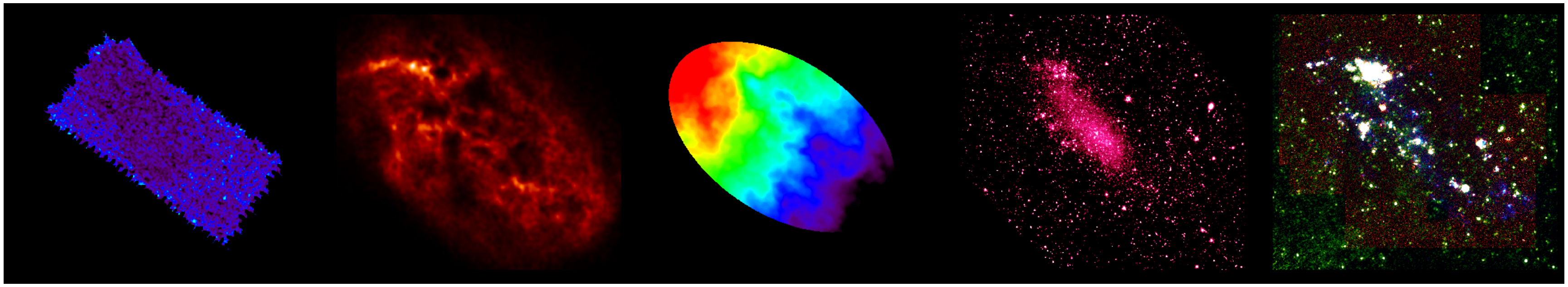
SCHRUBA, LEROY ET AL. '11, Leroy+ '08, Bigiel, Leroy+ '08, Kennicutt+ '07, Wong+ '02

But the ISM is Still Mostly HI in Outer Disks & Dwarfs

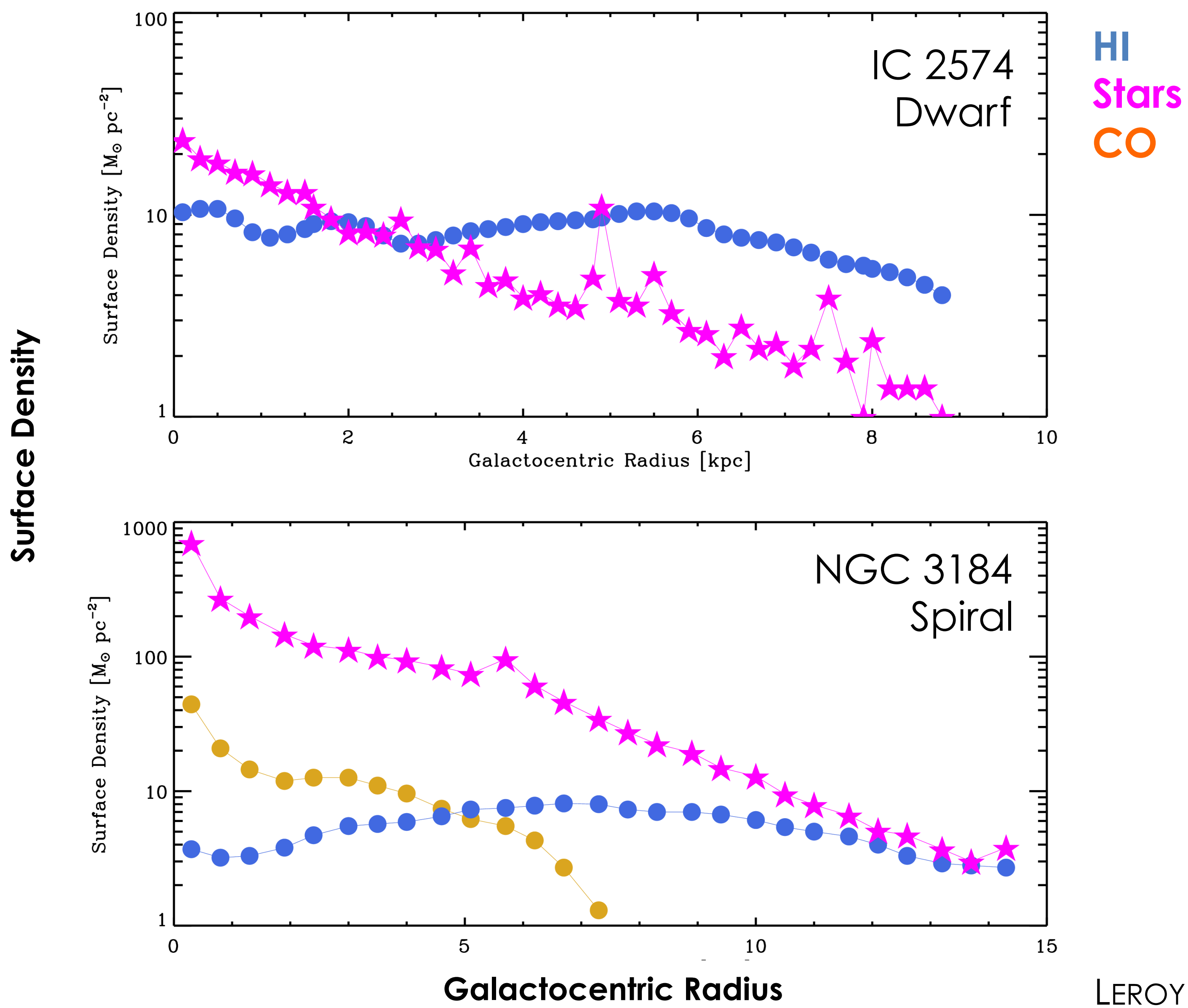
NGC 3184 - Spiral



IC 2574 - Dwarf



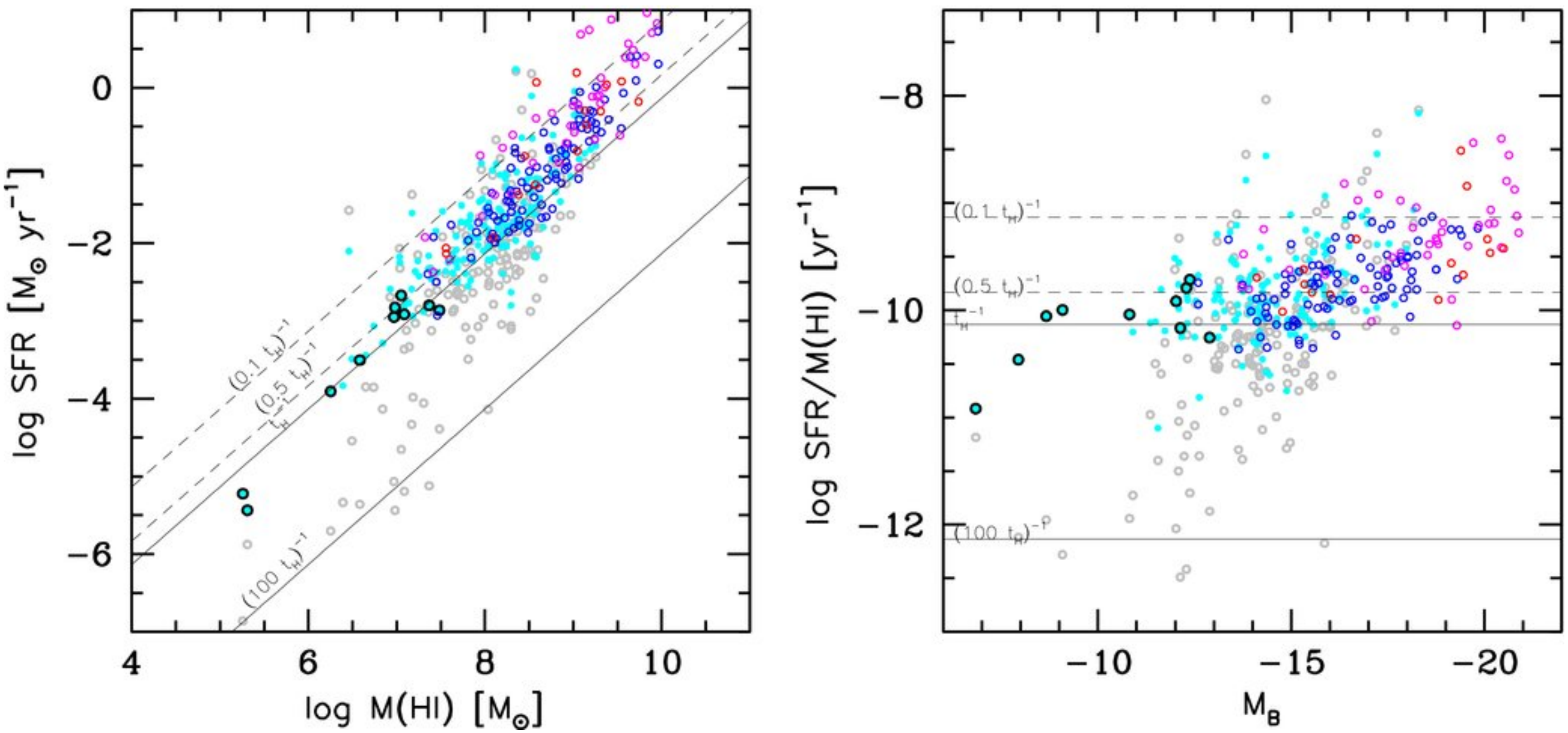
Rough Radial Structure of Dwarf & Disk



LEROY ET AL. (2008)

Integrated SFR-per-HI in the Local Volume

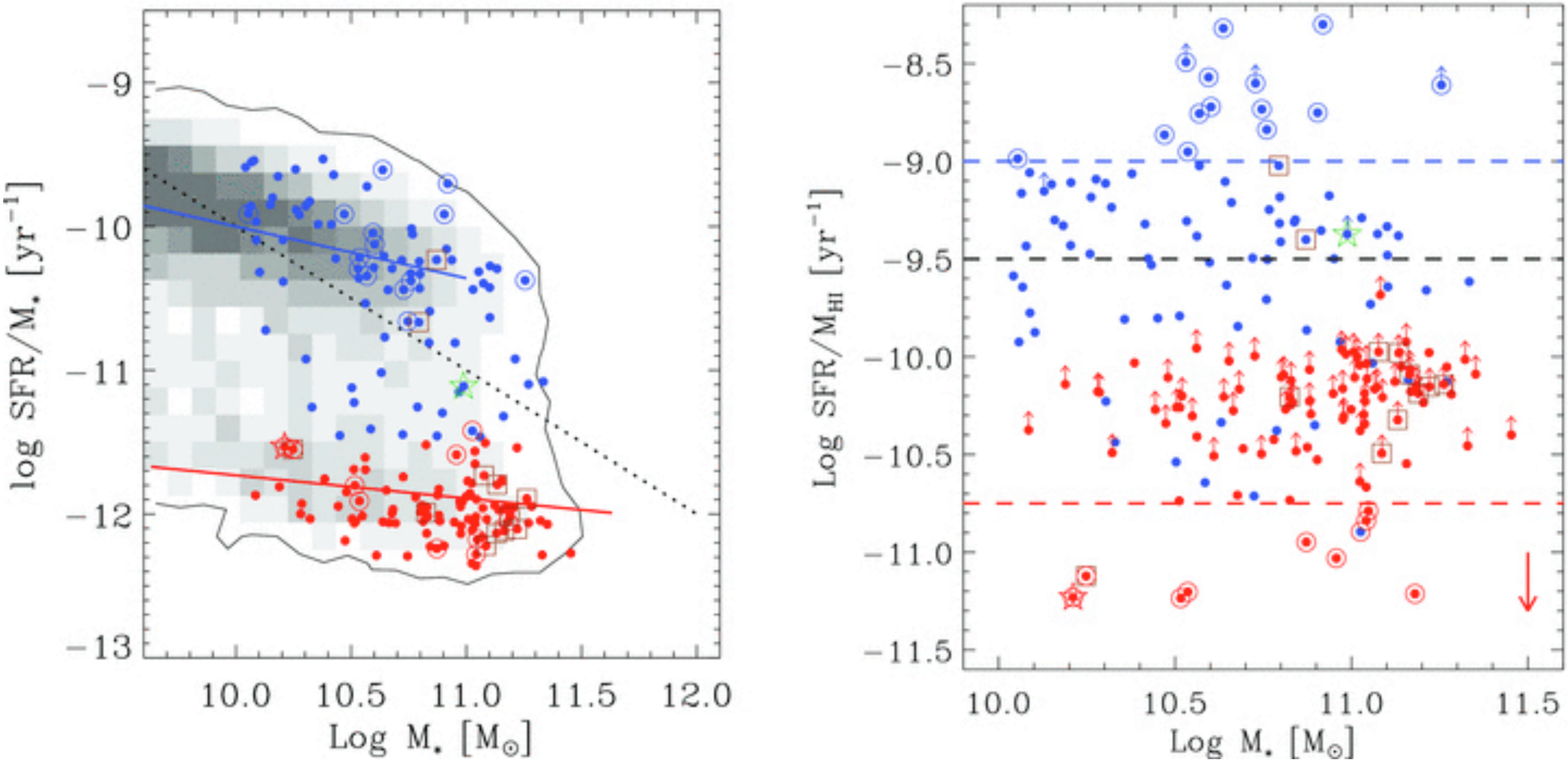
Mass-dependent SFR/HI of magnitude few to several Gyr



LEE ET AL. (2009)

Integrated SFR-per-HI in GASS

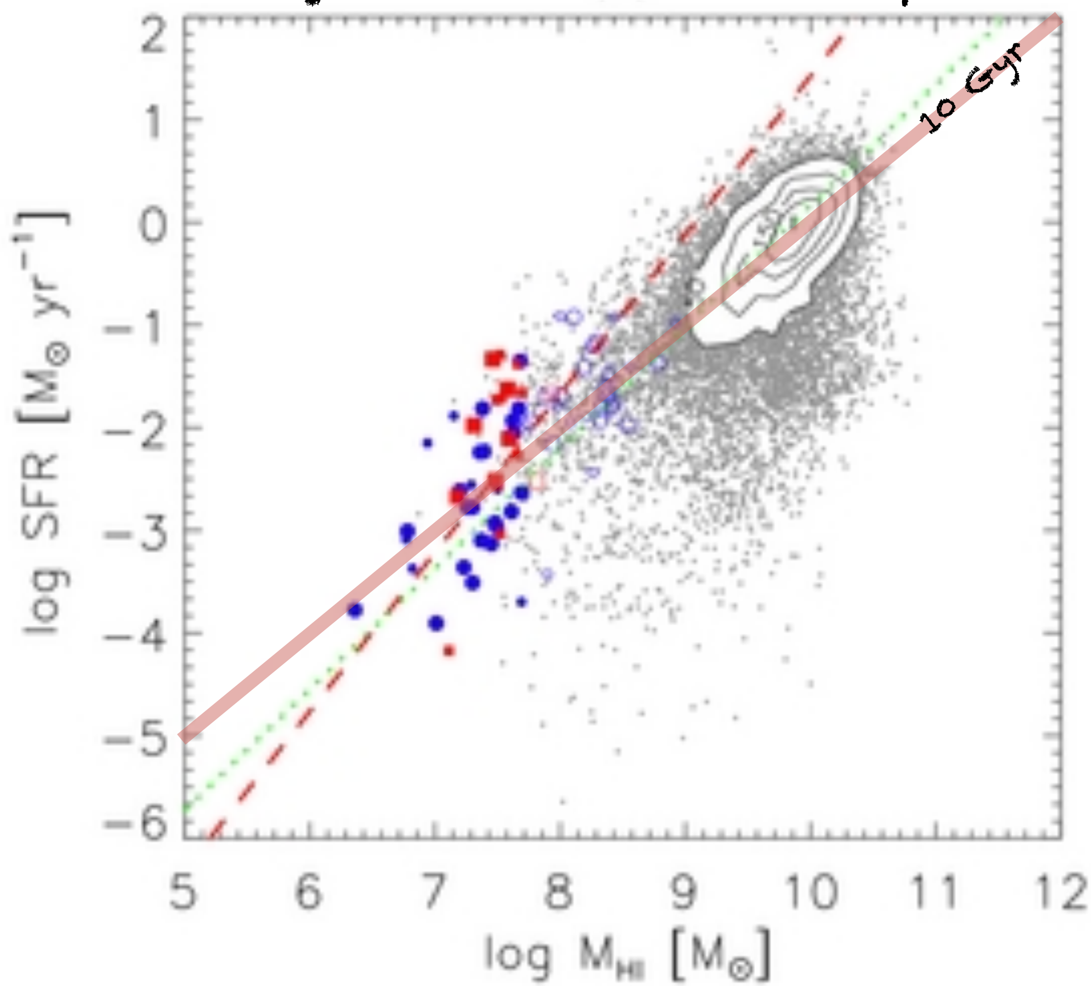
Mass-independent SFR/HI (c. 4 Gyr) but with big scatter.



SCHIMINOVICH+ '10

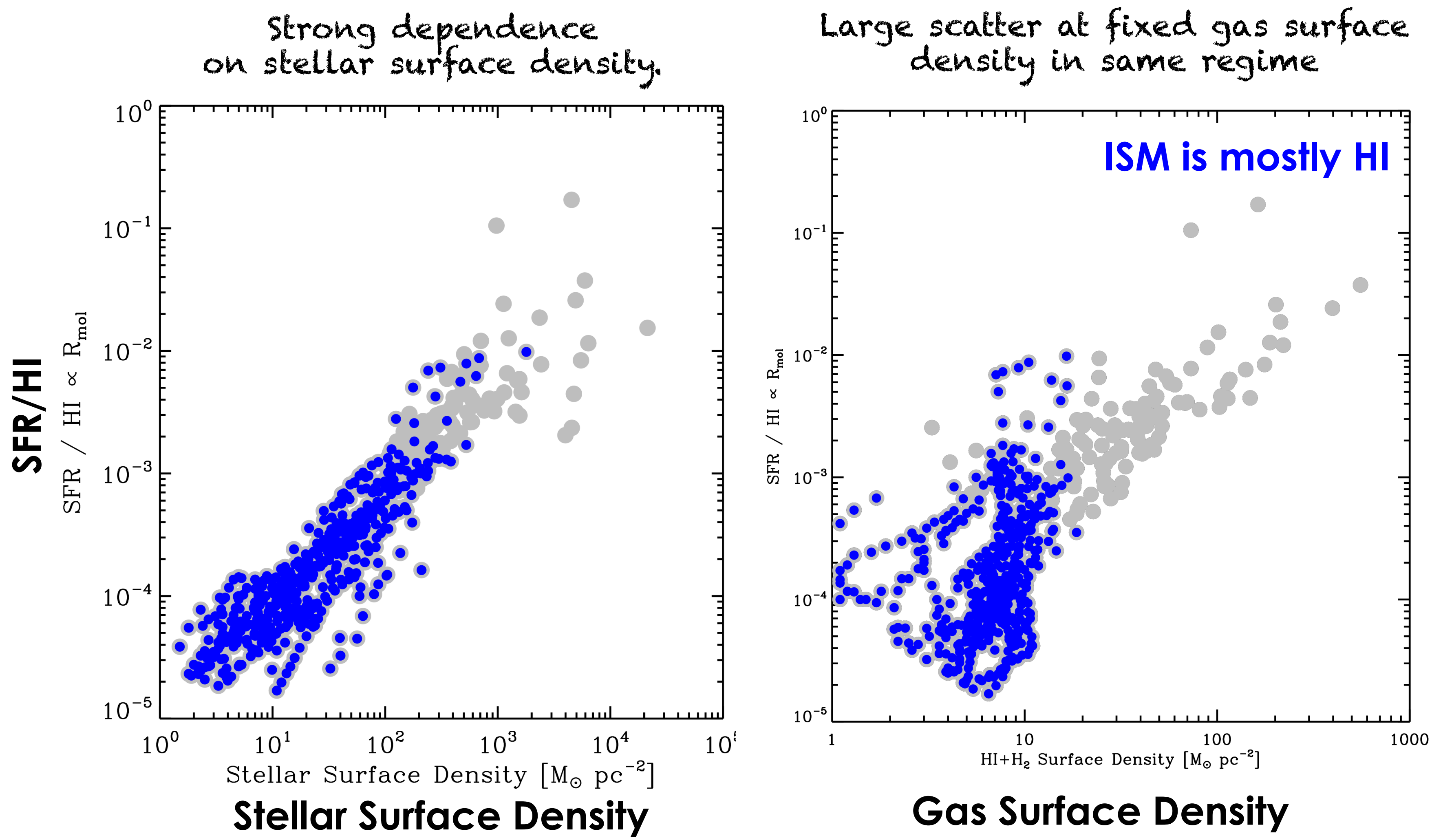
HI-SFR Balance in Larger ALFALFA Survey

Long (c. 10 Gyr) but variable HI depletion time



HUANG ET AL. (2012)

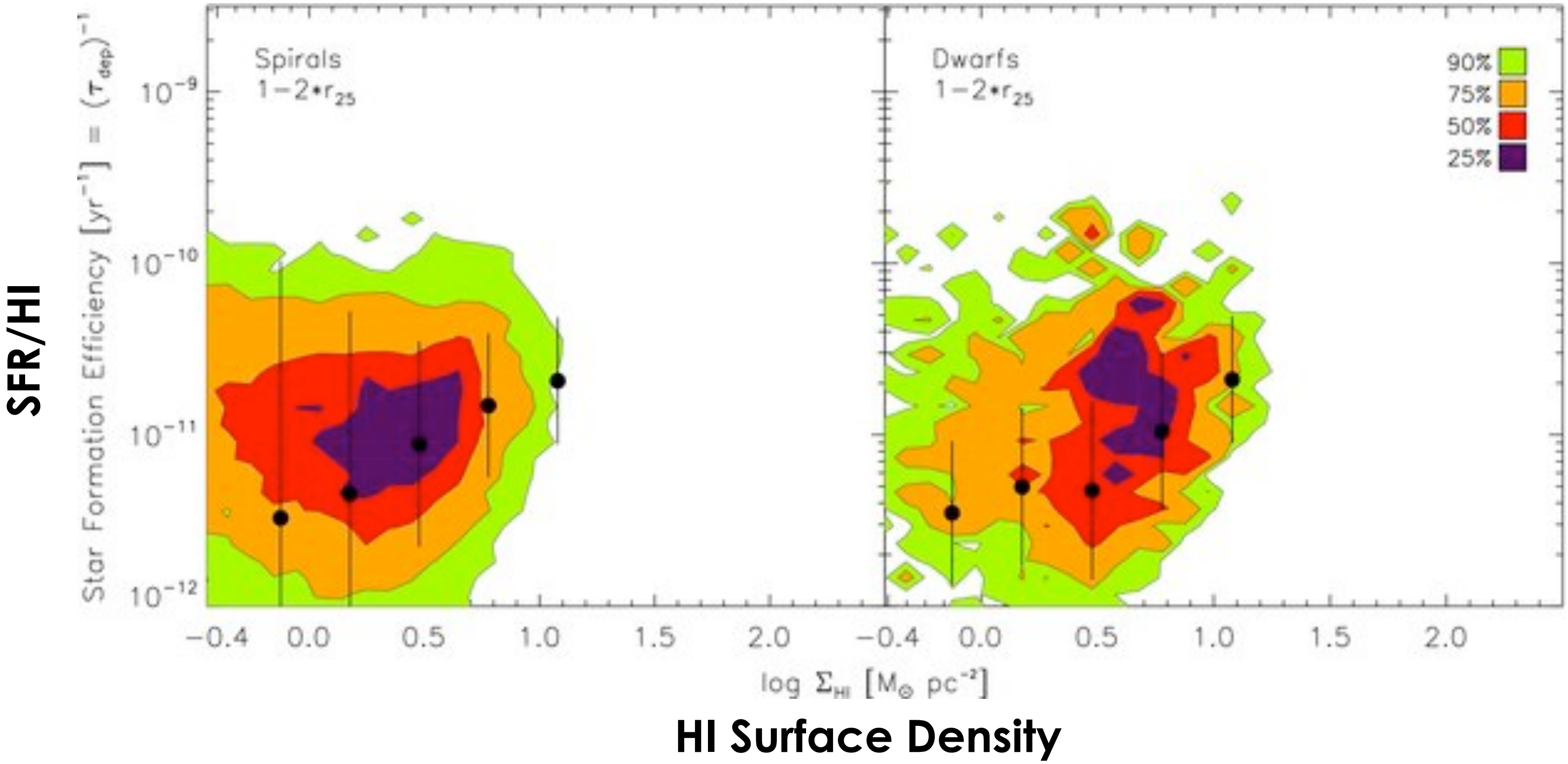
HI-SF Balance in the Disks of Galaxies



LEROY+ '08, '09, IN PREP.; SEE REAGAN+ '01, WONG & BLITZ '02, SHI+ '11, '14

HI-SF Balance in the Outskirts of Galaxies

With large scatter, SFR-per-HI increases with increasing gas surface density in the outer parts (1-2 optical radii) of galaxies...



BIGIEL, LEROY, WALTER ET AL. (2010)

SFR/HI Balance

1. HI makes up most of the ISM in dwarf galaxies and the outer parts of spirals.

2. In this regime SFR-HI captures the overall efficacy of the ISM at forming stars. This is often several Gyr (big galaxies) to roughly a Hubble time (smaller galaxies).

3. Measurements of the local volume and larger galaxy population show some mass dependence with the sense of higher efficiency at higher masses.

4. In the disks of galaxies where the stellar potential well is still strong, stellar surface density predicts SFR/HI.

5. In the outer parts of galaxies more gas means higher SFR/HI, though with significant scatter.

An Incomplete Look at Star Formation on Galactic Scales

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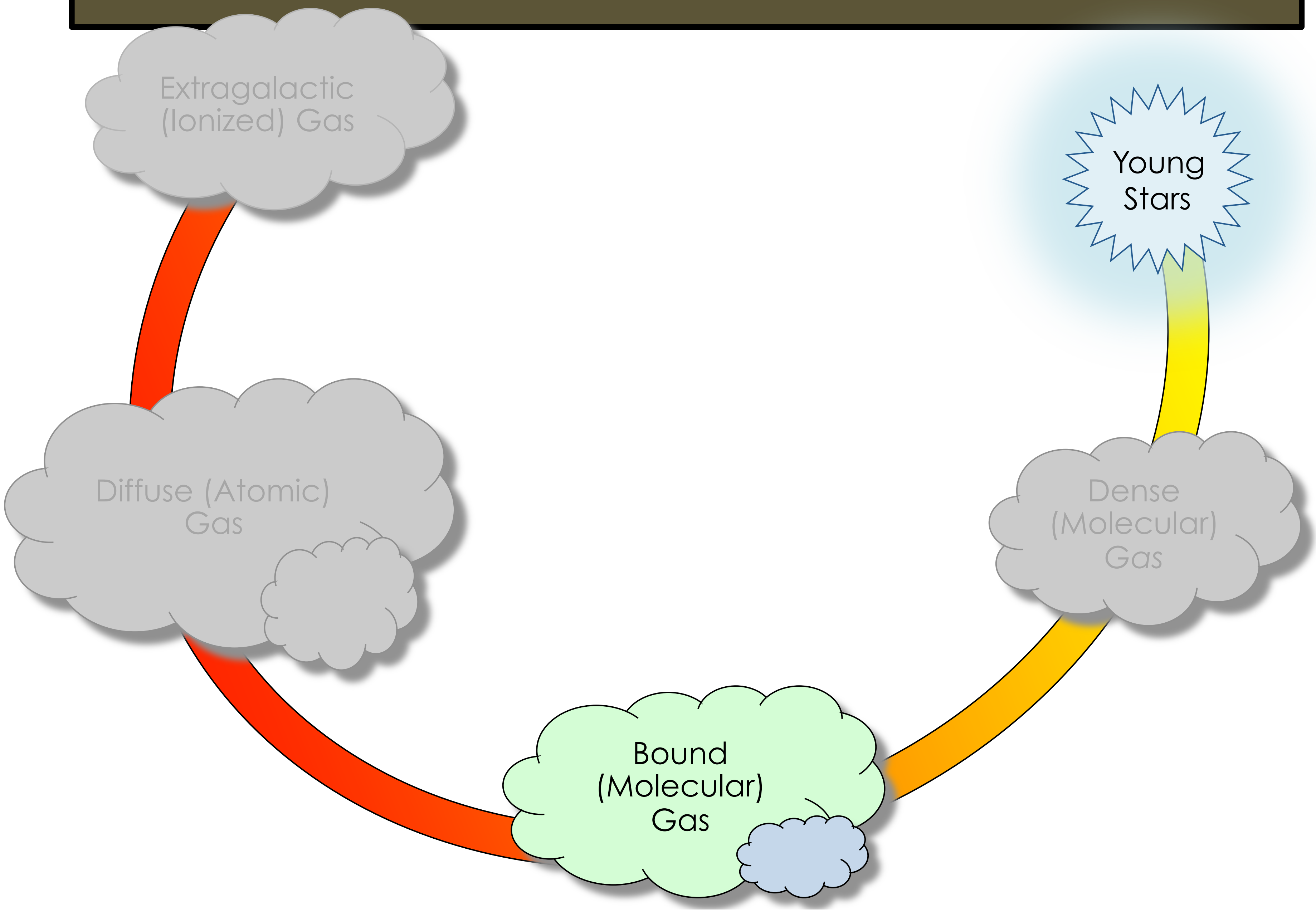
H_2-HI Balance

Cloud Structure / Dense Gas Fraction

Please Speak Up!

Star Formation from Molecular Clouds



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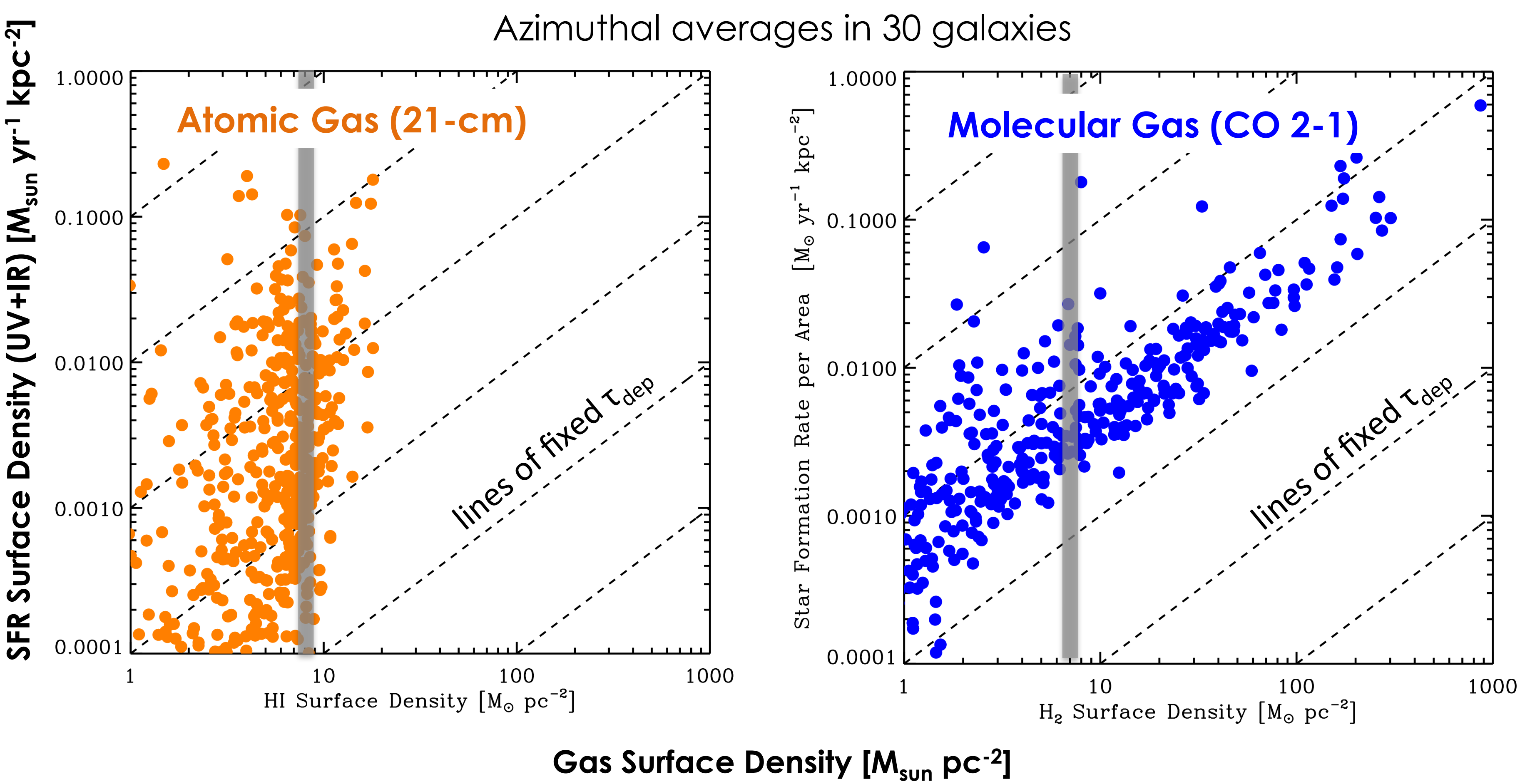
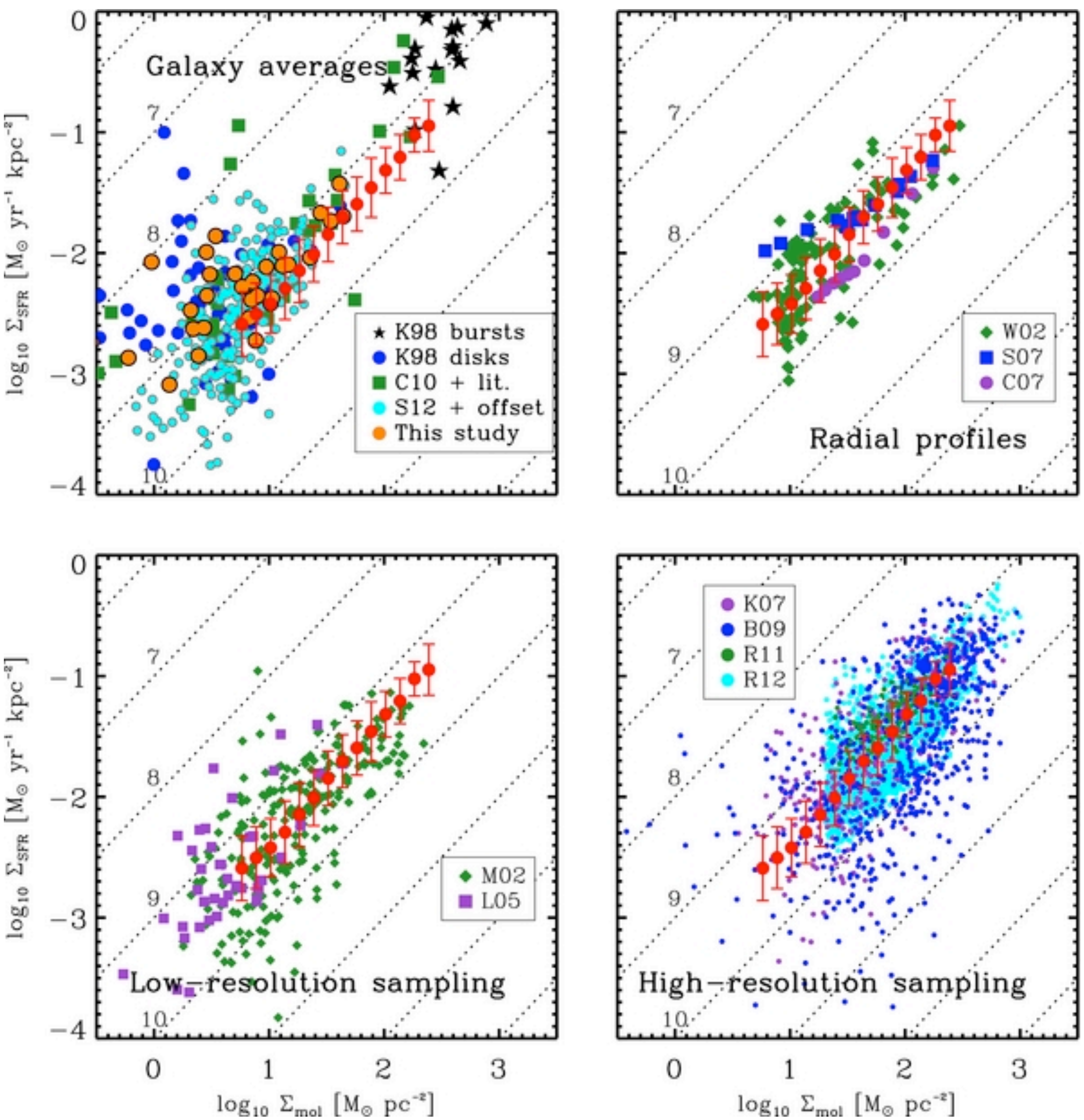
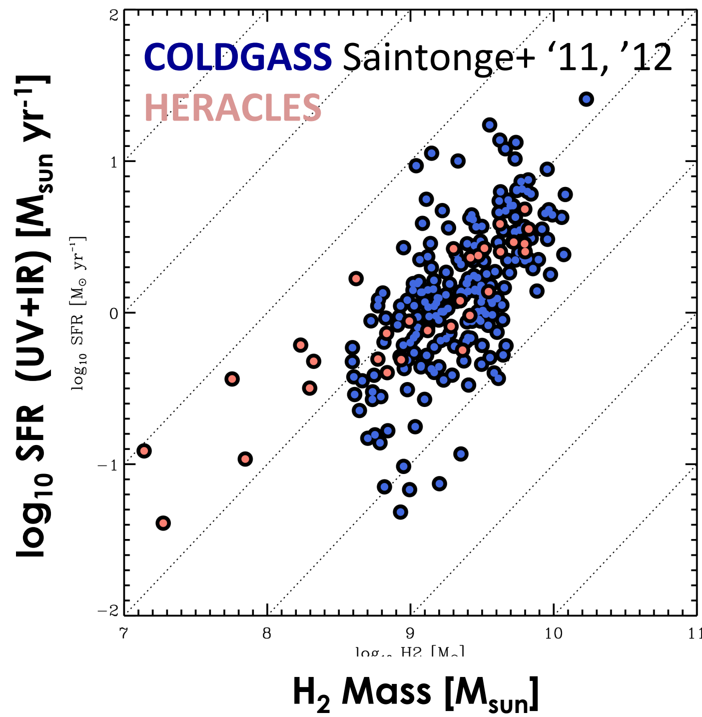


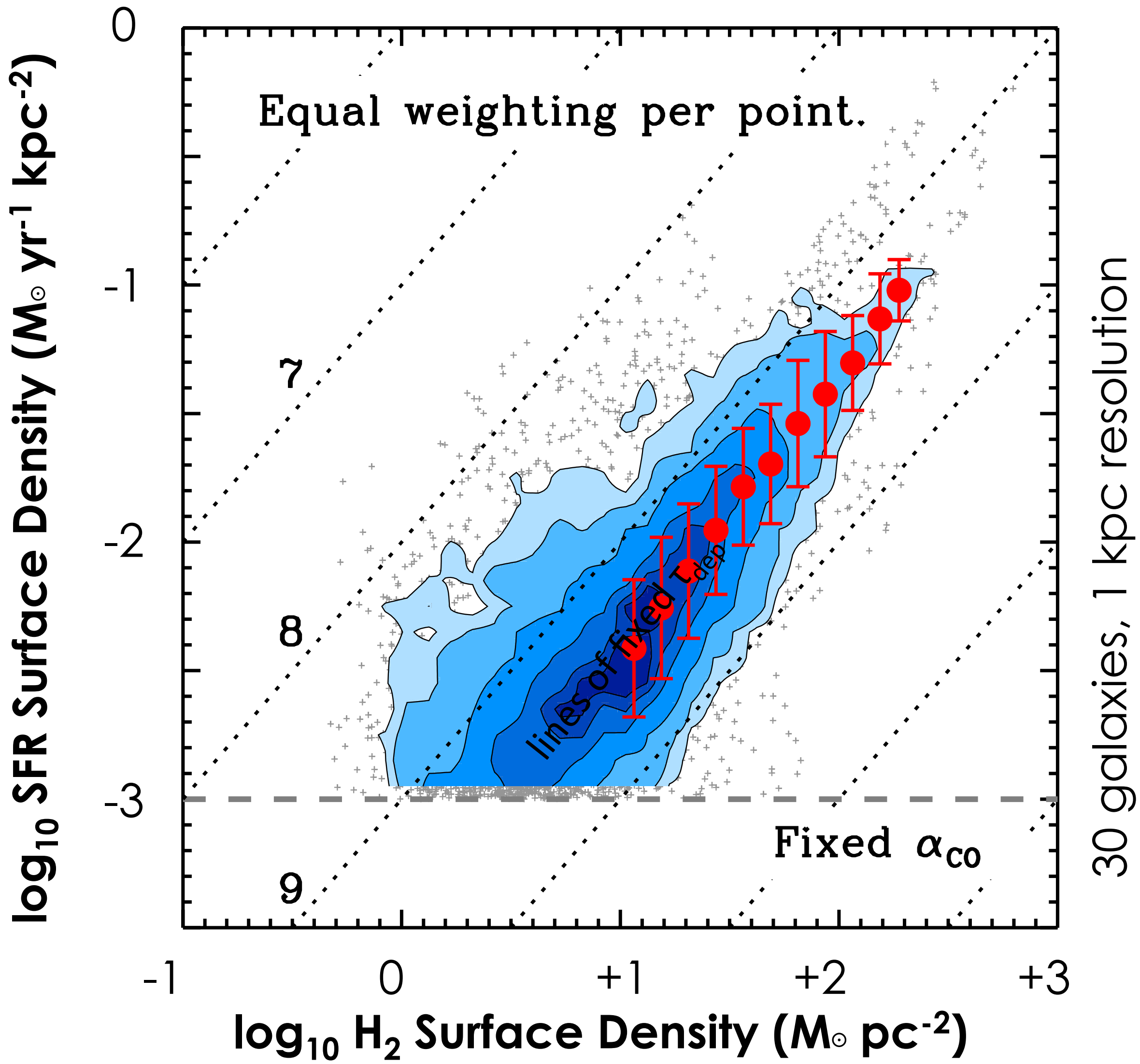
SCHRUBA, LEROY ET AL. '11, Leroy+ '08, Bigiel, Leroy+ '08, Kennicutt+ '07, Wong+ '02

Local Disks – Most Apparent Behavior 1-to-1



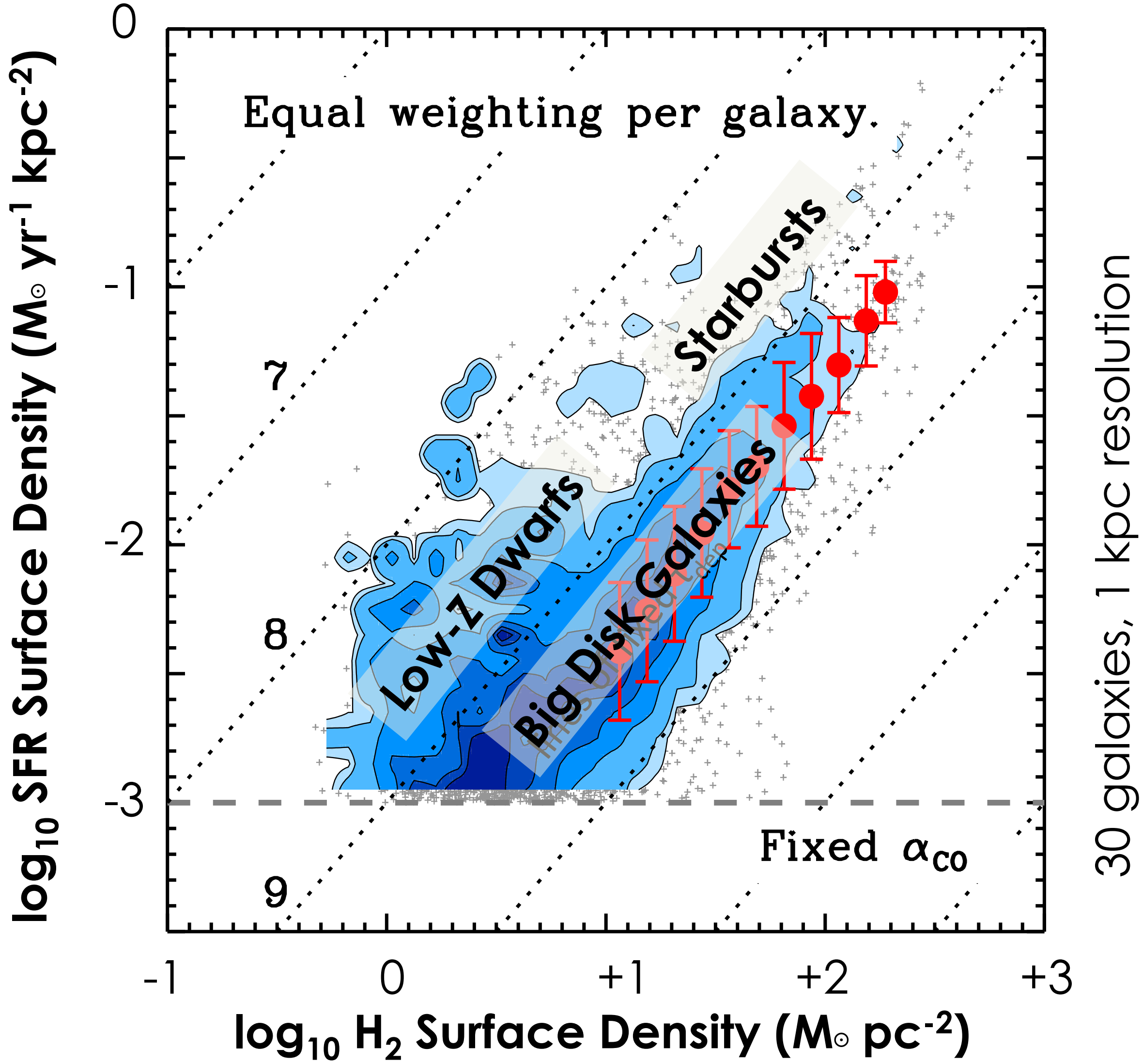


Local Disks - Most Apparent Behavior 1-to-1



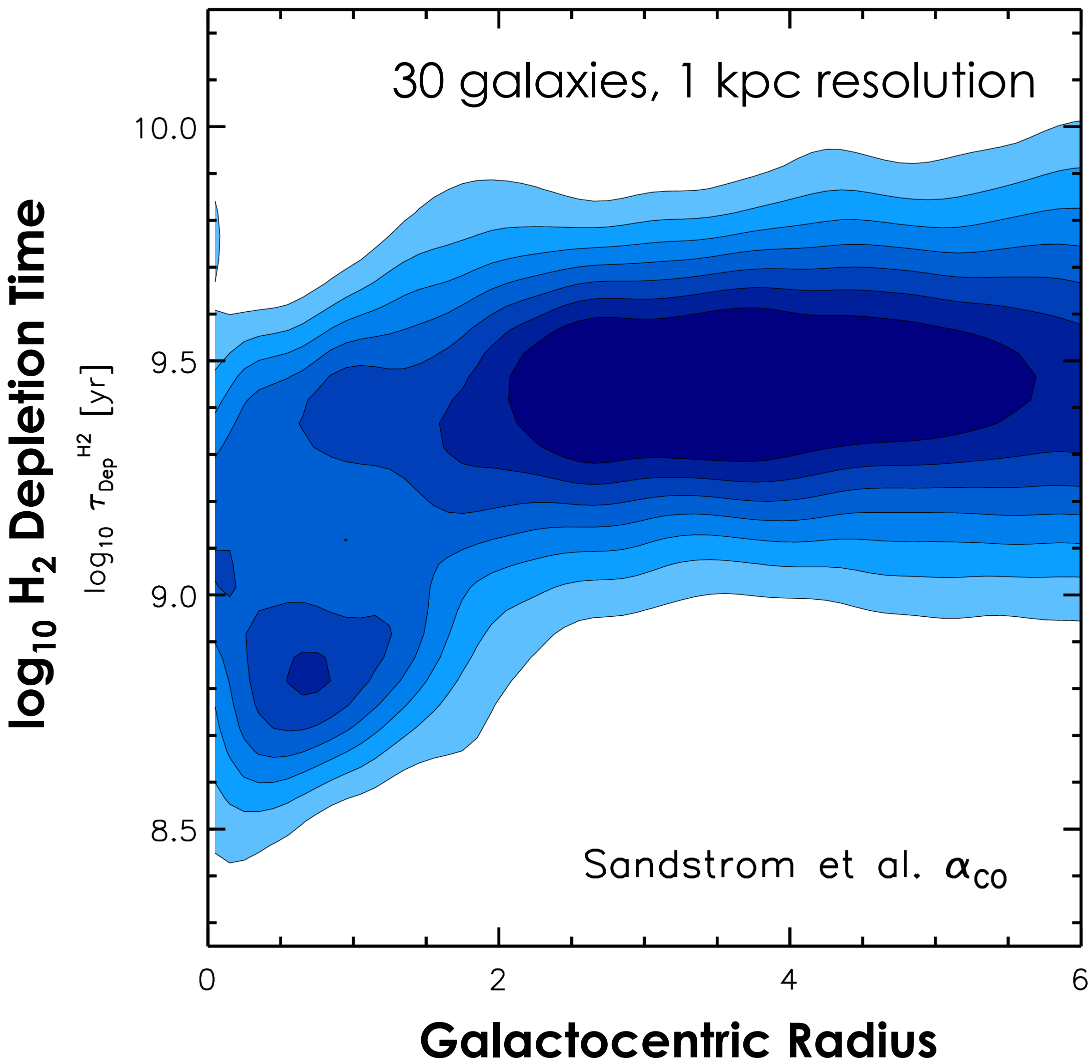
LEROY, WALTER, SANDSTROM+ '13, '08, SCHRUBA, LEROY+ '11, BIGIEL, LEROY+ '08

Local Disks - Most Apparent Behavior 1-to-1



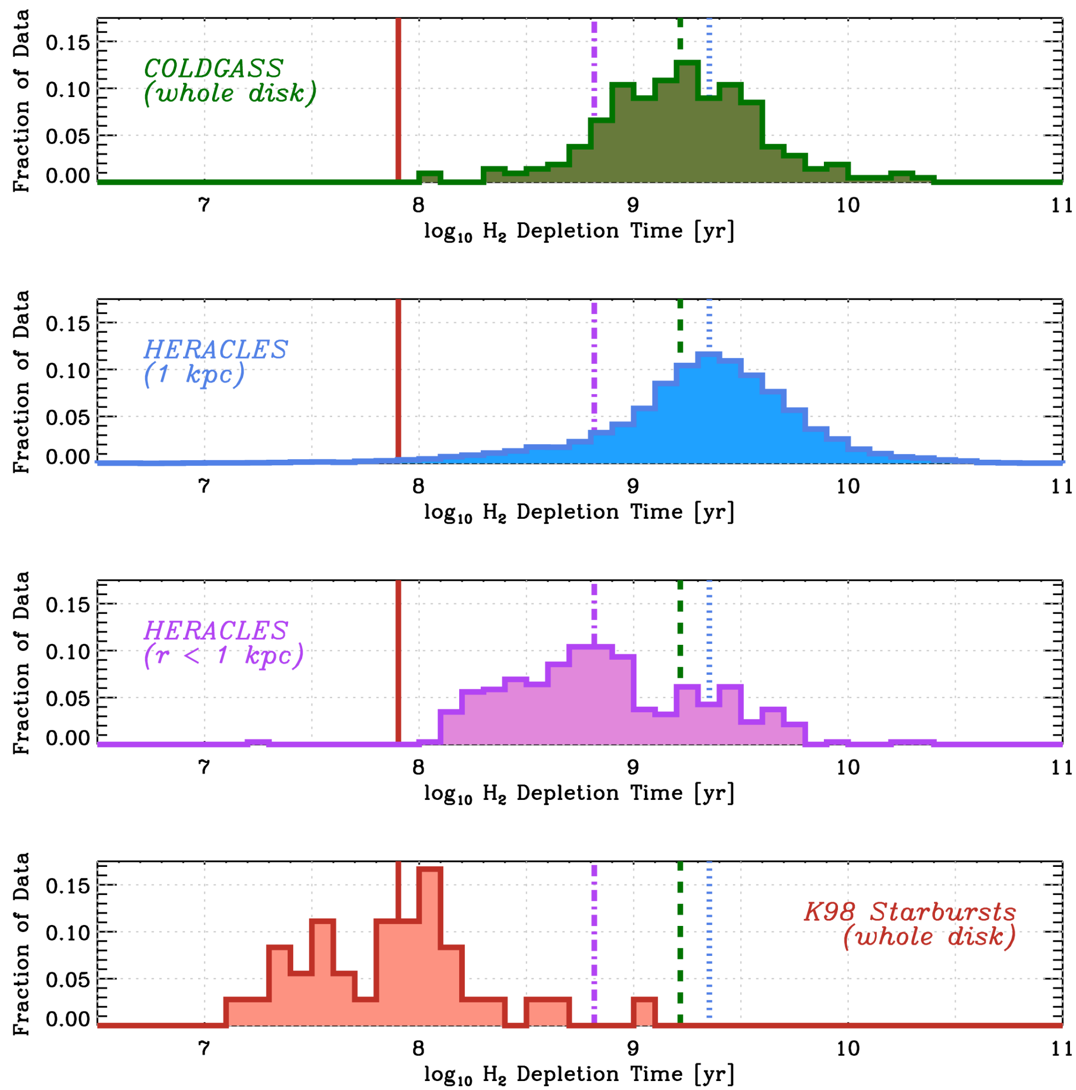
LEROY, WALTER, SANDSTROM+ '13, '08, SCHRUBA, LEROY+ '11, BIGIEL, LEROY+ '08

Many Galaxy Centers Show More Efficient SF

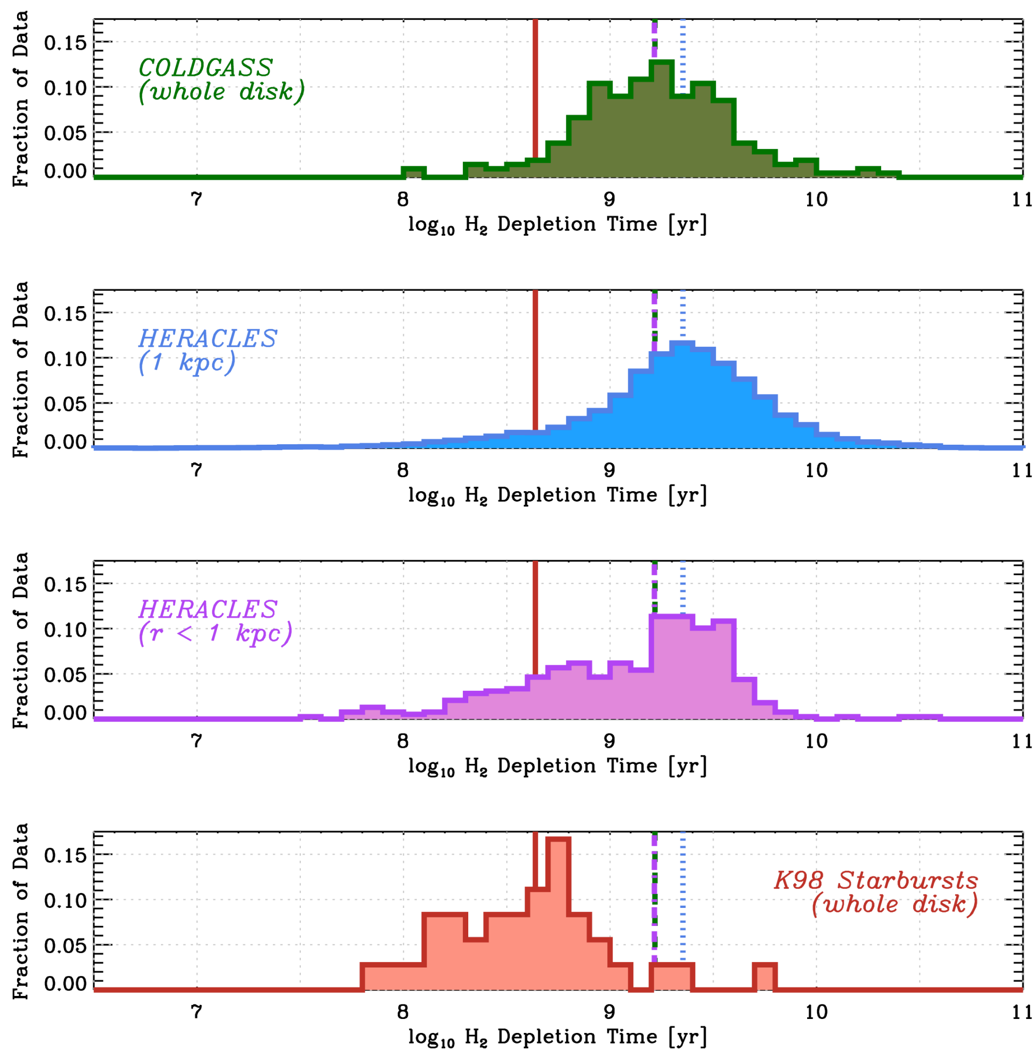


LEROY, WALTER, SANDSTROM+ '13, SANDSTROM, LEROY+ '13, '14

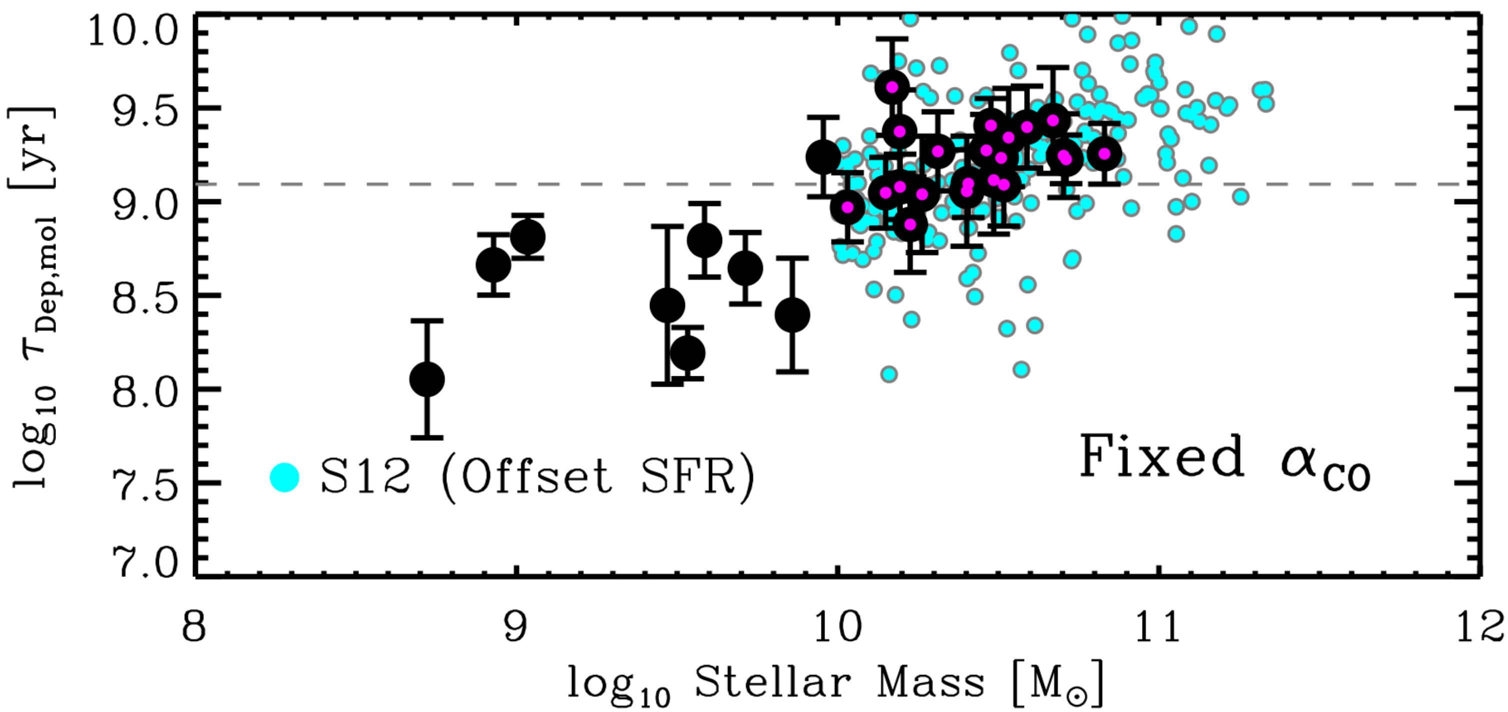
H_2-SF From Disks to Starbursts



H_2-SF From Disks to Starbursts

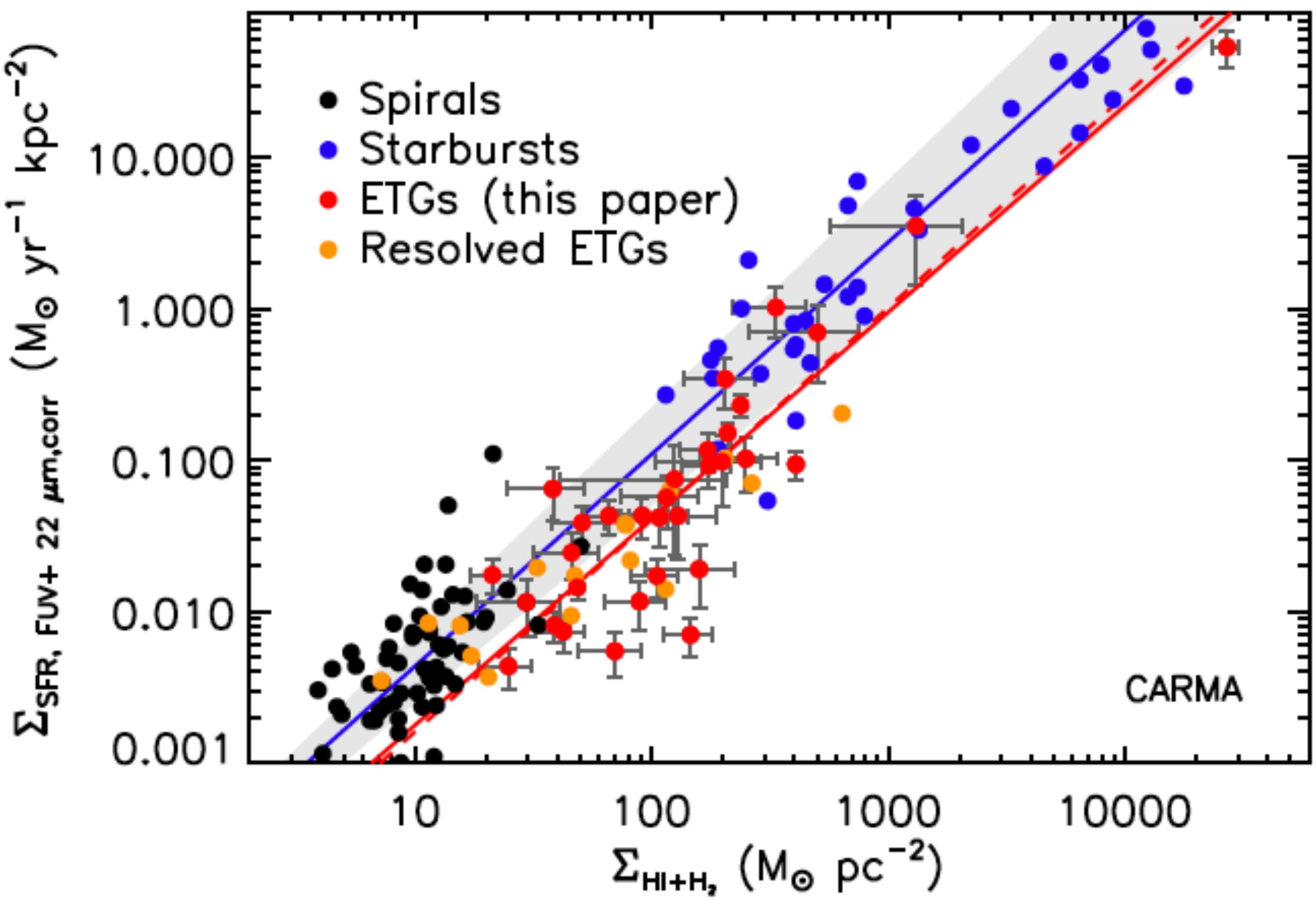


COLD GASS: Clear CO/SFR Correlation with M_*



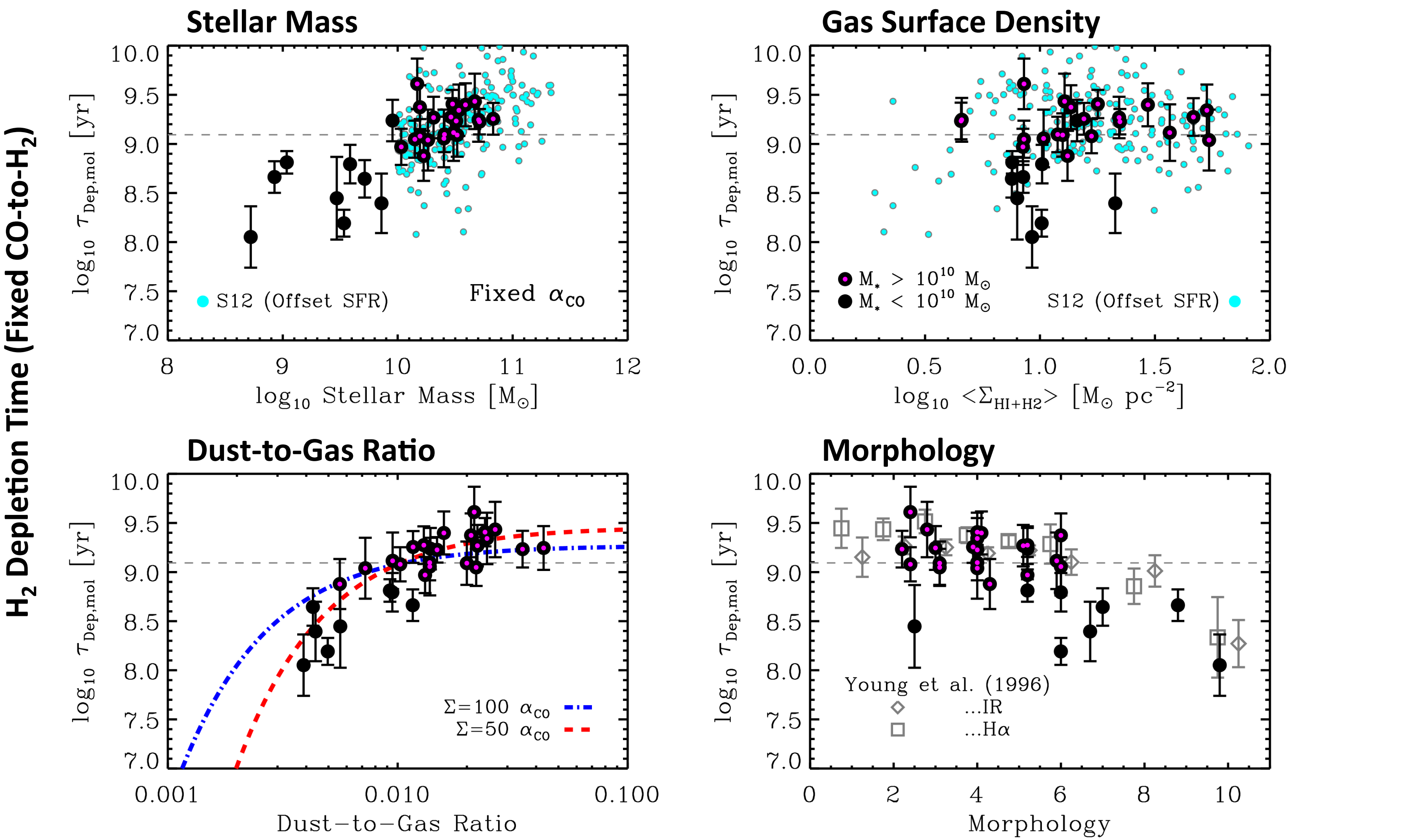
SAINTONGE+ '11, **'12**, '13; LRTOU+ '13

Early Type Galaxies: Same Qualitative M_* Trend



Davis et Atlas-3D '13; c.f. Alatalo, Young

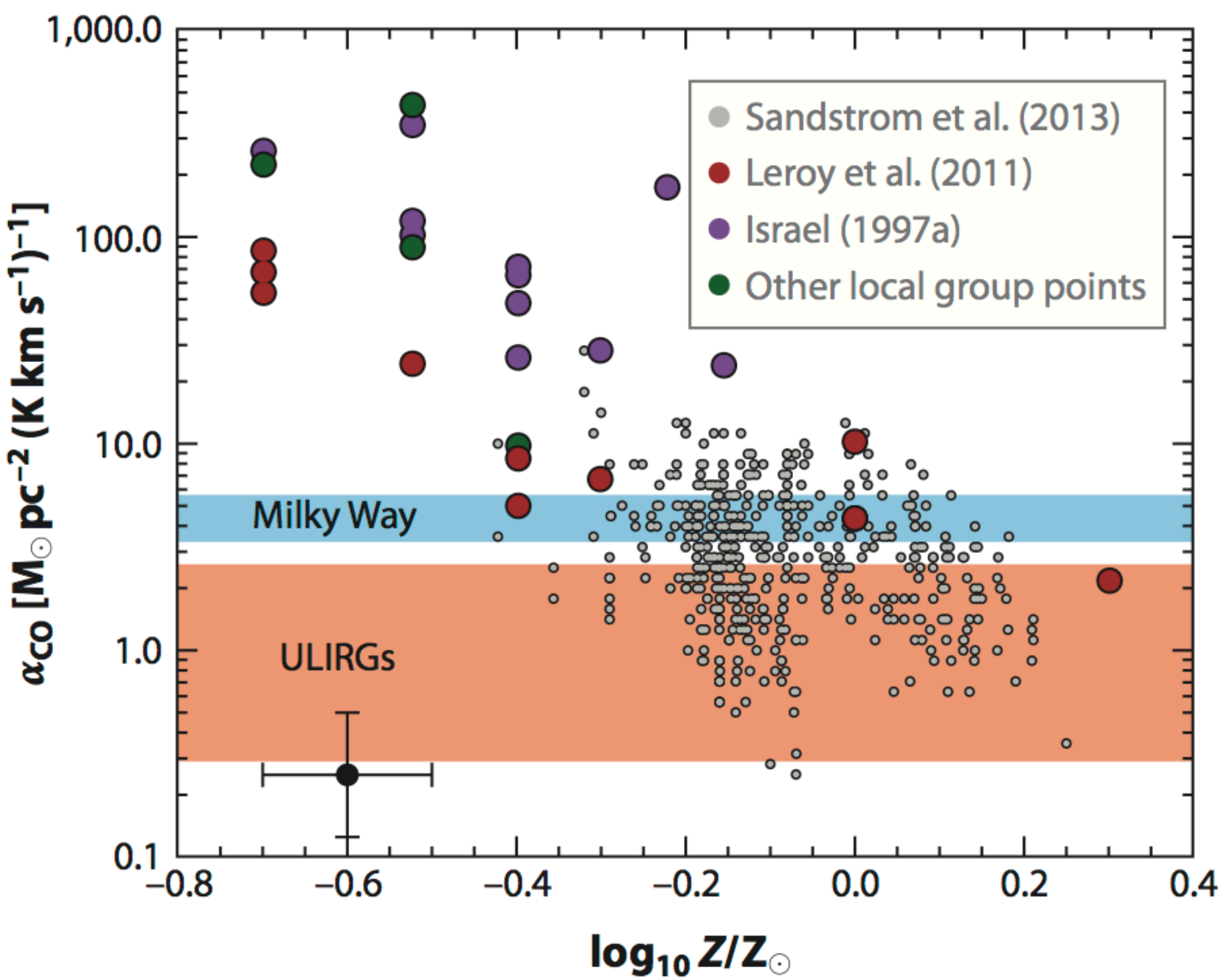
Trends With Integrated Galaxy Properties



Each Point:
Whole-galaxy average

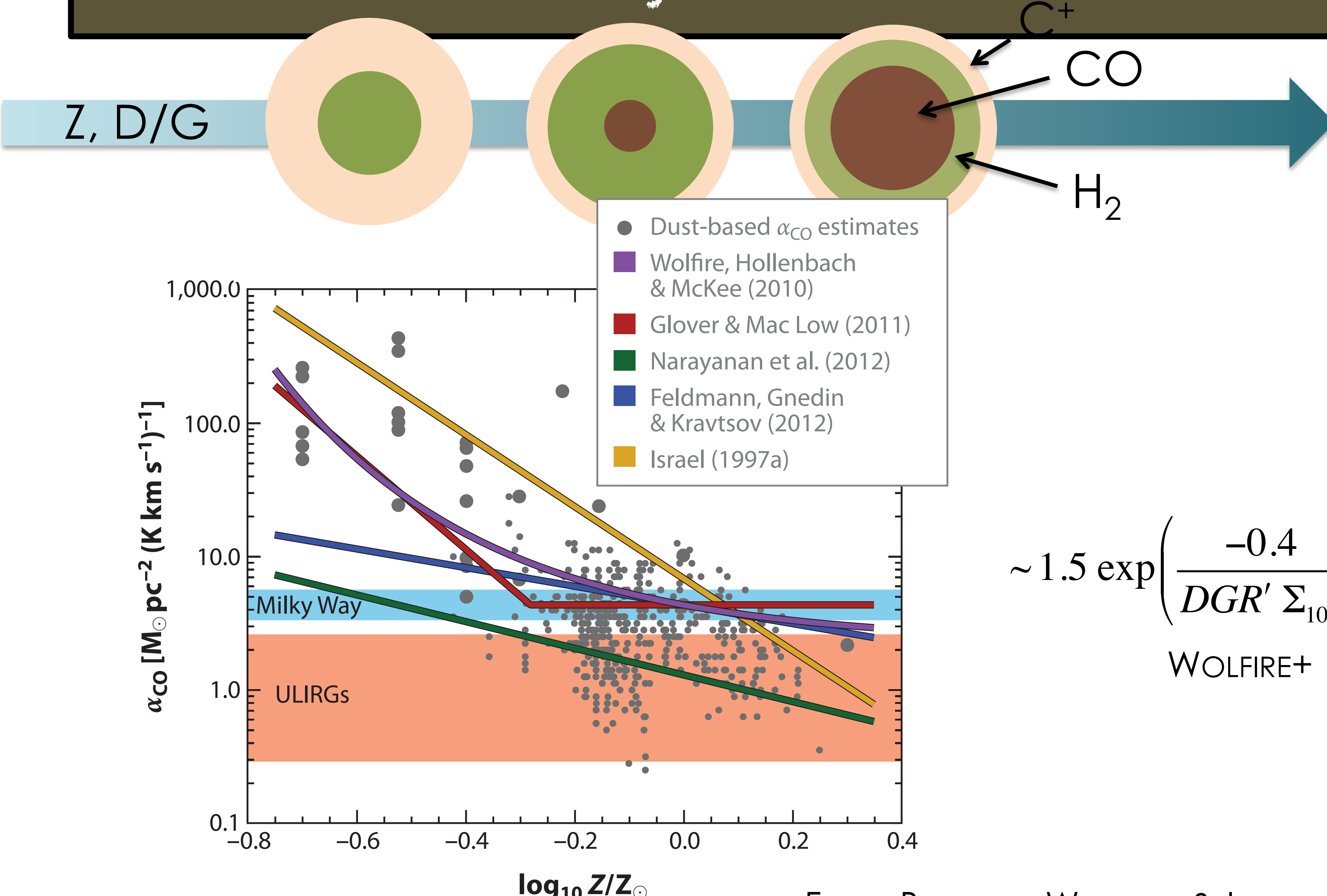
COLD GASS: SAINTONGE+ '12, YOUNG+ '95, LEROY+ '13

Metallicity/DGR and CO



BOLATTO, WOLFIRE, & LEROY '13; SANDSTROM, LEROY+ '13, LEROY+ '11

Metallicity/DGR and CO

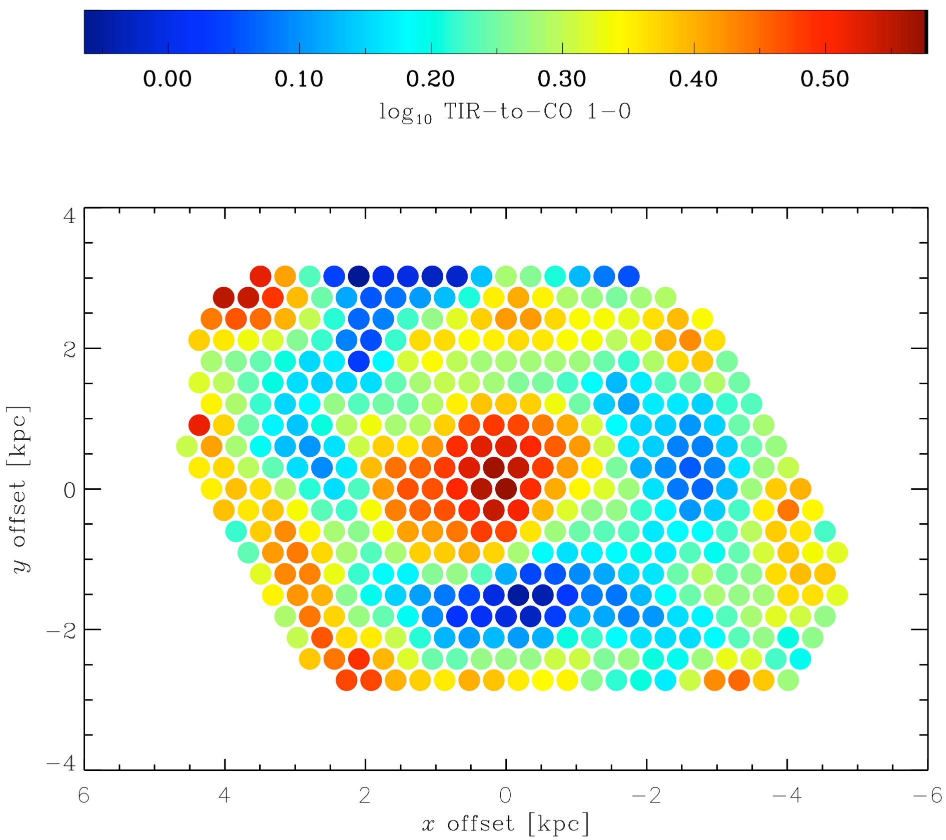


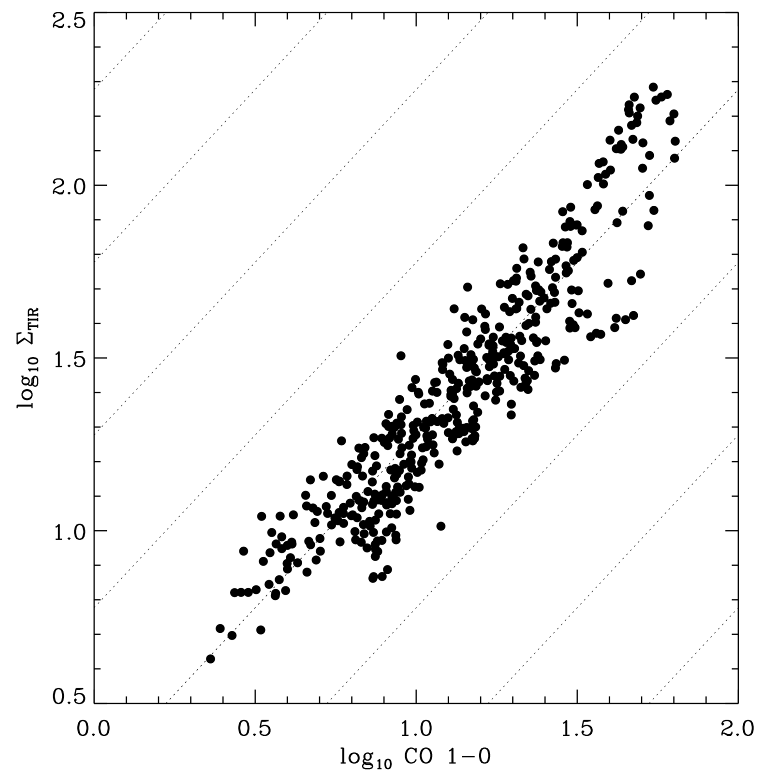
$$\sim 1.5\,\exp\left(\frac{-0.4}{DGR'\,\Sigma_{100}}\right)$$

Wolfire+ '10

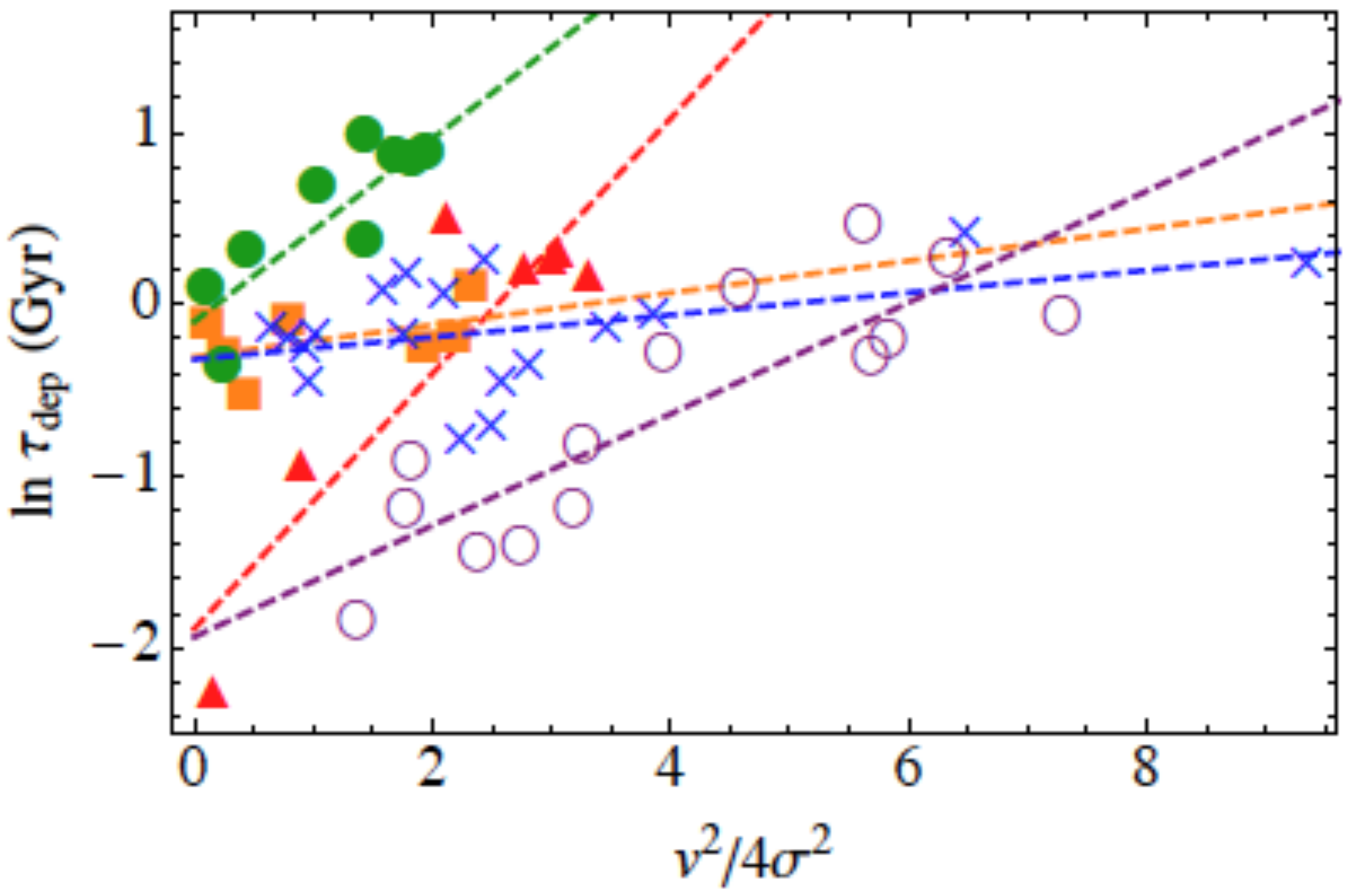
From Bolatto, Wolfire, & Leroy '13

SFR-H_2 Variations About a "Normal" Relation



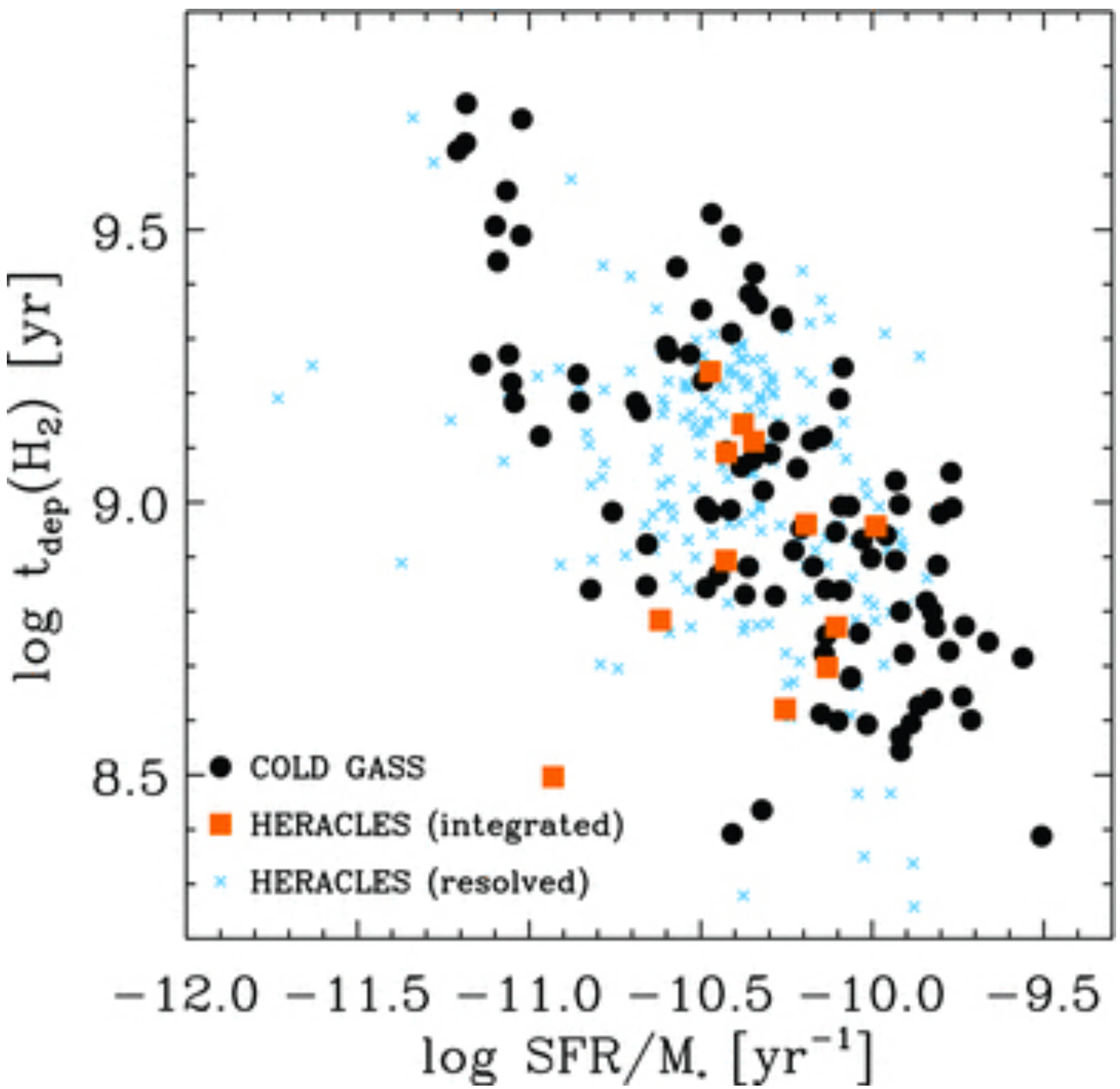


Local Depletion Time Predicted by Dynamical Pressure



Meidt et PAWS '13

Specific SFR in Gas and Stars



SFR/H_2 Balance

1. SFR traces H2 more directly than HI.

2. In the disks of big galaxies, the implied depletion time is 1 to a few Gyr.

3. Trends with galaxy properties:
   - depletion time increases with stellar mass
   - early type galaxies show the same trend
   - <u>apparent</u> depletion time shorter at low metallicity
   - specific star formation rate in gas and stars match

4. Within galaxies, centers show wide range of SFR/H2.

5. Even a "normal" scaling hides systematic variations. (e.g., dynamical suppression in M51 inner arms)

An Incomplete Look at Star Formation on Galactic Scales

Terminology / Framework

Scales

HI-SF Balance

H_2-SF Balance

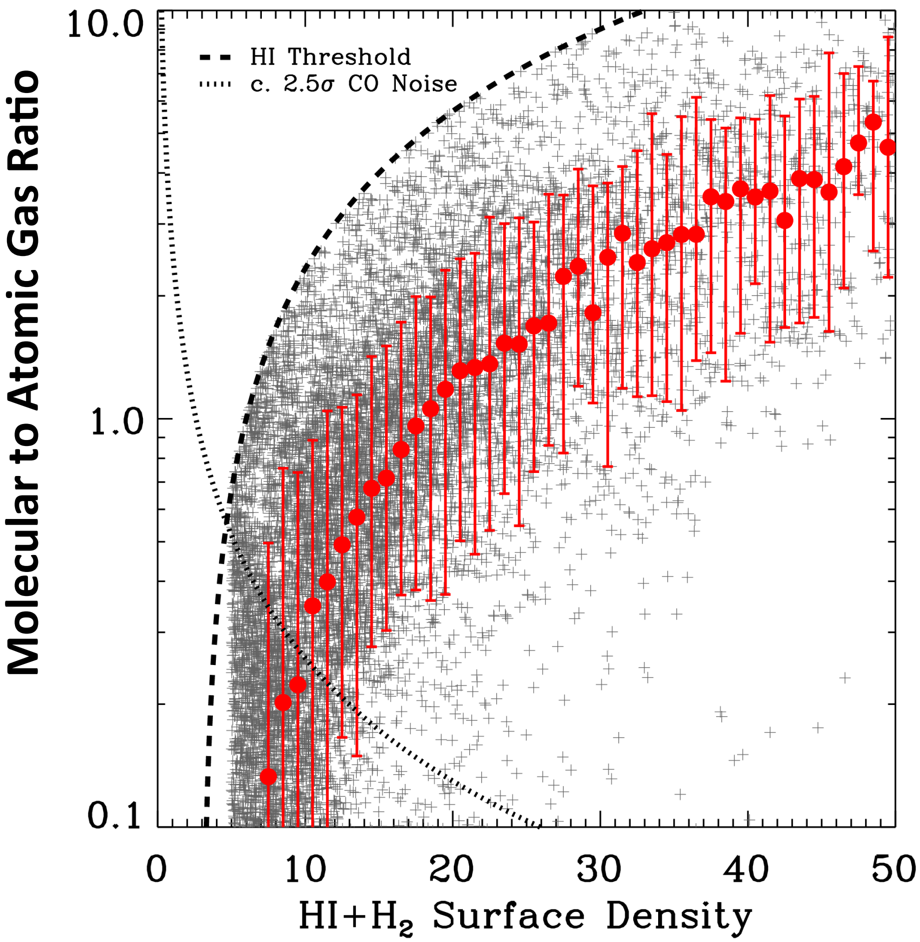
H_2-HI Balance

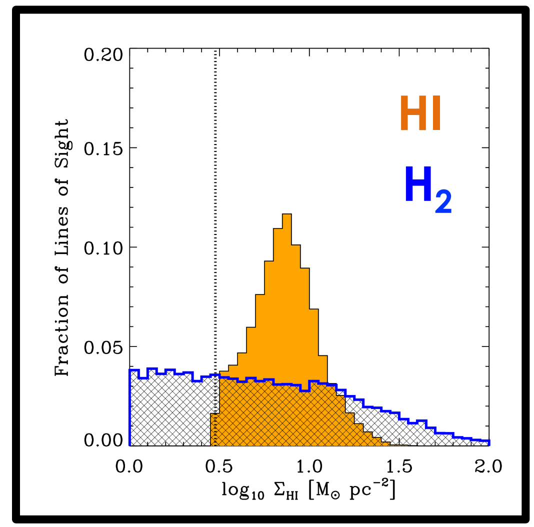
Cloud Structure / Dense Gas Fraction

Please Speak Up!

H_2-HI Balance

Column density predicts H_2 fraction, with HI showing a narrow distribution

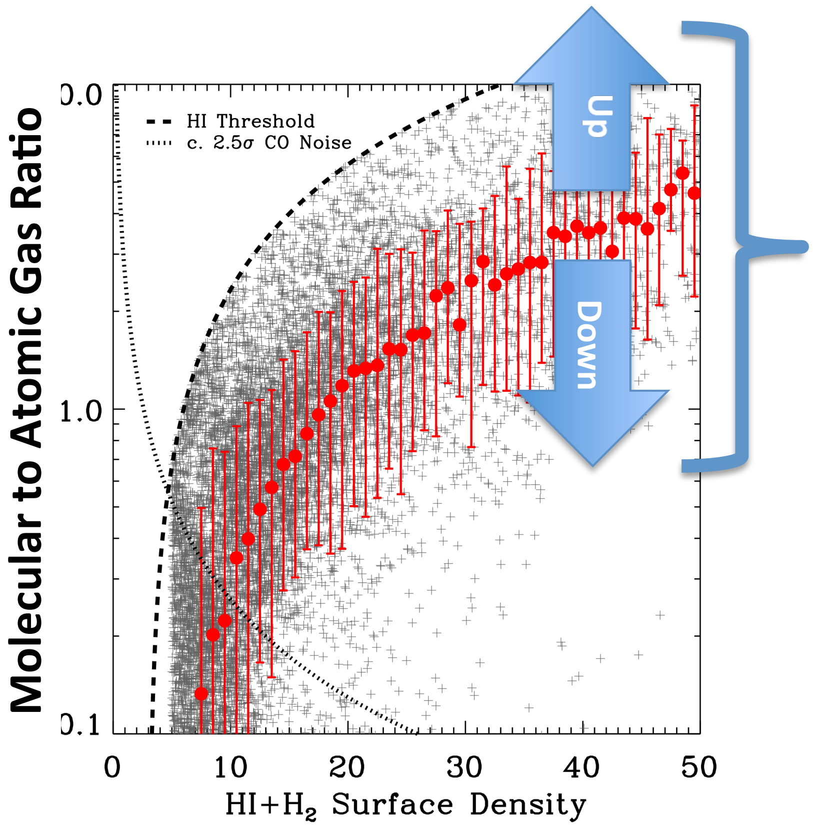


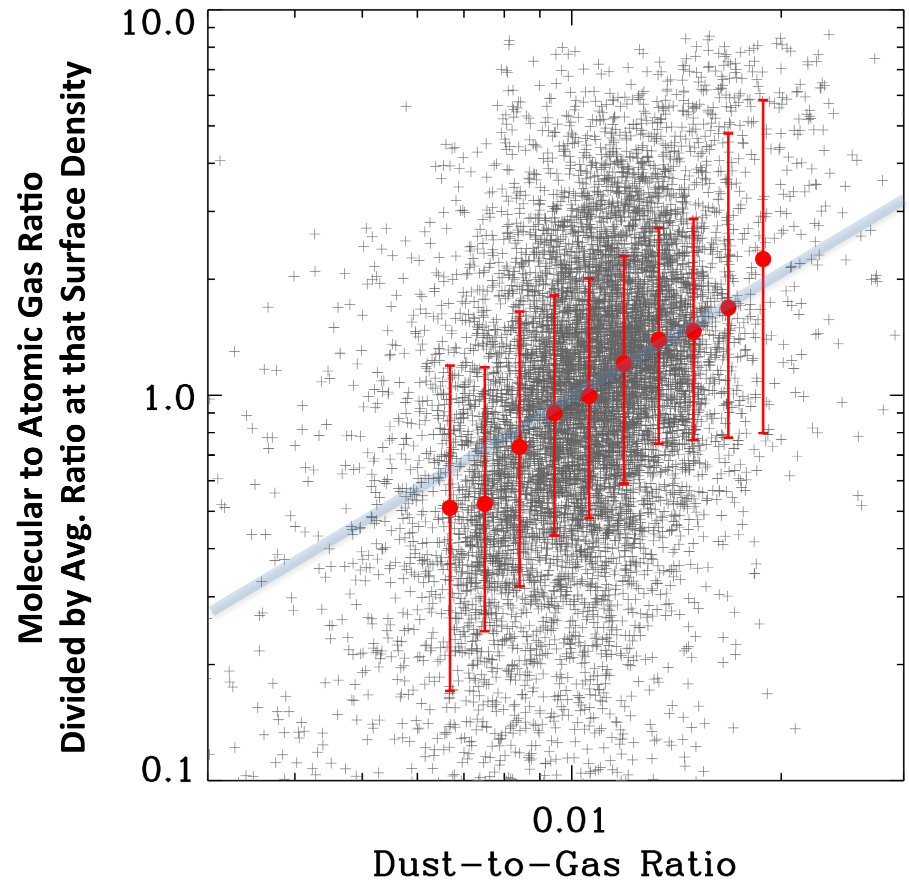


SCHRUBA, LEROY+ '11; LEROY+ '08; BIGIEL, LEROY+ '08; LEROY+ KINGFISH IN PREP.

H_2-HI Balance

Residuals in H_2/HI vs. column correlate with dust-to-gas ratio.
Expected for HI shielding layer in clouds.



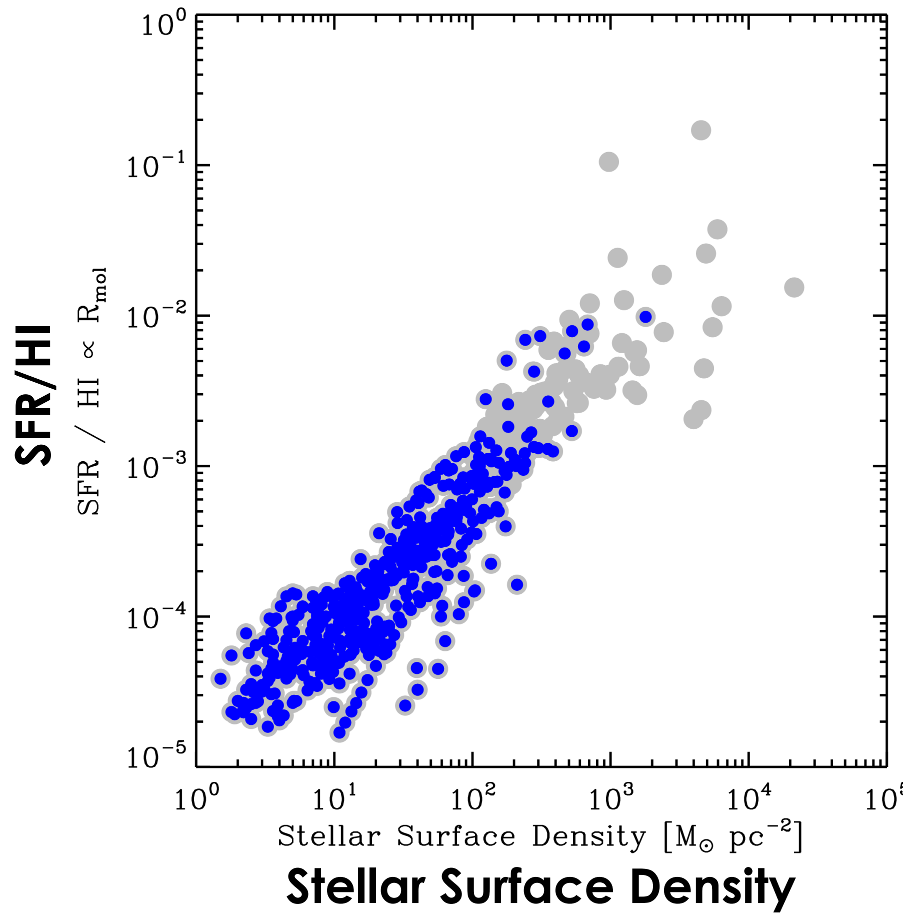


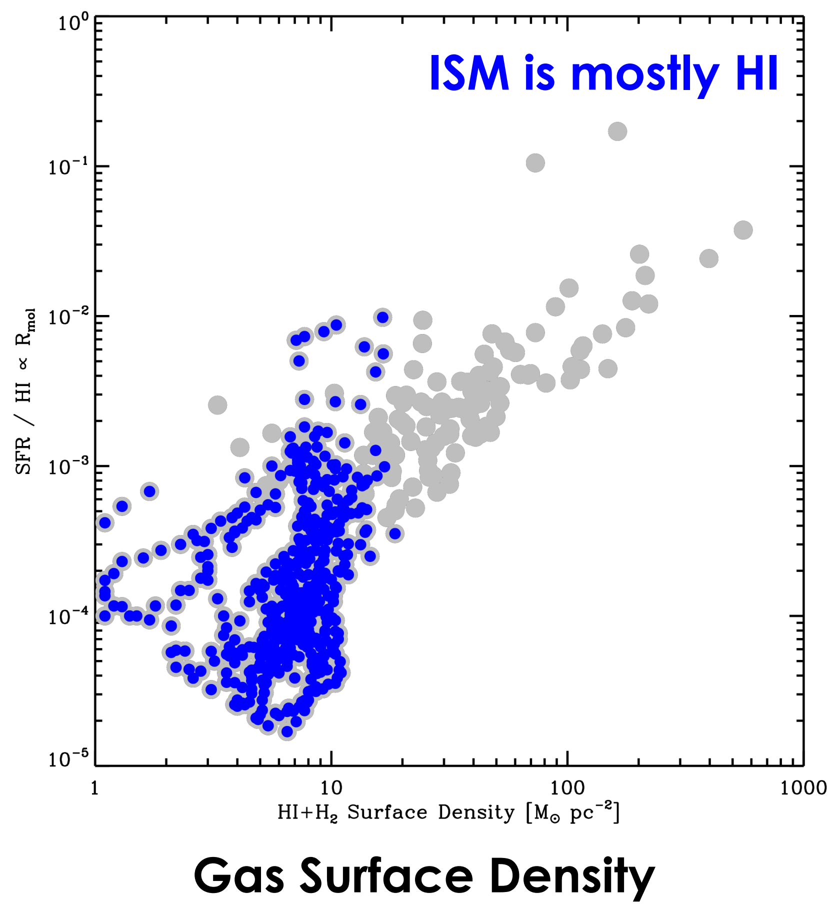
Leroy et KINGFISH (Aniano, Draine) + HERACLES + THINGS in prep.
Physics of HI shielding layer: Krumholz et al. 2009ab, Wolifre et al. 2010
12+log O/H more mixed: Wong+ (incl. Leroy) '13 but Watson, Martini+ '12

H_2-HI Balance

Strong dependence on stellar surface density.

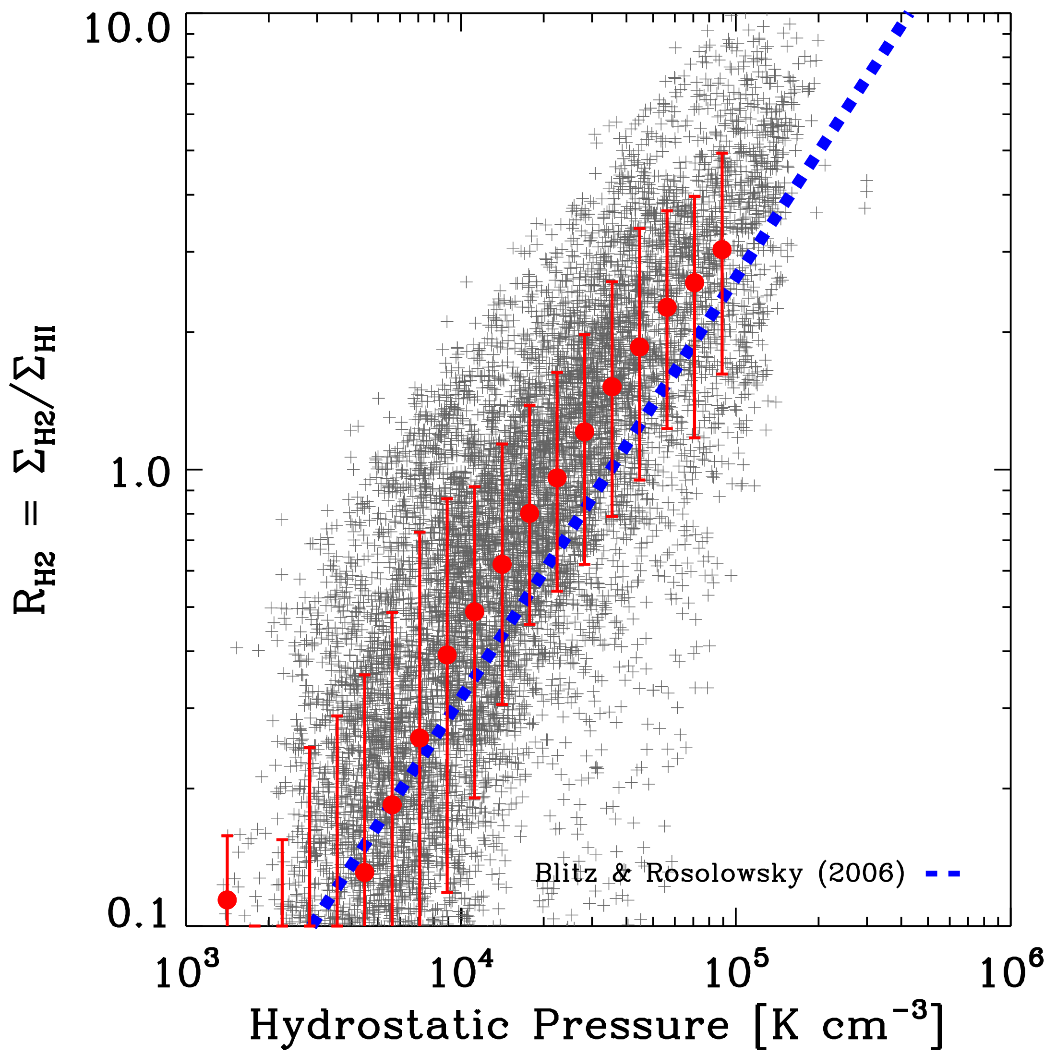
Large scatter at fixed gas surface density in same regime





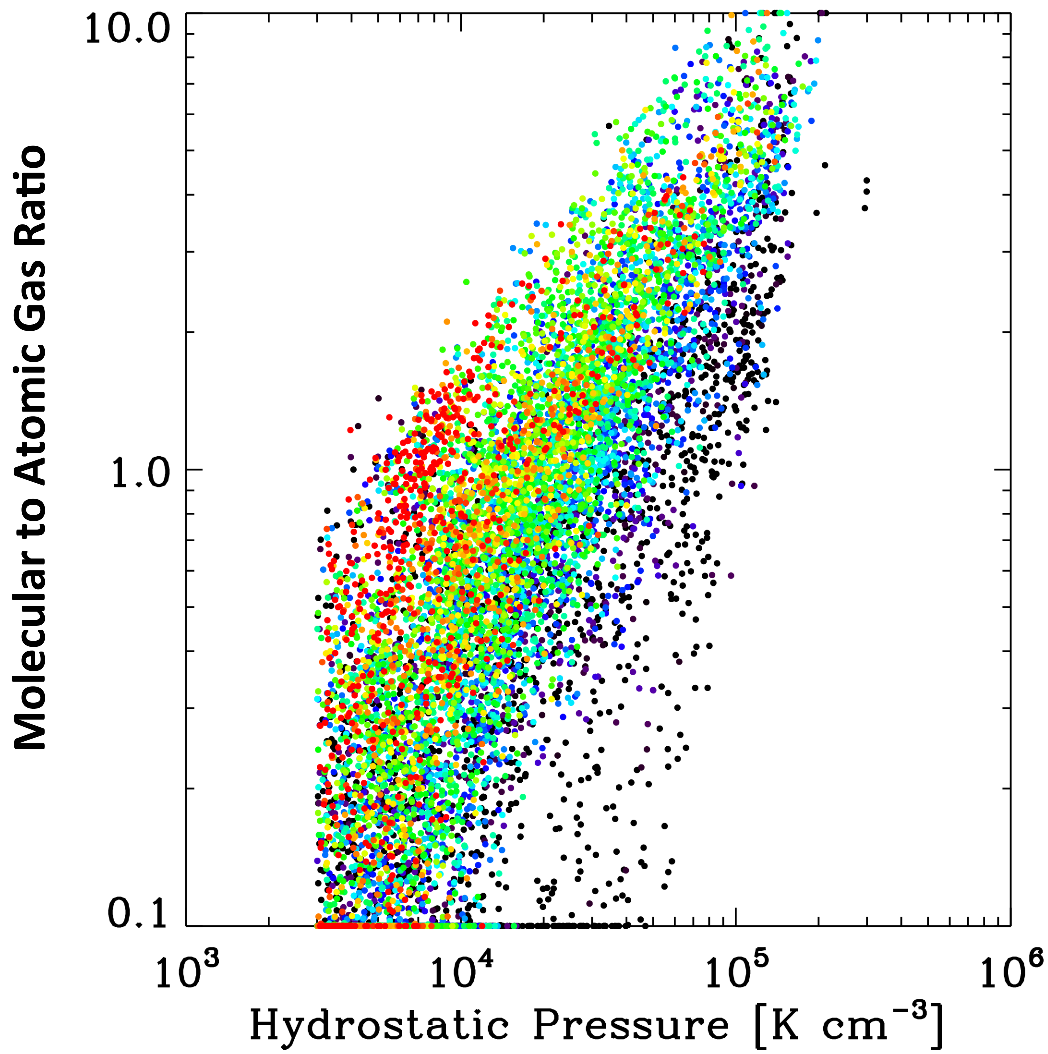
Leroy+ '08, '09, in prep.; see Reagan+ '01, Wong & Blitz '02 in the H_2-rich regime

Cloud Structure



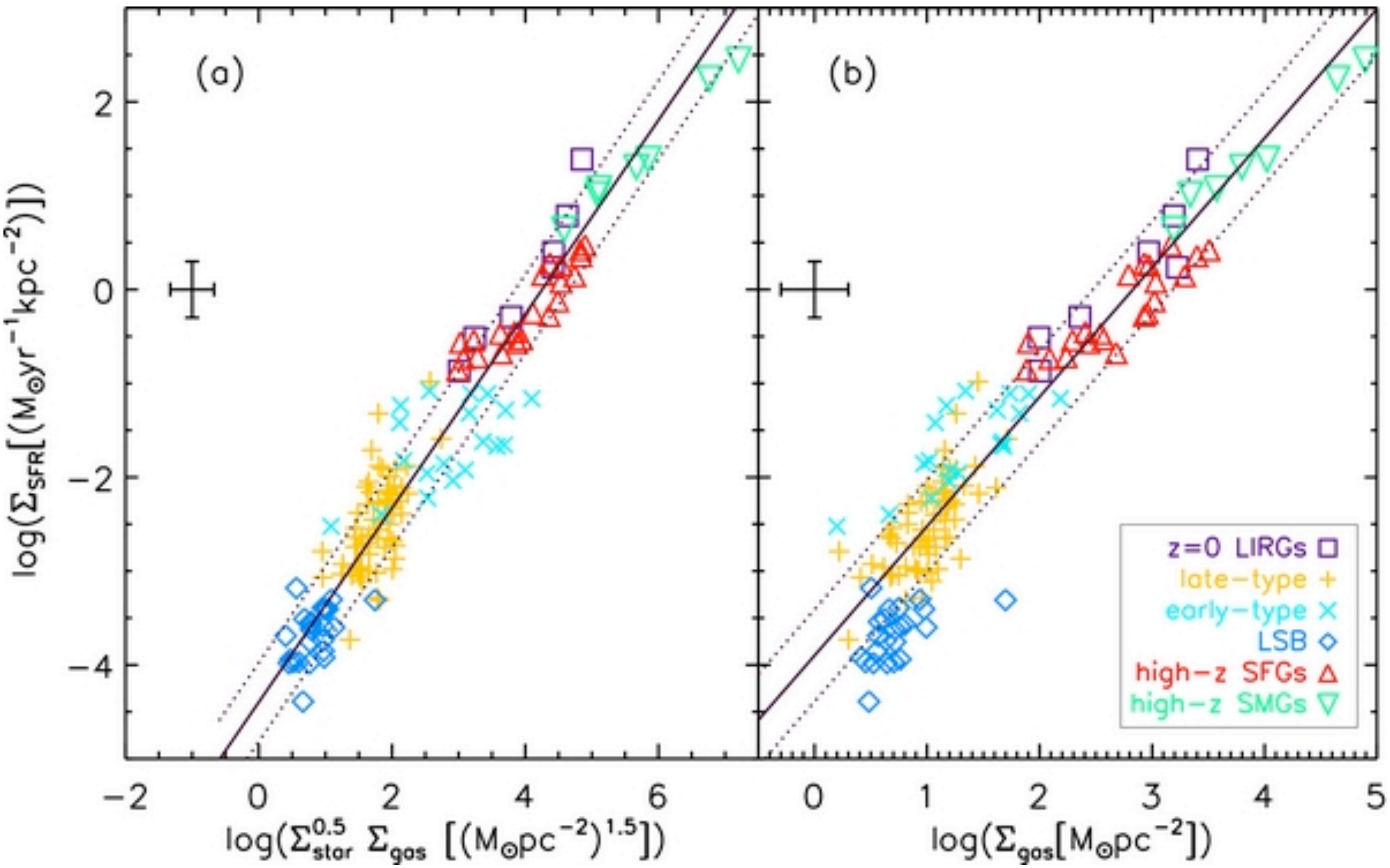
Leroy et KINGFISH (Aniano, Draine) + HERACLES + THINGS in prep.

Cloud Structure



Leroy et KINGFISH (Aniano, Draine) + HERACLES + THINGS in prep.

A Combined Gas-Stars Scaling



SHI+ '11, '14; DOPITA+ '93

H_2/HI Balance

1. Strong systematic changes in H2/HI across galaxies.

2. Dependences on gas column, stellar surface density.

3. Second order dependences on dust-to-gas ratio.

4. Other possible expressions:

- ISM pressure + DGR
- self-regulation to a roughly constant HI layer
- two parameter scaling law (stars and gas)

An Incomplete Look at Star Formation on Galactic Scales

Terminology / Framework

Scales

HI–SF Balance

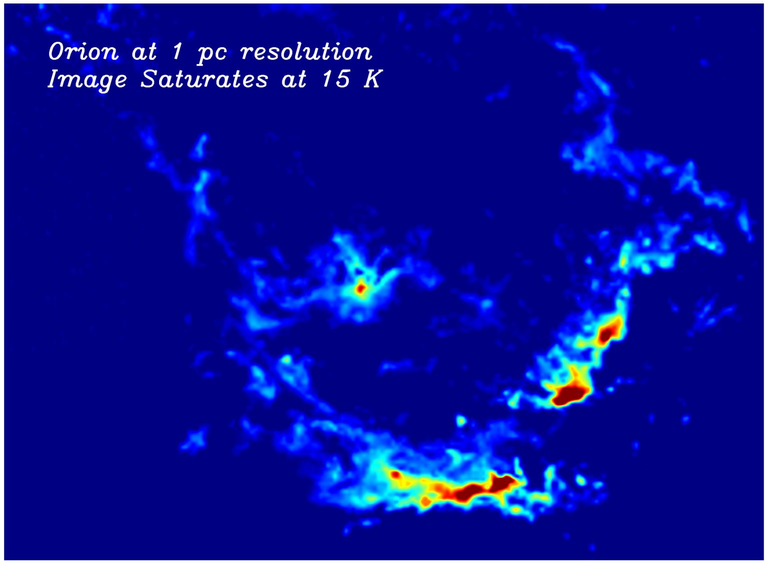
H_2–SF Balance

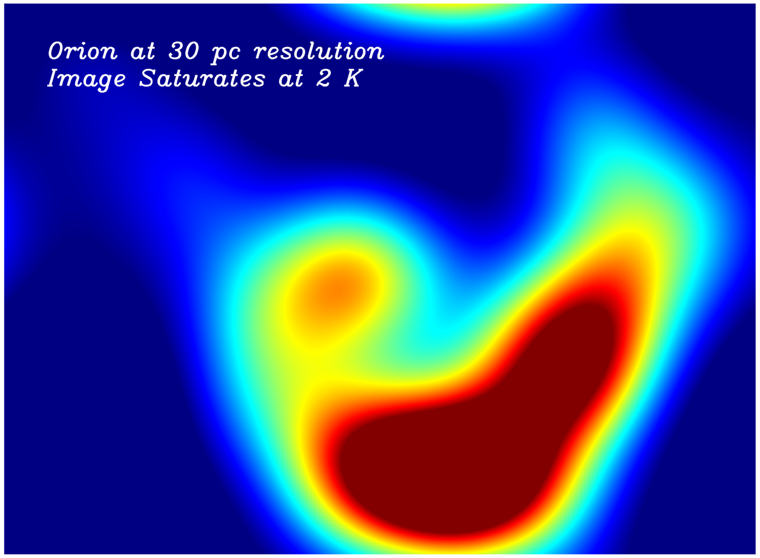
H_2–HI Balance

Cloud Structure / Dense Gas Fraction

Please Speak Up!

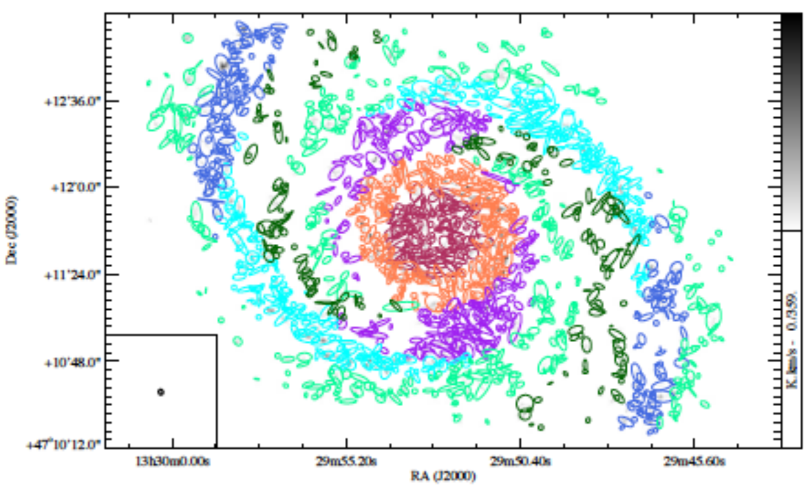
Cloud Structure Across the Local Universe

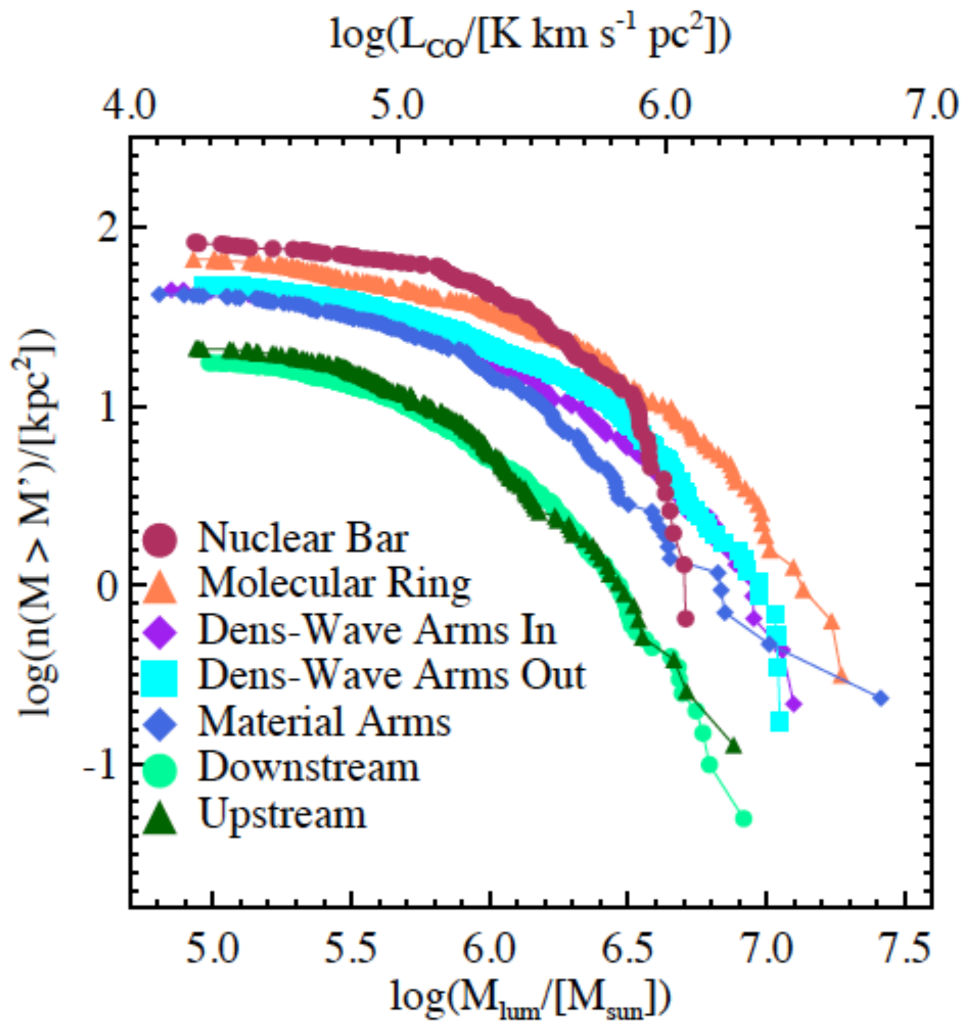




Wilson et al. (2005)

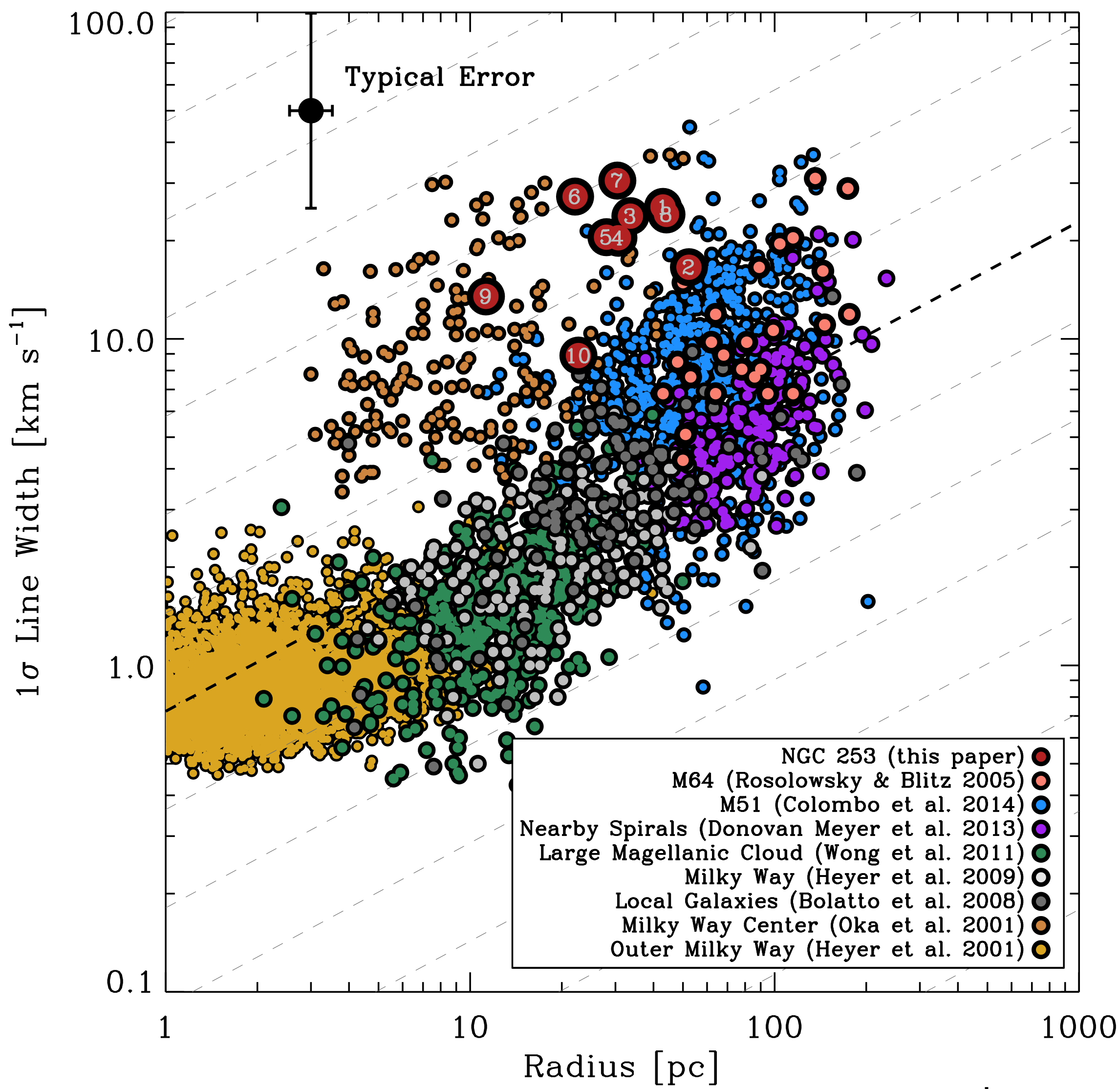
Cloud Structure – Environmental Dependence





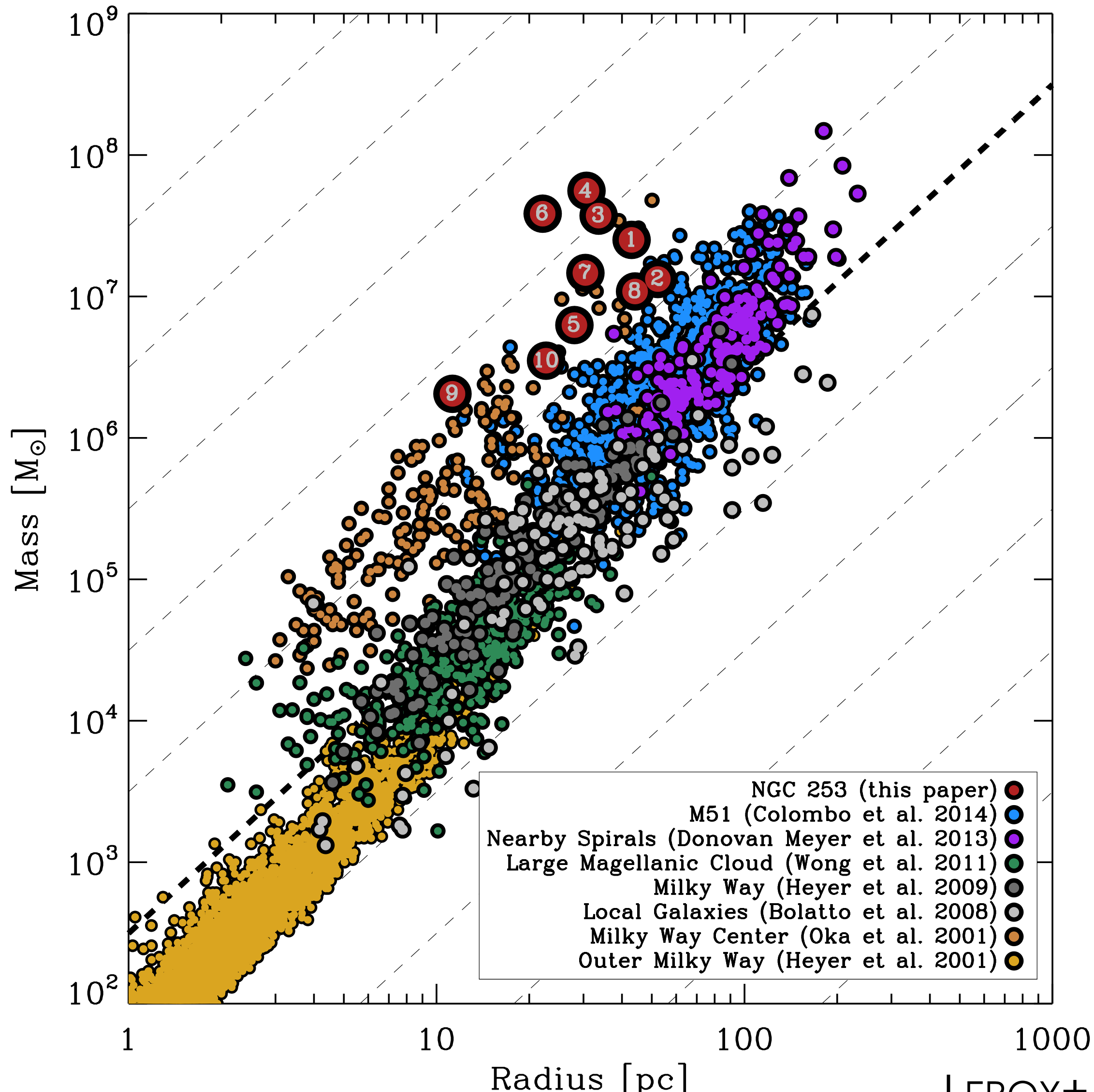
COLOMBO+ '14, HUGHES+ '13 (INCL MEIDT), SCHINNER+ '13, PETY+ '13; C.F. KODA+ '09

Turbulence - Line Width Size



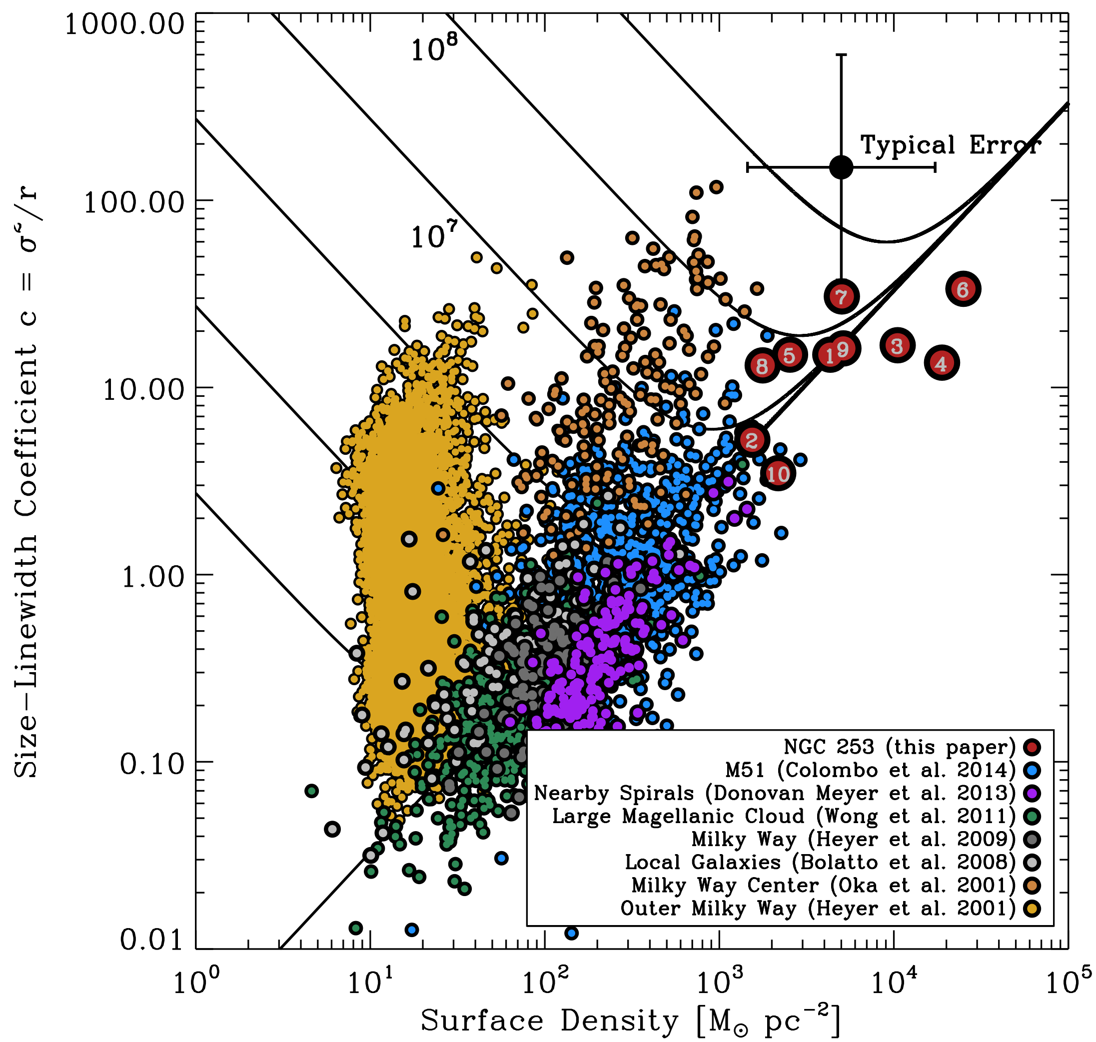
Leroy+ '14 - accepted

Cloud Density/Surface Density



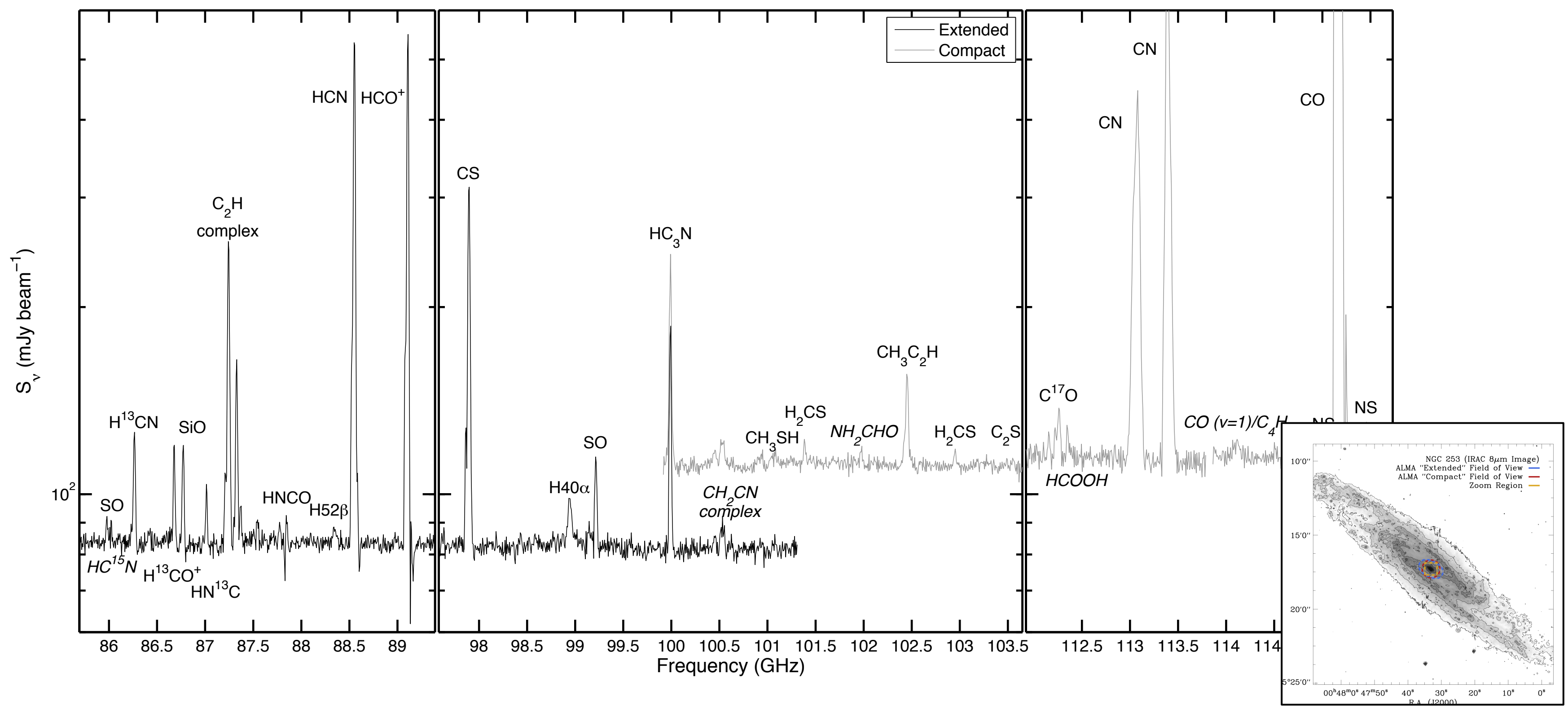
LEROY+ '14 - ACCEPTED

Dynamical State

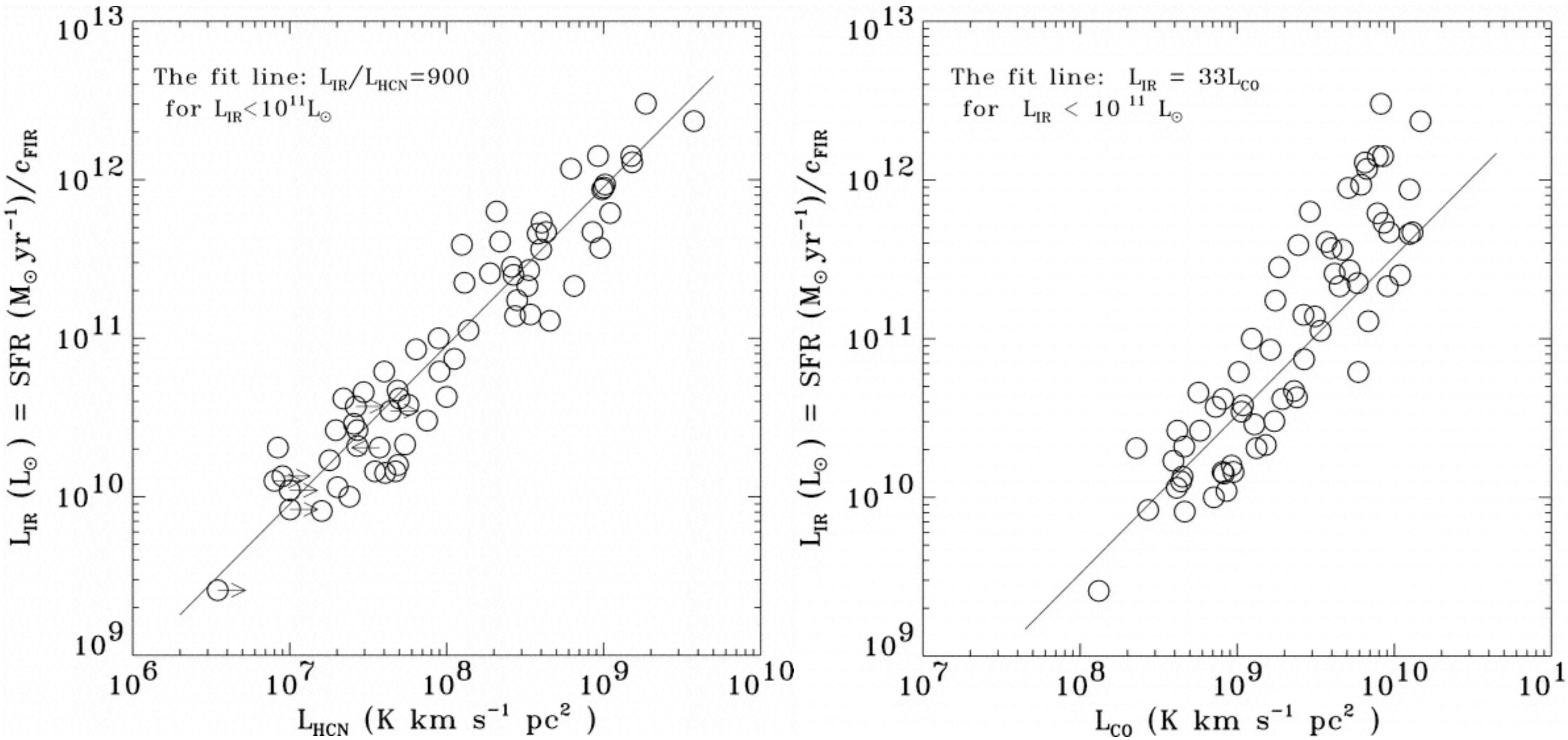


LEROY+ '14 - ACCEPTED

Spectroscopy to Get Cloud Structure

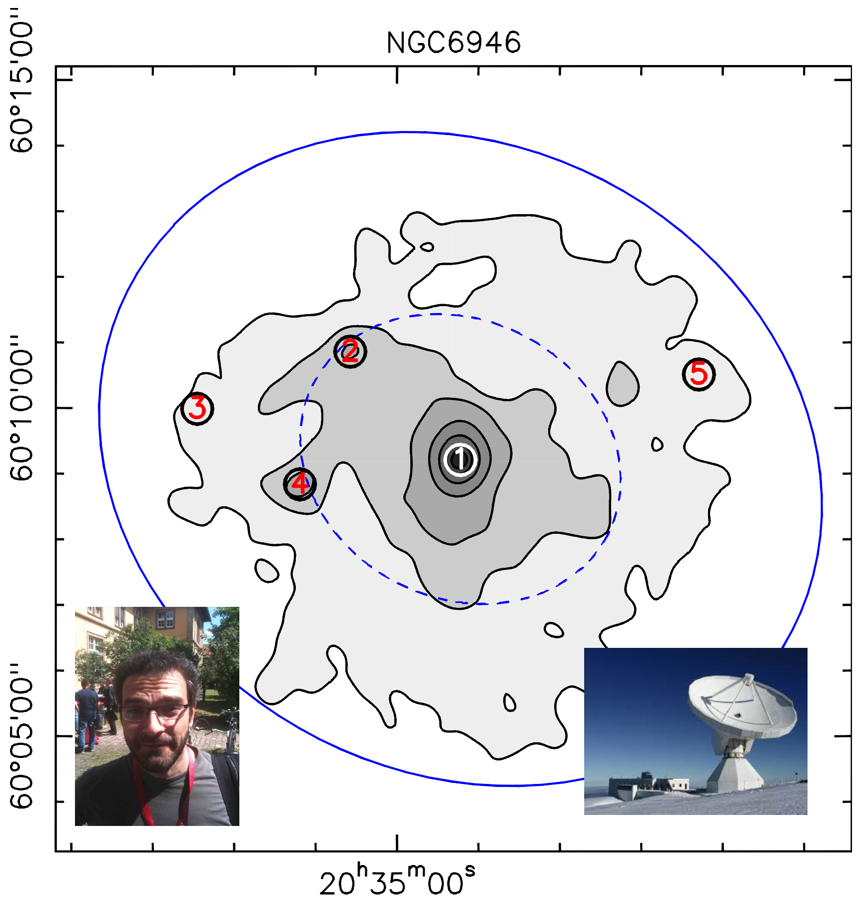


Just Dense Gas?



Gao & Solomon 04ab; see also *Garcia-Burillo et al.* (2012)

Dense Gas Surveys

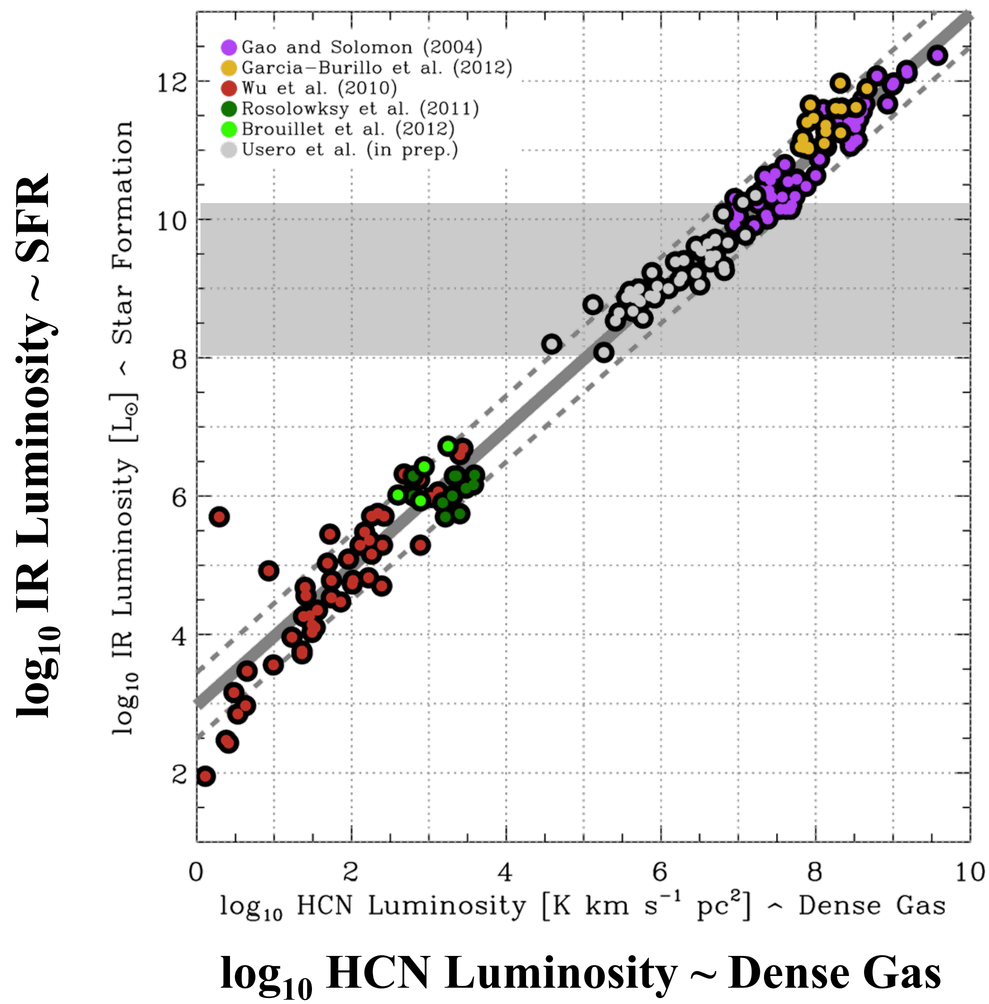


IRAM 30-m Survey of Disk Pointings
PI: Antonio Usero (OAN, Madrid)
Observations: 2008-2011

- Targeted 62 regions in 29 galaxies.
- Resolution ~ 1 – 2 kpc
- Drawn from HERACLES survey.
- Have SINGS, THINGS++, KINGFISH
- Also HCO+, other CO, HNC, more…
- Picked to:
  - Be detectable (bright CO)
  - Sample a range of radii, conditions

"Gao and Solomon for Disks"

Spectroscopic Cloud Structure: Dense Gas

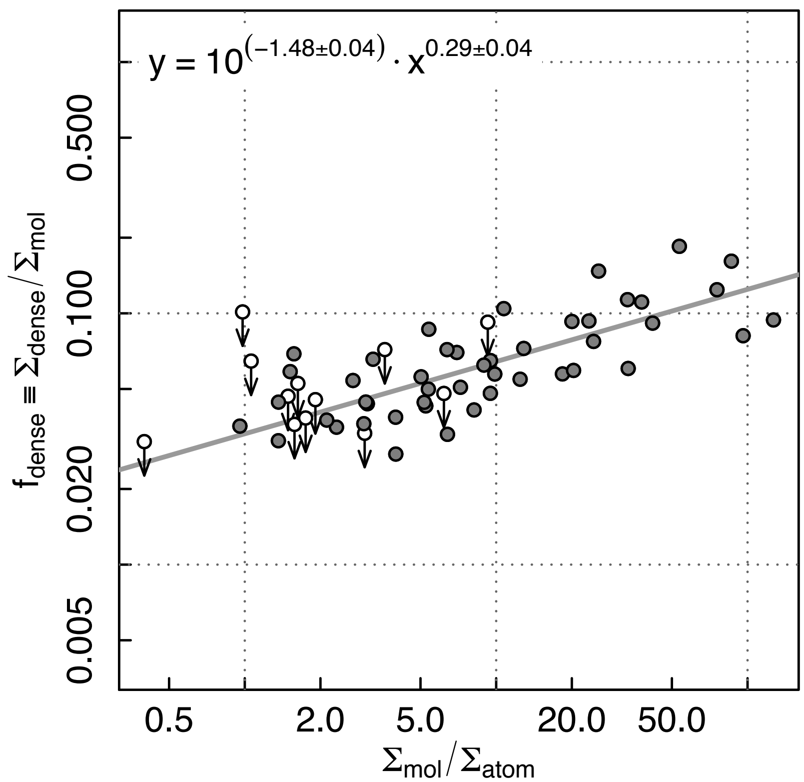


new survey: galaxy disks

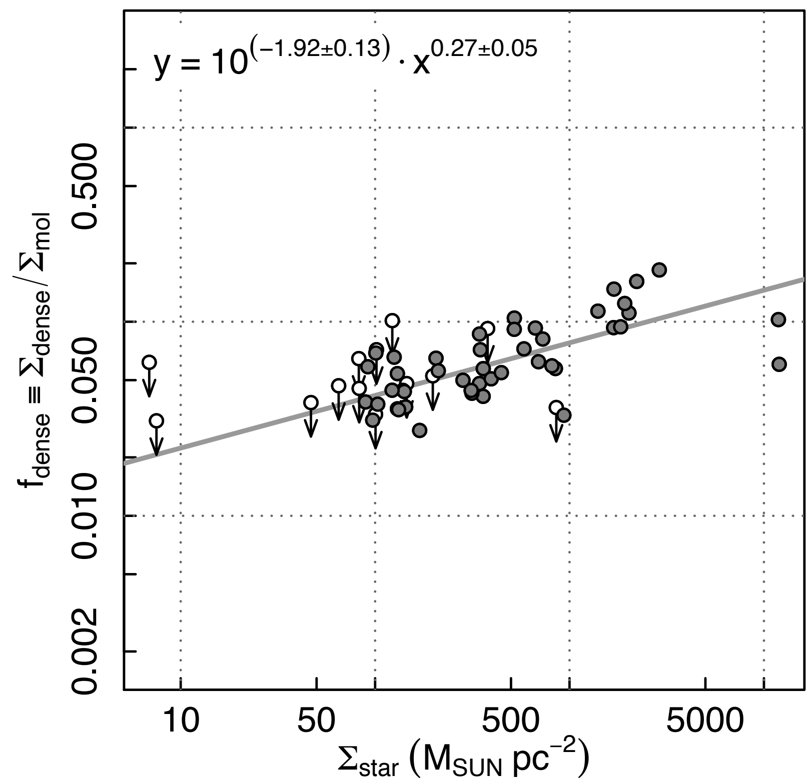
HCN-to-CO Increases With Surface Density

Apparent dense gas fraction a clear function of surface density inside galaxy disks.

HCN-to-CO vs. H_2/HI



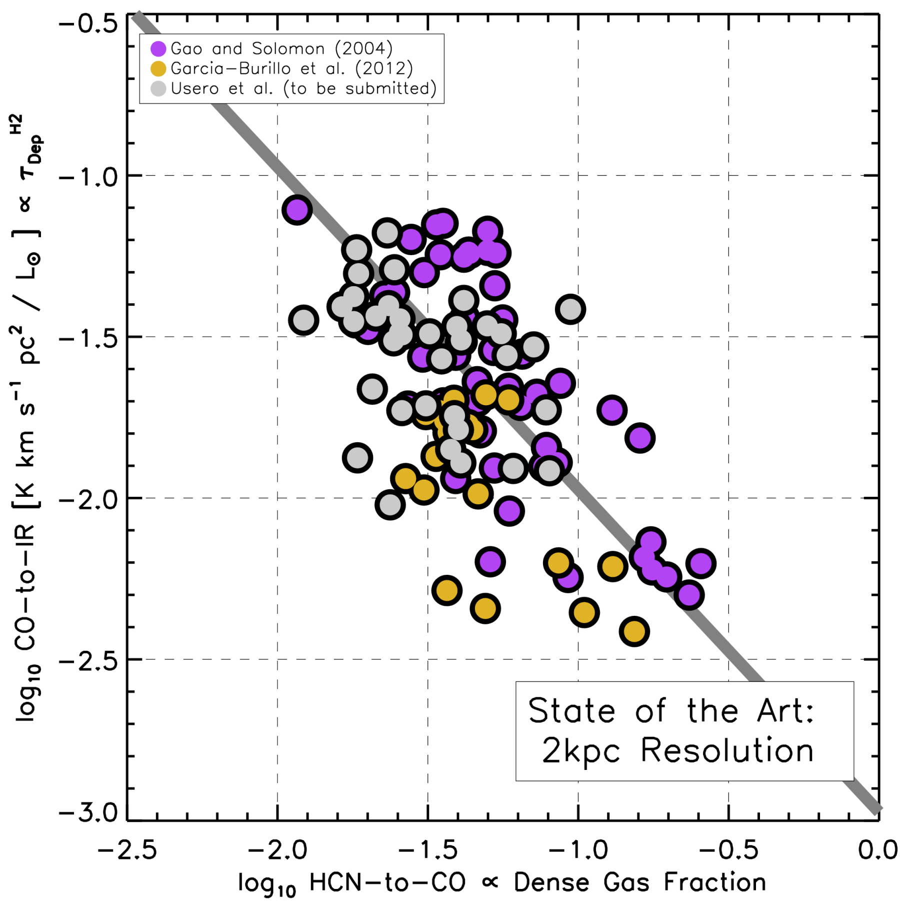
IR-to-HCN vs Stellar Surface Density



Usero, Leroy et al. to be submitted

Dense Gas Fraction As Driver

Apparent dense gas fraction predicts apparent depletion time but with huge scatter.



~ H_2 Depletion Time (CO-to-IR)

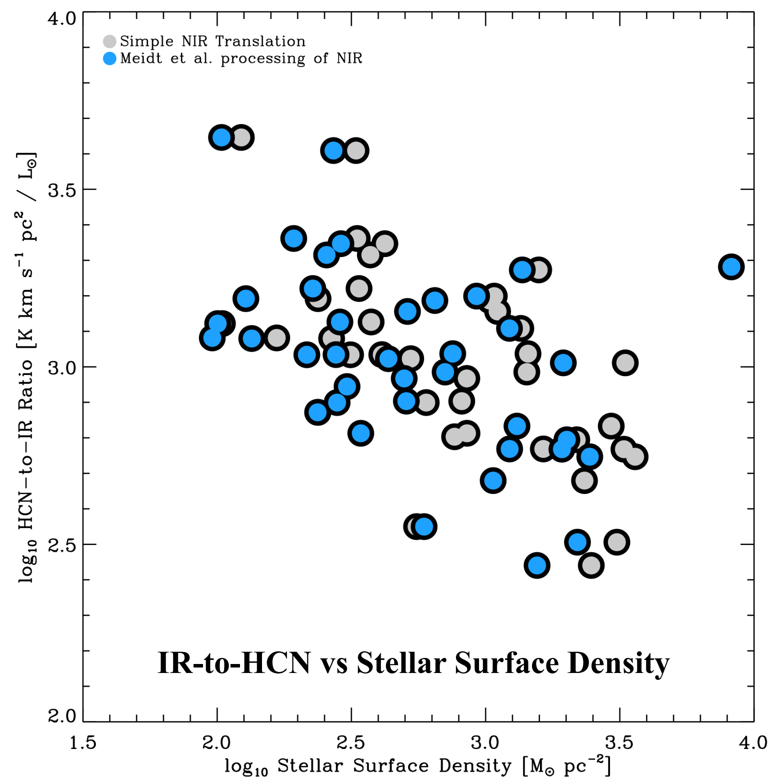
~ Dense Gas Fraction (HCN-to-CO)

Usero, Leroy et al. to be submitted

Non-Universal Dense Gas Efficiency

A universal density threshold can be rescued by playing with HCN “conversion factors,” though the plausible range is quite specific – it has to cancel the observed trend.

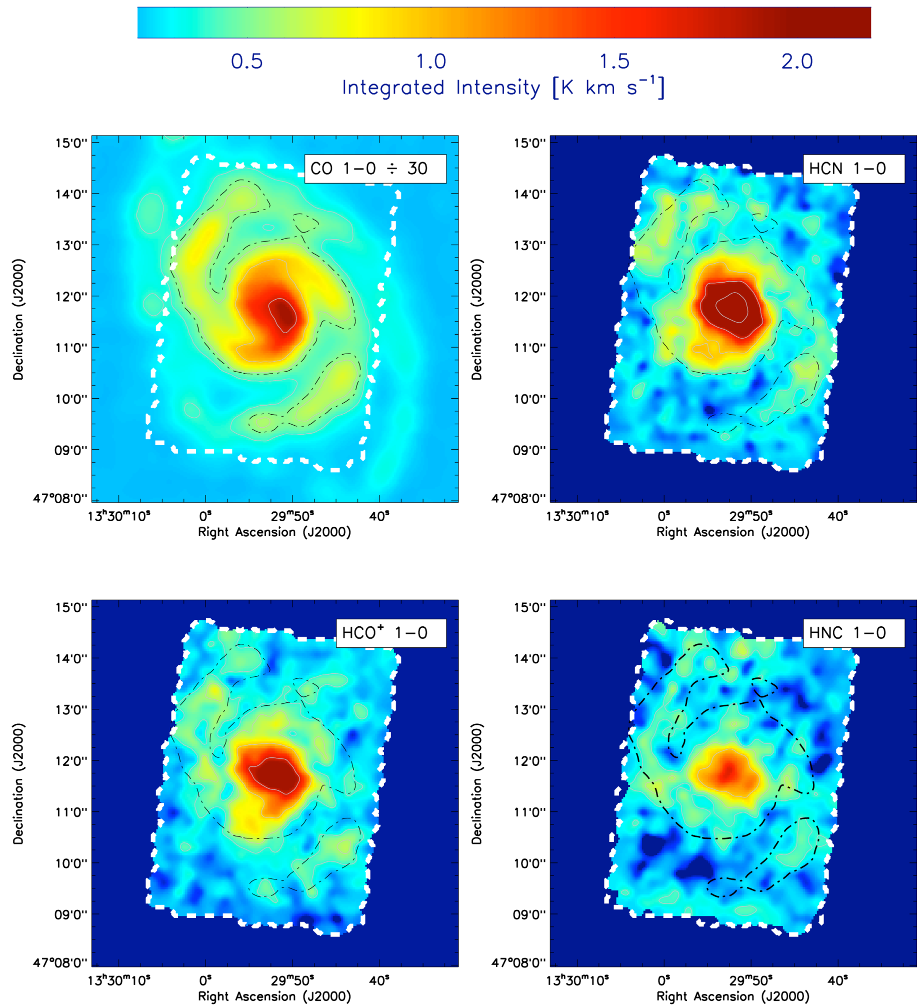
But, this removes the a major observational plank from the “universal” threshold idea.



Usero, Leroy et al. to be submitted

Dense Gas Maps

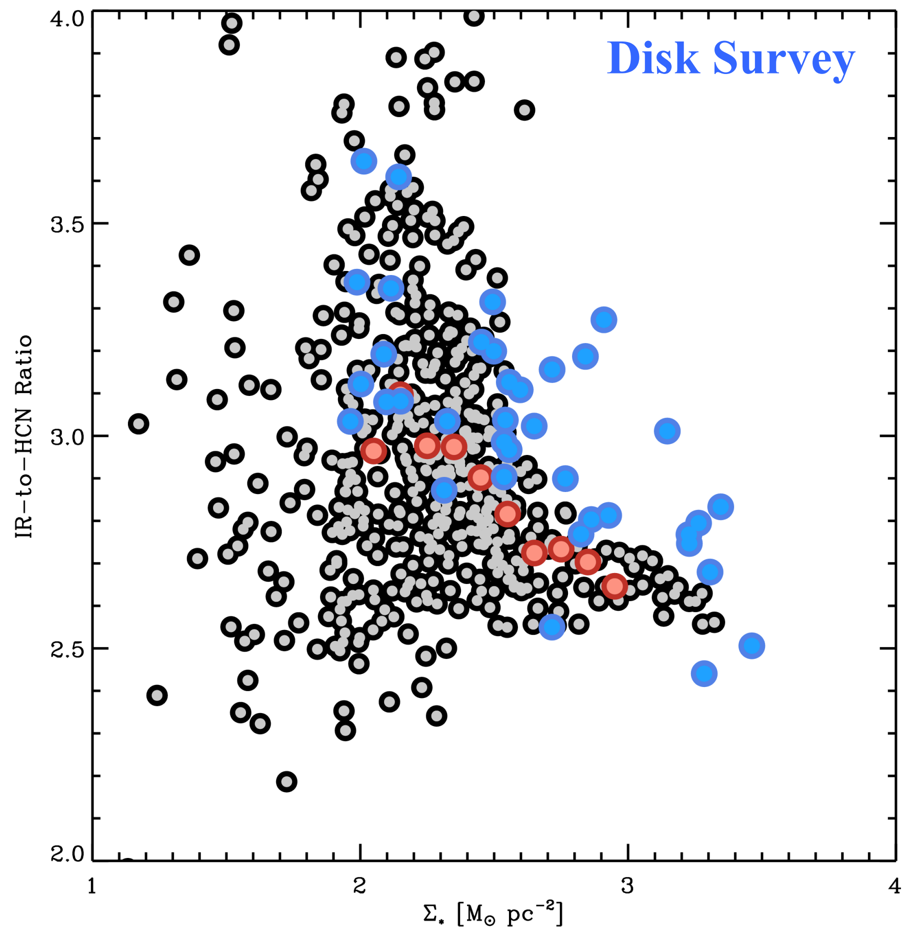
HCN, HCO+, HNC (1-0) mapping of M51 disk.



***Frank Bigiel** et PAWS (in prep.) – incl. Pety, Hughes, Schinnerer*

Non-Universal Dense Gas Efficiency

M51 whole-galaxy map agrees (to first order) with selected disk points.



IR-to-HCN vs Stellar Surface Density

Gray points: 1 kpc, Red points: binned data

Usero, Leroy to be submitted, M51: Bigiel et al. (in prep.)

Cloud Structure / Dense Gas Fraction

1. Cloud populations depend on environment.

2. Mass function, turbulence, dynamical state all vary.

3. Spectroscopic tracers of cloud structure (e.g., HCN/CO) also show systematic variations.

4. Perhaps surprisingly (or not) SFR per dense gas also shows substantial variation.