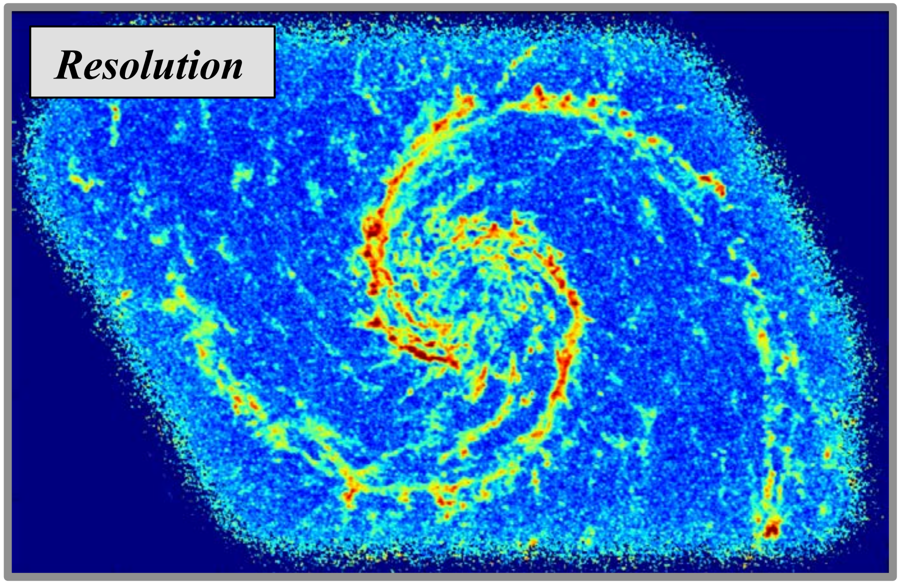
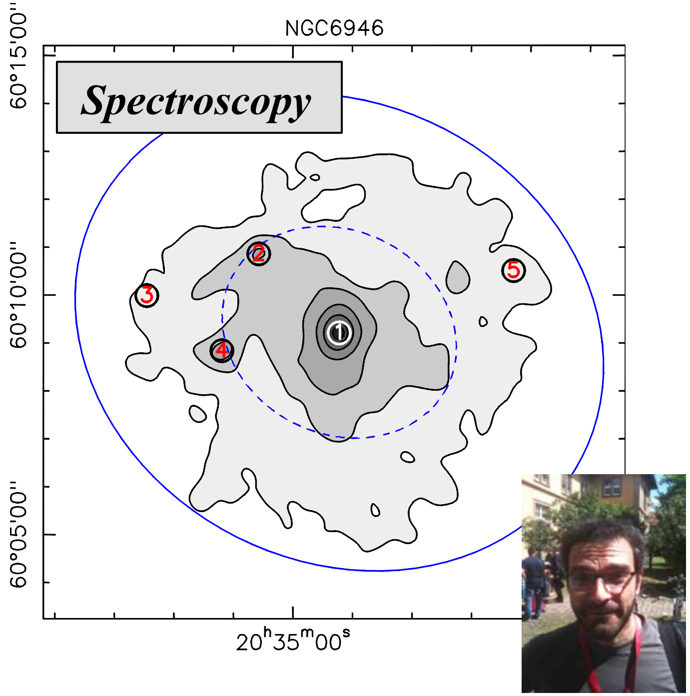
Physical Conditions in the ISM and Star Formation





Adam Leroy (Ohio State University)

Antonio Usero (OAN Madrid), Santiago Garcia-Burillo, Karin Sandstrom, Fabian Walter, and the HERACLES/THINGS Dense Gas Team; Annie Hughes, Sharon Meidt, Eva Schinnerer and the PAWS team
Frank Bigiel and the EMPIRE collaboration,, **Amanda Kepley**, Erik Rosolowsky

SFR Scalings

Overall scaling of molecular gas and recent star formation in local galaxy disks.

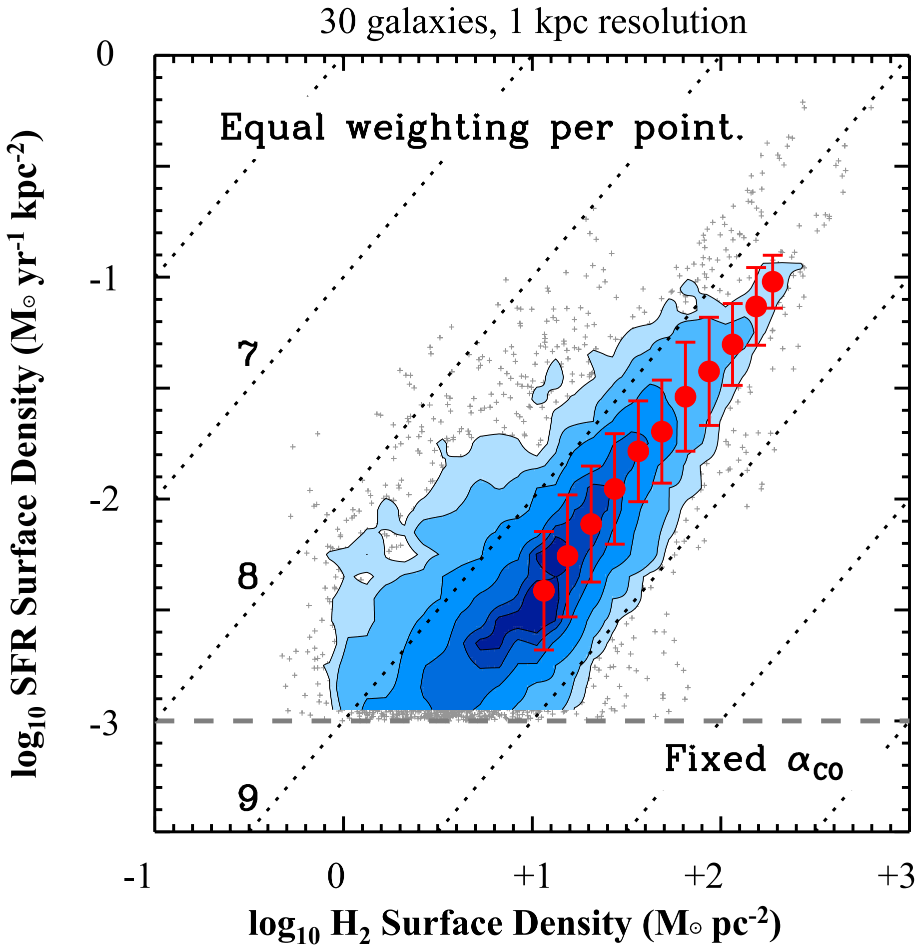


Figure of merit:

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

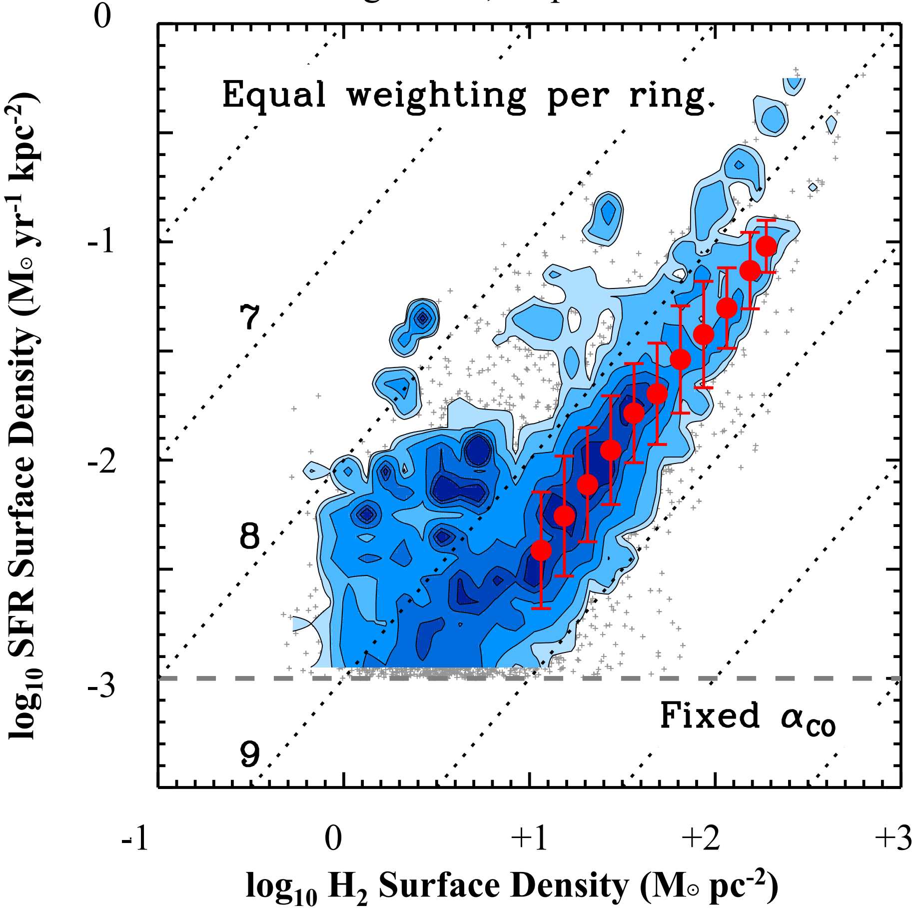
Intensive measure of star formation per unit gas. At large enough scales, the ratio captures a psuedo-equilibrium of collapse and feedback to give you an idea of the normalized ability of a patch of ISM to form stars.*

Leroy, Walter, Sandstrom et al. (2013)

Physical Variations in τ^{Dep}_{H2}

Substantial physically-driven variations present when you start to slice the data.

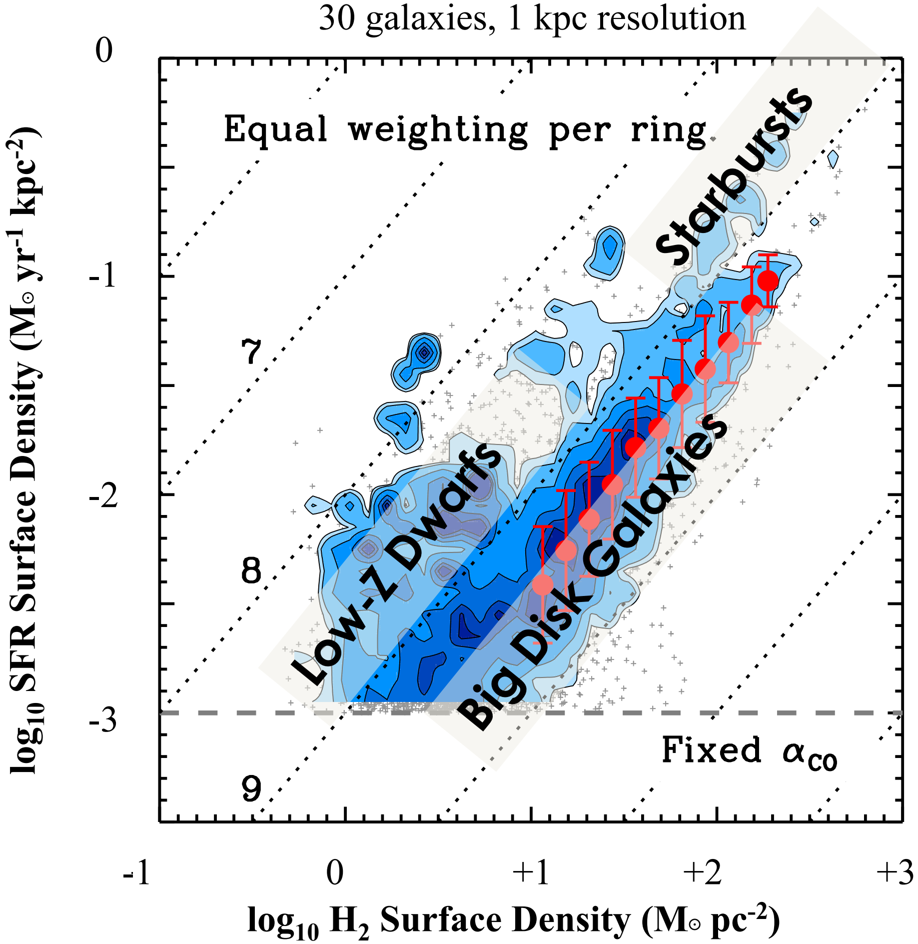
30 galaxies, 1 kpc resolution



Leroy, Walter, Sandstrom et al. (2013)

Systematic Variations in τ^{Dep}_{H2}

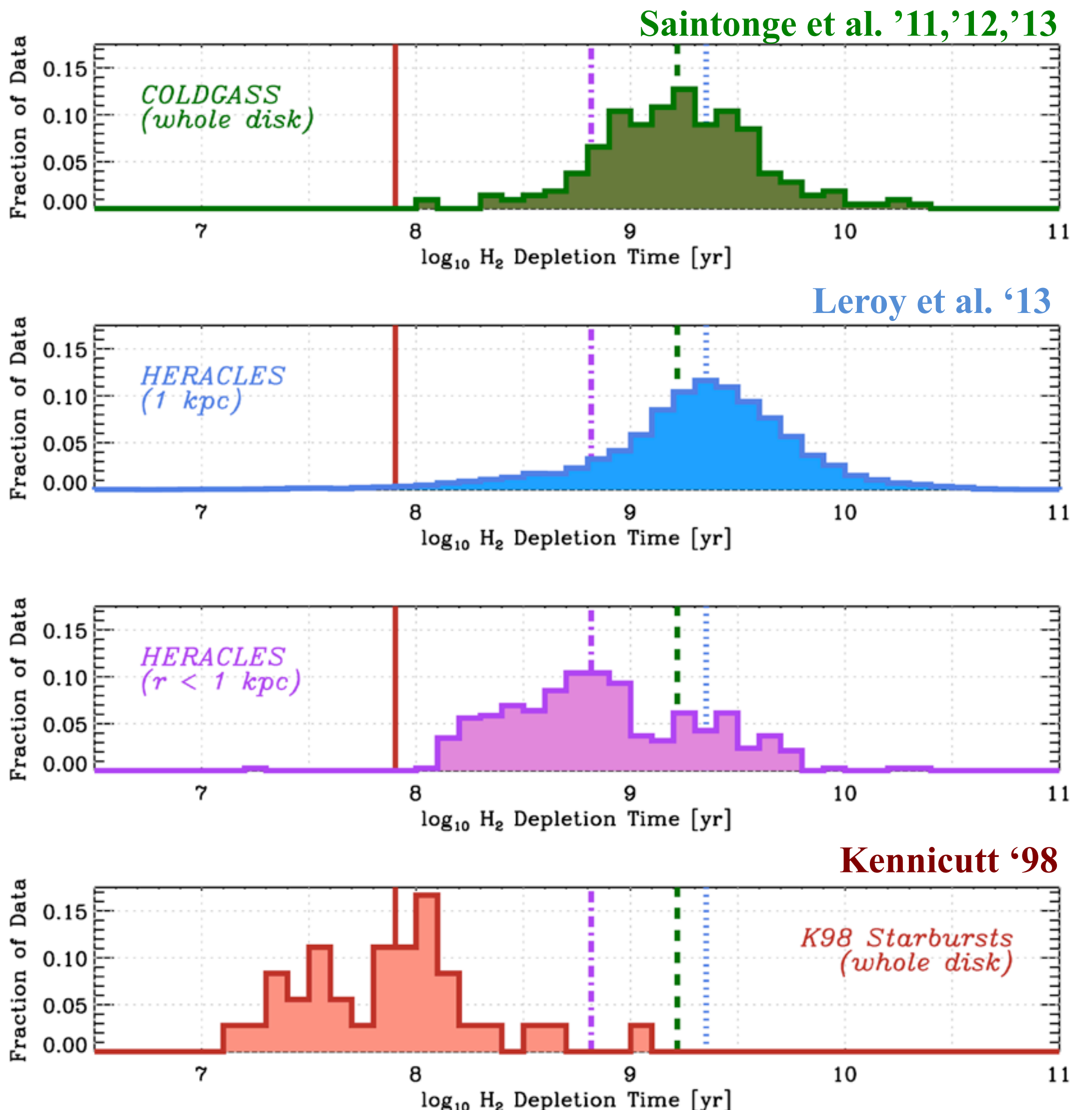
Substantial variations present when you start to slice or expand the data.



Leroy, Walter, Sandstrom et al. (2013)

Galaxies, kpc Regions, Centers, Starbursts

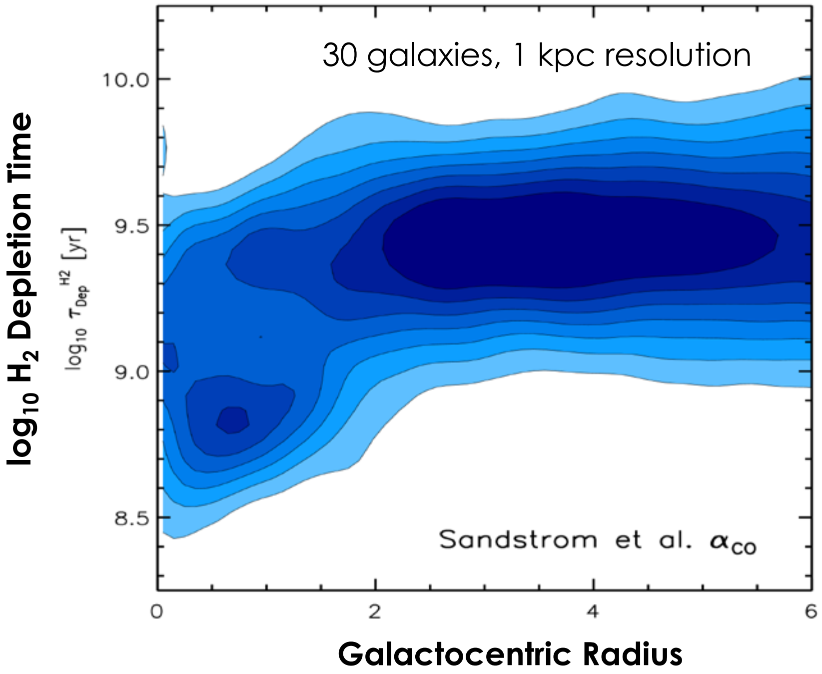
Substantial variations present when you start to slice the data.



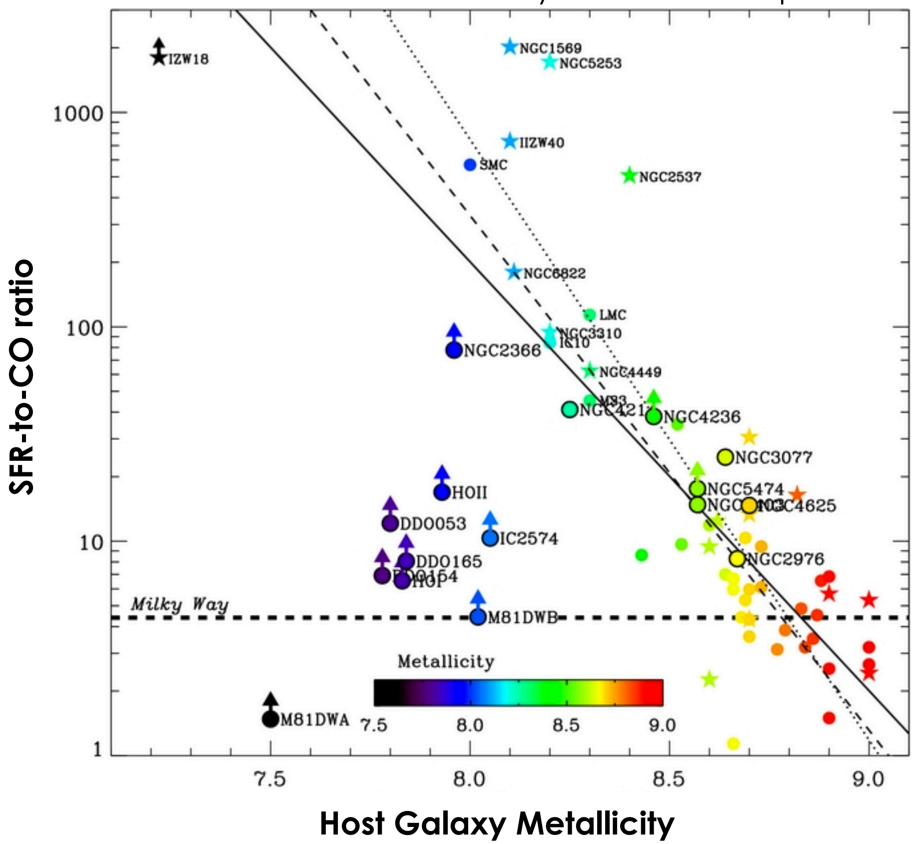
Inclues a best-estimate varying α_{CO} treatment.

Galaxy Centers and Low Metallicity Targets

Key variations: centers, starbursts, low metallicity galaxies (apparently)



Low metallicity literature compilation

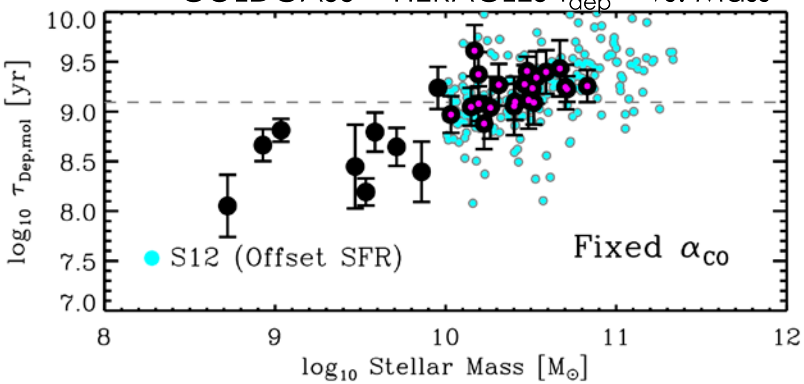


Leroy, Walter, Sandstrom et al. (2013), Schruba, Leroy et al. (2012)

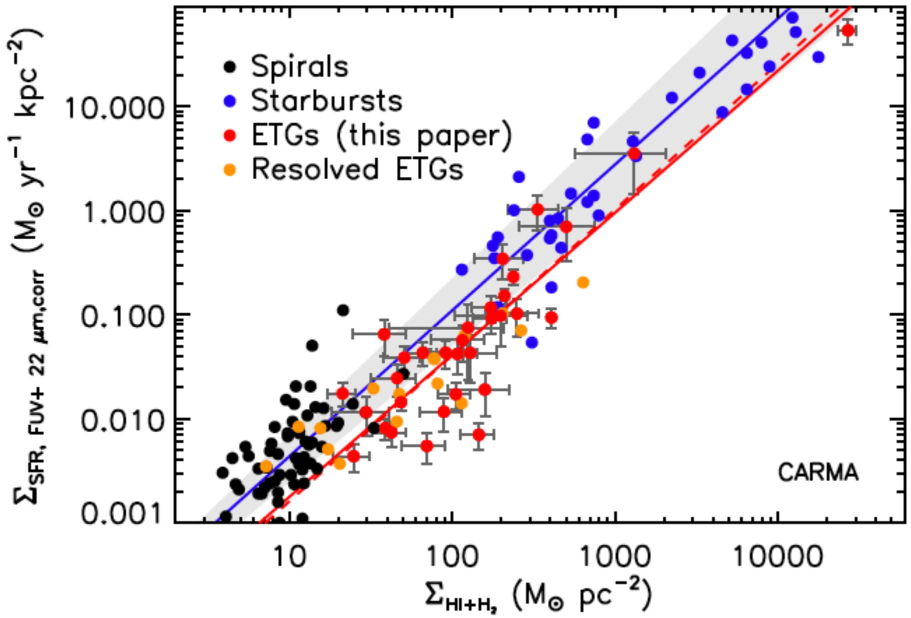
Galaxy Mass and Early Type Galaxies

Key variations: host galaxy mass, morphology (early types inefficient)

COLDGASS + HERACLES t_{dep}^{H2} vs. Mass



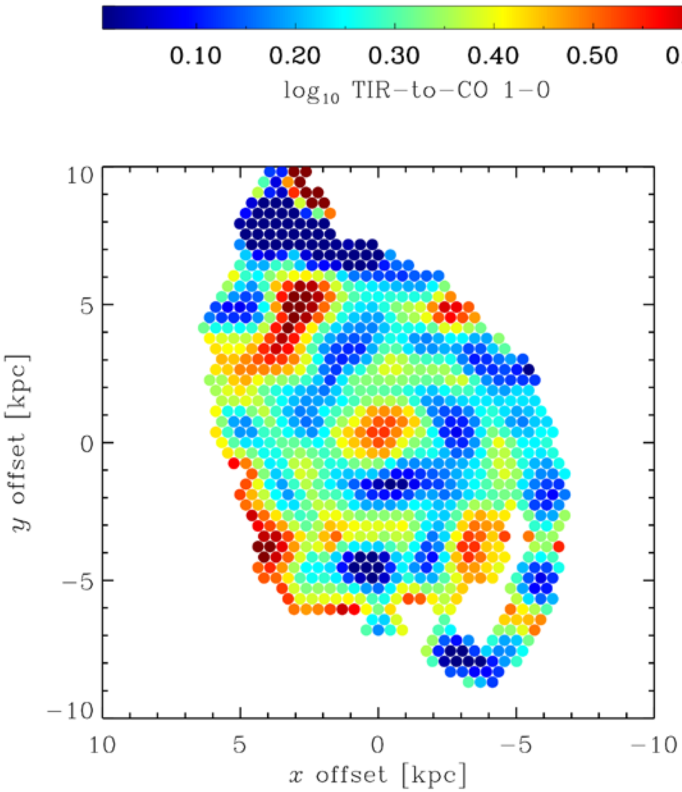
ATLAS 3D SFR vs total gas

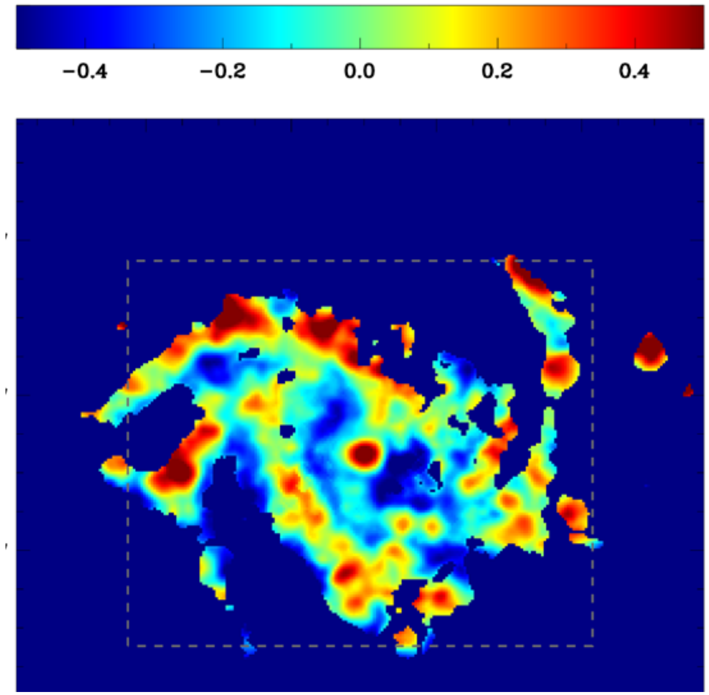


Davis et Atlas-3D ’13; c.f. Alatalo, Young; Saintonge+ ’11, **‘12**, ’13; Leroy, Walter, Sandstrom et al. ’13

Variations in τ^{Dep}_{H2} within galaxies

IR-to-CO ratio (~ τ^{Dep}_{H2}) region-by-region in M51 and NGC 6946 – significant and systematic variations from place to place.

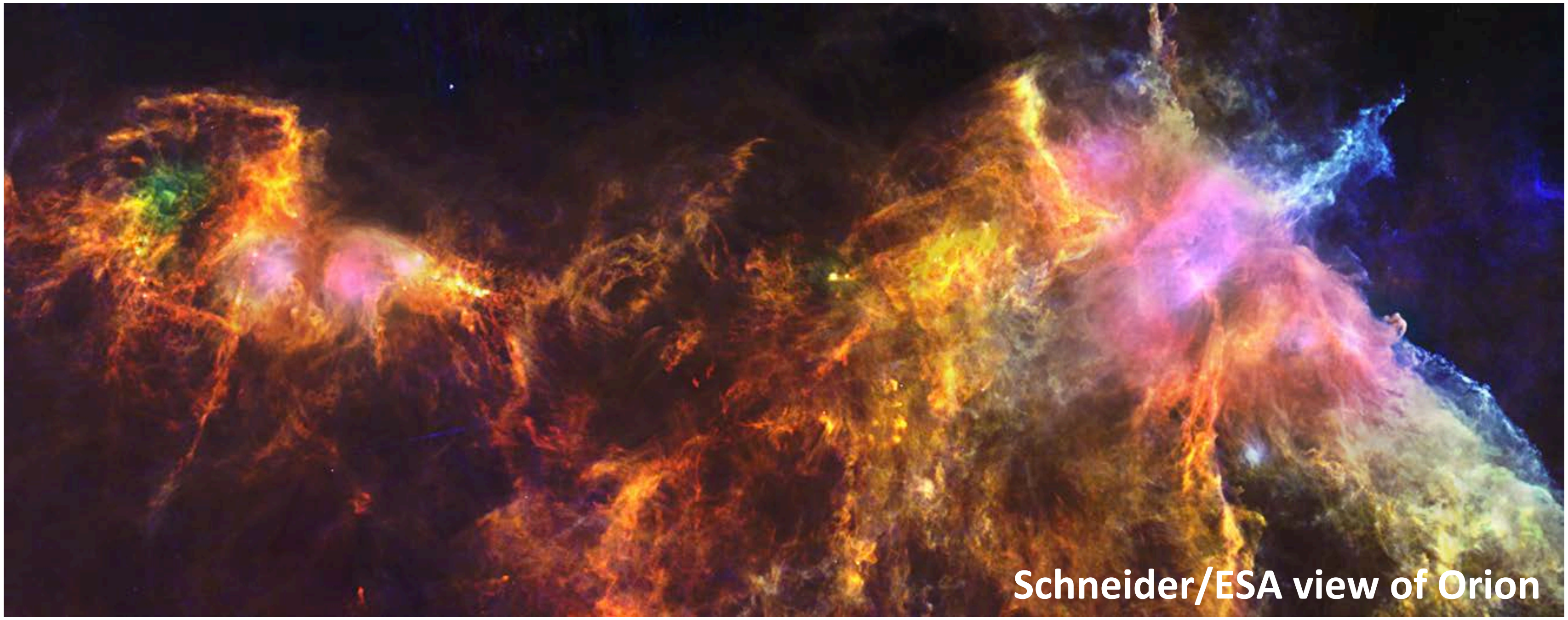




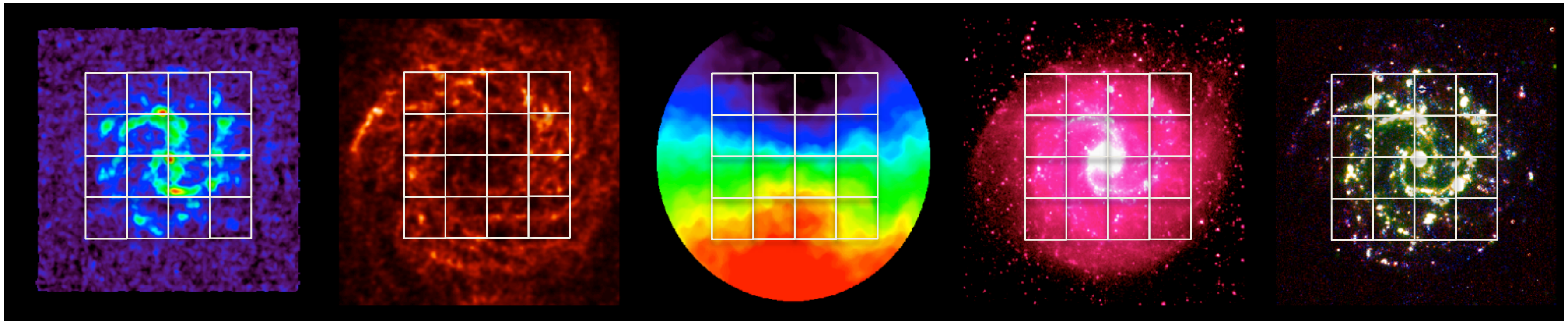
See Meidt et al. (2013), Rebolledo et al. (2013)

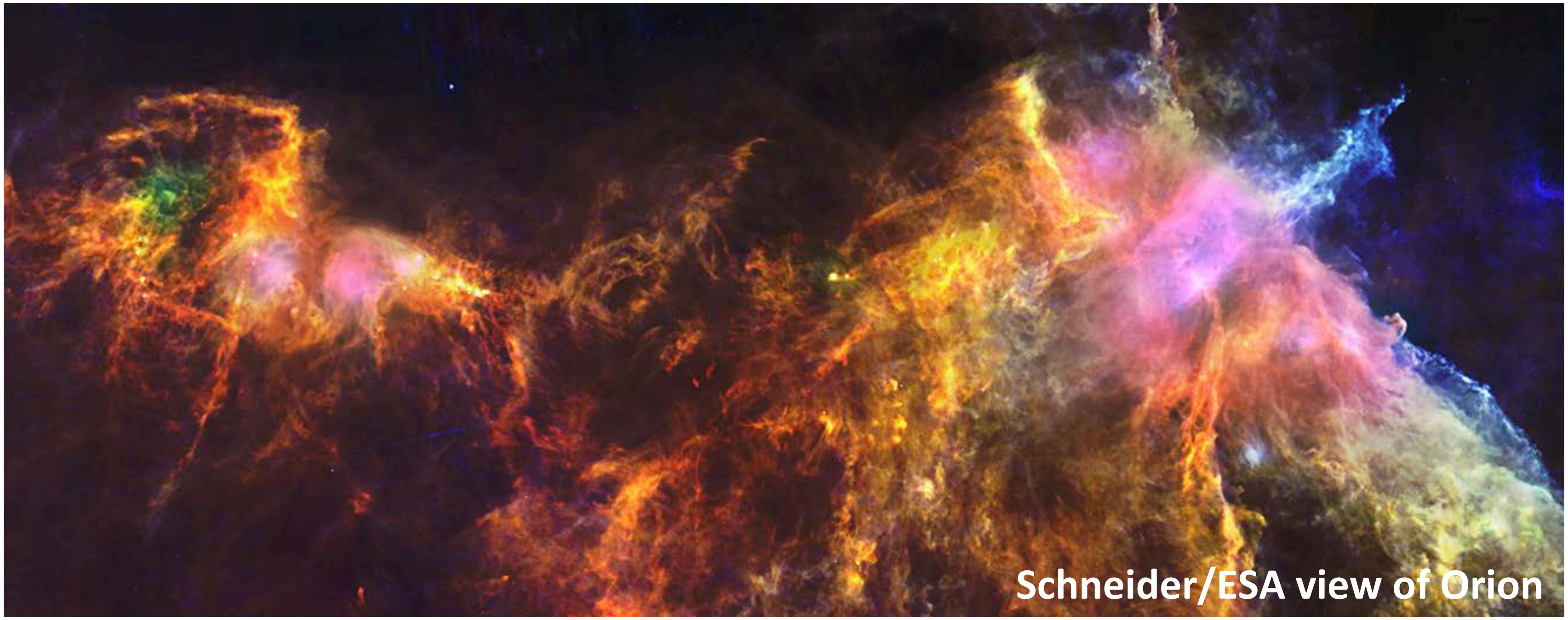
Star Formation is a Local Process

How do the local physics of clouds, galaxy disks, and the ISM connect to systematic variations seen across the galaxy population?



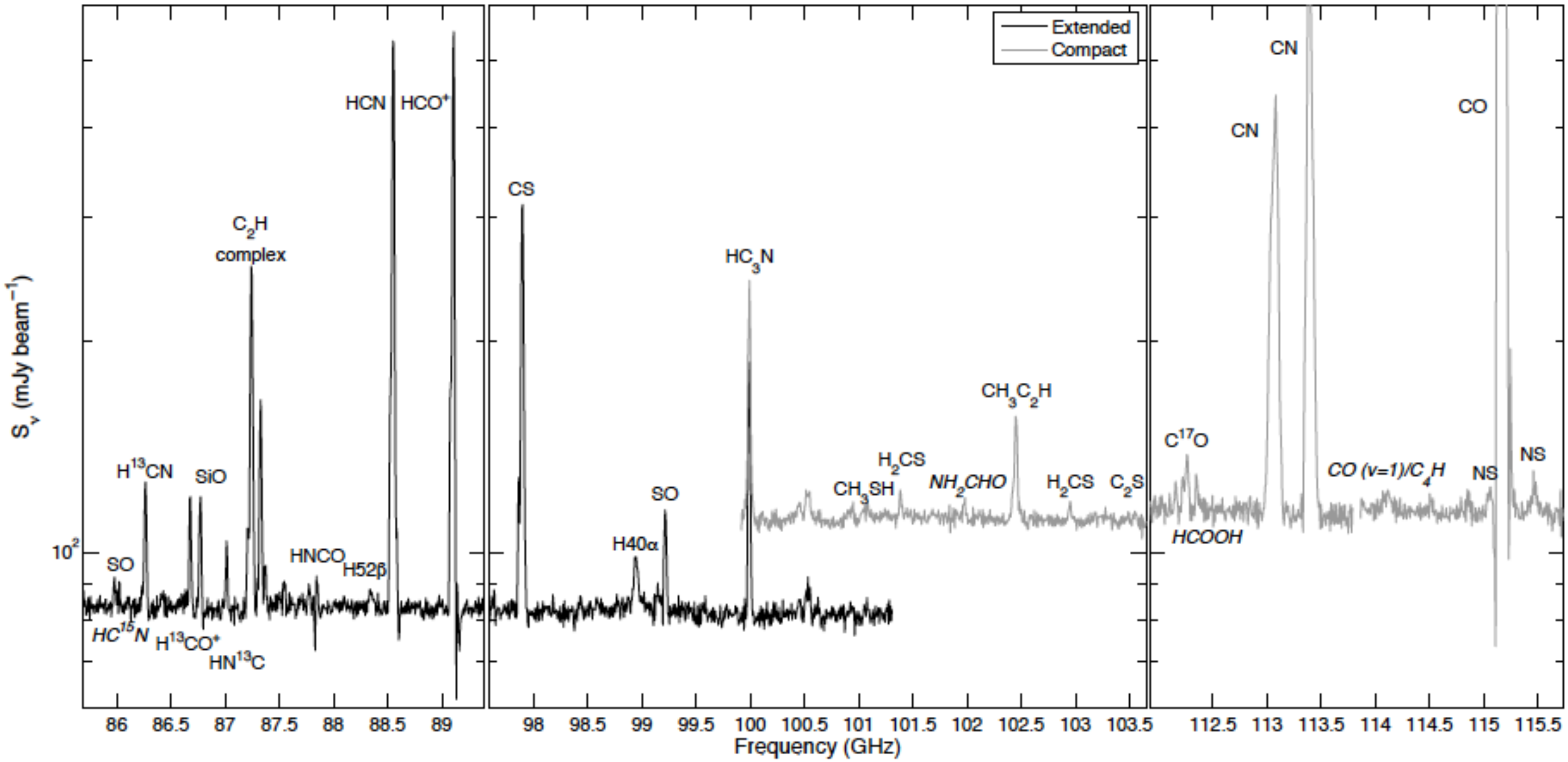
How to link these two views?





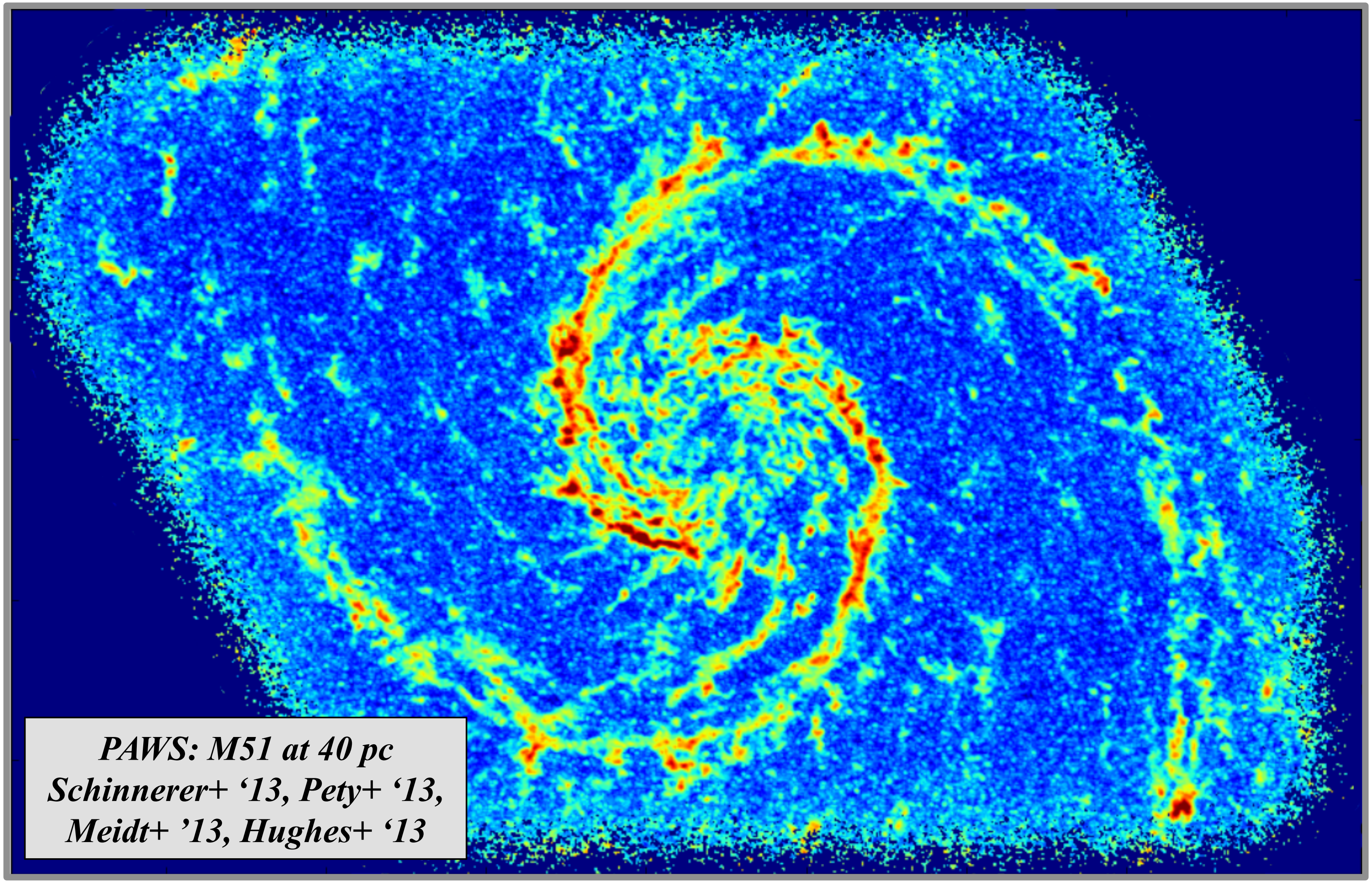
Scalpel 1: Spectroscopy

ALMA view in ~1 hour Cycle 0 (16 antennas) of NGC 253 starburst:



Meier et al. (2015); c.f. Leroy et al. (2015), Bolatto et al. (2013)

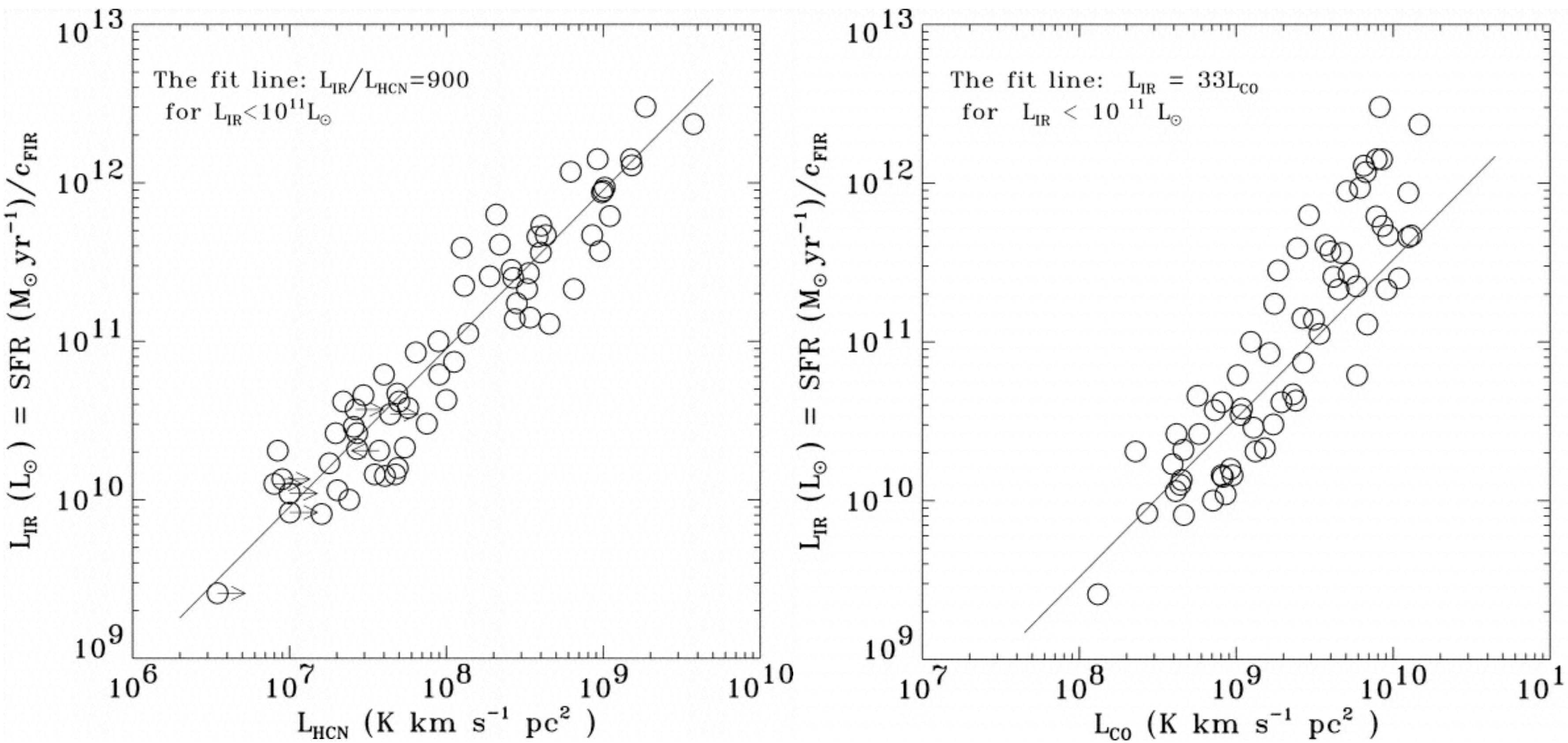
Scalpel 2: Resolution



PAWS: M51 at 40 pc
Schinnerer+ '13, Pety+ '13, Meidt+ '13, Hughes+ '13

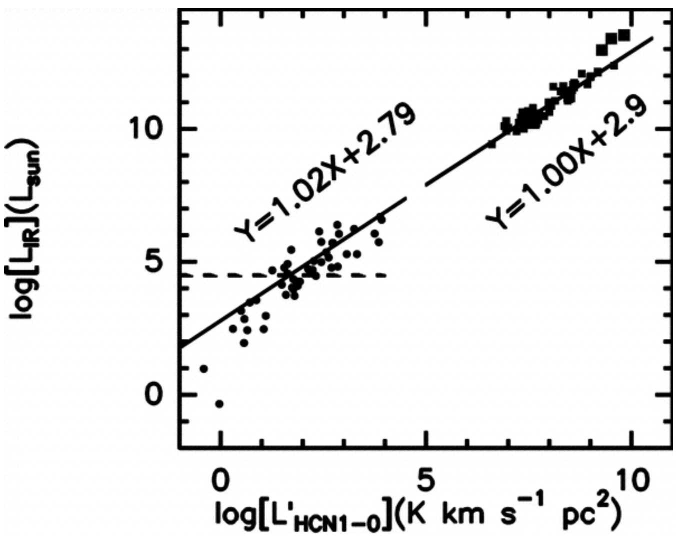
Spectroscopy: Dense Gas and Star Formation

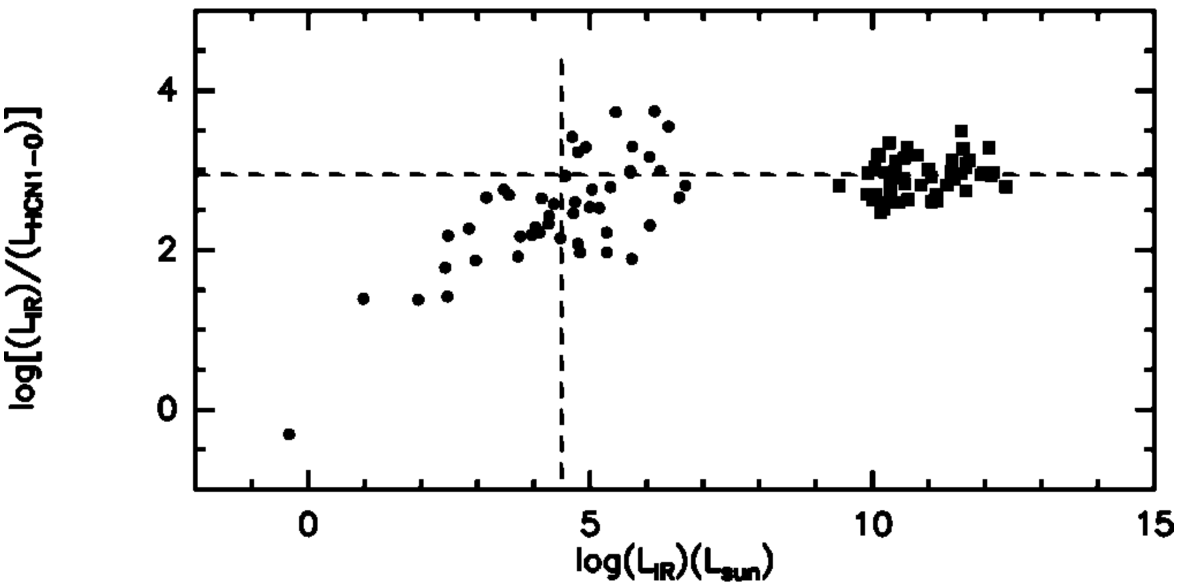
Gao & Solomon (2004): Linear correlation of HCN and IR across a wide range of systems (in contrast to CO) argues for a universal dense gas precondition for star formation.



Dense Gas in Milky Way Cores

Wu et al. (2005): The scaling in Galactic cores resembles that in whole bright systems.

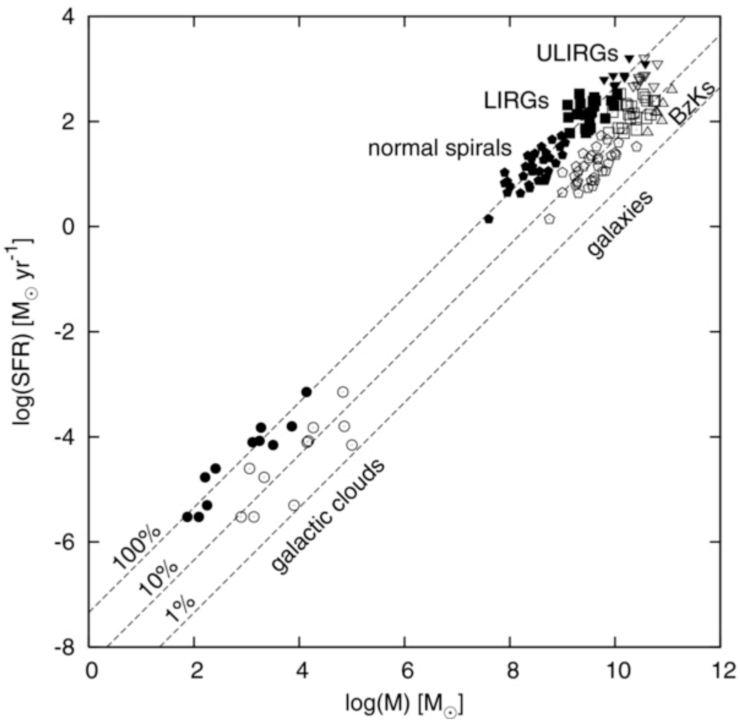




Dense Gas, Filaments, and Galaxies

Lada et al. (2012, 2014): HCN-IR correlation invoked along with local clouds to again argue for a universal dense gas efficiency based on similarities to local clouds.

Herschel's "universal" filaments (e.g., Andre et al. 2014) in Milky Way would support the idea of dense gas as the final step towards star formation.

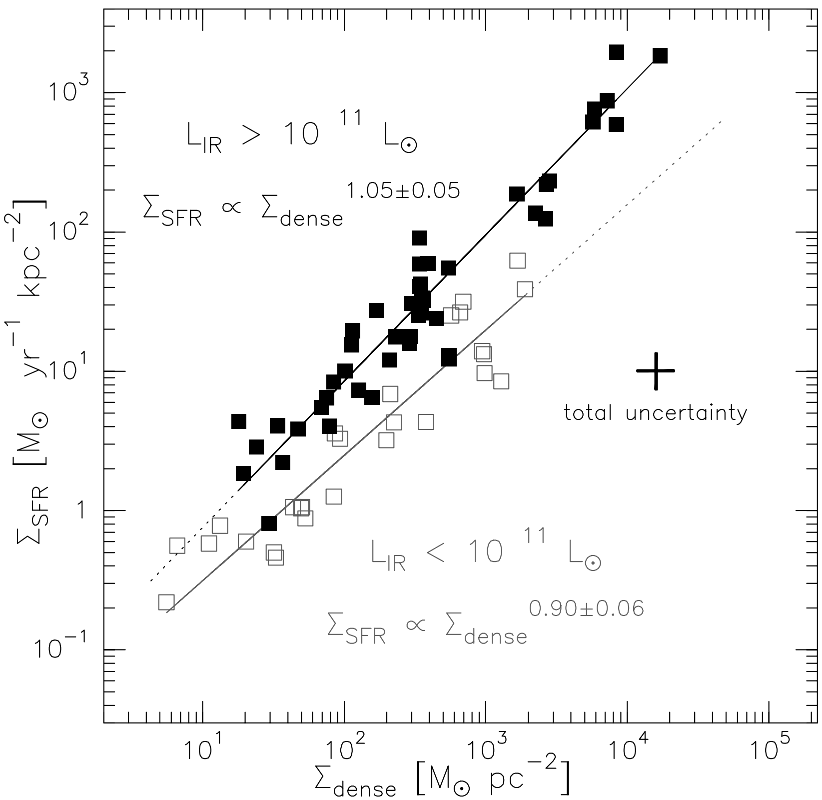


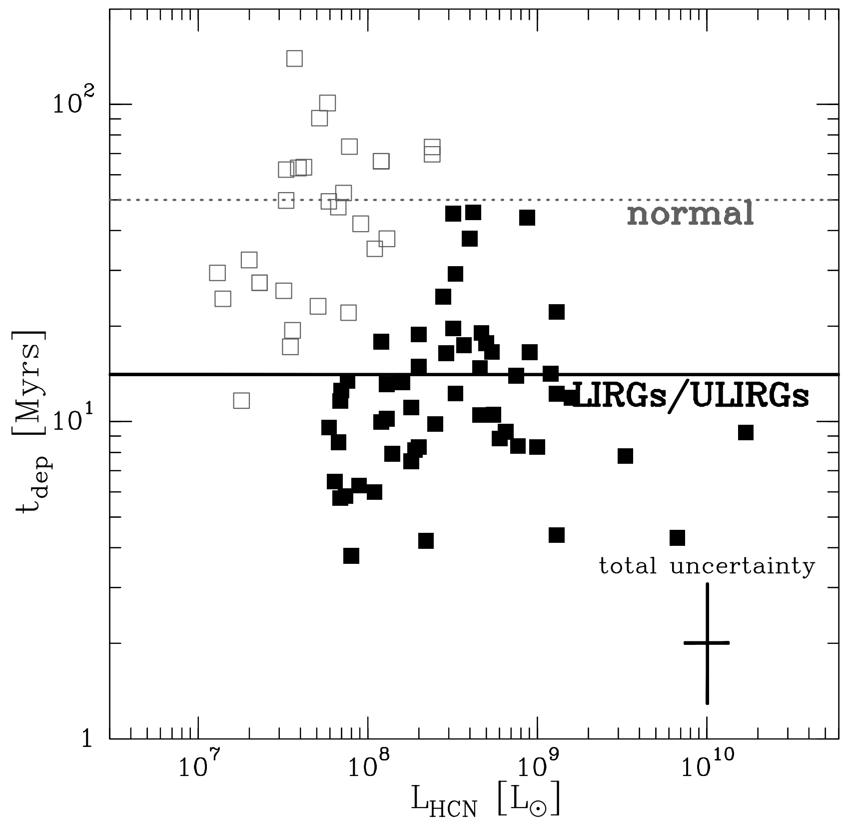
Arzoumanian et al. (2011)

See also *Heiderman et al. (2010), Evans et al. (2014)*

Differences Among Galaxy Populations

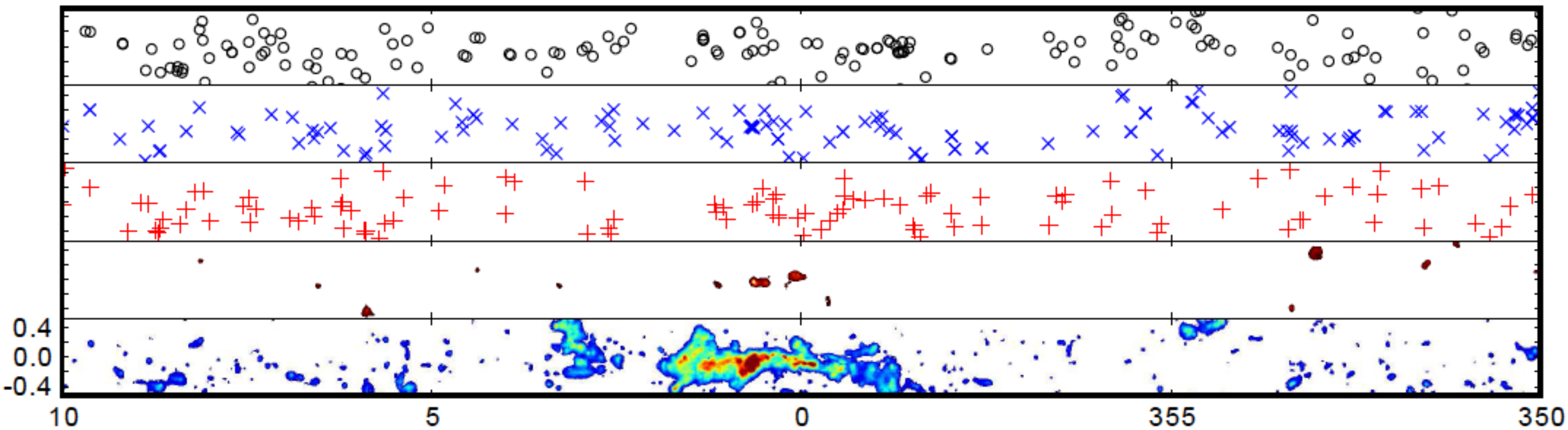
Garcia-Burillo et al. 2012: HCN and HCO+ vs. IR relations for disk-averaged starbursts (LIRG) and normal star forming galaxies appear different, especially accounting for conversion factors.





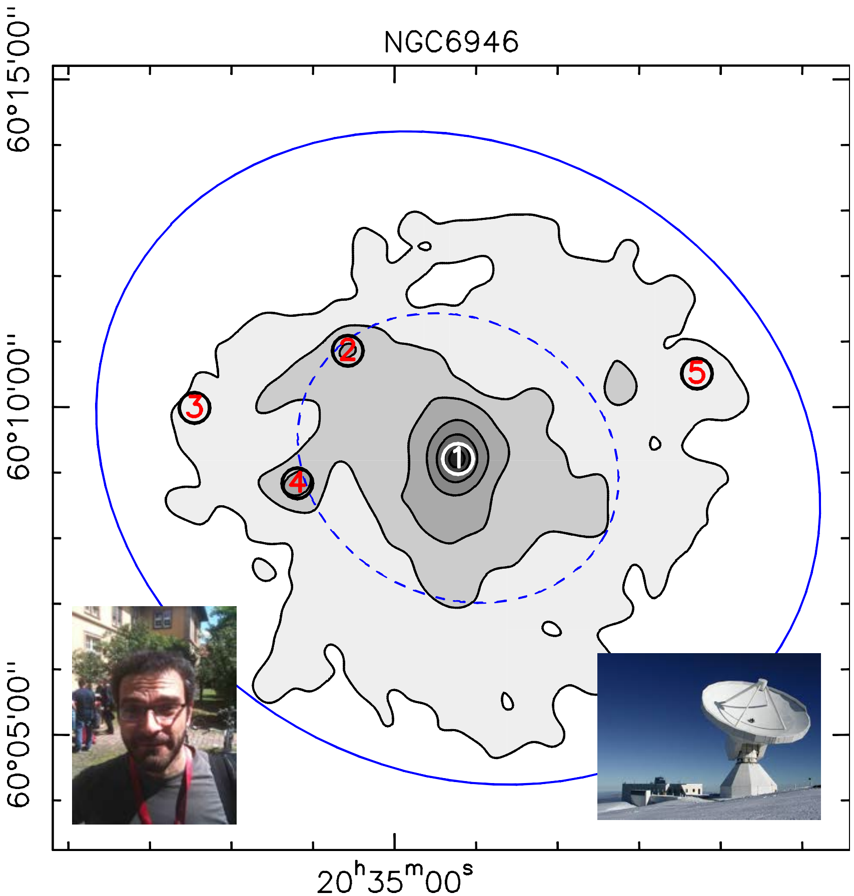
Dense Gas and Weak SFR in the Galactic Center

Longmore et al. 2013: Despite apparently abundant dense gas in the galactic center (bottom panel), the rate of massive star formation is comparatively low (top four panels).



All Just Dense Gas? HCN in Normal Disk Galaxies

Next logical frontier: big parts of normal star forming galaxies.



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

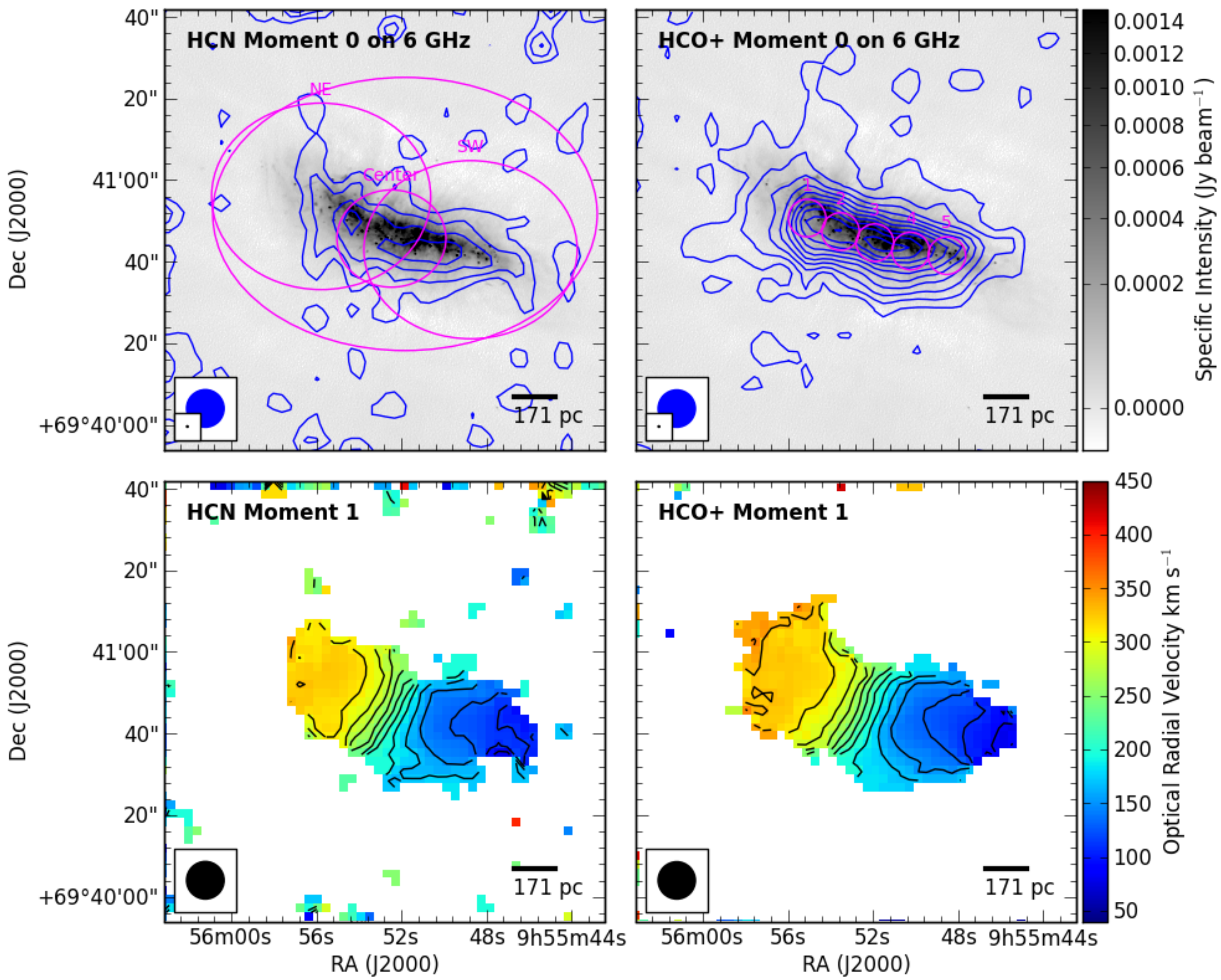
- Targeted 62 regions in 29 galaxies.
- Resolution ~ 1 – 2 kpc
- Drawn from HERACLES survey.
- Have SINGS, THINGS++, KINGFISH
- Also HCO+, other CO, HNC, more…
- Picked to:
  - Be detectable (bright CO)
  - Sample a range of radii, conditions

"Gao and Solomon for Disks"

Usero, Leroy et al. (incl. Garcia-Burillo, Sandstrom) – almost accepted

Whole Galaxy Maps of HCN – M82

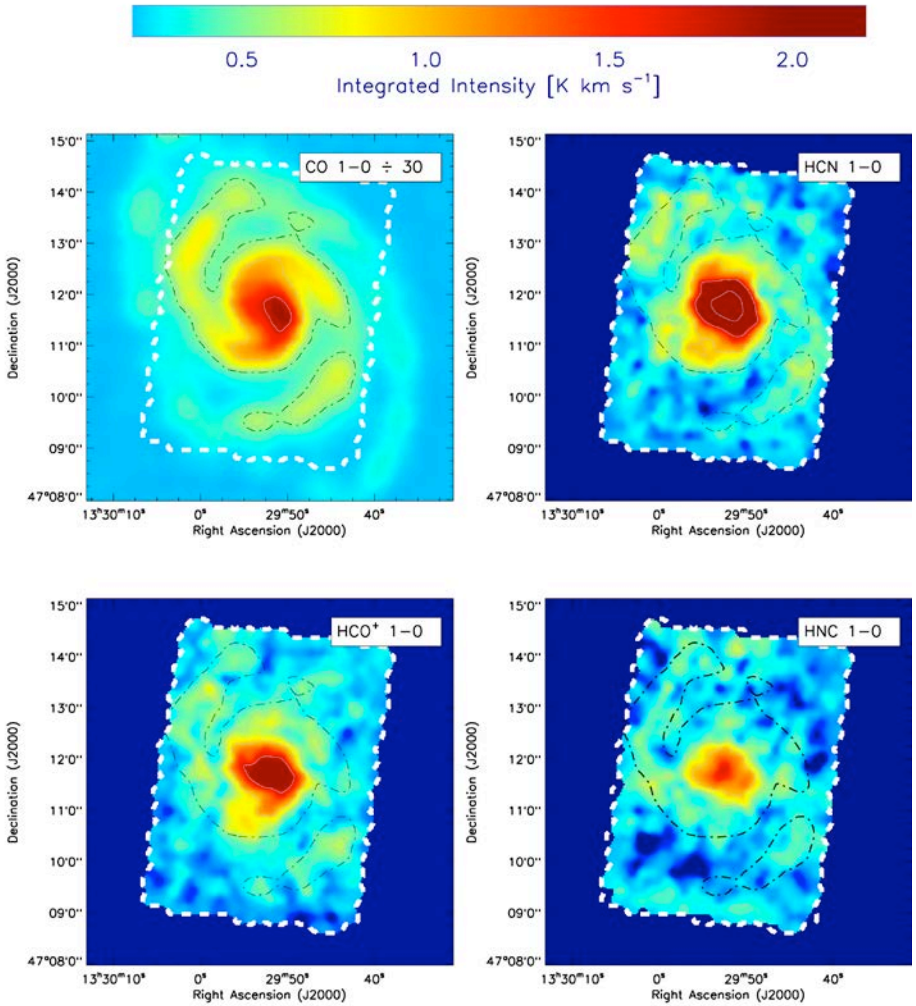
GBT maps of whole area around M82 burst in HCN and HCO^+ reveal systematic positional variations in IR/HCN.



***Amanda Kepley**, Leroy, Frayer, Usero, Marvil, Walter. (2014)*

Whole Galaxy Maps of HCN – M51

HCN, HCO+, HNC (1-0) mapping of the entire M51 disk in the context of PAWS.



EMIR Multi-line Probe of the ISM Regulating Galaxy Evolution

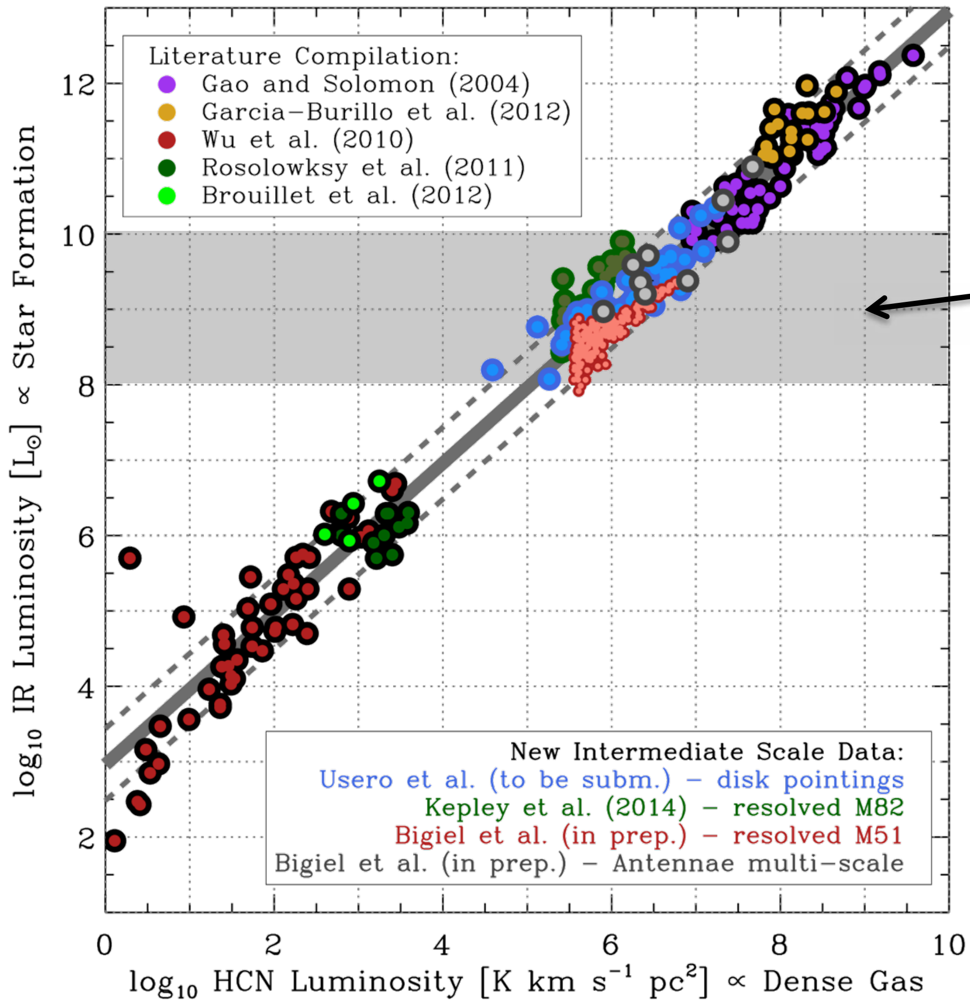
PI: Frank Bigiel (ITA, Heidelberg)
IRAM Large Program 2015-2017

- Full galaxy maps of HCN, HCO+, CS, ^{13}CO, $C^{18}O$ in 9 targets
- M51 – prototype done in the context of the PAWS survey.
- First results 2015

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

Filling in the "Luminosity Gap"

Points fill in luminosity range between whole galaxies and clouds – "big parts of disks."

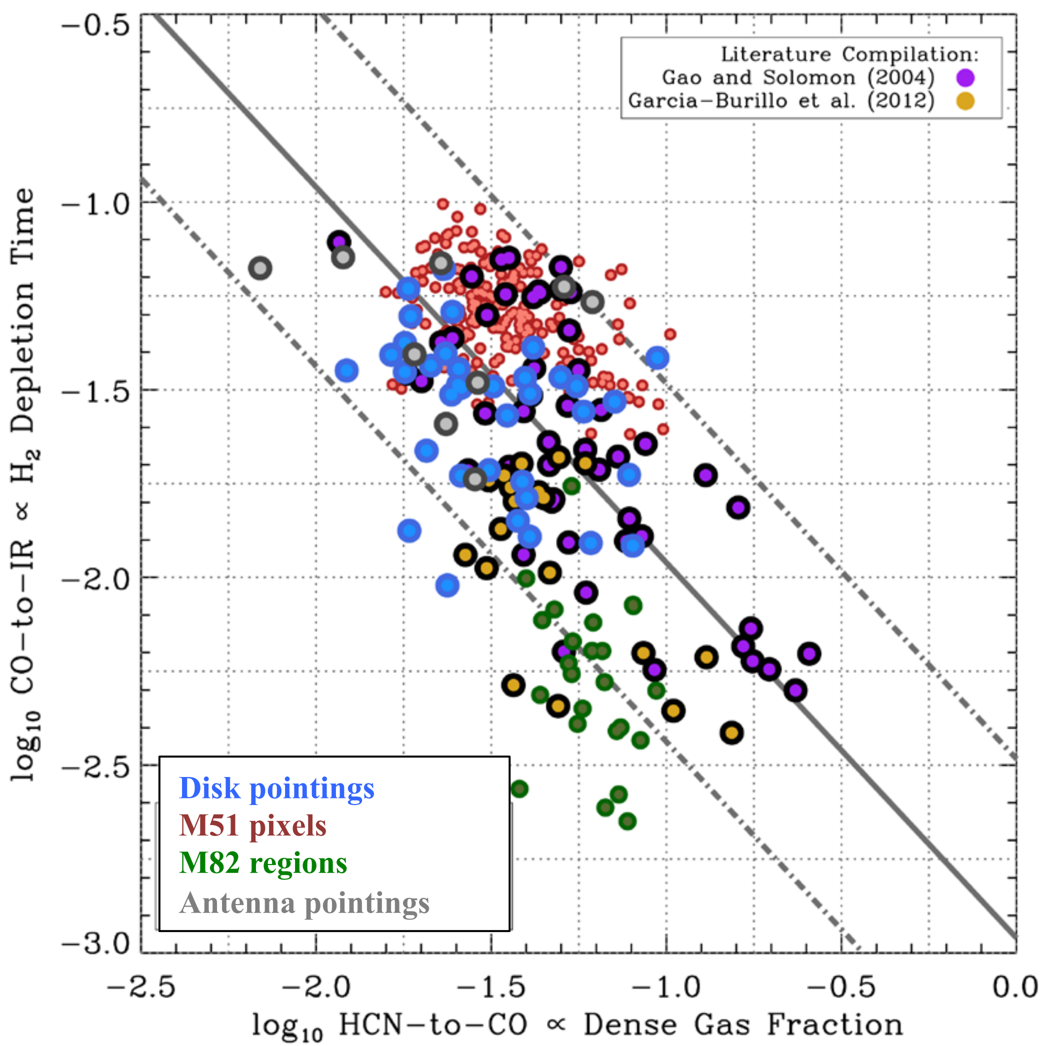


New surveys:

Disk pointings
M51 pixels
M82 regions
Antenna pointings

All Just Dense Gas? HCN in Normal Disk Galaxies

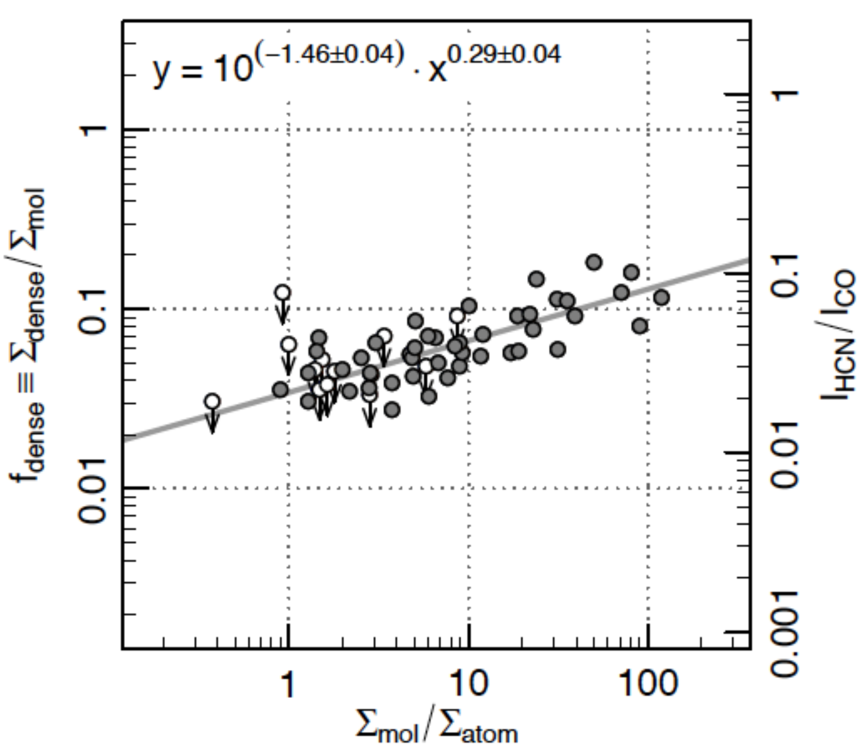
Apparent dense gas fraction predicts apparent depletion time but with huge scatter.



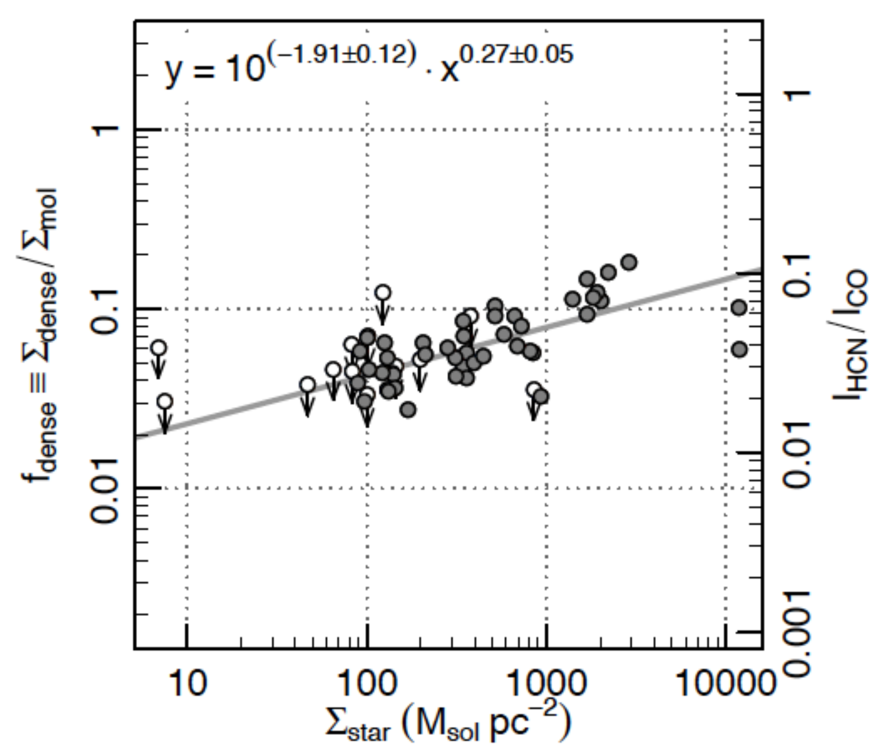
HCN-to-CO Rises With Increasing Surface Density

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

HCN-to-CO vs. H_2/HI



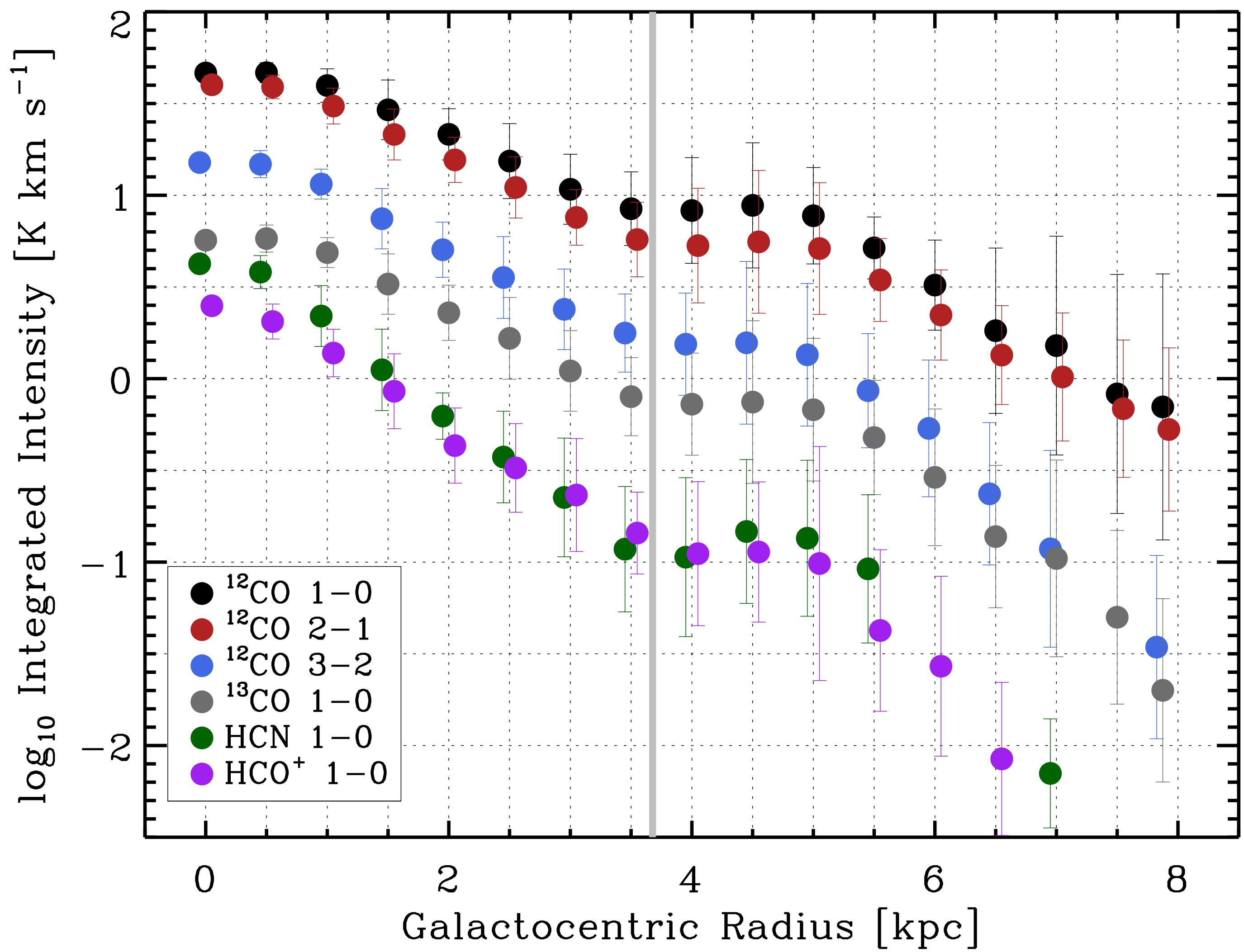
HCN-to-CO vs Stellar Surface Density



Usero, Leroy et al. (incl. Garcia-Burillo, Sandstrom) – almost accepted

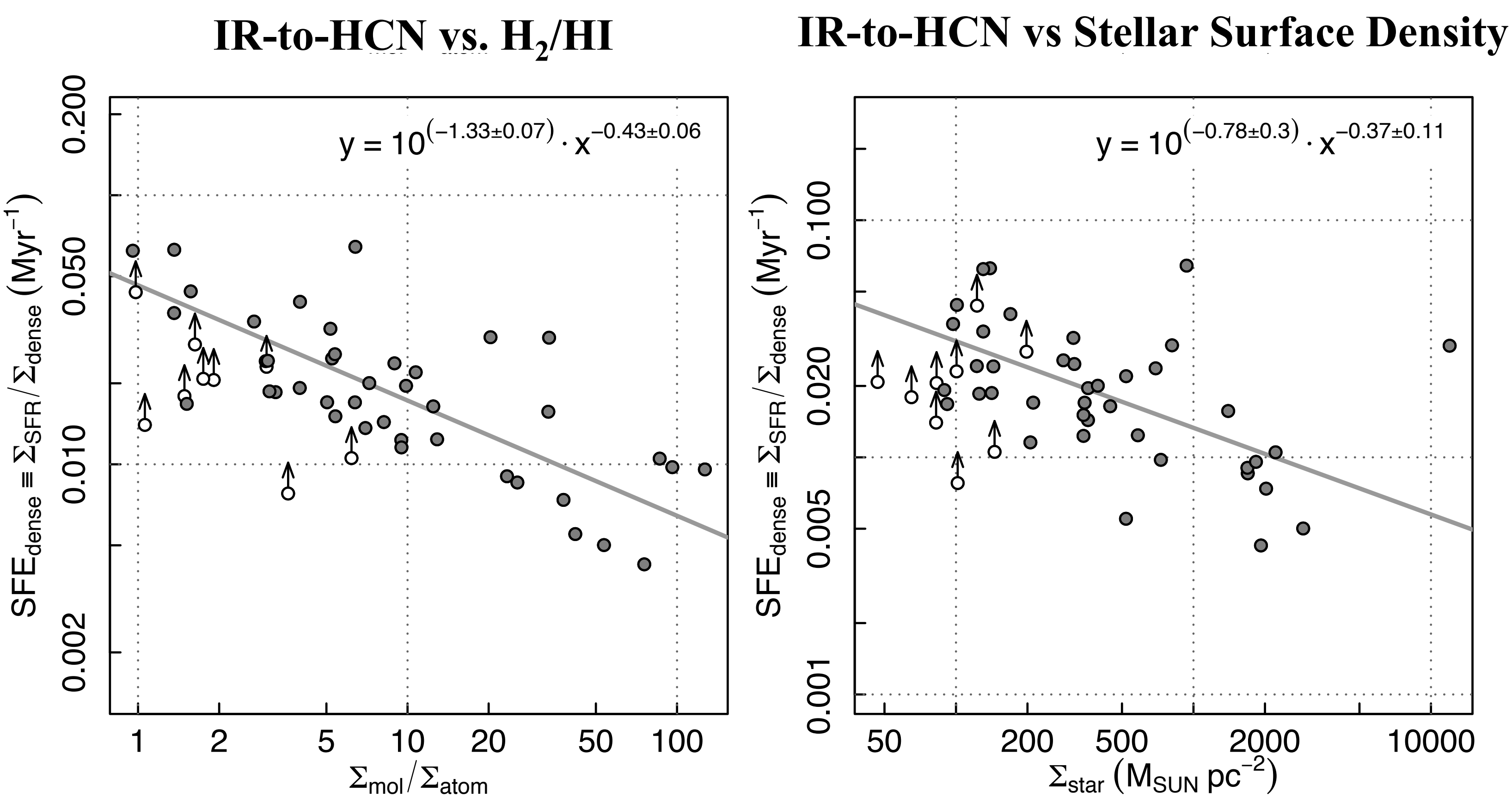
Aside - Why This is a "Next" Frontier

Radial profiles of line intensity in M51 – dense gas tracers down by a factor of 10-100.



IR-to-HCN Drops With Increasing Surface Density

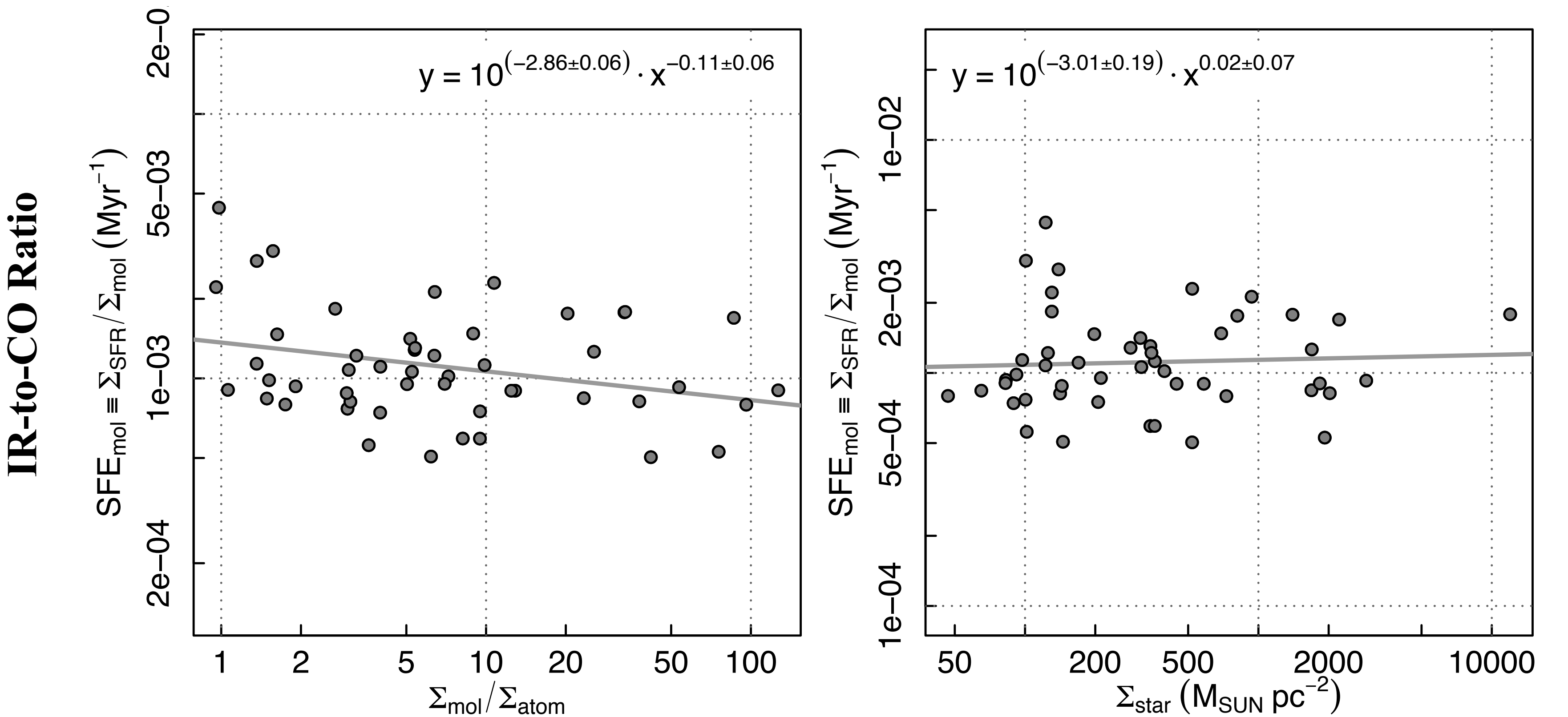
Apparent dense gas efficiency (IR-to-HCN ratio) *anti*-correlates with surface density.



Usero, Leroy et al. (incl. Garcia-Burillo, Sandstrom) – almost accepted

Competing Effects Wash Out?

Apparent fixed H_2 efficiency (IR-to-CO) must hide changing internal cloud conditions.

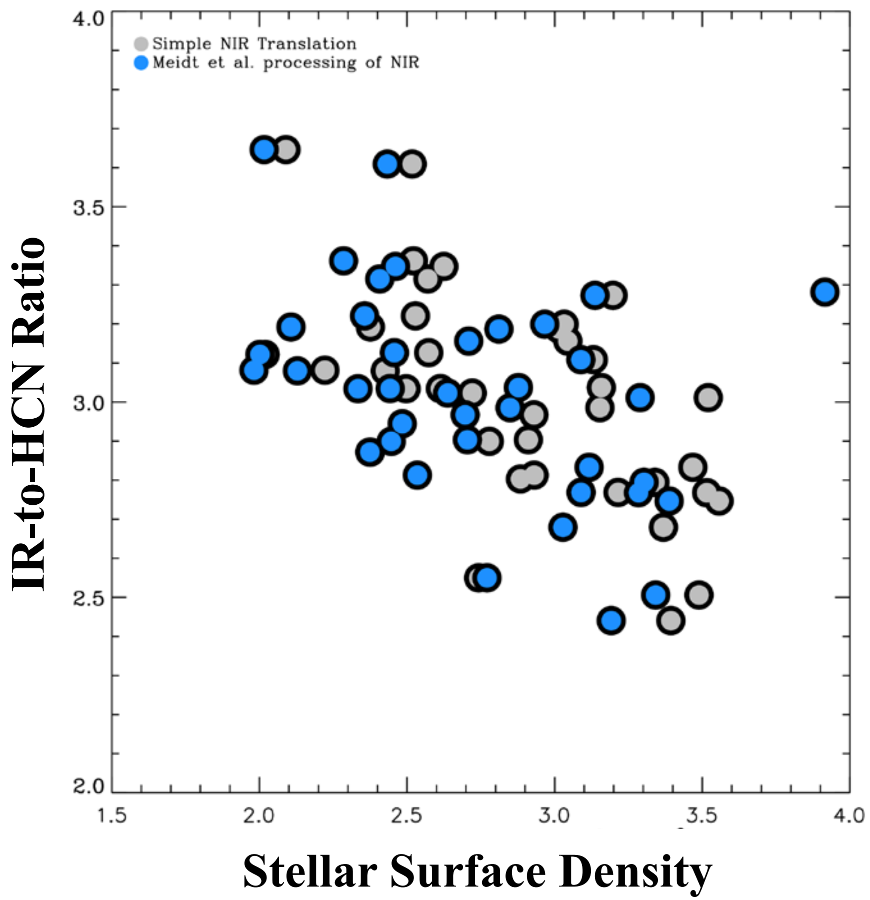


Usero, Leroy et al. (incl. Garcia-Burillo, Sandstrom) – almost accepted

Density Thresholds and Whole Clouds

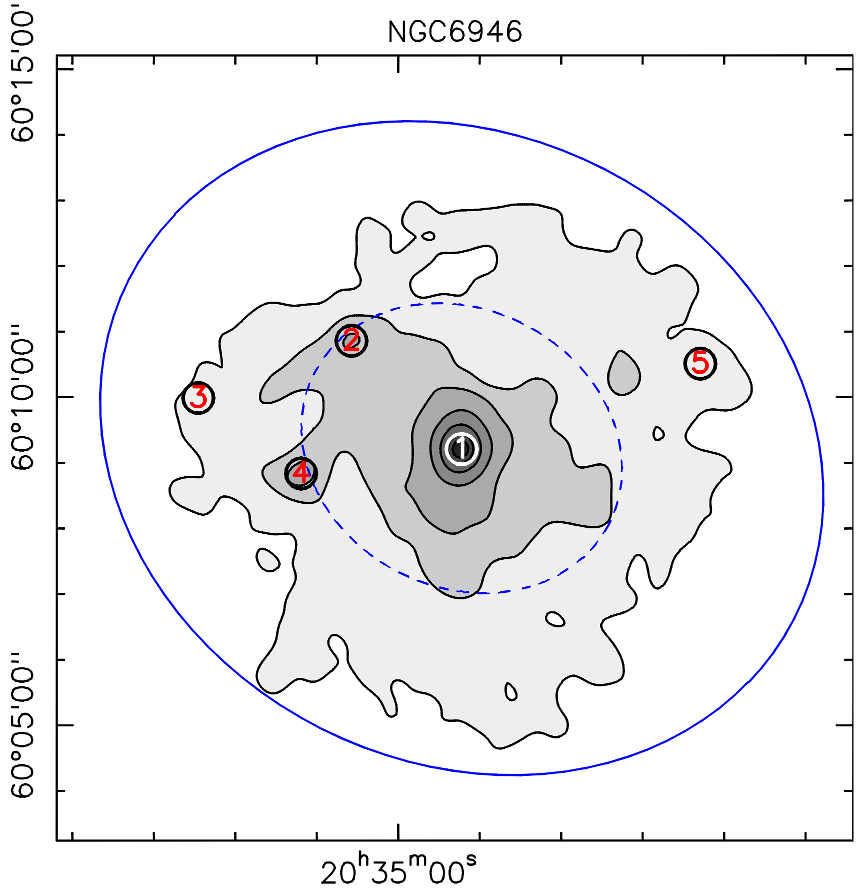
A universal density threshold can be rescued by playing with HCN "conversion factors," though the plausible range is quite specific – it has to cancel the observed trend.

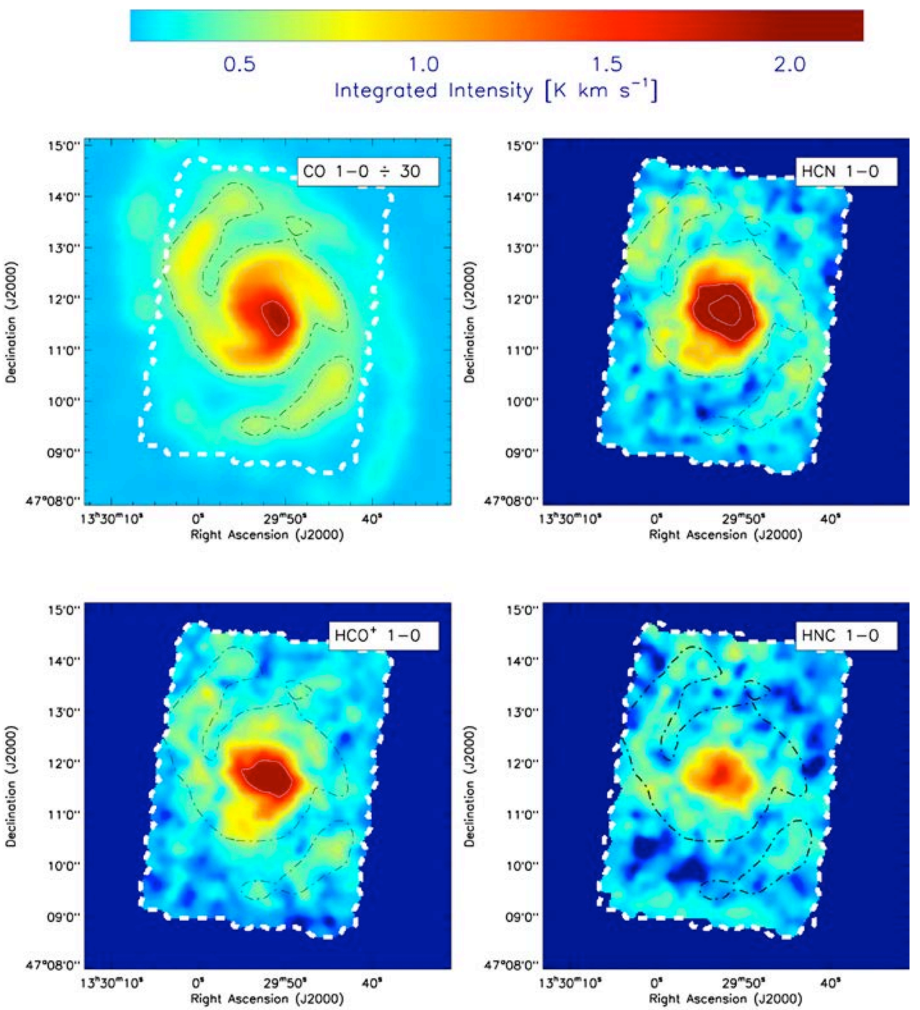
But, this removes the a major observational plank from the "universal" threshold idea.



Points: disk pointing with two stellar mass treatments

Do Results for Pointings Apply to Whole Disks?

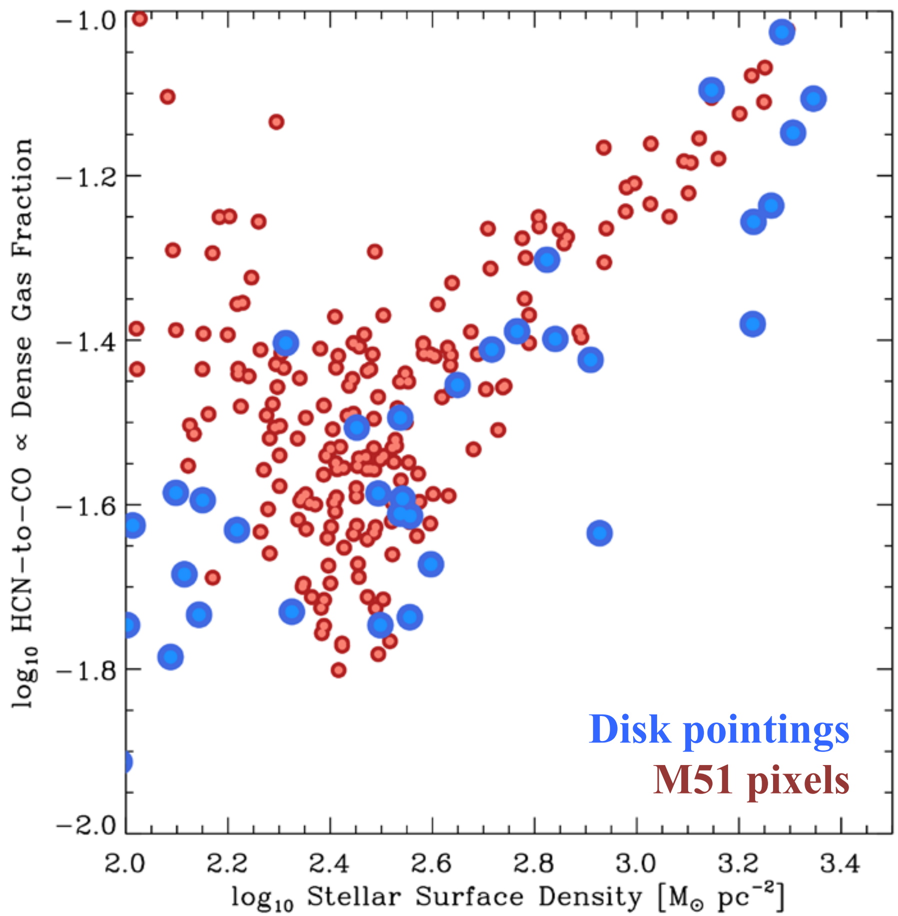




Usero, Leroy et al. (incl. Garcia-Burillo, Sandstrom) – almost accepted + Bigiel et al. (in prep.)

Pointings and Whole Disk of M51 Agree

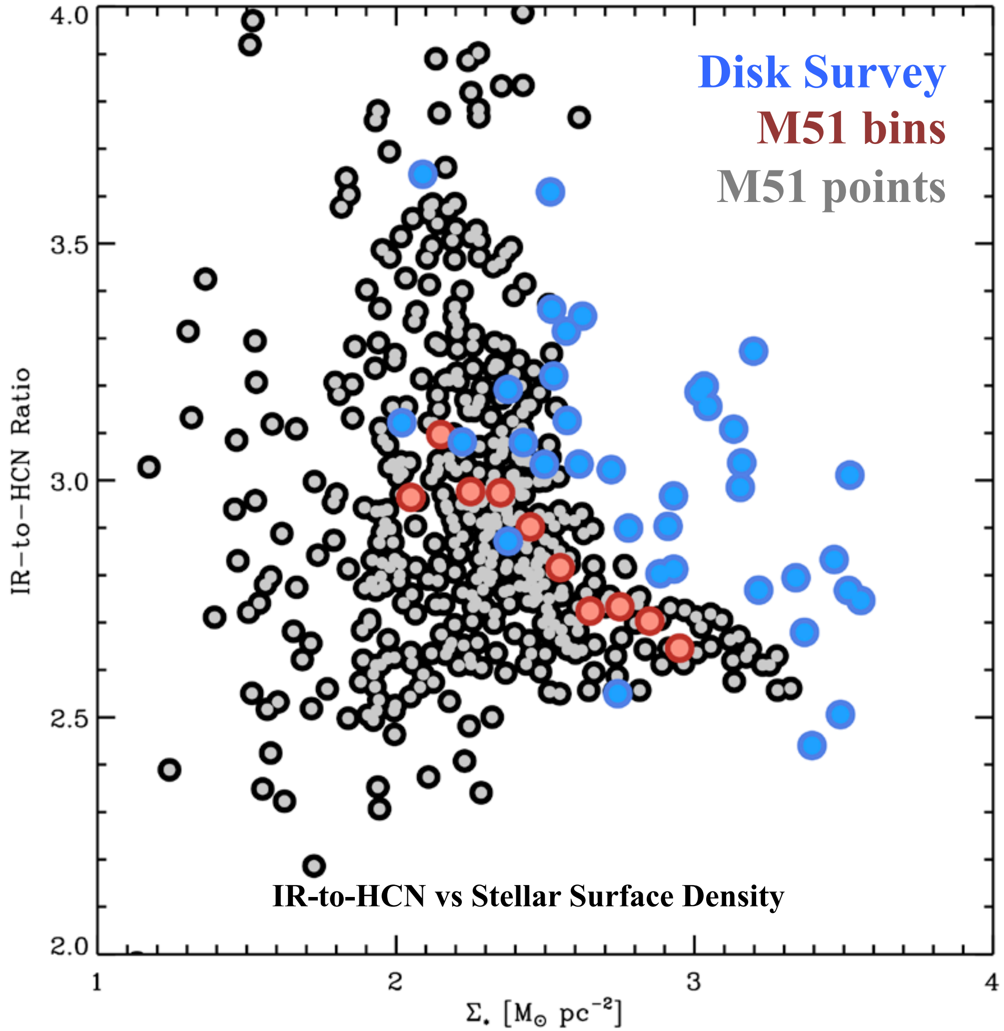
Pixelwise results in M51 agree (at least to first order) with the results from the broader sample of disk galaxy pointings in HCN-to-CO (dense gas fraction) ratio.



Usero, Leroy et al. (incl. Garcia-Burillo, Sandstrom) – almost accepted + Bigiel et al. (in prep.)

Pointings and Whole Disk of M51 Agree

Here all M51 points (pixels, gray) binned (red) with disk pointings overlaid

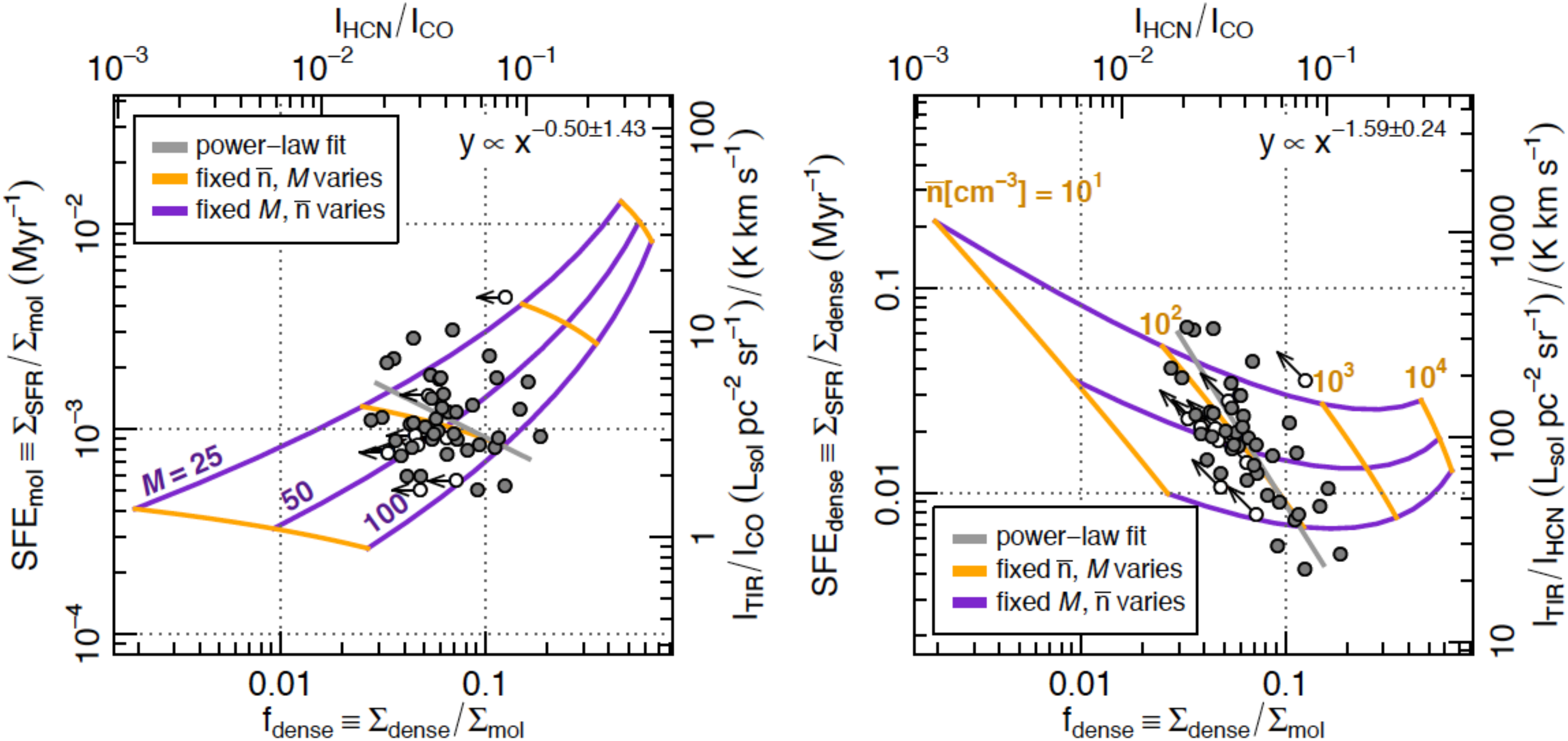


Gray points: 1 kpc, Red points: binned data

Usero et al. – almost there; M51: Bigiel et al. (in prep.)

Density Thresholds and Whole Clouds

Whole cloud models have the "knobs" to predict the full IR-HCN-CO space.
In the *Krumholz et al. (2005)* models our trends can be matched by Mach number variations.

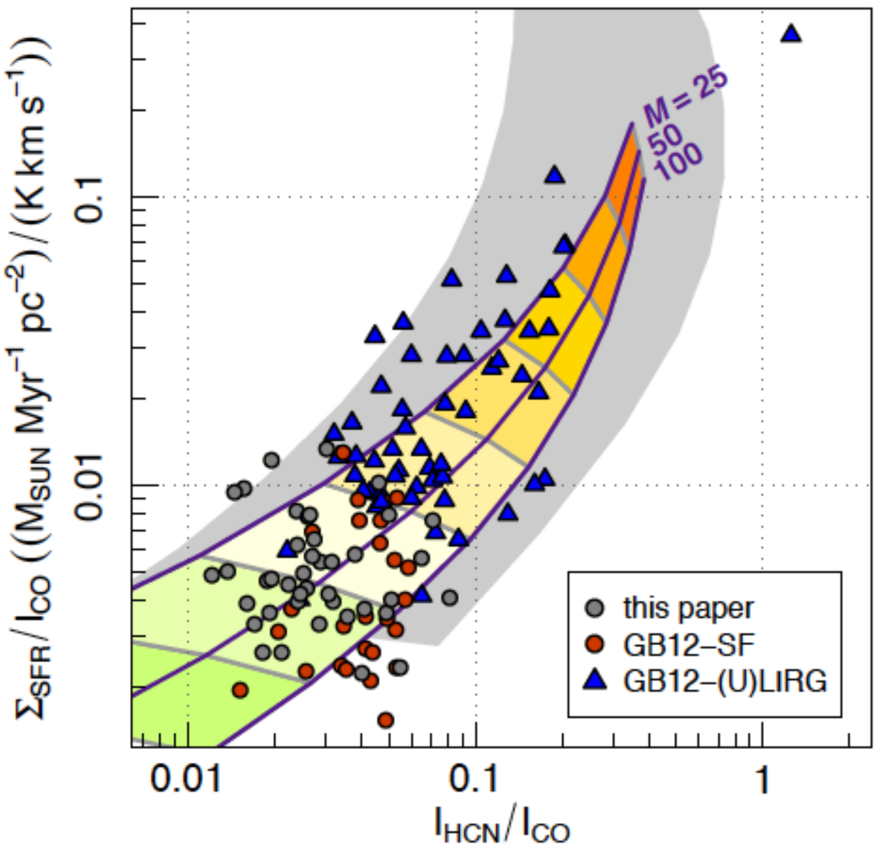


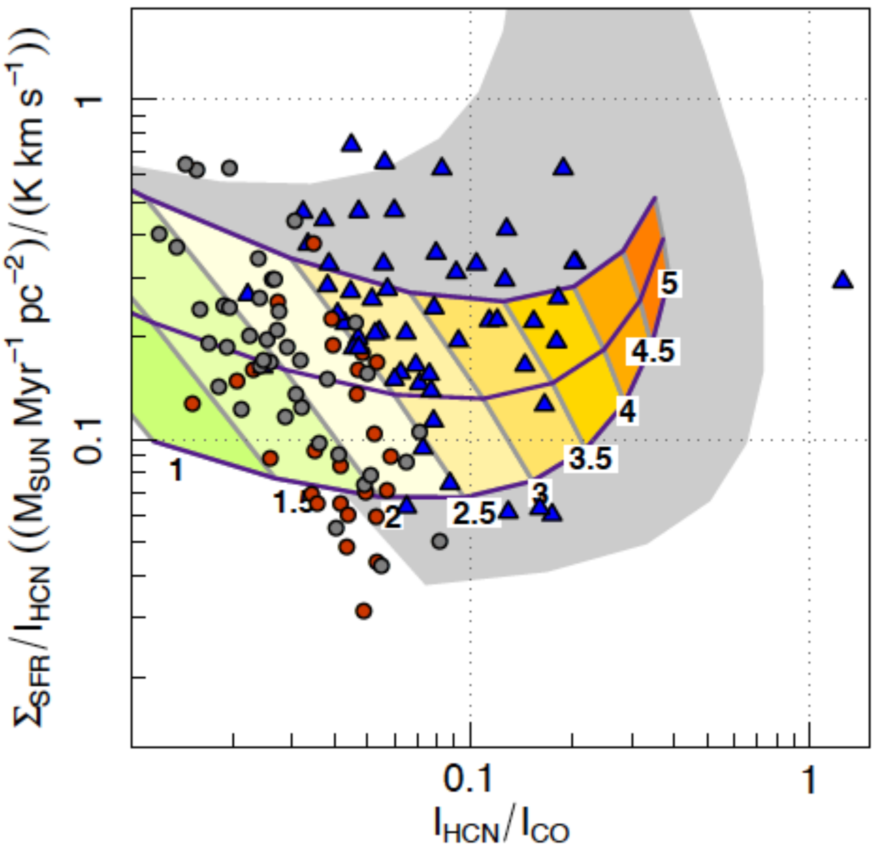
See also *Krumholz & Thompson* (2007), *Narayanan et al.* (2008), *Federrath & Klessen* (2012)

From Usero et al. – almost accepted

All Just Dense Gas? HCN in Normal Disk Galaxies

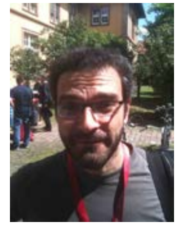
Combining with Garcia-Burillo et al (2012) a combination of density and Mach number can reproduce the ULIRG + disk combination. **But** this is testable!





Usero, Leroy et al. – almost accepted

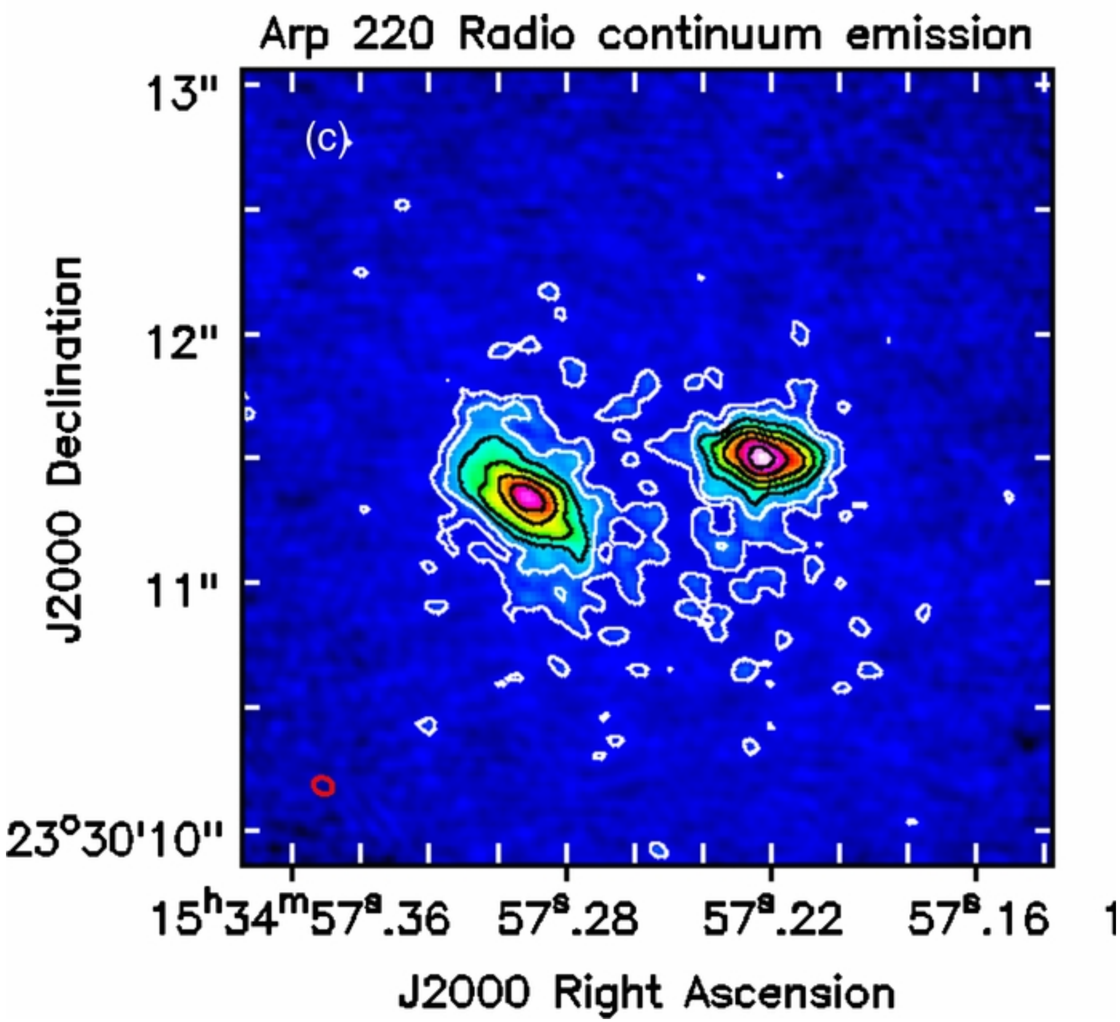
Dense Gas and Star Formation in Normal Galaxies



- New survey of HCN (and more, forthcoming) across galaxy disks.
- Large program EMPIRE (PI: Bigiel) underway – ALMA to be delivered.
- Observe systematic trends in IR-to-HCN ("dense gas efficiency") and HCN-to-CO ("dense gas fraction") as a function of surface density, molecular fraction.
- Seems to substantially weaken the extragalactic component of the simple density threshold model for star formation popular in the Galactic community.
- Maps of HCN with the GBT and IRAM 30-m (M51 especially!) show same qualitative behavior. Consistent with Garcia-Burillo et al. (2012), Longmore et al. (2013).
- There are very specific predictions of the HCN-to-dense gas "conversion" factor needed to save a universal density threshold.
- Whole cloud models have the "knobs" to unify disks, centers, U/LIRGs. But the knobs make observable predictions. Do they work?

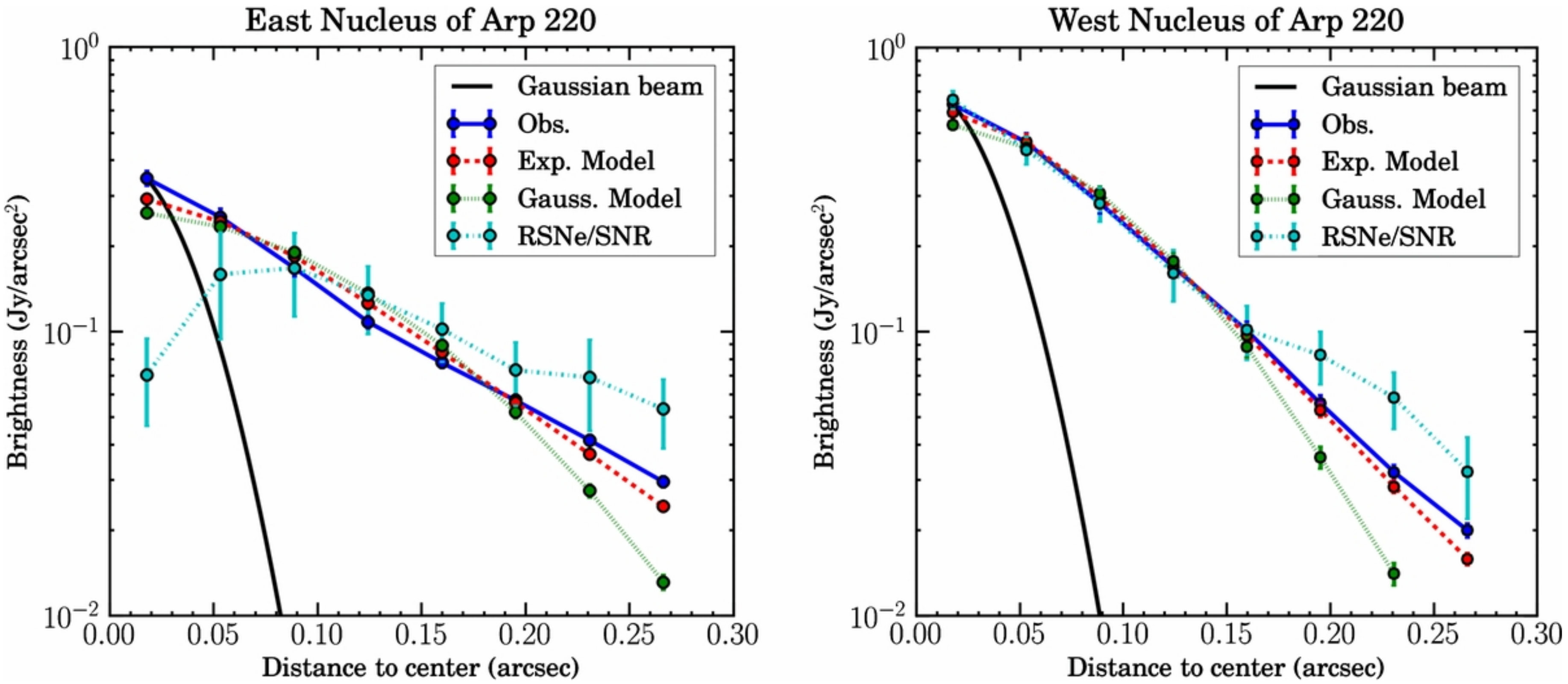
Arp 220 Resolved at Optically Thin Frequencies

Loreto Barcos-Munoz, Leroy, Evans et al. (2015) – resolved (0.06”) the disks of Arp 220 with full full flux recovery at optically thin frequency (33 GHz) – RC here traces SF



Arp 220 Resolved at Optically Thin Frequencies

Cleanly measure sizes (r_{50} of 50 and 35 pc) – key to implied surface/volume densities, opacity estimates, compare to predictions for radiation-pressure limited starburst disks.



Loreto Barcos-Munoz, Leroy, Evans et al. (2015)

A Semi-Empirical Prescription for α_{CO} vs Metallicity

Cheoljong Lee, Leroy, Schnee, Wong, Bolatto, Indebetouw, Rubio (2015) – astroph shortly

Treat CO-to-H_2 conversion factor (over a population average) as a separable, 1-d problem:

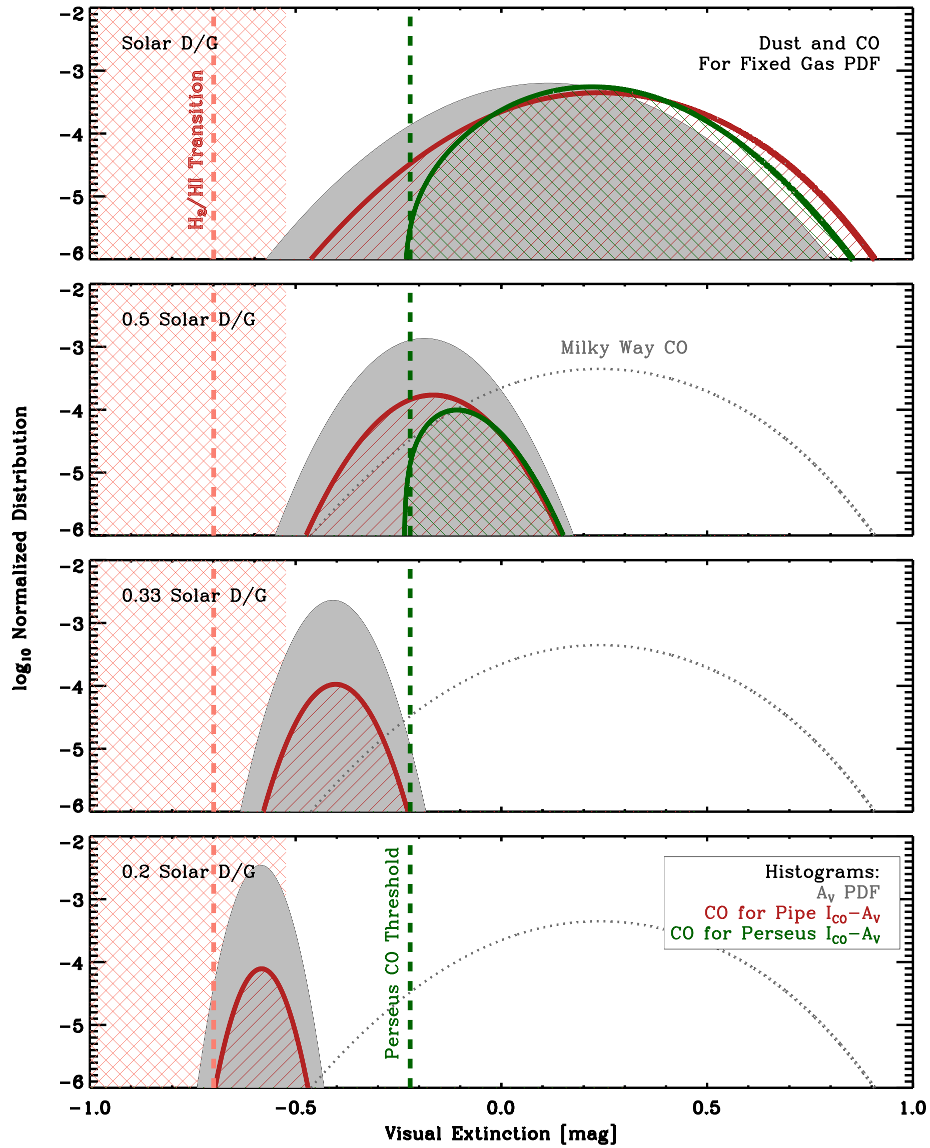
1. Gas Distribution: Clouds have some gas column distribution function.
The gas PDF is observable and a topic of intense study in the Milky Way.

2. Dust-to-Gas Ratio: Galaxies have some dust-to-gas ratio that translates gas column to A_V.
This is where metallicity enters the picture.

3. CO follows A_V: Treat dust shielding (A_V) as the driver for CO intensity.
e.g., Li, Rubio talks – makes sense if you view dust shielding as the prime driver for CO abundance. Agrees with PDR and theoretical cloud calculations. See next slide.

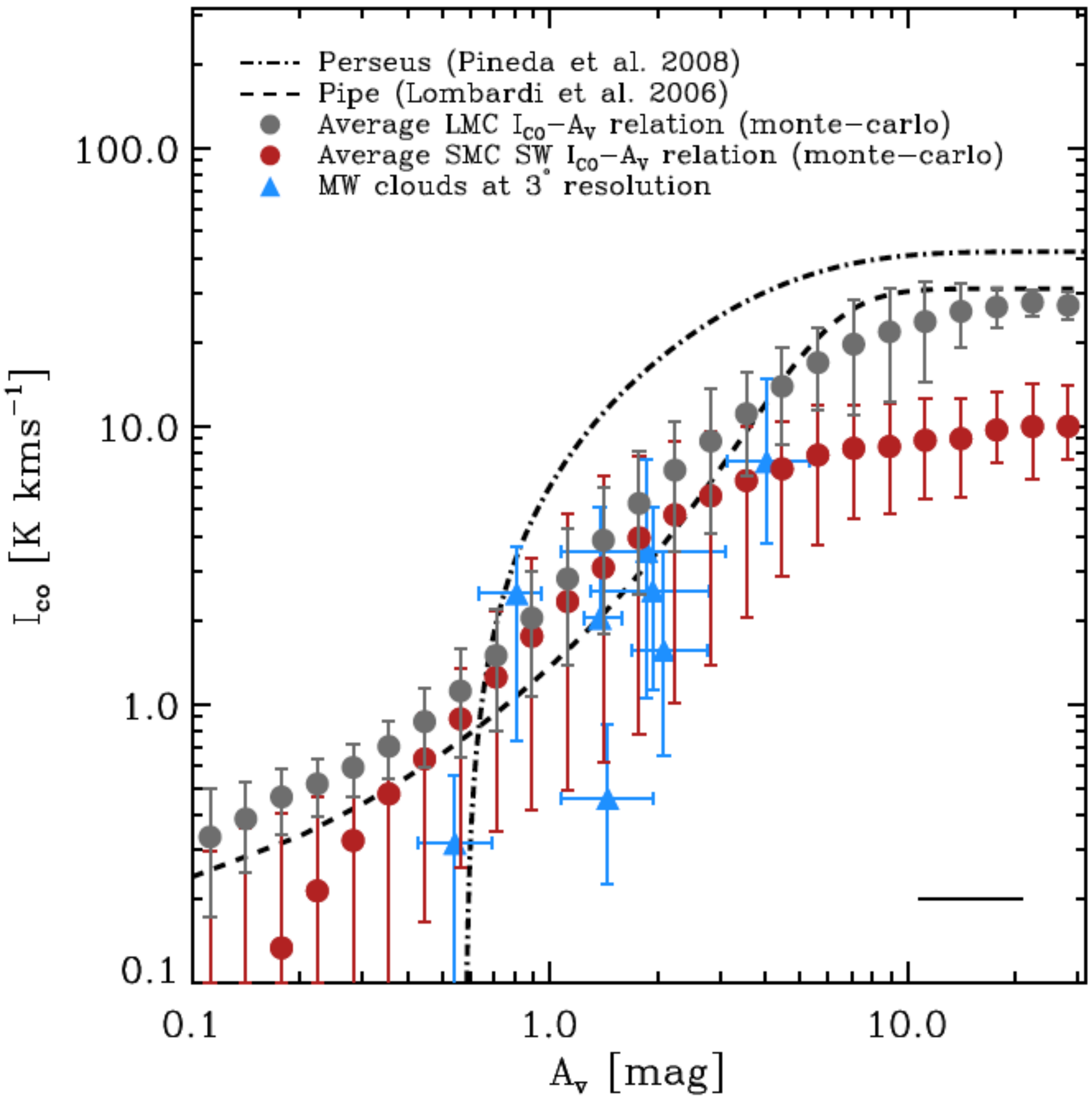
Lee et al. (2015) – test hypothesis that CO tracks A_V in a semi-universal way. Calculate the implied conversion factor using Milky Way gas PDFs at different metallicities.

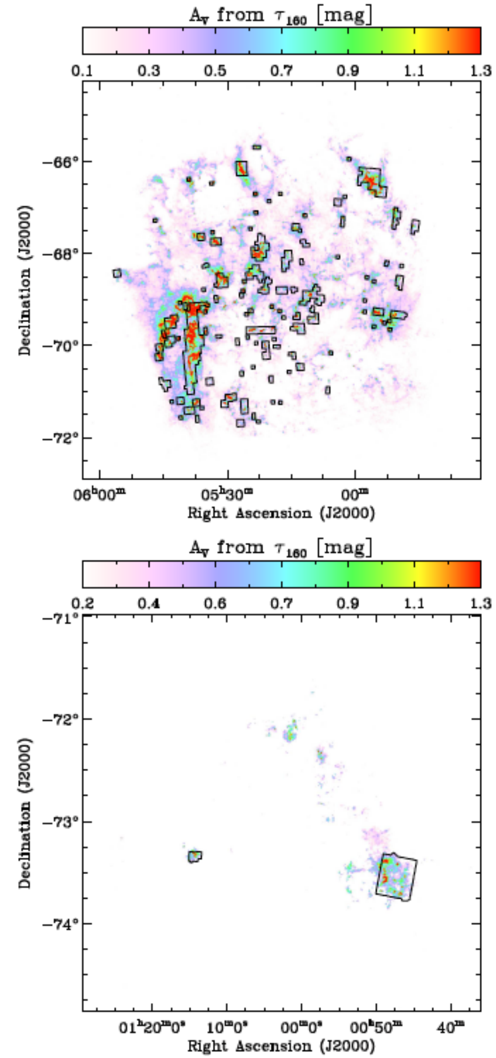
A Semi-Empirical Prescription for α_{CO} vs Metallicity



Cheoljong Lee, Leroy, Schnee, Wong, Bolatto, Indebetouw, <u>Rubio</u> (2015) – astroph shortly

Similar I_{CO} (A_V) in LMC, SMC, Milky Way

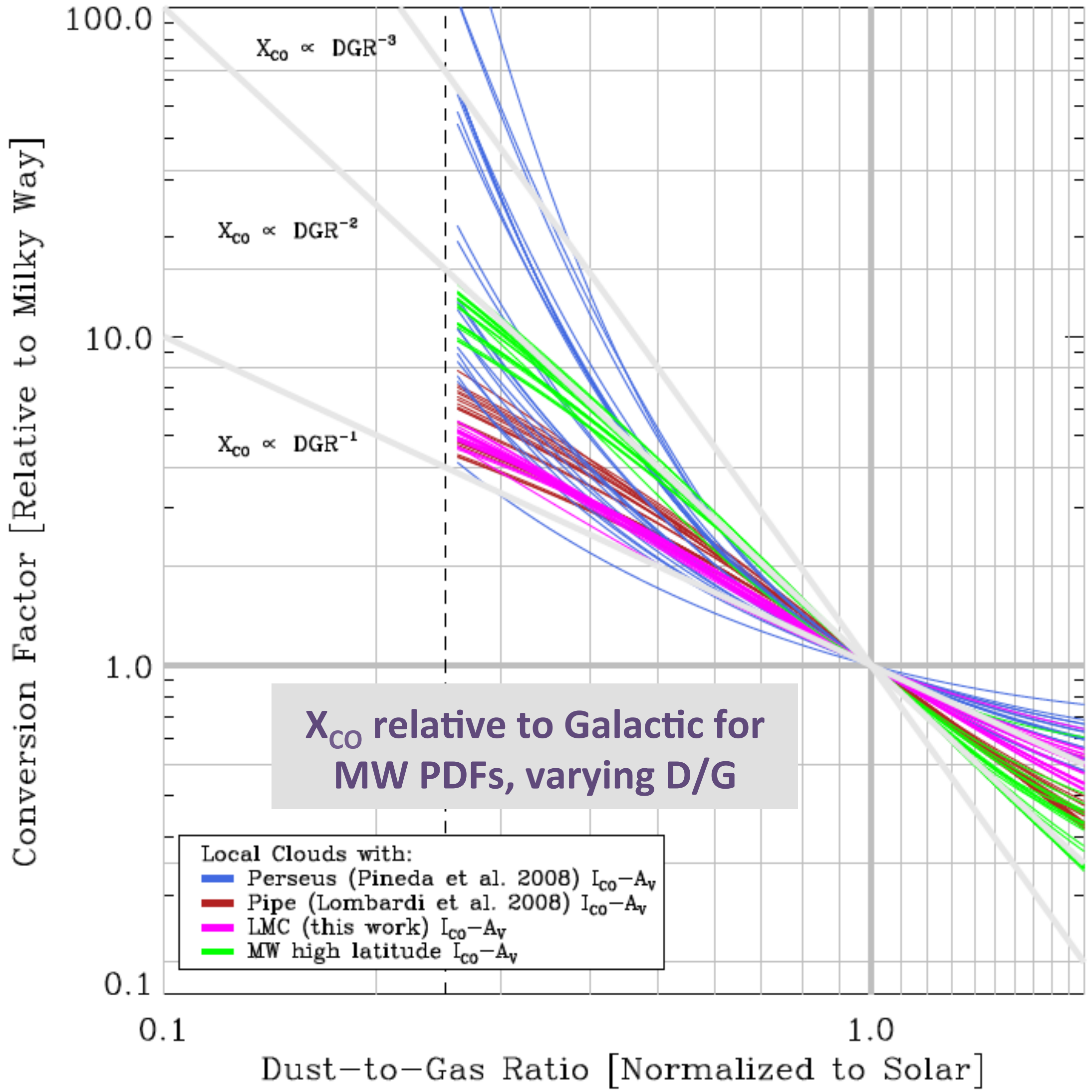




A_V estimated from HERITAGE (Meixner et al. 2013)

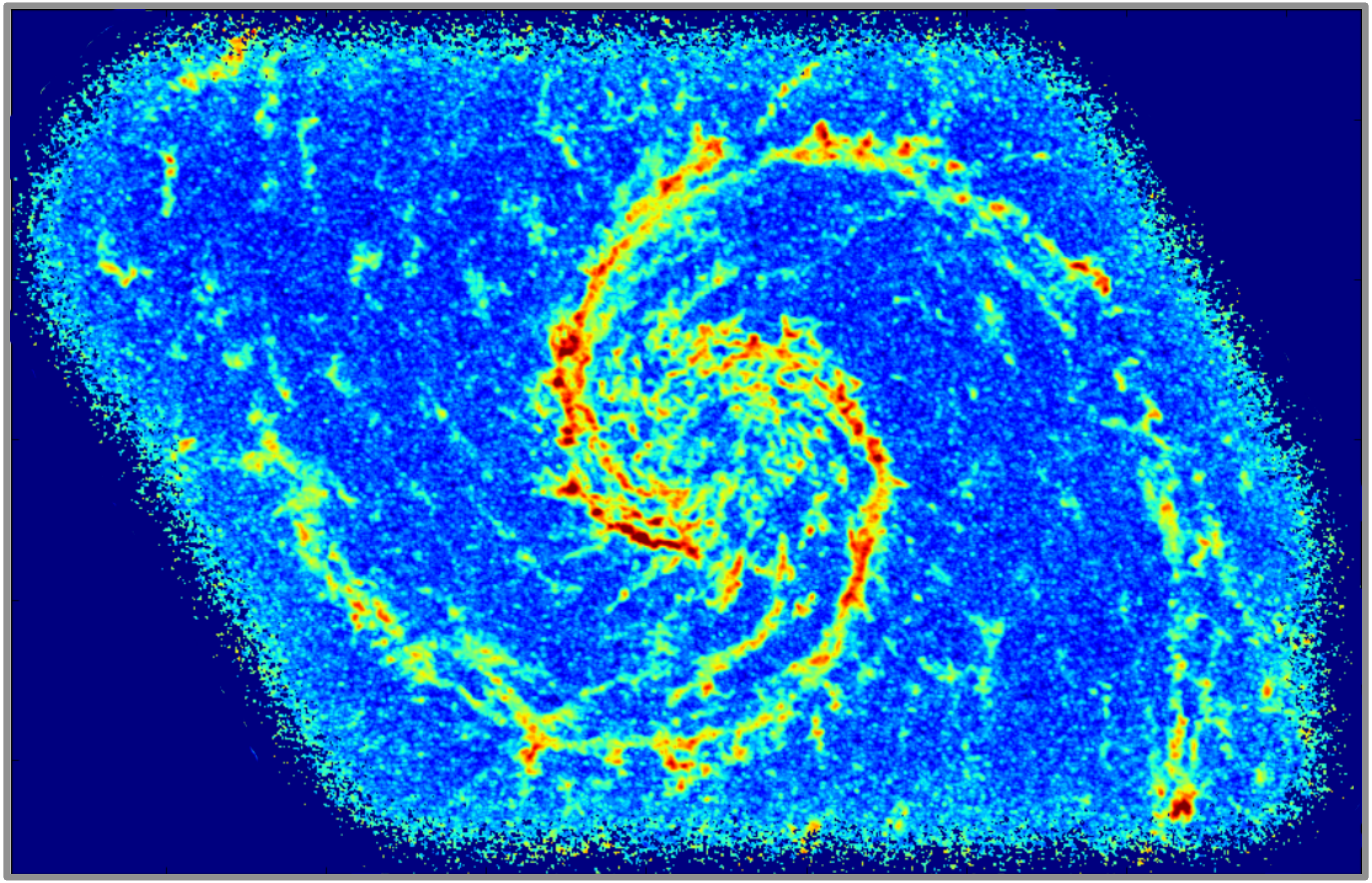
Cheoljong Lee, Leroy, Schnee, Wong, Bolatto, Indebetouw, Rubio (2015) – astroph shortly

A Semi-Empirical Prescription for α_{CO} vs Metallicity

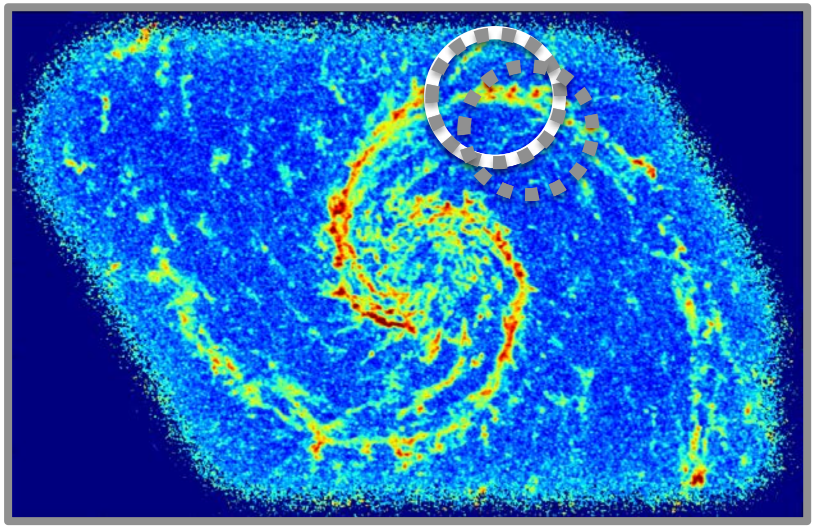


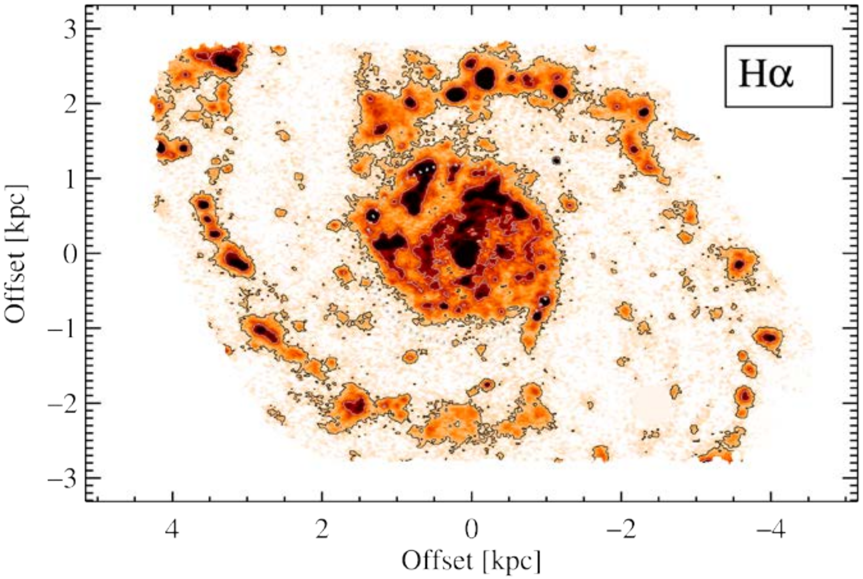
Cheoljong Lee, Leroy, Schnee, Wong, Bolatto, Indebetouw, <u>Rubio</u> (2015) – astroph shortly

Resolution – the Other Scalpel



Resolution – the Other Scalpel





Capture large scale processes (like time-averaged SF) with:

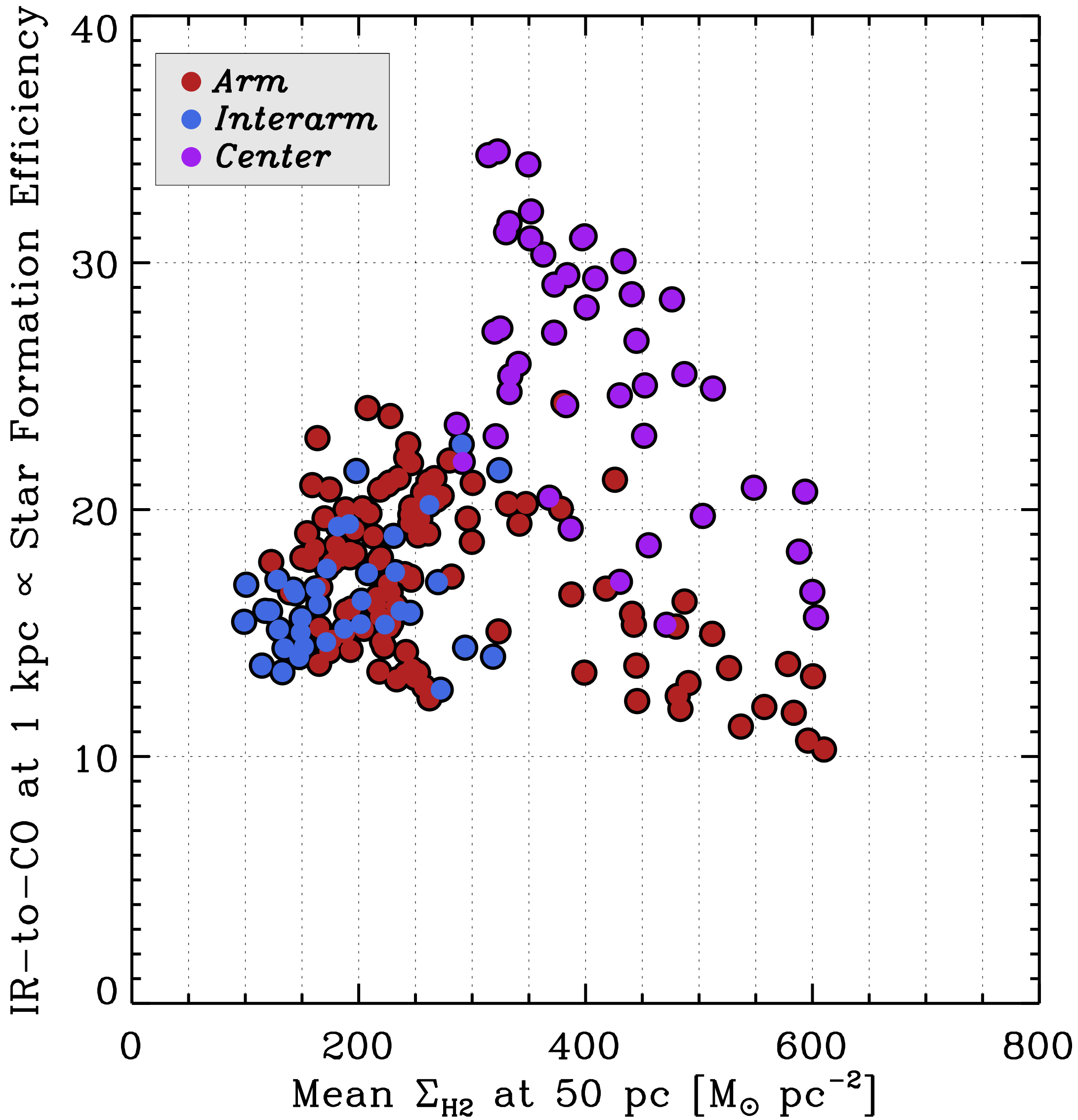
$$\tau^{H2}_{Dep} = \frac{M_{H2}}{SFR}$$

Capture small scale processes with appropriate weighting then convolution of local measurements:

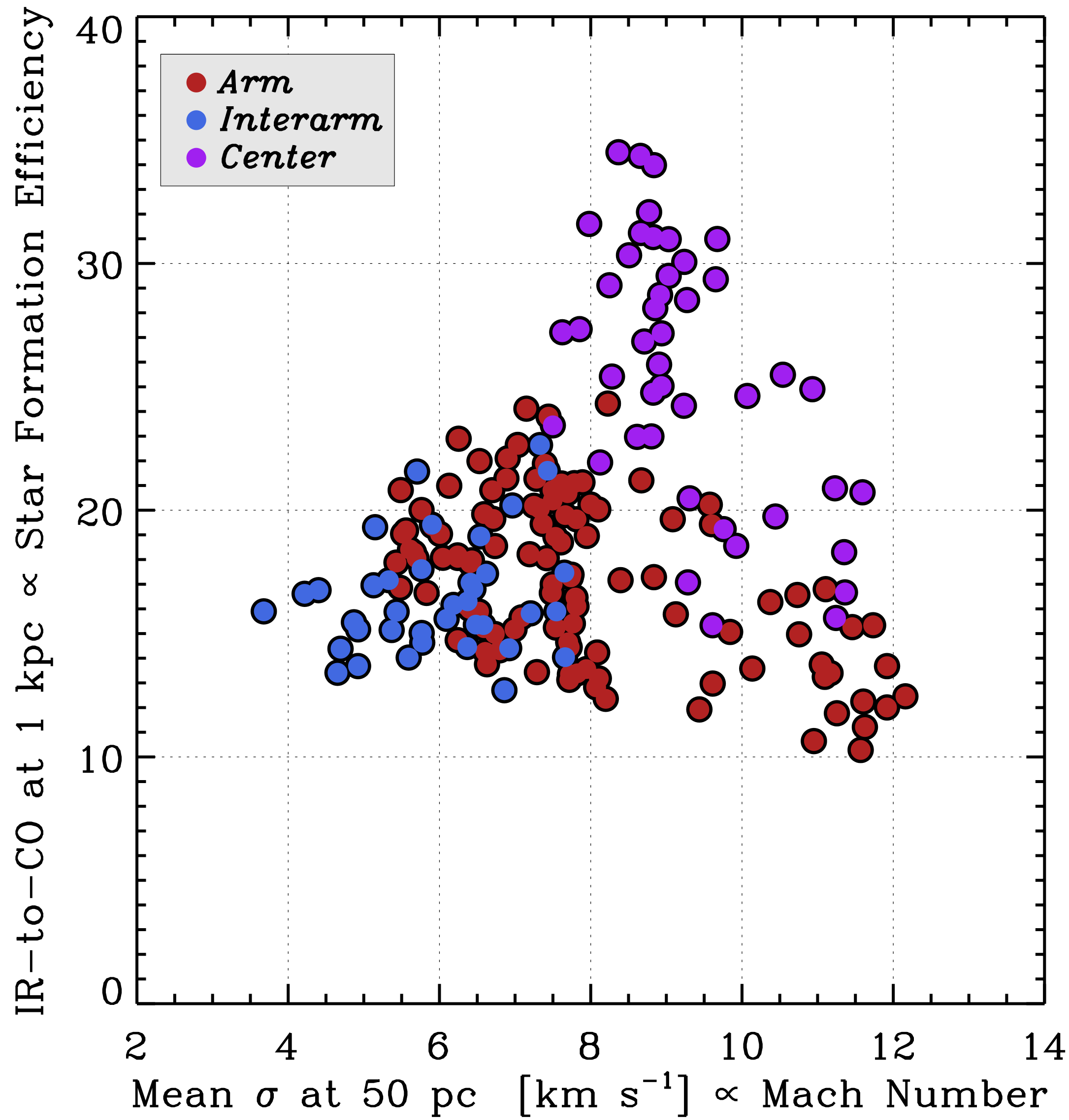
$$\langle \Sigma \rangle^{M} = \frac{\int_A \Sigma \times \Sigma \, dA}{\int_A \Sigma \, dA} = \frac{\int_A \Sigma^2 \, dA}{\int_A \Sigma \, dA}$$

Leroy, Hughes, Meidt, Schinnerer, PAWS in prep.; expanding on Leroy, Lee et al. 2013b

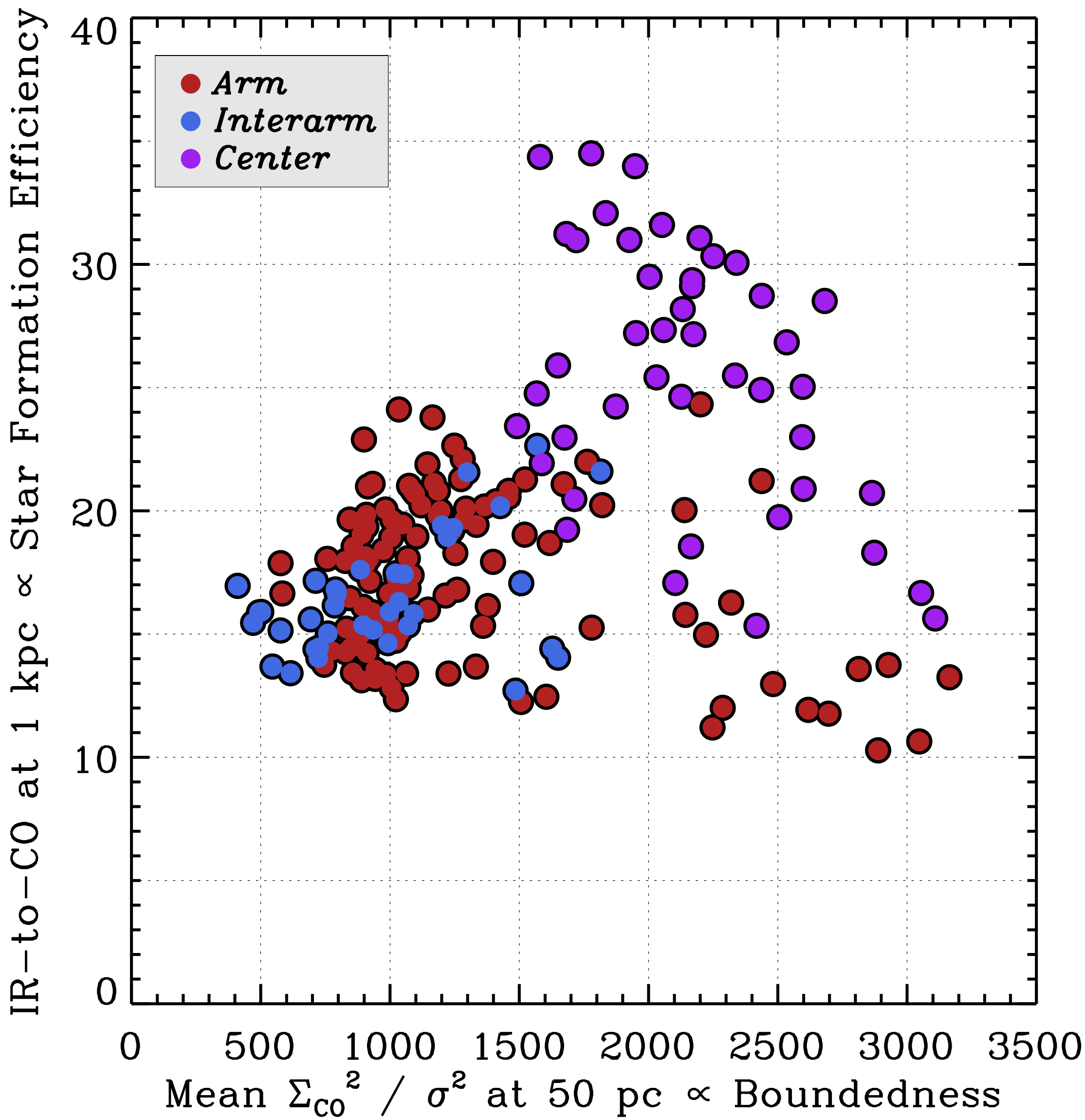
Cloud-Scale Surface Density, kpc-Scale SFR/H_2



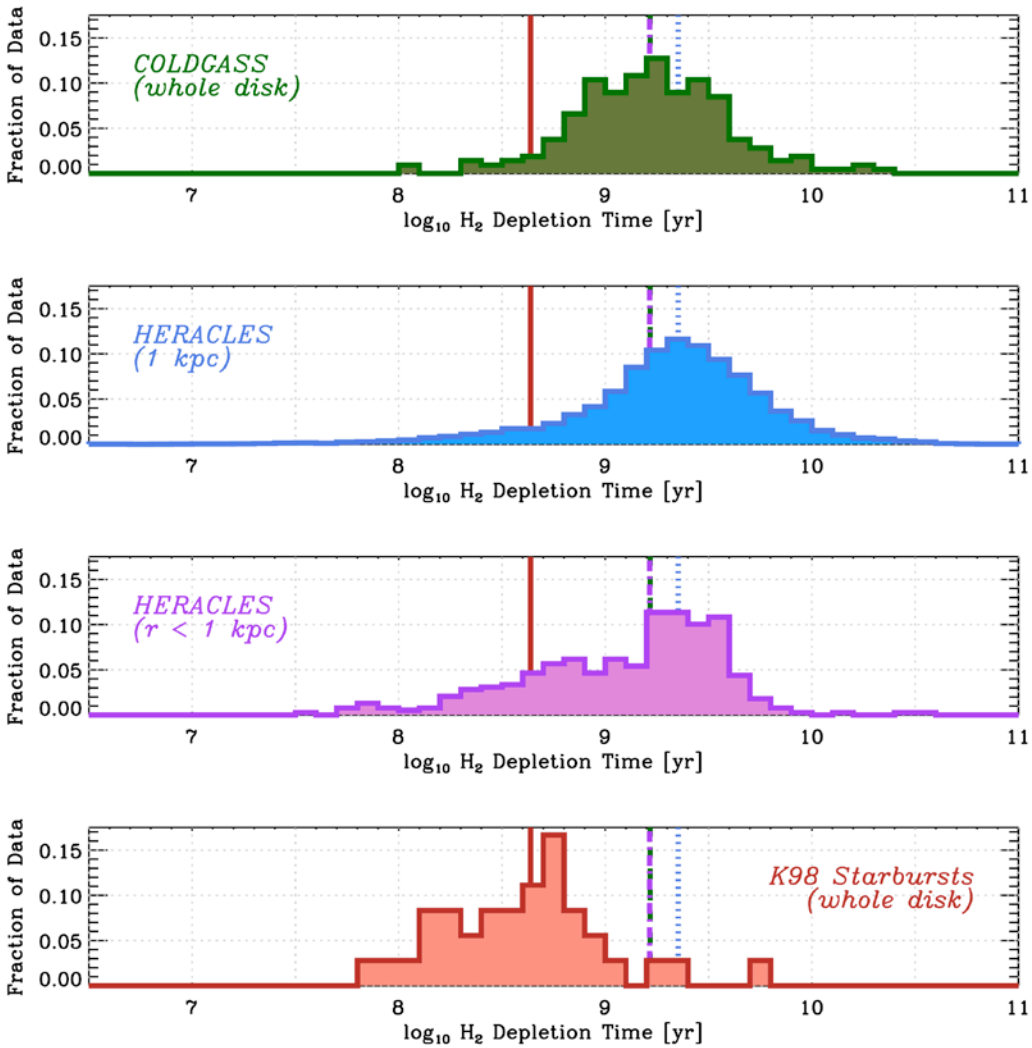
Velocity Dispersion ~ Mach Number as a Driver



Boundedness ~ Virial Parameter as a Driver

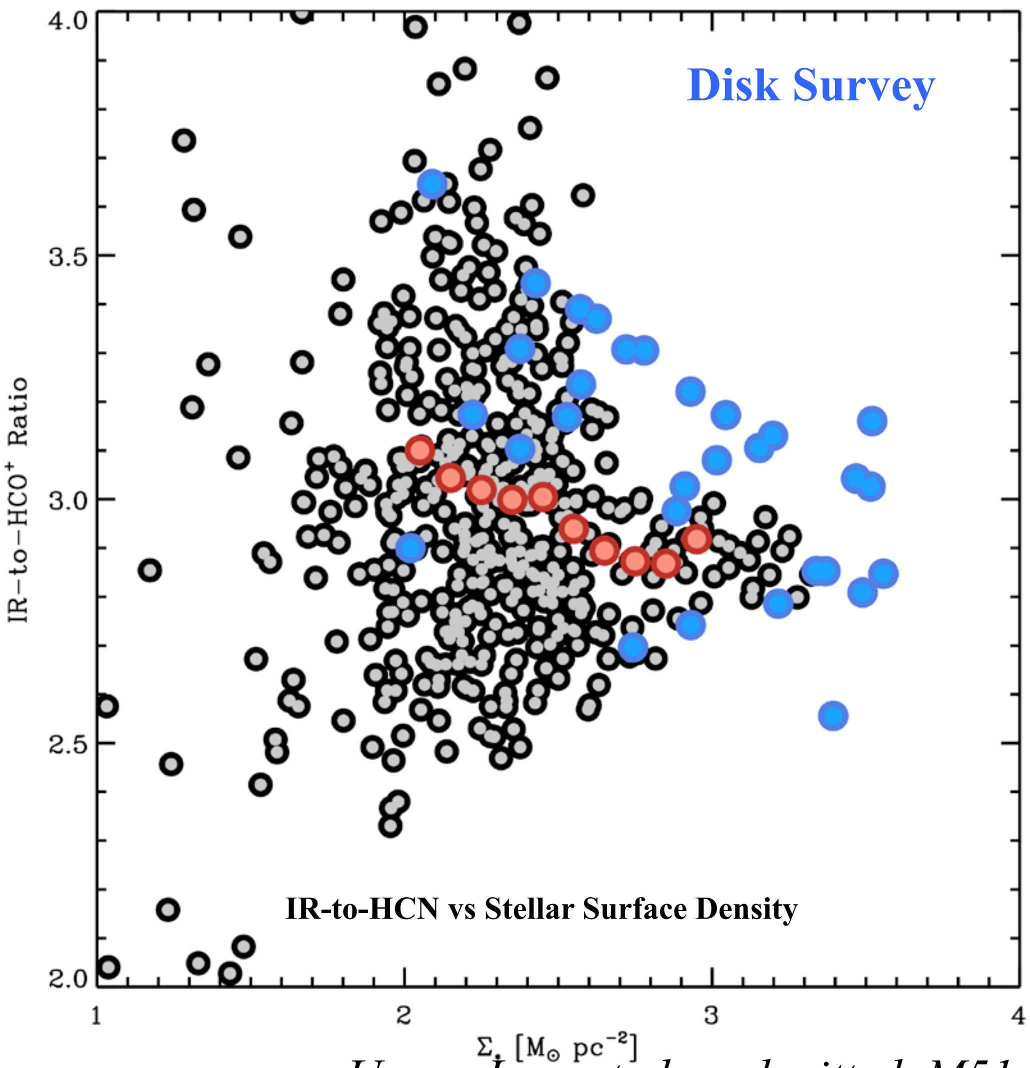


SFR Scalings



What about HCO+ ?

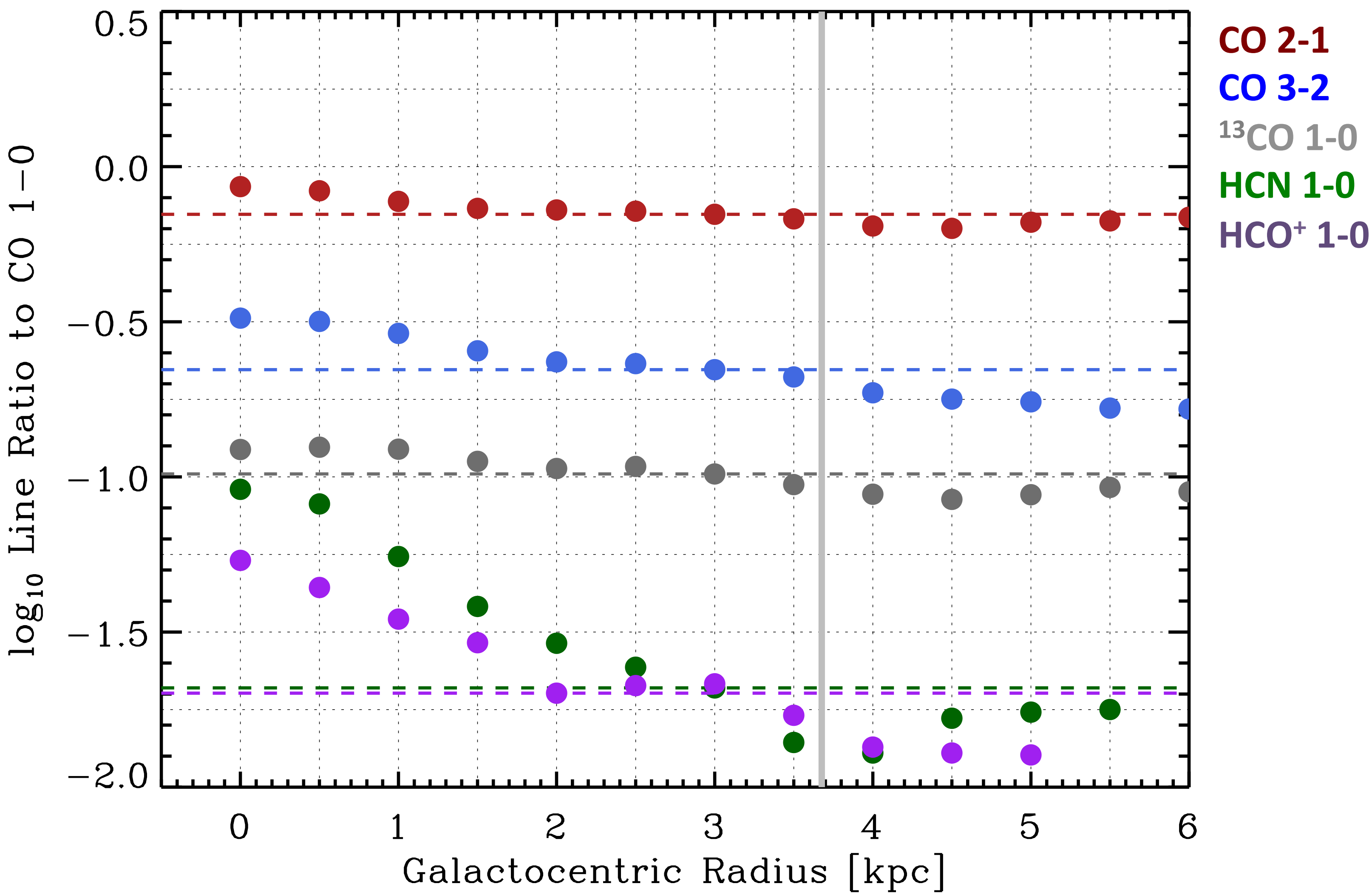
Shifting the tracer to HCO+



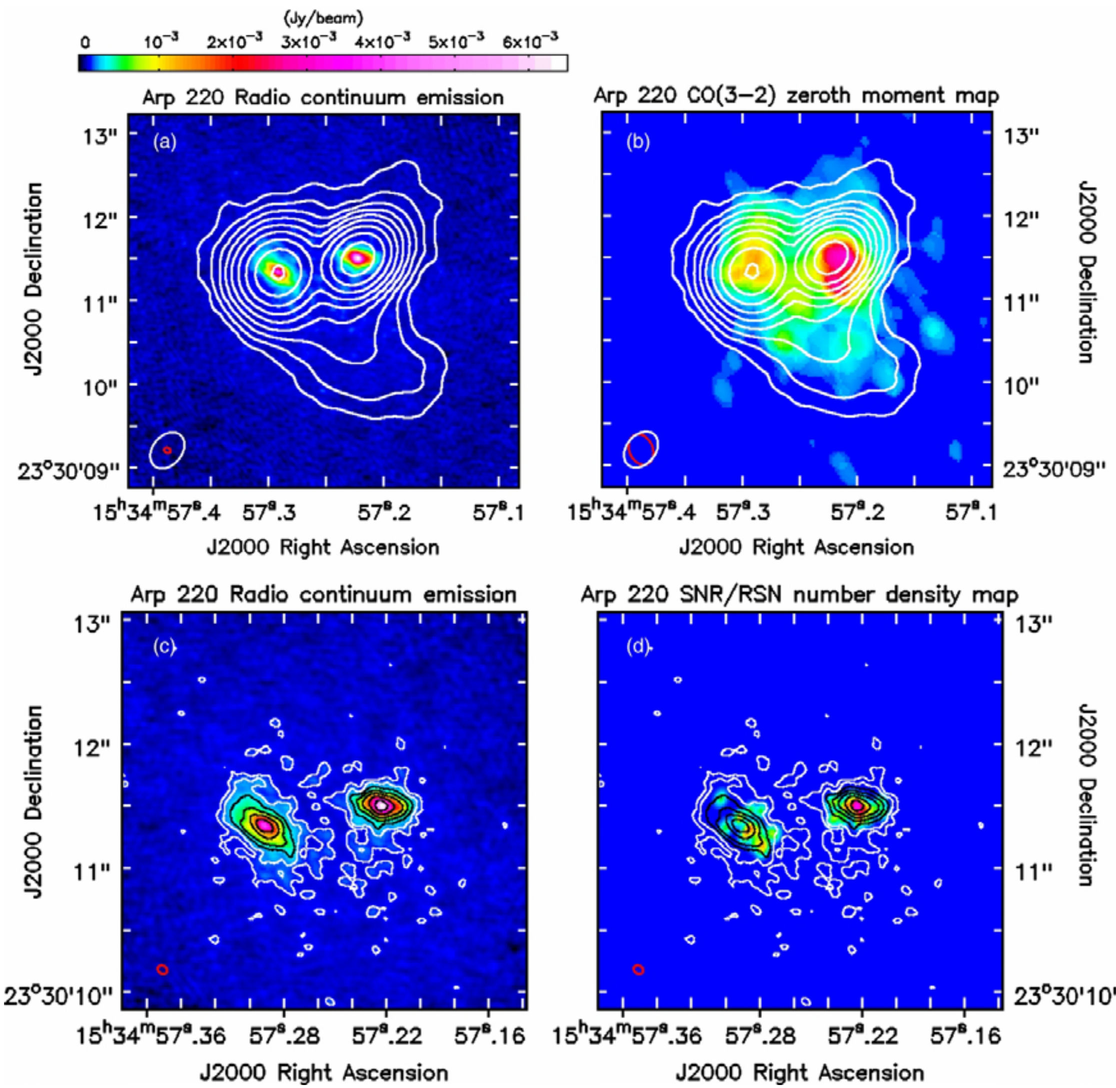
Gray points: 1 kpc, Red points: binned data

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

Full PAWS Line Ratios

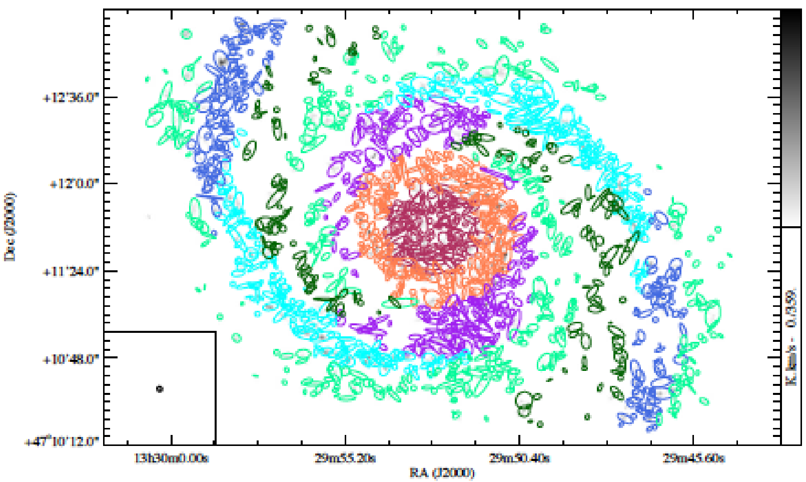


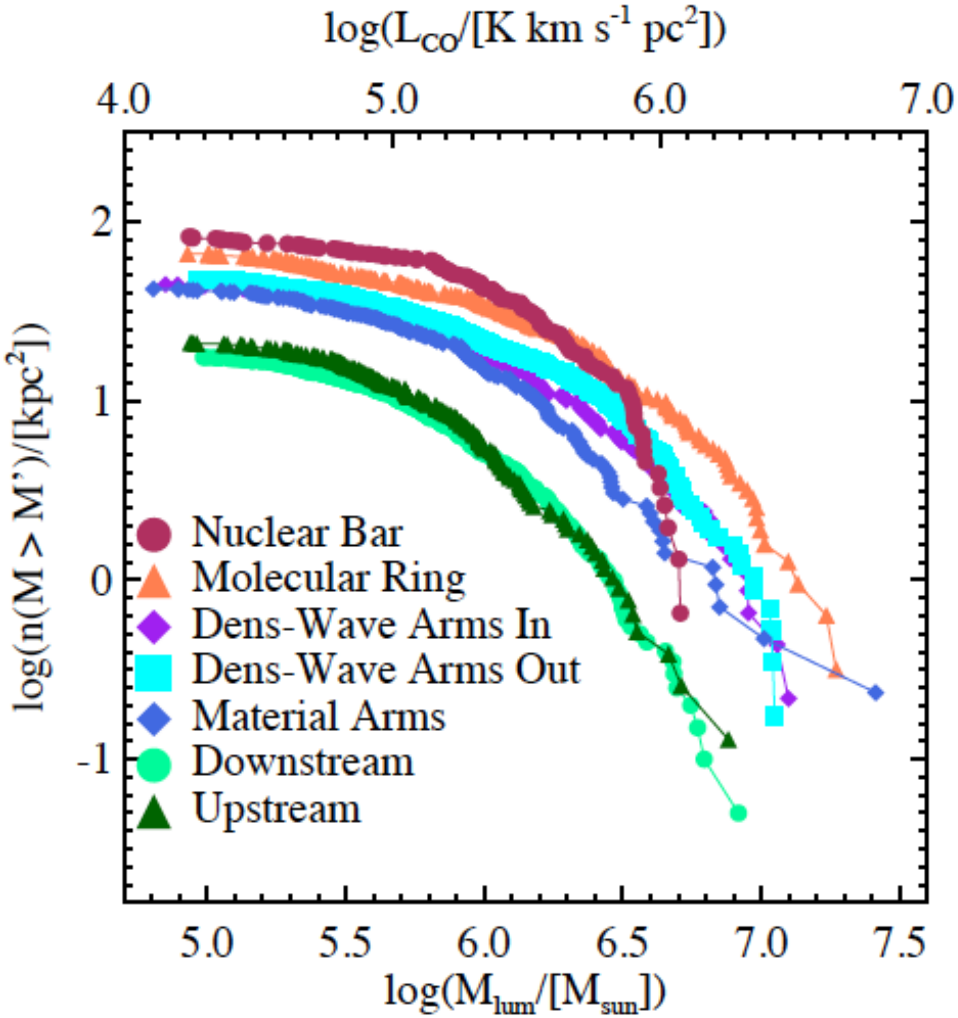
Arp 220 Resolved at Optically Thin Frequencies



Loreto Barcos-Munoz, Leroy, Evans et al. (2015)

Resolution – the Other Scalpel





Colombo+ '14, Hughes+ '13 (incl Meidt), Schinner+ '13, Pety+ '13; c.f. Koda+ '09

Resolution – the Other Scalpel