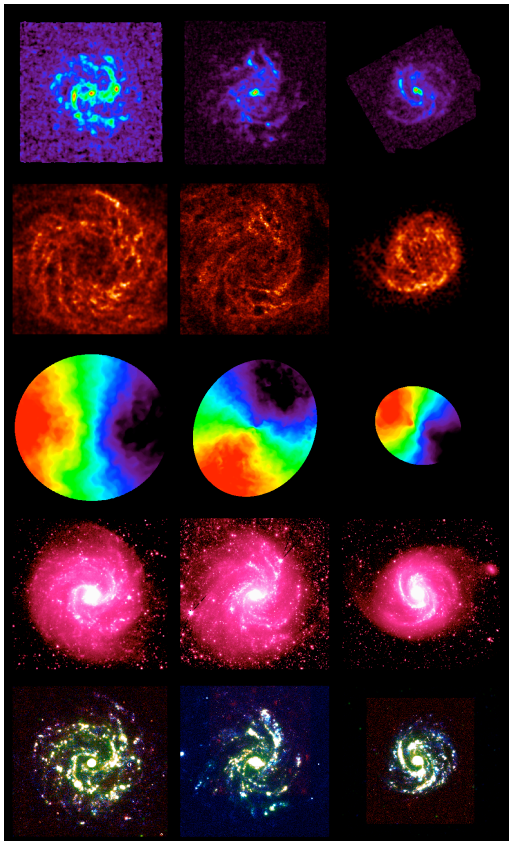
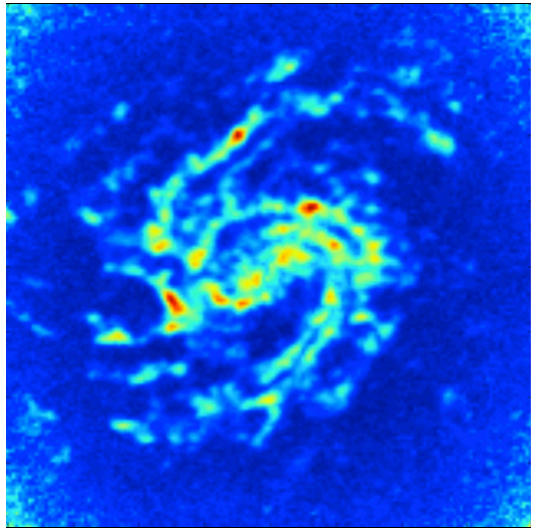
Molecular Gas in Low-Redshift Galaxies





Adam Leroy (NRAO, North American ALMA Science Center)

HERACLES & THINGS teams: **Fabian Walter, Andreas Schruba, Frank Bigiel**, Elias Brinks, Erwin de Blok, Kelly Foyle, Barry Madore, Hans-Walter Rix, Erik Rosolowsky, Karin Sandstrom, Eva Schinnerer, Karl Schuster, Michelle Thornley, Antonio Usero, Axel Weiss, Helmut Wiesemeyer

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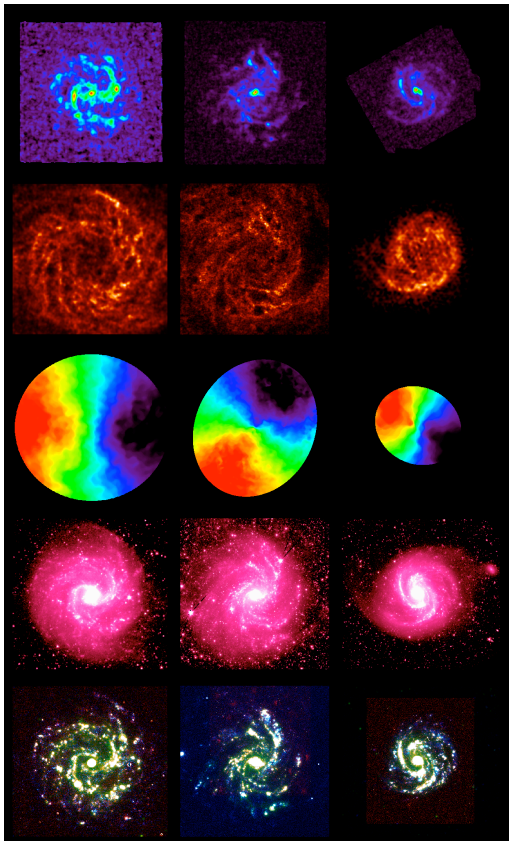

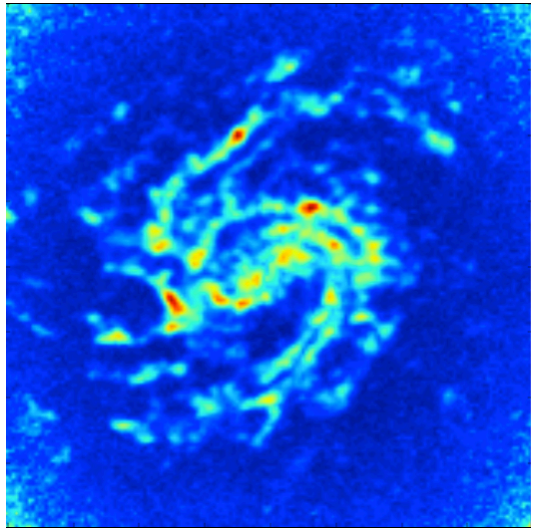

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Molecular Gas in Nearby Galaxies

1. **CO Surveys Past & Present**

2. 9 things we have learned from studying CO in nearby galaxies:

   - CO is distributed Like starlight (but not in Early Types)
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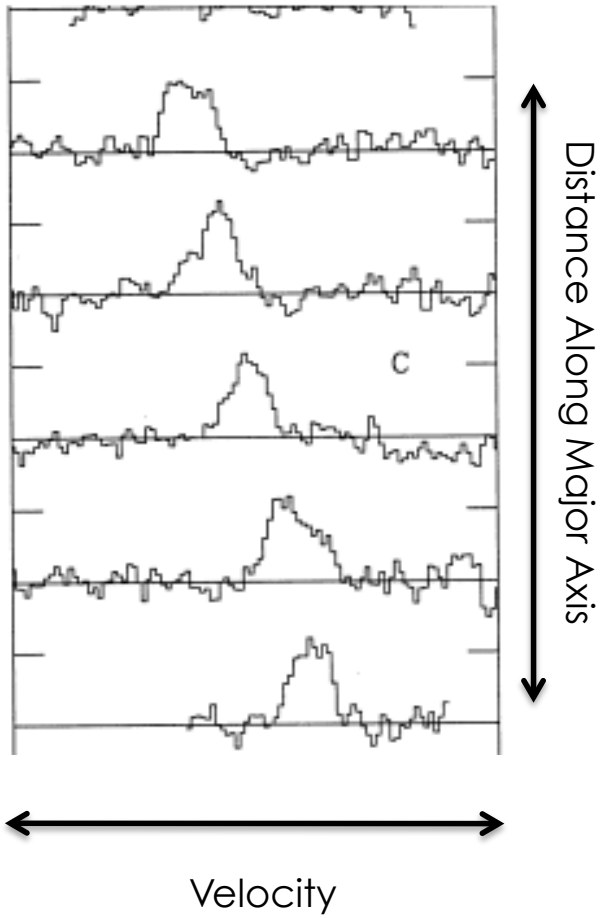
Early Big Single Dish Surveys

One FCRAO major axis cut.



(80s - 90s) Single Dish Surveys of Large Samples:

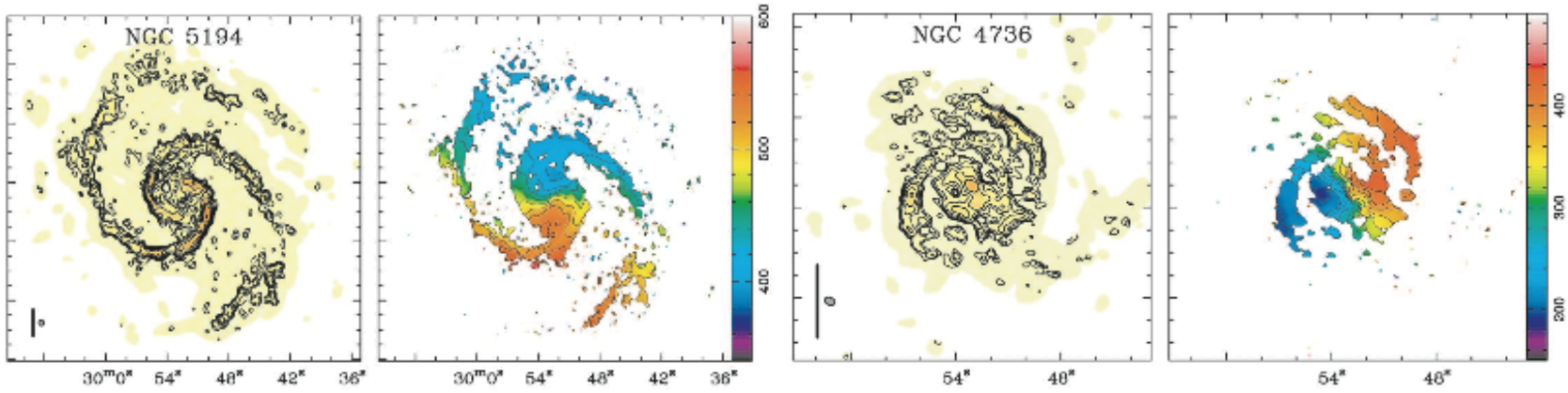
- FCRAO Extragalactic CO Survey
  YOUNG & SCOVILLE '91, YOUNG+ '95
- IRAM 30-m Surveys
  BRAINE & COMBES '92-'93, SOLOMON ET AL. 1997
- IRAM 30-m + 12m HCN Survey
  GAO & SOLOMON 2004AB

Early Interferometer Mapping Surveys

(90s – 00s) Interferometer Maps of Samples of Galaxies:

- BIMA Survey of Nearby Galaxies
  HELFER+ '03, REGAN+ '01
- OVRO Molecular Gas in Active/Inactive Nuclei
  BAKER+ '03
- PdBI Survey of ULIRGs
  DOWNES & SOLOMON '98
- IRAM PdBI Nuclear Gas in Active Galaxies
  GARCIA-BURILLO+ '03

BIMA SONG maps of NGC 5194, NGC 4736



Cloud-Scale Galaxy Surveys

IRAM 30-m map of M31 (NIETEN ET AL. 2006)

(90s – 00s) Complete Surveys of the Nearest Big Galaxies:

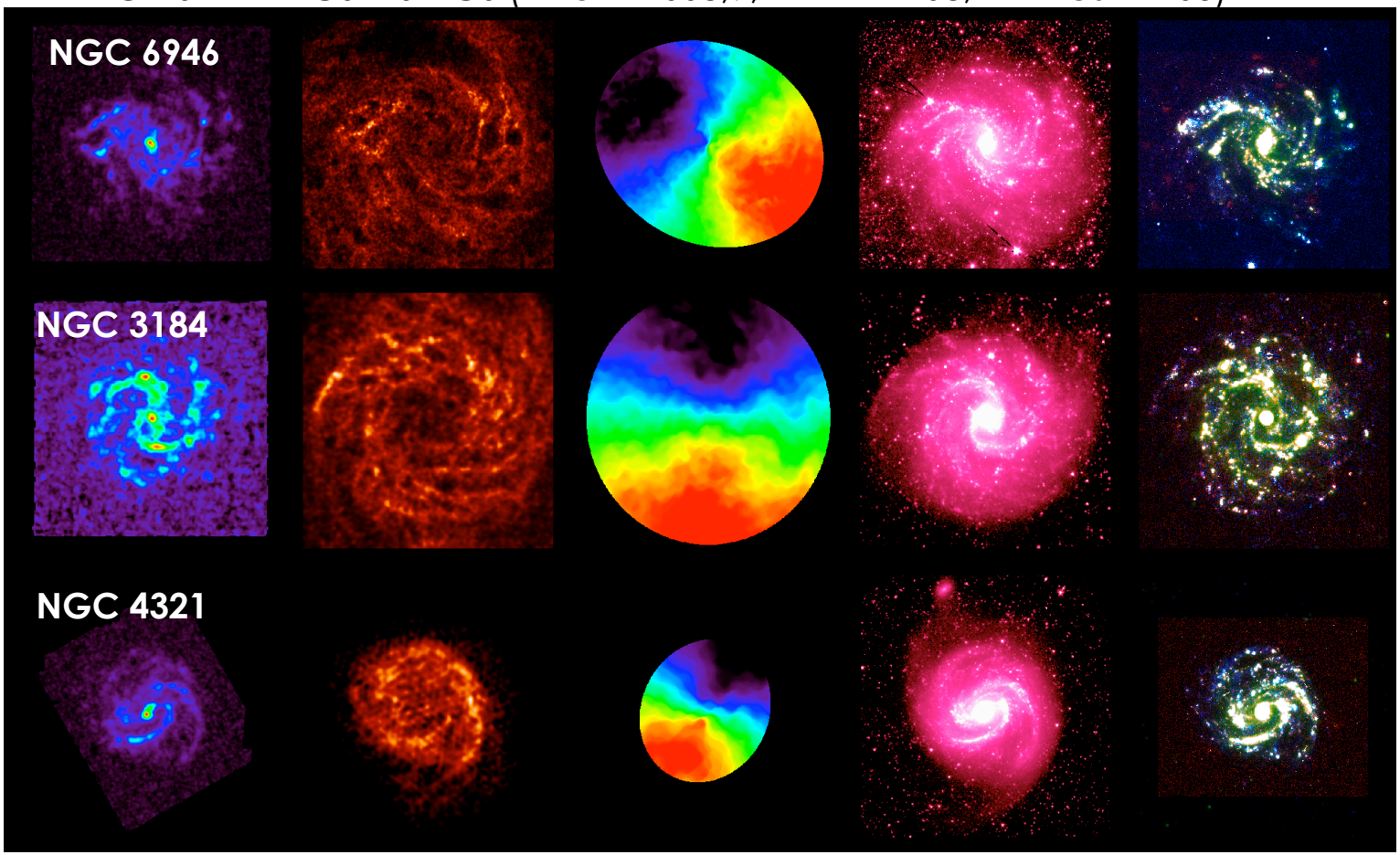
- M33 (ENGARGIOLA+ '03, GRATIER+ '11)
- M31 (NIETEN+ '06, pictured)
- LMC (FUKUI+ '99, '08, HUGHES, WONG, OTT+ '10)
- SMC (MIZUNO+ '01, MUELLER+ '10)
- IC10 (LEROY+ '06), NGC 6822 (GRATIER+ '10)

Receiver Arrays and Multi-λ Data

(Late 00s-10s) Receiver Arrays on Big Single Dishes:

- IRAM 30-m HERACLES (LEROY, WALTER+ '09)
- JCMT Nearby NGLS (WILSON+ '08, WARREN+ '08)
- Nobeyama Survey of CO in Spiral Galaxies (KUNO+ '07)

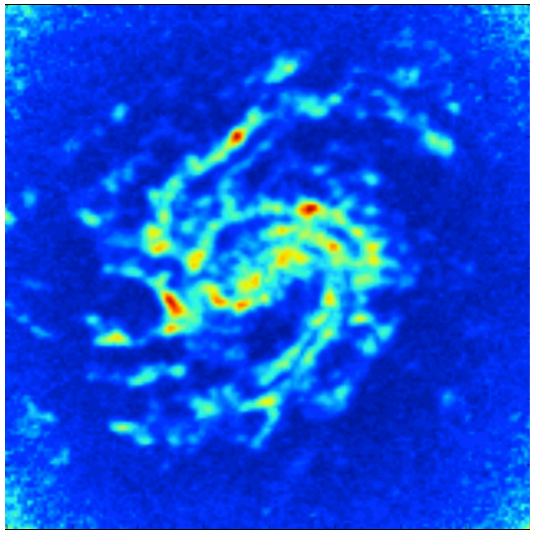
HERACLES + THINGS + SINGS (LEROY+ 2008,9; WALTER+ '08; KENNICUTT+ '03)



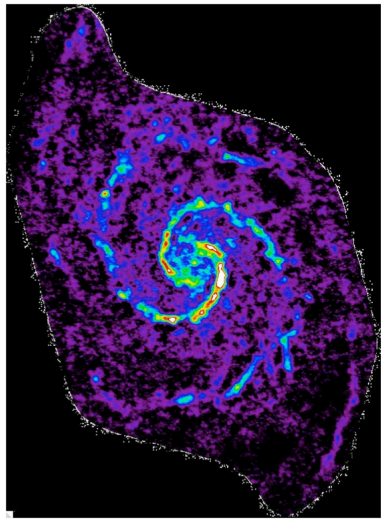
Current Interferometer and Single-Dish Work

(Late 00s-10s) Next Generation Interferometer Surveys (10-20 galaxies):

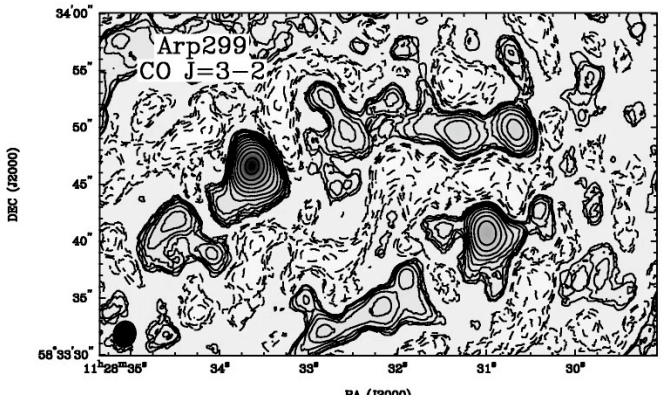
- CARMA STING Survey (PI: A. BOLATTO, RAHMAN+ '11)
- CARMA/Nobeyama Survey of Molecular Gas (KODA+ '10)
- SMA Survey of CO in LIRGs (WILSON+ '08)



CARMA STING Maps of M99
(RAHMAN, BOLATTO, WONG+ '11)



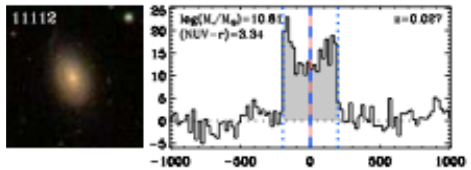
CARMA+Nobeyam M51
(KODA+ '10)



SMA Arp 299 (NGC 3690)
(WILSON+ '08)

(Late 00s-10s) Return to Single Dish Surveys of Large Samples (~200 galaxies):

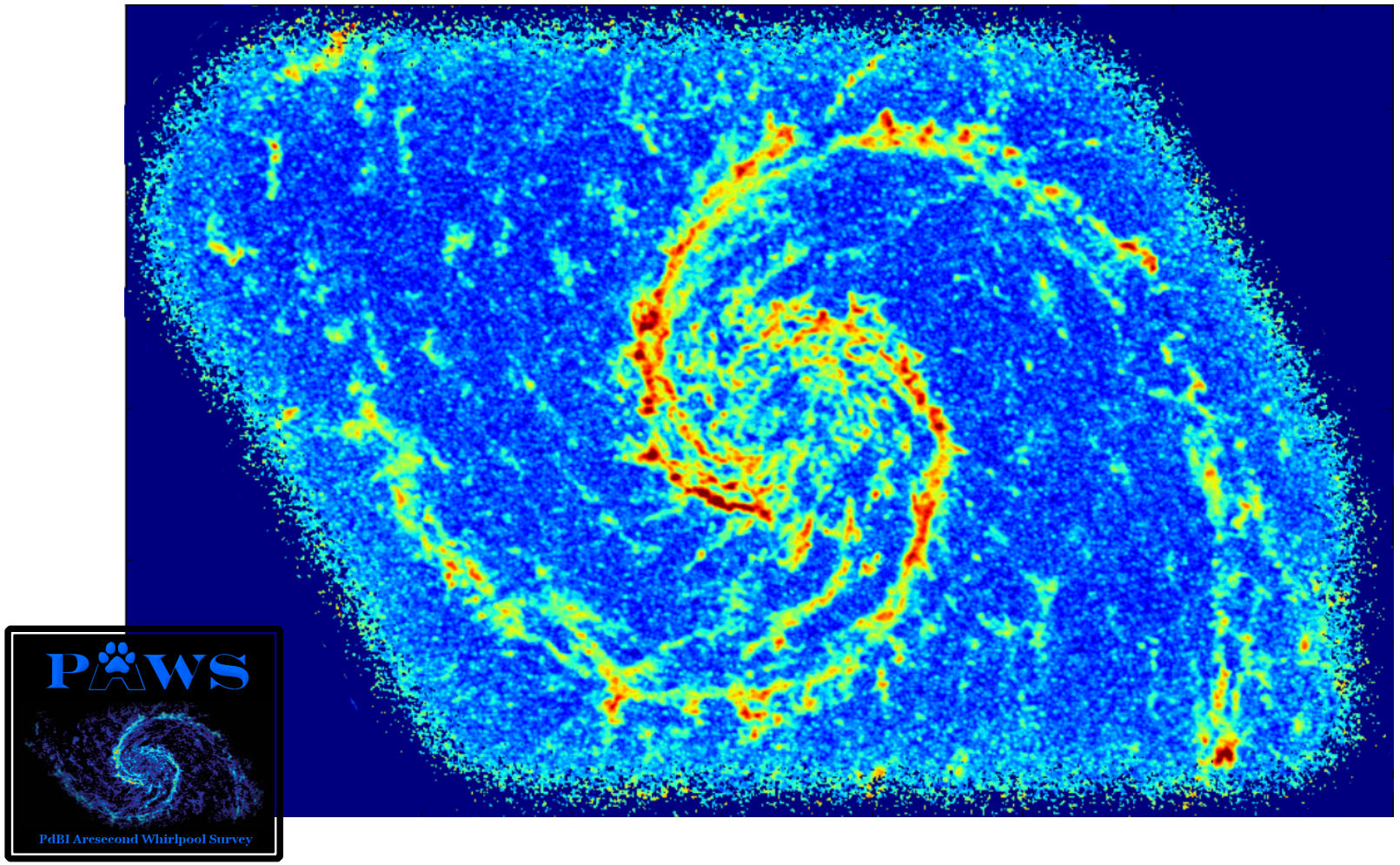
- IRAM 30-m COLD GASS (SANTIONGE+ '11AB)
- IRAM 30-m + FCRAO AMIGA Survey (PI: LISENFELD)
- IRAM 30-m + CARMA ATLAS3D (YOUNG+ '11, DAVIS+ '10, ALATALO+ '11)



A Preview of the Next 10 Years

('10s) ALMA! Maturation of Wide-Field Receivers, Big Surveys

An ALMA preview: the PAWS Survey (PI: E. Schinnerer) – PDBI 1" (50 pc) Map of M51:



Molecular Gas in Nearby Galaxies

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- **CO is distributed Like starlight (but not in Early Types)**
- **CO also follows starlight inside galaxies**

- **To first order CO and SFR track one another**
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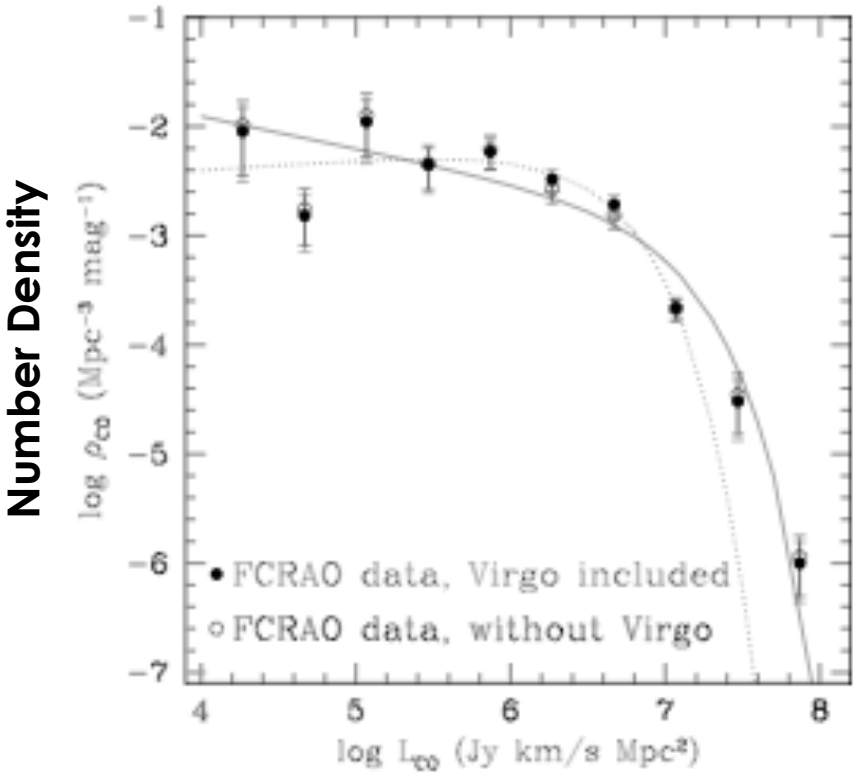
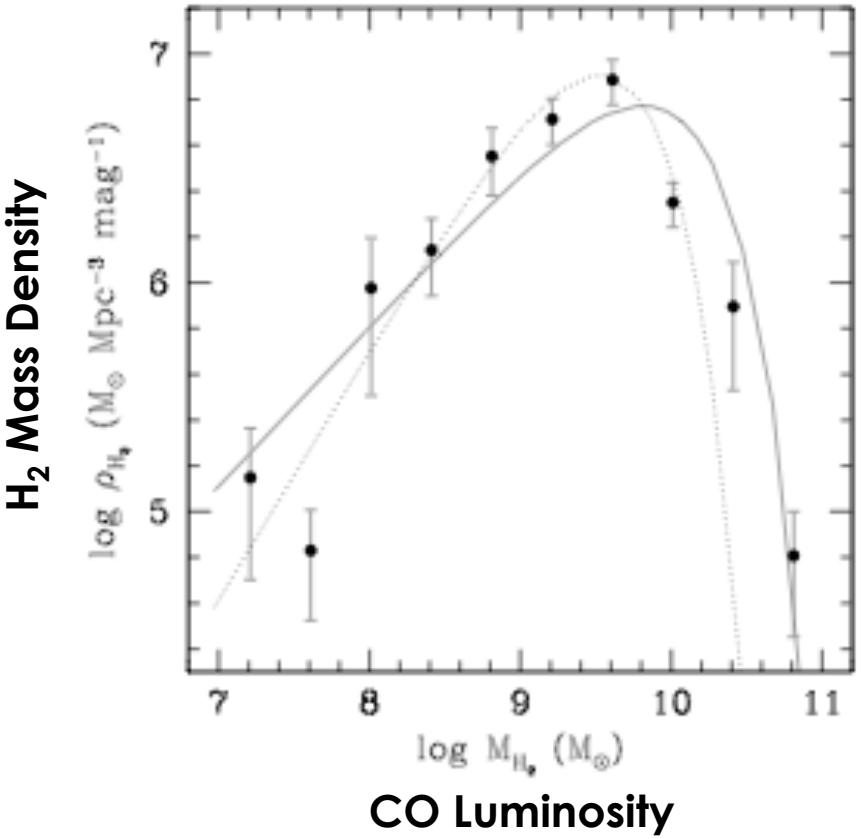
- **The CO-to-H_2 conversion factor is a multi-regime problem**
- **The CO-to-H_2 is a nonlinear function of metallicity**

#1. CO is Distributed Like Starlight

CO luminosity function Looks like optical version.
M^*_{H2} = 1-4 10^9 M_{sun} depending on methodology.
High luminosity tail. Most mass from ~ M^*_{H2} systems.

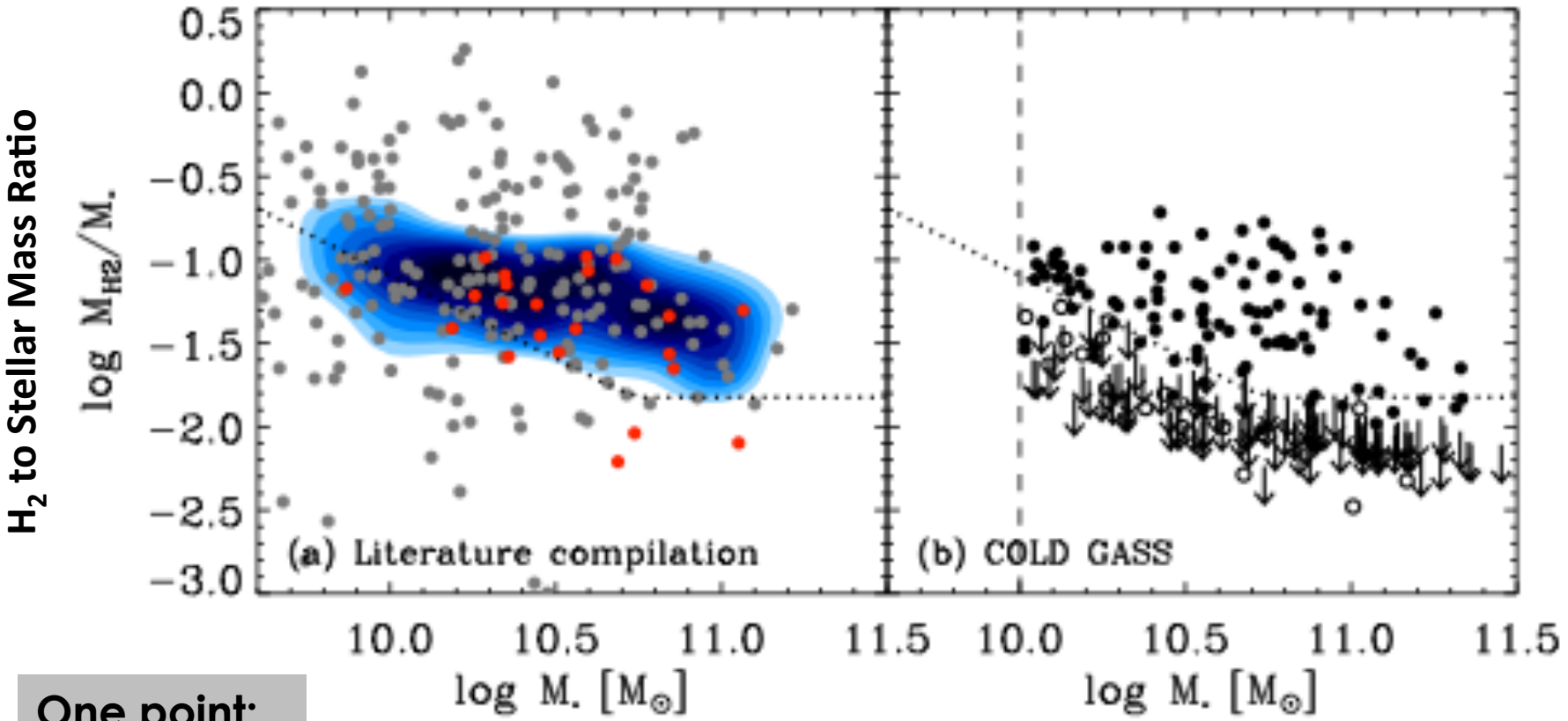




KERES+ '03 (FCRAO), OBRESCHKOW & RAWLINGS '09

#1. CO is Distributed Like Starlight

H_2–to-stars ratio not a strong function of stellar mass (with caveats).
Implied H_2 mass fraction just under 10%

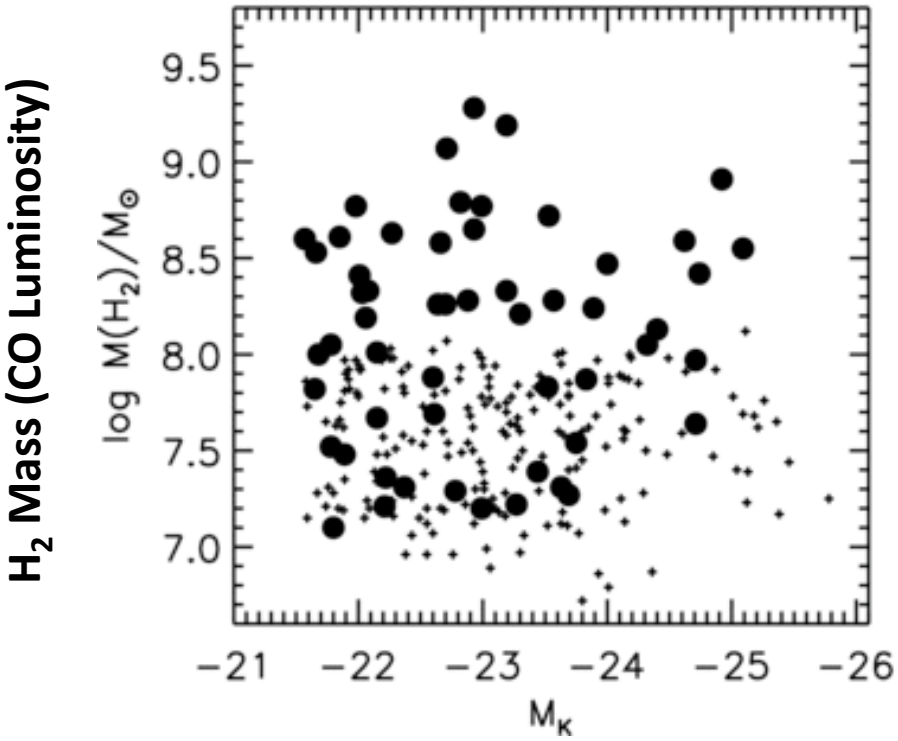


One point:
One galaxy

SAINTONGE+ '11, YOUNG & SCOVILLE '91, LEROY+ '05, BOTHWELL+ '09

(but not for Early Type galaxies)

Fixed H_2-to-stars ratio breaks down in Early Type galaxies.
Subtle correlations with rotation, environment but a lot of noise.

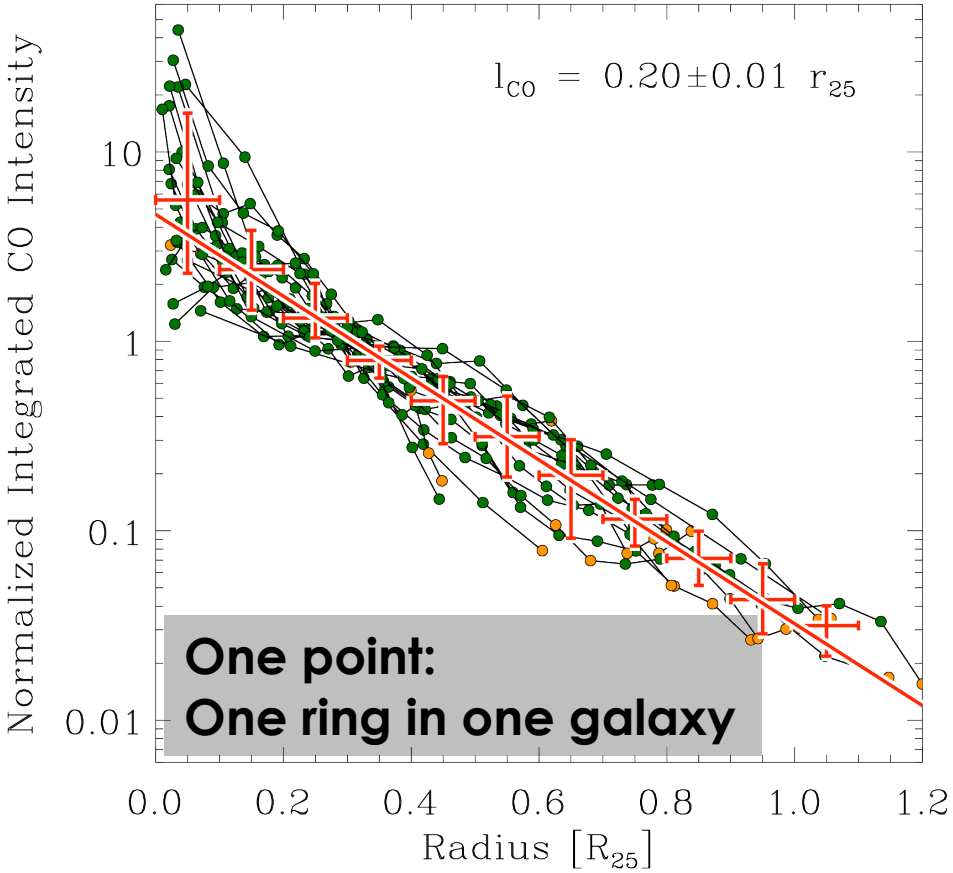


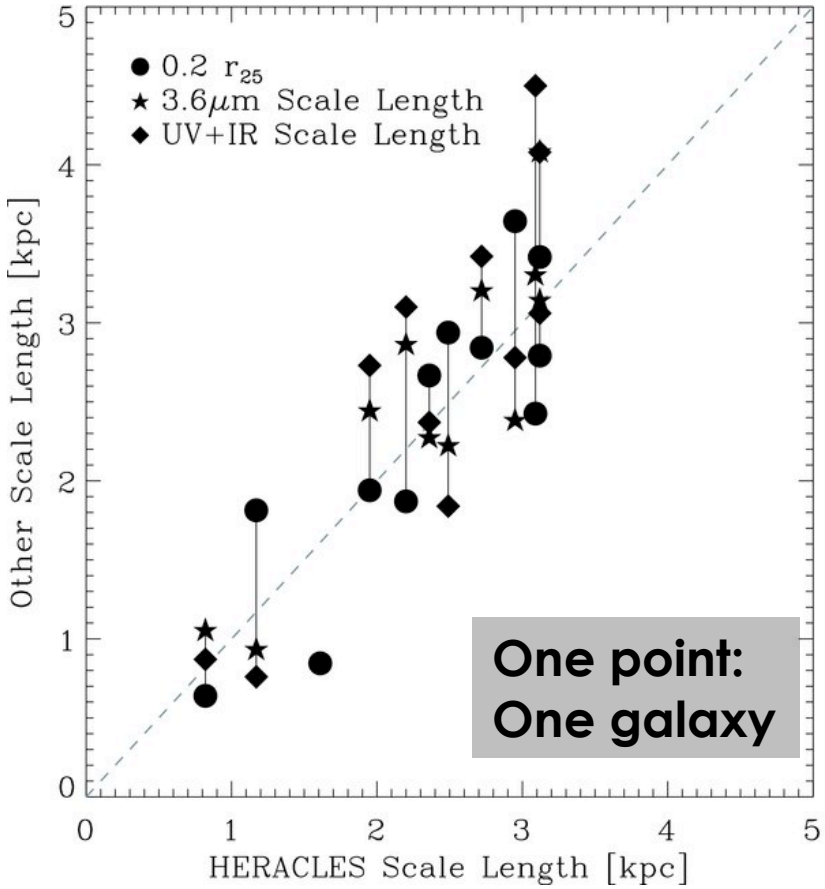
One point:
One galaxy

YOUNG+ '11

#2. CO Follows Stellar Light Inside Galaxies

To first order, CO in star forming galaxies looks exponential vs. radius with a sale length comparable to old starlight, SFR tracers.

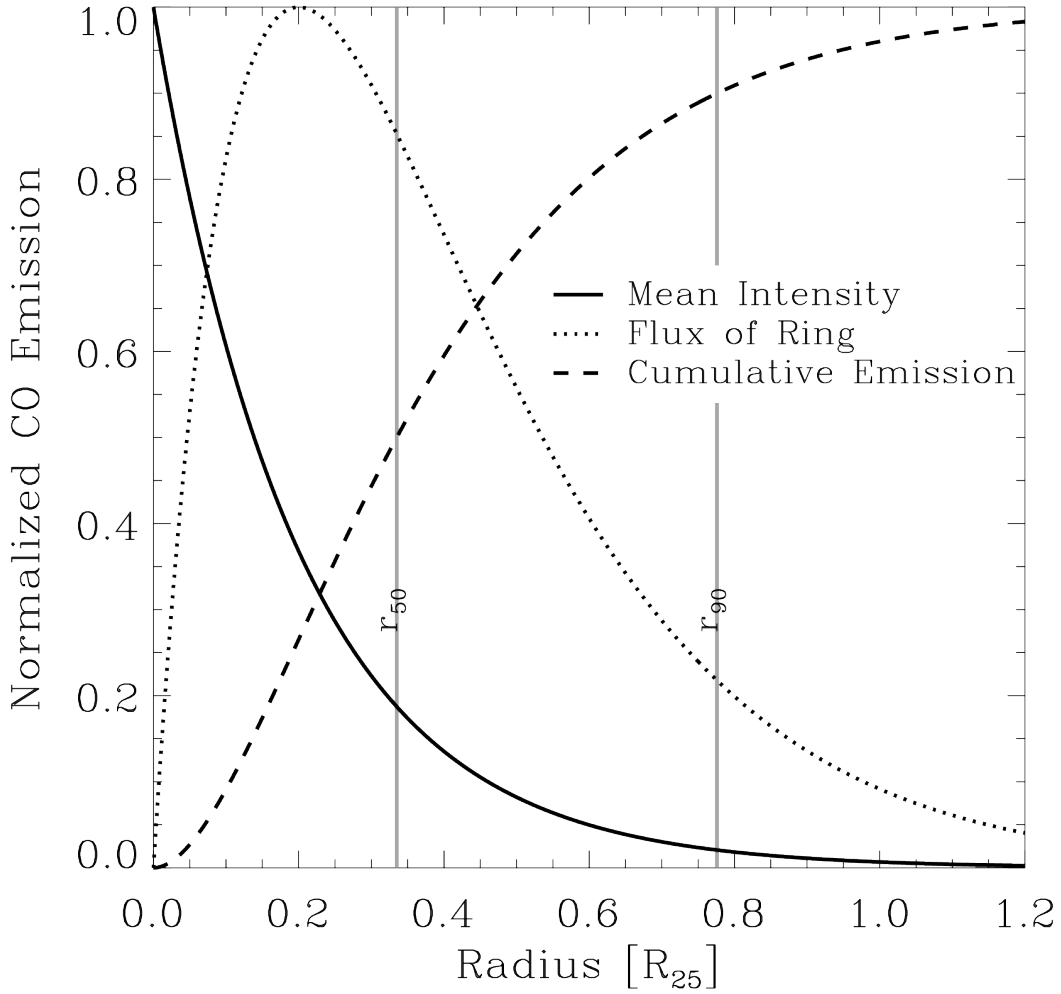




YOUNG+ '95, REGAN+ '01, **LEROY+ '08,'09**, **SCHRUBA, LEROY '11**

#2. CO Follows Stellar Light Inside Galaxies

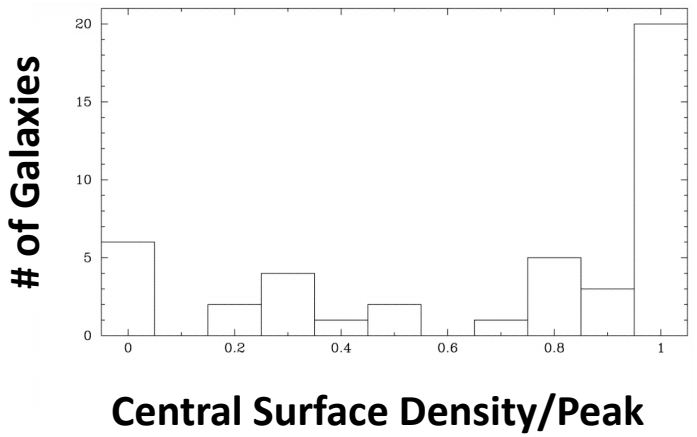
For such a disk 50% of the flux lies inside ~0.35 r_{25} and 90% insid ~0.8 r_{25}



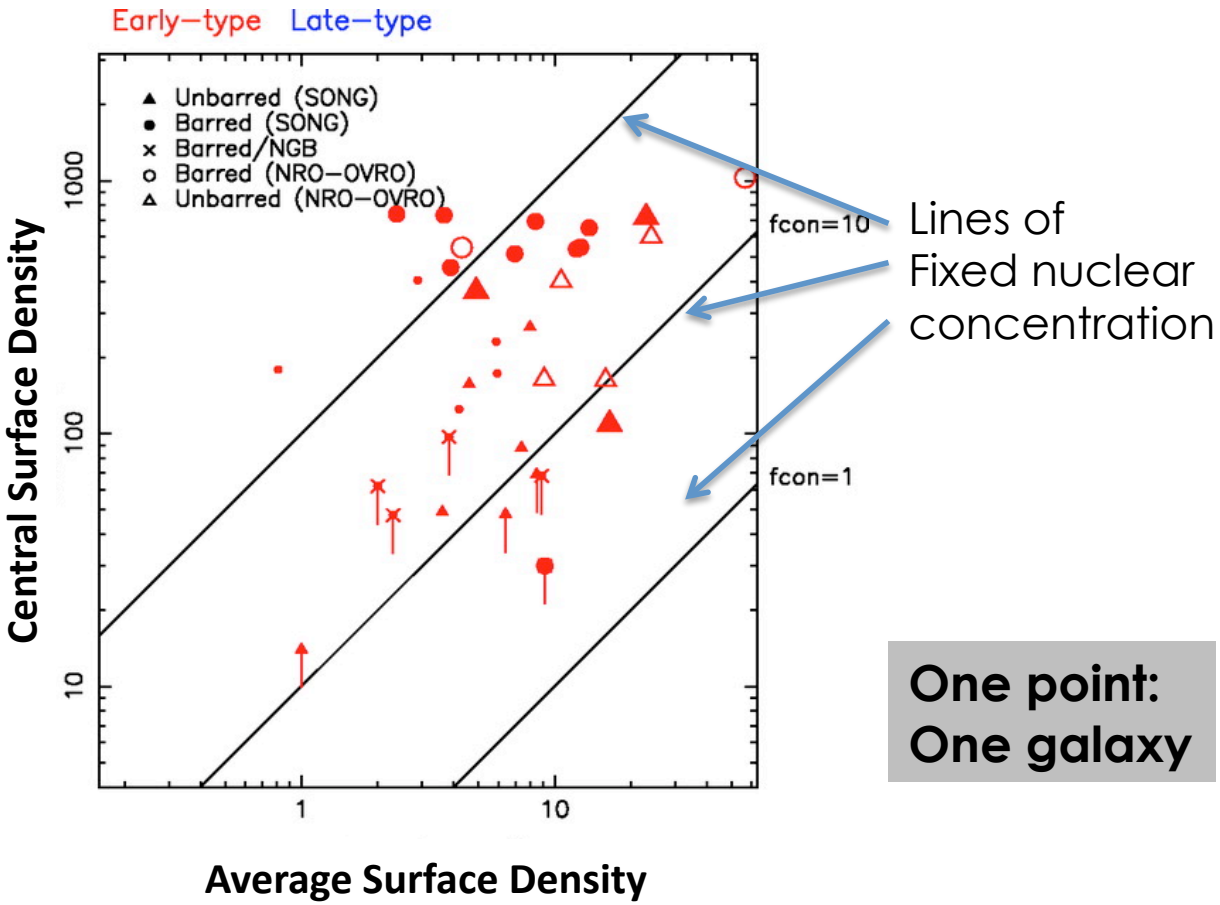
YOUNG+ '95, REGAN+ '01, LEROY+ '08,'09, **SCHRUBA, LEROY+ '11**

(But Important Second Order Variations)

Nuclear properties vary, apparently functions of dynamics (esp. bars).



About ½ of galaxies have their CO peak at the center.



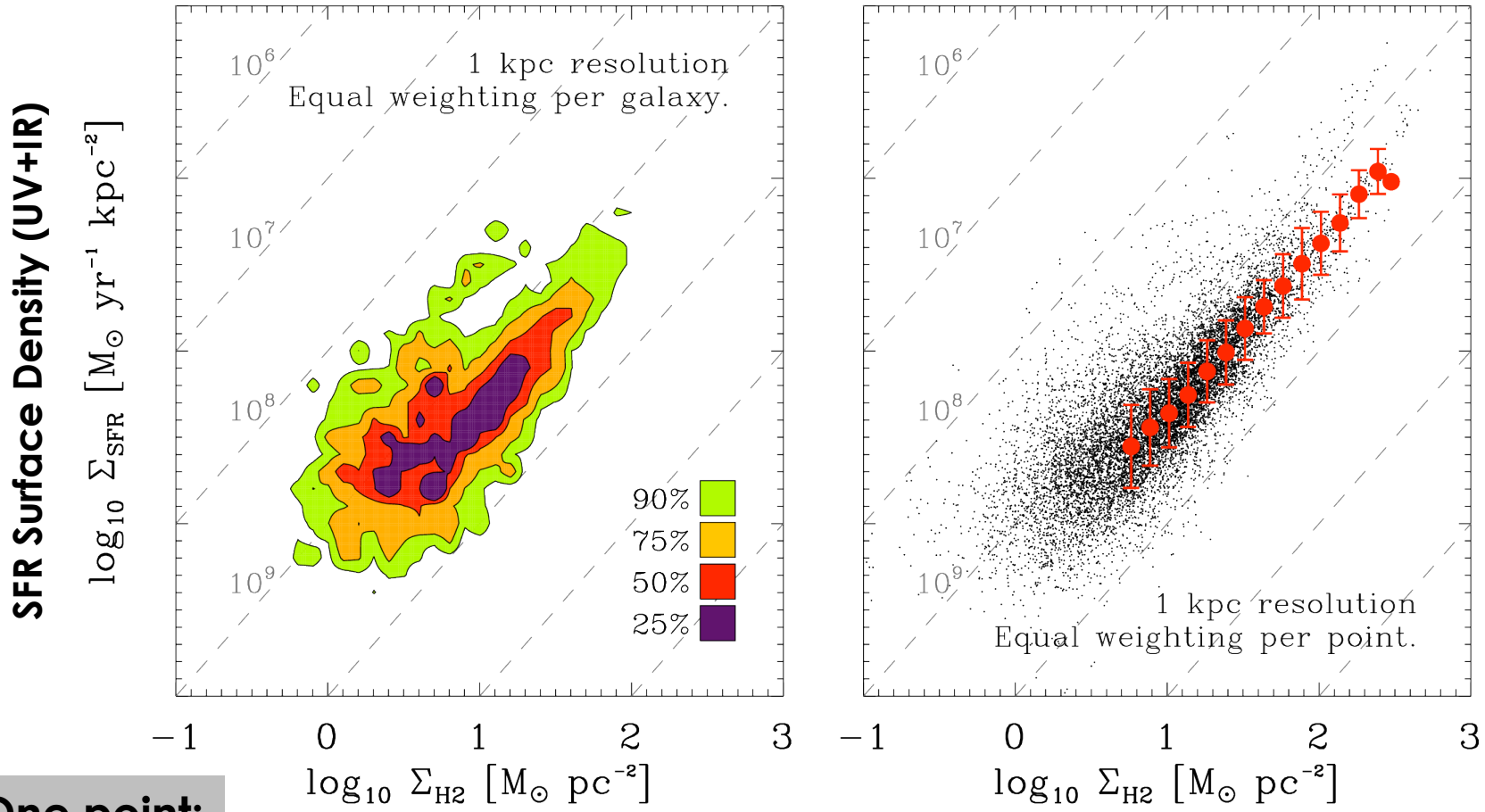
Lines of Fixed nuclear concentration

One point: One galaxy

SHETH+ '05, HELFER+ '03, KUNO+ '07

#3. To First Order, CO tracks Star Formation

Star formation and CO appear 1-to-1 in star-forming disk galaxies.

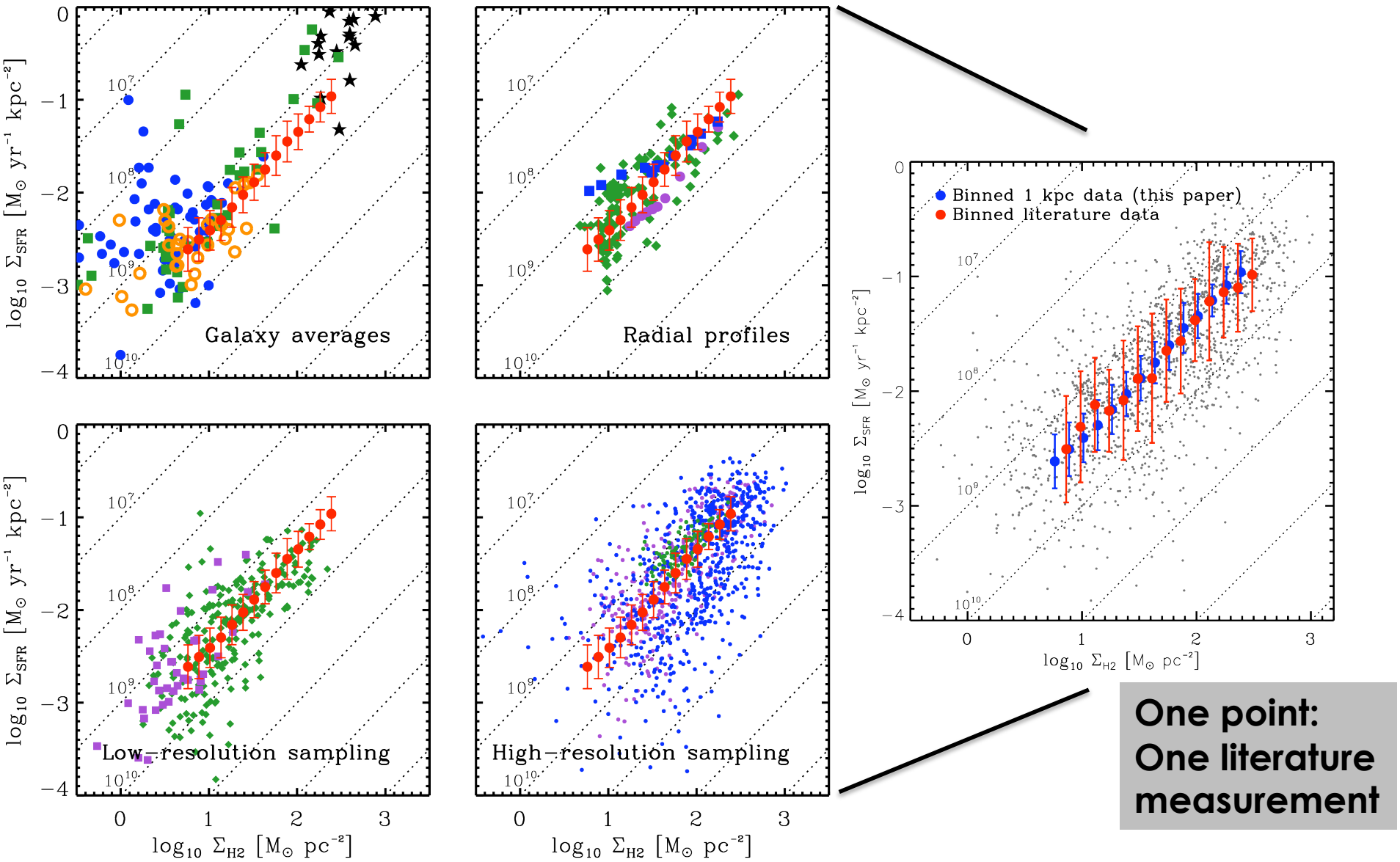


One point: One kpc²

H_2 Surface Density from CO

BIGIEL+ '08, LEROY+ '08, BLANC+ '09, GENZEL+'10, BIGIEL+ '11

#3. To First Order, CO tracks Star Formation

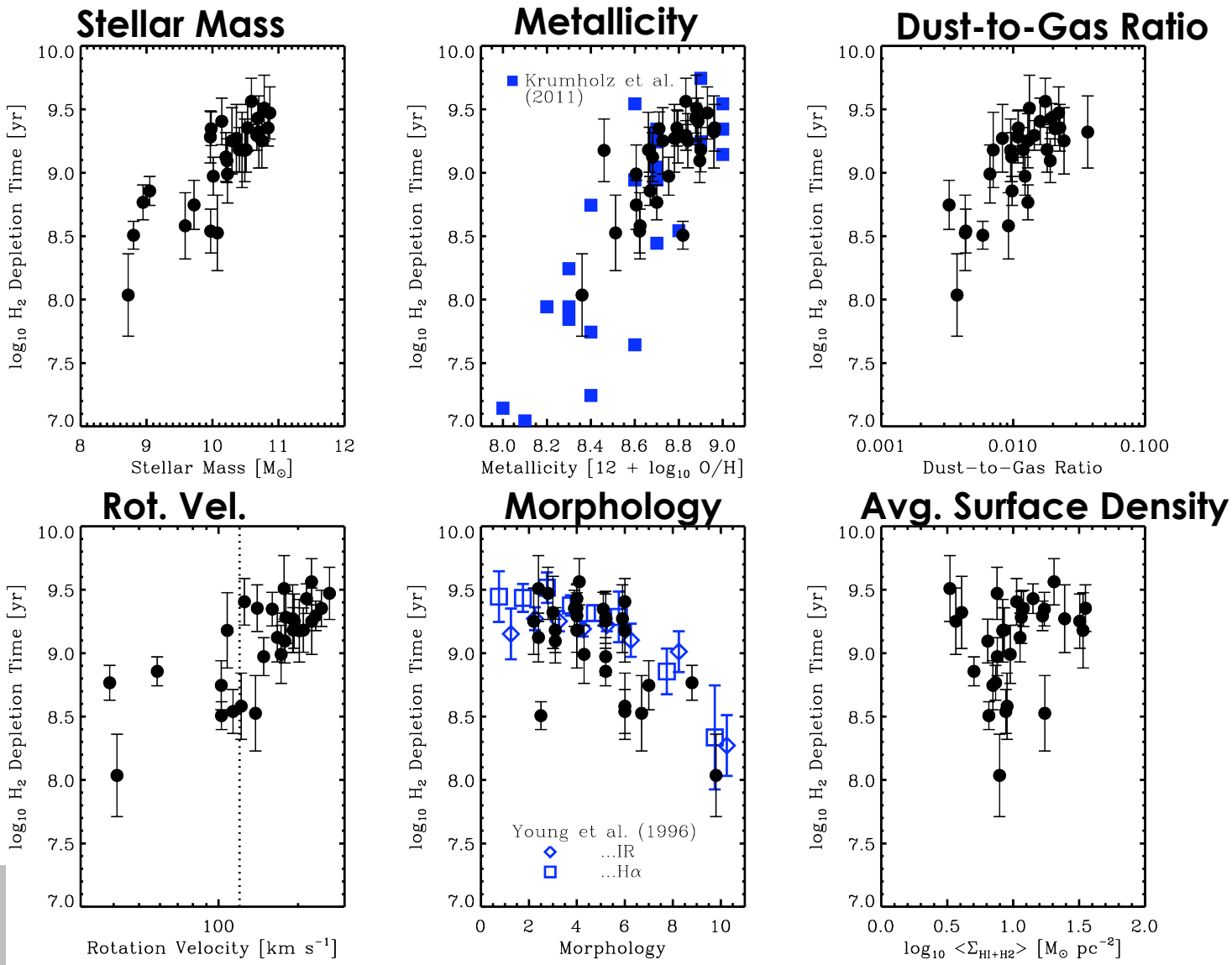


One point: One literature measurement

BIGIEL+ '11, LEROY+ IN PREP. compiling many others

#4. The Ratio of CO/SFR Varies By Galaxy

CO Divided by SFR [Gyr]
Each Point 1 Galaxy

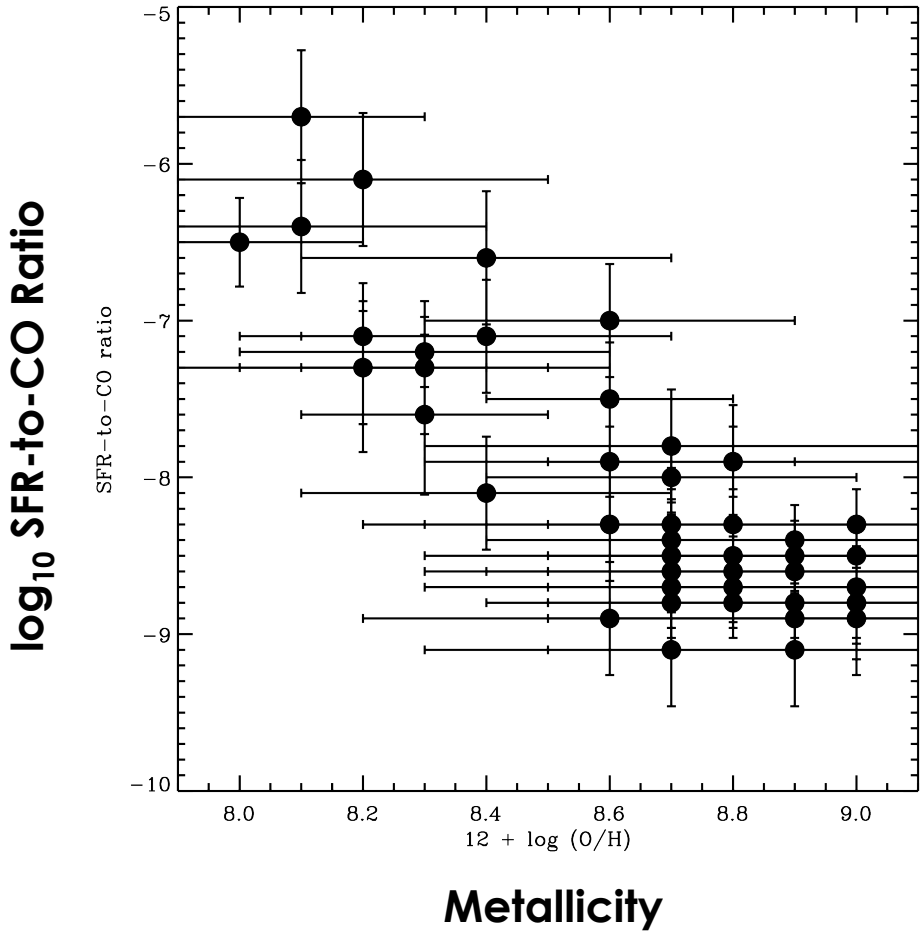


One point:
One galaxy

YOUNG+ '96, KRUMHOLZ+ '11, SAINTONGE+ '11, SCHRUBA+ '11, **LEROY+ IN PREP.**

#4. The Ratio of CO/SFR Varies By Galaxy

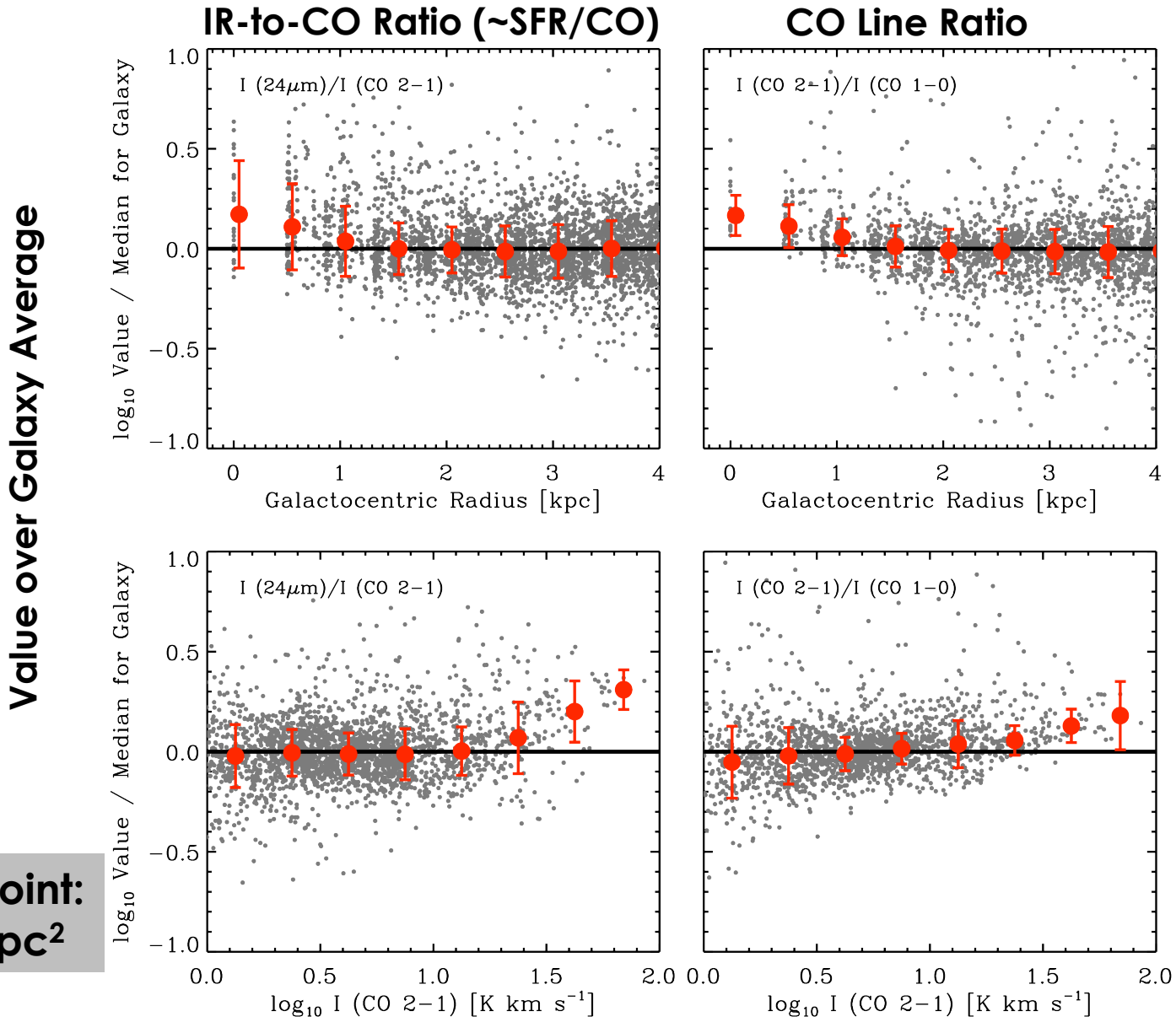
SFR/CO varies with metallicity: convolution of SFR/H_2 and H_2/CO



One point:
One galaxy

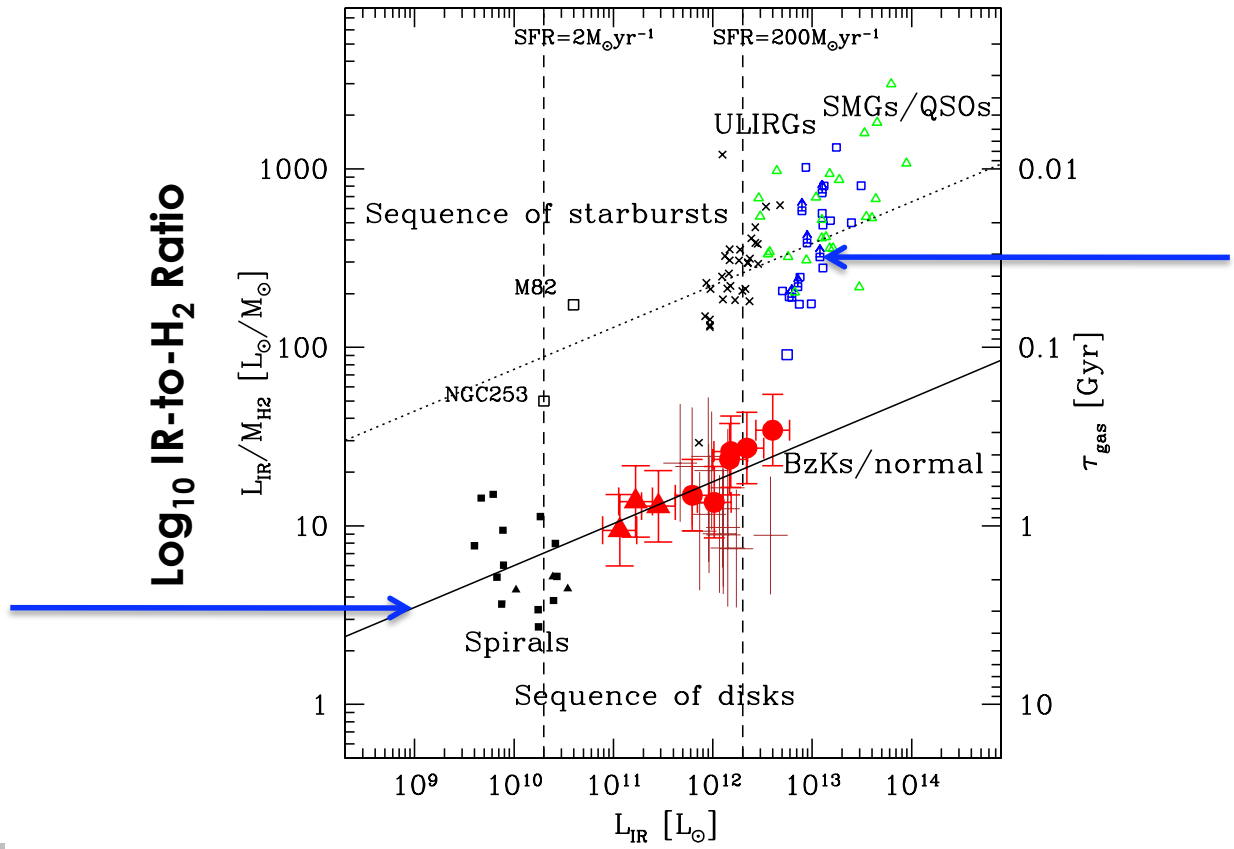
KRUMHOLZ, LEROY, & MCKEE '11

#5. Starbursts Show Enhanced SFR/CO



One point:
One kpc²

#5. Starbursts Show Enhanced SFR/CO



ULIRGs (merger-induced starbursts)

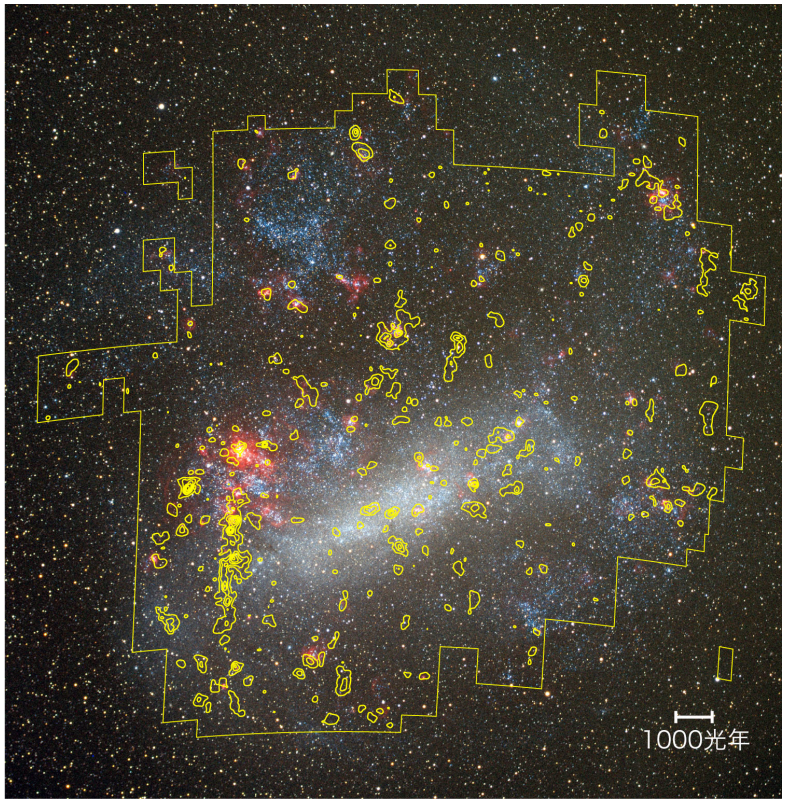
Normal Spirals

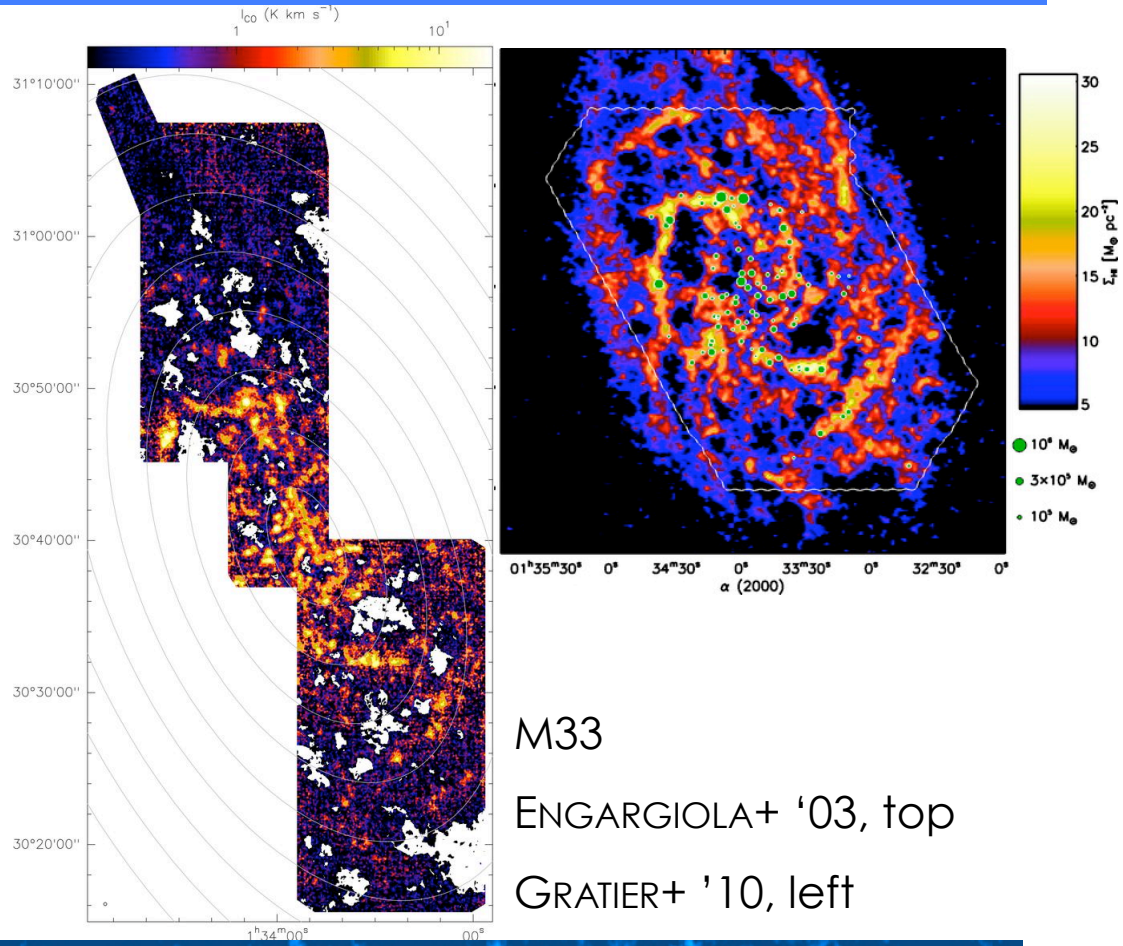
One point: One galaxy

DADDI+ '10

Small Scales: Giant Molecular Clouds

LMC (FUKUI+ 99,'08, NANTEN)

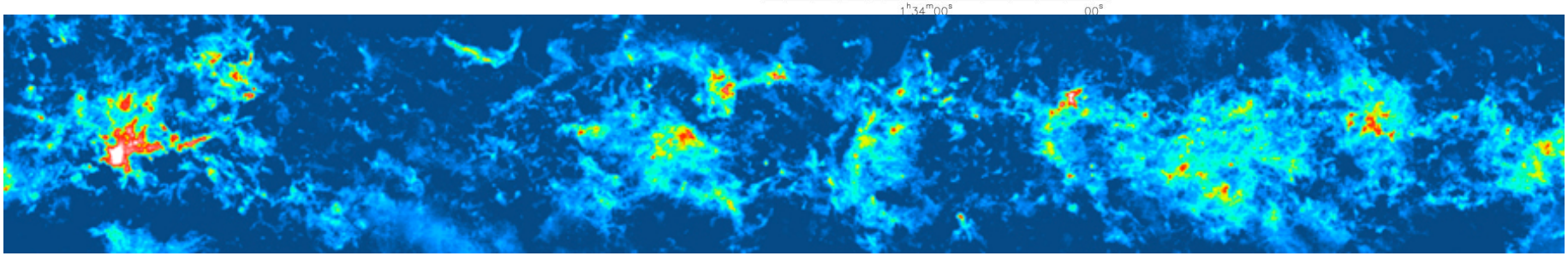




M33

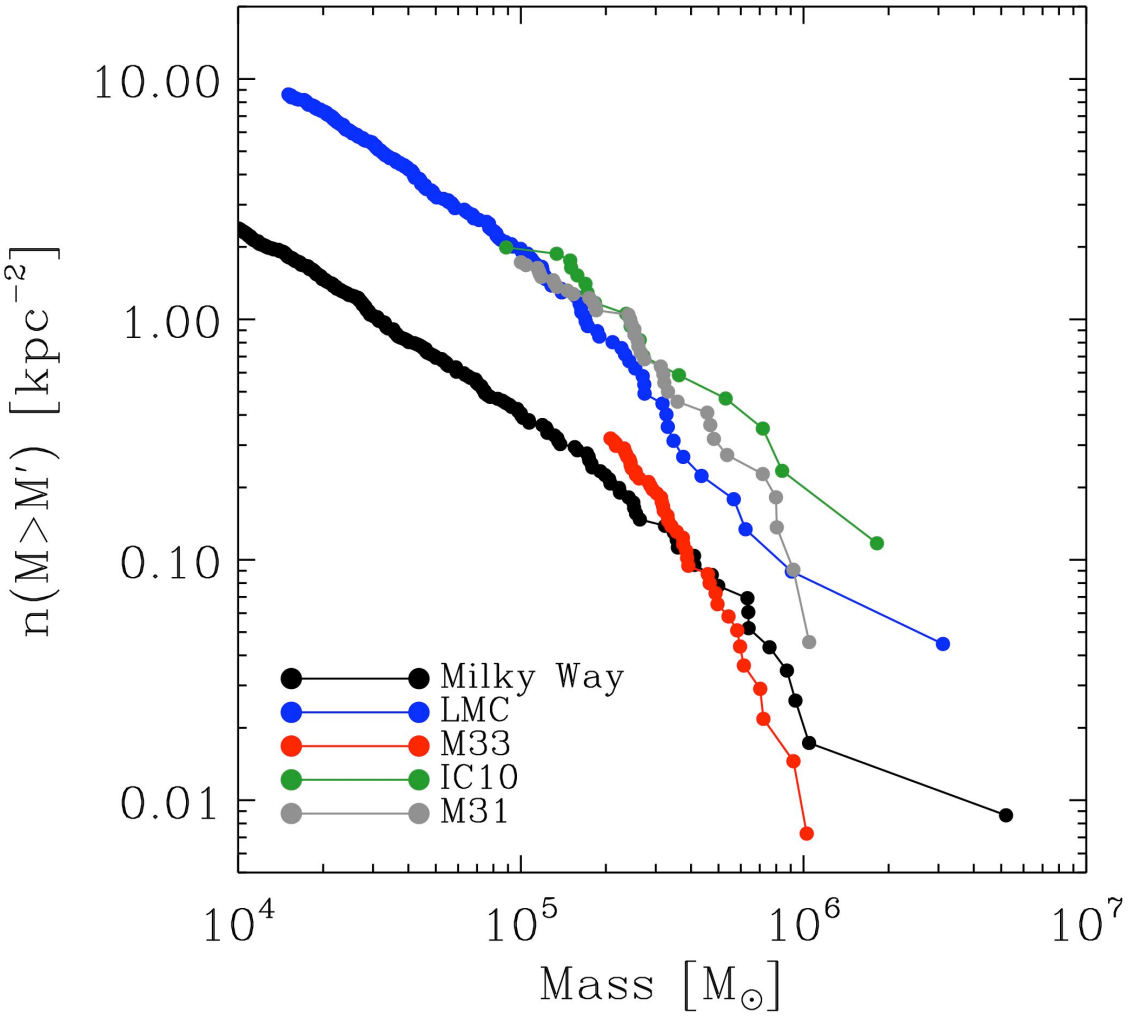
ENGARGIOLA+ '03, top

GRATIER+ '10, left



Galactic Ring Survey (JACKSON+ 06)

#6. Nearby GMCs Share Mass Function, Scalings



GMC Mass Function

dN/dM ~ $M^{-\gamma}$ with γ near -1.5

Most mass in 10^5 – few × 10^6 M_{sun}

Some environmental variation…

e.g., M33 is steep, outer MW steep

Little known beyond Local Group

ROSOLOWKSY+ '05, BLITZ+ '07, FUKUI & KAWAMURA '10

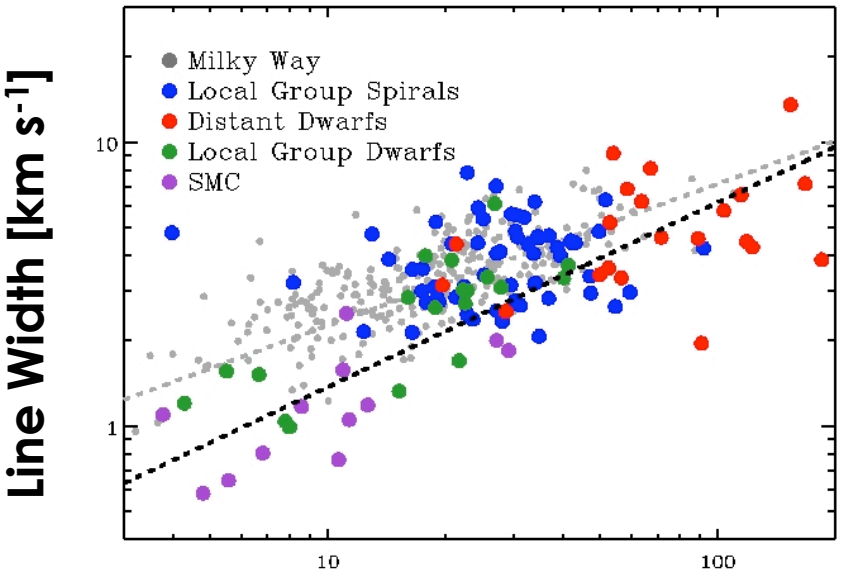
#6. Nearby GMCs Share Mass Function, Scalings

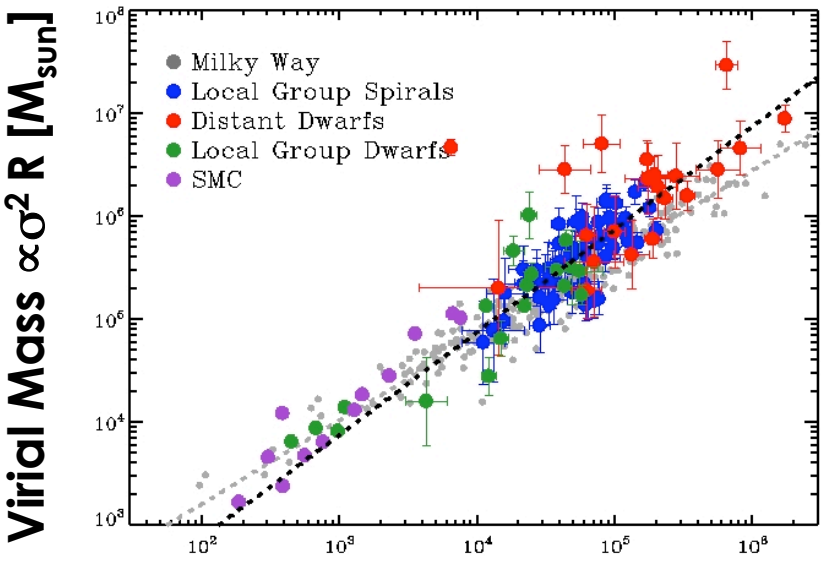
Observables: Luminosity, Line Width, Radius

Typical sizes: few 10s of parsecs
Line widths: few km/s (RMS)
Surface density (brightness): ~100 M_{sun} pc^{-2} (10-20 K km s^{-1})

Scaling relations among observables ("Larson's Laws")

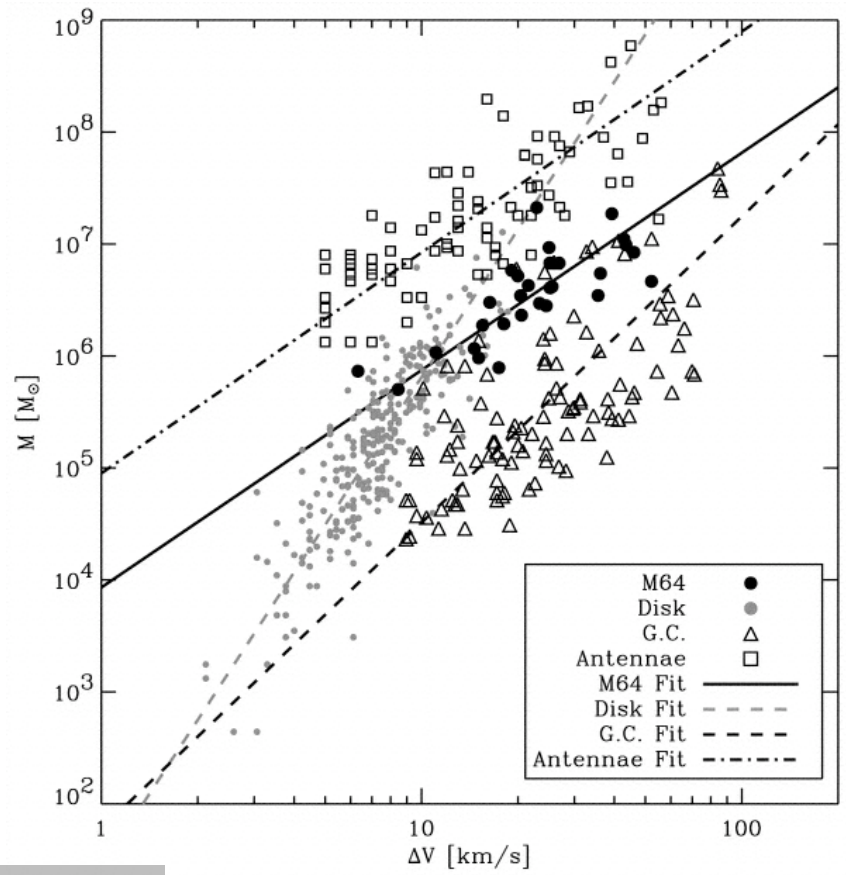
Milky Way, M31, M33, LMC, IC10, SMC, NGC 6822, handful of others
To first order, cloud in other galaxies look like Milky Way GMCs





BOLATTO, LEROY+ '08, BLITZ+ '07, HEYER+ '09 (MW), HUGHES+ '10, FUKUI & KAWAMURA+ '10

#7. Evidence for Different GMCs in Starbursts



Cloud Mass

Cloud Line Width

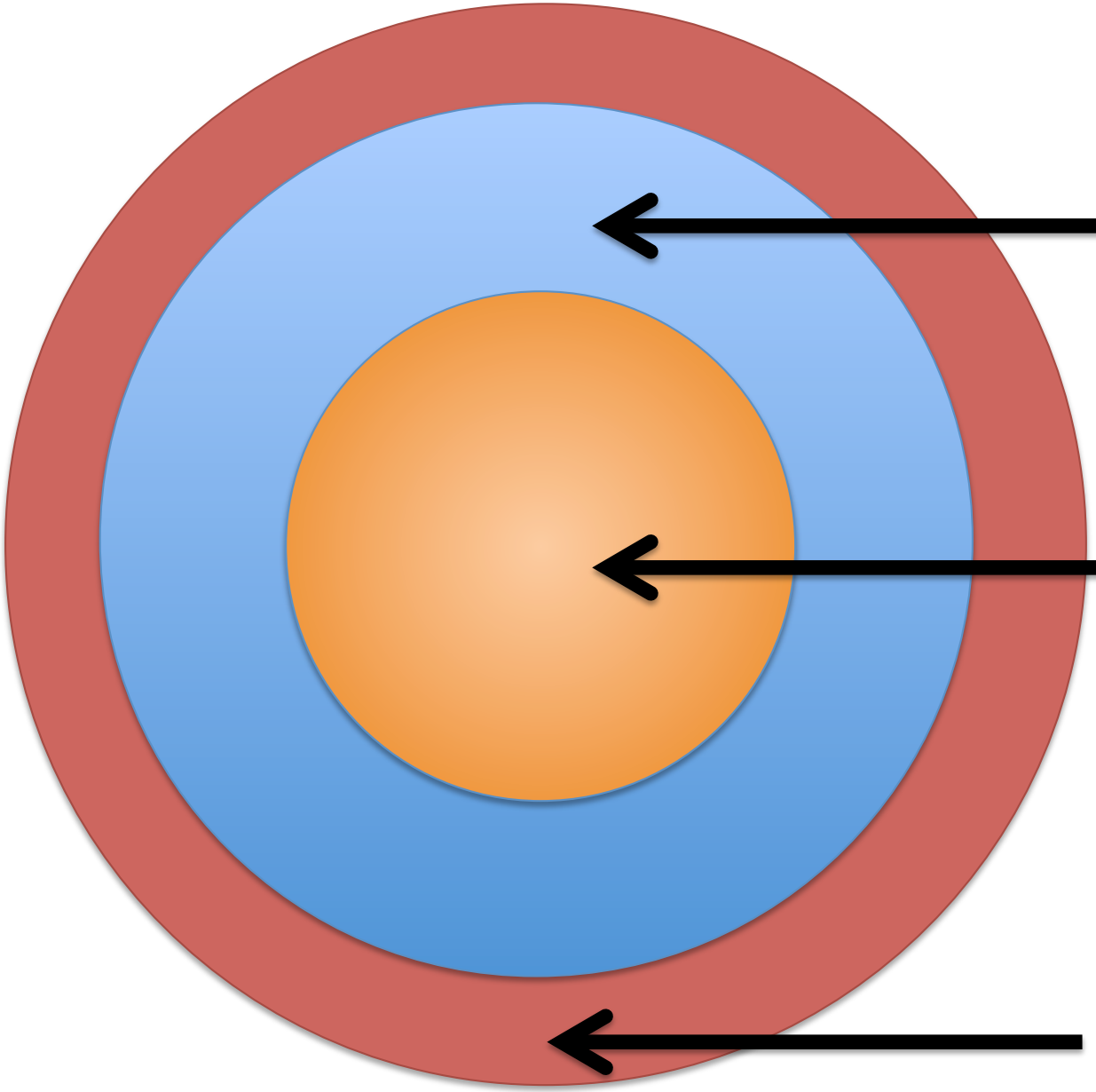
One point: One cloud

- o Scaling relations look different!
- o Most accessible: luminosity- line width
- o Much shallower in starburst galaxies: index ~2 instead of ~4
- o Consistent with pressure equilibrium
- o Bigger Clouds?
- o Largely unexplored territory:

Antennae, NGC 4826, MW Center, M82

ROSOLOWSKY & BLITZ '05, WILSON+ '03, OTA+ '01, SHEN & LO '95

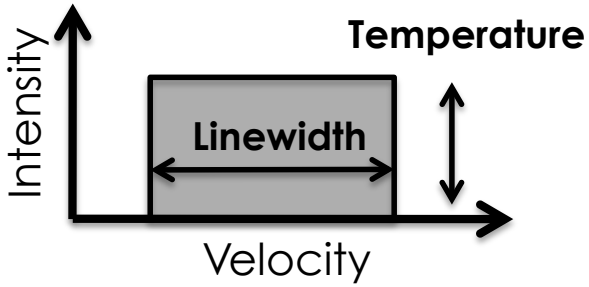
#8. CO-to-H_2 is a Multi-Parameter Problem



Hydrogen is H_2
Carbon is CII, little/no CO

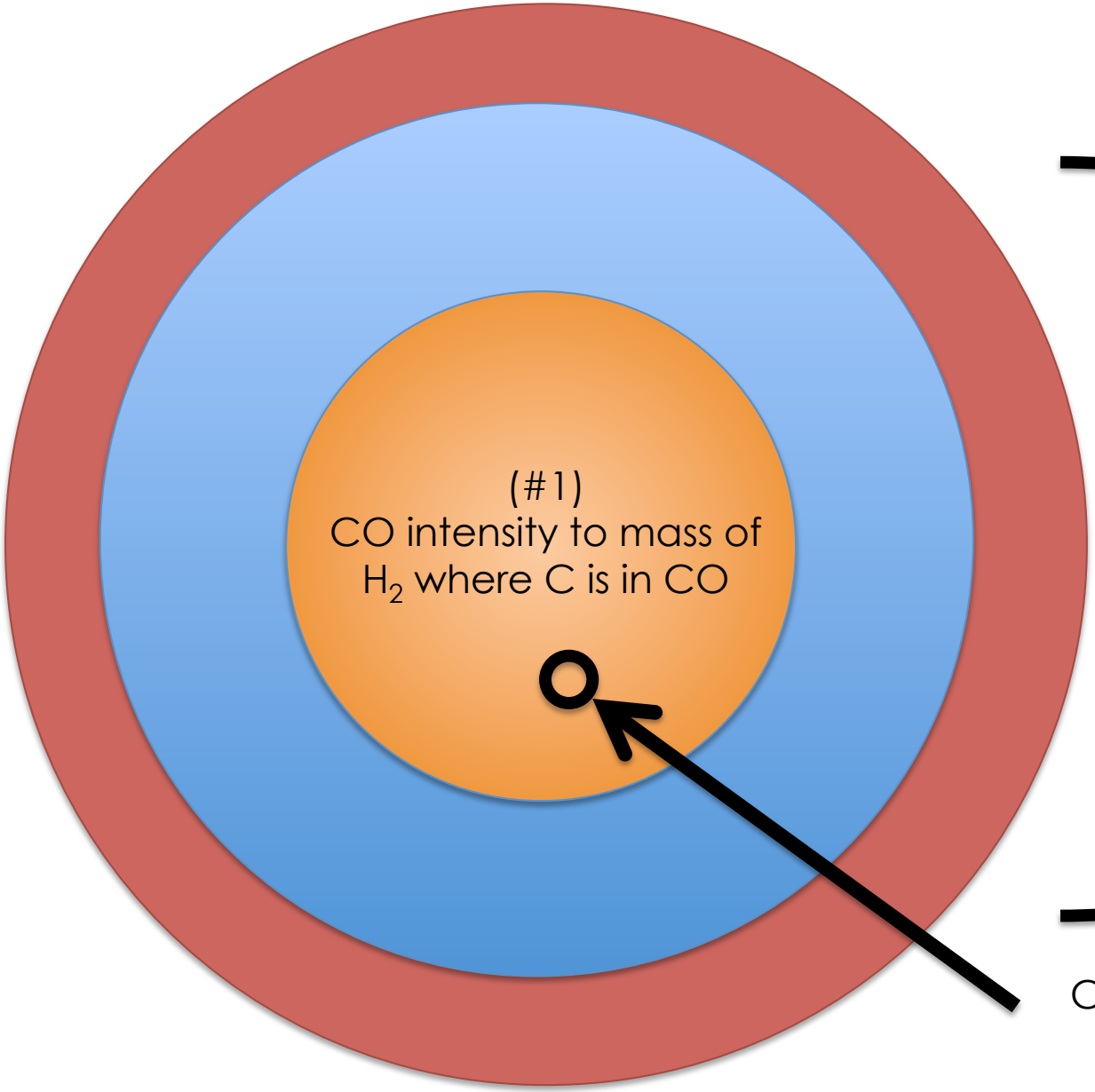
Size depends on **dust shielding**
Dust depends on **metallicity**.

Hydrogen is H_2
Carbon is CO … spectrum:



Hydrogen is HI
Carbon is CII

(and thus requires care with definitions)

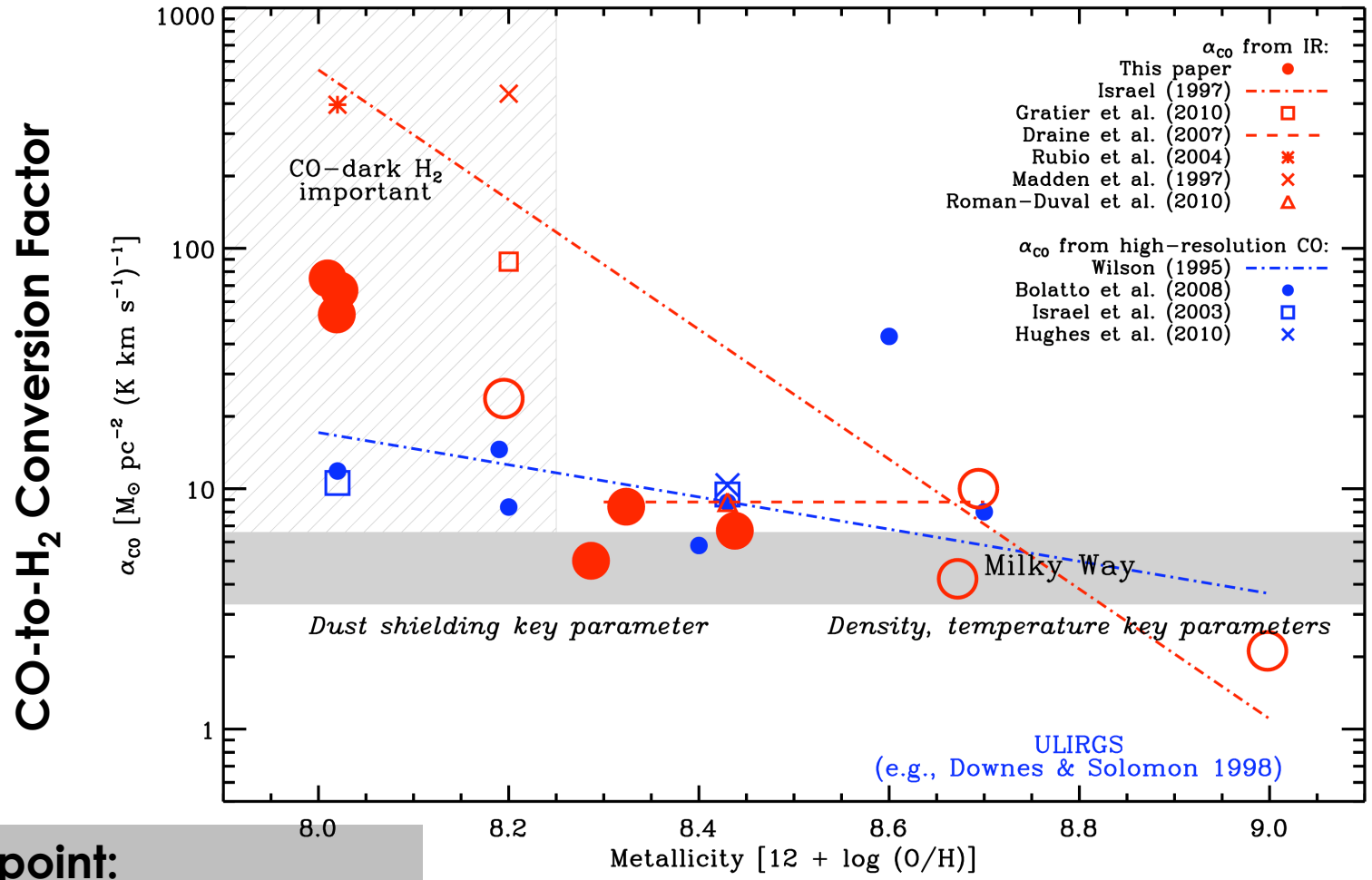


(#3)
CO to total mass of H2
in the cloud (or over a
part of a galaxy)

(#2)
CO intensity to total H_2 along
a single line of sight.

#9. X_{CO} is a Non-linear Function of Metallcity

- Synthesis of observations:



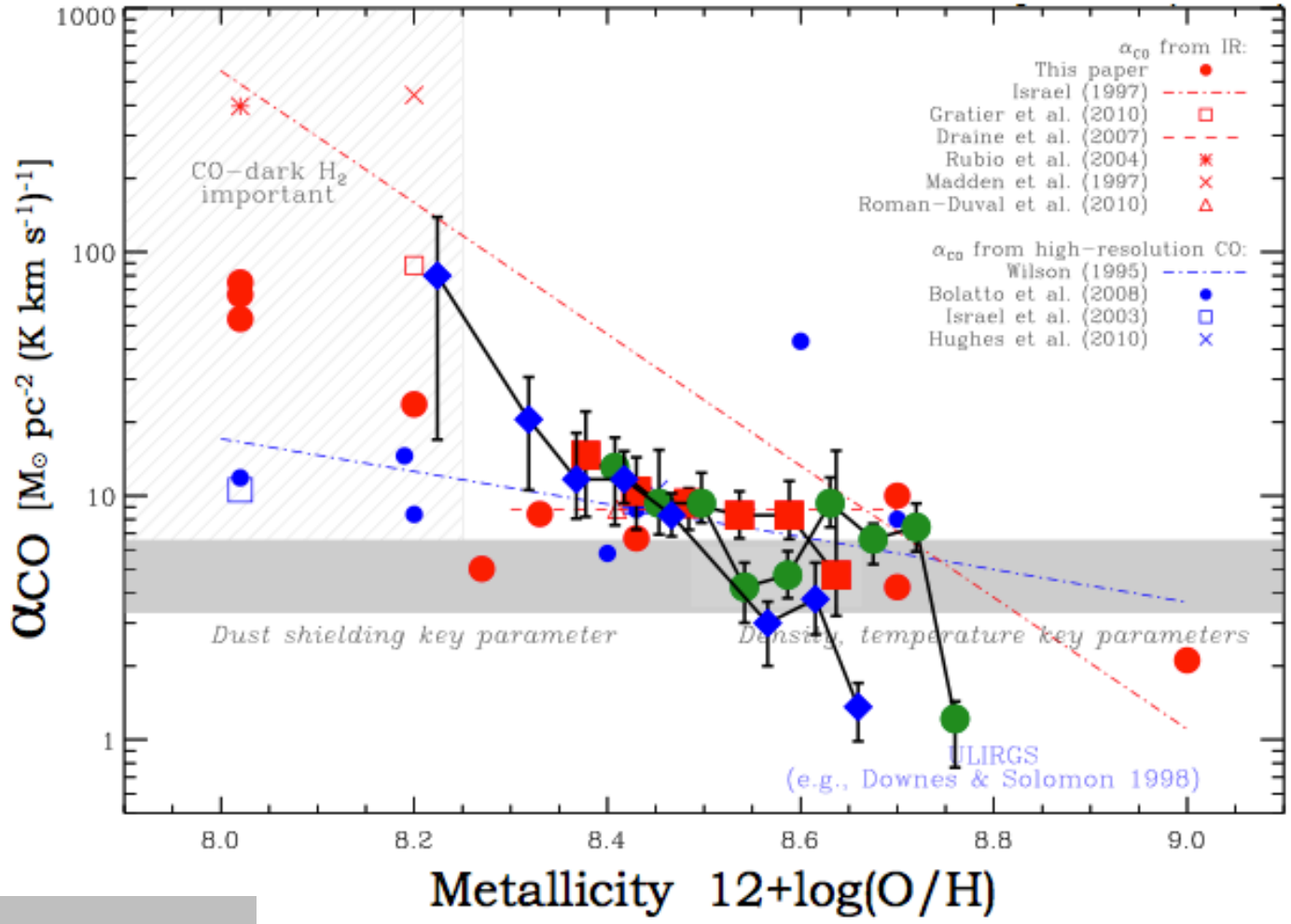
One point:
One part of one galaxy

Metallicity

LEROY+ '11 compiling many others

#9. X_{CO} is a Non-linear Function of Metallcity

- K. Sandstrom extending to KINGFISH/THINGS/HERACLES sample:



One point:
One part of one galaxy

Overlaid points show rings in three face-on spiral galaxies.

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2. 9 things we have learned from studying CO in nearby galaxies:

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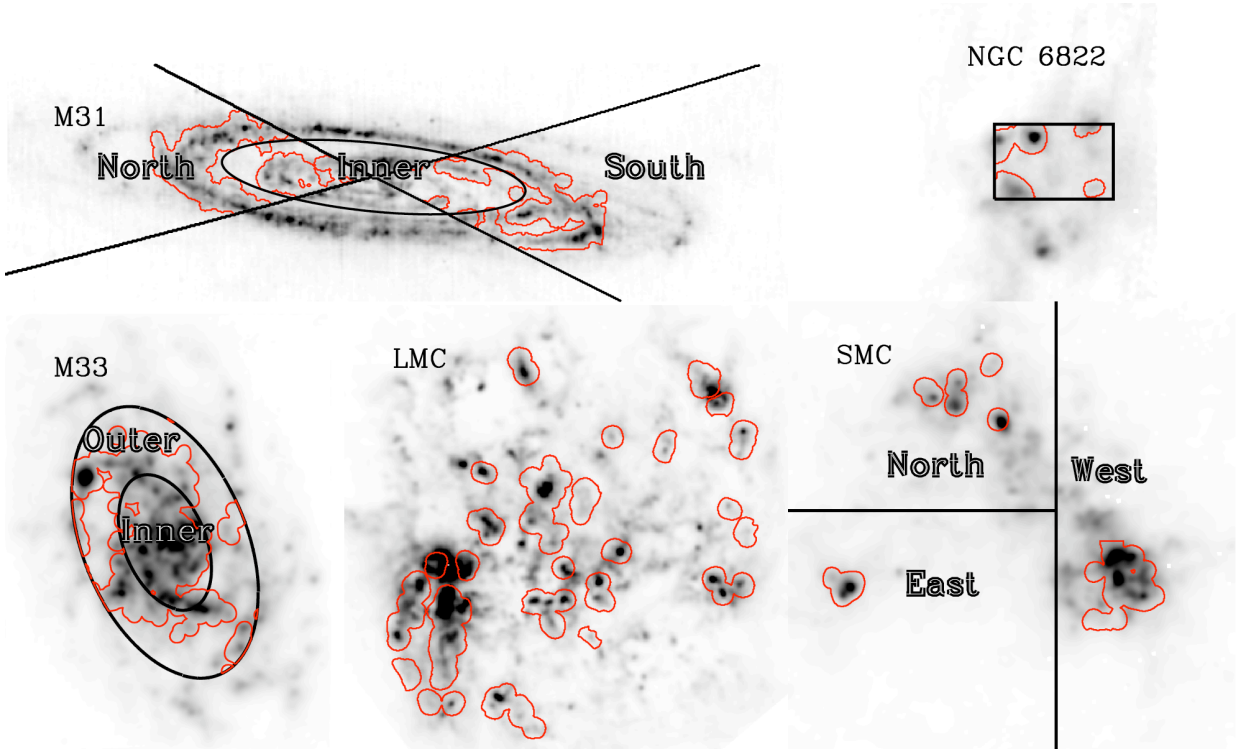
   - Nearby GMCs show similar mass functions, scalings
   - GMCs in starbursts look different

   - The CO-to-H_2 conversion factor is a multi-regime problem
   - The CO-to-H_2 is a nonlinear function of metallicity

#9. X_{CO} is a Non-linear Function of Metallcity

- X_{CO} vs. Metallicity: Dust-Based Solution
- Assemble IR (70,160), CO, and HI maps of Local Group Galaxies
- Focus on areas near molecular peaks, where H_2 ~ HI

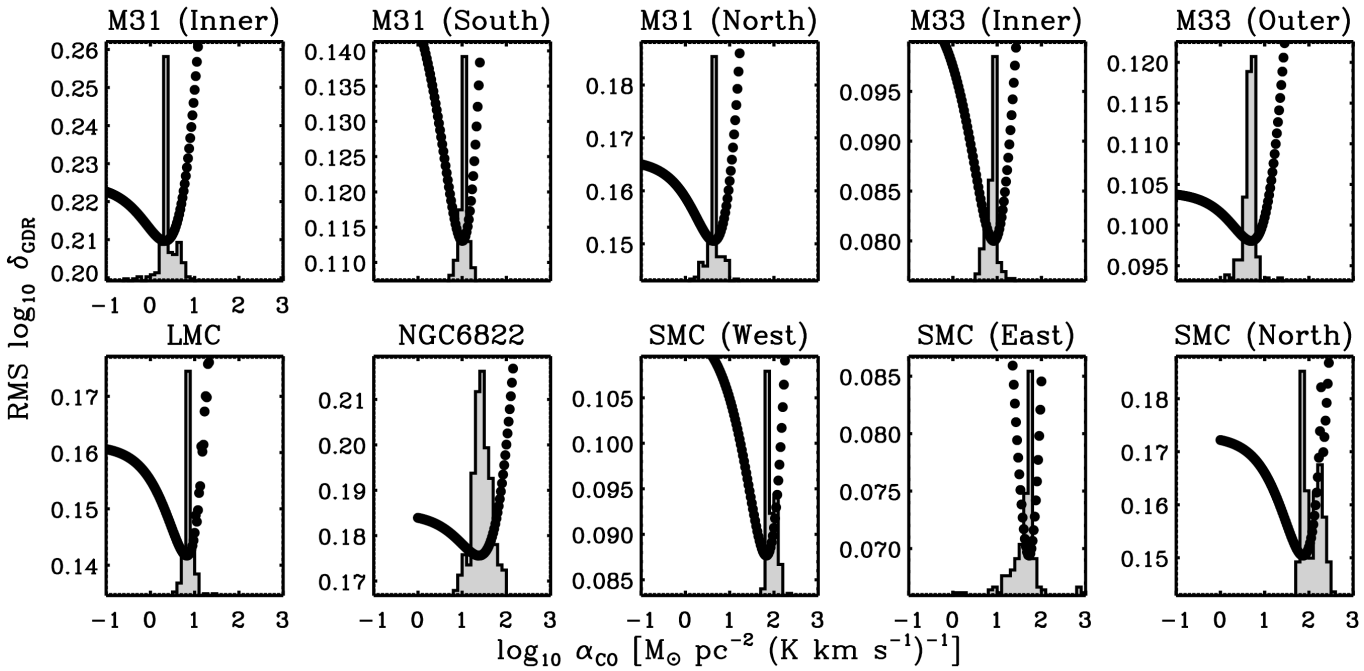


#9. X_{CO} is a Non-linear Function of Metallcity

- Estimate dust surface density from *Spitzer* IR maps
- Assume dust vs. gas and CO vs. H_2 linear, proportionalities unknown

$$\alpha_{CO}\, I_{CO} + \Sigma_{HI} = \Sigma_{dust} \times GDR$$

- Look for CO-to-H_2 conversion that minimizes scatter:



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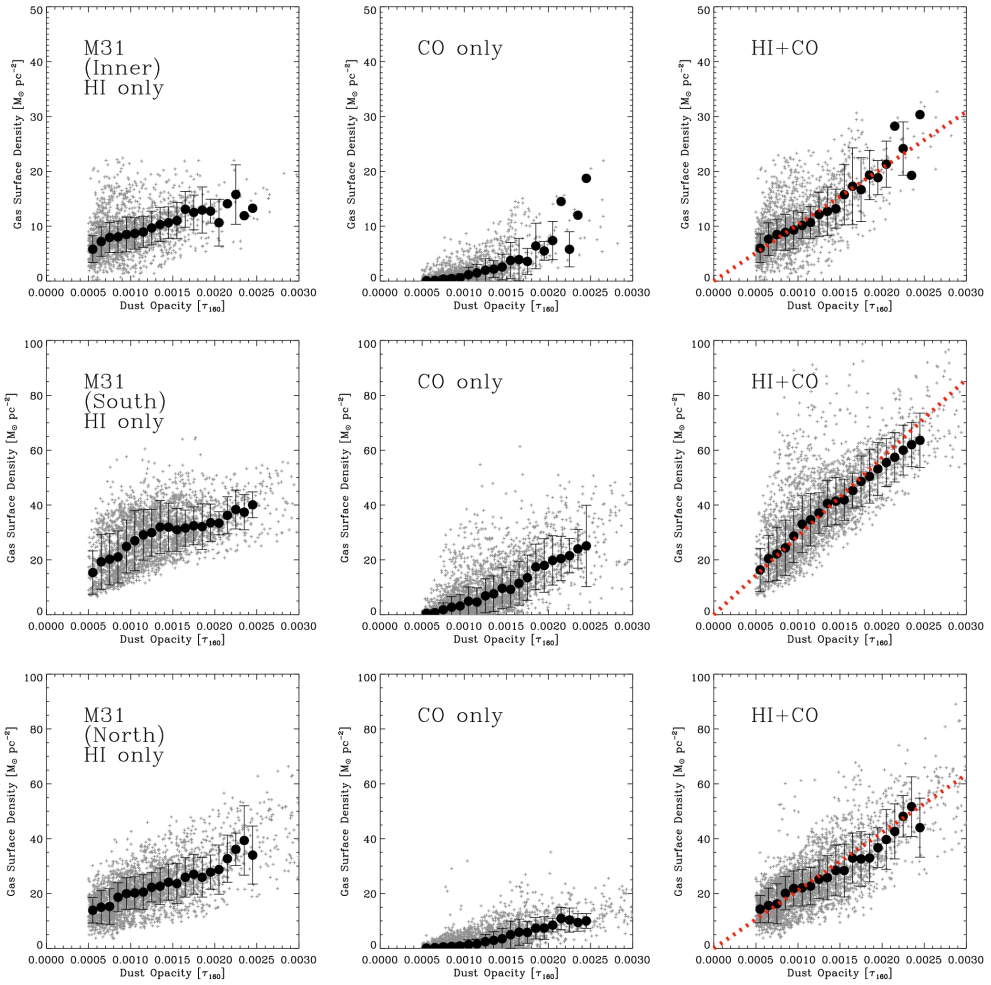

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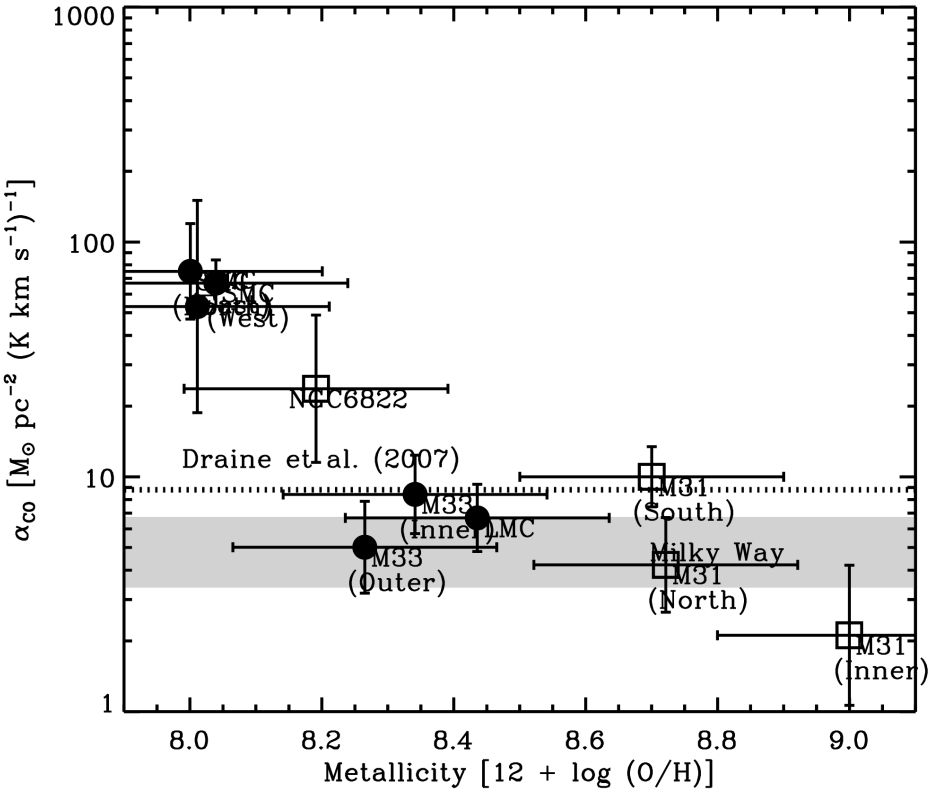
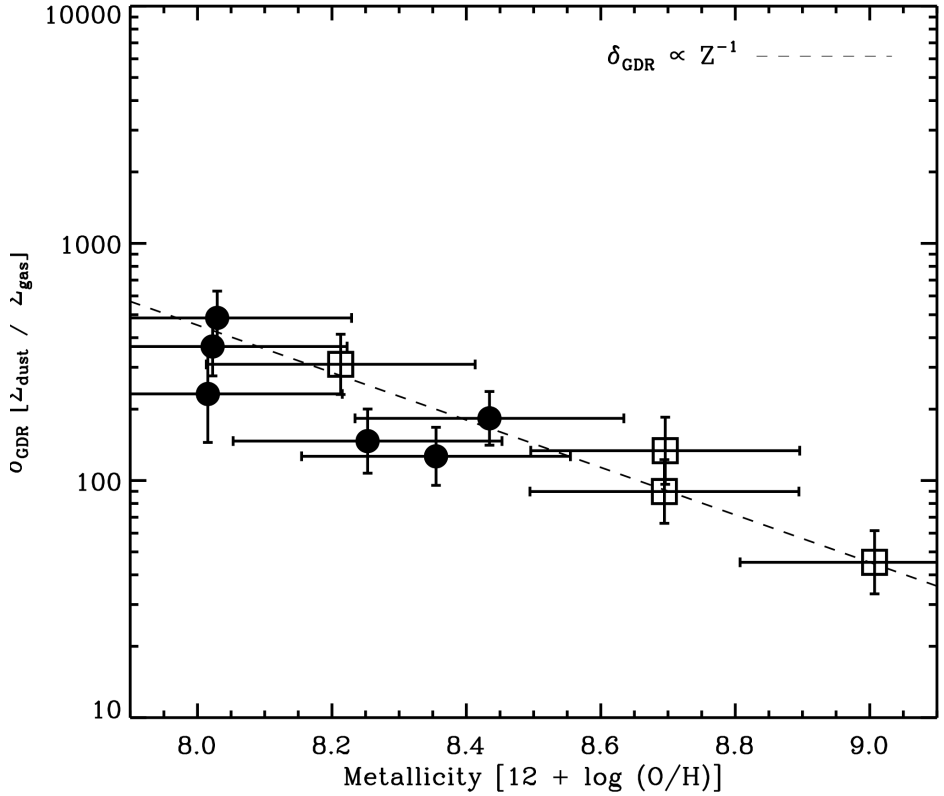
Conversion Factor



Gas-to-Dust Ratio

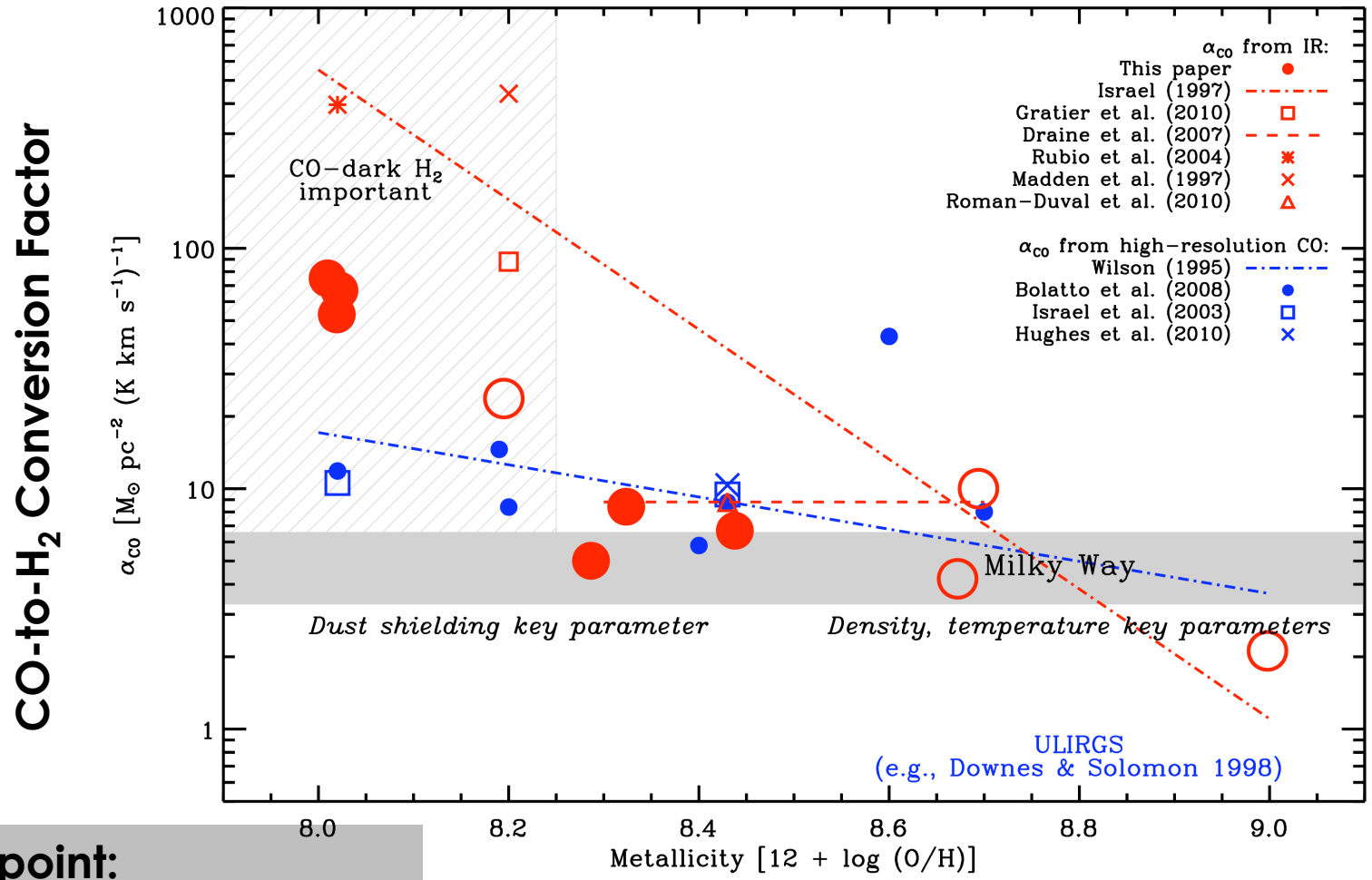


One point:
One part of one galaxy

Metallicity

#9. X_{CO} is a Non-linear Function of Metallcity

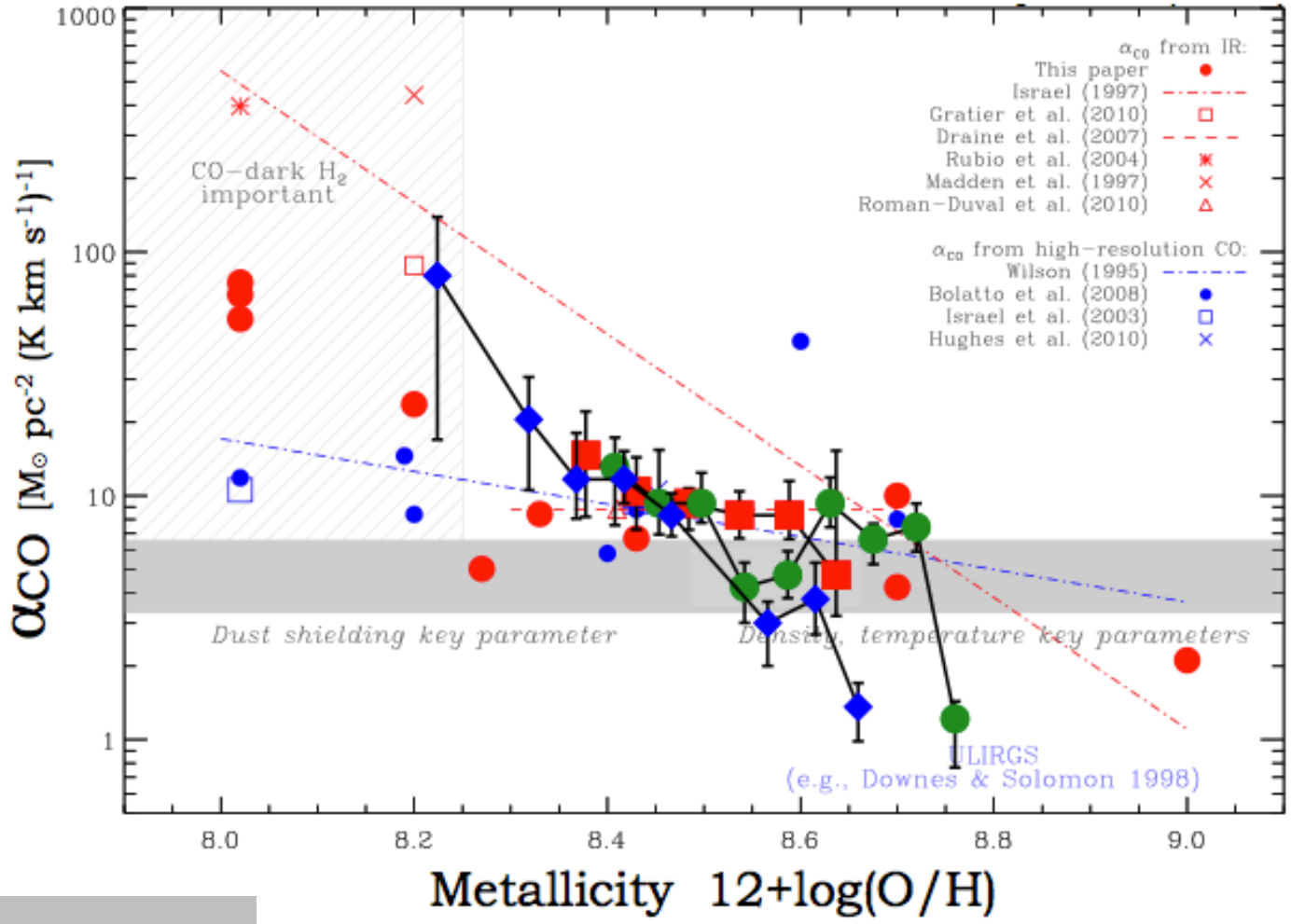
- Synthesis of observations:



One point:
One part of one galaxy

#9. X_{CO} is a Non-linear Function of Metallcity

- K. Sandstrom extending to KINGFISH/THINGS/HERACLES sample:



One point:
One part of one galaxy

Overlaid points show rings in three face-on spiral galaxies.

Molecular Gas in Nearby Galaxies

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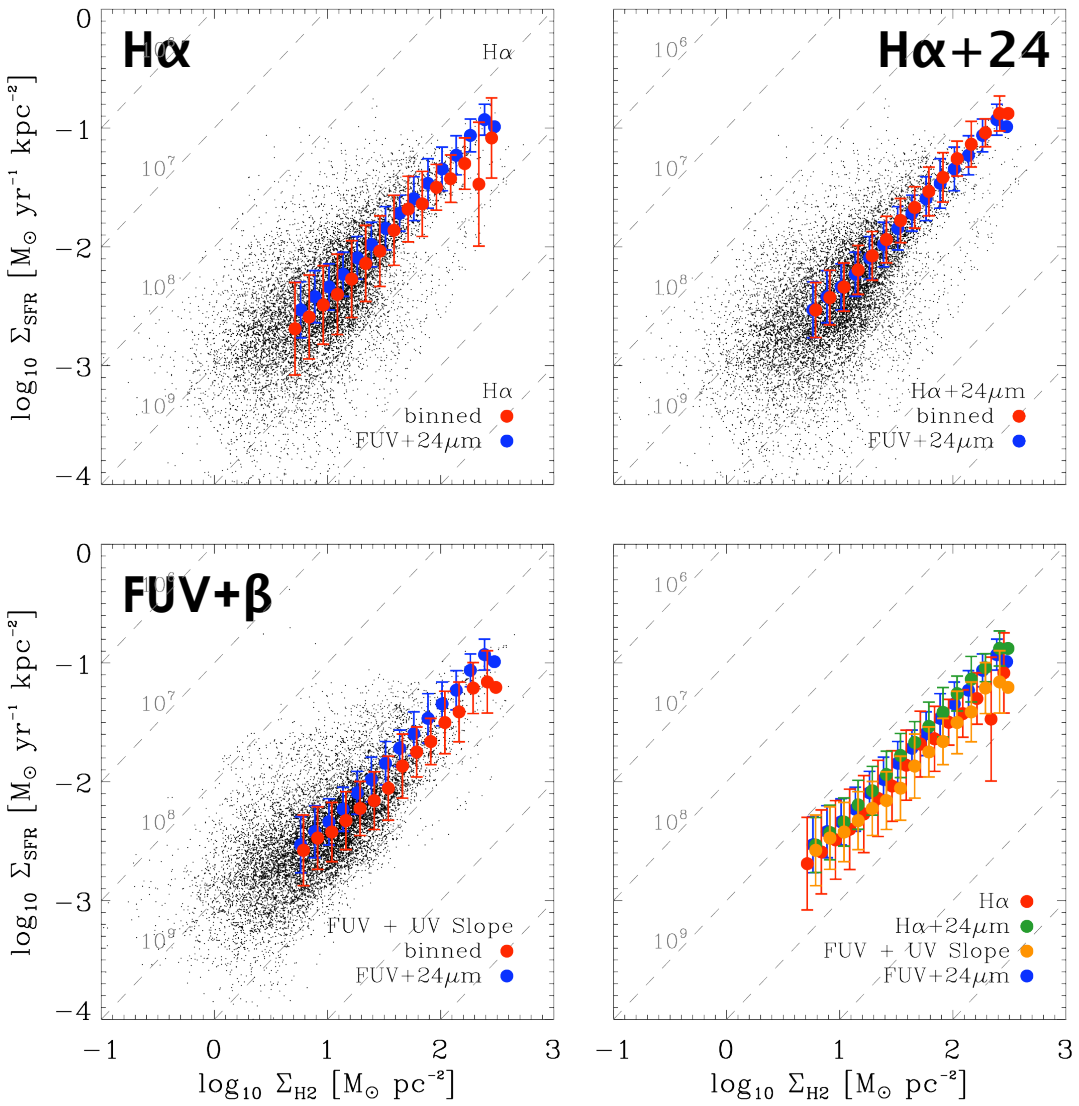
Observations of CO in Nearby Galaxies

- A few hundred (pushing 1000) galaxies with measured CO content …
- Many dozen (~100) galaxies with maps at several hundred pc resolution …
- A handful (~10) of maps of galaxies with cloud resolution …
- Efforts have been made on normal disks, dwarf galaxies, ellipticals, U/LIRGs …
- Missing:
  - Good statistics on low-mass, low-metallicity galaxies
  - Knowledge of early types (growing)
  - Detailed (cloud-scale) view of starbursts, L* spirals.
- Future is bright with ALMA …

Using Different SF Tracers



LEROY+ IN PREP.