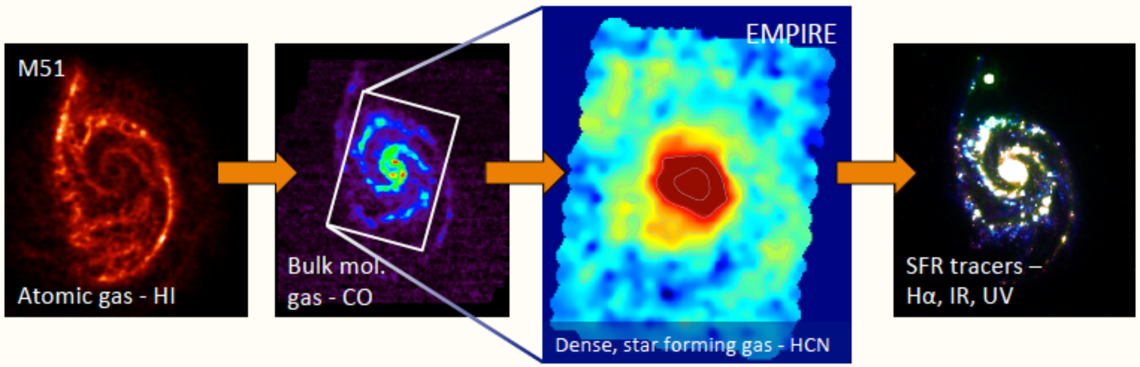
The EMPIRE survey: $^{13}CO(1\text{-}0)$ emission across nearby disks



Diane Cormier

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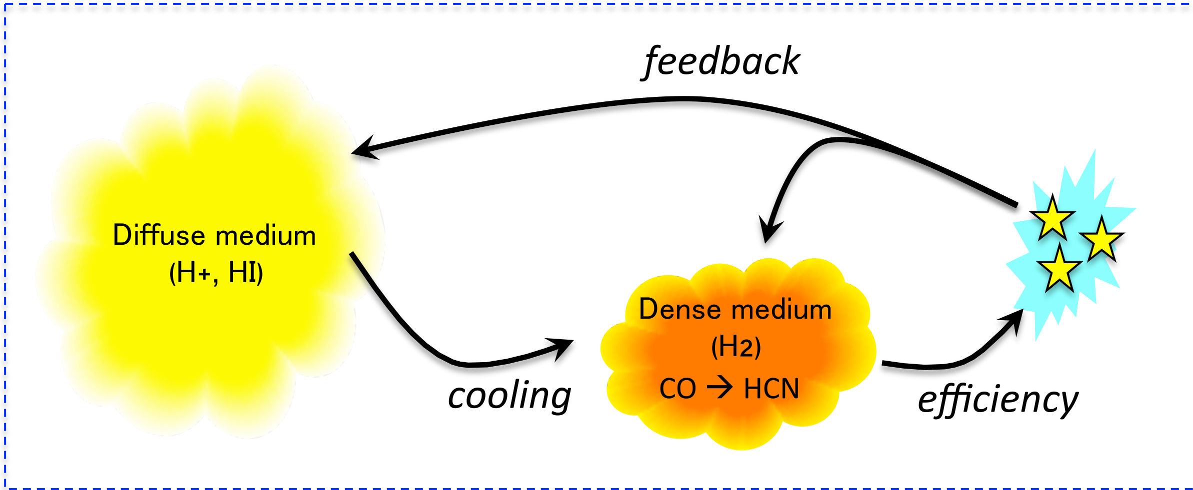
María-Jesús Jiménez-Donaire, Frank Bigiel (*U. Heidelberg*)
Adam Leroy, Molly Gallagher (*Ohio State*), Antonio Usero (*OAN Madrid*),
and the EMPIRE collaboration

Motivation: efficiency of star formation



From CO studies, efficiencies of star formation – SFR/H_2 – vary on global and kpc-scales in galaxies *(e.g. Kennicutt & Evans 2012, Leroy et al. 2013)*

How do efficiencies depend on physical conditions of the gas?
How does the dense gas mass fraction (HCN/CO) vary and why?
Is the rate of star formation in dense gas universal?

The EMPIRE survey

HCN, HCO+, HNC, CS, CO and isotopologues: ^{13}CO, C^{18}O, H^{13}CN, H^{13}CO+, H^{13}NC

EMIR Multi-line Probe of the ISM Regulating Galaxy Evolution

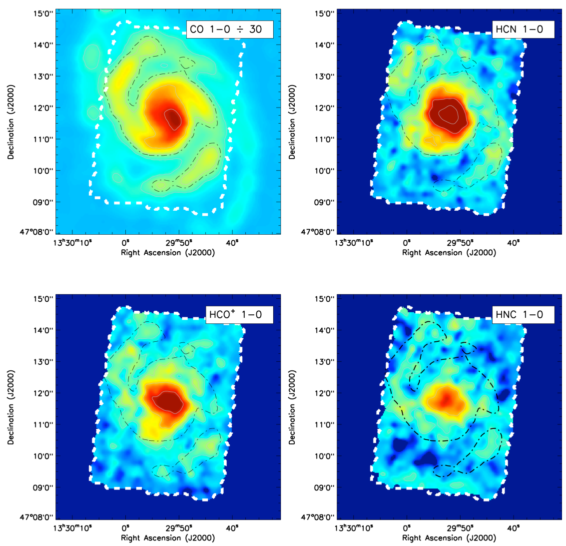
PI: F. Bigiel, 600 hr
IRAM Large Program 2015-2017

-- Full maps of 9 disk galaxies
-- 1.5 kpc linear resolution

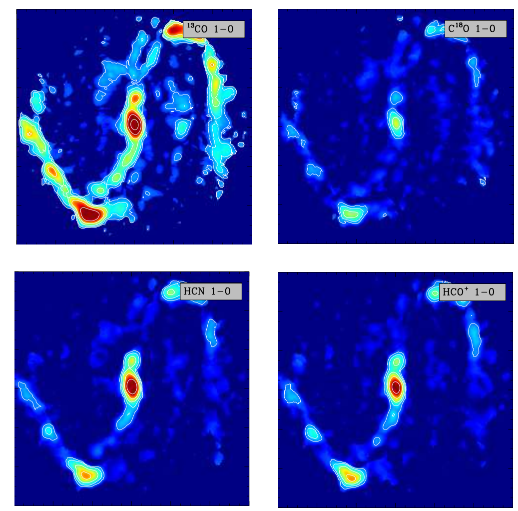
PI: A. Leroy, 10 hr
ALMA Cycle 3

-- Inner 1/3 disk of 4 galaxies
-- 300 pc linear resolution

M 51



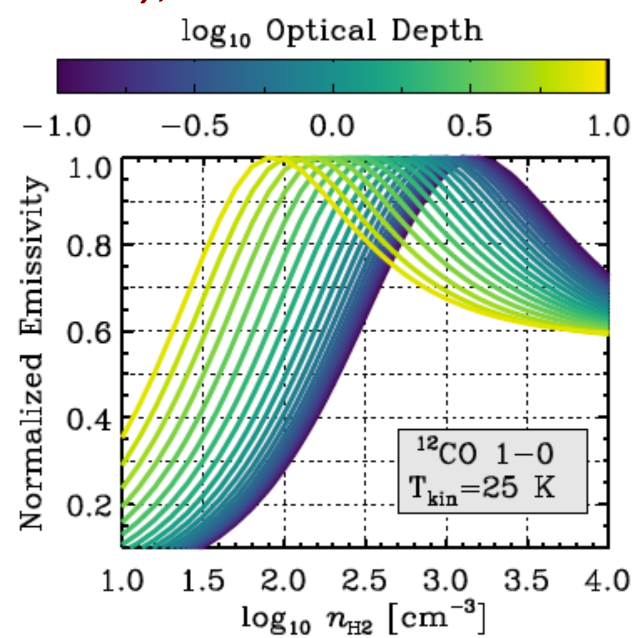
NGC 3627



Bigiel et al. 2016, Jiménez-Donaire et al. 2017a,b, Leroy et al. 2017a, Gallagher et al. subm., Cormier et al. to be subm.

The power of multi-line spectroscopy and importance of isotopologues

Leroy, …Cormier et al. 2017a

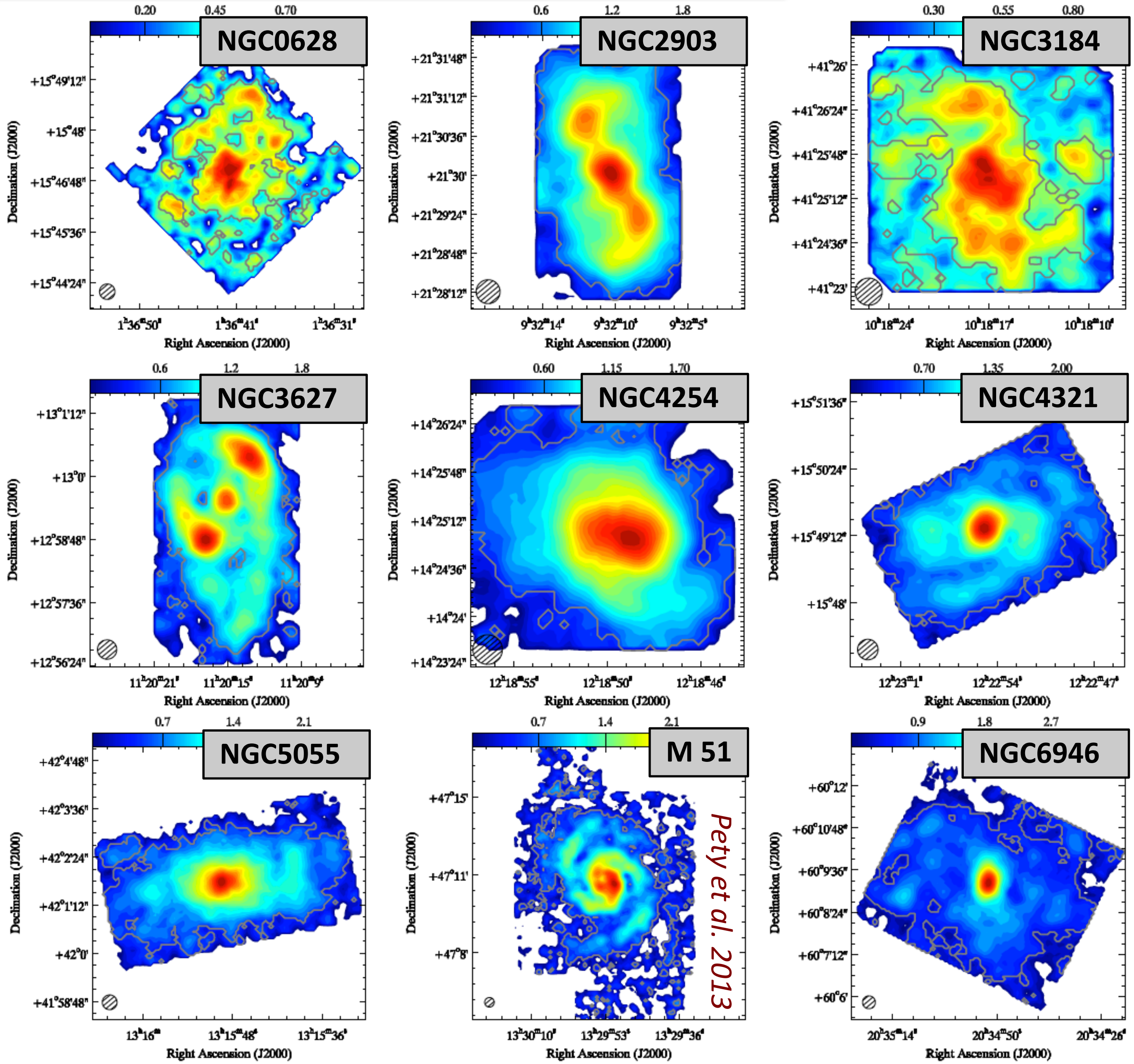


- Need a suite of lines to access physical conditions and, e.g., map the density distributions
- Sensitivity of lines to density depends on opacity (line trapping effect; *e.g. Shirley 2015*)
- Optically thin tracers provide a direct estimate of gas column densities and masses (with some assumptions…)

***Focus on ^{13}CO** – $H^{13}CN$, $H^{13}CO+$ tough to get, see Jiménez-Donaire et al. 2017b*

$^{13}CO(1\text{-}0)$ emission maps

Cormier et al. to be subm.

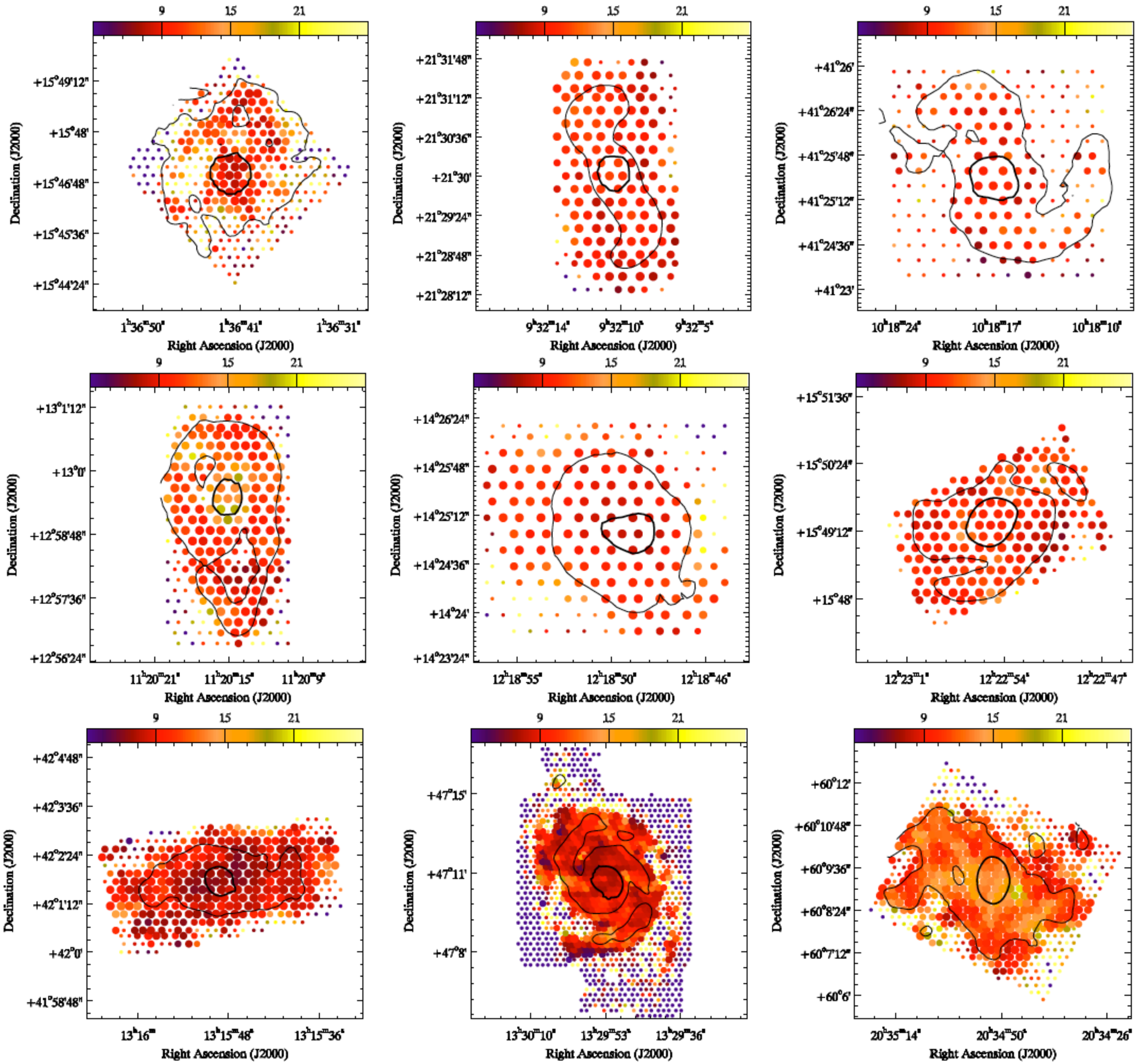


rms ≈ 3mK

resolution ≈ 1.5kpc

$\mathcal{R}$ = $^{12}CO(1\text{-}0)/^{13}CO(1\text{-}0)$ ratio maps

$[^{12}CO/^{13}CO] = 60$



Local thermodynamic equilibrium

- Assumptions:

  - $\tau_{13} \leq 1$ while $\tau_{12} >> 1$,
  - $T_{\mathrm{ex},12} = T_{\mathrm{ex},13} = 20\,\mathrm{K}$,
  - both lines have the same filling factor,

- Optical depths and column densities:

$$\tau_{13} = -\ln(1 - \frac{I_{13}}{I_{12}}) \qquad \tau_{12} = \left[\frac{^{12}\mathrm{CO}}{^{13}\mathrm{CO}}\right] \times \tau_{13}$$

$$N_{13} = \frac{3.0 \times 10^{14}}{1 - \exp(-5.29/T_{\mathrm{ex},13})} \times \frac{\tau_{13}}{1 - \exp(-\tau_{13})} \times I_{13} \;\; [\mathrm{cm}^{-2}]$$

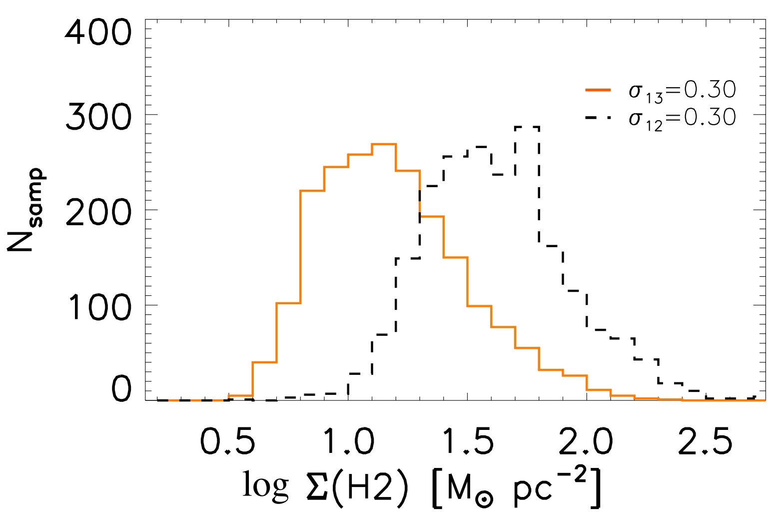
$$N_{\mathrm{H2}} = \left[\frac{\mathrm{H_2}}{^{13}\mathrm{CO}}\right] \times N_{13}$$

- Variations in the I_{12} / I_{13} ratio mostly linked to:
  - abundance effects
  - opacity effects

Column densities under LTE conditions

- Mean opacity of ^{13}CO is 0.1 (scatter of 0.1 dex in the maps) ⇔ $\tau_{12} \approx 6$
- Is ^{13}CO a more direct estimator of the column density?

  Mean column density of ^{13}CO around 10^{15} cm^{-2} ⇔ $N(H_2) \approx 10^{21}$ cm^{-2}
  ^{13}CO underestimates $N(H_2)$ by a factor of 2-3 compared to ^{12}CO and dust



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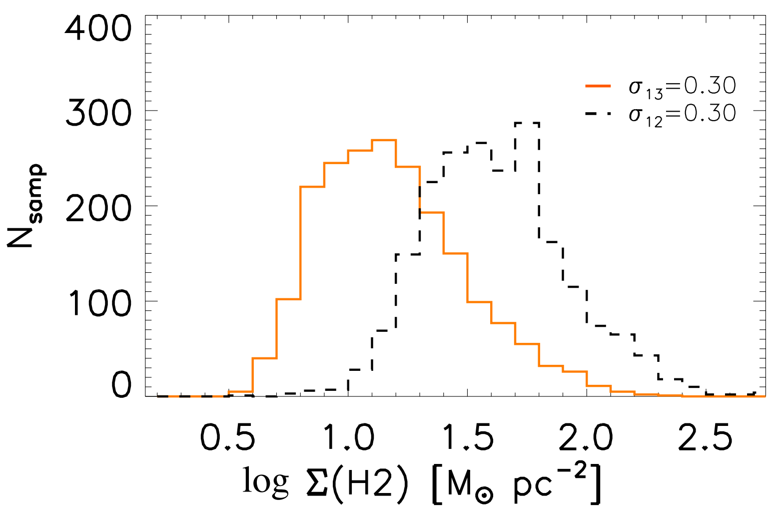
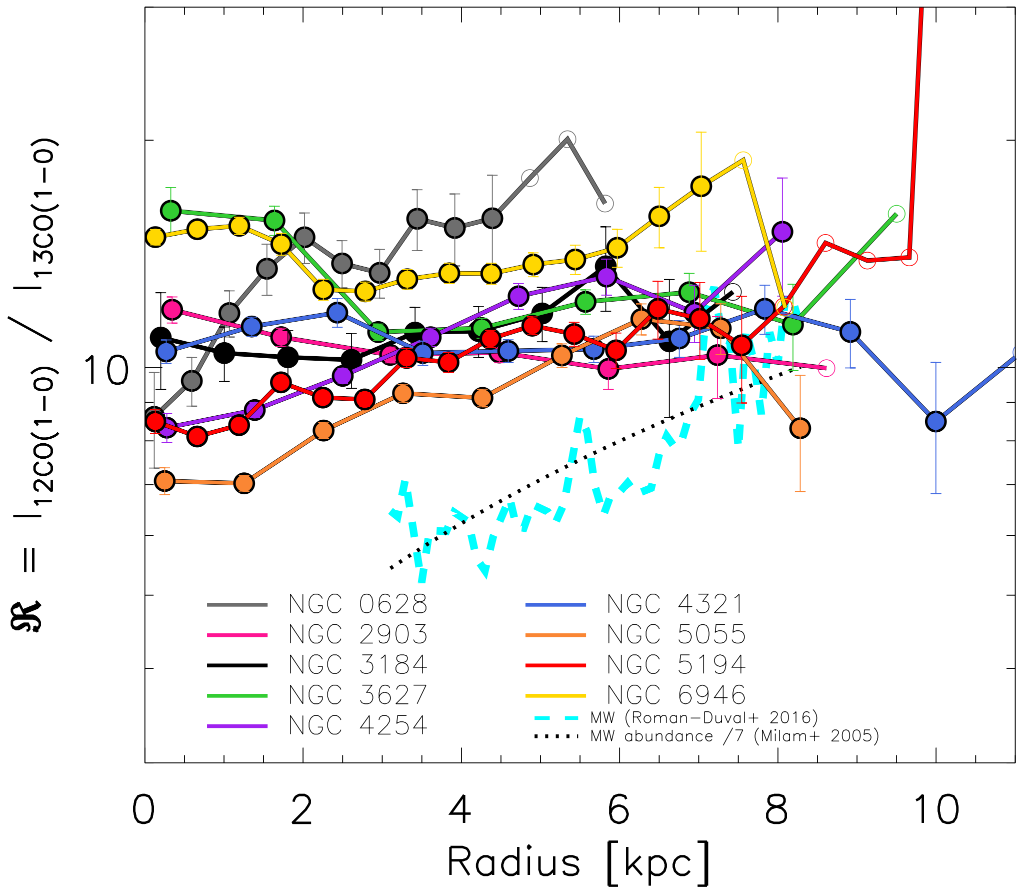


⇒ Non-LTE effects such as sub-thermal excitation of ^{13}CO (significant diffuse ^{12}CO emission in the beam) and abundance variations likely at play

see also, e.g., Goldsmith et al. 2008, Heyer et al. 2009
Meier & Turner 2004, Szucs et al. 2016

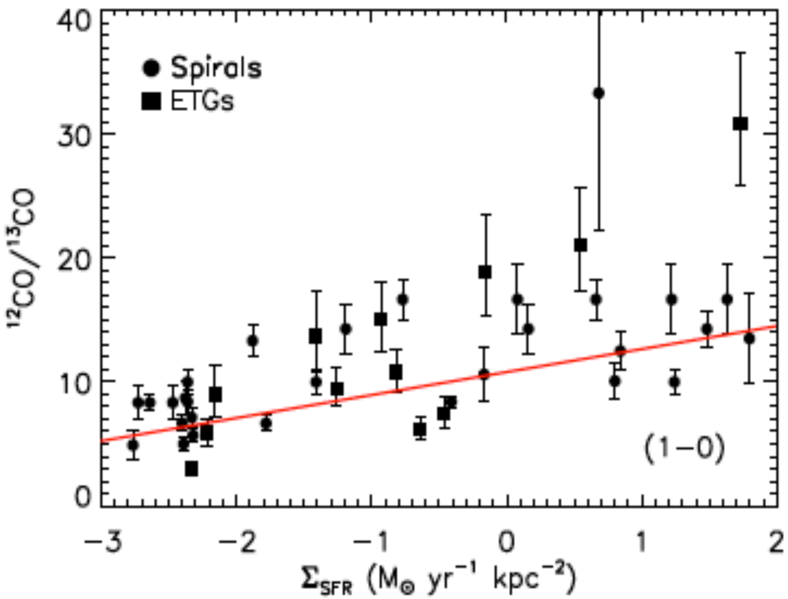
$\mathcal{R}$ = ^{12}CO(1-0)/^{13}CO(1-0) profiles

- More variations of the ^{12}CO/^{13}CO ratio in the centers
- High ratios are found in starburst-dominated nuclei galaxies
- Ratios higher than in the MW



$\mathcal{R} = {}^{12}CO(1\text{-}0)/{}^{13}CO(1\text{-}0)$ versus $\Sigma(SFR)$

Davis et al. 2014



+ constant $^{13}CO/C^{18}O$ ratios

$\Rightarrow$ high $\mathcal{R}$ to lower ^{12}CO optical depth

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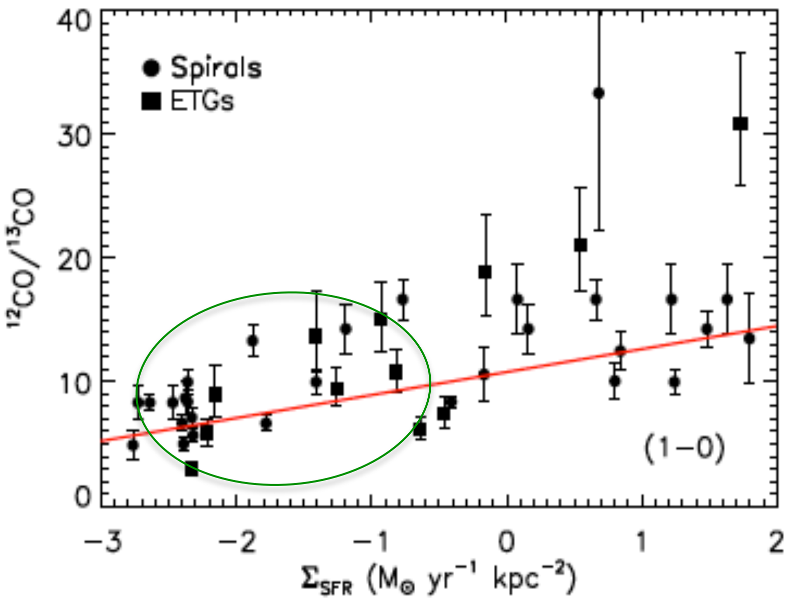
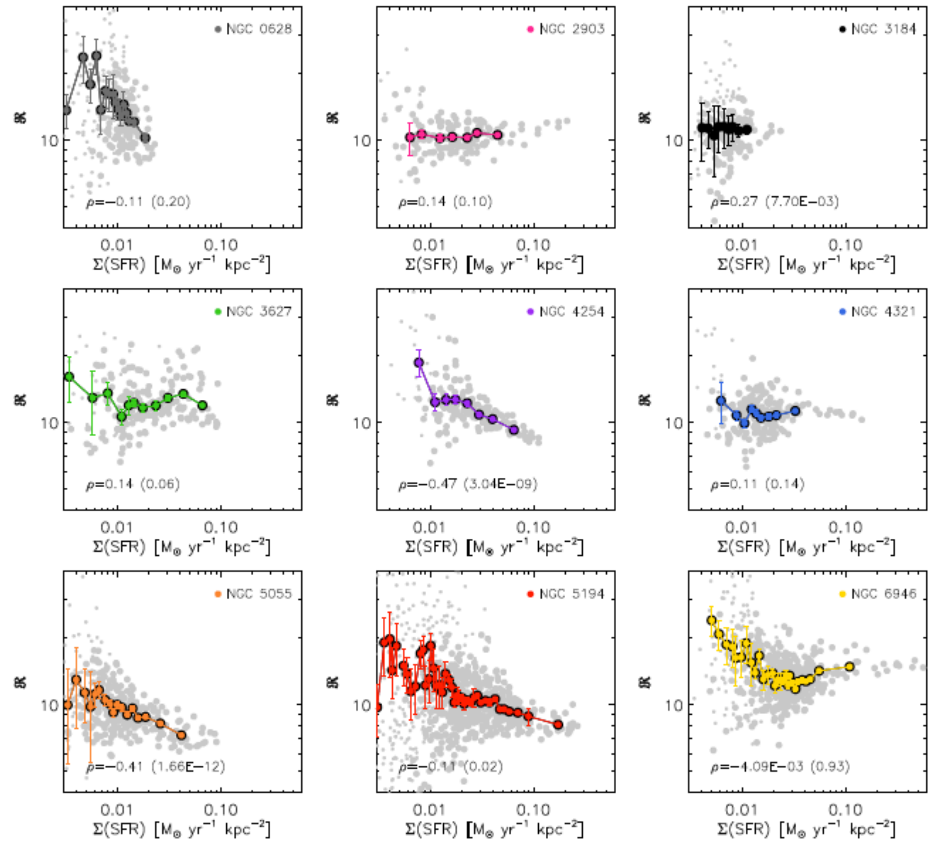


Cormier et al. to be subm.



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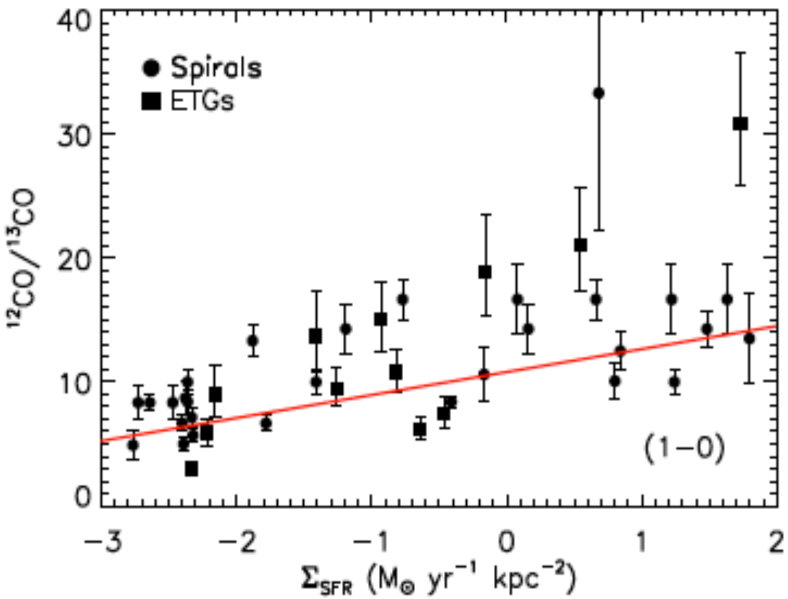
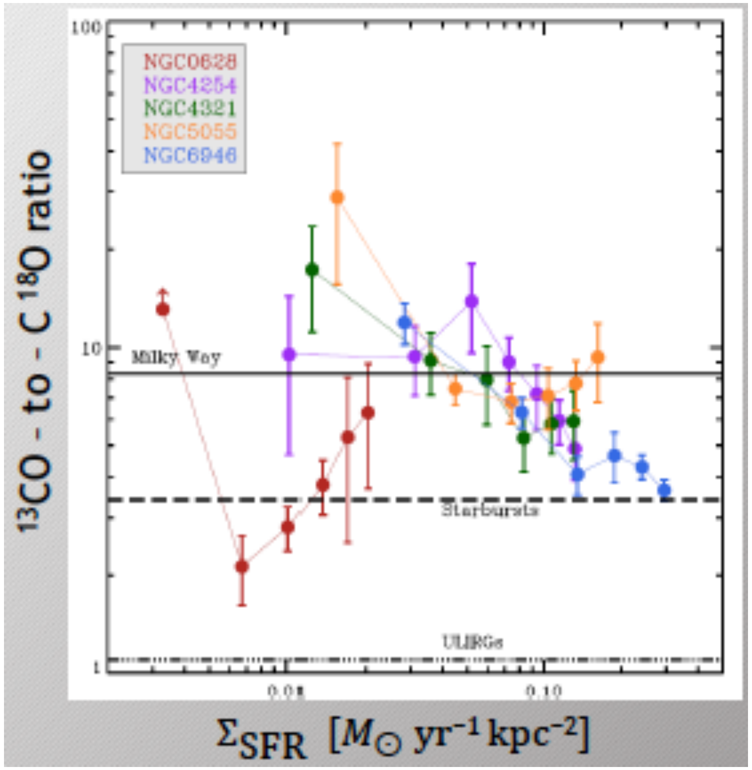


Jiménez-Donaire, Cormier et al. 2017a

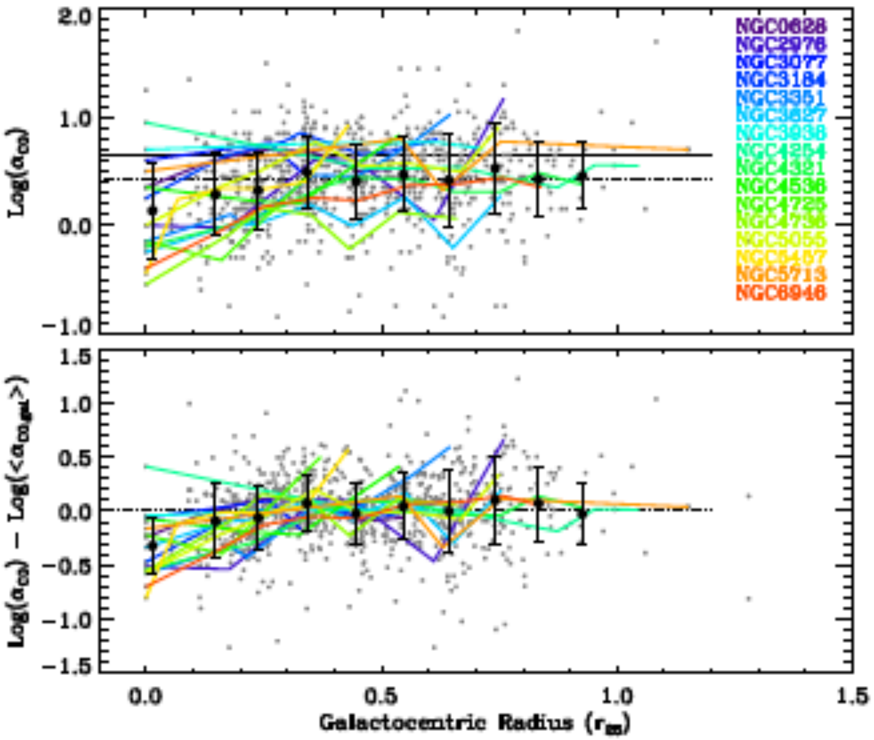


+ constant $^{13}CO/C^{18}O$ ratios
⇒ high $\mathcal{R}$ to lower ^{12}CO optical depth

⇒ Strong evidence for varying abundances within galaxies

A ^{13}CO(1-0)-to-H_2 conversion factor

Sandstrom et al. 2013

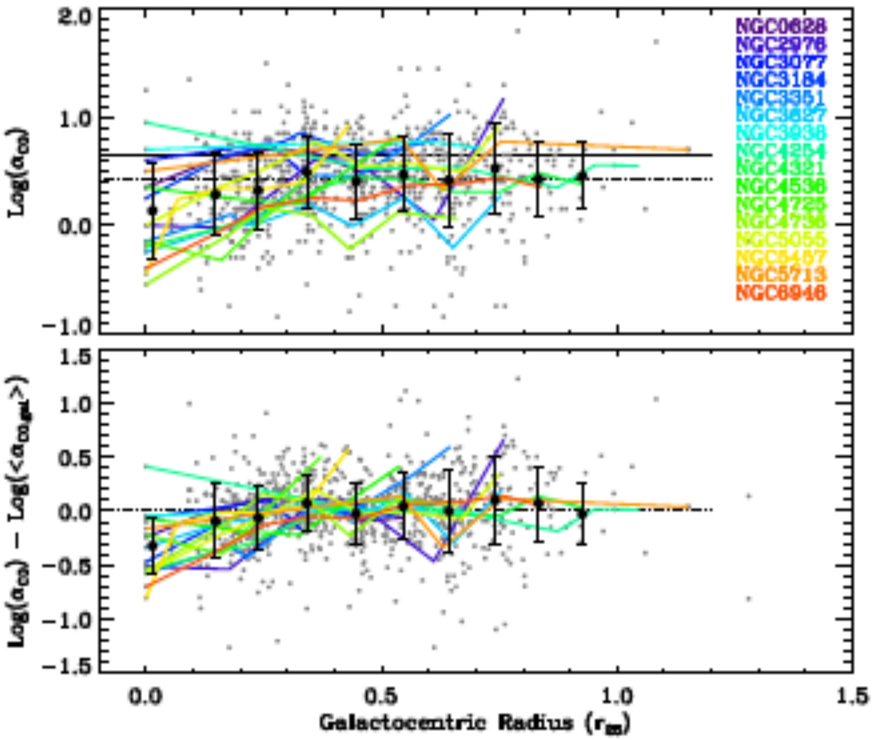


Suppressed α_{12CO} in the galaxy centers:

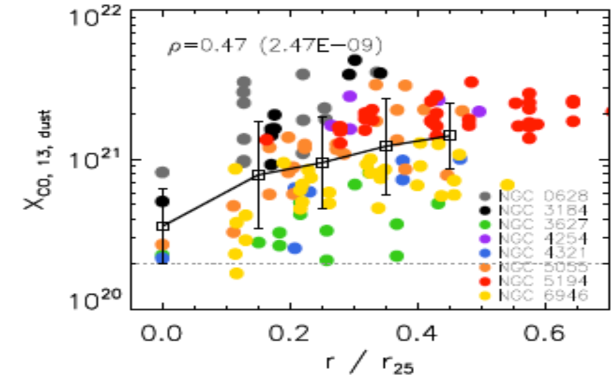
opacity (velocity gradients, diffuse gas) or excitation effects?

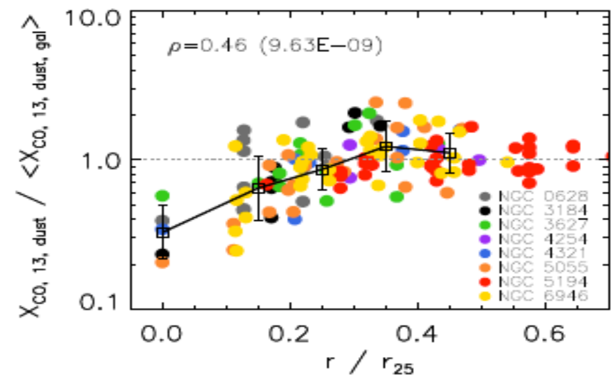
A ^{13}CO(1-0)-to-H_2 conversion factor

Sandstrom et al. 2013



$N(H_2)_{\mathrm{from\ dust}} = I(^{13}CO) \times X(^{13}CO)$





- Empirical derivation of $X(^{13}CO)$ still reveals a large variations
- Low α_{12CO} values in centers do not disappear with ^{13}CO – excitation dominates?
- Systematic problems in the dust method?

Conclusions

Cormier et al. to be subm.

- In LTE, ^{13}CO underestimates the H_2 column density compared to standard methods (^{12}CO, dust)
- ^{13}CO does not seem to trace better (more tightly) the molecular gas than ^{12}CO
- Variations in the $^{12}CO/^{13}CO$ intensity ratio mostly in galaxy centers and due to opacity <u>and</u> abundance effects

<u>*Next step*</u>: modeling for quantitative assessment of those effects in combination with dense gas observations

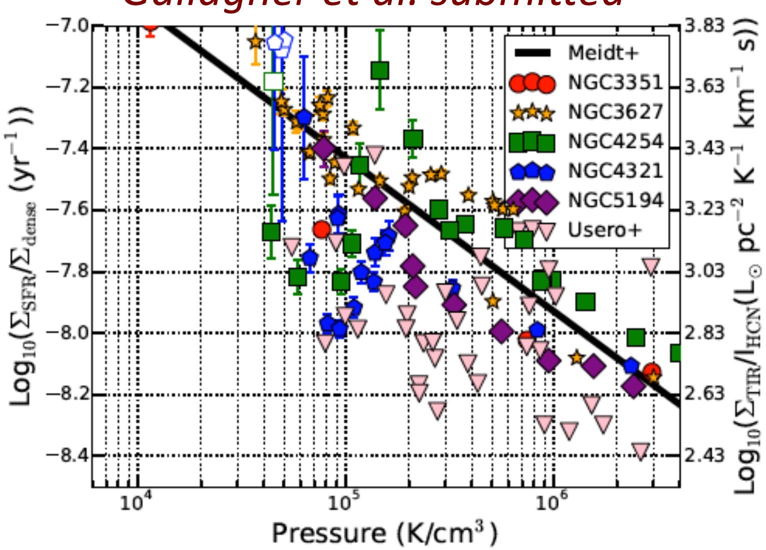
Conclusions

Follow-ups:

- direct abundance measurements in centers (IRAM, PI. MJ Jiménez-Donaire)
- higher J transitions for excitation
- starburst environments (IRAM, PI A. Usero)

More dense gas work to come

Gallagher et al. submitted



Jiménez-Donaire et al. in prep