Dense molecular gas and star formation across galaxy disks

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Galactic Scale Star Formation: Observation meets Theory

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Outline

- Background: molecular lines and star formation laws
- The project
- Preliminary results:
  - Dense gas fraction
  - Star formation efficiency of the molecular gas
  - Star formation efficiency of the dense molecular gas
- Conclusions
- Remark: conversion factors

Background / Empirical star-formation laws in galaxies

- Molecular lines with different excitation densities constrain:
  - Average properties of molecular clouds.
  - Star formation (SF) laws.

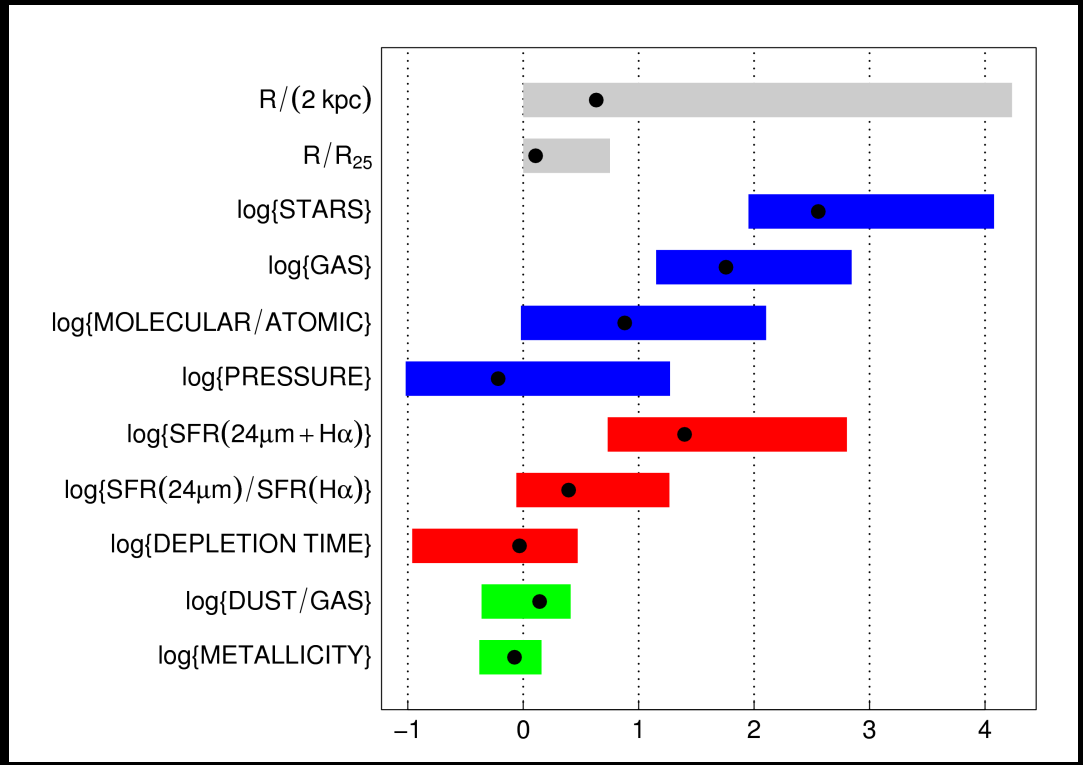
- Different slopes in plots SFR vs. CO(1-0) (~*most*) and HCN(1-0) (*dense*) →
  - Universal SF law for dense molecular gas (*threshold* theories).
  - Universal SF law for all molecular gas (e.g.,Krumholz'07, Narayanan'08).

- Most observations of dense gas in galaxies have poor resolution → local physics is lost.

- This project: study the relation between dense molecular gas, star formation and environment at kpc scales in nearby disk galaxies (centers and beyond!).
  - Probes ensembles of clouds.
  - Relations with local environment can be studied.

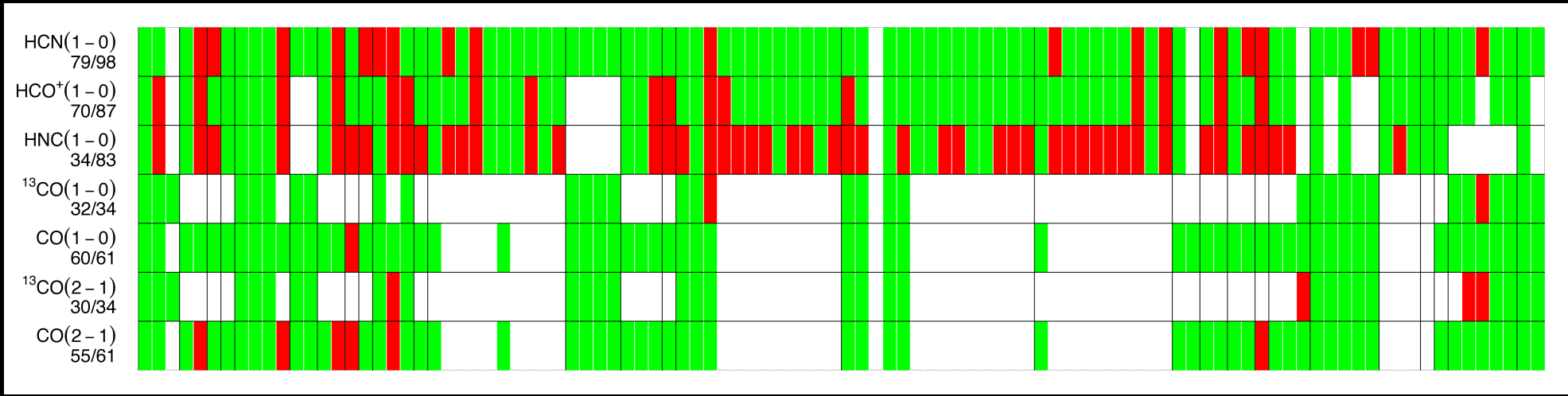
The project / Basics

- The HERA CO Line Extragalactic Survey (PI:F. Walter) → Multiwavelength data
  - CO(2-1) spectral cubes of ~50 nearby galaxies at ~1kpc common resolution
  - Overlap with THINGS (VLA), SINGS+LVL (*Spitzer*), KINGFISH (*Herschel*), NGS (*GALEX*)
- IRAM 30m observations of dense gas tracers
  - HCN(1-0) and HCO^+(1-0) in ~100 pointings in ~30 HERACLES galaxies
  - 28" working angular resolution → 1.5 kpc on average
  - $^{12/13}$CO data for most pointings + other dense gas tracers (e.g., C_2H, HNC) for free
- Pointings chosen so as to cover a wide range of ISM and SF conditions

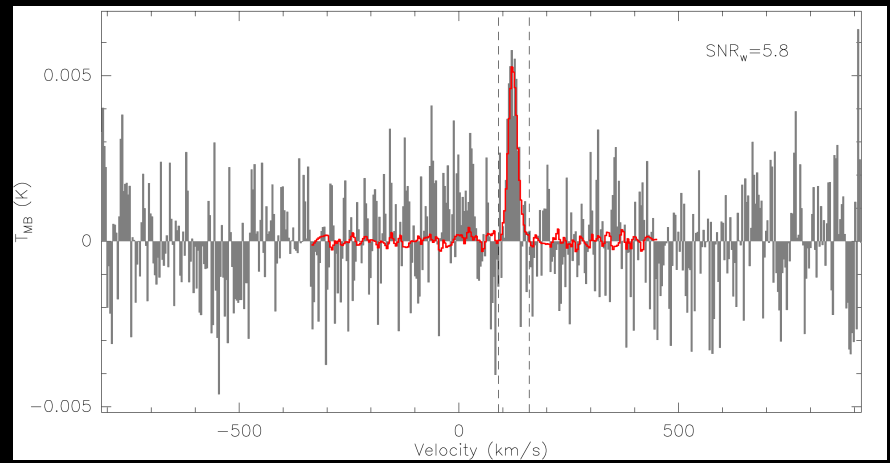


The project / Observations

- Summary of detections

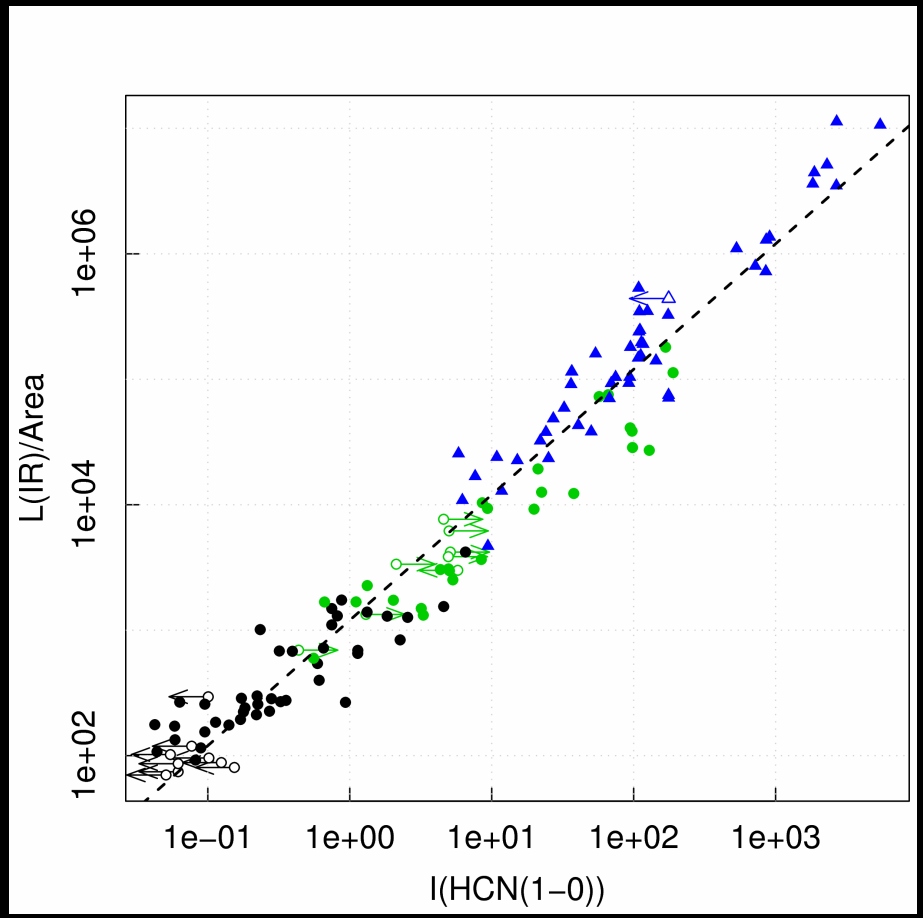


HCN(1-0) (gray) vs. CO(2-1) (red) at matching resolution observed at r~0.8R_{25} in NGC 6946



The project / the data in context

- HCN vs. IR plot compared with extragalactic data-set (Garcia-Burillo'12)
  - Compatible with previous results
  - Overlap with averages in normal star-forming galaxies
  - Covered ranges extended by ~1-2 orders of magnitude



This project (black) vs. GB12
(green: normal galaxies; blue: (U)LIRG).
X-units: K km/s; Y-units: L_{SUN}/pc^2.

The project / What we study here

- We focus on three ratios:
  - HCN/CO $\propto$ Dense Gas Fraction (f_{DENSE})
  - SFR/CO $\propto$ Star Formation Efficiency of the molecular gas (SFE_{MOL})
  - SFR/HCN $\propto$ Star Formation Efficiency of the dense molecular gas (SFE_{DENSE})
  - Fixed (molecular mass)/CO and (dense mass)/HCN conversion factors assumed (revised at the end of the talk)

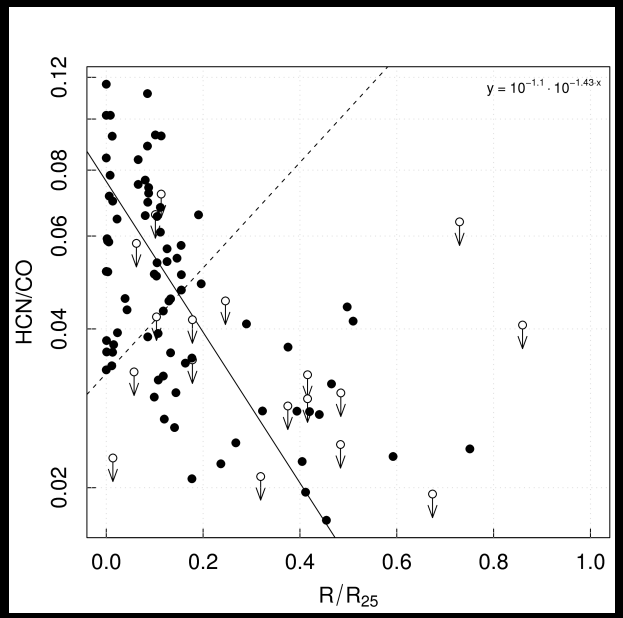
- We select two environmental parameters:
  - H2/HI mass ratio $\rightarrow$ process by which GMCs form
  - Metallicity (Moustakas'10) $\rightarrow$ "chemical" parameter

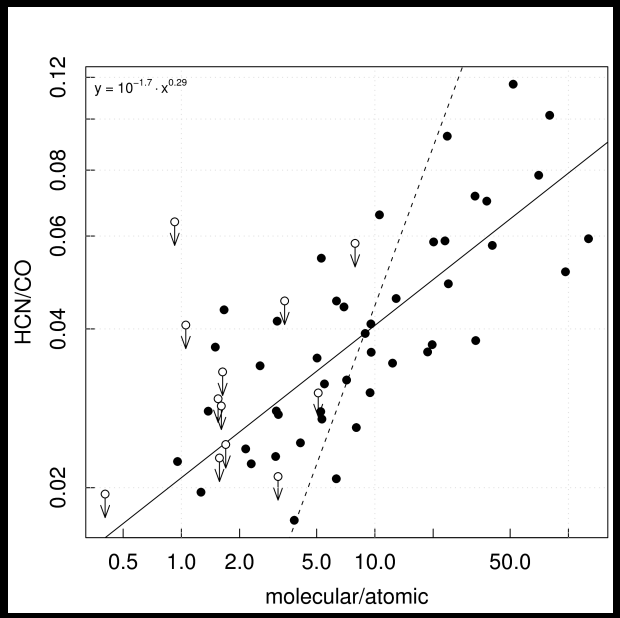
- SFR=Hα+MIPS24μm cirrus-corrected (Leroy et al. 2012), but not critical

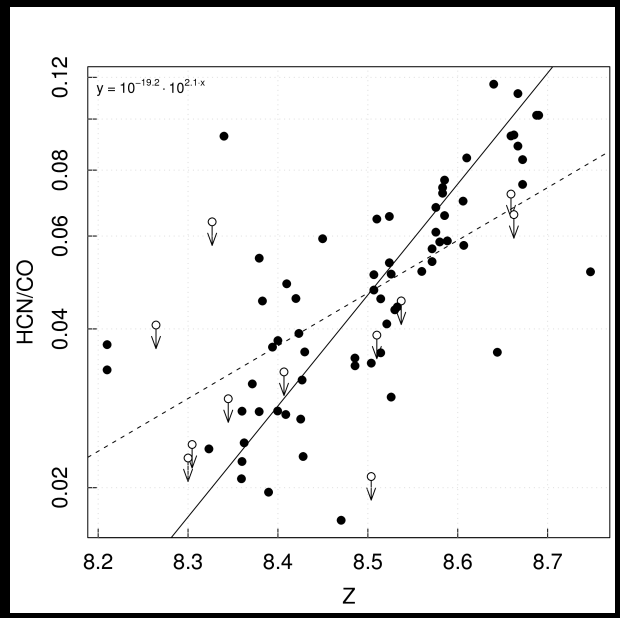
- Caveats:
- Most environmental parameters depend on radius
- The multi-λ array not fully assembled yet $\rightarrow$ some plots have more points that others

Results / HCN/CO ~ dense gas fraction (I)

- HCN/CO (~f_{DG}) ratio steeply decreases with radius.
- HCN/CO increases with H2/HI.
- HCN/CO increases with Z.



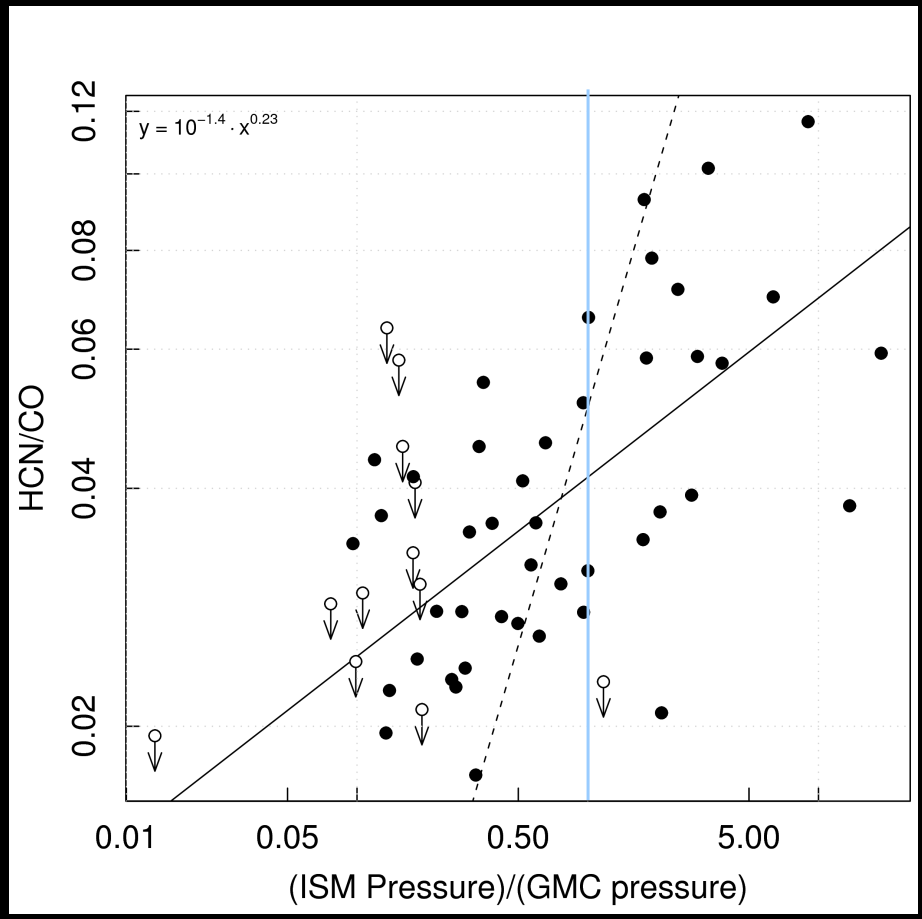




- Taken at face value → f_{DG} shows systematic dependence on environment.
- H2/HI and Z covariant → difficult to identify the main driver just from plots.

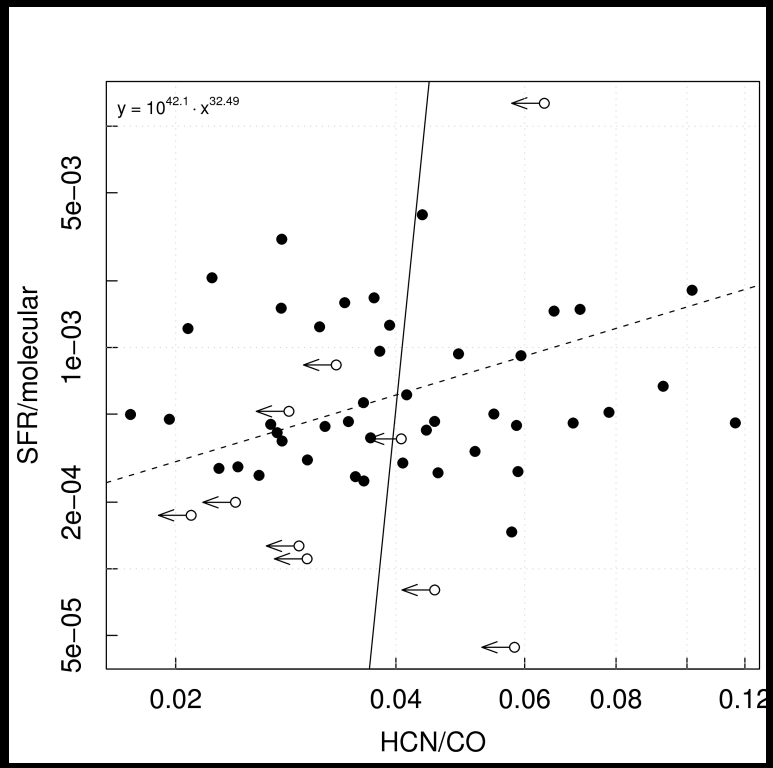
Results / HCN/CO ~ dense gas fraction (II)

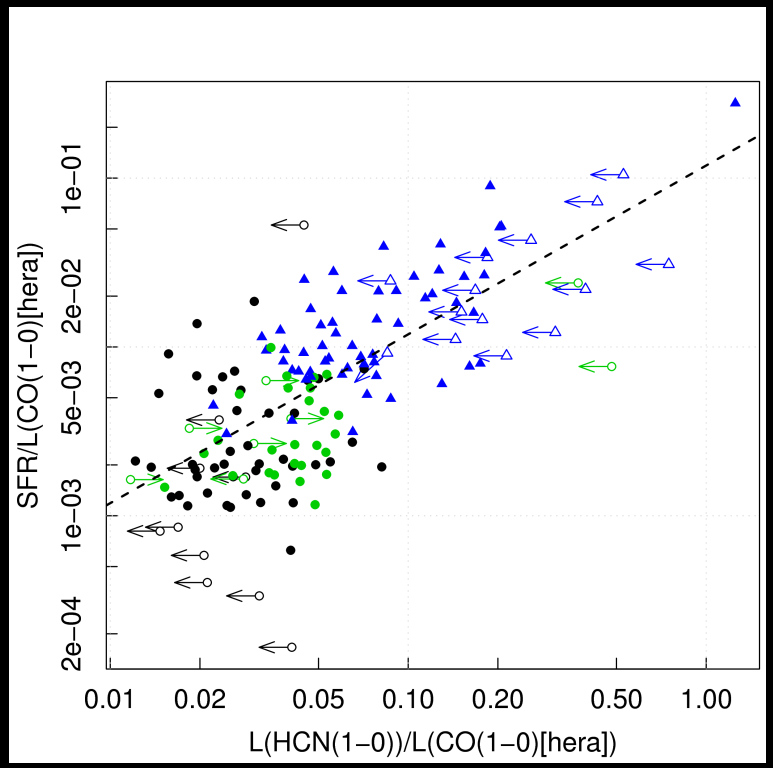
- We find evidence that HCN/CO (~f_{DG}) changes systematically across galaxy disks.
  - Driver?
  - Does it really reflect a change in true f_{DG} ?
- HCN/CO shows no clear transition at P_{ISM}~P_{GMC}



Results / SFR/CO ~ star formation efficiency

- $SFE_{MOL}=(f_{DG})x(\ SFE_{DENSE})$
- SFR/CO ($\sim SFE_{MOL}$) independent of HCN/CO (f_{DG}) in our sample
- Compatible with dispersion in extragalactic observations.
- Are the variations in SFE_{DENSE} random?

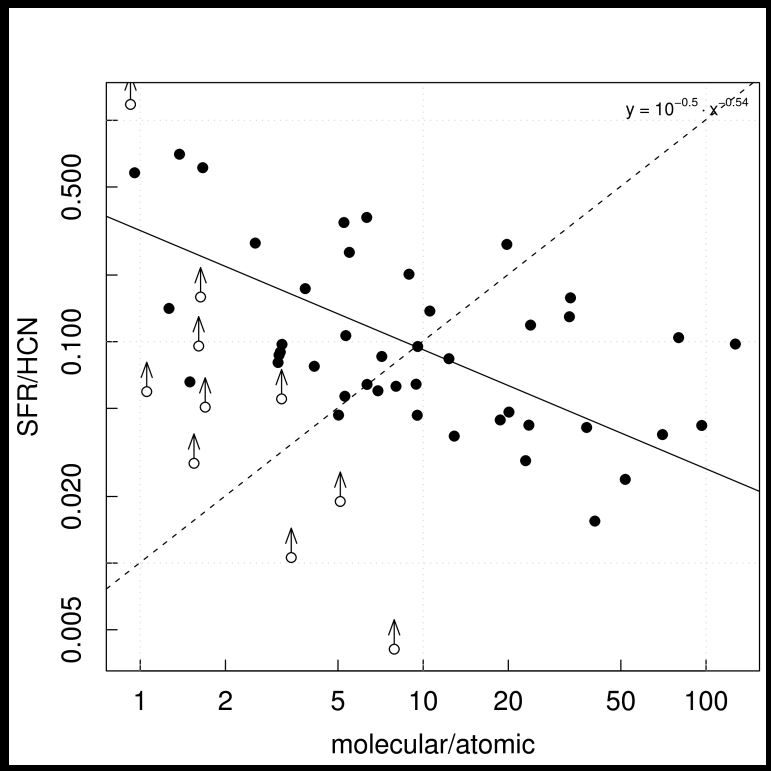


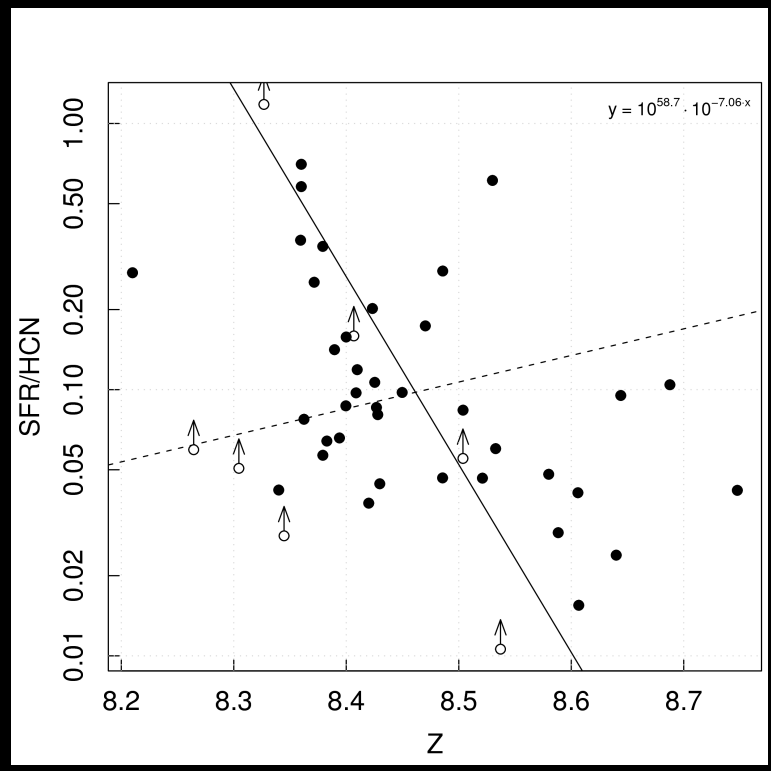


This project (black) vs. GB12
(green: normal galaxies; blue: (U)LIRG).
Y-units: 1/Myr.

Results/ SFR/HCN~star formation efficiency of dense gas

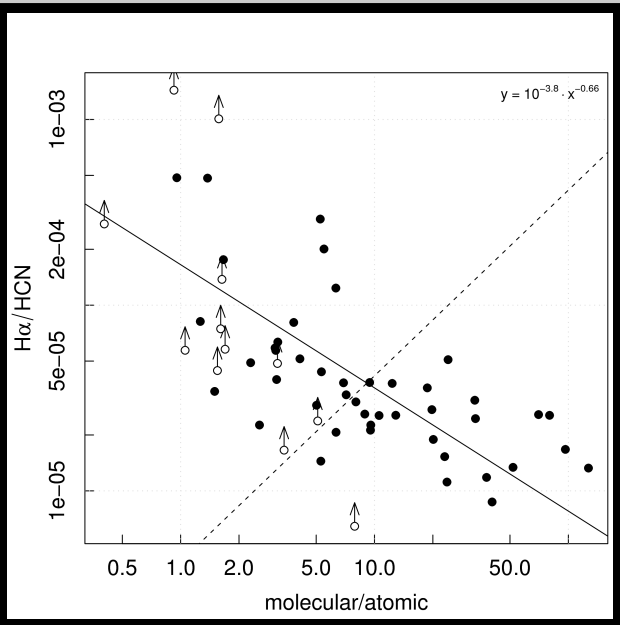
- SFR/HCN (~SFE_{DENSE}) decreases with H2/HI and Z.
- SFE_{DENSE} shows systematic dependence on environment (lower at galaxy centers!)

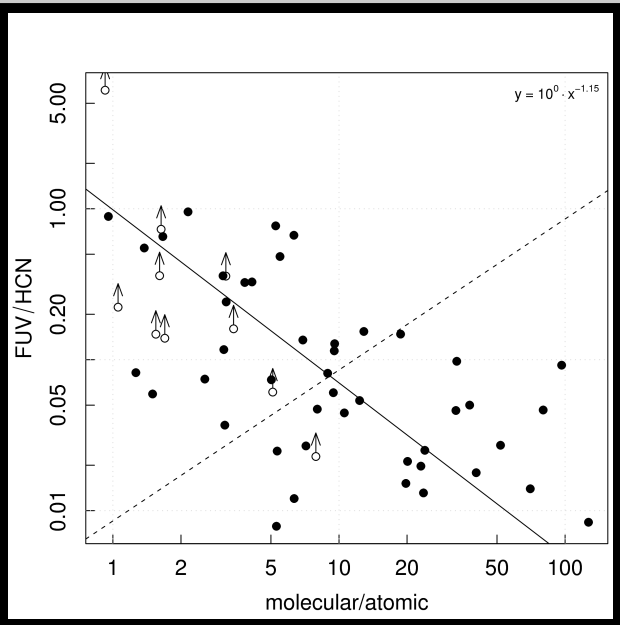


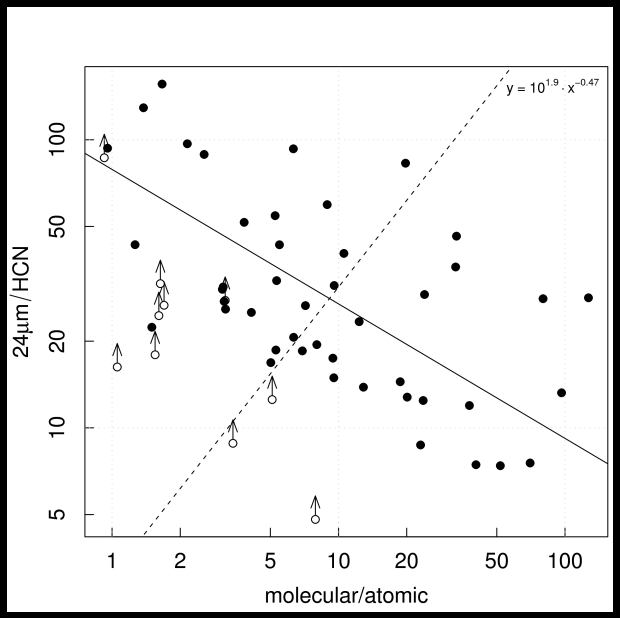


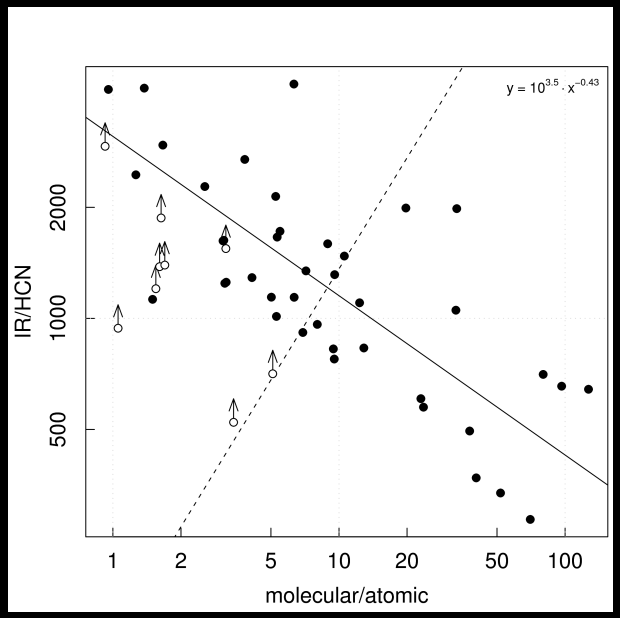
Y-units: (M_{SUN}/pc^2/Myr)/(Kkm/s).

Results / SFR/HCN~star formation efficiency of dense gas









- Systematic variations of SFR/HCN confirmed by all our SFR tracers.
- If you expect constant SFE_{DENSE}, blame HCN.

[Halpha]=erg/s/sr; [FUV]=MJy/sr; [24um]=MJy/sr; [IR]=L_{SUN}/pc^2 ; [HCN]=K km/s.

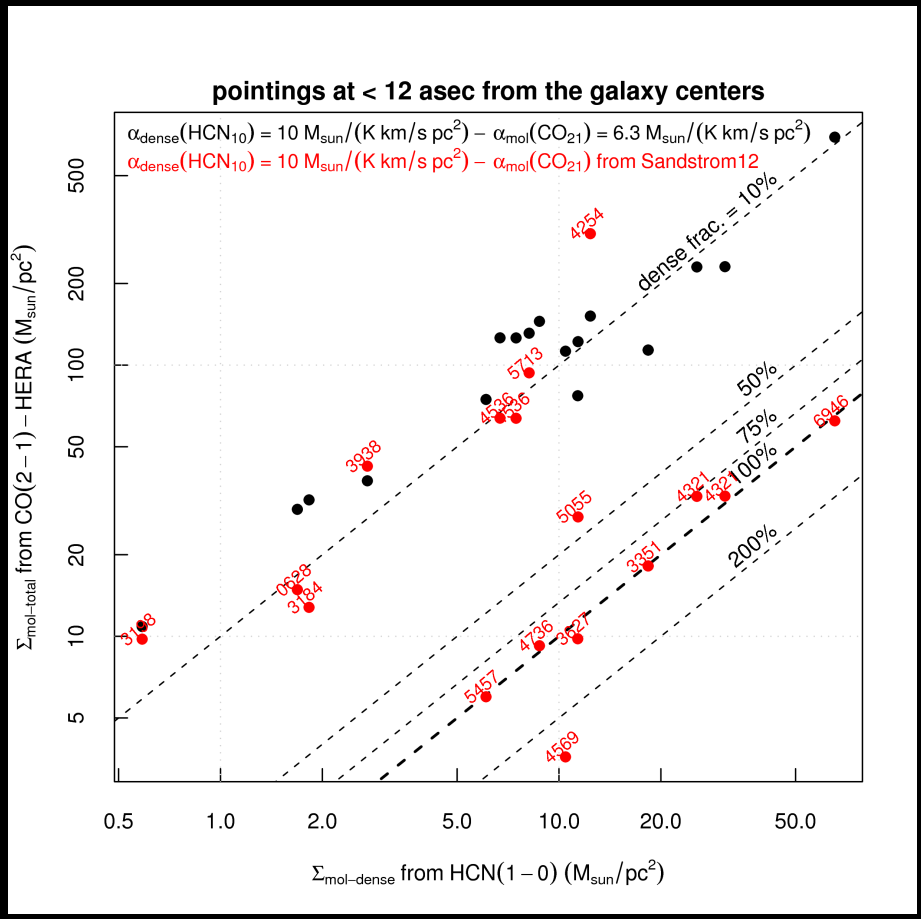
Conclusions

- Dense gas tracers (HCN, HCO^+) observed across the disks of HERACLES galaxies.
- We find systematic dependence of HCN/CO and SFR/HCN on environment →
  The average properties of molecular clouds change across galaxy disks.
- At face value, systematic trends in the dense gas fraction and the SFE of dense gas →
  - High f_{DG} at high molecular/atomic and high Z (galaxy centers).
  - High SFE_{DENSE} at low molecular/atomic and low Z (galaxy disks).
- The variations f_{DG} and SFE_{DENSE} would be shallower if the M_{DENSE}/L(HCN) factor increased with radius.

Last remark / Conversion factors

- If M_{DENSE}/L(HCN) ratio increased with radius, the trends in SFE_{DENSE} and f_{DG} would be alleviated, more consistently with expectations from *threshold* theories.

- Sandstrom'12 (previous talk) finds radial gradients in M_{MOL}/L(CO).



- New values for M_{MOL}/L(CO) → f_{DG}>100%!, unless M_{DENSE}/L(HCN)<< MW value at galaxy centers (as found in (U)LIRG).

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- The variations f_{DG} and SFE_{DENSE} would be shallower if the M_{DENSE}/L(HCN) factor increased with radius.
  - Results from Sandstrom'12 for M_{MOL}/L(CO) support this possibility.