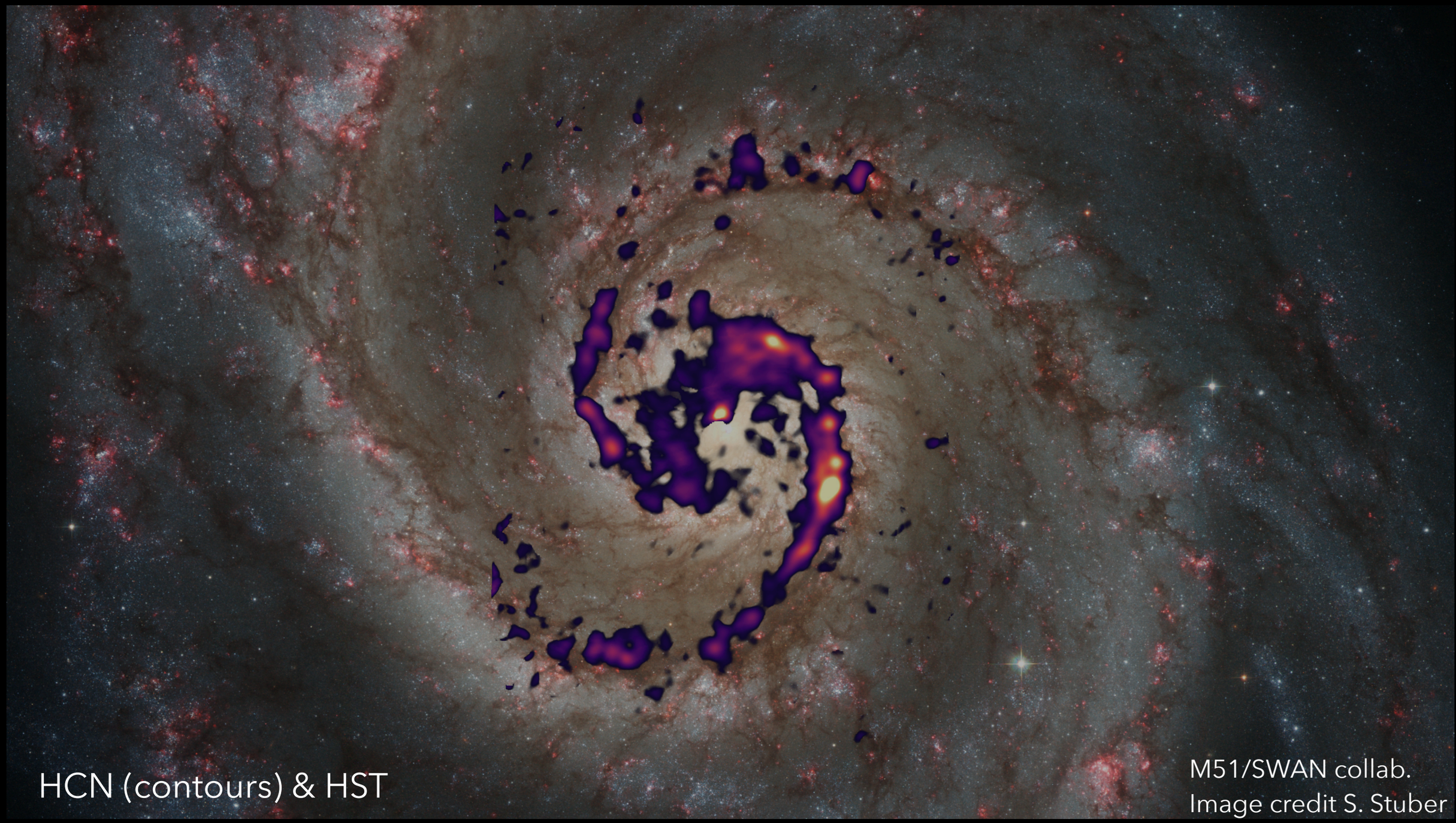
“mm-spectroscopy” Across Nearby Galaxies – Dense Gas Fraction and Star Formation Efficiencies from Cloud to Galaxy Scales



Frank Bigiel (Univ. Bonn)

TEAMS

SWAN

Grad. Students: **S. Stuber (HD), I. Galić (Bonn)**

and: **M. Thorp**, E. Schinnerer, J. Pety, A. Usero, I. Beslic, M. Querejeta, M.J. Jimenez-Donaire, FB, & PHANGS

Galaxy trends at 100pc cloud scales

ALMOND

Thesis work: **L. Neumann (Bonn, now ESO)**

and: M. Gallagher, A. Leroy, A. Barnes, A. Usero, J. den Brok, FB, & PHANGS

Galaxy trends on kpc scales

LEGO

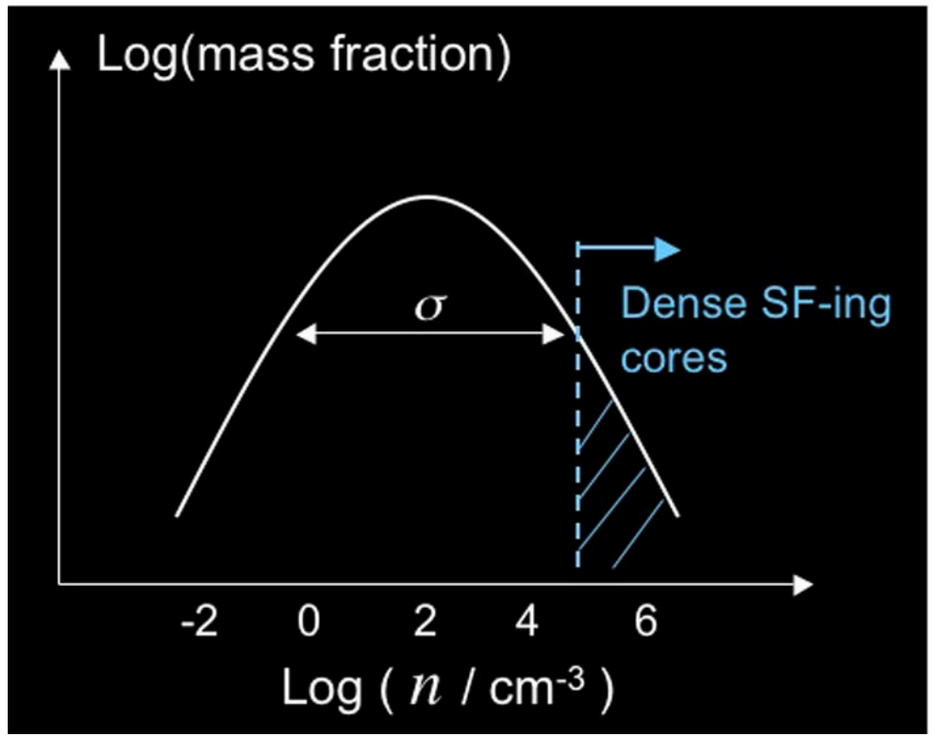
Thesis work: **L. Neumann (Bonn, now ESO)**

and: J. Kauffmann, A. Barnes, FB, D. Colombo, K. Menten, F. Wyrowski, N. Brinkmann ++

Massive local SF regions at pc-resol.

Frank Bigiel (Univ. Bonn)

Motivation



Many **theories** focus on cloud-scale properties (far below the kpc scale of disk averages) as the drivers of **star formation and feedback**. Turbulent theories focus on the distribution of **densities**, set by the mean density, Mach number and virial parameter.

Observations recover general behavior in local clouds.

e.g., Padoan ‘02, ‘11, ‘12, Krumholz+ ‘05, ‘12, Hennebelle & Chabrier ‘08, Bournard+ ‘11, Hopkins+ ‘12, Federrath & Klessen ‘12, ‘13, Burkhart ‘18, Elmegreen ‘18, Zakardjian’25, etc.

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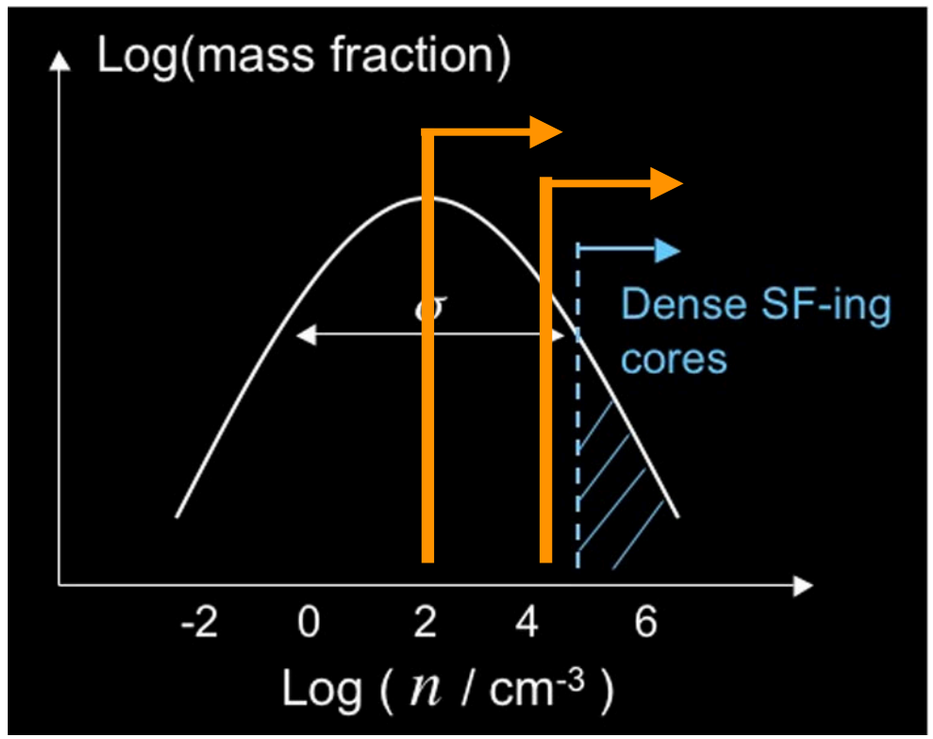

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Can we access the density distribution from observations across the disks of nearby galaxies?

Talks by Mélanie, Lise, Diederik

Cloud scale surface density (e.g. PHANGS-ALMA)

A diverse (different critical densities) suite of molecular lines should track the underlying volume density distribution to first order.
But: opacity, abundance, excitation

Motivation

Can we access the density distribution from
observations across the disks of nearby galaxies
despite the ~low resolution?

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Are variations in cloud properties reflected in changing line ratios (~beam-scale PDF)	How do density sensitive line ratios compare across (different) galaxies and scales?	How does the SFR-to-line ratio vary across galaxies and scales?

Motivation

Can we access the density distribution from **observations** across the disks of nearby galaxies despite the ~low resolution?

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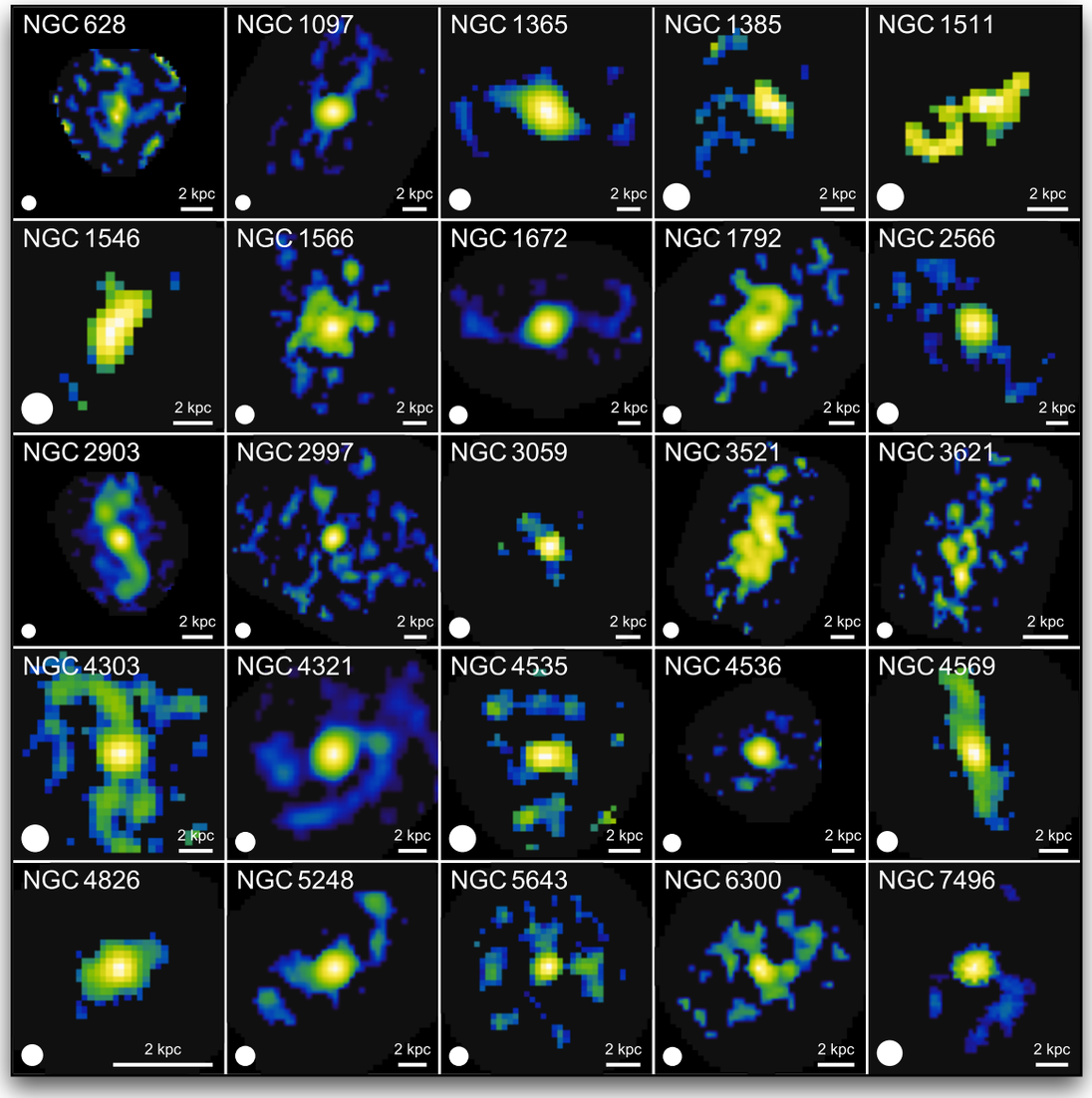
Are variations in cloud properties reflected in changing line ratios (~beam-scale PDF)	How do density sensitive line ratios compare across (different) galaxies and scales?	How does the SFR-to-line ratio vary across galaxies and scales?
Compare cloud-scale surf.dens or dispersion to e.g. HCN/CO, HCO^+/CO…	Measure e.g. HCN/CO, HCO^+/CO…	Measure e.g. SFR/HCN …

Kpc

The Almond Survey



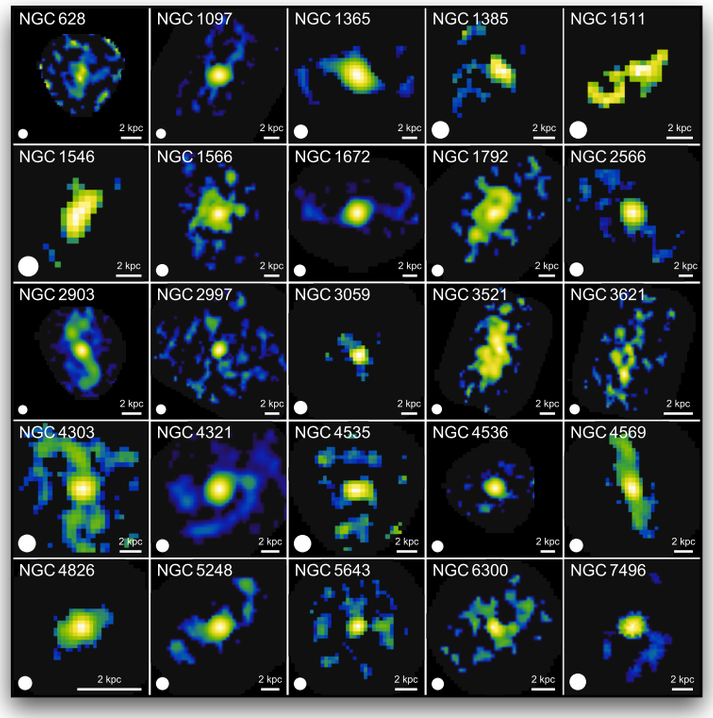
- 25 spiral, star-forming galaxies drawn from ALMA-PHANGS LP
- 400 hours with ALMA ACA+TP
- Higher critical density lines HCN, HCO+, CS
- Resolution 20 arcsec (1-2 kpc)

Neumann, Gallagher, FB+ 2023a

Kpc

The Almond Empire

Neumann, Gallagher, FB+ 2023a



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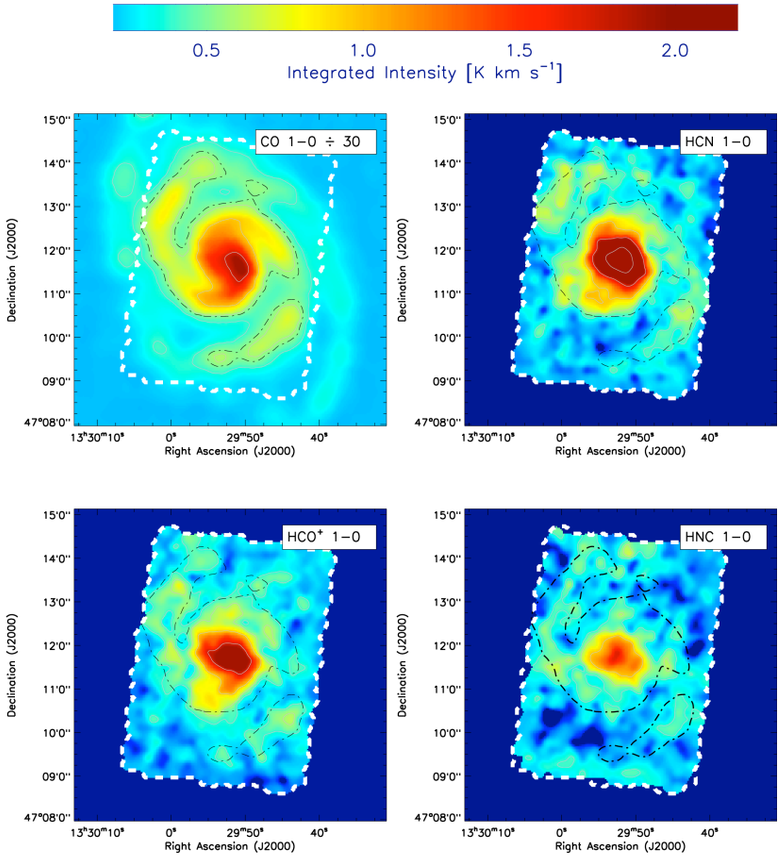
ALMOND



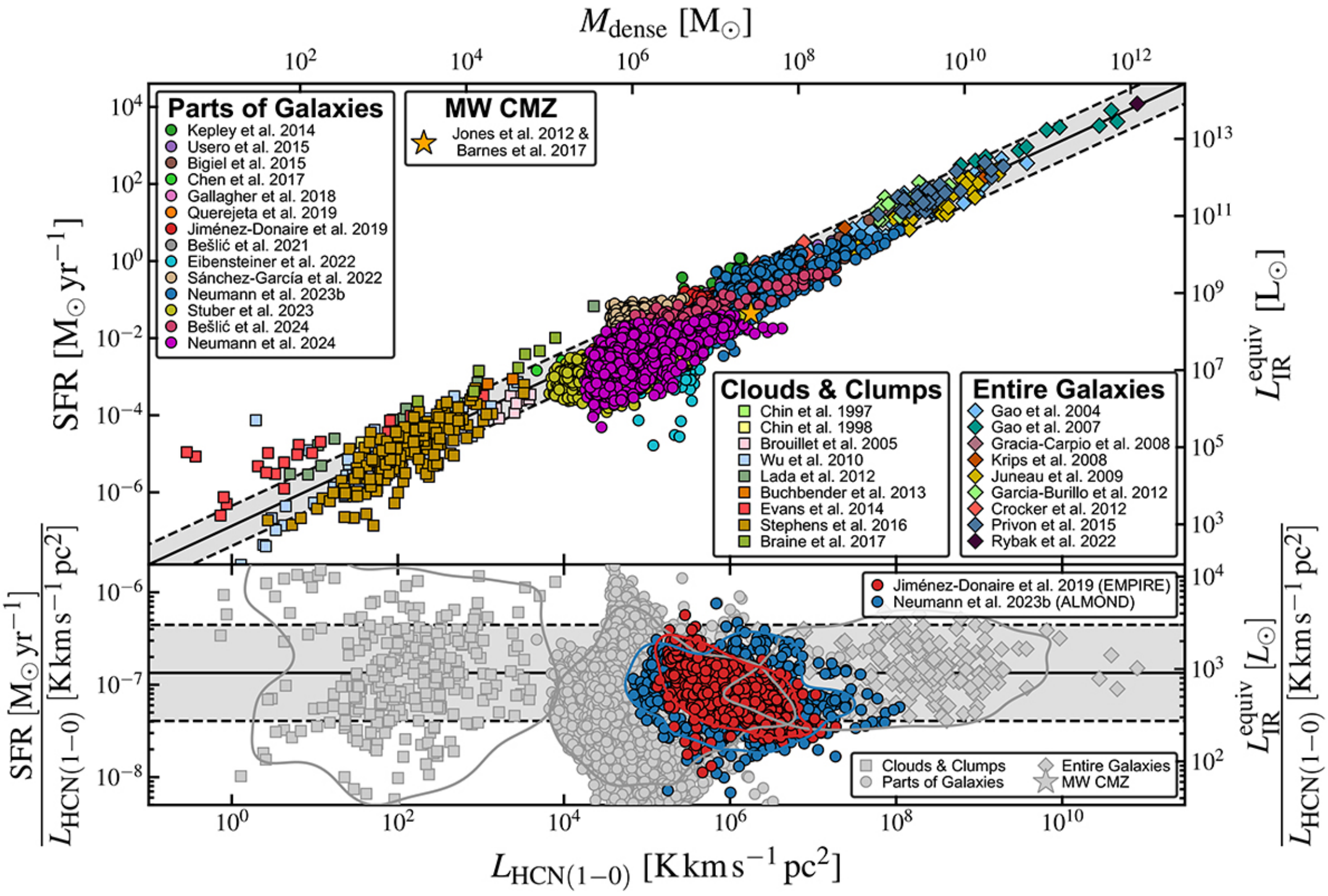
- 9 northern, spiral, star-forming galaxies
- ~600 hour LP with IRAM 30m
- Same lines at ~similar scale

EMPIRE

PI FB, Usero+ 2015, FB+ 2016, Leroy2017+, Jimenez-Donaire+ 2017a,b, 2019, Cormier+ 2018

Kpc

The Almond Survey - General Trends



Neumann et al. 2025

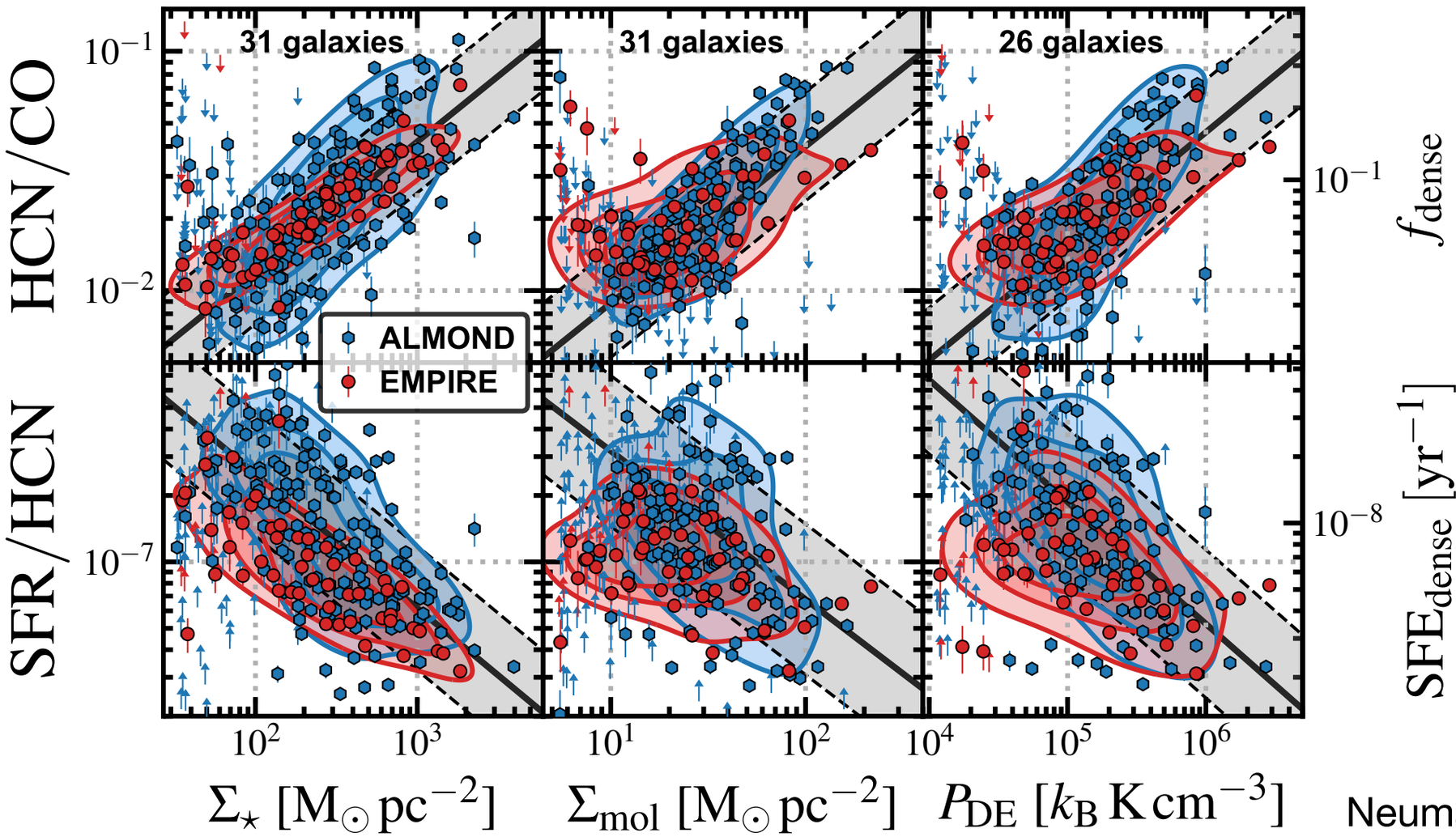
cf. Lada+ (2010, 2012), Gao and Solomon (2004ab), Wu+ (2005, 2010), Evans+ (2014)

Kpc

The Almond Survey - General Trends

- Scatter in SFR-HCN relationship is physical/systematic.
- HCN/CO ratio rises while SFR/HCN ratio drops across galaxy disks towards their centers. These observations are consistent for 30m and ACA.
- So we seem to have more dense gas on average in the inner parts of galaxies, the SFR in that gas does not scale correspondingly (qualitatively matches MW CMZ) .

Talk by Steve this morning

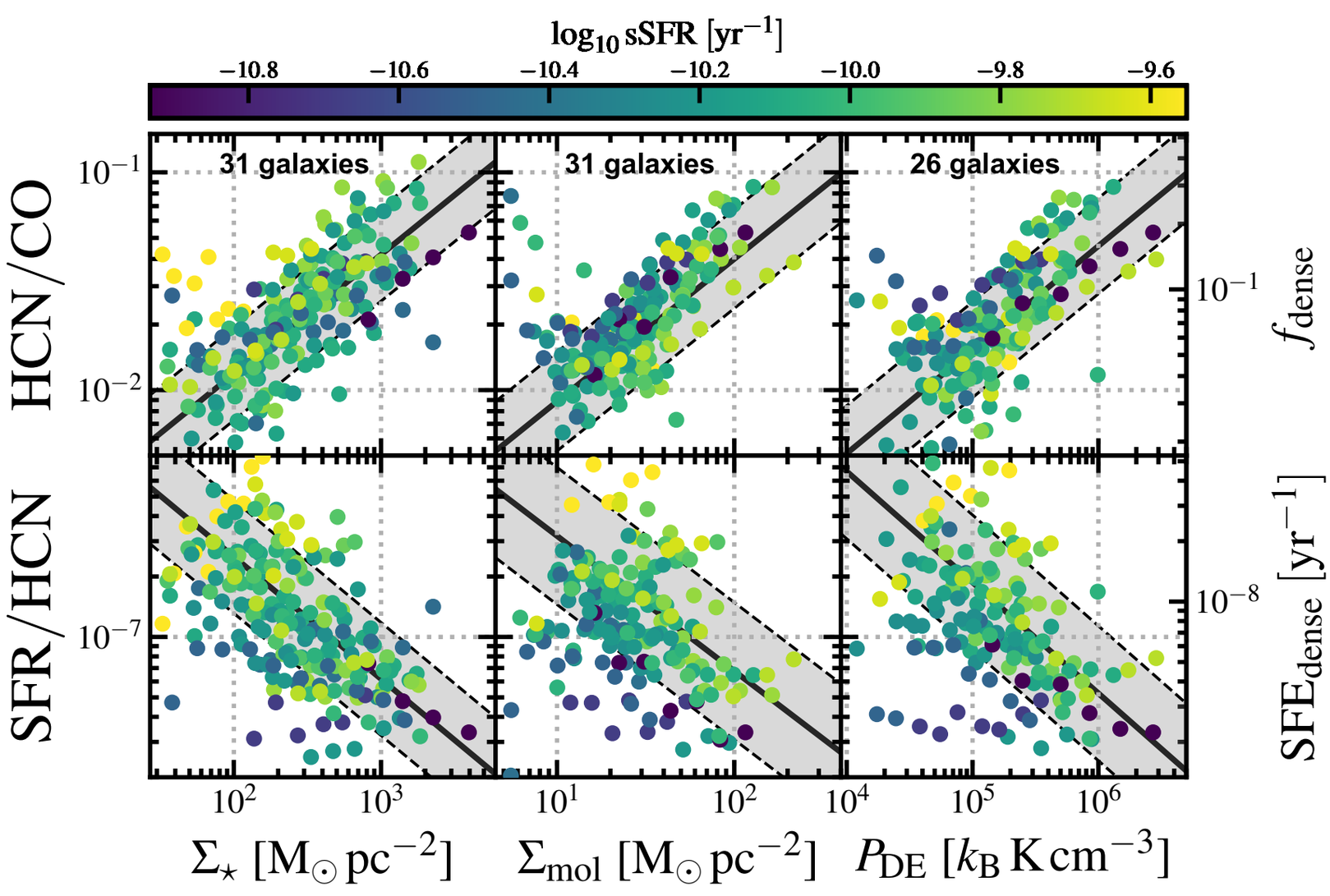


Neumann, Gallagher, FB et al. 2023a

Kpc

The Almond Survey - General Trends

- Scatter in SFR-HCN relationship is physical/systematic.
- In fact, we also see the galaxies with a higher SSFR (or main sequence offset) have elevated SFR/HCN and vice versa. Less clear in HCN/CO.

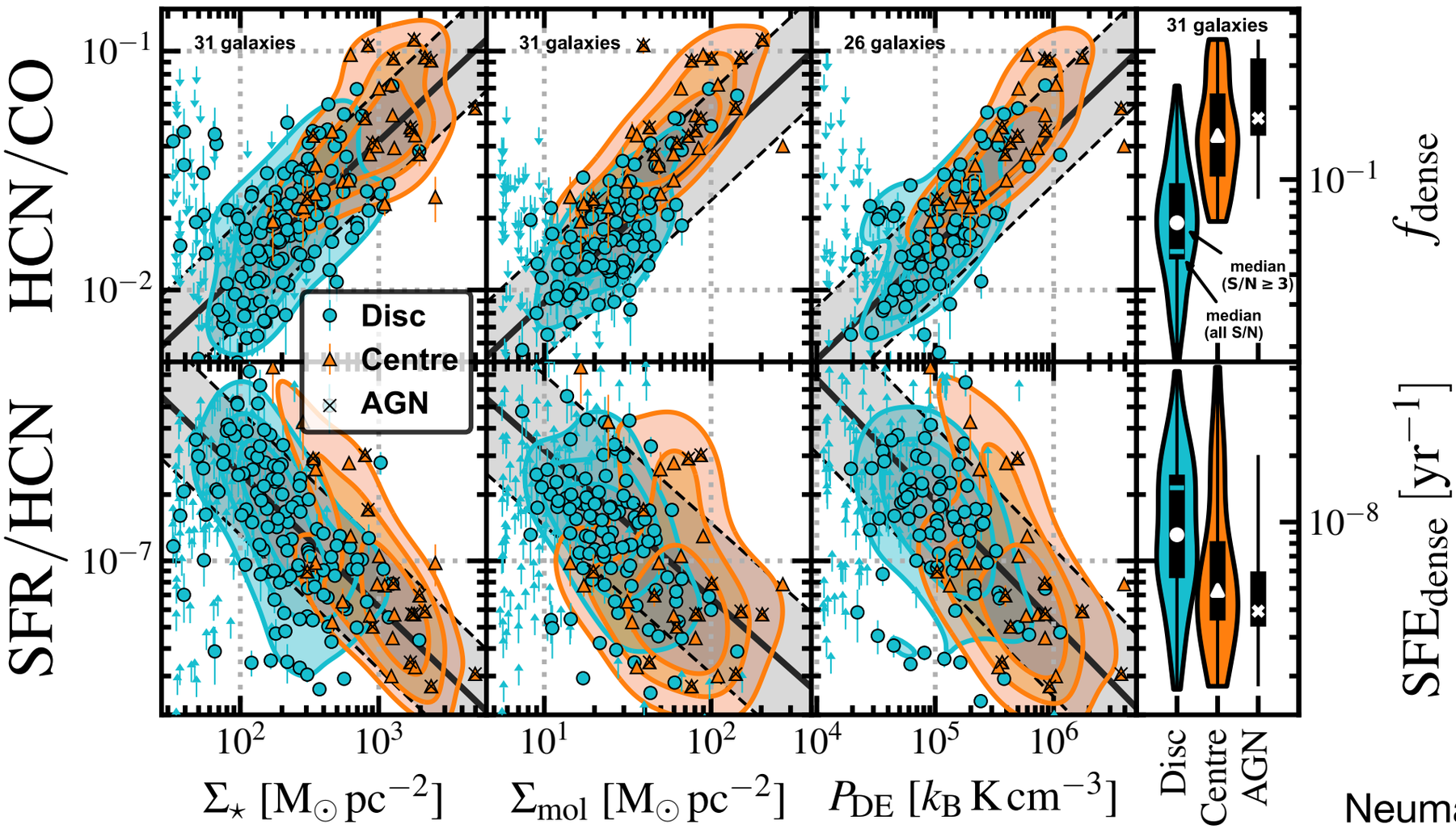


Thanks Lukas for making the plot yesterday afternoon!

Kpc

The Almond Survey - General Trends

- AGN (=central kpc pixel) do not stand out; AGN feedback imprint on molecular line ratios on scales << 1kpc?



Neumann et al. 2025

Kpc

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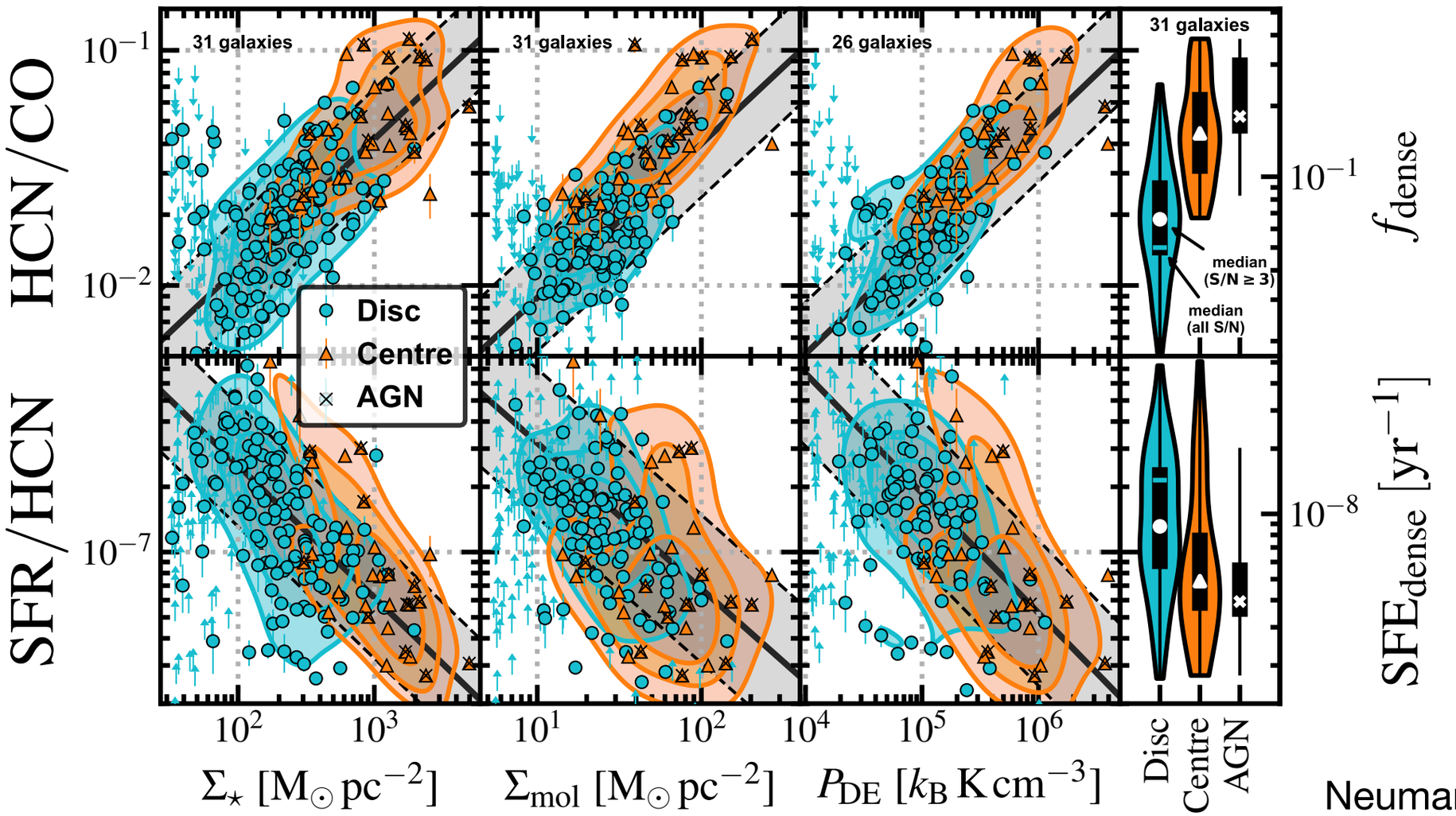


Neumann et al. 2025

Talk to Mallory if interested in high-resolution case study of M51 center

Kpc

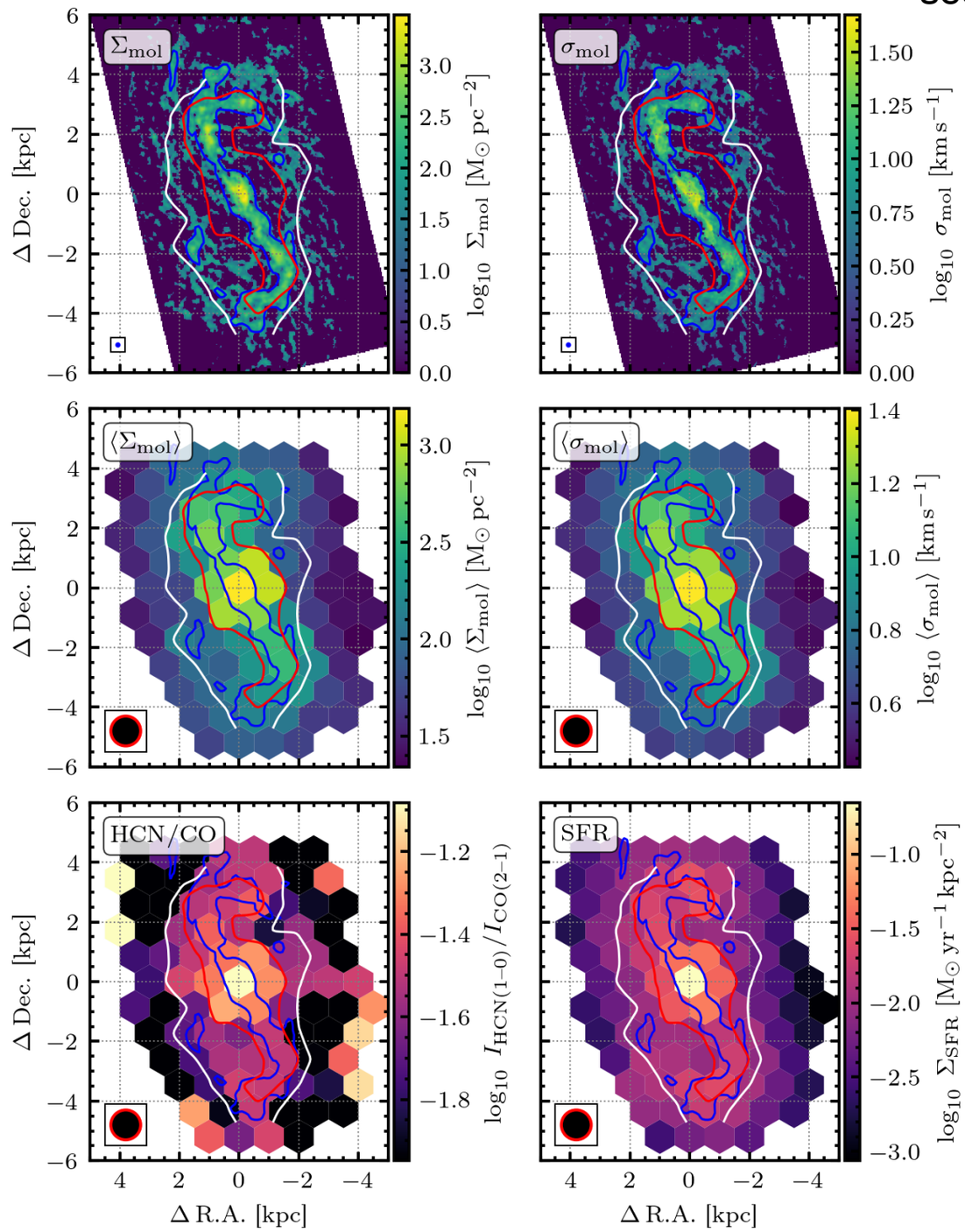
The Almond Survey - Link to Cloud Properties

- Link “spectroscopic line ratios” as density metrics to average cloud-scale properties spatially resolved across many galaxies.

see Sun+ 2018,20

PHANGS

ALMOND



Average

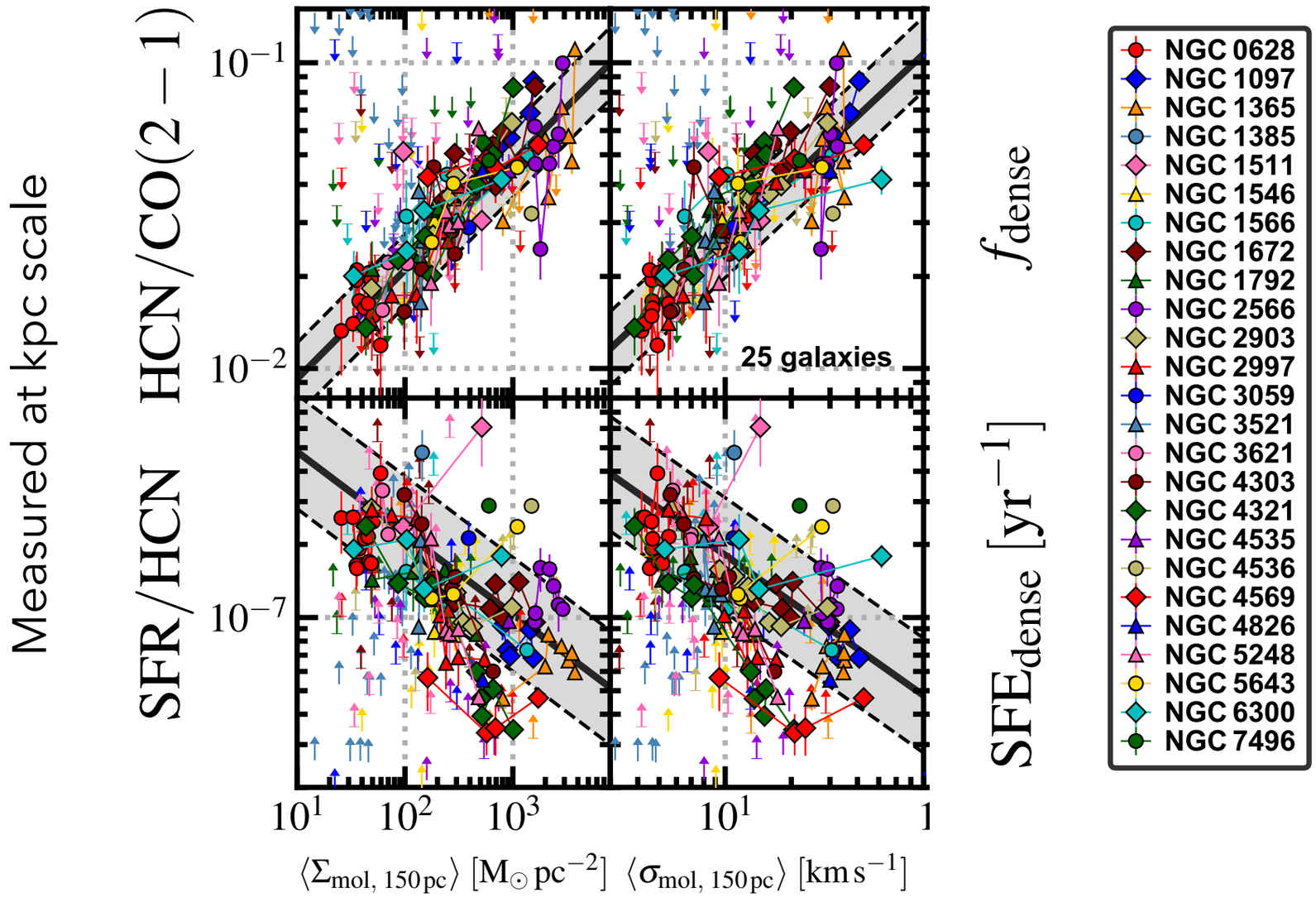
Compare

Neumann, Gallagher, FB et al. 2023a

Kpc

The Almond Survey - Link to Cloud Properties

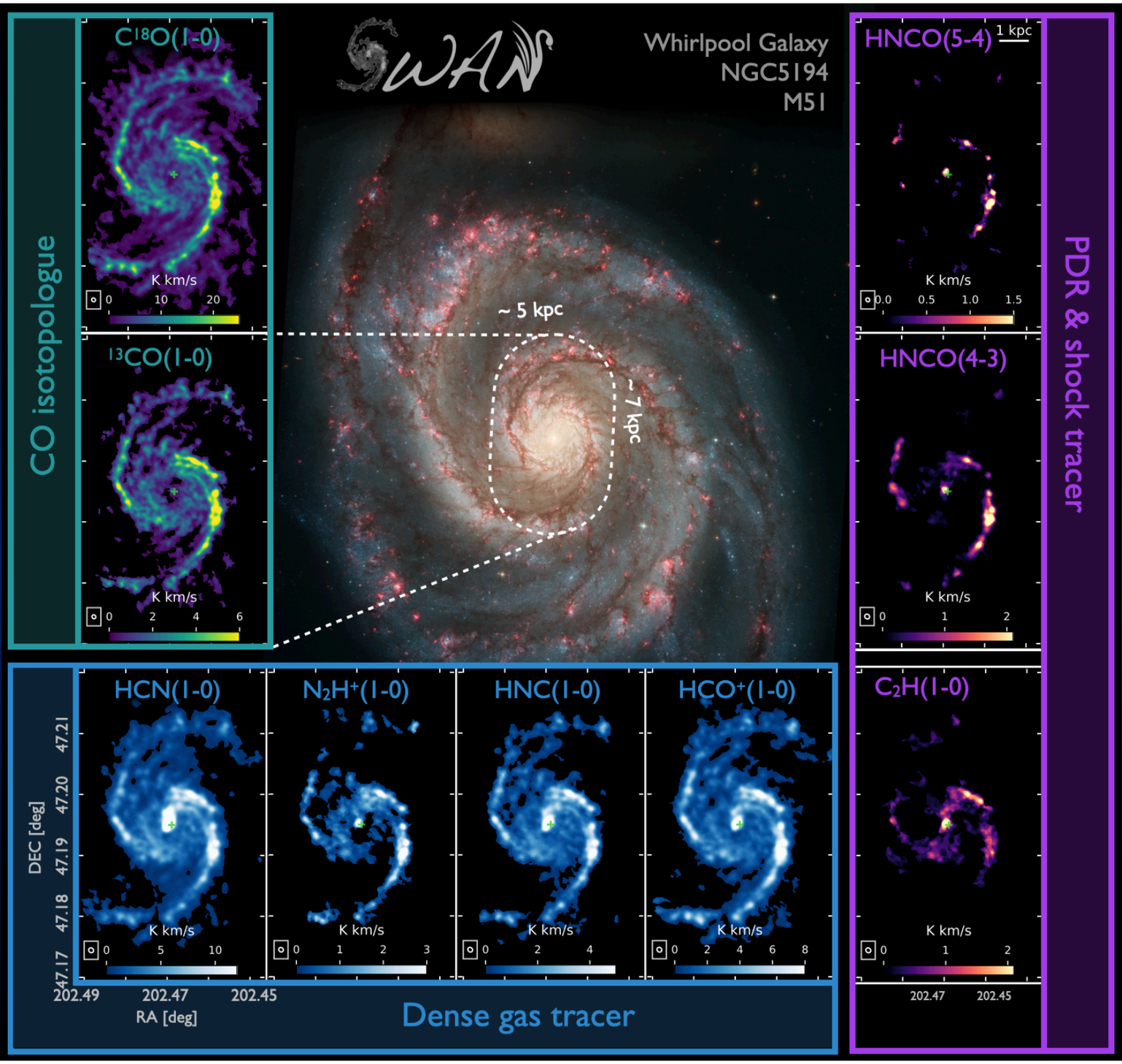
- Basic result: Density-sensitive line ratios and SFR per unit gas scale strongly with average, cloud-scale surface density and velocity dispersion, as expected from turbulent cloud models (this is also true for HCO^+/CO and CS/CO).



Neumann, Gallagher, FB et al. 2023a

100pc

Moving to Cloud Scales - the SWAN Survey



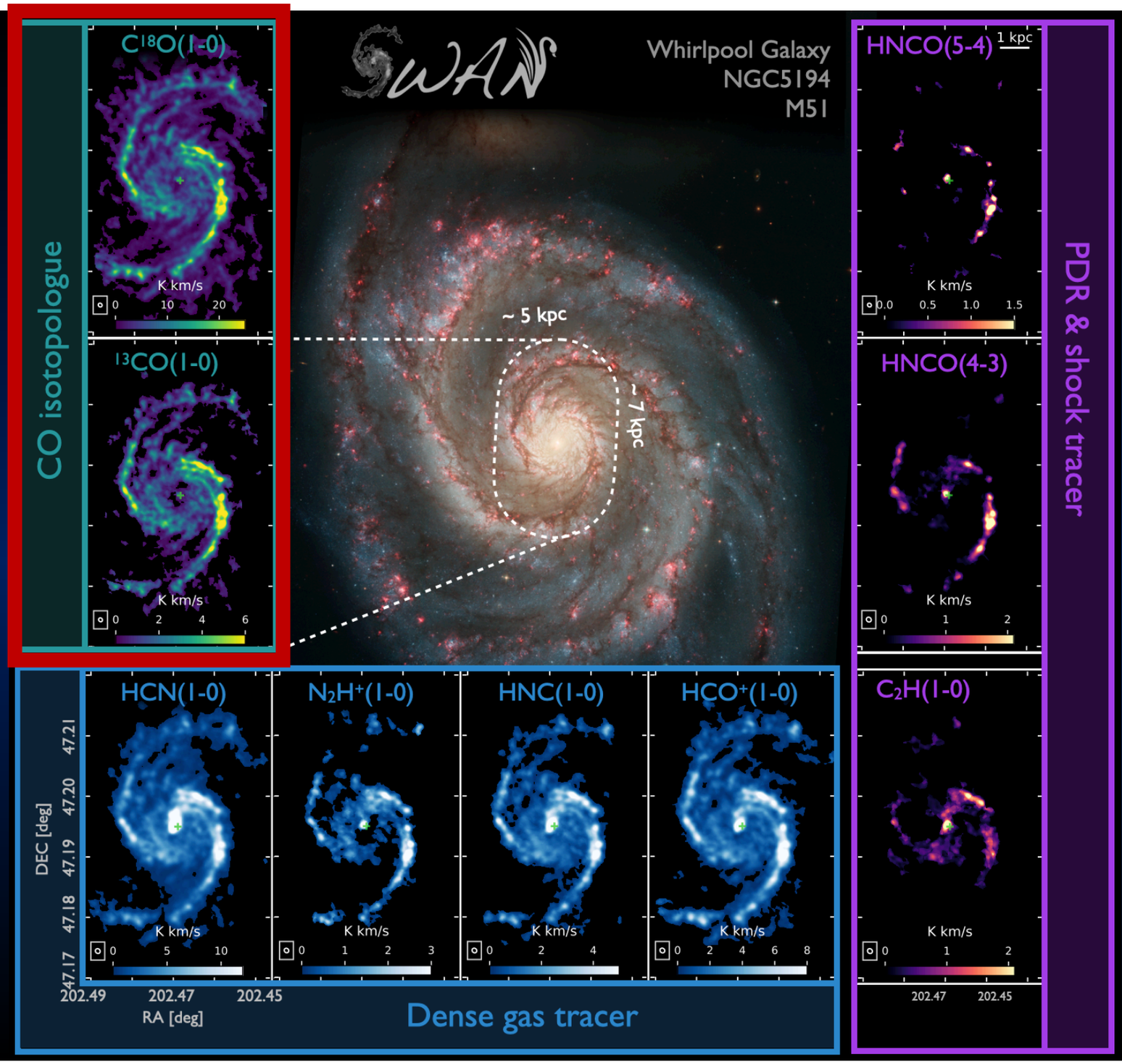
Surveying the Whirlpool galaxy at Arcsecond resolution with NOEMA

~200h NOEMA observations
~70h 30m
Resolution of 3" (125pc)
PIs E. Schinnerer, F. Bigiel

Stuber+ 2025

100pc

Moving to Cloud Scales - the SWAN Survey



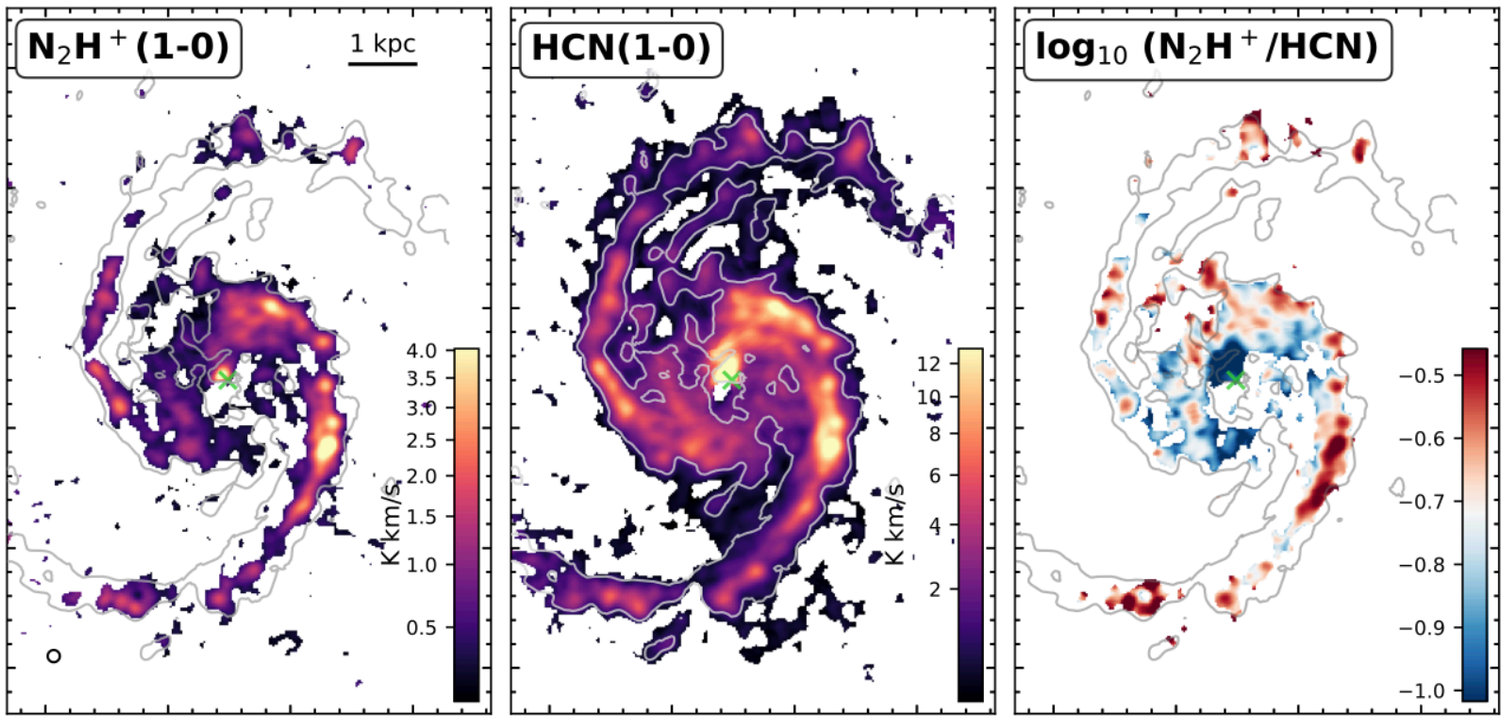
SWAN

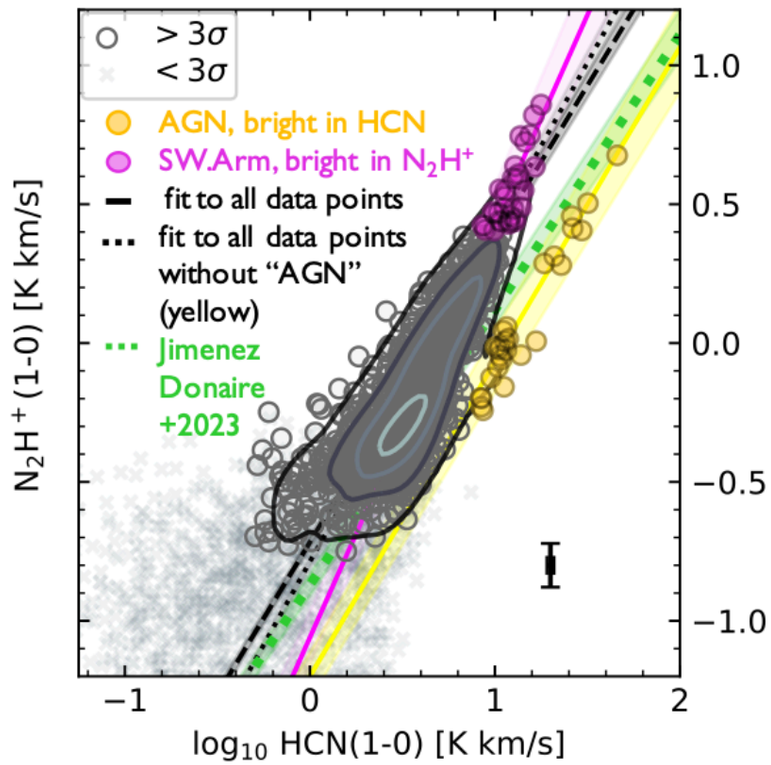
Surveying the Whirlpool galaxy at Arcsecond resolution with NOEMA

Talk to Ina if interested in CO isotopologues

100pc

Moving to Cloud Scales - the SWAN Survey





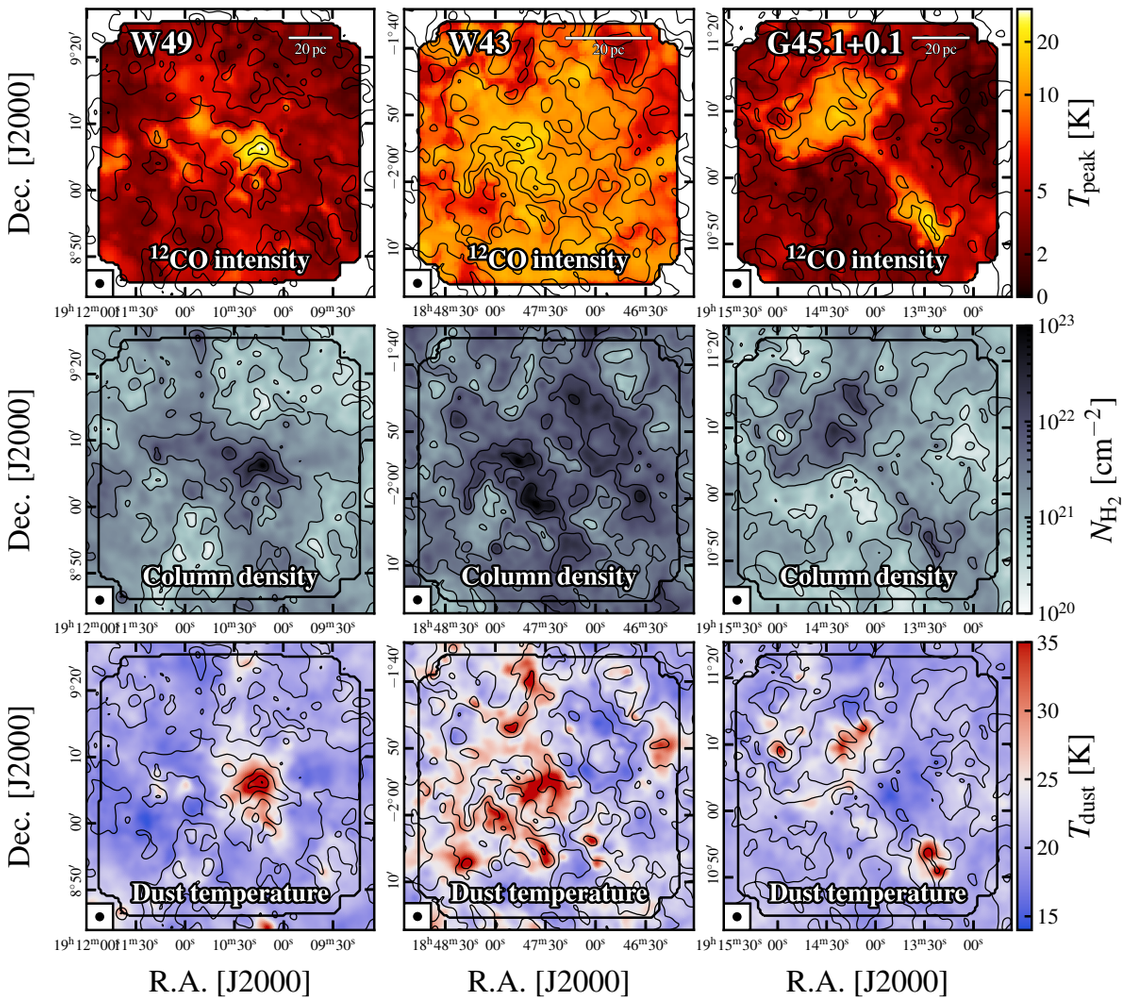
- Brightest N_2H^+ emission seen in spiral arm, coincides with coronation radius of m=3 mode (Colombo+14, Meidt+13), whereas HCN brightest in center (probably driven by AGN, see also Querejeta+16, Matsushita+04, 15)
- Center aside, HCN tracks N_2H^+ reasonably well (factor of ~2), though secondary effects (temperature, optical depth?) matter (see also Jimenez-Donaire+ 19).
- In prep.: direct comparison of cloud properties to HCN/CO, N_2H^+/CO and SFR/<gas>

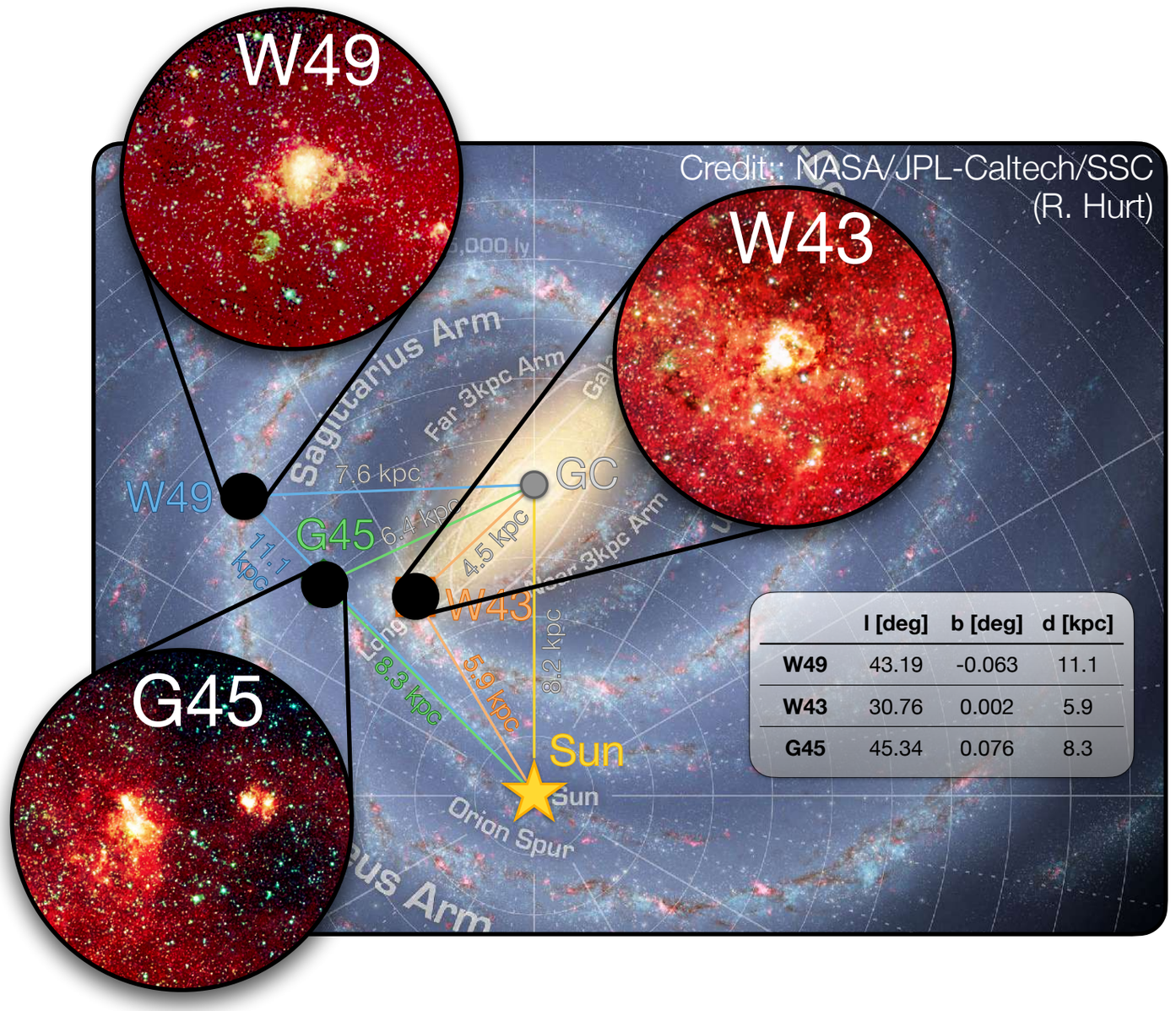
Stuber, Pety, Schinnerer, FB et al. 2023b

pc

Dissecting Local Massive SF Regions

- LEGO (PI J. Kauffmann) maps 30’ x 30’ regions at pc resolution for 25 star forming regions at 3mm. Focus here: 3 massive SF regions W49, W43, G45.1+0.1
- Key goal: link Galactic SF regions to extragalactic observations using same set of tracers





Barnes, Kauffmann, FB+ 2020, Neumann in prep.

pc

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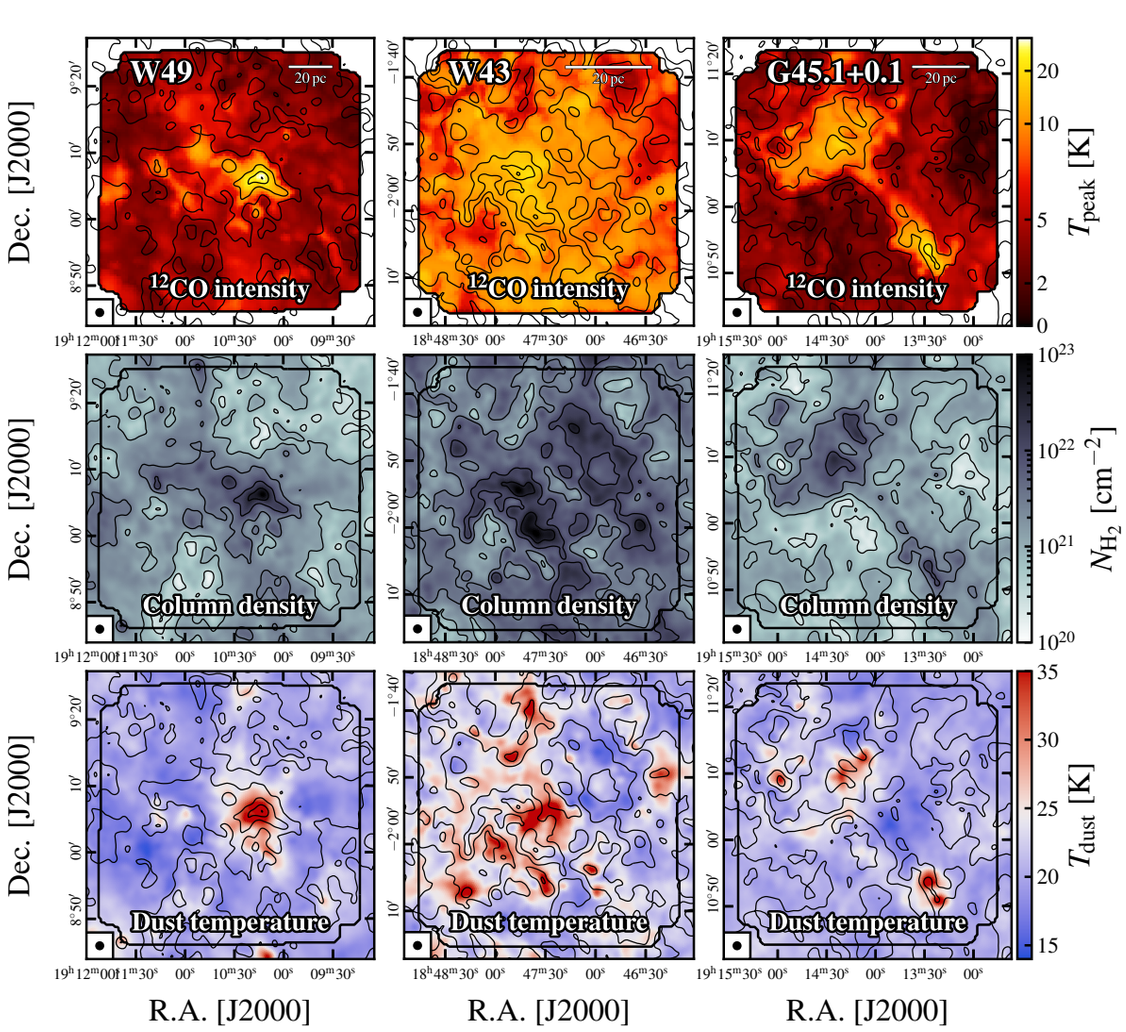
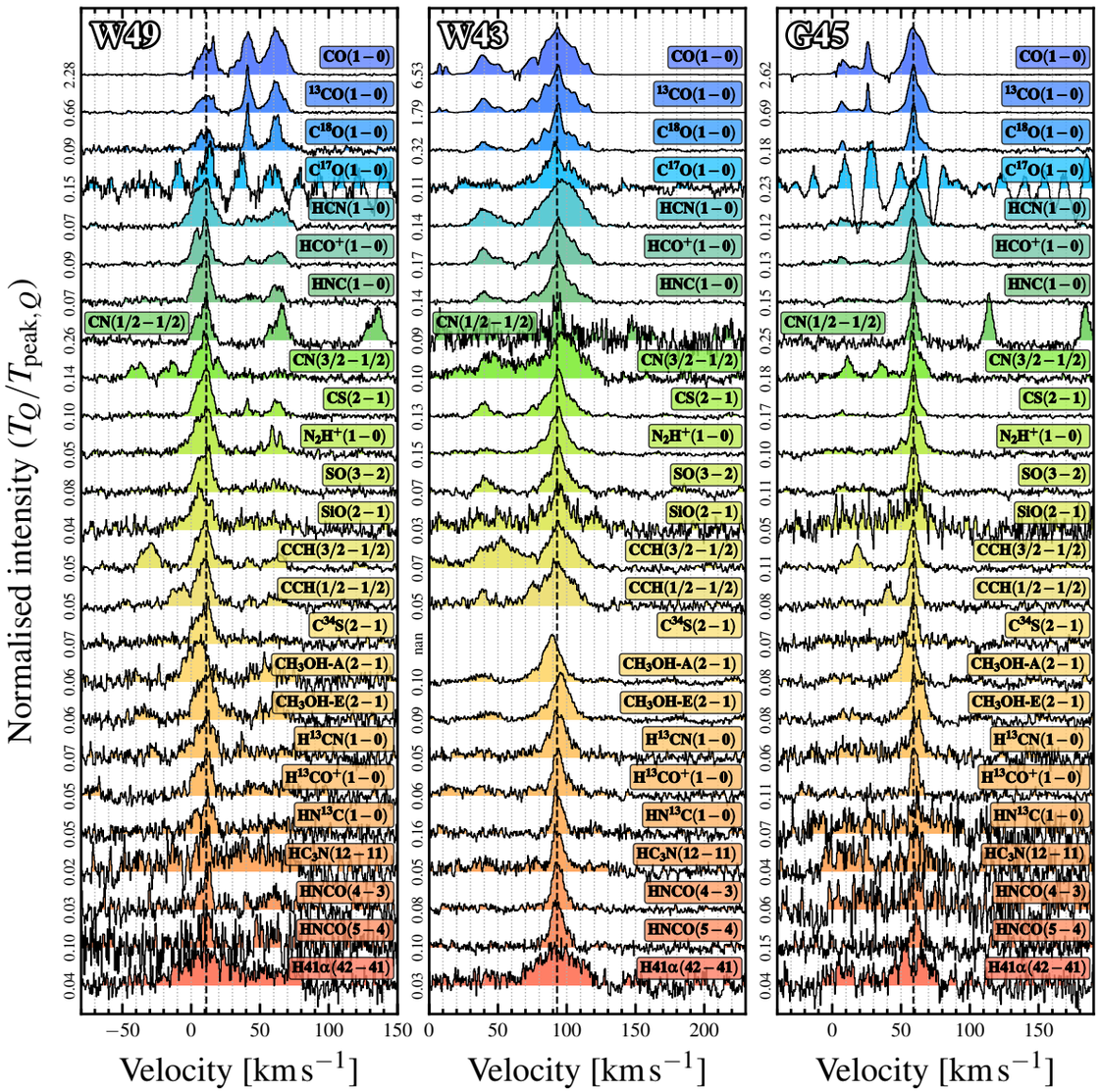
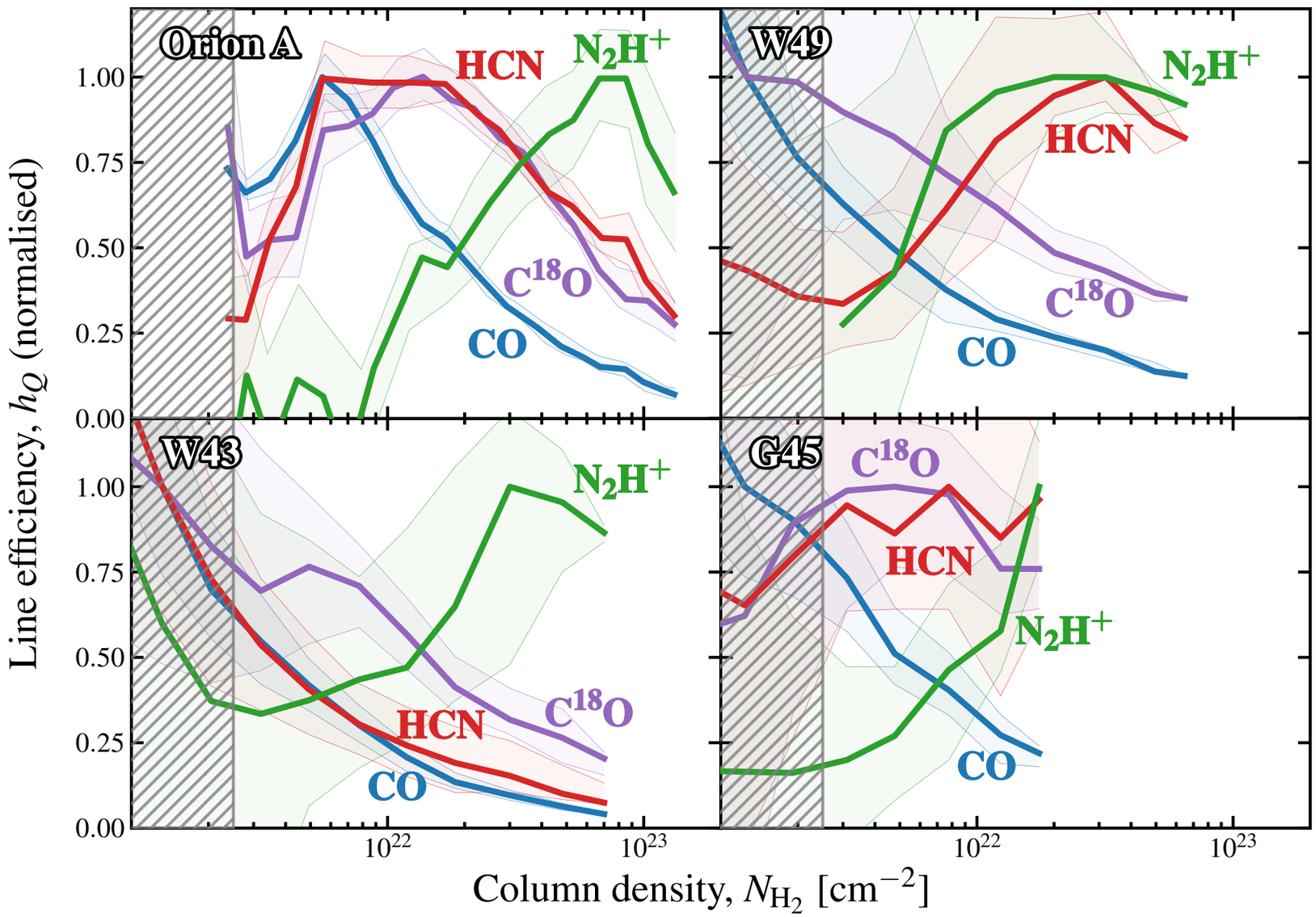




Barnes, Kauffmann, FB+ 2020, Neumann in prep.

Dissecting Local Massive SF Regions

- Once you resolve individual SF regions, at least in our sample picture becomes much more complex.
- Tricky to compare different tracers, emissivity driven by strong local variations (radiation fields, chemistry, etc.)



Barnes, Kauffmann, FB+ 2020, Neumann in prep.

Summary

- Galaxy-wide observations of higher-than-CO critical density molecular lines at a few 100pc to kpc-scale exist for about 30-40 nearby disk galaxies.

- Average gas density distribution and SFR per unit “dense gas” vary with environment across galaxy disks; denser gas seems to be abundant at smaller radii, yet this gas is increasingly inefficiently converted into stars, matching what we see in the Milky Way.

- High-to-low molecular line ratios as proxies for the (beam-scale) density PDF consistently track cloud surface density and dispersion.

- Once looking at substructure of individual clouds / star forming regions, less easy to consistently map molecular line ensemble or ratios to e.g. density across *different* regions.