

Molecular line studies towards nearby galaxies in the 2040's

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EA ALMA 2040 Community workshop July 16, 2026, NAOJ

What we heard yesterday...



With better sensitivity

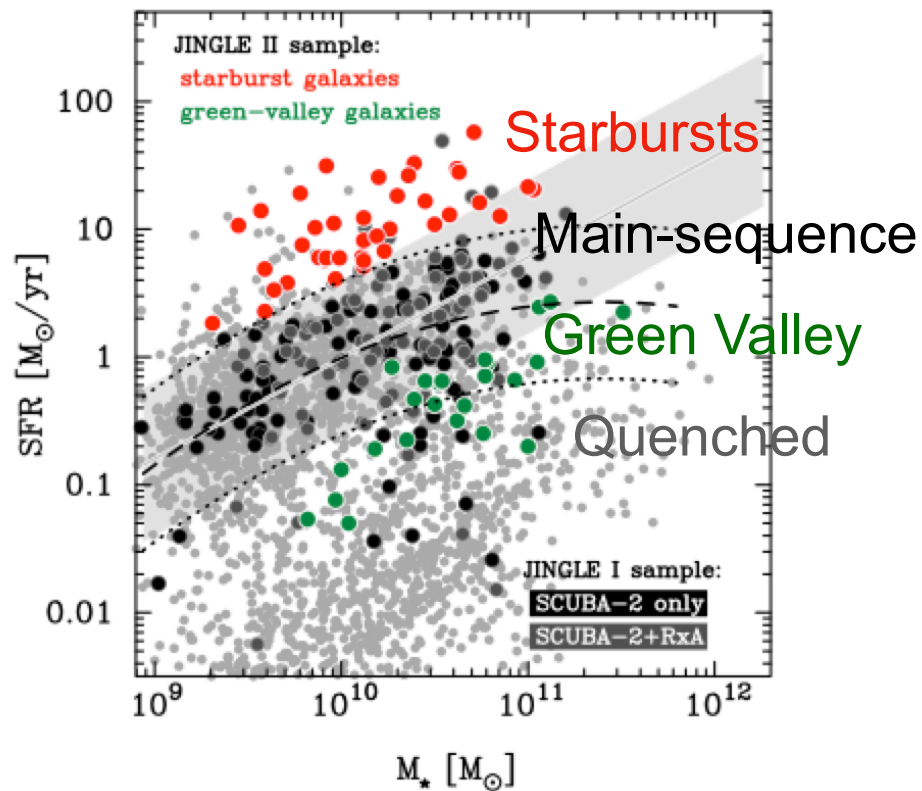
- For sensitivity limited targets
 - More targets
 - Better angular resolution
- Weaker lines
 - Dense gas (HCN, N₂H⁺, etc)
 - Shock tracers, PDR tracers, etc.
- Weaker targets/emission
 - Outflow features
 - Low-metallicity galaxies
 - Gas-poor galaxies

Outlines

- Survey of overall gas content (CO) •
 - kpc scale
 - GMC scale
 - low-metallicity galaxies
- Dense gas studies
- Astrochemical surveys
- AGN vs. starburst diagnostics

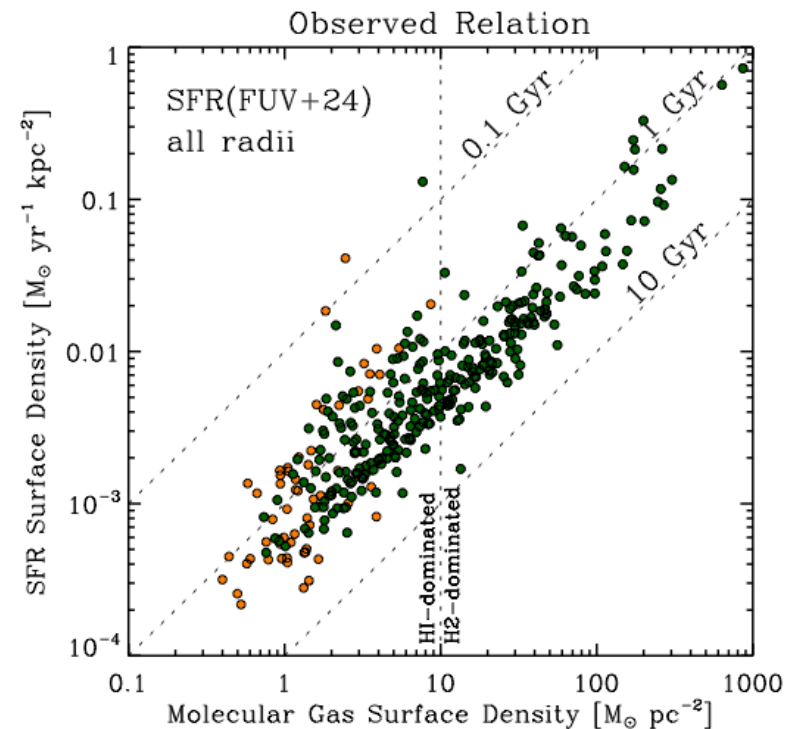
Galaxy molecular gas surveys

Variation of star formation rates



Credit: Candels collaboration

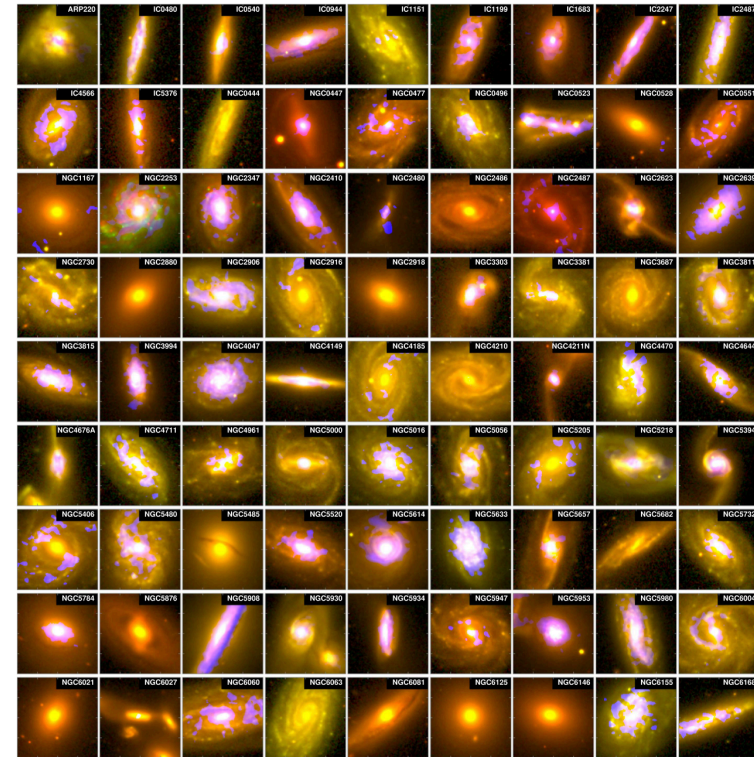
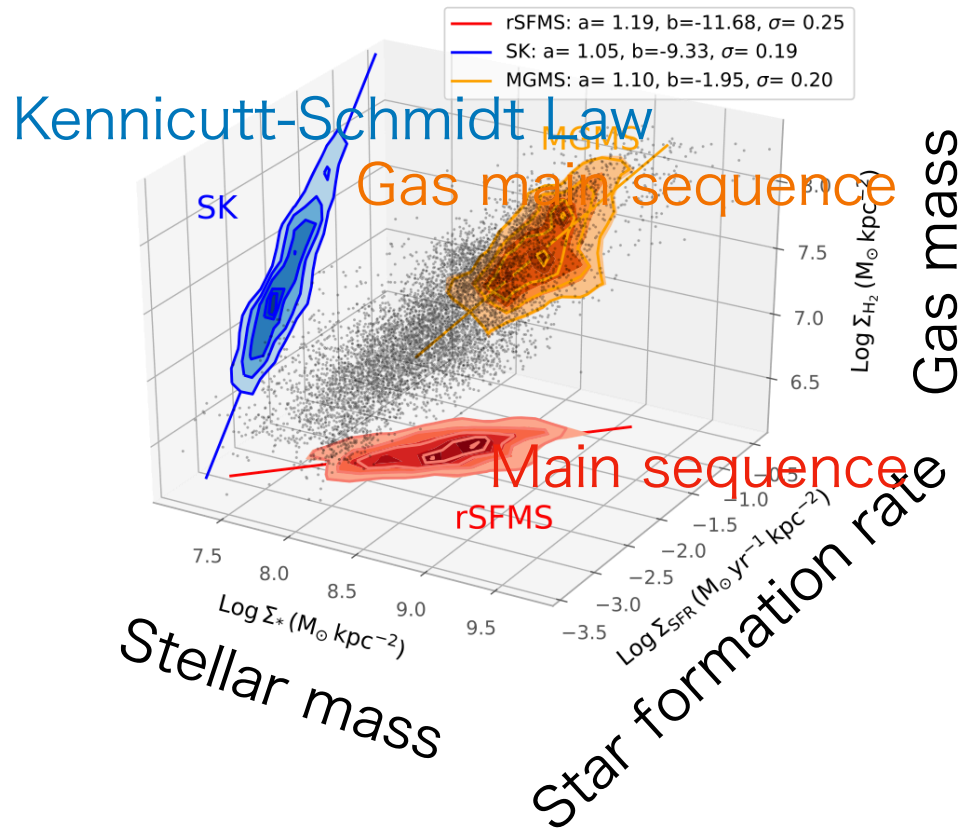
Kennicutt-Schmidt Law



Schruba et al. (2011)

Surveys of galaxies

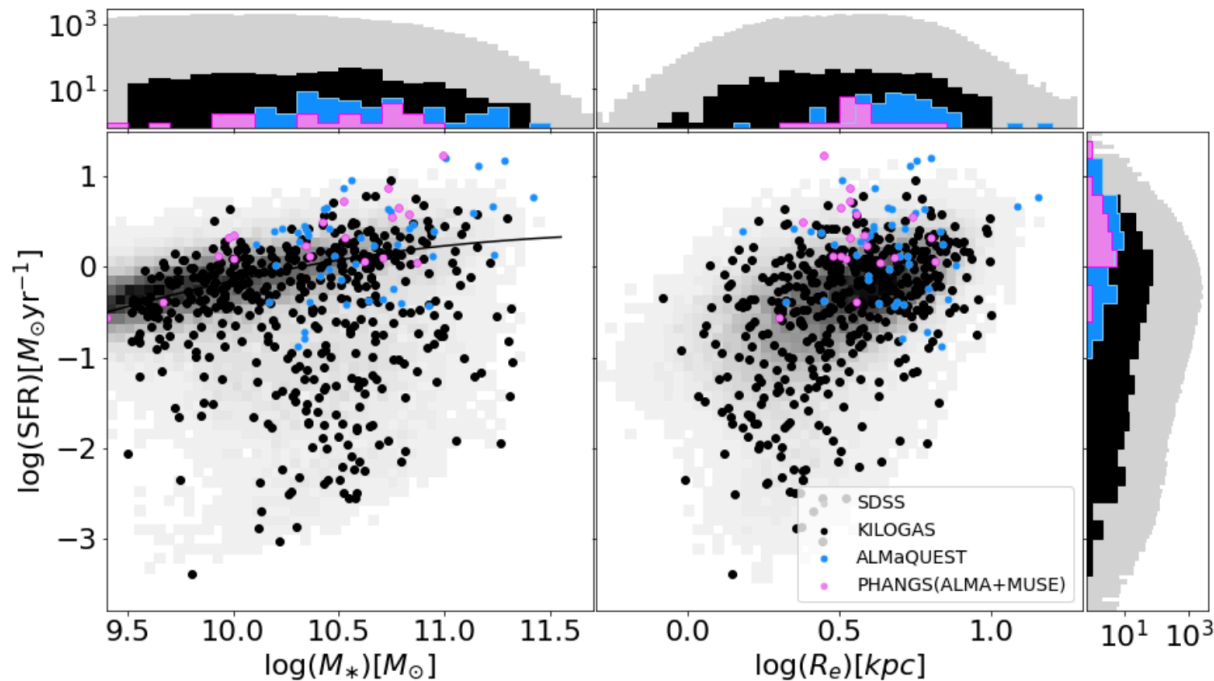
Lin et al. (2019)



Bolatto et al. (2017)

- Optical IFU + CO survey
 - ALMaQUEST (32 galaxies)
 - EDGE-CALIFA (126 galaxies)
 - KILOGAS (~500 galaxies)

Surveys of galaxies

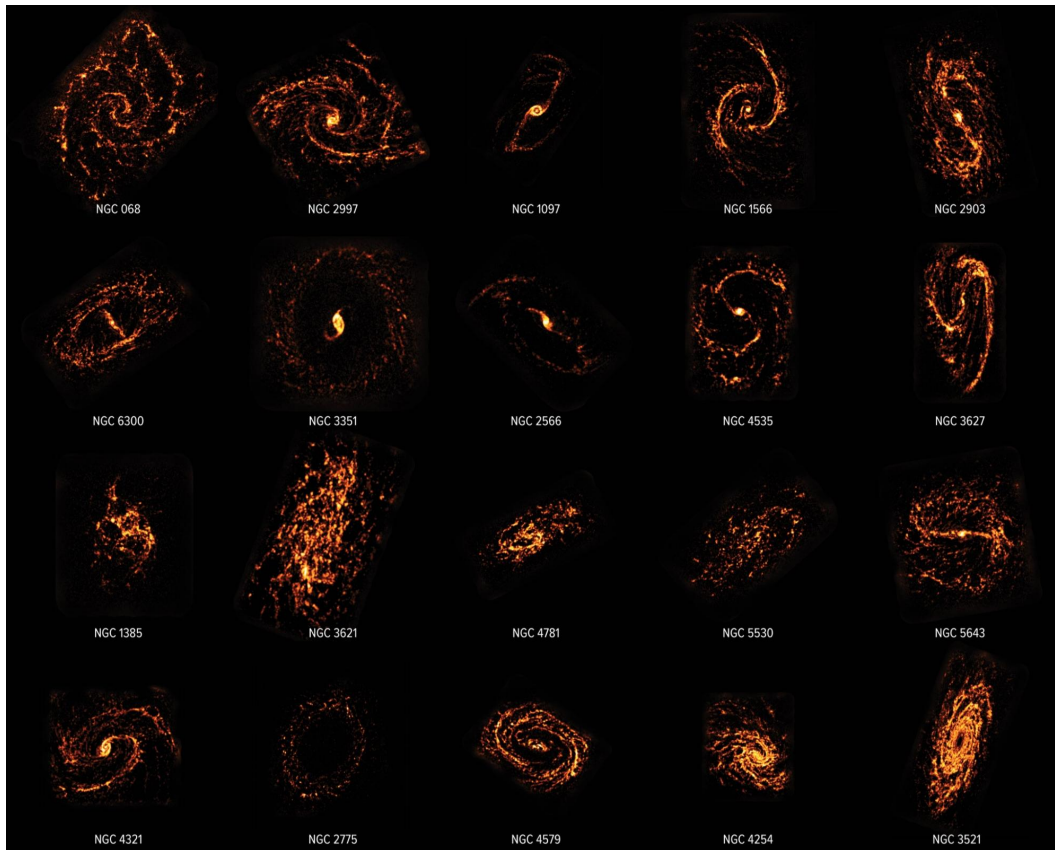


From KLOGAS website, (c) T. A. Davis

- Quenched / green valley galaxies need more time
- Some surveys ongoing, but higher sensitivity would help
→ **ALMA2040**

Surveys of giant molecular clouds

e.g., PHANGS survey

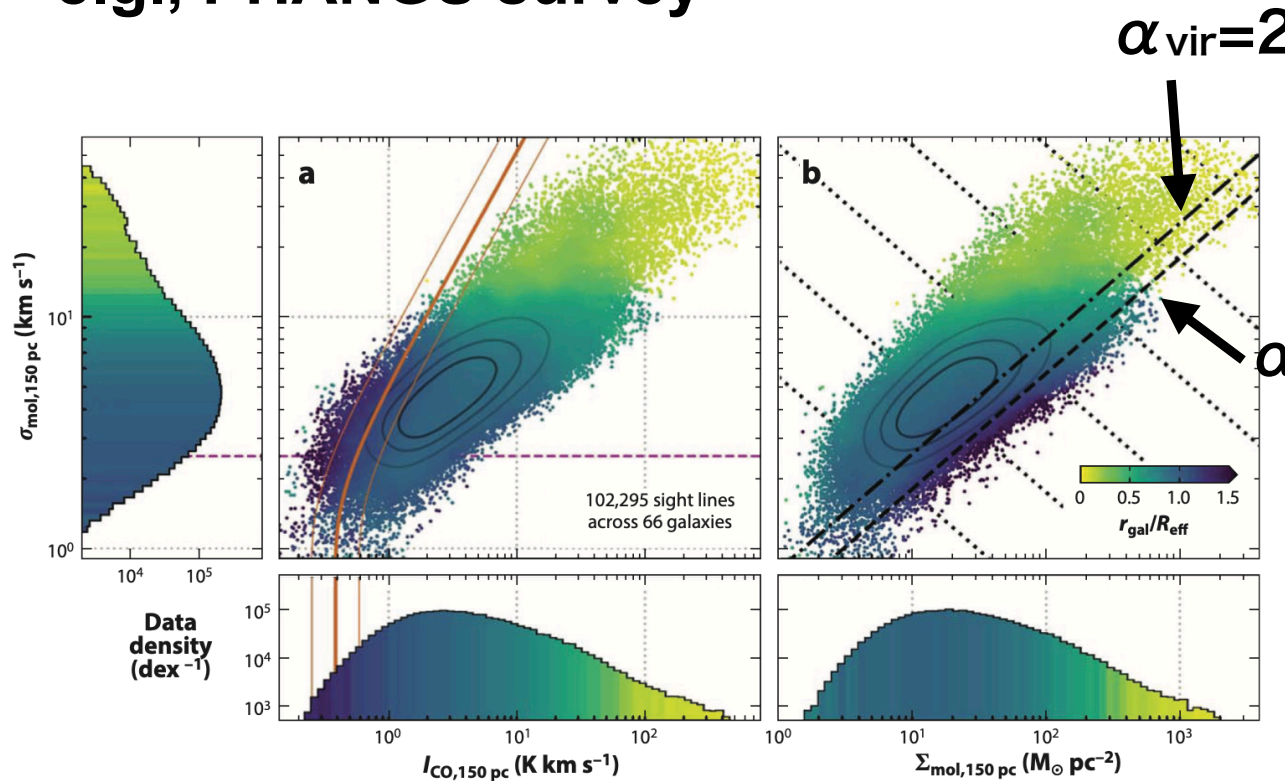


- ALMA surveys of 74 galaxies in the 100pc scale (scale of giant molecular clouds)
- Main-sequence, nearby ($d < 27$ Mpc, relatively face-on)
- MUSE, JWST, HST data for some of the sample

Credit: ALMA (ESO/NAOJ/NRAO)/PHANGS, S. Dagnello (NRAO)

Surveys of giant molecular clouds

e.g., PHANGS survey



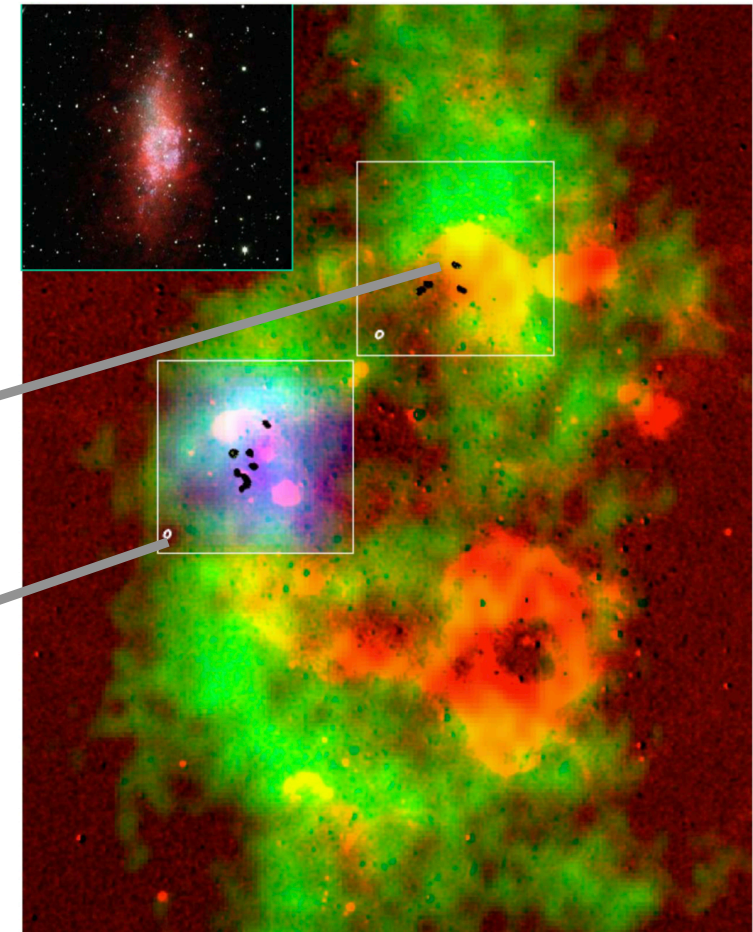
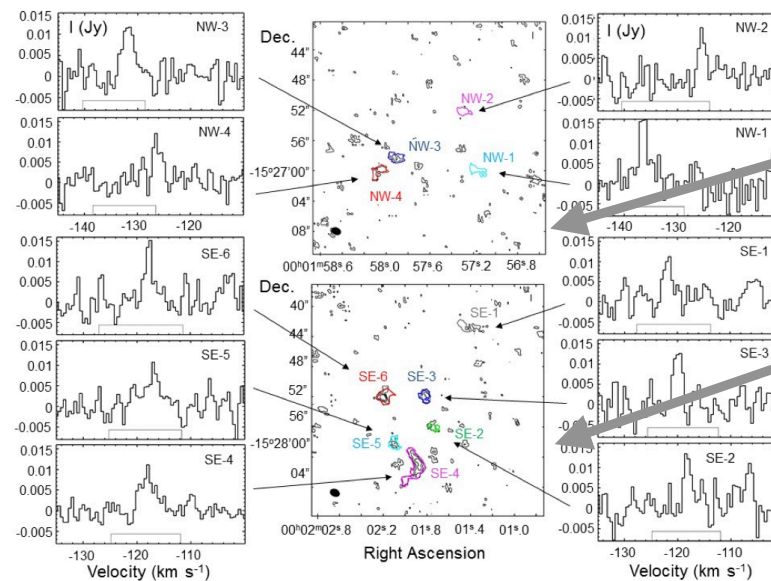
- Cloud mass, dispersion
→ Most clouds are close to virial equilibrium
- New ALMA large program 10pc-scale studies on-going (NGC 253, 300, 5236, and 7793)

Sun et al. (2020)

Low-metallicity galaxies

- Smaller clumps of CO clouds
- With ALMA2040
 - More samples of low-metallicity galaxies
- ➡ Environmental dependence
- ➡ Obtain high-z analogue template

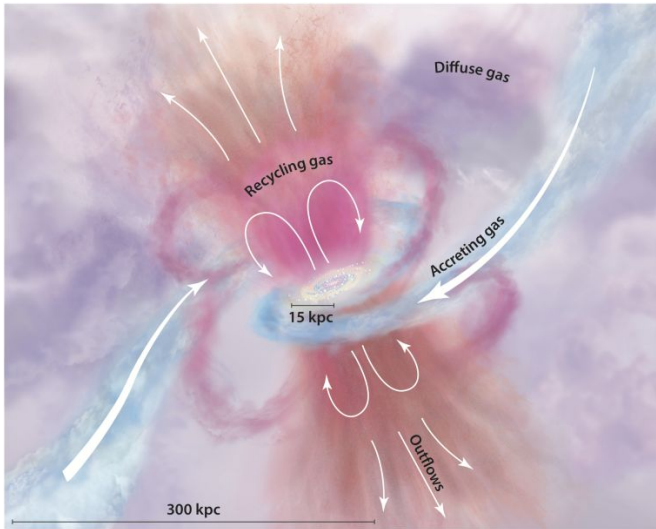
Molecular clumps



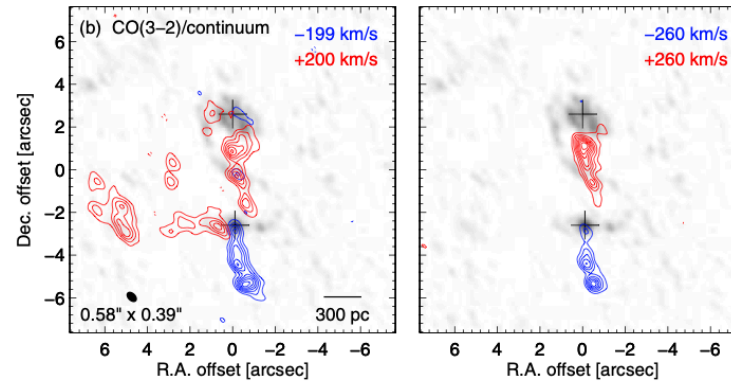
WLM (d~1 Mpc)

HI, H α , CII

Outflows

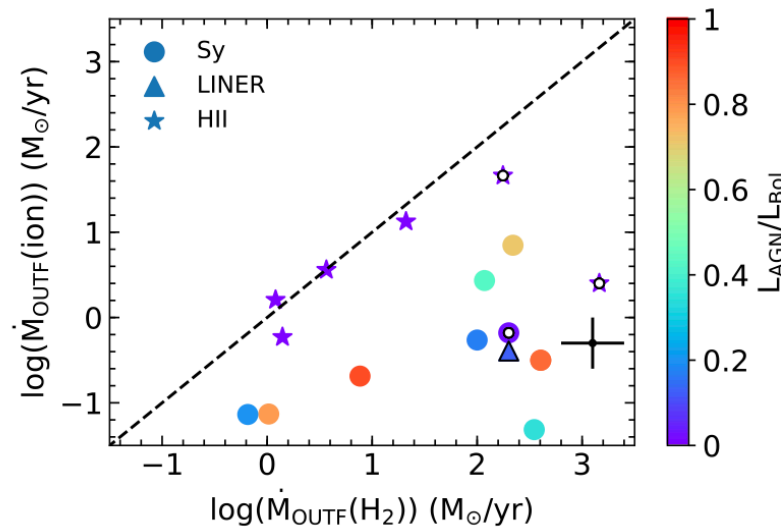


Tumlinson et al. (2017)



- High-velocity component needed to confirm outflows
- Weaker emission

Sakamoto et al. (2014)



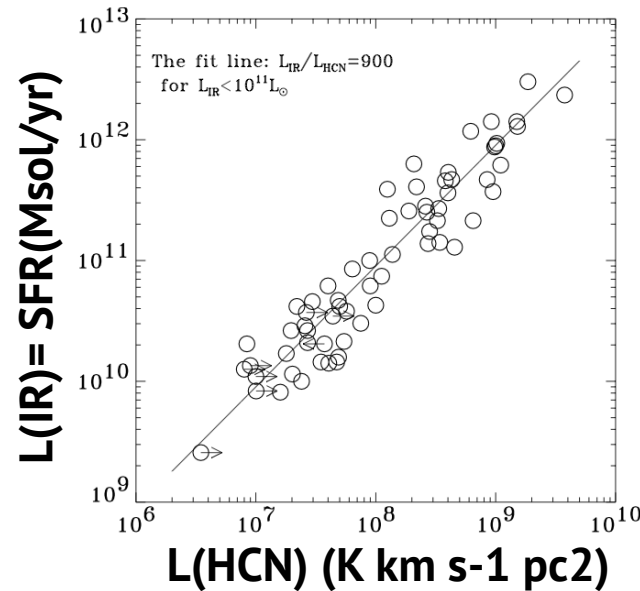
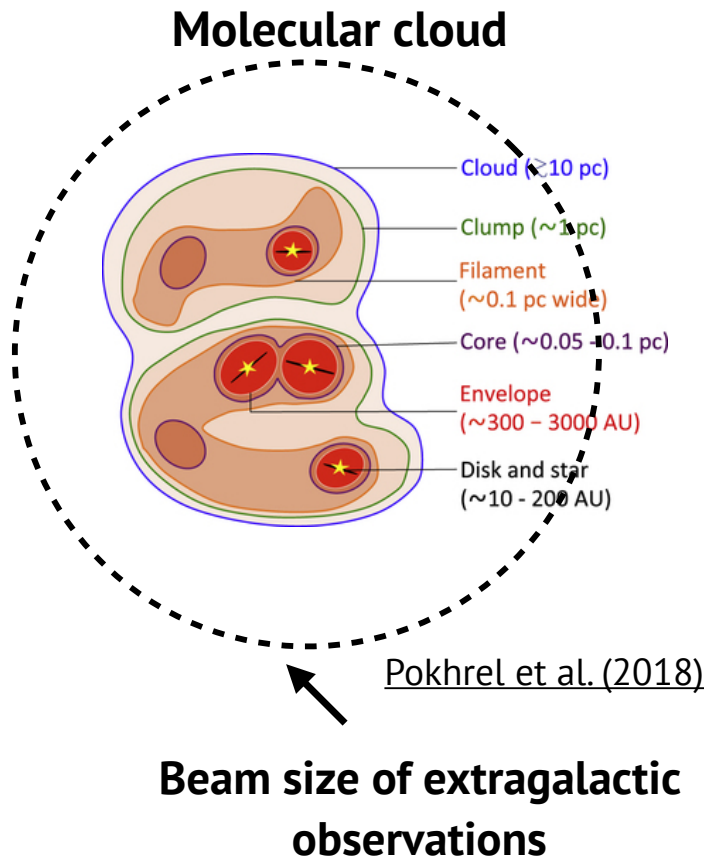
- Survey ~ 45 galaxies
- AGN-driven outflows -> higher molecular fraction

Fluetsch et al. (2019)

Dense gas studies

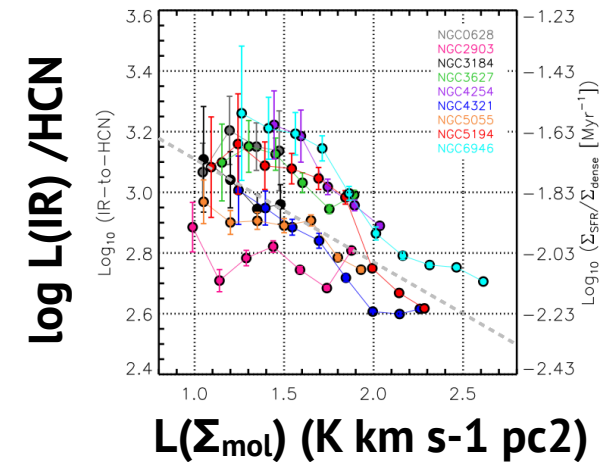
Dense gas tracer and star formation

Dense gas distribution



- HCN(1-0) - high critical density ($\sim 10^6 \text{ cm}^{-3}$)
- SFR-dense gas correlation

Gao & Solomon (2004) See also *Usero+(2015)* *Jiménez-Donaire+(2019)*

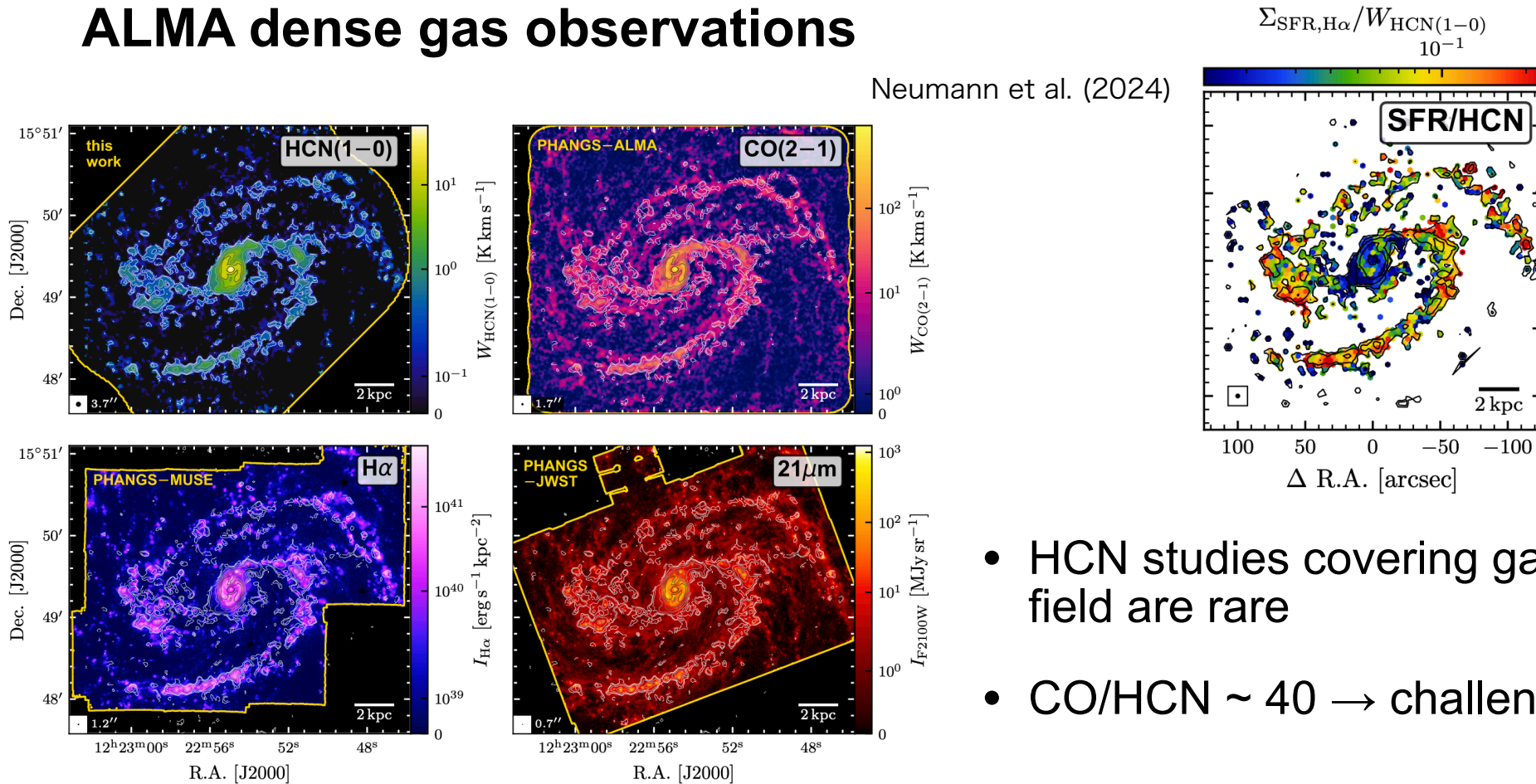


- Dense-gas star formation efficiency not constant

Dense gas tracer and star formation

ALMA dense gas observations

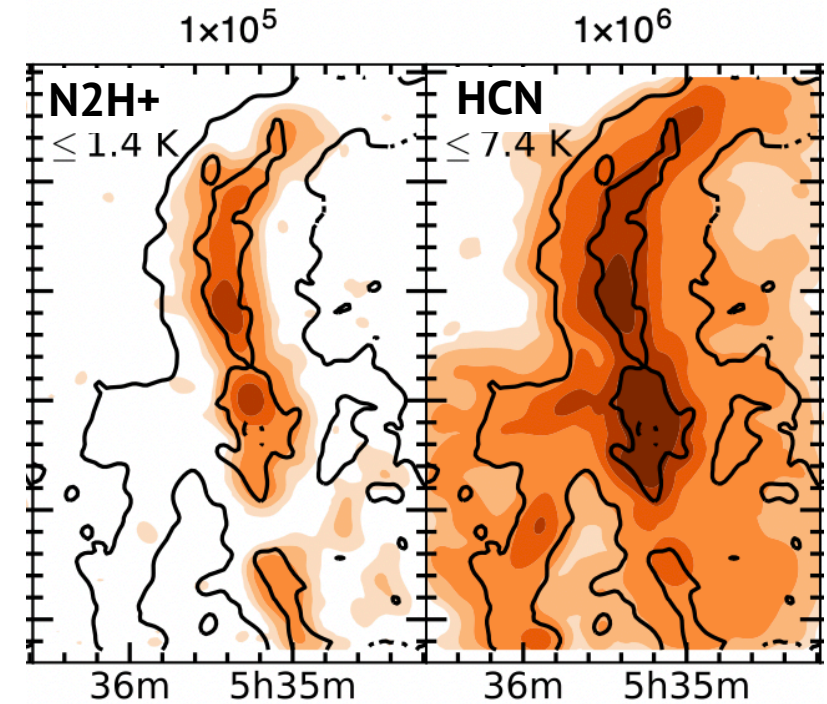
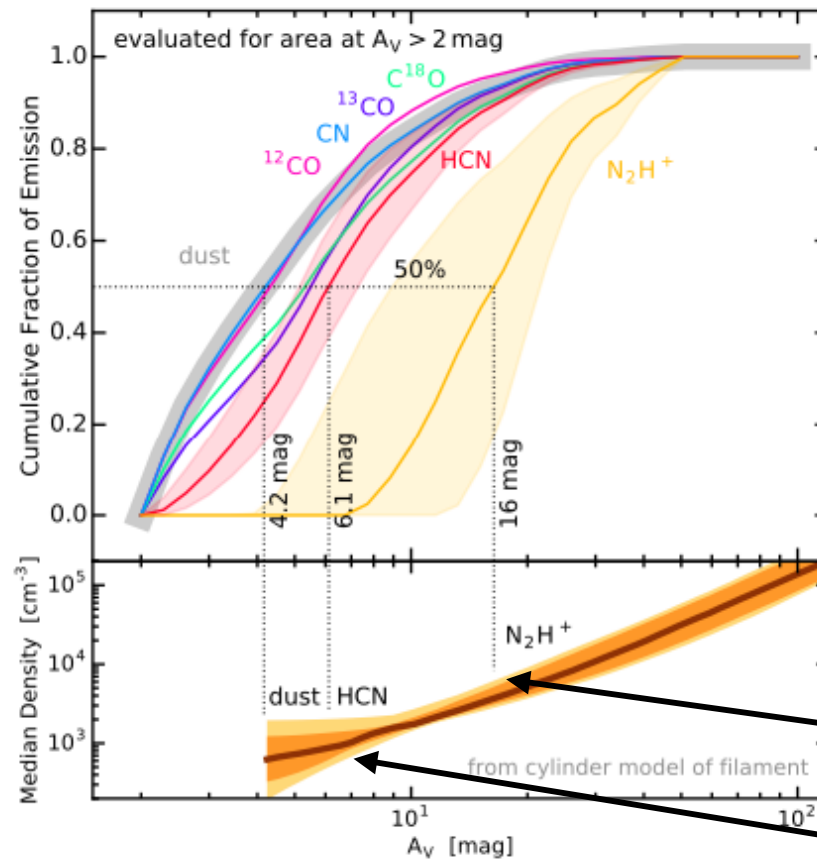
Neumann et al. (2024)



- HCN studies covering galaxy-scale field are rare
- CO/HCN $\sim 40 \rightarrow$ challenging

An alternative dense gas tracer N₂H⁺

Orion A



N_2H^+ : $n \sim 4 \times 10^3 \text{ cm}^{-3}$

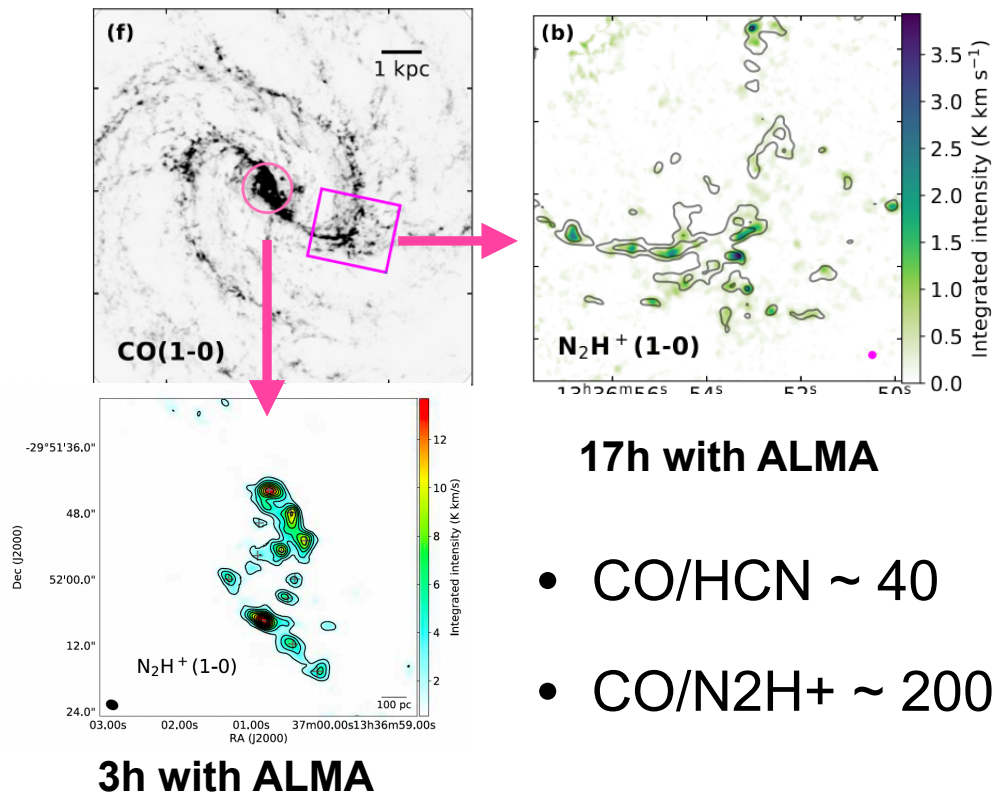
HCN : $n \sim 9 \times 10^2 \text{ cm}^{-3}$

Kauffmann et al. (2017)

An alternative dense gas tracer N_2H^+

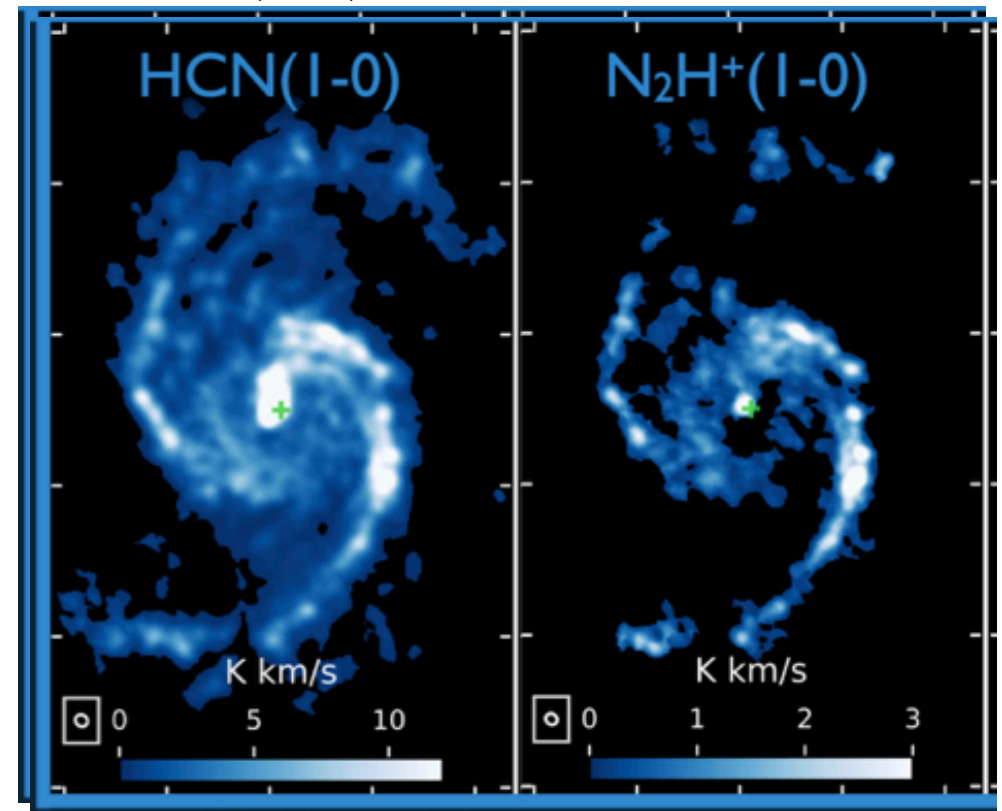
M83

Harada et al. (submitted)



M51: 200h of NOEMA

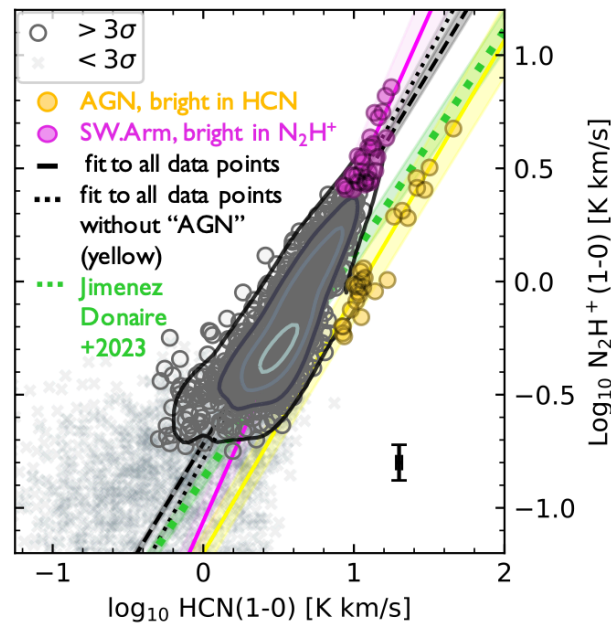
Stuber et al. (2025)



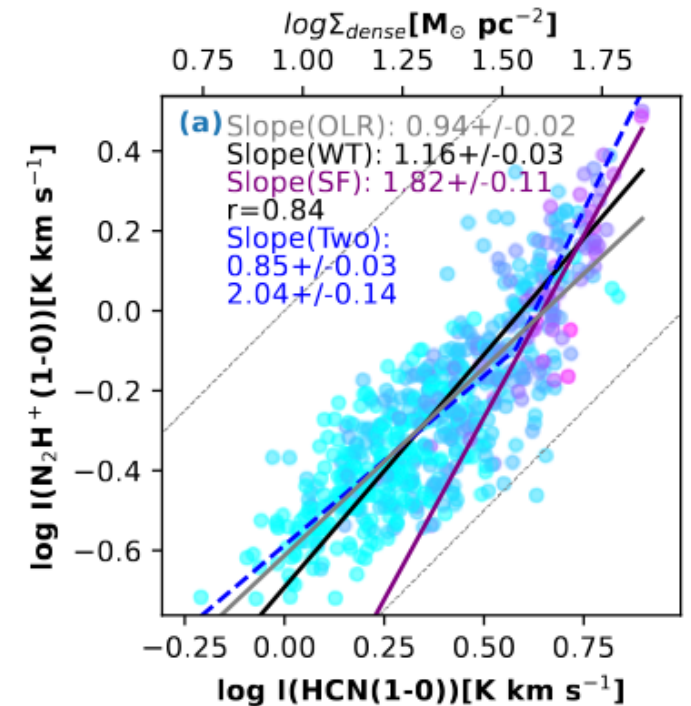
An alternative dense gas tracer N_2H^+

- N_2H^+ is preferentially emitted at higher column density regions
- This trend only seen with interferometric data →
- high resolution necessary

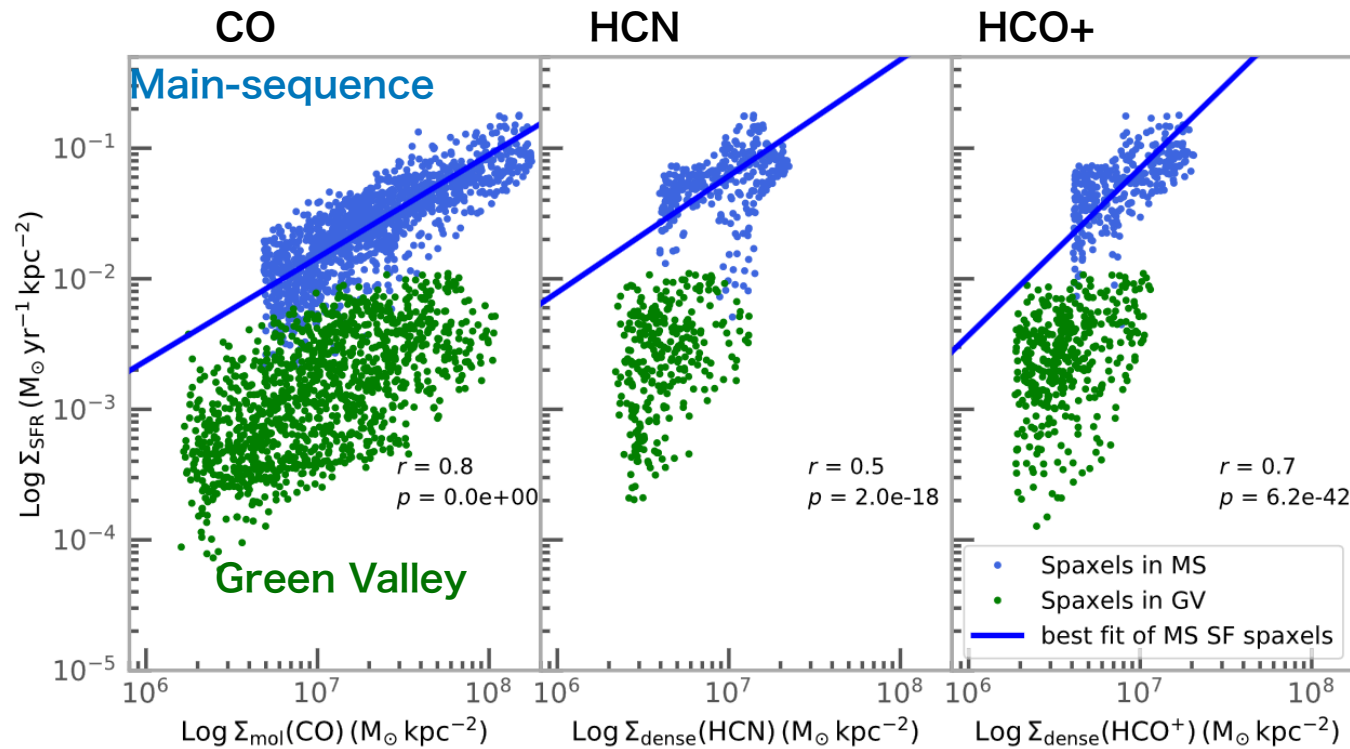
Stuber et al. (2023)
M51 125-pc resolution



Harada et al. (submitted)
M83 (bar-end) 50-pc resolution

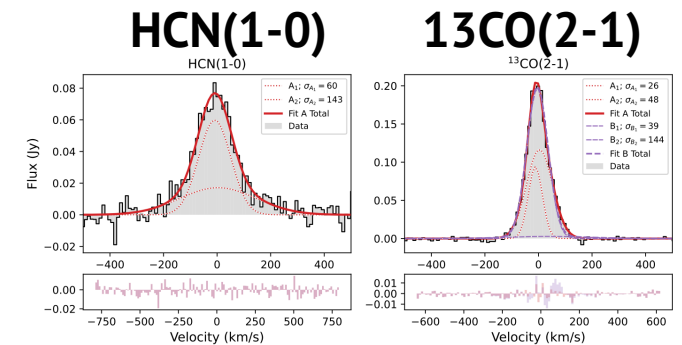


Dense gas survey in green valley/quenched galaxies



Lin, ...NH et al. (2024)

Post-starburst galaxy NGC 1266

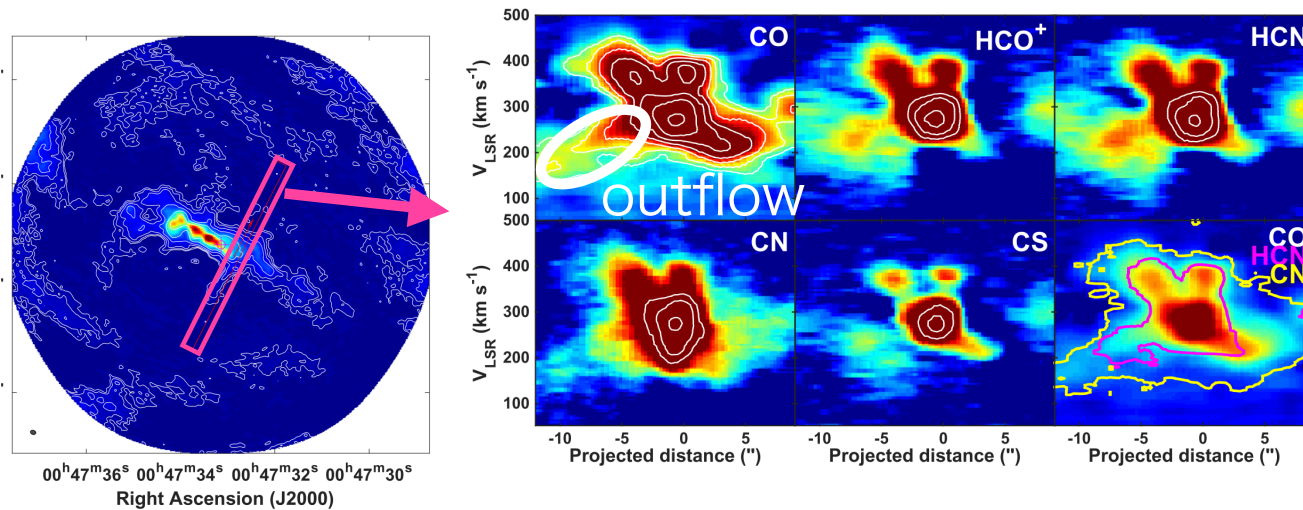


Otter, ...NH et al. (2026)

- Dense gas still exist in green valley or quenched galaxies
- Yet star formation rates are lower

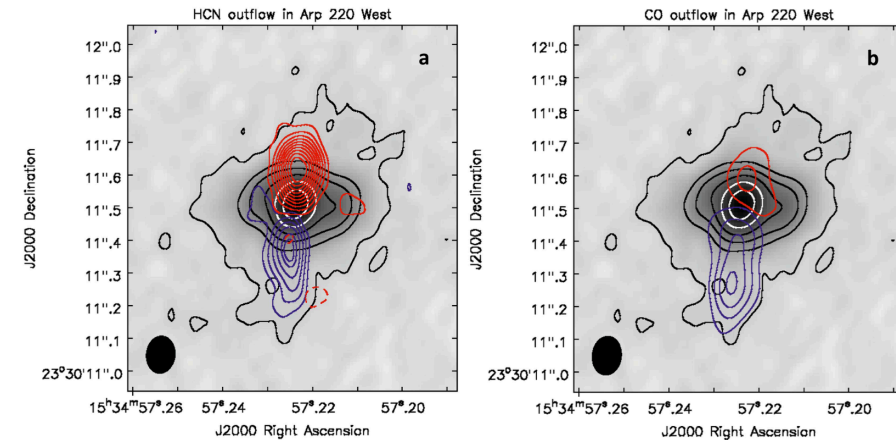
Dense gas in outflows

Starburst galaxy NGC 253 Walter et al. (2017)



- Now HCN detections in outflows are ubiquitous
- Outflows are supposed to be hot and tenuous...
- Higher sensitivity of ALMA2040 can help get a larger sample or resolve structure

ULIRG Arp 220 Barcos-Munoz et al. (2018)

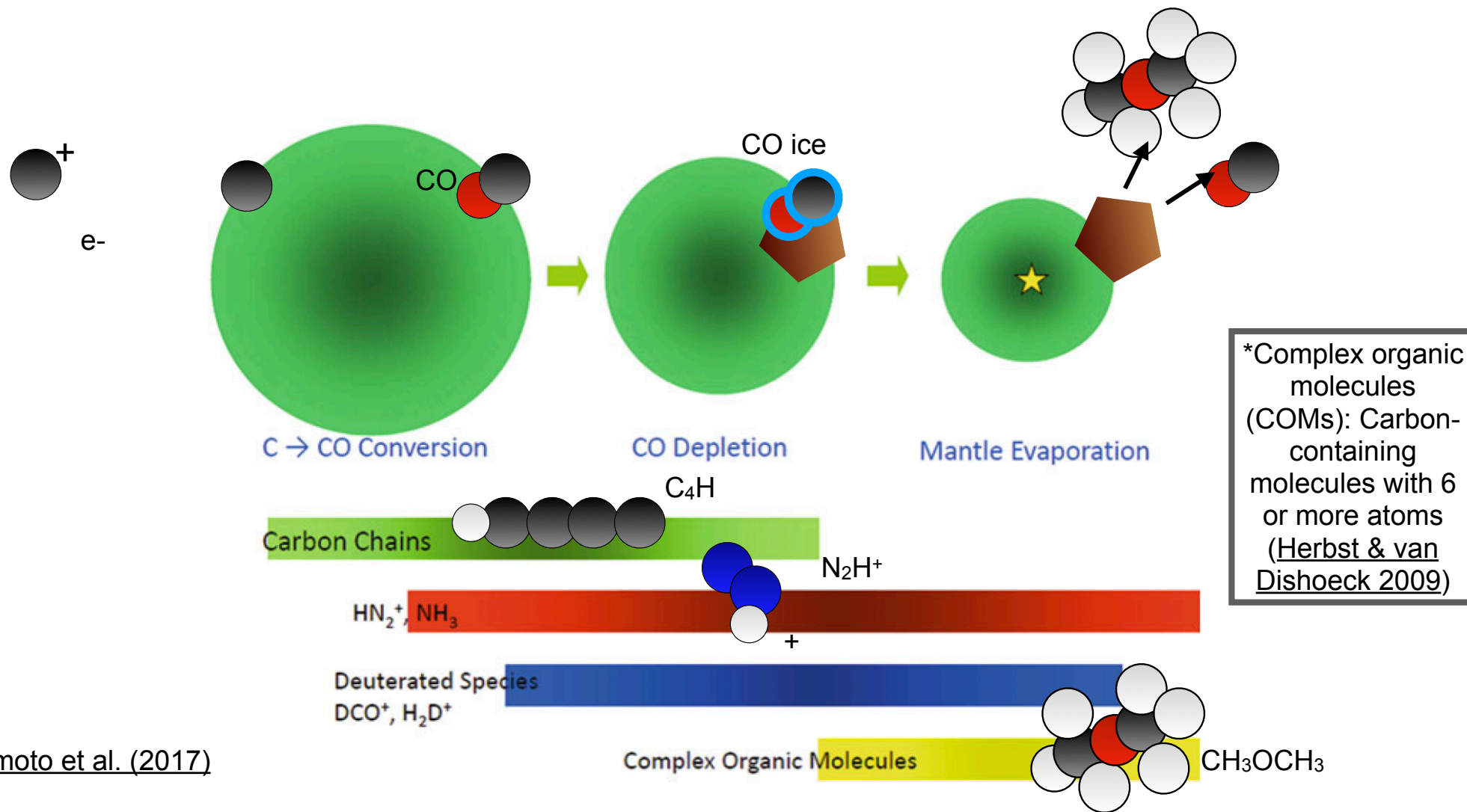


Quasar Mark 231 Aalto et al. (2015),

LIRG NGC 3256 Harada et al. (2018), Michiyama et al. (2020)

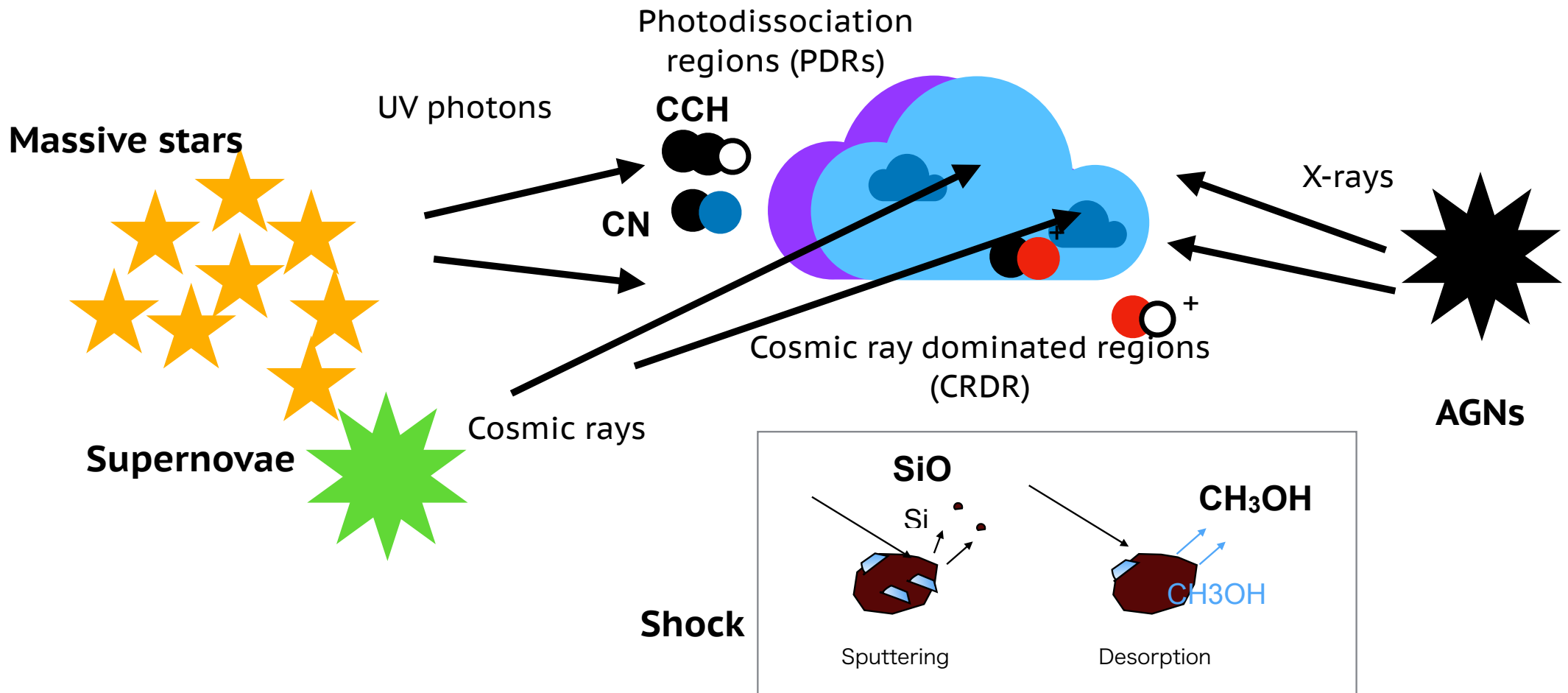
Astrochemical surveys

Molecular tracers - evolution of star formation



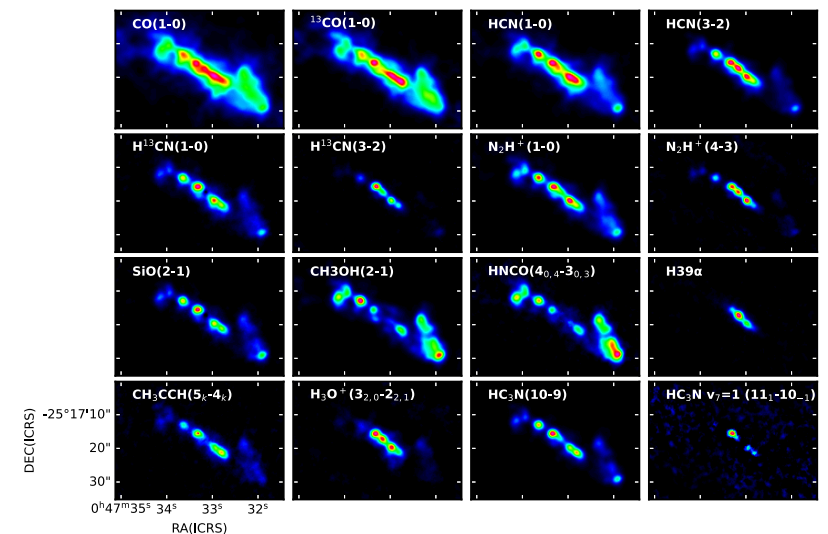
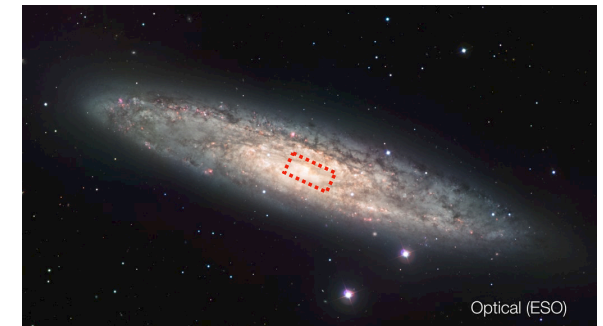
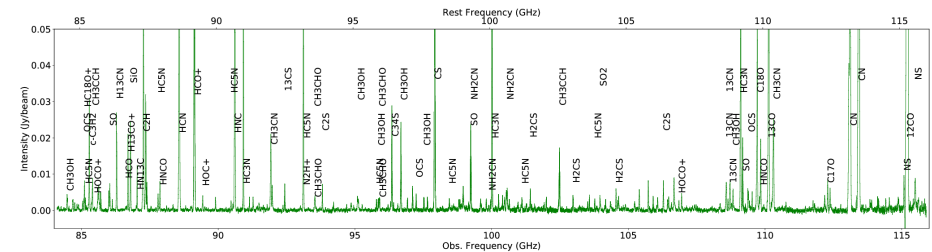
Yamamoto et al. (2017)

Molecular tracers - environmental dependence



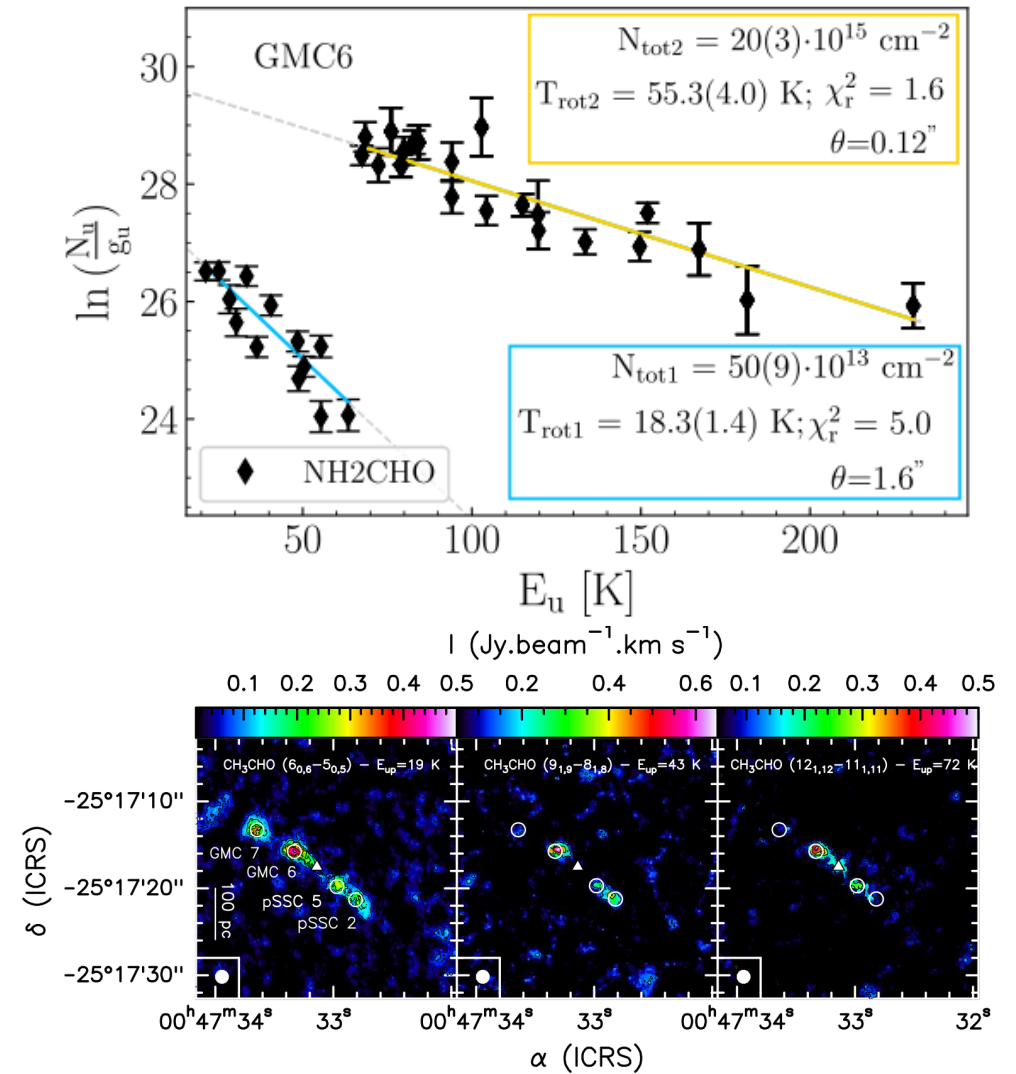
The ALCHEMI survey

- ALMA Cycle 5 Large program (PIs: Martin, Harada, Mangum; Martin et al. 2021)
- Target: NGC 253 ($d=3.5$ Mpc, $SFR \sim 2M_{\odot}/yr$)
- Mapping of the central molecular zone ($50'' \times 20'' = 850 \times 340$ pc)
- High-sensitivity observations (~ 20 mK)
- Angular resolution $1.6'' (= 27$ pc)
- Requested: $1''$, 50mK
- $t(\text{on-source})/t(\text{tuning}) \sim 5\text{hr}$ in Band 3 (85-116 GHz)
- **With ALMA2040, surveys towards other galaxies possible**



COMs in starbursts

- Complex organic molecules (COMs): C-bearing molecules with 6 or more atoms
- COMs can originate from protostars or shocks
- Two excitation components found

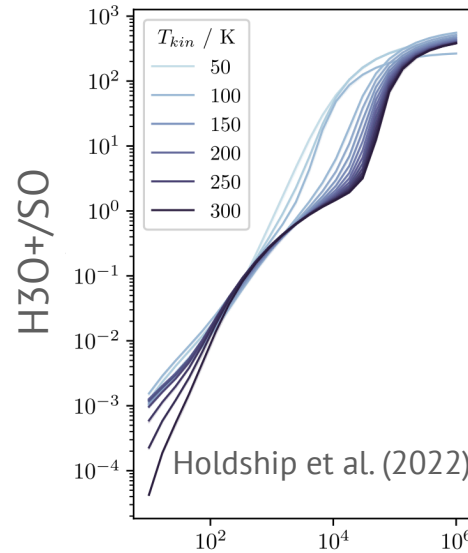


Bouvier et al. (2025)

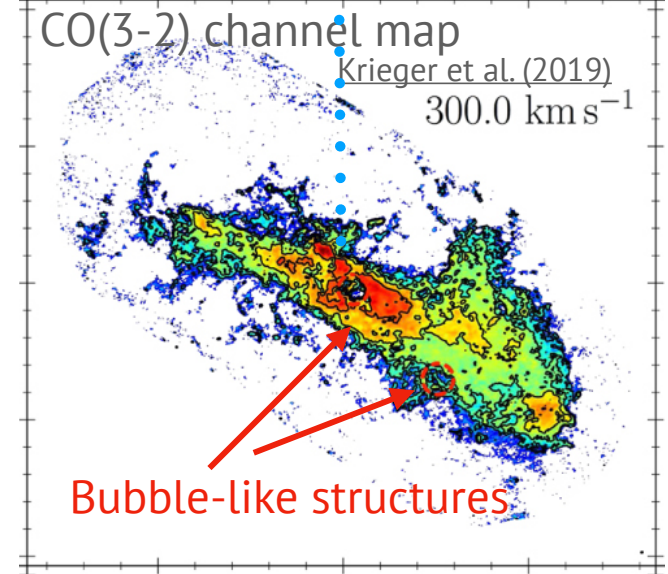
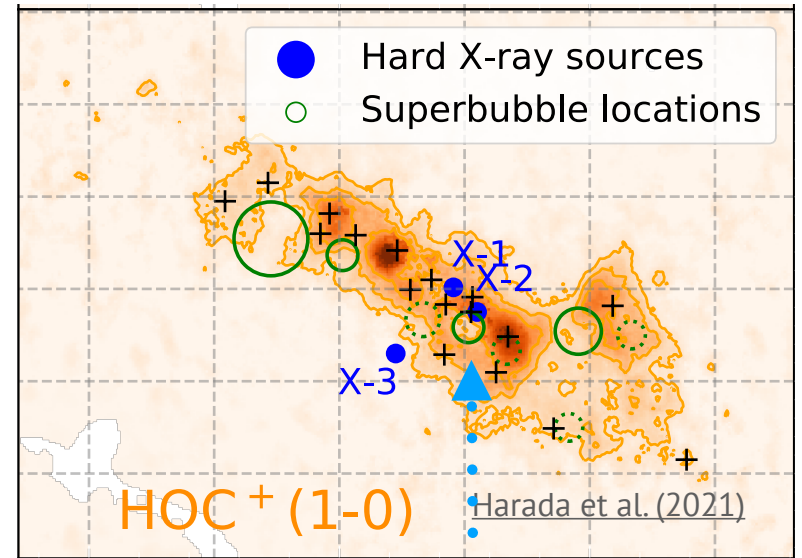
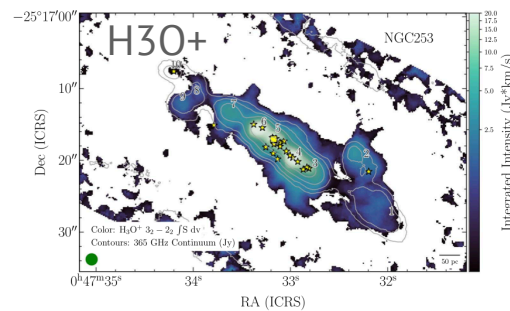
Starburst and feedback

Cosmic-ray dominated regions

- Cosmic-ray ionization rates likely higher in starburst galaxies
- Cosmic-ray ionization rate likely > 1000 times higher than Galactic disk clouds
- HOC+(1-0) tracing CRDRs show feature of superbubble

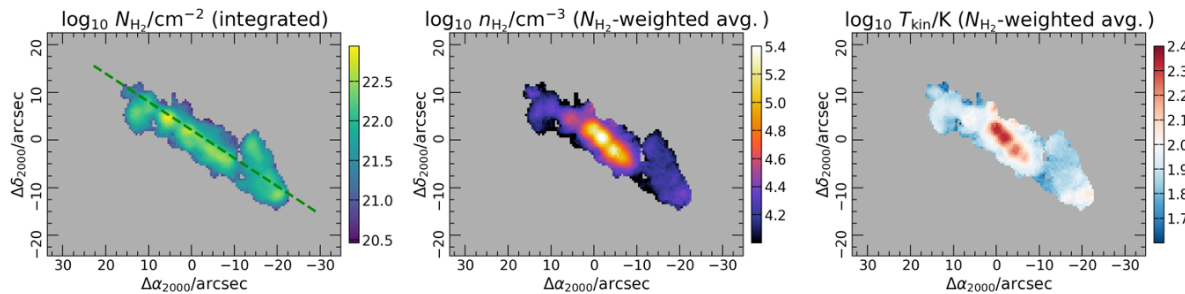
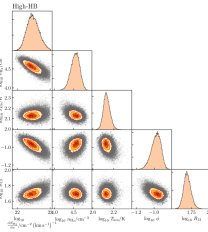


Cosmic-ray ionization rate ζ/ζ_0



Estimation of physical conditions

- Large-velocity gradient + hierarchical Bayesian method to derive density, temperature, and column densities (method: [Tanaka et al. 2018](#))
- Better constraints from **H₂CO as a T probe** + transitions of HCN, HCO⁺, HCN, HC₃N, and isotopologues

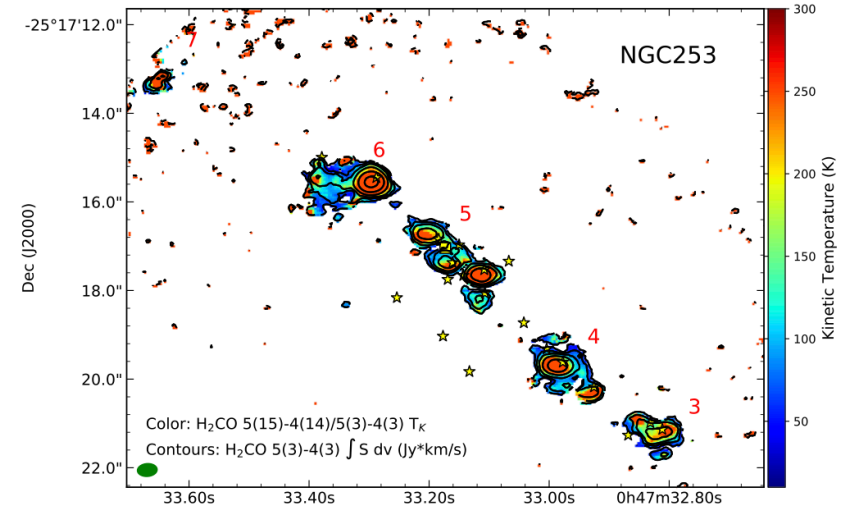
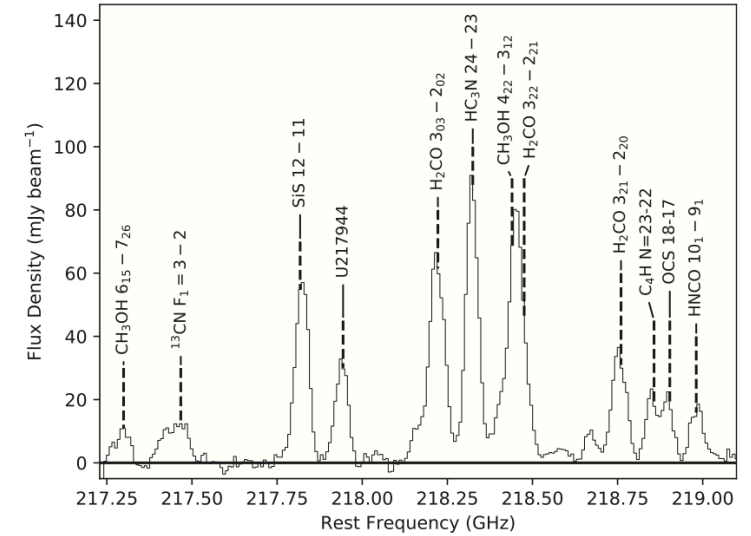


column density

volume density

temperature

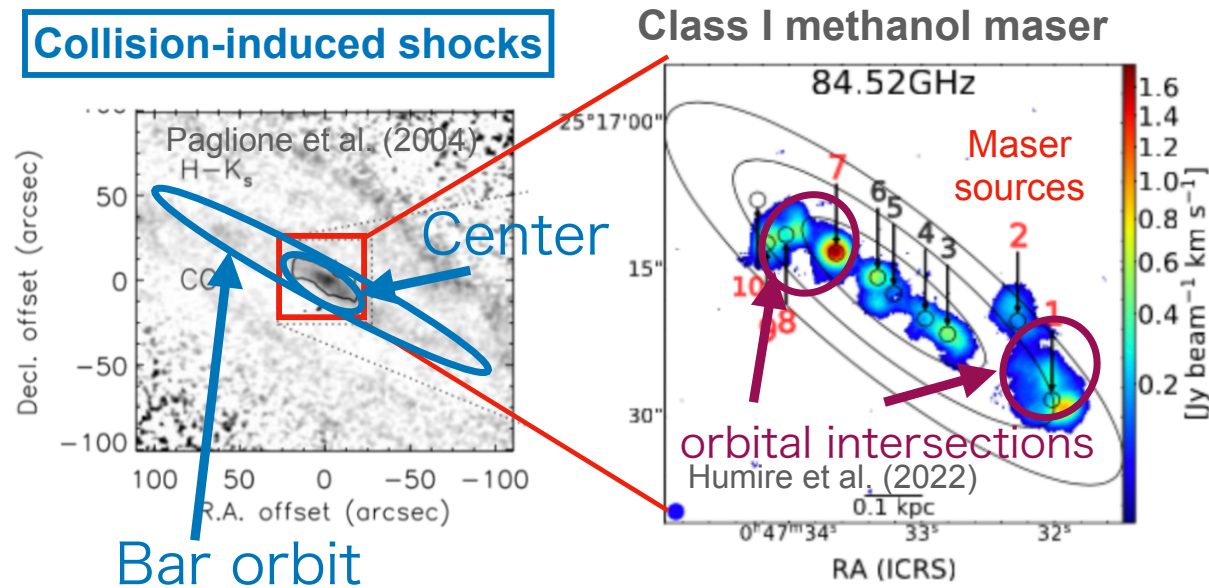
Tanaka et al. (2024)



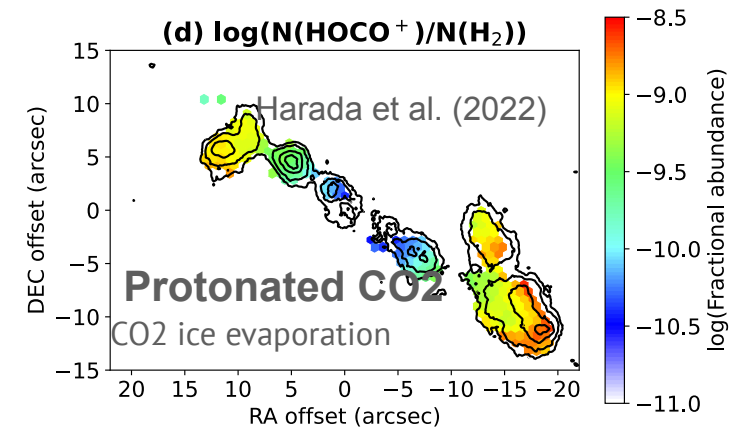
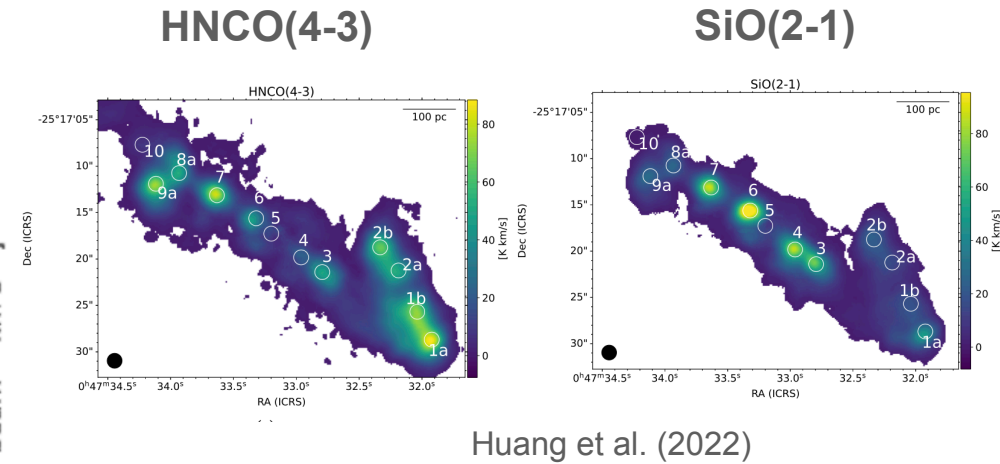
Mangum et al. (2019)

Shocks at orbital intersections, from star formation

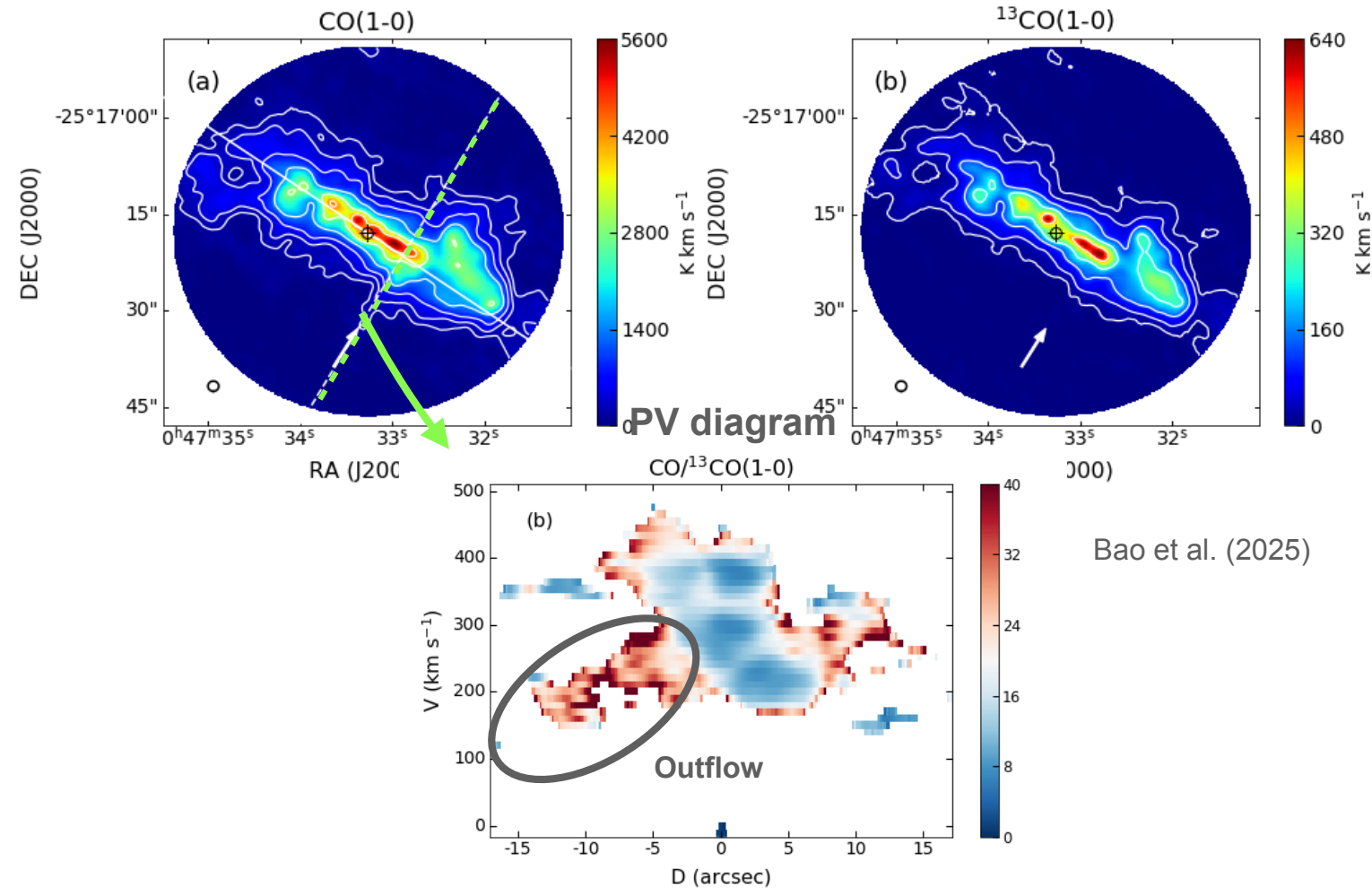
Collision-induced shocks



- Class I methanol masers at orbital intersections
- SiO, HNCO, protonated CO₂ at same locations



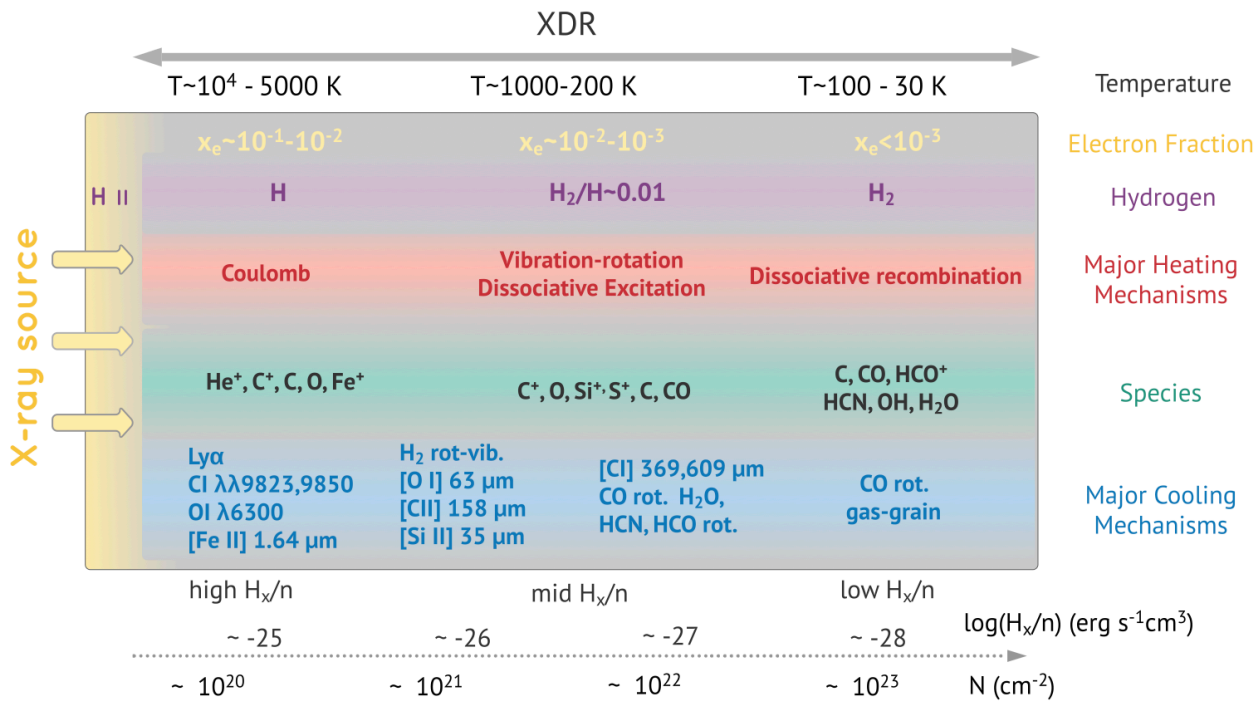
Outflow optical depth, outflow mass



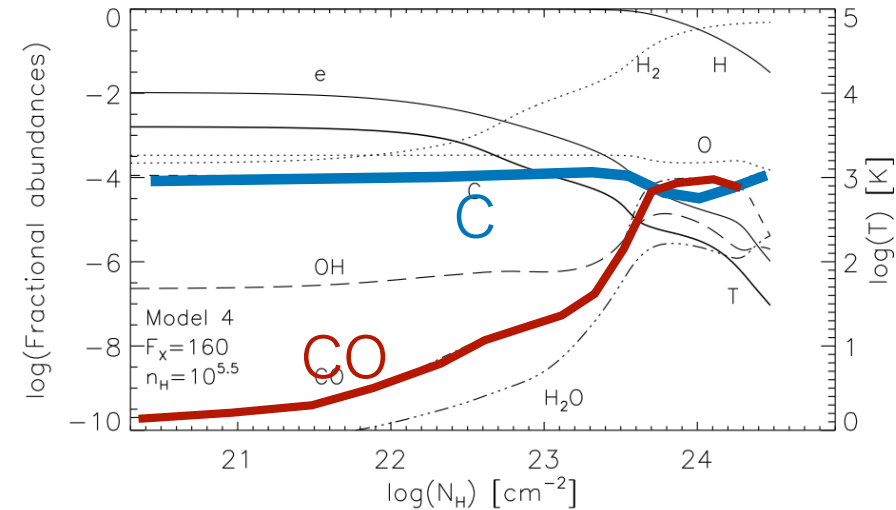
- $^{12}\text{C}/^{13}\text{C} \sim 20$ from Martin et al. (2019), ~ 40 from Tang et al. (2019) in NGC 253
- $^{12}\text{CO}/^{13}\text{CO}$ (1-0) ratios as high as $^{12}\text{C}/^{13}\text{C}$ ratio
- ^{12}CO (1-0) must be optically thin
- Important in constraining the outflow mass

AGN diagnostics

AGN feeding and feedback



Wolfire et al. (2022) based on Maloney et al. (1996)
 See also *Meijerink et al. (2007)*



Meijerink and Spaans (2005),

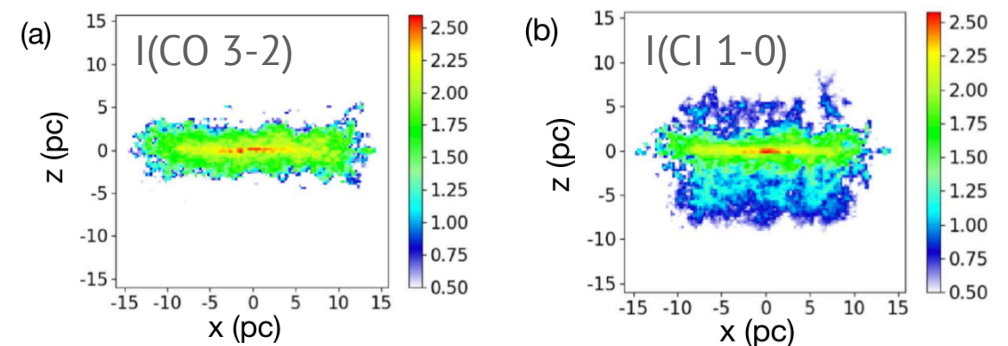
AGN feeding and feedback

X-ray dominated regions (XDRs)

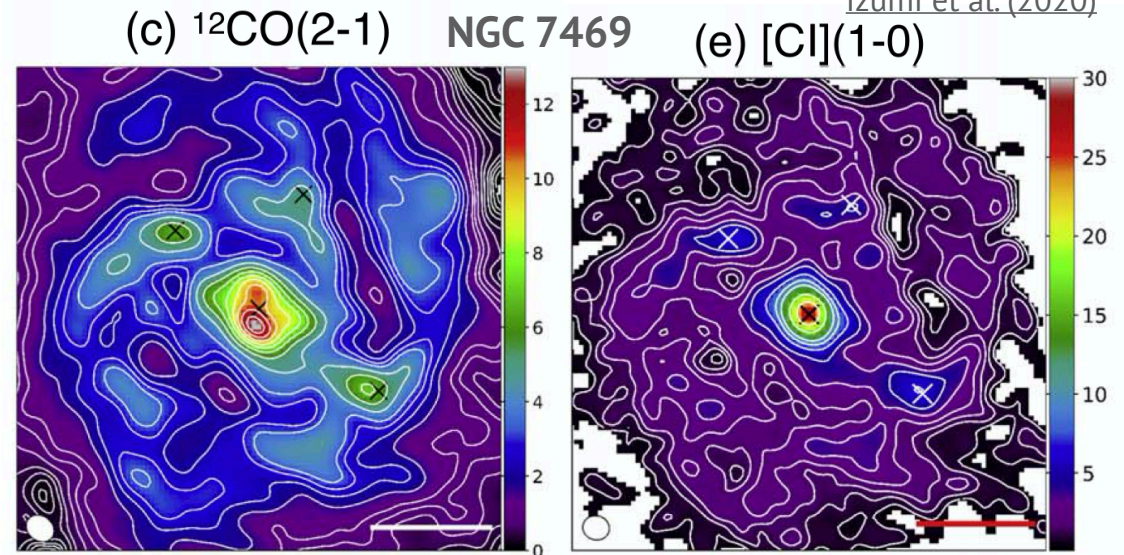
- X-ray dominated regions (XDRs) expected around AGNs
- Diagnostics useful in obscured nuclei
- CI/CO seems to be the only observationally supposed tracer
- **ALMA2040** can increase the sample of various AGN hosts

Simulated intensities

Izumi et al. (2018) based on Wada et al. (2016)



Izumi et al. (2020)

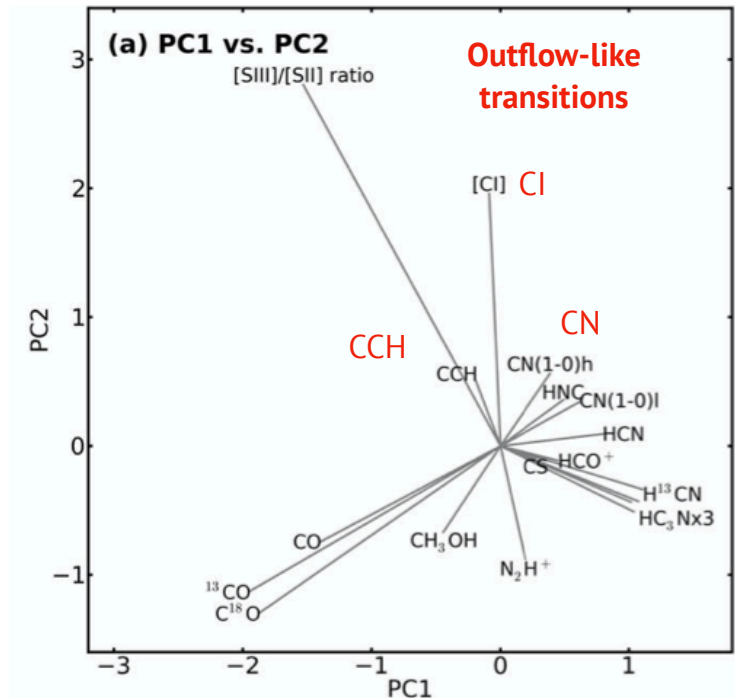
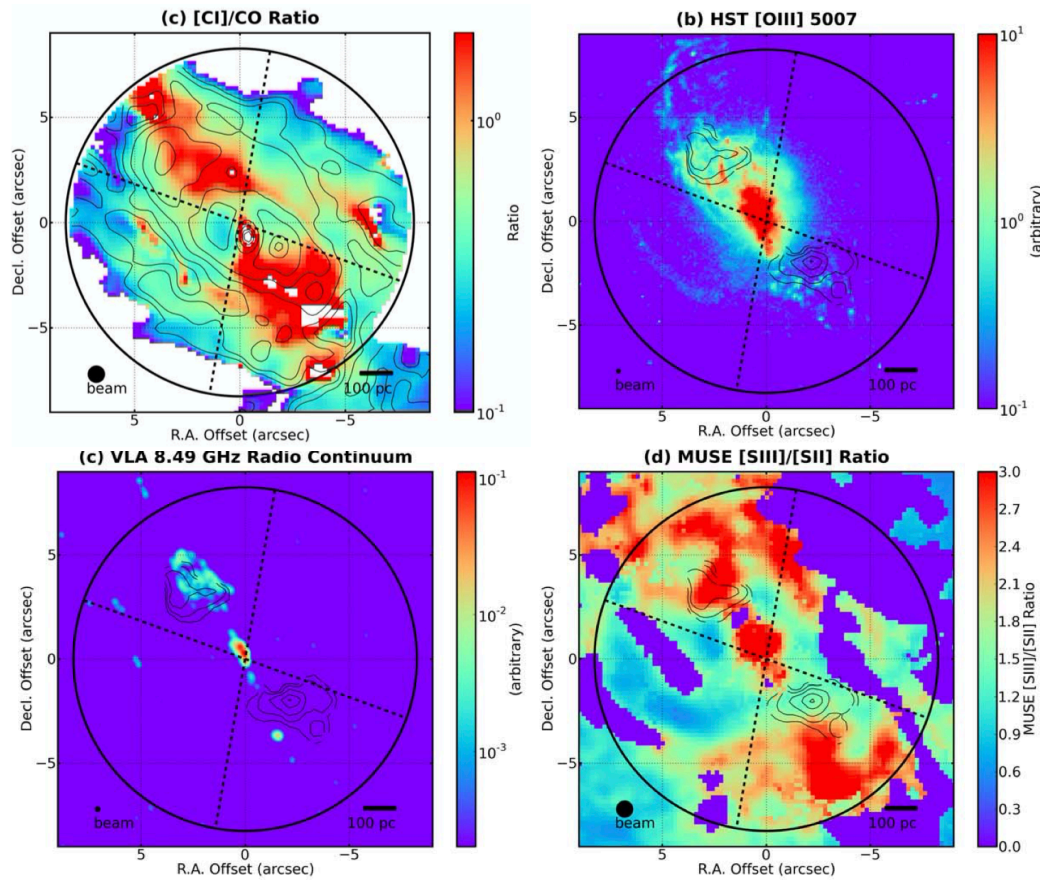


AGN outflows

Saito, ..., NH et al. (2022a, b)

CI/CO

NGC 1068



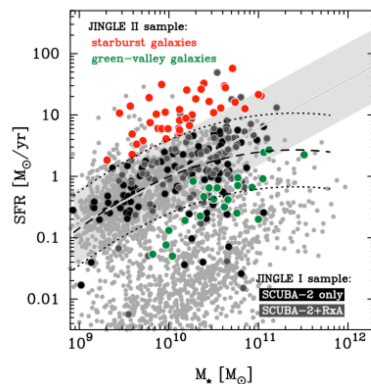
- Outflow features shown more in CCH, CN, and atomic carbon

Advantages of ALMA2040 to ngVLA

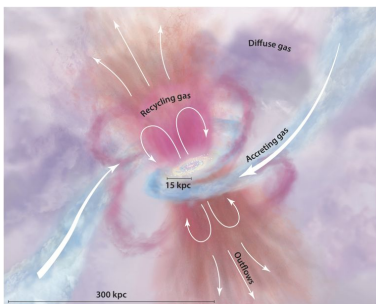
- CO survey (CO 2-1 more efficient)
- CI lines (AGN diagnostics, carbon budget for CO-dark gas?)
- Dense gas??? (HCN and N₂H⁺ 1-0; better for more compact uv-coverage)

Summary

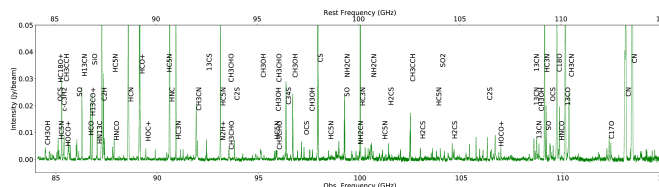
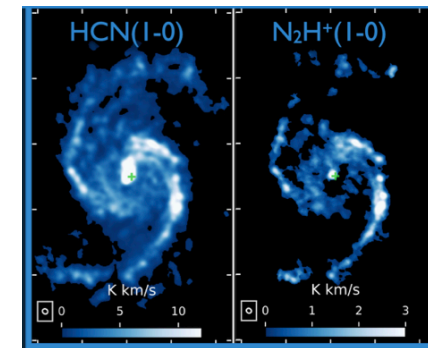
- Galaxy evolution esp. towards quenching



- Galactic eco system (outflows, inflows)



- Dense gas studies
- Astrochemical studies



- AGN diagnostics

