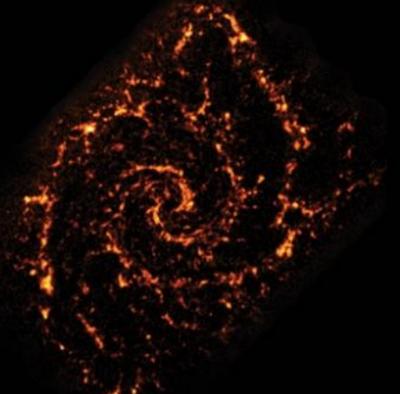


science opportunities
for studies
of nearby galaxies
using the new
ALMA Band 2 receiver



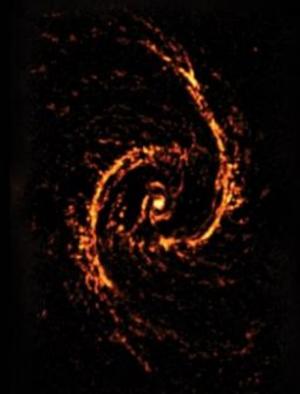
NGC 068



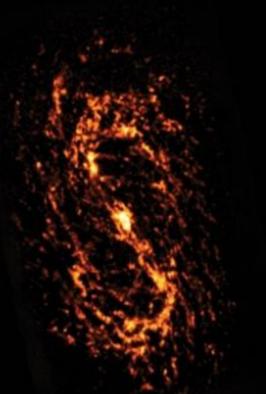
NGC 2997



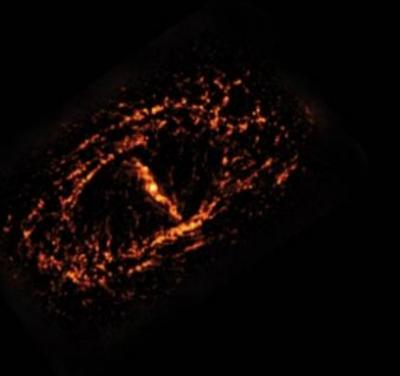
NGC 1097



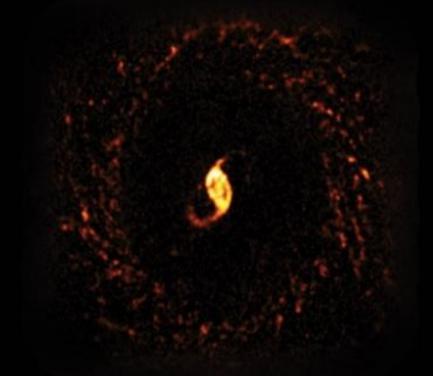
NGC 1566



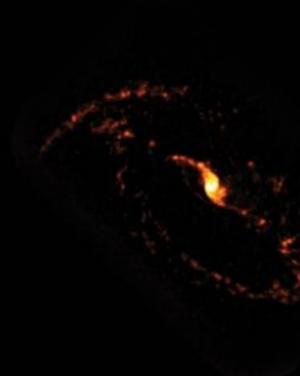
NGC 2903



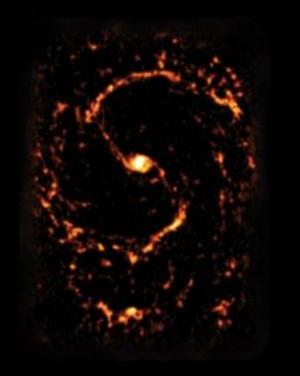
NGC 6300



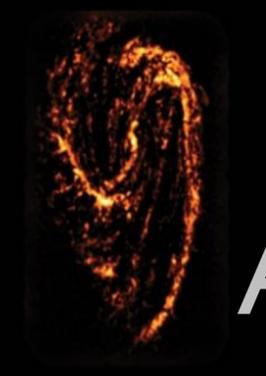
NGC 3351



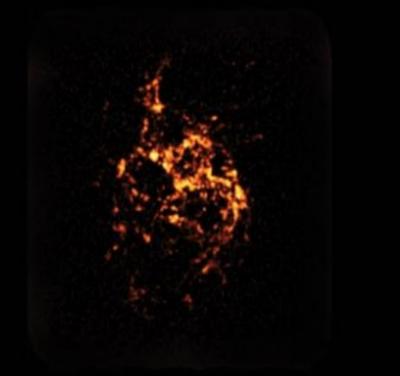
NGC 2566



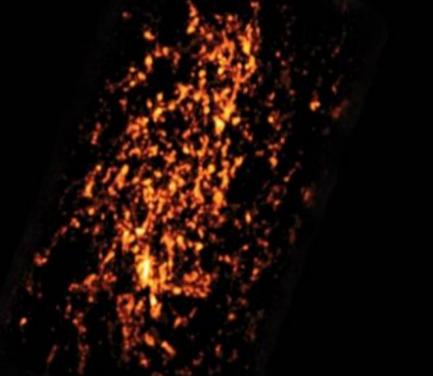
NGC 4535



NGC 3627



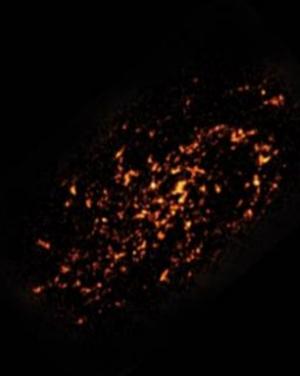
NGC 1385



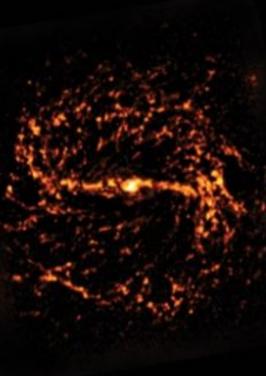
NGC 3621



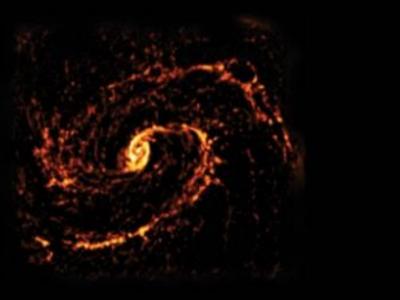
NGC 4781



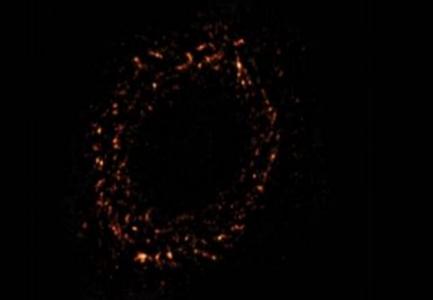
NGC 5530



NGC 5643



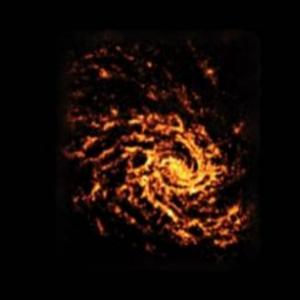
NGC 4321



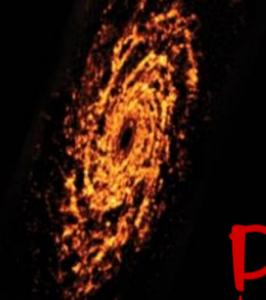
NGC 2775



NGC 4579



NGC 4254



NGC 3521

Eva Schinnerer
(MPIA)



a galactic ecosystem

gas from IGM

gas to halo, IGM

galactic structure

outflow: AGN, SF

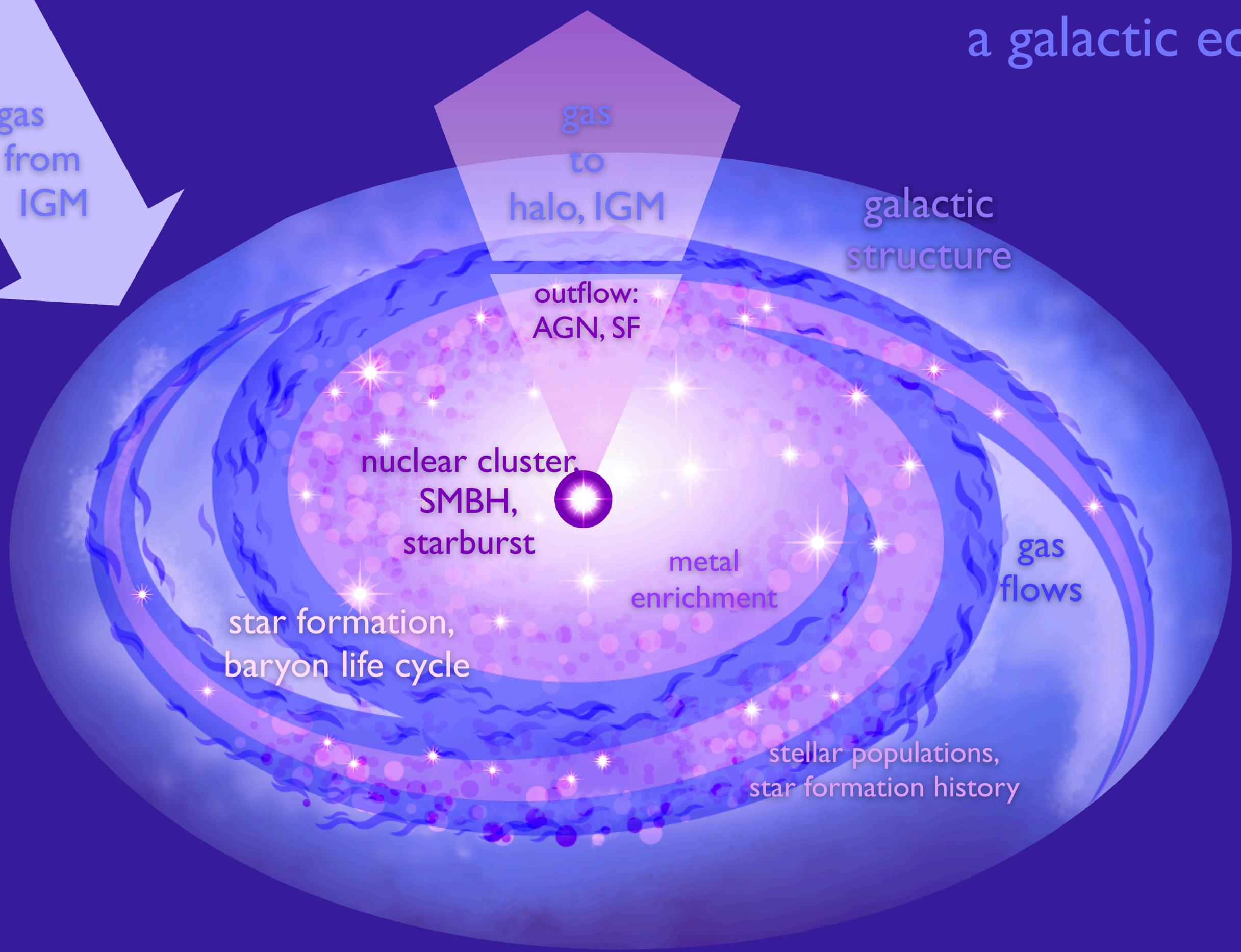
nuclear cluster, SMBH, starburst

metal enrichment

gas flows

star formation, baryon life cycle

stellar populations, star formation history



a galactic ecosystem

gas from IGM

gas to halo, IGM

galactic structure

outflow: AGN, SF

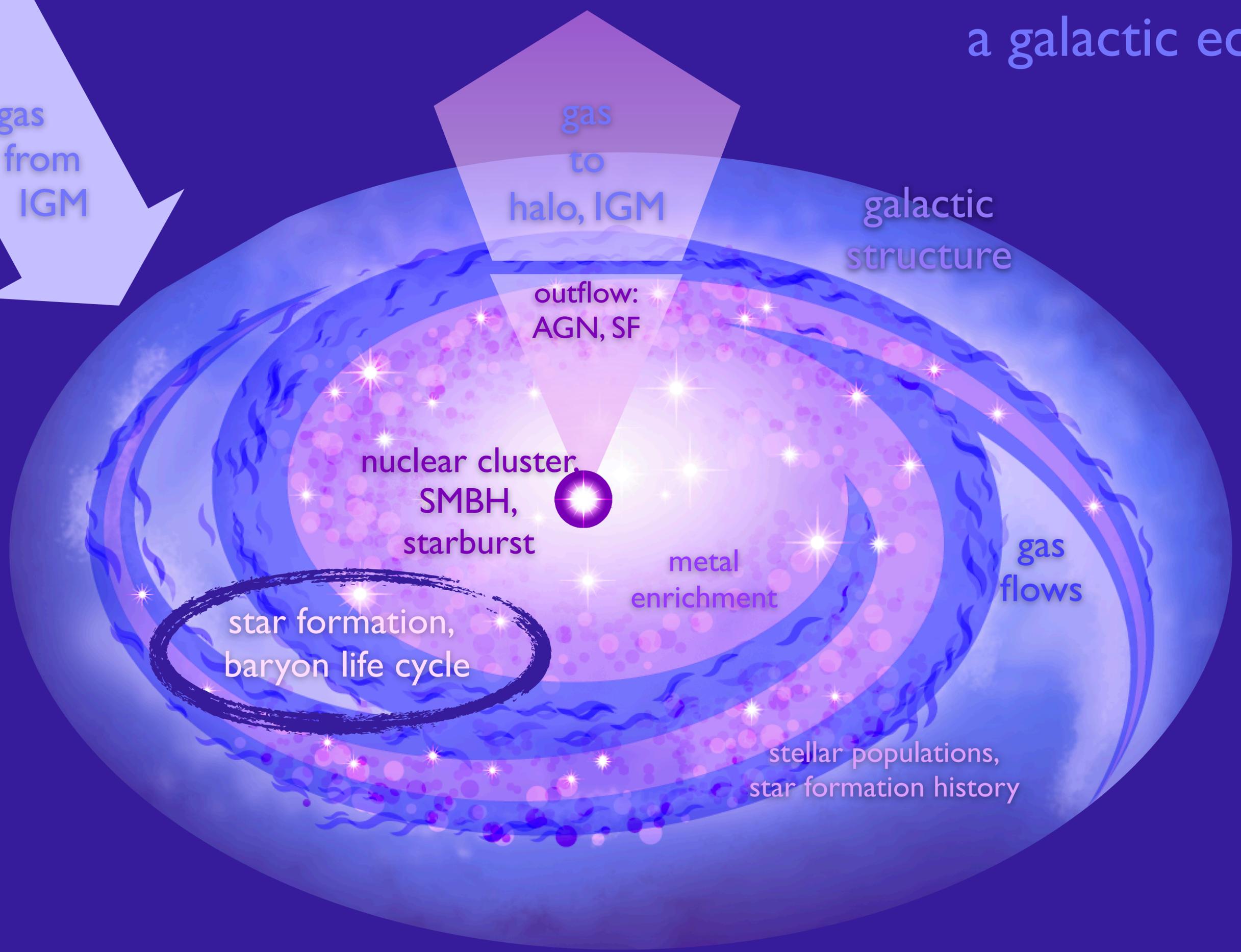
nuclear cluster, SMBH, starburst

metal enrichment

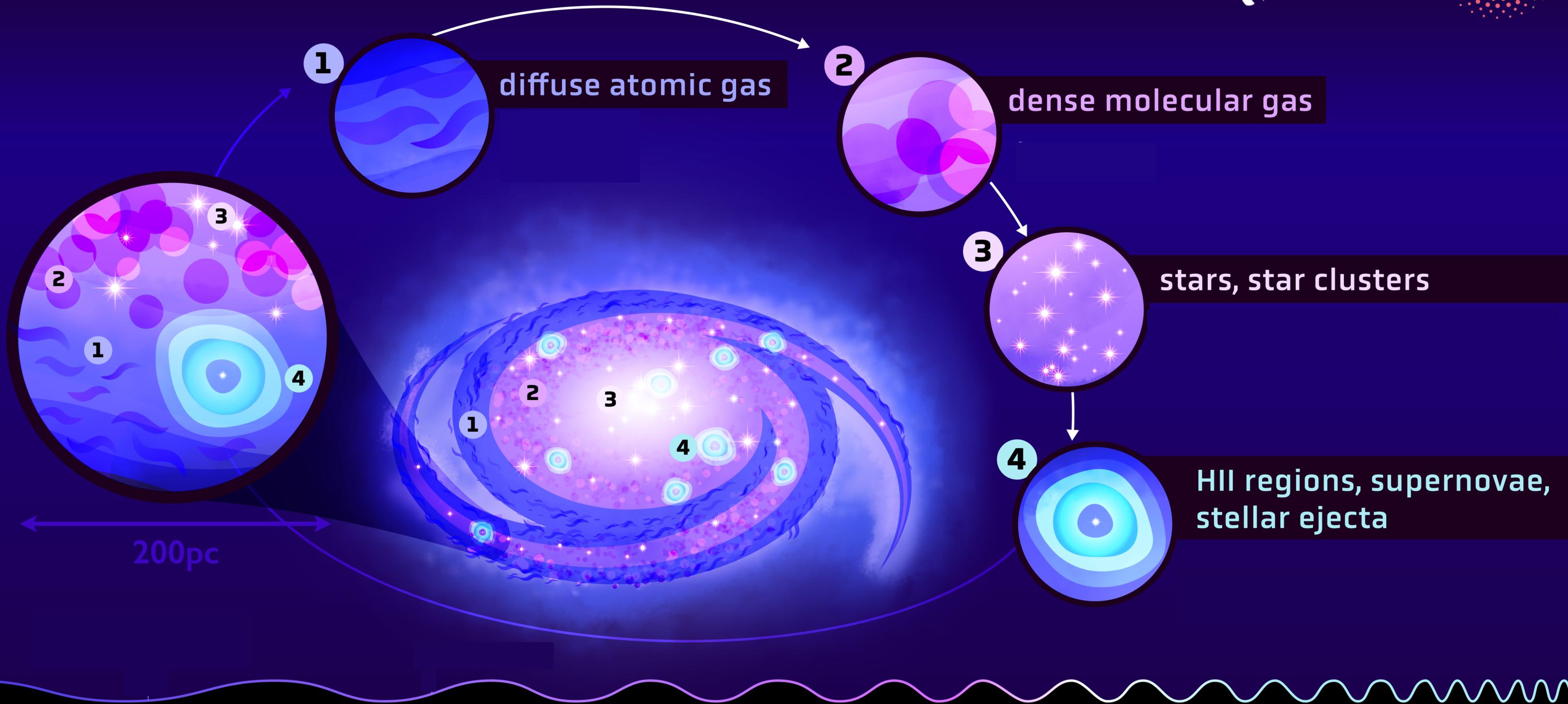
gas flows

star formation, baryon life cycle

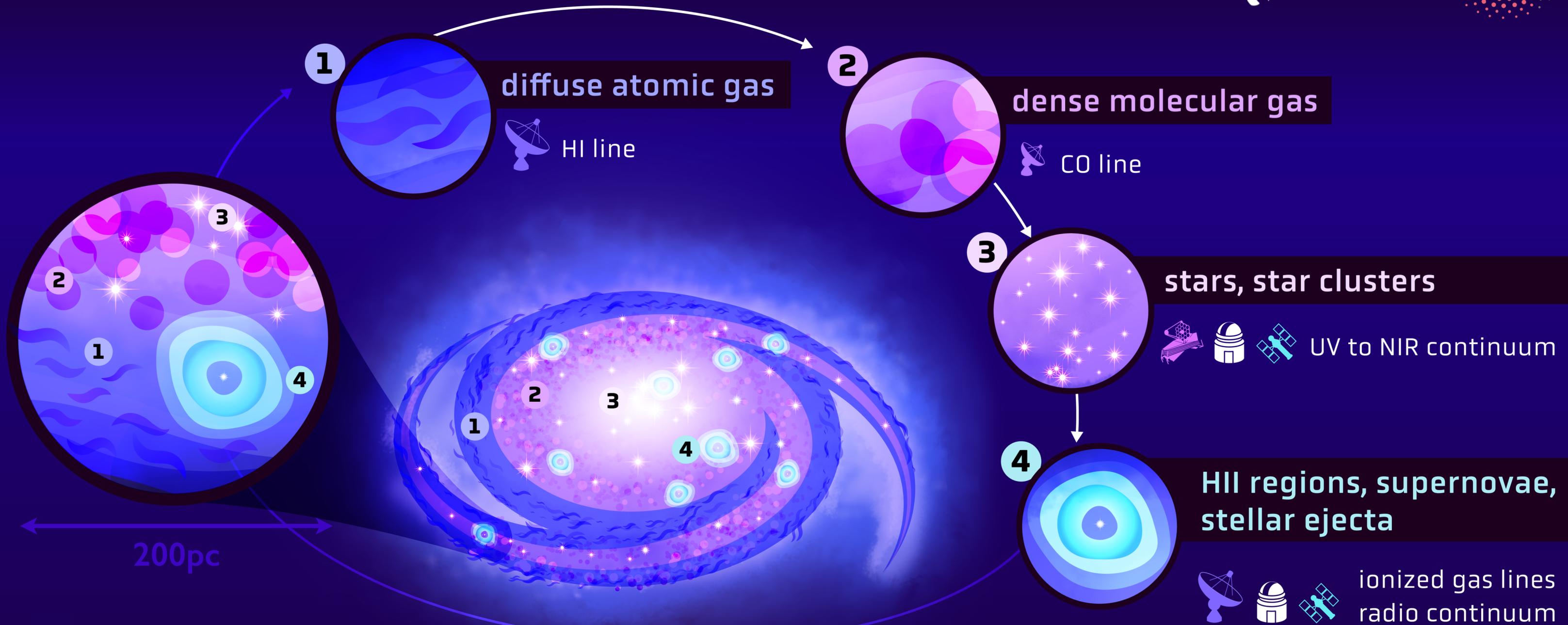
stellar populations, star formation history



BARYON LIFE CYCLE



BARYON LIFE CYCLE



HI [21cm]

CO [1,3mm]



radio waves



(sub-)millimeter



infrared

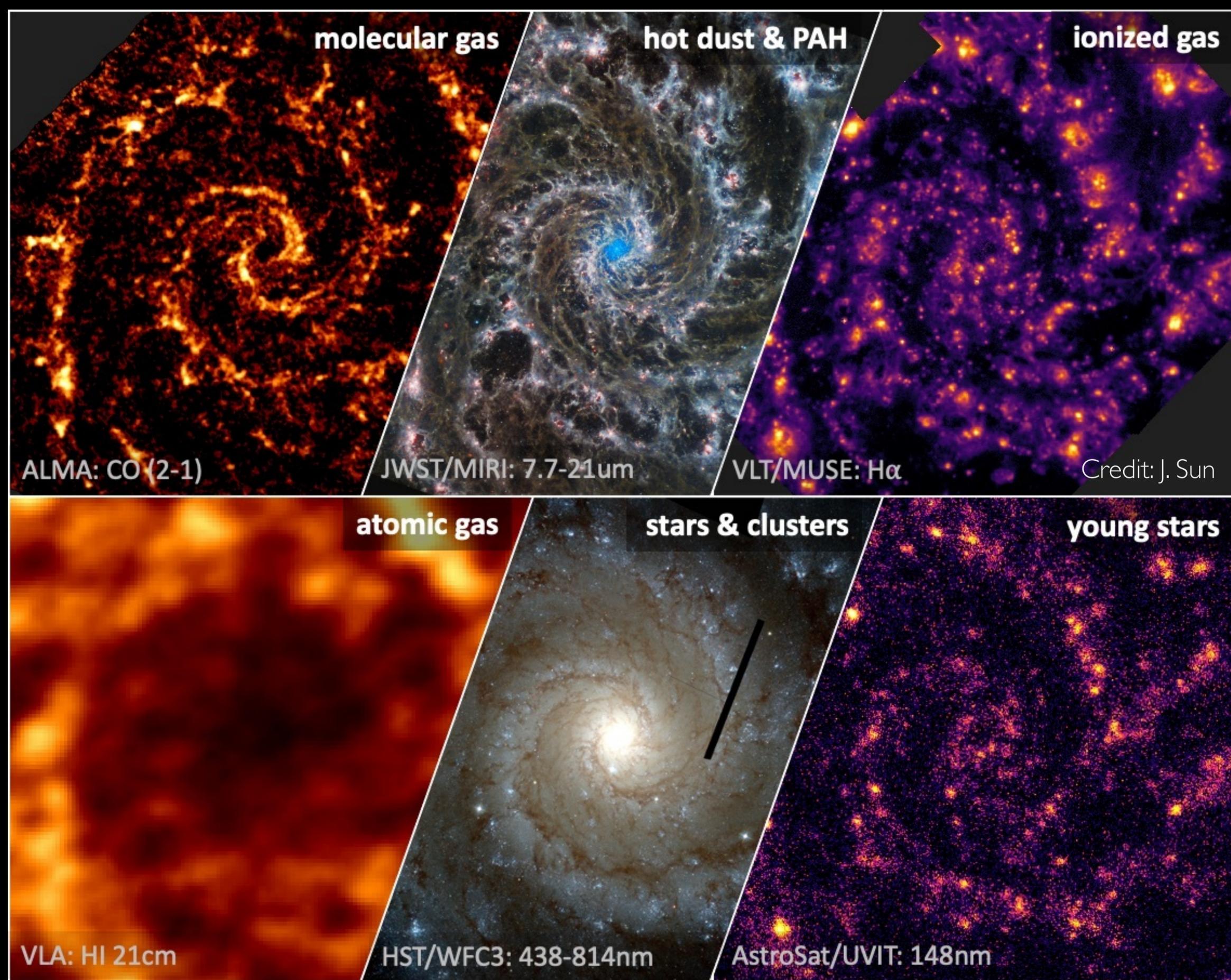


optical light



UV

need to reach
cloud scales*



* $\theta=50-150\text{pc}$; isolates
individual star-forming sites,
but does not resolved them

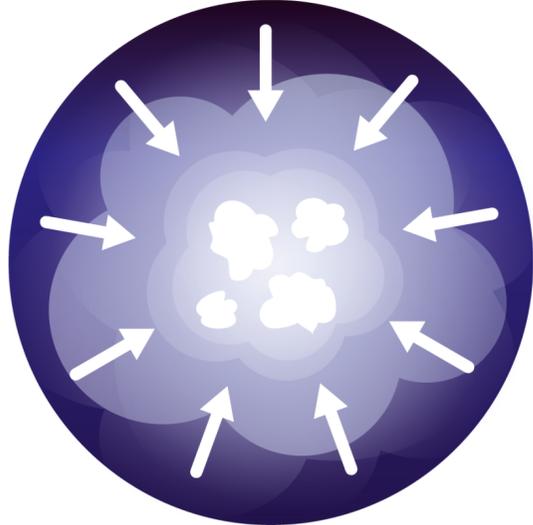
(see resolved cloud observations
with $\theta=5-20\text{pc}$)

cloud-scale observations resolve:

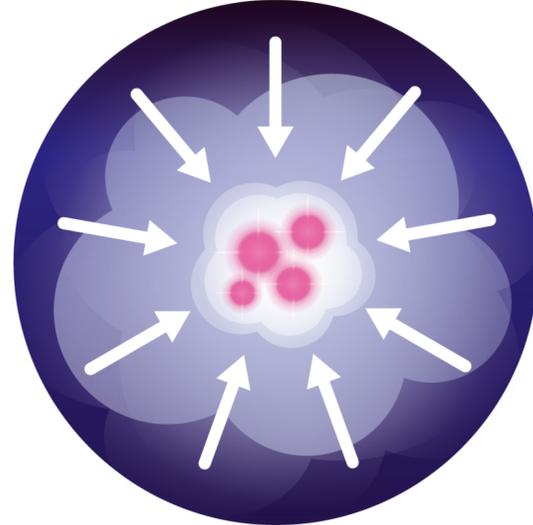
SCHEMATIC VIEW OF MOLECULAR CLOUD EVOLUTION



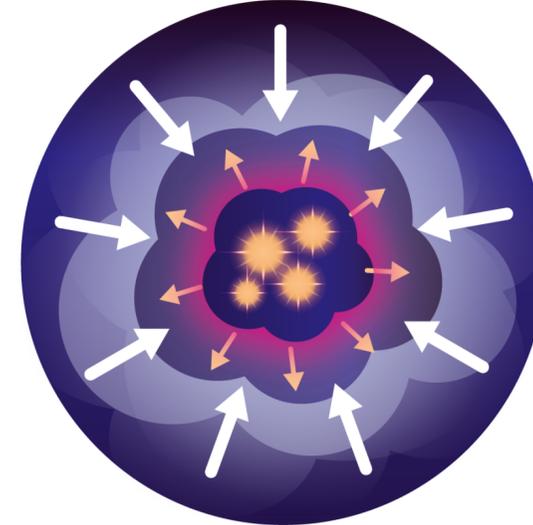
molecular cloud



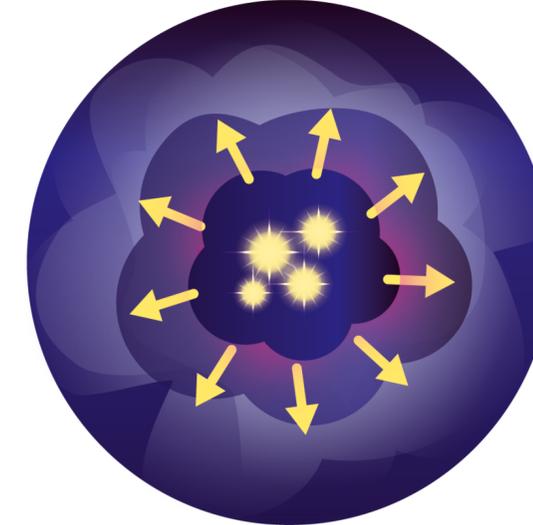
dense gas formation



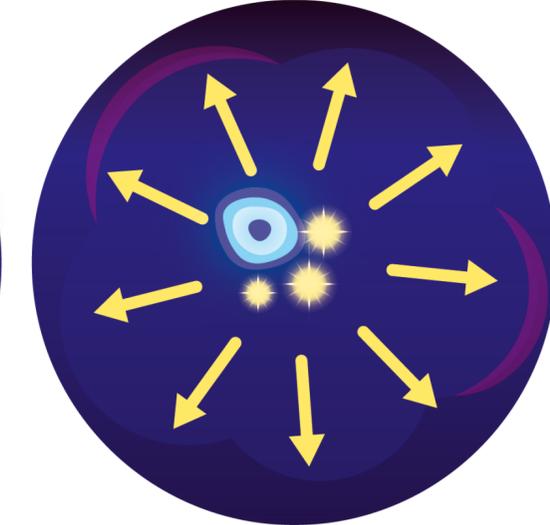
onset of star formation



pre-supernovae stellar feedback



cloud disruption



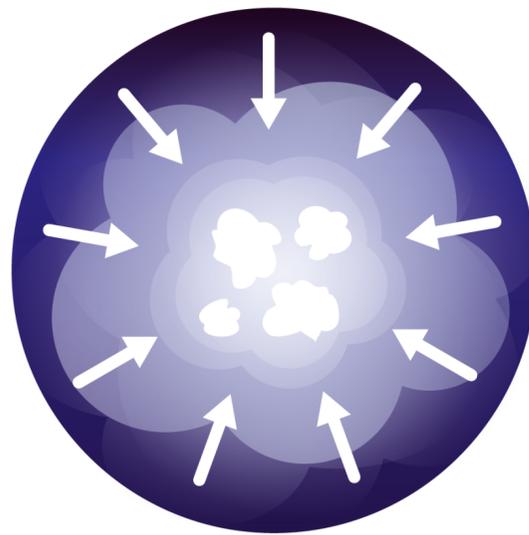
cloud dispersal & supernova explosions

cloud-scale observations resolve:

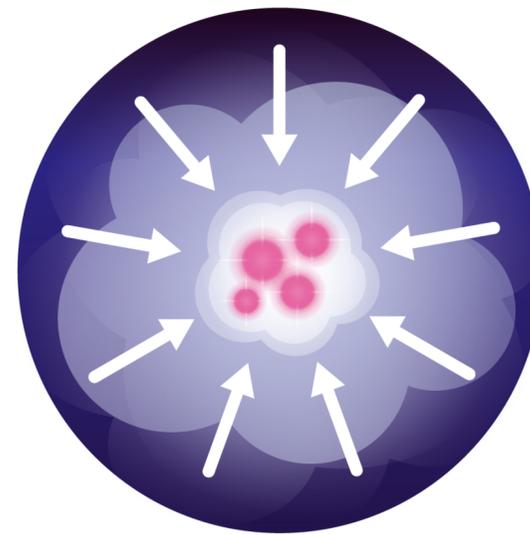
SCHEMATIC VIEW OF MOLECULAR CLOUD EVOLUTION



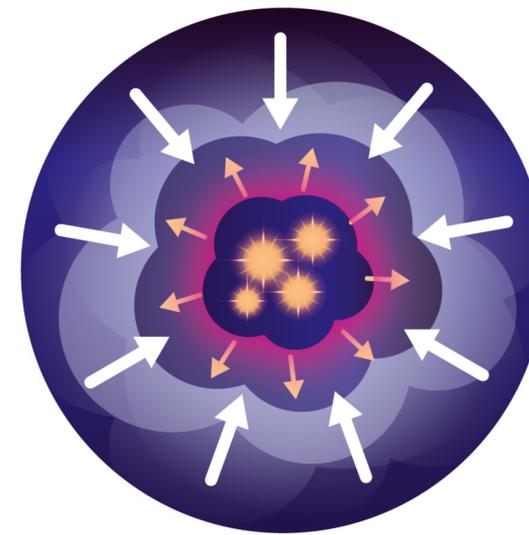
molecular
cloud



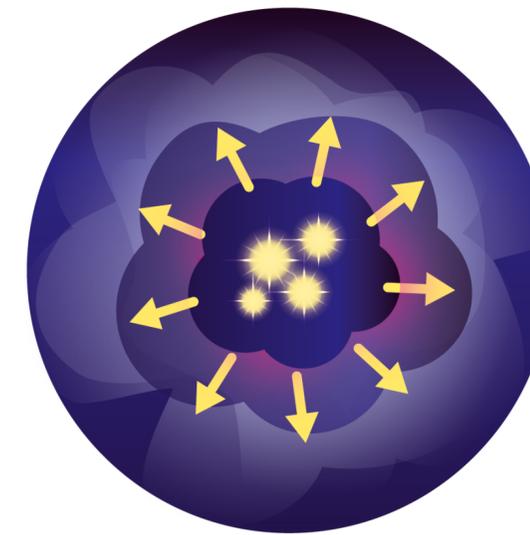
dense gas
formation



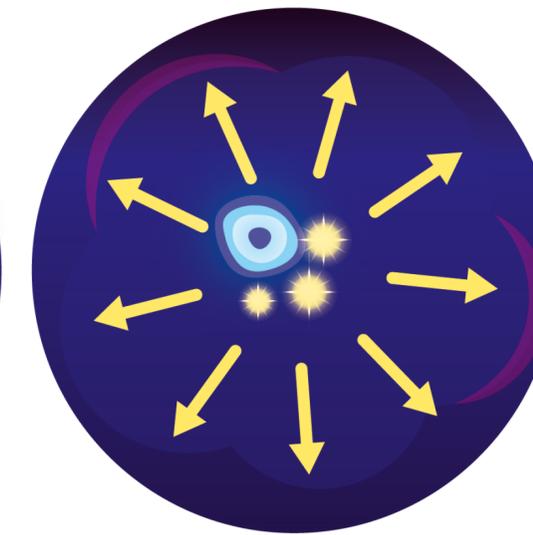
onset of star
formation



pre-supernovae
stellar feedback



cloud
disruption



cloud dispersal &
supernova explosions

and give access to

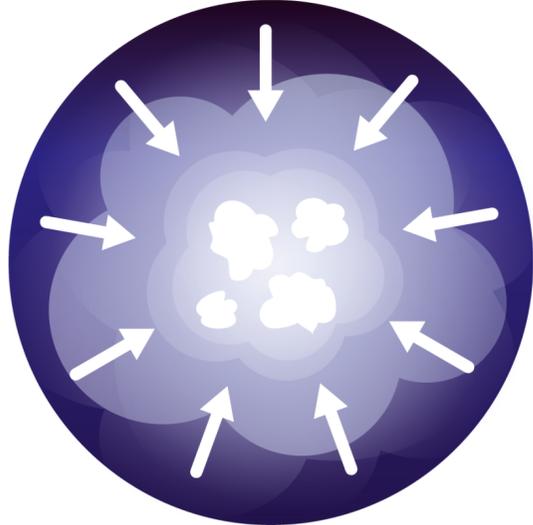
**molecular gas (cloud) properties, star formation efficiencies and timescales
as a function of galactic and physical environment**

cloud-scale observations resolve:

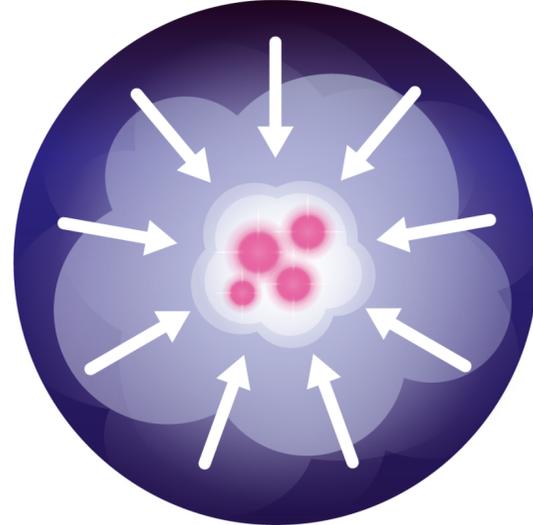
SCHEMATIC VIEW OF MOLECULAR CLOUD EVOLUTION



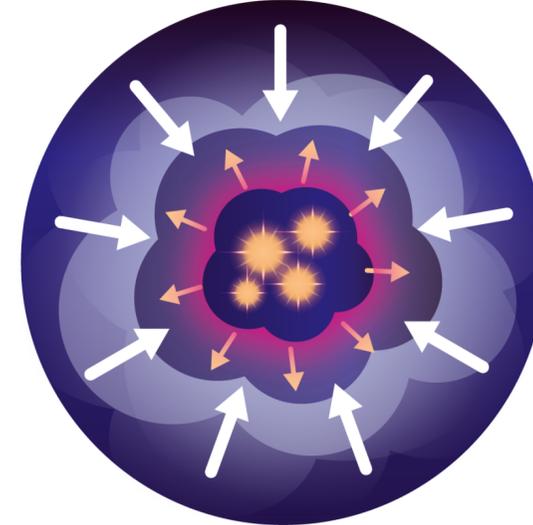
molecular cloud



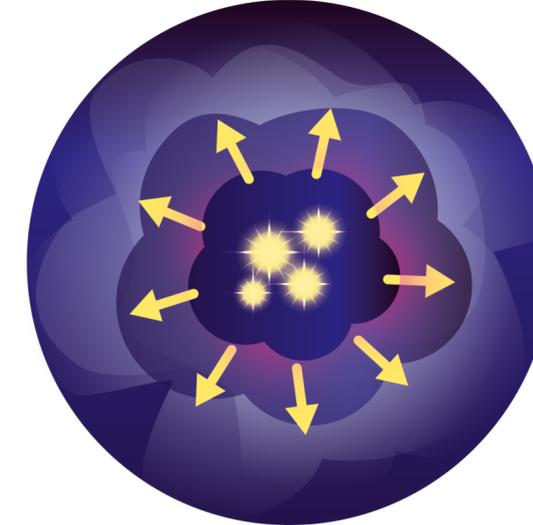
dense gas formation



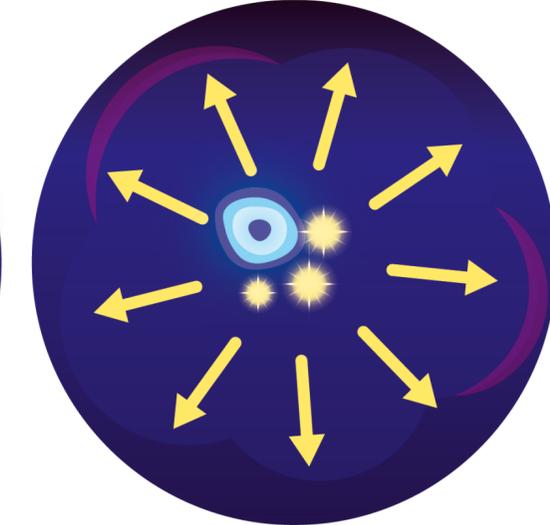
onset of star formation



pre-supernovae stellar feedback



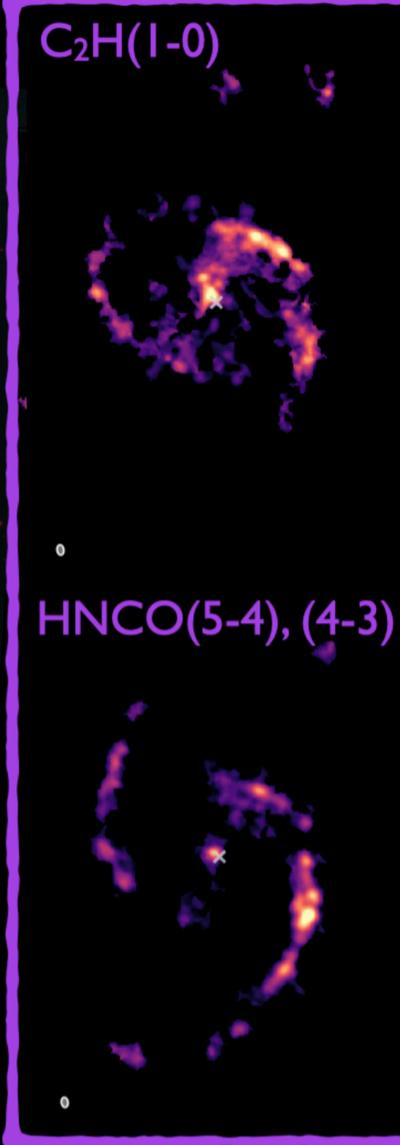
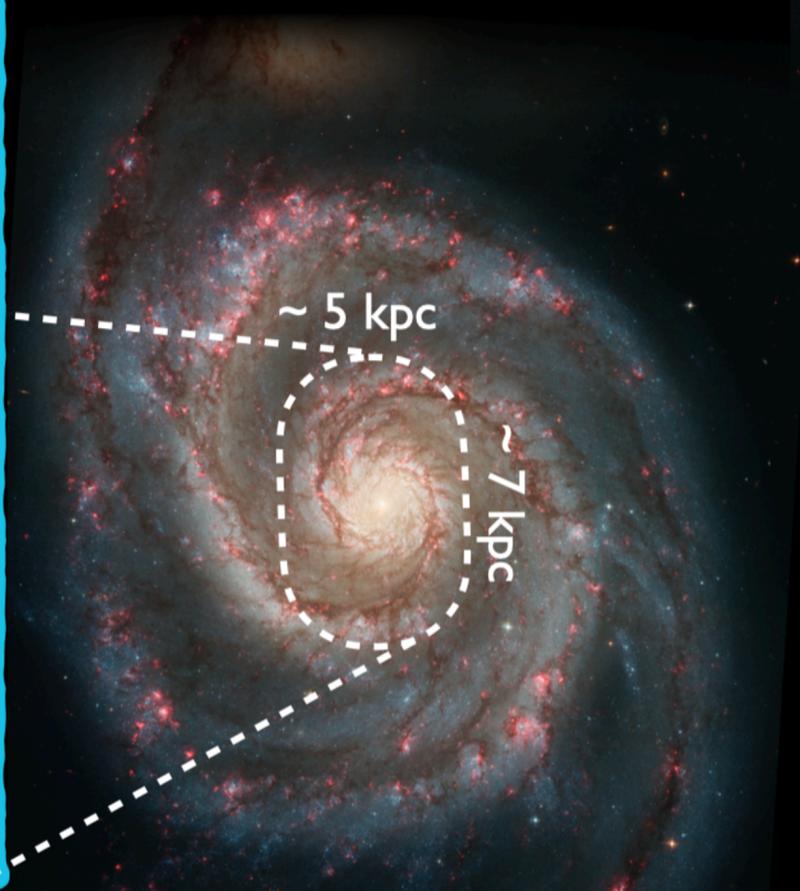
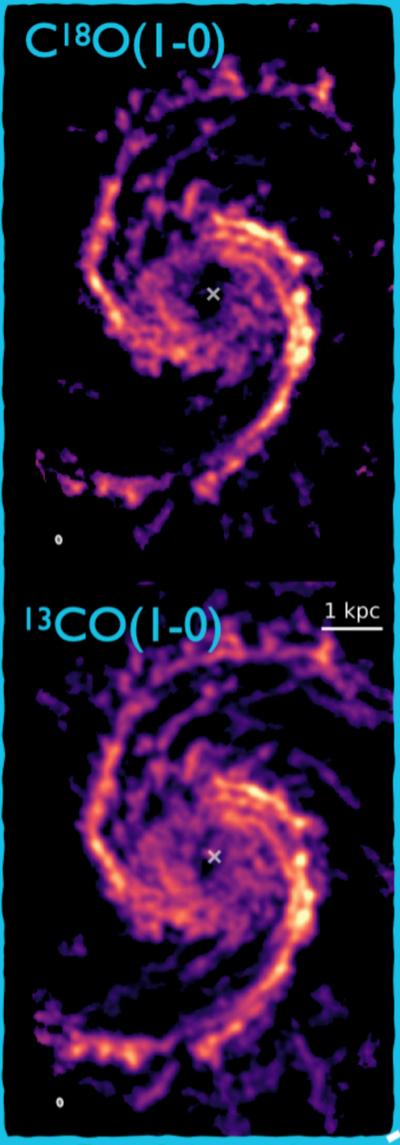
cloud disruption



cloud dispersal & supernova explosions

tracers in ALMA Band 2

CO isotopologue



PDR & shock tracer

SWAN

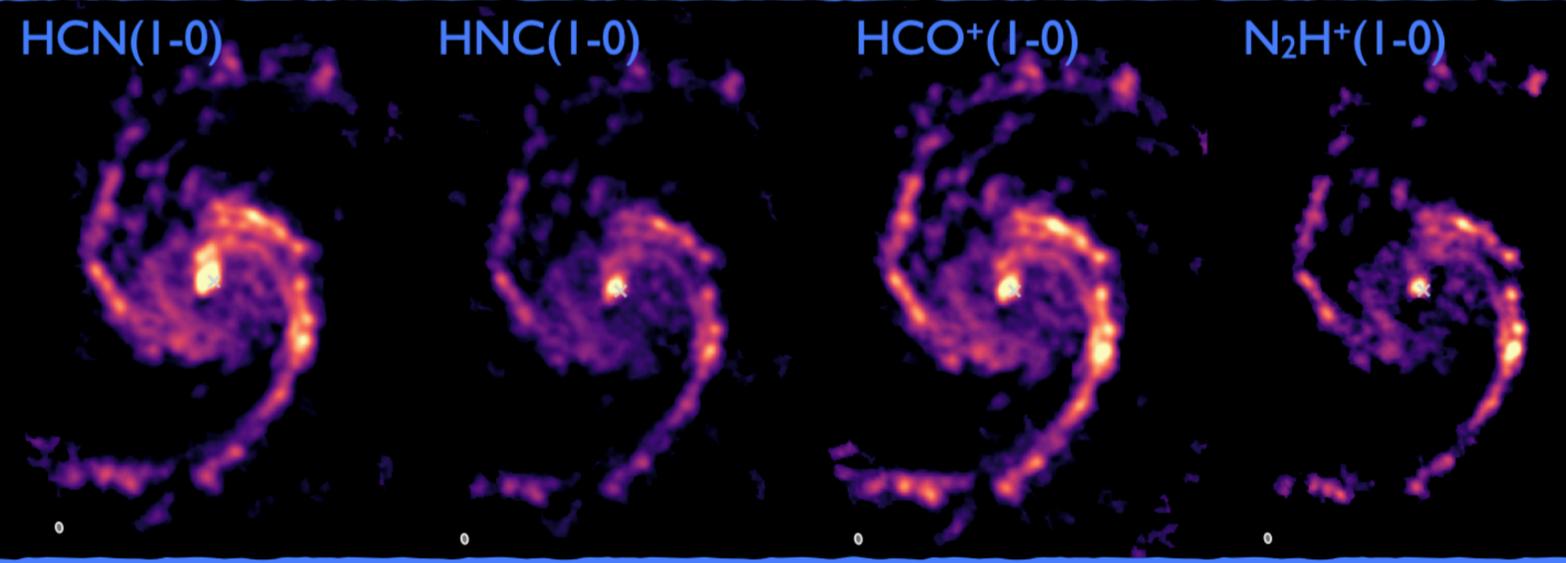
Surveying the Whirlpool at
 Arcseconds with NOEMA
 (PI: Schinnerer & Bigiel)

>200 hr with NOEMA
 + 55 hr with 30m

9 emission lines @ 3-4mm

3" ≈ 125 pc resolution

Resolution of 3" ~ 125pc



IRAM NOEMA+30m

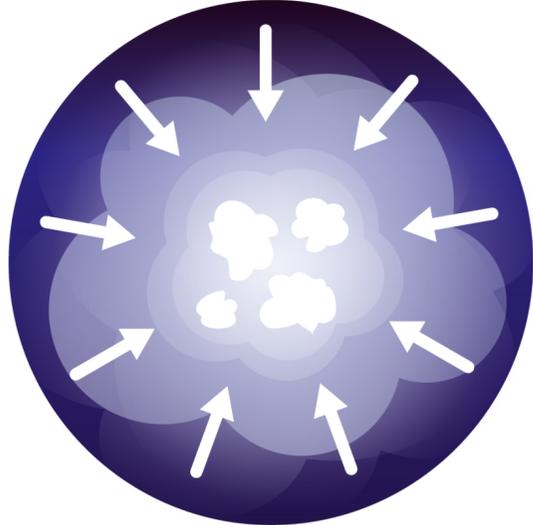
Dense gas tracer

cloud-scale observations resolve:

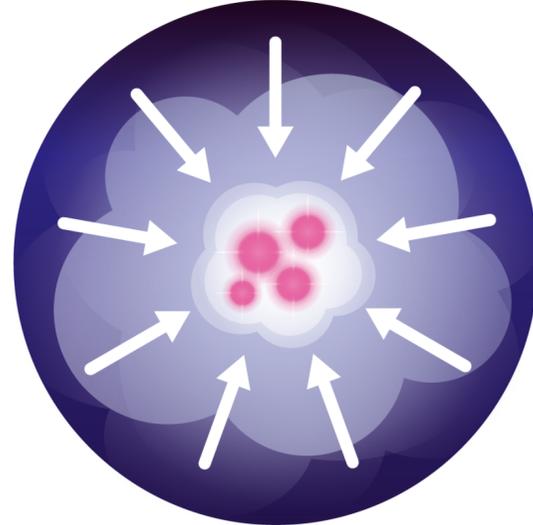
SCHEMATIC VIEW OF MOLECULAR CLOUD EVOLUTION



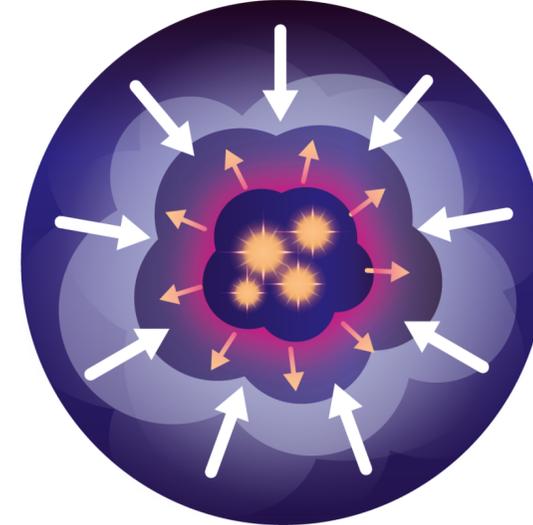
molecular cloud



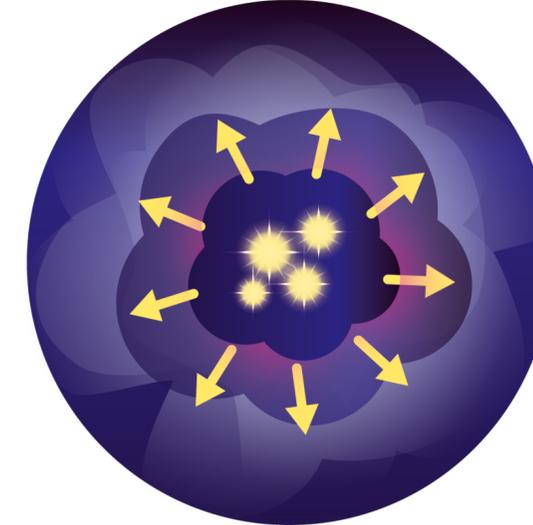
dense gas formation



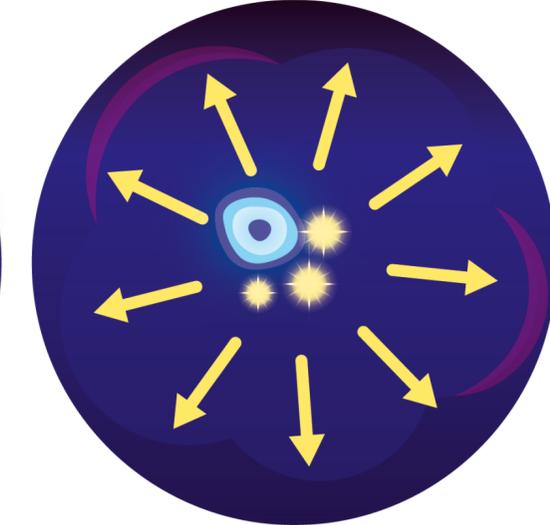
onset of star formation



pre-supernovae stellar feedback



cloud disruption



cloud dispersal & supernova explosions

tracers in ALMA Band 2

bulk gas

CO & isotopologues

measuring the bulk molecular gas mass— α_{CO}

conversion of CO luminosity into molecular (H_2) gas mass:

$$\alpha_{\text{CO}} = M_{\text{gas}}/L_{\text{CO}}$$

varies with density, temperature, opacity, abundance, ...

range of ~ 0.1 to several $10 \times M_{\text{W}}$ generic value of $4.35 M_{\odot} \text{ pc}^{-2} (\text{K km/s})^{-1}$ inferred in local galaxies

gas density tracer in ALMA Band 2

Schinnerer & Leroy (2024)

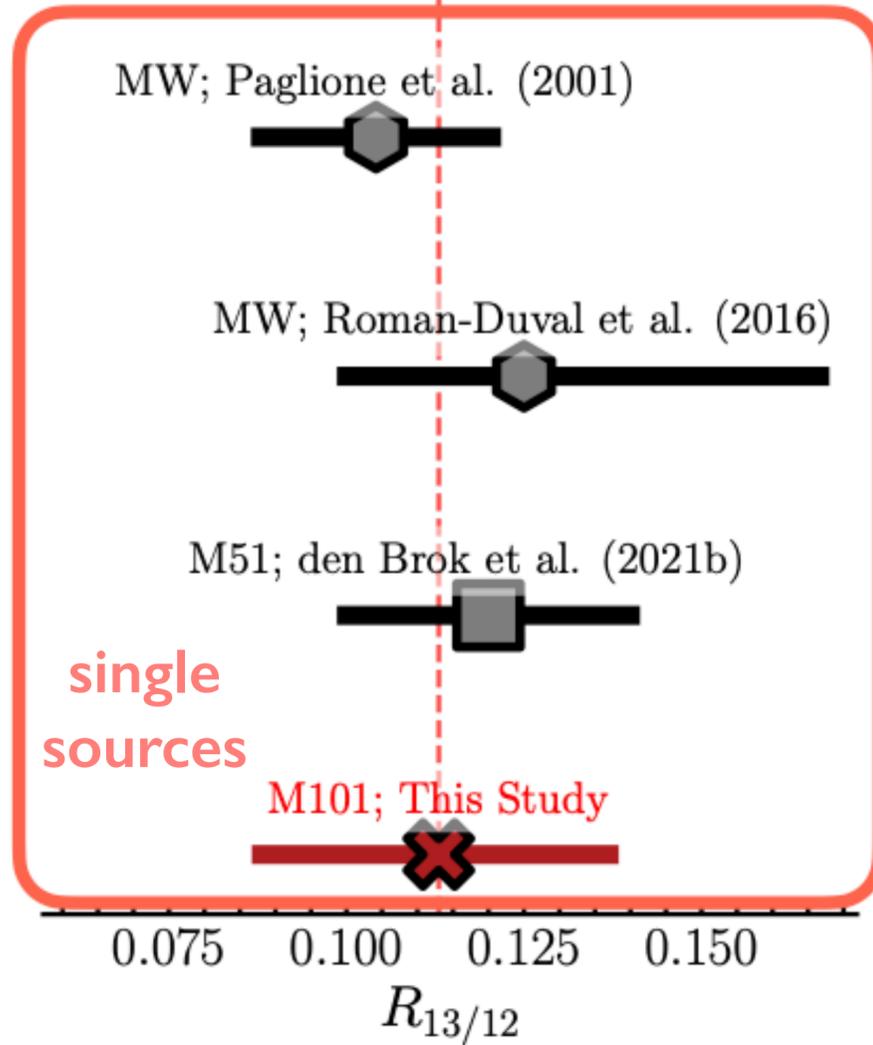
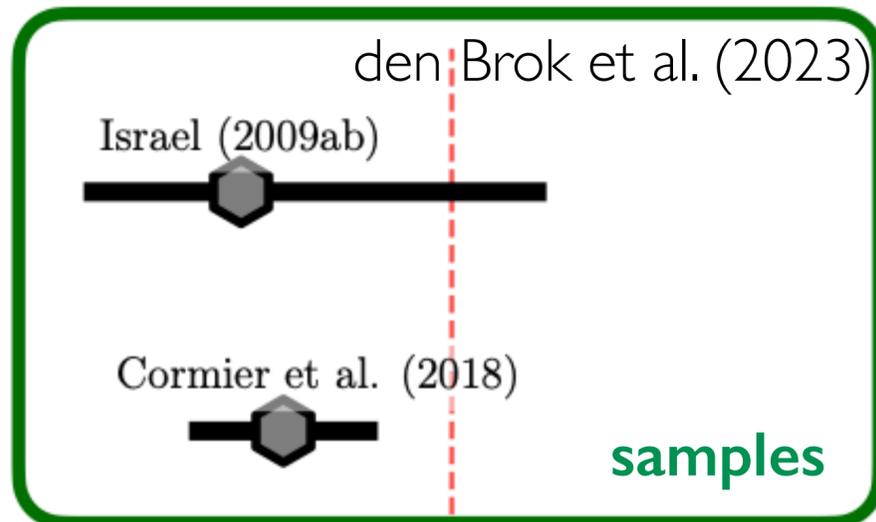
Species	Transition	CO(1–0) ratio ^a (K)	$n_{\text{crit}}^{\text{b}}$ (cm ⁻³)	References for line ratios	References for critical density calculations
¹² CO ^c	(1–0)	1.00	5.7×10^2		Yang et al. 2010
¹² CO ^c	(2–1)	0.65	4.4×10^3	Leroy et al. 2022 ^d	Yang et al. 2010
¹² CO ^c	(3–2)	0.31	1.5×10^4	Leroy et al. 2022 ^d	Yang et al. 2010
¹³ CO	(1–0)	0.091	4.8×10^2	Cormier et al. 2018 ^e	Yang et al. 2010
C ¹⁸ O	(1–0)	0.015	4.8×10^2	Jiménez-Donaire et al. 2017b ^f	Yang et al. 2010
HCN	(1–0)	0.024	3.0×10^5	Neumann et al. 2023 ^g	Dumouchel et al. 2010
HCO ⁺	(1–0)	0.0081	4.5×10^4	Neumann et al. 2023 ^g	Denis-Alpizar et al. 2020
CS	(2–1)	0.023	8.5×10^4	Neumann et al. 2023 ^g	Denis-Alpizar et al. 2018
HNC	(1–0)	0.011	1.1×10^5	Jiménez-Donaire et al. 2019	Dumouchel et al. 2010
CN	(1 _{3/2} –0 _{1/2}) ^h	0.022	2.4×10^5	Wilson 2018, Wilson et al. 2023 ⁱ	Lique et al. 2010
N ₂ H ⁺	(1–0)	0.0036	4.1×10^4	Jiménez-Donaire et al. 2023 ^j	Flower 1999 ^k

gas density tracer in ALMA Band 2

Schinnerer & Leroy (2024)

Species	Transition	CO(1–0) ratio ^a (K)	$n_{\text{crit}}^{\text{b}}$ (cm ⁻³)	References for line ratios	References for critical density calculations
¹² CO ^c	(1–0)	1.00	5.7×10^2		Yang et al. 2010
¹² CO ^c	(2–1)	0.65	4.4×10^3	Leroy et al. 2022 ^d	Yang et al. 2010
¹² CO ^c	(3–2)	0.31	1.5×10^4	Leroy et al. 2022 ^d	Yang et al. 2010
¹³ CO	(1–0)	0.091	4.8×10^2	Cormier et al. 2018 ^e	Yang et al. 2010
C ¹⁸ O	(1–0)	0.015	4.8×10^2	Jiménez-Donaire et al. 2017b ^f	Yang et al. 2010
HCN	(1–0)	0.024	3.0×10^5	Neumann et al. 2023 ^g	Dumouchel et al. 2010
HCO ⁺	(1–0)	0.0081	4.5×10^4	Neumann et al. 2023 ^g	Denis-Alpizar et al. 2020
CS	(2–1)	0.023	8.5×10^4	Neumann et al. 2023 ^g	Denis-Alpizar et al. 2018
HNC	(1–0)	0.011	1.1×10^5	Jiménez-Donaire et al. 2019	Dumouchel et al. 2010
CN	(1 _{3/2} –0 _{1/2}) ^h	0.022	2.4×10^5	Wilson 2018, Wilson et al. 2023 ⁱ	Lique et al. 2010
N ₂ H ⁺	(1–0)	0.0036	4.1×10^4	Jiménez-Donaire et al. 2023 ^j	Flower 1999 ^k

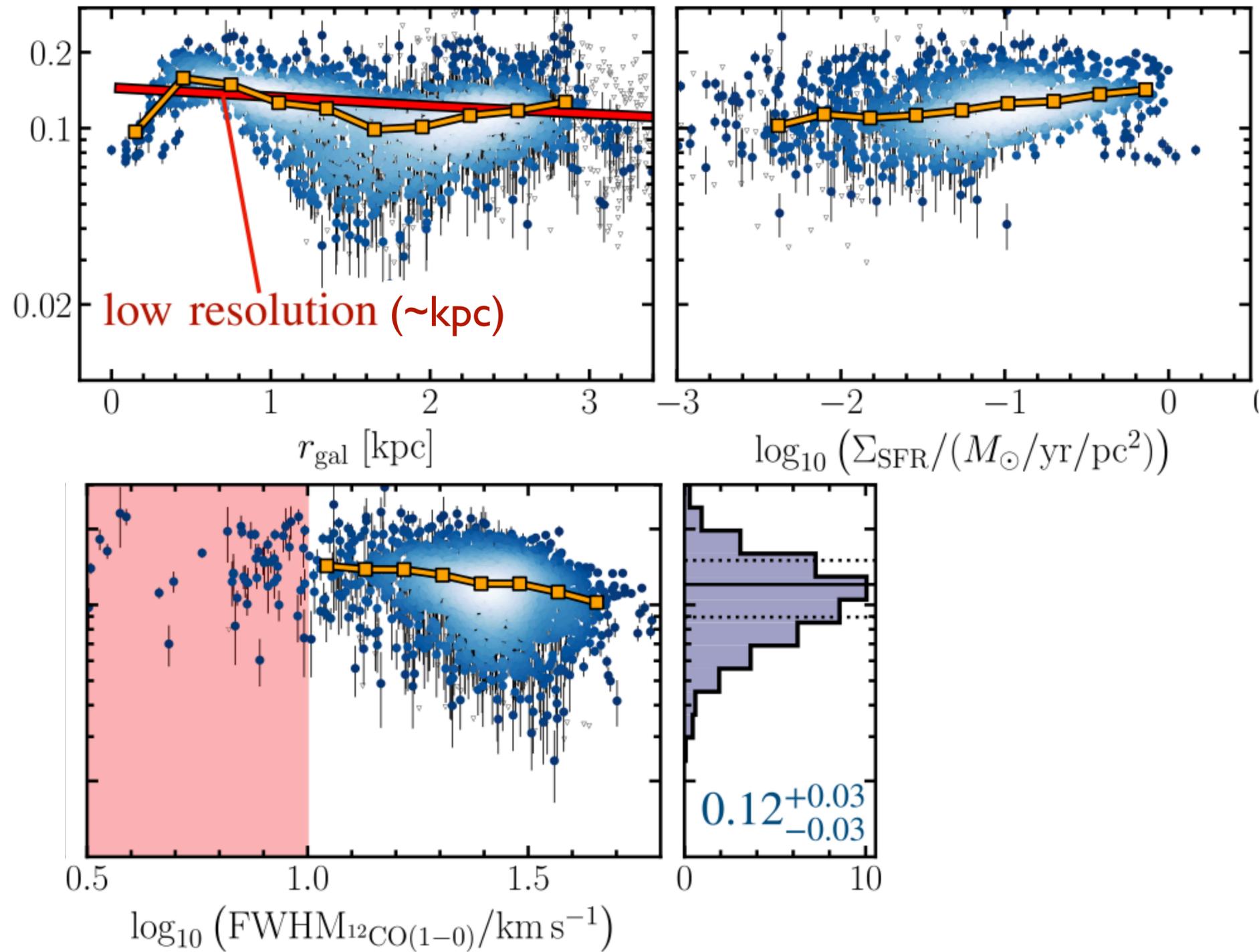
$^{13}\text{CO}/^{12}\text{CO}$ ratio variations sampled at (sub-)kpc-scale



$^{13}\text{CO}/^{12}\text{CO}$ ratio variations on cloud-scales

den Brok et al. (2025)

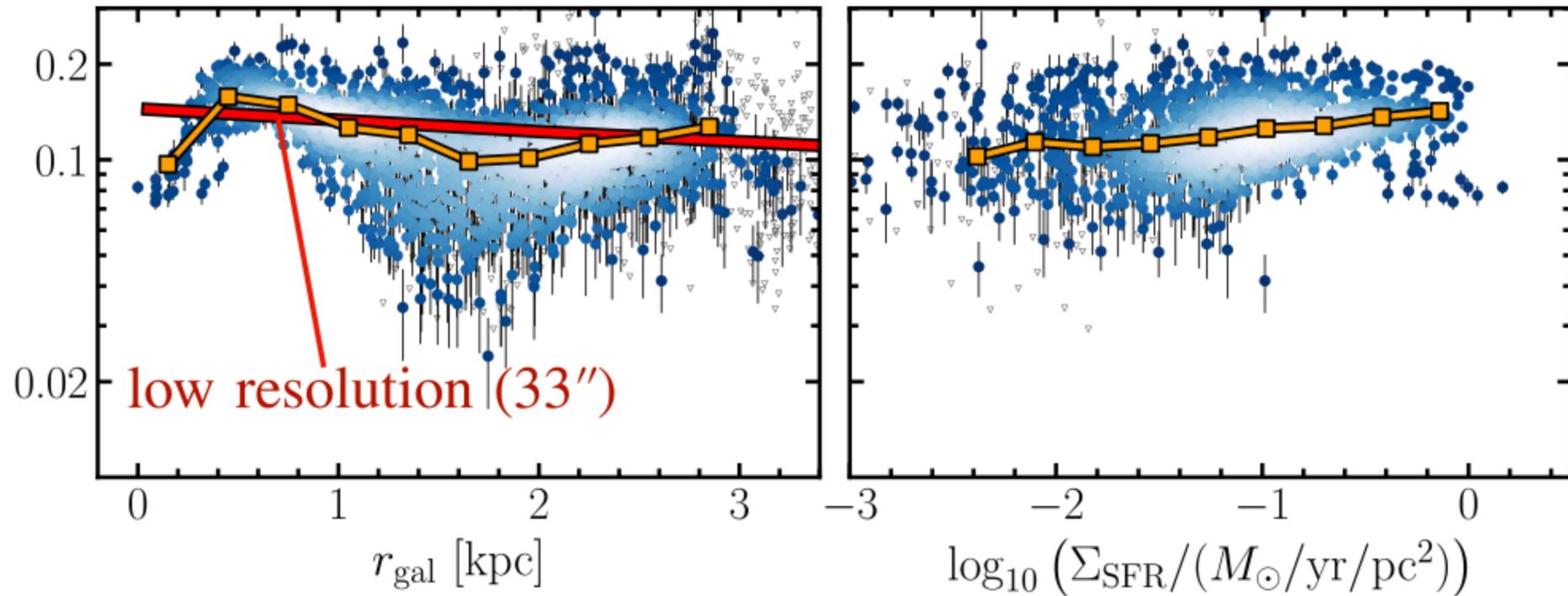
$$R_{10}^{13/12} \equiv W [^{13}\text{CO}(1-0)] / W [^{12}\text{CO}(1-0)]$$



$^{13}\text{CO}/^{12}\text{CO}$ ratio variations on cloud-scales

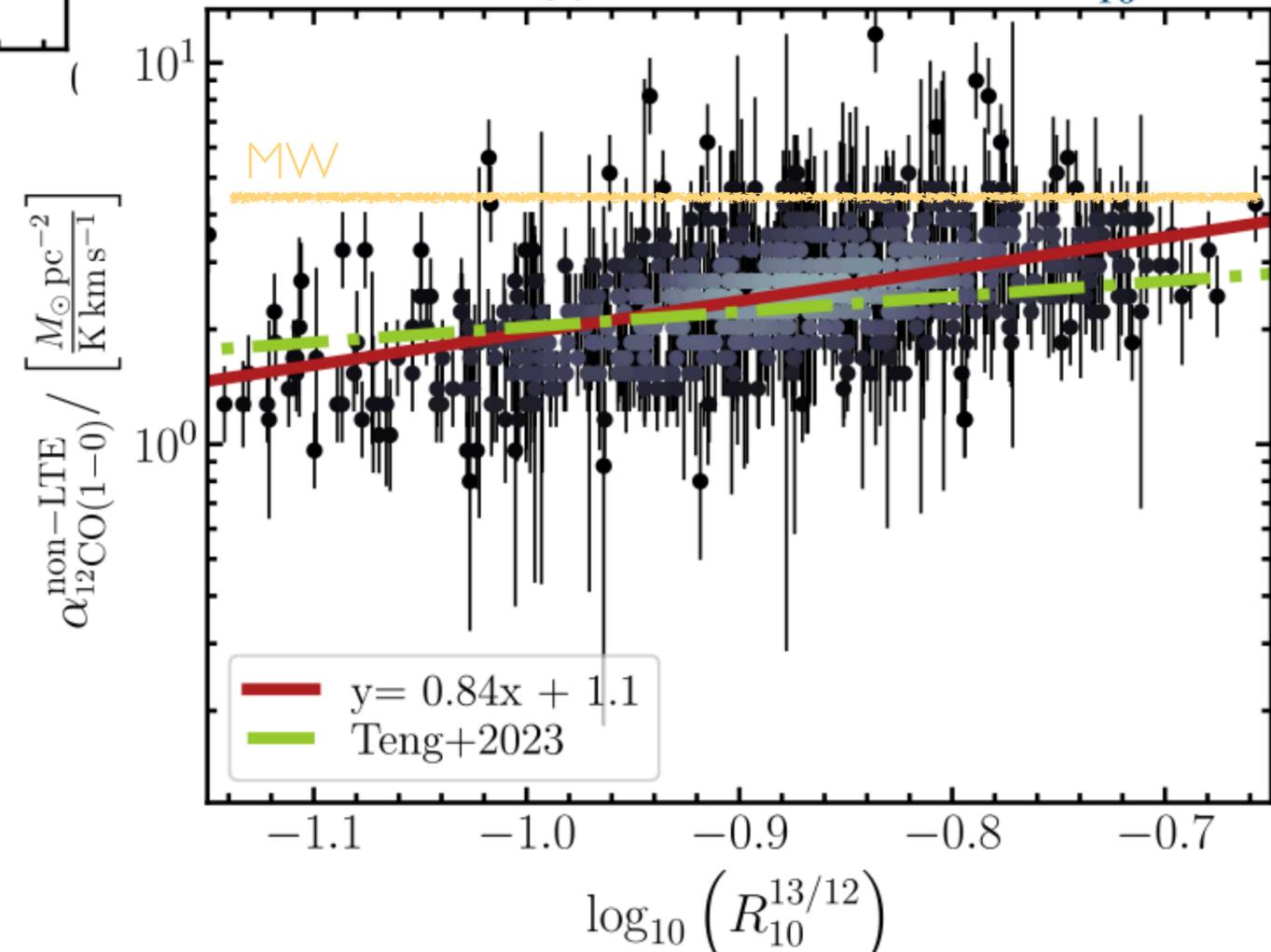
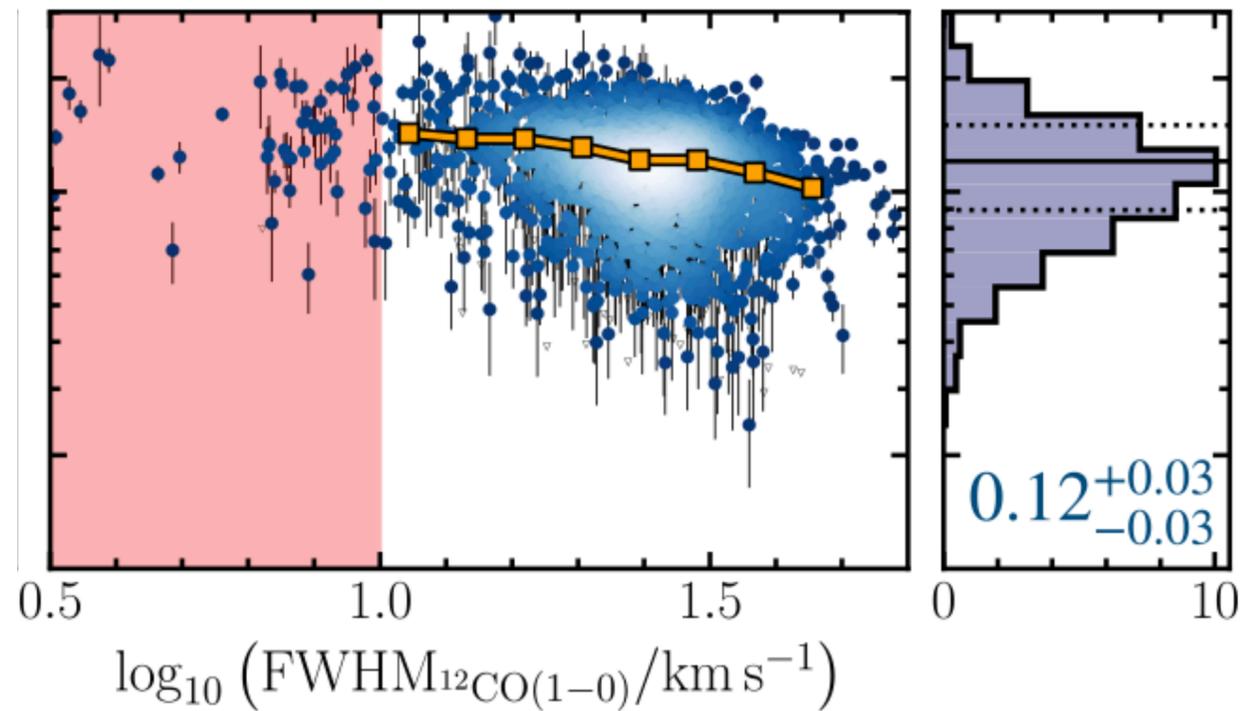
den Brok et al. (2025)

$$R_{10}^{13/12} \equiv W [^{13}\text{CO}(1-0)] / W [^{12}\text{CO}(1-0)]$$



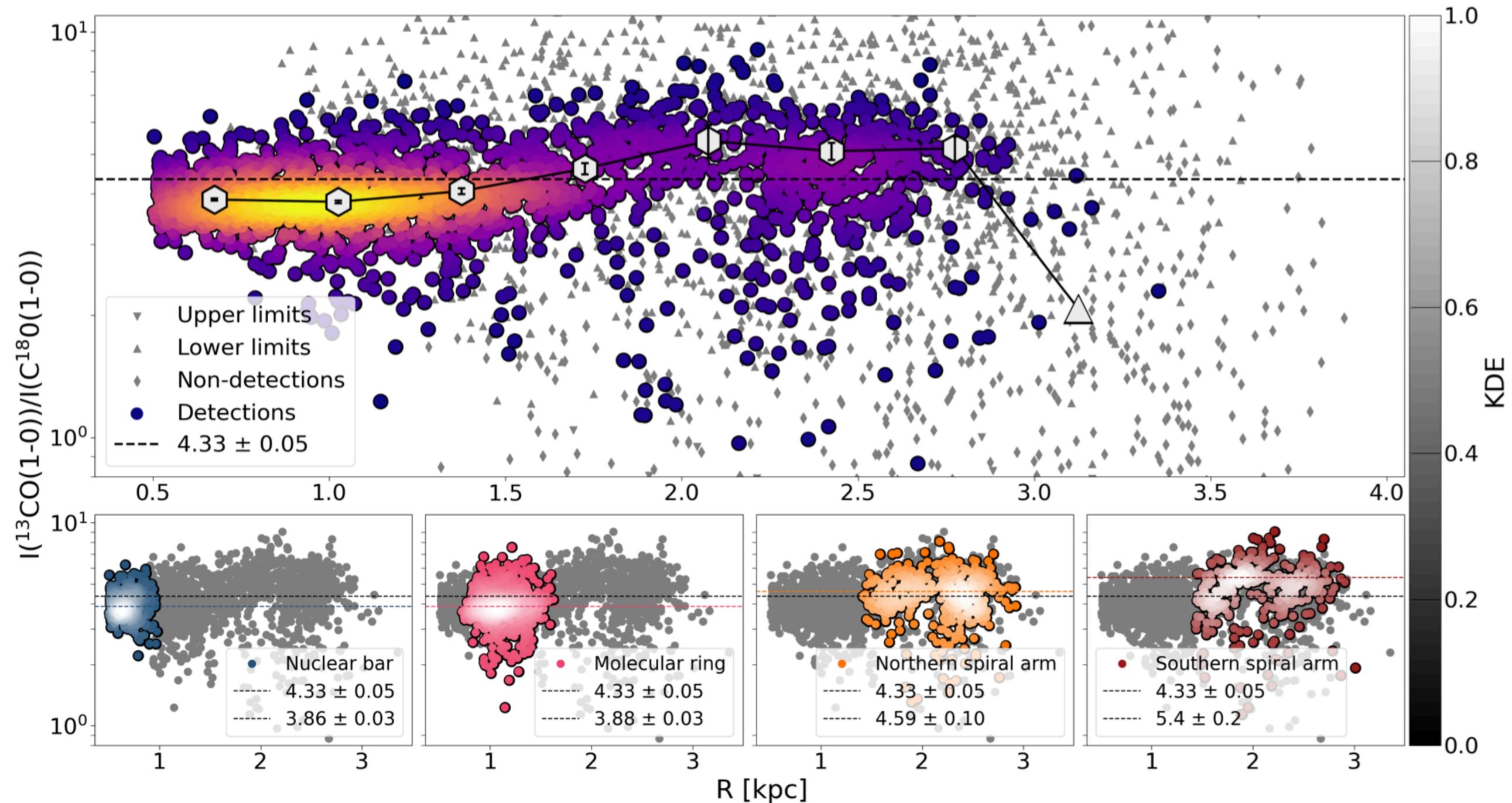
full non-LTE modelling of $J=1-0, 2-1$ of ^{12}CO & ^{13}CO

nonLTE α_{CO} and the line ratio $R_{10}^{13/12}$



$^{13}\text{CO}/^{18}\text{CO}$ ratio variations on cloud-scales

Galič et al. (2025)



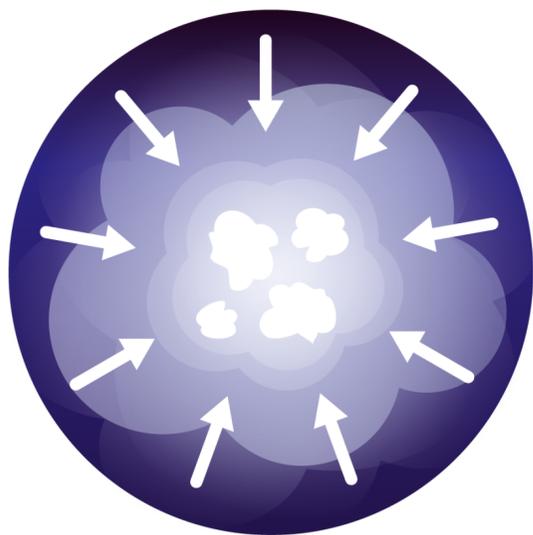
variation due to selective nucleosynthesis & optical depth effects

cloud-scale observations resolve:

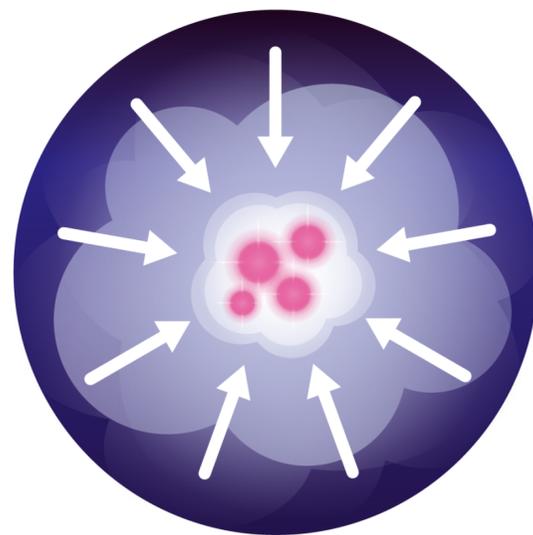
SCHEMATIC VIEW OF MOLECULAR CLOUD EVOLUTION



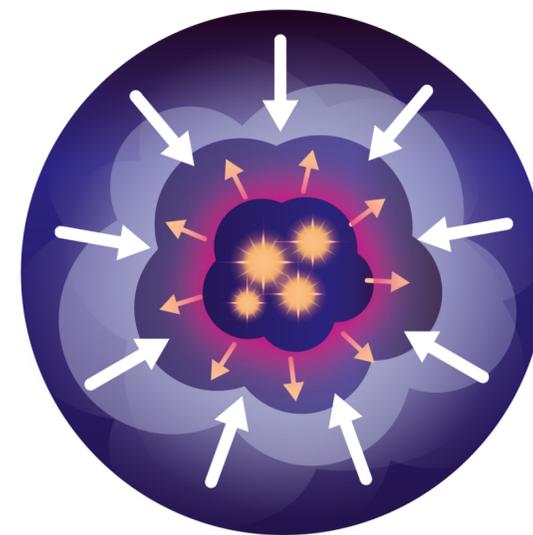
molecular cloud



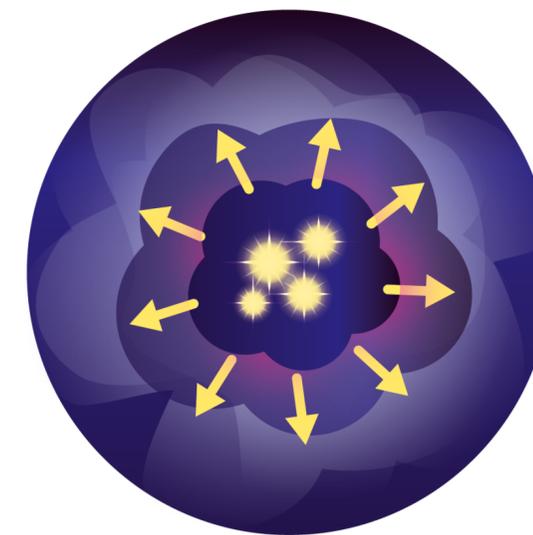
dense gas formation



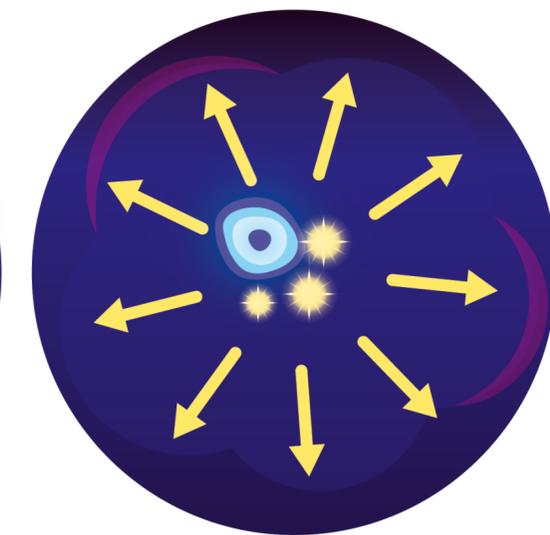
onset of star formation



pre-supernovae stellar feedback



cloud disruption



cloud dispersal & supernova explosions

tracers in ALMA Band 2

bulk gas

dense gas

CO & isotopologues

HCN, HNC, HCO+ etc. & deuterated species

dense gas tracer in ALMA Band 2

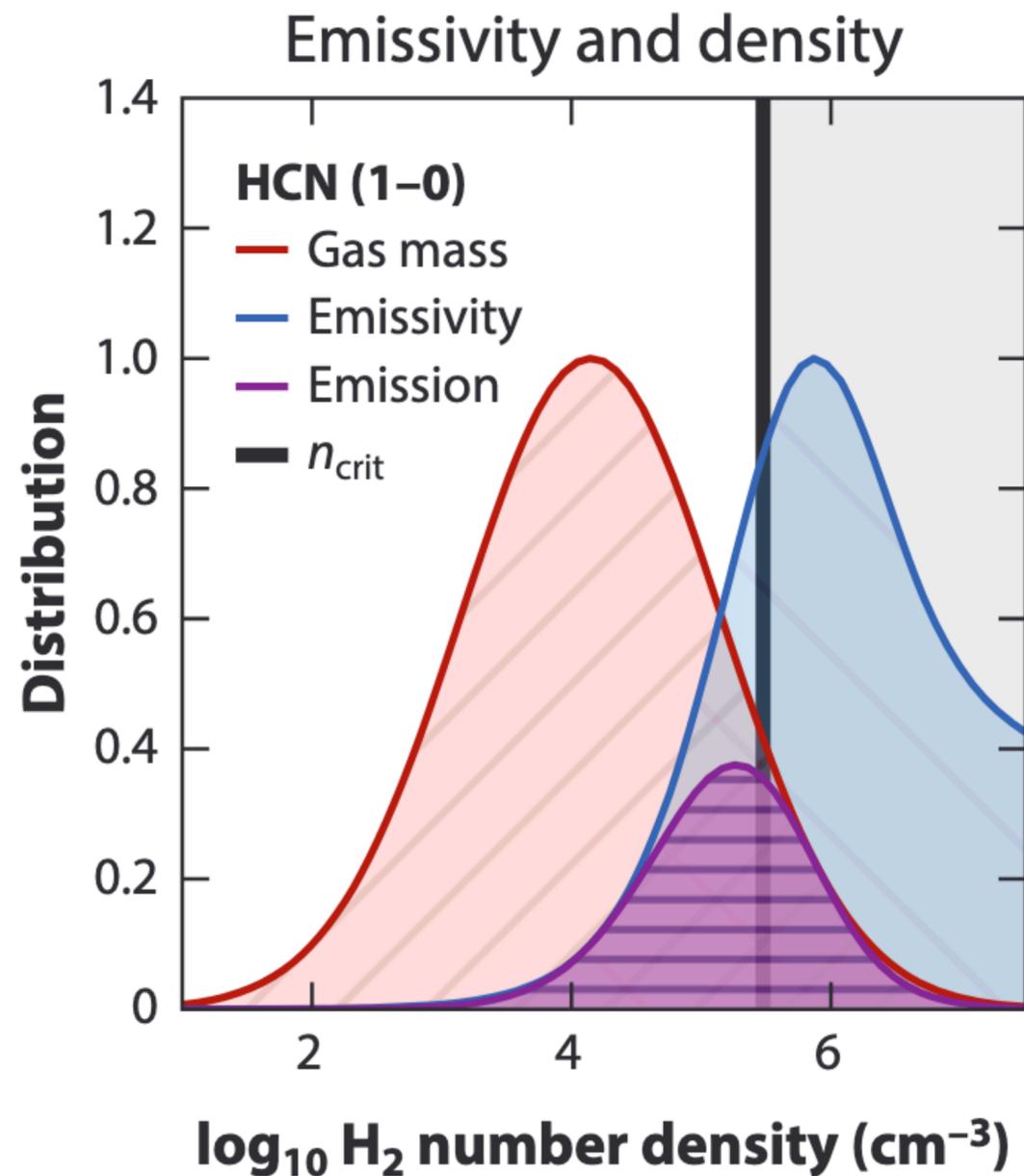
Schinnerer & Leroy (2024)

Species	Transition	CO(1–0) ratio ^a (K)	$n_{\text{crit}}^{\text{b}}$ (cm ⁻³)	References for line ratios	References for critical density calculations
¹² CO ^c	(1–0)	1.00	5.7×10^2		Yang et al. 2010
¹² CO ^c	(2–1)	0.65	4.4×10^3	Leroy et al. 2022 ^d	Yang et al. 2010
¹² CO ^c	(3–2)	0.31	1.5×10^4	Leroy et al. 2022 ^d	Yang et al. 2010
¹³ CO	(1–0)	0.091	4.8×10^2	Cormier et al. 2018 ^e	Yang et al. 2010
C ¹⁸ O	(1–0)	0.015	4.8×10^2	Jiménez-Donaire et al. 2017b ^f	Yang et al. 2010
HCN	(1–0)	0.024	3.0×10^5	Neumann et al. 2023^g	Dumouchel et al. 2010
HCO ⁺	(1–0)	0.0081	4.5×10^4	Neumann et al. 2023 ^g	Denis-Alpizar et al. 2020
CS	(2–1)	0.023	8.5×10^4	Neumann et al. 2023 ^g	Denis-Alpizar et al. 2018
HNC	(1–0)	0.011	1.1×10^5	Jiménez-Donaire et al. 2019	Dumouchel et al. 2010
CN	(1 _{3/2} –0 _{1/2}) ^h	0.022	2.4×10^5	Wilson 2018, Wilson et al. 2023 ⁱ	Lique et al. 2010
N ₂ H ⁺	(1–0)	0.0036	4.1×10^4	Jiménez-Donaire et al. 2023 ^j	Flower 1999 ^k

for **CN**, see work by, e.g., Ledger & Wilson

HCN and HCN/CO as dense gas or gas density tracer

Schinnerer & Leroy (2024)

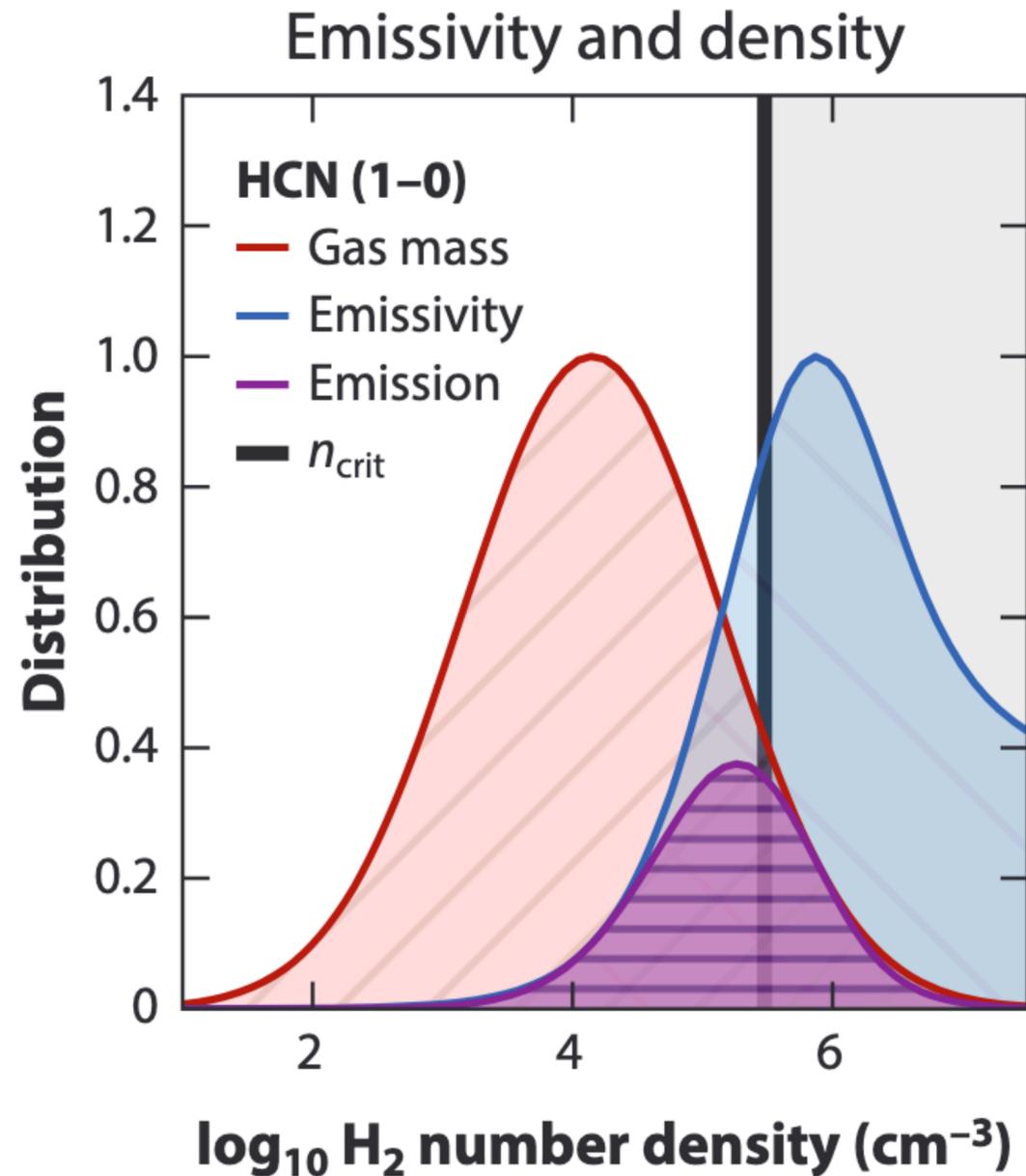


HCN

extragalactic dense gas tracer
~ 10-30x fainter than CO

HCN and HCN/CO as dense gas or gas density tracer

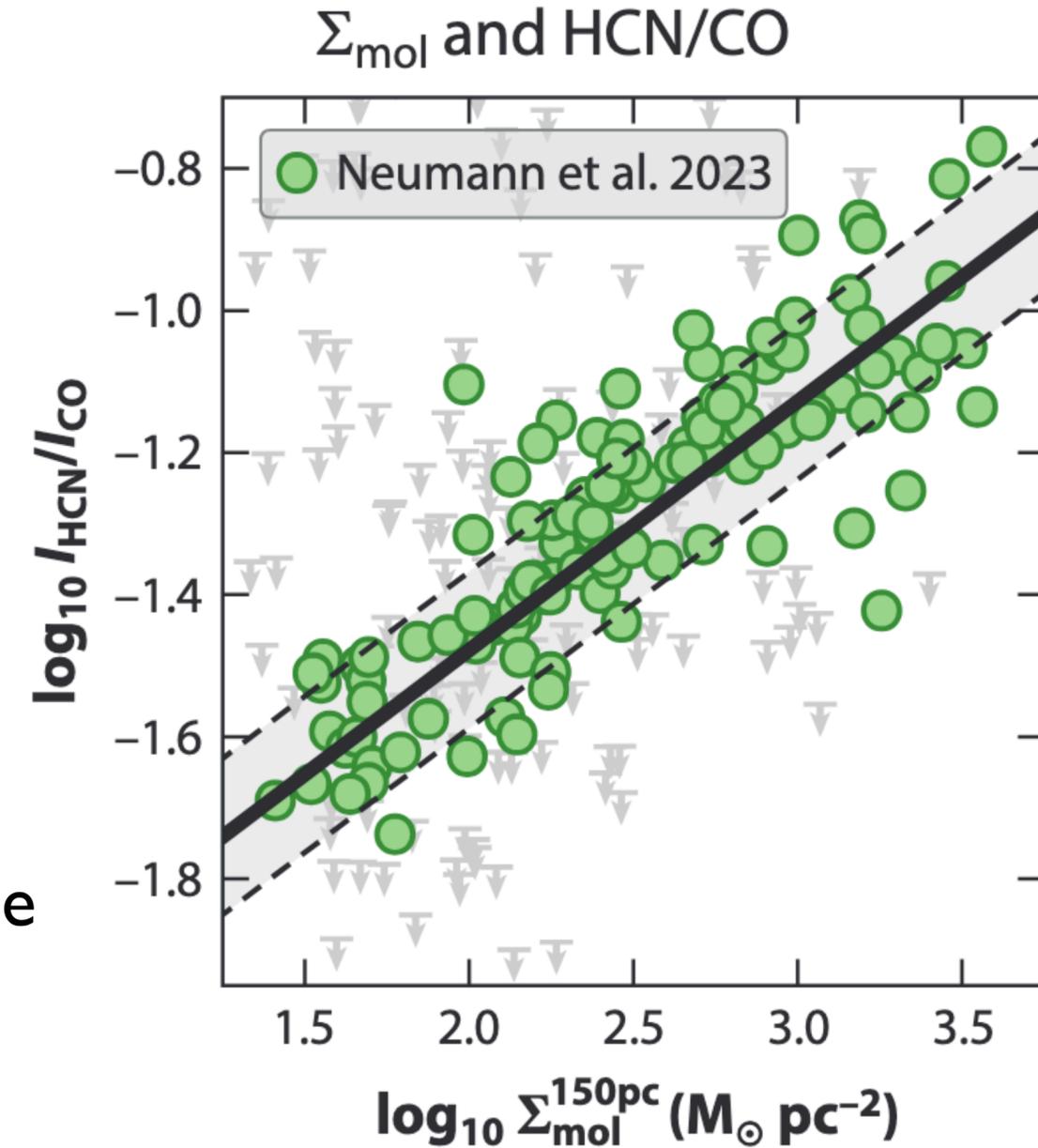
Schinnerer & Leroy (2024)



HCN

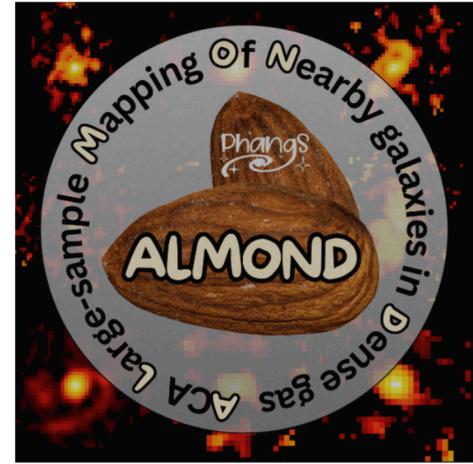
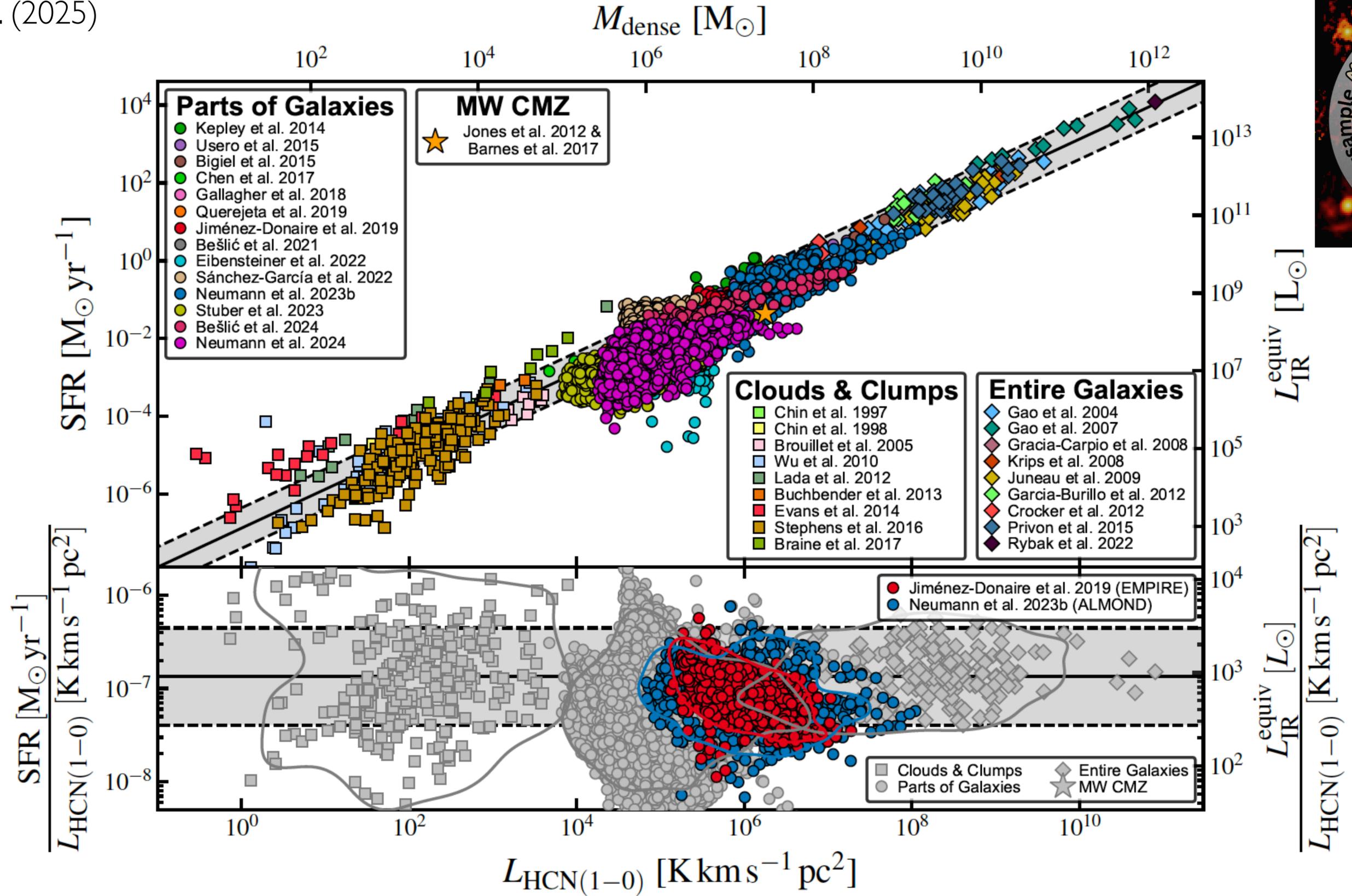
extragalactic dense gas tracer
 $\sim 10\text{-}30\times$ fainter than CO

HCN/CO @ kpc-scale
gas density tracer

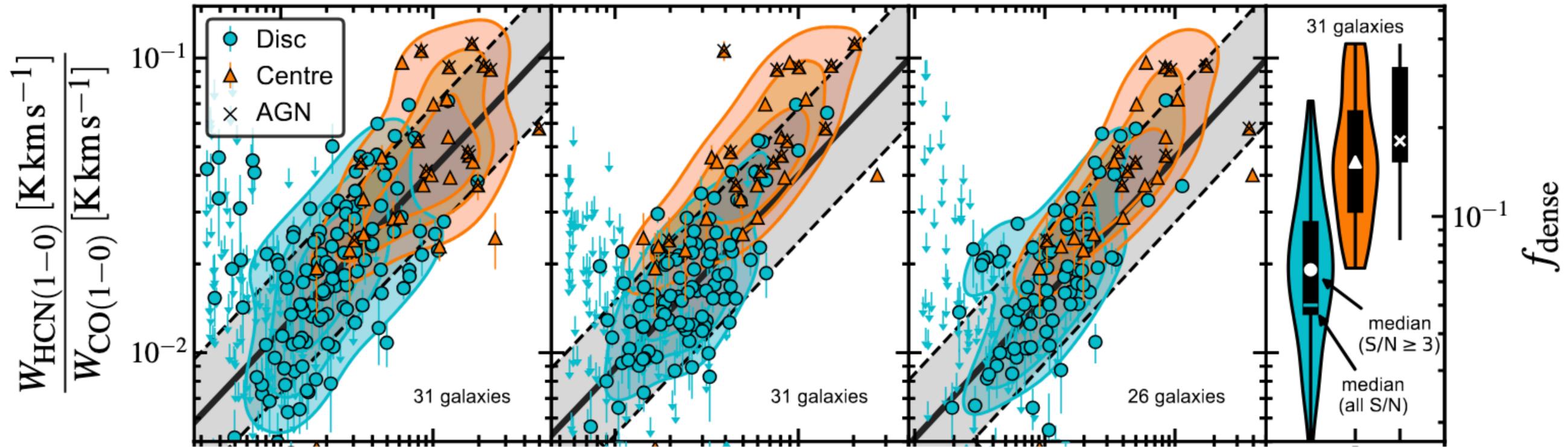


Gao-Solomon relation from Galactic clumps to entire galaxies

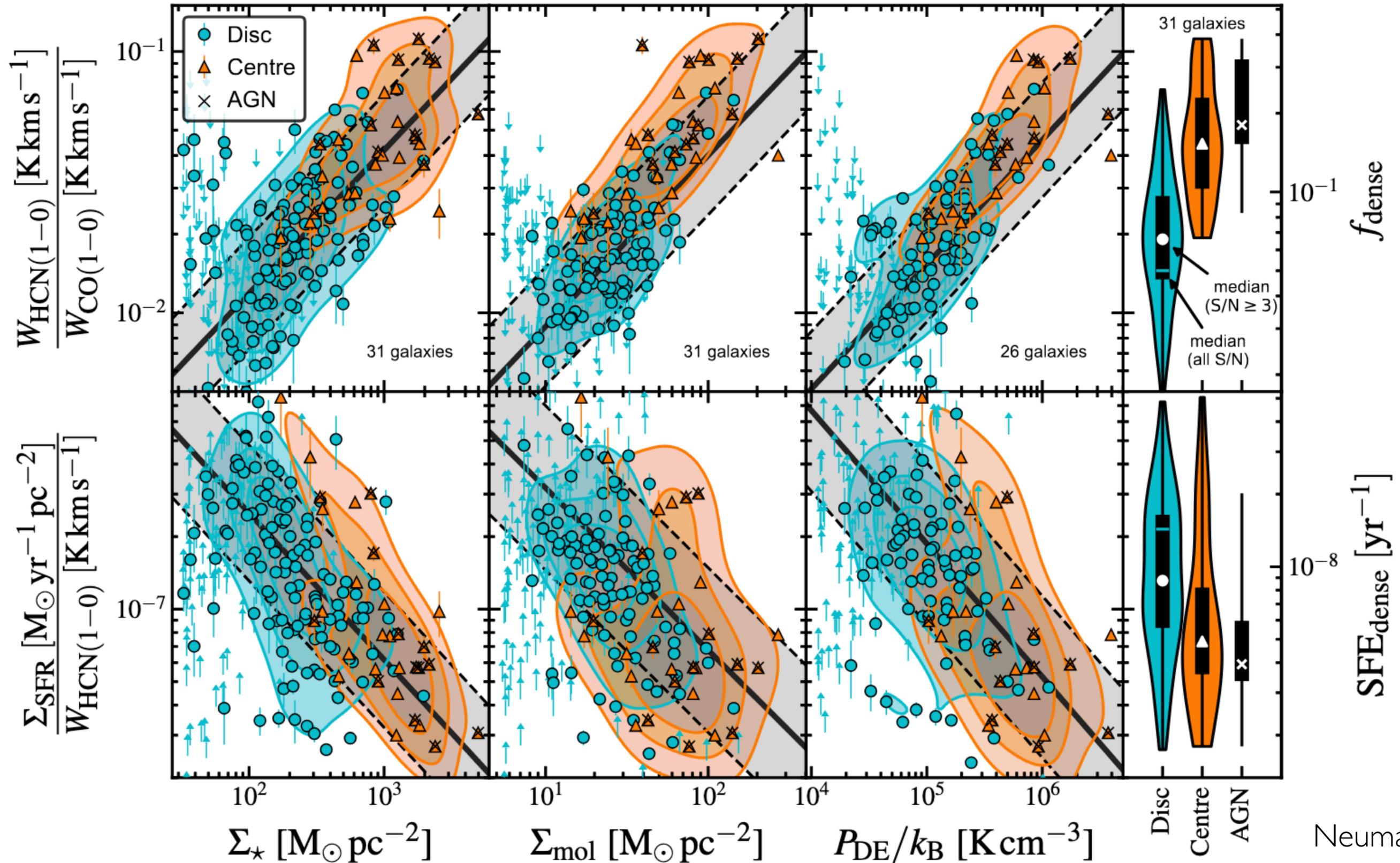
Neumann et al. (2025)



dense gas \neq collapsing gas \neq high SFR



dense gas \neq collapsing gas \neq high SFR



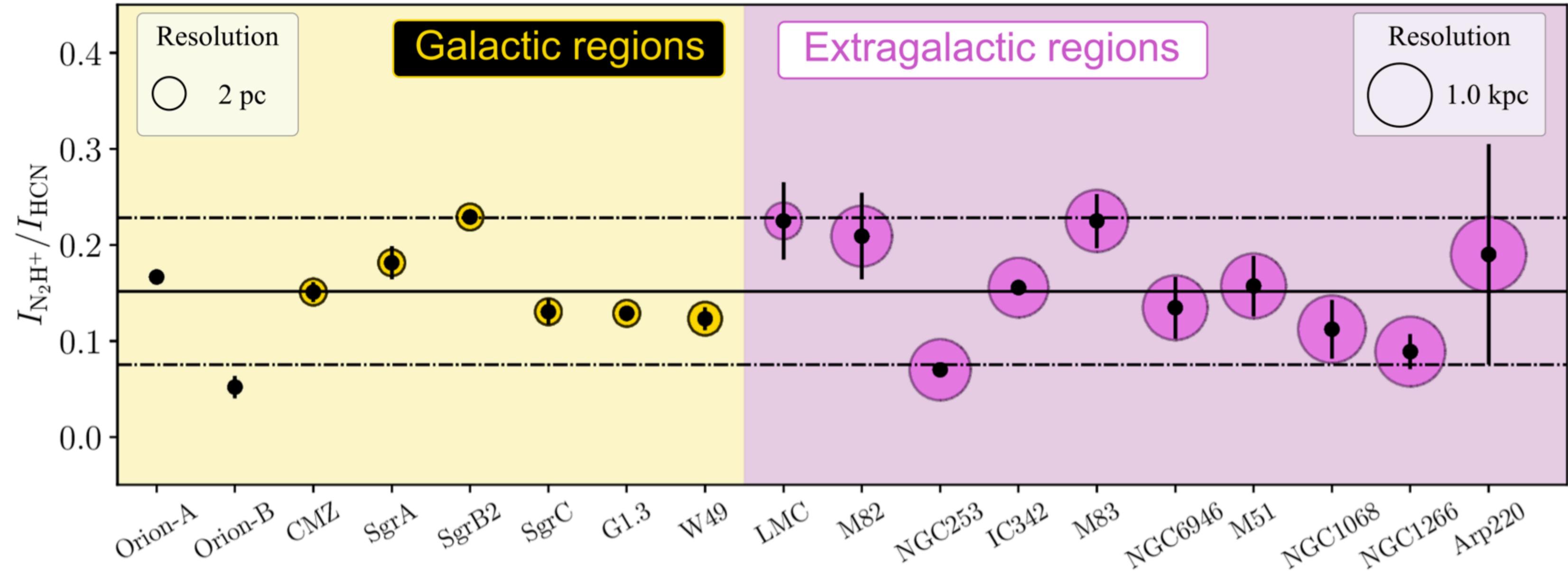
gas density tracer in ALMA Band 2

Schinnerer & Leroy (2024)

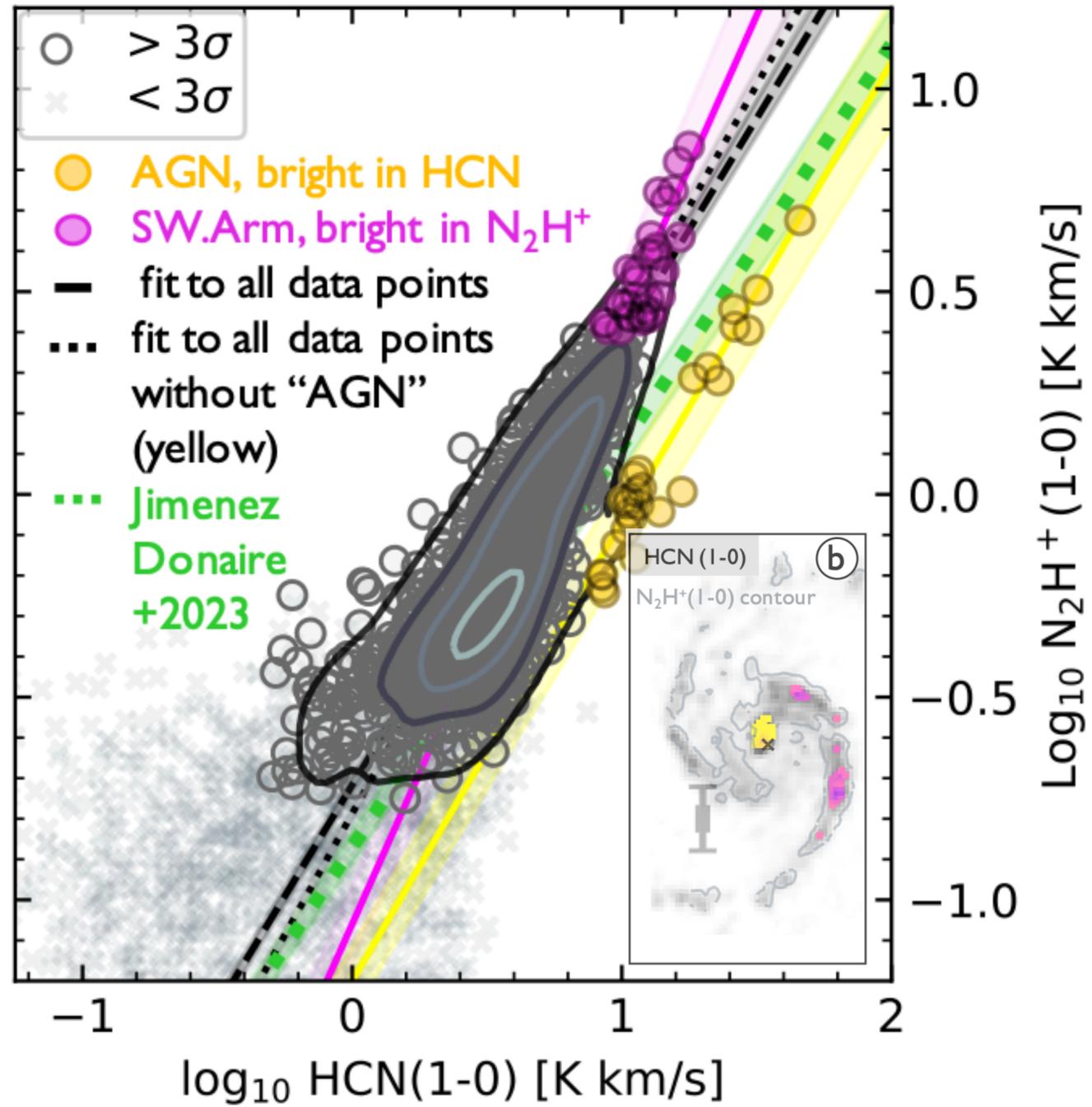
Species	Transition	CO(1–0) ratio ^a (K)	$n_{\text{crit}}^{\text{b}}$ (cm ⁻³)	References for line ratios	References for critical density calculations
¹² CO ^c	(1–0)	1.00	5.7×10^2		Yang et al. 2010
¹² CO ^c	(2–1)	0.65	4.4×10^3	Leroy et al. 2022 ^d	Yang et al. 2010
¹² CO ^c	(3–2)	0.31	1.5×10^4	Leroy et al. 2022 ^d	Yang et al. 2010
¹³ CO	(1–0)	0.091	4.8×10^2	Cormier et al. 2018 ^e	Yang et al. 2010
C ¹⁸ O	(1–0)	0.015	4.8×10^2	Jiménez-Donaire et al. 2017b ^f	Yang et al. 2010
HCN	(1–0)	0.024	3.0×10^5	Neumann et al. 2023^g	Dumouchel et al. 2010
HCO ⁺	(1–0)	0.0081	4.5×10^4	Neumann et al. 2023 ^g	Denis-Alpizar et al. 2020
CS	(2–1)	0.023	8.5×10^4	Neumann et al. 2023 ^g	Denis-Alpizar et al. 2018
HNC	(1–0)	0.011	1.1×10^5	Jiménez-Donaire et al. 2019	Dumouchel et al. 2010
CN	(1 _{3/2} –0 _{1/2}) ^h	0.022	2.4×10^5	Wilson 2018, Wilson et al. 2023 ⁱ	Lique et al. 2010
N₂H⁺	(1–0)	0.0036	4.1×10^4	Jiménez-Donaire et al. 2023^j	Flower 1999^k

comparing extragalactic HCN to the classical Galactic N_2H^+

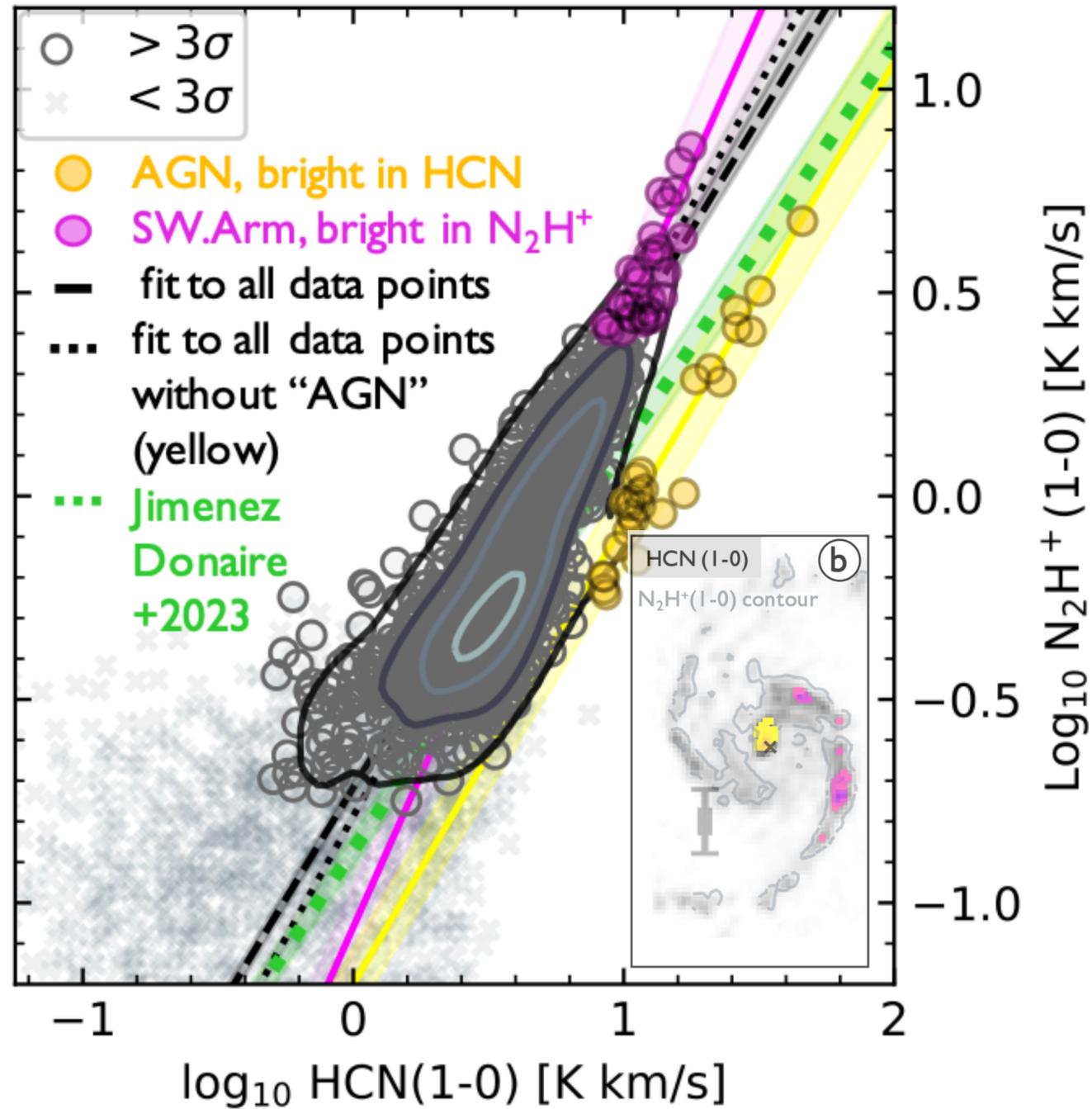
compilation of Galactic and extragalactic observations: N_2H^+ $\sim 6\times$ fainter than HCN



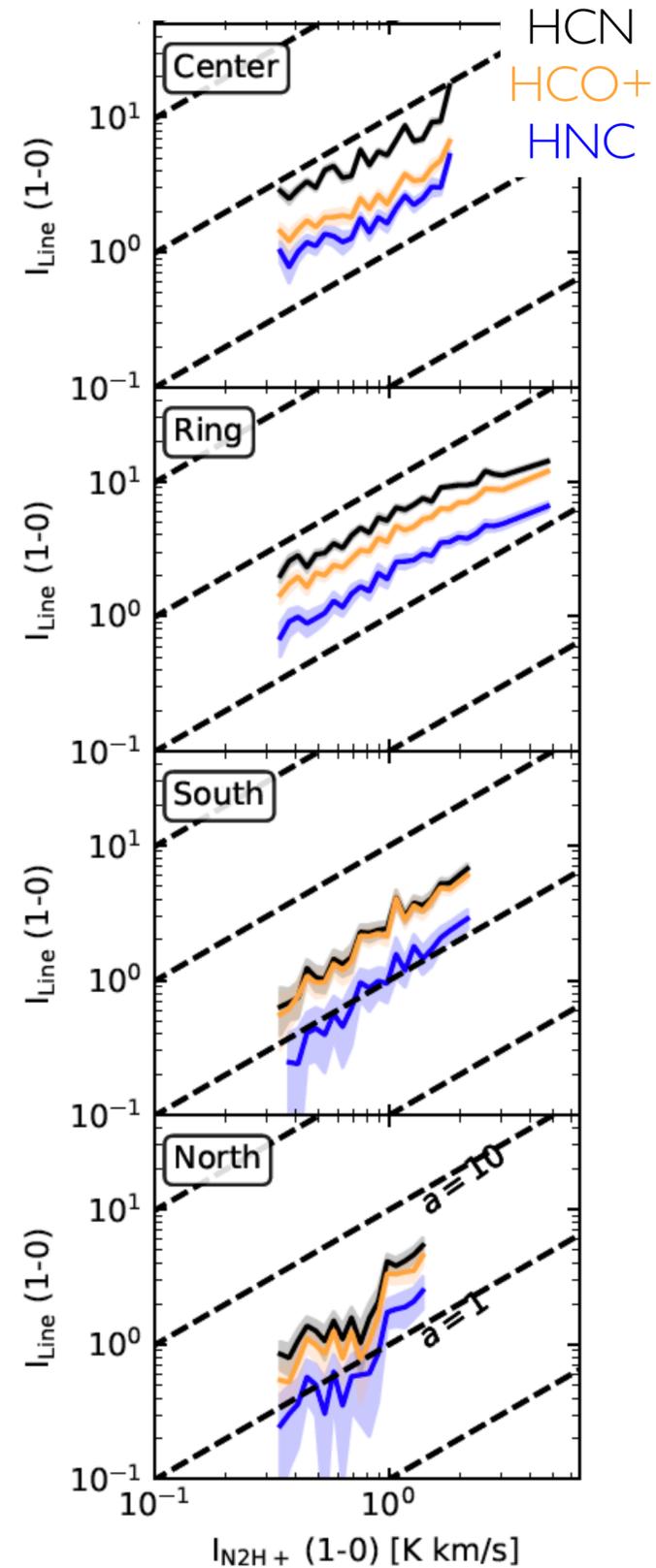
What are good tracers of gas density or dense gas at cloud-scales?



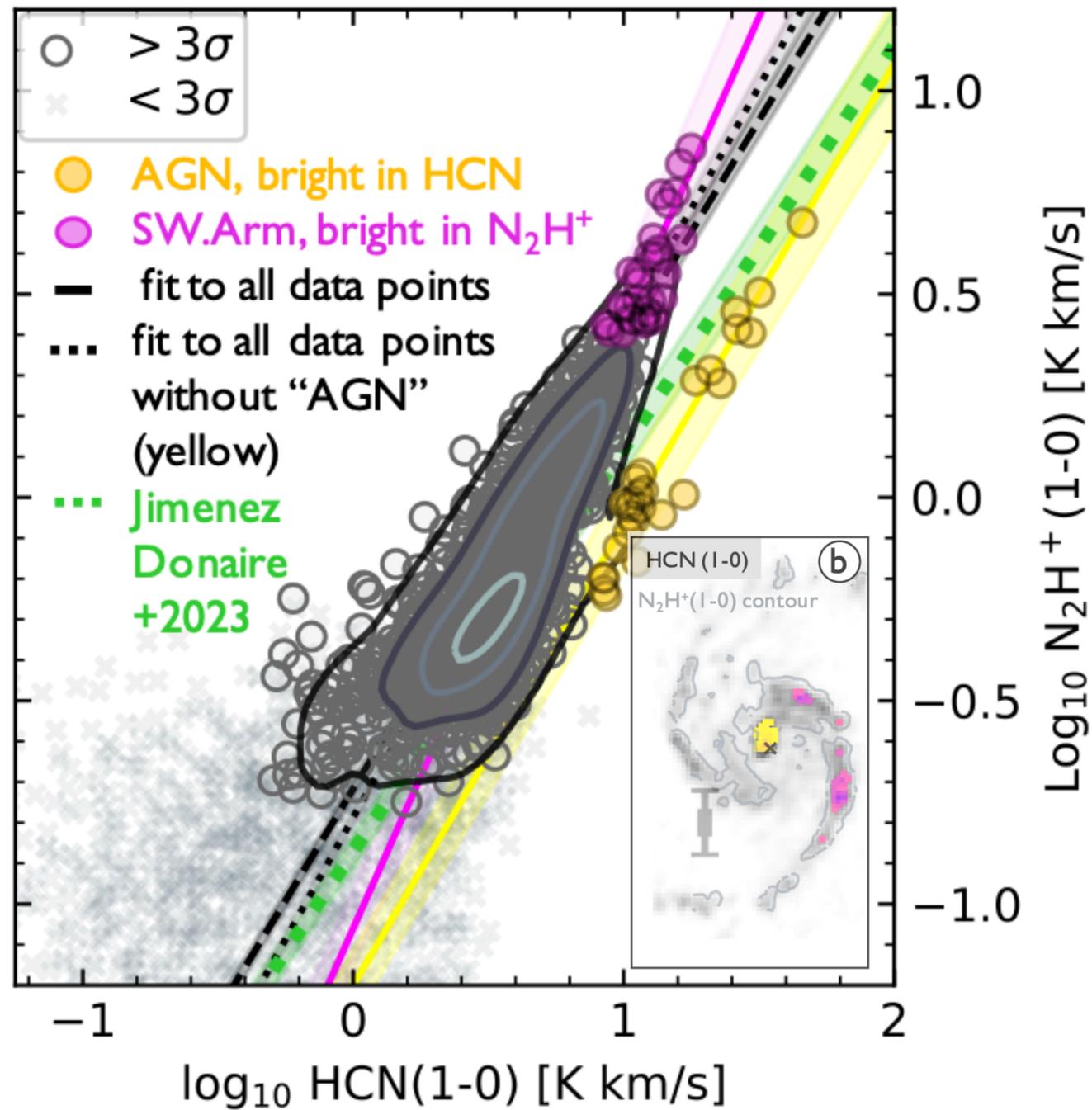
What are good tracers of gas density or dense gas at cloud-scales?



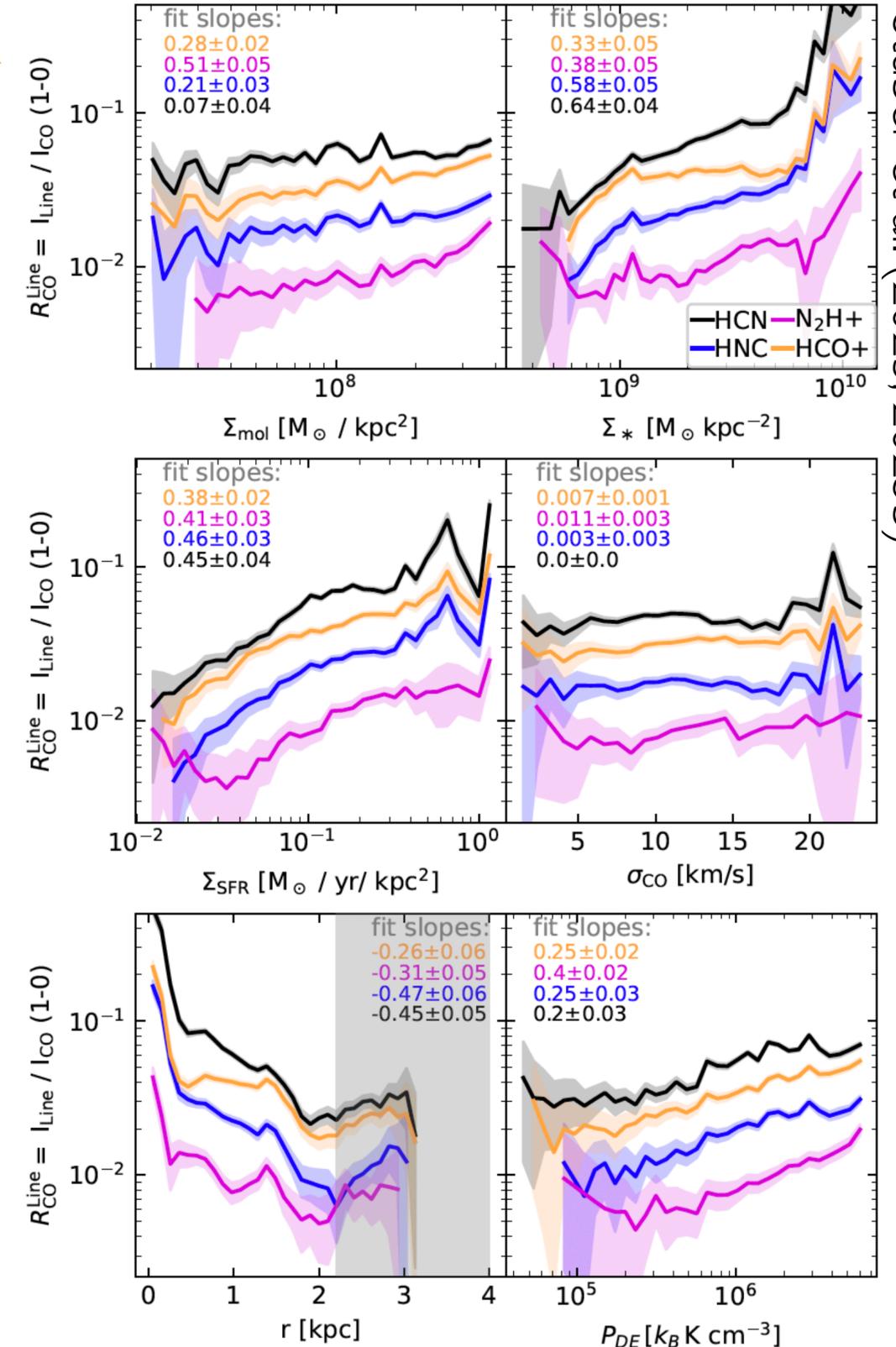
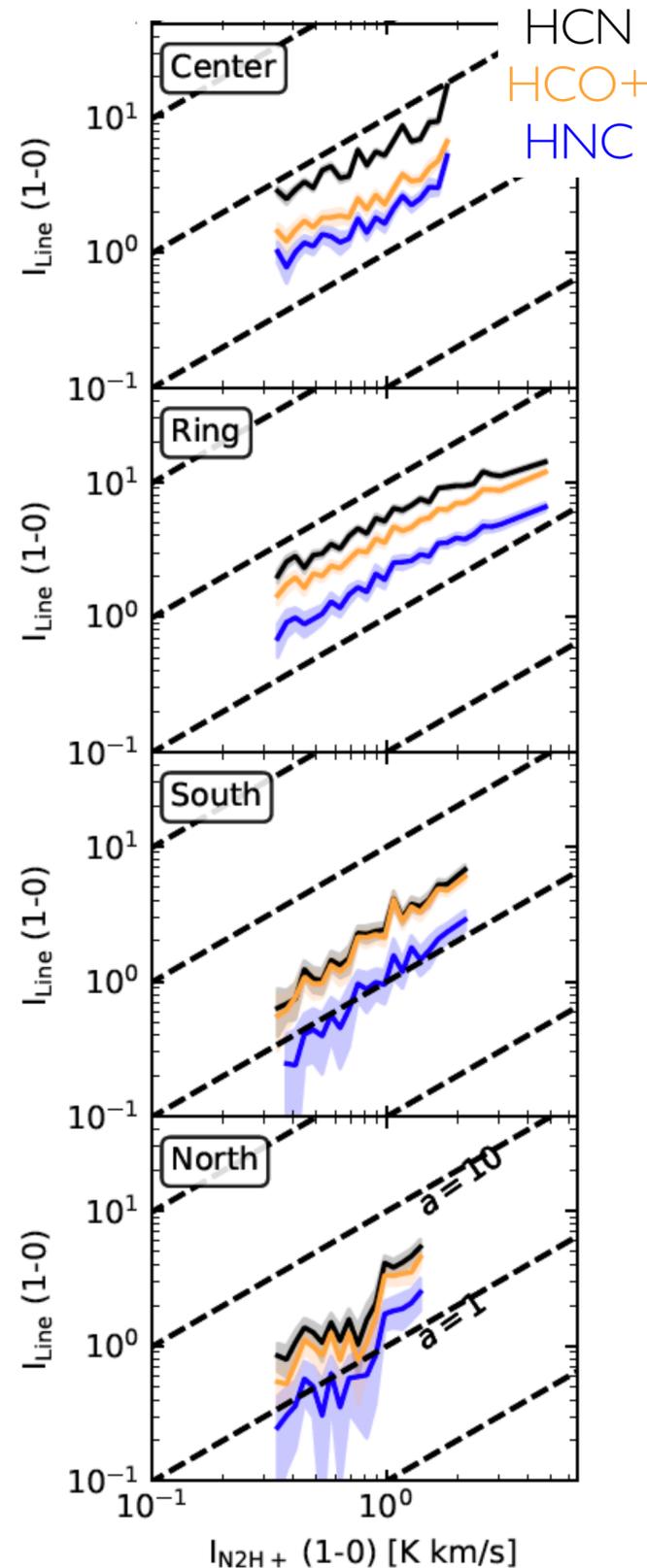
HCO+ probably more robust than HCN



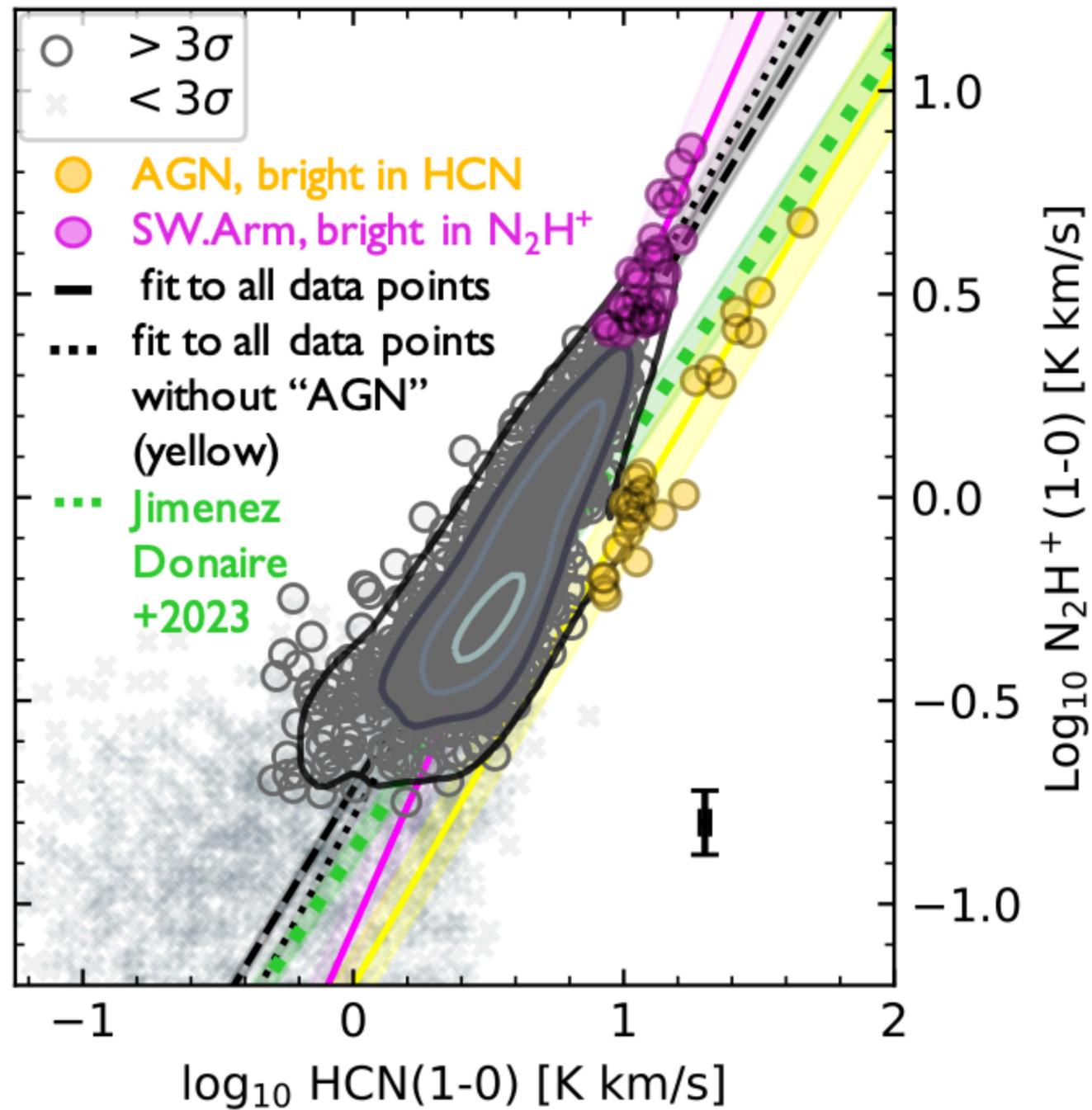
What are good tracers of gas density or dense gas at cloud-scales?



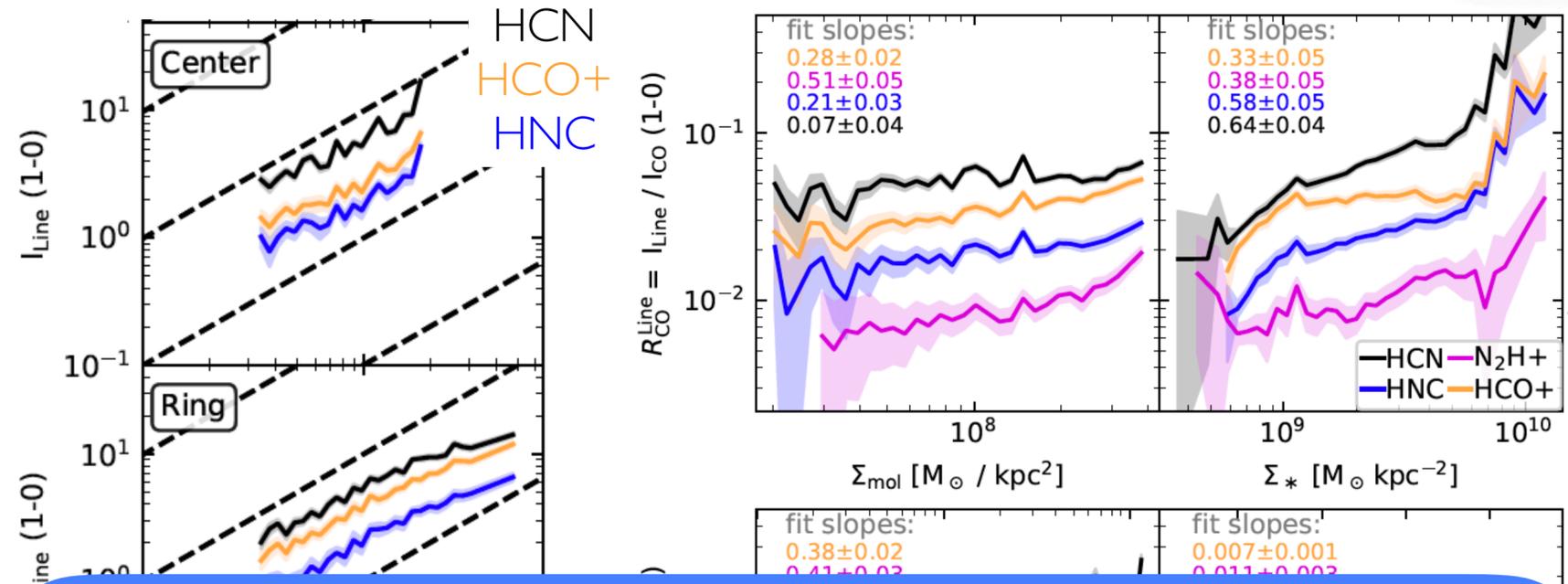
HCO+ probably more robust than HCN
 local conditions impact cloud-scale emission



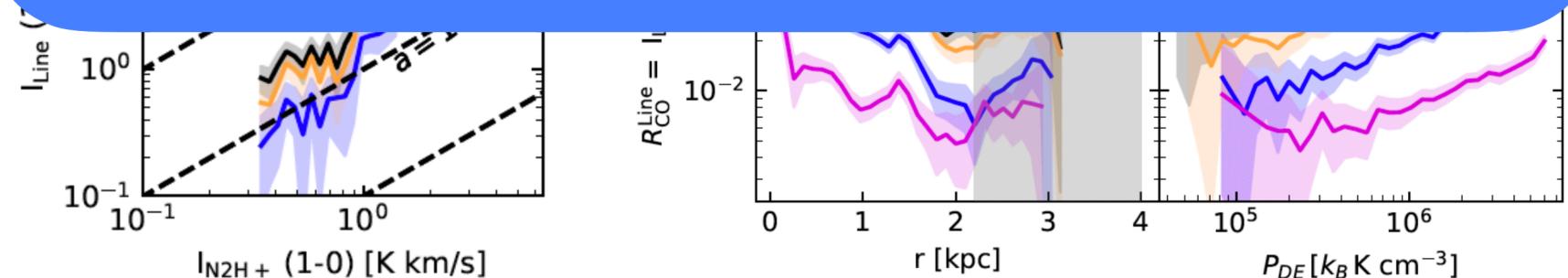
What are good tracers of gas density or dense gas at cloud-scales?



HCO+ probably more robust than HCN
 local conditions impact cloud-scale emission



astro-chemical surveys like ALCHEMI
 (center of NGC253, Martin et al. 2021)
 are critical to benchmark mm-lines as tracers



deuterated species as a new window on dense gas?

The Science Case for ALMA Band 2 and Band 2+3

G. A. Fuller¹ A. Avison¹ M. Beltrán² V. Casasola³ P. Caselli⁴
 C. Cicone⁵ F. Costagliola⁶ C. De Breuck⁷ L. Hunt² I. Jimenez-Serra⁷
 R. Laing⁷ S. Longmore⁸ M. Massardi³ T. Mroczkowski⁷ R. Paladino³
 S. Ramstedt⁹ A. Richards¹ L. Testi^{2,7,10} D. Vergani¹¹ S. Viti¹²
 J. Wagg¹³

Table 1: Deuterated Species and Transitions in ALMA Band 2

Deuterated Species					
Molecule		Freq. (GHz)	Molecule		Freq. (GHz)
CH ₂ D ⁺	1(1,0)-1(1,1)	67.273	DN ¹³ C	J=1-0	73.367
D ¹³ CO ⁺	J=1-0	70.733	DNC	J=1-0	76.306
D ¹³ CN	J=1-0	71.175	DOC ⁺	J=1-0	76.386
DCO ⁺	J=1-0	72.039	N ₂ D ⁺	J=1-0	77.108
C ₂ D	N=1-0	72.108	NH ₂ D	1(1,1)0 - 1(0,1)0	85.926
DCN	J=1-0	72.415			

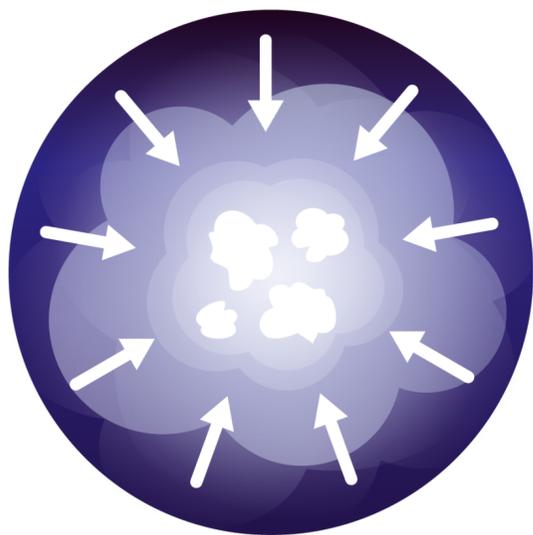
see next talk by Rosita Paladino

cloud-scale observations resolve:

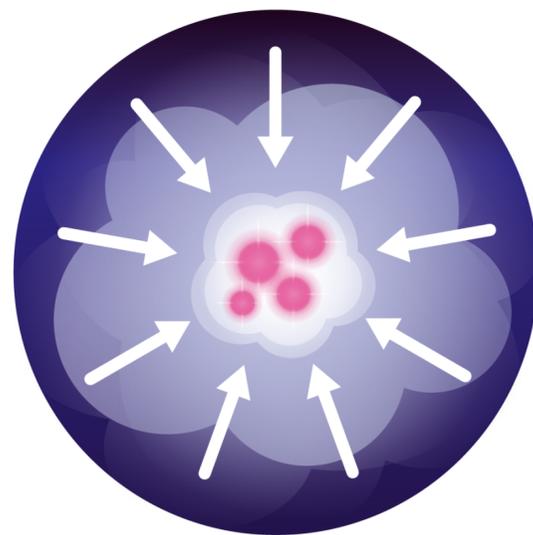
SCHEMATIC VIEW OF MOLECULAR CLOUD EVOLUTION



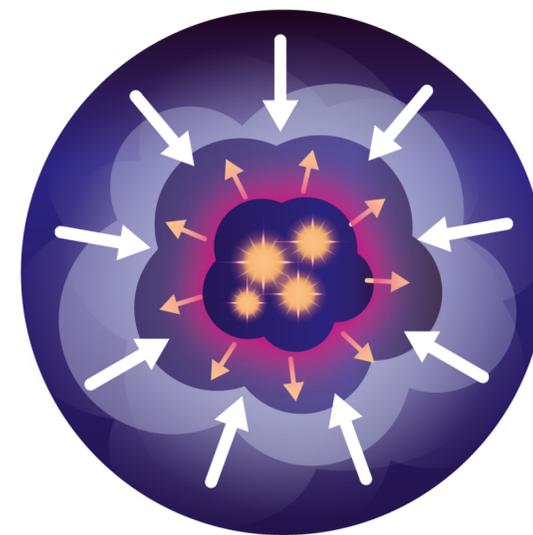
molecular cloud



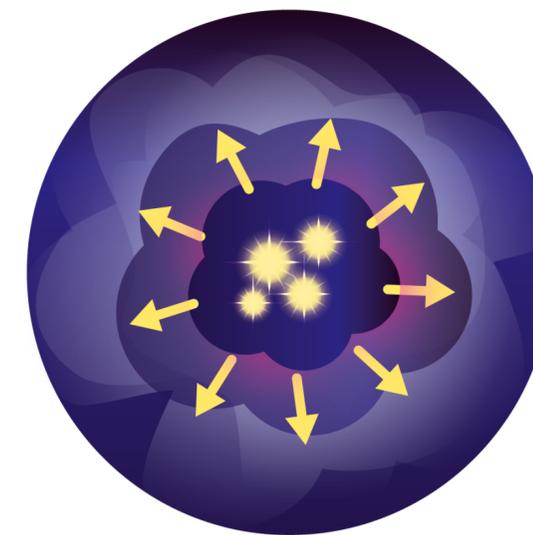
dense gas formation



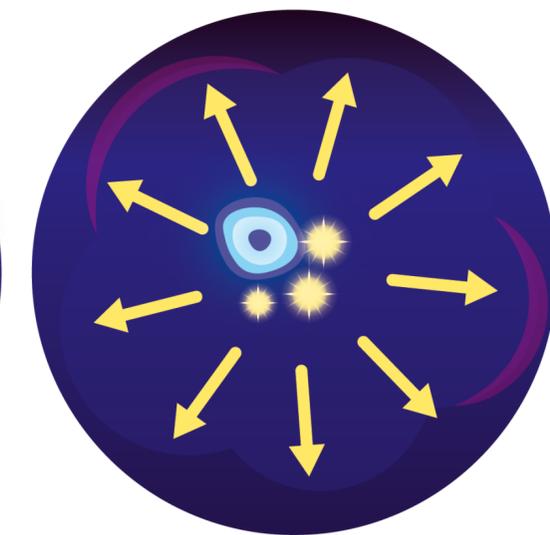
onset of star formation



pre-supernovae stellar feedback



cloud disruption



cloud dispersal & supernova explosions

tracers in ALMA Band 2

bulk gas

dense gas

star formation

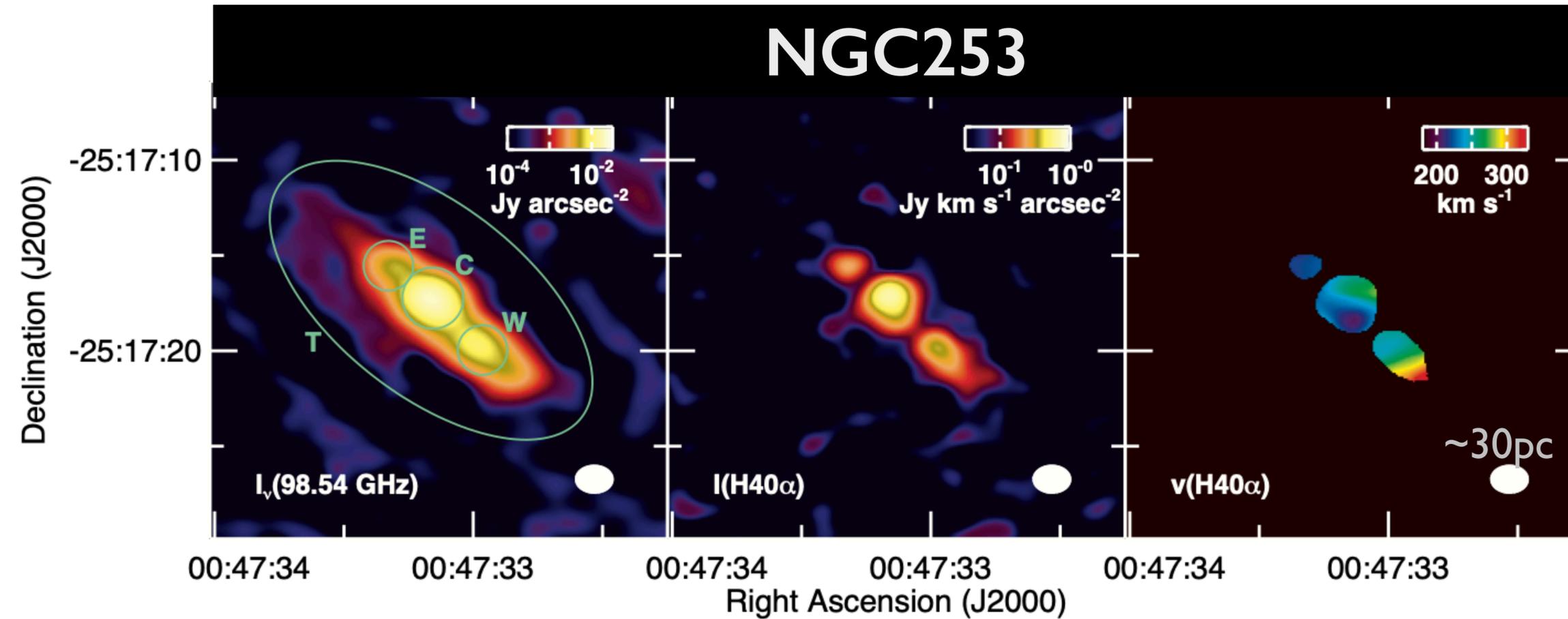
CO & isotopologues

HCN, HNC, HCO+ etc. & deuterated species

PDR (e.g., C₂H), RRLs (H70-75α), free-free

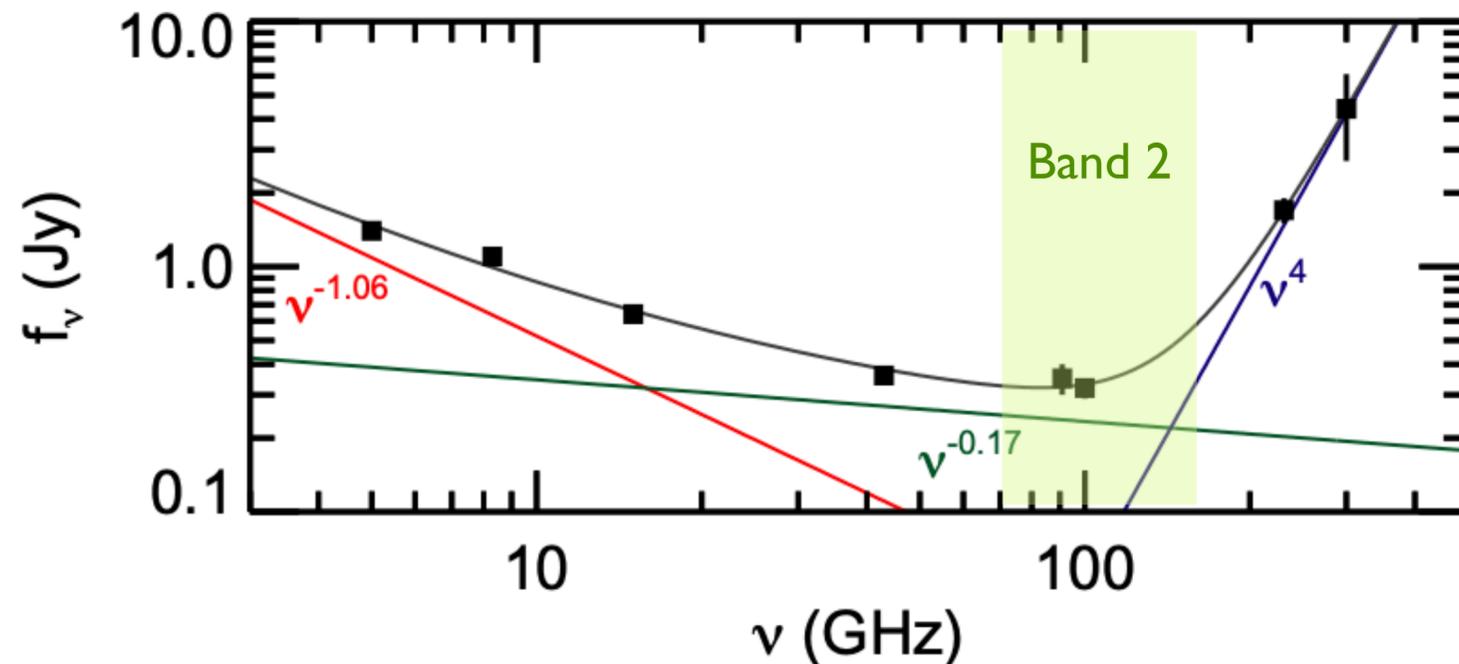
radio recombination lines (RRL) & free-free continuum

Bendo et al. (2015)



RRLs:

- very faint ($< 1\%$ CO)
- compact
- detected in $D < 5$ Mpc systems



free-free continuum emission

- similar SFR as from RRL
- low- ν end of Band 2 ideal

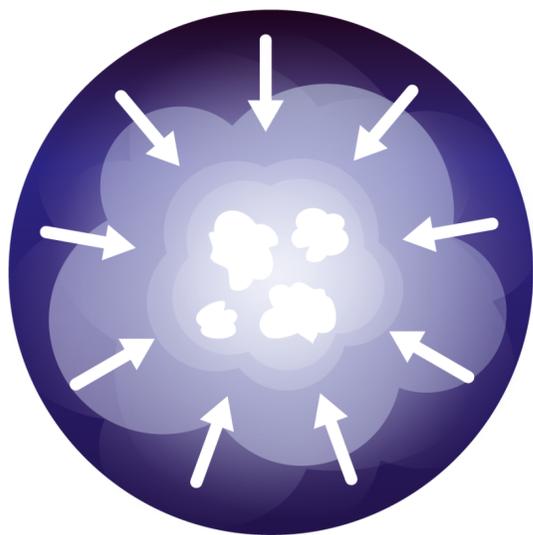
H43 α to H45 α become accessible with Band 2

cloud-scale observations resolve:

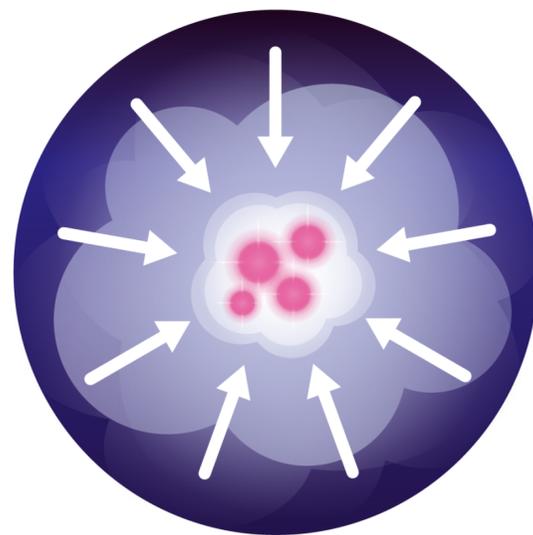
SCHEMATIC VIEW OF MOLECULAR CLOUD EVOLUTION



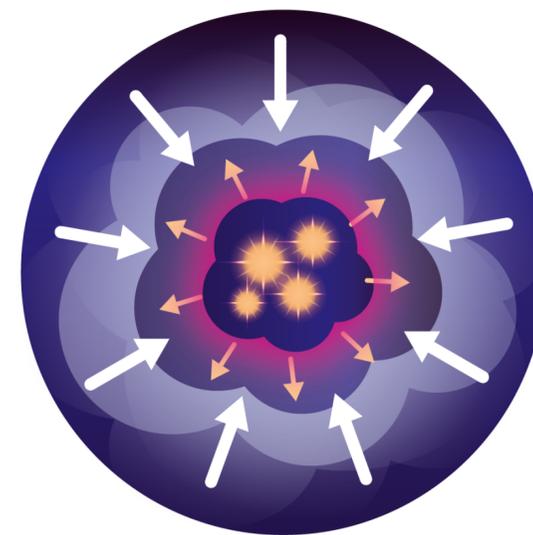
molecular cloud



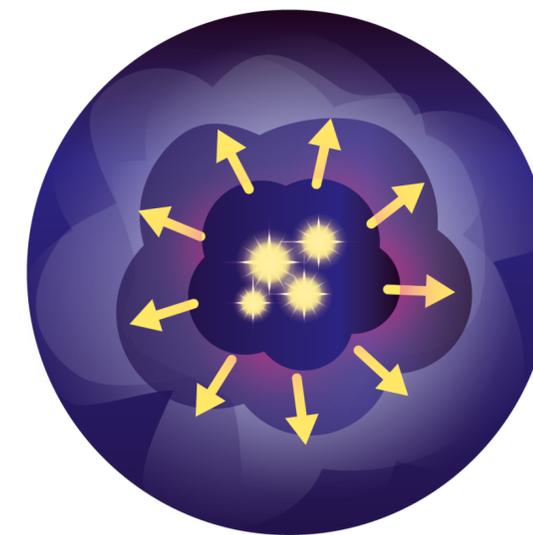
dense gas formation



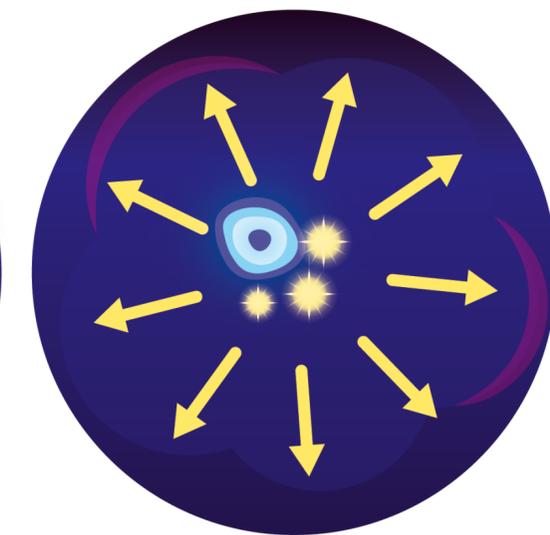
onset of star formation



pre-supernovae stellar feedback



cloud disruption



cloud dispersal & supernova explosions

tracers in ALMA Band 2

bulk gas

dense gas

star formation

shocks

CO & isotopologues

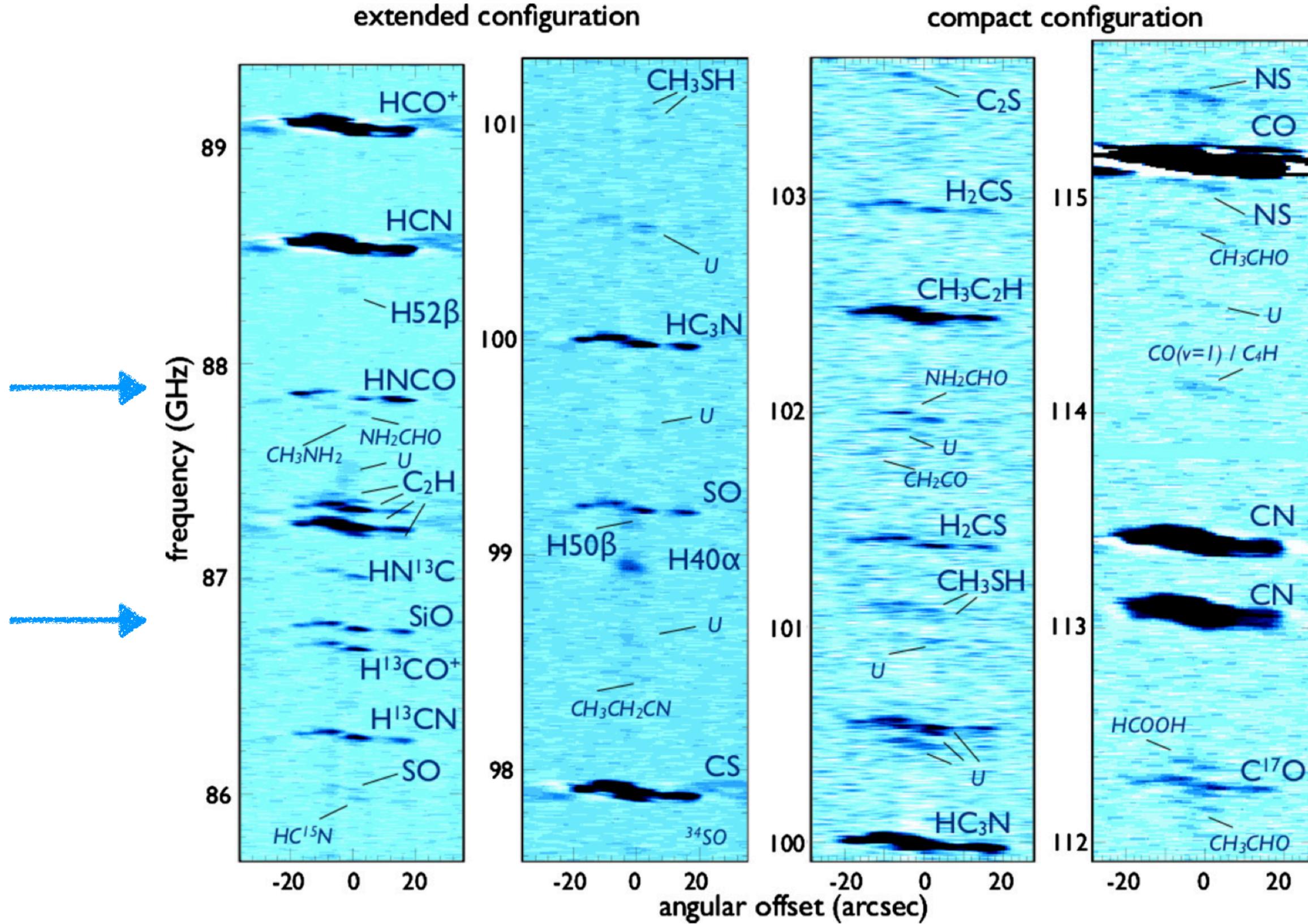
HCN, HNC, HCO⁺ etc. & deuterated species

PDR (e.g., C₂H), RRLs (H70-75α), free-free

SiO, HNCO, CH₃OH etc.

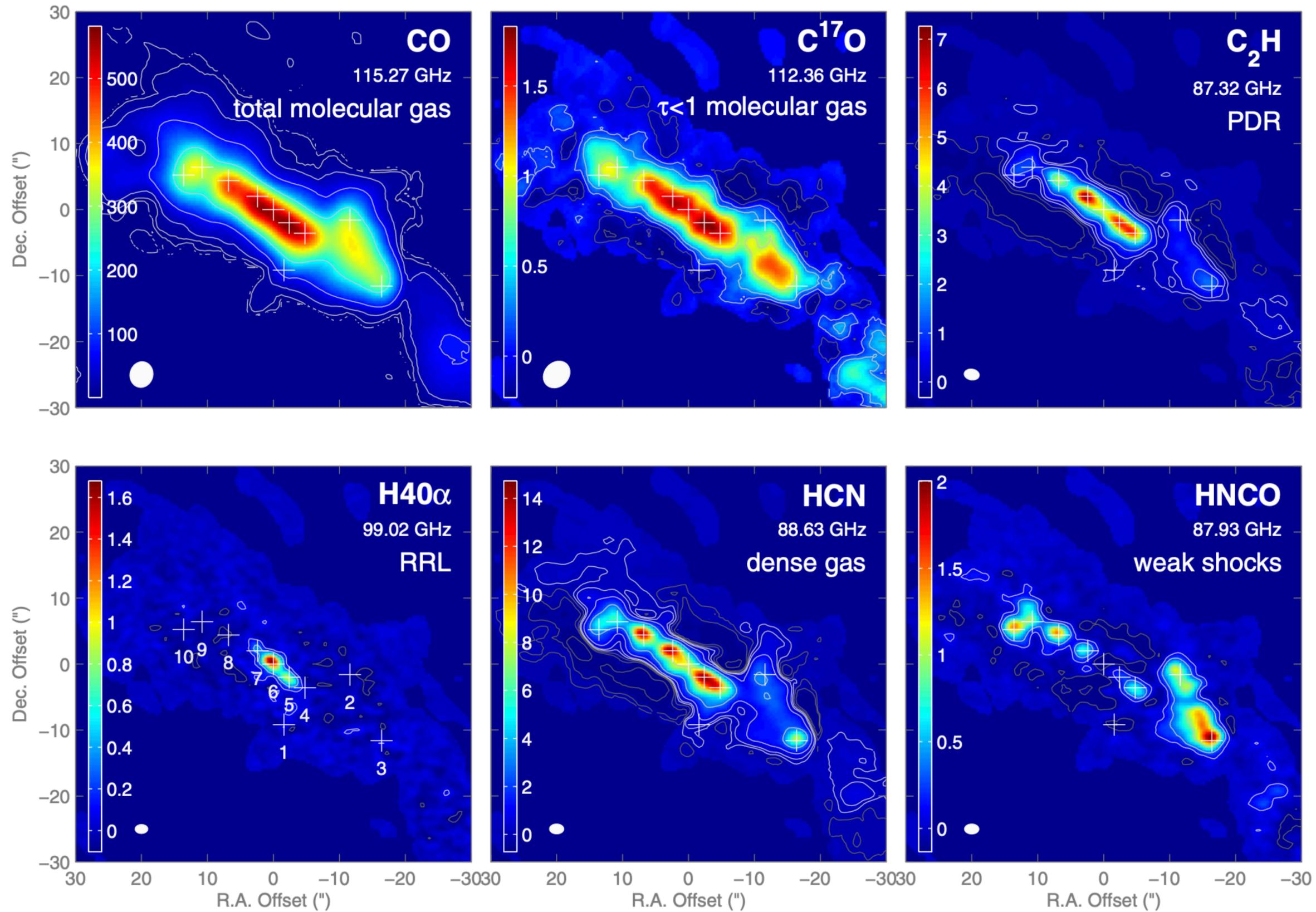
large-scale shock tracers

Meier et al. (2015)



Band 2 + WSU

Meier et al. (2015)



significant local variations in gas conditions

ALMA Band 2 is very rich in diverse tracers

- bulk molecular gas
- dense molecular phase
- star formation
- (large-scale) shocks

faintness of lines is a challenge

multiplexing will be essential \Rightarrow WSU is key

science opportunities
for studies
of nearby galaxies
using the new
ALMA Band 2 receiver