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Exploring dense gas in dusty star-forming galaxies with ALMA Band 1



Beth Westoby

PhD Student, Leiden Observatory

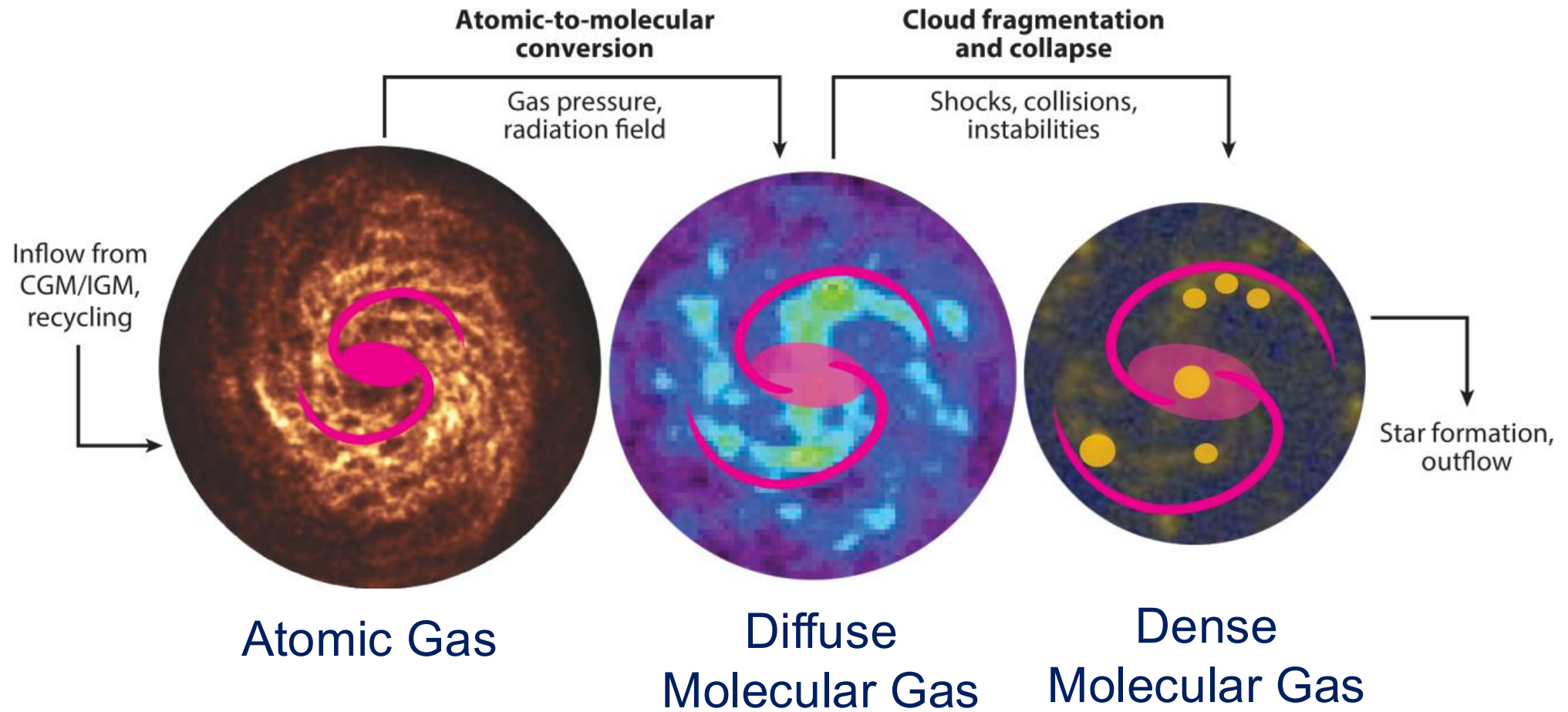
With M. Rybak, J. Hodge,
T. Greve, P. van der Werf, G. Sallaberry,
N. Geesink, M. Polvora da Fonesca,
J. van Marrewijk



Netherlands Astronomy Conference 2026

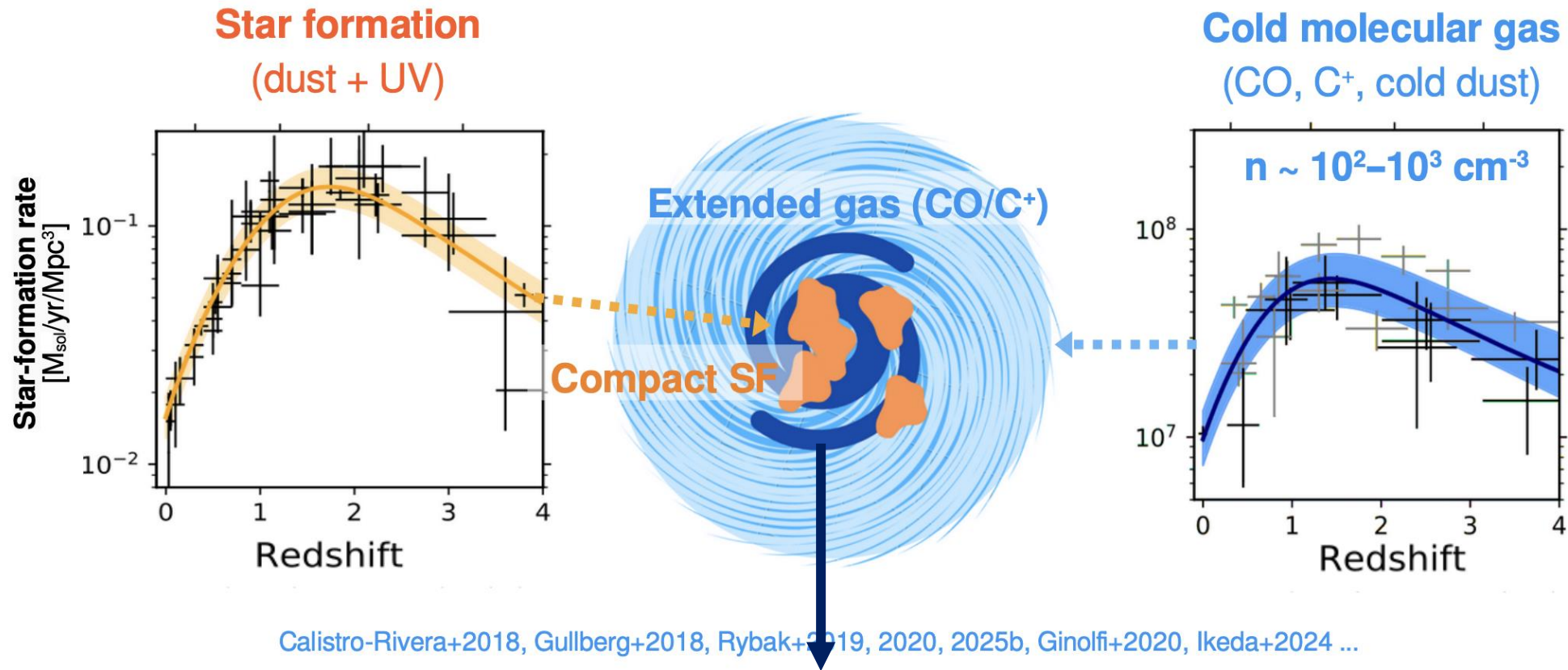


Galaxy Gas Content



Saintonge & Catinella 2022 Review

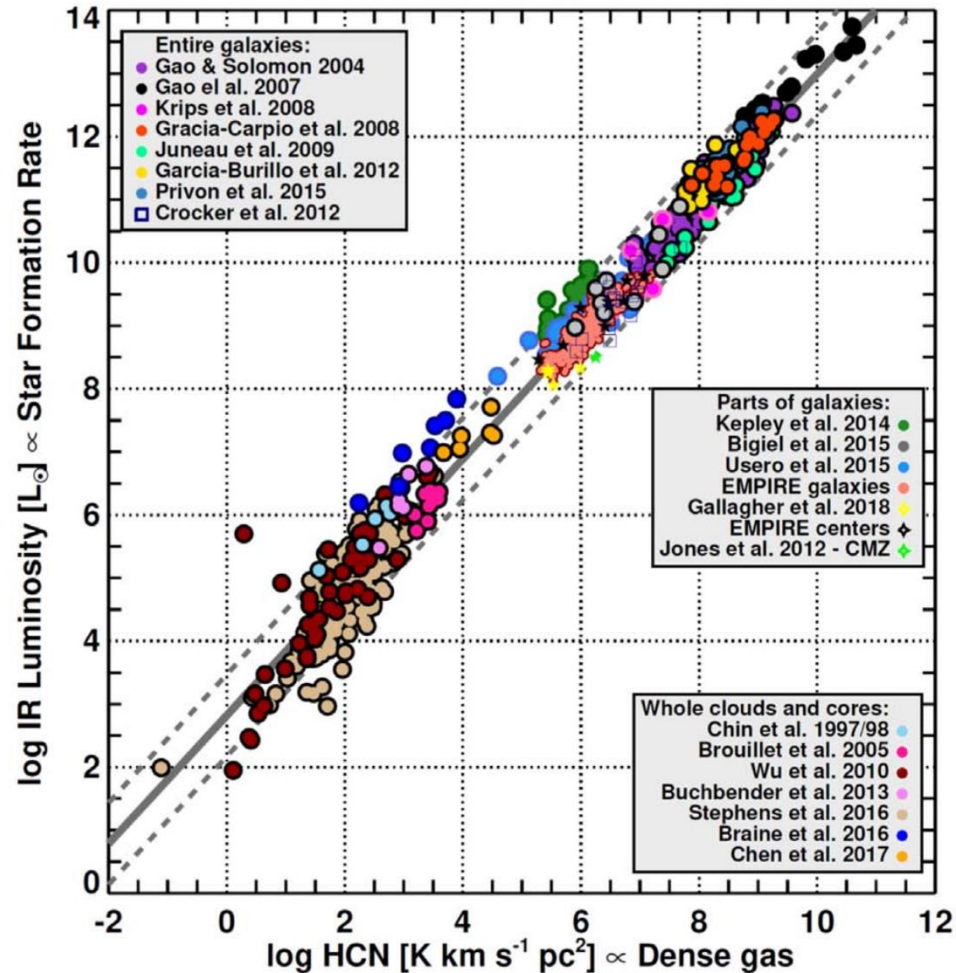
Galaxy Gas Content



What about dense gas?

Slide from Rybak *Monsters with empty bellies*

Dense Gas



Jiménez-Donaire+19

Observing HCN, HNC and HCO⁺ helps us to understand star-formation

Traces higher densities than CO and [CII] (10^5 vs $10^{2-3}/\text{cm}^3$)

HCN(1-0) linearly correlates with SFR over ~ 10 dex

HNC & HCO⁺ can probe thermodynamics of dense gas

10-100x fainter than CO and [CII]

History of High-z Dense Gas Observations

Few HCN(1-0) detections

(e.g. *Gao+07, Oteo+17*)

Handful of mid-J/high-J lines

-mainly from ALMA

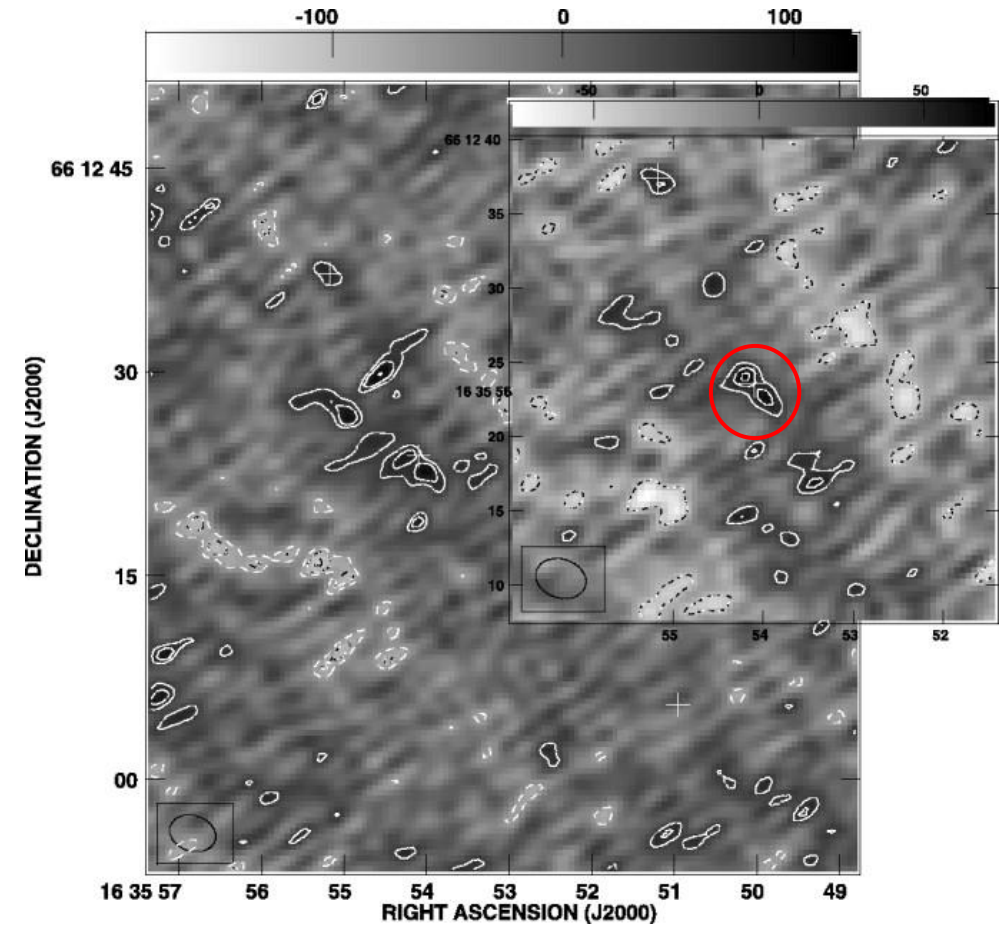
-sensitive to non-thermal heating

(e.g. *Oteo+17, Bethermin+18, Canameras+21, Yang+23*)

-stacking

(e.g. *Spilker+14, Reuter+22, Hagimoto+23*)

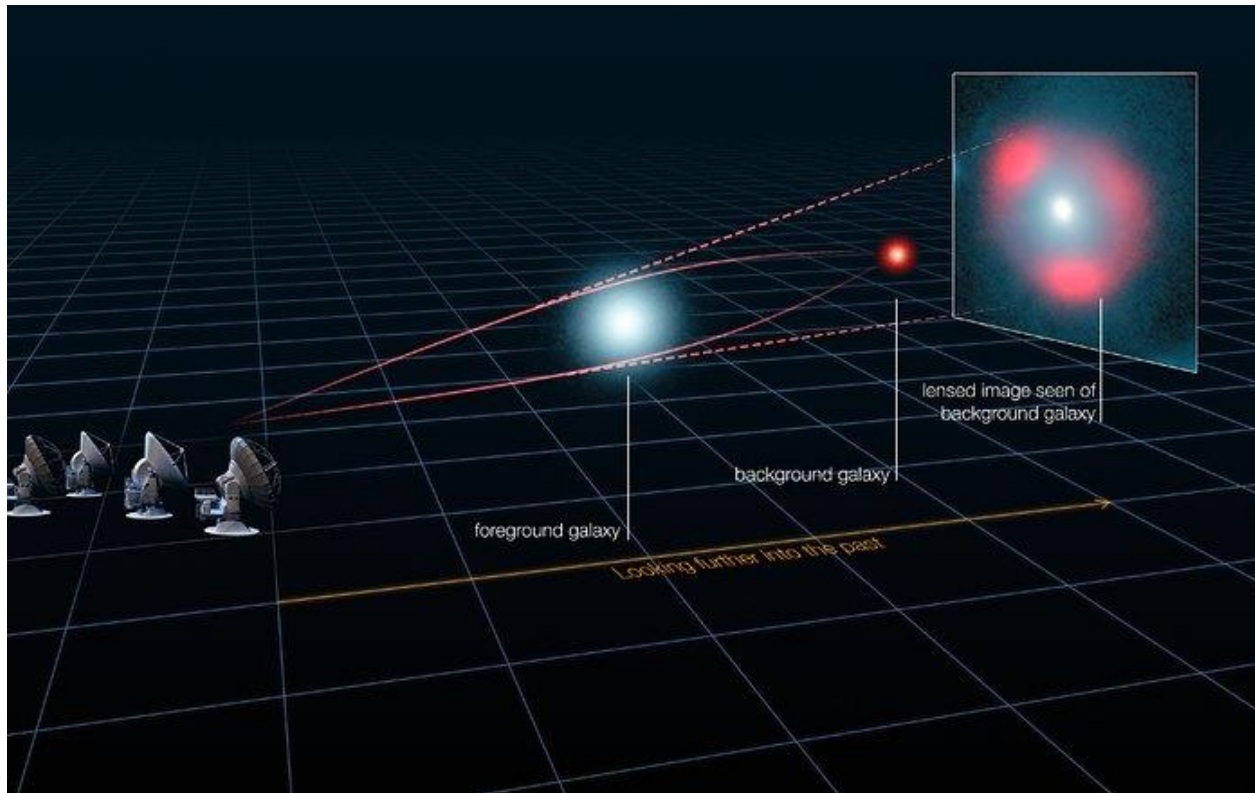
Difficult to draw conclusions



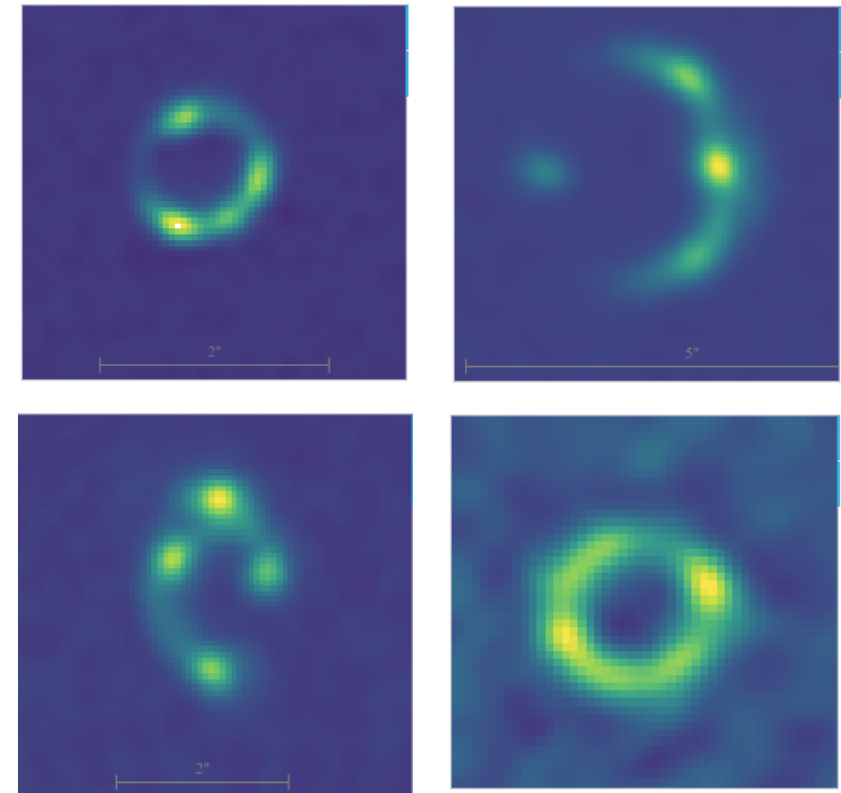
Gao+07

Gravitational Lensing

Reduces observing time!



ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.



Example SPT ALMA Band 7
Continuum Sky Maps (median $\mu \sim 6$)

PRUSSIC Dense Gas Survey

Prussic acid = HCN

Targeting HCN, HCO⁺ and HNC in z=1-5 strongly lensed galaxies

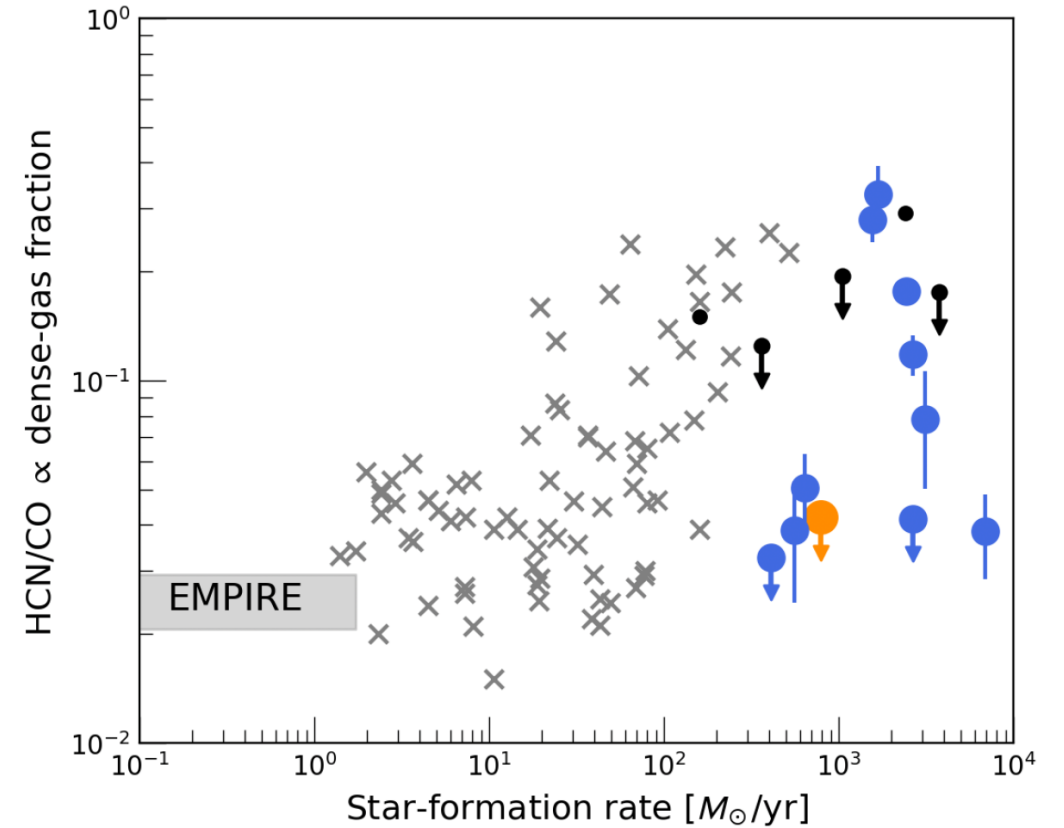
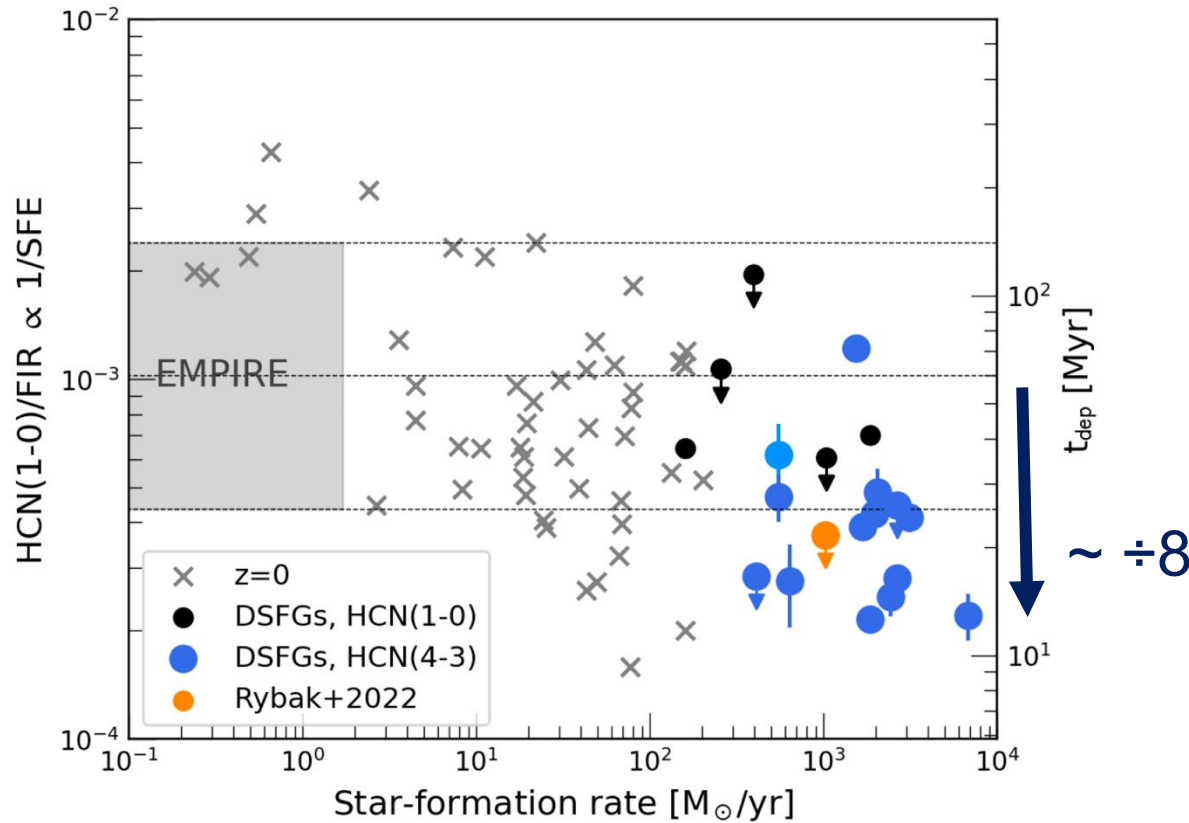
Presented in PRUSSIC I, II and III (Rybak+2022, 2023 & 2026)



PRUSSICIII: 10 mid-J HCN detections

HCN/FIR is a proxy for SFE

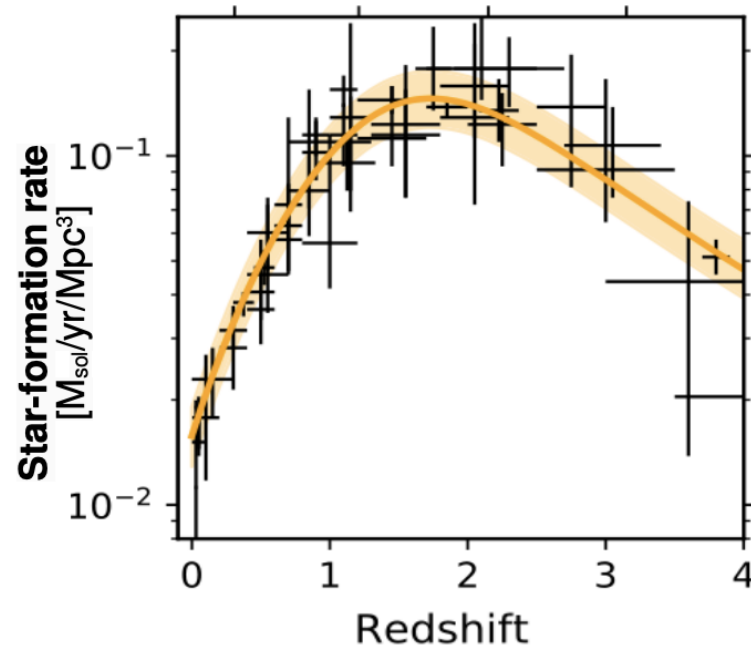
HCN/CO is a proxy for dense gas fraction



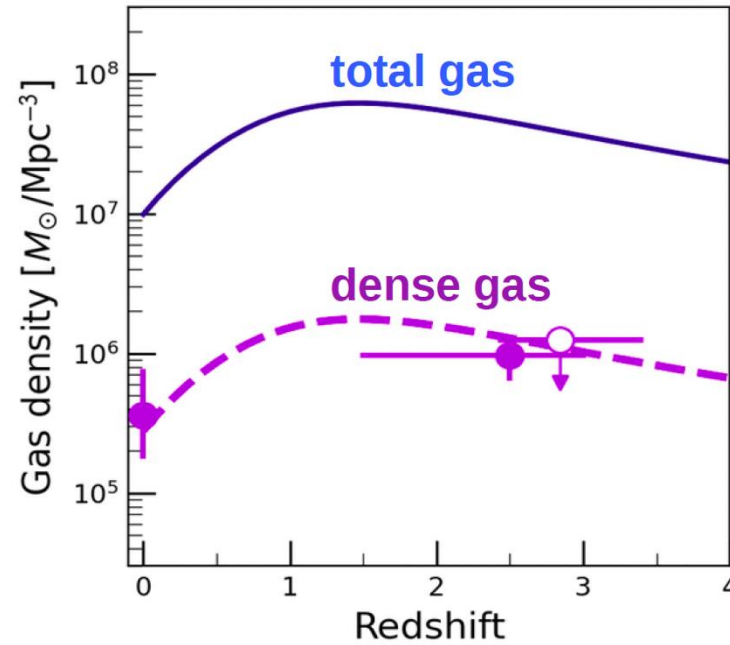
Rybak+26

Galaxy Gas Content

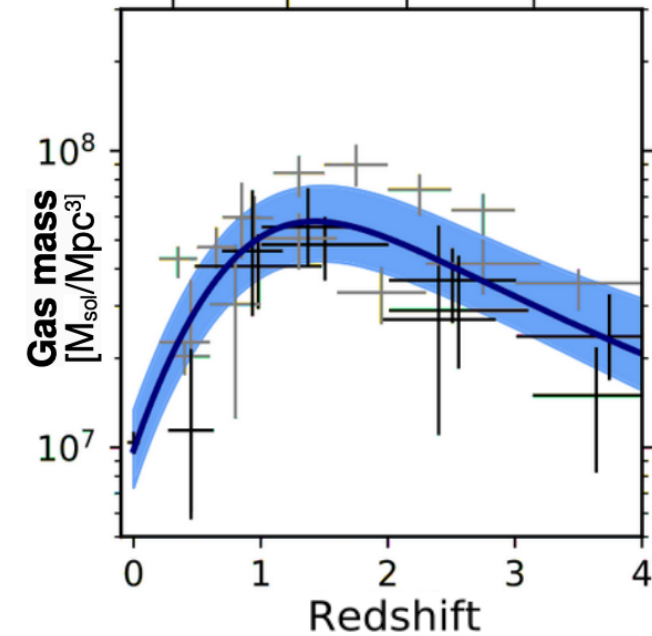
Star formation



Dense gas



Molecular gas

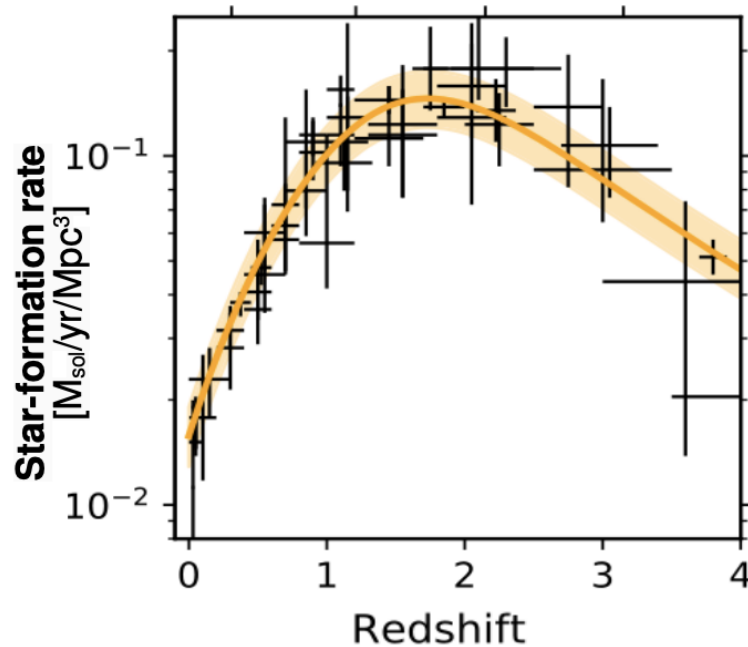


From PRUSSIC III, Rybak+26

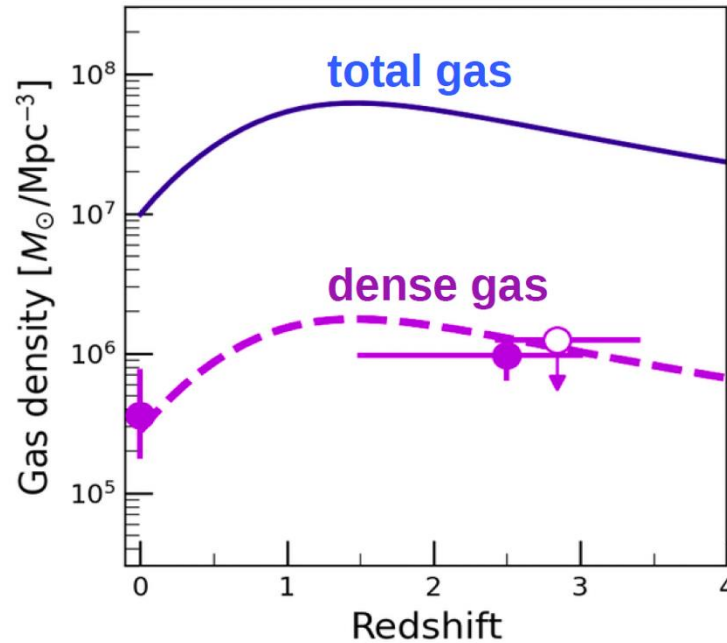
Galaxy Gas Content

Limitations: Only 10 detections
Inhomogenous sample
Excitation correction

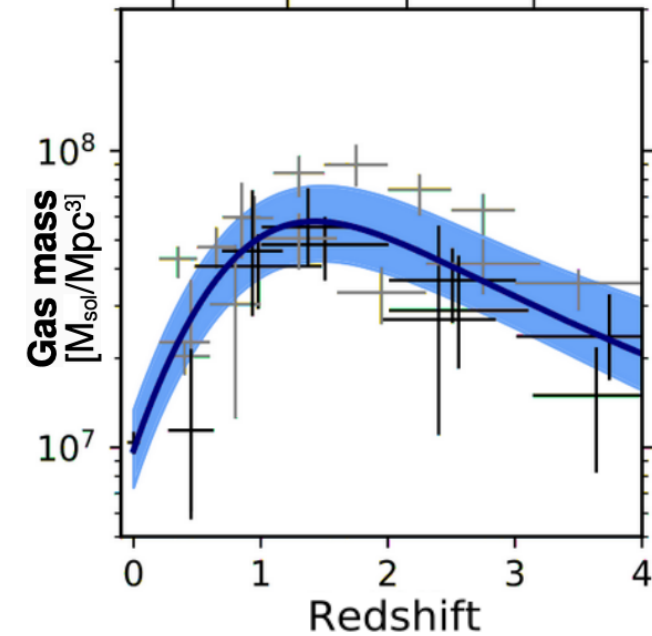
Star formation



Dense gas



Molecular gas



From PRUSSIC III, Rybak+26

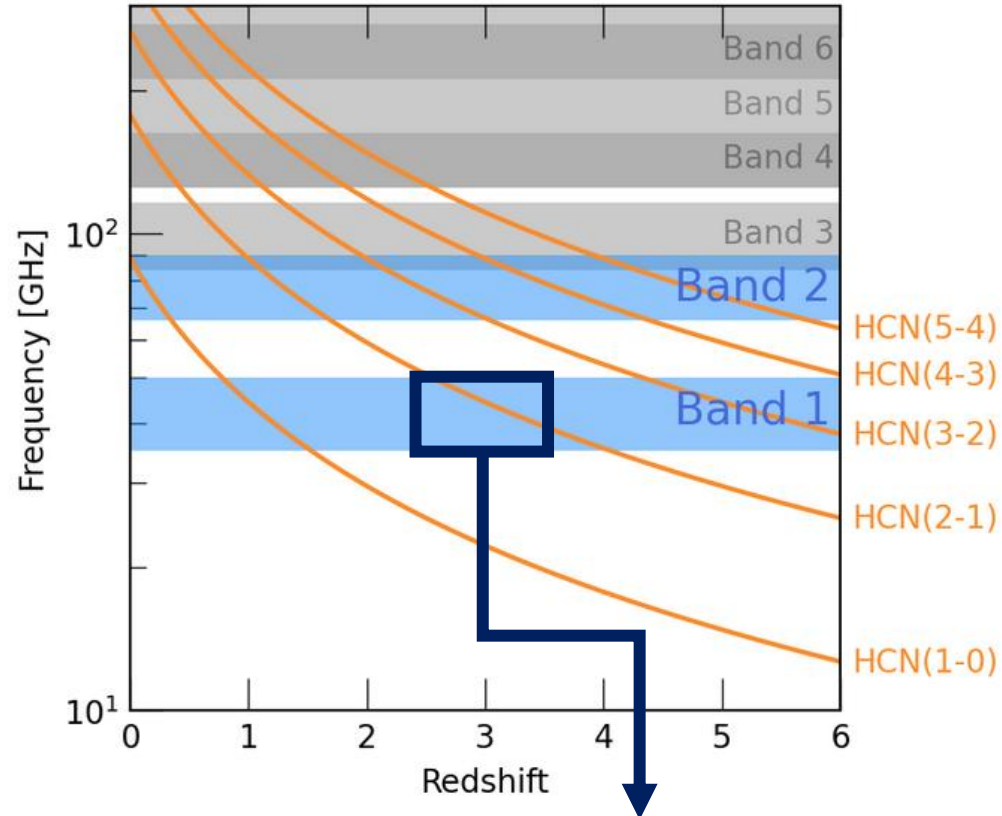
SPT Dense Gas Survey

Aiming for detections of (2-1) emission lines of HCN, HCO⁺ and HNC

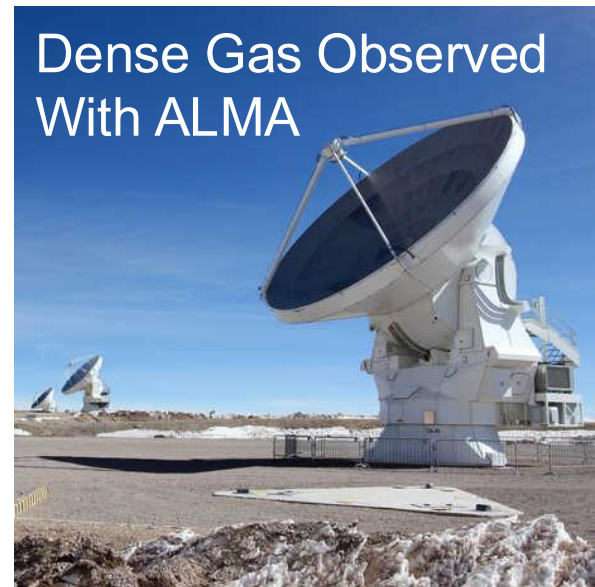
10 SPT galaxies
(Weiß+13, Reuter+20, Reuter+23)

$z=2.5-3.5$ with beam $\sim 2-8''$
Previous CO detections
(Reuter+20)

Band 6/7 Continuum
(Archive: Reuter, McKean, Strandet, Hezaveh, Bethermin)

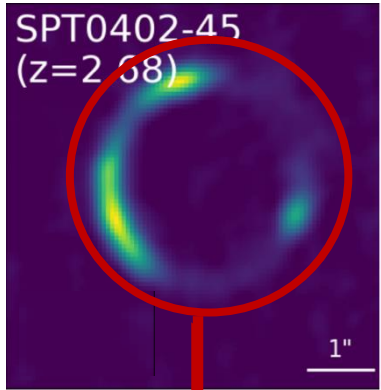


25hrs with
ALMA Band 1



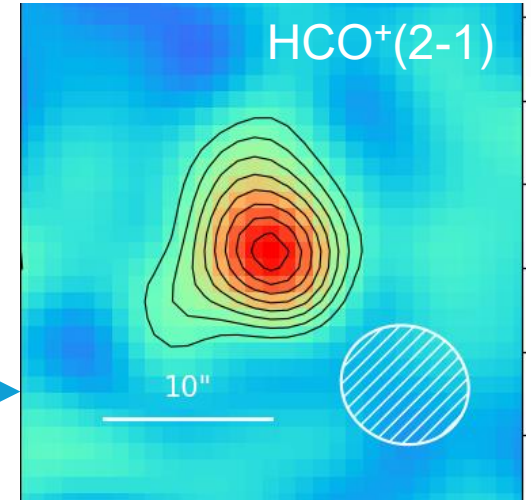
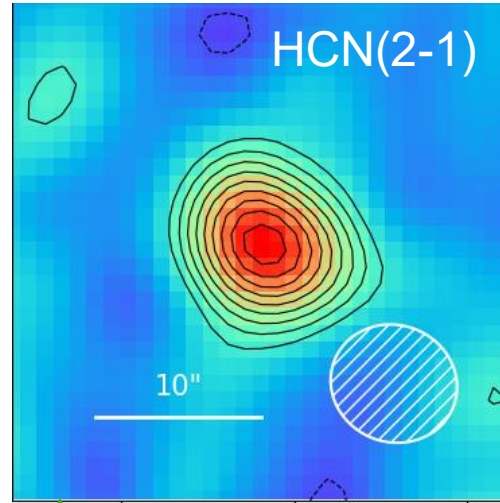
Detections of HCN, HNC & HCO⁺ in all 10 sources!

WORK IN PROGRESS

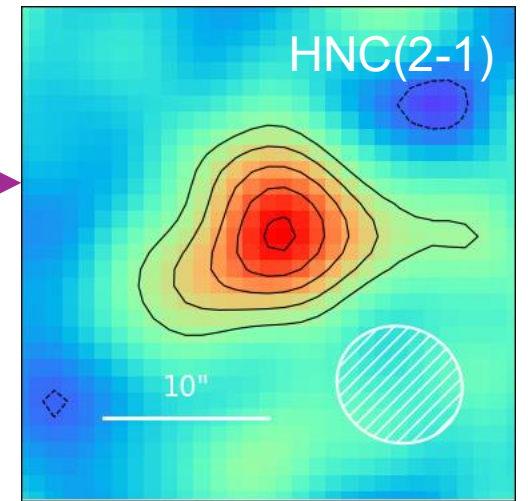
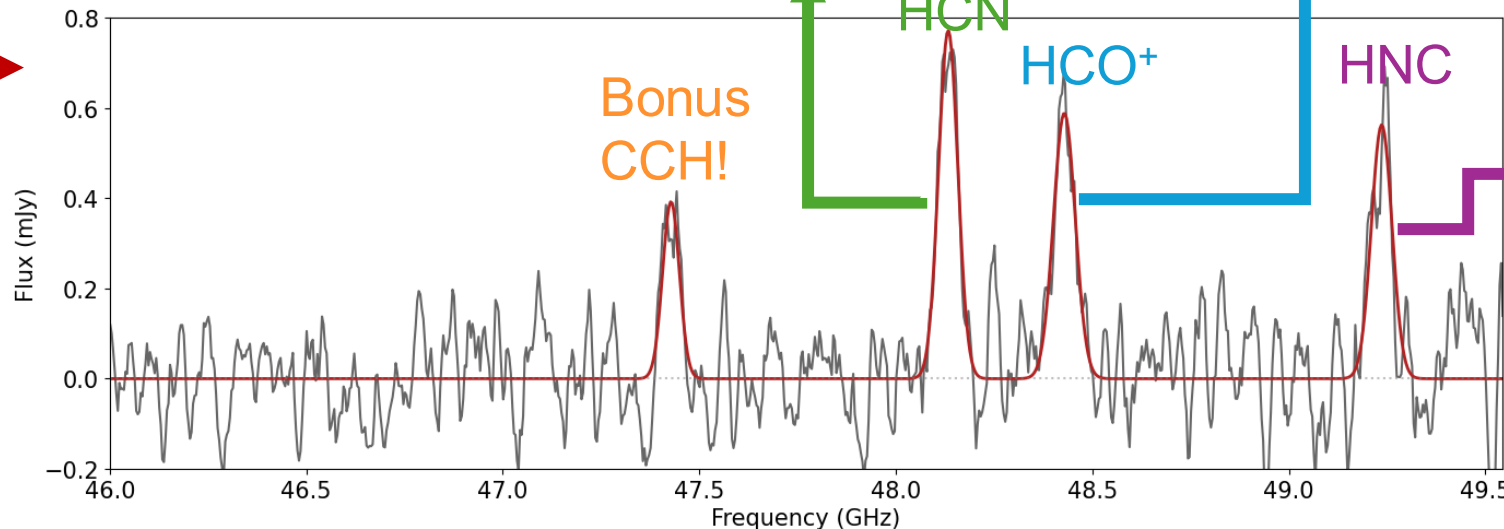


High-res
ALMA
Band 7
Continuum

Example:
SPT402-45
z=2.68

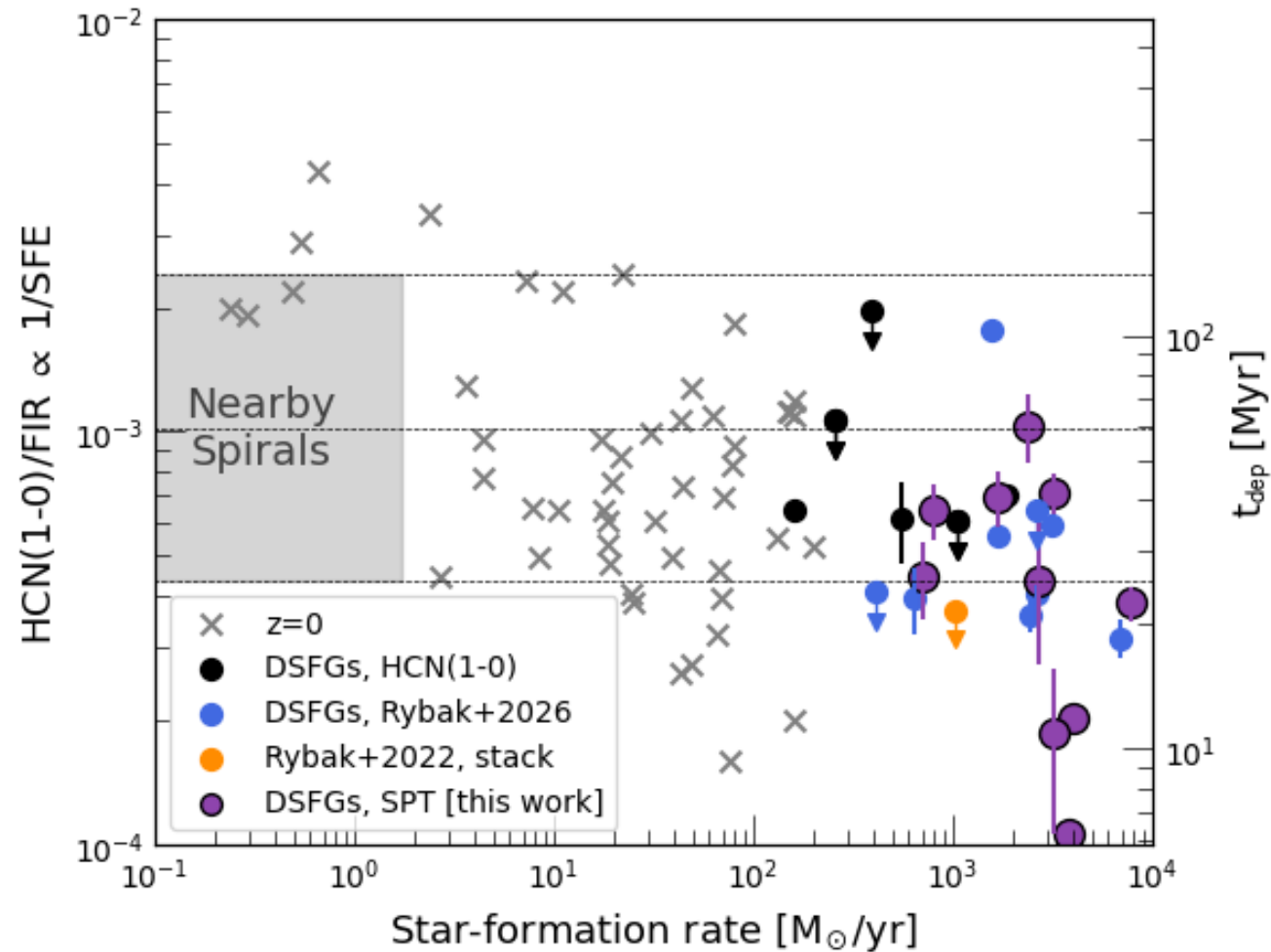
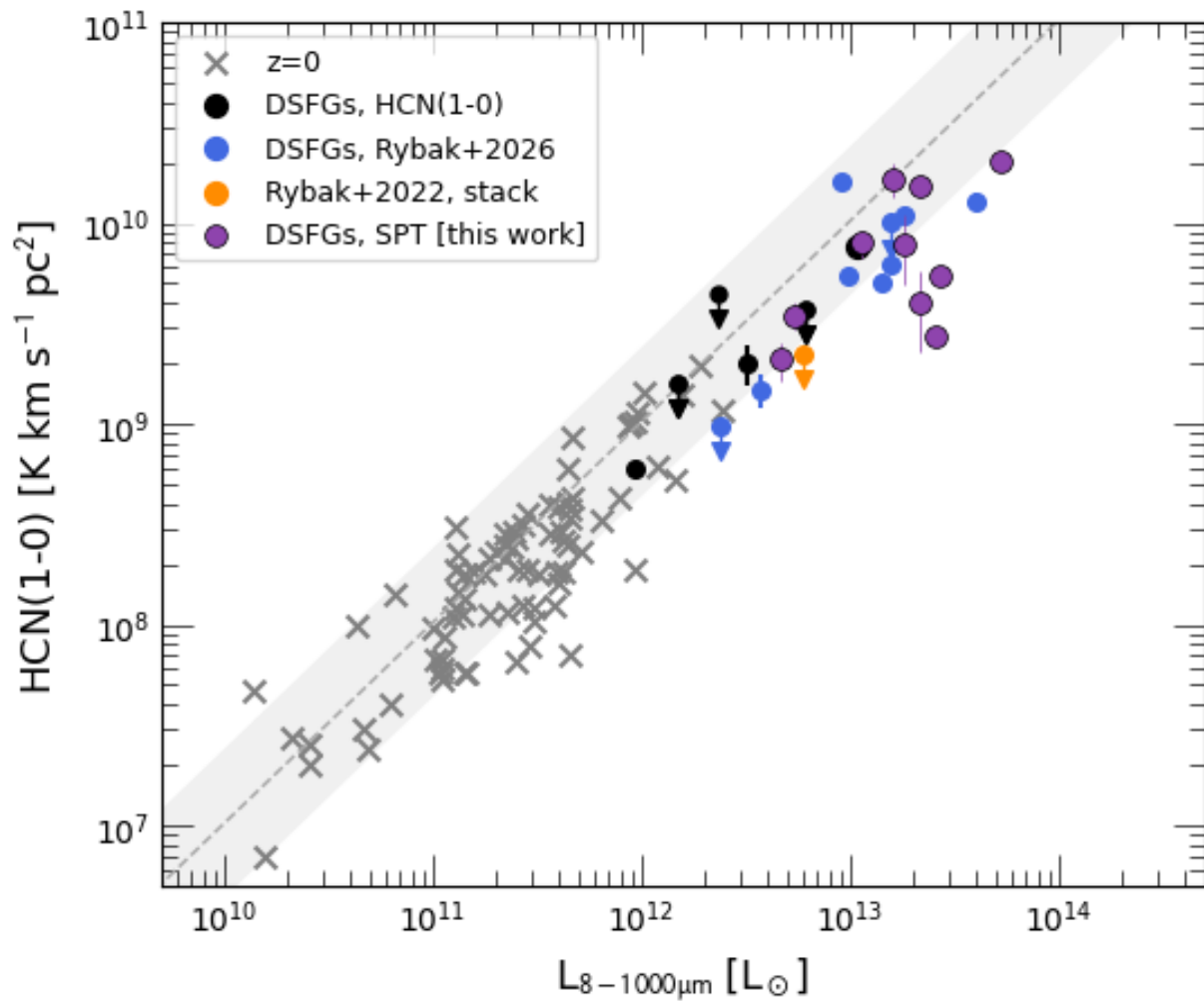


Unresolved
ALMA
Band 1
Emission
Lines



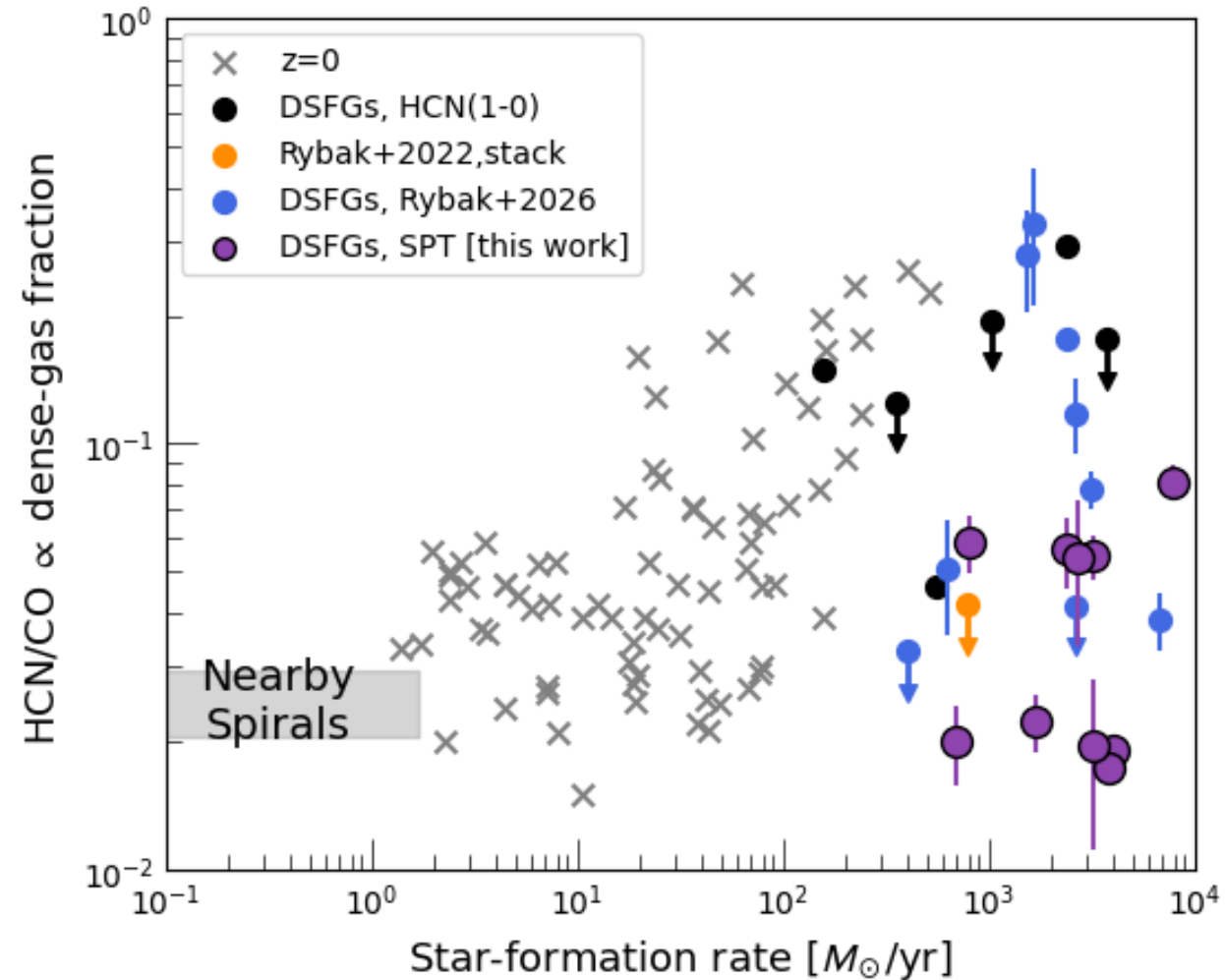
Enhanced SFE

WORK IN PROGRESS



Low dense gas fractions

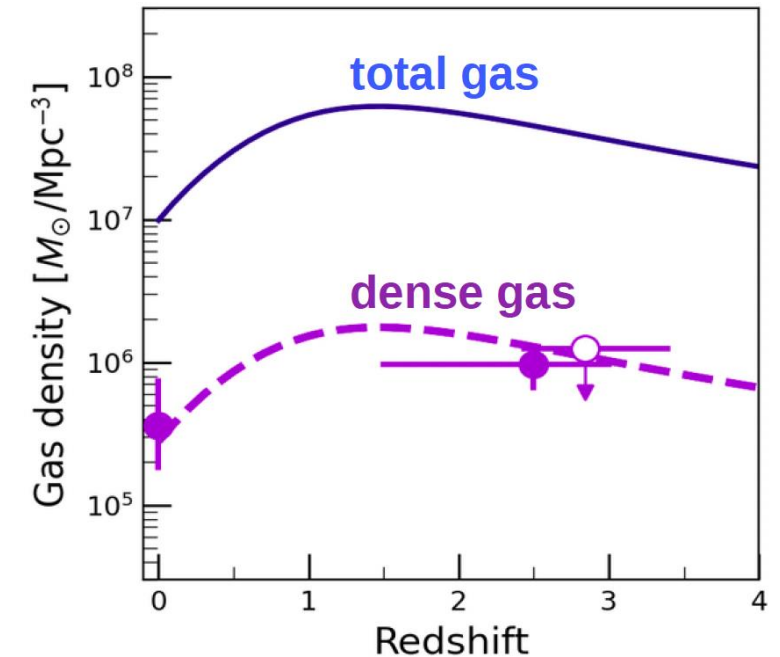
WORK IN PROGRESS

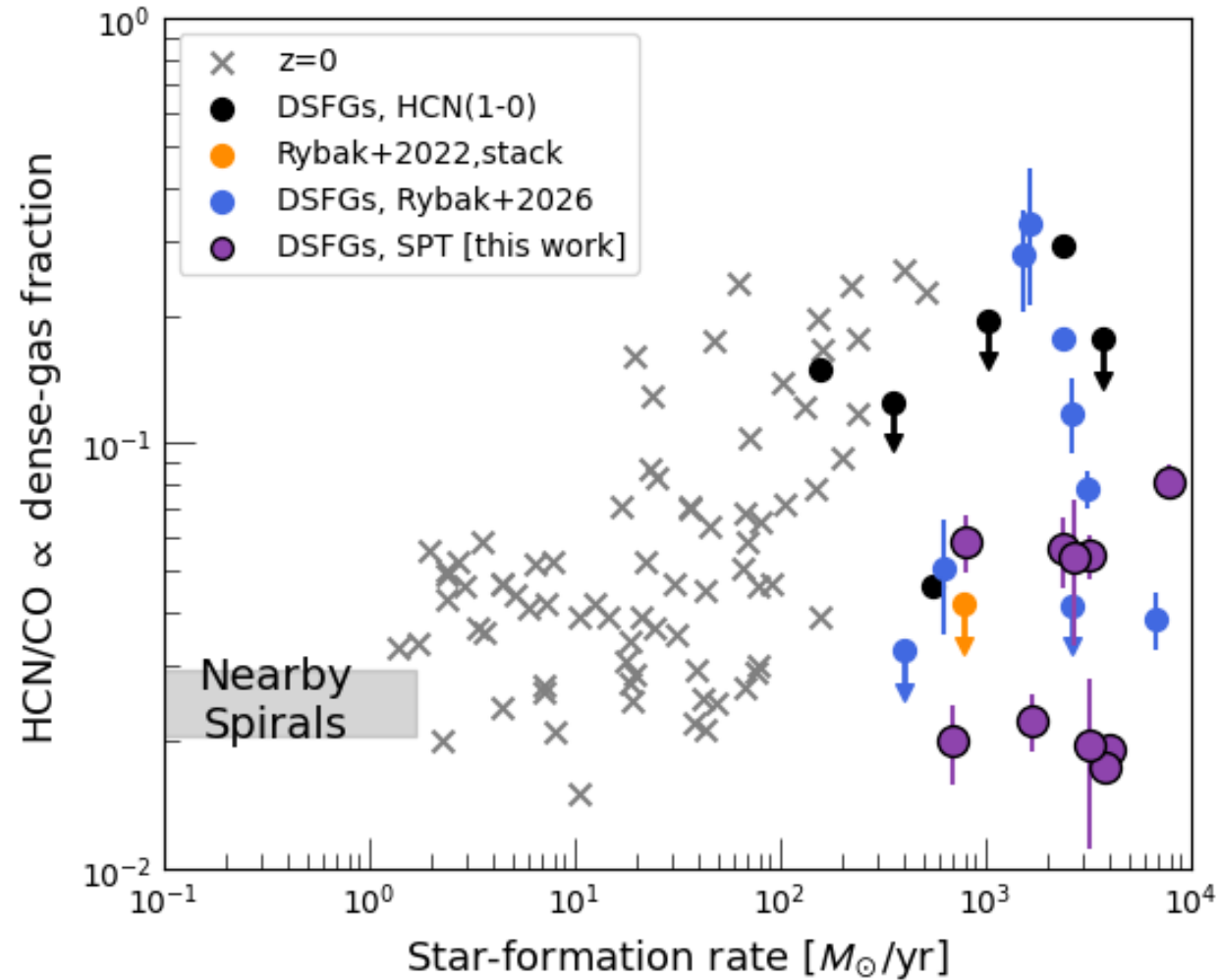
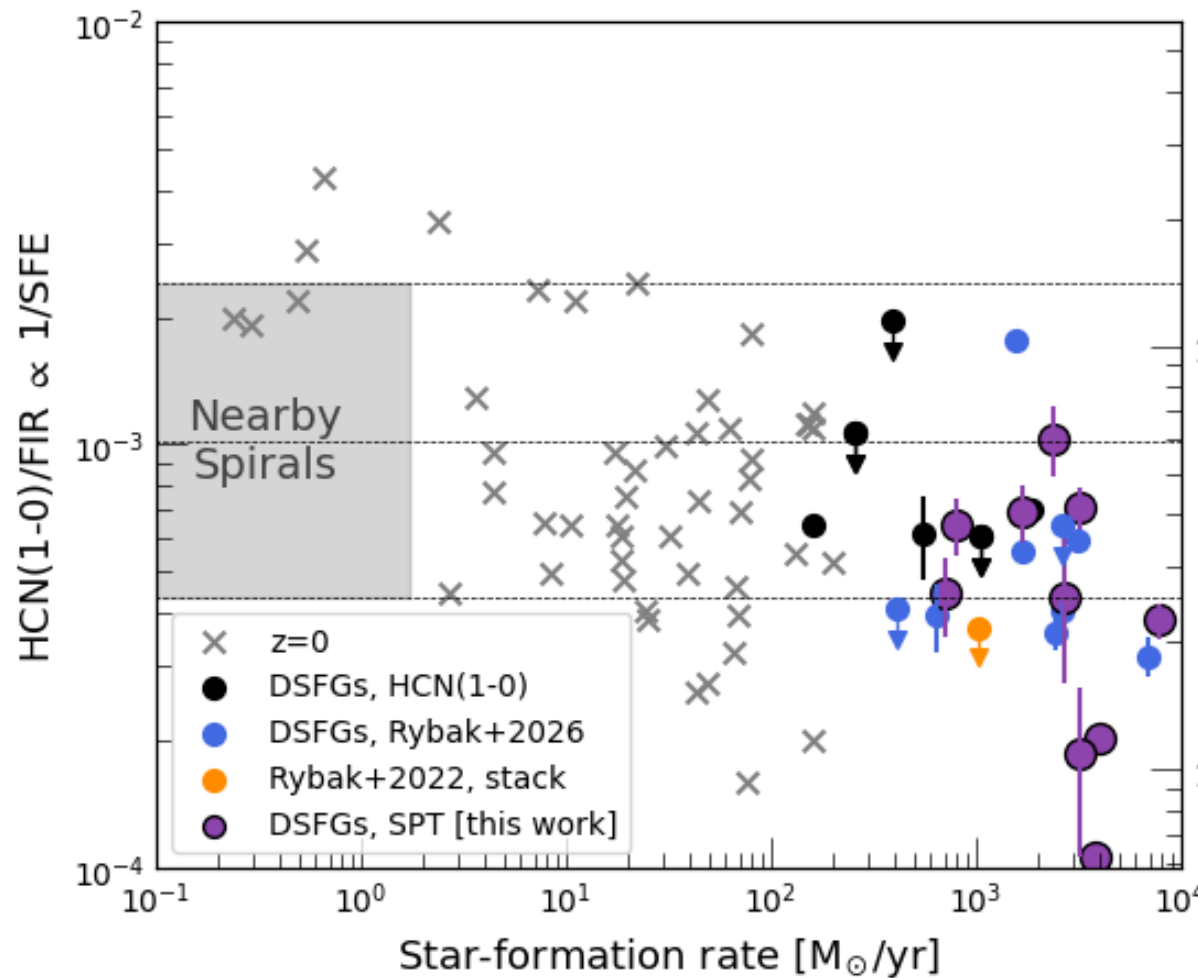


What next?

- Stack spectra to increase sensitivity to fainter species
- Improve constraints of cosmic dense gas density
- Compare the dense gas lines to other lines available (eg OH+, [CI])
- Expand parameter space with larger samples

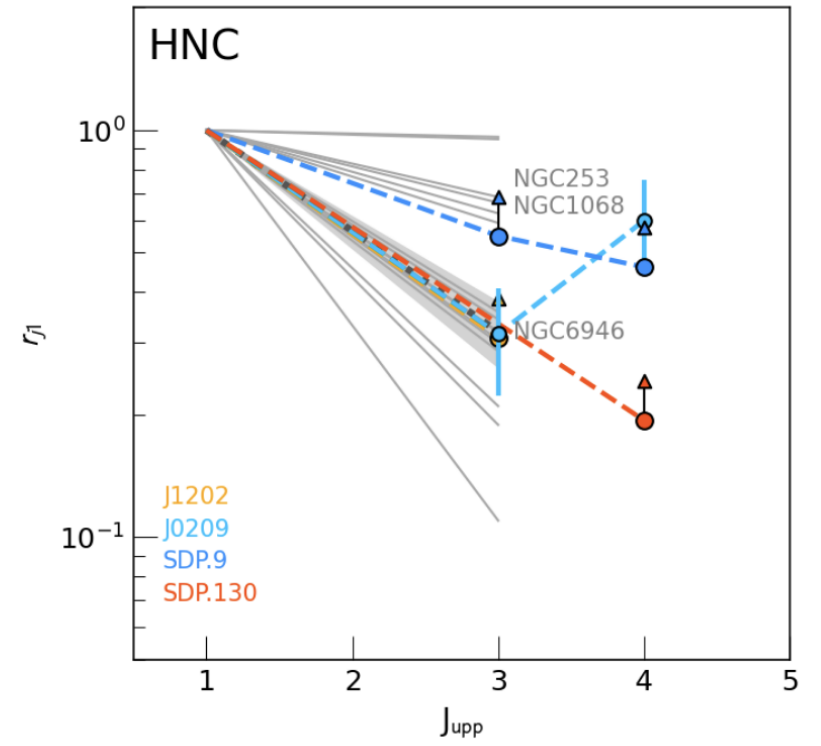
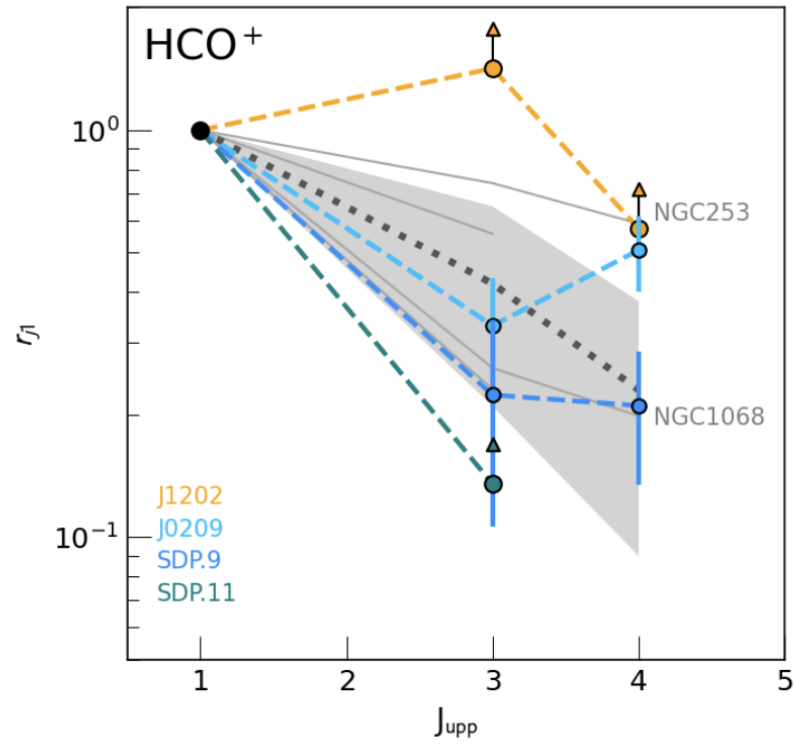
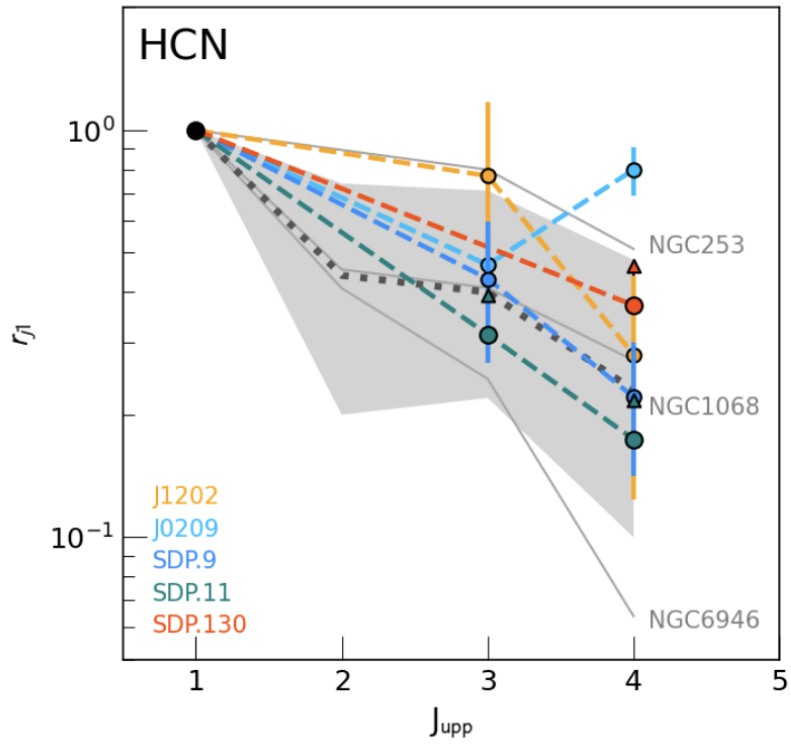
PRUSSICIII
Rybak+26



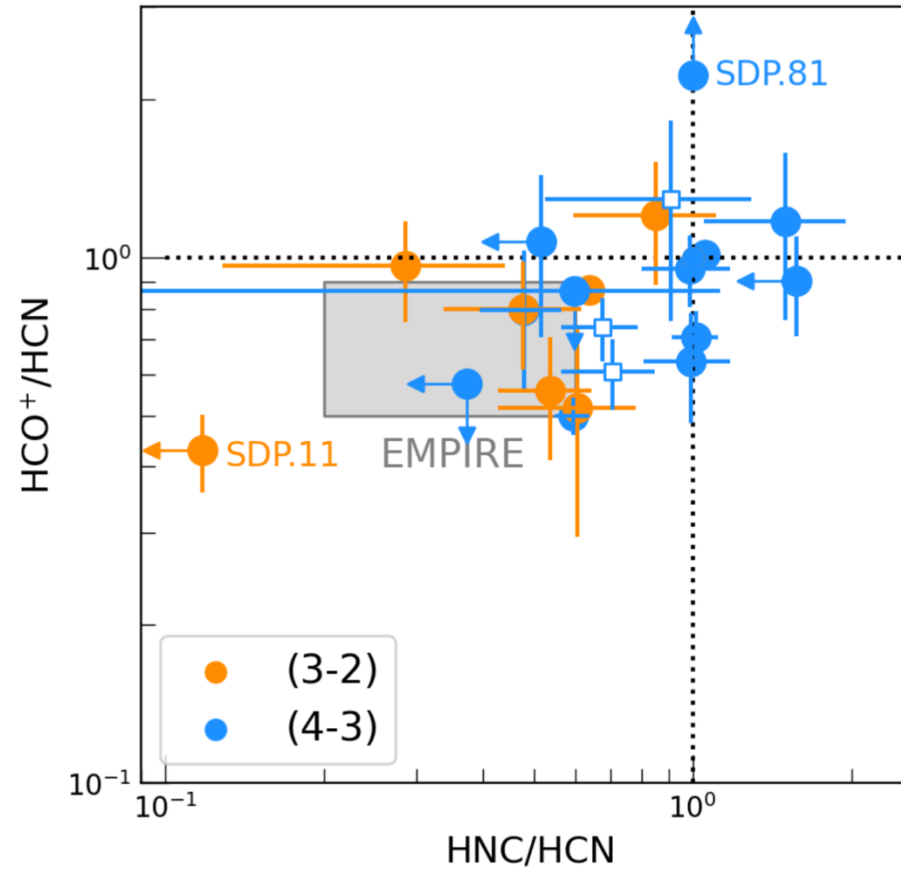
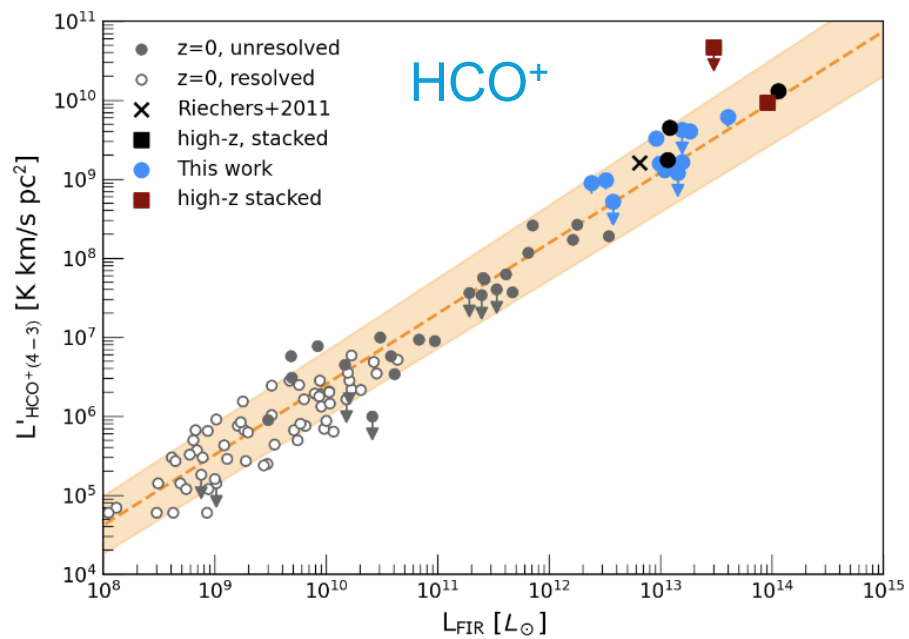
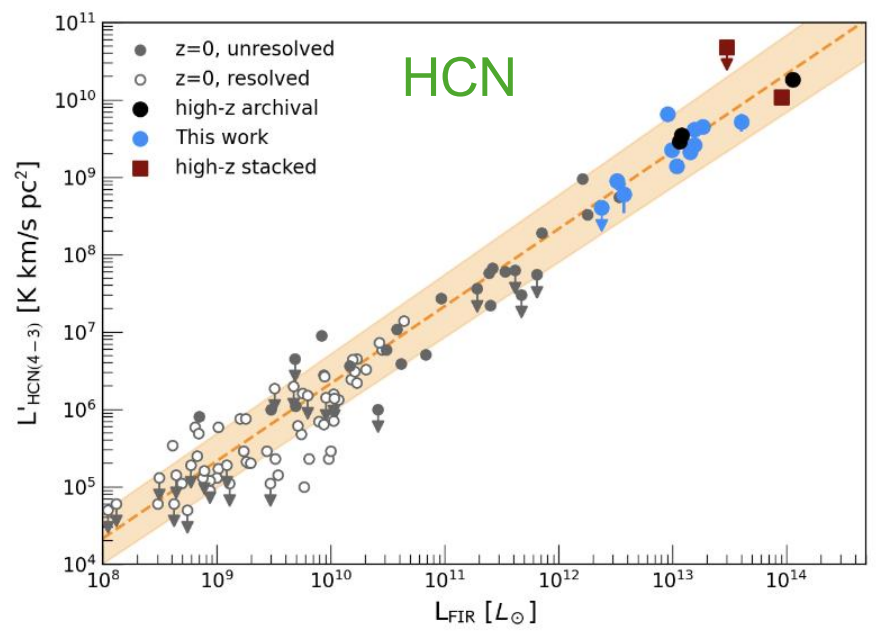


Thank you

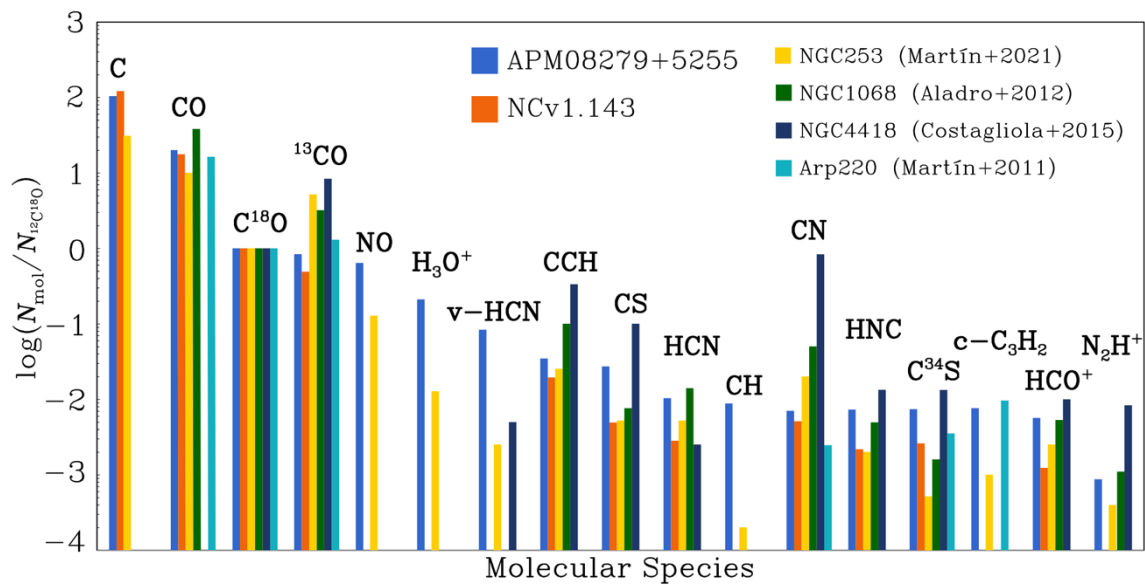
Back-up Slides



PRUSSICIII
Rybak+26



PRUSSICIII
Rybak+26



SUNRISE
Yang+23

