LEGO: Characterizing Galaxy Ecosystems from Wide-Field Line Mapping at Millimeter Waves

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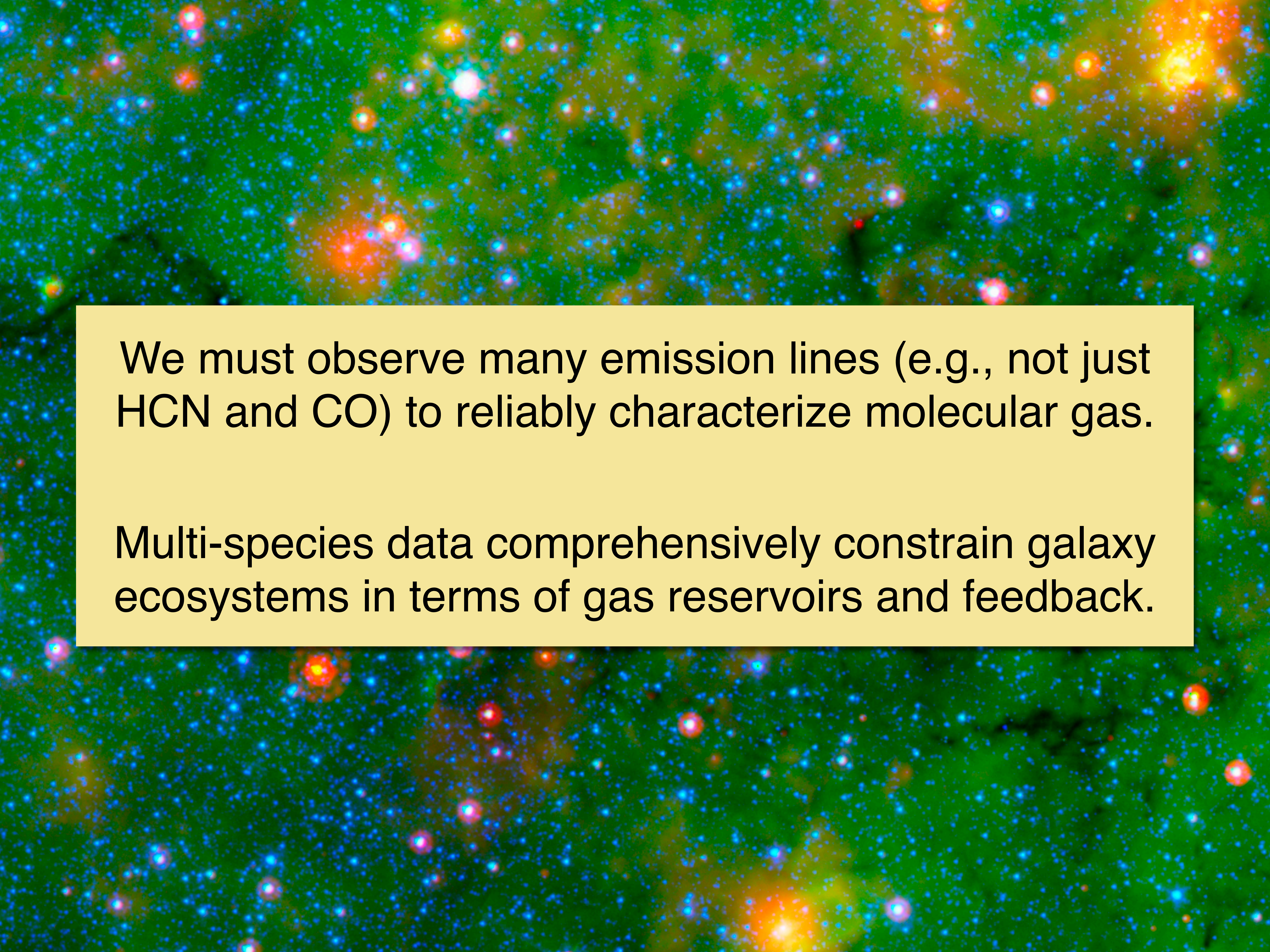
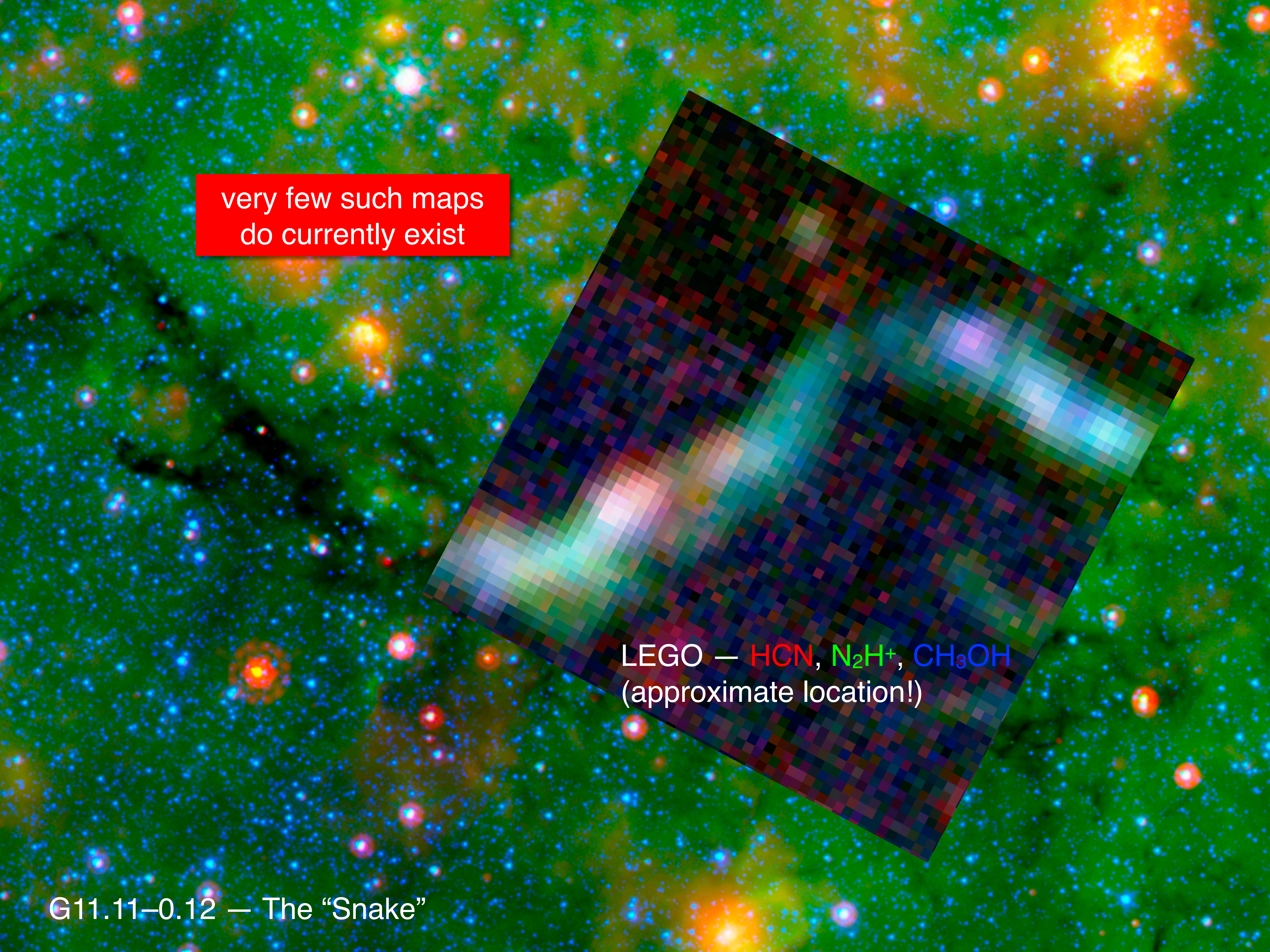
Haystack Observatory, Massachusetts Institute of Technology

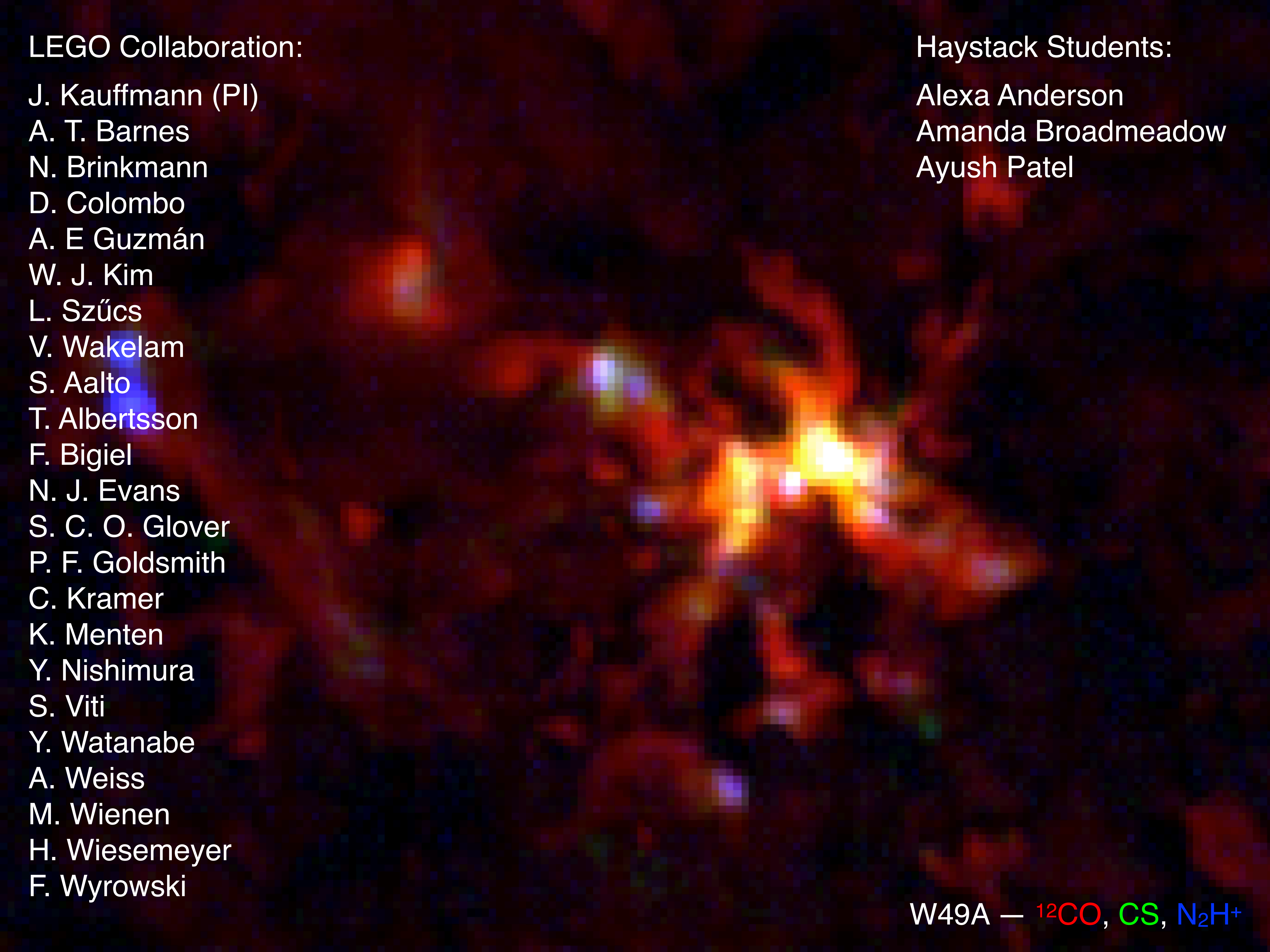
Our Galactic Ecosystem, Lake Arrowhead ● 2022 Mar. 3



We must observe many emission lines (e.g., not just HCN and CO) to reliably characterize molecular gas.

Multi-species data comprehensively constrain galaxy ecosystems in terms of gas reservoirs and feedback.


very few such maps
do currently exist
LEGO — HCN, N_2H^+, CH_3OH
(approximate location!)
G11.11–0.12 — The “Snake”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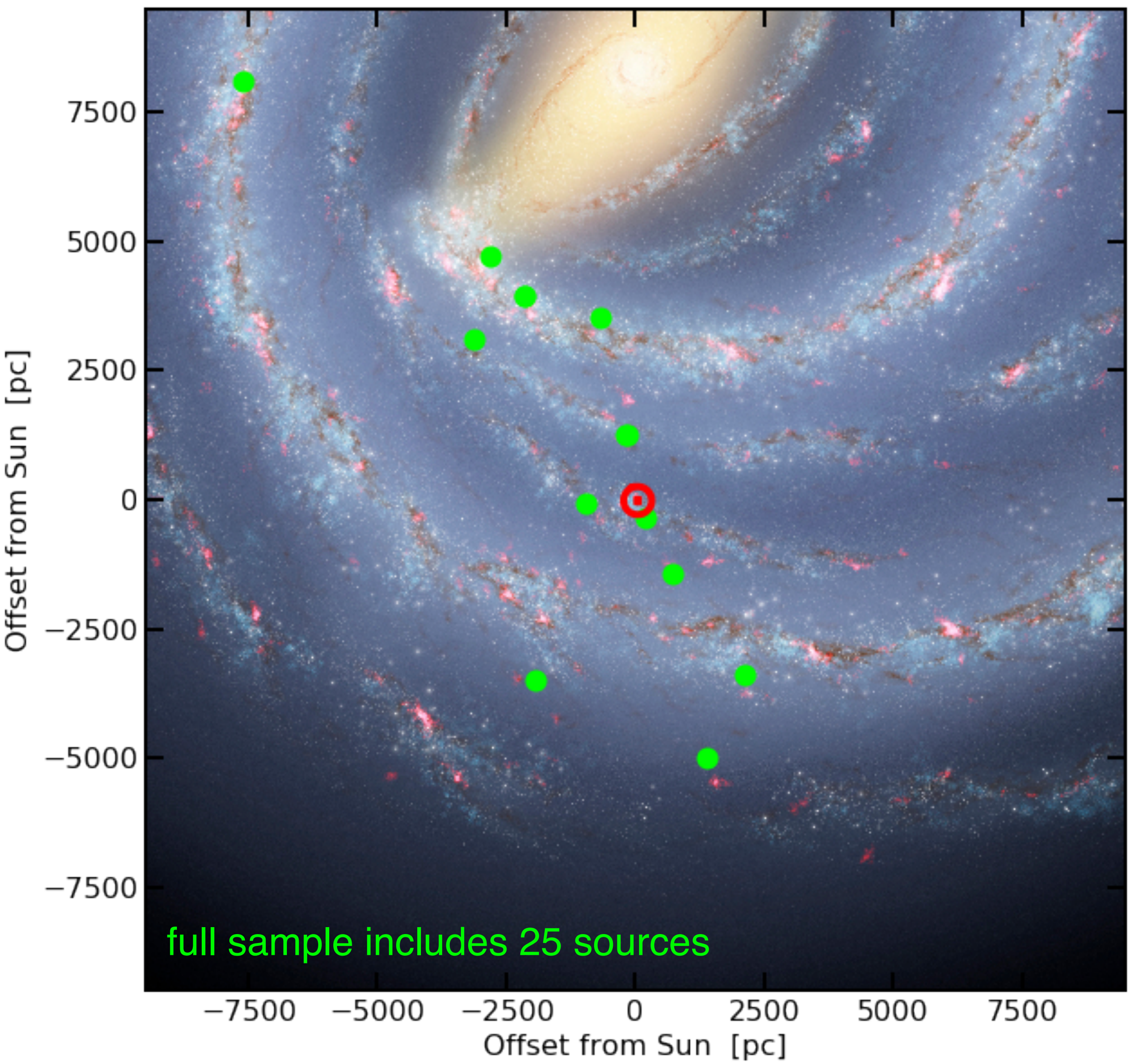
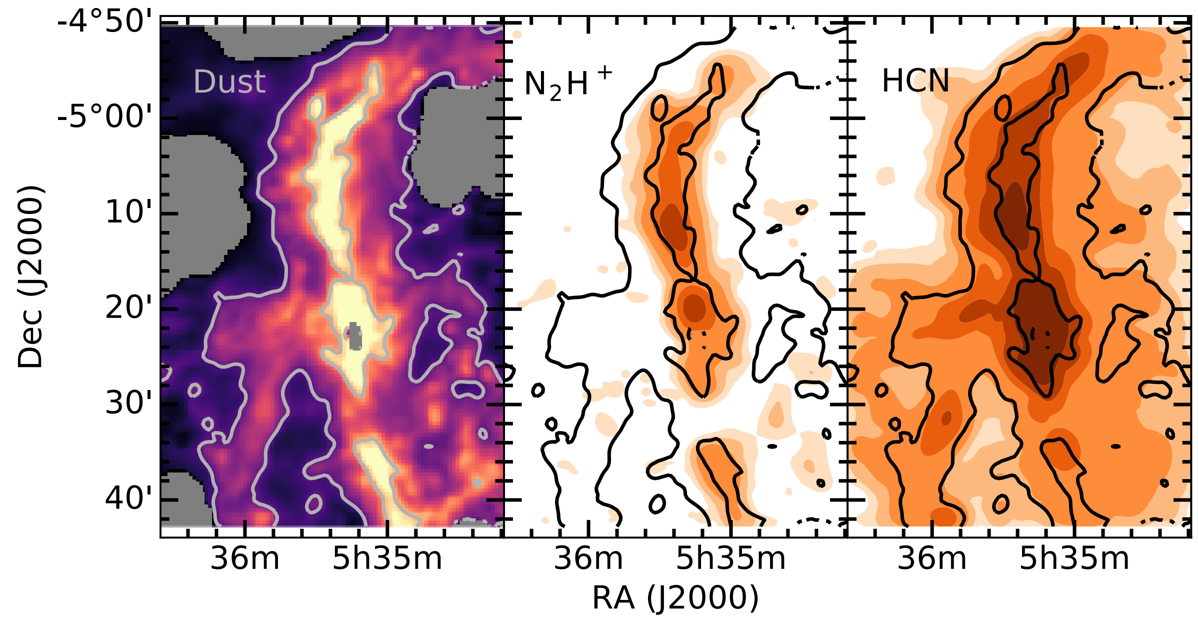
W49A — ^{12}CO, CS, N_2H^+

Line Emission in Galaxy Observations (LEGO)

LEGO targets with well–established distances





studies at IRAM:

~750 h taken, covers 70–115 GHz

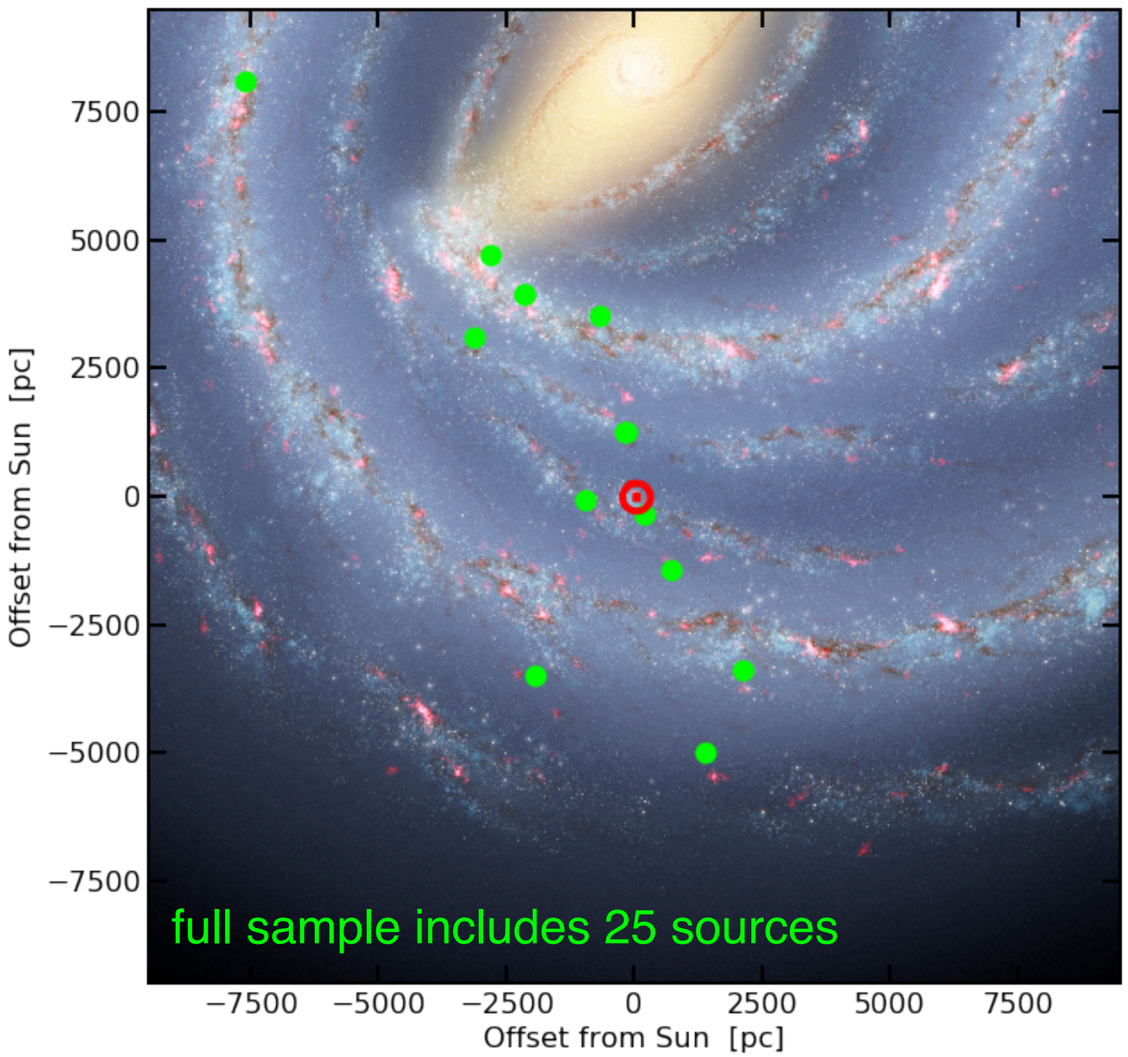
studies at APEX:

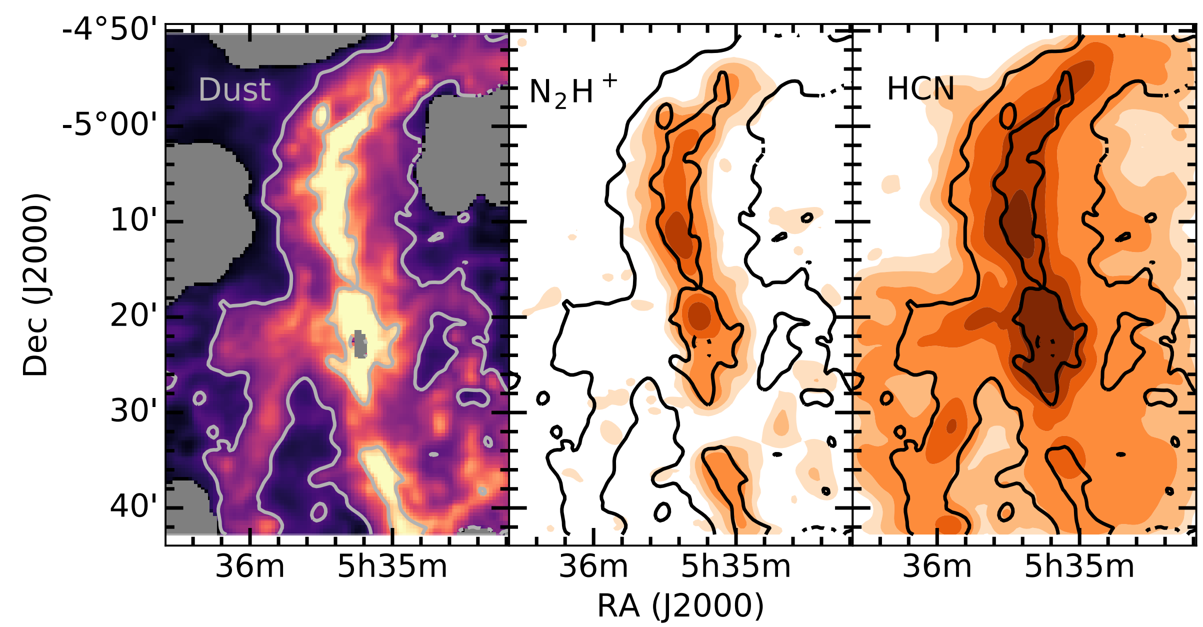
~100 h taken so far

data from FCRAO:

archival data for Orion

Line Emission in Galaxy Observations (LEGO)



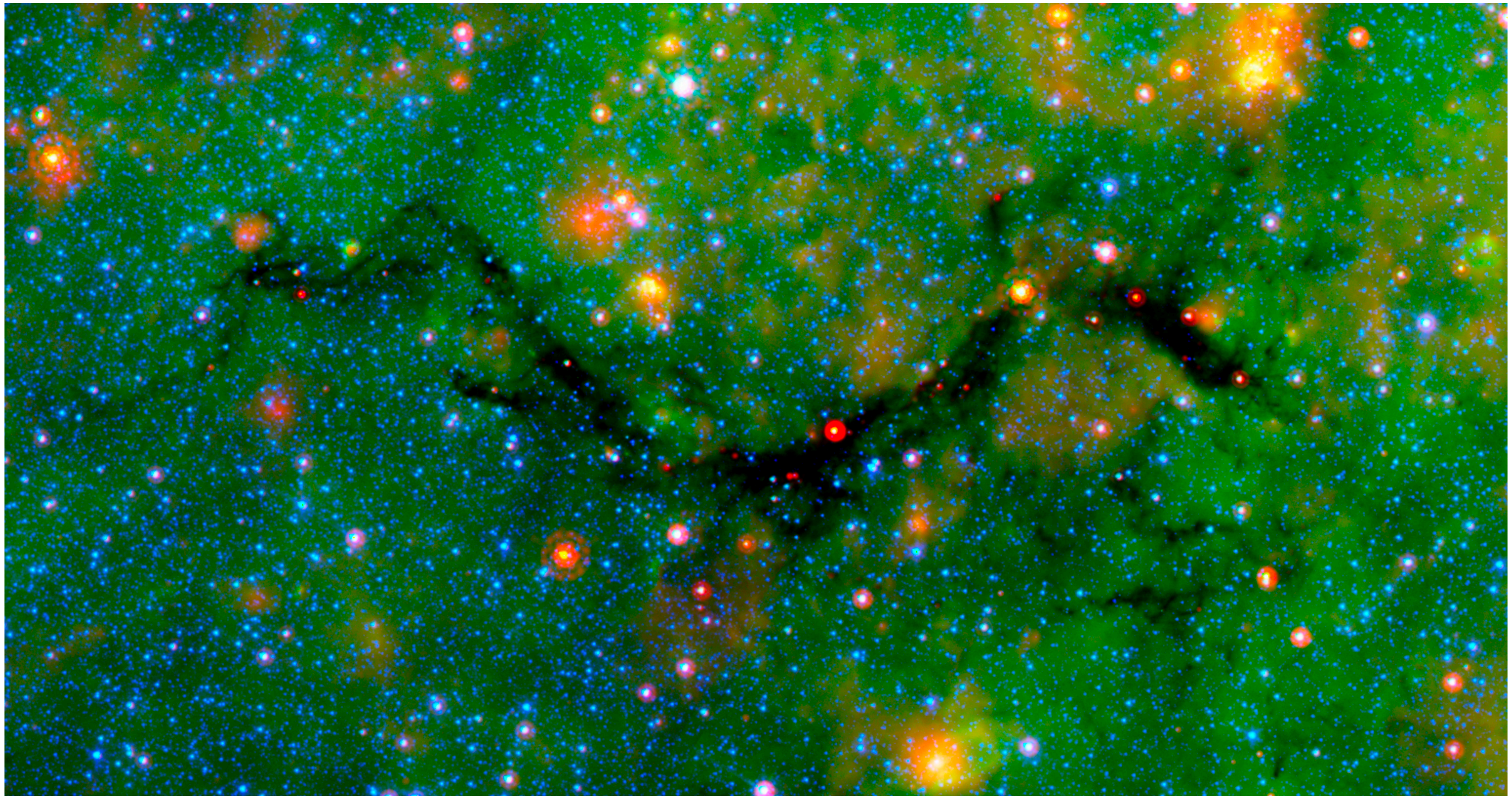


additional groups are working on this:

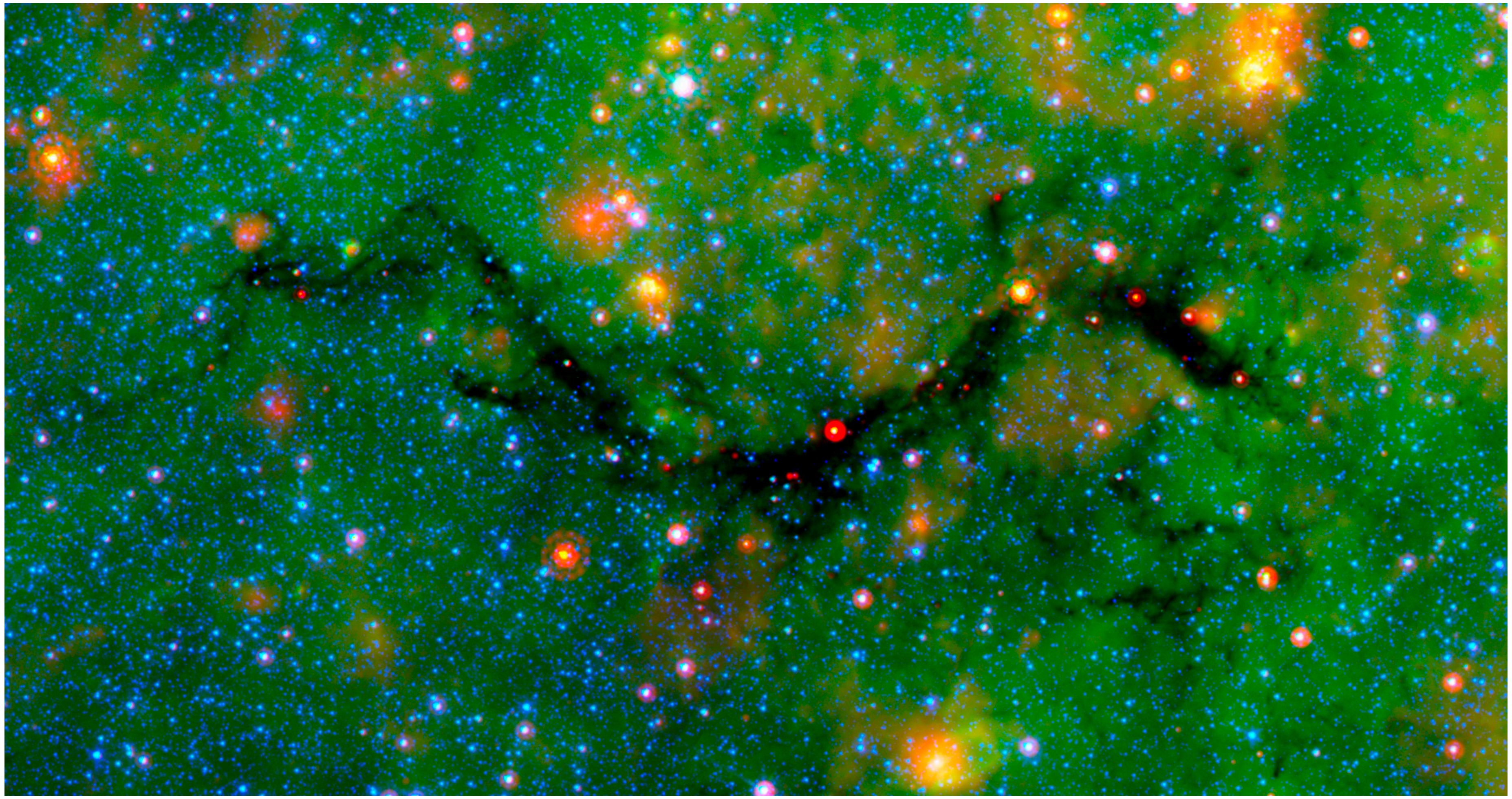
- Pety et al. (Orion B in detail)
- Shimajiri et al. (densest parts of nearby clouds)
- Watanabe et al. (W51 in detail)
- Stephens et al. (clumps in clouds)
- Mills et al. (CMZ)

LEGO provides the only systematic wide-field survey of a diverse sample

Observing few Lines gives unreliable Results



Constraining Galaxy Physics with LEGO



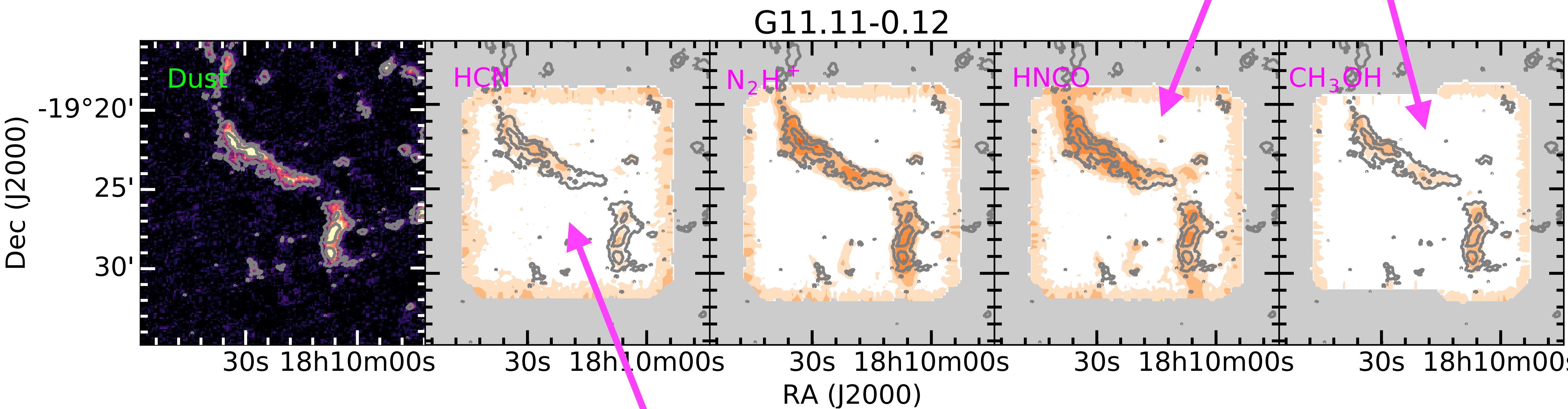
frequent approach in extragalactic research:

use HCN to constrain mass of dense gas

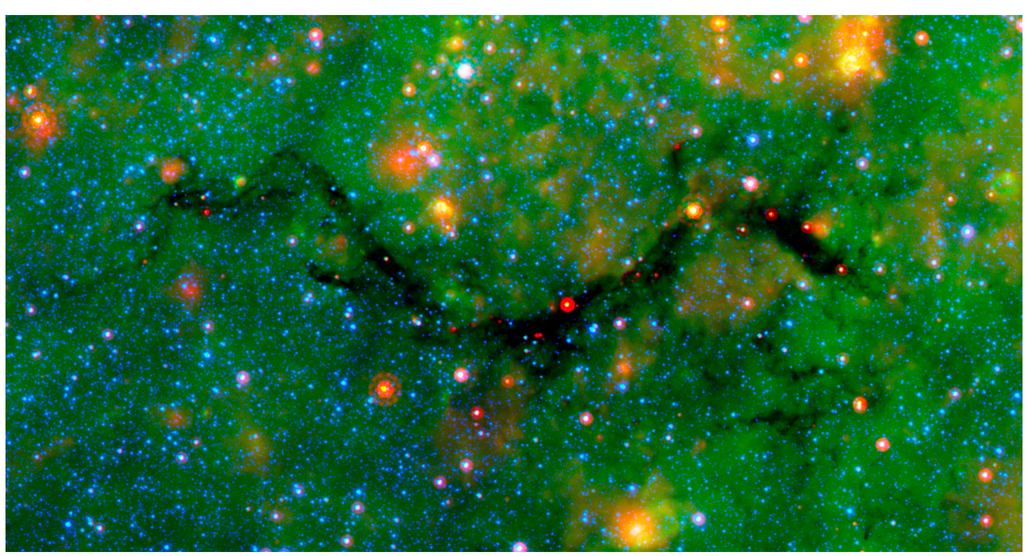
$$M_{\mathrm{dense}} = \alpha_{\mathrm{HCN}} \cdot L_{\mathrm{HCN}}$$

Constraining Galaxy Physics with LEGO

extended emission from supposed shock tracers



faint HCN from a dense cloud



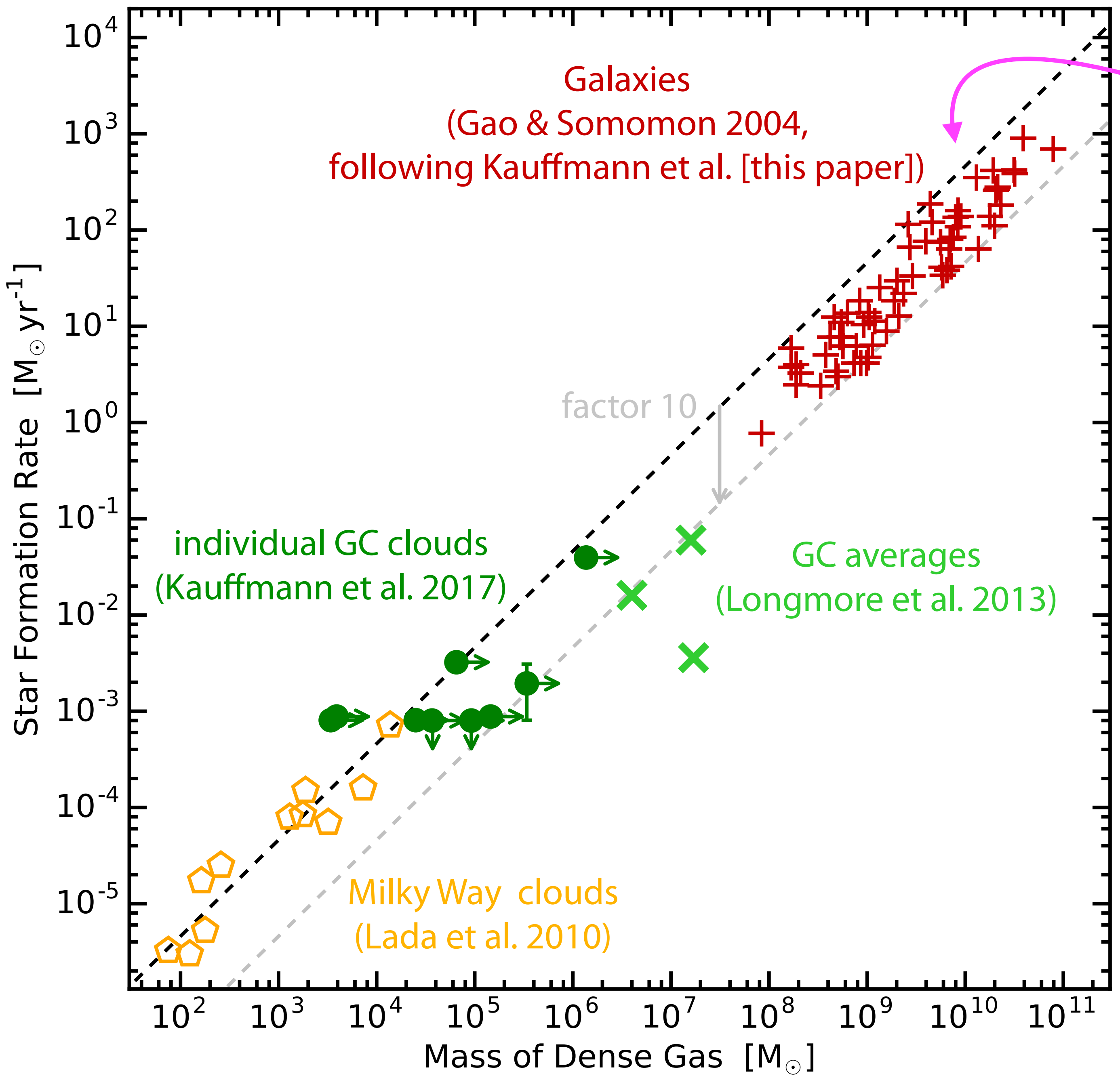
frequent approach in extragalactic research:

use HCN to constrain mass of dense gas

$$M_{\mathrm{dense}} = \alpha_{\mathrm{HCN}} \cdot L_{\mathrm{HCN}}$$

faint HCN $\Rightarrow$ large α_{HCN} $\Rightarrow$ large M_{dense}

Star Formation Relations



Kauffmann et al. (2017c)

offset by factor 5

arguably significant, since errors should cancel out

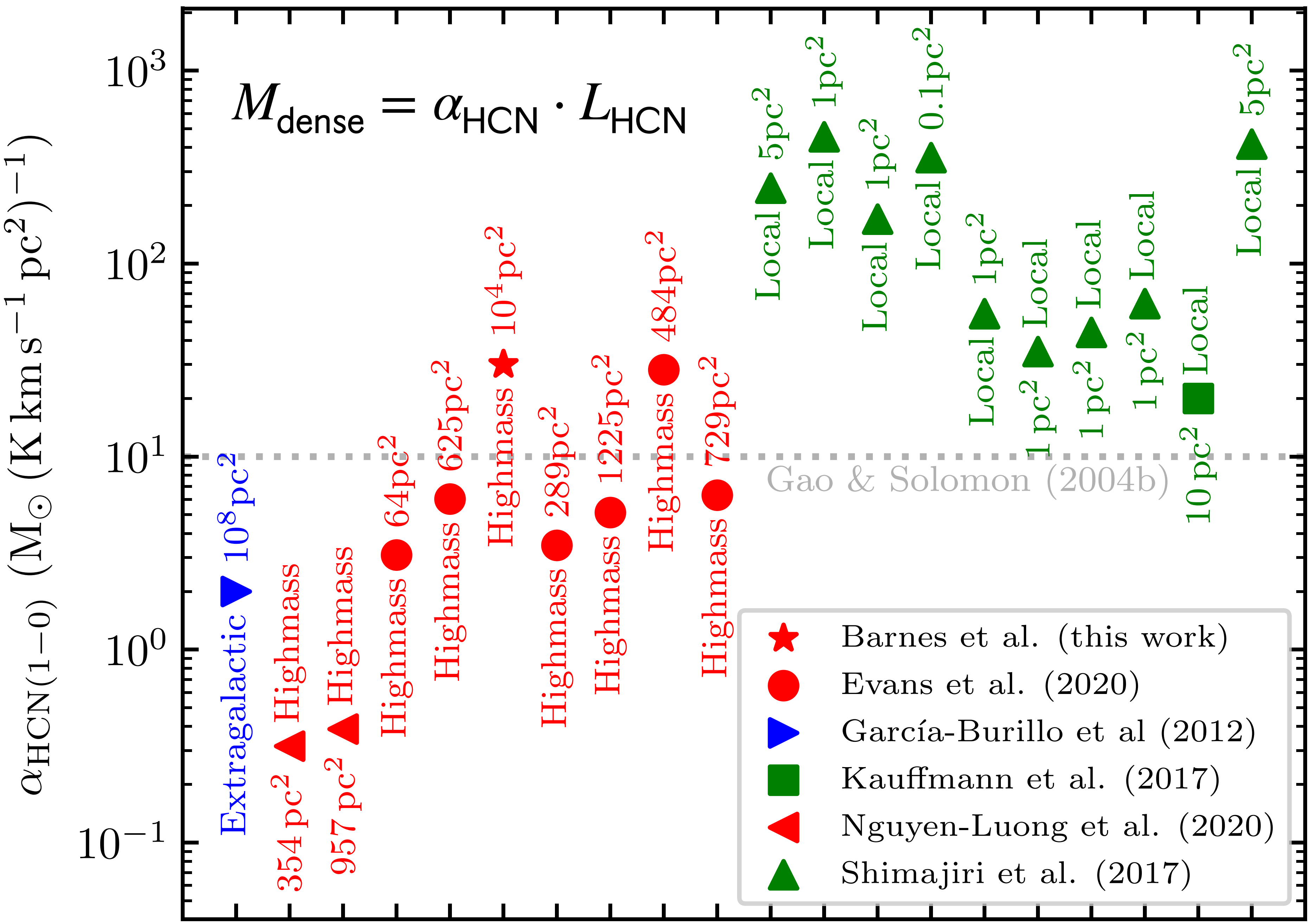
⇒ SF relations are not universal?

or HCN emission not understood well as dense gas tracer…

$$M_{\text{dense}} = \alpha_{\text{HCN}} \cdot L_{\text{HCN}}$$

faint HCN ⇒ large α_{HCN} ⇒ large M_{dense}

It is difficult to “calibrate” HCN



Barnes et al. (2021)

not clear now to find representative values for $\alpha_{\rm HCN}$…

Consequences for Galaxy Exploration

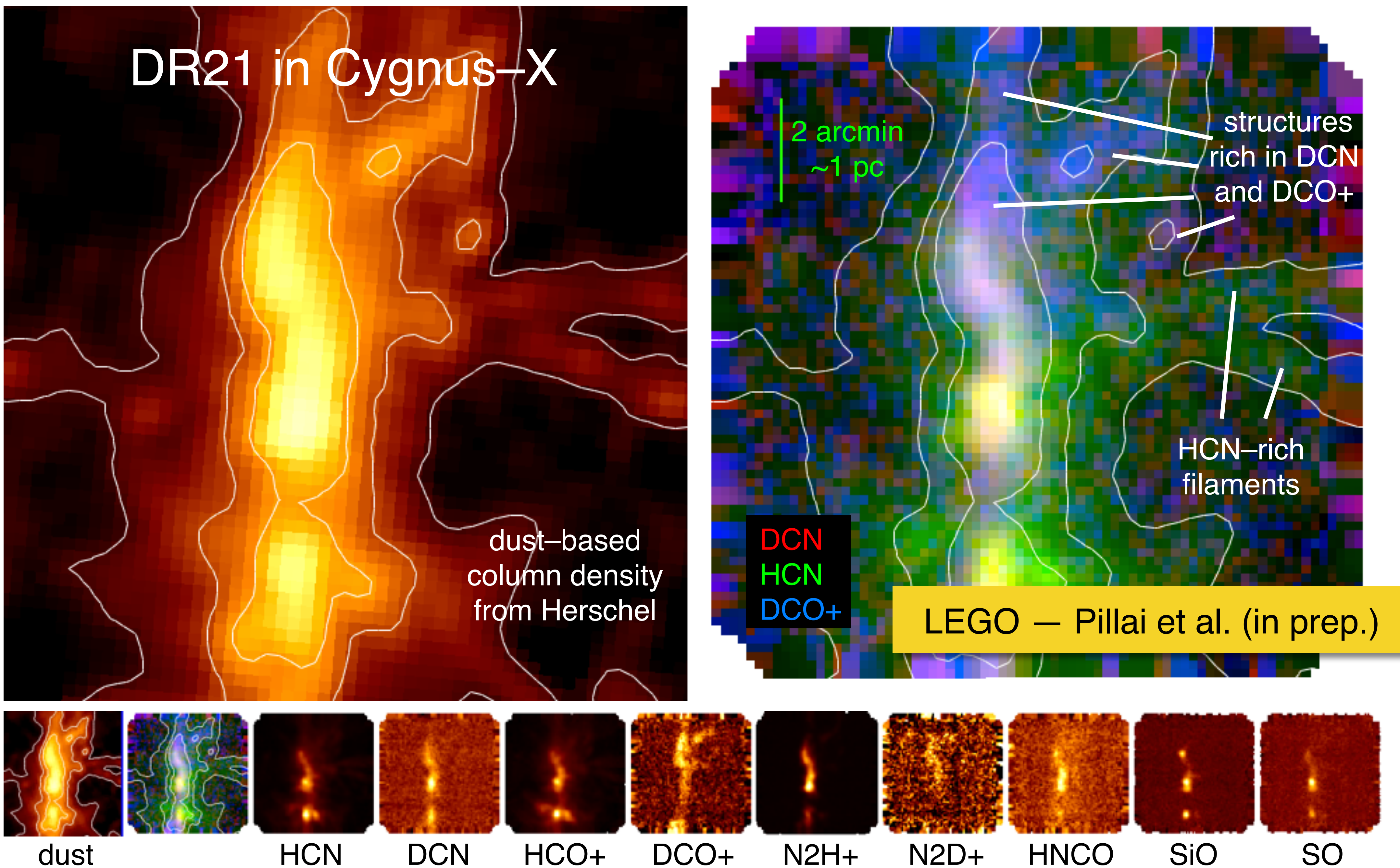
reliance on single emission lines is risky

e.g., α_{HCN} varies by factor ~10 between clouds

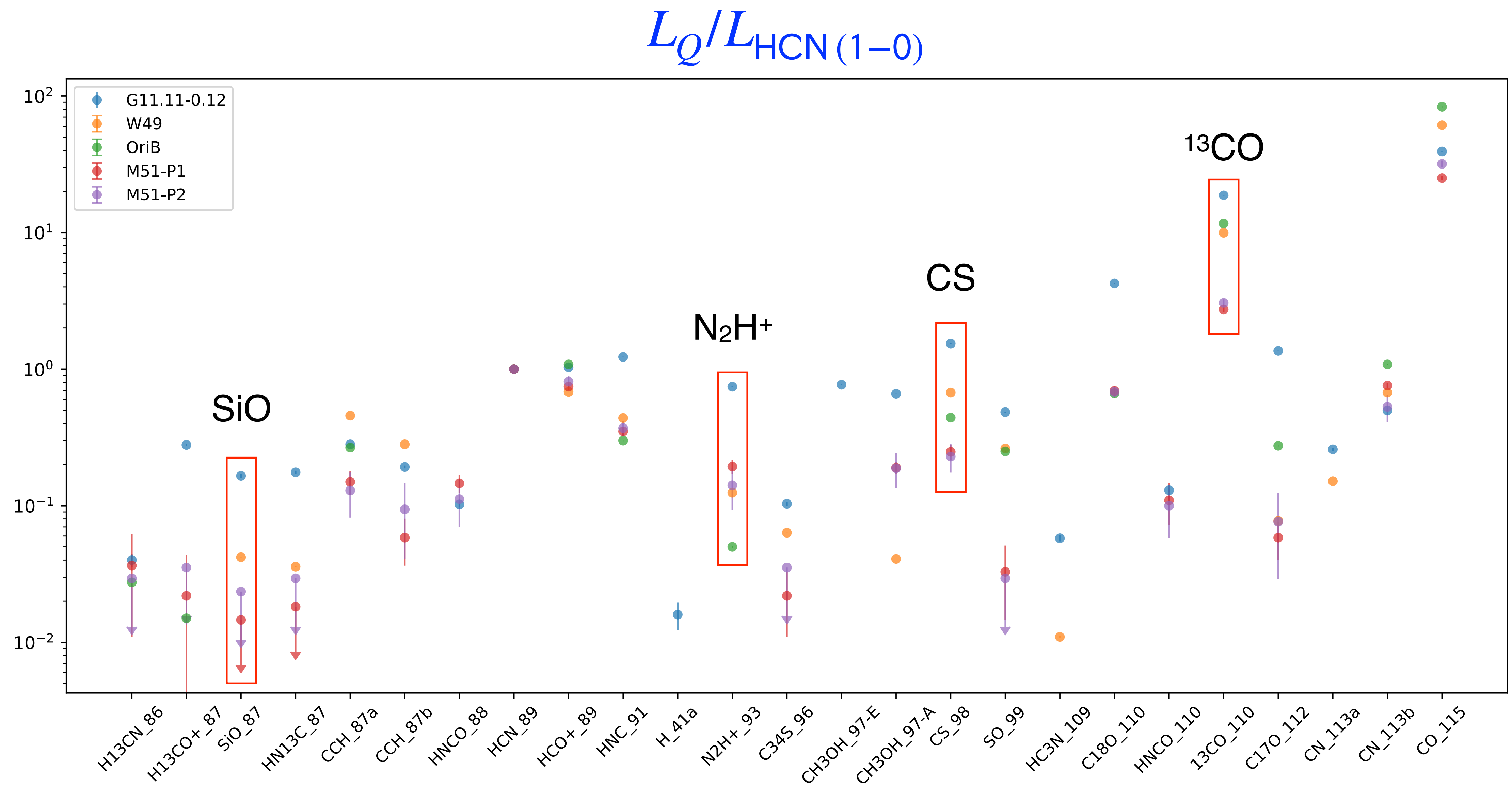
many (all?) emission lines respond to cloud physics

e.g., variation in α_{HCN} must be result of how HCN responds to cloud densities and temperatures

Data on many lines constrain entire Ecosystems



Cloud-to-Cloud Variation: Evidence for Cloud Diversity

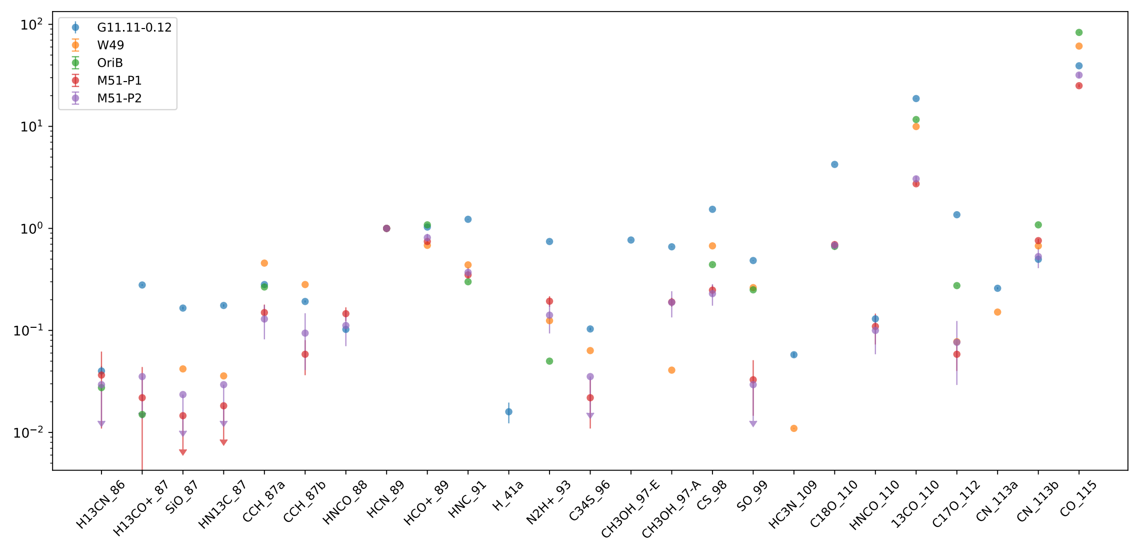


Broadmeadow et al. (in prep.)

Q-to-HCN line ratios observed to vary by factors >10 between clouds

Cloud-to-Cloud Variation: Evidence for Cloud Diversity

$L_Q/L_{\mathrm{HCN\,(1-0)}}$

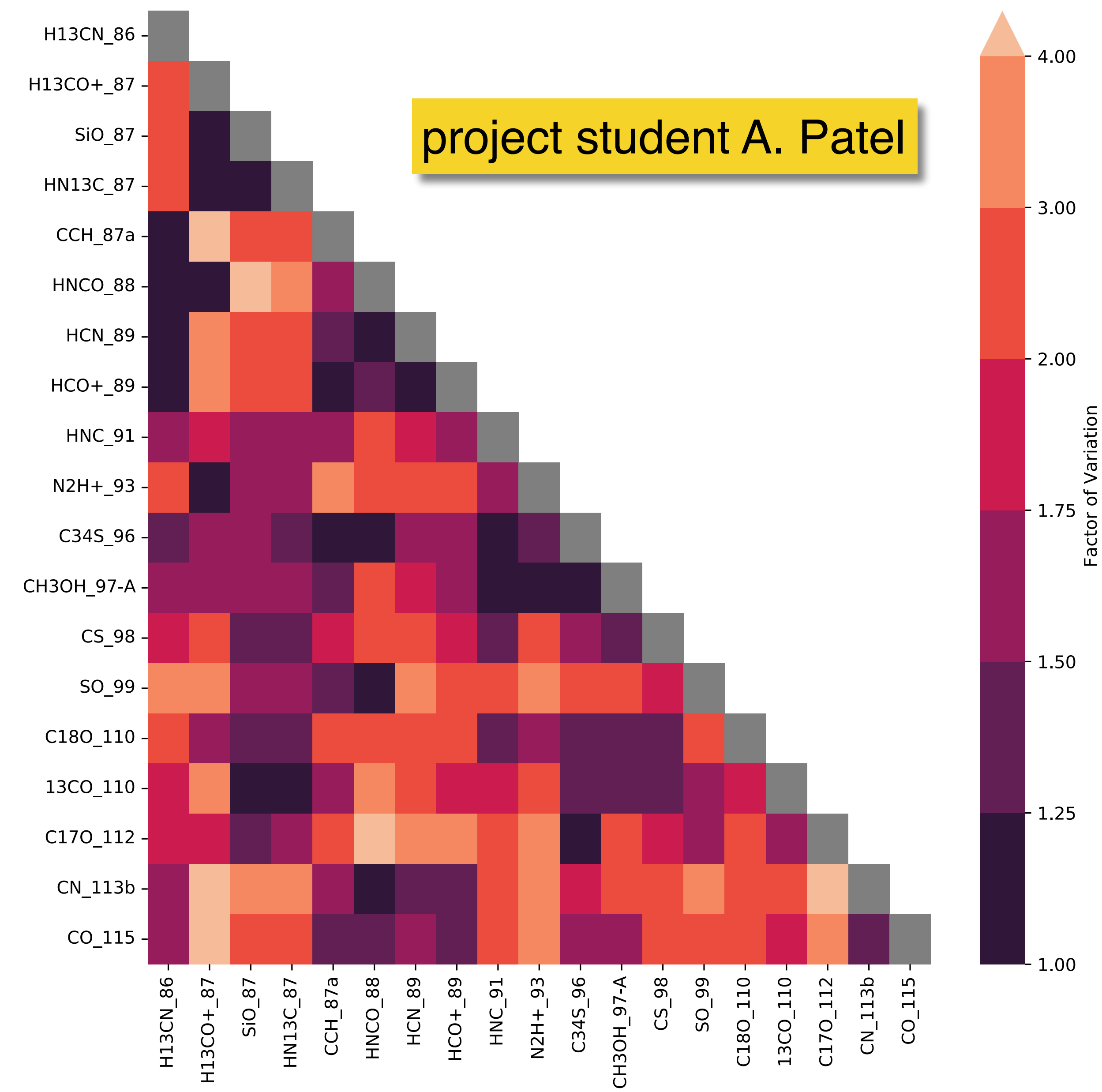


Broadmeadow et al. (in prep.)

L_i/L_j typically varies between clouds

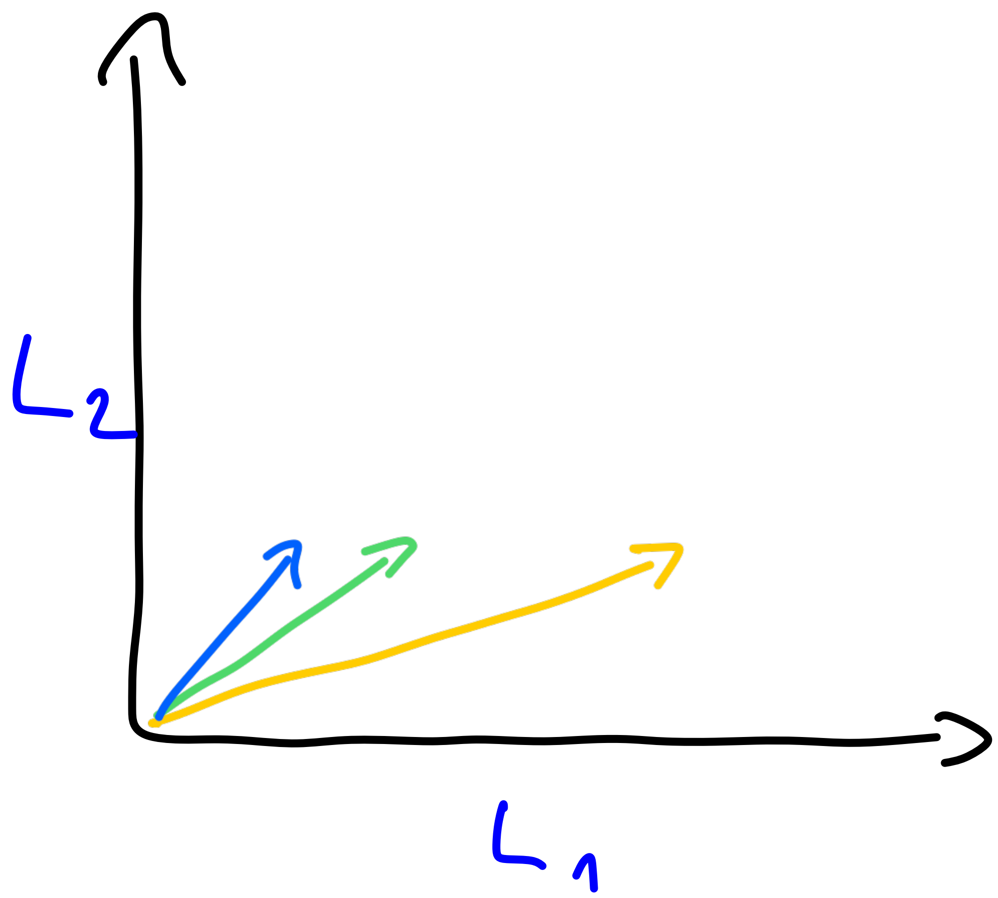
⇒ clouds differ substantially in properties

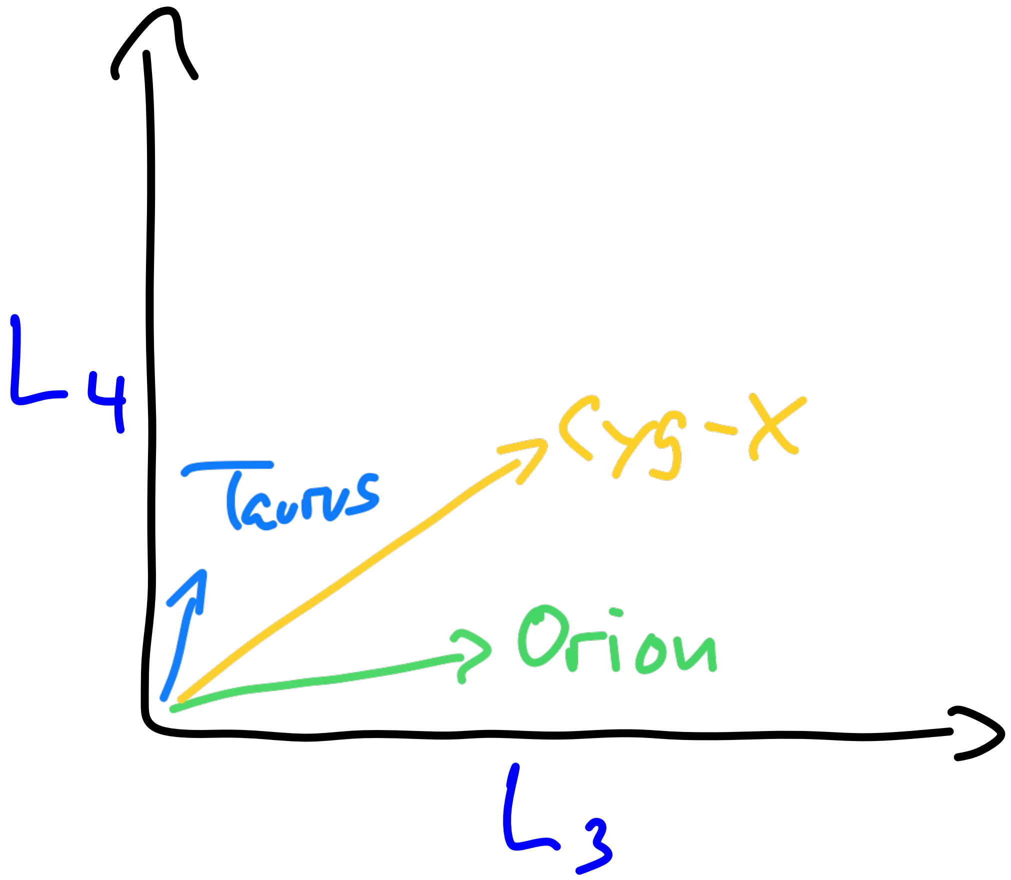
cloud-to-cloud variation in L_i/L_j



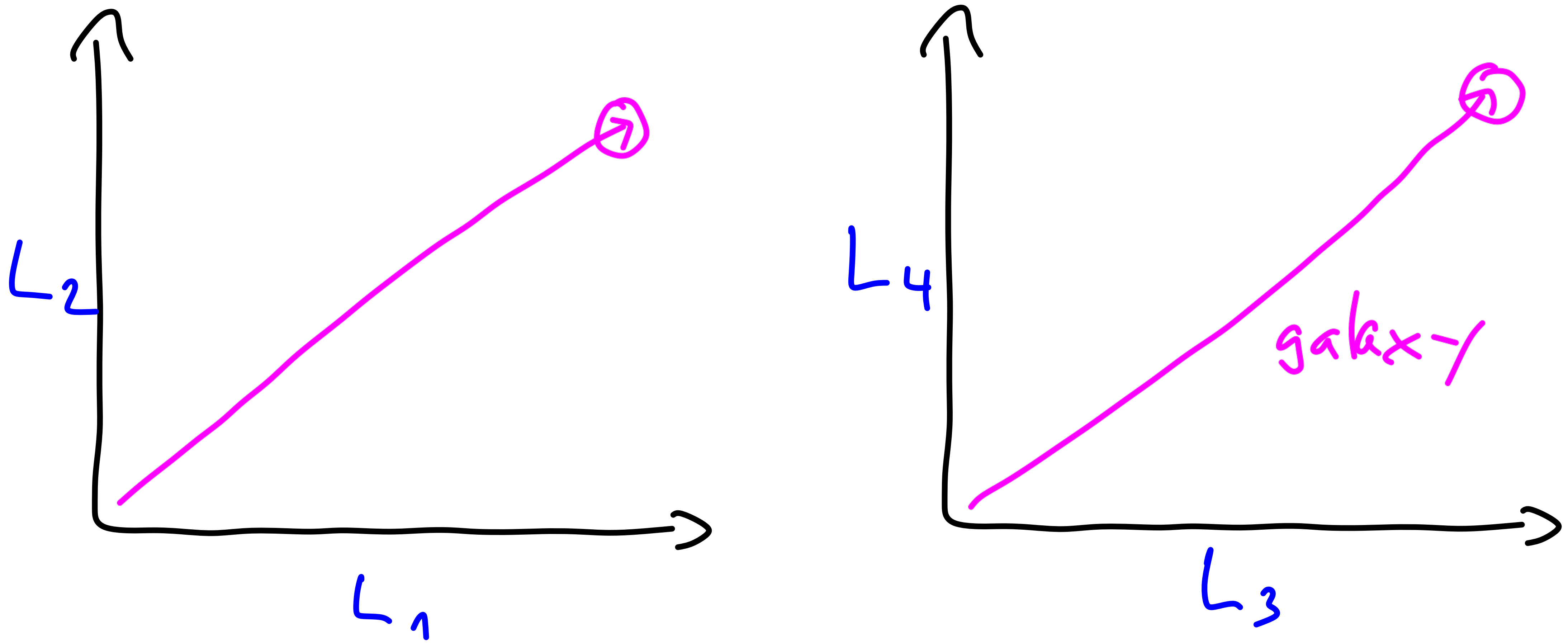
project student A. Patel

Cloud Population Synthesis in Line Ratios

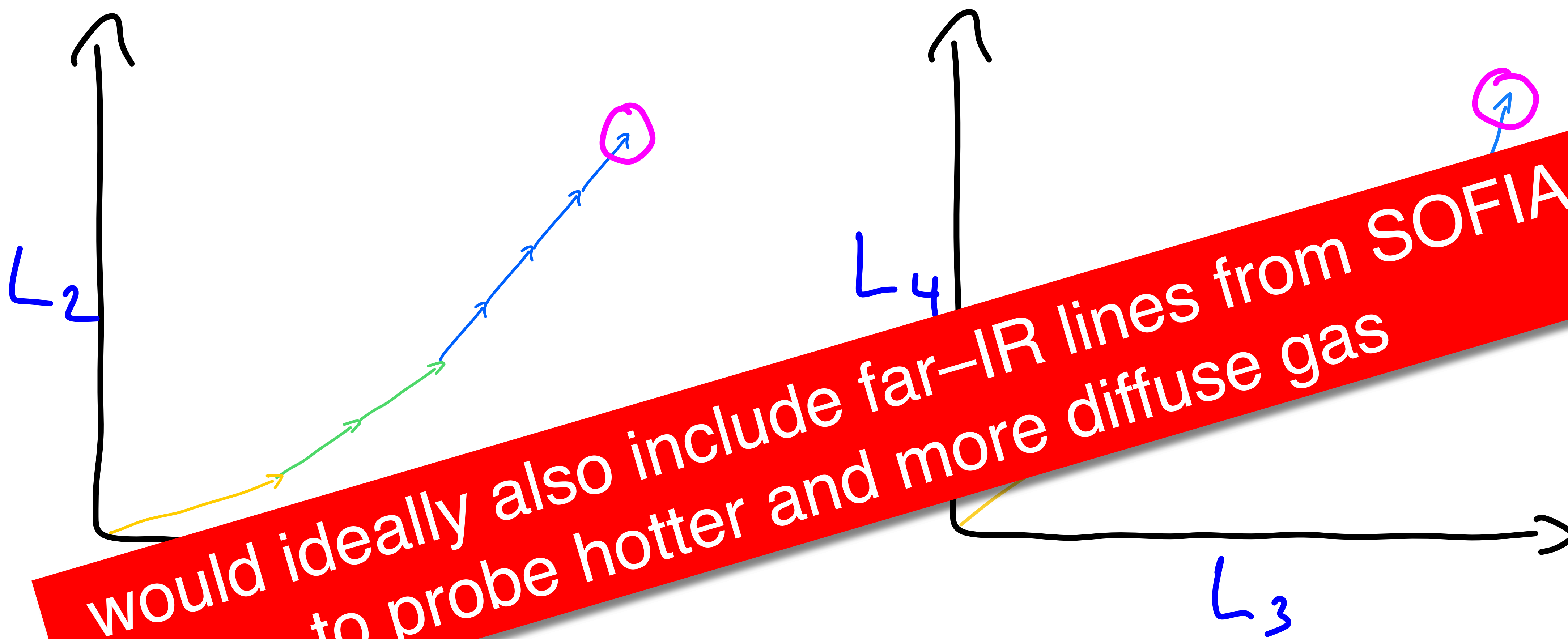




Cloud Population Synthesis in Line Ratios



Cloud Population Synthesis in Line Ratios



would ideally also include far–IR lines from SOFIA to probe hotter and more diffuse gas

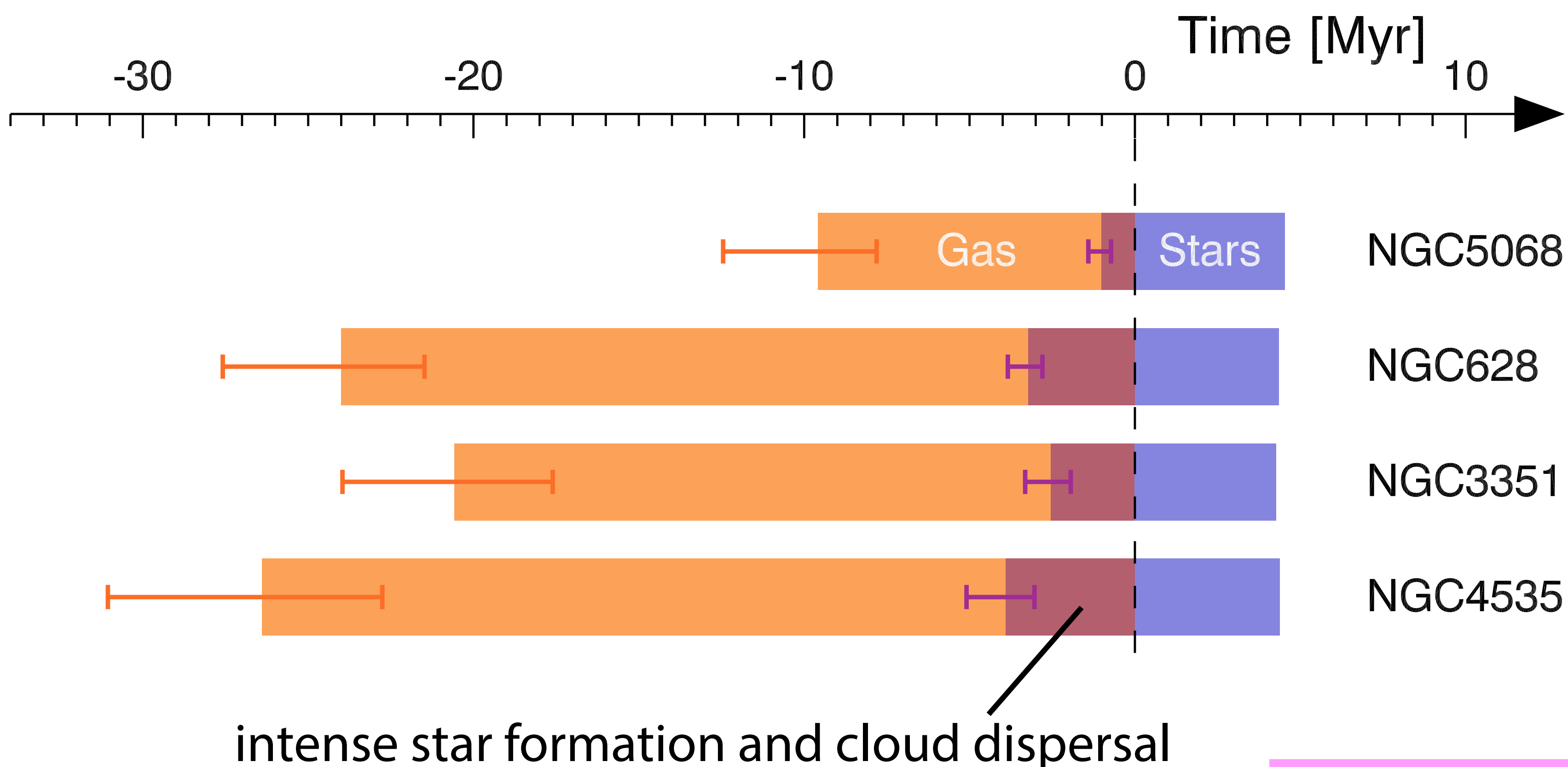
population synthesis:

$$\vec{T}_{\rm gal} = 1 \cdot \vec{S}_{\rm Cyg\ X} + 2 \cdot \vec{S}_{\rm Orion} + 4 \cdot \vec{S}_{\rm Taurus}$$

could use machine learning to establish more sophisticated basis system

$$\vec{T}_{\rm gal} = w_{\rm dissolve} \cdot \vec{S}_{\rm dissolve} + w_{\rm SF} \cdot \vec{S}_{\rm SF} + w_{\rm cold} \cdot \vec{S}_{\rm cold}$$

Application: Constraining Extragalactic Cloud Evolution



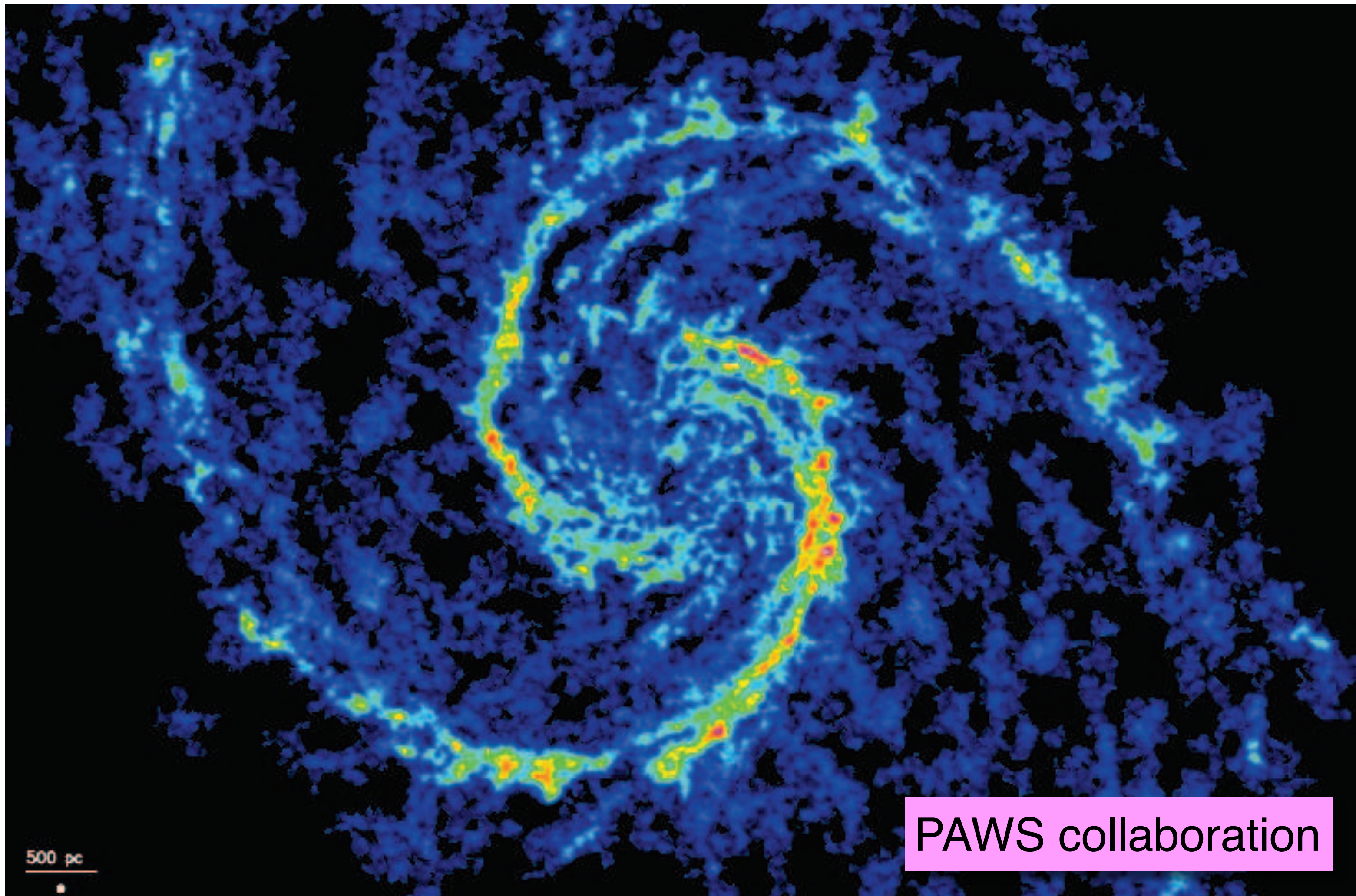
Chevance et al. (2020)

these phase durations should be reflected in population synthesis

$$\vec{T}_{\rm gal} = w_{\rm dissolve} \cdot \vec{S}_{\rm dissolve} + w_{\rm SF} \cdot \vec{S}_{\rm SF} + w_{\rm cold} \cdot \vec{S}_{\rm cold}$$

Relevance: Key Science Goals of ALMA and ngVLA

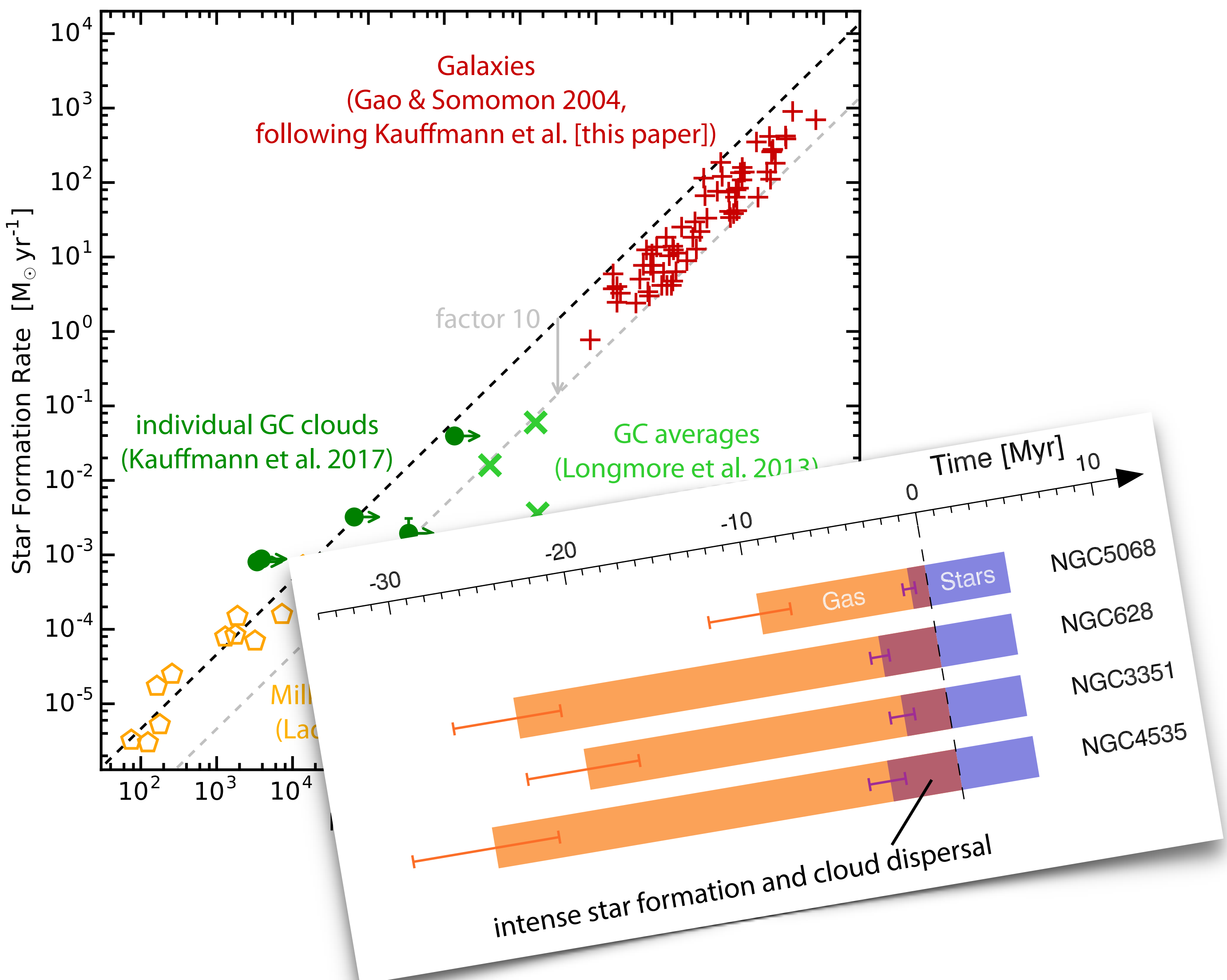
CO (1–0) in M51 from NOEMA

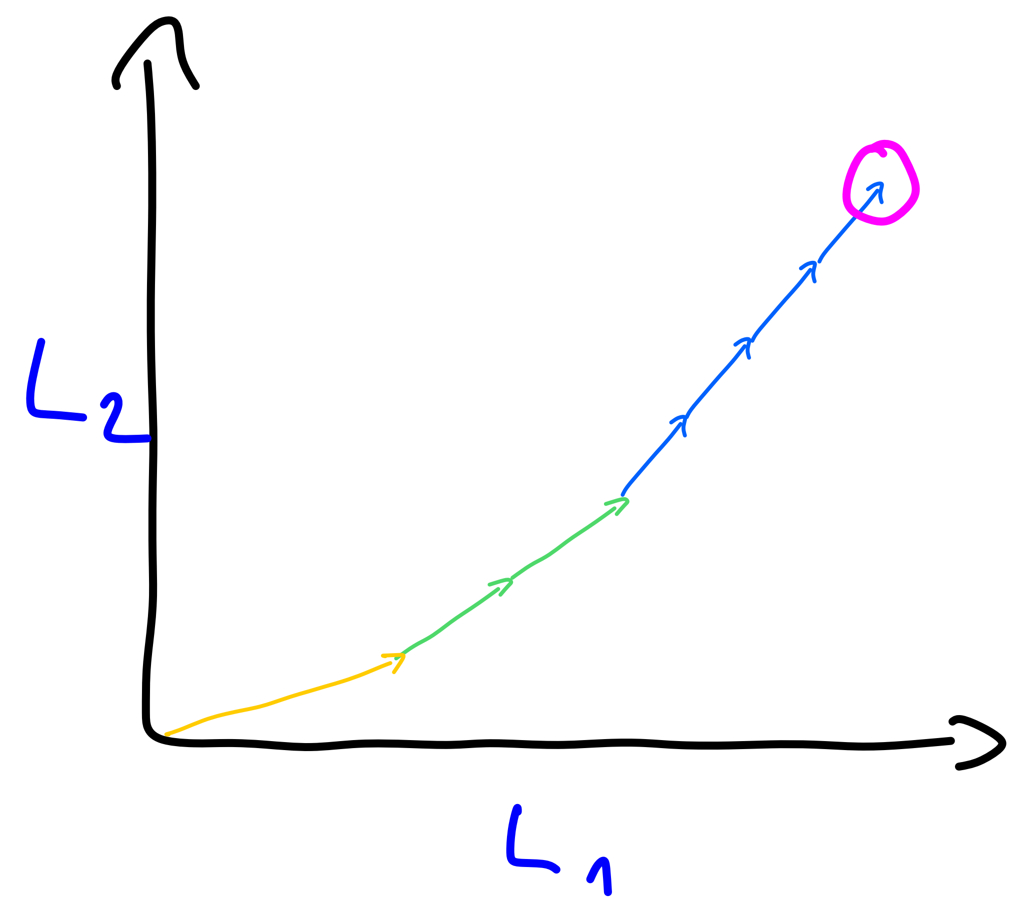


millimeter-wave studies of extragalactic molecular clouds are a key science goal of ALMA and ngVLA

massive wide-field imaging of Milky Way with single dish telescopes needed to "calibrate" these observations

Summary



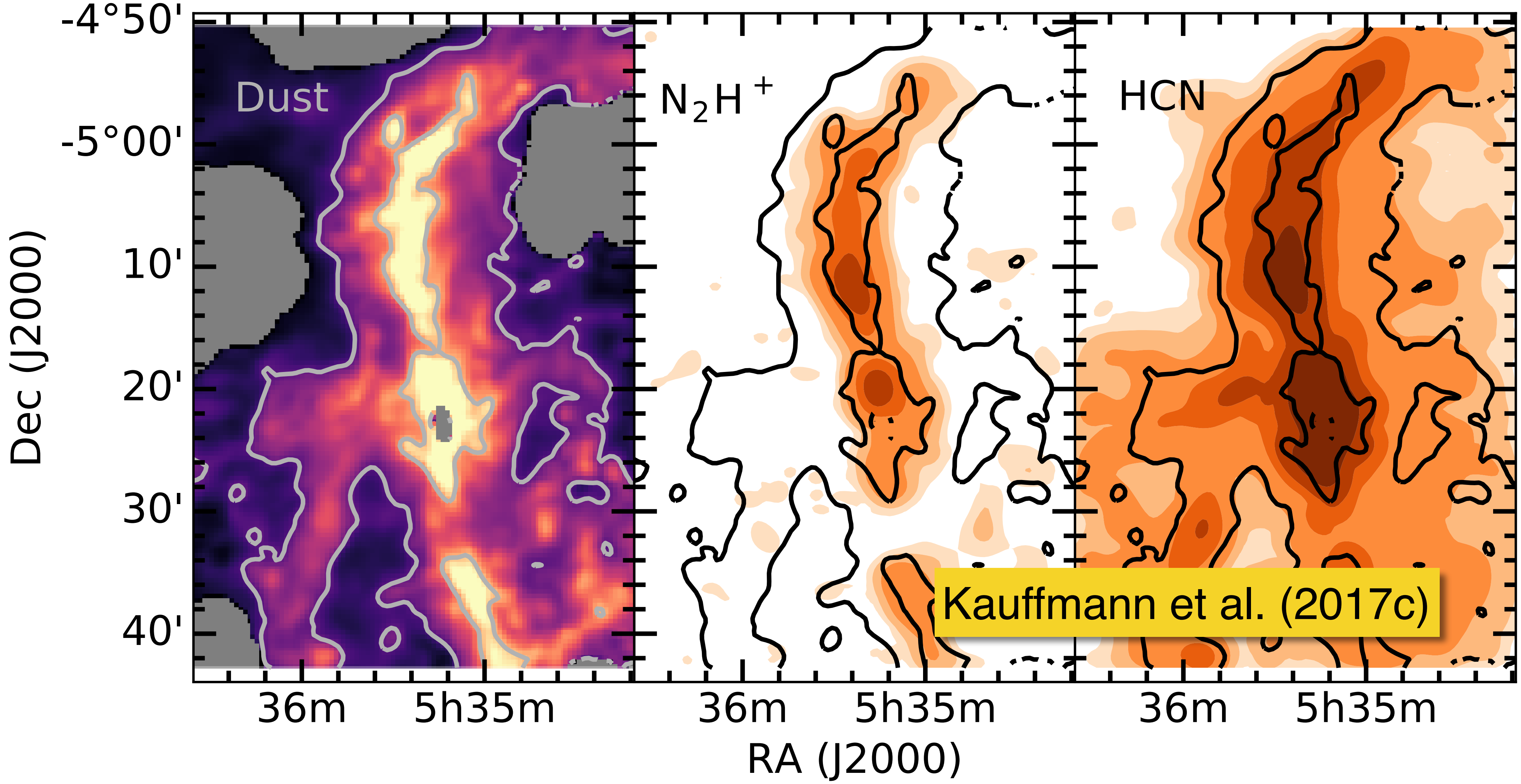


need many lines for best constraints

millimeter-wave line observations critically constrain SF and cloud life cycles

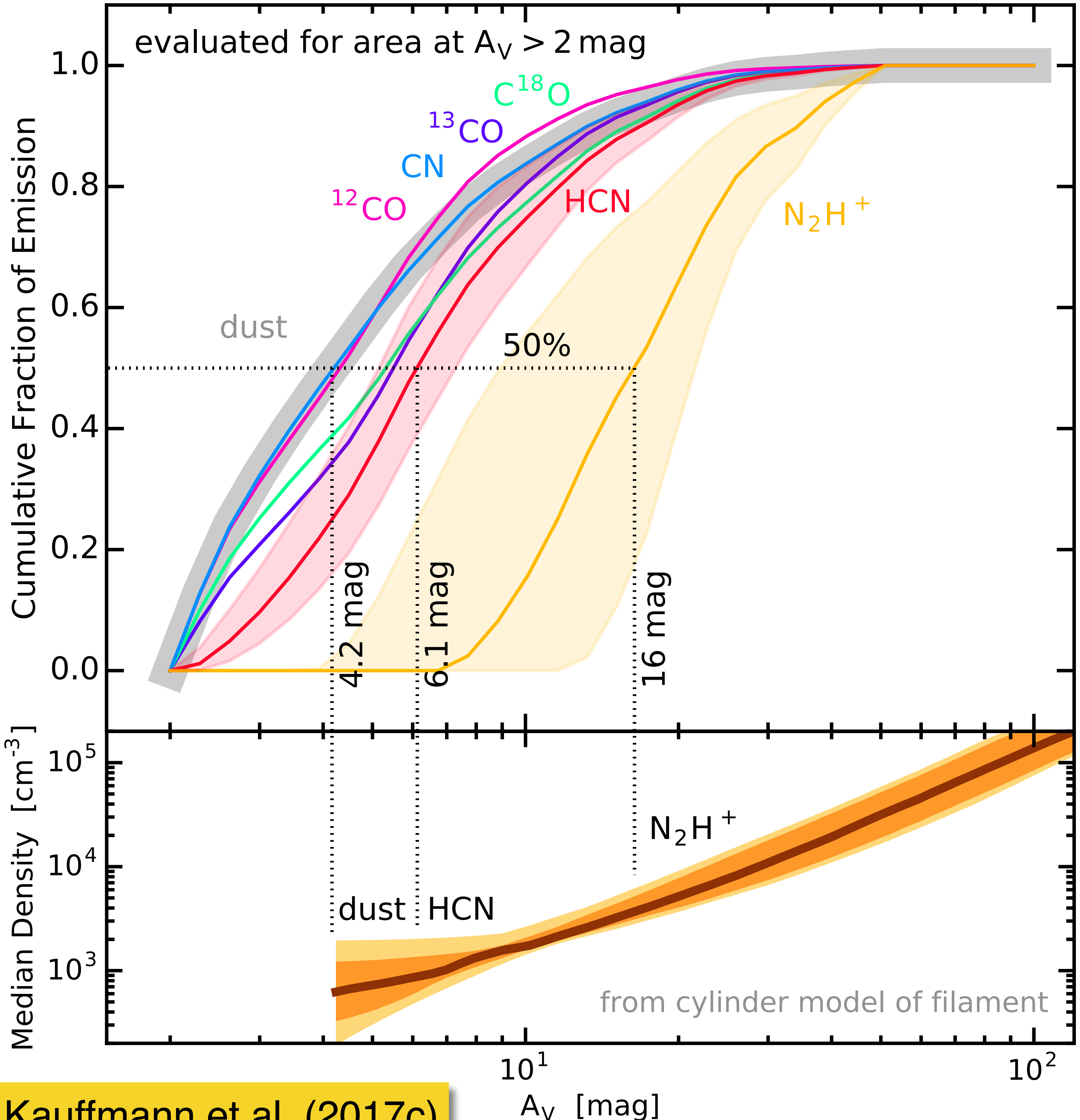
wide-field imaging for “calibration” in MW difficult to do

Supporting Material

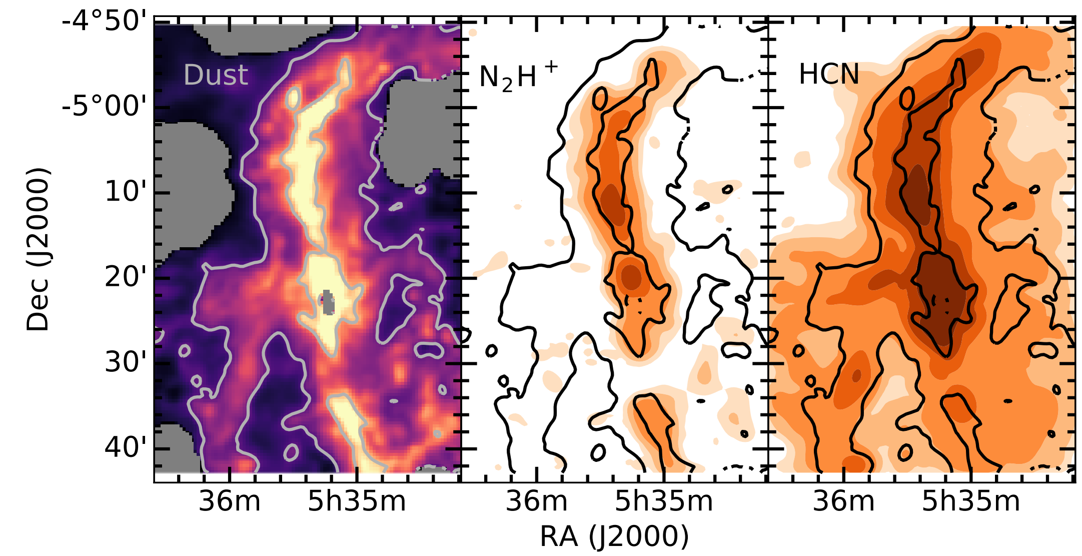


HCN (1–0) line rather spatially extended…

Tracing Gas in Molecular Clouds

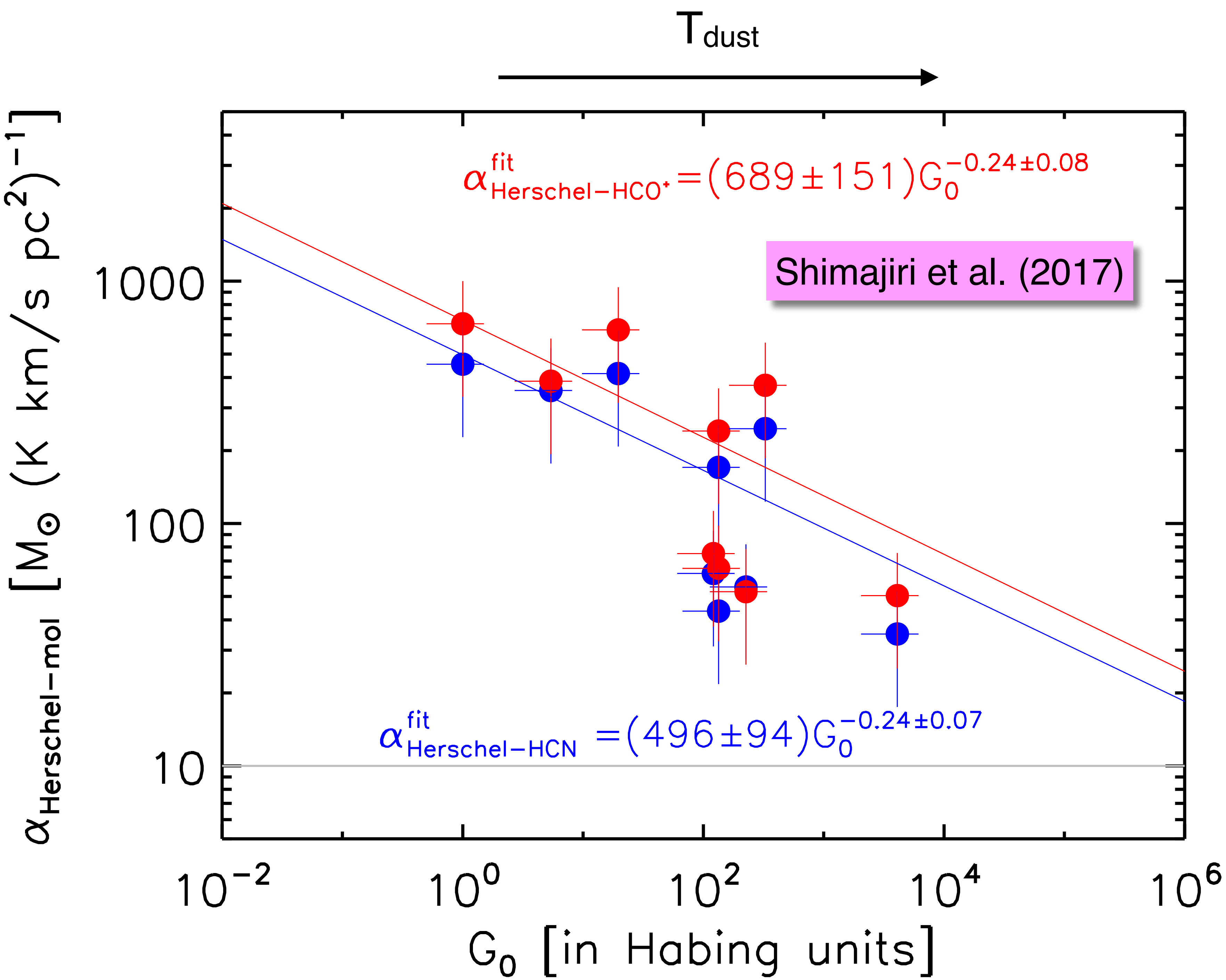


Kauffmann et al. (2017c)



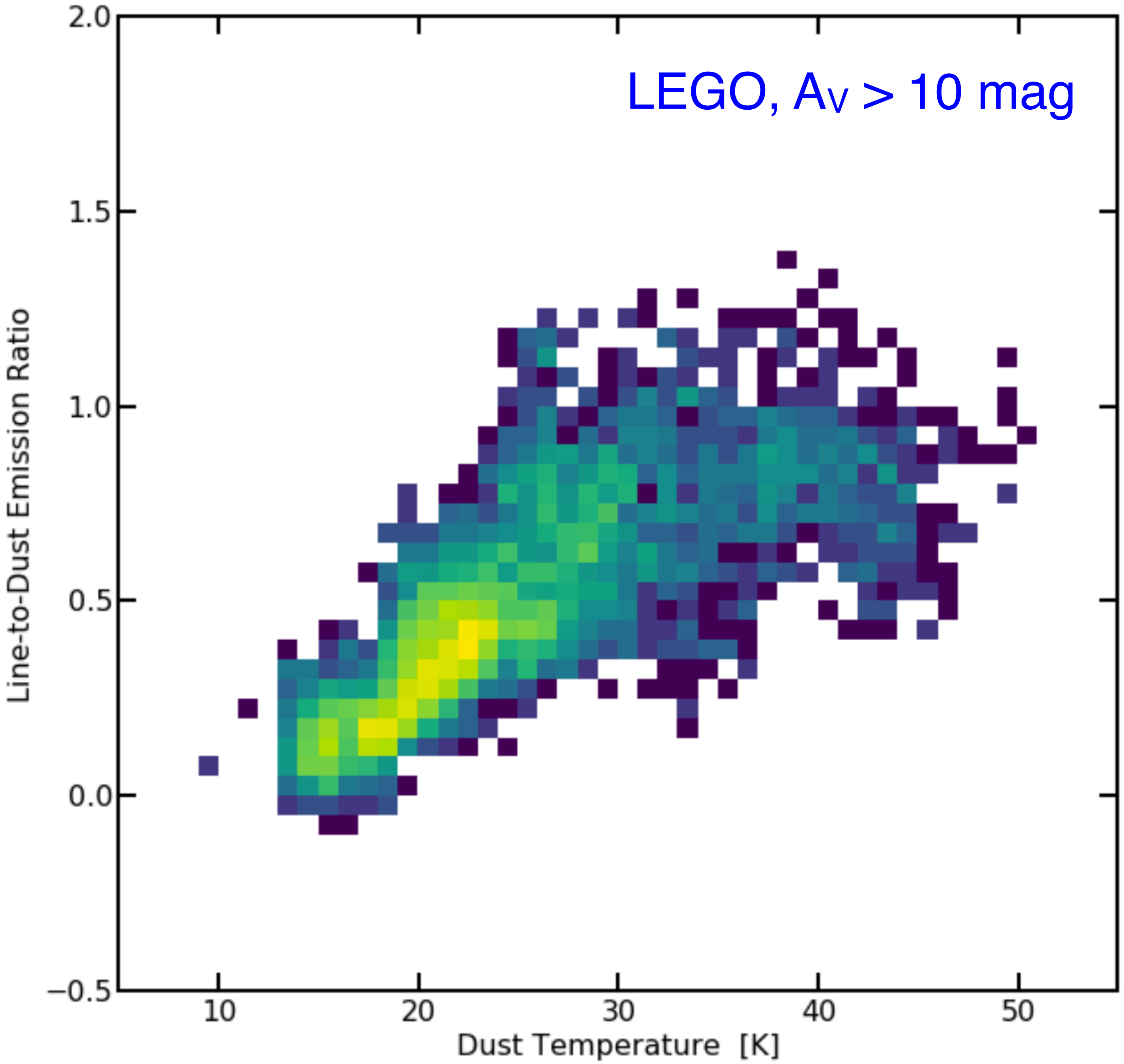
⇒ HCN (1–0) traces density ~10^3 cm^{-3}

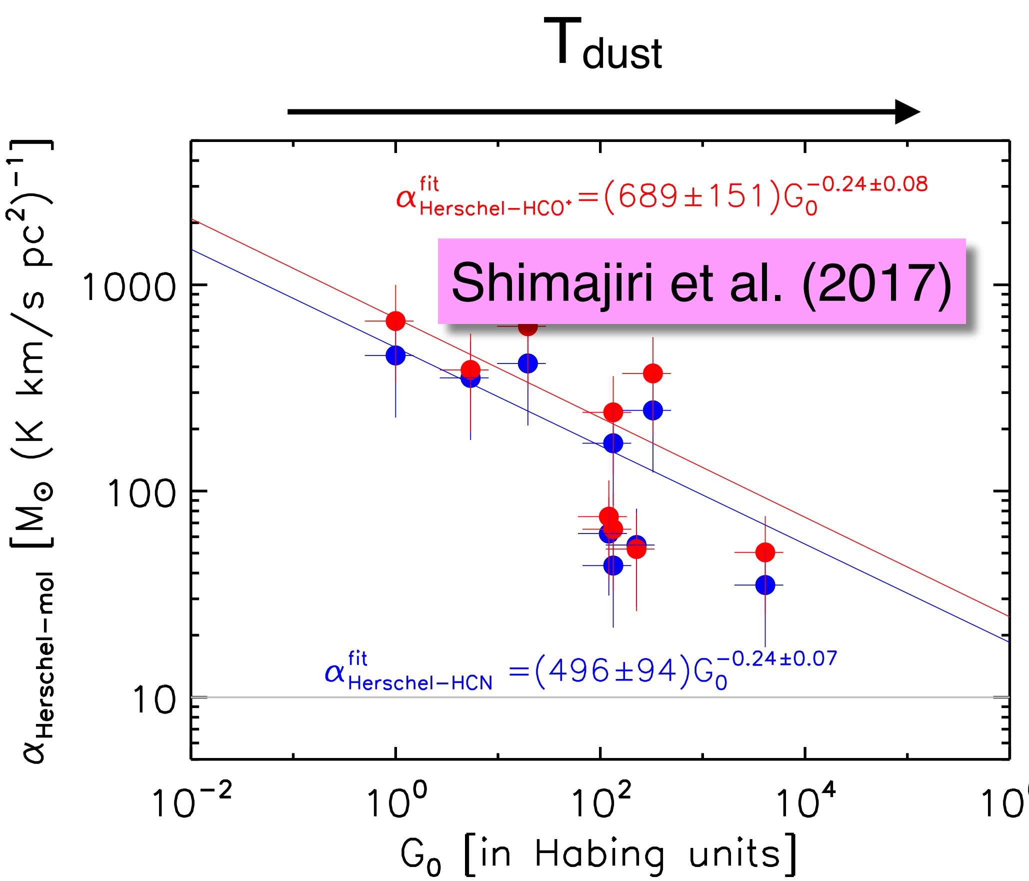
typical literature value: ≫10^4 cm^{-3}



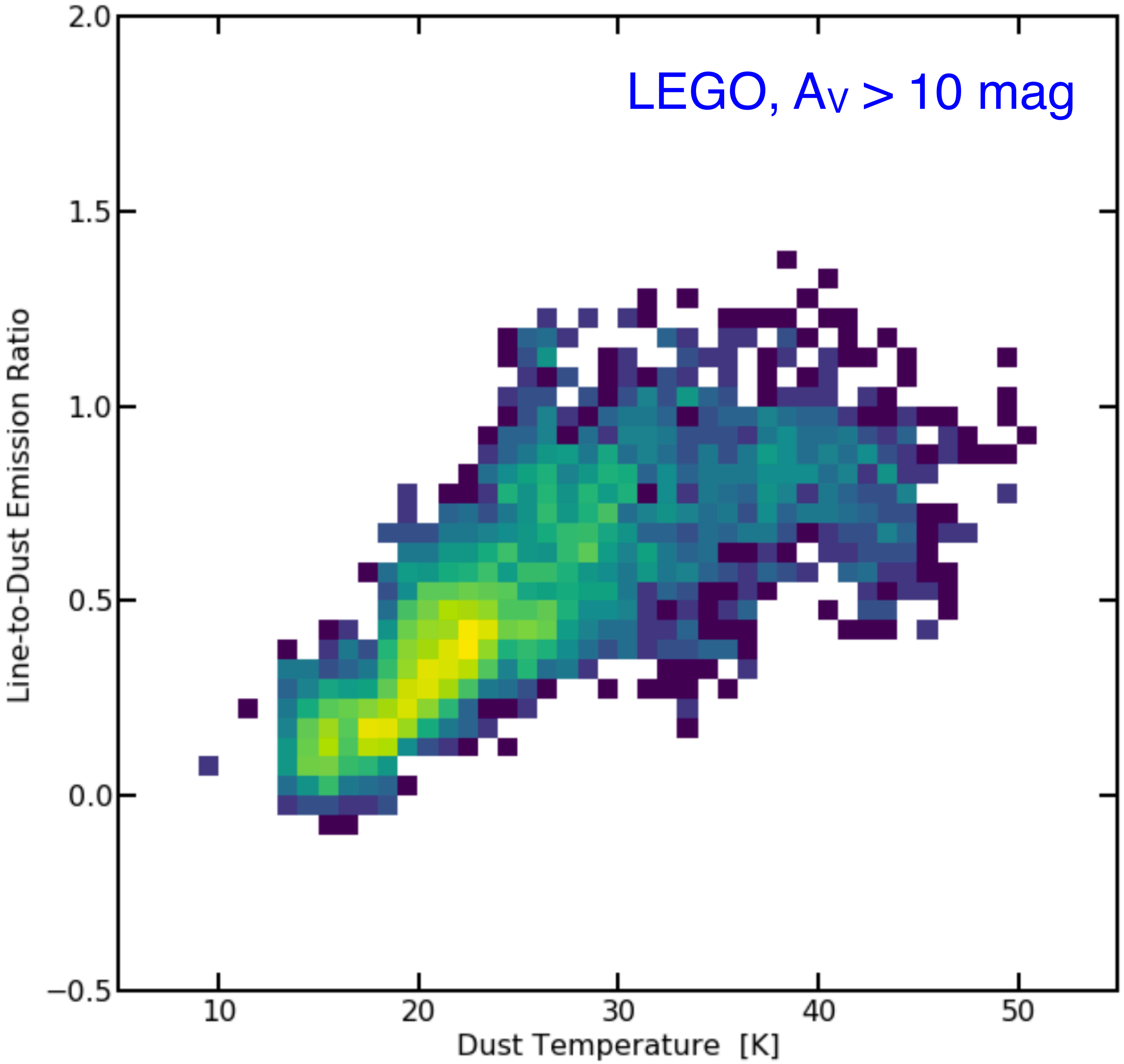
…or is $\alpha_{HCN\ (1–0)}$ greatly depending on environment?

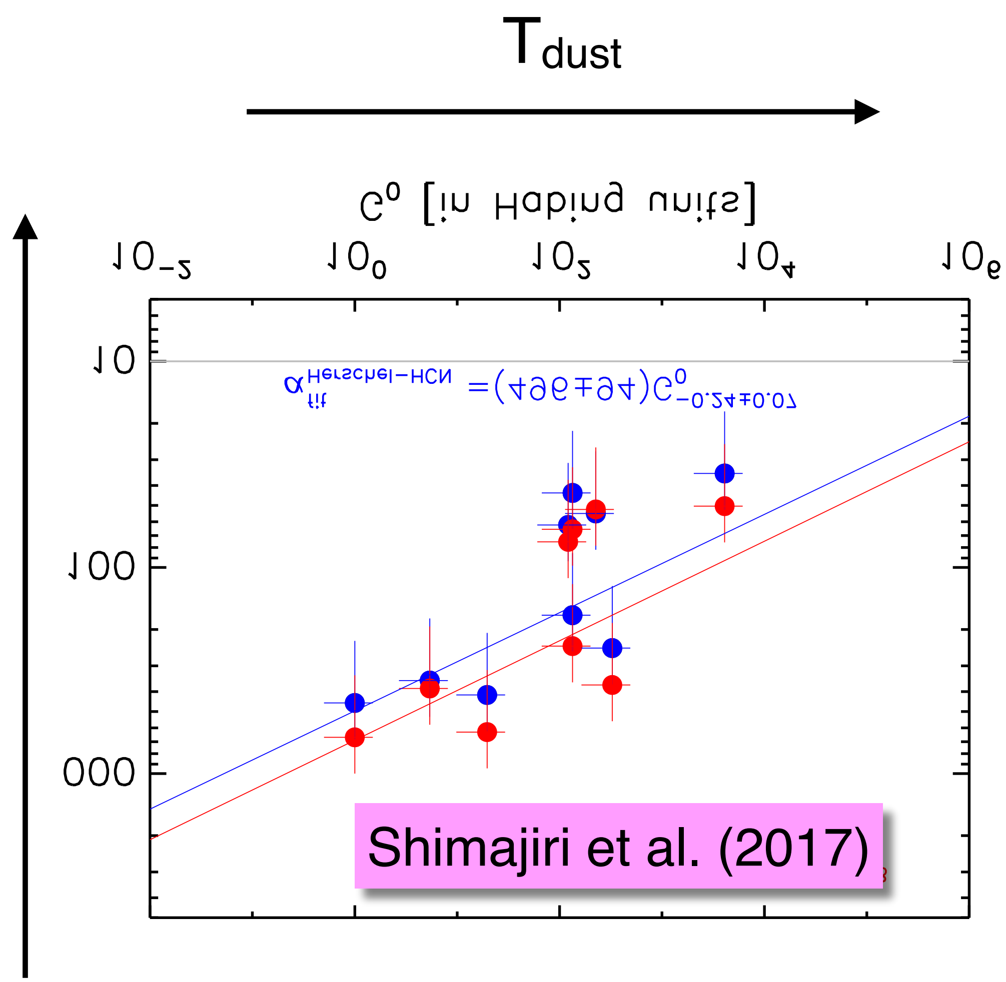
Tracing Dense Gas in Molecular Clouds





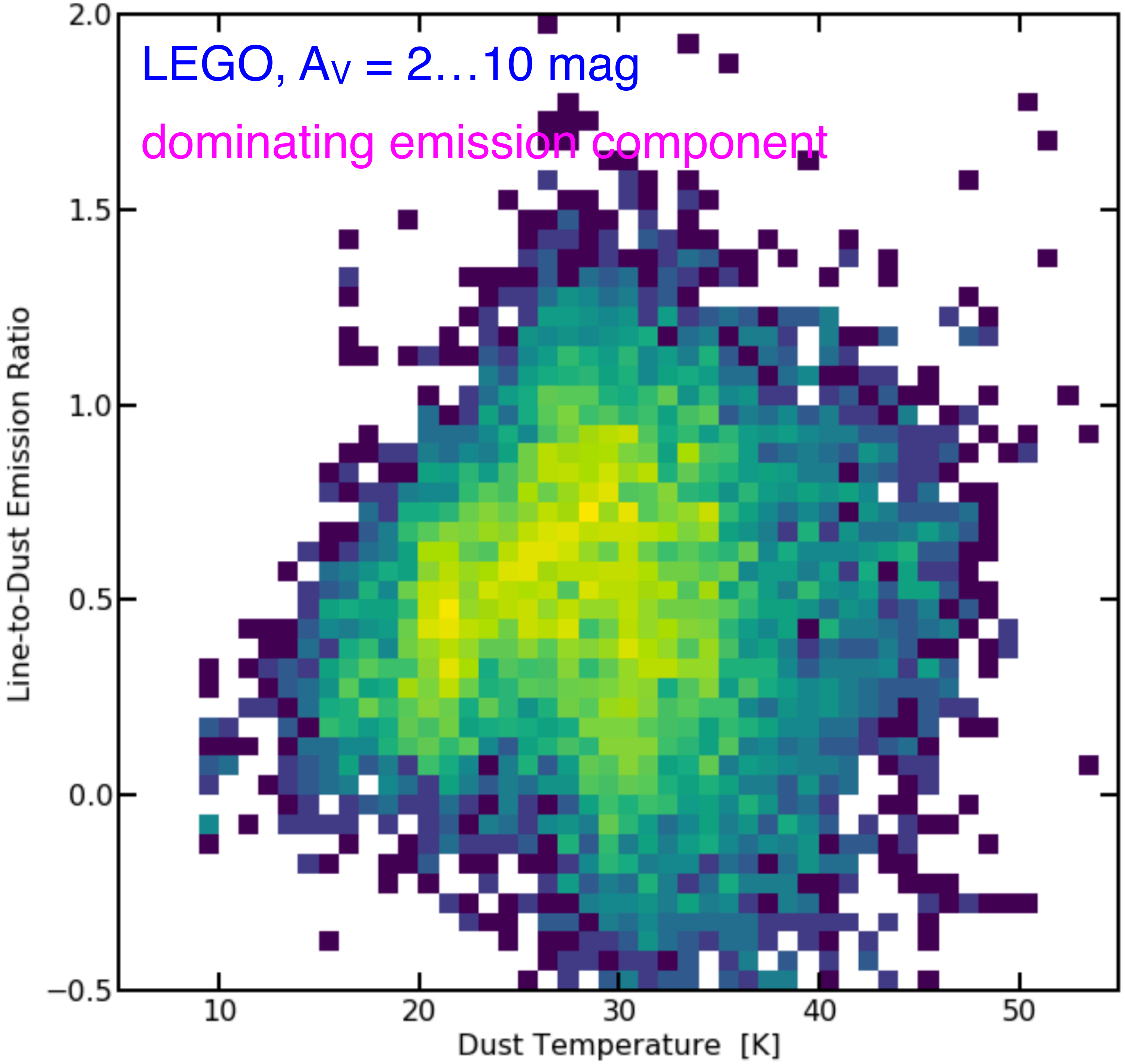
Tracing Dense Gas in Molecular Clouds

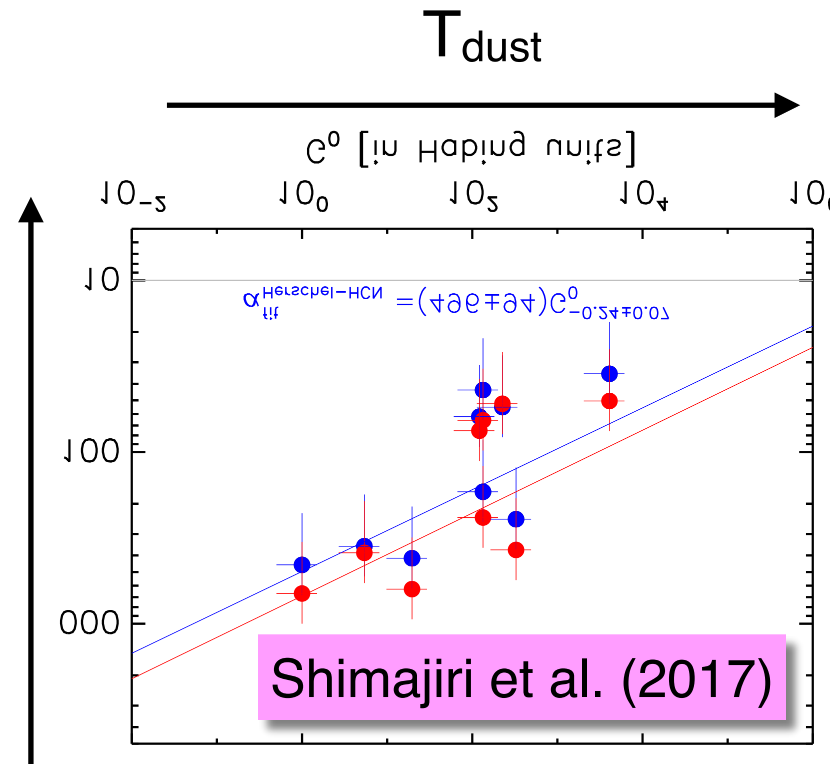




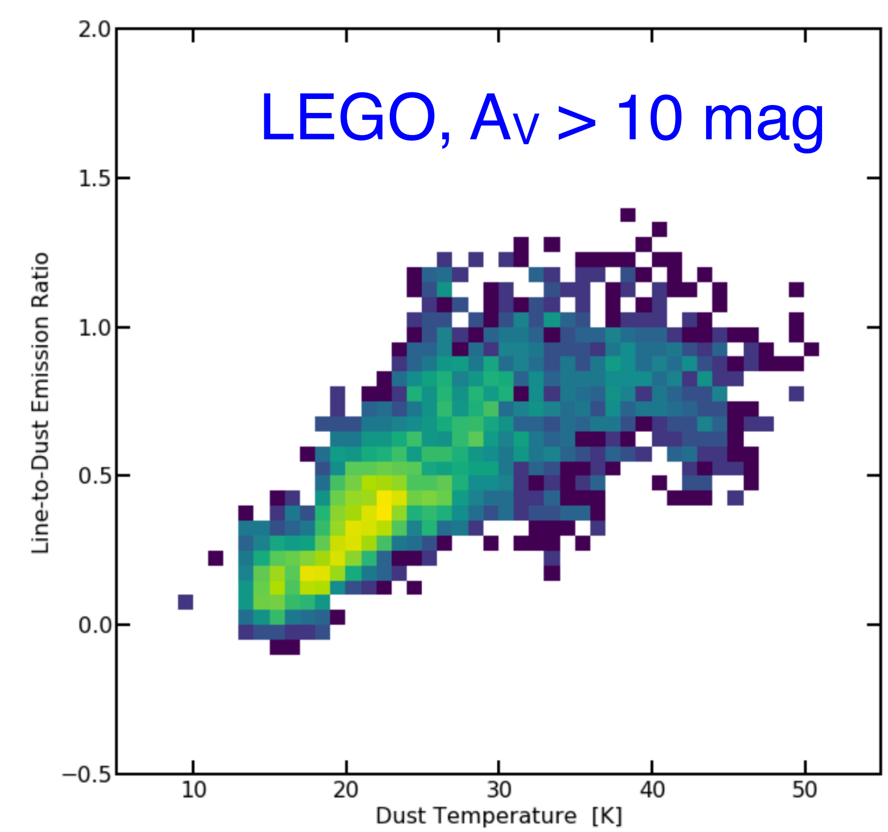
line–to–dust ratio

Tracing Dense Gas in Molecular Clouds





line–to–dust ratio



converting W_{Line} to mass needs more research