Feeding the CMZ:
Gas Accretion Flows in the Galactic Bar

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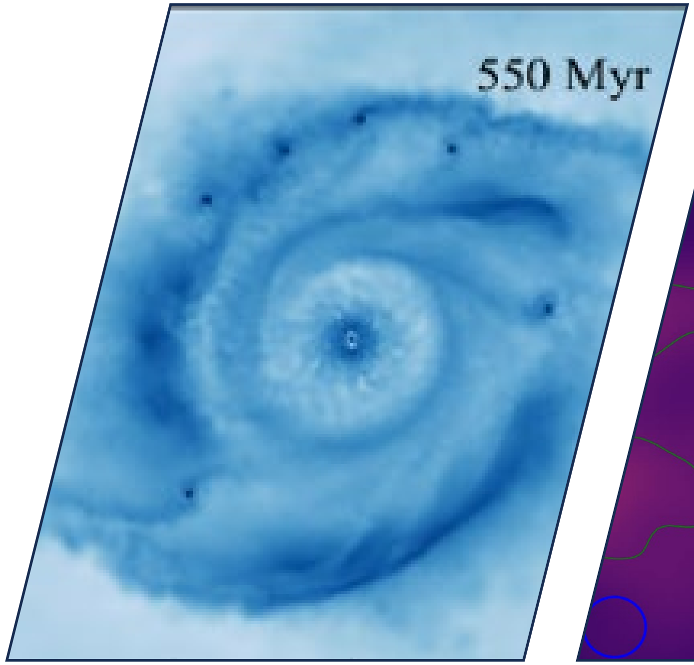
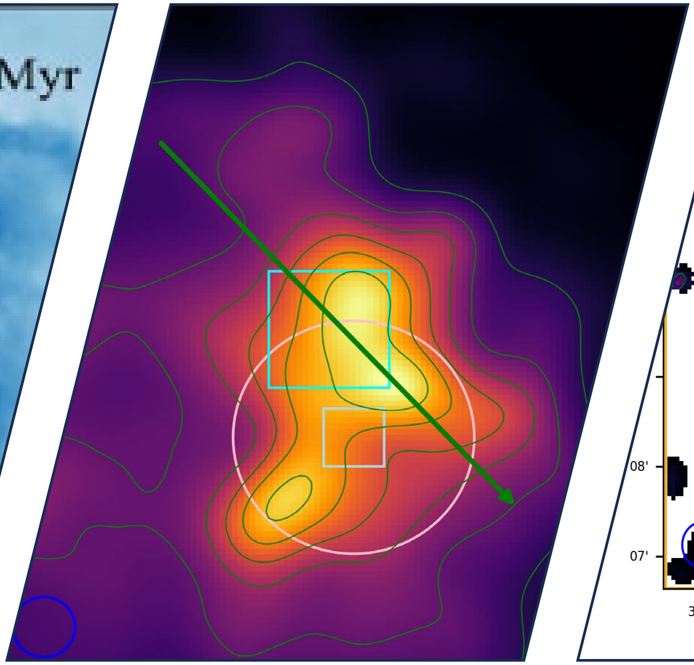
Yale

NRAO
National Radio Astronomy Observatory

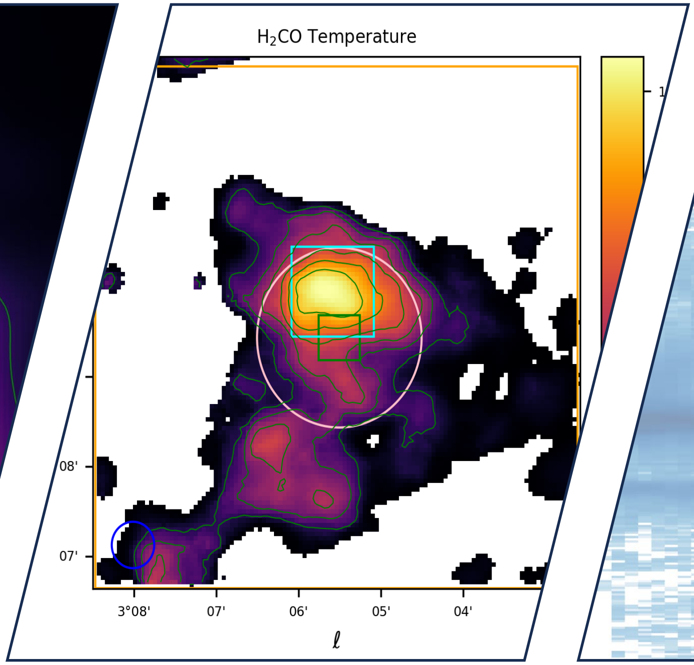
Outline



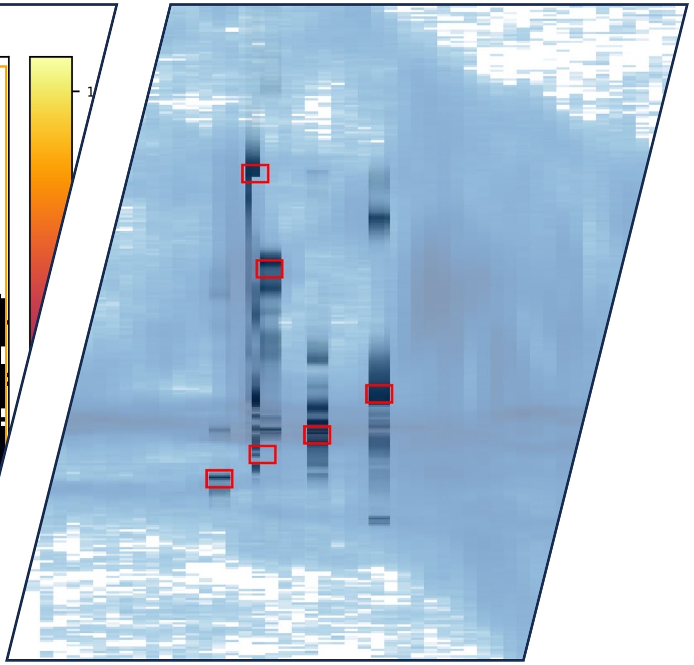
Background



Data



Properties

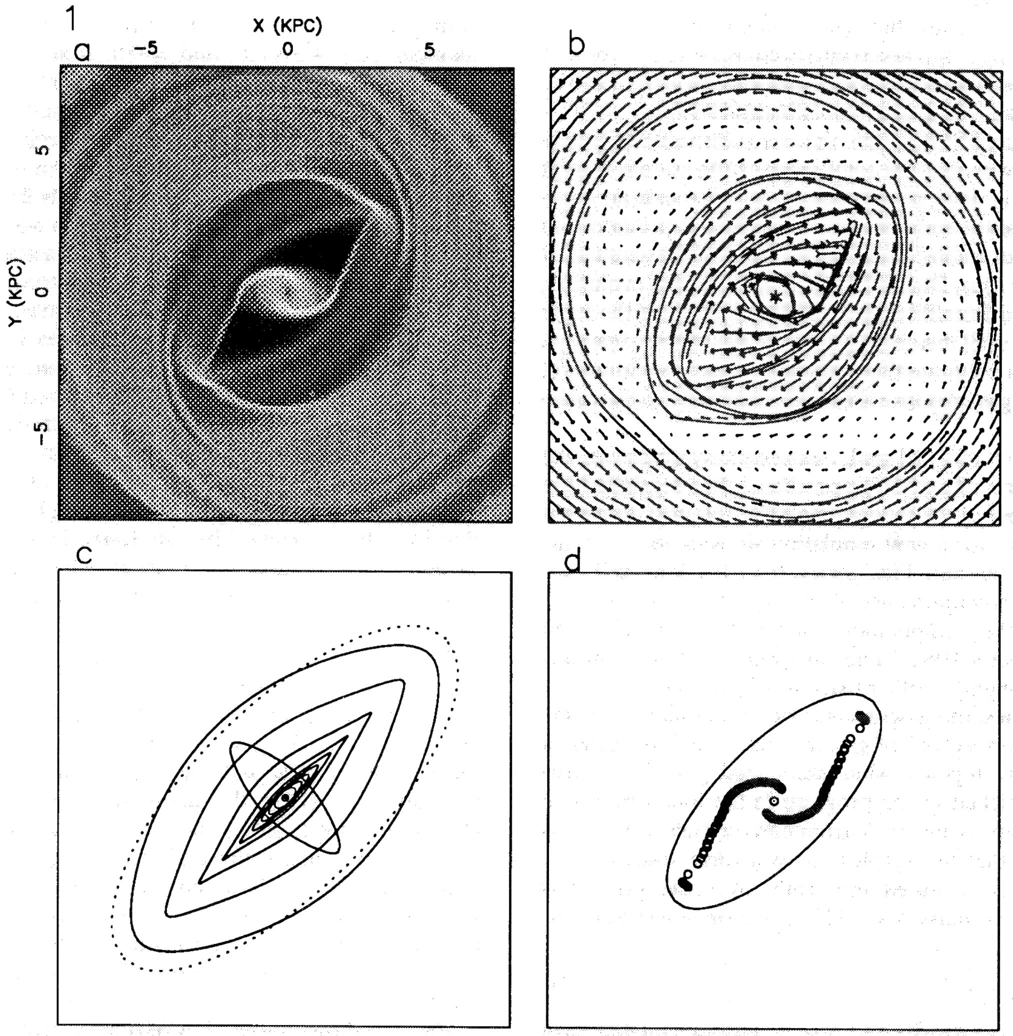


Discussion

Background

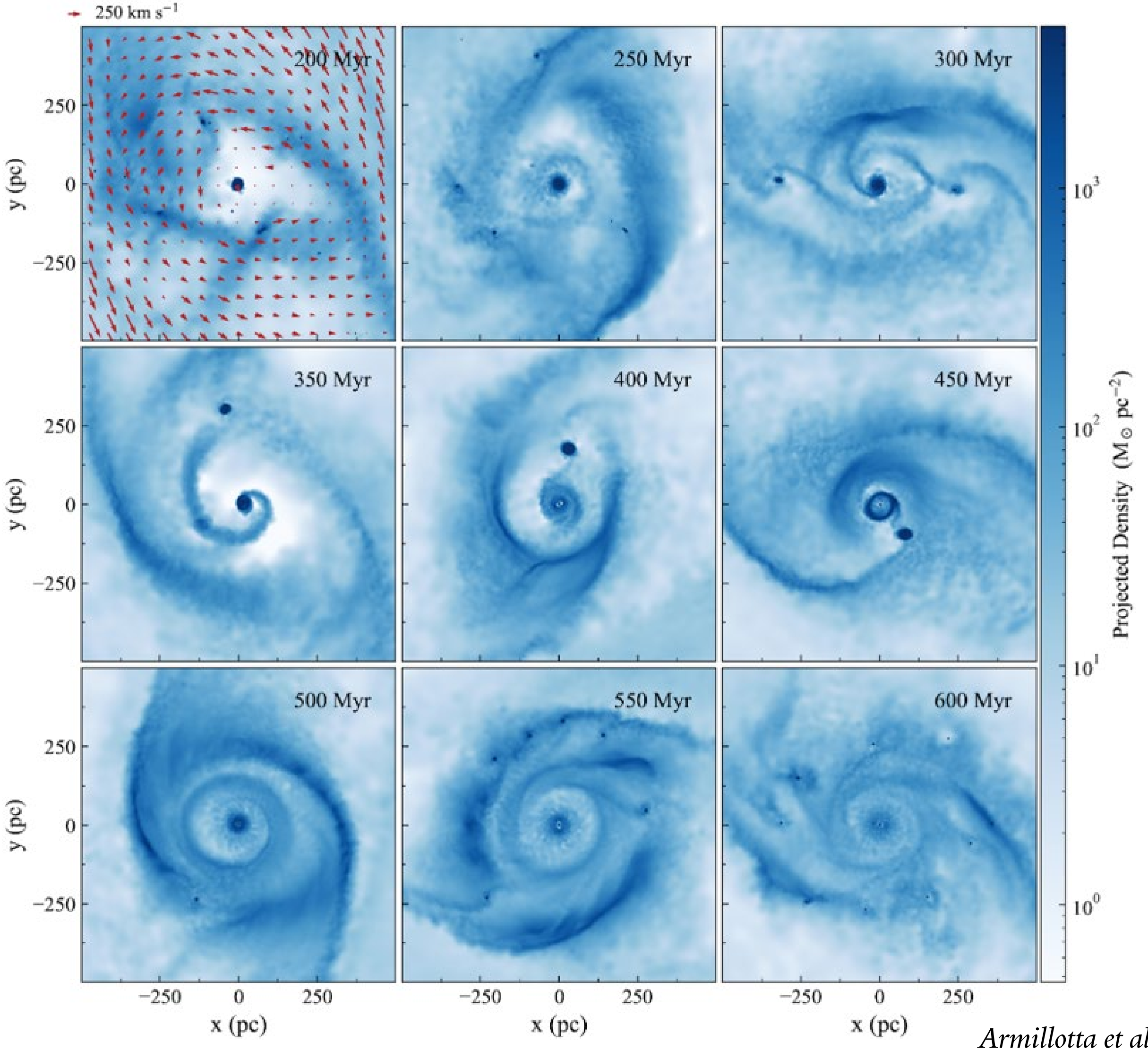
CMZ and CMZ Inflows

Orbits in the Inner Milky Way



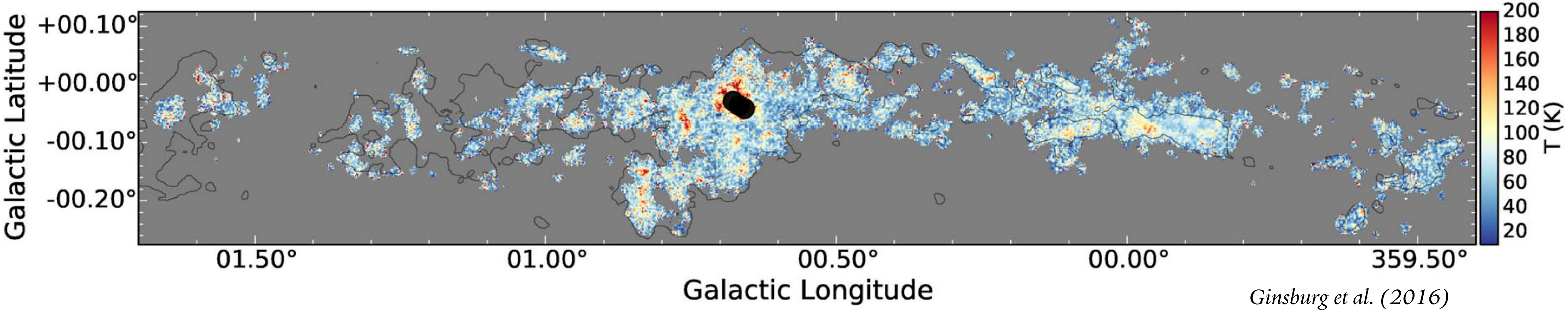
Athanassoula (1992)

Central Molecular Zone (CMZ)



Armillotta et al. (2019)

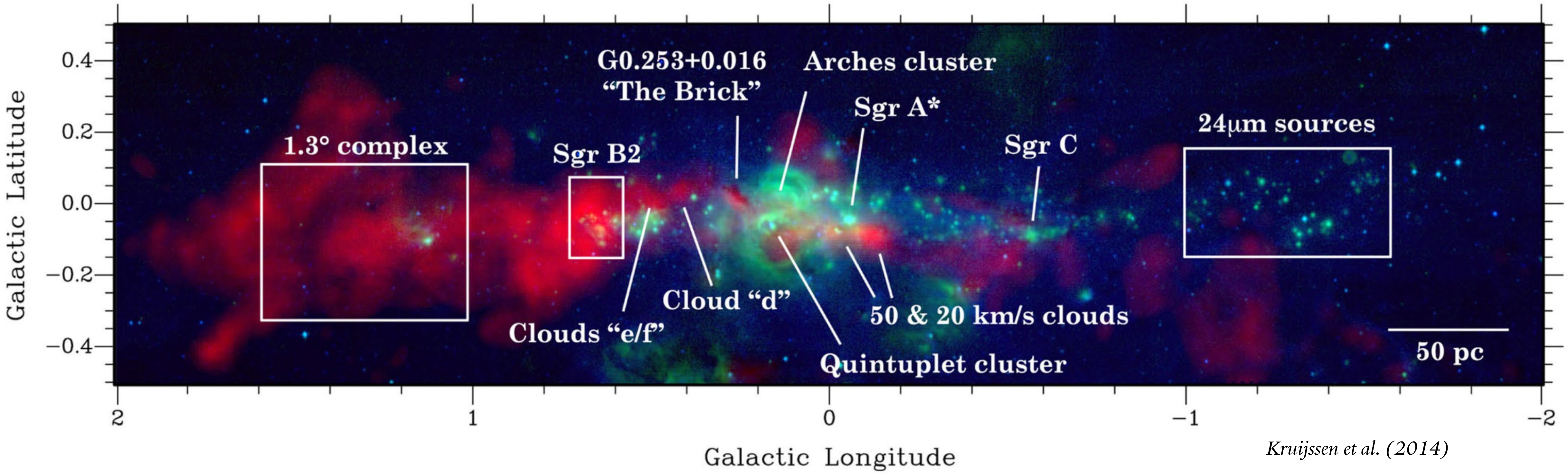
Central Molecular Zone (CMZ)



Ginsburg et al. (2016)

Dense, warm, and turbulent

Central Molecular Zone (CMZ)

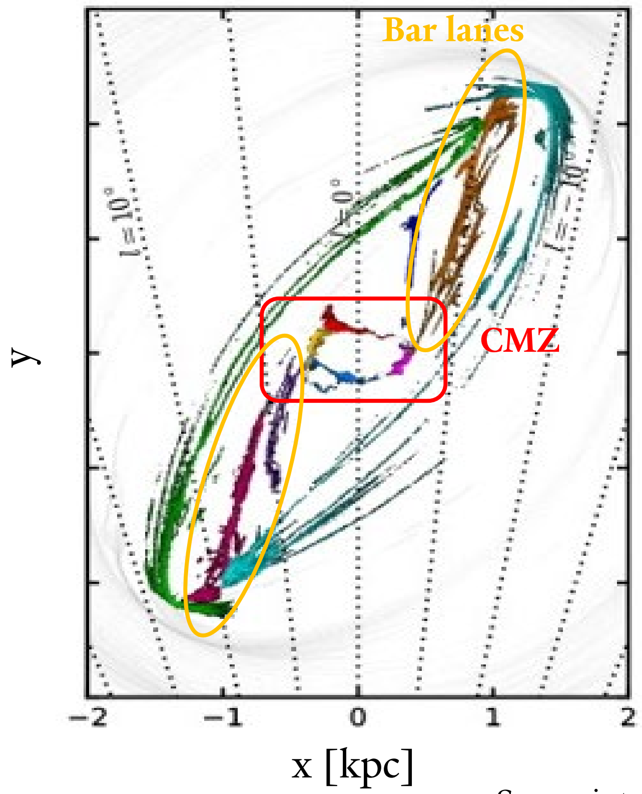


Kruijssen et al. (2014)

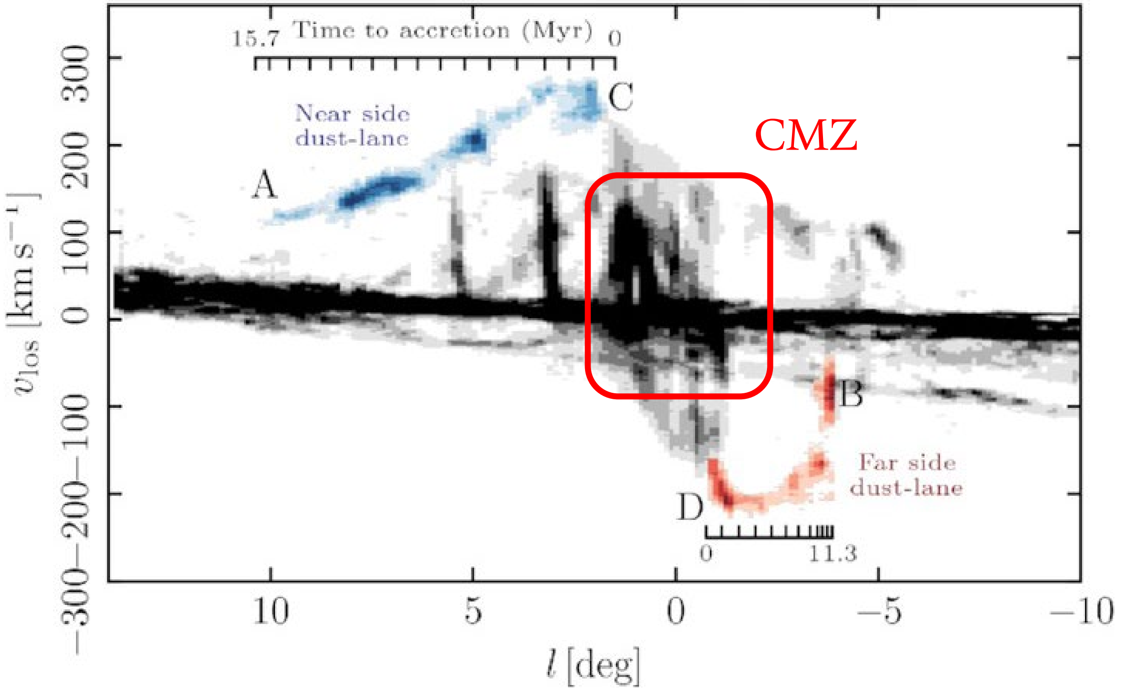
Well studied at many wavelengths

CMZ Inflows

Bar potential drives inflows towards the CMZ



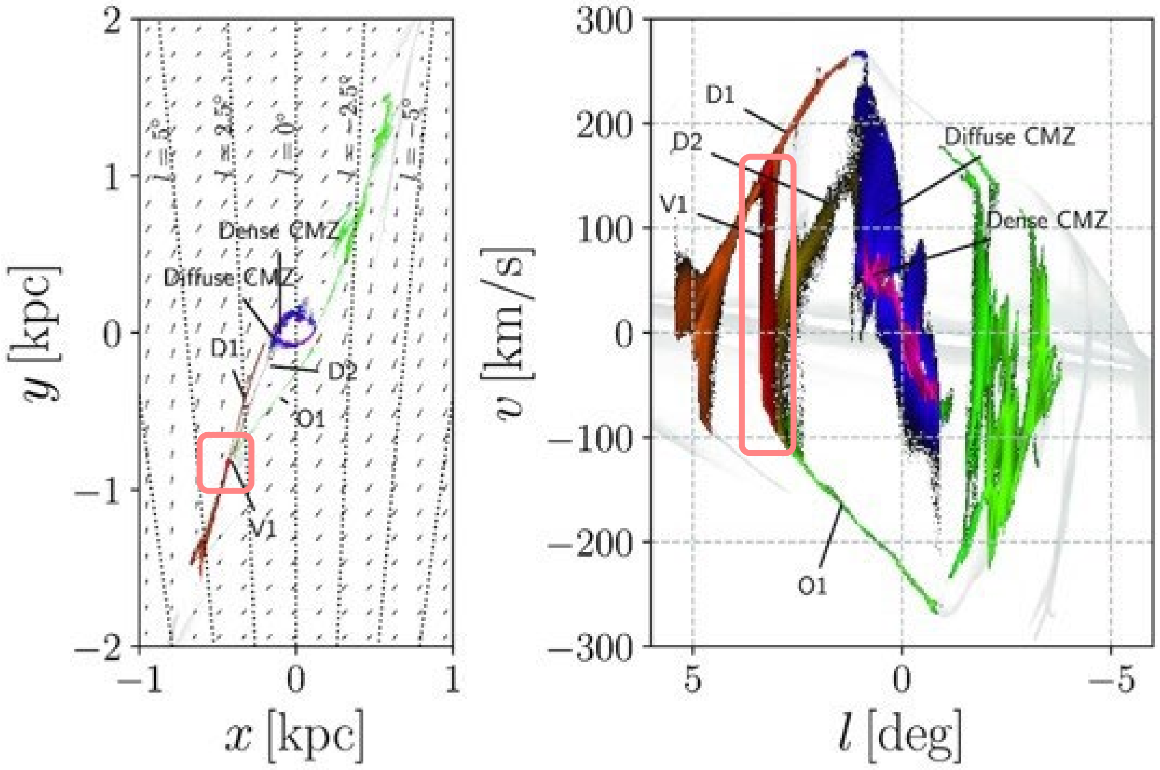
Sormani et al. (2018)



Sormani & Barnes (2019)

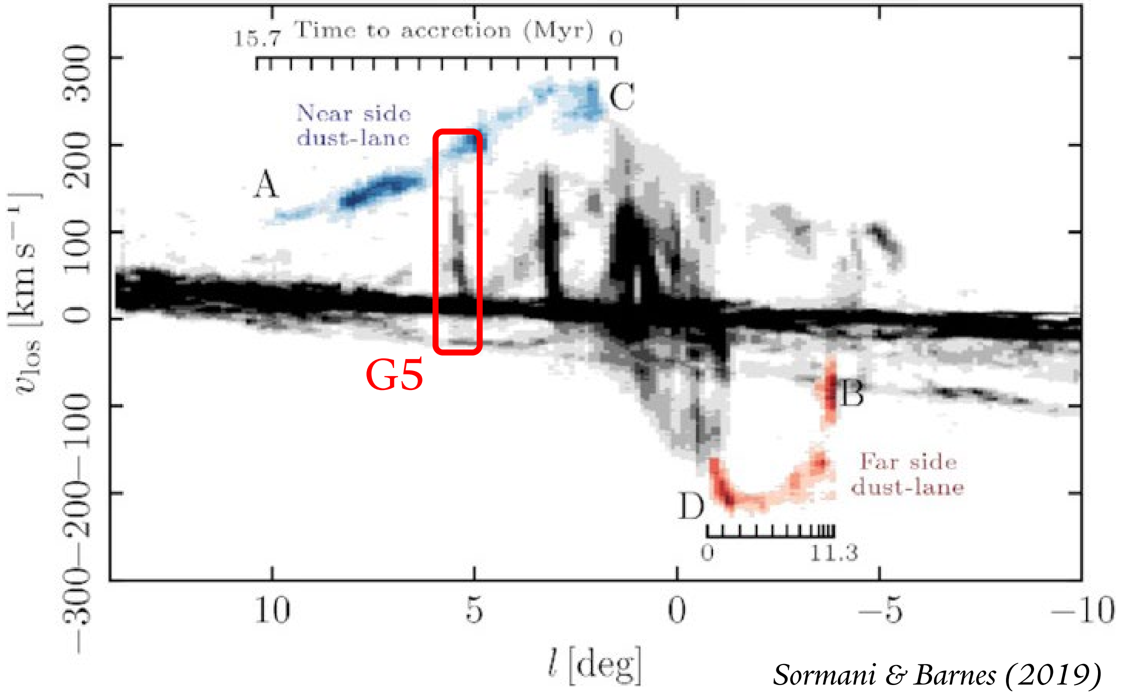
CMZ Inflows

Overshooting gas and collision sites

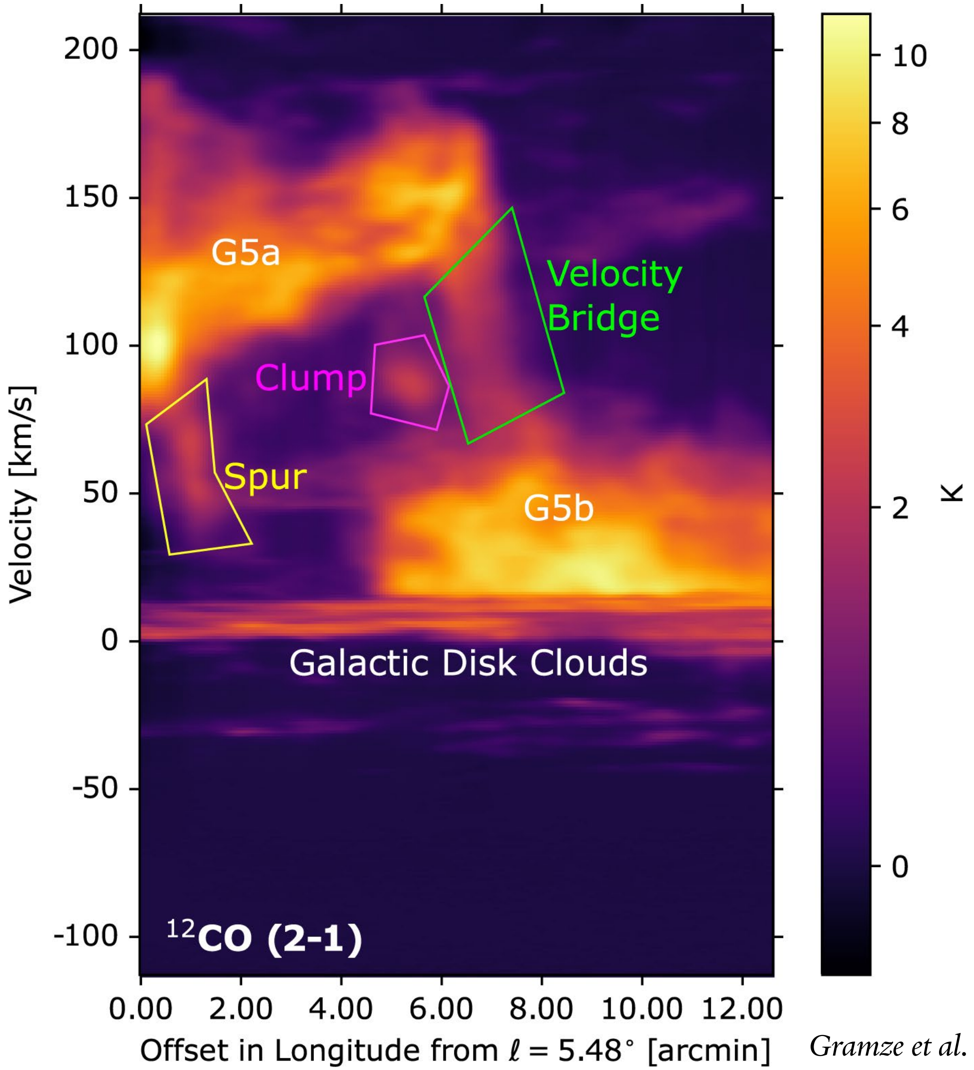


Sormani et al. (2019)

G5



Sormani & Barnes (2019)

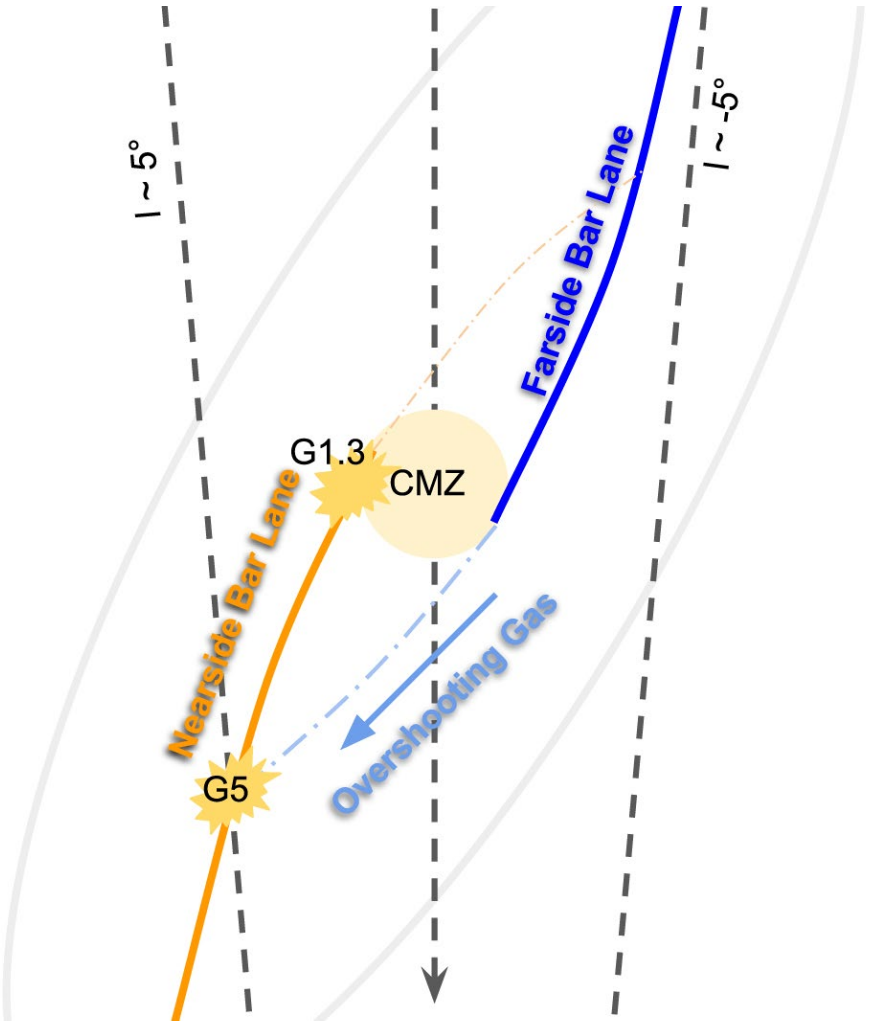


Gramze et al. (2023)

Gramze et al. (2023) found G5 to be warm, shocked, turbulent, and containing two distinct velocity features, concluding that it is comprised of two colliding clouds

G5

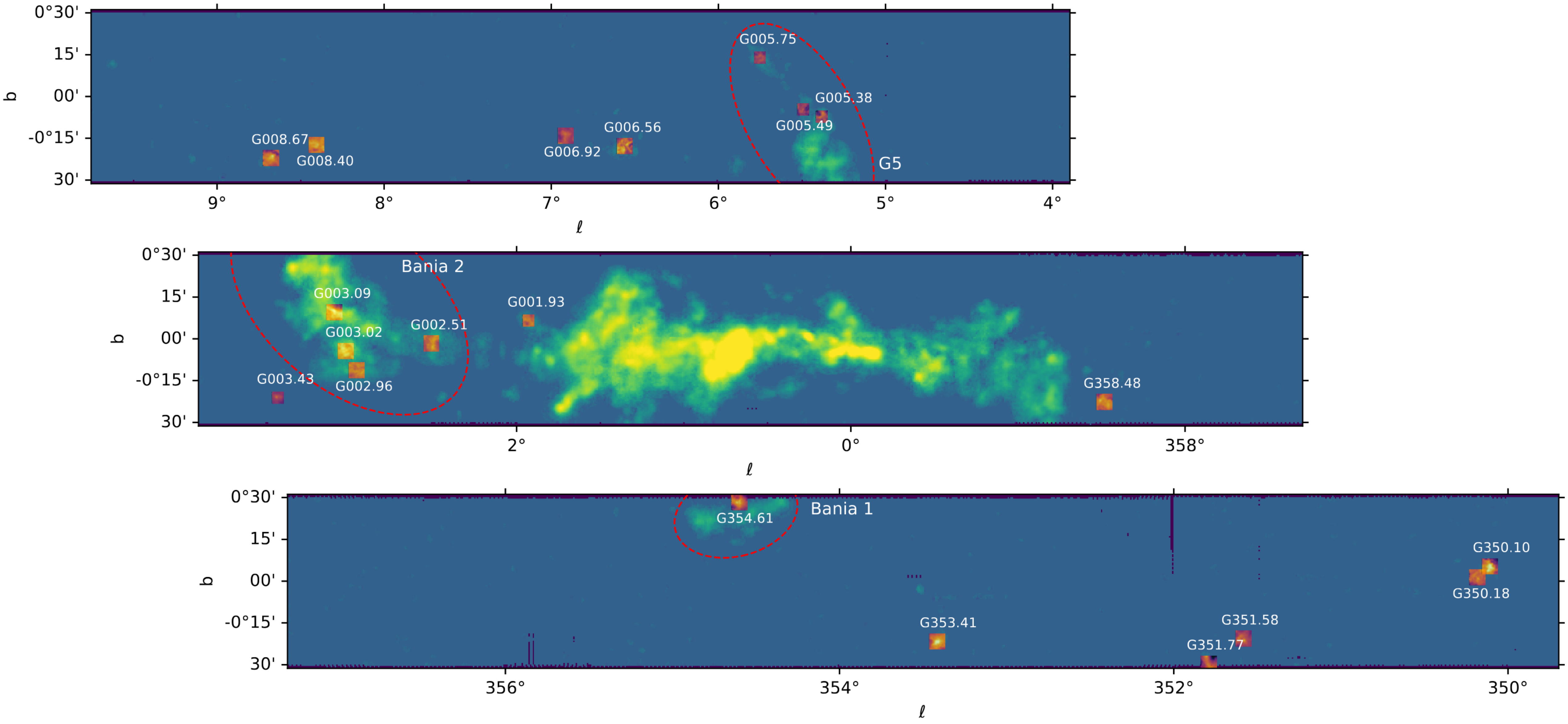
Proposed geometry of G5, the CMZ, and CMZ inflows



Gramze et al. (2023)

Data

Selected 20 warm, broad-lined clouds outside the CMZ

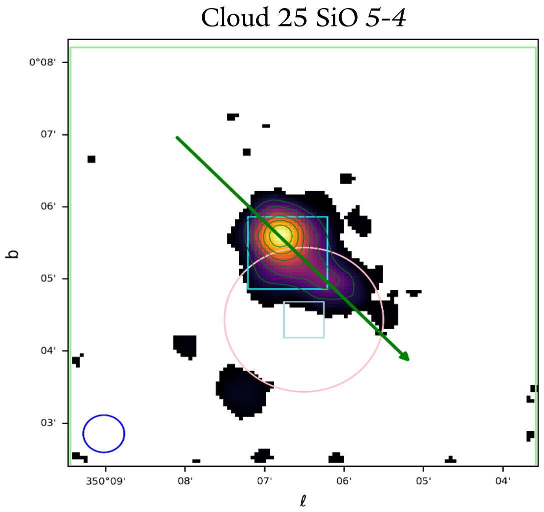


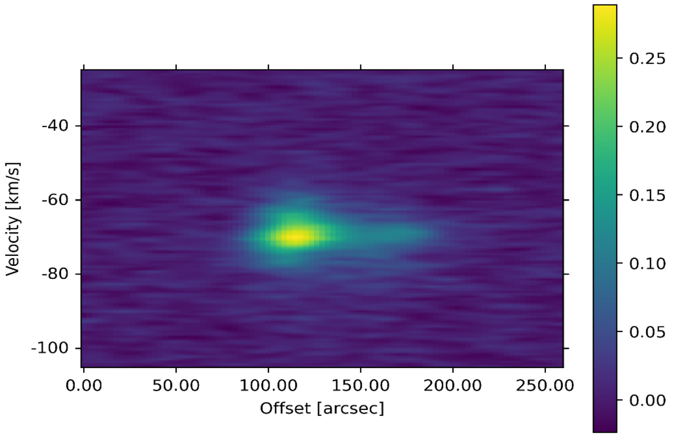
Atacama Compact Array

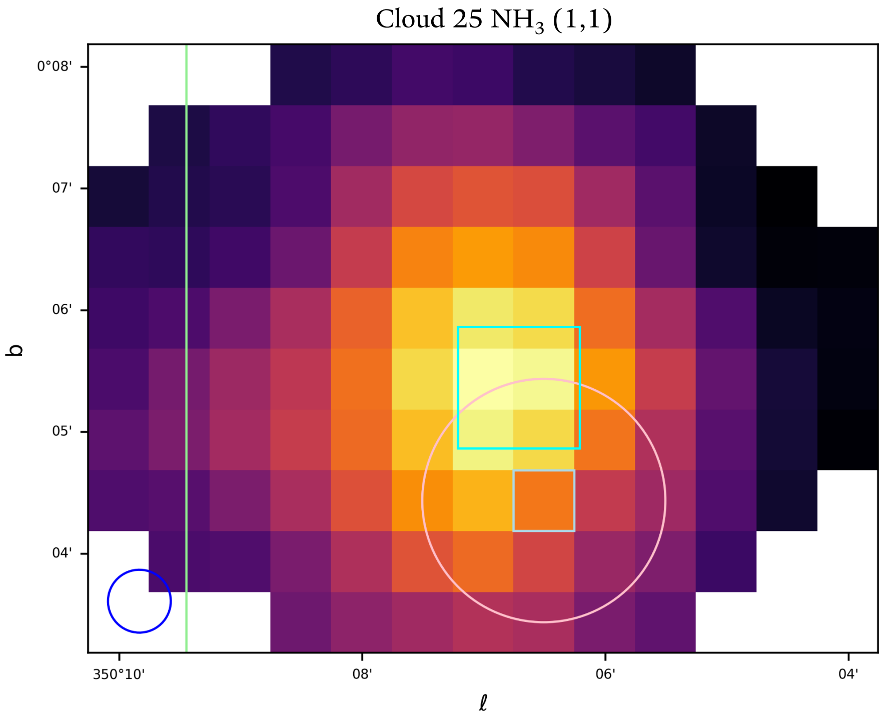
ALMA (ESO/NAOJ/NRAO)

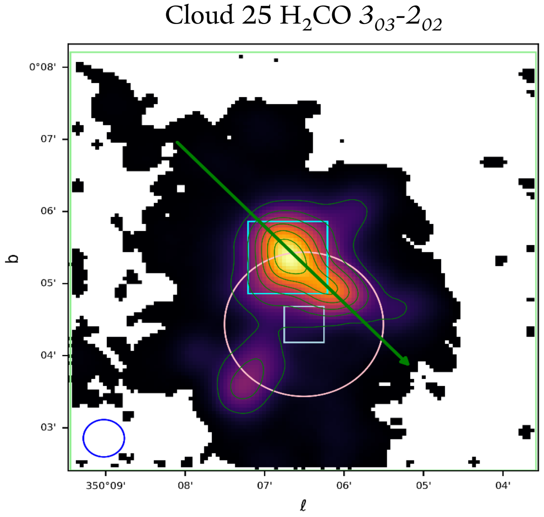
Shortest baselines of ALMA

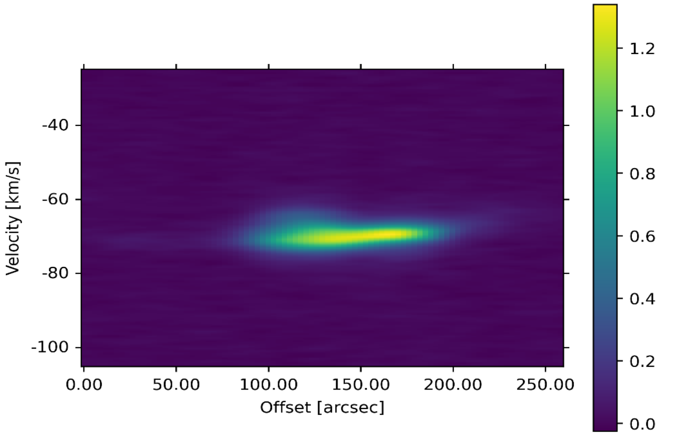
Data











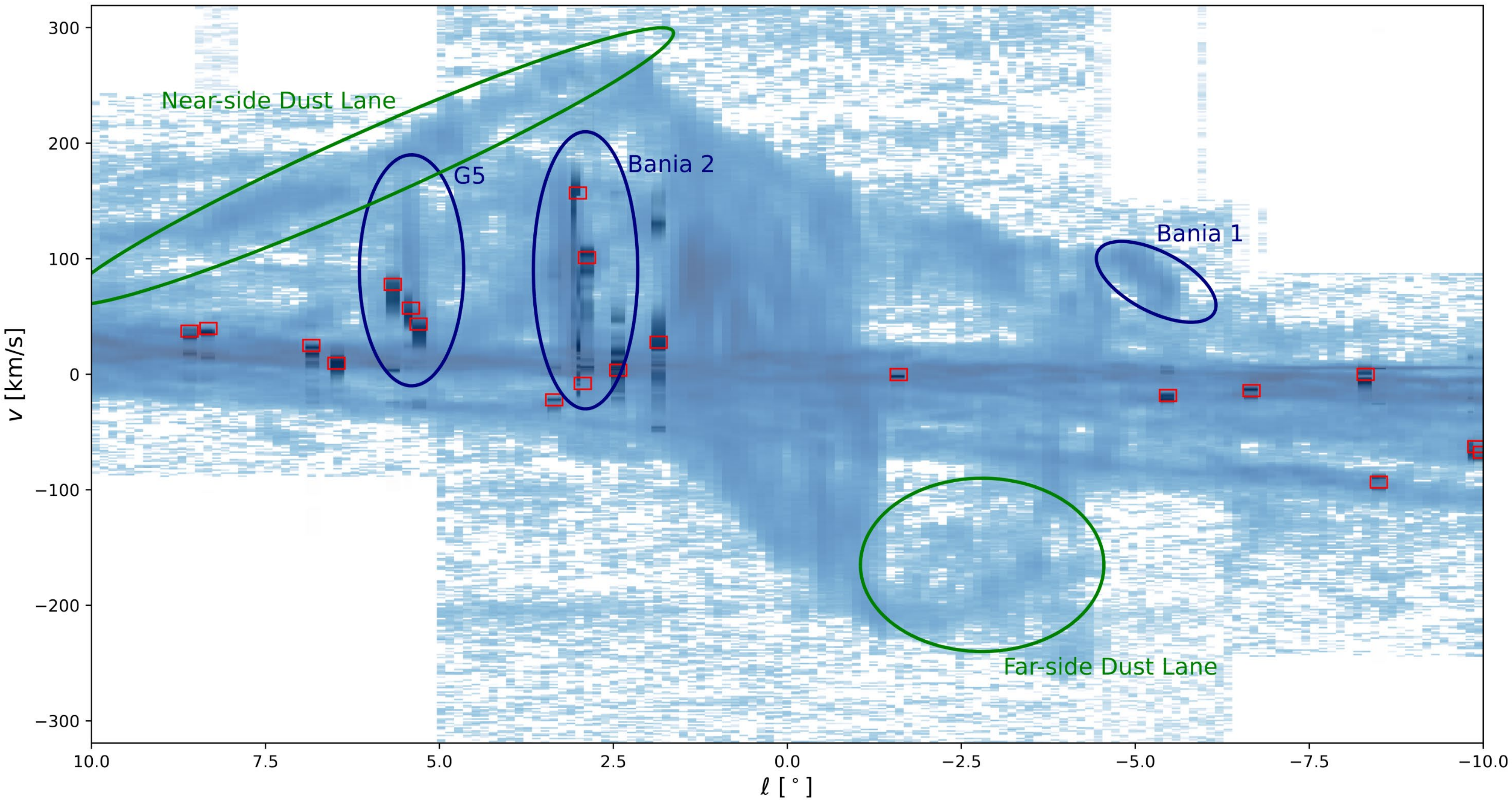
ALMA (30" beam) Band 6:

- SiO $J = 5 \rightarrow 4$
- H_2CO $J = 3_{21} \rightarrow 2_{20}$, $J = 3_{03} \rightarrow 2_{02}$
- HC_3N $J = 24 \rightarrow 23$
- CH_3OH $J = 4_{22} \rightarrow 3_{12}$
- $C^{18}O$, ^{13}CO, ^{12}CO $J = 2 \rightarrow 1$
- H30α

Mopra (2' beam) HOPS (H_2O southern Galactic Plane Survey):

- NH_3 (1,1), (2,2), (3,3), (6,6)

Cloud Locations

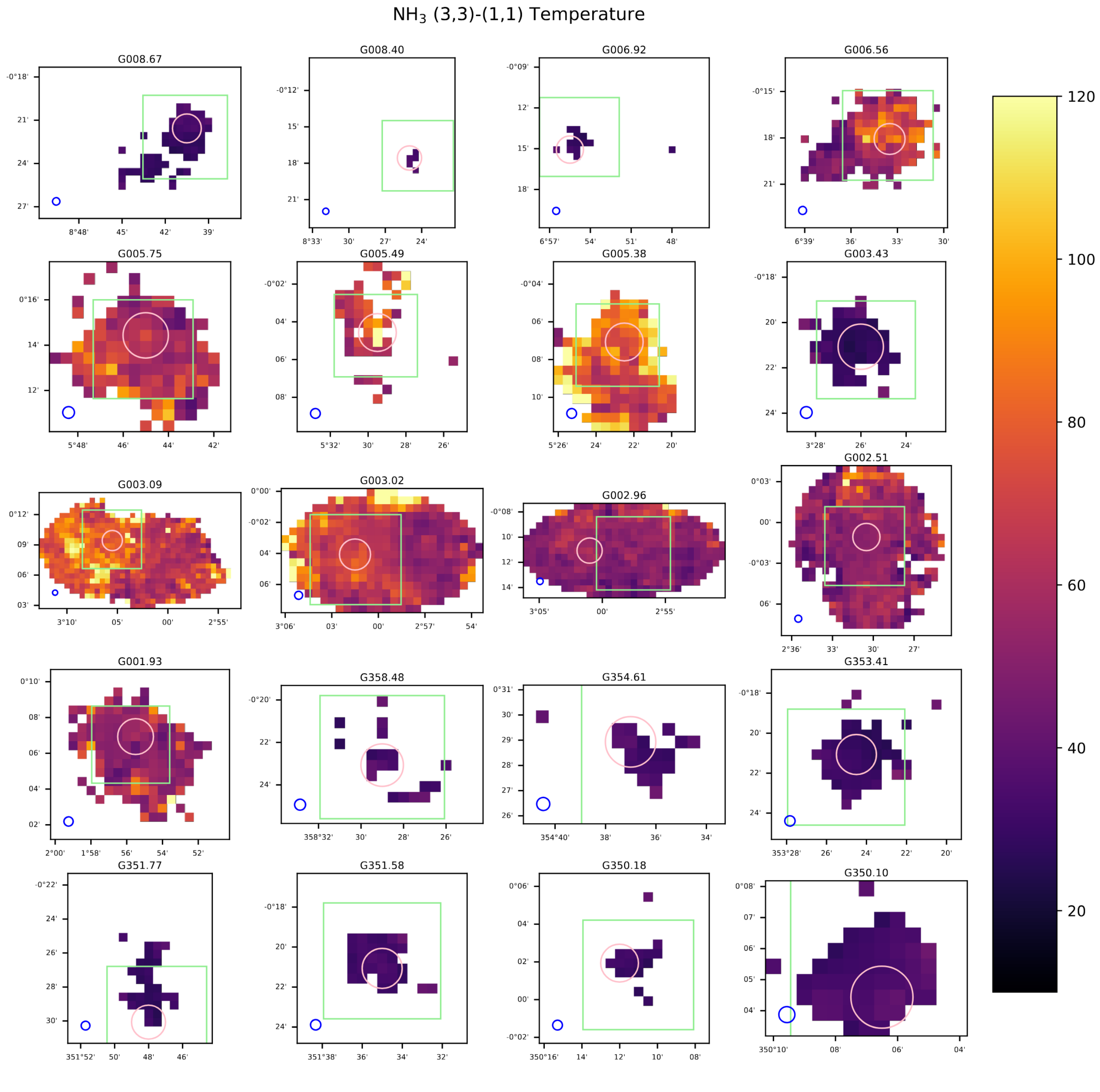


From l-v diagram and ammonia line widths, we preliminarily find 9/20 clouds to be in the bar region

Properties

Temperature, SFR, Turbulence, Shocks

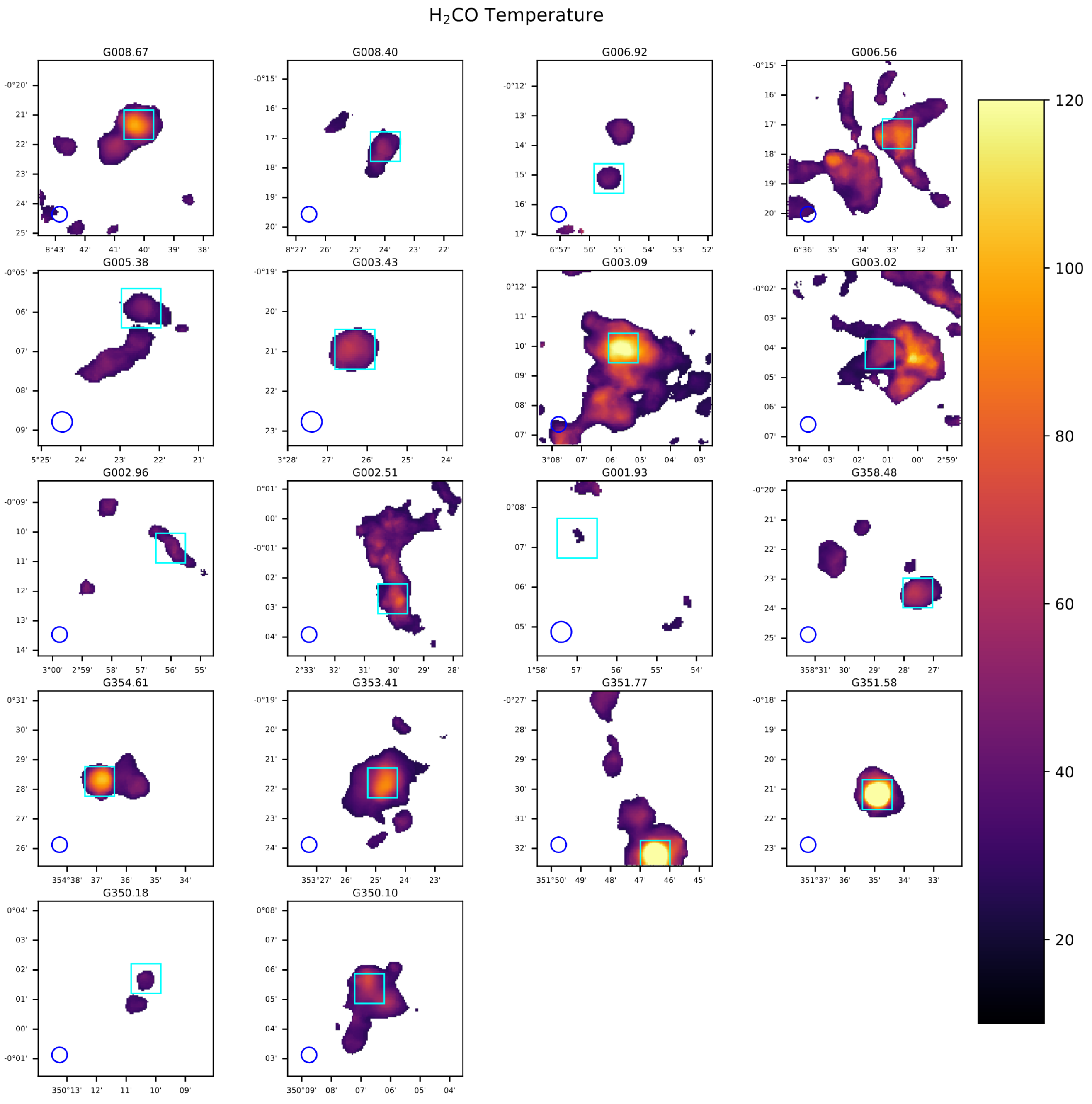
Ammonia Temperature



(a)

Formaldehyde Temperature

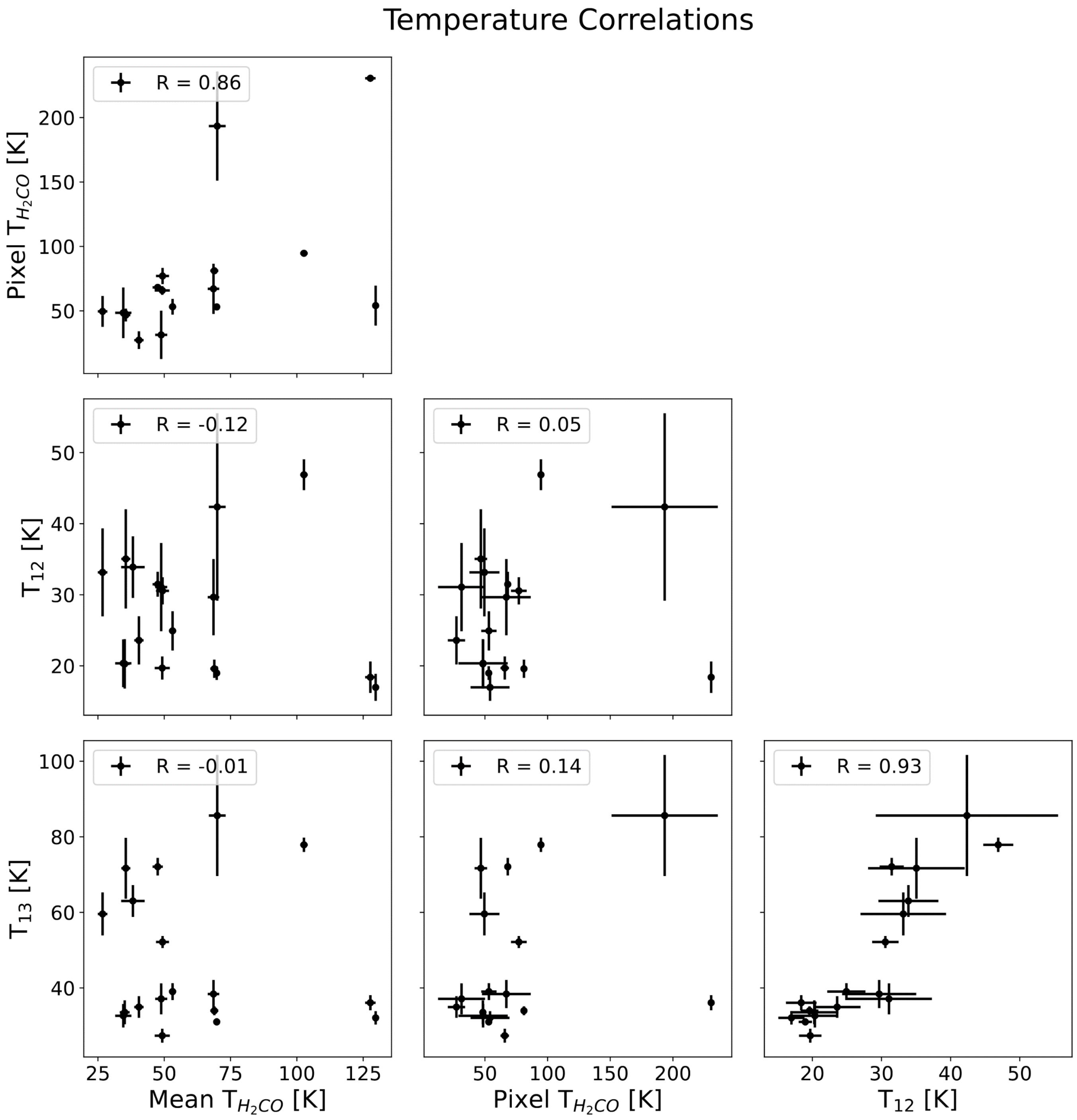
Presence of hot molecular cores not seen in ammonia



(a)

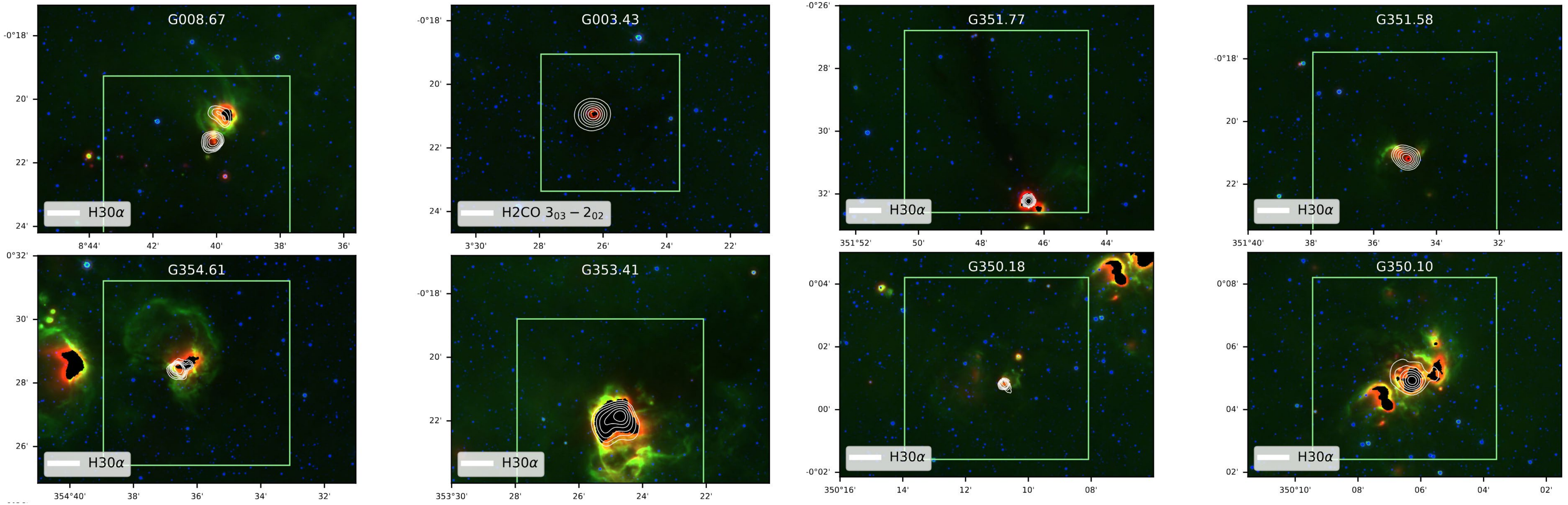
Temperature Comparisons

Ammonia and formaldehyde seem to trace different gas



Star Formation from *Spitzer*

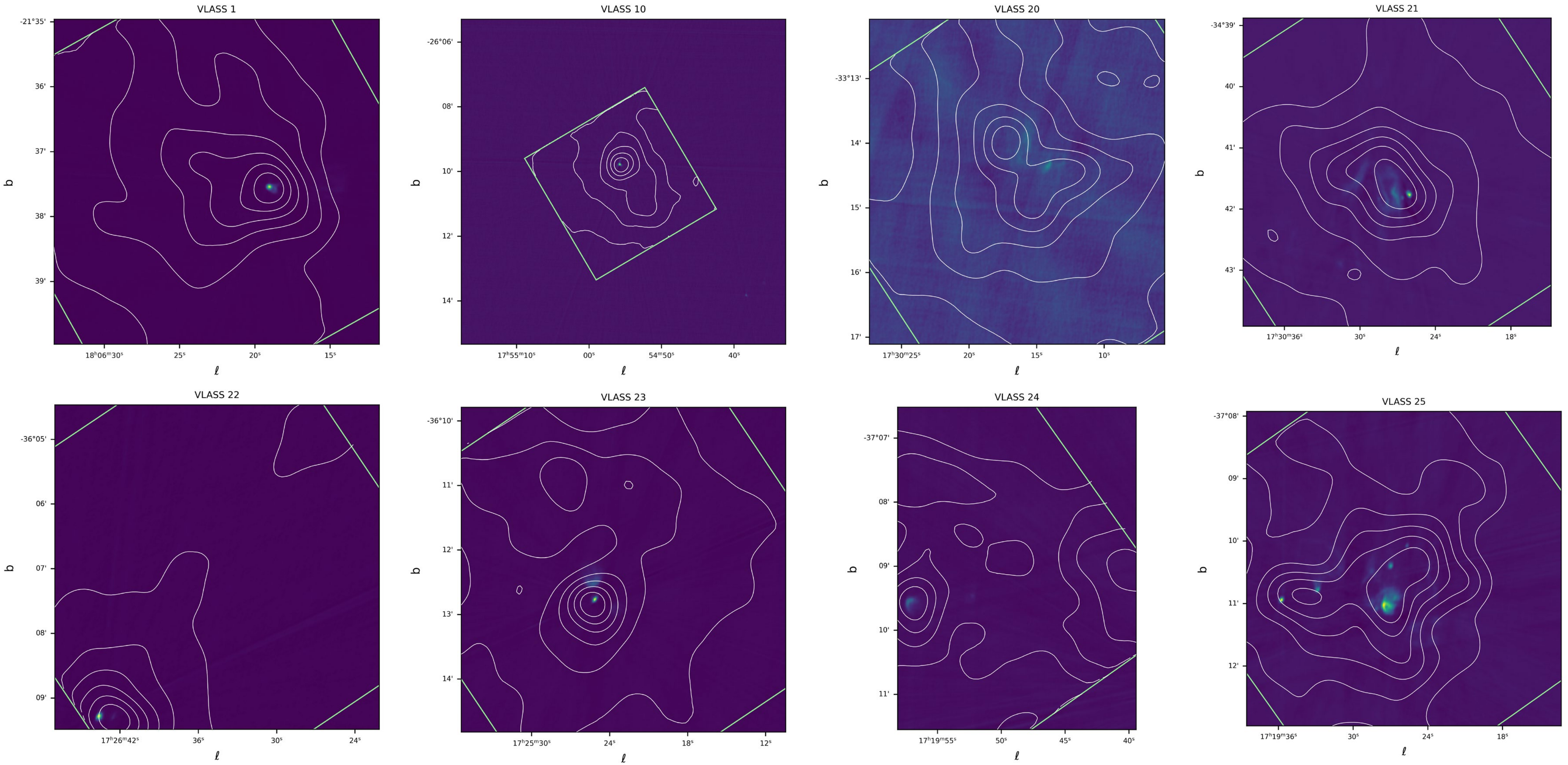
Three-color *Spitzer* images (4.5, 8, and 24 micron) with H30α contours



Same clouds as with hot cores in H_2CO

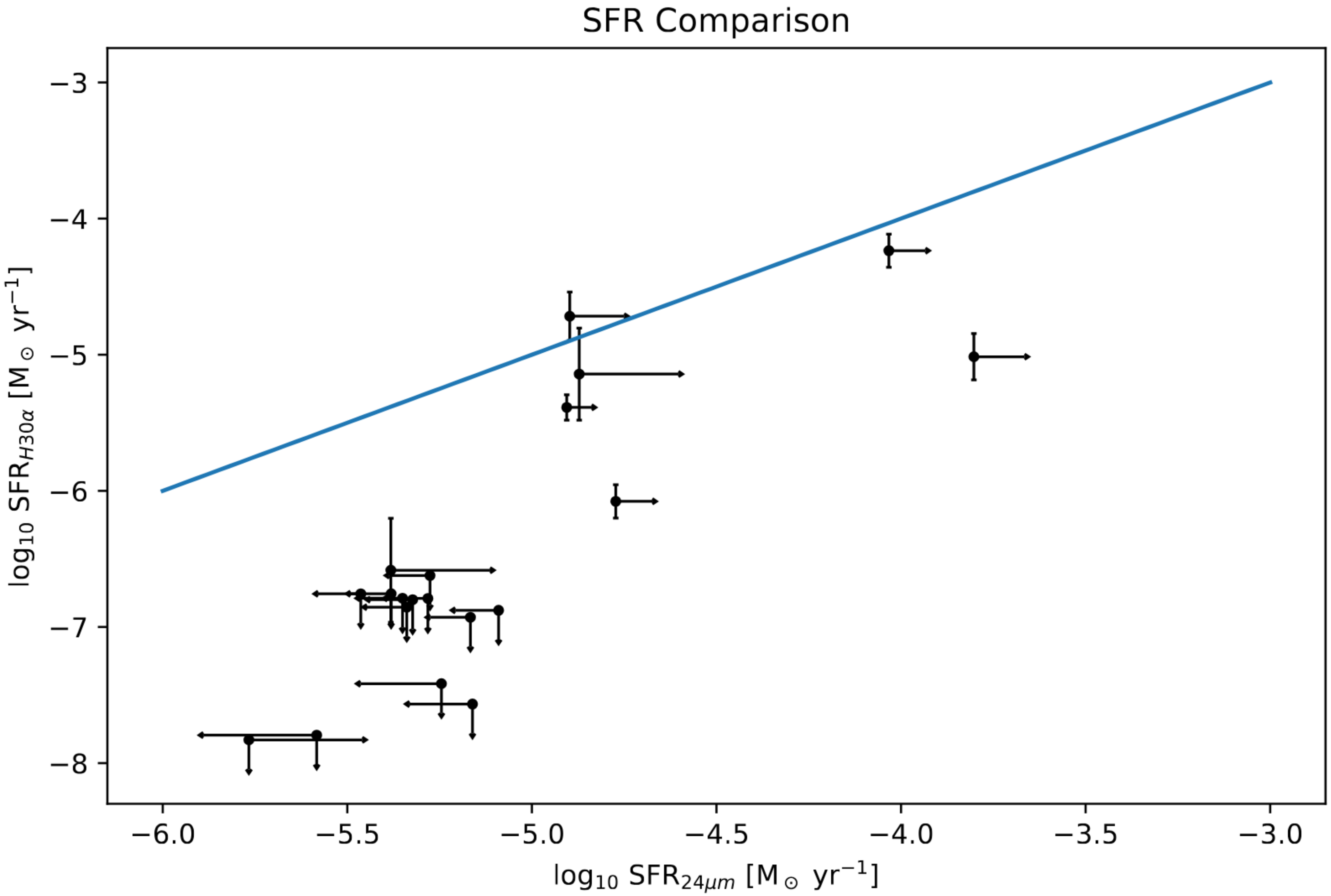
VLASS Detections

VLASS cutouts with ^{13}CO contours



Star Formation Comparison

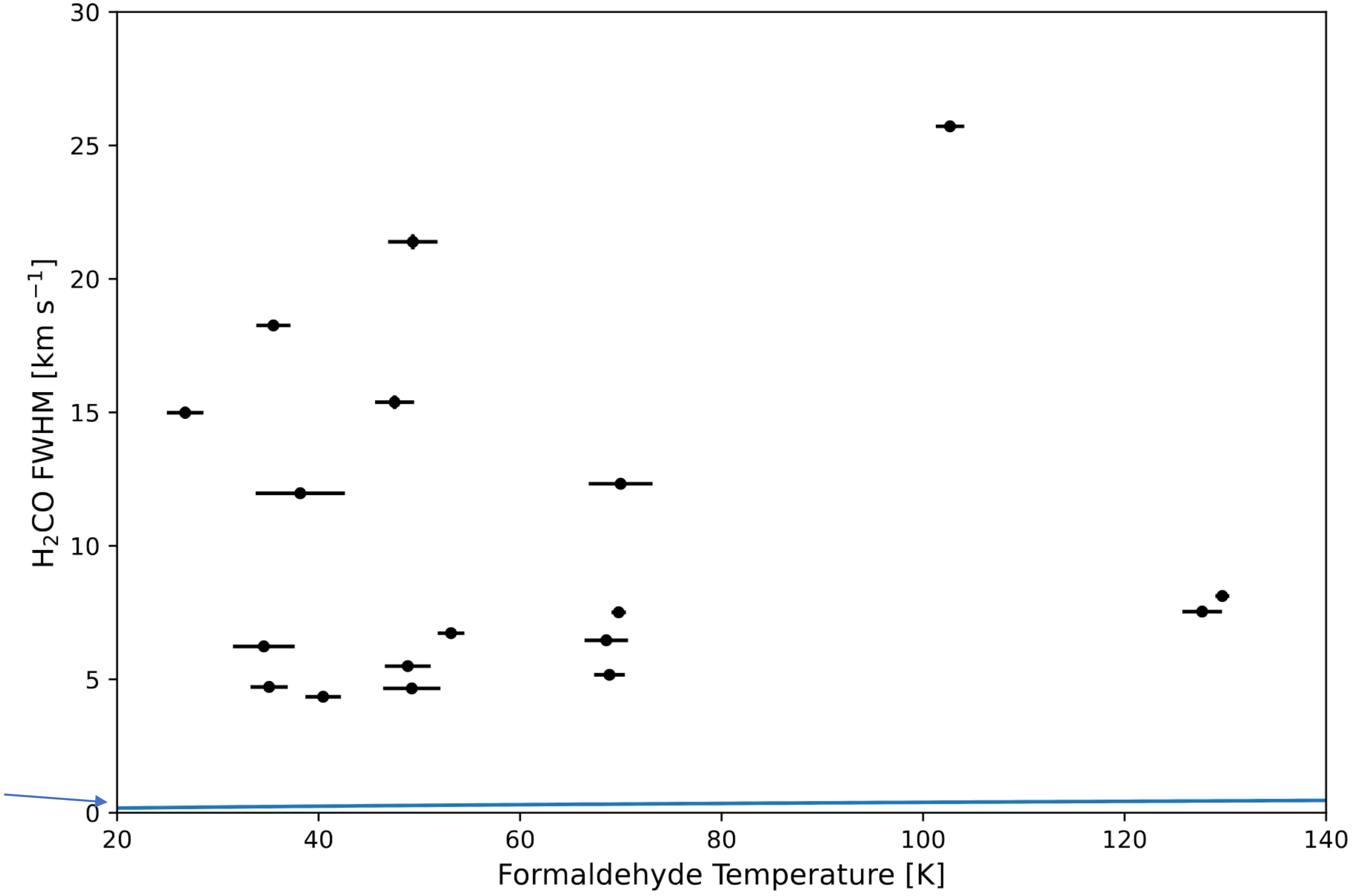
These conversions generally apply to larger spatial scales, so may not hold here



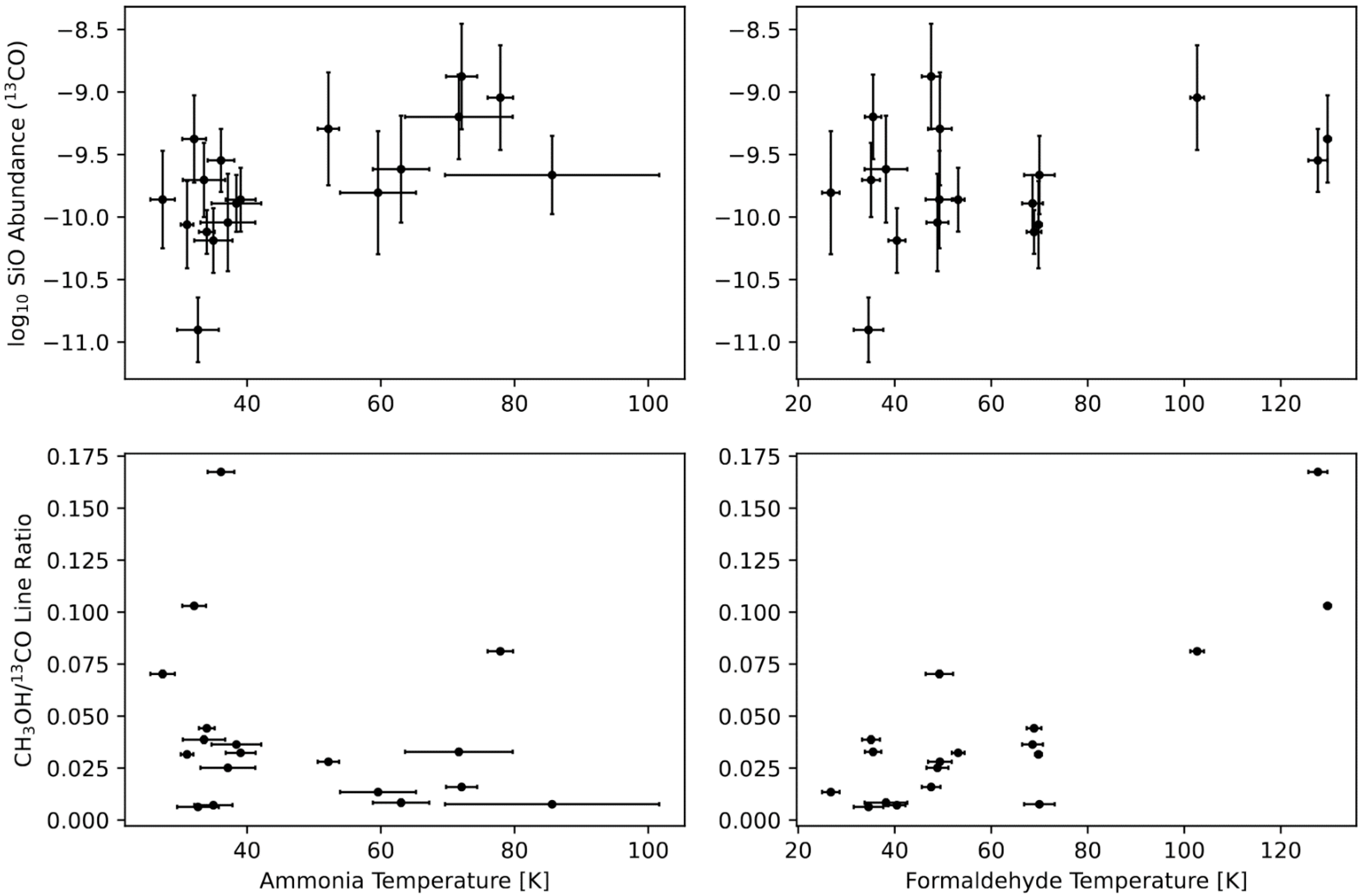
Turbulence

Non-thermal contributions
(e.g. turbulence) dominate

Thermal Contribution

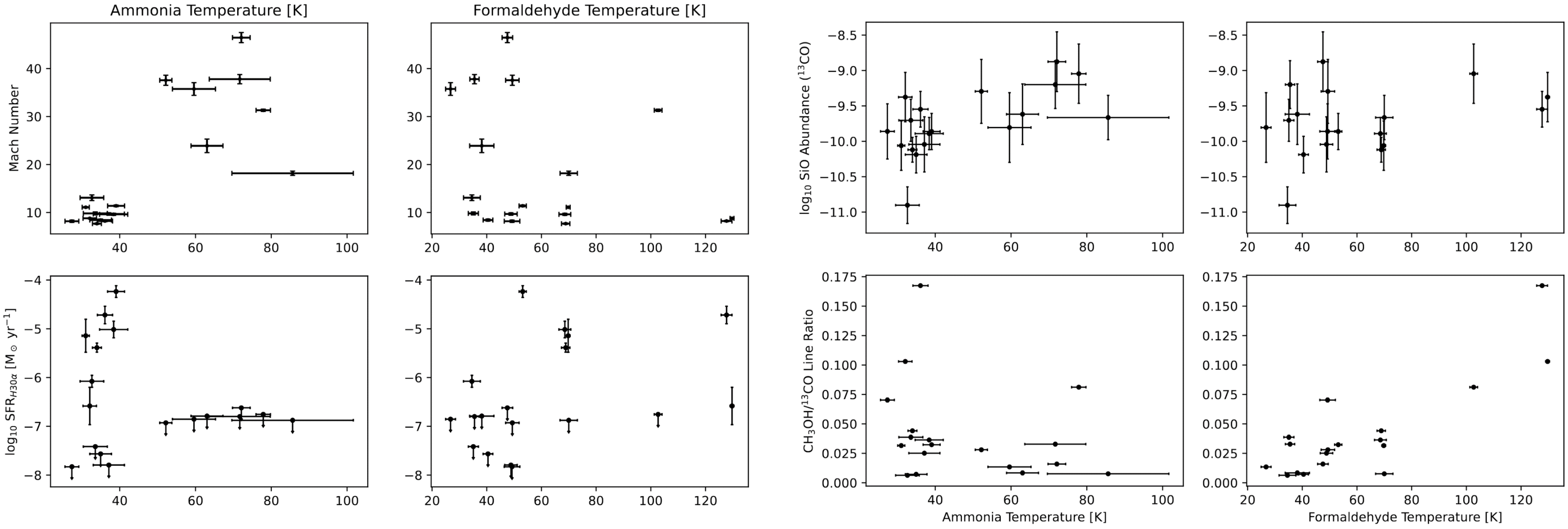


Shocks

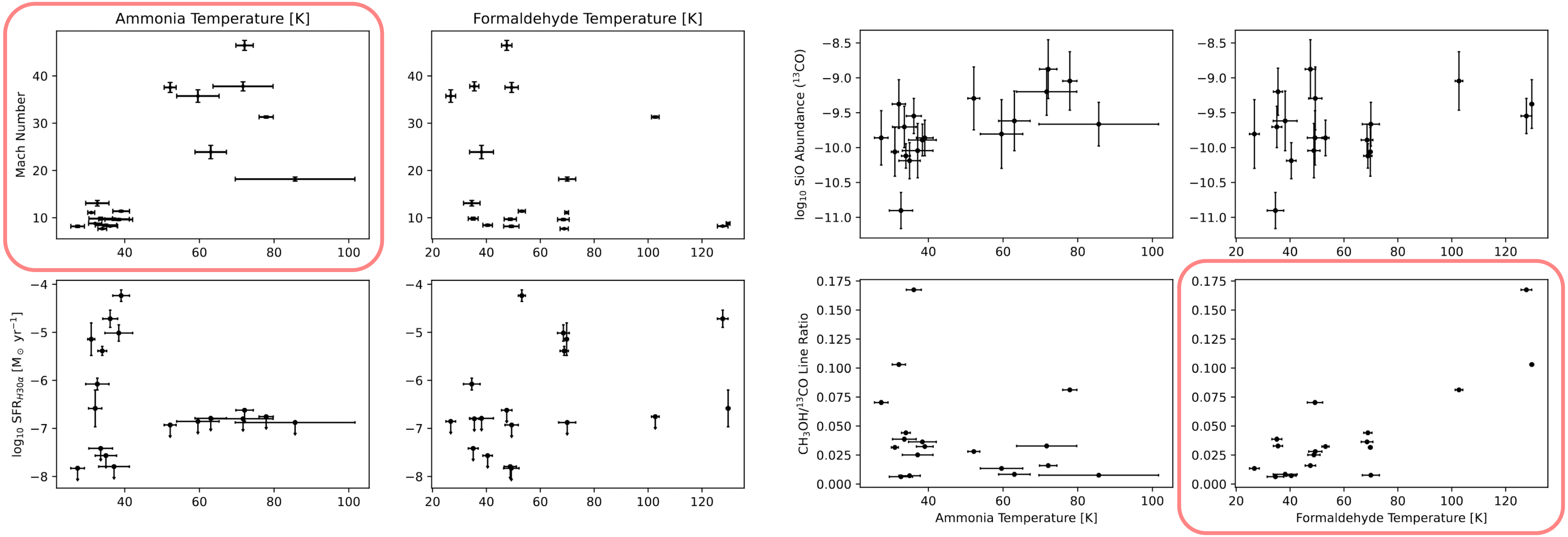

log10 SiO Abundance (13CO)
CH3OH/13CO Line Ratio
Ammonia Temperature [K]
Formaldehyde Temperature [K]

Discussion

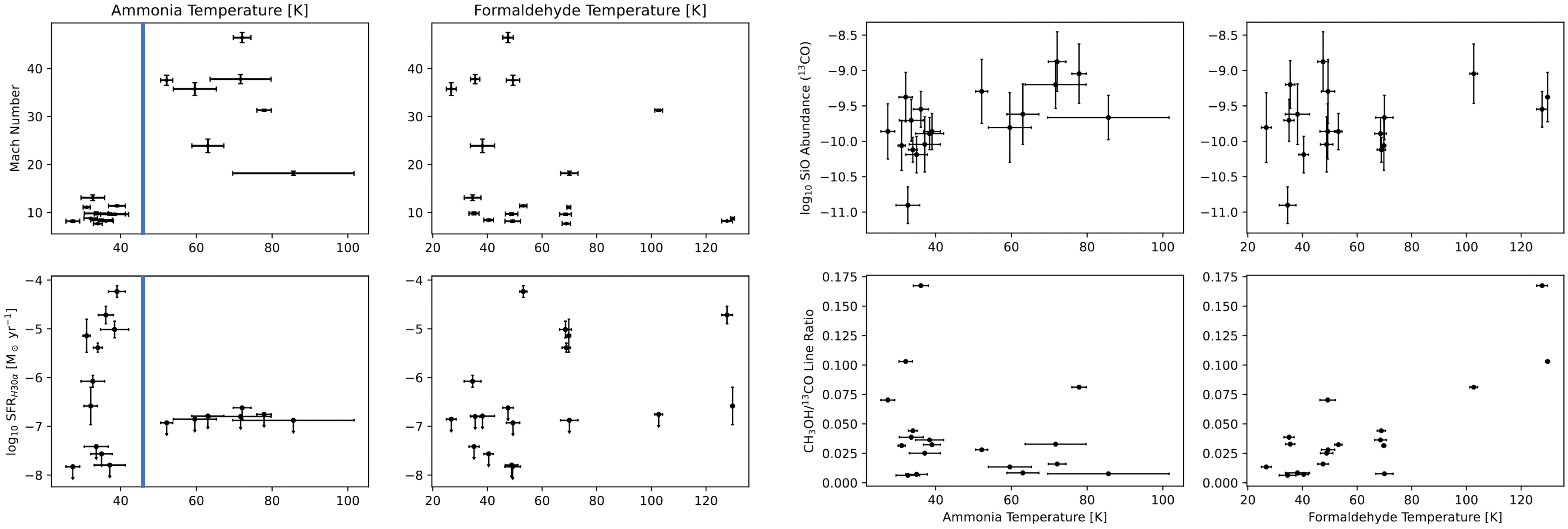
Ammonia vs Formaldehyde Thermometers



Ammonia vs Formaldehyde Thermometers

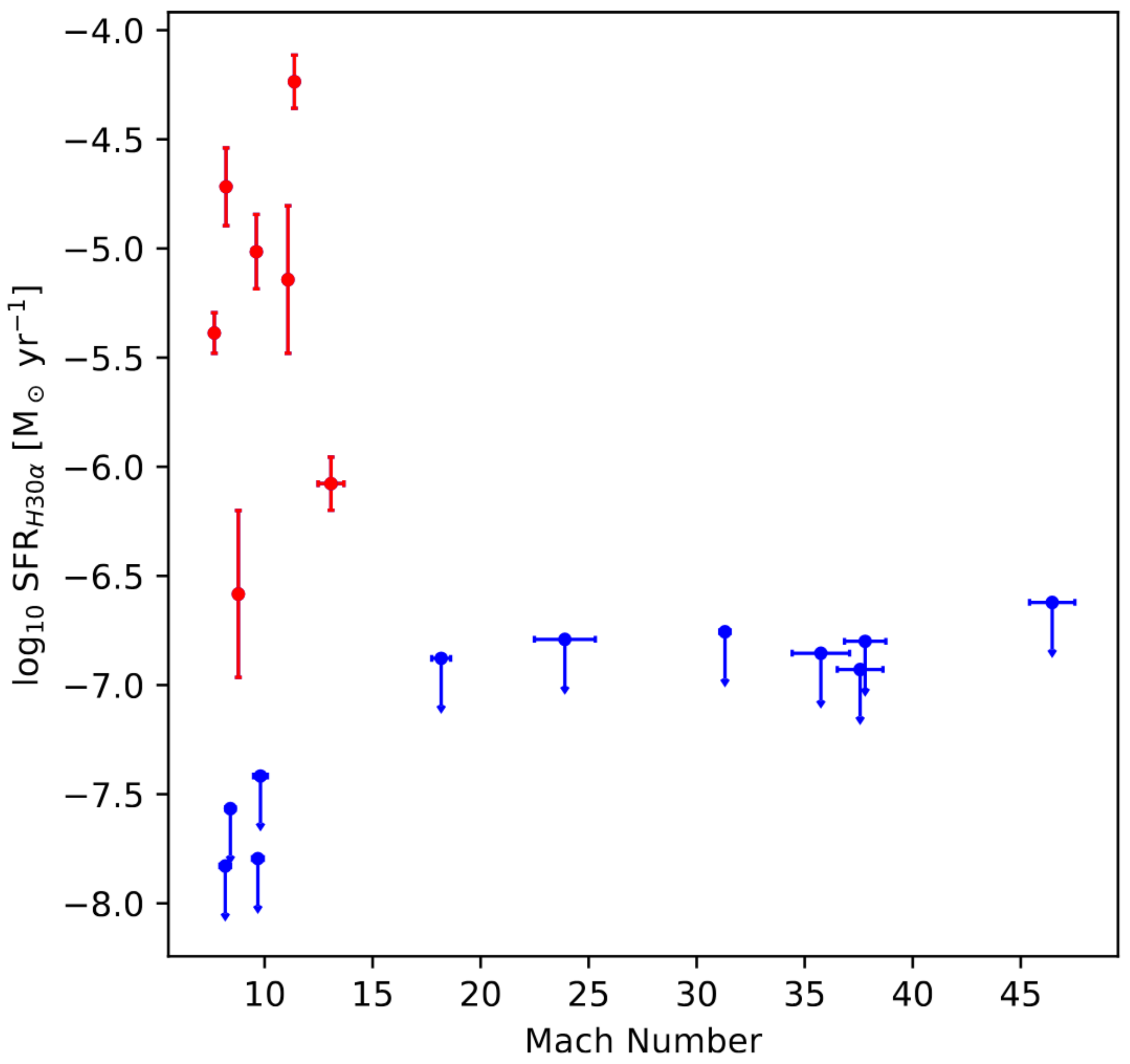


Ammonia vs Formaldehyde Thermometers



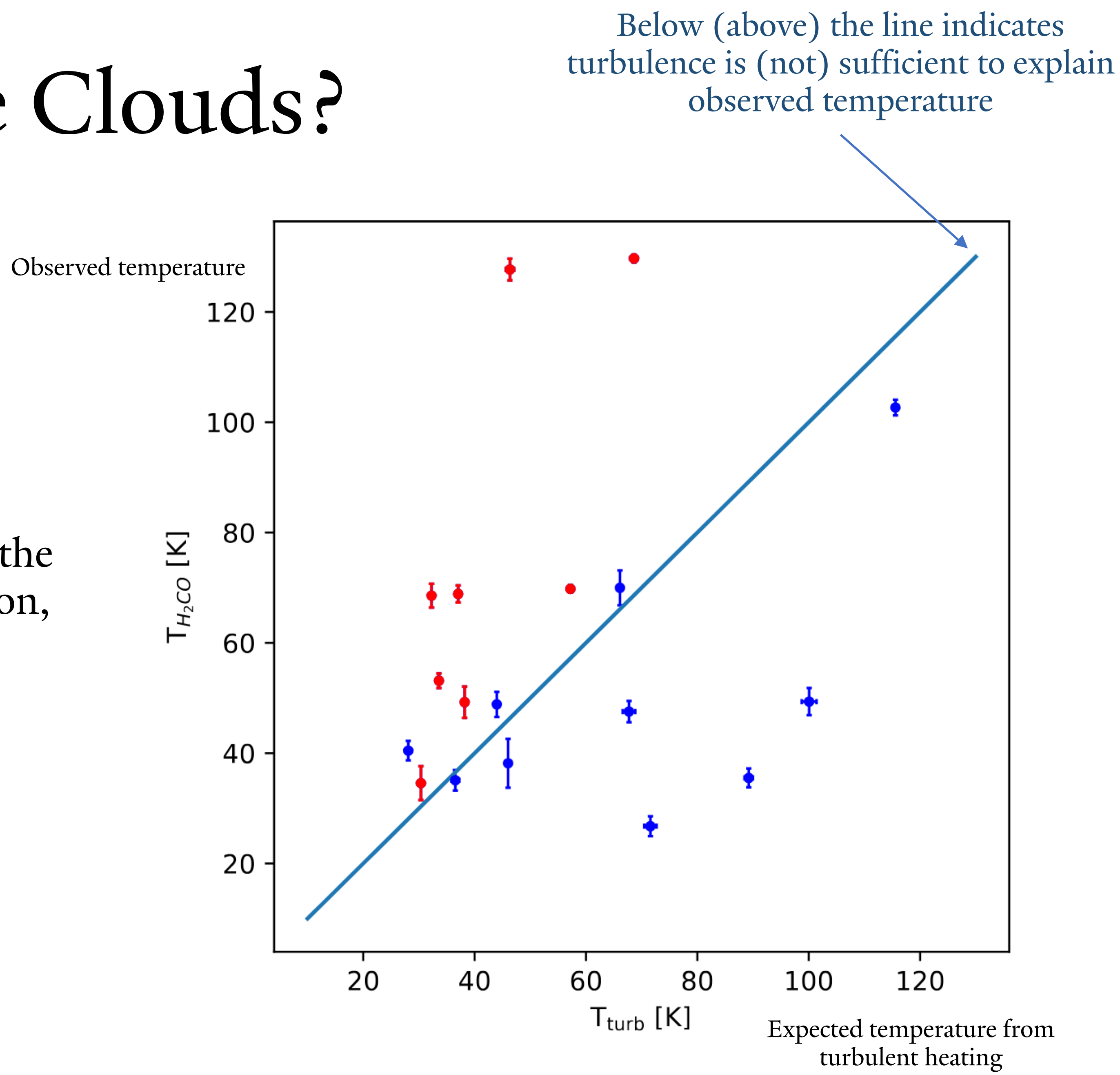
SFR vs Turbulence

Turbulence may be inhibiting star formation to some degree

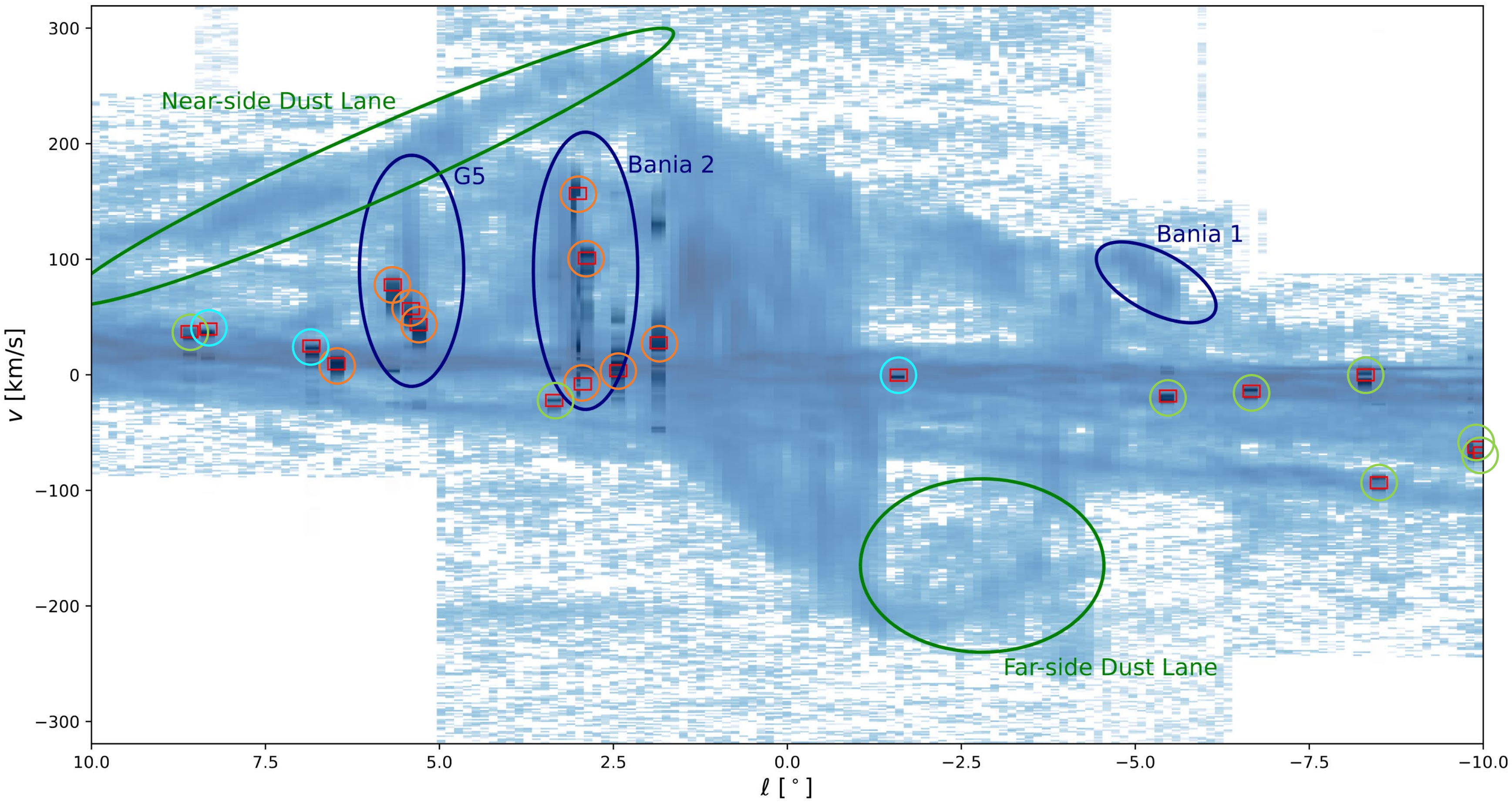


What is Heating the Clouds?

Turbulence is generally sufficient to explain the temperatures in clouds without star formation, but not in those with star formation



Cloud Locations

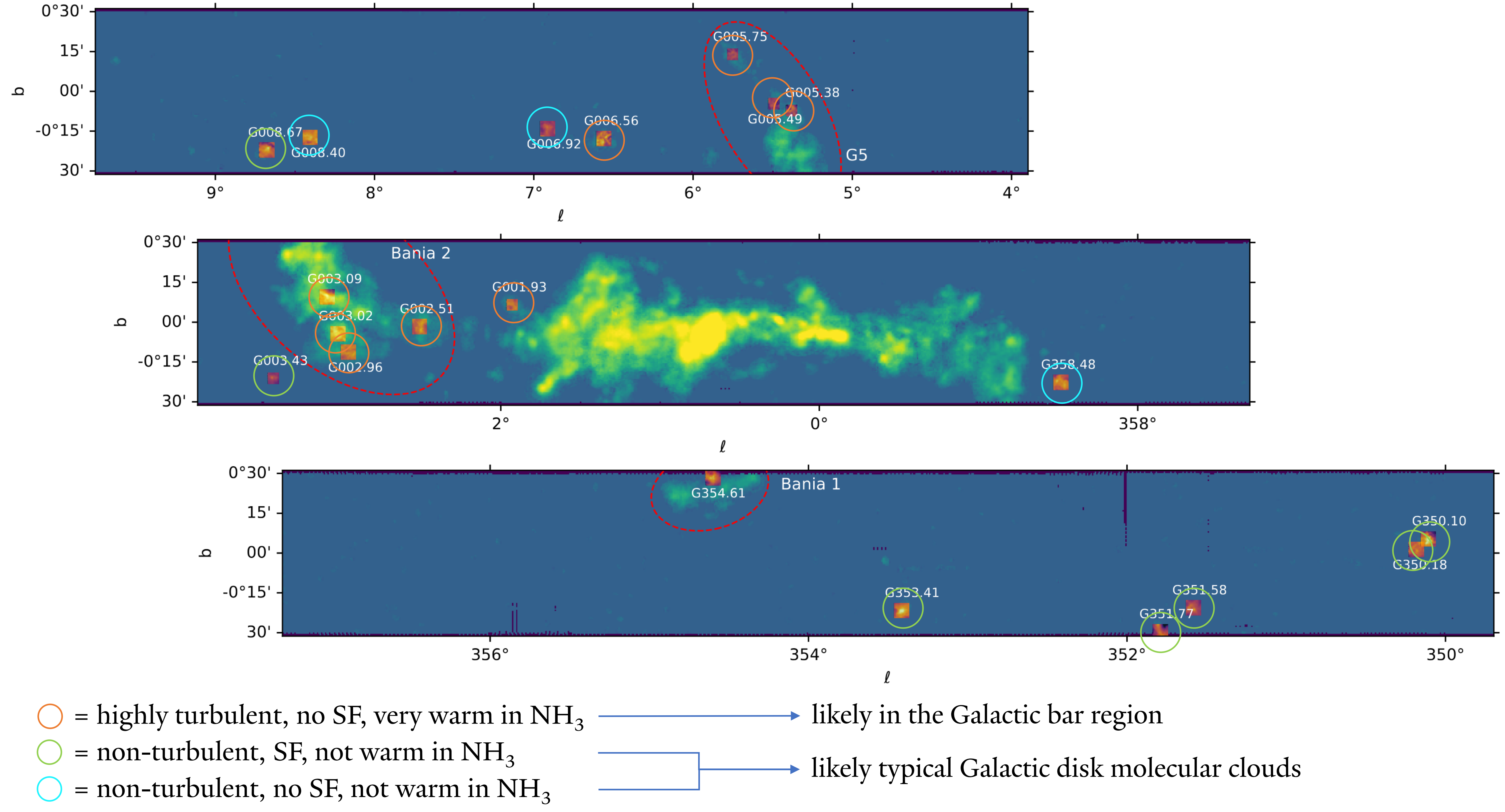


= highly turbulent, no SF, very warm in NH_3 → likely in the Galactic bar region

= non-turbulent, SF, not warm in NH_3

= non-turbulent, no SF, not warm in NH_3

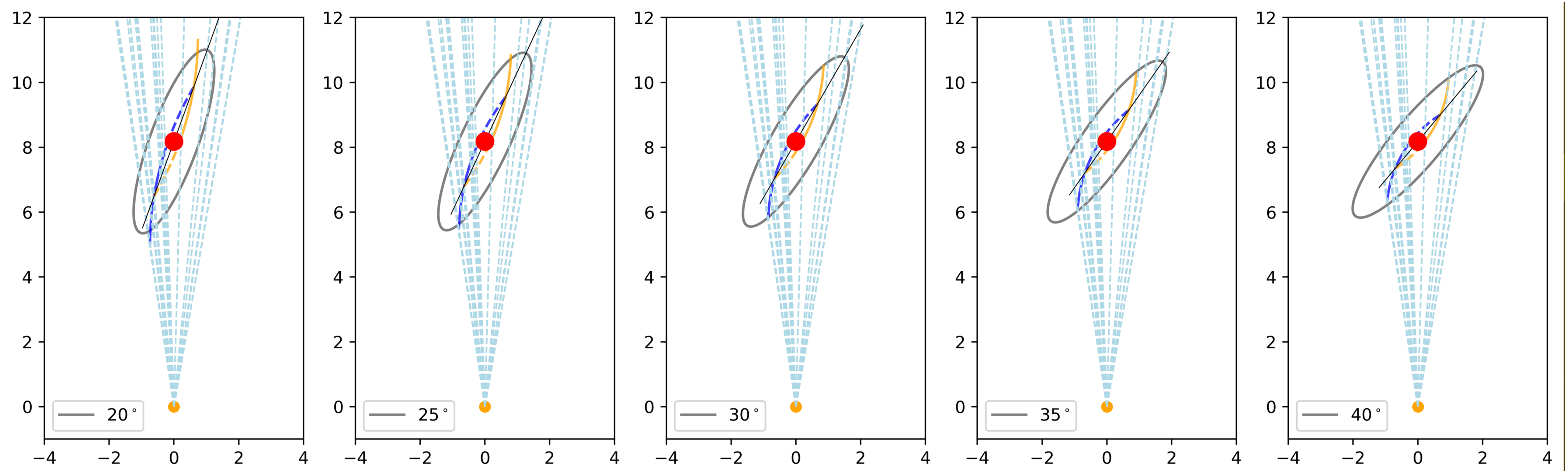
→ likely typical Galactic disk molecular clouds


0°30'
15'
00'
-0°15'
30'
b
ℓ
9°
8°
7°
6°
5°
4°
G008.67
G008.40
G006.92
G006.56
G005.75
G005.38
G005.49
G5
Bania 2
G003.09
G003.02
G002.96
G003.43
G002.51
G001.93
G358.48
2°
0°
358°
Bania 1
G354.61
G353.41
G351.58
G351.77
G350.10
G350.18
356°
354°
352°
350°
= highly turbulent, no SF, very warm in NH_3
= non-turbulent, SF, not warm in NH_3
= non-turbulent, no SF, not warm in NH_3
likely in the Galactic bar region
likely typical Galactic disk molecular clouds

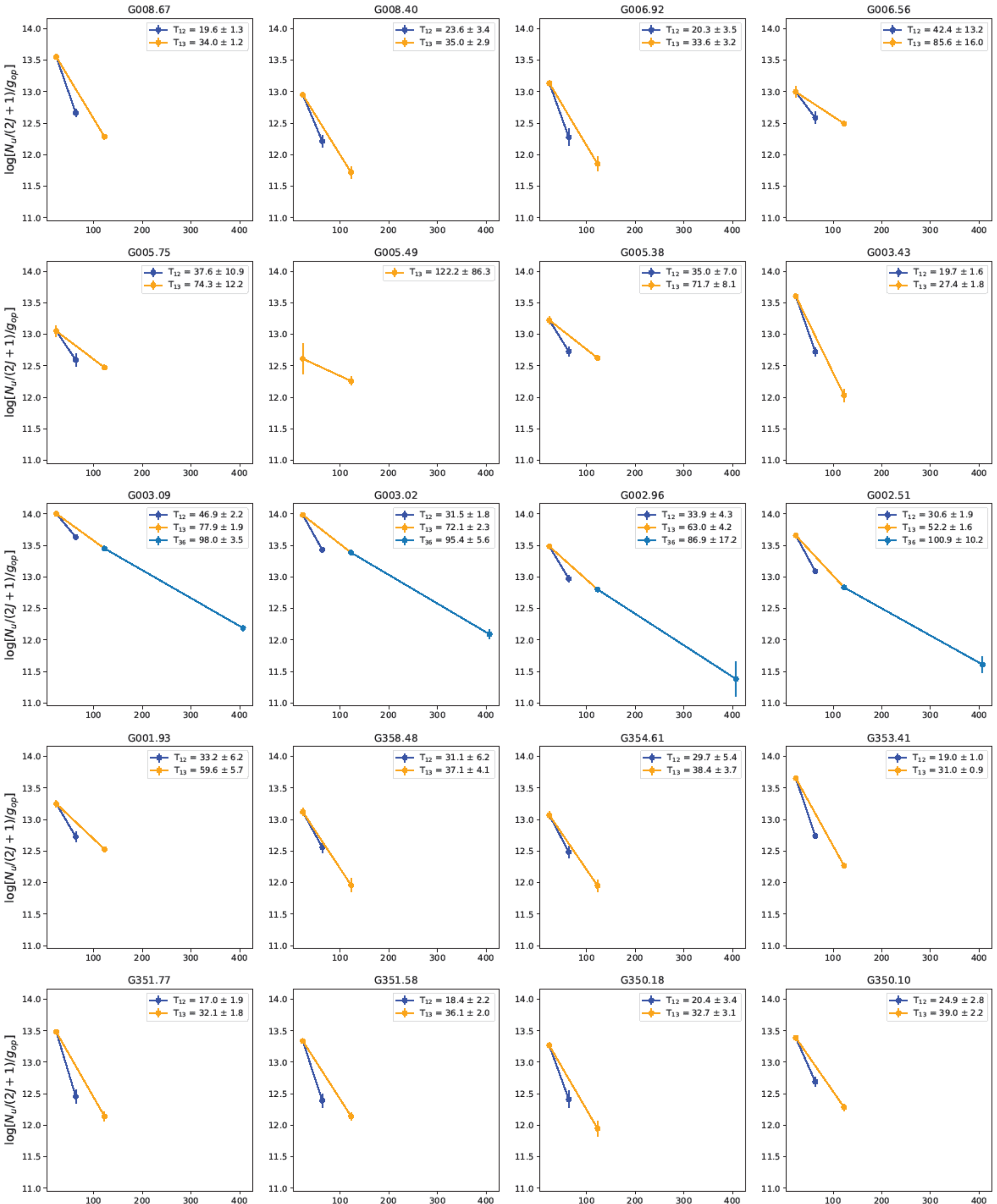
Conclusions

- Observed 20 clouds on the Galactic plane
- Measured various properties
  - Temperature, turbulence, star formation, and shocks
- Ammonia and formaldehyde thermometers tracing different gas
- Turbulence inhibiting SF and heating clouds
- Some clouds at collision sites between inflowing gas, overshooting gas, and the CMZ

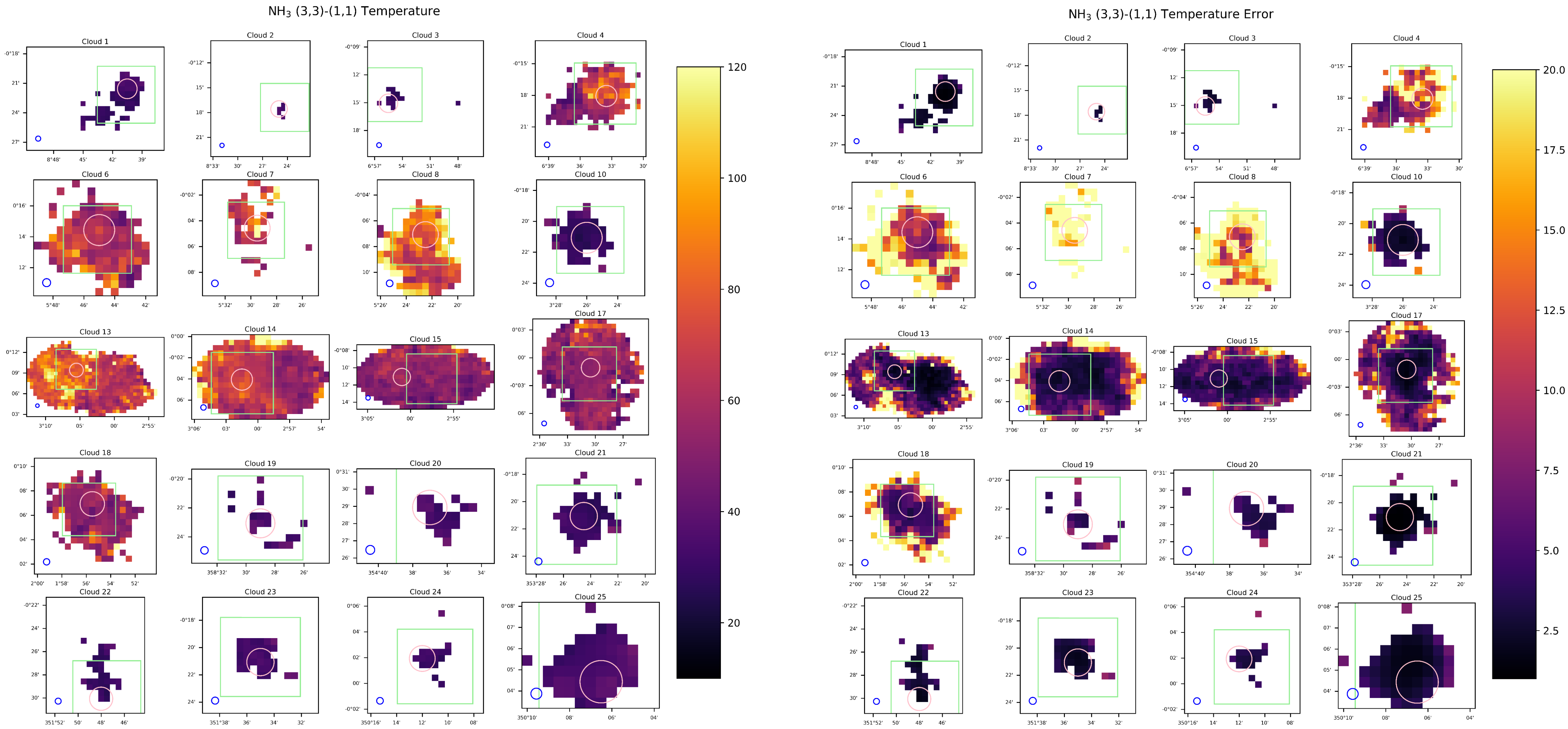
Geometry of the Bar



Ammonia BDs

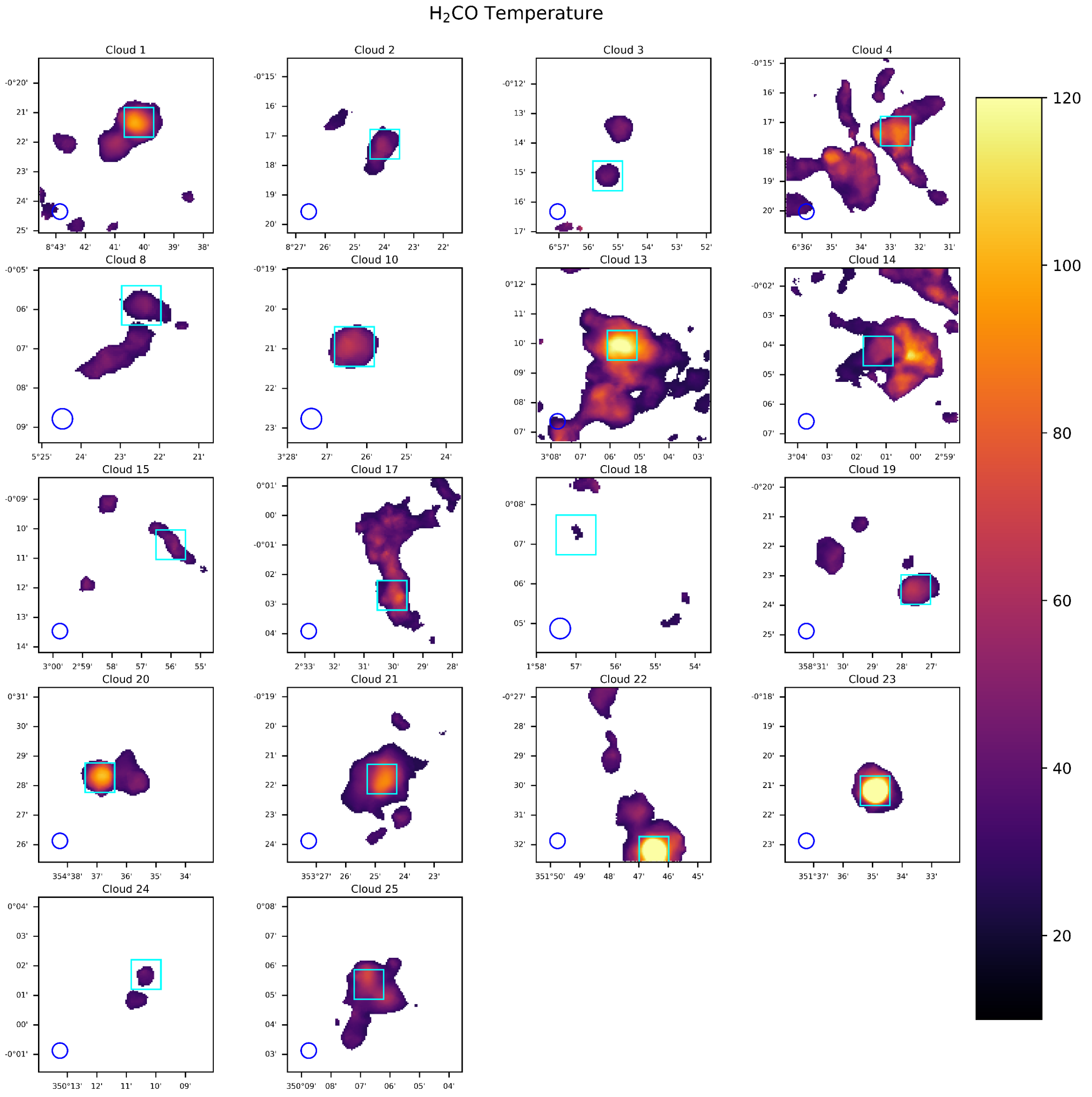


G008.67
T12 = 19.6 ± 1.3
T13 = 34.0 ± 1.2
G008.40
T12 = 23.6 ± 3.4
T13 = 35.0 ± 2.9
G006.92
T12 = 20.3 ± 3.5
T13 = 33.6 ± 3.2
G006.56
T12 = 42.4 ± 13.2
T13 = 85.6 ± 16.0
G005.75
T12 = 37.6 ± 10.9
T13 = 74.3 ± 12.2
G005.49
T13 = 122.2 ± 86.3
G005.38
T12 = 35.0 ± 7.0
T13 = 71.7 ± 8.1
G003.43
T12 = 19.7 ± 1.6
T13 = 27.4 ± 1.8
G003.09
T12 = 46.9 ± 2.2
T13 = 77.9 ± 1.9
T36 = 98.0 ± 3.5
G003.02
T12 = 31.5 ± 1.8
T13 = 72.1 ± 2.3
T36 = 95.4 ± 5.6
G002.96
T12 = 33.9 ± 4.3
T13 = 63.0 ± 4.2
T36 = 86.9 ± 17.2
G002.51
T12 = 30.6 ± 1.9
T13 = 52.2 ± 1.6
T36 = 100.9 ± 10.2
G001.93
T12 = 33.2 ± 6.2
T13 = 59.6 ± 5.7
G358.48
T12 = 31.1 ± 6.2
T13 = 37.1 ± 4.1
G354.61
T12 = 29.7 ± 5.4
T13 = 38.4 ± 3.7
G353.41
T12 = 19.0 ± 1.0
T13 = 31.0 ± 0.9
G351.77
T12 = 17.0 ± 1.9
T13 = 32.1 ± 1.8
G351.58
T12 = 18.4 ± 2.2
T13 = 36.1 ± 2.0
G350.18
T12 = 20.4 ± 3.4
T13 = 32.7 ± 3.1
G350.10
T12 = 24.9 ± 2.8
T13 = 39.0 ± 2.2
log[Nu/(2J + 1)/gop]

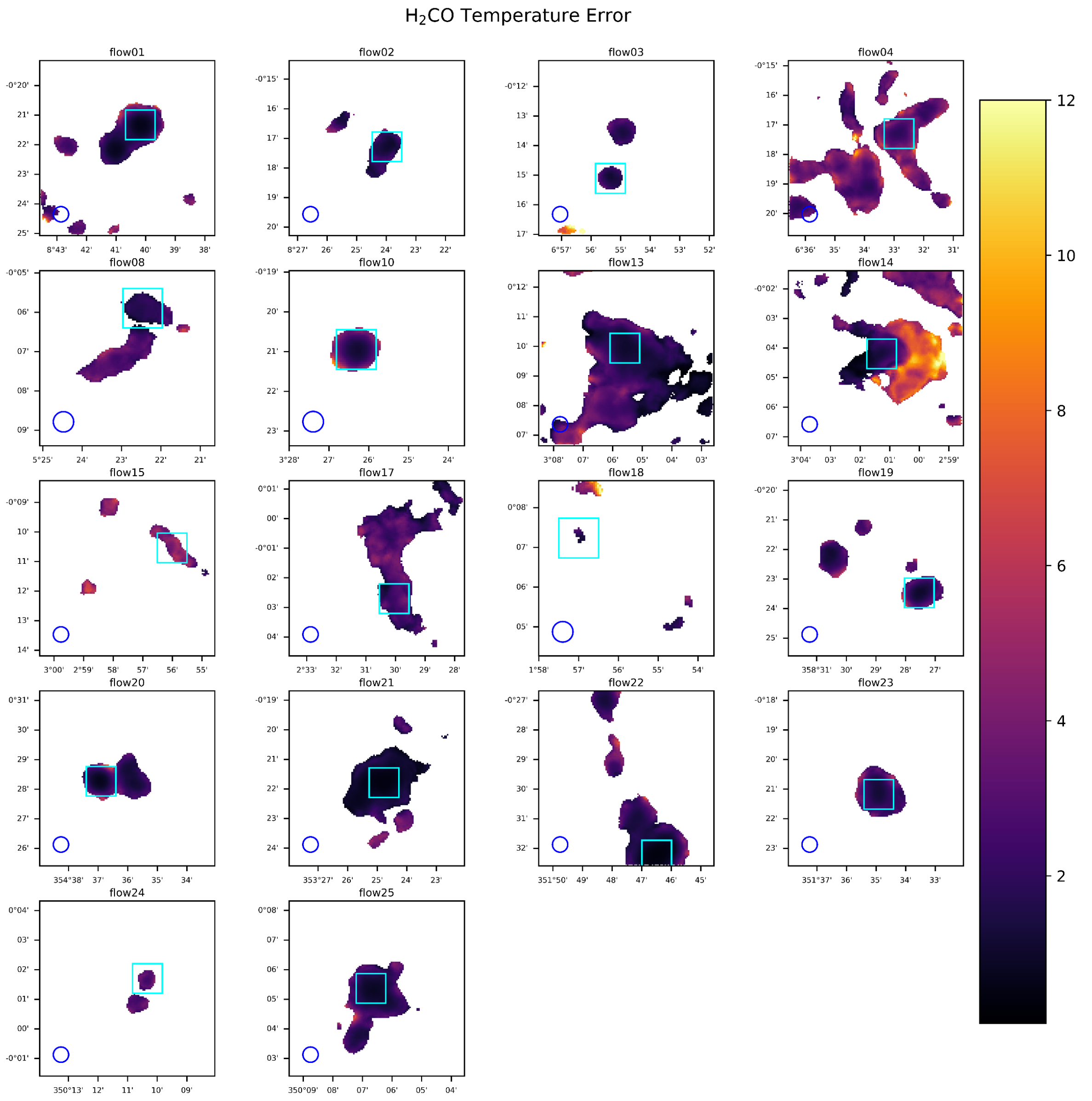


NH_3 (3,3)-(1,1) Temperature
Cloud 1
Cloud 2
Cloud 3
Cloud 4
Cloud 6
Cloud 7
Cloud 8
Cloud 10
Cloud 13
Cloud 14
Cloud 15
Cloud 17
Cloud 18
Cloud 19
Cloud 20
Cloud 21
Cloud 22
Cloud 23
Cloud 24
Cloud 25
120
100
80
60
40
20
NH_3 (3,3)-(1,1) Temperature Error
Cloud 1
Cloud 2
Cloud 3
Cloud 4
Cloud 6
Cloud 7
Cloud 8
Cloud 10
Cloud 13
Cloud 14
Cloud 15
Cloud 17
Cloud 18
Cloud 19
Cloud 20
Cloud 21
Cloud 22
Cloud 23
Cloud 24
Cloud 25
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5

(a) (b)


H$_2$CO Temperature
Cloud 1
Cloud 2
Cloud 3
Cloud 4
Cloud 8
Cloud 10
Cloud 13
Cloud 14
Cloud 15
Cloud 17
Cloud 18
Cloud 19
Cloud 20
Cloud 21
Cloud 22
Cloud 23
Cloud 24
Cloud 25
120
100
80
60
40
20

(a)


H$_2$CO Temperature Error
flow01
flow02
flow03
flow04
flow08
flow10
flow13
flow14
flow15
flow17
flow18
flow19
flow20
flow21
flow22
flow23
flow24
flow25
12
10
8
6
4
2

(b)