PCCs in the LMC with Mopra and ALMA

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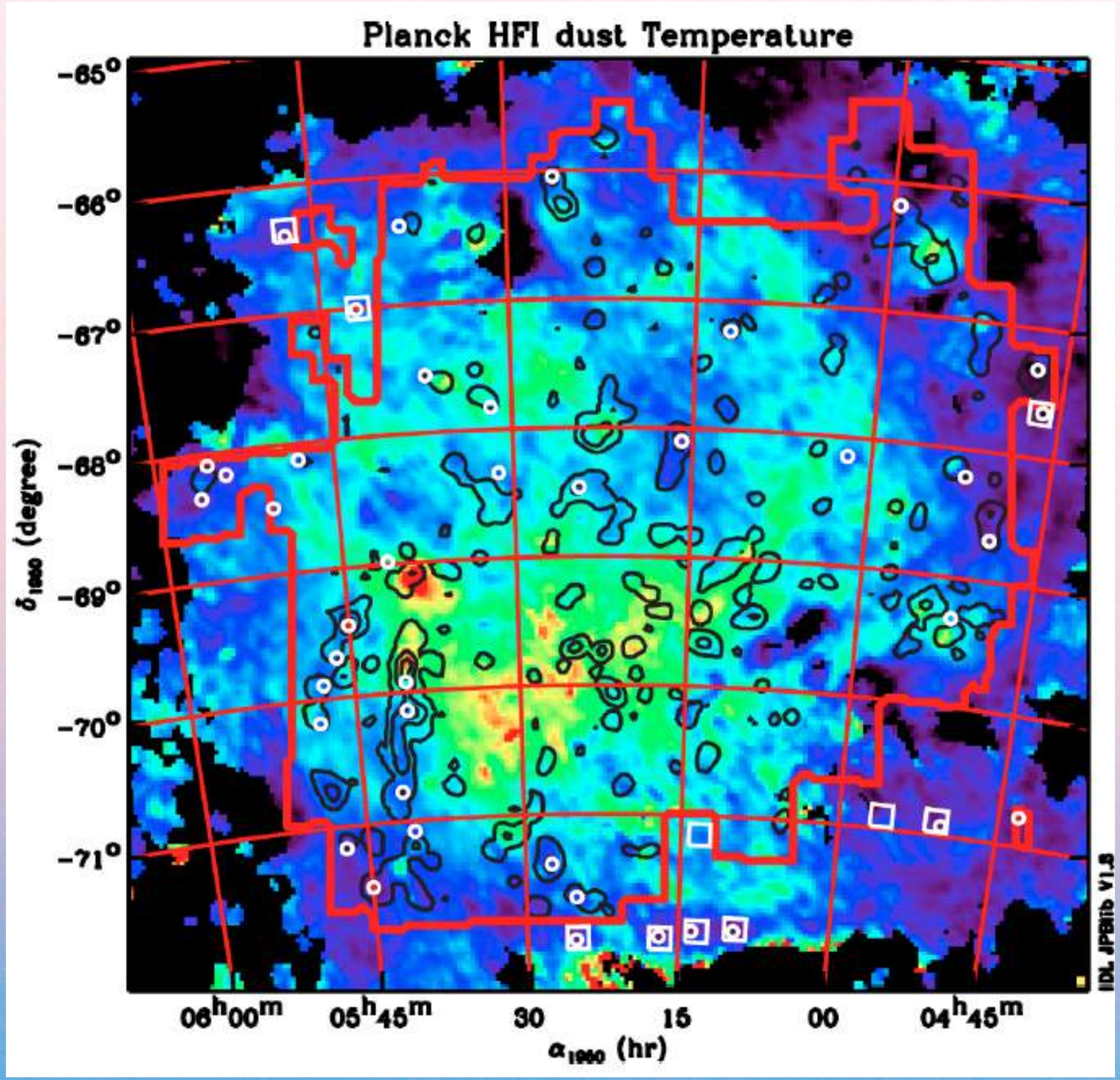
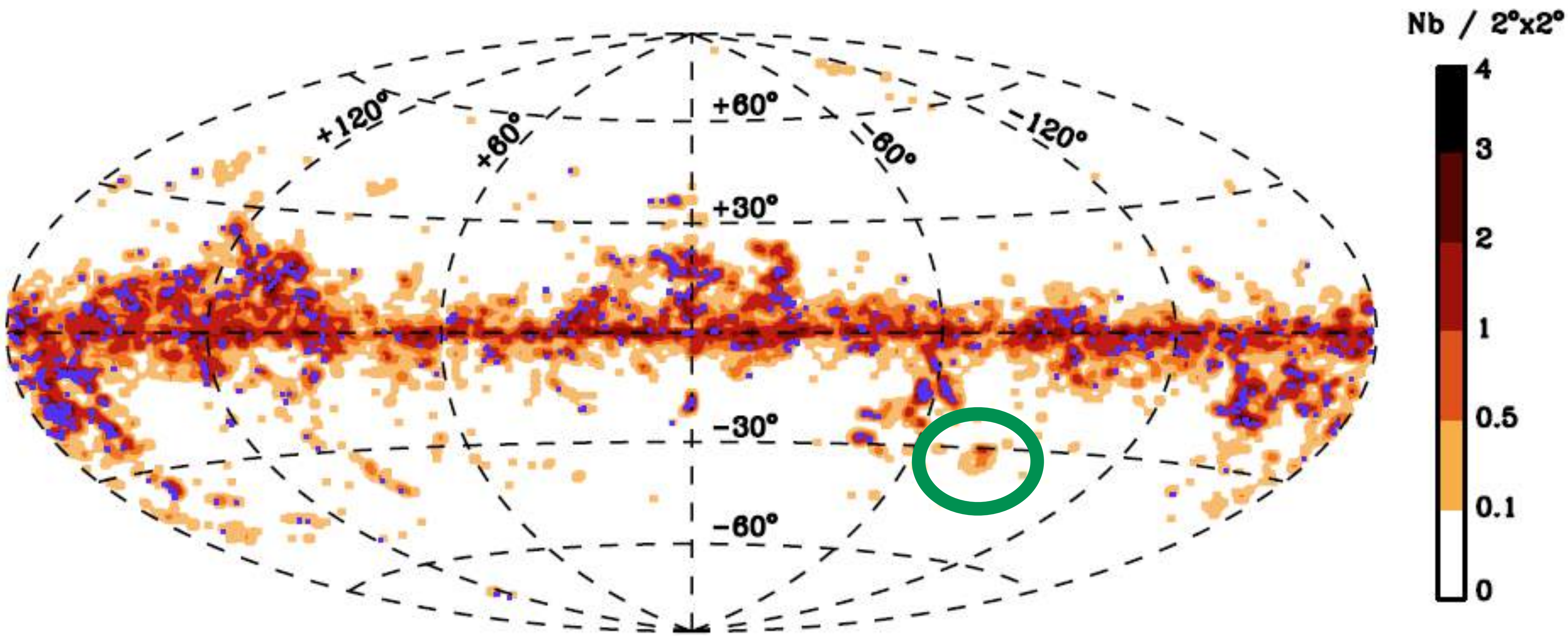


This Talk:

- PCC follow-up with Mopra
- CO properties of LMC PCCs
- ALMA observations of PCCs

C3PO, now PG*CCC



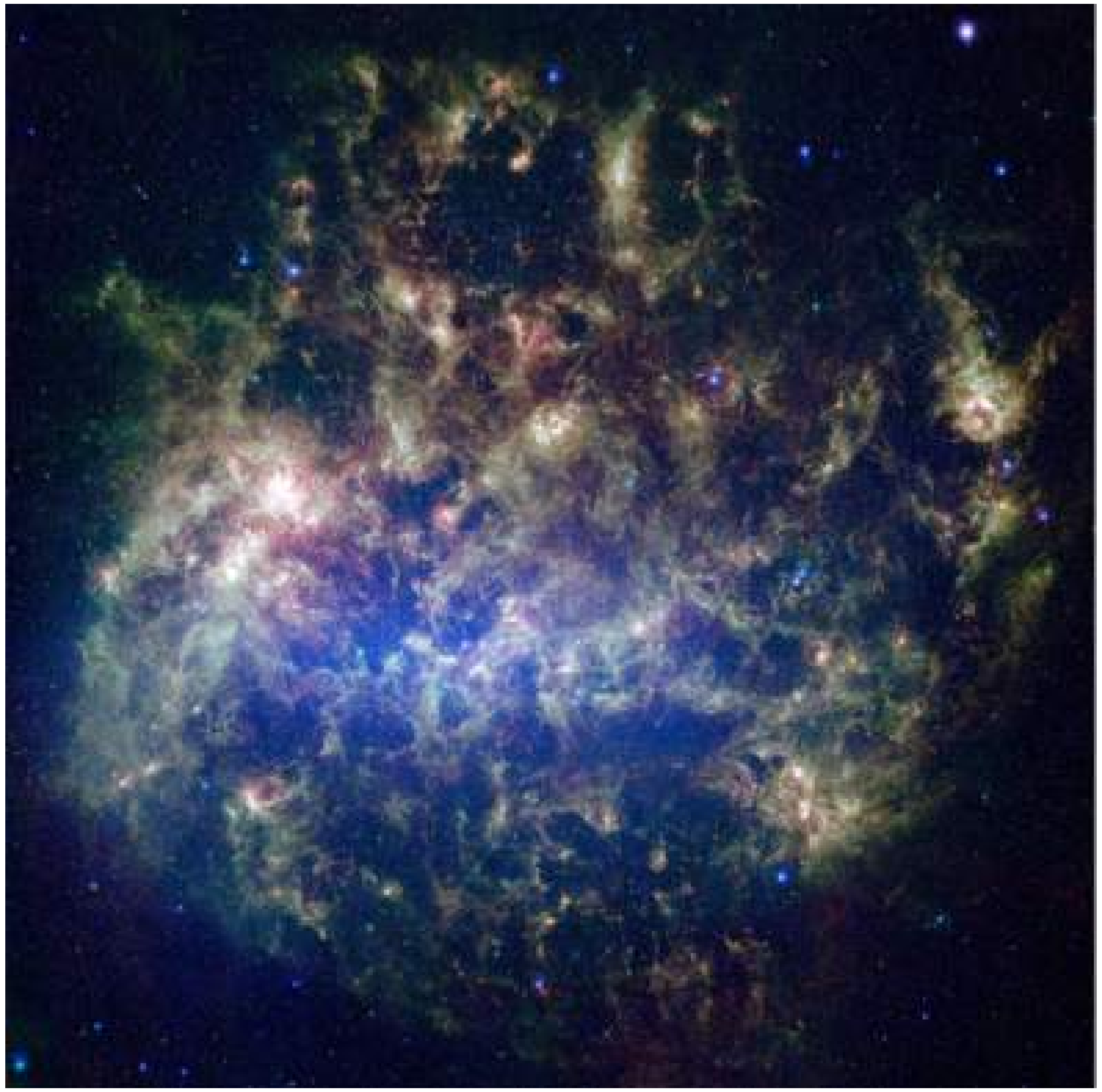
Cold Clump Density Map

IRAS 100um + Planck 857, 545 & 353 GHz ➡

all-sky catalogue of ~13,000 cold sources at 5' resolution

*mostly Galactic!

The Magellanic Clouds

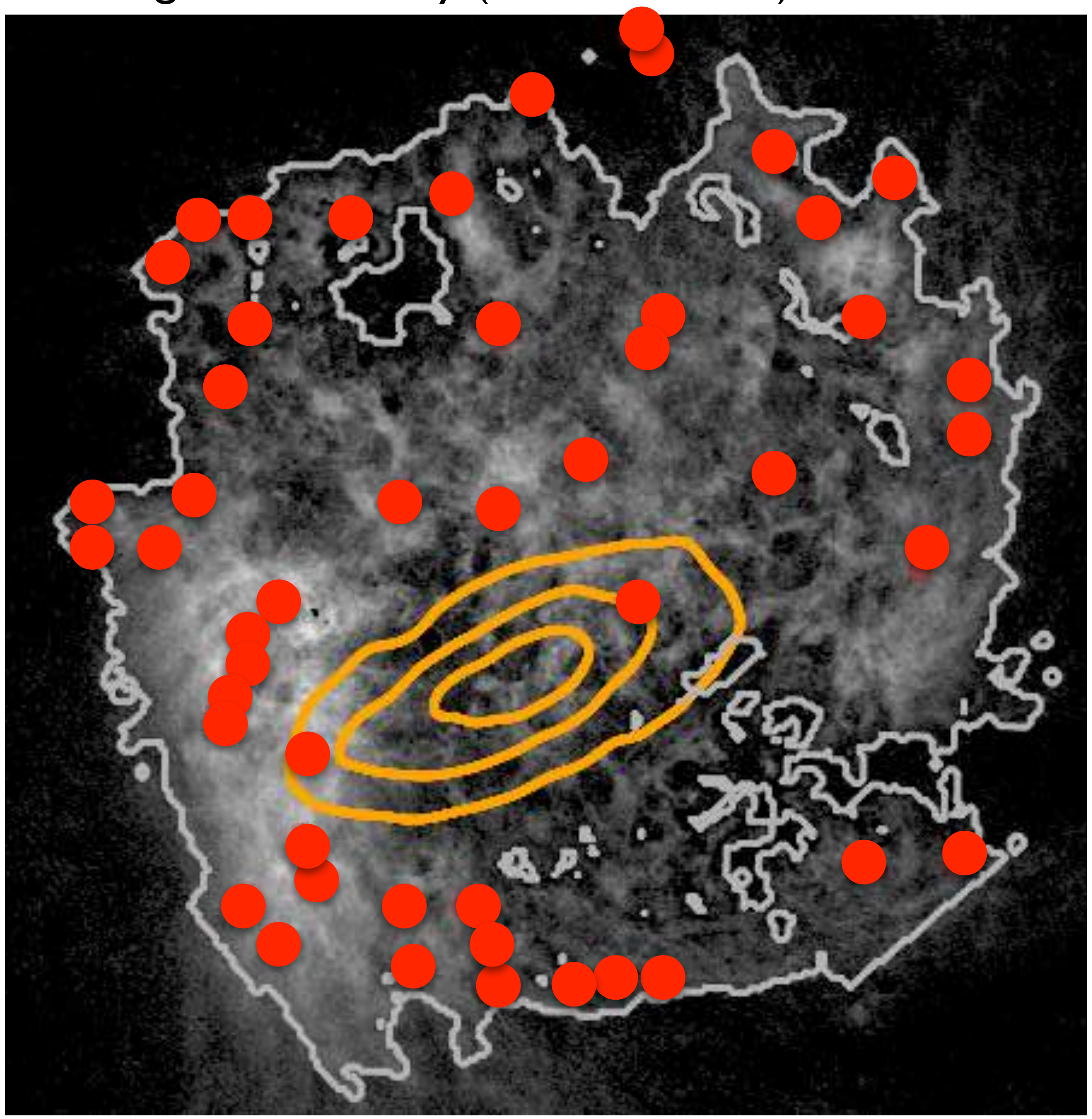


Fully mapped by the Spitzer SAGE and Herschel HERITAGE key programmes (Meixner ea 2006, 2013)

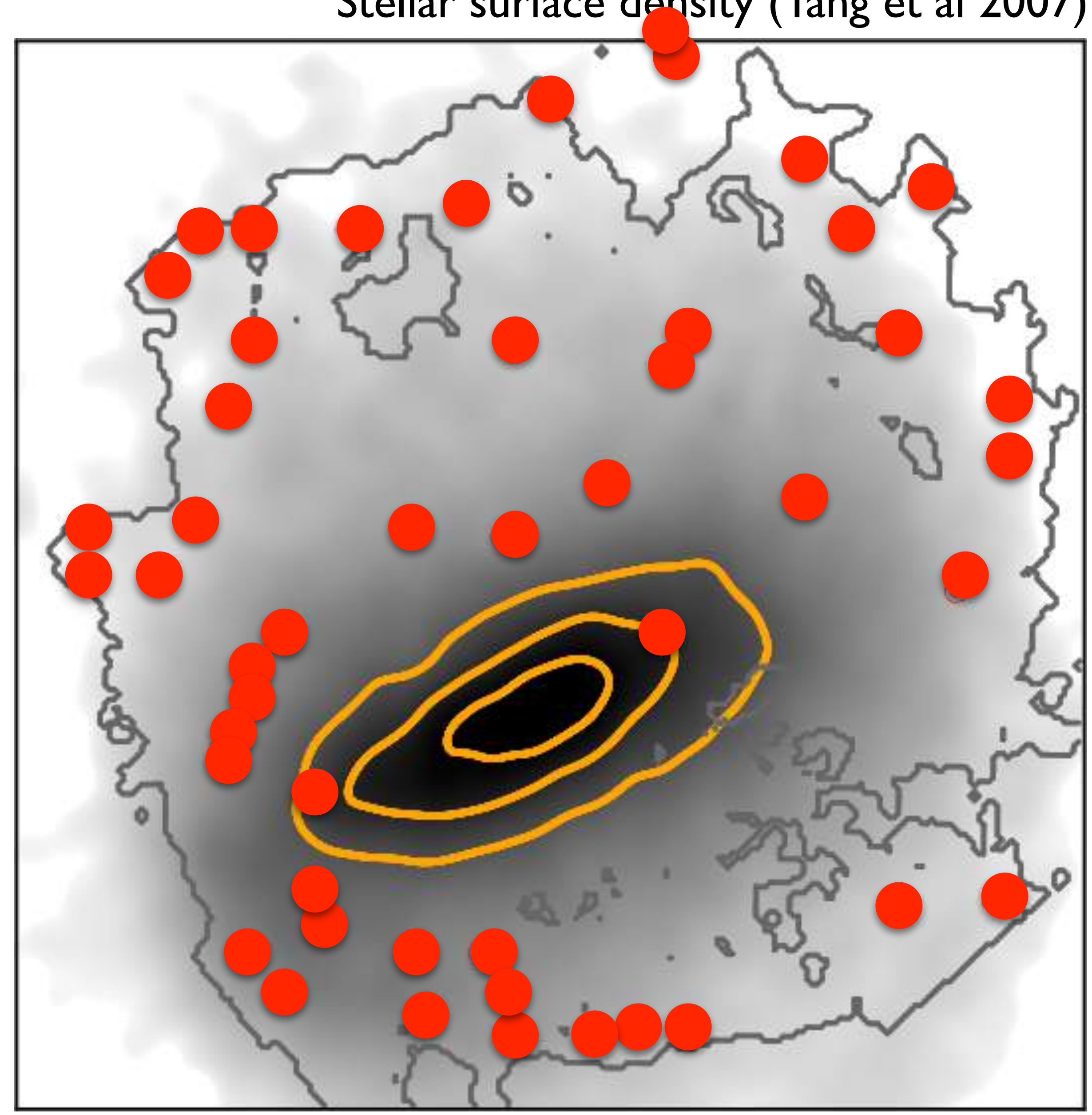
- **Nearby:** high resolution (~15pc) observations of dust and gas tracers
- **Low metallicity:** LMC~1/2 and SMC ~1/6 solar
- **External vantage point:** study influence of galactic environment, known distance
- Excellent laboratories for ISM+SF studies
- PCCs in the Magellanic Clouds are clouds, not clumps or cores

Spatial Distribution of PCCs in the LMC

HI integrated intensity (Kim et al 2003)



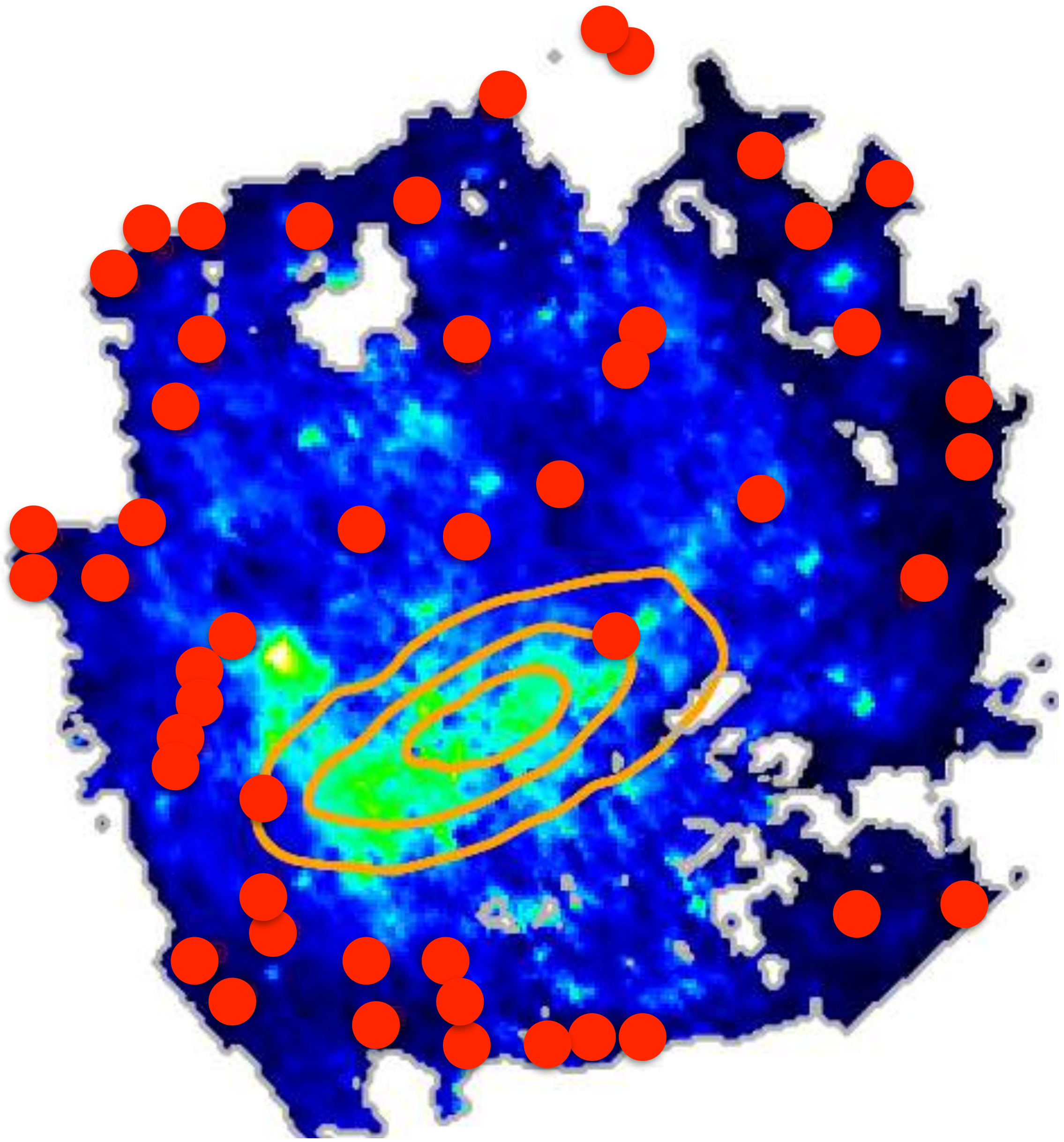
Stellar surface density (Yang et al 2007)



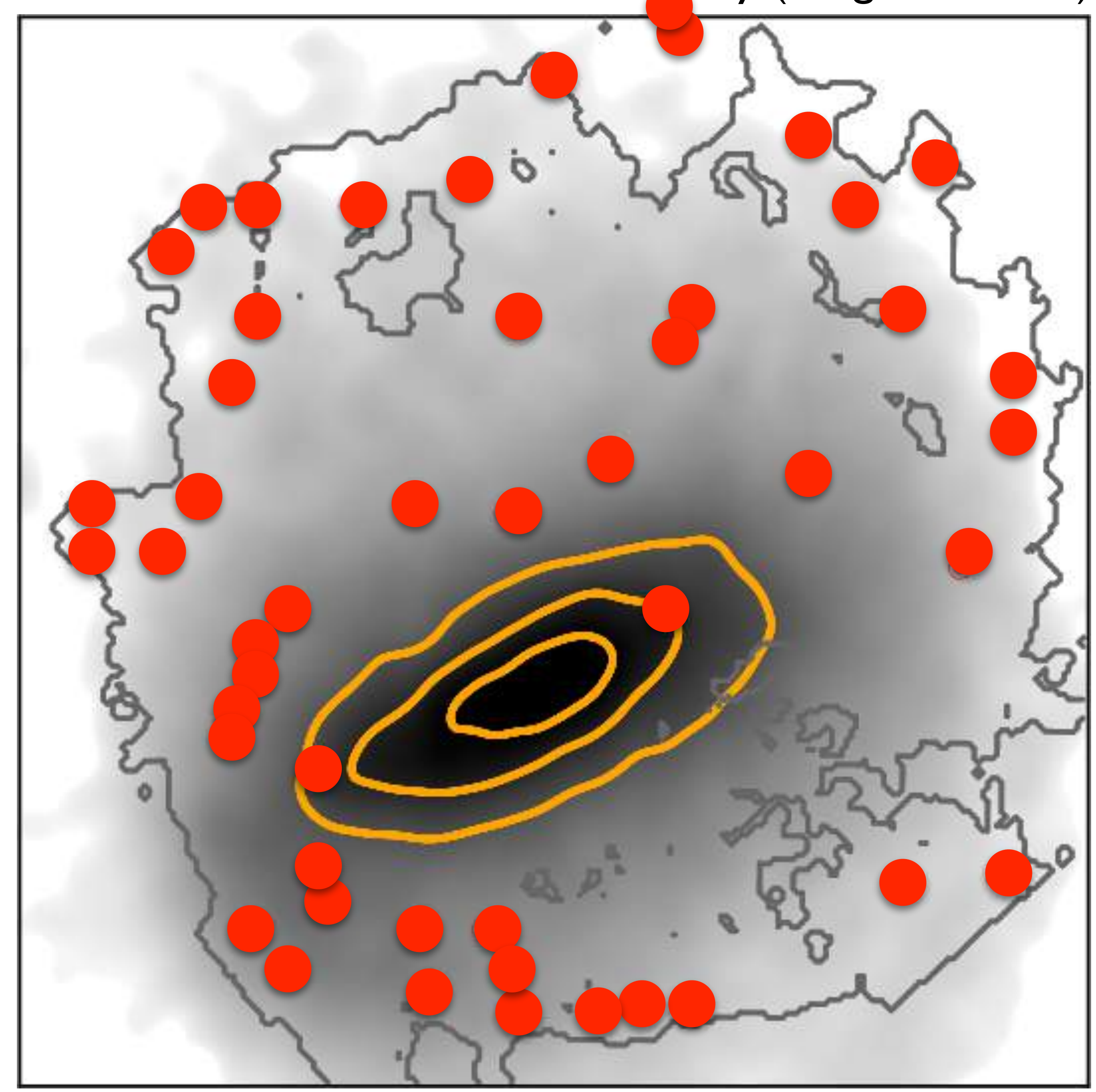
- PCCs appear to prefer the outer disk (avoid the stellar bar)
- Other LMC molecular clouds do not avoid the bar
- Planck compact sources prefer the bar: 34 % of sources in 18% of area

Spatial Distribution of PCCs in the LMC

Planck Dust Temperature (Planck 2011)



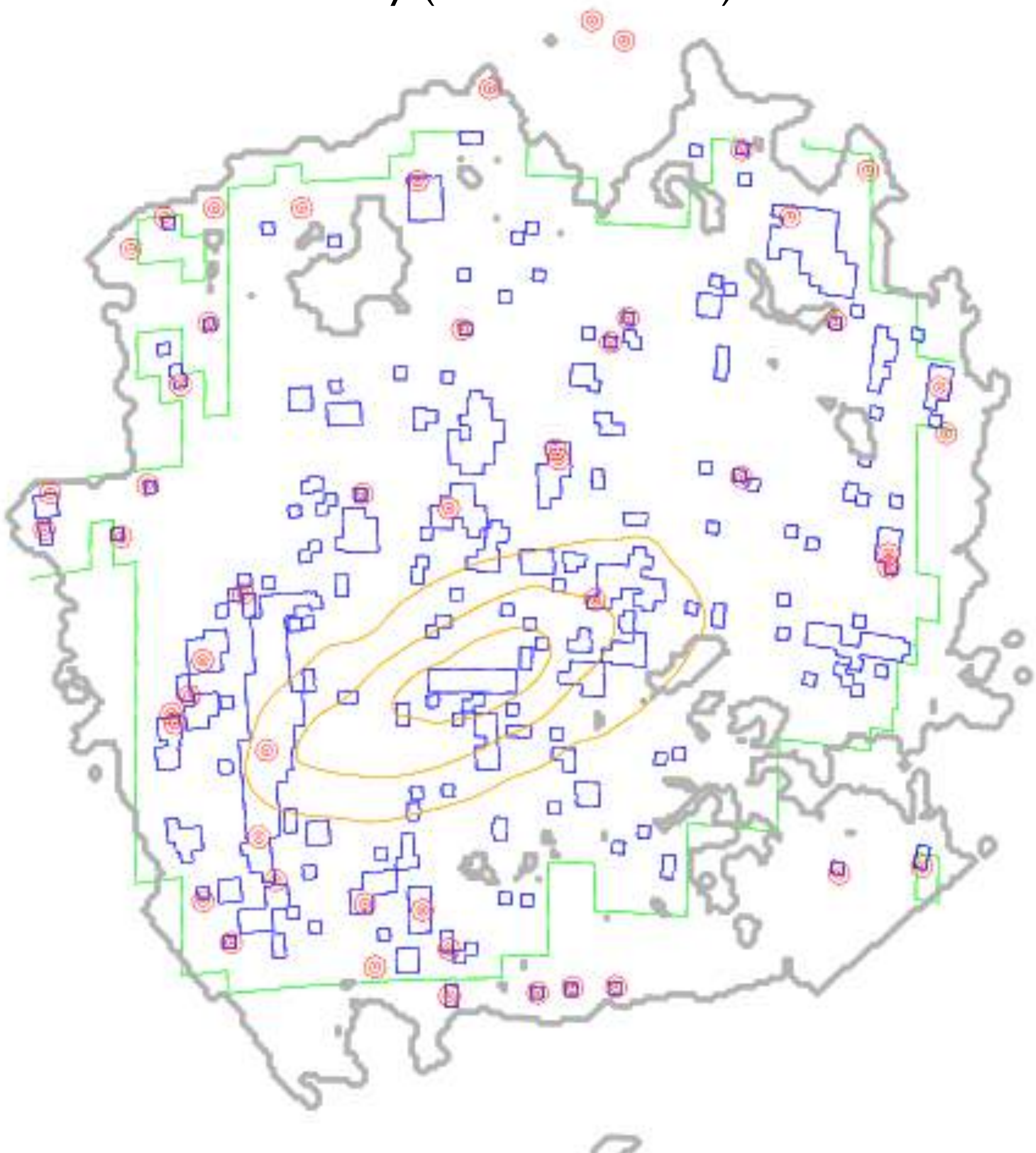
Stellar surface density (Yang et al 2007)



- PCCs appear to prefer the outer disk and cold dust regions
- some aligned within cold southern HI arm evident in Planck dust temperature map

Comparison to Existing CO Surveys

MAGMA CO survey (Wong et al 2011)
NANTEN CO survey (Fukui et al. 2008)



- 38 of PCCs in NANTEN FoV
- 28 are inside MAGMA FoV (all show CO emission)

25% of PCCs are outside area covered by previous CO surveys:

- is this CO-dark molecular gas?
- H2+SF in outer galaxy disks?

Circles: Planck PCCs
Green area: NANTEN survey limits
Blue contours: CO fields (to 2014)
Orange: Stellar Bar (>80Msol/pc2)
reliable Tdust (from Spitzer)

Follow-up Mopra Observations: History & Strategy

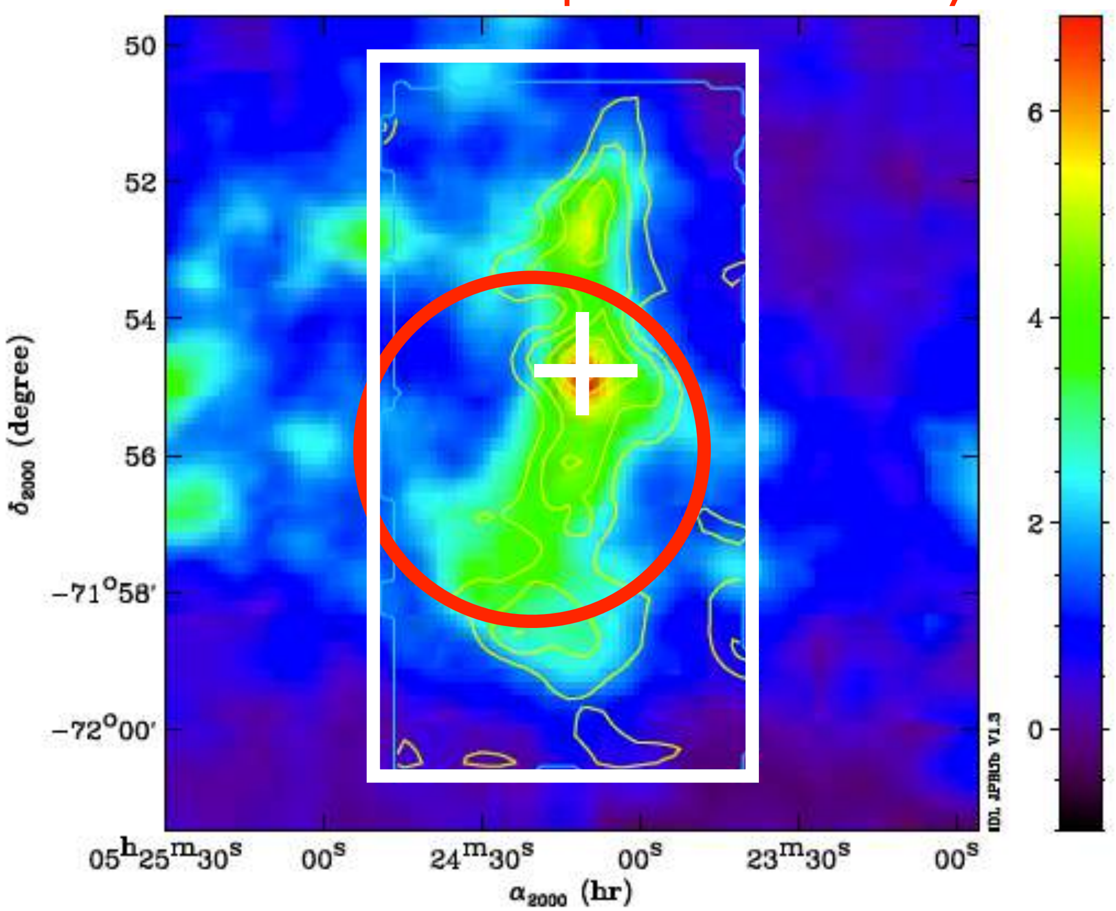
Mopra Observations: 2012 to 2015.

Data integrated into MAGMA survey and DR3:

http://mmwave.astro.illinois.edu/magma/DR3/

Background: Herschel 500um

Red circle: Planck positional accuracy



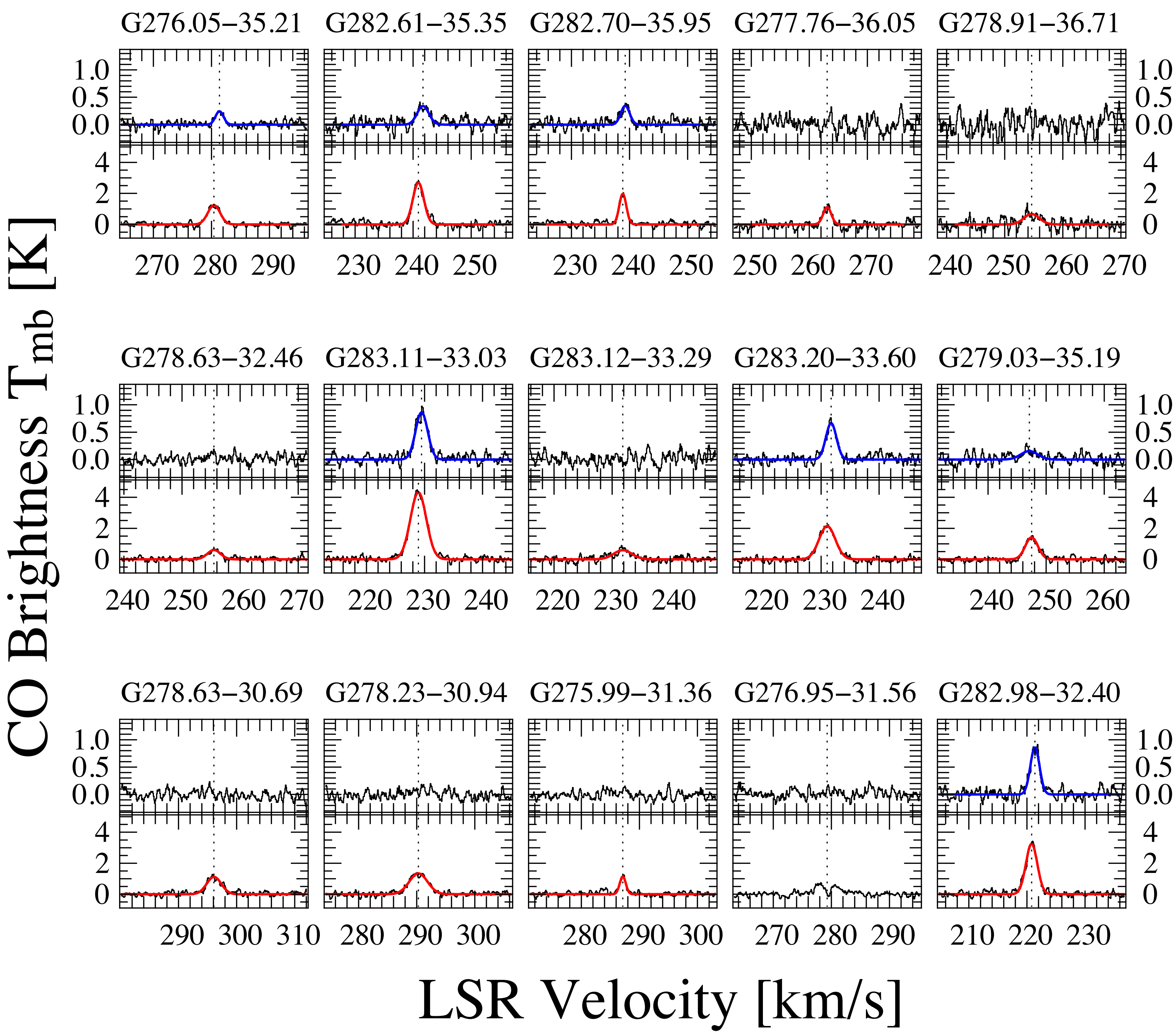
Pointed Observations

- nearest 500μm peak to PCC position
- ~30 minute integrations (ON+OFF)
- RMS T_{A*} ~ 50mK per 0.53 km/s channel

Mapping Observations

- MAGMA strategy
- 2 orthogonal scans (RA + dec)
- mosaic of 5' x 5' fields per target PCC
- θ_{fwhm} = 45'' (11pc), Δv = 0.53 km/s
- RMS T_{mb} ~ 0.4 K per channel

Example CO spectra from LMC PCCs



^{13}CO(J=1-0)

^{12}CO(J=1-0)

Newly observed PCCs:

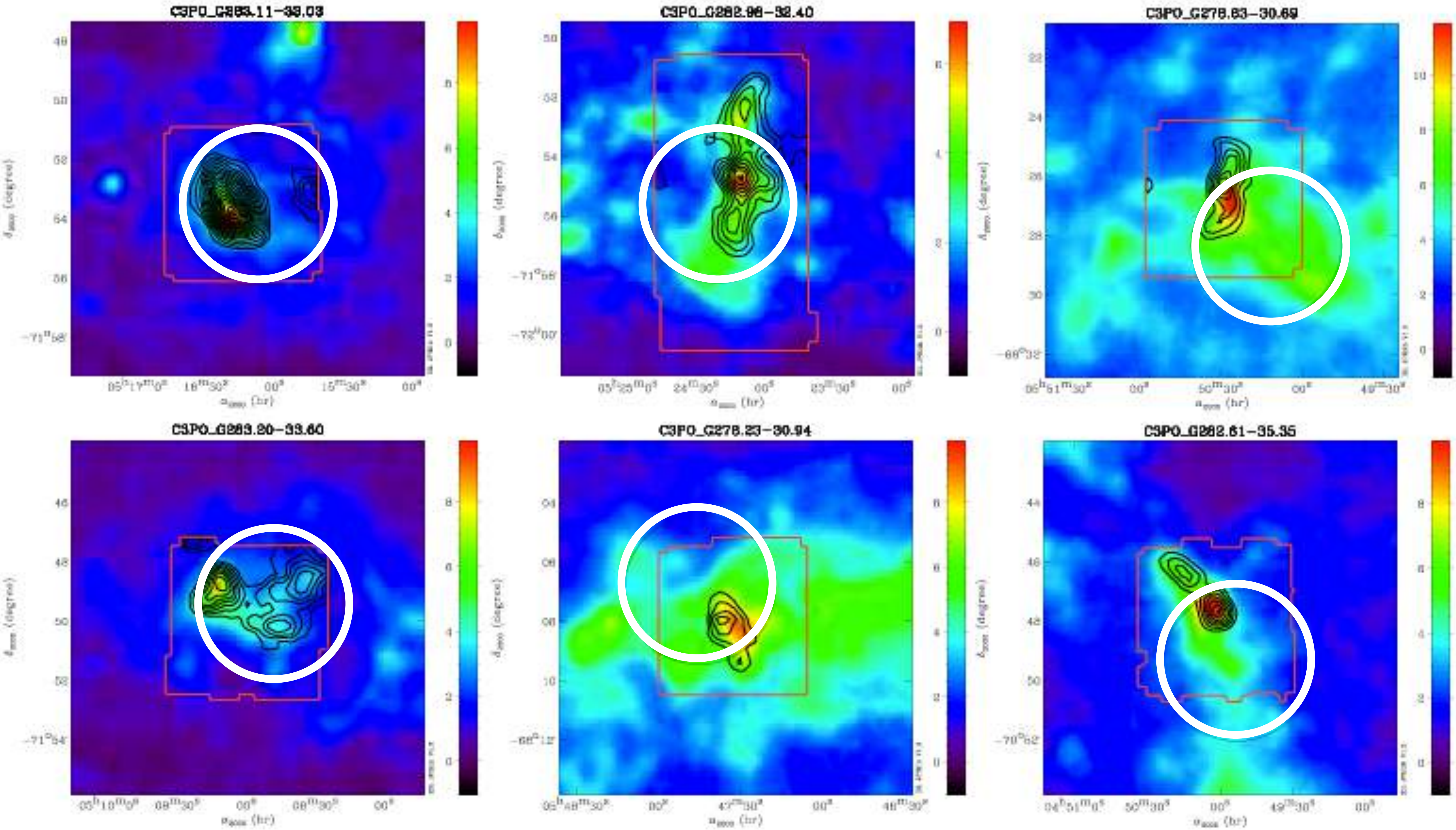
- 15/17 ^{12}CO detections
- 7 also detected in ^{13}CO

PCCs already observed by MAGMA:

- 43/45 have ^{12}CO

Algorithm very efficient at detecting CO. Even PCCs rejected from final version of catalogue usually showed 12CO emission

Example CO Maps of LMC PCCs



CO and 500um emission sometimes co-extensive

but sometimes CO only traces a small part of 500um structure

Circle: PCC, Color: 500 um, Contours: Mopra I_{CO}

Physical Properties of GMCs in the LMC

GMC Scaling Relations ('Larson Laws')

"The fact that nearly all of the regions studied show approximately the same power-law dependence of velocity dispersion on region size suggests that the observed motions are all part of a common hierarchy of interstellar turbulent motions…"

Larson 1981

The Larson scaling relations:

i) size-linewidth relation:

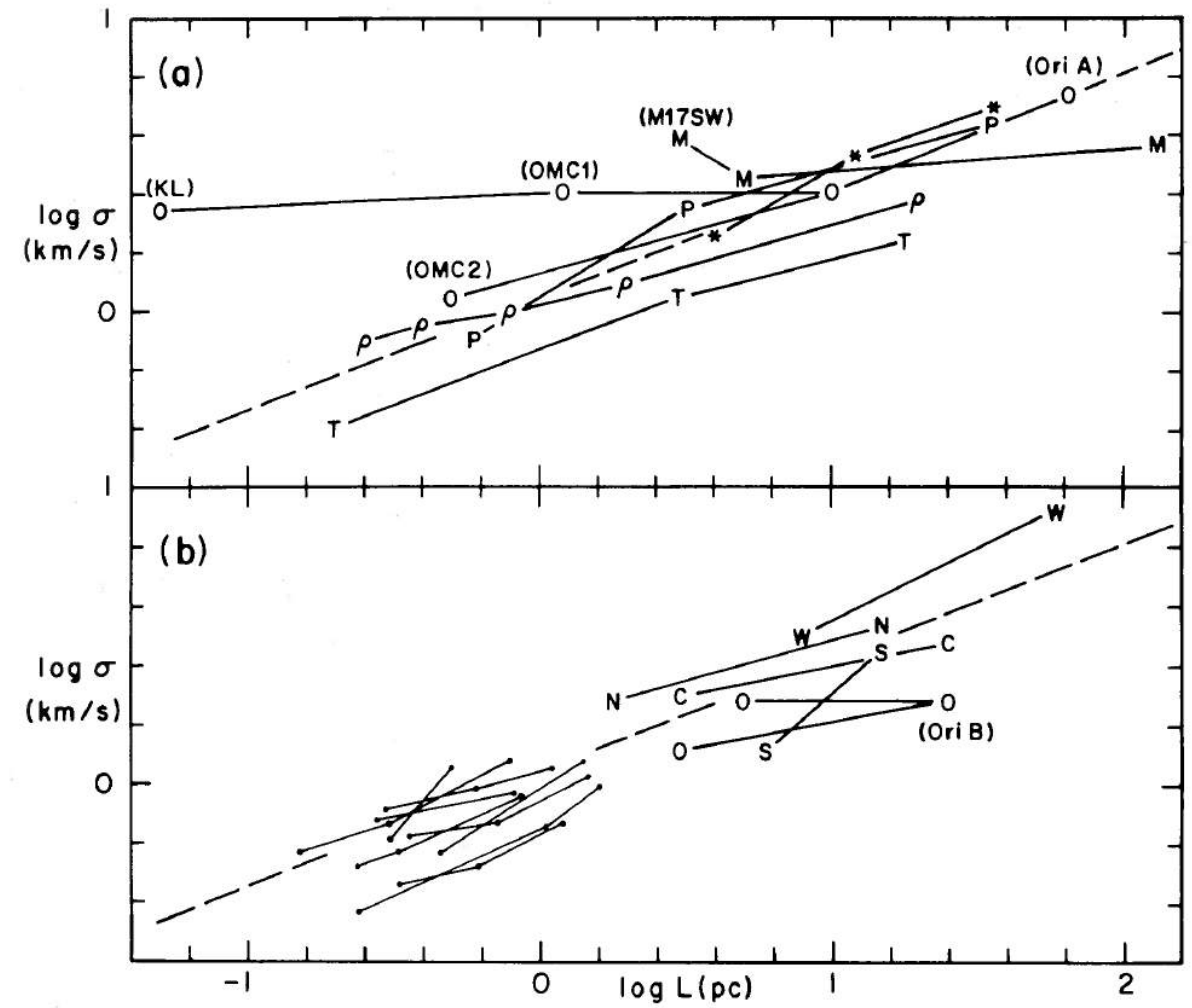
σ_v (km s^{-1}) = 0.72 (R/pc)$^{0.5\pm0.1}$

ii) gravitational equilibrium:

$M = 5\sigma_v^2 R/G$

iii) constant surface density:

$\langle\Sigma_{H2}\rangle = M/(\pi R^2) \sim 100\ M_\odot\ pc^{-2}$

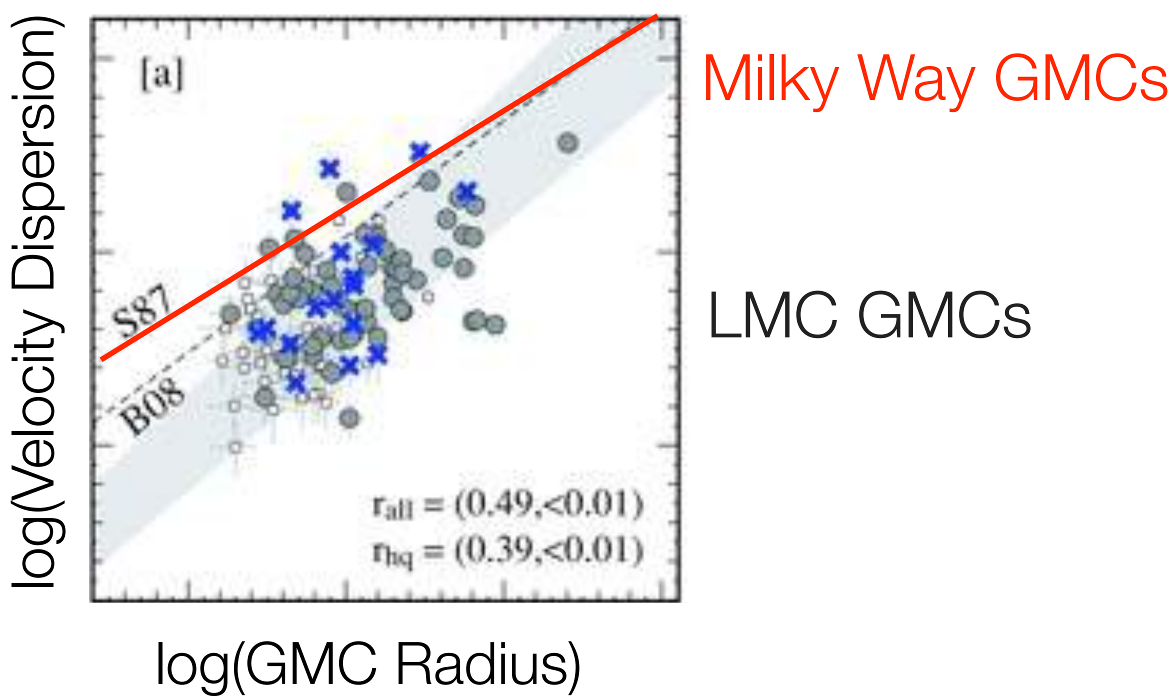


NB: not independent: ii) → $\sigma_v = (\pi G/5)^{1/2}\,\Sigma^{1/2}\,R^{1/2}$ → i), given iii)

Physical Properties of GMCs in the LMC

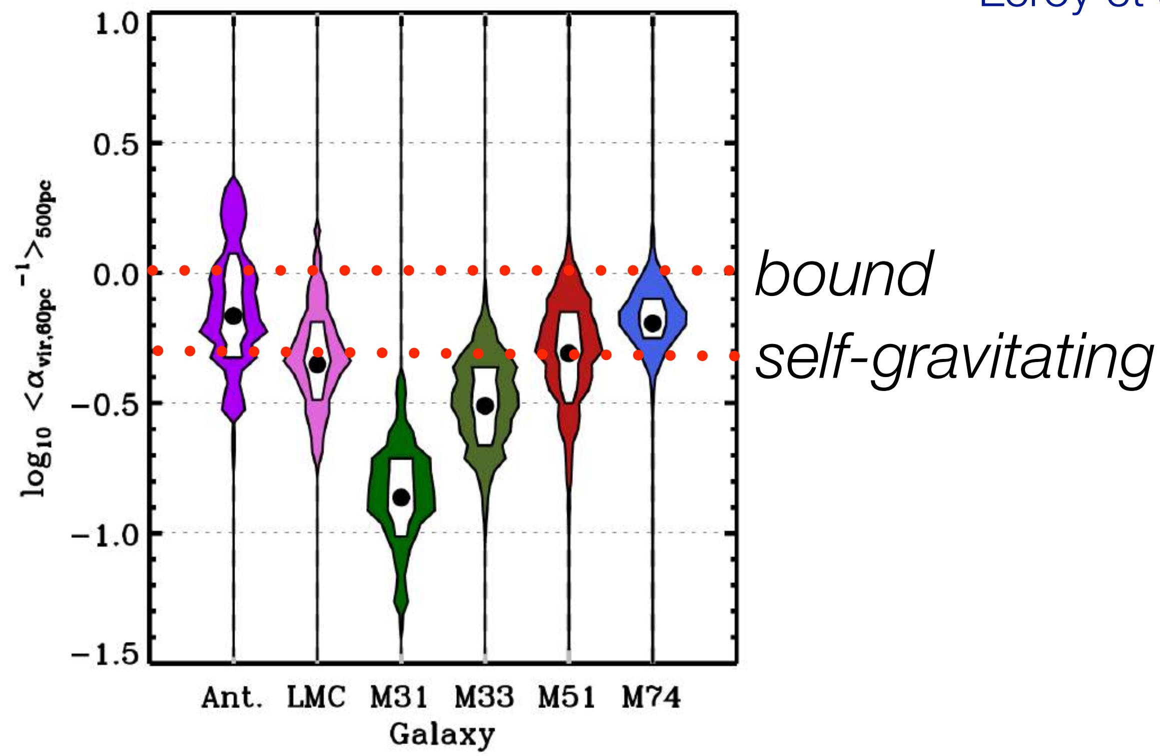
GMCs have universal properties

e.g. Bolatto et al 2008

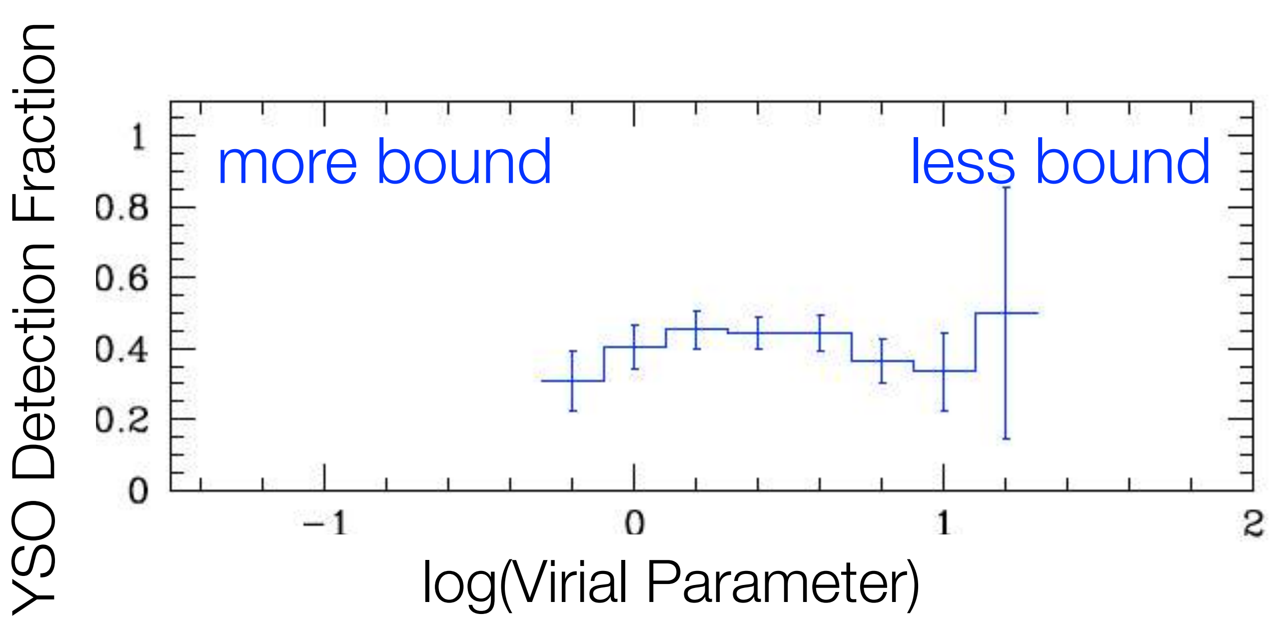


Cold gas dynamical self-regulation?

Leroy et al. 2016

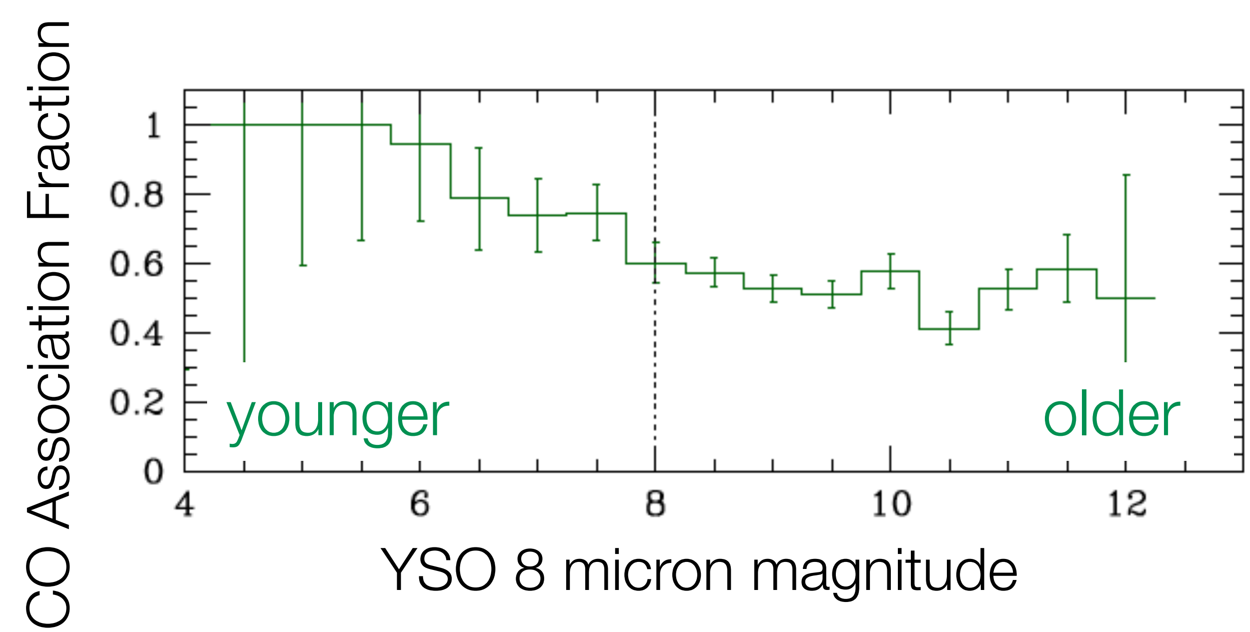


GMCs must be globally bound before star formation starts



GMCs are long-lived (30+Myr)

e.g. Krumholz & McKee 2005, Kawamura et al. 2009



Measuring Turbulence in the Cold ISM

What do observed cloud-scale CO line widths actually measure?

Meidt et al (submitted)

intrinsic turbulent gas dispersion + unresolved in-plane motions

$$\sigma_{obs} = \left[\sigma_{true}^2 + (\Delta v_{cnt} \sin i)^2\right]^{1/2}$$

component due to galactic rotation only

$$\Delta v_{cnt} \sin i = (dV_c/dR)\, \theta_{beam} \sin i.$$

component due to spiral-arm streaming (a simple model)

$$V_{sp}/(w/2) \sin i \theta_{beam} \qquad V_{sp} \approx \frac{\Sigma_a}{\Sigma_0} \tan i_p V_c$$

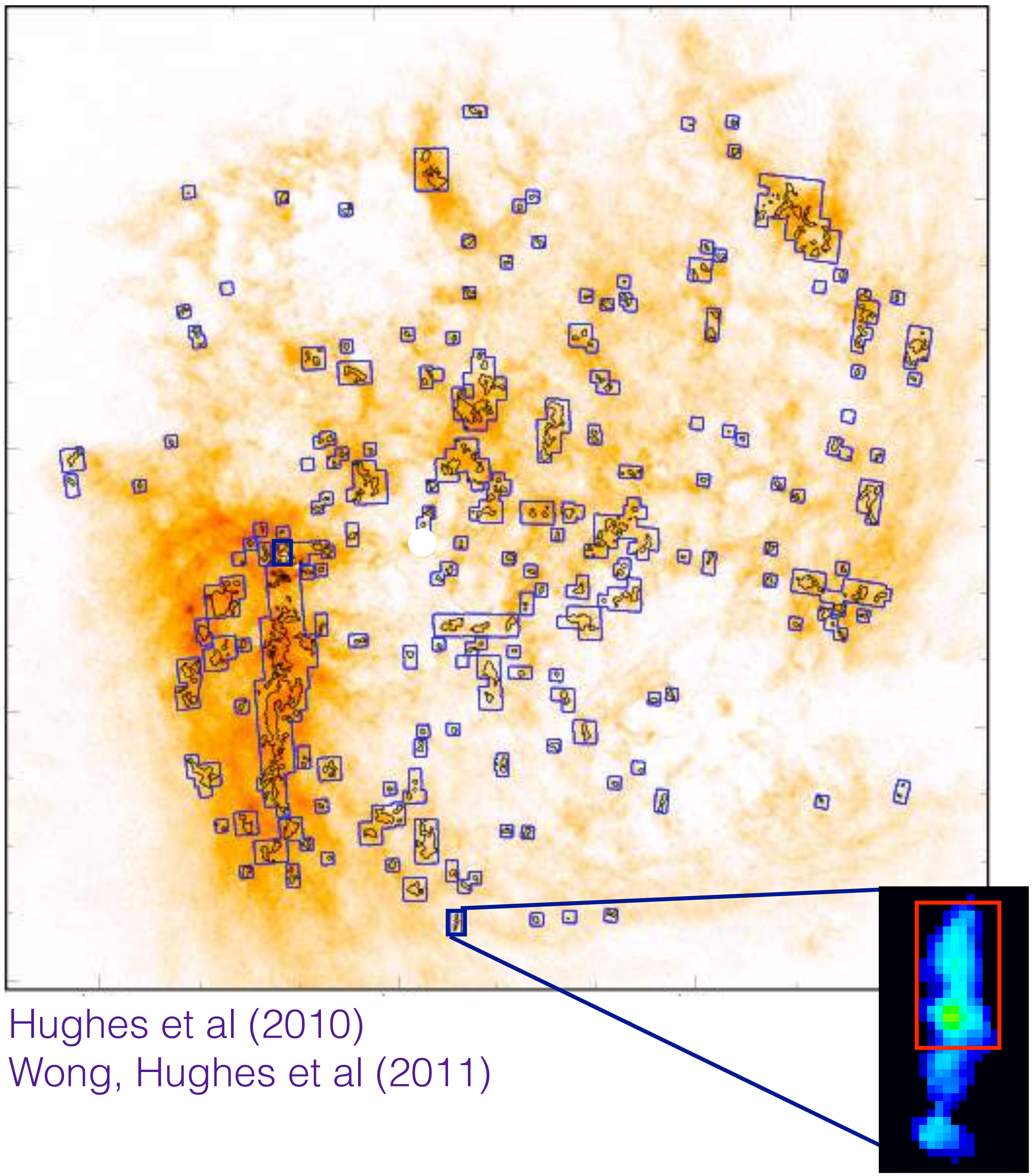
Contribution from unresolved bulk motions (galactic rotation, streaming motions) to the cloud-scale line width can be significant

Depends on galactocentric radius, galaxy mass, inclination

ALMA Cycle 2 Observations of a PCC

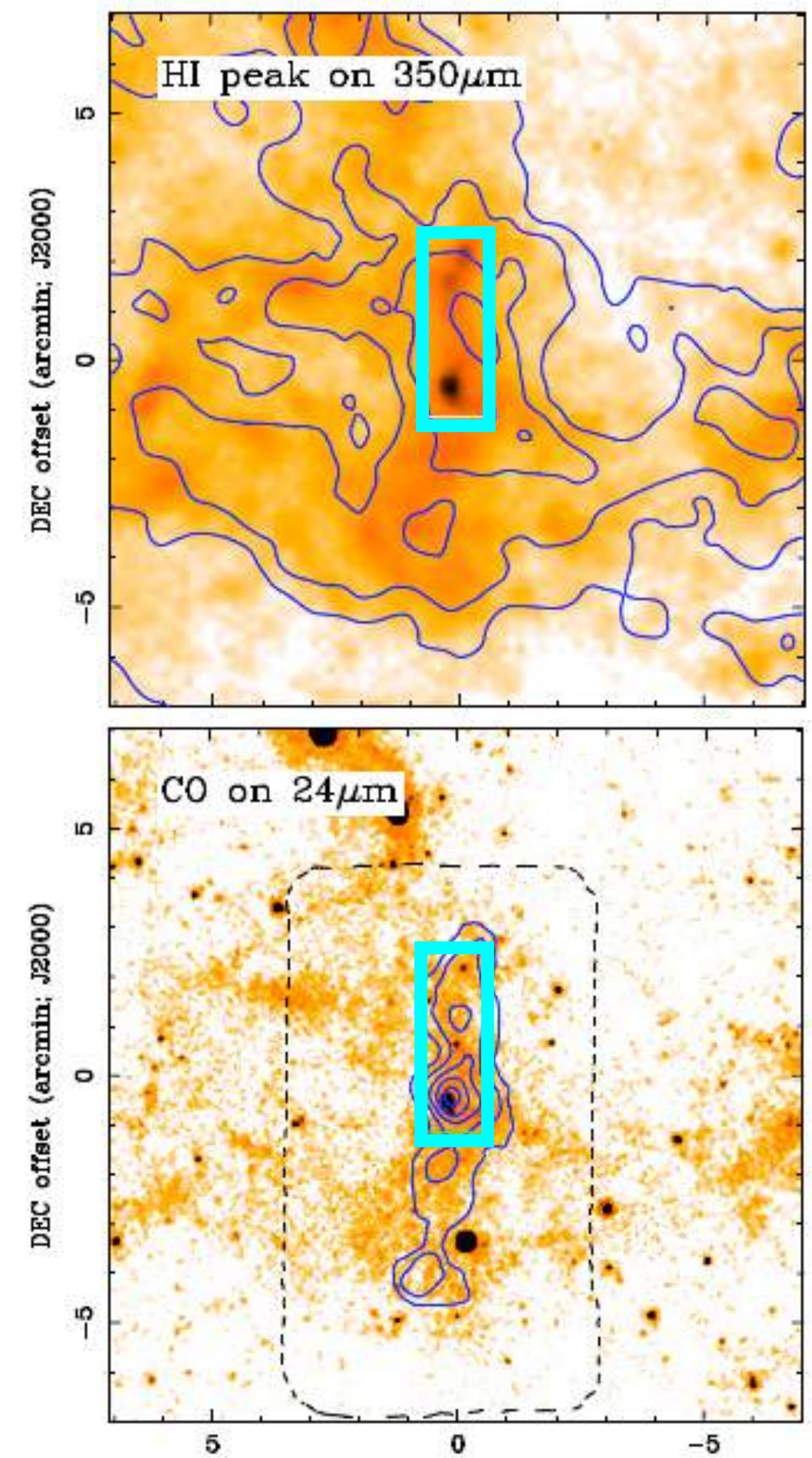
MAGMA LMC survey, 10pc resolution

~8 degrees



Hughes et al (2010)
Wong, Hughes et al (2011)

350um + HI contour



24um + CO contour

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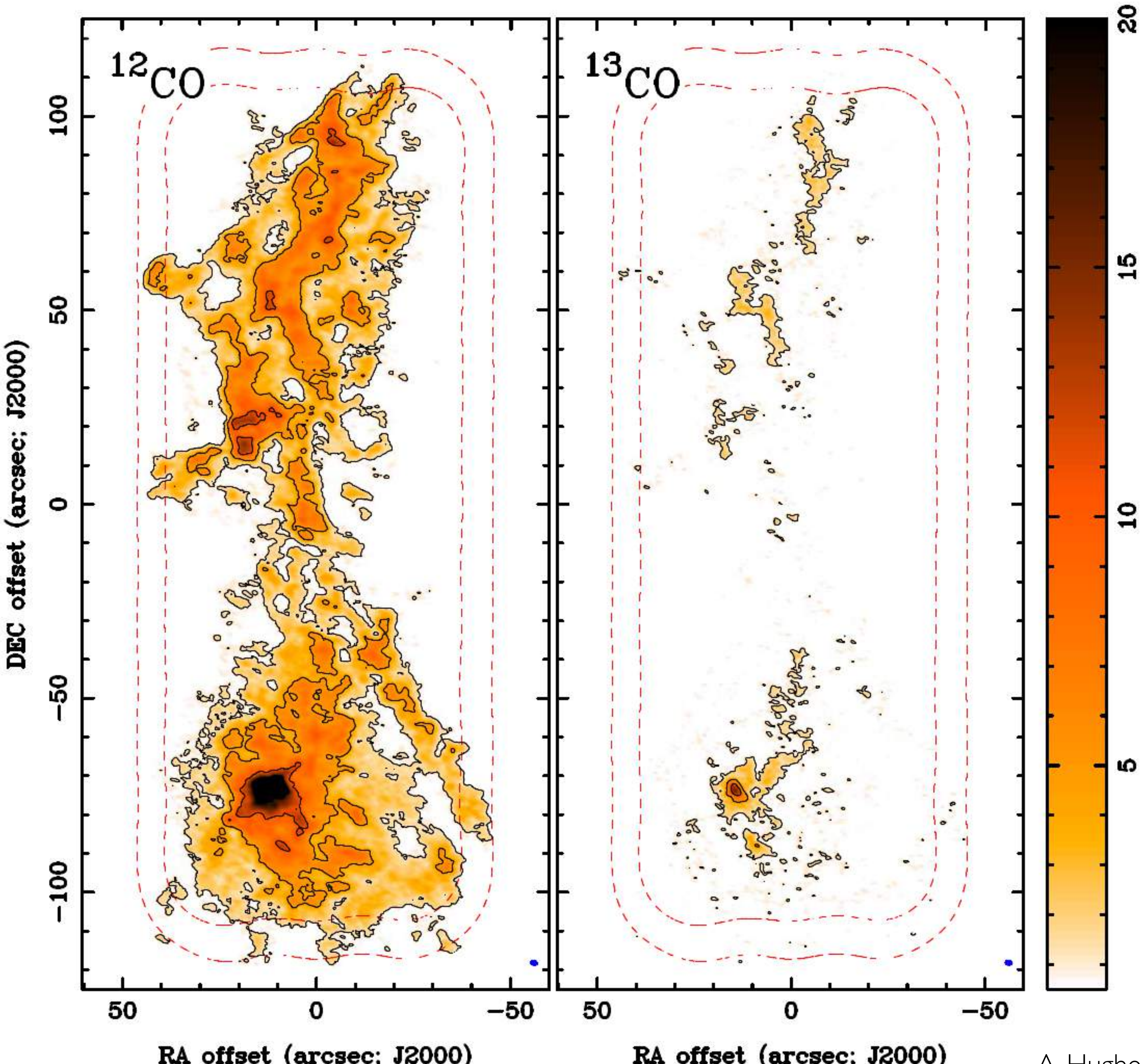
PCC: 12CO and 13CO integrated intensity



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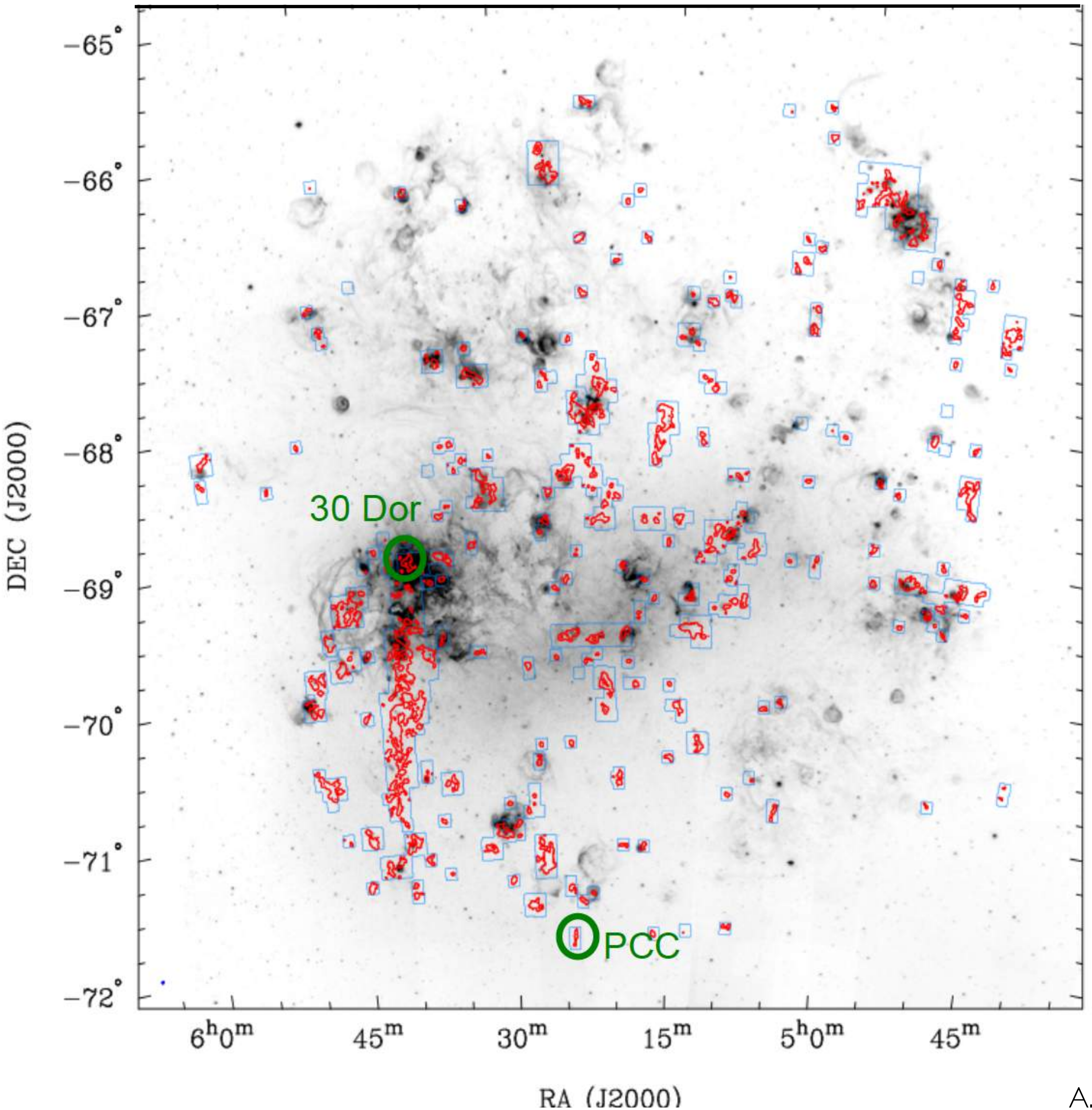
Properties of PCC vs 30Dor cloud



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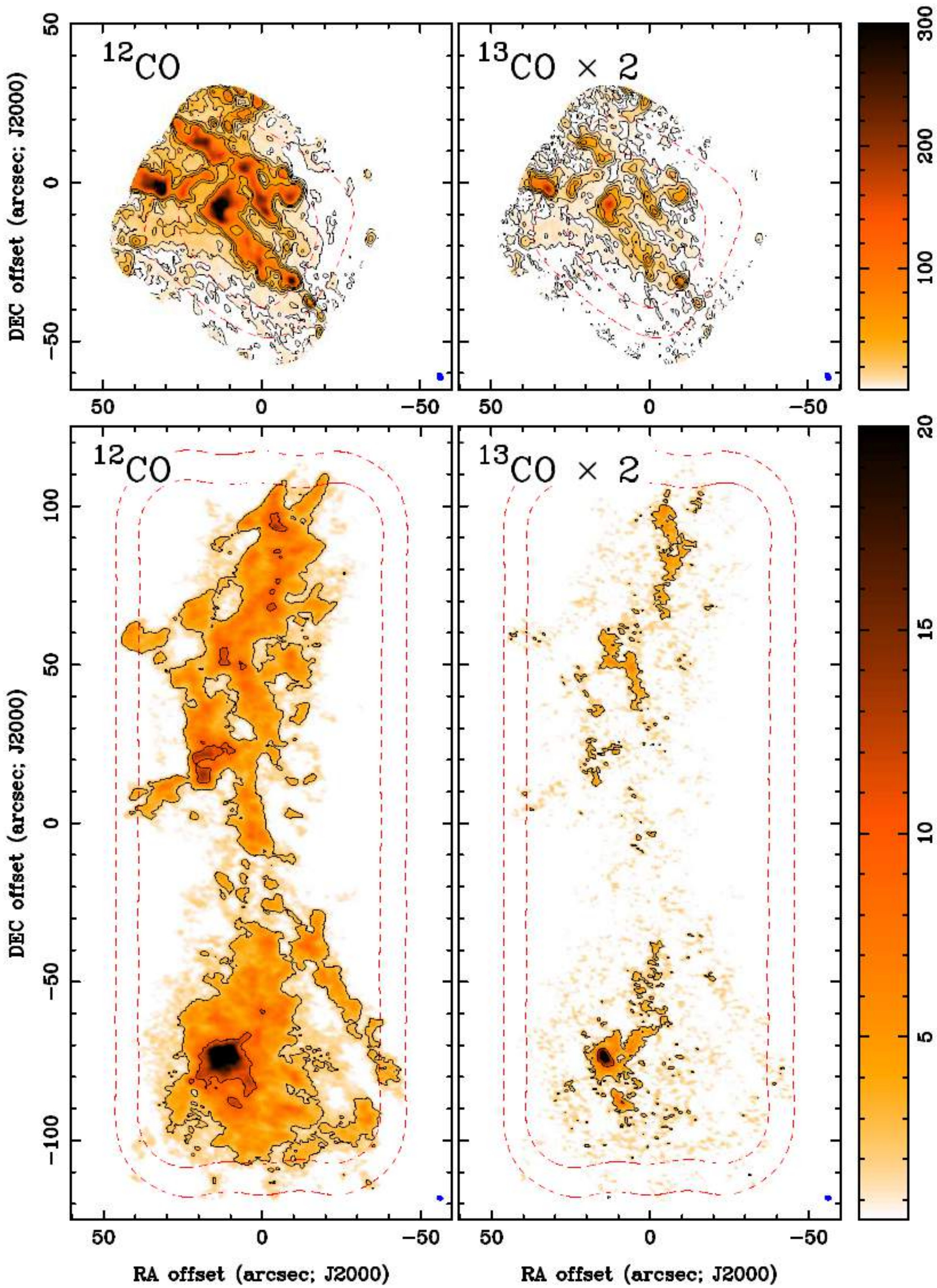
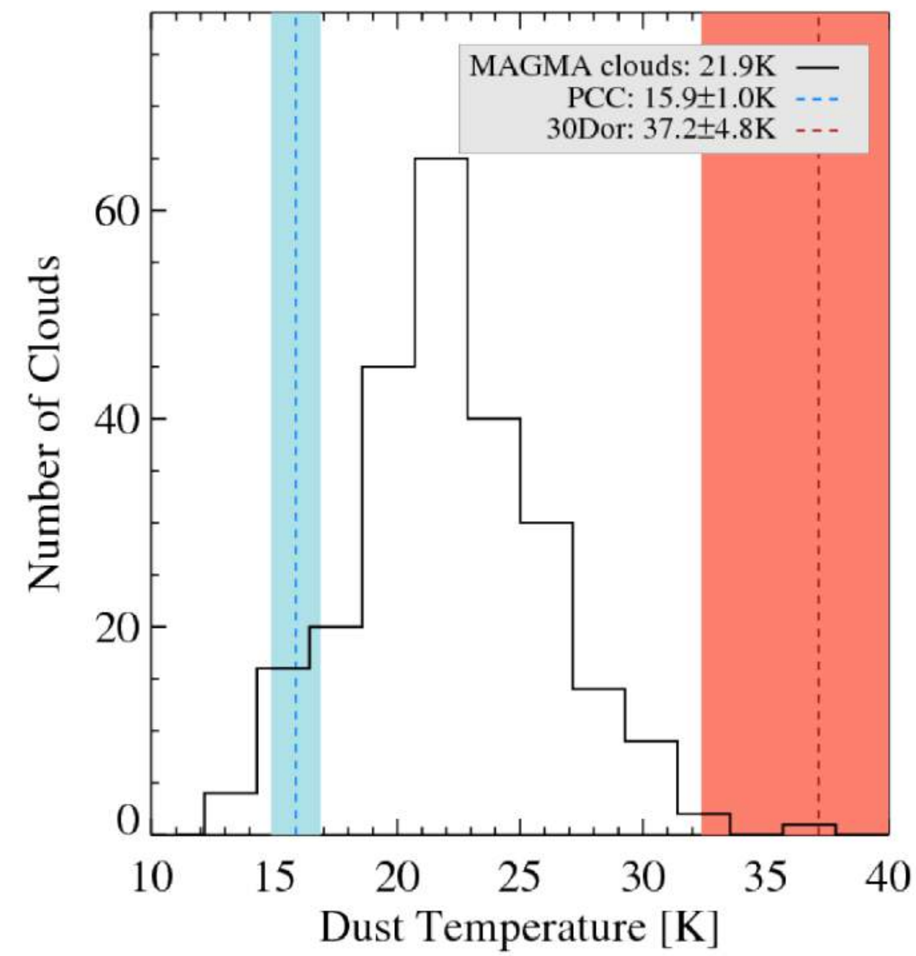
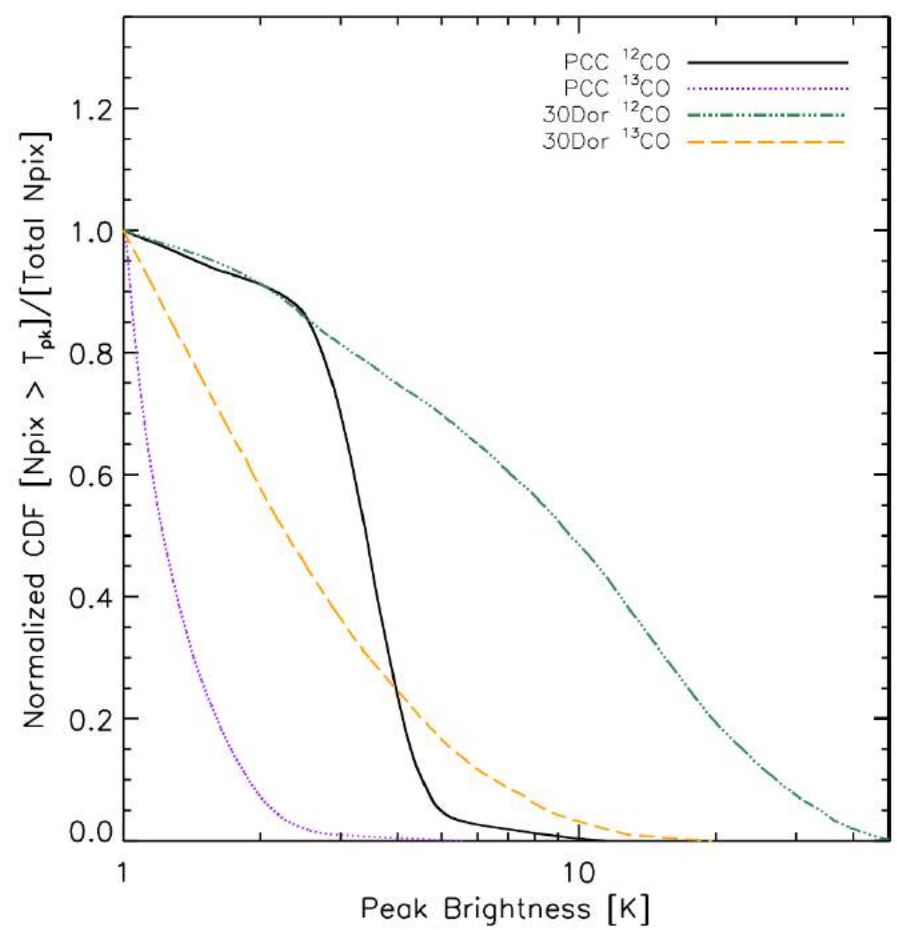
PCC vs 30Doradus







Hierarchical Decomposition: Dendrograms

Segmentation

Clumpfind
Gauss Clumps
CPROPS

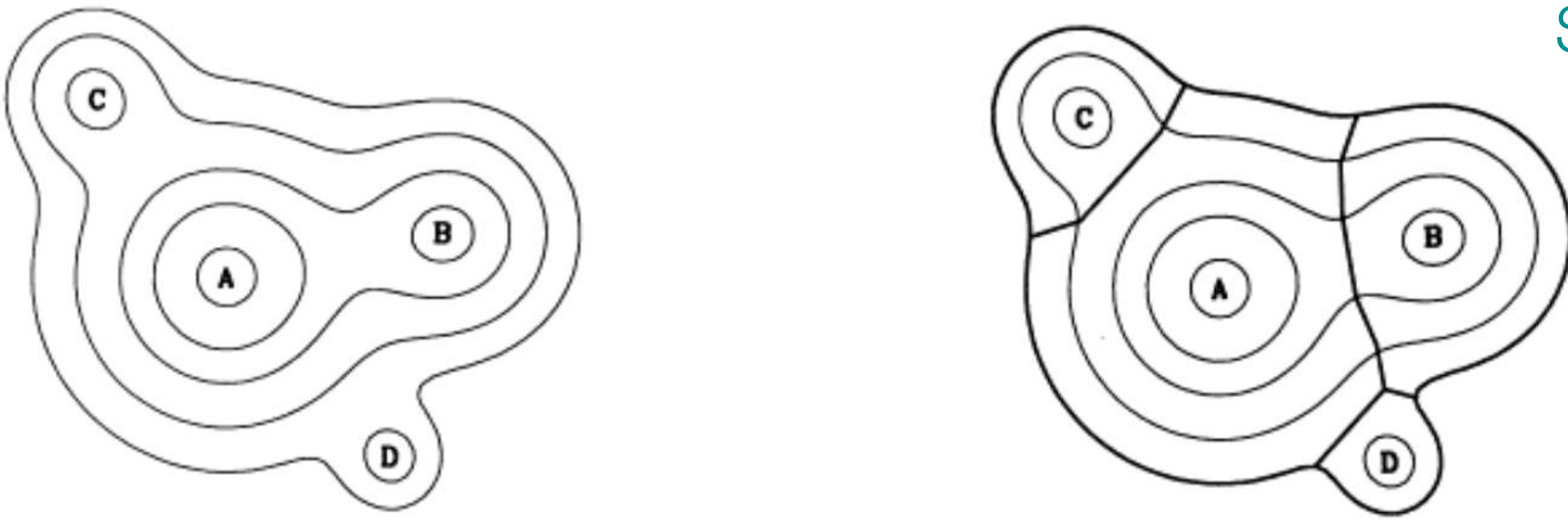
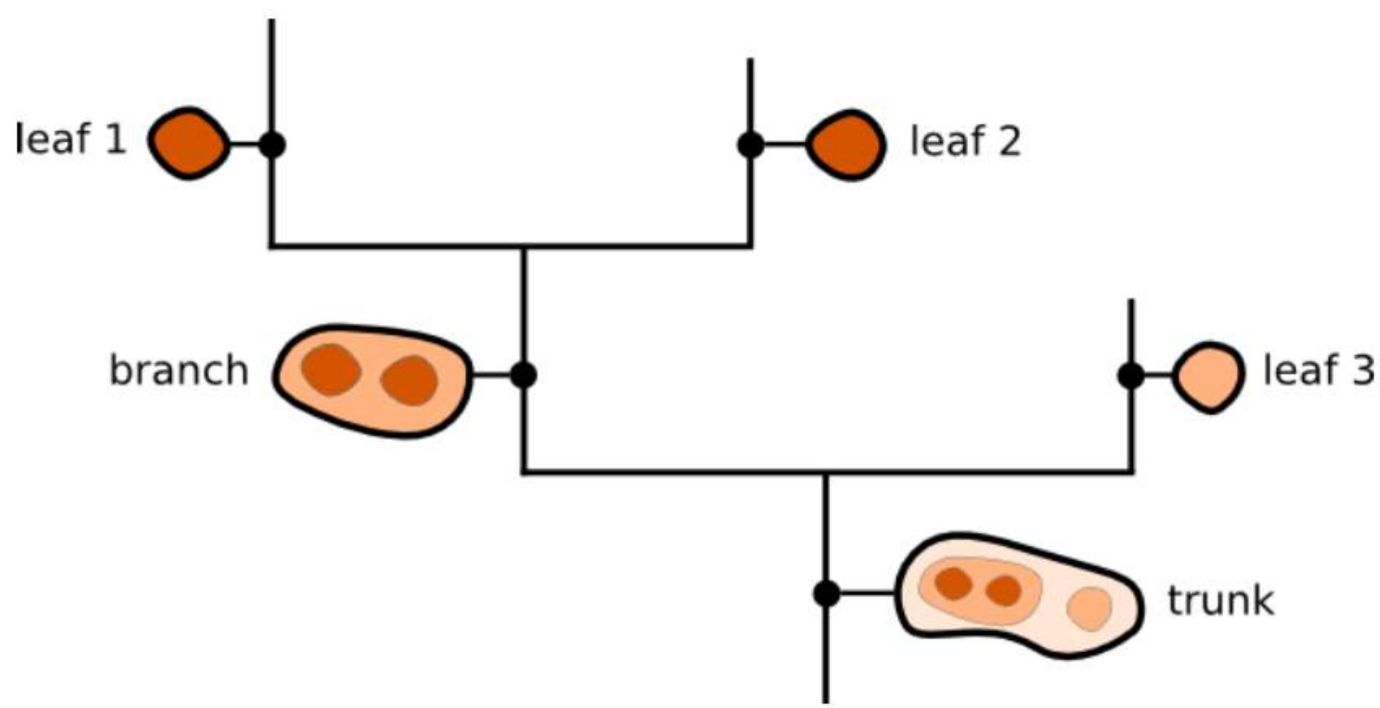


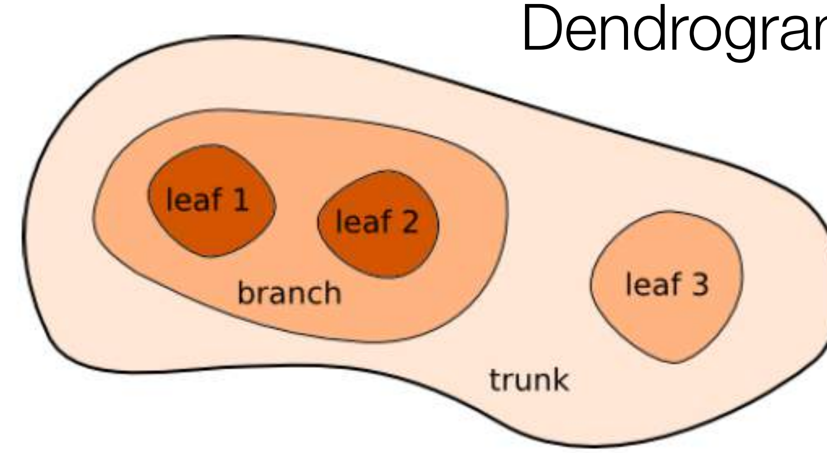
FIG. 2a   FIG. 2b

FIG. 2.—(*a*) Sample contour map to demonstrate how Clumpfind works. (*b*) The clumps found by Clumpfind.

Hierarchical

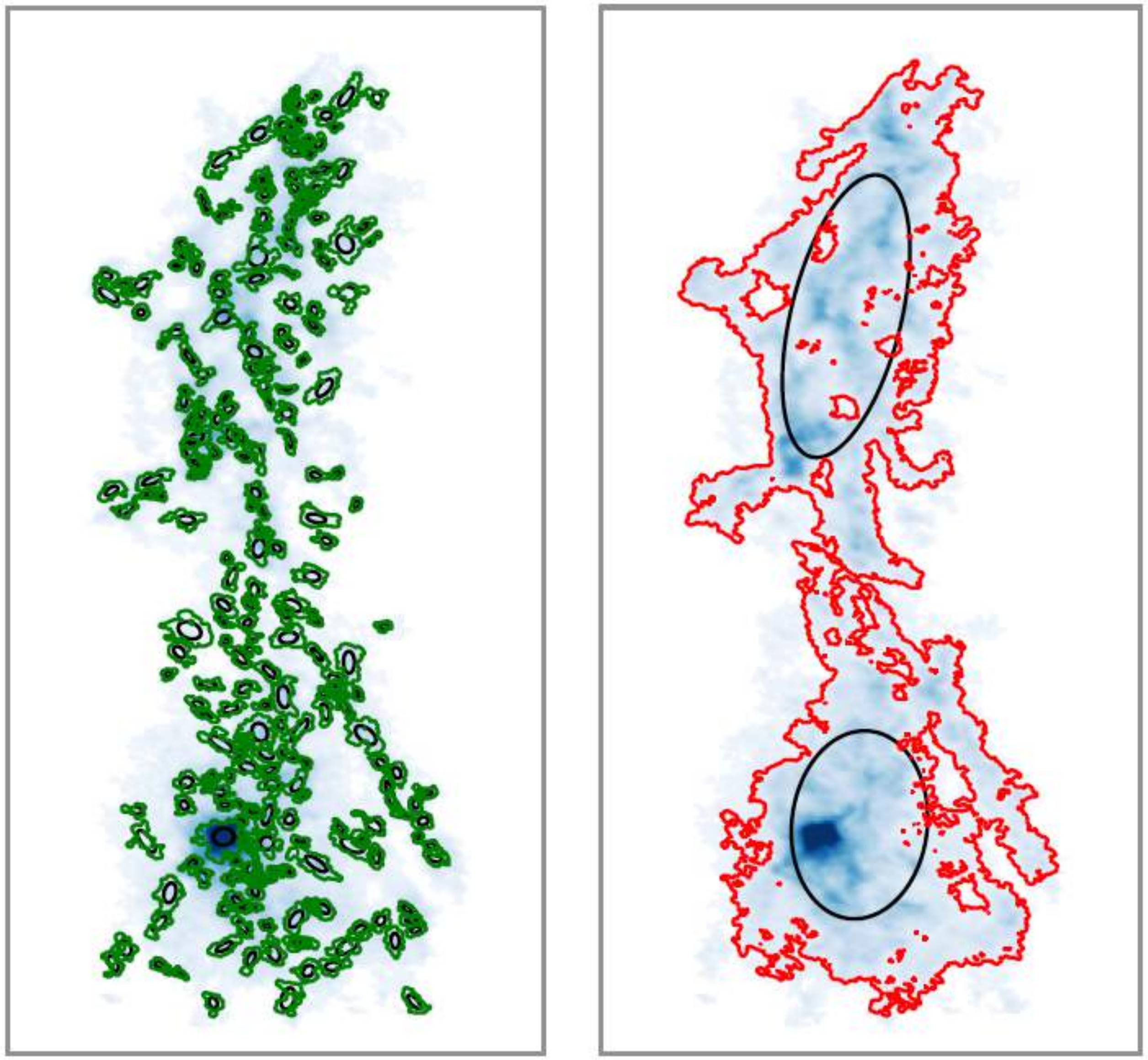
Dendrograms

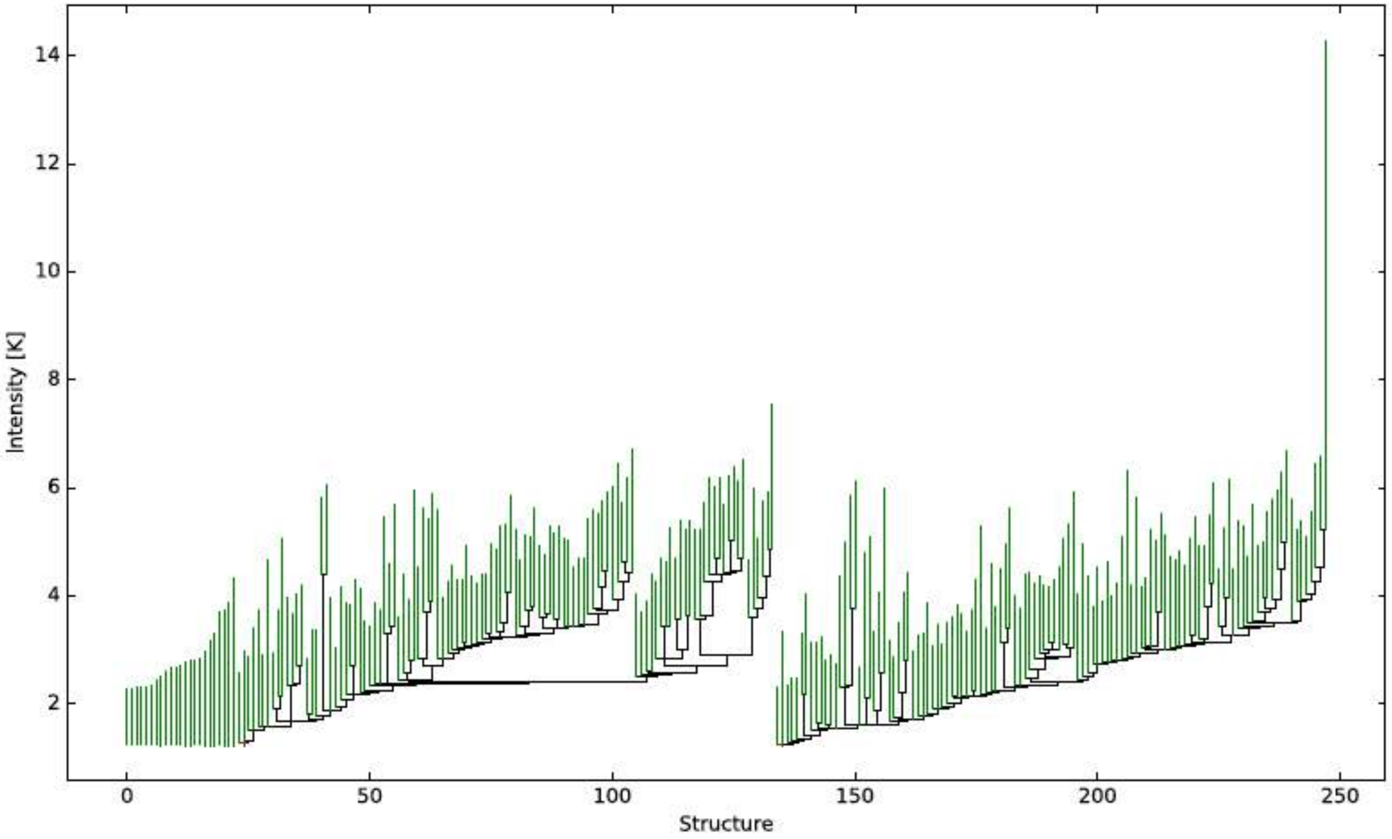




Dendrogram decomposition: PCC

ALMA Cycle 2 (PI: Wong)
1.81” x 1.24” (0.44 x 0.3 pc)



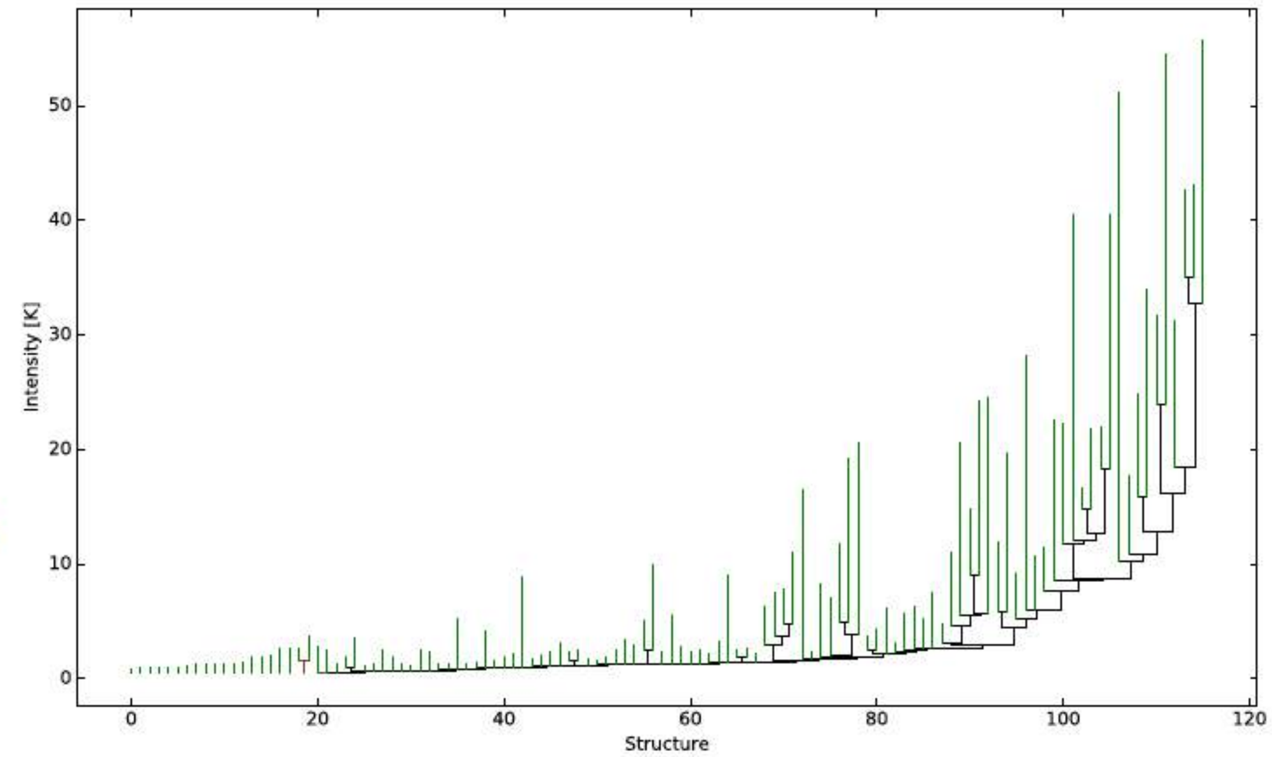


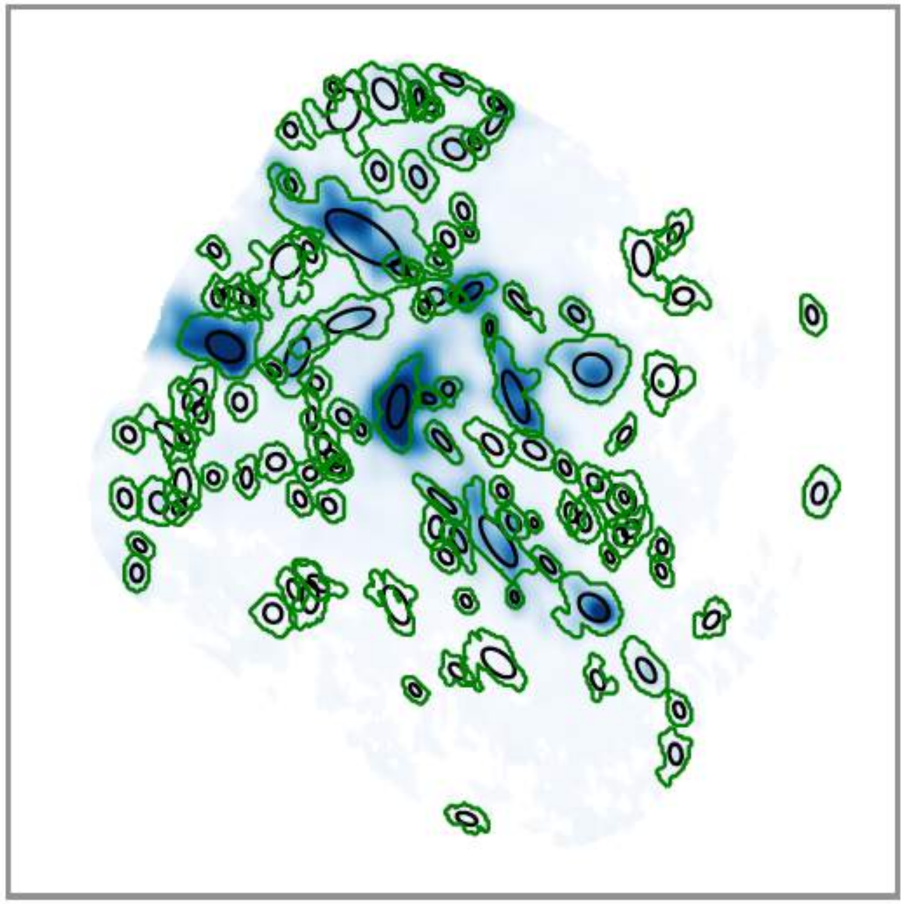
2 trunks
221 branches
248 leaves

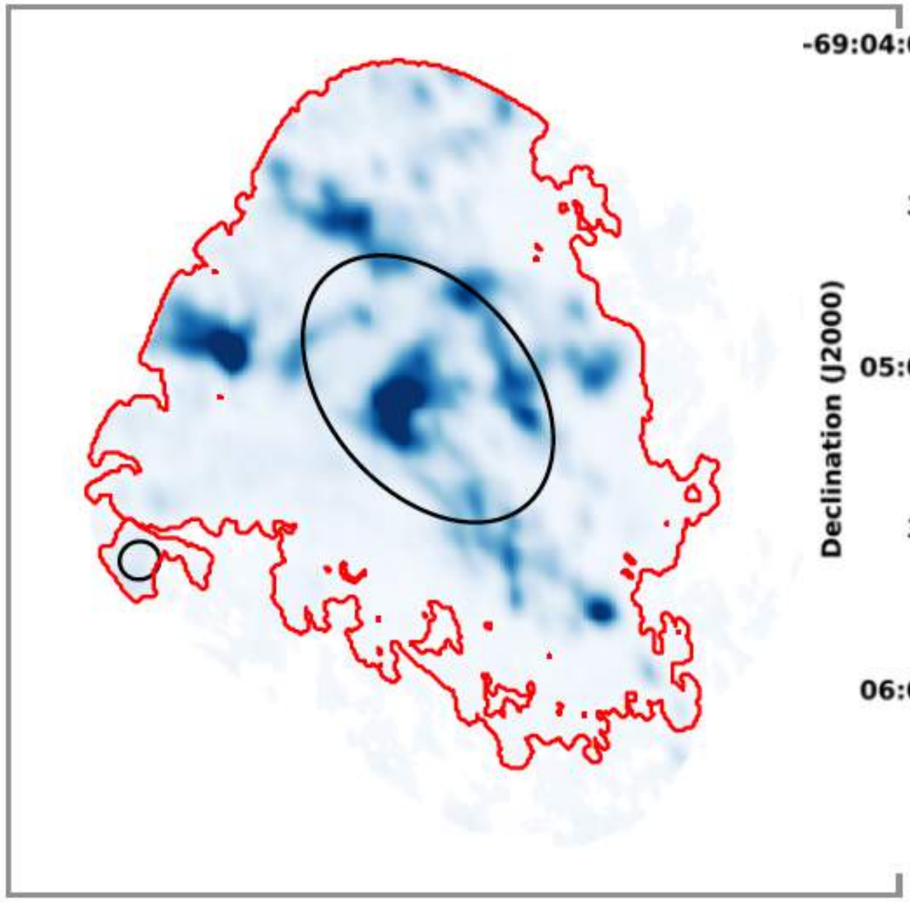
Dendrogram decomposition: 30Dor

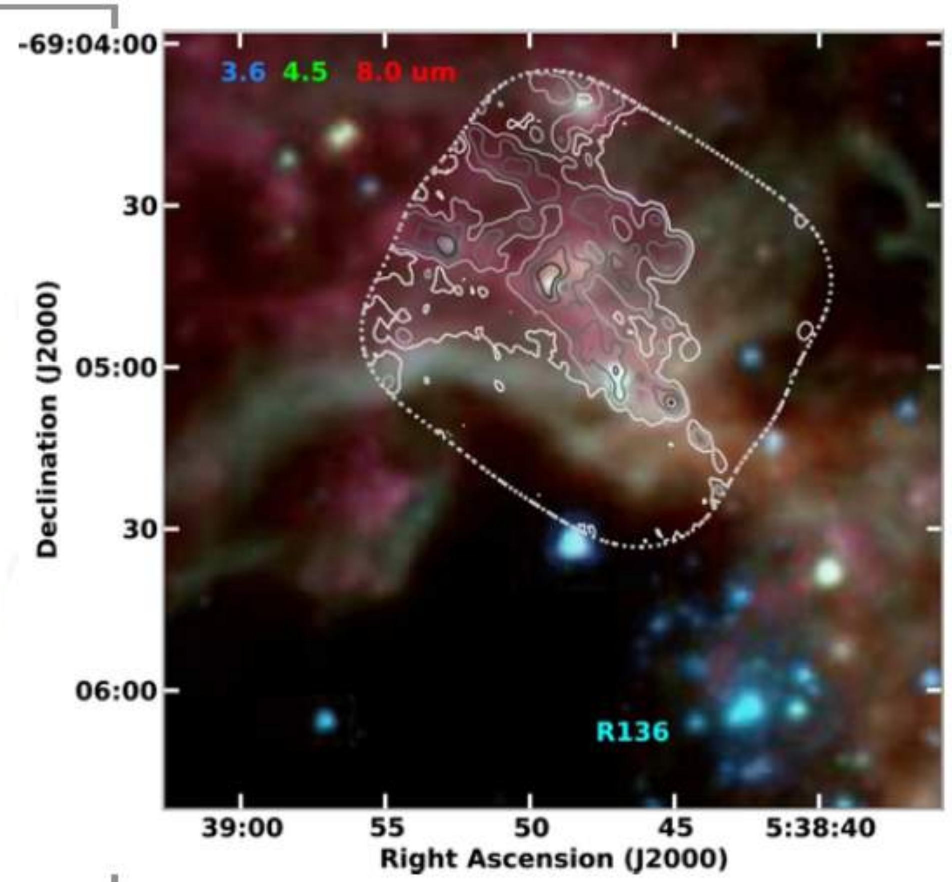
ALMA Cycle 0 (PI: Indebetouw)
2.47" x 1.59" (0.6 x 0.4 pc)

1 trunk
94 branches
116 leaves









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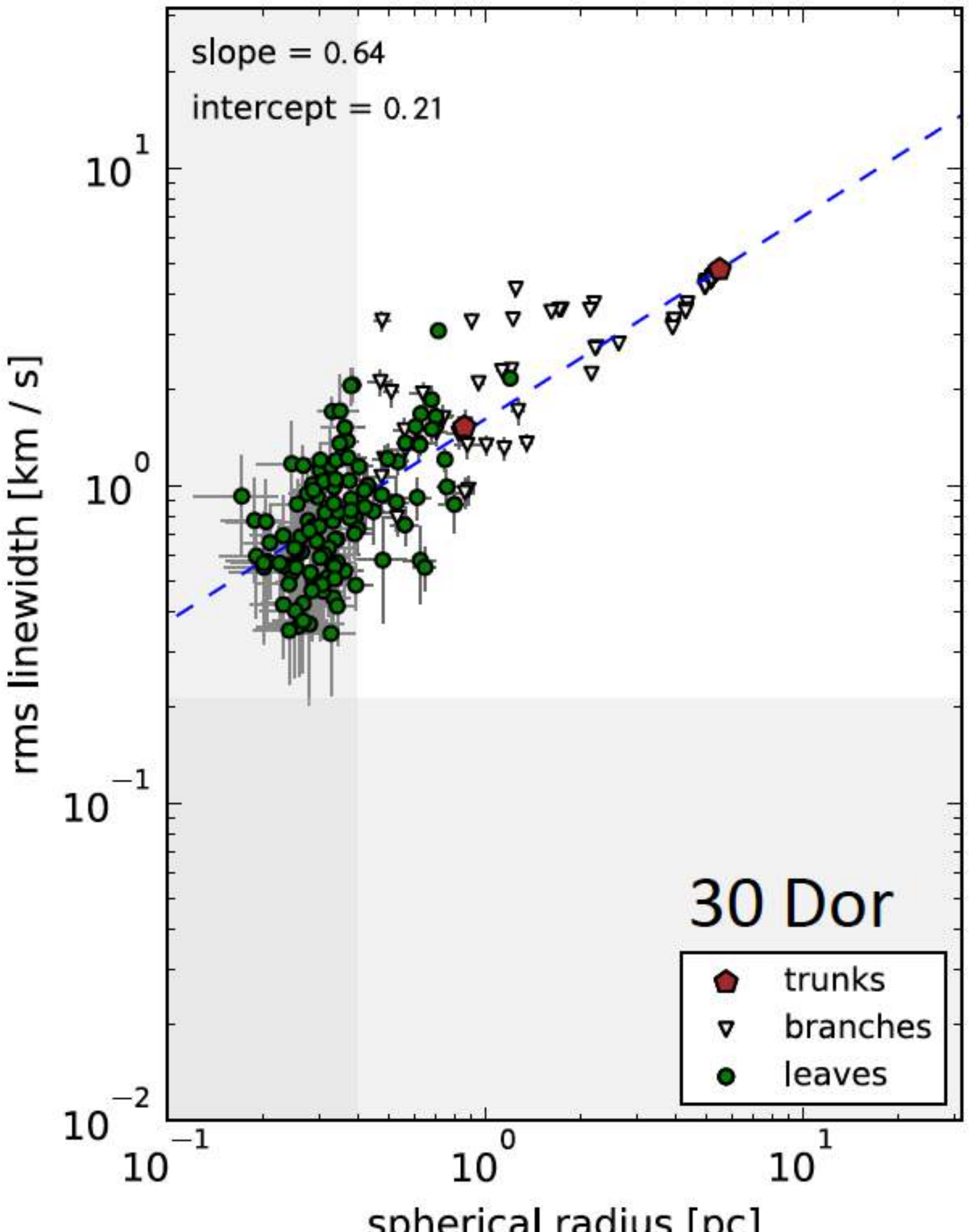
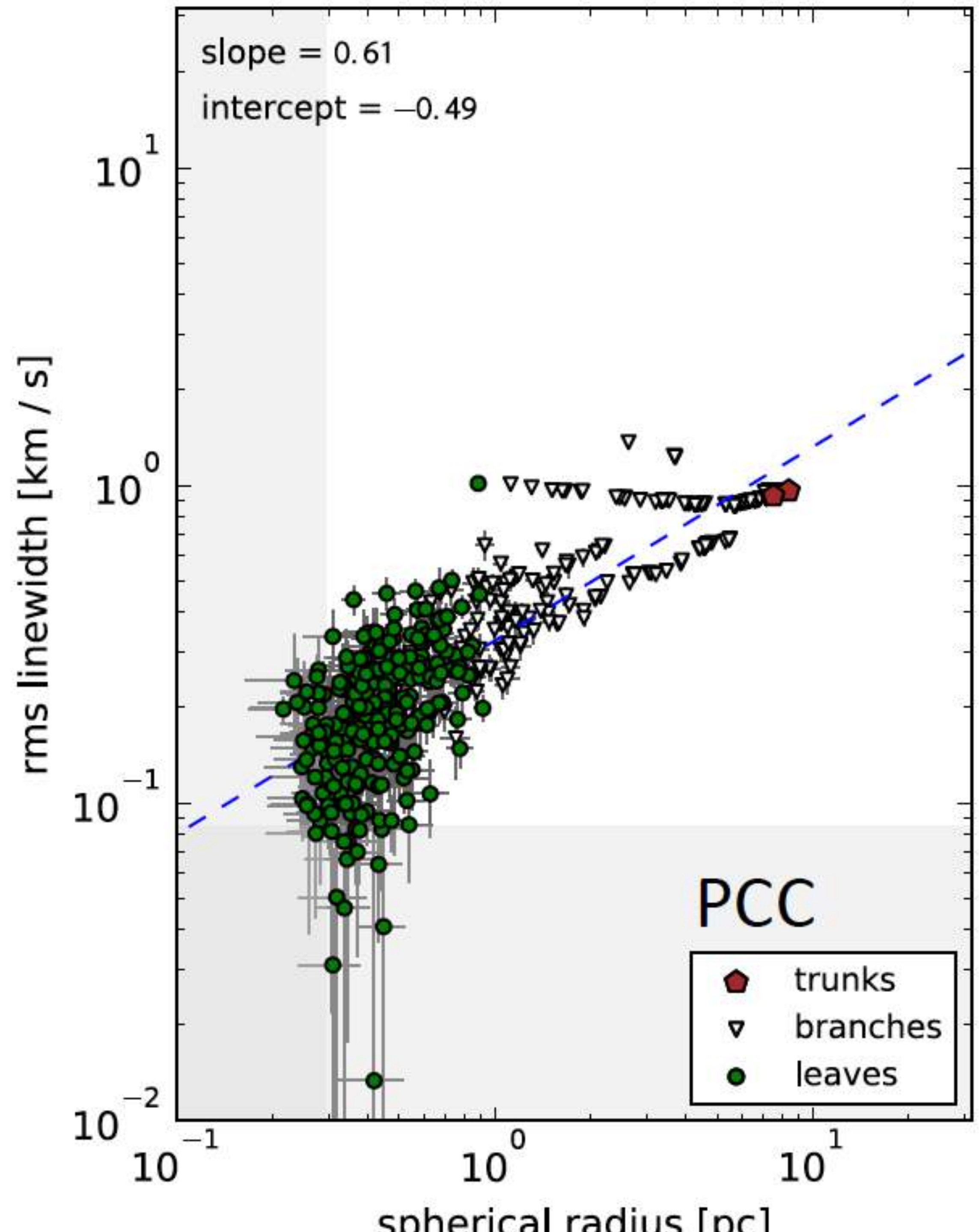
Size-Linewidth Relation: 30Dor vs PCC

Line widths larger in 30Dor by a factor of ~5

Leaves span large range of line widths

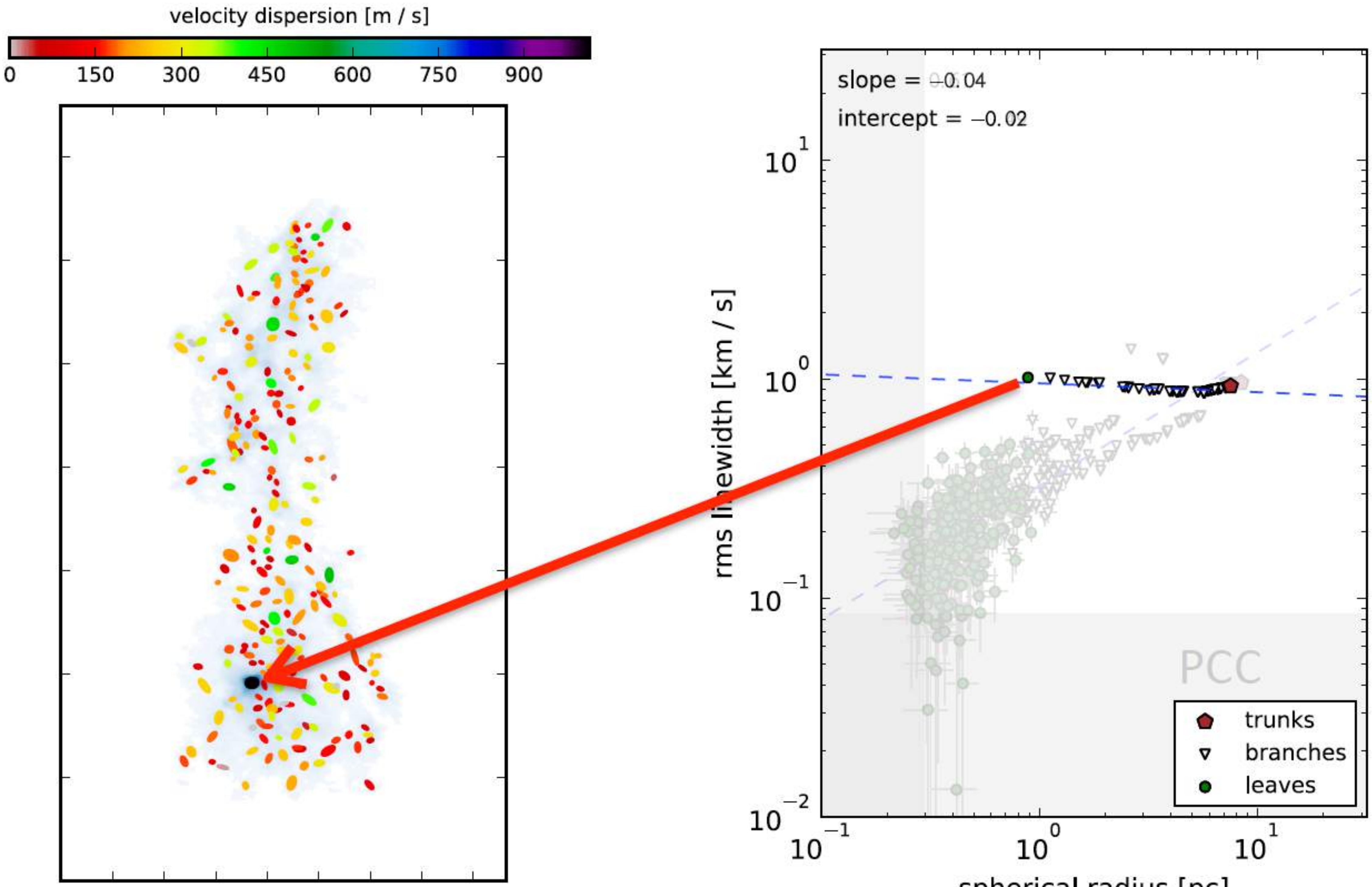




Line widths in the PCC

Highest dispersion leaf dominates line width on largest scales

Negligible contribution from external large-scale motions?

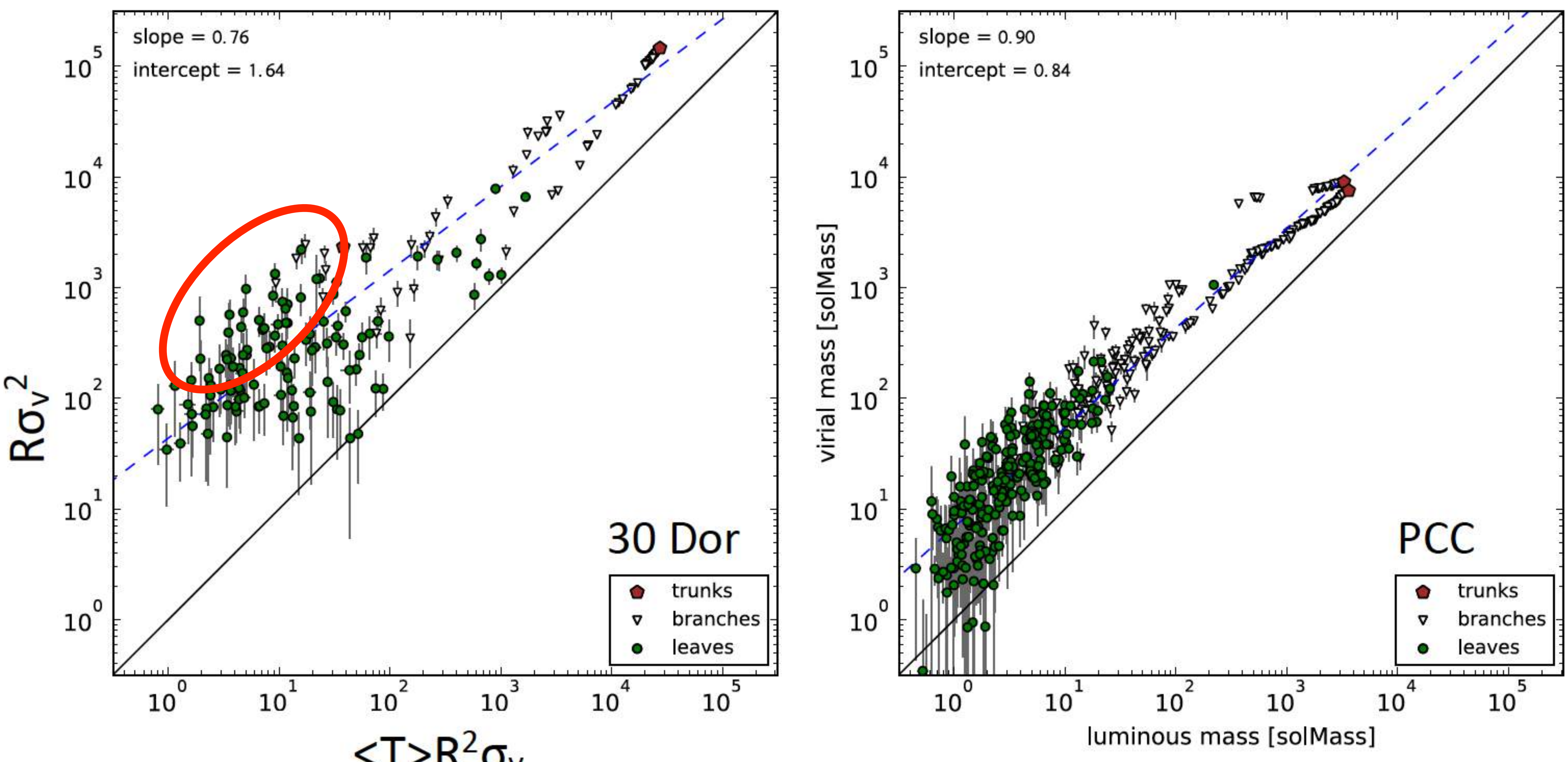


Mass-Luminosity Relation: 30Dor vs PCC

Assumes Galactic XCO, may party explain shift from equality

30 Dor leaves are further from virialisation

PCC structures in similar dynamical state, even high-dispersion core



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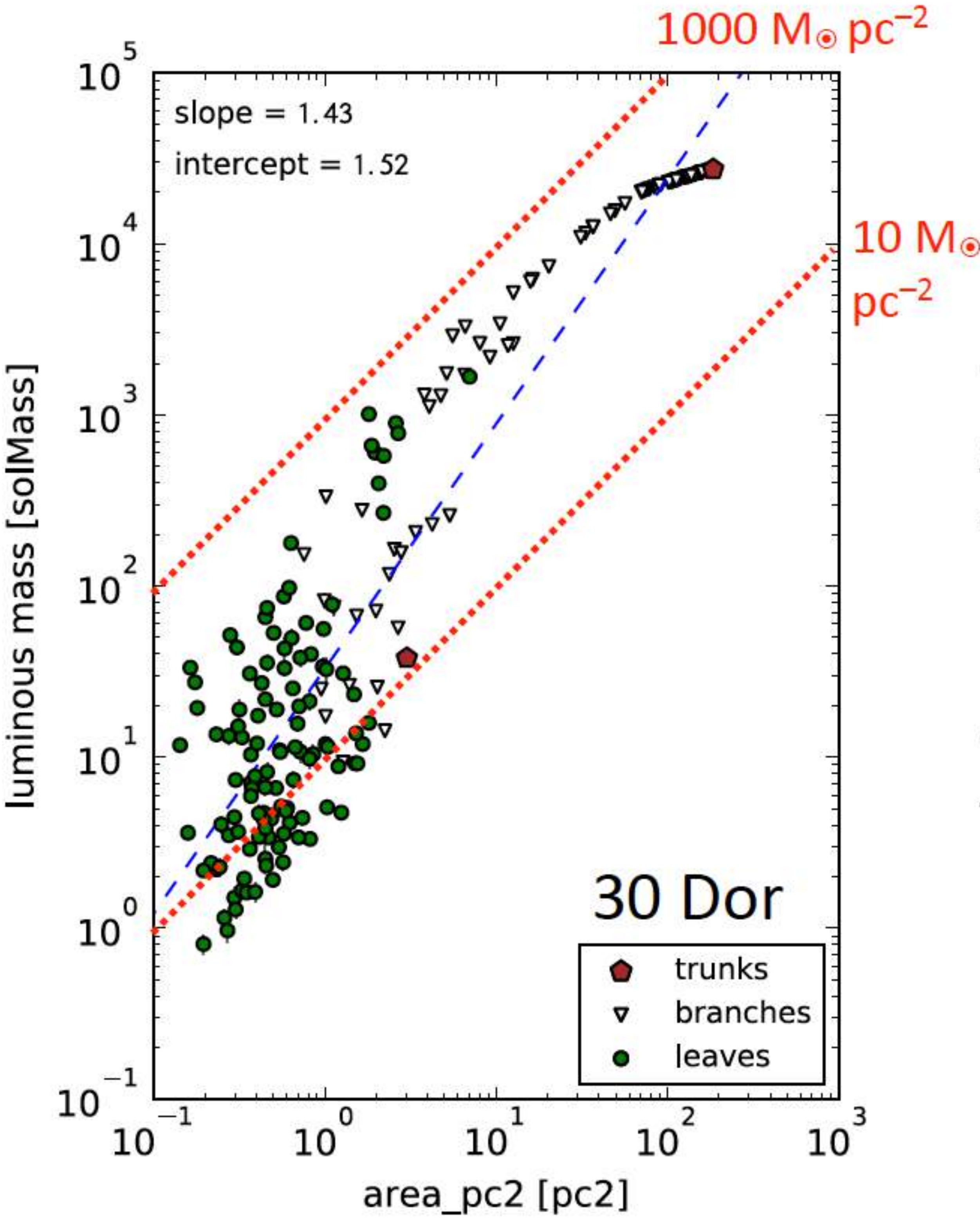
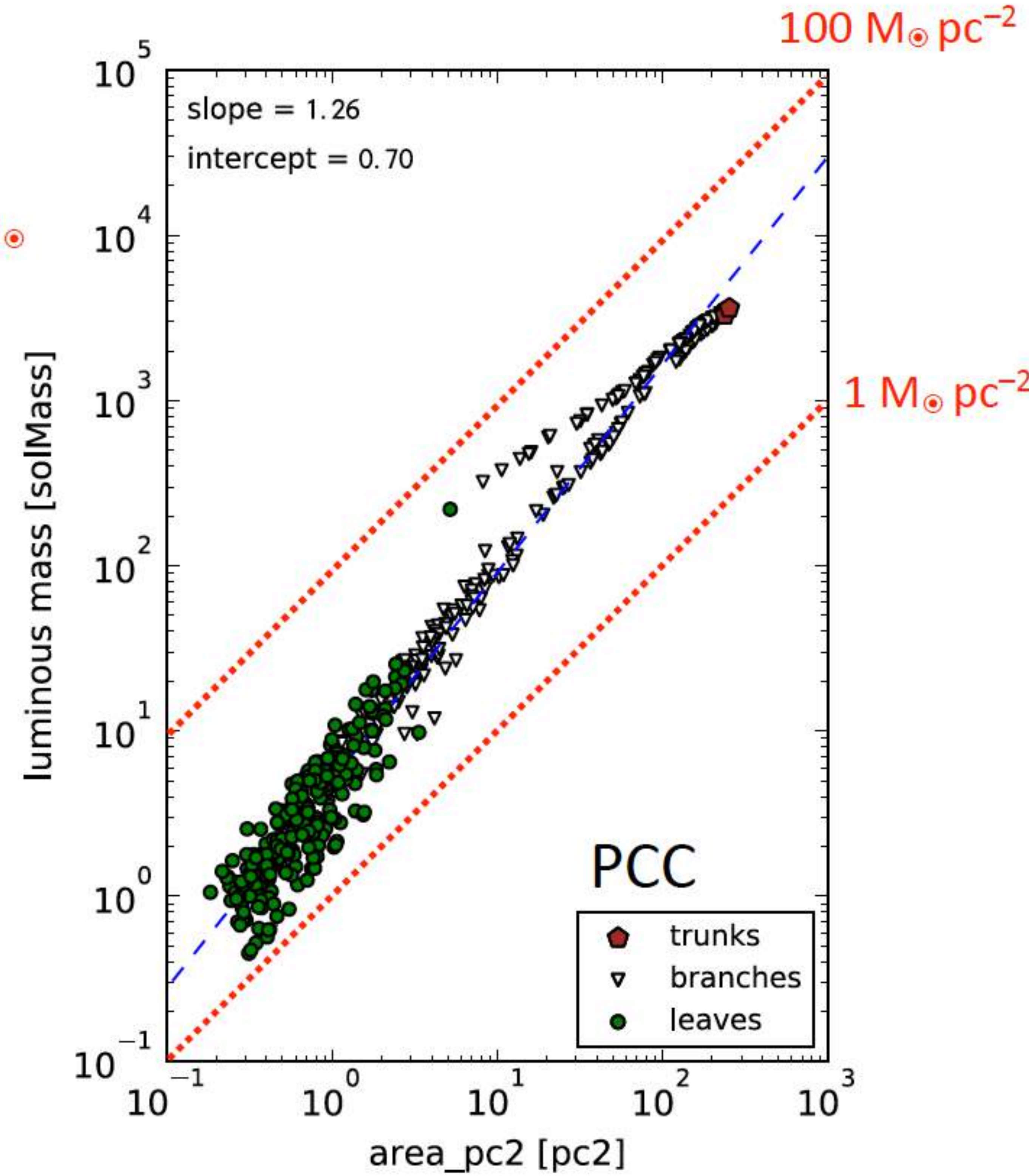
Gas Surface Density: 30Dor vs PCC

Mass surface density of leaves span 1-2 orders of magnitude

Overall higher gas surface densities in 30Dor

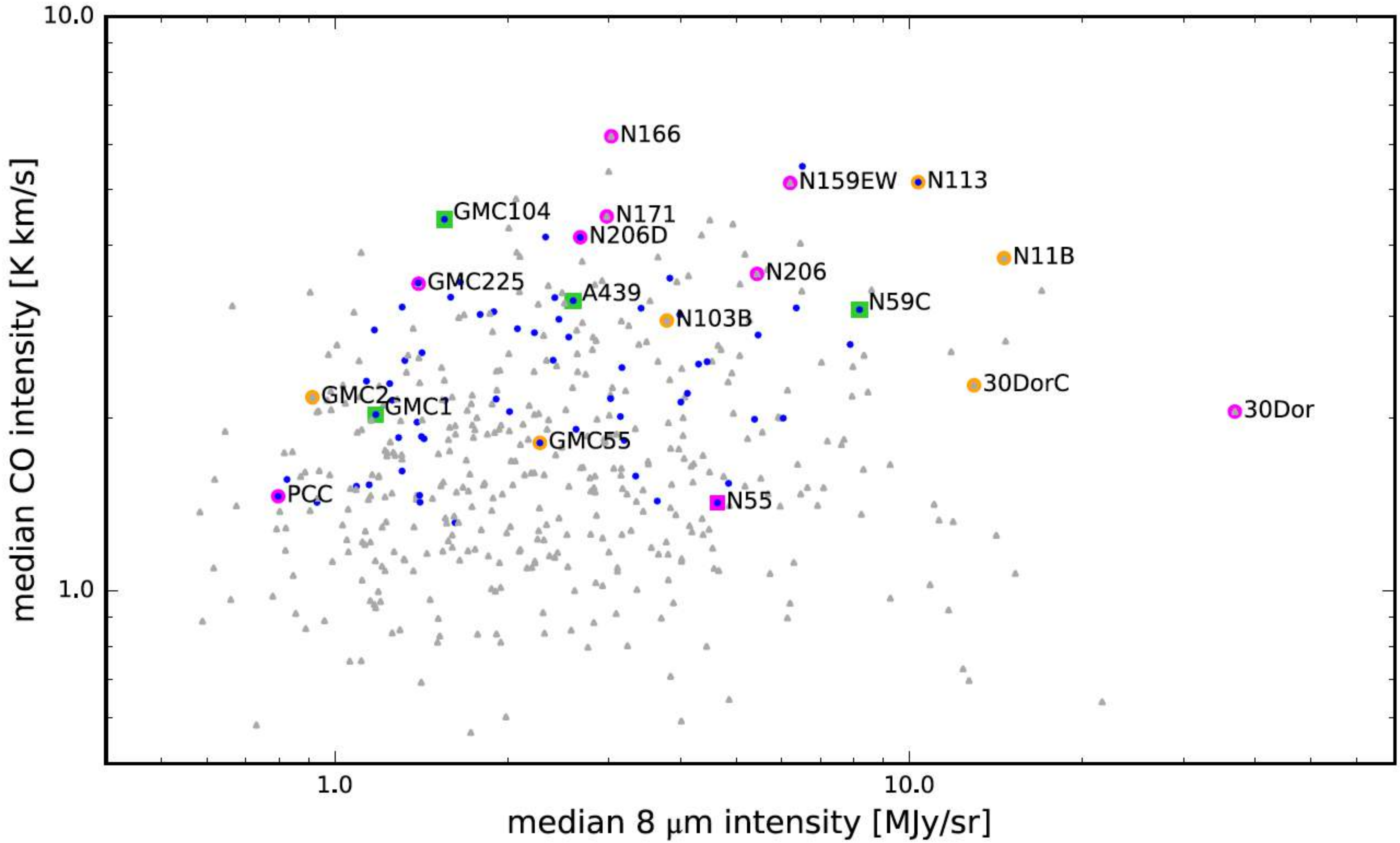




Cycle 4: Spanning a Wider Range of Cloud Properties

Cycle 4 ALMA Observations

ALMA observations of LMC clouds exist, but are heterogeneous



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Cycle 4 ALMA Observations

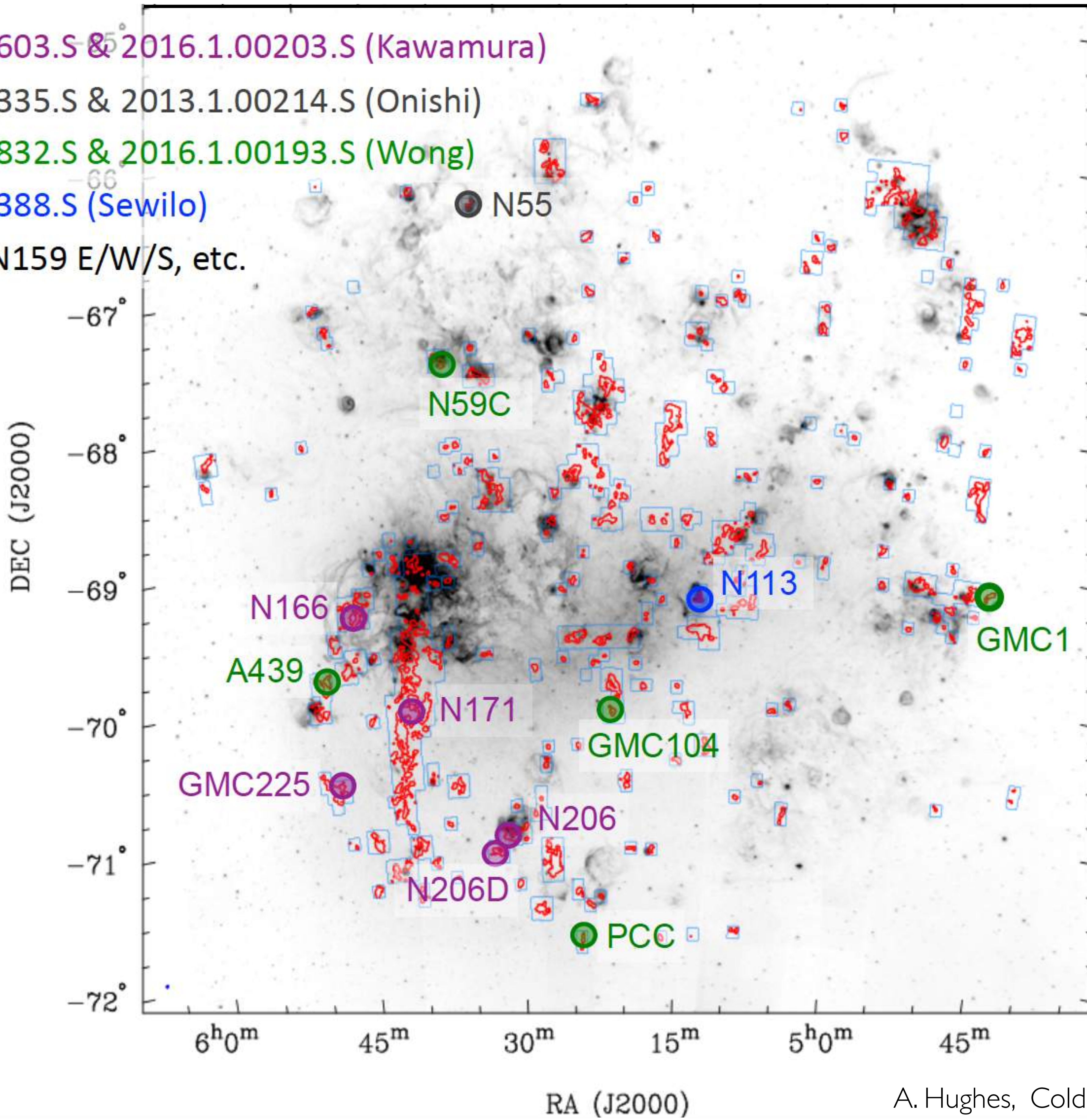
2012.1.00603.S & 2016.1.00203.S (Kawamura)

2012.1.00335.S & 2013.1.00214.S (Onishi)

2013.1.00832.S & 2016.1.00193.S (Wong)

2015.1.01388.S (Sewilo)

+ 30 Dor, N159 E/W/S, etc.



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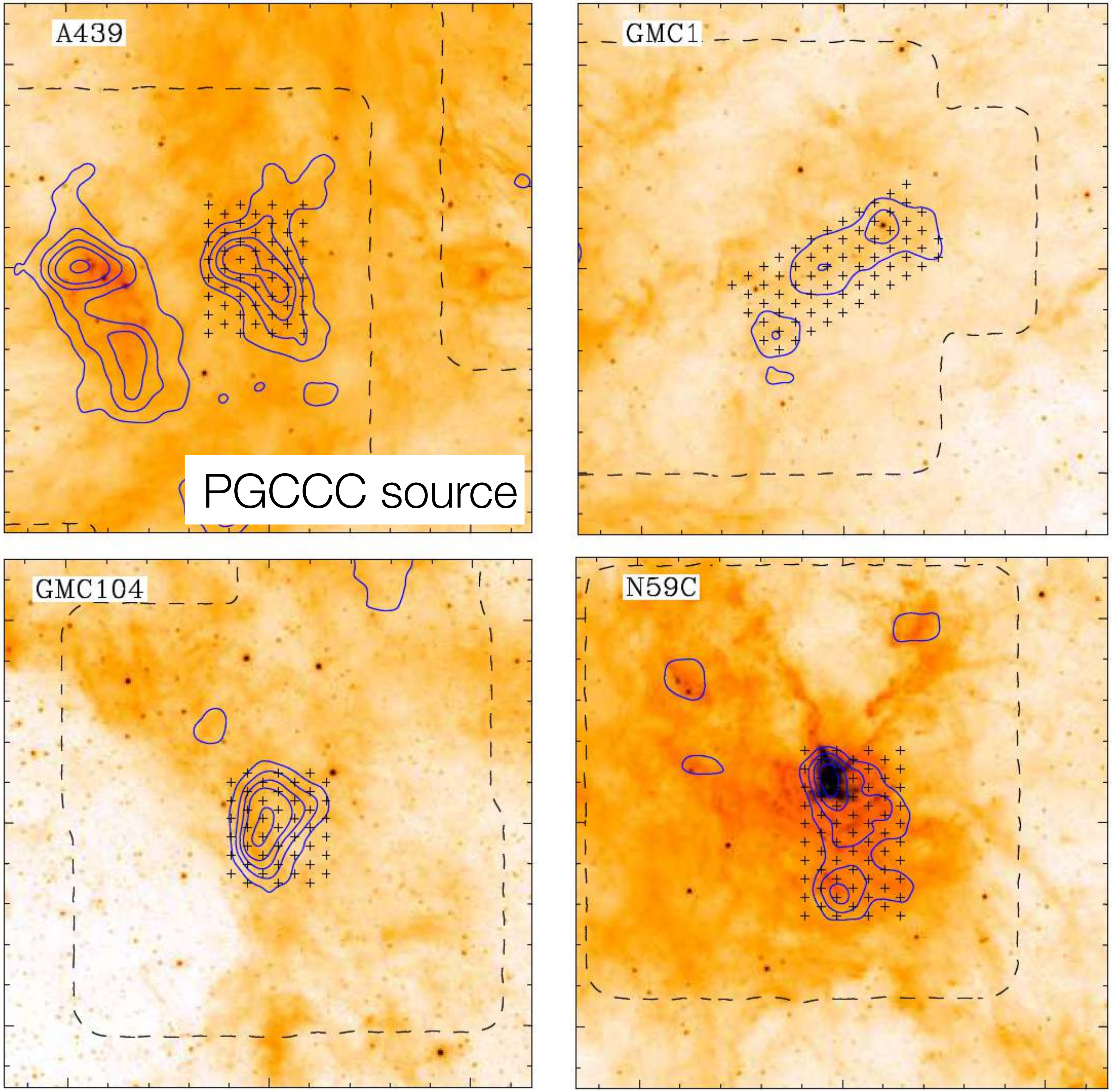
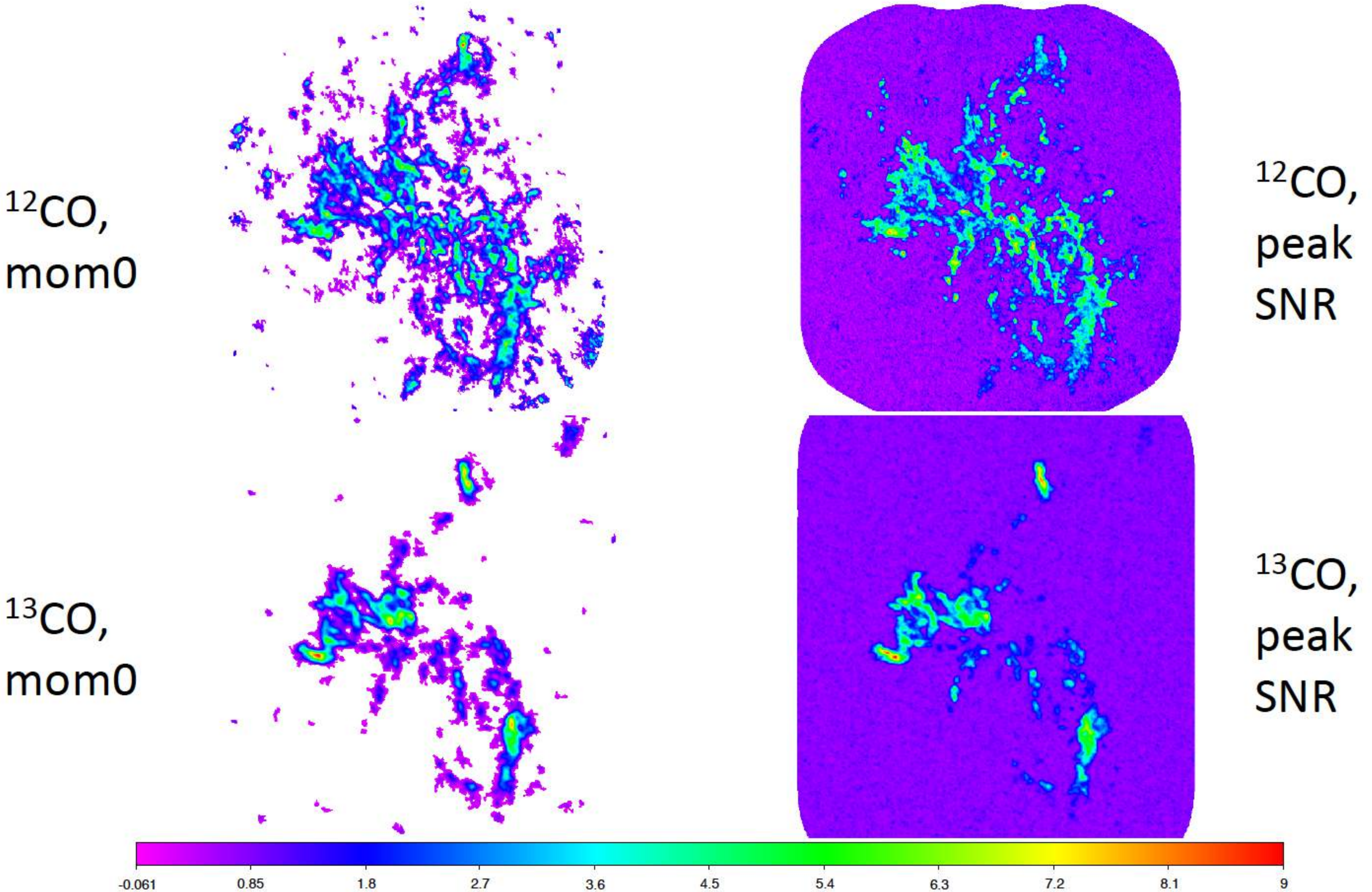
Cycle 4 ALMA Observations

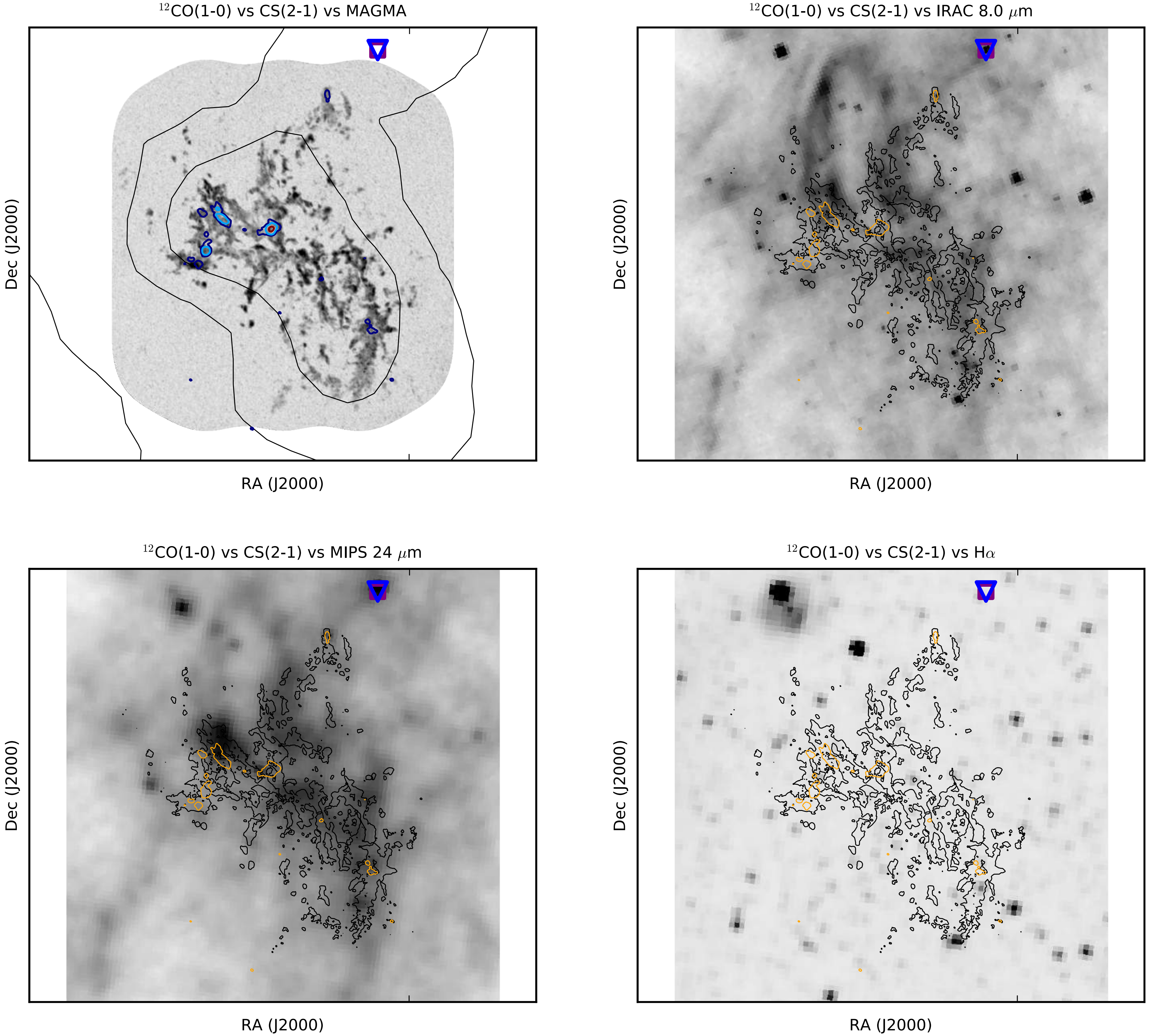


Ideally want to map entire GMC

A439: ALMA 12m-only data



A439: ALMA 12m-only data + SF tracers



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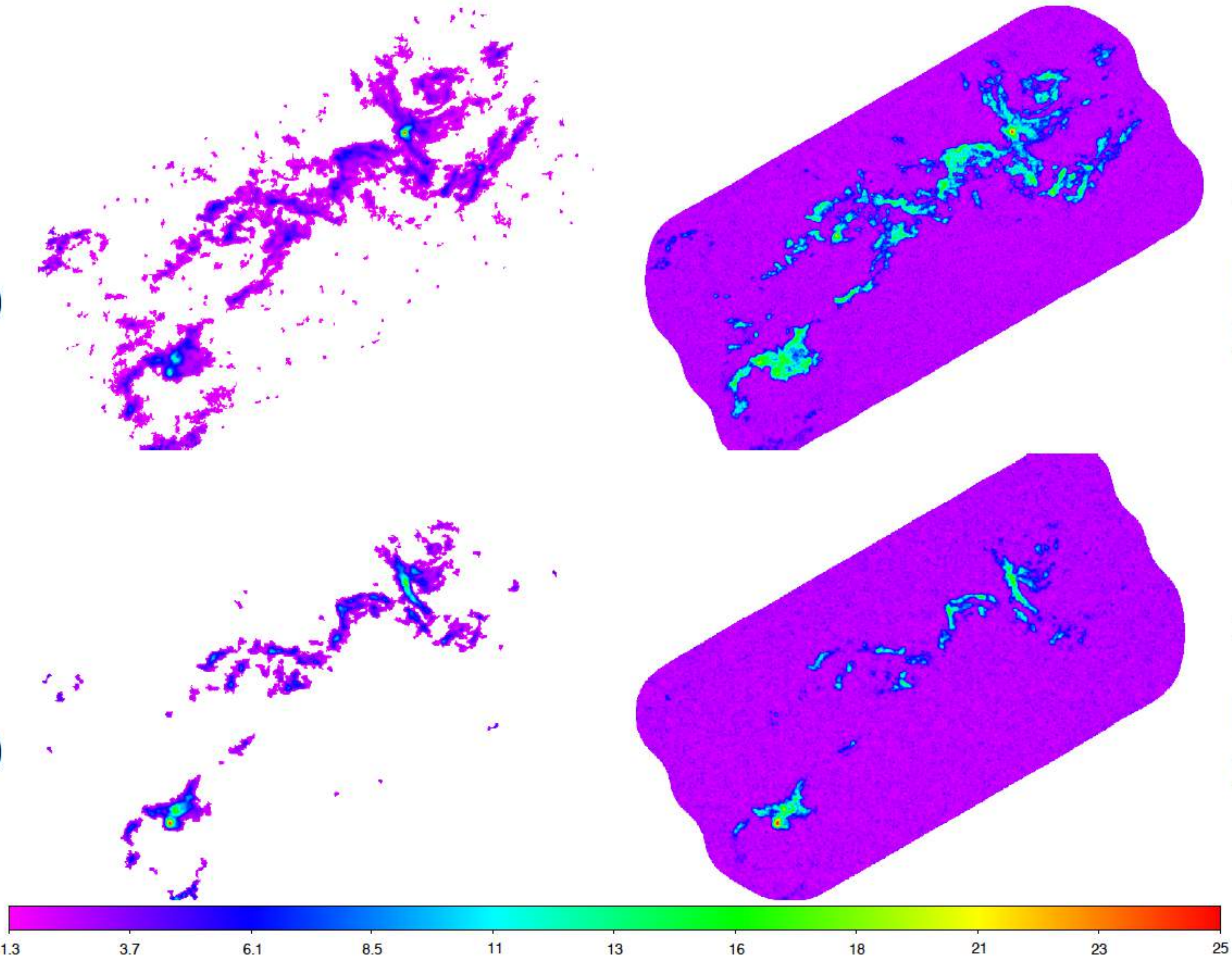
GMC1: ALMA 12m-only data

^{12}CO, mom0

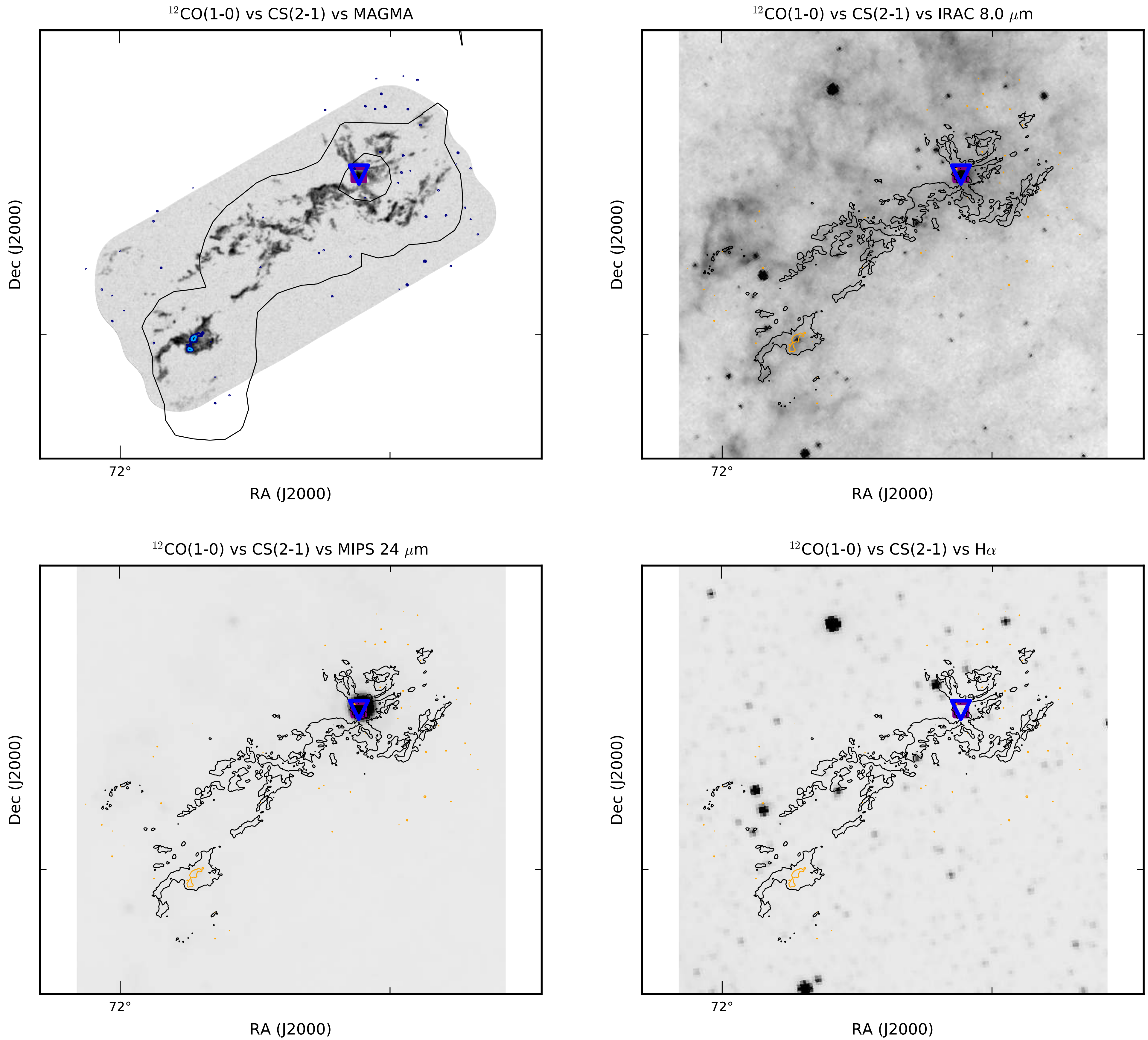
^{12}CO, peak SNR

^{13}CO, mom0

^{13}CO, peak SNR



GMC1: ALMA 12m-only data + SF tracers



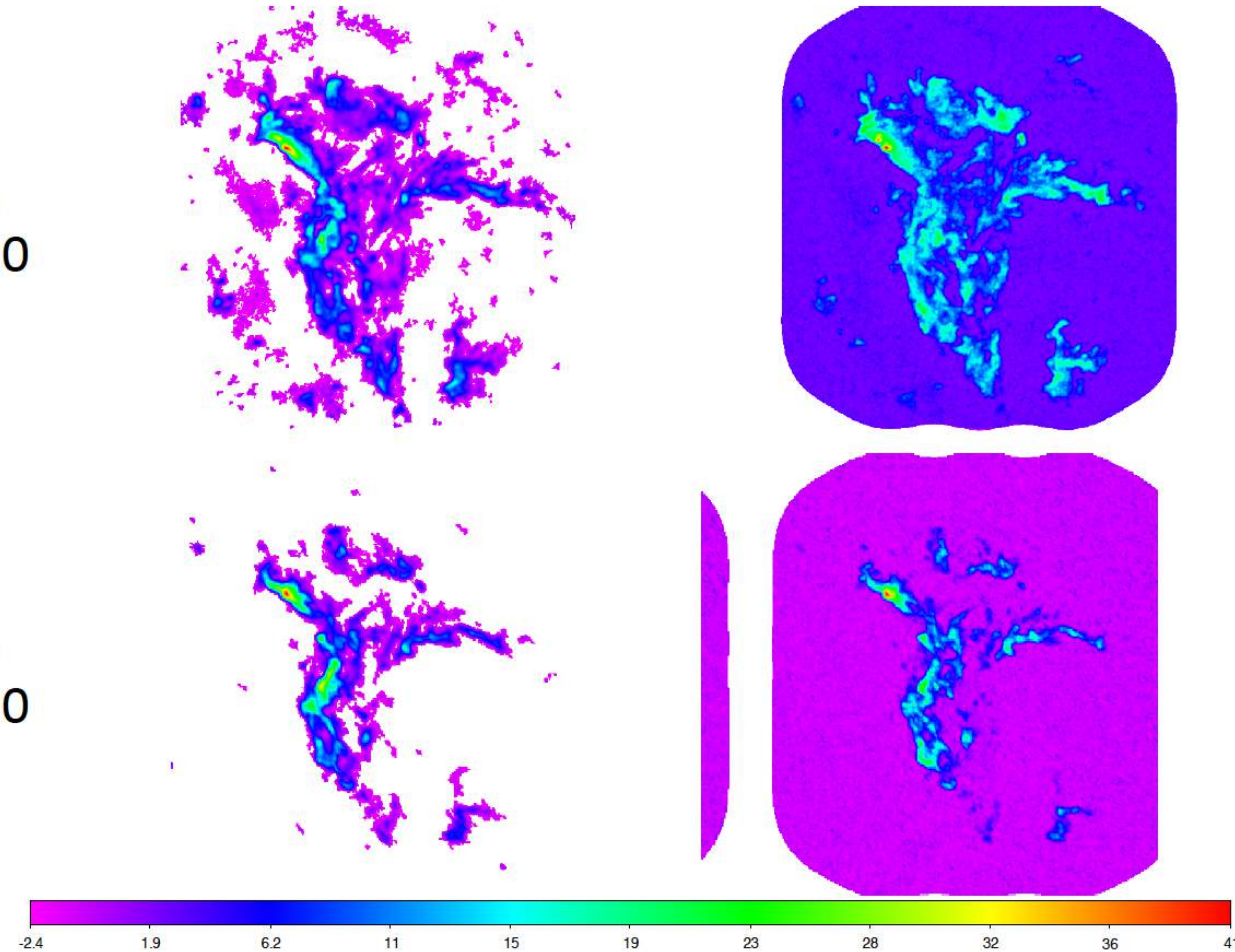
GMC104: ALMA 12m-only data

^{12}CO, mom0

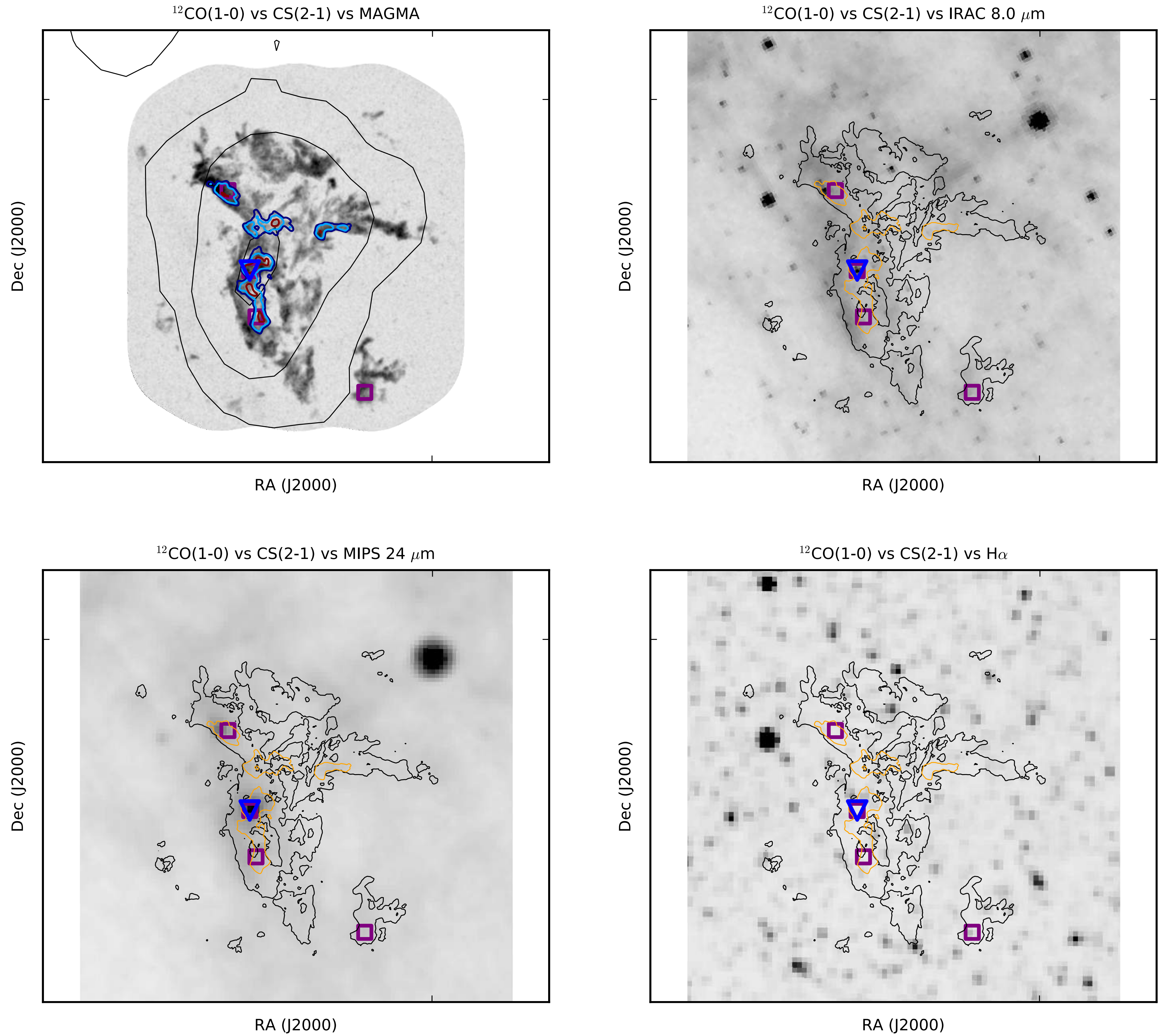
^{12}CO, peak SNR

^{13}CO, mom0

^{13}CO, peak SNR



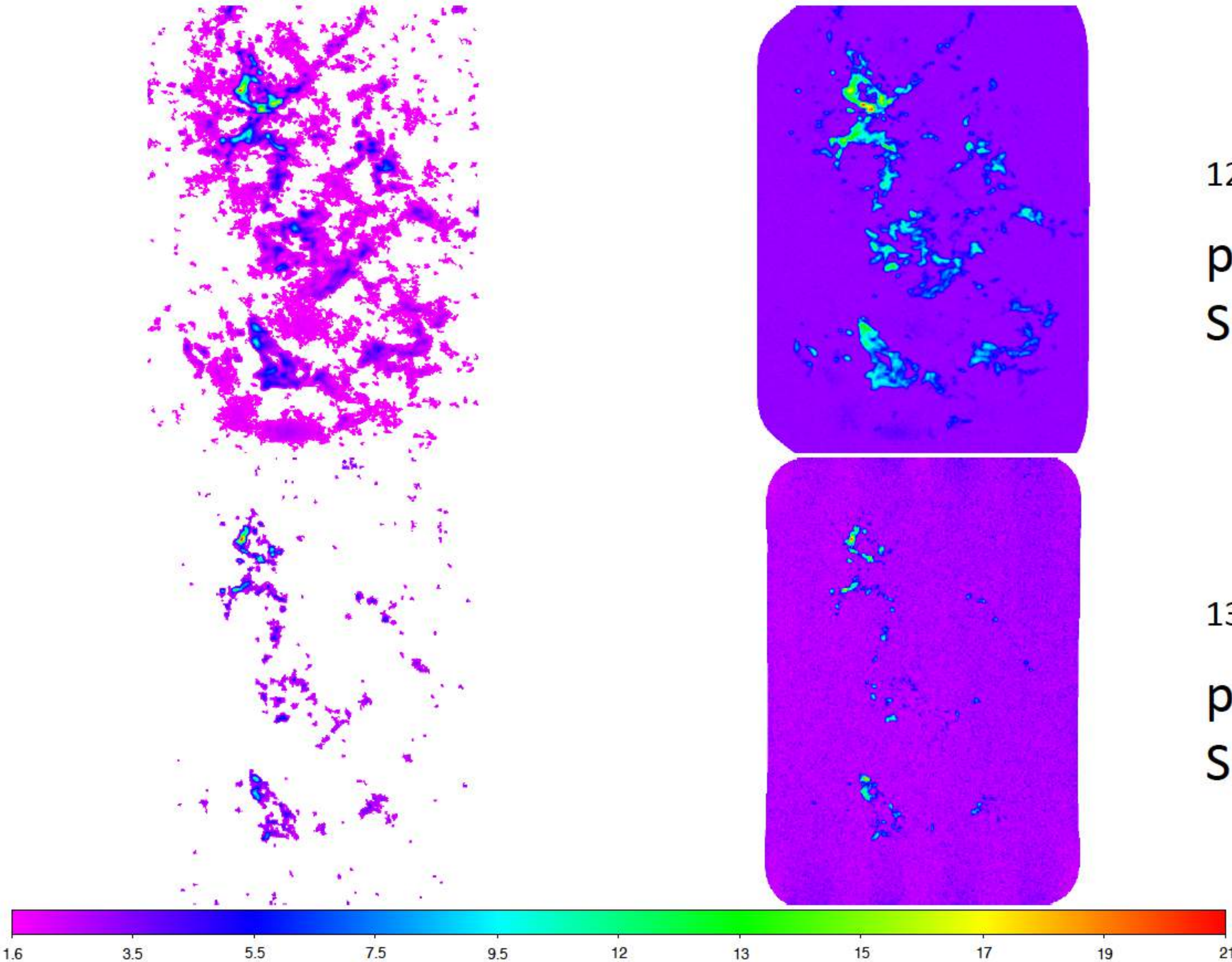
GMC104: ALMA 12m-only data + SF tracers



N59C: ALMA 12m-only data

^{12}CO, mom0

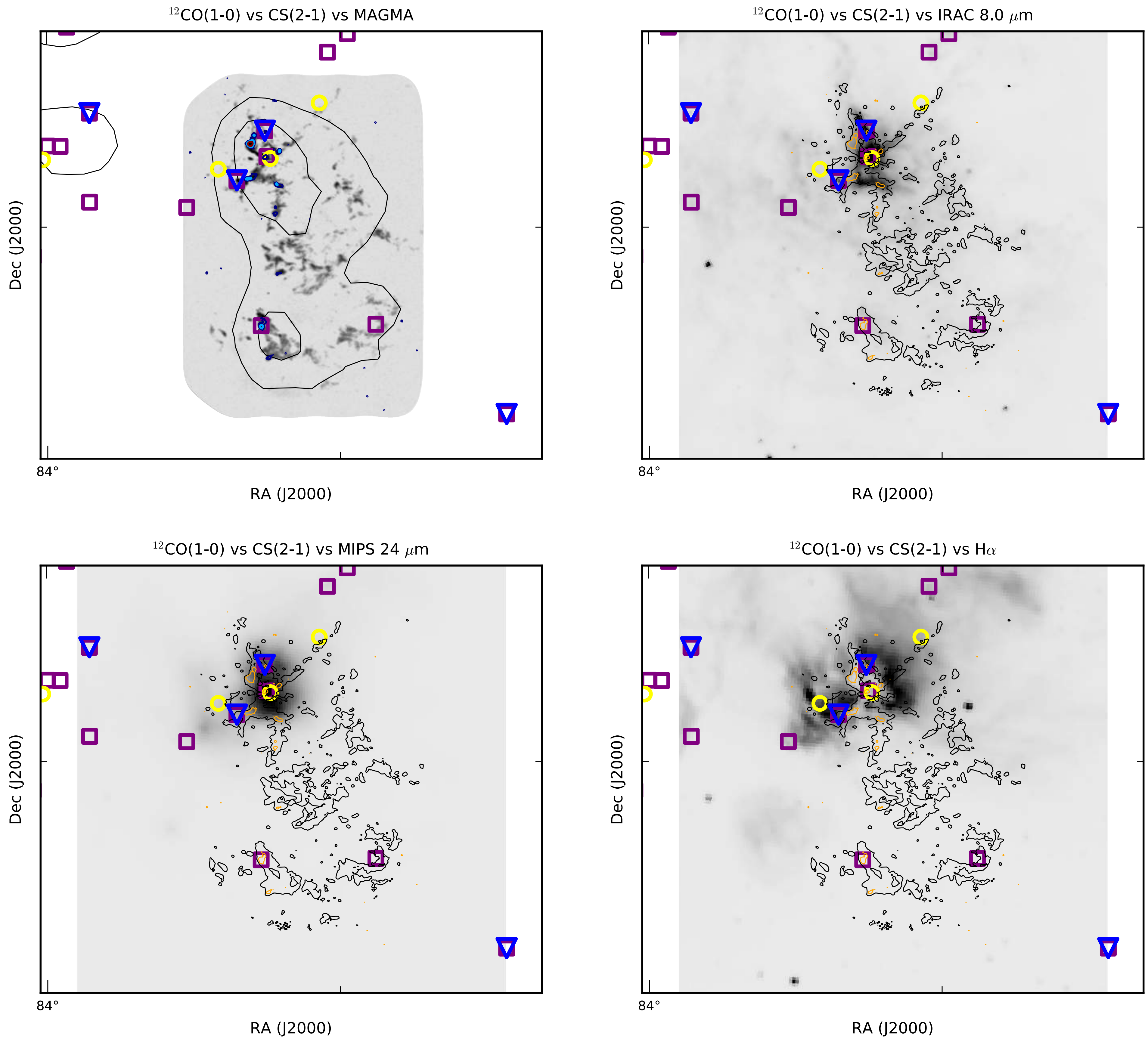
^{12}CO, peak SNR



^{13}CO, mom0

^{13}CO, peak SNR

N59C: ALMA 12m-only data + SF tracers



Conclusions & To Do List

PCCs in the LMC:

- cold molecular clouds that are preferentially distributed in outer HI disk
- dynamical properties overall consistent with general GMC population
- star formation activity is below LMC average, but not completely absent

Resolving the Structure and Kinematics of LMC GMCs with ALMA

- gas motions near IR source dominate global line width of PCC
- gas around 30 Dor has higher line widths and mass surface densities

Star Formation and Molecular Gas Properties in the LMC:

- Evolution or environment dominates?

To Do List:

- paper draft exists, but work to do (Herschel YSOs, SED analysis)
- feedback and ideas for new analysis welcome

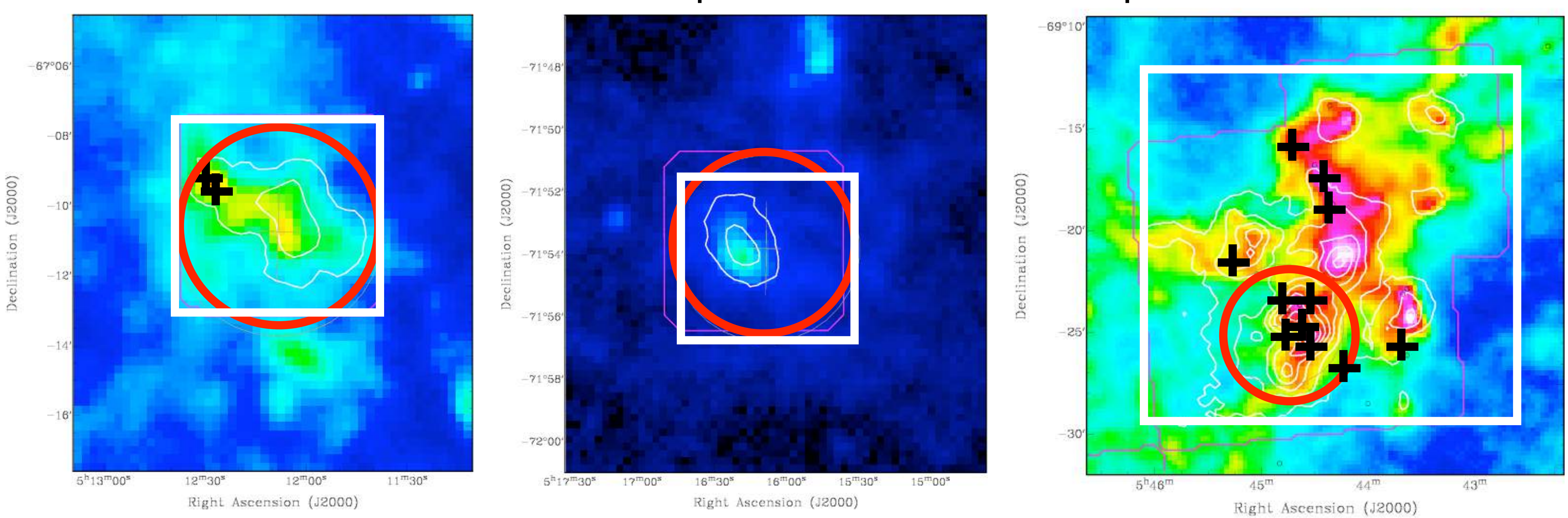
Questions

Star Formation Activity in LMC PCCs

- PCCs show some signs of high-mass star formation, but tend to be less active relative to general GMC population

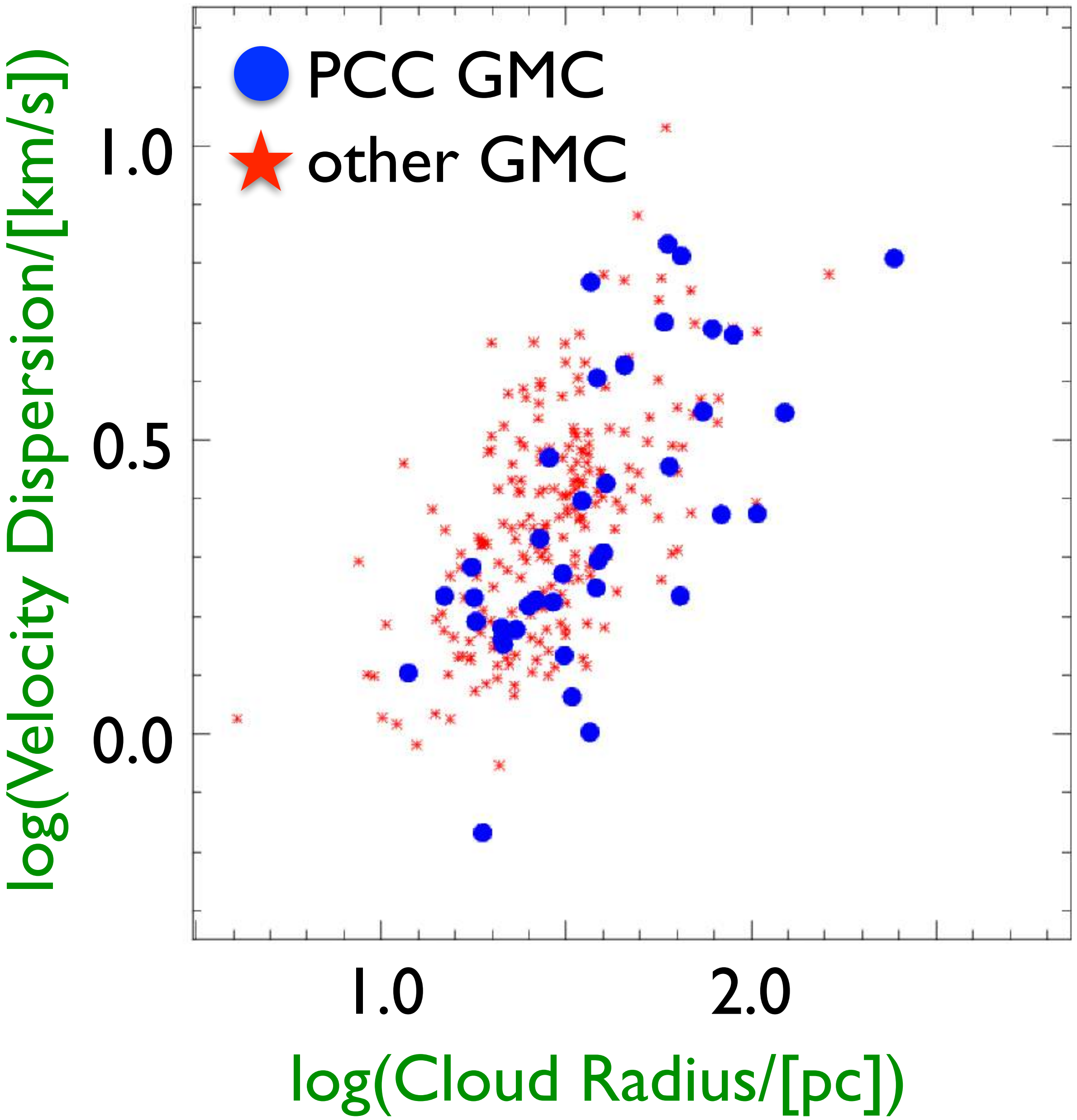
- Herschel PS catalogue now in-hand (YSO, dust clumps, EGs)
- connection between PCCs and Herschel YSOs still under study

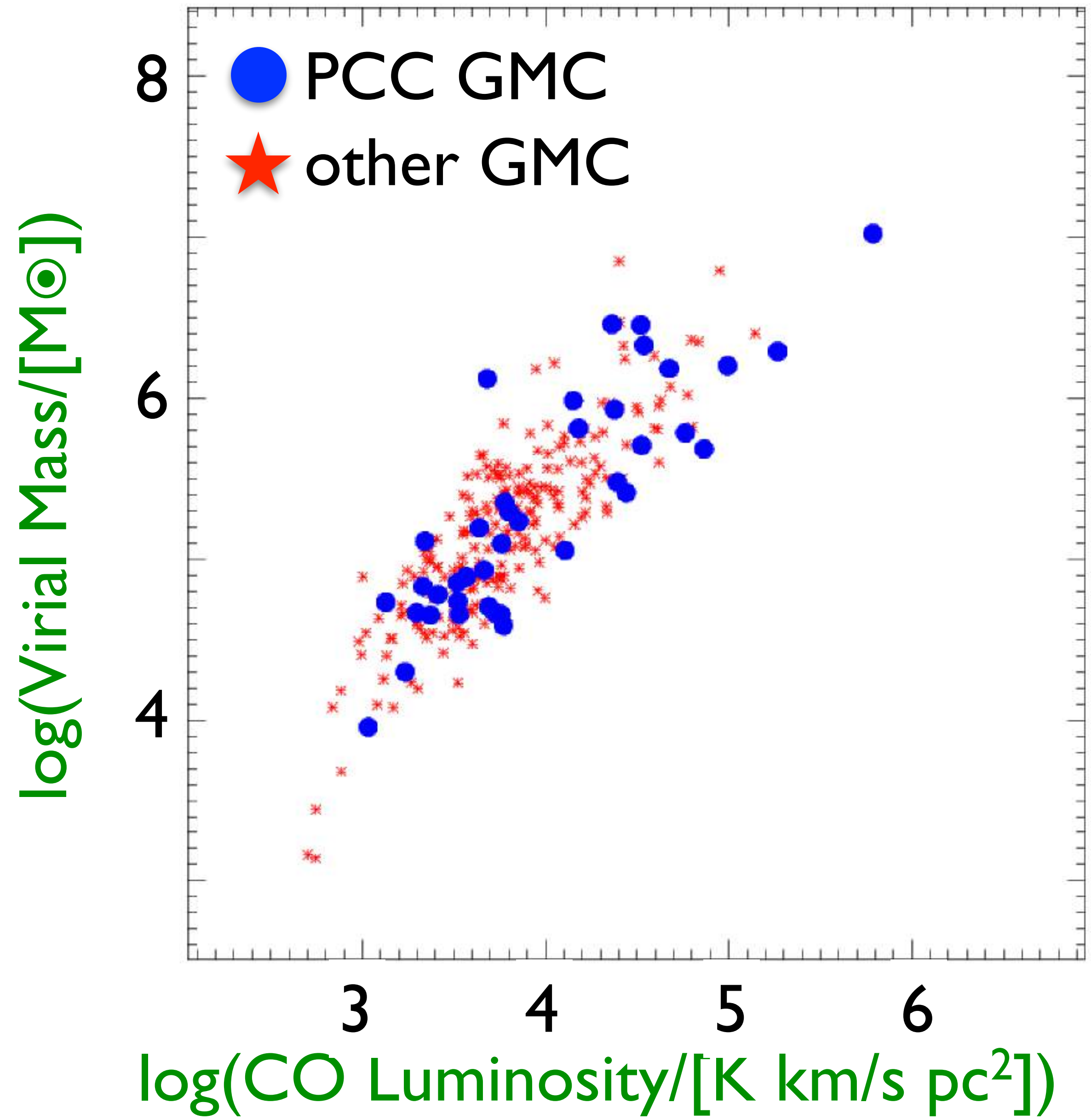
Circle: PCC, Color: 500 um, Crosses: Spitzer YSOs, Contours: Mopra I_{CO}



CO-derived Physical Properties of LMC PCCs

- PCCs mostly consistent with other LMC GMCs
- linewidth (slightly) narrow for size
- no evidence for different 'dark gas' content within CO boundary



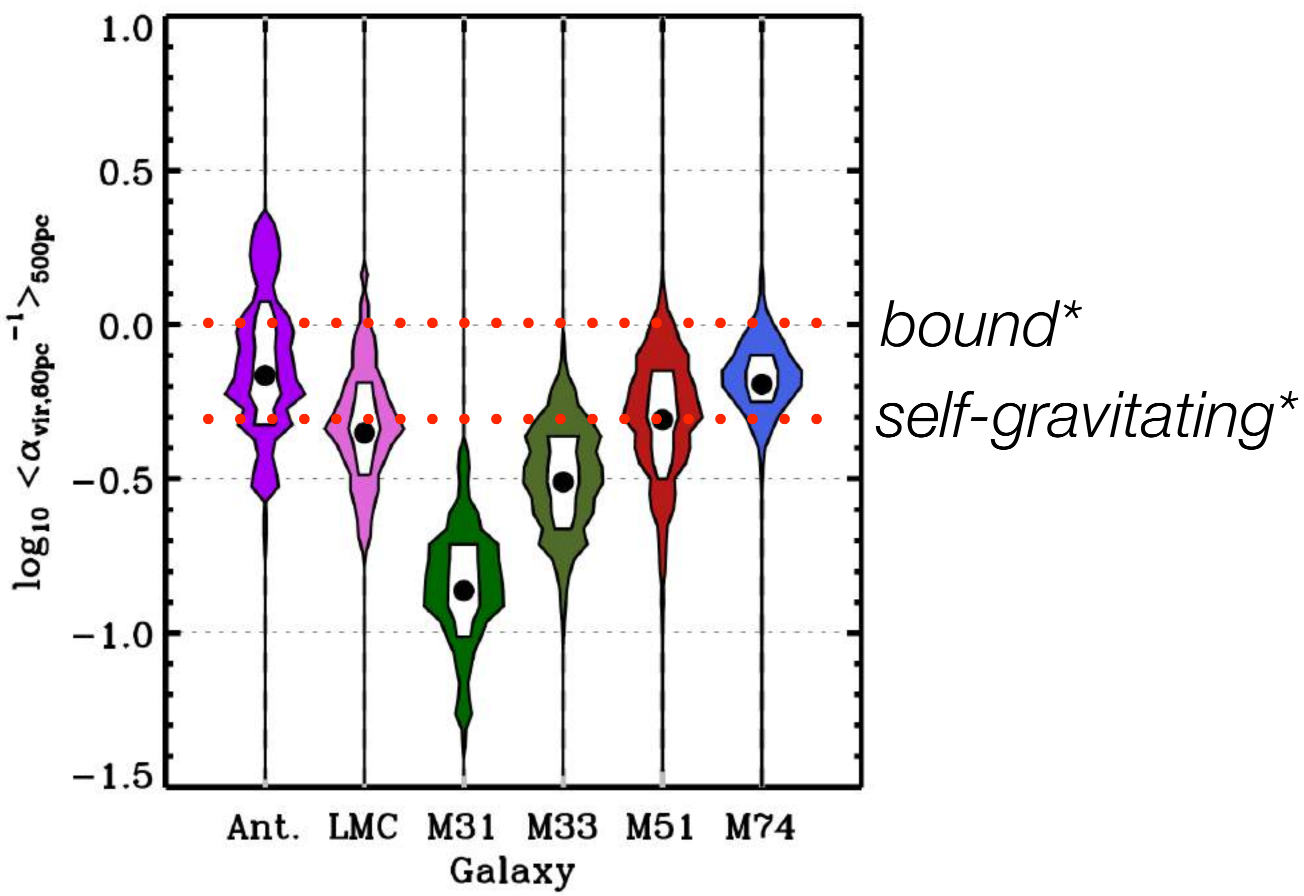


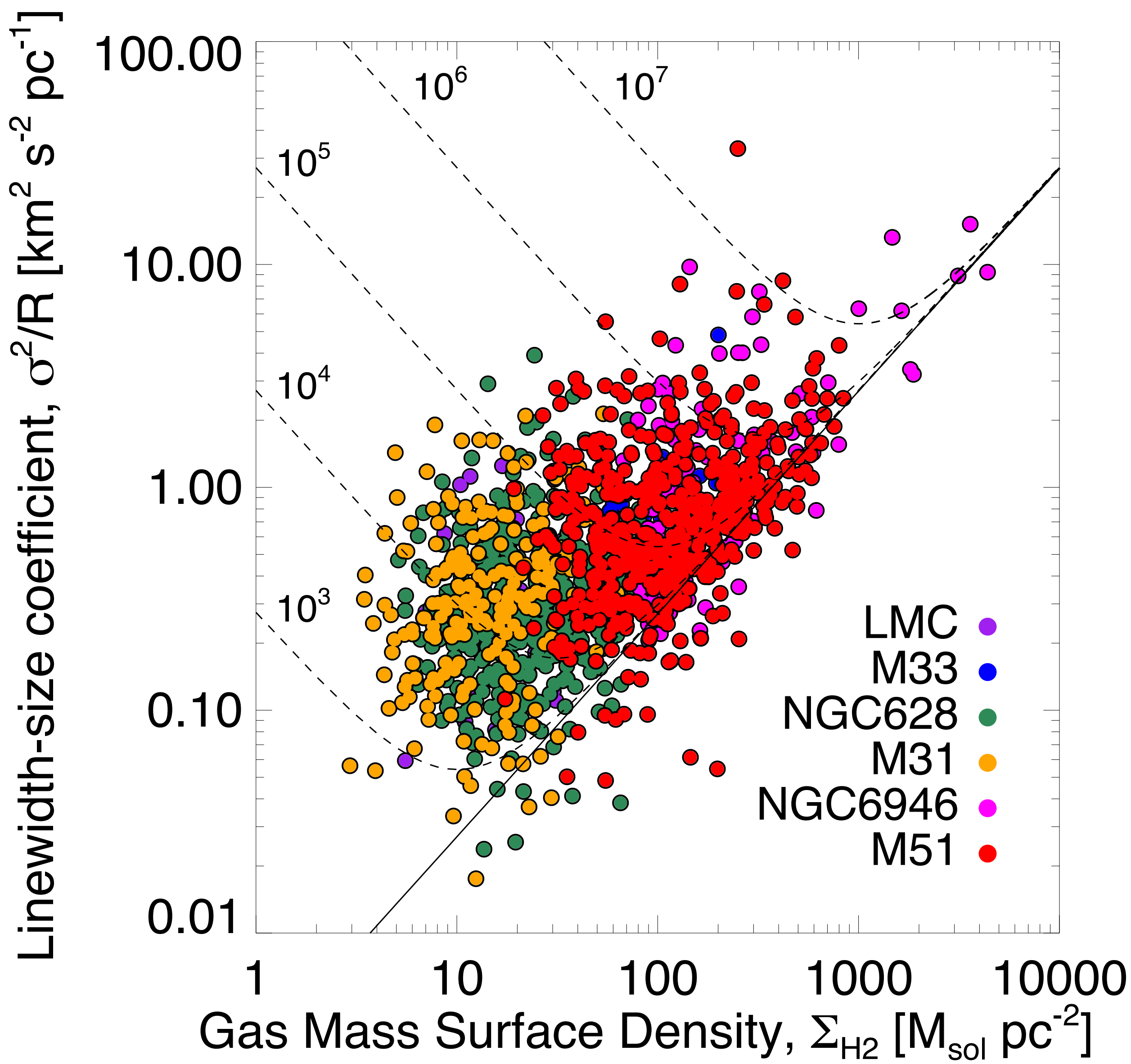
Evidence for Dynamical Self-Regulation?

Cold gas in galaxies achieves a similar dynamical state on 60pc scales

*for assumed XCO and density profile

Virialisation





- line width and density variations among galaxies yield similar values for gas self-gravity

LTE vs XCO Mass: 30Dor vs PCC