TRAO Key Science Program: mapping Turbulent properties In star-forming MolEcular clouds down to the Sonic scale (TIMES)

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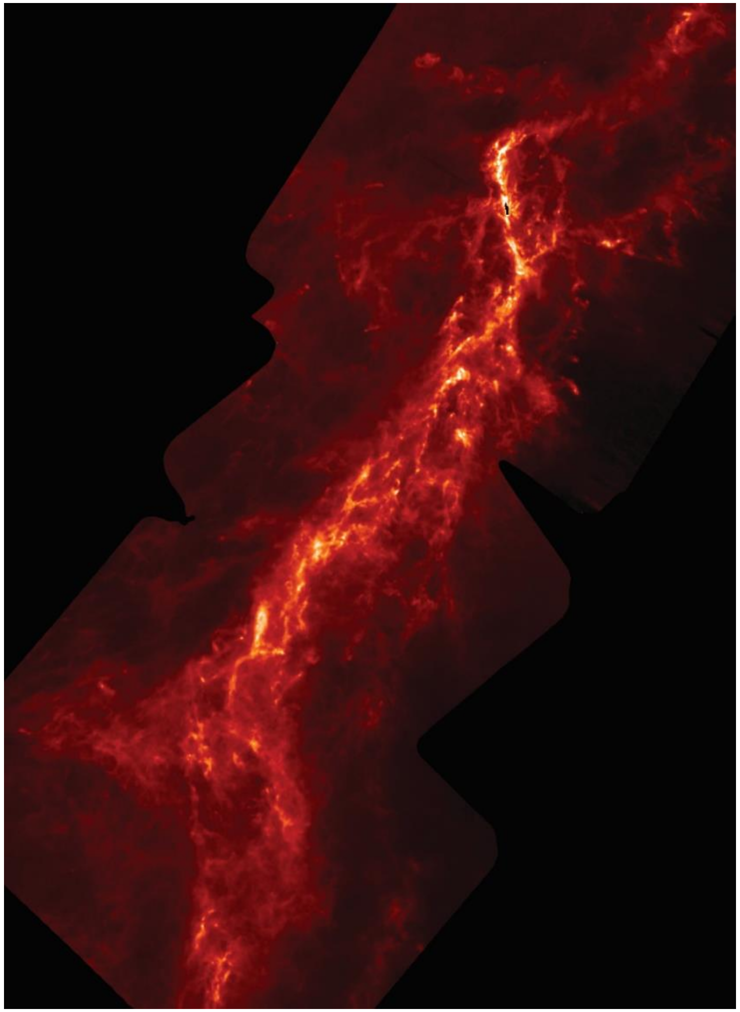
Turbulence and Starformation



- **High-mass & low-mass star forming regions**
  - Different star-formation environments.
  - Turbulent properties may be different.

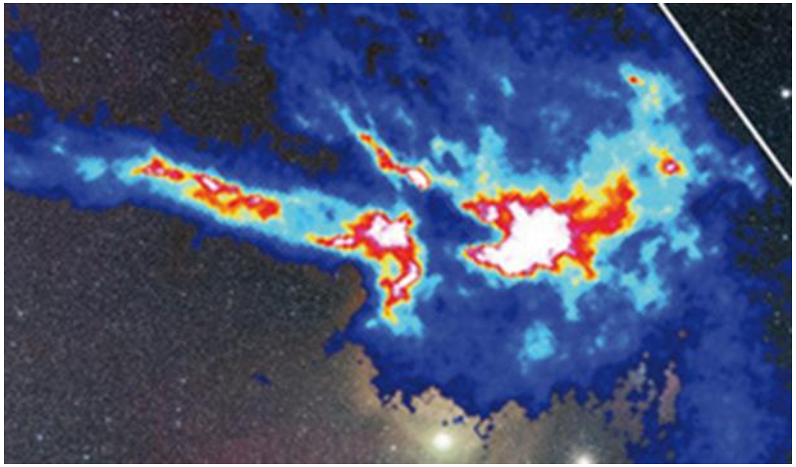


Image credit: Left: Stutz & Kainulainen (2015), Right: J. Kainulainen, MPIA

TRAO Key Science Program (KSP)

- TIMES project (PI: Jeong-Eun Lee)

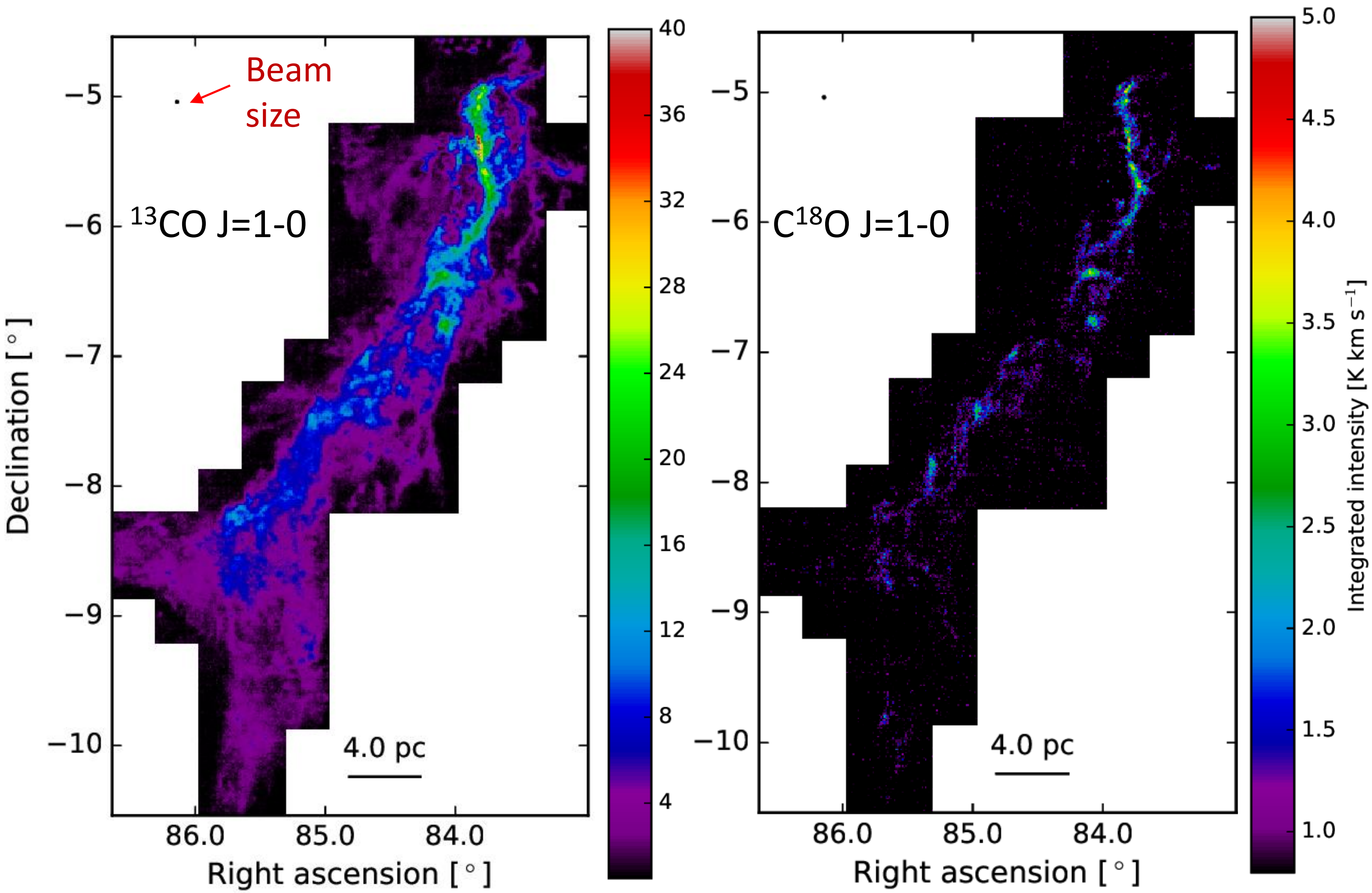
Objective

- Mapping turbulence across a **broad range of densities and scales** in **various star formation environments**.
  - Various density tracers (^{13}CO, $C^{18}O$, HCN, HCO^+, CS, and N_2H^+)
  - Various scales (from the whole cloud scale to the sonic scale)
  - Various environments (high- & low-mass star forming regions)

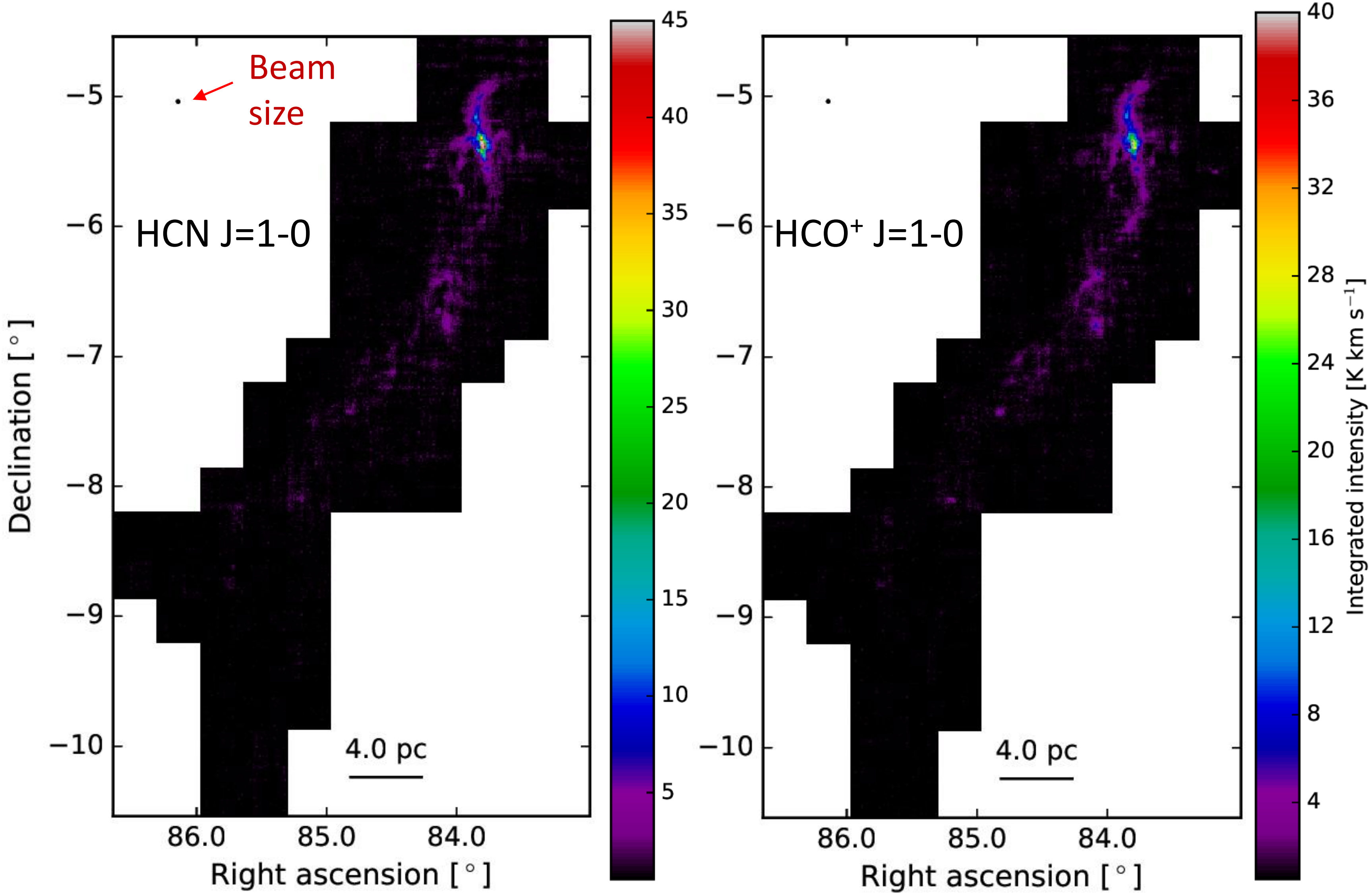
▶ Map fully the **Orion A** and **Ophiuchus** molecular clouds.

Cloud	Area	Obs. Time
Orion A	8.7 deg.^{2}	1059
Ophiuchus	3.9 deg.^{2}	540

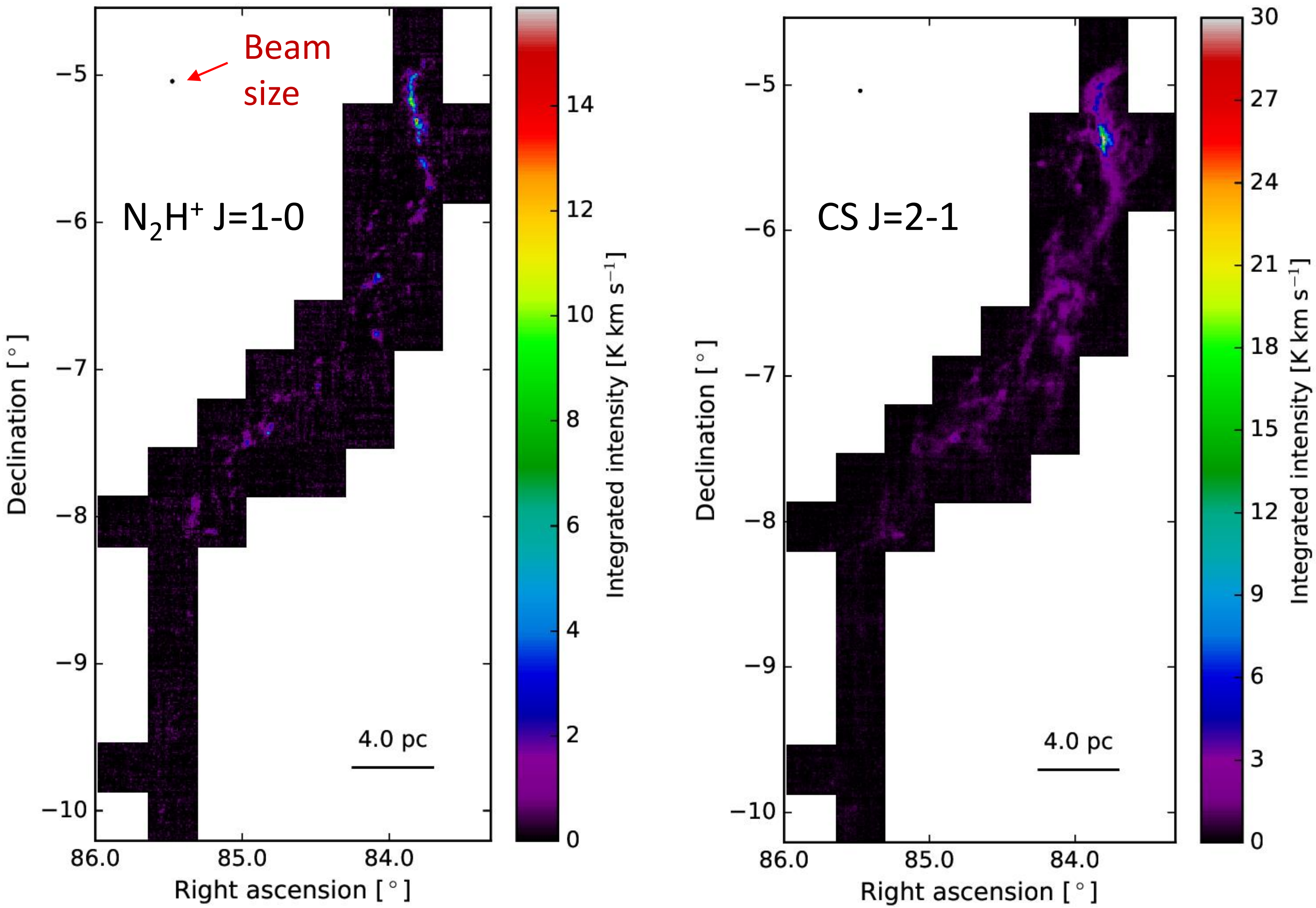
Observed data (Orion A cloud)



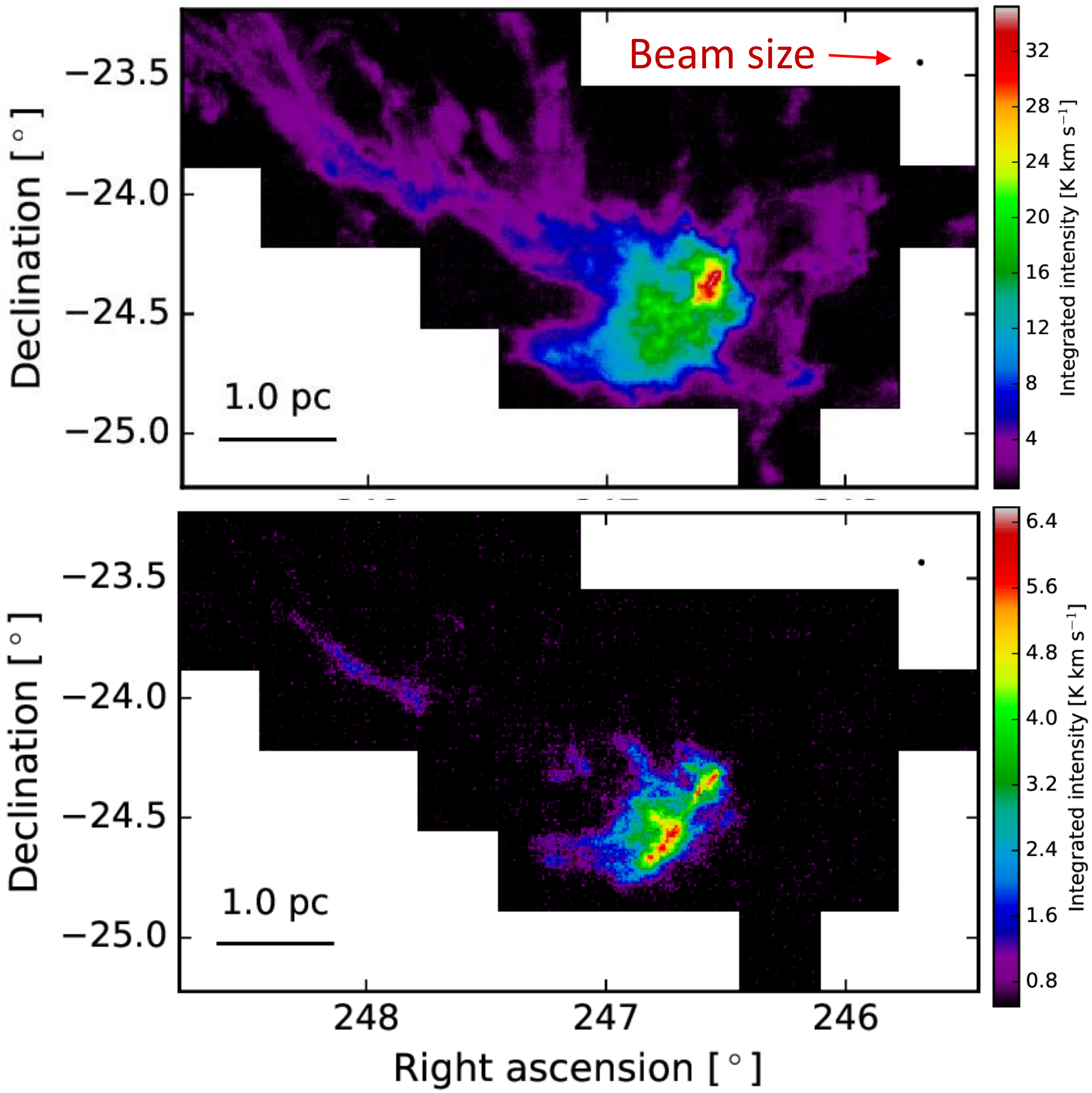
Observed data (Orion A cloud)



Observed data (Orion A cloud)



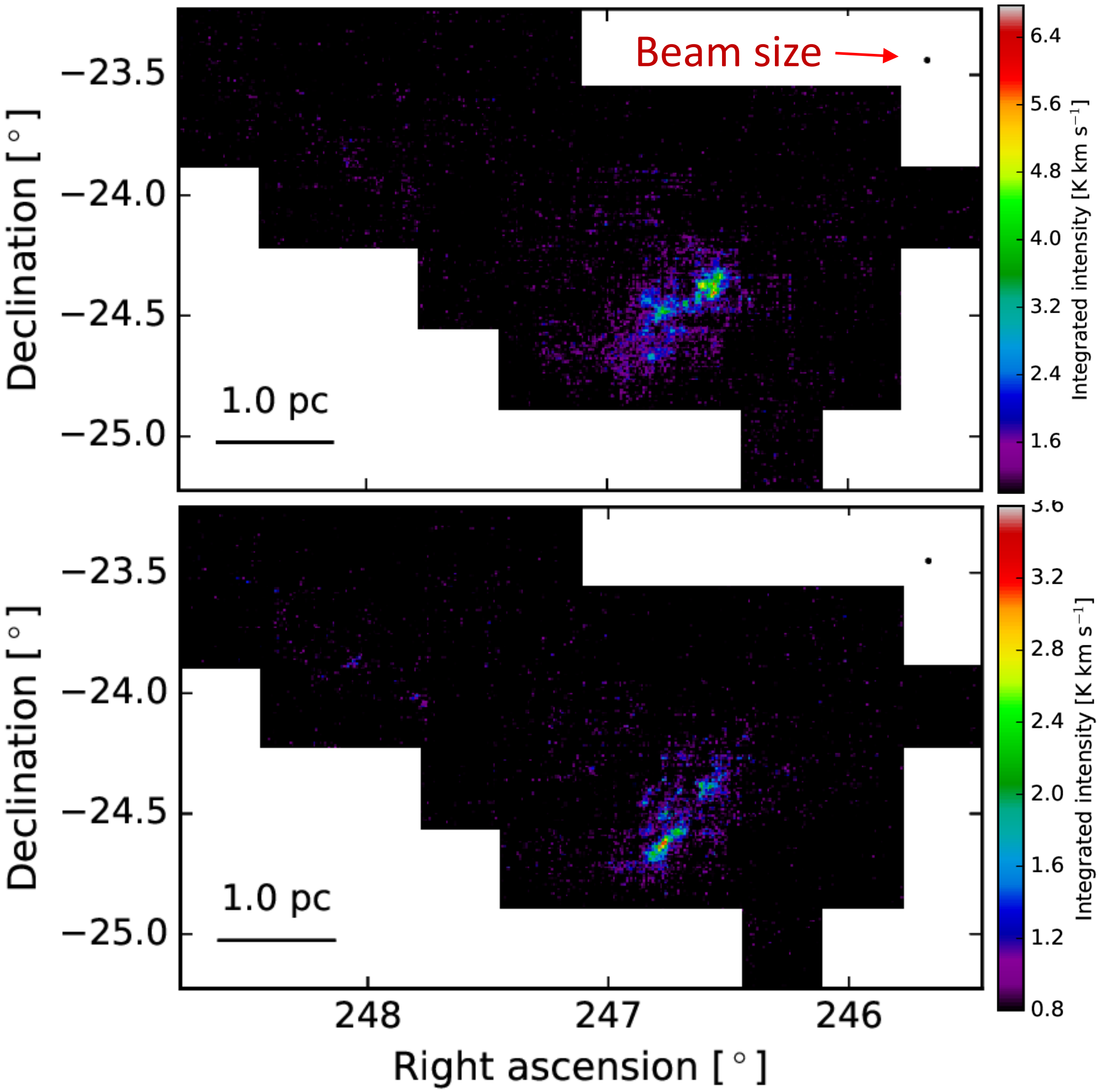
Observed data (Ophiuchus cloud)



^{13}CO J=1-0

C^{18}O J=1-0

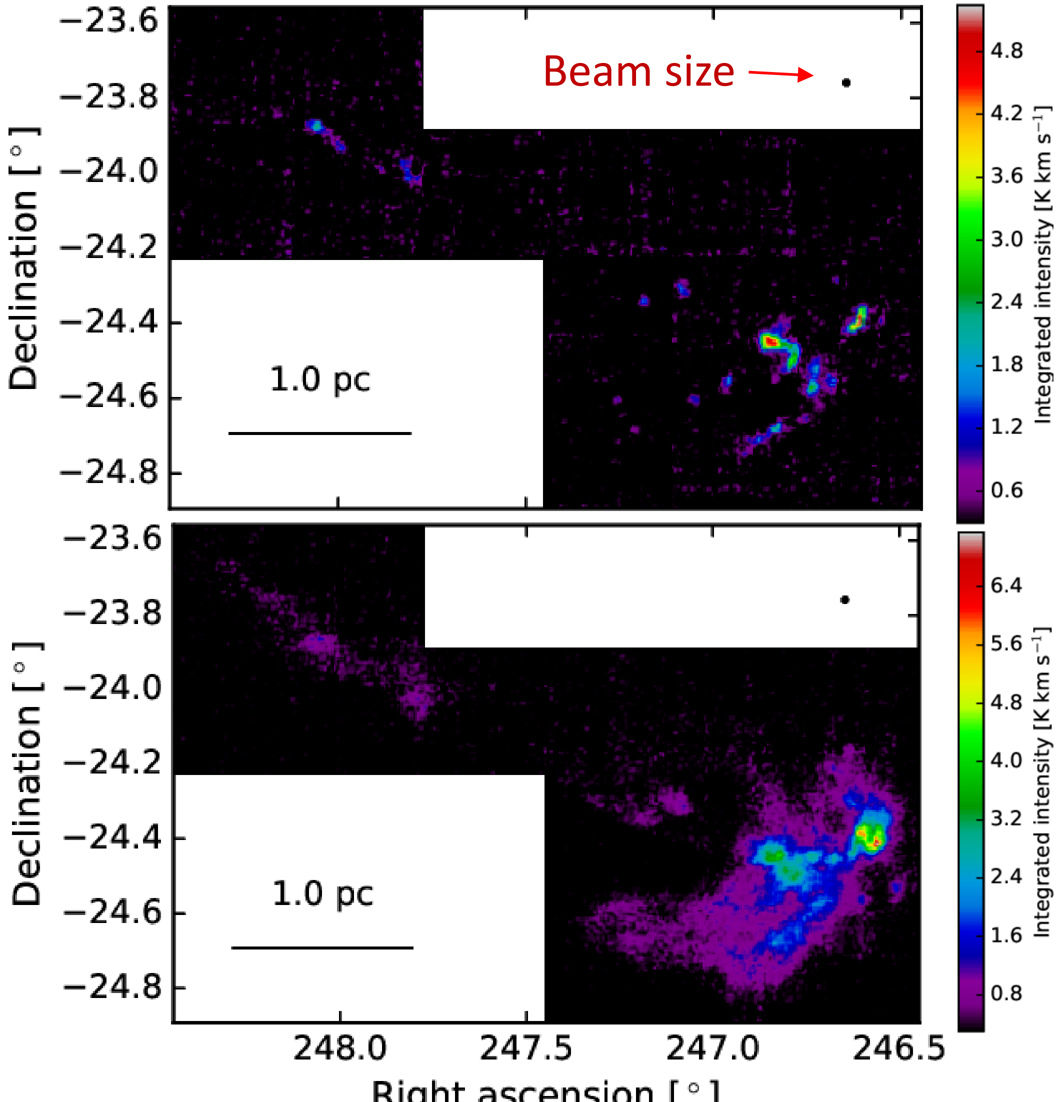
Observed data (Ophiuchus cloud)



HCN J=1-0

HCO^+ J=1-0

Observed data (Ophiuchus cloud)

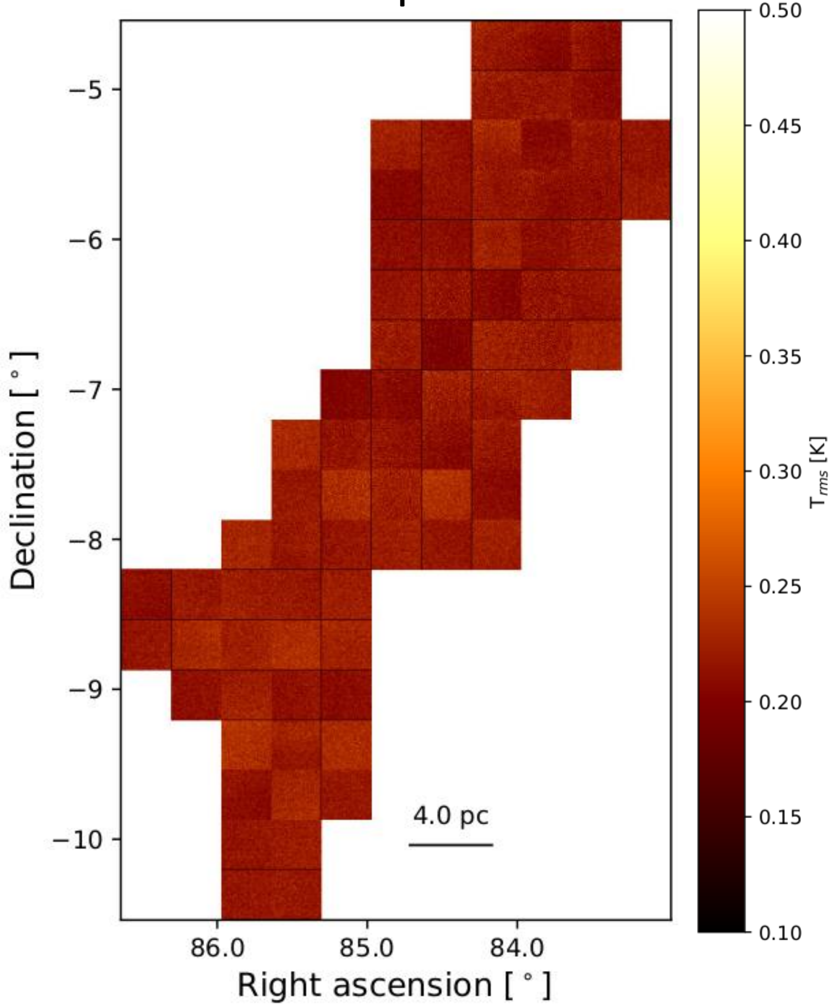


N_2H^+ J=1-0

CS J=2-1

Homogeneous observation through the entire clouds

RMS map for ^{13}CO



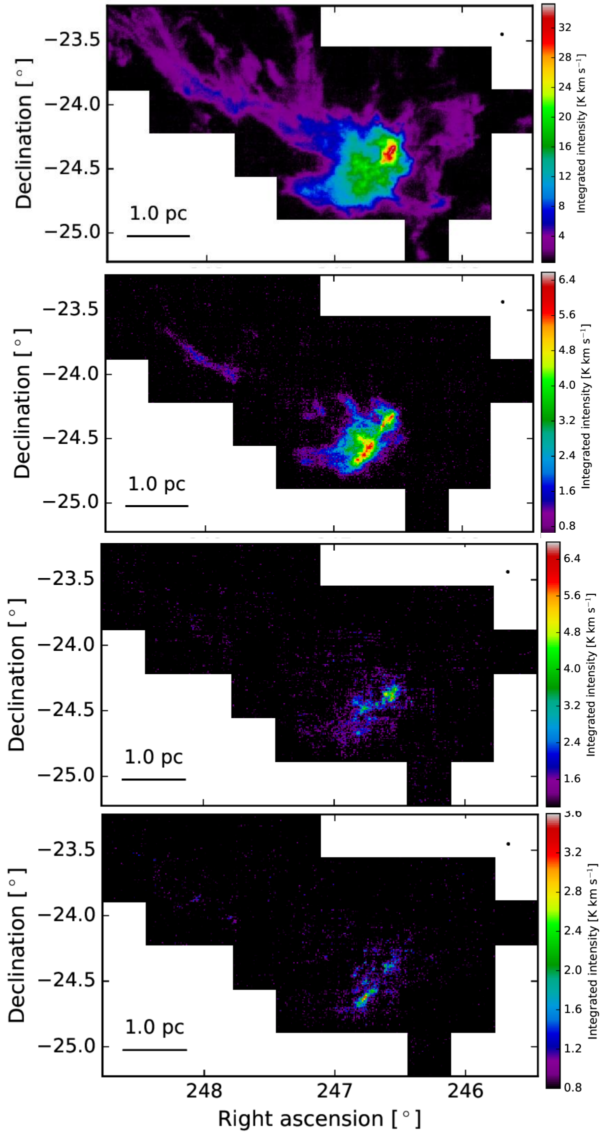
	Orion A	Ophiuchus
^{13}CO	0.22 K	0.23 K
$C^{18}O$	0.20 K	0.21 K
HCN	0.19 K	0.21 K
HCO^+	0.20 K	0.20 K
N_2H^+	0.11 K	0.10 K
CS	0.11 K	0.11 K

$\sigma_{Trms} < 0.03$ K for all maps

- Prevent a suspected side effect on the statistics from the non-uniform rms noise.

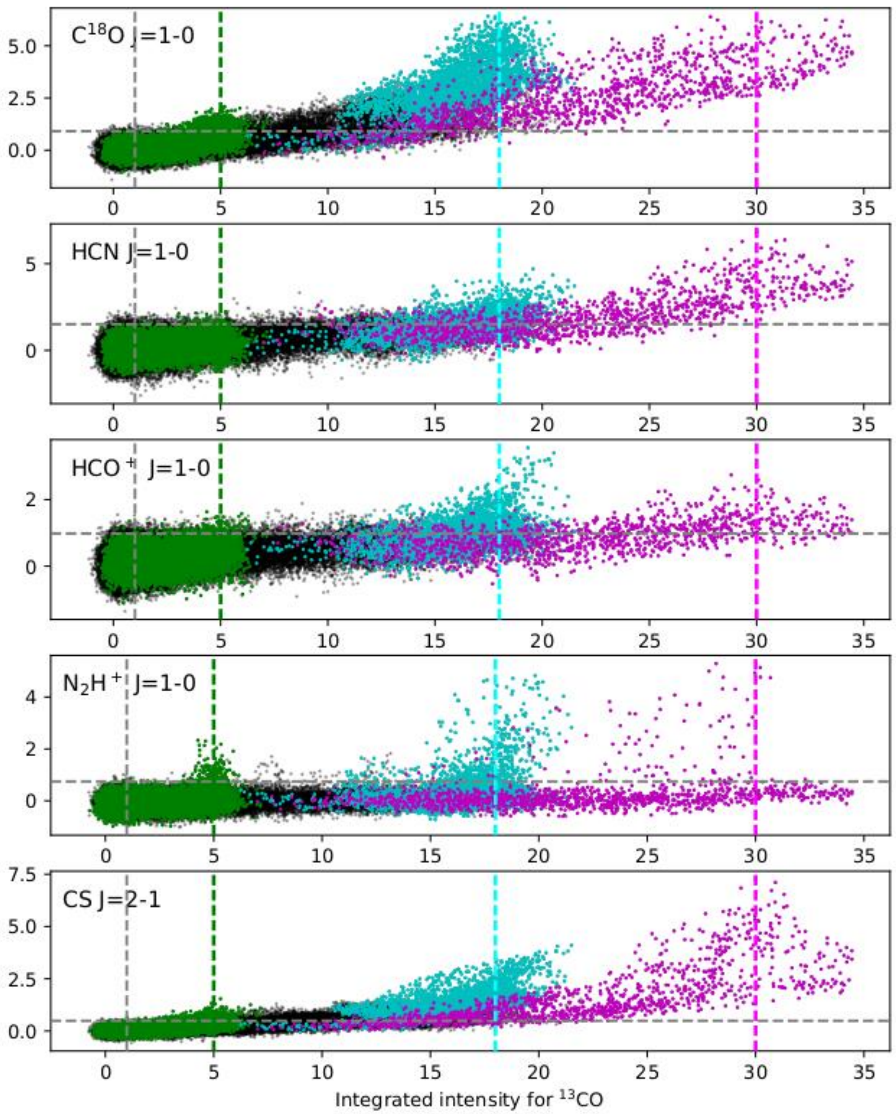
Line correlation in the clouds

- Correlations between different molecular tracers can be traced thanks to
  - Homogeneous observation
  - Unbiased mapping in both clouds
- Different physical/chemical environments might be traced
  - In different clouds
  - In different position in a cloud



Bumps at similar Int(^{13}CO)

Ophiuchus cloud

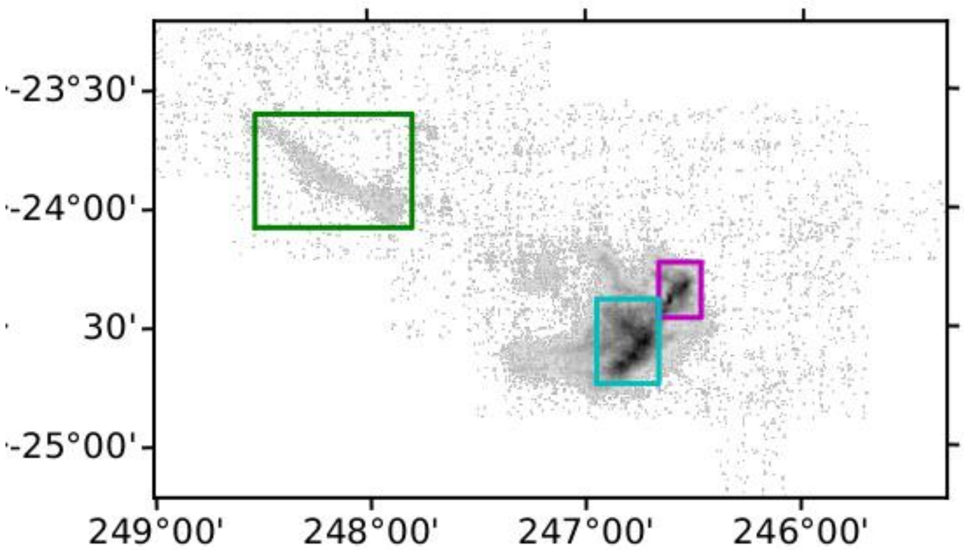


- Different sub-regions in the Ophiuchus cloud show different relations between the observed lines.

Oph A

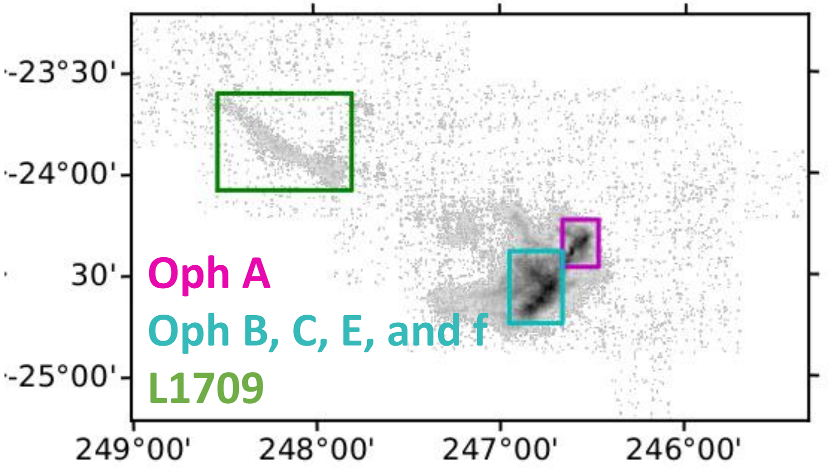
Oph B, C, E, and f

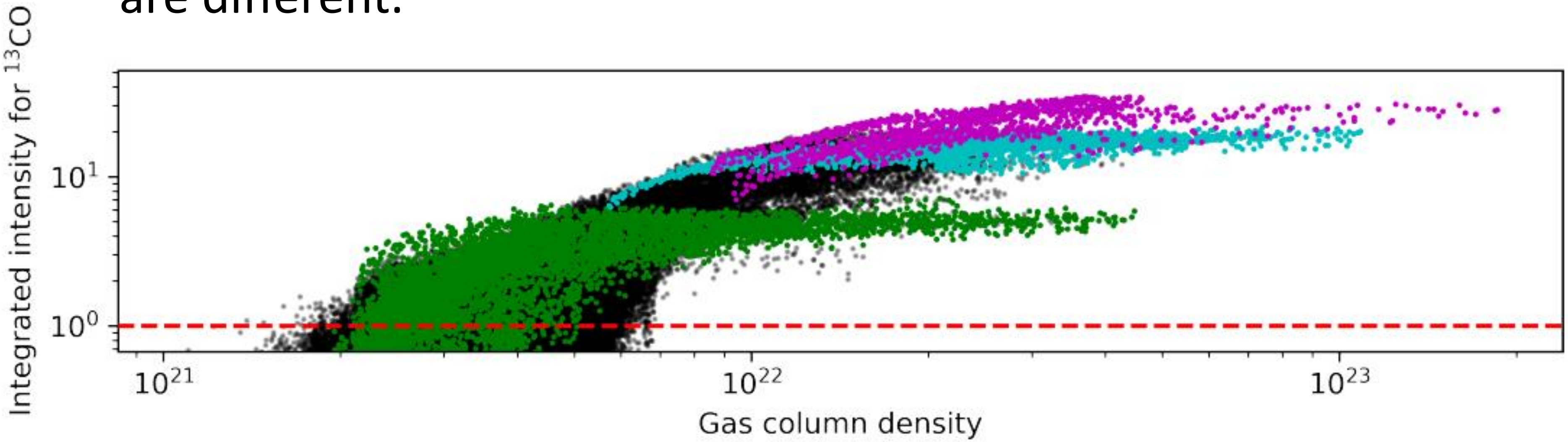
L1709



Column density and integrated intensity of ^{13}CO

- Multiple branches in the same gas column density.
- Different branches represent different sub-regions
- Their chemical environments are different.





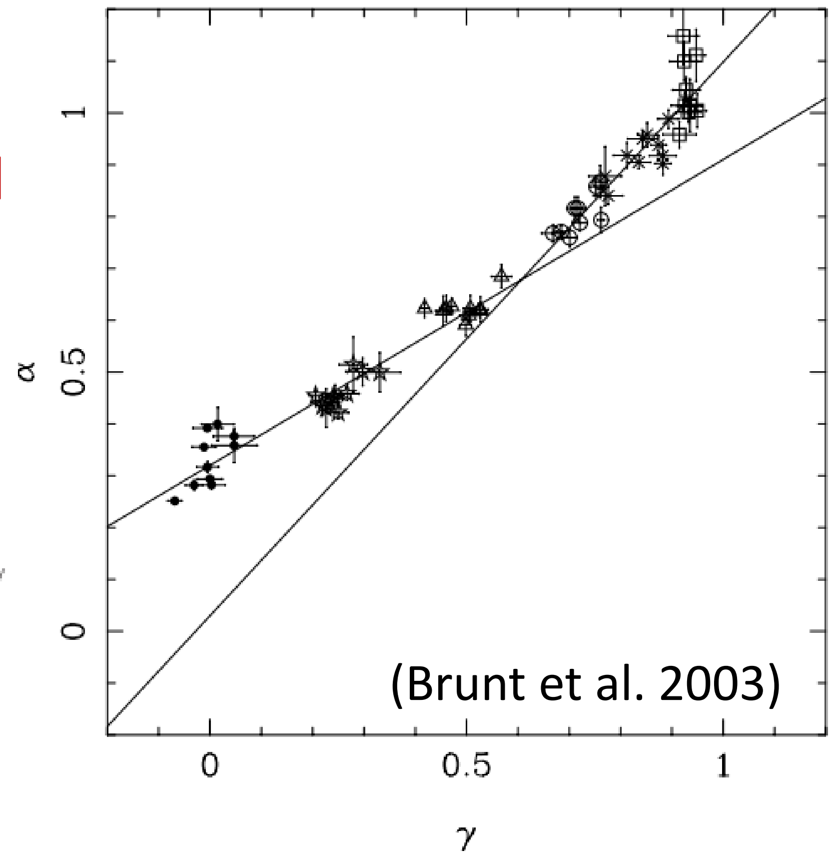
❖ The gas column density map is derived from the Herschel images

Principal Component Analysis

- One of the multivariate analyses that **can recover a underlying turbulent power-law slope** (Heyer & Peter Schloerb 1997).
- PCA describes the observed data as an ensemble of independent components.
- Determine a relation between the **velocity dispersion (δv)** and **spatial scale (*L*)** and convert to the power-law slope of turbulent power spectra (Brunt et al. 1999, 2003).

$$\delta v \propto L^{\alpha} \Rightarrow \left(\left\langle |\delta v|^2 \right\rangle\right)^{1/2} \propto L^{\gamma}$$

$$\Rightarrow \gamma = (\beta - 1)/2$$

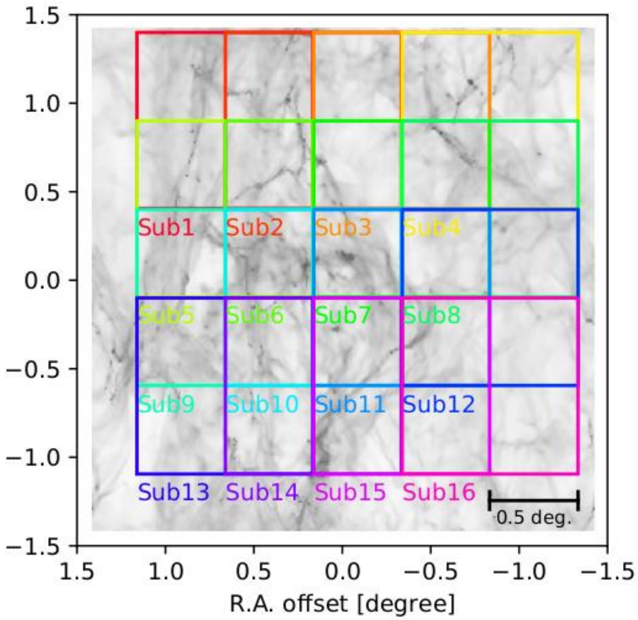


(Brunt et al. 2003)

Correction method using the eigenvalues

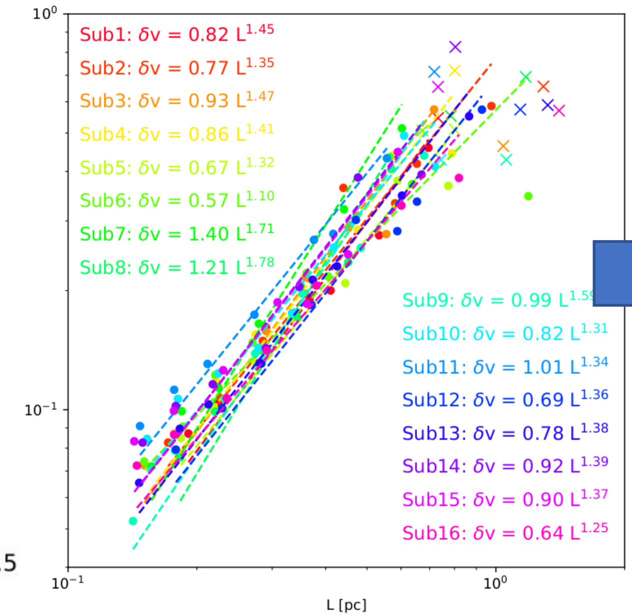
- Eigenvalue correction corrects the scale dependent column density effect within a region.
- PCA slopes (α) for the simulated clouds become 0.5.

Hydrodynamic simulation



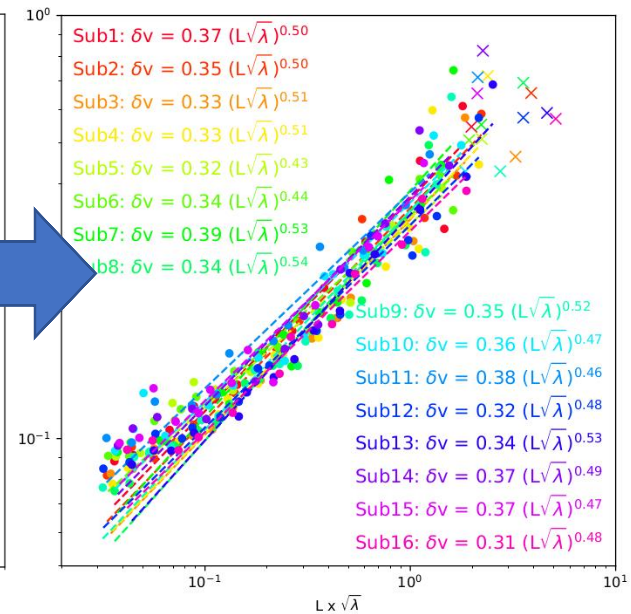
Simulated by Quan et al. (2015)

Original PCA results



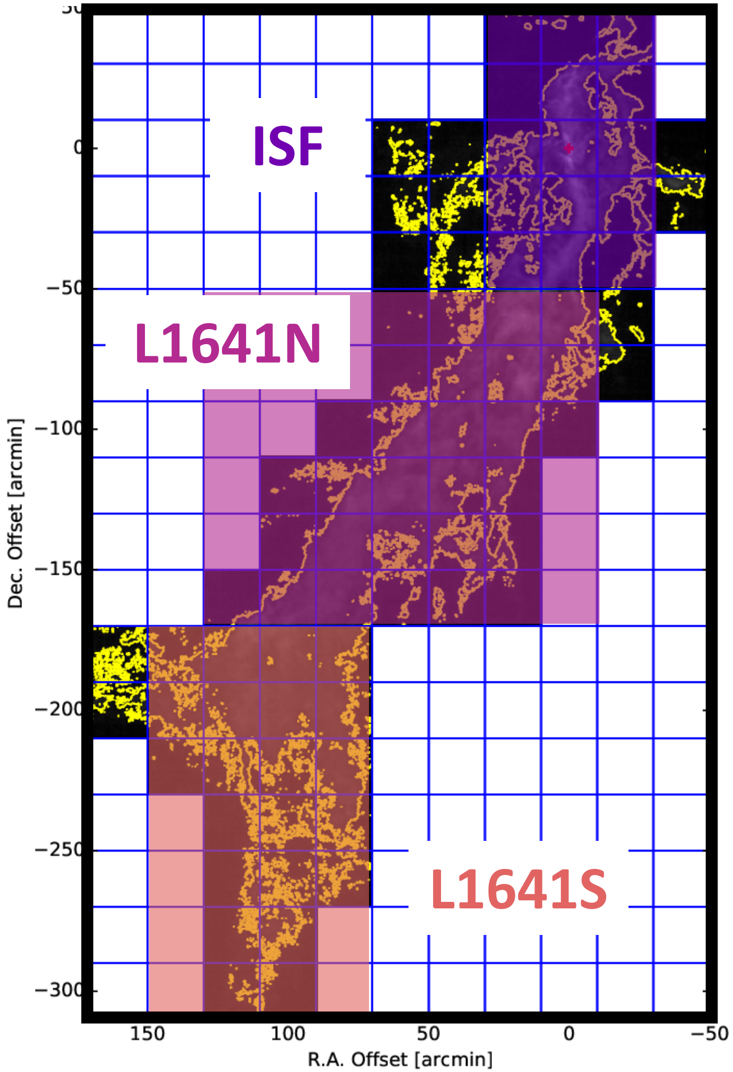
$\alpha = 1.41 \pm 0.16$

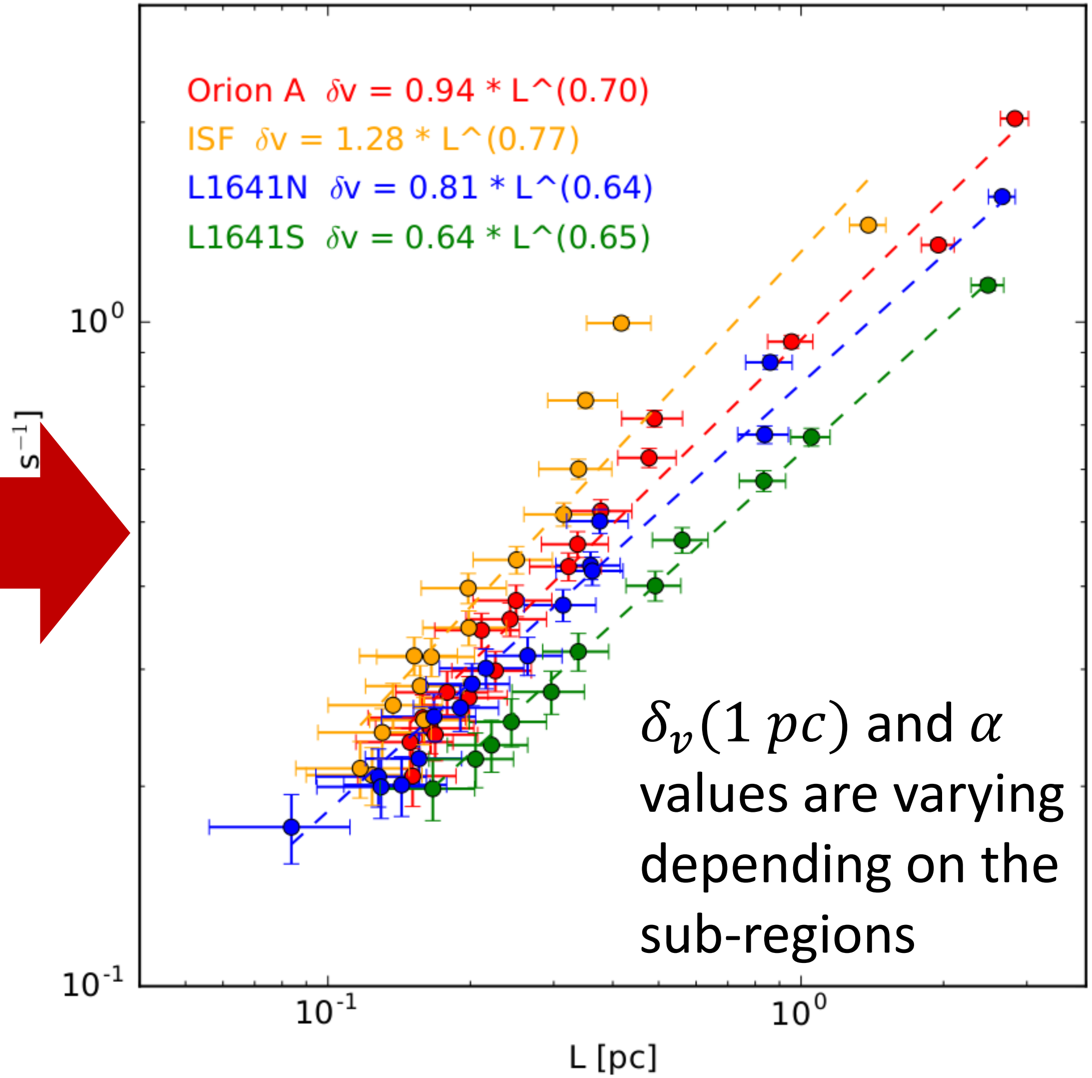
After correction



$\alpha = 0.49 \pm 0.03$

PCA results for ^{13}CO in different sub-regions





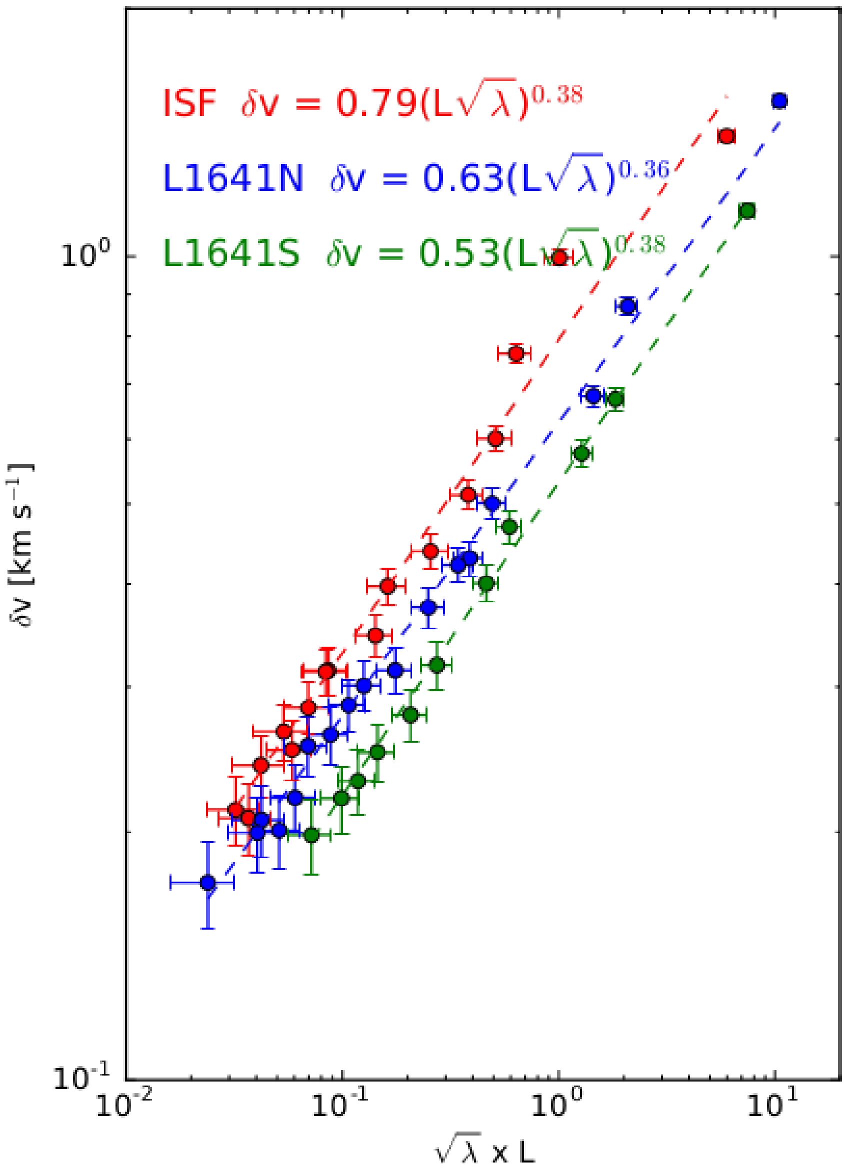
$\delta_v(1\ pc)$ and α values are varying depending on the sub-regions

Corrected PCA results for the Orion A cloud

- Slope values become relatively constant after correction.
  [0.65, 0.77] ➡ ~ 0.37
- The difference in δv remains with this correction
  - different δv for a given $\sqrt{\lambda}L$ might be related to the overall star-forming activities in each sub-regions

	ISF	L1641N	L1641S
# of YSOs	111	97	84

References: Furlan et al. (2016), Megeath et al. (2012)

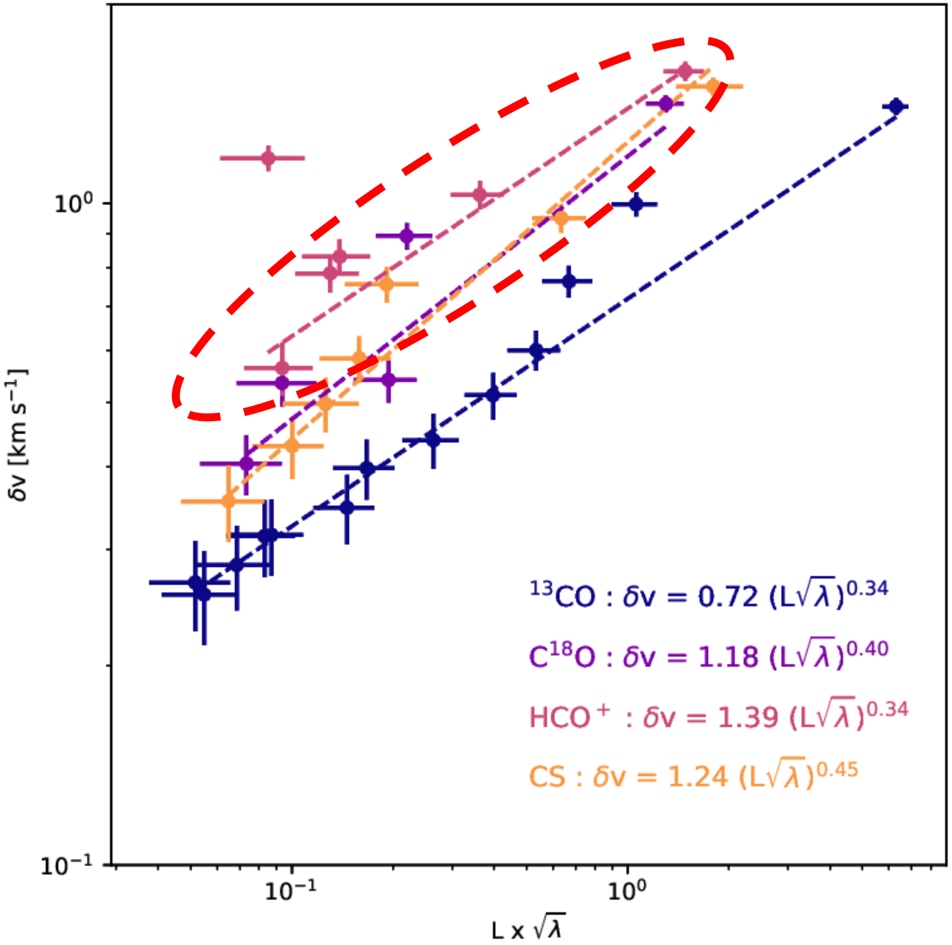


Corrected PCA results for the observed lines in ISF

Fitted $\delta v - L$ relations

Line	α	Y-inter.
^{13}CO	0.34 ± 0.01	0.72 ± 0.02
$C^{18}O$	0.40 ± 0.08	1.18 ± 0.21
HCO^+	0.34 ± 0.06	1.39 ± 0.16
CS	0.45 ± 0.03	1.24 ± 0.09

- **Different δv** values for a given $\sqrt{\lambda}L$ depending on the lines
  1. Gas column density effect in different regions
  2. Effect of the Feedback



Summary

- We observed **the Orion A and Ophiuchus clouds** in six different molecular tracers. Our **homogeneous data set** prevents suspected side effect on the statistical analyses.
- Because of the homogeneous, unbiased mapping in six different lines, our data is proper for the study of line intensity distributions in the observed clouds.
- We find the sub-regions which show different relations between the observed lines. Those sub-regions show **different ^{13}CO intensities** even though they have **similar gas column densities**. It provides a great chance to probe the chemical evolution in the molecular clouds.
- The PCA results show the **different δv-L relations** depending on the sub-regions in the Orion A cloud as well as which molecular tracer is used

Summary

- The PCA results for the observed data **do not show a Larson's slope (~0.5)** in their δv-L relations. It might be caused by the non-uniform gas column density in the observed molecular cloud
- **We correct the scale dependent gas column density effect** using the eigenvalues for a given PCA result. On the simulation without any winds/outflows, **PCA shows the Larson's slope after correction**
- The corrected PCA results for the ^{13}CO line still exhibits the different δv values for a given $\sqrt{\lambda}L$. **The different δv values might related to the overall star-forming activity** in those sub-regions
- The higher **δv for the HCO^{+} line might be related to the star-formation feedbacks**