Submillimetre Spectroscopy of Star Formation

Structure and Kinematics of NGC 2068

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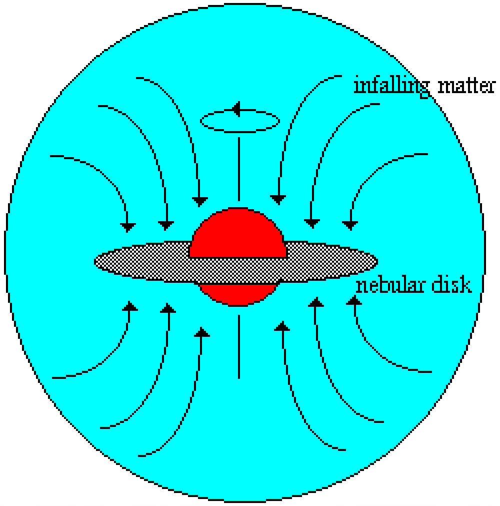
Outline

- Introduction to star formation
  - Background and basics
- NGC 2068
  - Observations, overall structure and kinematics
- Clump decomposition
  - Calculating clump masses and bound ratio
- Velocity dispersions
  - Inter- and intra-clump dispersions to differentiate type of turbulence

Basics of Star Formation

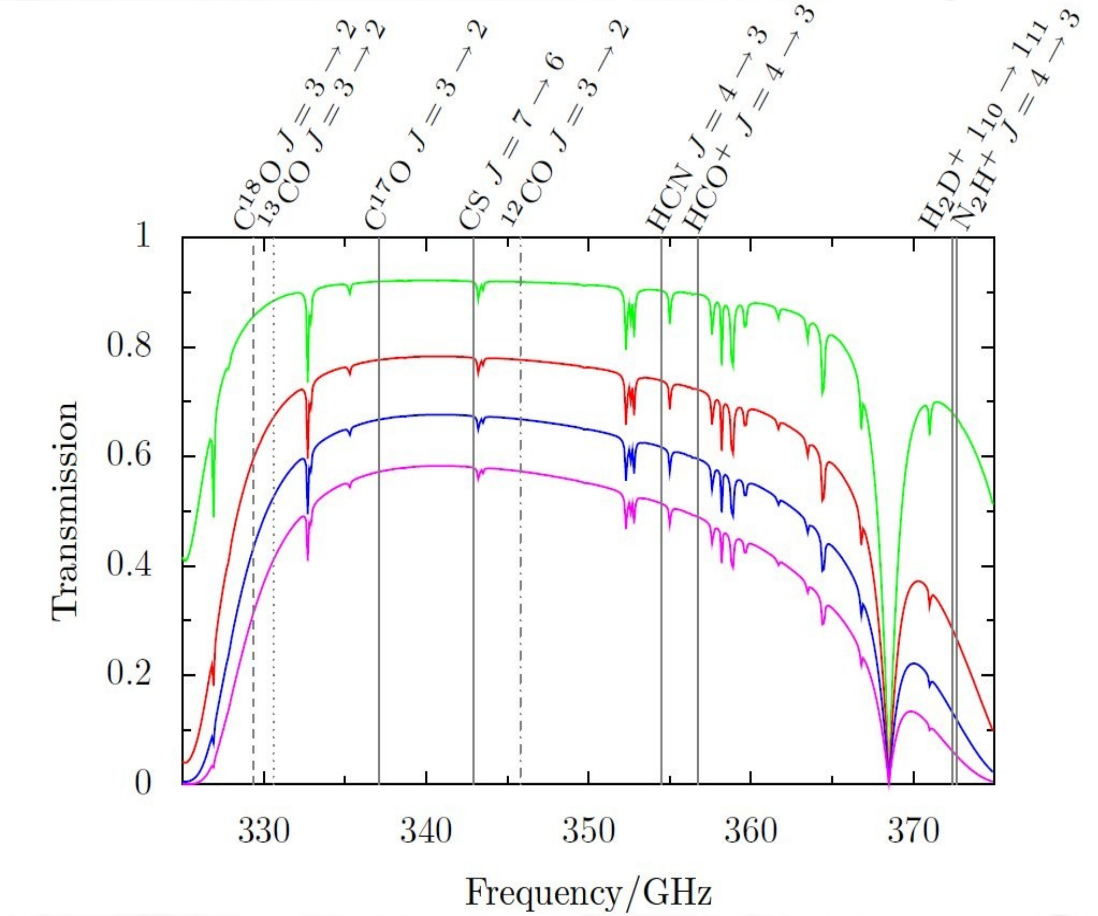
- Molecular clouds (H_2, dust) are the birthplaces of stars
- Denser regions collapse under gravity to form centrally-condensed cores
- Infall and accretion of matter from surrounding disk
- Form in clusters which complicates matters



Centrally condensed protostar (red), accreting from disk with matter infalling from the surrounding envelope (blue)

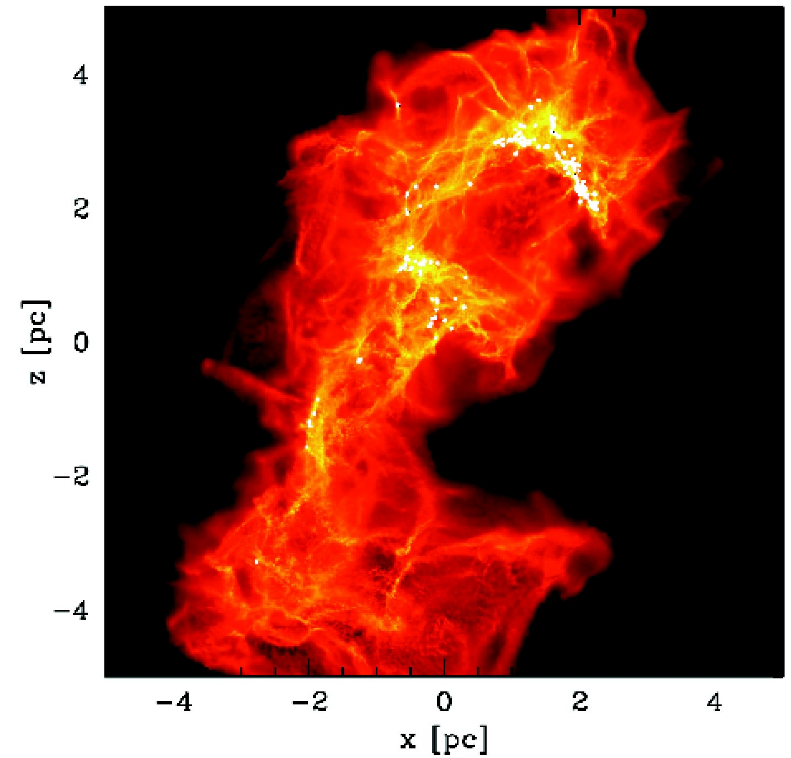
Observation Techniques

- Molecular clouds are cold as they are opaque to visible light.
- Emit at (sub)millimetre wavelengths via rotational transitions
- Absorbed by water vapour – require high dry sites



Role of Turbulence

- Gravoturbulent fragmentation
- Forms density enhancements in molecular clouds by a network of interacting shock
- Densest regions at the shock intersections form the prestellar cores
- Provides support against collapse



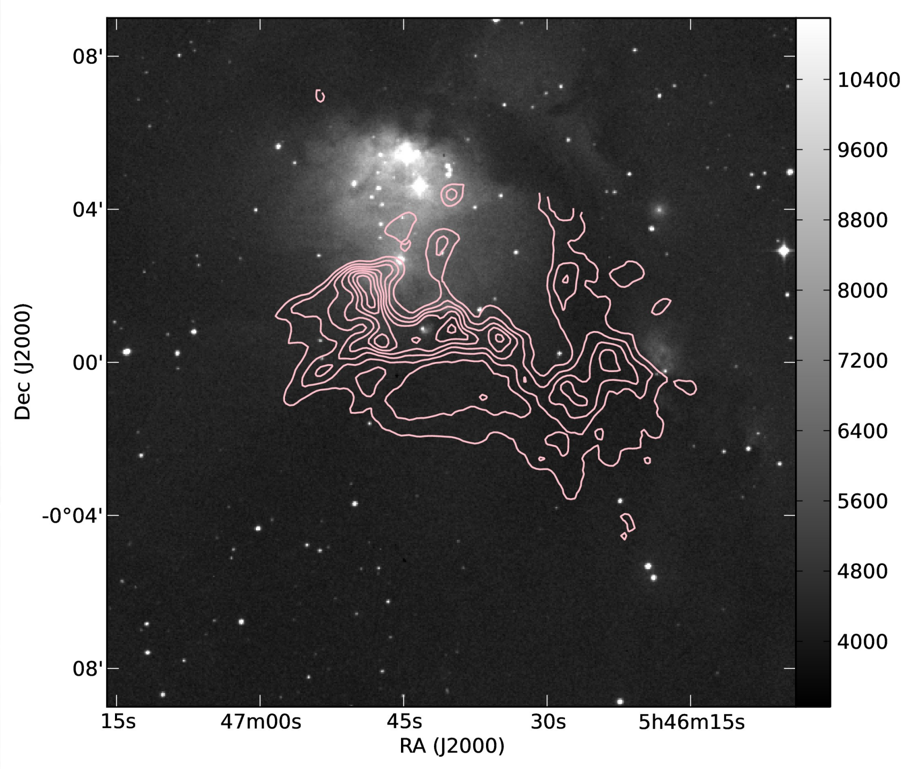
A simulated giant molecular cloud, showing clear filamentary structure (taken from Smith et. al. (2010))

Questions to be answered

- Length scales over which turbulence dominates, and timescale of turbulent decay
  - Decaying vs driven turbulence
- General properties of cores produced in differing turbulent environments at low resolution are insufficiently different to dismiss a particular environment
- Tracing kinematics (instead of spatial and structural properties) of star-forming dense gas may help with differentiation

NGC 2068

- One of the star formation regions in the Orion Molecular Cloud (d~400pc)
- Turbulent, produces fairly high mass stars
- Extensively studied using different molcules (and dust), at different resolutions



Near-IR image of NGC 2068 (reflection nebula), with $C^{18}O$ molecular emission overlaid

Observations

- Carried out at the JCMT in Hawaii, Sep-Oct 2010.
- 15m single dish
- Both spectral line data (HARP) and continuum/dust emission (SCUBA-2)

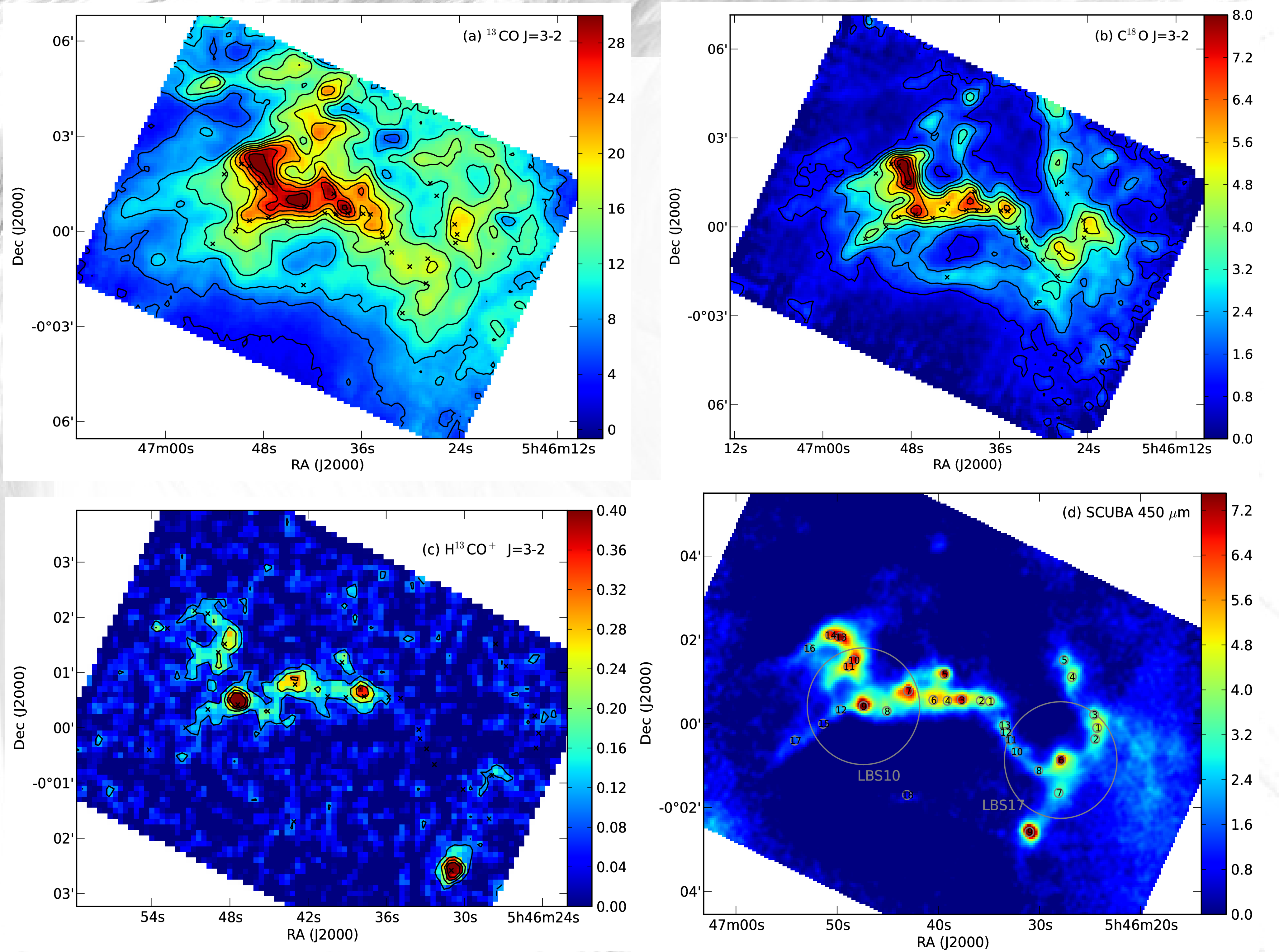
James Clerk Maxwell Telescope, Mauna Kea, Hawaii

Molecules observed

- Different molecules have varying abundances, and have different critical densities
  - Therefore trace different structures and scales within the molecular clouds.
- Emission from 3 different molecules observed – ^{13}CO, $C^{18}O$ and $H^{13}CO^+$

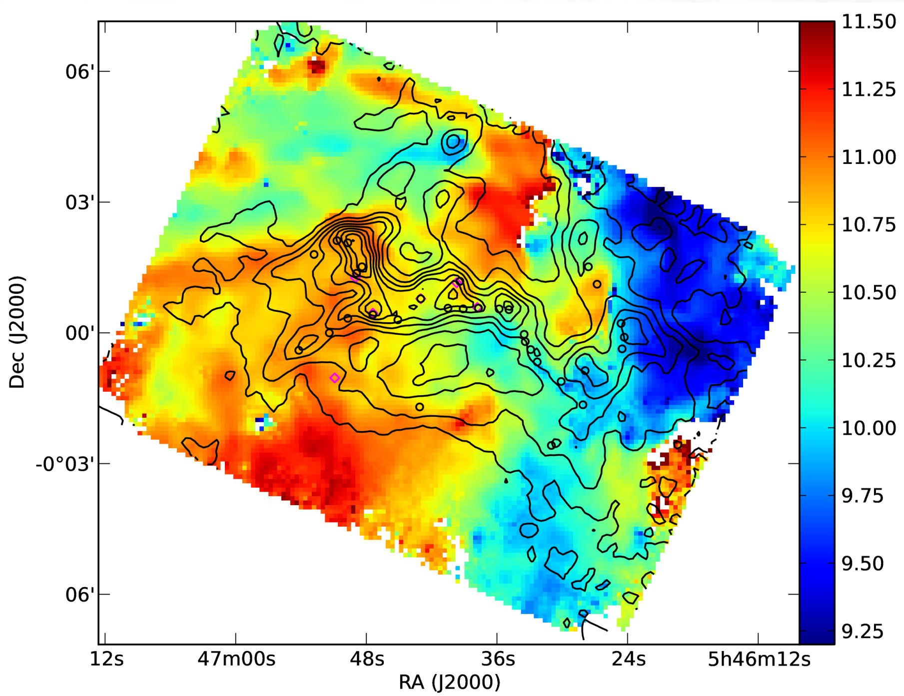
•Dust emission also observed for comparison

Molecule	Δ J	ν_{trans} / GHz	n_{crit} /cm^{-3}
^{13}CO	3 - 2	330.58	2×10^4
$C^{18}O$	3 - 2	329.33	2×10^4
$H^{13}CO^+$	4 - 3	346.99	3×10^7

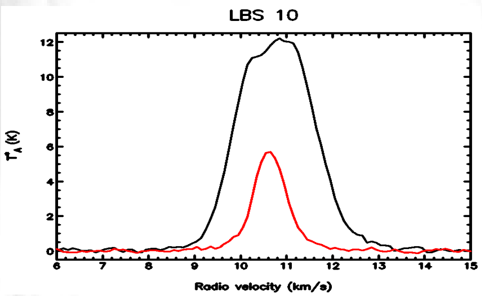


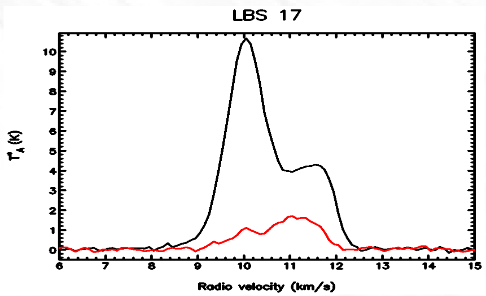
(a) ^{13}CO J=3-2
(b) C^{18}O J=3-2
(c) H^{13}CO^{+} J=3-2
(d) SCUBA 450 μm
Dec (J2000)
RA (J2000)
06'
03'
00'
-0°03'
06'
47m00s
48s
36s
24s
5h46m12s
12s
28
24
20
16
12
8
4
0
8.0
7.2
6.4
5.6
4.8
4.0
3.2
2.4
1.6
0.8
0.0
0.40
0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
02'
01'
-0°01'
54s
42s
30s
5h46m24s
04'
-0°02'
50s
40s
5h46m20s
LBS10
LBS17

Velocity Structure/ Kinematics

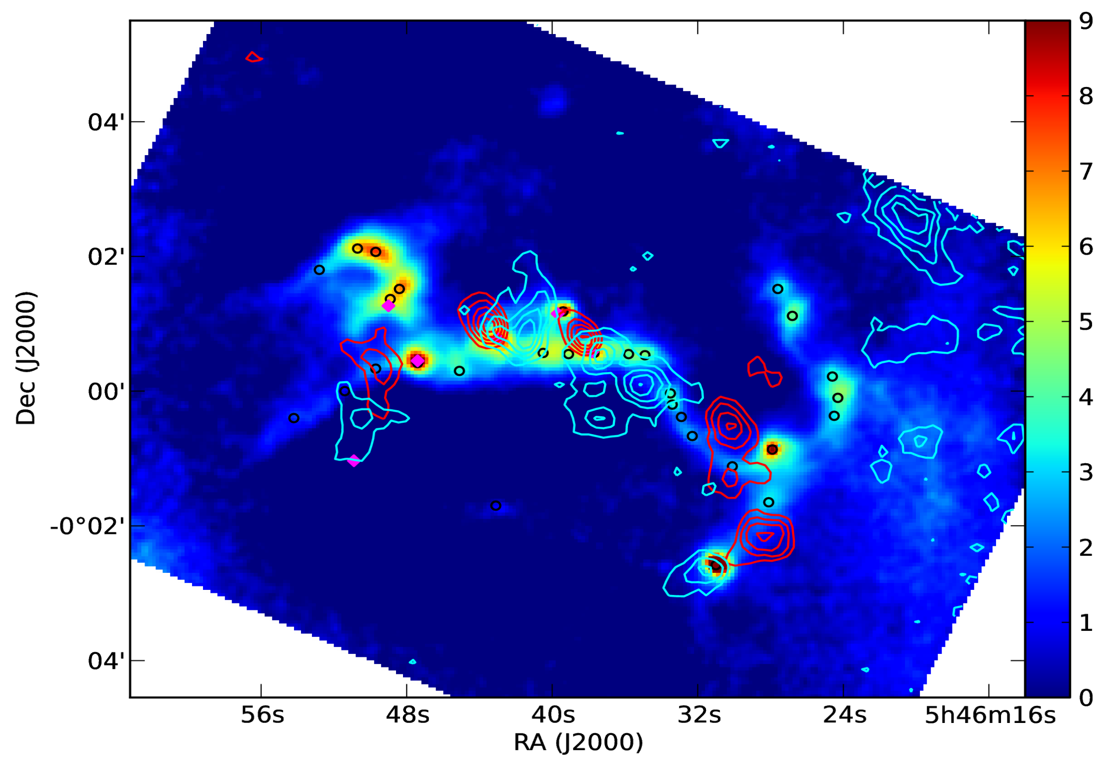


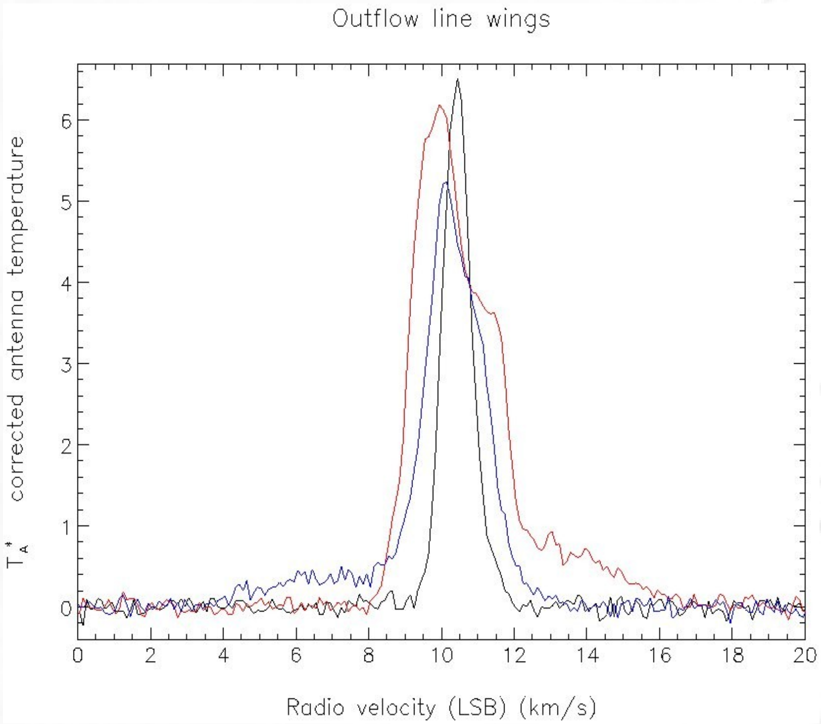
- Gradient across the region from W (9 kms^{-1}) to E (11 kms^{-1})
  - Indicative of large-scale rotation
- Evidence of multiple components along the line of sight
  - Double-peaked emission at the same velocity for both ^{13}CO and $C^{18}O$





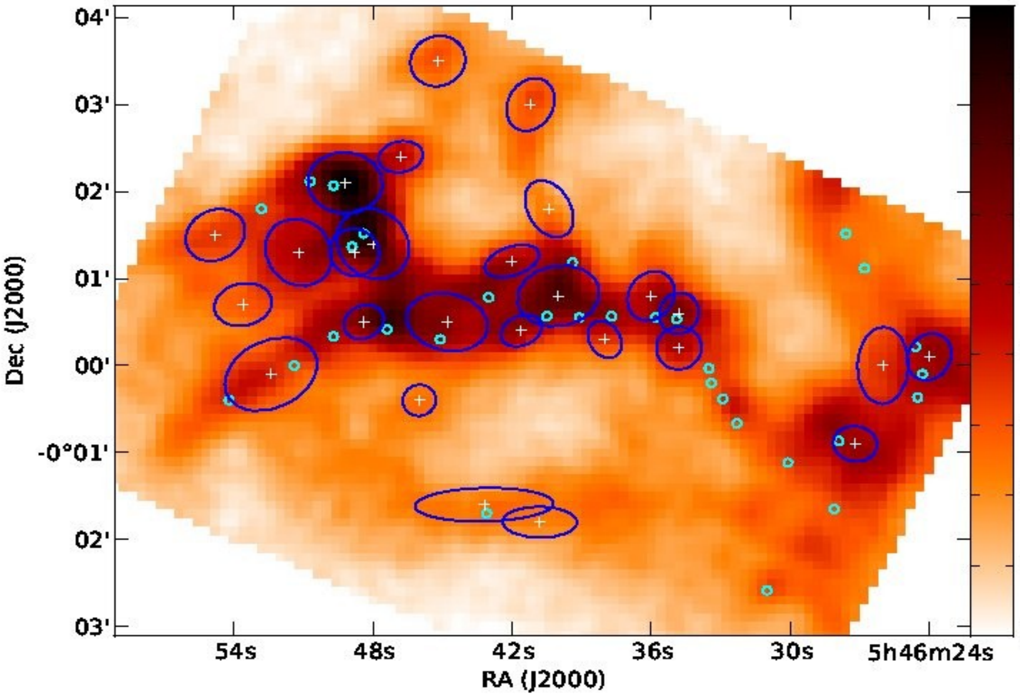
Outflows

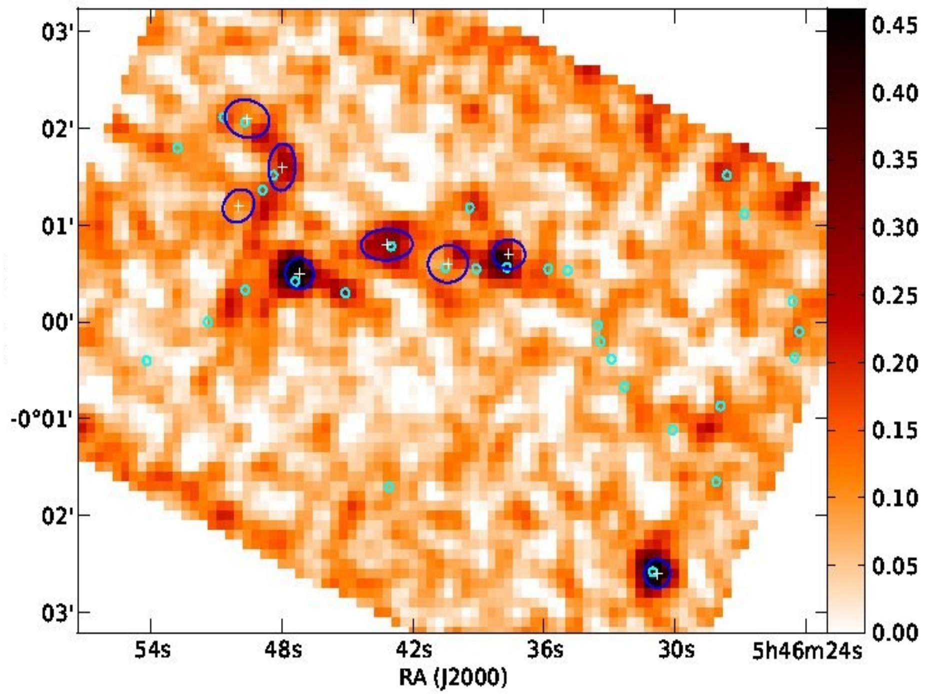




- Ubiquitous in star formation regions
- Seen in spectra as red and blue linewings
- Can be matched to known SCUBA dust cores to pinpoint protostellar cores

Clump Decomposition



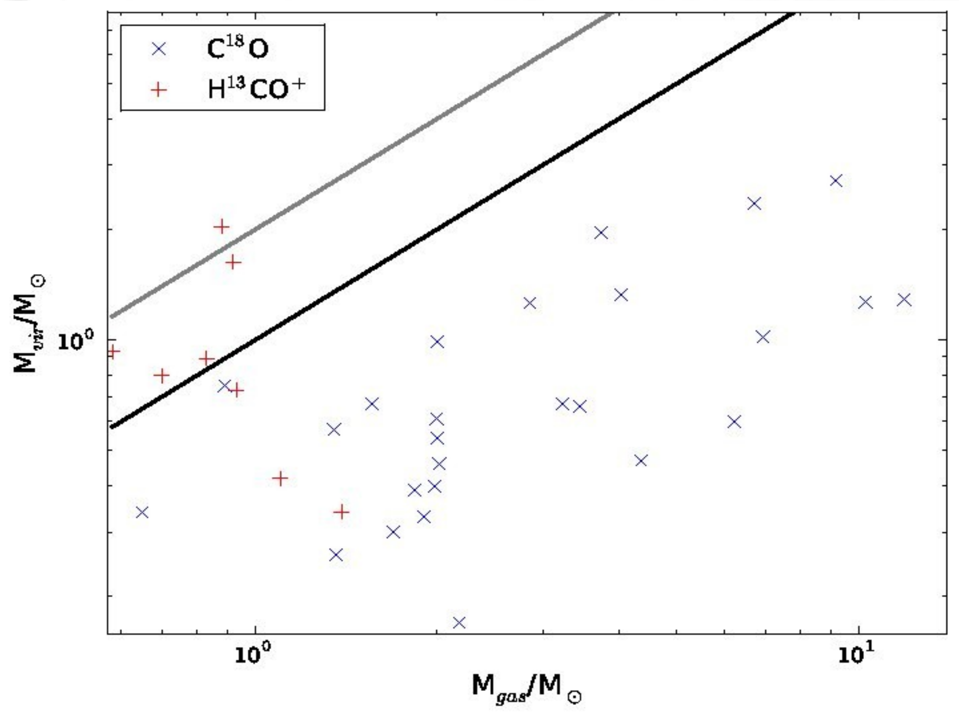


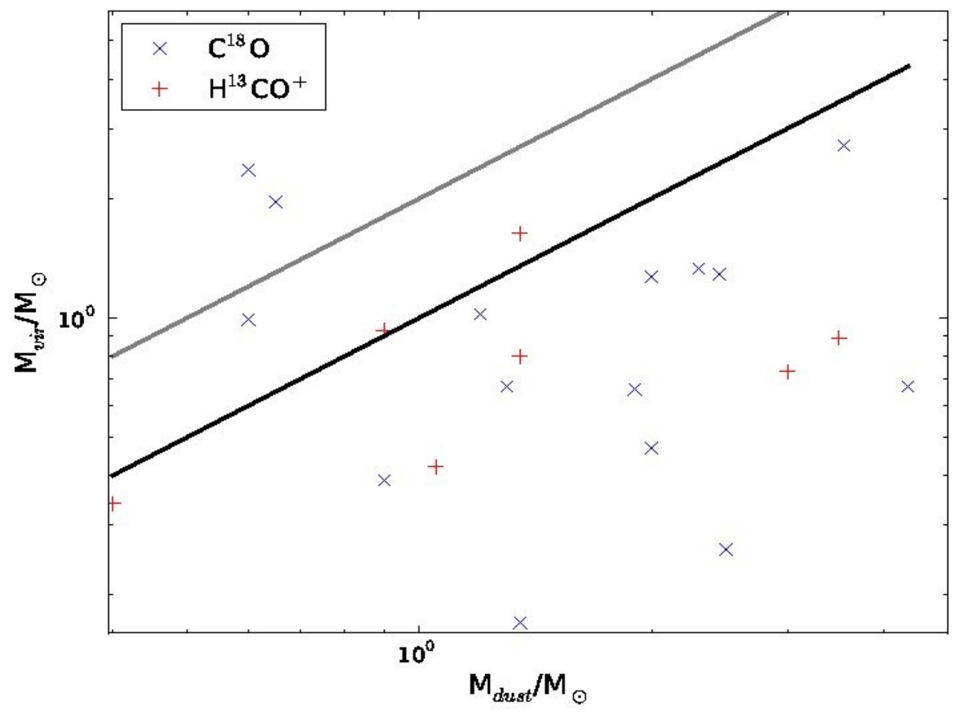
- Break down the emission into smaller clumps/cores
- Gaussclumps algorithm
- Comparisons with SCUBA dust cores/protostellar objects can be made

Calculating Clump Masses

- Virial Mass M_{vir}: measure of the internal energy of the clump
- Gas Mass M_{gas}: measure of the potential energy of the clump
- Simplistically, comparing the two should determine if the clumps are bound
  - $M_{vir} \leq 2M_{gas}$: Bound
  - $M_{vir} \leq M_{gas}$: Equipartition

How bound are the clumps?





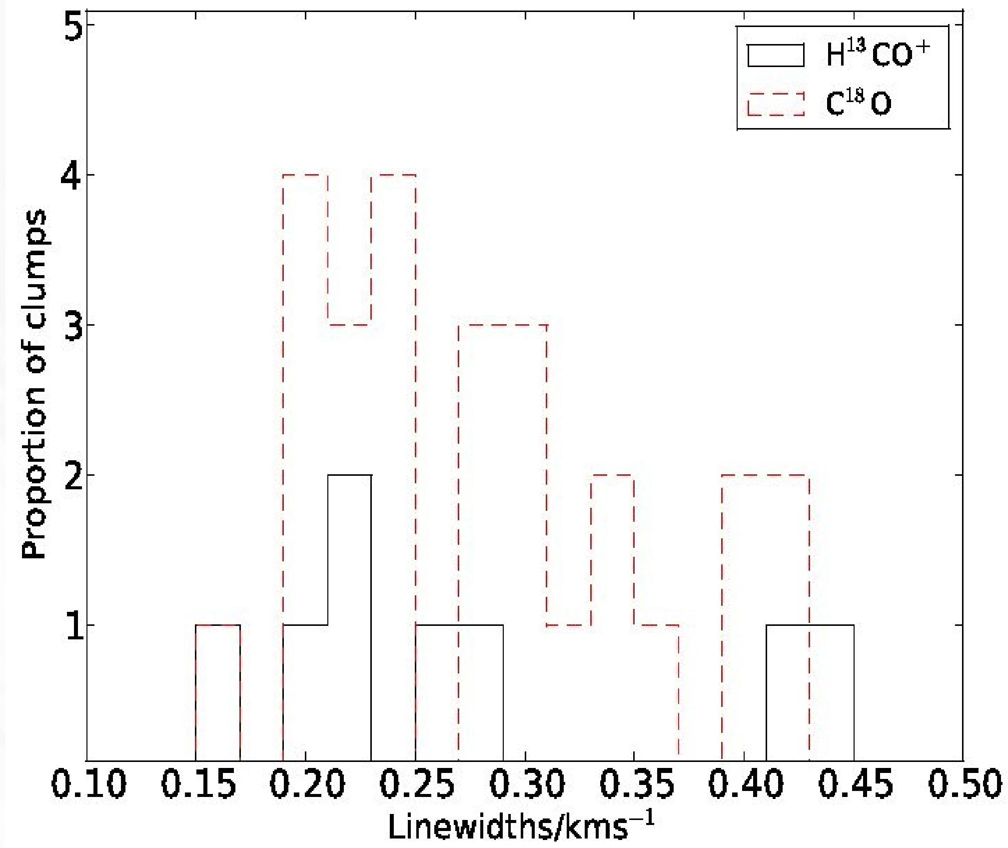
- Using M_{gas} values can give an overestimate

  - $C^{18}O$ appears more bound despite tracing larger, less dense structures

- Using SCUBA dust masses M_{dust} gives a good estimate for $H^{13}CO^+$

Internal velocity dispersions

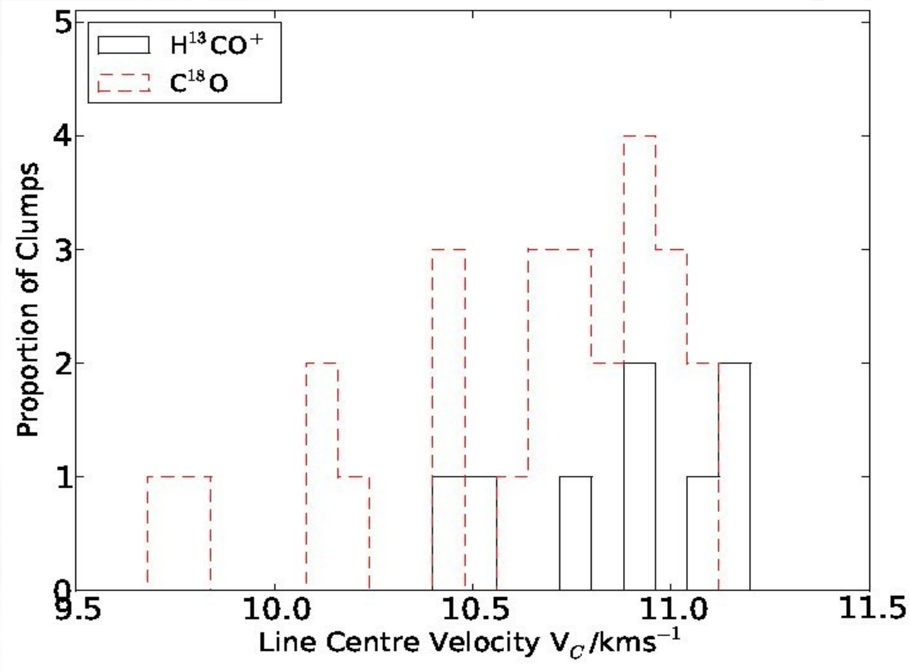
- Comparing linewidths for different molecules shows the different regions traced
- $C^{18}O$ linewidths are on average larger than $H^{13}CO^+$
- $C^{18}O$ traces the more turbulent envelopes, $H^{13}CO^+$ traces the denser, less turbulent core



Inter-clump velocity dispersions σ_{ν}

- Comparing inter-clump σ_{ν} to bulk gas linewidth σ_{g}
  - Ratio value closer to 1 means the clumps are still coupled to the bulk gas

- σ_{ν} also tells us the nature of turbulence present
  - Lower dispersions indicate turbulence has been dissipated in shocks



Conclusions

- $H^{13}CO^+$ starless clumps have subsonic linewidths: formed at local turbulence minima, consistent with gravoturbulent fragmentation.
- $\sigma_\nu \sim \sigma_g$ indicates coupling between star-forming cores and bulk gas.
- Inter-clump velocity dispersions match predictions of decaying turbulence from numerical simulations
- A larger statistical sample is required to conclusively determine type of turbulence.

Thanks for listening!

Questions?