Thesis (Phase 1)

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Under the guidance of

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Spectroscopic Modelling of Cold ATLASGAL Dust Clumps

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MOTIVATION

- High mass star formation is poorly understood.
- Detailed **spectroscopic analysis** of molecular emission from multiple molecules to study the physical properties & kinematics dense clumps.

Molecular Cloud Tracers

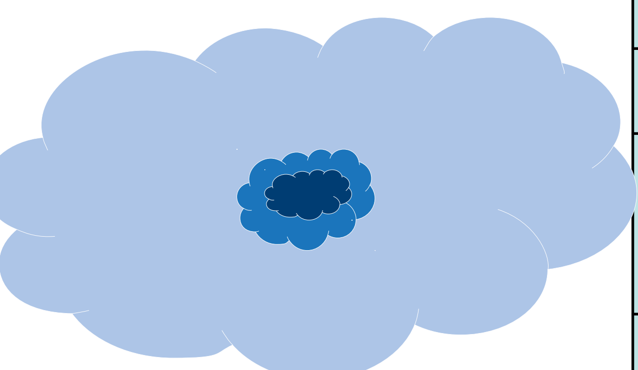
Indirect probes for estimation of H_2

- H_2 **(μ~0)**; has a small Inertia & its first rotational transition (J=2-0) at 28.2 μm corresponding to $h\nu/k \simeq 508$K, requires $T_{kin} \sim 150$K.

$$E_{\mathrm{rot}} = \frac{J(J+1)\hbar^2}{2I}, \qquad J = 0,\ 1,\ 2, \ldots$$

- **Critical Density** (n_{crit})

  for rotational transitions : $\mathbf{n}_{crit} \propto \boldsymbol{\mu}^2 \boldsymbol{\nu}^3$



	CO	HCN	HCO$^+$
μ (Debye)	0.11	2.98	3.889
n_{crit} (cm^{-3})	300	10^4	10^5
n_{H2} (cm^{-3})	10^2-10^3	10^4-10^5	10^5-10^6
Properties	Less dense gas, Extent, structure & kinematics	Denser gas, Kinematics of Infall tracer, Outflows	
Abundance Ratio with H_2	10^{-5}	10^{-10}	2.5×10^{-10}

Goldsmith, 1999
Klessen, 2011

LTE Model

CO & its Isotopologues

Radiative transfer equation

$$I_\nu(\tau_\nu) = [S_\nu - I_\nu(0)]\,(1 - e^{-\tau_\nu})$$

(hν/kT << 1)

$$T_{MB} = \eta \frac{h\nu}{k_B}\left[\frac{1}{e^{h\nu/kT_{ex}} - 1} - \frac{1}{e^{h\nu/kT_{bg}} - 1}\right](1 - e^{-\tau_\nu})$$

Step 1 :
Excitation Temperature
for CO (τ >>1)

Step 2 : **Optical Depth** for ^{13}CO & C^{18}O

$$\alpha_\nu = \frac{h\nu}{4\pi}\phi(\nu)\,[n_{J-1}B_{J-1,J} - n_J B_{J,J-1}]$$

$$\tau_\nu = \int \alpha_\nu ds$$

$$N = \frac{3}{16\sqrt{\pi^5 \log 2}} \frac{\Delta v k T_{ex}}{J\mu^2 B_o} \frac{e^{J(J+1)hB_o/kT_{ex}}}{(e^{2B_oJh/kT_{ex}} - 1)}\tau_\nu$$

Step 3 : **Column Density** for ^{13}CO & C^{18}O

Goldsmith and Langer, 1999
Padoan et al., 1997

LTE Model

for two Optically Thin Species

- Taking example of optically thin *HCO^+ & $H^{13}CO^+$*

$$\frac{\tau_{12}}{\tau_{13}} = \frac{(NJ\mu^2 B_o)_{12}}{(NJ\mu^2 B_o)_{13}} \frac{\Delta v_{13}}{\Delta v_{12}} \left[\frac{(e^{2B_o Jh/kT_{ex}} - 1)_{12}}{(e^{2B_o Jh/kT_{ex}} - 1)_{13}} \right] \left[e^{(J(J+1)hB_o/kT_{ex})_{13} - (J(J+1)hB_o/kT_{ex})_{12}} \right]$$

$$\frac{T_{MB_{12}}}{T_{MB_{13}}} = \left[\frac{J_{\nu_{12}}(T_{ex}) - J_{\nu_{12}}(T_{bg})}{J_{\nu_{12}}(T_{ex}) - J_{\nu_{13}}(T_{bg})} \right] \frac{\tau_{12}}{\tau_{13}}$$

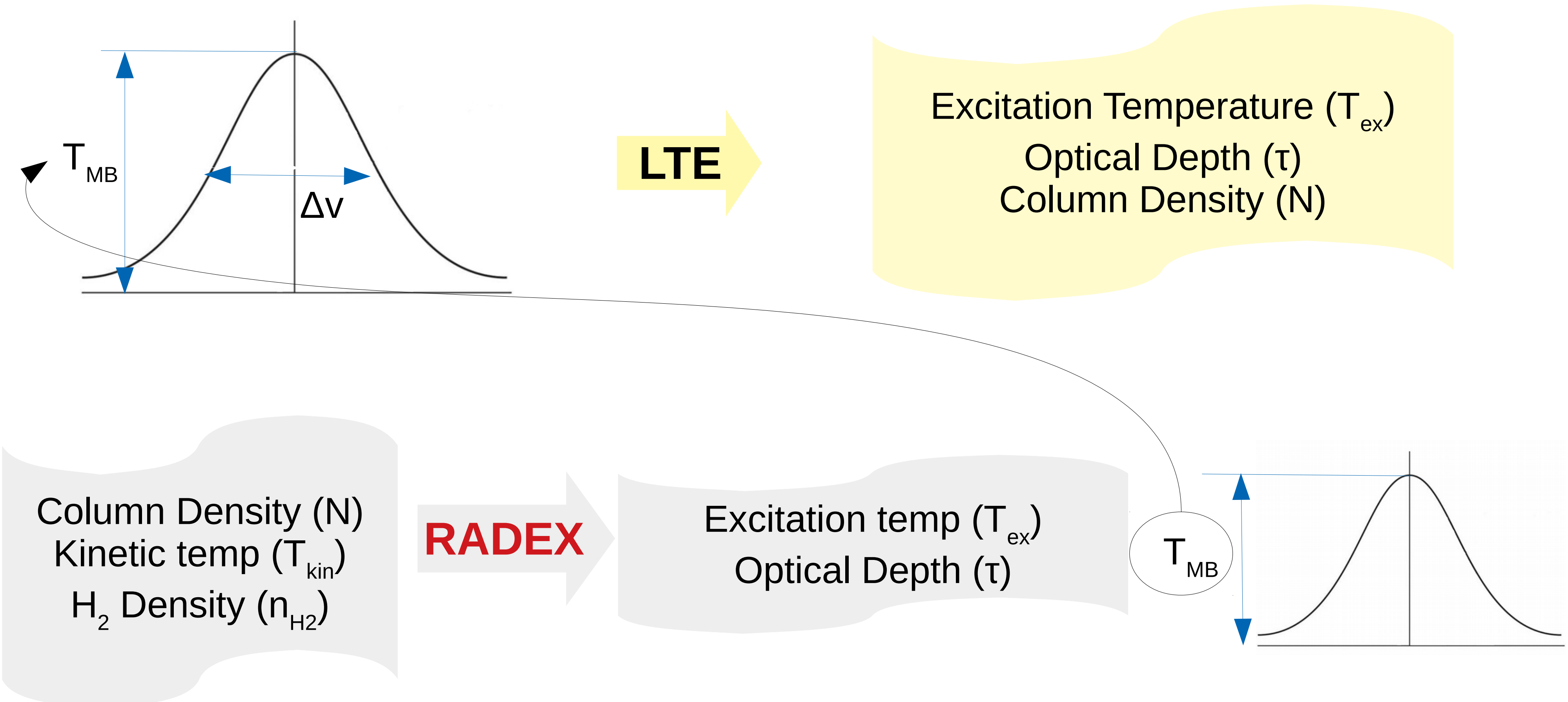
$[HCO^+/H^{13}CO^+]$ =
$[^{12}CO/^{13}CO]$ = 50-90

Step 1 :
Excitation Temperature

Step 2 : **Optical Depth**

Step 3 : **Column Density**

LTE & RADEX Model



Van der Tak et al., 2007

LTE & RADEX Model

- *CO & its Isotopologues*

Method	CO				^{13}CO				C^{18}O			
	T_{MB} (K)	T_{ex} (K)	τ	N (cm^{-2})	T_{MB} (K)	T_{ex} (K)	τ	N (cm^{-2})	T_{MB} (K)	T_{ex} (K)	τ	N (cm^{-2})
RADEX	10.8	14.318	4.753	5×10^{16}	0.55	9.039	0.1	5×10^{14}	0.114	8.899	0.026	1×10^{14}
LTE	10.8	14.27	-	4×10^{16}	0.55	14.27	0.05	5.75×10^{14}	0.114	14.27	0.01	1.19×10^{14}

- *Two Optically Thin Species : HCO^+ & $H^{13}CO^+$*

Method	HCO$^+$				H^{13}CO$^+$			
	T_{MB} (K)	T_{ex} (K)	τ	N (cm^{-2})	T_{MB} (K)	T_{ex} (K)	τ	N (cm^{-2})
RADEX	1.982	10.56	0.64	5×10^{12}	0.024	10.75	0.005	5×10^{10}
LTE	1.982	8.33	0.81	1.1×10^{13}	0.024	8.33	0.009	1.2×10^{11}

Project

- ***AIM :*** To study *physical properties & kinematics* of dense clumps selected from ATLASGAL 870 µm survey.

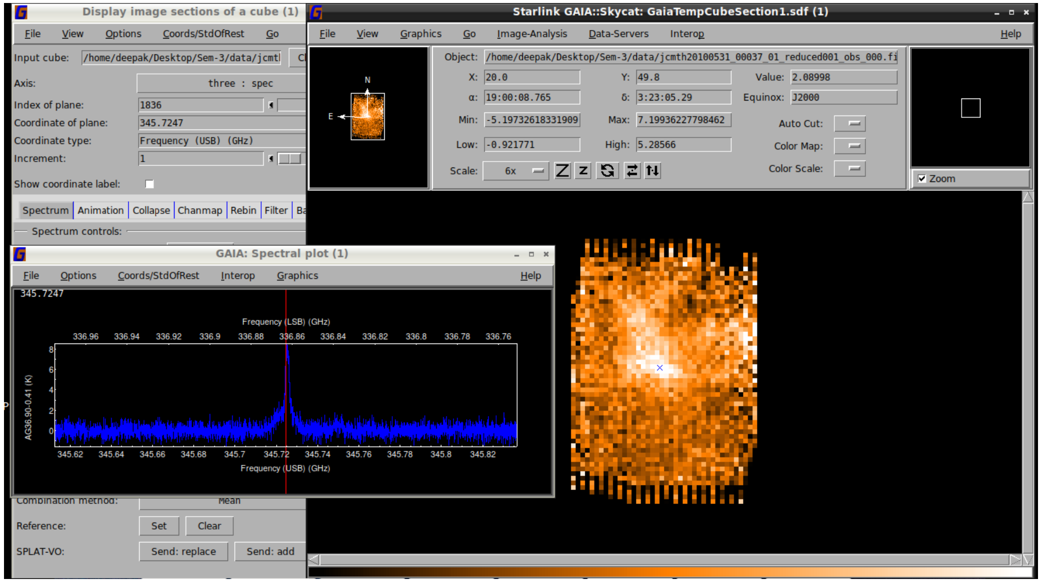
S.N.	Name	α (J2000) (h,m,s)	δ (J2000) ($^\circ$ $'$ $''$)	S_P at 870 μm (Jy/beam)	V_{LSR} (km/s)
1	AG 36.899-00.409	19:00:08.48	03:20:35.70	0.93	80
2	AG 36.794-00.204	18:59:13.11	03:20:36.80	0.69	78.1
3	AG 36.826-00.039	18:58:41.31	03:26:49.60	0.64	60.2
4	AG 41.049-00.247	19:07:12.48	07:06:19.30	1.05	66
5	AG 41.077-00.124	19:06:49.15	07:11:14.10	0.65	63.3
6	AG 46.174-00.524	19:17:49.80	11:31:07.50	0.8	50.1
7	AG 46.426-00.237	19:17:16.48	11:52:30.50	0.94	52.3
8	AG 47.031-00.244	19:16:41.18	12:38:05.90	0.95	54.9
9	AG 47.051-00.251	19:16:42.03	12:39:20.70	1.19	56
10	AG 49.253-00.411	19:23:21.22	14:17:22.10	1.16	66.1

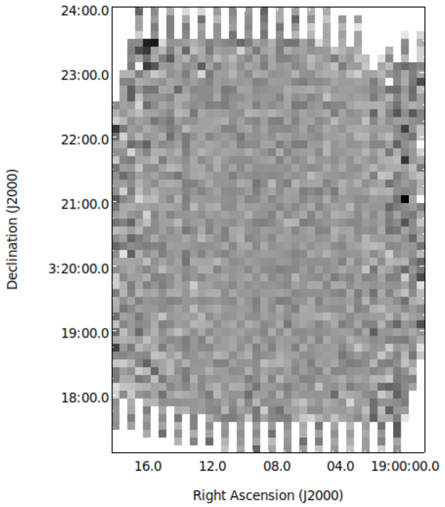
- Sources were mapped in multiple molecules such as ^{12}CO, ^{13}CO, $C^{18}O$ & high gas tracers HCO^+, $H^{13}CO^+$, HCN, N_2H^+.

Schuller et al., 2009

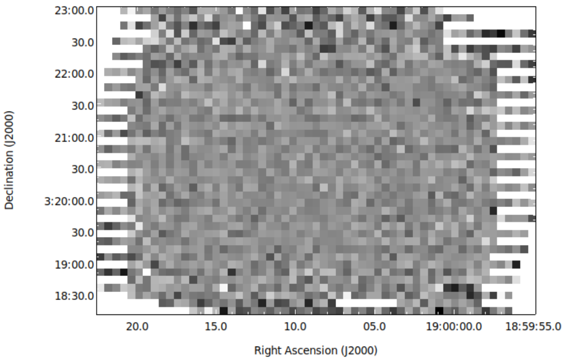
Analyzing Data

Modifying DATA in STARLINK

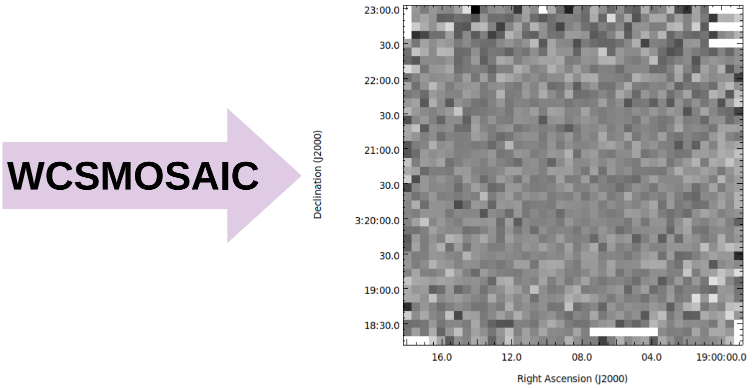




Scan 1



Scan 2



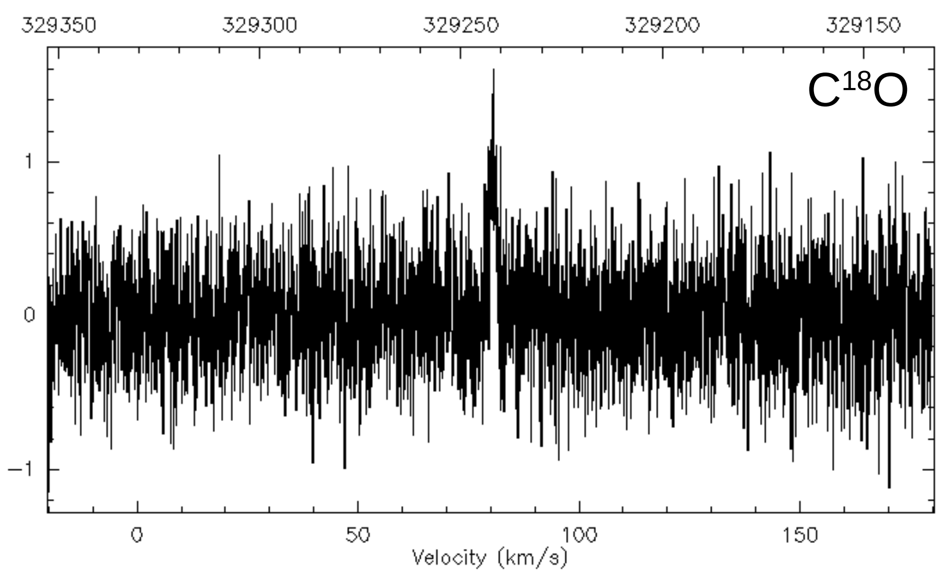
Analyzing Data for Single Pixel

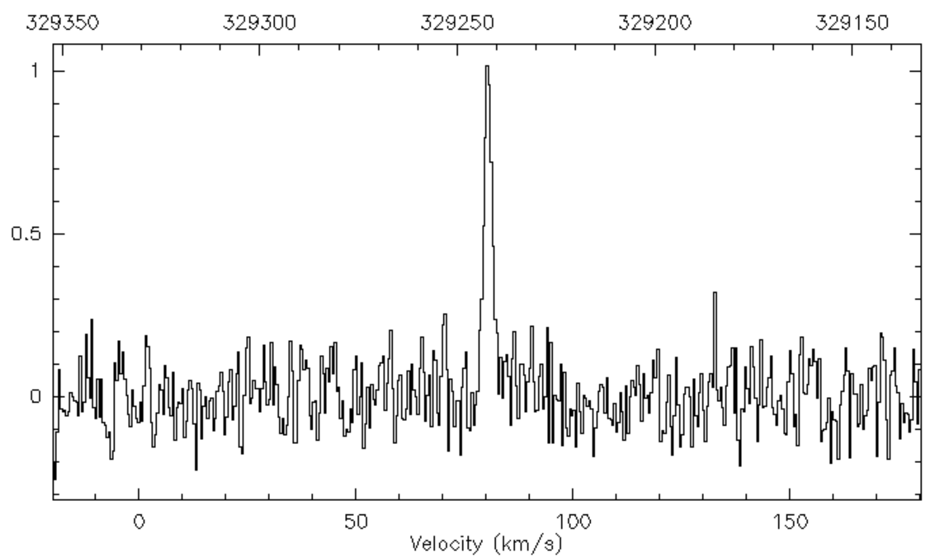
Smoothing & Fitting using CLASS (GILDAS)

- Barycentric to **LSRK** frame

$$V_{LSR} = V_{bary} + (10.3\cos l + 15.3\sin l)\cos b - 7.7\sin b$$

- **Hanning** Smoothing



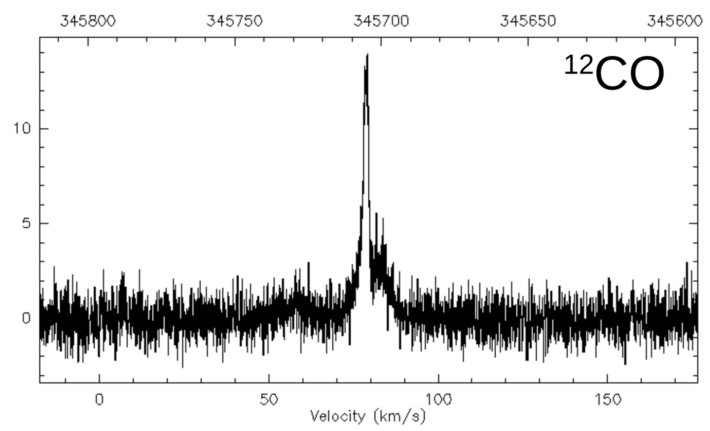


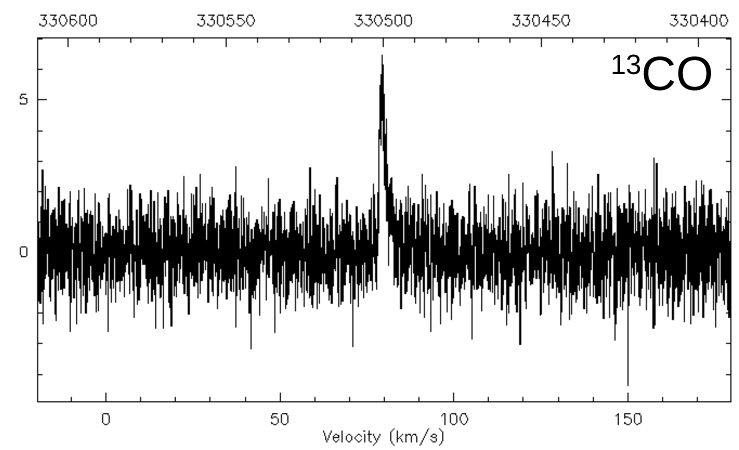
Analyzing Data for Single Pixel

Smoothing & Fitting using CLASS (GILDAS)

Molecules	Before HANNING		After HANNING		
	Velocity Resolution (km/s)	S/N	No. of Channels Smoothed	Velocity Resolution (km/s)	S/N
CO	0.0553	12.059	2	0.1106	19.28
^{13}CO	0.0553	4.506	4	0.2212	10.96
$C^{18}O$	0.0553	1.172	8	0.4424	4.008

- **Baseline** Subtraction **:** polynomial of degree **0**



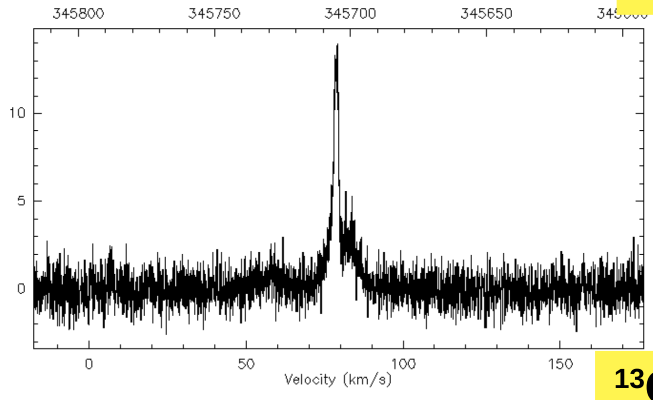


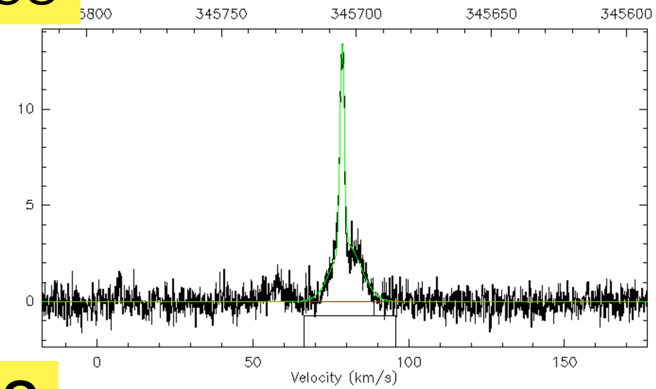
- **Gaussian** fitting : Multiple Gaussian fitting for ^{12}CO & ^{13}CO, while only one for $C^{18}O$

Analyzing Data for Single Pixel

Smoothing & Fitting using CLASS (GILDAS)

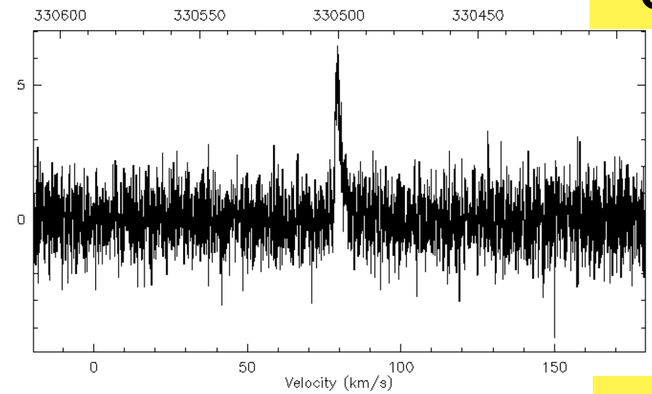
^{12}CO

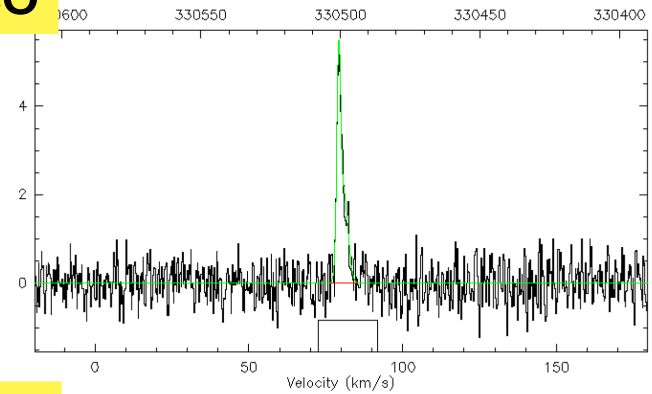




Component	Peak	Line-width	Position	RMS
1	10.5	1.63	78.65	0.52
2	2.987	10.9	80.01	0.52

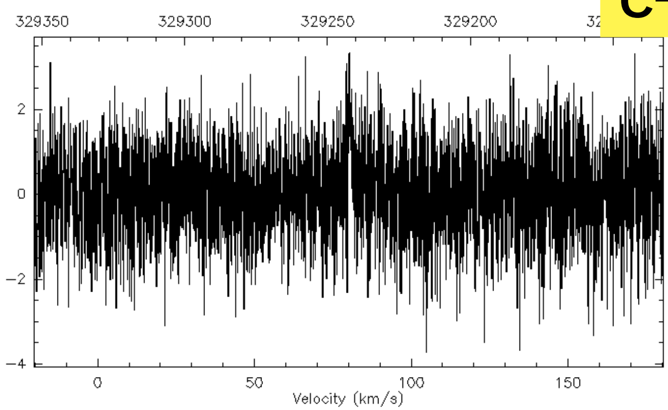
^{13}CO

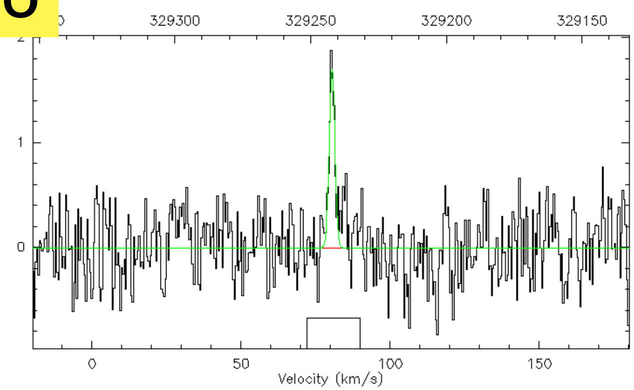




1	4.41	1.46	79.2	0.39
2	2.02	3.34	80.8	0.39

$C^{18}O$



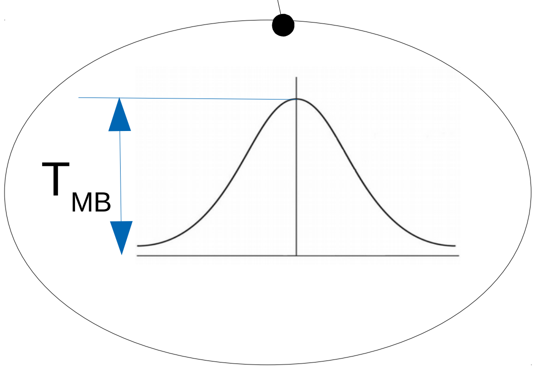


1	1.71	2.22	80.5	0.30

Analyzing Data for Single Pixel

Modelling in CASSIS

CASSIS PARAMETERS						
COLUMN DENSITY - N (cm^{-2})	Excitation Temp - T_{exc} (K)	FWHM (km/s)	SIZE (arcsec)	V_{LSR} (km/s)	ISOTOPIC RATIO	LTE / RADEX



Step 1 :
Optical Depth

Step 2 :
Main Beam Temperature

Step 3 :
Regular Grid/
Markov Chain Monte Carlo

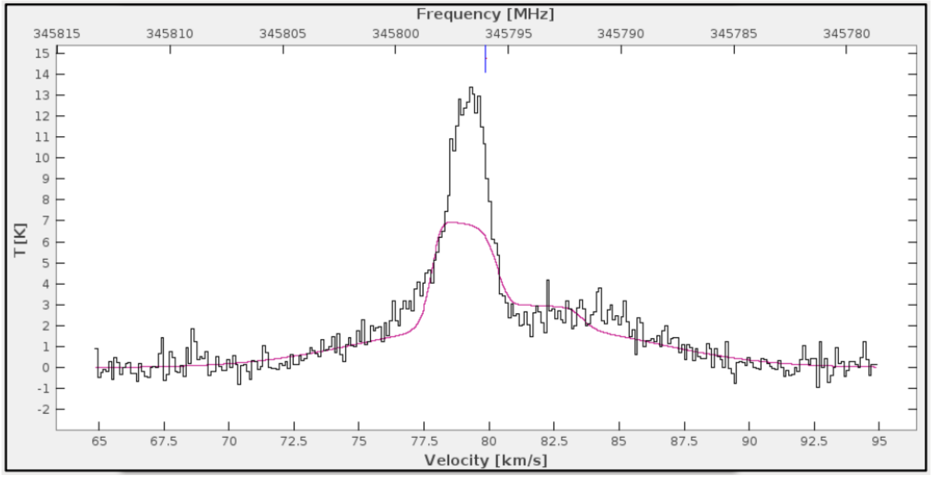
Optimum Fit

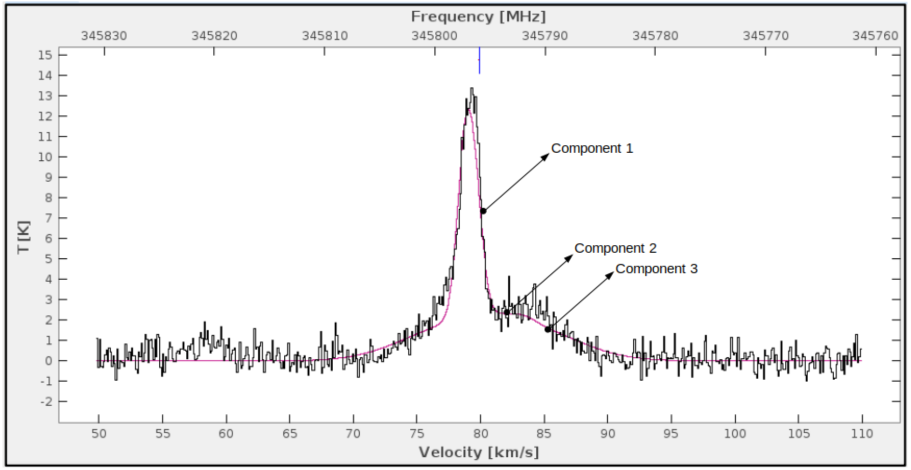
Analyzing Data for Single Pixel

Modelling in CASSIS

- *LTE Model*

T_{ex} (K)	20-25
SIZE ('')	14.7
N (cm^{-2})	6×10^{16}





T_{ex} (K)	90-100
SIZE ('')	14.7
N (cm^{-2})	4×10^{17}

Analyzing Data for Single Pixel

Modelling in CASSIS

- *Main Beam Efficiency (T_{ant} / T_{MB})*

N (cm^{-2})	T_{ex} (K)	TMB (K) (CASSIS)	TMB (K) (LTE)	η_{eff}
10^{16}	40	5.676	10.35	0.55
10^{16}	70	5.34	9.72	
10^{17}	40	17.64	31.64	
10^{17}	70	27.91	50.74	

Tm2bta : False & η_{MB} = 0.64

- *Beam Dilution Factor ($\Theta_s^2 / \Theta_s^2 + \Theta_B^2$)*

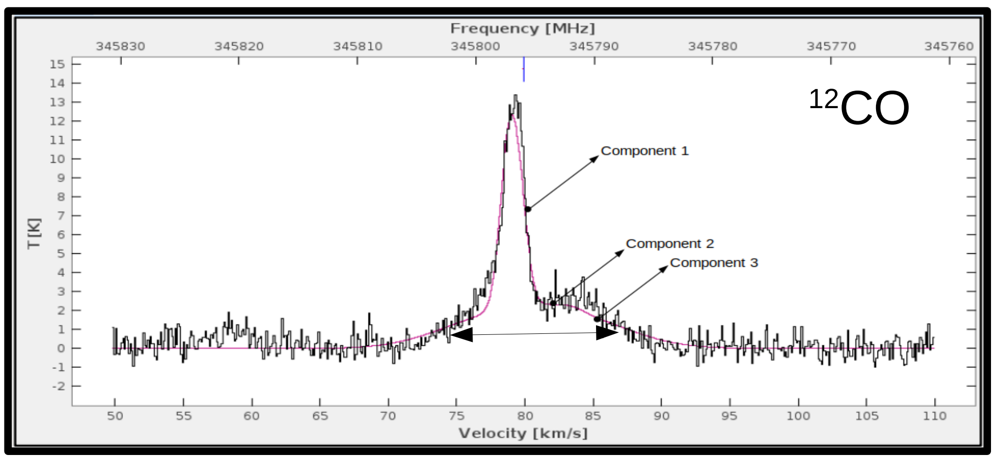
SIZE (")	N (cm^{-2})	T_{ex} (K)	T_{MB} (K) (CASSIS)	T_{MB} (K) (LTE)	($\Theta_s^2 / \Theta_s^2 + \Theta_B^2$)
10	10^{17}	40	10.03	32.36	0.31
40	10^{17}	40	27.84	31.64	0.88
80	10^{17}	40	30.97	31.93	0.97
1000	10^{17}	40	32.4	32.1	1.01

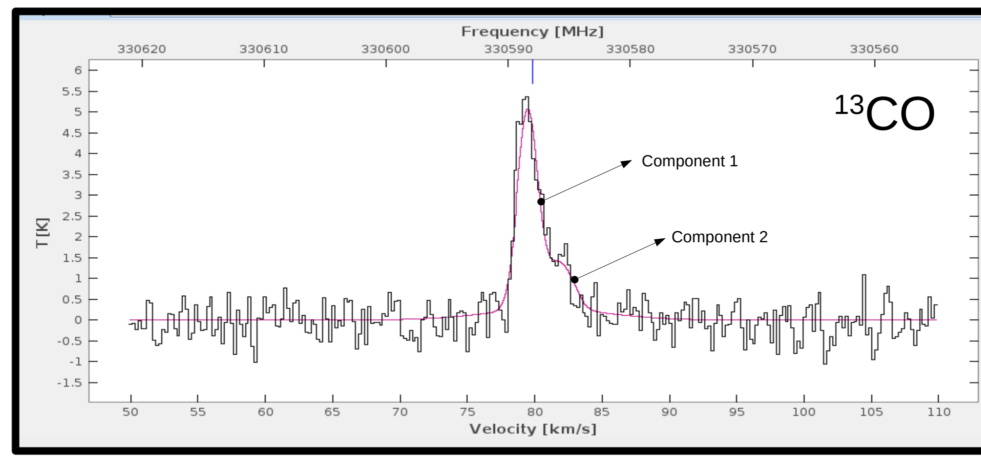
To model source independently of telescope, SIZE = 1000''

Analyzing Data for Single Pixel

Simultaneous Modelling in CASSIS

- Modelling ^{12}CO *with* ^{13}CO



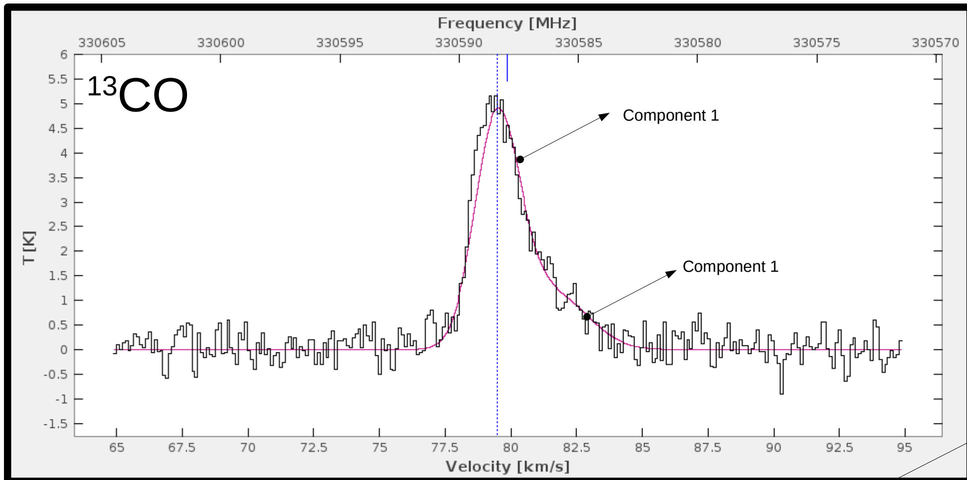


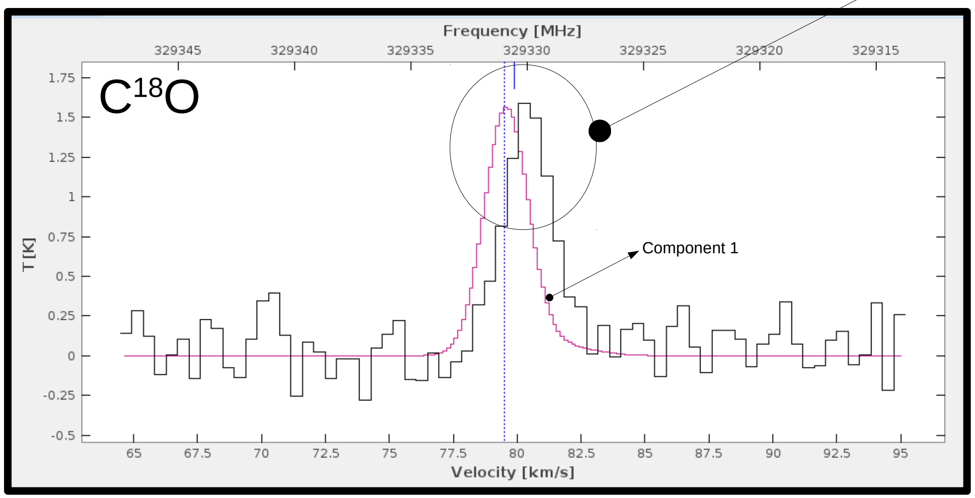
N (cm^{-2})	2 - 4×10^{17}
T_{ex} (K)	35 - 45
Iso	40 - 50

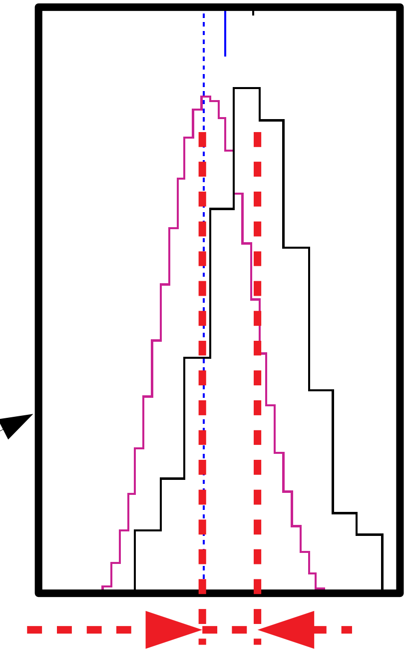
Analyzing Data for Single Pixel

Simultaneous Modelling in CASSIS

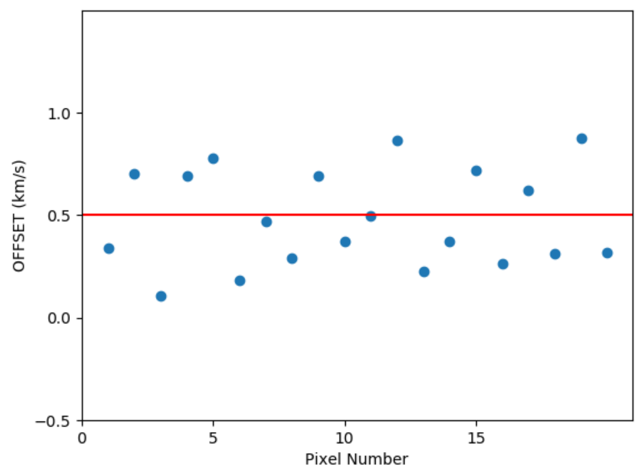
- Modelling ^{13}CO *with* $C^{18}O$



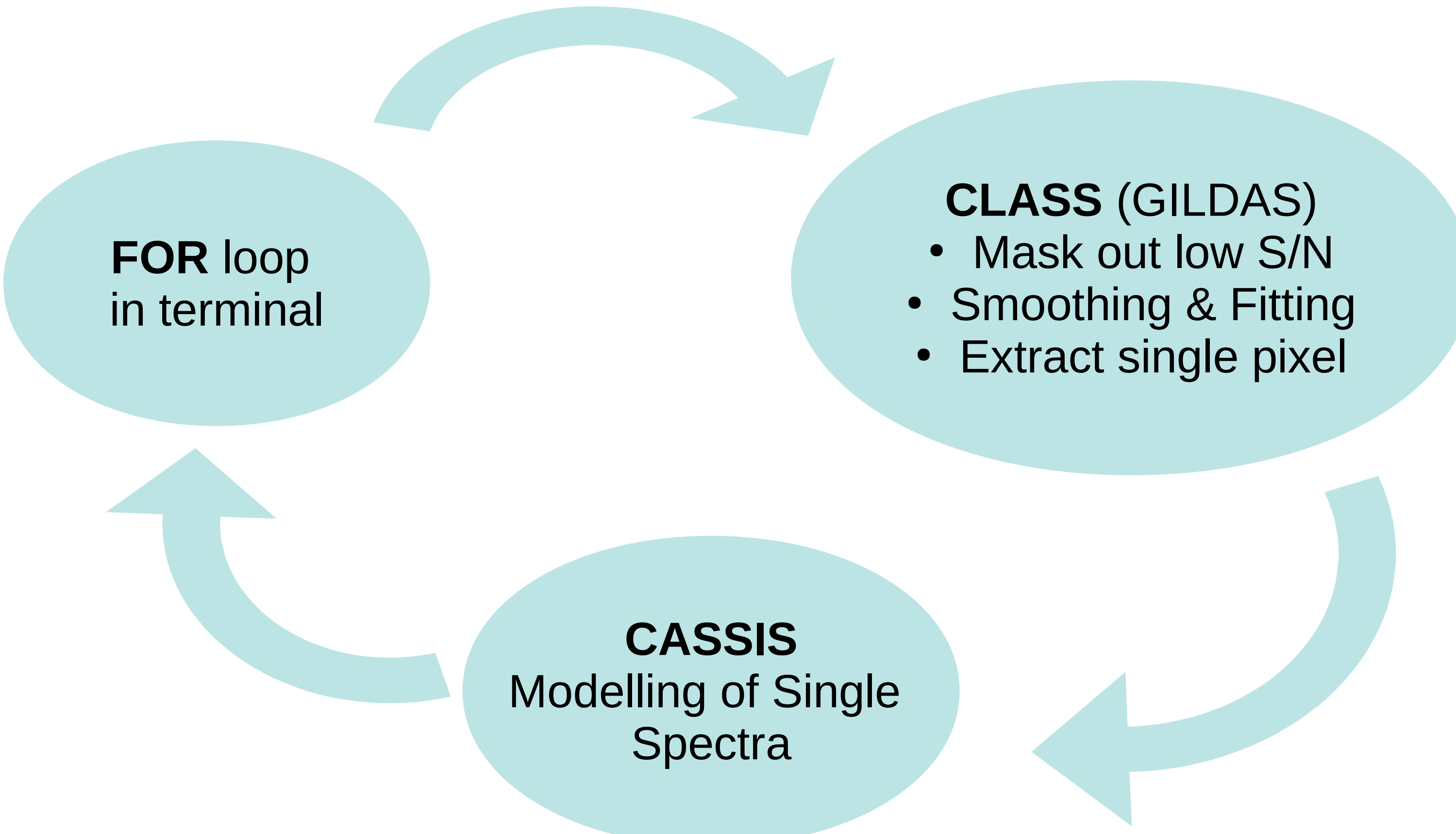




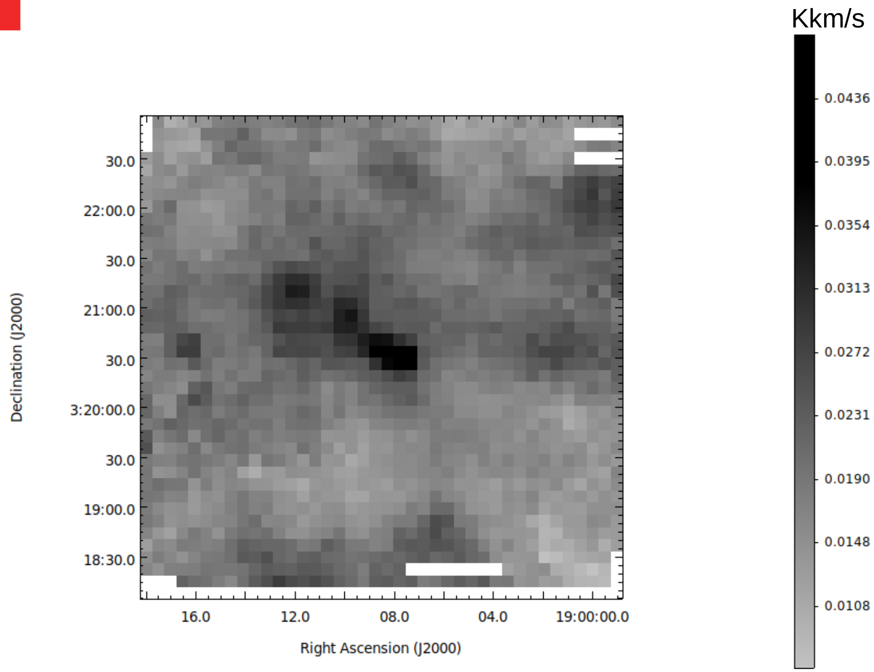
0.5 km/s



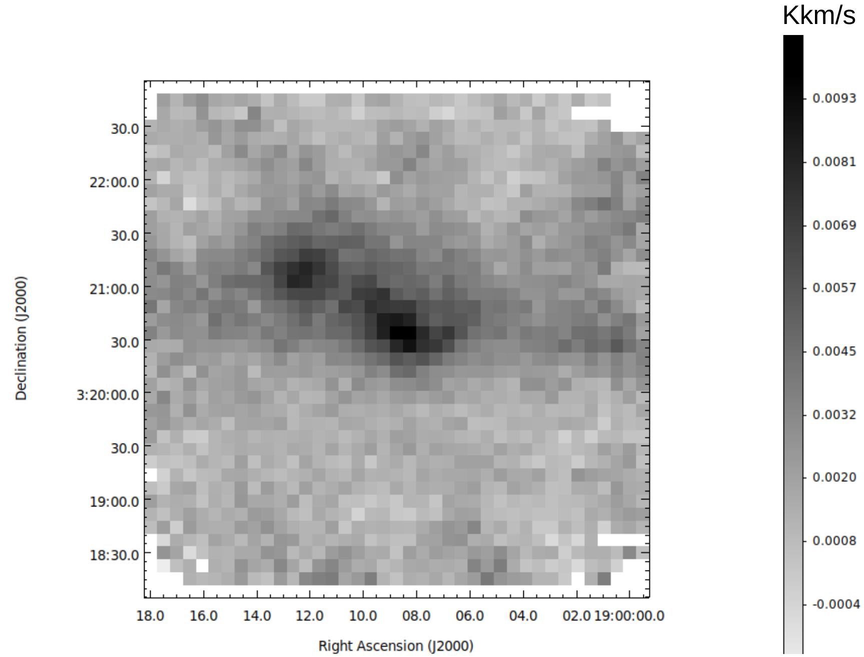
Analyzing Data for All Pixels



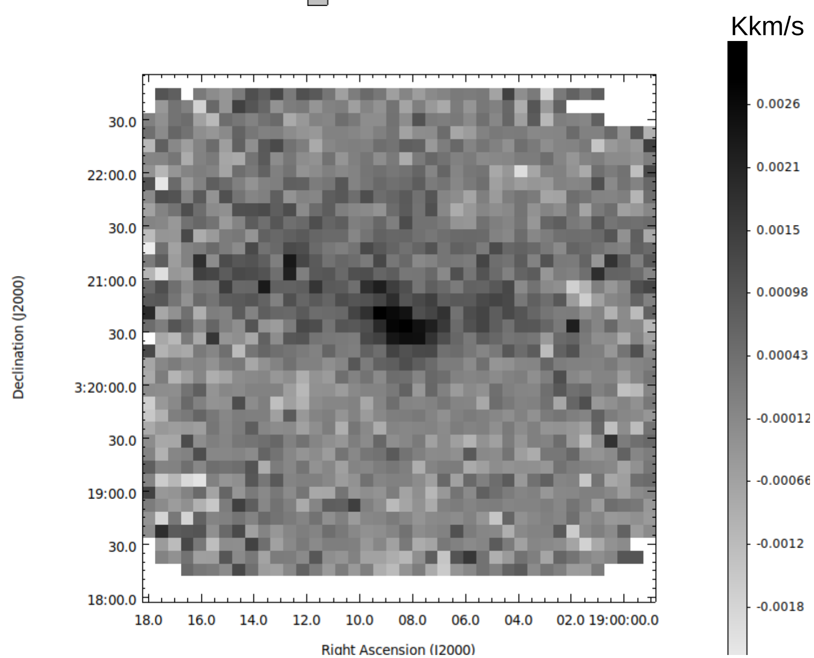
Integrated Intensity Maps



^{12}CO



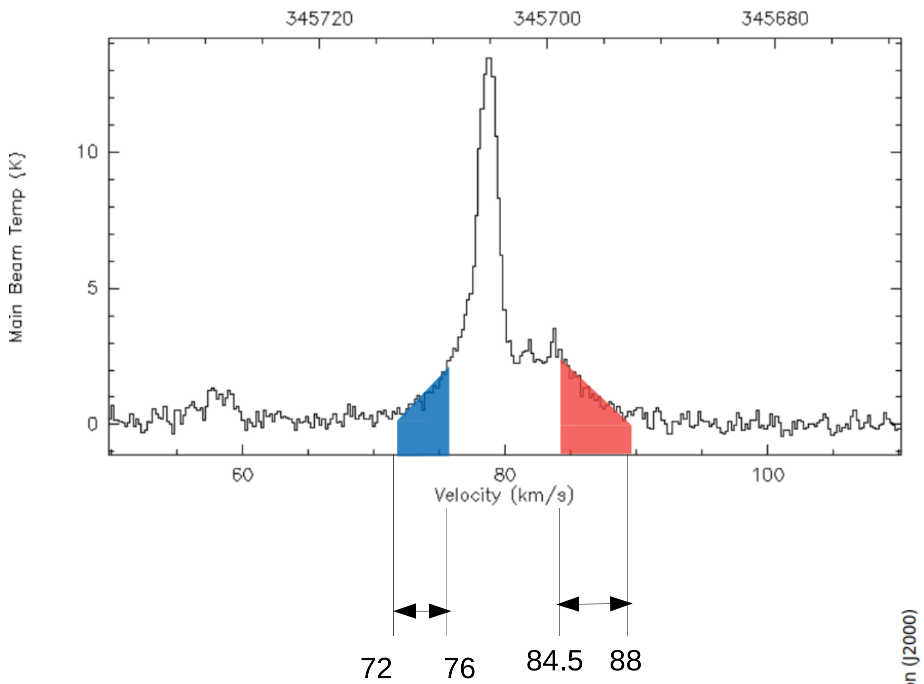
^{13}CO

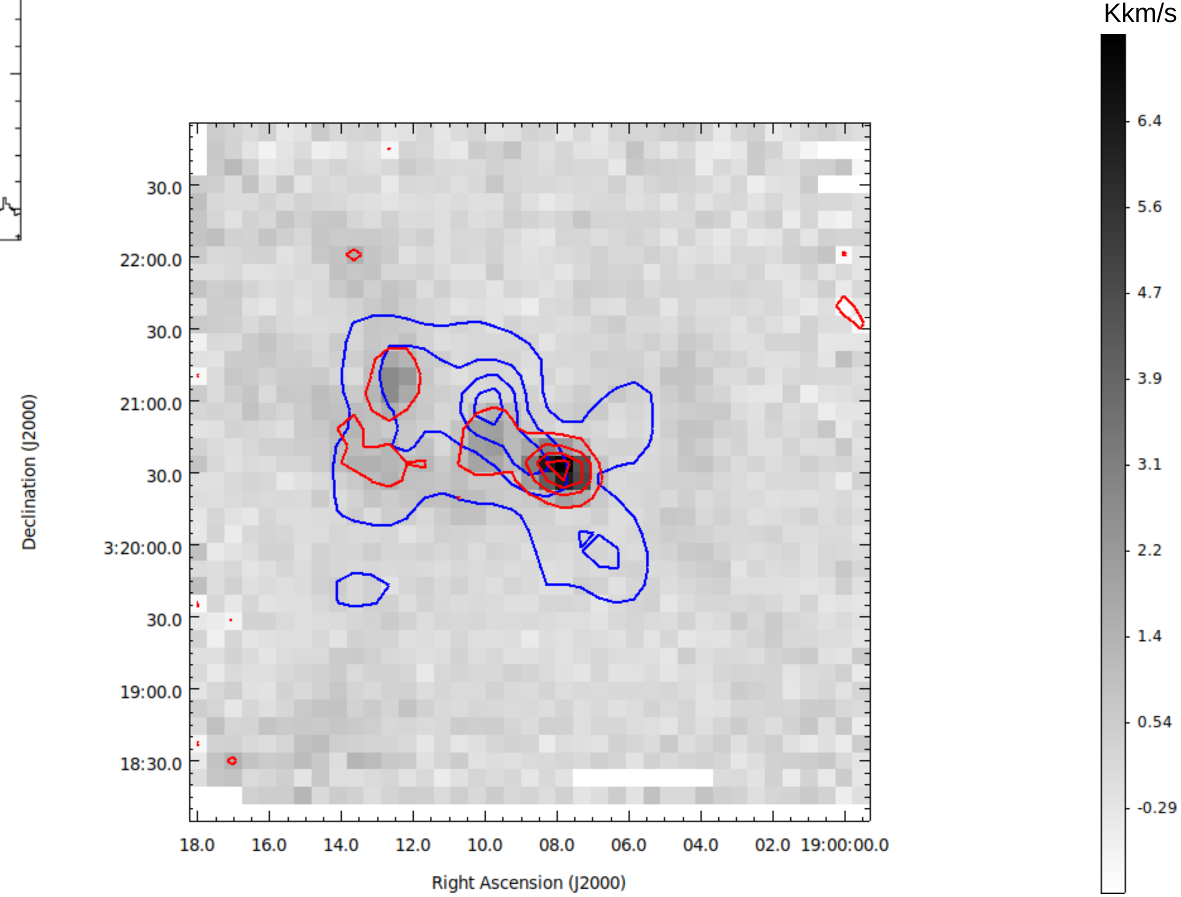


$C^{18}O$

Integrated Intensity Maps

Outflows in CO map



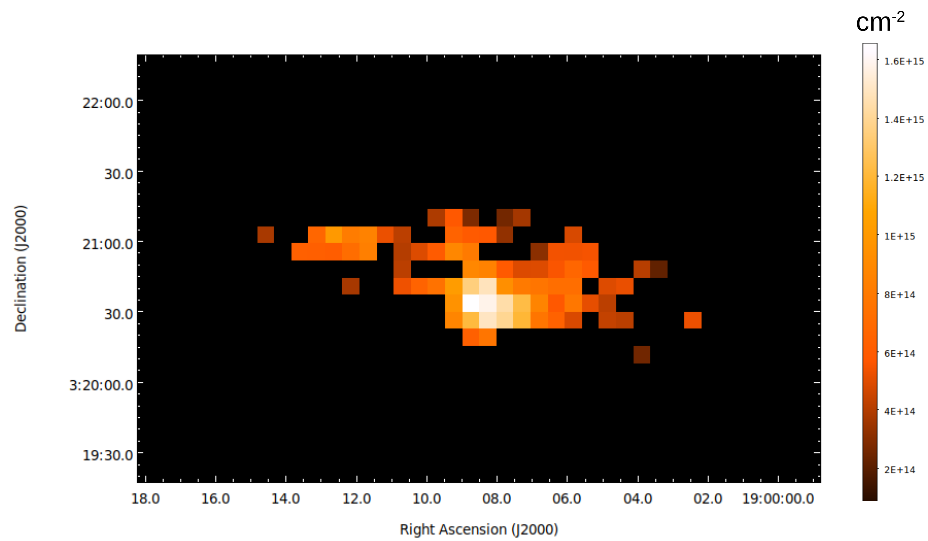


^{12}CO

Modelling Results

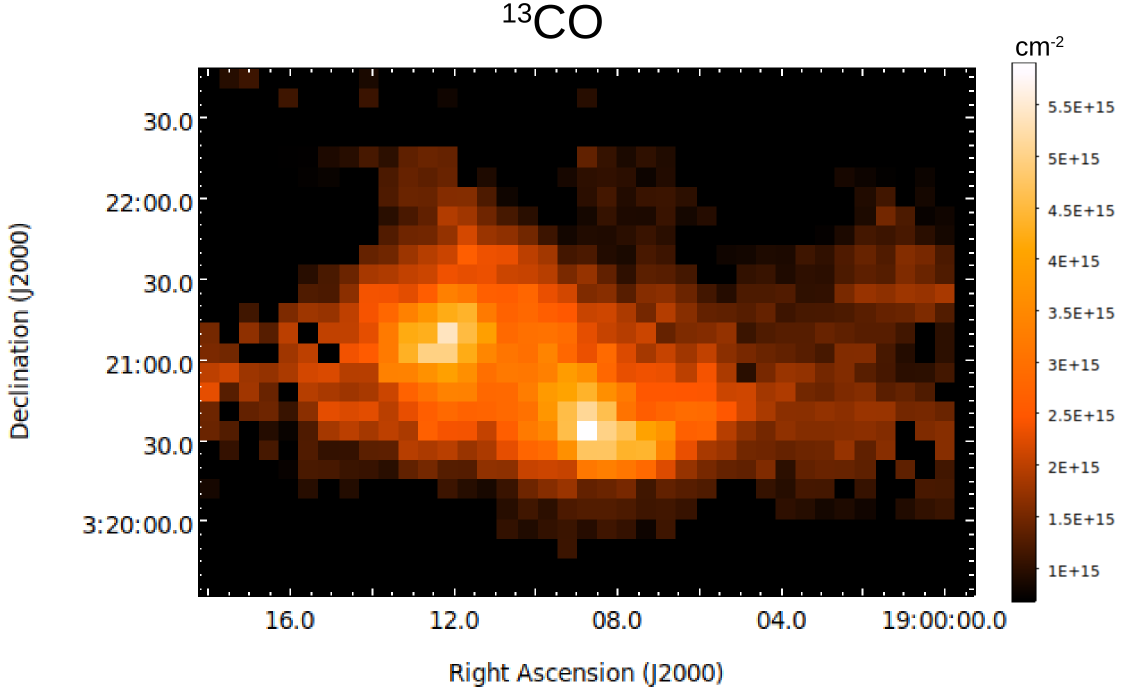
Column Density Maps

^{13}CO	Core 1	Core 2
N (cm^{-2})	5.86×10^{15}	5.2×10^{15}
T_{ex} (K)	29	26
Iso	3.5	6.52



$C^{18}O$

^{13}CO



Modelling Results

Column Density

- *H_2 Column Density* from ATLASGAL 870µm

$$\boxed{I_\nu = B_\nu(T)(1 - e^{-\tau}) = B_\nu(T)\tau}$$

$$\boxed{I_\nu = B_\nu(T)\kappa\mu m_{\mathrm{H}} \int \frac{\rho ds}{\mu m_{\mathrm{H}}}}$$

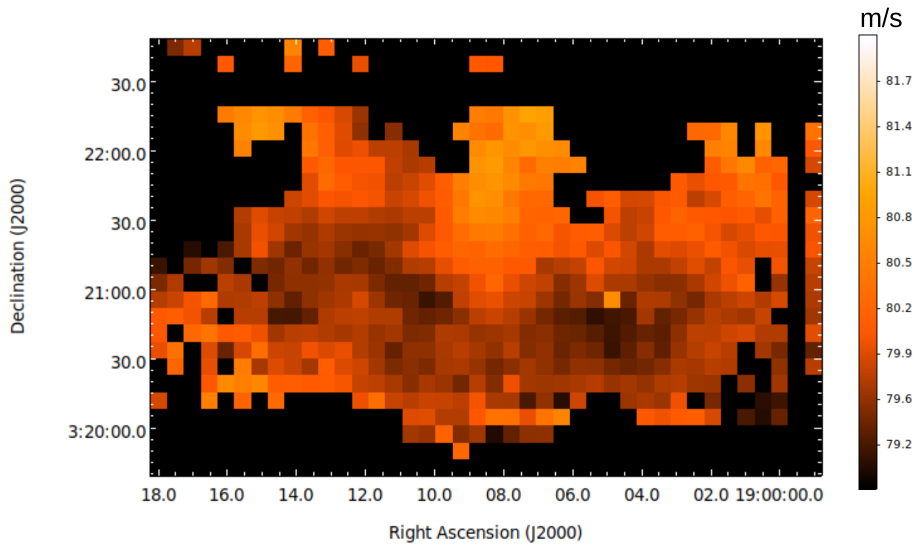
$N(H_2) = 2.2\times10^{22}\mathrm{cm}^{-2}$

$N(^{13}CO) = 5.86\times10^{15}\mathrm{cm}^{-2}$

- $[^{13}CO/H_2] = 2.6\times10^{-7}$, typically observed is $1\text{-}2\times10^{-7}$

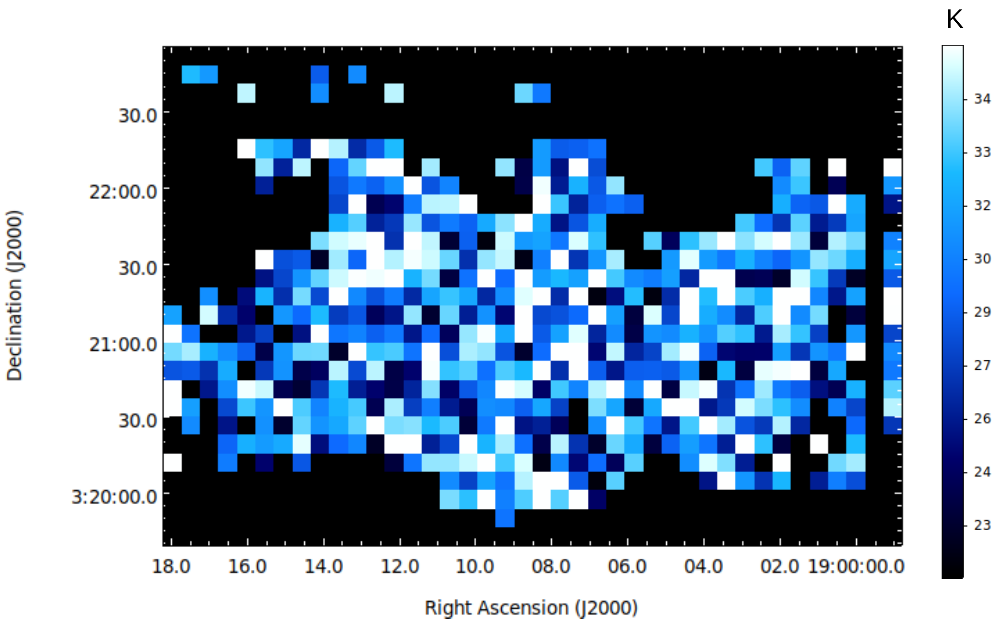
Modelling Results

Excitation Temperature & Velocity



- *Excitation Temperature*

  uniformly distributed (26-34 K)



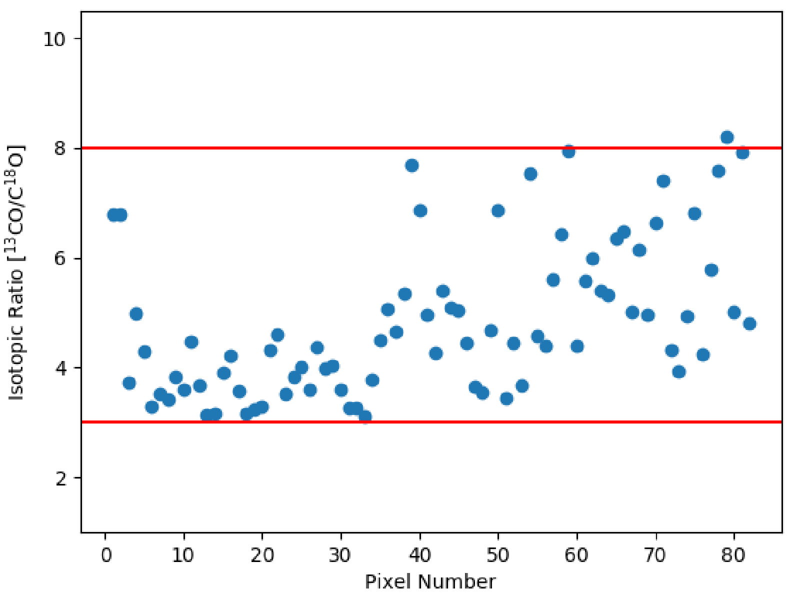
- *Velocity Distribution*

  velocity gradient of 0.5 km/s

Modelling Results

Isotopic Ratio

- Lower abundance ratio ***[$^{13}CO/C^{18}O$] = 3-8***, while typically observed is 7-10.
- Due to dependency of X($^{13}CO/C^{18}O$) on **galactocentric distance** and also on the **physical** conditions of the region.
- LTE Analysis found that average value of abundance ratio is 5, varying from **1.5 to 10.5**.



Wilson and Rood, 1994
Paron et al. 2018

FUTURE WORK

- Estimation of **core** radius, mass, virial ratio etc which will provide more deeper insights about their physical properties.
- **Outflow** properties such as velocity, momentum, energy etc need to be estimated
- Estimation of $\mathbf{T_{dust}}$ **&** $\mathbf{N(H_2)}$ from **ATLASGAL** dust emission at 870μm, 350μm, 250μm, 160μm , using SED fitting.
- **Dense gas** tracers such as HCO^+ ,$H^{13}CO^+$, HCN and N_2H^+ also have to be modelled, corresponding maps need to be generated.
- Other 9 dense clumps also need to be modelled.

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THANK YOU