A Search for Outflows in the SEDIGISM survey

Aiyuan Yang & the SEDIGISM Team

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The SEDIGISM survey: a search for molecular outflows

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Affiliations are listed in the end of the paper

Received , ; accepted ,

Outline

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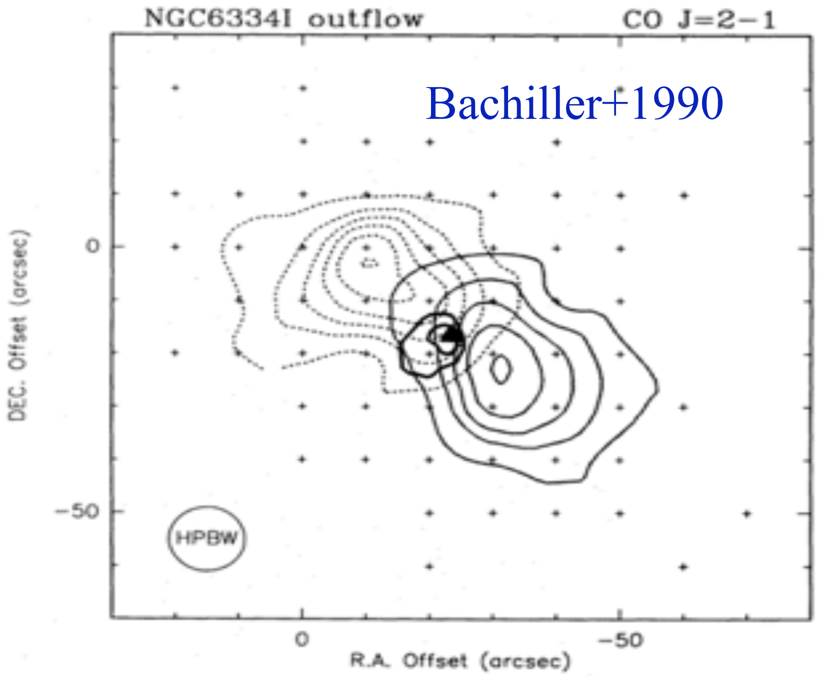
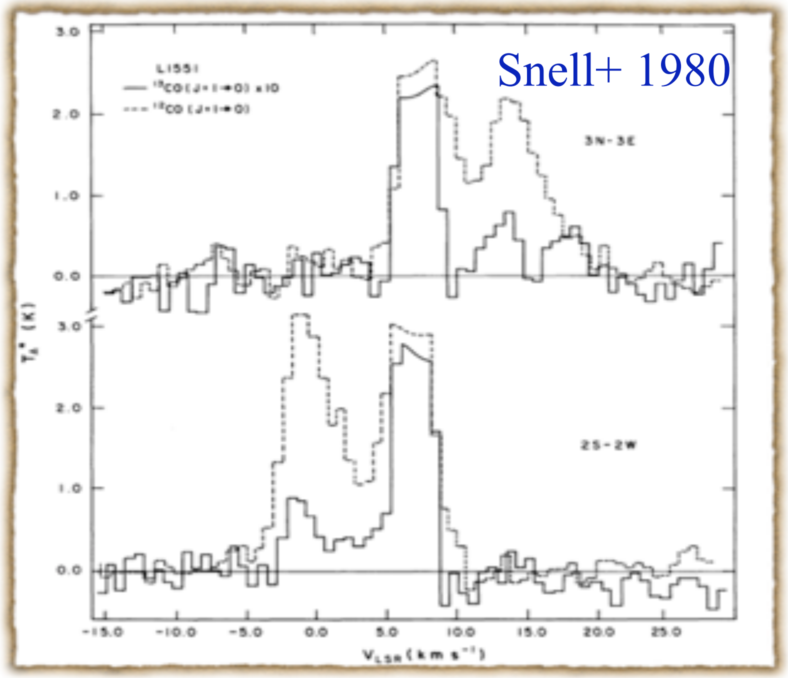
- Background
- Motivation
- Data analysis
- Main results
- Future Aspects
- Summary

Background: outflows

- Star fromation: collapse+accretion+outflows.
- Outflows
  - Injecting energy from few AU to several pc (Arce+2007).
  - the earliest observable signatures (e.g.,Arce+2007).
  - First detection in 1976 (Zuckerman+1967), non-Gaussian molecular lines
  - High-velocity wings and spatially separated lobes at blue and red velocity shifted





Snell+ 1980

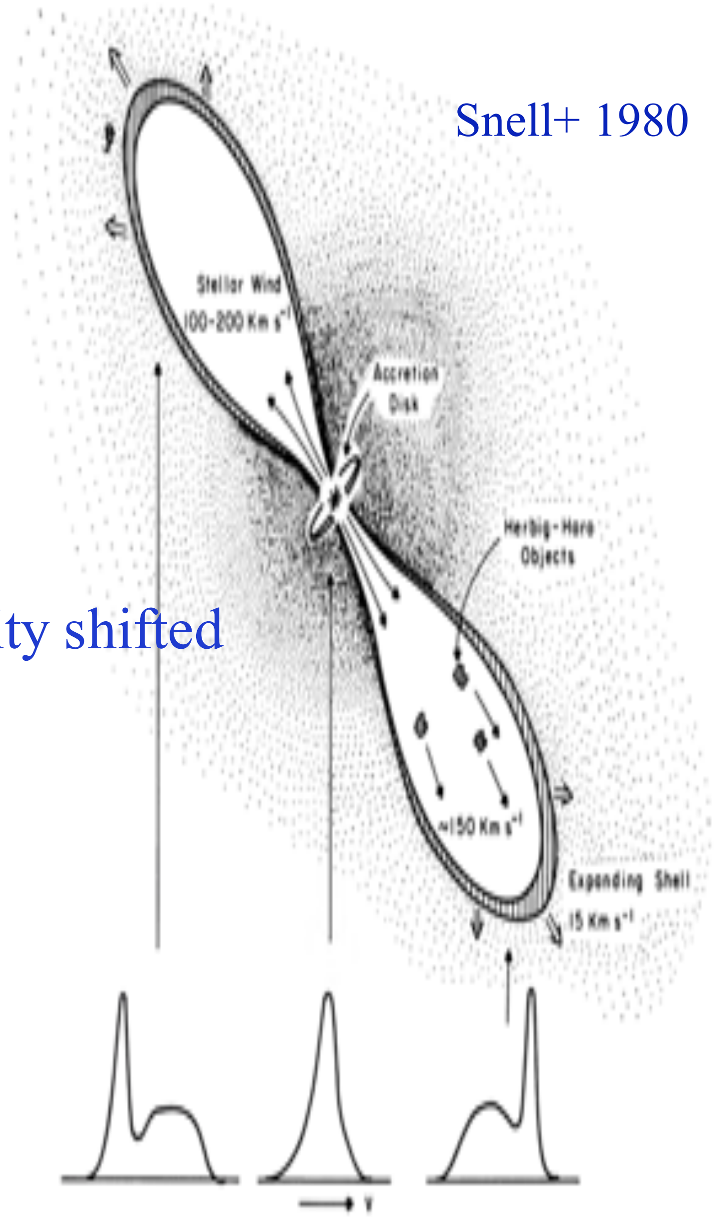


FIG. 5.—A schematic picture of the stellar wind driven shock model for L1551, indicating the CO line profiles which wou
at different positions across the source. The Herbig-Haro objects are not necessarily located inside the shell; because of th
ities, they may have been ejected through the shell and into the surrounding medium.

Background:outflows

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- Therefore, outflow is a useful tool to understand star formation for all masses
  - High-mass star: high extinction + large distance + short timescale
    - How do massive star form?
    - Two competitive models:
    - Core Accretion? (e.g., MeKee+2003) Or Competition accretion? (e.g., Bonnell +2001)
    - Massive collimated outflows VS less collimated outflows
  - Outflows
    - Theoretical models: highly ordered outflows of massive starless core candidate
    - Observations: outflows is observed from IRDC(Feng+2016) to UCHII(Codella+2004)

Background: outflows

❖ Observations: Outflows have been observed in high-mass protostars

- Possible evolutionary sequences suggested by Zinnecker & Yorke 2007

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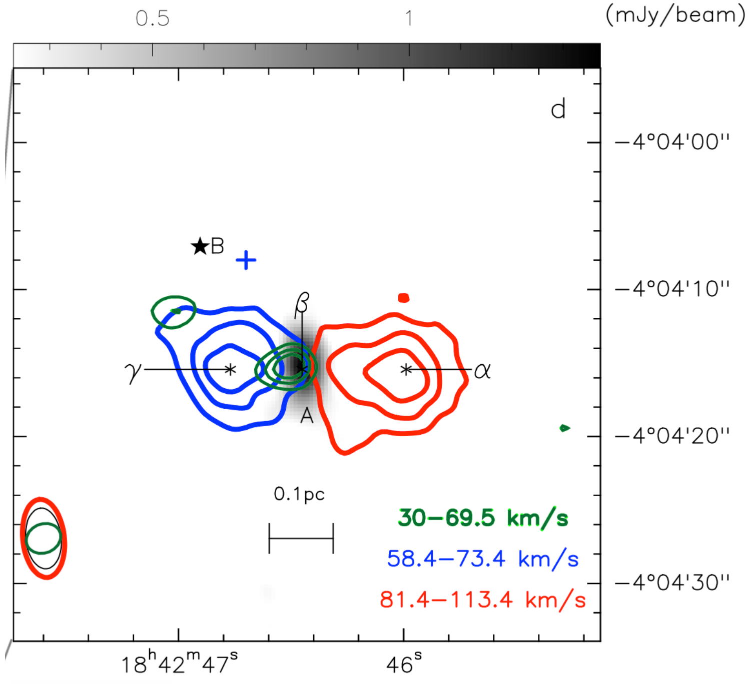
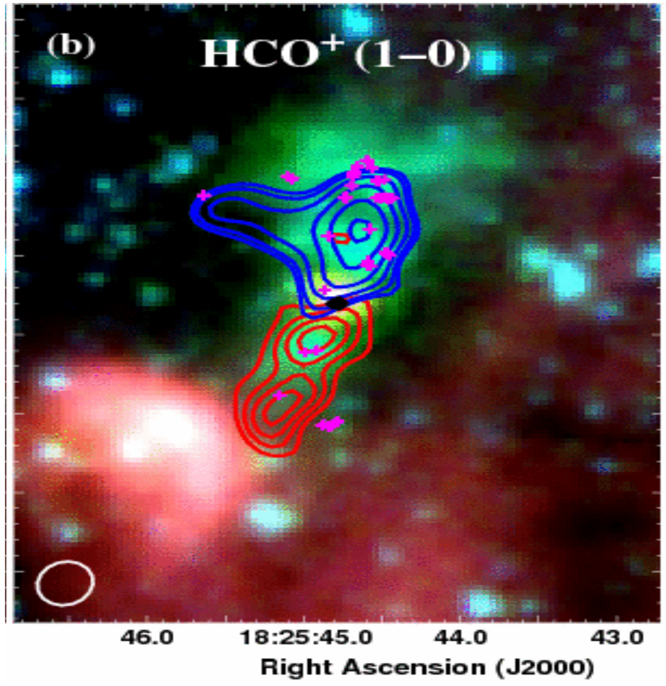
IRDC → Hot cores → Hyper/ultra-compact HII regions → compact/classic HII regions

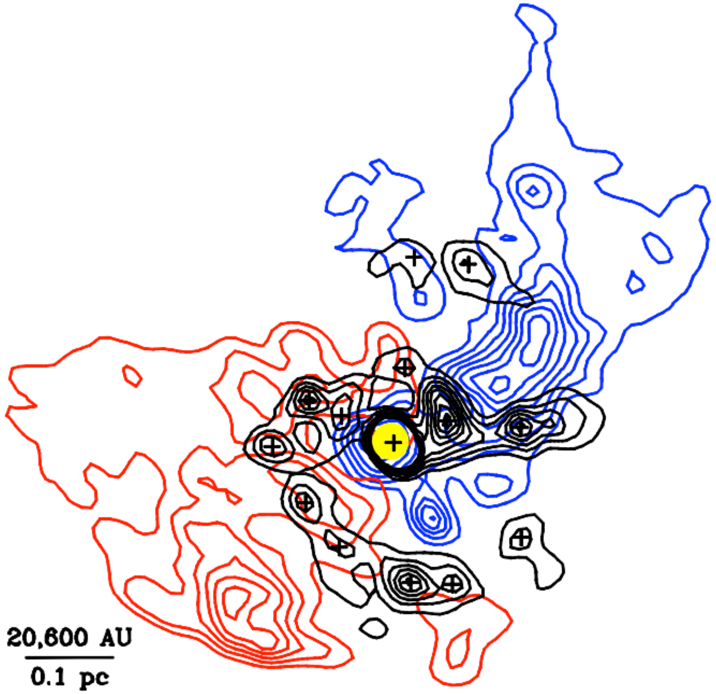
IRDC (Feng+ 2016)



Hot core (Cyganowski+ 2010)



UCHII region (Frau+ 2014)



Background: outflows

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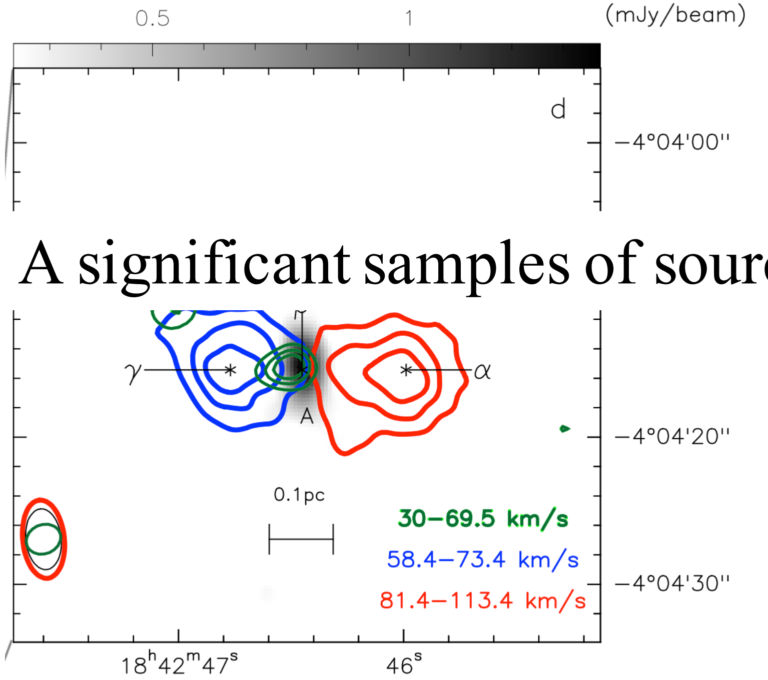
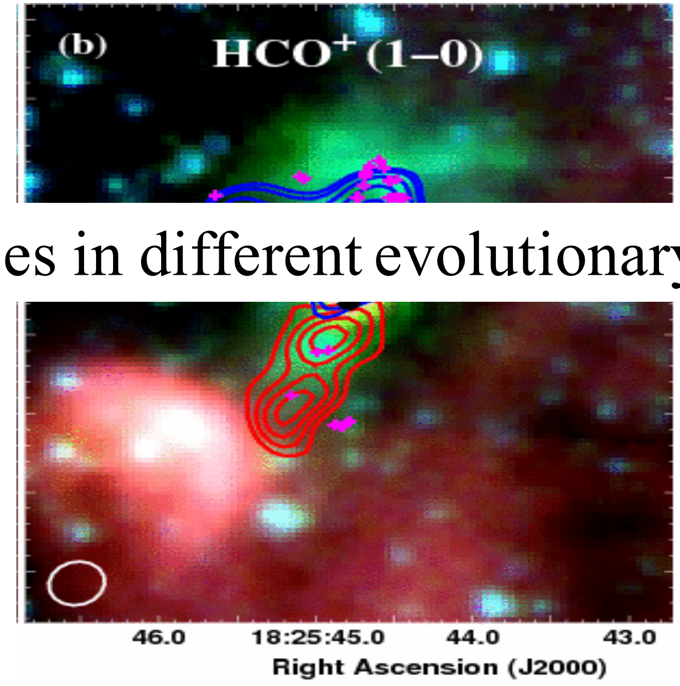
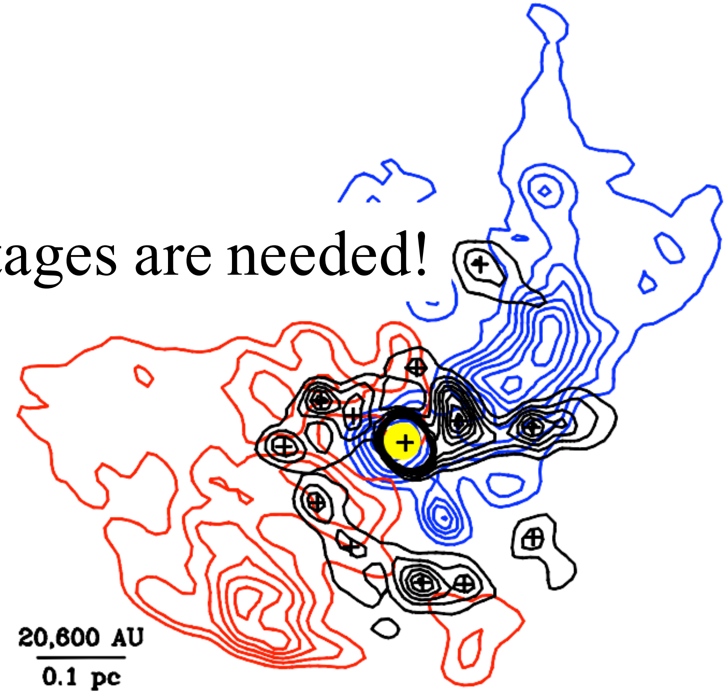
IRDC (Feng+ 2016)



Hot core (Cyganowski+ 2010)



UCHII region (Frau+ 2014)



A significant samples of sources in different evolutionary stages are needed!

Background: Outflows statistics

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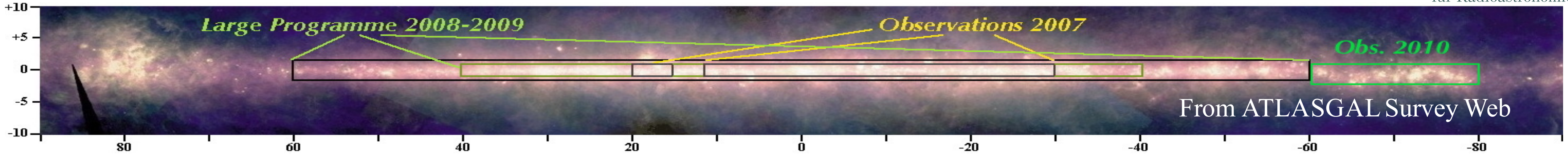
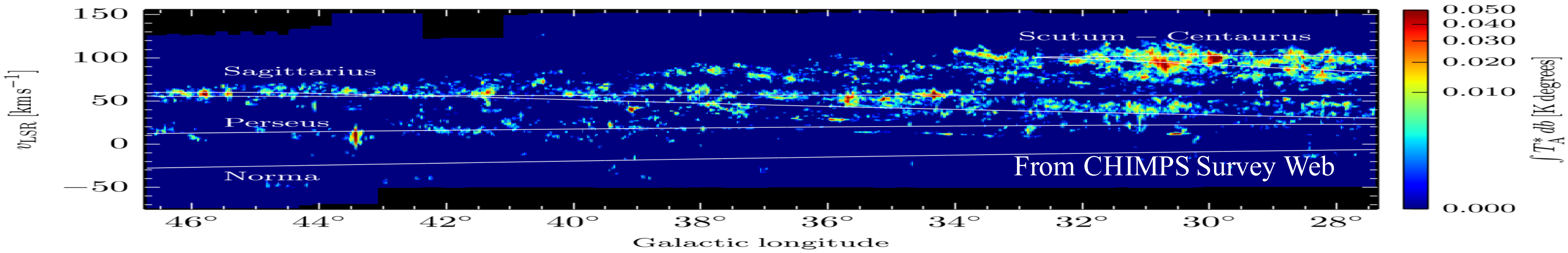
- ATLASGAL: unbiased survey of massive star-forming clumps in a variety of stages in the Galactic plane.



- CHIMPS: CO survey trace high density gas associated with star formation



Names	Survey Area	Band	Sensitivity(1σ)	Resolution	telescope	Ref.
CHIMPS	**28<l<46, |b|<0.5**	$^{13}CO+C^{18}O$	0.6K	15”	JCMT	Rigby+ 2016
ATLSGAL	180<l<60, |b|<2	870μm	50mJy	19”	APEX	Schuller+ 2009

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Background: Outflows statistics

- Köing+ 2017, Giannetti+ 2017: classify the evolutionary sequences for clumps
- Urquhart+ 2018: determine the physical properties for ATLASGAL clumps

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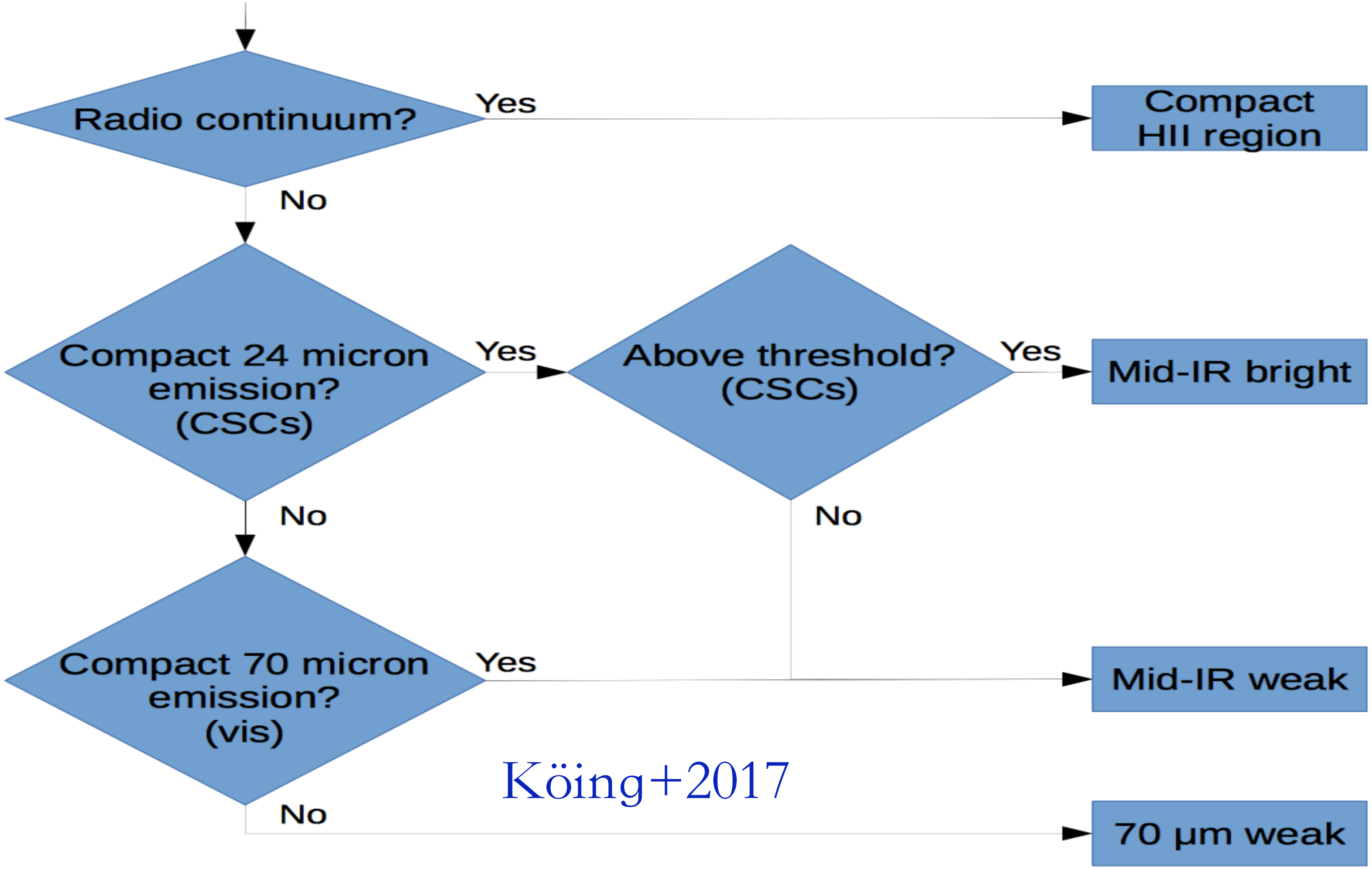

Köing+2017

D, MSF stage/Compact HII region: bright mid-infrared emission, with maser/radio emission

C, YSO-forming: strong and compact in 8 μm and 24 μm

B, Protostellar stage: 24 μm weak

A, Starless/pre-stellar stage: 70 μm weak

Background: Outflows properties

- 325 clumps → 225 with outflows → 153 can be used to determine outflow properties.
- Determination of outflowproperties

$$N\left(^{13}\mathrm{CO}\right) = 5\times10^{12}\mathrm{T_{ex}}\exp\left(\frac{\mathrm{T_{trans}}}{\mathrm{T_{ex}}}\right)\int \mathrm{T_{mb}dv}\ (\mathrm{cm^{-2}}), \quad (1)$$

$$M_{\mathrm{out}} = \mathrm{M_r} + \mathrm{M_b} = (\mathrm{N_b}\times\mathrm{A_b} + \mathrm{N_r}\times\mathrm{A_r})\,\mathrm{m_{H_2}},$$

$$p = \sum_{A_b}\left[\sum_{i=v_b} M_{b_i} v_i\right]\Delta v + \sum_{A_r}\left[\sum_{i=v_r} M_{r_i} v_i\right]\Delta v$$

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$$t_d = \frac{l_{max}}{(\mathrm{V_{maxb}} + \mathrm{V_{maxr}})/2}.$$

$$E = \frac{1}{2}\sum_{A_b}\left[\sum_{i=v_b} M_{b_i} v_i^2\right]\Delta v + \frac{1}{2}\sum_{A_r}\left[\sum_{i=v_r} M_{r_i} v_i^2\right]\Delta v$$

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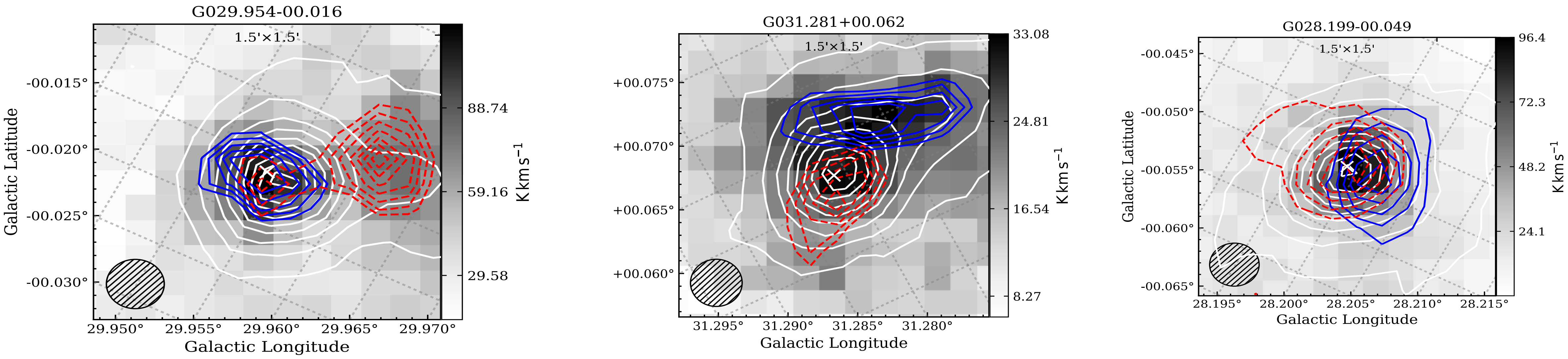

Background: Outflows properties

- Outflows activity evolves with time–its properties at different stages
  3. Outflow properties as a function of the physical properties of clumps

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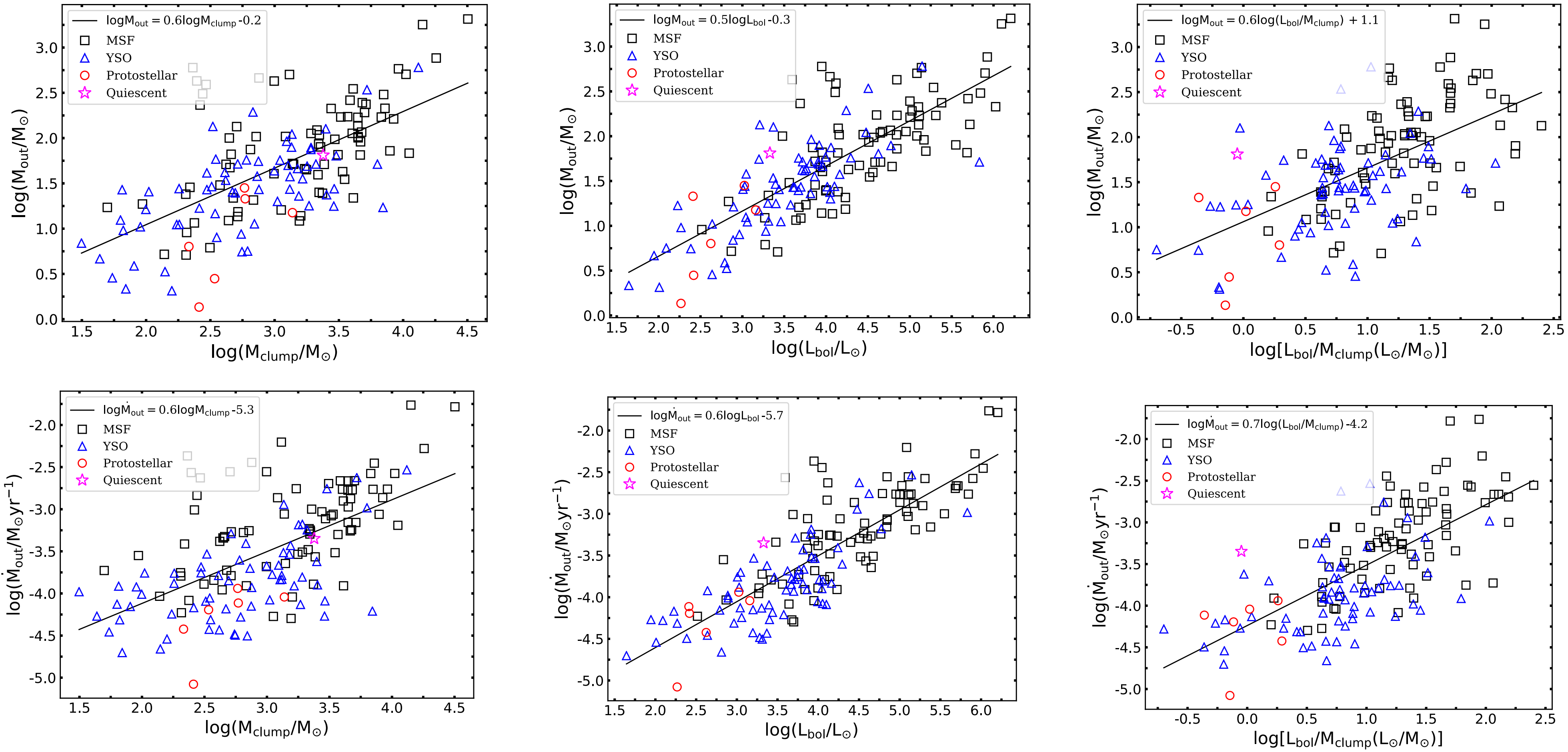
$M_{out} \propto$ Clump

$\dot{M}_{out} \propto$ Clump



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Background: Outflows properties

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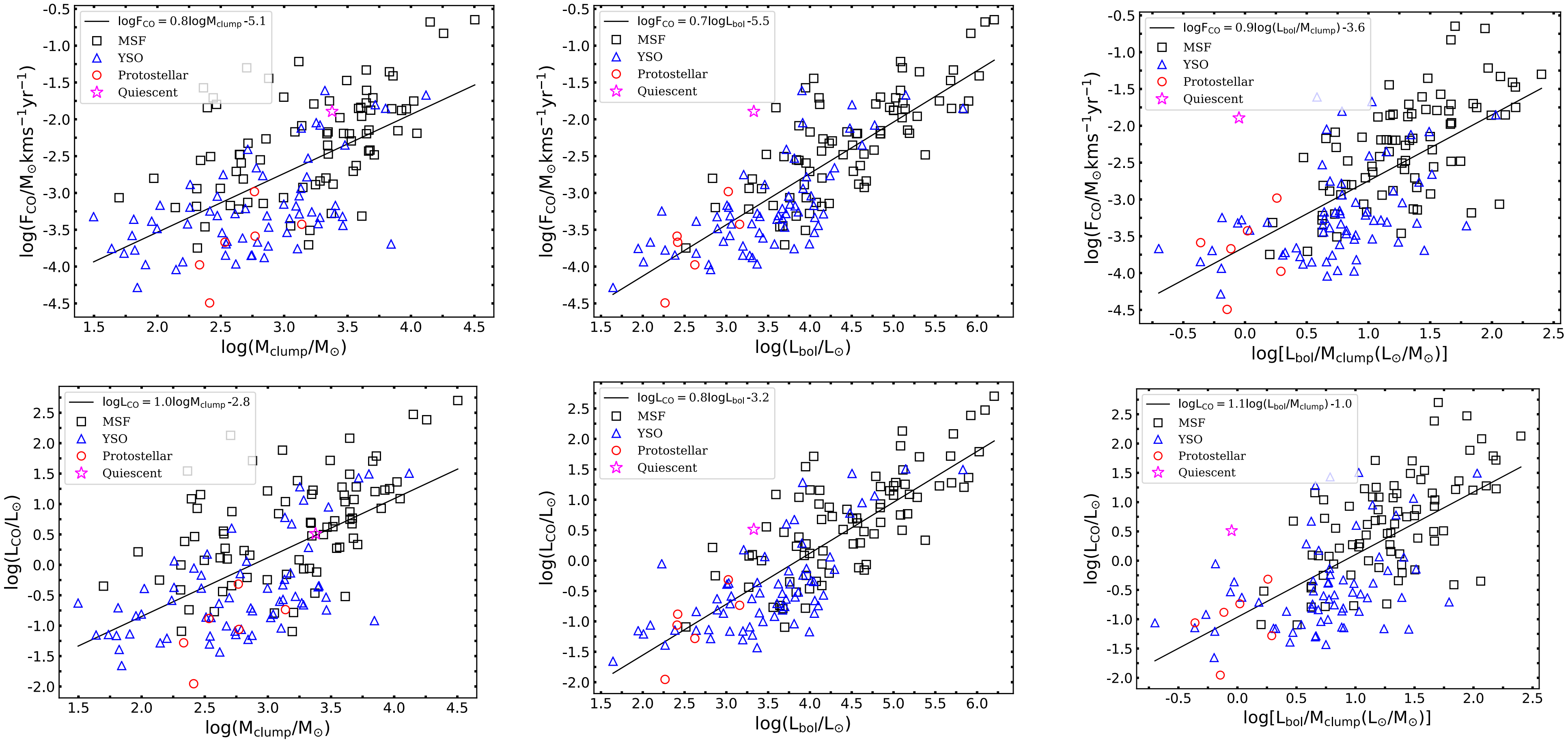
$F_{CO} \propto$ Clump

$L_{CO} \propto$ Clump



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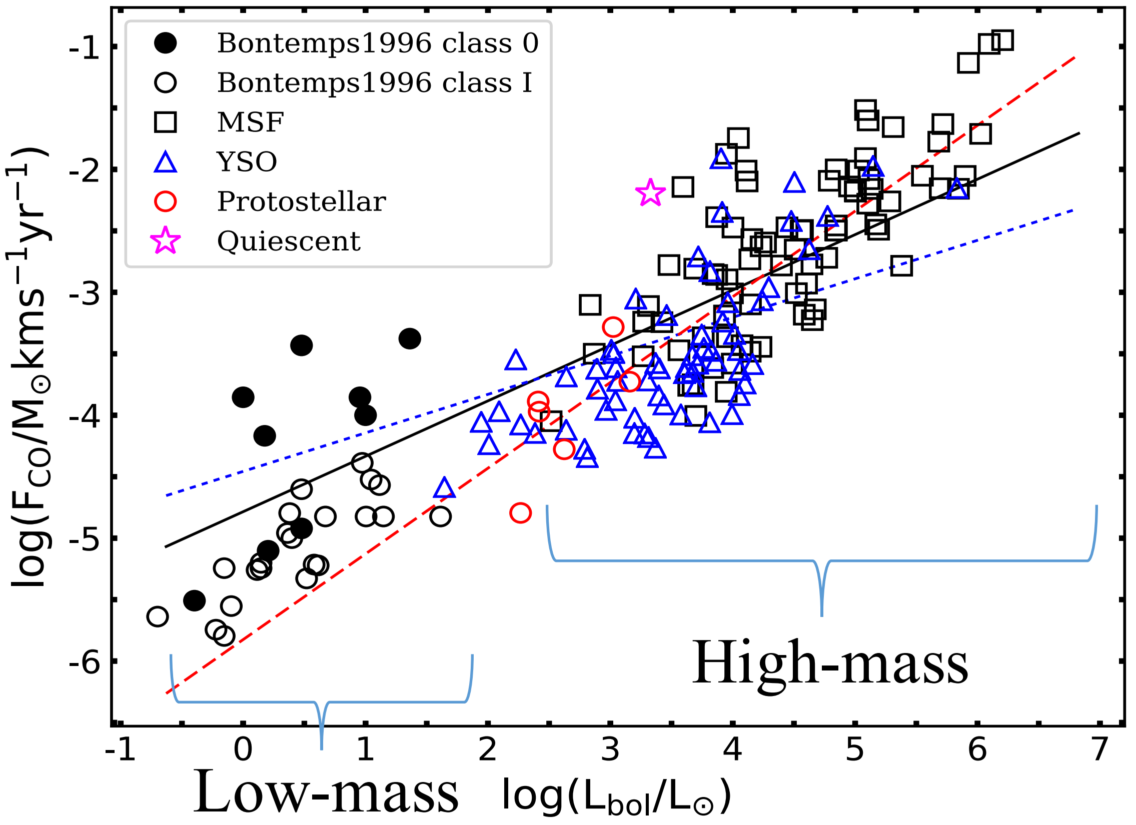
Background: Outflows properties

❖ Low-mass VS high-mass

Table 1
Typical Values for Low-mass and High-mass Outflows

Parameters	Low-mass Outflows[a]	High-mass Outflows[b]
M_{out}	$0.1 \sim 1\ M_{\odot}$	$10 \sim 10^3\ M_{\odot}$
$\dot{M}_{out}$	$10^{-7} \sim 10^{-6}\ M_{\odot}$ yr^{-1}	$10^{-5} \sim 10^{-3}\ M_{\odot}$ yr^{-1}
F_{out}	$10^{-6} \sim 10^{-5}\ M_{\odot}$ km s^{-1} yr^{-1}	$10^{-4} \sim 10^{-2}\ M_{\odot}$ km s^{-1} yr^{-1}
L_{out}	$0.1 \sim 1\ L_{\odot}$	$0.1 \sim 100\ L_{\odot}$
ℓ_{out}	$0.1 \sim 1$ pc	$0.5 \sim 2.5$ pc
t_d	$(0.1 \sim 10) \times 10^5$ years	$(0.1 \sim 10) \times 10^5$ years

Notes.
[a] E.g., Bontemps et al. (1996), Wu et al. (2004), Arce et al. (2007), Hatchell et al. (2007).
[b] E.g., Richer et al. (2000), Beuther et al. (2002), Wu et al. (2004), Zhang et al. (2005), Kim & Kurtz (2006), Arce et al. (2007), de Villiers et al. (2014), de Villiers et al. (2015), Maud et al. (2015).



A statistically significant samples of clumps in the early evolutionary stages are needed!

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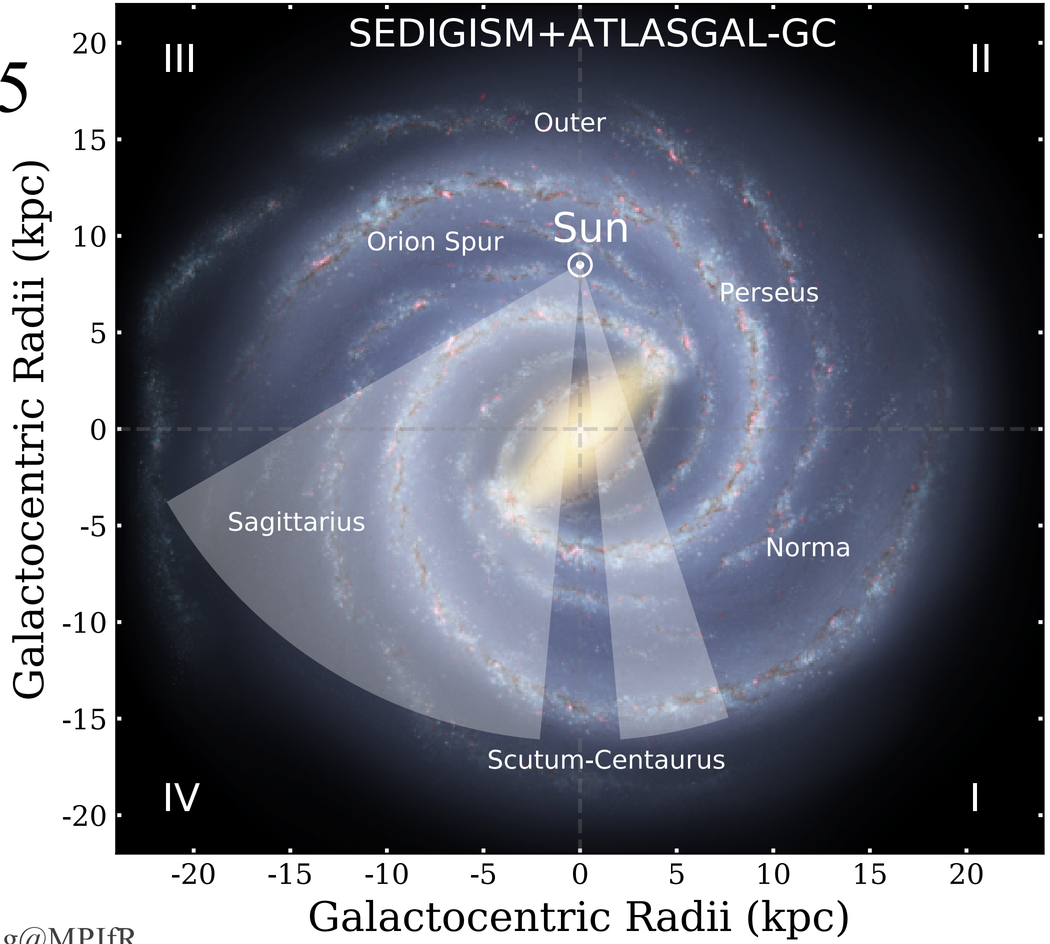
Two Surveys

Names	Survey Area	Band	Sensitivity(1σ)	Resolution	telescope	Ref.
SEDIGISM	-60<l<18°, |b|<0.5°	$^{13}CO+C^{18}O$	0.8K	28''	APEX	Schuller+ 2017
ATLASGAL	$\|\ell\| < 60°$, $\|b\| < 1.5°$	870μm	50mJy	19''	APEX	Schuller+ 2009

Overlap sky region: -60<l<18;|b|<0.5

Excluding GC: 68 square degree!



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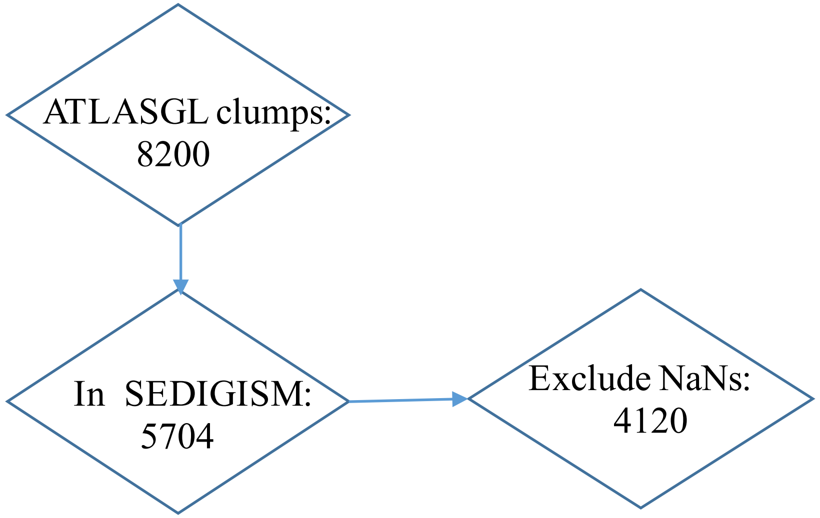
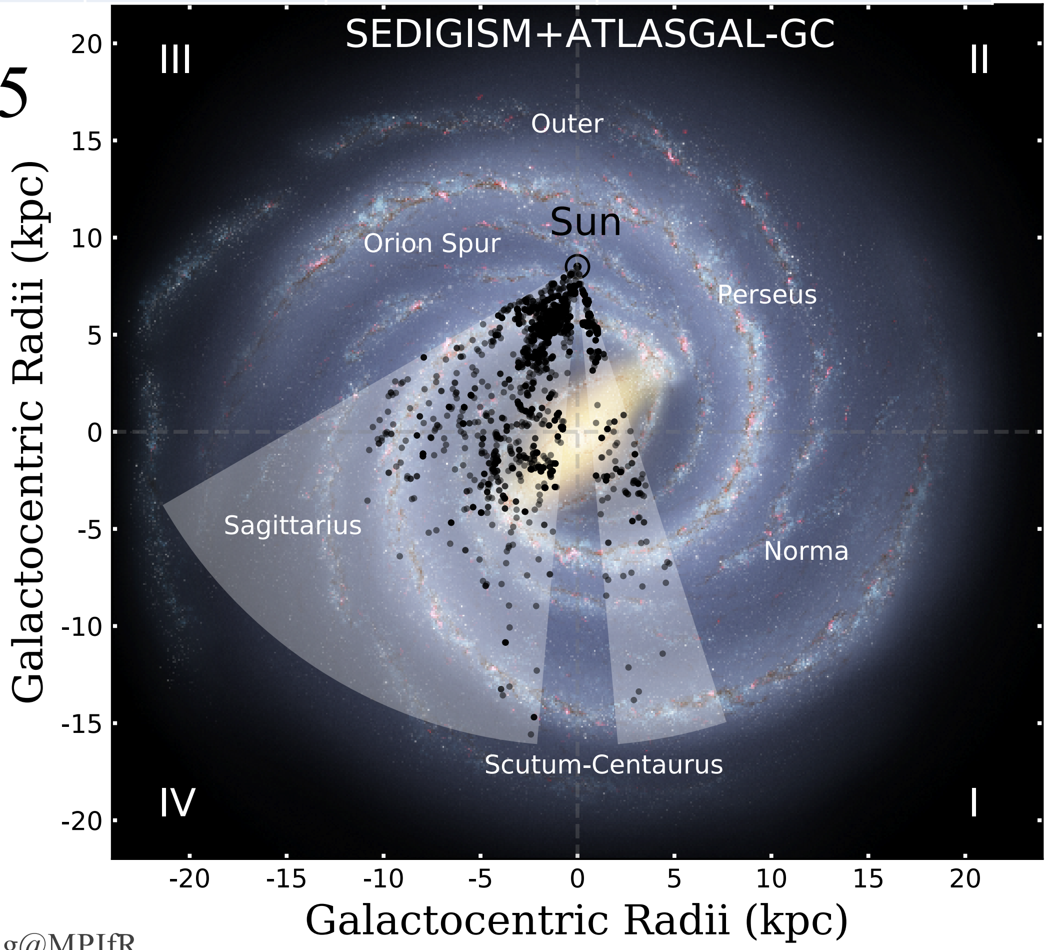
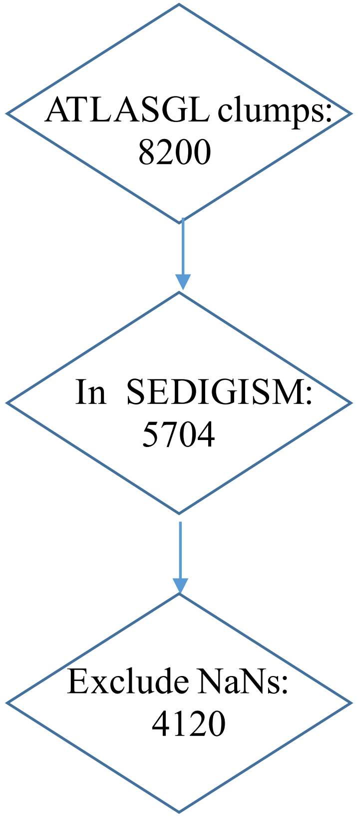


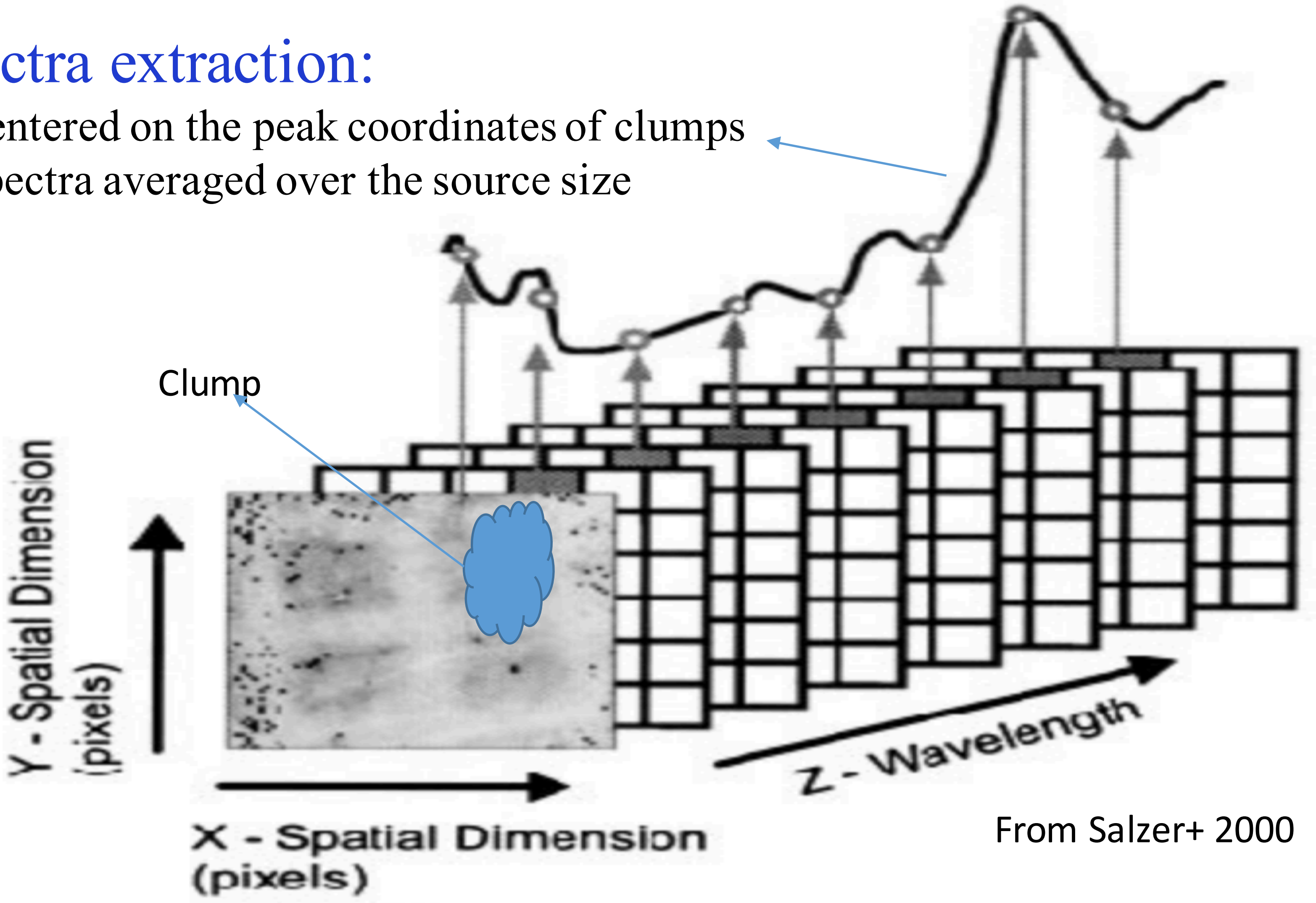




Surveys	Freq./Beam	Rms(1σ)	Sky coverage
ATLASGAL	345GHz@19″	~~50mJy	-60<l<60;|b|<2
SEDIGISM	219GHz@28″	~0.8K@0.25km/s	-60<l<18;|b|<0.5

Spectra extraction:

- Centered on the peak coordinates of clumps
- Spectra averaged over the source size



From Salzer+ 2000

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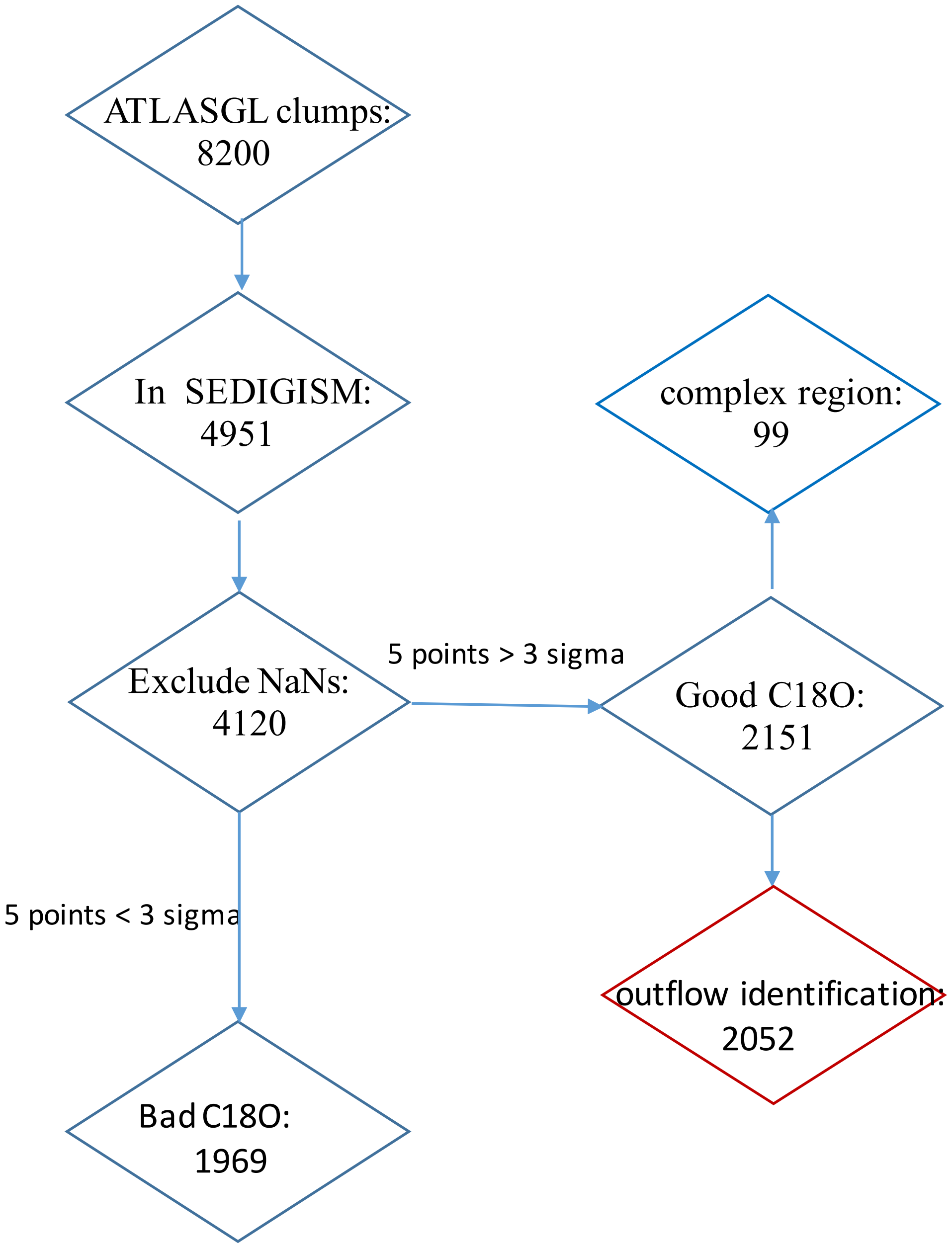
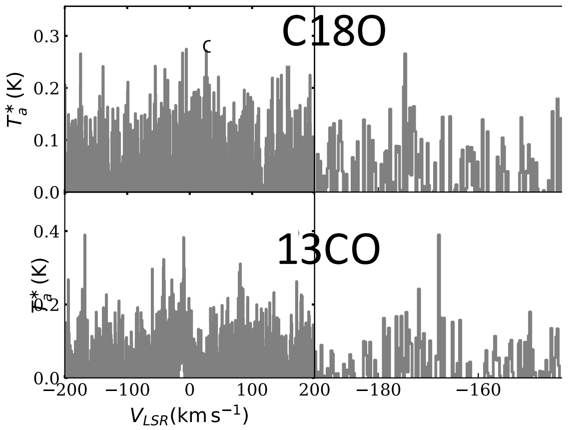
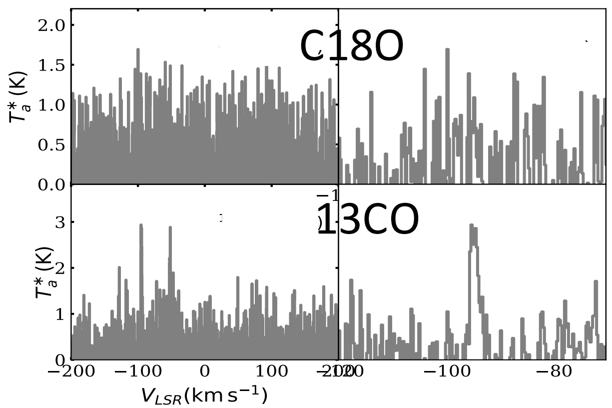


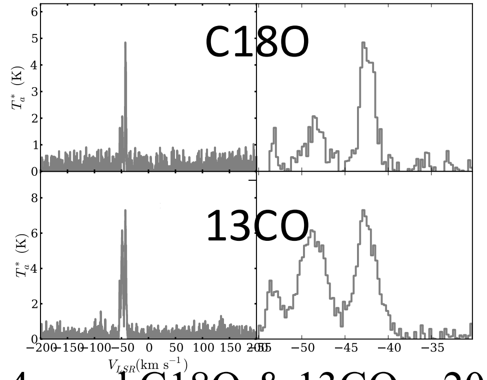
1, No C18O & No 13CO : 147

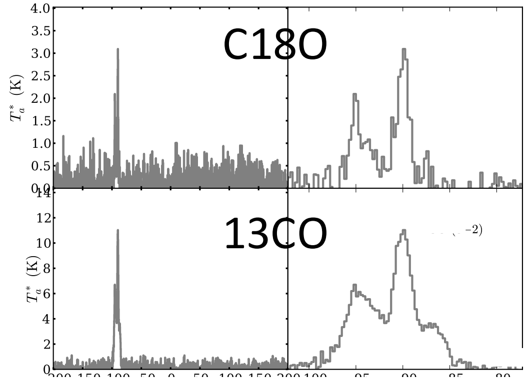


2, No/weak C18O & Weak 13CO : 1969

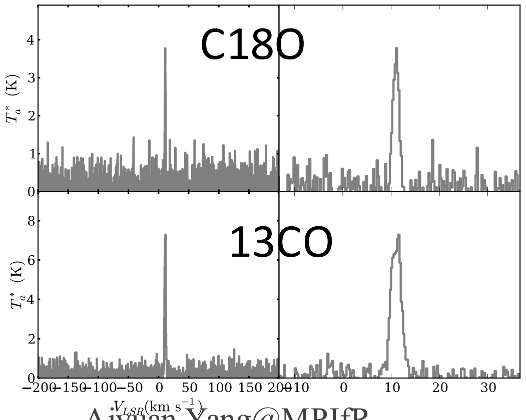


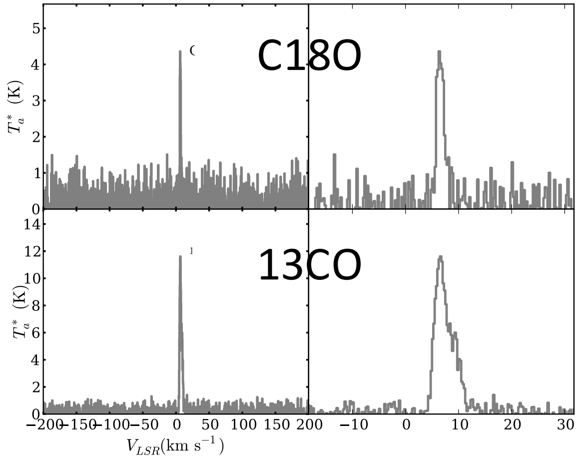
3, complex C18O &/ 13CO : 99





4, used C18O & 13CO : 2057





Surveys	Freq./Beam	Rms(1σ)	Sky coverage
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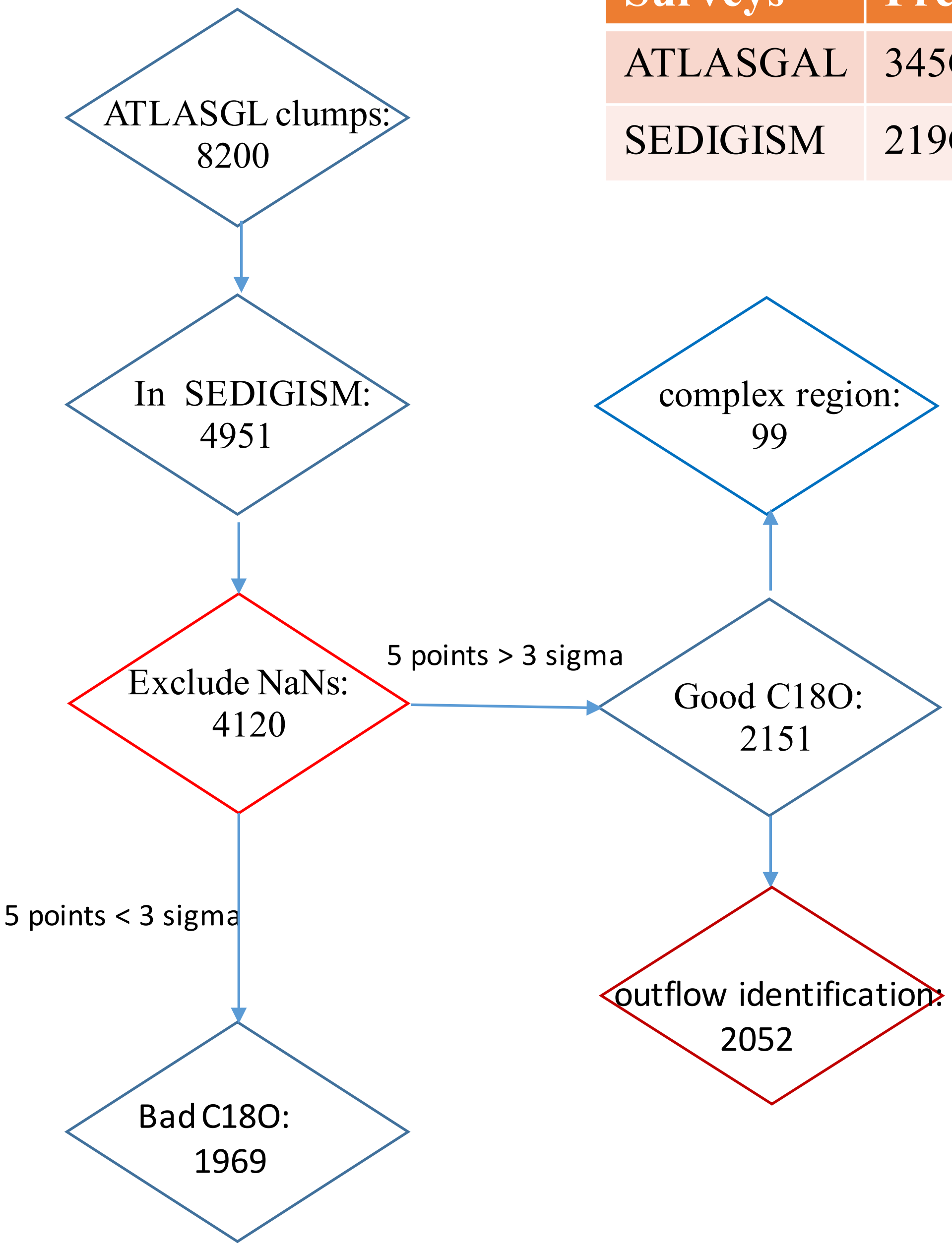
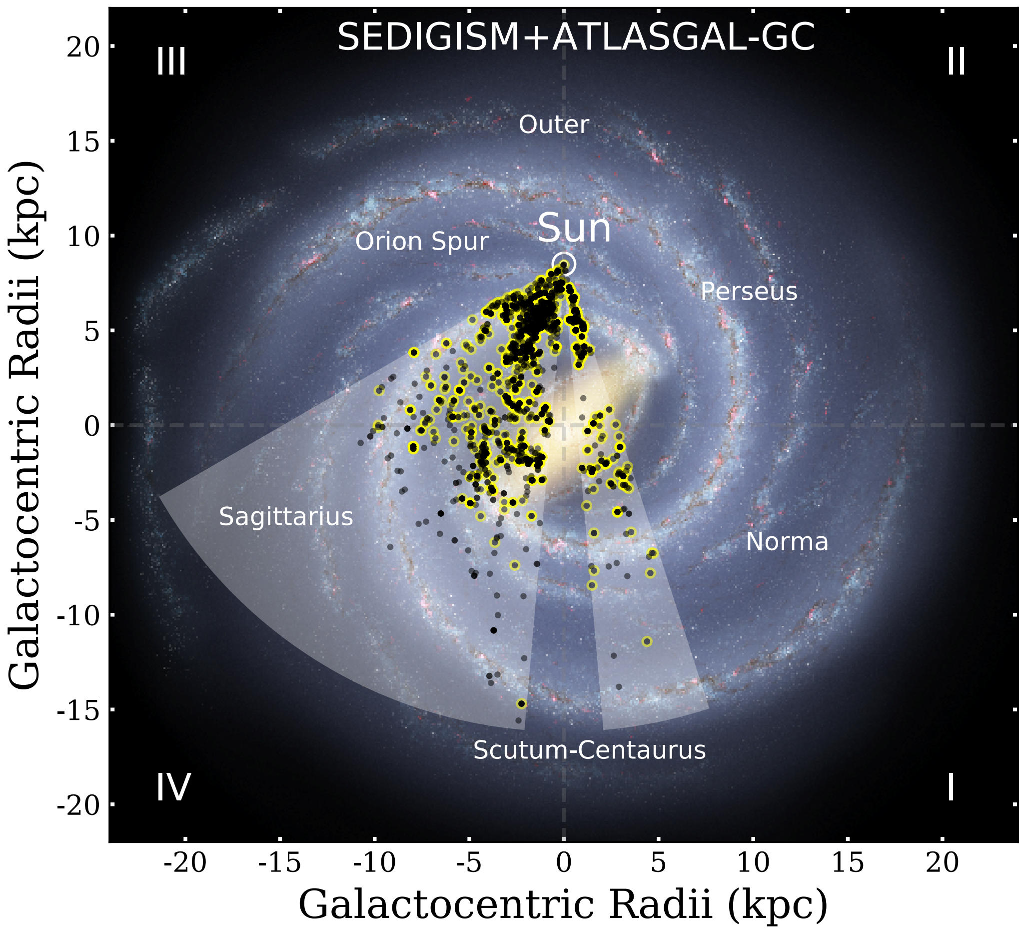
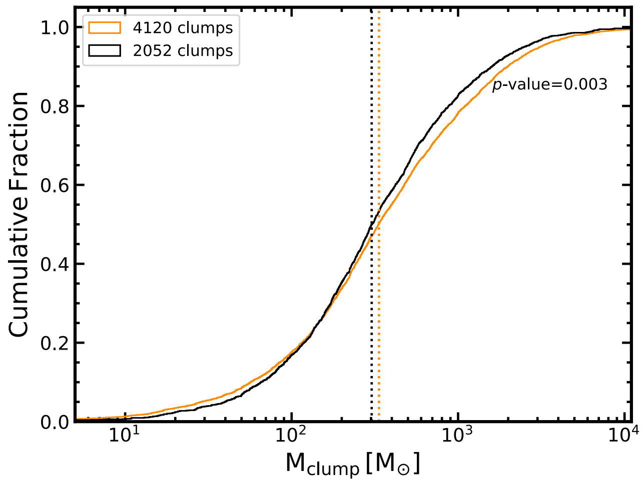
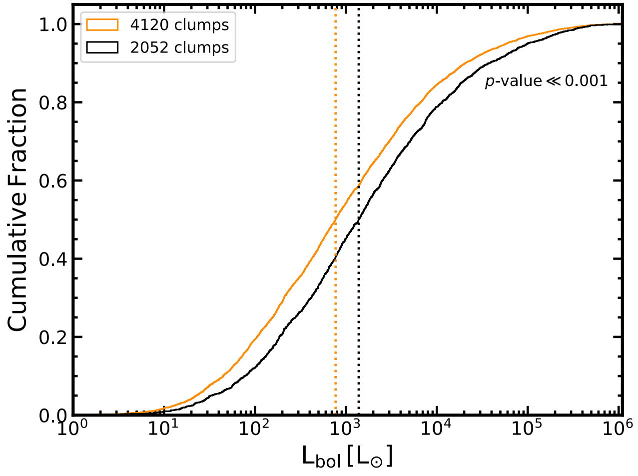
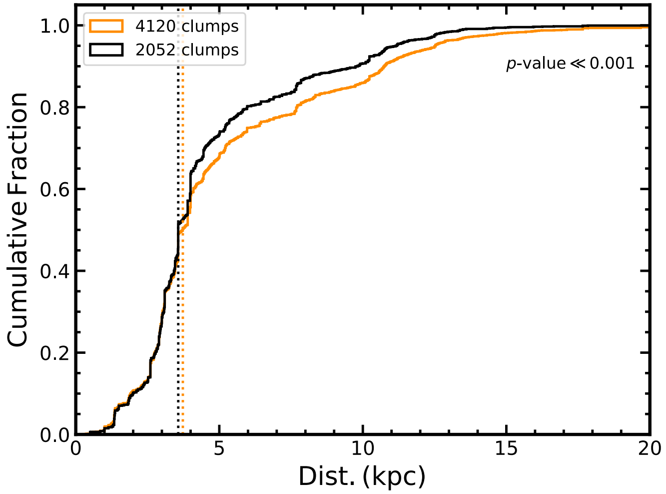


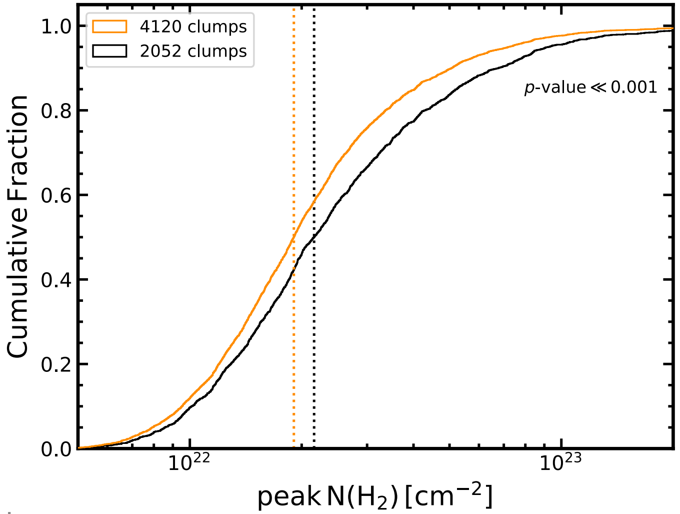


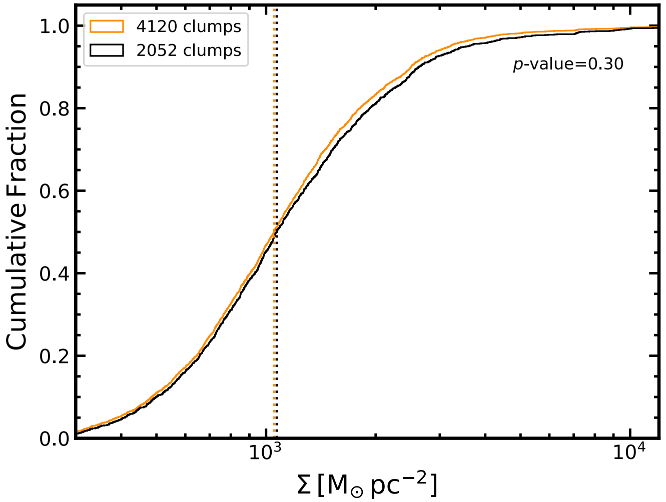
The selected sample VS the total sample

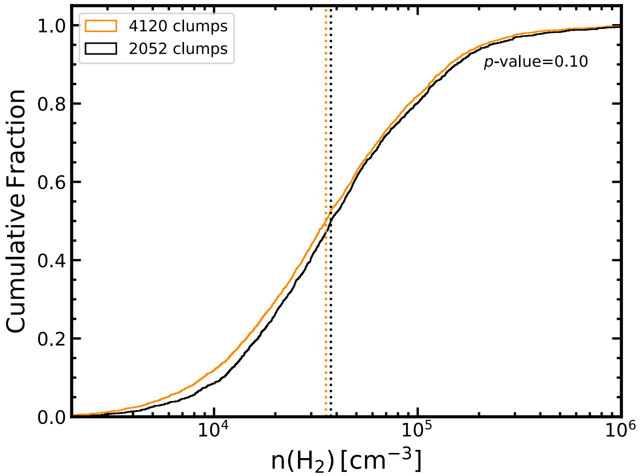












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The selected sample VS the total sample

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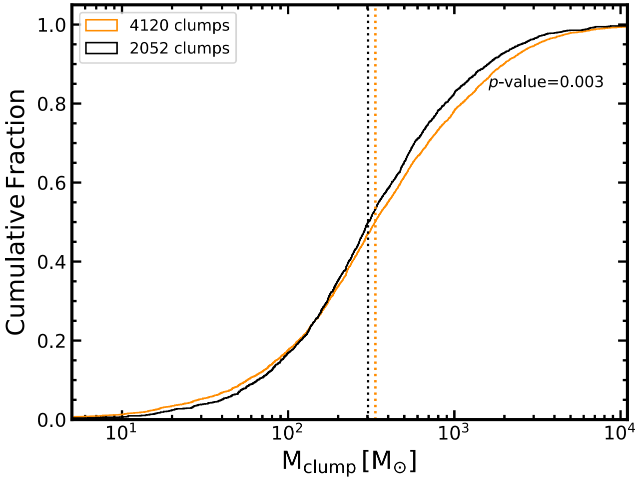
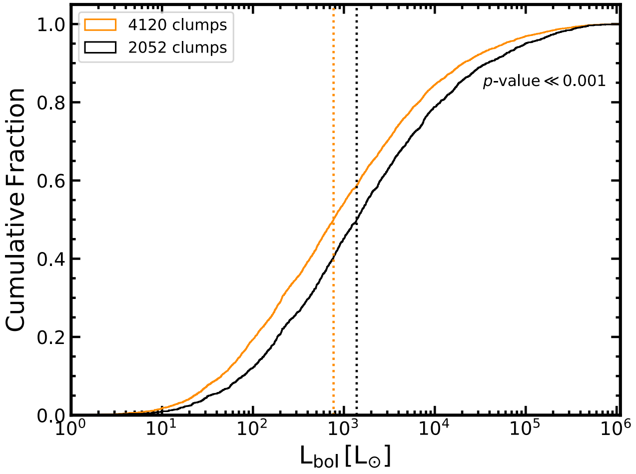
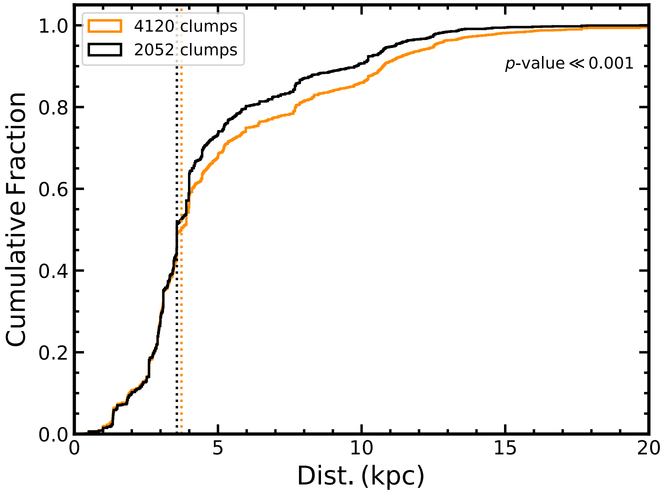
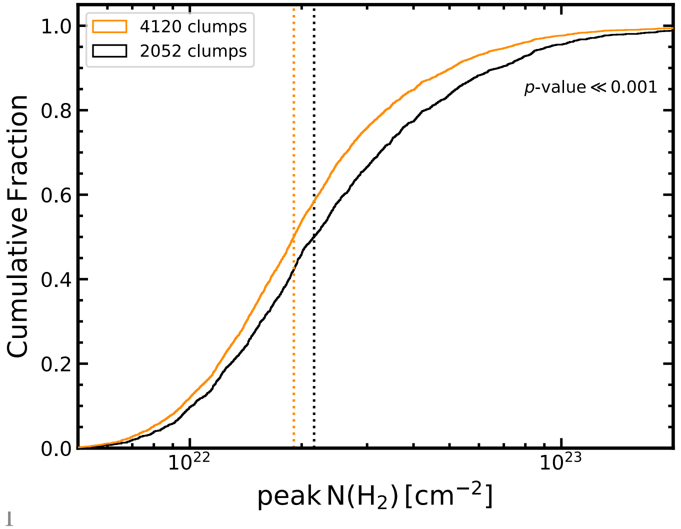
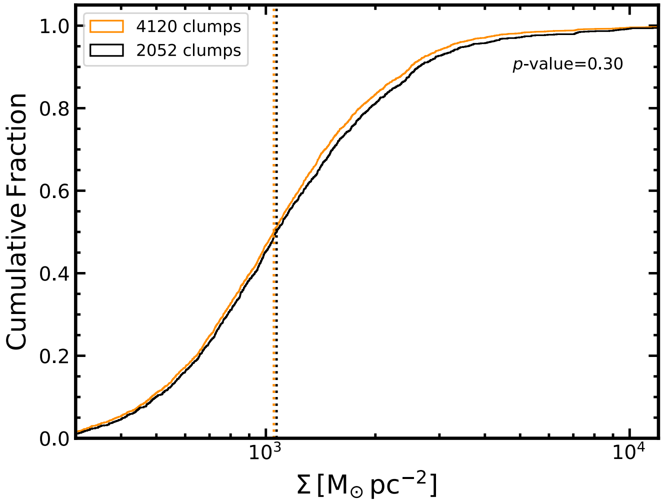


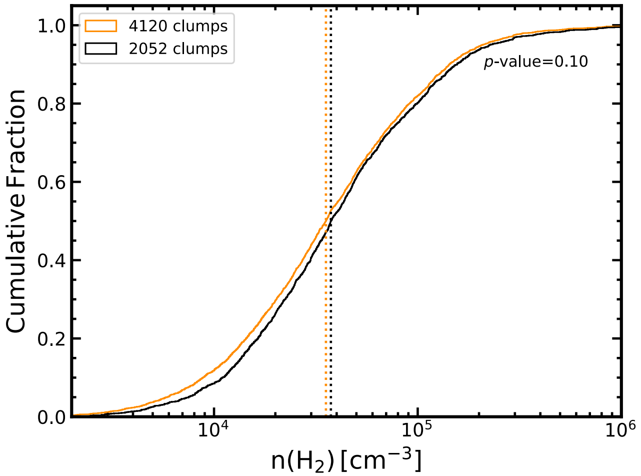




The selected clumps are closer and brighter than the total clumps.

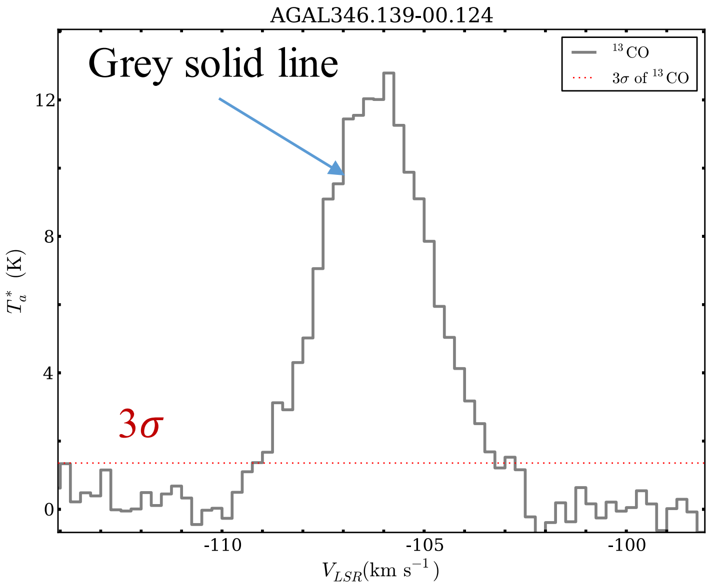




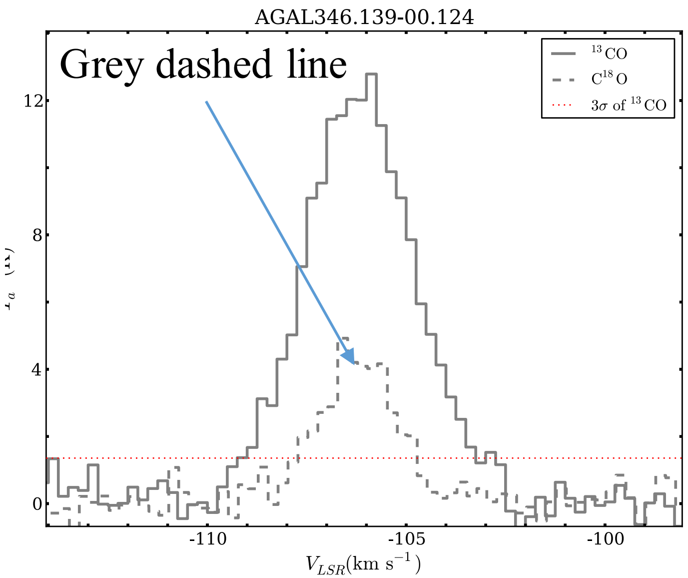


- **Outflows identification**: 13CO: high-velocity wings; C18O: core emission

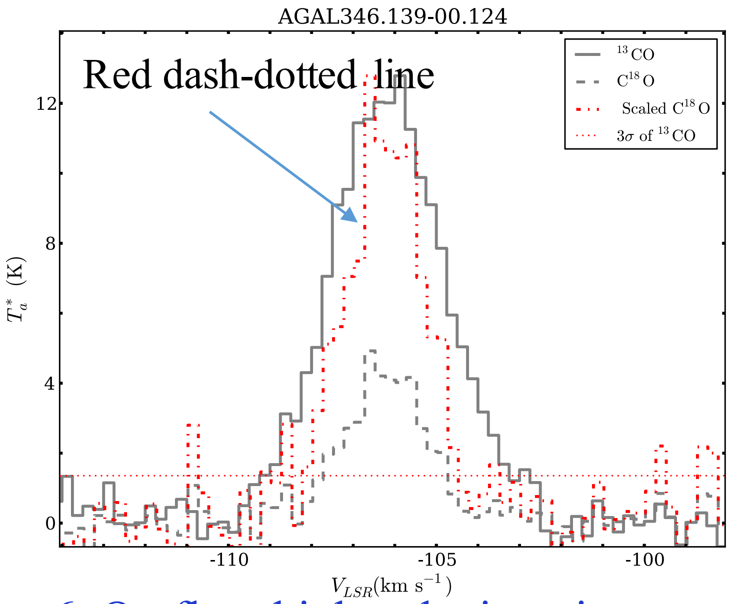
1, ^{13}CO emission



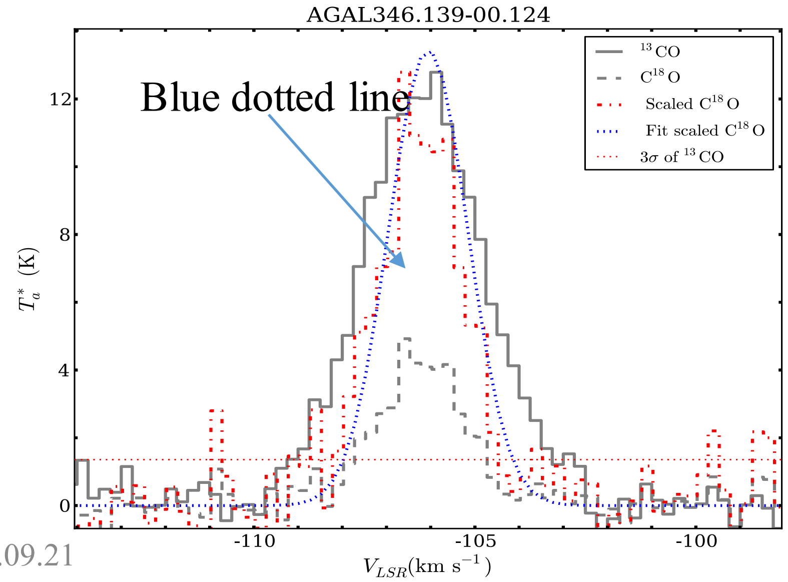
2, C^{18}O emission



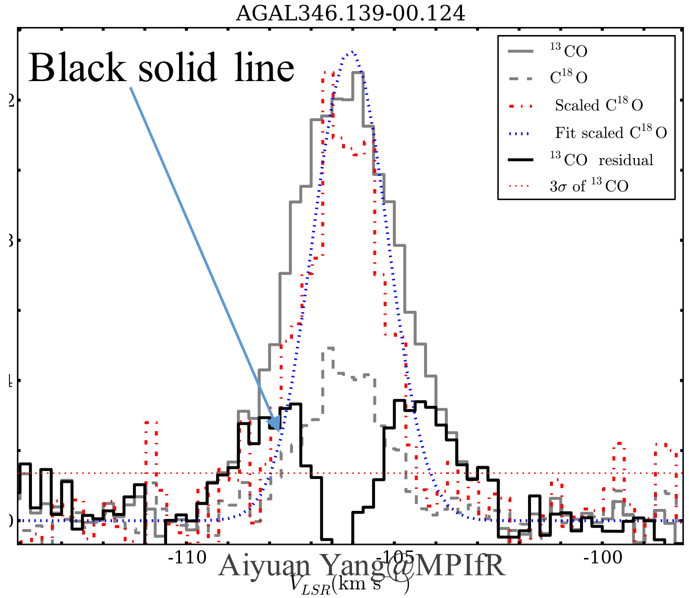
3, scaled C^{18}O emission



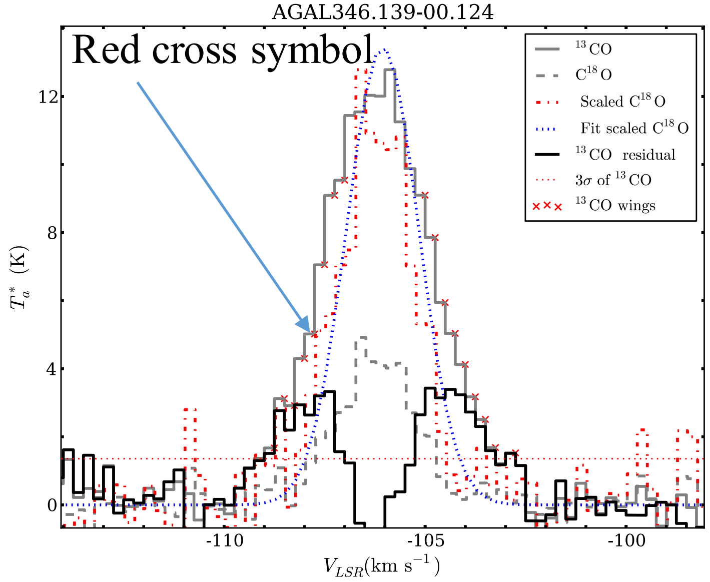
4, Gaussion fitting to scaled C^{18}O



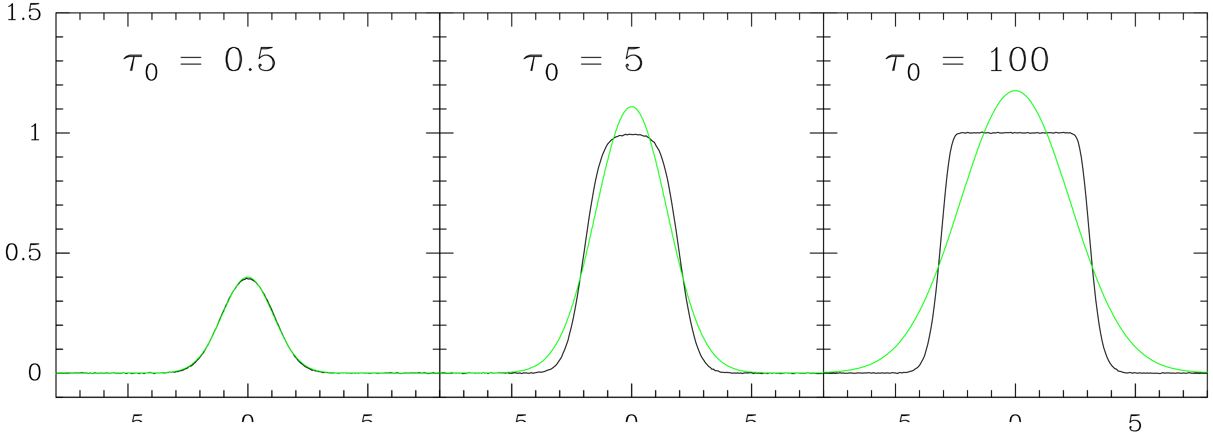
5, (^{13}CO) − (fitted-scaled C^{18}O)



6, Outflow high-velocity wings



• Outflows identification: opacity broadening

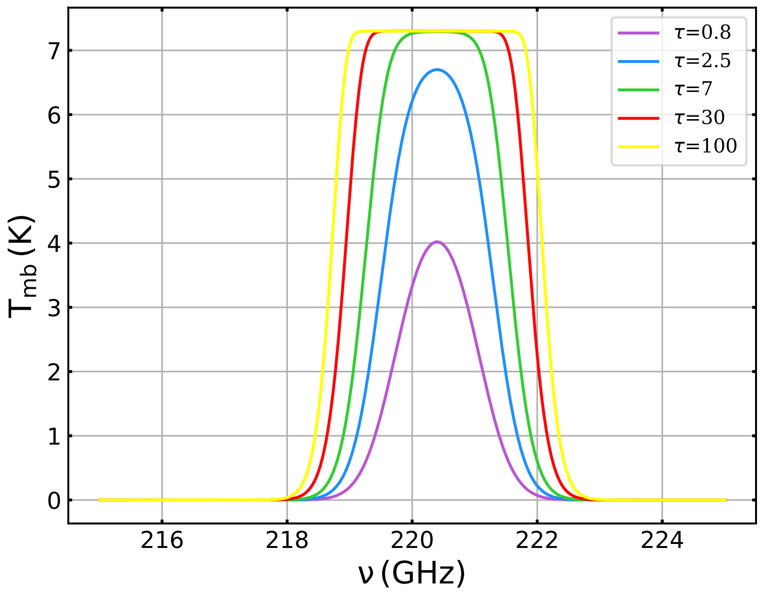


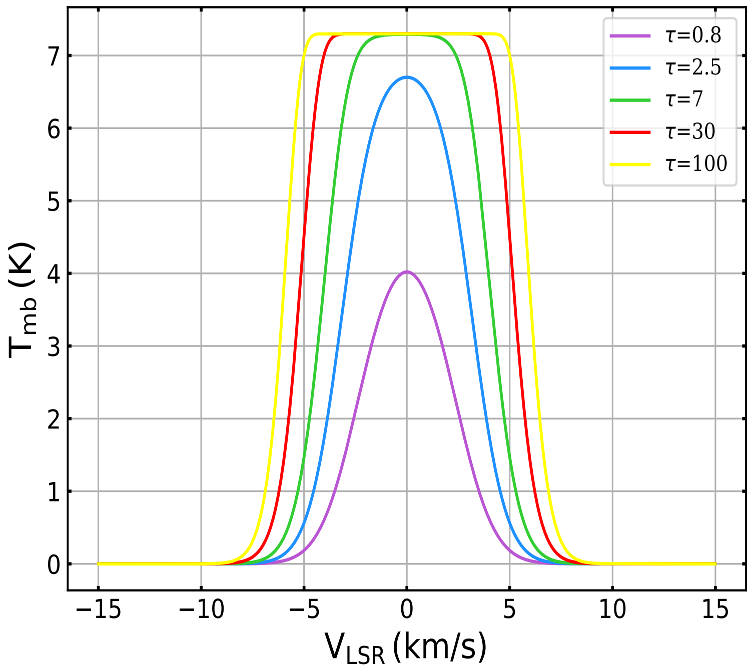
$$T_{\mathrm{mb},\nu} = (J_\nu(T_{\mathrm{ex}}) - J_\nu(T_{\mathrm{bg}})) \cdot (1 - \exp(-\tau_\nu)),$$

The line opacity follows a Gaussian distribution as:

$$\tau_\nu = \tau_0 \cdot \exp\left(-(\nu - \nu_0)^2/2\sigma^2\right)$$

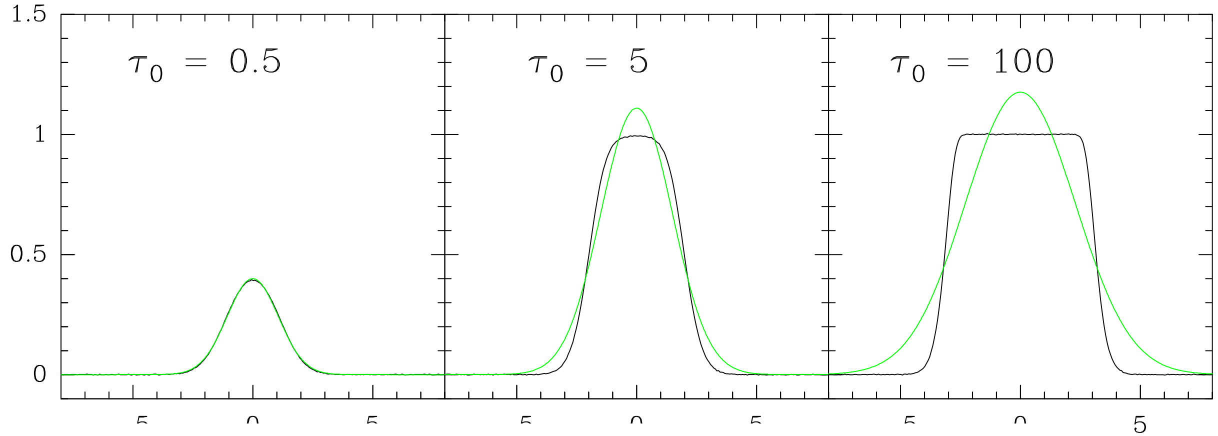
$$\frac{\nu - \nu_0}{\nu_0} = \frac{v_{\mathrm{lsr}} - v_{\mathrm{lsr},0}}{c}$$





Hacar et al. 2016, A&A, 591 A140

• Outflows identification: opacity broadening



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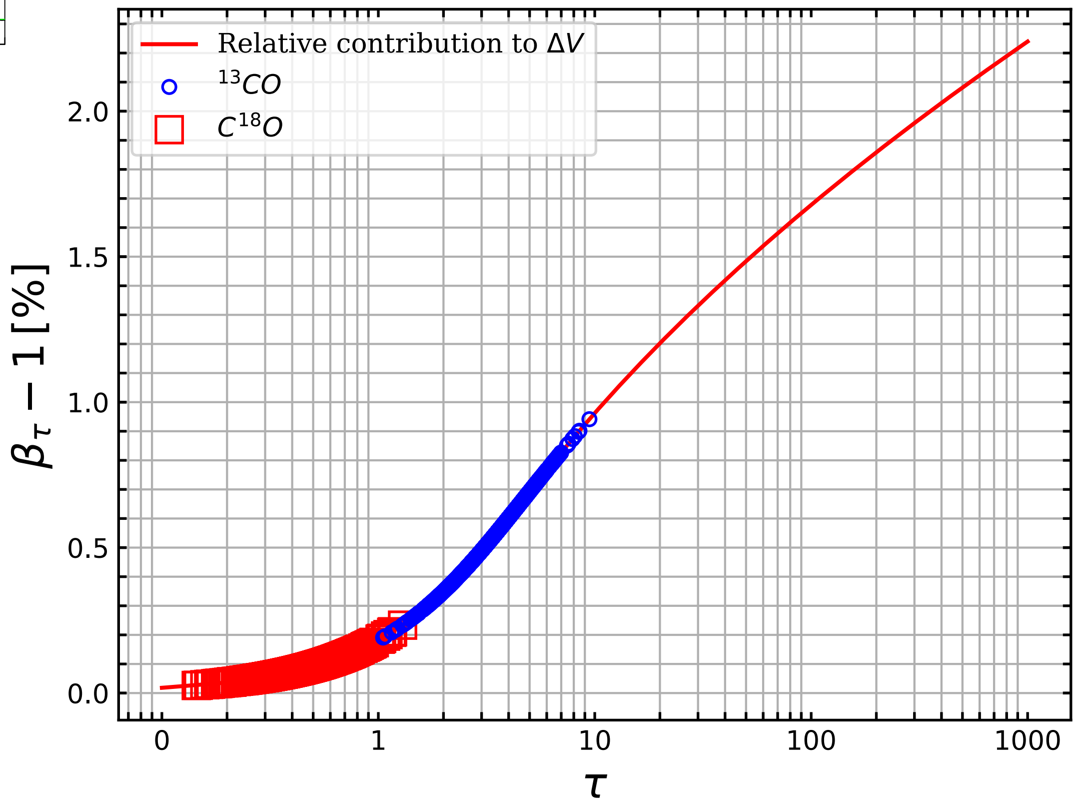
- ➢ FWHM(observed)/FWHM(intrinsic)

$$\beta_\tau = \frac{\Delta V}{\Delta V_{\mathrm{int}}} = \frac{1}{\sqrt{\ln 2}}\left[\ln\left(\frac{\tau_0}{\ln\left(\frac{2}{\exp(-\tau_0)+1}\right)}\right)\right]^{1/2}, \qquad (4)$$

Hacar et al. 2016, A&A, 591 A140

- ➢ $X_{iso} = \frac{N_{13CO}}{N_{C18O}}$=7.3;
- ➢ $\frac{I_{C18O}}{I_{13CO}} = \tau_{C18O}$;
- ➢ $\tau_{13CO} = X_{iso}\tau_{C18O}$;
- ➢ 13CO optical thick & C18O optical thin;

Ref: Jimenez-Donaire+ 2017, Goldsmith+1984



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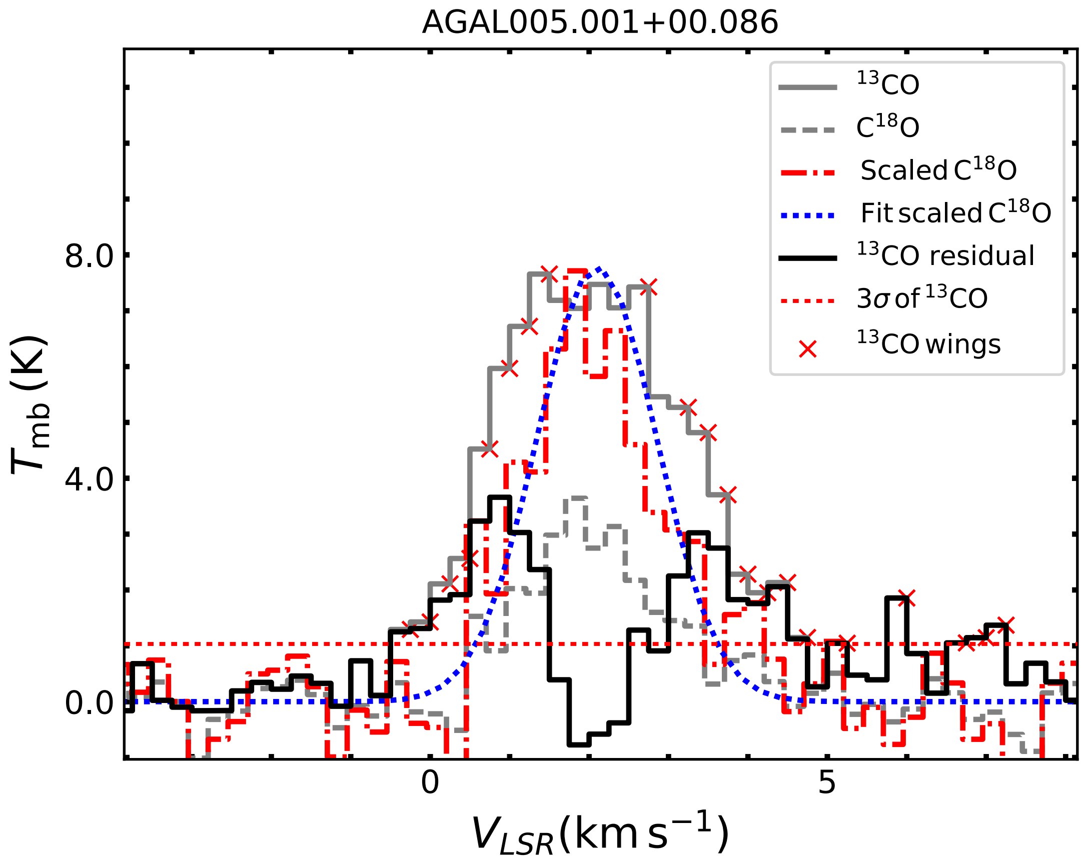
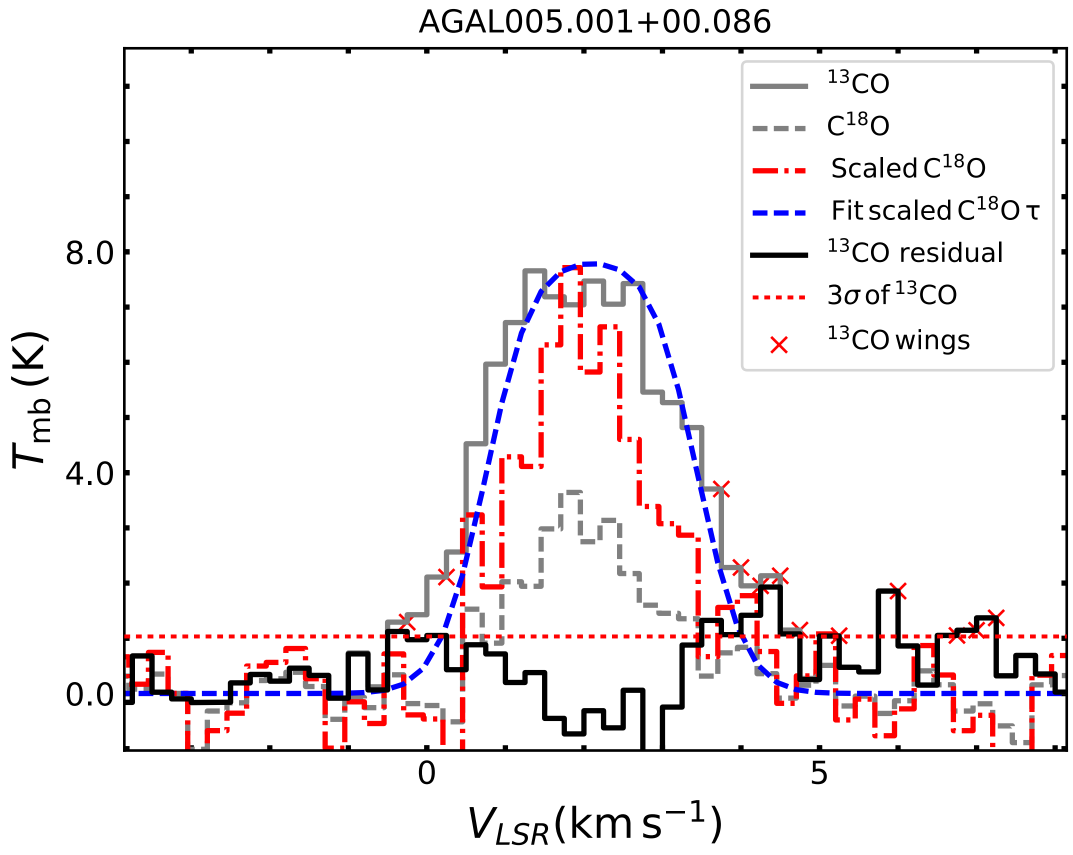
• Outflows identification: after considering the opacity broadening



Not consider the opacity broadening



Consider the opacity broadening

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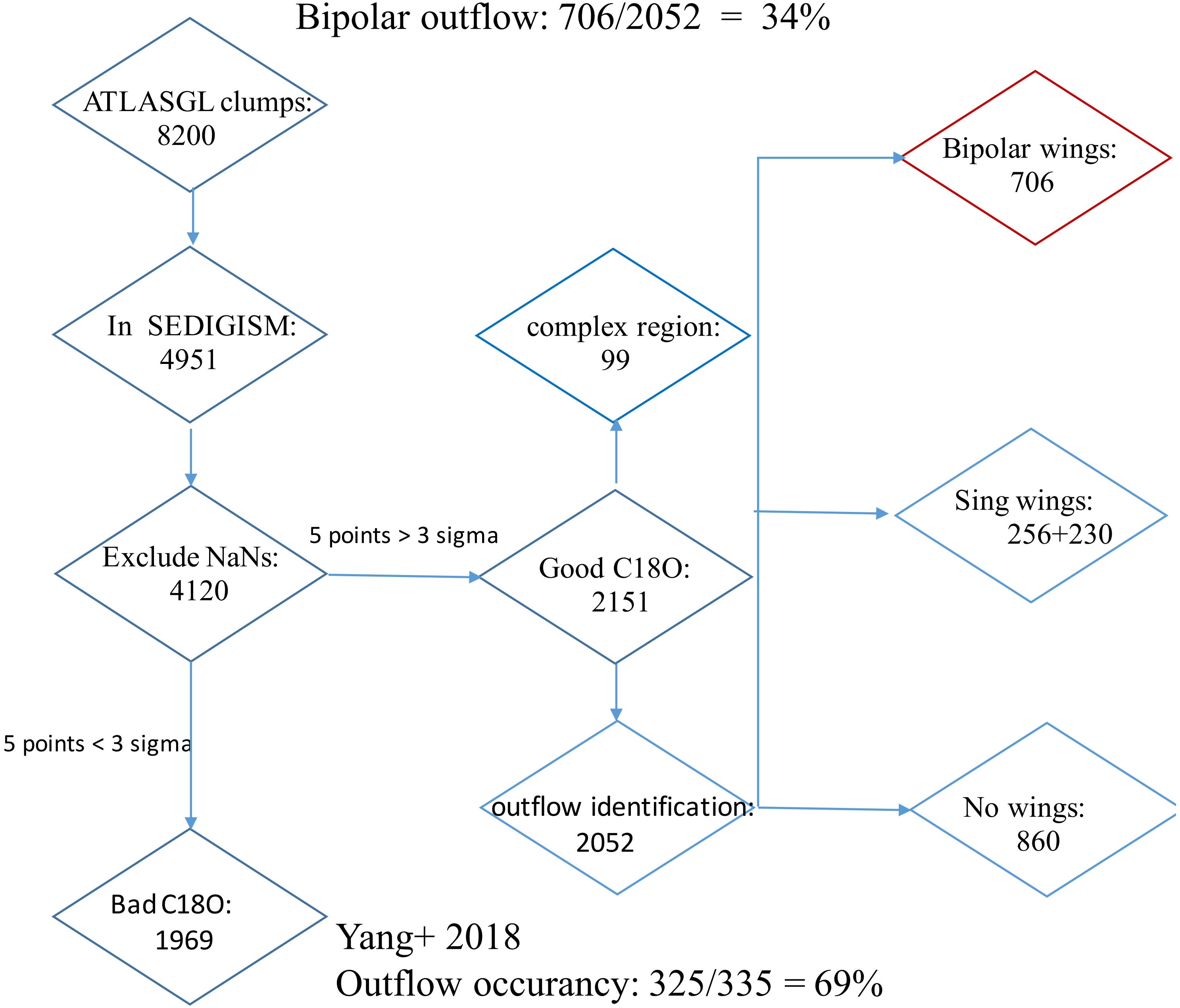
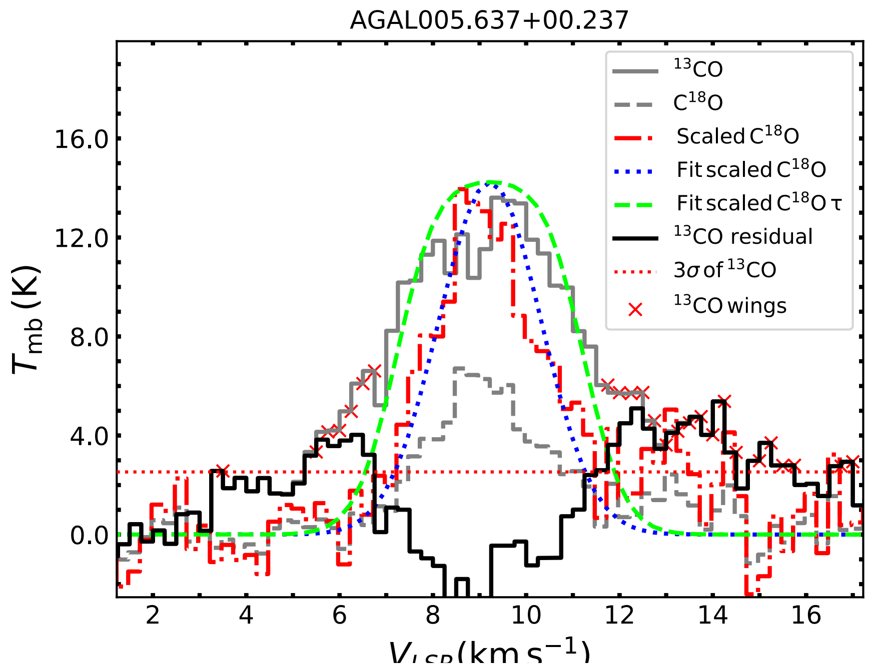
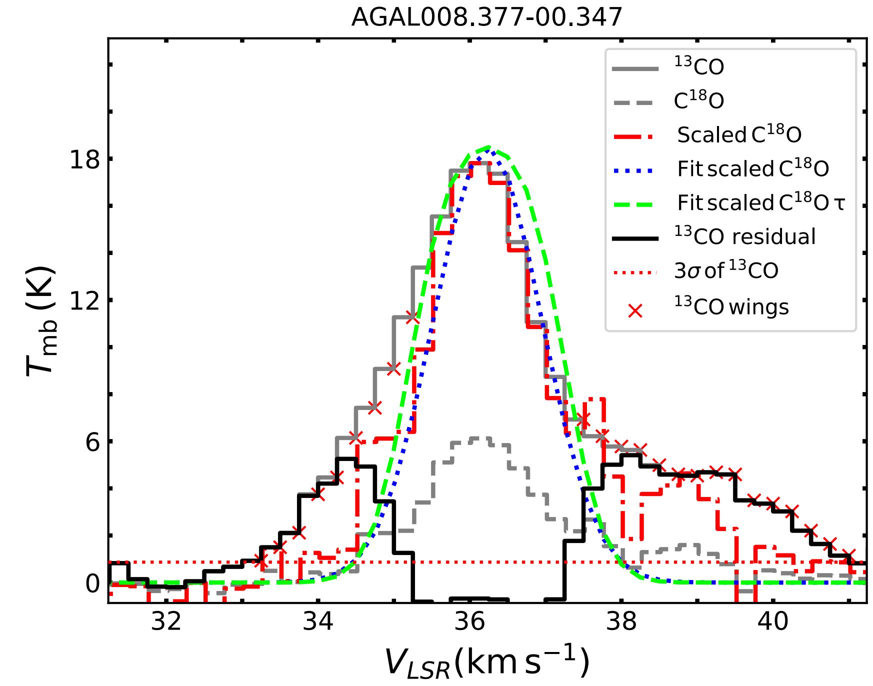
Outflow occurancy: 1192/2052 = 58%

Bipolar outflow: 706/2052 = 34%







Yang+ 2018

Outflow occurancy: 325/335 = 69%

Bipolar outflow: 225/325 = 66%

Outflow occurancy: 1192/2052 = 58%

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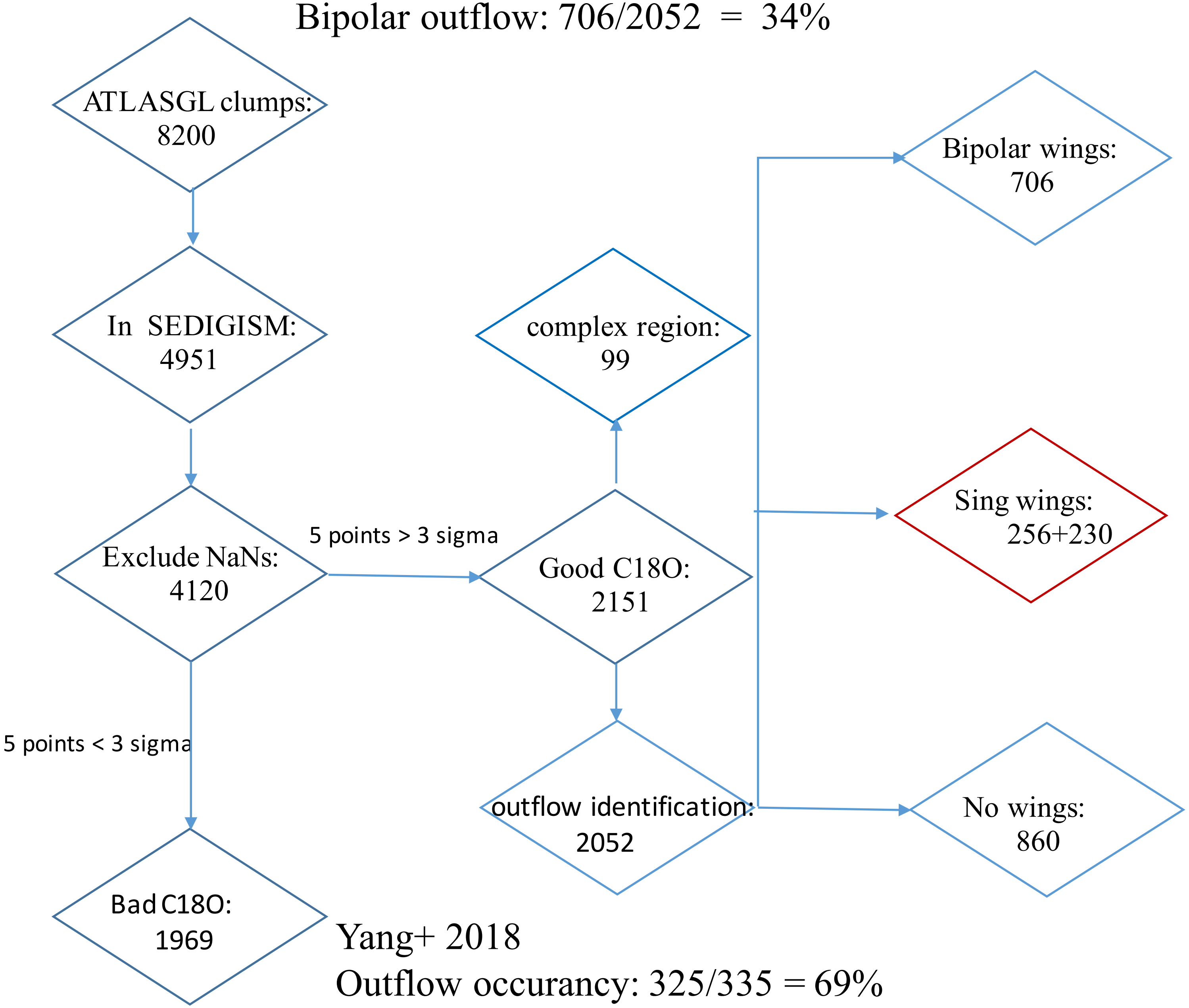

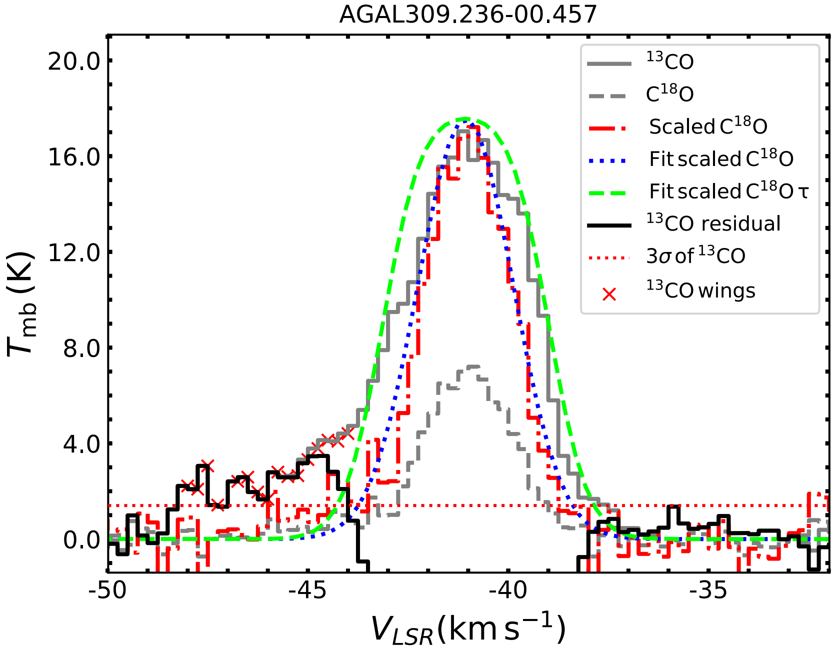

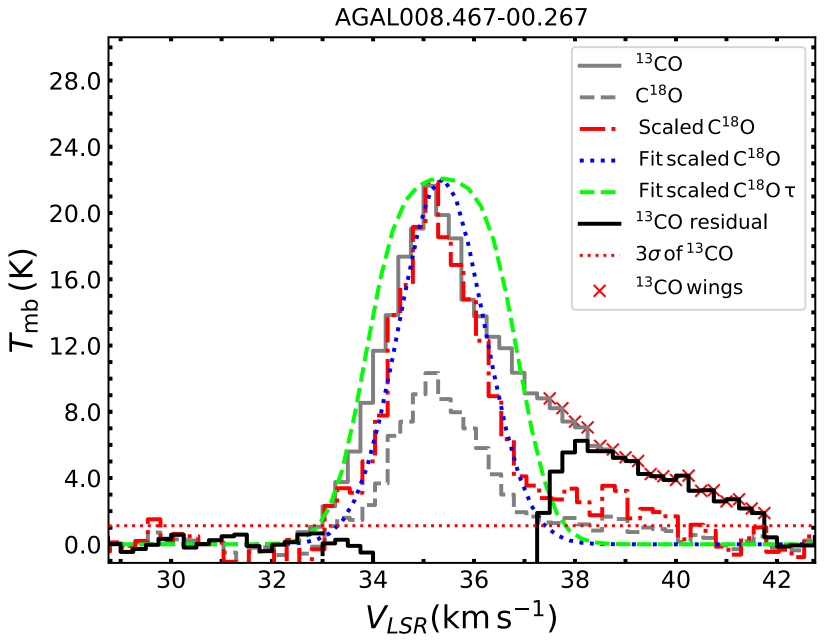

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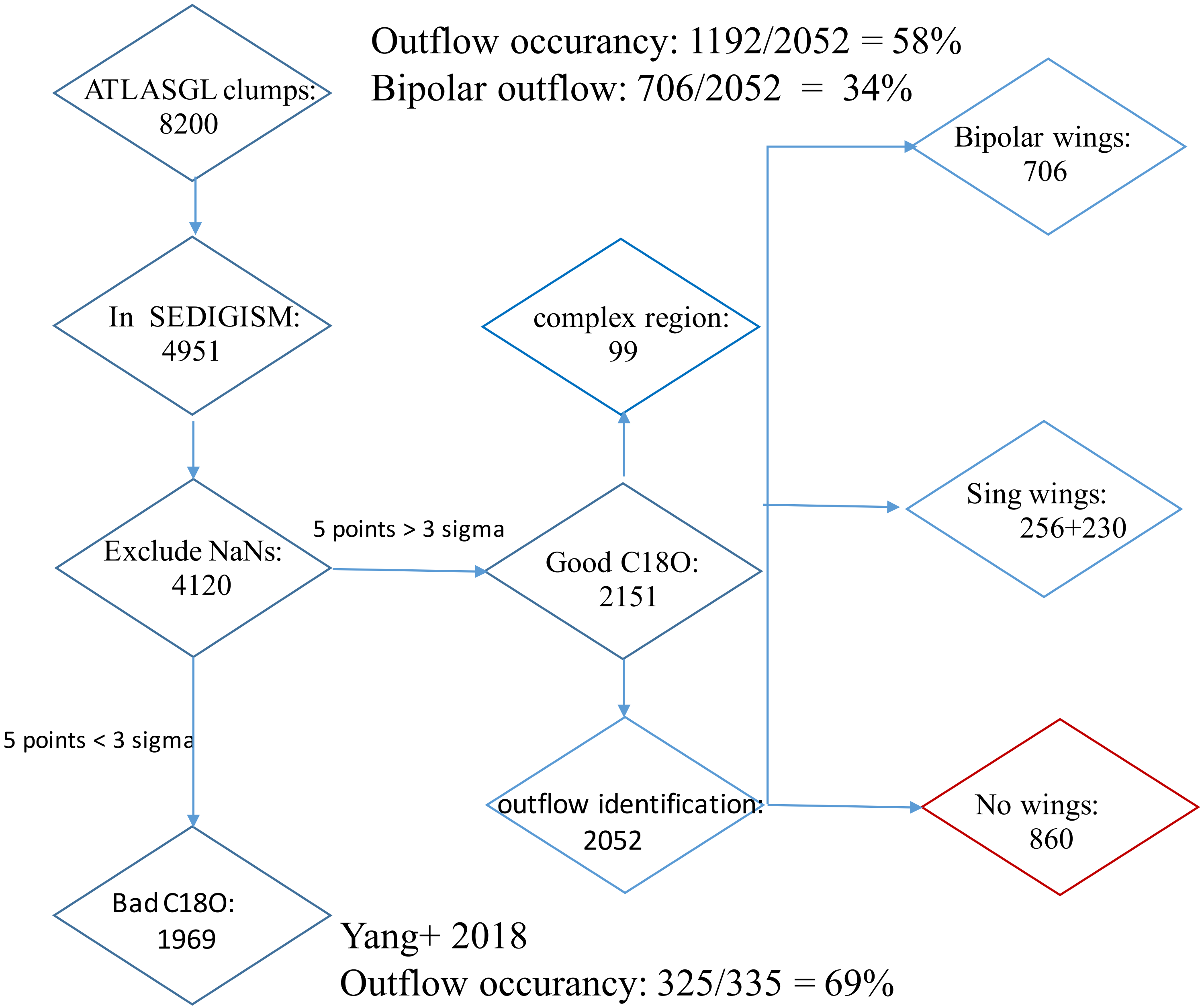

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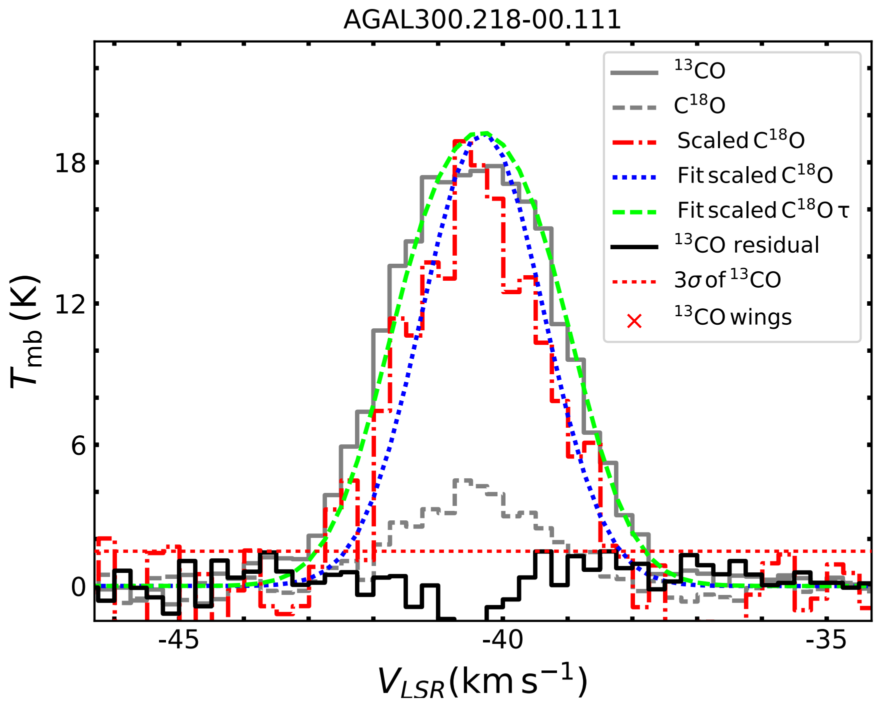
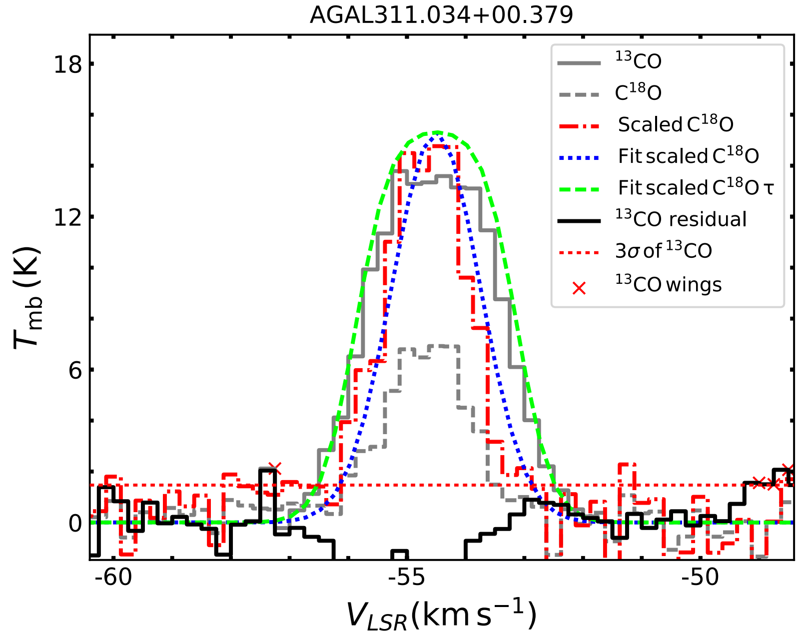
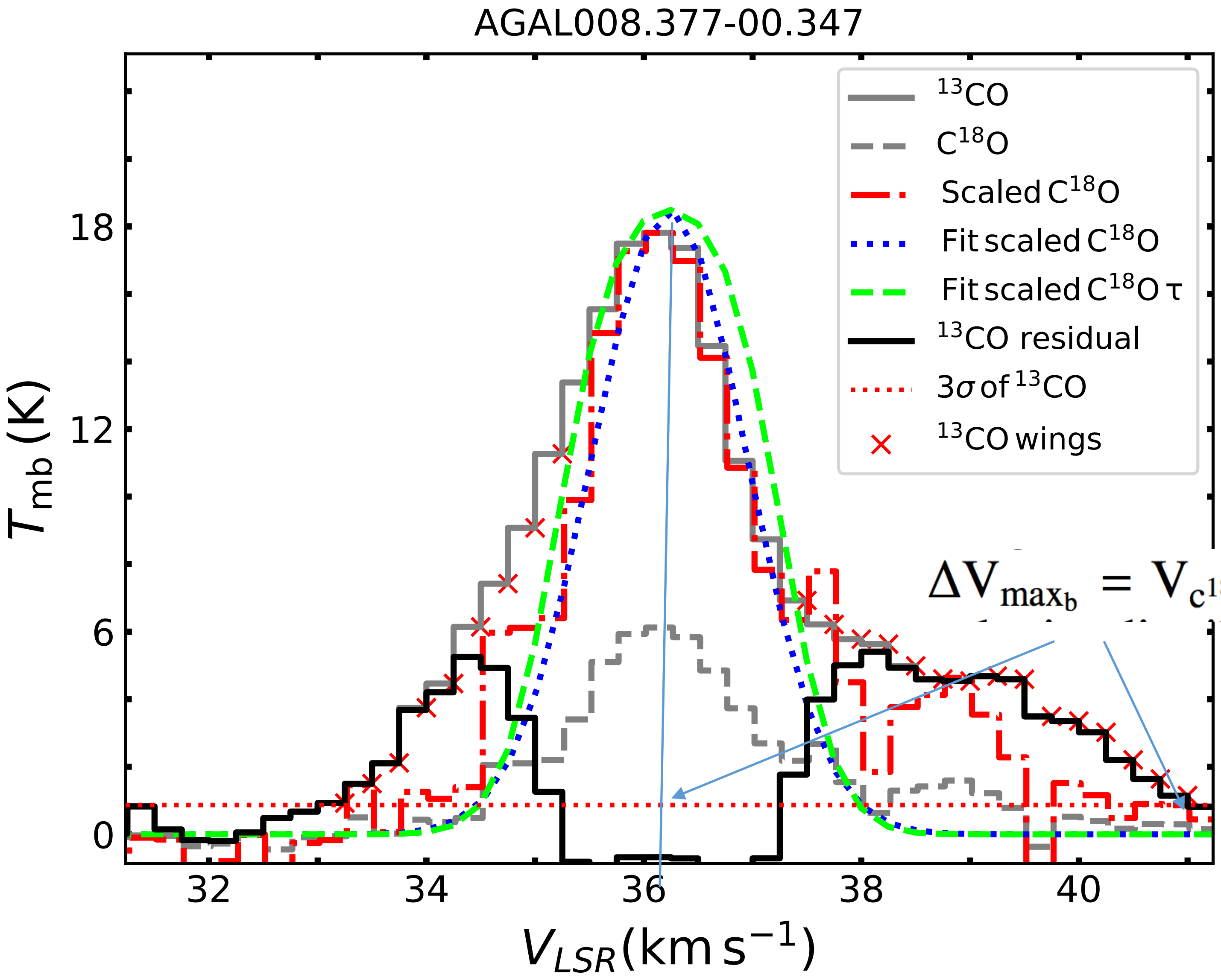




Velocity ranges of the outflow wings



Blue/Red velocity range
$\Delta Vmax_{(r/b)}$

$$\Delta V_{max_b} = V_{c^{18}o} - V_{min_b} \text{ and } \Delta V_{max_r} = V_{max_r} - V_{c^{18}o}$$

Aiyuan Yang@MPIfR

Velocity ranges of the outflow wings

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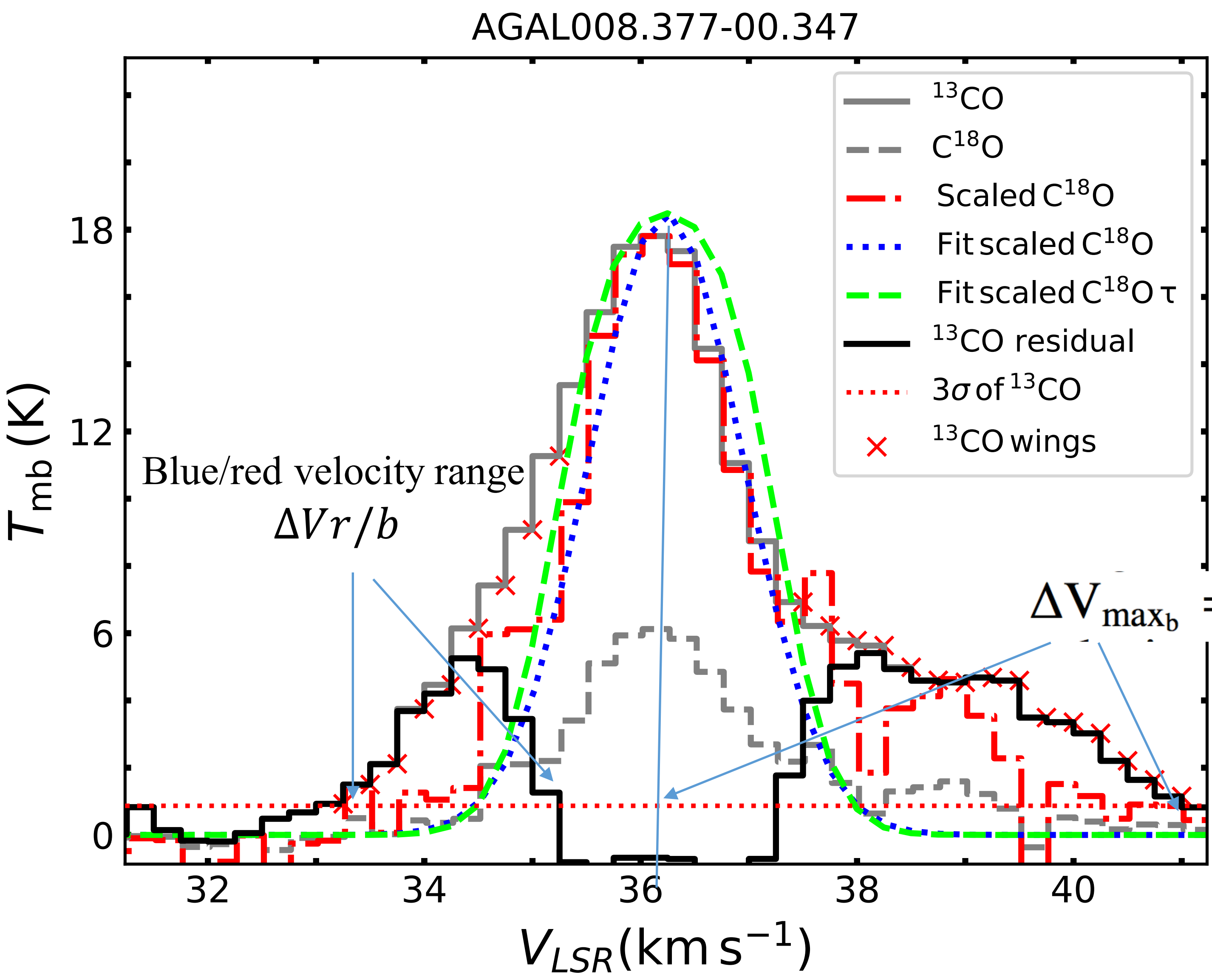
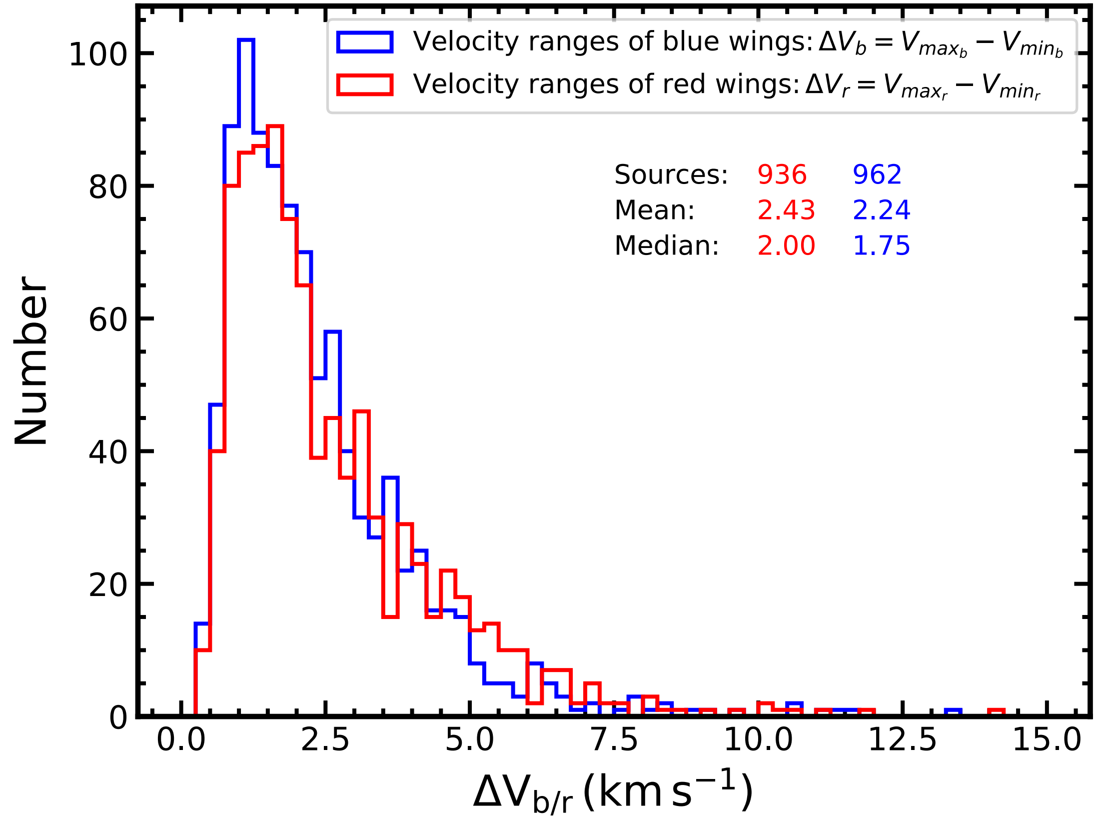


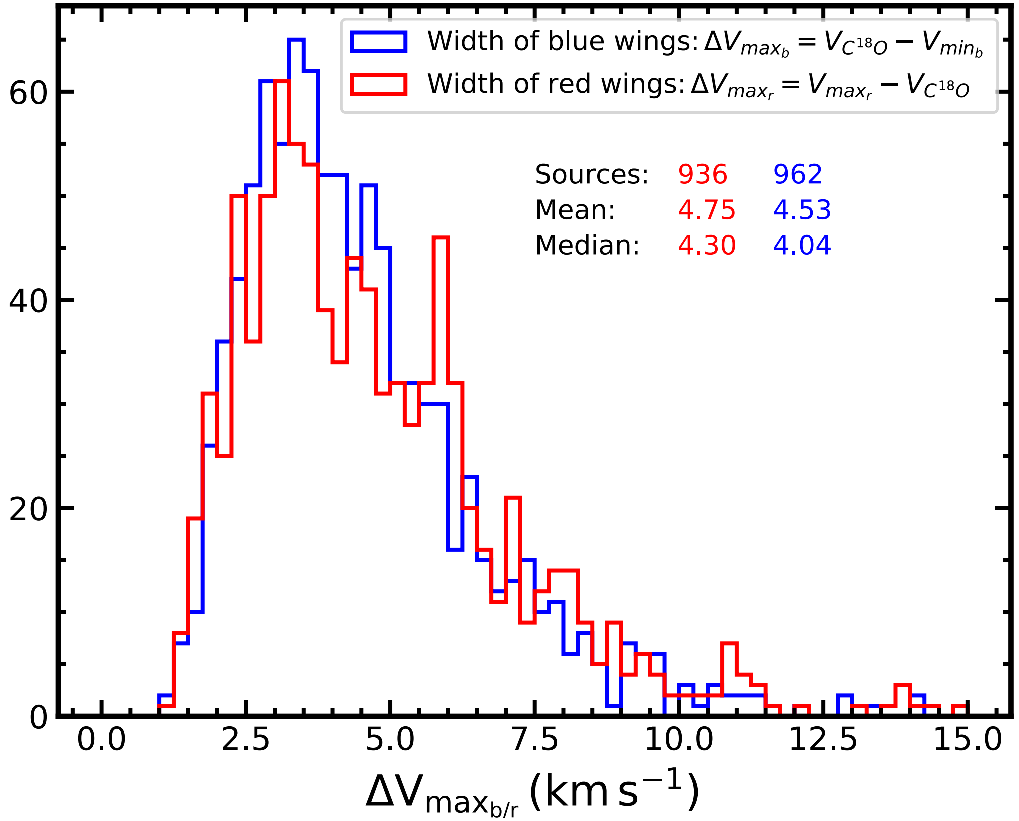
$$\Delta V_{b/r} = |V_{max_{b/r}} - V_{min_{b/r}}|$$

Blue/Red velocity range
$\Delta Vmax_{(r/b)}$

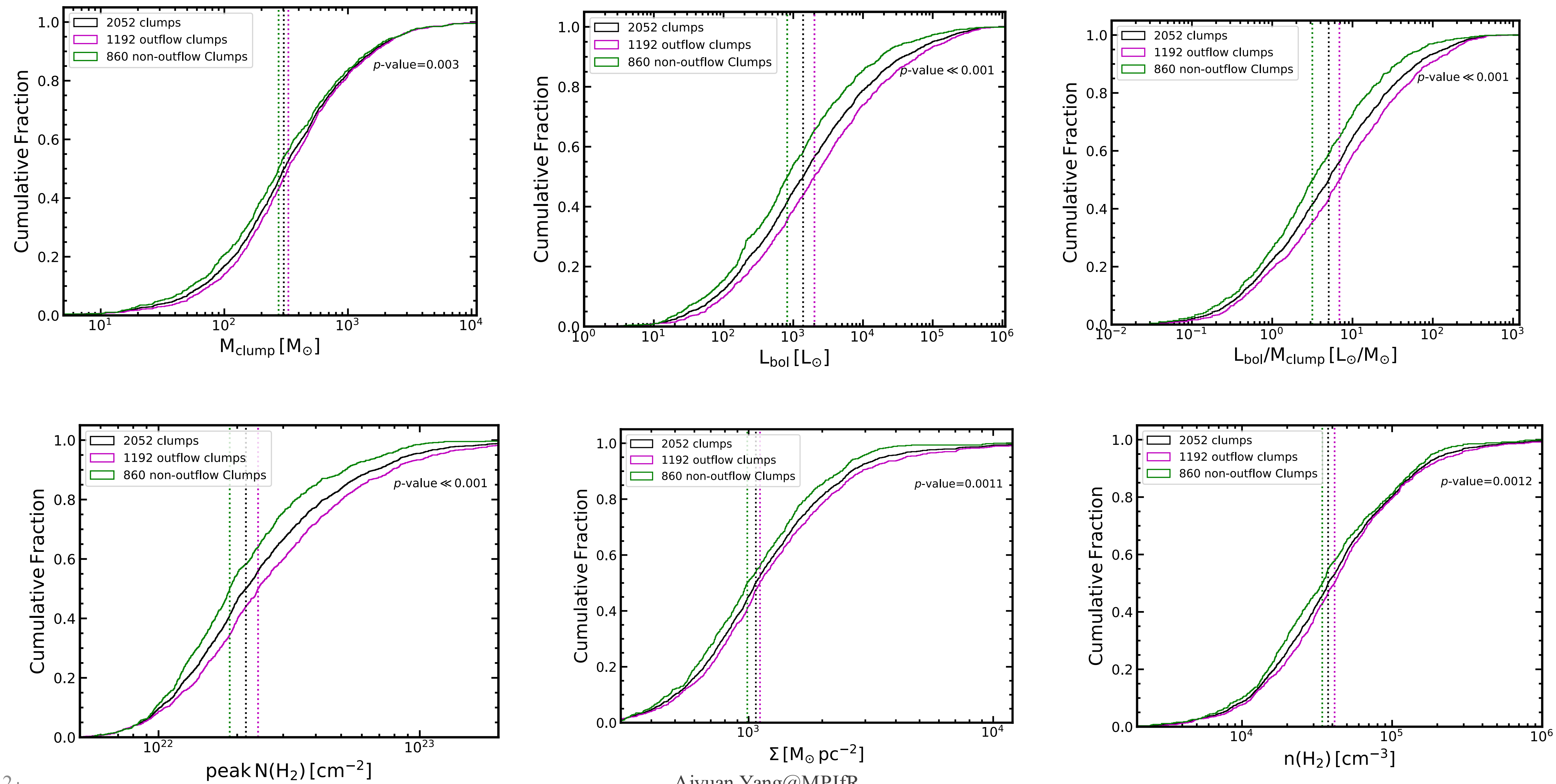
$$\Delta V_{max_b} = V_{c^{18}O} - V_{min_b} \text{ and } \Delta V_{max_r} = V_{max_r} - V_{c^{18}}$$

Velocity ranges of outflow wings





Outflow clumps VS non-outflow clumps



Outflow detection rate statistics

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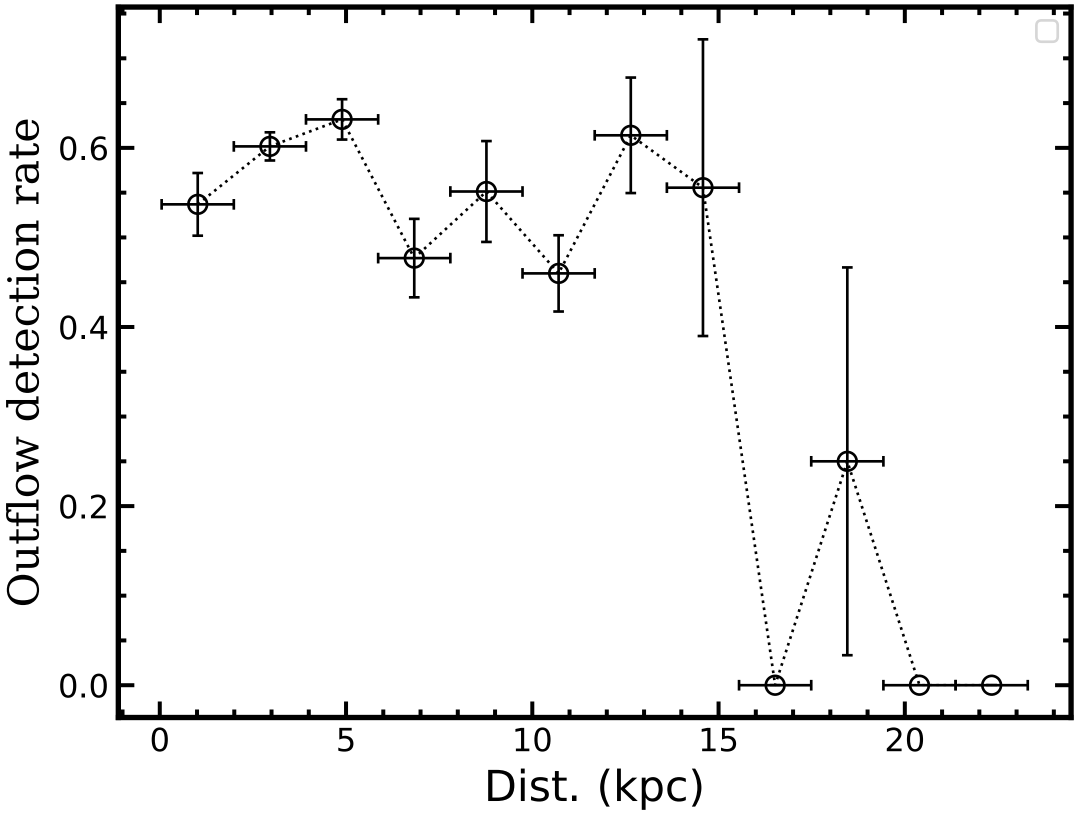
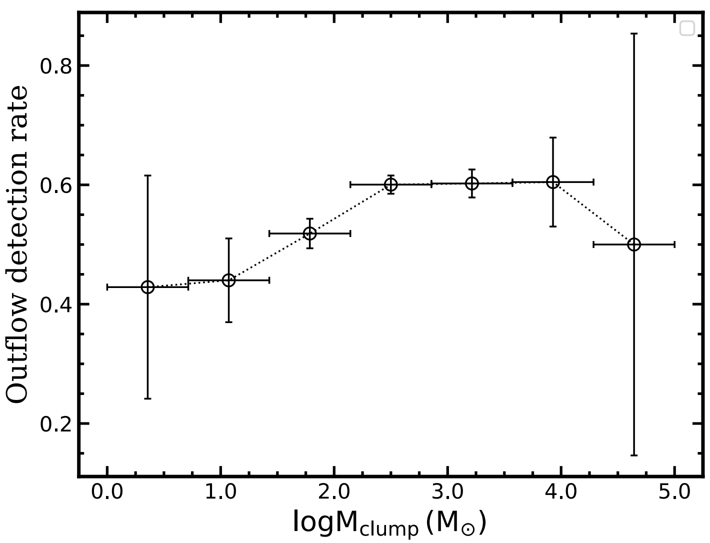
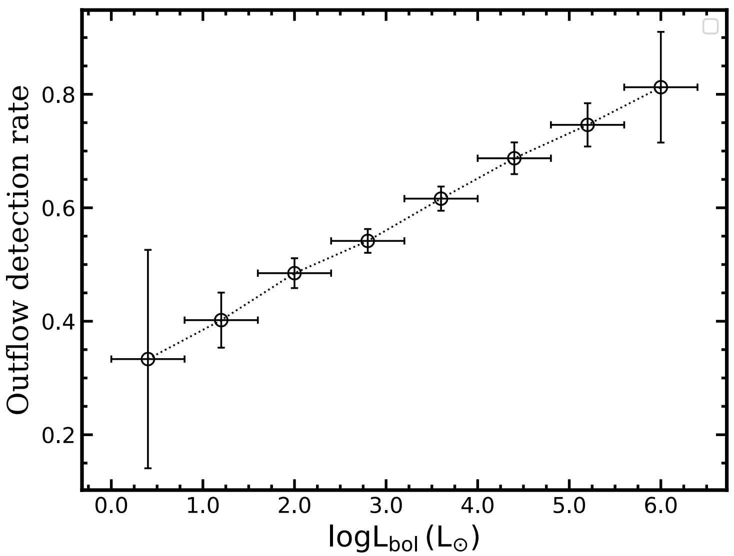
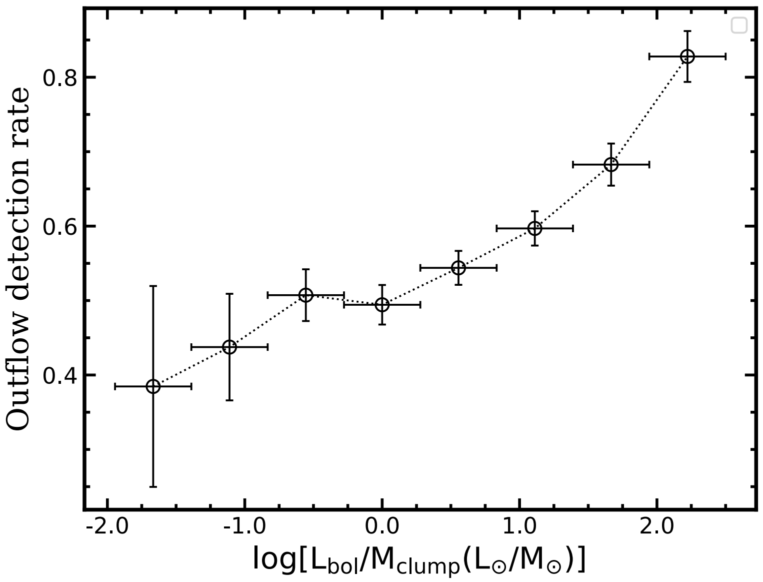


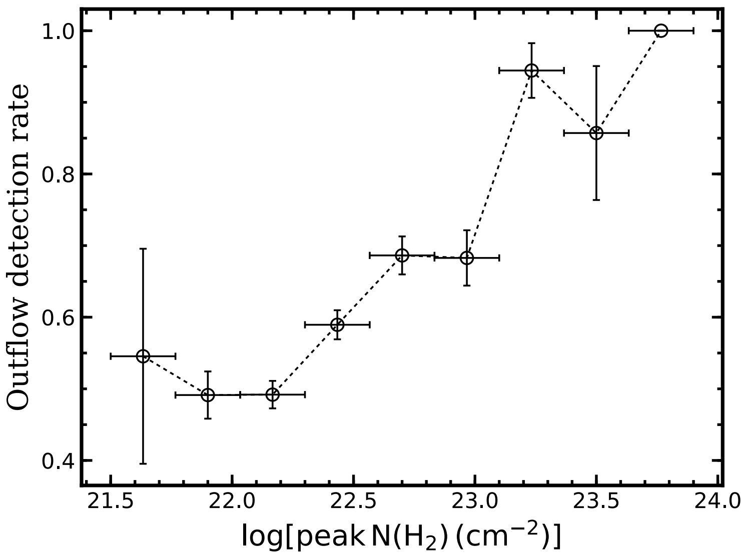
The detection rates are more or less similar for clumps with d < 1,kpc and sharply decrease when d > 14 kpc, however, only <1 % of the sources with d> 14 kpc in the sample.
The distances bias for the outflow identification wouldn't be significant and the systematical analysis of the detection rate is valid.

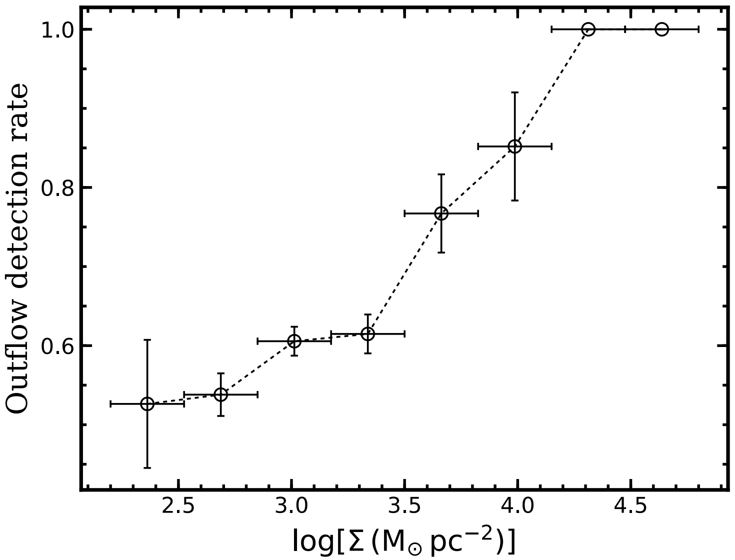
Outflow detection rate statistics

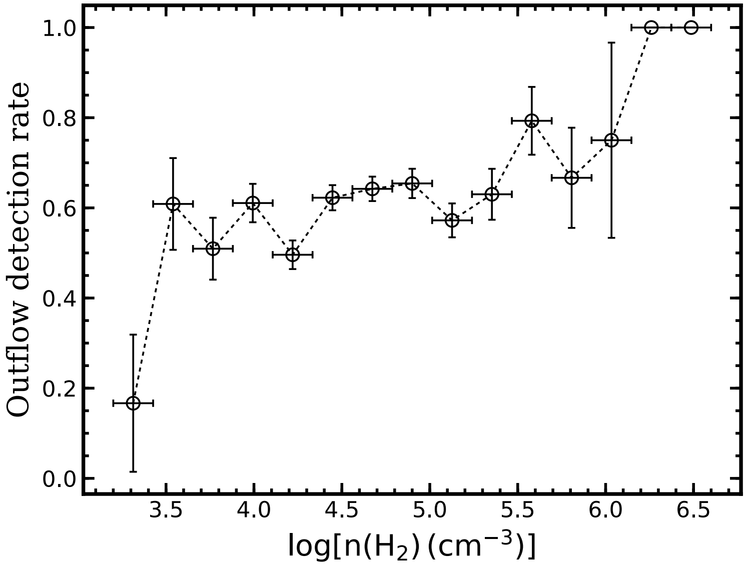








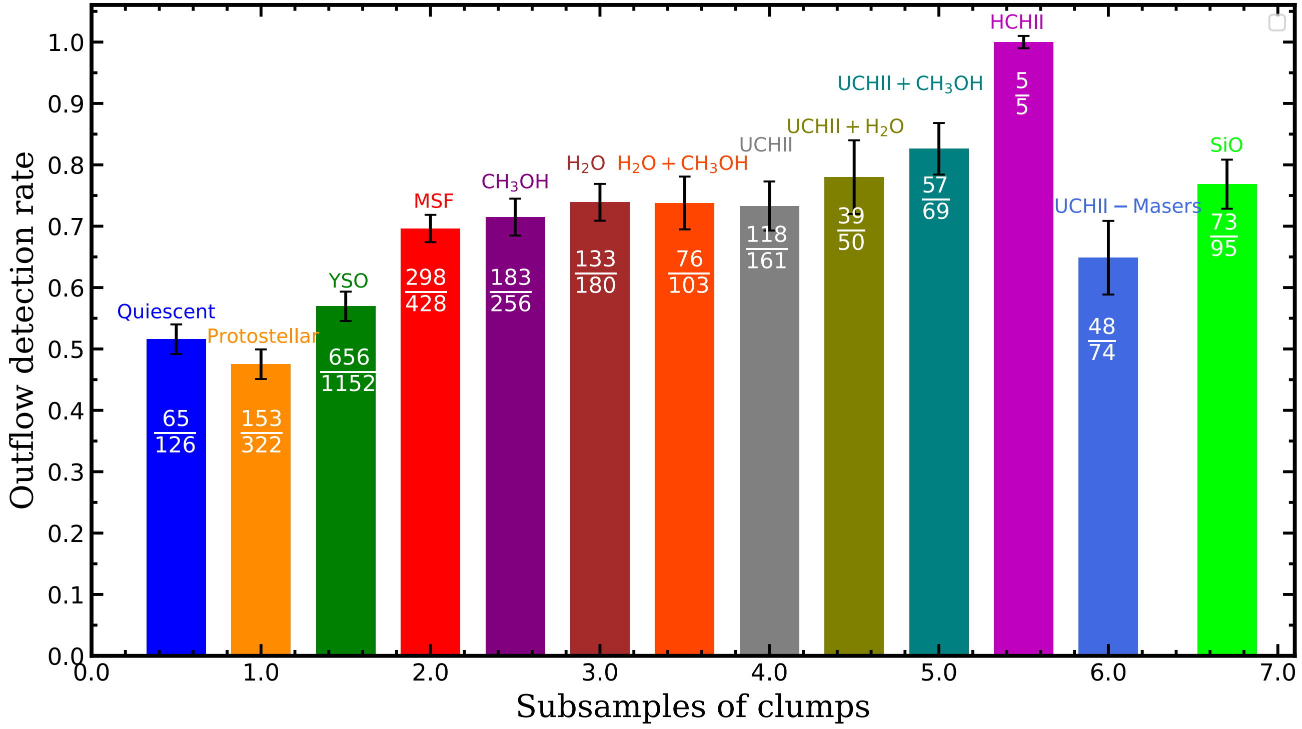




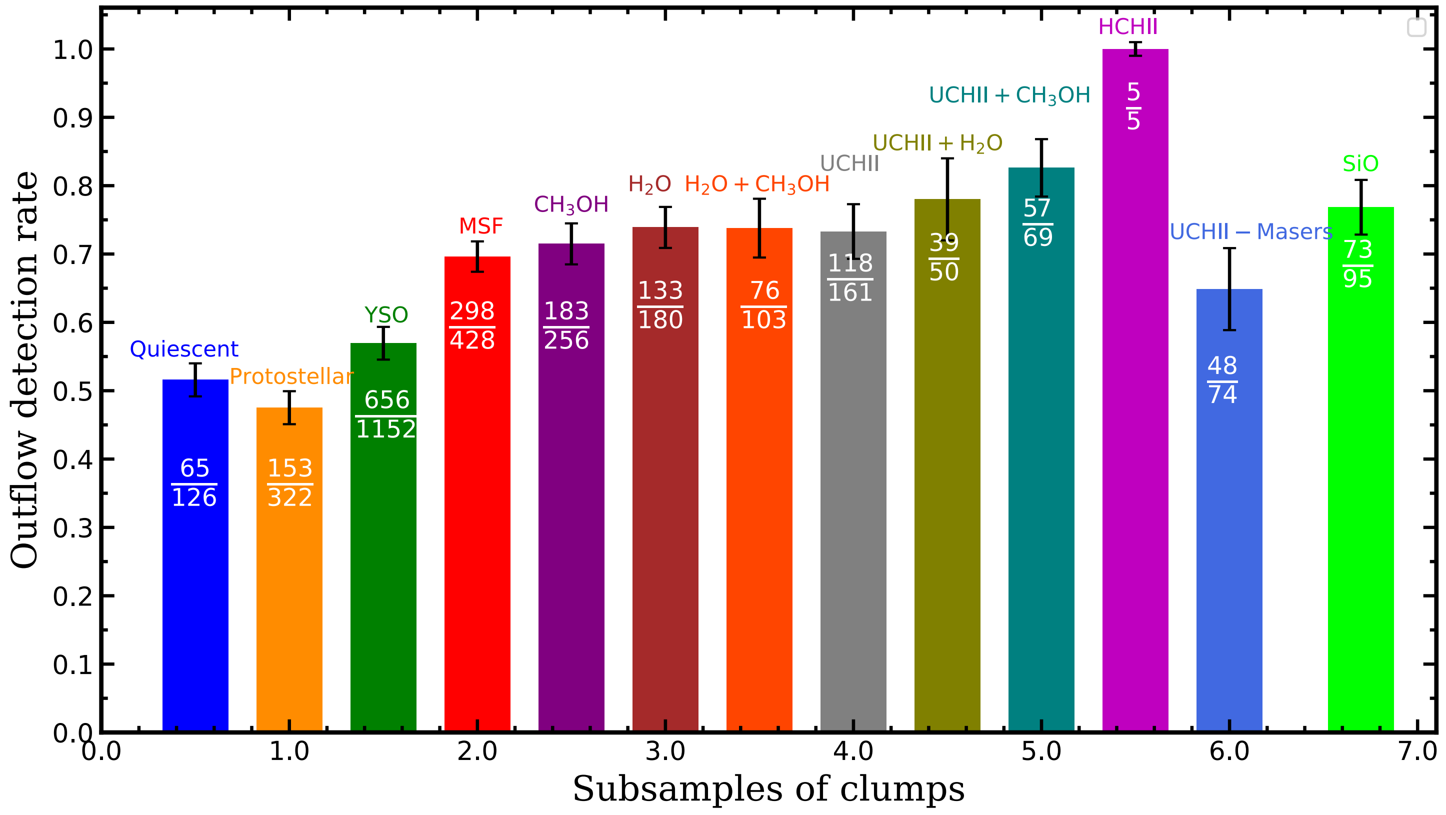
Outflow detection rate statistics

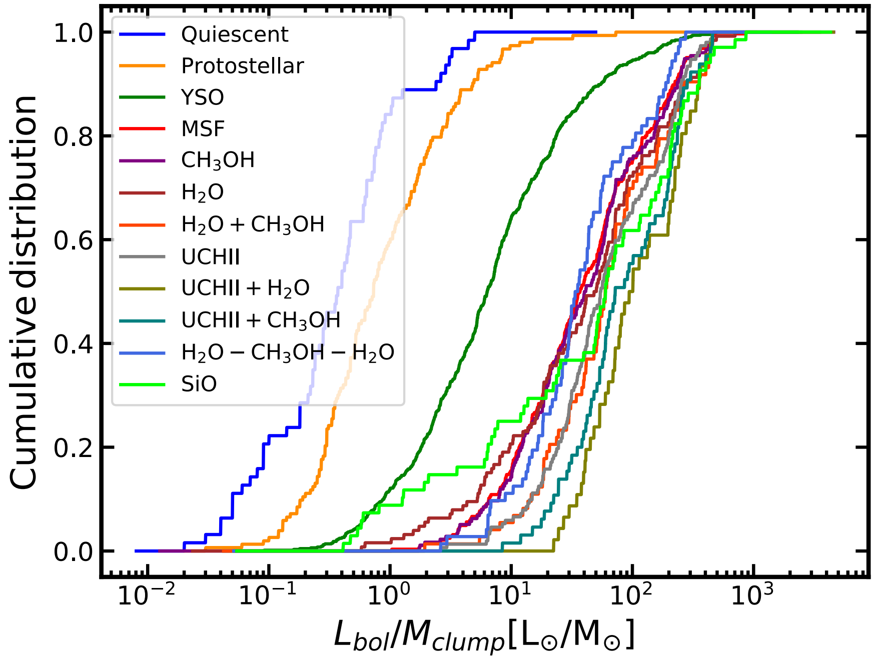
Table 4. Results of outflow detection rate for clumps in different evolutionary stages.

Clumps	Number	With outflow
Total	2052	1192 (58%)
Quiescent	126	65 (51%)
Protostellar	322	153 (47%)
YSO	1152	656 (57%)
MSF	428	298 (70%)
SiO	95	73 (77%)
CH_3OH Masers	256	183 (71%)
H_2O Masers	180	133 (74%)
CH_3OH + H_2O	103	76 (74%)
UC H II regions	161	118 (73%)
UC H II +H_2O	50	39 (78%)
UC H II +CH_3OH	69	57 (86%)
HC H II regions	5	5 (100%)
UC H II −Masers	74	48 (65%)



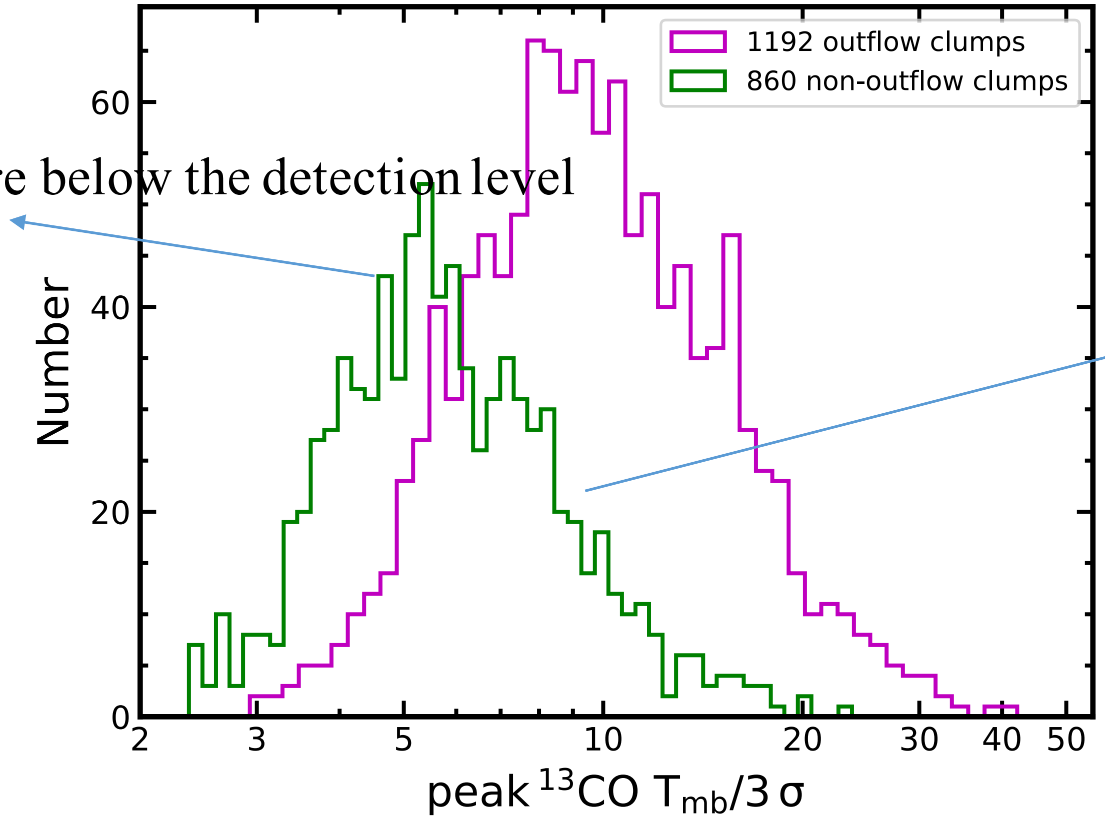
Outflow detection rate statistics





detectability

non-outflow sources,
or have weak wings that are below the detection level



non-outflow sources,
or have wings that cannot be detected

The non-outflow sources shows a lower peak value than the outflow sources, indicating that part of the sources without wings (and hence classified as non-outflow sources) could just have wings that fall below the noise level.

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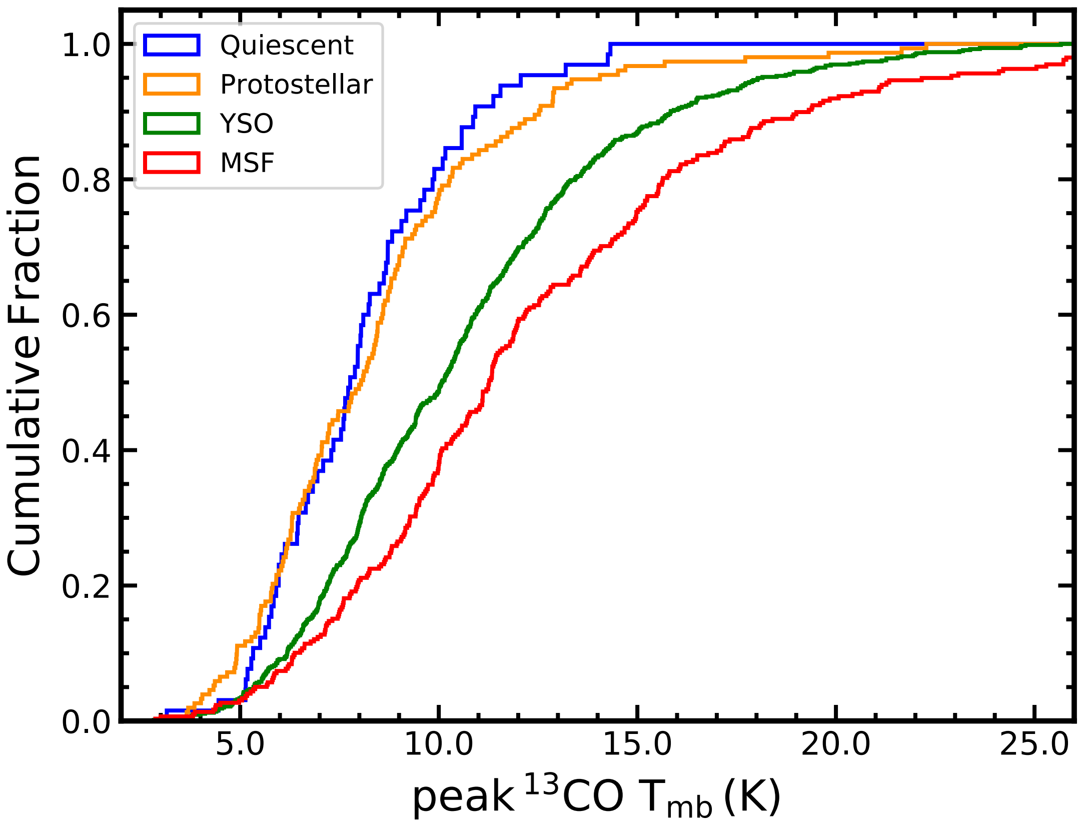
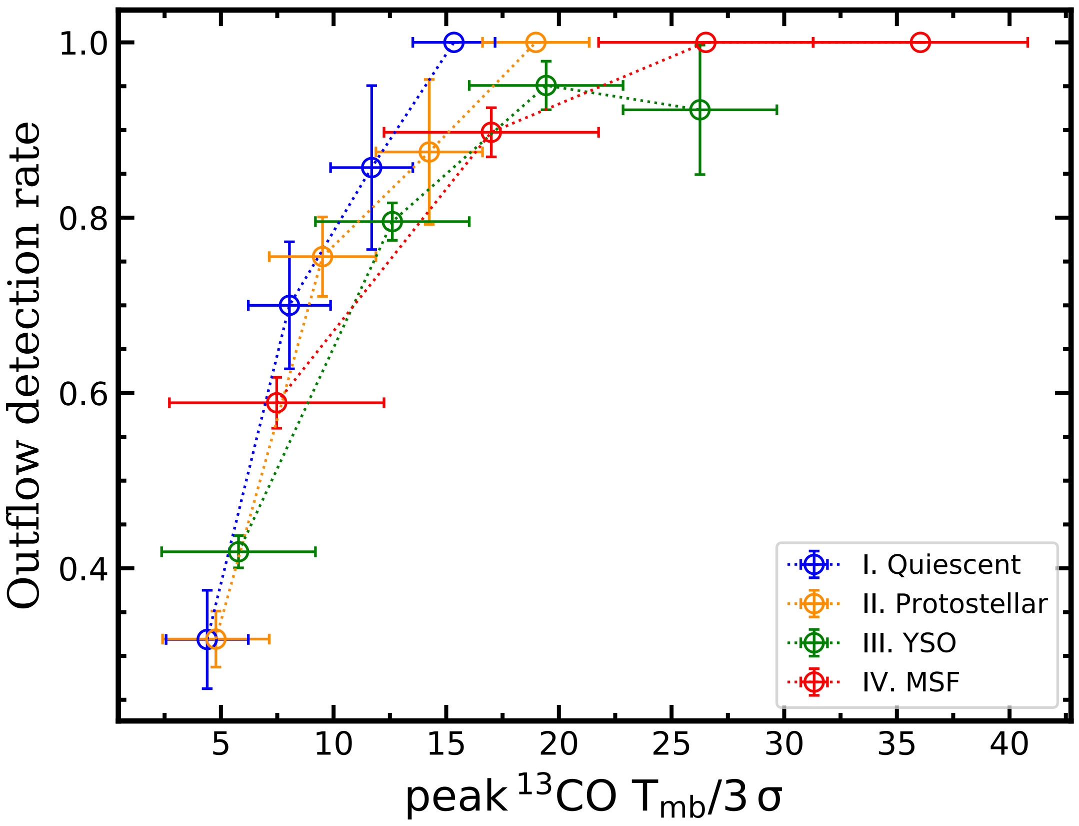
detectability

Are the increase in detection rate significant?





Furture aspects

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1, Follow-up SiO line survey toward the outflow clumps

The outflow identification process can be affected by:

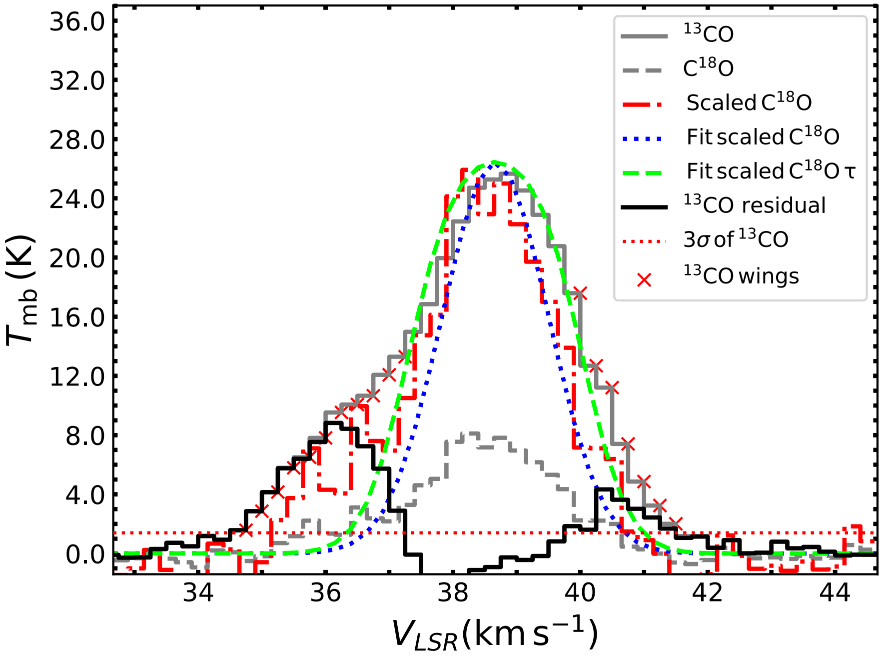
1, confusion (the observed sources lie along the Galactic plane where most of the molecular material resides)
2, spectral noise (in the case of weak sources);
3, outflow geometry;
4, the beam filling factor of CO line emission;
5, the opacity variations in the CO line wings;

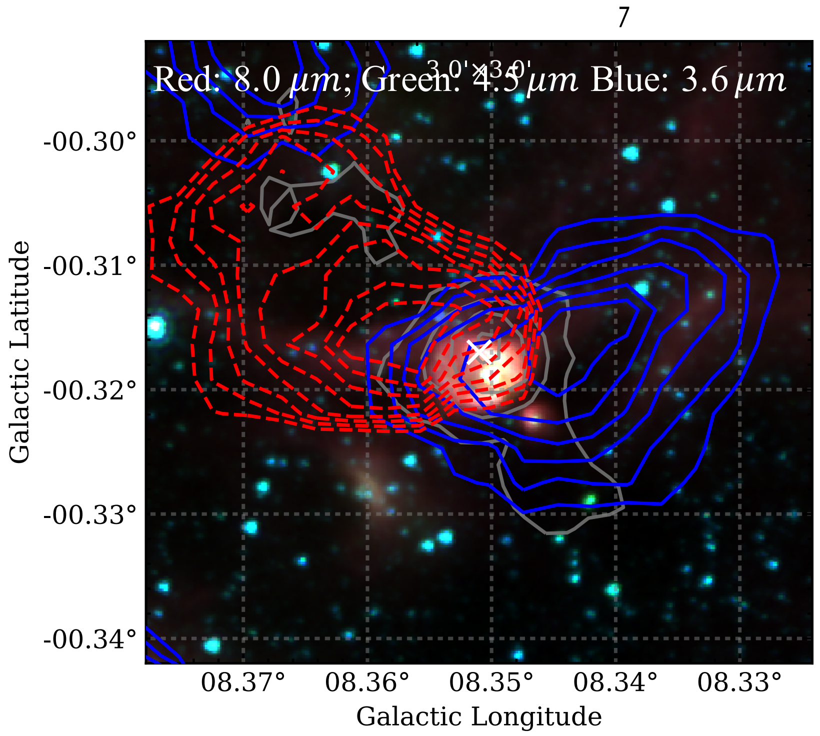
→it is possible to miss outflows or mis-identification

Unlike CO, SiO emission suffer much less from confusion with ambient material, and would be a better traces of outflows.
The observation of SiO toward the sample allows us to obtain a more rigorous sample of outflow clumps.

Future prospects

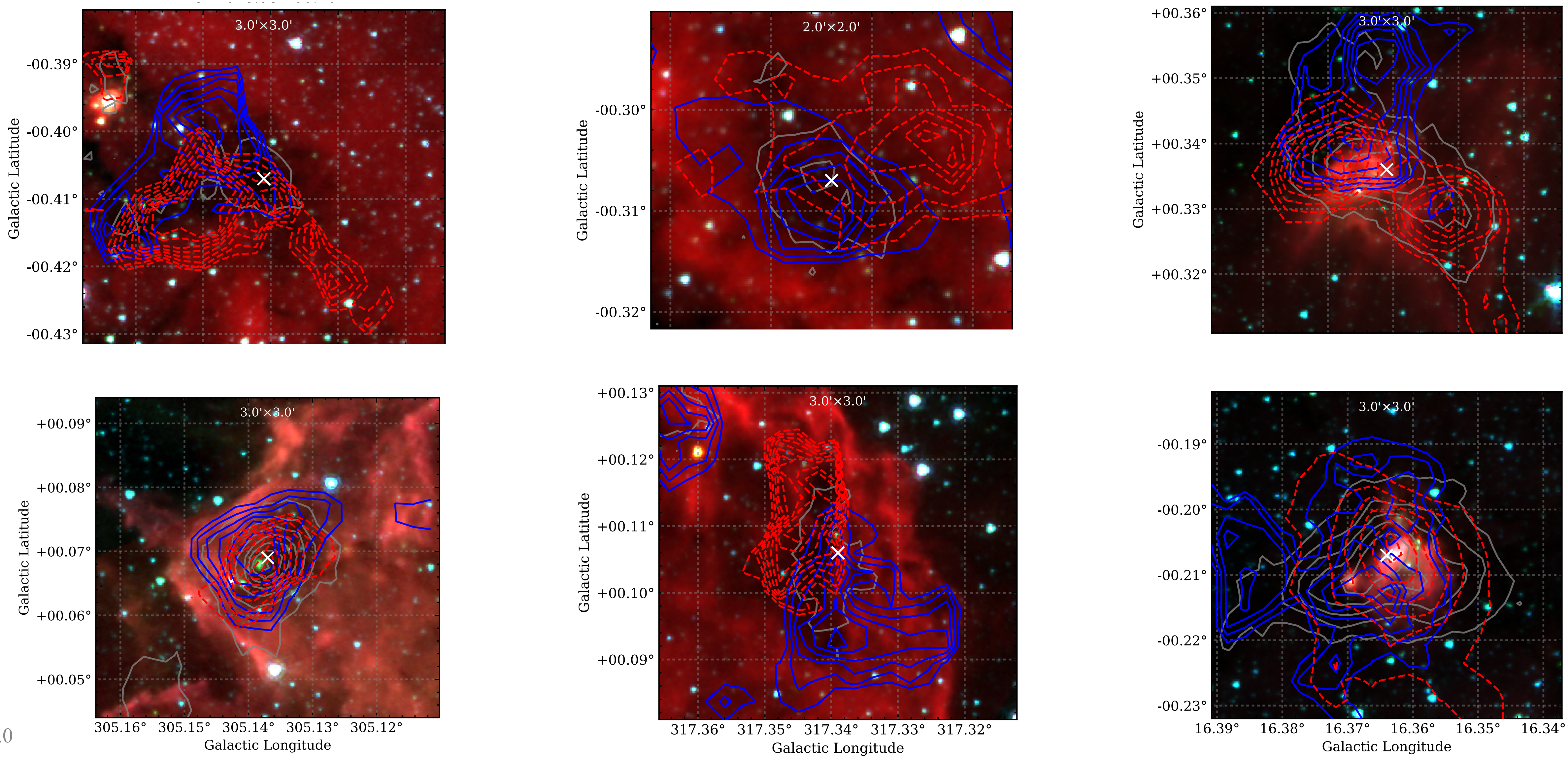
2, Outflow mapping at higher resolution:





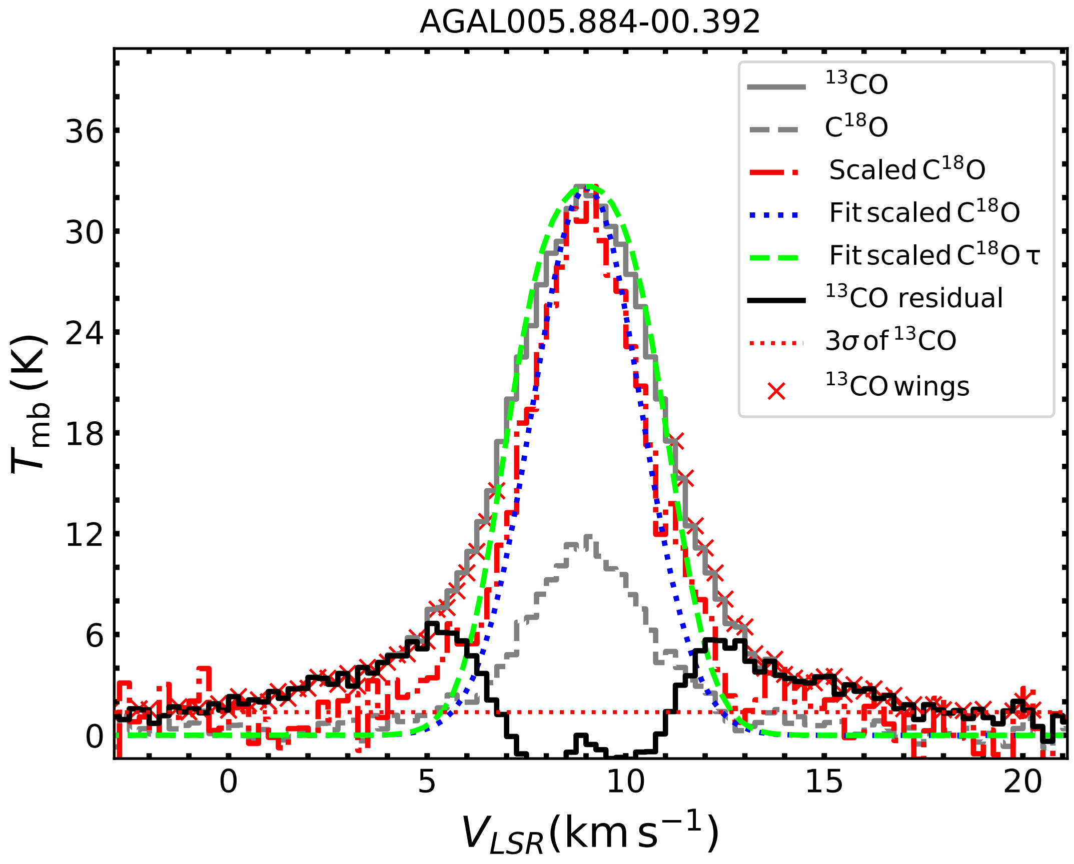
Future prospects

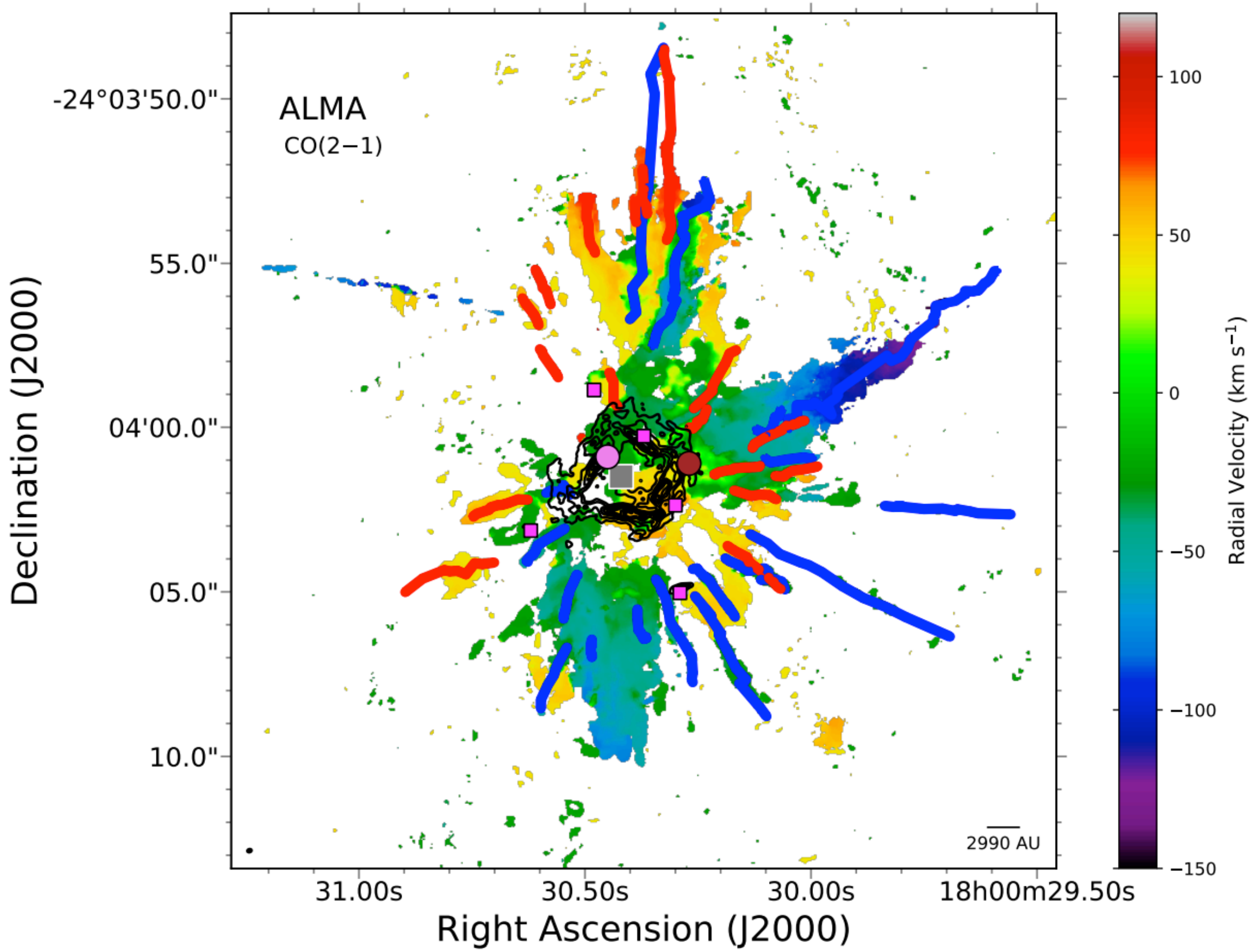
Outflow mapping at higher resolution:



Future prospects

Extremely high-velocity outflow source? Explosive Outflow?





Zapata+ 2019,2020

Future prospects

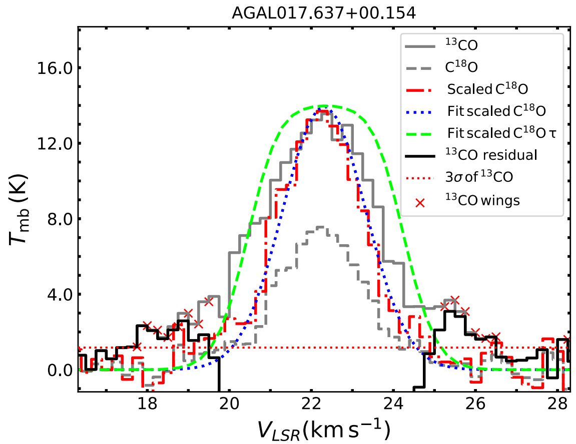
Keplerian disc candidates around O-type high-mass stars?

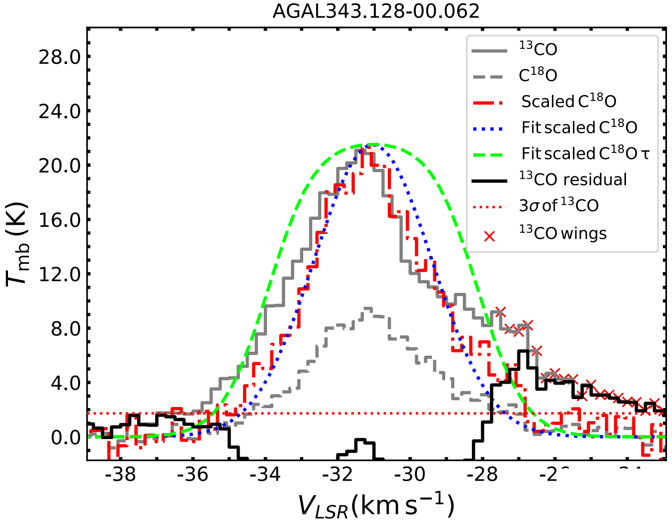
Table 3. Properties of Keplerian disk candidates around HMYSOs as observed with ALMA to date.

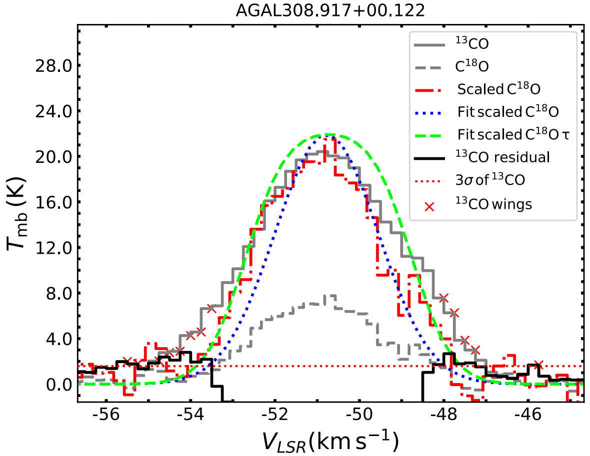
Object	Distance [kpc]	Luminosity [$L_\odot$]	Star Mass [$M_\odot$]	Disk Mass [$M_\odot$]	Disk Radius [AU]	References
			B-type YSOs			
Orion Source I	0.4	$\sim 10^4$	15 ± 2	< 0.2	75-100	[1,2]
IRAS 20126+4104	1.6	$\sim 10^4$	12	1.5	860	[3,4]
IRAS 18162–2048[a]	1.7	$\sim 10^4$	18	4	300	[5]
G339.88-1.26	2.1	4×10^4	11 ± 5	—	430–630	[6]
G35.20-0.74N	2.2	$\sim 10^4$	18 ± 3	3	2500	[7]
G35.03+0.35 A	3.2	6×10^3	9 ± 4	0.75	2200	[8,9]
G16.59–0.05	3.6	3×10^4	10 ± 2	1.8 ± 0.3	500	[10]
			O-type YSOs			
S255IR NIRS3	1.8	1.6×10^{5}[b]	20	0.3	500	[11]
G351.77-0.54	2.2[c]	1.7×10^4	14-25[d]	0.1-0.49[e]	250-500[b]	[12]
G17.64+0.16	2.2	$\sim 10^5$	45 ± 10	< 2.6	120	[13,14]
IRAS16547-4247	2.9	$\sim 10^5$	20	4	870	[15,16]
G11.92-0.61 MM1	3.4	$\sim 10^{4}$[f]	34 ± 5	2.2-5.8	480	[17]
AFGL 4176	4.2	$\sim 10^5$	20	2–8	1000	[18,19]
G023.01–00.41	4.6	4×10^4	20	1.6	2500	[20]

NOTE— When mass error bars are not given, the measurements should be taken as loose estimates, e.g., based on consistency checks between a stellar type and the upper-limit luminosity. Radius estimates are wavelength-dependent.

Goddi+2019







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Summary

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- Outflow is a common activity in the massive star formation process
  - 1192 clumps out of the 2052 show outflows~ 58%, 34% for bipolar wings; 24% for unipolar wings
  - higher values for HCHII(100%), UCHII(93%), Masers(84%).
- Outflow switches on the youest stages of clump i.e. 70 μm dark;
- Obtain a sample of sources in the 70 μm dark and 24 dark phases;
- Outflow detection rate increases as clumps evolve, the increasing of L;
  - From Prestellar(51%), Protostellar (47%), YSO-forming(58%), MSF(70%)
- However, the increase in detection rate are more likely to be due to an increase in detectability rather than a lower fraction of outflow frequency.
- This is the largest outflow sample so far, providing interesting targets: (1) 70 μm dark outflow clumps, and (2) extremely high-velocity outflow clumps

Thank you very much for your attention~

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