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Clustering the Interstellar Medium for Galactic Gamma-Ray Modelling

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Astronomical Society of Australia

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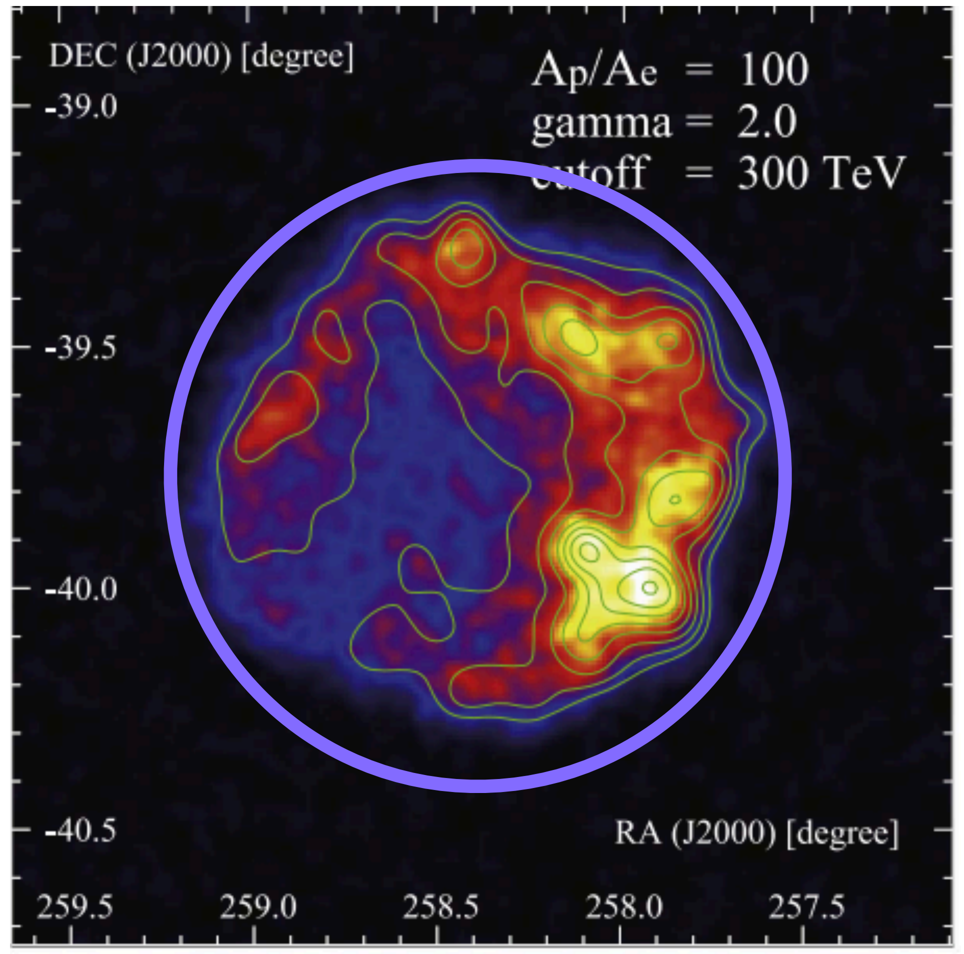
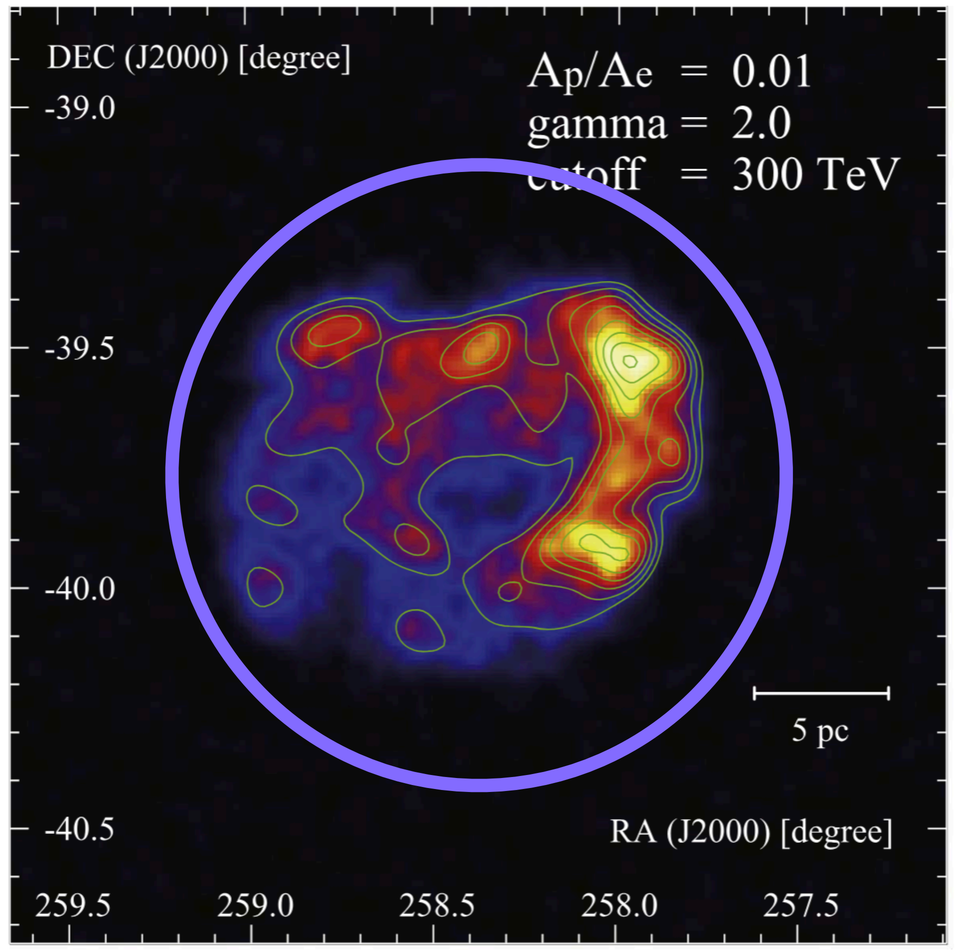
Importance of Modelling the Gamma-Ray Morphology

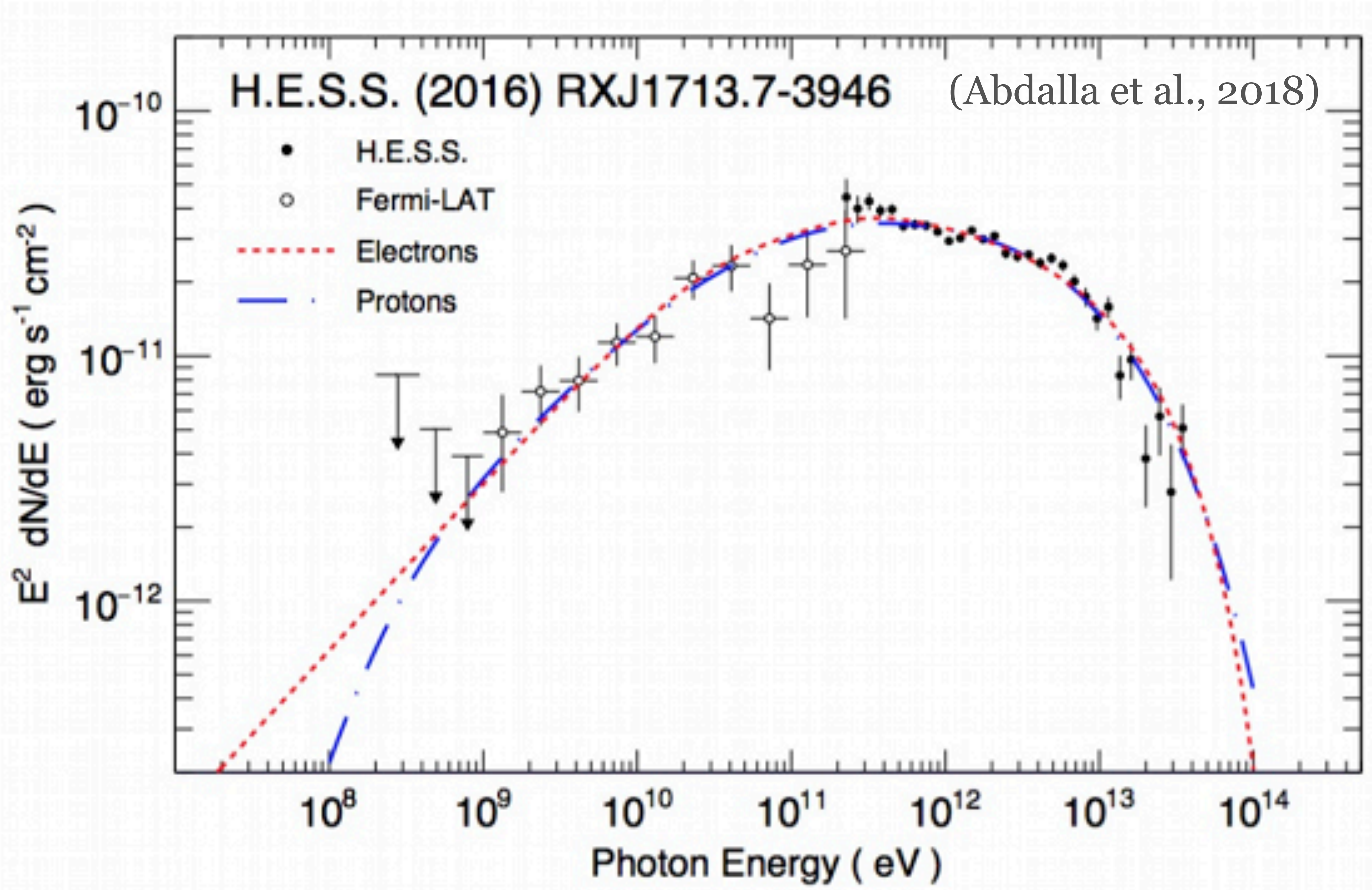
Gamma-ray model #1



Gamma-ray model #2



(Acero et al. 2017)



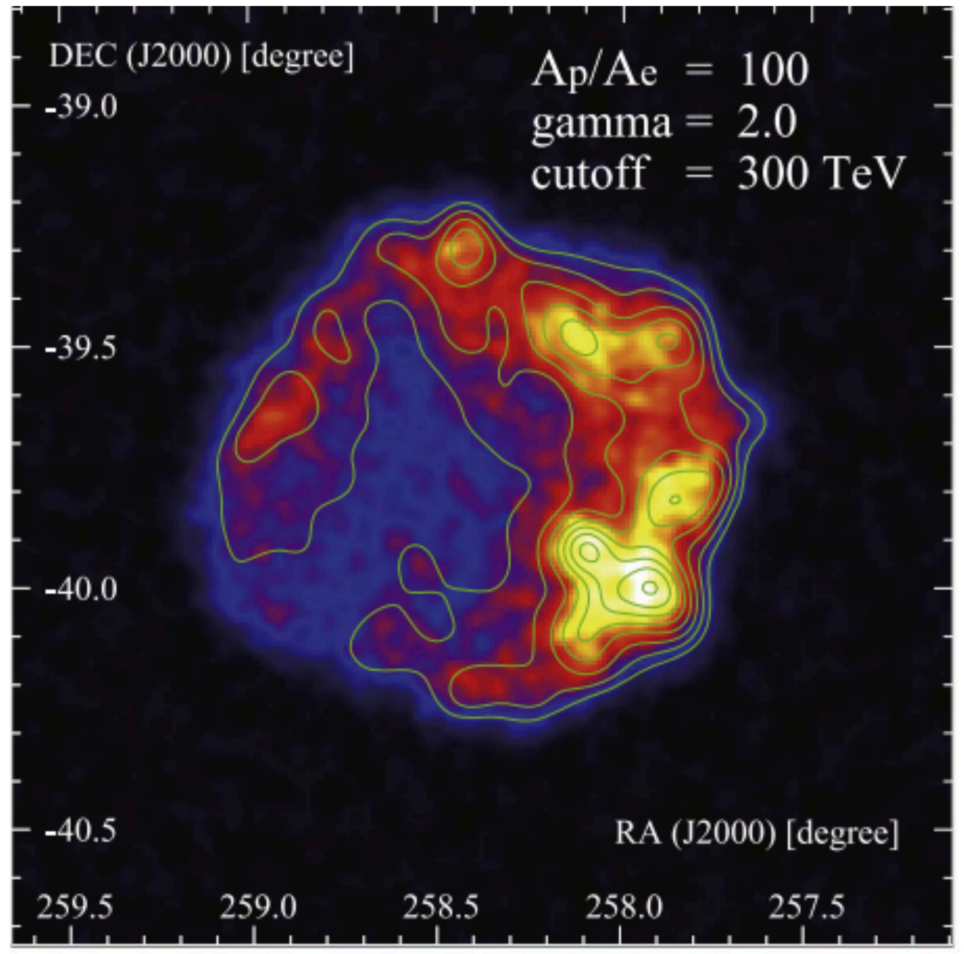
(Abdalla et al., 2018)

Models including different physics processes can produce very similar spectra

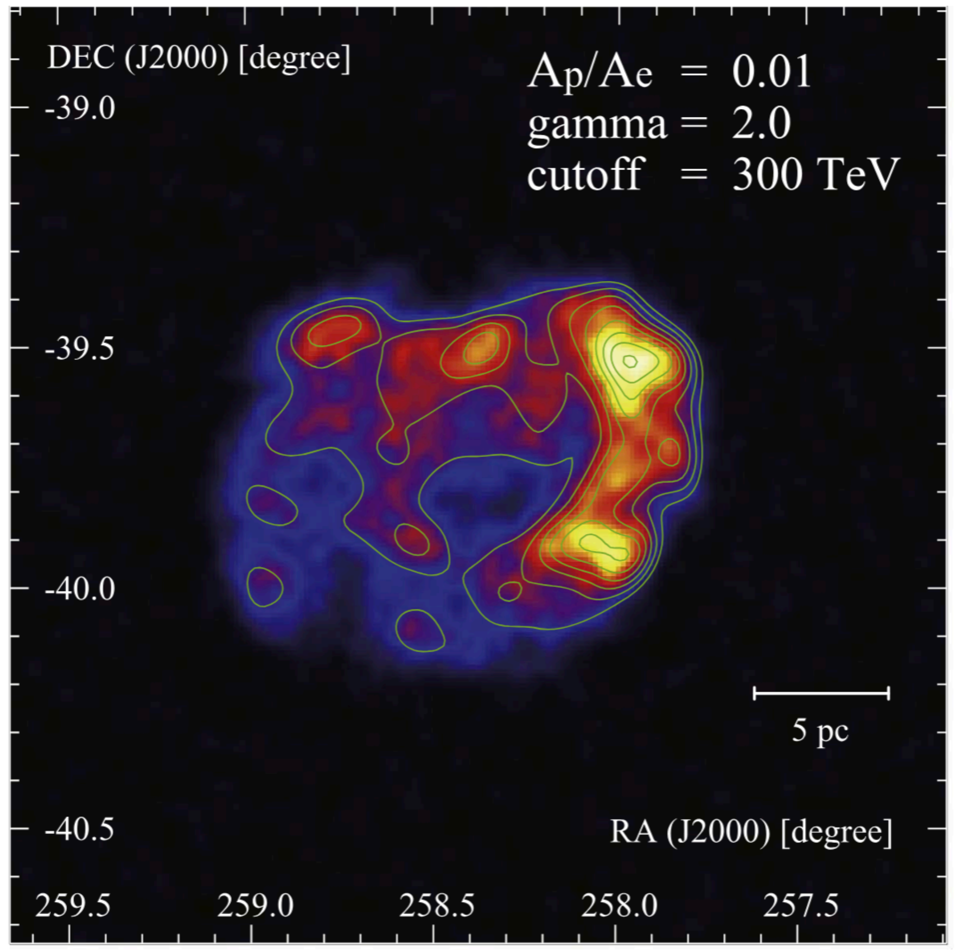
Need to model morphology as well

Importance of Modelling the Gamma-Ray Morphology

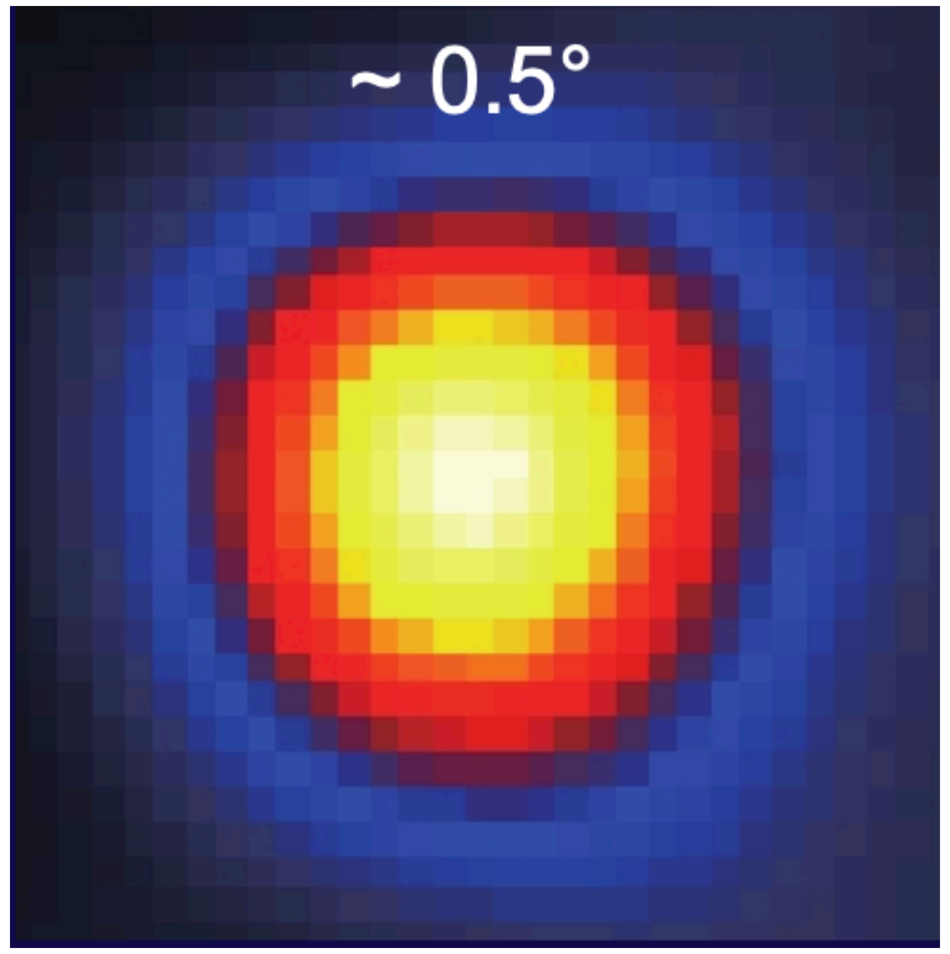
Gamma-ray model #1



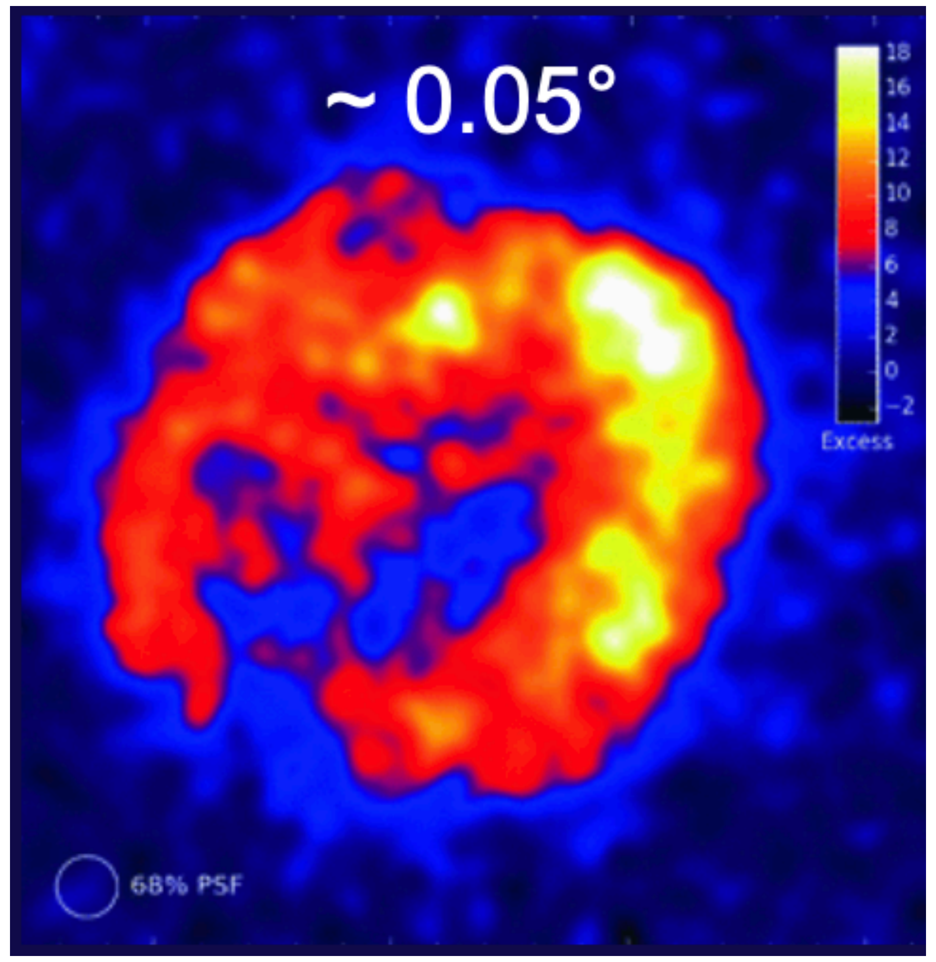
Gamma-ray model #2



(Acero et al. 2017)



CTAO-like observation



Need observations with arc-minute scale resolution to resolve morphology

- **Models require similar resolution**
- **Interstellar medium measurements' resolution needs to match**

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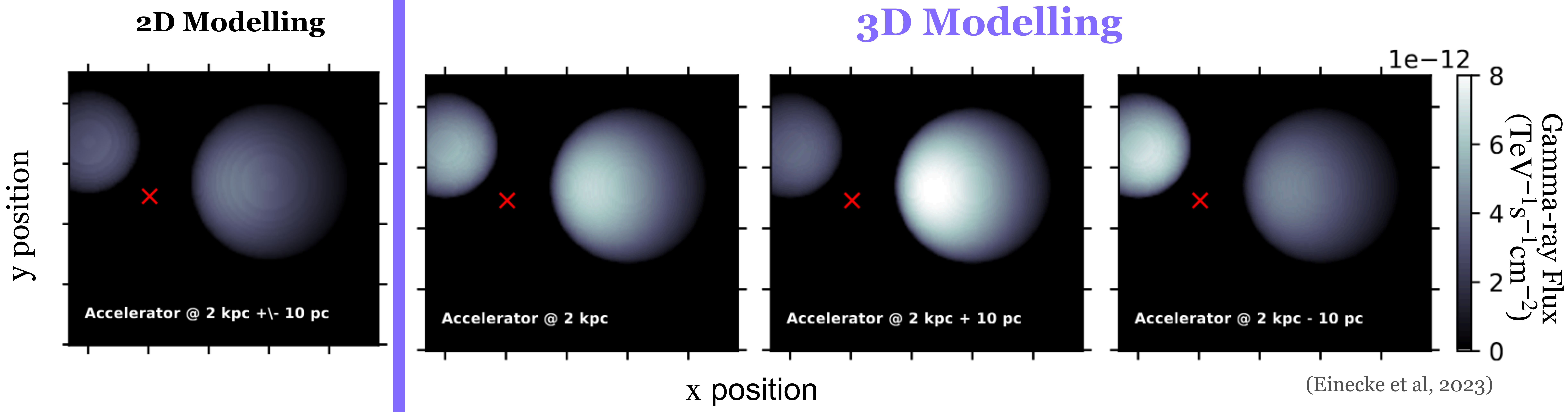
Importance of Modelling the Gamma-Ray Morphology in 3D

- Gamma-ray **morphology is very sensitive to position of gas clouds** from accelerator
- 3D ISM measurements are needed to more accurately model gamma-ray emission

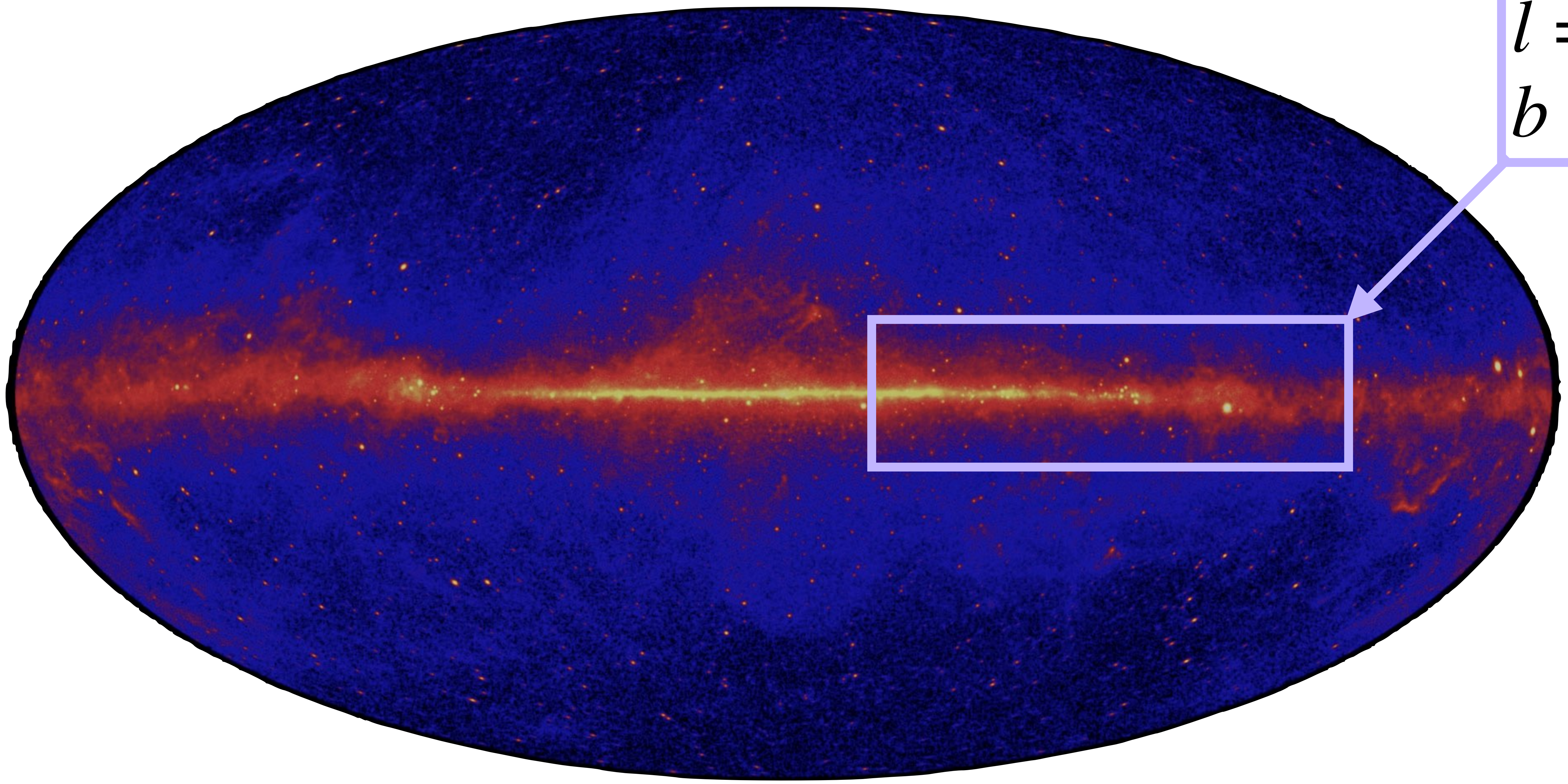


(Einecke et al, 2023)

Mopra Southern Galactic Plane Survey
(Cubuk et al., 2023)

- Survey contains CO(J=1-0) isotopologues of ^{12}CO, ^{13}CO, C^{18}O and C^{17}O
- Resolution of $30'' \approx 0.0083^\circ$ and $0.1\ \mathrm{km\,s^{-1}}$
- Resolution comparable with highest energy observations from CTAO ~0.01°

High-Energy Gamma-Ray Map

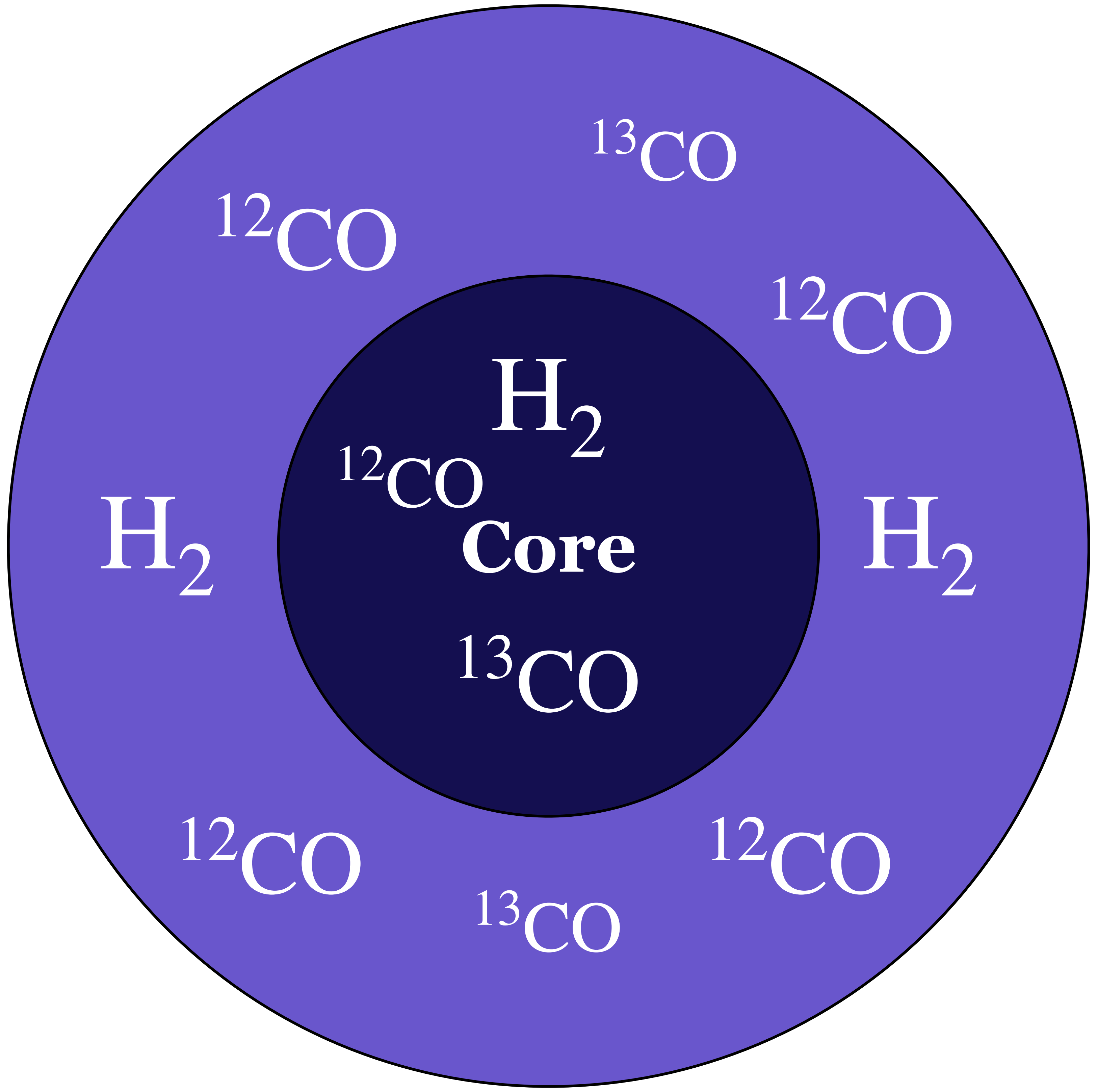


Mopra SGPS covers
$l = 250^\circ - 355^\circ$,
$b = -1^\circ - 1^\circ$

Image Credit: NASA/Fermi-Lat Collaboration

Molecular Clouds

- Molecular hydrogen (H_2)
  - Most abundant molecule in dense ISM clouds
  - Invisible to radio telescopes (cold gas without permanent dipole)
- Carbon monoxide (^{12}CO)
  - Very high abundance (=optically thick)
  - Traces gas with $\sim 10^2 - 10^3\,\mathrm{cm}^{-3}$
- Carbon monoxide (^{13}CO)
  - Low abundance (=optically thin)
  - Traces gas with $\sim 10^3 - 10^4\,\mathrm{cm}^{-3}$



(Longair, 2011)

	Radius / pc	Mass $/M_\odot$	Number density $/\mathrm{cm}^{-3}$
Cores/ Clumps	$10^{-1} - 10$	$10 - 10^3$	$10^3 - 10^4$
Clouds	$10 - 10^2$	$10^3 - 10^5$	$10^2 - 10^3$

Preparing ISM Measurements for Modelling

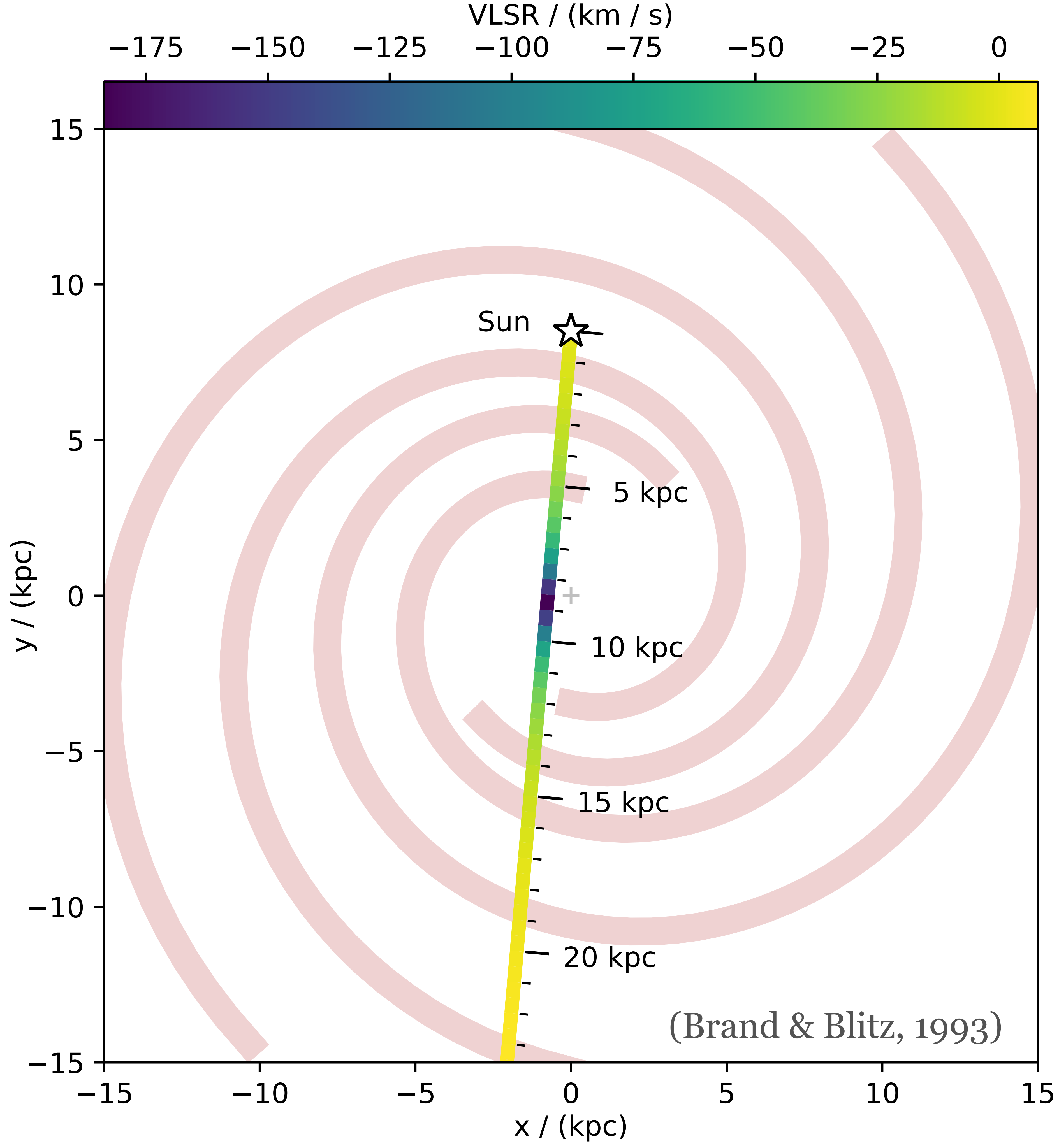
Challenges

- Radio observations measured in position-position-velocity space
  - > Use Galactic rotation curve model to transform velocity to distance
- Ambiguous distance solutions
- Model assumes motion solely due to Galactic rotation
  - > Large uncertainties in distance estimates

→ Iterate over different distances to optimise gamma-ray model

→ Need to obtain all 3D pixels belonging to a individual cloud structure

→ **CLUSTERING**



(Brand & Blitz, 1993)

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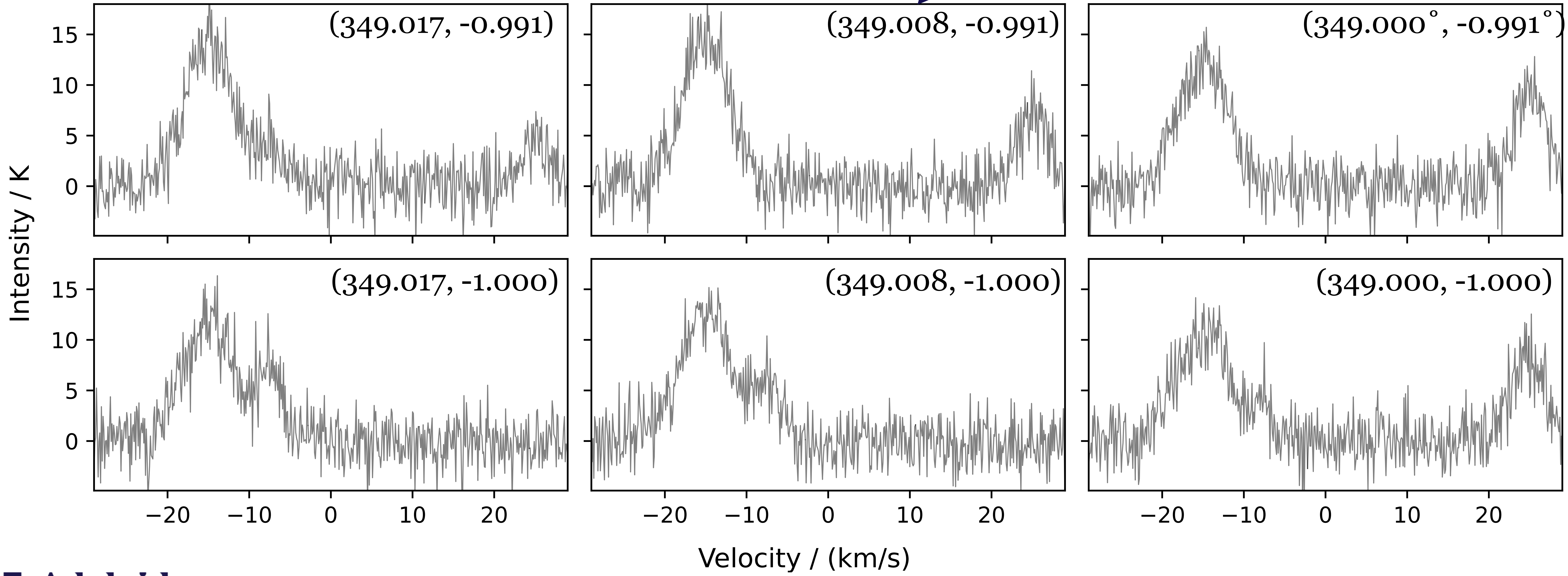
Cloud Identification Method

Raw Spectral Emission Line Data

Galactic longitude & latitude



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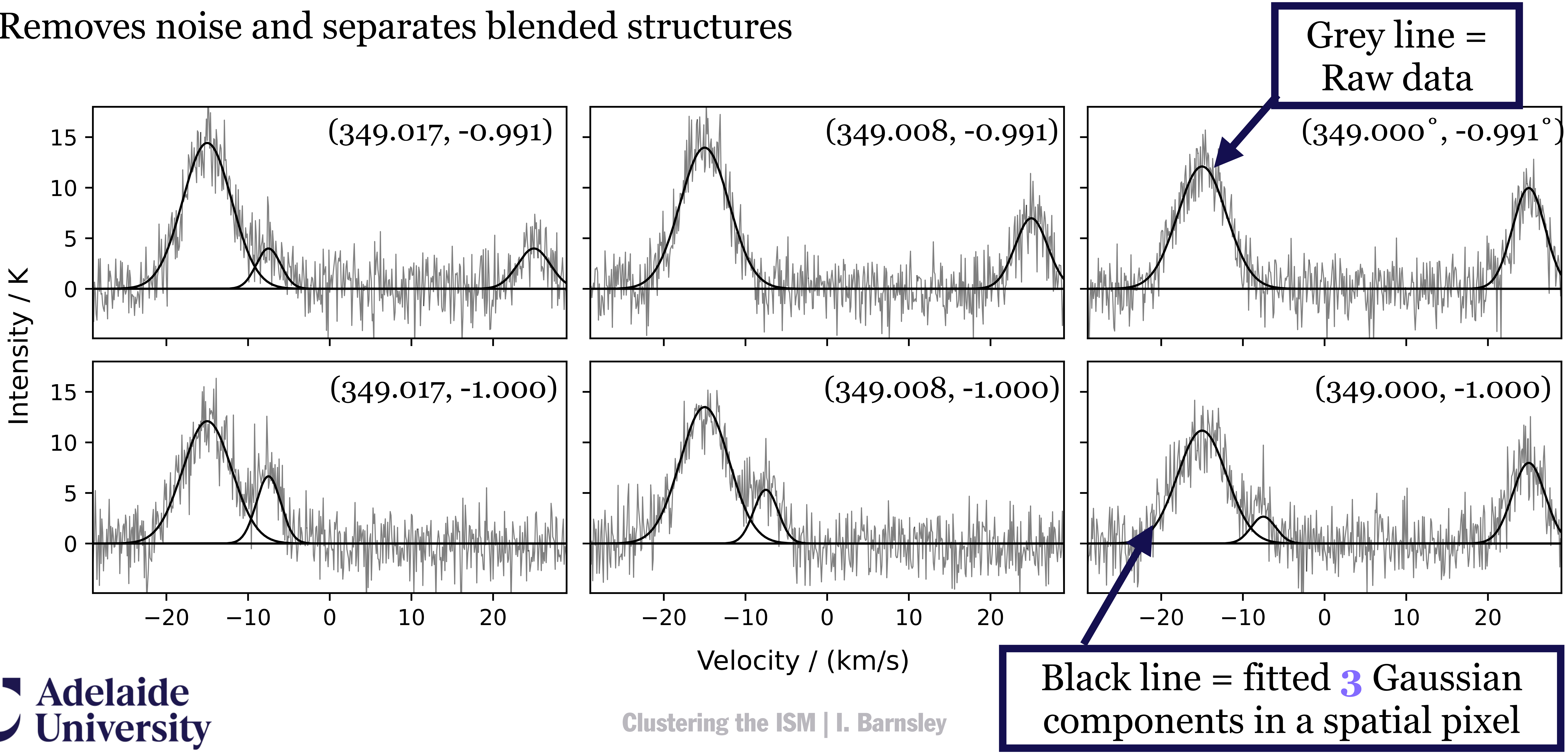
Cloud Identification Method

Gaussian Decomposition

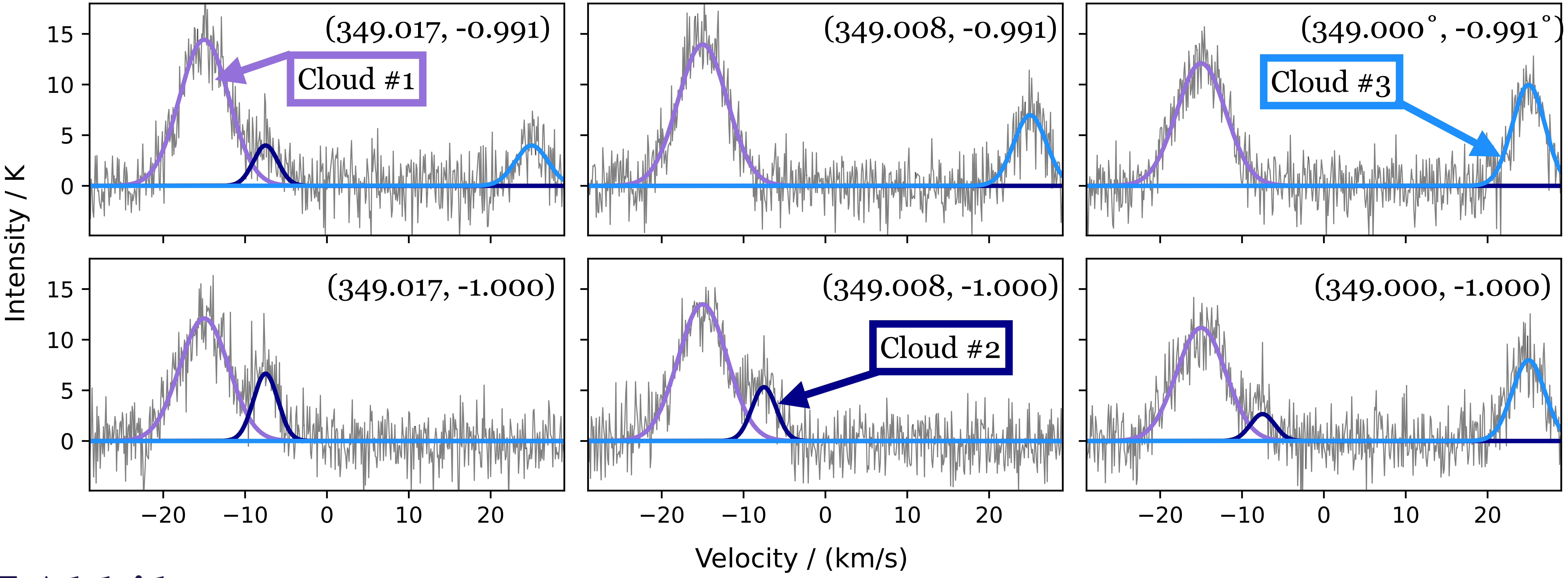
- Decompose emission line spectra into Gaussian components using GaussPy+ (Reiner et al., 2019)
- Removes noise and separates blended structures



Cloud Identification Method

Cluster Gaussian Components

- astrodendro identifies the hierarchical structure of interstellar gas clouds (Rosolowsky et al., 2018)
- Facilitates grouping of Gaussian components into cloud structures

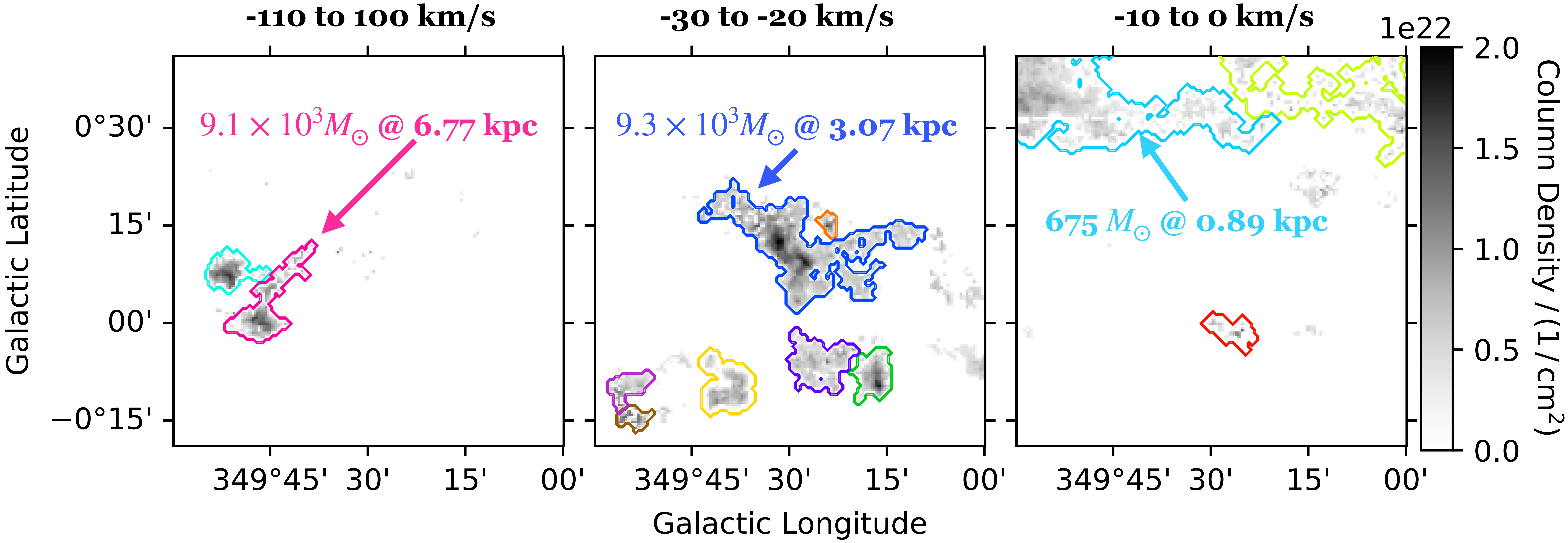


PRELIMINARY

^{13}CO Cloud Structures

Assuming near distance solution

Example Region



→ Majority of decomposed emission assigned to cloud structures

For ^{13}CO, $N_{\mathrm{H}_2} = 2\,X_{\mathrm{CO}} W_{CO}$ with $X_{\mathrm{CO}} = 4.92 \times 10^{20}\,\mathrm{cm}^{-2} / (\mathrm{K\,km\,s}^{-1})$ (Simon et al., 2001)

PRELIMINARY

Comparison with Existing Catalogue

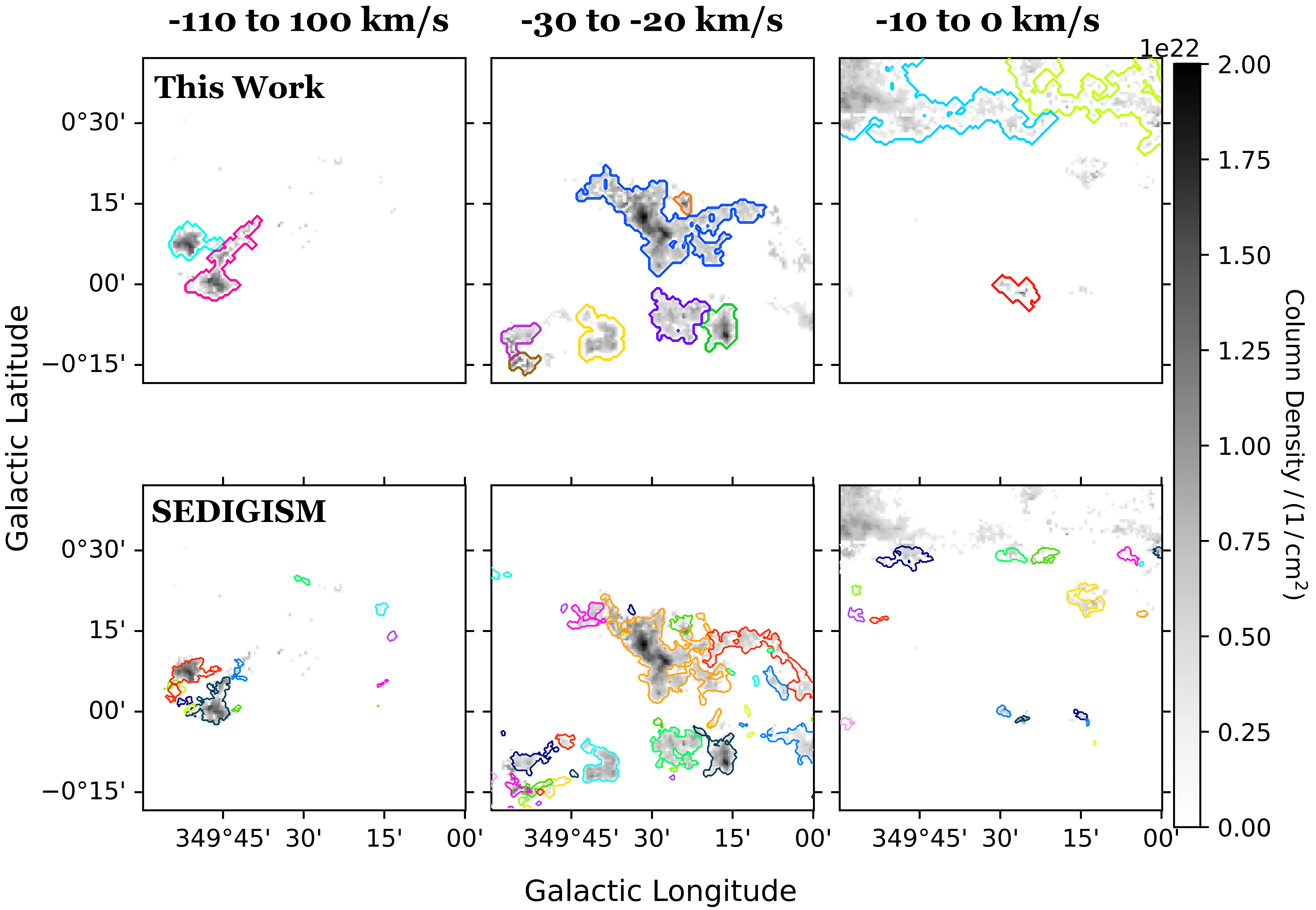
SEDIGISM Catalogue

Created with SCIMES using $^{13}CO(J = 2 - 1)$

Resolution of $20'' \approx 0.002^\circ$ and $0.2\,\mathrm{km\,s^{-1}}$

Structures agree well

- SEDIGISM focuses on denser core structures
- ^{13}CO larger core structures are identified as desired



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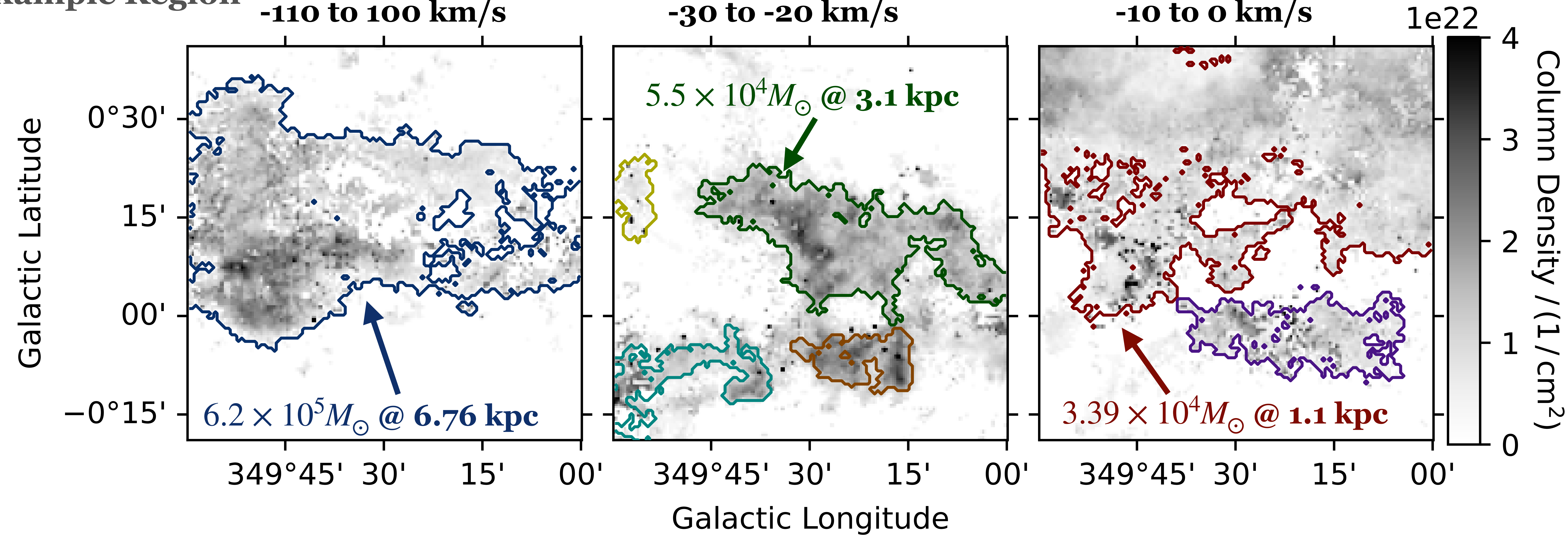
PRELIMINARY

^{12}CO Cloud Structures

Assuming near distance solution

Example Region

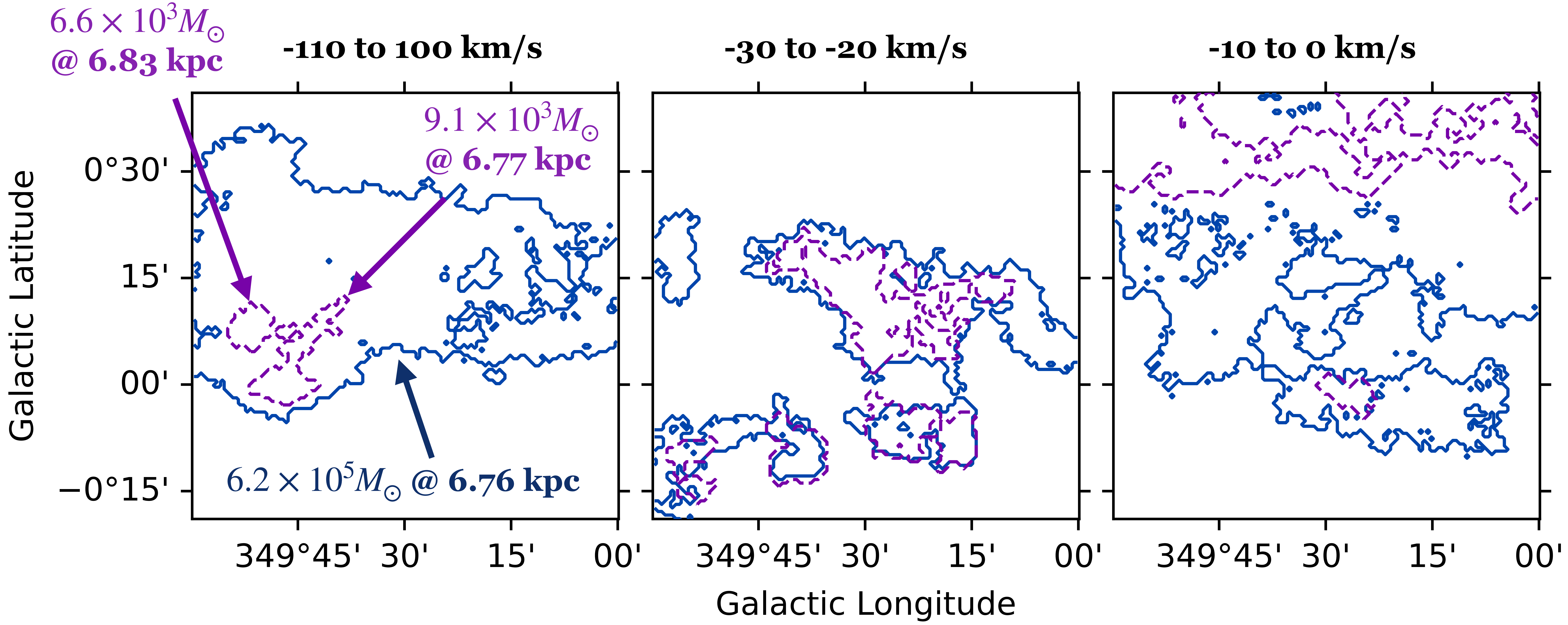


➡ Majority of decomposed emission assigned to cloud structures

For ^{12}CO, $N_{H_2} = 2\,X_{CO} W_{CO}$ with $X_{CO} = 2 \times 10^{20}\,\mathrm{cm}^{-2} / (\mathrm{K\,km\,s^{-1}})$ (Bolatto et al., 2013)

^{13}CO and ^{12}CO Cloud Structures

Assuming near distance solution



Combining cloud structures provides more detailed 3D morphology

Data Products

- For each gas tracer, table of Gaussian components with assigned cloud ID produced
- From combined gas tracers, molecular hydrogen distribution can be created with arbitrary spectral resolution and exact cloud structure

➡ **Can iterate over different cloud positions to optimise gamma-ray modelling**

Excerpt of ^{12}CO Derived Gaussian Components

x	y	l / °	b / °	A / K	ΔA / K	VLSR / km s^{-1}	ΔV / km s^{-1}	σ_v / km s^{-1}	$\Delta\sigma_v$ / km s^{-1}	W_{CO} / K km s^{-1}	ΔW_{CO} / K km s^{-1}	χ^2_{red}	N_{comps}	Cloud ID	...
0	29	349.994	-0.752	3.185	0.404	-17.994	0.513	3.503	0.513	27.973	8.163	1.202	1	14	...
4	29	349.960	-0.752	3.012	0.230	-19.673	0.395	4.478	0.395	33.812	5.797	1.230	1	14	...
6	29	349.944	-0.752	5.094	0.394	-18.530	0.198	1.856	0.220	23.698	4.859	1.030	2	14	...
0	30	349.994	-0.744	3.344	0.351	-17.399	0.626	5.171	0.626	43.341	10.343	1.196	1	14	...
1	30	349.985	-0.744	5.328	0.497	-18.231	0.291	2.701	0.291	36.076	7.611	1.022	1	14	...
2	30	349.977	-0.744	5.206	0.470	-18.959	0.211	2.025	0.211	26.422	5.385	1.060	1	14	...
4	30	349.960	-0.744	7.340	0.435	-19.049	0.080	1.163	0.080	21.395	2.816	1.704	1	14	...
5	30	349.952	-0.744	8.520	0.500	-18.892	0.099	1.455	0.099	31.079	4.053	1.166	1	14	...
6	30	349.944	-0.744	6.022	0.317	-19.398	0.178	2.926	0.178	44.168	5.144	1.456	1	14	...
0	31	349.994	-0.734	3.867	0.357	-17.713	2.691	4.856	0.518	47.062	9.834	1.207	1	14	...
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Data Products

- For each gas tracer, table of identified structures with cloud properties produced

Useful for ISM studies including investigating Galactic cloud property relations

Excerpt of ^{12}CO Cloud Properties

Cloud ID	l / $^\circ$	b / $^\circ$	v / $\mathrm{km\,s^{-1}}$	σ_v / $\mathrm{km\,s^{-1}}$	$\mathrm{N_{comps}}$	$N_{\mathrm{H_2}}$ / $10^{22}\,\mathrm{cm^{-2}}$	R_G / kpc	$\mathrm{d_{near}}$ / kpc	$\mathrm{d_{far}}$ / kpc	$\mathrm{R_{near}}$ / pc	$\mathrm{R_{far}}$ / pc	$\mathrm{M_{near}}$ / $10^4\mathrm{M_\odot}$	$\mathrm{M_{far}}$ / $10^4\,\mathrm{M_\odot}$	...
1	349.613	0.222	-107.0	38.8	5872	0.63	2.21	6.8	10.0	20.4	30.1	61.6	134.0	...
2	349.122	0.094	-74.8	8.3	169	1.99	2.96	5.9	10.8	2.7	5.0	4.2	14.3	...
3	349.036	0.283	-73.3	12.9	73	0.59	3.01	5.8	10.9	2.1	4.0	0.5	1.9	...
4	349.358	-0.019	-72.5	29.4	8	0.64	2.97	5.8	10.9	0.5	1.0	0.1	0.2	...
5	349.517	0.156	-62.9	6.2	1861	1.55	3.23	5.5	11.2	9.5	19.3	31.9	131.0	...
6	349.393	0.065	-63.5	26.5	11	1.08	3.23	5.5	11.2	0.6	1.2	0.1	0.5	...
7	349.039	0.049	-61.4	29.9	12	1.26	3.37	5.4	11.3	0.9	1.8	0.2	0.7	...
8	349.915	0.221	-46.6	22.7	30	0.57	3.78	4.9	11.8	1.3	3.1	0.1	0.9	...
9	349.725	0.520	-41.1	8.1	1777	1.29	4.10	4.6	12.2	8.1	21.6	17.3	123.0	...
10	349.964	0.518	-45.4	10.4	80	1.32	3.83	4.8	11.9	1.9	4.7	0.9	5.4	...
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Distance Estimation

- Data products will include probability score for near and far cloud distances
- Indicates most likely cloud distance
- Determined using cloud properties
  - Expected turbulence behaviour from velocity cloud profile
  - Larson scaling relationship eg. size-line width relation by Rice et al. (2016)
  - Clouds located at high latitudes (z_{Gal}) more likely to be ‘near’ distances (eg. Fish et al. 2003)

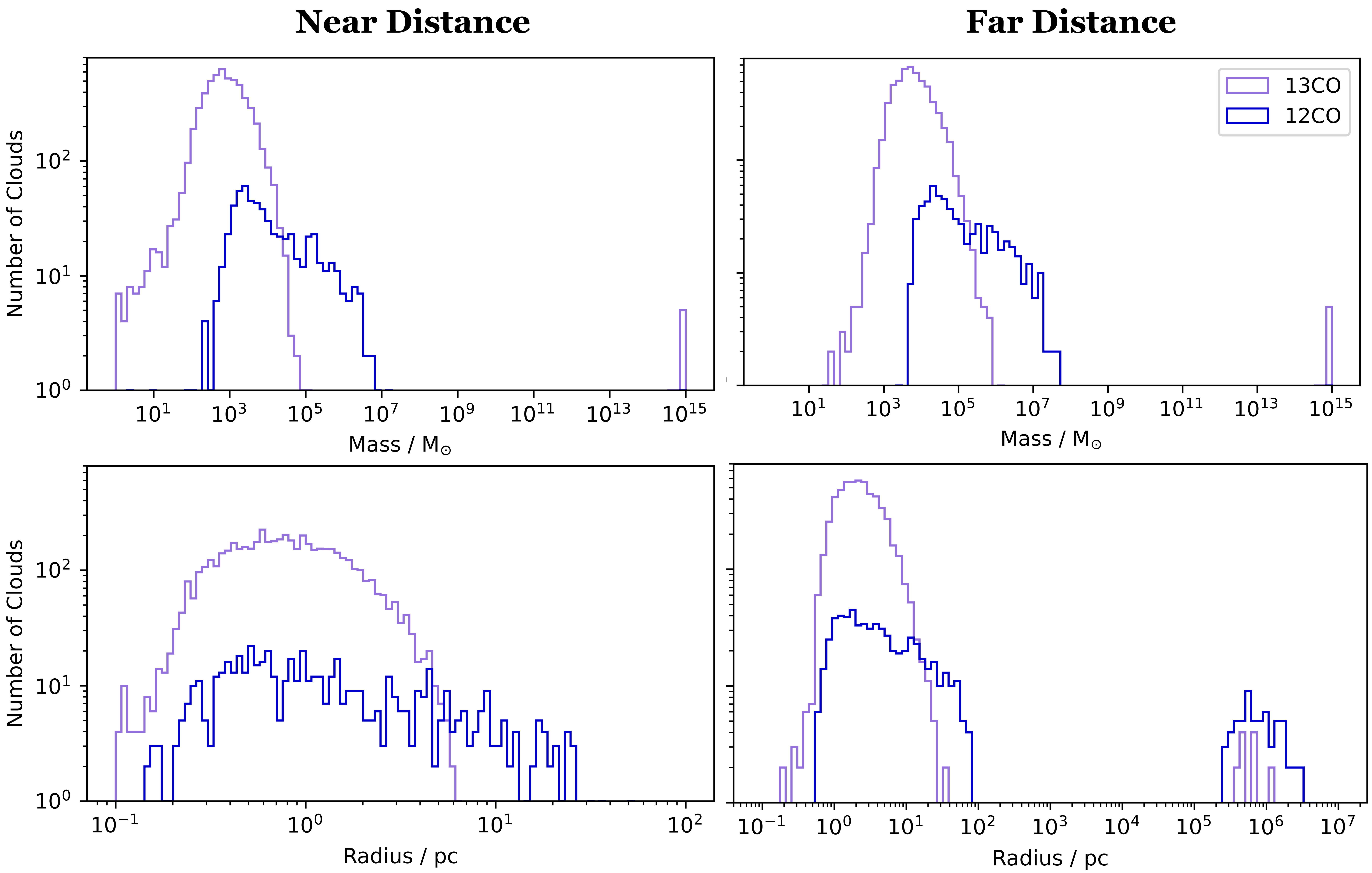
Cloud Structures Identified from Mopra SGPS

Identified:

5579 ^{13}CO clump/ core structures

670 ^{12}CO cloud structures

Majority of structures follow expected radius and mass behaviour



Conclusions

- Need to model gamma-ray morphology
  - Arcminute ISM observations required, as from Mopra, to resolve morphology
- Cloud distances have large uncertainties
  - Want to iterate over different positions
  - Need clustering to select pixels belonging to individual clouds
- Developed cloud identification method which successfully identifies 3D pixels
- Data product of assigned Gaussian components allows users to construct ISM distributions with exact cloud structure
- Data product of cloud property table useful for ISM studies
- Allows for first of its kind combination of ^{13}CO and ^{12}CO structures based on arbitrary structure
- Paper in progress

Thank you for your attention!

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Appendix

Cloud Identification Method

Gaussian Decomposition

- Decompose the brightness temperature in spatial pixels (position-position) into components

Number of components　　　　Peak velocity

$$T_B(v) = \sum_{i=1}^{N_{comp}} A_i \exp\left(\frac{-(v - v_i)^2}{2\sigma_i^2}\right).$$

Velocity　　Amplitude　　Velocity dispersion

- Using python package GaussPy+ (Reiner et al., 2019)
- Extensive fitting settings guide noise estimation and fitting of signal region

Clustering with Dendrograms

- Assign Gaussian components using dendrograms from astrodendro (Rosolowsky et al., 2008)
- Identifies hierarchy of structures within distribution
- Represents density regions in a binary tree
- Settings define minimum structure size (leaves)
- Select cloud structures from leaves