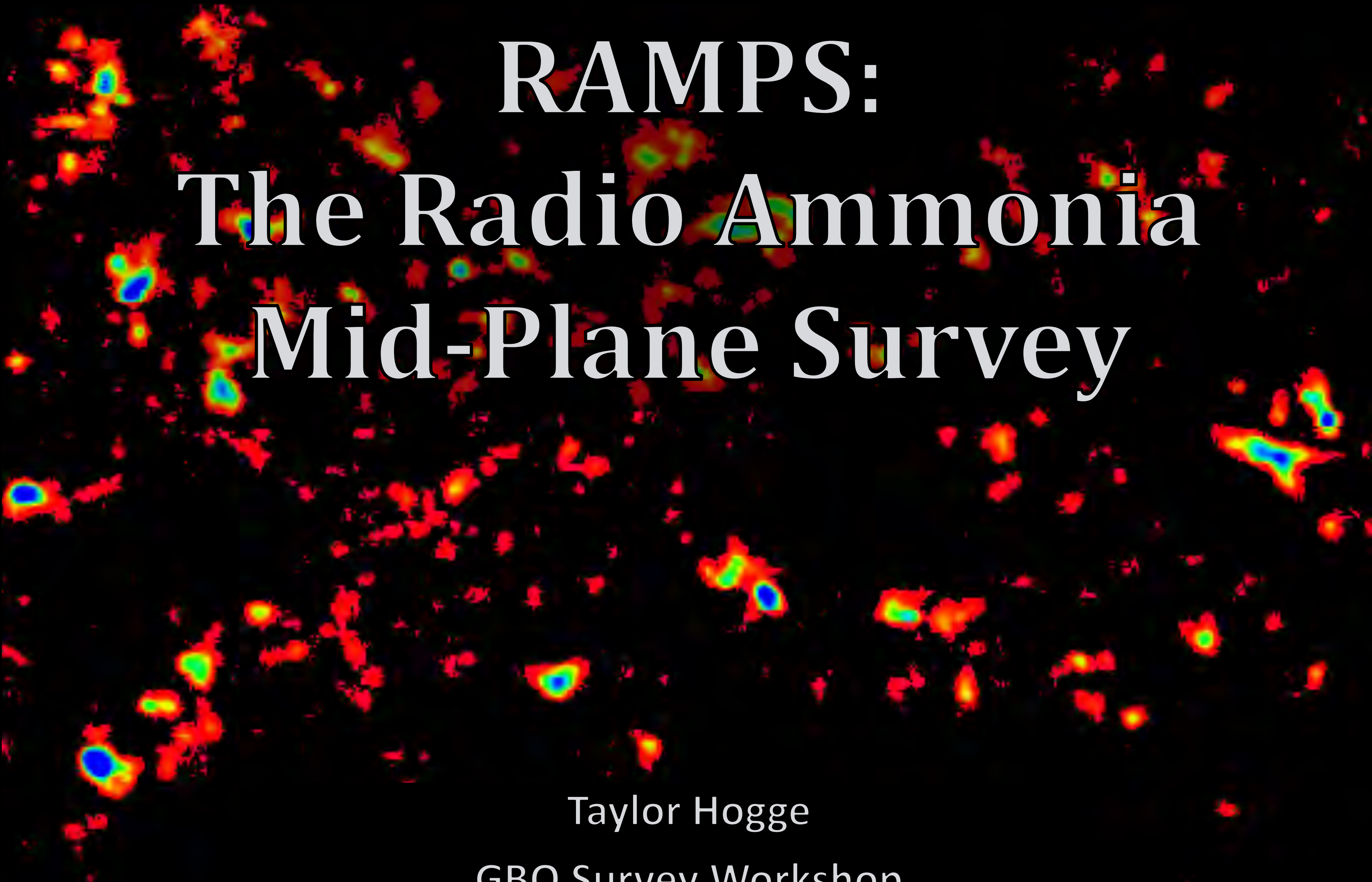
RAMPS: The Radio Ammonia Mid-Plane Survey



Taylor Hogge

GBO Survey Workshop

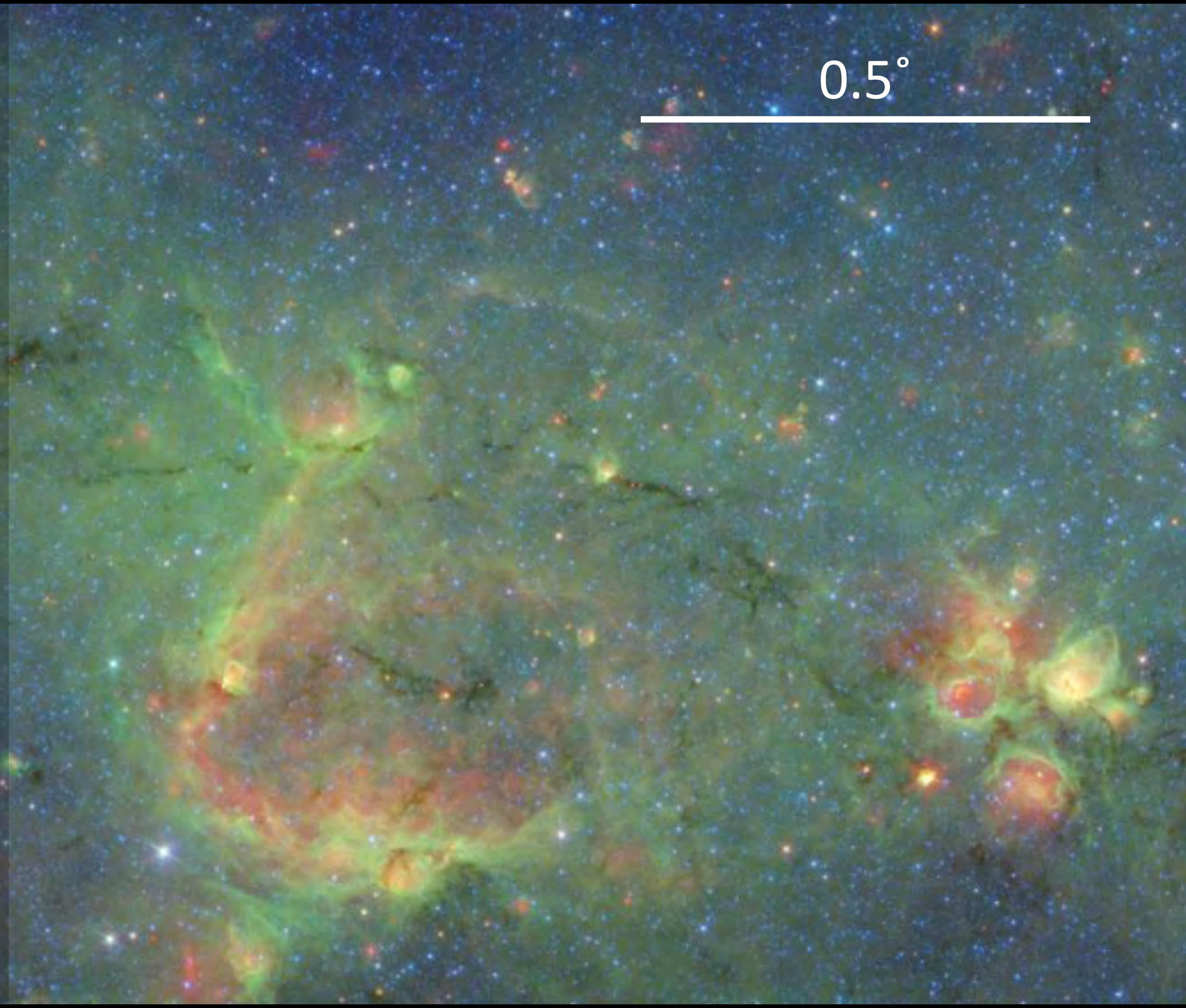
11/14/18

Collaborators

- James Jackson (SOFIA)
- Ian Stephens (CfA)
- Scott Whitaker (BU)
- Jonathan Foster (Yale)
- Anish Roshi (NRAO)

Why is high-mass star formation important?

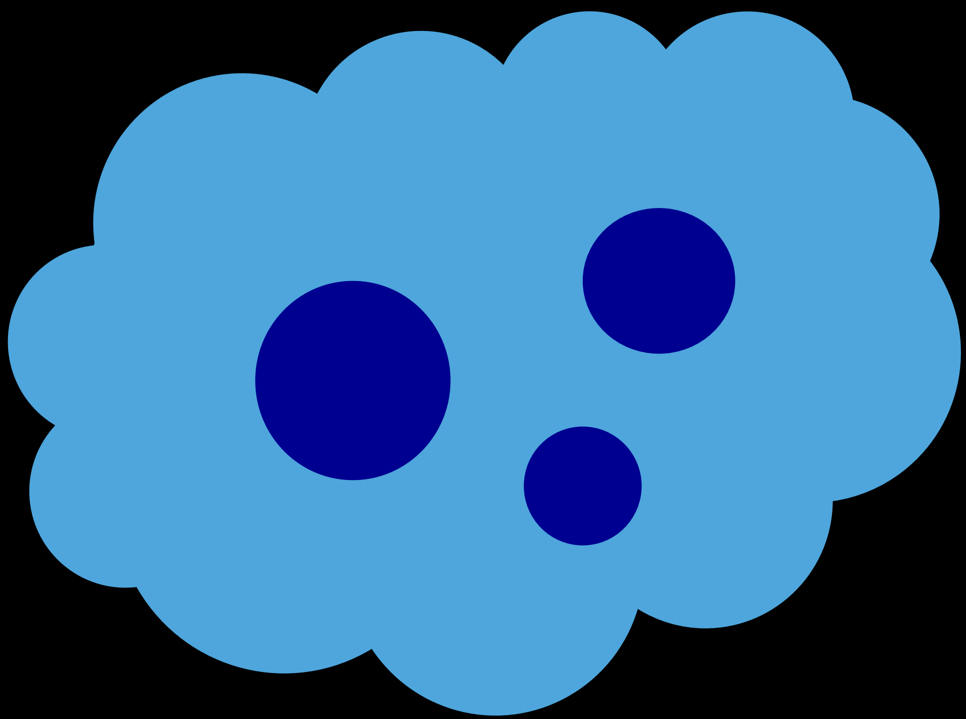
- Dominate the energetic input and chemical enrichment into the interstellar medium (ISM)
- Disrupt surrounding medium through outflows, H II regions, and supernovae
- ISM chemistry and kinematics is driven by the life cycle of high-mass stars



Credit: GLIMPSE/MIPSGAL

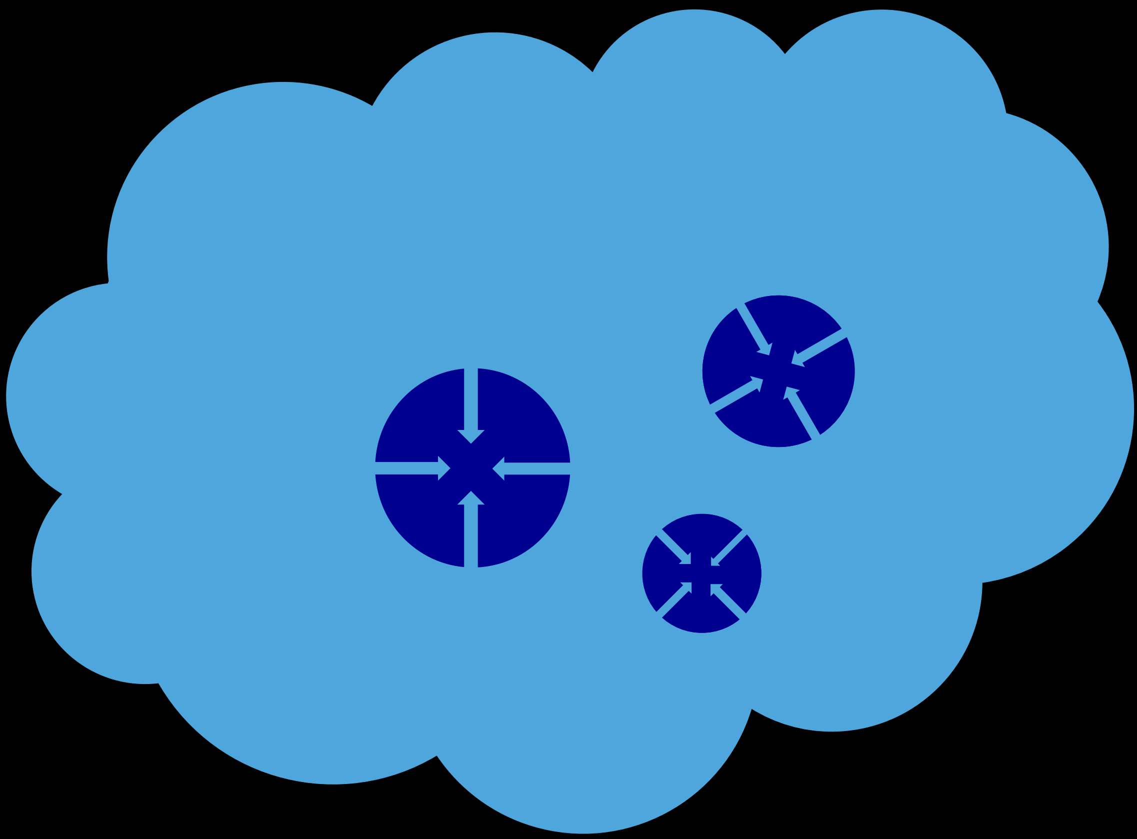
High-Mass Star Formation

Molecular clump ($M \sim 200$–$5{,}000\ M_{\odot}$, $R \sim 1$ pc)



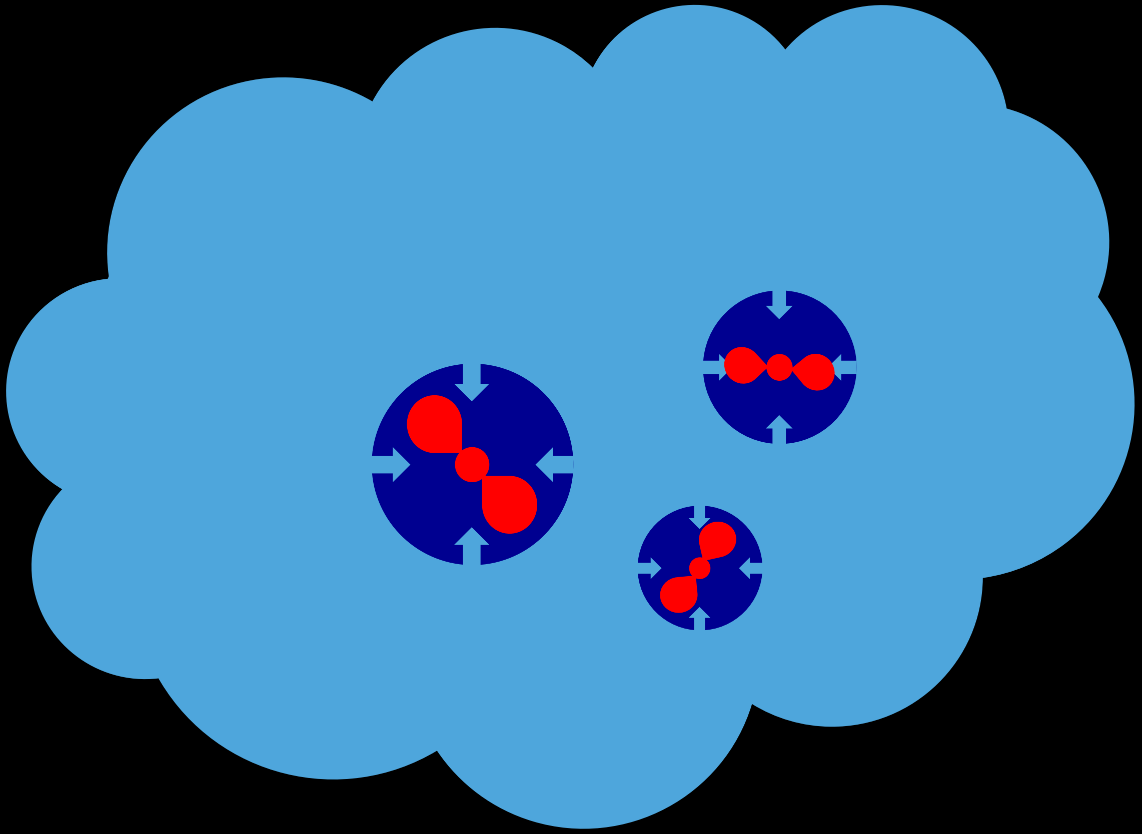
High-Mass Star Formation

Collapse of pre-stellar cores ($M \geq 1\ M_{\odot}$, $R \sim 0.05$ pc)



High-Mass Star Formation

Cores collapse into protostars



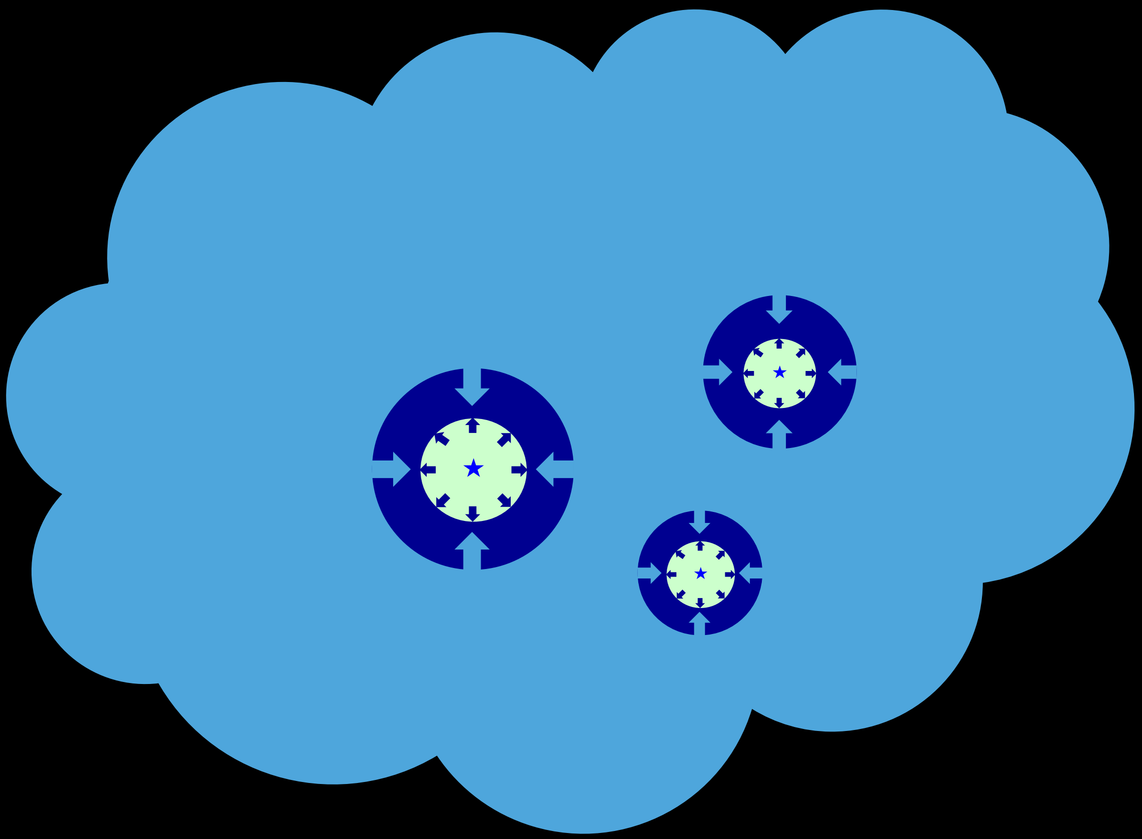
High-Mass Star Formation

Protostars launch outflows

Credit: ALMA Observatory

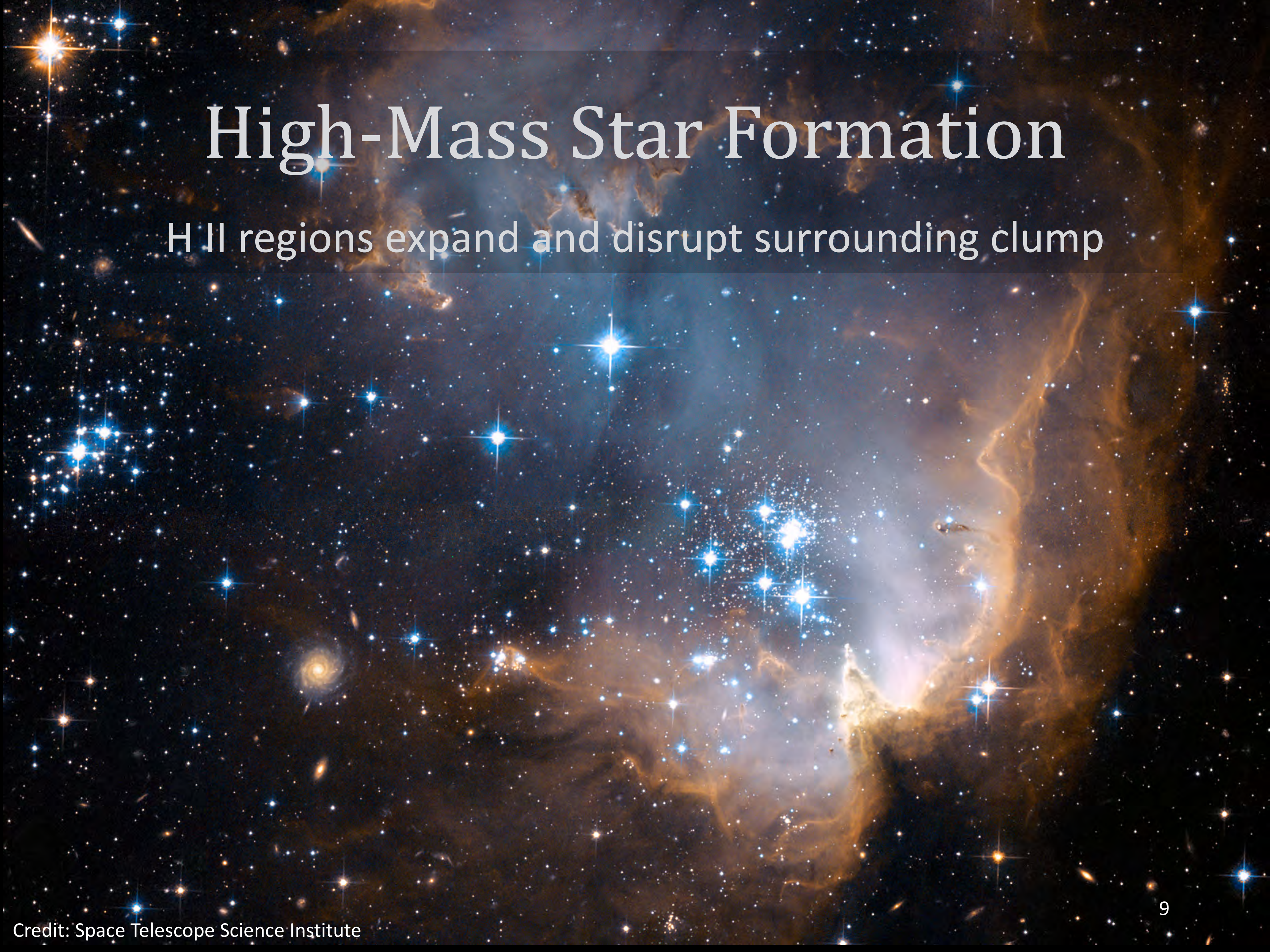
High-Mass Star Formation

Begin fusion, ionize surrounding material



High-Mass Star Formation

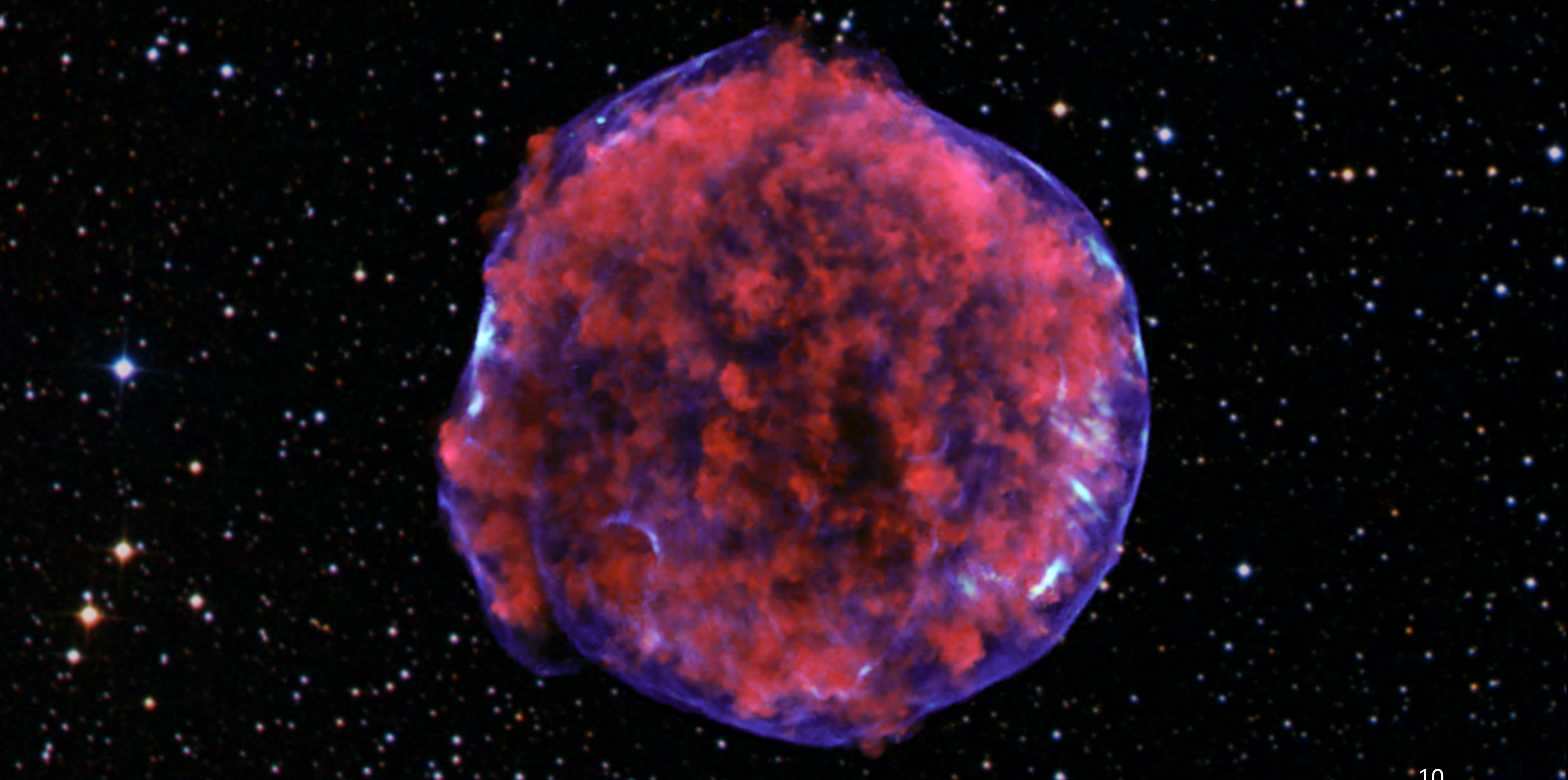
H II regions expand and disrupt surrounding clump



Credit: Space Telescope Science Institute

High-Mass Star Formation

Supernovae inject turbulence into ISM

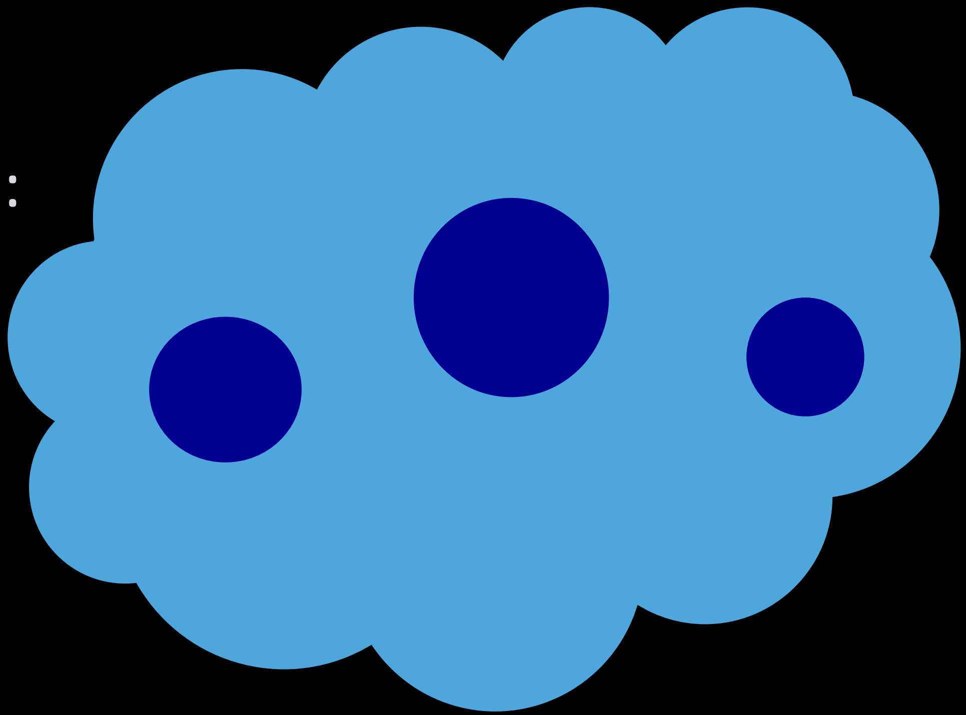


Credit: nasaviz.gsfc.nasa.gov

Early Stages

Early stages are hard to observe:

- Rare
- Form quickly
- Form within opaque gas and dust



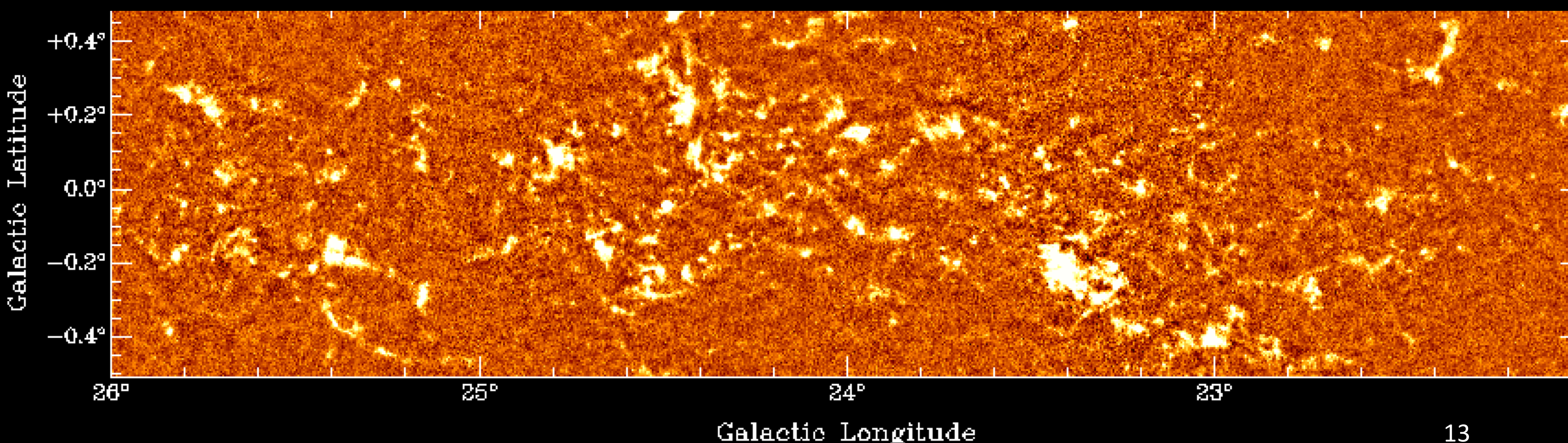
Open Questions

- How do cluster-forming clumps evolve?
- How does gas flow along filaments?
- What is the distribution of high-mass star formation in the Galaxy?
- How does maser activity in star-forming regions evolve?

Continuum Surveys of the Galactic Plane

- 1.1 mm Bolocam Galactic Plane Survey (BGPS)
- 870 µm Apex Telescope Large Area Survey of the Galaxy (ATLASGAL)
- 70-500 µm *Herschel* Infrared Galactic Plane Survey (HiGAL)

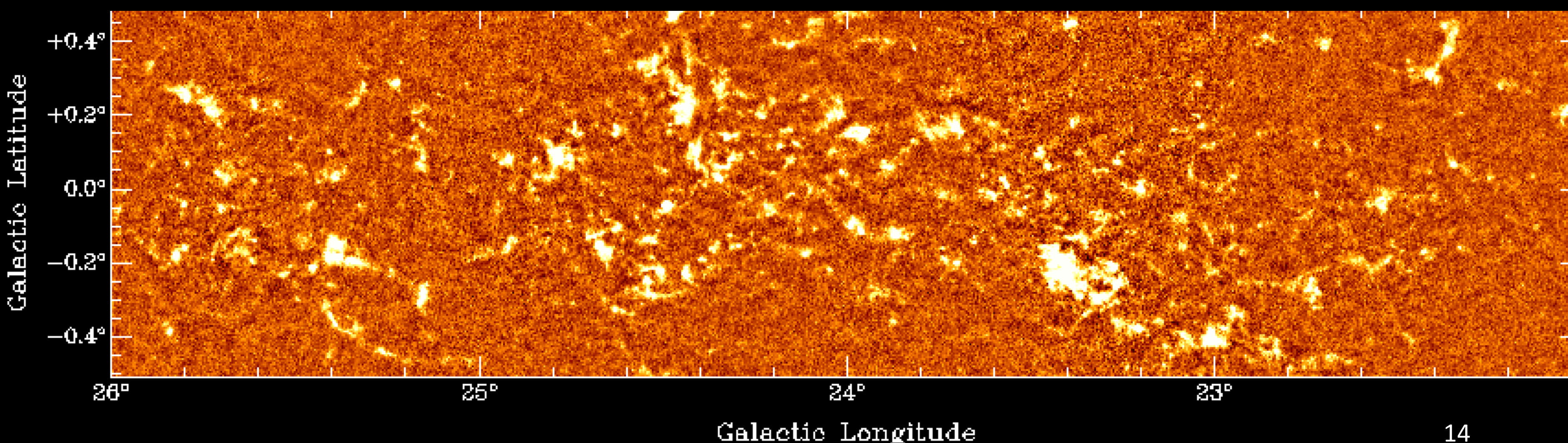
ATLASGAL: Schuller, Menten, Contreras et al. 2009



Limitations of Continuum Surveys

- Blending of emission along line of sight
- Uncertain assumptions used to derive dust temperatures and column densities
- No kinematic information
- Unknown distances, thus size, mass, luminosity, and Galactic position are also unknown

ATLASGAL: Schuller, Menten, Contreras et al. 2009



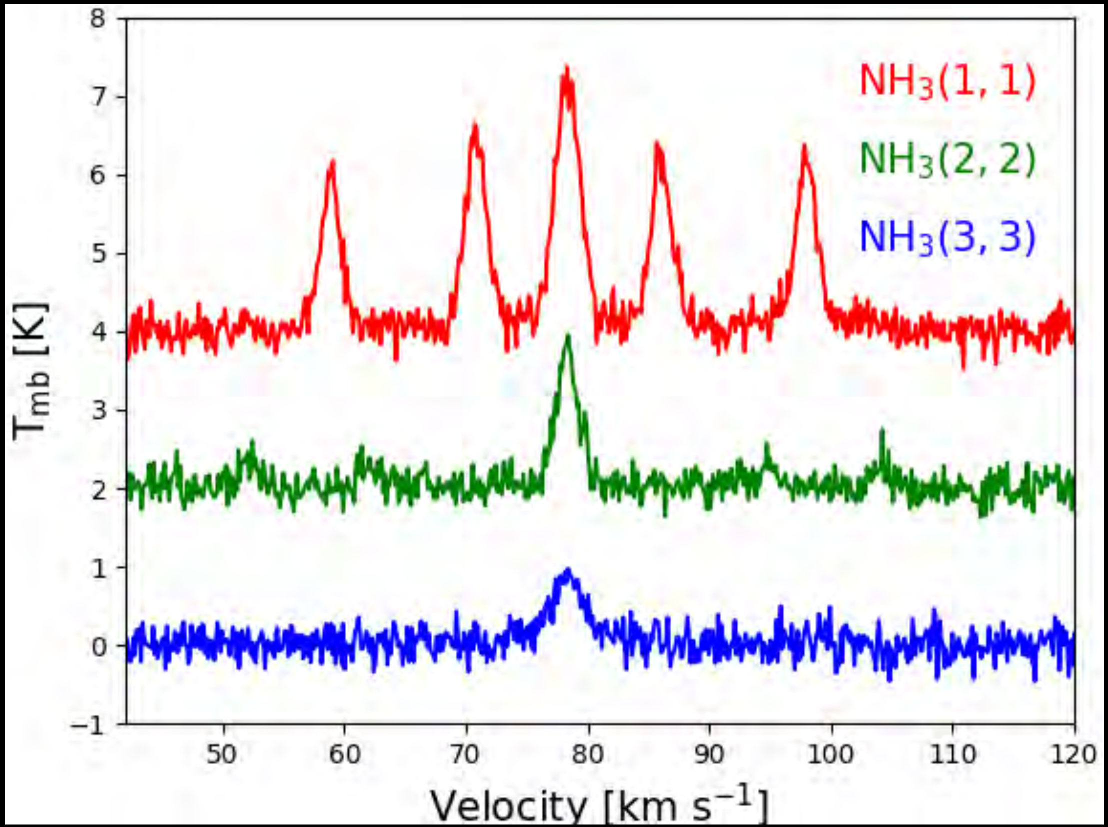
RAMPS

Credit: *bonappetit.com*

- Molecular line survey of Galactic mid-plane
- Uses the Green Bank Telescope (GBT)
- Primary lines are NH_3 inversion lines and an H_2O maser line

Advantages of NH_3

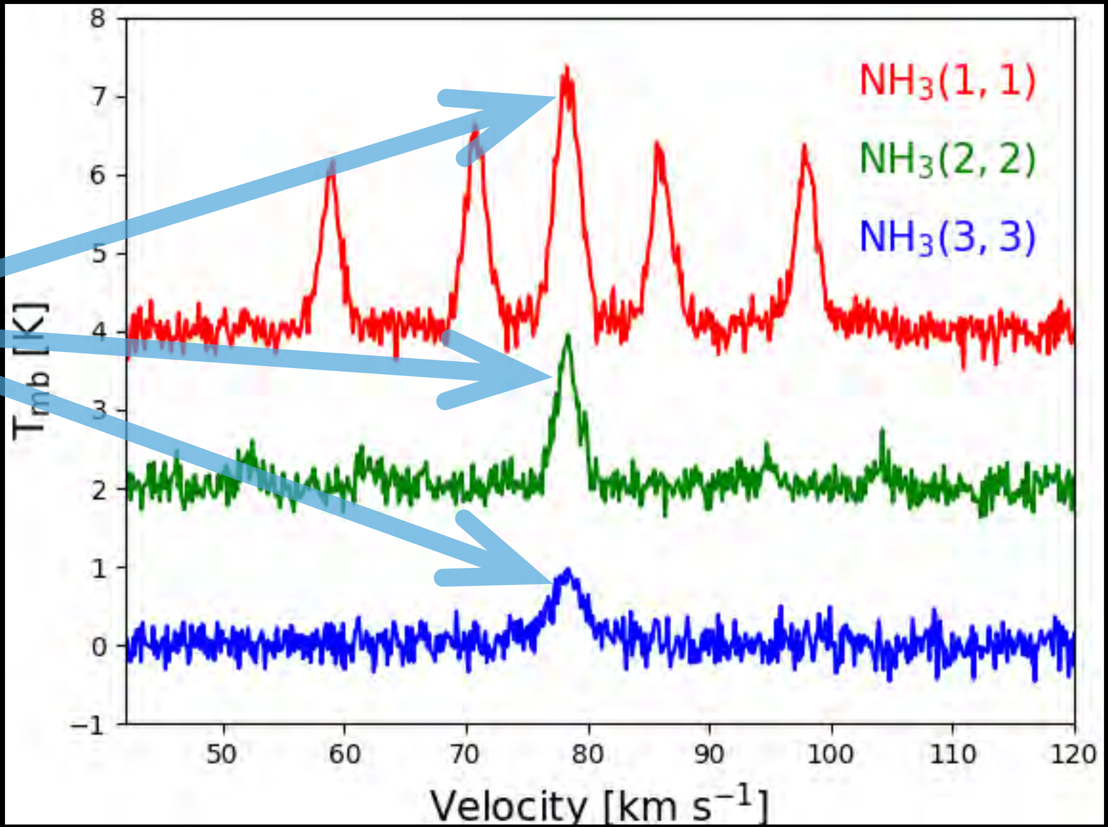
NH_3 inversion spectra of a dense molecular clump



- Brightness ratios robustly indicate gas temperature
- Hyperfine lines are sensitive to optical depth
- Traces dense gas (~ 10^4 cm^{-3})
- Velocity yields kinematic distances and reveals internal motions

Advantages of NH_3

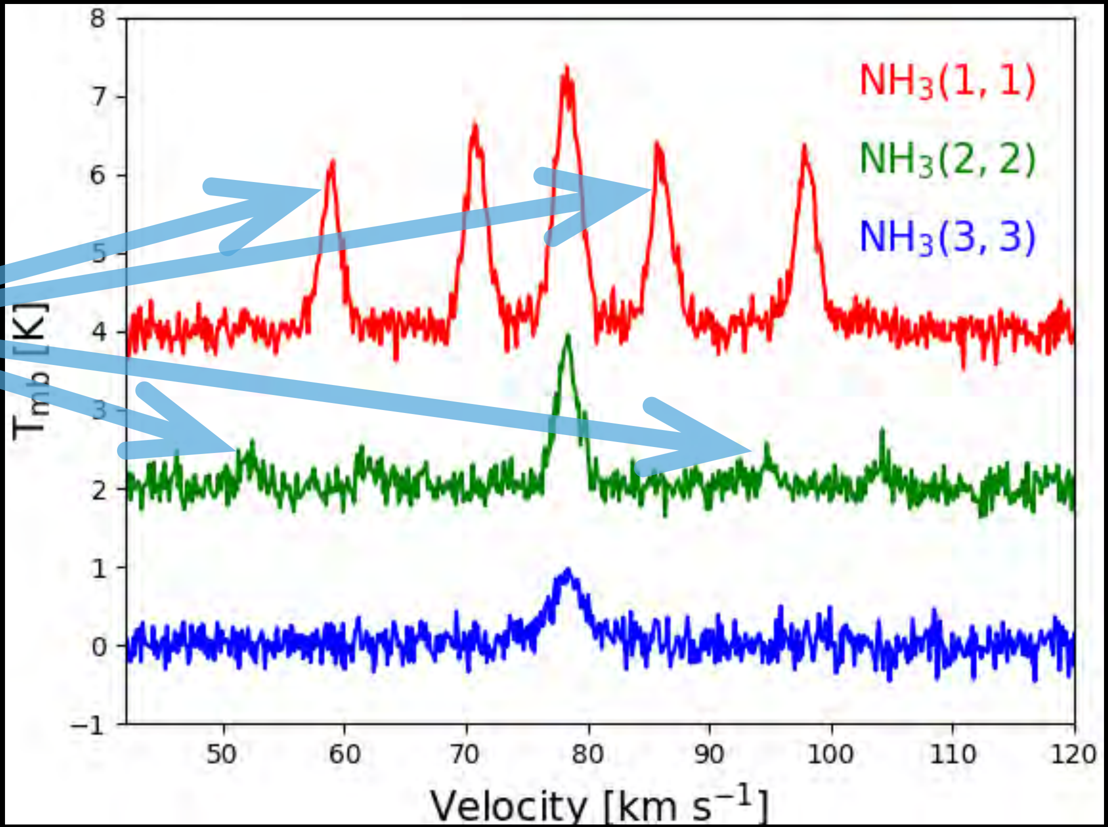
Gives T_{gas}



- **Brightness ratios robustly indicate gas temperature**
- Hyperfine lines are sensitive to optical depth
- Traces dense gas (~ 10^4 cm^{-3})
- Velocity yields kinematic distances and reveals internal motions

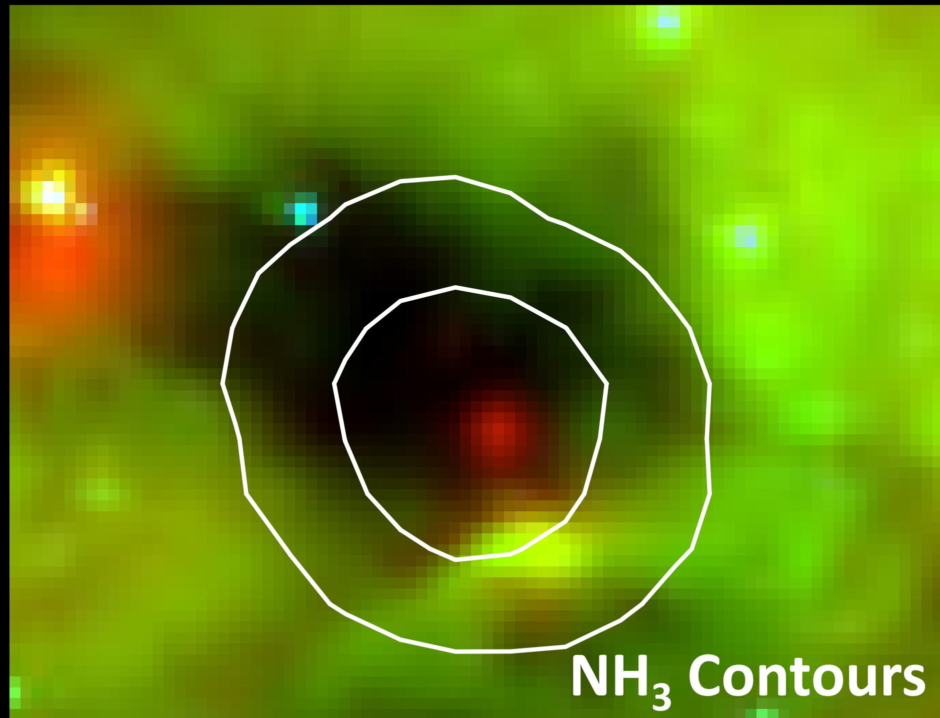
Advantages of NH_3

Gives τ



- Main line brightness ratios robustly indicate gas temperature
- **Hyperfine lines are sensitive to optical depth**
- Traces dense gas (~ 10^4 cm^{-3})
- Velocity yields kinematic distances and reveals internal motions

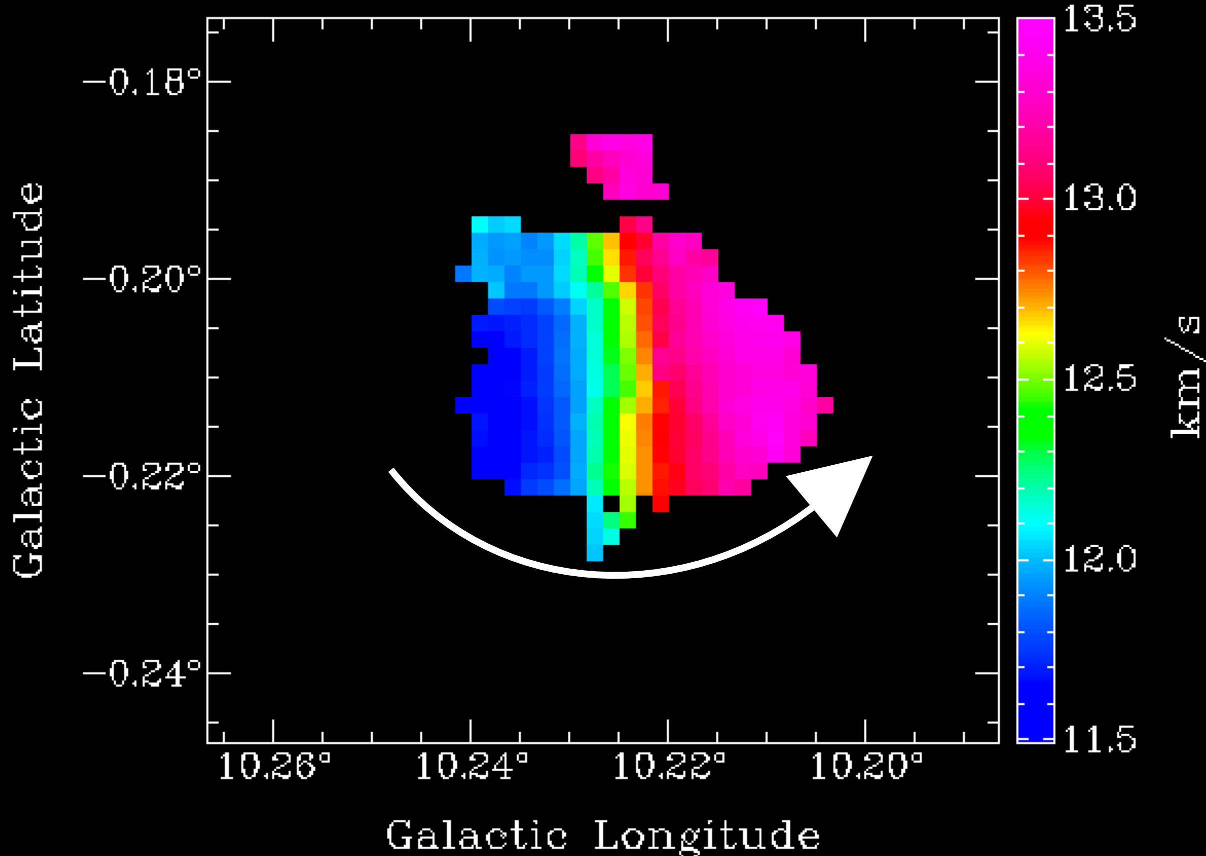
Advantages of NH_3



GLIMPSE and MIPSGAL
3.6 µm 8 µm 24 µm

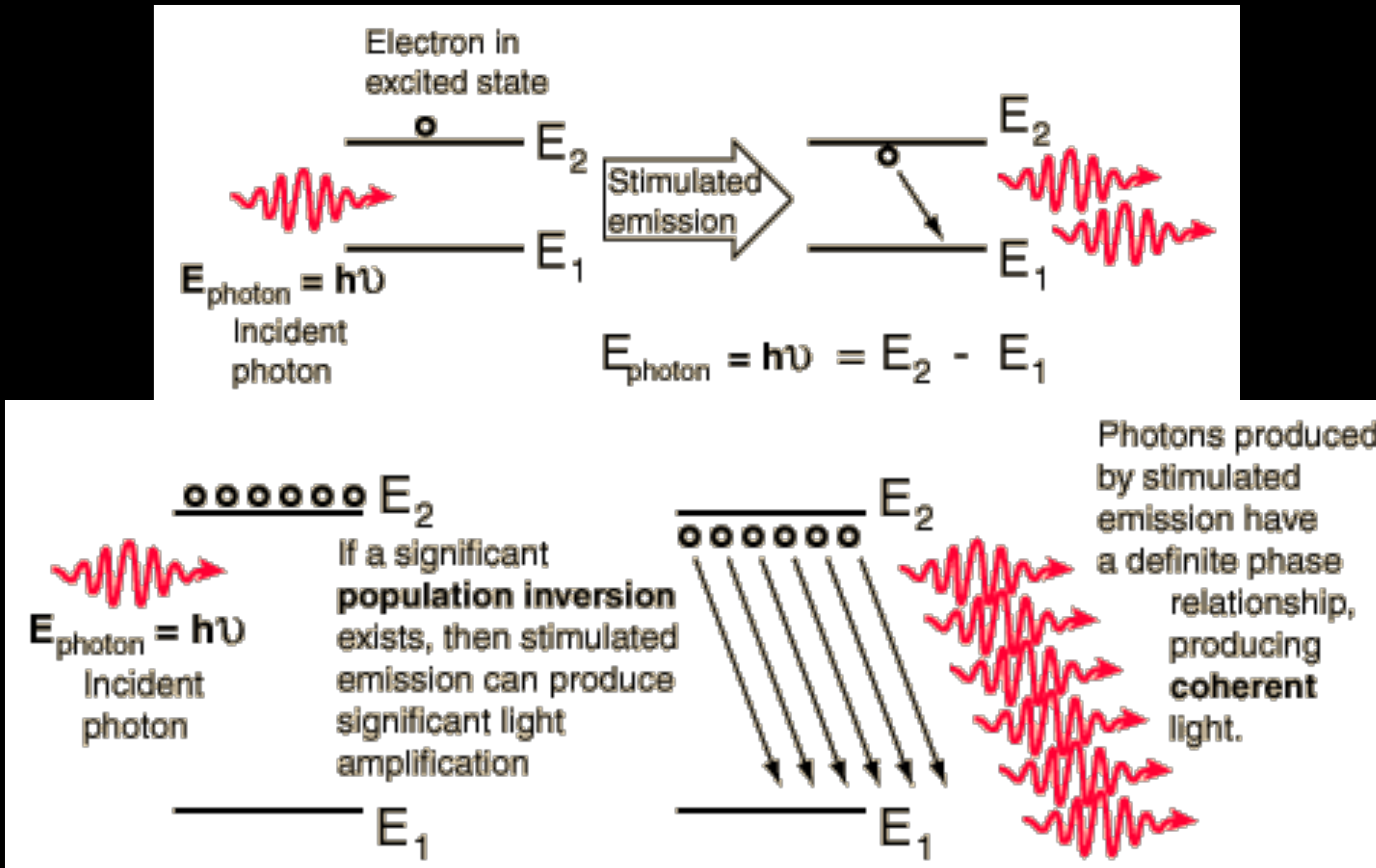
- Brightness ratios robustly indicate gas temperature
- Hyperfine lines are sensitive to optical depth
- **Traces dense gas (~ 10^4 cm^{-3})**
- Velocity yields kinematic distances and reveals internal motions

Advantages of NH_3



- Brightness ratios robustly indicate gas temperature
- Hyperfine lines are sensitive to optical depth
- Traces dense gas (~ 10^4 cm^{-3})
- **Velocity yields kinematic distances and reveals internal motions**

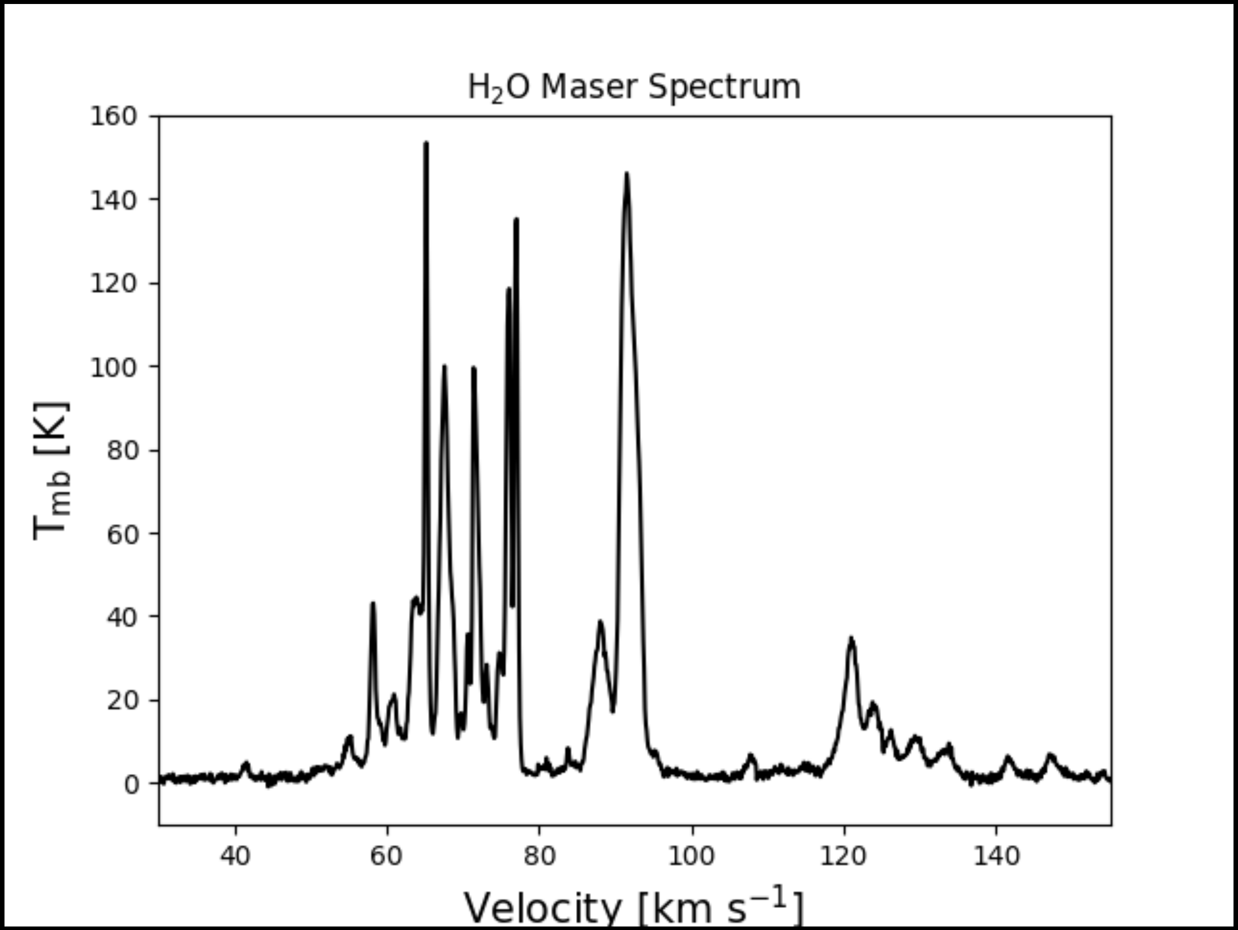
Advantages of H_2O Masers



Credit: mwit.ac.th/~physicslab/hbase/mod5.html

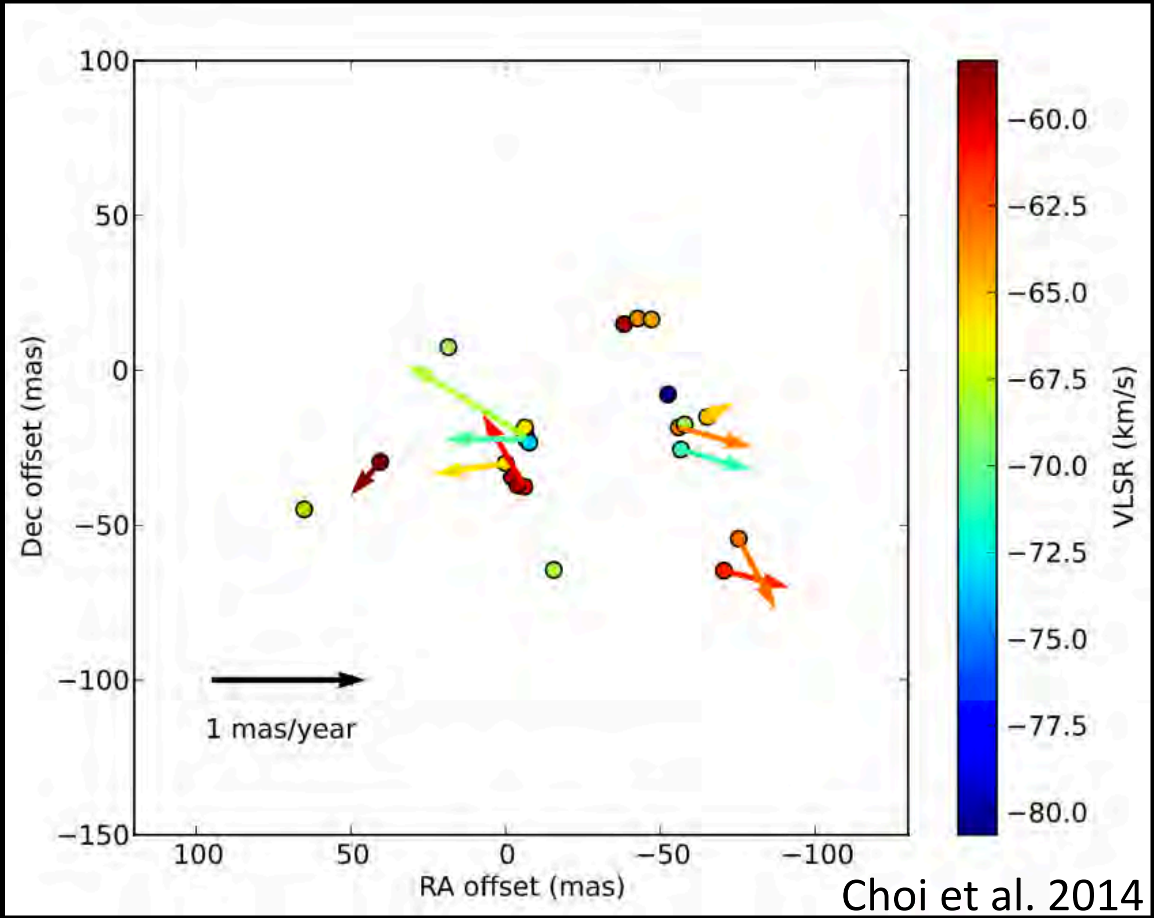
Microwave **A**mplification by **S**timulated **E**mission of **R**adiation

Advantages of H_2O Masers



- Traces regions of active star formation
- Used to measure distances to star-forming regions across the Galaxy through parallax
- Associated with Asymptotic Giant Branch (AGB) stars

Advantages of H_2O Masers



Choi et al. 2014

- Traces regions of active star formation
- Used to measure distances to star-forming regions across the Galaxy through parallax
- Associated with Asymptotic Giant Branch (AGB) stars

RAMPS

Credit: *bonappetit.com*

- High density gas
- Gas temperature
- NH_3 column density
- Linewidths (turbulence)
- Kinematics (ordered flows)
- Kinematic distances

RAMPS

Molecule	Transition	Frequency [MHz]	E_{upper}/k [K]	Number of Receivers
NH_3	(J,K) = (1,1)	23694.47	23	7
NH_3	(J,K) = (2,2)	23722.60	64	7
NH_3	(J,K) = (3,3)	23870.08	124	7
NH_3	(J,K) = (4,4)	24139.35	201	7
NH_3	(J,K) = (5,5)	24532.92	295	7
CH_3OH	$J_{K_p} = 10_1 - 9_2\ A^-$	23444.78	143	7
HC_5N	$J = 9 - 8$	23963.90	6	7
HC_5N	$J = 8 - 7$	21301.26	5	1
HC_7N	$J = 19 - 18$	21431.93	10	1
CH_3OH	$J_{K_p} = 12_2 - 11_1\ A^-$	21550.34	479	1
HNCO	$J(K_p, K_o) = 1(0,1) - 0(0,0)$	21981.57	1	1
H_2O	$J(K_p, K_o) = 6(1,6) - 5(2,3)$	22235.08	644	1
CCS	$J = 2 - 1$	22344.03	2	1

- 20 deg^2 molecular line survey of Galactic mid-plane in 1st Quadrant
- Mapping in 13 lines
- NH_3 inversion transitions and H_2O maser line are most important
- Additional lines are CH_3OH maser lines and several high density tracers

The Green Bank Telescope

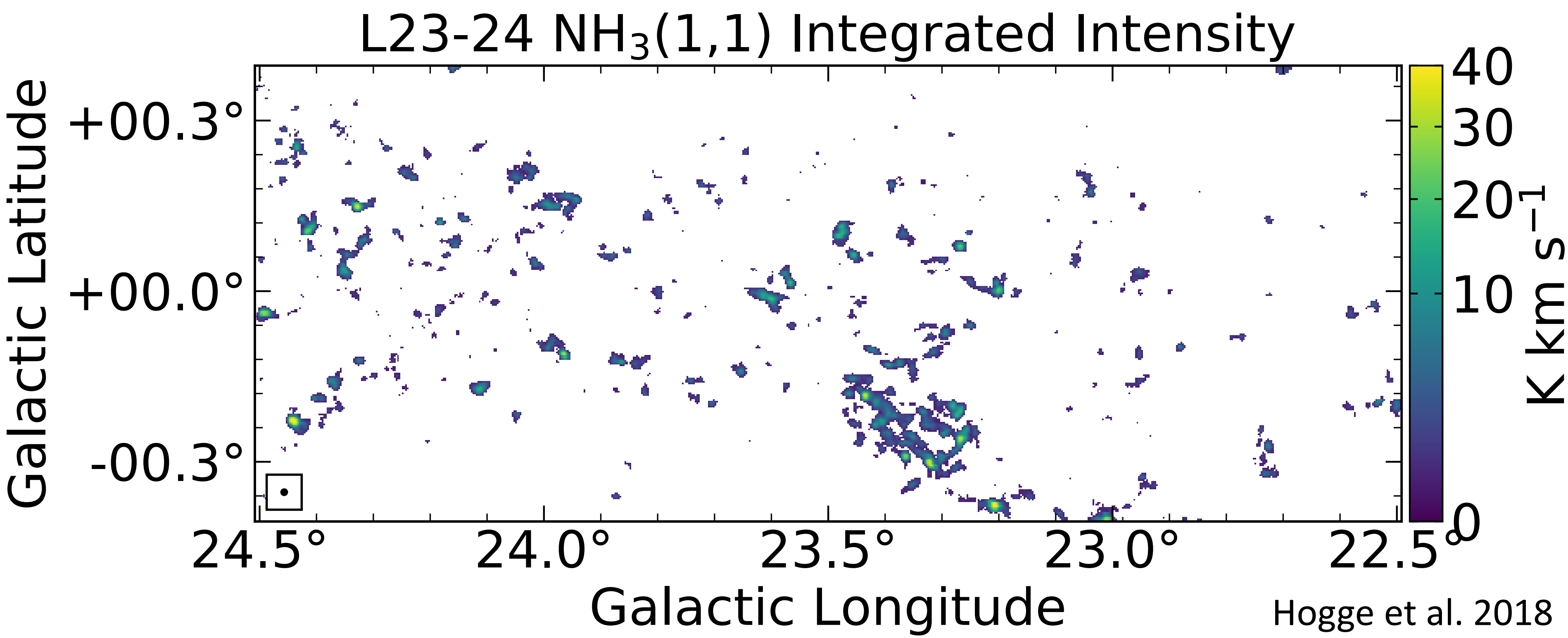
- Large collecting area (100 meter dish)
- K-band Focal Plane Array (KFPA; 18-27.5 GHz) is a 7-element array
- VEGAS spectrometer has multi-line capabilities and works with receiver arrays
- Fast/sensitive K-band mapping (T_{rms}~ 0.15 K in 0.2 km/s channels), high spatial resolution (32" beam), and high spectral resolution (0.02 km/s)

Credit: *gb.nrao.edu*

Current Status

- RAMPS was allocated 210 hours of GBT time for a pilot study to test the feasibility of the project and to help commission the VEGAS spectrometer
- Pilot survey completed (Hogge et al. 2018), mapped 6.5 deg^2
- Allocated >400 hours to complete the survey
- Use gbt-pipeline and gbtgridder software to reduce data, custom pipeline for processing
- Data to be released publicly after verification at sites.bu.edu/ramps (only NH_3(1,1), (2,2), and H_2O pilot data currently available)

Results from RAMPS Pilot Survey



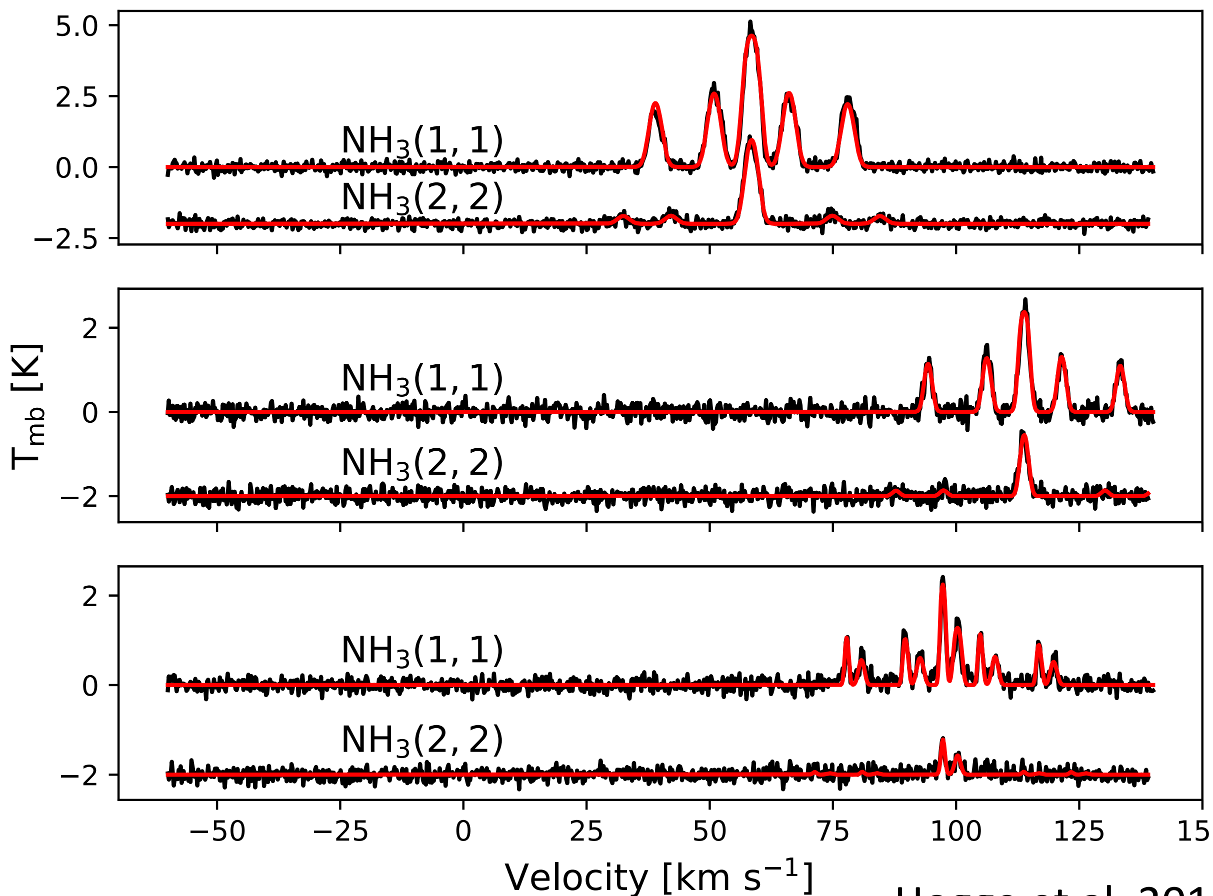
Hogge et al. 2018

NH_3(1,1) integrated intensity map of RAMPS fields L23 and L24

NH_3 Modeling with PySpecKit

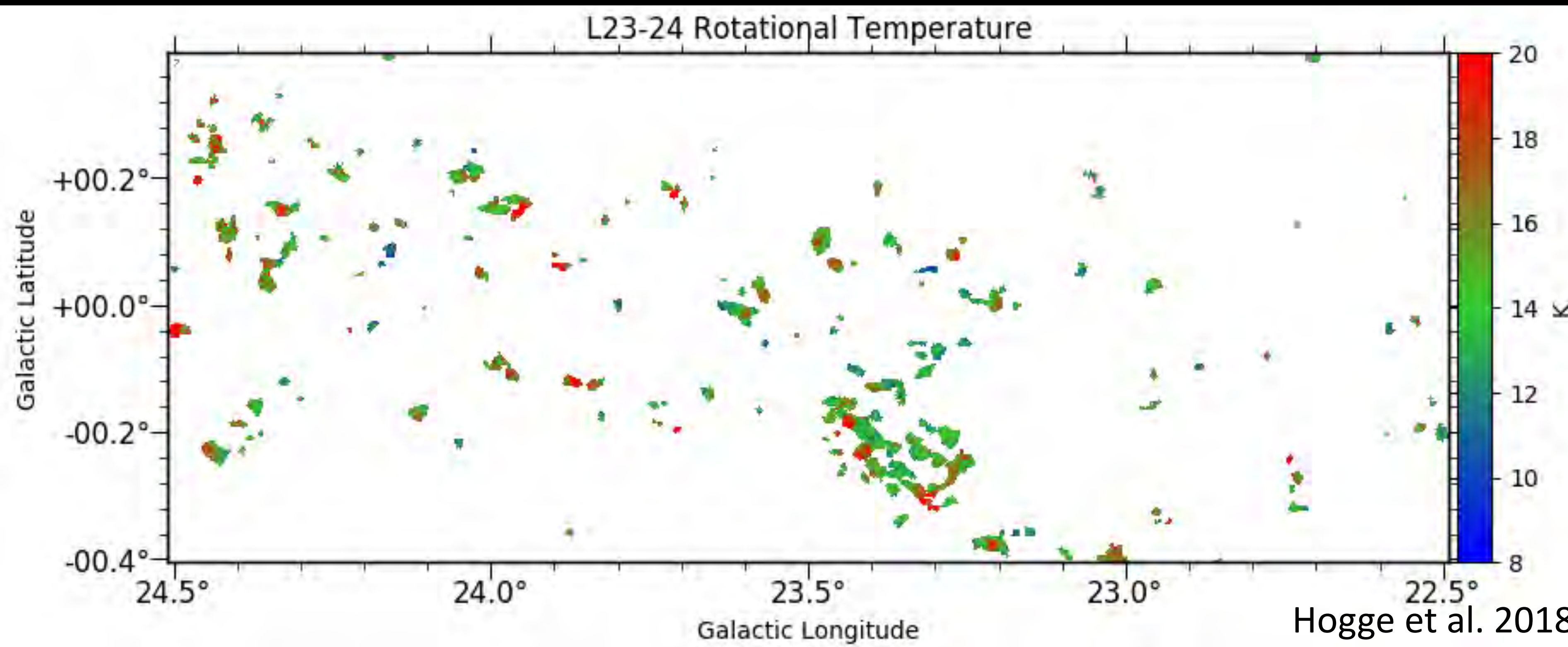
Fit Parameters

- Temperature
- Column density
- Linewidth
- Velocity
- Filling Fraction



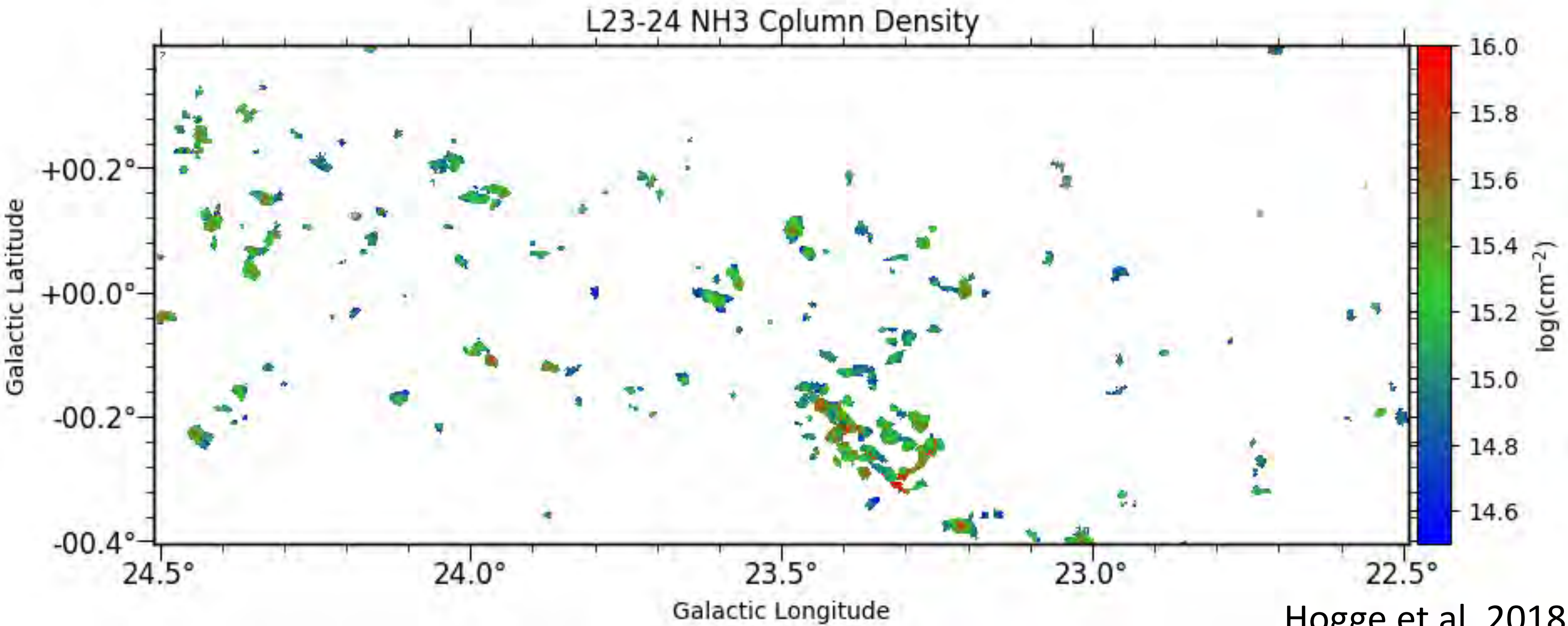
Hogge et al. 2018

Temperature



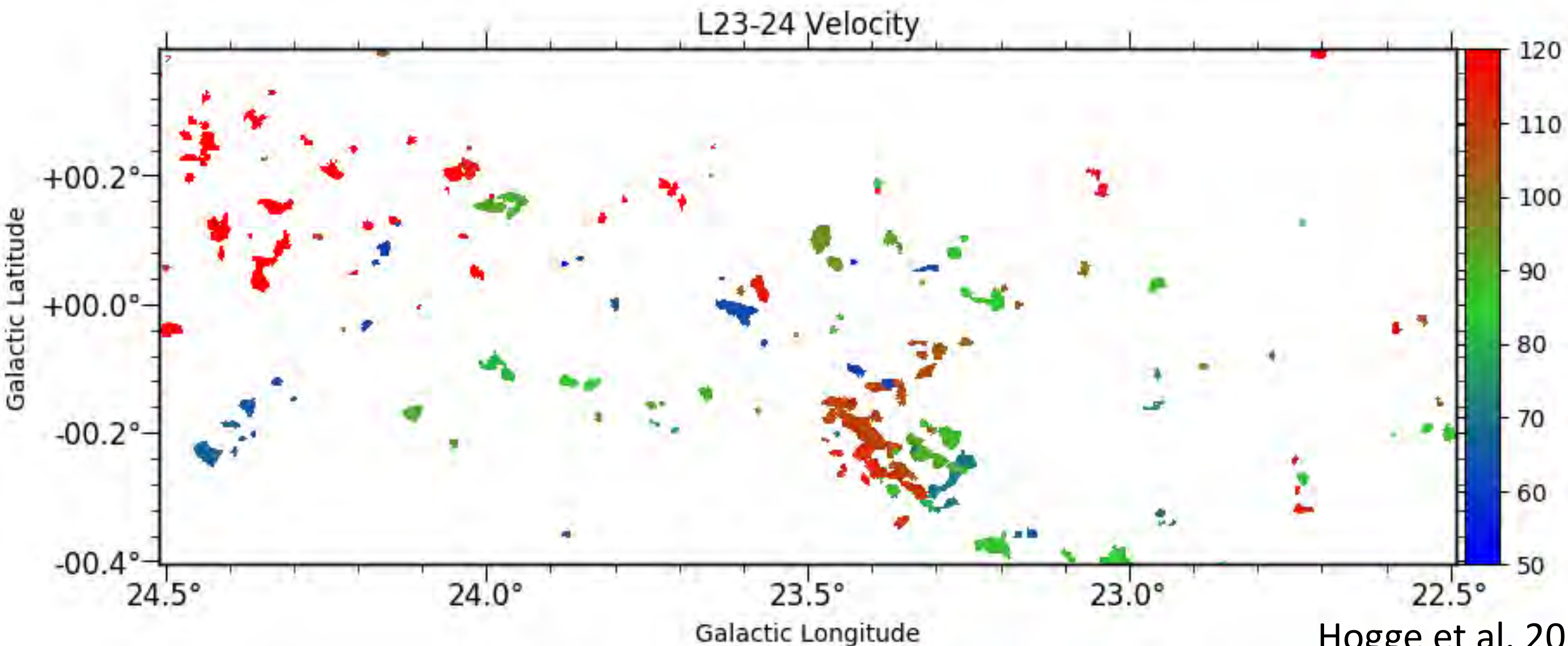
Hogge et al. 2018

Column Density



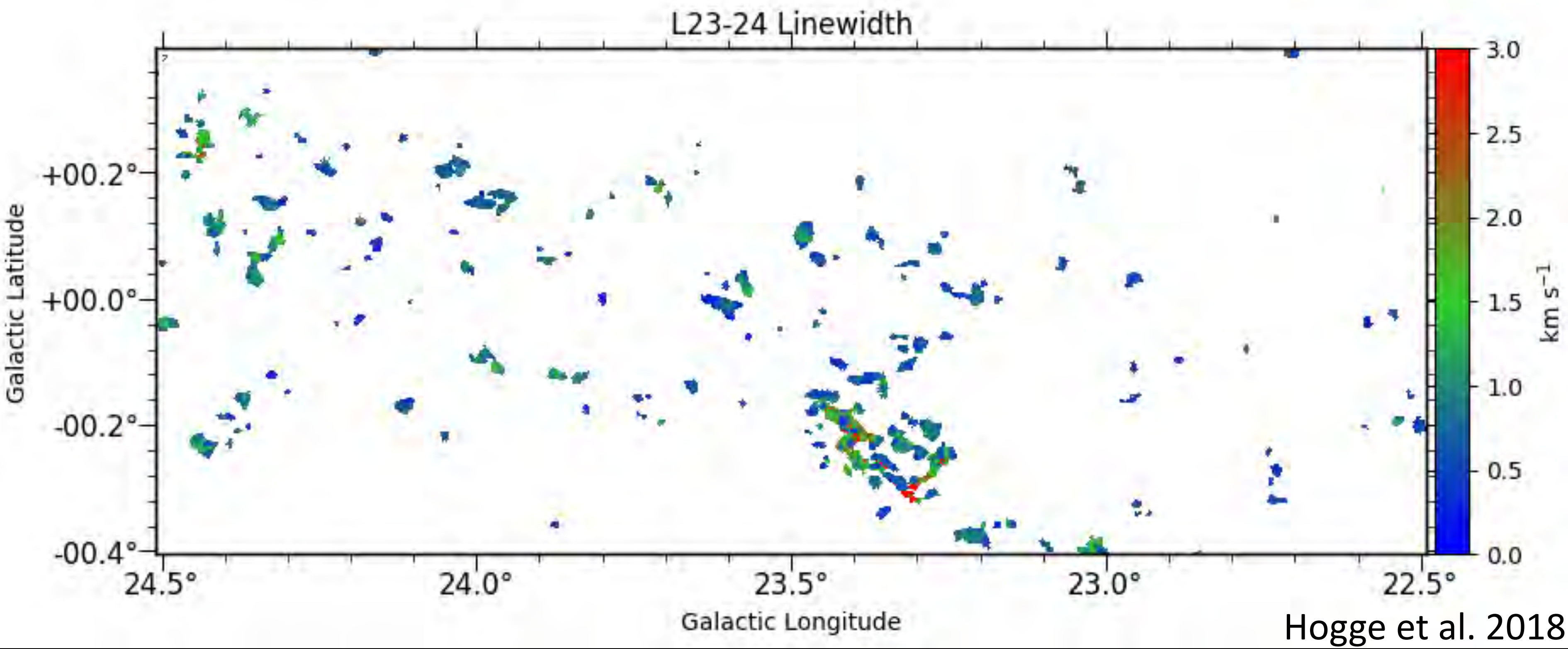
Hogge et al. 2018

Velocity



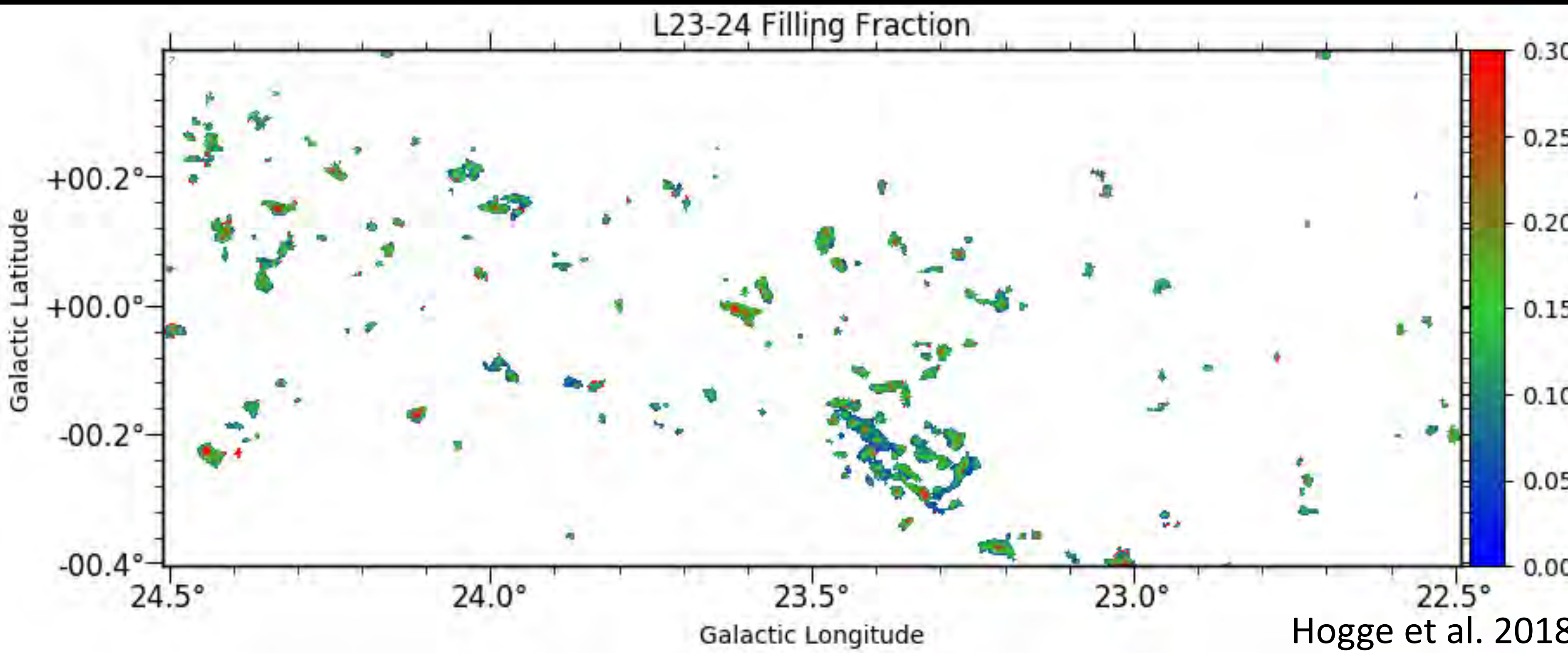
Hogge et al. 2018

Linewidth



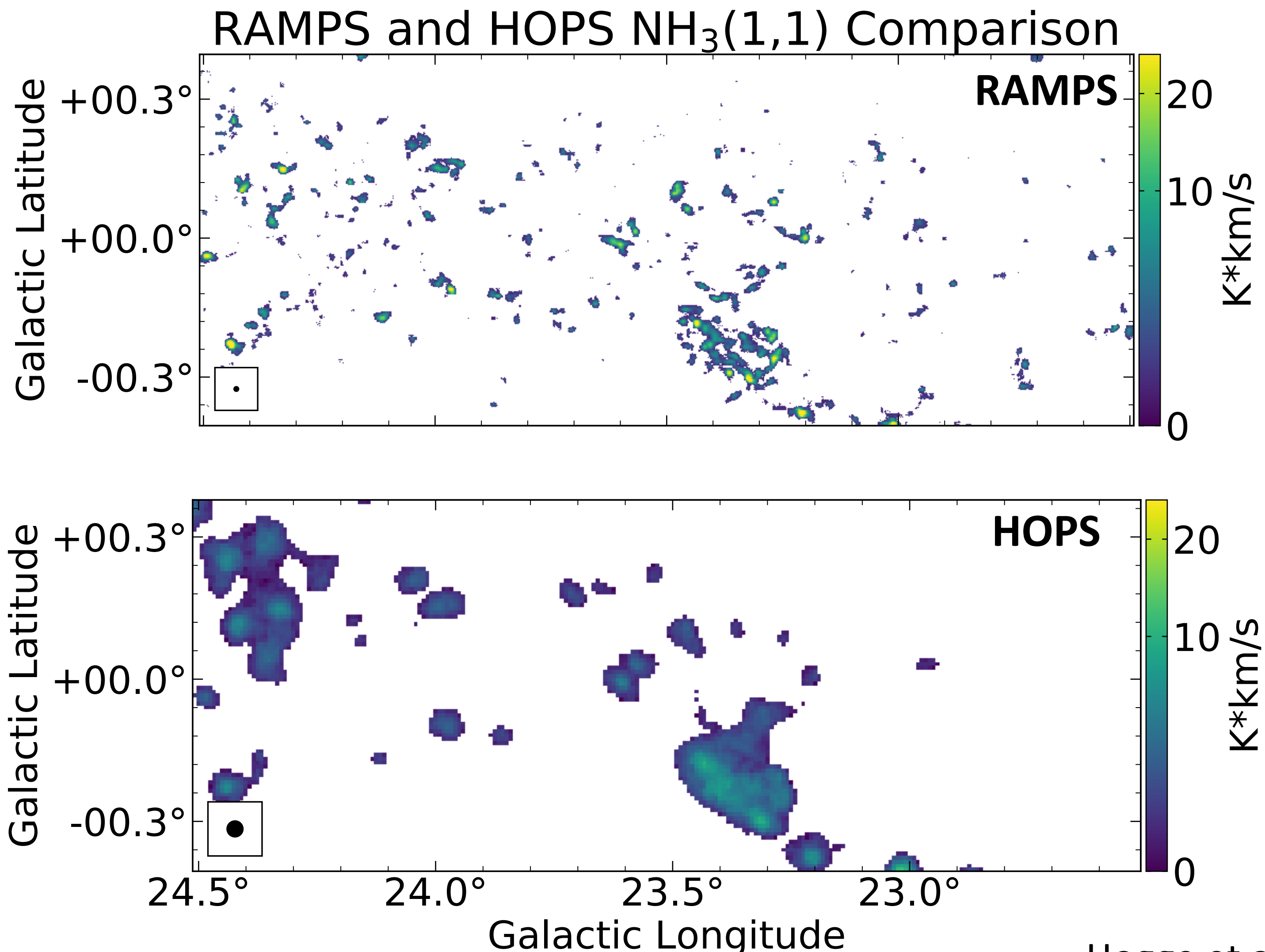
Hogge et al. 2018

Filling Fraction



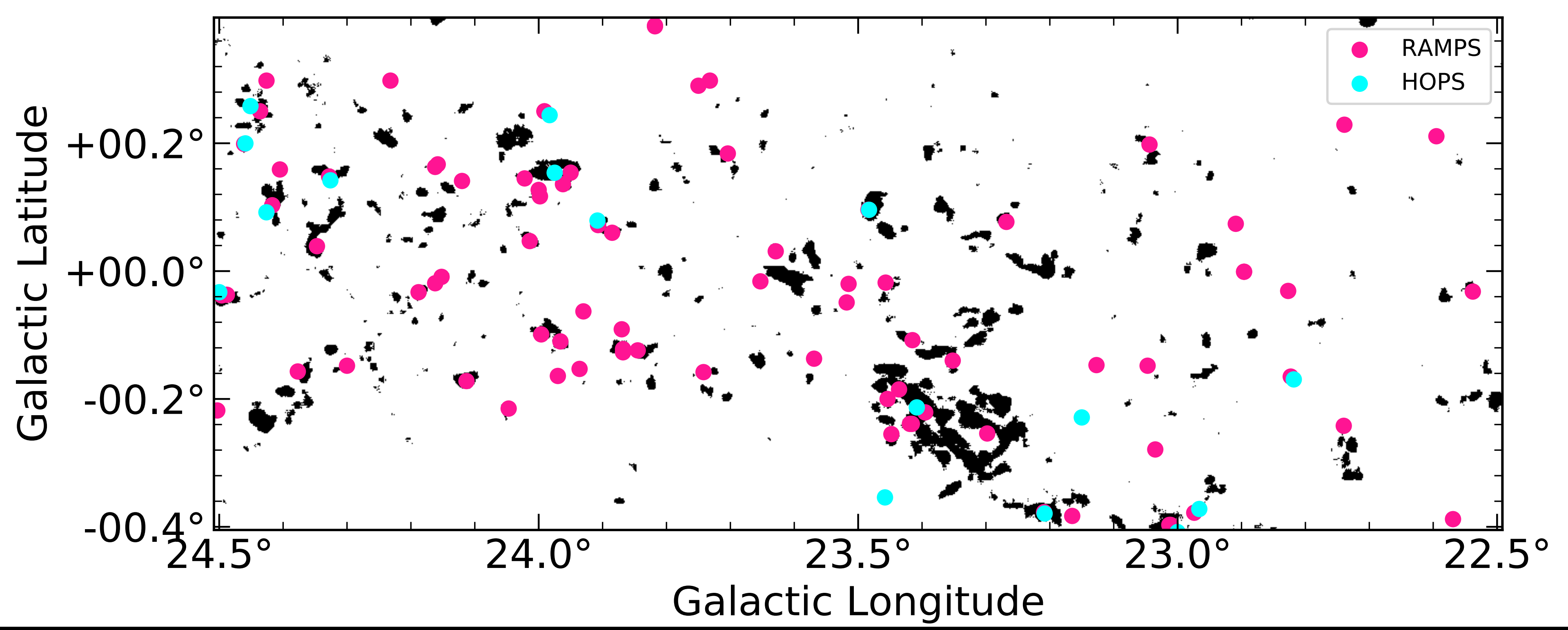
Hogge et al. 2018

Comparison with HOPS – NH_3



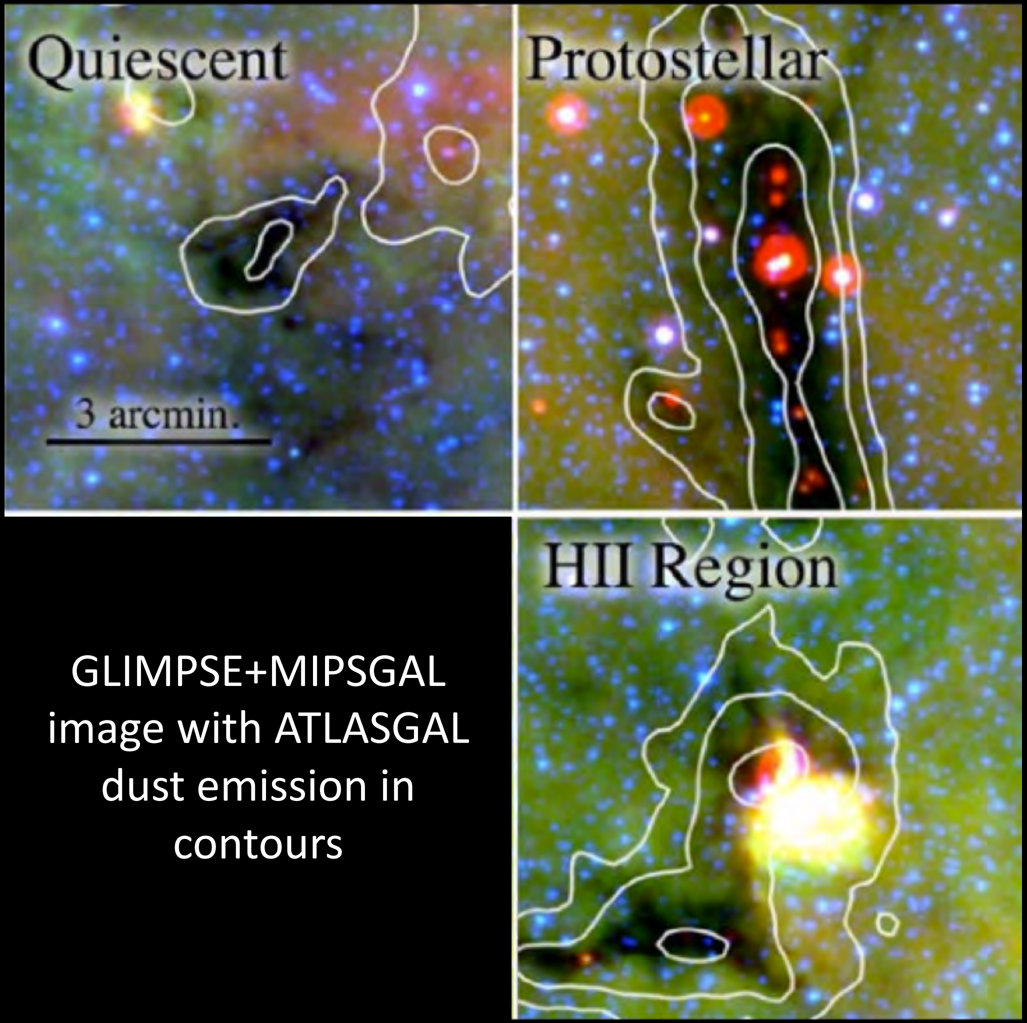
Hogge et al. 2018

Comparison with HOPS – H_2O



- RAMPS detected 82 masers in L23-24, while HOPS detected 15.
- RAMPS detected 325 in 6.5 deg^2, HOPS detected 540 in 100 deg^2.

Clump Evolution

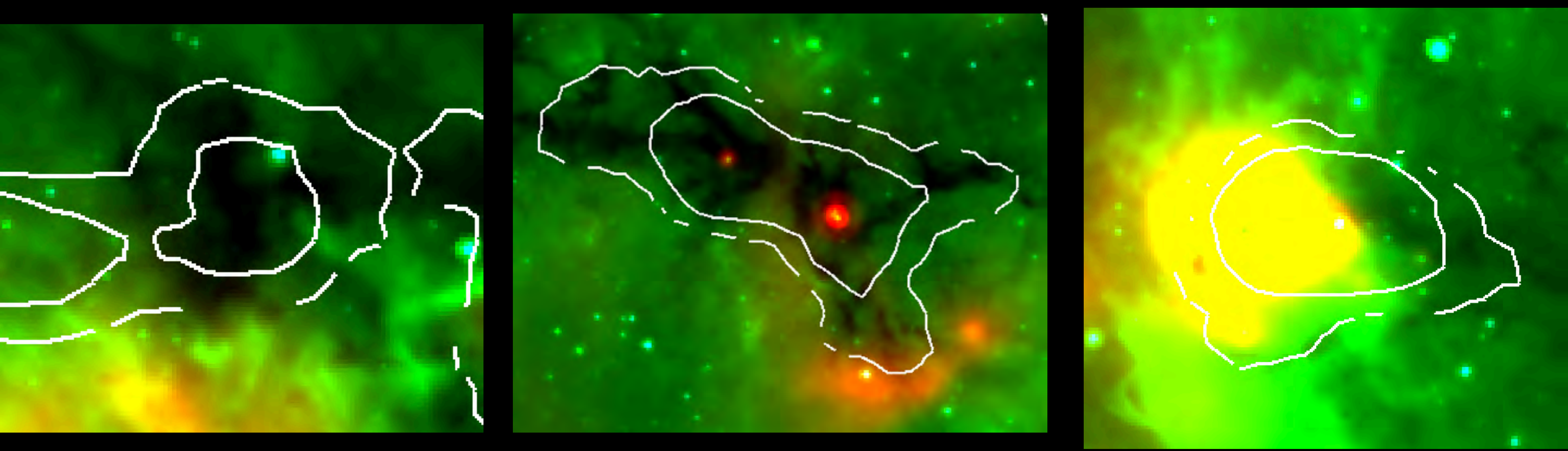


GLIMPSE+MIPSGAL image with ATLASGAL dust emission in contours

- Classify evolutionary state with MIR images
- NH_3 data will give temperature, column density, and kinematics
- Look for trends as a function of evolutionary state

Classify with MIR Data

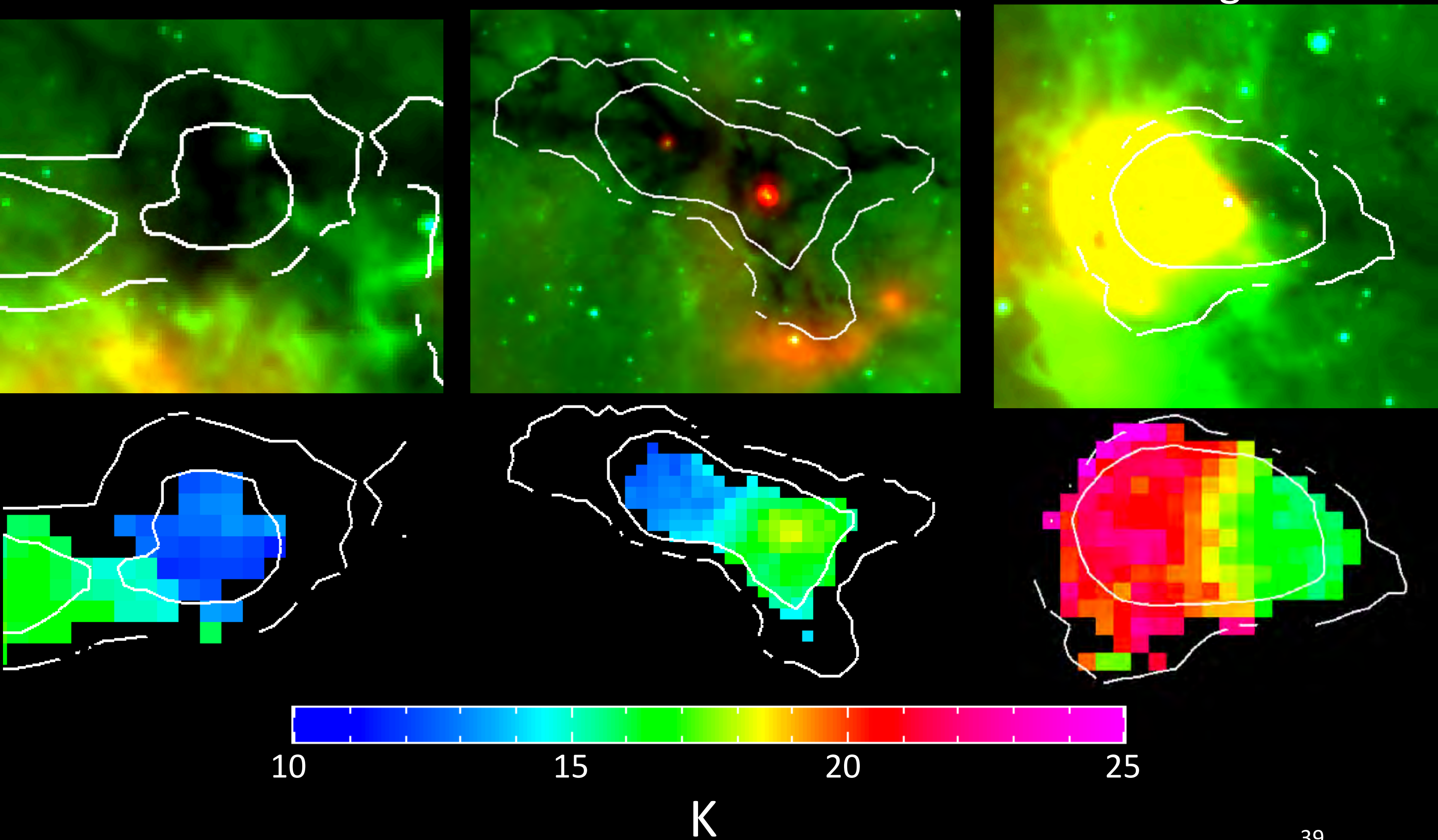
Quiescent Protostellar H II Region



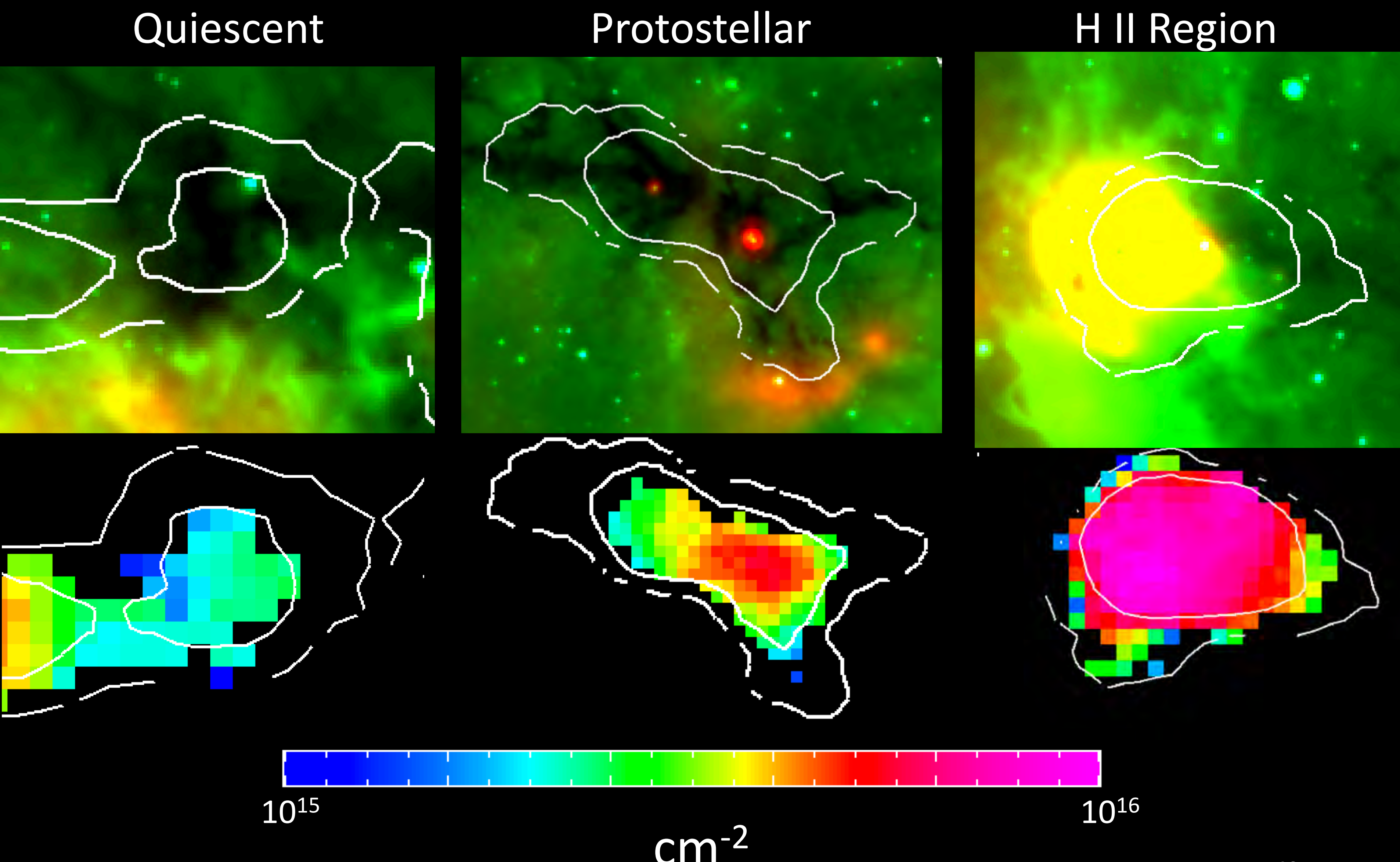
Color is GLIMPSE and MIPSGAL 3.6 µm (blue), 8 µm (green), and 24 µm (red).
Contours are RAMPS $NH_3(1,1)$ integrated intensity.

NH_3 Rotational Temperature

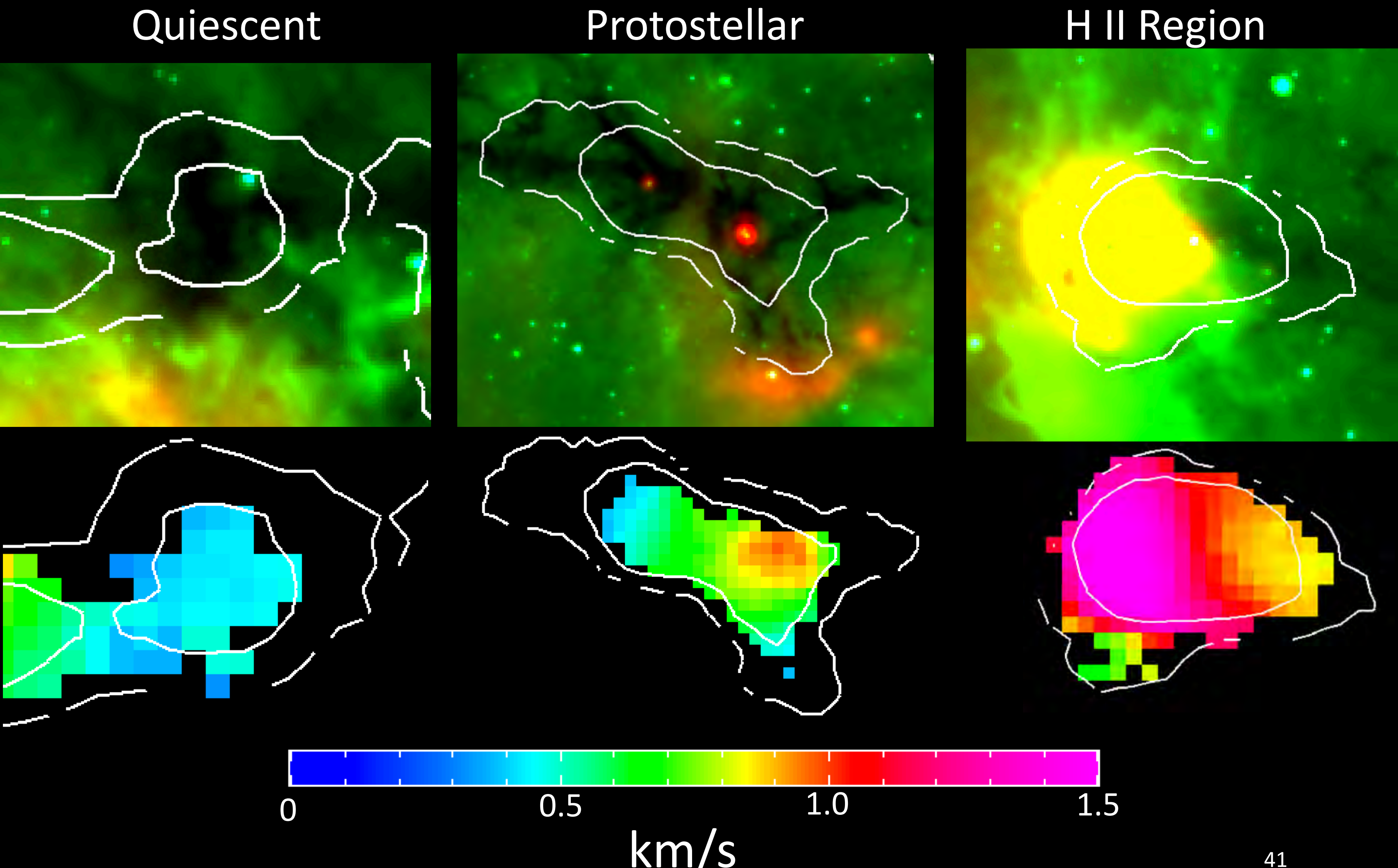
Quiescent | Protostellar | H II Region



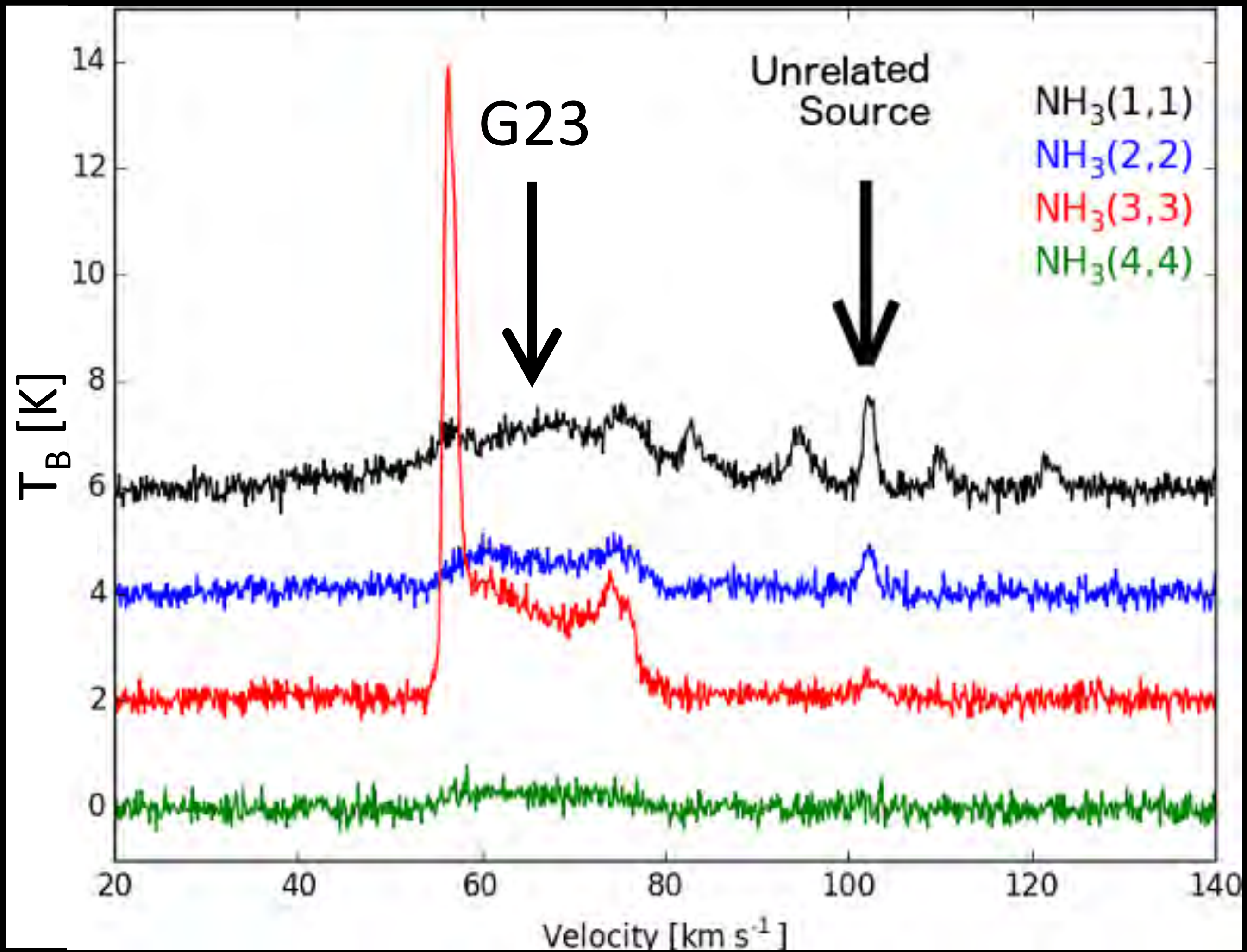
NH_3 Column Density



Linewidth

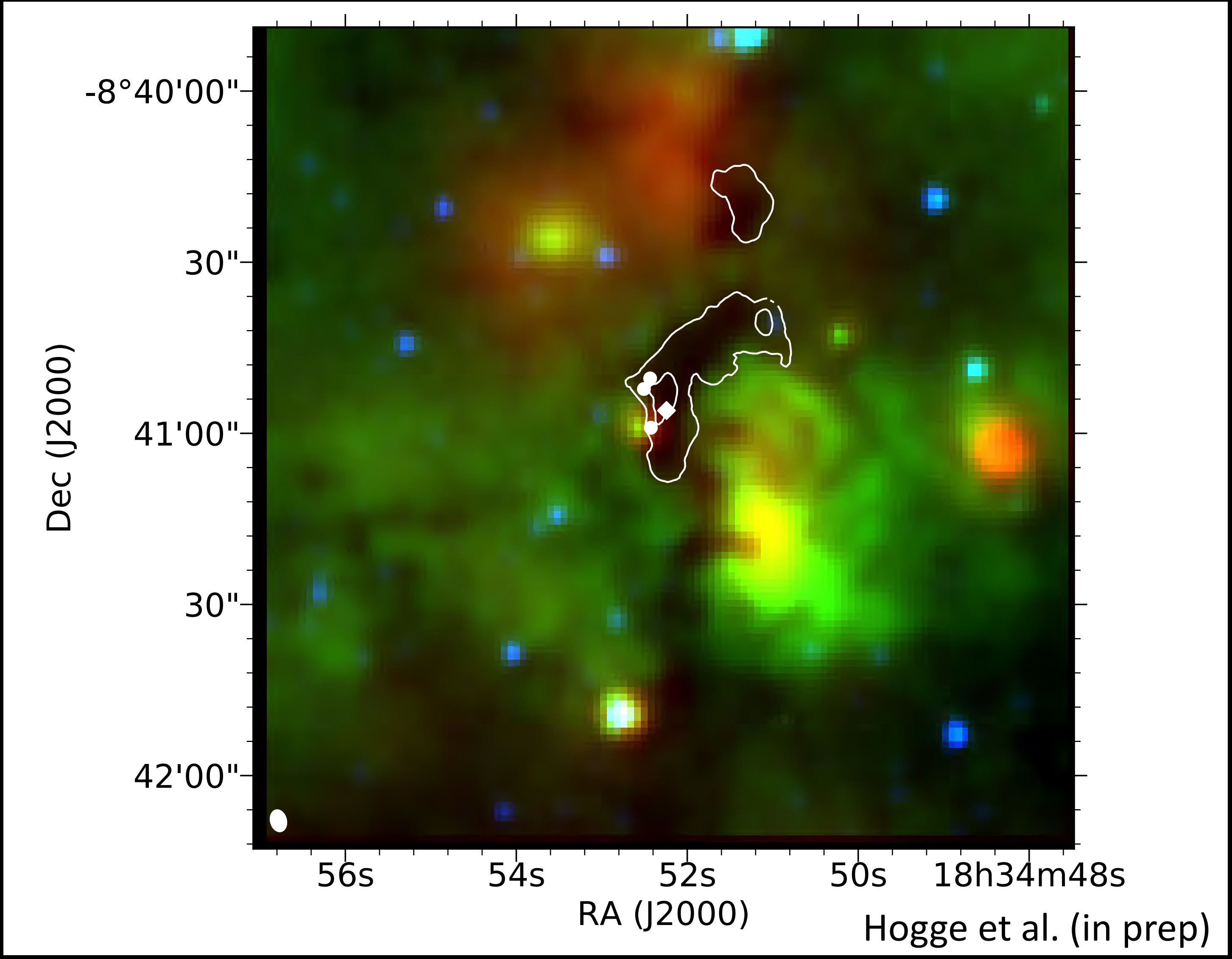


Extreme Kinematics in G23.33-0.30

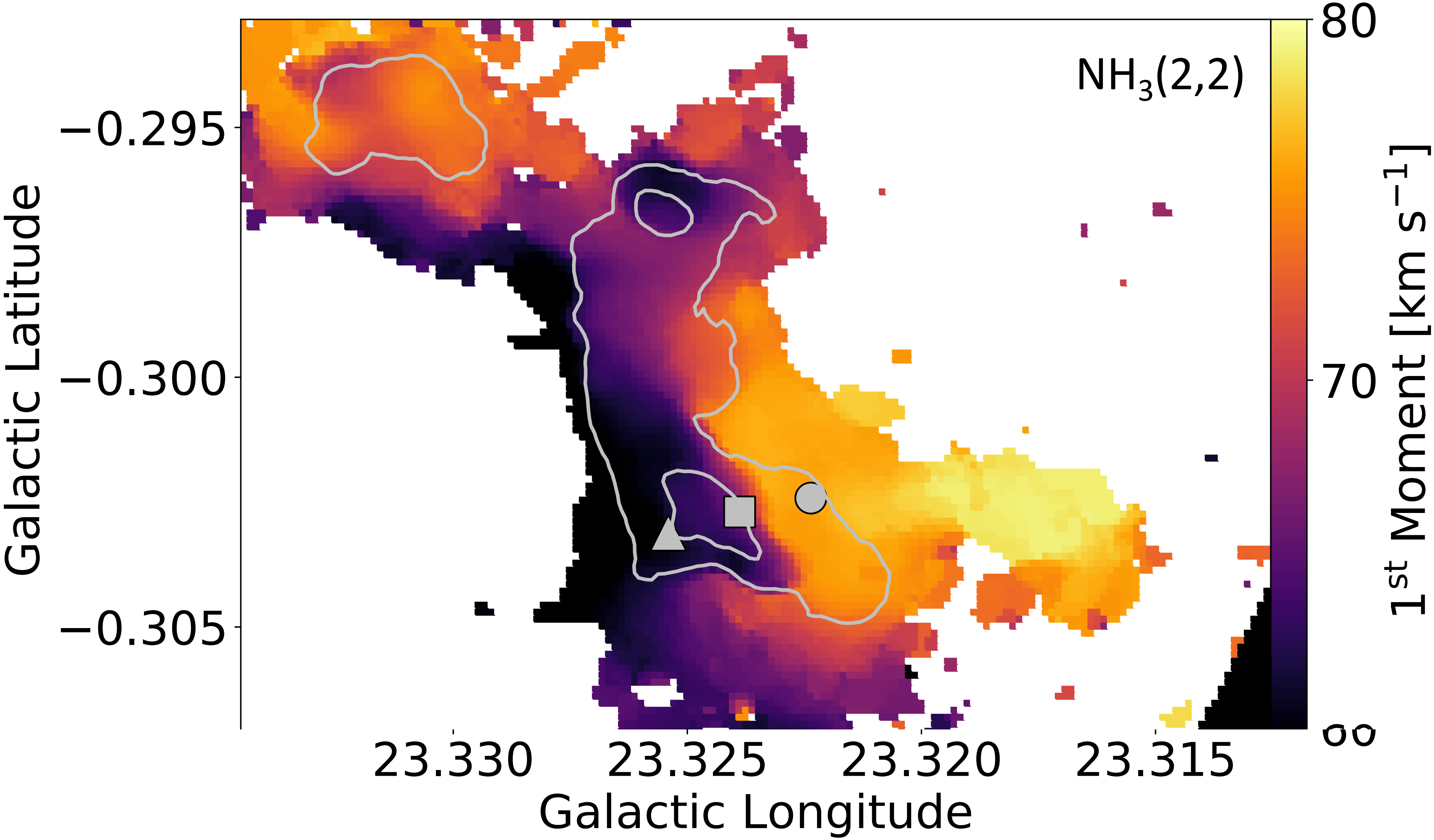


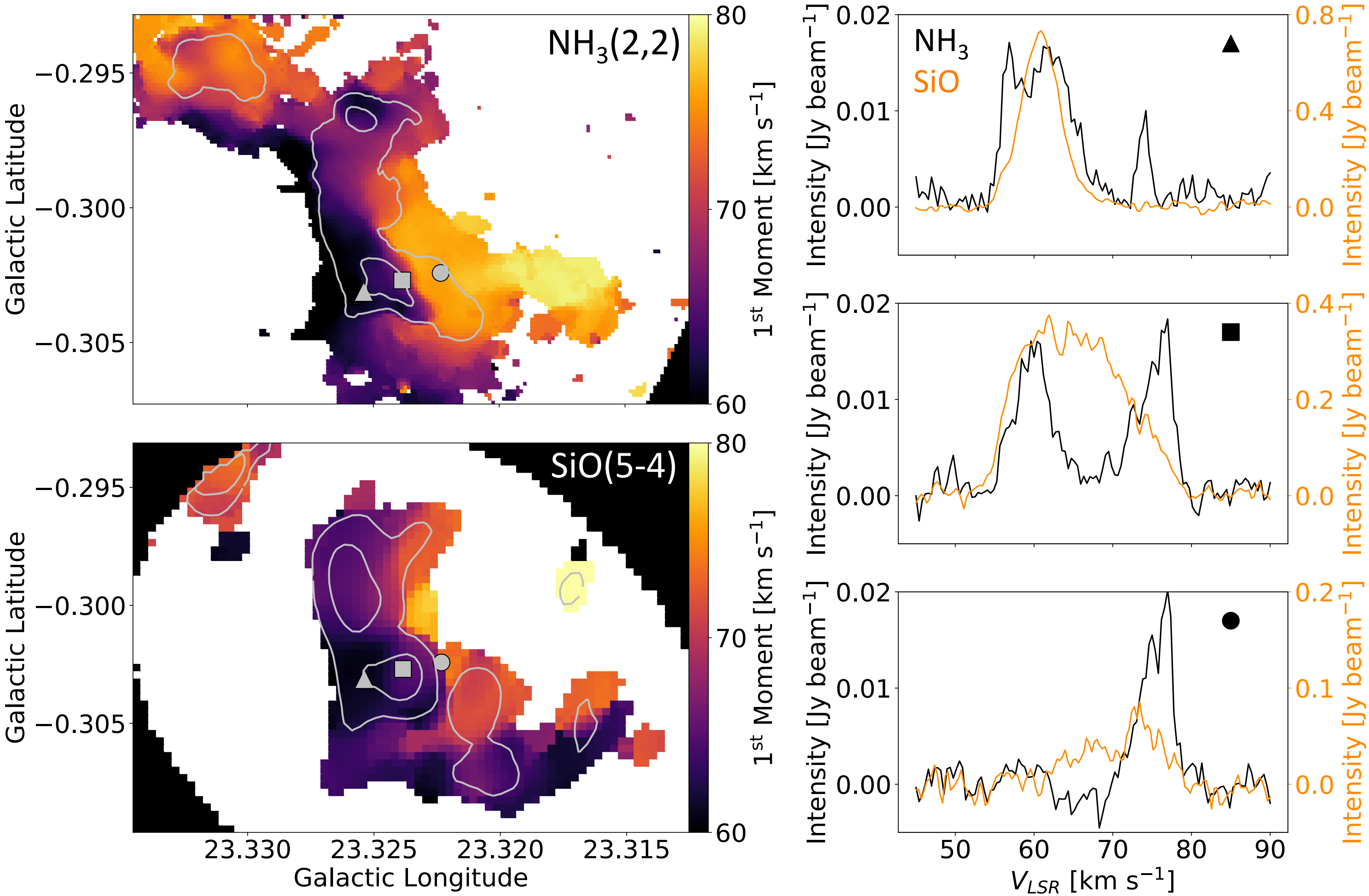
Linewidth of G23.33-0.30 is ~20 km/s, 10 X larger than typical NH_3-emitting clumps.
Rare NH_3(3,3) maser may be associated with high-mass star formation.

VLA data reveals multiple $NH_3(3,3)$ masers - are they tracing outflows?



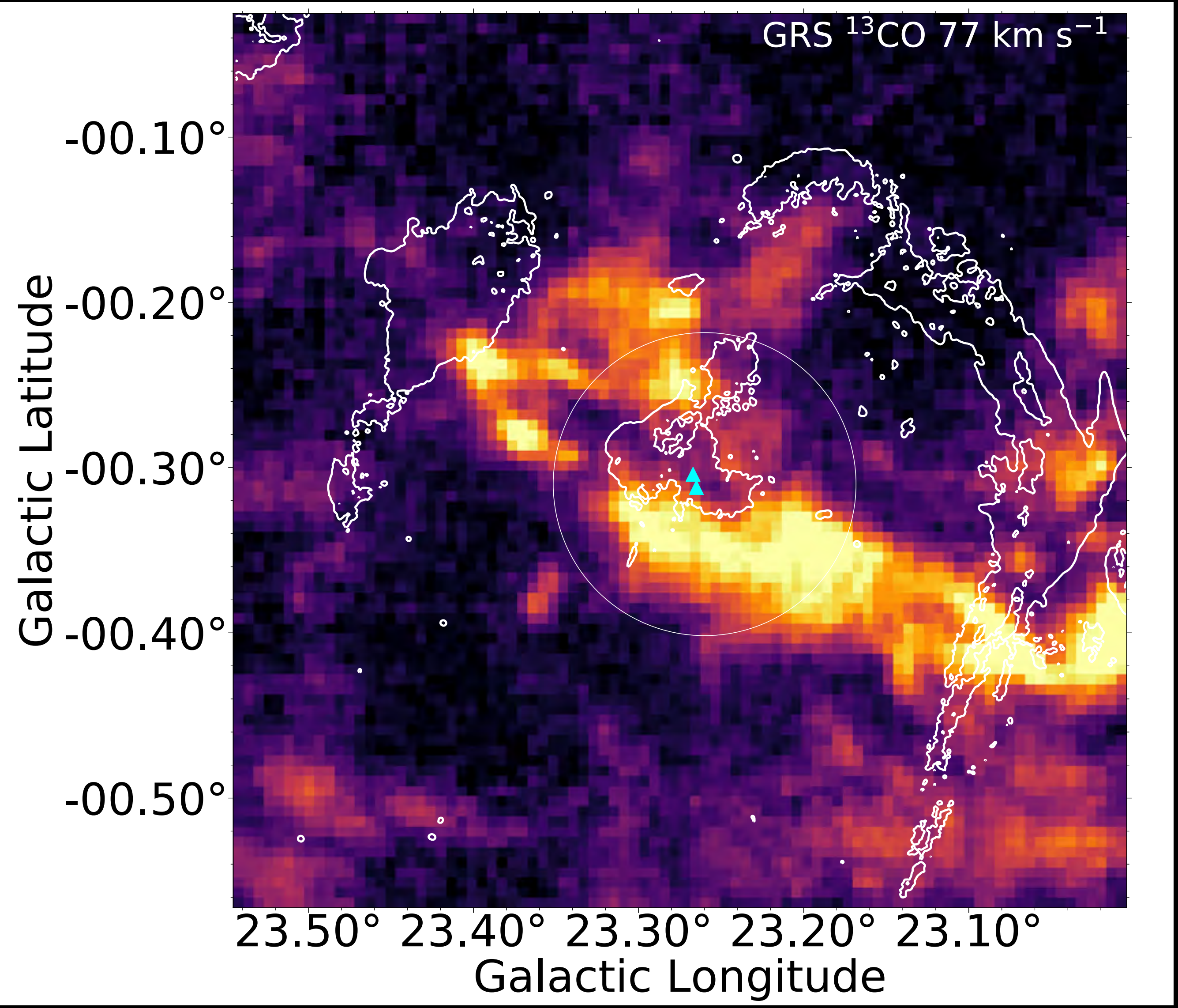
NH_3 kinematics reveal velocity gradient across filament





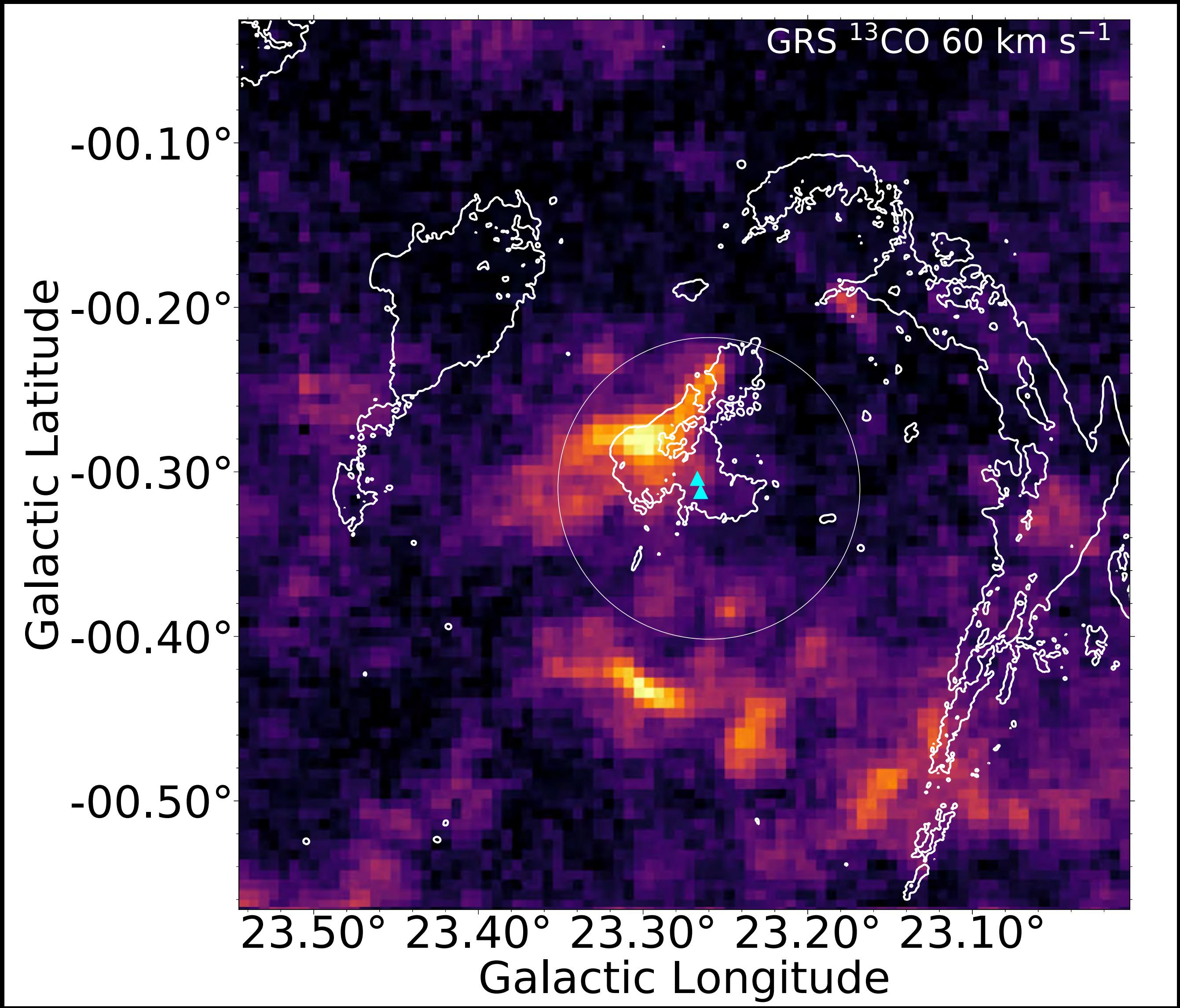
Hogge et al. (in prep)

SNR W41 interacting with 77 km/s filament?



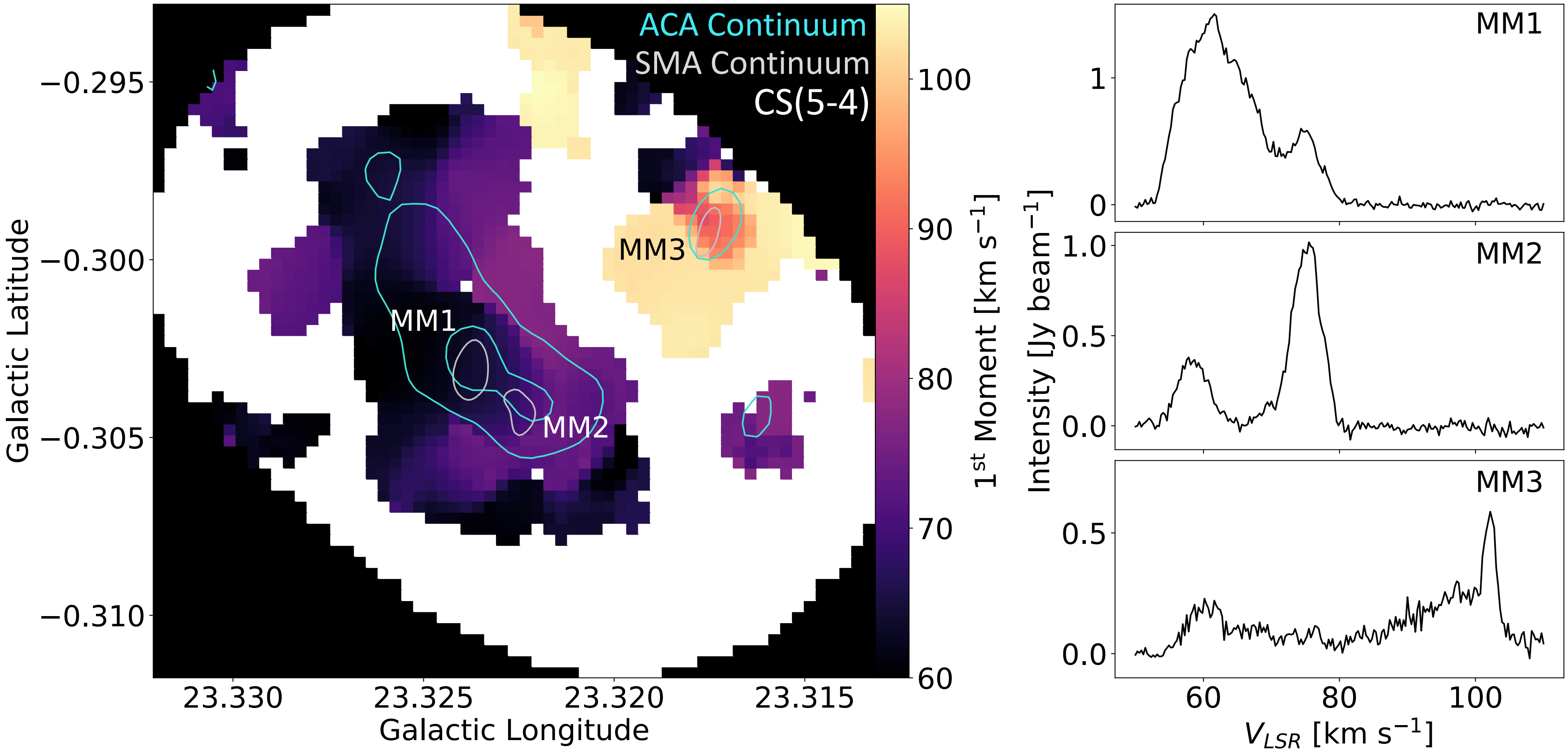
Hogge et al. (in prep)

Is 60 km/s component accelerated gas?



Hogge et al. (in prep)

SMA and ACA detect cores: is the star formation process being triggered, inhibited, neither?



Hogge et al. (in prep)

Summary

- Many open questions, only partial answers from continuum surveys
- Molecular lines provide additional information, RAMPS and GBT offer significant improvements in mapping NH_3 and H_2O
- RAMPS pilot detected ~500 clumps and can measure temperature, column density, line width, and velocity
- Large surveys are critical for the study of high-mass star formation and allow for the discovery of rare and unique sources
- Publicly available RAMPS dataset will support many future scientific investigations

Questions?

Velocity Corresponds to Distance