



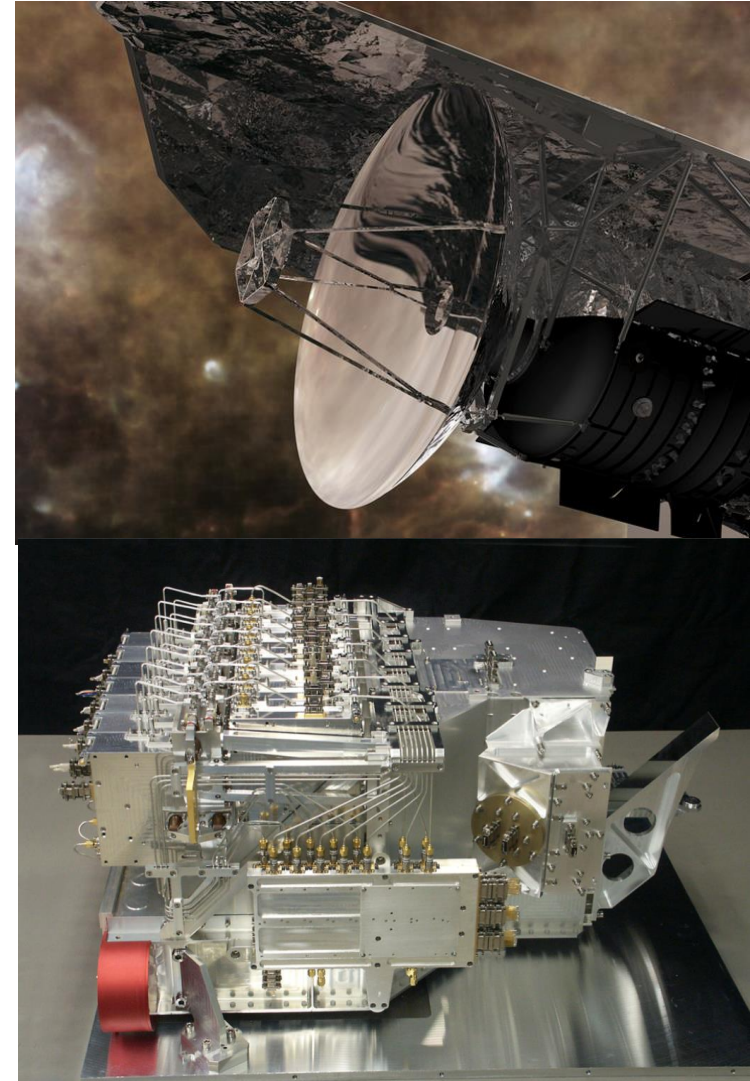
Catherine Walker, Luyao Zou, Shiya Wang, Dariusz Lis, and Susanna Widicus
Weaver

Chemical Inventories of Molecular Clouds Revealed by Herschel HIFI Spectral Line Surveys

The 76th International Symposium on Molecular Spectroscopy
22nd June 2023, Urbana-Champaign
RIO2

Broadband line surveys

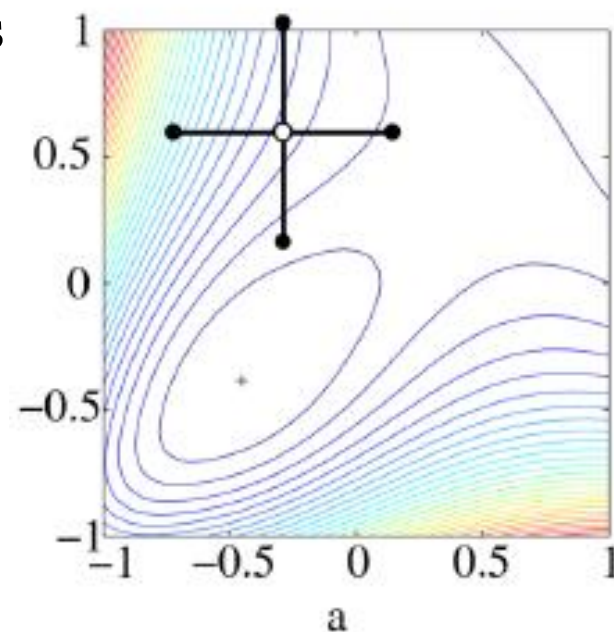
- Collected by the Heterodyne Instrument for the Far-Infrared (HIFI) aboard the Herschel telescope in 2011-2012
- 12 GHz windows centered at 670 GHz and 1.16 THz (24 GHz after deconvolution)
- HPBW $\sim 31''$ (B2); $\sim 18''$ (B5)
- Cleaned and deconvolved by Shiya Wang
- First pass with GOBASIC by Luyao Zou



Credit: ESA/NASA/JPL-Caltech
<https://www.cosmos.esa.int/web/herschel/hifi-overview>

GOBASIC Spectral Analysis Software

- **Global Optimization and Broadband Analysis Software for Interstellar Chemistry**
- MATLAB program optimized for parallel computing
- Input catalog files from JPL or CDMS
- Enter initial guess and range for LTE parameters (N , T , Δv , δv_{lsr})
- Generate simulated spectrum from catalog based on initial LTE parameters
- Best-fit parameters determined through least-squares fitting using the MATLAB PatternSearch algorithm (derivative-free, global minimum)
- Fit molecules in specified order (simultaneous)

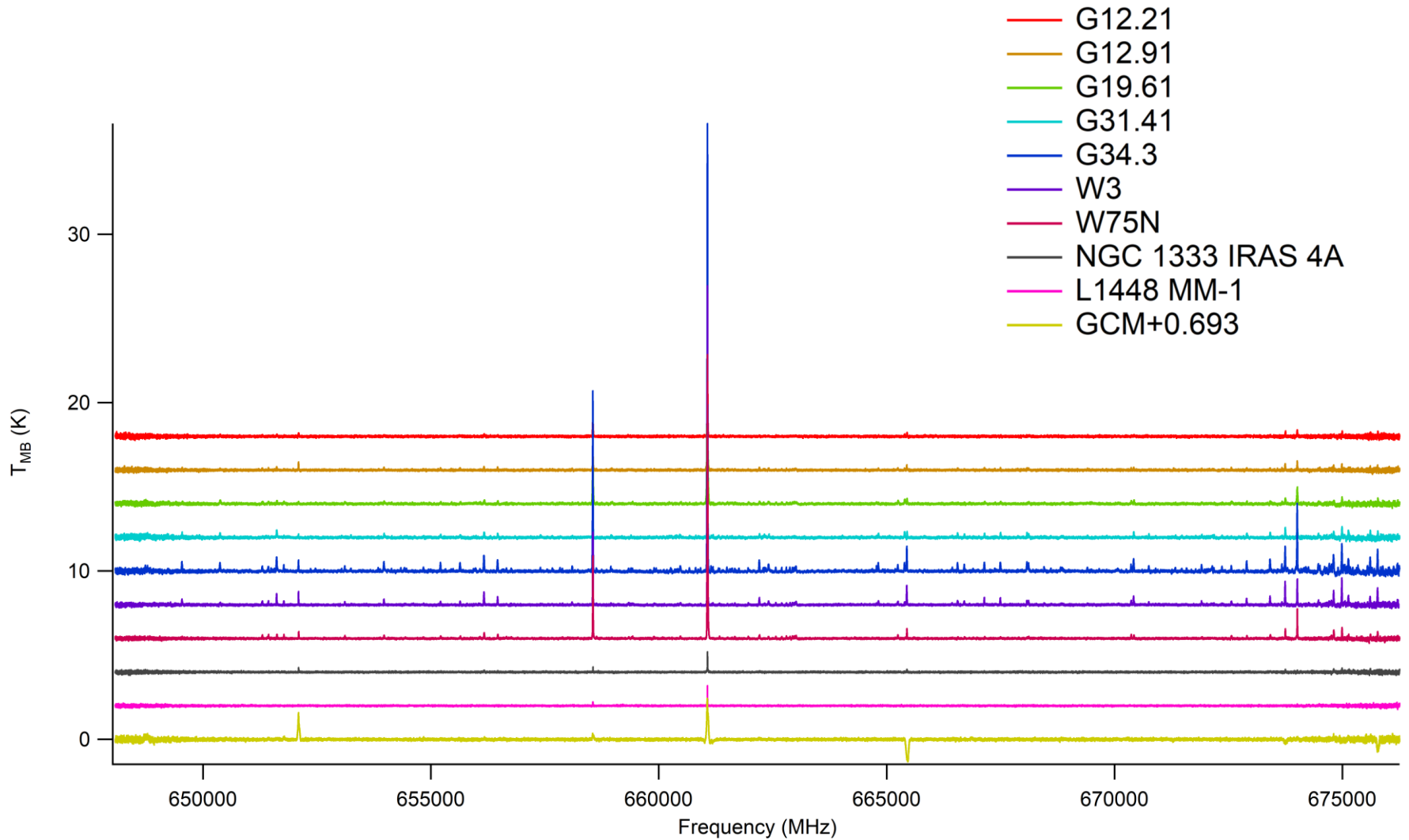


Source Name	Source Type
GAL 12.21-0.10	HII region
GAL 012.91-00.26	Hot core
GAL 19.61-0.23	Hot core
GAL 31.41+0.31	Hot core
GAL 034.3+00.2	Hot core
W ₃	Hot core
W ₇₅ N	Hot core
NGC 1333 IRAS 4A	Hot corino
L1448MM-1	Class 0 protostar + outflow
GCM +0.693-0.027	Shocked region

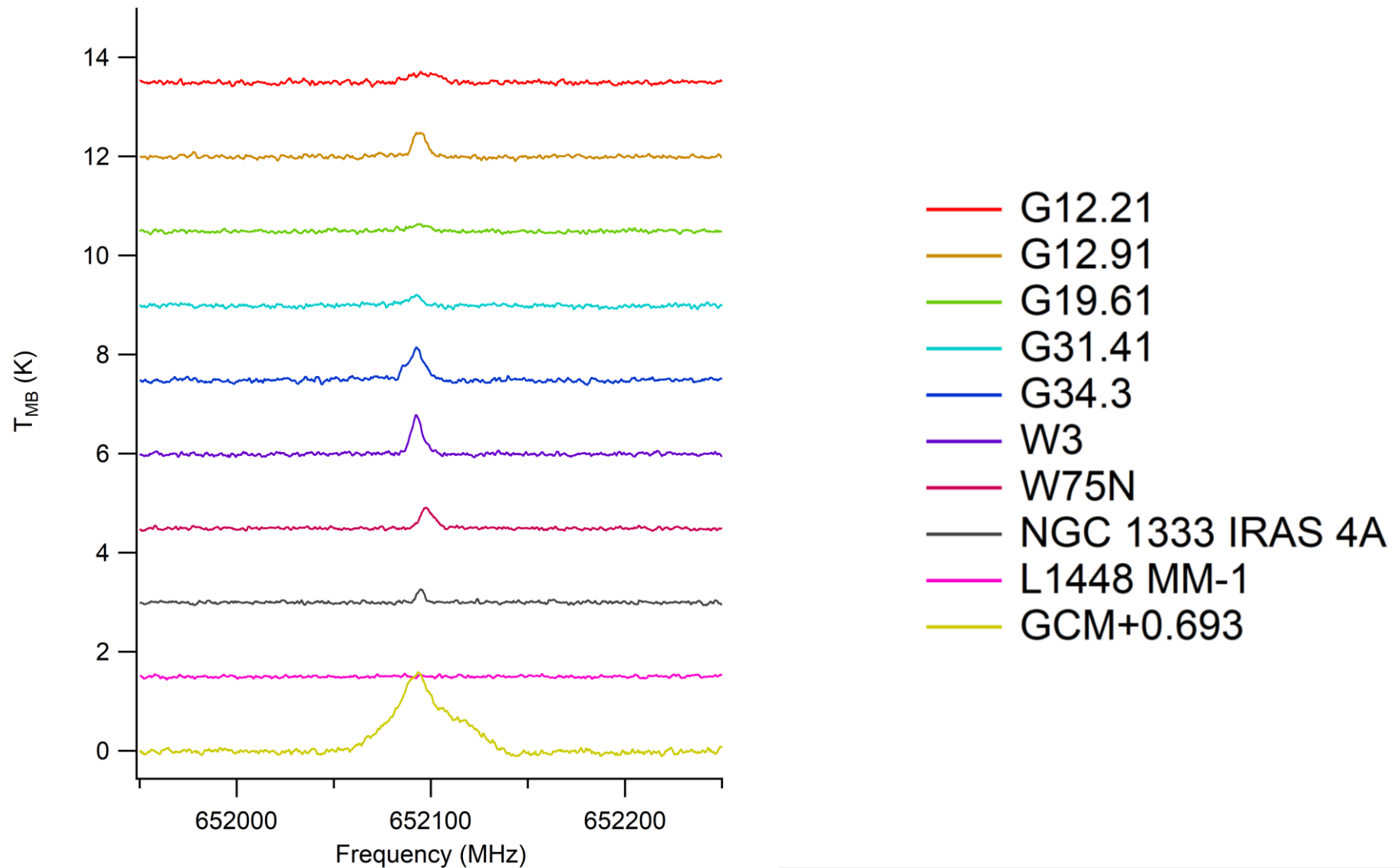
All previously observed with CSO ~220-270 GHz¹

1. Widicus Weaver, S. L., et al. *Astrophys. J. Suppl. Ser.* **2017**, 232, 3.

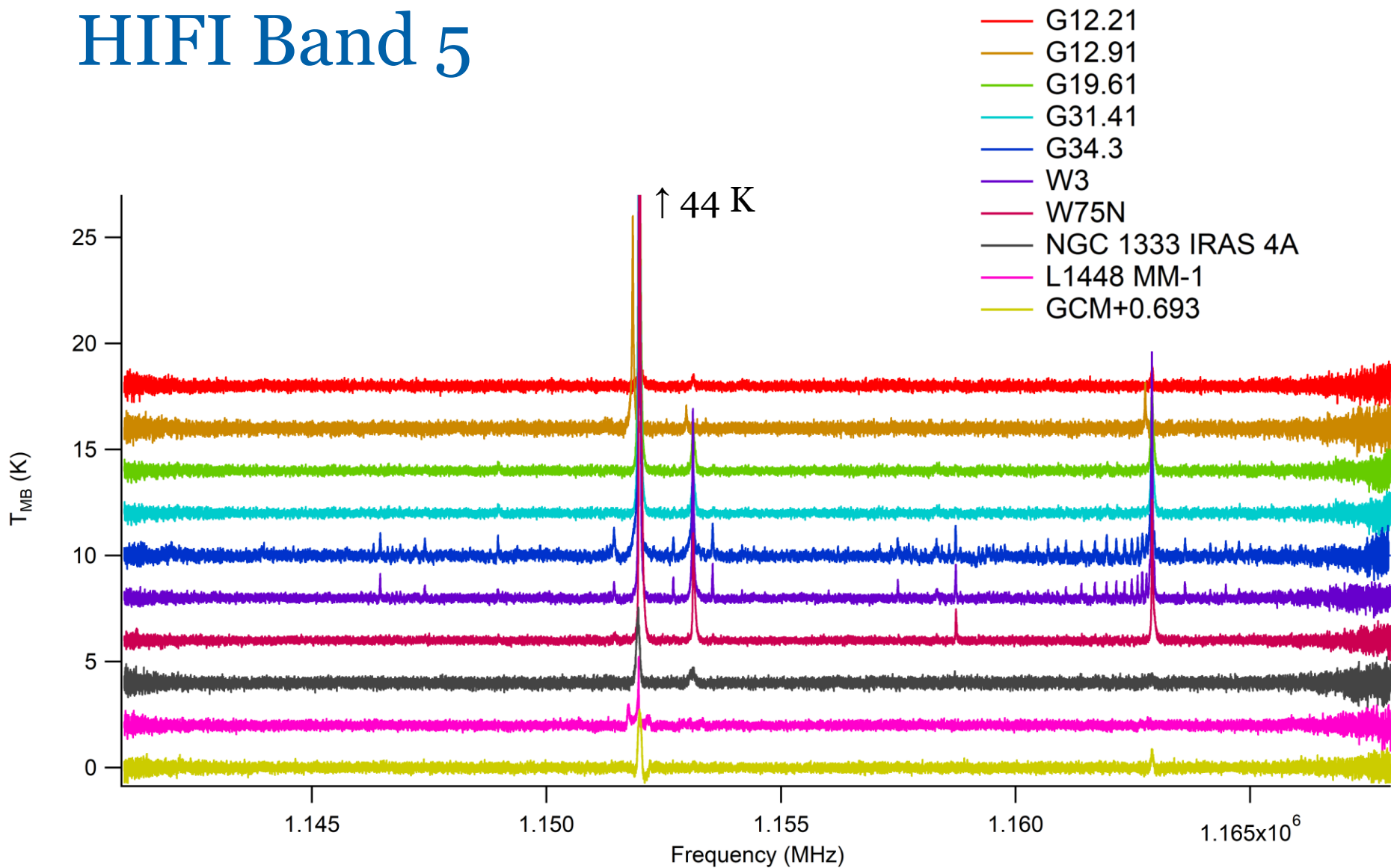
HIFI Band 2



N_2H^+ J = 7-6 652096 MHz

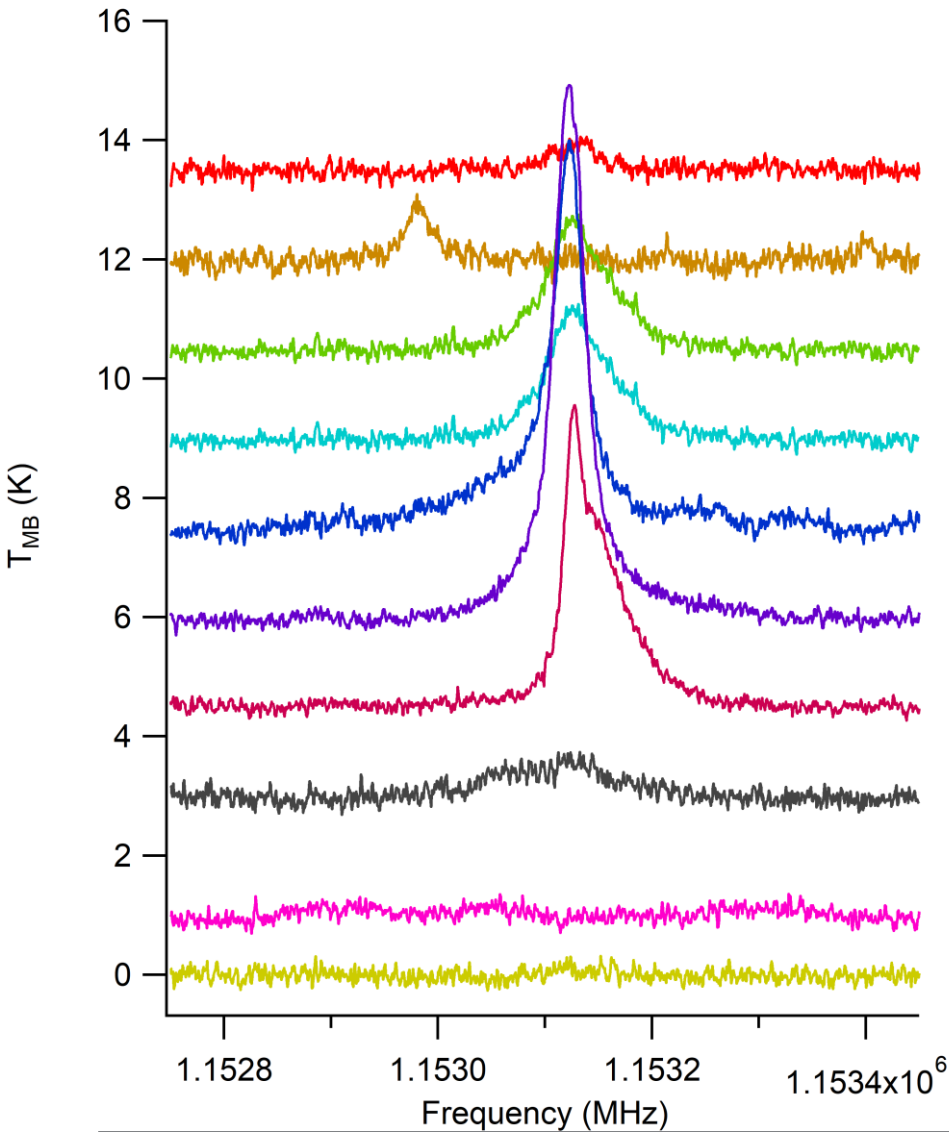


HIFI Band 5

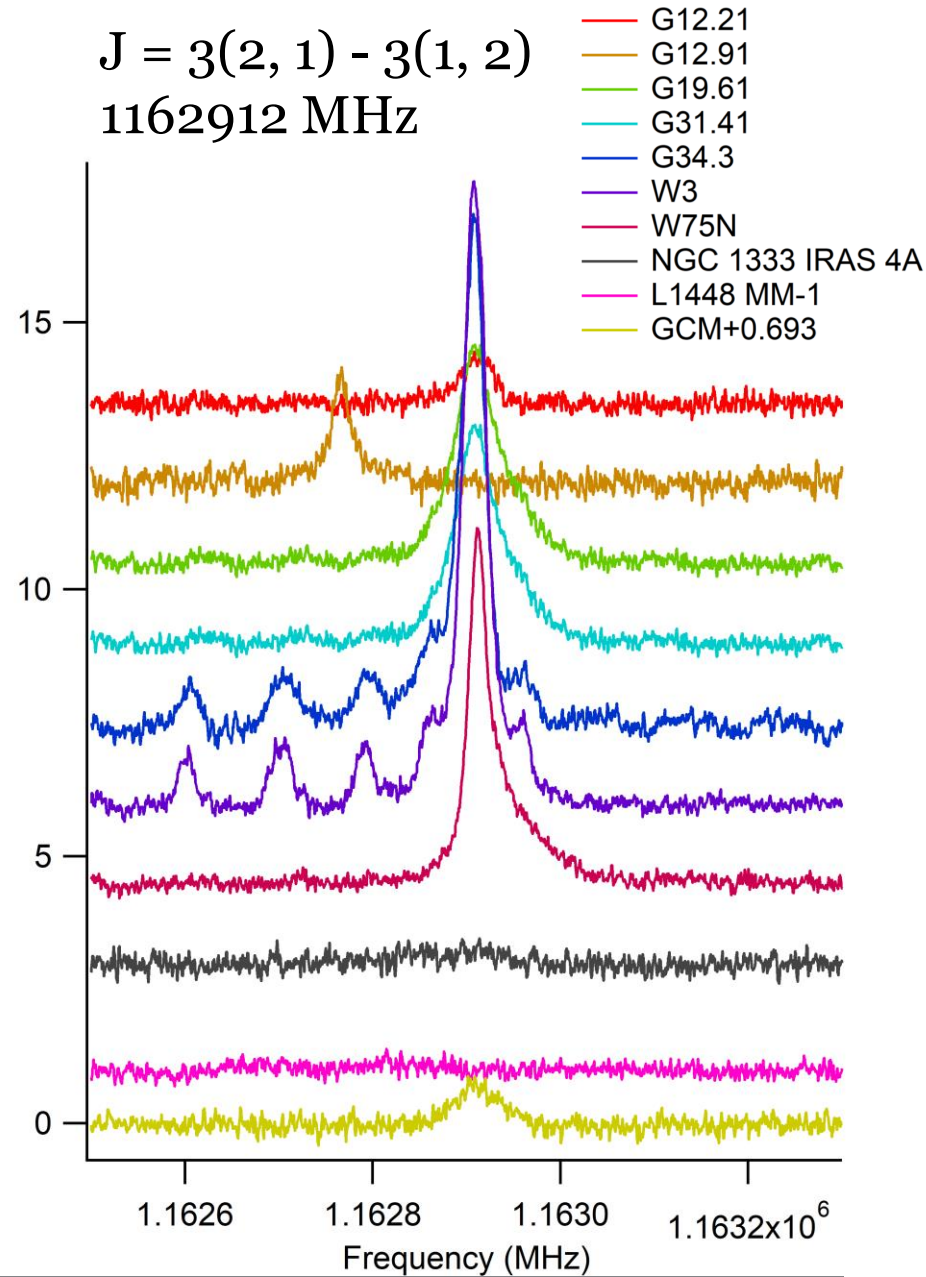




$J = 3(1, 2) - 2(2, 1)$
1153127 MHz



$J = 3(2, 1) - 3(1, 2)$
1162912 MHz



Preliminary detections

	G12.21	G12.91	G19.61	G31.41	G34.3	W3	W75N	NGC 1333 IRAS 4A	L1448 MM-1	GCM+ 0.693
CH ₃ OH	✓	✓	✓	✓	✓	✓	✓	✓	-	-
H ₂ CO	✓	✓	✓	✓	✓	✓	✓	✓	-	✓
¹³ CH ₃ OH	-	✓	✓	✓	✓	✓	✓	-	-	-
CH ₃ OCH ₃	-	✓	✓	✓	✓	✓	✓	-	-	-
CH ₂ NH	-	✓	✓	✓	✓	-	-	-	-	-
CH ₃ CN	-	✓	✓	?	✓	✓	-	-	-	-
H ₂ CS	-	✓	✓	✓	✓	-	-	-	-	-
C ₂ H ₅ OH	-	-	✓	✓	✓	?	-	-	-	-
H ₂ ¹³ CO	-	✓	✓	✓	✓	-	-	-	-	-
HCOOCH ₃	-	-	✓	✓	✓	-	?	-	-	-
C ₂ H ₅ CN	-	-	?	?	✓	?	-	-	-	-

Preliminary detections

	G12.21	G12.91	G19.61	G31.41	G34.3	W3	W75N	NGC 1333 IRAS 4A	L1448 MM-1	GCM+ 0.693
H ₂ O	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
N ₂ H ⁺	✓	✓	✓	✓	✓	✓	✓	✓	-	✓
H ₂ S	✓	✓	✓	✓	✓	✓	-	-	-	-
NO	-	✓	✓	✓	✓	✓	✓	-	-	?
C ³⁴ S	-	✓	✓	✓	✓	✓	-	-	-	-
SO ₂	?	✓	✓	-	✓	✓	✓	-	-	-
³⁴ SO	-	✓	-	-	✓	✓	✓	-	-	-
HCN	-	-	-	-	✓	✓	✓	-	✓	-
HCO ⁺	-	-	-	-	✓	✓	✓	-	-	-
³⁴ SO ₂	-	✓	✓	?	✓	-	-	-	-	-
HDO	-	-	✓	-	✓	✓	-	-	-	-
NS	-	-	✓	-	✓	-	-	-	-	-

Methanol (CH₃OH)

Source	$\log_{10}N_T \text{ (cm}^{-2}\text{)}$	Temperature (K)
G12.21	14.24 ± 0.01	99.66 ± 2.2
G12.91	14.44 ± 0.01	153.48 ± 1.88
G19.61	14.61 ± 0.01	167.56 ± 1.88
G31.41	14.84 ± 0.01	181.49 ± 1.75
G34.3	15.32 ± 0.003	180.24 ± 0.84
W3	15.01 ± 0.002	107.27 ± 0.39
W75N	14.61 ± 0.004	98.48 ± 0.68
NGC 1333 IRAS 4A	13.93 ± 0.02	80.76 ± 3.01
L1448MM-1	-	-
GCM+0.693	-	-

Methanol (CH₃OH)

Source	This Work		CSO ¹	
	$\log_{10}N_T$ (cm ⁻²)	Temp. (K)	$\log_{10}N_T$ (cm ⁻²)	Temp. (K)
G12.91	14.44 ± 0.01	153.48 ± 1.88	14.95 ± 0.01	178.20 ± 4.79
			14.98 ± 0.01	13.89 ± 0.19
G19.61	14.61 ± 0.01	167.56 ± 1.88	15.25 ± 0.01	176.85 ± 2.99
			14.61 ± 0.01	14.29 ± 0.42
G31.41	14.84 ± 0.01	181.49 ± 1.75	15.57 ± 0.01	268.05 ± 4.63
			15.08 ± 0.01	38.41 ± 0.45
G34.3	15.32 ± 0.003	180.24 ± 0.84	15.84 ± 0.00	190.17 ± 1.55
			15.36 ± 0.00	16.46 ± 0.17
W3	15.01 ± 0.002	107.27 ± 0.39	15.24 ± 0.01	151.50 ± 1.72
			15.24 ± 0.01	149.92 ± 1.29
			14.96 ± 0.00	16.74 ± 0.12
W75N	14.61 ± 0.004	98.48 ± 0.68	15.50 ± 0.01	206.76 ± 2.89
			15.17 ± 0.00	19.18 ± 0.19

Methanol (CH₃OH)

Source	This Work		CSO ¹	
	log ₁₀ N _T (cm ⁻²)	Temp. (K)	log ₁₀ N _T (cm ⁻²)	Temp. (K)
G12.21	14.24 ± 0.01	99.66 ± 2.2	14.93 ± 0.01	161.98 ± 3.57
			14.98 ± 0.00	15.76 ± 0.17
NGC 1333 IRAS 4A	13.93 ± 0.02	80.76 ± 3.01	14.05 ± 0.14	17.64 ± 7.19
			14.71 ± 0.06	16.48 ± 2.65
L1448MM-1	-	-	13.10 ± 0.13	17.71 ± 2.79
GCM+0.693	-	-	15.76 ± 0.00	14.90 ± 0.10

1. Widicus Weaver, S. L., et al. *Astrophys. J. Suppl. Ser.* **2017**, 232, 3.

Formaldehyde (H₂CO)

Source	$\log_{10}N_T \text{ (cm}^{-2}\text{)}$	Temperature (K)
G12.21	12.86 ± 0.05	291.47 ± 42.44
G12.91	13.09 ± 0.02	157.87 ± 7.35
G19.61	13.31 ± 0.03	392.56 ± 32.68
G31.41	13.32 ± 0.02	316.59 ± 17.23
G34.3	13.83 ± 0.01	292.97 ± 8.55
W3	13.57 ± 0.01	124.46 ± 2.02
W75N	13.31 ± 0.01	174.94 ± 4.45
NGC 1333 IRAS 4A	12.77 ± 0.03	127.78 ± 11.41
L1448MM	-	-
GCM+0.693	-	-

Next Steps

- Finish analysis
- Correlate N, T, and molecular diversity with source characteristics (luminosity, mass, distance, etc.)

Next Steps

Source Name	Source Type	v_{lsr} (km s ⁻¹)	Distance (pc)	Luminosity (L _⊙)	Mass (Gas and Dust) (M _⊙)
G12.21	HII region	24.0	13.5 k	<10 ⁶	<14000
G12.91	Hot core	37.5	13.6 k	10 ⁵	>70
G19.61	Hot core	40.0	12.0 k	<2 x 10 ⁵	450
G31.41	Hot core	97.0	7.9 k	~2 x 10 ⁵	~2000
G34.3	Hot core	58.0	3.7 k	~9 x 10 ⁴	7000
W3	Hot core	-47.0	2040	>10 ⁵	26
W75N	Hot core	10.0	1.7 k	<5 x 10 ⁴	<2
NGC 1333 IRAS 4A	Hot corino	6.8	235	7.7	1.1
L1448MM-1	Class o protostar + outflow	0.0	232	11.6	<2
GCM +0.693-0.027	Shocked region	68.0	8.4 k	-	≤0.36

Widicus Weaver, S. L., et al. *Astrophys. J. Suppl. Ser.* **2017**, 232, 3.
Zeng, S., et al. *Mon. Notices Royal Astron. Soc.* **2020**, 497, 4896-4909.

Acknowledgements



The Widicus Weaver
Group

NASA ROSES SSW:
80NSSC18M0053

