Interferometric and single-dish observations of 44, 84 and 95 GHz Class I methanol masers

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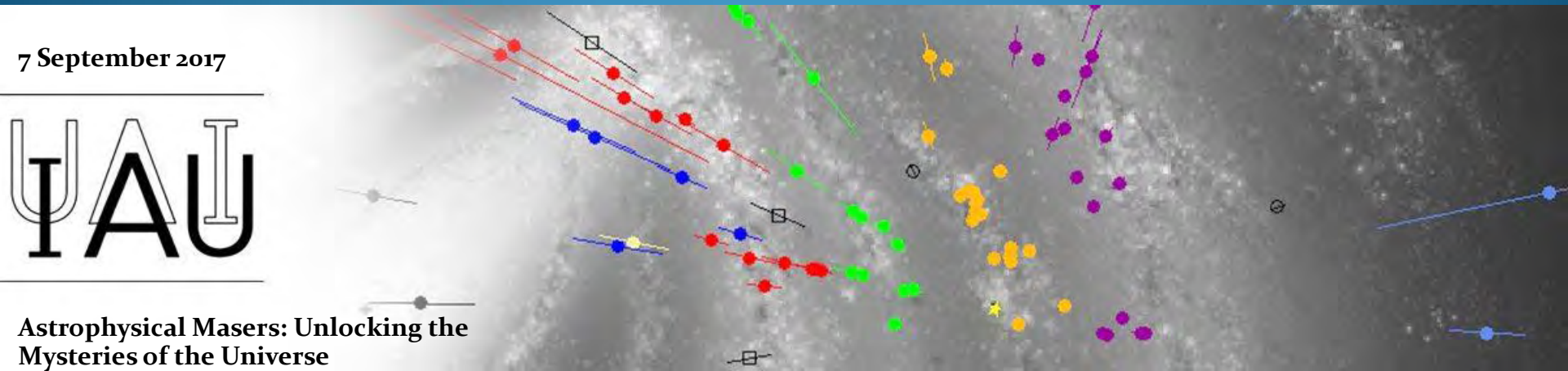

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IAU

Astrophysical Masers: Unlocking the Mysteries of the Universe

Motivation

- Accurately characterize the maser properties of a large sample of sources.
- Search for associations at arcsecond precision with star formation phenomena such as:
  - molecular outflows
  - UCHII regions
  - other maser species

PART I:

Interferometric surveys of 44 GHz Class I methanol masers.



Three northern VLA surveys.

44 GHz methanol maser line

The surveys were made using VLA during 2000, 2007 and 2008.

- 1’ primary beam
- 4” synthesized beam for Survey I
- 2” synthesized beam for Surveys II and III.
- 3σ detection limit of 0.15 Jy
- Spectral resolution of 0.17 km s^{-1}
- Velocity coverage of 21 km s^{-1}

Survey I: Kurtz et al. (2004)

Survey II: Gómez-Ruiz et al. (2016)

Survey III: Rodríguez-Garza et al. (submitted)



VLA surveys of 44 GHz Class I methanol masers.

The heterogeneous sample

Survey I: Kurtz et al. (2004)

- 44 massive star-forming regions.
- Young SFRs from Molinari et al. (1996)
- More-evolved SFRs with compact or UCHII regions from Bachiller et al. (1990), Haschick et al. (1990) and Slysh et al. (1994).

Results:

- 84% detection rate
- 163 masers detected

The homogeneous samples

Survey II: Gómez-Ruiz et al. (2016)

- 69 HMPO candidates of Molinari et al. (1996)
- 32 with colors of UCHII regions; 37 with colors of cold clouds.
- CO outflows in 35 of 69 (Zhang et al. 2005).

Results:

- 40% detection rate
- 95 masers detected

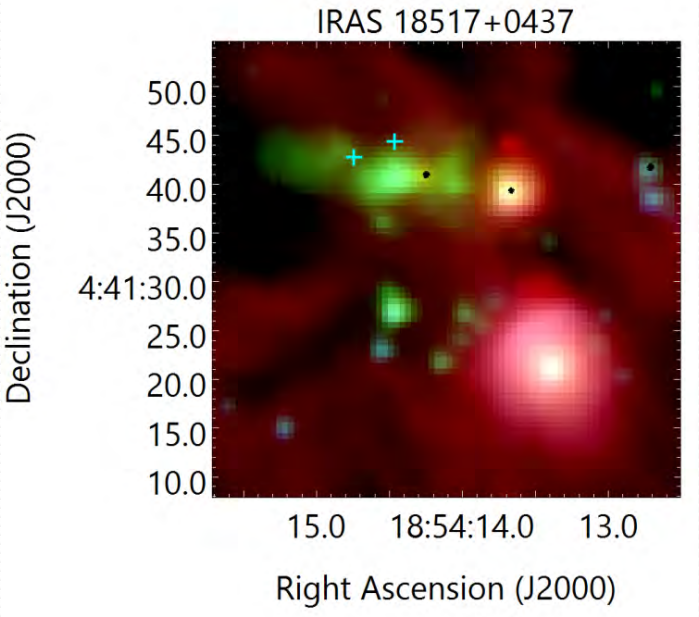
Survey III: Rodríguez-Garza et al. (submitted)

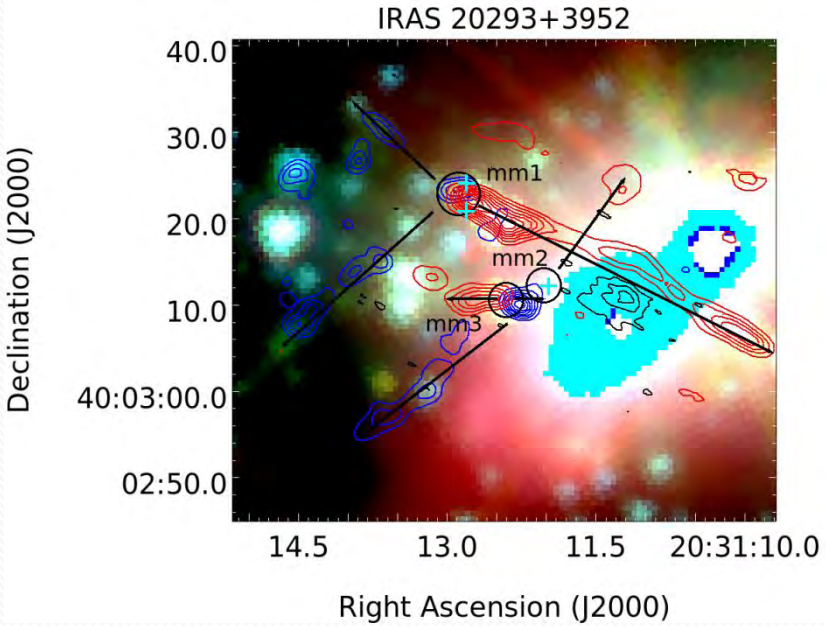
- 56 HMPO candidates of Sridharan et al. (2002)
- Colors of UCHII regions but 5 GHz flux < 25 mJy
- CS emission and 100 μm > 500 Jy
- CO outflows/line wings in 46 of these.

Results:

- 43% detection rate
- 83 distinct masers detected

Survey III results: outflow relation





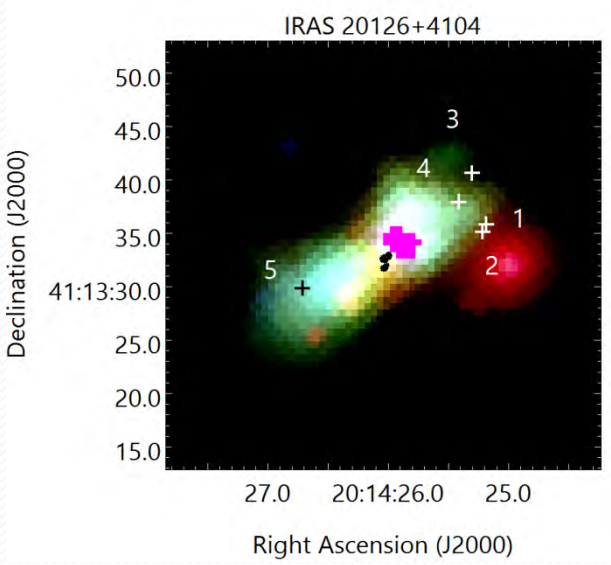
Extended Green Objects
Extended infrared sources with emission **excess at 4.5 μm** (**EGOs**) trace shocked gas (Cyganowski et al. 2008; 2009).

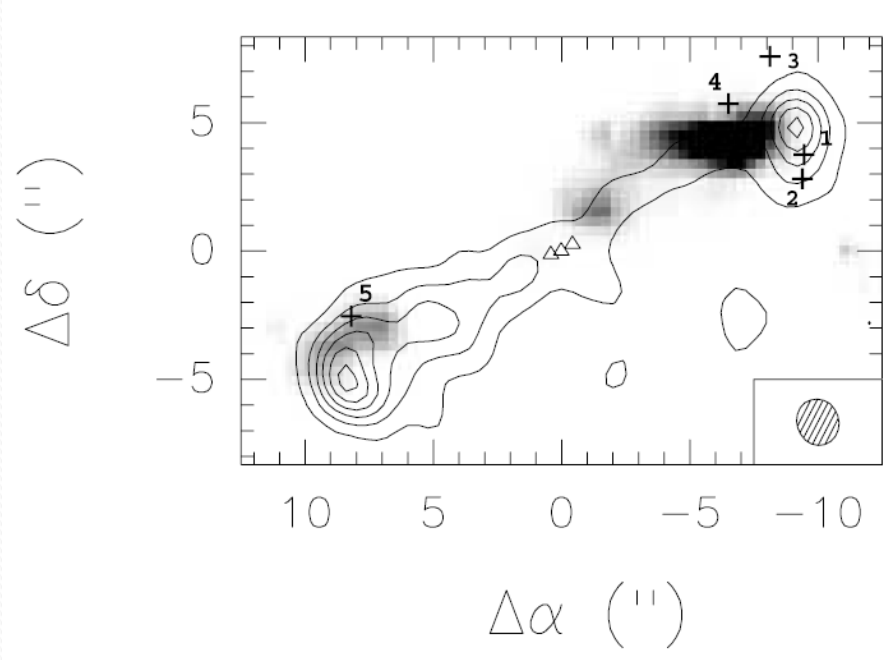
Infrarred Array Camera
Band 1: blue (3.6 μm)
Band 2: green (4.5 μm)
Band 3: red (8.0 μm)

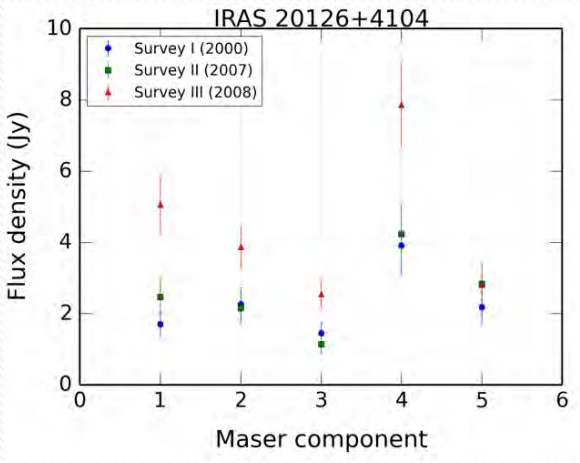
Band 2 contains CO and H_2 lines

Beuther et al. (2004)
Red/Blue contours: CO emission
Black contours: UCHII region

Survey III results: maser variability



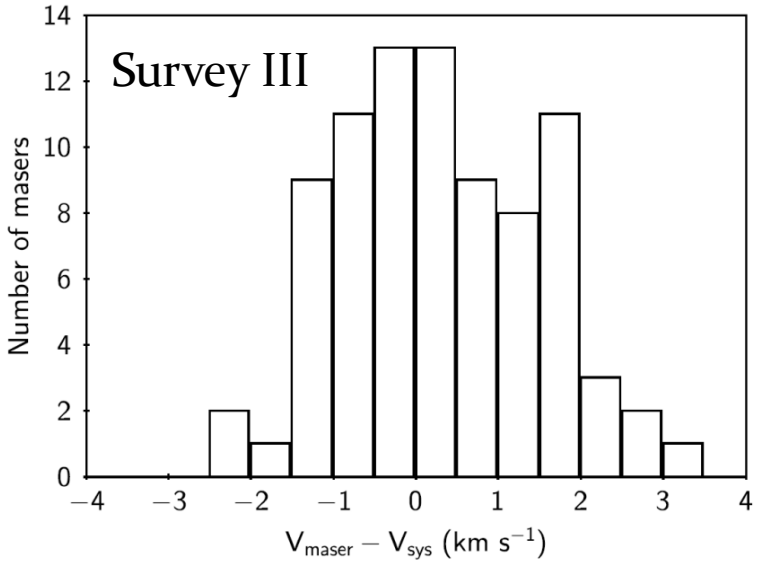


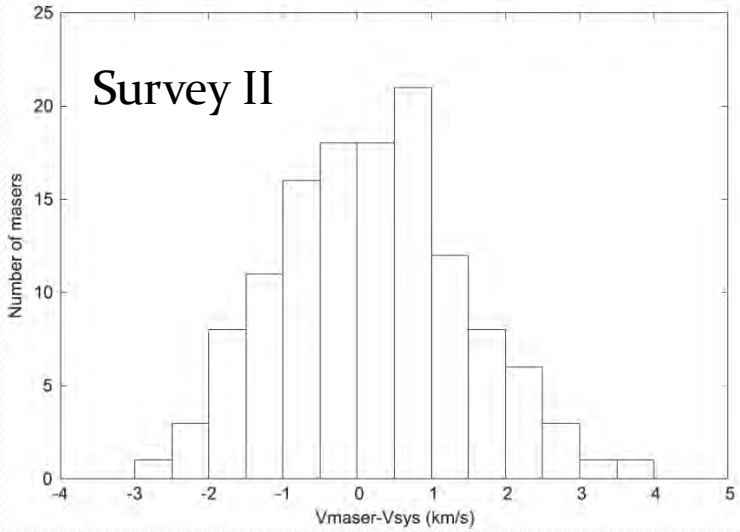


We detect masers ~ 20 Jy toward IRAS 05358+3543 and 18264-1152.

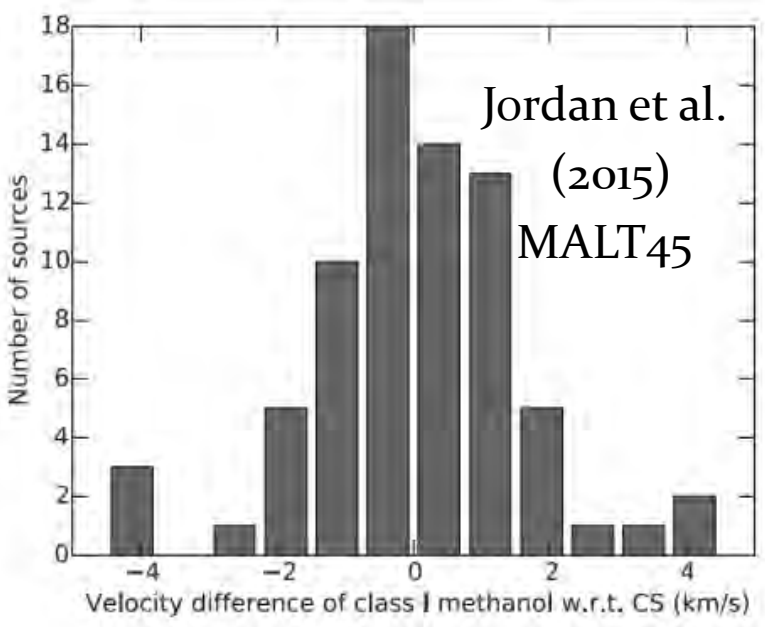
These were *not* detected by Litovchenko et al. (2011) at 1σ noise level of ~ 1 Jy.

Survey III results: velocity distribution





- Maser velocities generally within ±2 km s^{-1} of the HMPO.
- Redshifted masers?



Part II:

Single-dish search for 84 and 95 GHz methanol emission.

Search for 84 and 95 GHz Class I masers.

Large Millimeter Telescope

Surface of 32-m.

Angular resolution: 20" at 90 GHz

Sierra Negra in Mexico, 4600 m altitude

- 38 HMPOs with 44 GHz masers
  - 19 HMPOs from Survey II
  - 19 HMPOs from Survey III



Redshift Search Receiver

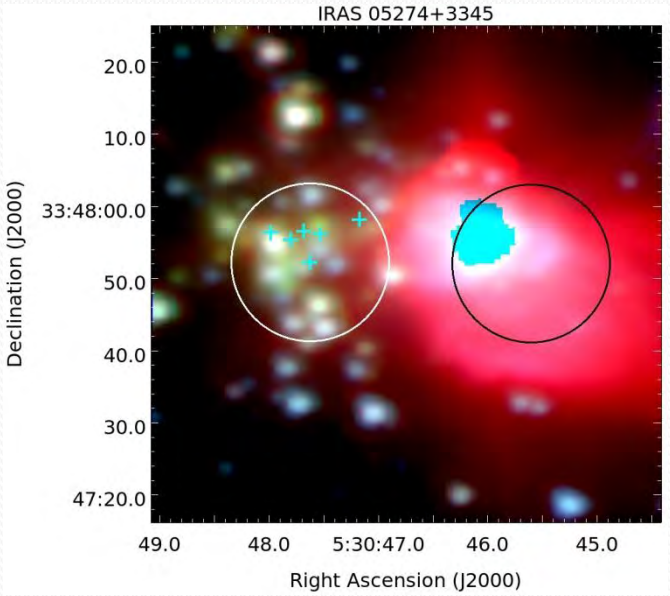
Bandwidth: 73-111 GHz

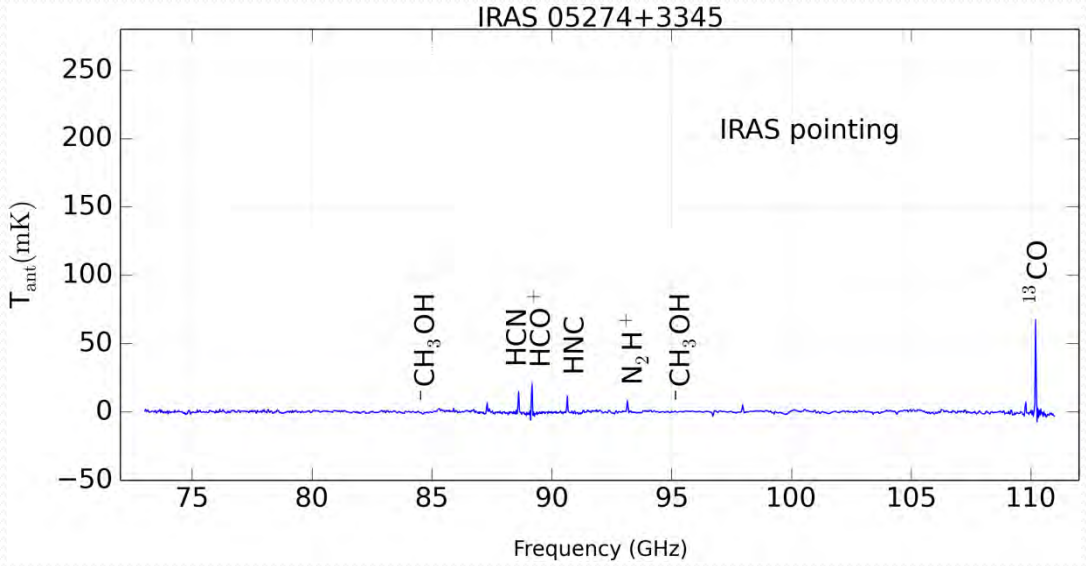
Spectral resolution: 100 km s^{-1}

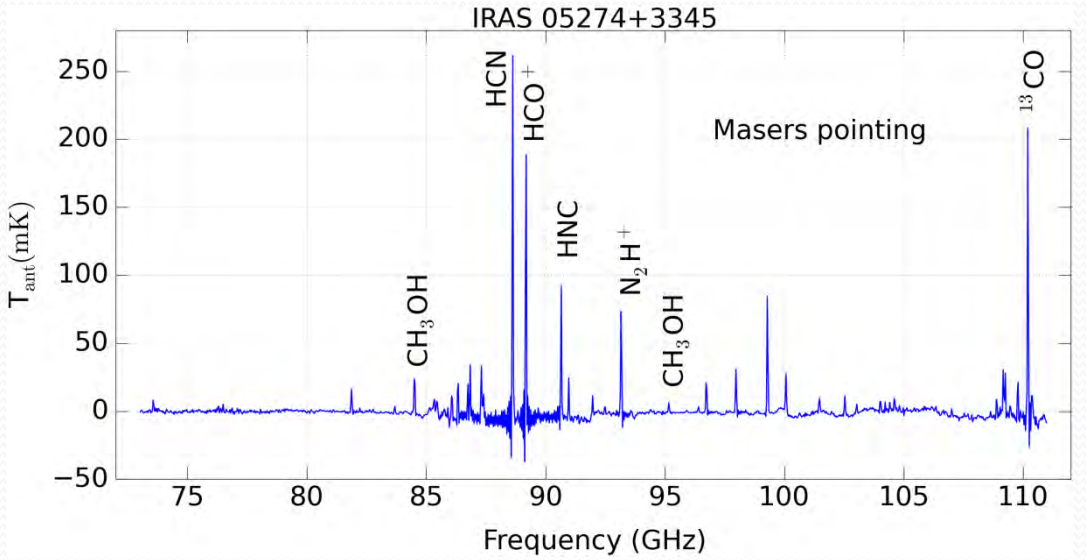


Search for maser candidates

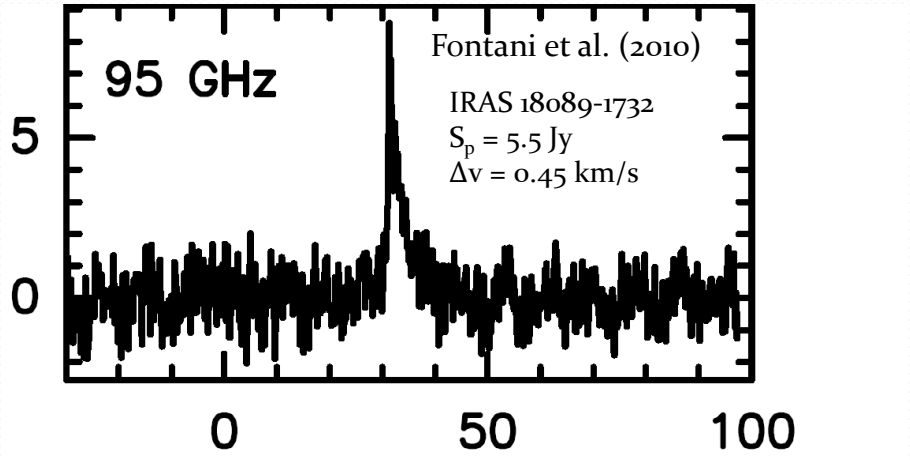
- Low spectral resolution precludes definitive interpretation.
- Data serve to identify promising candidates.

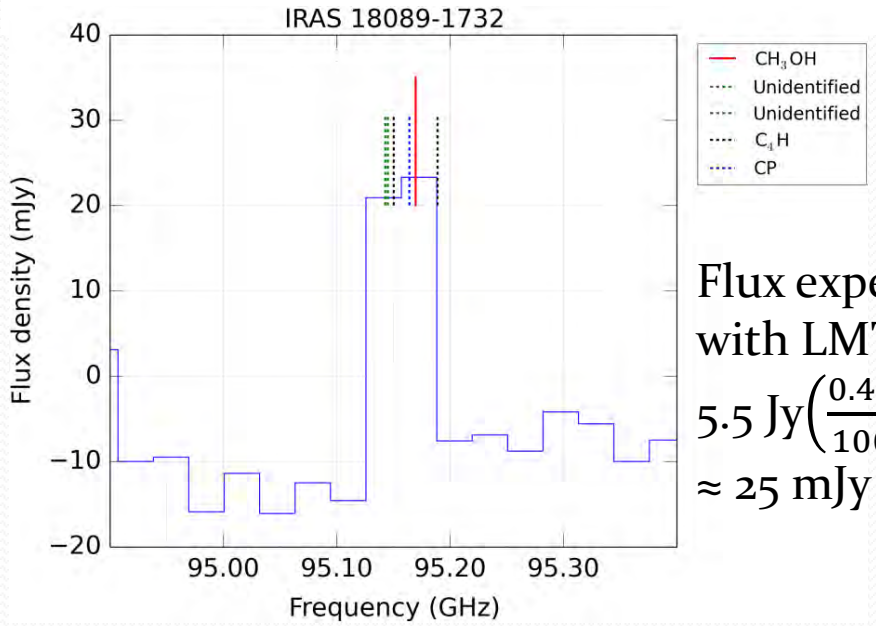






Spectral dilution





Flux expected with LMT:

$5.5\ \text{Jy}\left(\frac{0.45}{100}\right)$

≈ 25 mJy

Detection rates

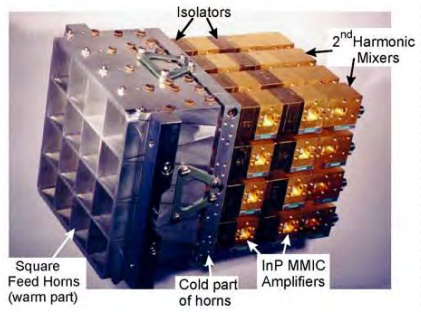
Methanol transitions in the passband	Detection rate
84.5 GHz	74% (28/38)
95.1 GHz	55% (21/38)
96.7 GHz	100% (38/38)
107.0 GHz	3% (1/38)
108.8 GHz	45% (17/38)

100% detection rate in other lines common in MSFRs: HCN, HNC, N_2H^+, HCO^+, ^{13}CO, etc.

Future work

- Statistical analysis of 90 sources with 44 GHz masers detected in Surveys I, II and III.

- Re-observe sources with 84 and 95 GHz masers when LMT surface is complete (50 m) and equipped with better resolution spectrometer.



SEQUOIA
Bandwidth = 85-115 GHz
Spectral resolution = 0.1 – 1.1 km s^{-1}

Thank you

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Spectral Modes:

Mode	Bandwidth (ΔV_B)	Number of Channels (N_{CH})	Resolution
A	200 MHz (600 km/s)	8192	24 kHz (0.072 km/s)
B	400 MHz (1200 km/s)	4096	98 kHz (0.294 km/s)
C	800 MHz (2400 km/s)	2048	391 kHz (1.173 km/s)

** Bandwidth and resolution values in velocity units have been estimated at 100 GHz (midband).

Central frequency = nu0 [GHz] (between 85 - 115 GHz)

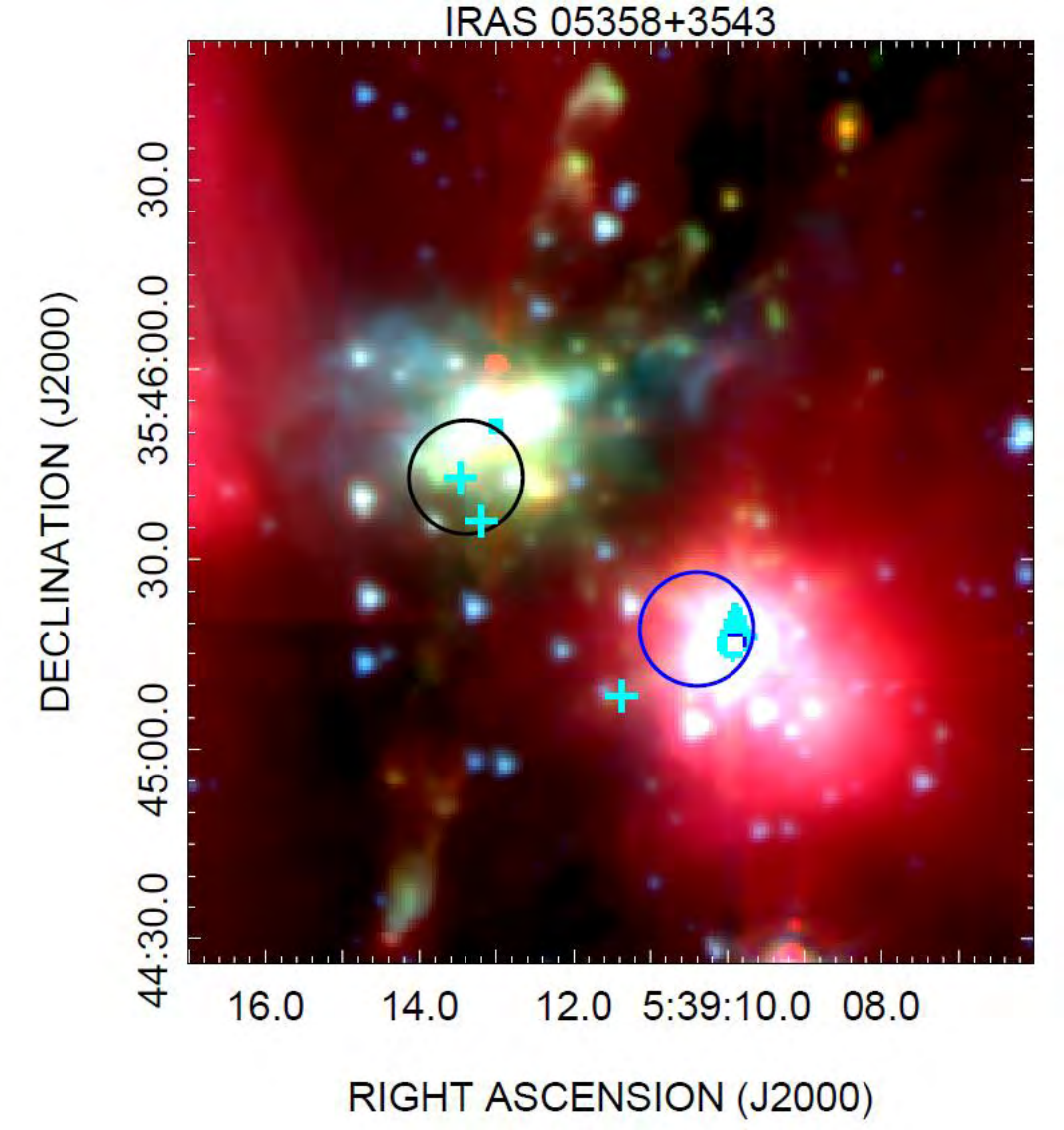
Table 1. LMT observing log for the data taken during the Early Science Phase in 2016.

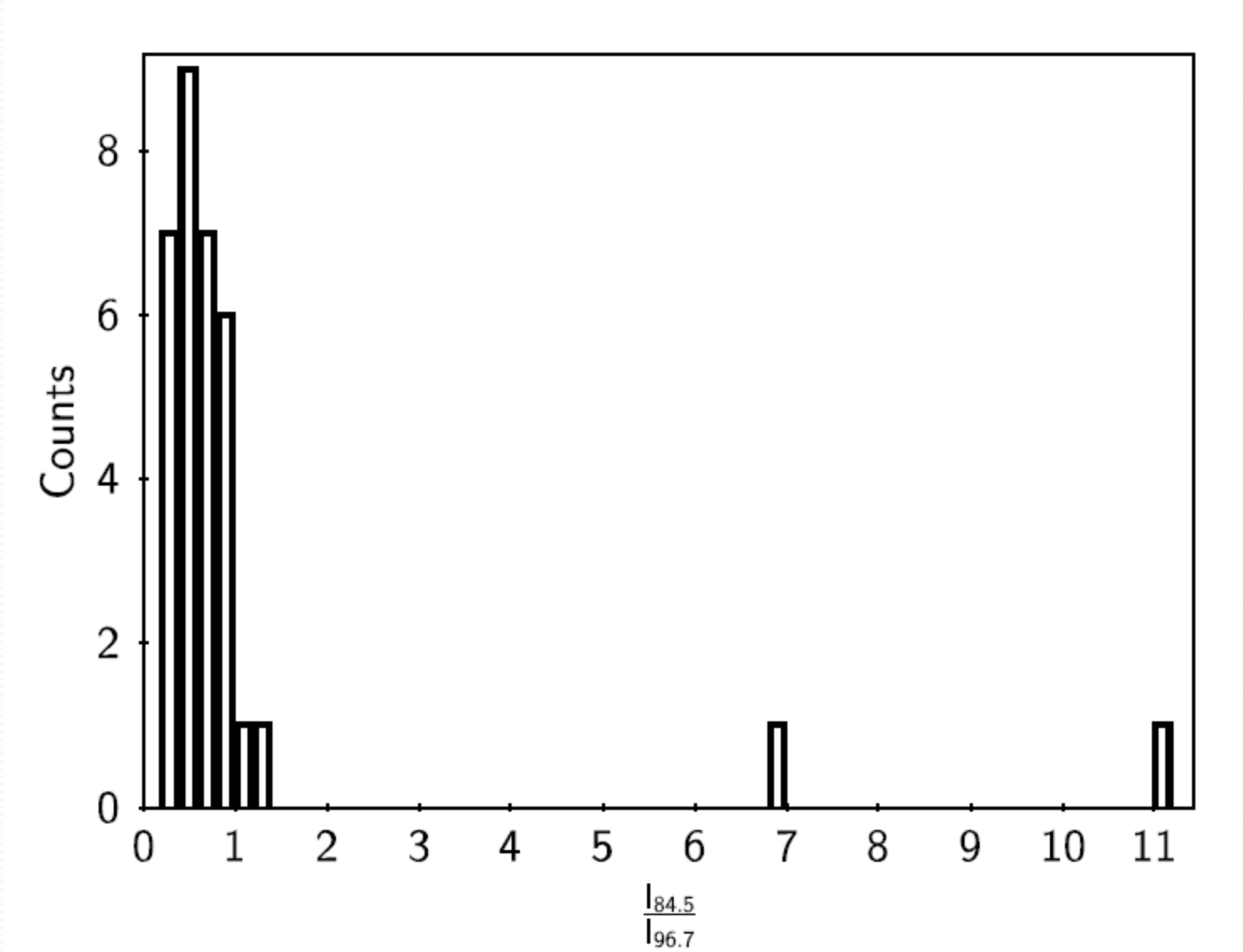
Date 2016	Opacities τ_{225GHz}	T_{sys} K	Elevation degrees	Pointing† calibrators
Feb 11	0.14 – 0.15	102 – 111	30.5 – 46.2	J0533+483
Feb 12	0.06 – 0.07	97	34.3 – 46.0	3C111
Feb 14	0.07 – 0.08	94	49.8 – 64.7	3C111
Mar 18	0.16 – 0.18	100 – 116	27.8 – 55.6	NRAO530
				J1743–038
Apr 10	0.20 – 0.25	102 – 115	36.2 – 63	J1743–038
				J1911–201
Apr 11	0.14	100 – 102	46.1 – 58.0	NRAO530
Apr 12	0.24 – 0.26	102 – 111	41.0 – 80.5	J1751+096
Apr 13	0.20	99 – 100	48.2 – 56.4	NRAO530
Apr 14	0.23 – 0.28	100 – 148	31.2 – 80.3	NRAO530
				J1743–038
				J1751+096
Apr 15	0.24 – 0.32	101 – 115	40.6 – 80.8	J1751+096
Apr 16	0.20 – 0.22	–	63.1 – 72.9	J2023+318
Apr 17	0.26 – 0.29	102 – 105	61.2 – 78.0	J1751+096
				J2015+371

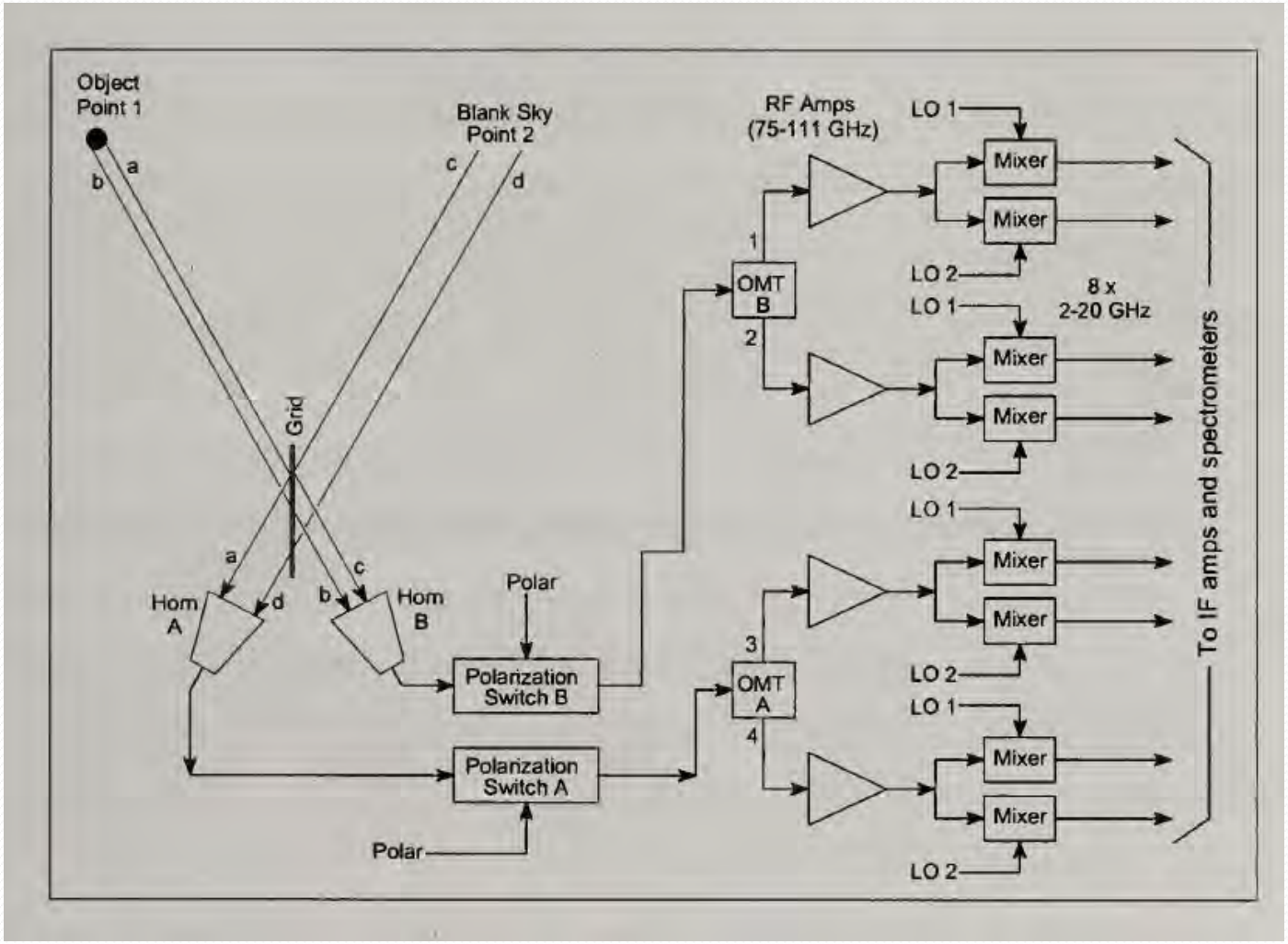
† Typical pointing uncertain for the LMT is 1″.

Table 2. Methanol line transitions in the pass-band.

Transition	Frequency MHz	E_u K	Maser class or Thermal
$5_{-1} \rightarrow 4_0E$	84521.169	40.1	Class I
$6_{-2} \rightarrow 7_{-1}E$	85568.084	74.7	Class II
$7_2 \rightarrow 6_3A^-$	86615.602	102.7	Class II
$7_2 \rightarrow 6_3A^-$	86902.949	102.7	Class II
$8_3 \rightarrow 9_2E$	94541.778	131.1	Class II
$8_0 \rightarrow 7_1A^+$	95169.440	83.6	Class I
$2_{-1} \rightarrow 1_{-1}E$	96739.39	12.6	Thermal
$2_0 \rightarrow 1_0A^+$	96741.42	7.0	Thermal
$2_0 \rightarrow 1_0E$	96744.58	20.1	Thermal
$2_1 \rightarrow 1_1E$	96755.51	28.0	Thermal
$3_1 \rightarrow 4_0A^+$	107013.812	28.3	Class II
$0_0 \rightarrow 1_{-1}E$	108893.948	13.1	Class II


IRAS 05358+3543
DECLINATION (J2000)
30.0
35:46:00.0
30.0
45:00.0
44:30.0
16.0
14.0
12.0
5:39:10.0
08.0
RIGHT ASCENSION (J2000)


Counts
0
2
4
6
8
0
1
2
3
4
5
6
7
8
9
10
11
$\frac{I_{84.5}}{I_{96.7}}$


Object
Point 1
Blank Sky
Point 2
a
b
c
d
Grid
Hom
A
Hom
B
Polar
Polarization
Switch B
Polarization
Switch A
Polar
OMT
B
OMT
A
1
2
3
4
RF Amps
(75-111 GHz)
LO 1
LO 2
Mixer
8 x
2-20 GHz
To IF amps and spectrometers