Studies of Methanol Masers with ATNF Facilities

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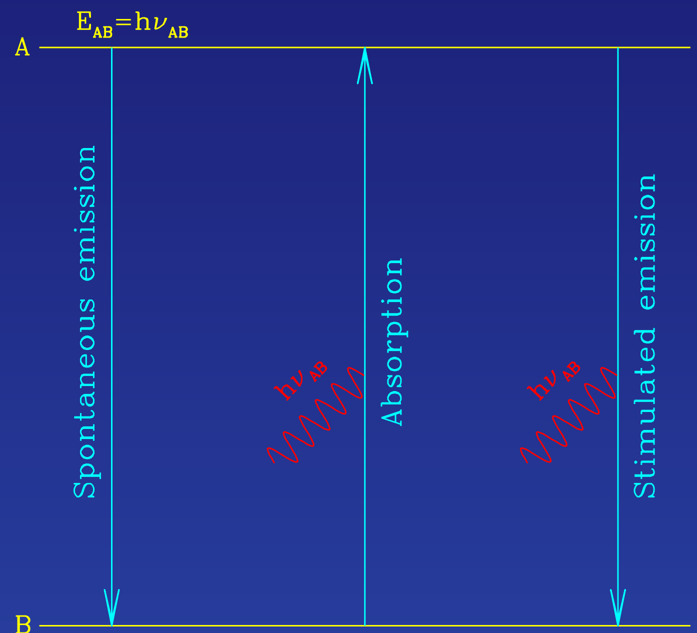
- What is a maser?
  - A spectral line formed under special conditions (population inversion)
  - Strong masers have narrow lines
  - High brightness temperature



- Maser action is possible in a limited number of molecular transitions
- In general, it is harder to create a maser at high frequency (ALMA is unlikely to find many new masers)
- Different masers have different behavior, a presence of a particular maser says something about physical conditions
- Bright masers are often used as tools (e.g. to locate regions of star-formation, to measure the parallax, to be a calibrator source, etc)

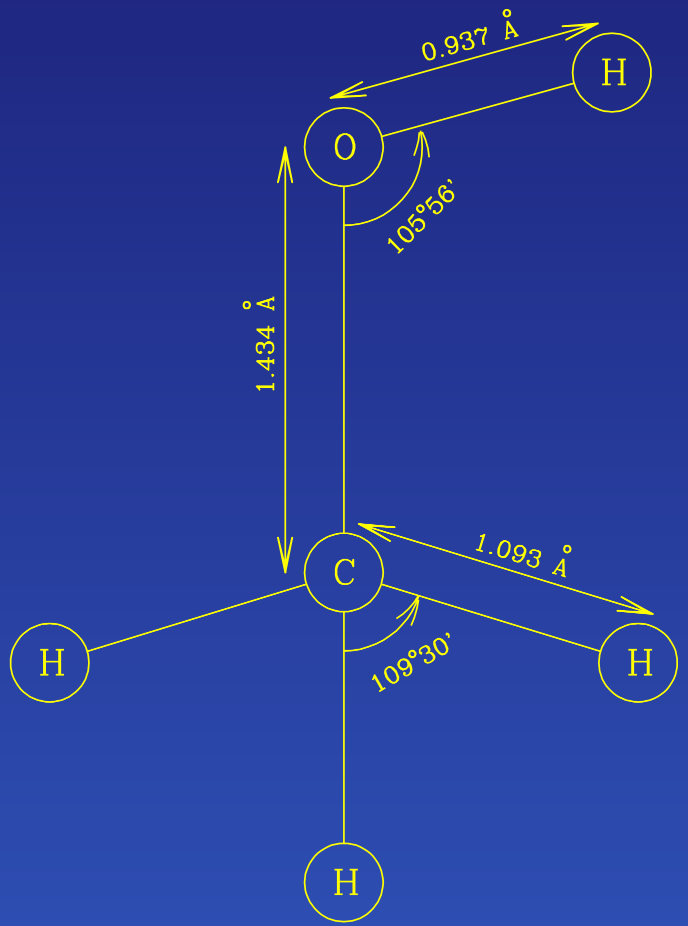
Where do we find masers?

- Star-forming regions in our Galaxy
  - High-mass (OH, H_2O, methanol (both classes), NH_3, a few SiO)
  - Low- and intermediate-mass (OH, H_2O, class I methanol)
- Supernova remnants (OH)
- Late-type stars and circumstellar environment (OH, H_2O, SiO, SiS, probably HCN)
- Extragalactic masers

  (also known as kilomasers, megamasers, etc)
  - Star-forming regions in LMC (OH, H_2O, class II methanol)
  - Late-type stars in LMC (SiO, OH)
  - Star-forming regions in other galaxies (OH, H_2O)
  - galactic nuclei (H_2O)

I will concentrate on methanol masers...

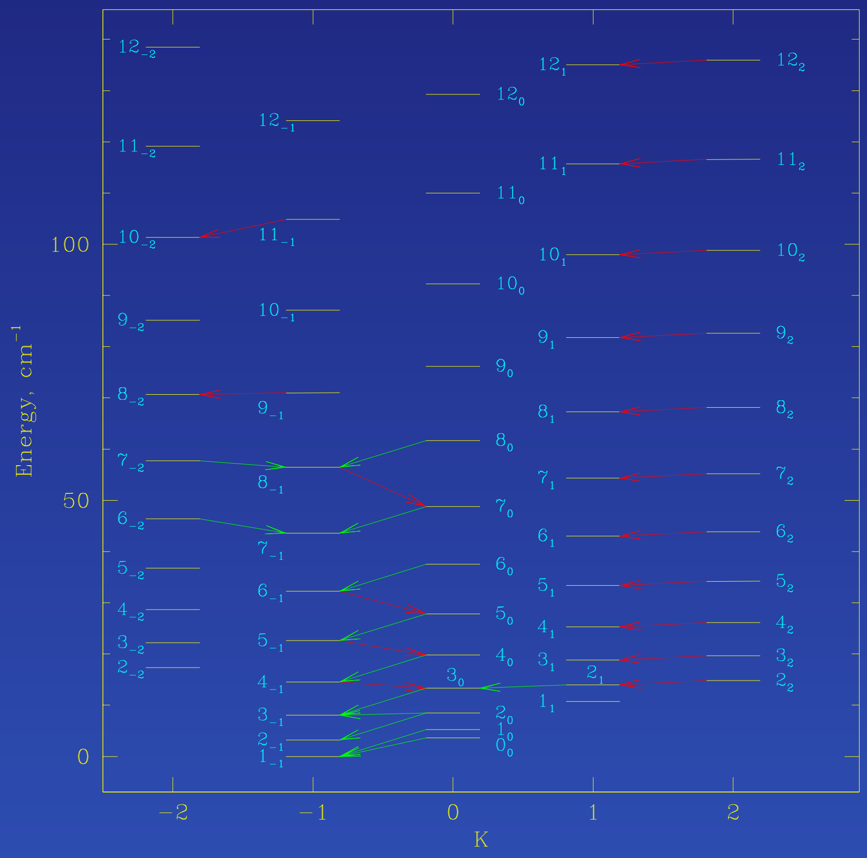
Why methanol is so exciting?



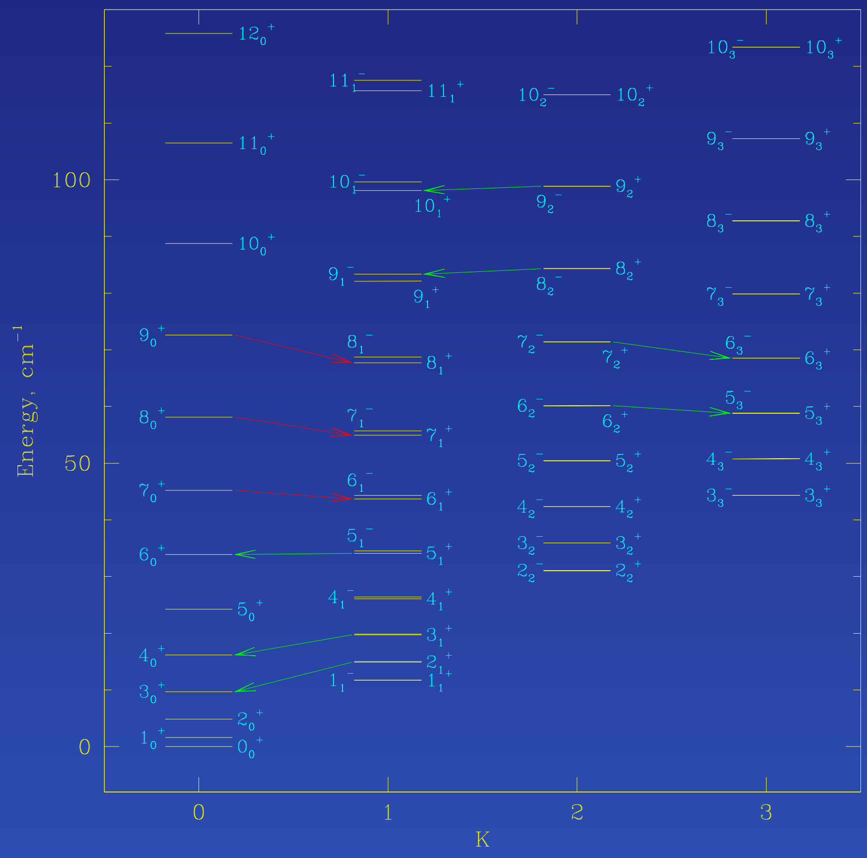
- Large number of observed transitions
  - with a different behavior
- Some masers are very strong (second strongest after H_2O masers)
  - good VLBI targets
- Masers are more stable than H_2O masers
  - monitoring is getting easier
- Simplest organic molecule
  - links with astrochemistry

Energy levels of methanol

E-methanol



A-methanol



$\Delta J = 0, \pm 1$; $\Delta K = \pm 1$

$\Delta J = \pm 1$; $\Delta K = 0$

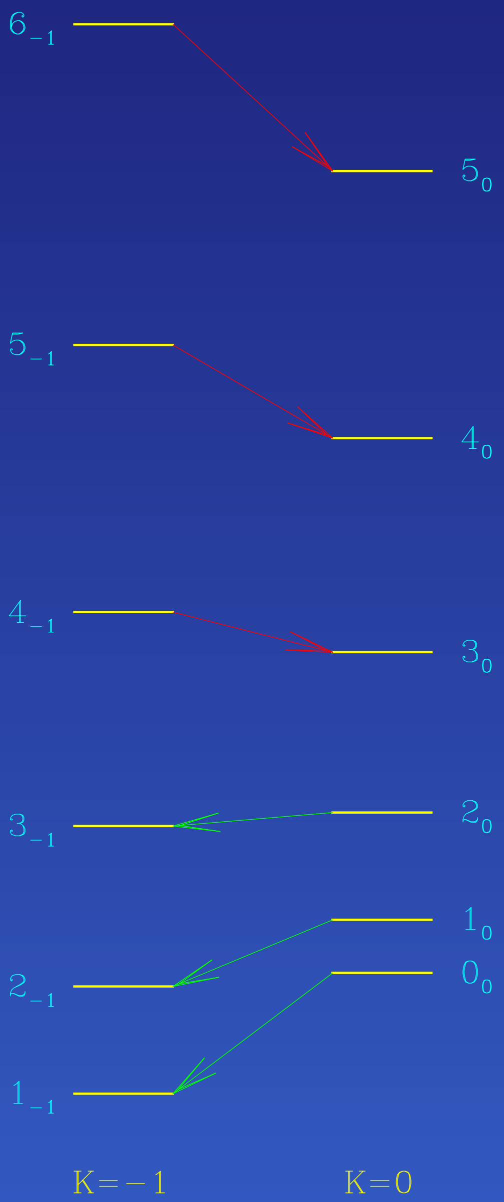
$J_{-2} - J_1$ series at $\sim$ 101 GHz

$\Delta J = 0, \pm 1$; $\Delta K = \pm 1$; $A^{\pm} \leftrightarrow A^{\pm}$

$\Delta J = \pm 1$; $\Delta K = 0$; $A^{\pm} \leftrightarrow A^{\pm}$

$\Delta J = 0$; $\Delta K = 0$; $A^{\pm} \leftrightarrow A^{\mp}$

Pumping



- Class I masers $\Rightarrow$ collisional pumping
- Class I| masers $\Rightarrow$ pumping by the dust radiation
- Strong masers of different classes should never co-exist in the strict theoretical sense (or co-propagate in other words)
- Masers of different classes are often present in the same star-forming region at some distance from each other. A projection to the same apparent direction is also possible
- The case of weak masers requires a special study

Known Class I maser transitions

Transition	Frequency GHz	Reference
• $9_{-1}-8_{-2}$ E	9.9	Slysh et al. (1993)
• J_2-J_1 E series	$>$24.9	Barrett et al. (1971); Menten et al. (1986)
• $4_{-1}-3_0$ E	36	Turner (1972)
• 7_0-6_1 A^+	44	Haschick et al. (1990)
• $5_{-1}-4_0$ E	84	Zuckerman et al. (1972)
• 8_0-7_1 A^+	95	Ohishi et al. (1986)
• $11_{-1}-10_{-2}$ E	104	Voronkov et al. (2005)
• $6_{-1}-5_0$ E	133	Slysh et al. (1997)
• 9_0-8_1 A^+	146	Menten (1991a)
• $8_{-1}-7_0$ E	229	Slysh et al. (2002)

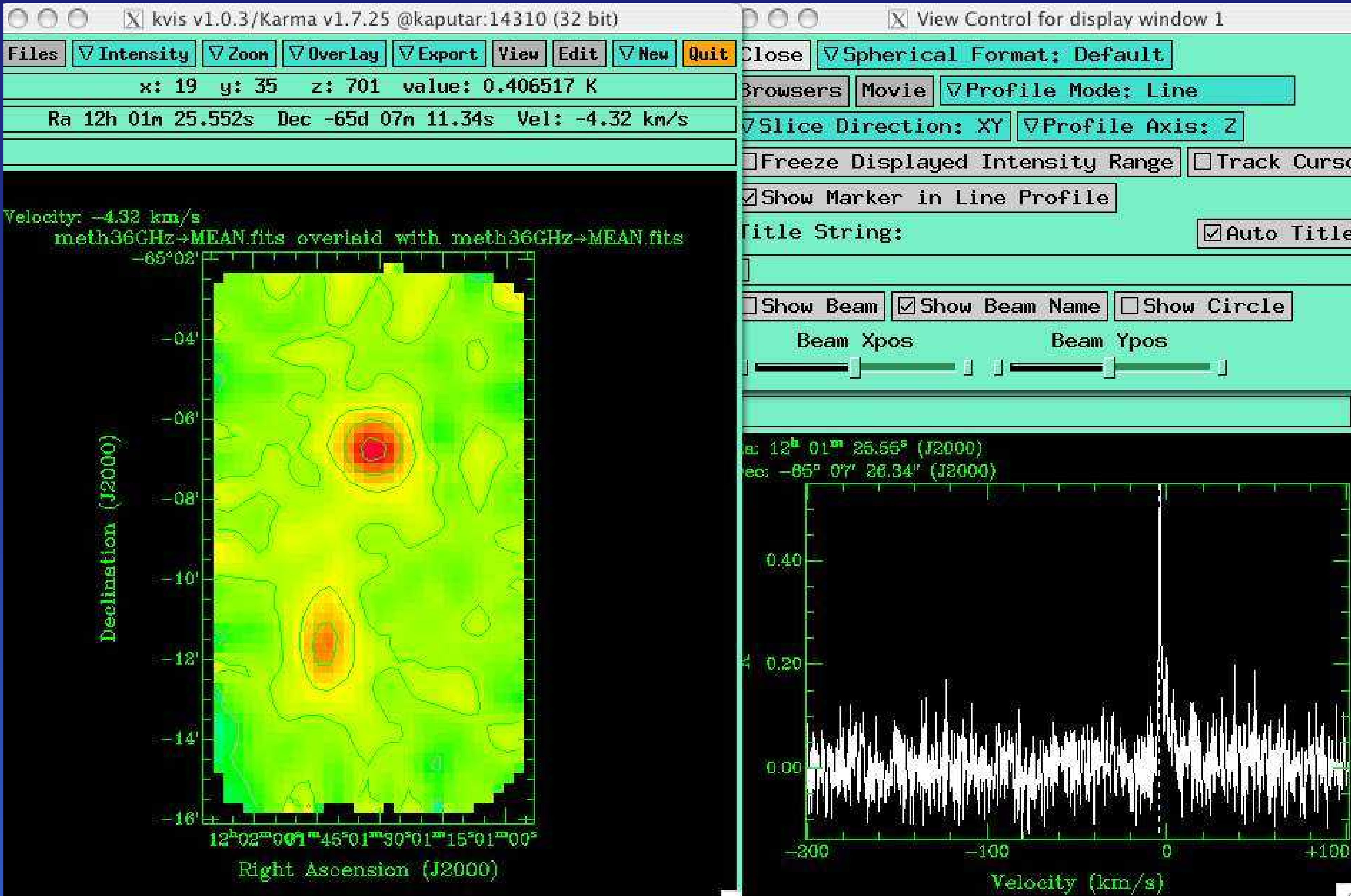
Known Class II maser transitions

Transition	Frequency, GHz	Reference
$5_1 - 6_0$ A$^+$	6.7	Menten (1991b)
$2_0 - 3_{-1}$ E	12.2	Batrla et al. (1987)
$2_1 - 3_0$ E	19.9	Wilson et al. (1985)
$9_2 - 10_1$ A$^+$	23.1	Wilson et al. (1984)
$8_2 - 9_1$ A$^-$	28.9	Wilson et al. (1993)
$7_{-2} - 8_{-1}$ E	37.7	Haschick et al. (1989)
$6_2 - 5_3$ A$^-$	38.2	Haschick et al. (1989)
$6_2 - 5_3$ A$^+$	38.4	Haschick et al. (1989)
$6_{-2} - 7_{-1}$ E	85.5	Cragg et al. (2001)
$7_2 - 6_3$ A$^-$	86.6	Cragg et al. (2001)
$7_2 - 6_3$ A$^+$	86.9	Cragg et al. (2001)
$3_1 - 4_0$ A$^+$	107	Val'tts et al. (1995)
$0_0 - 1_{-1}$ E	108	Val'tts et al. (1999)
$2_1 - 3_0$ A$^+$	156.6	Slysh et al. (1995)
$J_0 - J_{-1}$ E series	$\sim$157	Slysh et al. (1995)

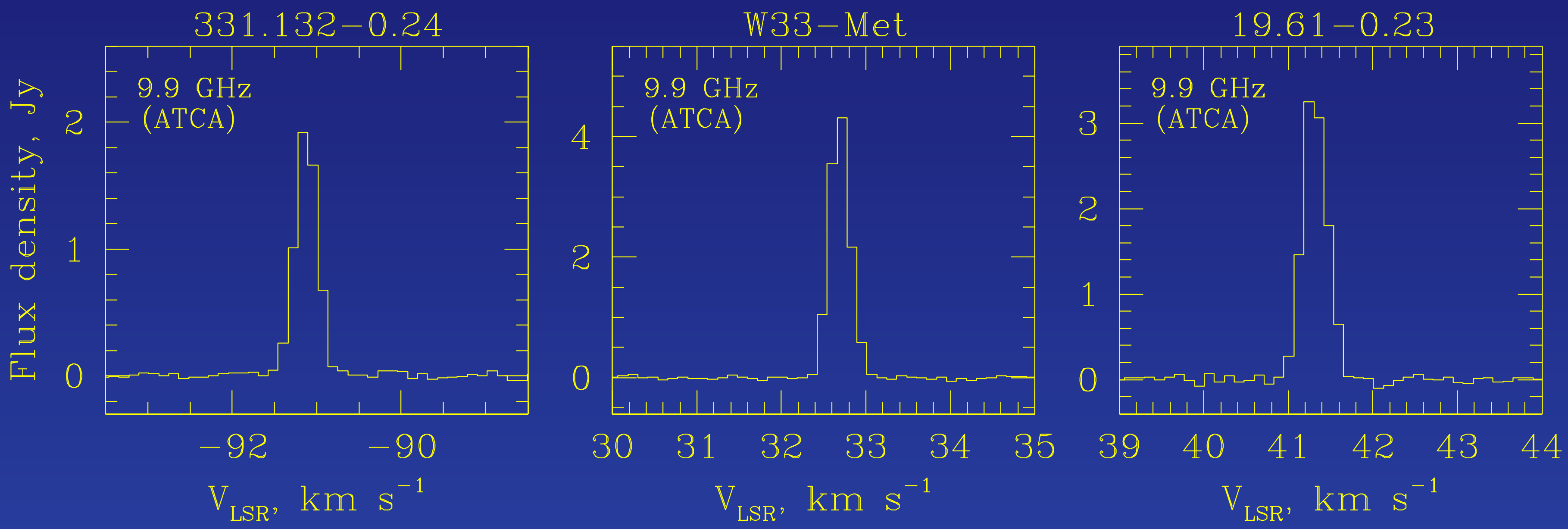
Science: searches for new masers

- Widespread transitions
  - I 1. Active project: search towards low-mass star-forming regions.
    2. Active project: 95 and 84 GHz search (Ellingsen et al.)
  - II Mostly masers appearing under unusual circumstances
    1. Voronkov et al. 2005, MNRAS, 362, 995 – 6.7 GHz in Orion,
    2. Minier et al. 2003, A&A, 403, 1095 – 6.7 GHz towards low-mass star-forming regions
- Blind surveys
  - I 1. Active project: Mopra untargeted survey (Pratap et al.)
  - II 2. Active project: 6.7 GHz - Methanol multibeam (Green et al.)
- Rare/weak masers
  - I 1. Active projects: 9.9, 25 and 104 GHz search (Voronkov et al.)
  - II 1. Ellingsen et al. 2003, MNRAS, 344, 73 – 85.5 and 86.6 GHz,
    2. Ellingsen et al. 2004, MNRAS, 354, 401 – 19.9 GHz,
    3. Cragg et al. 2004, MNRAS, 351, 1327 – 23.1 GHz

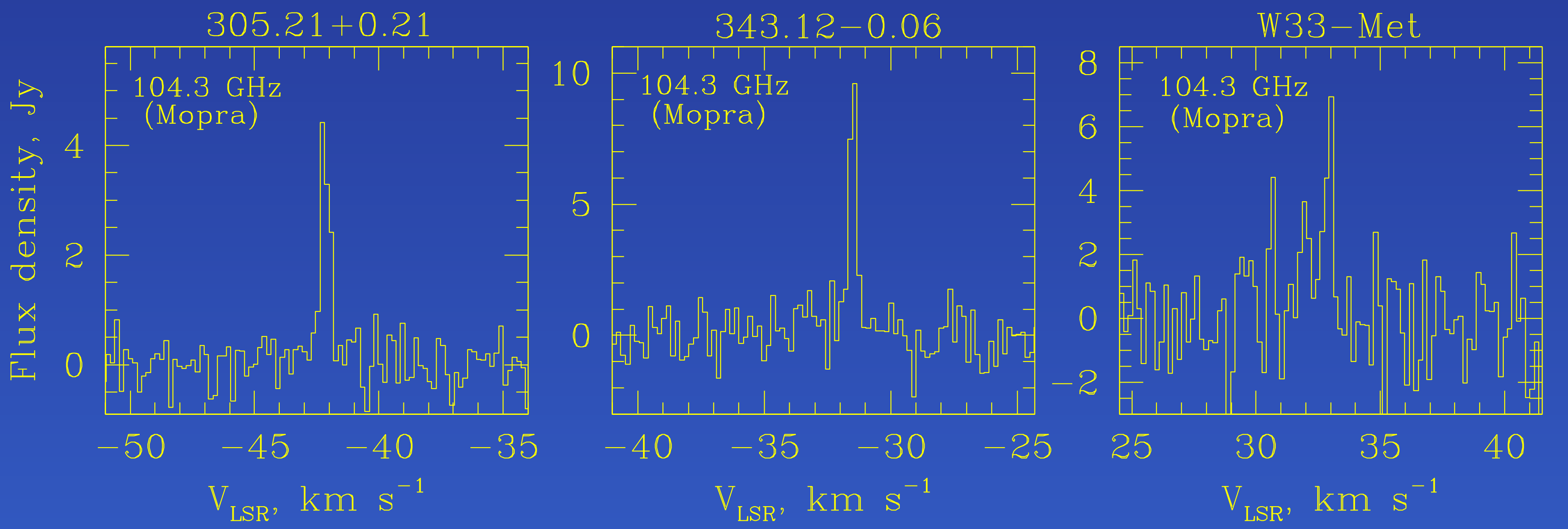
Search towards low-mass star-forming regions at 36 and 44 GHz: BHR71



Searches for 9.9 and 104 GHz masers

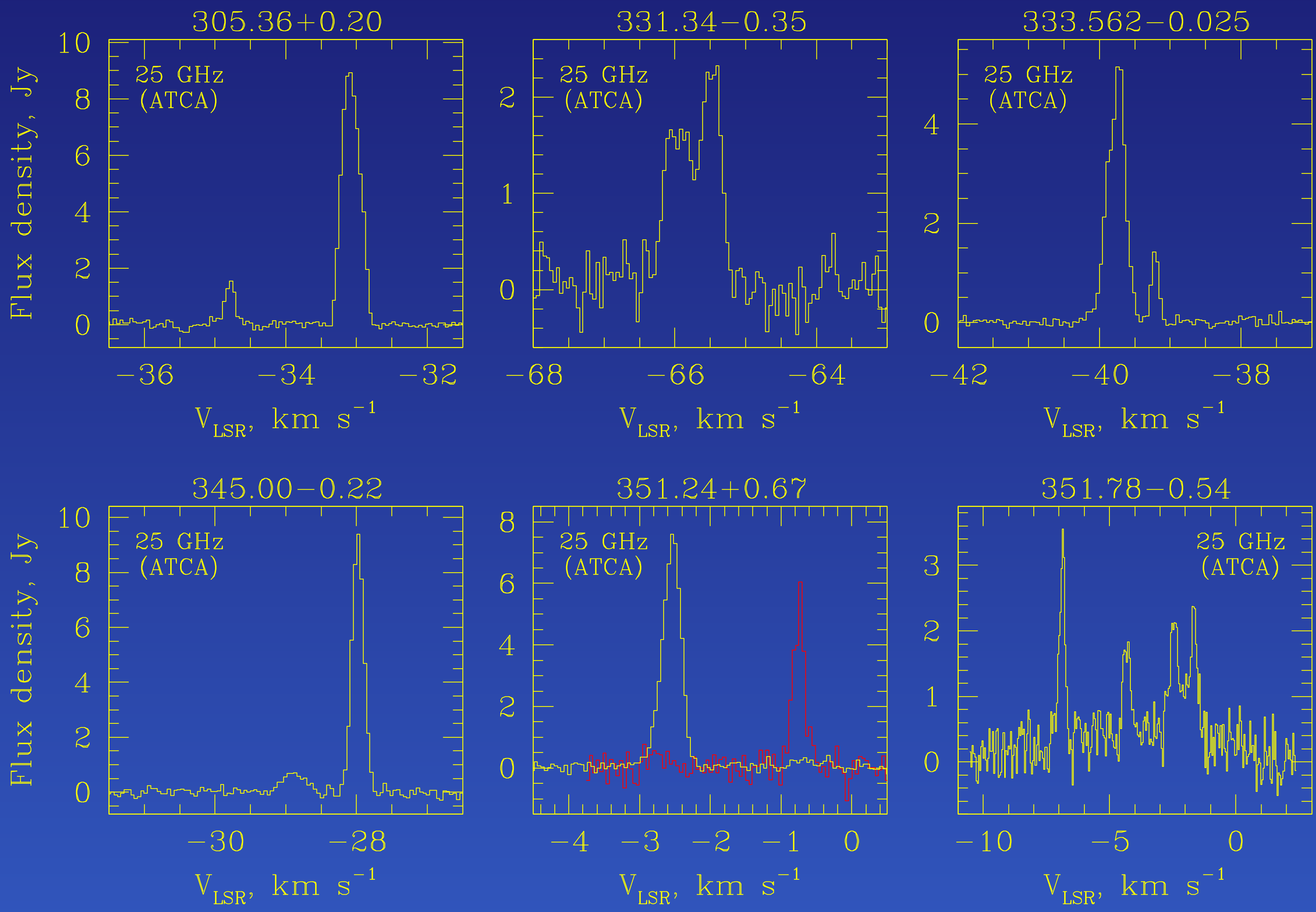


3 out of 47



3 masers +
3 thermal,
out of 69

Search for 25 GHz masers



thought to be rare

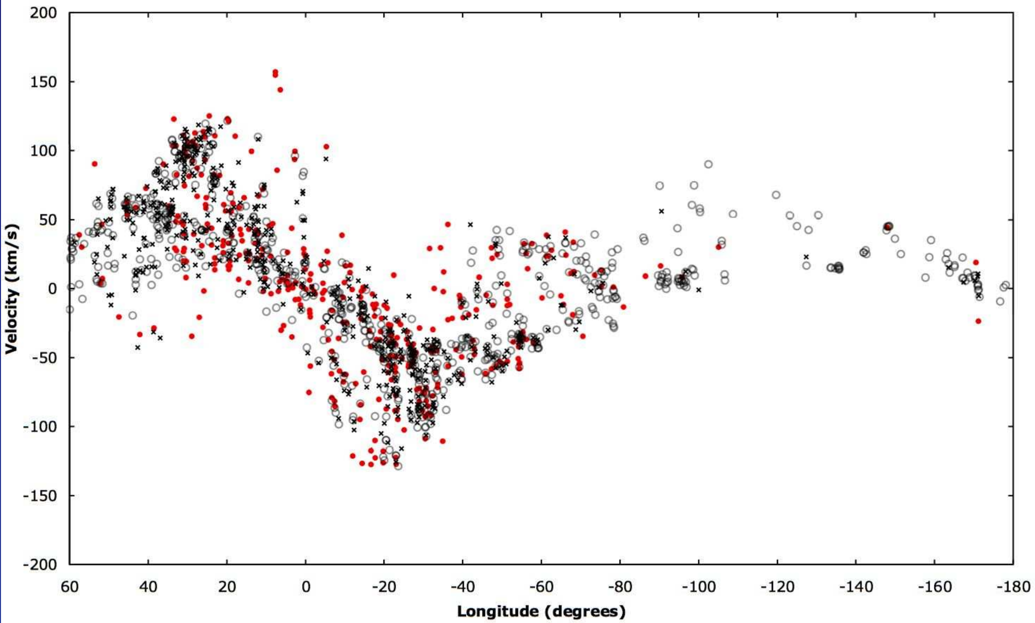
67 masers out of 102 targets

Methanol multi-beam project

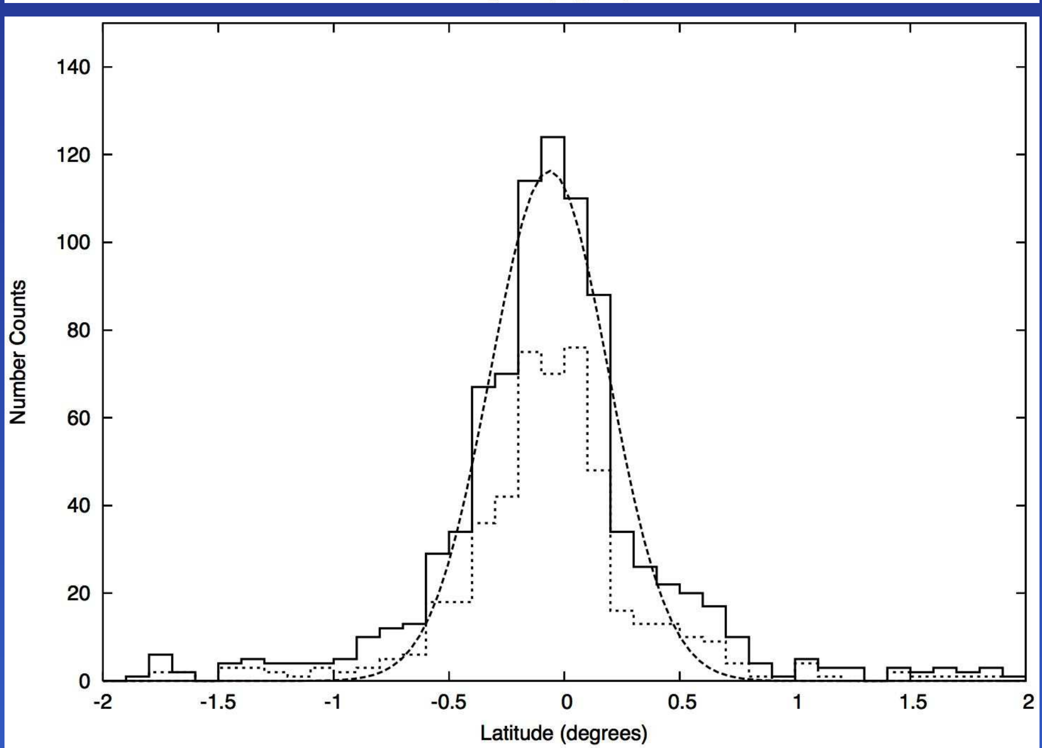
- Unbiased survey of the Galactic plane (l from -174 to $+60$ degrees, b from -2 to $+2$ degrees) at 6.7 GHz
- Census of the massive star formation in the Galaxy
- LMC and SMC observed when the galactic plane was not visible
- In total, 941 detection, 567 known and 374 new masers
- Completeness about 80% $\Rightarrow$ in line with population estimate of 1200 sources.
- Overall detection rate 0.9 sources per deg^2
- Magellanic Clouds part is published: Green et al. , 2008, MNRAS, 385, 948, techniques paper accepted (Green et al.)
- Future plans/priorities:

  Galactic centre (most likely -15 to $+20$ degrees)
  Northern region (latitude $+20$ to $+40$ degrees)
  The rest of the southern sky

Methanol multi-beam project



- Velocity versus longitude
- Red dots – new detections,
- Black dots – previously known sources
- Open circles – CS 2–1 emission sources (Bronfman et al.,1996)



- Latitude distribution
- Solid histogram– all sources,
- Dashed histogram – previously known sources
- Gaussian fit has FWHM of 0.6 degrees

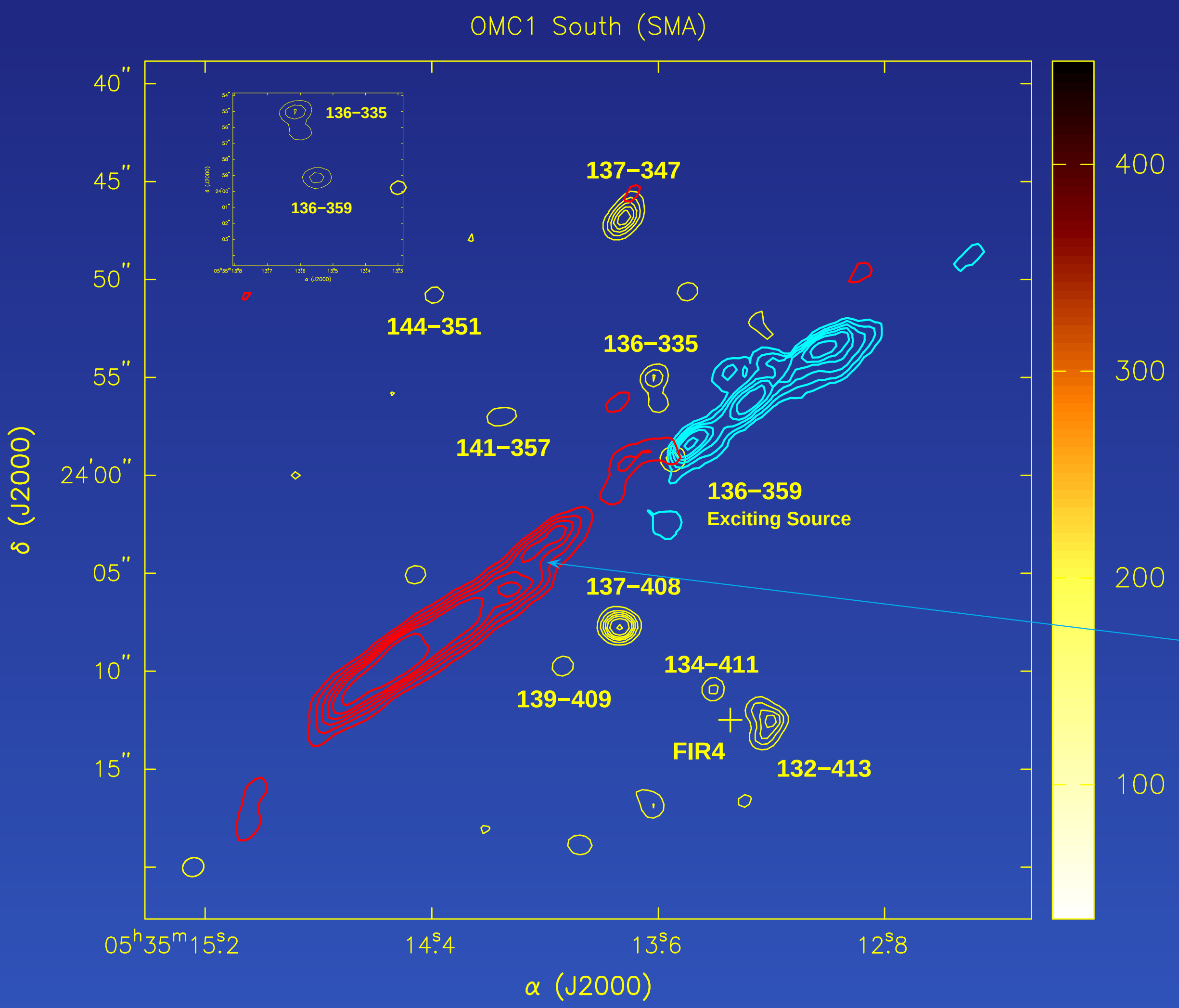
Science: Absolute positions

- VLBI astrometry
  - Parallaxes, proper motions
  - Structure of class II masers
- ATCA resolution is enough to search for identification with other phenomena in star-forming regions
  - Accurate positions for rare masers
  - Search for association of class I masers with shocks/outflows
  - Such search is largely limited now by images of the shock tracers, as more and more masers have their accurate positions measured

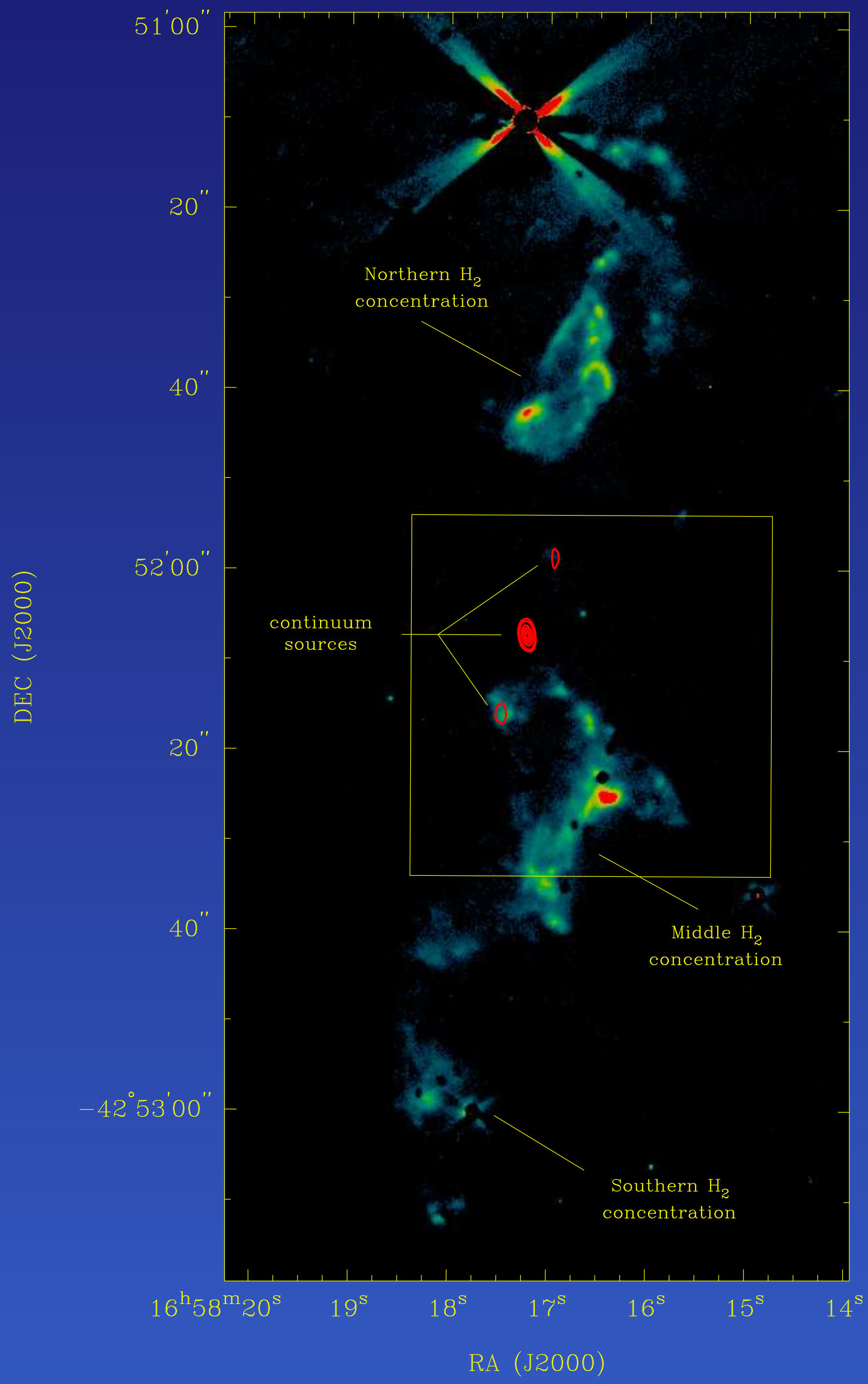
$\Downarrow$

- Thermal environment of methanol masers
  - This is also important for modelling (state of quiescent gas surrounding the maser)

Example: class II maser in Orion-South

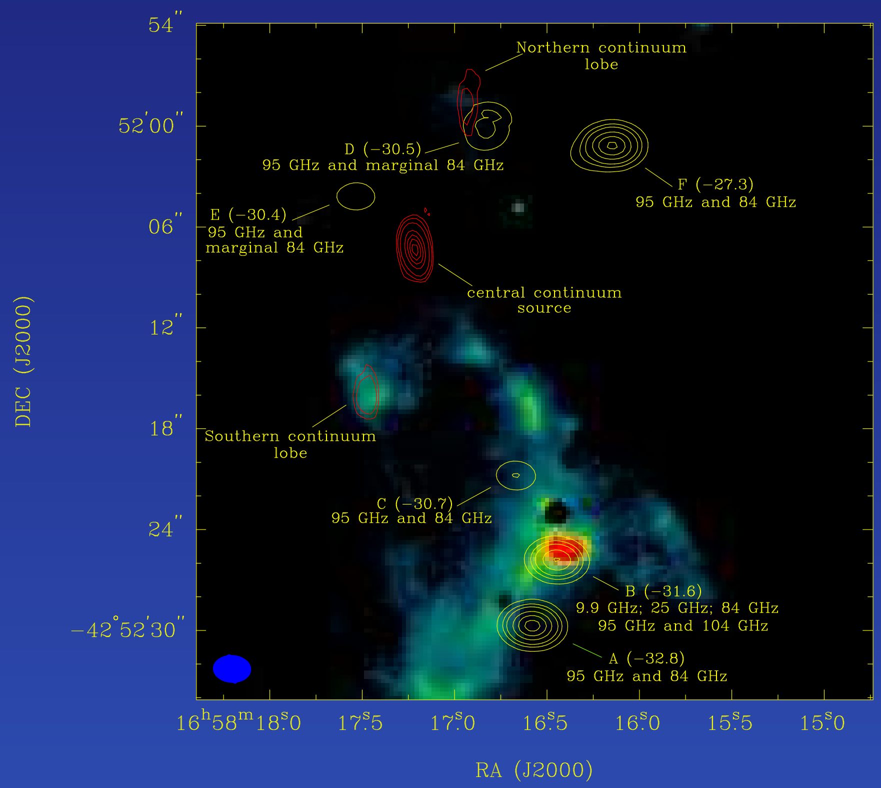


- The -1.1 km/s feature is associated with an outflow found by Zapata et al. (astro-ph/0505045)
- The maser is here



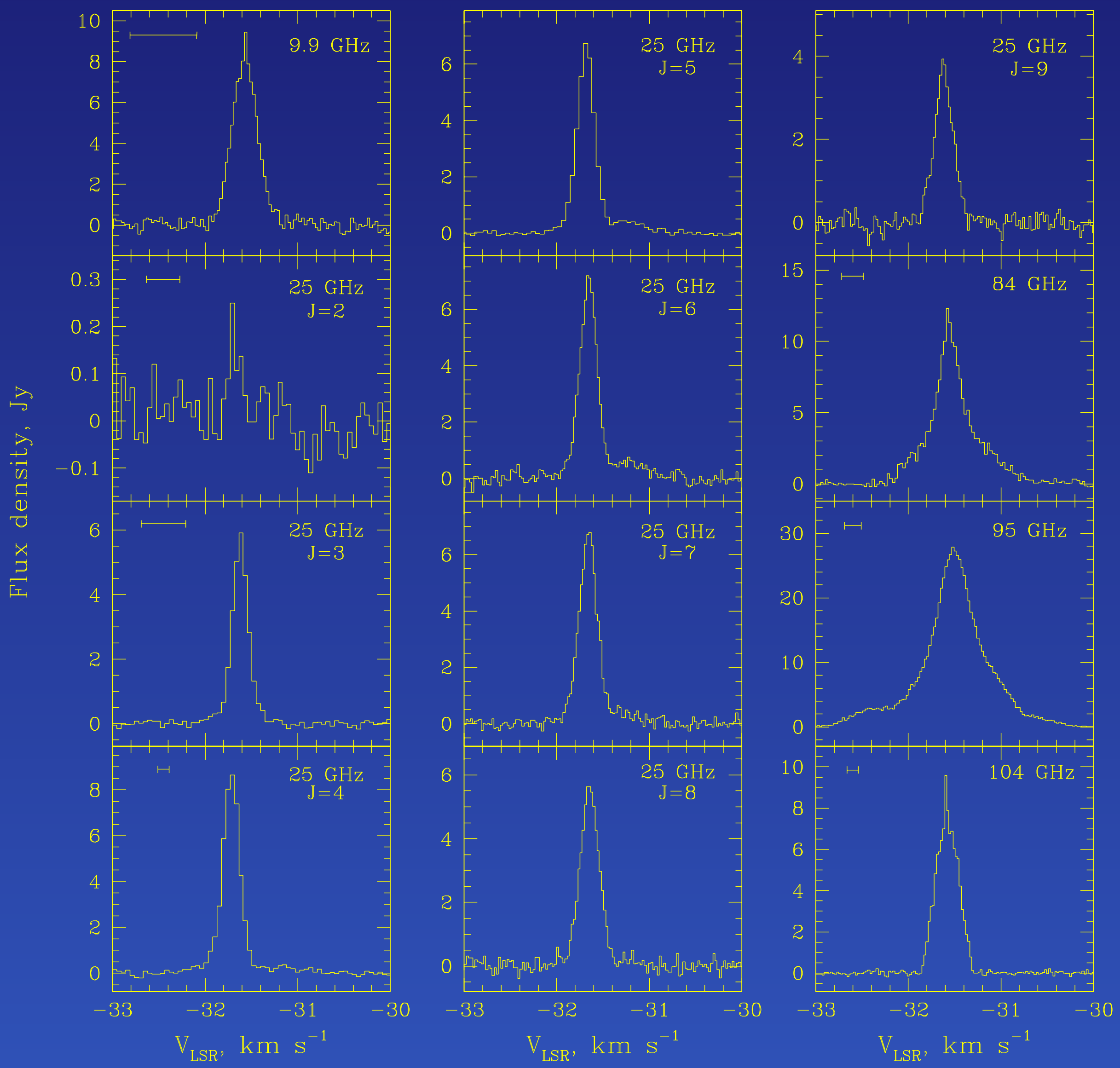
Astrometry and multi-transition study

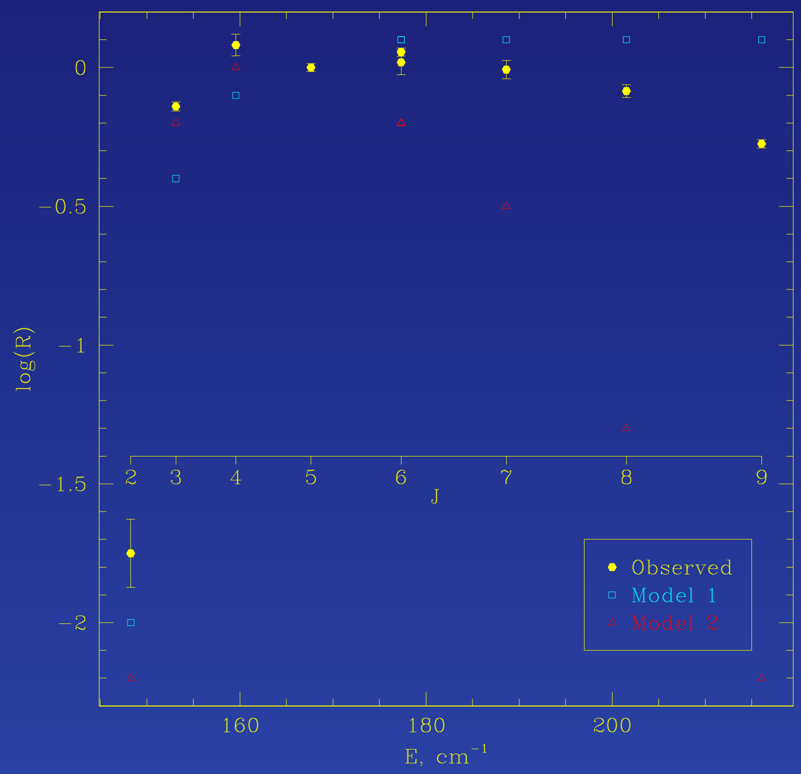
G343.12-0.06 (IRAS 16547-4247)



- Association of class I masers with the outflow
- Spots are spread over a large area: need an interferometer to study relative fluxes
- Need spectral resolution of 0.02 km/s or better

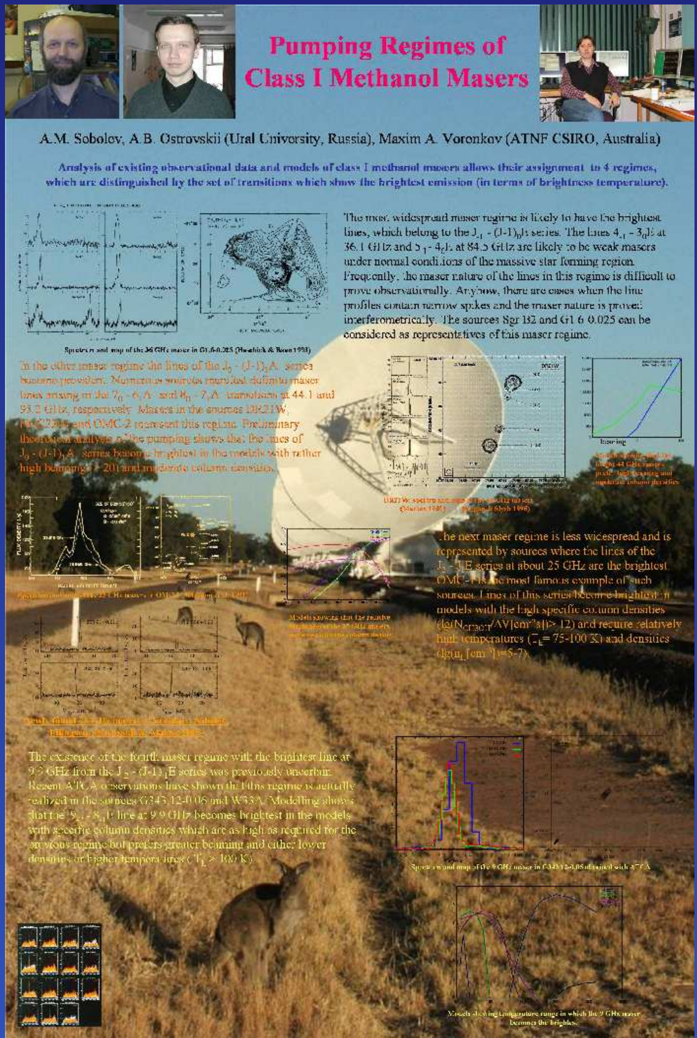
Spectra of the spot B





- Large number of transitions observed allows to test pumping models
- Theory predicts relative fluxes ⇒ parameter estimate
- Narrow spike at 9.9 and 104 GHz

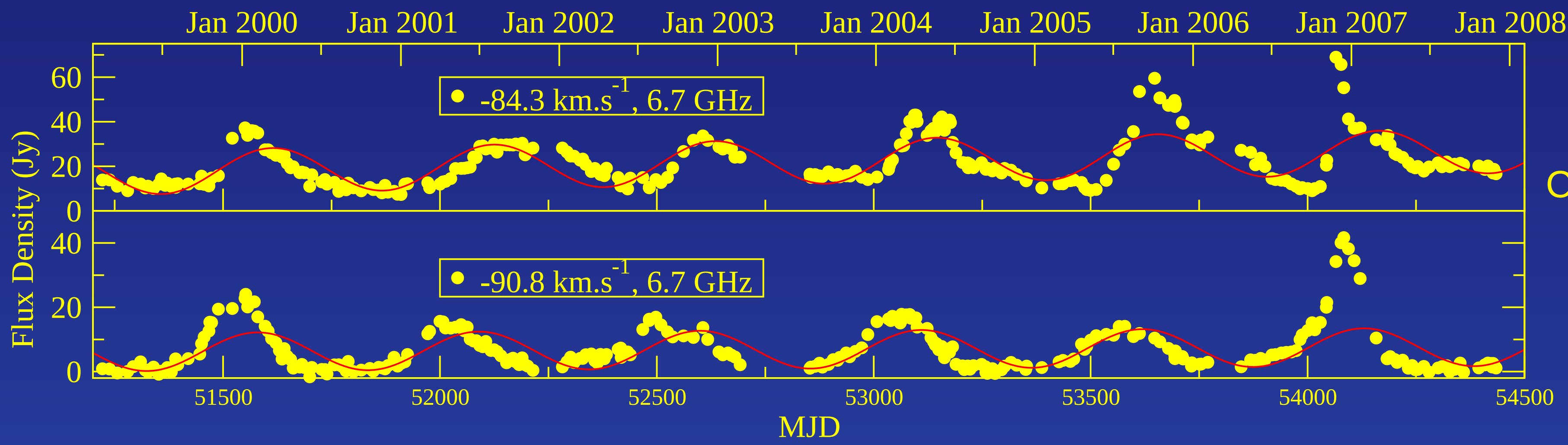
4 regimes of the Class I methanol masers



Poster at IAUS227
(Sobolev et al.)

1. The 36 GHz and 84 GHz transitions are the brightest. This is the most widespread regime, but masers are weak.
2. The 44 GHz and 95 GHz transitions are the brightest. This regime requires a high beaming (elongated geometry).
3. The transition series near 25 GHz is the brightest. This is a rare regime and requires a high methanol column densitiy and relatively high temperature and hydrogen density.
4. The 9.9 GHz and 104 GHz transitions are the brightest. The parameters are similar to 3, but a greater beaming and either lower density or higher temperature are required.

Monitoring of class I and class II masers in G331.132−0.24



Class II maser

- A few class |I methanol masers at 6.7 GHz are known to show periodic flares
- The nature of these flares still remains a mystery
- Class I and class II masers have different pumping mechanisms and react on a pumping disturbance in the opposite sense
- We started a long term monitoring of the 9.9 GHz maser (class I) in this source

Summary

- ATNF instruments are involved in a range of maser surveys
  - Unbiased survey of class II masers at 6.7 GHz
  - Targeted searches for various rare class I masers: 9.9, 25, 104 GHz
  - Pilot blind survey at 44 GHz
  - Pilot survey of low-mass star-forming regions at 36 and 44 GHz
- Accurate positions and multi-transition follow-up allow to
  - Search for associations (e.g. class I and outflows)
  - Study the pumping mechanism of class I masers and possibly characterize the geometry of the source
- Combined monitoring of class I and class II transitions may shed light on the nature of periodic flares

Acknowledgments

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