Southern sky maser surveys II

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Outline

- Facilities operated by CSIRO Astronomy & Space Science
- Methanol, methanol, methanol….
  - Two classes of methanol masers, theoretical understanding
  - Rare/weak masers
  - Southern surveys for methanol masers cont'd
  - More on the maser based evolutionary sequence
- Galactic structure – intro
- A few words about variability

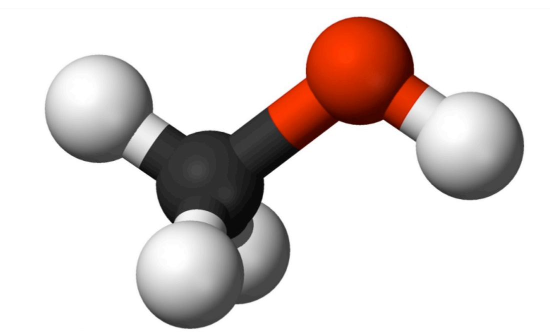


Image credit: wikimedia

CASS (ATNF) observatories

+ Tidbinbilla (space tracking), but sometimes available to do astronomy

ATCA,Parkes are open access instruments

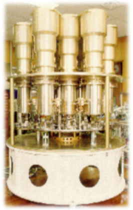
http://opal.atnf.csiro.au


CSIRO
Celebrating 50 years of the Dish
Opera
at The Dish
Proudly supporting the McGrath Foundation

Parkes Radio Telescope

Current capabilities





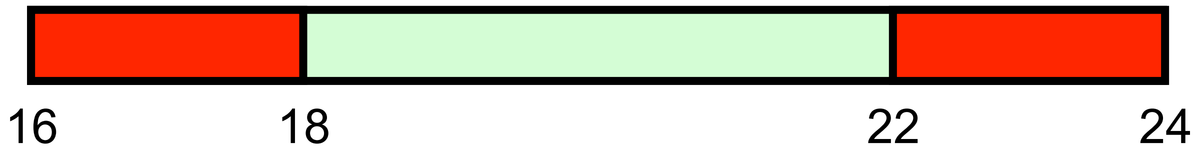
- 700 MHz to ~25GHz across 8 receivers
  - Including 13-beam ‘multibeam’ system

- Spectral and temporal back end capabilities
  - For single-beam time domain (events < 1s) and spectrometry (“DFB4”)
  - For single-beam time domain and new limited piggyback spectrometry (“CASPSR”)
  - For multi-beam (13 beams) time domain and spectrometry (“HIPSR/BPSR”)
    - Real-time Fast Radio Burst detection
  - Best spectral resolution is about 1 kHz (with 8 MHz coverage)

Australia Telescope Compact Array

Present wide-band capabilities

- 4 GHz instantaneous bandwidth, two 2-GHz blocks in 8 GHz
- Either 1 MHz or 64 MHz spectral resolution

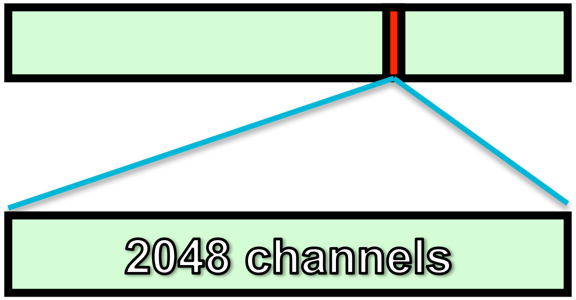


- 16-cm receivers: a single 2-GHz band from 1.1 to 3.1 GHz
- 4-cm receivers: from 4.4 to 10.1 GHz (almost covered with a single receiver tuning)
- 12-mm receivers: from 16 to 26 GHz
- 7-mm receivers: from 30 to 50 GHz (note, restrictions on tuning)
- 3-mm receivers: from 84 to 105 GHz (5 antennas only)

- (East-West) baselines up to 6 km
- 2-D (hybrid) arrays up to ~250 m   (good for mm observations)

Zoom modes: high spectral resolution

- Up to 16 “zoomed in” channels per each 2 GHz window (user selected)
- Positioned in steps equal to half of the wide-band spectral resolution (i.e. 0.5 MHz or 32 MHz)
- Each zoom window has 2048 spectral channels



Projects with large number of sources & lines are tricky in 1 MHz mode

Australian SKA Pathfinder

- 36-antenna multi-beam interferometer in a radio-quiet zone
  - Frequency range: 700 MHz – 1.8 GHz, baselines from 23m to 6km
- Survey instrument – pushing wide instantaneous field of view
  - 3-axis mount (whole antenna can rotate) – can fix or rotate beam pattern
    - potentially better images at low frequencies (higher dynamic range)
  - Automatic processing eventually – necessary for the full instrument
    - Additional difficulties with high spectral resolution data
- Not very useful for masers in its current form
  - But it can observe mainline OH (both Galactic and red-shifted)

Wide Field of View

- Required 1200 hours observing with the Australia Telescope Compact Array

- ASKAP will take about 10 minutes

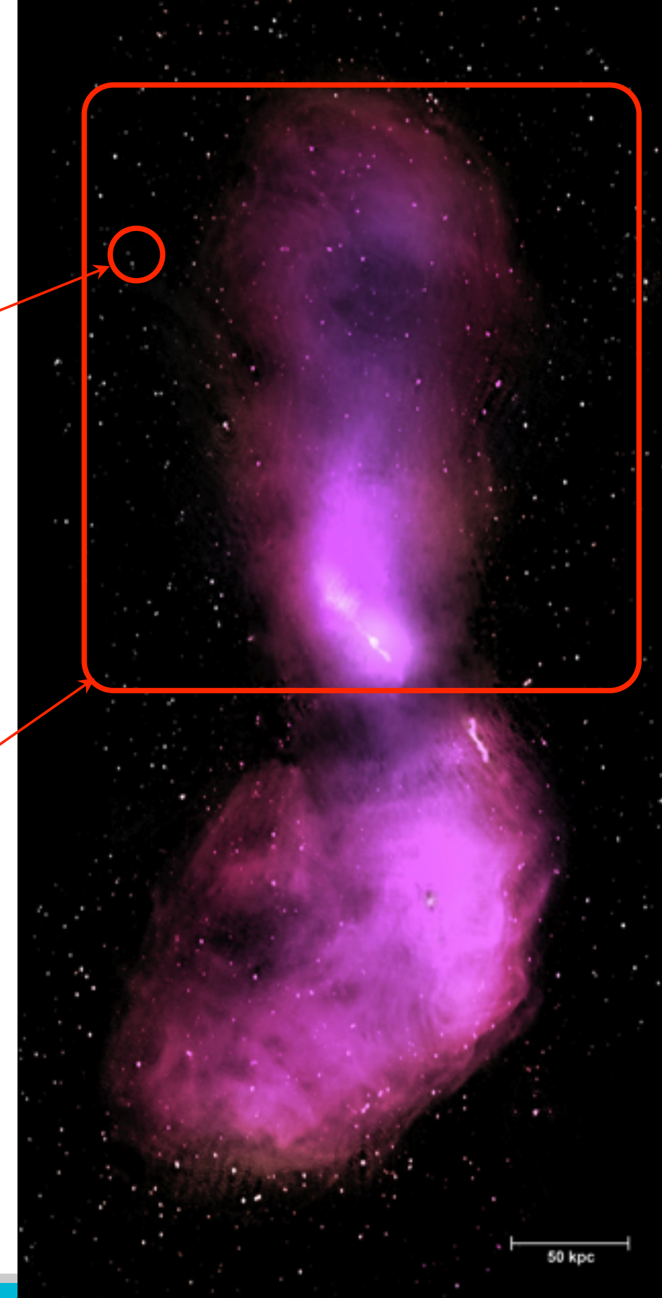
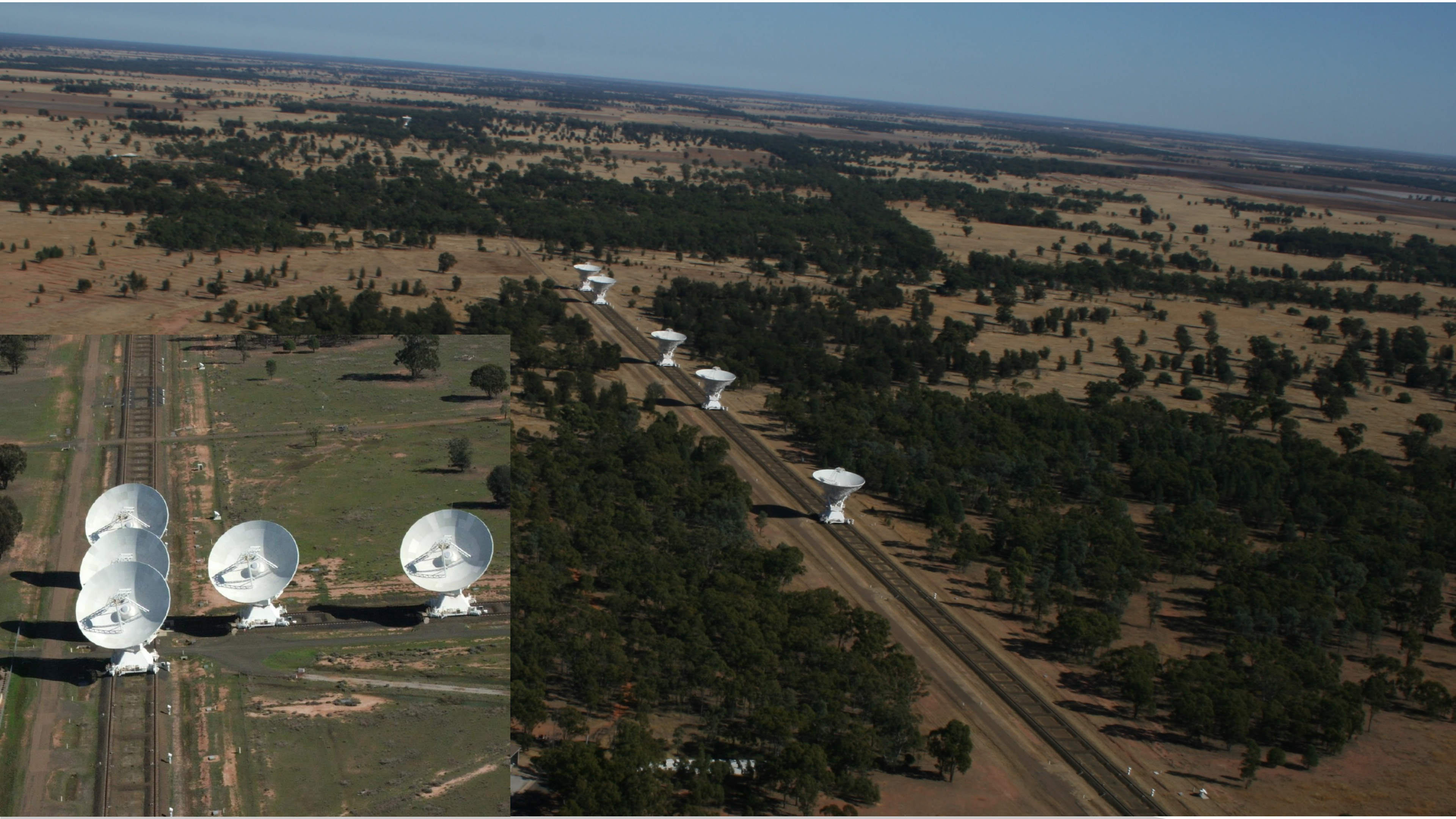


Image credit: Tim Cornwell/Ilana Feain

ATCA can observe lots of maser transitions!



Surveys for methanol masers

① Blind surveys + interferometric follow ups

- Methanol multi-beam survey for 6.7 GHz masers. See Breen et al. (2015, MNRAS, 450, 4109) and ref. therein
- MALT45 and the extension: 44 GHz masers
- HOPS covered some methanol masers too (although not very sensitive), see Voronkov et al. (2011, MNRAS, 413, 2339)

② Targeted searches for other masers

- More or less biased as the sample is not complete
- One of the least biased: 12.2 GHz follow-up of all of the MMB detections, see Breen et al. (2014, MNRAS, 438, 3368) and ref. therein

Shari's lecture

③ Targeted searches for rare/weak masers

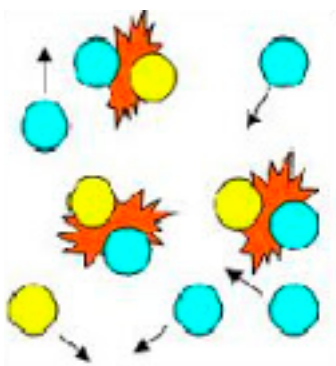
④ Interferometric follow-ups

Methanol Masers

different transitions of the molecule

Class I

Pumped by collisions



Less understood

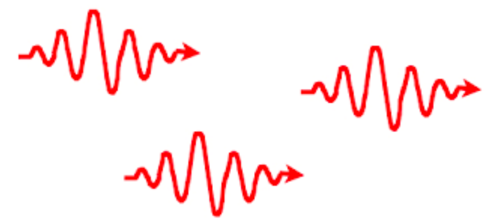
Shocks caused by various phenomena

Widespread:
44 and 36 GHz,
84 and 95 GHz

Rare/weak:
9.9, 23.4,104 GHz,
25 GHz series

Class II

Pumped by radiation



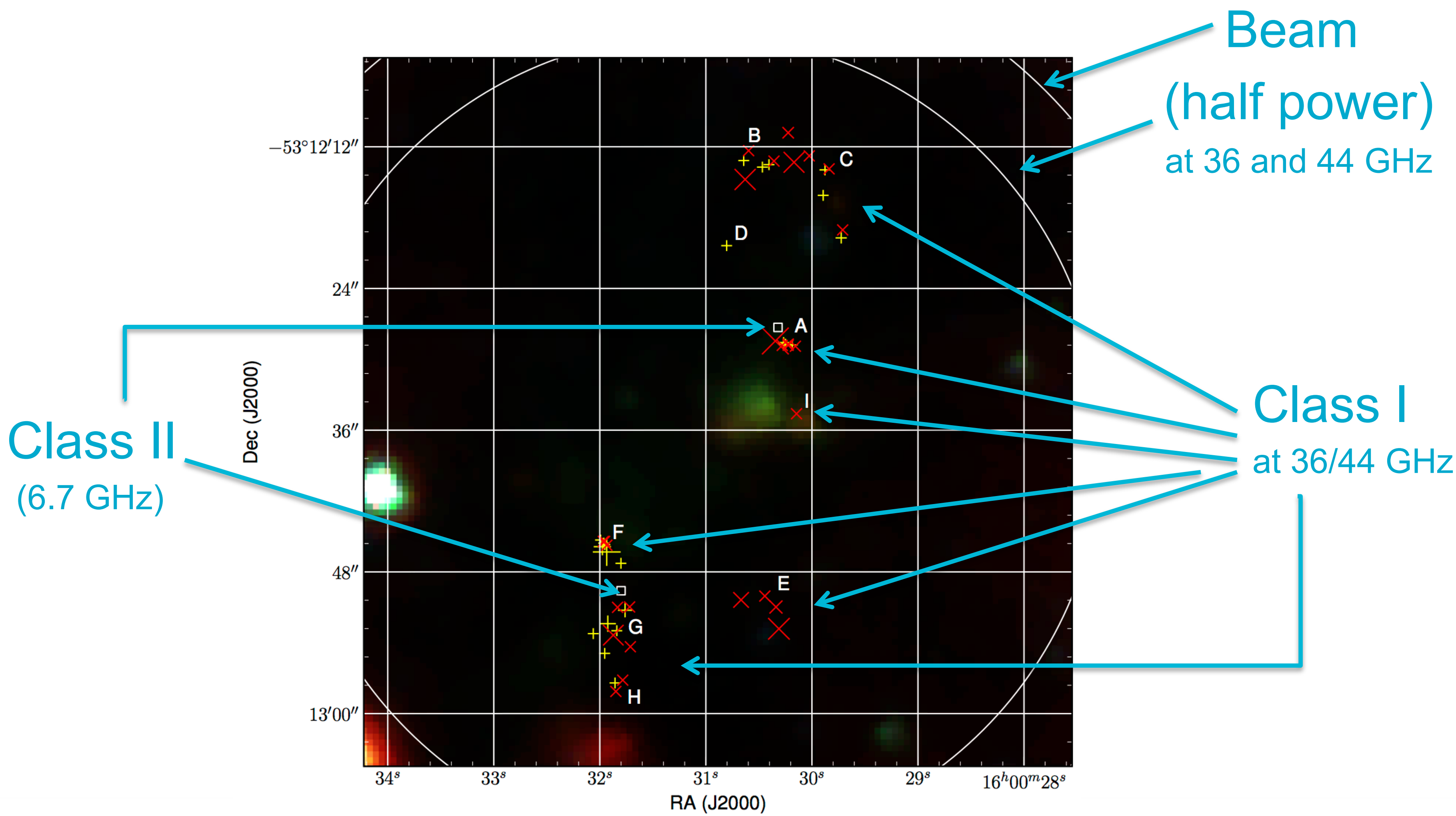
High-mass star formation only

Close to YSO

Rare/weak:
19.9, 23, 28.9,
37/38, 85/86,
107/108 GHz

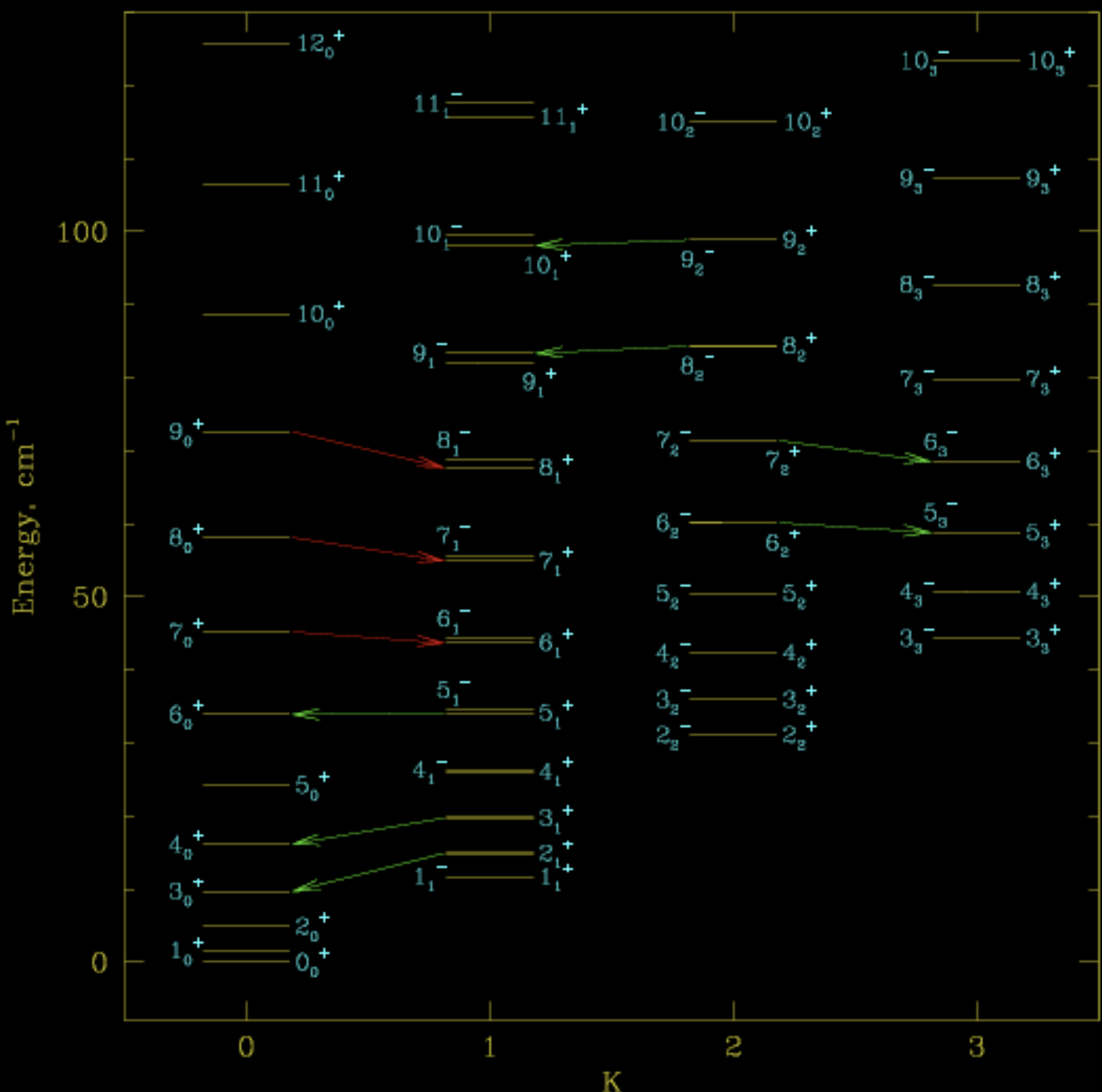
Widespread:
6.7 & 12 GHz

Class I/II methanol masers at arcsec resolution



G329.03-0.20 (from Voronkov et al.; 2014, MNRAS, 439, 2584)

Methanol masers – two classes



Energy levels for A-methanol

Red is class I

Green is class II

Series of transitions between K-ladders

Similar properties are expected within each series (but note boundary condition for class II)

Interestingly, all but one class II maser series go downwards (as we go up in frequency) and eventually terminate at the lowest possible level for that particular series

Rare/weak class II masers

- Lower J counterparts of widespread masers
    - J_1-$(J+1)_0$ A^+, e.g. J=3 at 107 GHz (note J=5 is the famous 6.7 GHz maser)
    - J_0-$(J+1)_{-1}$ E, e.g. J=0 at 108 GHz (note J=2 is the 12 GHz maser)
- J_1-$(J+1)_0$ E, e.g. J=2 at 19.9 GHz. Probably just typically weak. Boundary effect?
- J_{-2}-$(J+1)_{-1}$ E series (e.g. J=7 at 37 GHz and J=6 at 85 GHz). Strong in the isotropic case, i.e. no beaming and same optical depth in all directions.
    - A.k.a. "Horsemen of the apocalypse" - Ellingsen et al. 2011, ApJ, 742, 109
- J_2-$(J+1)_1$ A^+ series (e.g. J=9 at 23 GHz). Narrow range of density and methanol abundance, quite high densities of 10^7-10^8 cm^{-3}.
- J_2-$(J+1)_1$ A^- series (e.g. J=8 at 28.9 GHz). Only one maser source known, but not entirely clear to me why. Lack of extensive searches? Rather weak?
- J_2-$(J-1)_3$ $A^\pm$ series, each member is a pair of maser transitions for A^+ and A^- methanol at closer frequencies (e.g. J=6 at 38 GHz and J=7 at 87 GHz). The only class II maser series which does not terminate. These masers seem to require rather low densities about 10^4 cm^{-3}.

See also the table in Sobolev et al. (1997, MNRAS, 288, L39)

Modelling of class I masers

Not very mature yet, but a lot of progress in the last decade

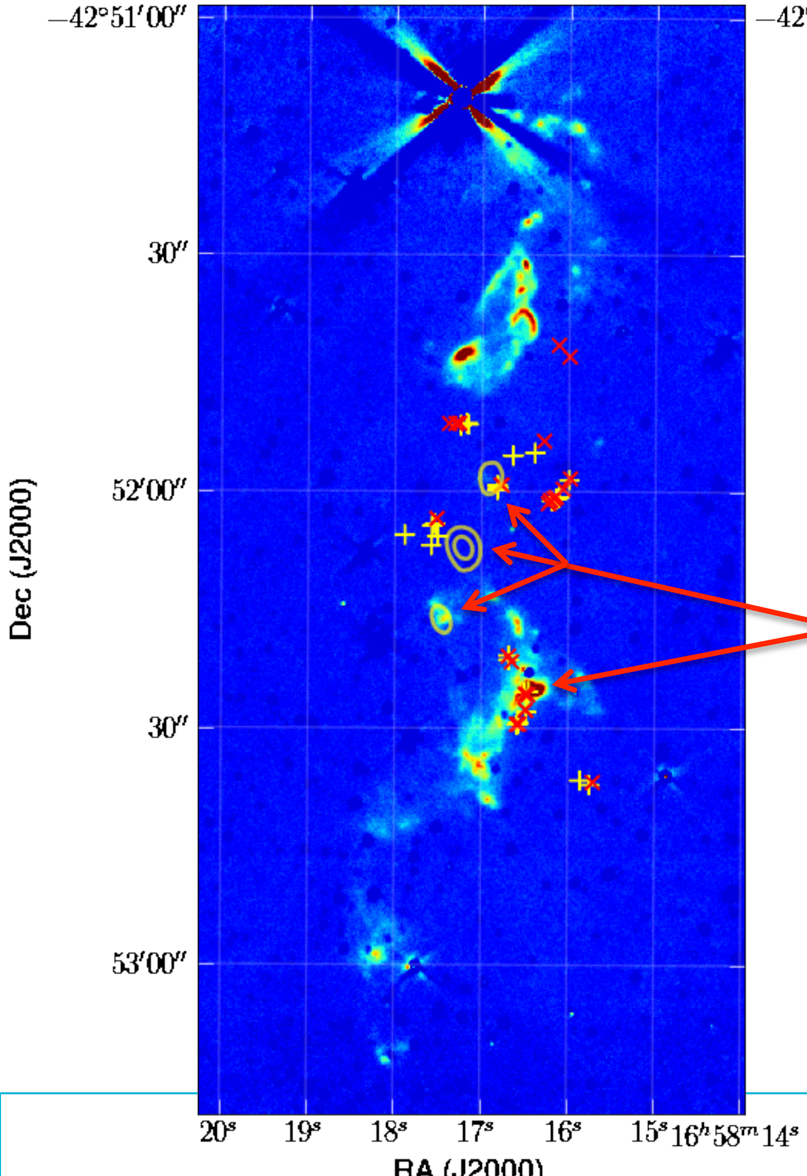
- Sobolev et al. (2005, IAUS, 227, 174)
  - There are different pumping regimes, each favours a separate transition series.
  - The orientation of maser region w.r.t. the observer has a great influence on the 36/44 GHz flux density ratio (the same is true for the 84/95 GHz flux density ratio)
    - Maser region elongated along the line of sight is stronger at 44 GHz
    - Maser region elongated in the plane of the sky is stronger at 36 GHz
  - Higher temperature and density for rare/weak class I masers

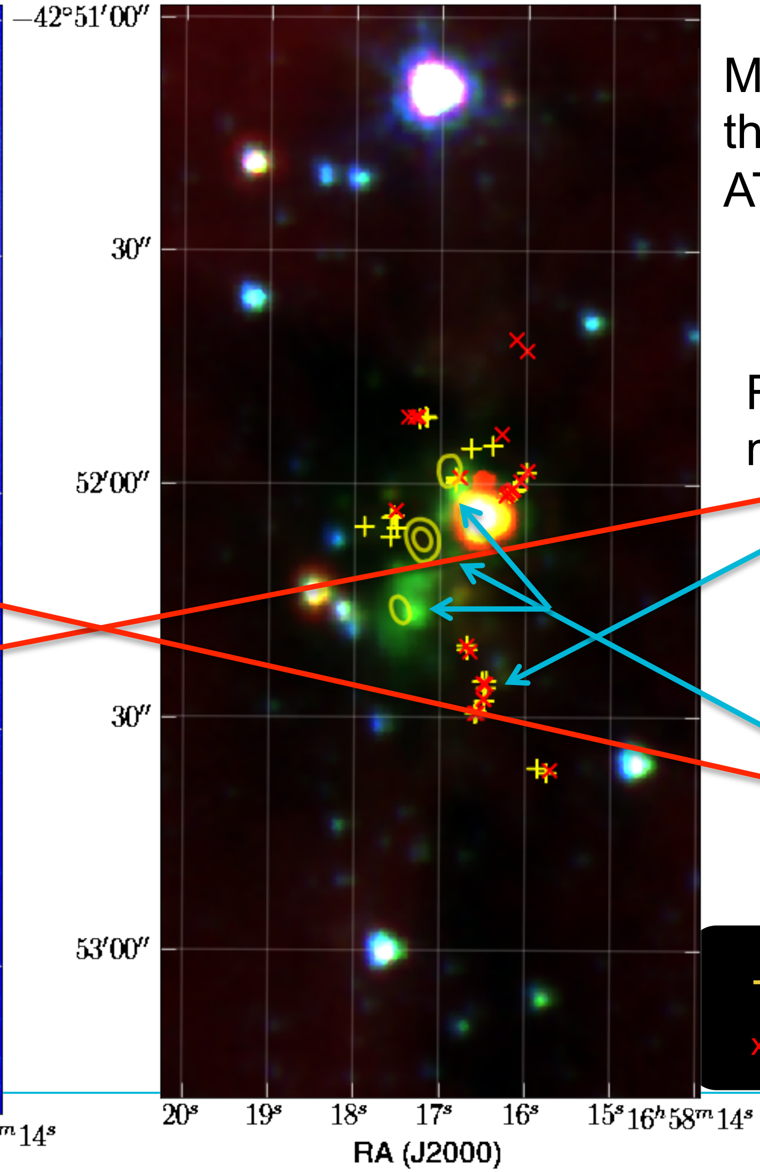
See also Leurini et al. (2016, A&A, 592A, 31)

We still need to accurately test these predictions on a large sample of sources.

G343.12-0.06 (IRAS16547-4247)

See Voronkov et al. (2006, MNRAS, 373, 411) for more info on the source





Maser data are from the new 36/44 GHz ATCA observation

Rare/weak class I methanol masers

There is no 6.7 GHz maser

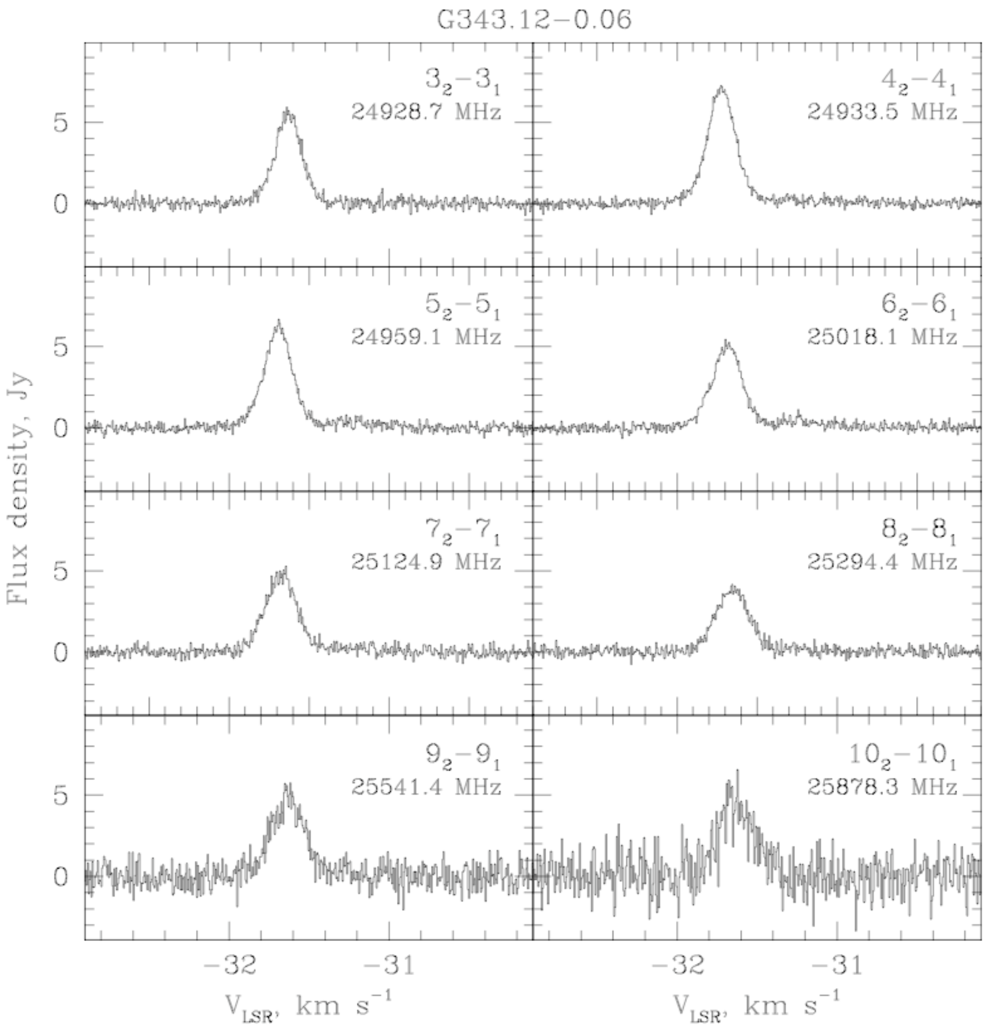
Thermal jet

+ 44 GHz masers

x 36 GHz masers

H_2 image from Brooks et al. (2003, ApJ, 594, L131); Spitzer 3-colour image: 8.0, 4.5 and 3.6 micron

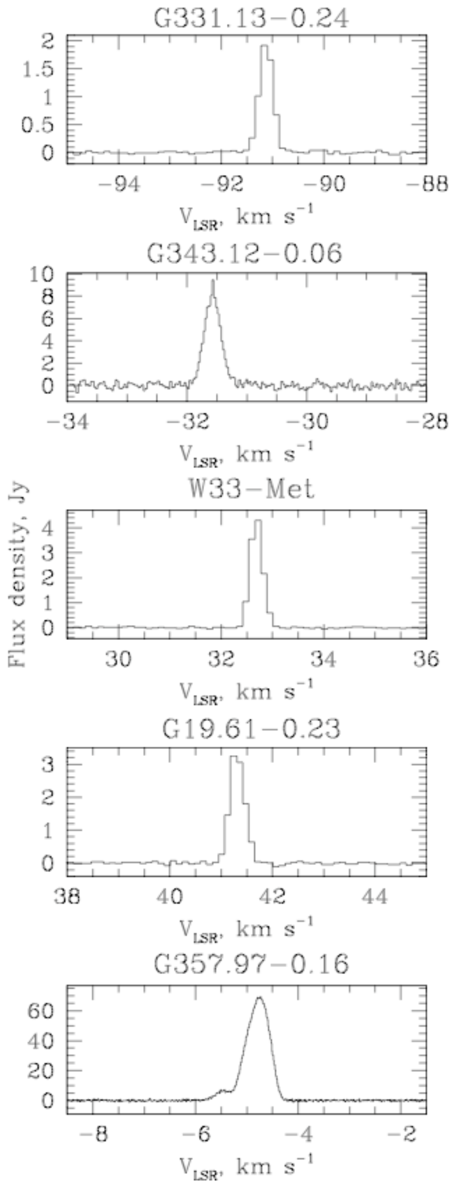
J_2-J_1 E (25 GHz) class I methanol masers



Example of simultaneous 25 GHz spectra with CABB (Wilson et al., 2011, MNRAS, 416, 832)

- Historically, the first methanol maser found in space (Barrett et al., 1971, ApJ, 168, 101)
- Believed to be rare
- Survey of known class I maser sites brought up 66 detections out of 102 targets observed (Voronkov et al. 2007, IAUS, 242, 182); the majority are weaker than 1 Jy
- Now reobserved with ATCA + CABB (yet to be published)
- There are other detections, e.g. Brogan et al. (2011, ApJ, 739, 16)

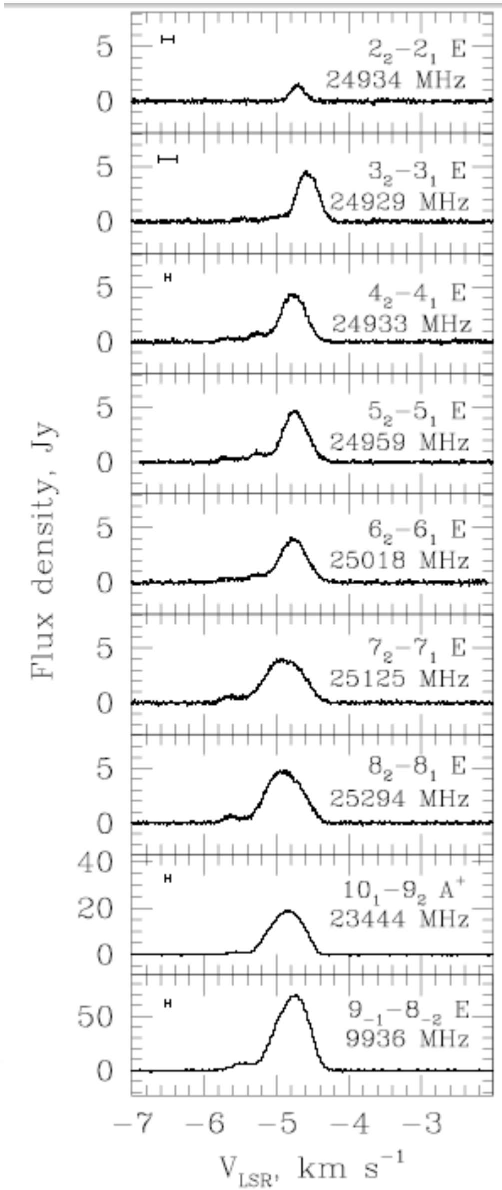
Rare 9.9/104 GHz class I methanol masers



These masers belong to J_{-1}-$(J-1)_{-2}$ E series.

- 9_{-1}-8_{-2} E at 9.9 GHz
  - Maser in W33-Met was known from the single dish work of Slysh et al. (1993, ApJ, 413, L133)
  - Sensitive (limits as low as 0.1 Jy) ATCA survey of Voronkov et al. (2010, MNRAS, 405, 2471): two new detections out of 46 new targets observed
  - Two single source papers: Voronkov et al. (2011, MNRAS, 413, 2339 and 2006, MNRAS, 373, 411)
- 11_{-1}-10_{-2} E at 104 GHz
  - Single dish surveys: Voronkov et al. (2005, Ap&SS, 295, 217; Voronkov et al. 2007, IAUS, 242, 182)
  - The only additional source is G305.21+0.21
  - Interferometry - single source G343.12-0.06, Voronkov et al. (2006, MNRAS, 373, 411)

G357.97-0.16 - new 23.4 GHz class I maser



- First maser in J_1-$(J-1)_2$ A^- series (J=10)
- Found in HOPS (blind survey at 12mm; PI: Andrew Walsh) towards only one location
  - HOPS is not sensitive to weak masers (< 10 Jy)
- Predicted in models (e.g. Cragg et al. 1992) as a class I maser
- Followed up with ATCA
  - Observed the new maser transition + 7 lines of the 25 GHz maser series
  - Also discovered an unusually strong 9.9-GHz maser (and only 5th found so far)
- There is at least one more 23.4 GHz maser (in G343.12-0.06 - the jet/outflow source shown before)

See Voronkov et al. (2011, MNRAS, 413, 2339) for details

Masers as tracers of evolution

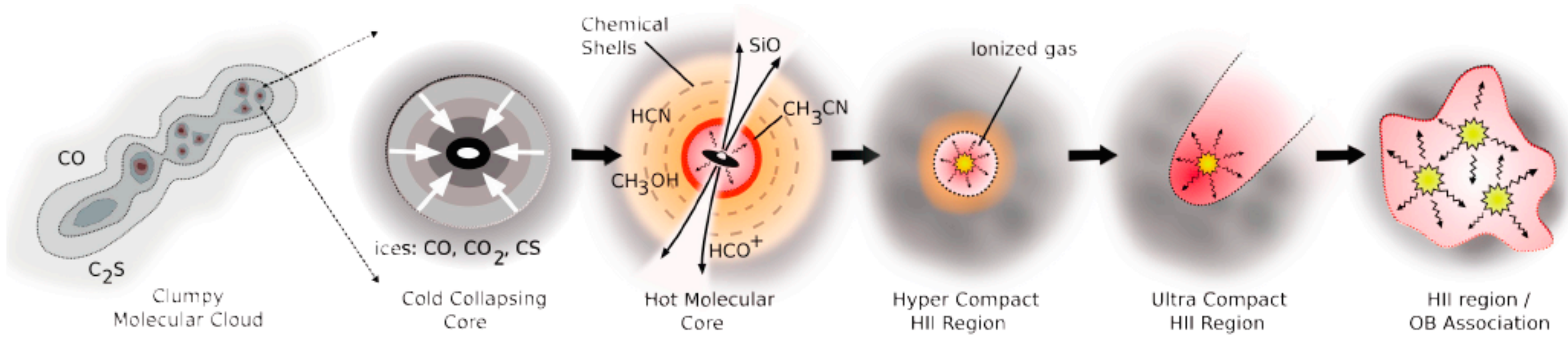
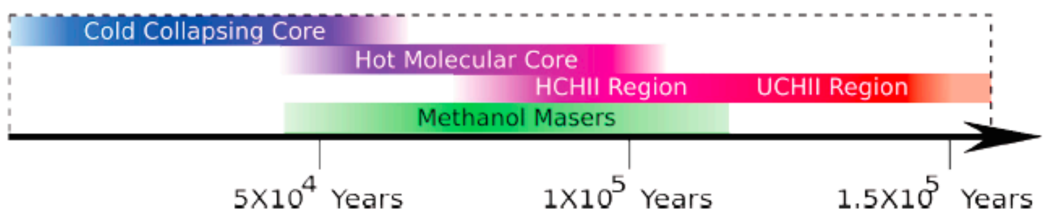


Image credit:
Cormac Purcell

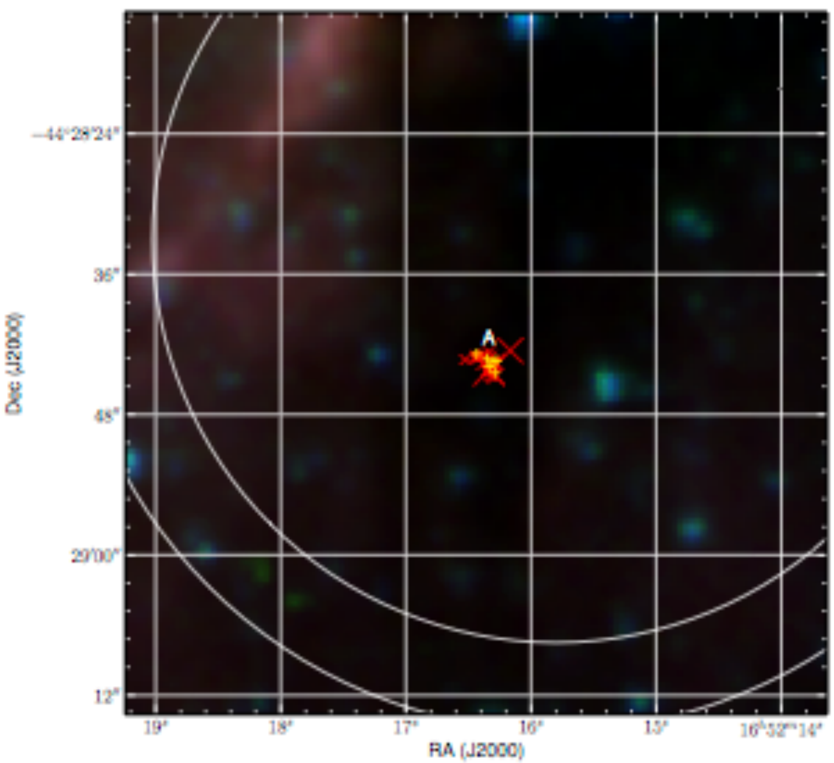


- Mainline OH masers outlast 6.7 GHz methanol masers
- Both the 6.7 and 12 GHz masers increase their luminosity with age
- The 37.7 GHz masers appear towards the end of the class II maser stage
- Class I masers are tricky – possibly appear at both early and late stages
  - + Multiple scenarios giving rise to class I masers
  - + Difficulty identifying very young sources

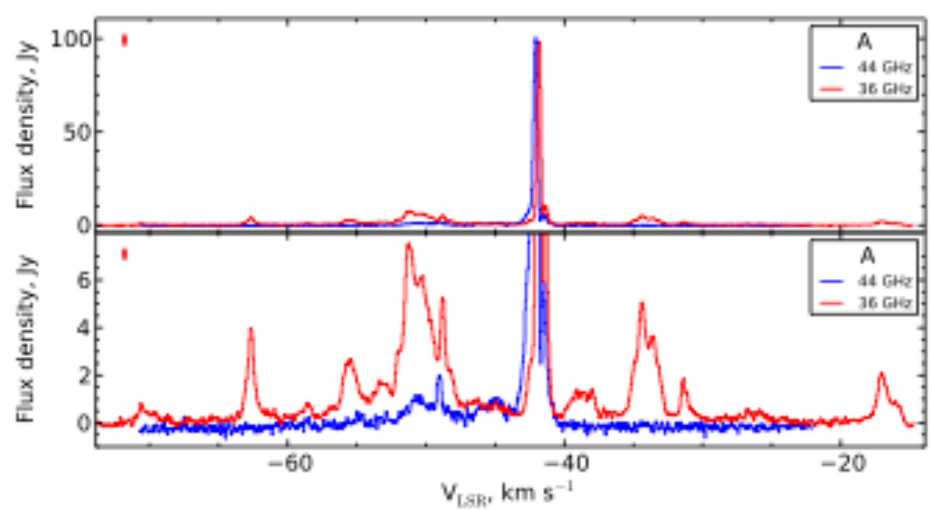
See Forster & Caswell 1989, A&A, 213, 339; Ellingsen et al. 2011, ApJ, 742, 109; Breen et al. 2010, MNRAS, 401, 2219; Voronkov et al. 2010, MNRAS, 405, 2471; Chen et al. 2011, ApJS, 196, 9

Evolutionary stages with class I masers

- It was initially (and implicitly) assumed that class I masers are only associated with outflows which turn on at the earliest stages
- Sources with class I masers tend to have redder colours
- However, later on an increasing number of very evolved sources with no class II masers, but with class I masers were found
- Are there young ones?

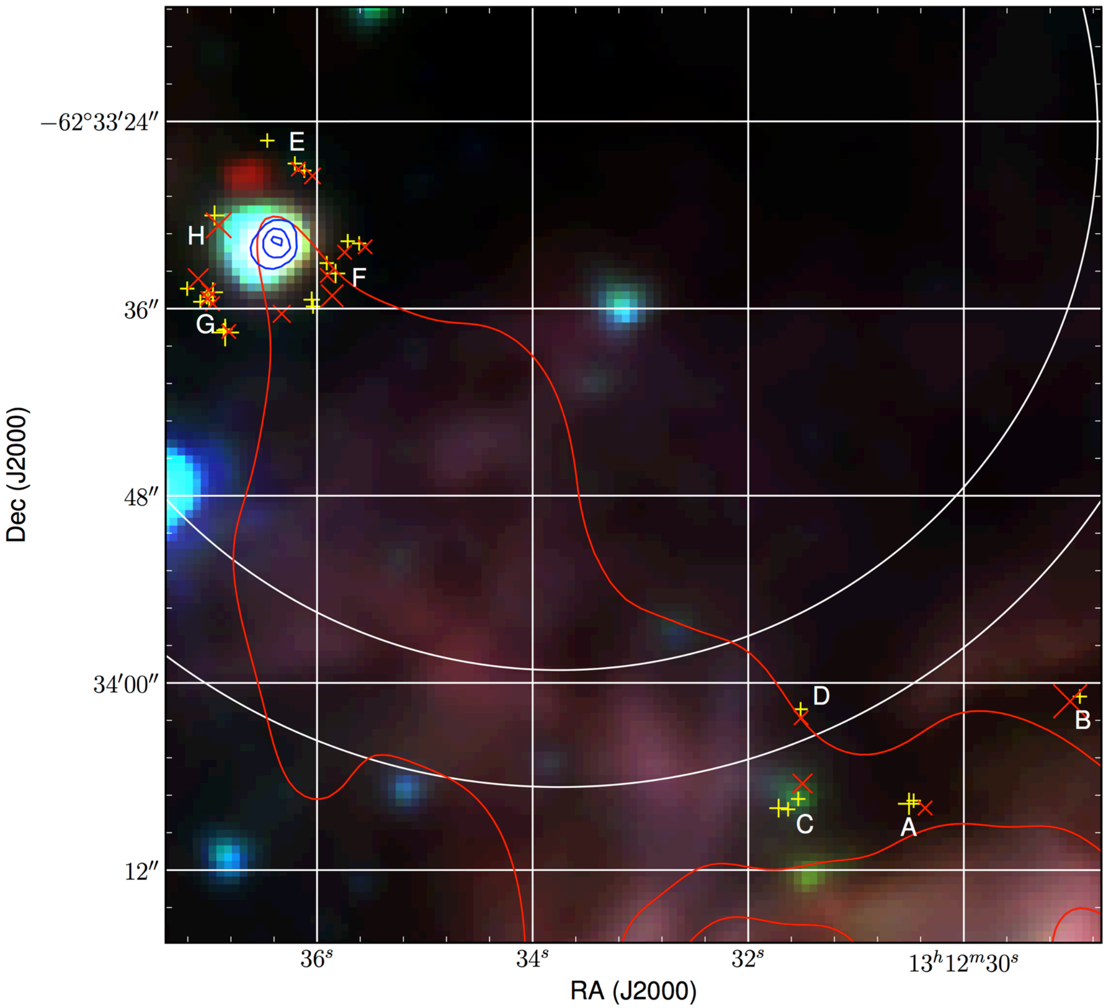


G341.19-0.23 – no other masers, association with dark cloud. Good candidate to be a very young source.



Evolutionary stages with class I masers

- Study of interferometric maps revealed that class I masers are shock tracers in general, rather than outflow tracers

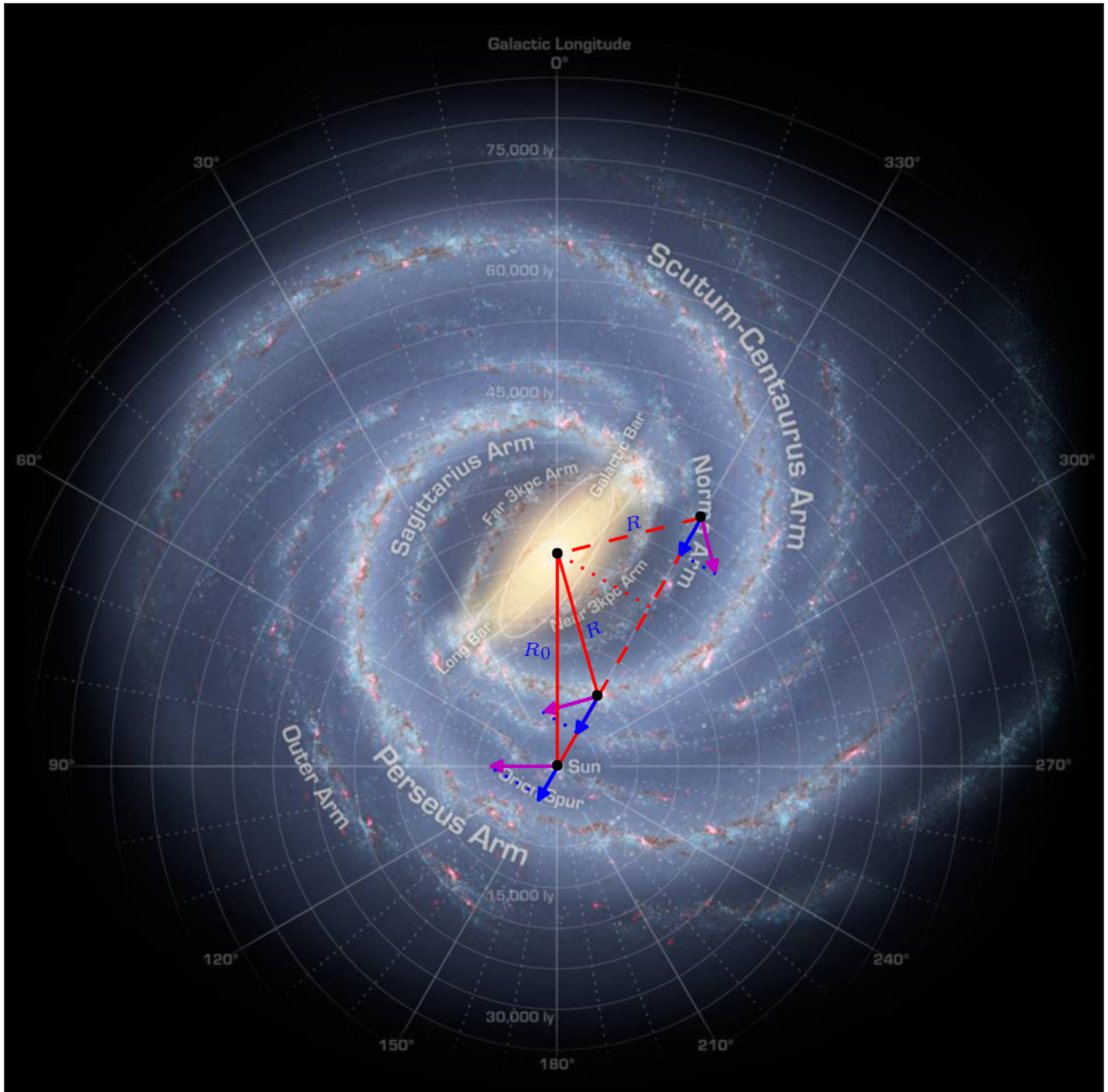


- Multiple scenarios (outflows, expanding HII regions, even SN remnants)
- Also found in low-mass star-forming regions
- May be present multiple times, turning on and off during the evolution

G305.37+0.21: class I masers at 36 and 44 GHz tend to be in a circle around an HII region.

See Voronkov et al. 2014, MNRAS, 439, 2584

Kinematic distances / structure of the Galaxy



Background image by by NASA/JPL-Caltech/R. Hurt

Rotation curve

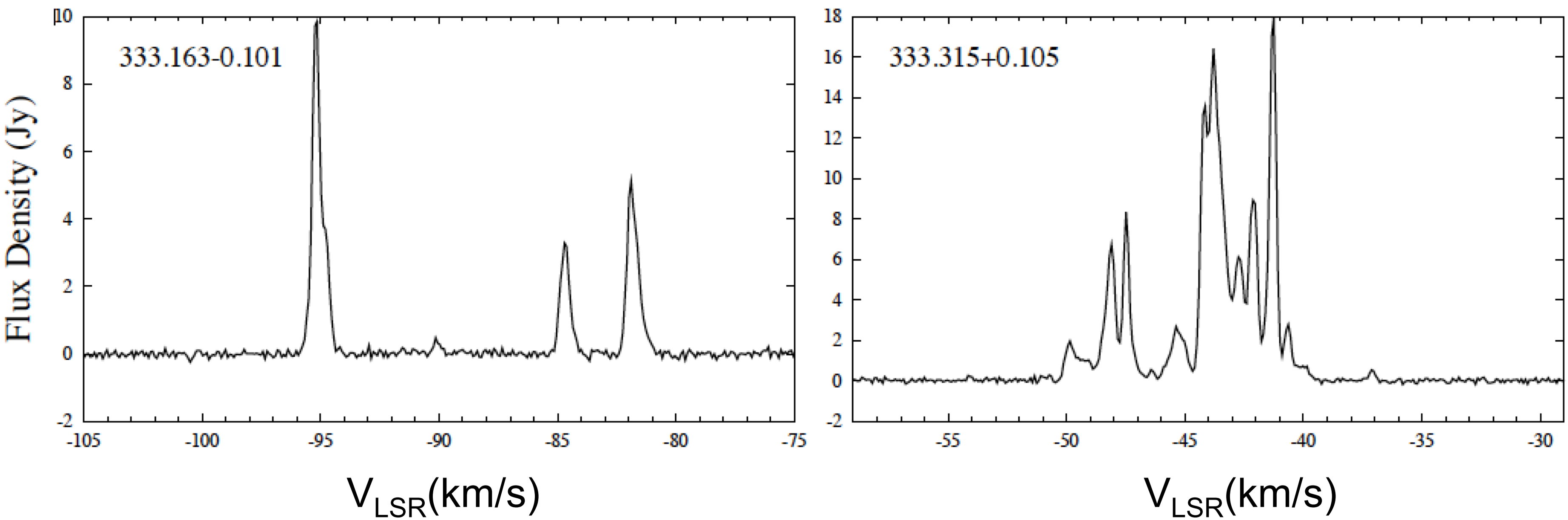
$$V_{rad} = R_0 \left(\frac{V(R)}{R} - \frac{V(R_0)}{R_0} \right) \sin l$$

Observed radial velocity

- Near / far ambiguity in the inner Galaxy
- Depends on the model (R_0, rotation curve, solar motion)
- Doesn't work towards centre/anti-centre
- Peculiar motions

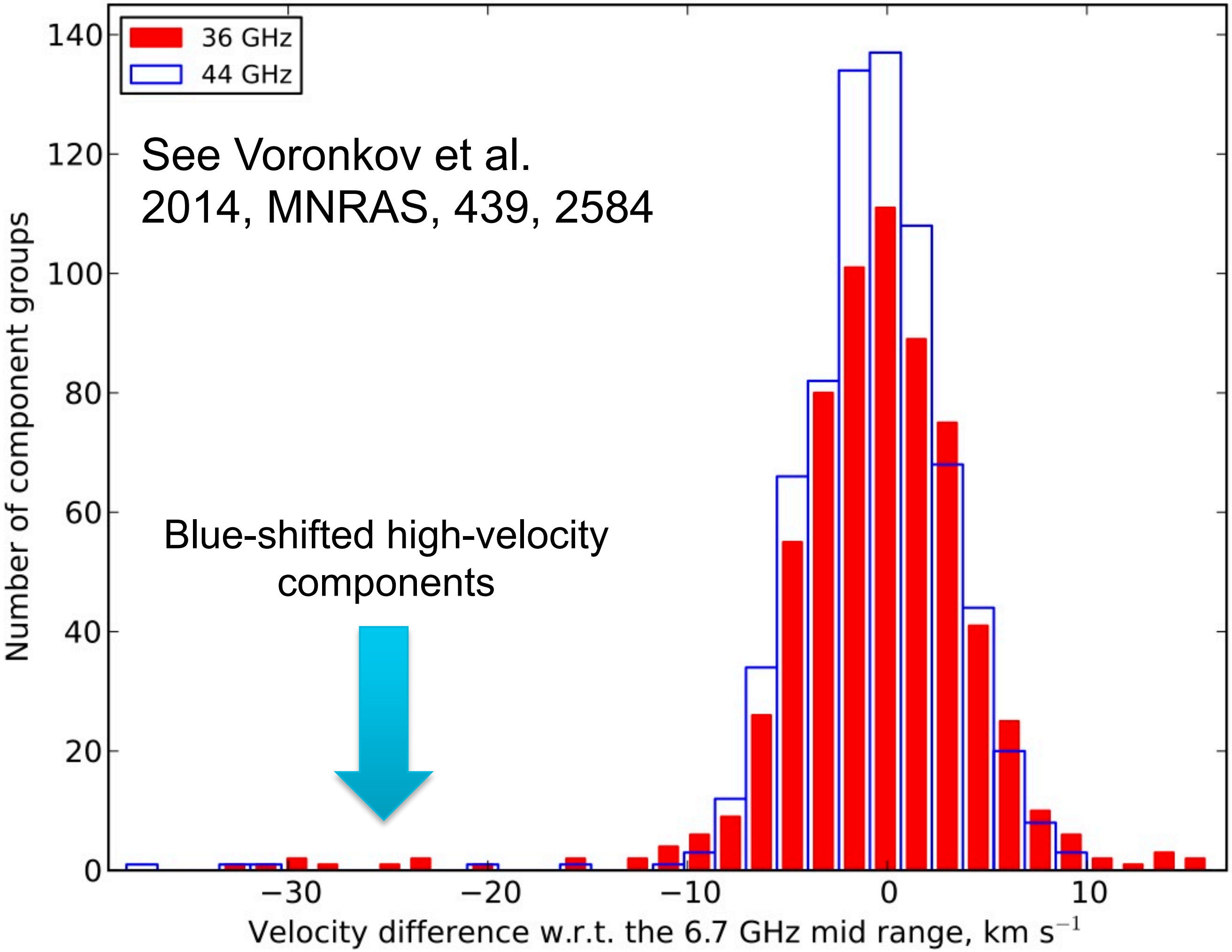
Which velocity to take?

Typical spectra of the 6.7 GHz masers (from the MMB survey):



- Peak velocity doesn't give good results
- The middle of the range, i.e. $(V_{max}+V_{min})/2$, was adopted throughout the MMB papers
- There is evidence that the middle of the velocity range of the 6.7 GHz masers is a worse estimator of the systemic velocity than the velocity of dense gas (e.g. CS) or class I methanol masers

Relative velocities of class I and class II masers



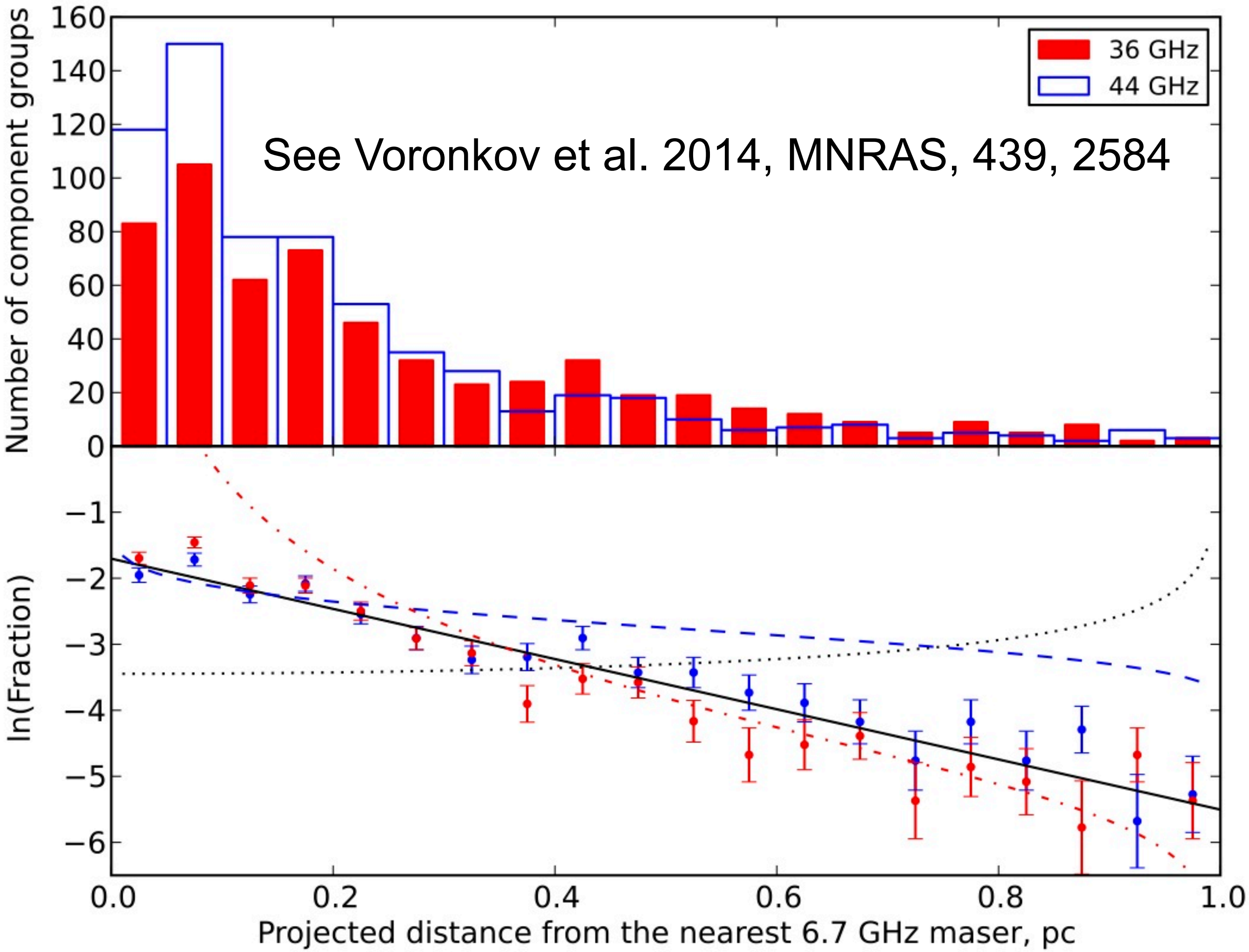
- Middle of the 6.7 GHz velocity range as an estimate of the systemic velocity
- Small but significant mean – systematics
- High-velocity components are blue-shifted and seen predominantly at 36 GHz

- MALT45: velocities of 44 GHz methanol masers vs. various molecular tracers (e.g. CS), σ ~1.5 km s^{-1}

36 GHz: mean -0.57±0.06 km s^{-1}, σ=3.65±0.05 km s^{-1}
44 GHz: mean -0.57±0.07 km s^{-1}, σ=3.32±0.07 km s^{-1}

Orientation of the maser region?

Separations of class I masers from YSO



The class II methanol maser at 6.7 GHz traces the YSO location, class I masers are scattered around

The distribution is well approximated as an exponential decay with 263±15 mpc scale

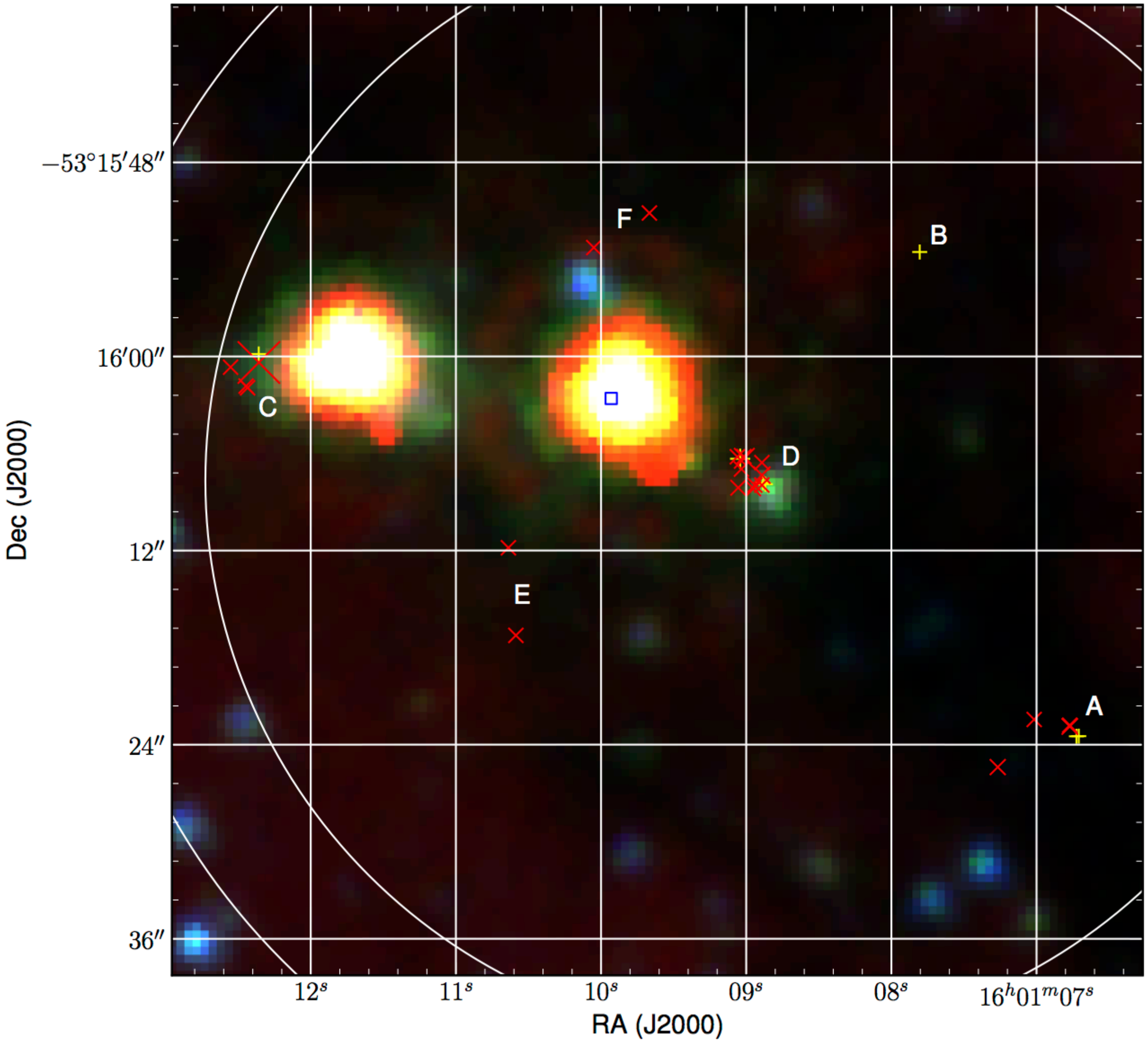
The same distribution within uncertainties for 36 and 44 GHz masers

Distance estimate?

$D_{kpc} \approx 54/\langle d_{arcsec} \rangle$

See arXiv:1712.06777

Spatial spread and near/far distance



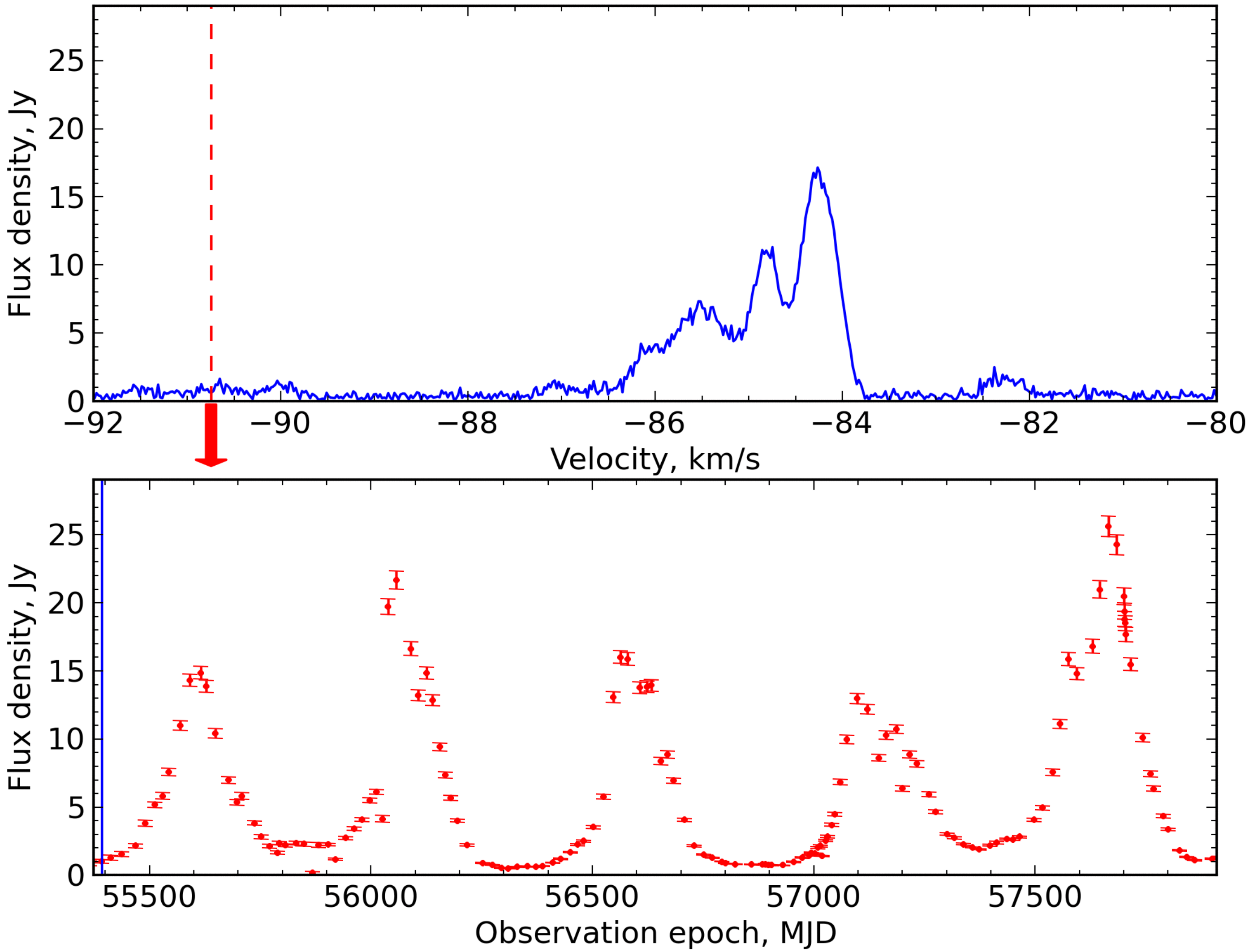
G329.07-0.31

Class I masers can serve as a "statistical ruler" to help with near/far distance ambiguity resolution

Linear offsets are expected to be well below 1 pc

Larger offsets probably mean that a wrong distance has been assumed

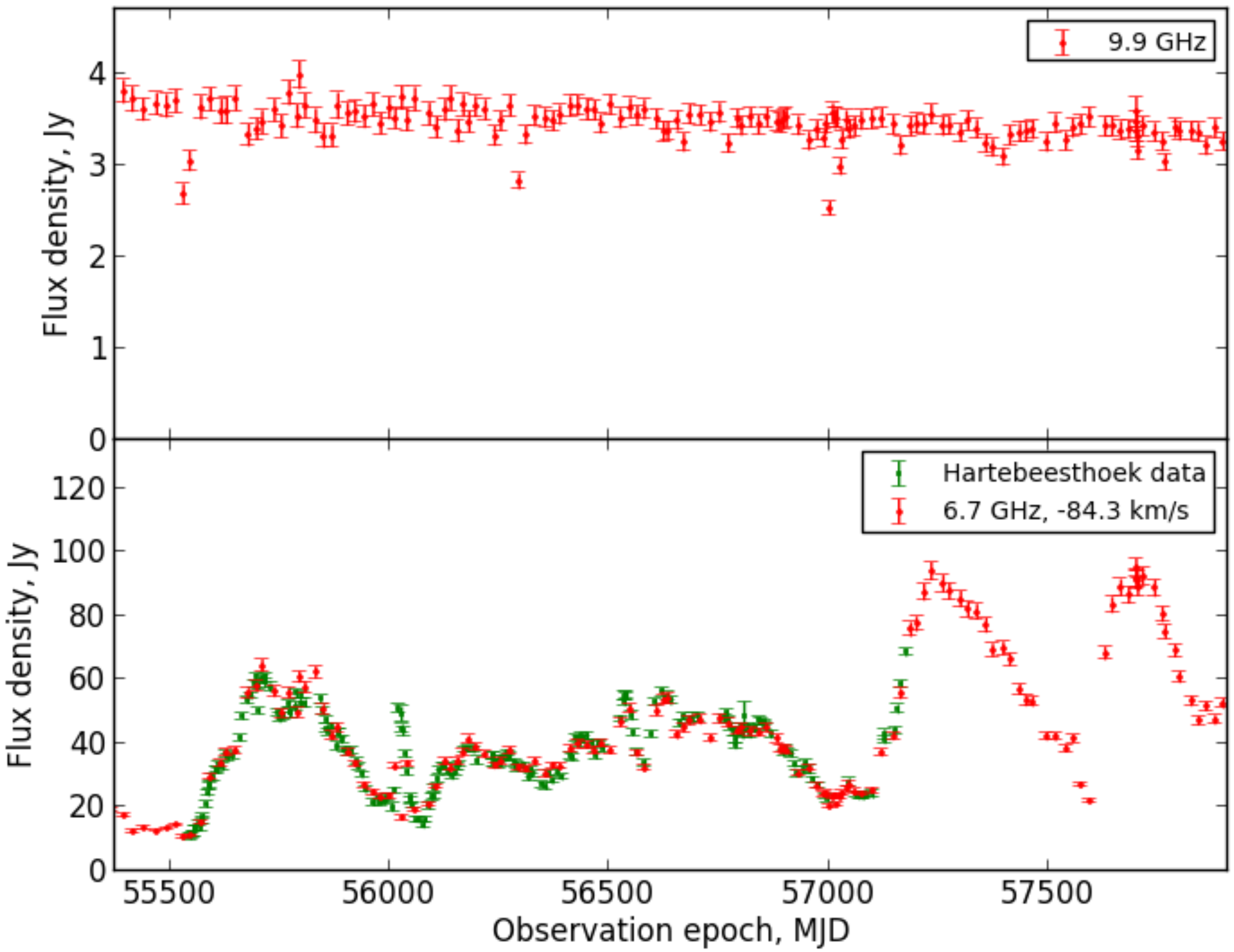
Periodic variability of some 6.7 GHz masers



G331.13-0.24 was monitored by ATCA at 6.7 and 9.9 GHz for a few years

The 6.7 GHz spectrum and time series for the most periodic feature

Variability of G331.13-0.24



G331.13-0.24 was monitored by ATCA at 6.7 and 9.9 GHz for a few years

The time series for the 9.9 GHz maser and the strongest 6.7 GHz feaure

Summary

- All methanol maser transitions do not behave the same way
  - Class I masers are pumped by collisions and trace shocks of various origin. Often spread over an arcmin around the YSO position.
  - Class II masers are pumped by radiation from the YSO. Present only in the regions of high-mass star formation regions. Compact at arcsec resolution.
  - Rare/weak masers of both classes often give additional insights
- Masers surveys are a rich source of information
  - Constrain evolutionary stages
  - Kinematics and morphology of the region
  - Discriminate between high- and low-mass star formation
  - Galactic structure (distances, both kinematic and through parallax)
- Variability and periodic class II masers
  - Need monitoring in as many transitions and species as we can (both classes CH_3OH, OH, ex-OH, H_2O, etc), ideally simultaneously

Thank you

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