Studies of stellar evolution using masers

Anna Bartkiewicz

Owing to masers we can study dense, hidden regions...

NICOLAUS COPERNICUS UNIVERSITY IN TORUŃ

Introduction – where are masers?

Maser action (microwave amplification by stimulated emission radiation) occurs when LTE conditions are violated and velocity coherence is achieved between a group of population-inverted molecules. In the presence of a pumping mechanism that can maintain a higher population in the excited level, the corresponding transition can exhibit the exceptionally high intensity typical of maser sources (Elitzur 1992).

Maser emission (OH, H_2O, CH_3OH, SiO) appears in regions close to **newly born high-mass and low-mass stars, evolved stars**.
E.g., Qiao et al. (2016) using ATCA surveyed the 1.6 GHz OH maser line and identified 122 (57% of the sample) sites associated with **evolved stars** (one of which is a planetary nebula), 64 (30%) with **star formation**, two sites with **supernova remnants** and 27 (13 %) of unknown origin.

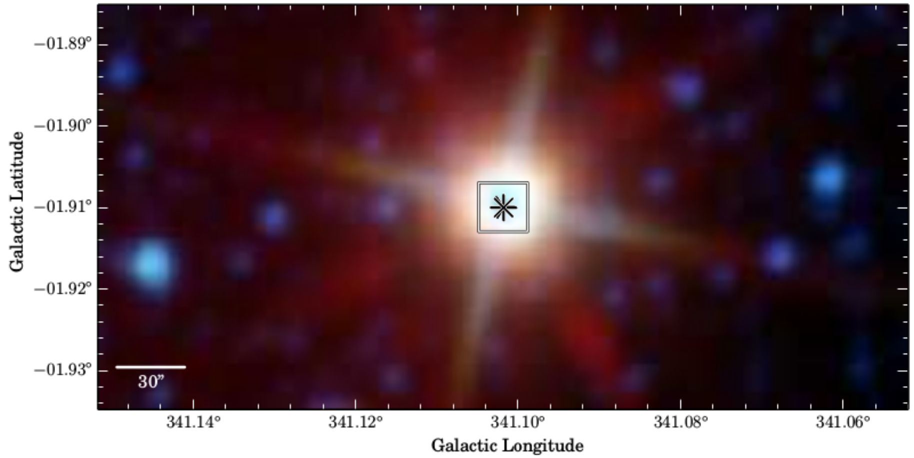


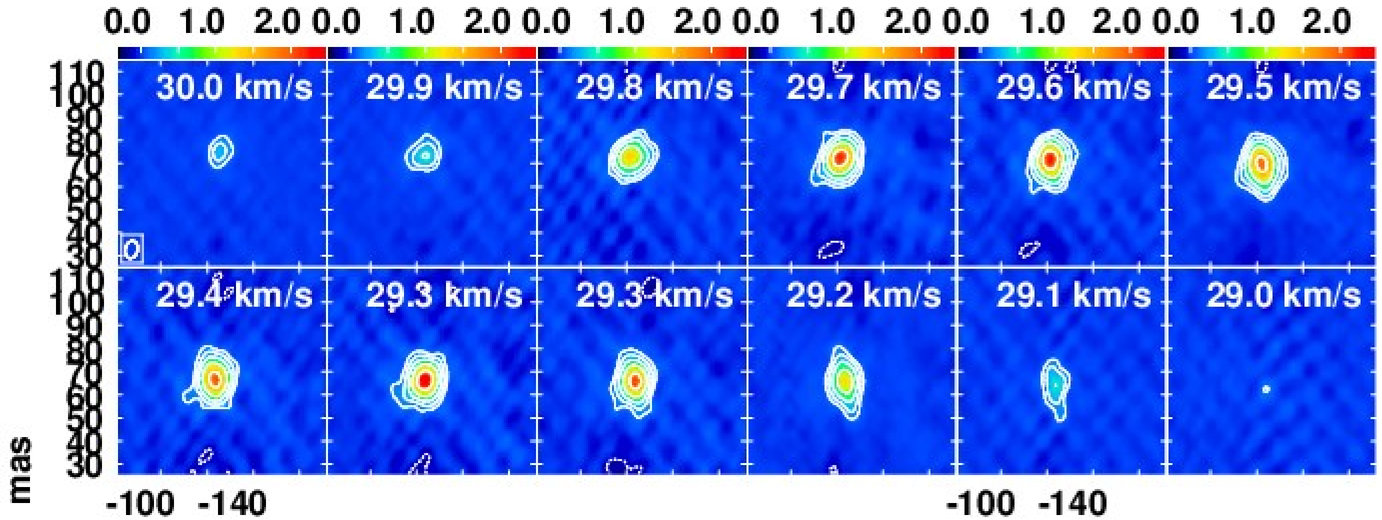
Fig. 16.— G341.102−1.910 – ES

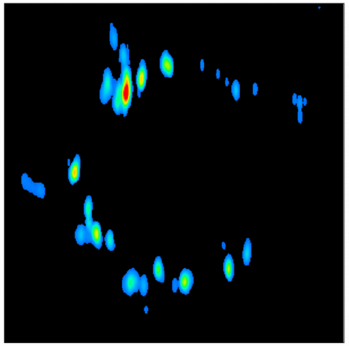
IAU Symposium 336 in Cagliari, Astrophysical Masers: Unlocking the Mysteries of the Universe, Italy 2017

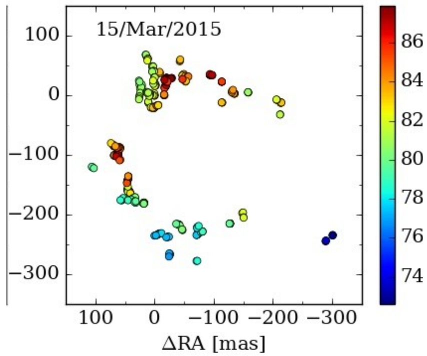
- 105 proceedings in total, 39 presented results obtained using the VLBI, nine using the EVN.

Spectral line observations

- Typically, the 2 MHz bandwidth is divided into 1024 (or 2048) spectral channels yielding 90 m/s (or 45 m/s) spectral resolution for 6.7 GHz methanol maser observations.







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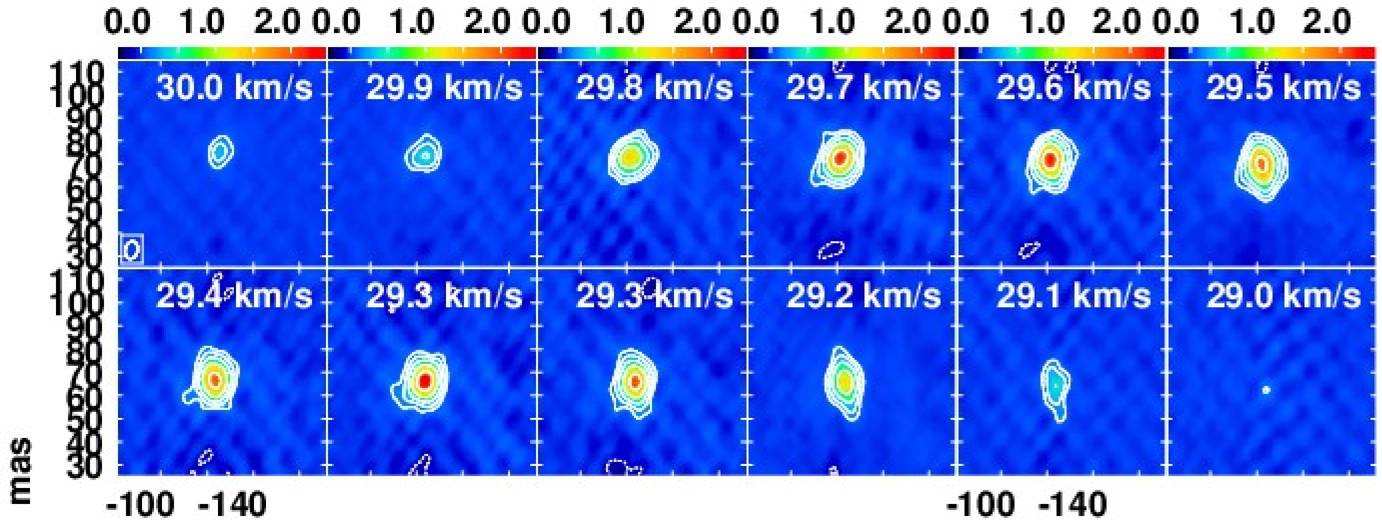
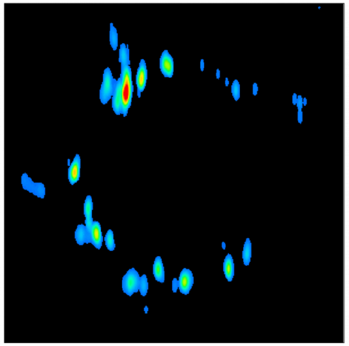
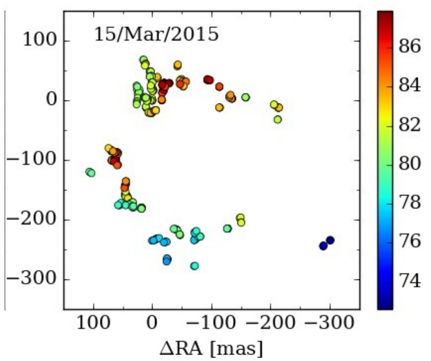


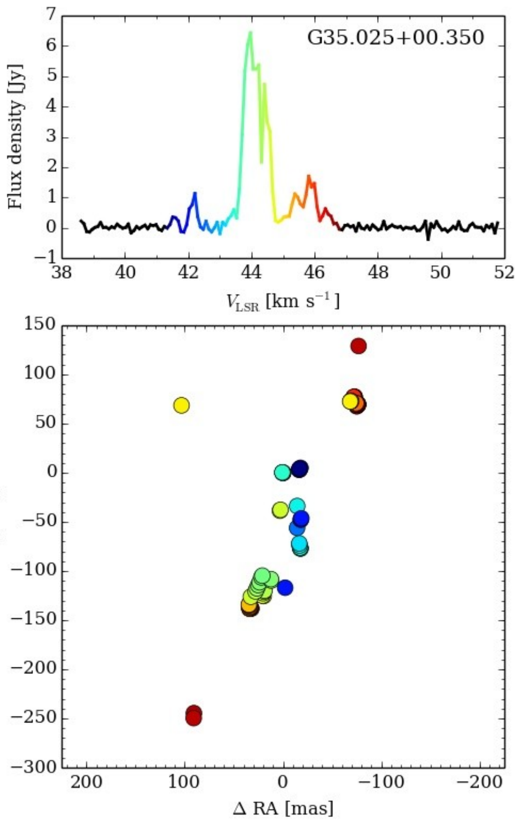


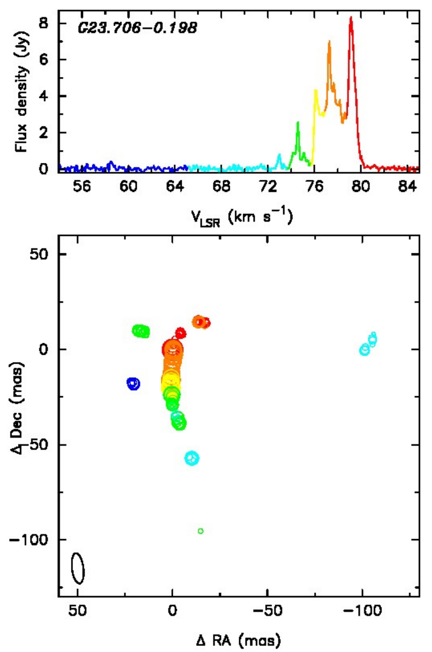


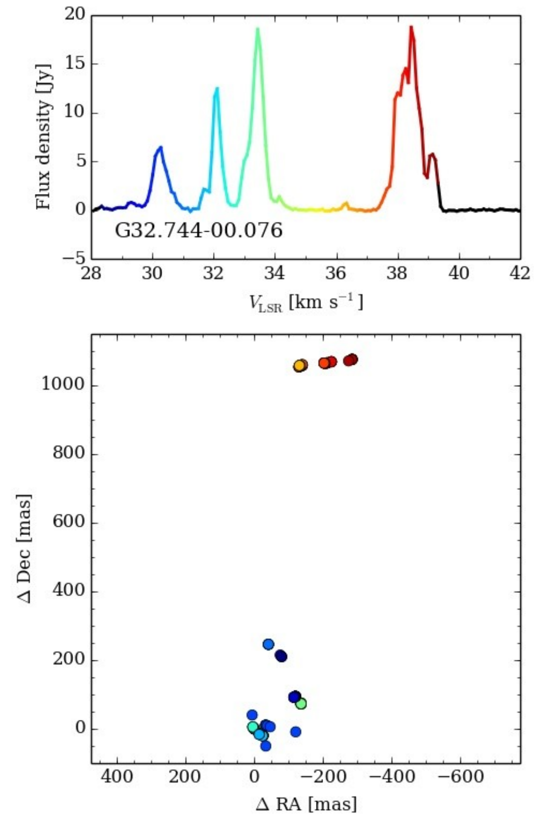
- We make hundreds images and we love JMFIT ;)

EVN & maser science:

- EVN has played a role in the 6.7 GHz methanol maser science. Especially, the morphology of this emission in **high-mass star-forming regions** was studied. Using 8-10 radio telescopes we obtained a diversity of structures.

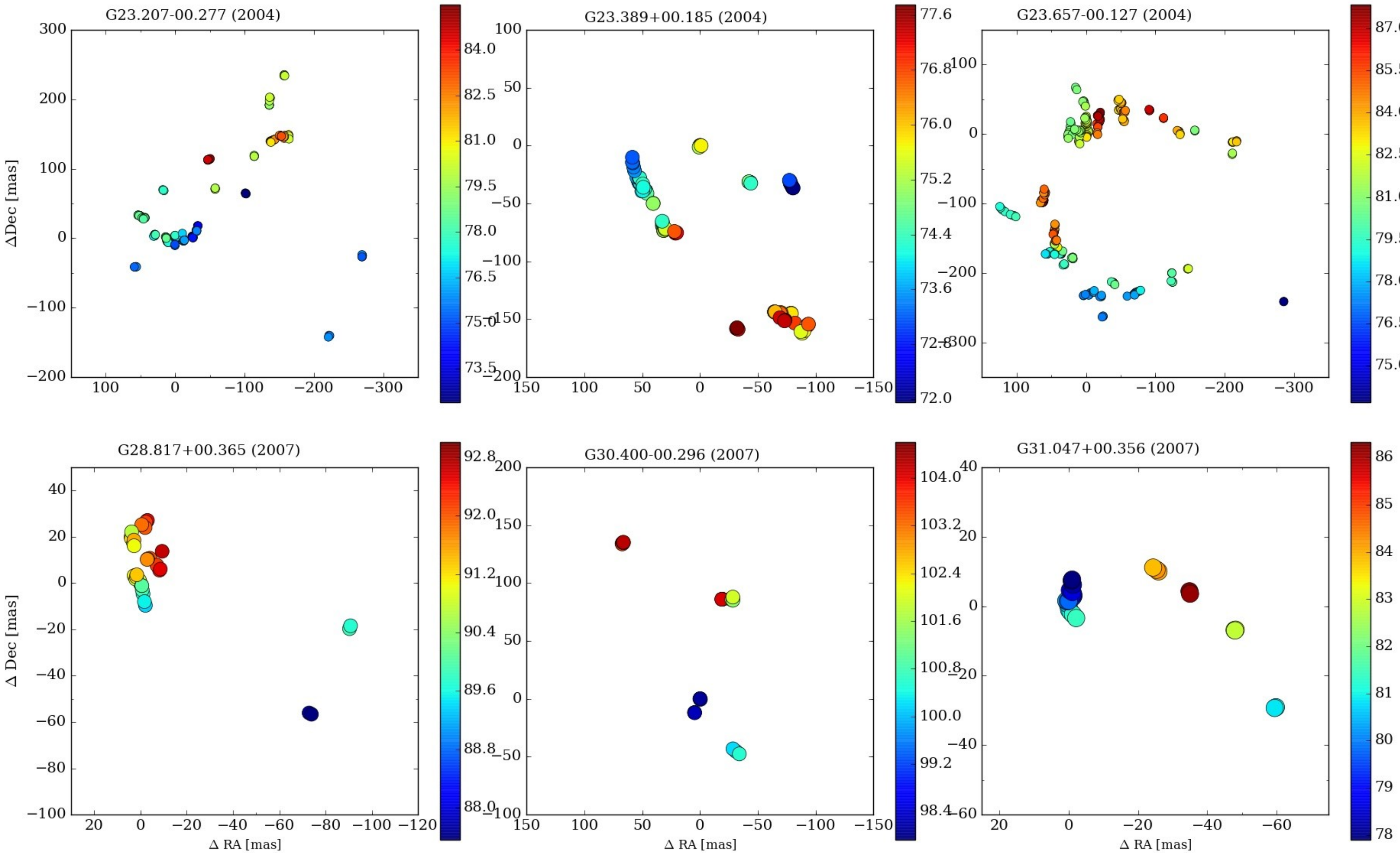






Bartkiewicz et al. 2009, 2016

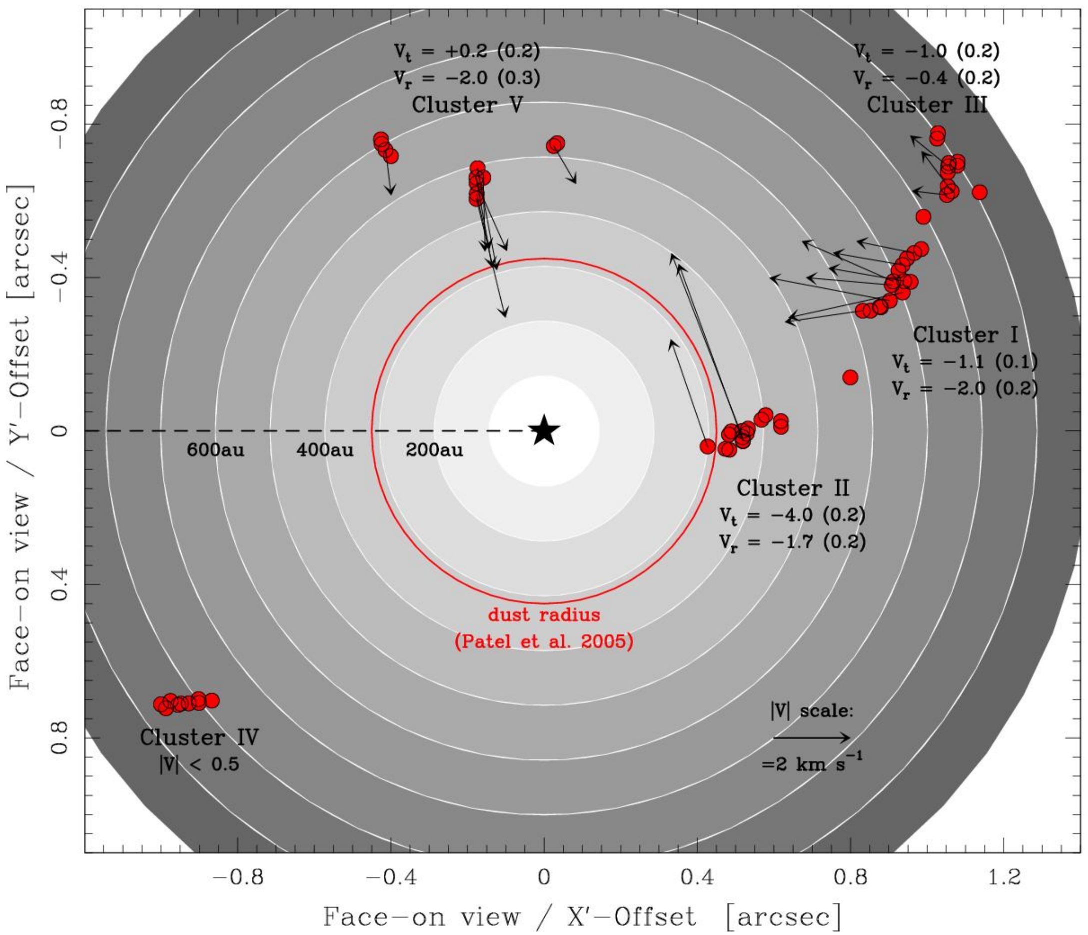
Maser morphologies



Kinematics at the milliarcsecond scale

We can trace motions of the gas at the level of a few km/s!

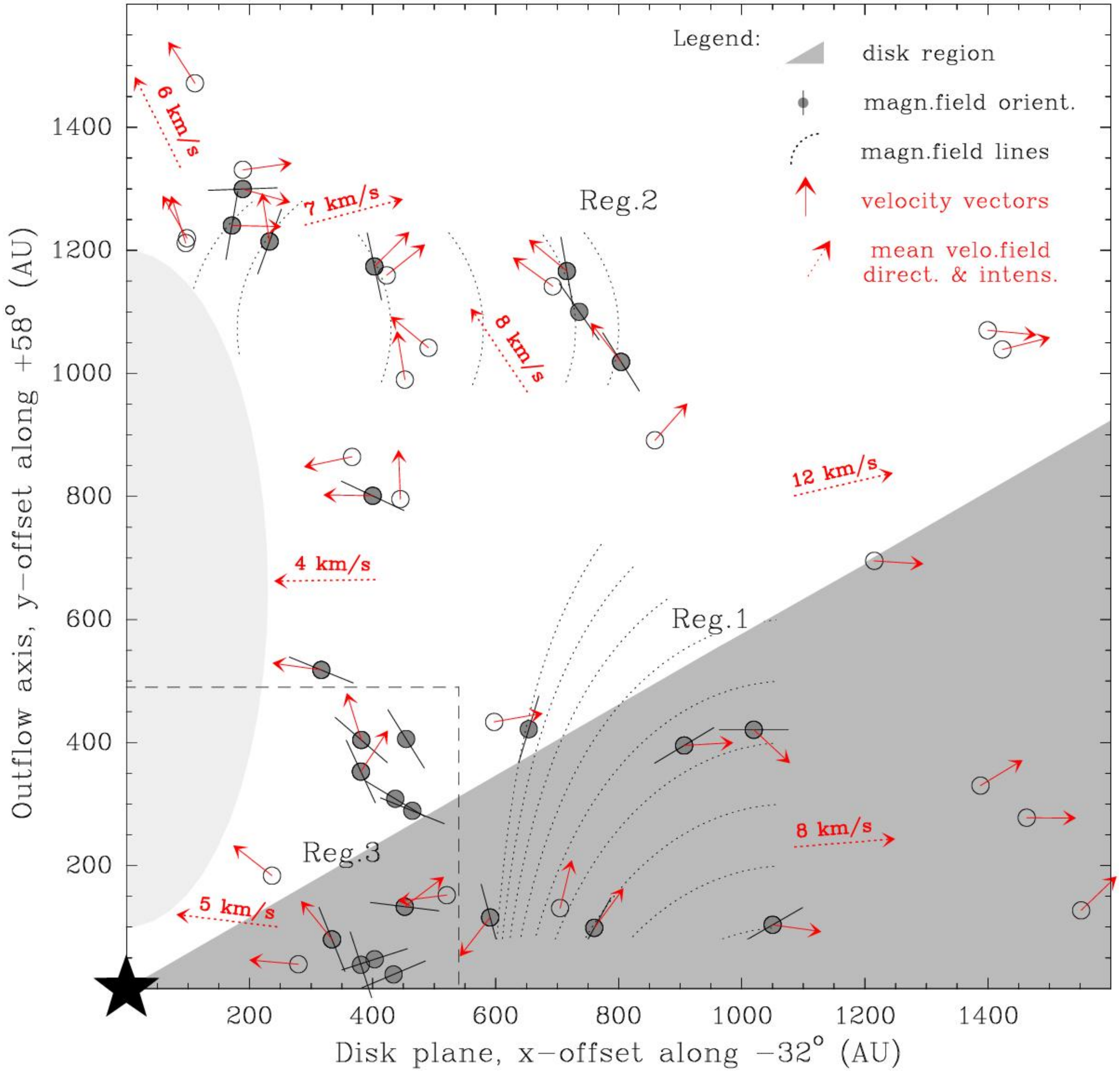
E.g.
Sanna et al. (2017):
- planar infall of CH_3OH gas around **HMSFR** Cepheus A HW2.
- contraction of the gas,
- central mass of 5–6 M_{Sun}



Kinematics and magnetic field - proper motions and polarimetry

Detailed picture of the gas dynamics and magnetic field configuration within a radius of 2000 AU of **a massive YSO** in G023.01−00.41 (Sanna et al. 2015).

Talk by G. Surcis

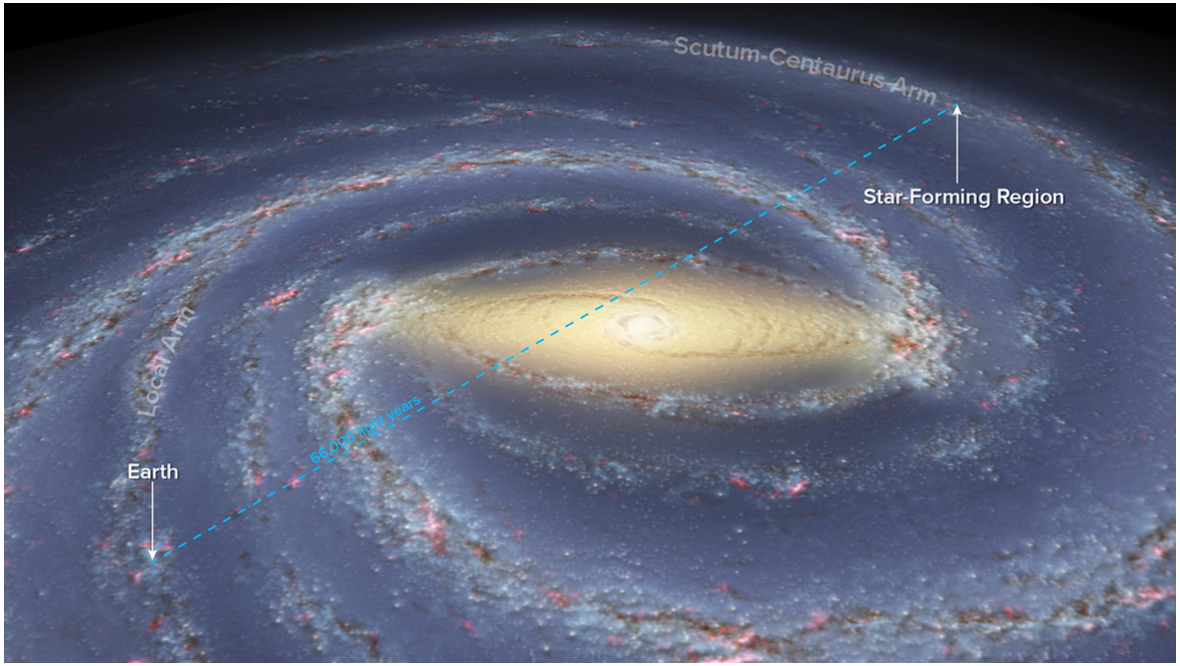


Astrometry (review talk by M. Rioja): distances and kinematics

- Owing to masers, their **compactness**, we can estimate exact distances to stars with the uncertainty of a few per cent through trigonometric parallaxes and kinematics of the masing regions.
- Mostly used VLBA, VERA to know the structure of the Milky Way.
- Recent achievement in the distance measurements is the distance to a star-forming region on the opposite side of our Milky Way Galaxy from the Sun: 20.4 kpc with 10% accuracy by Sanna et al. (2017).

  Talks by K. Immer, K. Rygl,

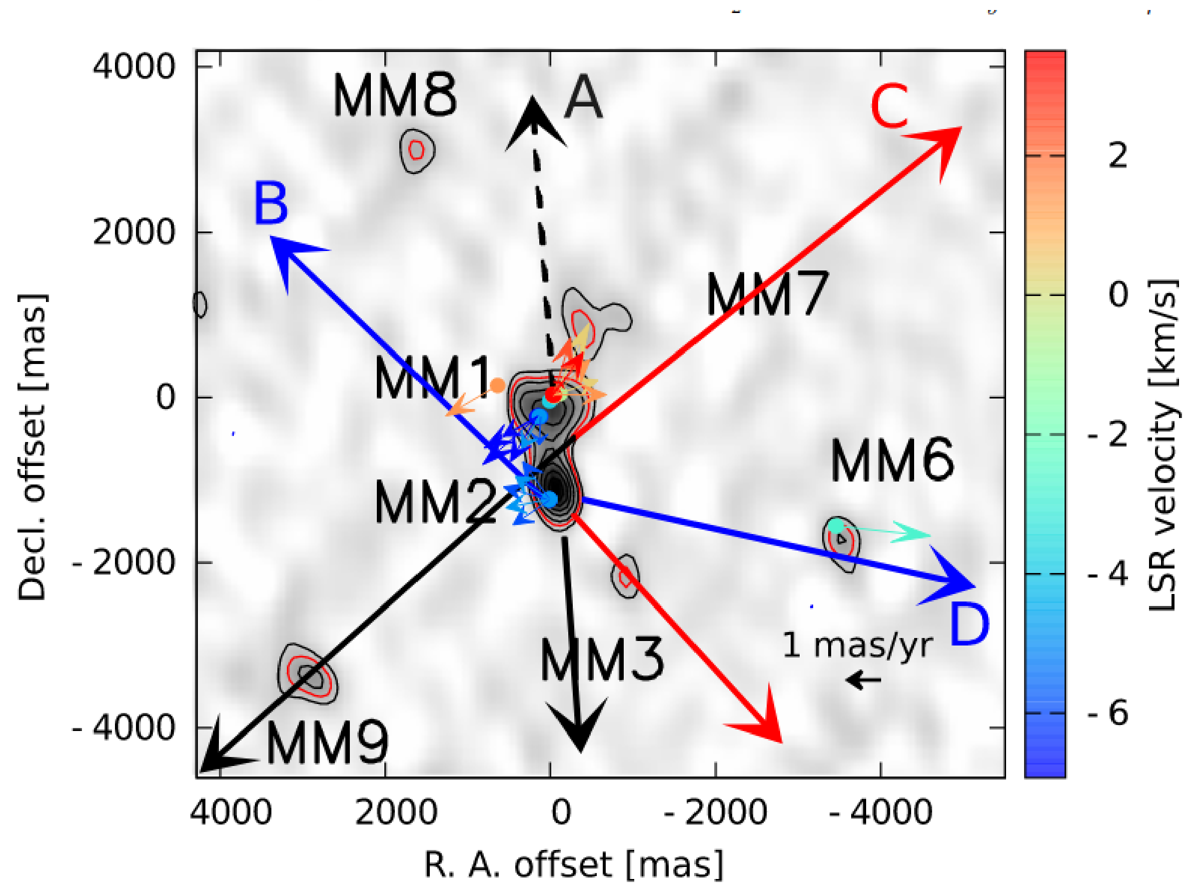
  H. van Langevelde



Distances and kinematics

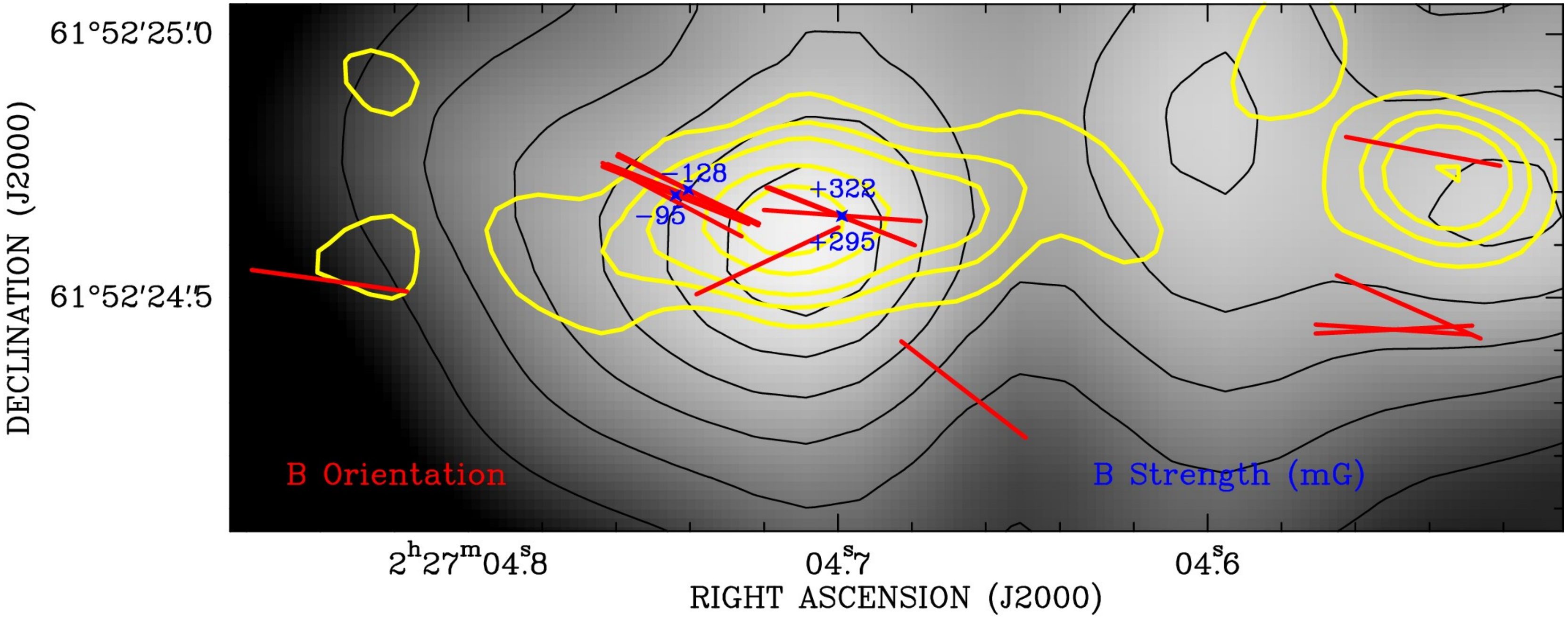
- E.g. Burns et al. (2017) estimated the distance to a **massive SFR** AFGL 5142 as 2.14 kpc with 2% uncertainty. They found remarkable bipolar bowshocks expanding from the most massive member.

  VERA observations.



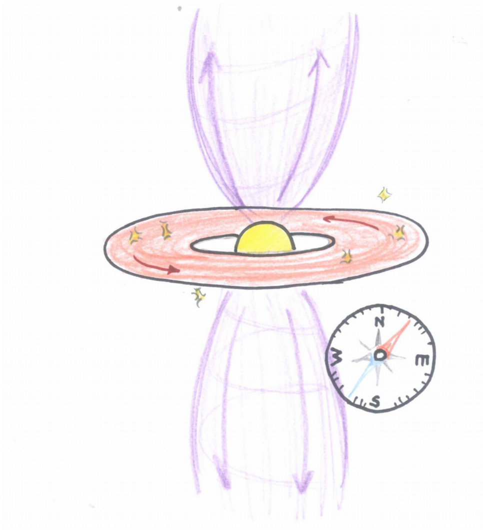
Magnetic field

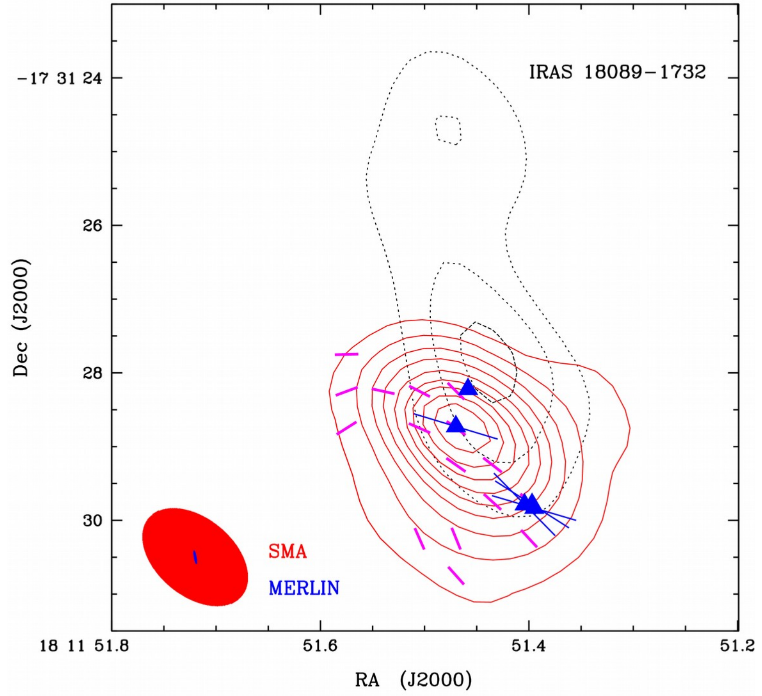
- Goddi et al. (2017) presented the first VLBI polarization measurements of H_2O masers in W3(H_2O) - **the high-mass SFR** containing a synchrotron jet driven by an embedded high-mass YSO. The inferred magnetic field strength and orientation was directly compared to the kinematics of the molecular outflowing gas, on scales of order of tens to hundreds AU. Talk by C. Goddi.



In a few minutes...

- Dall'Olio et al. (2017) using MERLIN observations at 6.7 GHz of a **massive protostar** IRAS 18089-1732 found that the magnetic field in the maser region has the same orientation as in the disk. Thus the large-scale field component, even at the AU scale of the masers, dominates over any small-scale field fluctuations. Talk by D. Dall'Olio.





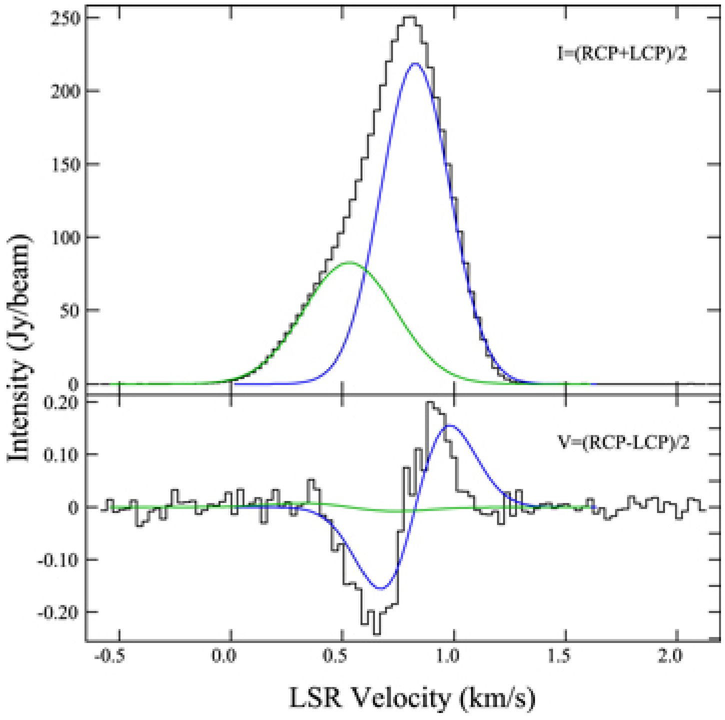
Progress due to...

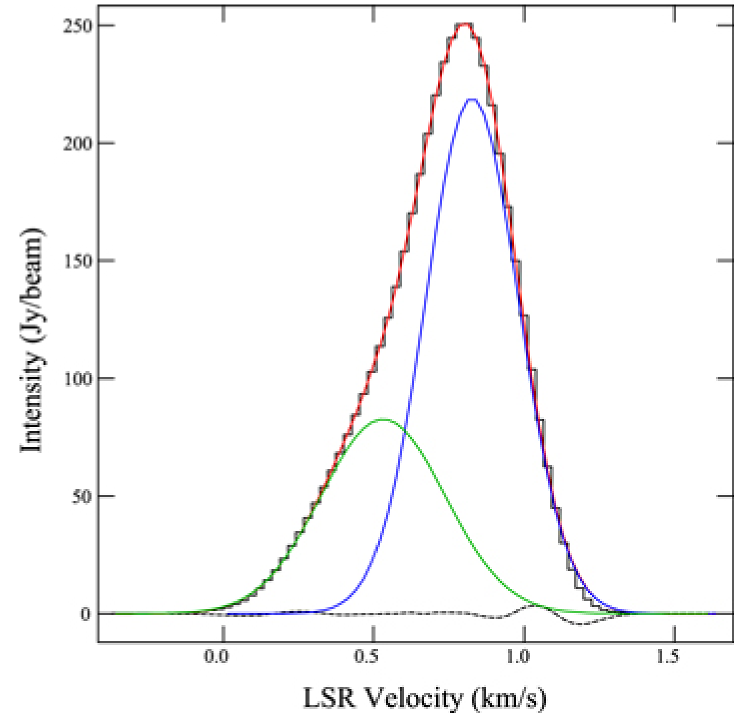
- Lankhaar et al. (2018) reported a quantitative theoretical model of the magnetic properties of methanol, including the complicated hyperfine structure that results from its internal rotation. New calculations of Landé g-factors for all the hyperfine transitions of the methanol molecule.

  “A team of scientists, led by Boy Lankhaar at Chalmers University of Technology, has solved an important puzzle in astrochemistry - how to measure magnetic fields in space using methanol, the simplest form of alcohol.”

Higher frequency

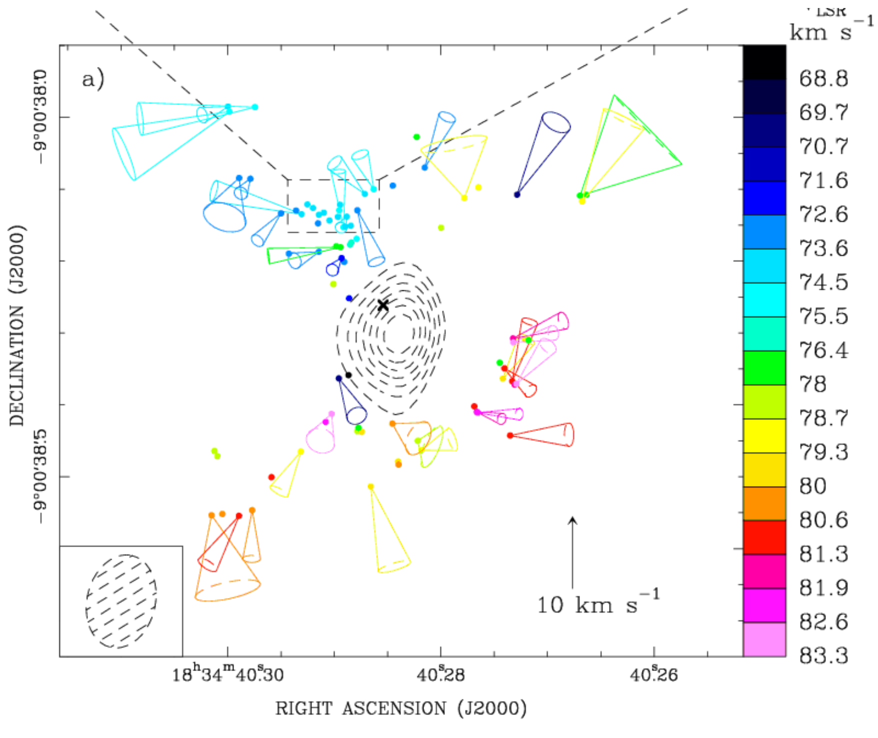
- Momjian and Sarma (2017) detected Zeeman effect in the 44 GHz Class I methanol maser line towards **the star forming region** DR21(OH) using VLA. Stokes I and V profiles:

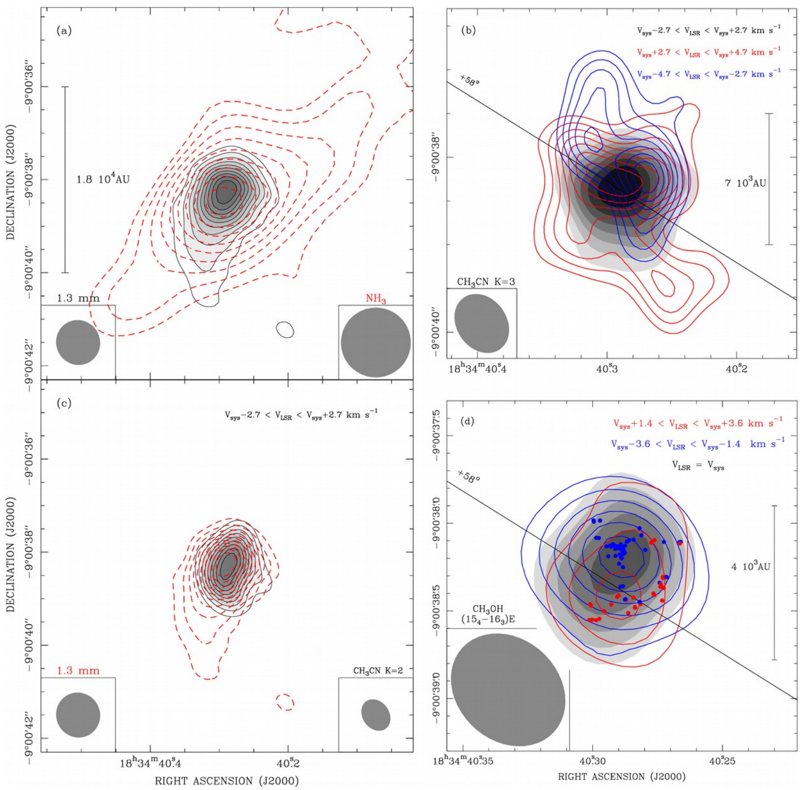




Masers push us for searching: *what is inside?*, *nearby?*, *where is a driving source?*

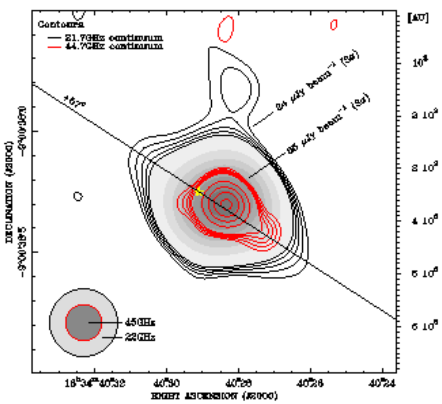
- Sanna et al. (2010): EVN kinematic studies of 6.7 GHz methanol masers in **HMSFR** G23.01-0.41. Later observations using SMA (Sanna et al. 2014).

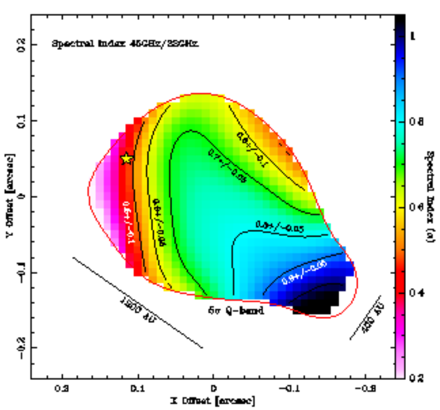




Masers push us for searching: *what is inside?*, *nearby?*, *where is a driving source?*

- Next, searches using VLA and ALMA of 22, 45 GHz and 200 GHz continuum (Sanna et al. 2016, 2018). Masers are deep inside tracing the inner outflow cavity.
  Talk by L. Moscadelli.





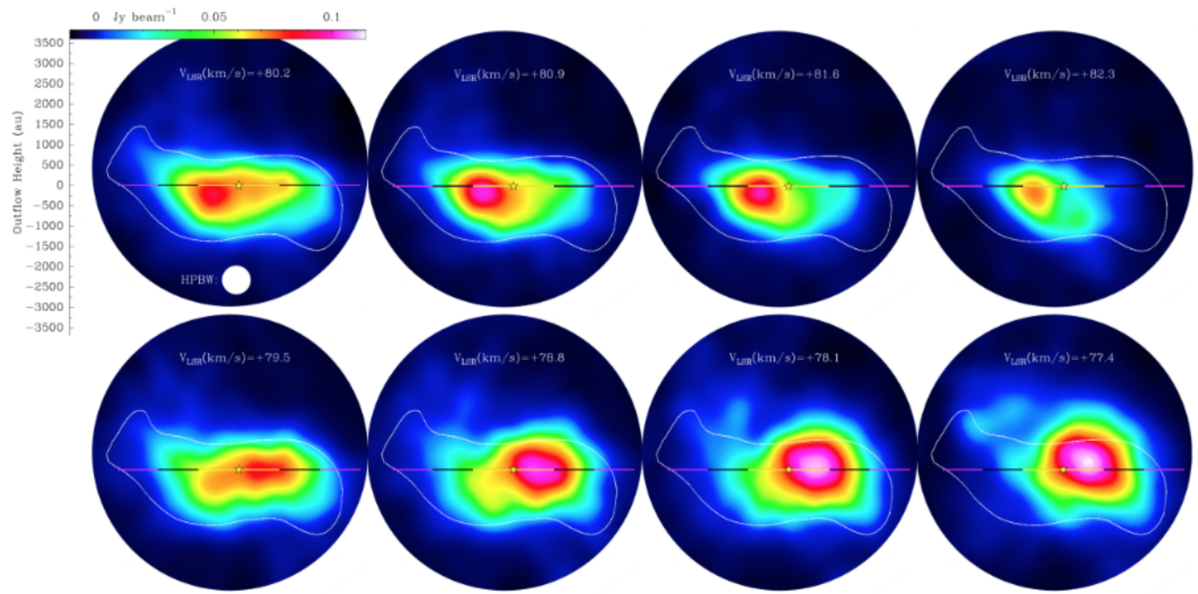


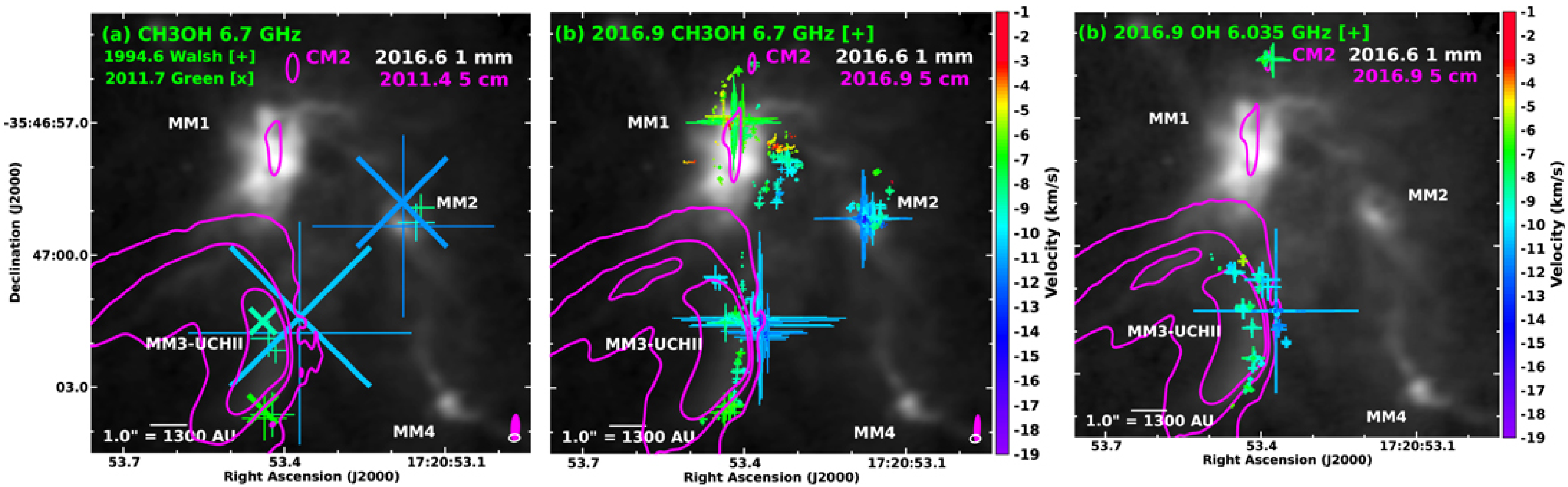
Fig. 2. Channel maps of the CH_3OH ($10_{2,8}$–$9_{3,7}$) A^+ line emission (colors) observed at 700 au resolution with ALMA (synthesized beam in white). Each map is labeled by its central velocity (V_{LSR}). The brightness scale of the line emission is quantified by the wedge on the top left panel. The reference system and symbols in each channel map are the same used in Fig. 1. For comparison, the white contour corresponds to the dotted black contour of Fig. 1.

Projects:

- **POETS** (Protostellar Outflows at the EarliesT Stages) by Sanna et al. (2018). The purpose of studying the dynamical properties of the outflow emission in the vicinity of luminous young stars. Selection of young stars showing water masers (outlows) using VLA – searching for continuum. Talk by F. Bacciotti.
- **KaVA** (Korean and VERA Array) project to do a systematic observational study of the 22 GHz water masers and 44 GHz class I methanol masers in high-mass star-forming regions followed by JVN and ALMA observations. Talk by T. Hirota.

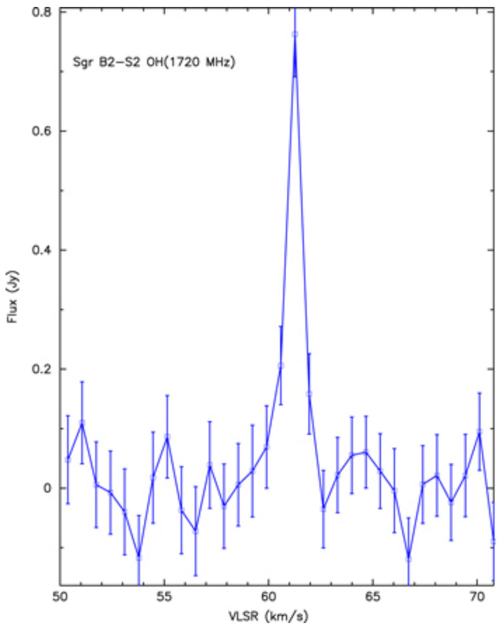
Masers may help...

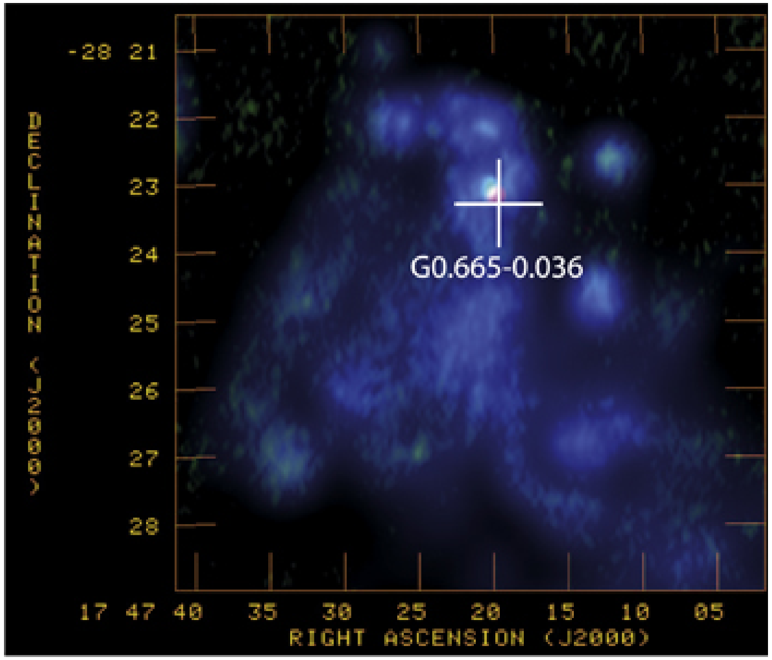
- Hunter et al. (2018) the first sub-arcsecond VLA imaging of 6 GHz continuum, methanol maser, and excited-state hydroxyl maser emission toward the **massive protostellar cluster** NGC 6334I following the recent 2015 outburst in (sub)millimeter continuum toward MM1, the strongest (sub)millimeter source in the protocluster. Flaring the water masers by Brogan et al. (2018). Talk by J. Chibueze.



SNR maser OH 1720 MHz

- Yusef-Zadeh et al. (2016) found the 1720 MHz OH maser coinciding with a 150 MHz nonthermal radio source in Sgr B2(M), a part of the well known **star-forming molecular cloud**. It comes from shocked gas and imply either the site of a SNR – molecular gas interaction or a wind-wind collision in a massive binary system. VLA data.





Evolved star masers

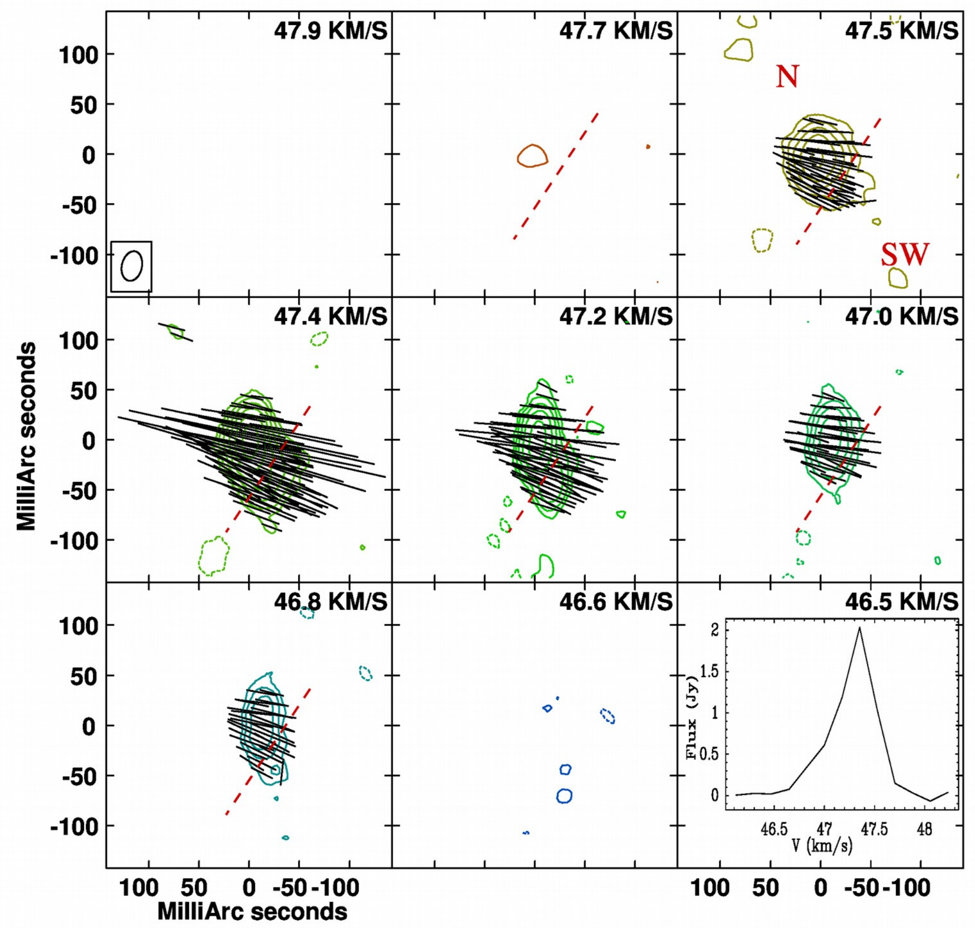
- Vicente et al. (2016) presented the monitoring using the 40m dish of the 43 GHz SiO emission from evolved stars. Emission seems to come from the very inner circumstellar layers. Some of them are maser lines and can be suitable for the EVN imaging although the missing flux is a problem (Desmurs et al. 2017).

- Messineo et al. (2018) using the IRAM telescope found that the 86 GHz SiO masers are common in O-rich AGB stars.

  Talks by A. Richards, J.F. Desmurs,
  Y. Yun

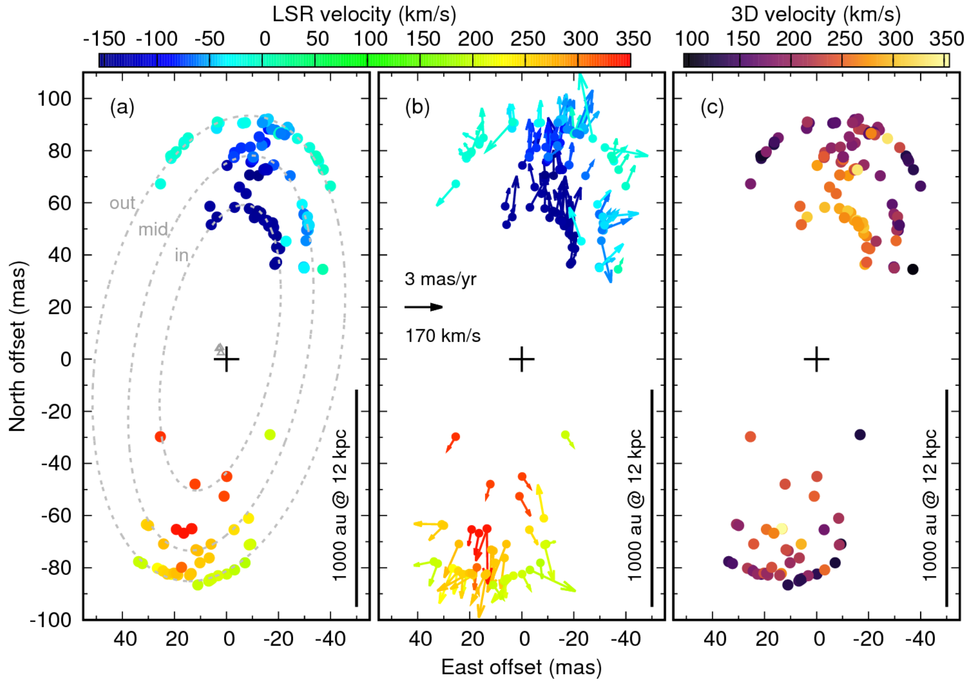
Evolved star masers

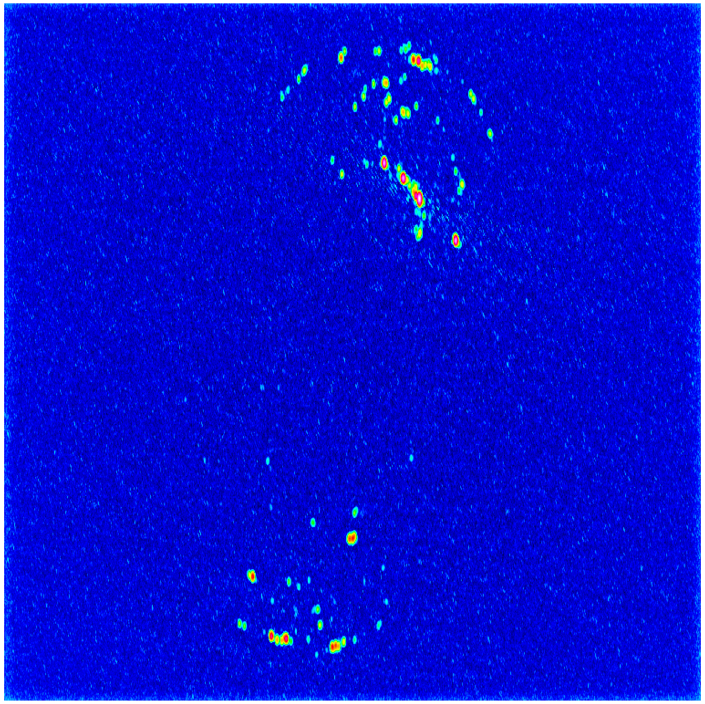
- Etoka et al. (2017) presented OH and H_2O observations towards o Ceti (Mira star) with the Nançay, Medicina and Effelsberg Radio Telescopes, MERLIN and EVN-(e)MERLIN. The flaring regions are found to be less than 40 ± 4 AU, unusual the OH maser zone coincides with the H_2O zone. The magnetic fields in the circumstellar envelope are found to be important, as can be seen from the highly ordered linear polarization vectors observed in the OH maser components of o Ceti.



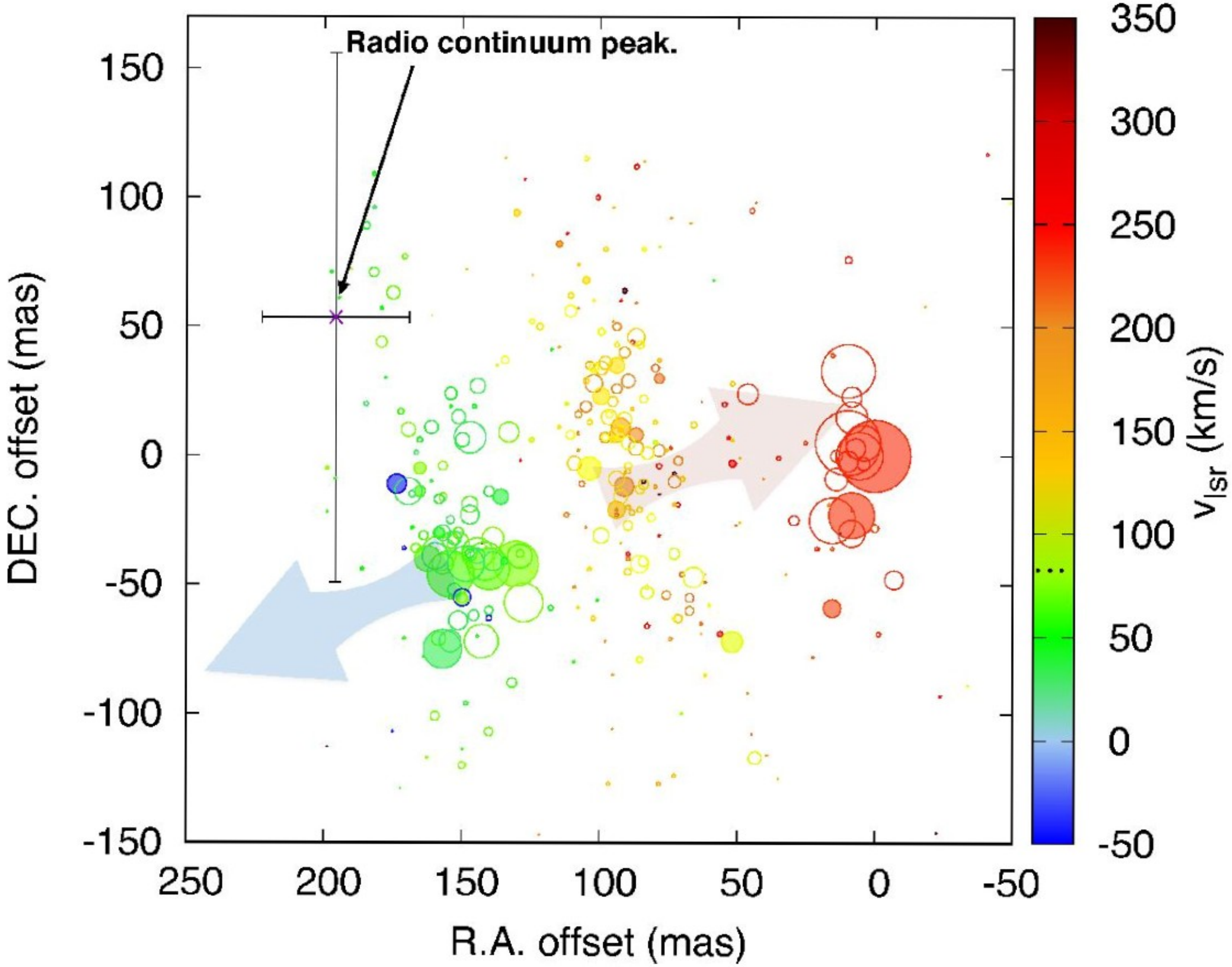
Tracing outflows

Orosz et al. (2018) two remarkable and unusual 22 GHz water fountains at **post-AGB star** IRAS 18113-2503 with spectacular bipolar bow shocks in their high-speed collimated jet-driven outflows. The jets are formed in very short-lived, episodic outbursts, which may indicate episodic accretion in an underlying binary system. VLBA observations. (Talk by G. Orosz by R. Burns)





- Perez-Sanchez et al. (2017) analysed the H_2O masers (water fountain) in the circumstellar envelope of **the post-AGB star**: nebula IRAS 18043−2116: The high-velocity H_2O maser spectral features, and the shock-excited H_2 emission detected could be produced in molecular layers around high-velocity outflows. Observations using ATCA, JVLA and VLT.



ATCA, MMB surveys:
“Golden age for surveys!” Shari Breen

- Avison et al. (2016) studied the associations of the 6035 and 6030 MHz OH and 6668 MHz CH_3OH masers in the southern sky.
- Breen et al. (2018) compared the occurrence of 6.7-GHz and 12.2-GHz methanol masers with 22-GHz water masers and 6035-MHz excited-state OH masers. Ex-OH comes from the warmest sites.
- Another ATCA studies by McCarthy et al. (2018): The 95-GHz maser components appear to be preferentially located closer to the driving sources in HMSFRs comparing to other I class methanol masers (36 and 44 GHz). This may indicate that this transition is more strongly inverted nearby to background continuum sources.
- Ellingsen et al. (2018) the first high-resolution observations (ATCA) of 37.7-, 38.3- and 38.5-GHz class II methanol masers.

More masers in low-mass star-forming regions:

- Owing to Rodriguez-Garza et al (2017) we know more regions where 44 GHz methanol masers exist (VLA observations), some may be related to low-mass protostars. Class I methanol masers are associated with postshock gas in the lobes of chemically active outflows in low-mass star formation regions (Kalenskii et al. 2018).

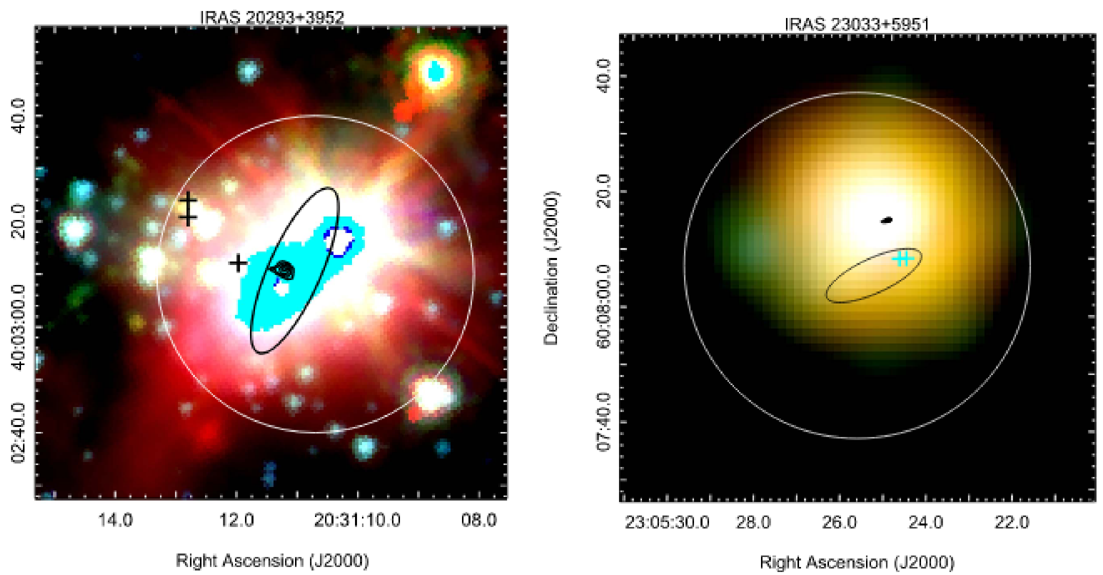
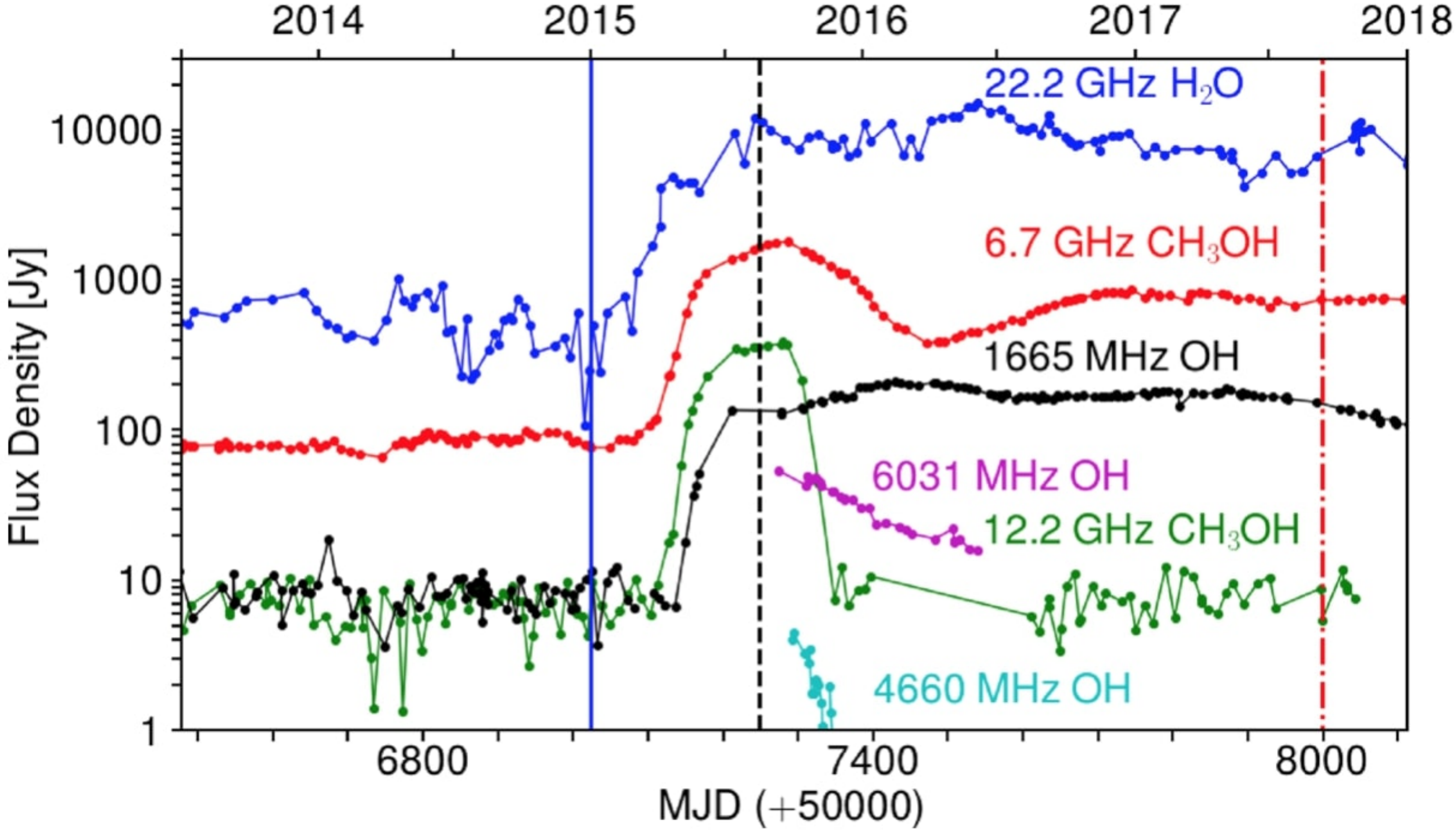


Figure 1. (Continued.)

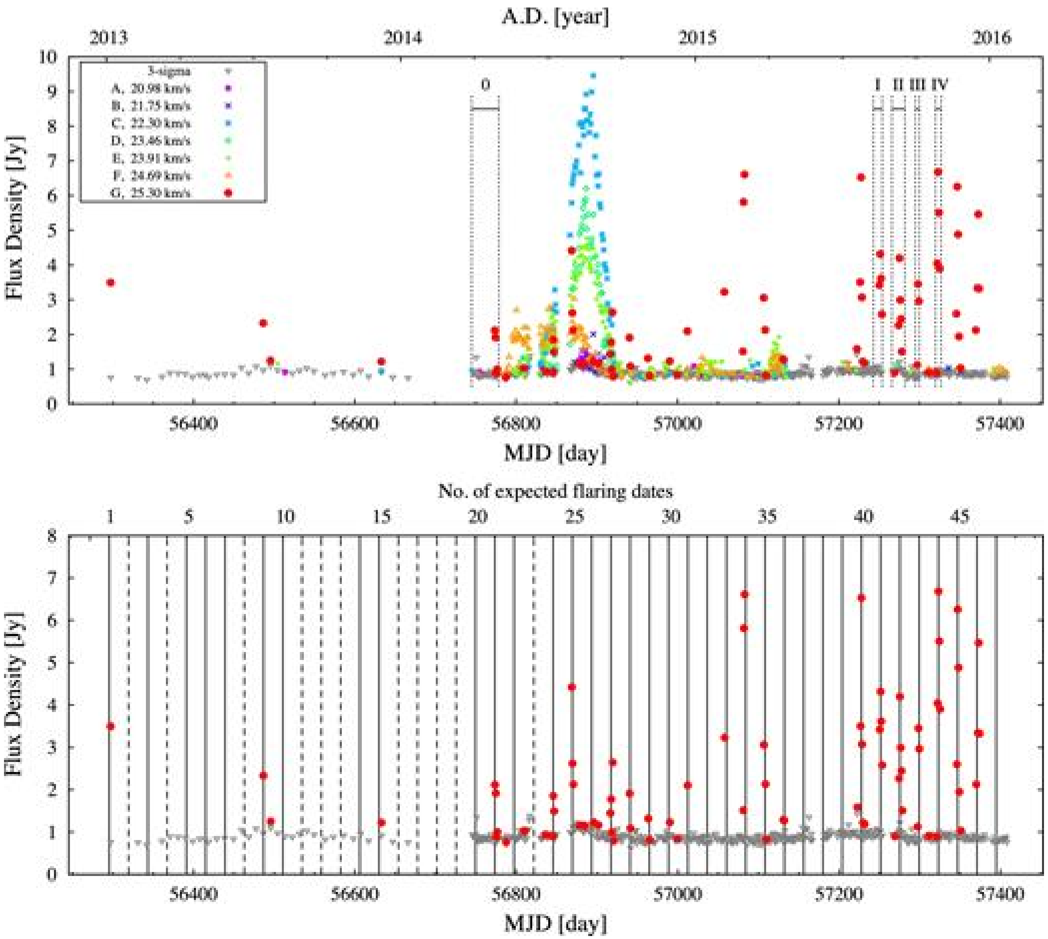
Variability of masers

- MacLeod et al. (2018) presented masing event in NGC 6334I. Hydroxyl, methanol and water masers are flaring! Talks by M. Olech, M. Gray, R. Burns.



Variability

- Sugiyama et al. (2017) presented the shortest periodic (a period of 23.9 days) and flaring flux variability of a methanol maser emission at 6.7 GHz in G014.23−00.50 using the Hitachi 32-m radio telescope.

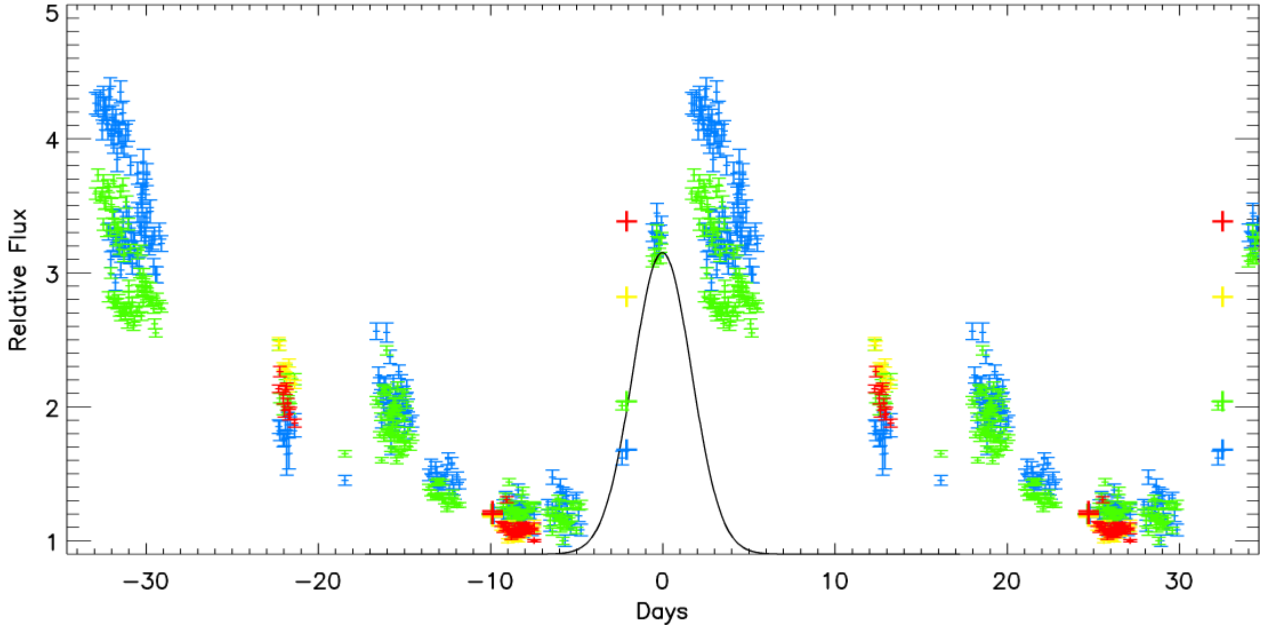


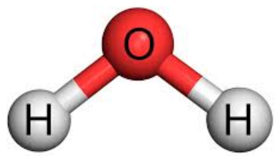
Monitoring

- Sudou et al. (2017) monitored using Kagoshima 6-m telescope the H_2O maser emission of the semi-regular variable R Crt. It seems reasonable to consider that the velocity variation of the maser source is caused by the shock propagation in the envelope due to stellar pulsation.

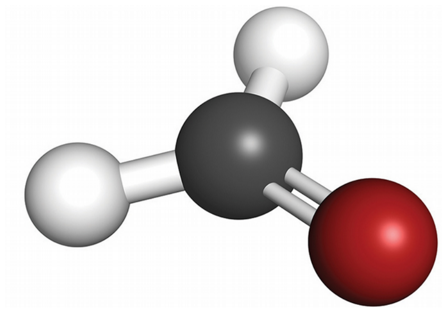
Maser & infrared varibility

- “Infrared variability, maser activity, and accretion of massive young stellar objects” by Stecklum et al. (2018). They extracted the IR light curve from NEOWISE data for the intermediate mass YSO G107.298+5.639. Thus, for the first time a relationship between the maser and IR variability was established. While the IR light curve shows the same period of ∼34.6 days as the masers, its shape is distinct from that of the maser flares.

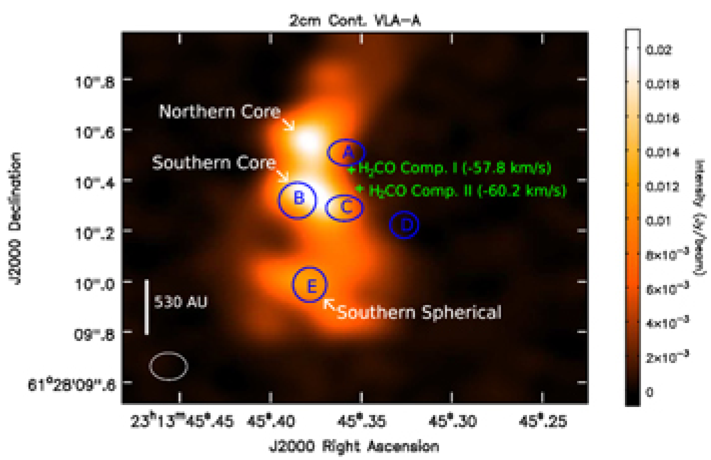


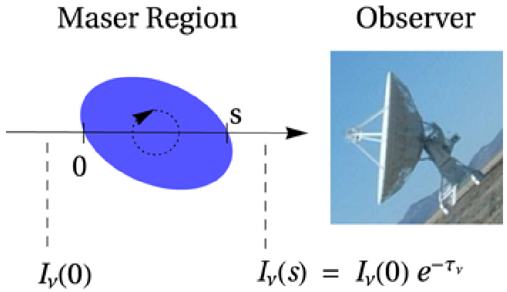


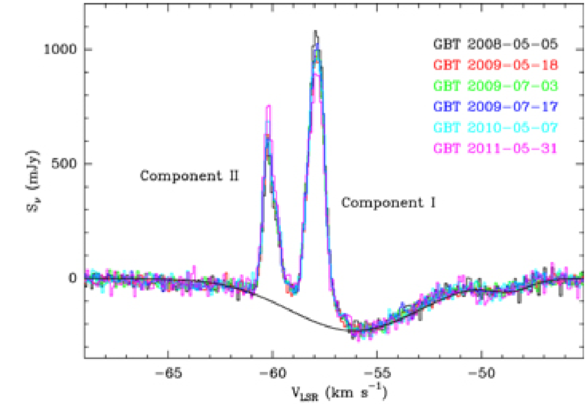
Formaldehyde maser

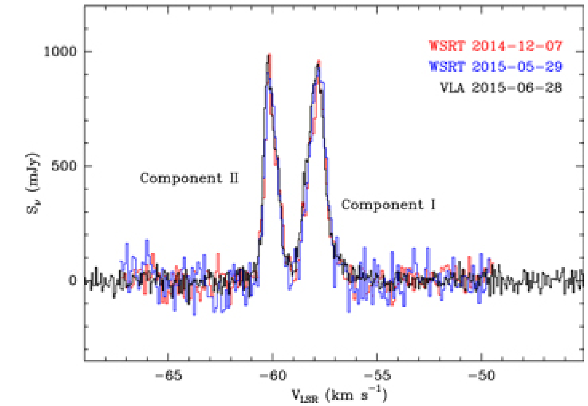


- Andreev et al. (2017) presented results of a multi-epoch monitoring program on variability of 6 cm formaldehyde (H_2CO) masers in the **massive star forming region** NGC 7538 IRS 1 from 2008 to 2015 conducted with the GBT, WSRT, and VLA. Also the 12.2 GHz methanol and 22.2 GHz water masers were observed and the decreases in fluxes were noticed. The variability may be caused by changes in the maser amplification path in regions with similar morphology and kinematics.



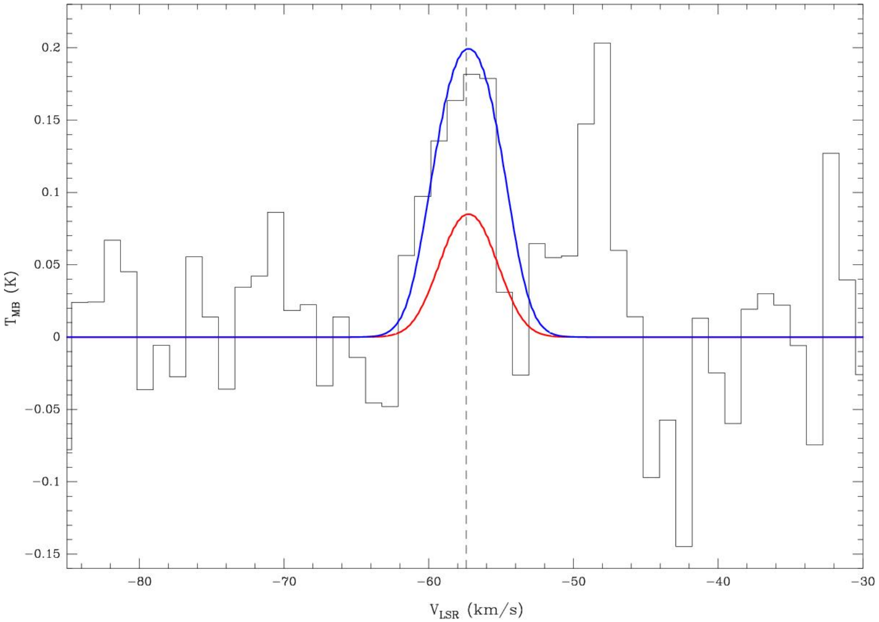


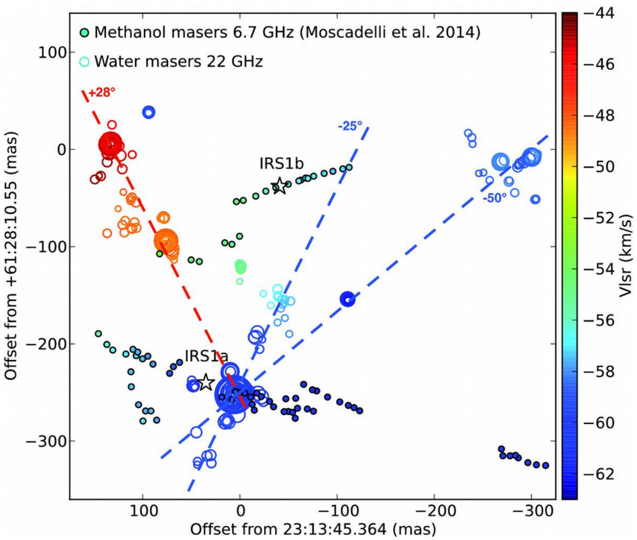




News

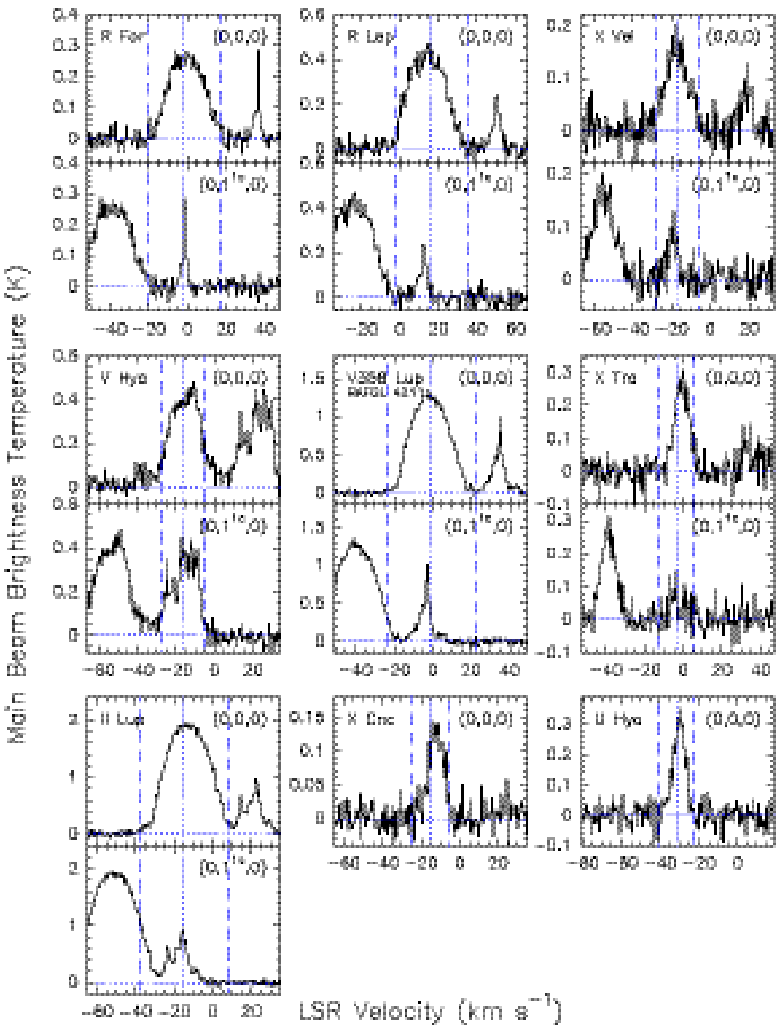
- Herpin et al. (2017): first detection of THz water maser in NGC7538-IRS1 with SOFIA.





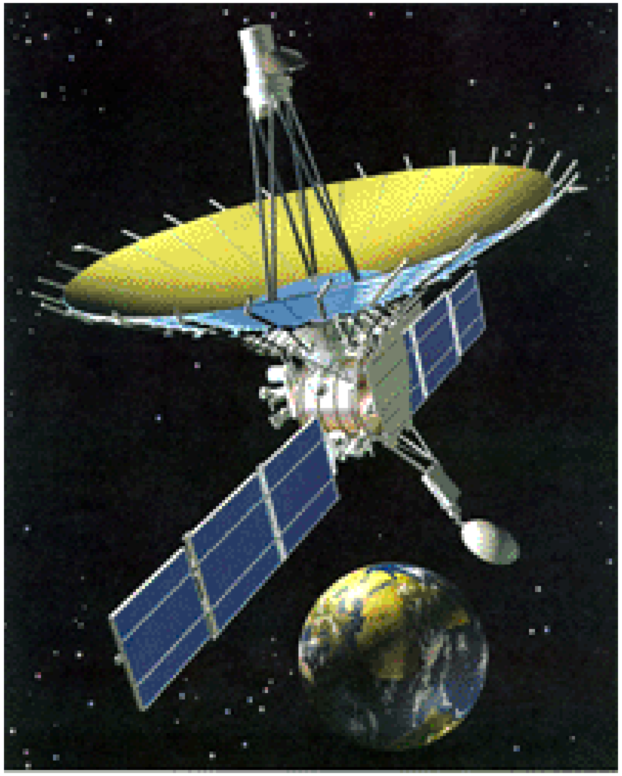
Hydrogen cyanide masers

- Menten et al. (2018) widespread HCN maser emission in carbon-rich evolved AGB stars observed by APEX ("*Our observations were made on 2015 May 28 under excellent weather conditions with the 12 m diameter APEX submillimeter telescope...*").



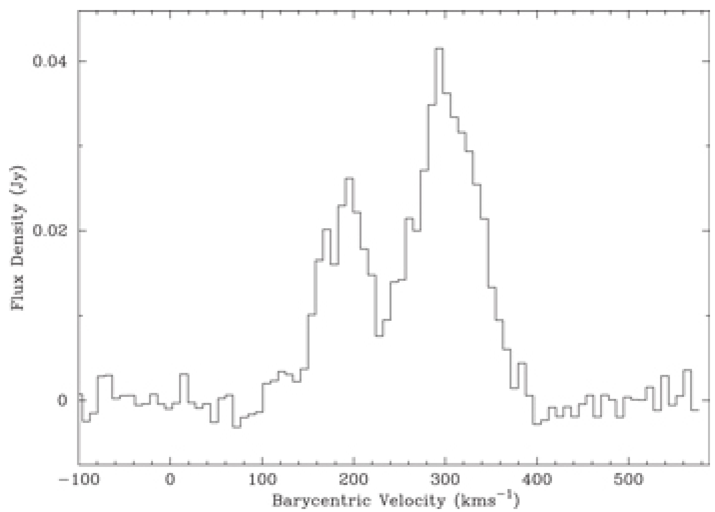
Knowing the sizes of maser spots: RadioAstron space-VLBI project

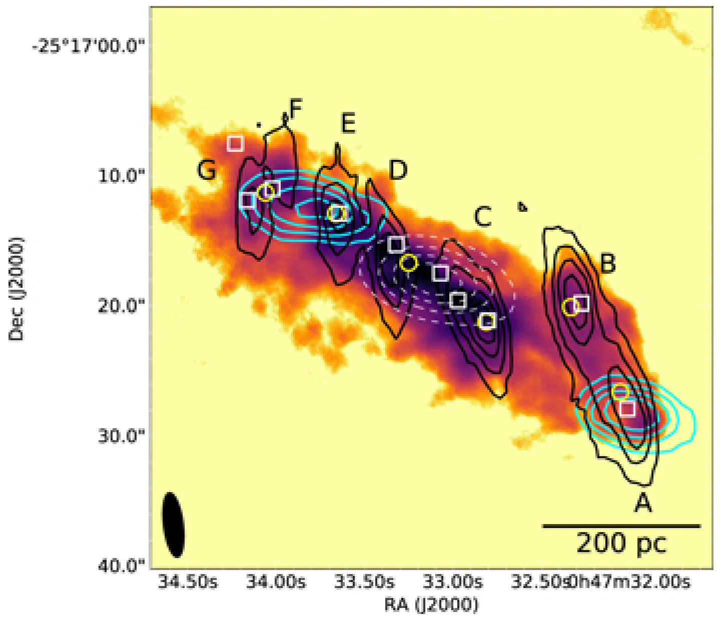
- Talk by A. Sobolev: OH and H_2O very compact features with angular sizes about 20-60 μas have been detected in star-forming regions of our Galaxy.



Far, far away… Cyanoacetylene HC_3N maser

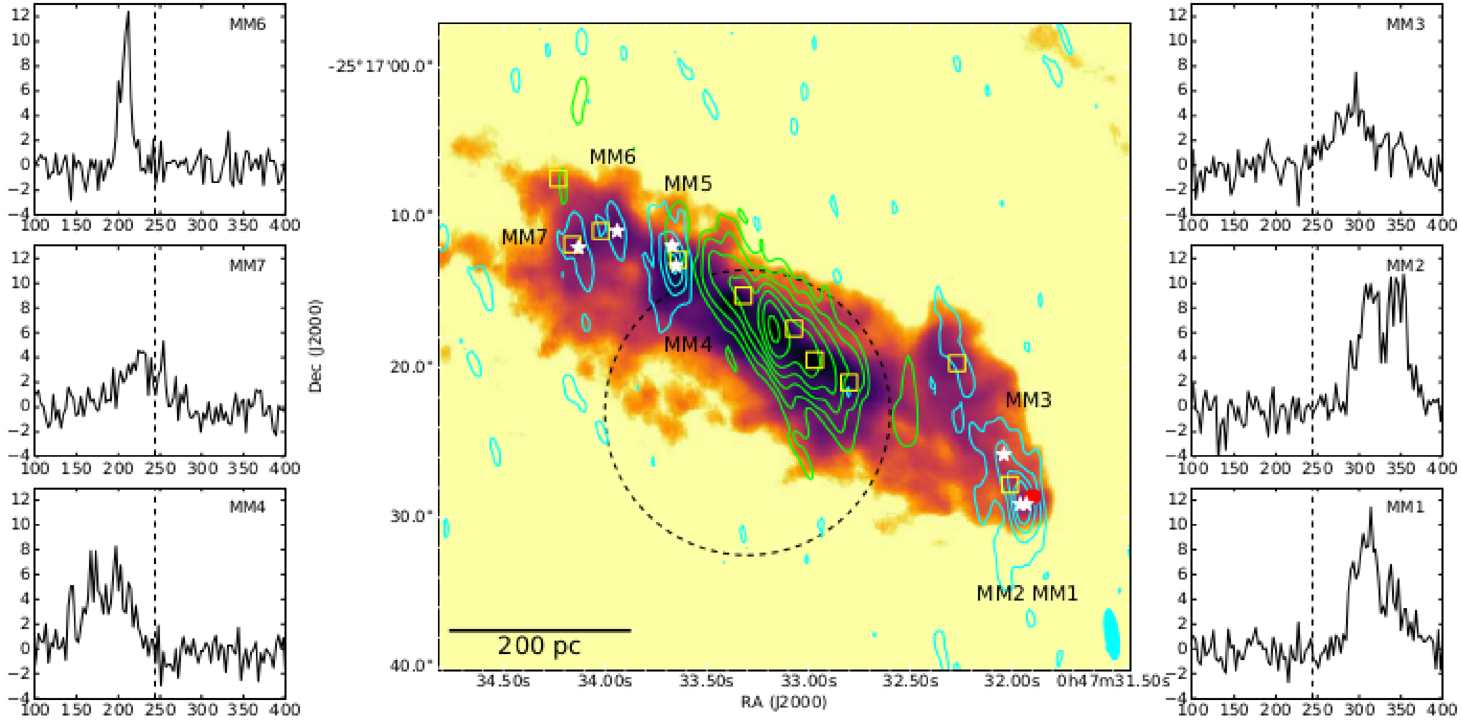
- Ellingsen et al. (2017a) high-resolution observations of the 36.4 GHz transitions of HC_3N in NGC 253 have detected weak maser emission offset from the nucleus of the galaxy. This emission appears to be associated with a region of the galaxy close to the inner edge of the bar, where there is a significant abundance of molecular gas and widespread low-velocity shocks.





Far, far away… Class I methanol masers in NGC 253: Alcohol at the end of the bar

- Ellingsen et al. (2017b) found 36.2 and 44.1 GHz (for the first time) class I methanol masers towards the nuclear region of the NGC 253 galaxy. The methanol emission is located towards the edges of the nuclear molecular gas in regions where there is ionising radiation to dissociate the molecules. They occur there due to large-scale cloud-cloud collisions.
- Similar studies by McCarthy et al. (2018a,b) for NGC 4945.



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