WP7 F2F meeting

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Stars: formation and evolutionary stages

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&

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We appreciate input from: Gabriele Surcis, Huib van Langevelde, Alberto Sanna, Wouter Vlemmings, Anita Richards, Sandra Etoka, Danielle Fenech, Luca Moscadelli, Marcin Gawronski, Jack Radcliffe
and we still need you!

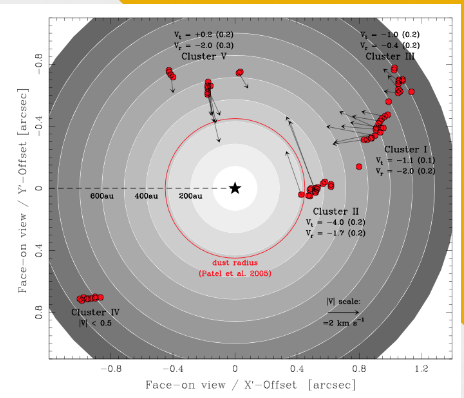
Stars: formation and evolutionary stages using EVN

- High mass star formation
  - Maser astrometry
  - Maser polarimetry
- Exoplanets and brown dwarfs
- Stellar winds and colliding-wind binaries
- Evolved stars

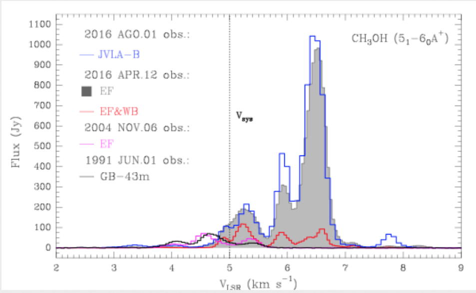
High mass star formation –
– first thoughts and needs

VLBI is providing an important contribution to the understanding of HMSF:

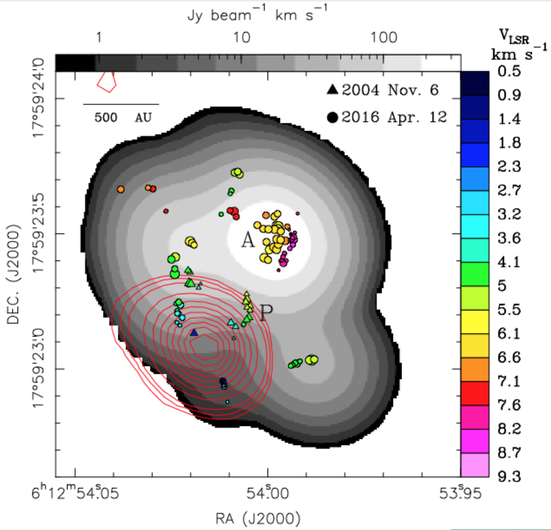
- Accretion disks kinematics (Torstensson+2011, Sanna+ 2015)
- High resolution magnetic fields correlated with disks/outflows (Surcis+ 2015, Dall'Olio+ 2017)
- Accretion burts (Caratti o Garatti+ 2016, Moscadelli+ 2017)
- All thanks to high resolution kinematics, polarimetry and astrometry <u>only possible with VLBI</u>
- Need better NS uv coverage to map SFRs on Galactic plane (like AVN+EVN)
- Maser monitoring (incl. pol) for accretion bursts and structure evolution
- Millimeter VLBI of maser sources

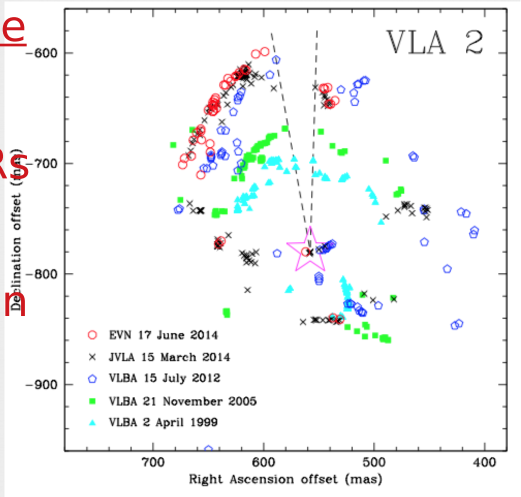


Face on view of CepA with CH3OH maser (Sanna+ 2017)



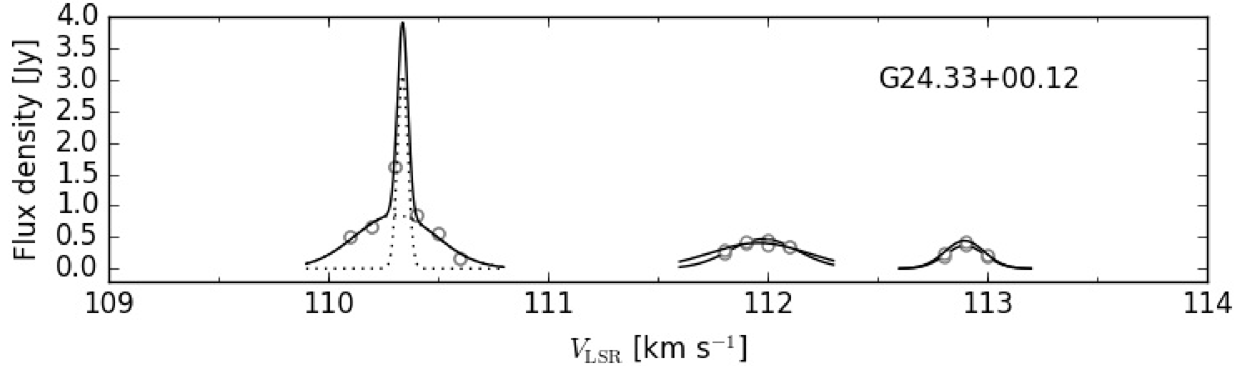
CH3OH maser burst in S255 NIRS3(Moscadelli+ 2017)

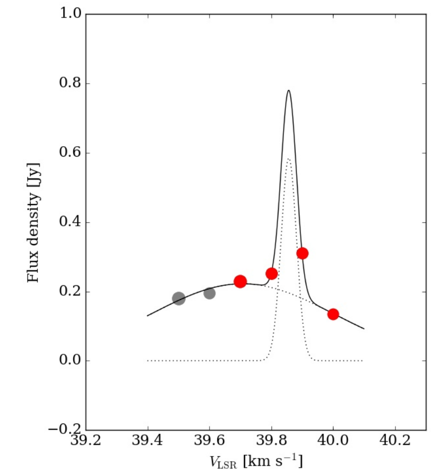


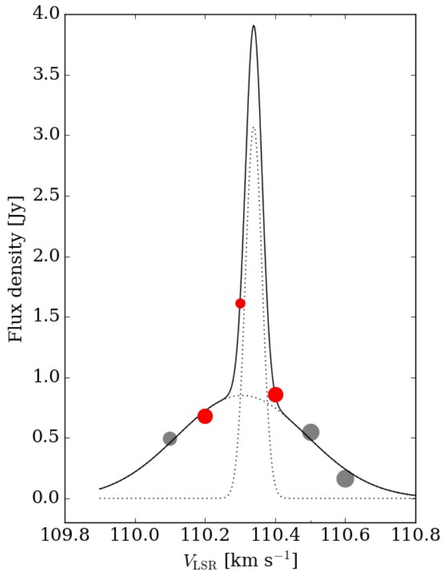


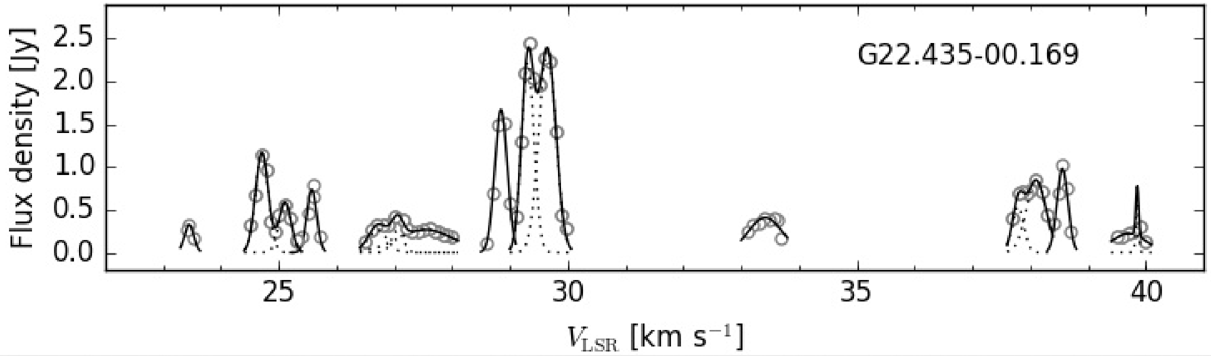
Evolving watermaser structure in W75 (Surcis+ 2014)

Methanol masers



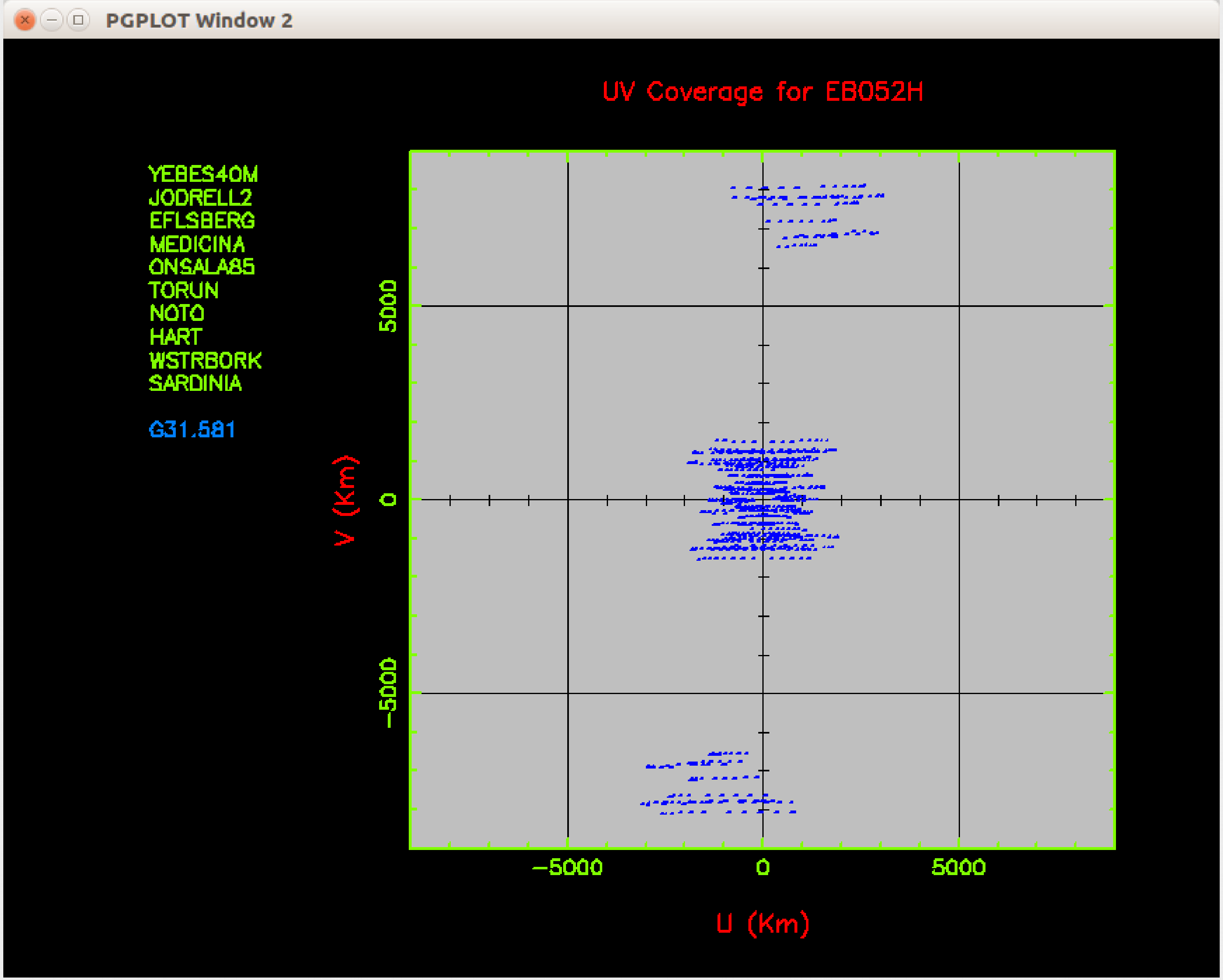




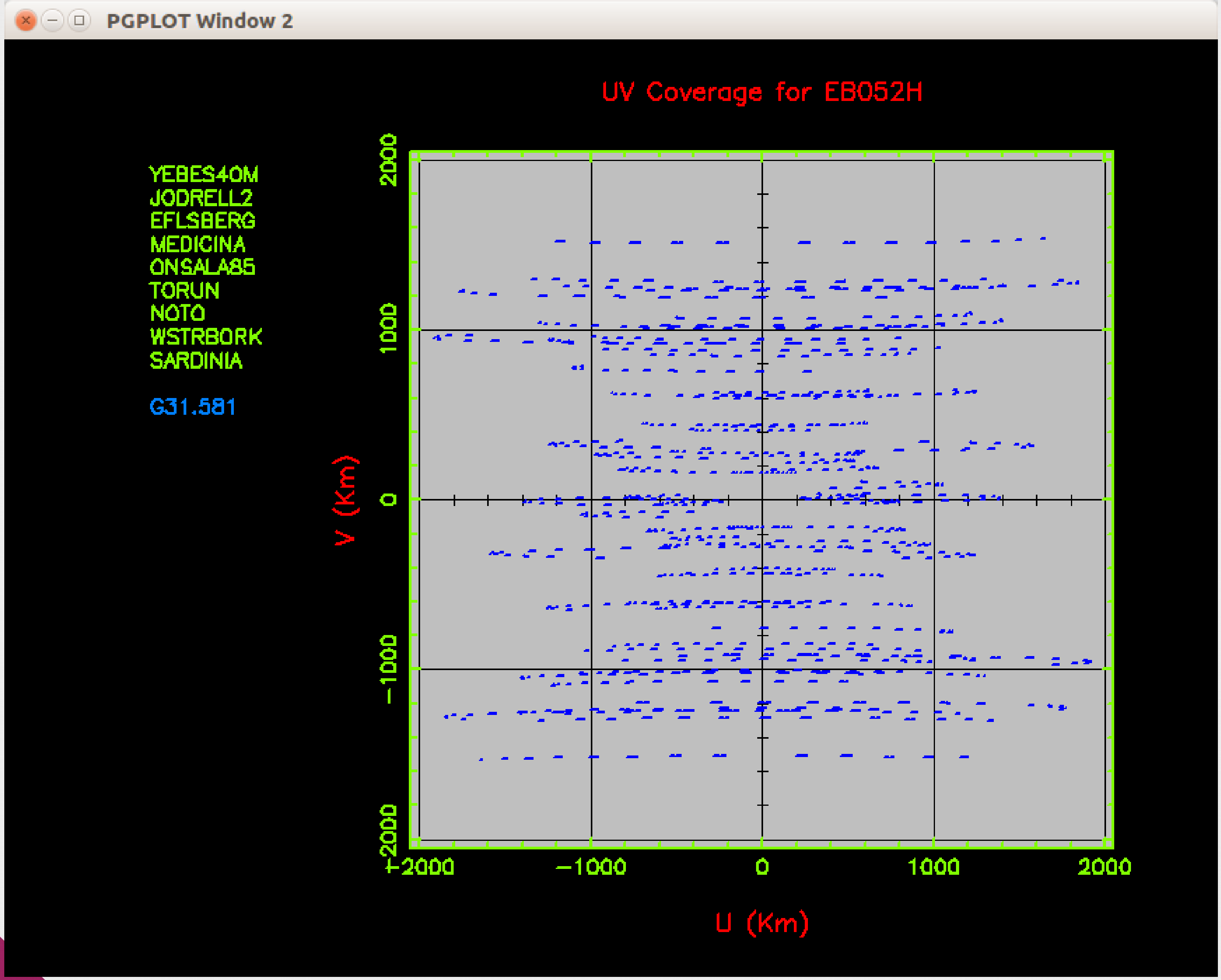


The spectral resolution of ca. 90 m/s is enough, but...
Among 17 methanol masers (6.7 GHz) showing 201 maser clouds there are two interesting cases “amplification-bounded” masers (Bartkiewicz et al. 2016).

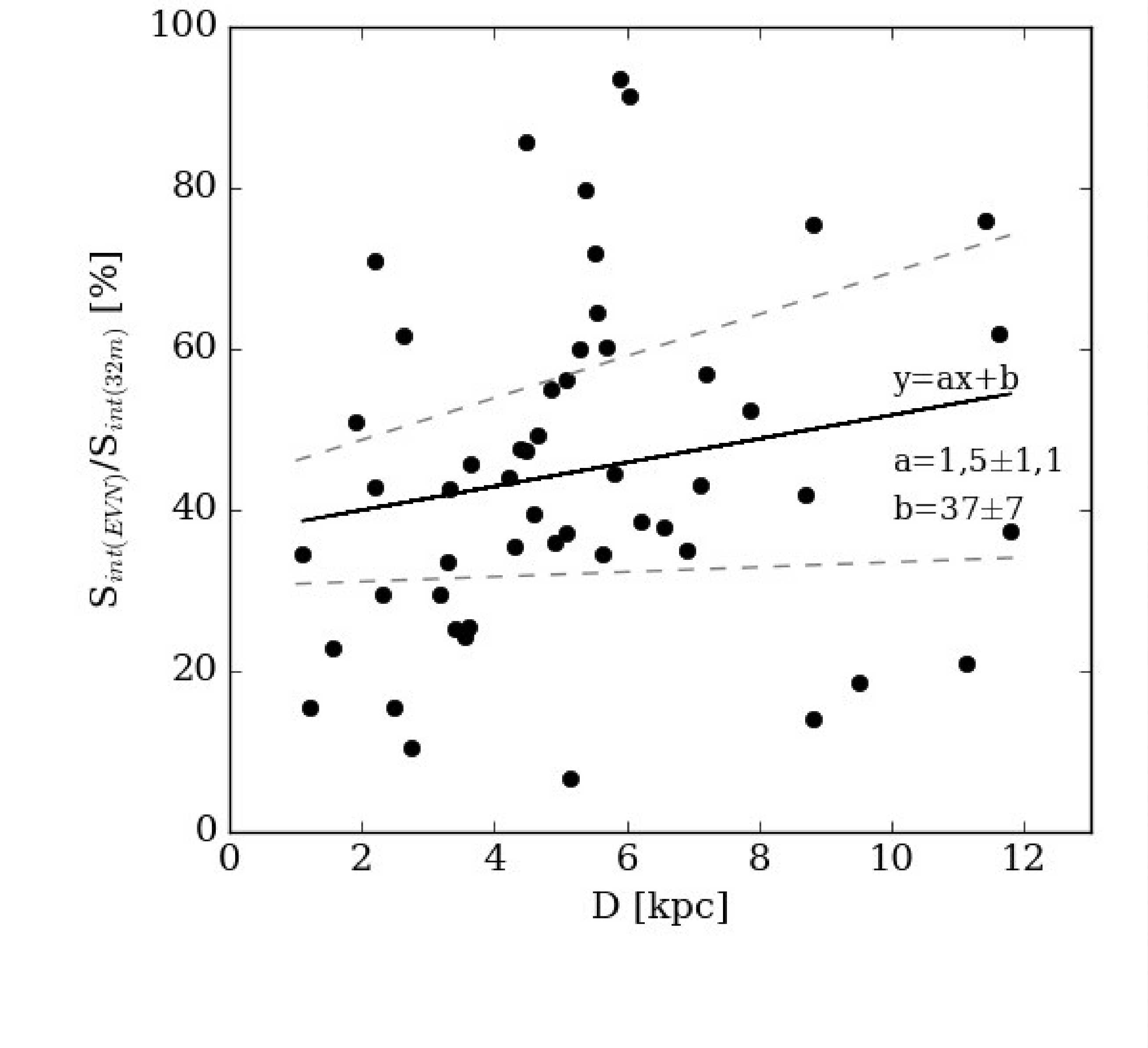
Typical observations using EVN since 2007 (3-6 masers during 10 hr session). Targets are at close to 0deg declinations.



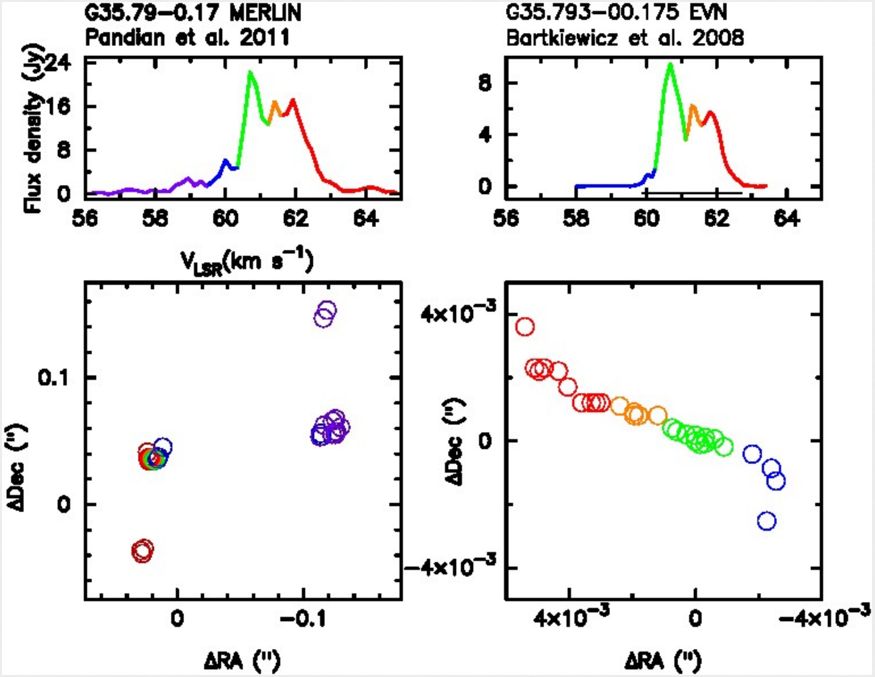
Usually FRING does not find solutions on the longest baselines with Hart (RPA), so the uv-coverage is like this:

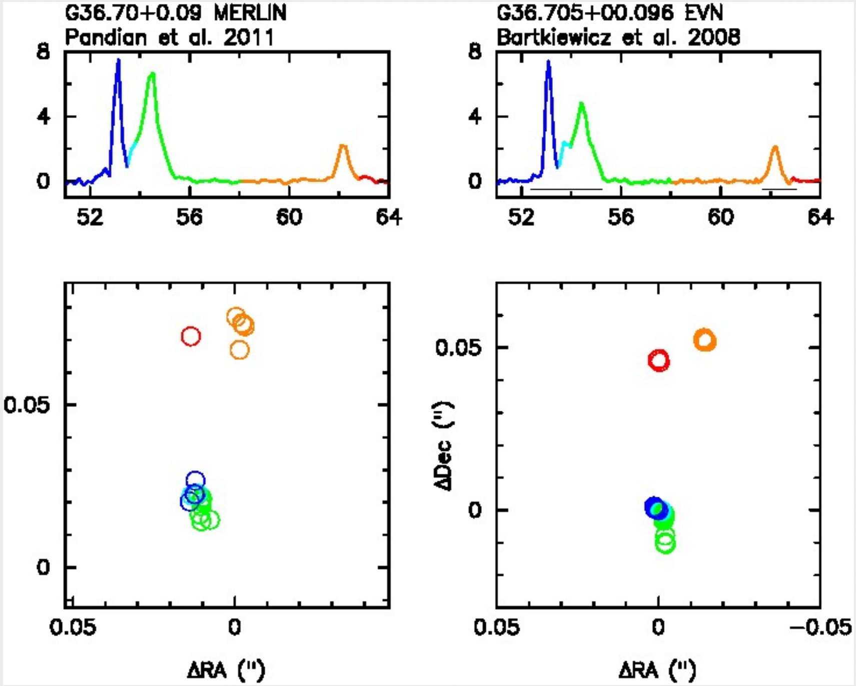


Ratios of integral fluxes obtained using EVN and Torun 32m dish vs. distances (from BeSSeL or kinematic ones) to 52 masers. The maser flux density obtained using the EVN is typically at a level of 30-50% of that detected by the single-dish. The missing flux does not strongly depend on the distance to the source – the least-square fitting is presented (Bartkiewicz et al. 2016).



Missing flux – a problem in studying the masing regions.





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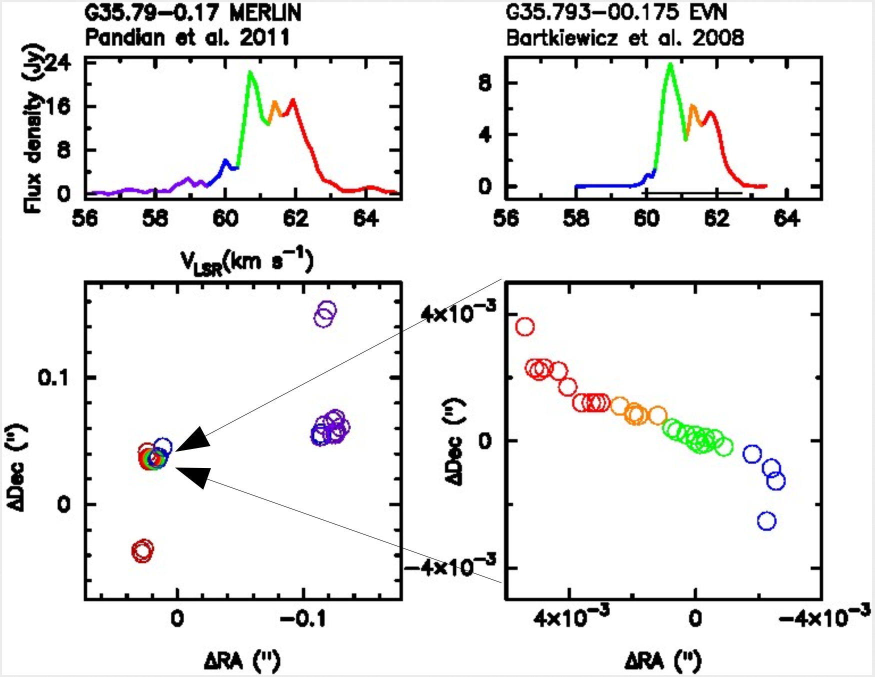
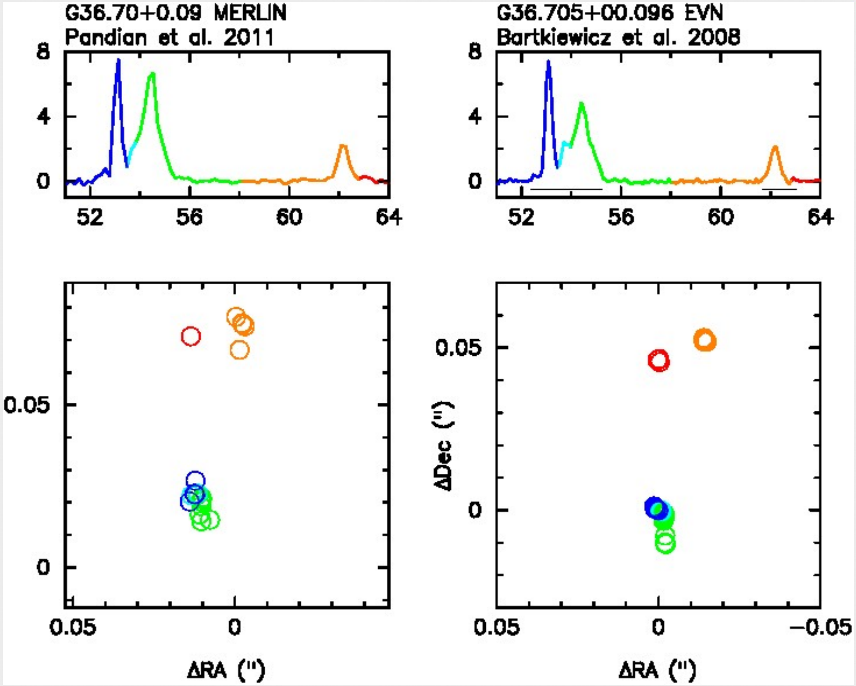
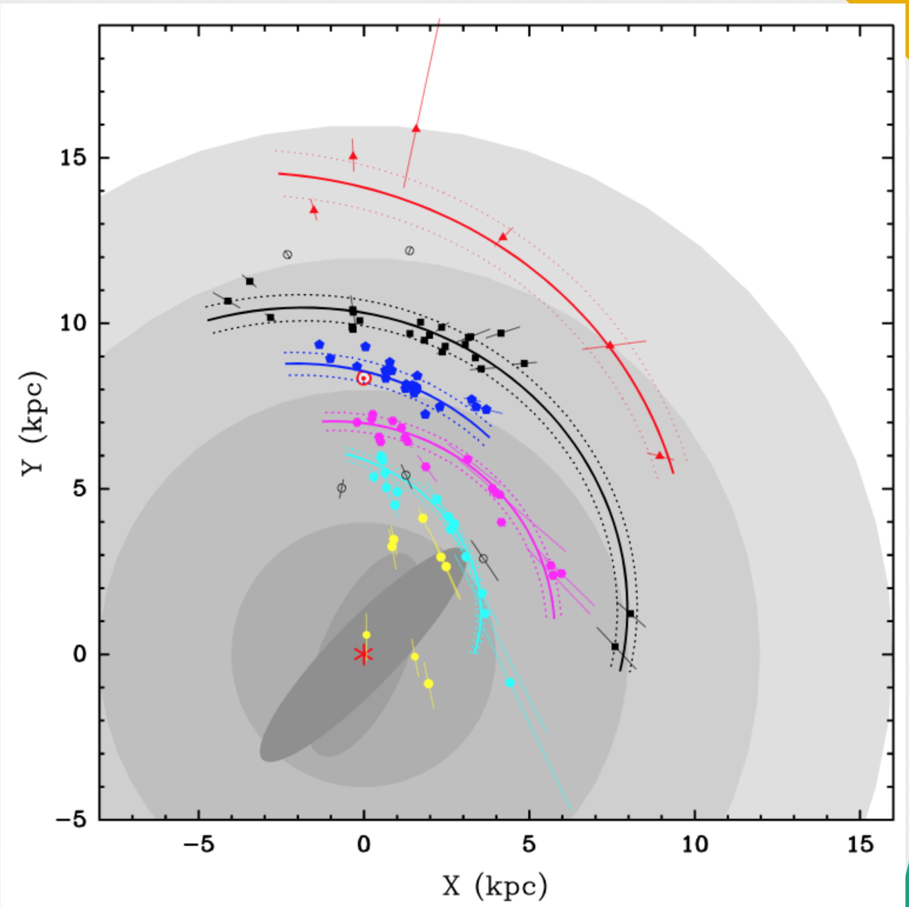




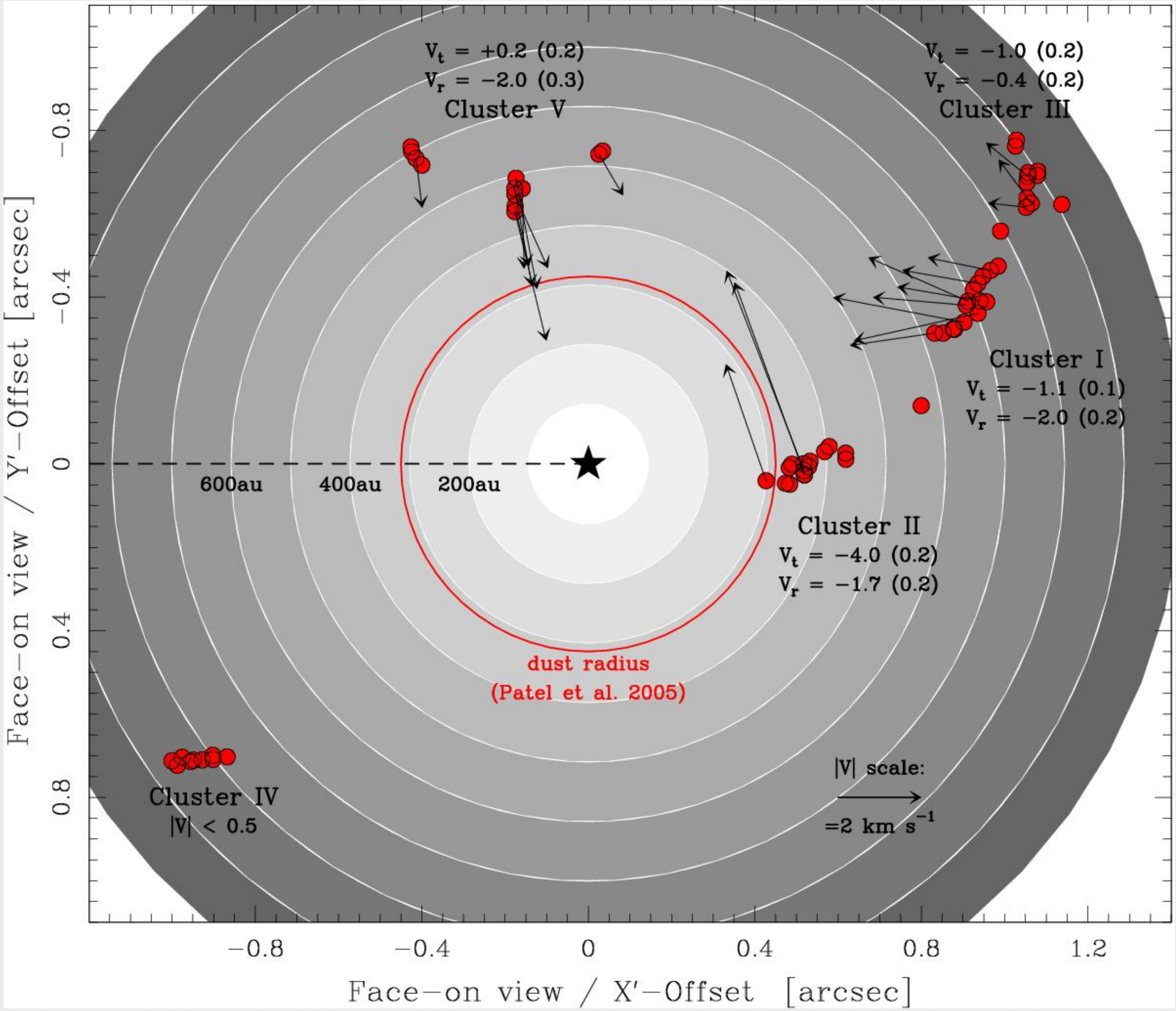
Maser astrometry

Methanol, water and SiO masers and continuum stars are frequently being used for astrometry (proper motions and parallaxes):

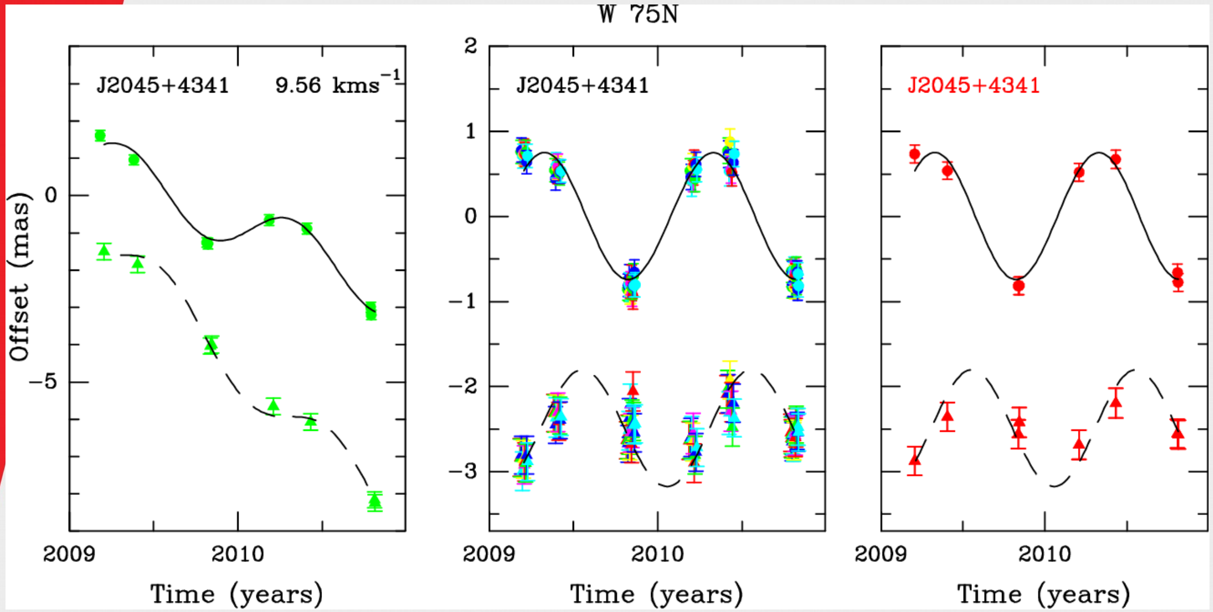
- VLBA, VERA, LBA, EVN:s (Sakai+2015, Reid+ 2014, Krishnan+2015, Ortiz-Leon+ 2016, Burns+2017, Sanna+ 2017 and many more)
- EVN input – first 6.7 GHz methanol masers parallaxes with 10% accuracy (Rygl+ 2010, 2012)
- Proper motion and tracing velocities of order a few km/s (e.g. Sanna et al. 2017)
- Study of Galactic parameters and large scale structure
- VLBI complements Gaia astrometry!



Reid et al. 2014

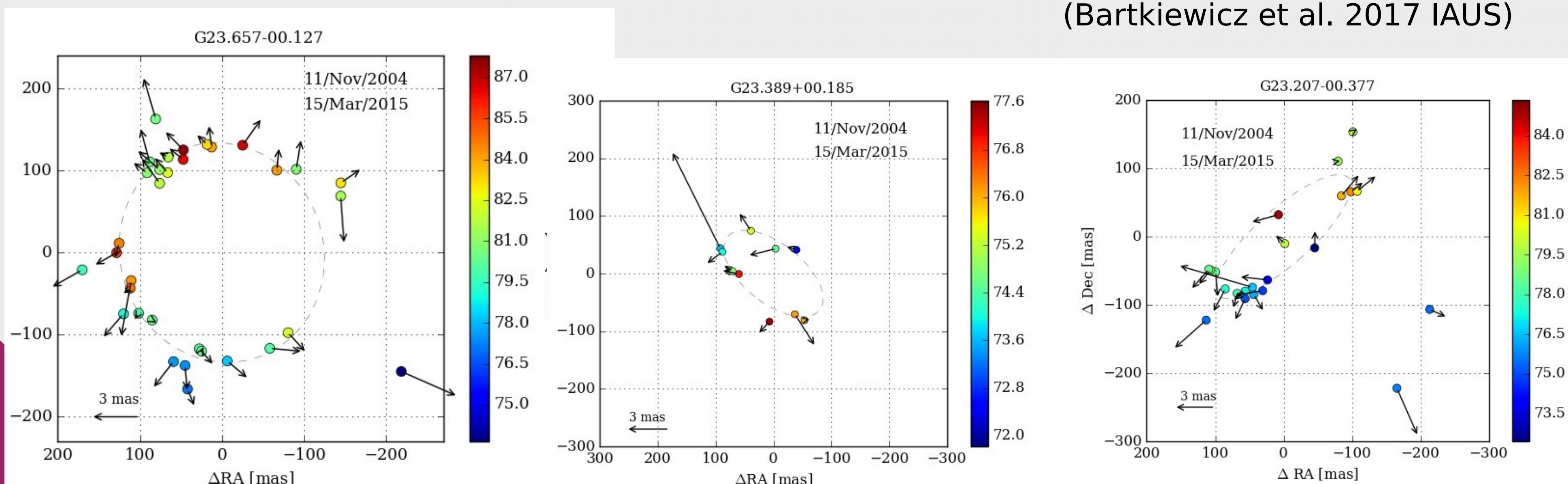


The full-space motions of the 6.7 GHz CH_3OH maser cloudlets in Cep A HW2. An infall component of about 2 km/s and a rotational component of 4 km/s are seen. (Sanna et al. 2017).



Results of the parallax fit for W 75N. (Rygl et al. 2012)

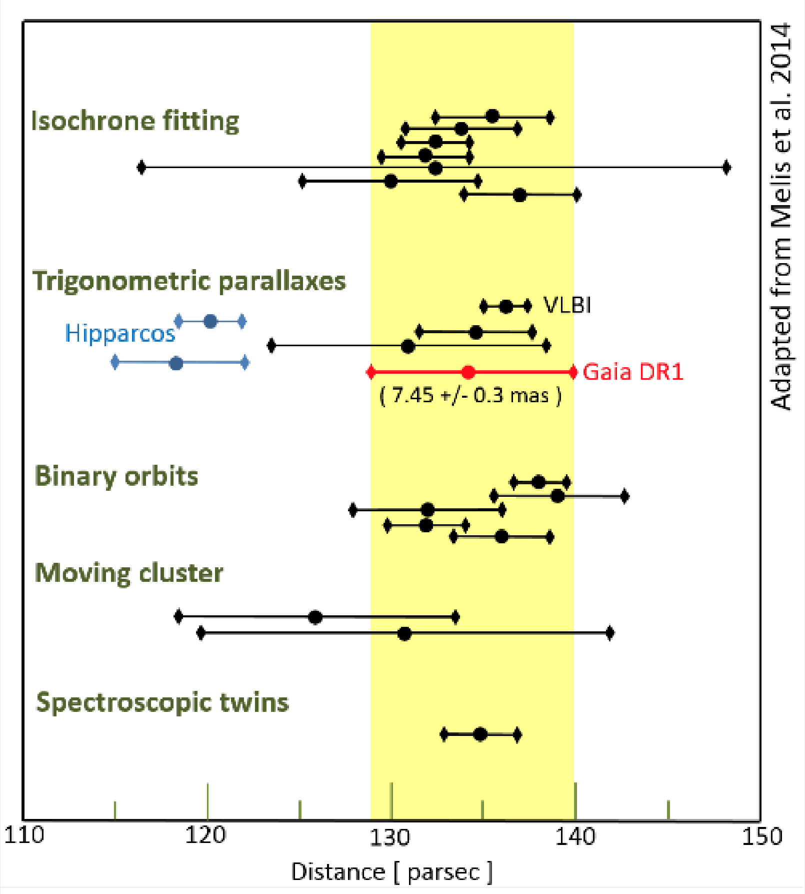
Expansion of methanol maser rings measured after 9 years (Bartkiewicz et al. 2017 IAUS)



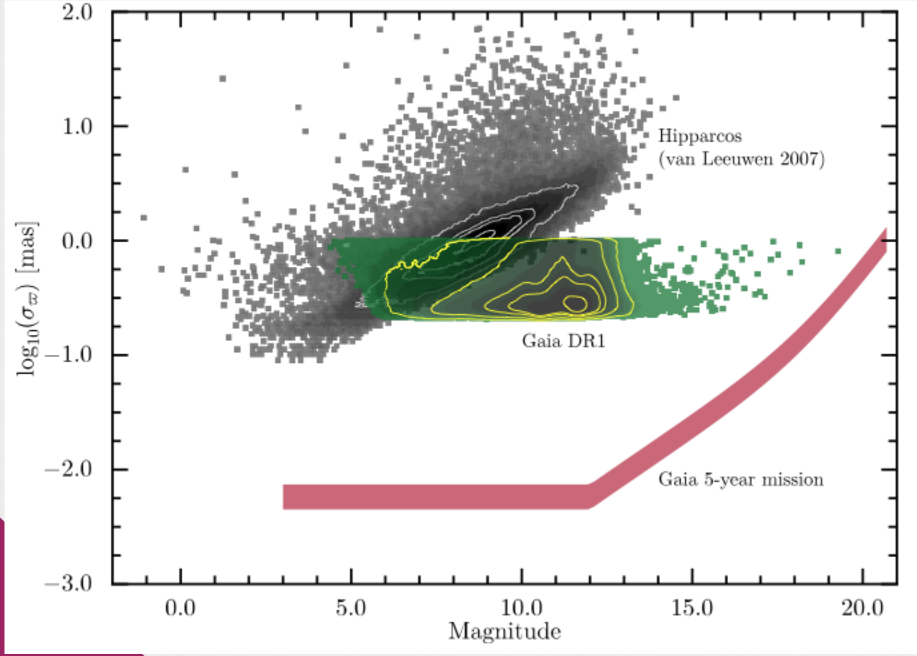
VLBI and Gaia astrometry

Long-standing dispute about the difference of the Pleiades distance from Hipparcos and VLBI (and other methods) settled by Gaia.

- VLBI (Melis+ 2014) distance is in agreement with Gaia DR1 distance
- Gaia will vastly improve over the current DR1 release



Various distance measurements to the Pleaiades cluster (Gaia collaboration+ 2016)

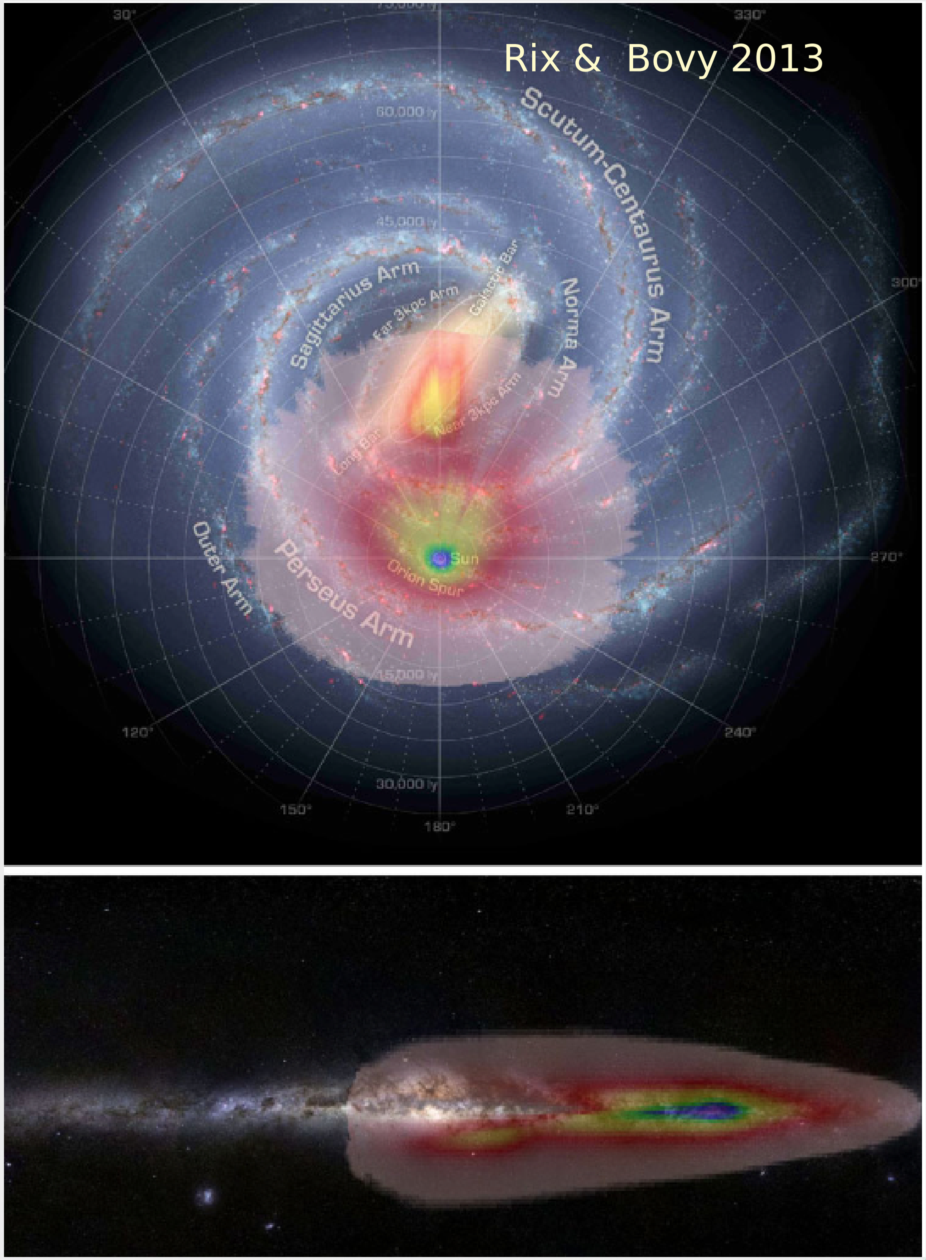


Parallax uncertainty as a function of magnitude for DR1, Gaia final release and Hipparcos (Gaia collaboration+ 2016)

VLBI astrometry and Gaia are complementary

The effective volume that Gaia will cover in our Milky Way based on Gaia mock catalog simulations.

- Despite much increased sensitivity w.r.t. Hipparcos, Gaia's reach in the Galactic plane is limited by dust extinction and image crowding
- VLBI astrometry does not suffer from dust extinction and can be used for star forming regions, evolved stars, and radio stars which have typically high extinction (Reid & Honma 2014)



We need:

- High continuum sensitivity (increased bandwidth) for detecting extragalactic reference sources nearby the maser (preferable 3 or more see Reid+ 2017).
- Flexible scheduling to sample the parallax curve optimally, dishes are slow, sessions are not optimal for covering parallax.
- Proper software for geodetic-like observations (Brunthaler+ 2003) necessary to calibrate tropo- and iononosphere.
- Extension with AVN (good they will have C-band receivers) to increase target towards the inner Galaxy, more antennas in Middle East are also needed.
- New receivers for 12 GHz CH_3OH and 43 GHz SiO astrometry with EVN.

EVN parallaxes
https://www.aanda.org/articles/aa/abs/2012/03/aa18211-11/aa18211-11.html
https://www.aanda.org/articles/aa/full_html/2010/03/aa13135-09/aa13135-09.html

EVN proper motions
https://www.aanda.org/articles/aa/full_html/2017/07/aa30773-17/aa30773-17.html

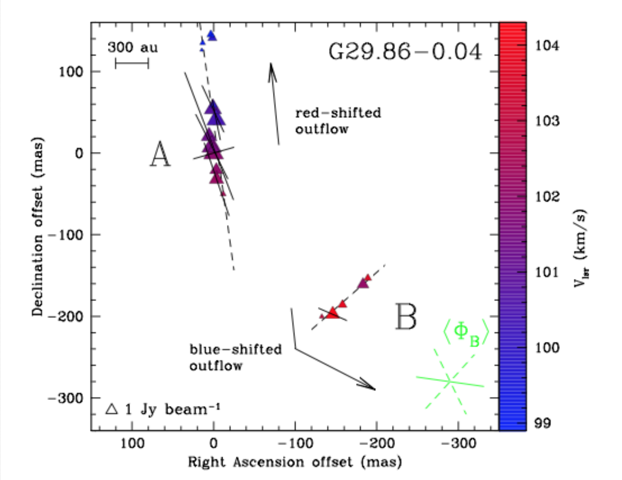
Polarimetry of HMSFR

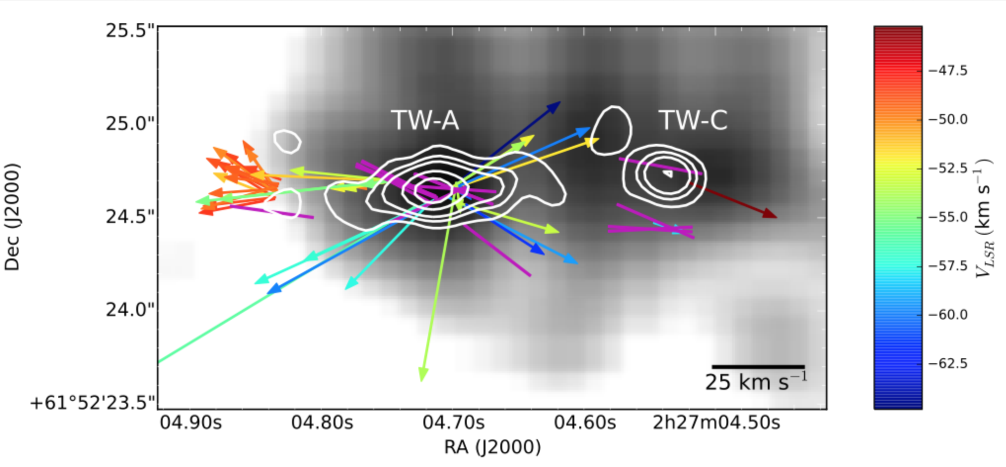
(we all noted "an outburst" of articles using the EVN and polarization measurements of 6.7 GHz maser for 9 years)

VLBI is providing an important contribution to the understanding of HMSF:

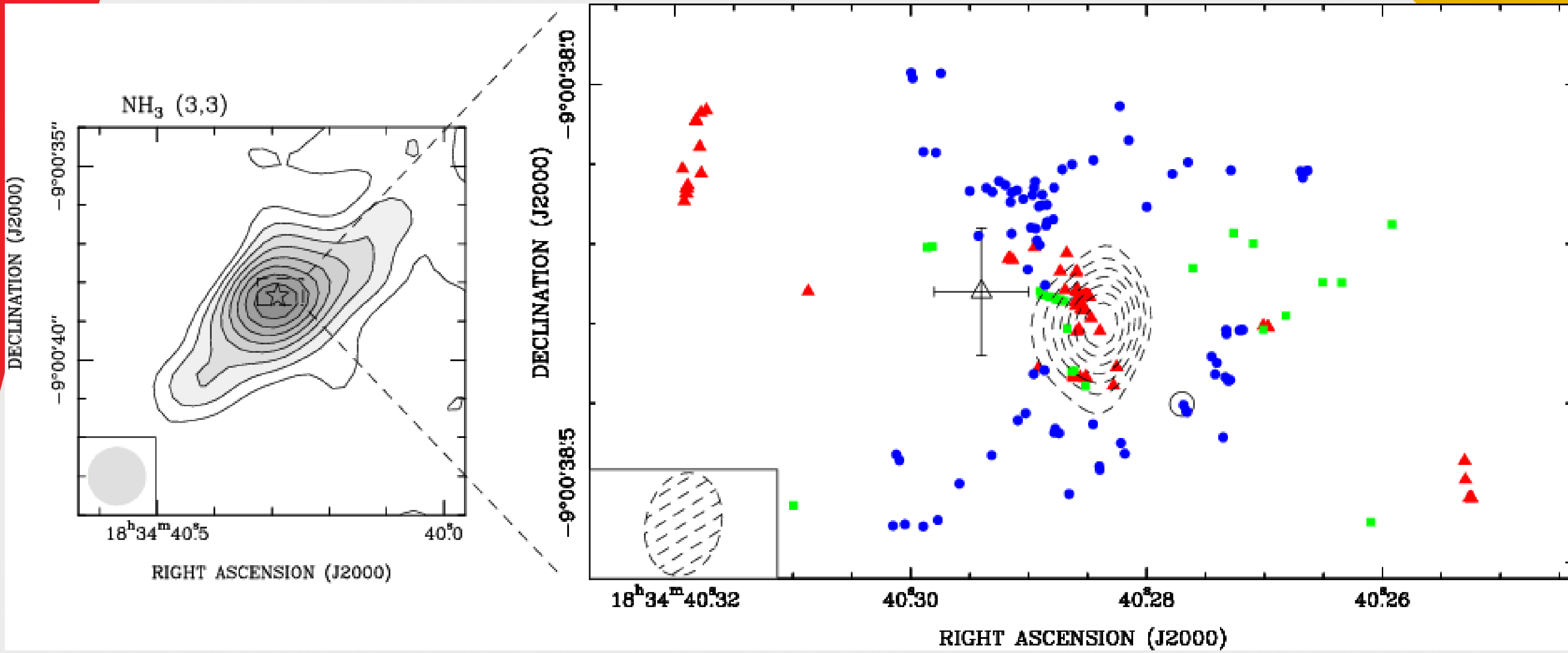
- High resolution maser polarization mapping correlated with disks/outflows structures (Surcis+ 2015, Dall'Olio+ 2017)
- Important to correlate maser cloudlet proper motion with polarimetry – B field follows the maser velocity field (Sanna+ 2015, Goddi+2017)
- Measure B field strength (Lankhaar+ 2018)
- Long term and large projects are going on the EVN to investigate magnetic field and proper motion in different massive YSO by using methanol and water maser lines.

Methanol maser polarization vectors and outflow axis of G29 (Surcis+ 2015)



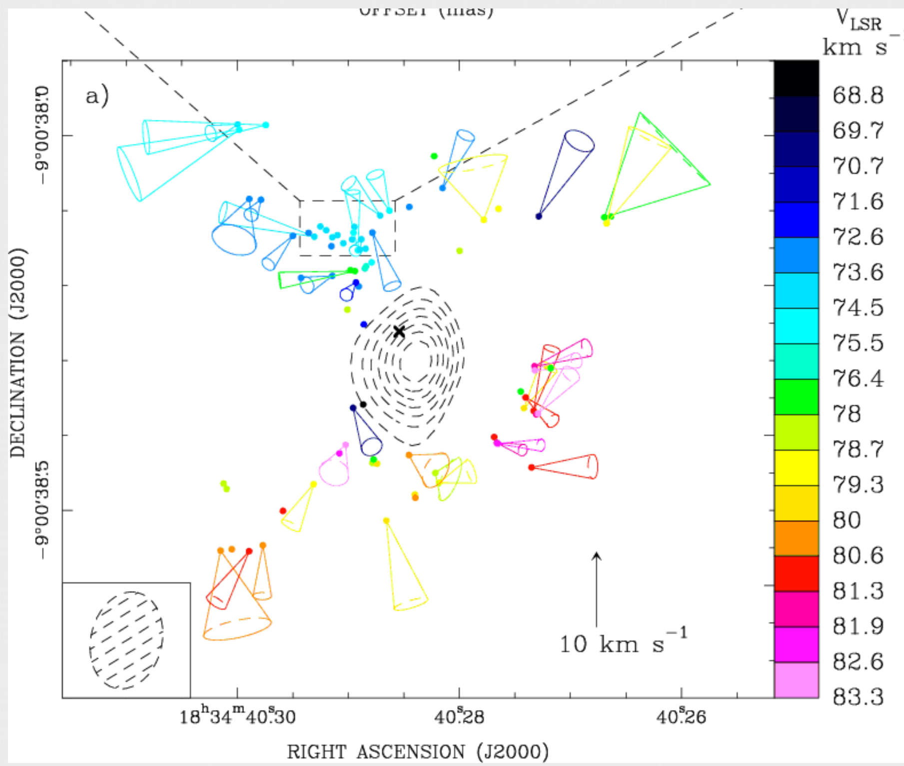


Water maser proper motions (arrows) and B field orientations (purple line) along the synchrotron outflow of TW1 in W3 (Goddi+ 2017)



Example: HMSFR G23.01-0.44

From imaging to proper motions (Sanna et al. 2010) and further to...



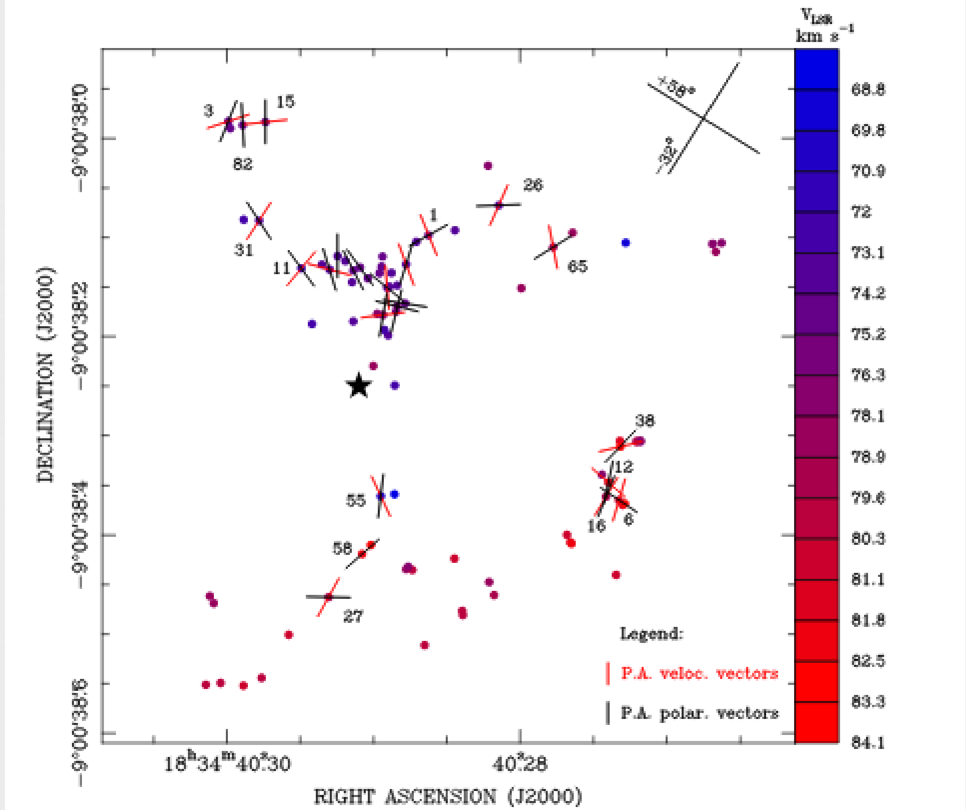
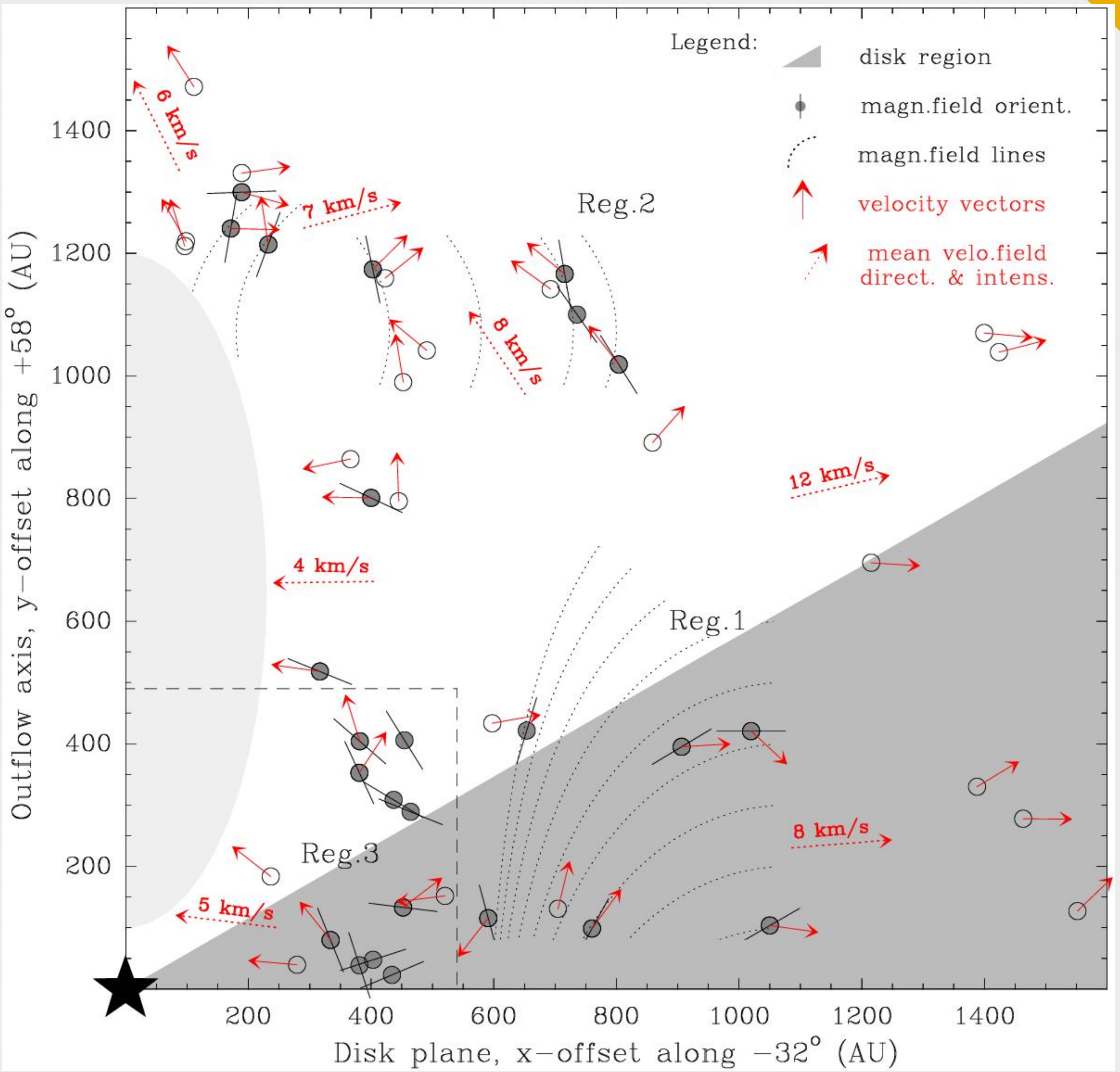


Fig. 2. Comparison of the velocity and polarization vectors across the CH_3OH maser distribution in G023.01−00.41. We show the distribution of the 6.7 GHz maser cloudlets (dots) within a field of view of about 2000 AU, following Sanna et al. (2010b, their Fig. 6). Maser velocities

.. a comparison of the proper motions of 6.7 GHz maser clouds (cloudlets) and polarization vectors. A field of view is about 2000 AU. (Sanna et al. 2015).



And final 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).

We need:

- Multifrequency receivers to observe water and methanol masers simultaneously and monitoring programmes.
- Polarization in extragalactic objects requires more sensitivity (larger collecting area).
- Studies of targets from southern hemispheres: the AVN is crucial.
- New receivers at 12 GHz and 25 GHz (class I methanol masers, however they might be resolved out on the longest VLBI baselines).
- Getting 12+6.7 GHz methanol together. A new hyperfine models (work by Boy Lankhaar and Andrej Sobolev on the pumping and it looks like the hyperfine components have a strong effect) potentially provide interesting probes of physical conditions (in addition to magnetic fields and kinematics).

References

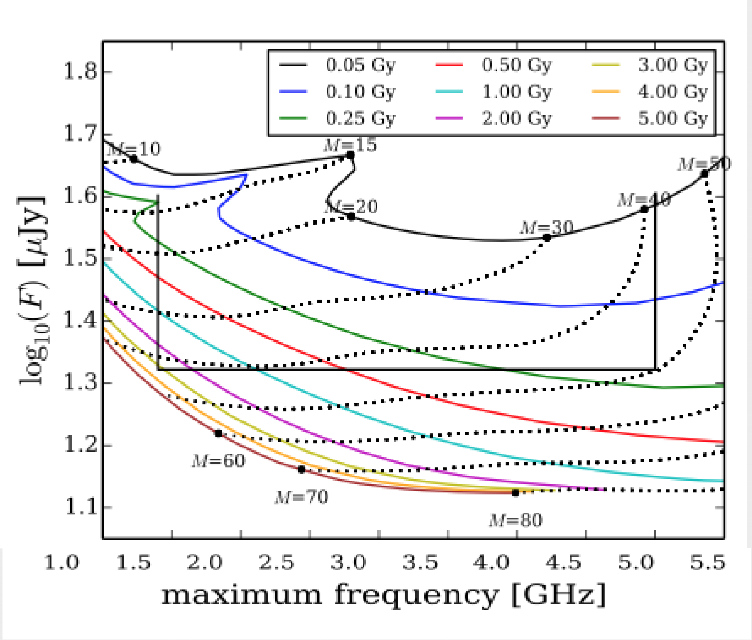
Polarization (EVN 6.7 GHz data with VLBA 22 GHz ones):
https://www.aanda.org/articles/aa/full_html/2009/41/aa12790-09/aa12790-09.html
https://www.aanda.org/articles/aa/abs/2011/09/aa17108-11/aa17108-11.html
https://www.aanda.org/articles/aa/abs/2014/03/aa22795-13/aa22795-13.html
EVN sample
https://www.aanda.org/articles/aa/abs/2012/05/aa18658-11/aa18658-11.html
https://www.aanda.org/articles/aa/abs/2013/08/aa21501-13/aa21501-13.html
https://www.aanda.org/articles/aa/abs/2015/06/aa25420-14/aa25420-14.html
Proper motion and polarization
https://www.aanda.org/articles/aa/full_html/2015/11/aa26806-15/aa26806-15.html
VLBA
https://www.aanda.org/articles/aa/full_html/2017/01/aa29321-16/aa29321-16.html
MERLIN
https://www.aanda.org/articles/aa/full_html/2017/11/aa31297-17/aa31297-17.html

Magnetic characteristic of methanol
https://www.nature.com/articles/s41550-017-0341-8

Exoplanets and brown dwarfs

Feasibility study to observe exoplanets with VLBI (Katarzynski+ 2016) shows:

- Dominant radio emission of exoplanets (Jupiters) in the MHz regime, however in case of strong B field can reach also L band.
- Advantage is higher resolution and sensitivity of EVN/VLBA w.r.t. LOFAR/GMRT.
- Stellar wind with planet magnetosphere detectable for planets of 1–50 Mjup with 25 pc.
- Radiation induced by planet-moon interaction too weak to be detected.

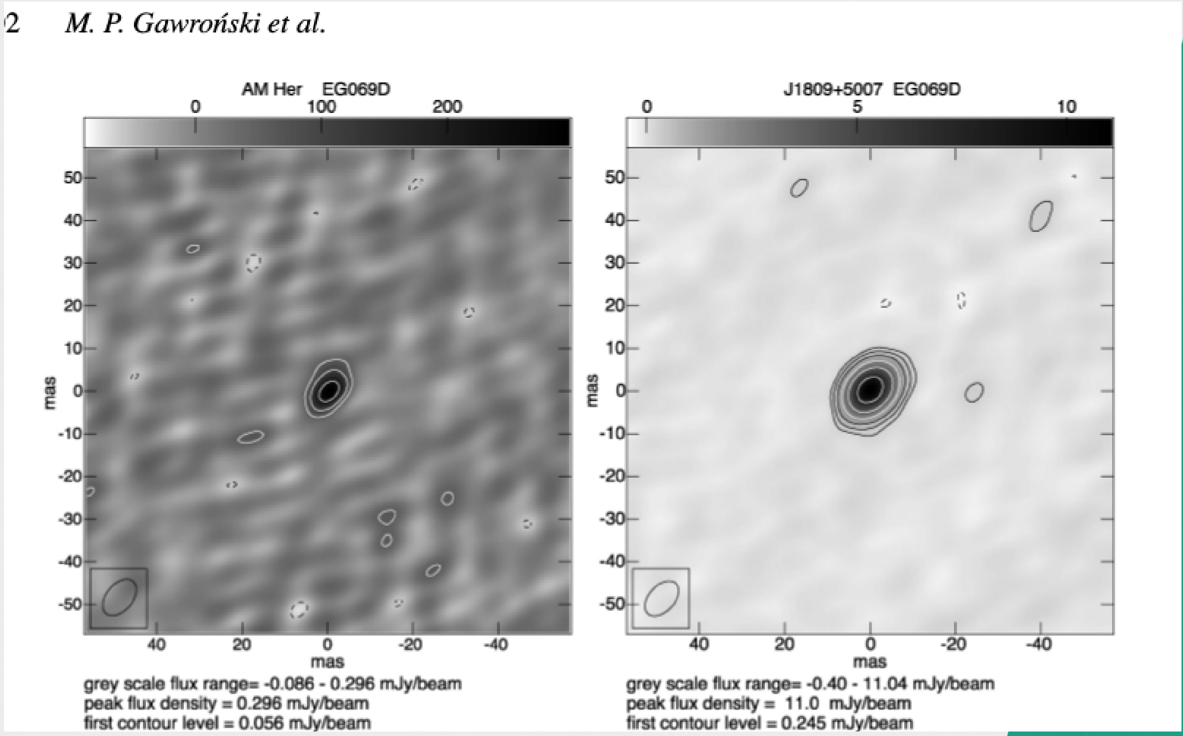


Expected flux densities of stellar wind / planetary magnetosphere interaction at GHz ranges. Within the U feasible with 5h of EVN at 1 GB/s (Katarzynski+ 2016)

We need

- High continuum (and polarization) sensitivity crucial (increased bandwidth, collection area), "lots happening in μJy sky", more targets,
- More flexibility about observing dates (PI must be able to optimize for parallax, proper motion separation)
- Ionosphere/geo blocks
- Accurate station positions
- Time for studying the plasma kinematics during bursts in red dwarfs?

ca. 50 μJy rms in ca. 2hrs on-source time (Gawronski et al. 2018)

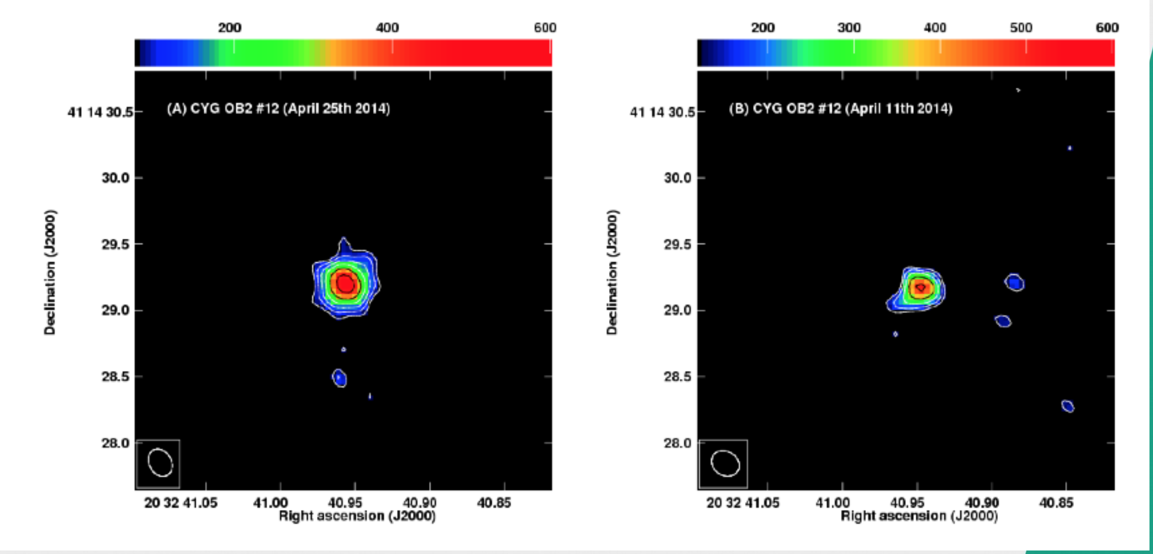


Stellar winds

The evolution of early type stars (OB) is characterized by their mass loss rate via their strong, possibly clumpy as seen in radio, stellar winds. “How is (clumpy) mass lost from stellar surface?”

- Radio measurements of mass loss rate are the most robust – COBRaS eMerlin project: upper limits of 4.5x10^-6 Msun/yr for O3I star (Morford+2016)
- Massive stellar wind surveys started with upgraded arrays: eMerlin, ASKAP
- eMerlin+EVN interesting to reveal the stellar wind structure (of the brighter targets)
- Masers polarimetry to determine the magnetic field in stellar winds

- Continuum sensitivity better than 70uJy at 21cm to detect the weak thermal free free emission from stellar winds.



First resolved radio observations of Cyg OB2#12 at 21cm with eMerlin. Note the variability in structure and flux. Morford+ 2016

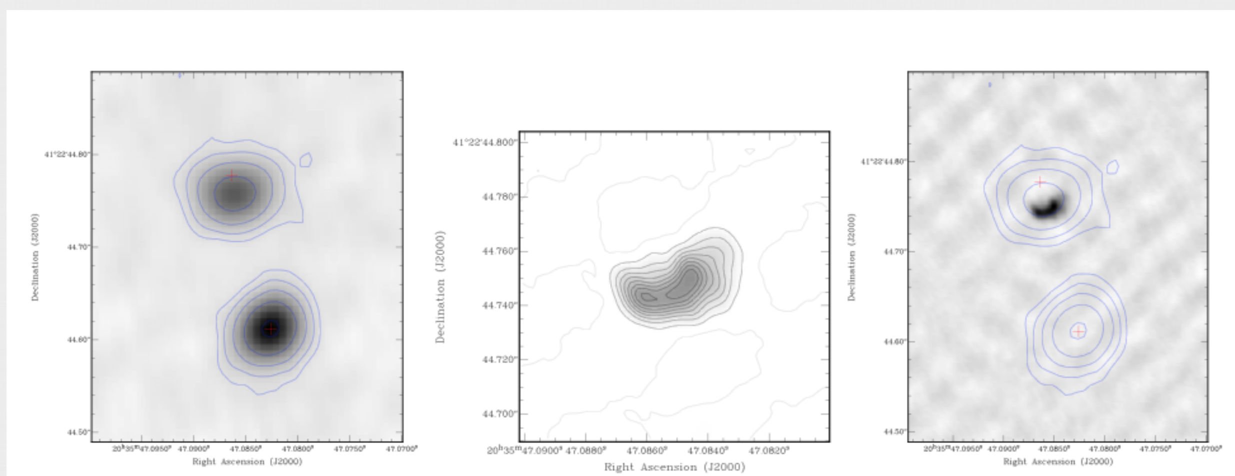
Colliding wind binaries

Colliding stellar winds of massive binaries (OB type or WR) that can produce accelerated particles. De Becker+ (2017) estimate that pre-SN massive binaries can constitute a significant part of Galactic CR power.

- CWB should be common as most OB stars in binaries
- Main tracer synchrotron emission
- Only a few systems mapped to date

We need:

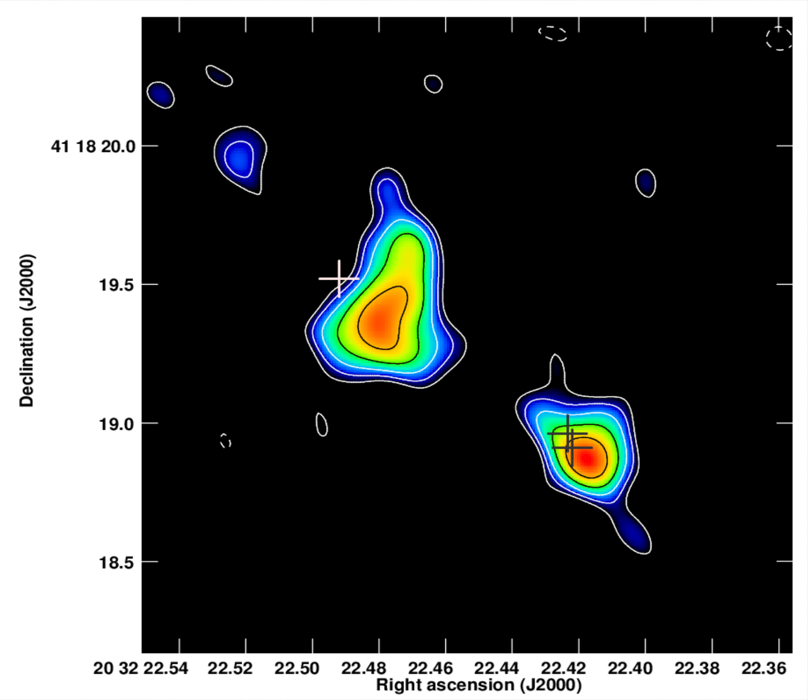
- Continuum sensitivity, inclusion of short spacing (eMerlin) crucial for the bow shock. VLBI reveals kinematics of superb resolution, however resolves the emission and hampers interpretation of physical conditions. Need good sampling at different baselines, from tens to thousands km.
- Flexibility in frequency and time for multifrequency and multi-epoch observations to observe at various orbital phases
- Good polarization capabilities.

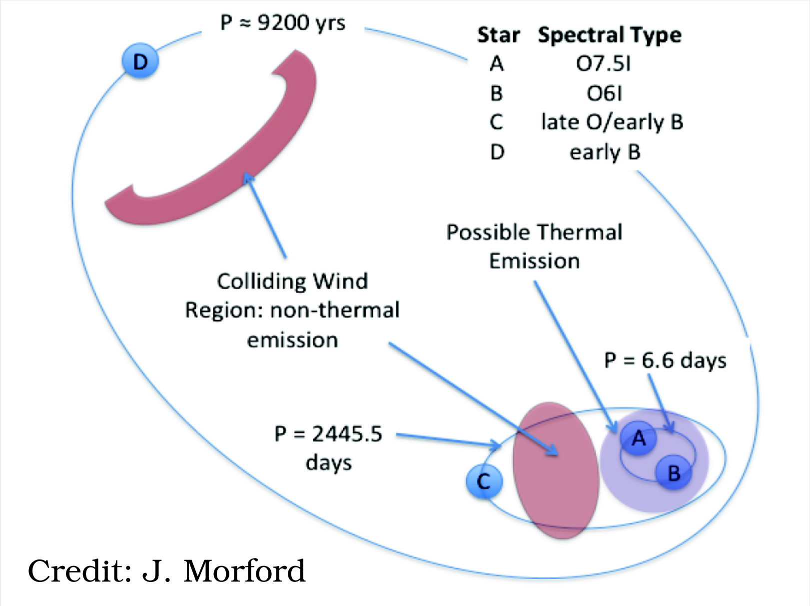


CWB WR146, left:VLA 43GHz – stars, centre: 5GHz EVN bow shock, right: combined (O’Connor+ 2005)

Cyg OB2#5 CWB

Correct combination of baselines like eMERLIN and inner EVN can potentially start to do more targeted observations of brighter objects to study potential variability and structure in the stellar wind.

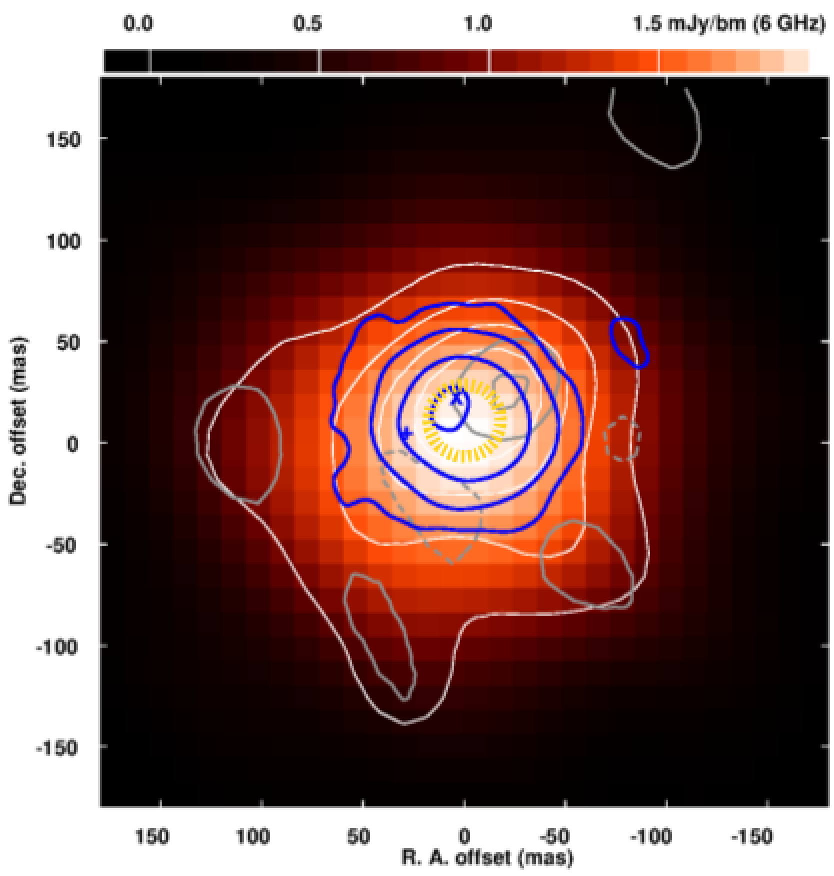




eMerlin COBRaS survey: CWB Cyg OB2#5 (Fenech, Morford priv. comm.)

Compare 0.89 mm - 5 cm λ

- Background e-MERLIN 5cm low-resolution 2015 Jun
- White: 5cm 60-mas beam
- Grey: 5cm hot/cold spots
- Blue: 0.089cm ALMA
- Yellow ring: photosphere
  - Alignment by eye
- No hotspot correlation
  - Depth difference 1.3-4.5 $R_\star$
    - ~3.2 yr travel at 20 km/s: outflow timescale too slow
    - Radiative effects needed?



Studying Betelgeuse – star spots, optimal combination of resolution and sensitivity. (Richards, priv.comm.)

References

http://adsabs.harvard.edu/abs/2016MNRAS.463..763M
http://adsabs.harvard.edu/abs/2005mshe.work...81O
http://adsabs.harvard.edu/abs/2017A%26A...600A..47D

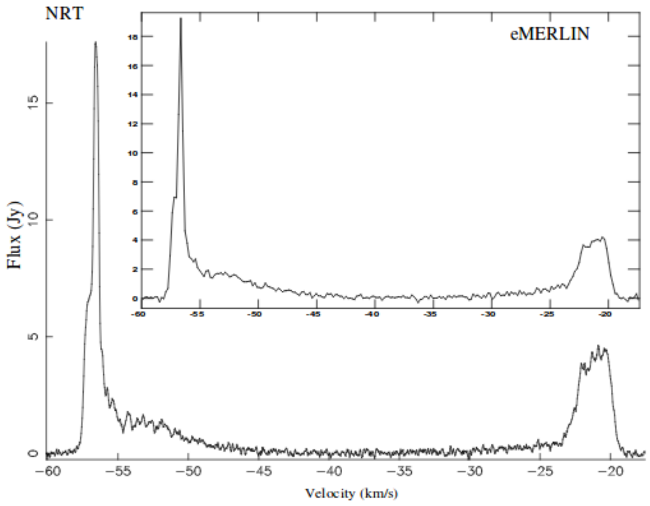
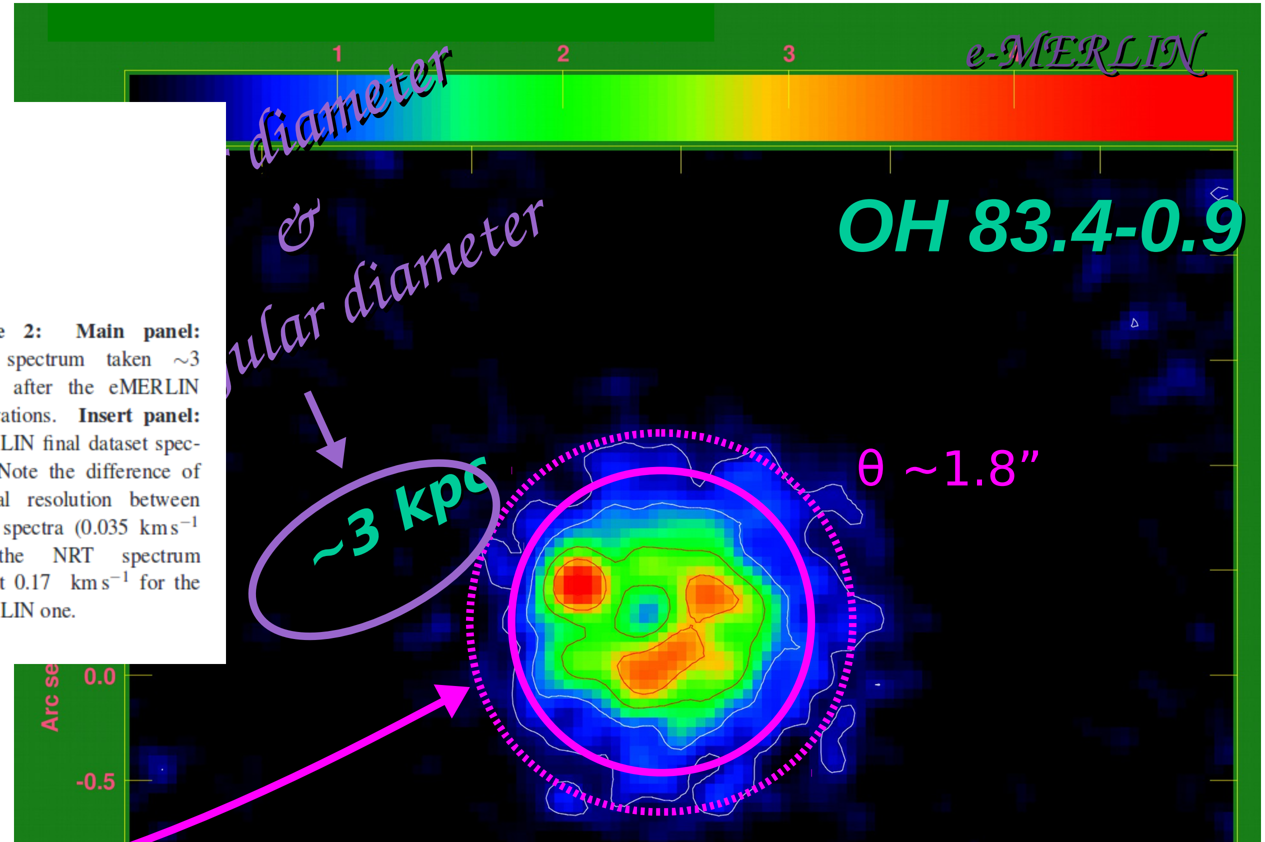
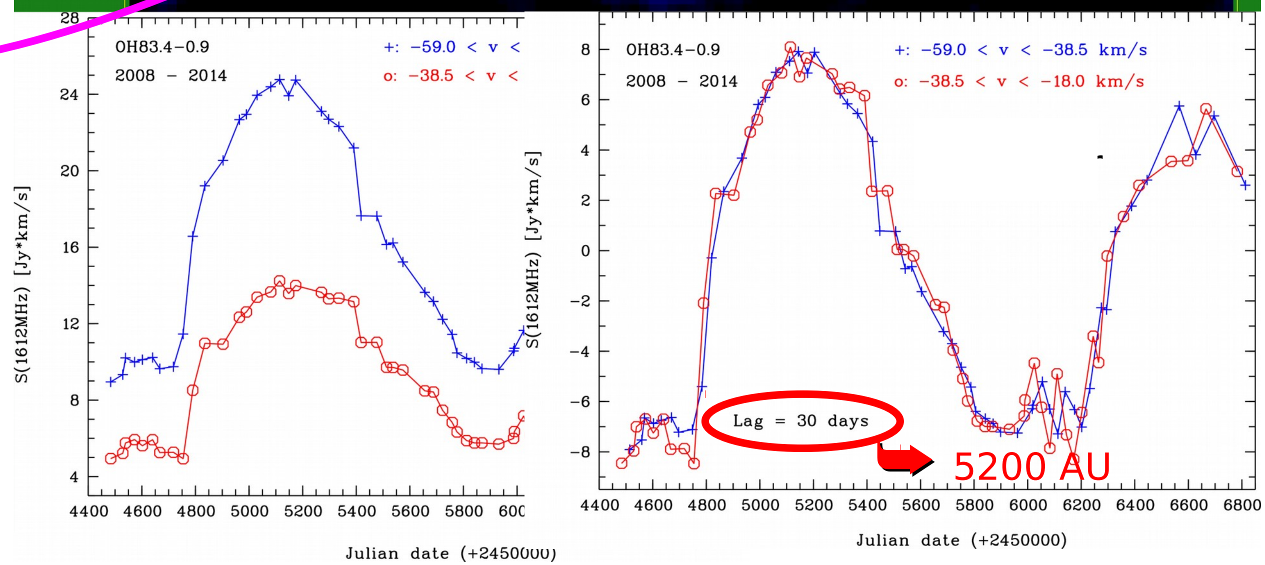


Figure 2: **Main panel:** NRT spectrum taken ~3 weeks after the eMERLIN observations. **Insert panel:** eMERLIN final dataset spectra. Note the difference of spectral resolution between the 2 spectra (0.035 km s^{-1} for the NRT spectrum against 0.17 km s^{-1} for the eMERLIN one.



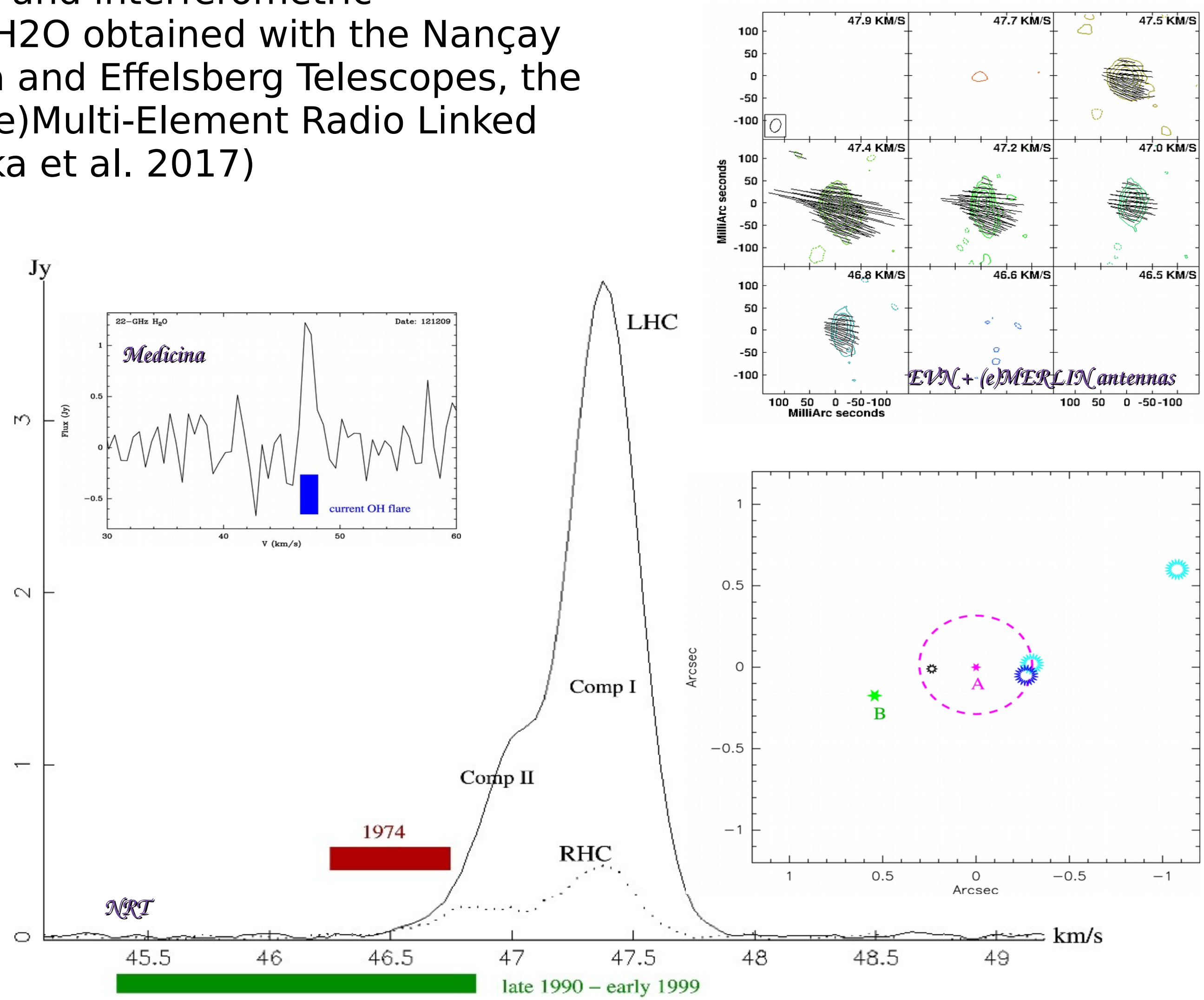


Phase-lag method
to estimate distances:
- sensitivity and resolution
of intermediate baselines,
- "quick response" (ToO).

Etoka et al. 2018, IAUS 336, in press

NRT

The analysis of the onset of the new 2010s OH flaring event detected in the OH ground-state main line at 1665 MHz towards o Ceti and compare its characteristics with those of the 1990s' flaring event. This is based on a series of complementary single-dish and interferometric observations both in OH and H_2O obtained with the Nançay Radio telescope, the Medicina and Effelsberg Telescopes, the European VLBI Network and (e)Multi-Element Radio Linked Interferometer Network. (Etoka et al. 2017)

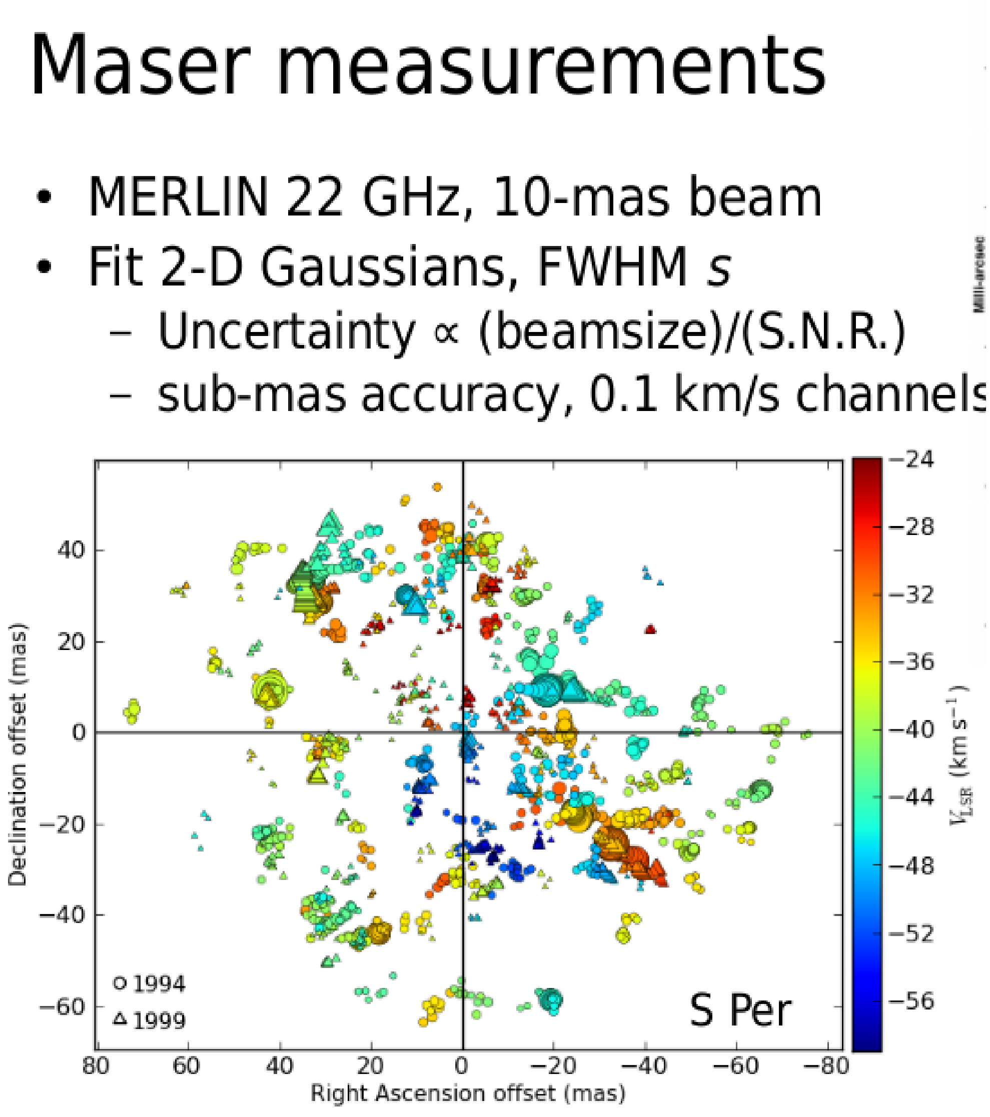


Etoka et al. 2017

Masers in AGB:

We need:

- For H_2O and SiO sensitivity of 20 mJy per beam per ca. 0.1 or 0.2 km/s or even better for polarization.
- For OH tens mJy sensitivity on 0.1 km/s channel.



A. Richards, priv. comm.

We need:

- better uv coverage: TNRT being build in Chiang Mai Thailand, its location is ideal (not only for the A-VLBI but also the the VLBI/EVN)

- inclusion of reasonably short & intermediary baselines and also "north/south" (for a better beam shape and hence a more "uniform” RA & Dec astrometry)

- at least LHC – RHC polarizations for as many antennas as possible (i.e., some of them have only one hand available only), but full would be the best.

Summary

- Lots of diverse stellar/ISM/star formation/Galactic structure science done with VLBI,
- But we want to do more (the EVN is still mostly an extragalactic instrument) and better science for which we would need:
- Extension of EVN to the south (AVN) and east.
- Increase of dish diameters, continuum bandwidth for higher sensitivity.
- More flexible scheduling (dynamic and more eEVN) for parallax signal and orbital phases of colliding wind binaries.
- Maser monitoring programs (incl. polarization) – more observing time.
- New receivers 12 GHz and 43 GHz.