Methanol maser VLBI with the Long Baseline Array (LBA)

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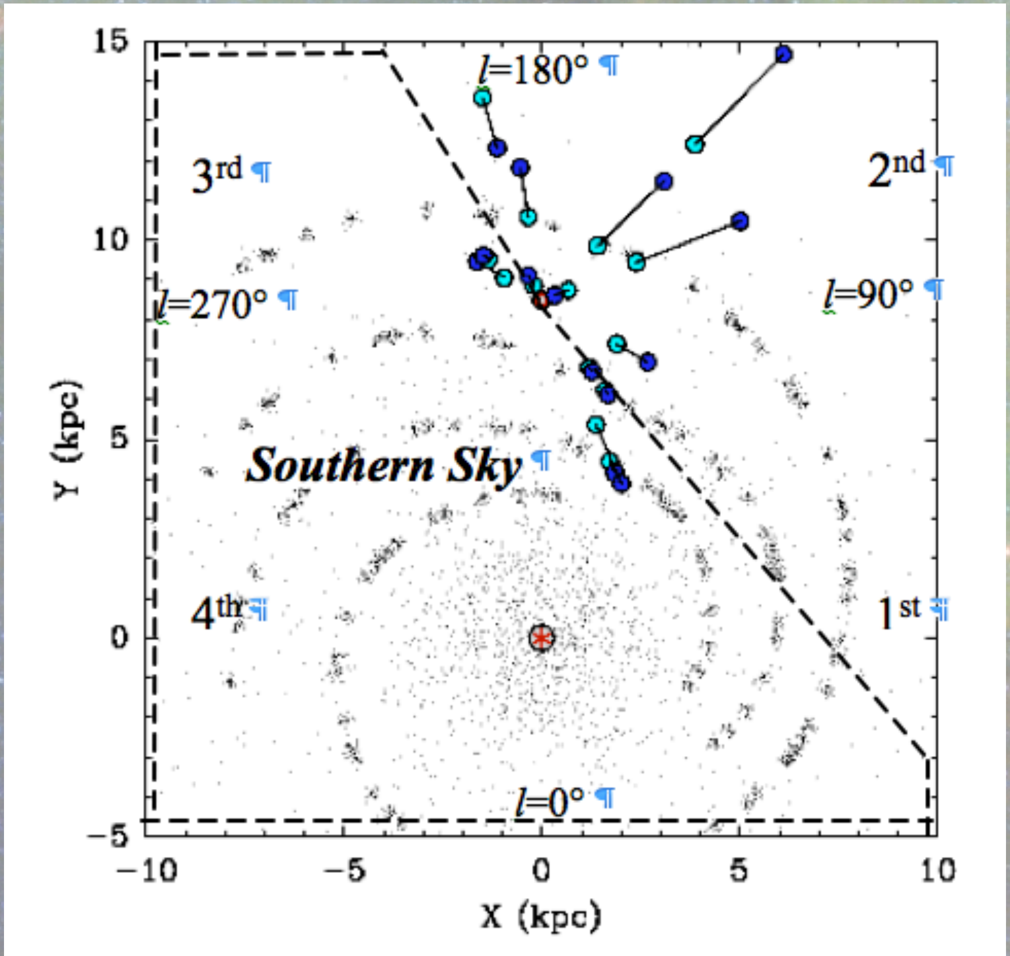
Outline

- Maser parallax with the LBA – current status of the V255 project.
- LBA & VLBA observations of the 6.7 & 12.2 GHz methanol masers in G9.62+0.20.
  – Measuring the expansion of a hypercompact HII region?

Maser Parallax in the South



- The Long Baseline Array (LBA) is currently the only southern astronomical VLBI array.
- In 2009 a large project (V255) was started to measure distances to 30 southern 6.7 GHz methanol masers.

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Collaborators

- UTAS : ***Vasaant Krishnan***, Joanne Dawson.
- CASS : ***Jimi Green***, Chris Phillips, Maxim Voronkov, Jim Caswell, Shari Breen
- CfA : Mark Reid
- MPIfR : Karl Menten, ***Bo Zhang***, Andreas Brunthaler
- NAOJ & Yamaguchi : Mareki Honma, Kenta Fujisawa
- Shanghai, Nanjing & PMO : Eric Shen, Kazuya Hachisuka, Xi Chen, Xingwu Zheng, Ye Xu
- Hartebeesthoek : Sharmila Goedhart
- UWA & Curtin : Richard Dodson, Maria Rioja, Andrew Walsh

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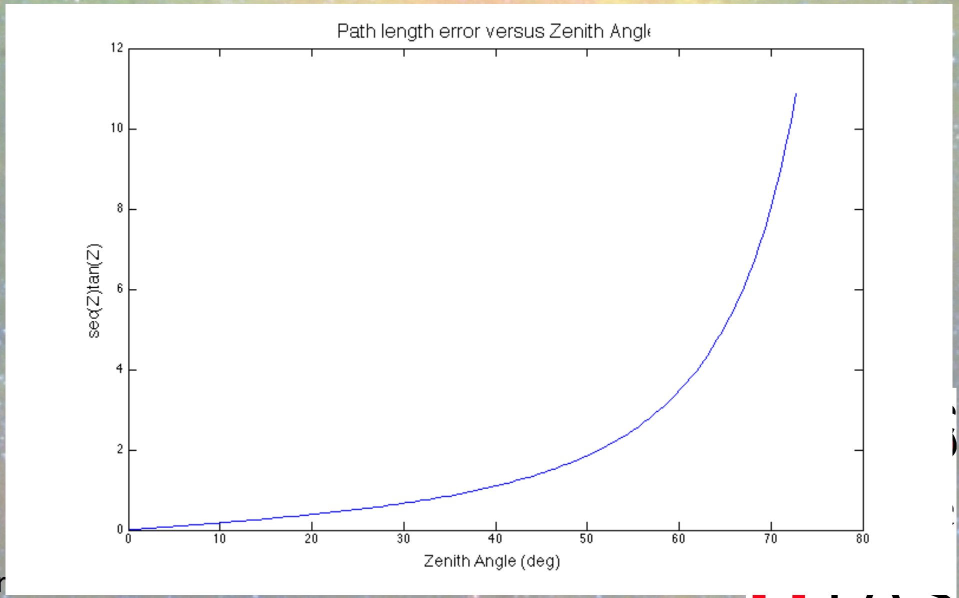
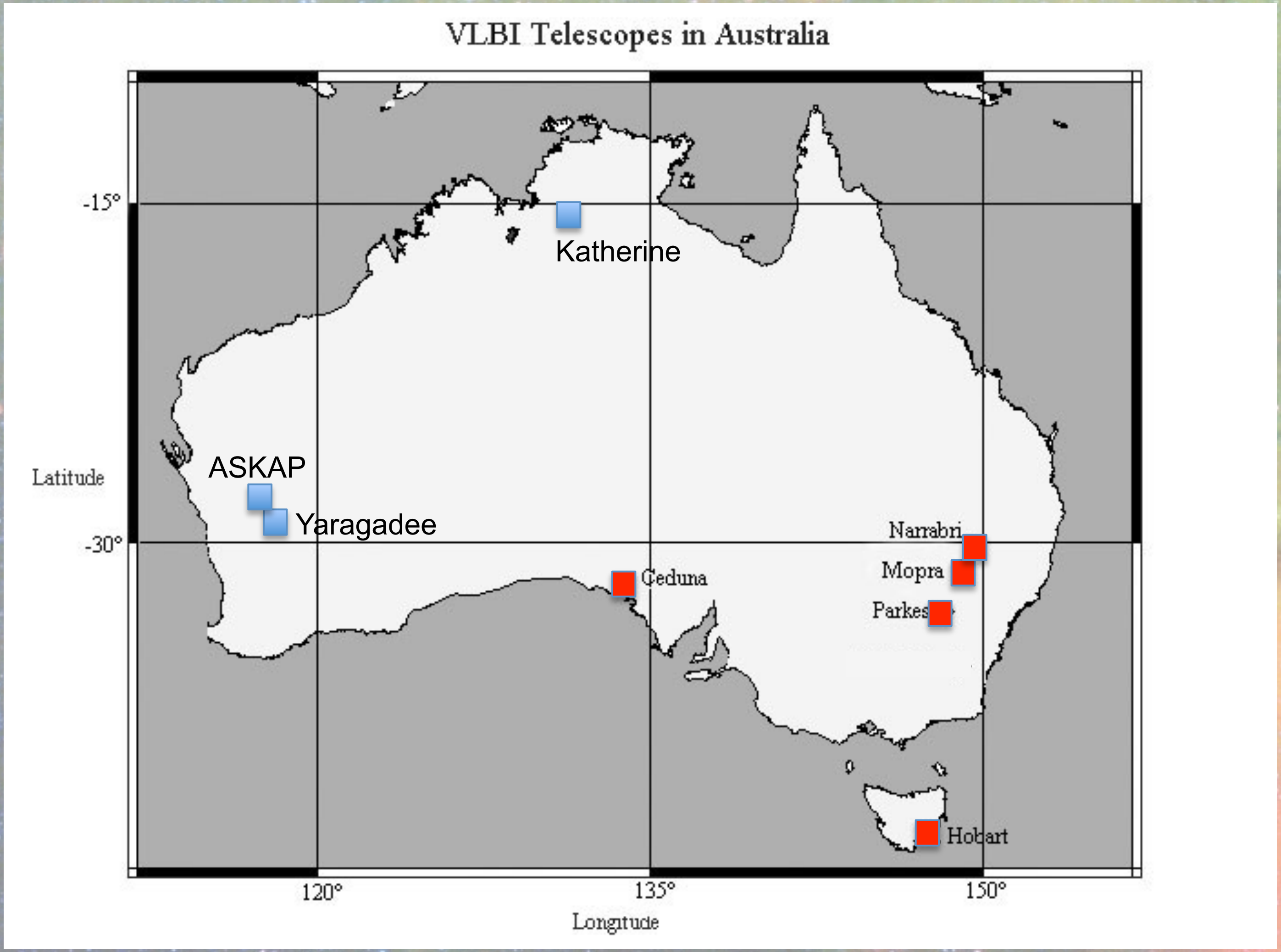
Astrometry & Zenith Angle

- The atmospheric contribution to the path length to a source at zenith angle Z is $l = \frac{c\tau_{zen}}{\cos Z}$ (e.g. Honma et al. 2008).
- So an error in the estimated zenith delay σ_τ will produce an error in the calibrator-target source path length difference Δl of

$$\Delta l = \sigma_\tau \frac{\partial}{\partial Z}(\sec \bar{Z})\Delta Z$$
$$= \sigma_\tau \sec \bar{Z} \tan \bar{Z} \Delta Z$$

- With corresponding astrometric error of $\frac{\Delta l}{B_{\max}}$





- Australian telescopes with 6.7 GHz receivers (red), possible future sites (blue)
- Maximum current baseline length ~1700 km (Hobart-Ceduna).
- Narrabri receivers upgraded 2012, factor of ~5 more sensitive.
- 6.7 GHz astrometric accuracy should be better than 100 µas

Including Hartebeesthoek increases baseline lengths to ~9000 km, but limited mutual coverage and lack of intermediate baselines adds complications.

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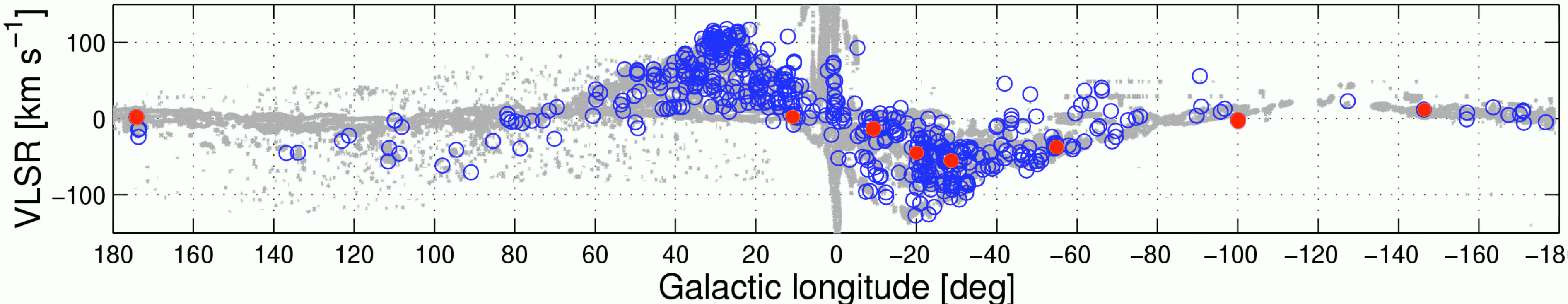
- **Aim:** Measure parallax to 30 southern 6.7 GHz methanol masers (2010-2014).
- **To date :**
  - We have received 158 hours spread over 18 separate observations (total request for project 600 hours).
  - Observations complete for 8 sources (G9.62+0.20, G8.68-0.37, NGC6334F, NGC6334I(N), G329.03-0.20, G329.06-0.31, Mon R2, G188.95+0.89).
  - Observations underway for a further 5 sources (G339.88-1.26, G339.68-1.21, G305.21+0.21, G305.20+0.02, G263.25+0.51).



Observing Strategy

- Phase reference observations of 6.7 GHz target(s) and nearby (1-2°) calibrators with a switching time of 2 minutes.
  - Calibrator observations have dual polarization 32 MHz bandwidth (2x16 MHz adjacent bands).
  - Maser observations have dual polarization 2 MHz bandwidth with 2048 spectral channels (~0.05 km/s velocity resolution)
- "Geodetic-style" tropospheric delay calibration is done about every 4 hours.
  - 45 minutes spent observing ~15 different ICRF2 sources at a wide range of azimuths.
  - Observations made with single polarization and 2x16 MHz adjacent bands at each of 6.316 GHz and 6.658 GHz.

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Challenges

- **Suitable calibrators :**
  - VLBI calibrator lists in the southern hemisphere contain a far lower density of sources than in the north. This is particularly true for the region near the Galactic Plane.
  - "All-sky" catalogues typically avoid the Galactic Plane (e.g. the PMN survey does not observe $|b| < 2°$). We have been using PMN & the AT20G surveys to identify possible calibrators.
- **Hetrogeneous telescopes and receiver systems :**
  - The exact frequency range available for the tropospheric delay calibration differs from telescope to telescope
  - Some telescopes are slow and have limited elevation ranges (e.g. Parkes).
- **The atmosphere :**
  - At 6.7 GHz the ionospheric and tropospheric contributions to the atmospheric delay are of comparable magnitude.

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The Future

- 3 months :
  - First astrometric measurements of 6.7 GHz methanol masers with the LBA (processing of two epochs near complete).
- By end of 2013:
  - Publication describing LBA maser astrometry and showing initial results for G9.62+0.20
  - Assessment of relative importance of tropospheric and ionospheric delay determination, refinement of pipeline.
- 2014 :
  - Publication of first parallax measurements of southern masers.

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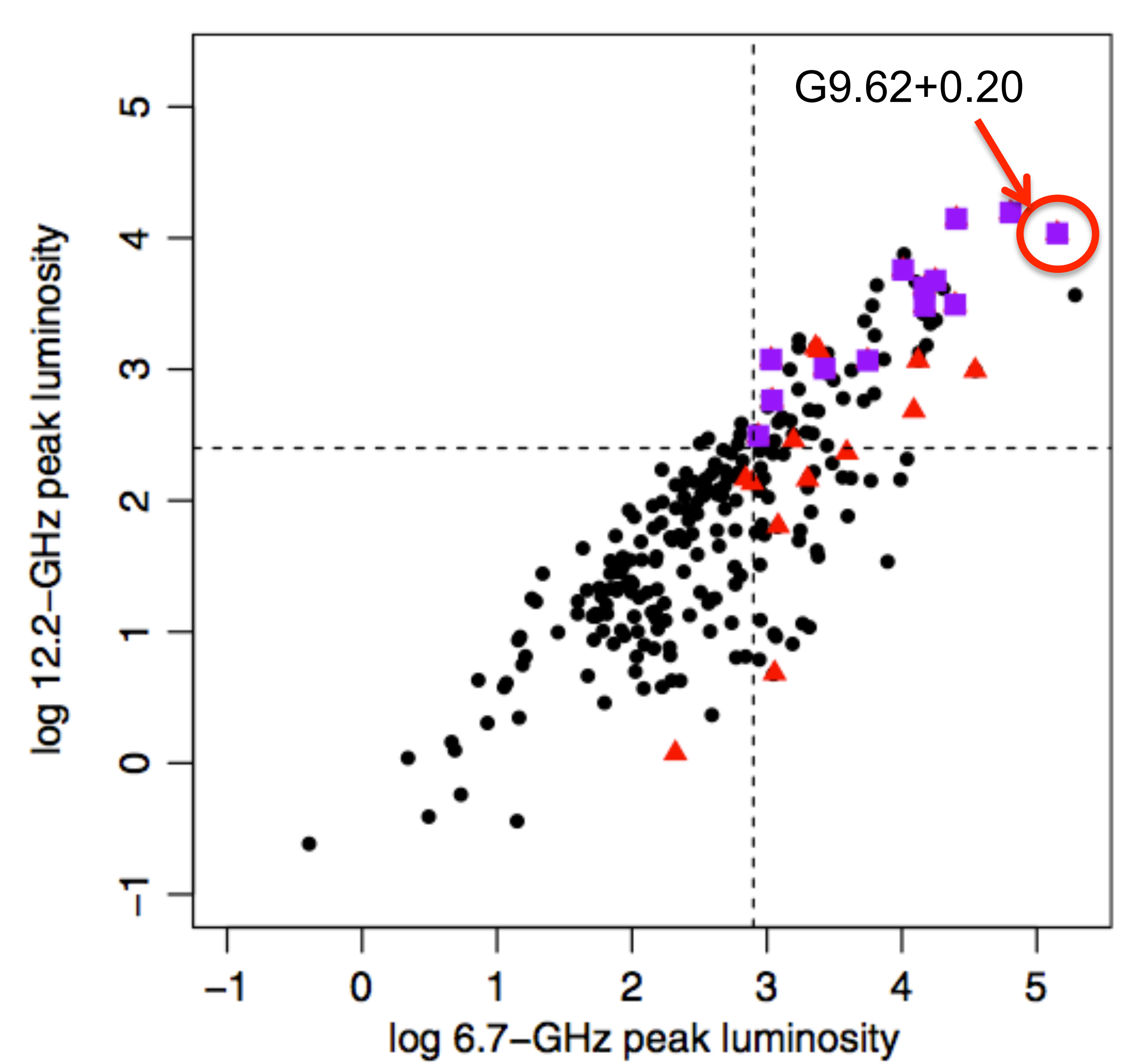
G9.62+0.20

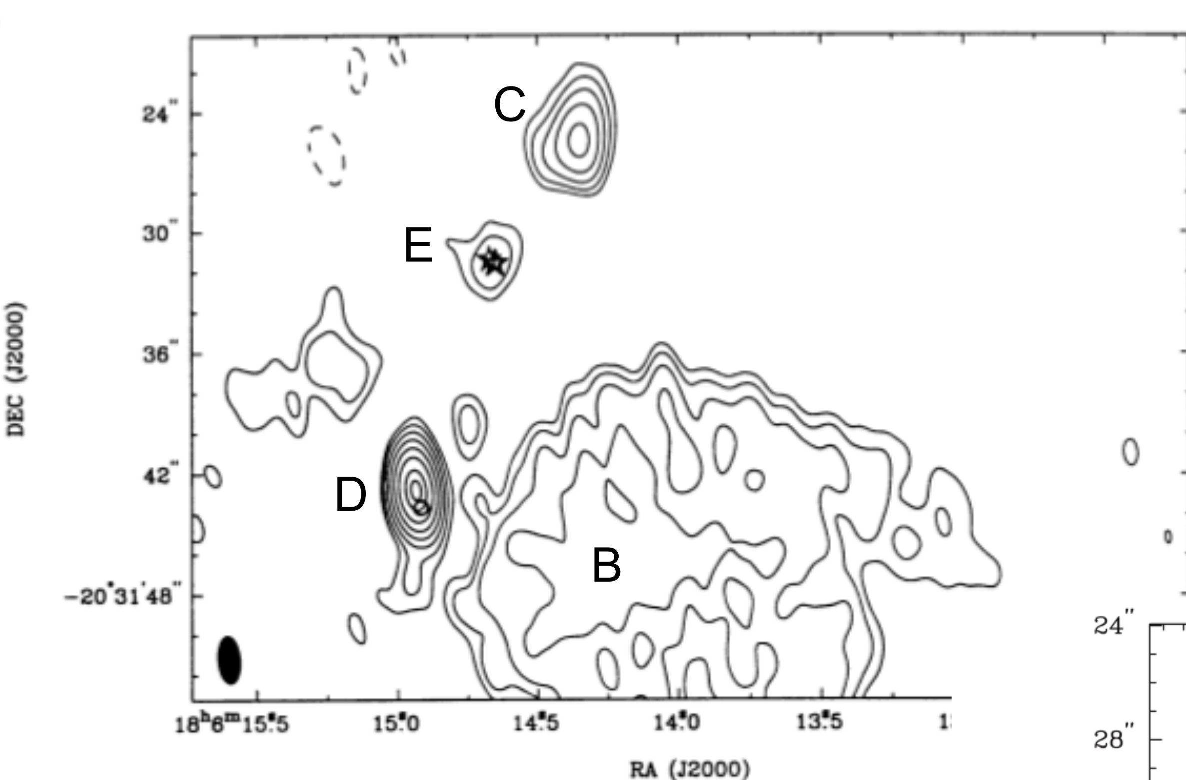
- G9.62+0.20 is the highest flux density 6.7 GHz methanol maser (peak flux density ~5500 Jy).
- It shows periodic variations in flux density (Goedhart et al. 2004 ; 2005).
- It is at a distance of 5.2±0.6 kpc (parallax measurement by Sanna et al. 2009).
- It has 6.7, 12.2, 37.7, *38.3*, 85.5 & 107.7 GHz class II methanol masers.



G9.62+0.20 is one of the most luminous class II methanol maser sources (Ellingsen et al. 2011)

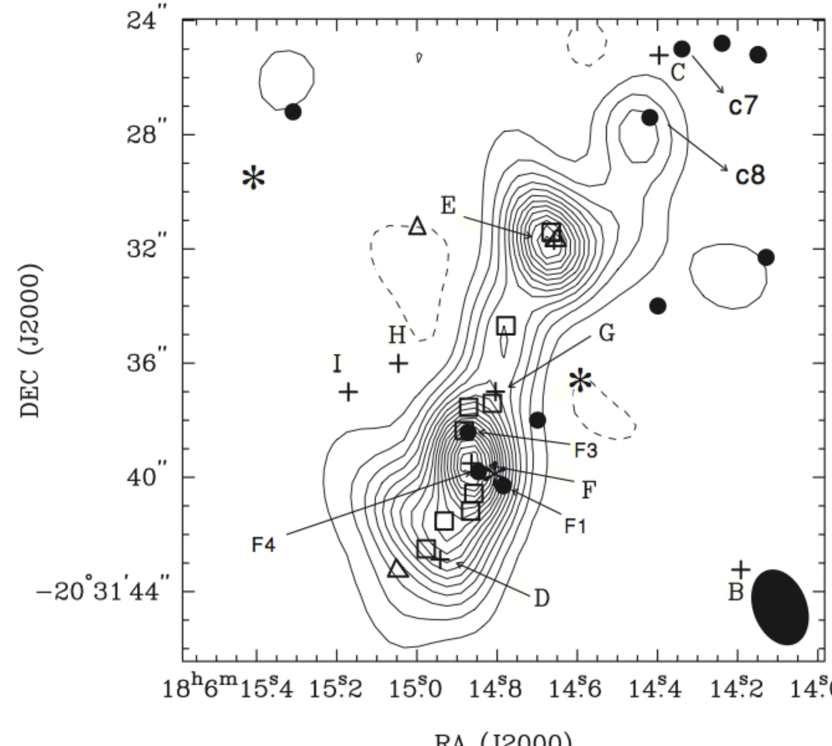
G9.62+0.19 Radio Continuum

- There are numerous high-mass stars forming in the G9.62+0.19 region.
- Strong cm radio continuum is seen from HII region B, UCHII regions D & C and hypercompact HII region E.
- The strong class II methanol masers are associated with E, weaker masers towards D
- Region F is a hot molecular core driving a bipolar outflow. The weak (few Jy) class I methanol masers may be associated with this outflow.



8.5 GHz ATCA (Phillips et al. 1998).

6.7 GHz methanol masers marked as stars



860 µm SMA (Liu et al. 2011)

6.7 GHz methanol masers marked as triangles, 22 GHz water masers squares, NIR sources circles, mm sources crosses

G9.62+0.19 Continuum

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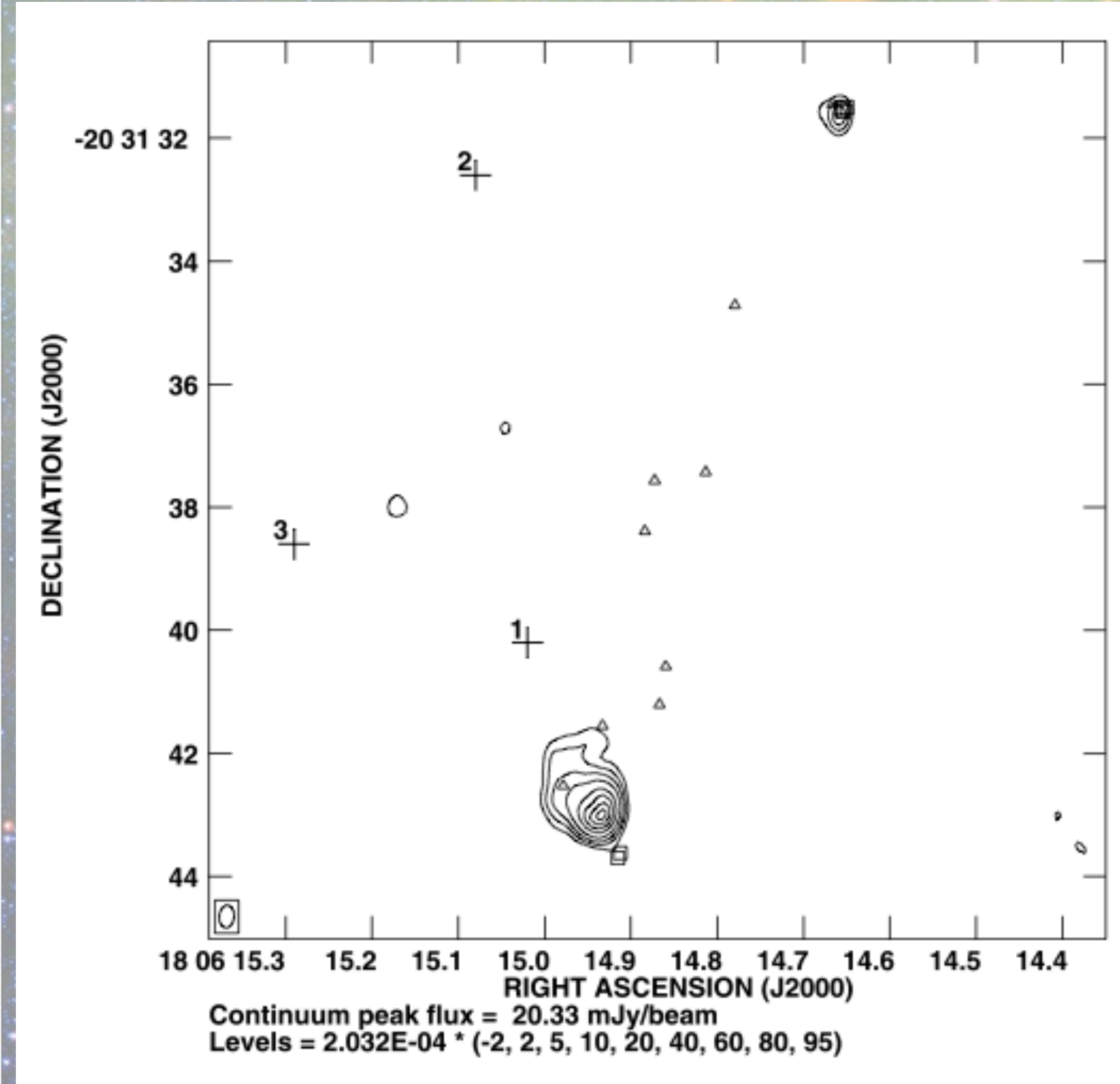

Numbered crosses: 44 GHz class I methanol masers (Kurtz et al. 2004)

Triangles : 22 GHz water masers (Hofner et al. 1996)

Squares : 6.7 GHz class II methanol masers

Contours 3.6 cm continuum (Testi et al. 2000)

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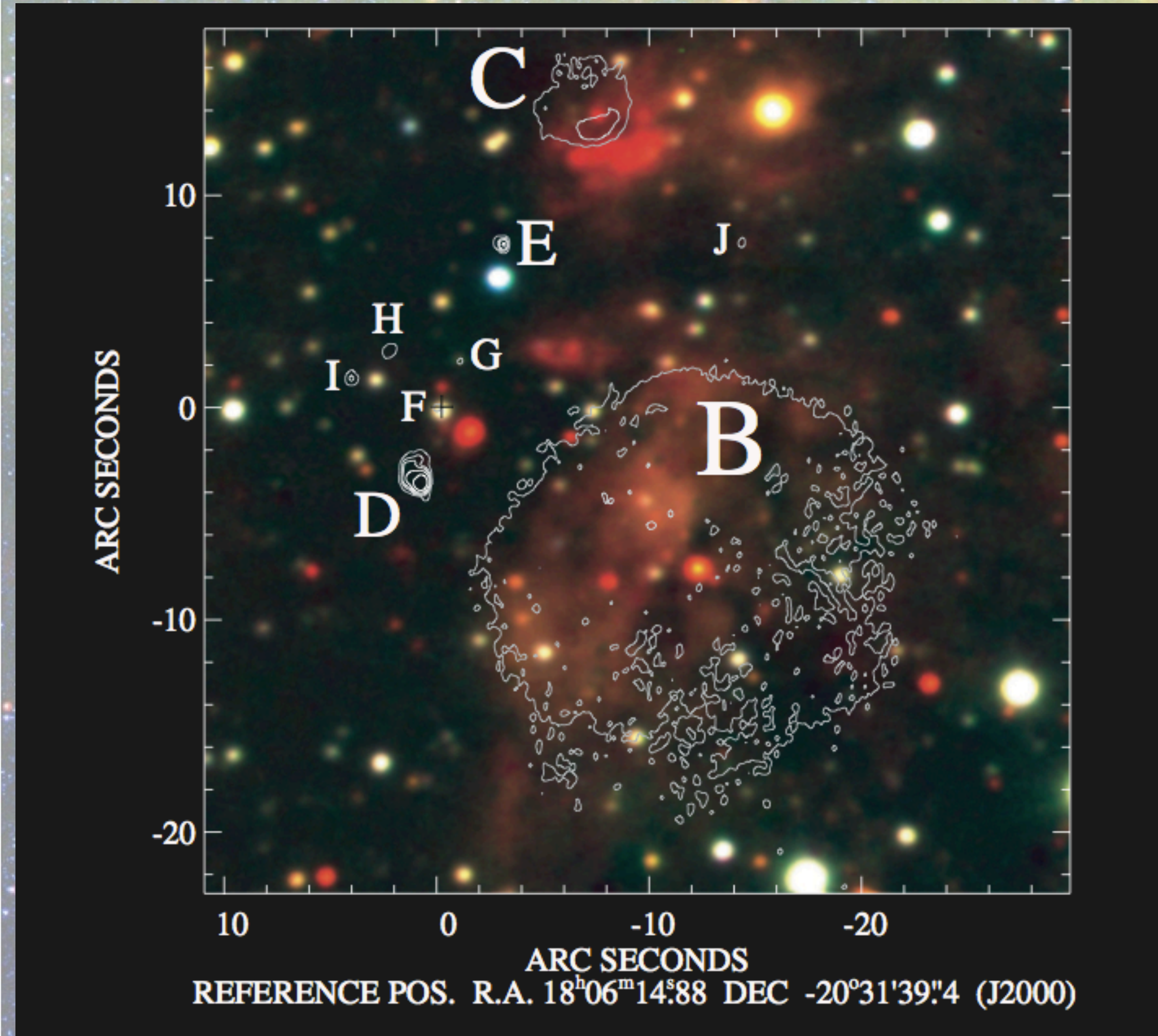

JHK-band image (Linz et al. 2005).

3.6cm radio continuum emission from Testi et al. (2000)

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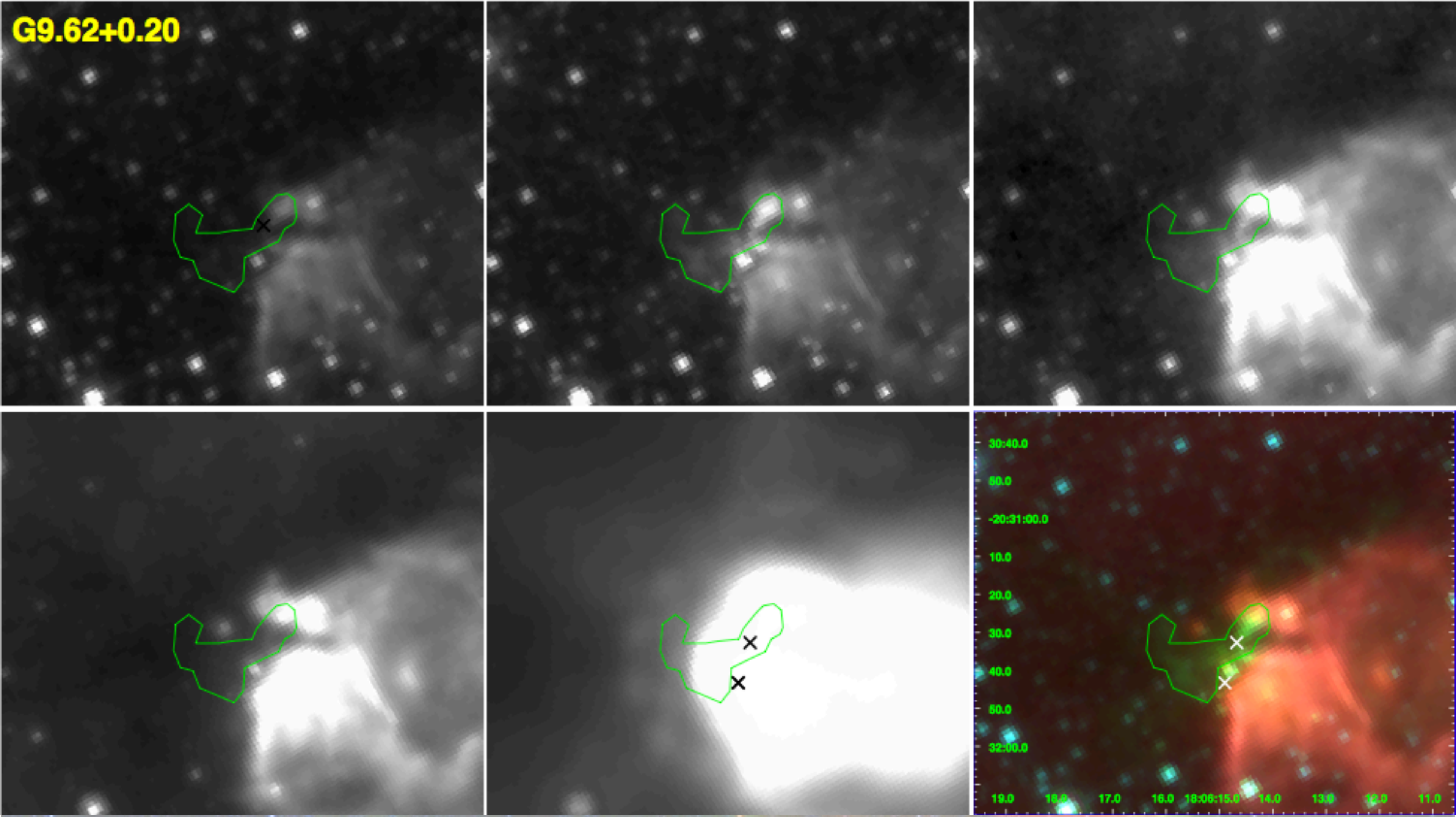
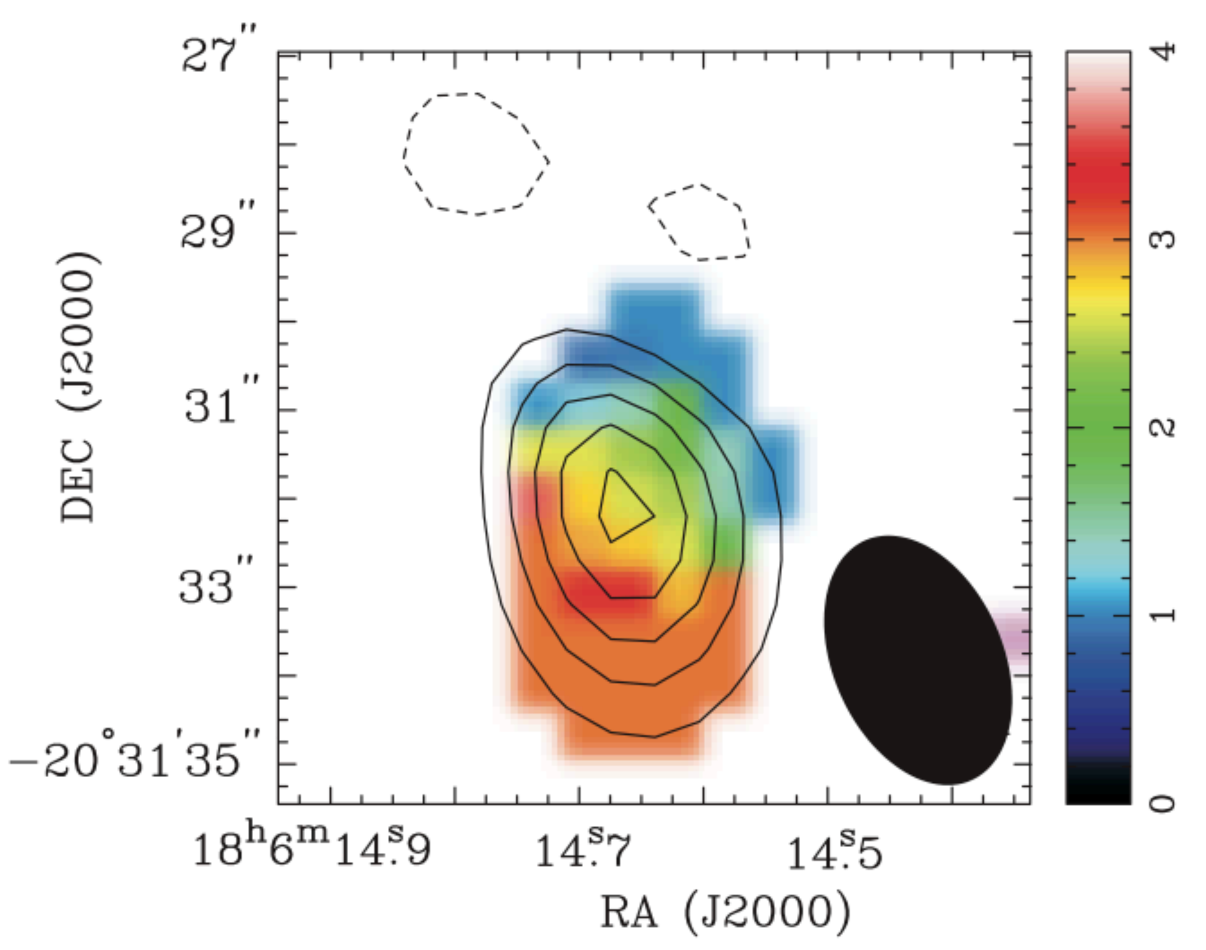


Spitzer images of the G9.62 region. From upper left : 3.6 μm, 4.5 μm, 5.8 μm. From lower left 8.0 μm, 24 μm, 3-colour composite (Chen et al. 2013)



Infall at a rate of 4.3×10^{-3} $M_{\odot}yr^{-1}$ has been inferred for source E from SMA HCN(4-3) and CS(7-6) observations (Liu et al. 2011).

Density of dust emission associated with E is 1.5×10^{7} cm^{-2}.

Hot methanol seen towards E, but not F (Hofner et al. 2001)

Integrated intensity (contours) and first moment (colours) of H_2CS (10-9) emission towards G9.62+0.20E (Liu et al. 2011)

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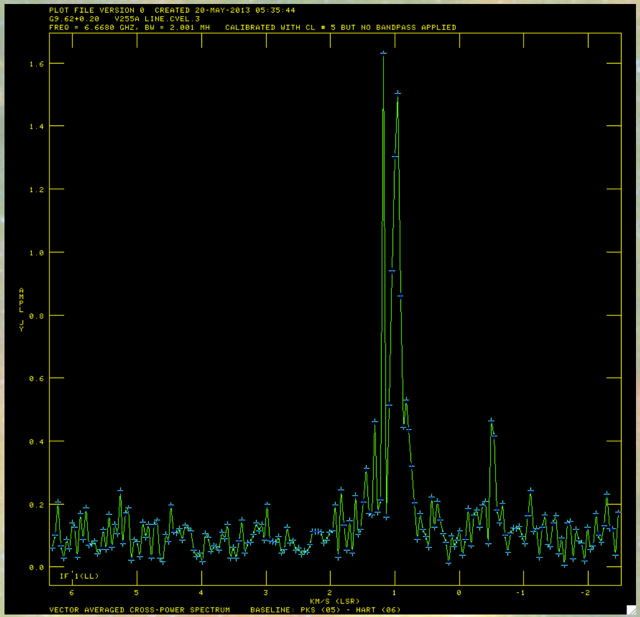
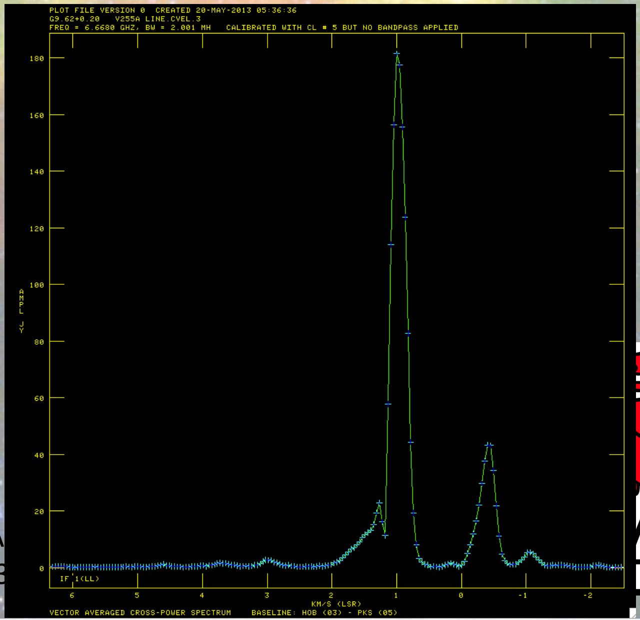
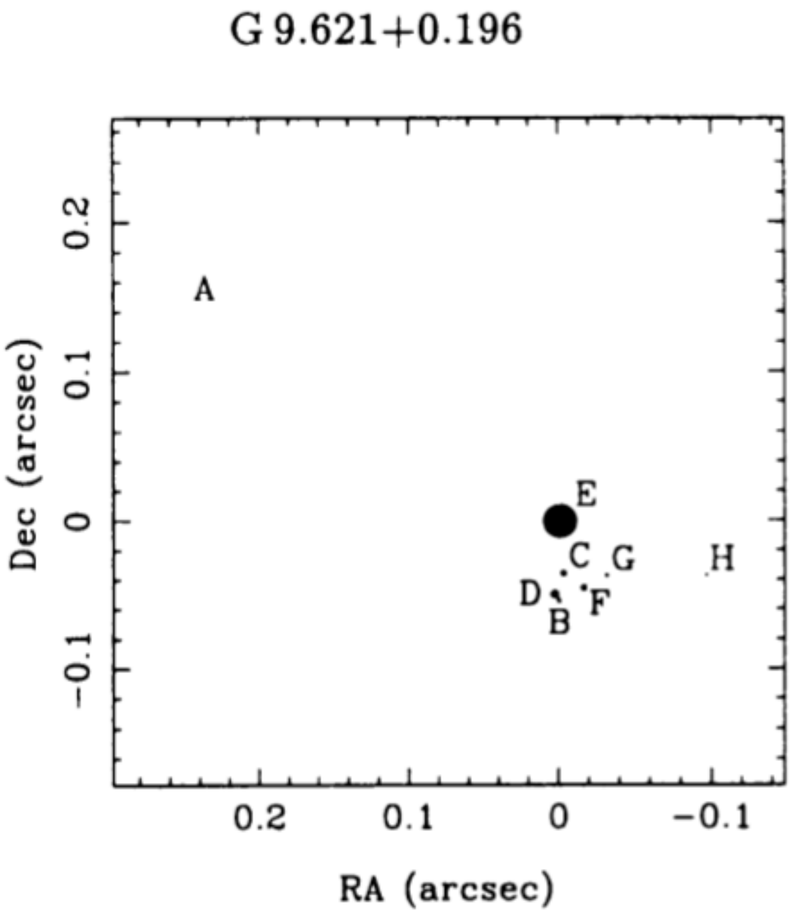
LBA observations of G9.62+0.20

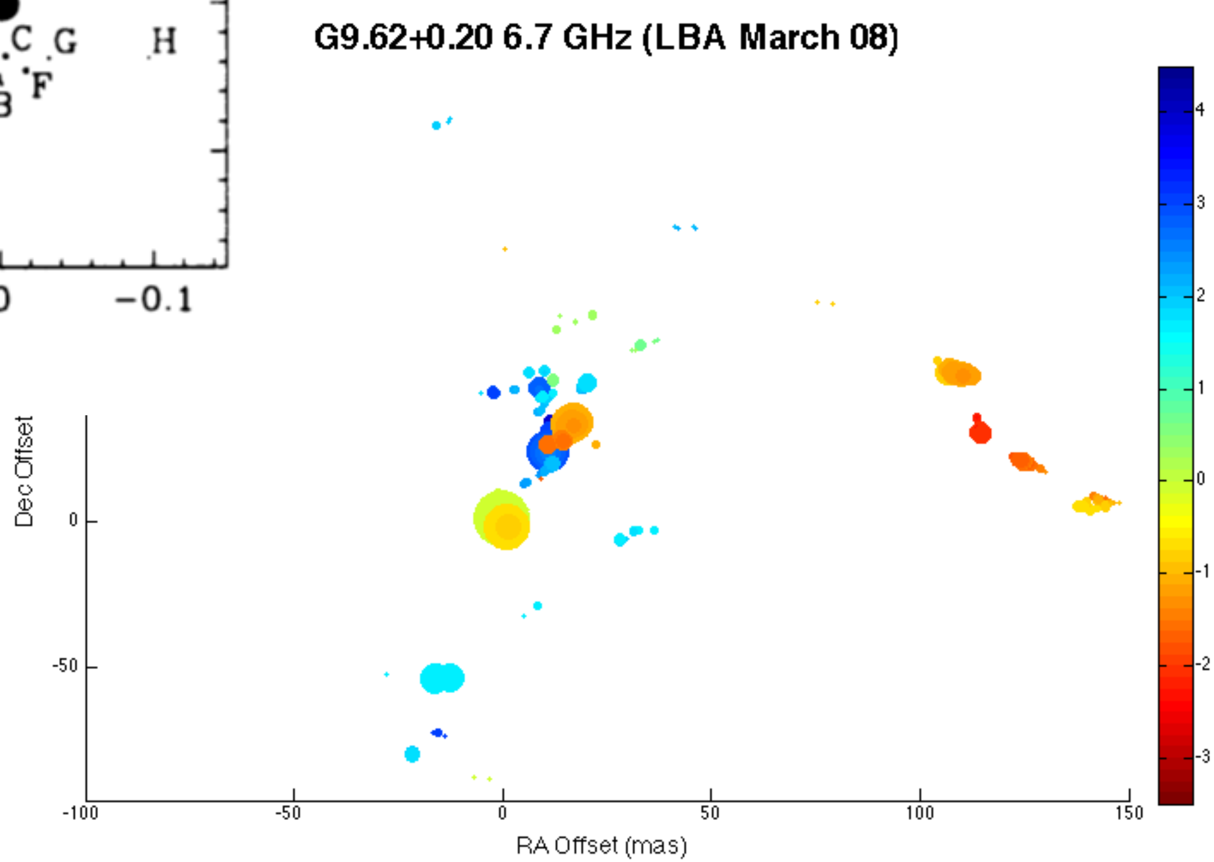
- Observations made in March 2008 with array of AT,HO,CD,MP,PA & *HA*.
- First of the V255 parallax observations.
- Detection of G9.62+0.20 on baselines to Hartebeesthoek, but issues with the delay calibration, so not included in imaging.





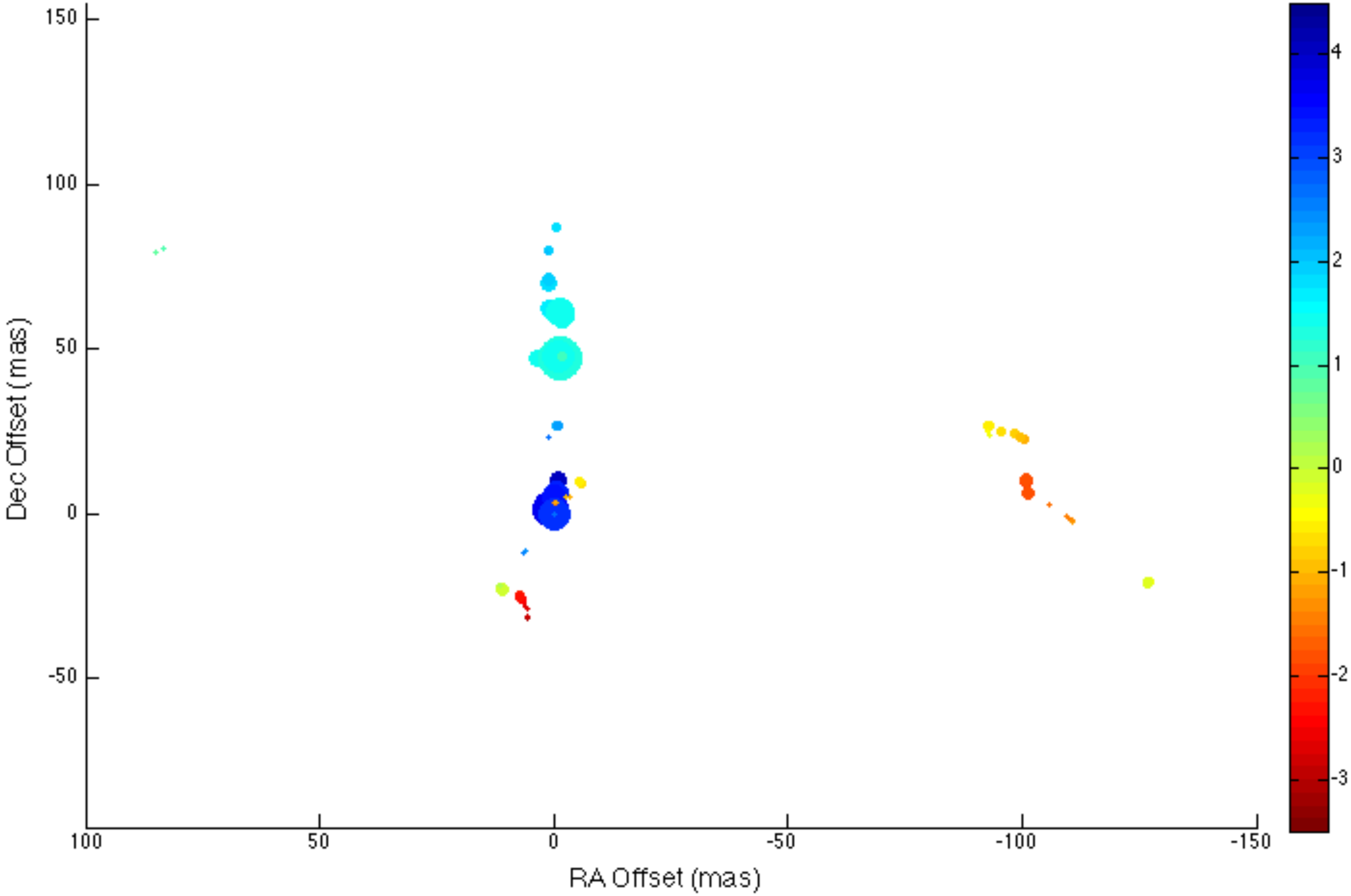


Right: Distribution of 6.7 GHz methanol masers in G9.62+0.20 E from Phillips et al. (1998).
Below: Distribution of 6.7 GHz methanol masers from LBA



NOTE: The maser velocity colours are reversed from the standard convention

G9.62+0.20 12.2 GHz (VLBA May95)



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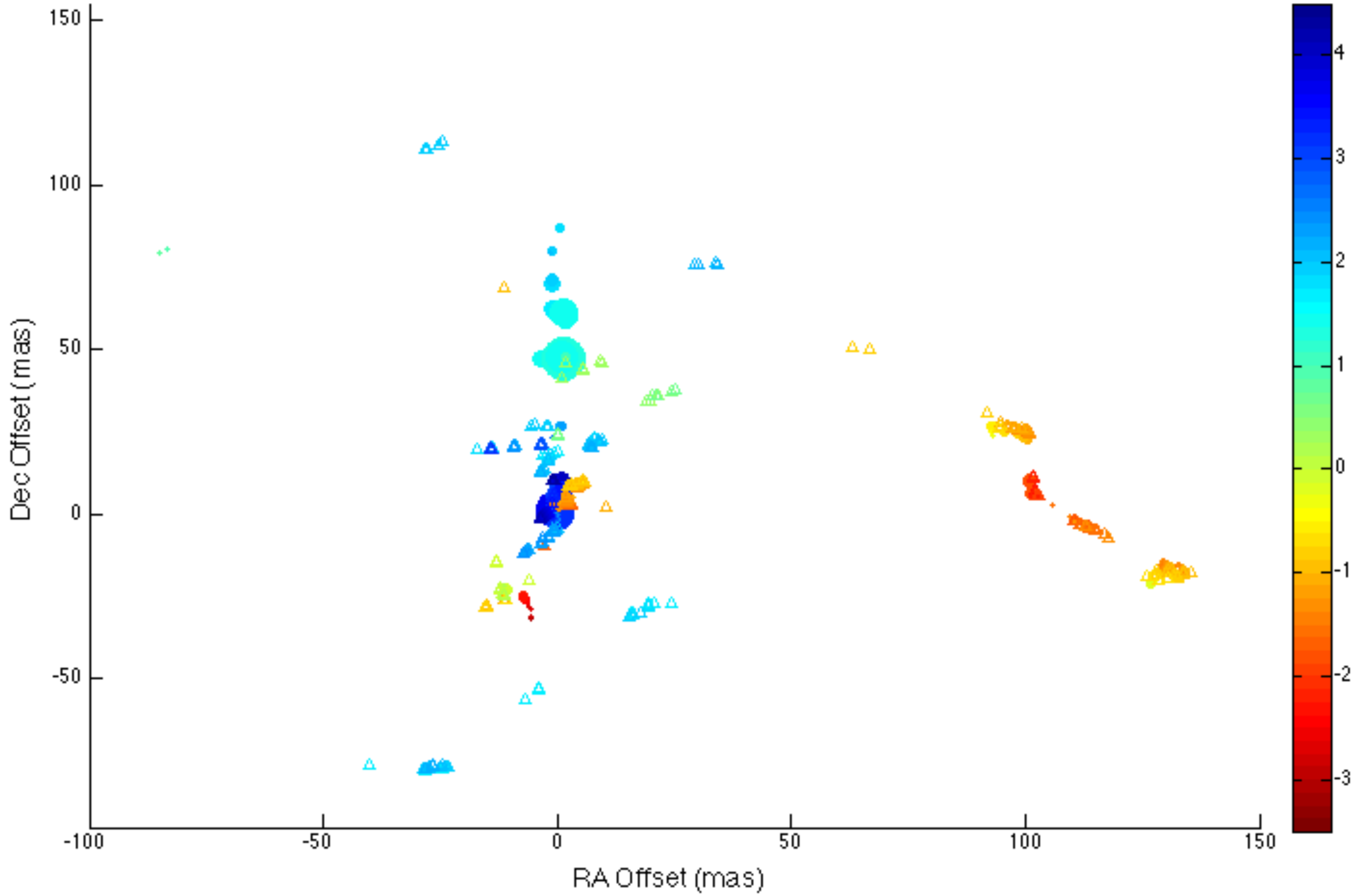
G9.62+0.20 6.7/12.2 GHz comparison



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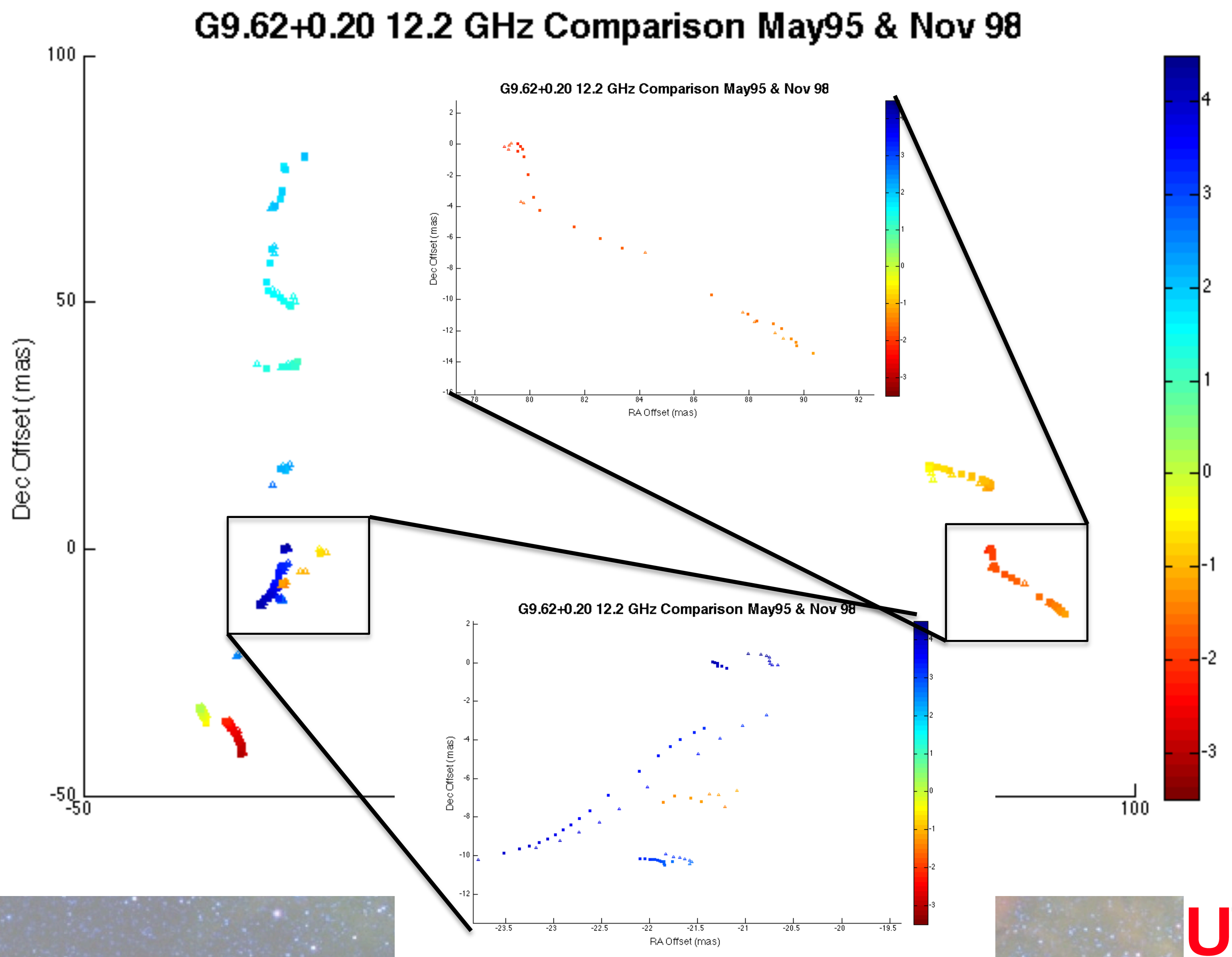
Triangles = May 1995, Squares = November 1998 (in collaboration with Vincent Minier)



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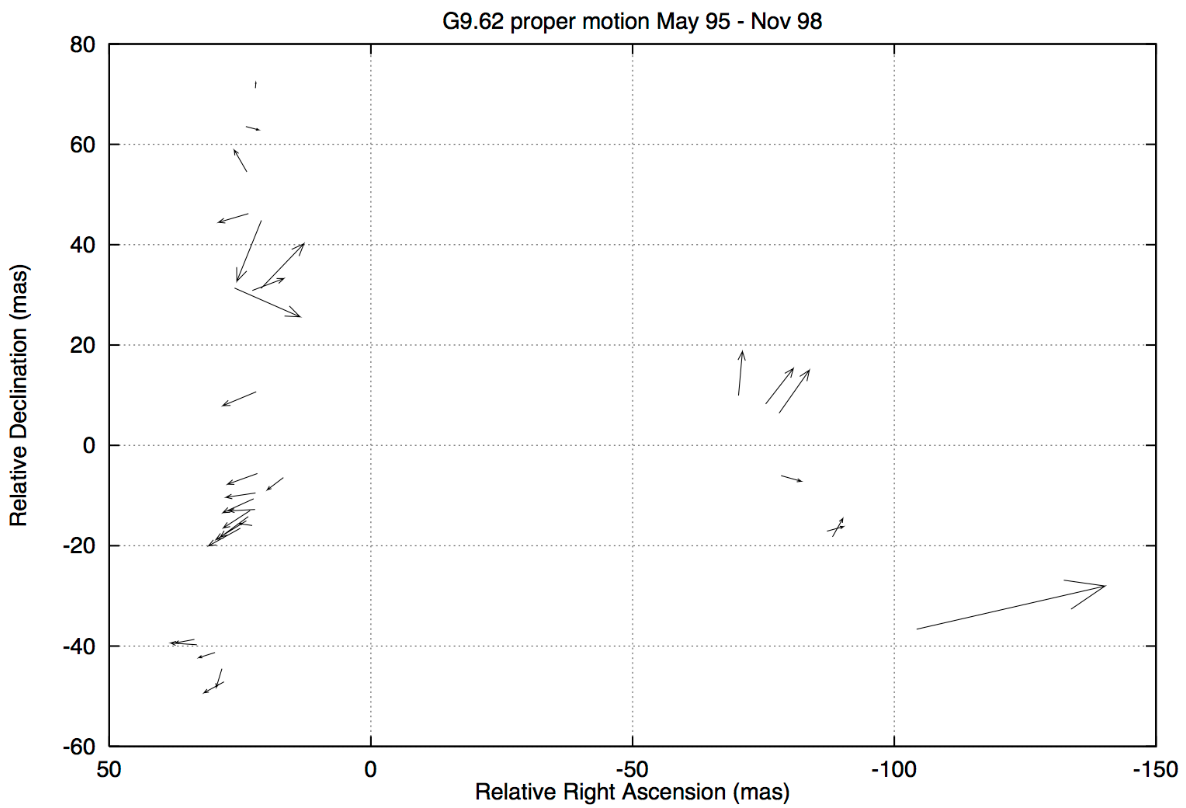

The relative proper motion between the two regions of 12.2 GHz masers is 0.2 mas yr^{-1}.

If we interpret this as expansion the inferred rate is 2.5 kms^{-1}.

An order of magnitude less than the Acord et al. (1998) observation of G5.89-0.39

Conclusions

- Trigonometric parallax observations of southern methanol masers are currently in progress (first results expected within 12 months).
- VLBI observations of the methanol masers towards G9.62+0.20 reveal a complex morphology.
  - Comparison of two epochs of 12.2 GHz VLBA observations suggest region where the maser emission arises is expanding at a rate of around 2.5 km/s.
  - Observations of molecular gas on larger scales observe infall in the same source.

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