# Studies of galactic masers in RadioAstron space VLBI mission

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& **RadioAstron maser team**

Granada 2018

# TEAM

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M.Voronkov

# Related papers:

- **A.M.Sobolev, J.M.Moran, M.D.Gray et al. 2018ApJ...856...60S**

  ***Sun-sized Water Vapor Masers in Cepheus A***

- **A.M.Sobolev, N.N.Shakhvorostova, A.V.Alakoz, W.A.Baan 2018IAUS...336...417S**
  ***RadioAstron space-VLBI project: studies of masers in star forming regions of our Galaxy and megamasers in external galaxies***

- **N.N.Shakhvorostova, A.V.Alakoz, A.M.Sobolev 2018IAUS...336...447S**
  ***Brightness temperatures of galactic masers observed in the RadioAstron project***

# Related posters:

- **N.N.Shakhvorostova, A.M.Sobolev , A.V.Alakoz & RA maser team**

***“Ultra-compact structures in galactic masers observed in the RadioAstron project“***

- **Olga Bayandina & Maser Monitoring Organization (M2O)**

***“Bursting H2O maser source G25.65+1.05: from single-dish to space VLBI"***

***Observations of Maser Sources in the Galaxy***

***with high angular resolution allow:***

- **Study star formation phenomena on the scales from a.u. (the Solar system) to ~ 15 kpc (the whole Galaxy)**
- **Study mass loss phenomena in evolved stars**
- **Locate new interesting objects**
- **Study nature of these sources:**
- \- study structure of the sources
- \- study kinematics
- \- determine physical parameters in the regions where masers are formed and their vicinity, including characteristics of magnetic fields and turbulence
- measure distances to the sources by direct method of trigonometric parallax
- Study distribution of the sources in the Galaxy
- et al.

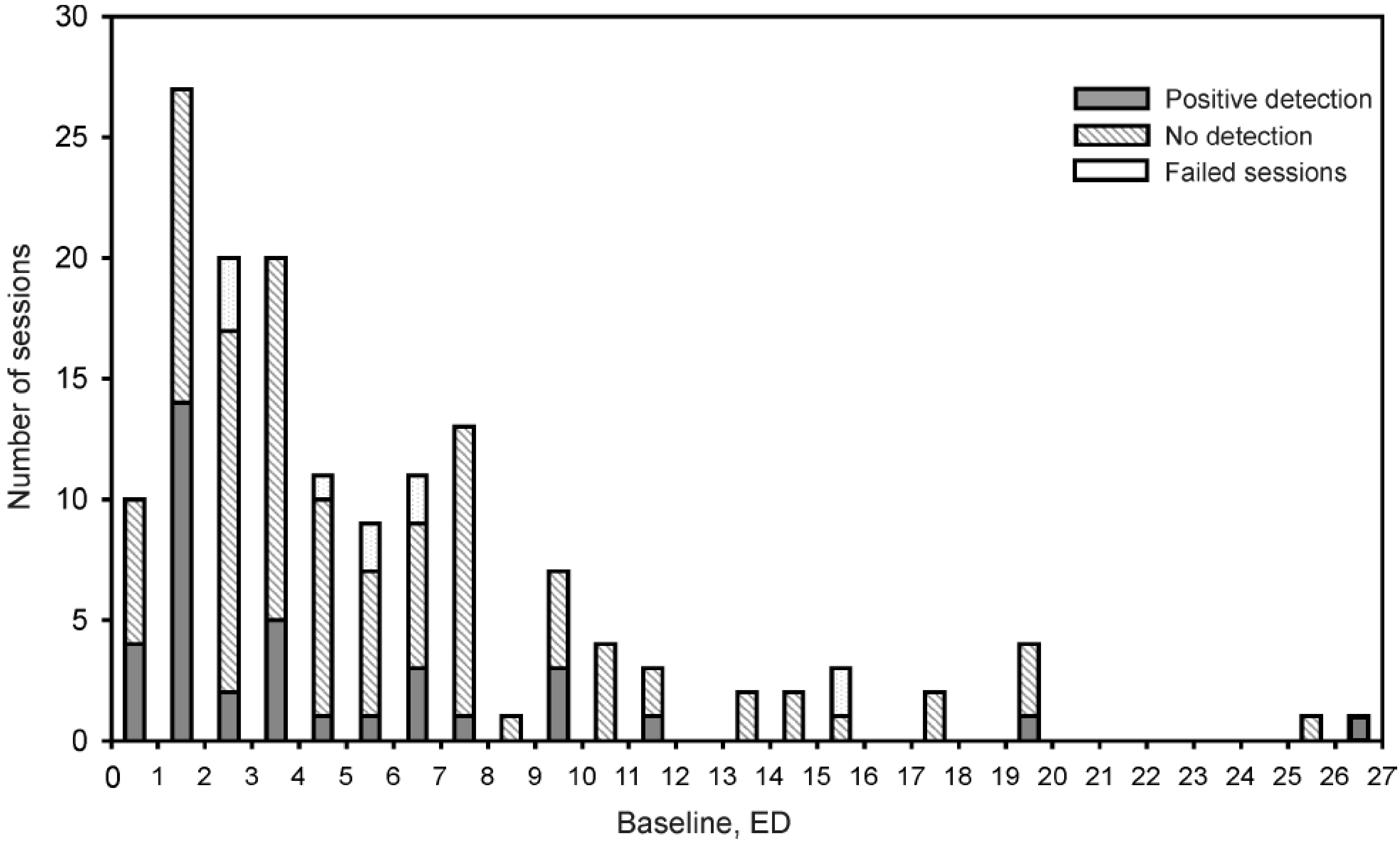
# What can prevent making a step from Milli- to Micro-arcsecond studies using space VLBI?

- Maser beaming
- Scattering in the line-of-sight: dithering and scintillation
- Time variability and ultra-fine structure of the source: instabilities and turbulence

# Masers with RadioAstron:

- OH @1665 & 1667 MHz
- $H_2O$ @ 22235.08 MHz – several bands
  (allow us to observe doppler-shifted Megamasers)
- SiO
- CH
- $H_2CO$
- $CH_3OH$
- $NH_3$
- $HC_3N$
- HCN

# Statistics of detections



# Summary of RadioAstron unsuccessful observations of evolved stars in the Galaxy

| Source name | Line | Number of sessions | Projected baselines (approx. ED range) | Note |
|---|---|---|---|---|
| S Persei | $H_2O$ (22 GHz) | 7 | 2,3,4,7,10,20 | |
| VY CMa | $H_2O$ (22 GHz) | 7 | 3,4,5,7,10 | 1 session RA form. error |
| VY CMa | OH (1.665/1.667 GHz) | 3 | 2.5,5 | |
| U Her | $H_2O$ (22 GHz) | 1 | 2.5 | |
| VX SGR | $H_2O$ (22 GHz) | 1 | 2.0 | RA pointing error! |
| NML Cyg | $H_2O$ (22 GHz) | 1 | 1.7 | |

# Masers in Star-Forming Regions

## Galactic water masers

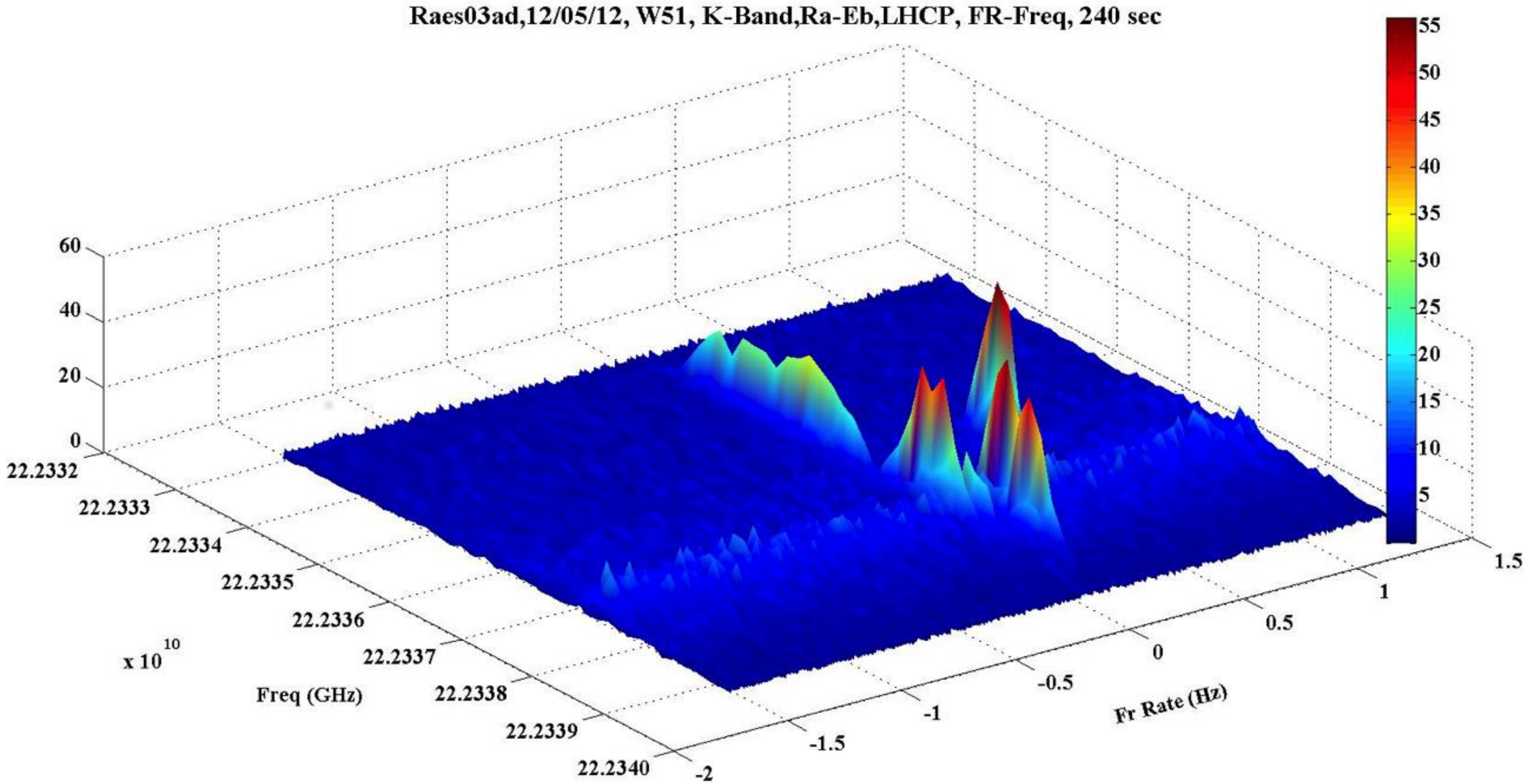
| Source | Molecule | Baseline (ED) | Max Resolution (mas) |
|---|---|---|---|
| W3 Irs5 | H2O | 2.5-2.8; 3.5; 3.9; 5.4; 6.0; 6.0-10.0 | 22 |
| W49 N | H2O | 2.2-3.0; 4.5; 7.9; 9.4 | 23 |
| W3 OH | H2O | 3.9 | 56 |
| Cepheus A | H2O | 0.9-1.7; 1.1; 3.1-3.5 | 62 |
| Orion KL | H2O | 1.9; 3.4 | 64 |
| W51 M/S | H2O | 0.4-2.3; 1.3; 1.4-1.8; 1.7 | 95 |
| G43.8-0.13 | H2O | 1.2; 1.2 | 182 |

## Galactic hydroxyl masers

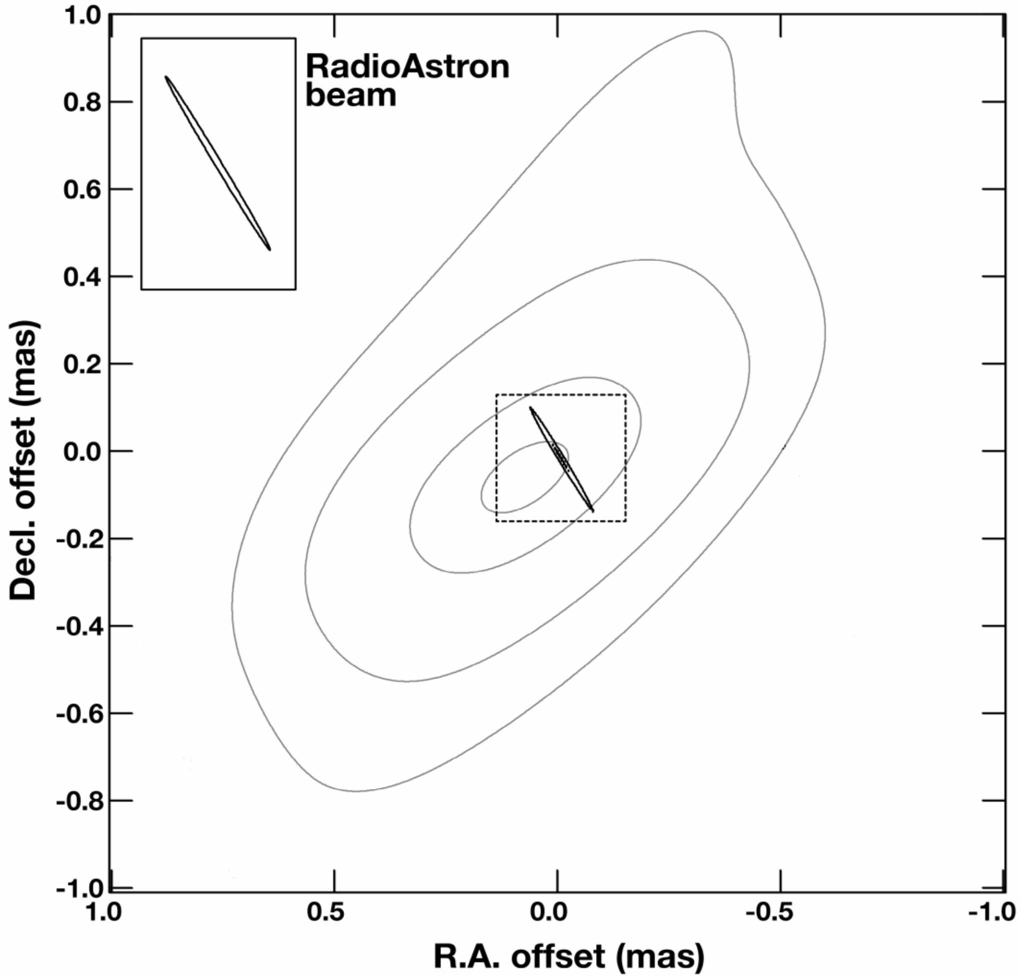
| | | | |
|---|---|---|---|
| Onsala 1 | OH | 0.2-0.7; 1.0-1.9 | 1540 |
| W75 N | OH | 0.1-0.3; 0.1-0.8 | 3660 |

# Galactic water masers

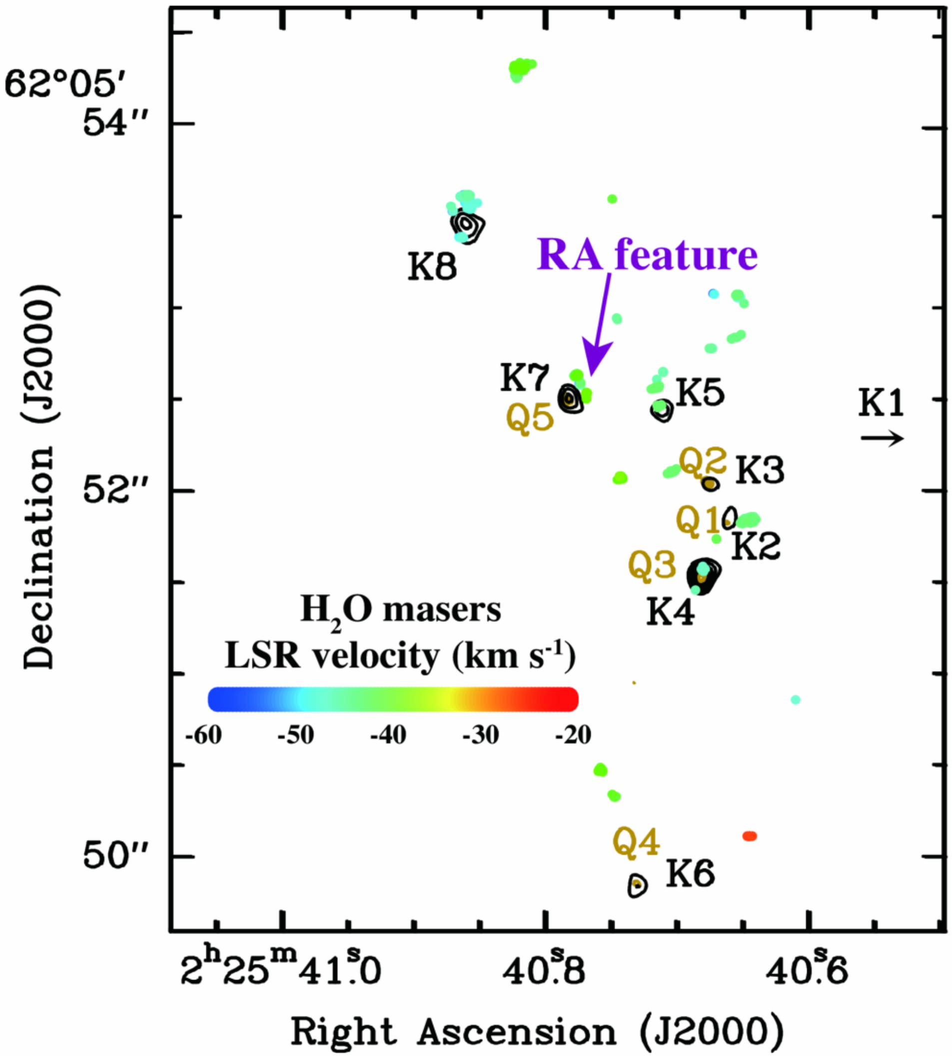
W51M , first fringes at 22GHz
($H_2O$ maser line RA-Eff, 1.14 Earth D.)
Now- fringes at 2 Earth D.



# W3IRS5, 22GHz, 5.4 Earth Diameters




Contour map with RA-GRT baselines: 0.2, 0.32 Jy/beam
Contour map with GRT baselines: 3, 5, 7, 7.6 Jy/beam



$$T_b = \frac{\pi}{2k} \frac{B^2 V_0}{\ln(V_0/V_q)}$$

$$T_{b,\min} = \frac{\pi e}{2k} B^2 V_q \approx 3.09 \left(\frac{B}{\mathrm{km}}\right)^2 \left(\frac{V_q}{\mathrm{mJy}}\right) [\mathrm{K}].$$

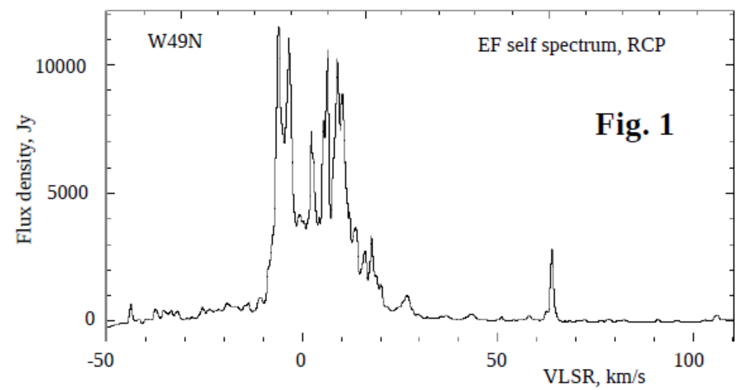
## DETECTION RESULTS

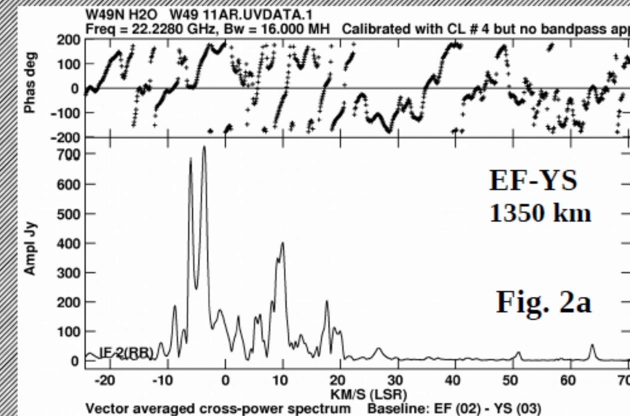
| Source (Alias) | RA J2000 (h m s) | DEC J2000 (d m s) | Baselines on which the source was detected, Earth diameters (ED) | Max resolution (mas) | Max detected brightness temperature, K |
|---|---|---|---|---|---|
| W49 N | 19 10 13.41 | 09 06 12.80 | 2.2-3.0; 4.5; 8.6; 9.6 | 23 | 1.4e+16 |
| W3 Irs5 | 02 25 40.71 | 62 05 52.52 | 2.5-2.8; 3.5; 3.9; 5.4; 6.0 | 36 | 8.1e+15 |
| W3 OH | 02 27 04.84 | 61 52 24.61 | 3.9 | 56 | 7.1e+14 |
| Ceph A | 22 56 17.97 | 62 01 48.75 | 0.9-1.7; 1.1; 3.1-3.5 | 62 | 3.0e+14 |
| Orion KL | 05 35 14.13 | -05 22 36.48 | 1.9; 3.4 | 64 | 6.0e+15 |
| W51 M/S | 19 23 43.87 | 14 30 29.45 | 0.4-2.3; 1.3; 1.4-1.8; 1.7 | 95 | 2.2e+14 |

**Poster by N.N.Shakhvorostova, A.M.Sobolev, A.V.Alakoz & RA maser team**

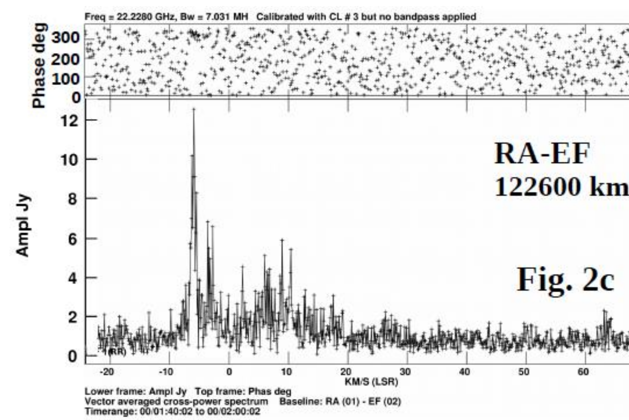
# W49N

| Epoch | Ground array | Band | Observing time | Baseline length | Angular resolution |
|---|---|---|---|---|---|
| 2015 April 27 | Ef, Ys, Tr, Hh<br>*(for details see the box in the left bottom corner)* | K ( 22 GHz ) | 1 hour | 9.6 ED<br>~122 000 km | 23 μas |




The brightest feature at the velocity $V_{LSR}$ ~ **–6 km/s** is unresolved at space-ground baseline. The brightness temperature **Tb ~ 2.3e+15 K** with the size estimate equal to angular resolution ~ 23 μas. Correlated flux density at the space-ground baseline RadioAstron – Effelsberg is ~ **12.6 Jy**, what is **~ 0.1%** of the single dish flux density.

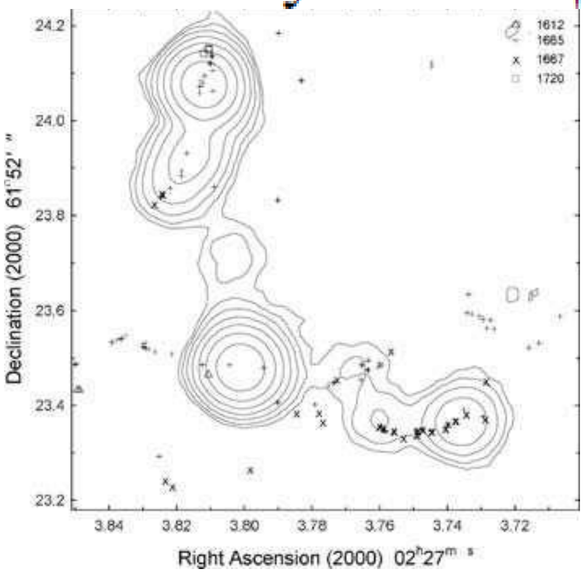


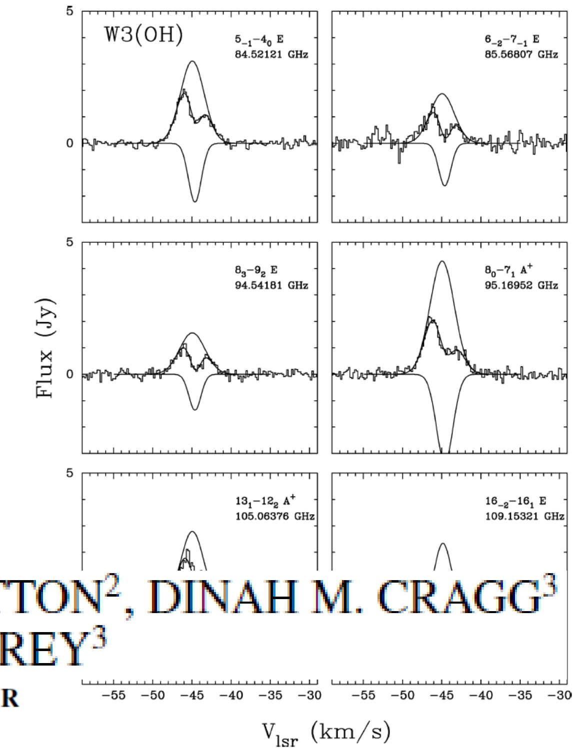

**Poster by N.N.Shakhvorostova, A.M.Sobolev, A.V.Alakoz & RA maser team**

Mon. Not. R. Astron. Soc. 371, 1550–1558 (2006)

# Discovery of large-scale methanol and hydroxyl maser filaments in W3(OH)

L. Harvey-Smith★† and R. J. Cohen




ANDREI M. SOBOLEV[1], EDMUND C. SUTTON[2], DINAH M. CRAGG[3] and PETER D. GODFREY[3]

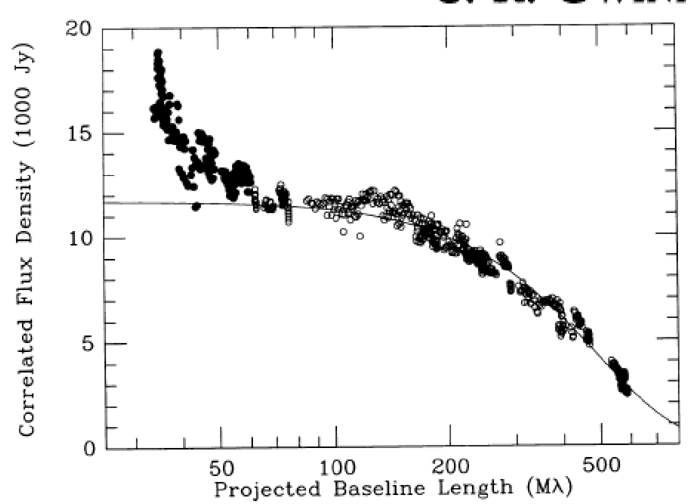
## MODEL OF THE W3(OH) ENVIRONMENT BASED ON DATA FOR BOTH MASER AND "QUASI-THERMAL" METHANOL LINES

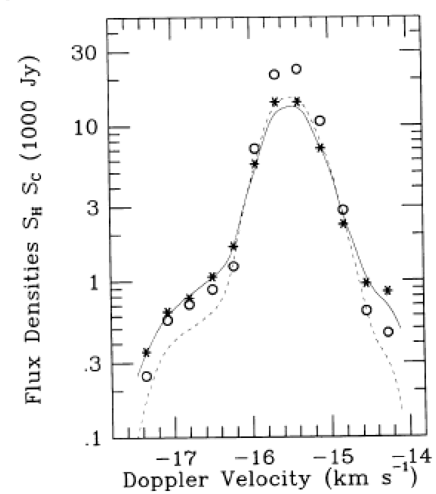
*Astrophysics and Space Science* **295:** 189–196, 2004.

THE ASTROPHYSICAL JOURNAL, 431:L123–L126, 1994 August 20

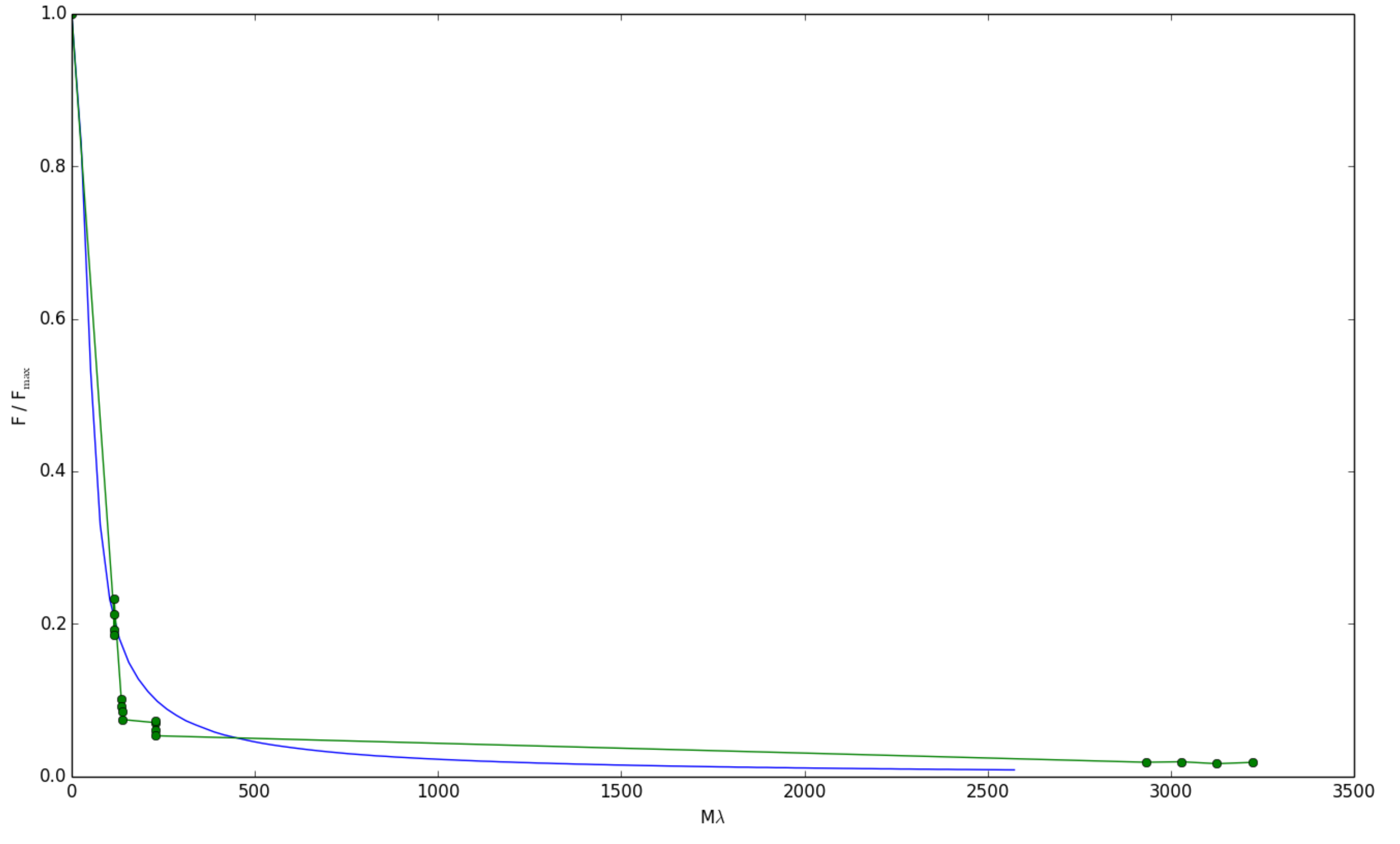
# SCATTERED HALOS AROUND $H_2O$ MASERS

C. R. GWINN



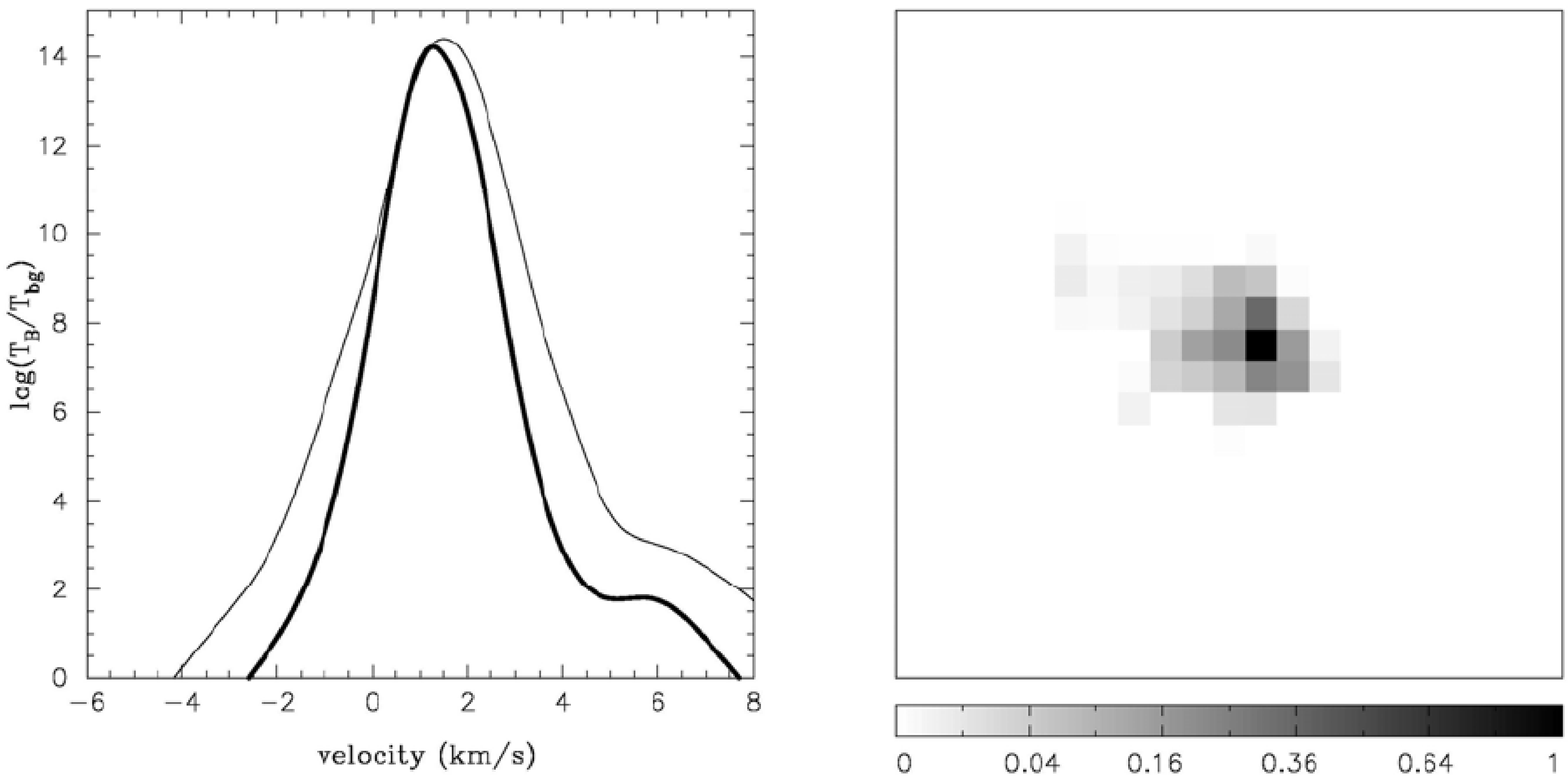



# Change of the size due to saturation



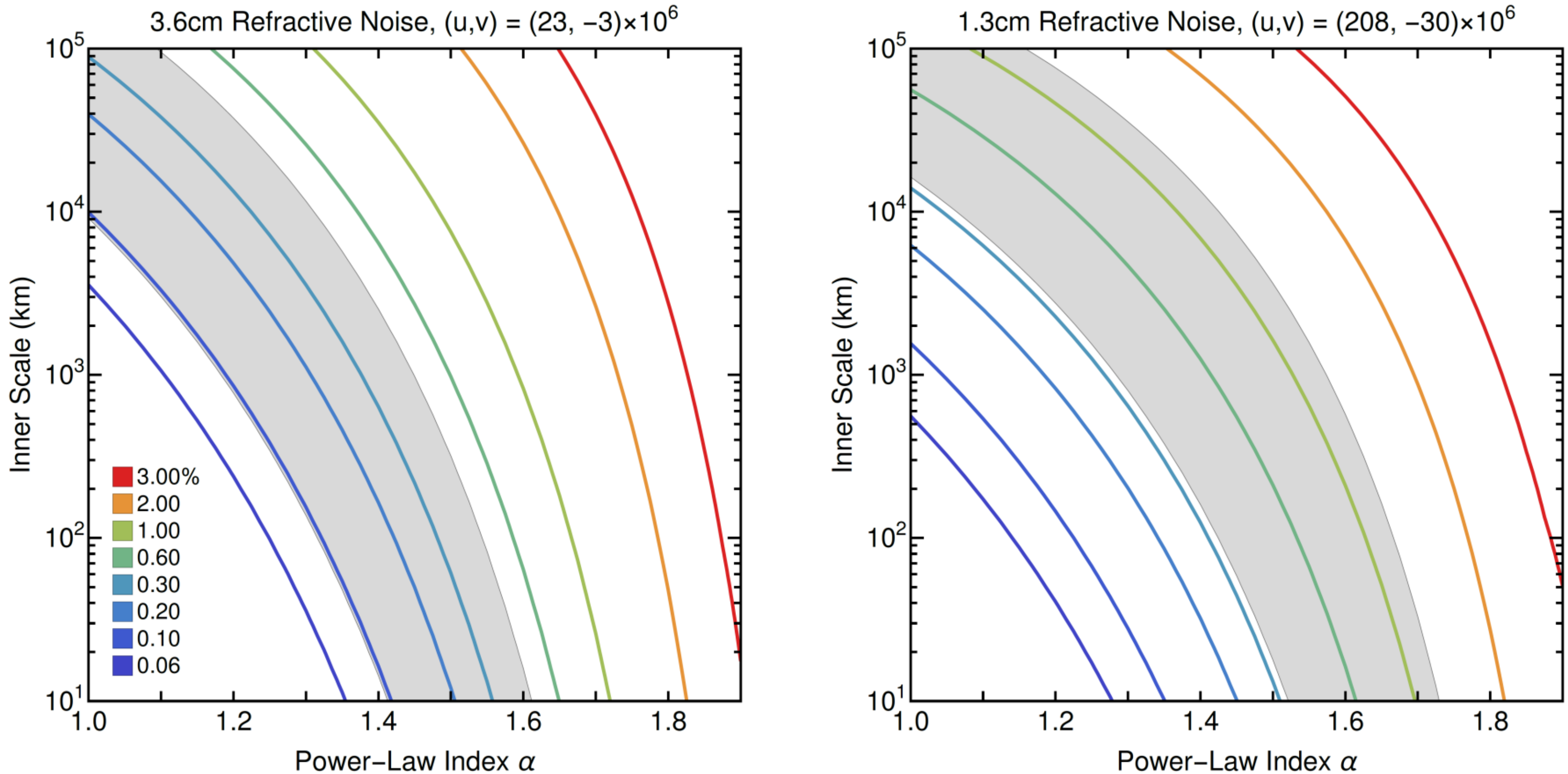

Model of **W.D.Watson & H.W.Wyld (2003)**
Apparent Sizes and Spectral Line Profiles for Spherical and Disk Masers: Solutions to the Full Equations

# Correlation paths in the turbulent medium




Model of the turbulent layer by
**A.M.Sobolev, E.C.Sutton, W.D.Watson et al. (2008)**
Sizes of Masing Parts of Massive Star Forming Regions

# Scattering



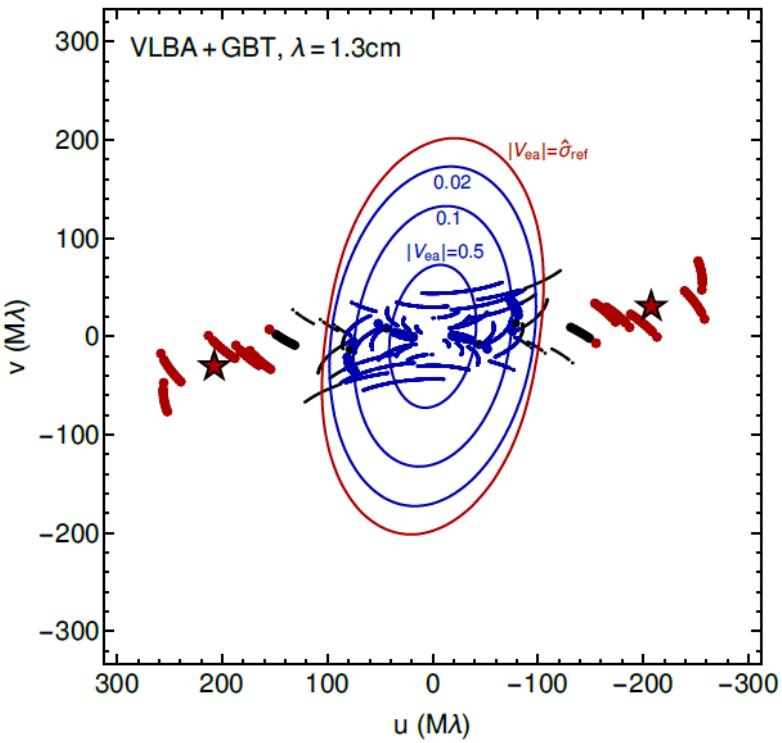

**M.Johnson et al. (2018ApJ…865…104J)**

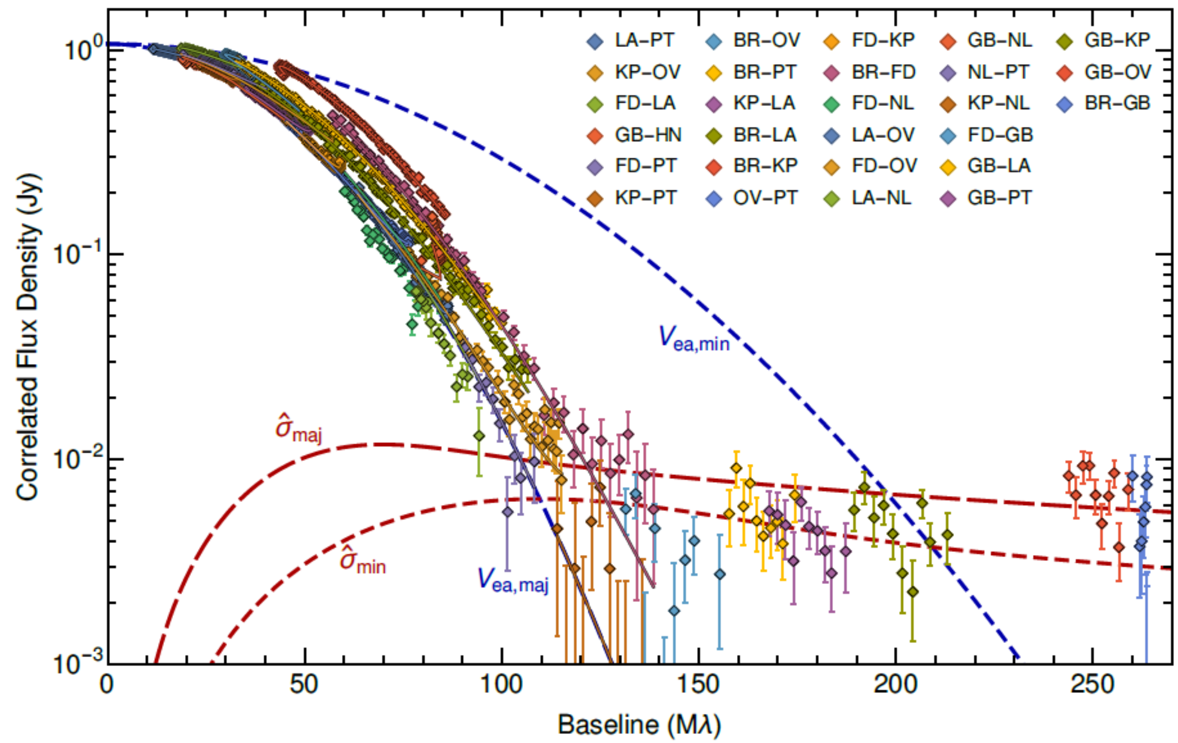
The Scattering and Intrinsic Structure of Sagittarius A* at Radio Wavelengths

**M.Johnson et al. (2018cosp…42E1629J)**

Implications of Refractive Scintillation for Observations of Active Galactic Nuclei with RadioAstron

# Scattering

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# Summary 1
## (brightness temperatures and lost flux)

Space-ground interferometer proved working in the spectral regime :

More than 7 water maser sources (W51, W3IRS5, Cep A, W3(H2O), W49N, etc.) were detected in the 22 GHz water maser line with projected baselines up to 9.6 Earth diameters.

2 OH maser sources (W75N and ON1) were detected with projected baselines 0.75 and 1.8 Earth diameters.

Model of the correlation paths in the turbulent medium and scattering have potential to account for the lost flux. Further studies are necessary to make solid conclusions on the nature of the lost flux.

# Summary 2 (basic statements)

✓Interstellar scattering (both on the way to the object and in the object itself) does not prevent observations of the bright galactic $H_2O$ and OH masers with the space-ground interferometer. (see also VSOP observations of OH masers in G34.26 , W48, and Cep A )

➢ future: study influence of the interstellar scattering (characteristic times, changes in positions and dithering radii, difference of scattering in different directions) and its role in the maser image formation.

✓It has been shown that the maser spots with very small sizes are numerous, at least in Cep A, W51, W49N and W3IRS5 several maser features show up and contain very small spots each, spots of small sizes are connected to highly variable features showing strong velocity gradient

➢ future: prove this statement for the other sources, mapping with RA, several epochs with VERA to establish stability of the source presence, follow up with ALMA to establish nature of associated sources: discs or turbulent eddies

# Cep A water maser

Experiment code raes02q

Date: 18 Nov 12:00-12:40 UTC

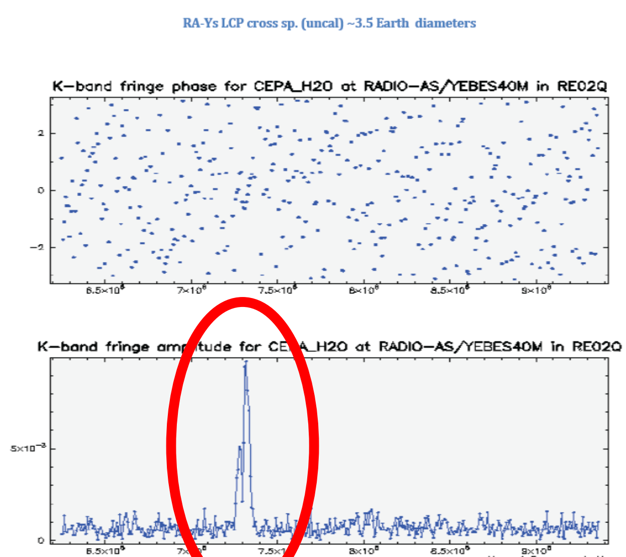
Stations in experiment :Zelenchuk, Noto, Yebes

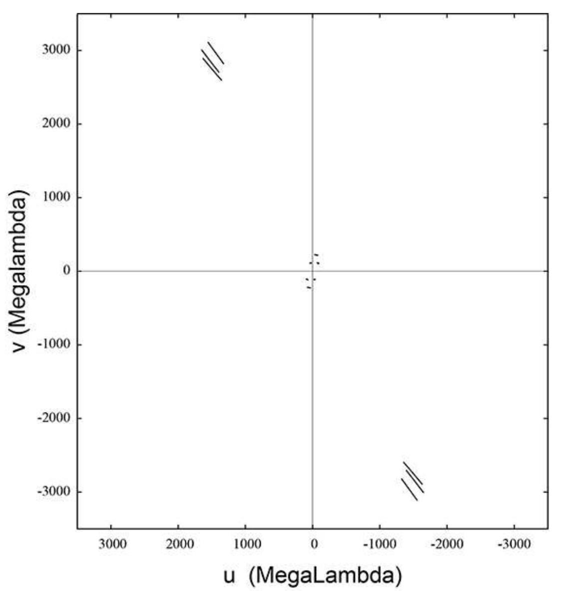
Space- earth projections : ~3.5 Earth diameters

Data were correlated with DiFX corr.

Postcorrelation: PIMA

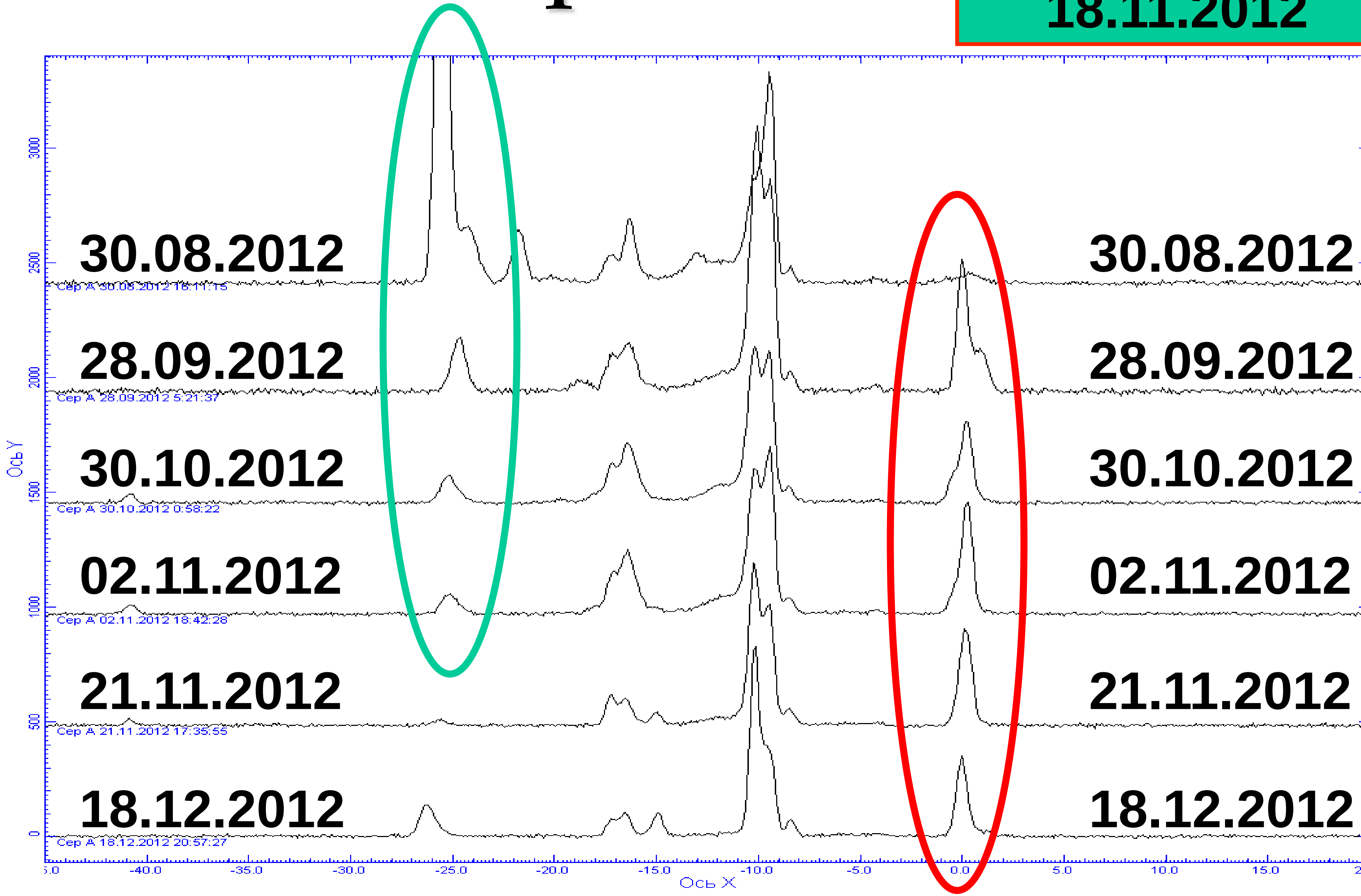
(http://astrogeo.org/pima/)



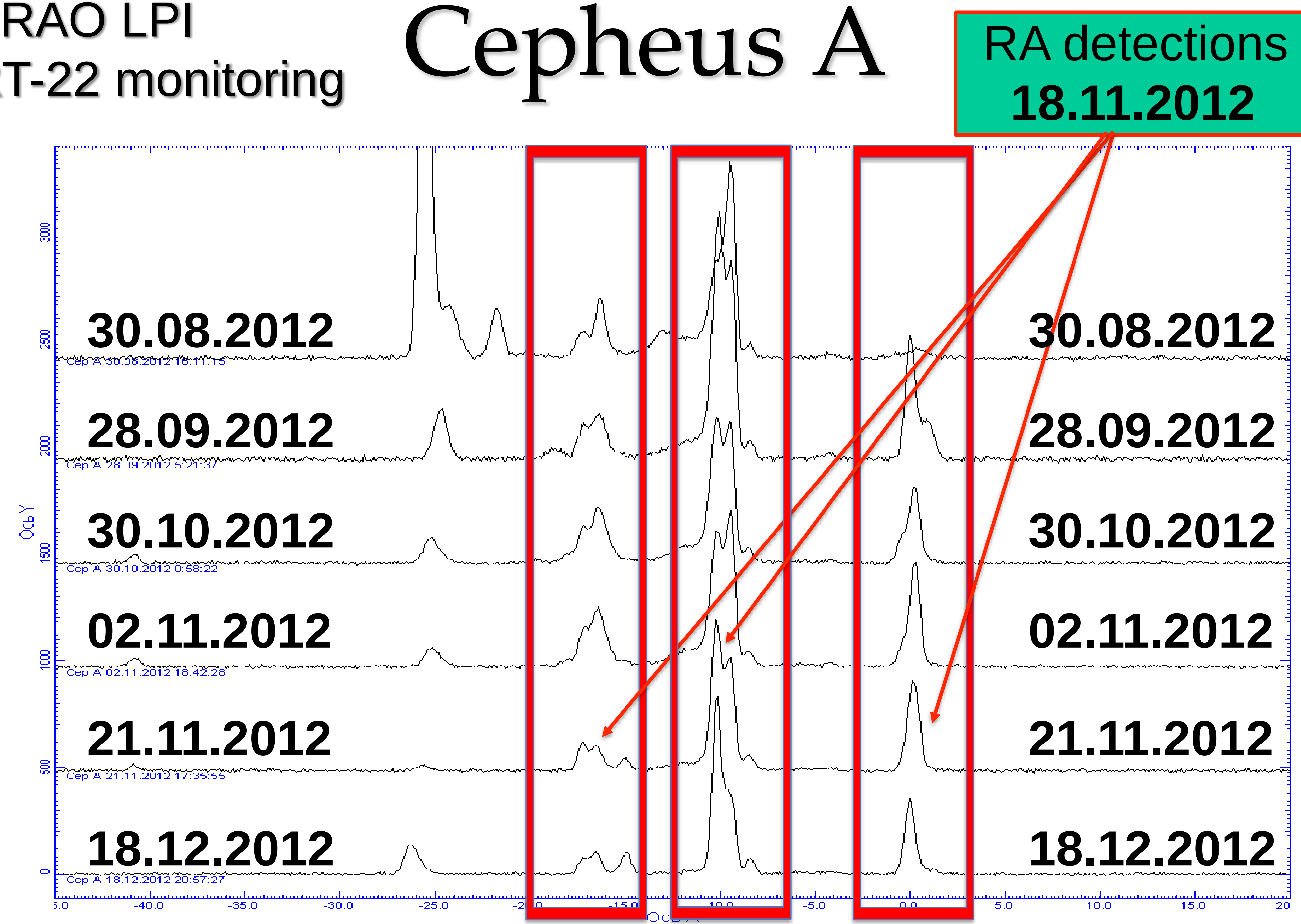
# Cepheus A

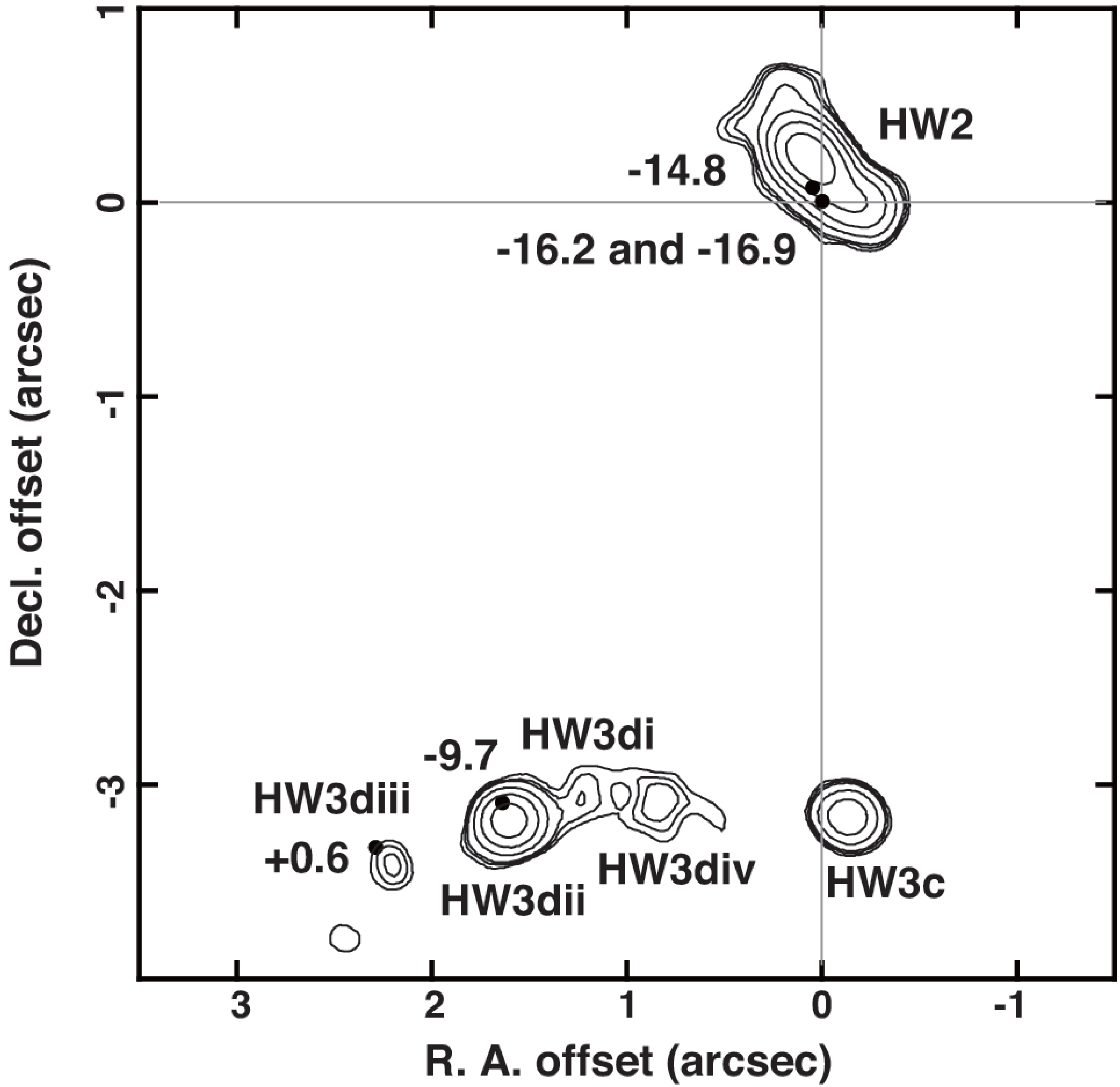
**RA observations**
**18.11.2012**



PRAO LPI
RT-22 monitoring

# Cepheus A




HW2
-14.8
-16.2 and -16.9
HW3di
-9.7
HW3diii
+0.6
HW3dii
HW3div
HW3c
Decl. offset (arcsec)
R. A. offset (arcsec)
1
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-1
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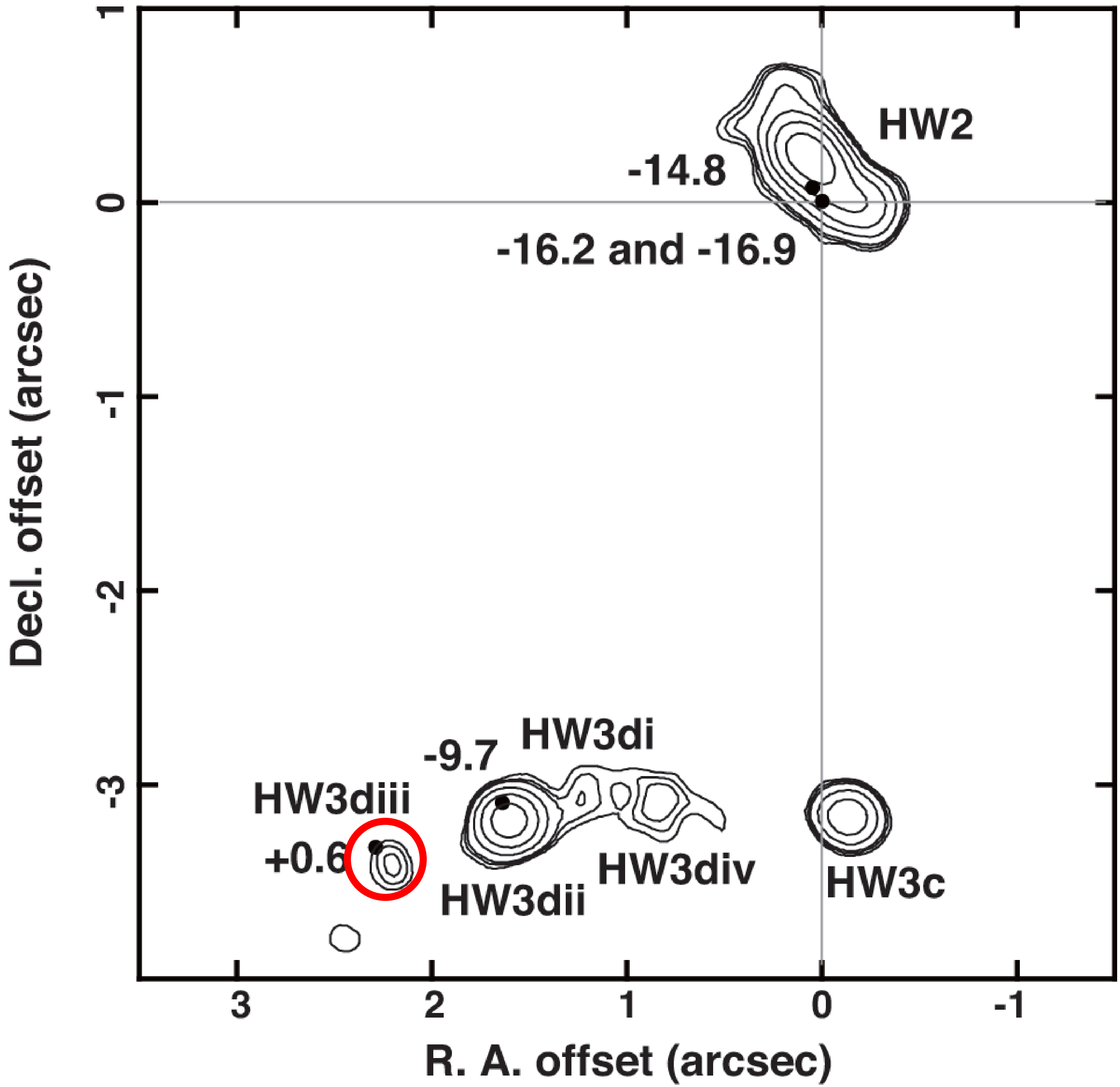
2
1
0
-1



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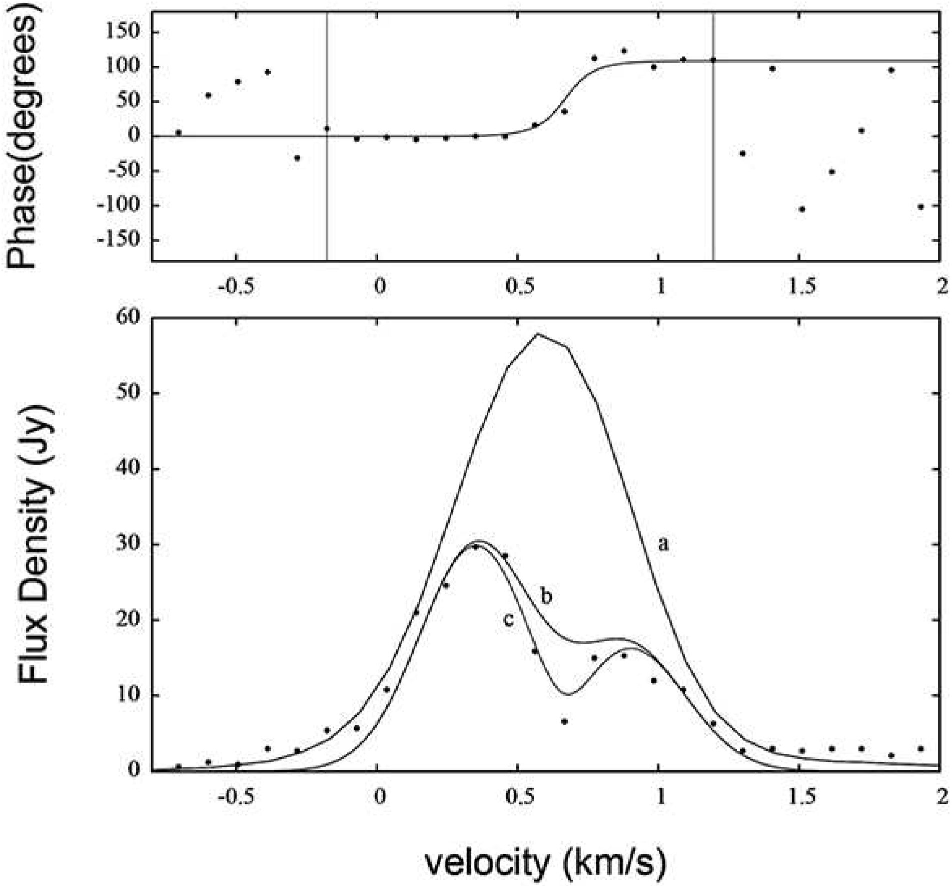
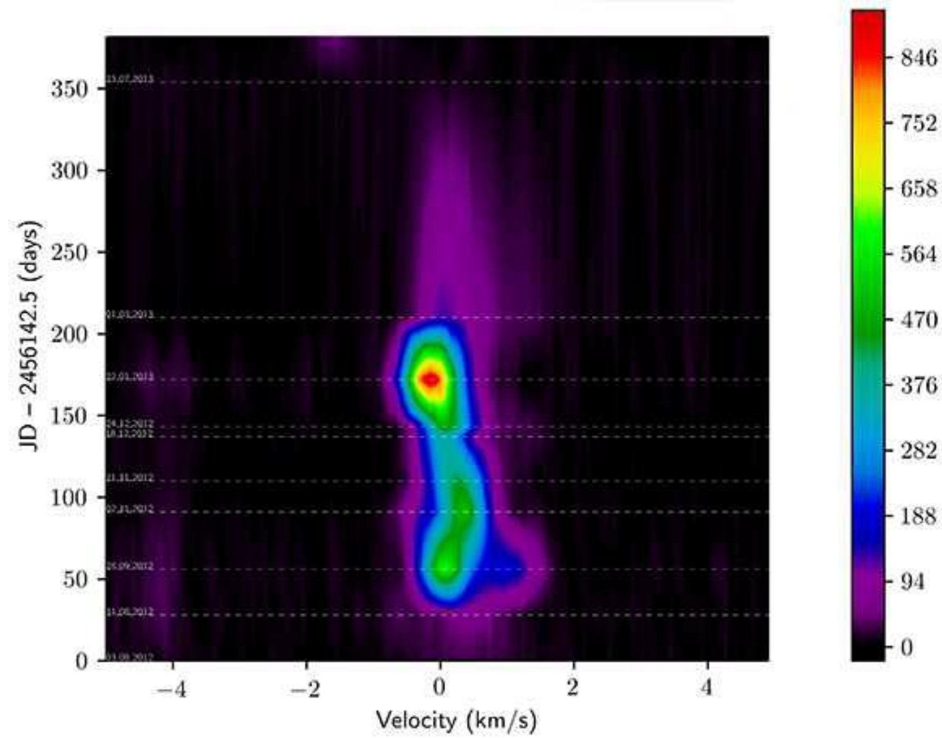
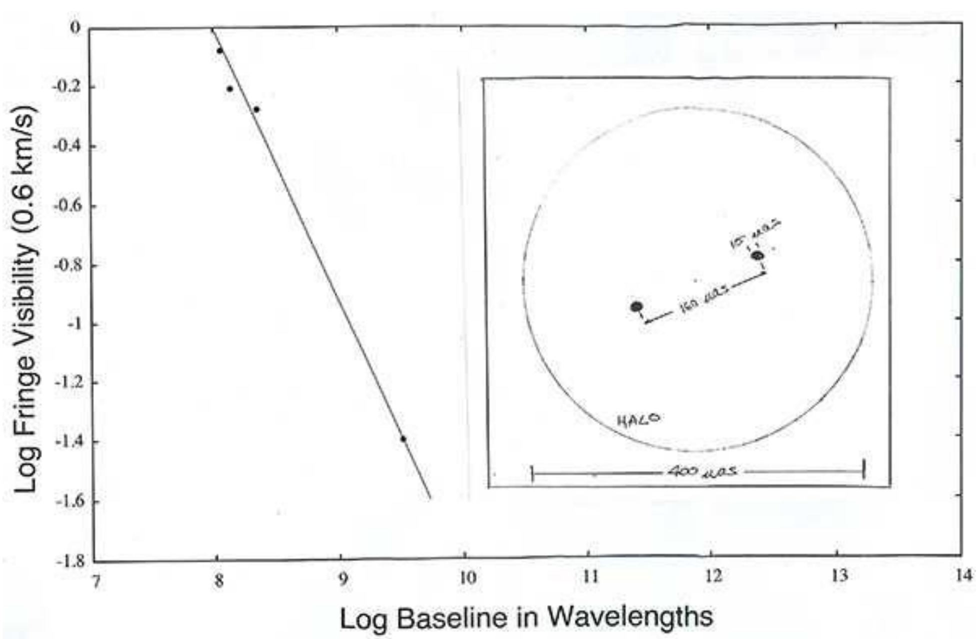
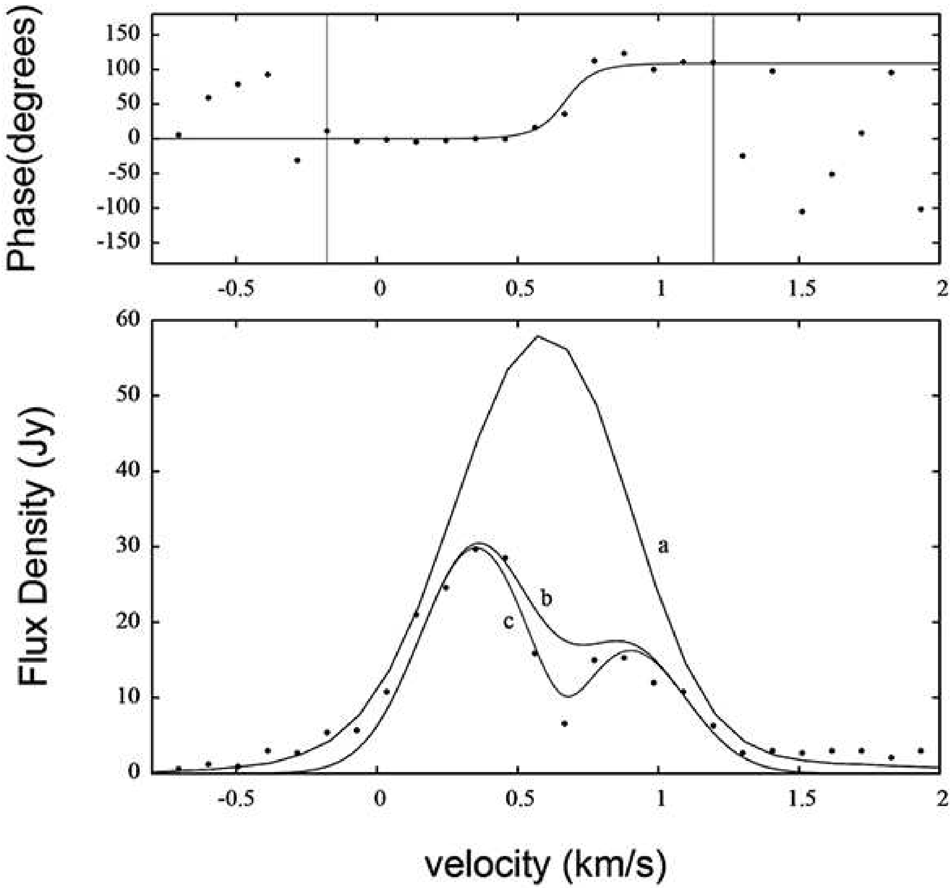
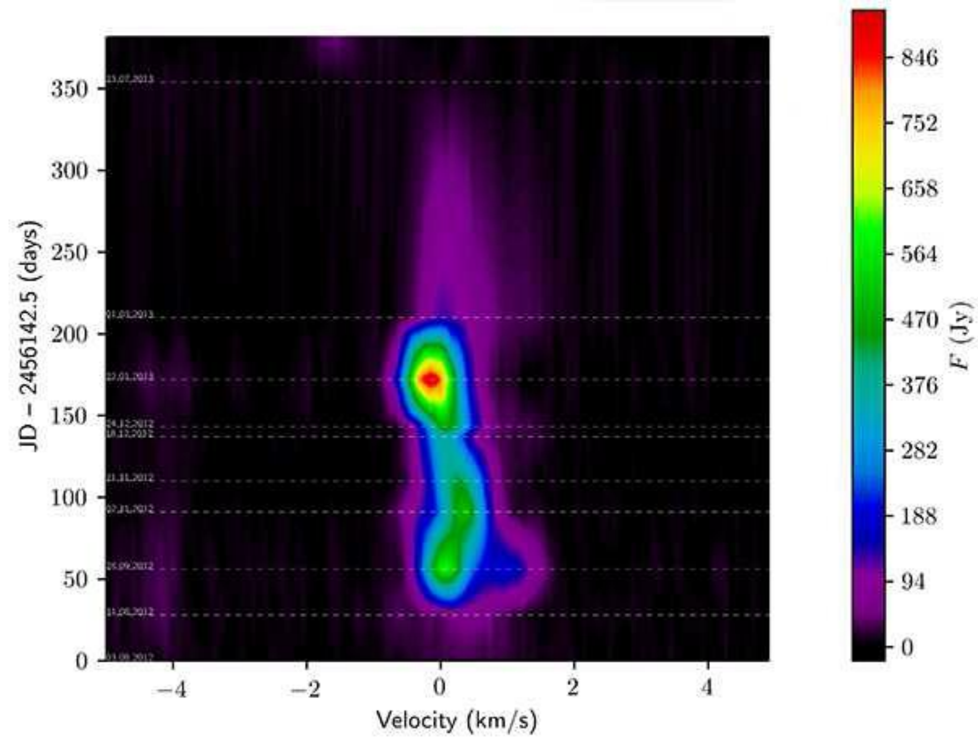


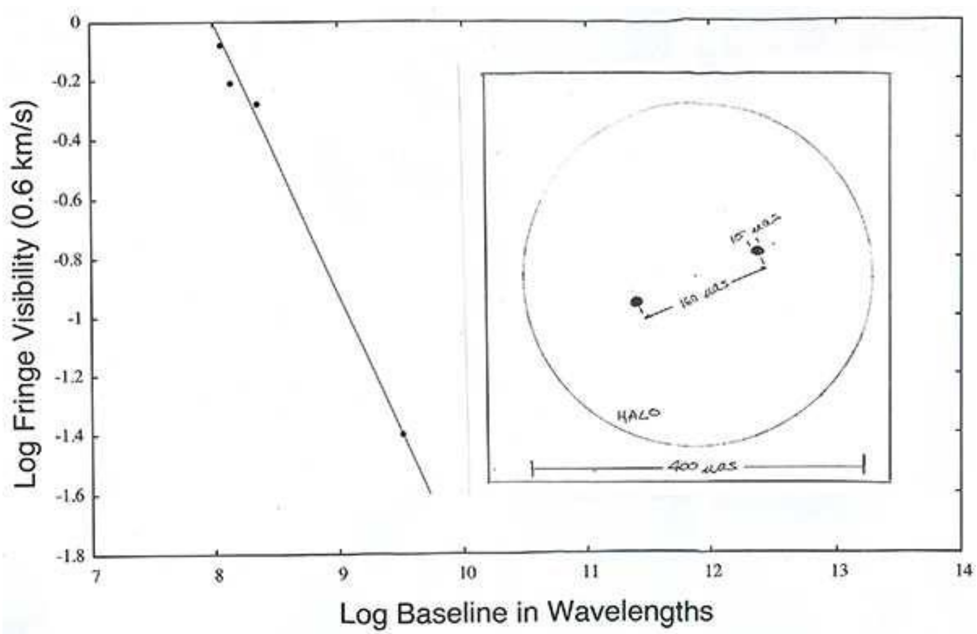




1) doublet structure at space–ground baselines
2) non-systemic radial velocity
3) strong variability with velocity drift

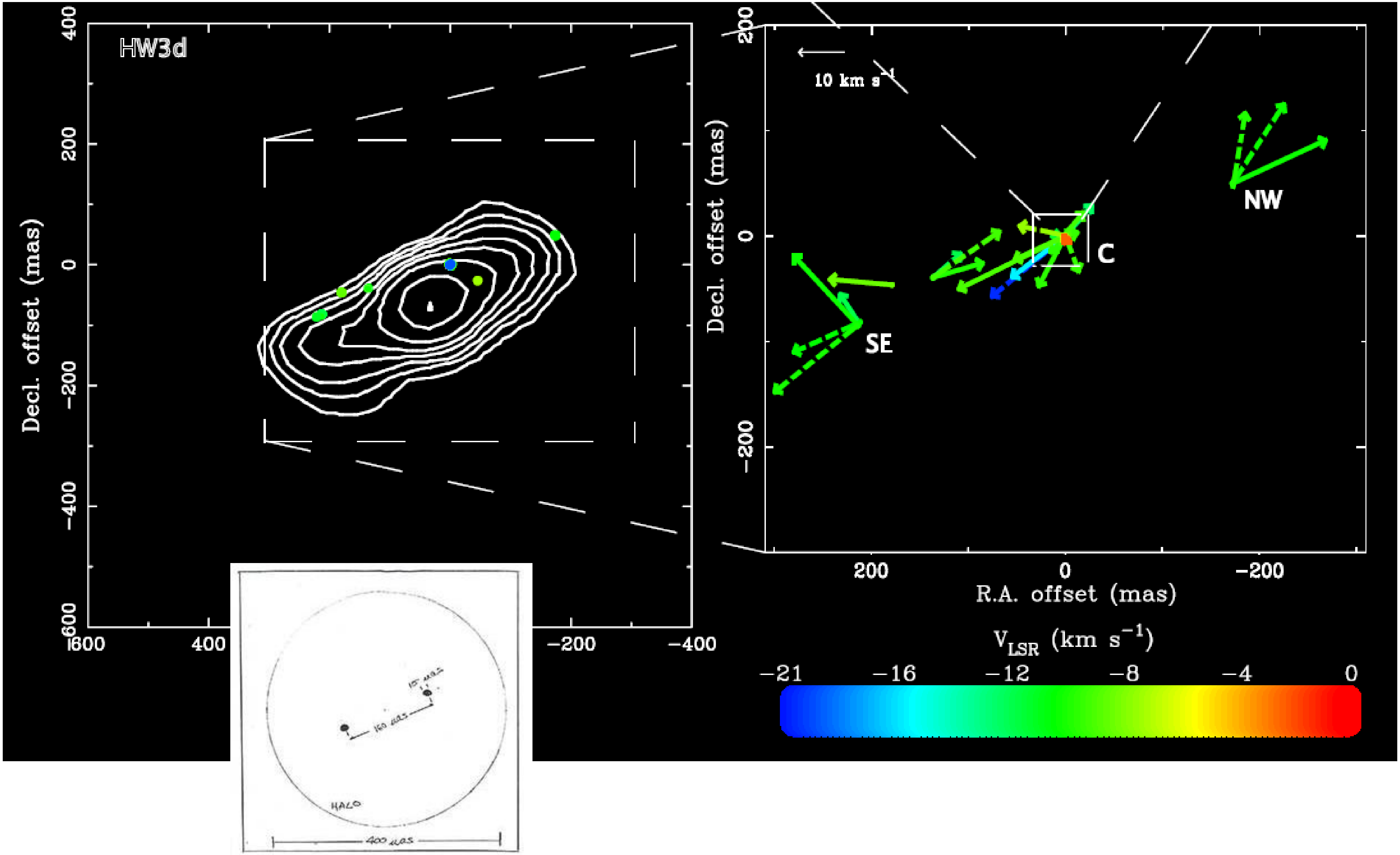



maser structures
of about Sun size !

87 per cent of flux
is in halo




Chibueze et al. (2012) $V_{RA}$

# Keplerian rotation around central object

$M = rv^2/G = 6.6{\times}10^{24}$ kg

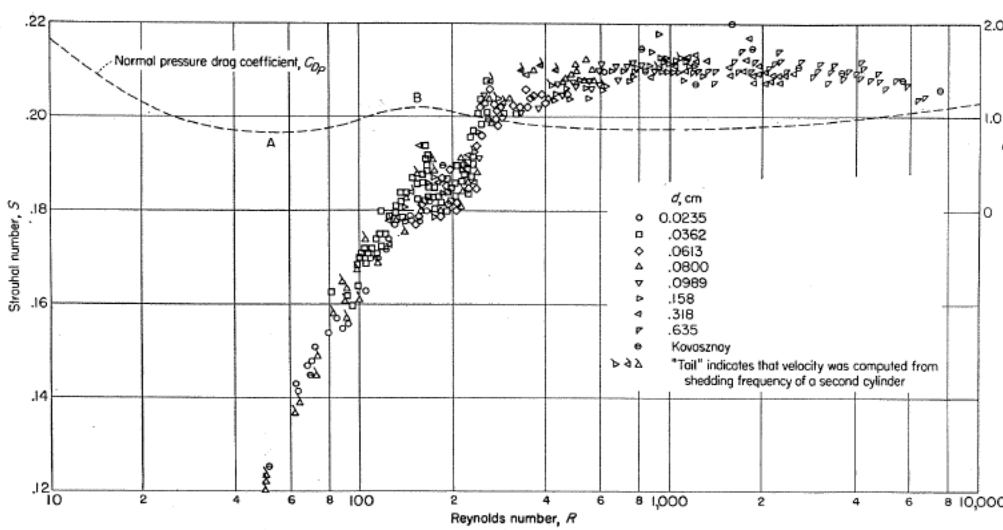
$= 1.1$ Earth masses

Fails to explain

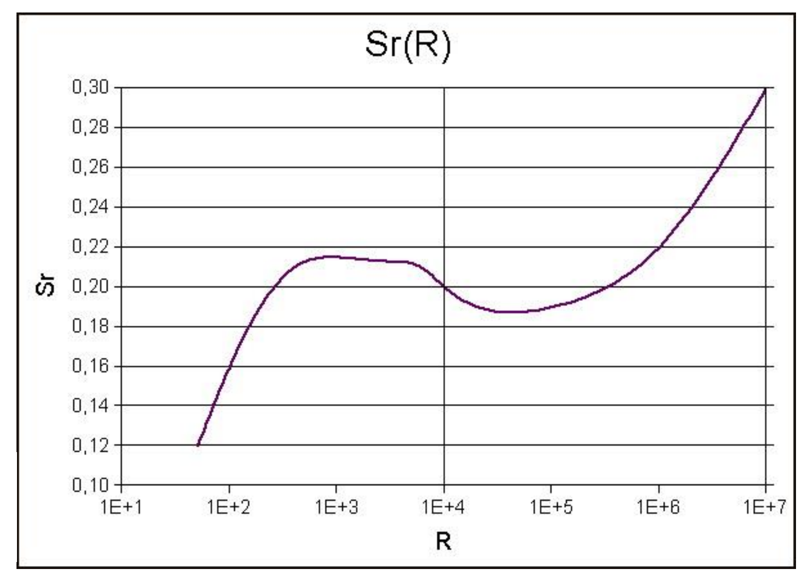
- Difference from systemic velocity
- Variability pattern of single-dish monitoring

# Turbulence described by Strouhal number (criterion)

$$St = R/(\tau\, v) =$$
$$56.8\, R_{AU}/(\tau_m v_{kms})$$



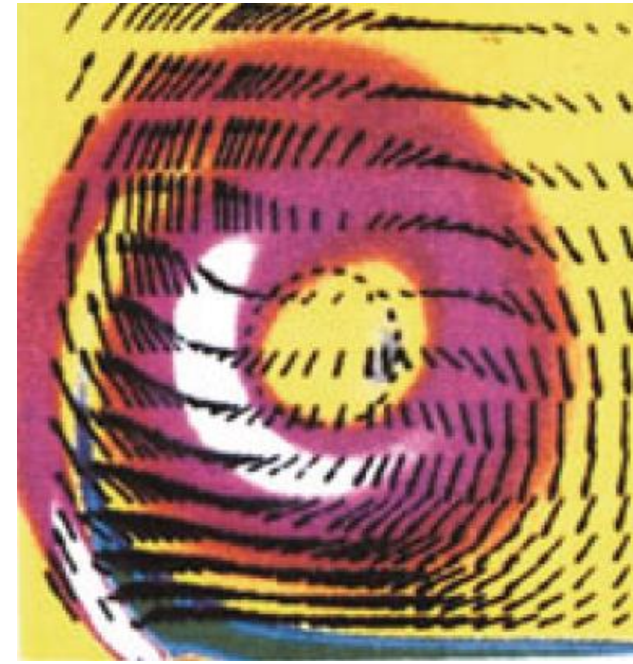

Roshko (1954)

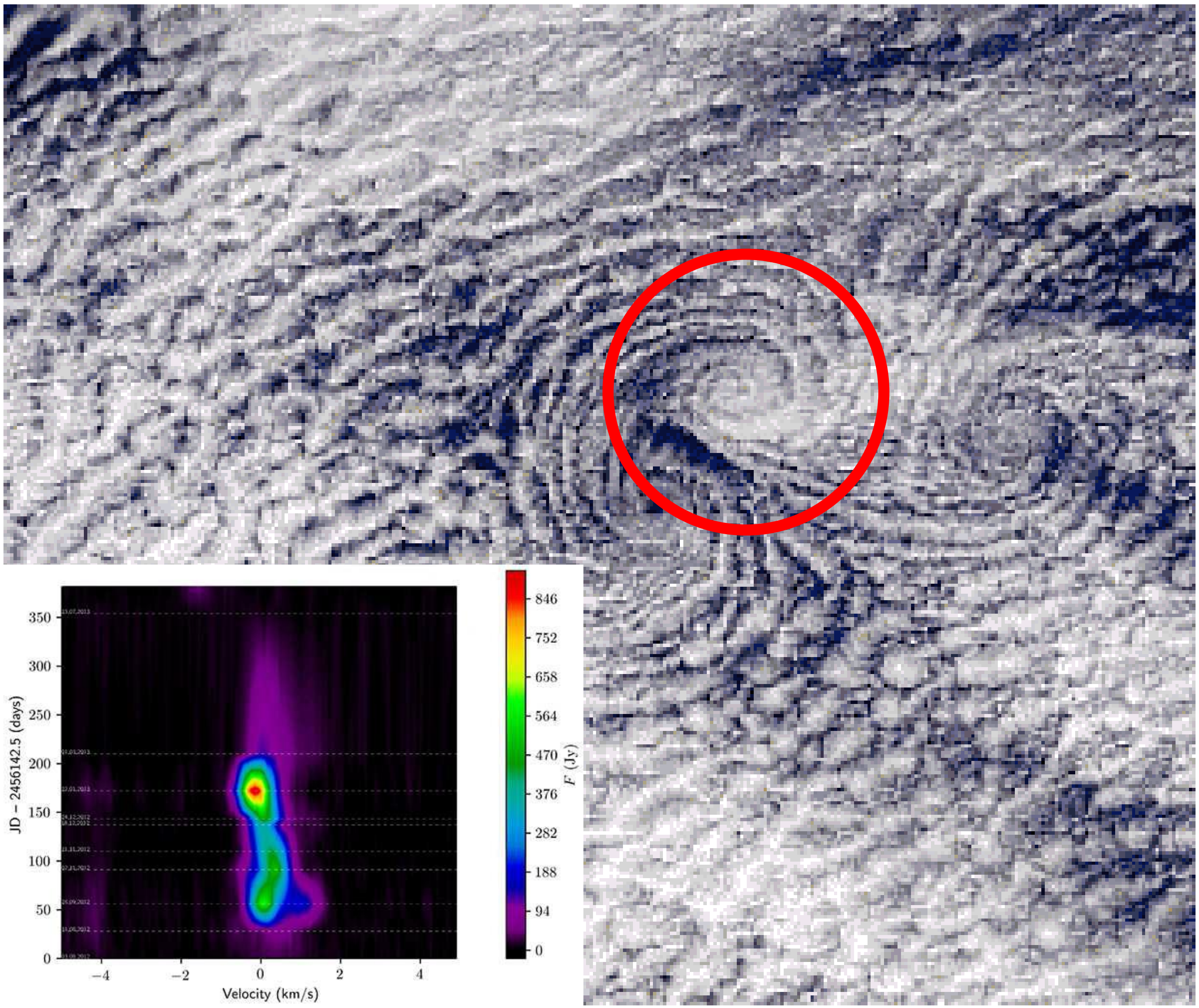



wikipedia

# Turbulent vortex

Fluid vortices 1995
edited by Sheldon I. Green






$R = 0.112$ a.u.

$\tau = 2*4$ months

$V = 0.54/2$ km/s

St = 2.95

# Turbulent vortex

Fluid vortices 1995
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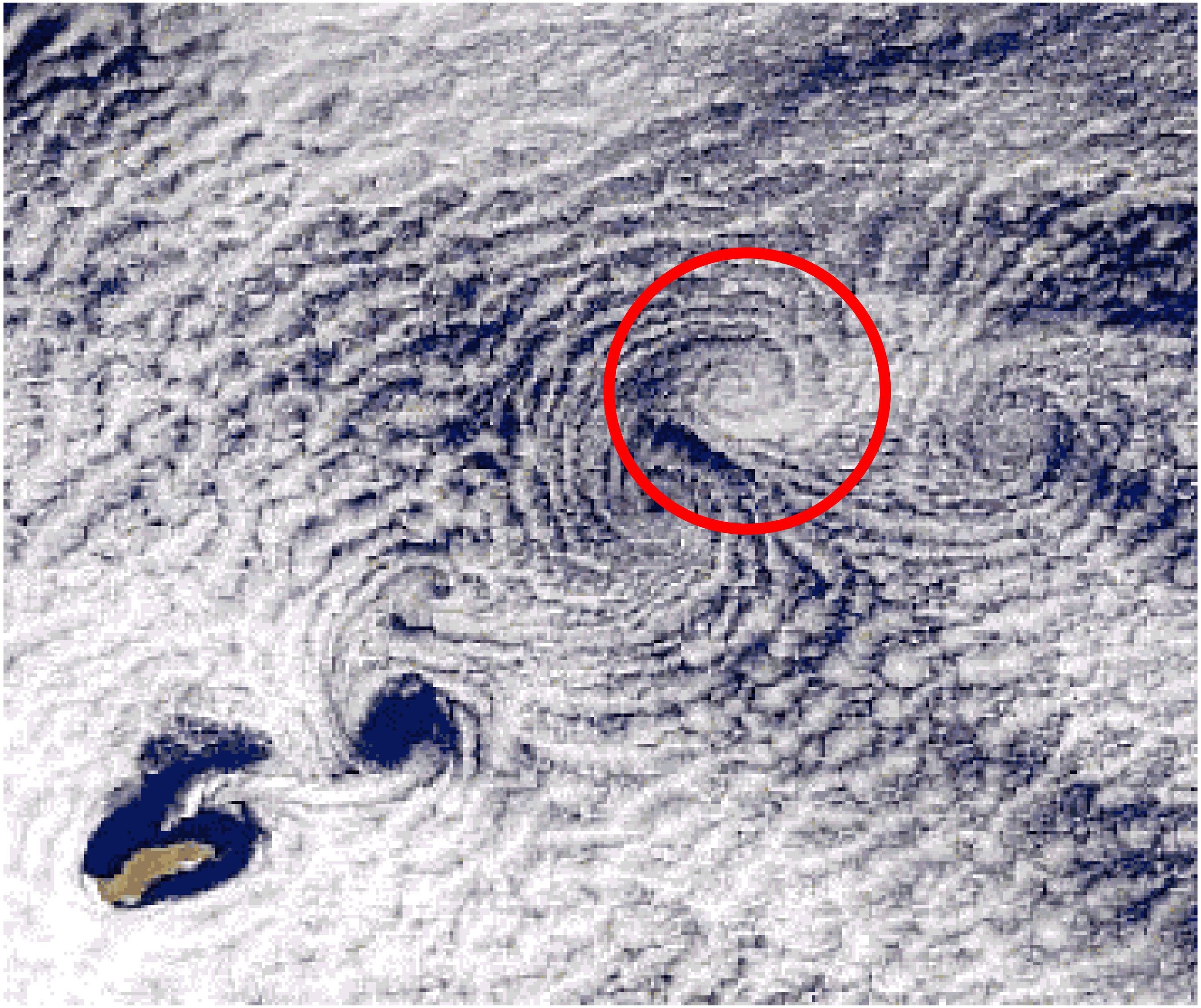
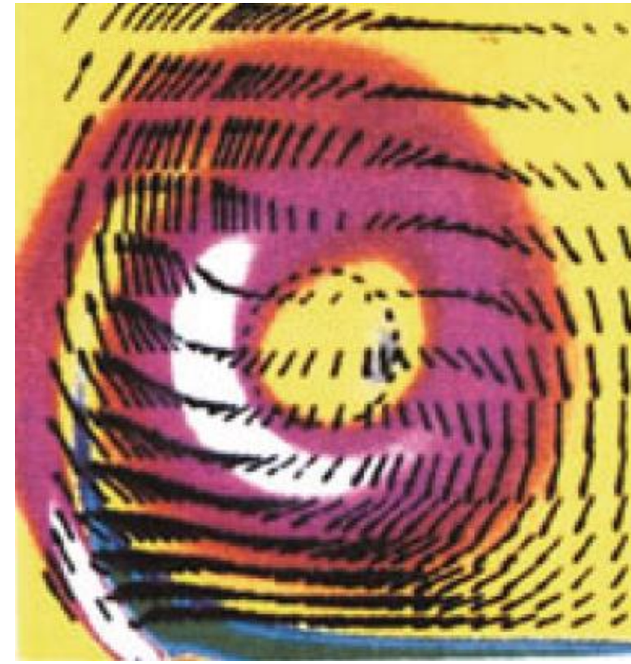


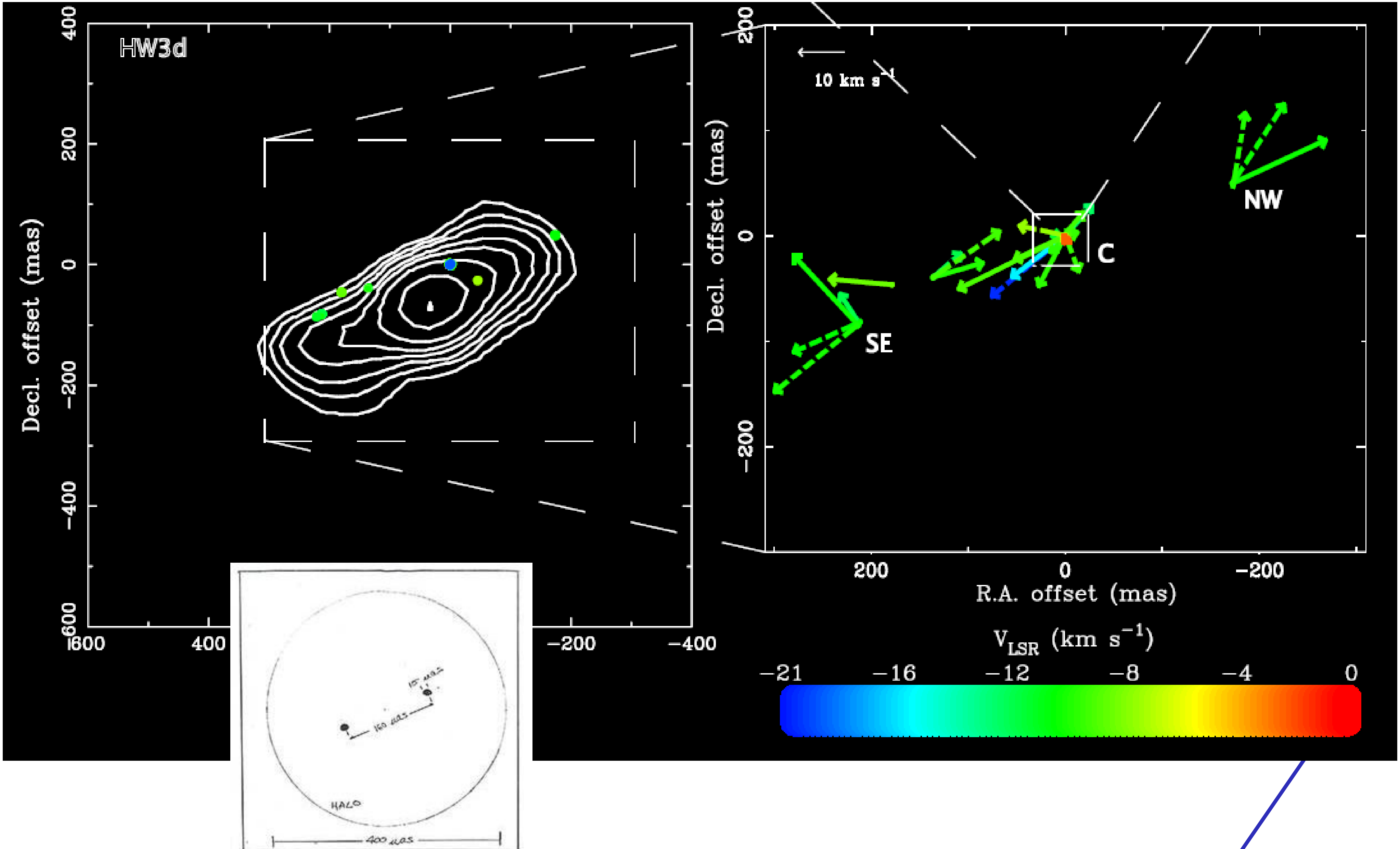


R=0.112 a.u.

$\tau$= 2*4 months

V=0.54/2 km/s

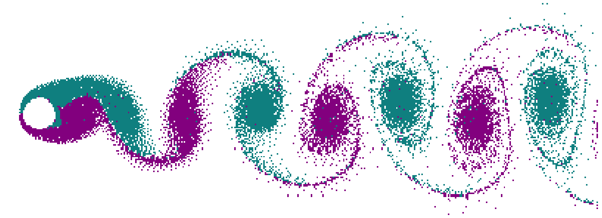
St = 2.95

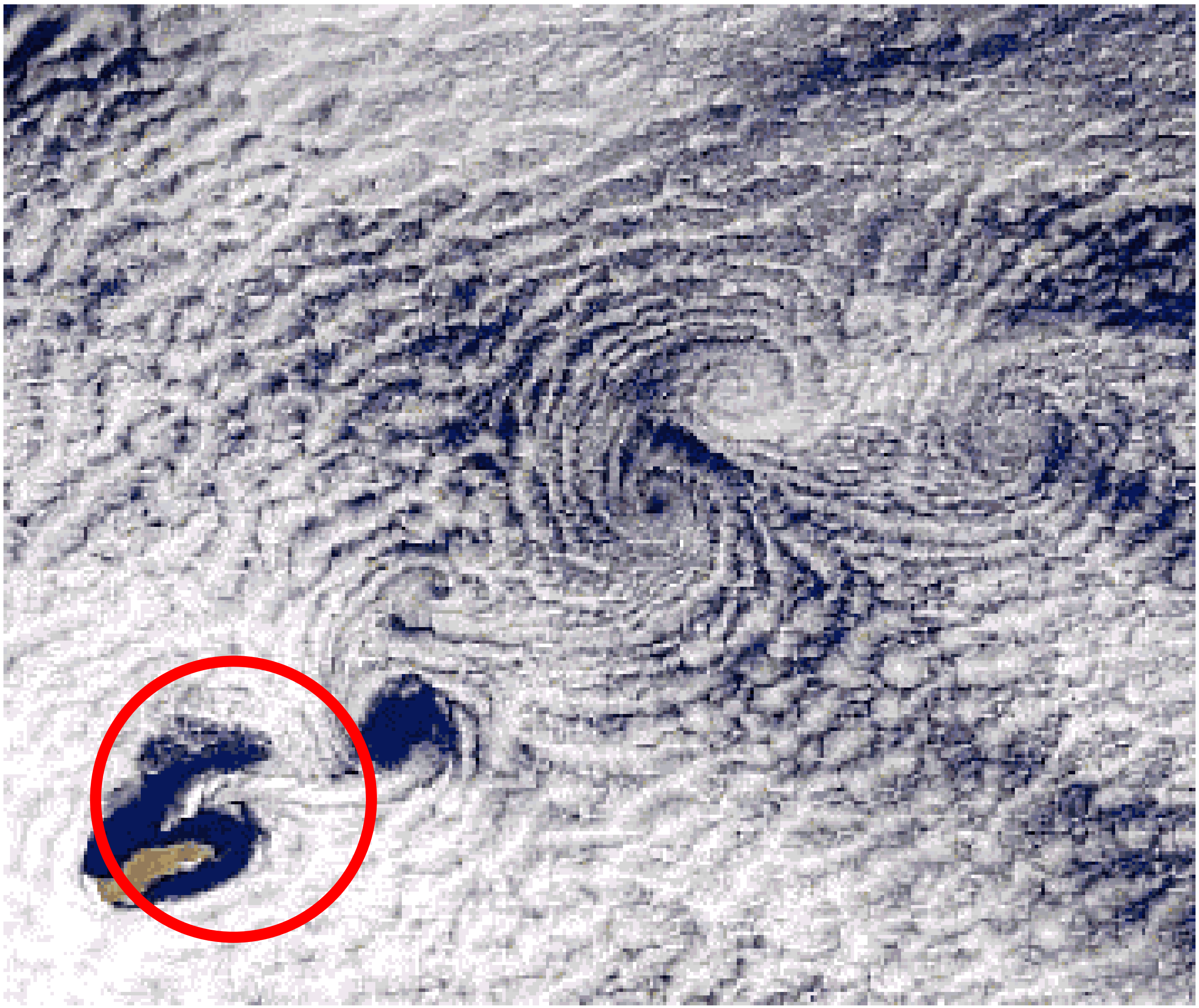


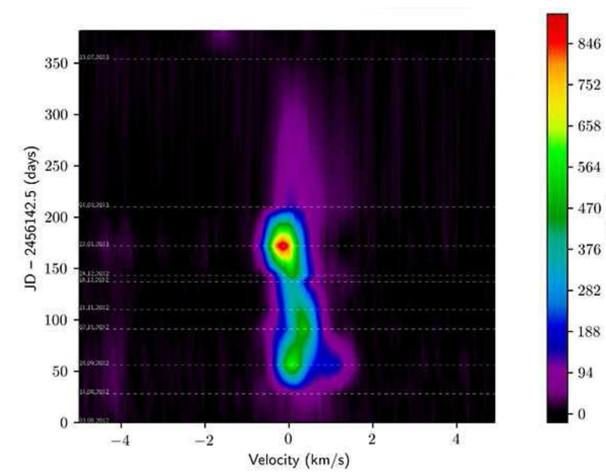

Chibueze et al. (2012)

$V_{RA}$

# Von Karman vortex street







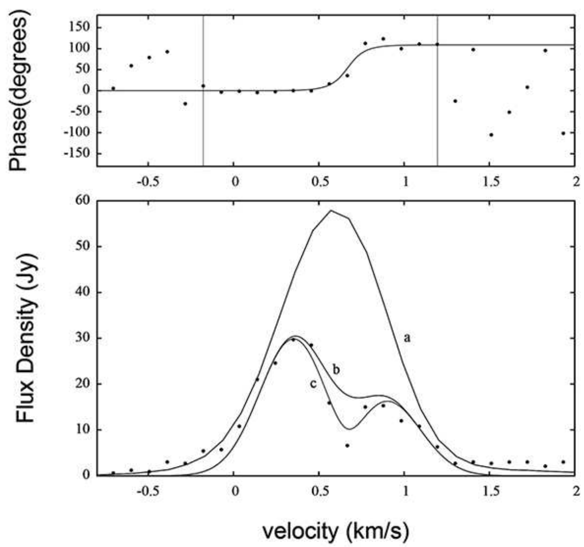

R=0.112 a.u.

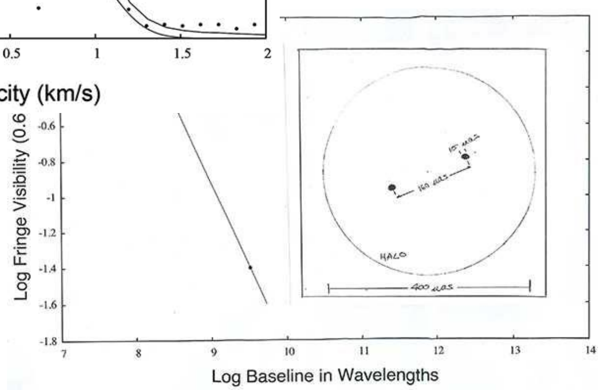
τ= 4/2 month

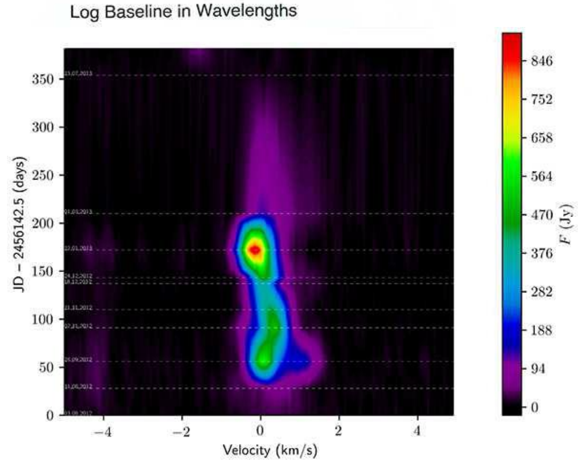
V=10 km/s

St = 0.3

# Summary (Cep A)




3 features are detected, in total

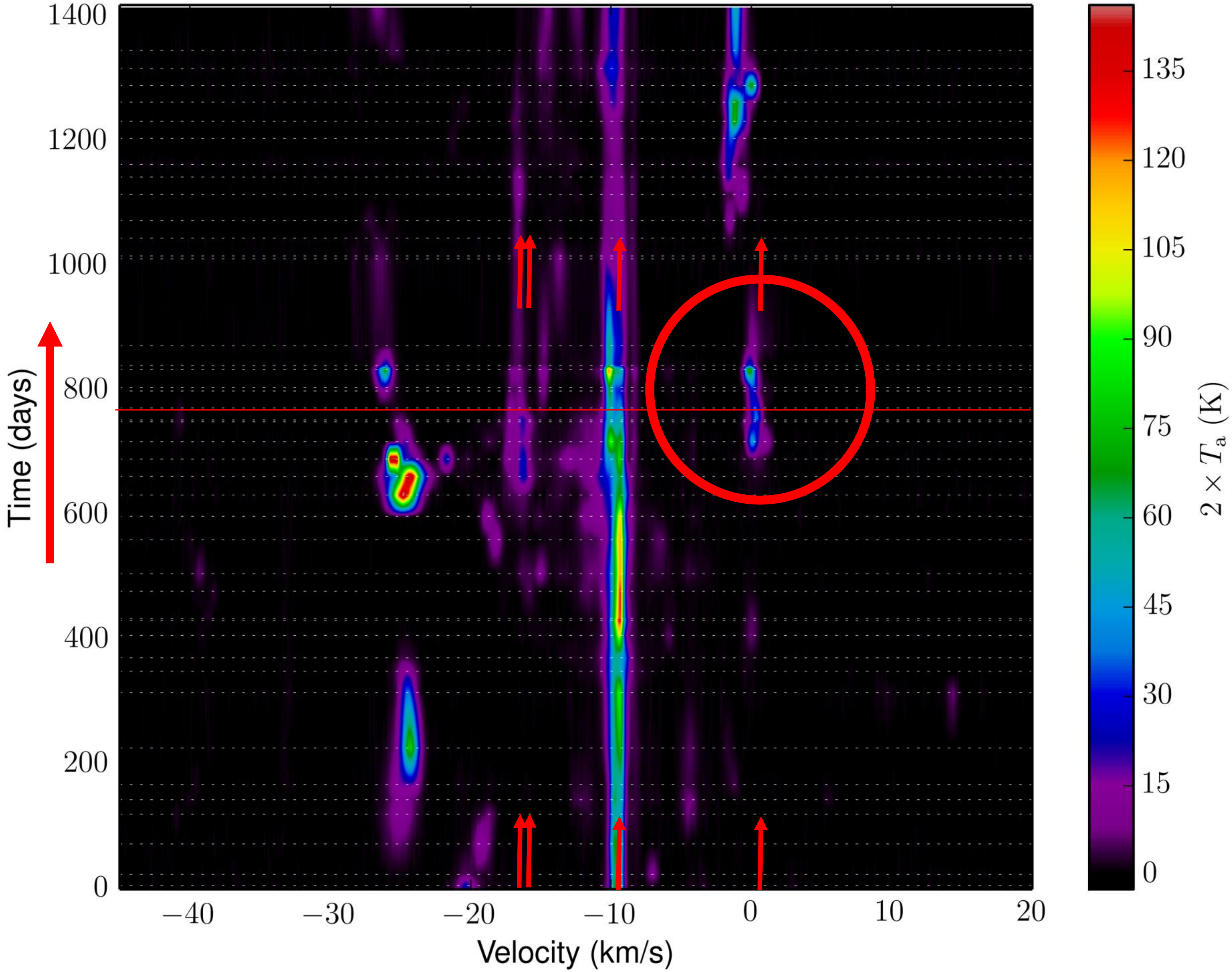
This feature at 0.6 km/s is single-peaked in the single dish observations and ground-ground baselines . On the space- ground baseline the feature shows 2 pronounced peaks.

The data can be fitted by a model of a spot consisting of 2 hotspots of approximately Sun size with surrounding halo .

Remarkably high velocity gradient: More than order of magnitude higher than previously detected.

The results can be explained in the model of turbulent vortices shed by the outflow from the obstacle on the disc surface

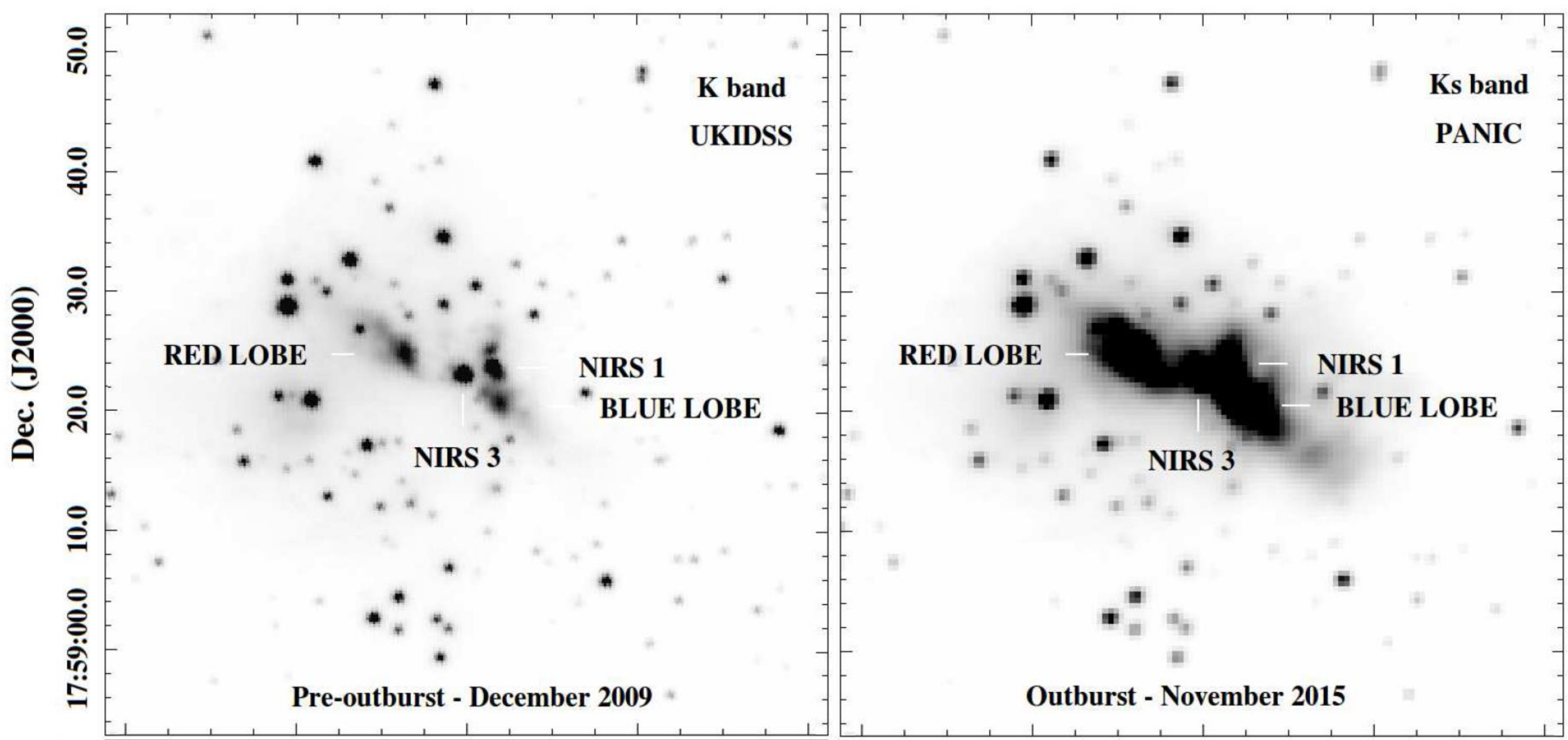
# PRAO LPI RT-22 monitoring



2017NatPh..13..276C

# Disk-mediated accretion burst in a high-mass young stellar object

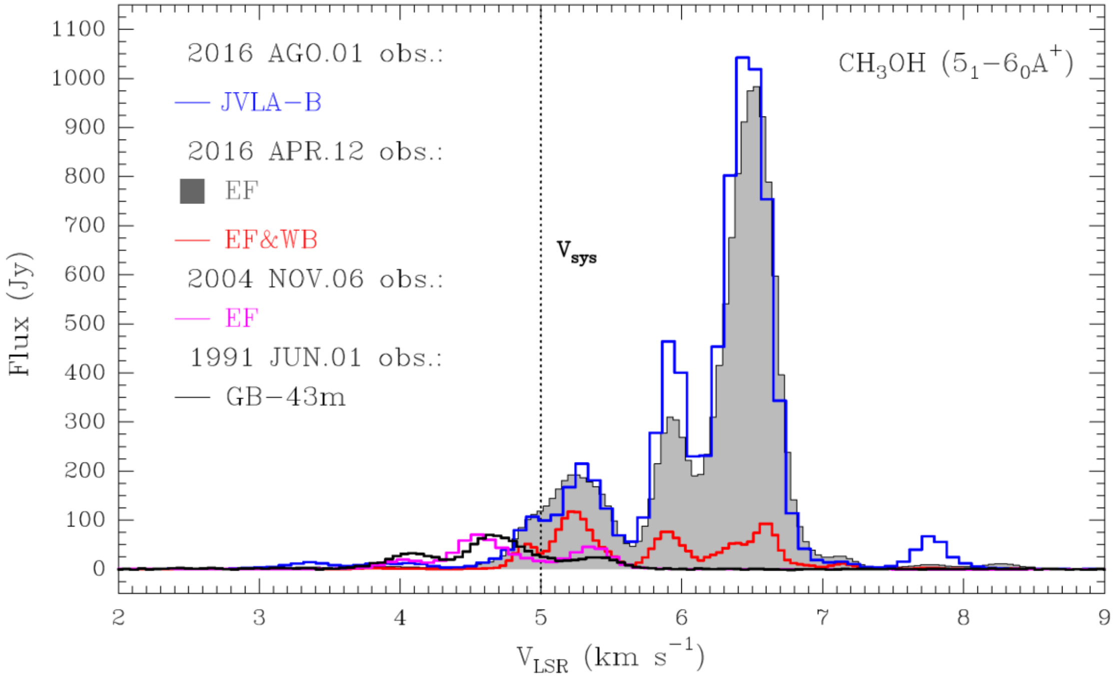
A. Caratti o Garatti[1], B. Stecklum[2], R. Garcia Lopez[1], J. Eislöffel[2], T.P. Ray[1], A. Sanna[3], R. Cesaroni[4], C.M. Walmsley[1,4], R.D. Oudmaijer[5], W.J. de Wit[6], L. Moscadelli[4], J. Greiner[7], A. Krabbe[8], C. Fischer[8], R. Klein[9], J.M. Ibañez[10]

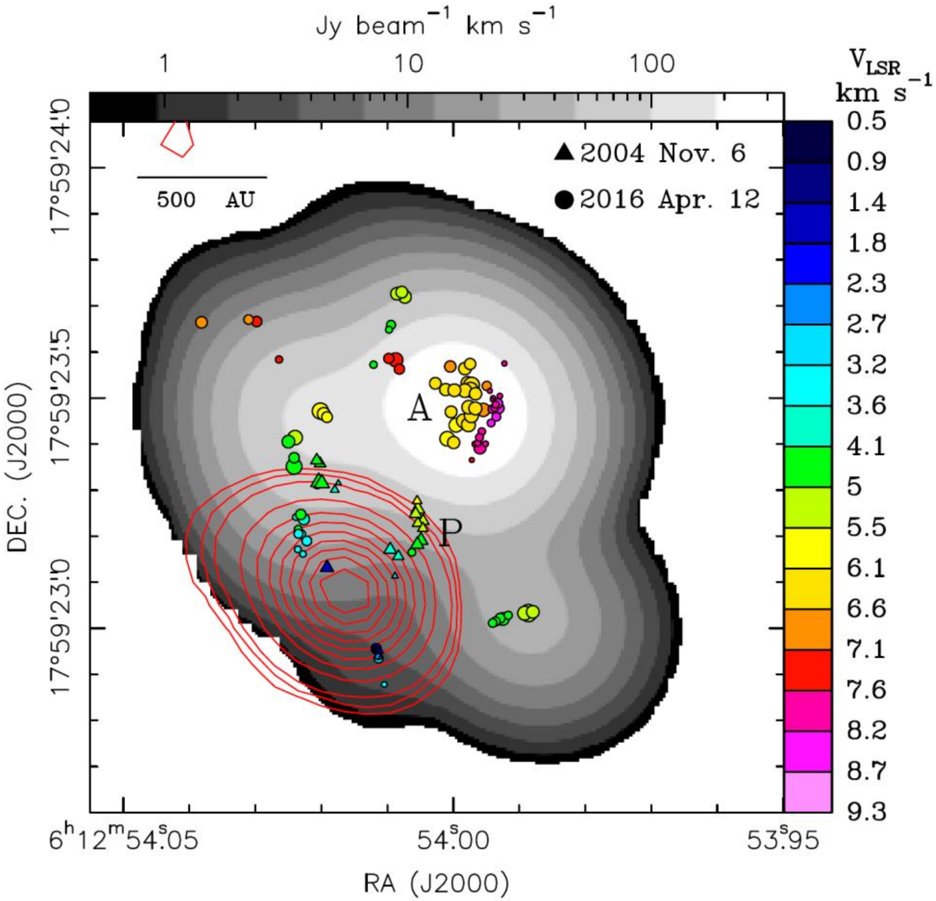


# A&A 600, L8 (2017)

## Extended $CH_3OH$ maser flare excited by a bursting massive YSO

L. Moscadelli[1], A. Sanna[2], C. Goddi[3], M. C. Walmsley[1,4], R. Cesaroni[1], A. Caratti o Garatti[4], B. Stecklum[5], K. M. Menten[2], and A. Kraus[2]

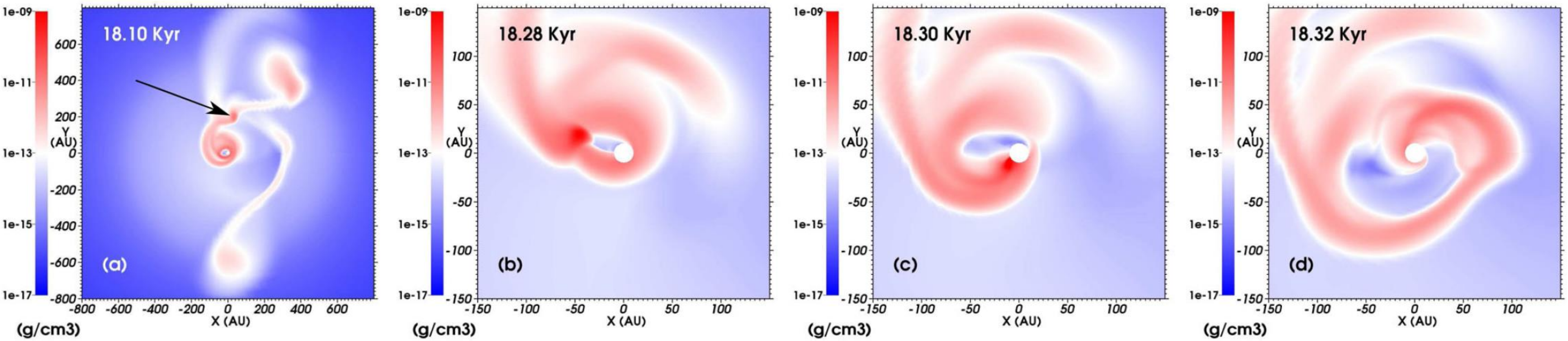


D. M.-A. Meyer,[1★] E. I. Vorobyov,[2,3] R. Kuiper[1] and W. Kley[1]

# On the existence of accretion-driven bursts in massive star formation

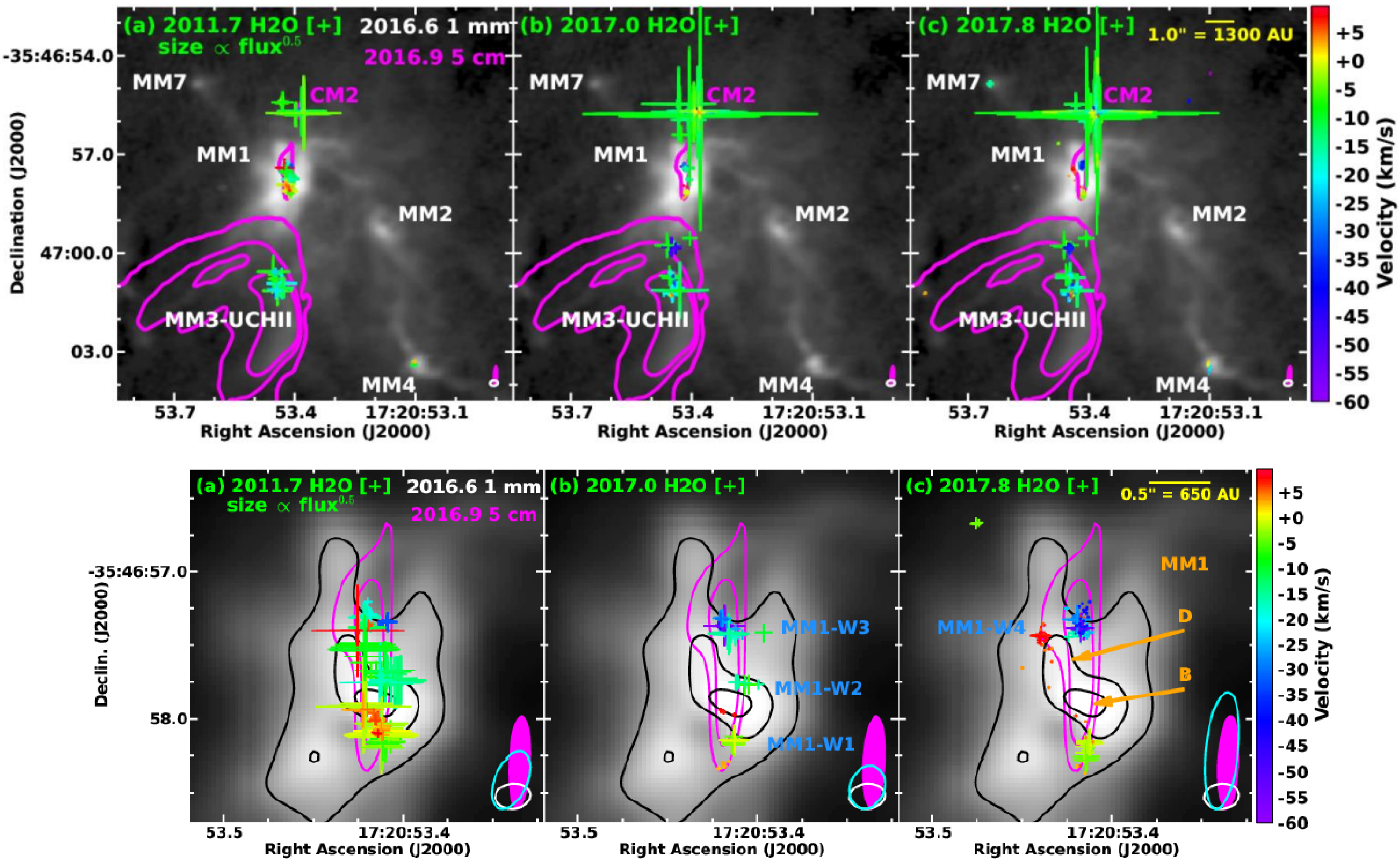
MNRAS **464,** L90–L94 (2017)



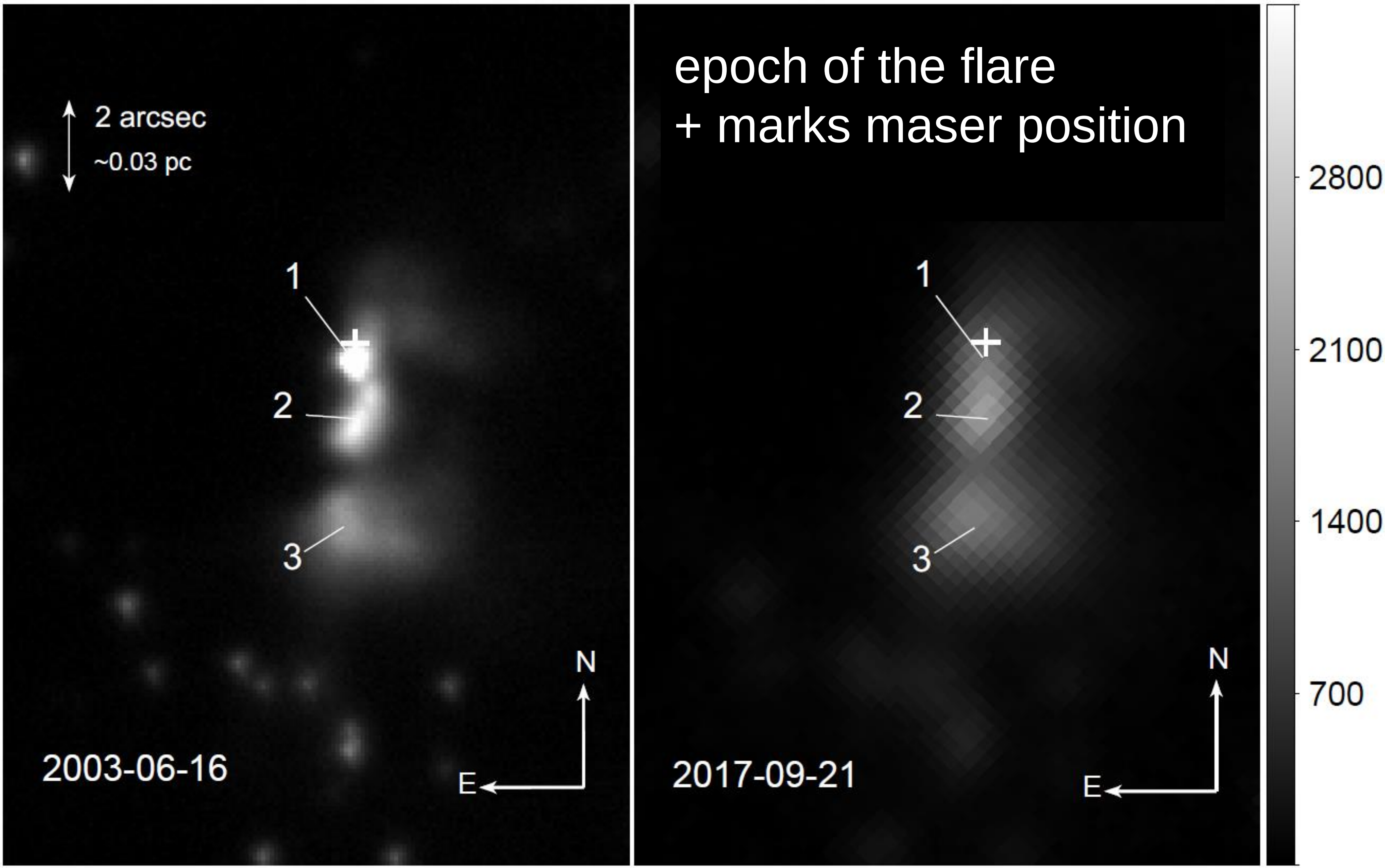
The extraordinary outburst in the massive protostellar system NGC 6334I-MM1: Flaring of the water masers in a north-south bipolar outflow driven by MM1B

C. L. Brogan,[1] T. R. Hunter,[1] C. J. Cyganowski,[2] J. O. Chibueze,[3,4,5] R. K. Friesen,[1] T. Hirota,[6] G. C. MacLeod,[7,8] B. A. McGuire,[1,*] and A. M. Sobolev[9]

ApJ 2018, accepted

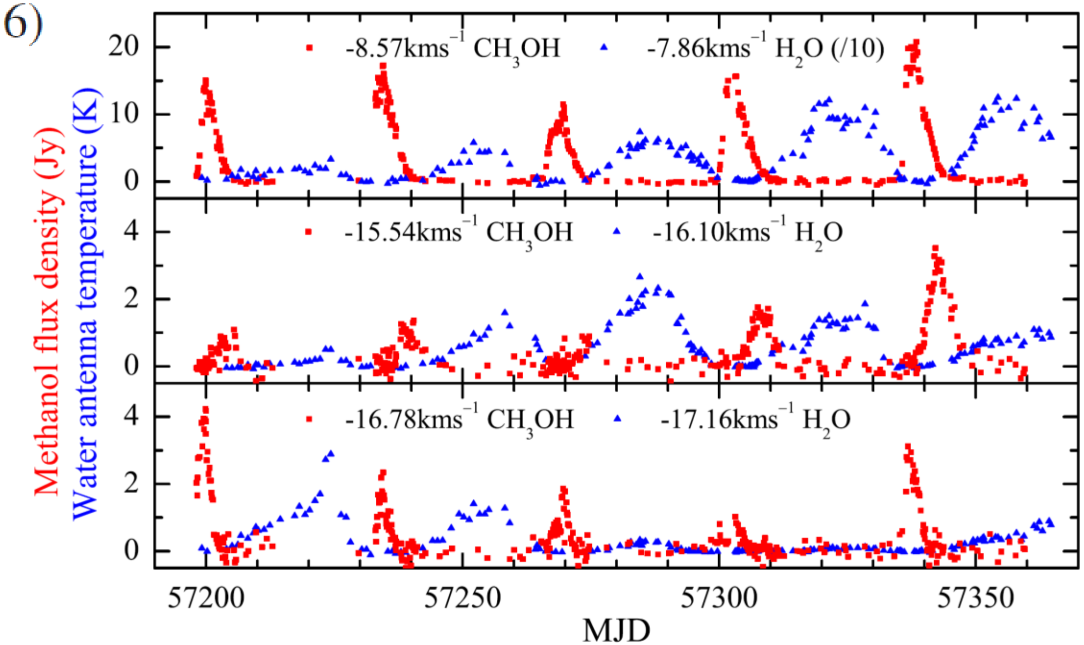


A.M.Sobolev, A.P.Bisyarina, A.M.Tatarnikov, I.Antokhin, A.E.Volvach
2017ATel10788....1S G25.65+1.05



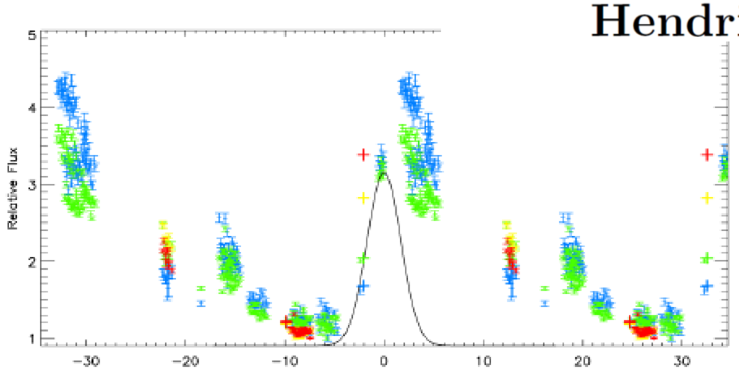
# Discovery of periodic and alternating flares of the methanol and water masers in G107.298+5.639

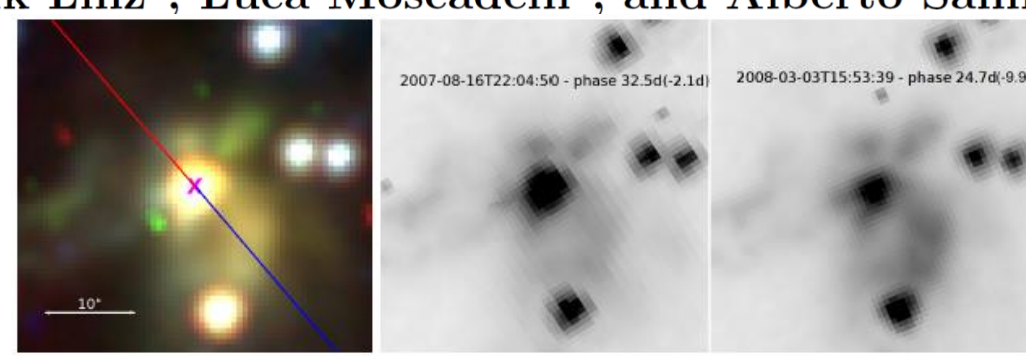
M. Szymczak,★ M. Olech, P. Wolak, A. Bartkiewicz and M. Gawroński
MNRAS **459**, L56–L60 (2016)




# Infrared variability, maser activity, and accretion of massive young stellar objects

Bringfried Stecklum[1], Alessio Caratti o Garatti[2], Klaus Hodapp[3], Hendrik Linz[4], Luca Moscadelli[5], and Alberto Sanna[6]



¡Muchas gracias!

Thank you very much!

Благодарю!

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