Magnetic field measurements around young and old stars using masers

Huib van Langevelde, JIVE & Leiden

Wouter Vlemmings, Onsala

Nikta Amiri, Leiden & JIVE
Gabriele Surcis - Bonn University, soon JIVE
Kalle Torstensson - Leiden & JIVE
Anna Bartkiewicz - Toruń

Credits...

- **Wouter Vlemmings**
  - Masers, polarimetry, evolved stars, MYSOs, pulsars, ALMA
  - Formerly at Bonn University, now at Onsala
  - Joint supervisor of:
- **Nikta Amiri**
  - Evolved stars evolution, magnetic fields
  - Leiden/JIVE, defense 26/10/11
- **Kalle Torstensson**
  - High mass star formation, methanol, masers/mm
  - Leiden/JIVE, thesis this fall
- **Gabriele Surcis**
  - Star formation, masers, polarimetry
  - Bonn, defense in 2 weeks, JIVE afterwards
- **Anna Bartkiewicz**
  - masers, star formation, astrometry
  - staff at Toruń, Poland

JOINT INSTITUTE FOR VLBI IN EUROPE

Sterrewacht Leiden

CHALMERS

estrela

Argelander-Institut für Astronomie

Torun Centre for Astronomy of the Nicolaus Copernicus University
Department of Radio Astronomy
National Facility

Credits...

Why Magnetic Fields?

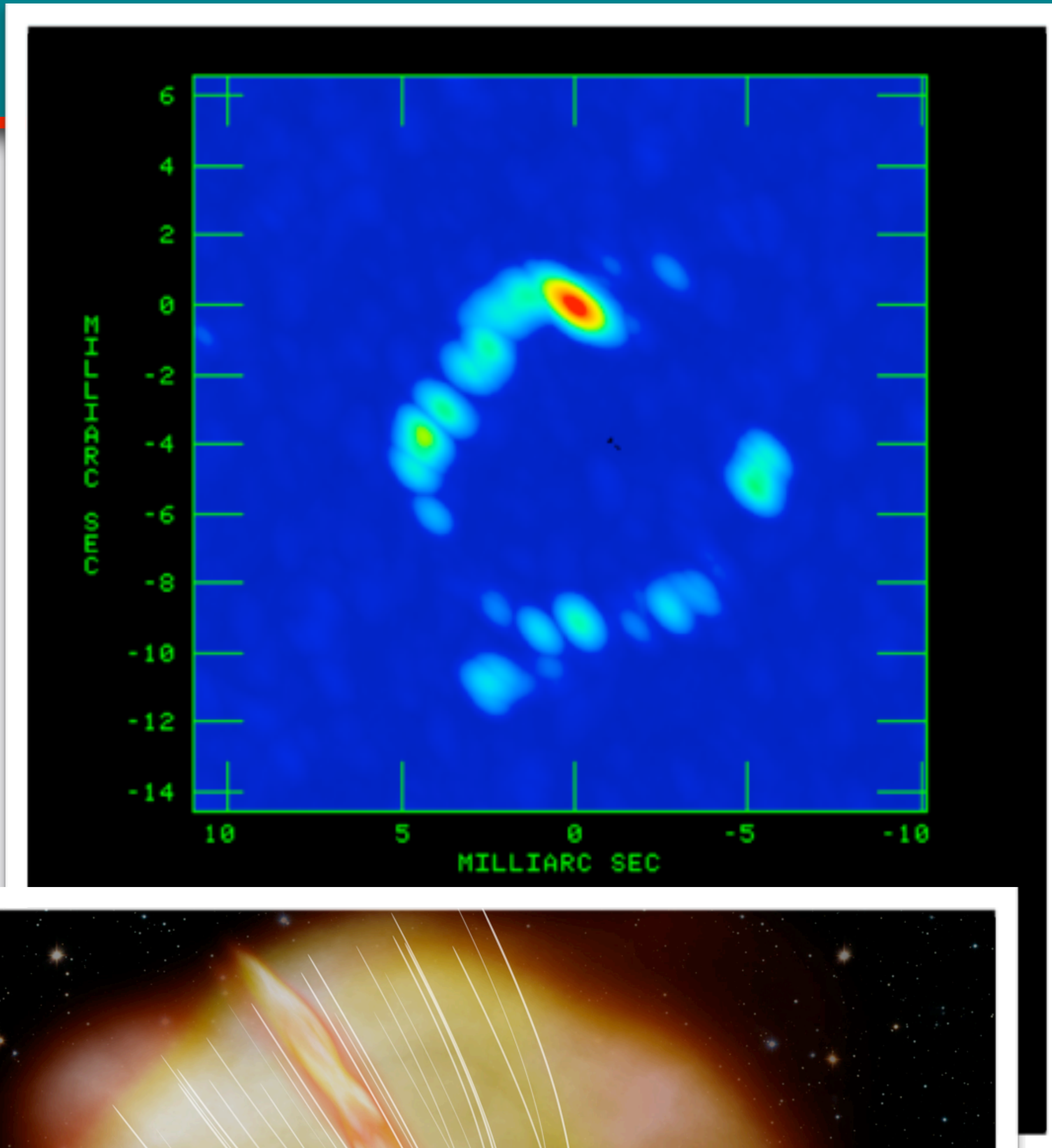
"Magnetic fields are to astrophysicists what sex is to psychoanalysts."

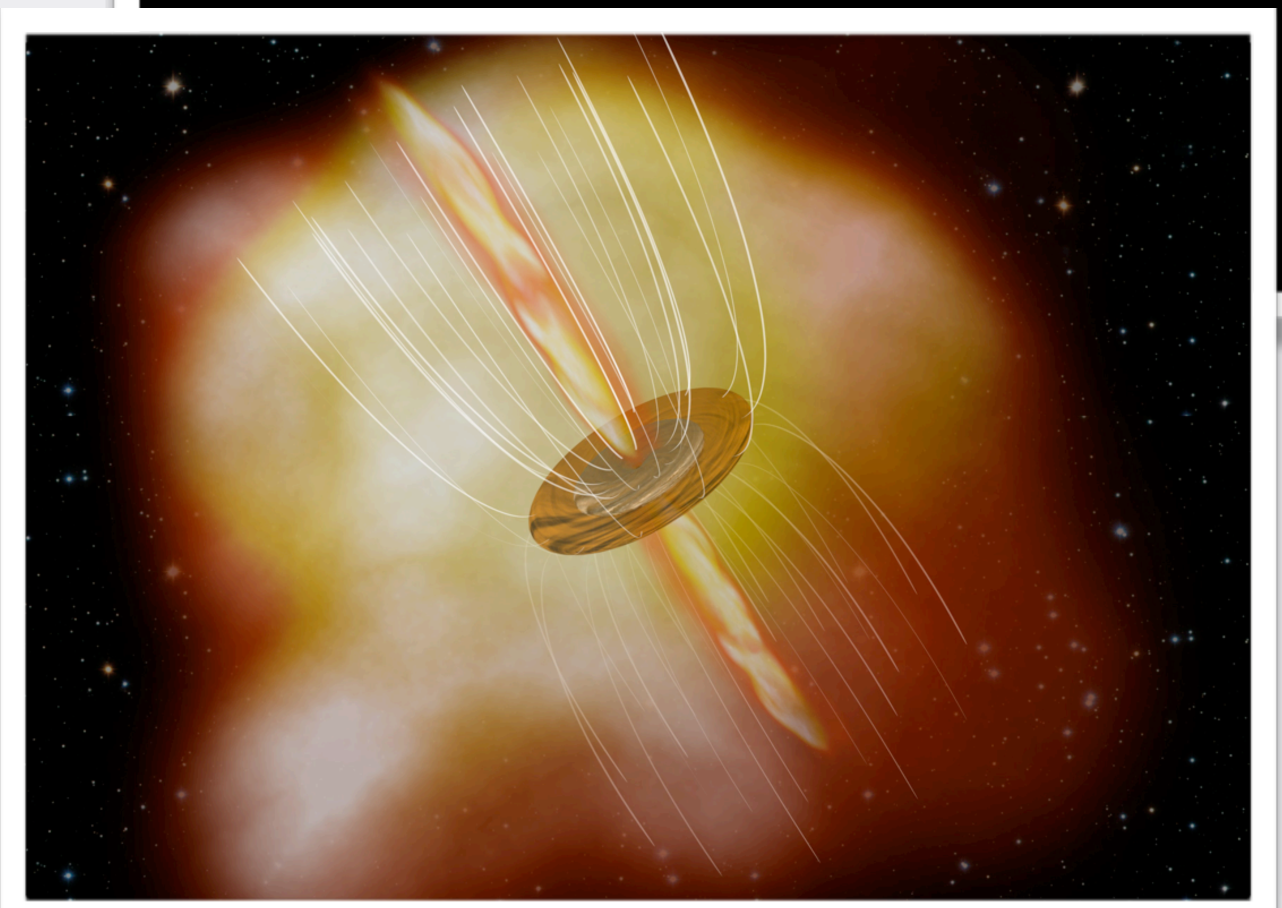
- H. C. van de Hulst

- staff at Toruń, Poland

Outline

- **Background**
  - Masers
  - Masers and magnetic fields
  - Analysing maser polarisation
- **Evolved stars**
  - Open questions in evolved stars
  - Maser polarisation:
    - AGB stars
    - Water fountains/Proto-PNe
- **Star-forming regions**
  - Topics in high mass star formation
  - Focus on methanol masers
- **Future perspectives**





Cosmological Masers

- **Interstellar molecules**
  - Can be away from equilibrium relatively long
    - $t_{rad} < t_{col}$ in low density
  - Can be easily excited by ambient radiation
    - In presence of heated dust
  - Can build up substantial path
    - Velocity structure important
  - Resulting in high brightness maser
    - Lots of flux from small area

- **Unique probes of (very) small scales**
    - Can even do VLBI, mas or µas resolution
  - Physical processes
  - Dynamics, proper motions
  - Astrometry, distances
  - Polarisation....

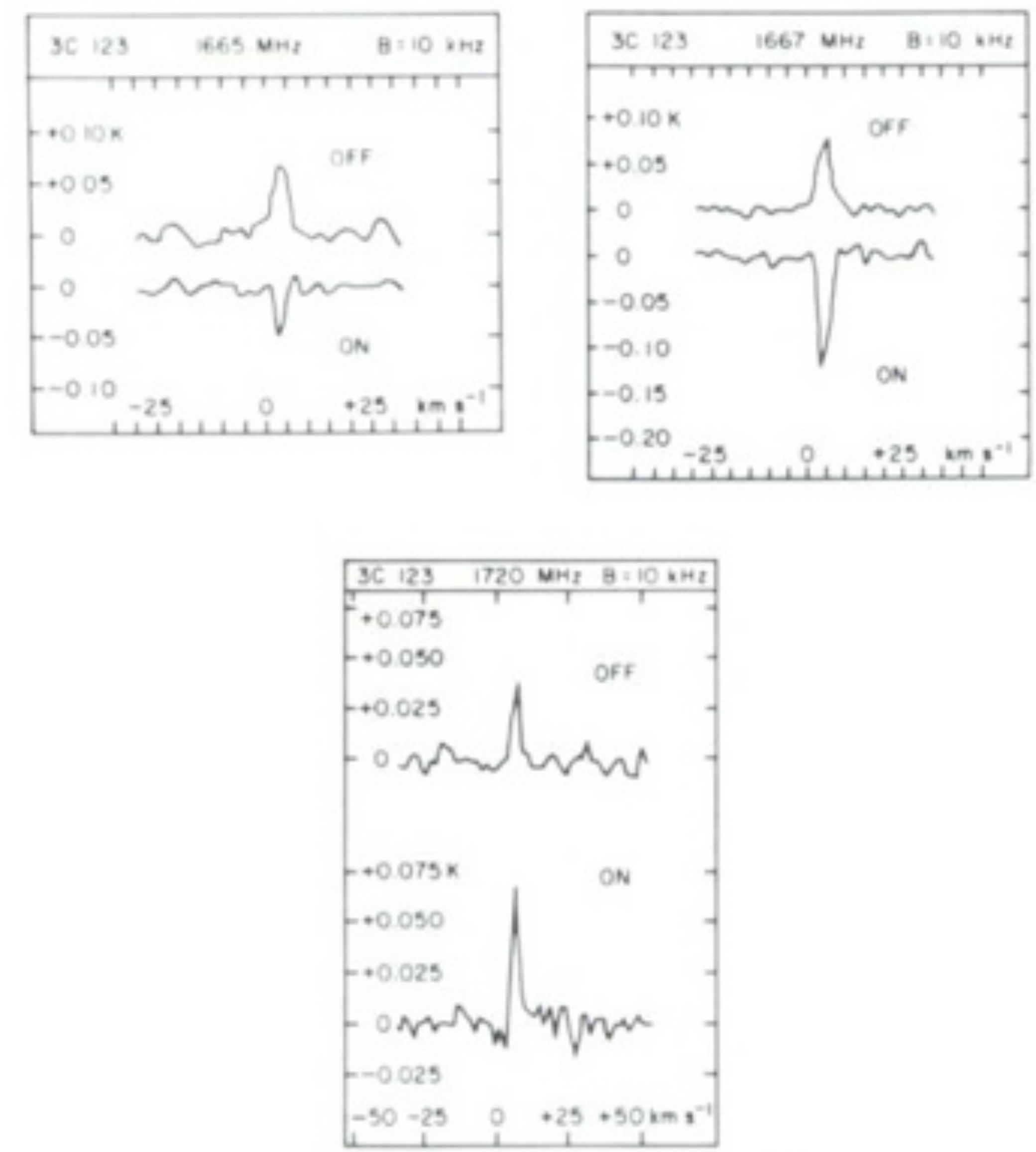


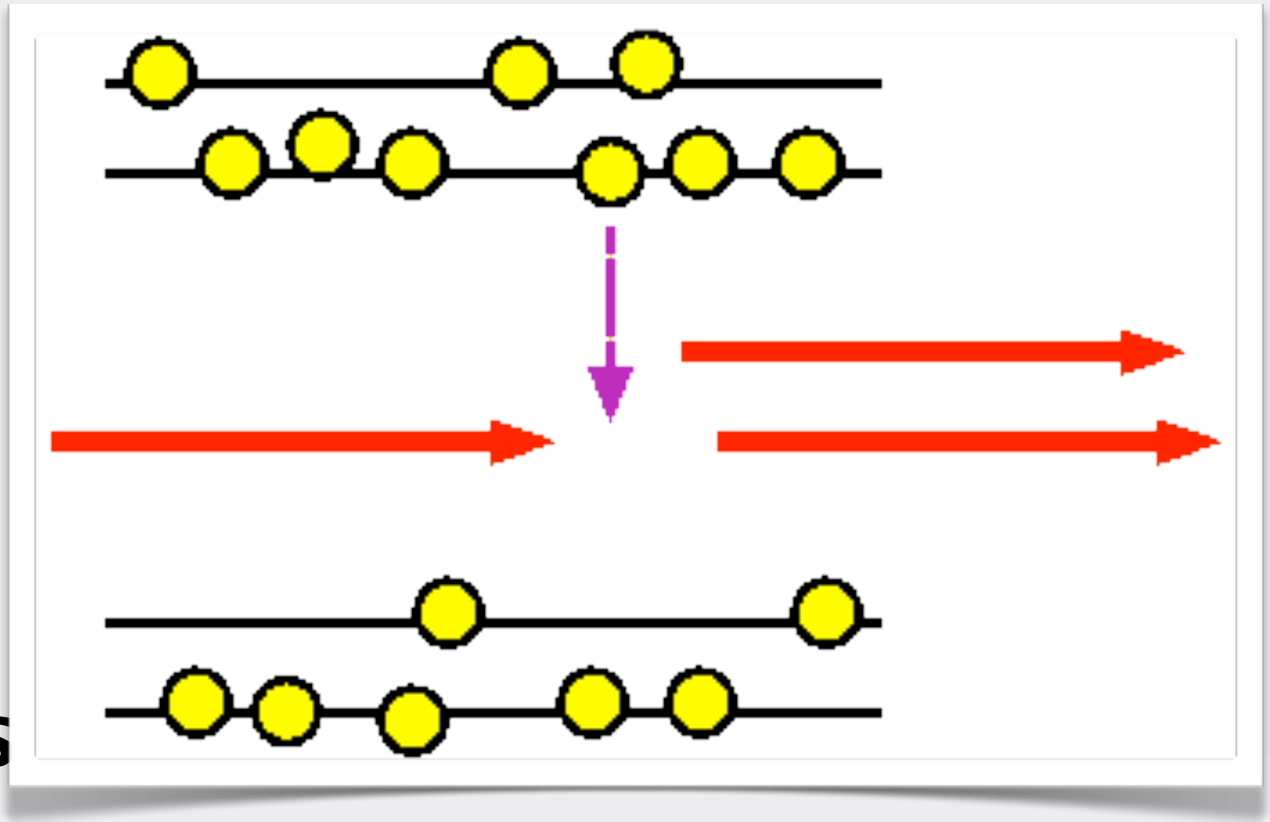
Fig. 3.4 OH spectrum toward the interstellar cloud in front of 3C123 (from Rieu et al. 1976a)

Maser species

- **Most common are:**
  - OH at 1612, 1665, 1667 MHz, 18cm
    - Also excited OH at 4765 MHz
  - H_2O at 22 GHz
    - Also in sub-mm
  - SiO at 43 GHz, (both v=1, v=2)
    - Also at 86 GHz (difficult for VLBI)
  - CH_3OH (methanol) at 6.5 and 12.1 GHz
    - And 25, 33, 43 GHz
  - Rare masers in H_2CO, NH_3, H recombination lines..
- **Environments are**
  - Star forming regions,
    - IR fields near young stars and shocks (H_2O, OH main line, CH_3OH)
  - Circumstellar (SiO, H_2O, OH)
  - Megamasers in AGN and starbursts: H_2O and OH
- **Thousands known**
  - Used as beacons from blind surveys
  - Or found from IR surveys

Maser Beaming

- **Maser is amplifying line radiation:**
  - Masers grow exponentially
  - As long as velocity overlaps
  - Until it saturates
- **Self-amplifying?**
  - Or cosmic background
  - Or background radiation:
- **Images does not reflect gas distribution**
  - As it does for optical thin
  - Or τ=1 surface for optical thick
  - Hard to derive N, T or n
- **Imposes preferred direction**
  - could result in polarisation



But high brightness…
Must be active excitation
Must be abundant gas
Can be modelled
Allows high resolution
Gas motions!
Through VLBI

Molecules & Magnetic fields

- **Basic Zeeman splitting:**
  - Breaks degeneracy of magnetic sub-states
    - m_F with g, the Landé factor:

$$\Delta E = g\mu B m_F$$

- **Paramagnetic:**
  - Notably: OH

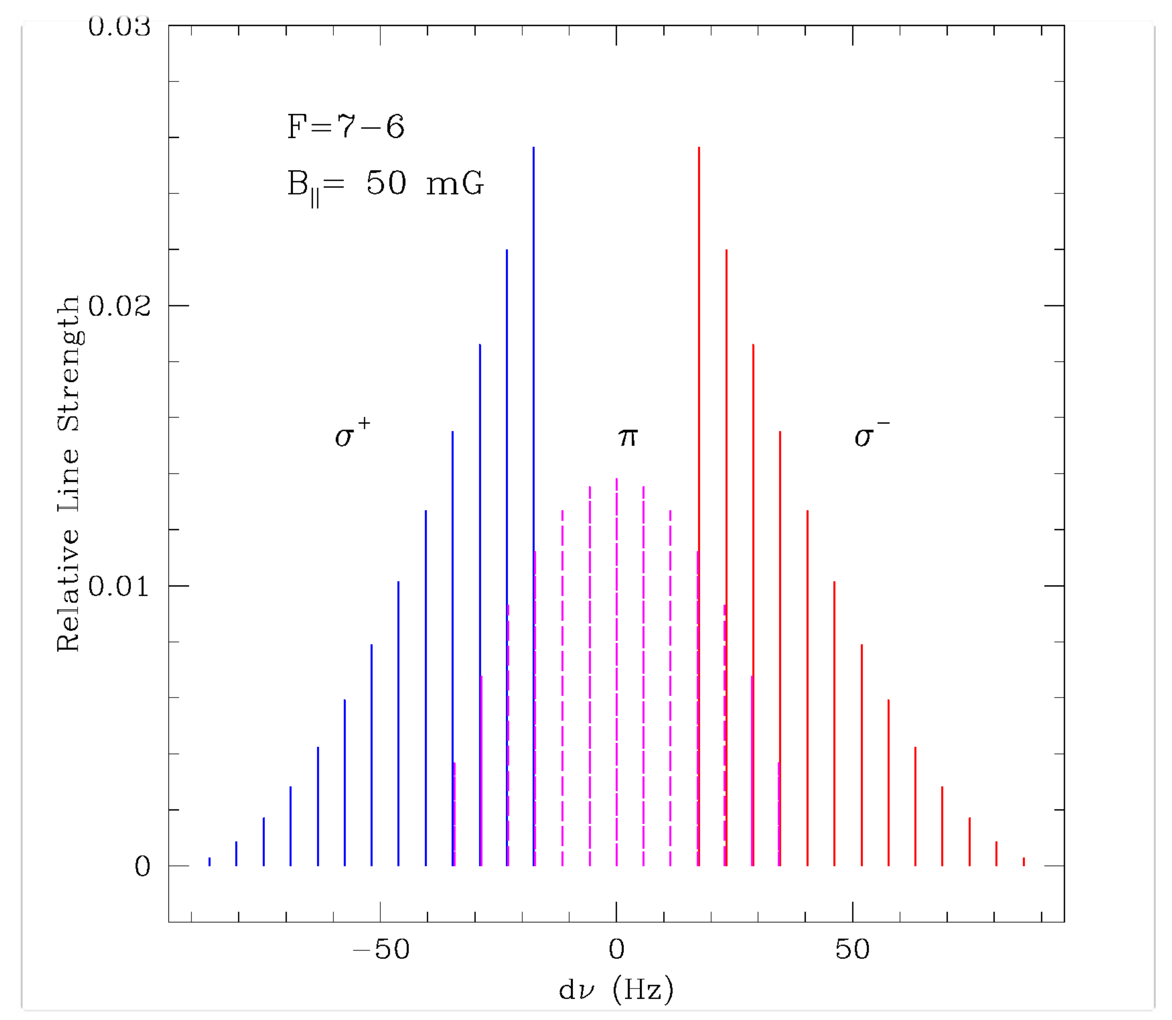
$$\mu_B = \frac{e\hbar}{2m_e c}$$

- **Non-Paramagnetic:**
  - SiO, H_2O, CH_3OH

$$\mu_N = \frac{e\hbar}{2m_n c}$$

  - 3 orders weaker effect
    - But compensated as these operate in higher density regimes

$$\mu_B \approx 10^3 \mu_N$$



$$\Delta m_F = \pm 1; \quad \sigma^{\pm} - \textit{circularly polarized} \perp B$$
$$\Delta m_F = 0; \quad \pi - \textit{linearly polarized along } B$$

Zeeman splitting regimes

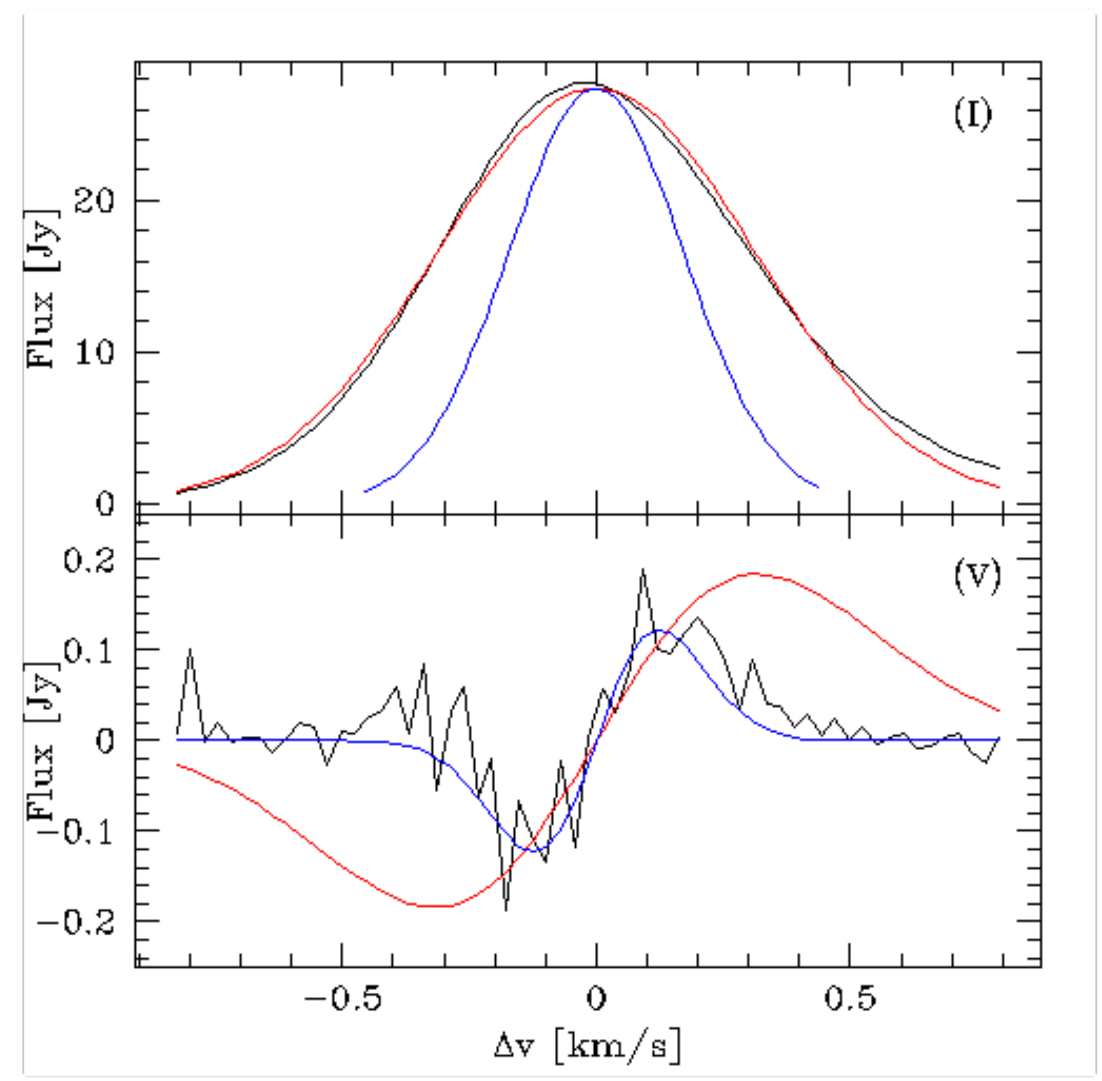
- **Two regimes, depending on frequency overlap**

- **Large splitting (typically OH)**
  - $r_Z > 1$ (or $r_Z \sim 1$)
  - B strength follows directly from measured splitting of Zeeman pairs
  - Linear polarisation || or ⊥ to B depends on observation of σ (⊥) or π (||) components
- **Small splitting (most others)**
  - $r_Z < 1$
  - B ∞ m_c (fractional circular polarisation)
    - But: depends on B-field angle to the l.o.s.,
    - maser saturation
  - not always simply related to dI/dv !
  - Extensive theory, modelling and controversy

$$r_Z = \frac{\Delta\nu_Z}{\Delta\nu_D}$$

$$\Delta\nu_Z = \textit{Zeeman splitting}$$

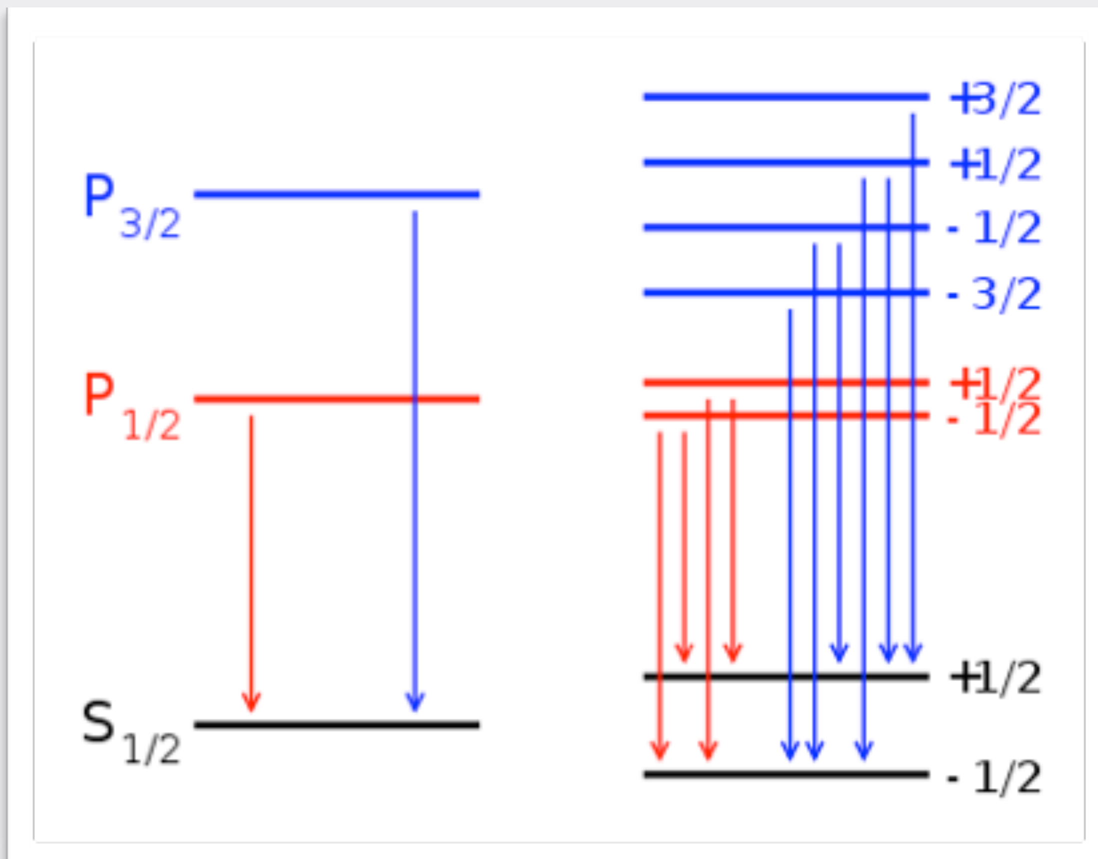
$$\Delta\nu_D = \textit{Doppler linewidth}$$



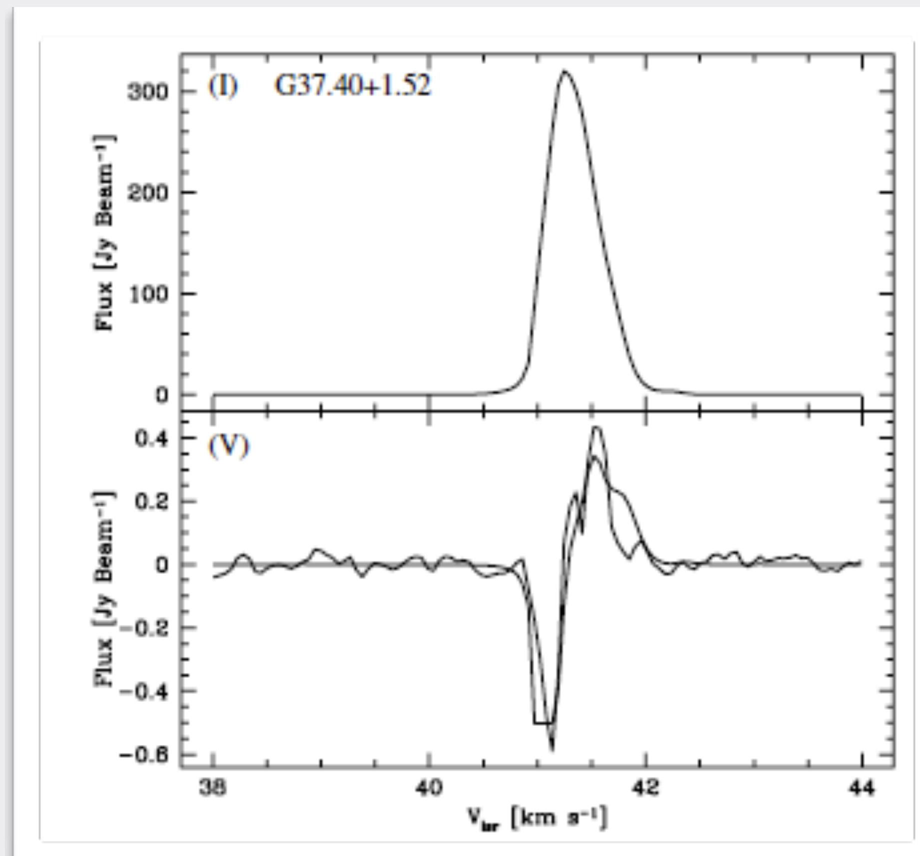
S Per H2O (Vlemmings et al., 2001, A&A 375 L1)

Zeeman Splitting

- **Further complicated when astrophysical line is composed of several spectral components**



B=0 **B≠0**

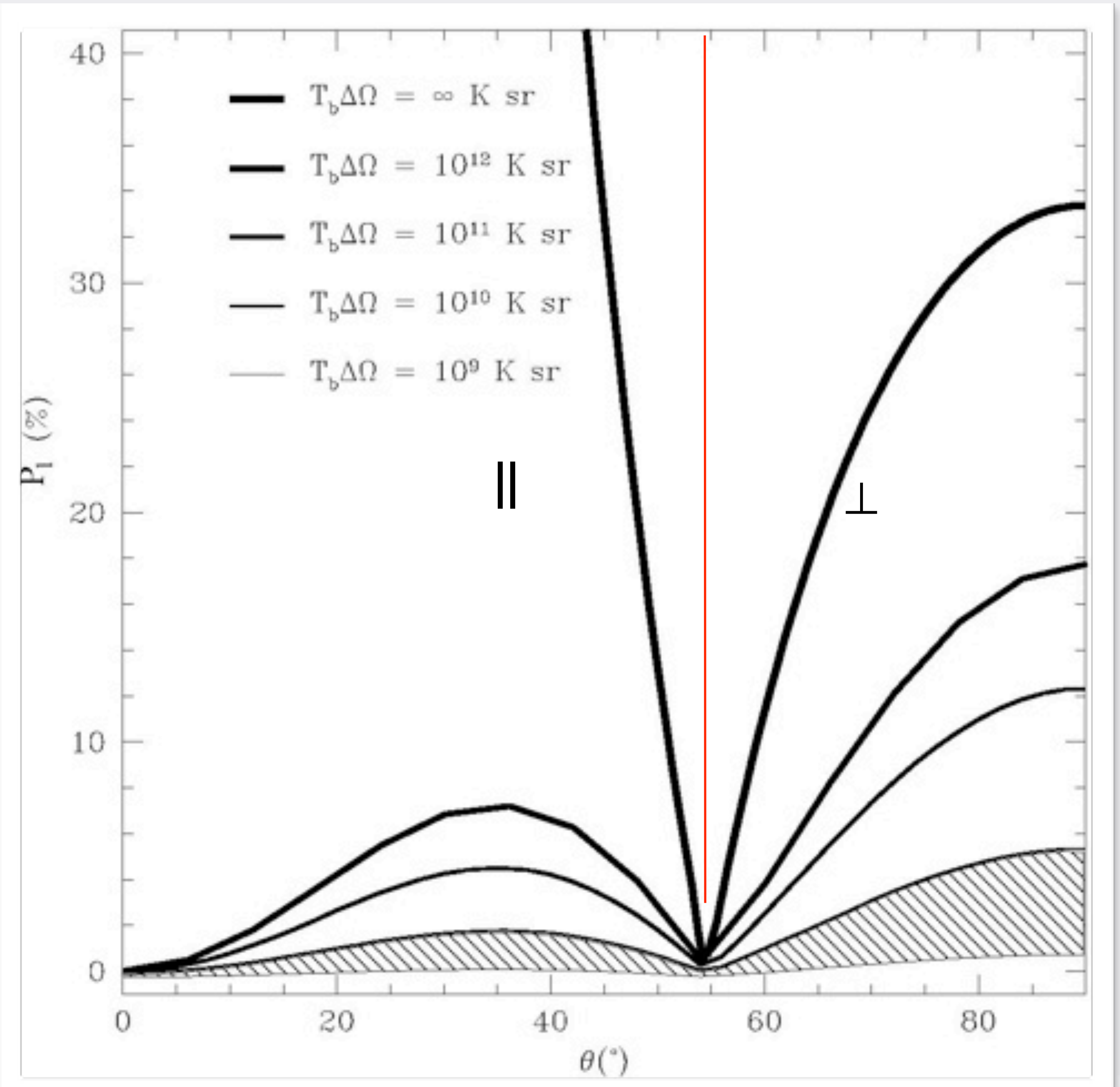


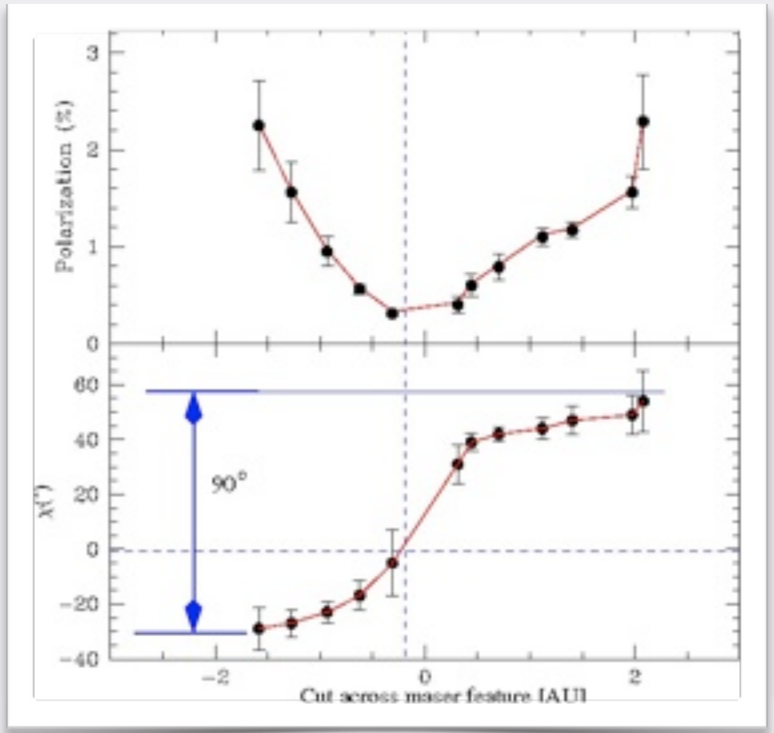
Circular polarisation: V∝dI/dv
Not true for all masers!

Linear polarisation

- **In small splitting regime governed by θ, angle B and line-of-sight**
  - Polarisation fraction
    - function of θ
    - and maser saturation level
  - Polarisation direction
    - Depends directly on θ, either || or ⊥ to magnetic field direction
    - || when $\theta < 55^\circ$
    - ⊥ when $\theta > 55^\circ$

H_2O maser linear polarisation





Theory predicted 90º flip with accompanying decrease in linear polarisation fraction observed in W43A
(Vlemmings & Diamond 2006 ApJ 648 L59)

Analysing maser polarisation

- Magnetic fields result in maser polarisation....
- Interpret polarisation in terms of magnetic fields?

- Non magnetic polarisation possible
  - Must verify magnetic field dominates over radiation rates
    - Seems OK in most, but the strongest masers
- Radiation effects influence magnetic signature
  - Must model spectral line components
  - And determine maser saturation level
  - Almost impossible to interpret linear pol in terms of field strength
  - Linear polarisation has ambiguity depending on angle B and l.o.s.
    - Parallel or perpendicular to projected B field

- Pure Zeeman on circular polarisation fairly robust
  - If we just knew the Landé factors
    - Often come from extrapolating old laboratory measurements
    - For non-paramagnetic molecules

More....

- **In astrophysical sources**
  - Velocity gradients along maser propagation direction
    - Lead to significant underestimate of the magnetic field strength
  - Low spatial resolution observations
    - Blending and typically also underestimate field strength
    - Can be addressed by using interferometry/VLBI
- **Faraday rotation:**
  - Example: for typical ISM values Φ = 190º toward W3(OH) at 1.6 GHz
  - Internal faraday rotation along maser path

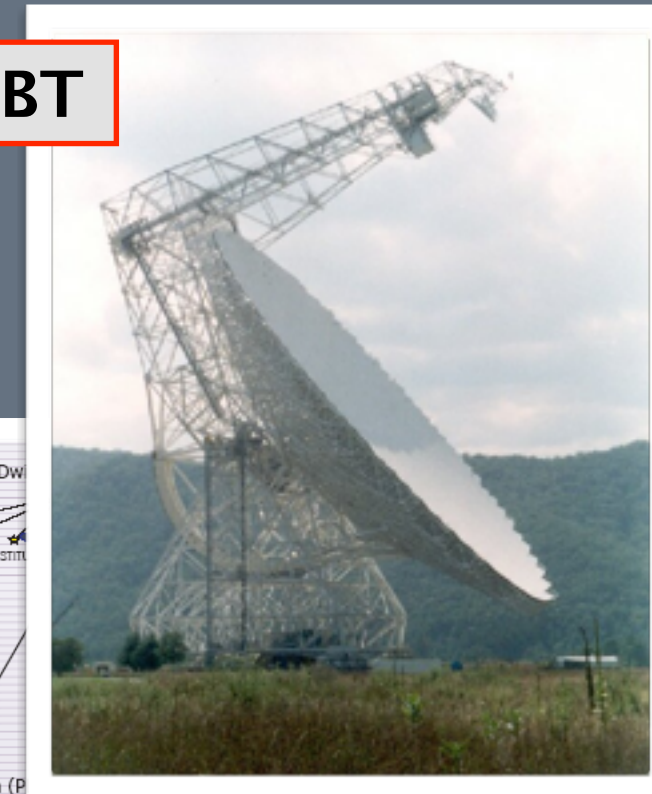
$$\Phi\left[{}^{\circ}\right] = 4.17 \times 10^{6} D[\mathrm{kpc}] n_e\left[\mathrm{cm}^{-3}\right] B_{\parallel}[\mathrm{mG}] \nu^{-2}[\mathrm{GHz}]$$

- **Calibration**
  - Often looking for LCP and RCP differences of few % of total flux
    - Telescopes, instruments and software not optimised for polarisation
  - Good calibrators rare
    - Especially for linear pol position angle
- **Analysis**
  - Looking for Zeeman shifts much narrower than line width
    - In case of non-paramagnetic fields
  - Signature not simple derivative of integrated profile

MERLIN

EVN

GBT



VLBA

Effelsberg

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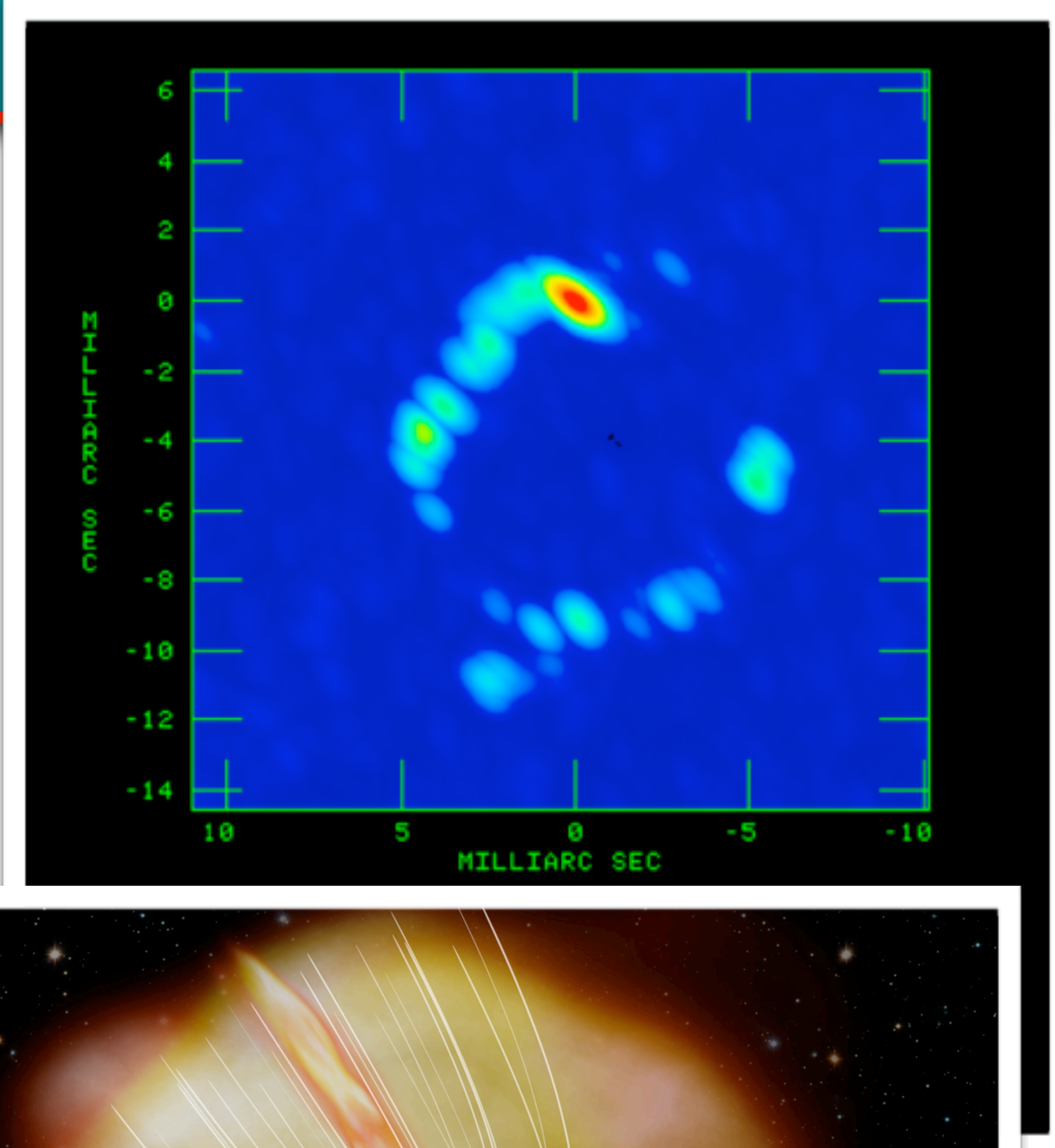
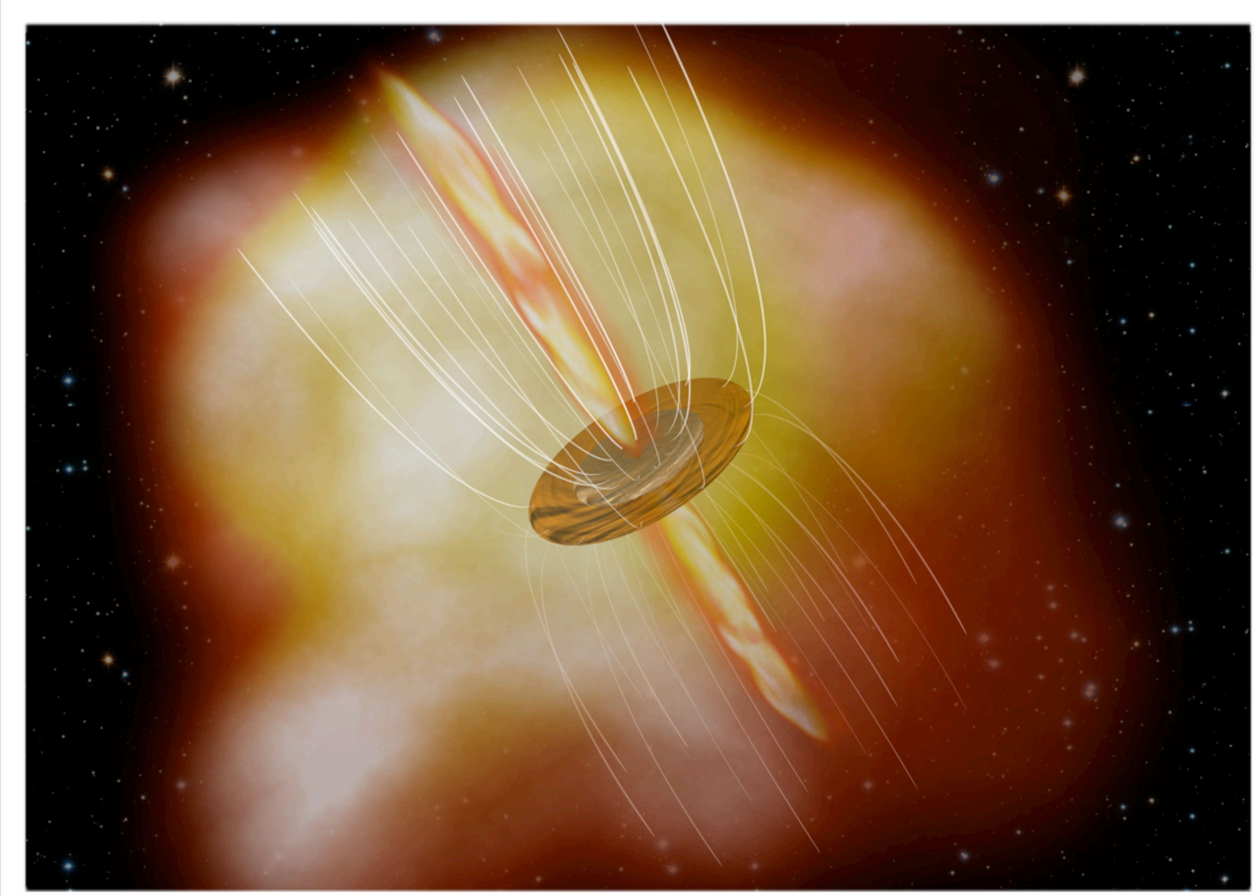
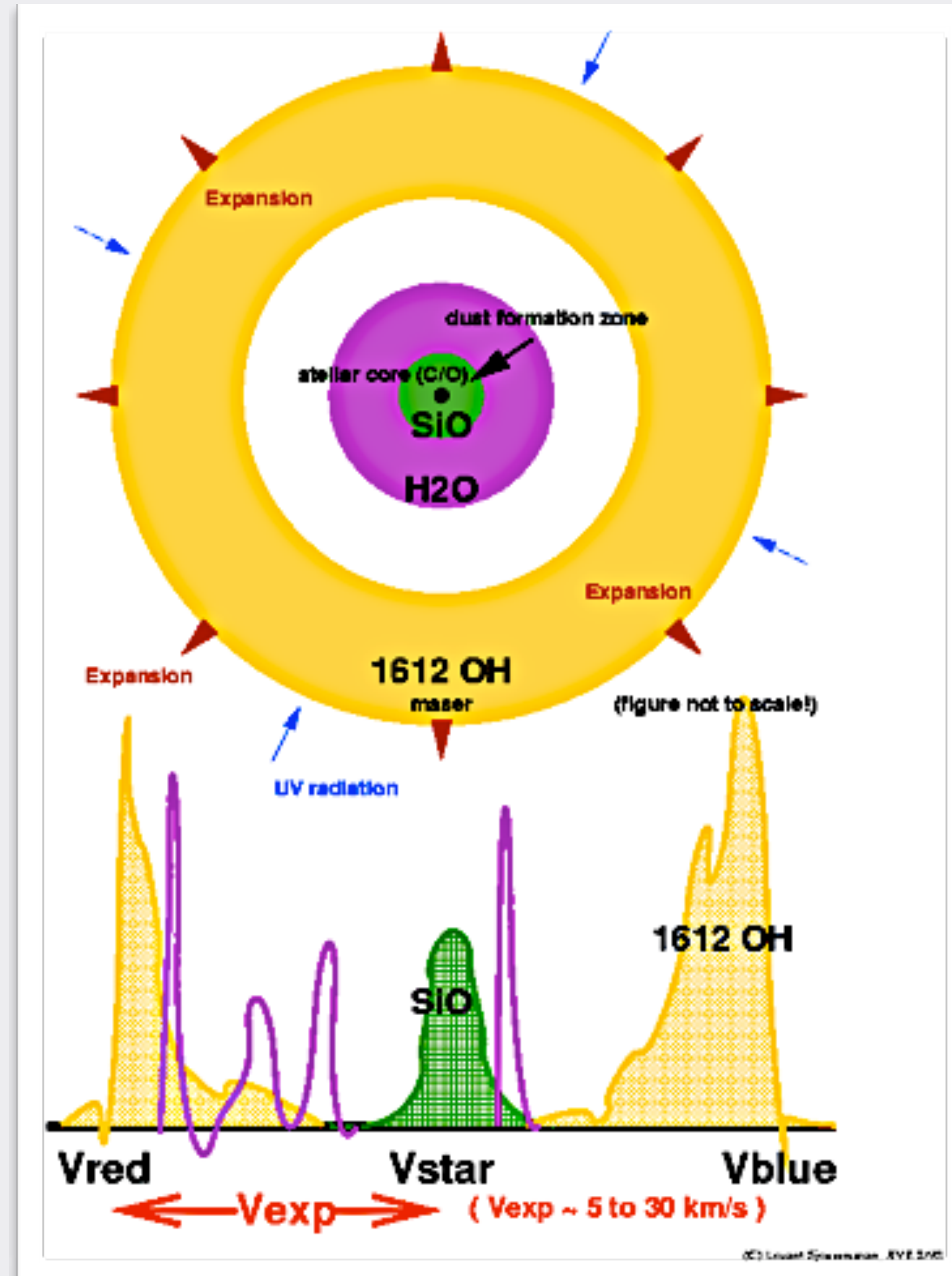


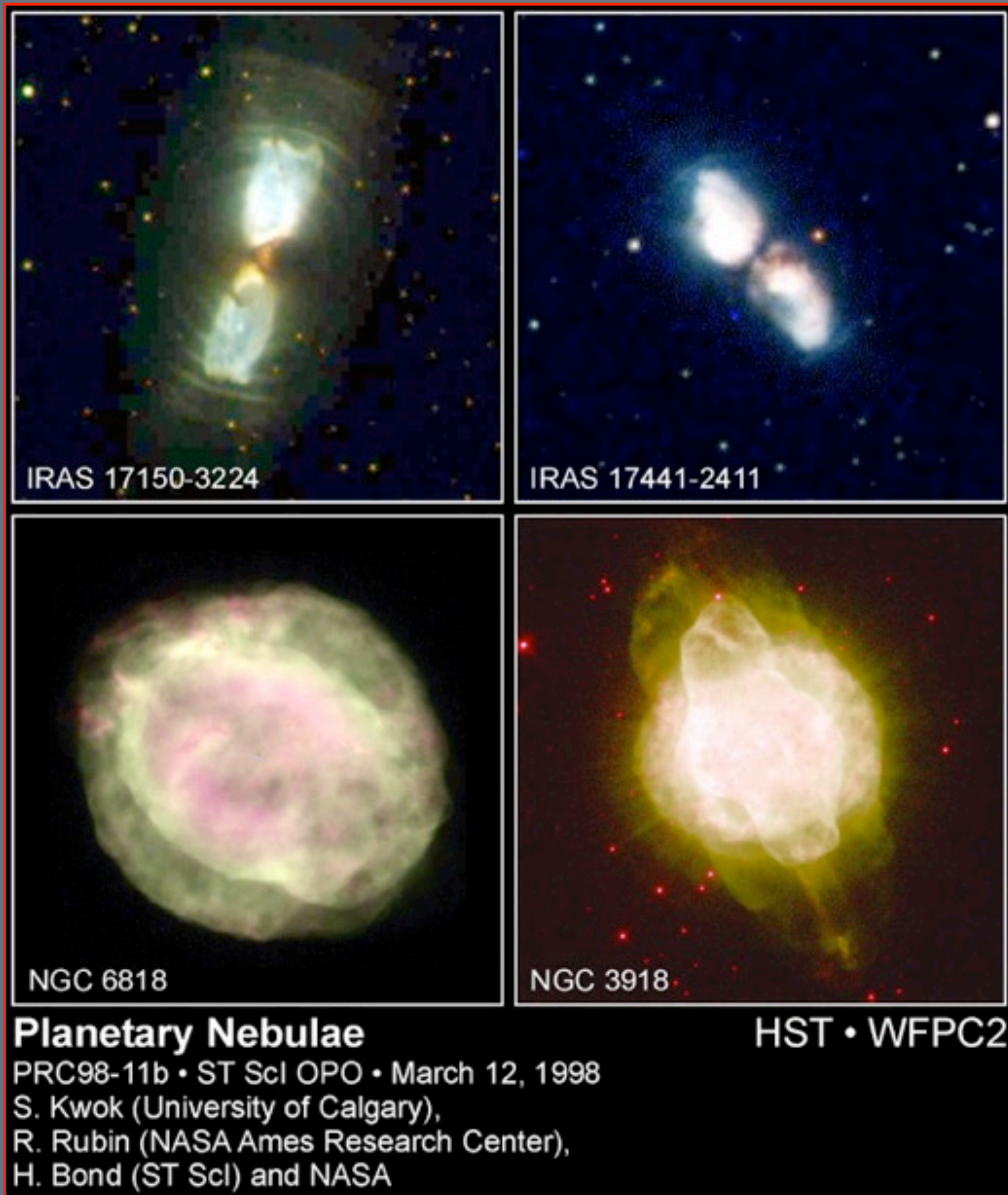


Evolved stars

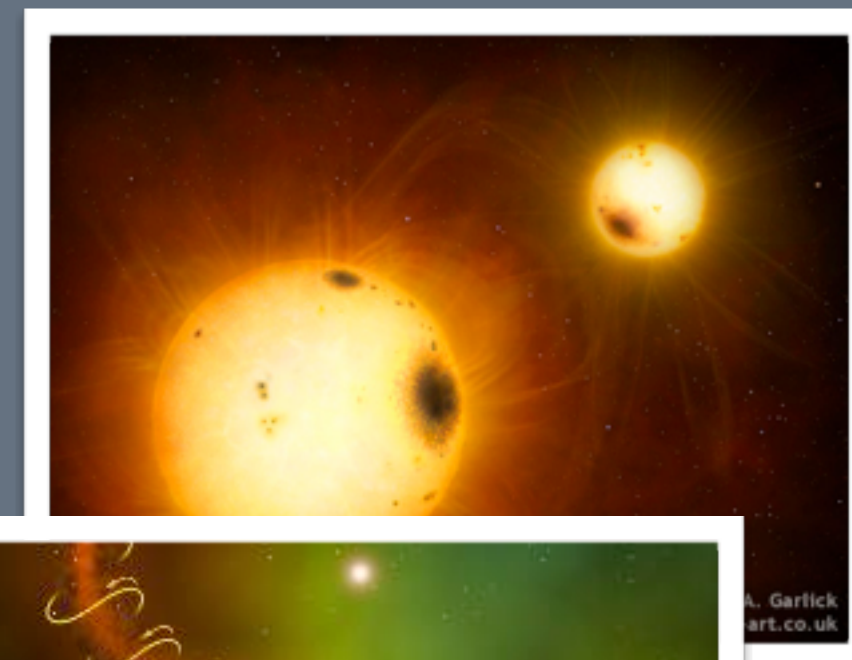
- AGB stars becoming PNe
  - Mass loss origin of Circumstellar Envelope
  - Harbours various masers
- Key questions related to PN formation
  - Role of the magnetic field in shaping CSE
  - Correlation with evolutionary stage
  - Common phenomena
- Onion shell model of masers
  - SiO in the extend atmospheres (2-6 AU)
  - H_2O intermediate distances (5-100 AU).
  - OH: outer envelope (100-10000 AU).
- High Brightness
  - targets for VLBI
  - Polarimetric observations

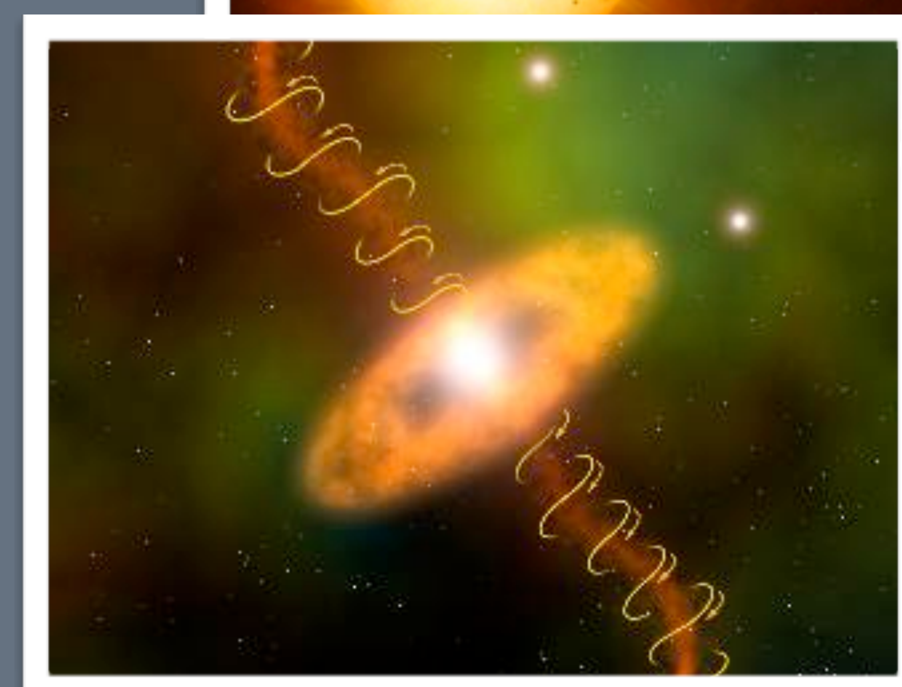


Can Magnetic field shape CSEs?



Interacting wind model requires remnant density structure





Then what can maintain magnetic fields in old giants?

CSE Fields: H_2O Masers

- **Full maser modelling required**
  - Multiple components
  - Dependence on saturation level
- **Accurate magnetic field strengths**
  - at intermediate distances
  - No linear polarisations
- **VLBA observations:**

- **VX Sgr:**
  - H2O: 0.3 – 3 G
  - OH: 1-2 mG (Szymczak et al. 2001, A&A 371 1012)
  - SiO: 80 G (Barvainis et al. 1987, Nature 329 613)

- **U Ori:**
  - H2O: 2-3 G
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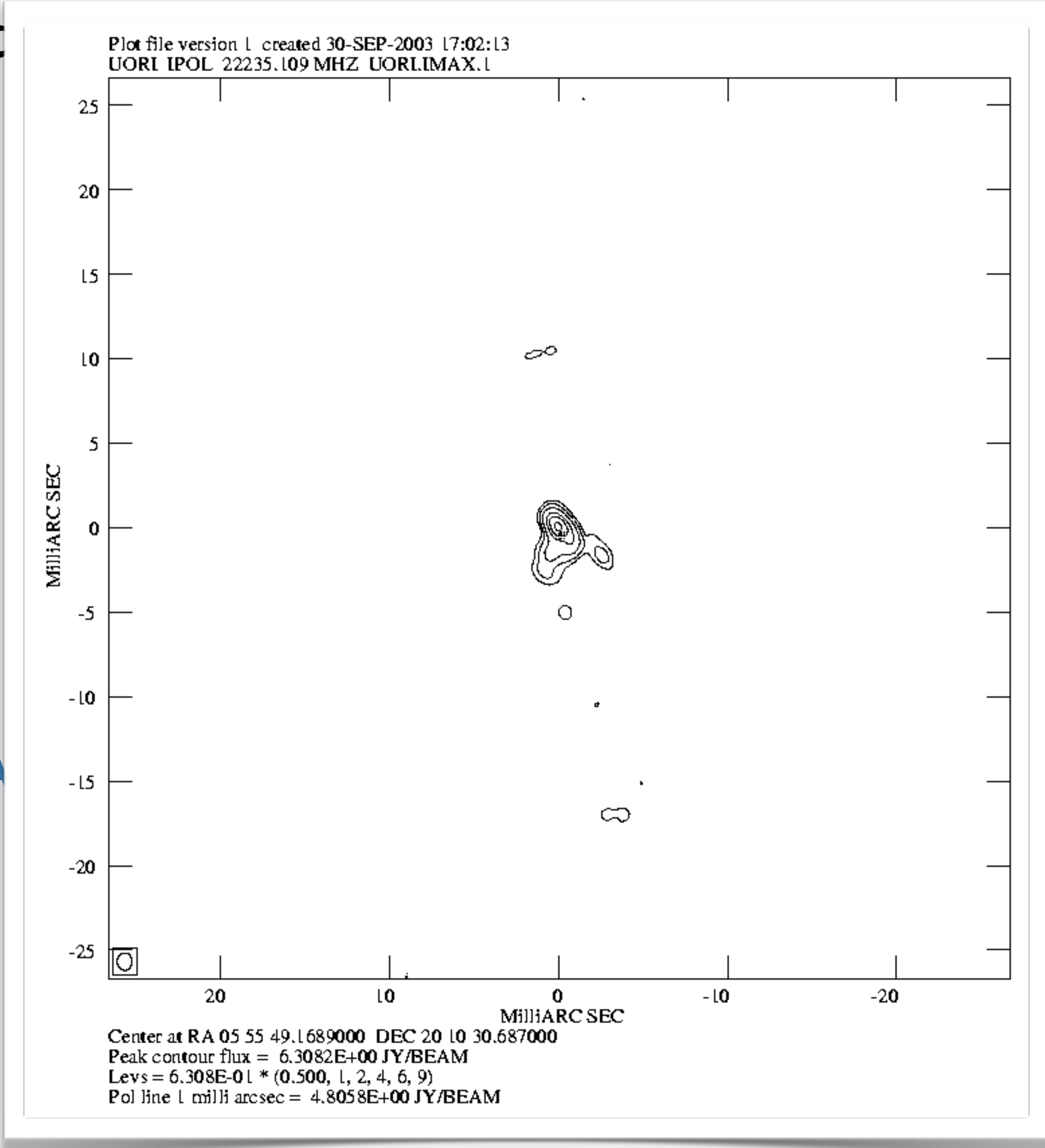

(Vlemmings et al. 2002, A&A 394 589 and 2005, A&A 434 1029)

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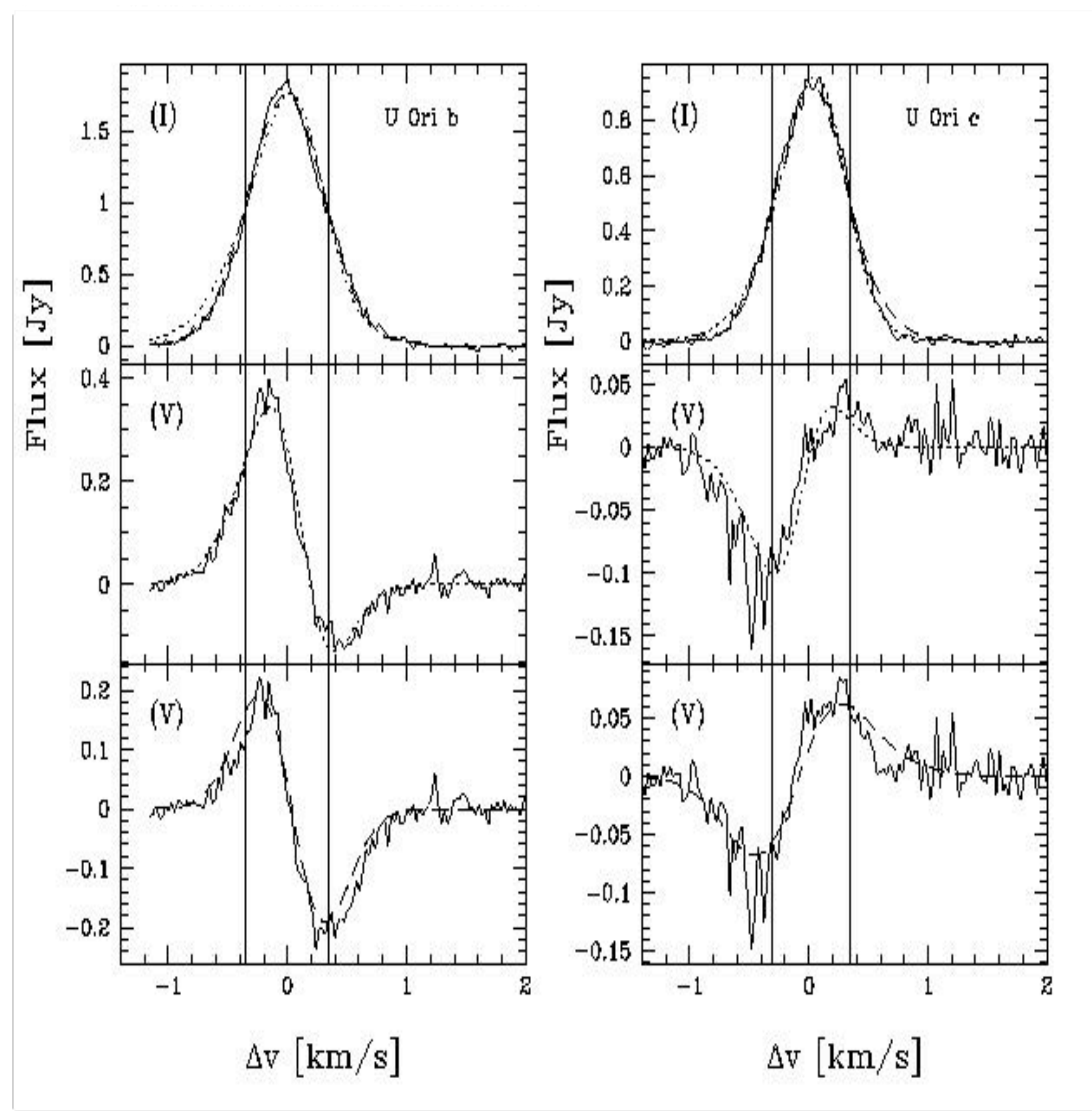

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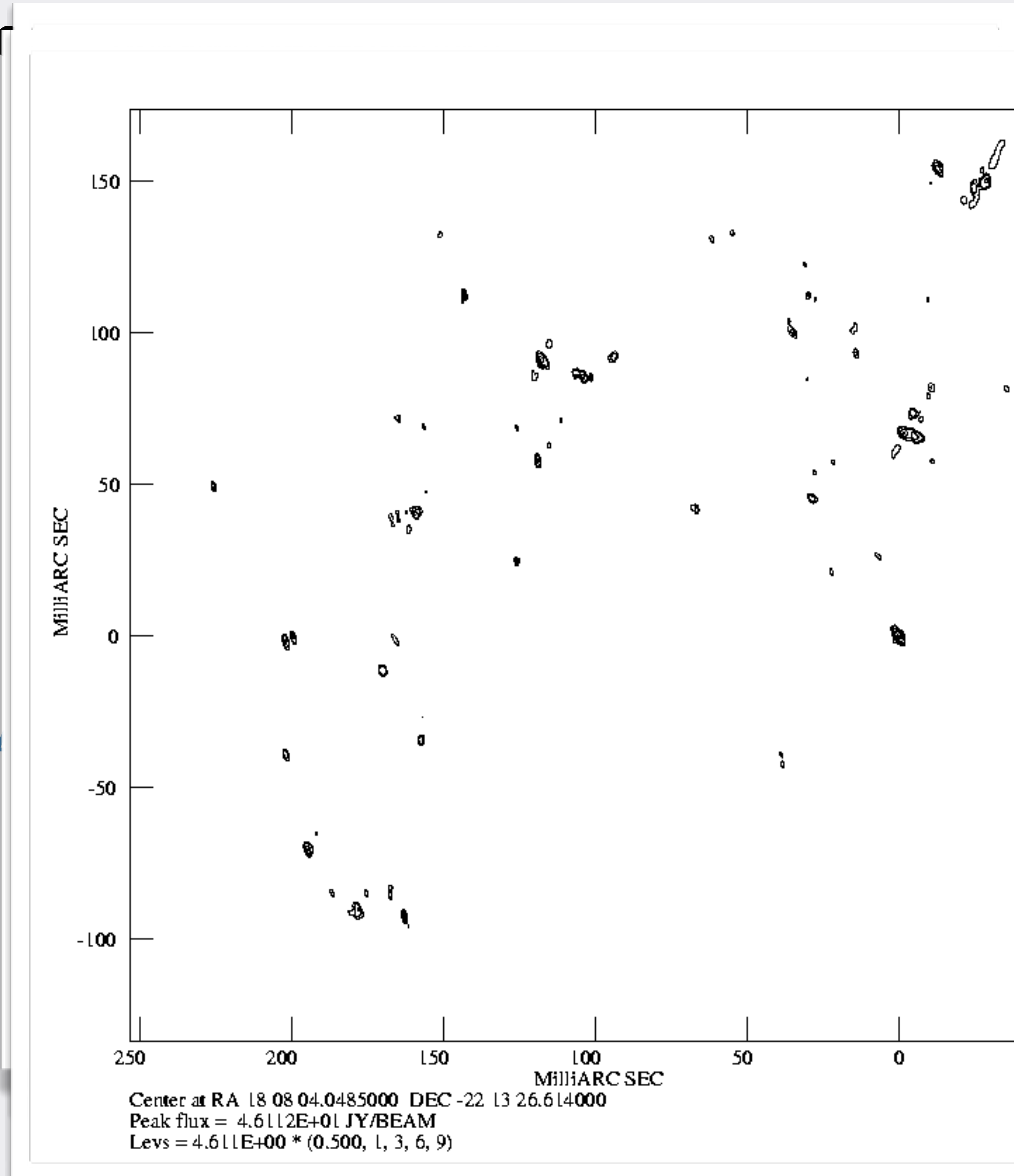

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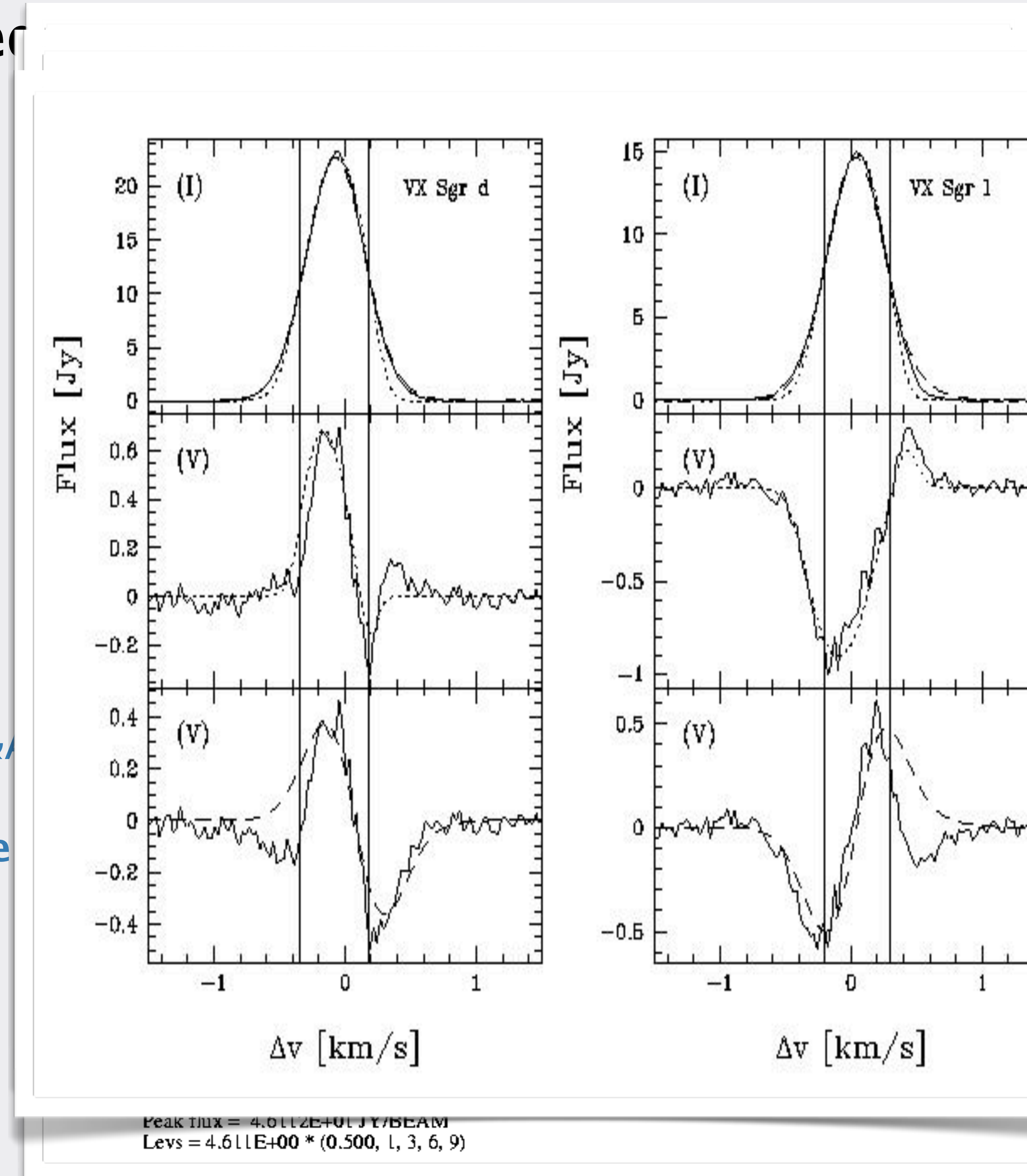
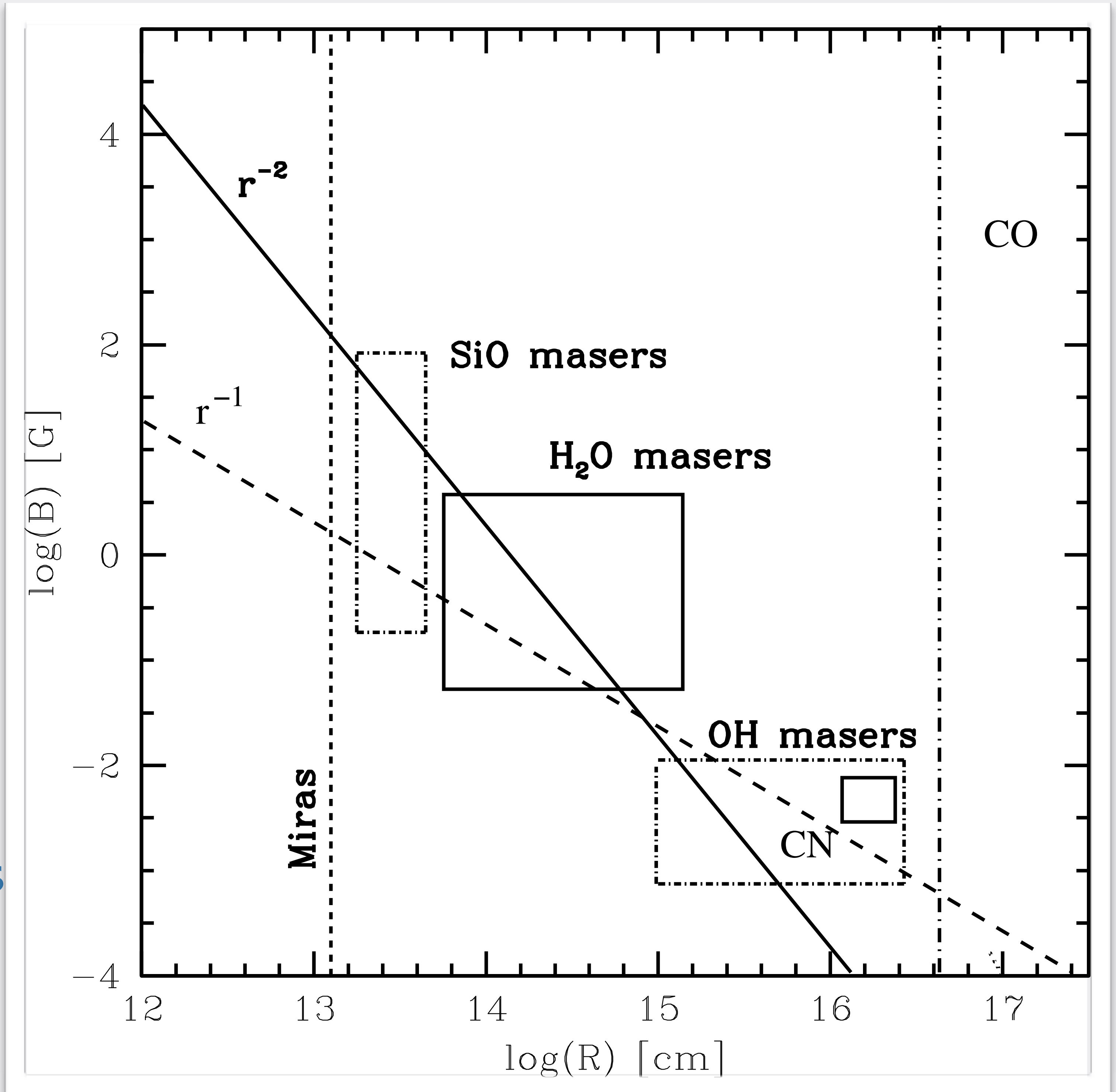


(Vlemmings et al. 2002, A&A 394 589 and 2005, A&A 434 1029)

AGB envelopes

- **Oxygen rich:**
  - SiO at 2 R*
    - B~3.5 (up to 10s) G
  - H2O at ~5-80 AU
    - B~0.1-2 G
  - OH at ~100-10.000 AU
    - B~1-10 mG
- **Carbon rich:**
  - CN at ~2500 AU
    - B~7-10 mG
- **Caveat**
  - Density goes down
  - Maser preferred conditions



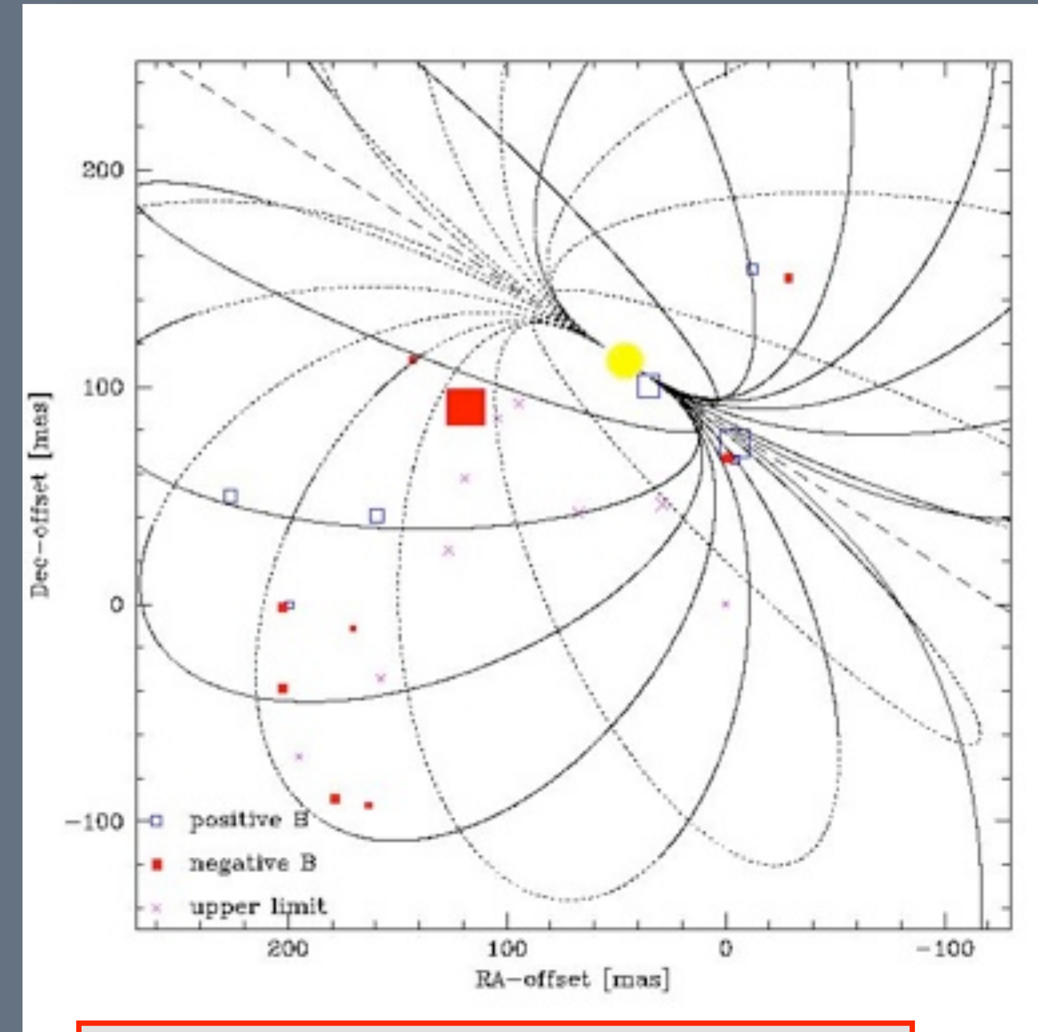
Vlemmings et al. 2002, 2005
Kemball et al. 1997, 2009
Herpin et al. 2006, 2009
Etoka et al. 2004
Reid et al. 1976

Energy densities

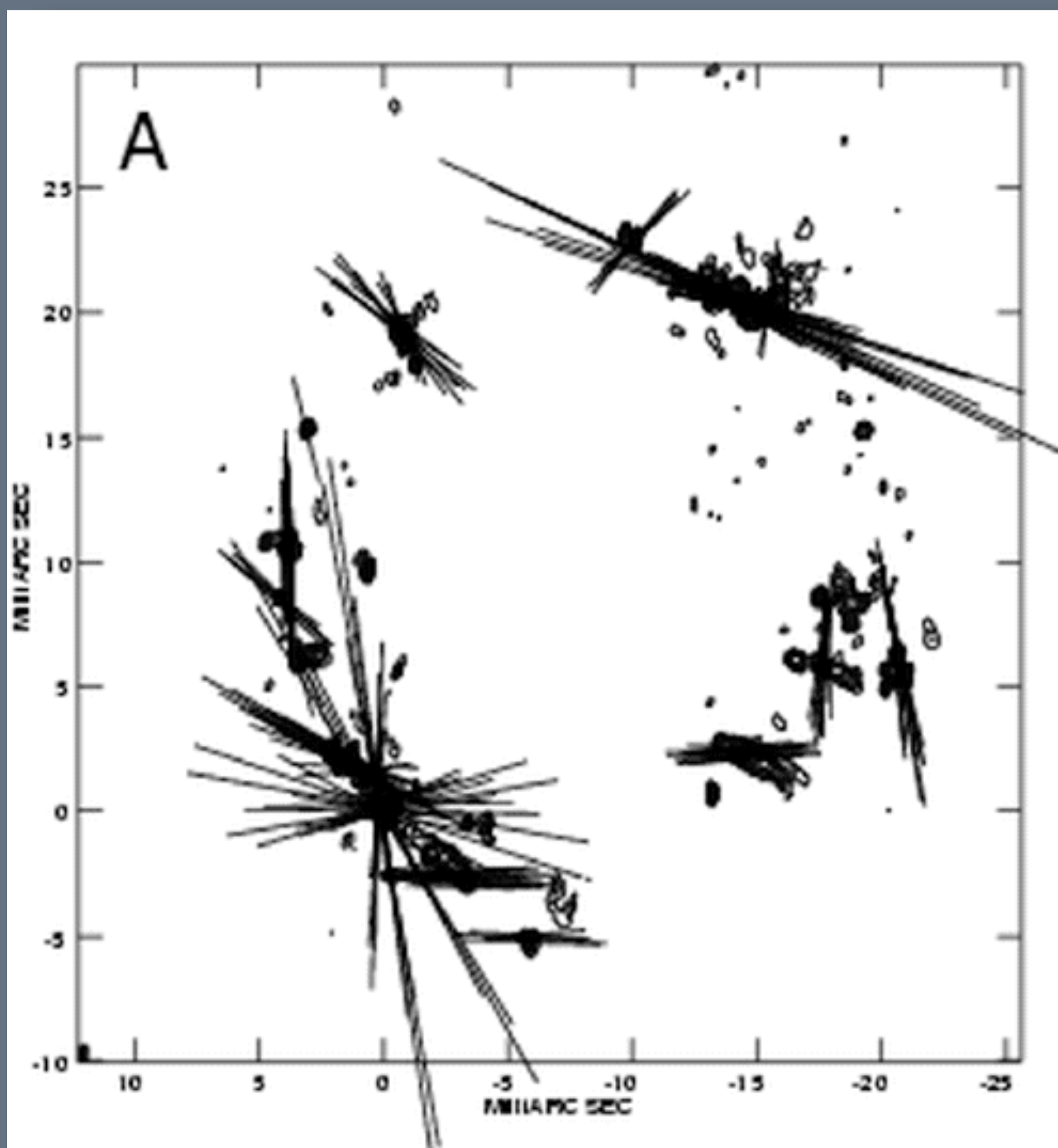
Maser	V_{exp} [km/s]	R_{star} [AU]	B [G]	n_{H2} [cm^{-3}]	T [K]	$B^2/8\pi$ [dyne/cm^2]	nkT [dyne/cm^2]	ρV^2_{exp} [dyne/cm^2]	Alfvén Speed [km/s]
OH	~10	~500	~0.003	~10^6	~300	$10^{-6.4}$	$10^{-7.4}$	$10^{-5.9}$	~8
H_2O	~8	~25	~0.3	~10^8	~500	$10^{-2.4}$	$10^{-5.2}$	$10^{-4.1}$	~300
SiO	~5	~3	~3.5	~10^{10}	~1300	$10^{+0.1}$	$10^{-2.7}$	$10^{-2.5}$	~100
photo-sphere	~5		~50?	~10^{14}	~2500	$10^{+2.0}$?	$10^{+1.5}$	$10^{+1.5}$	~15

Magnetic energy dominates to ~50 AU
Coud it be important for mass loss mechanism too?

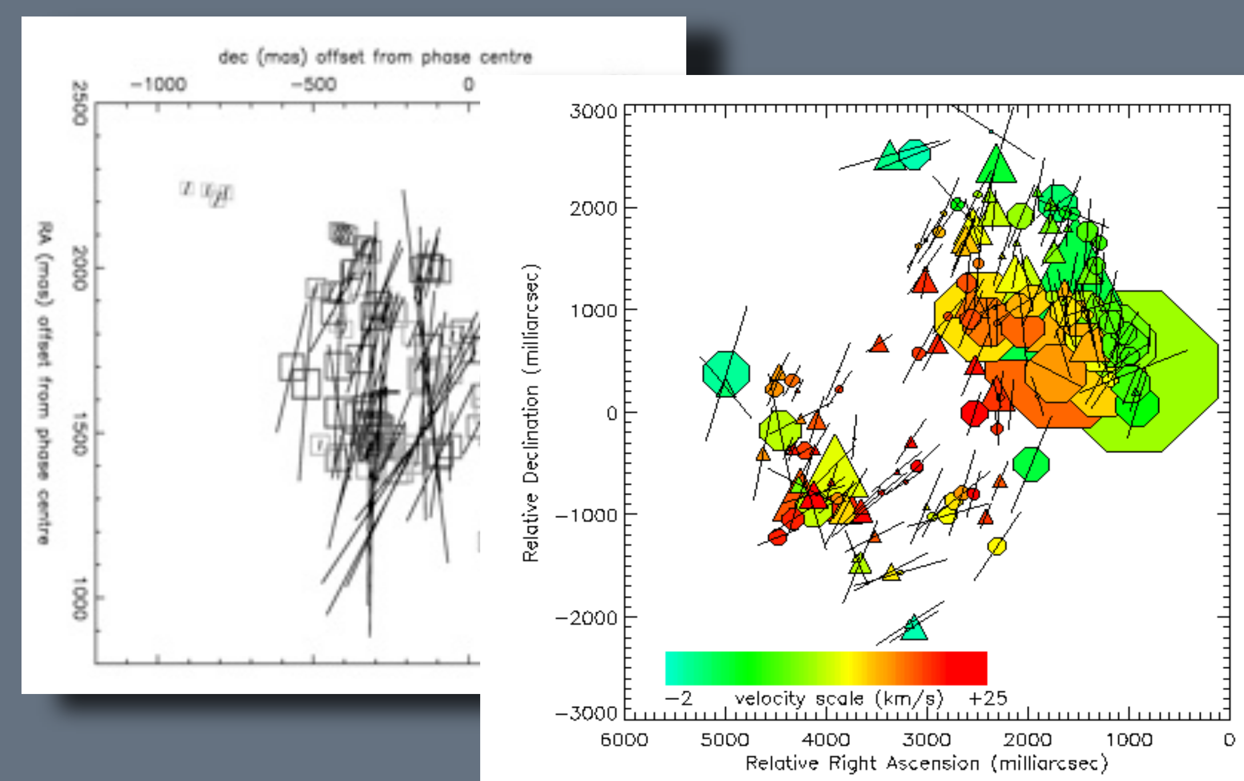
Arguments for large scale fields seem pretty convincing



VX Sgr, H_2O
Vlemmings et al. 2005, AA 434 1029

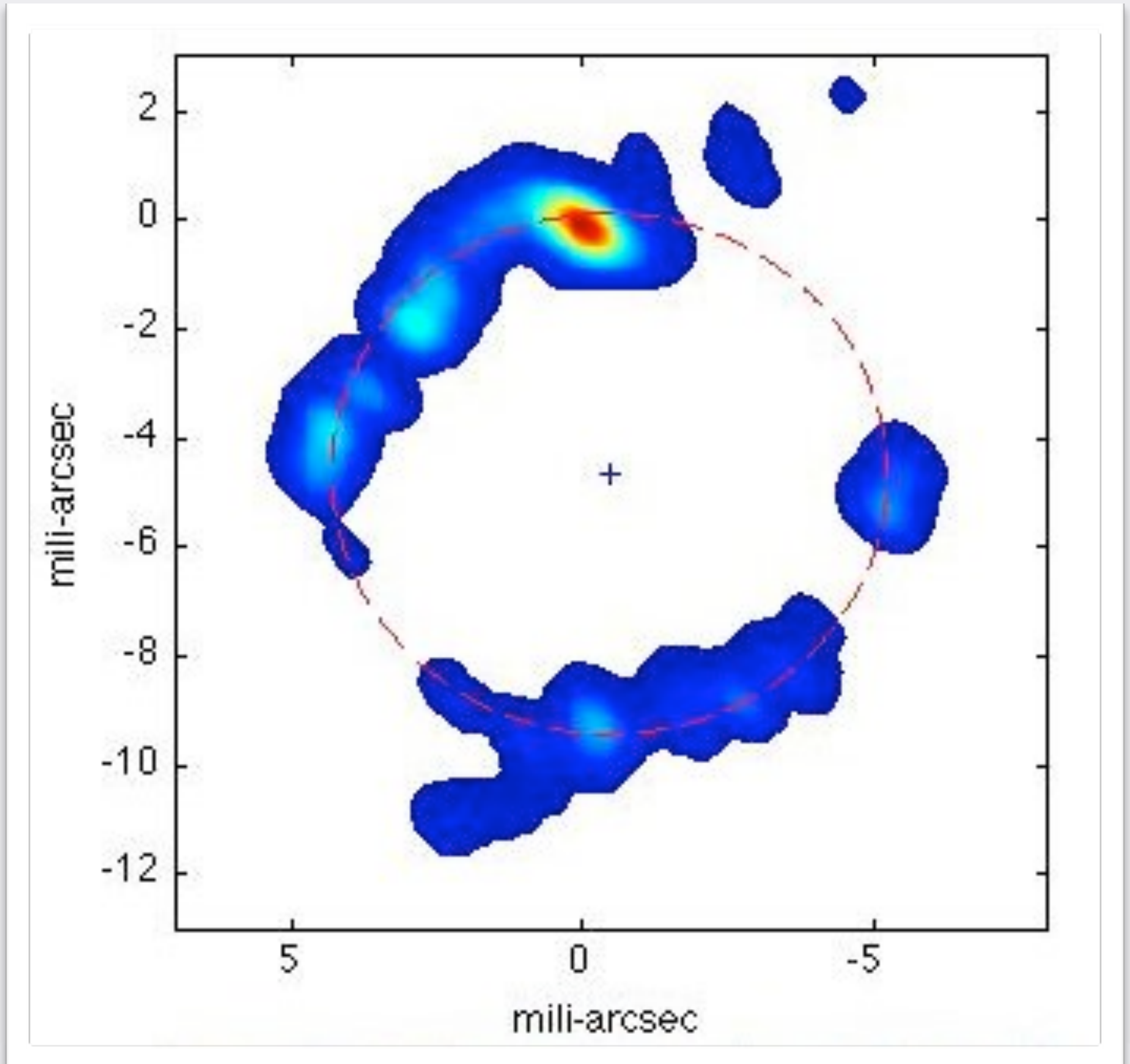


TX Cam, SiO
Kemball and Diamond, 1997, ApJ 481 L111



Looking in OH/IR stars

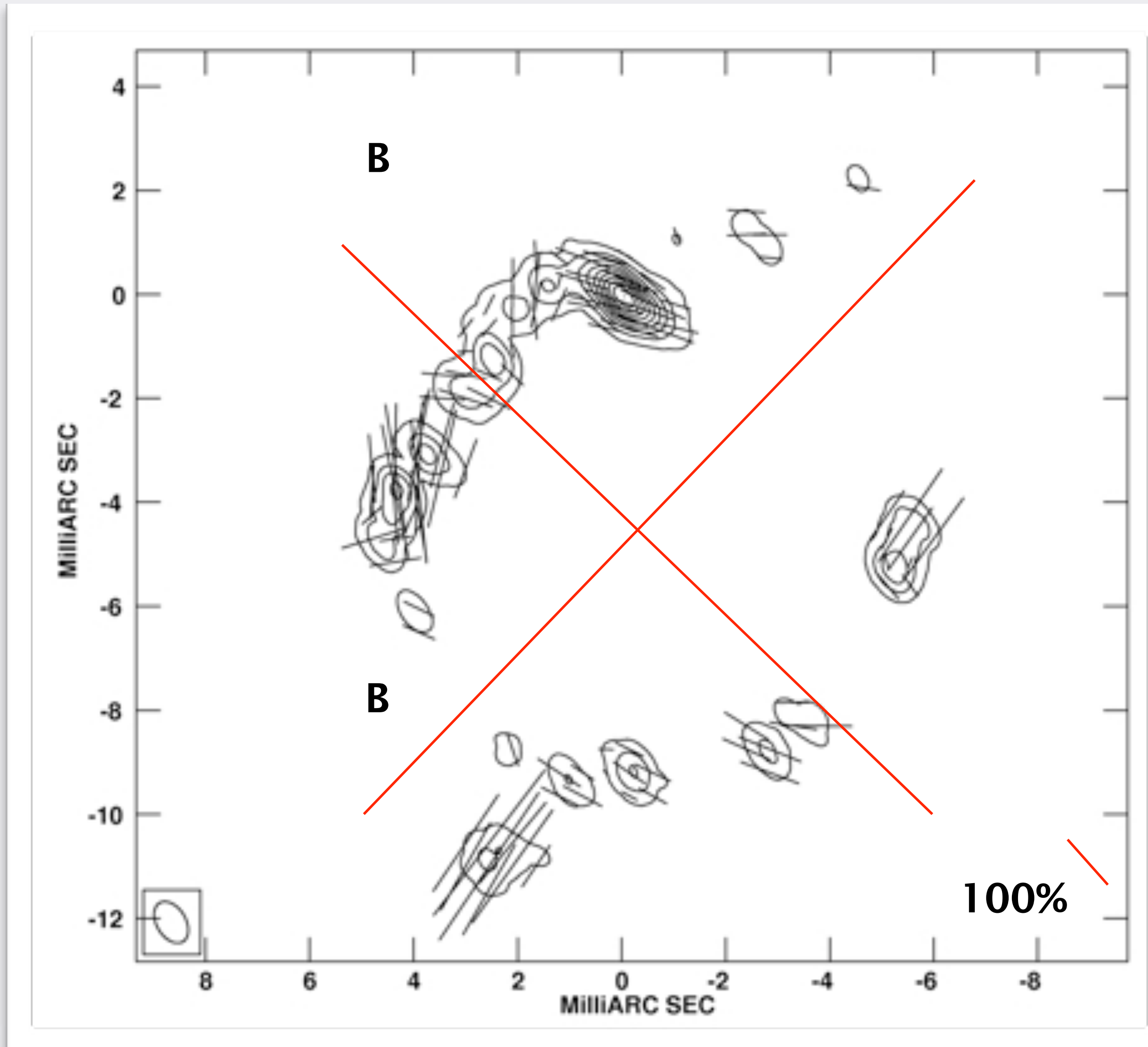
- **OH/IR stars: larger CSE**
  - further evolved
  - higher mass-loss
- **VLBA observations**
  - Resolution of ~0.5×0.2 mas.
  - distance of 1.13±0.34 kpc (van Langevelde et al. 1990)
- **Ring pattern detected**
  - tangential amplification
  - Acceleration zone
  - 5.4 AU radius = 2 stellar radii



Amiri et al. 2011, submitted

Polarisation properties

- **Highly linearly polarised, up to 100%**
  - Complex polarisation theory
    - Nedoluha & Watson 1990
  - Vectors still trace the magnetic field
  - Magnetic field either parallel or perpendicular
- **Evidence for non-spherical signature**
  - Aligned with structure
  - Possibly aligned with 1000 AU OH structure
- **Tentative detection of circular polarisation**
  - at ~0.7% of 1.5+/0.5 G



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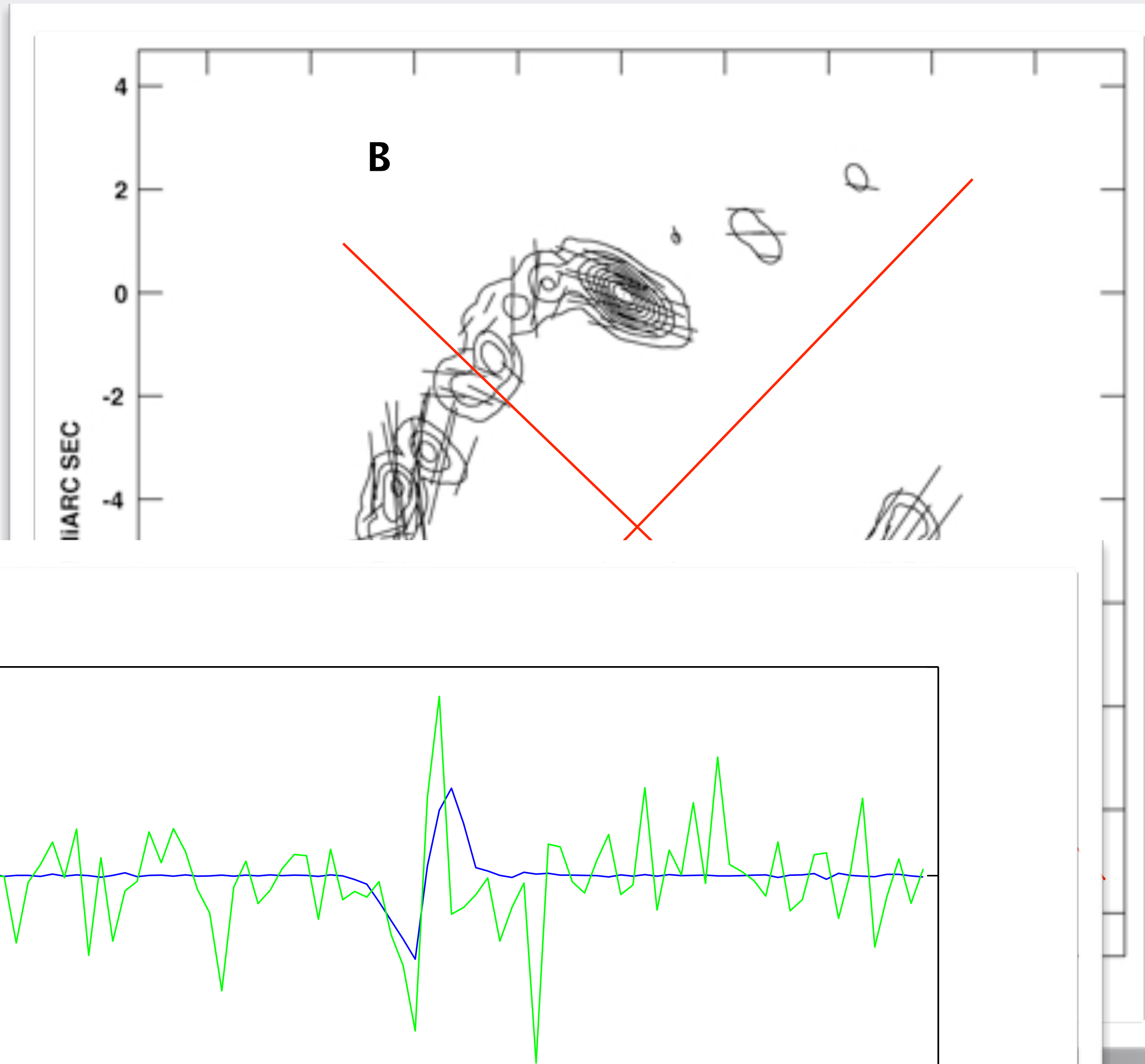

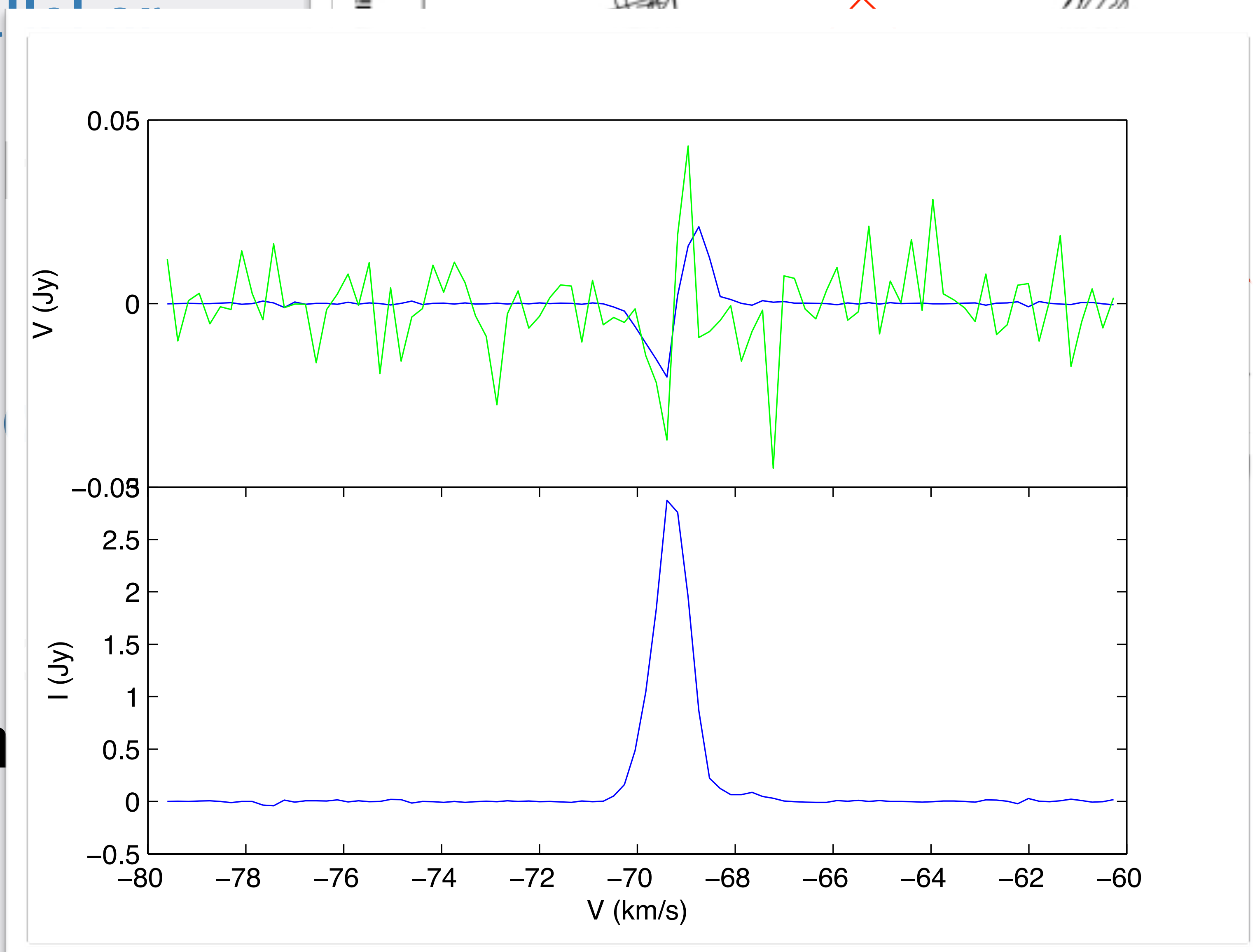

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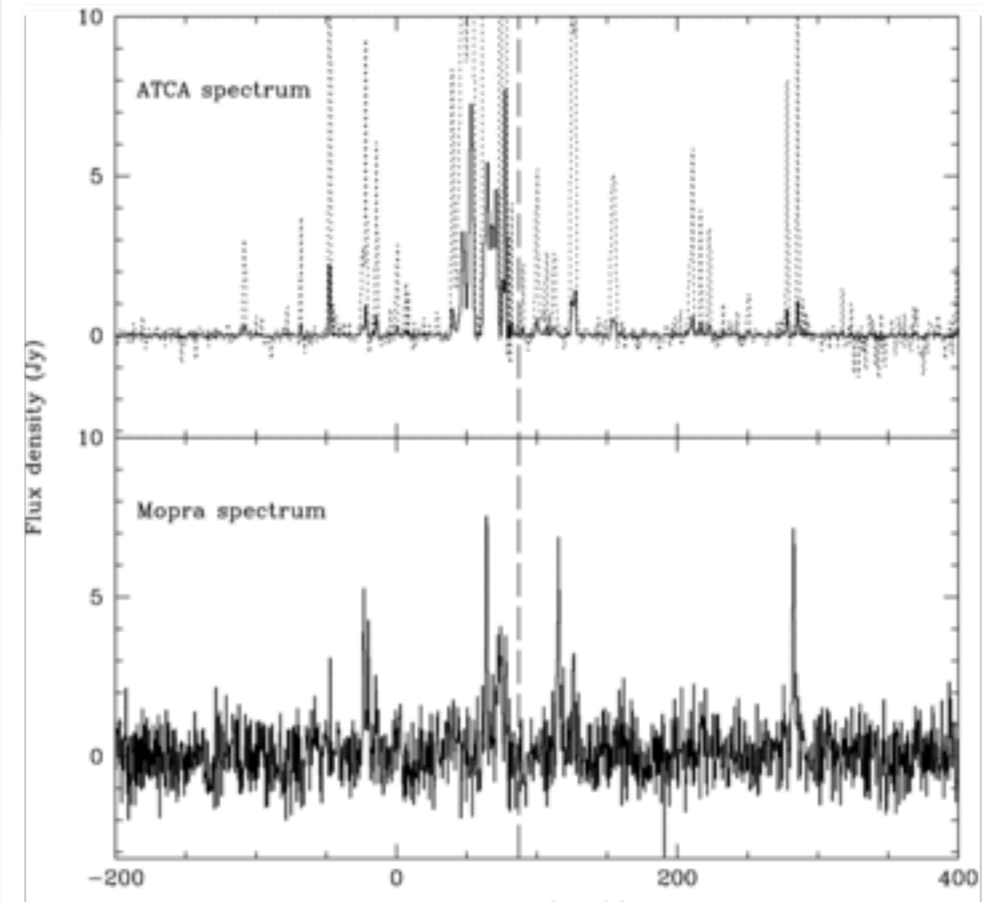
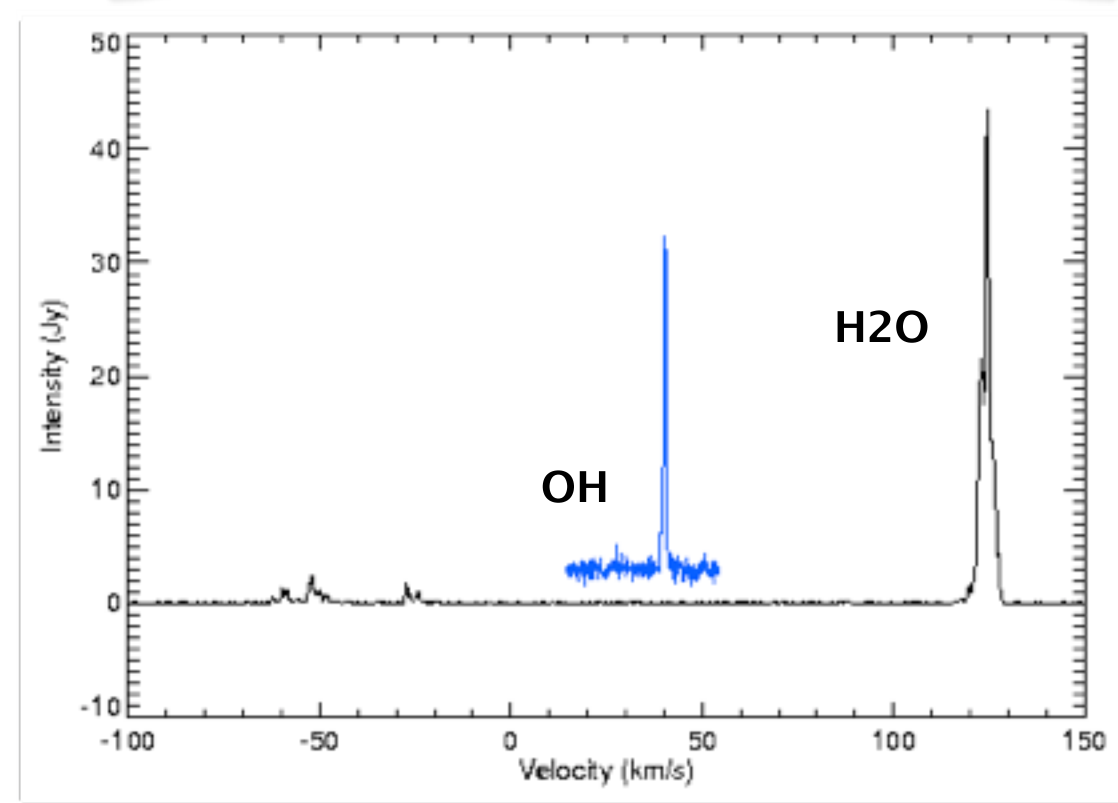
Water Fountain Sources

- Special post-AGB and PPNe objects
  - From IR characteristics
  - Defined to have high velocity water
- Relatively rare
  - So far, ~14 water fountains have
- Seemed to have jets
  - Water masers associated with shocks
- Outer OH shell still intact
  - Dynamic timescale <1000y

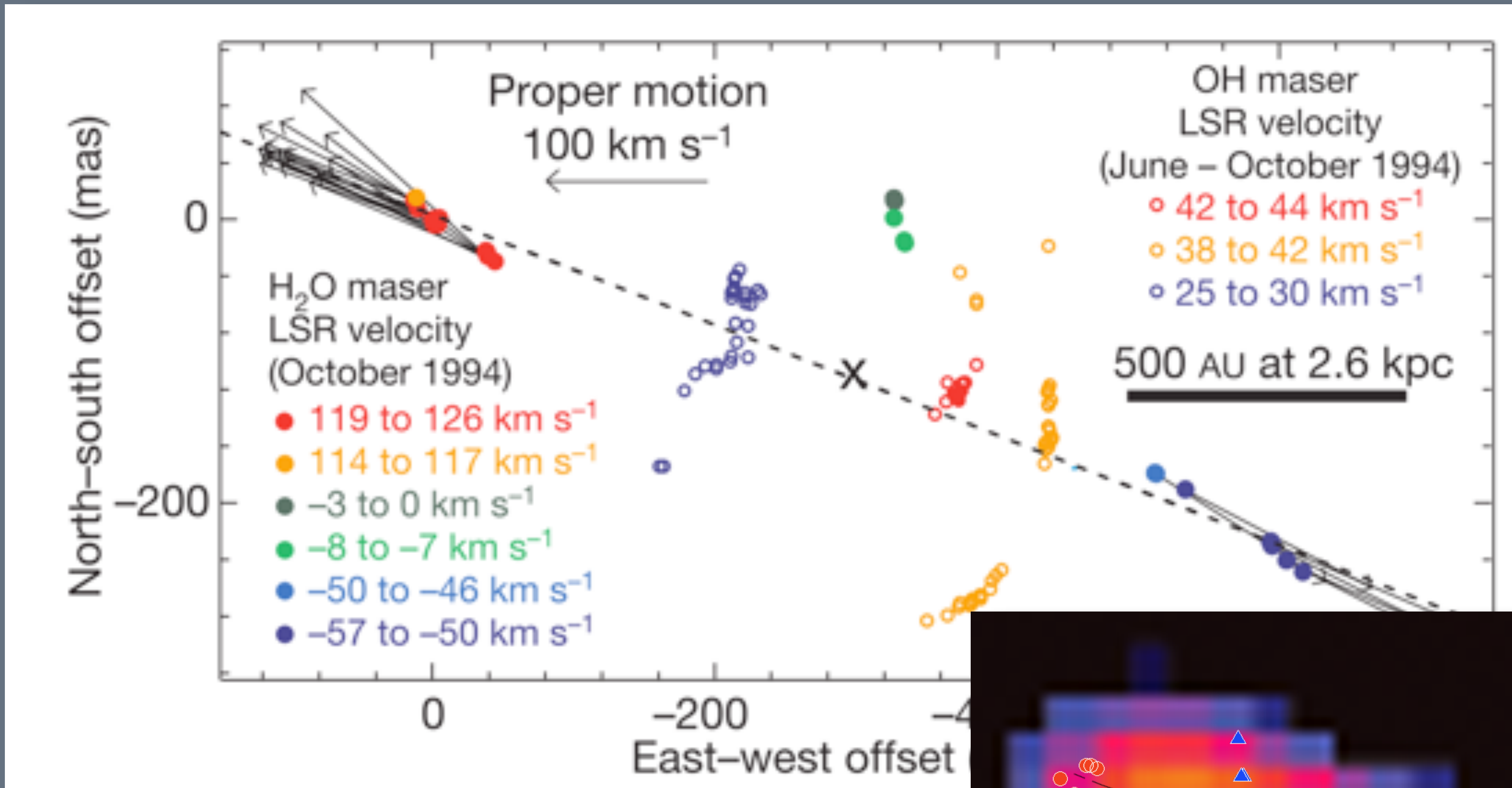


OH 009.1-0.4,Walsh et al. 2009

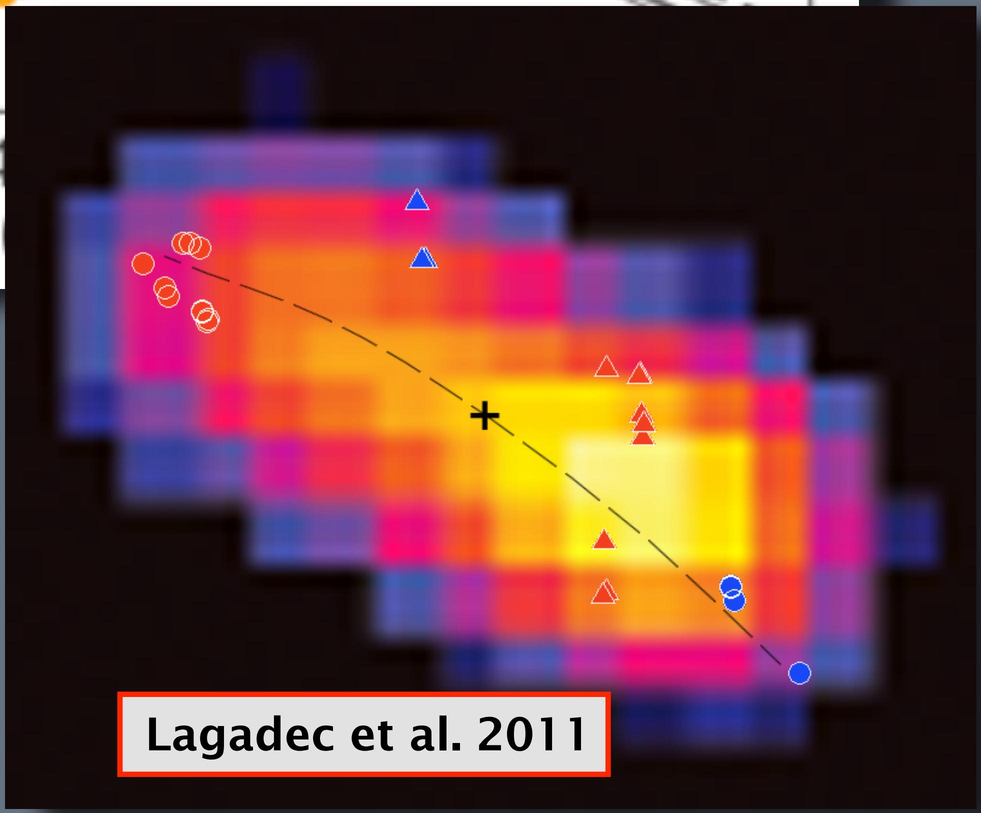


W43A, (e.g. Amiri et al. 2010)

Most famous water fountain: W43A

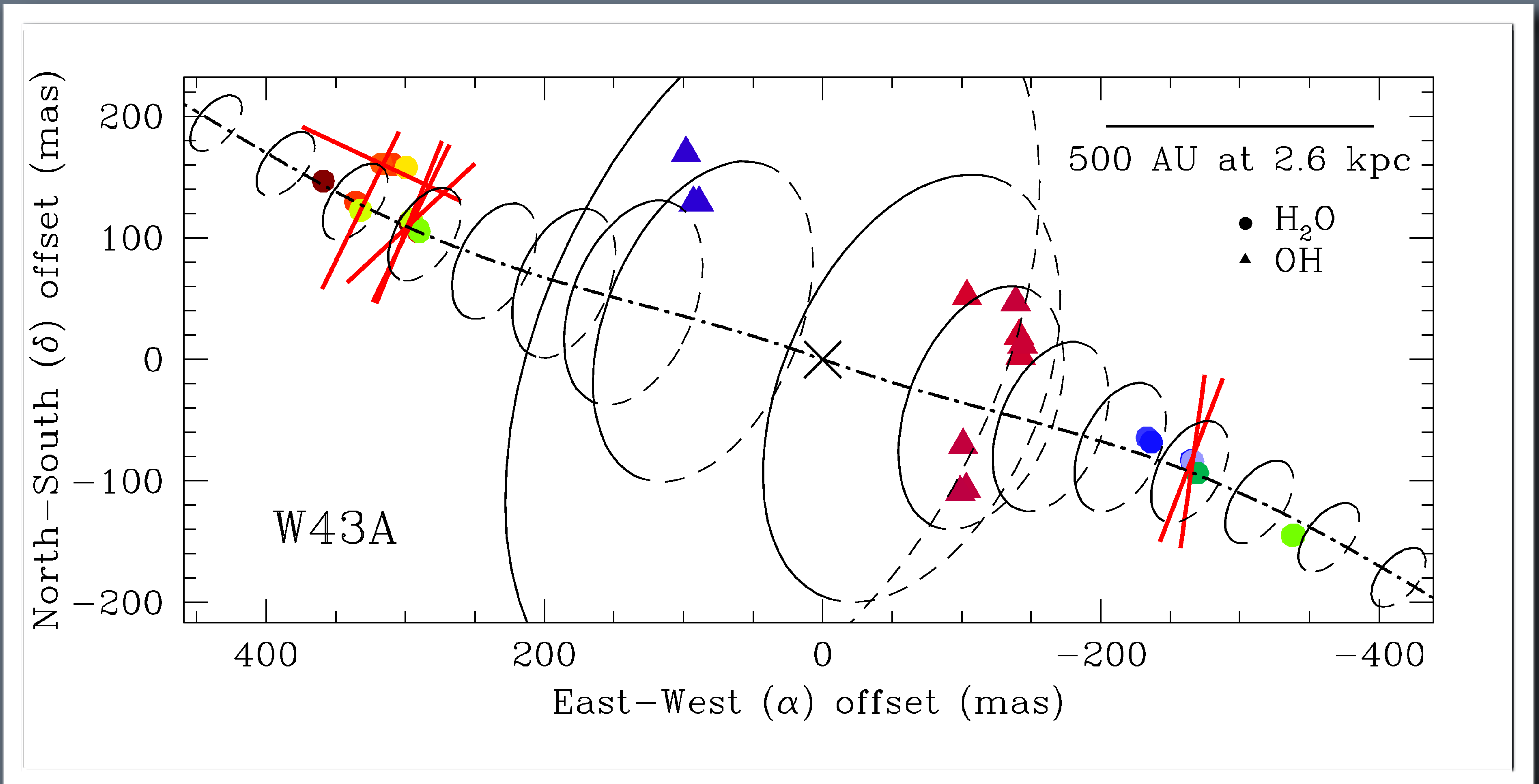


Imai et al. 2002



Lagadec et al. 2011

Toroidal, collimating magnetic field: Bϕ = 80 mG
(Vlemmings et al. 2006)



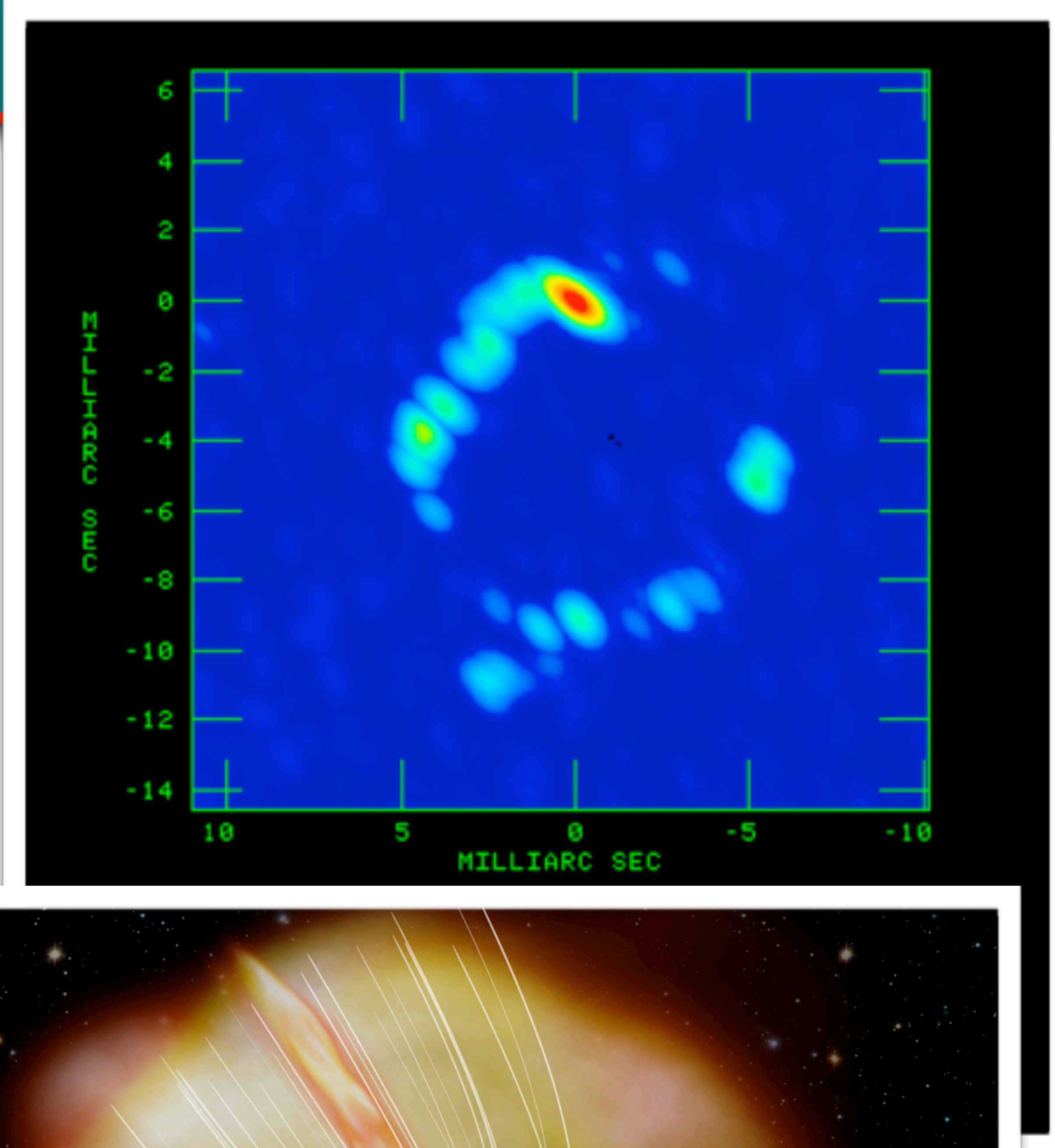
Around the jet B = 100 μG from OH masers
Amiri et al. 2010

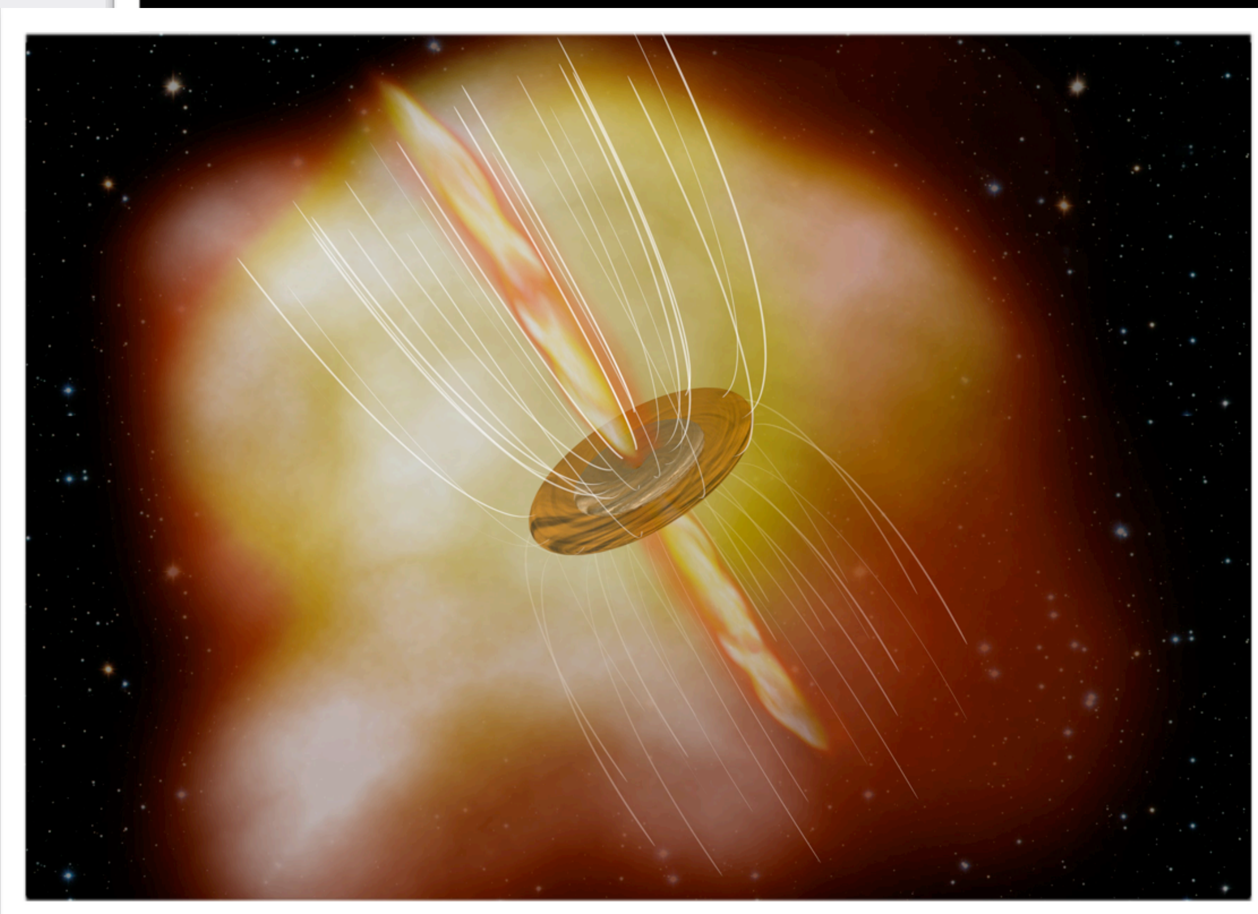
Conclusions

- Magnetic fields could have an important role in shaping the circumstellar environment of evolved stars
- OH masers show signs of aspherical expansion in water fountain sources
  - And these seem to be connected with a large-scale field
- OH/IR stars also show significant magnetic fields
- Need to do much better statistics to constrain evolution

Outline

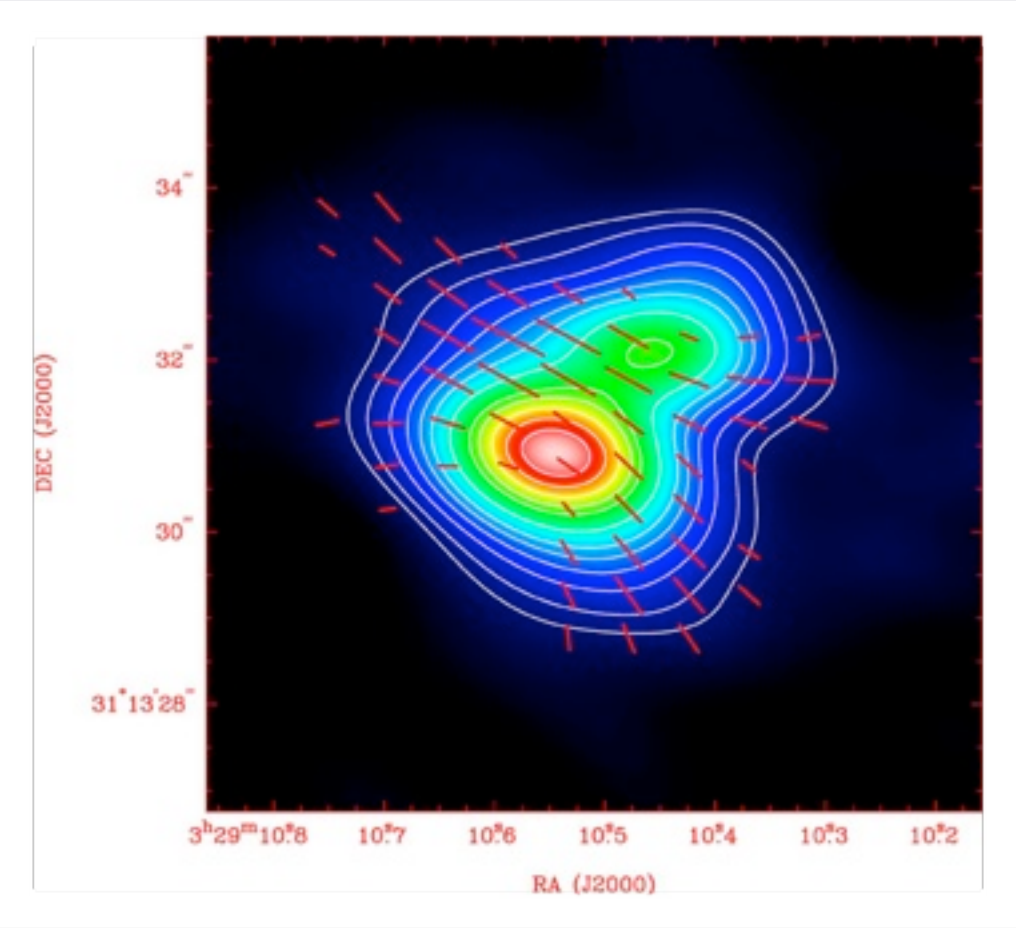
- Background
  - Masers
  - Masers and magnetic fields
  - Analysing maser polarisation
- Evolved stars
  - Open questions in evolved stars
  - Maser polarisation:
    - AGB stars
    - Water fountains/Proto-PNe
- Star-forming regions
  - Topics in high mass star formation
  - Focus on methanol masers
- Future perspectives





Magnetic fields during SF

- Do magnetic fields influence the dynamics in star-forming regions?
- Accepted for low-mass YSO
  - Magnetic fields regulate cloud collapse
  - launching outflow
  - disk support
- High-mass star-formation:
  - Scenario has been debated
    - Merging low-mass stars?
  - Recent observations of accretion disks
  - And outflows
    - Role of magnetic fields or turbulence
- Not easy accessible
  - Lots of obscuration
  - Fast time scale
  - Far away
  - But bright masers...

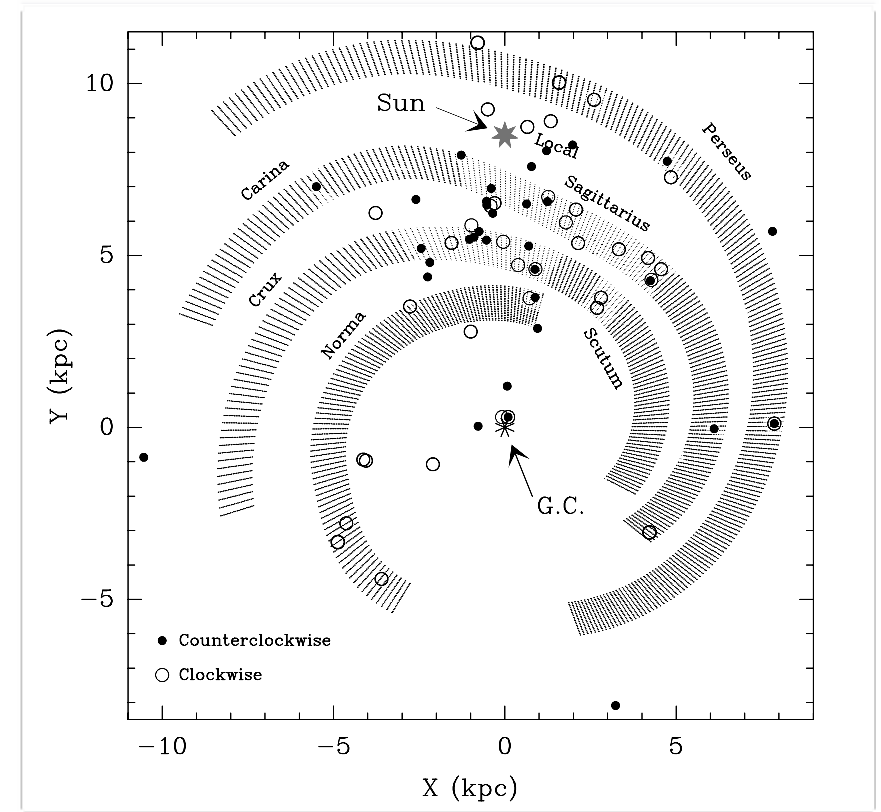


NGC 1333 dust polarisation:
Girart et al (2006) Science, 313(5788), 812

Interstellar Masers

- **Associated mostly with High Mass Star Formation**
  - Some with supernovae shocks
  - Intermittent (at best) in low mass stars

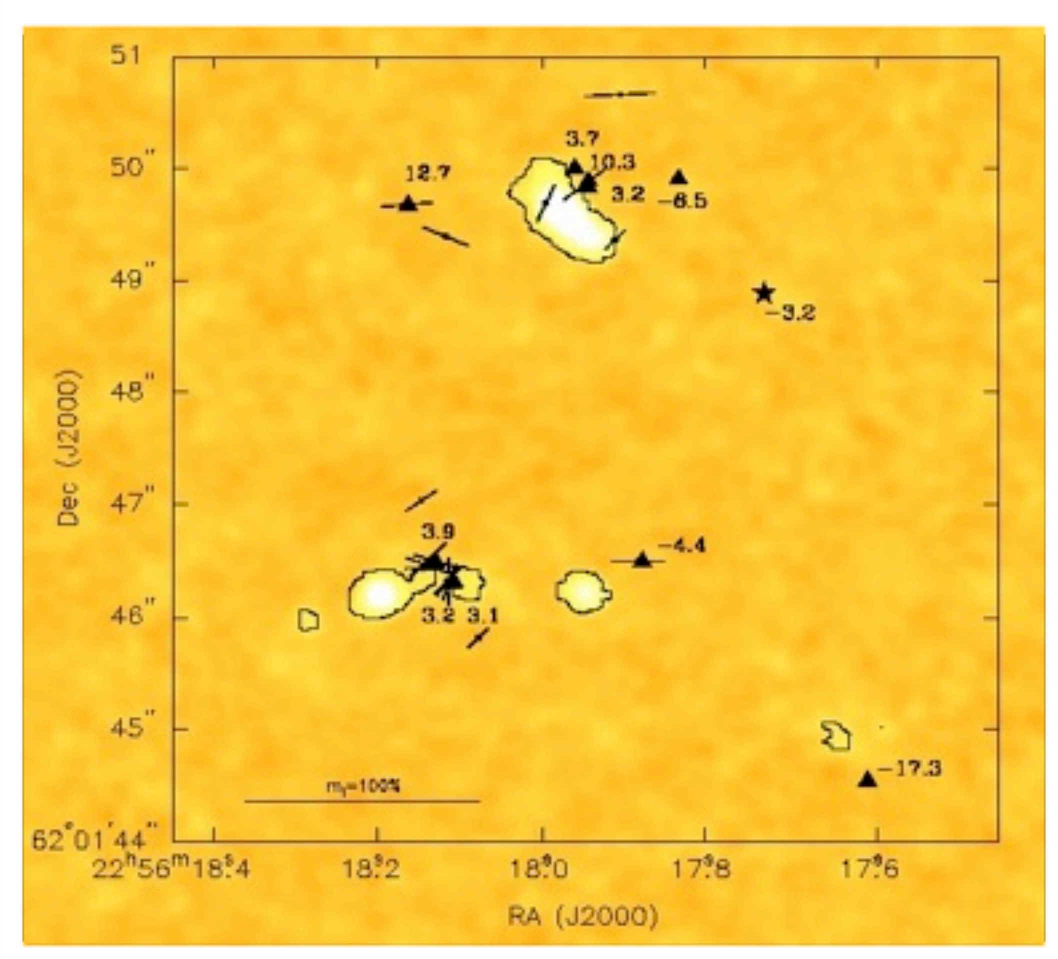
- **Typical masers environments**
  - OH (1.6 and 6 GHz)
    - Often at low densities, away from central object
    - Suffers from Faraday rotation
    - Good for mapping polarisation structure Galaxy
  - H2O (22 GHz)
    - Associated with shocks
    - Outflow and cavity walls
  - SiO (43 and 86 GHz)
    - rare, polarisation interpretation difficult
  - CH_3OH (methanol, 6.7, 12.2, 36 GHz)
    - Common MSF maser, very strong
    - Physical agent not quite clear
    - non-paramagnetic, Lande factor unknown



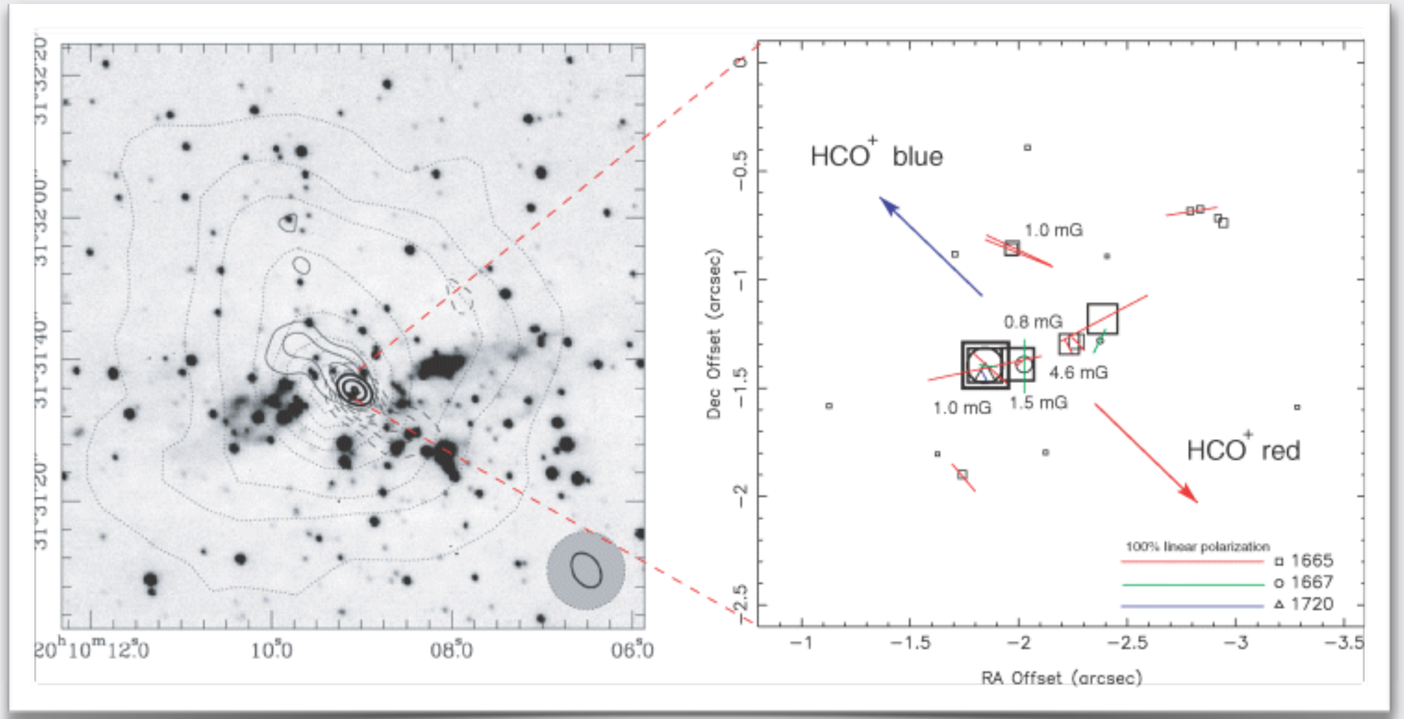
Fish et al 2003

Interstellar OH maser

- OH Zeeman |B| ≈ 1-10 mG
- Large scale structures
  - Zero or one field reversal
  - Ambient B-direction preserved
- Both σ and π components seen
  - Faraday rotation complicates interpretation
    - Internal and external



OH in Cep A
Bartkiewicz et al. 2005 MNRAS 361 623)



OH in ON1
Nammahachak et al. 2006 MNRAS 371 619

Methanol masers

- 6.7 GHz discovery only 20y ago (Menten 1991)
  - 5cm receivers on EVN offer unique coverage

- Methanol masers exclusively associated with high mass star formation
  - Small percentage of (H/U)CHII regions association
  - High mass cores in all other cases

- Not clear what the physical agent is
  - Not clear what the evolutionary stage is
  - How can we use methanol masers for understanding star formation?
  - Or for measuring the Galaxy

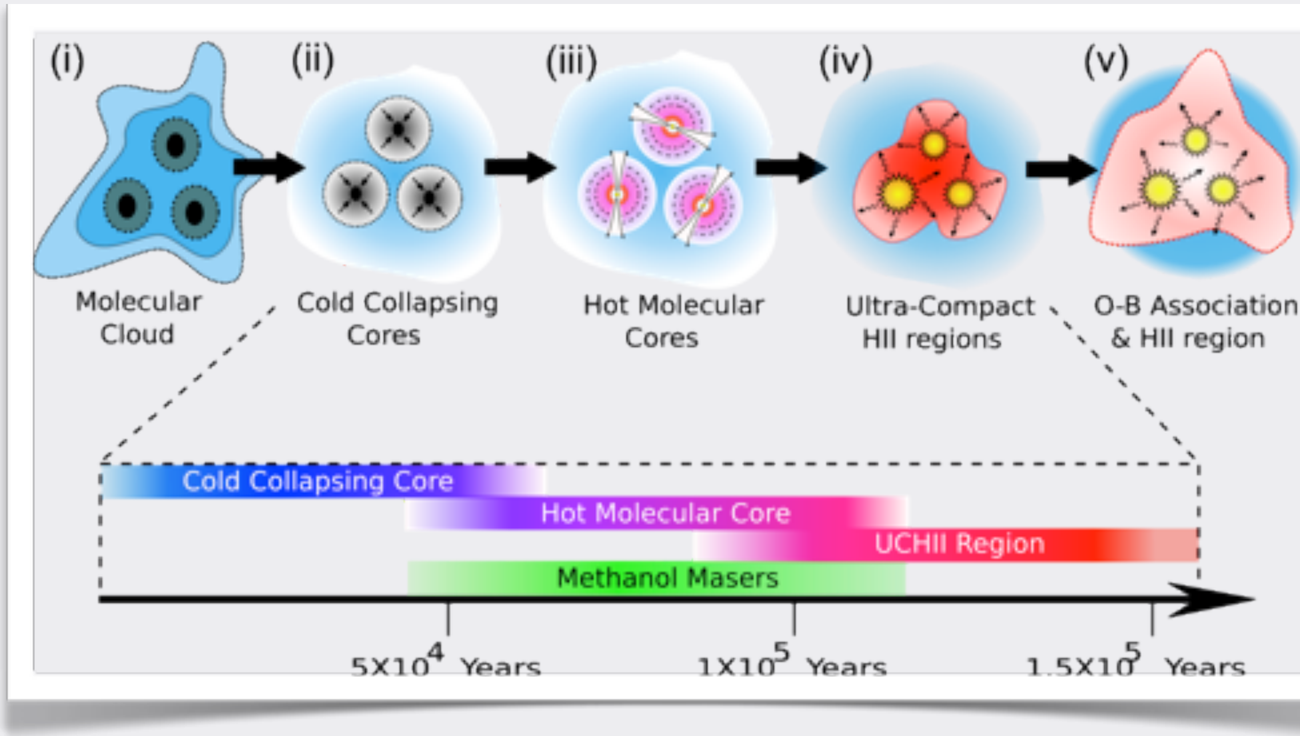
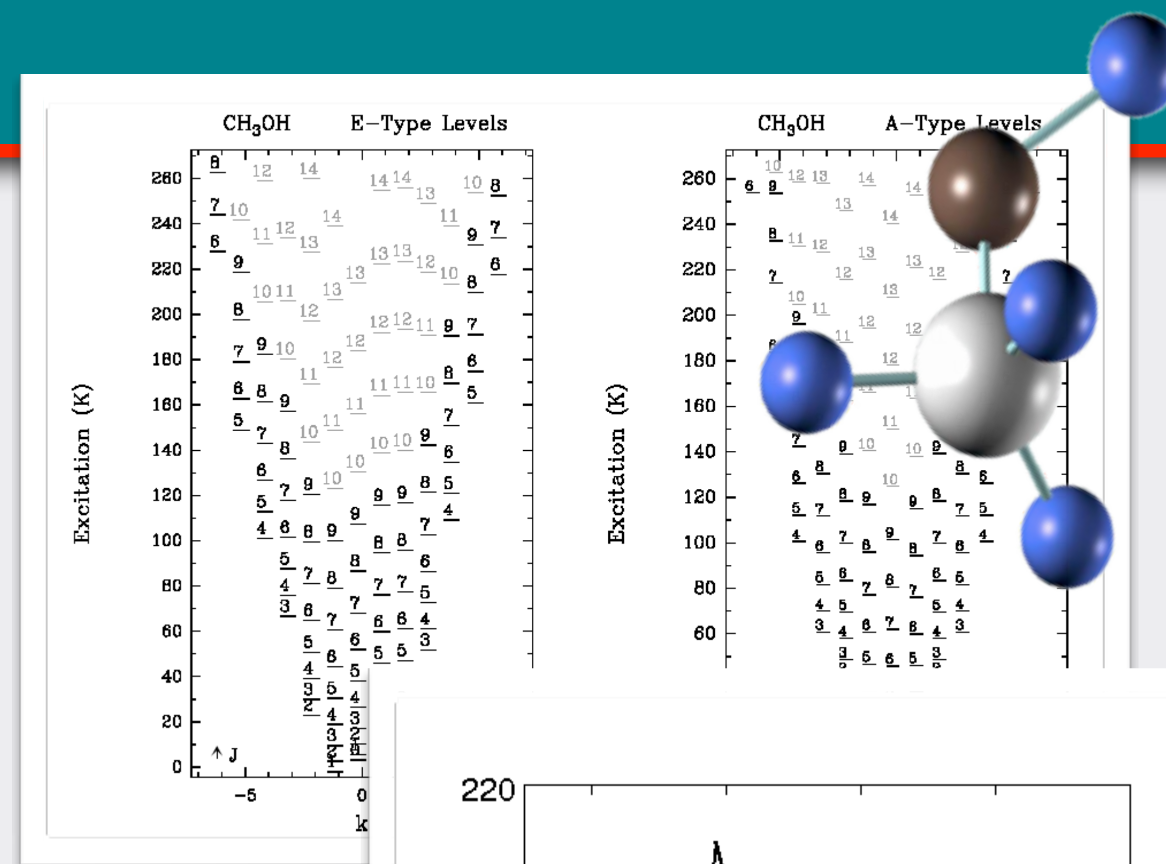
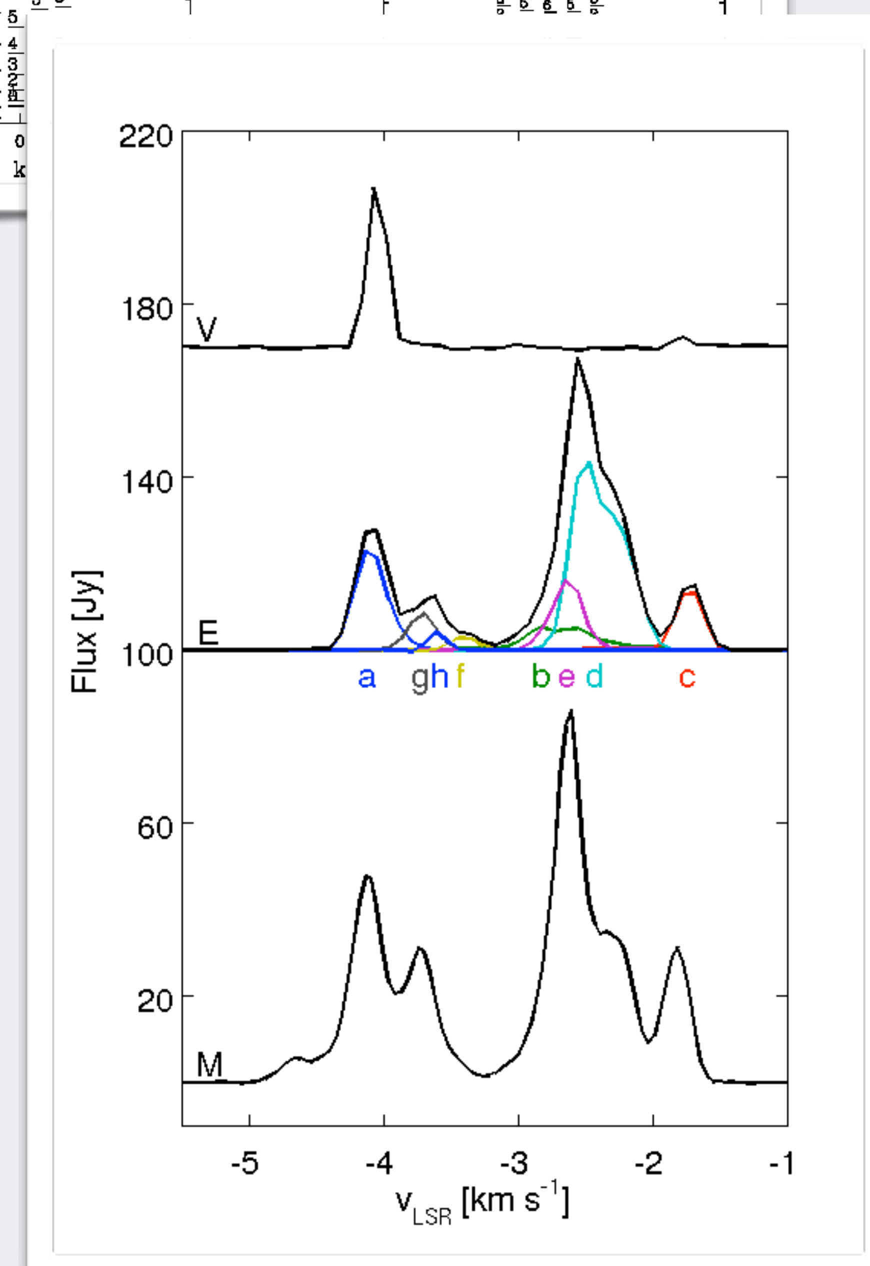


Image credit: Cormac Purcell

Methanol

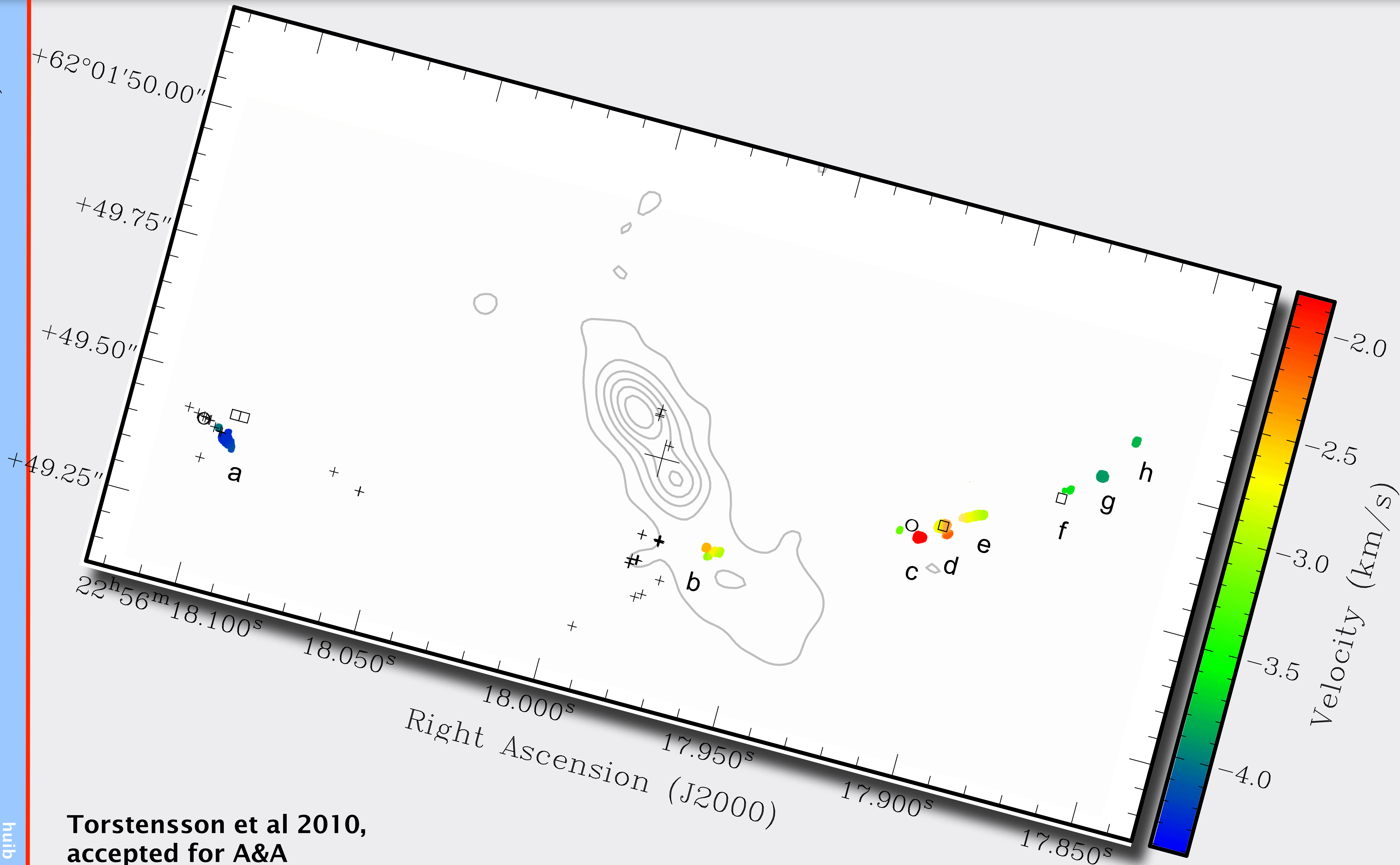


- Very rich spectrum
- Maser modelling shows (Cragg et al '05)
  - High abundance of methanol
    - Requires grain chemistry and shocks
  - T: 100-300 K
  - n: 10^4-10^9 cm^{-3}
  - For long amplification paths
  - IR from dust
- 6.7 GHz can be studied with EVN with AU resolution
  - Even if most emission resolves out
  - Trace kinematics
  - 12 GHz slightly less abundant



Cep A spectra MERLIN, EVN, VLBA (12GHz)

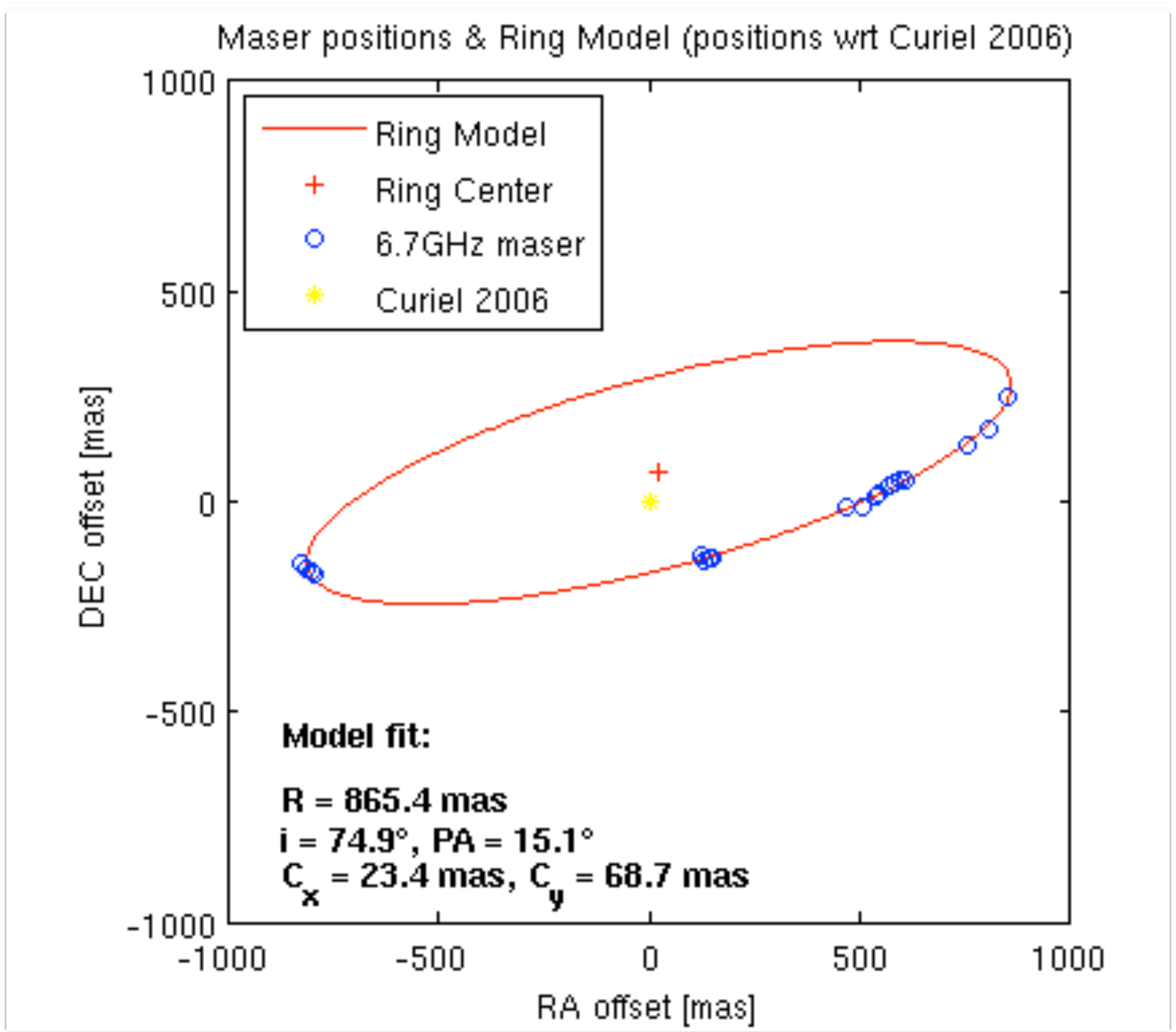
Close massive SFR Cep A

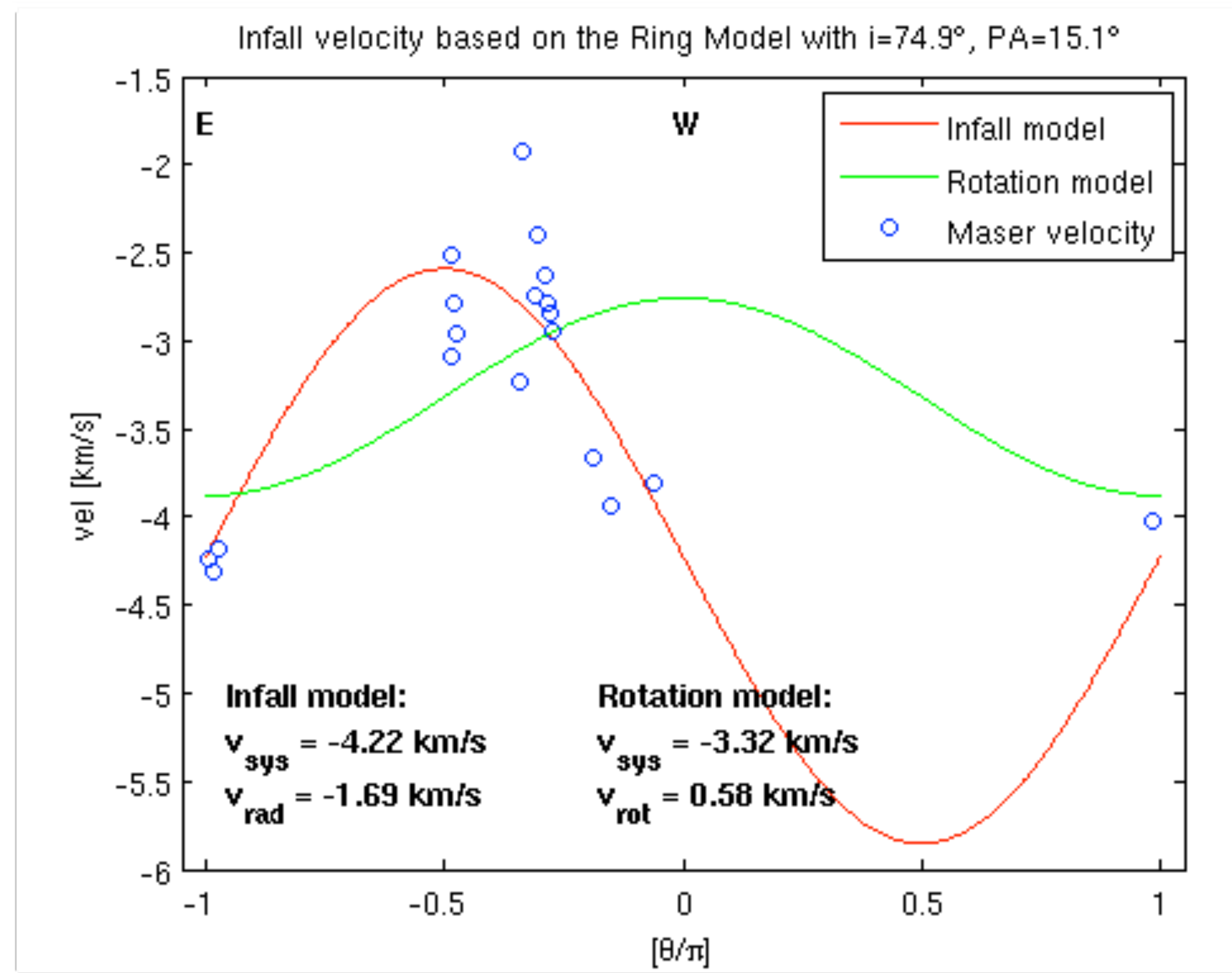


Torstensson et al 2010, accepted for A&A

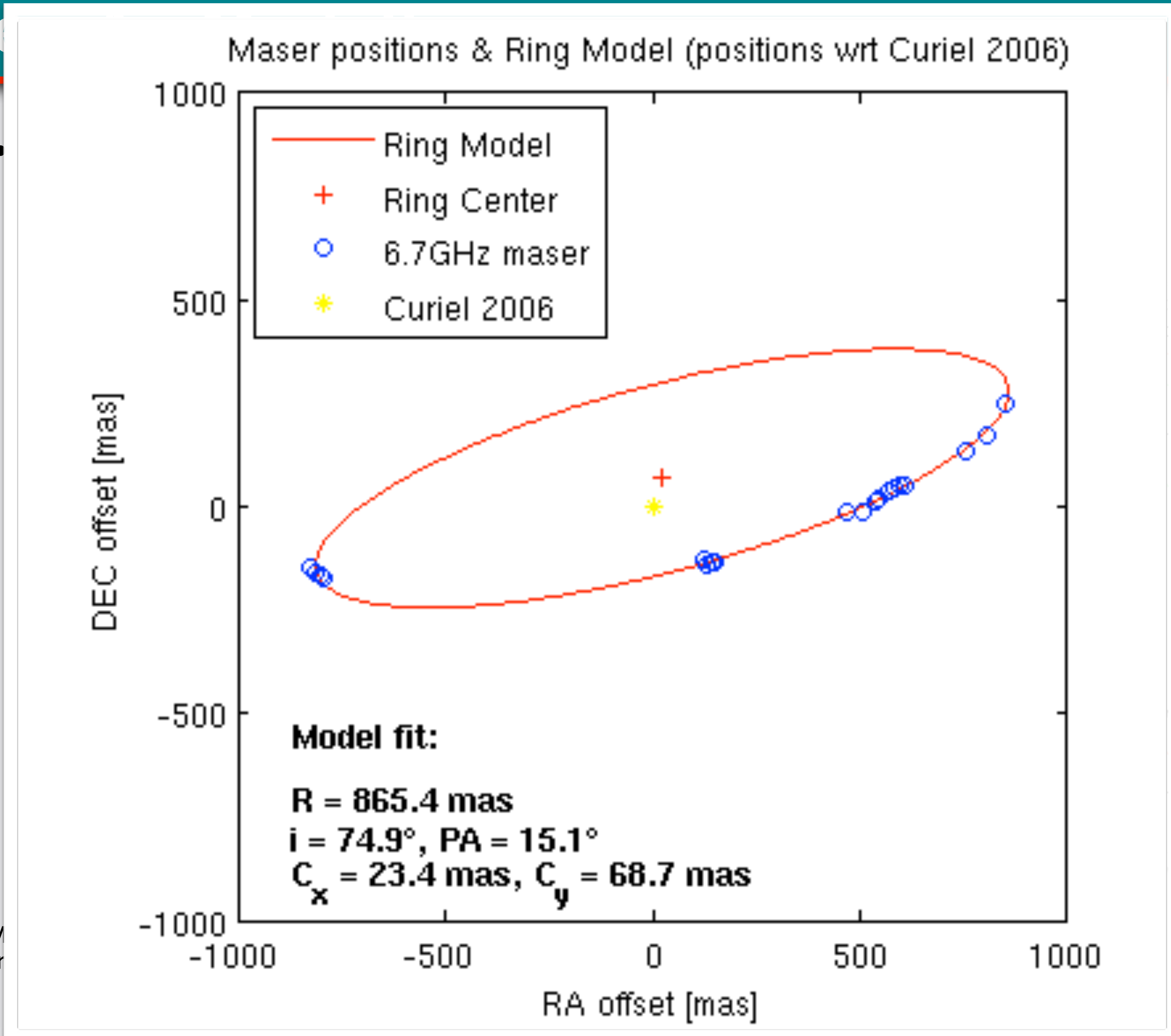
Cep A - Modelling

- **Fit ellipse to maser positions r ~ 600 AU**

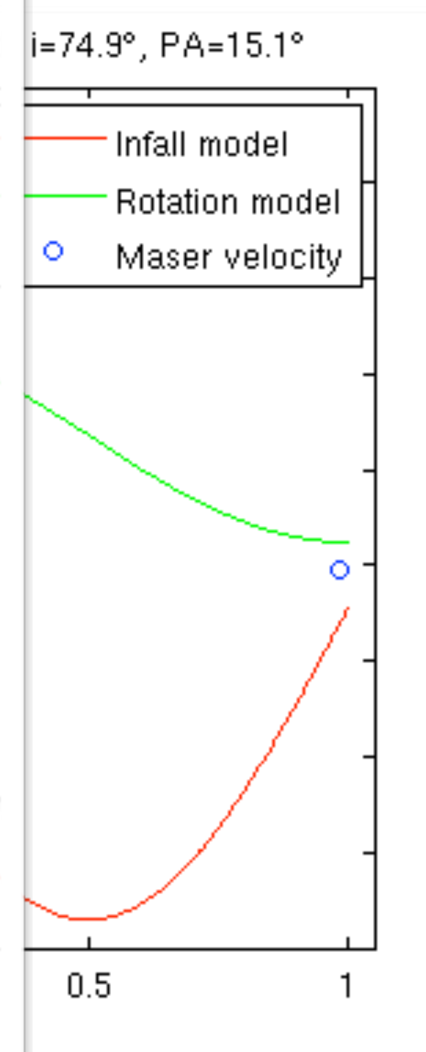




Model the velocity field based on the fit
Infall velocity of 1.7km/s



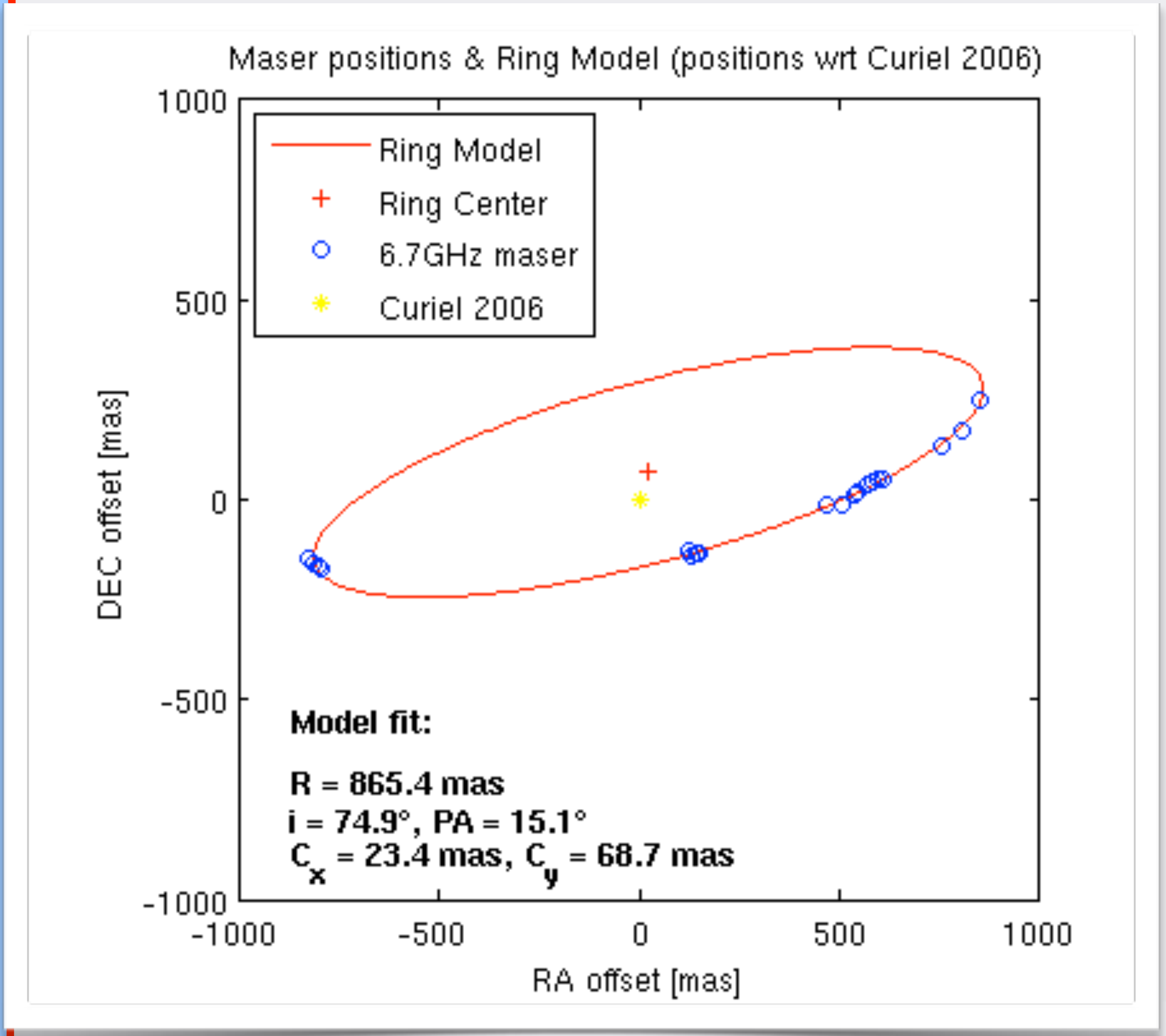
Maser positions & Ring Model (positions wrt Curiel 2006)
Ring Model
Ring Center
6.7GHz maser
Curiel 2006
DEC offset [mas]
RA offset [mas]
1000
500
0
-500
-1000
-1000
-500
0
500
1000
Model fit:
R = 865.4 mas
i = 74.9°, PA = 15.1°
C_x = 23.4 mas, C_y = 68.7 mas

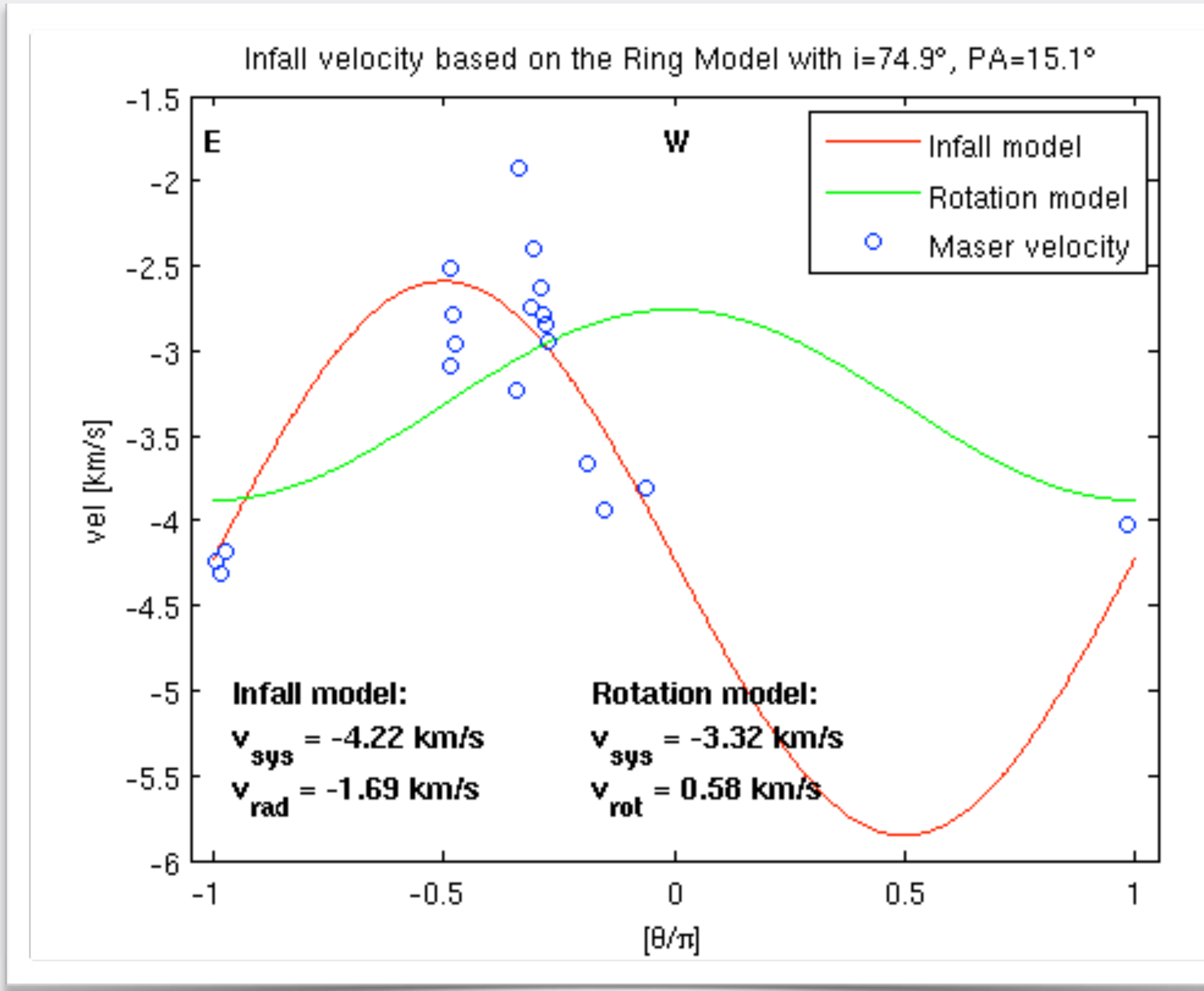


i=74.9°, PA=15.1°
Infall model
Rotation model
Maser velocity
0.5
1

Cep A - Modelling

- **Fit ellipse to maser positions r ~ 600 AU**





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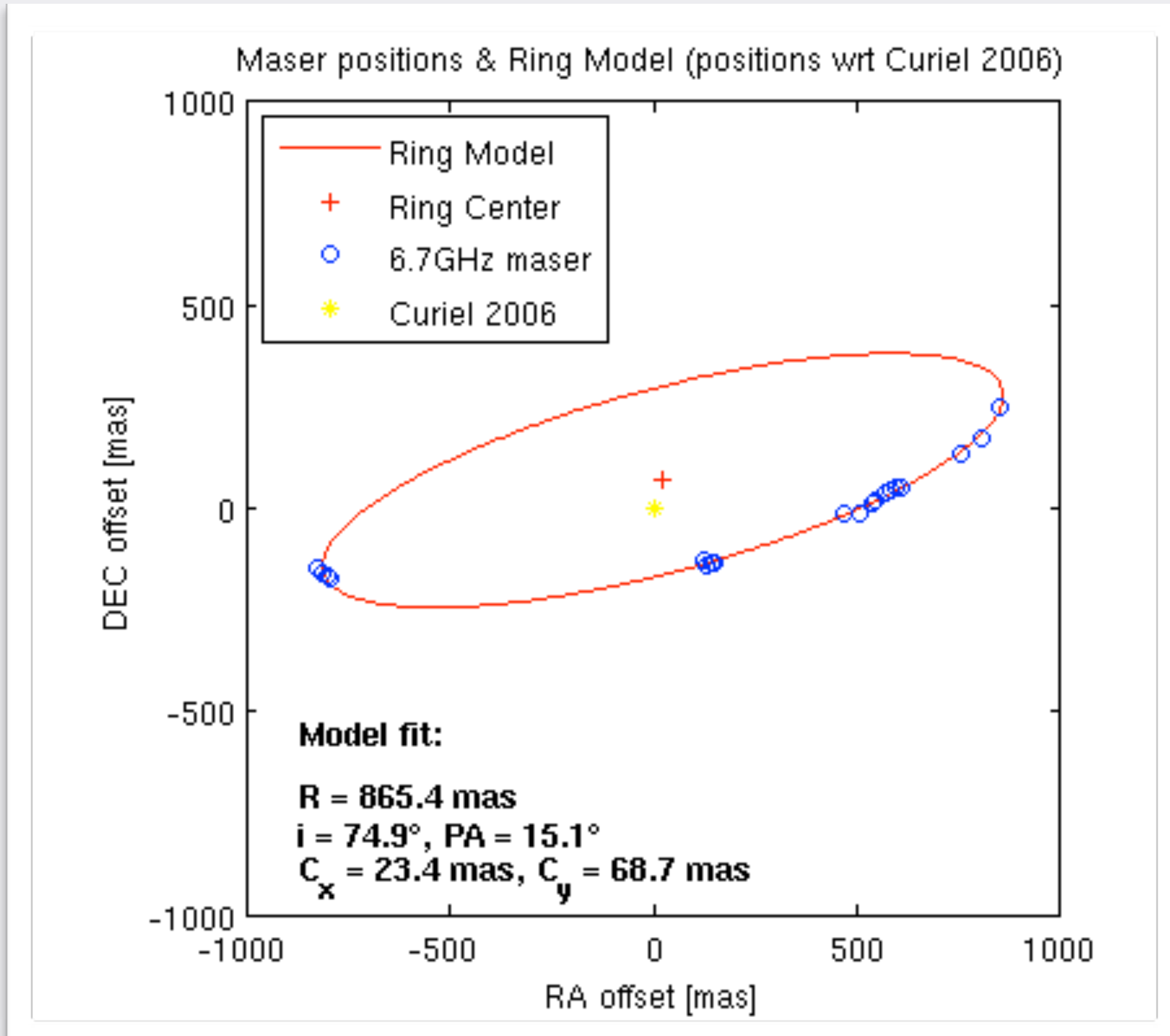
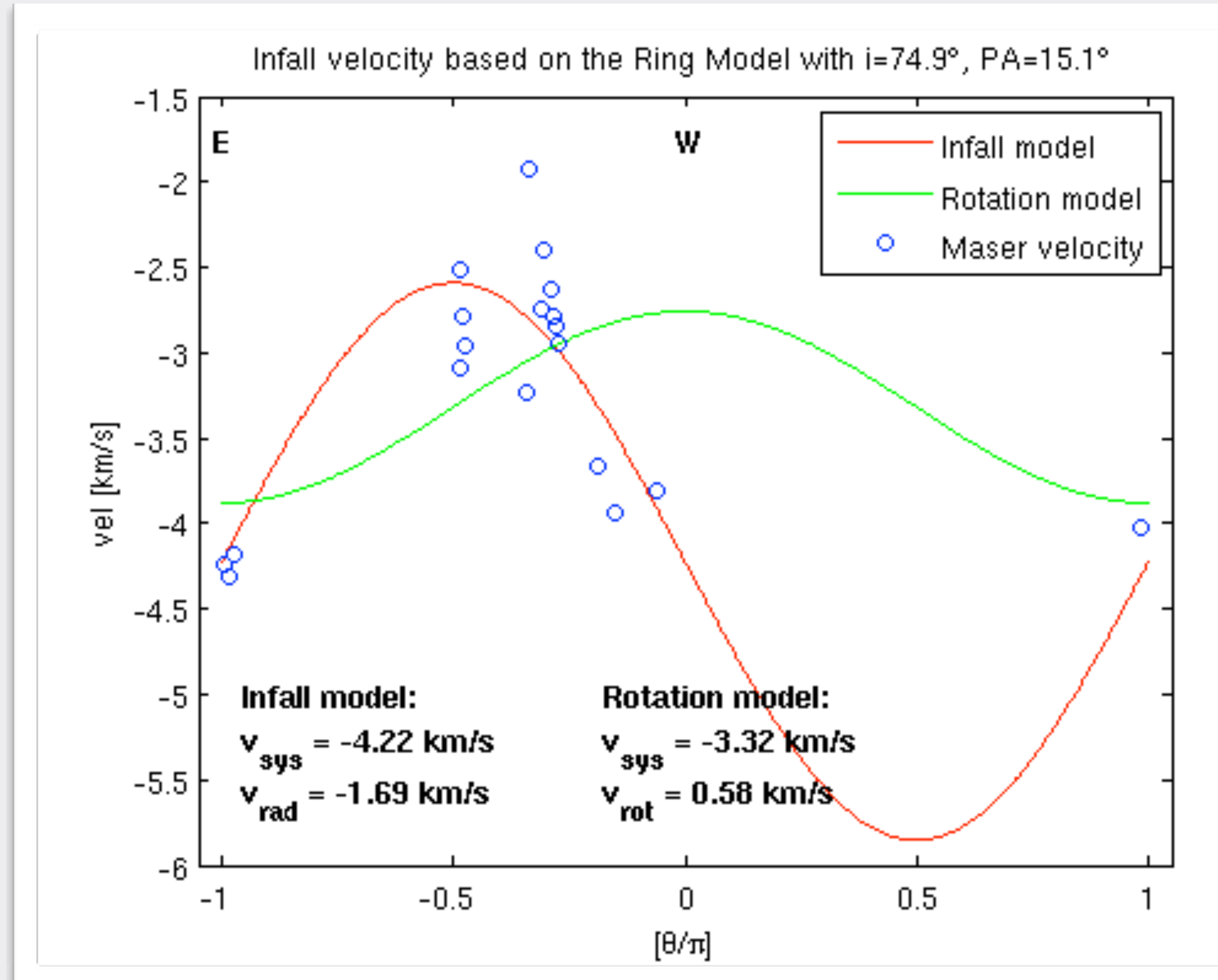
Infall velocity of 1.7km/s

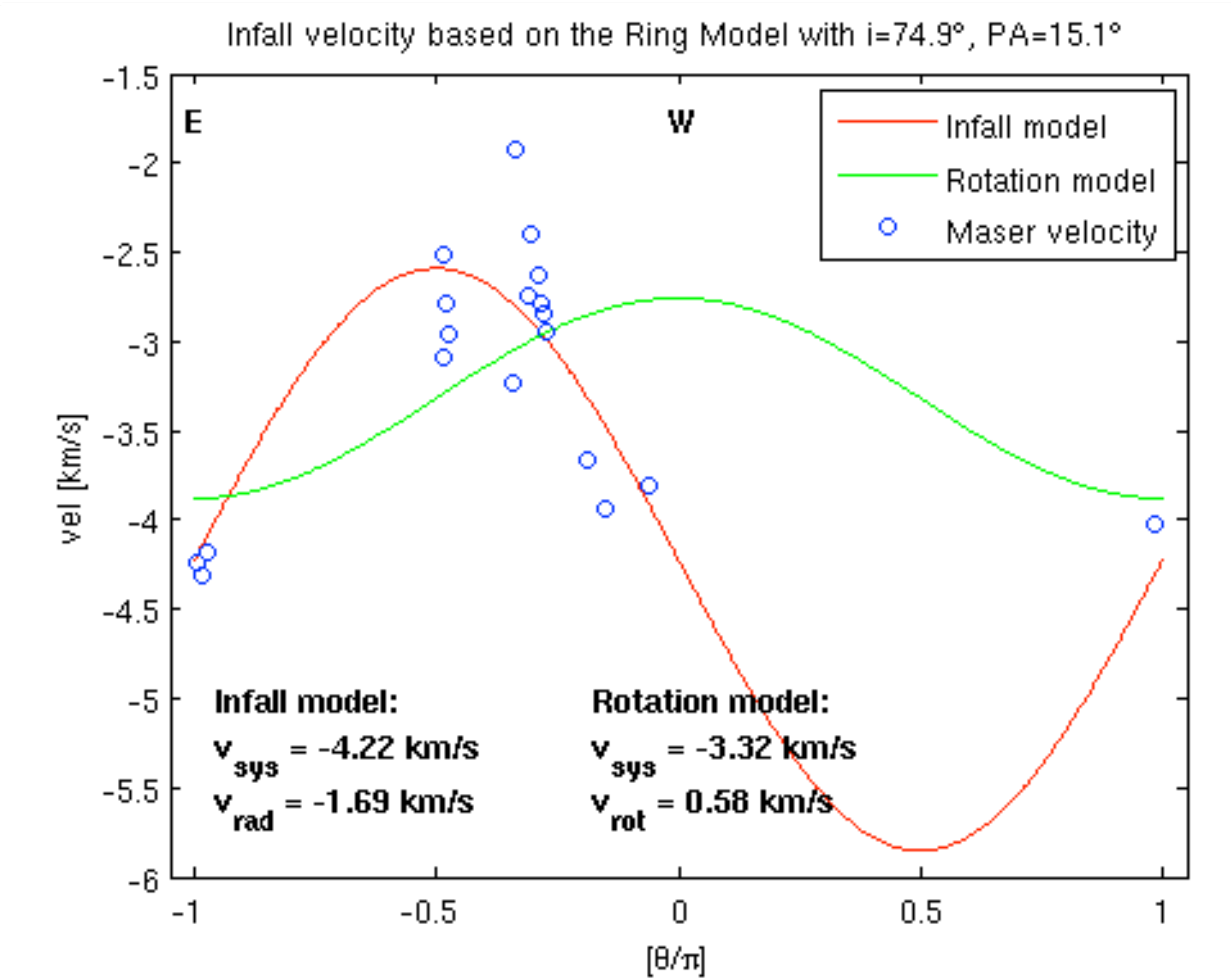
Cep A - Modelling

- **Fit ellipse to maser positions r ~ 600 AU**



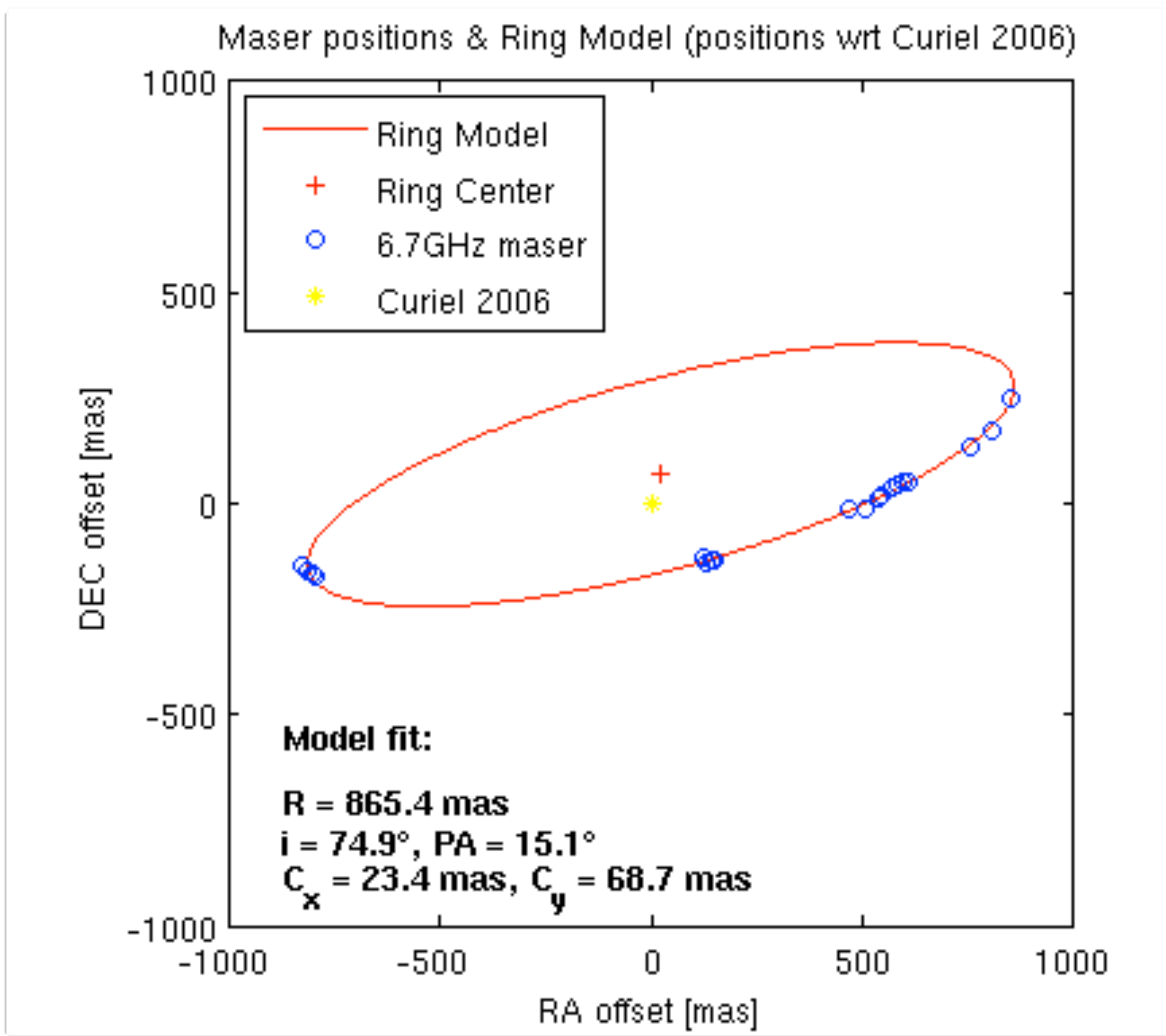


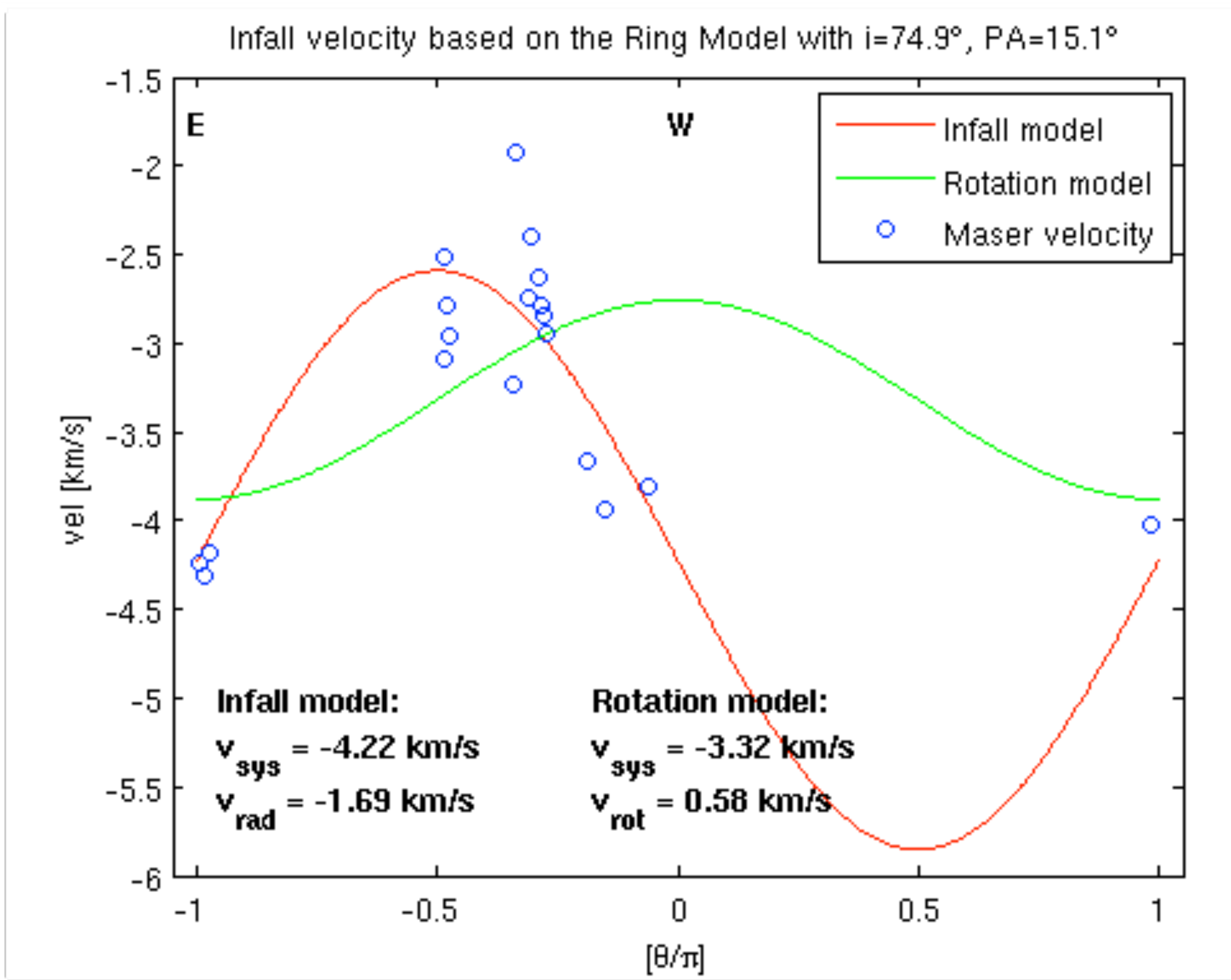
Model the velocity field based on the fit
Infall velocity of 1.7km/s


Infall velocity based on the Ring Model with i=74.9°, PA=15.1°
E
W
Infall model
Rotation model
Maser velocity
vel [km/s]
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
-1
-0.5
0
0.5
1
[θ/π]
Infall model:
v sys = -4.22 km/s
v rad = -1.69 km/s
Rotation model:
v sys = -3.32 km/s
v rot = 0.58 km/s

Cep A - Modelling

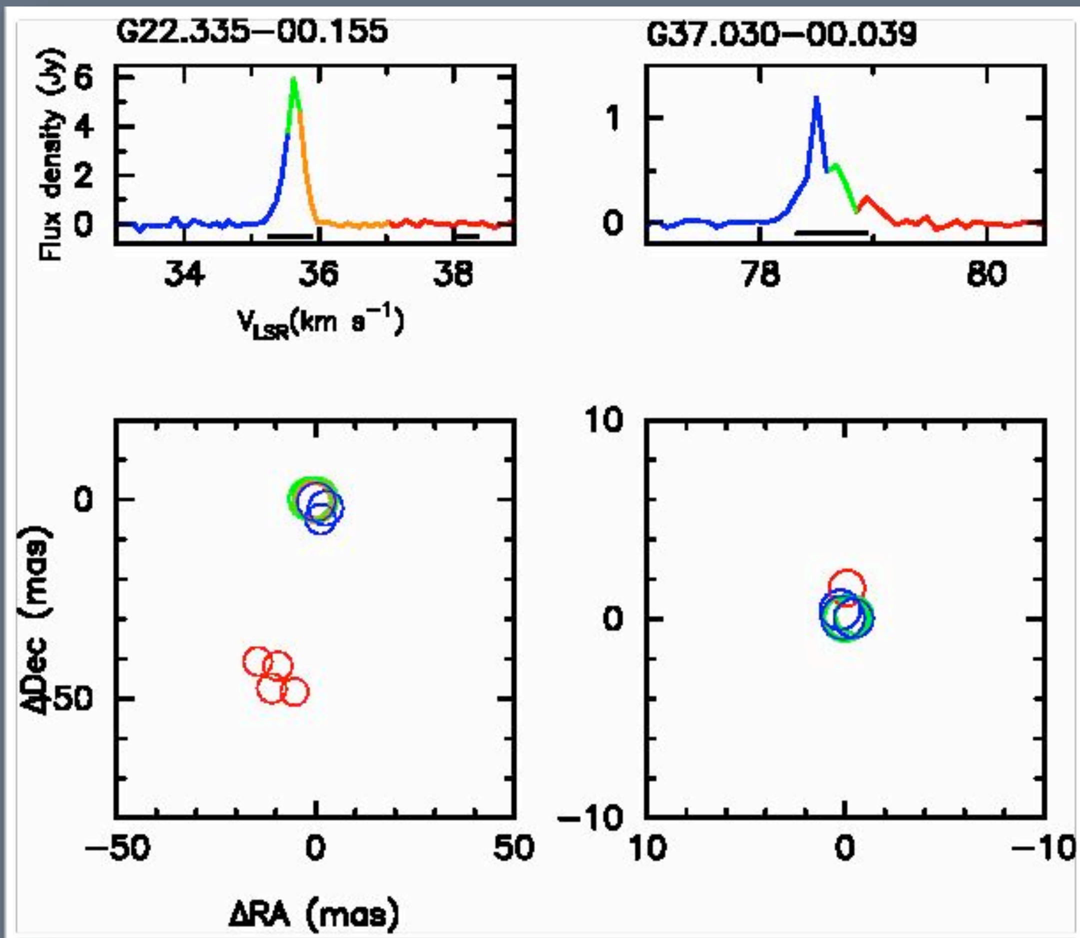
- **Fit ellipse to maser positions r ~ 600 AU**



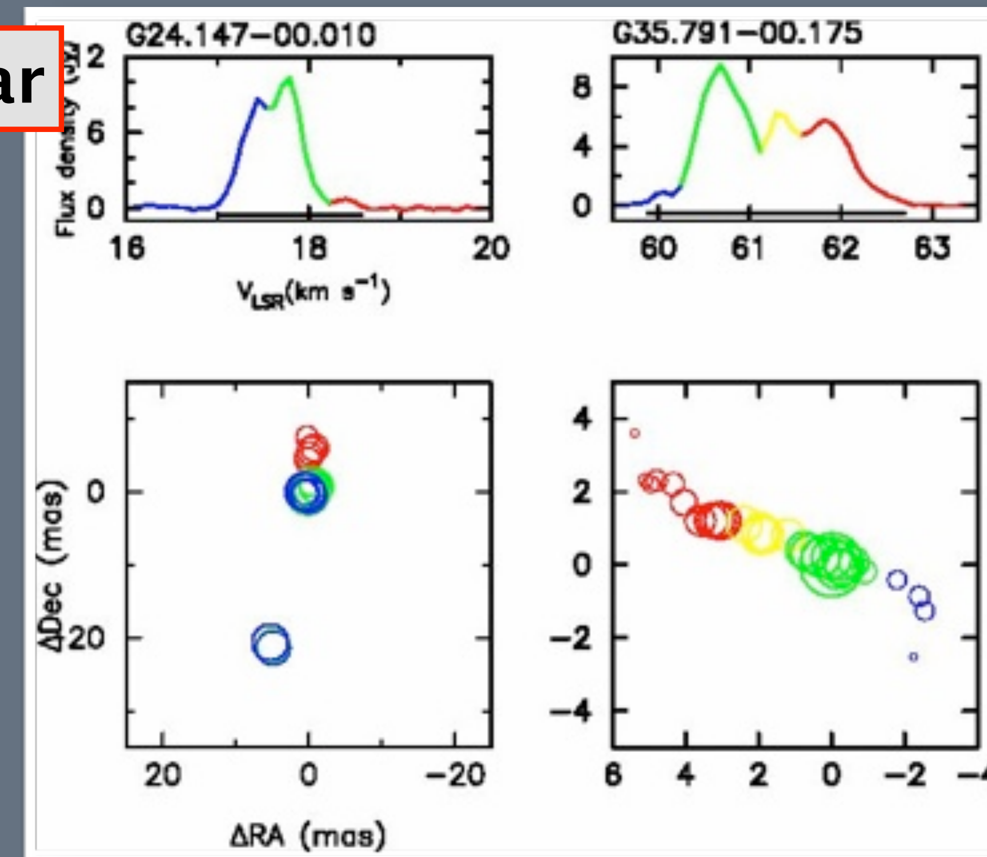


Model the velocity field based on the fit
Infall velocity of 1.7km/s

9.5% simple

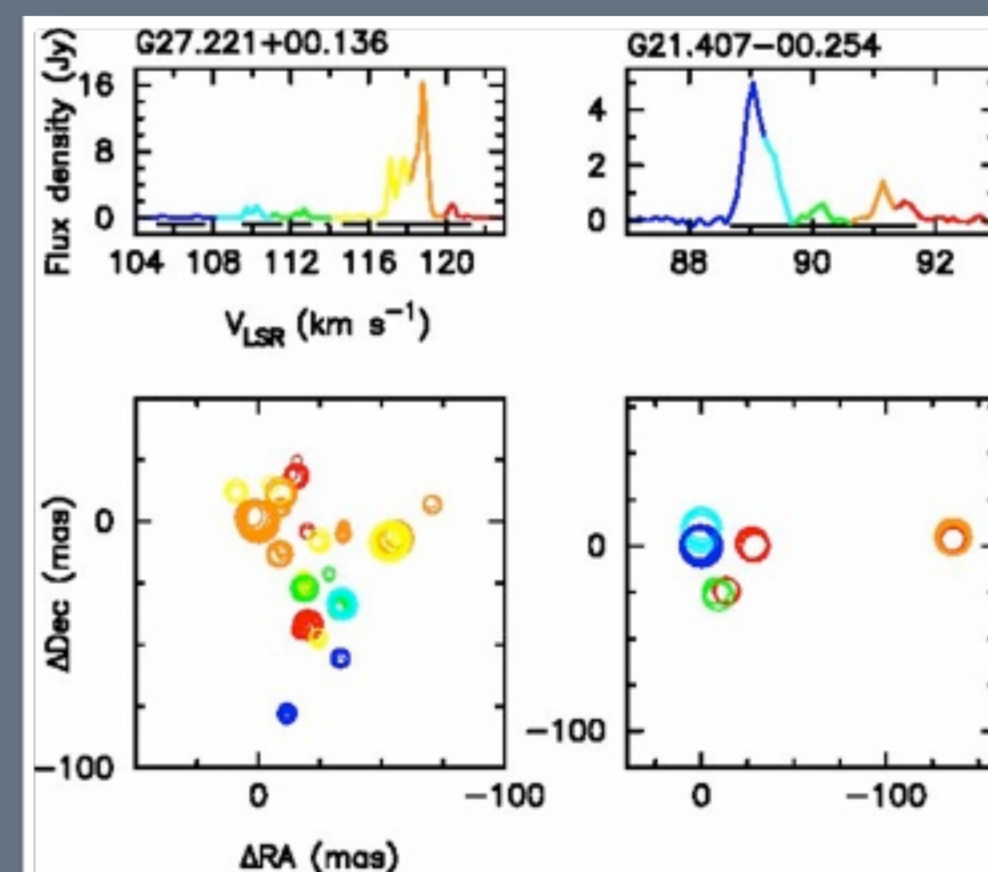


9.5% linear



6.5% triple, 9.5% arcs, 3% pairs

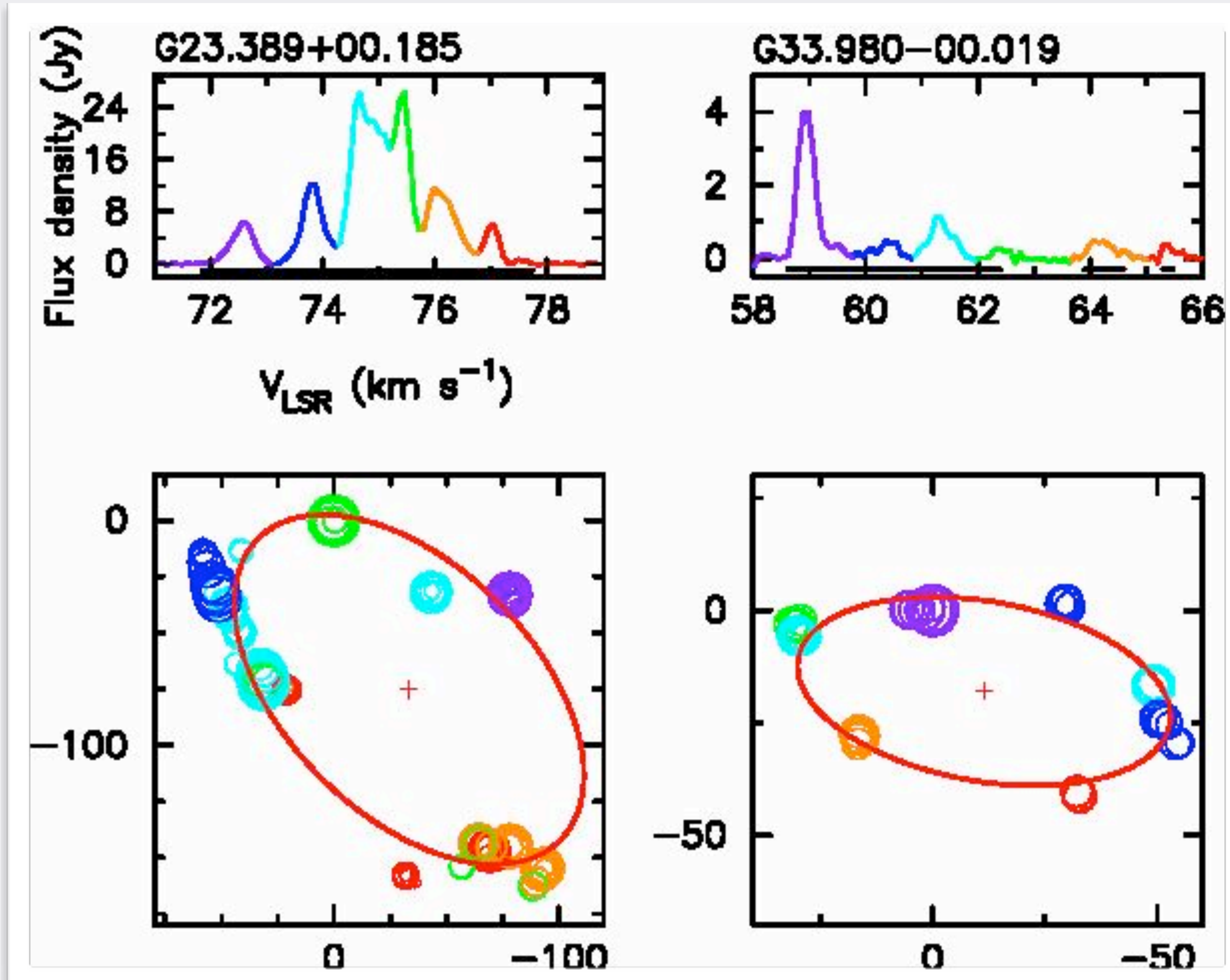
23% complex



Important EVN result

- 9/31 (30%) masers look elliptical
  - From blind maser survey
  - EVN sensitivity and 8 station imaging

Bartkiewicz et al 2009,
A&A 502 155



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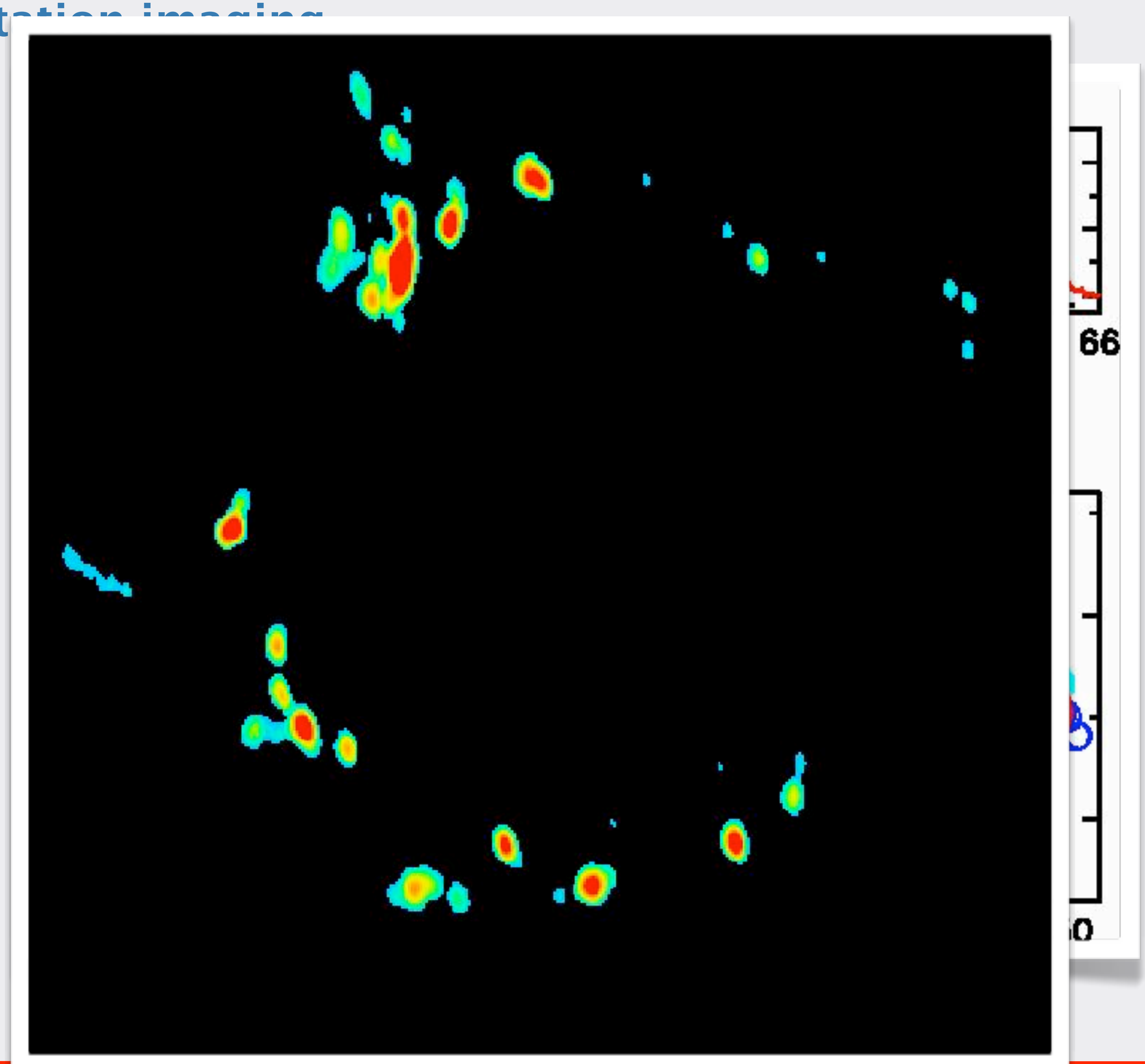
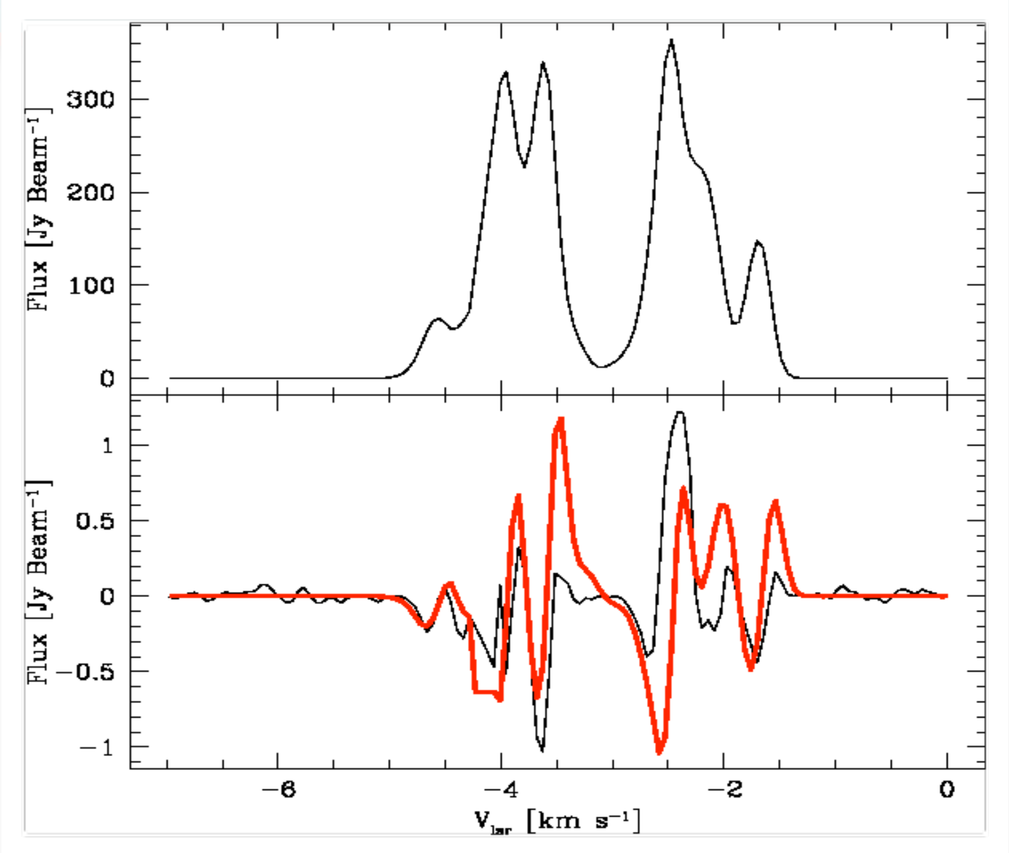


Bartkiewicz et al 2009, A&A 502 155

Bartkiewicz et al 2005, A&A 442 L61

Methanol Masers

- **Non-paramagnetic:**
  - Zeeman splitting << doppler line-width
  - Using g-Landé estimated
  - from 25 GHz laboratory (Jen 1951)
  - And subject to discussion
    - Orders of magnitude accurate at best
- **Linear polarization weak**
    - Ellingsen 2002; Vlemmings et al. 2006; Dodson 2008
  - Typical 2-3% for 6.7 and 12.2 GHz masers
  - Analysis requires maser radiative transfer
- **Zeeman splitting subtle...**
  - SNR > 5000 needed to detect mG fields
    - ≈ 5 $ms^{-1}G^{-1}$ (recent correction Vlemmings et al 2011 AA 529 A95)
  - Strong masers (>50Jy)
  - Big Effelsberg 100m telescope
  - Pioneered by Vlemmings 2008

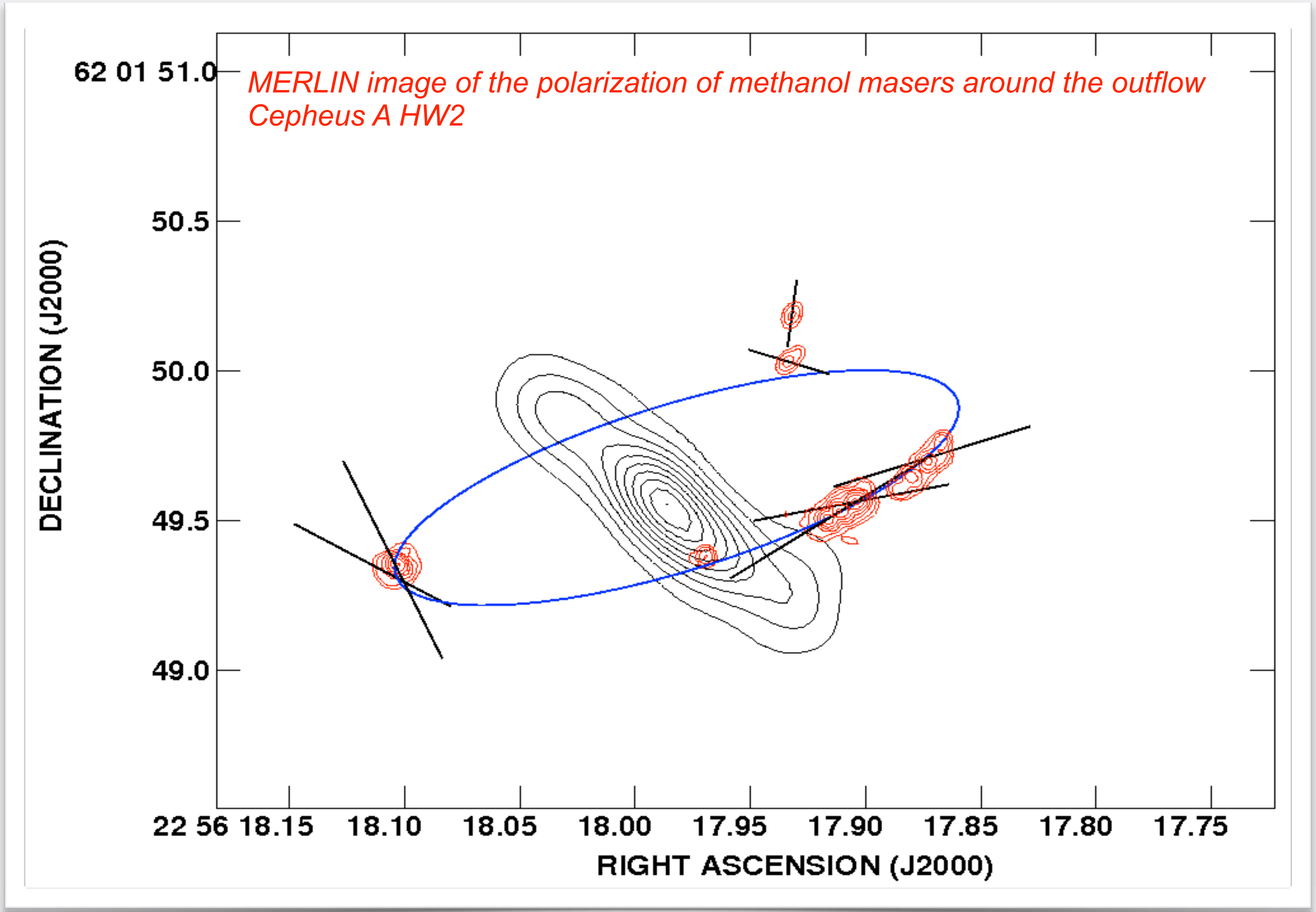


Cep A with Effelsberg
Vlemmings 2008 A&A 484 773

huib 25/08/11

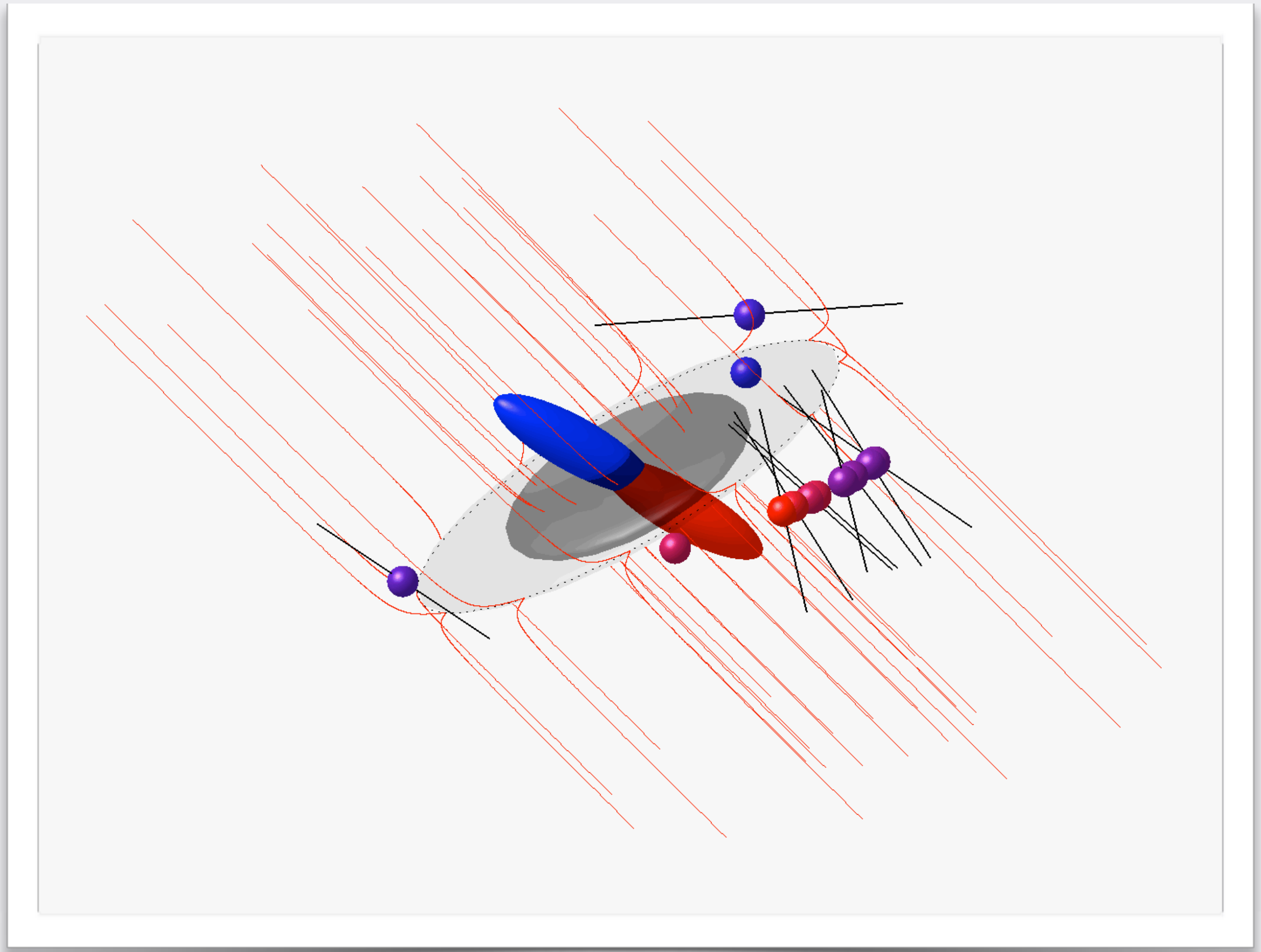
Pre-shock, post-shock, spurs

- **Gravity is not the dominant force at maser location**
  - So what is?
  - Thermal pressure, radiation pressure, magnetic fields?



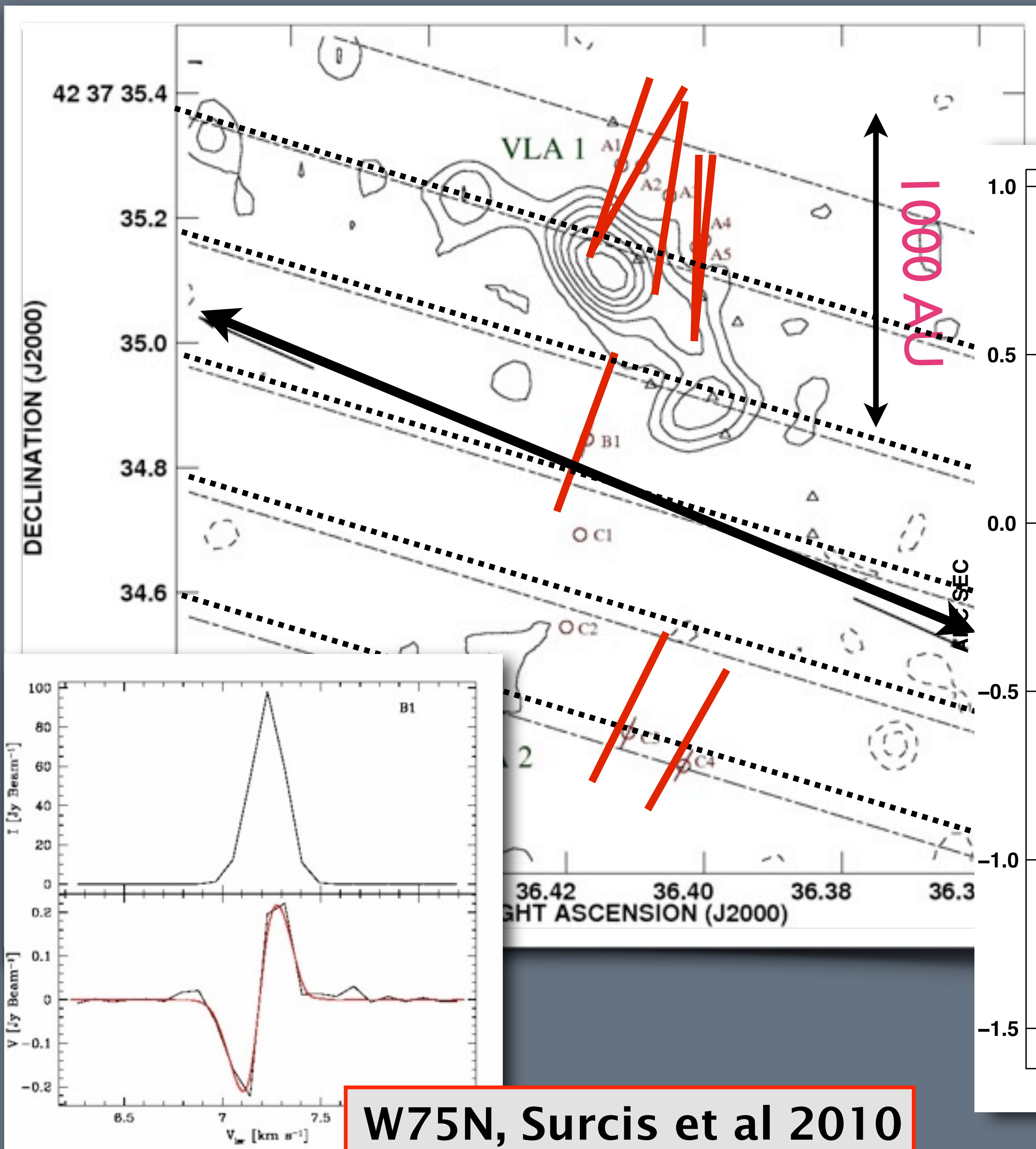
Magnetic force

- Detected a 23 mG field
  - By combining Effelsberg and MERLIN data
- De-projection structure perpendicular to “disc”
  - Similar orientation as outflow
- Conditions for collapse along field lines
  - Magnetic field dominates over turbulent support
- Admittedly strength uncertain
  - Molecular data not complete

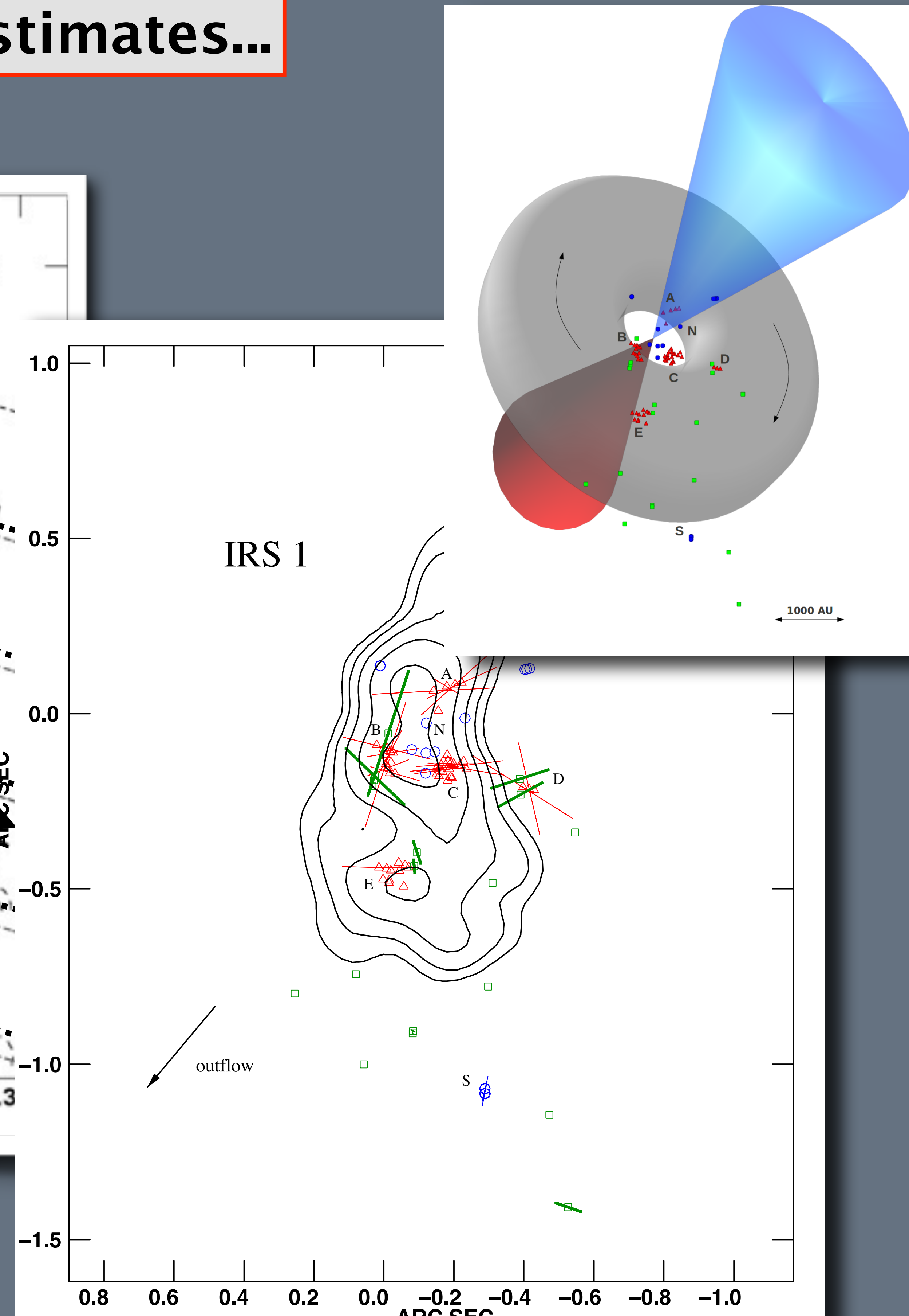


Vlemmings et al 2010

Obtaining more magnetic field estimates...



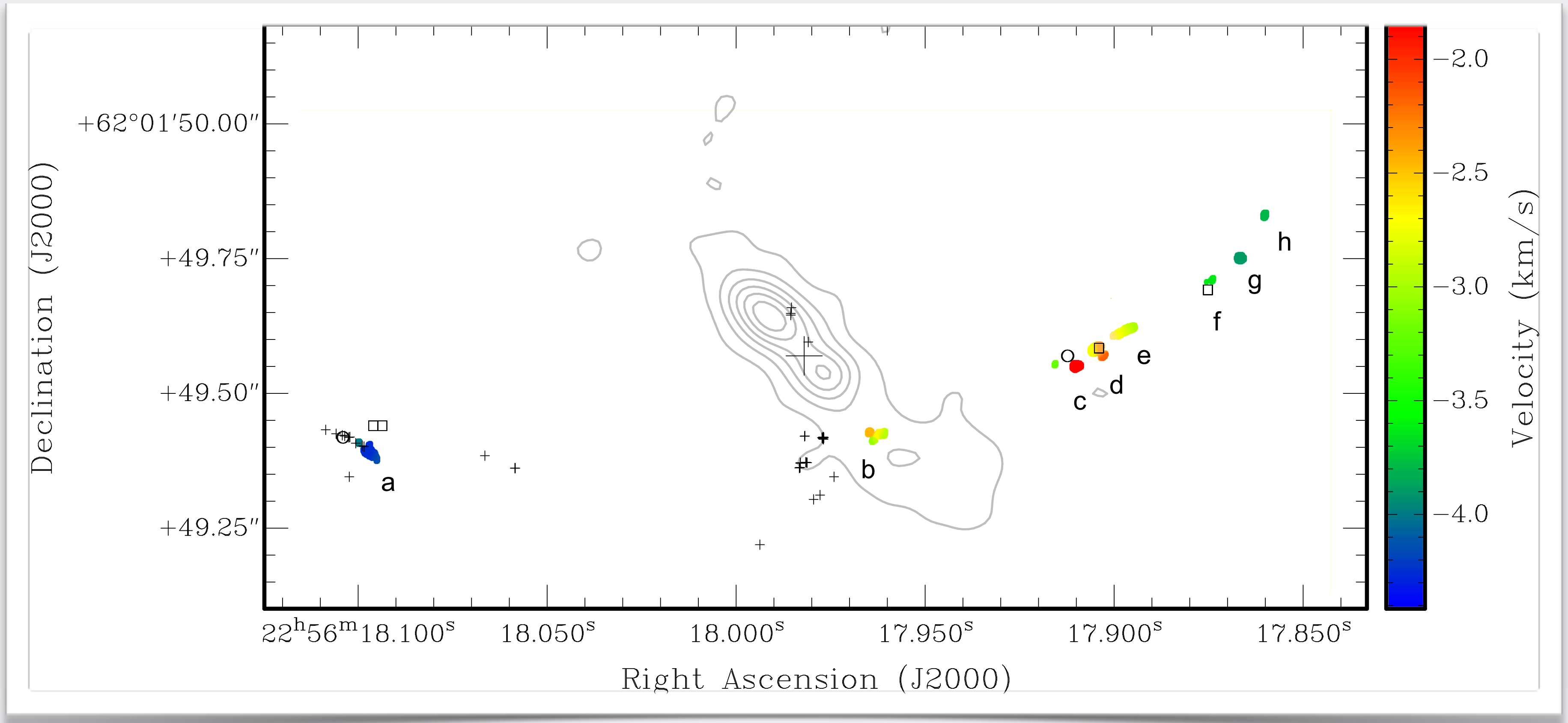
W75N, Surcis et al 2010



NGC7538 Surcis et al 2011

Working hypothesis

- **Radial motions in Cep A seems to be infall**
  - See only front side masers
  - Possible absorption of back side by free-free optical depth
  - Or maser effect, amplifying background



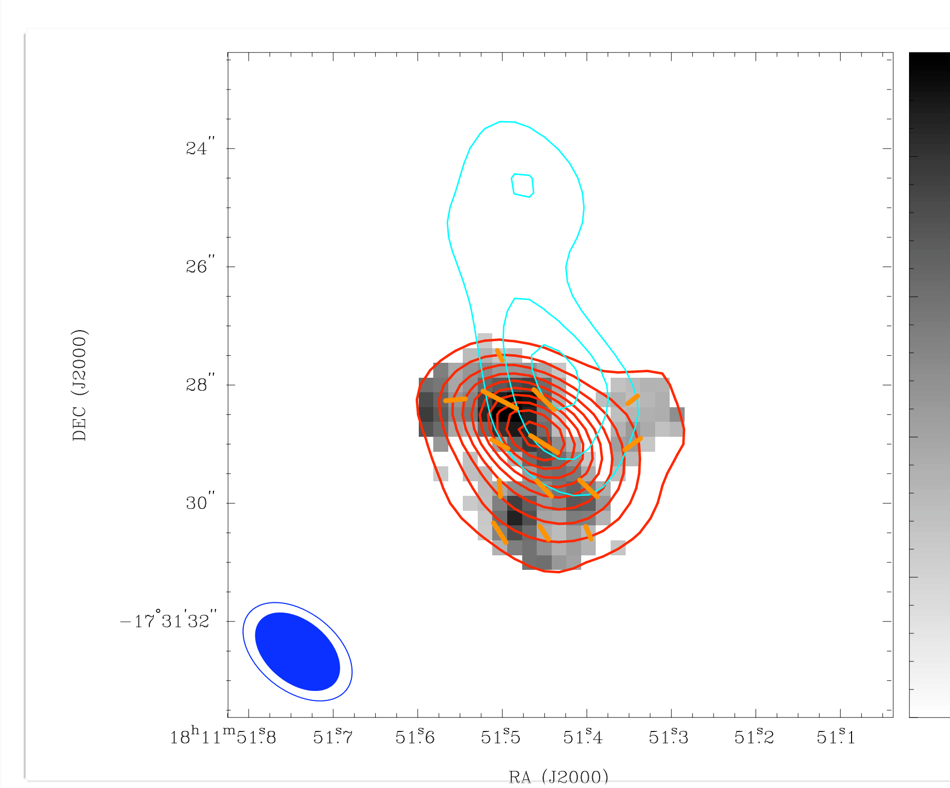
- **Masers on interface accretion and the disk**
  - Methanol masers in pre-shock gas?
  - Also identify as the place where methanol is released from grains
    - Such large scale structures unique to high mass sources?

Conclusion

- **Significant Zeeman in 6.7 GHz methanol masers**
  - Associated with high mass star formation
  - Indicates 10s of mG, probably dynamically important
- **Linear polarisation shows large scale fields**
  - Still very much small number statistics
  - Must verify it is not tied with density
- **Evidence methanol masers originate in the accretion disk/infall interface**
  - At least in a fraction of sources
    - Can possibly explain few more non-ring sources
  - But quite possibly association with outflow also exist
  - Identification of physical structure and evolutionary stage closer
    - Makes them really suited to use for signposts
    - Good news for astrometry
    - Dynamics of the masers connected to shock internals

The Next Generation

- 6.7 on VLBA statistical studies
  - Combined with BeSSel programme
- EVLA gives access to high excitation masers
  - New results on 25, 44 GHz
- eMERLIN legacy project
  - Statistics, combined with high sensitivity contin
- ALMA
  - dust polarisation
  - molecular (non-maser) lines
  - maser excitation constraints
  - high-frequency masers
- MeerKAT key projects
  - maser polarisation part of number of proposals
  - More targets in southern hemisphere
- SKA
  - sensitivity allows for unique database



IRAS 18089 SMA dust and CO polarizatio
Beuther et al 2011

The End