茨城大学
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Understanding the magnetic field structure in the star formation to the Galactic scales through the maser observations for Zeeman splitting and polarization

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0. Brief introduction for masers

Interstellar masers

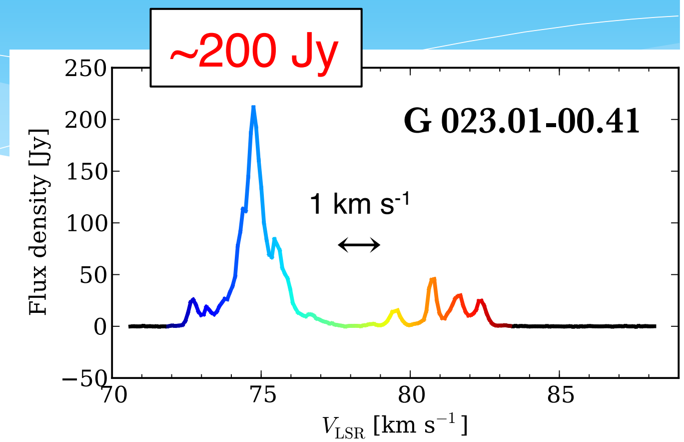
✓ Masers in the star-forming regions

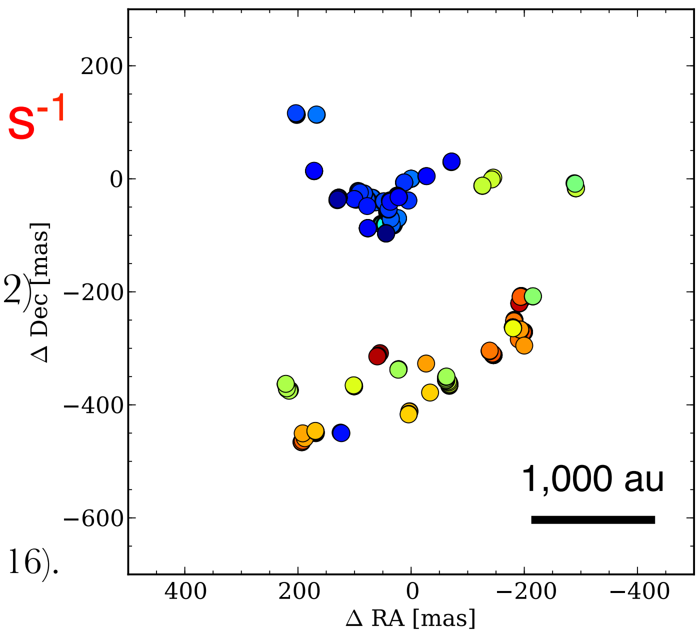
- Major : OH, H_2O, CH_3OH
- Minor : NH_3, H_2CO, SiO, radio RL

✓ Characteristics

- Much brighter than thermal lines
- **<u>Narrow line width</u>** : Δv ~0.2-0.5 km s^{-1}
- Compact size of spot : ~1-10 au
  - Some spots consist of core/halo (Minier+ 02)

☞ **<u>very bright</u>** : T_B ~10^7-10^{12} K



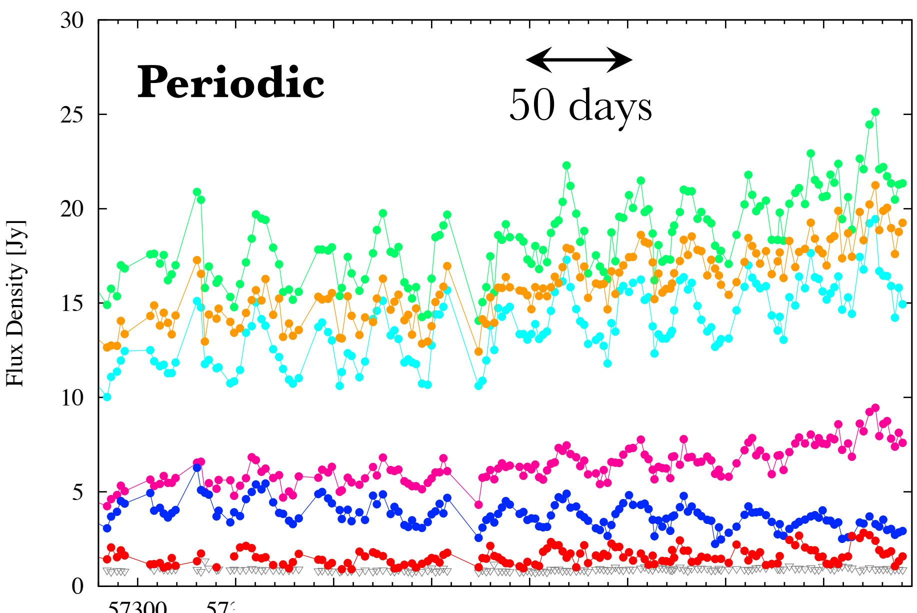


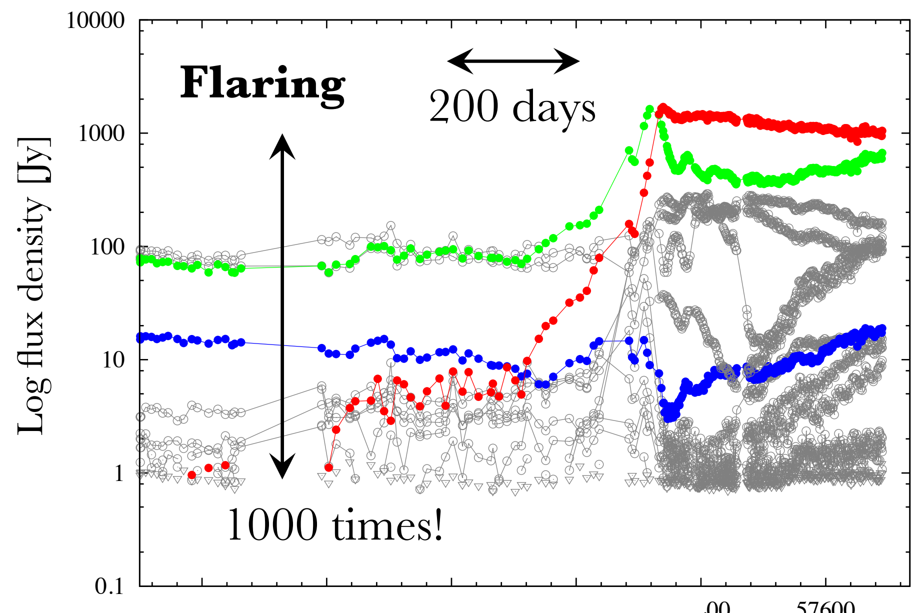
European VLBI spectrum and map of the 6.7 GHz CH_3OH maser (Bartkiewicz+ 16).

Usable characteristics of masers

✓ Flux variability

- Various times-scales : < 1 day – a few month – 1 year <
  - Provide information in 0.1-1 au spatial scales from Keplerian time-scale
- Remarkable variation : Periodic, Flaring
  - Periodic : stellar pulsation / binary system ?
  - Flaring : flare of exciting star / accretion burst / magnetic reconnection ?





Flux variation monitor project results with Ibaraki (Hitachi) single-dish radio telescope.

Usable characteristics of masers

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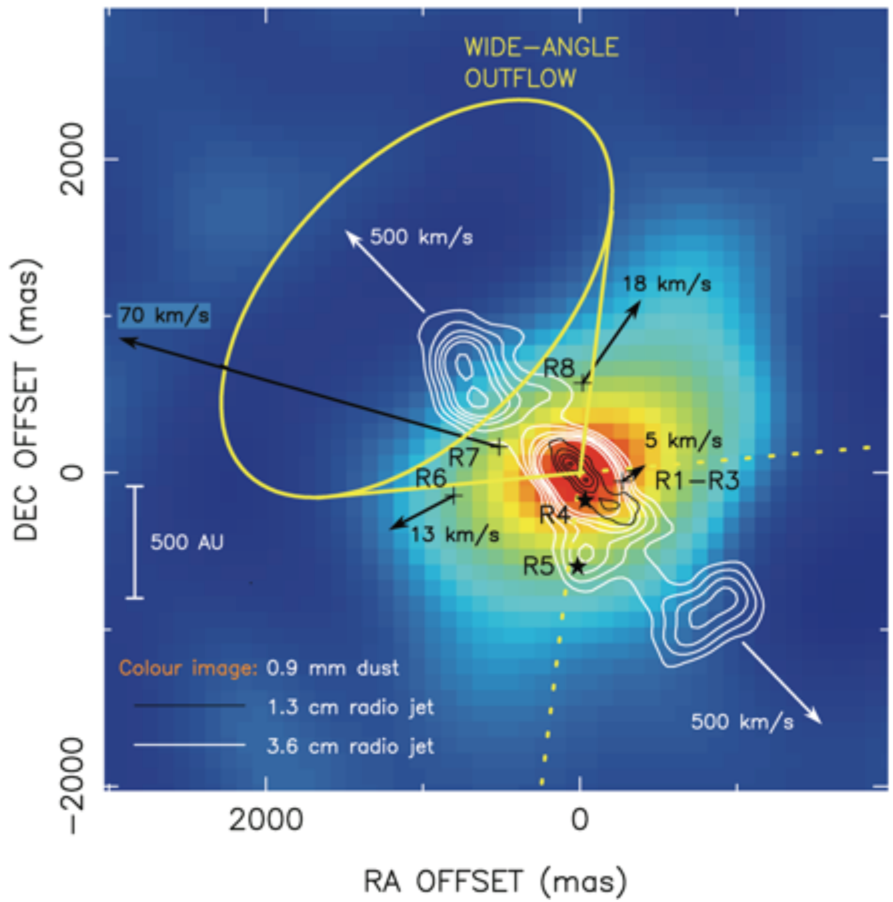
✓ Proper motion with VLBI (a few milliarcsec (mas) spatial resolution)

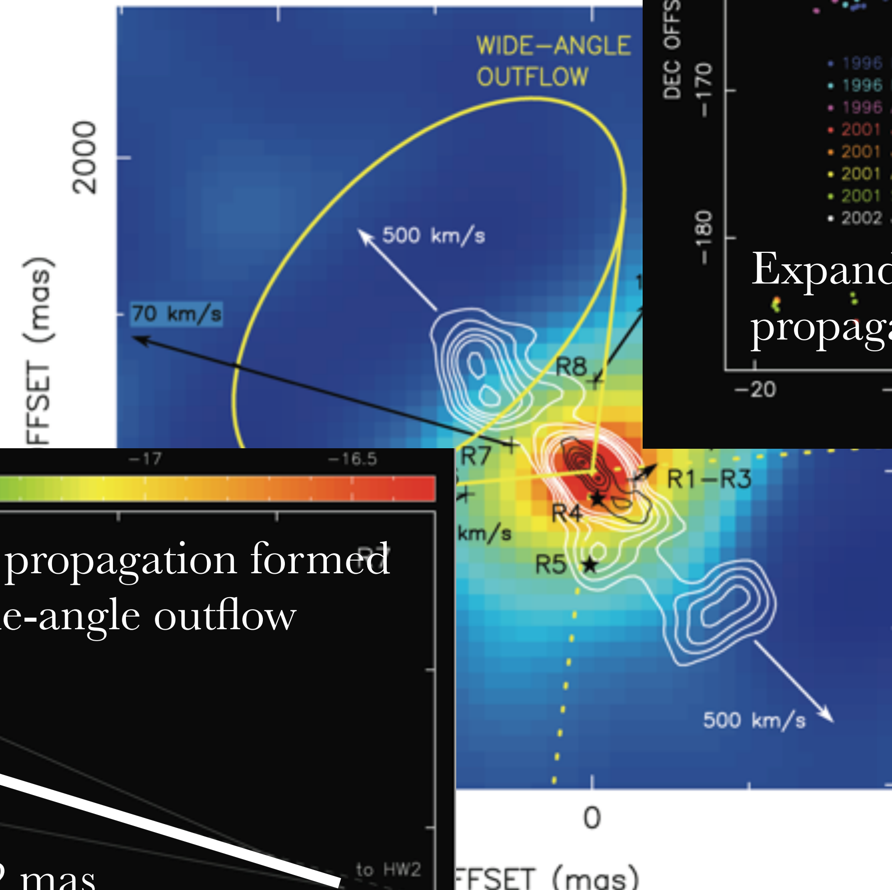
- Enable us to detect tiny motions of a few mas yr^{-1} on disk/outflow/jet
- Reveal 3-D velocity structure with LSR velocity information

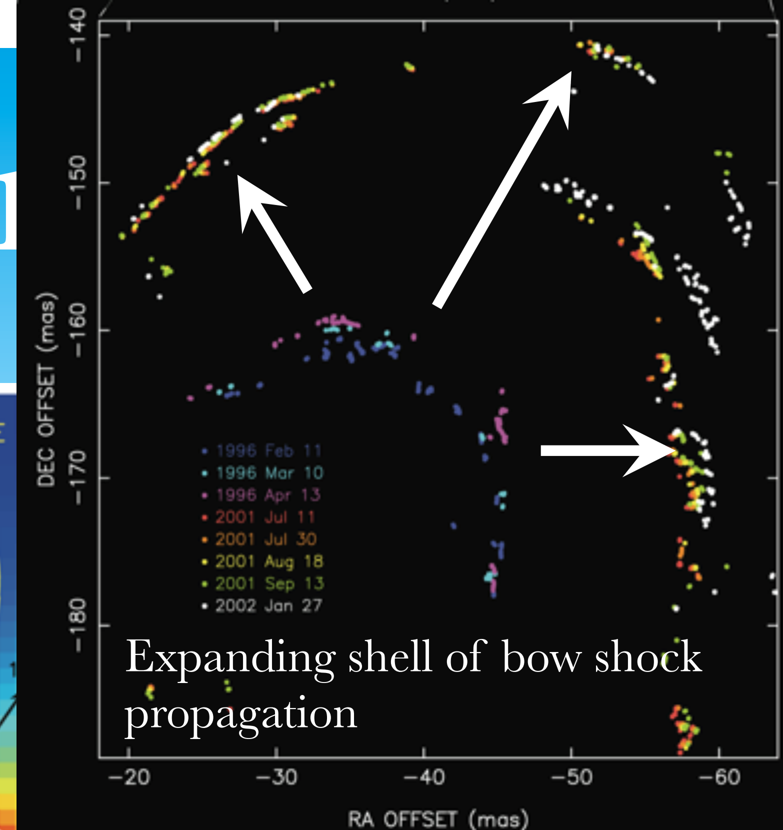
Proper motion with VLBI

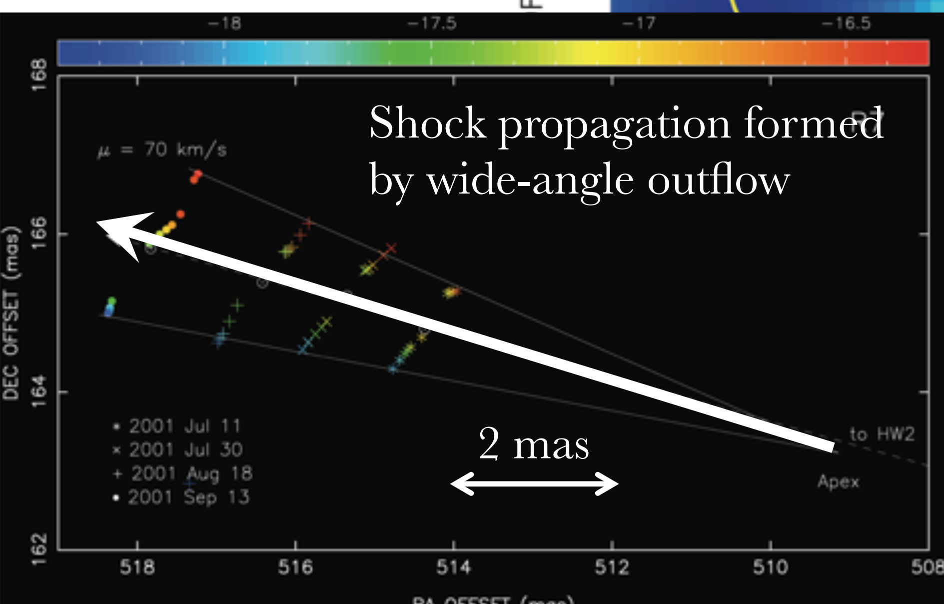


Wide-angle outflow and jet scenario observed in high-mass SFR Cepheus A (Torrelles+ 11). Proper motions of 22 GHz H_2O masers showed expanding motions emanated by wide-angle outflow, while a radio jet was observed by radio continuum observation.

Proper motion wit







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Usable characteristics of masers

- ✓ Flux variability
  - Various times-scales : < 1 day – a few month – 1 year <
    - Provide information in 0.1-1 au spatial scales from Keplerian time-scale
  - Remarkable variation : Periodic, Flaring
    - Periodic : stellar pulsation / binary system ?
    - Flaring : magnetic reconnection / flare of exciting star / accretion burst ?

- ✓ Proper motion with VLBI (a few milliarcsec (mas) spatial resolution)
  - Enable us to detect tiny motions of a few mas yr^{-1} on disk/outflow/jet
  - Reveal 3-D velocity structure with LSR velocity information

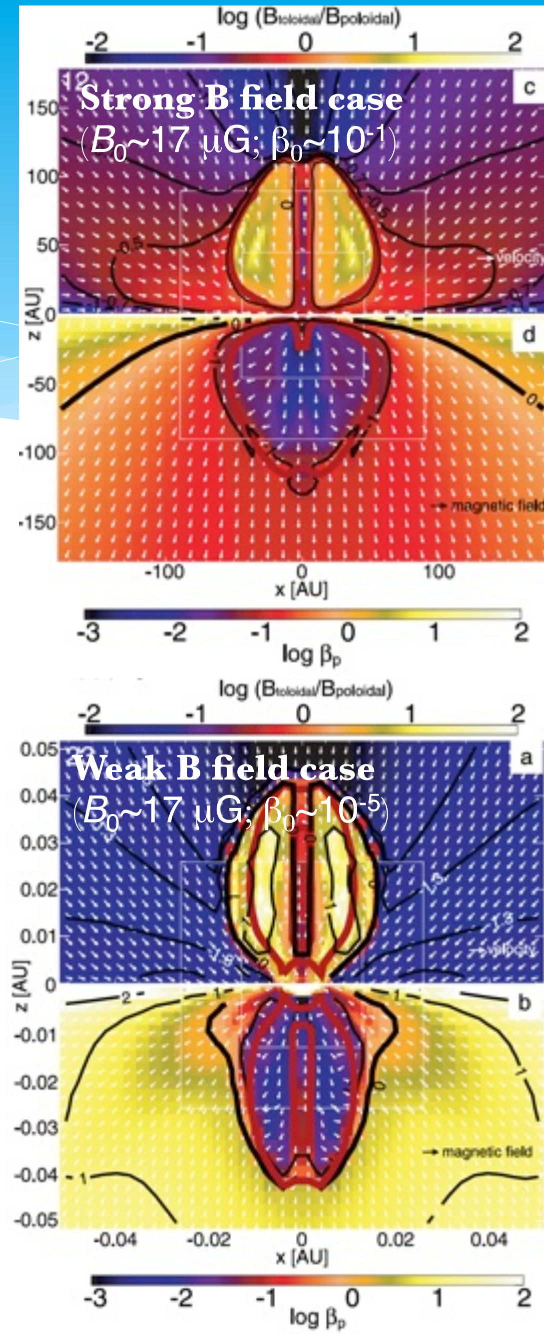
- ✓ Magnetic field strength and 3D structure
  - Circular polarization => Zeeman splitting
  - Linear polarization => Polarization vector
    - Convertible to the direction of the magnetic field axes

1. What's advantages of maser obs. for magnetic (B) field?

Importance of *B* field

- ✓ Launch outflow/jets and magnetic braking
  - Removal of angular momentum
  - Maintain accretion through disk

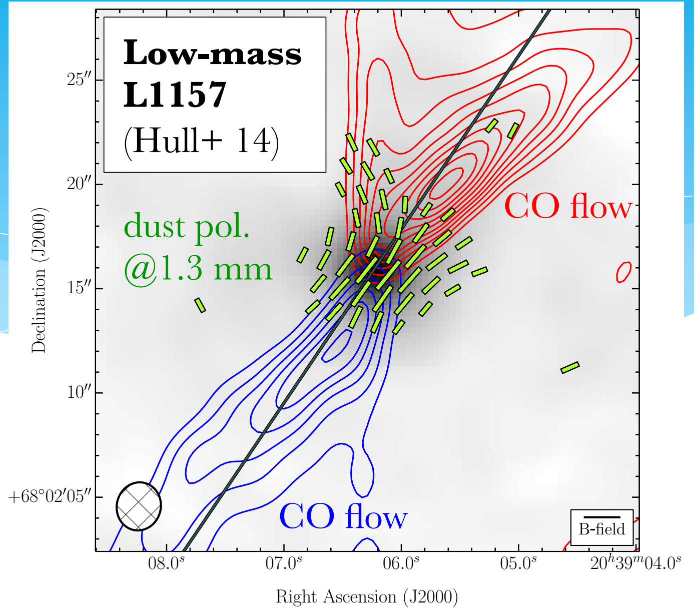
- ✓ Launch mechanism and morphology of outflow/jets affected by the strength and the configuration of the ***B*** field (Machida+ 08)
  - Outflow : low-velocity and hourglass-like, caused by strong ***B*** field and the magnetocentrifugal force
  - Jet : high-velocity and well-collimated, caused by weak ***B*** field and the magnetic pressure gradient force



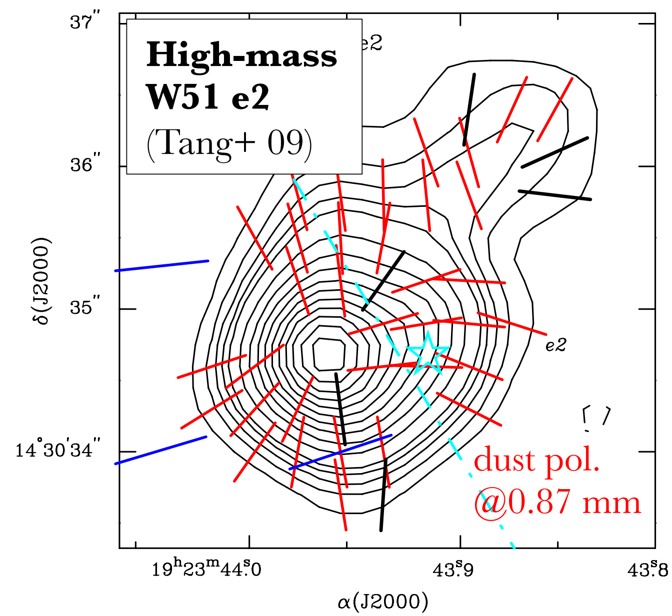
3D MHD simulations to understand the outflow/jet launching mechanism and morphology in the star-forming core (Machida+ 08). These figures show the relation among velocities, collimations, ***B*** field strength, and morphology.

e.g.) Dust pol. obs.

- ✓ Aligned dust by ***B*** field
- ✓ Measure polarization vector, convertible to the ***B*** field on the plane of sky
  - e.g., "hourglass" shape (e.g., Girart+ 06)



- ✓ Weak points
  - Impossible to direct measurement of the strength of ***B*** field
    - may be estimated by comparing the gravitational force as an upper limit at collapse phase
  - Hard to trace high-density area (> 10^8 /cc)

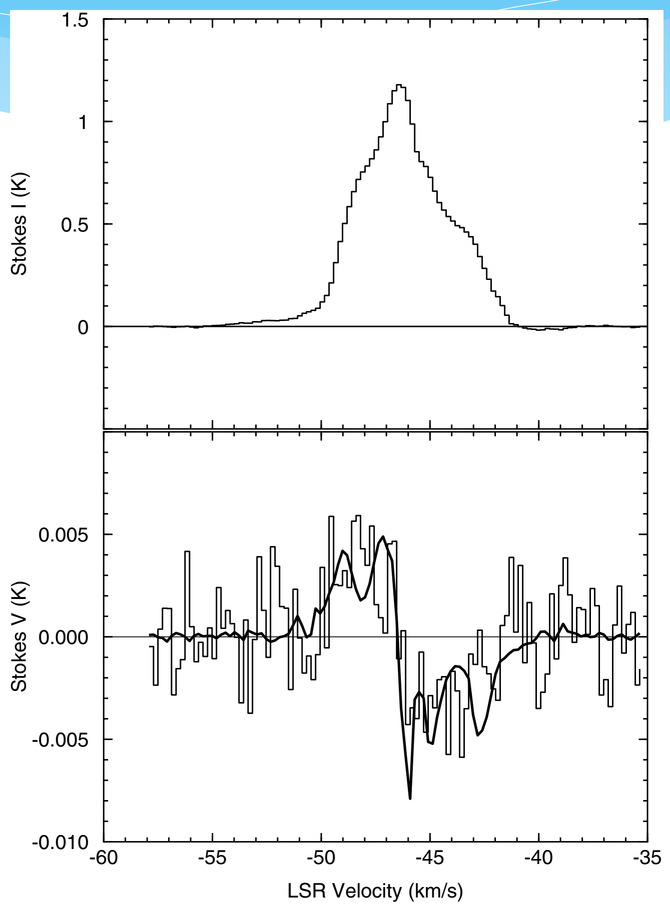


e.g.) Zeeman splitting obs.

- ✓ Energy quantum state is split by the ***B*** field into multiple states
- ✓ Measure the strength of the ***B*** field directly!
- ✓ To date in thermal lines, measured from HI, OH, and CN (e.g., Crutcher+ 99; Falgarone+ 08)
  - Low-density ($< 10^4$ /cc) : HI, OH
  - High-density (10^4-10^6 /cc) : CN

- ✓ Weak points
  - Split coefficient is much smaller than thermal line-width : ~1 Hz/μG
  - Signal-to-noise ratio is not enough to detect circular polarized spectrum

☞ a few detections in the high-density tracer



CN Zeeman spectra of Stokes I (top) and V (bottom) in W3(OH) (Falgarone+ 08).

Advantages of the masers

i. Narrower line-width and brighter emission than thermal lines
   - Enable us to measure for small Zeeman split with high S/N

ii. Pumped in compact and high-dense cloud, called as "spot"
   - Enable us to trace higher-density area than thermal emissions

iii. Both linearly and circularly polarized emission
   - Full stokes parameters (I, Q, U, V) usable to determine 3D ***B*** field structure

iv. Combined with dynamics (3D velocity structure) information
   - Understand dynamical motions and magnetic structures, simultaneously

ii. High-density tracer (> 10^6 /cc)

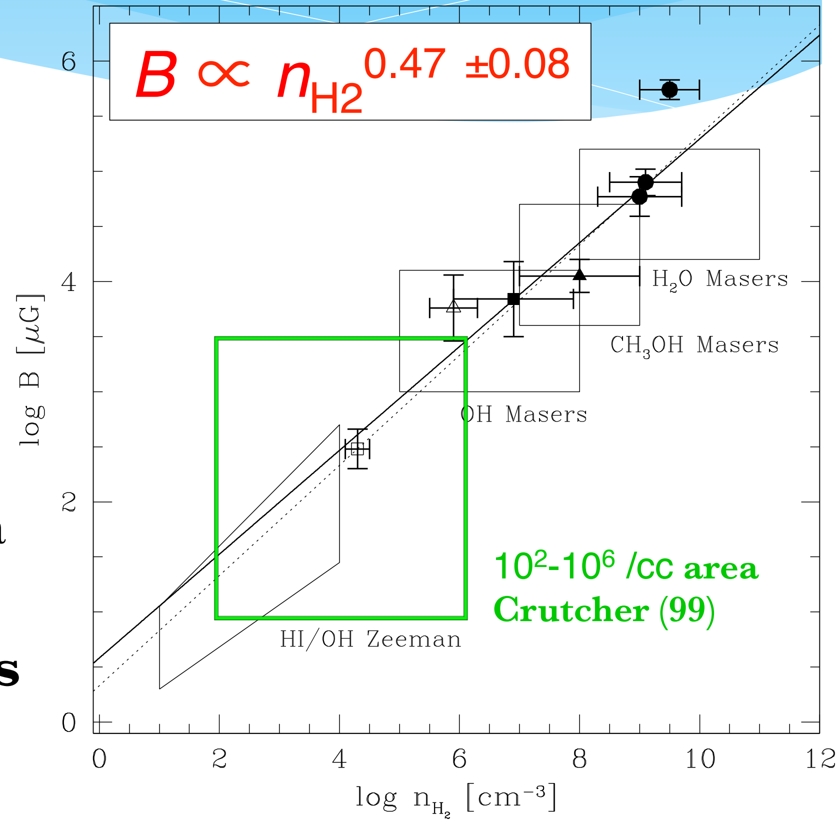
✓ $n_{H2} > 10^6$ /cc

- OH : 10^5-10^8 /cc (Cragg+ 02)
- CH_3OH : 10^4-10^9 /cc (Cragg+ 05)
- H_2O : 10^8-10^{11} /cc (Elitzer+ 92)

✓ $B \propto n_{H2}^{0.47 \pm 0.08}$ (Vlemmings 08)

- Consistent with Crutcher (99) relation
- Connect from low to high-density area

☞**Zeeman splitting measurements**
extensible to high-density area !



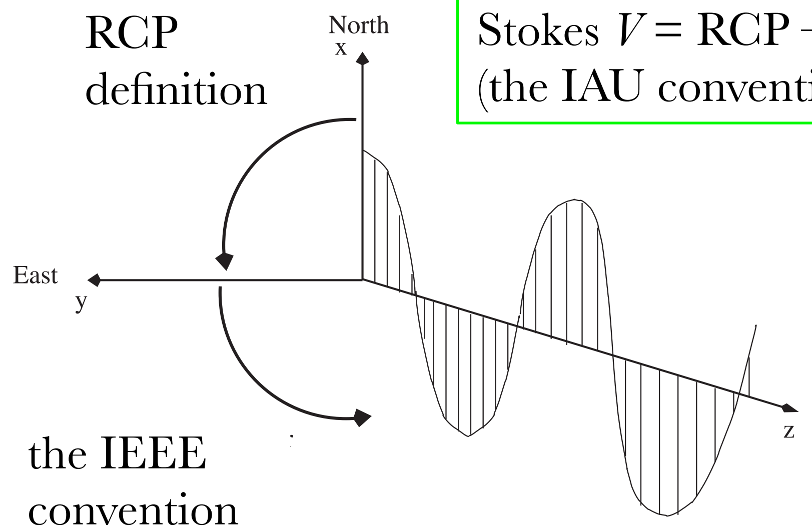
Magnetic field strangth B vs the number density n_{H2} in high-mass SFR Cepheus A (Vlemmings 08).

iii. Full stokes (linear and circular)

✓ Masers linearly and circularly polarized **3D *B* field structure**

- Linear : 2D pol. vector on the plane of sky
- Circular : Strength and radial 1D pol. vector through Zeeman split

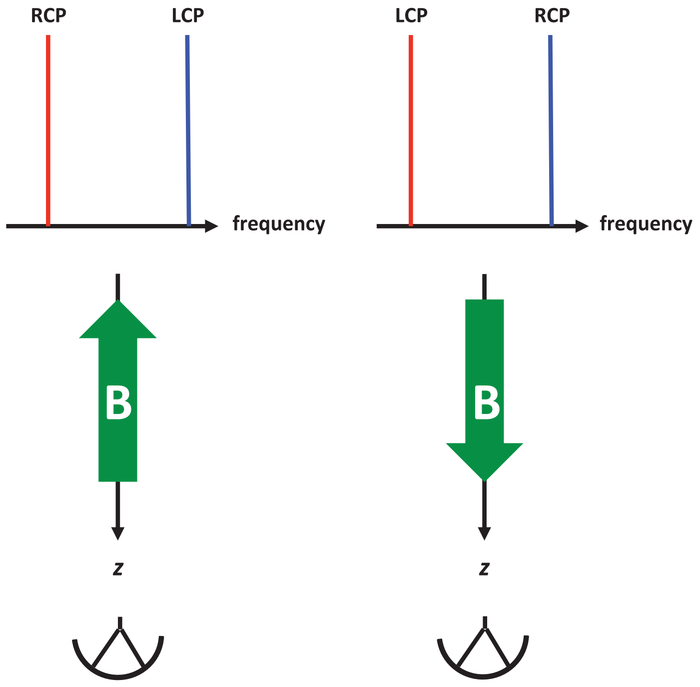
RCP definition



the IEEE convention

Stokes V = RCP – LCP (the IAU convention)

Image credit: Green+ (14)



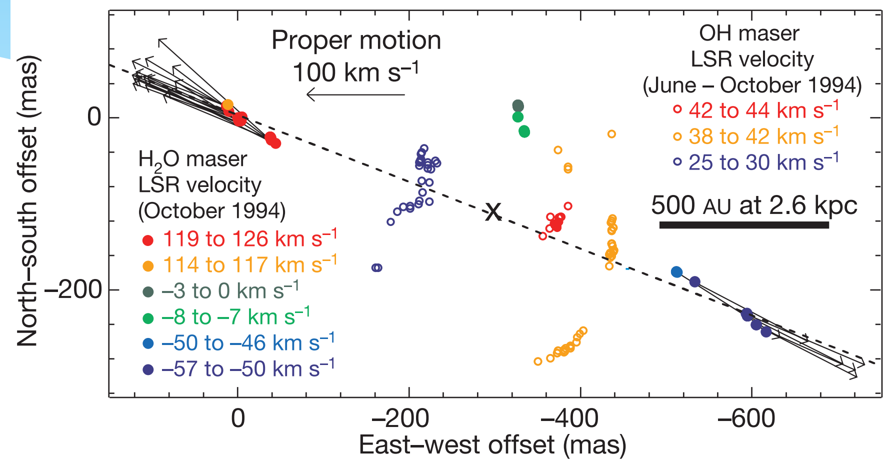
iv. Combined with 3D vel. structure

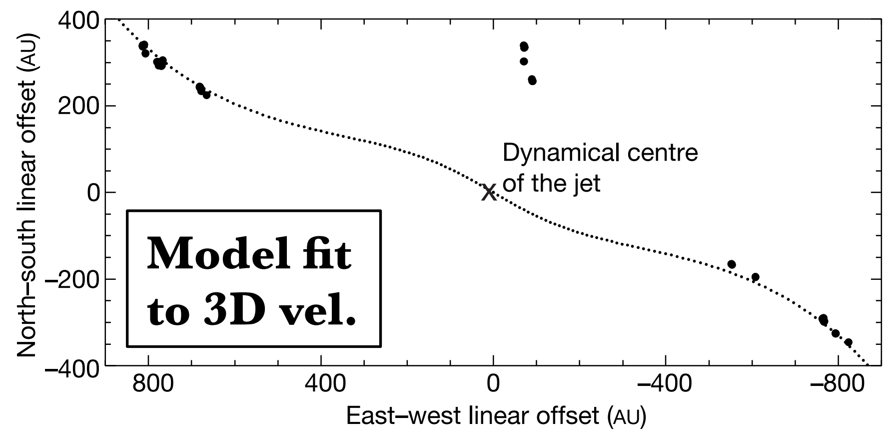
✓ Totally understanding through the compact gas cloud "spot"

- Spatial distribution
- Dynamics from 3D vel. structure
- ***B*** field structure

e.g.) evloved AGB star W43A case

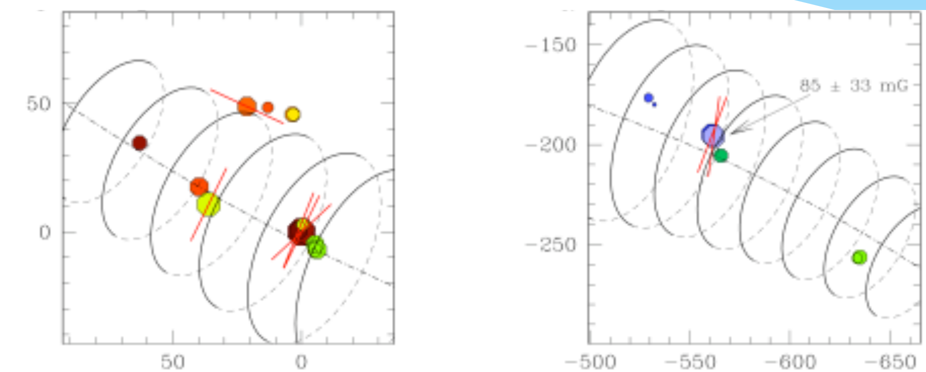
- 3D vel. structure well fitted by precessing jet model (Imai+ 02)
- Toroidal B field structure measured through linear pol. of H_2O masers (Vlemmings+ 06a)

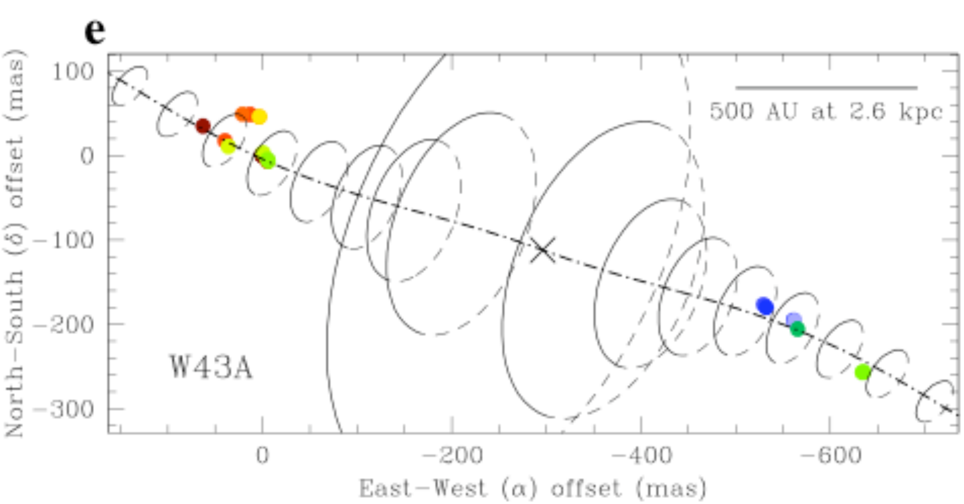


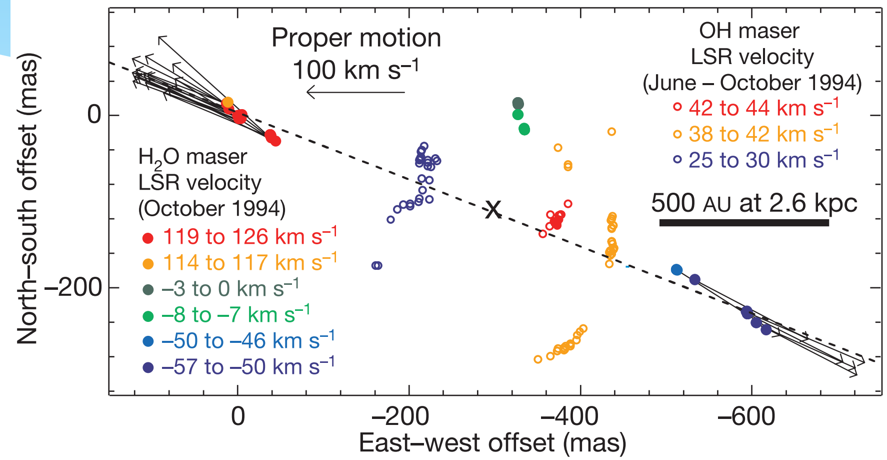


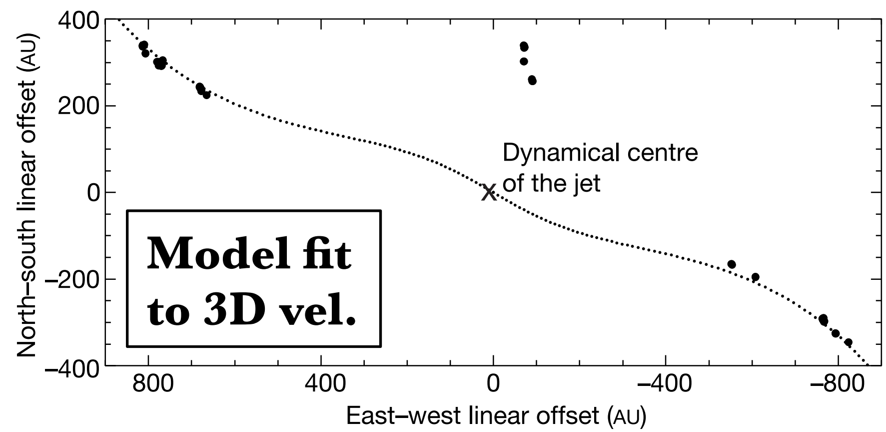
↑ : Proper motions detected for H_2O masers in the evolved AGB star W43A (Imai+ 02). ↓ : Precessing jet model fit to 3D velocity structure of H_2O masers.

iv. Combined with 3D vel. structure









↑ : ***B*** field direction converted from linear pol. vector of the H_2O masers in W43A (Vlemmings+ 06a). ↓ : Toroidal ***B*** field model inferred of H_2O maser results.

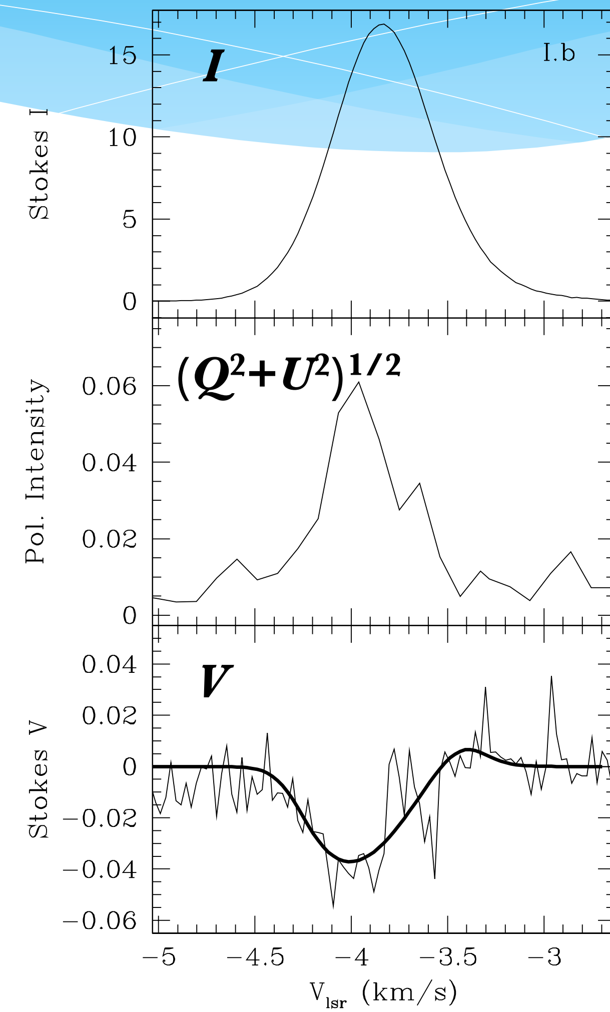
↑ : Proper motions detected for H_2O masers in the evolved AGB star W43A (Imai+ 02). ↓ : Precessing jet model fit to 3D velocity structure of H_2O masers.

2. Remarkable works of maser obs. for the magnetic field

B field parameters of the masers

	OH	CH_3OH	H_2O
ν [GHz]	1.6-1.7	6.7	22.2
Coefficient [Hz/μG]	2-3	~10^{-4} * (Jen 1951)	~10^{-3}
Trace	Edeg of HII region	Accretion disk	Outflow/ jet
fraction L fraction C	~10-20% ~50-60%	<1-20% <1-5%	<1-10% <1-5%
Strength [mG]	~10-50	~10-100 *	~10-1000
Note.	Strongly affected by RM	* Large uncertainty of coefficient	

Ref. --- e.g., Szymczak & Gerard (09); Surcis+ (12, 15); Vlemmings (08, +11)



H_2O maser spectra in Cepheus A (Vlemming+ 06b)

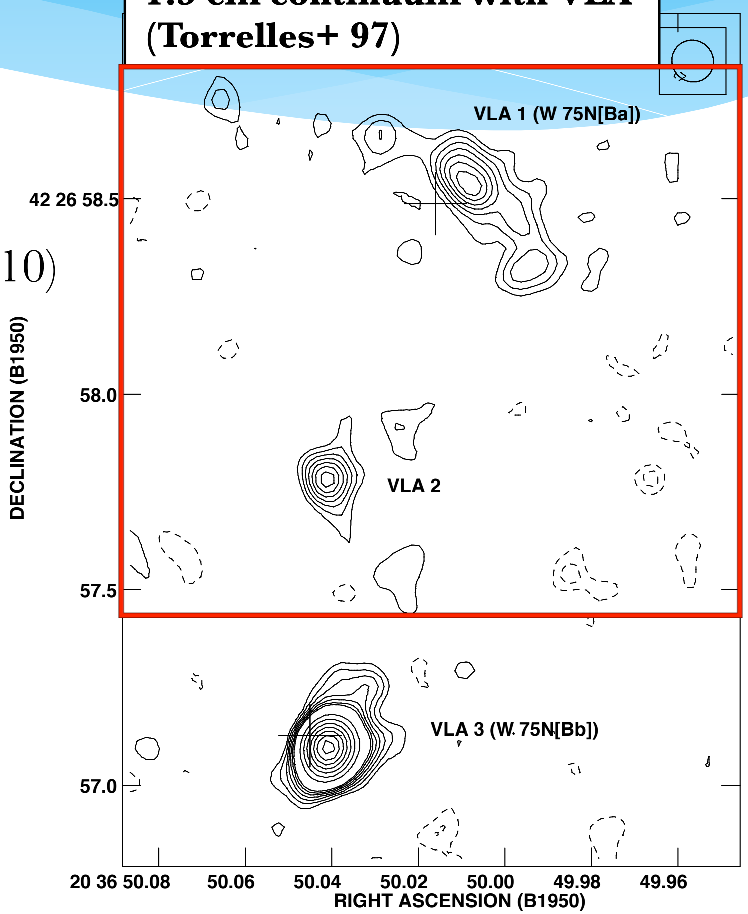
Case 1. W75 N

~ rapidly evolution of outflow morphology and *B* field structures ~

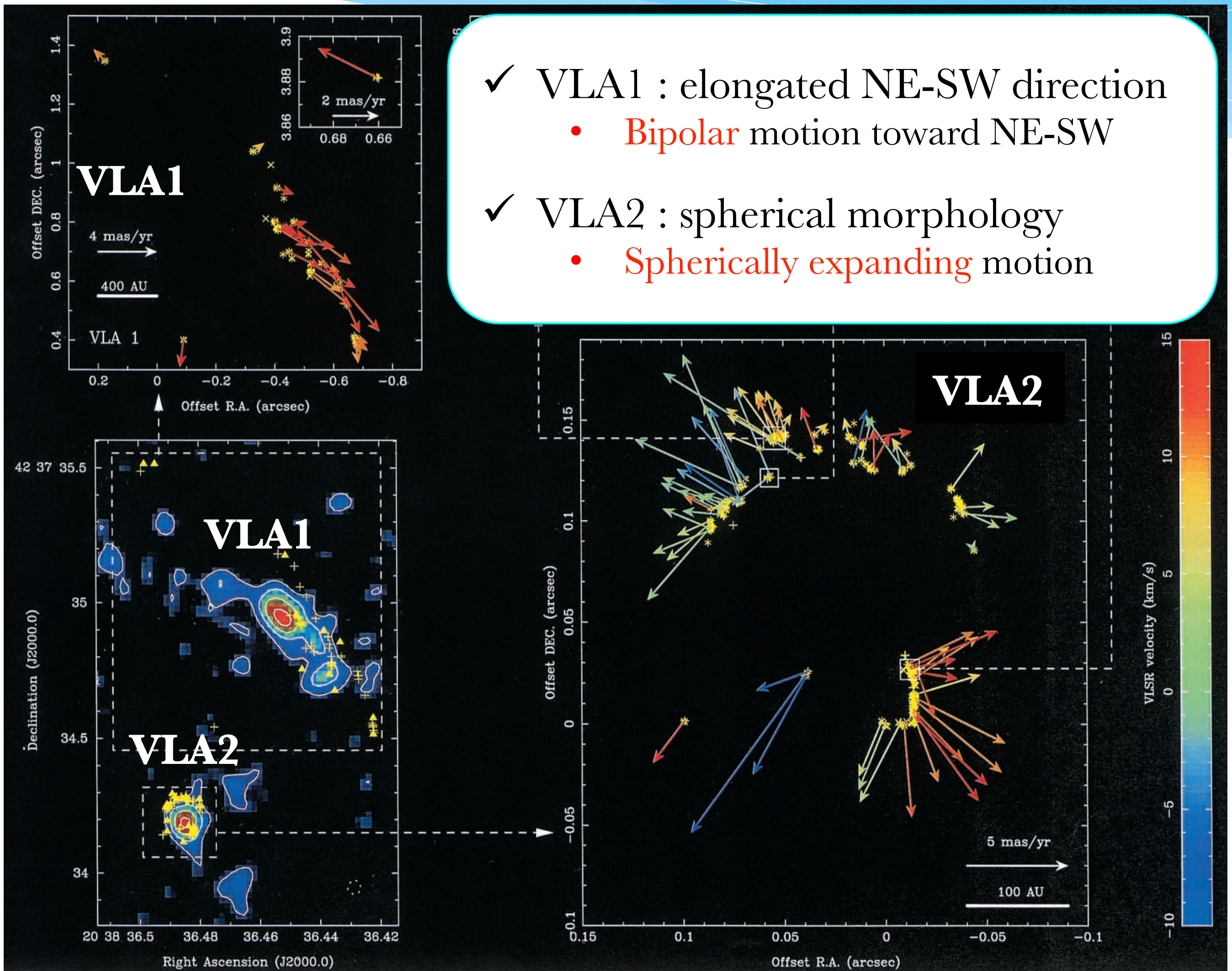
High-mass star-forming region W75 N

- ✓ Part of Cygnus X region
- ✓ Distance: 1.30 kpc (Rygl+ 12)
- ✓ Three YSO candidates at different evolutionary phase (Carrasco-Gonzalez+ 10)
  - VLA1: oldest
    - Index: -0.4 ±0.1 => optically thin, free-free
  - VLA2: younger than VLA1
    - Index: 2.2 ±0.3 => optically thick, free-free
  - VLA3: youngest
    - Index: 0.6 ±0.1 => thermal jet

1.3 cm continuum with VLA (Torrelles+ 97)



H_2O maser distributions and motions



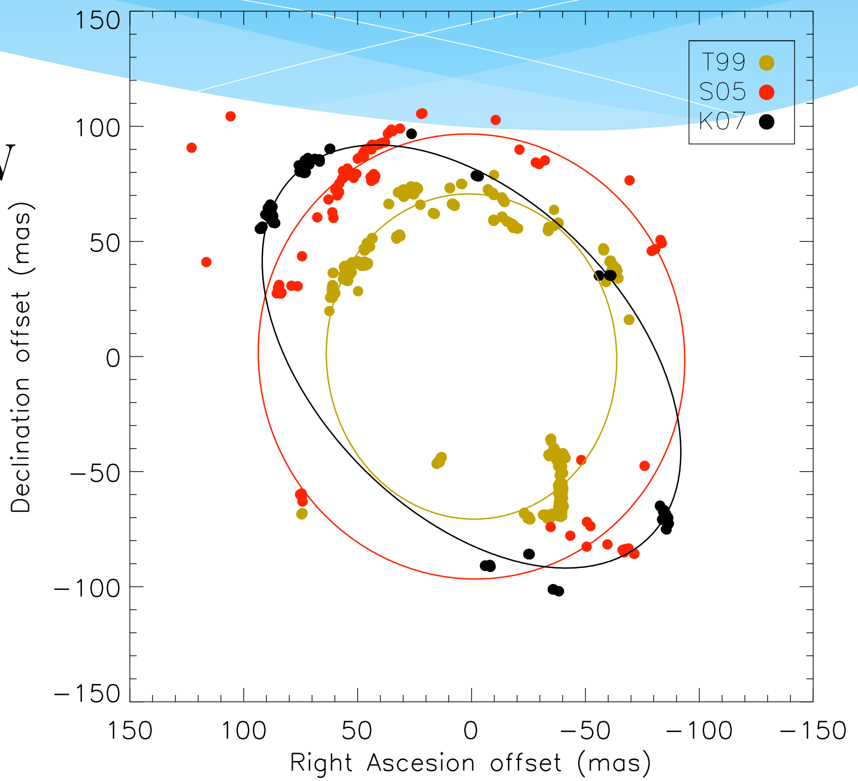
- ✓ VLA1 : elongated NE-SW direction
  - Bipolar motion toward NE-SW
- ✓ VLA2 : spherical morphology
  - Spherically expanding motion

Torrelles+ (03)

Rapidly change of spatial distribution and *B* field structure of H_2O maser in VLA2

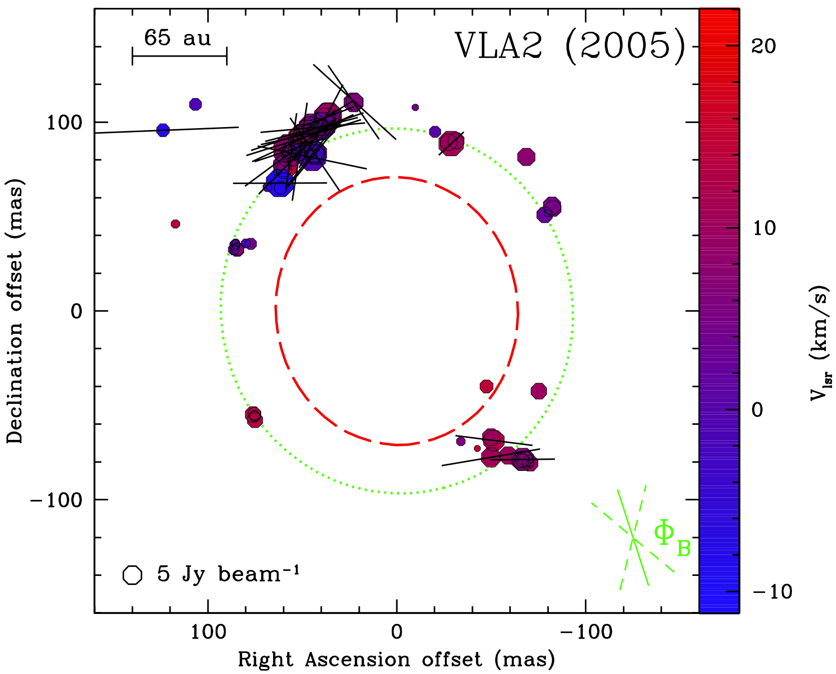
✓ Spatial distribution of H_2O maser in VLA2 in ~8 yrs (Kim+ 13)

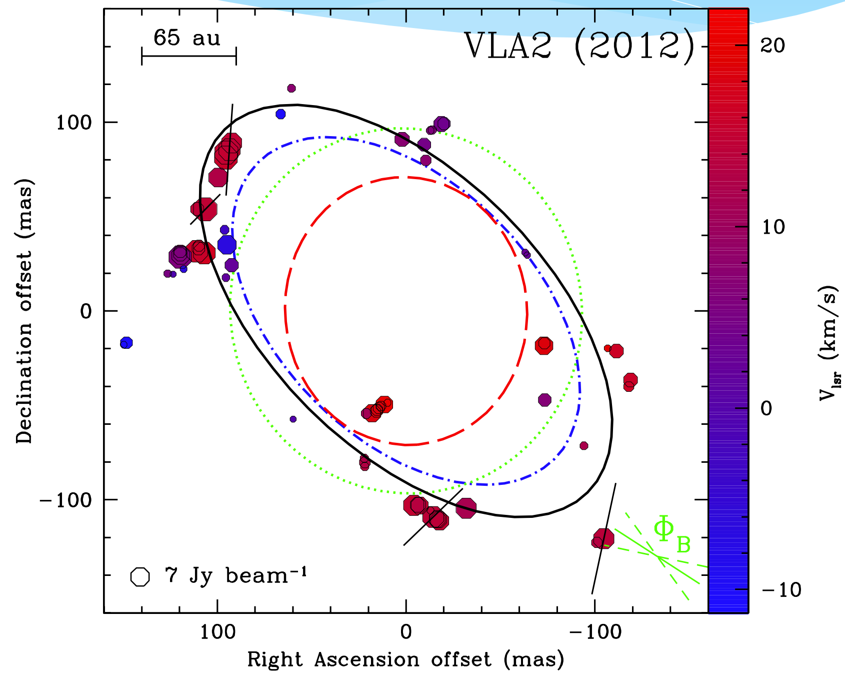
- Spherical ⇒ Elongated to NE-SW



VLBI maps at 3 epochs
(Torrelles+ 03; Surcis+ 11; Kim+ 13).

Rapidly change of spatial distribution and *B* field structure of H_2O maser in VLA2





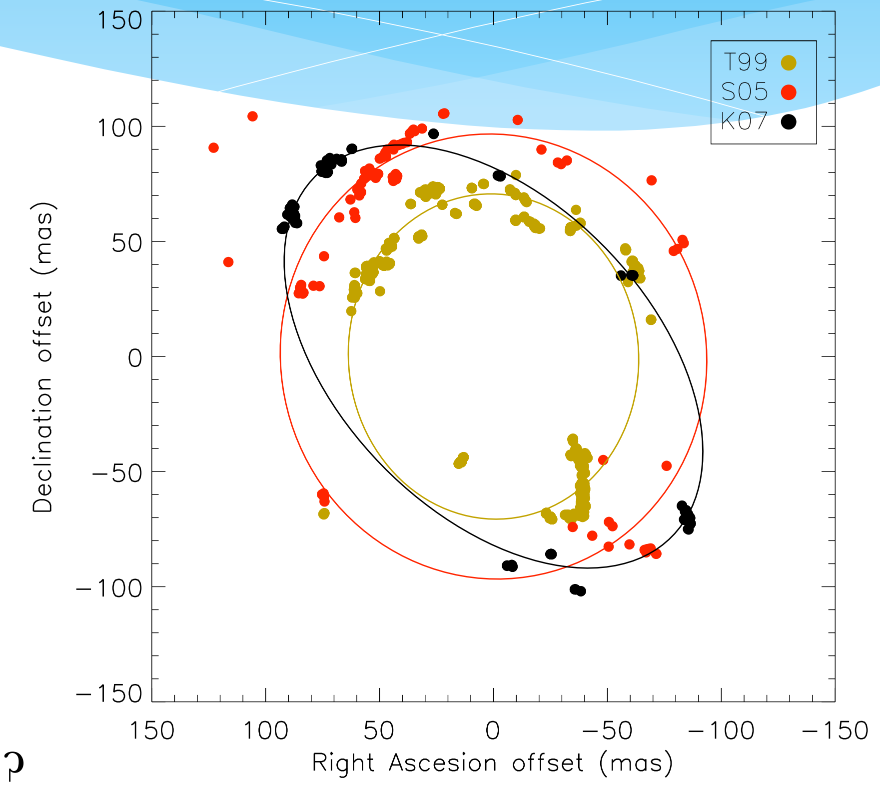
✓ Surcis+ (14) detected rapidly changes of the ***B*** field structure in 7 yrs
- the direction of the B field : +18 ⇒ +57 deg
- the strength of the B field : 345 mG ⇒ 128 mG

Rapidly change of spatial distribution and *B* field structure of H_2O maser in VLA2

- ✓ Spatial distribution of H_2O maser in VLA2 in ~8 yrs (Kim+ 13)
  - Spherical ⇒ Elongated to NE-SW
- ✓ ***B*** field structure of H_2O maser in VLA2 in ~7 yrs (Surcis+14)
  - Direction : +18 ⇒ +57 deg
  - Strength : 345 mG ⇒ 128 mG

☞short-lived, isotropic, ionized wind in the strong ***B*** field predicted by MHD simulation ?
(e.g., Machida+ 08; Seifried+ 12)

- Collimated as being evolved ??

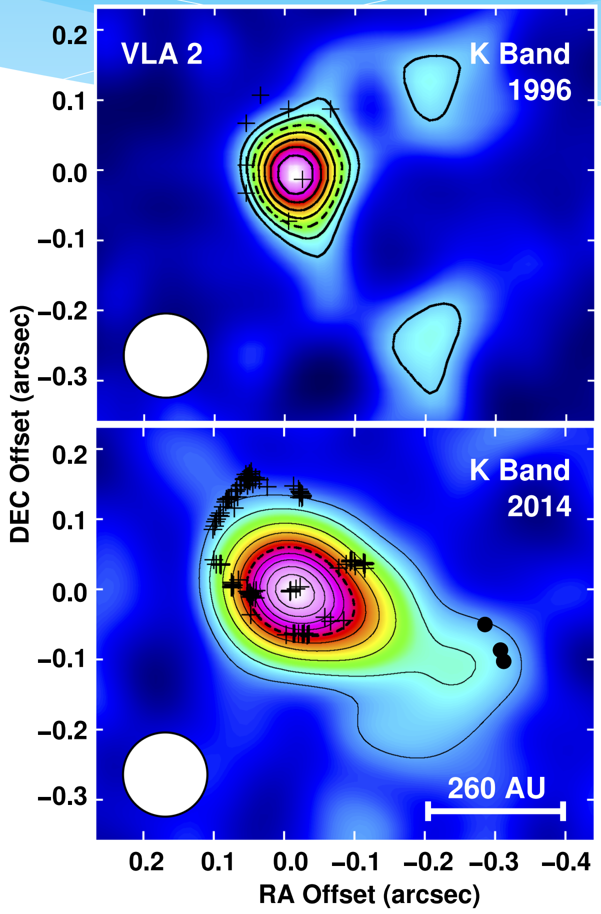


VLBI maps at 3 epochs
(Torrelles+ 03; Surcis+ 11; Kim+ 13).

Verified by radio continuum obs.

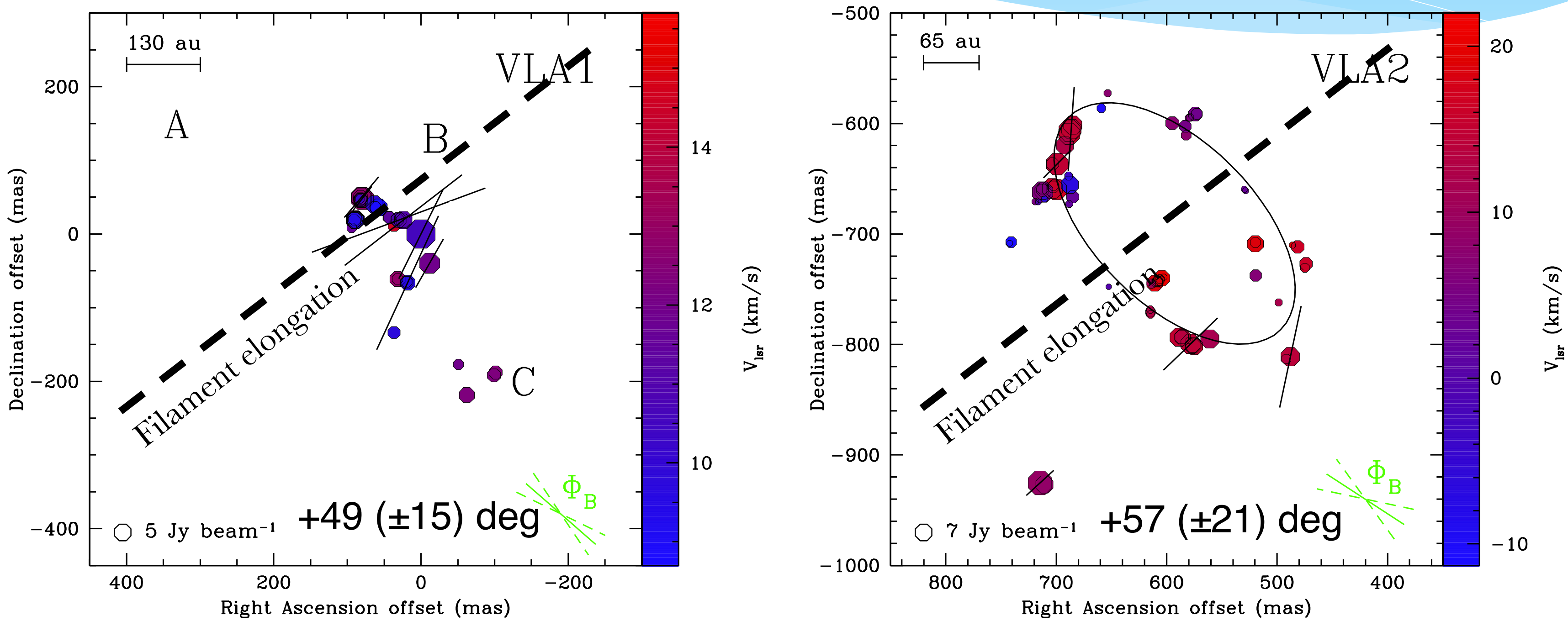
- ✓ 1.3 cm continuum distribution was also changed in ~20 yr in VLA2 (Carrasco-Gonzalez+ 15)
  - Spherical ⇒ Elongated to NE-SW

- ✓ Verified short-lived, isotropic, ionized wind whose morphology evolves into elongated to NE-SW inferred from H_2O maser observations (dynamics & $\boldsymbol{B}$) !!



Carrasco-Gonzalez+ (15)

Alignment of the *B* direction ?



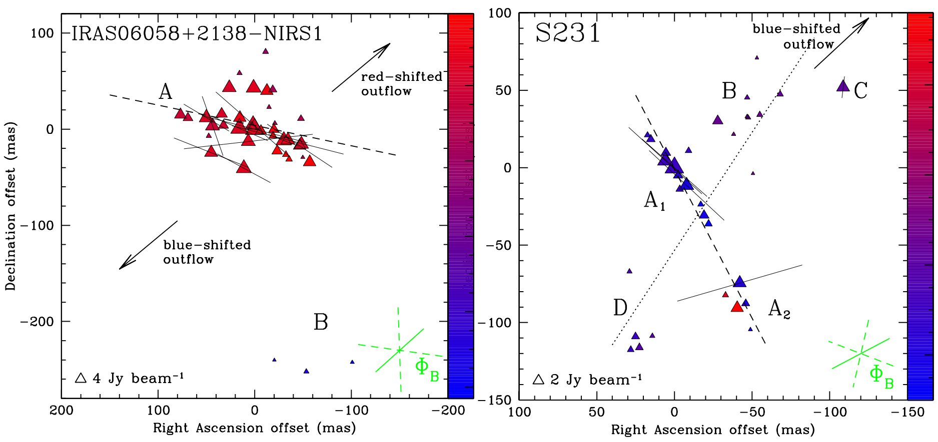
- ✓ Surcis+ (14) detected alignment of ***B*** field direction in VLA1 and VLA2
  - VLA1 : +49 (±15) deg, VLA2 : +57 (±21) deg
  - Nearly perpendicular filament structure traced by NH_3 emission ??

Case 2. Statistical study in star-formation scale

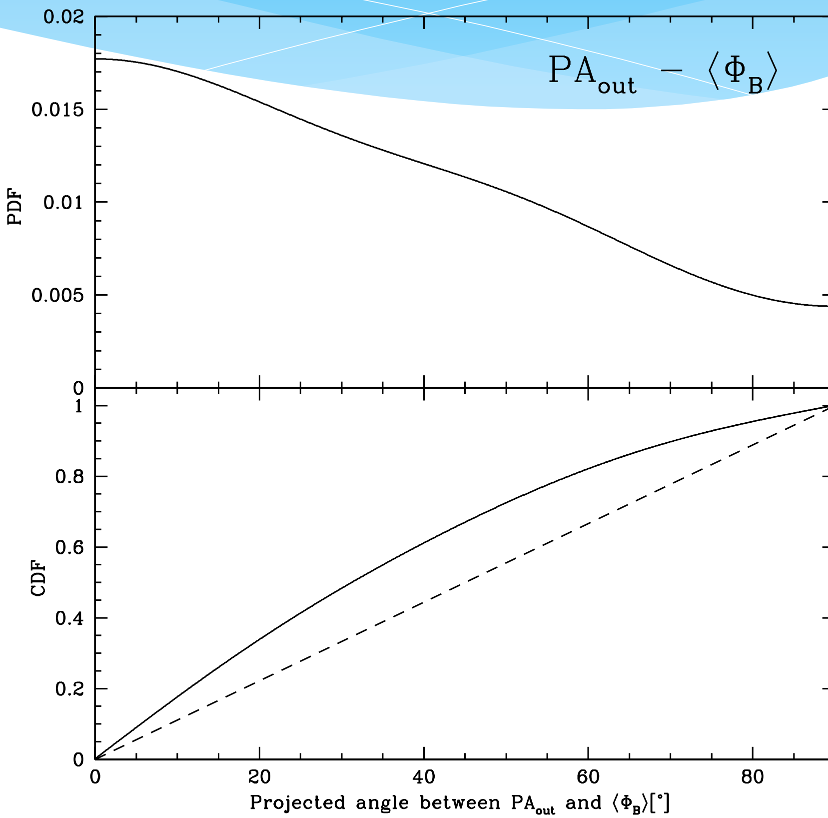
~ relationship of the orientations between *B* field and outflow axes ~

B field vs outflow axes

- ✓ Measured ***B*** field of CH_3OH masers in ~20 high-mass YSOs (Surcis+ 12, 13, 15)
- ✓ Orientation of the ***B*** field along the outflow axes, preferentially
  - At least, on scales of **10-100 au**



Comparison of the ***B*** field orientation from CH_3OH maser obs. to the outflow axes (Surcis+ 13).

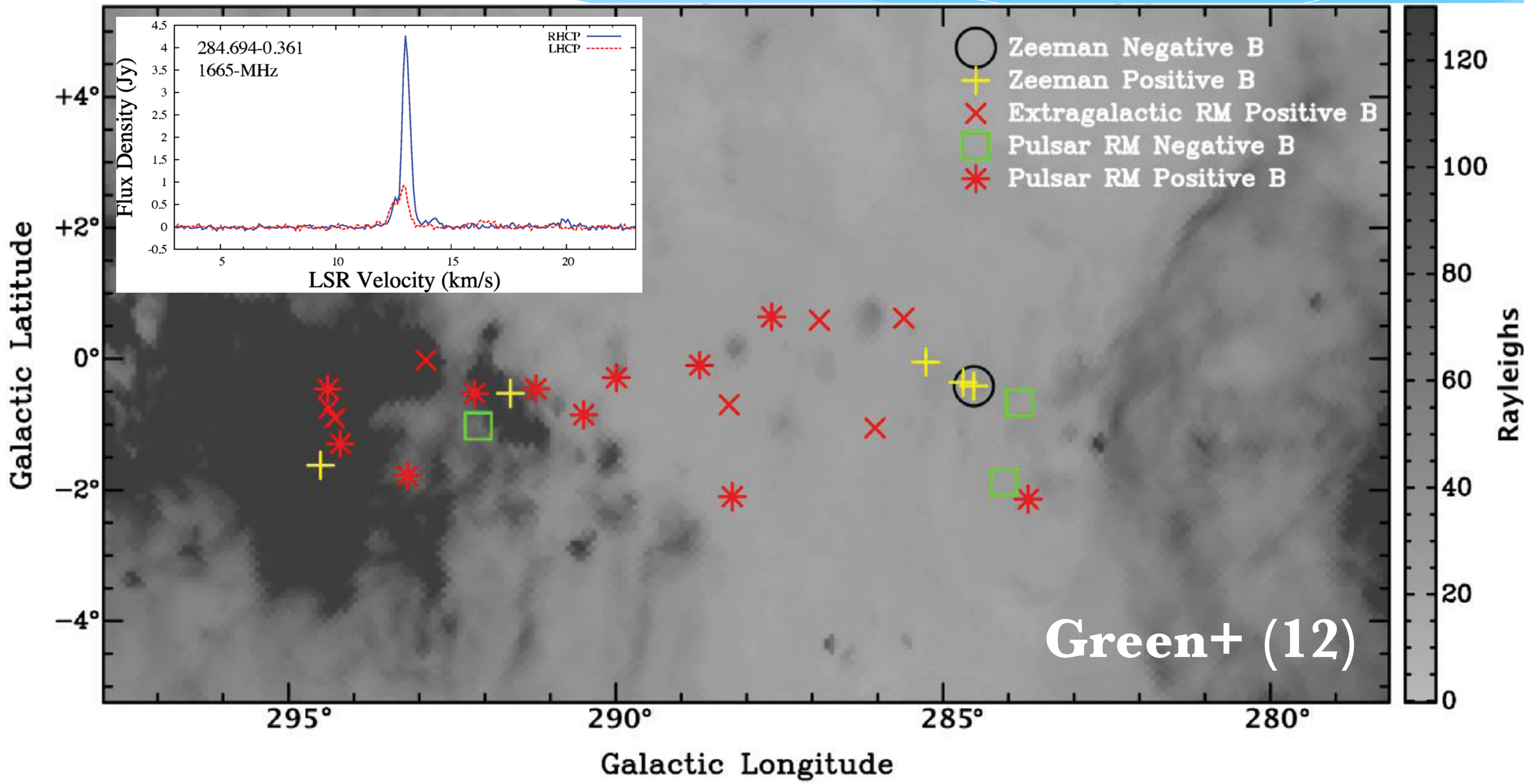


PDF and CDF of the projected angle between the ***B*** field and the outflow axes (Surcis+ 13).

Case 3. Statistical study in the Galactic scale

~ Galactic structure of the *B* field ~

'MAGMO' project through Zeeman splitting of OH masers



- MAGMO : the Magnetic field of the Milky Way through OH masers (e.g., Green+ 12)
  - Pilot survey : 6 high-mass sources 280<l<295°, $|B_{||}|$~1-10 mG, Same orientation

4. Summary

Summary

✓ ***B*** field observations of the masers is usable

- Narrower line-width and brighter emission than thermal one
- Pumped in compact dense cloud (10^6-10^{11} /cc)
- Both linearly and circularly polarized (full stokes *I, Q, U, V*)
- Combined with dynamics (3D velocity structure) information

✓ Remarkable works of the maser ***B*** field obs.

- W75 N : short-lived, isotropic, ionized wind in the strong ***B*** field whose morphology evolves into elongations (e.g., Surcis+ 14; Carrasco-Gonzalez+ 15)
- Statistical study (e.g., Surcsis+ 12, 13, 15; Green+ 12)
  - in the star formation scale : Alignment of the B field along the outflow axes
  - in the Galactic scale : Zeeman splitting measurements throughout the Milky Way 'MAGMO'