Magnetic field generated by the extreme oxygen-rich red supergiant resides in HII region

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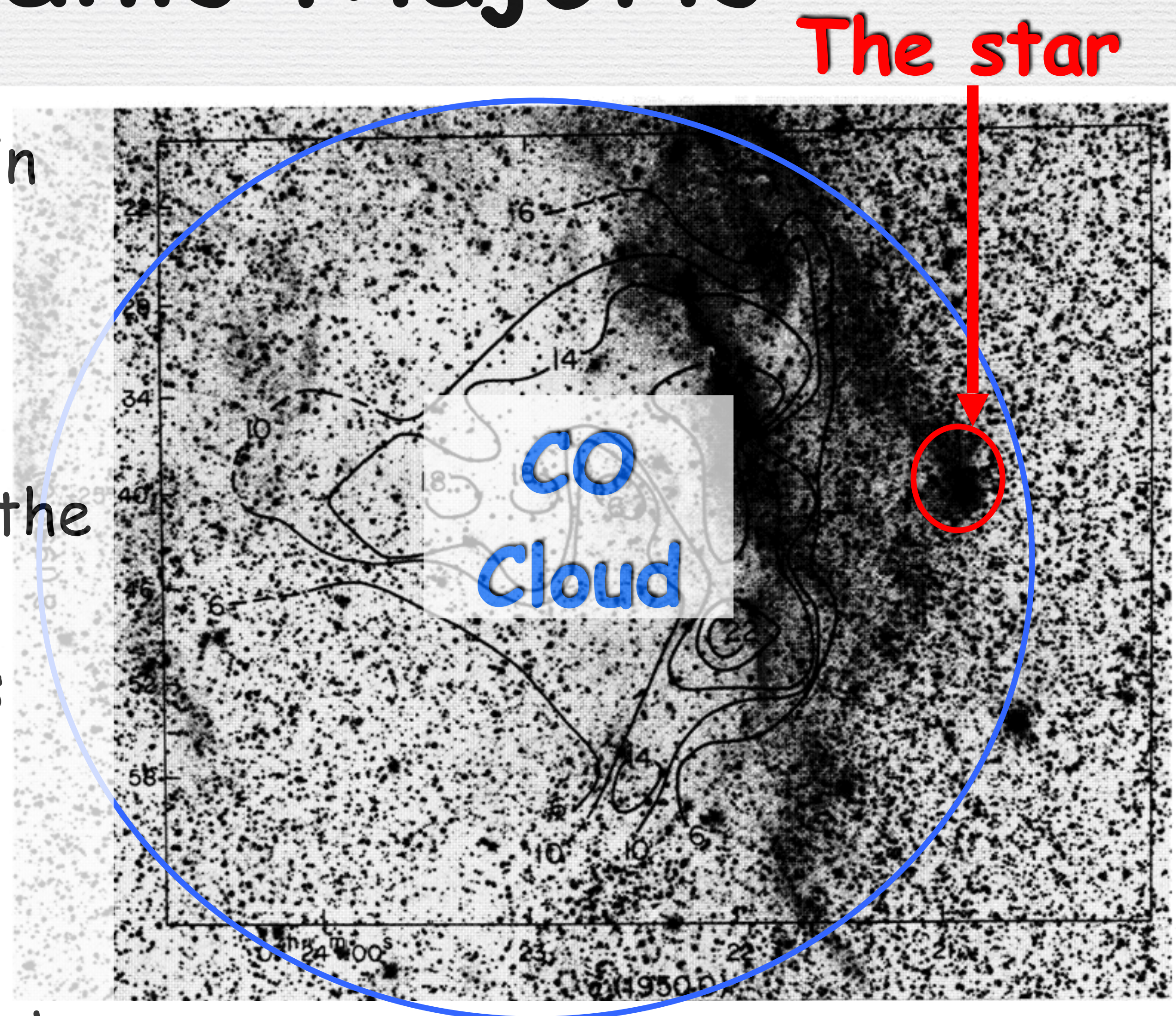
Outline

- We measured circumstellar magnetic field of an extreme red supergiant (RSG) VY CMa (25 Msun).
- Magnetic field is turned out to be very strong (up to 150-650G, at least ~10G) within 20 — 80 R_* from the star
  - Due to large expanded stellar envelope, RSGs were expected not to generate strong field.
- At least for VY CMa, powerful dynamo processes must be still active to generate intense magnetic field.

VY Canis Majoris

- Edge of huge (5 deg in diameter) HII region Sharpless 310 (5Myr; open cluster).
- Still near the rim of the parent cloud.
- Asymmetric nebula is found at optical and infrared.
- Complicated dust structure surrounding the source.



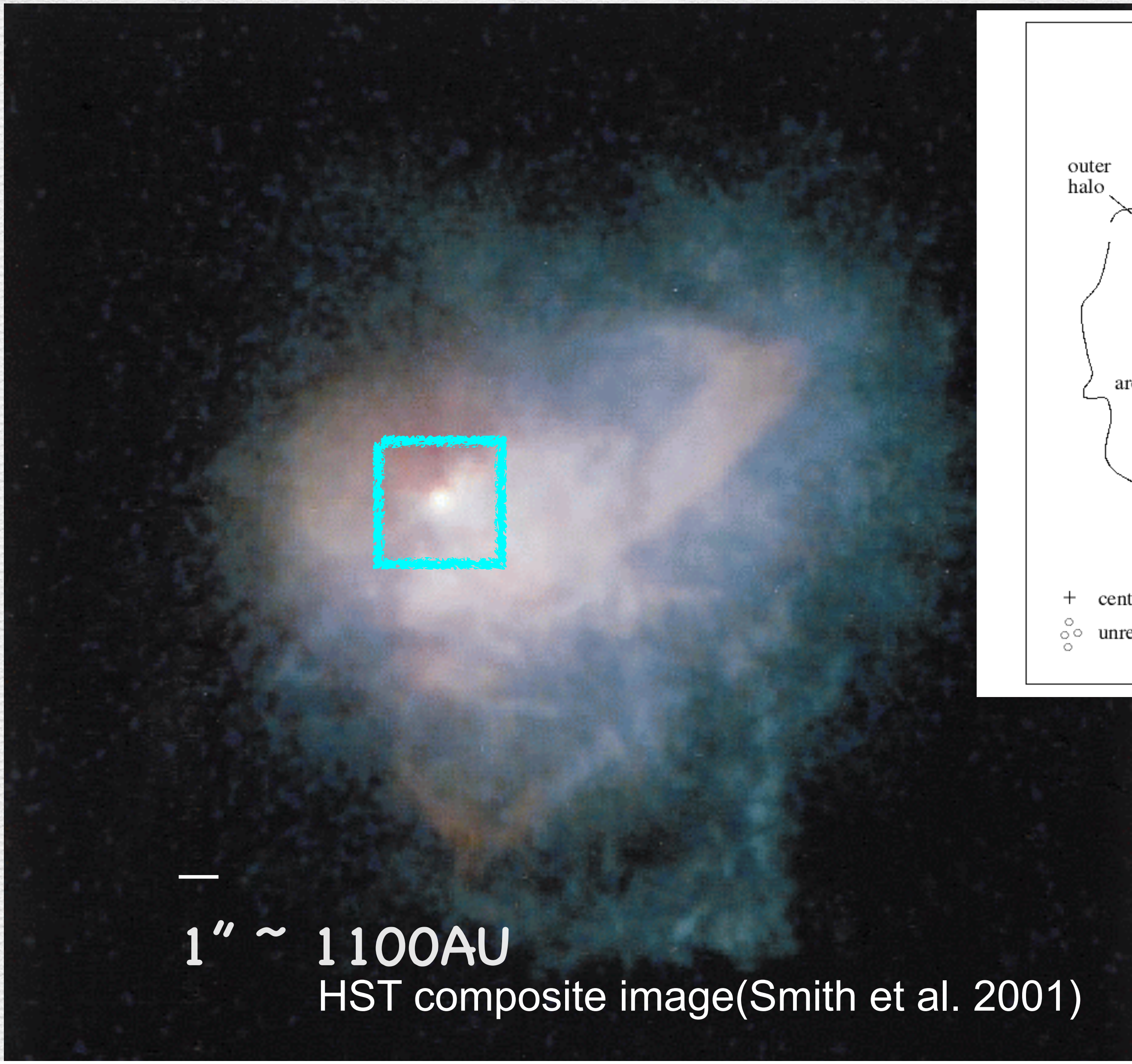
Contours..CO; Grey scale..K band

(Lada&Reid1973)

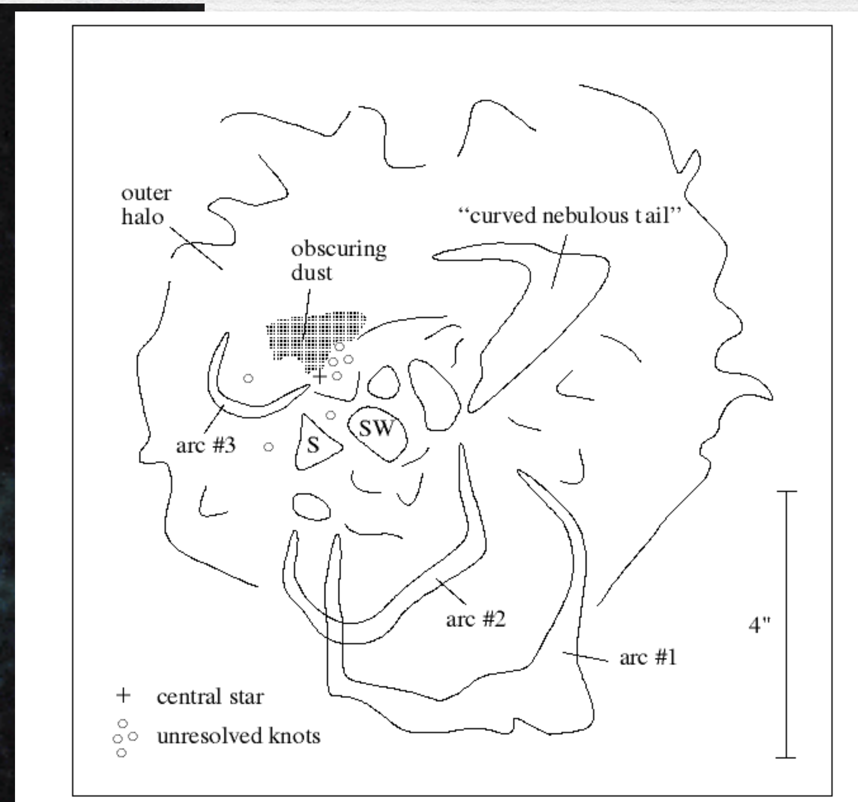
VY Canis Majoris

- M-type red supergiant (M5 Ib)
- Distance of 1.14 kpc (Choi+'08 by VERA)
  - $M_* \sim 25M_{sun}$
  - $L_* \sim 5 \times 10^5\ L_{sun}$
  - $R_* \sim 1400\ R_{sun}$ (~ 6.6AU)
  - $T_* \sim 3500$ K
  - Extremely high mass loss rate 3×10^{-4} Msun/yr
  - Very complex dust features surrounding the star

VY Canis Majoris

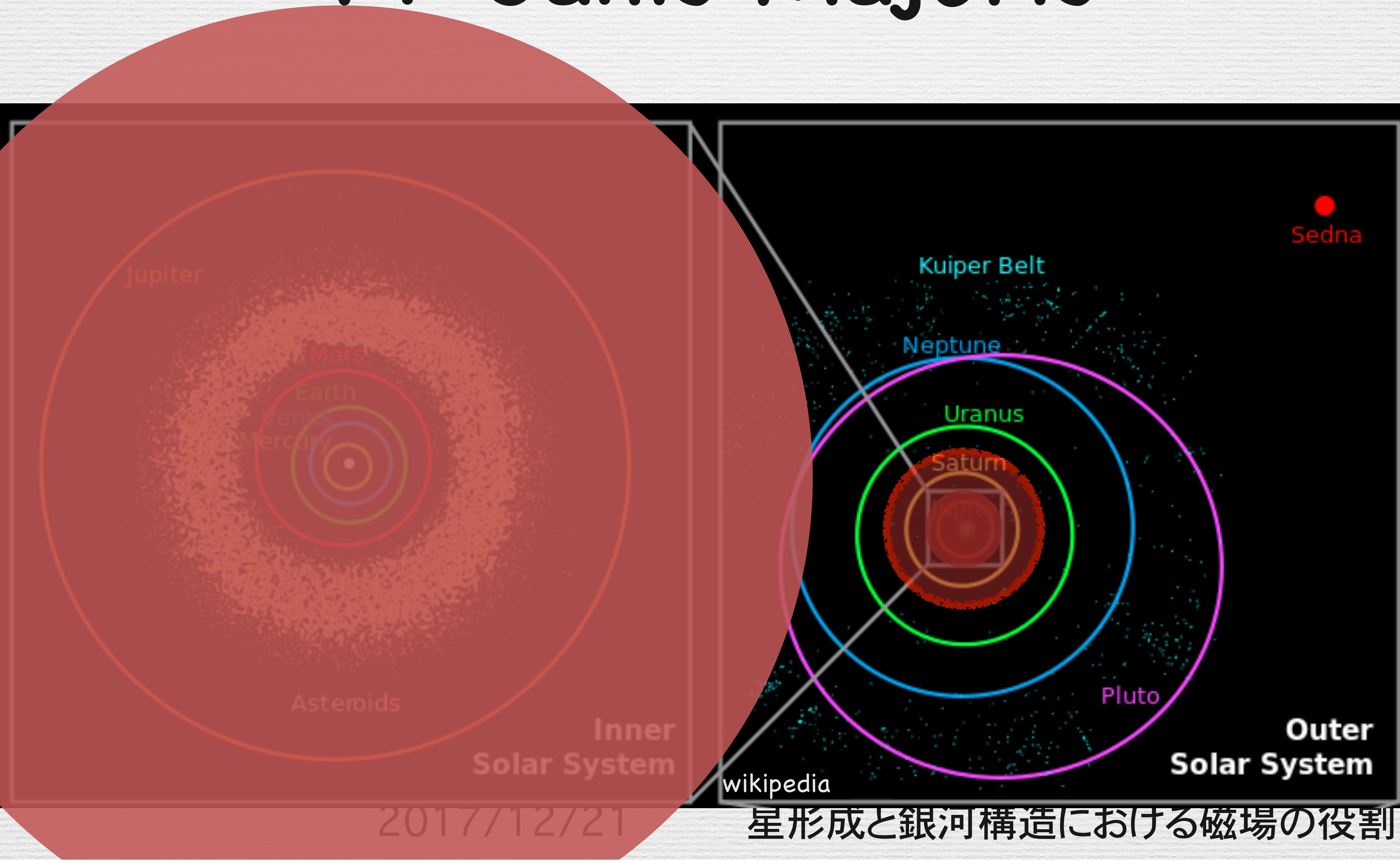


HST composite image(Smith et al. 2001)



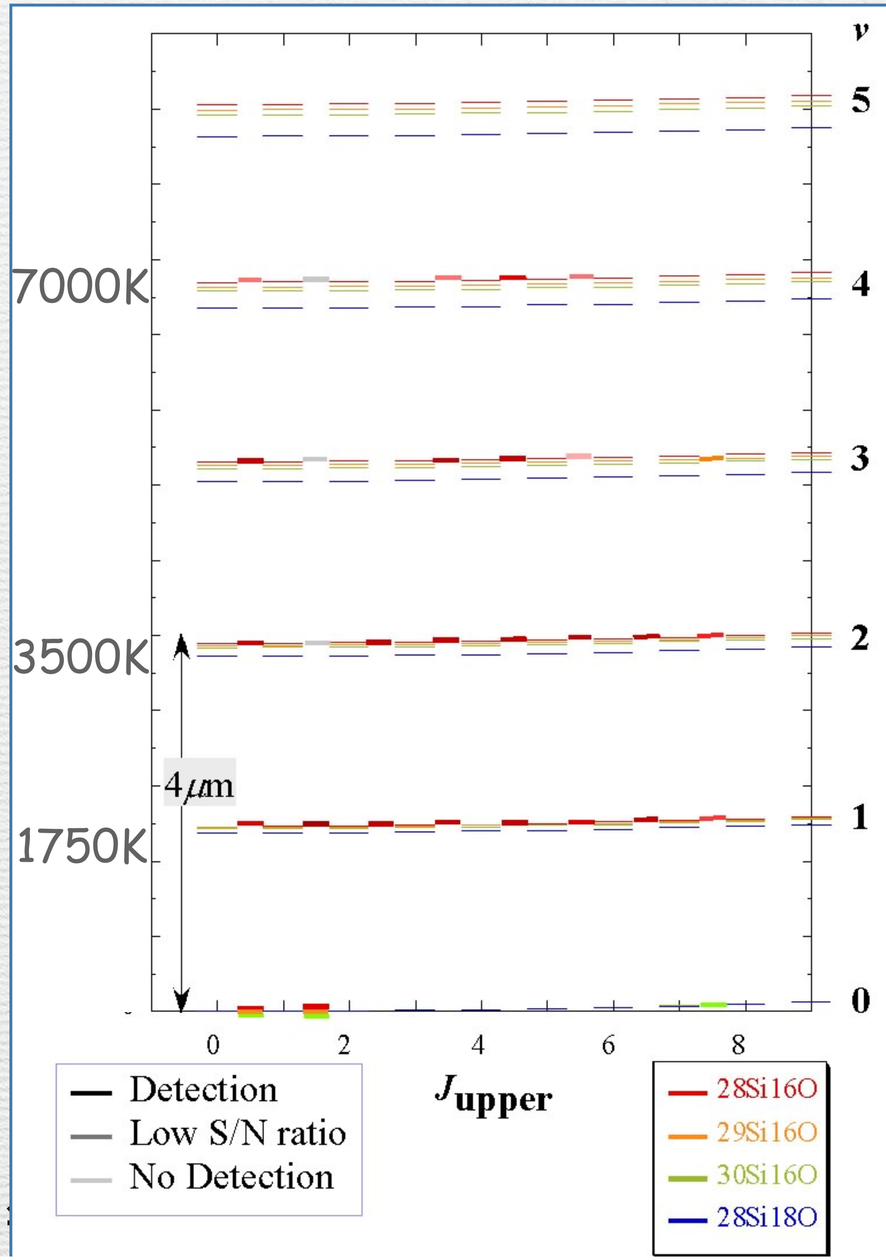
Sketch of dust features (Smith et al. 2001)

VY Canis Majoris



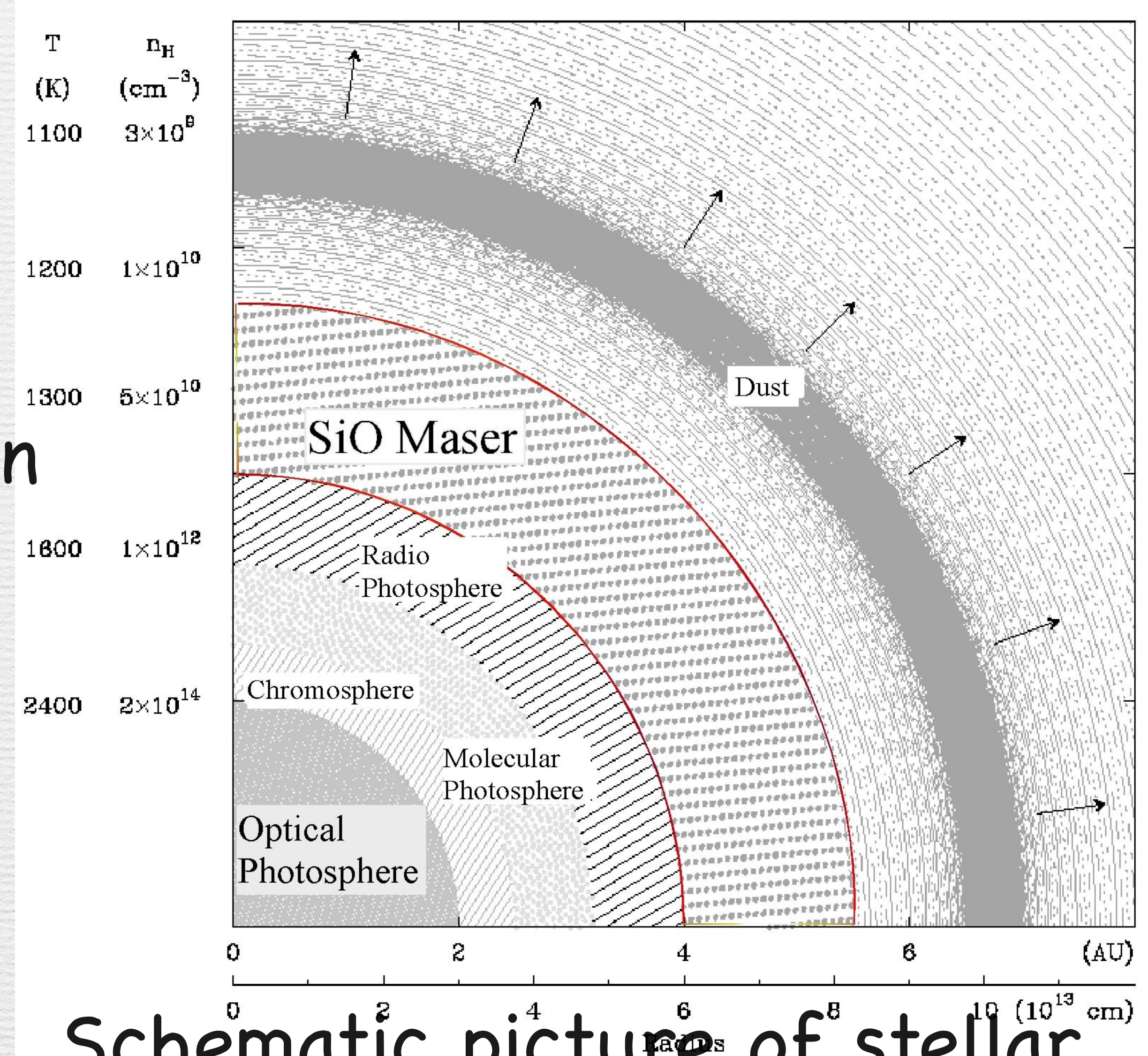
Highly Excited SiO Transitions

- SiO rotational transitions at different vibrational states have been observed towards the source
- Many of SiO transitions are highly linearly polarised.



SiO v≧1 maser: Above radio photosphere

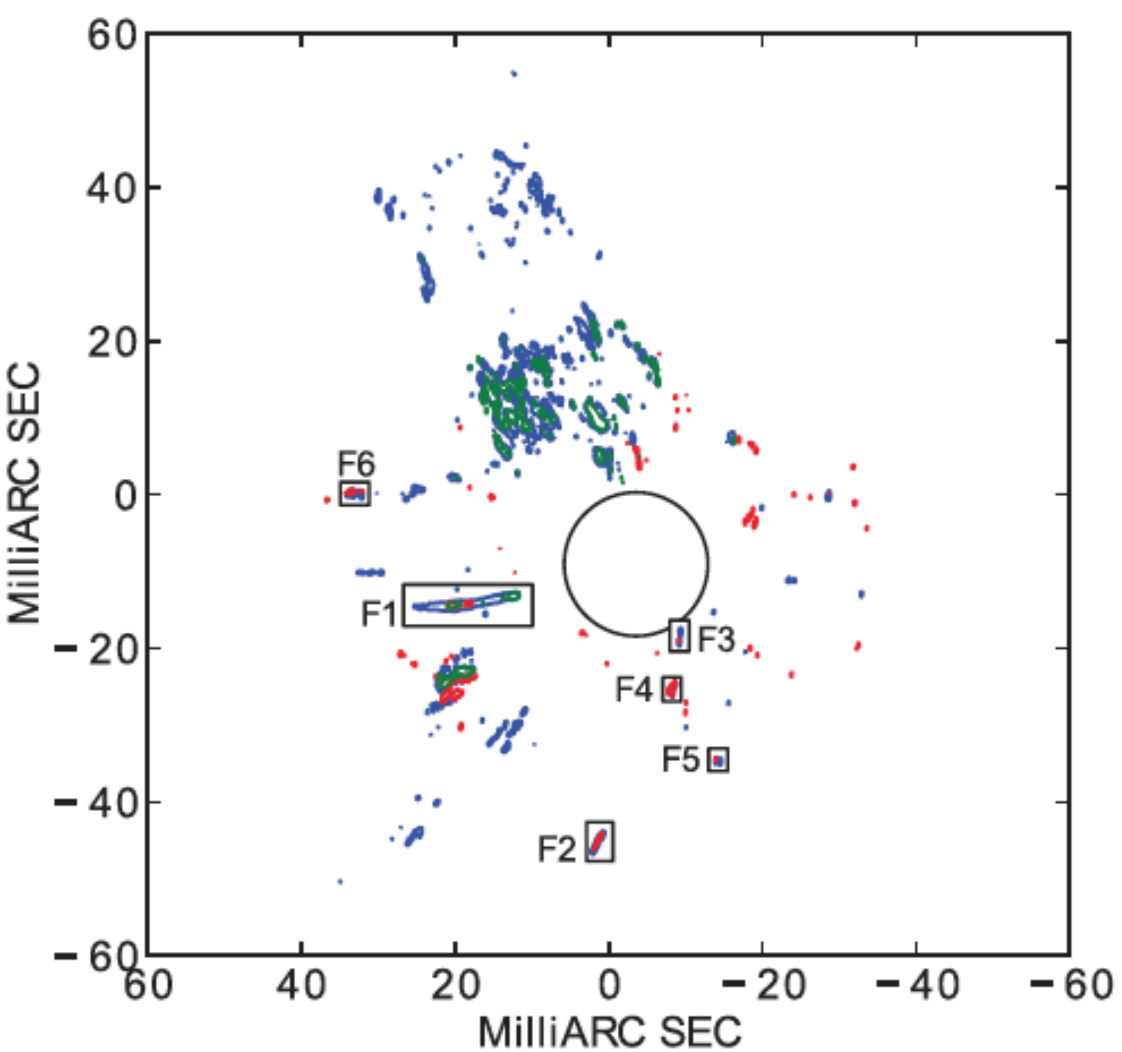
- SiO v≧1 rotational emission traces inner edge of the circumstellar region
- Just above the photosphere
- The pumping mechanism still remains unclear.



Schematic picture of stellar atmosphere (Reid&Menten'97)

SiO v≧1 maser: Above radio photosphere

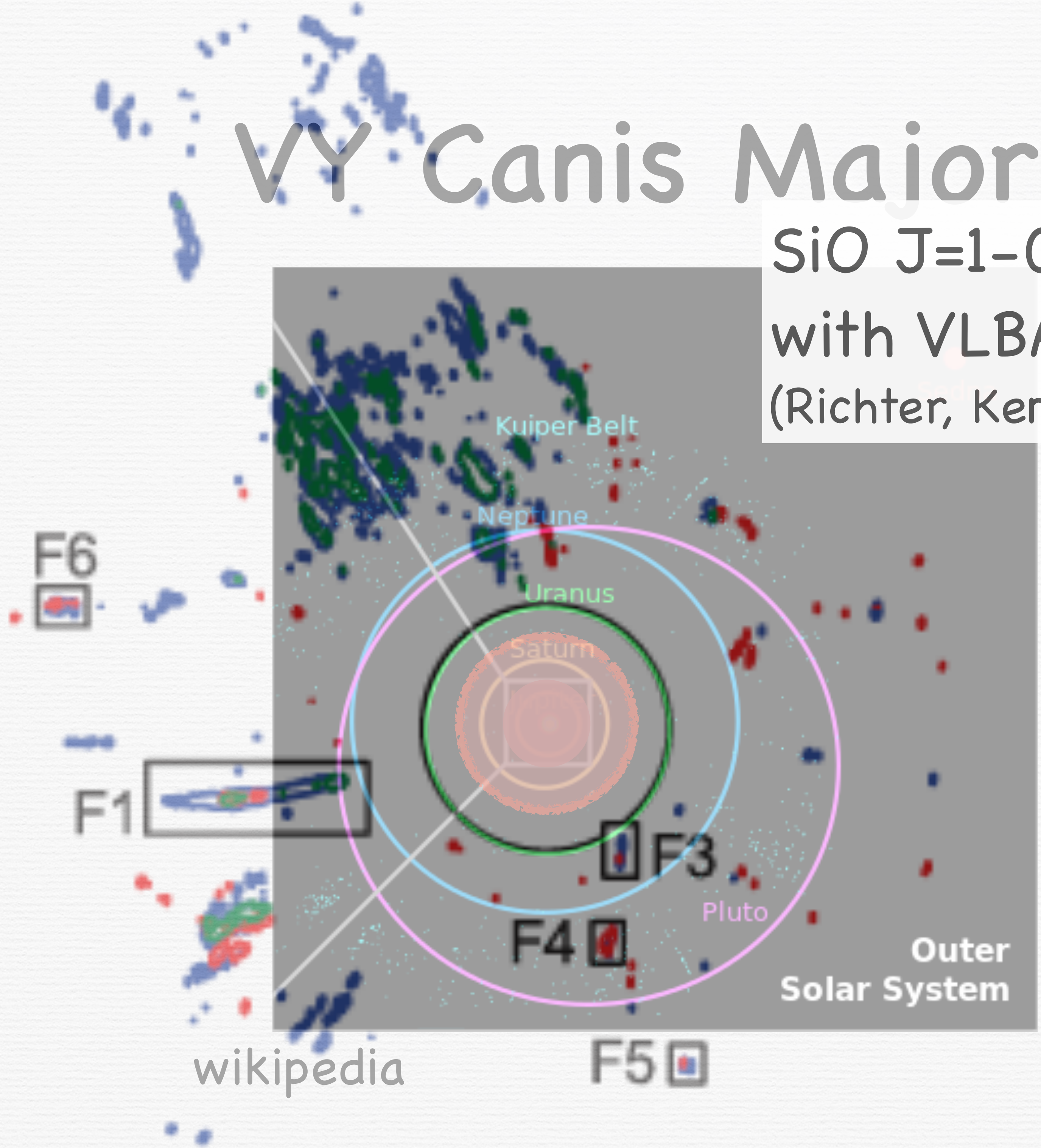
- SiO v≧1 rotational emission distributes in irregular manner
  - far different from circular distribution
  - not mainly from stellar radiation



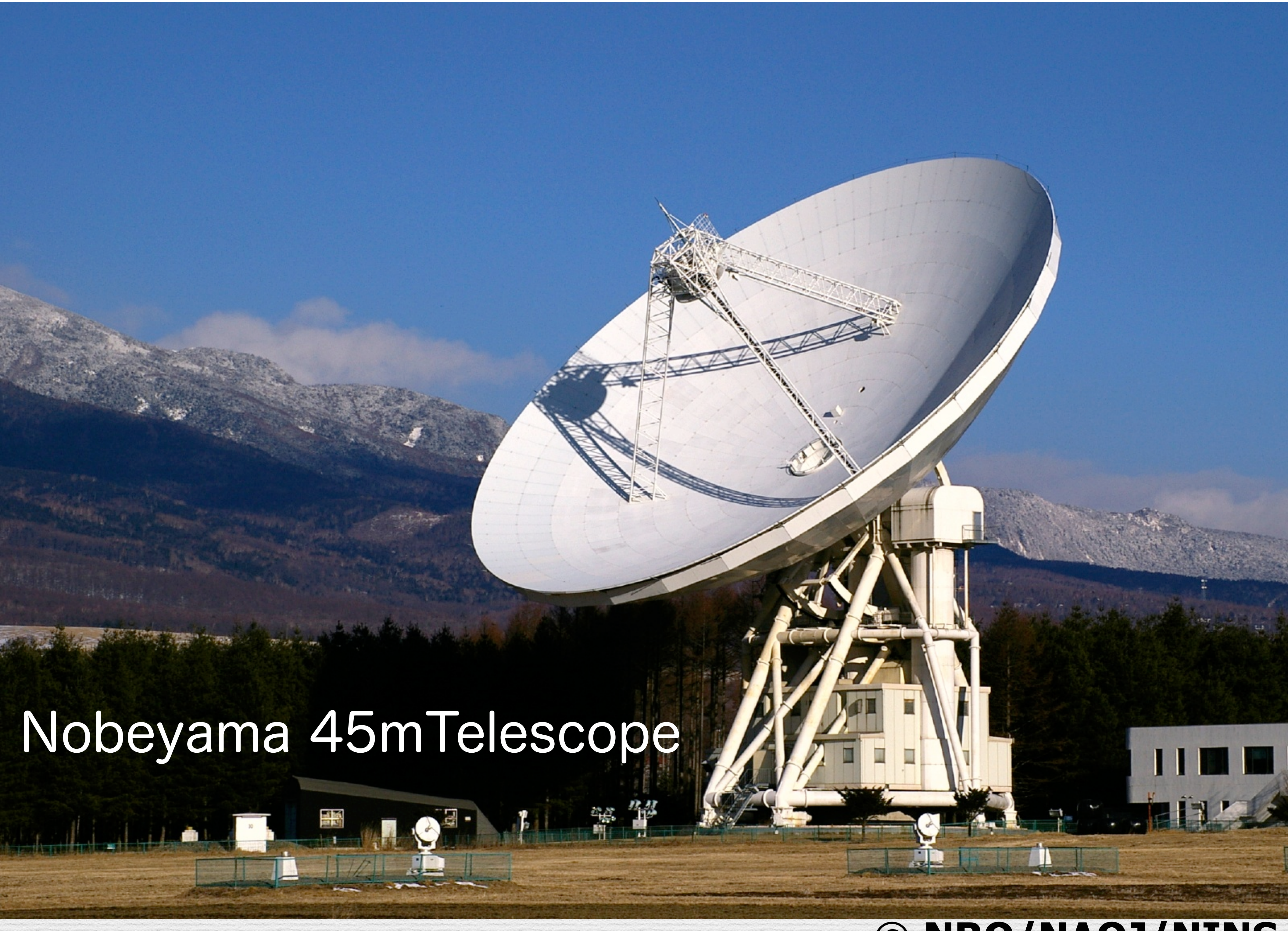
SiO J=1-0(blue v=1/green v=2), 2-1(red) in v=1 with VLBA (Richter, Kemball, Jonas 2016)

VY Canis Majoris

SiO J=1–0, 2–1 in v=1,2
with VLBA
(Richter, Kemball, Jonas 2016)

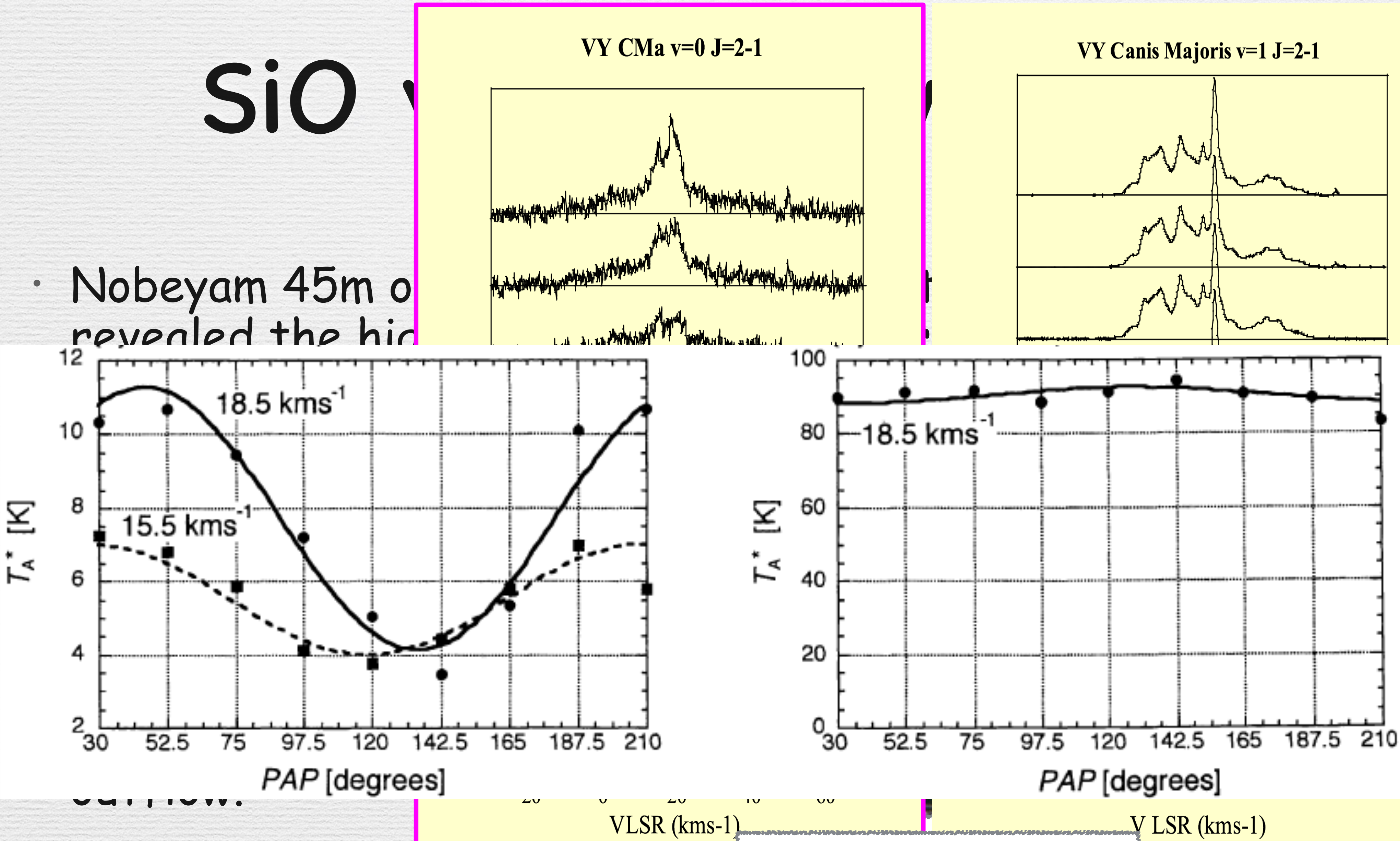


wikipedia

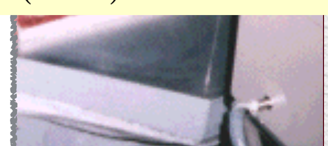

Nobeyama 45mTelescope

SiO v

- Nobeyam 45m o
  revealed the hig
  outflow.
- Indicate well-ordered



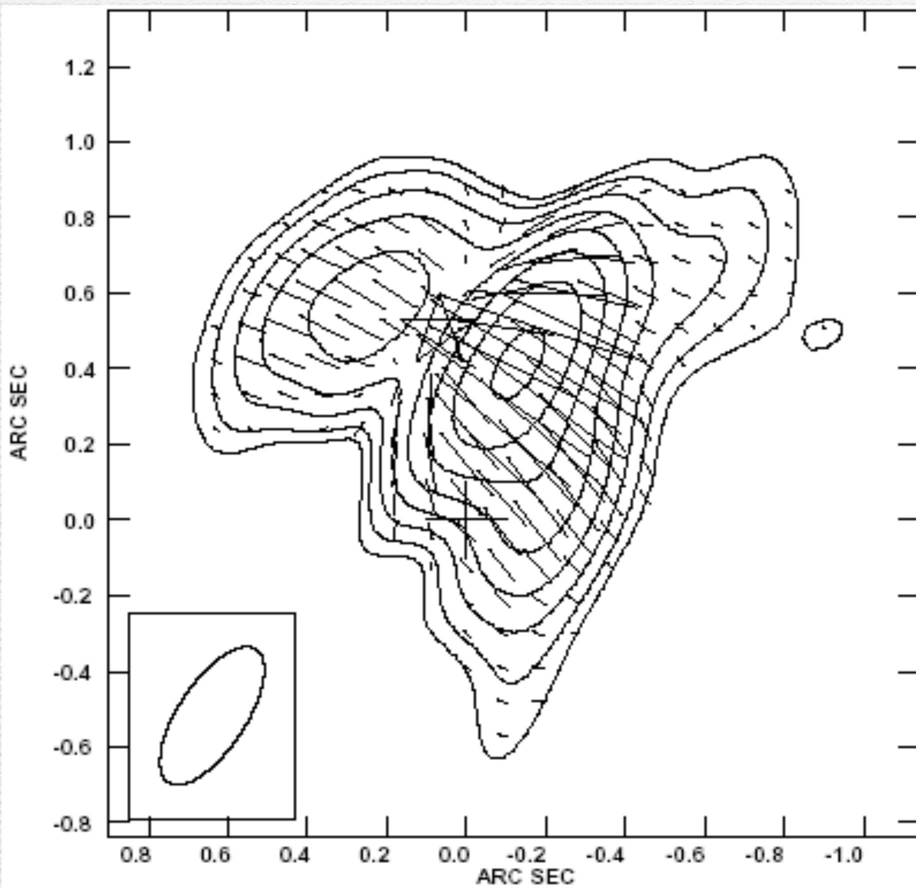
Millim (Shinnaga+'99) er
(Shinnaga+'99)



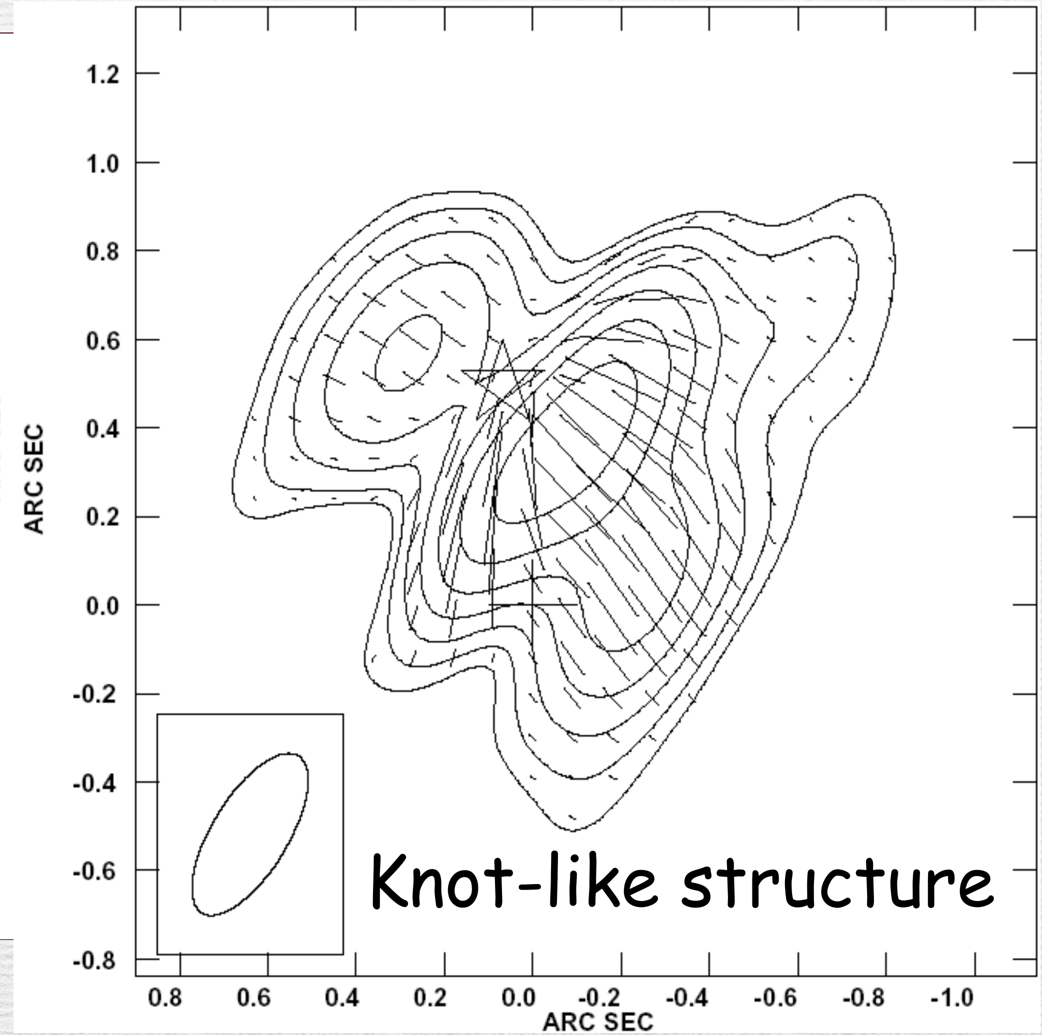
2017/12/ る磁場の役割


Very Large Array at NRAO
© NRAO

SiO v=0 Observations



Butterfly-shape outflow
(Shinnaga et al. '03)



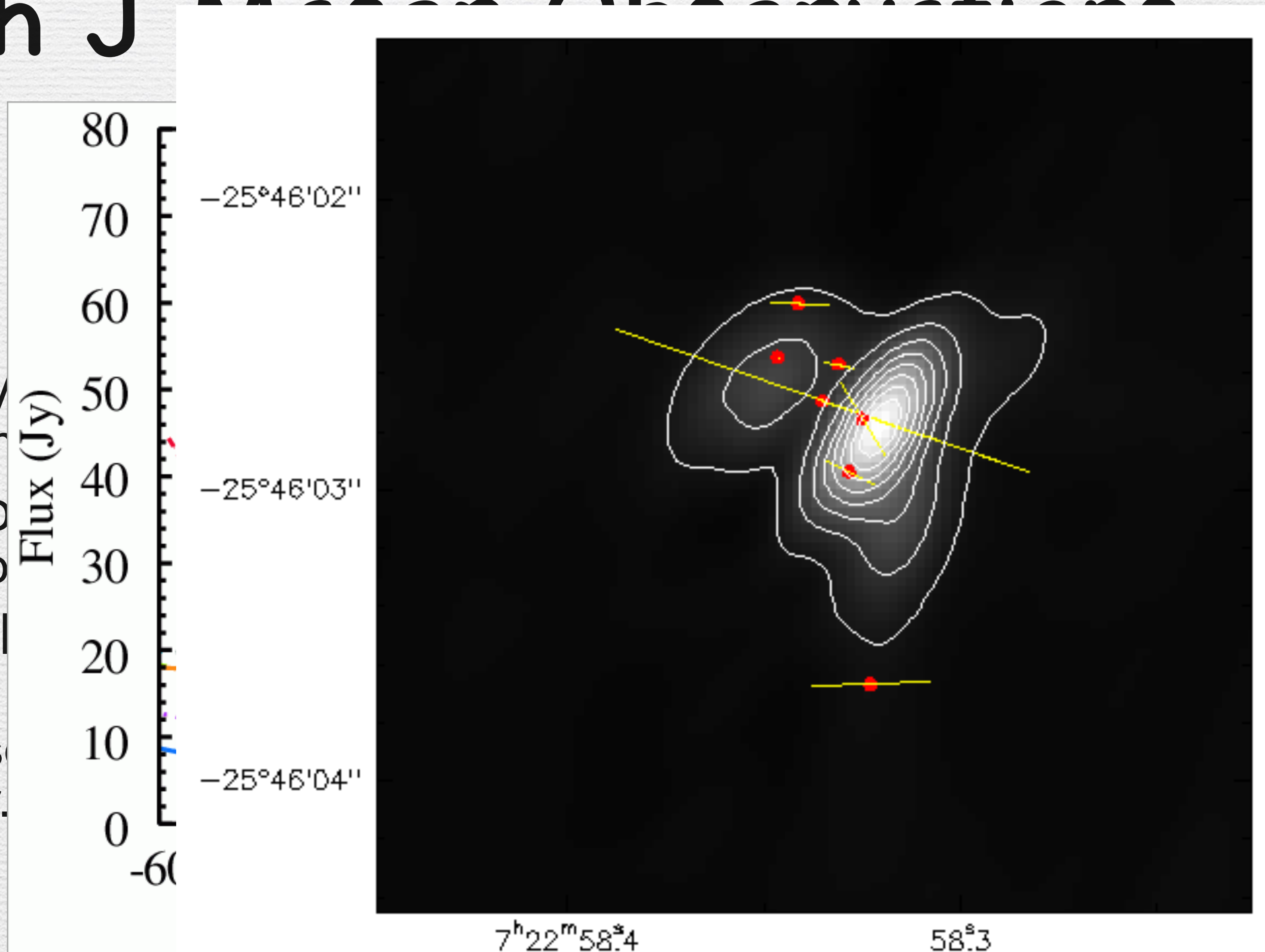
Shinnaga et al. '03

SiO High J Maser Observations

- SiO high J maser transition (5-4, v=1) with SMA
  - 215.596 GHz (1.39mm)
- 3 Antennas
  - 6.25 – 18.12 kλ
- Dec 2002.
  - Δv = 0.5 km/s.
  - Δf = 358 kHz

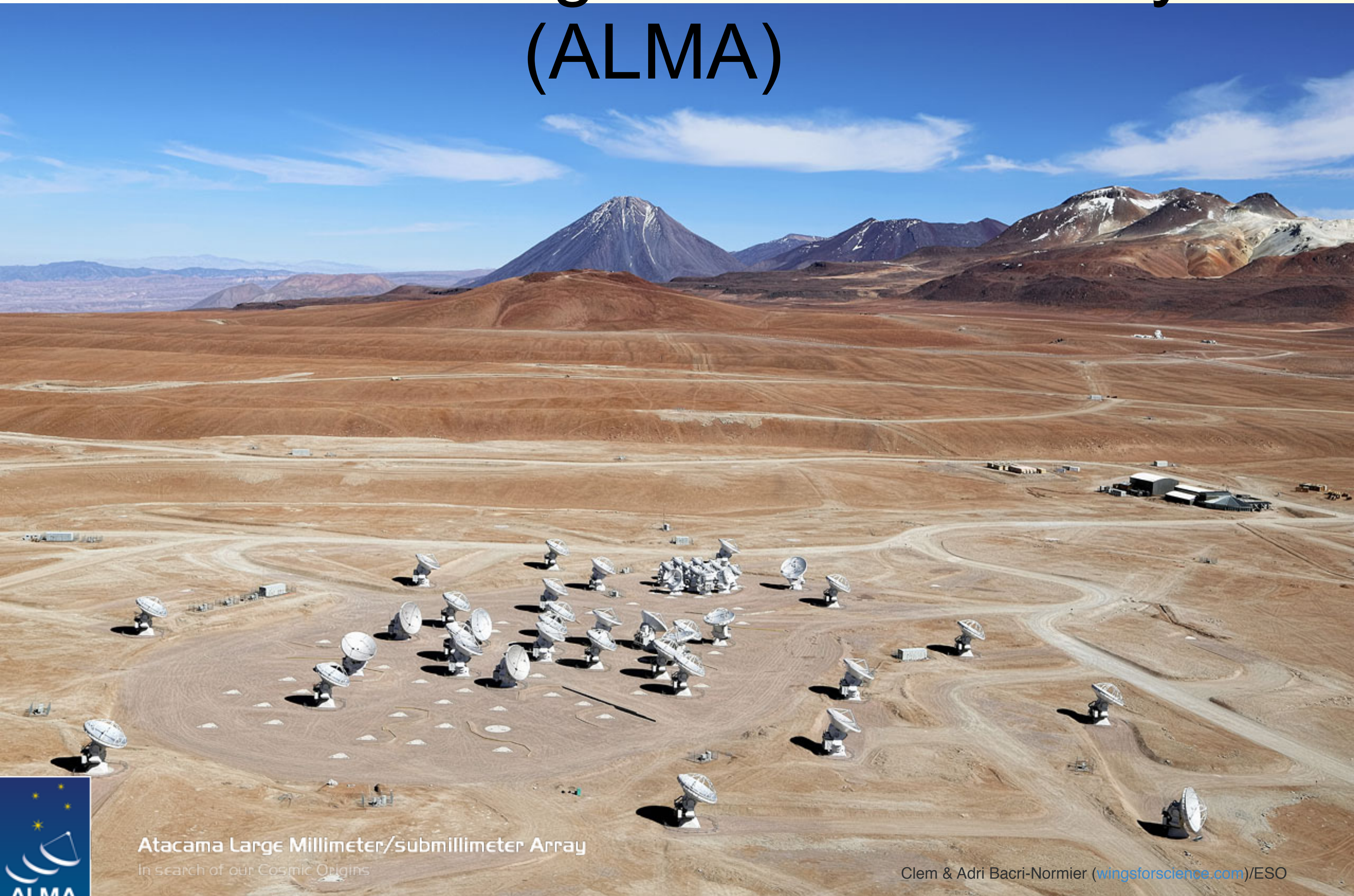
SiO High J

- Broad velocity
  - over > ~60km
- Main 7 compo
  - Spiky line pro
- Comp. 2 → l
  prominent.
  - Must be close
  the central star.



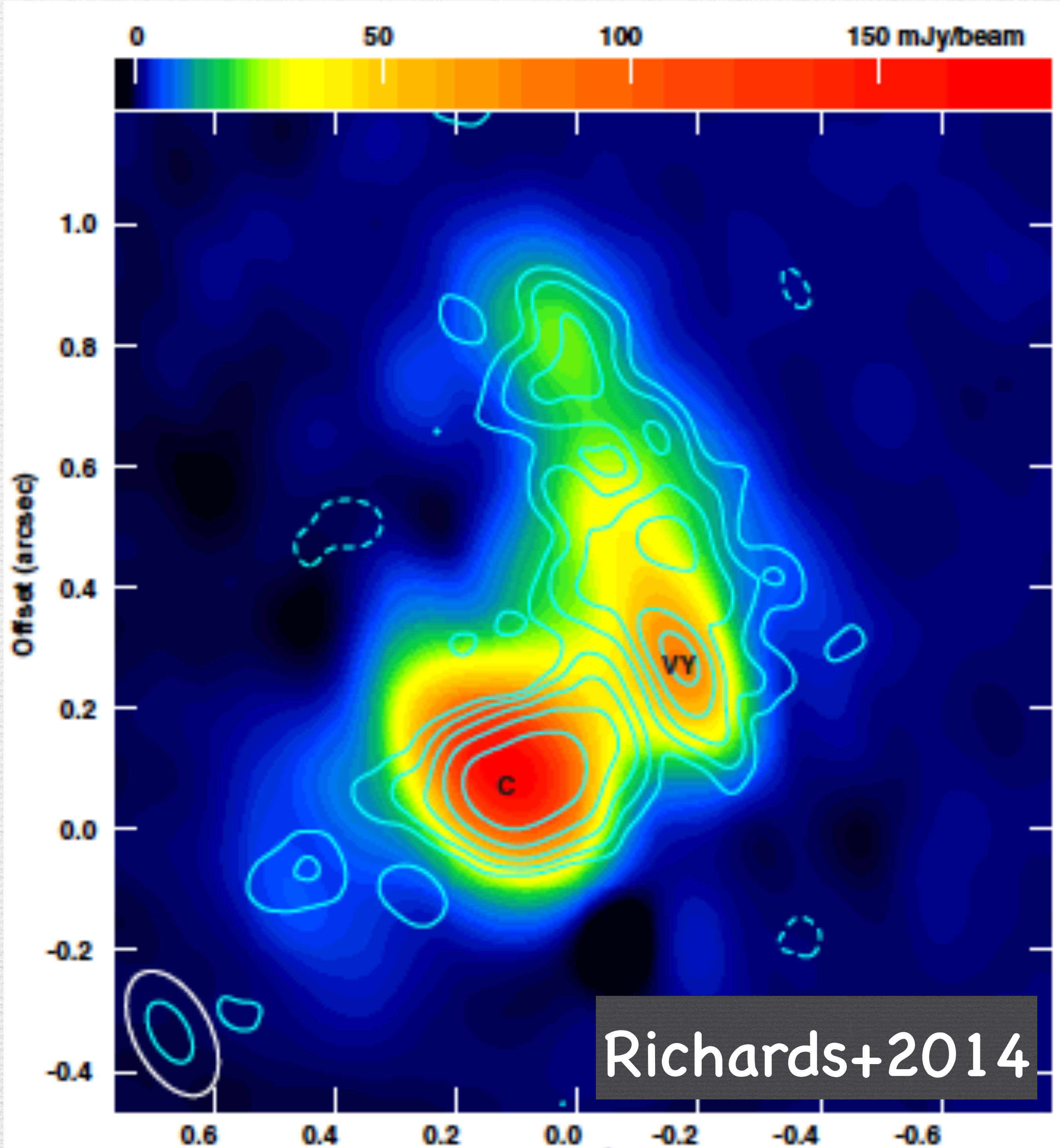
Shinnaga+2004

Atacama Large Millimeter Array (ALMA)

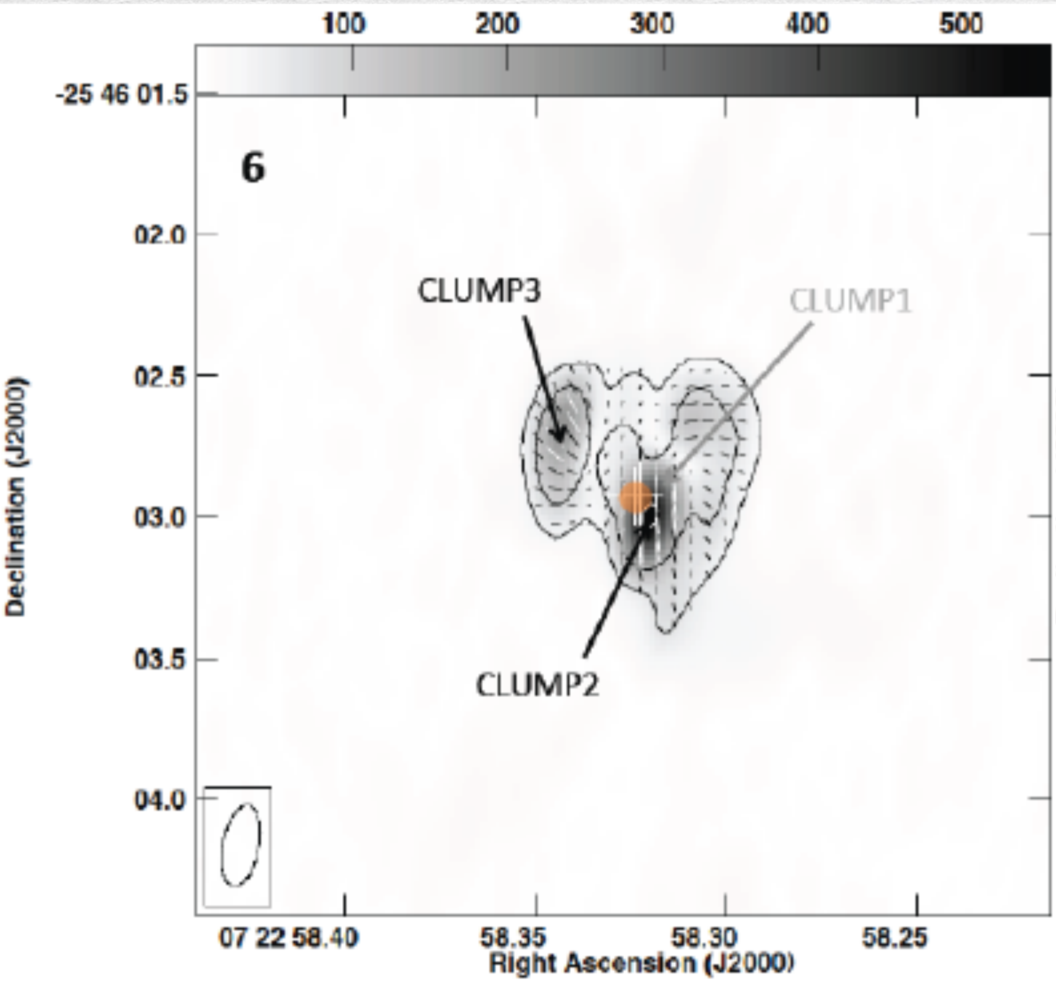


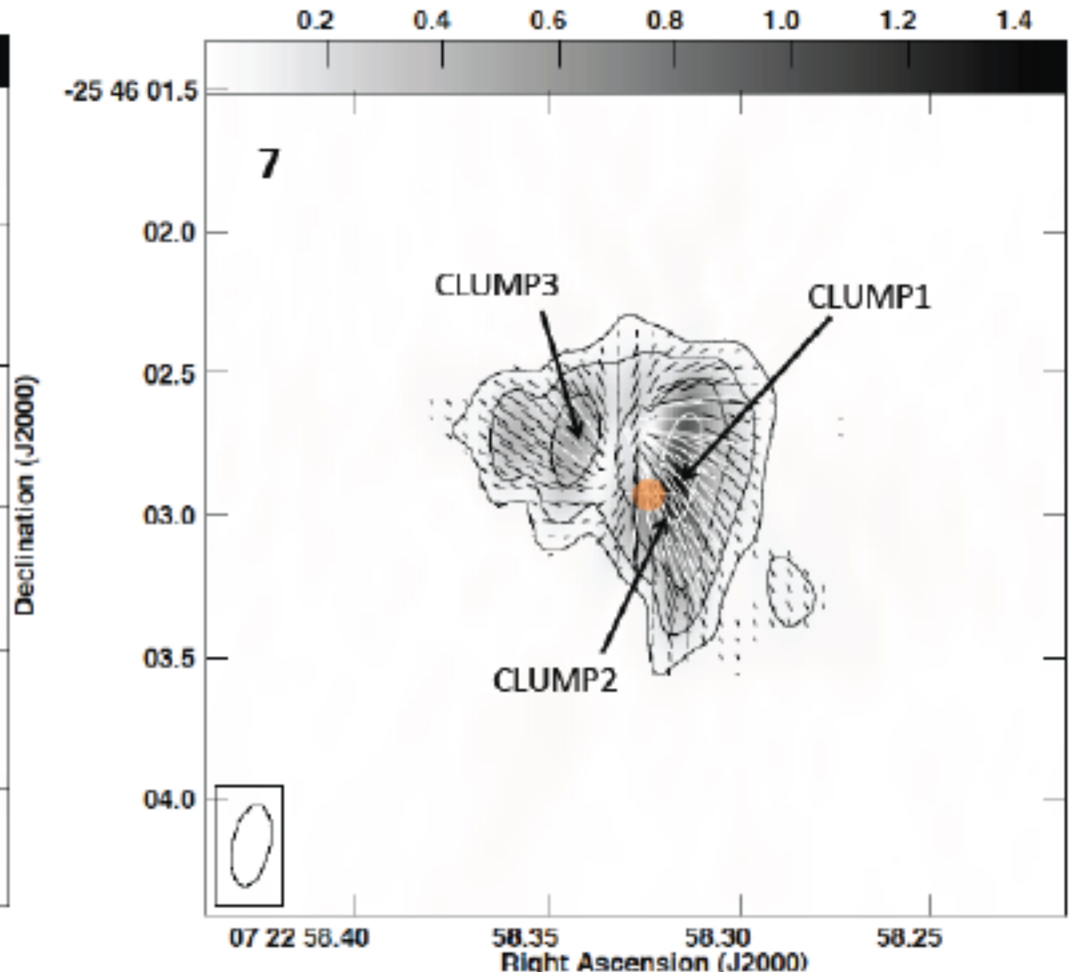
Clem & Adri Bacri-Normier (wingsforscience.com)/ESO

Color scale: 321GHz continuum
Contours: 658GHz continuum



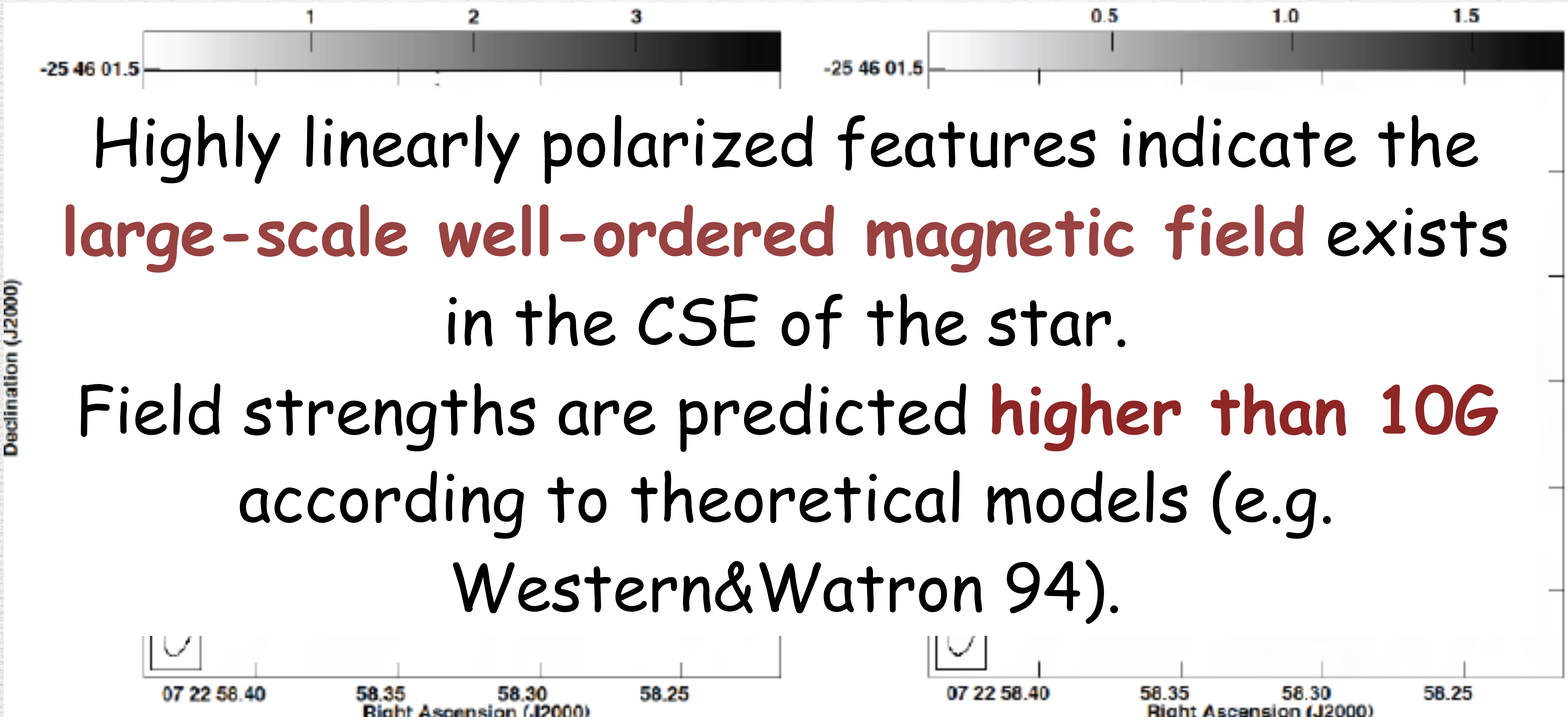
SiO v=0 : inner CSE





Shinnaga et al. 2017

SiO v=0 : inner CSE



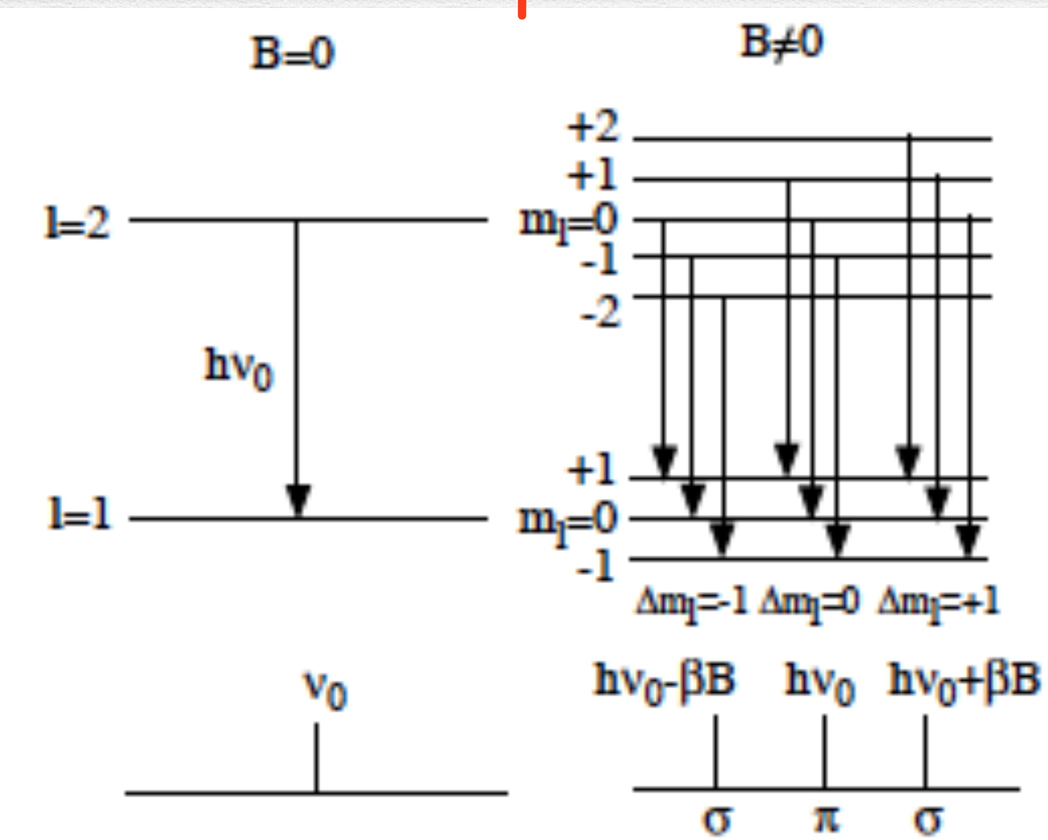
Highly linearly polarized features indicate the **large-scale well-ordered magnetic field** exists in the CSE of the star.

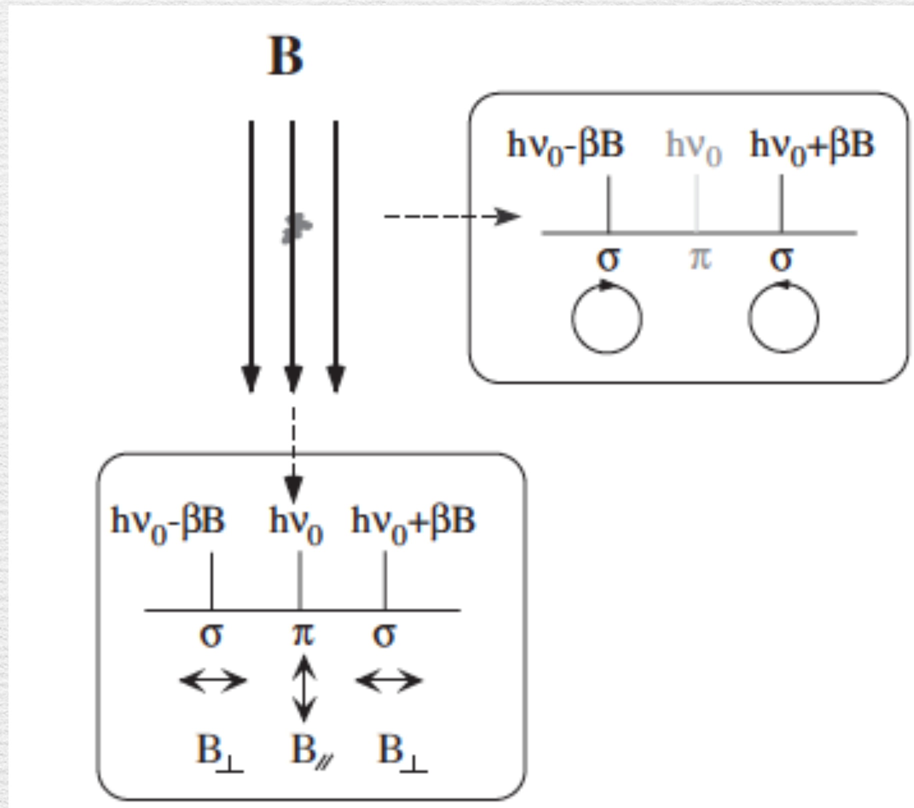
Field strengths are predicted **higher than 10G** according to theoretical models (e.g. Western&Watron 94).

Shinnaga et al. 2017

Zeeman Effect

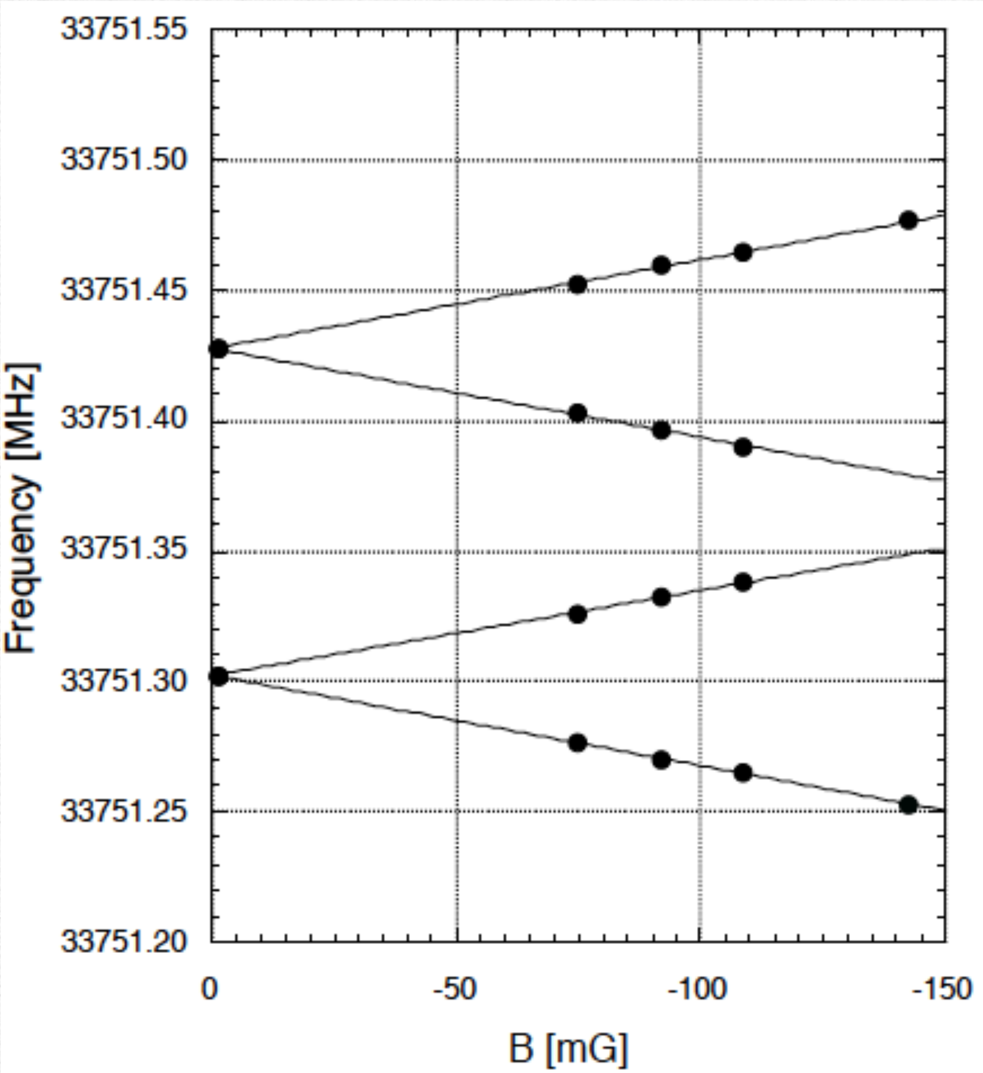
The only method to measure the LOS field strength without assumption

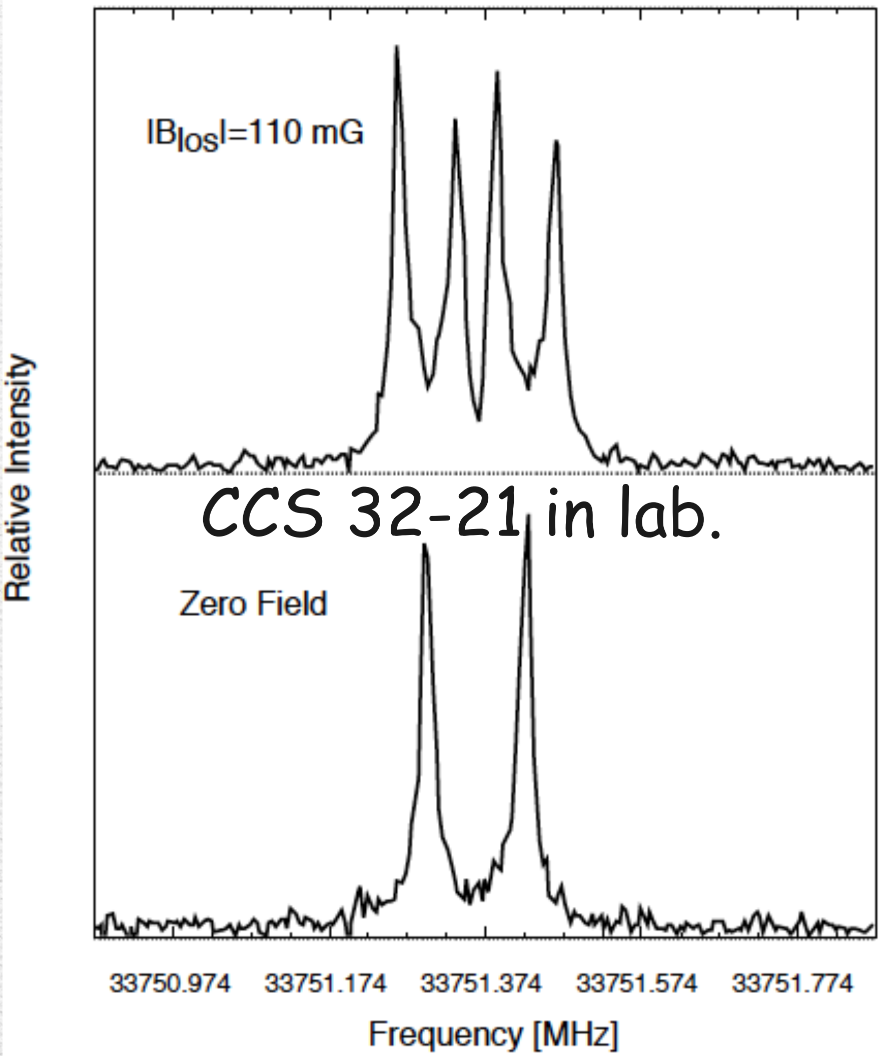




Shinnaga+ 2008

Zeeman Effect





CCS 32-21 in lab.

Shinnaga&Yamamoto '00

Zeeman Effect

ZEEMAN SPLITTING OF LOW ROTATIONAL TRANSITIONS OF SO RADICAL[a]

J'	$N' \rightarrow J''$	N''	ν^b (MHz)	This Paper (Hz μG^{-1})	Bel & Leroy[c] (Hz μG^{-1})
1	$0 \rightarrow 0$	1	30001.630	1.740	$\leq 10^{-3}$
2	$1 \rightarrow 1$	0	62931.731	1.379	...
3	$2 \rightarrow 2$	1	99299.875	1.043	1.0
4	$3 \rightarrow 3$	2	138178.548	0.800	0.8
5	$4 \rightarrow 4$	3	178605.168	0.634	...

[a] Zeeman splitting is defined as $2\Delta\nu B^{-1}$.
[b] Tiemann 1974.
[c] Bel & Leroy 1989.

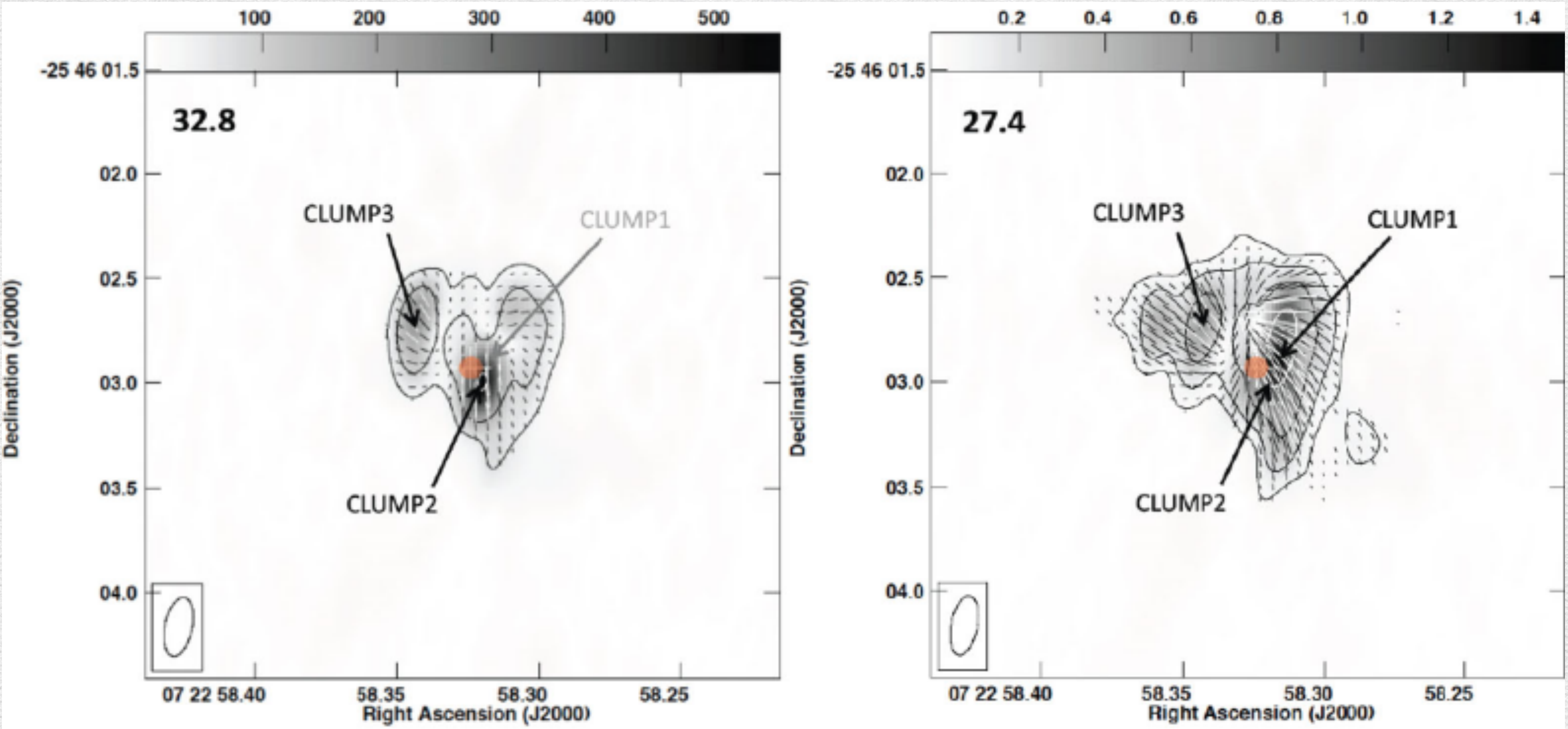
Shinnaga&Yamamoto '00

Zeeman splitting of SiO v=0 J=1-0 :

2.3×10^{-4} Hz/uG

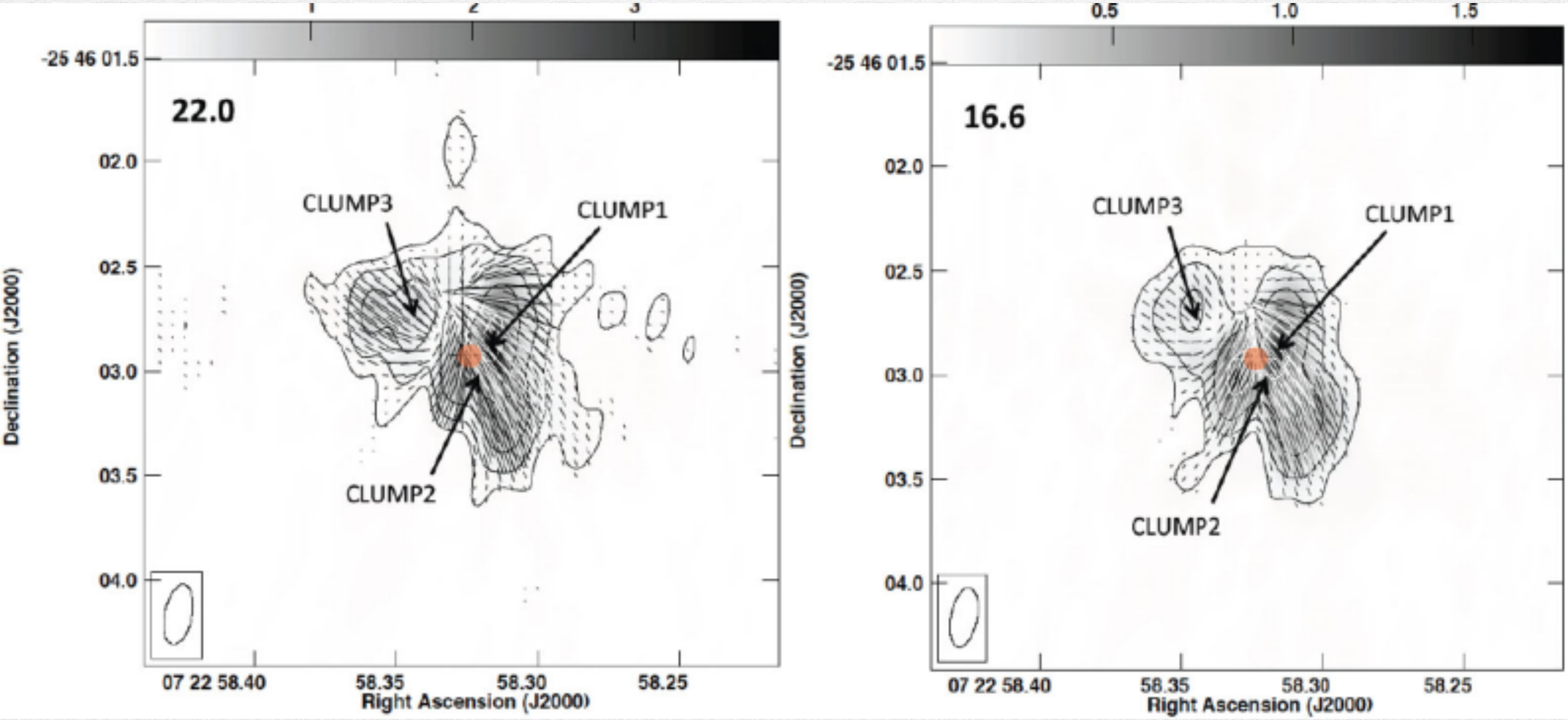
(Honerjäger &Tischer'74)

SiO v=0 : inner CSE



Shinnaga et al. 2017

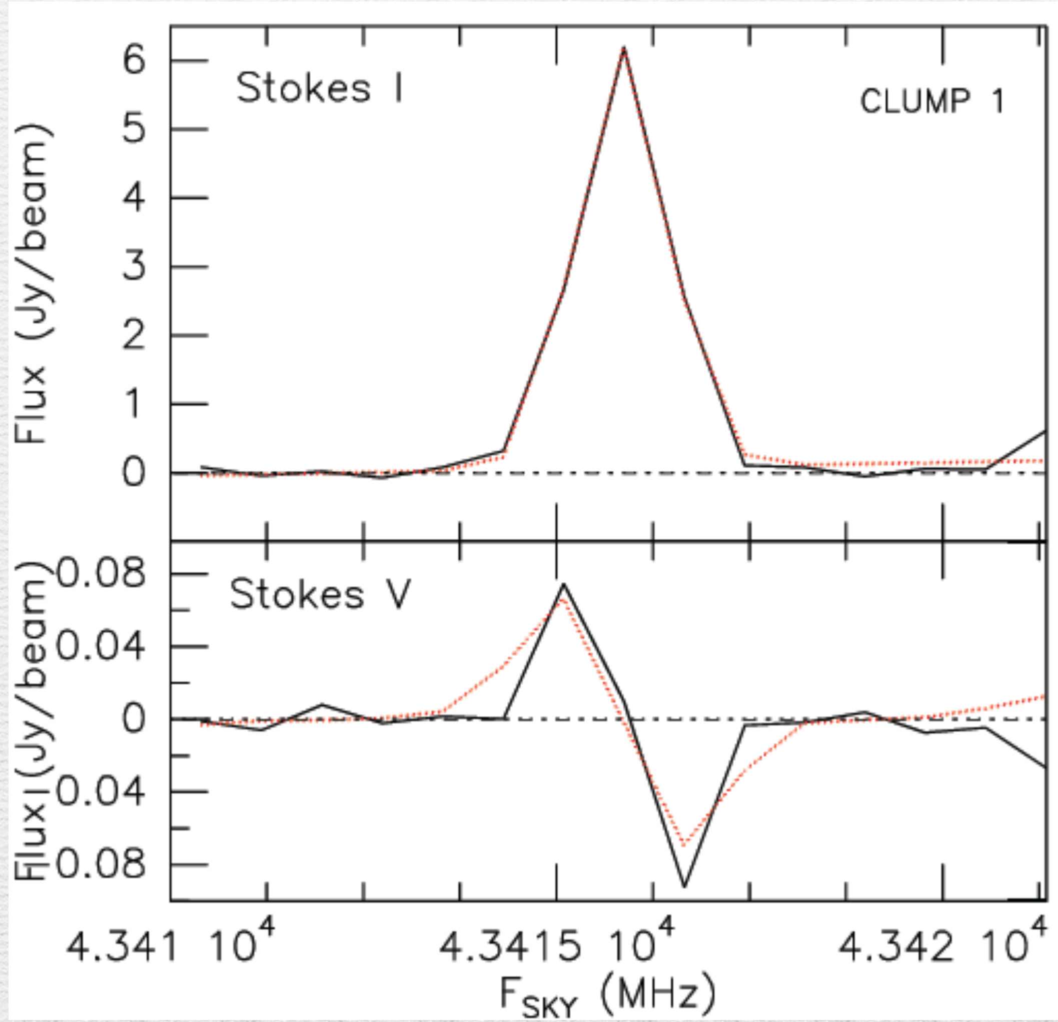
SiO v=0 : inner CSE



Shinnaga et al. 2017

SiO v=0 Strong Magnetic Field

- Zeeman shift was detected towards three clumps
- Field strengths ranging from 150 — 650G
  - within 500AU from the central star



Shinnaga et al.2017

SiO v=0 Strong Magnetic Field

Table 1. Parameters of SiO $v = 0$, $J = 1$–0 clumps identified in the observed field.*

ID	Position (J2000.0)	Peak intensity [Jy beam^{-1}]	Zeeman splitting (error) [kHz]	B strength (error) [G]	Line width† (error) [kHz]	Distance‡ [$R_{*\mathrm{Optical}}$]
Clump 1	$7^h22^m58^s.3137$, $-25°46'02''.80$	6.20	35 (6)	153 (26)	$\lesssim$860 (310)	46 (272 mas; 310 au)
Clump 2	$7^h22^m58^s.3182$, $-25°46'02''.94$	3.91	39 (14)	169 (61)	$\lesssim$960 (270)	20 (121 mas; 138 au)
Clump 3	$7^h22^m58^s.3418$, $-25°46'02''.66$	1.07	150 (21)	652 (91)	1900 (60)	80 (461 mas; 526 au)

*There is 35 mas uncertainty in the VY position and about twice the positional uncertainty for Clumps 1–3.
†Line width of FWHM.
‡Distance from VY (stellar position).

SiO v=0 Strong Magnetic Field

- Assuming magnetic configuration to (r^{-1} ; toroidal), max of 50kG of stellar B is estimated.
  - c.f 20kG was detected towards high-mass (30Msun) star NGC1624-2 (Wade +'12)

Shinnaga et al.2017

SiO v=0 Strong Magnetic Field

- Supergiant has a convective shell around the helium core, the convective shell may play a critical role in generating the strong magnetic field, with an extraordinarily high mass-loss rate (Shenoy et al. 2016).

Shinnaga et al.2017

Summary

- VY CMa has a intense magnetic field, evidenced by Zeeman effect of SiO v=0 line (the first detection ever!) along with well-organized large-scale magnetic field.
- Contrary to the expectation, magnetic field of RSG, progenitor of core-collapse supernova, is turned out to be very strong.
- At least for VY CMa, powerful dynamo processes must be still active to generate intense magnetic field.