

Maser Polarization

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INAF - OACagliari

Collaborators:

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S.-W. ***Kim*** *(KASI, Republic of Korea); A.* ***Sanna*** *(MPIfR, Germany); A.* ***Bartkiewicz*** *(Nicolaus Copernicus Uni, Poland); et al.*

More about Maser Polarization

Session 1

Boy Lankhaar – *Quantum-chemical calculations revealing the effects of magnetic fields on methanol* ✓

Taylor Tobin – *Constraining Theories of SiO Maser Polarization: Analysis of a π/2 EVPA Change*

Session 2

Tim Robishaw – *Zeeman Splitting of OH Megamasers as a Probe of Magnetic Fields in Starburst Galaxies*

Session 4

Luca Moscadelli – *Masers as probes of the gas properties close to forming stars*

Ciriaco Goddi – *Measuring Magnetic Fields from Water Masers in the Synchrotron Protostellar Jet in W3(H_2O)*

Jihyun Kang – *Linear Polarization of Class I Methanol Masers in Massive Star Forming Regions*

Posters

N. 11 Daria Dall'Olio – N. 16 Eodam Hwang – N. 21 Gordon MacLeod – N. 24 Hiroko Shinnaga – N. 38 Kitiyanee Asanok – N. 42 Lucero Uscanga – N. 49 Olga Bayandina – N. 53 Soon-Wook Kim – N. 55 Thanapol Chanapote – N. 64 Yuta Kojima

OUTLINE

- INTRODUCTION
  - NEDOLUHA & WATSON 1992'S MODEL
- METHANOL MASERS
  - THEORETICAL RESULTS
  - OBSERVATIONAL RESULTS
- SIO MASERS
  - RED SUPERGIANT VY CMA
- WATER MASERS
  - W75N(B) – TO BE CONTINUED
- LOOK FORWARD

NEDOLUHA & WATSON 1992'S MODEL

Paramagnetic molecules: OH

Non – Paramagnetic molecules: H_2O, CH_3OH, SiO

1992ApJ...384..185N

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THE ZEEMAN EFFECT IN ASTROPHYSICAL WATER MASERS AND THE OBSERVATION OF STRONG MAGNETIC FIELDS IN REGIONS OF STAR FORMATION

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ABSTRACT

The transfer equations for the polarized radiation of astrophysical, 22 GHz water masers are solved in the presence of a magnetic field which causes a Zeeman splitting that is much smaller than the spectral line breadth. We focus upon the relationship between the recently detected circular polarization in this maser radiation and the strength of the magnetic field. In initial assessments, others have found that the observed polarization is indicative of the strongest magnetic fields yet detected in regions of star formation ($\simeq 50$ mG).

In these estimates for the magnetic field, important ways in which the transfer of the 22 GHz maser radiation differs from the transfer of nonmaser radiation due to a single transition have not been considered. These include the narrowing and rebroadening of the spectral line with increasing optical depth, the merging of hyperfine components, deviations of the molecular velocities from a Maxwellian distribution, unequal populations of the magnetic substates, the influence of cross-relaxation, and the generation of circularly polarized radiation due to changes in direction of the linear polarization.

Major uncertainties in the inferred strengths of the magnetic fields due to these considerations tend to occur mostly when the flux of maser radiation is high and the maser is saturated. The observed spectral line breadths are found to be good indicators of whether the radiative flux is high enough that such effects are significant. For example, when the breadth is smaller than about 0.8 km s^{-1} (FWHM), we calculate that the uncertainty is less than a factor of about 2. The accuracy is improved significantly when the angle between the line of

NEDOLUHA & WATSON 1992'S MODEL

Zeeman splitting << spectral line breadth — **unsaturated maser emission**

$g\Omega >> R$;

- Landé g-factor
- $2\mu_N B/\hbar$
- Rate of stimulated emission

$g\Omega >> \Gamma$;

- Decay rate

$g\Omega >> \Gamma_\nu$

- Cross-relaxation between the magnetic substates

This regime is met for H_2O, CH_3OH, and SiO masers

H_2O ⟶ $g\Omega = 100\ s^{-1}$ $R \sim 0.015\ s^{-1}$ $\Gamma < 1\ s^{-1}$ $\Gamma_\nu < 5\ s^{-1}$

(for B=10 mG, $T_b\Delta\Omega = 10^8$ Ksr^{-1}, T_{gas}<1000 K; Deguchi &Watson 1990; Anderson & Watson 1993)

CH_3OH —6.7 GHz⟶ $150\ s^{-1} < g\Omega < 12\ s^{-1}$ $0.8\ s^{-1} < R < 6\ s^{-1}$ $\Gamma \sim 1\ s^{-1}$ $\Gamma_\nu < 5\ s^{-1}$

(for B=10 mG and $T_b\Delta\Omega = 10^{10}$ Ksr^{-1} ; Vlemmings, Surcis et al., *in prep.*)

^{28}SiO ⟶ $g\Omega \sim 150\ s^{-1}$ $R < 50\ s^{-1}$ $\Gamma \sim 5\ s^{-1}$ $\Gamma_\nu <$ few s^{-1}

(for B=100 mG and $T_b\Delta\Omega = 10^{11}$ Ksr^{-1} ; Pérez – Sánchez & Vlemmings, 2013)

NEDOLUHA & WATSON 1992'S MODEL

The equations of radiative transfer for the Stokes parameters per unit angular frequency $I(\omega)$, $Q(\omega)$ and $V(\omega)$ which represent the total intensity, linearly polarized intensity, and circularly polarized intensity, respectively, are (Deguchi & Watson 1990)

$$\frac{dI(\omega)}{ds} = (A_\omega^{76} + A_\omega^{65} + A_\omega^{54})I(\omega) + (B_\omega^{76} + B_\omega^{65} + B_\omega^{54})Q(\omega) + (C_\omega^{76} + C_\omega^{65} + C_\omega^{54})V(\omega)\,, \tag{8}$$

$$\frac{dQ(\omega)}{ds} = (A_\omega^{76} + A_\omega^{65} + A_\omega^{54})Q(\omega) + (B_\omega^{76} + B_\omega^{65} + B_\omega^{54})I(\omega)\,, \tag{9}$$

and

$$\frac{dV(\omega)}{ds} = (A_\omega^{76} + A_\omega^{65} + A_\omega^{54})V(\omega) + (C_\omega^{76} + C_\omega^{65} + C_\omega^{54})I(\omega)\,. \tag{10}$$

Here, s is the distance measured along the direction of propagation and the coefficients are determined from the populations of the magnetic substrates,

$$A_\omega^{FF'} = \frac{2\pi\omega}{c\hbar}\sum_{a,b}\int dv\{[n(F,a,v) - n(F',b,v)]\gamma_{ab}(\langle Fa|d_+|F'b\rangle^*\langle Fa|d_+|F'b\rangle + \langle Fa|d_-|F'b\rangle^*\langle Fa|d_-|F'b\rangle)\}\,, \tag{11}$$

$$B_\omega^{FF'} = -\frac{2\pi\omega}{c\hbar}\sum_{a,b}\int dv\{[n(F,a,v) - n(F',b,v)]\gamma_{ab}(\langle Fa|d_+|F'b\rangle^*\langle Fa|d_-|F'b\rangle + \langle Fa|d_-|F'b\rangle^*\langle Fa|d_+|F'b\rangle)\}\,, \tag{12}$$

and

$$C_\omega^{FF'} = \frac{2\pi\omega}{c\hbar}\sum_{a,b}\int dv\{[n(F,a,v) - n(F',b,v)]\gamma_{ab}(\langle Fa|d_+|F'b\rangle^*\langle Fa|d_+|F'b\rangle - \langle Fa|d_-|F'b\rangle^*\langle Fa|d_-|F'b\rangle)\}\,. \tag{13}$$

THEORETICAL RESULTS

Full Radiative Transfer Metod (FRTM) code

Differences w.r.t. the old version (e.g., Surcis et al. 2014):

- **8 hyperfine transitions taken into consideration,**
- **new values of *g-factors* and *Einstein coefficients*,**
- **new calculated Clebsch-Gordan coefficients**

(Lankhaar et al. 2017, *submitted*)

Assumptions:

- **B = 10 mG,**
- **$T_{incoming\ radiation}$ = 25 K,**

Code Inputs:

- **$\Delta V_{thermal}$**
- **$\Delta V_{linewidth}$**
- **θ**

See Boy Lankhaar's talk

THEORETICAL RESULTS

Full Radiative Transfer Metod (FRTM) code

(Lankhaar et al. 2017, *submitted*)

6.7 GHz

$(5_{15}\ A_2 \rightarrow 6_{06}\ A_1)$

F_{up}	F_{down}	ΔE (kHz)
7	8	2.500
6	7	−4.397
6	7	3.541
5	6	−2.889
5	6	3.015
4	5	1.240
4	5	−2.835
3	4	−4.417

36 GHz

$(4_{-1}\ E \rightarrow 3_0\ E)$

F_{up}	F_{down}	ΔE (kHz)
5	4	5.402
4	3	−4.791
4	3	−3.395
3	2	−3.032
5	4	4.042
4	3	4.303
4	3	−3.395
3	2	−6.802

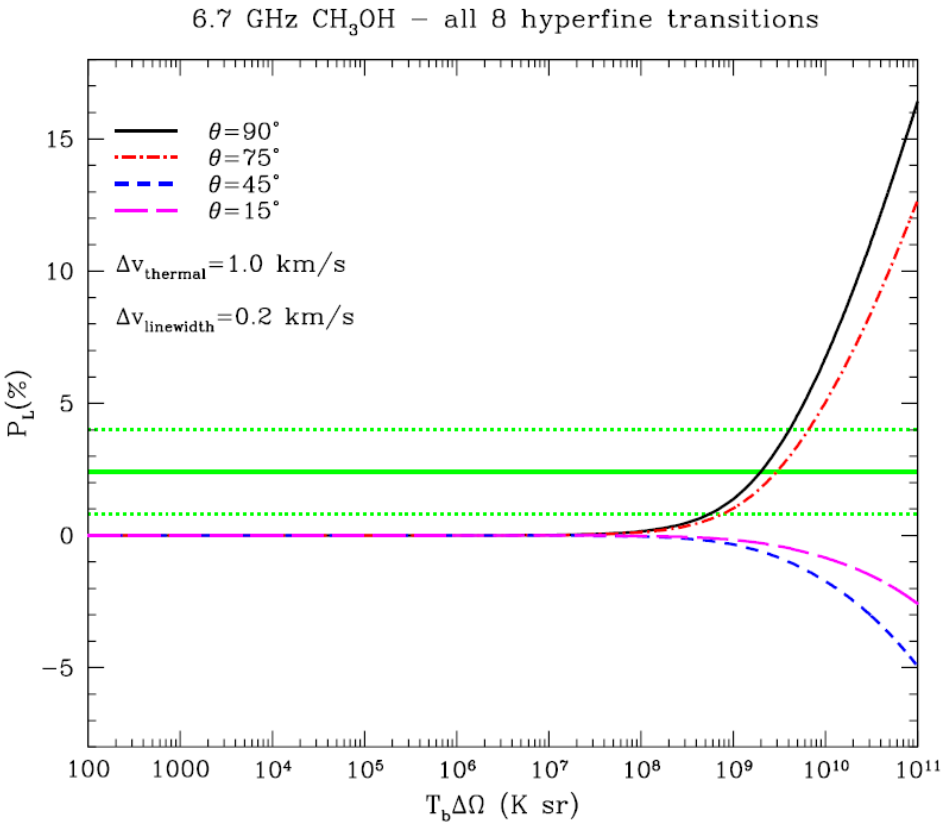
44 GHz

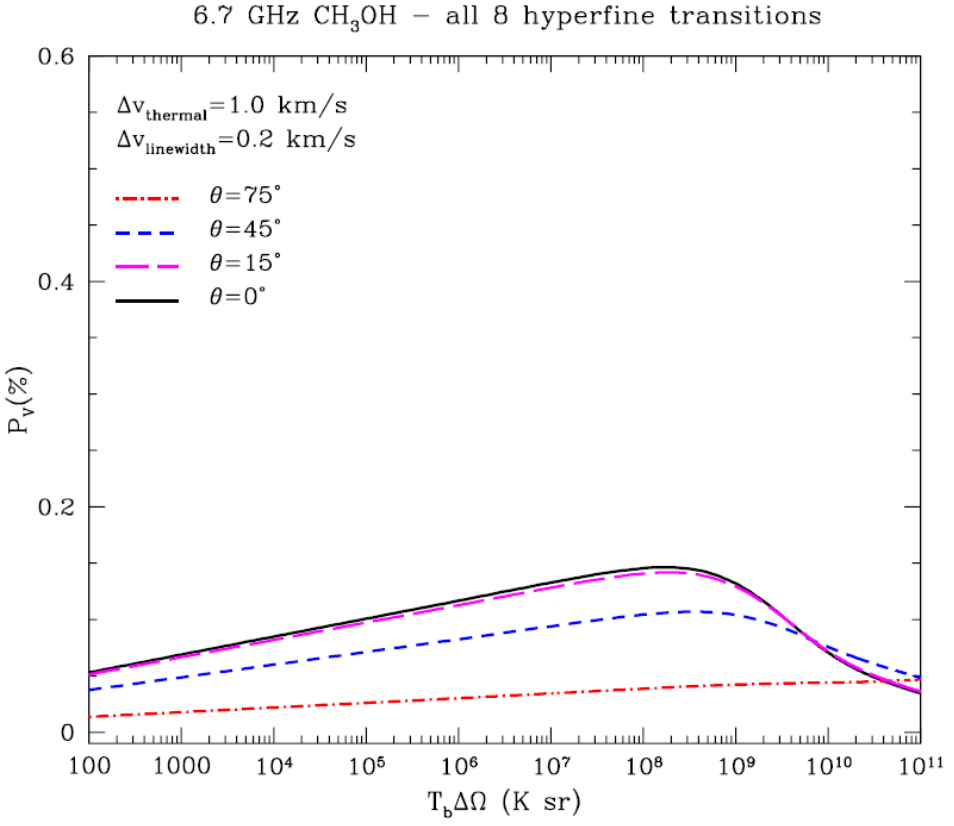
$(7_{07}\ A_2 \rightarrow 6_{16}\ A_1\ )$

F_{up}	F_{down}	ΔE (kHz)
9	8	−2.444
8	7	3.934
8	7	−3.216
7	6	2.897
7	6	−2.897
6	5	−1.684
6	5	2.863
5	4	3.998

THEORETICAL RESULTS: 6.7 GHz

(Vlemmings, Surcis et al., *in prep.*)





THEORETICAL RESULTS: 6.7 GHz

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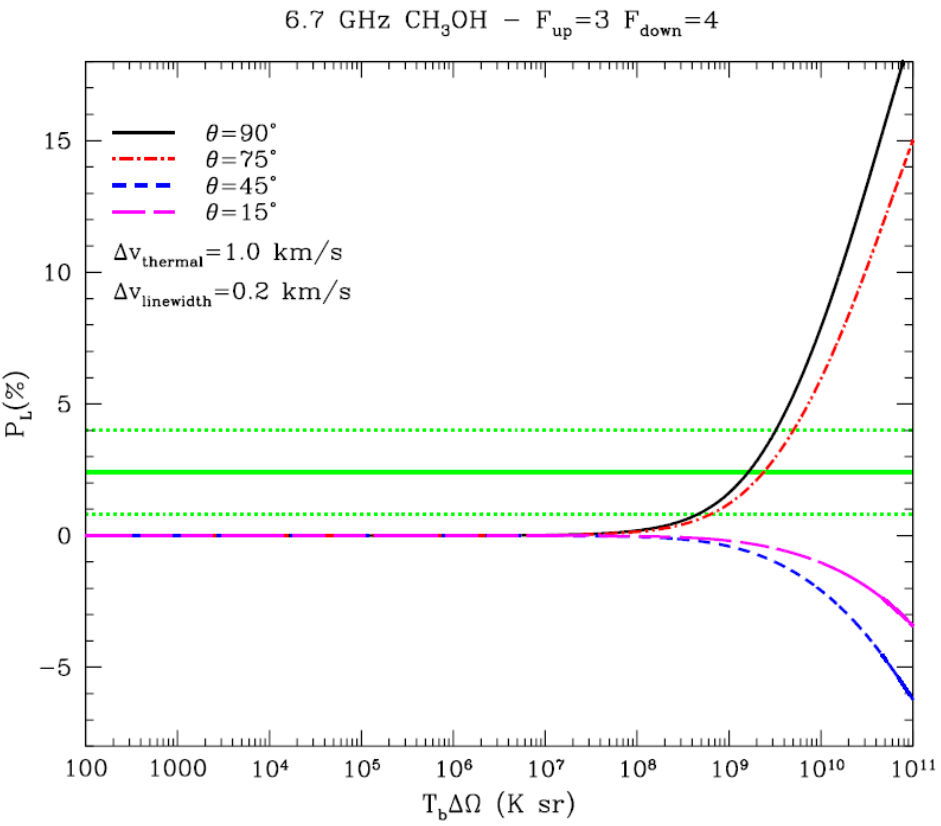

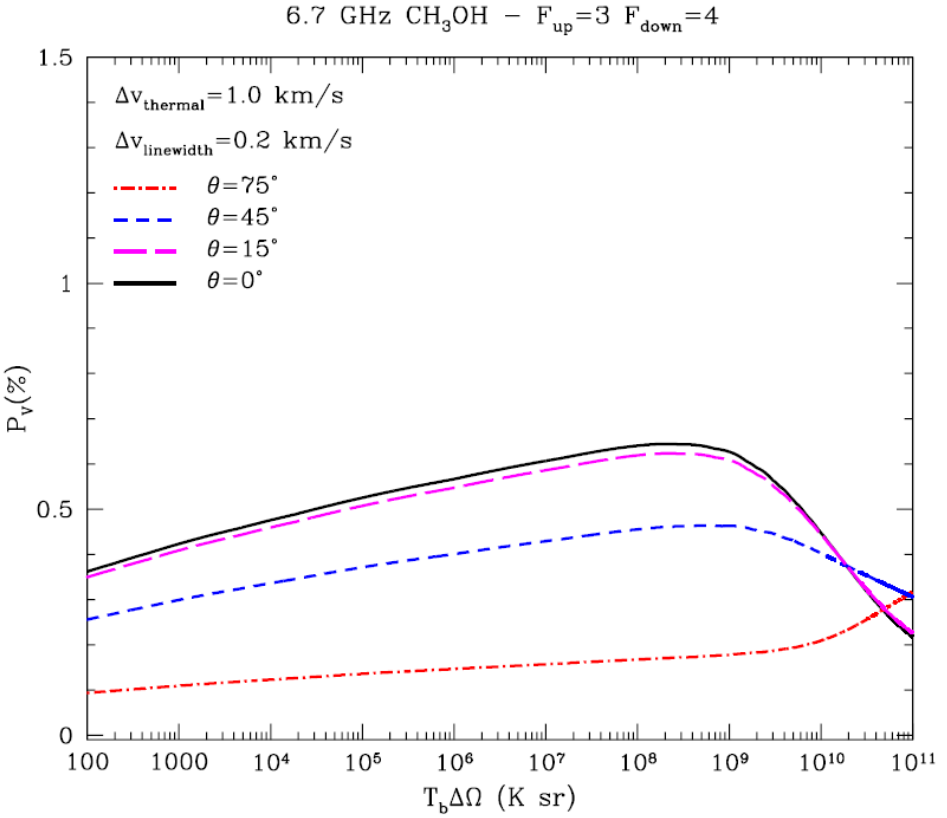

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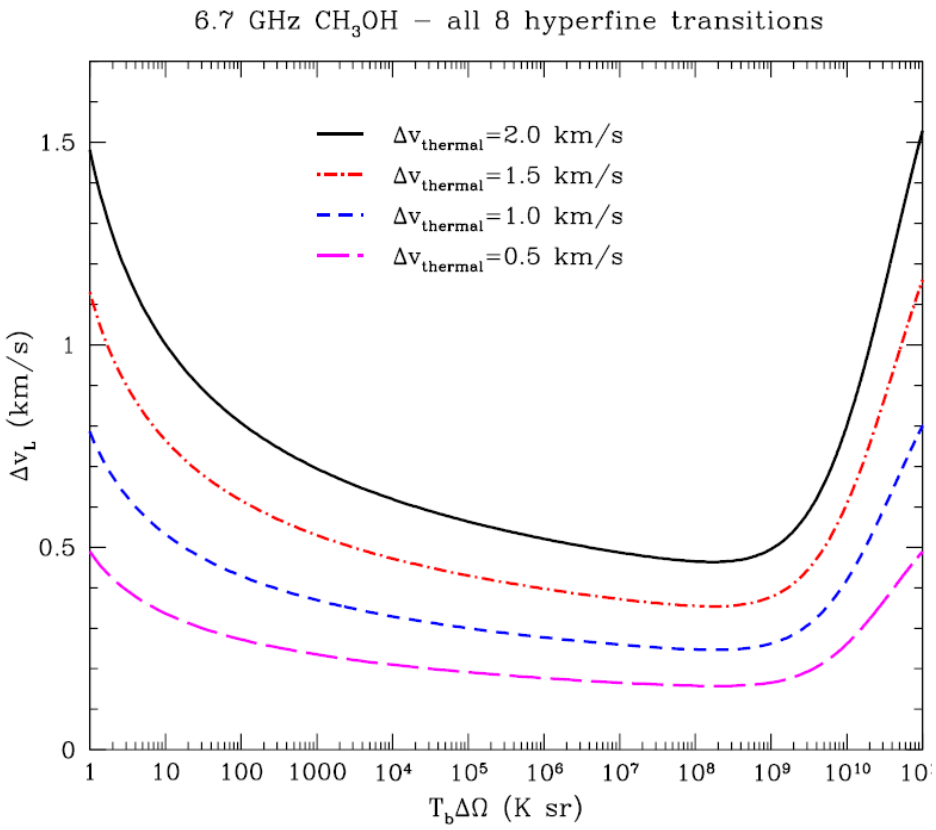

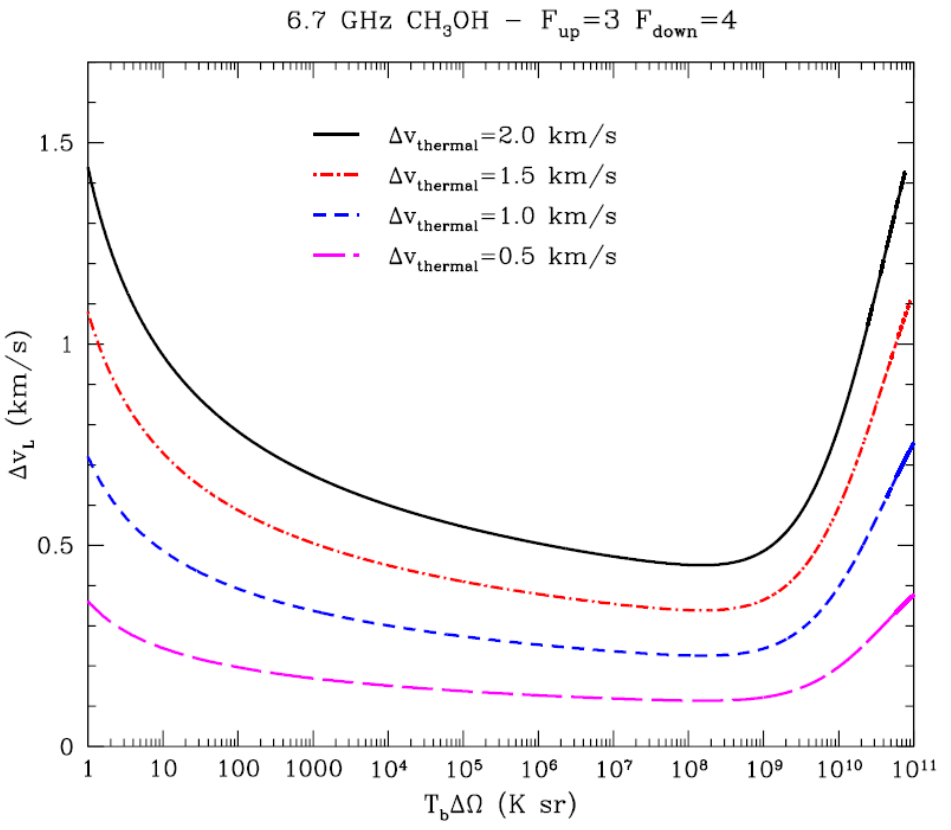

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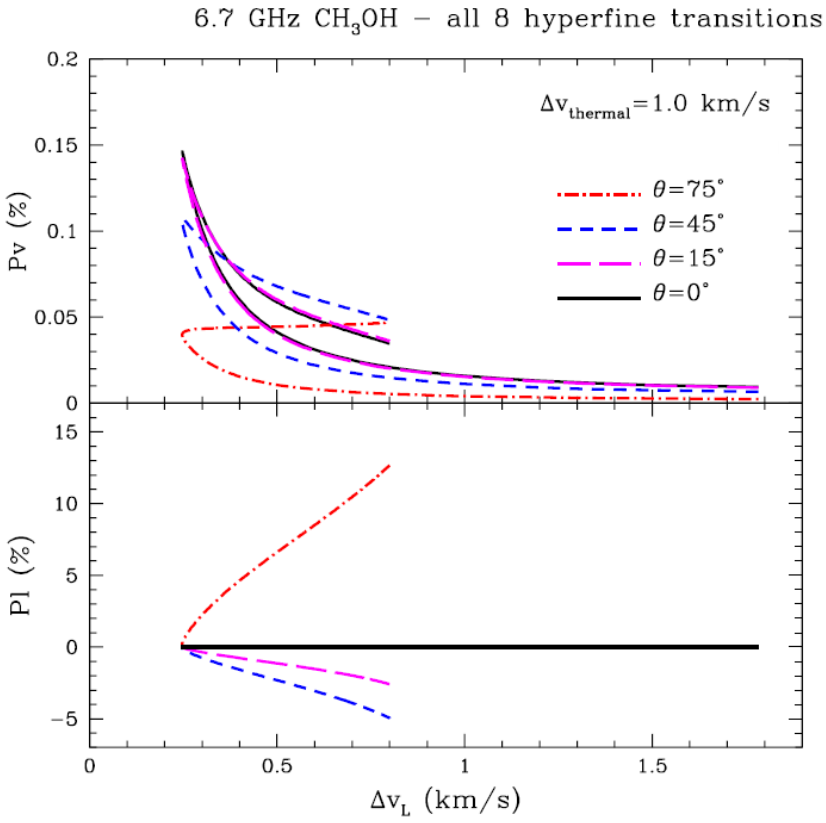
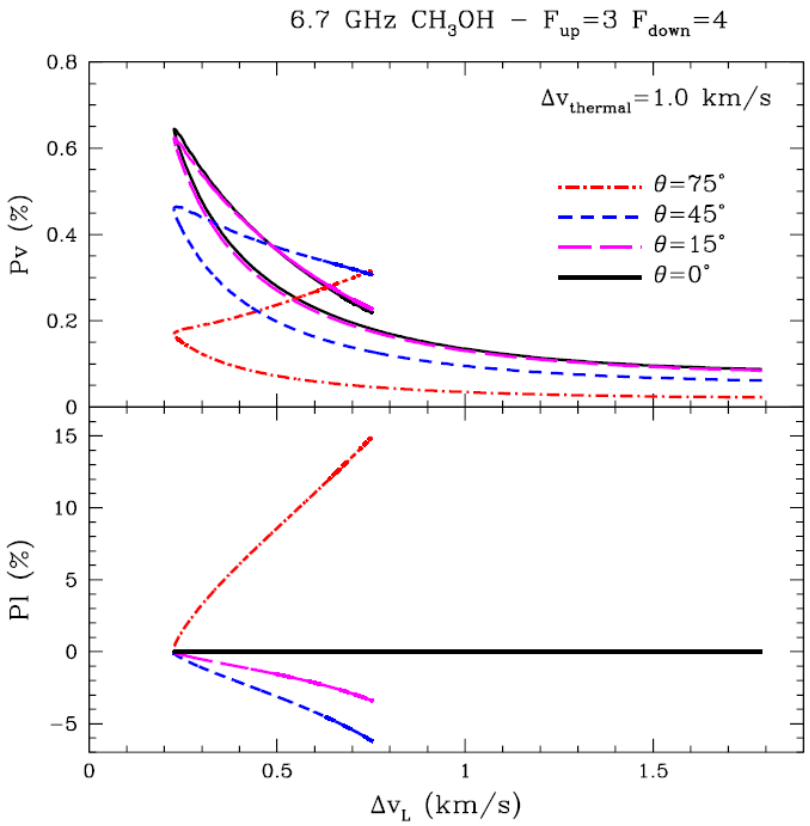
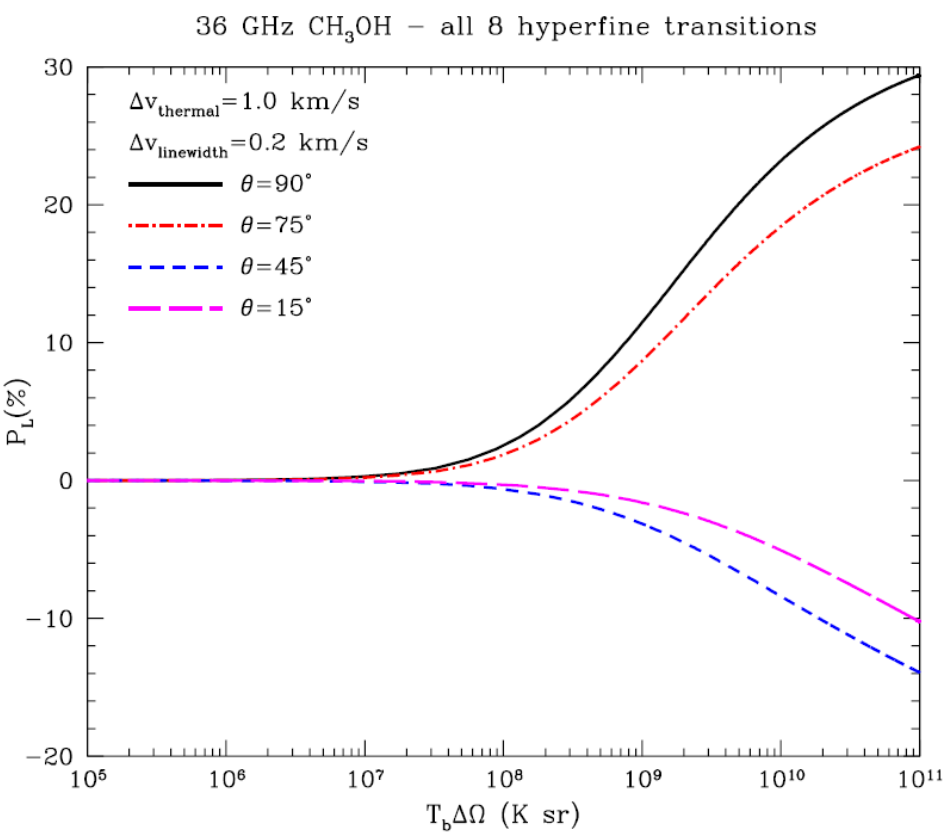
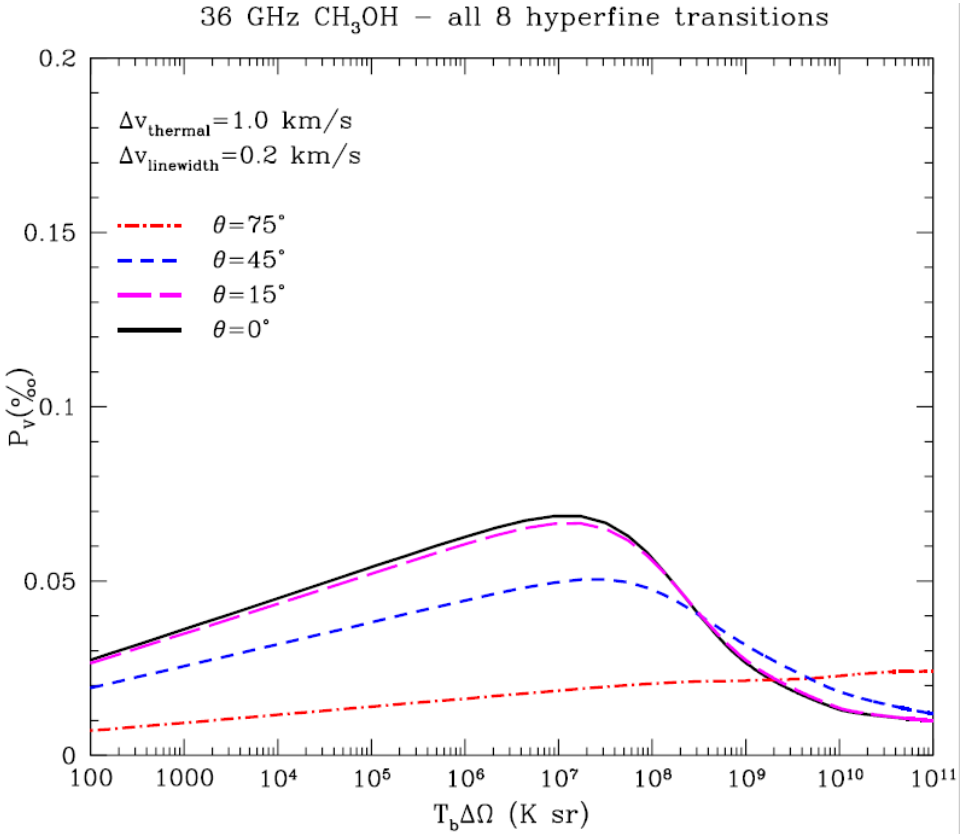




THEORETICAL RESULTS: 36 GHz

(Vlemmings, Surcis et al., *in prep.*)





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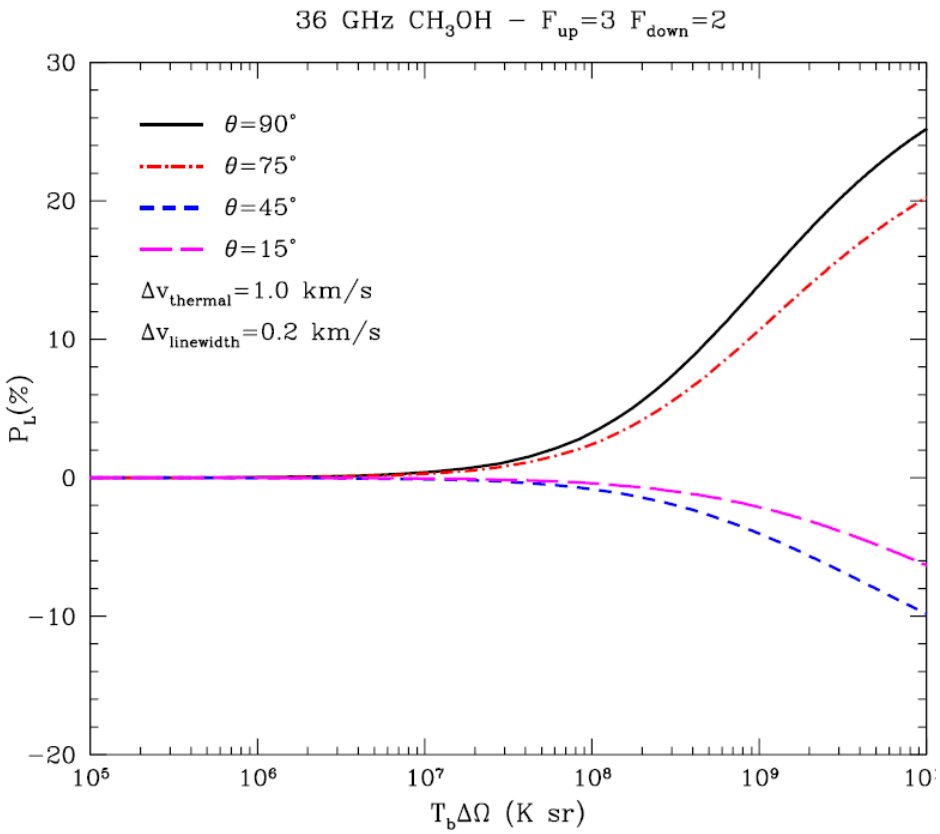

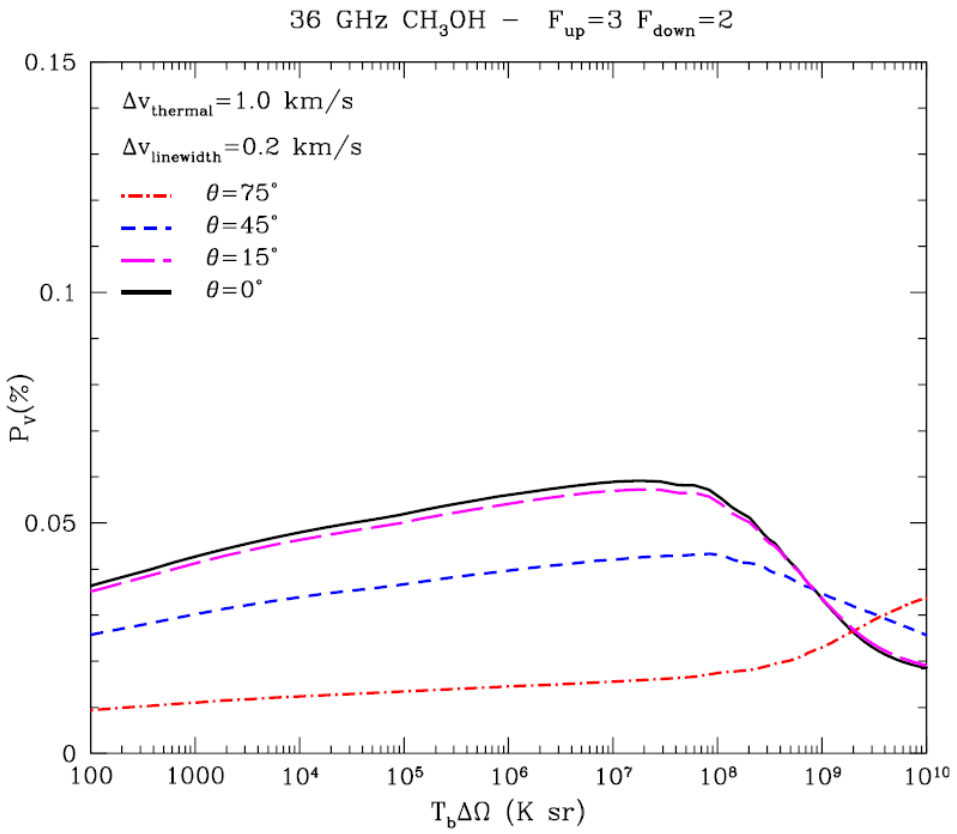

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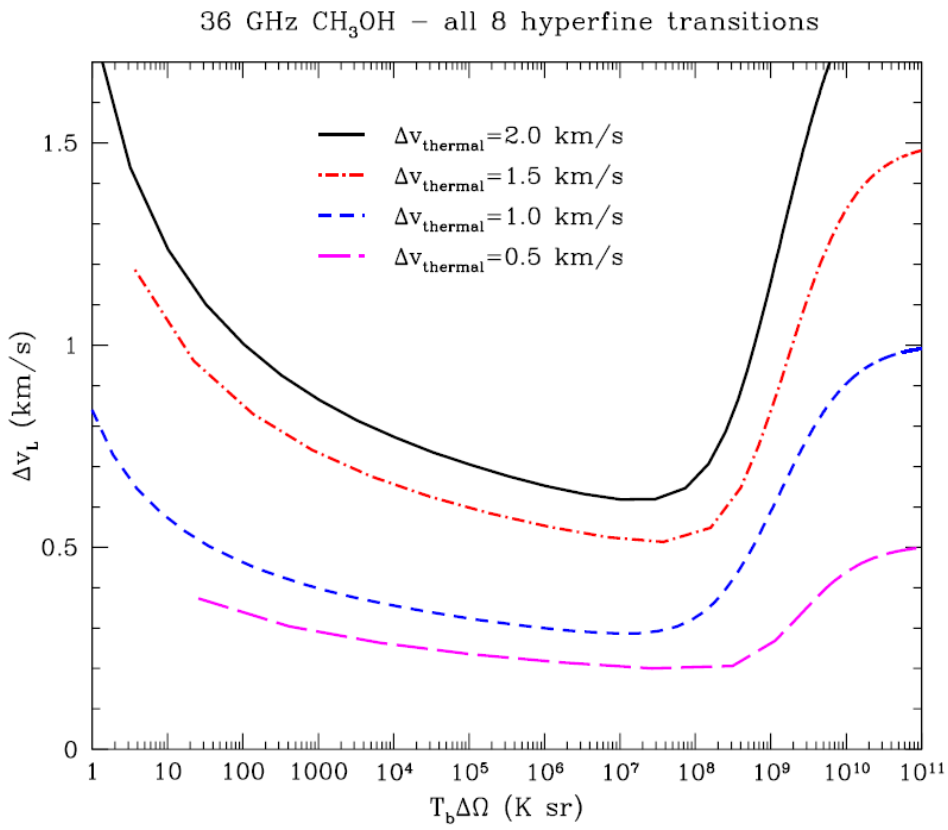

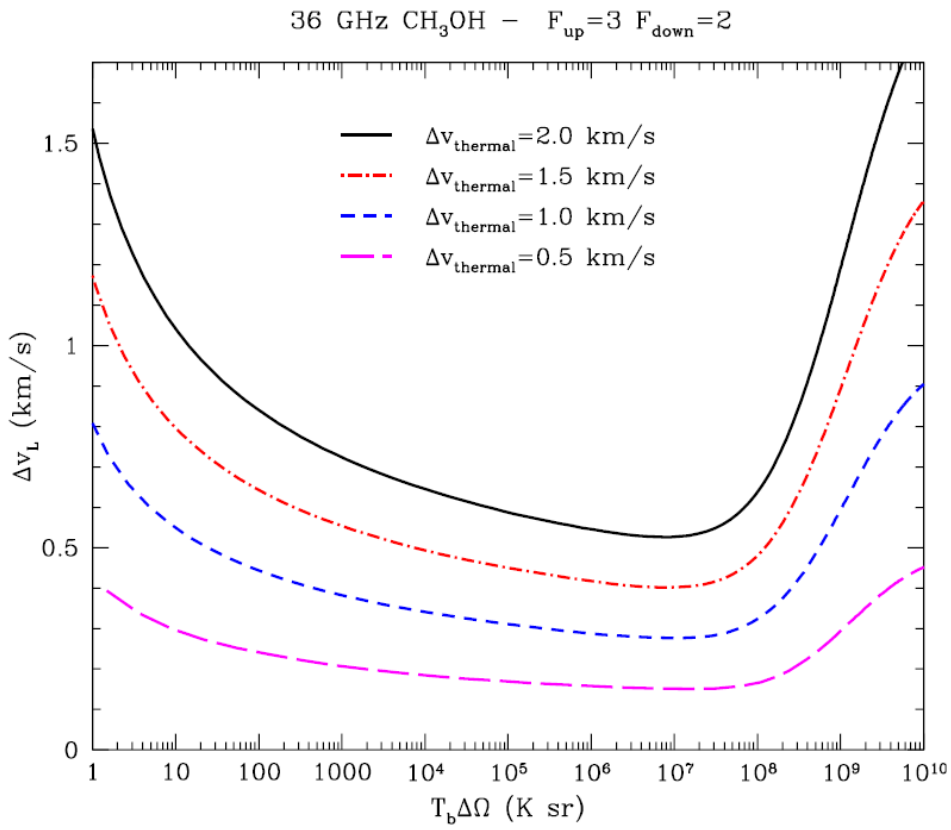

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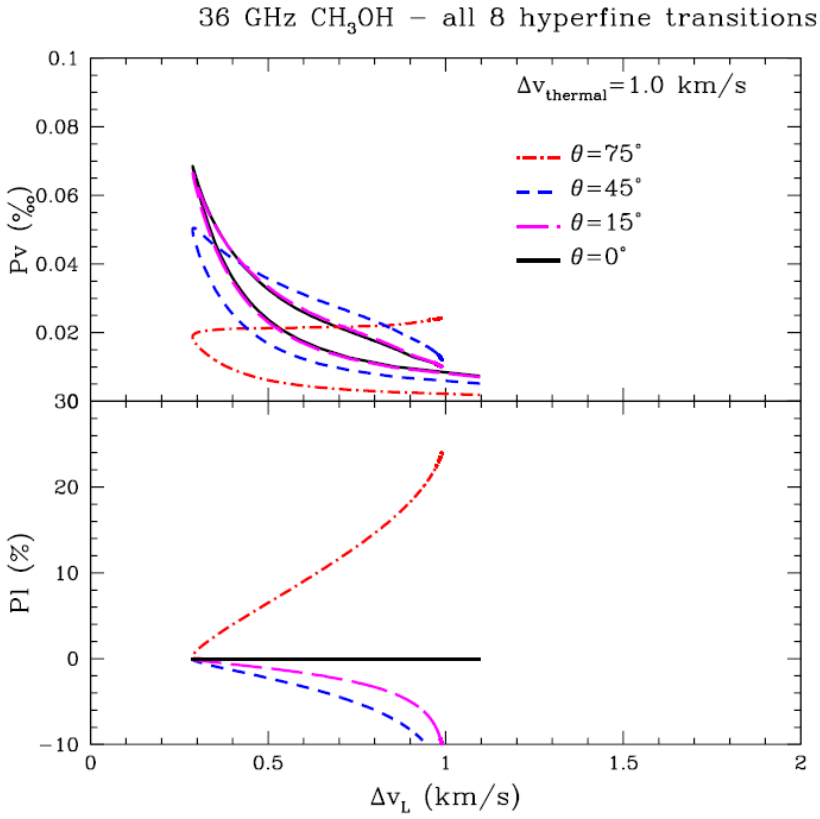
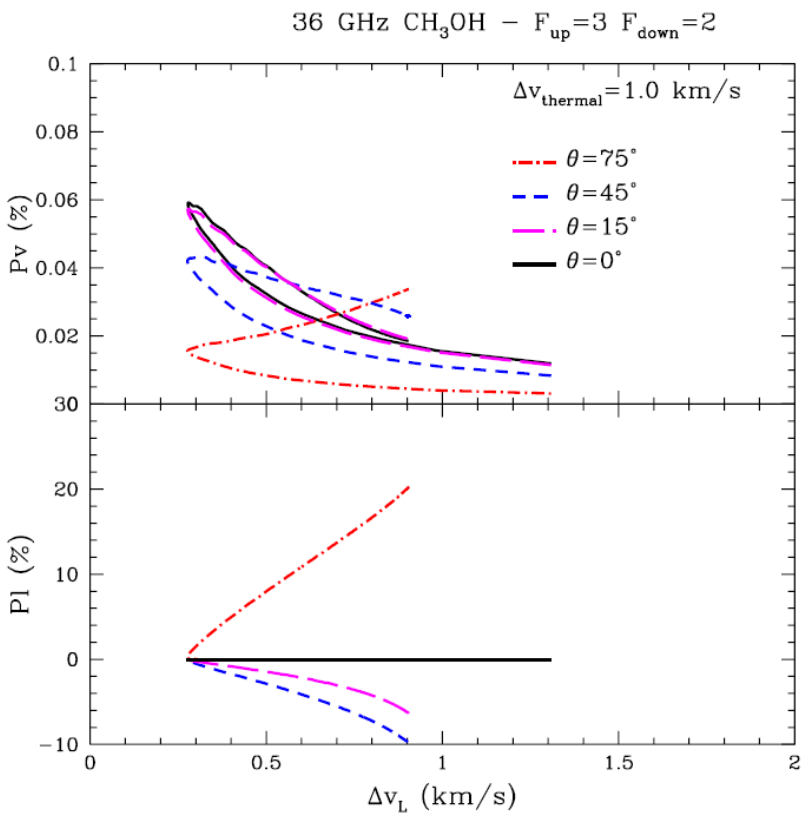
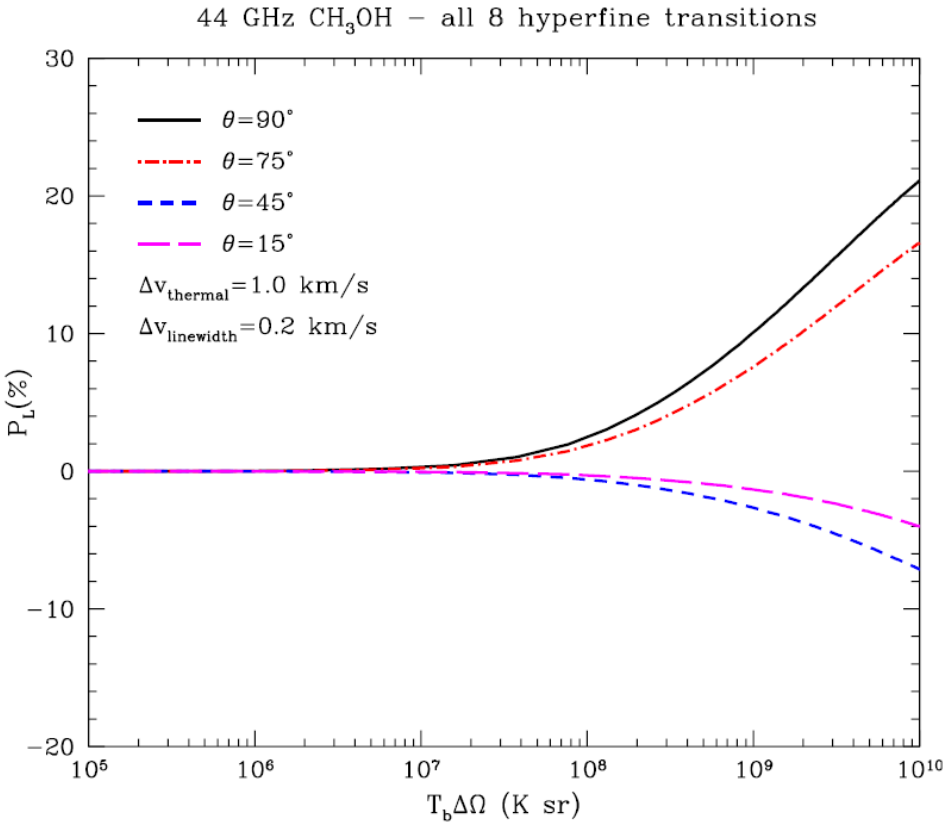
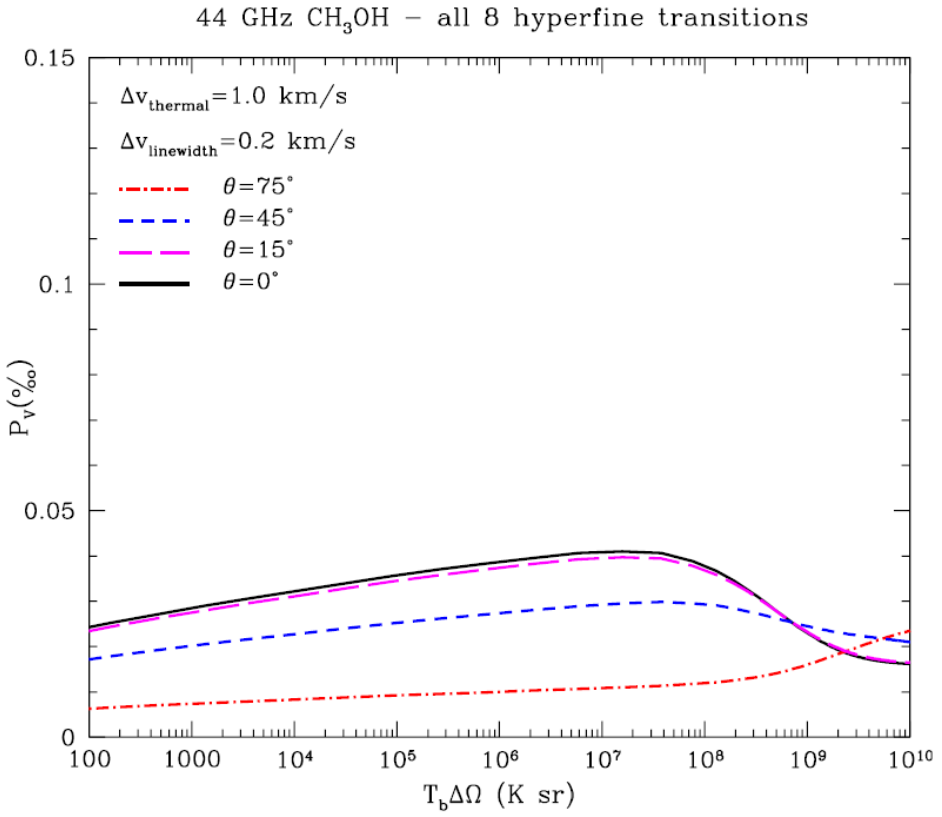




THEORETICAL RESULTS: 44 GHZ

(Vlemmings, Surcis et al., *in prep.*)





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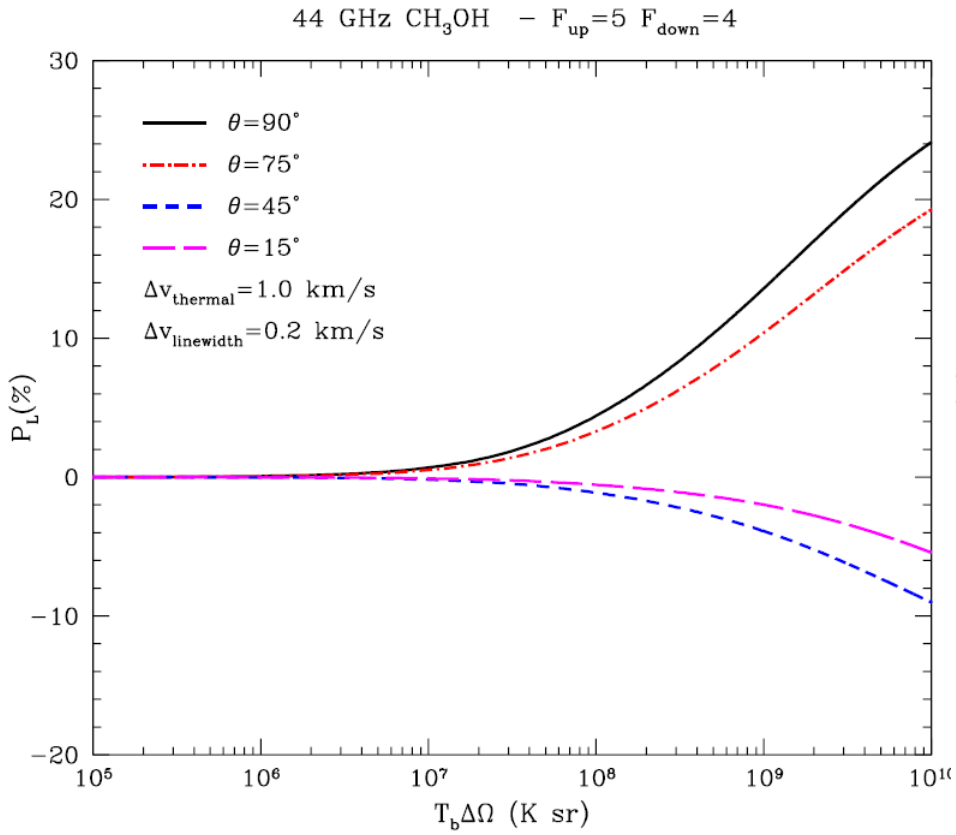

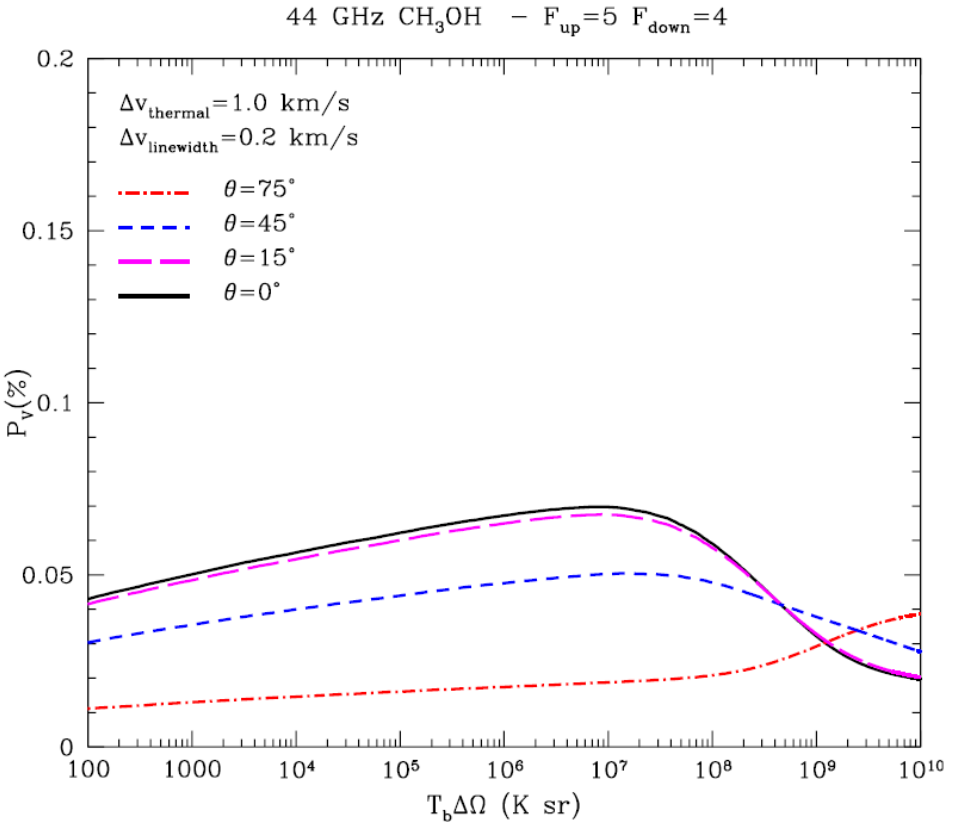

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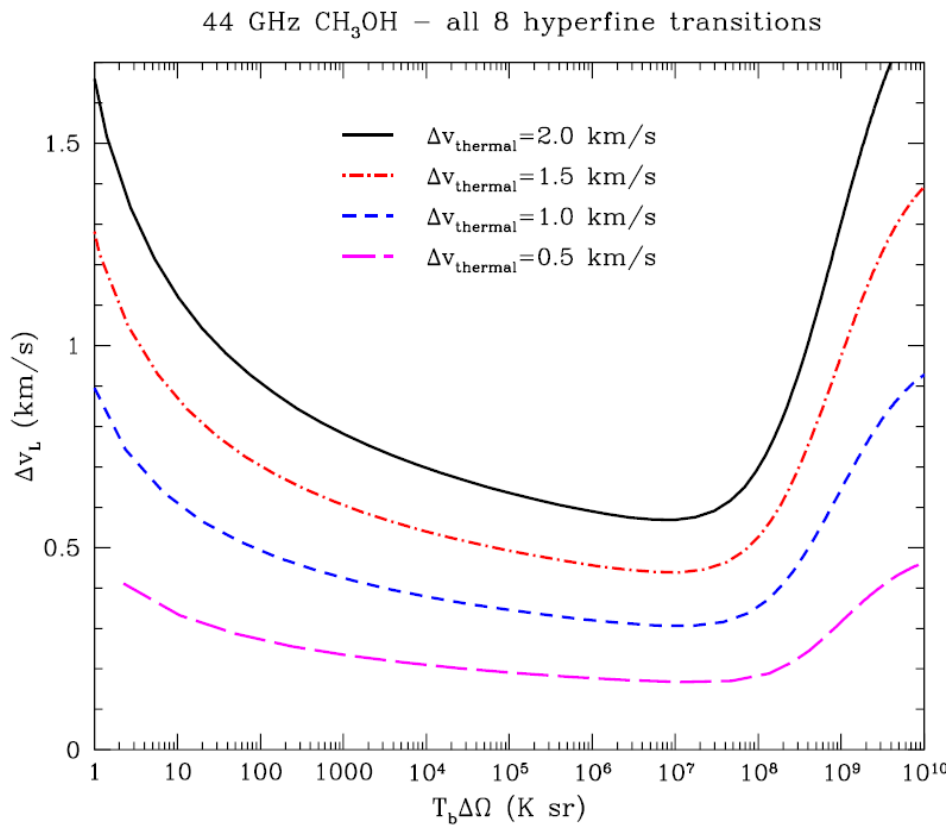

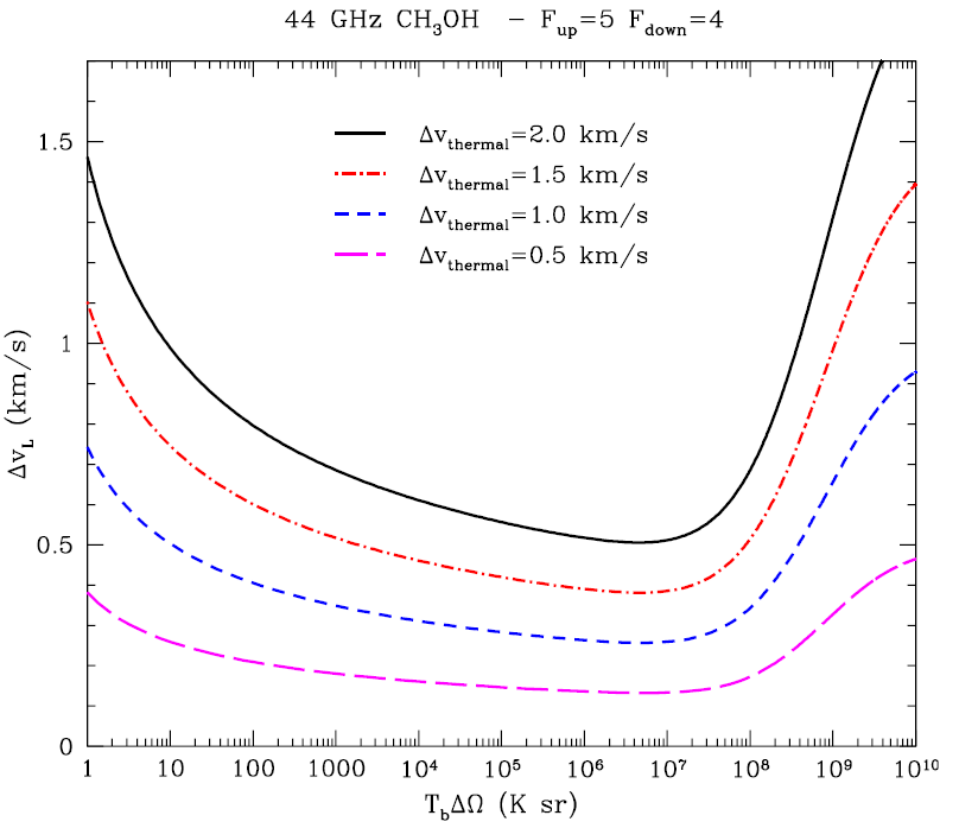

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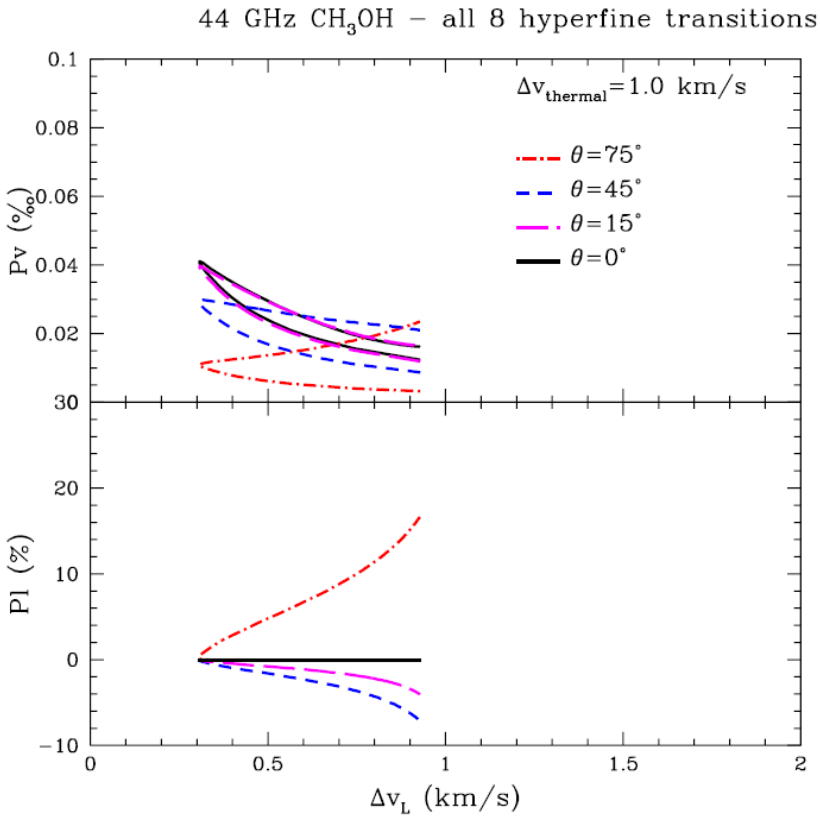
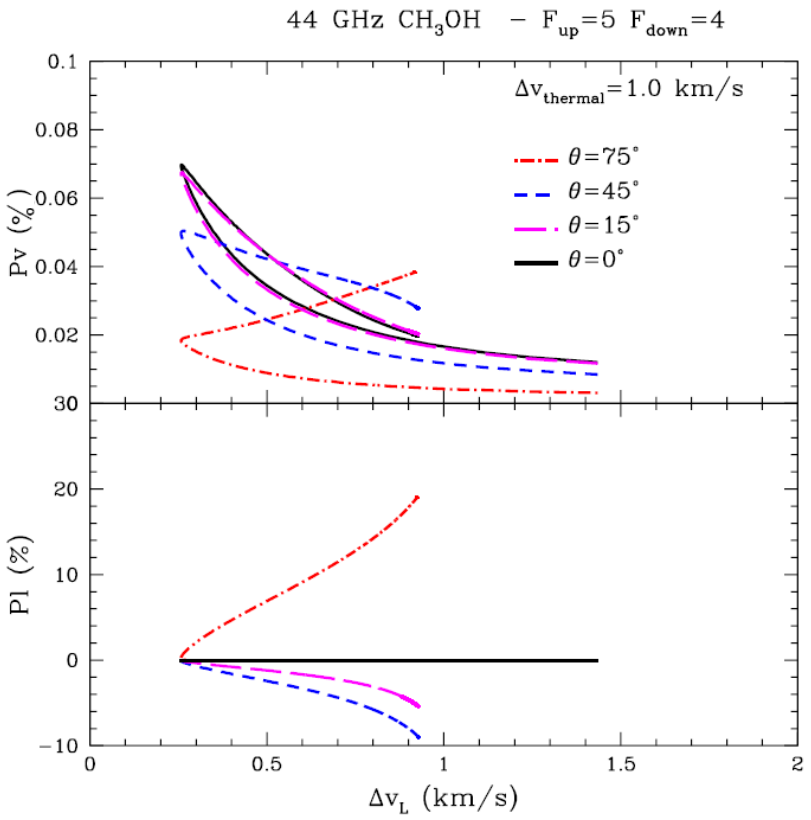




THEORETICAL RESULTS: 6.7 GHz

(Vlemmings, Surcis et al., *in prep.*)

Non – Zeeman effects

- **instrumental effects** (Vlemmings et al. 2011)

  RULED OUT!

  measurements confirmed by using different instruments (single-dish & VLBI)

- **propagation of strong linear polarization when B changes direction along maser propagation path** (Vlemmings et al. 2011)

  for a smooth change of ~1 rad ⟶ $m_V = (m_l)^2/4$

  for $m_l < 0.04 \equiv 4\%$ ⟶ $m_V < 4 \cdot 10^{-4} \equiv 0.04\%$

  SMALL CONTRIBUTION!

- **rotation of the axis of simmetry for the molecular quantum states**
  (Vlemmings, Surcis et al., *in prep.*)

$$g\Omega/R \simeq 5.8 \times 10^{-8} g_J \frac{B}{[\mathrm{mG}]} \frac{[10^{10}\mathrm{K}]}{T_b} \frac{[10^{-2}\mathrm{sr}]}{\Delta\Omega} \frac{\nu}{[\mathrm{GHz}]} \frac{[\mathrm{s}^{-1}]}{A}.$$

  ONLY FOR THE MOST SATURATED!

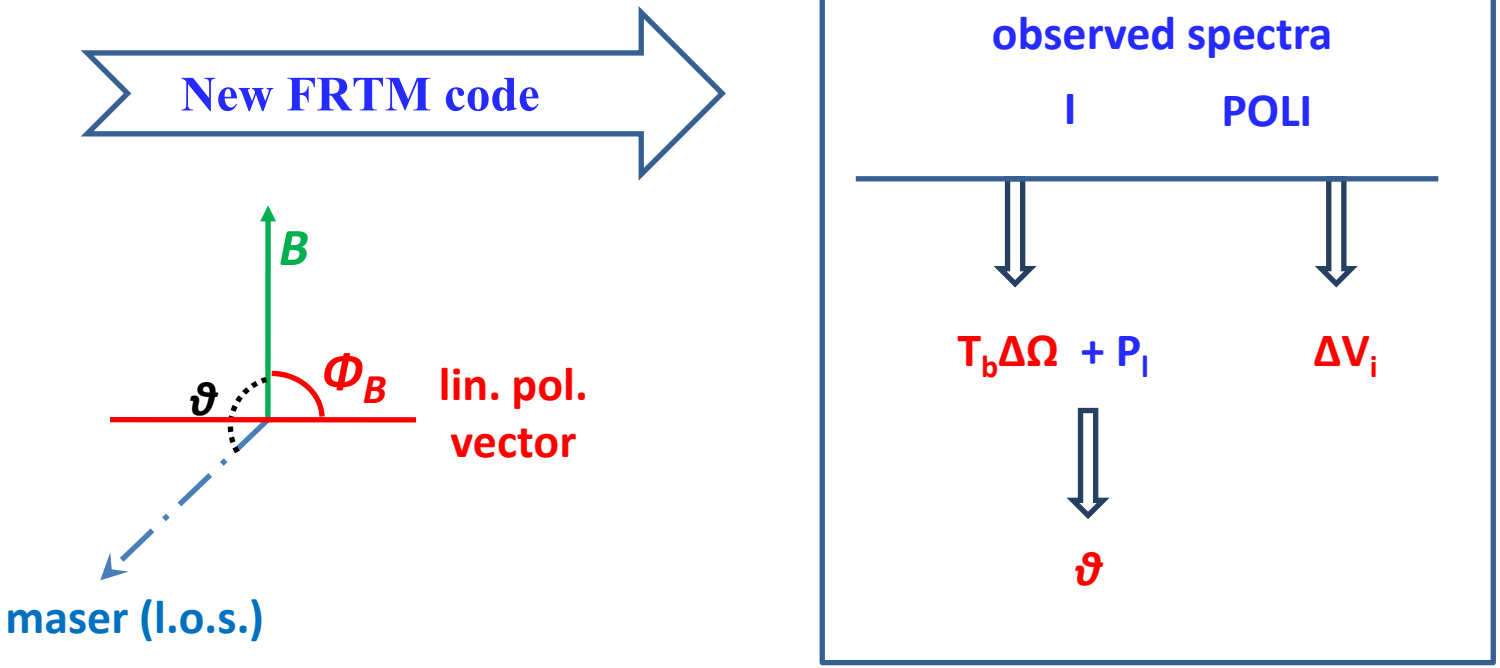
- **anisotropic resonant scattering** (Vlemmings, Surcis et al., *in prep.*)

  following *Houde (2014)* we estimate that P_l produces P_V when B > 100 mG

  UNLIKELY!

OBSERVATIONAL RESULTS: 6.7 GHz

g-factors DO NOT influence the linear polarization analysis



The new calculation of CG coefficients produces:

$T_b\Delta\Omega$ is 1% larger; Δv_i is 1% smaller; ϑ is 1% - 2% larger

(Surcis, Vlemmings et al., 2018 *in prep.*)

OBSERVATIONAL RESULTS: 6.7 GHz

European VLBI Network

Flux limited sample

Pestalozzi et al (2005): catalogue of 6.7-GHz methanol masers Declination > -9°; Flux$_{single\text{-}dish}$ > 50 Jy

11 massive star-forming regions observed from 2008 and 2011

+

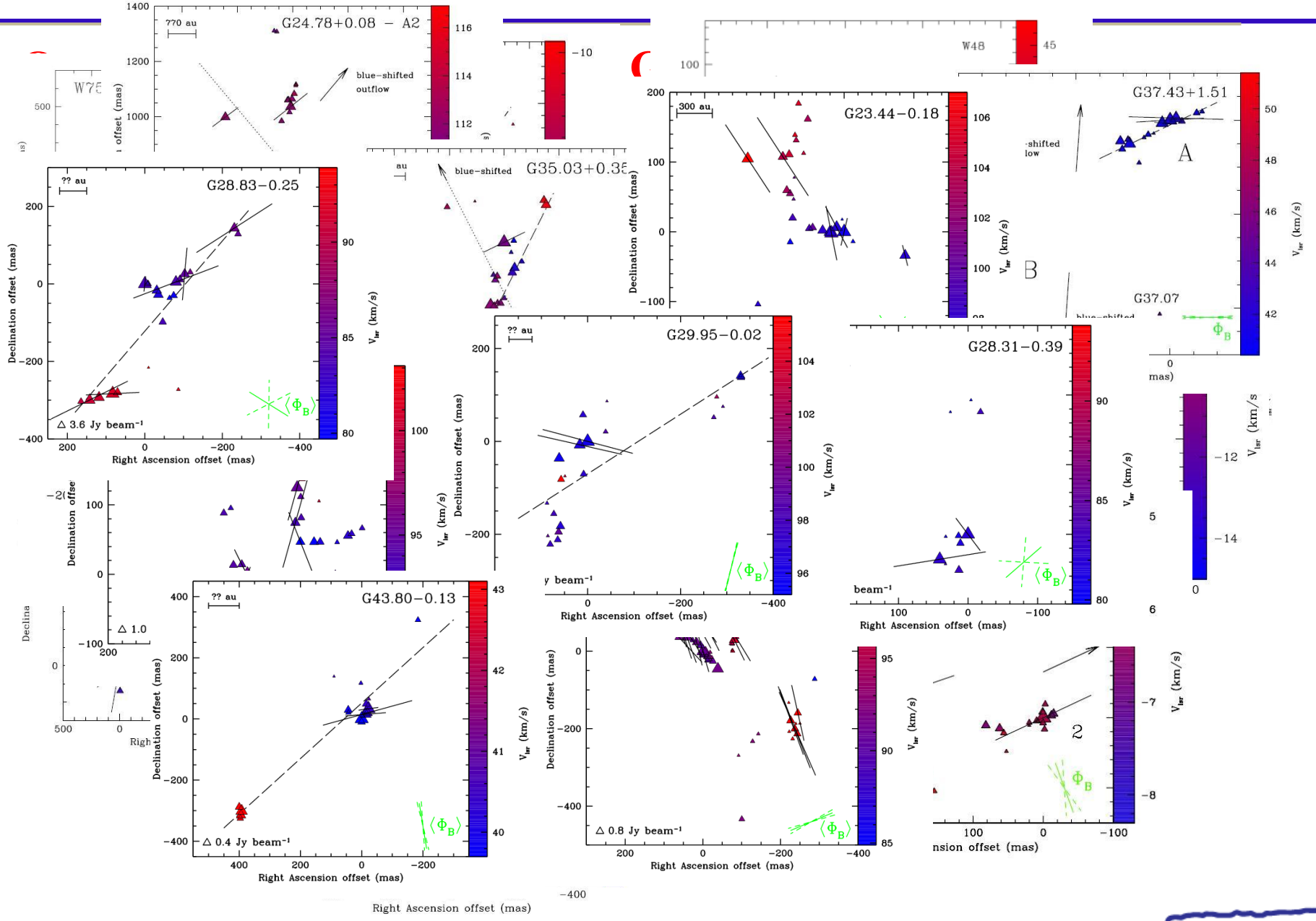
19 massive star-forming regions observed from 2012 and 2015

---

25 sources analysed so far (Surcis et al., *2009, 2011, 2012, 2013, 2014, 2015, 2018 in prep.*)

+ 8 sources observed in 2016 (*see Moscadelli's talk on Wednesday @ 9:45*)

METHANOL MASERS



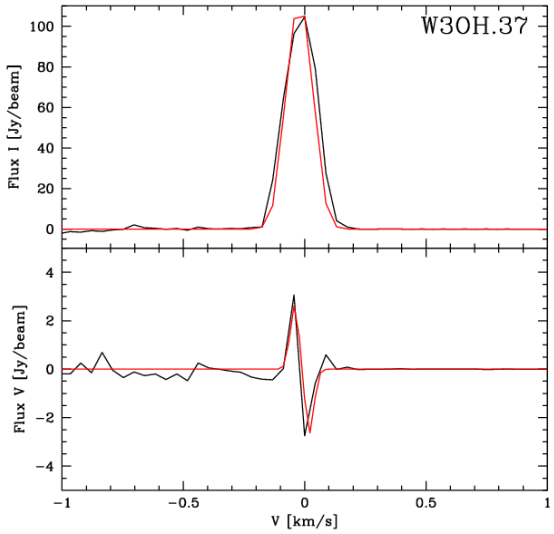
OBSERVATIONAL RESULTS: 6.7 GHz

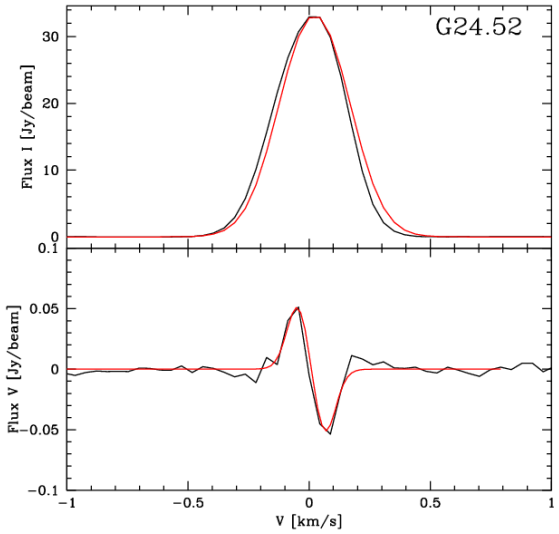
$F_{up} = 3$ - $F_{down} = 4$

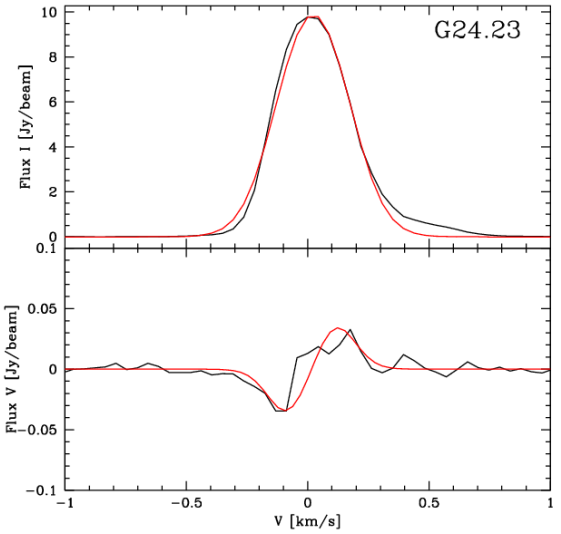
(1) Source name	(2) Maser ID	(3) Peak flux Density(I) (Jy/beam)	(4) V_{lsr} (km/s)	(5) ΔV_i[a] (km/s)	(6) $T_b\Delta\Omega$[a] (log K sr)	(7) θ (°)	(8) P_V (%)	(9) $B_{\parallel}$[b] (mG)	(10) B^c (mG)	ref.[d]
W75N(B)	A4	47.58	+5.82	–	–	–	0.5	-15.7 ± 0.6[e]	–	(1)
	A5	39.39	+5.12	–	–	–	0.5	-14.7 ± 2.6[e]	–	(1)
	B1	95.38	+7.23	–	–	–	0.4	-10.4 ± 0.8[e]	–	(1)
NGC7538	E02	16.82	-50.49	1.0	9.41	77^{+13}_{-11}	1.7	-52.9 ± 5.9[e]	-235.2 ± 26.2	(2)
	E26	95.15	-55.92	0.5	11.39	86^{+5}_{-19}	1.0	-31.4 ± 5.9[e]	-450.1 ± 84.6	(2)
	E48	23.68	-58.03	1.2	9.26	75^{+15}_{-35}	1.7	$+52.9 \pm 5.9$[e]	$+204.4 \pm 22.8$	(2)
W51-e2	W51E.13	65.78	+57.86	1.7	8.9	77^{+13}_{-37}	0.4	$+0.4 \pm 0.1$	$+1.8 \pm 0.5$	(3)
	W51E.14	217.32	+59.26	1.7	8.8	67^{+11}_{-42}	0.1	-0.11 ± 0.03	-0.26 ± 0.08	(3)
	W51E.18	27.56	+59.35	–	–	–	1.1	$+1.1 \pm 0.2$[f]	$+5.8 \pm 1.1$[f]	(3)
	W51E.32	8.11	+57.86	0.6	8.8	75^{+14}_{-35}	–[g]	–[g]	–[g]	(3)
W48	W48.14	294.68	+44.49	1.0	9.5	73^{+16}_{-32}	0.7	$+0.52 \pm 0.08$	$+1.8 \pm 0.3$	(3)
W3(OH)	W3OH.11	212.03	-42.60	–	–	–	2.9	$+2.6 \pm 0.4$[h]	$+12.5 \pm 1.9$[h]	(3)
	W3OH.22	2051.30	-45.41	1.0	10.0	73^{+10}_{-5}	2.1	-15.3 ± 2.3	-52.3 ± 7.9	(3)
	W3OH.25	156.18	-43.74	1.1	8.8	68^{+7}_{-45}	2.3	-1.6 ± 0.2	-4.3 ± 0.5	(3)
	W3OH.35	347.43	-42.86	0.9	9.2	71^{+18}_{-33}	3.8	-2.7 ± 0.4	-8.3 ± 1.2	(3)
	W3OH.37	110.11	-42.51	1.4	9.2	76^{+13}_{-37}	5.0	$+3.4 \pm 0.5$	$+14.1 \pm 2.1$	(3)
	W3OH.40	178.62	-45.14	–	–	–	1.2	$+0.9 \pm 0.1$[i]	–	(3)
	W3OH.48	19.97	-41.81	1.0	9.0	76^{+11}_{-40}	–[g]	–[g]	–[g]	(3)
IRAS 06058+2138-IRS 1	IRAS06.22	93.29	+10.86	1.2	9.6	73^{+17}_{-7}	0.2	-0.4 ± 0.2	-1.4 ± 0.7	(4)
S255-IR	S255.30	10.64	+4.61	1.1	9.5	82^{+8}_{-18}	0.3	-0.4 ± 0.1	-2.9 ± 0.7	(4)
IRAS 20126+4104	M05	27.84	-6.10	2.0	8.8	75^{+10}_{-43}	0.7	$+1.5 \pm 0.2$	$+5.8 \pm 0.8$	(5)
G24.78+0.08	G24.16	13.70	+110.41	1.7	8.6	82^{+8}_{-44}	0.3	$+0.5 \pm 0.1$	$+3.6 \pm 0.7$	(6)
	G24.23	9.79	+107.69	1.9	8.8	67^{+9}_{-44}	0.7	-1.4 ± 0.3	-3.6 ± 0.8	(6)
	G24.43	11.48	+114.23	1.6	8.9	88^{+1}_{-1}	0.7	$+1.3 \pm 0.2$	$+37.2 \pm 5.7$	(6)
	G24.52	32.97	+113.40	1.8	8.8	73^{+2}_{-40}	0.3	$+0.6 \pm 0.1$	$+2.1 \pm 0.3$	(6)
G29.86-0.04	G29.09	19.26	+100.39	1.8	8.6	74^{+15}_{-37}	0.6	$+1.1 \pm 0.2$	$+4.0 \pm 0.7$	(6)
G213.70-12.6	G213.15	91.58	+12.57	1.1	9.5	82^{+8}_{-17}	0.7	$+0.7 \pm 0.1$	$+5.0 \pm 0.7$	(6)

(Surcis, Vlemmings et al., 2018 *in prep.*)

OBSERVATIONAL RESULTS: 6.7 GHz





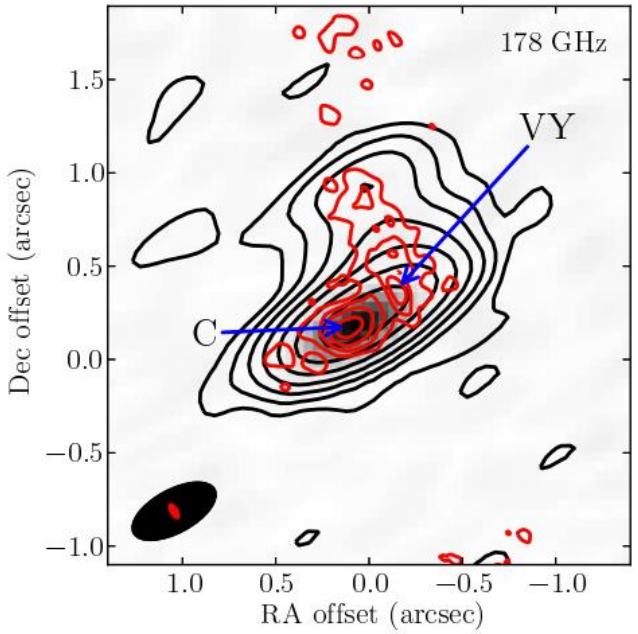


(Surcis, Vlemmings et al., 2018 *in prep.*)

Red Supergiant VY CMa

Mass	25 M_{sun}
Distance	1.2 Kpc
Mass loss rate	~10^{-4} M_{sun} yr^{-1}
Angular diameter	11 mas
Luminosity	2 – 5 · 10^5 L_{sun}

See Anita Richards' talk on Thursday @15:20 and Hiroko Shinnaga's Poster (#24) for more details on VY CMa

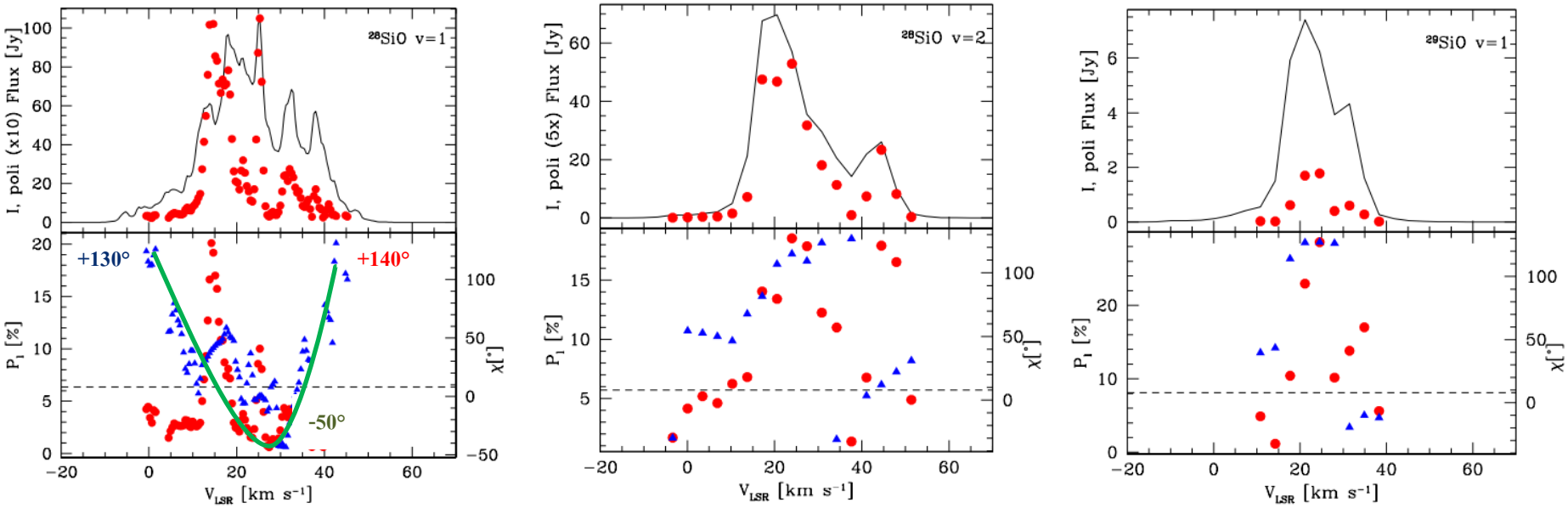


(Vlemmings et al., 2017)

Observed with ALMA Band 5 on October 16th 2016 to detect linear and circular polarization from ^{28}SiO (J=4 – 3, ν = 1 and ν = 2) and ^{29}SiO (J=4 – 3, ν = 1) masers

Red Supergiant VY CMa

(Vlemmings et al., 2017)



Similar to 86 GHz ^{28}SiO (J=2 – 1, v = 1)

observed by Herpin et al. (2006)

- EVPA indicates a possible complex toroidal magnetic field morphology
- The circular polarization needs to be confirmed with further observations

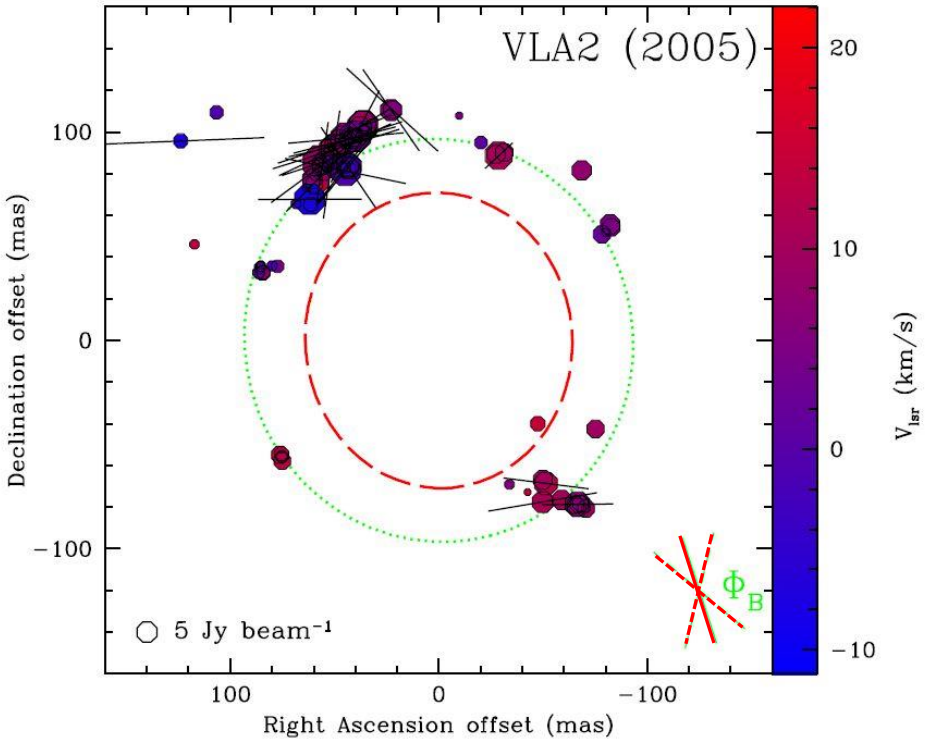
INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS
OAC Osservatorio Astronomico di Cagliari

W75N(B) – TO BE CONTINUED

see Poster 53 by Soon-Wook KIM

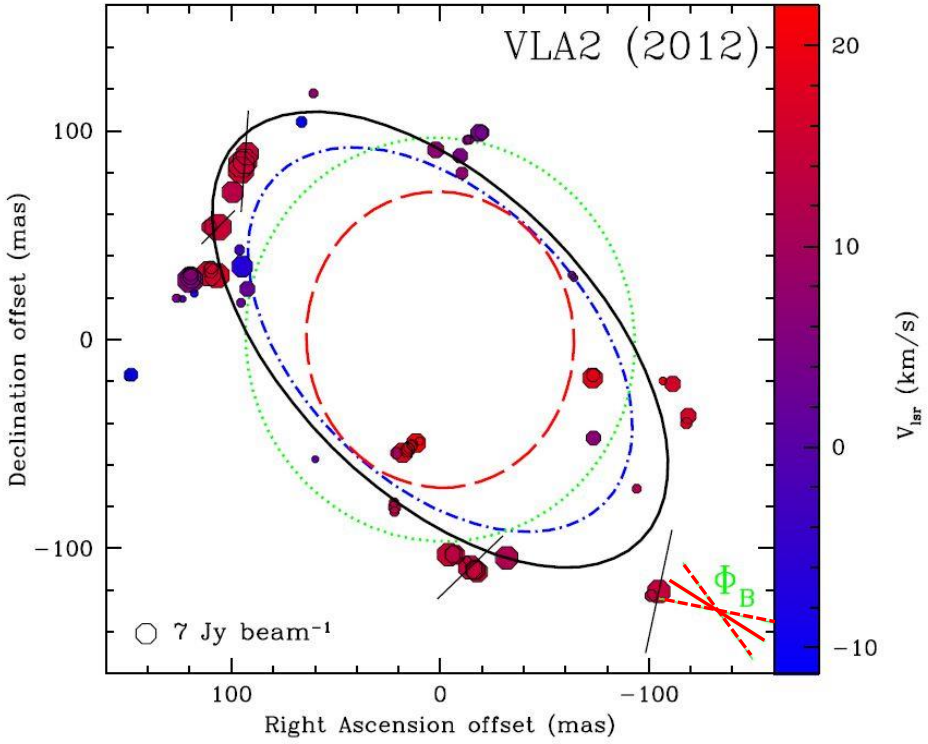
"Transition of outflow from wind-like to collimated morphology in the massive star-forming region W75N"

$\overline{|B_{\parallel}|}^{2005.89}_{VLA2}$ = 345 mG



Surcis, G.et al. 2011, A&A, 527, 48

$\overline{|B_{\parallel}|}^{2012.54}_{VLA2}$ = 128 mG



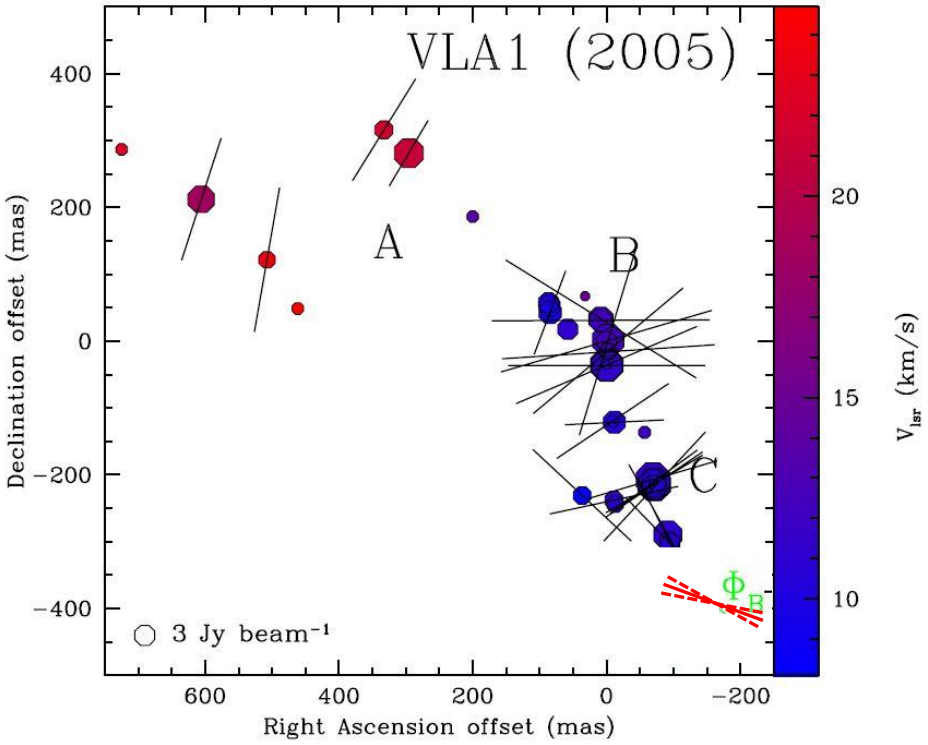
Surcis, G.et al. 2014, A&A, 565, L8

W75N(B) – TO BE CONTINUED

see Poster 53 by Soon-Wook KIM

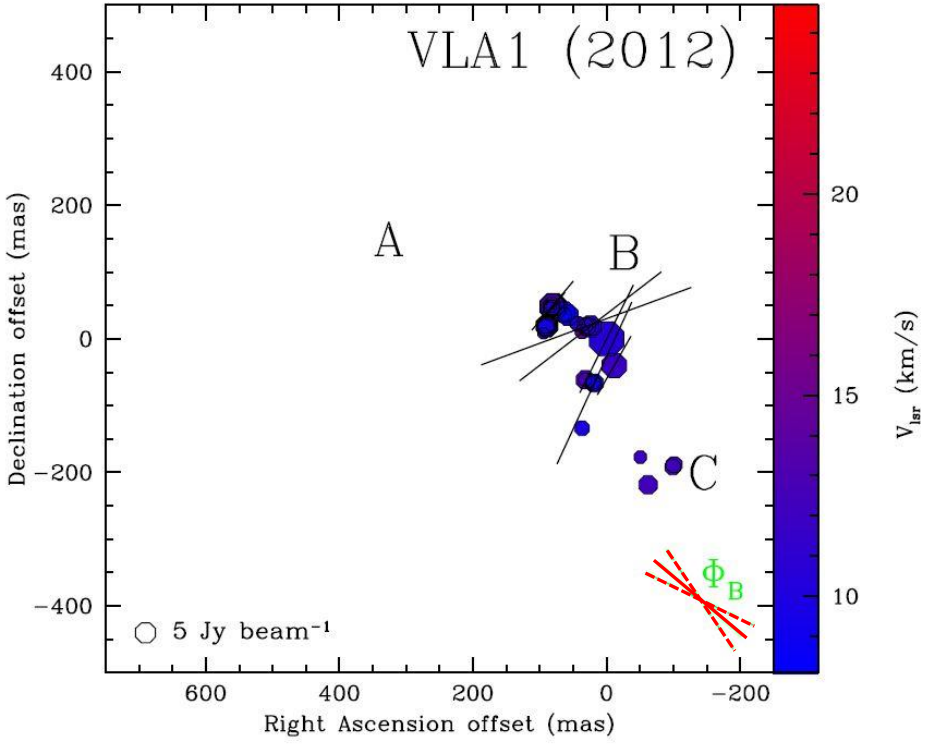
"Transition of outflow from wind-like to collimated morphology in the massive star-forming region W75N"

$\overline{|B_{\parallel}|}^{2005.89}_{\text{VLA 1}}$ = 263 mG



Surcis, G.et al. 2011, A&A, 527, 48

$\overline{|B_{\parallel}|}^{2012.54}_{\text{VLA 1}}$ = 281 mG

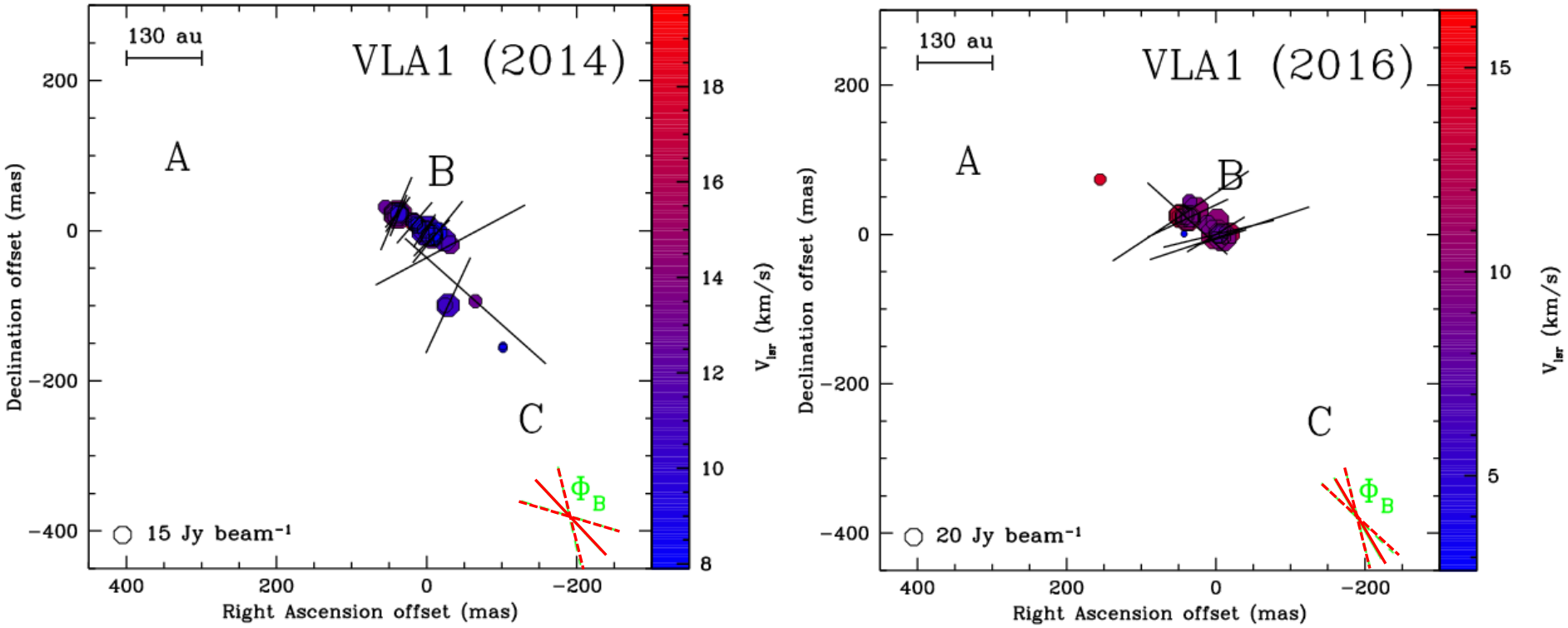


Surcis, G.et al. 2014, A&A, 565, L8

W75N(B) – TO BE CONTINUED

A monitoring programme begun in 2014 with the EVN: 4 epochs spaced by 2 yrs (total 6 yr)

$\overline{|B_{\|}|}^{2016.45}_{\text{VLA 1}}$ = 676 mG

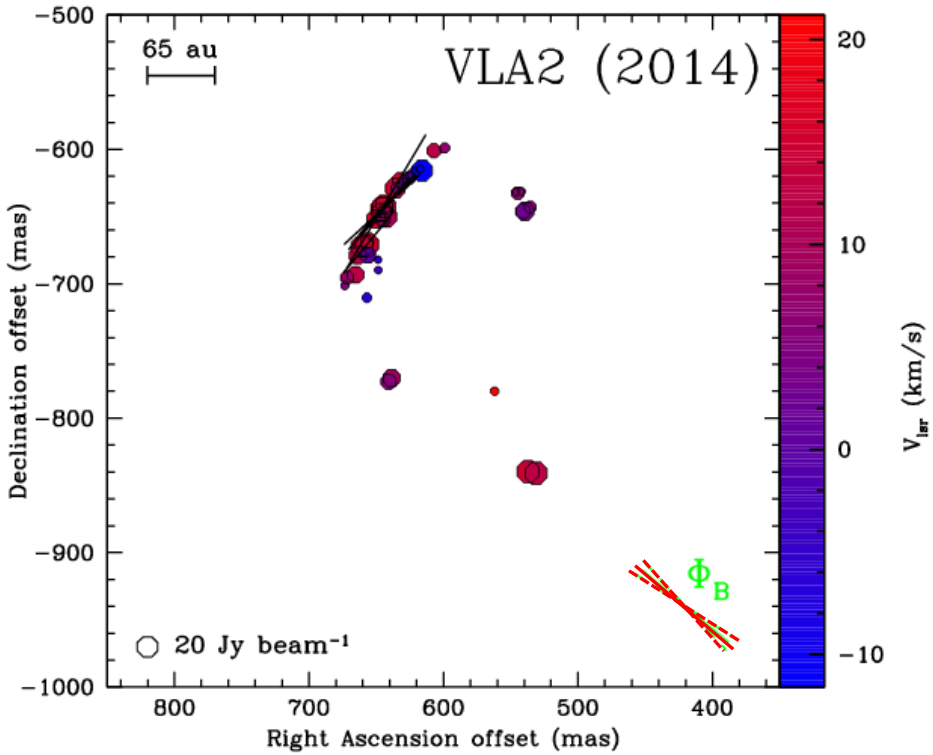


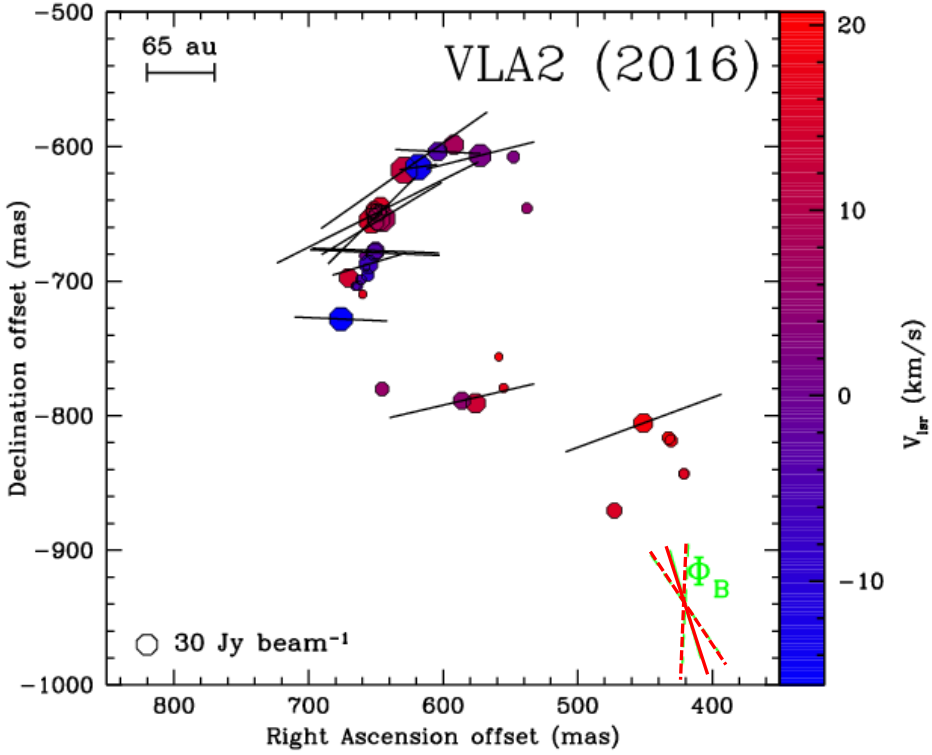
Surcis, G. et al. 2018 (?), in prep.

W75N(B) – TO BE CONTINUED

A monitoring programme begun in 2014 with the EVN: 4 epochs spaced by 2 yrs (total 6 yr)

$\overline{|B_{\parallel}|}^{2016.45}_{\mathrm{VLA2}}$ = 1962 mG





Surcis, G. et al. 2018 (?), in prep.

W75N(B) – TO BE CONTINUED

A monitoring programme begun in 2014 with the EVN: 4 epochs spaced by 2 yrs (total 6 yr)

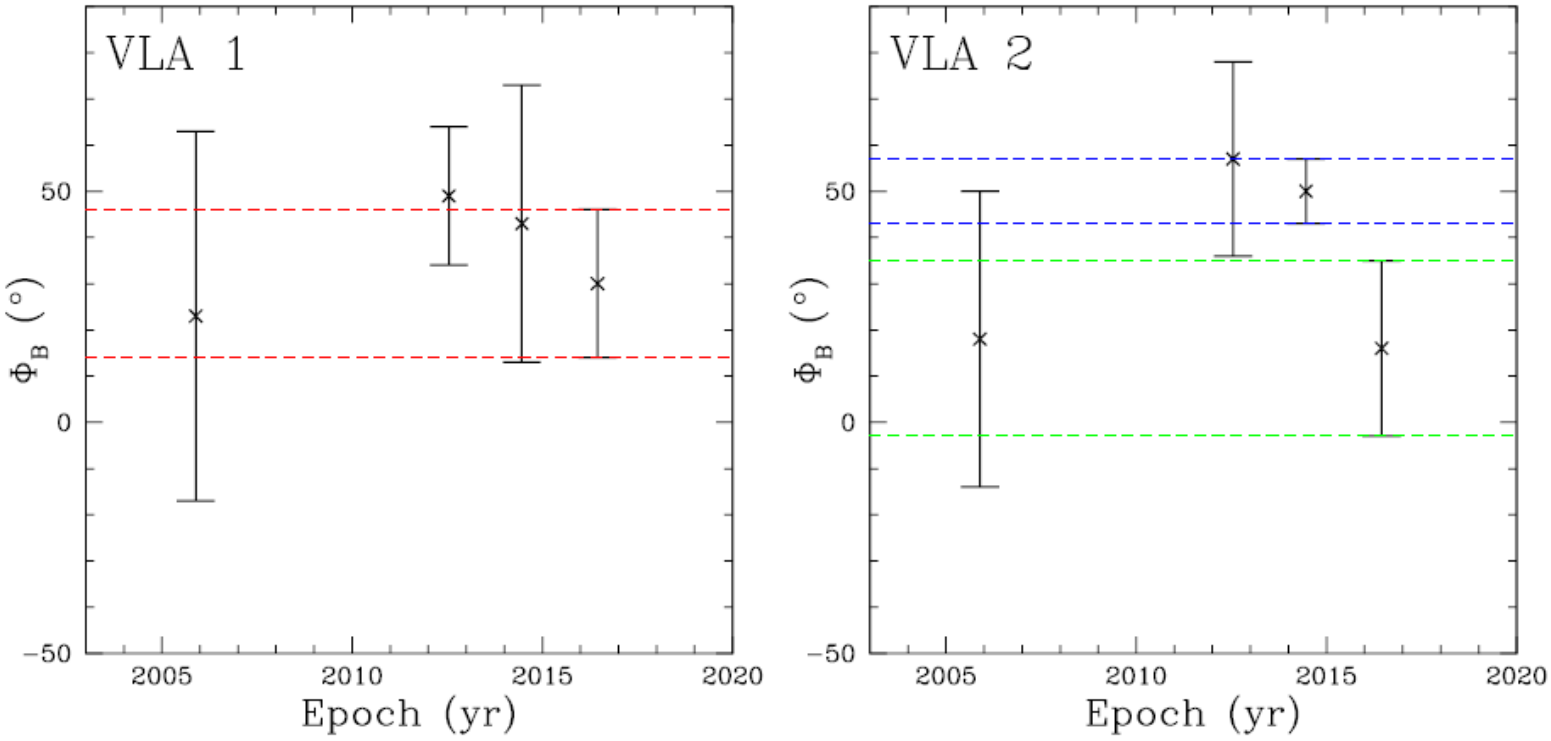


Figure 3: Multi-epoch comparison of Φ_B angles for VLA 1 (left panel) and VLA 2 (right panel). The red dashed lines indicate the common range of angles among the four epochs (2005.89, 2012.54, 2014.46, and 2016.45). The green dashed lines indicate the common range of angles between epochs 2005.89 and 2016.46, and the blue ones between epochs 2012.54 and 2014.46.

Surcis, G. et al. 2018 (?), in prep.

LOOK FORWARD

- Modify and run the FRTM code for the CH_3OH maser transitions:
  9.9 GHz, 12 GHz, 25 GHz, 85 GHz, 95 GHz, 104 GHz, 107 GHz,
- Model the pumping mechanisms for Class I and Class II CH_3OH masers
  (anyone interested in helping us? )
- Finish to analyse the Flux Limited Sample
- Complete the monitoring project of W75N(B) – next epochs in June 2018 and 2020
- Confirm observationally the theoretical predictions
- Modify the FRTM code for the SiO masers (*consider the anisotropic pumping*)

THANK YOU

More about Maser Polarization

Session 1

Boy Lankhaar – *Quantum-chemical calculations revealing the effects of magnetic fields on methanol* ✓

Taylor Tobin – *Constraining Theories of SiO Maser Polarization: Analysis of a π/2 EVPA Change*

Session 2

Tim Robishaw – *Zeeman Splitting of OH Megamasers as a Probe of Magnetic Fields in Starburst Galaxies*

Session 4

Luca Moscadelli – *Masers as probes of the gas properties close to forming stars*

Ciriaco Goddi – *Measuring Magnetic Fields from Water Masers in the Synchrotron Protostellar Jet in W3(H_2O)*

Jihyun Kang – *Linear Polarization of Class I Methanol Masers in Massive Star Forming Regions*

Posters

N. 12 Daria Dall'Olio – N. 17 Eodam Hwang – N. 22 Gordon MacLeod – N. 25 Hiroko Shinnaga – N. 39 Kitiyanee Asanok – N. 43 Lucero Uscanga – N. 50 Olga Bayandina – N. 54 Soon-Wook Kim – N. 56 Thanapol Chanapote – N. 65 Yuta Kojima