可視域の偏光 vs. サブミリ波偏波– 星間塵の整列機構

Polarization in the optical and submm regions: Grain alignment theories

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My Talk:

- A brief review of grain theories
  - Davis and Greenstein theory (DG)
  - Radiative Torque (RAT)
    - # Sorry, but some slides are the same as in my previous talk…

  - The observed direction of pol (position angle) really shows B-field?

- Optical vs. submm polarizations

- An example: L1689 stream

Some phrases by an author…

- Cugnon P. (1987)

"… What concerns coherent derivations of the magnetic field strength, my general impression remains rather pessimistic, but not desperate."

in the proceedings of "Interstellar Magnetic Fields" ed. Beck & Graeve, pp.100-109

Grain alignment with DG mechanism

- Discovery of polarization in distant stars   Hall 1949, Hiltner 1949
- Alignment with paramagnetic relaxation   Davis and Greenstein 1951
  - Phase lag of magnetization → torque that makes angular momentum J // B
  - Alignment time scale τ_{DG}:   Draine & Weingertner 1996

$$\tau_{DG} = \frac{2\alpha_1 \rho a_{eff}^2}{5K(\omega)B_0^2} = 1.5 \times 10^6 \alpha_1 \rho_3 a_{-5}^2 \left[\frac{10^{-13}\ \mathrm{s}}{K(\omega)}\right]\left(\frac{5\ \mu\mathrm{G}}{B_0}\right)^2\ \mathrm{yr}$$

(Davis & Greenstein 1951), where $K(\omega) \equiv \mathrm{Im}\,[\chi(\omega)]/\omega \approx 10^{-13}$ s for normal paramagnetism at $T \approx 18$ K

  - Rotational damping by gas drag:

$$\tau_{drag,gas} = \frac{\pi \alpha_1 \rho a_{eff}}{3\delta n_H (2\pi m_H kT)^{1/2}} = (8.74 \times 10^4\ \mathrm{yr}) \times \frac{\alpha_1}{\delta} \rho_3 a_{-5} T_2^{1/2} \left(\frac{3000\ \mathrm{cm}^{-3}\ \mathrm{K}}{n_H T}\right)$$

where $\rho_3 \equiv \rho/3$ g cm^{-3}, $a_{-5} \equiv a_{eff}/10^{-5}$ cm, and $T_2 \equiv T/10^2$K.

α_1, δ: shape factor, $\alpha_1 \sim \delta$

  - $\tau_{DG} >> \tau_{drag}$ DG is very slow process. No alignment? A “mystery” in 1950-1980s.

Some phrases by other authors…

- Draine and Weingartner (1996)

"… It therefore appears that the longstanding mystery has been solved -- the observed alignment of interstellar grains is due to radiative torques produced by anisotropic starlight!"

AAS 189, 1602

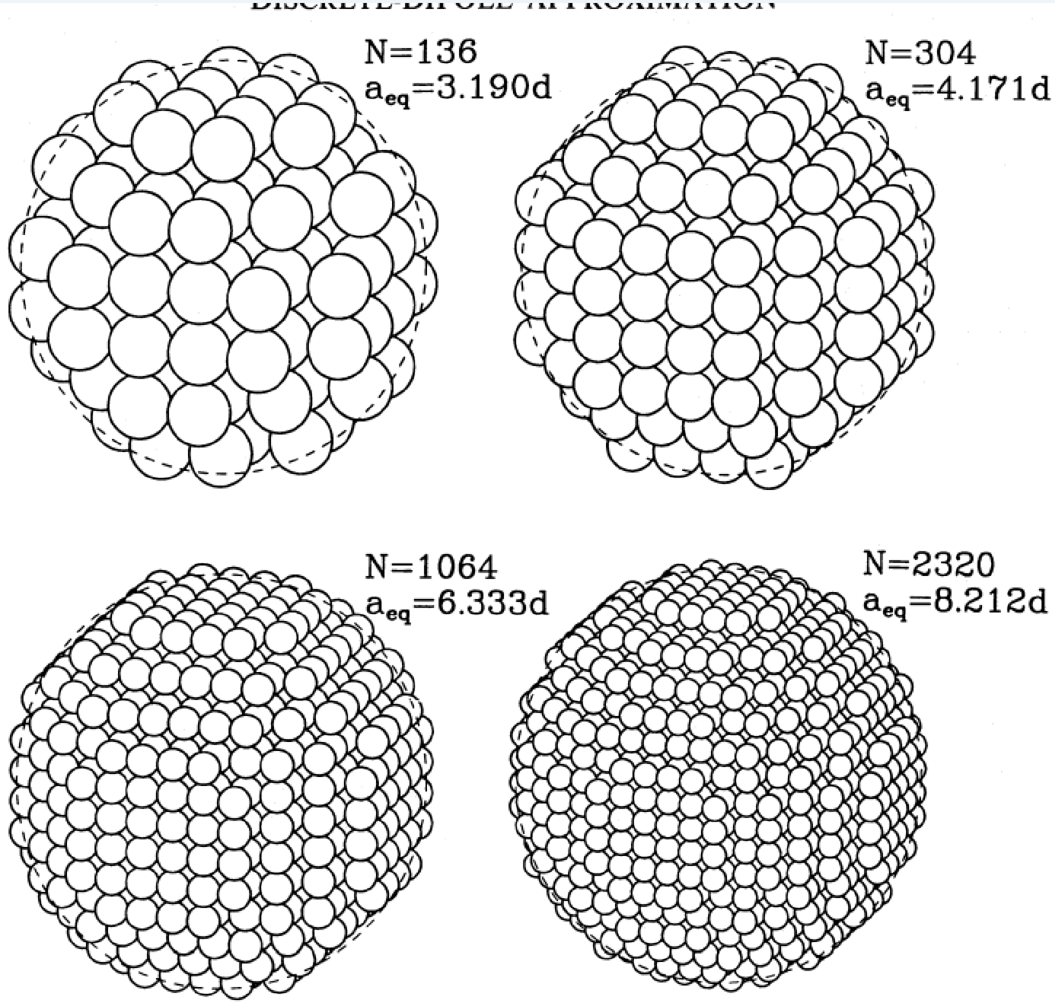


FIG. 1.—"Spherical" discrete dipole arrays considered in this paper, with N = 136, 304, 1064, and 2320

- Breakthrough:

  light scattering calculation

"Dicscrete-Dipole Approximation"

(DDA)

Draine 1988 ApJ 333, 848

Grain alignment by Radiative Torque (RAT)

- Dolginov & Mytrophanov 1976, Draine & Weingartner 1996, 1997, Lazarian et al. many papers
  - Breakthrough "Discrete Dipole Approximation" (DDA) method Draine 1988
- Irregular Grains rotate rapidly by RAT → magnetized by the Barnett effect

The Barnett magnetic moment is

$$\mu = -\frac{\chi(0) V \hbar}{g \mu_B} \omega ,$$

where V is the grain volume, μ_B is the Bohr magneton, $g \approx 2$ is the gyromagnetic ratio, and $\chi(0)$ is the static susceptibility.

DW 1997

- → Larmor precession around interstellar magnetic field B_0, i.e. directions of J and B_0 is related, with frequency Ω_B

$$\Omega_B = \frac{\mu B_0}{I_1 \omega} = \frac{5 \hbar \chi(0) B_0}{2 \alpha_1 g \mu_B \rho a_{\rm eff}^2}$$

$$\approx 7.5 \text{ yr}^{-1} a_{-5}^{-2} \left(\frac{3 \text{ g cm}^{-3}}{\alpha_1 \rho}\right)^{1/2} \left[\frac{\chi(0)}{10^{-4}}\right] \left(\frac{B_0}{5 \ \mu\text{G}}\right)$$

where we have set $g \approx 2$. It is therefore clear that interstellar grains will precess around $\boldsymbol{B}_0$ very rapidly compared to all other timescales except the grain rotation period itself.

- Period of the Larmor precession $\tau_B = 1/\Omega_B \sim$ 0.1 year ... very rapid!

Observations of Grain Alignment

- Not all grains are aligned…
  - Smaller grains are poorly (or not?) aligned: polarization is small in UV

- Polarization is enhanced under strong radiation:
  - Andersson, B-G et al. 2011, AA 534 A19
    - HD 97300 in Chamaeleon I cloud
  - Matsumura et al. 2011, PASJ 63, L43
    - P_λ / A_λ in Pleades and other regions

- Grains in in very dense regions: Starless cores   Av > 20 mag.
  - Jones et al. 2015, AJ 149, 31

- All those observations support alignment by radiative torque (RAT)!

Ext. vs. Pol. in optical

- Extinction: A_λ increases with 1/λ
- Polarization P_λ takes a maximum $\lambda_{max} \simeq 0.4 \sim 0.8\mu m$
- → Polarization is relatively small in shorter wavelength.
- → Grains effective for shorter wavelength, i.e. smaller grains, are less aligned.

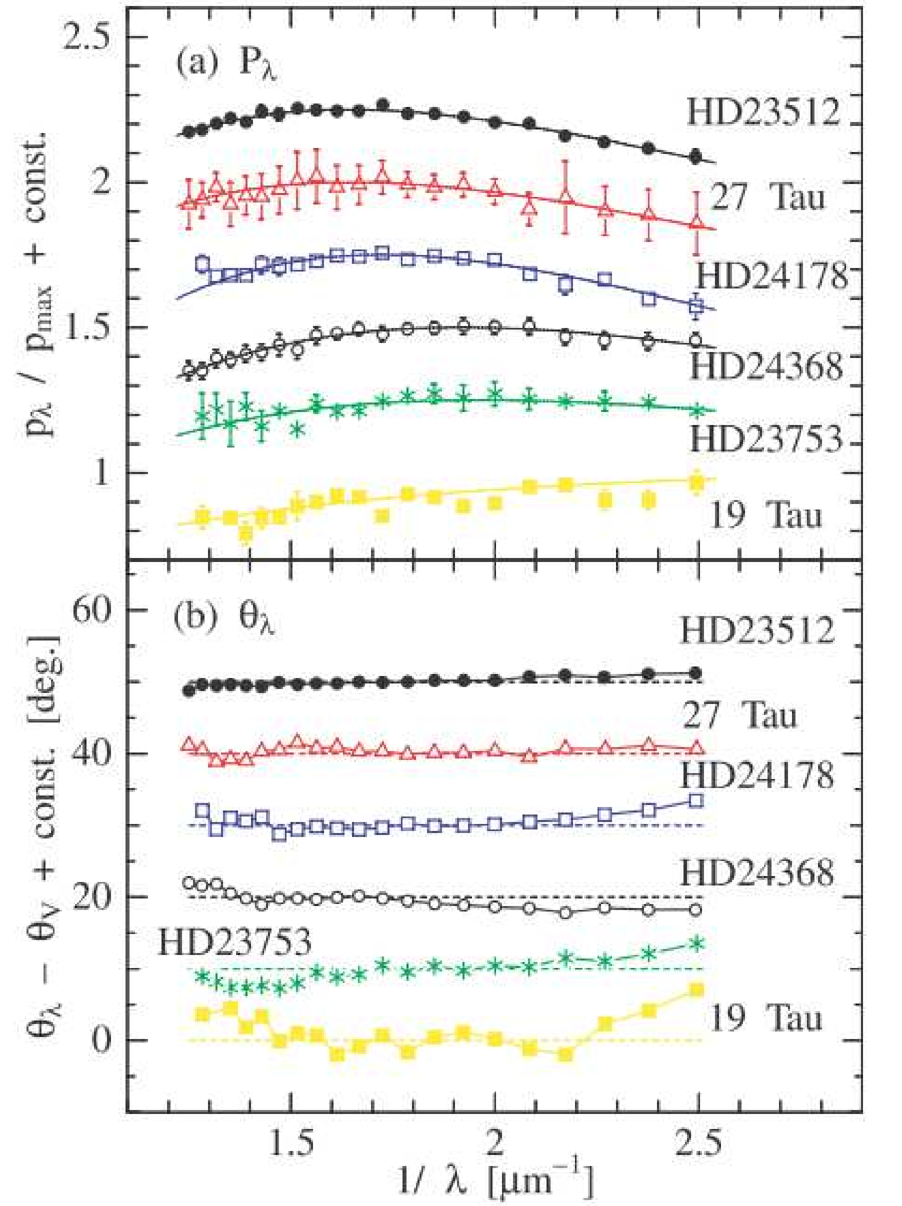


Fig.: Matsumura +2011 PASJ 63, L43

Fig. 1. Wavelength dependence of (a) fractional polarization p_λ and (b) position angle θ_λ for the Pleiades stars. Solid lines in (a) show results of fitting by equation (1), and dashed lines in (b) the values of θ_V. Data of each object are moved vertically in steps of 0.25 in (a) and 10° in (b).

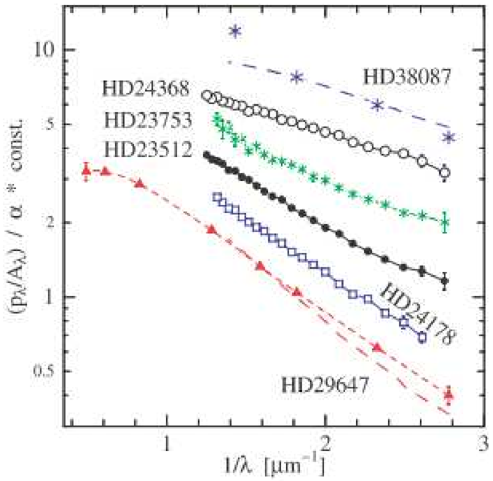


Fig. 2. Wavelength dependence of the polarization efficiency, p_λ/A_λ, deduced with Method 1 (See text). Asterisks show the results of HD 38087 (Serkowski et al. 1975) and filled triangles HD 29647 (Whittet et al. 2001), while other symbols are for the Pleiades stars, as in figure 1. Long dashed lines are the results by Weitenbeck (1999). The data were normalized by α [see equation (2)], and moved vertically in steps of factor 1.5.

Table 2. Polarization properties deduced from the literature.

HD or SAO (Sp. type)	α [% mag^{-1}]	β [μm]	T_{dust} [K]	Ref.*
14889 (K0)†	2.12 ± 0.21	0.46 ± 0.05	18.0	(1)
29647 (B8 III)	0.65 ± 0.02	1.06 ± 0.05	15.0	(5)
—	0.62 ± 0.03	1.25 ± 0.08	—	(3)
30675 (B3 V)	2.70 ± 0.13	0.83 ± 0.07	16.0	(5)
37367 (B2 IV–V)	0.74 ± 0.04	0.76 ± 0.04	15.8	(4)
38087 (B5 V)	1.47 ± 0.07	0.40 ± 0.06	21.0	(3)
—	1.51 ± 0.07	0.51 ± 0.03	—	(2)
192001 (O9.5 IV)	0.84 ± 0.04	0.92 ± 0.05	19.8	(4)
193322 (O9 V)	1.57 ± 0.10	0.91 ± 0.08	20.4	(4)
210121 (B3 V)	1.76 ± 0.16	0.79 ± 0.11	17.4	(4)
216532 (O8.5 V)	0.87 ± 0.02	0.74 ± 0.04	18.9	(4)
S149760 (K5)†	2.06 ± 0.21	1.03 ± 0.13	16.4	(1)

* References: (1): Seki and Matsumura (1996), (2): Serkowski et al. (1975), (3): Weitenbeck (1999), (4): Weitenbeck (2004), (5): Whittet et al. (2001). The data in the R-band of HD 38087 in Serkowski et al. (1975) is not used for fitting.

† Luminosity class is assumed as V, and the values of (R_V, A_V) are estimated to be $(3.08 \pm 0.20, 1.17 \pm 0.11)$ for HD 14889, and $(2.74 \pm 0.54, 1.15 \pm 0.12)$ for SAO 149760.

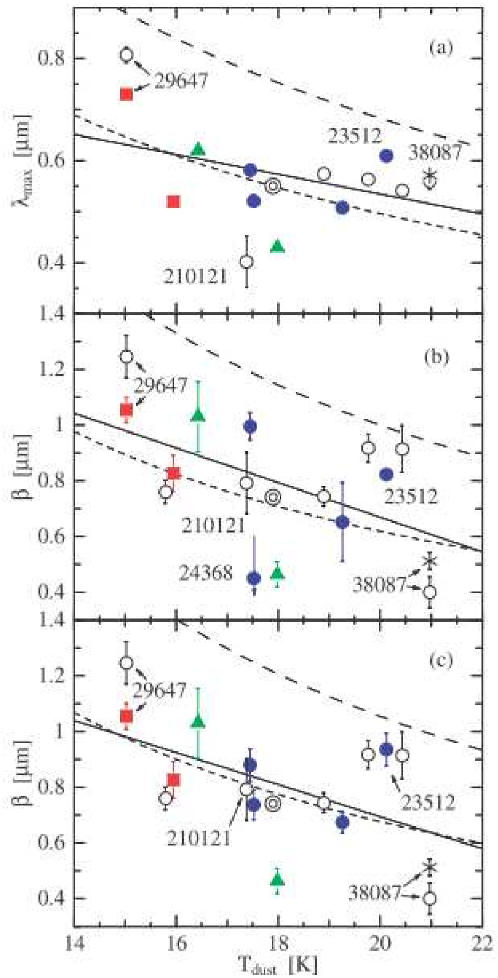


Fig. 3. (a) Correlation between T_{dust} and λ_{max}. Filled circles are the Pleiades stars, open circles the results by Weitenbeck (1999, 2004), filled squares those by Whittet et al. (2001), and filled triangles those by Seki and Matsumura (1996). Double circle is the average of interstellar medium. Result of linear fitting for 14 stars is drawn as solid line. Short dashed line presents a model prediction for $a' = a_{lower}$, while long dashed line $a' = 2a_{lower}$. See text for details. (b) Same as (a) but for T_{dust} and β with Method 1. (c) Same as (b) but with Method 2.

$$\ln(p_\lambda/A_\lambda) = \ln\alpha - \beta(1/\lambda - 1/0.55\,\mu\mathrm{m}),$$

T_{dust} is high, i.e. strong radiation,

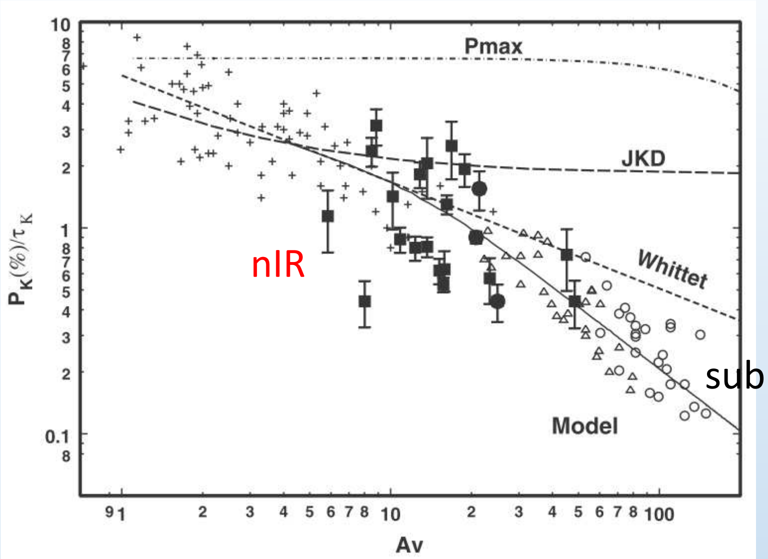
→ then λ_{max} & β are small.

(= Smaller grains are also aligned.)

... This evidence supports RAT.

T_{dust}: Schlegel+ 1998. COBE & IRAS

Matsumura + 2011, PASJ 63, L43

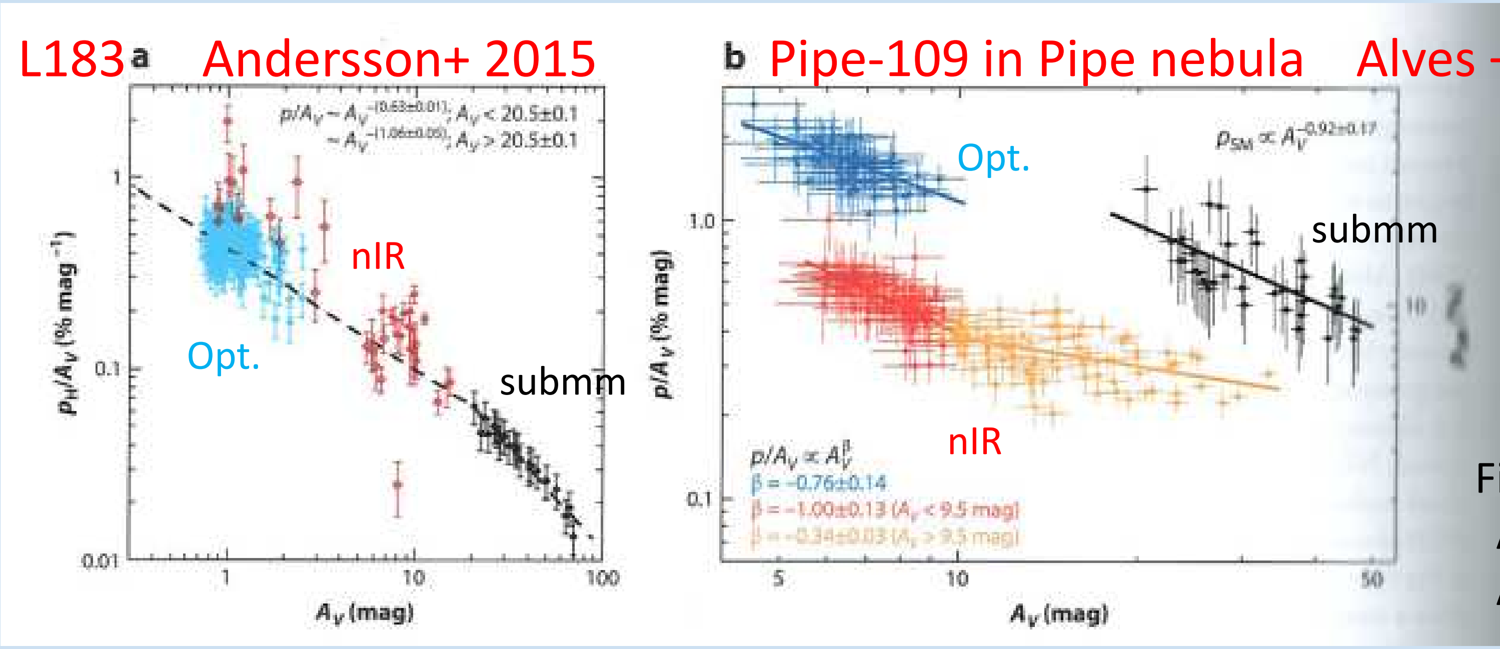


Starless Cores: L183 & L43. Jones + 2015

$p/\tau \propto 1/\tau$ for A_v > 20 mag.

→ They suggest that grains are not aligned in A_v > 20 mag.

But, systematic difference exists between observational methods?



Figs are from:
Andersson+ 2015
ARAA 53, 501

Optical Polarization vs. Submm Polarization

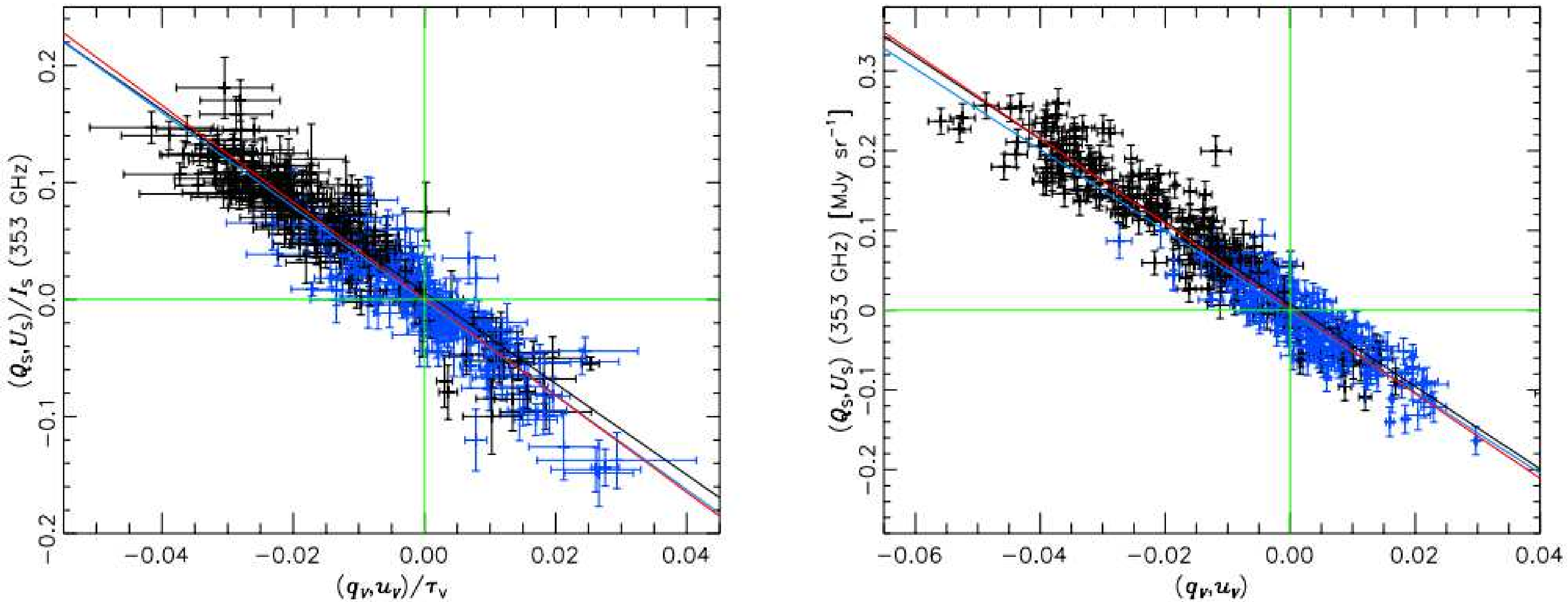


Fig. 7. *Left:* Correlation of polarization fractions in emission with those in extinction for the joint fit in Q (black) and U (blue). Using Eq. 15 the best linear fit (red line) has slope and y-intercept -4.13 ± 0.06 and 0.0006 ± 0.0007, respectively. The Pearson correlation coefficient is -0.93 and $\chi^2_r = 1.64$. *Right:* Correlation of polarized intensity in emission (MJy sr^{-1}) with the degree of interstellar polarization. Using Eq. 16, the best linear fit (red line) has slope and y-intercept (-5.32 ± 0.06) MJy sr^{-1} and (0.0020 ± 0.0009) MJy sr^{-1}, respectively. The Pearson correlation coefficient is -0.95 and $\chi^2_r = 2.29$. Lines for the independent fits to Q (black) and U (blue) are also shown.

- Planck Collaboration 2015, intermediate results XXI, AA 576, 106

Optical Polarization vs. Submm Polarization (cont.)

Grains in diffuse regions:
E(B-V) < 0.8 mag.

- Beam size and los components
- Dust properties in optical and submm
  - (Psubmm/Isubmm) / (p_v/τ_v)
    - ~ 4.2±0.2 compatible with dust models
  - Ps/p_v
    - ~ 5.4±0.2 MJy/sr too low by factor of 2.5
  - → constraining dust models
- Good correlations are amazing, but is it always the case?

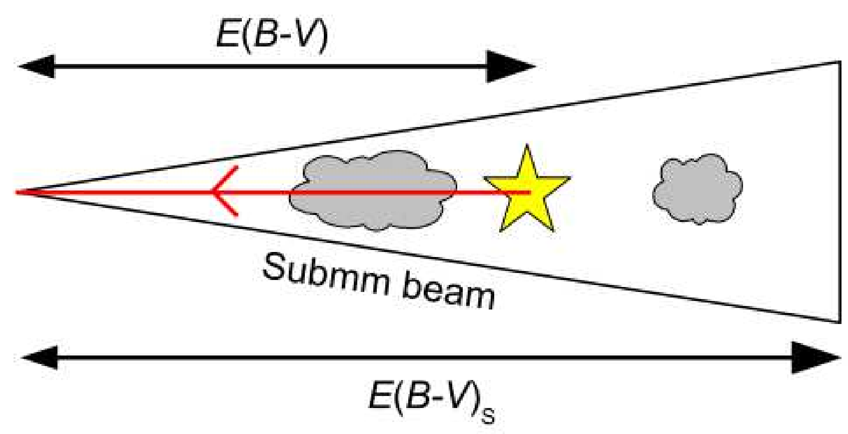


Fig. 1. Instrumental-beam and line-of-sight components affecting the comparison of polarized emission with interstellar polarization from differential extinction of a star. $E(B-V)$ is the colour excess to the star, while $E(B-V)_S$ is the submillimetre optical depth converted to a colour excess (Sect. 3.3).

Planck Collaboration 2015, intermediate results XXI, AA 576, 106

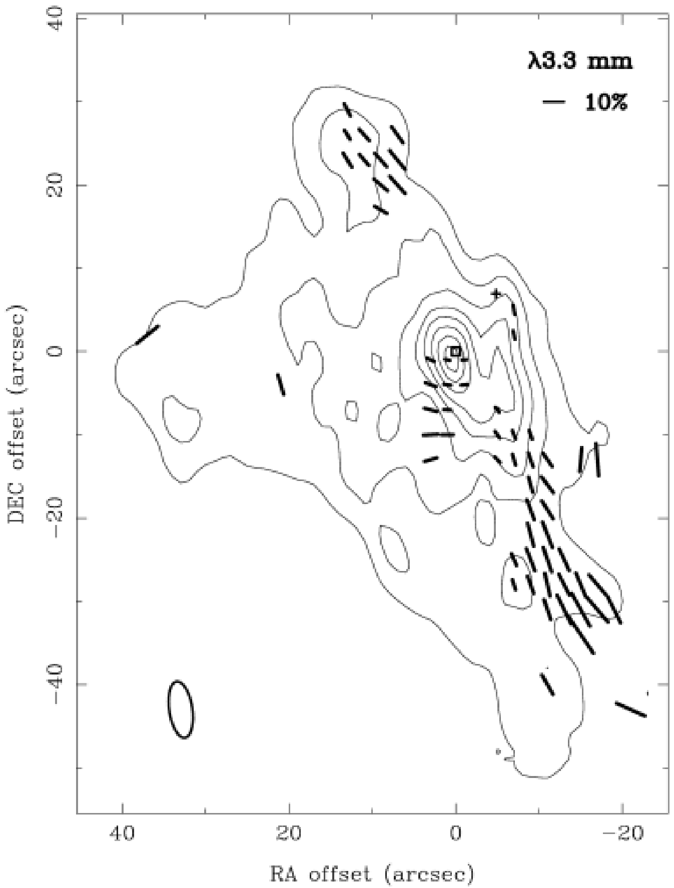


FIG. 1.—Polarization map of Orion-KL at 3.3 mm. Contours indicate the total 3.3 mm flux density (Stokes I) and are drawn at 12, 25, 38, 50, 60, 72, 84, 95 percent of the peak value of 360 mJy beam^{-1}. The noise level was ~15 mJy beam^{-1}. Vectors show the percentage polarization and position angle wherever linearly polarized flux was detected with 3 σ or greater significance. Offsets are relative to IRc2-source I at $\alpha = 5^h35^m14^s.505$, $\delta = -5°22'30''.45$ (J2000). The position of IRc2 is indicated by a hollow square, BN by a cross. The $6''.8 \times 2''.8$ synthesized beam is shown by the ellipse at lower left.

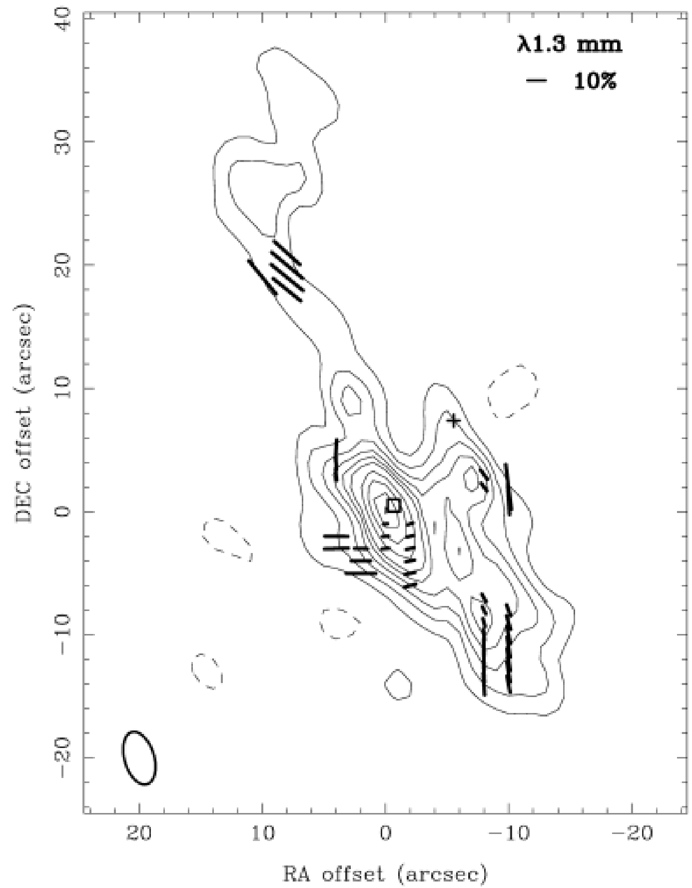


FIG. 2.—Polarization map of Orion-KL at 1.3 mm. Contours indicate the total 1.3 mm flux density and are drawn at −7, 7, 14, 21, 28, 35, 42, 56, 70, 84, 98 percent of the peak of 2.4 Jy beam^{-1}. The noise level was ~46 mJy beam^{-1}. Vectors and beam representation as in Fig. 1. The synthesized beam is $4''.4 \times 2''.4$.

BUT,
PA really shows the B-field?

The alignment of grains might changes?

Orin KL

Rao+ 1998 ApJL 502, L75

Fortunately,
this is not the case...

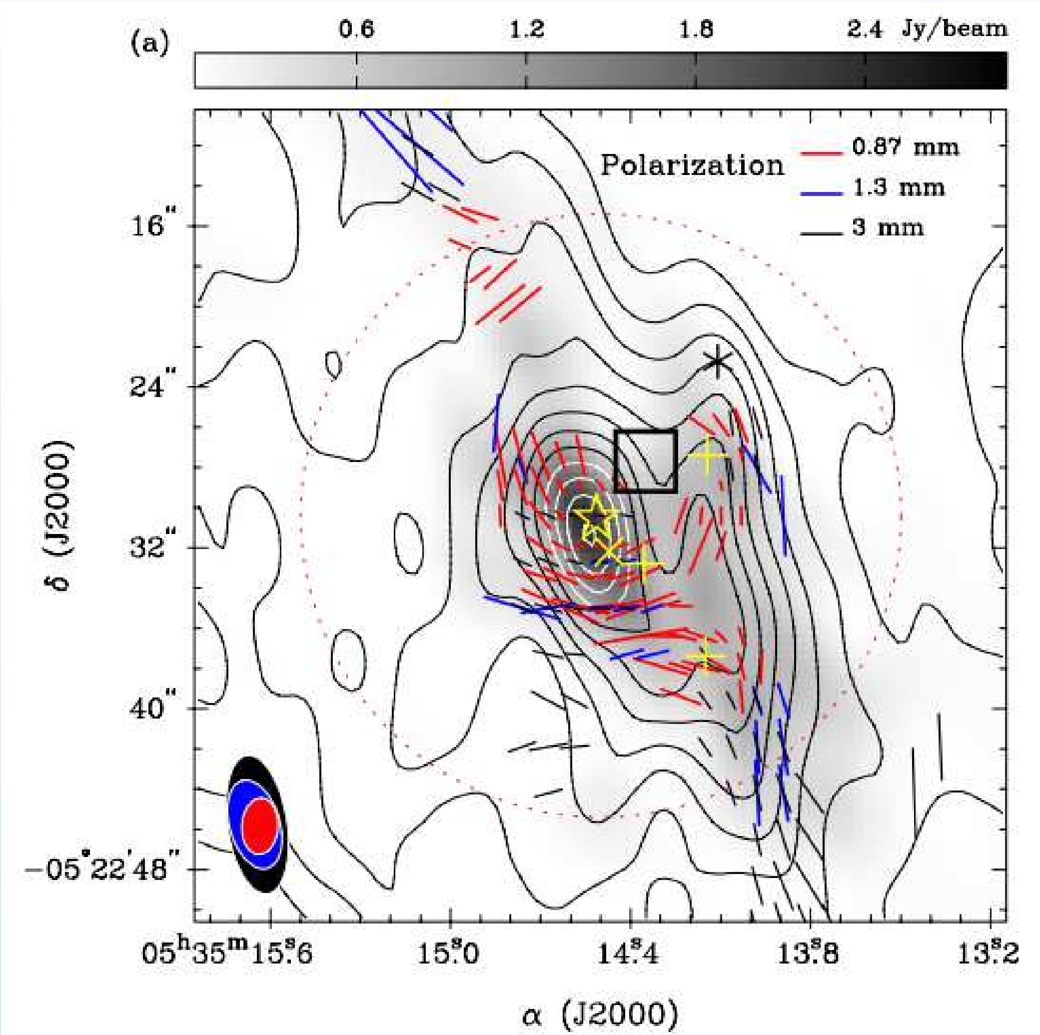
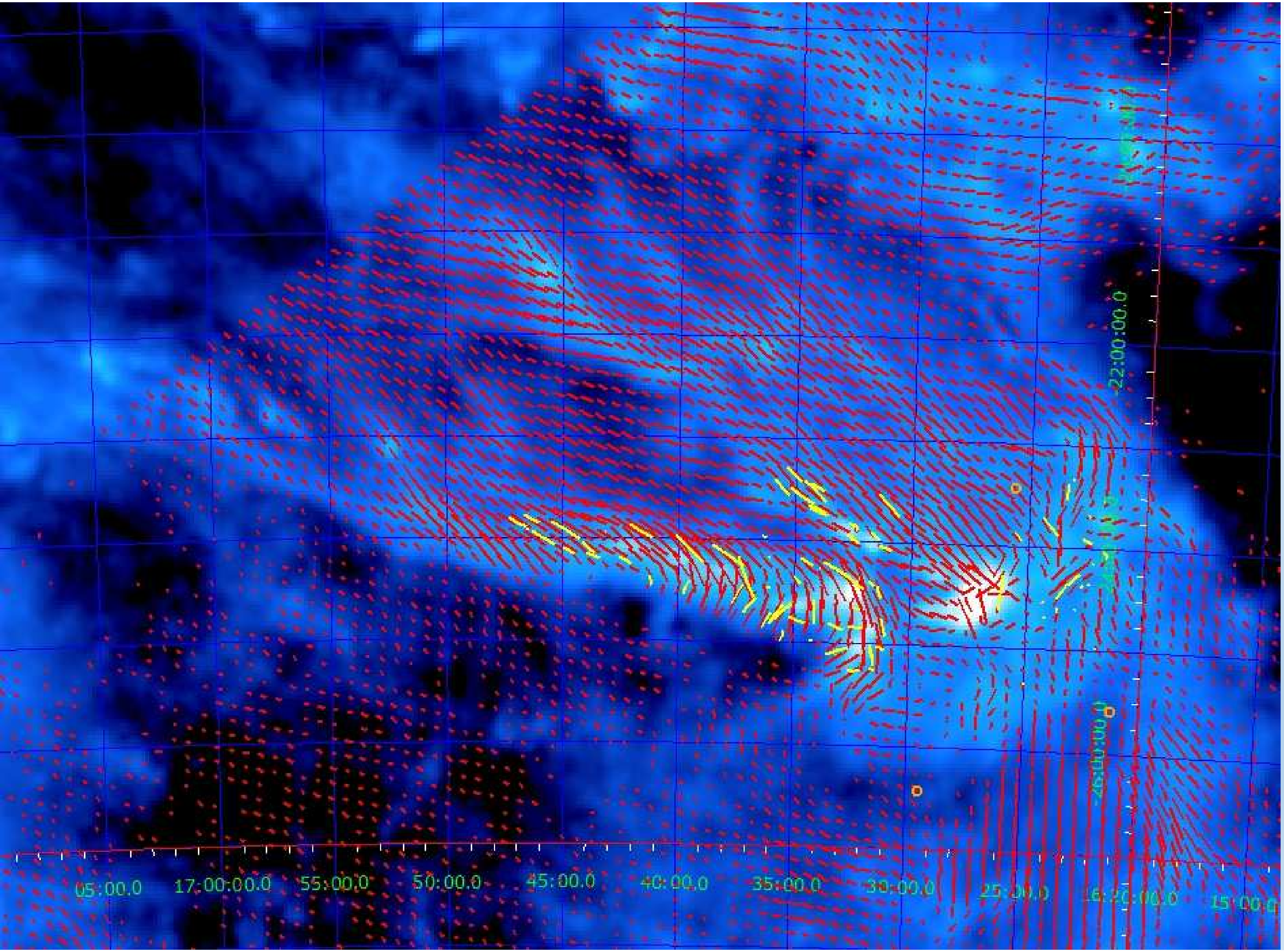


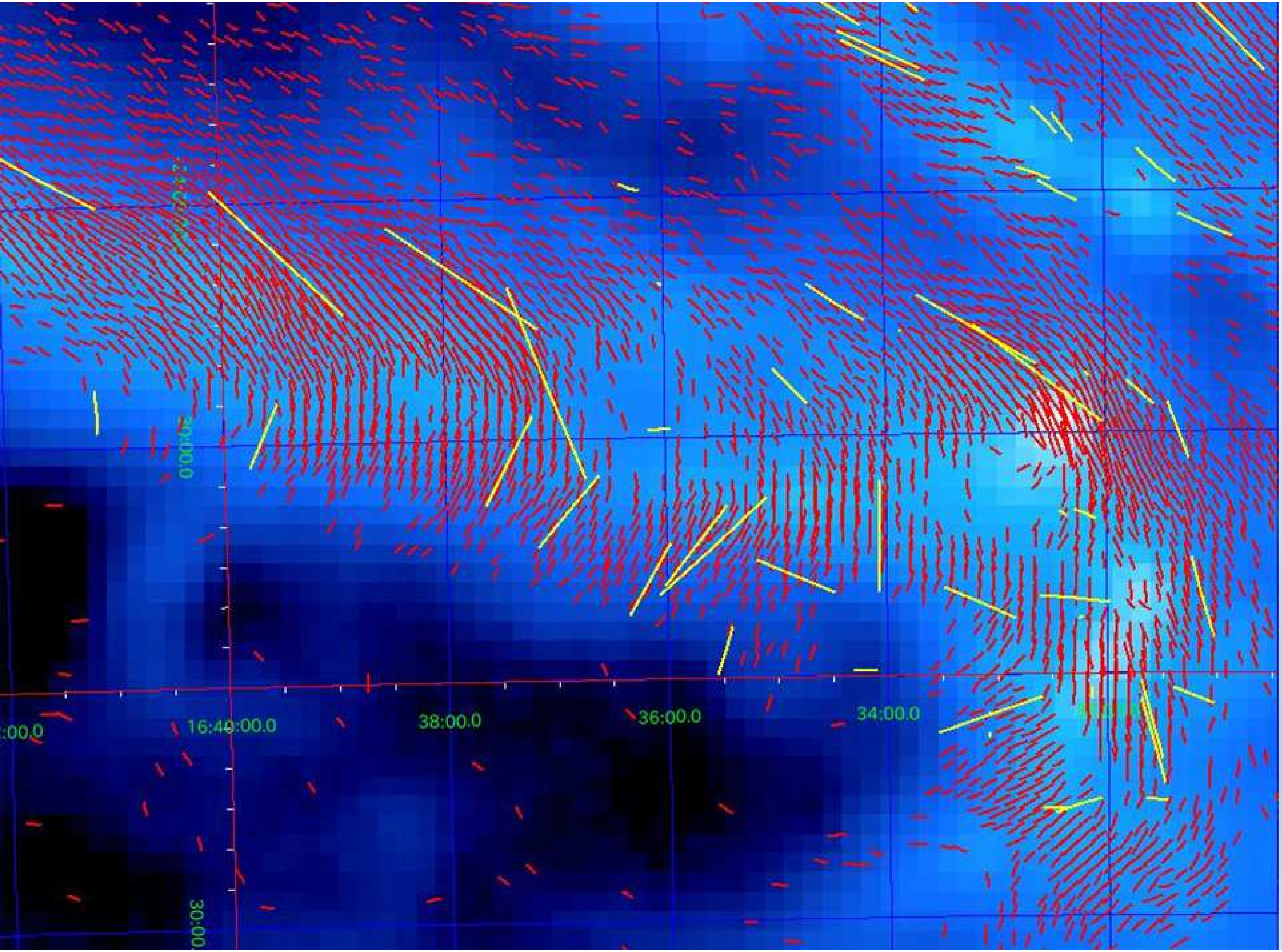
Figure 3. (a) Polarization maps at 3 mm (black segments) and 1 mm (blue segments) obtained with BIMA (Rao et al. 1998) and at 870 μm (red segments; the same as in Figure 2(c)) obtained with the SMA. The black contours are the 3 mm continuum emission strength at 3, 6, 9, . . . , 33, 36, 39 × 0.01 Jy beam^{-1}. The 1 mm continuum emission is shown in grayscale. The sizes of the synthesized beams are plotted in the lower-left corner in the corresponding color as indicated in the upper-right corner. The length of the indicated segments in these three wavelengths represents the polarization percentage of 8%. The large circle in red dots marks the field of view of the SMA. All the other symbols are the same as in Figure 1(a). (b) 870 μm dust continuum (grayscale) of the combined tracks with natural weighting and CO outflows

- Tang + 2010 ApJ 717, 1262



L1689 Stream

- Red: Planck 353GHz submm polarized flux
  - binning: 8.5′ × 8.5′
  - The directions are 90 deg. rotaed, i.e., the B-field.
- Yellow: Optical polarization by Vrba + 1976

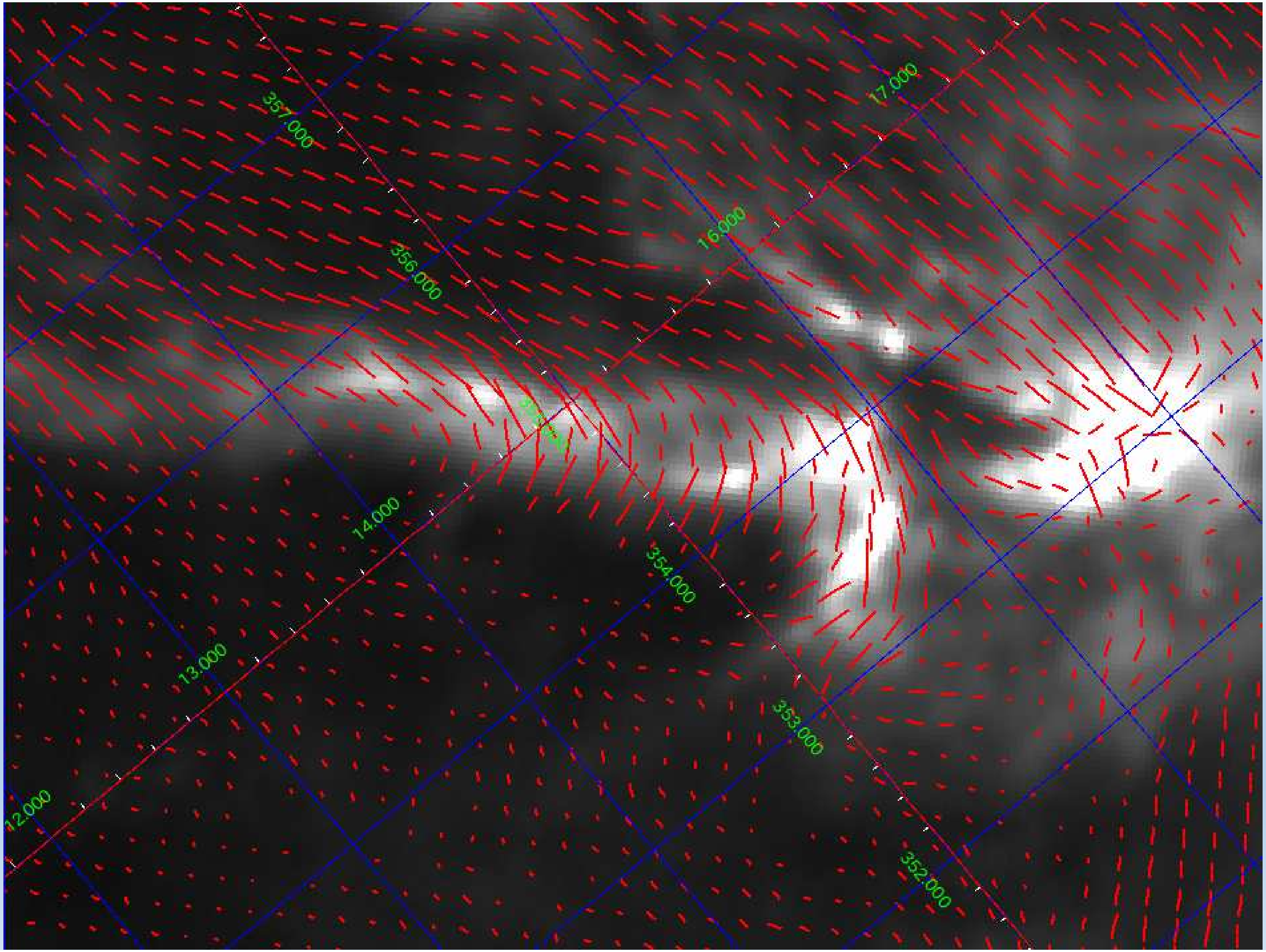


Polarization around L1689 (enlarged)

- Red: Planck 353GHz submm polarized flux
  - no binning
    1.7′ × 1.7′
- Yellow: Optical polarization by Vrba + 1976

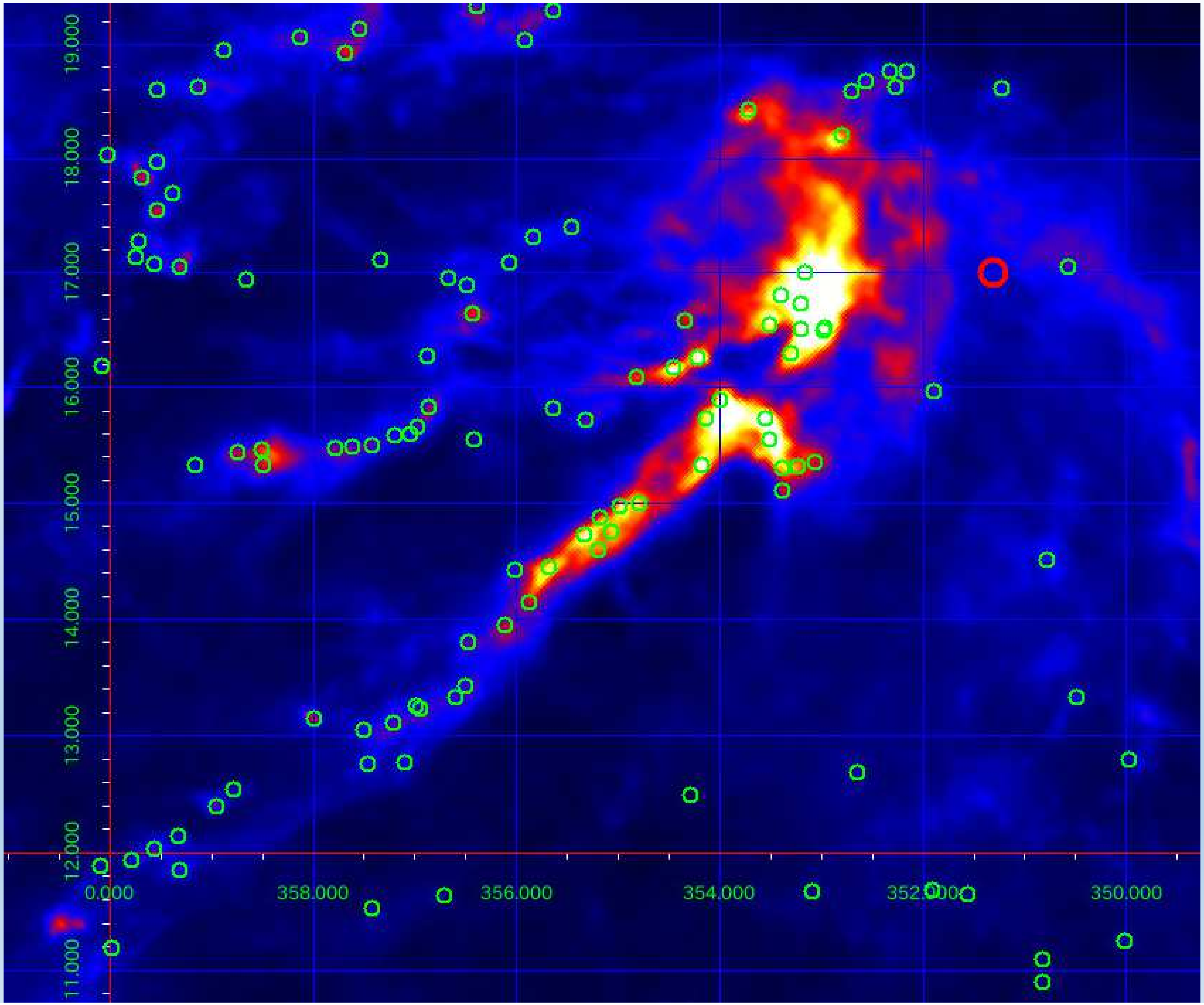
Binning 5x5,

i.e.
8.5’ × 8.5’



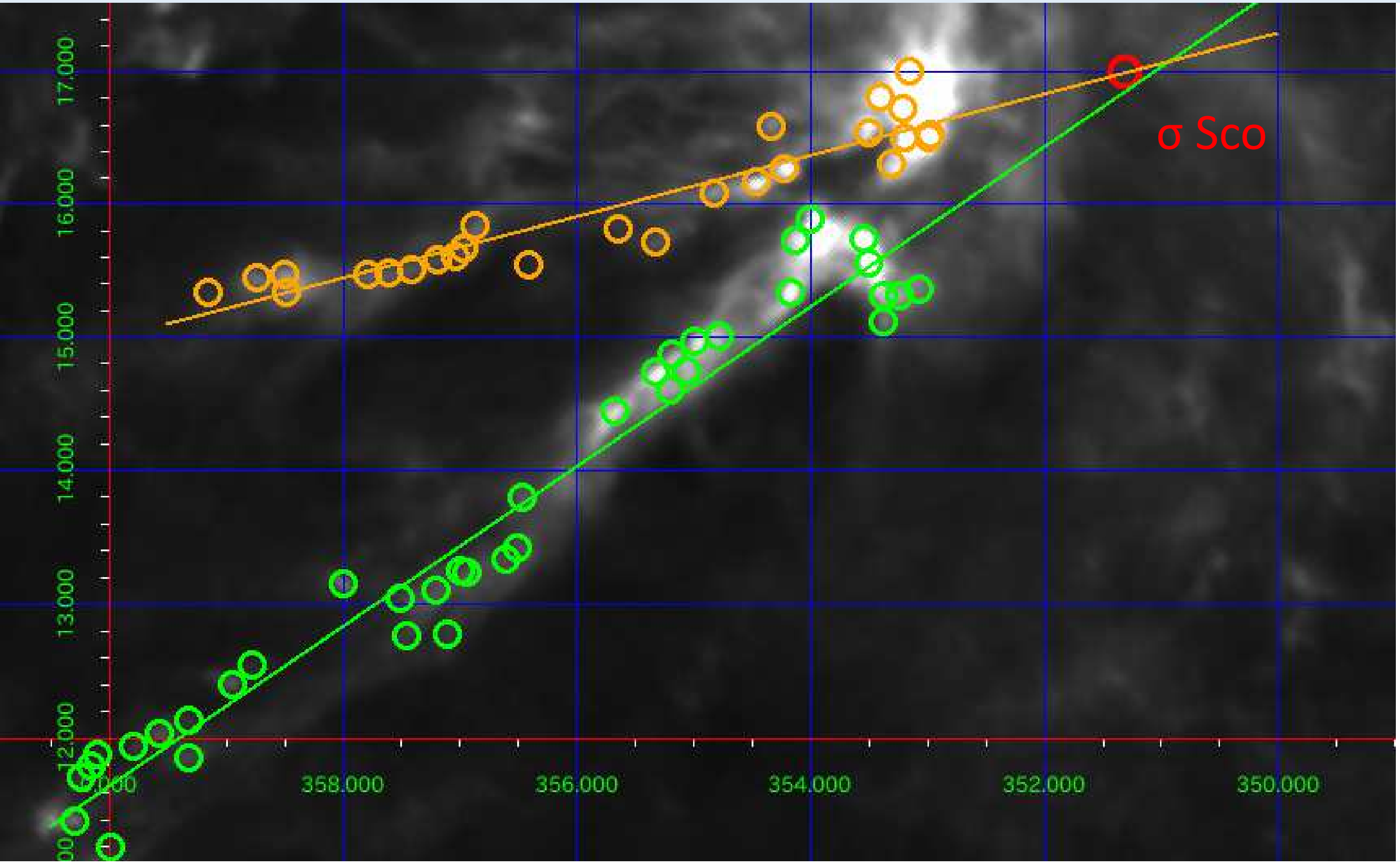
Catalog of Galactic cold clumps

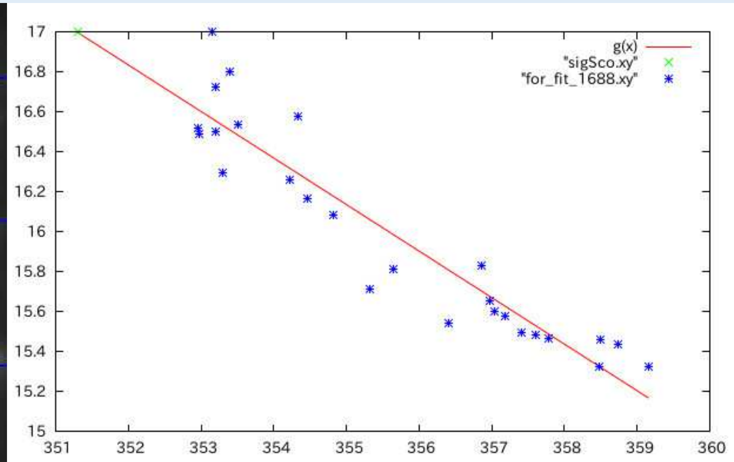
- Planck Coll. 2015 AA 594, A28

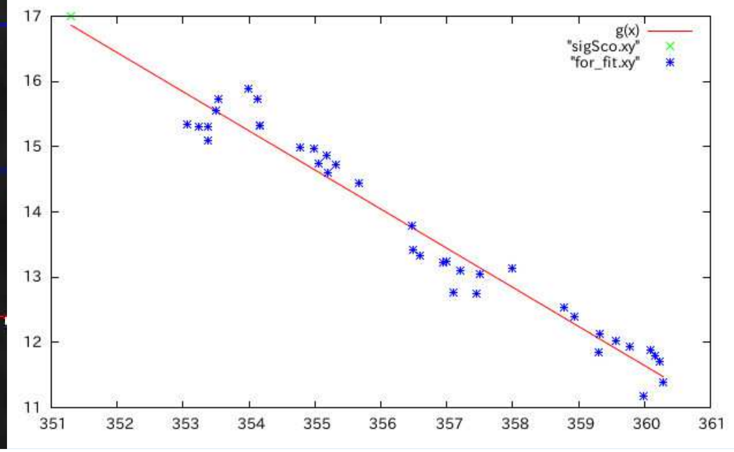


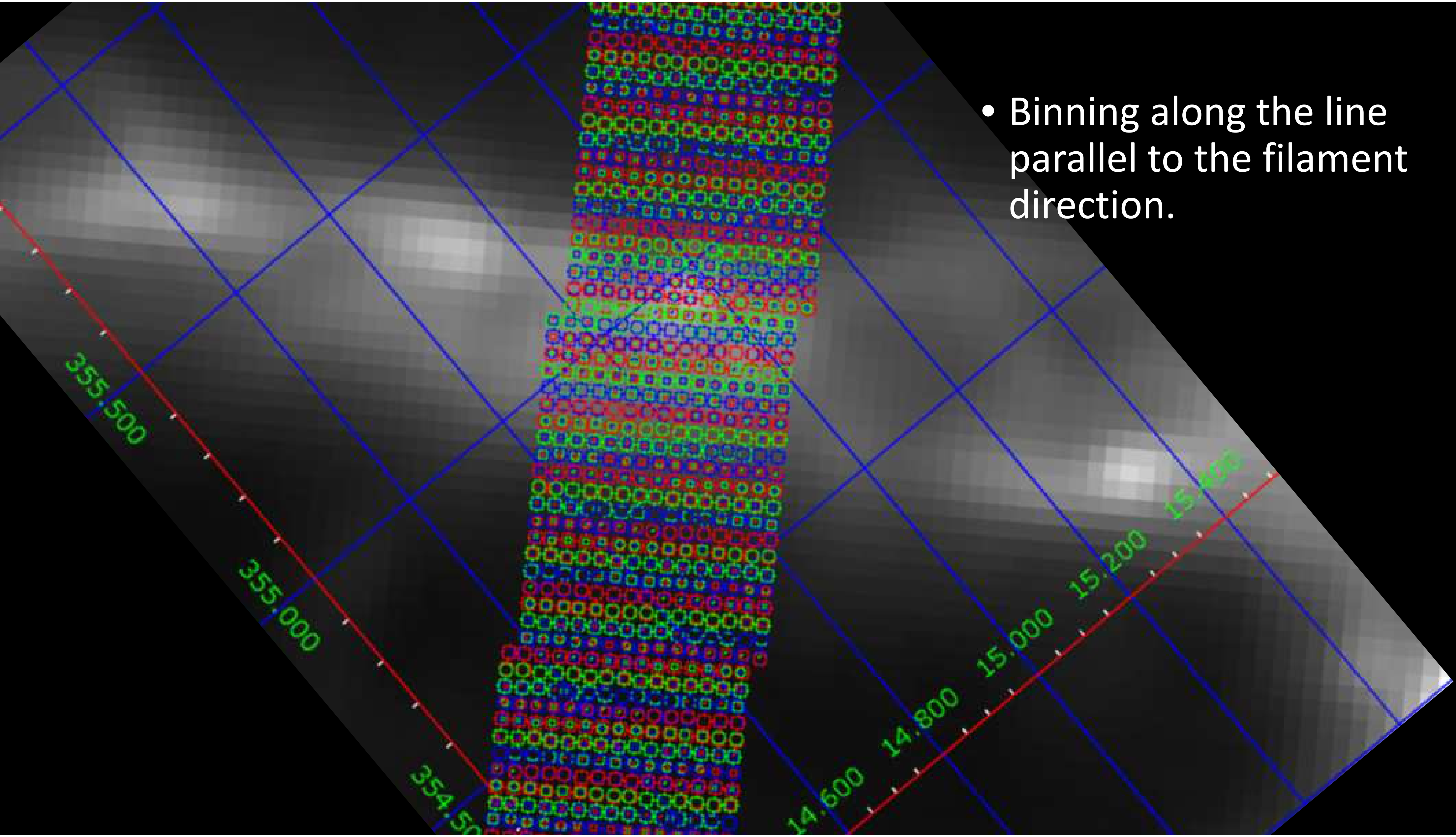
Directions of the streams estimated cold clumps

- Planck Coll. 2015 AA 594, A28

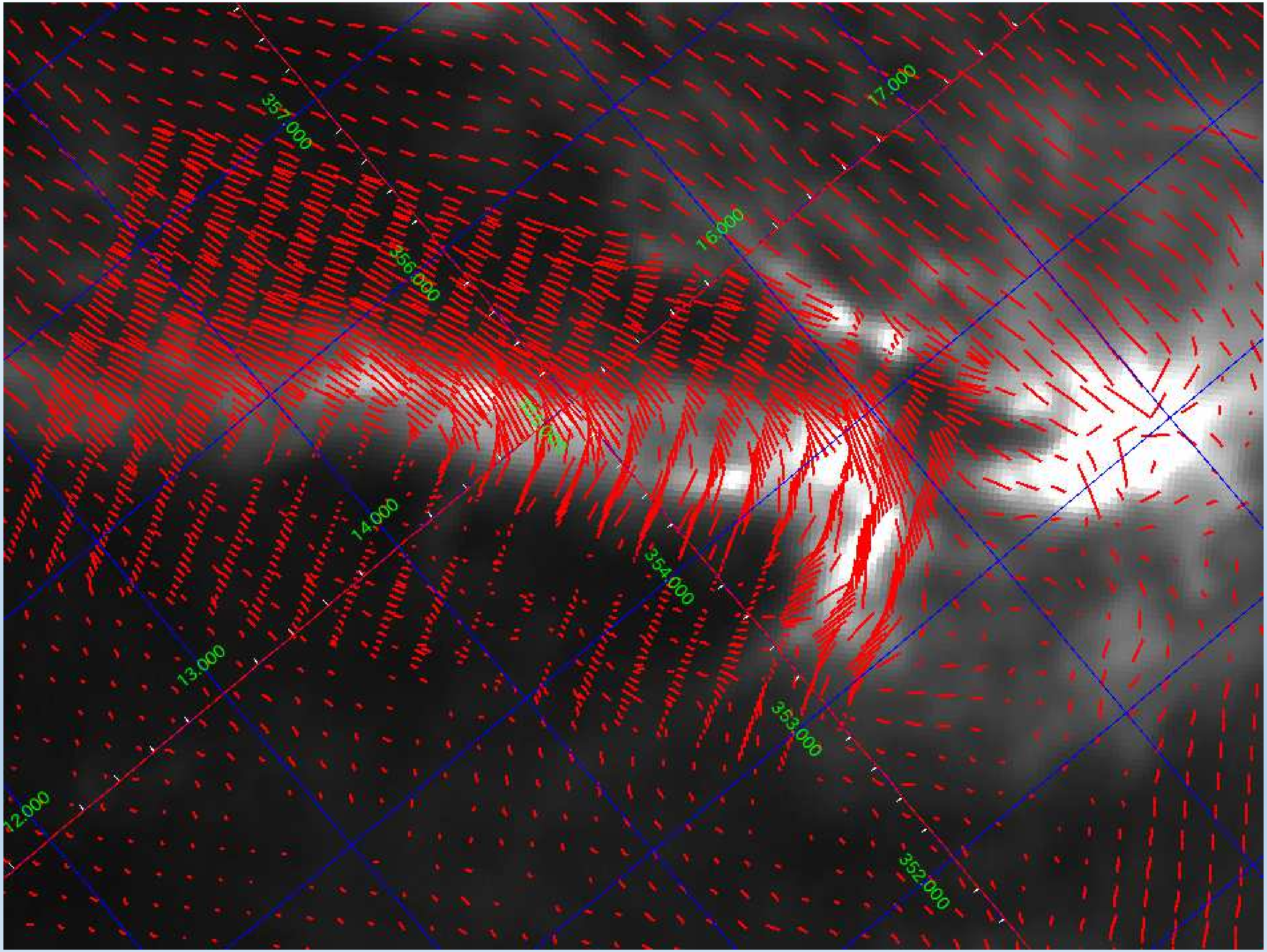




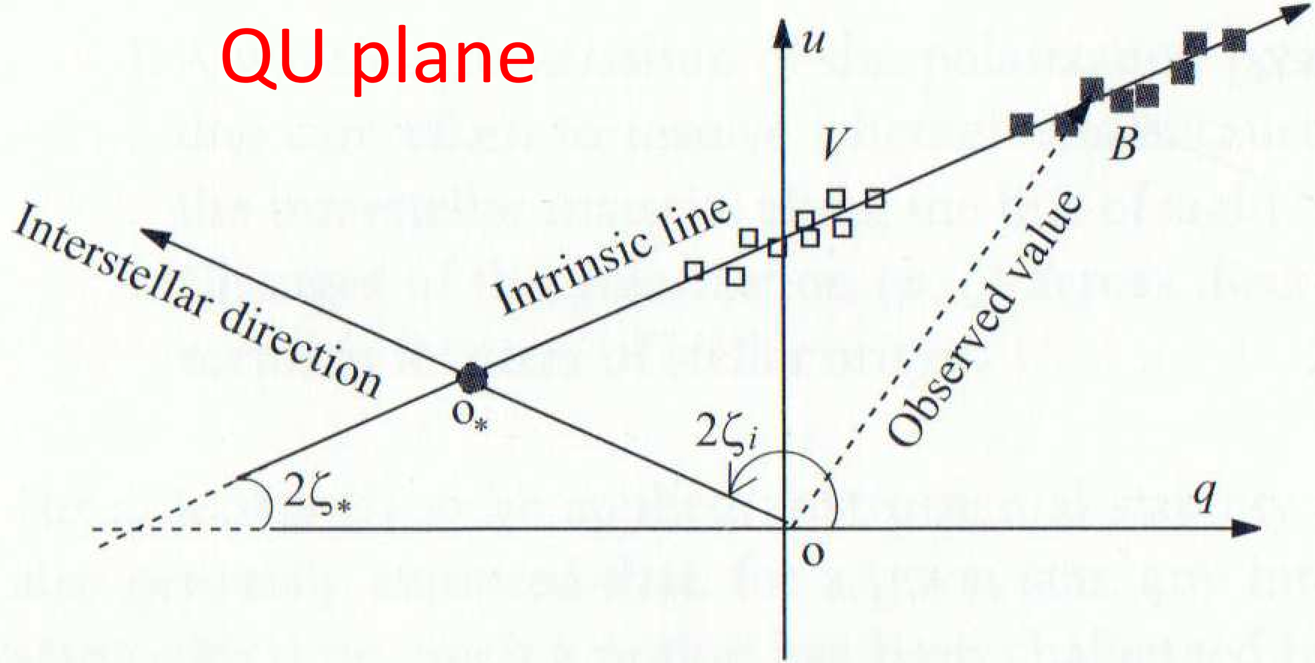




- Binning along the line parallel to the filament direction.


357.000
17.000
16.000
356.000
14.000
354.000
13.000
353.000
12.000
352.000

QU plane



p: distance from the origin:

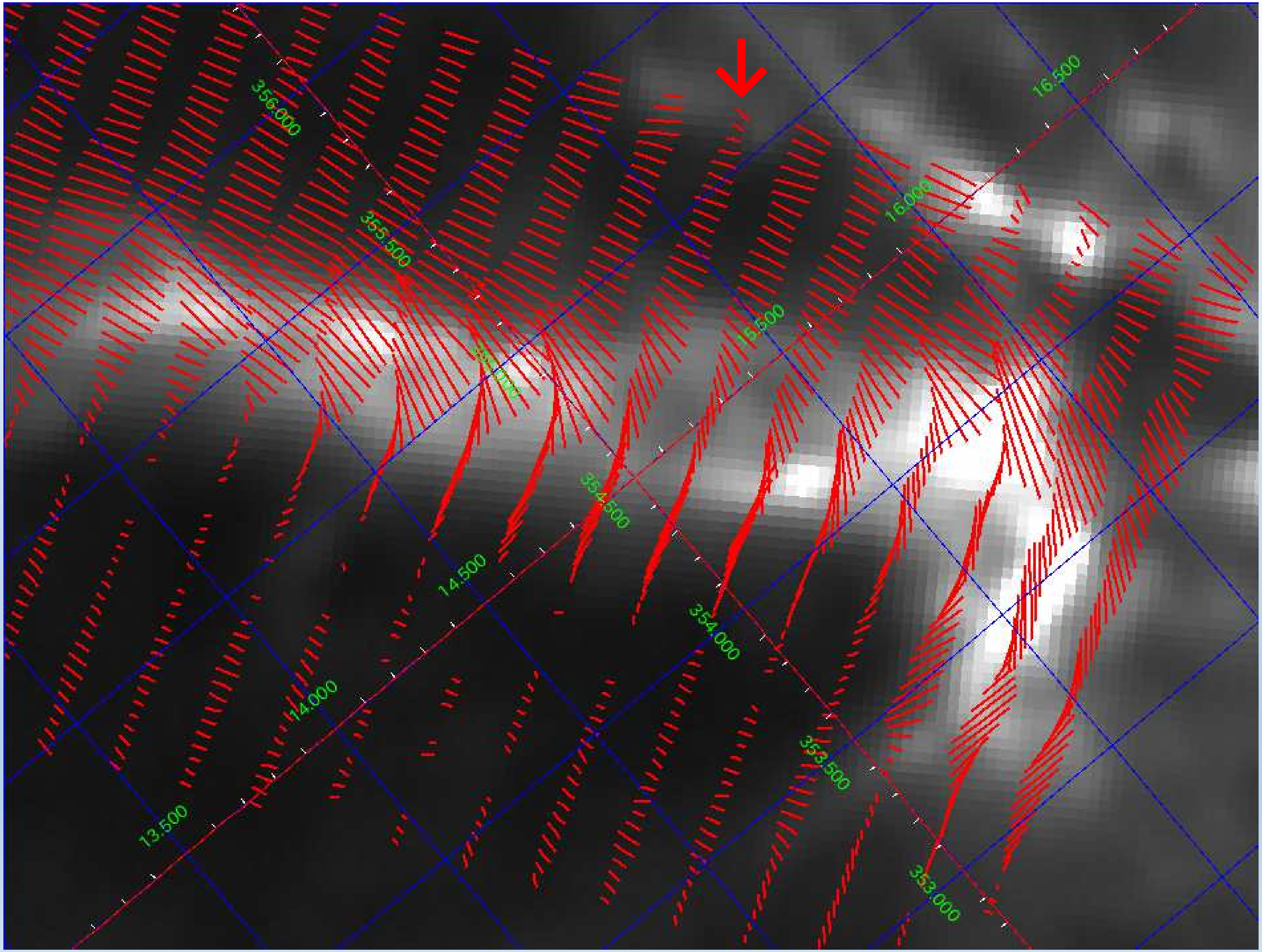
$p = (q^2+u^2)^{0.5}$

Position Angle:

$PA = 0.5*atan(u/q)$

Clark, D. 2010 "Stellar Polarimetry" p.92

Fig. 5.7 A schematic normalized Stokes vector diagram of *B* and *V* data of a polarimetric variable star. The intrinsic line is obtained by taking the best fit to the direct measurements; the interstellar direction is obtained from the polarization vectors for stars in the neighbourhood of the program star. The origin ($O_\star$) for the degree of intrinsic polarization corresponds to the intersection of the intrinsic and interstellar lines. Following the construction, the vector length, $O - O_\star$, should be checked to see if it matches the estimated value for degree of interstellar polarization affecting the star.


356.000
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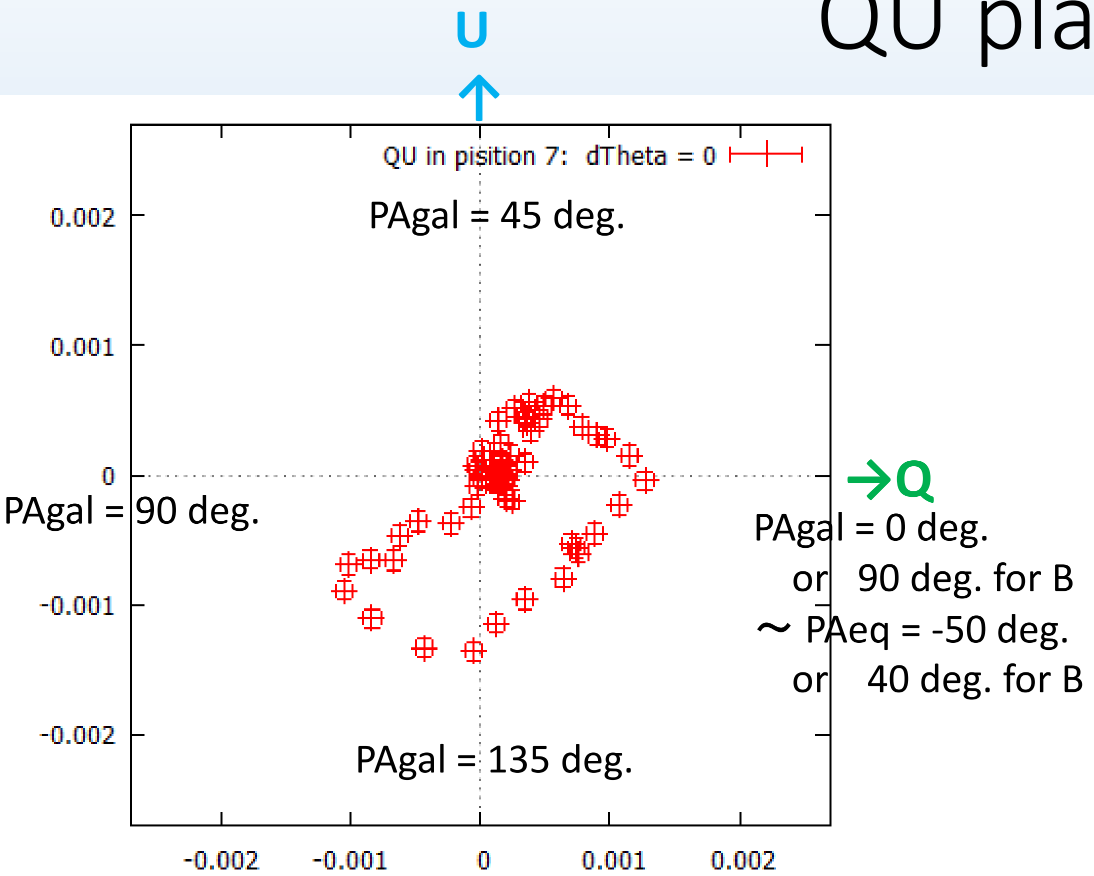
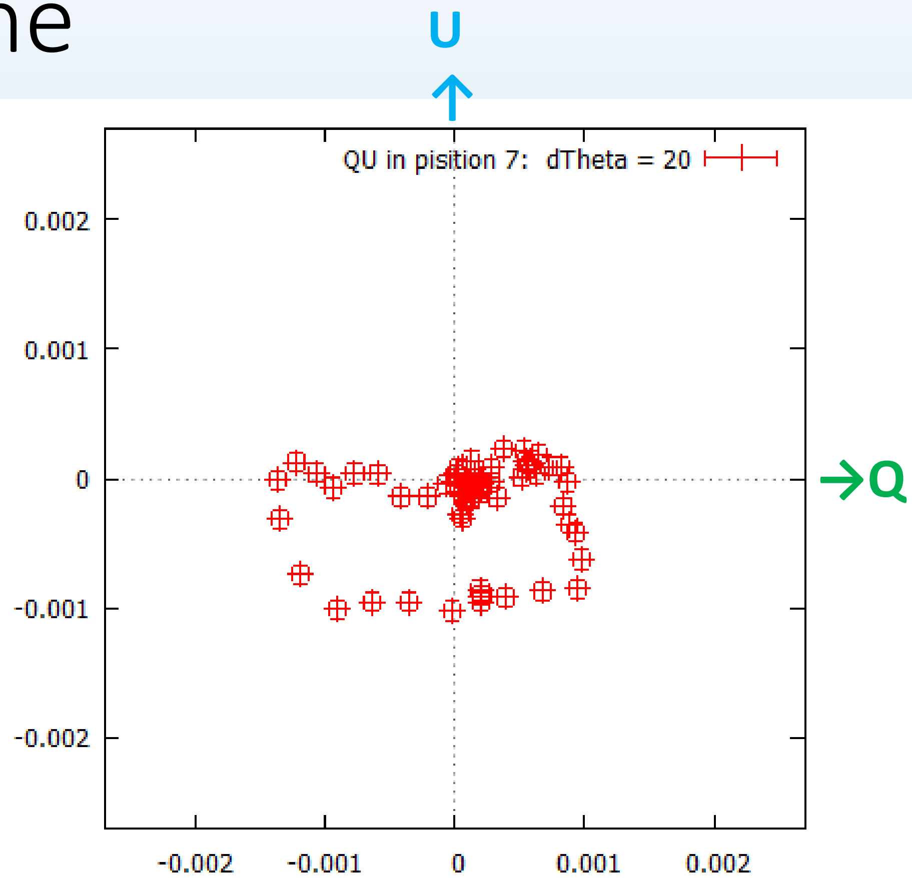
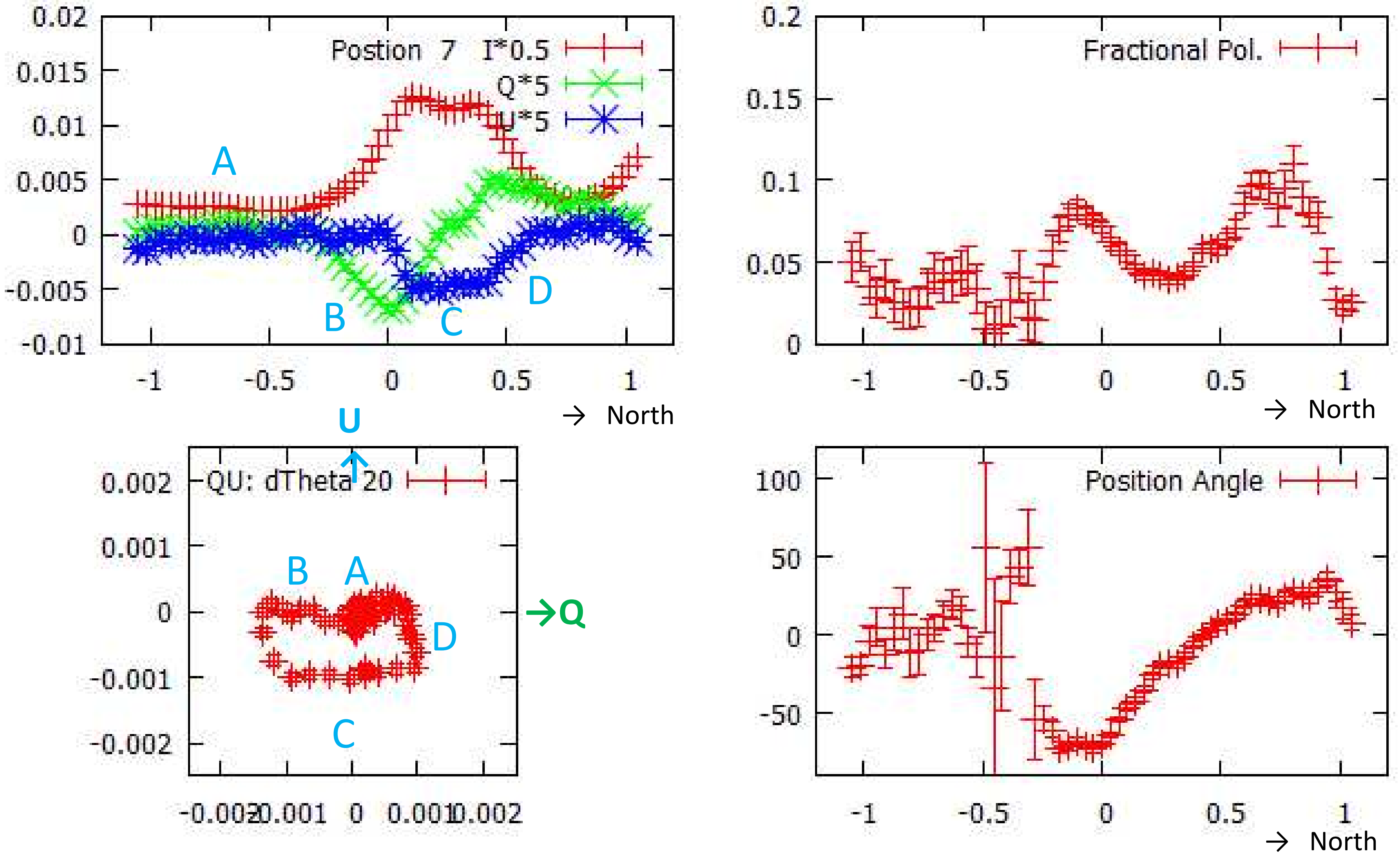
QU plane





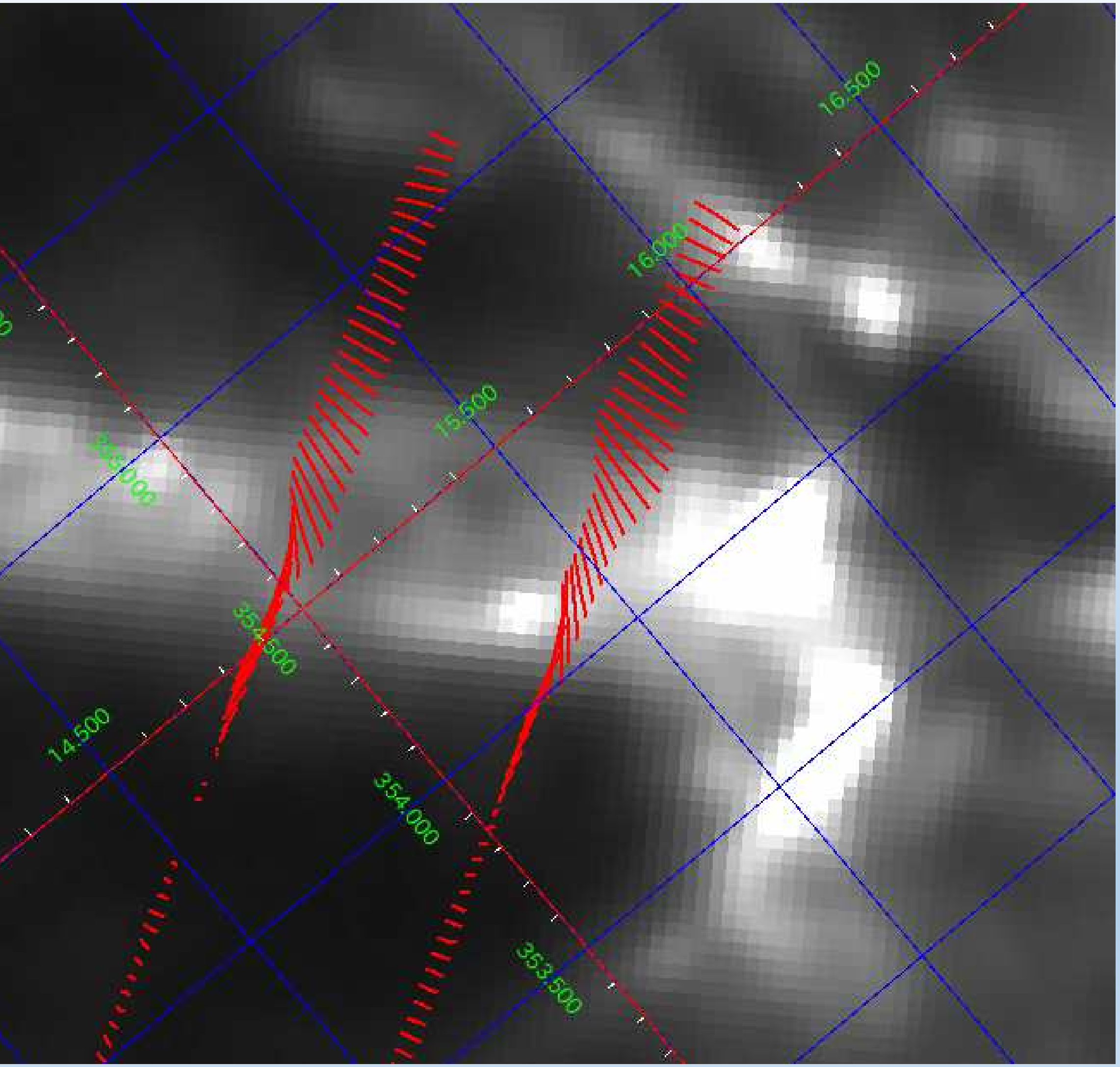
- Direction of submm pol. No rotaion.

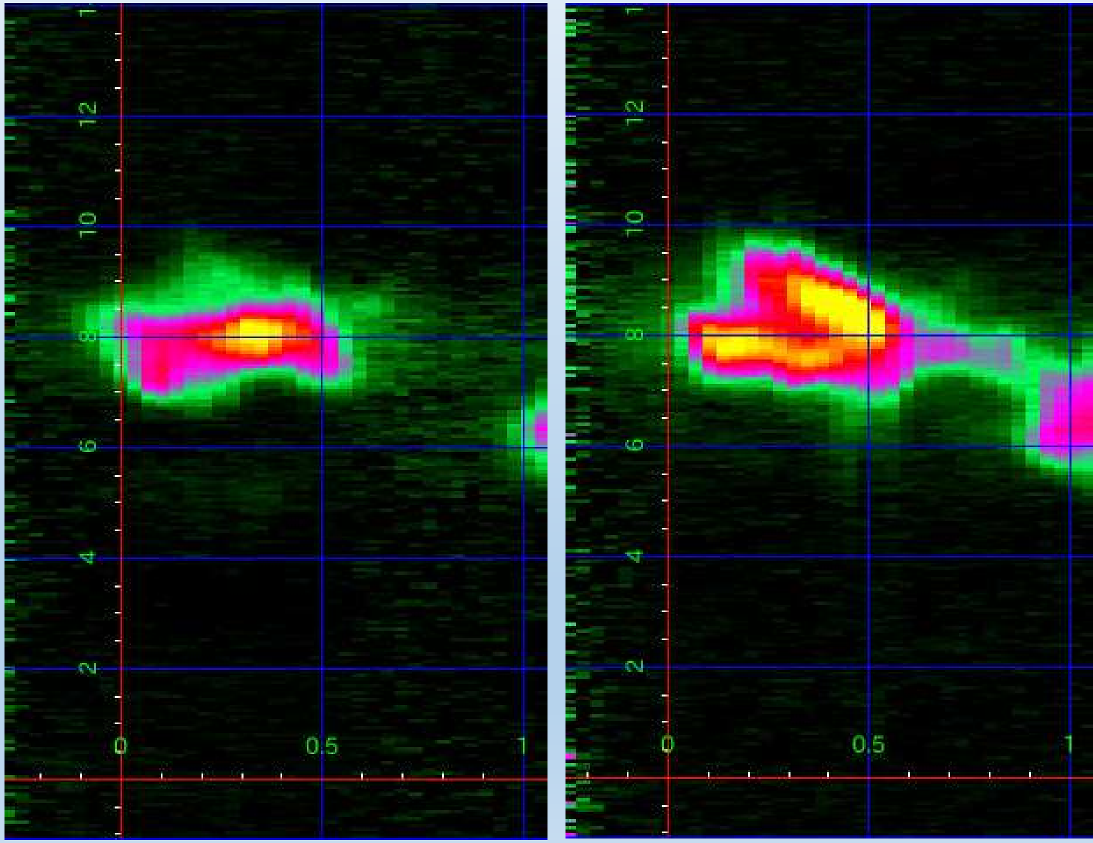
- 40 deg. Rotation in QU
  (= 20 deg. Rotaion in PA)

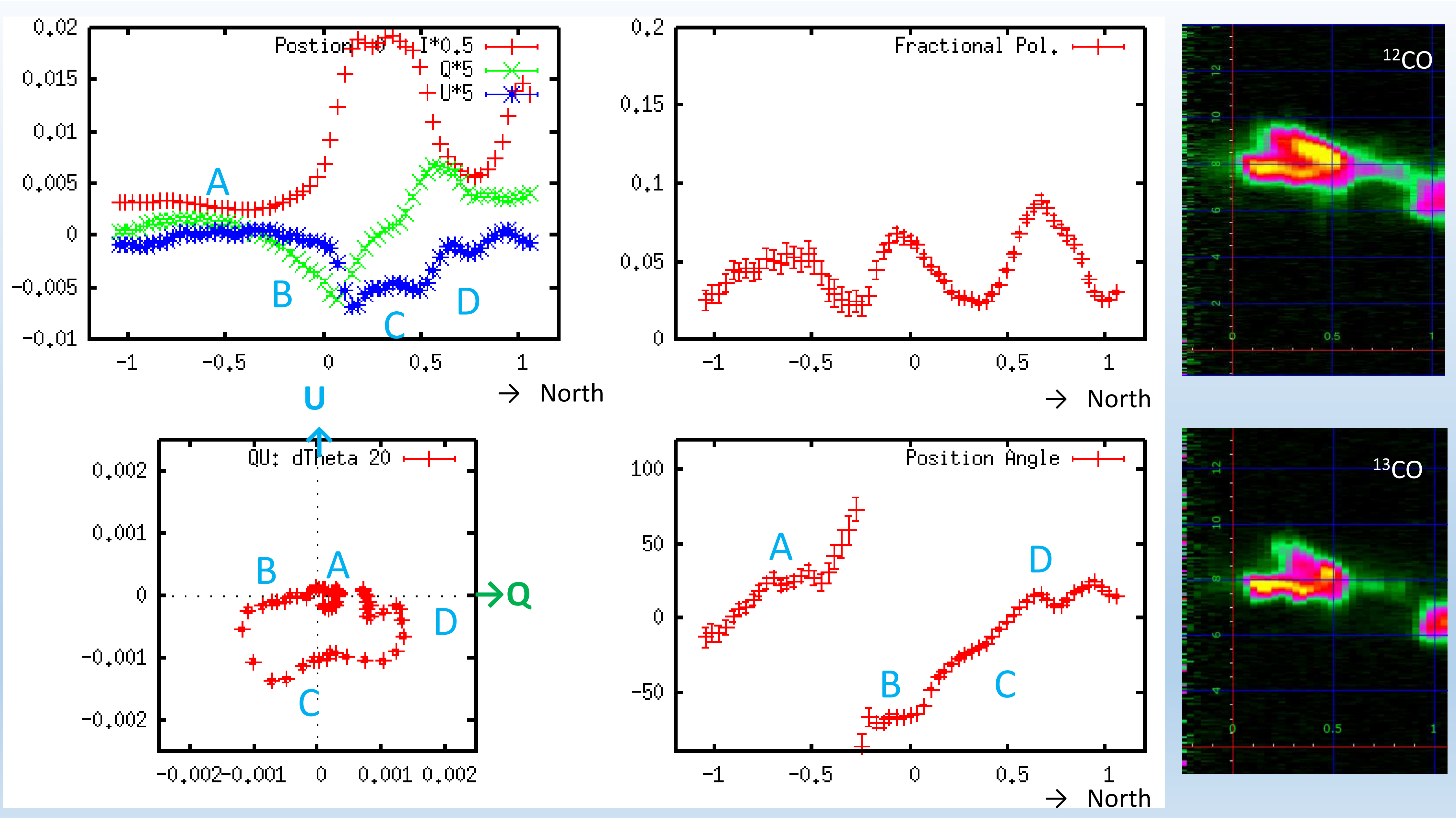


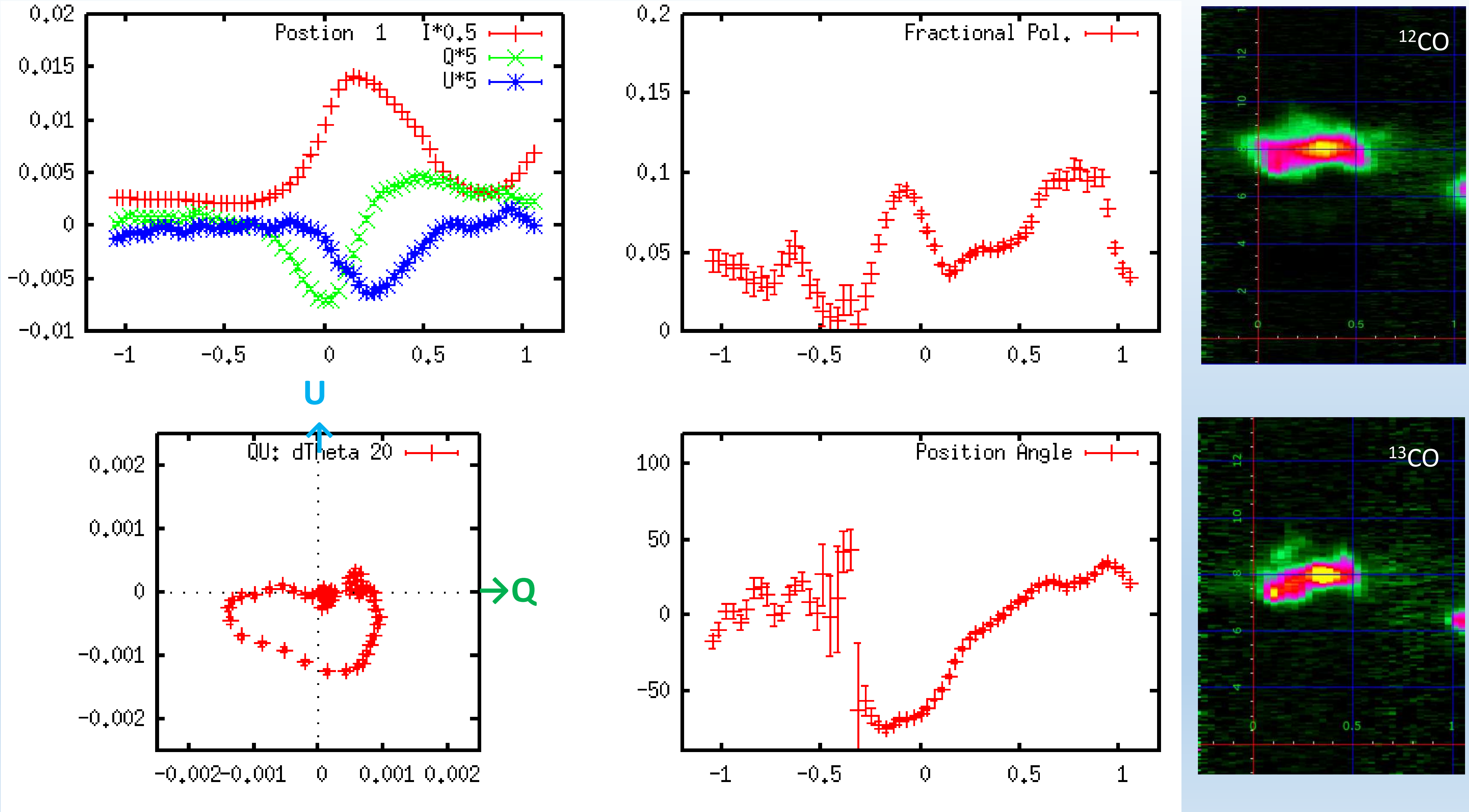
Postion 7 I*0.5
Q*5
U*5
A
B
C
D
→ North
Fractional Pol.
→ North
QU: dTheta 20
U
Q
B
A
D
C
Position Angle
→ North

• ^{12}CO FCRAO data

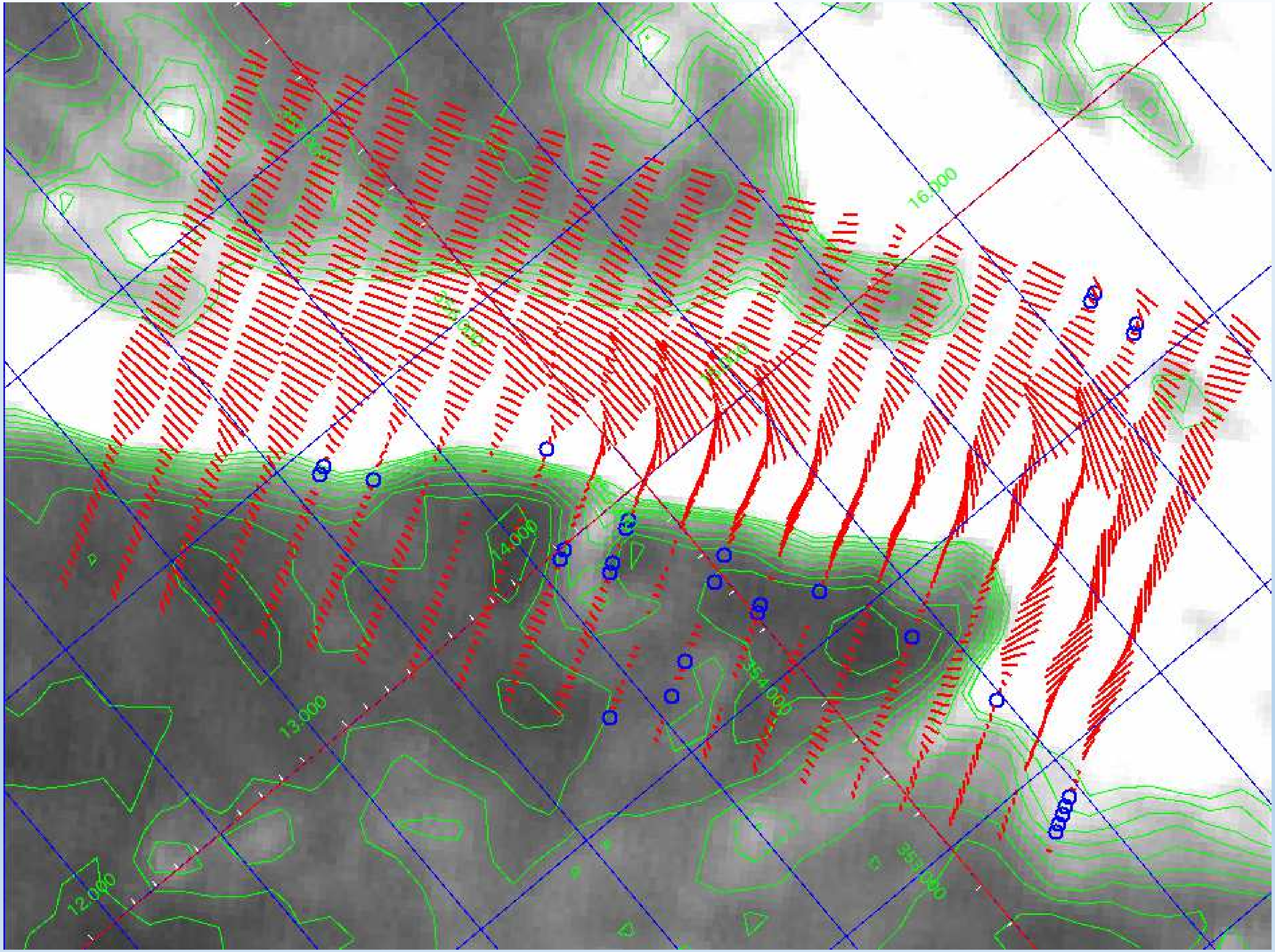





Postion 0
I*0.5
Q*5
U*5
A
B
C
D
→ North
Fractional Pol.
→ North
¹²CO
QU: dTheta 20
U
Q
A
B
C
D
Position Angle
A
B
C
D
→ North
¹³CO



Postion 1
I*0.5
Q*5
U*5
Fractional Pol.
^{12}CO
U
Q
QU: dTheta 20
Position Angle
^{13}CO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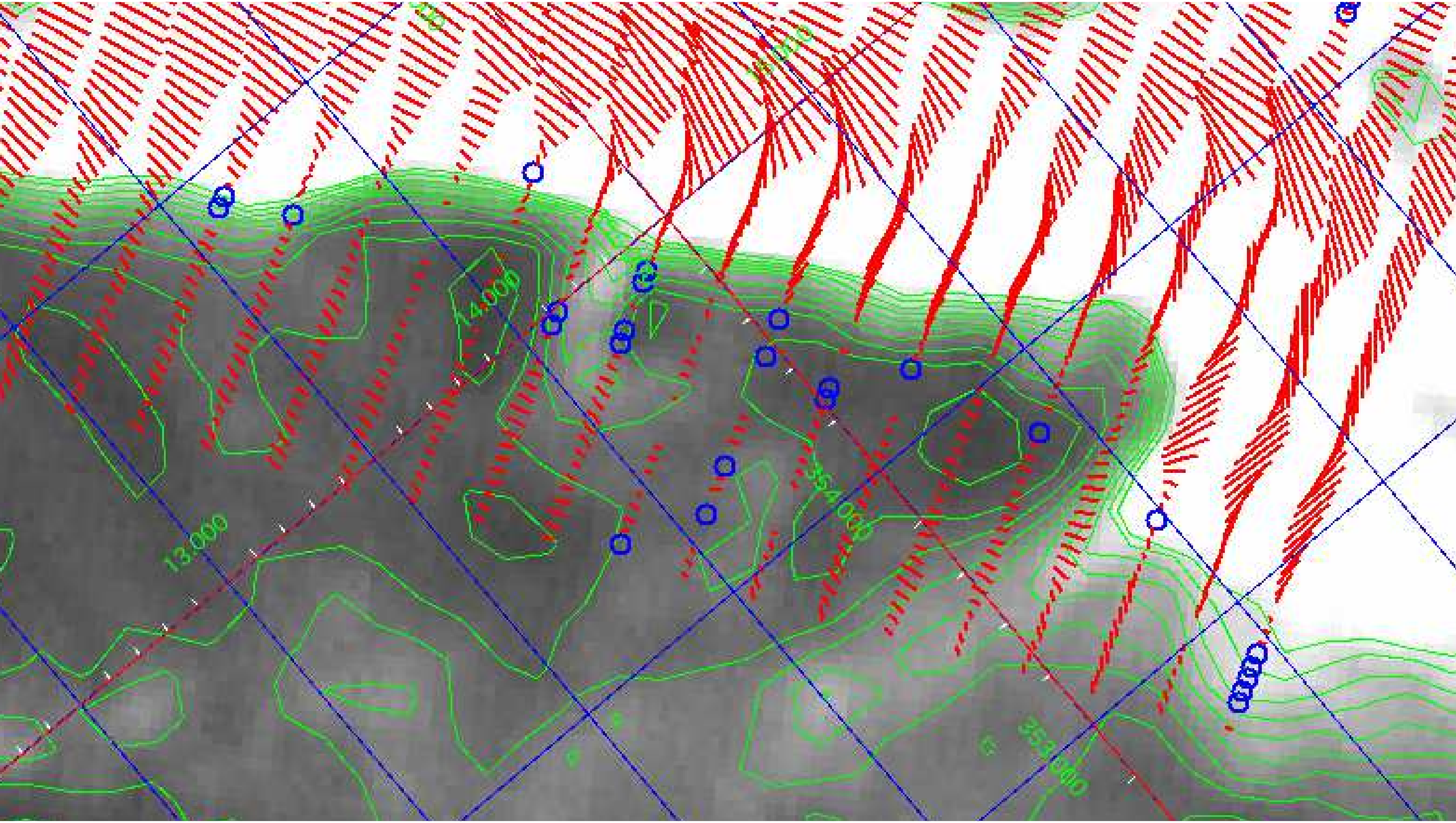
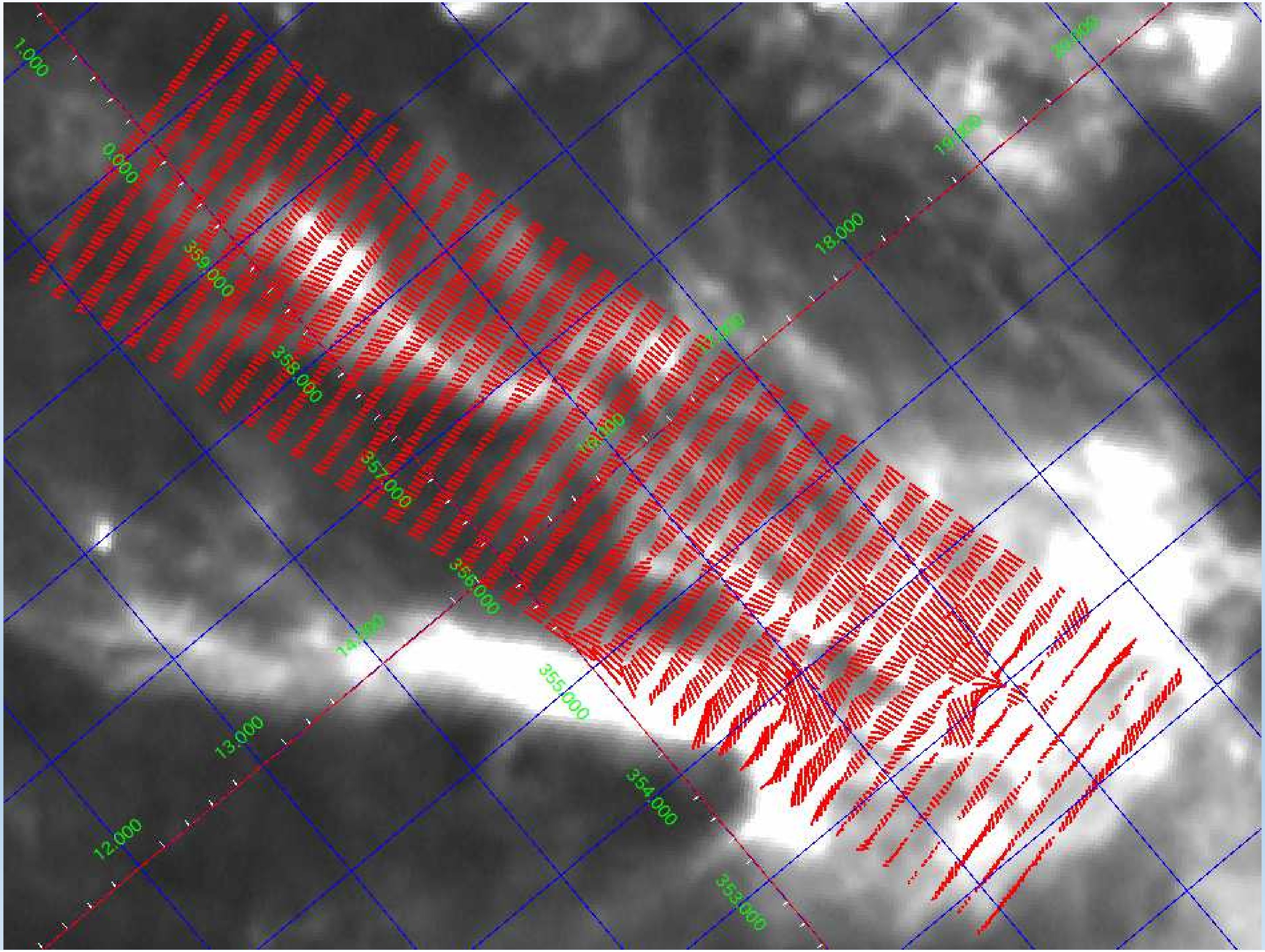
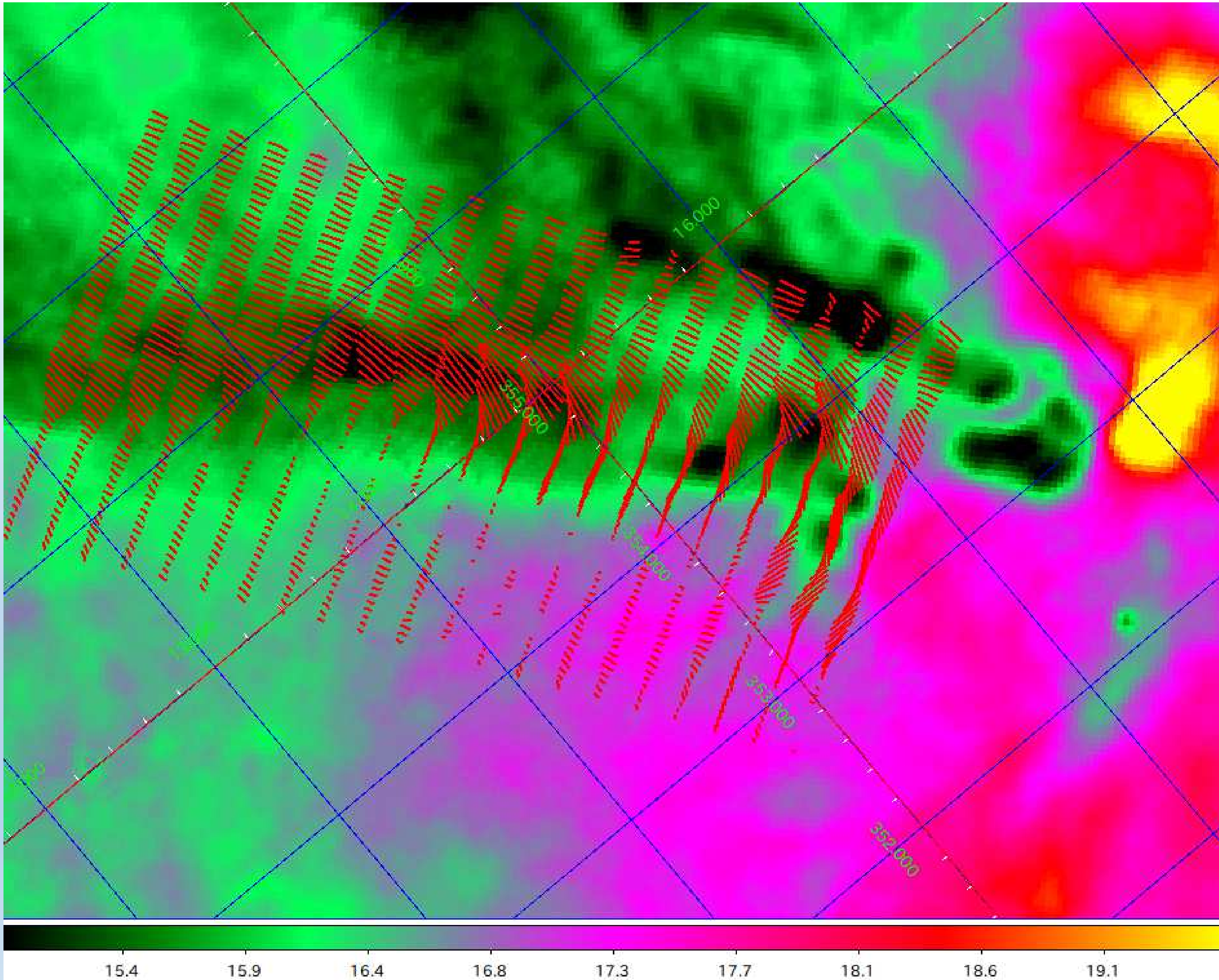

14.000
13.000

- L1688 Stream
  - Only “50 deg.” component



Temperature T_2 in 2comp-model

Meisner & Finkbeiner 2015



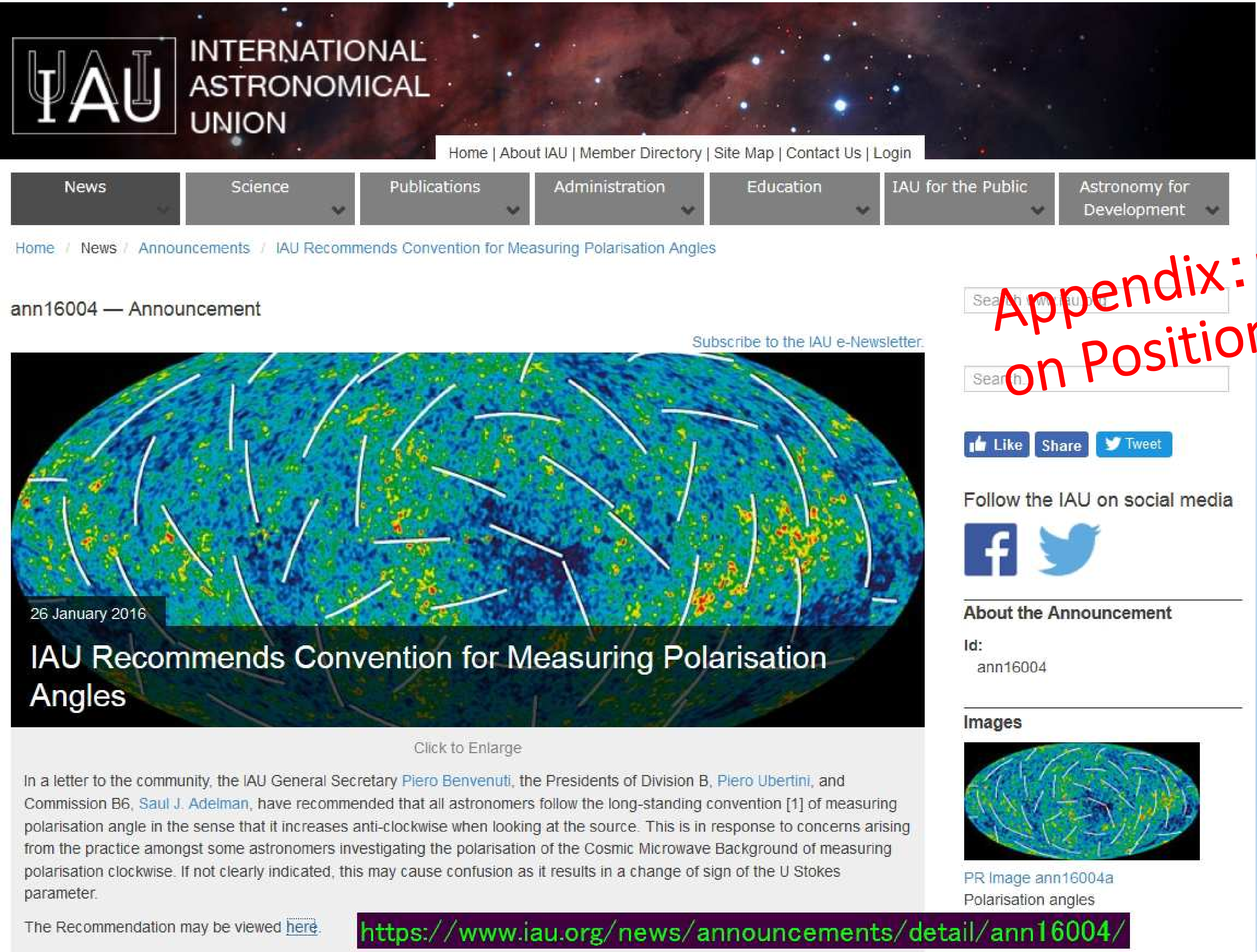
Summary

- We can now understand grain alignment qualitatively.
- Optical and Submm polarization:
  - Correlations are good!
    - It can be understood that both are due to aligned, probably larger, grains.
  - So far, at least in diffuse clouds, no evidence is reported that grains are aligned other than to B-fields.
  - Comparing those properties, we can understand more about dust grains and/or B-fields structures.

- New 2D information in submm pol. by Planck, POL2, ALMA, etc. has been significantly advancing our understandings of ISM.
  - E.g. ρ Oph streams

That’s it!   Thank you!

Appendix: recommendation on Position Angle



https://www.iau.org/news/announcements/detail/ann16004/

- … that all astronomers follow the long-standing convention …

https://www.iau.org/news/announcements/detail/ann16004/

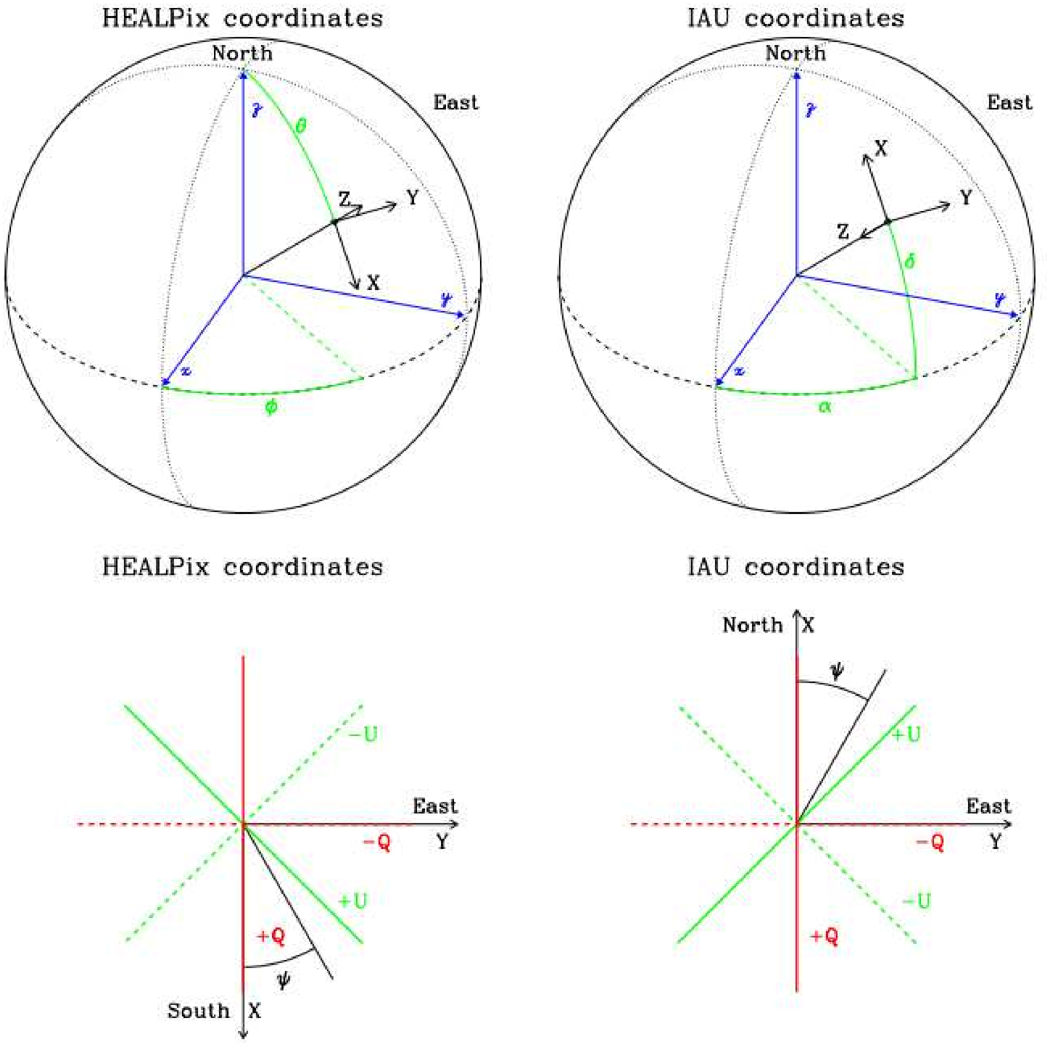


Figure 5: Coordinate conventions for **HEALPix** (*lhs* panels) and IAU (*rhs* panels). The upper panels illustrate how the spherical coordinates are measured, and the lower panel how the Q and U Stokes parameters are identified in the tangential plan.

The position angle in the HEALPix is different than that in IAU coordiantes, which have been used by astronomers!

- Gorski + 2010 “The HEALPix Primer”

https://healpix.jpl.nasa.gov/html/intronode12.htm

"Letter" from Piero Benvenuti – General Secretary

- The issue: Scientists working on the polarization of the Cosmic Microwave Background (CMB) use a convention for the polarization angle (PA) which is opposite to the IAU approved standard. This may cause confusion and misunderstandings.
- Background: The convention astronomers follow for the PA (Polarization Angle) goes back to the 19th century and it has been in use for observations going from radio to gamma rays: the PA increases counter-clockwise when looking at the source.   …
- Recommendation: The IAU recommends that all astronomers, including those working on the CMB, follow the IAU Resolution for the Polarization Angle in all their publications.

Paris, December 8th, 2015

https://www.iau.org/news/announcements/detail/ann16004/