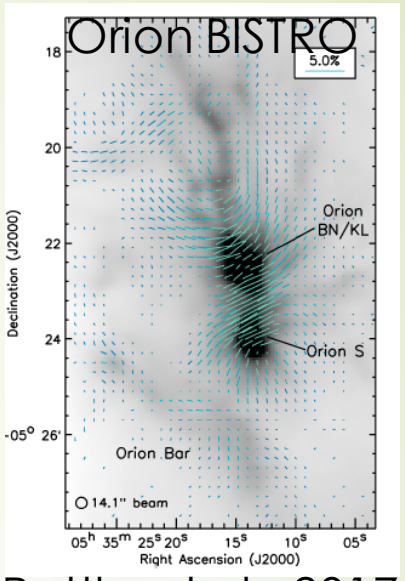
原始星形成における磁場の観測的可視化

Effect of interferometer observation on observed polarization map

Kazuya Saigo (NAOJ Chile Observatory)

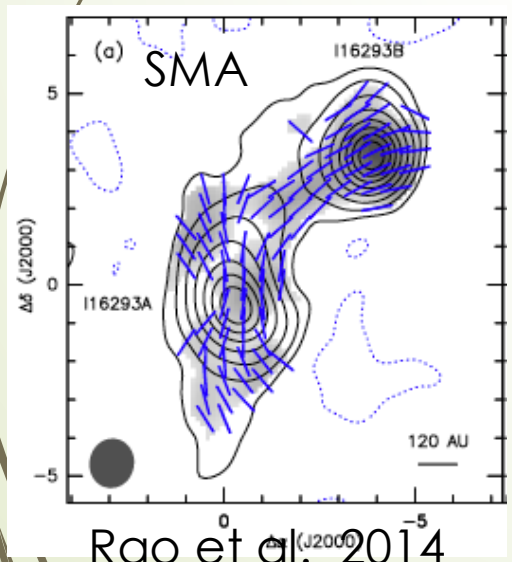
Polarization in protostellar system

- *L* >~2000AU
  Magnetic field structure of a cloud/filament/core
  ➔Initial condition/environment of star formation



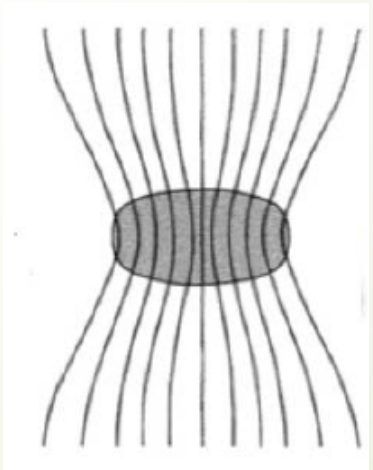
Pattle et al. 2017

- *L* <~2000AU ➔ obs. by interferometer
  Magnetic field structure of a protostellar disk/envelope
  ➔ kinematics



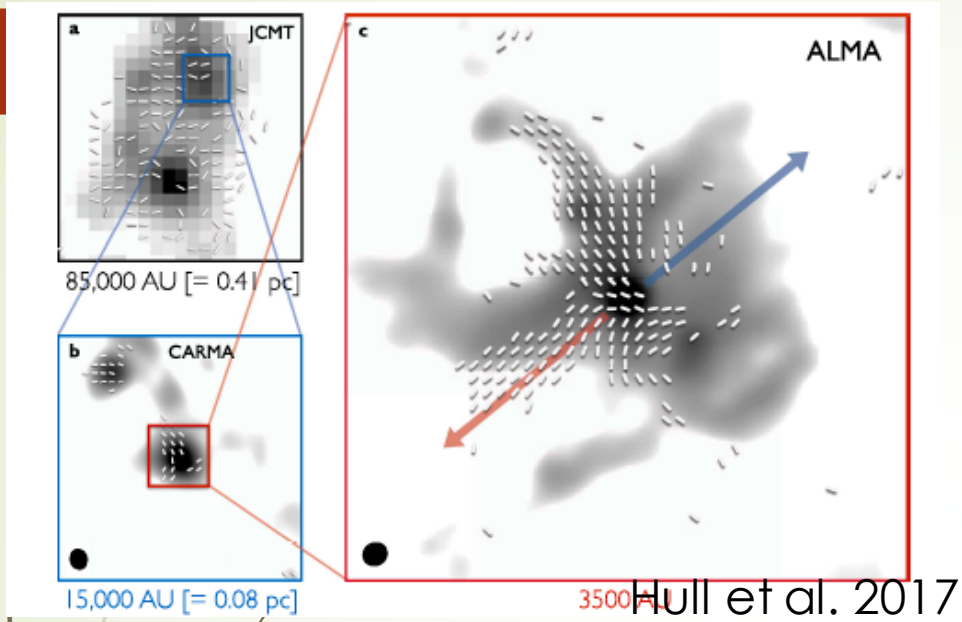
Rao et al. 2014

Hourglass Shape
=> Infall



Intro.

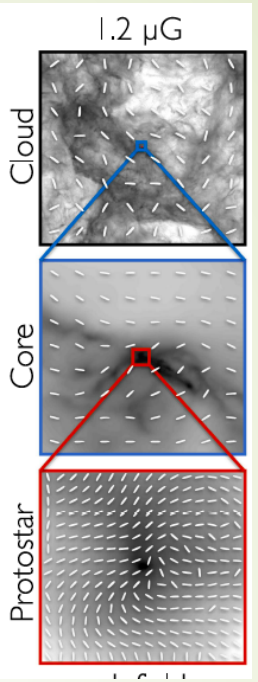
Ser-emb 8



Hull et al. 2017

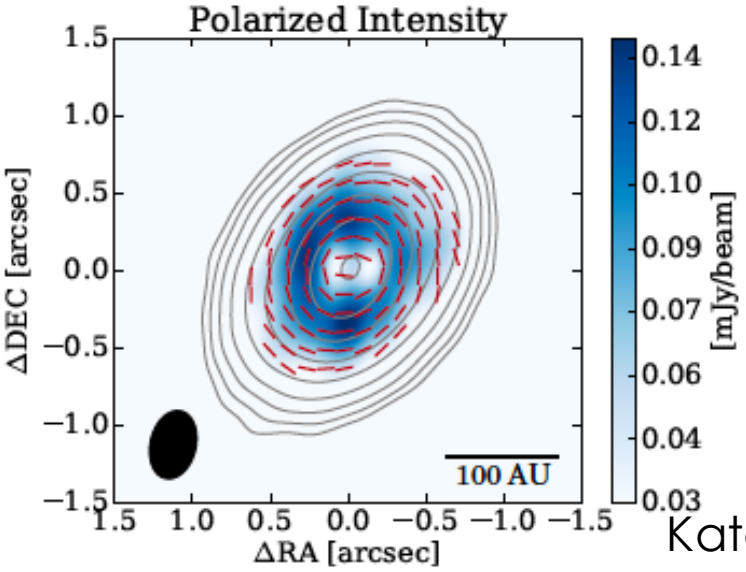
Turbulent
weak field
Outflow

Consistent



Numerical Simulation
Turbulent Weak Magnetized Cloud

HL Tau



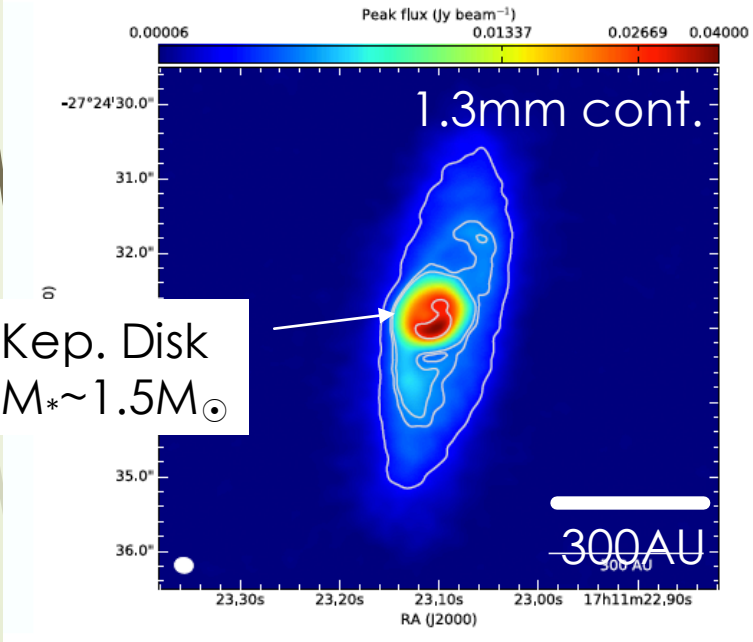
Kataoka et al. 2017

Analysis of the direction and fraction of polarization give us information about dust property, magnetic filed, etc.

BHB11 Class I Protostar

ALMA Cycle 2 Data

500AU scale Spiral
M_{gas}~0.17$M_\odot$

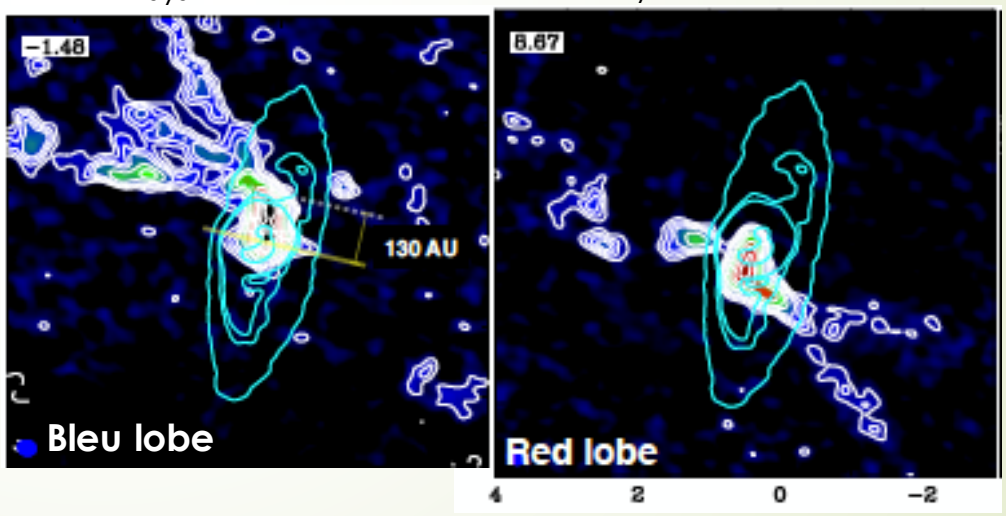


Kep. Disk
M_*~1.5$M_\odot$

12CO(2-1) outflow

v-v_{sys}~ -4km/s

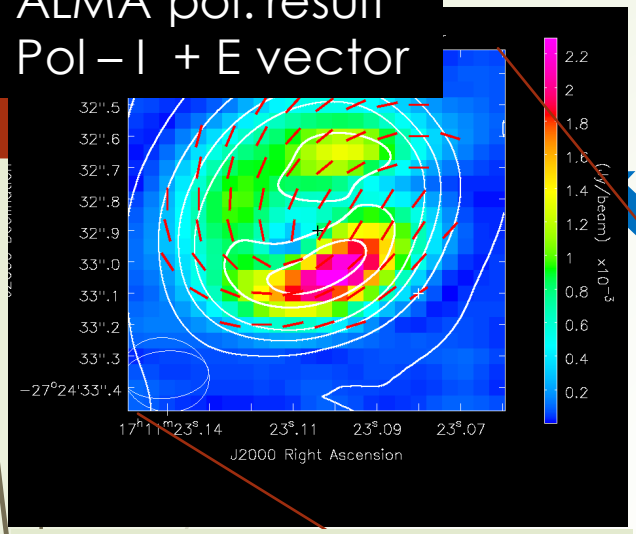
v-v_{sys}~ +4km/s



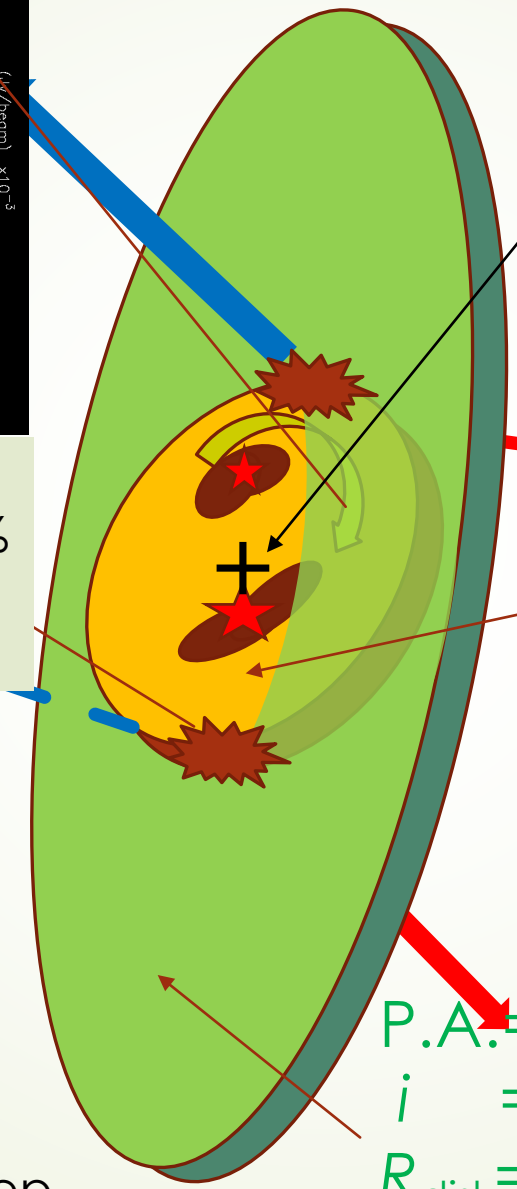
Alves et al. 2017 (ALMA Cycle2)

BHB 11 Protostar

ALMA pol. result
Pol – I + E vector



Spiral E-vector
Polarization fraction ~ 6%
Is this correct?
We should check!



M_{star} = 1.45$M_{\odot}$
v_{sys} = 3.7 km/s

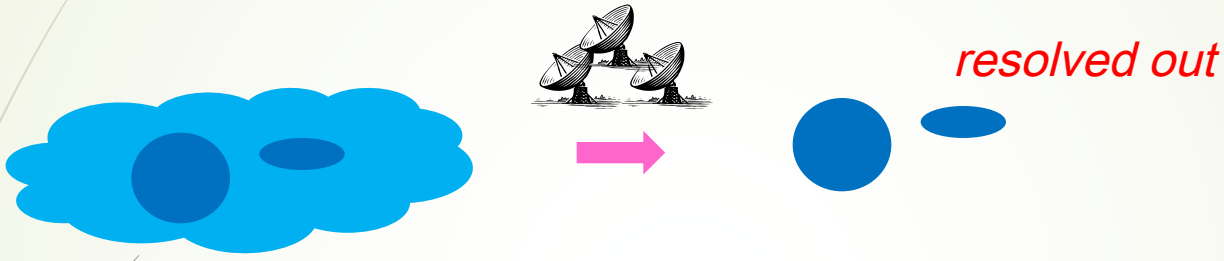
P.A.=54.deg
i = 35deg
R_{disk}~ 90AU

P.A.= 69.deg
i = 70deg
R_{disk}= 400AU

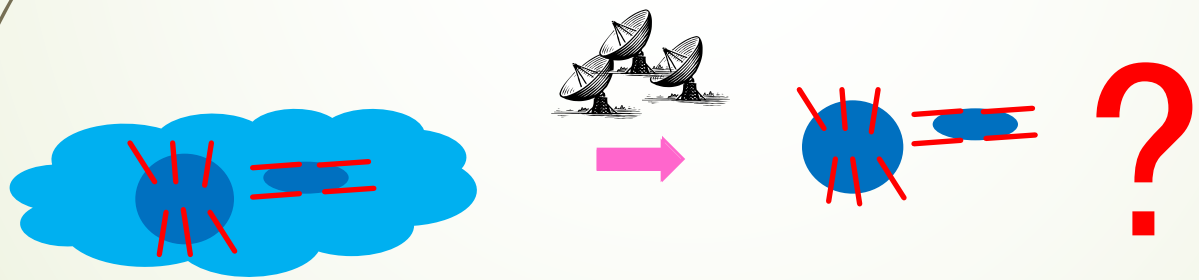
Saigo et al, In prep.

Problems of interferometer observation

Observation by interferometer can not reproduce the extended emission.



In the case of polarization observation, it may change polarization structure and polarization fraction.



Does the interferometer observation reproduce the actual polarization structure? How to check?

How does ALMA observe polarization?

correlator

$V_{X1} \times V_{X2}$

$V_{Y1} \times V_{Y2}$

$V_{X1} \times V_{Y2}$

$V_{Y1} \times V_{X2}$

X -Y Corr. ⇄ Stokes Parameters

$$\hat{V}_{X_m}\hat{V}^*_{X_n} = I + Q\cos(2\psi_m) + U\sin(2\psi_m)$$

$$\hat{V}_{Y_m}\hat{V}^*_{Y_n} = I - Q\cos(2\psi_m) - U\sin(2\psi_m)$$

$$\hat{V}_{X_m}\hat{V}^*_{Y_n} = I(D_{X_m} + D^*_{Y_n}) - Q\sin(2\psi_m) + U\cos(2\psi_m) + iV$$

$$\hat{V}_{Y_m}\hat{V}^*_{X_n} = I(D_{Y_m} + D^*_{X_n}) - Q\sin(2\psi_m) + U\cos(2\psi_m) - iV$$

Ψ: parallactic angle

Uncertainty of leak between the orthogonal polarizations (called D-term)

$$\hat{V}_X = V_X + D_X V_Y$$

$$\hat{V}_Y = V_Y + D_Y V_X$$

Determine *D-term* using variation of *Parallactic angle* ψ by long observation.

Accuracy of D-term after calibration is ~1% for each antenna
➔ ~0.1% for integrated data (どんなにSNが高くてもこれが検出限界)

CASA Interferometer Simulator

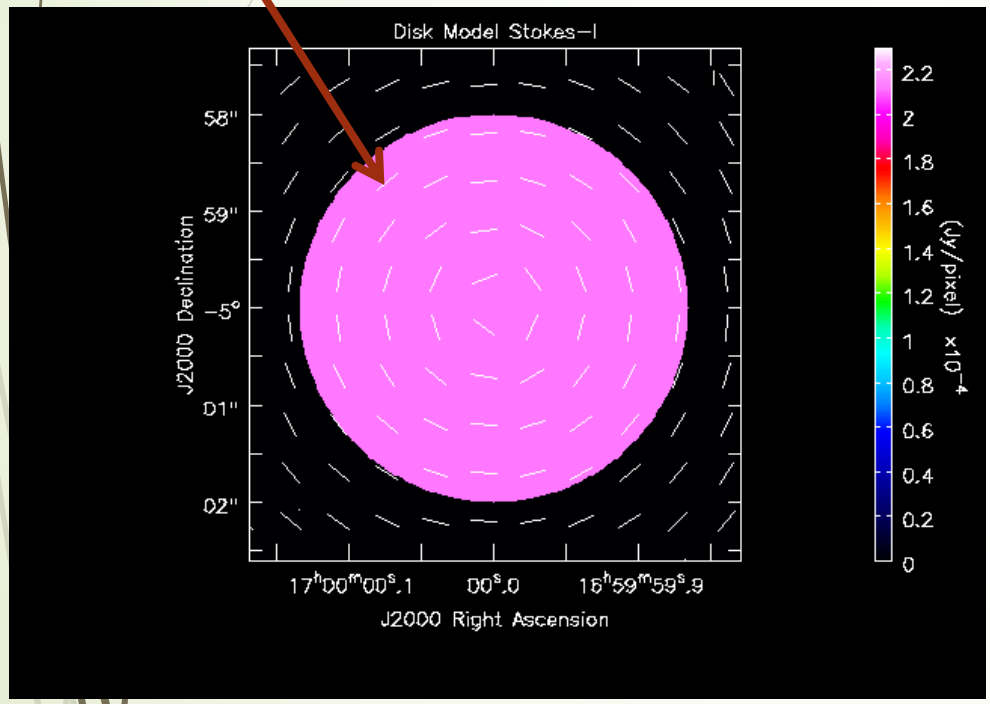
- We can check effect of interferometer observation with the CASA interferometer simulator.

- 4 steps of CASA interferometer simulation

1. Full Stokes Model Images (FITS file)
   ➔ XX, YY, XY, YX images
2. Virtual observation by “simobserve” task
   Output is “Measurement Sets” (“ms”) format same as real ALMA observation
3. Imaging by the “clean” task or “simanalyze” task.
4. XX,YY,XY,YX ➔ Full Stokes images (I,Q,U,V)

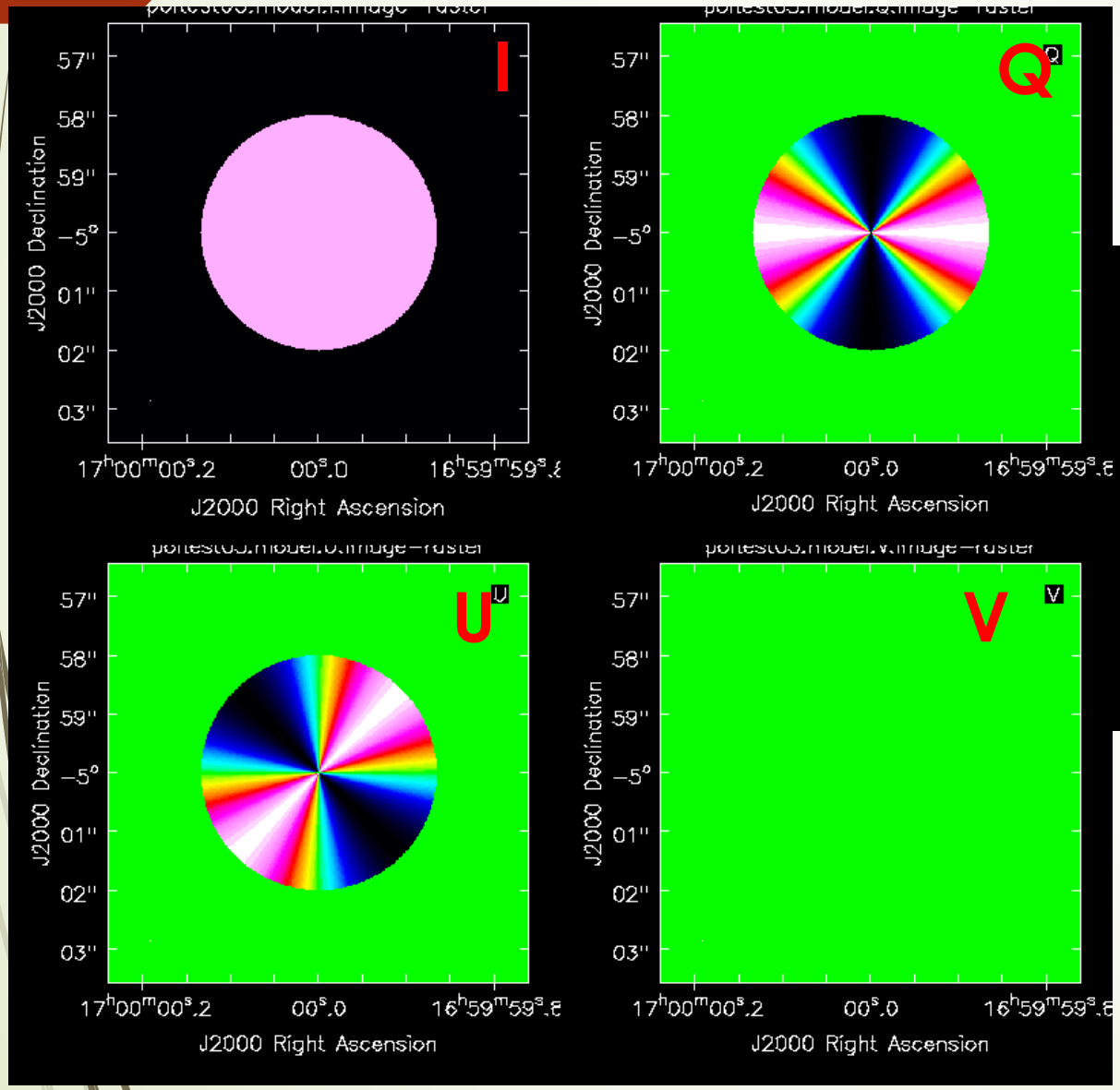
1. Disk Model

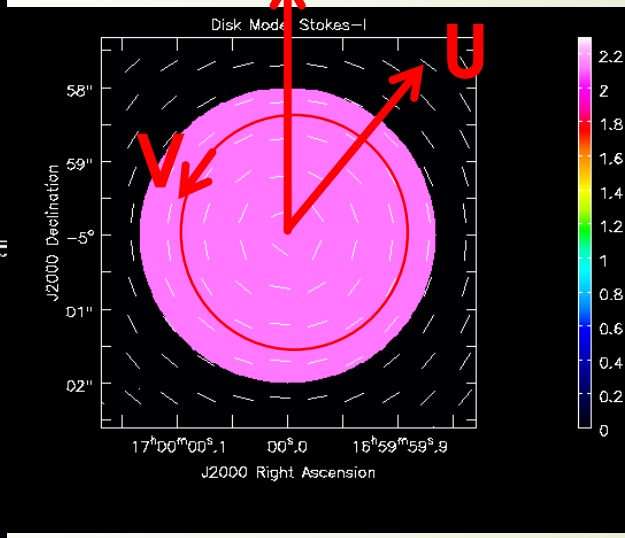
Polarization Vectors



- Disk with Radius = 2 arcsec
  $\Leftrightarrow R$ = 280AU at d = 140pc
- Polarization is Concentric Circles
  * Magnetic Field => Radial Direction
- Uniform Polarization fraction = 2.5%

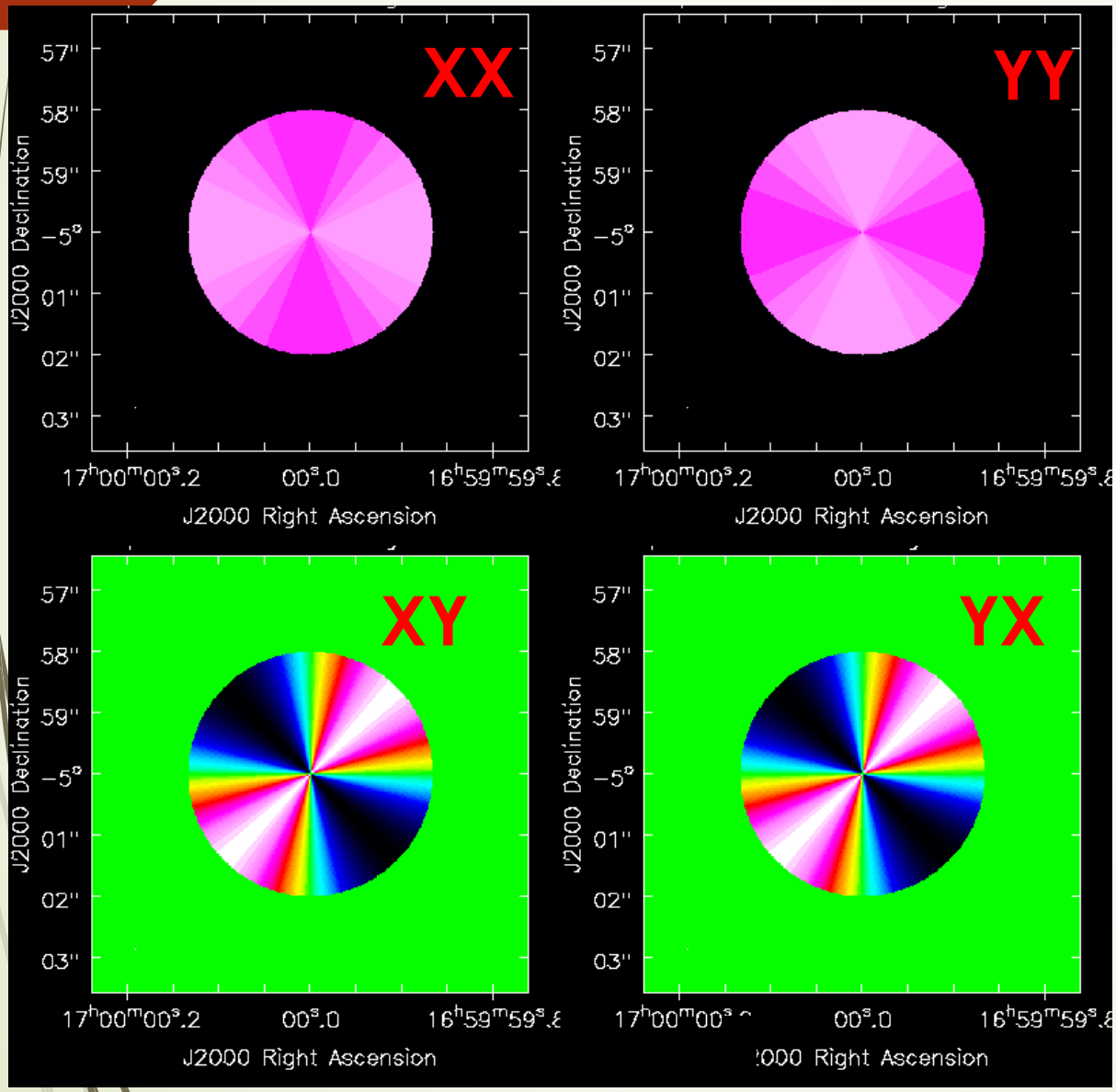
Stokes Model images





Spatial distribution and spatial scale is different in each Stokes map.

Convert to orthogonal polarization map



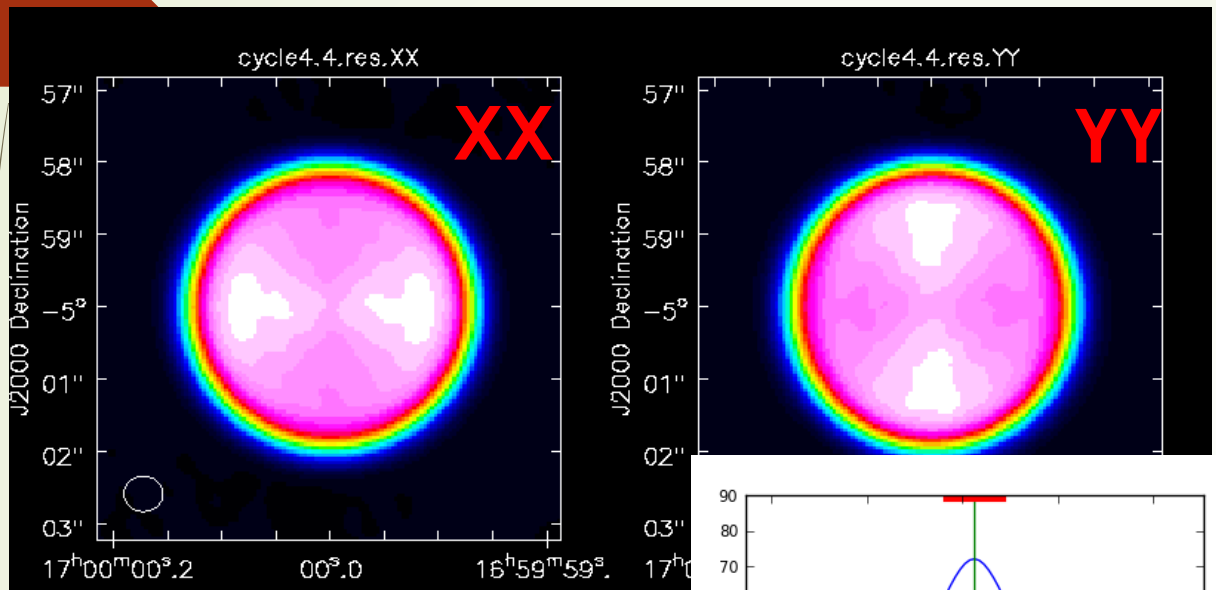
At transit (ψ=0)

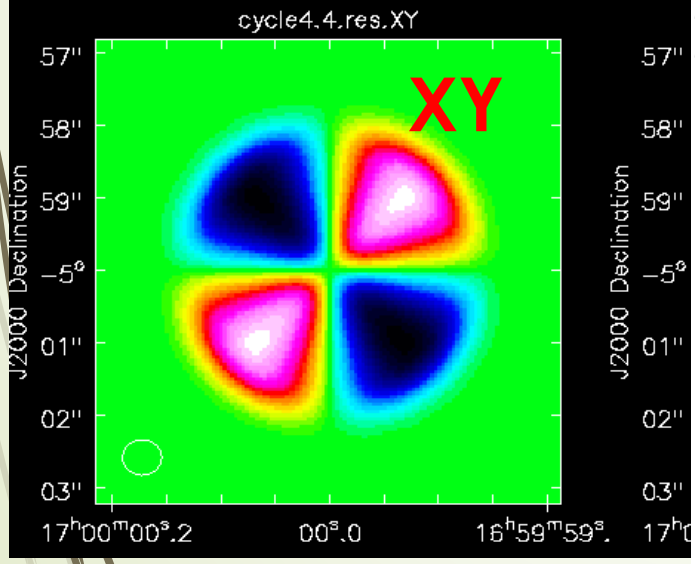
$$XX = I + Q$$
$$YY = I - Q$$
$$XY = U + iV$$
$$YX = U - iV$$

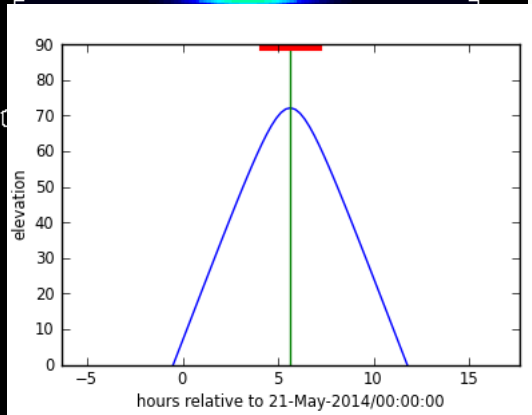
Assuming Stokes V = 0

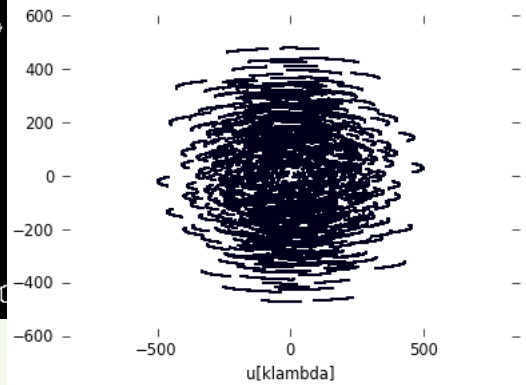
Ex. 1. Disk Model

1 . Virtual observation by CASA Simulator

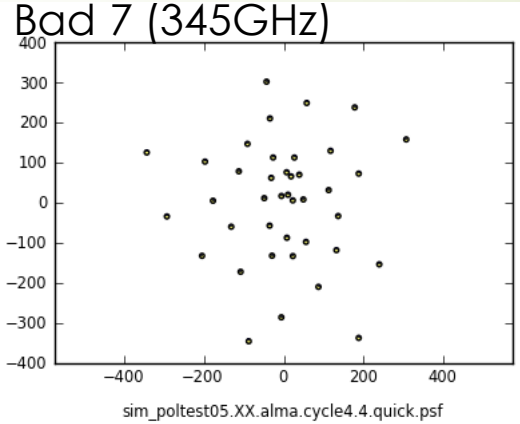


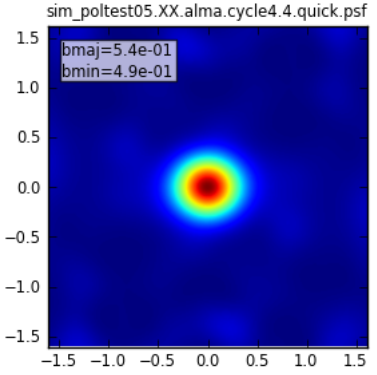






ALMA Cycle4 C40-4
Bad 7 (345GHz)



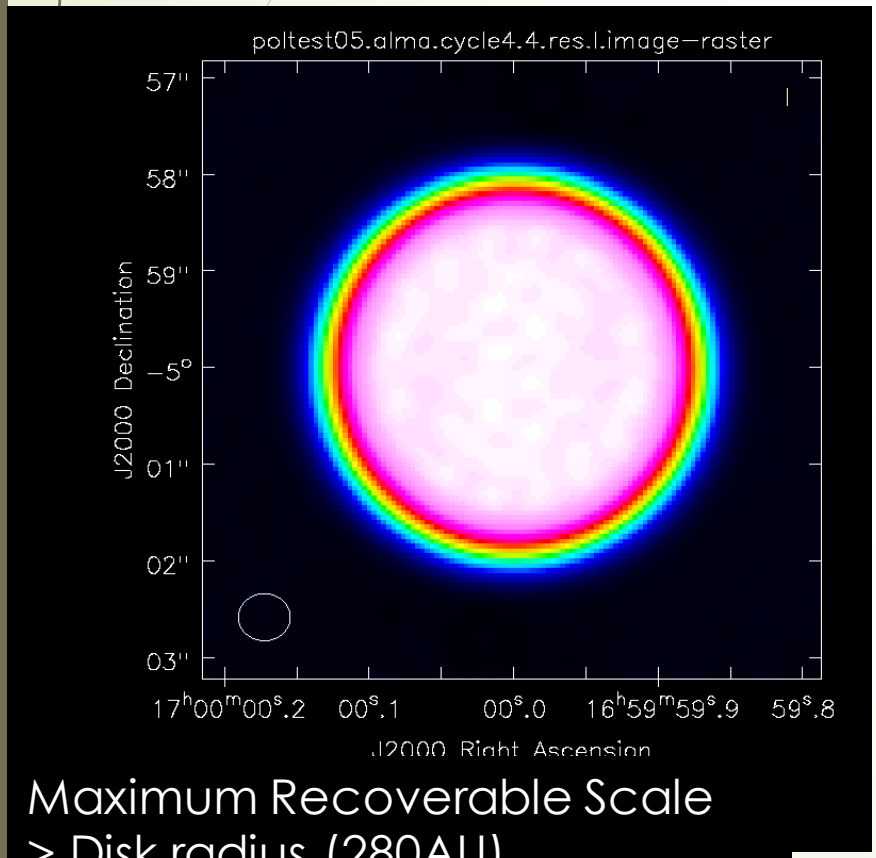


Results: Stokes I and polarized flux (Pol-I)

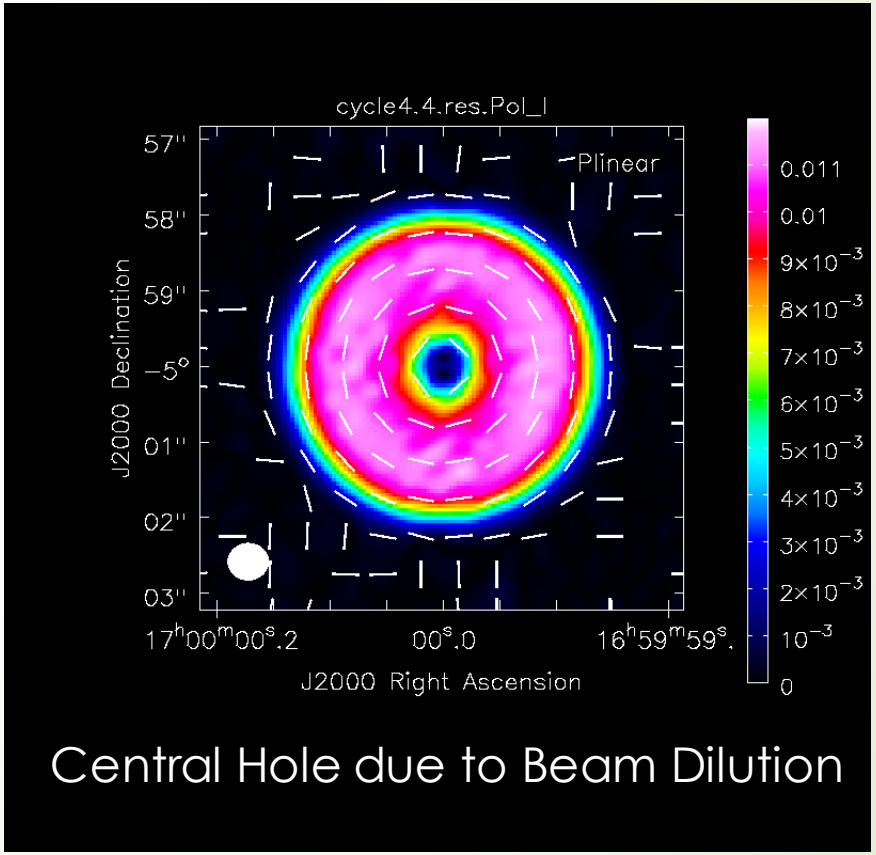
Pol-I $$P = (Q^2 + U^2 + V^2)^{\frac{1}{2}}$$

direction $$X = \frac{1}{2}\,\mathrm{atan}\left(\frac{U}{Q}\right)$$

Stokes I



Maximum Recoverable Scale
> Disk radius (280AU)
It reproduces the flux of model.



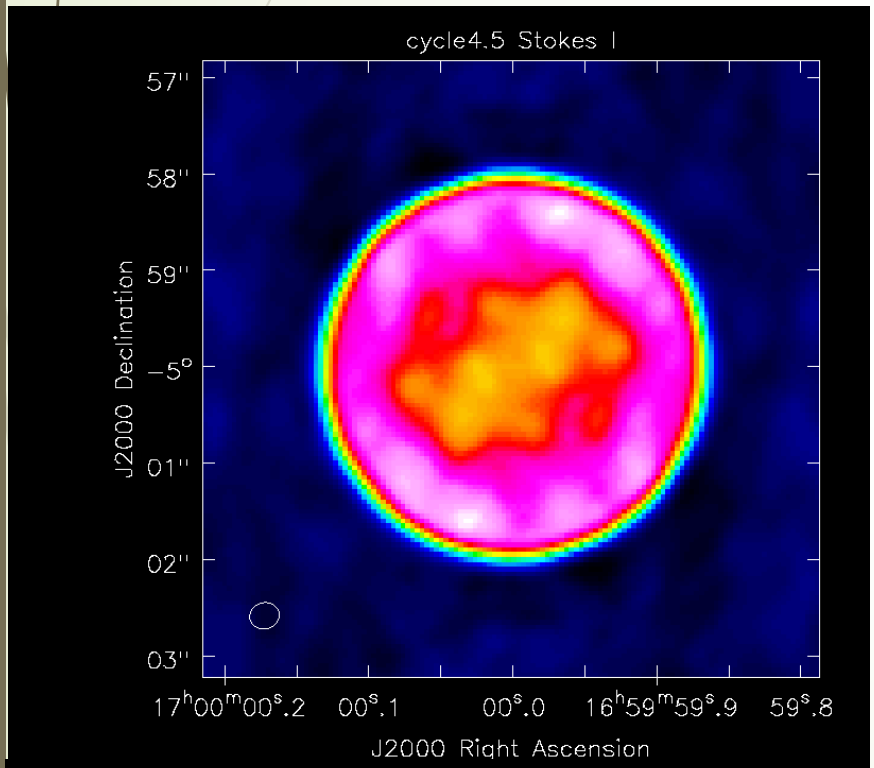
Central Hole due to Beam Dilution

Extended Configuration

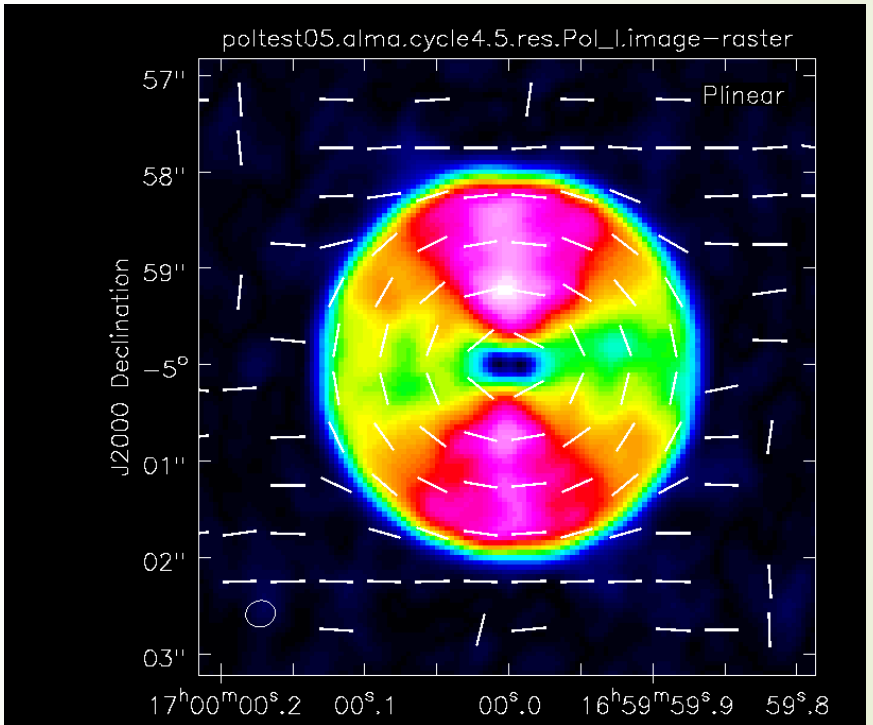
Pol-I $P = (Q^2 + U^2 + V^2)^{\frac{1}{2}}$

direction $X = \frac{1}{2}\,\mathrm{atan}\left(\frac{U}{Q}\right)$

Stokes I

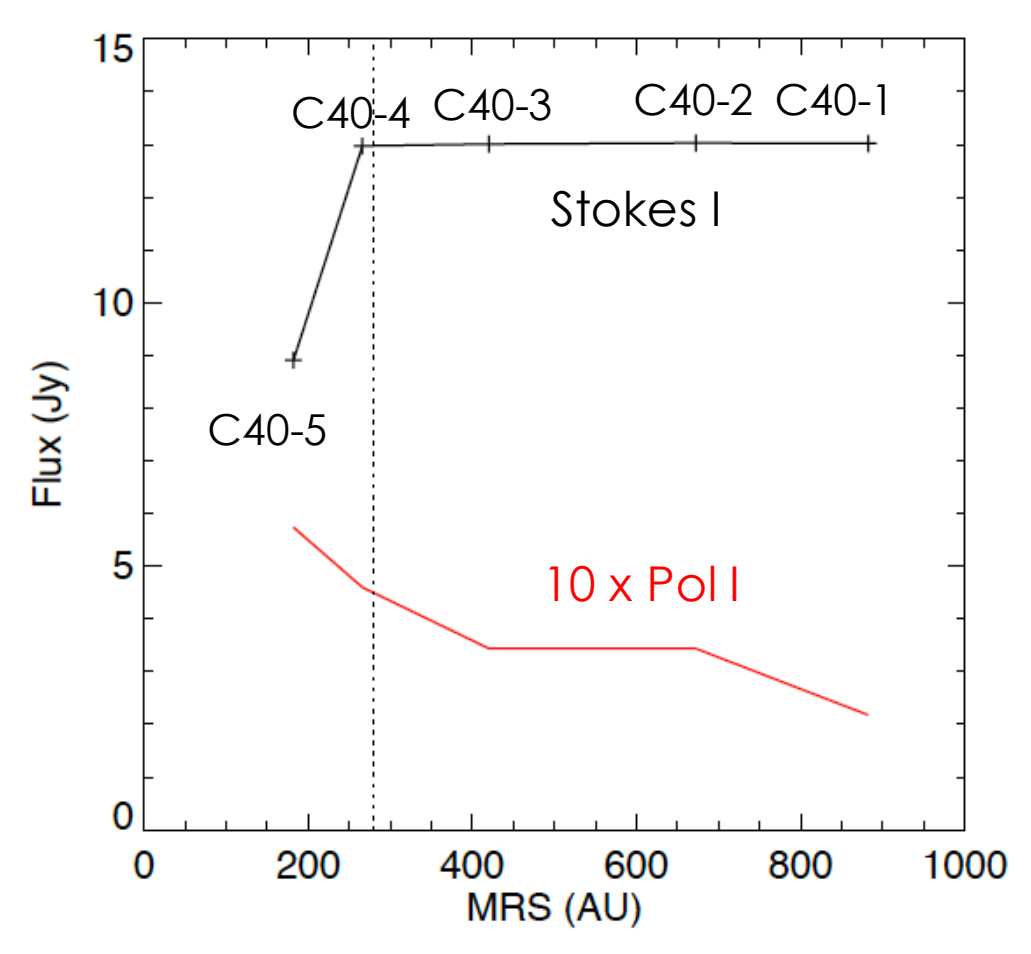


Maximum Recoverable Scale > R
Significant missing Flux

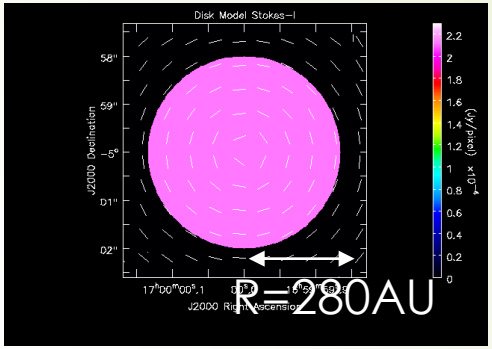


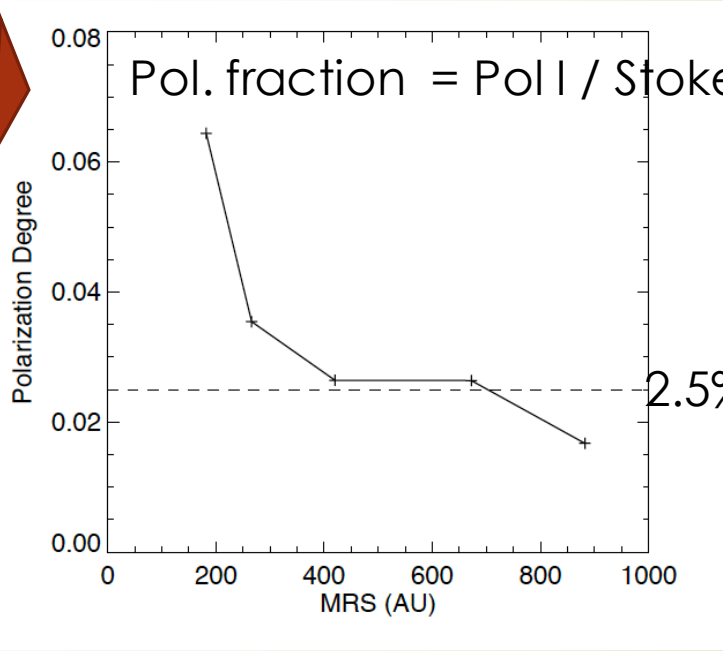
Beam Dilutionの穴
+ Non-axisymmetric structure
+ slightly distortion

Influence of interferometer observation

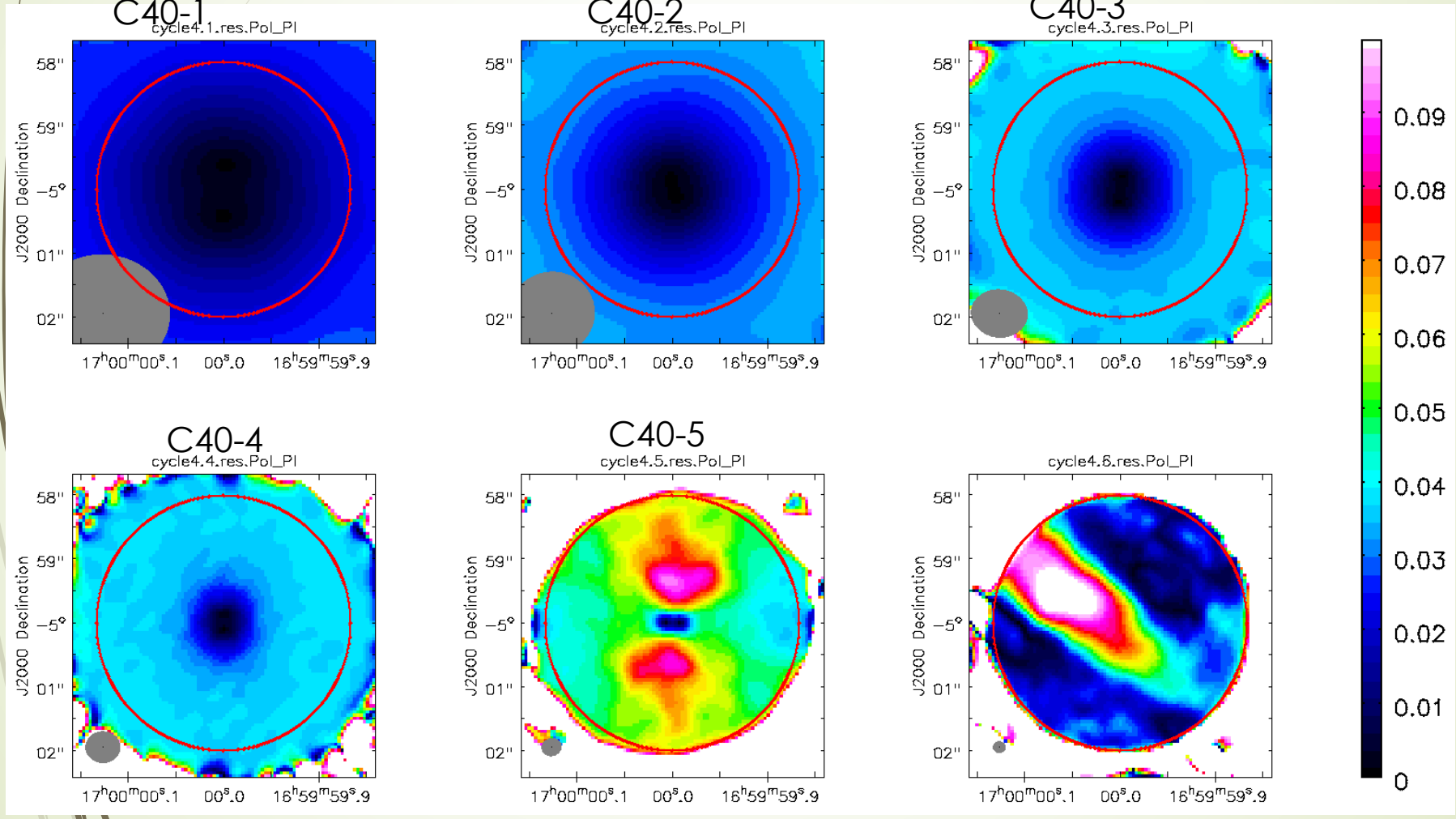


Maximum Recoverable Scale
(see ALMA Proposers Guide)

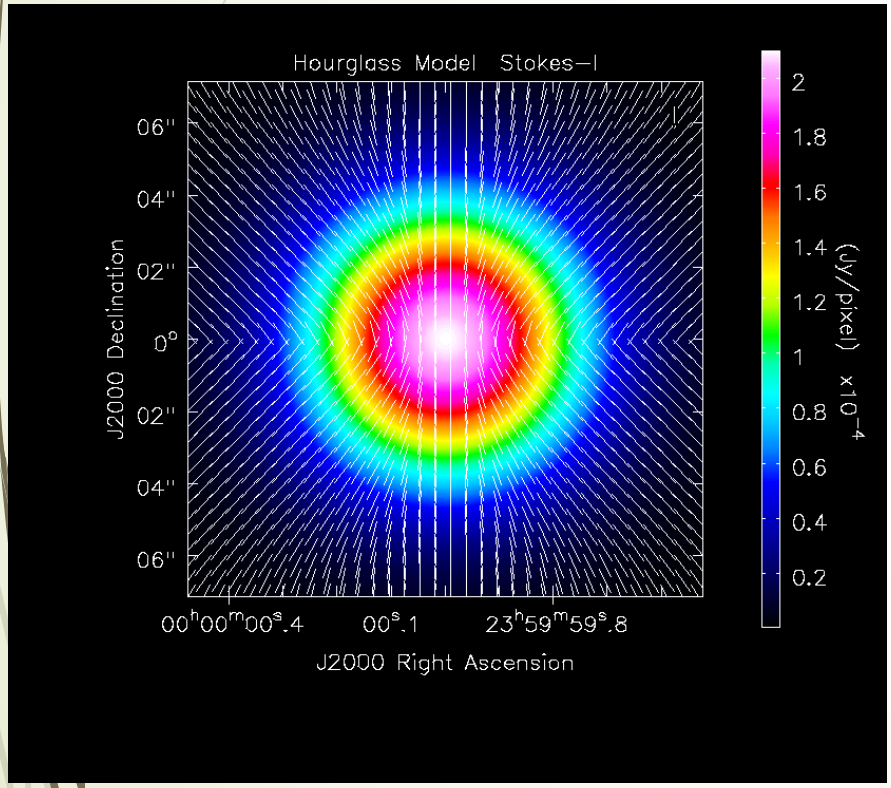




偏波率の空間分布


C40-1
cycle4.1.res.Pol_PI
C40-2
cycle4.2.res.Pol_PI
C40-3
cycle4.3.res.Pol_PI
C40-4
cycle4.4.res.Pol_PI
C40-5
cycle4.5.res.Pol_PI
cycle4.6.res.Pol_PI
J2000 Declination
58"
59"
−5°
01"
02"
17h00m00s.1
00s.0
16h59m59s.9
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

2. Hourglass Model



- Gaussian Core
  FWHM = 400AU (5.7 arcsec)
  at d = 140pc
- Hourglass Polarization
  * これは*E vector*です。*Hourglass*としては90度間違えました。ので、磁場と解釈すると*Hourglass*ではないですが、空間スケールの議論なので結果はあまり変わらないと思います。
- Uniform Polarization Degree = 3%

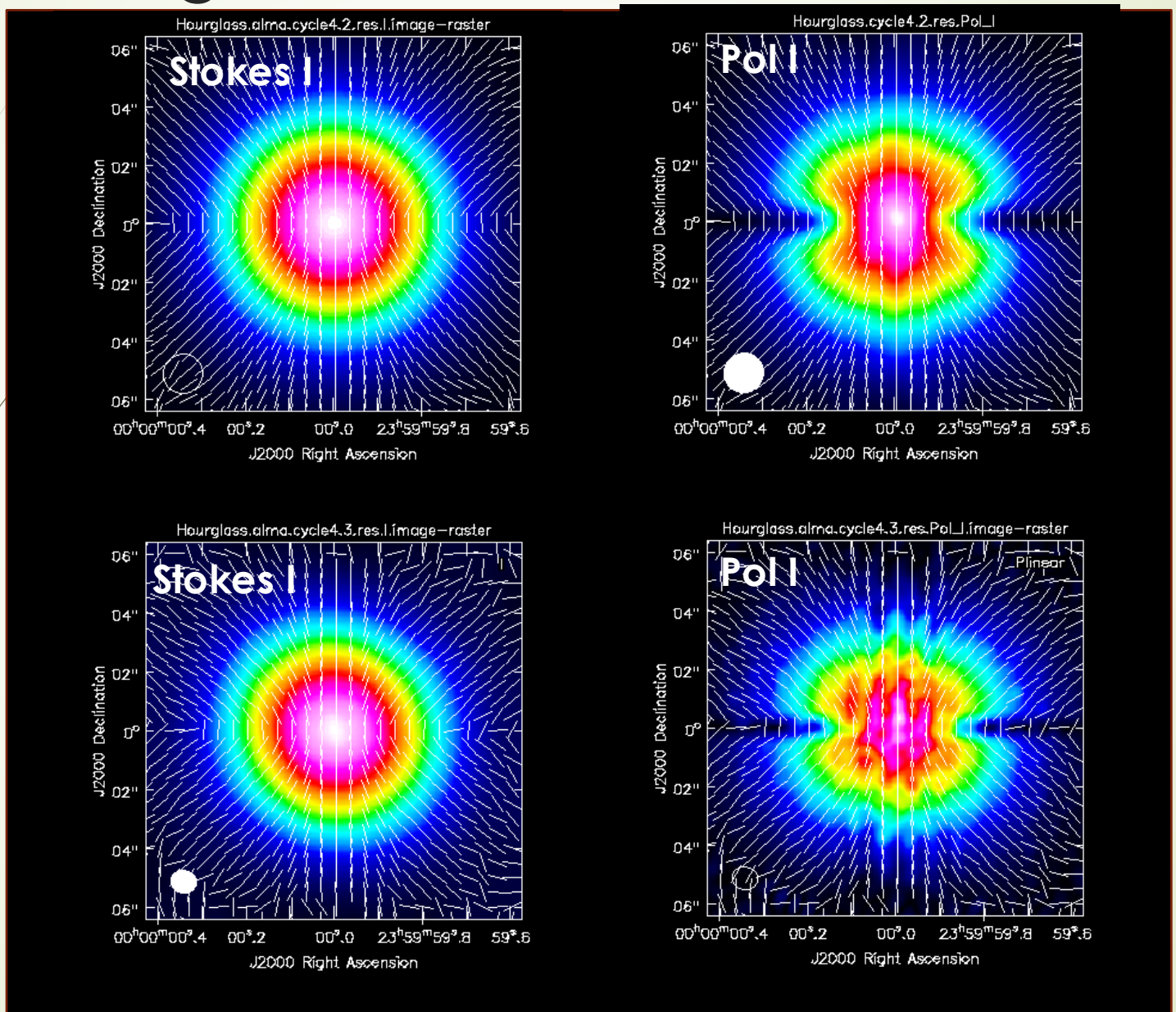
2. Hourglass Model

FWHM < MRS

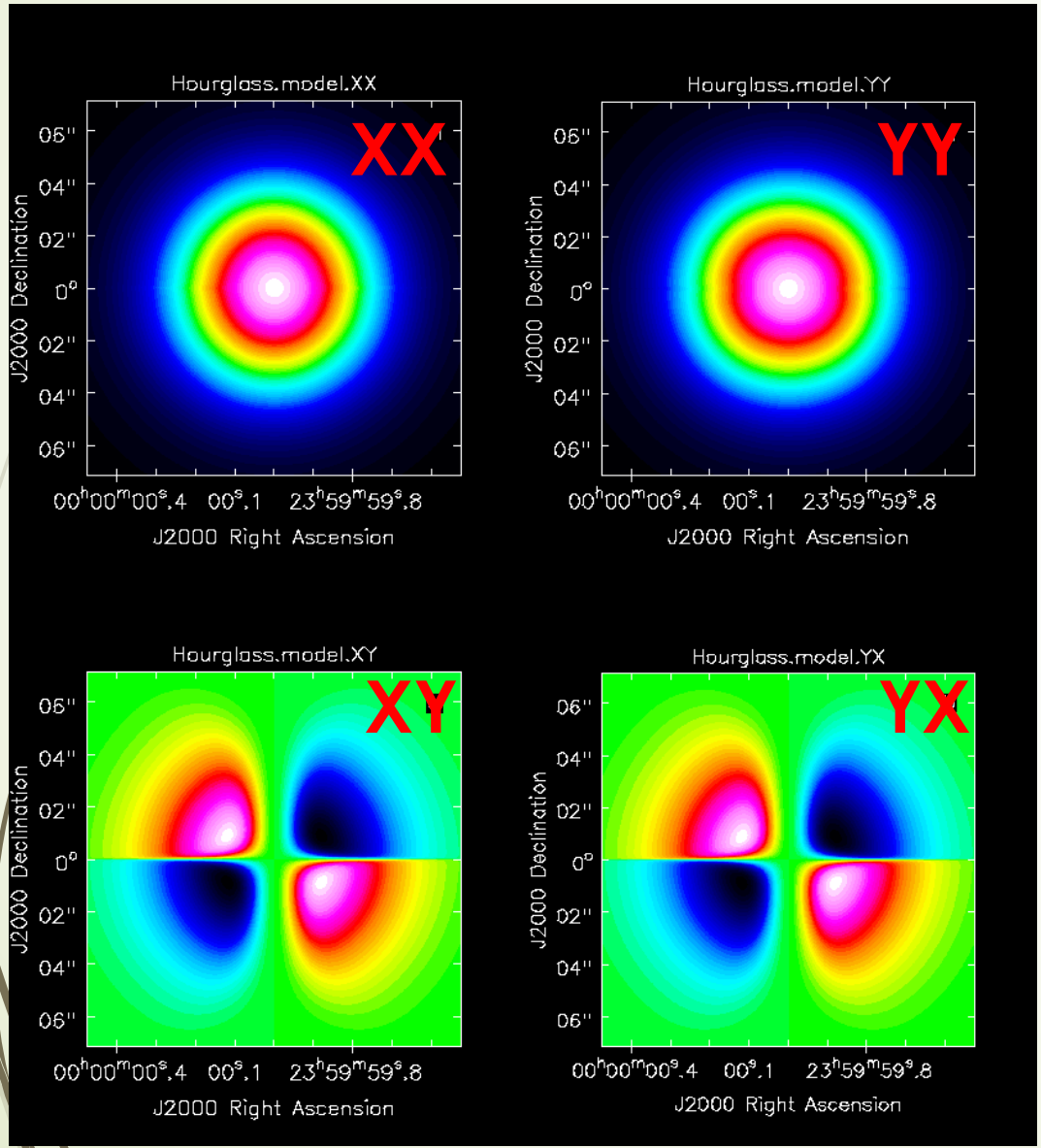
Compact
C40-2

FWHM > MRS

Extend
C40-3

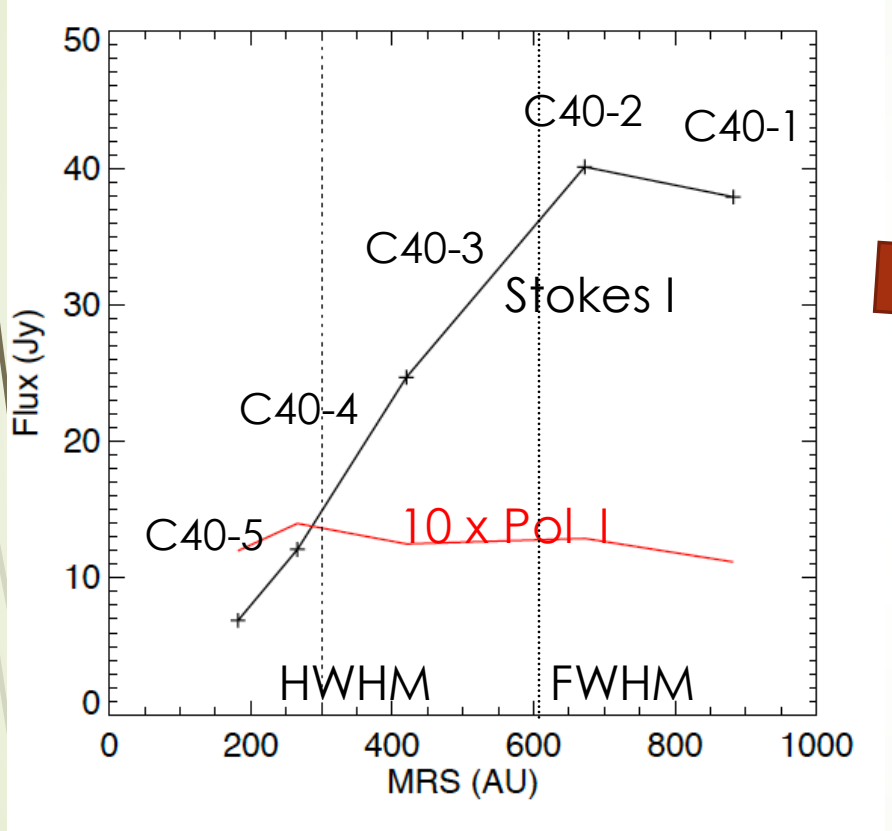


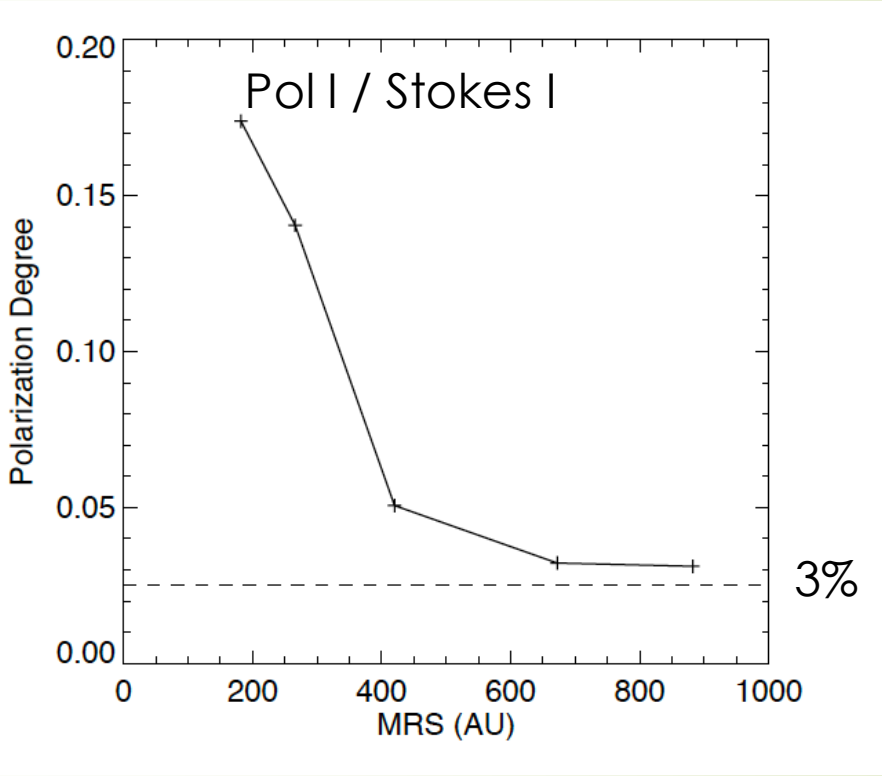
2. Hourglass Model



Size scale of polarized flux
~ 1/4 of Stokes I

2. Hourglass Model

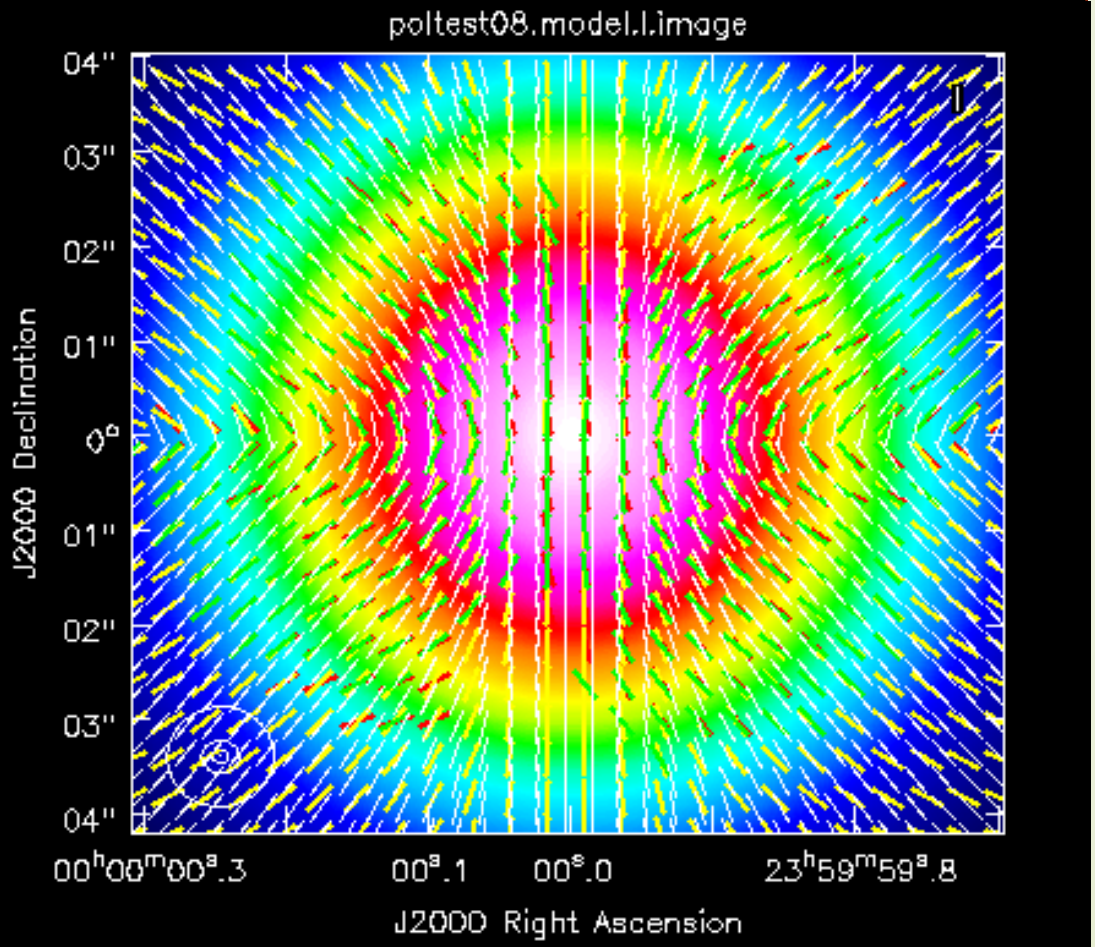




- Plateau size > MRS : Interferometer can not reproduce Stokes I
  Special care is needed for observation of embedded protostellar objects.
- In the case of uniform magnetic field, Stokes I and Pol I decreases same rate
  ➔ Polarization fraction ~ constant

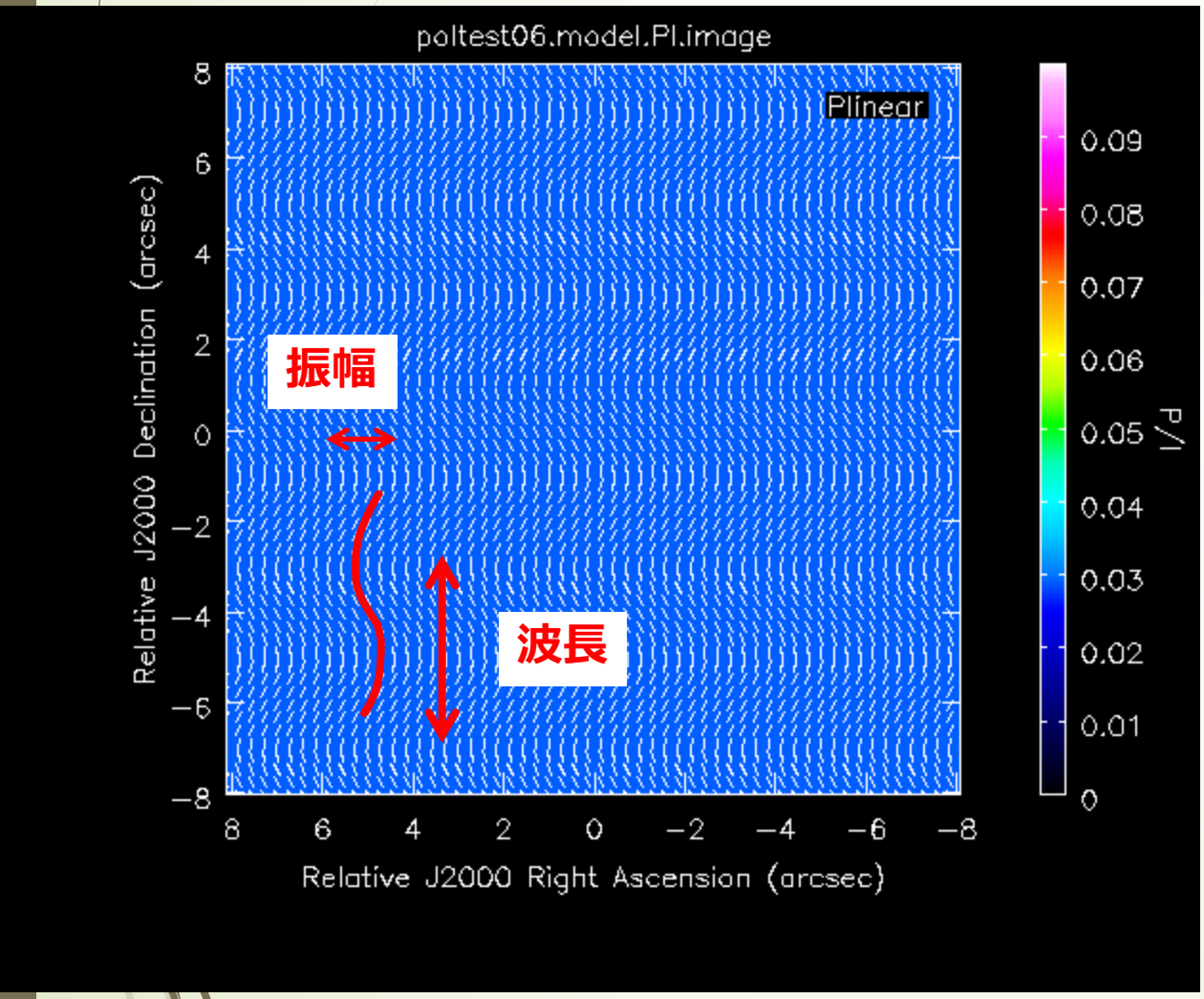
Hourglass 偏波ベクトル構造
Effect of Antenna Configuration

- **Model**
- **Compact Conf.**
- **Medium Conf.**
- **Extended Conf.**



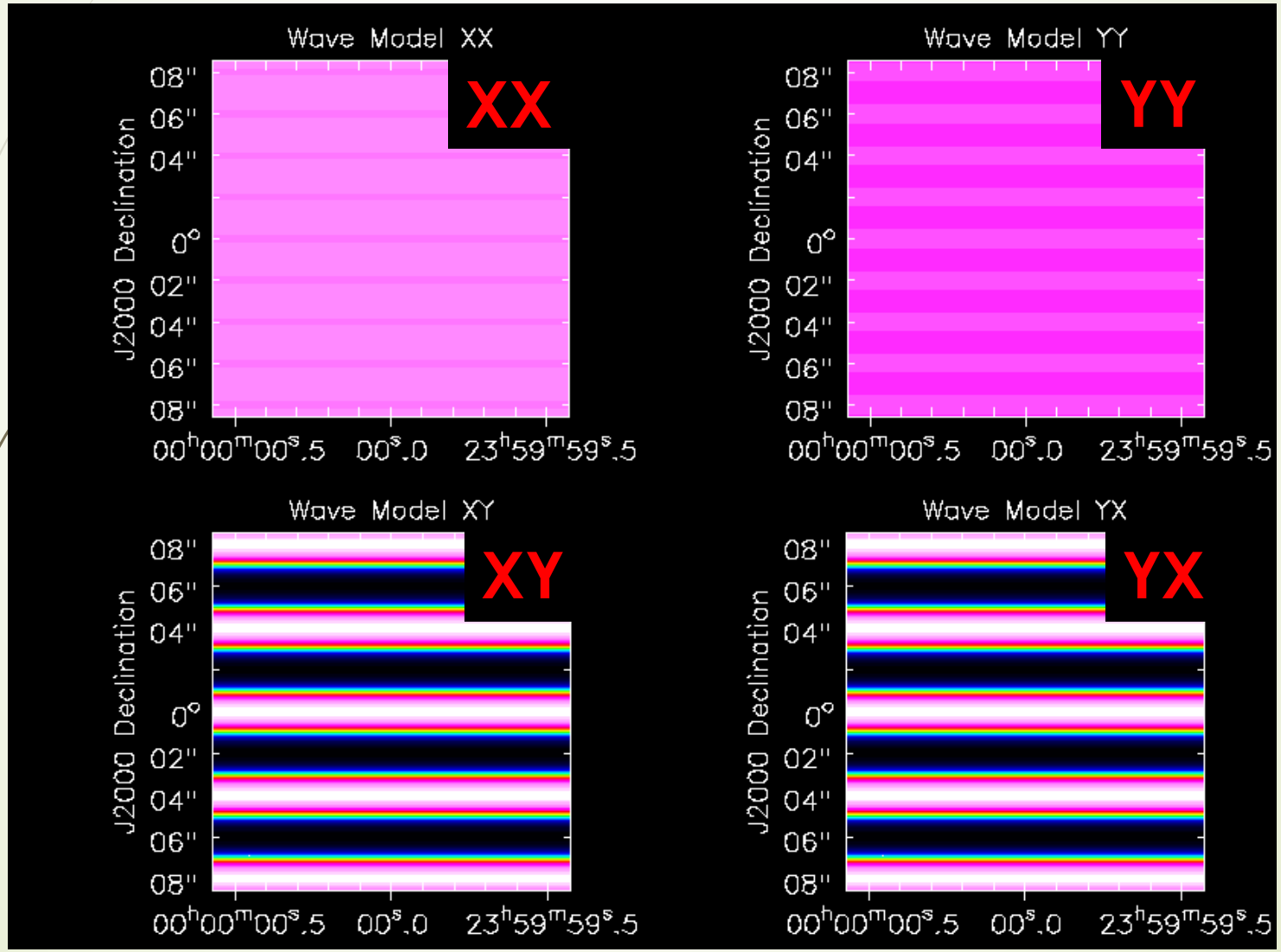
Slightly distorted, influence is small in this case

Ex.3 Wave Structure in an uniform density cloud



- Stokes I = constant
- Polarization: Wave
  Wave length 4 arcsec,
  Amplitude: 1 arcsec
- Polarization fraction 3%

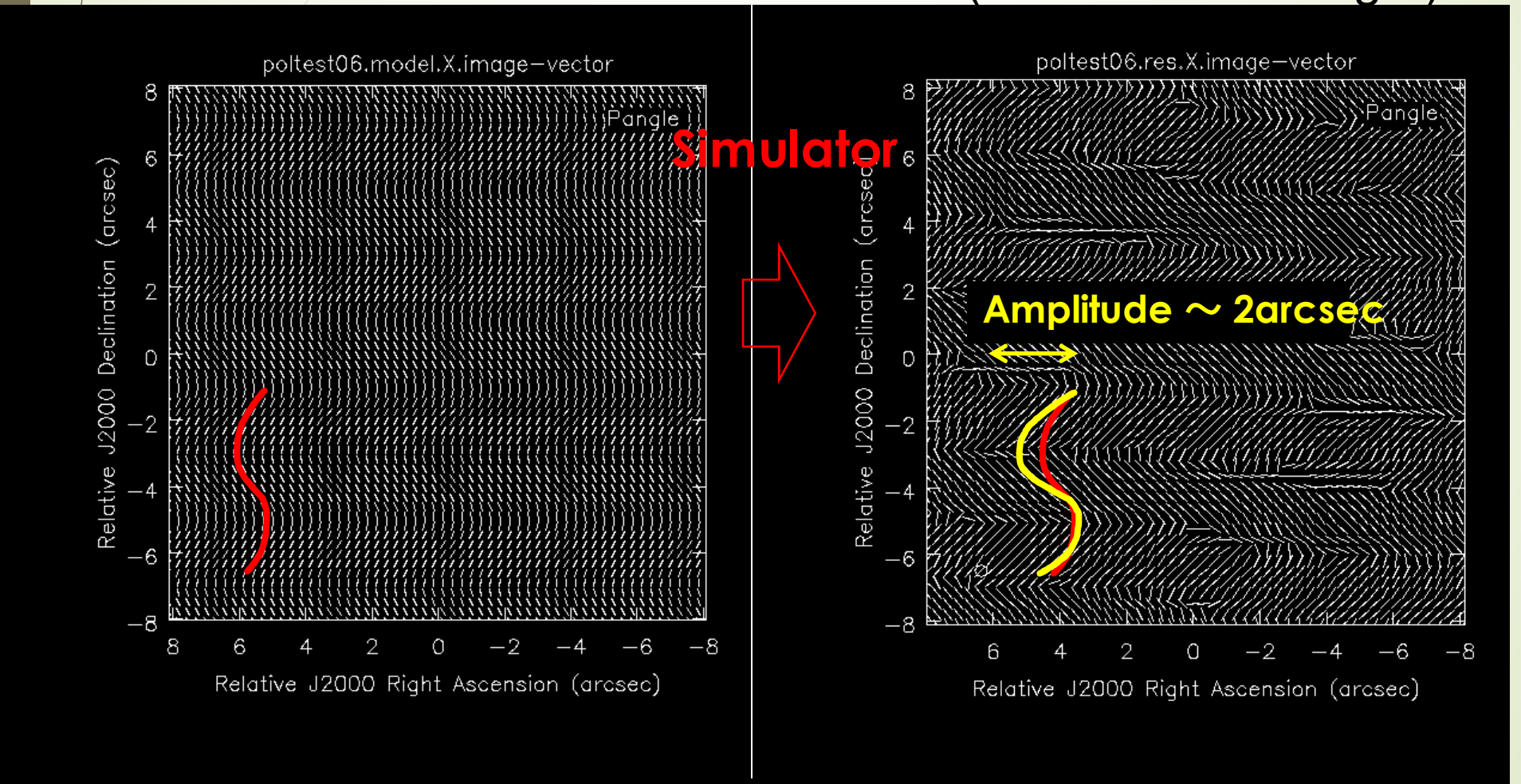
Wave Model XX,YY,YX,XY images



Ex.3 Wave Structure

Model

C40-4 (MRS ~ wave length)



In this case, amplitude of wave become lager with decreasing MRS

Summary of Simulation Tests

To examine the effect of spatial sampling of interferometer observation on observation results, I made virtual observations for simple models using CASA simulator.

- In Disk model, polarization fraction suddenly increases when the MRS size becomes smaller than the disk radius. Direction of polarization does not change.
- In Gaussian (or Plateau + envelope) core model, polarization fraction increases gradually. Direction of polarization change slightly in the non-straight line polarization case (ex. Hourglass).
- In uniform Stokes I case, polarization structure changes largely with MRS.

Package: scripts for polarization simulation of CASA + Disk and Hourglass Model

http://alma-intweb.mtk.nao.ac.jp/~saigo/Resources/

Finally

ALMA Cycle 6 Capability

- Single pointing observation by 12m array (Only 1/3 of the center of FoV).
- Band 3,4,5,6,and 7 continuum (TDM), spectral(FDM)
- Detectable polarization fraction
  - Compact Source: 0.1% in TDM, 1% in FDM
  - Extended Source: 0.3% in TDM, 3% in FDM

＋

- In Cycle 6 (proposal deadline ~ next April), observation mode of **circularly polarization** will open!! Continuum observation, spectral line observation? * Detectable polarization fraction >1~2% (may be,,)

Do you have any requests about future plan?
Mosaic observation? ACP observation?

以下、参考

参考 MRS

参考資料

Table A-1: Angular Resolutions (AR) and Maximum Recoverable Scales (MRS) for the Cycle 5 Array configurations

Config	Lmax	Band	Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10
	Lmin	Freq	100 GHz	150 GHz	183 GHz	230 GHz	345 GHz	460 GHz	650 GHz	870 GHz
7-m Array	45 m	AR	12.5"	8.4"	6.8"	5.4"	3.6"	2.7"	1.9"	1.4"
	9 m	MRS	66.7"	44.5"	36.1"	29.0"	19.3"	14.5"	10.3"	7.7"
C43-1	161 m	AR	3.4"	2.3"	1.8"	1.5"	1.0"	0.74"	0.52"	0.39"
	15 m	MRS	29.0"	19.0"	15.4"	12.4"	8.3"	6.2"	4.4"	3.3"
C43-2	314 m	AR	2.3"	1.5"	1.2"	1.0"	0.67"	0.50"	0.35"	0.26"
	15 m	MRS	22.6"	15.0"	12.2"	9.8"	6.5"	4.9"	3.5"	2.6"
C43-3	500 m	AR	1.4"	0.94"	0.77"	0.62"	0.41"	0.31"	0.22"	0.16"
	15 m	MRS	16.2"	10.8"	8.7"	7.0"	4.7"	3.5"	2.5"	1.9"
C43-4	784 m	AR	0.92"	0.61"	0.50"	0.40"	0.27"	0.20"	0.14"	0.11"
	15 m	MRS	11.2"	7.5"	6.1"	4.9"	3.3"	2.4"	1.7"	1.3"
C43-5	1.4 km	AR	0.54"	0.36"	0.30"	0.24"	0.16"	0.12"	0.084"	0.063"
	15 m	MRS	6.7"	4.5"	3.6"	2.9"	1.9"	1.5"	1.0"	0.77"
C43-6	2.5 km	AR	0.31"	0.20"	N/A	0.13"	0.089"	0.067"	0.047"	0.035"
	15 m	MRS	4.1"	2.7"		1.8"	1.2"	0.89"	0.63"	0.47"
C43-7	3.6 km	AR	0.21"	0.14"	N/A	0.092"	0.061"	0.046"	0.033"	0.024"
	64 m	MRS	2.6"	1.7"		1.1"	0.75"	0.56"	0.40"	0.30"
C43-8	8.5 km	AR	0.096"	0.064"	N/A	0.042"	0.028"	N/A	N/A	N/A
	110 m	MRS	1.4"	0.95"		0.62"	0.41"			
C43-9	13.9	AR	0.057"	0.038"	N/A	0.025"	N/A	N/A	N/A	N/A
	368 m	MRS	0.81"	0.54"		0.35"				
C43-10	16.2	AR	0.042"	0.028"	N/A	0.018"	N/A	N/A	N/A	N/A
	244 m	MRS	0.50"	0.33"		0.22"				

2. Hourglass Model Stokes map