Modeling M51 as a multilayer Burn slab

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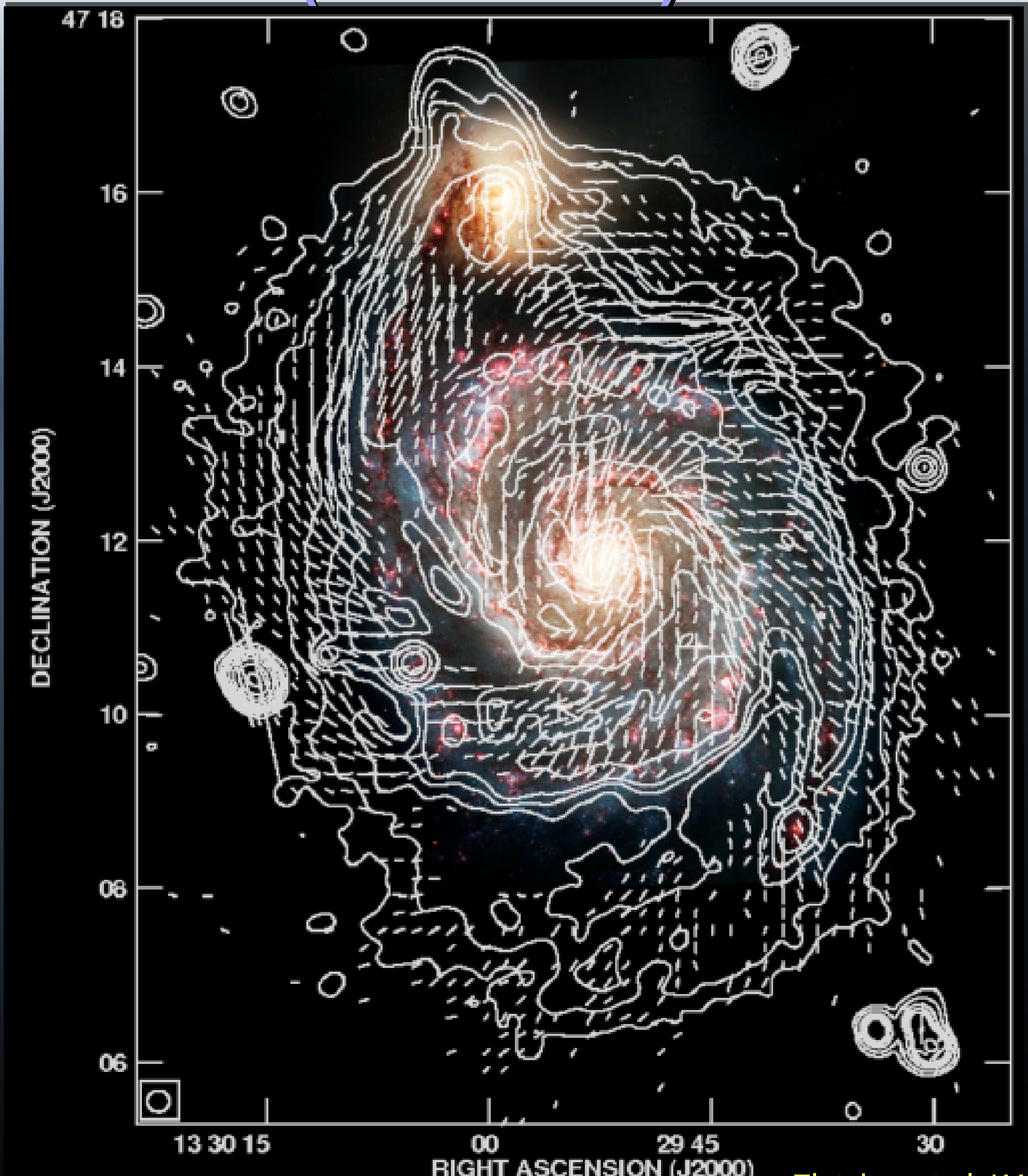
Scientific Goals

- Determine Magnetic Field Strengths in M51
- Estimate Thermal and Cosmic Ray Electron Densities in the Disk and Halo

M51 (NGC 5194)



Fletcher et al. '11

- Magnetic Fields
  Thermal Electrons
  Cosmic Ray Electrons
- Observed Total Intensity:
  $I_{tot} = I_{syn} + I_{th}$
- Degree of Polarization
  $DoP = PI / I_{tot} \sim PI / I_{syn}$
- Cosmic Rays → Polarized signal
- Thermal Electrons → Faraday Rotation
- $\psi = \psi_0 + RM*\lambda^2$
  where
  $RM = 0.81 \int n_e * B_{||} \, dz$
- Synchrotron radiation is polarized with max polarization degree of 70%
- peaks at Radio Frequencies

Project in a Nutshell

- Builds on previous work by Berkhuijsen et al. '97 and Fletcher et al. '11

> "A more productive approach will be to develop a new model that takes into account depolarizing effects directly..."

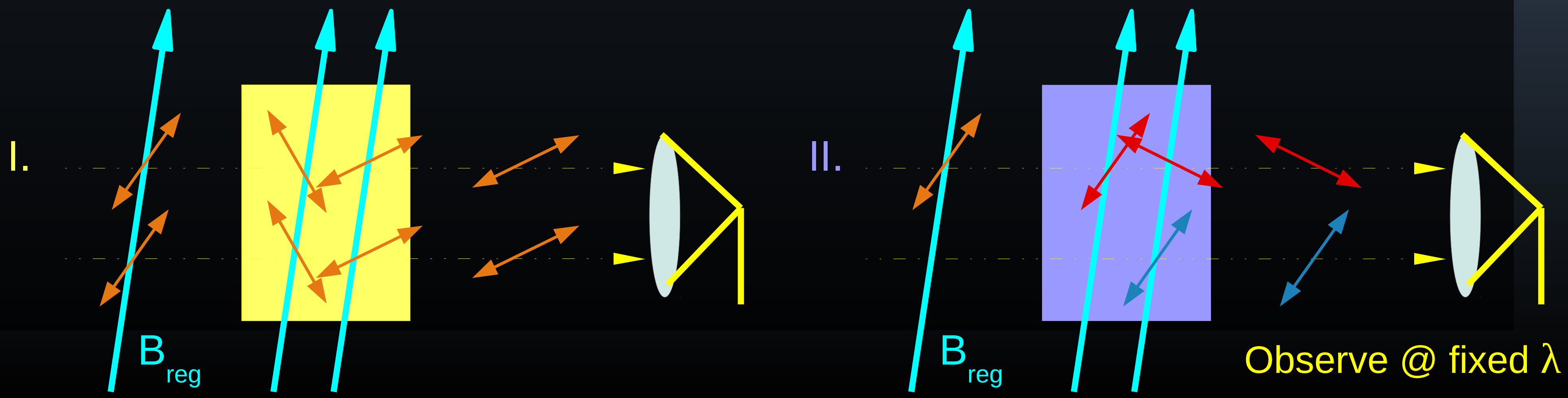
- Model M51 as a multilayer medium (e.g. disk + halo, halo + disk + halo) in terms of *regular* magnetic fields, constant thermal (n_e) and cosmic ray electron densities (n_{cr}) in each layer (no Faraday dispersion).
- Constrain strength of magnetic fields in the entire M51 galaxy by comparing the degree of polarization values predicted by our model with those observed using *multiwavelength* observations.
- en route to zooming in on thermal and cosmic ray electron densities in M51

Project in a Nutshell

- Dealing with wavelength-dependent depolarization effects (exclusively) involving only *regular* fields
- Two possible approaches to modeling layers :

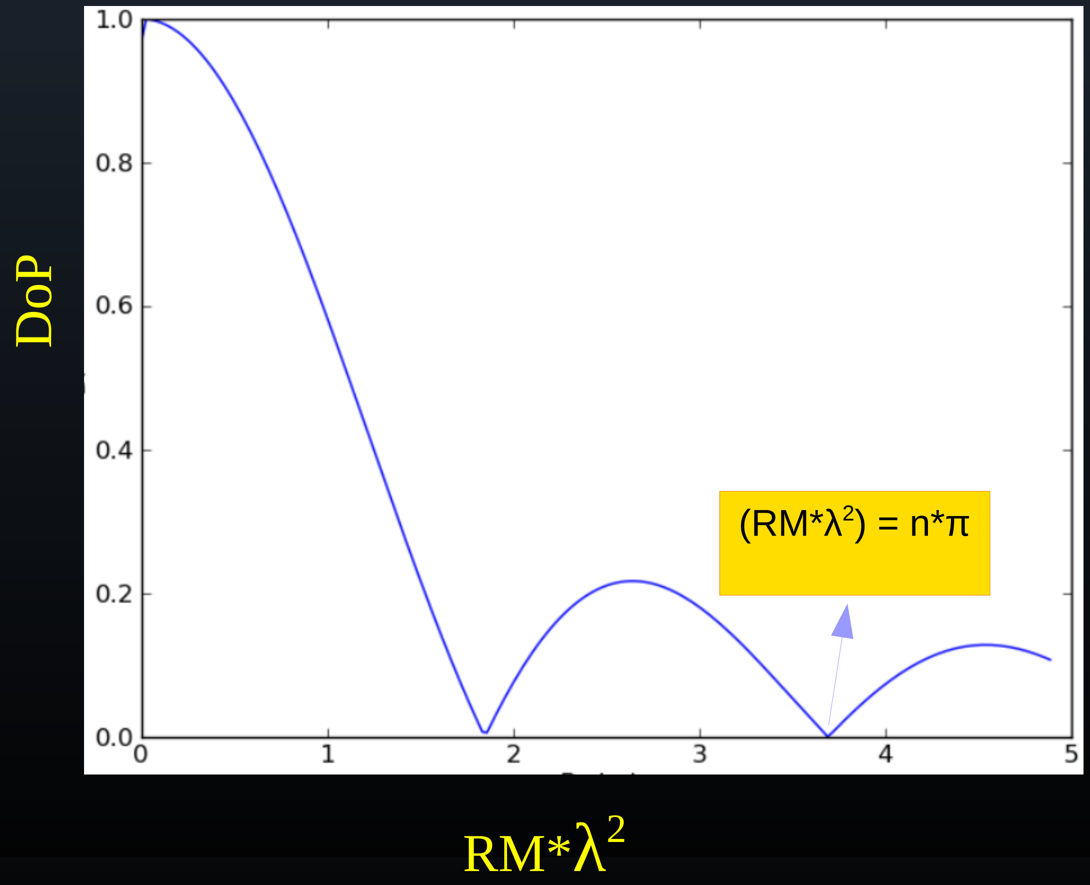
I. Faraday Screen: only Thermal electrons present in layer
→Rotation at each point along line of sight (los)
~ wave plate behavior → No depolarization

II. Burn Slab: both Thermal electrons and Cosmic rays occur in layer
→Rotation and Emission at each point along los
→ Differential Faraday Rotation → Depolarization



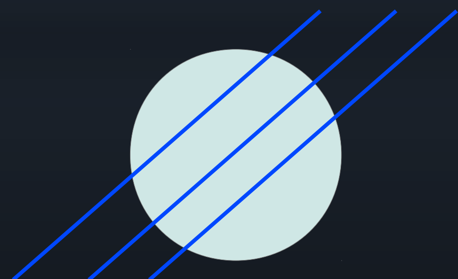
DoP as a Sinc function

- Only $B_{||}$ contributes to Faraday rotation; $B_{\perp}$ contributes to emission
- In a slab with multiple uniform layers in terms of regular magnetic fields, constant thermal and non-zero cosmic ray electron densities, the DoP varies as a Sinc function.



Why DoP useful as a probe of magnetic fields?

- DoP is a very useful *observable*
  - Encapsulates magnetic field content



PI = 1 Jy
I_{syn} = 2 Jy
→ DoP = 50 %

PI = 1 Jy
I_{syn} = 100 Jy
→ DoP = 1 %

  - Combines Stokes parameters I,Q,U into an absolute number

$$DoP = \frac{PI}{I_{syn}} = \frac{\sqrt{Q^2 + U^2}}{I_{syn}}$$

  - Tracer of transverse regular to transverse total magnetic field for external galaxies

Attractive features of M51

- Classic grand-design spiral galaxy
- Historically
  - First external spiral galaxy from which linearly polarized radio emission detected 36 years ago, in turn making M51 the first galaxy for which global structure of regular field studied
  - Magnetic field pattern famously claimed to be bisymmetric (Tosa & Fujimoto '78)
- Similarity with Milky Way
  - Type: Sc and Sbc
  - Linear dimension
  - ISM

Attractive features of M51

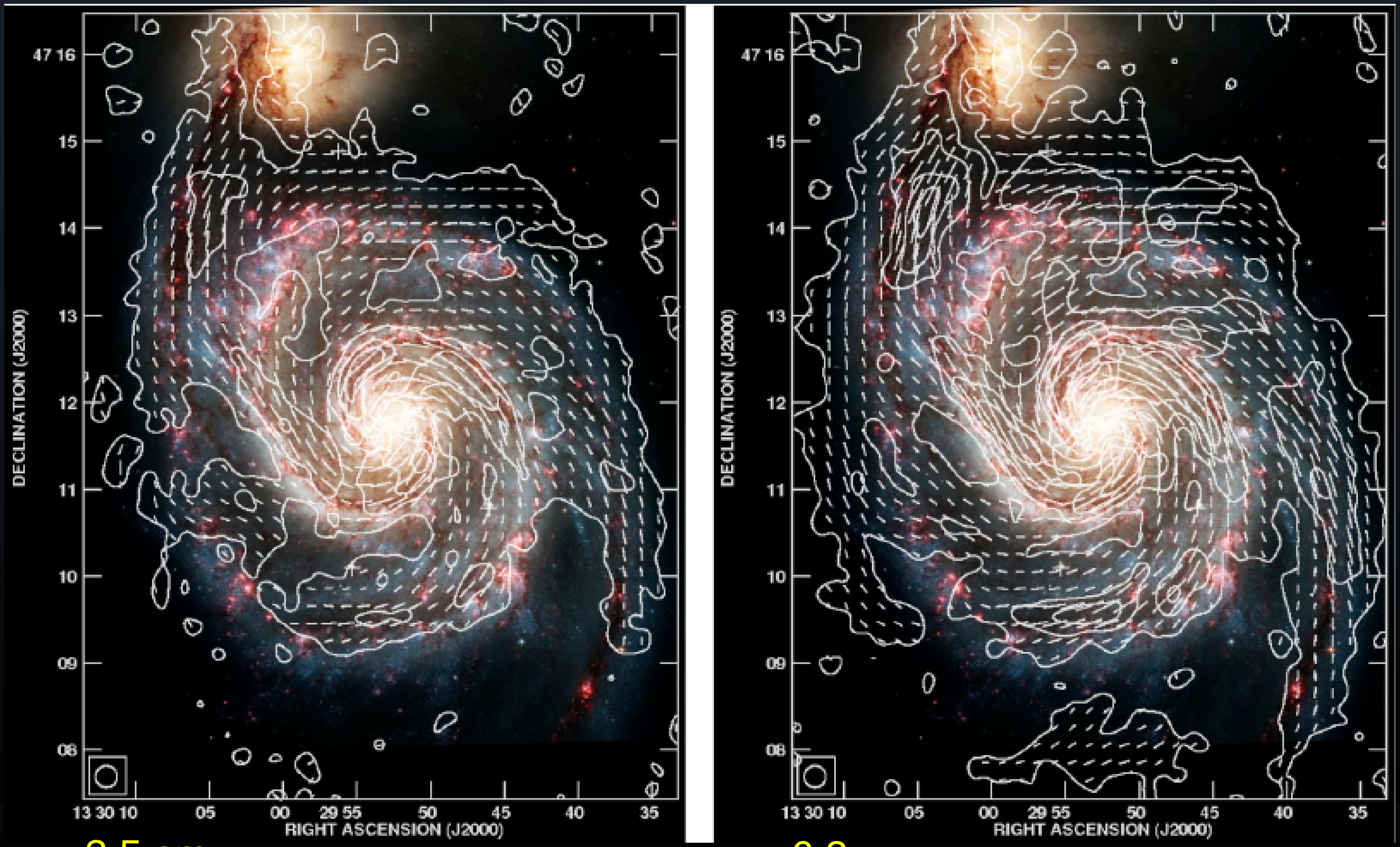
- For this Project in particular
  - Angle of inclination of -20˚

    (i) if was exactly face-on (0˚) no Faraday effect because regular fields are entirely in plane of galaxy and multiwavelength observations would yield no extra information

    (ii) if angle greater, then lines of sight preferentially pick up more disk or halo and multilayer modeling become extremely complicated
  - High galactic latitude (b = +68.5607)

Fletcher et al. '11 Model

- Observations



3.5 cm

6.2 cm

Fletcher et al. '11

Fletcher et al. '11 Model

- Observations
- Measure polarization angles ψ against azimuth in the galaxy plane for $\lambda\lambda\lambda\lambda$ 3.5,6.2,18.0,20.5 cm per radial bin
- Partition these polarization angle maps into 4 rings of 18 radial bins each with an opening angle of 20˚
- Radial ranges: 2.4 – 3.6 kpc, 3.6 – 4.8 kpc, 4.8 – 6.0 kpc and 6.0 – 7.2 kpc
- Total of 288 data points   (4 rings x 18 sectors x 4 polarization angles)

Fletcher et al. '11 Model

- Inputs

Exponential scale heights of thermal disk and halo as well as thermal electron density values from Berkhuijsen et al. '97

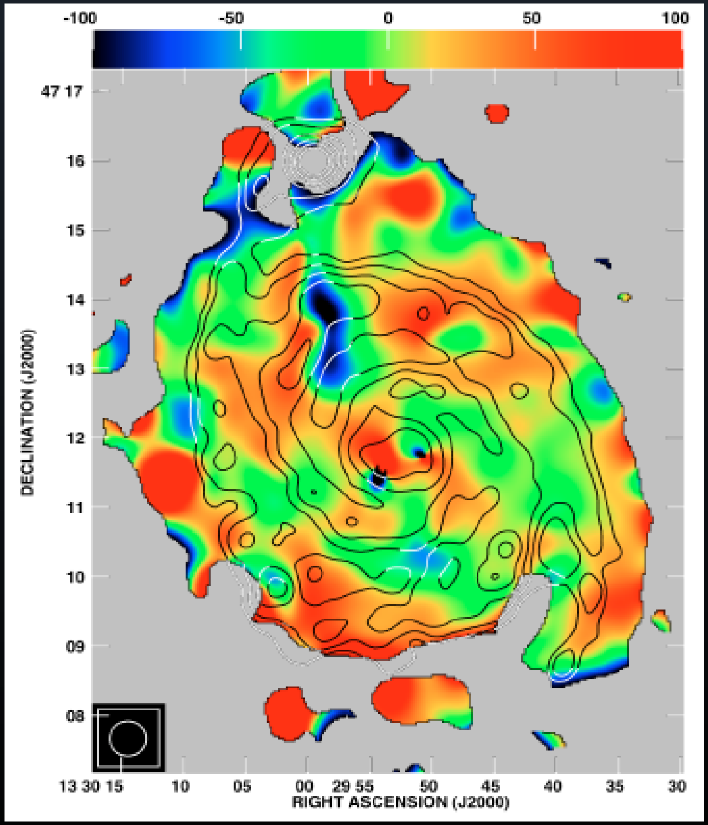
- Model

- Statistically good fits to polarization angles using a superposition of azimuthal magnetic field modes
- Best magnetic field configuration at each radial bin is that which yields best fit to polarization angles at all four wavelengths in that bin
- Working Assumptions:
  - Disk and Halo as Faraday screens with synchrotron illumination
  - Disk fully depolarized at λλ 18.0 and 20.5 cm
  - Include foreground Faraday *rotation* due to Milky Way magnetic field

Fletcher et al. '11 Model

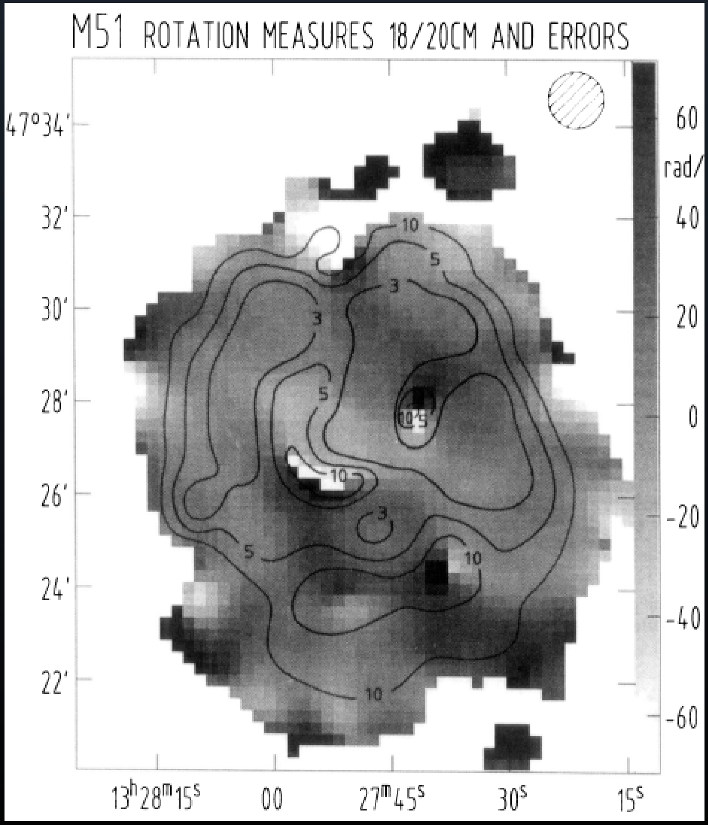
- Pattern in observed Faraday rotation very different between pair of short and long wavelengths → presence of two Faraday rotating layers
- Faraday thin at shorter wavelengths

Rotation Measures λλ 3.5/6.2 cm



Fletcher et al. '11

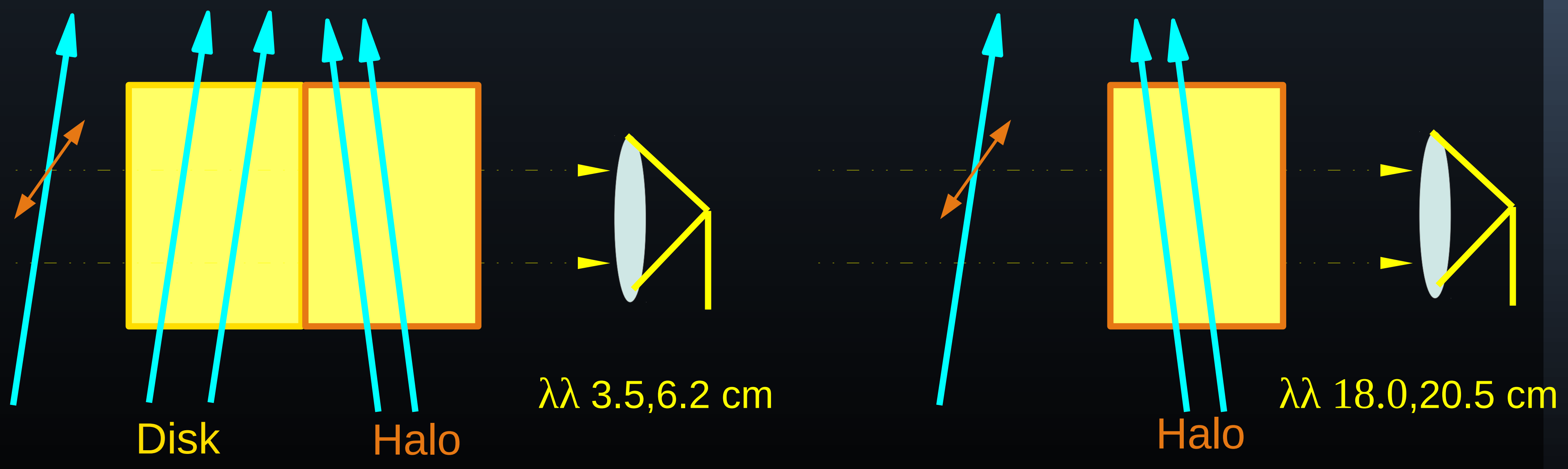
Rotation Measures λλ 18.0/20.5 cm



Horellou et al. '92

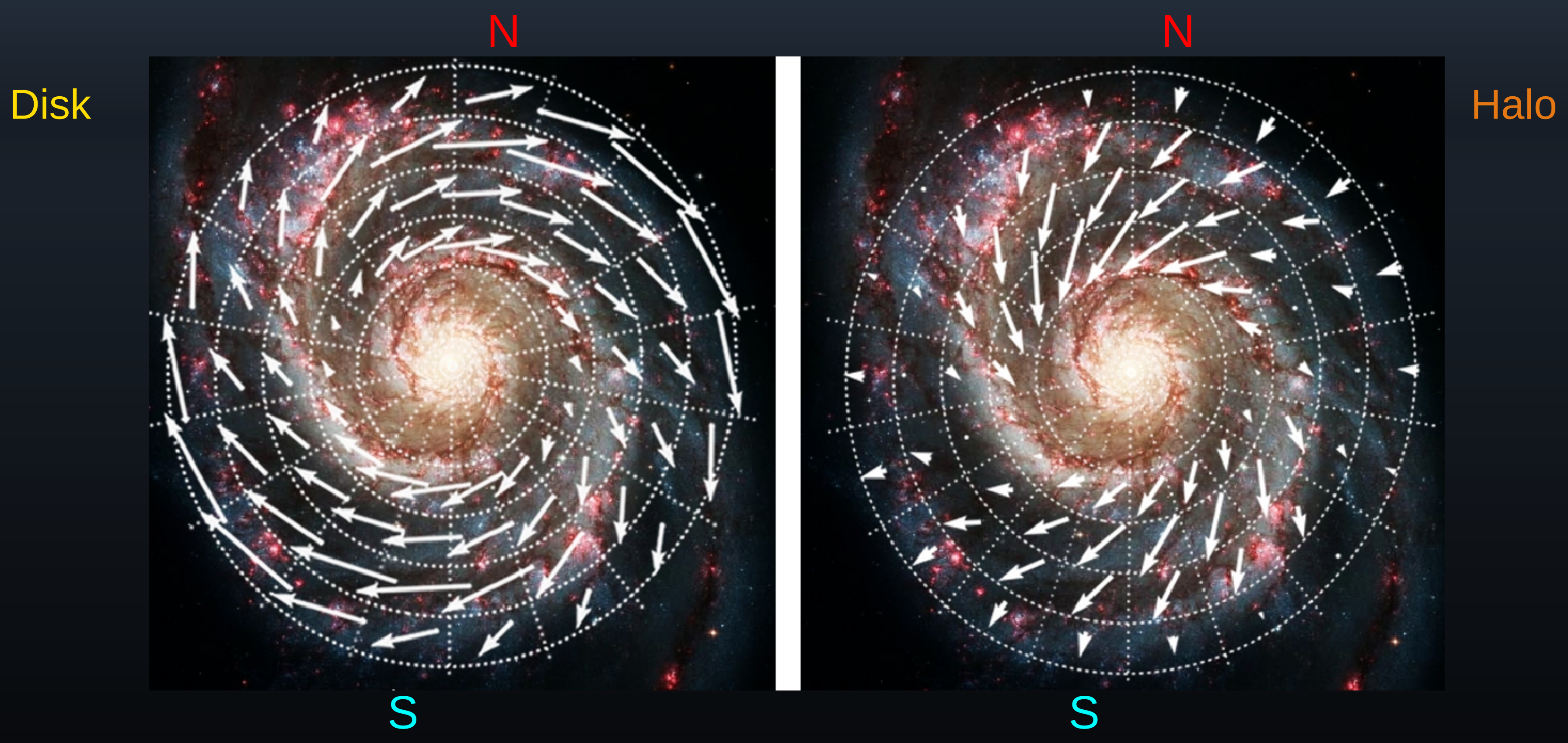
Fletcher et al. '11 Model

- 2 possible explanations:
  - $\Delta\psi \neq RM *\Delta\lambda^2$, non-linear behavior in ψ vs λ^2 indicating emission and rotation in same layer which means $n_{cr} \neq 0$
  - $\Delta\psi = RM *\Delta\lambda^2$, caveat that this linearity holds in two separate layers



Fletcher et al. '11 Model

- Outputs
- Disk and Halo *regular* magnetic field strengths between 1 – 3 μG
- Magnetic fields: no vertical components to disk or halo fields

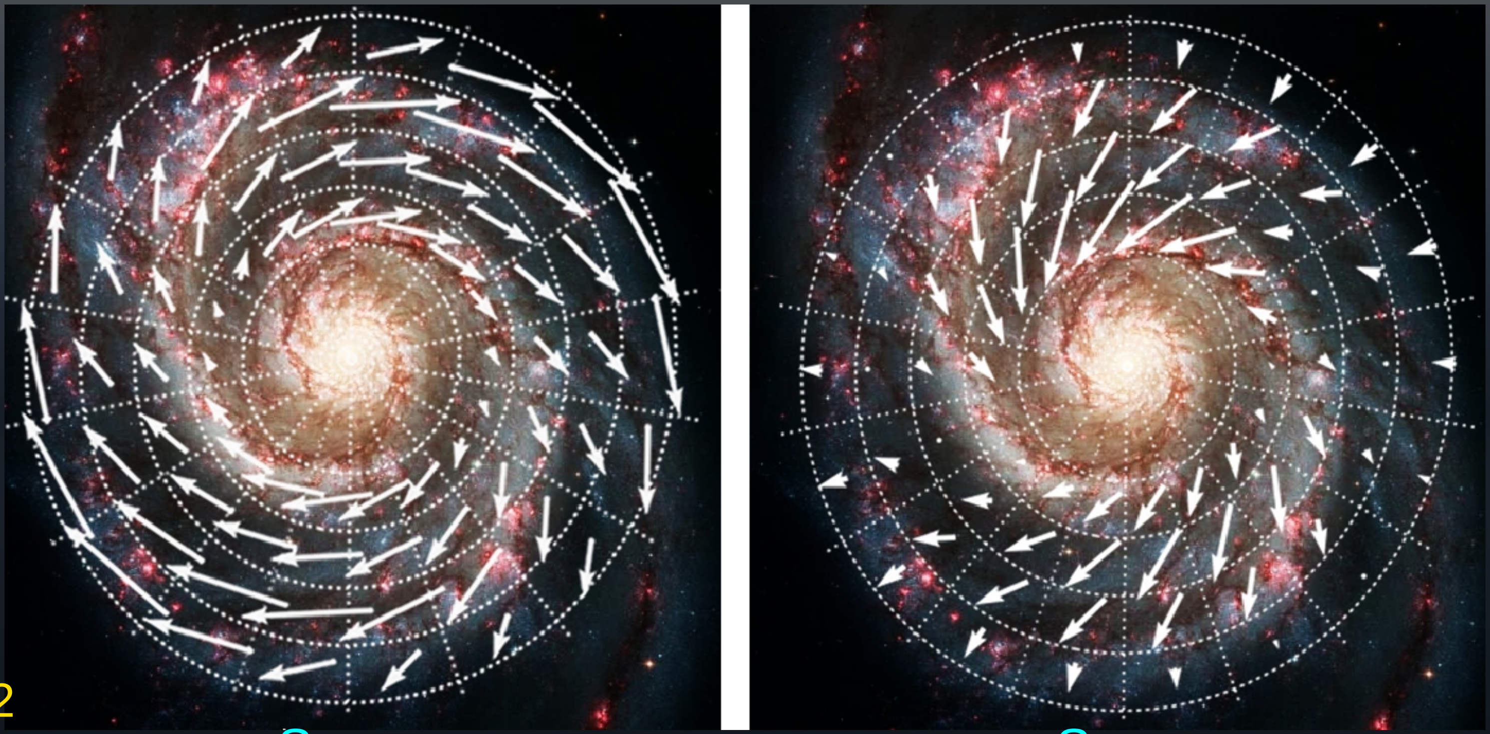


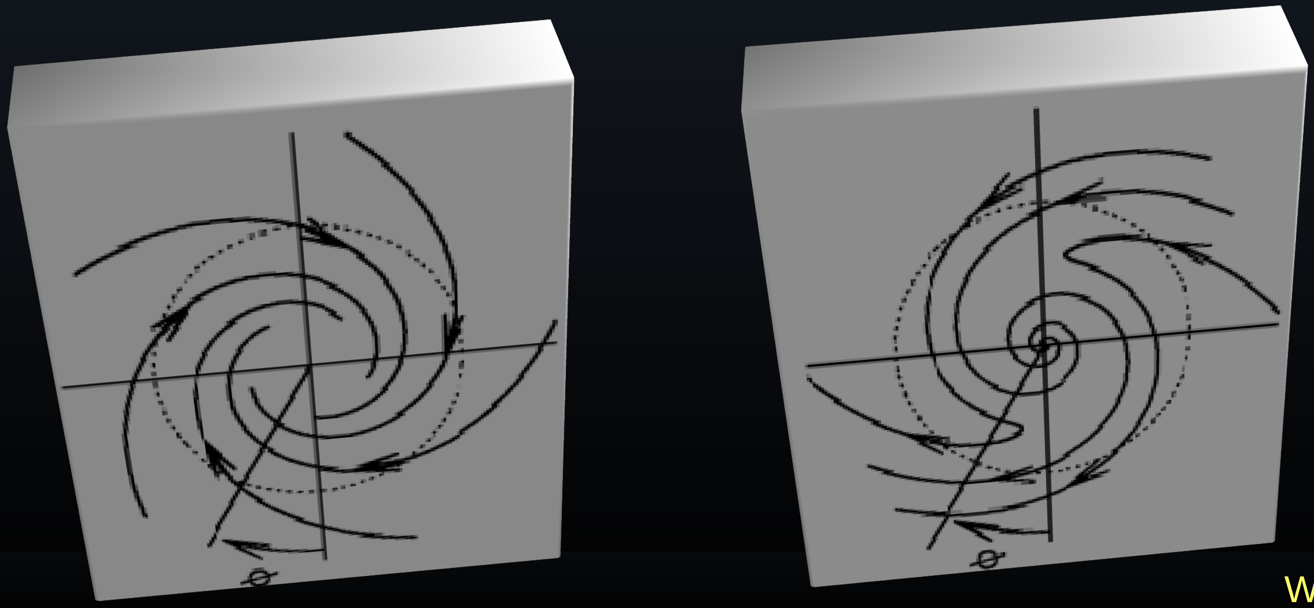
N = North Major Axis

S = South Major Axis

Outputs per radial bin for a given ring *not* independent

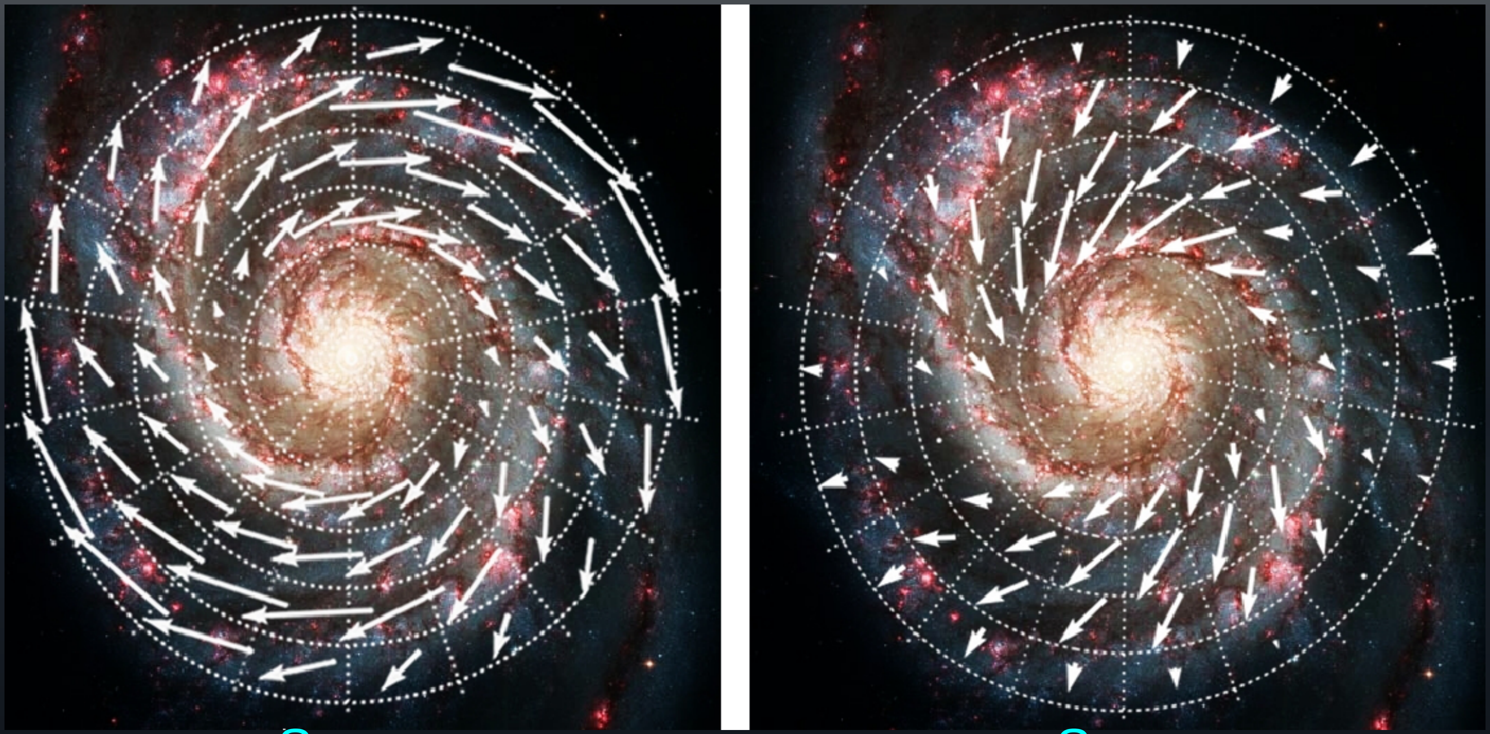
Fletcher et al. '11 Model





Widrow '92

Fletcher et al. '11 Model



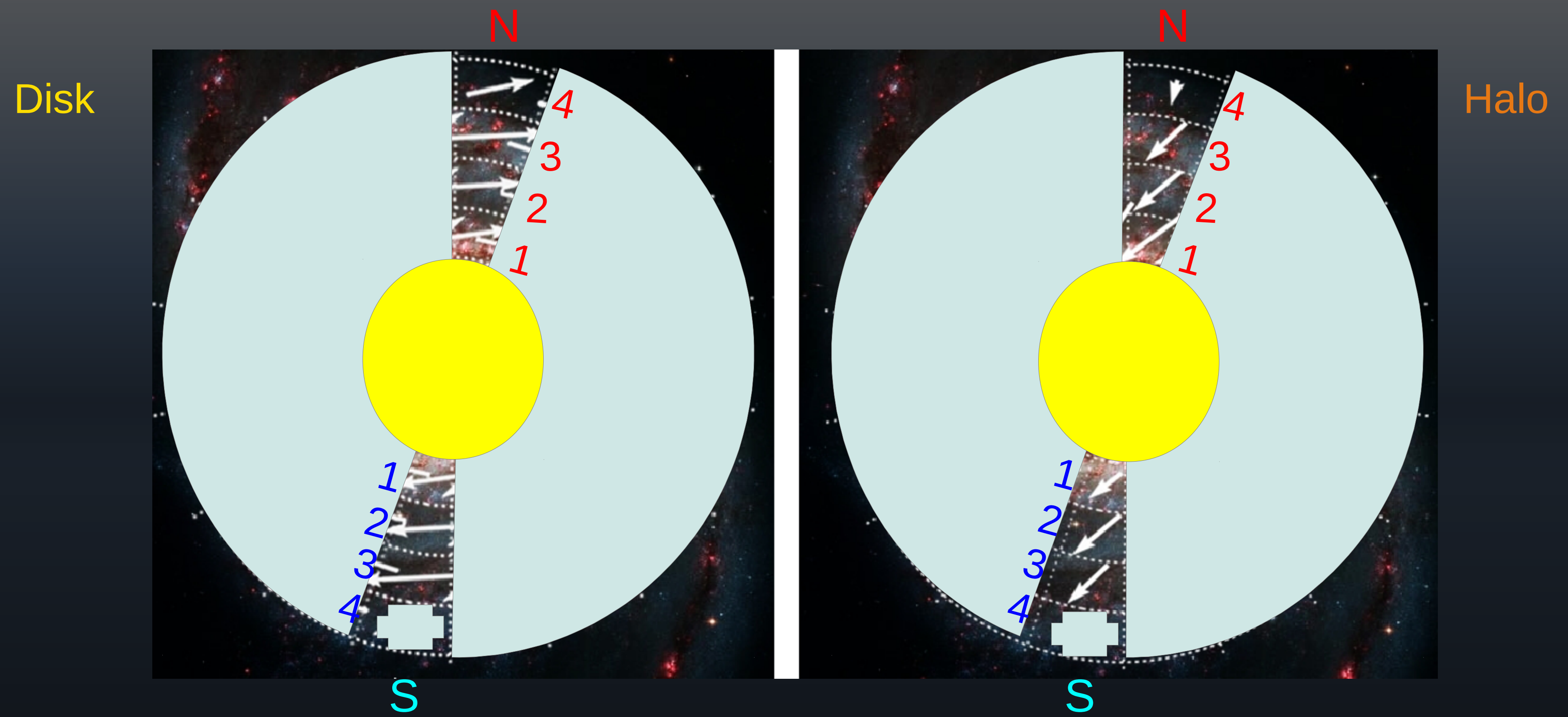
M = 0,2
(M = 0 is axisymmetric)

M = 1 (bisymmetric)

N = North Major Axis

S = South Major Axis

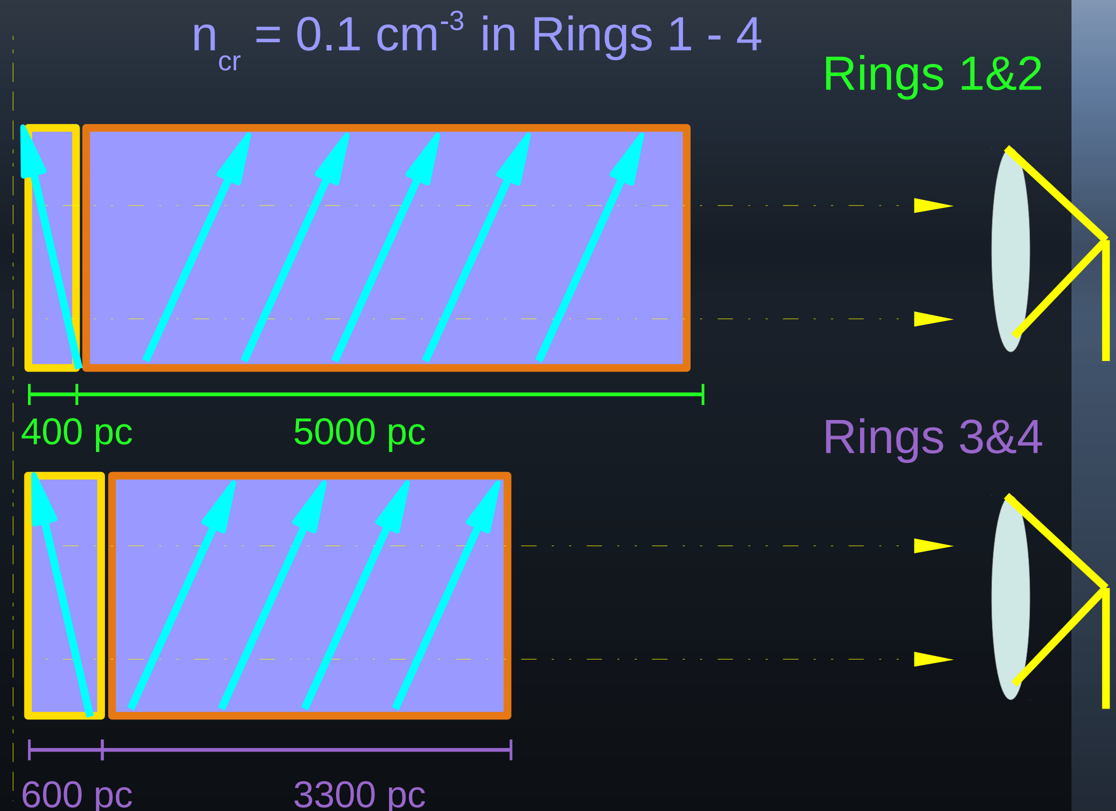
Our Model



		Ring 1	Ring 2	Ring 3	Ring 4
3.5 cm	N	0.2400	0.2156	0.1670	0.2398
	S	0.1809	0.3051	0.3032	0.2162
6.2 cm	N	0.2577	0.1851	0.1249	0.2334
	S	0.1091	0.2511	0.2391	0.0
20.5 cm	N	0.0779	0.0515	0.0386	0.0488
	S	0.0555	0.0594	0.0502	0.0562

Our Model

2 Layer Medium: Disk + Halo



	Disc	Halo
Rings 1&2	n_e = 0.11 B_{tot_disc}	n_e = 0.01 B_{tot_halo}
Rings 3&4	n_e = 0.06 B_{tot_disc}	n_e = 0.006 B_{tot_halo}

Our Model

- Working Assumptions:
  - M51 can be modeled as a medium comprised of multiple uniform layers with regular magnetic fields and both thermal and cosmic ray electron densities
  - All scale height values and the thermal electron densities in the disk are those proposed by Berkhuijsen et al. '97
  - Thermal electron densities in the halo estimated as a tenth of the values of those in the disk (private comm. by Andrew Fletcher)
  - Neglecting Galactic Foreground

Our Model

- Working Assumptions:
  - Fletcher et al. '11 model outputs of magnetic field *directions* in respective bins are our model inputs.
  - Magnetic field *strengths* in disk and halo are free parameters

Our Model

- Recipe
  - Input Fletcher et al. '11 model magnetic field *directions* and the inclination angle of M51
  - Vary over a range of field strengths in disk and halo while keeping the ratio of M = 2 to M = 0 mode in the disk constant
  - Test the model using analytical formula for depolarization in a multilayered medium (Sokoloff et al. 1998)

Our Model

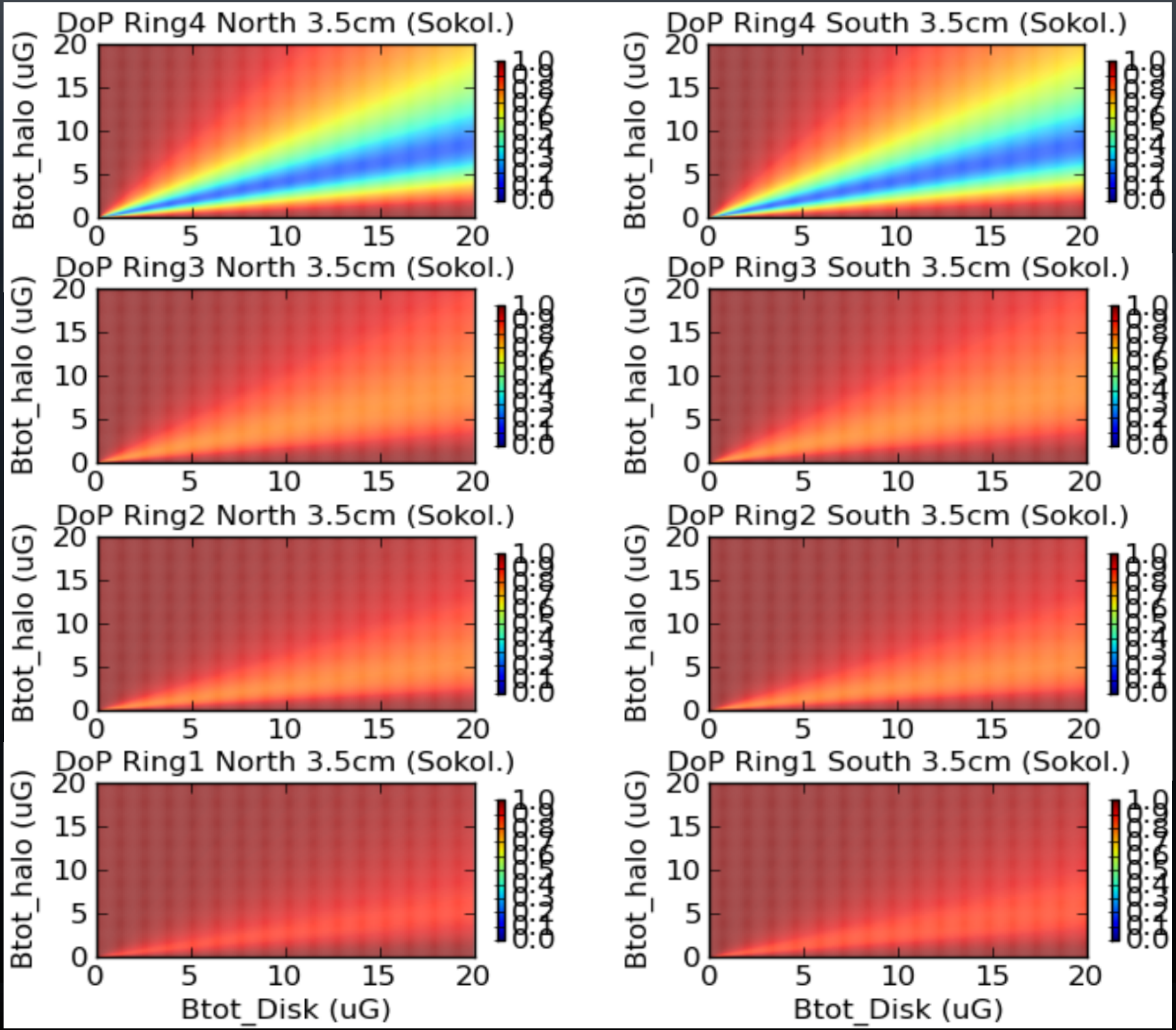
- Recipe
  - Compute normalized squared difference of the computed DoP with the observed DoP at each of the three wavelengths and sum these together for each north and south bin

$$\delta(\mathrm{DoP})^2_{rel} = (\mathrm{DoP}_{obs} - \mathrm{DoP}_{model})^2 / (\mathrm{DoP})^2_{obs}$$

  - Then sum the normalized residual maps for each north and south bin together per ring to obtain N + S residual maps per ring
  - A value of zero for the residual indicates spot on agreement. Regions of zero residual values constrain the optimum magnetic field configurations of total Bdisk and total Bhalo
  - Presence of zeros in all four north bins and all three south bins would indicate existence of magnetic field configurations describing the full extent of the north and south major axis
  - Presence of zeros for N + S bins in all four rings would indicate magnetic field configurations describing the entire M51 galaxy

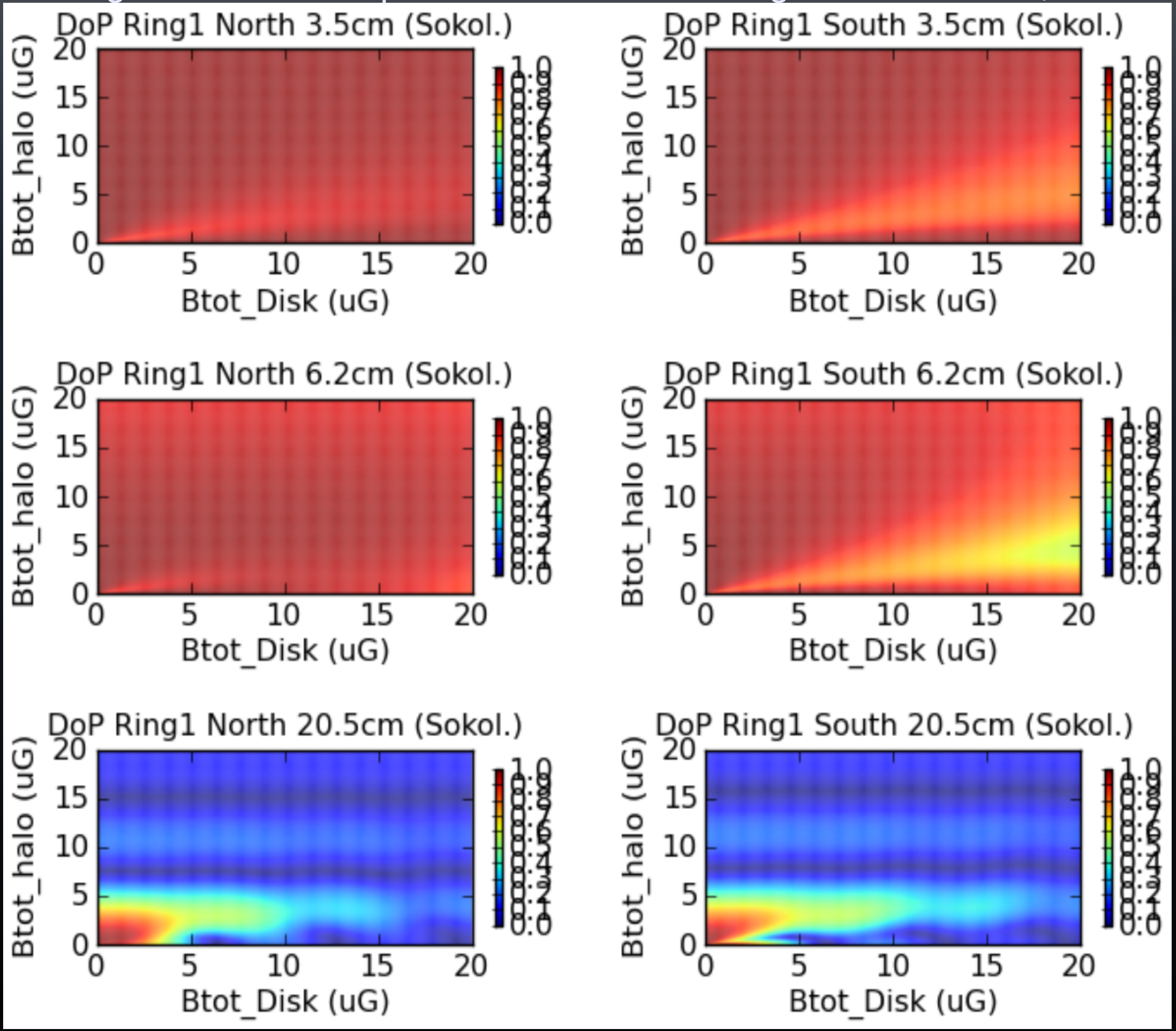
Our Model

- If M51 were exactly face-on (i = 0°):

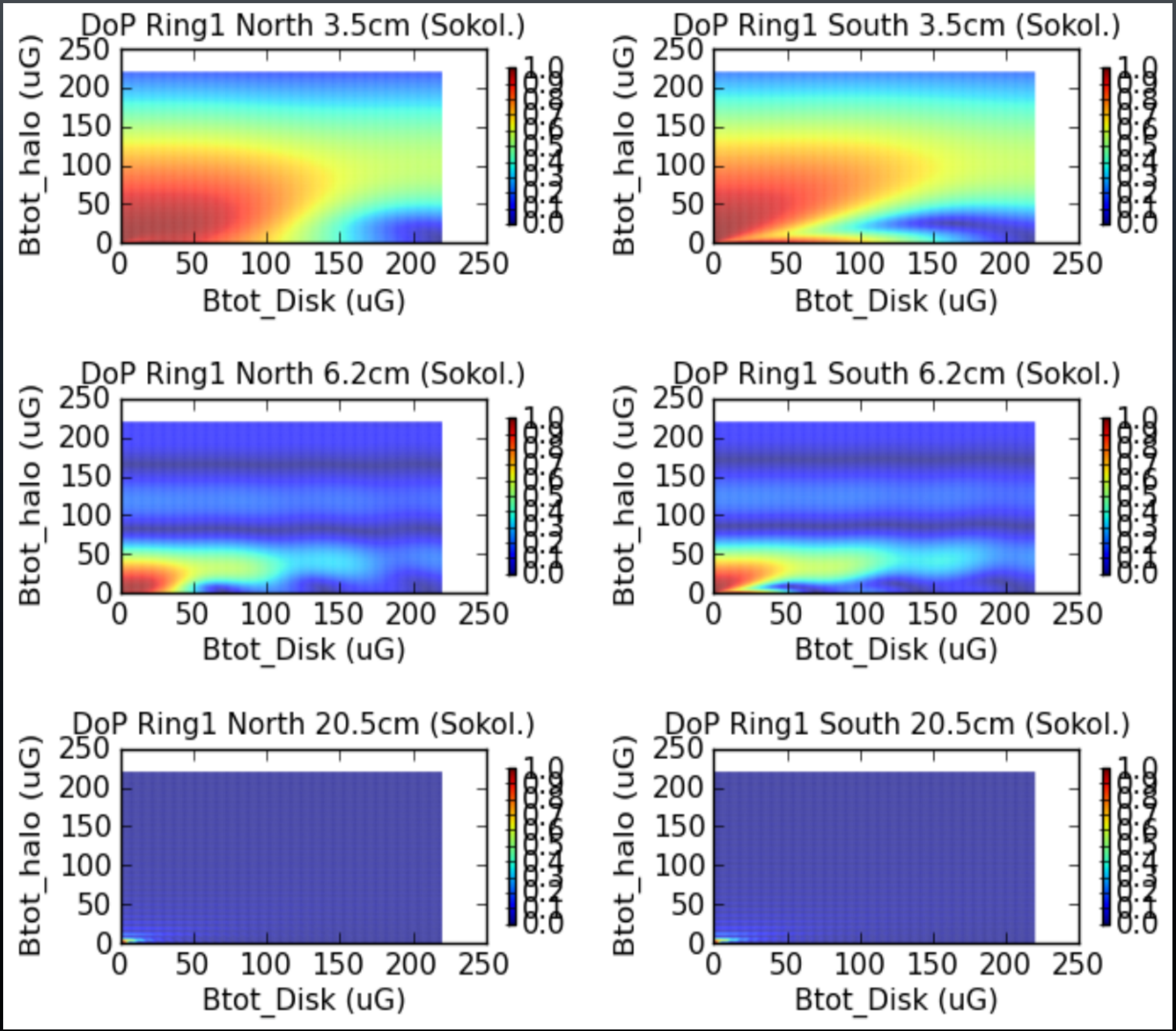


Our Model

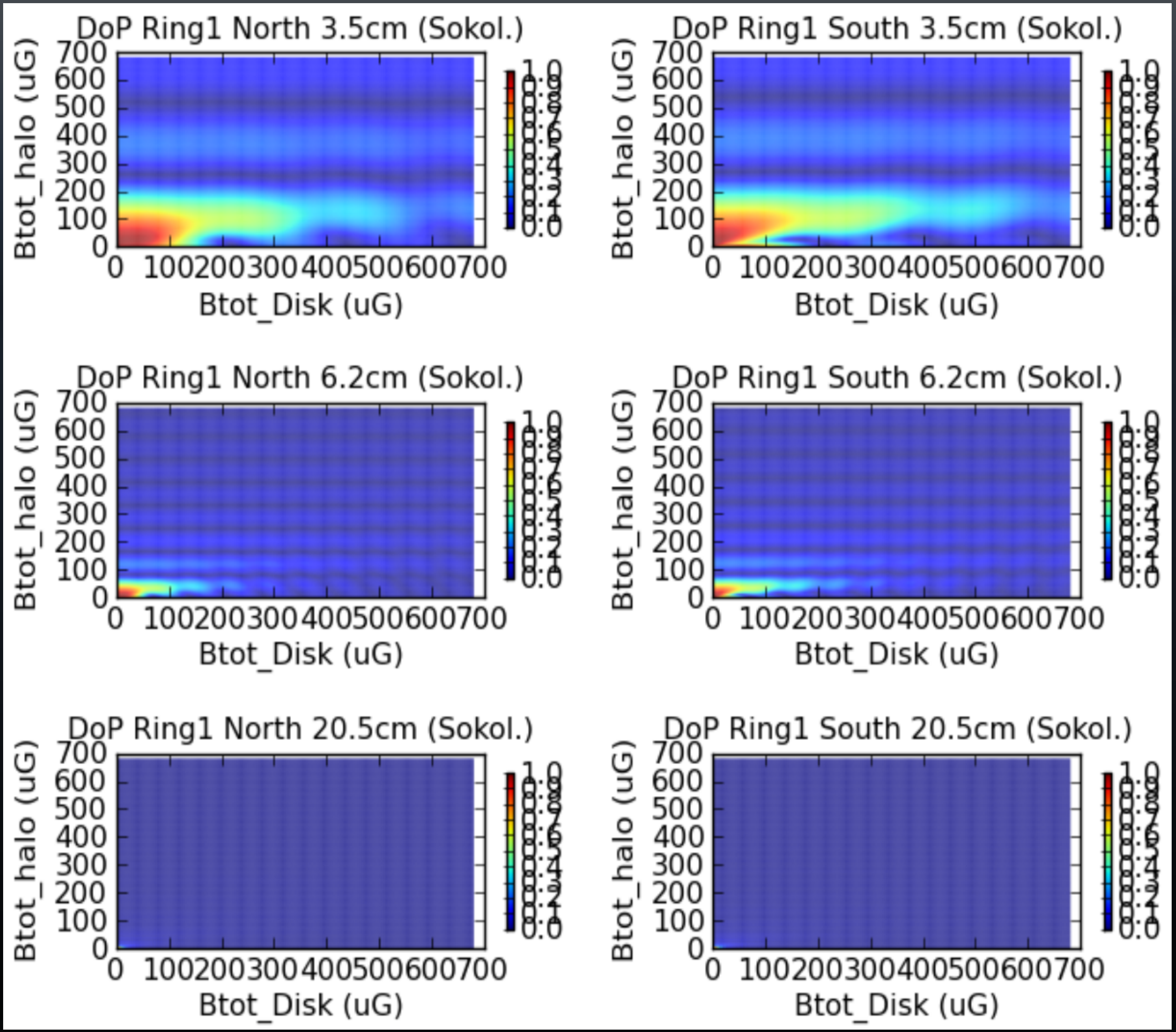
Scaling Relation: DoP pattern at λ 20.5 cm migrates to λλ 6.2, 3.5 cm



Our Model

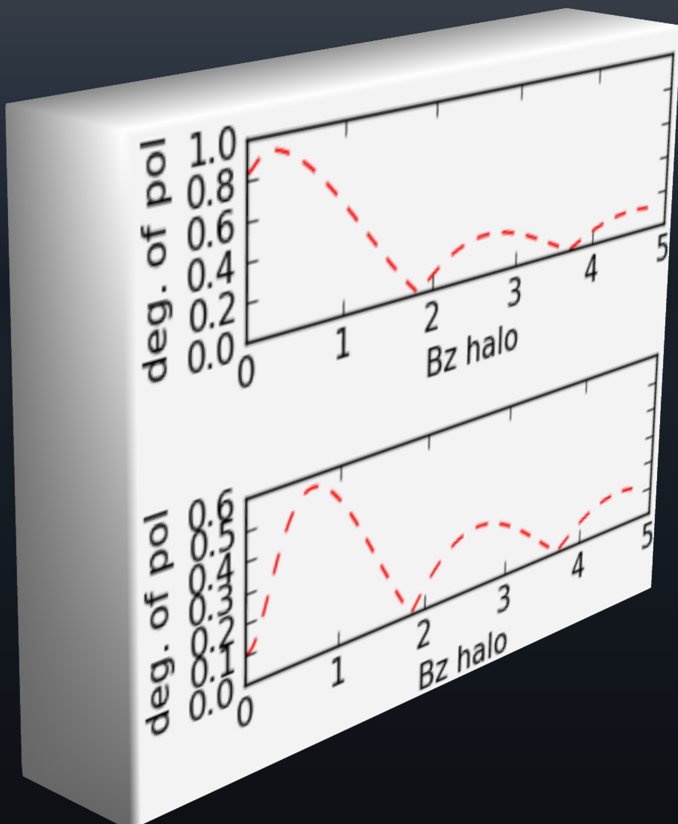

DoP Ring1 North 3.5cm (Sokol.)
DoP Ring1 South 3.5cm (Sokol.)
DoP Ring1 North 6.2cm (Sokol.)
DoP Ring1 South 6.2cm (Sokol.)
DoP Ring1 North 20.5cm (Sokol.)
DoP Ring1 South 20.5cm (Sokol.)
Btot_halo (uG)
Btot_Disk (uG)
0 50 100 150 200 250
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0

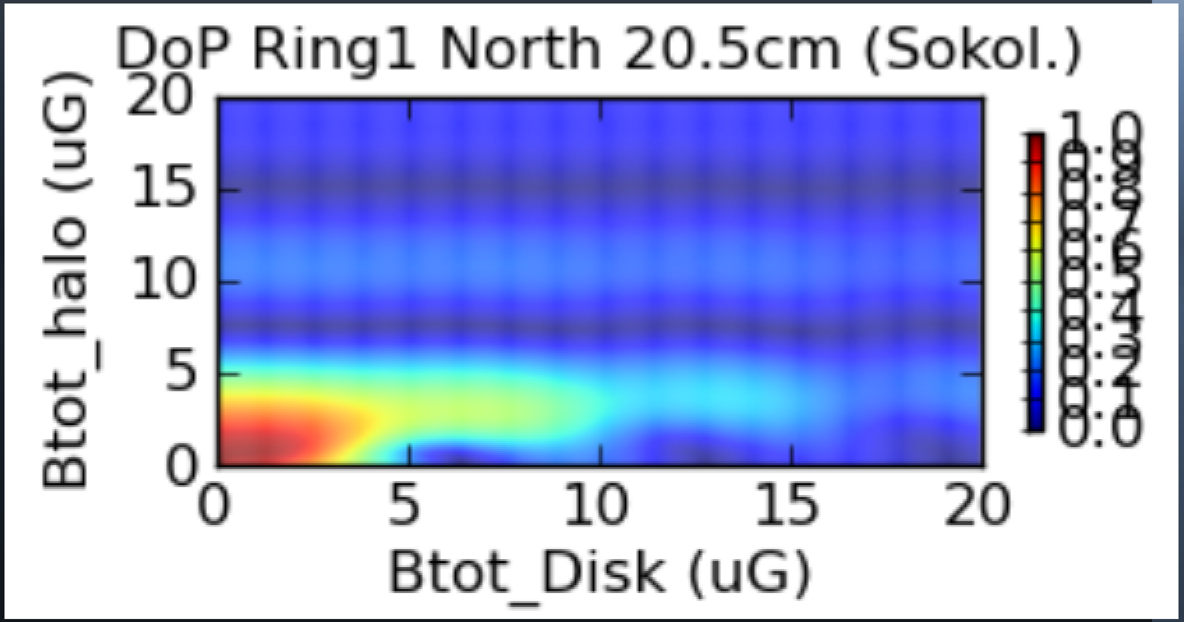
Our Model

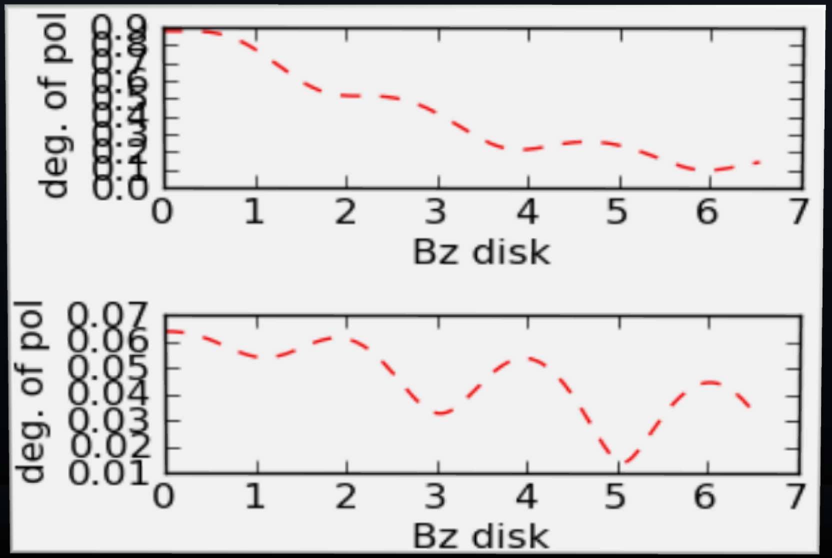

DoP Ring1 North 3.5cm (Sokol.)
DoP Ring1 South 3.5cm (Sokol.)
DoP Ring1 North 6.2cm (Sokol.)
DoP Ring1 South 6.2cm (Sokol.)
DoP Ring1 North 20.5cm (Sokol.)
DoP Ring1 South 20.5cm (Sokol.)
Btot_halo (uG)
Btot_Disk (uG)
0 100 200 300 400 500 600 700
0.0 1.0

Our Model

DoP as a Sinc Function

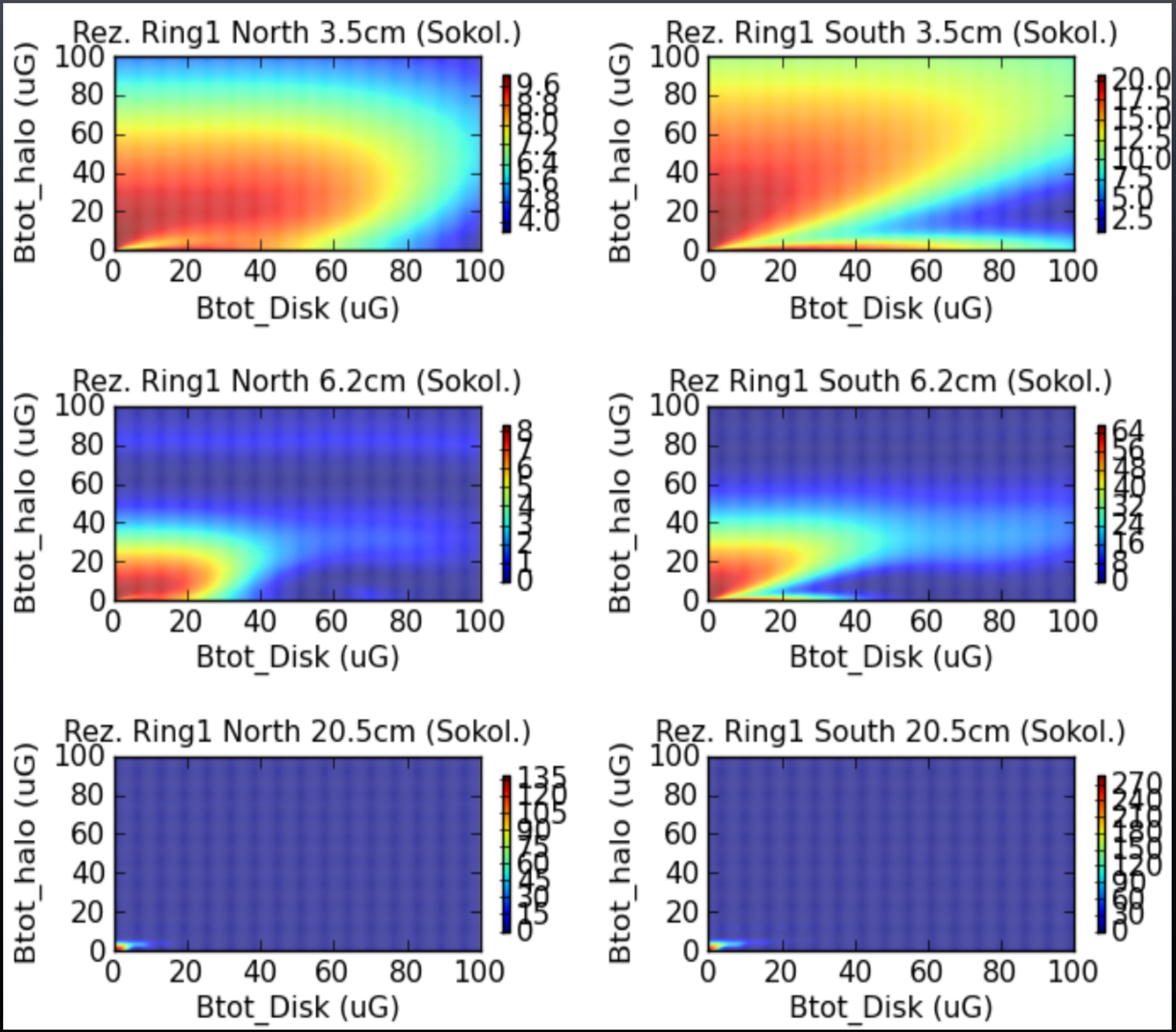




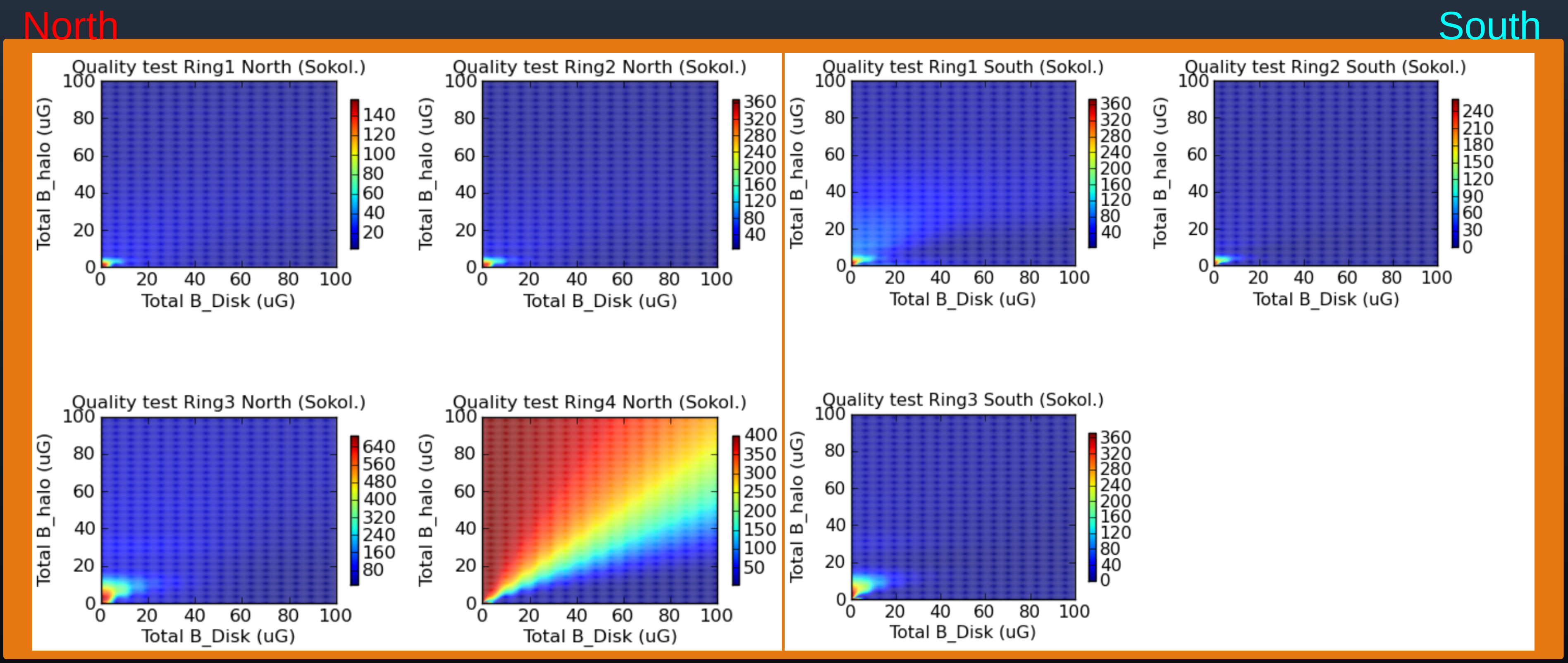


Our Model

Ring 1 Residuals

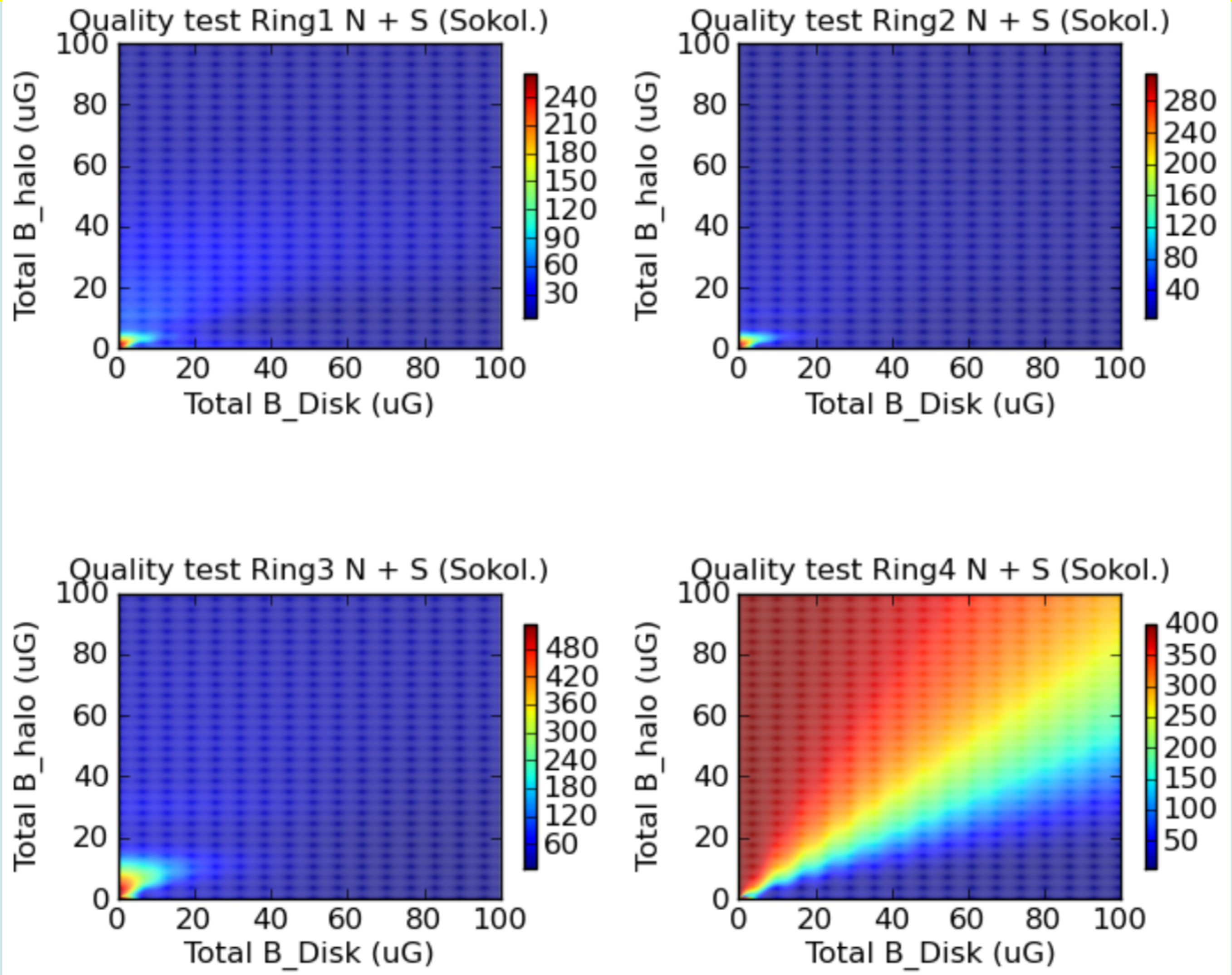


Our Model


North
South
Quality test Ring1 North (Sokol.)
Quality test Ring2 North (Sokol.)
Quality test Ring1 South (Sokol.)
Quality test Ring2 South (Sokol.)
Quality test Ring3 North (Sokol.)
Quality test Ring4 North (Sokol.)
Quality test Ring3 South (Sokol.)
Total B_halo (uG)
Total B_Disk (uG)

Our Model

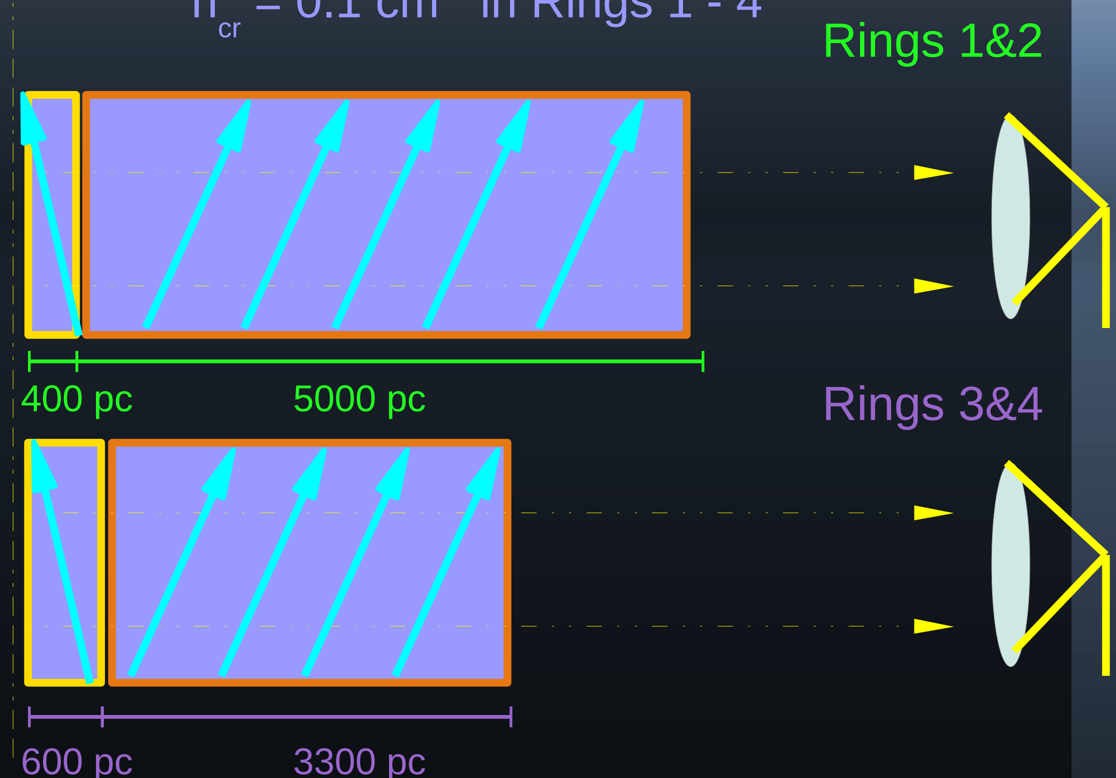
North + South



Our Model

2 Layer Medium: Disk + Halo

$n_{cr} = 0.1\ cm^{-3}$ in Rings 1 - 4

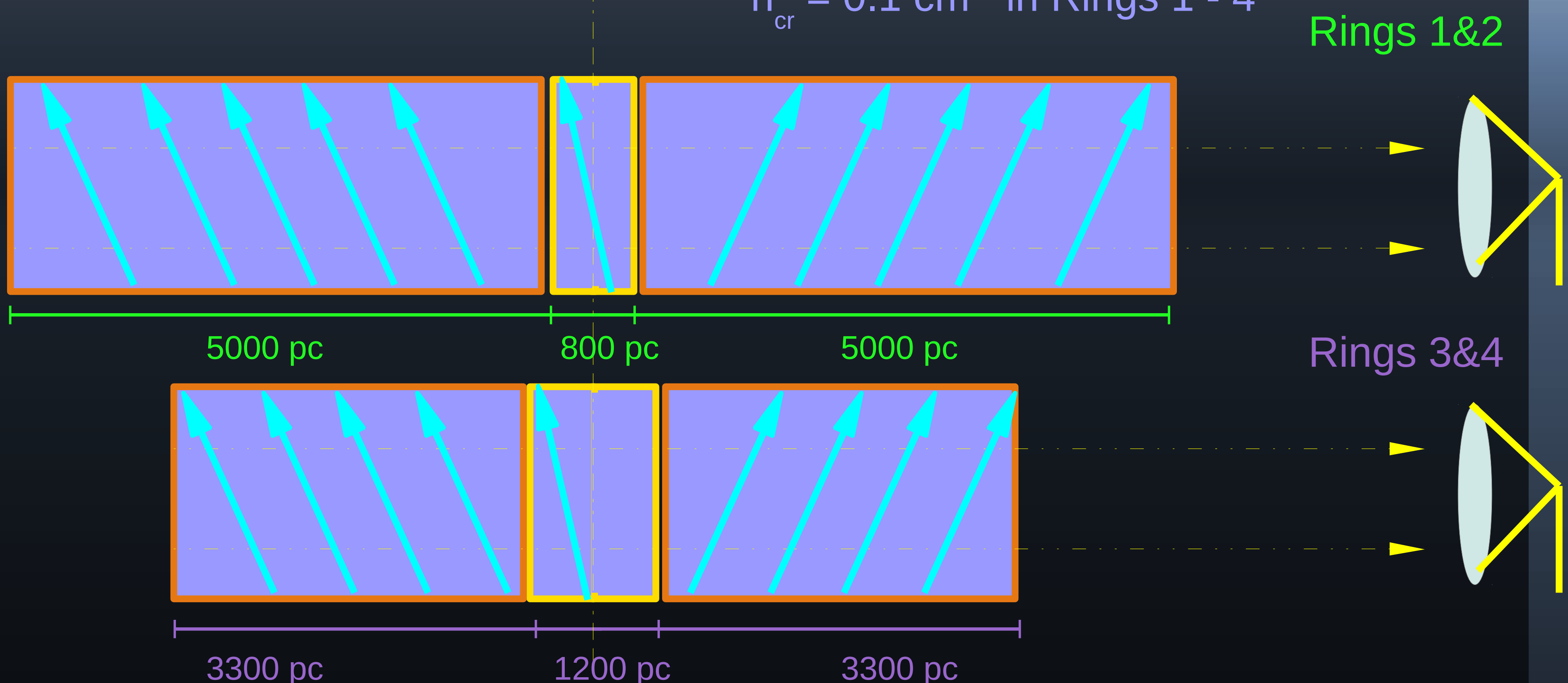


	Disc	Halo
Rings 1&2	$n_e = 0.11$ B_{tot_disc}	$n_e = 0.01$ B_{tot_halo}
Rings 3&4	$n_e = 0.06$ B_{tot_disc}	$n_e = 0.006$ B_{tot_halo}

Our Model

3 Layer Medium: Halo + Disk + Halo

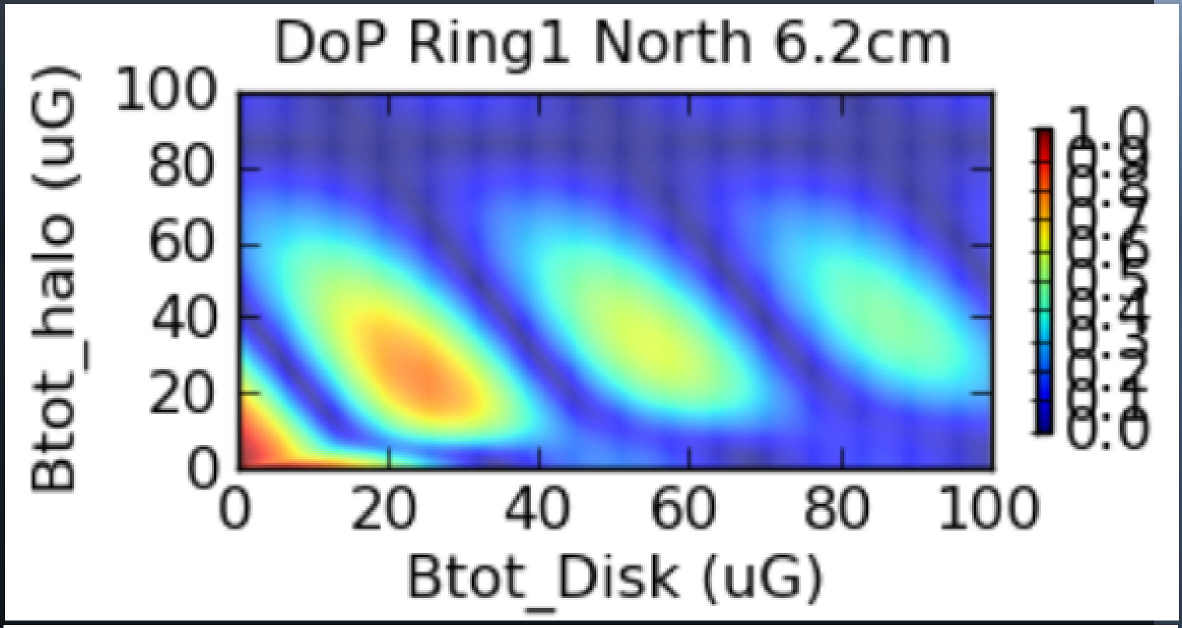
$n_{cr} = 0.1\ \mathrm{cm}^{-3}$ in Rings 1 - 4



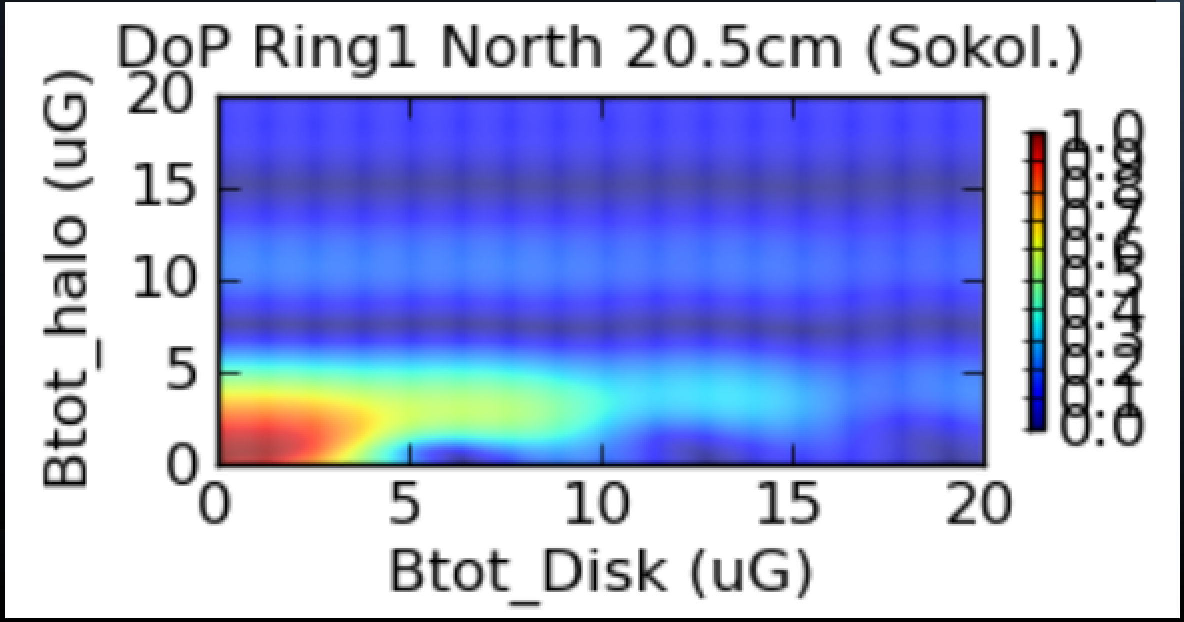
	Disc	Halo
Rings 1&2	$n_e = 0.11$ B_{tot_disc}	$n_e = 0.01$ B_{tot_halo}
Rings 3&4	$n_e = 0.06$ B_{tot_disc}	$n_e = 0.006$ B_{tot_halo}

Our Model

3 Layer Medium
Global DoP pattern



2 Layer Medium
Global DoP pattern



Conclusion

- Regular fields alone can not explain observed DoPs in M51 for a 2 layer model
- A 3 layer model possibly works
- Isotropic turbulence in a 2 layer model may prove a better descriptor

Further Steps

- Examine all sectors through full azimuth to address inter-arm regions in DoP
- Introduce divergence free, isotropic turbulence with a range of spectral indices and examine statical properties of corresponding Stokes I,Q,U maps
- Zoom in on optimal thermal and cosmic ray densities for optimized total disk and halo magnetic field configurations established from prior modeling
- Wrote codes to address above issues

“to $\vec{\mathbf{B}}$oldly go...”