The uniqueness problem of ZDI with Stokes *V* spectra

lessons from τ Sco inversions

Kochukhov & Wade (2016, A&A, 586, A30)

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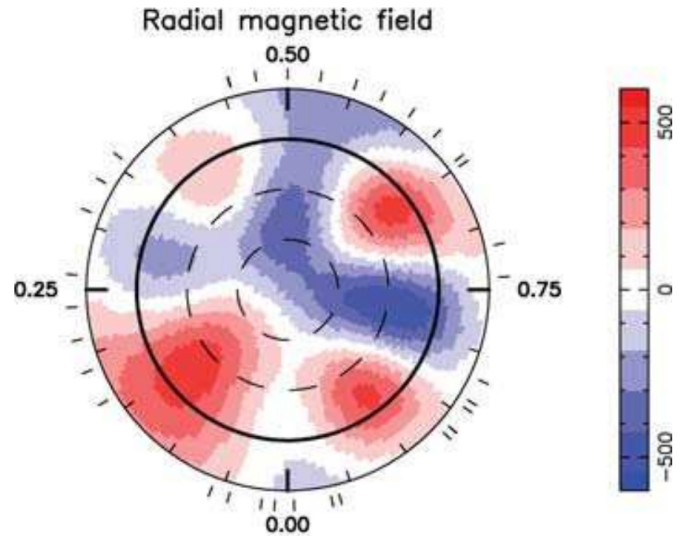
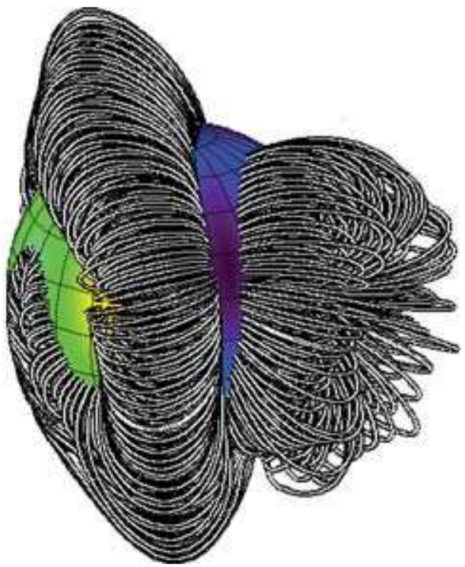
Motivation

- τ Sco: bright, slowly rotating, benchmark B0V star
- Weak and unusually complex magnetic field (Donati et al. 2006)
- Provides important observational constraints for fossil field theory
- Variability of the magnetospheric X-ray emission is not compatible with extrapolation from the surface ZDI maps (Ignace et al. 2010)





Goals

◆ Perform an independent ZDI analysis of τ Sco based on archival Stokes V data

◆ Assess reliability of ZDI inversions and role of Stokes QU observations

◆ Explore sensitivity of inversions to different forms of magnetic field parameterisation

◆ Address the question of self-consistency between ZDI and potential field extrapolation

Methodology

- InversLSD ZDI code (Kochukhov et al. 2014)
- 49 ESPaDOnS Stokes V observations (Donati & Landstreet 2009 + MiMeS), LSD
- Local Stokes profiles approximated with a Milne-Eddington analytical solution
- Field parameterizations
  - Direct
  - General harmonic (α≠β,γ≠0)
  - Restricted harmonic (α≠β,γ=0 and α=β,γ≠0)

poloidal toroidal

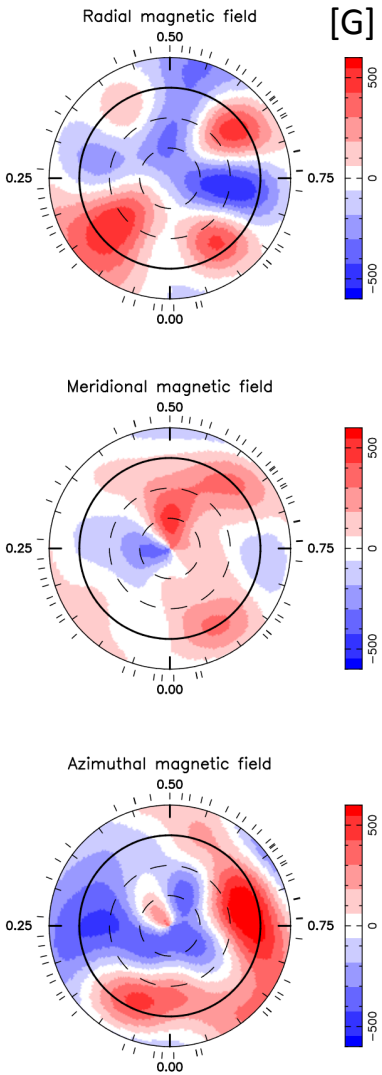
$$B_{\rm r}(\theta,\phi) = -\sum_{\ell=1}^{\ell_{\rm max}}\sum_{m=-\ell}^{\ell} \alpha_{\ell,m} Y_{\ell,m}(\theta,\phi),$$

$$B_{\theta}(\theta,\phi) = -\sum_{\ell=1}^{\ell_{\rm max}}\sum_{m=-\ell}^{\ell} [\beta_{\ell,m} Z_{\ell,m}(\theta,\phi) + \gamma_{\ell,m} X_{\ell,m}(\theta,\phi)],$$

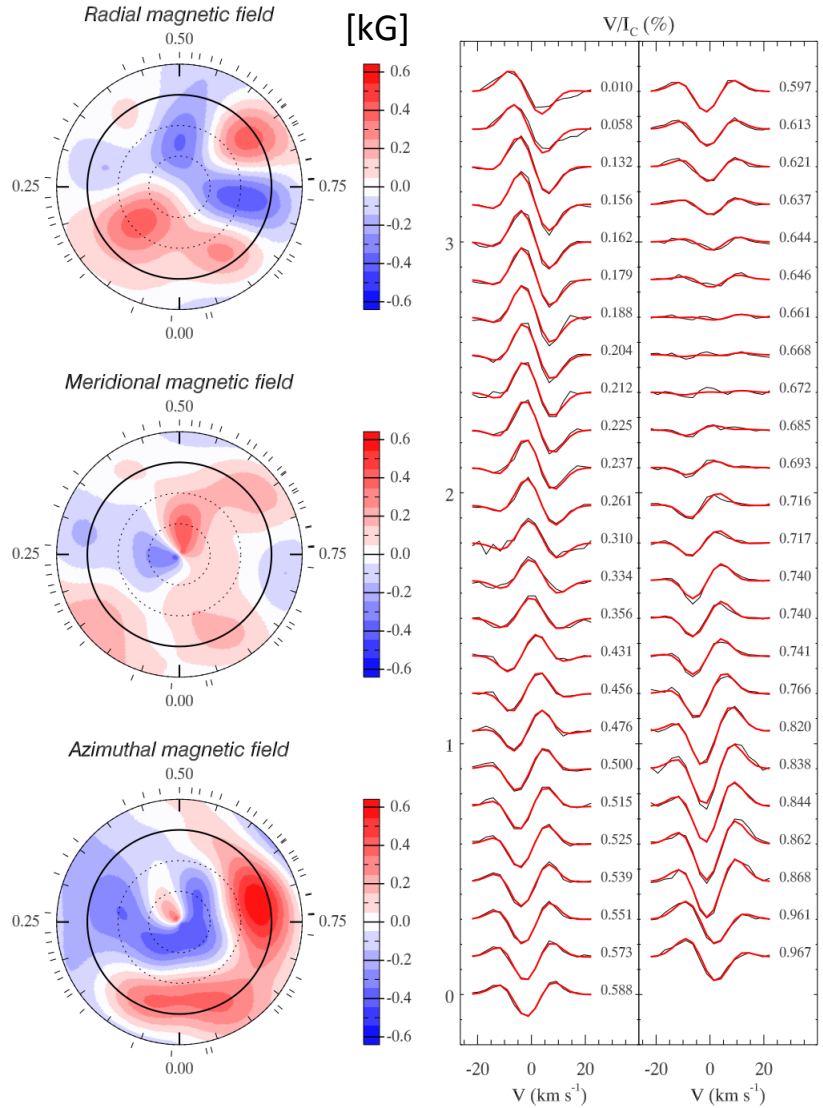
$$B_{\phi}(\theta,\phi) = -\sum_{\ell=1}^{\ell_{\rm max}}\sum_{m=-\ell}^{\ell} [\beta_{\ell,m} X_{\ell,m}(\theta,\phi) - \gamma_{\ell,m} Z_{\ell,m}(\theta,\phi)],$$

Comparison of ZDI codes

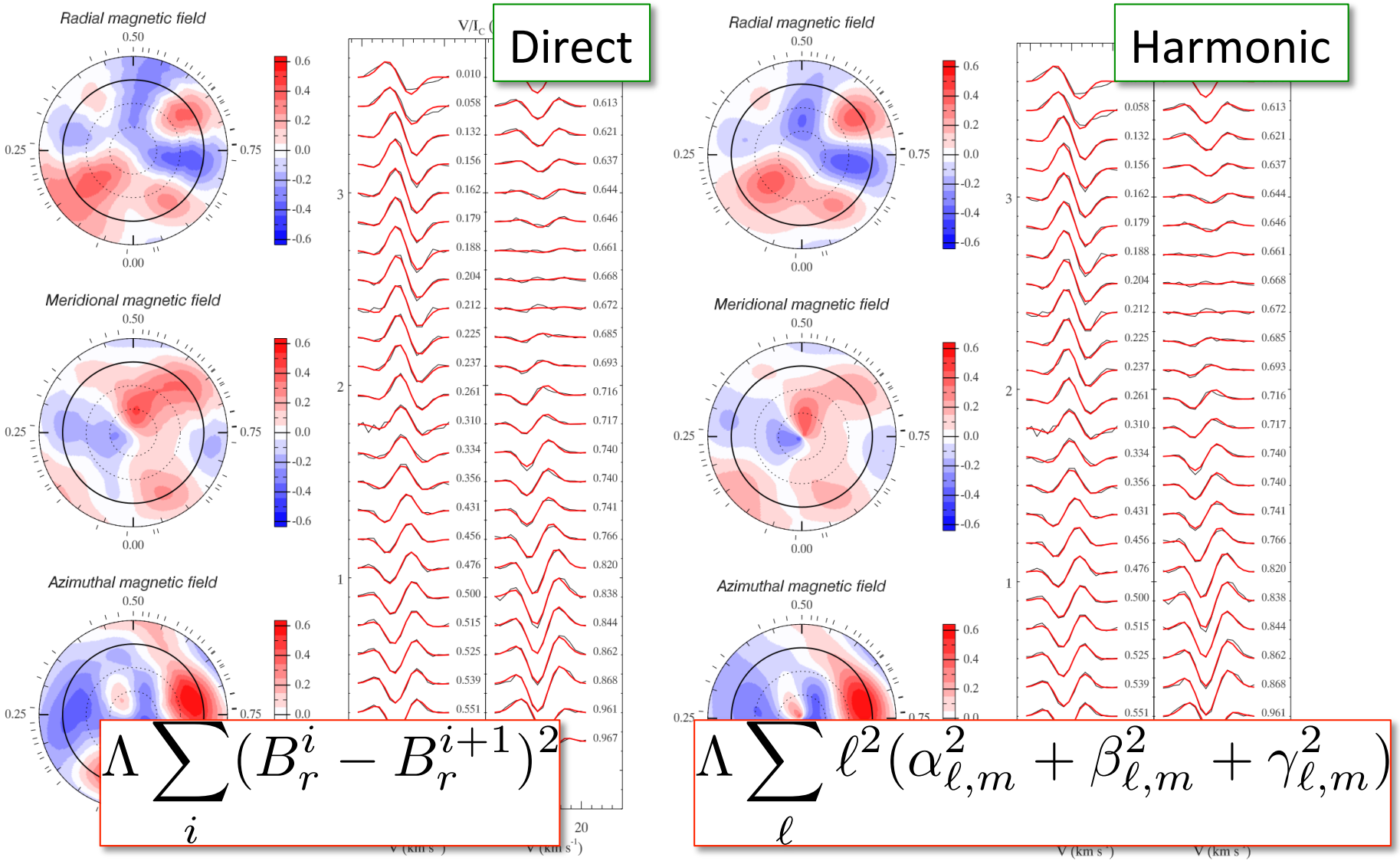
Donati & Landstreet (2009)



Kochukhov & Wade (2016)



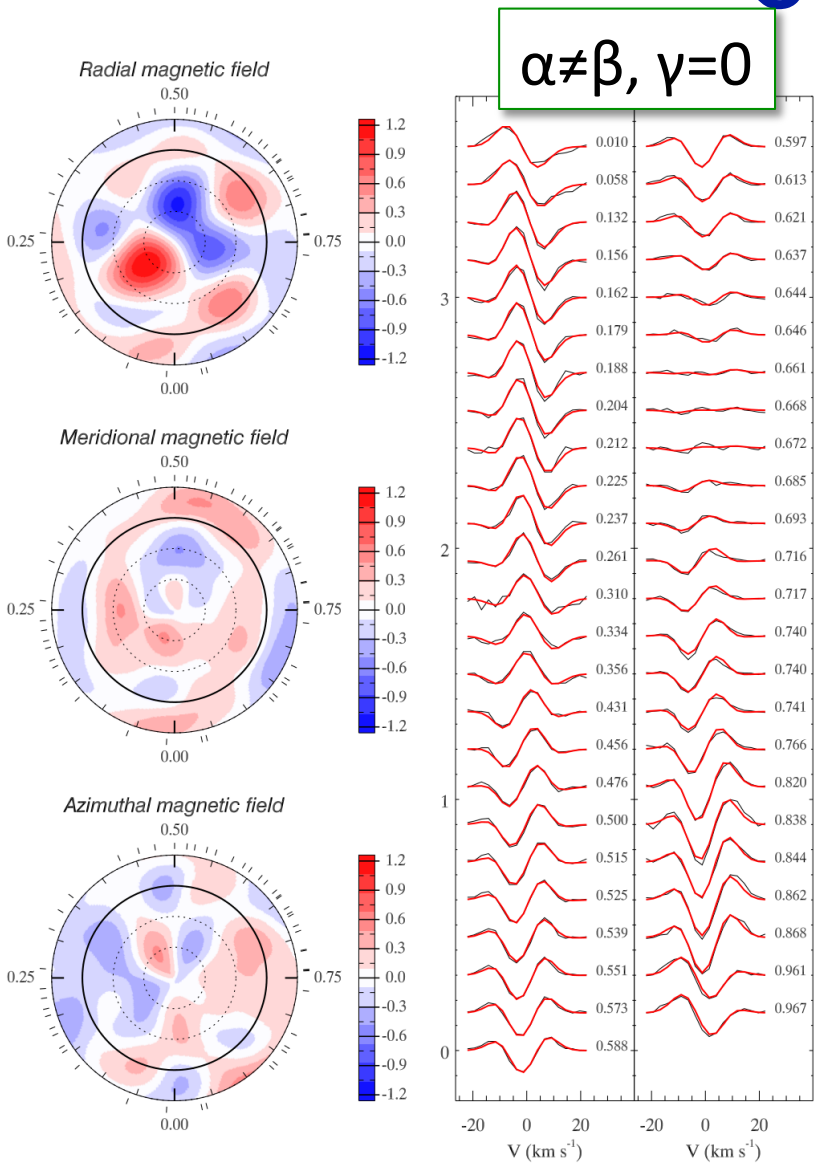
Harmonic vs. direct ZDI

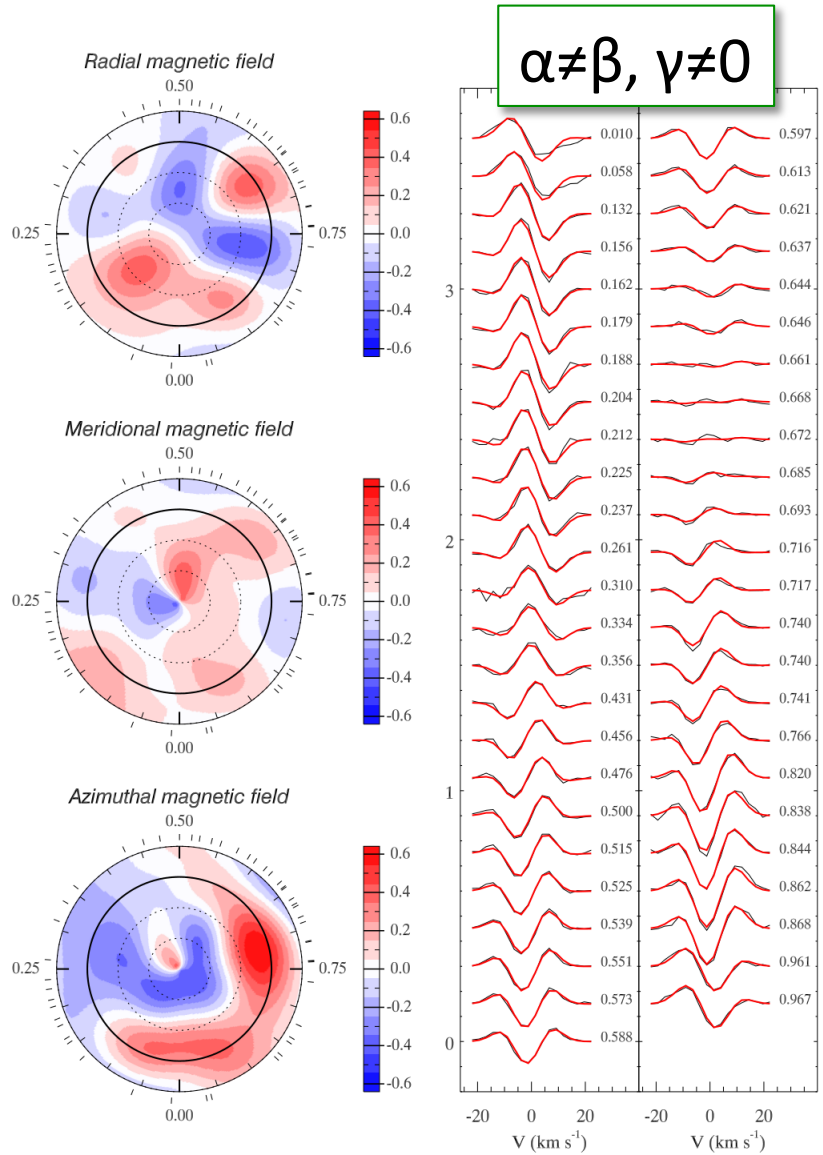


$$\Lambda \sum_i (B_r^i - B_r^{i+1})^2$$

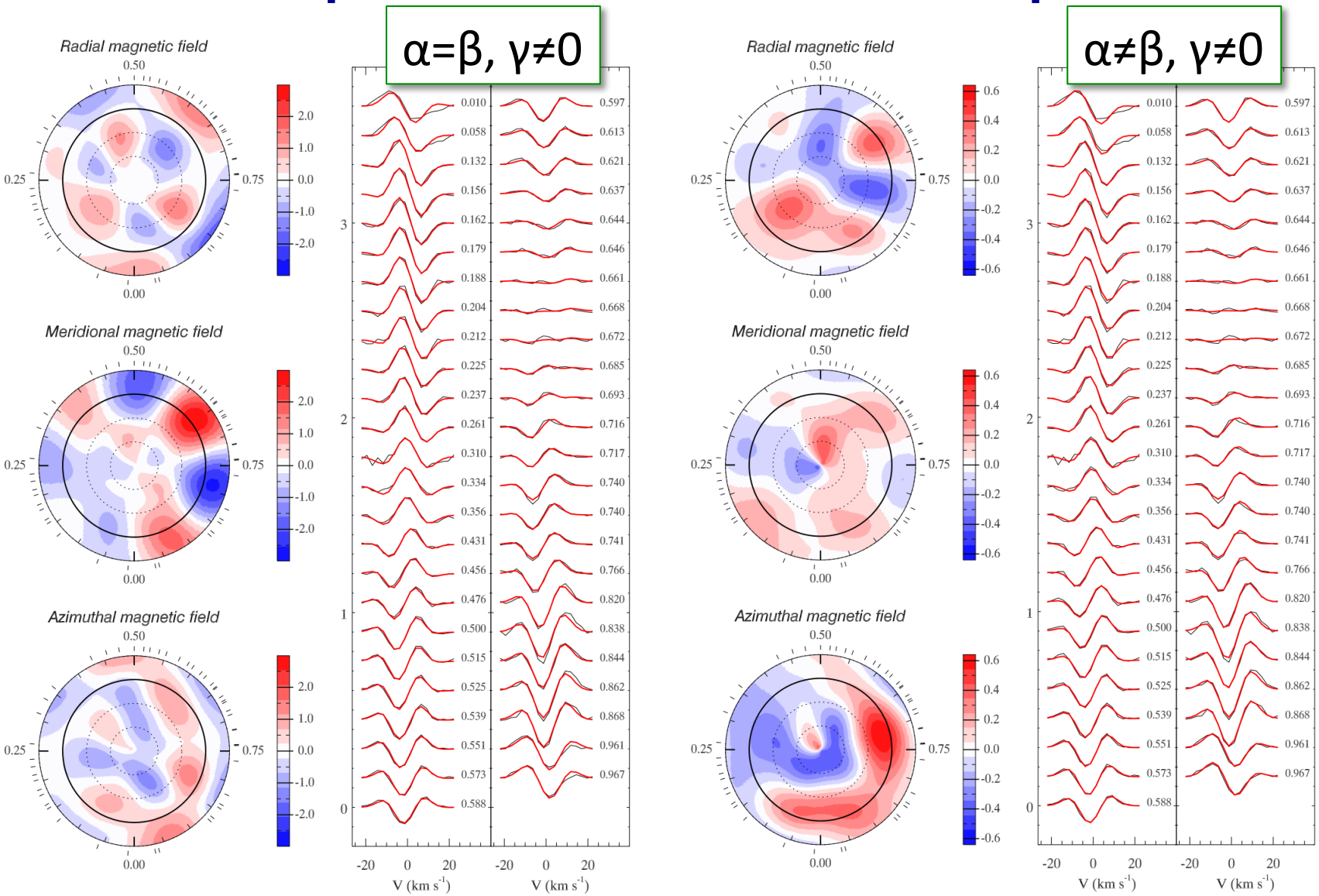
$$\Lambda \sum_\ell \ell^2 (\alpha_{\ell,m}^2 + \beta_{\ell,m}^2 + \gamma_{\ell,m}^2)$$

Is there *really* a toroidal field?





Linked poloidal field components



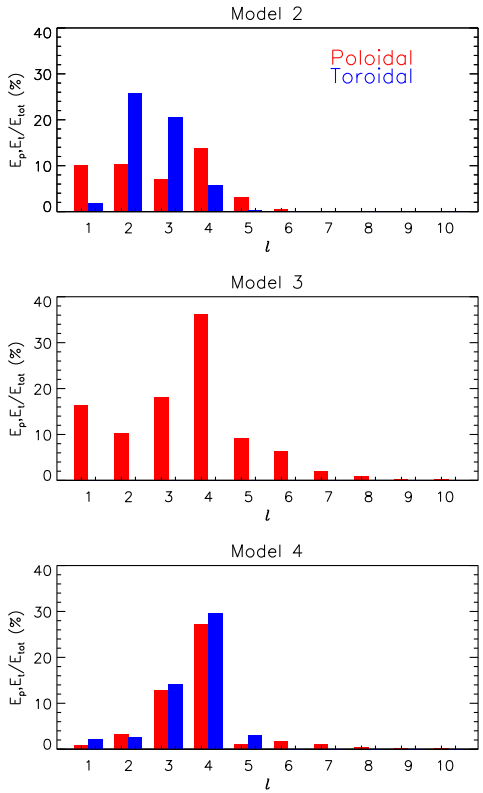
Summary for different parameterisations

Parameterisation of magnetic maps	σ_V $\times 10^{-5}$	RMS field (G) $\langle B_r \rangle$	$\langle B_\theta \rangle$	$\langle B_\varphi \rangle$	Magnetic energy Total	pol:tor	$\ell < m/2$:$\ell \geq m/2$
direct	7.9	168	142	211	1.18	–	–
harmonic, $\beta_{\ell,m} \neq \alpha_{\ell,m}, \gamma_{\ell,m} \neq 0$	8.1	160	118	215	1.09	45.6:54.4	25.6:74.4
harmonic, $\beta_{\ell,m} \neq \alpha_{\ell,m}, \gamma_{\ell,m} = 0$	8.2	356	206	223	2.76	100.0:0.0	34.3:65.7
harmonic, $\beta_{\ell,m} = \alpha_{\ell,m}, \gamma_{\ell,m} \neq 0$	8.4	663	900	598	20.34	48.6:51.4	6.3:93.7

- α≠β may be preferred on mathematical grounds (simplicity, regularisation)
- α=β is preferred on physical grounds (matching to exterior field)

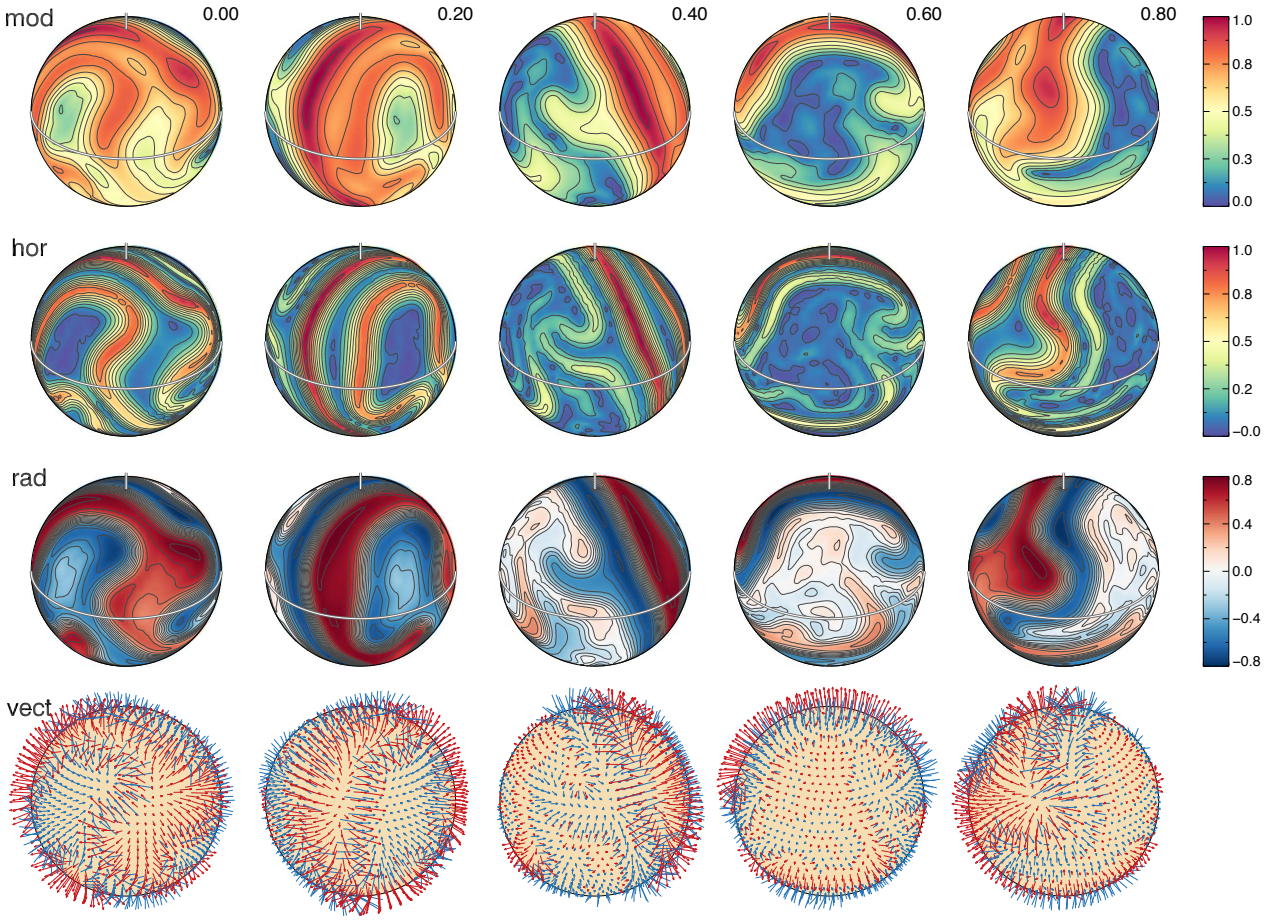
$$\beta_{\ell,m} = 0.996\alpha_{\ell,m} \text{ for } R_s/R_\star = 2 \text{ and } \ell = 4$$

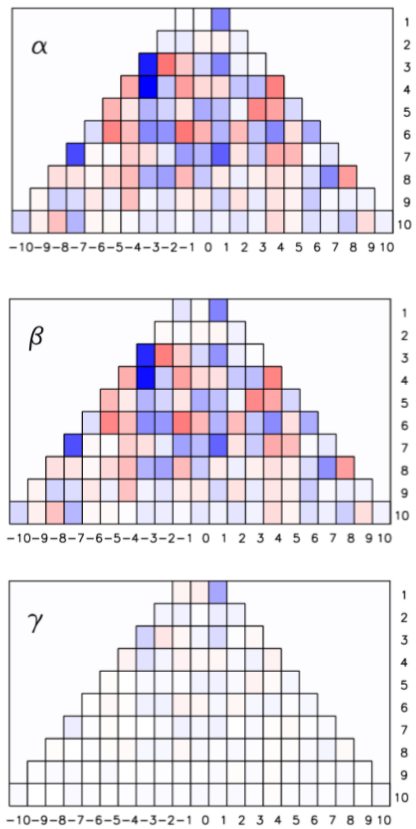
$$\frac{(\ell+1)(R_s/R_\star)^{2\ell+1} - \ell - 1}{(\ell+1)(R_s/R_\star)^{2\ell+1} + \ell}$$



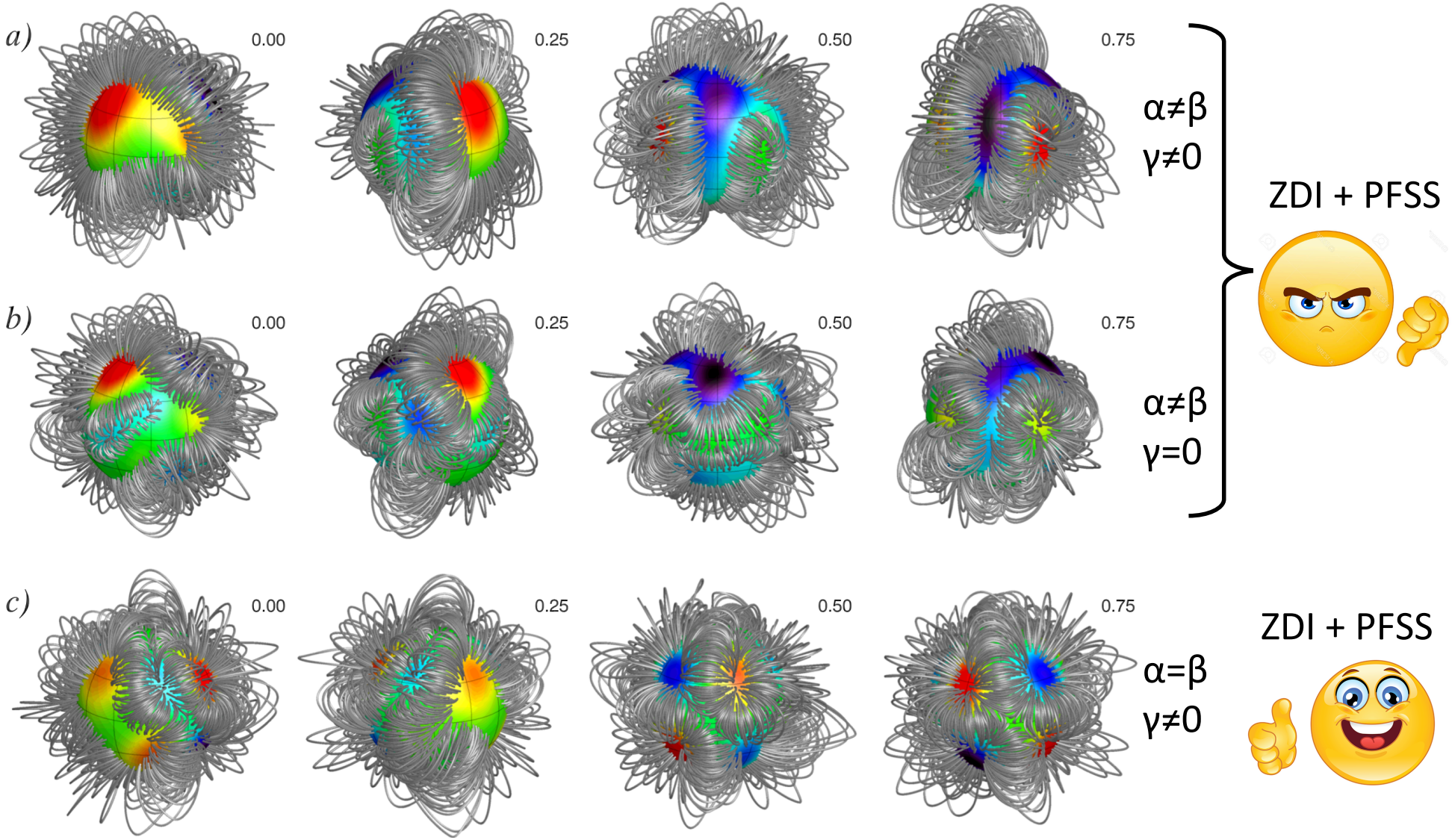
Theoretical MHD models

Fossil field relaxation simulations (Braithwaite et al.)



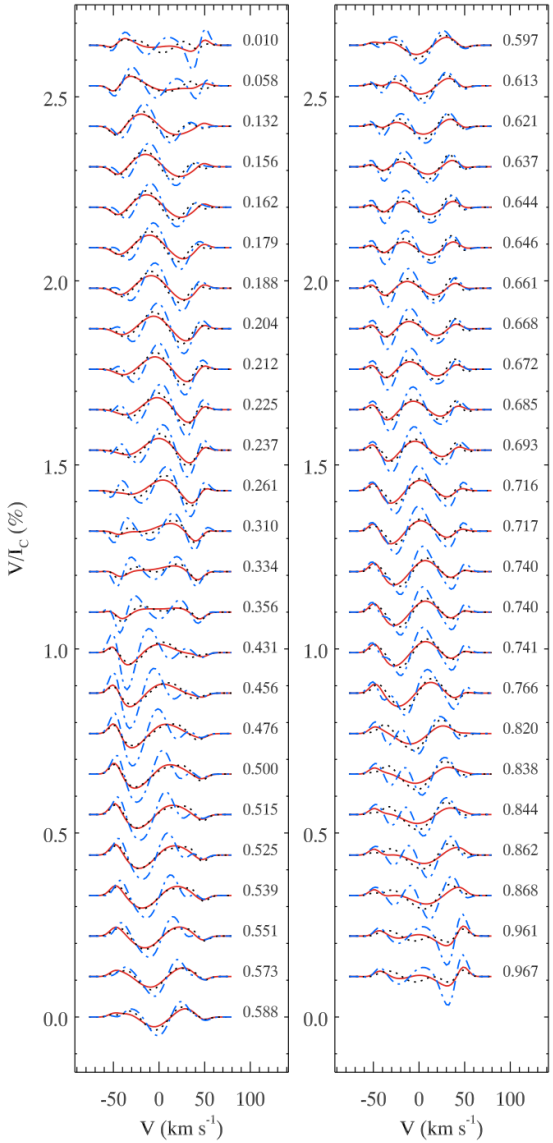


Potential field extrapolation



Breaking degeneracies

- Faster rotation helps a bit

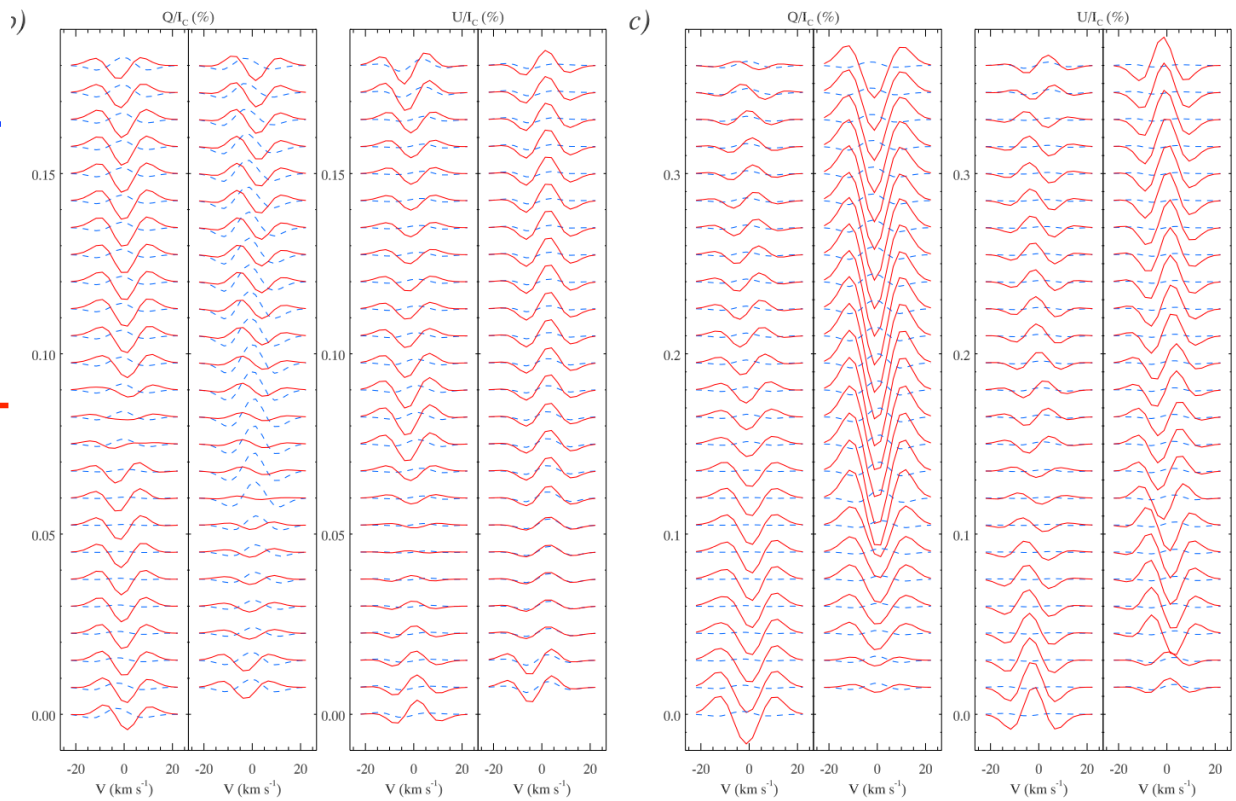


Breaking degeneracies

- Faster rotation helps a bit
- Stokes *QU* profiles is an ultimate solution

α≠β
γ≠0

α≠β
γ=0



α≠β
γ≠0

α=β
γ≠0

Conclusions

- Good agreement of independent ZDI inversions if the same field parameterisation is adopted

- Different harmonic field parameterisations yield significantly different ZDI solutions, which fit the same Stokes V data

- "Unlinking" of radial and horizontal poloidal field components is an important (but physically unjustified) degree of freedom

- PFSS extrapolation can be done consistently with ZDI, resulting in a different surface field topology

- Non-uniqueness can be avoided by incorporating linear polarisation information in ZDI inversions. ESPaDOnS Stokes QU of τ Sco will take place in 2016B

Cool Stars 19
Uppsala, June 6-10

Plenary session:

- Magnetic activity and its impact on planets

Splinter sessions:

- Surface magnetism
- Solar & stellar activity and variability