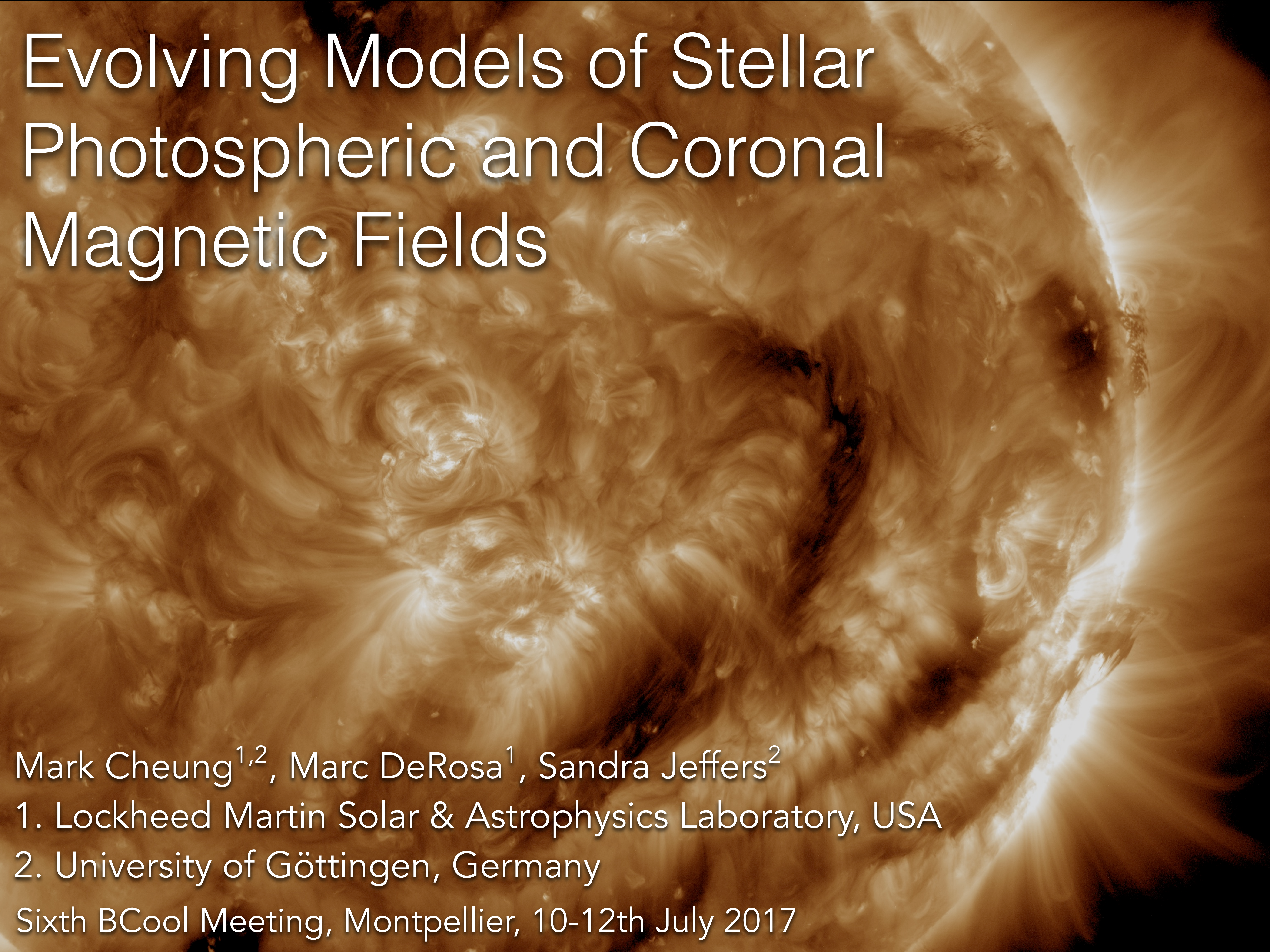

Evolving Models of Stellar Photospheric and Coronal Magnetic Fields

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Sixth BCool Meeting, Montpellier, 10-12th July 2017

Context

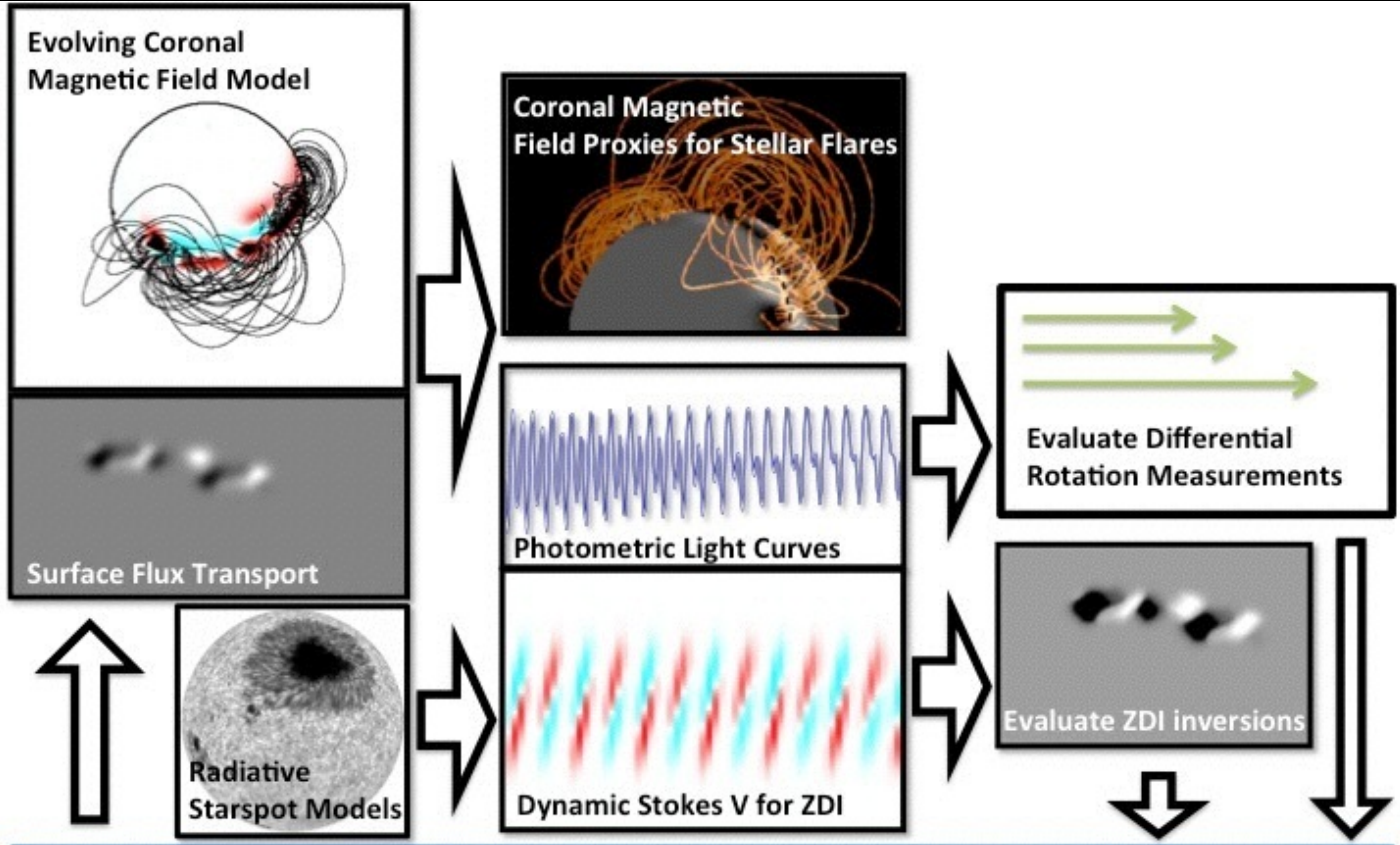
This 4-year project (starting Jan 2016) is part of NASA's Living With A Star Focus Science Team (FST) on Solar-Stellar Connections.

- Ben Brown (U. Colorado), *Stellar Insights into Solar Magnetism: Exploring Fundamental Dynamo Physics Across the Lower Main Sequence*
- Derek Buzasi (Florida Gulf Coast U), *Exploring the Solar-Stellar Connection Using K2*
- Ofer Cohen (SAO), *The Heliosphere in Time: Scaling Heliospheric Parameters with Stellar Evolution of Solar Analogs and Studying Heliospheric Consequences of Young Active Suns*
- Marc DeRosa (LMSAL), *Evolving Models of Stellar Photospheric and Coronal Magnetic Fields <- +Cheung, +Jeffers*
- Jay Johnson (PPPL), *Identifying Causal Relationships in Stellar Activity Cycle Dynamics*
- Steve Saar (SAO), *Observational Constraints and Tests for Dynamos in Solar-like Stars*

Science Questions

- What constraints can measurements of magnetic spots, differential rotation, and flares on other stars teach us about the solar dynamo?
- What are the limits of observational inference of magnetic fields and differential rotation on other stars?
- What are the coronal magnetic configurations associated with superflare events (as observed, e.g., in white light photometric data in Kepler)?
- What is the importance of well-known physical processes on the Sun (including flux emergence, differential rotation, turbulent diffusion) for magnetic activity on other stars?

Outline of project



Collaborate with other members of the Focus Science Team:

- 3D convective dynamo simulations can provide parameters for Surface Flux Transport model
- Our tasks evaluating Zeeman Doppler Imaging (ZDI) and Differential Rotation measurements can inform the modeler about the robustness of these measurement techniques and what constraints they put on dynamo theory.

Surface Flux Transport

From Yeates & Mackay, 2012 (Living Reviews in Solar Physics)

2.2.1 Standard model

The standard equation of magnetic flux transport arises from the radial component of the magnetic induction equation under the assumptions that $v_r = 0$ and $\partial/\partial r = 0$.[1] These assumptions constrain the radial field component to evolve on a spherical shell of fixed radius, where the time evolution of the radial field component is decoupled from the horizontal field components. Under these assumptions, the evolution of the radial magnetic field, B_r, at the solar surface ($R_\odot = 1$) is governed by

$$\frac{\partial B_r}{\partial t} = \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\left(-u(\theta)B_r + D\frac{\partial B_r}{\partial\theta}\right)\right) - \Omega(\theta)\frac{\partial B_r}{\partial\phi} + \frac{D}{\sin^2\theta}\frac{\partial^2 B_r}{\partial\phi^2} + S(\theta,\phi,t), \qquad (1)$$

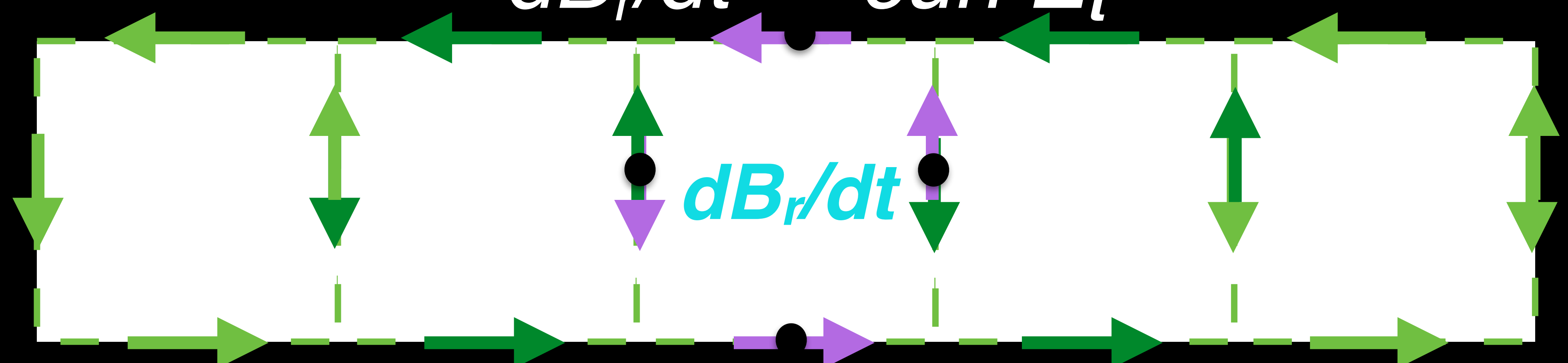
[1] Alternatively, the magnetic flux transport equation may be obtained through spatially averaging the radial component of the induction equation (see DeVore *et al.*, 1984 and McCloughan and Durrant, 2002).

In the standard flux transport model, the evolutionary equation is in terms of B_r, its gradients, transverse flows **u**, a turbulent diffusivity and a source/sink term S. S captures flux emergence and submergence.

Constrained Surface Flux Transport

- MF and MHD codes need $\boldsymbol{E_t}$ at the bottom boundary.
- To have a well-defined interface between the SFT code and overlying 3D magnetic model, it is best to be physically consistent.
- Think of a FT model that operates with **E**-electric fields. Instead of Eq. (1) on the previous slide, just start with Faraday's Equation:

$$dB_r/dt = -curl\ \boldsymbol{E_t}$$

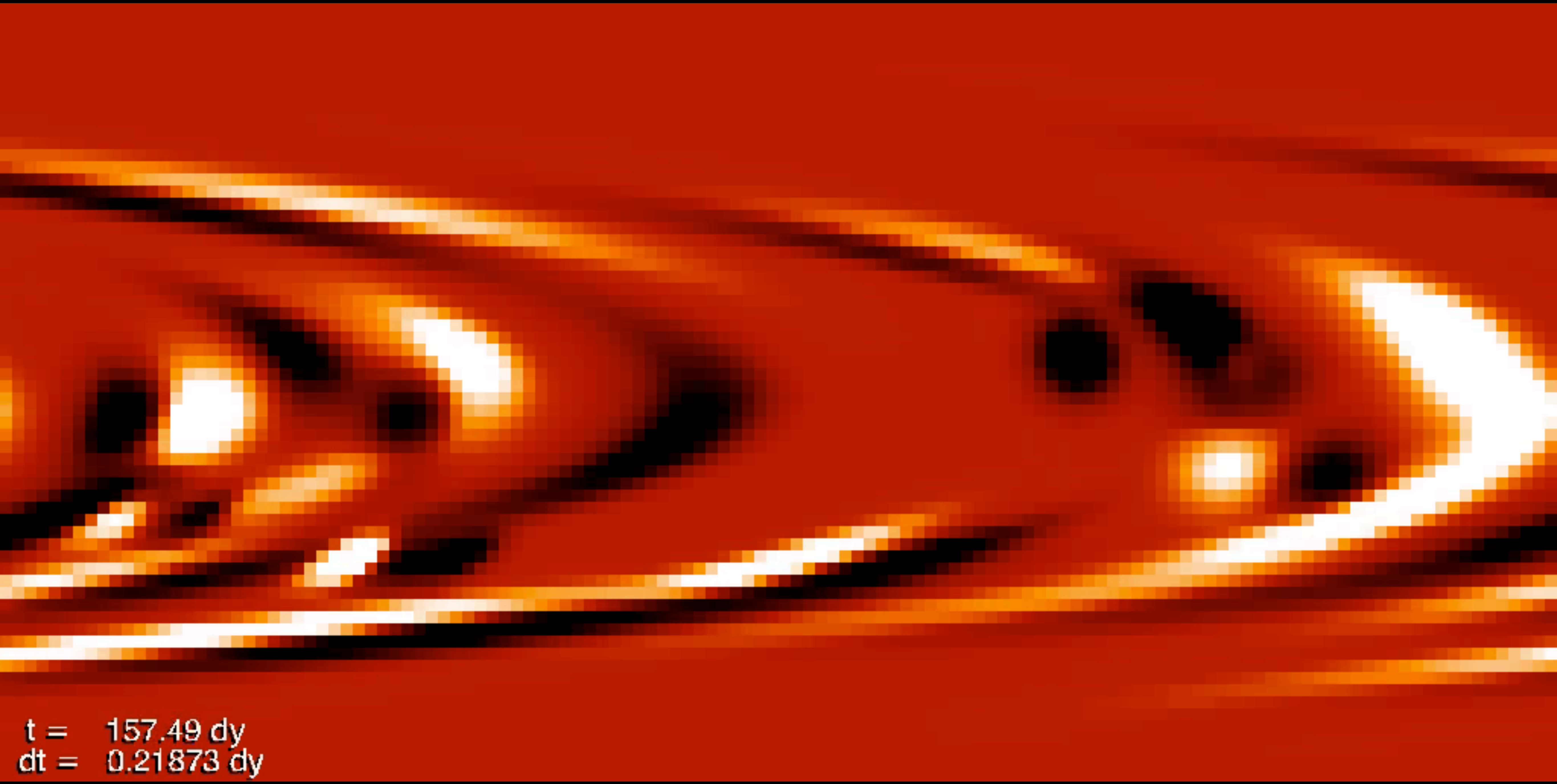


Calculate ***dB_r/dt*pixel area*** of each pixel as

- circulation of E_t about the pixel.

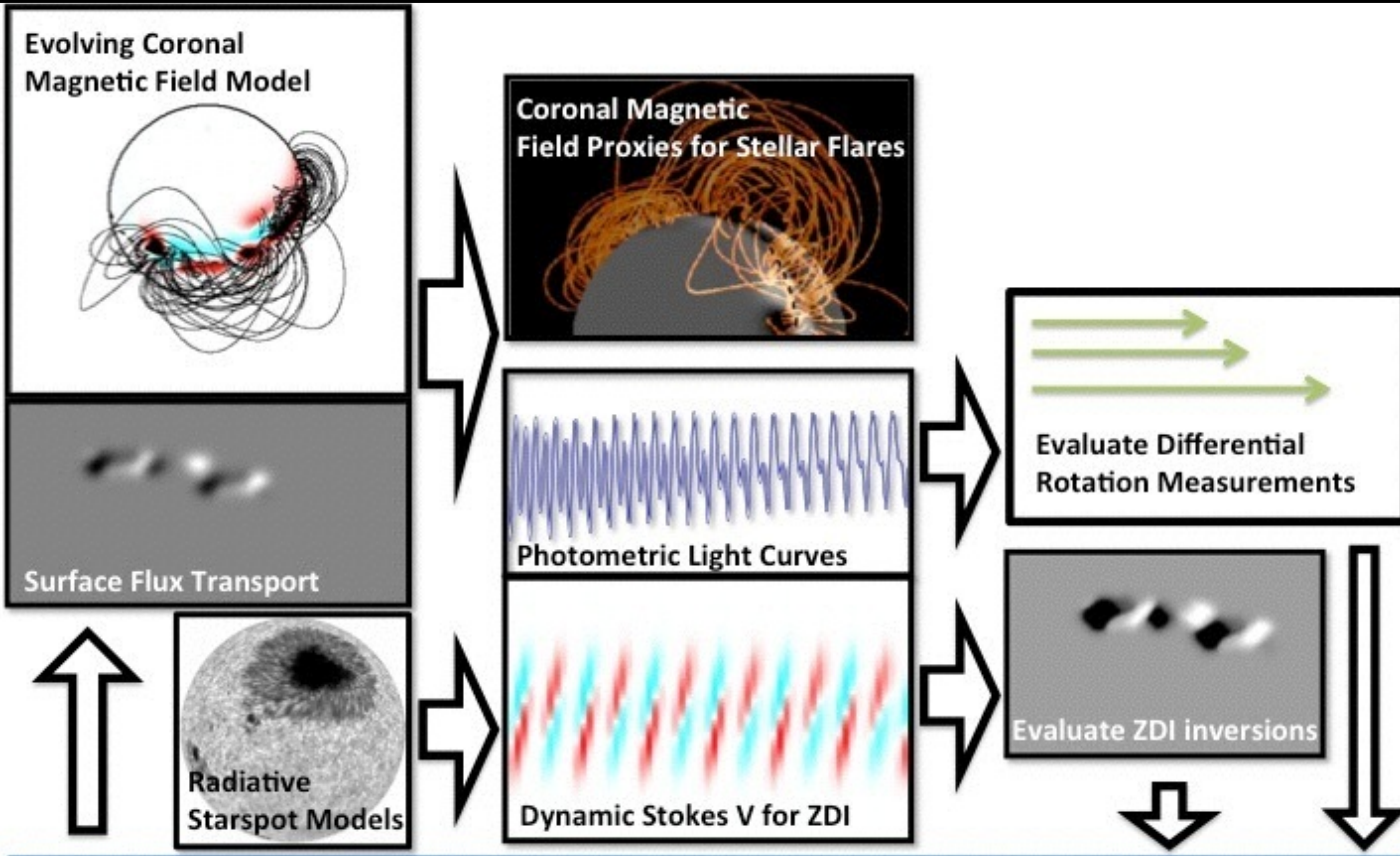
Benefit: No need to do inverse problem to get E-fields from output of SFT model.

Example of Constrained Surface Flux Transport



AR emergence by setting v_r contribution to transverse E.

Supergranule diffusion and meridional circulation switched off for this run.



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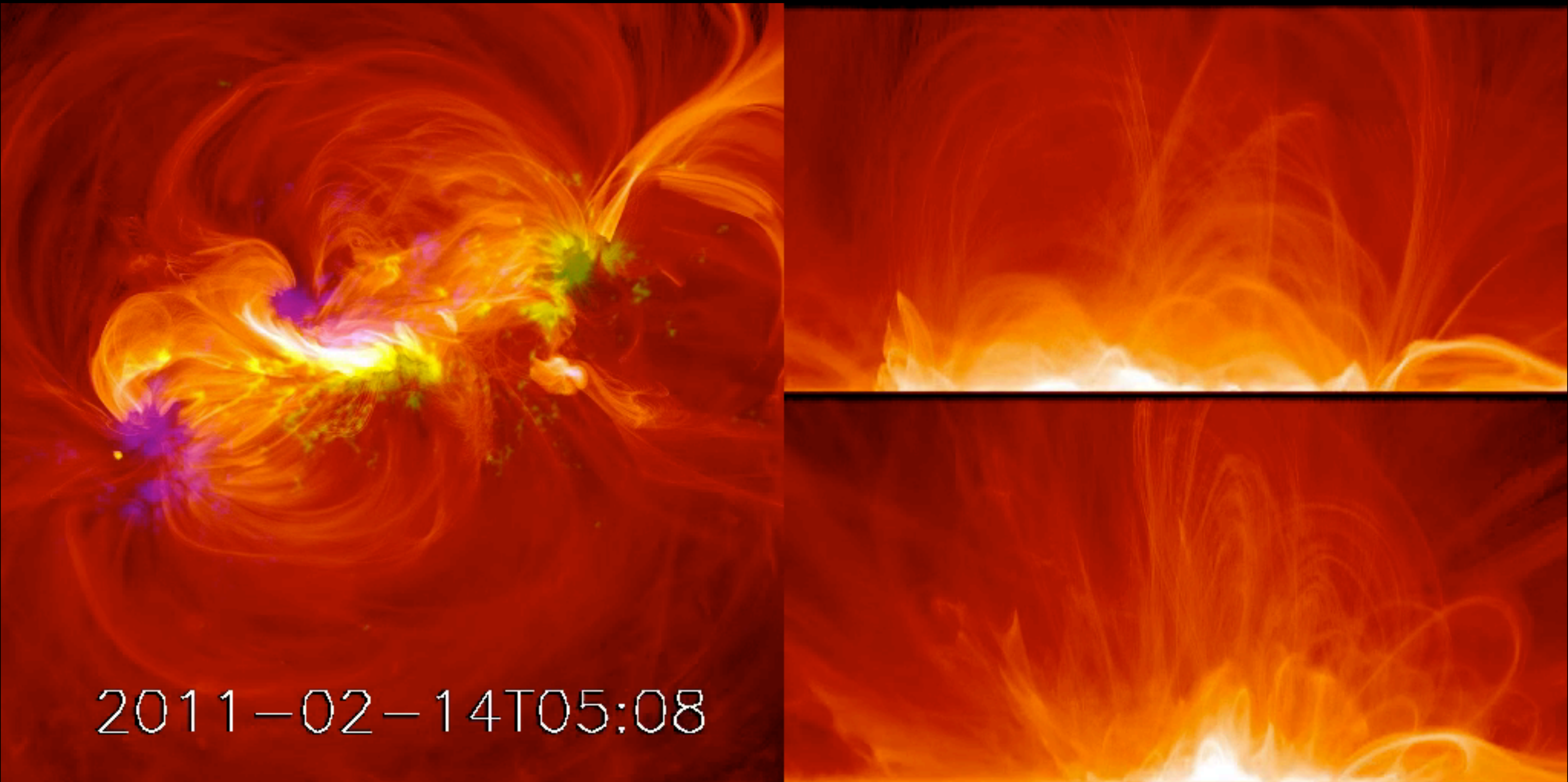
Evolving Coronal Magnetic Field Model

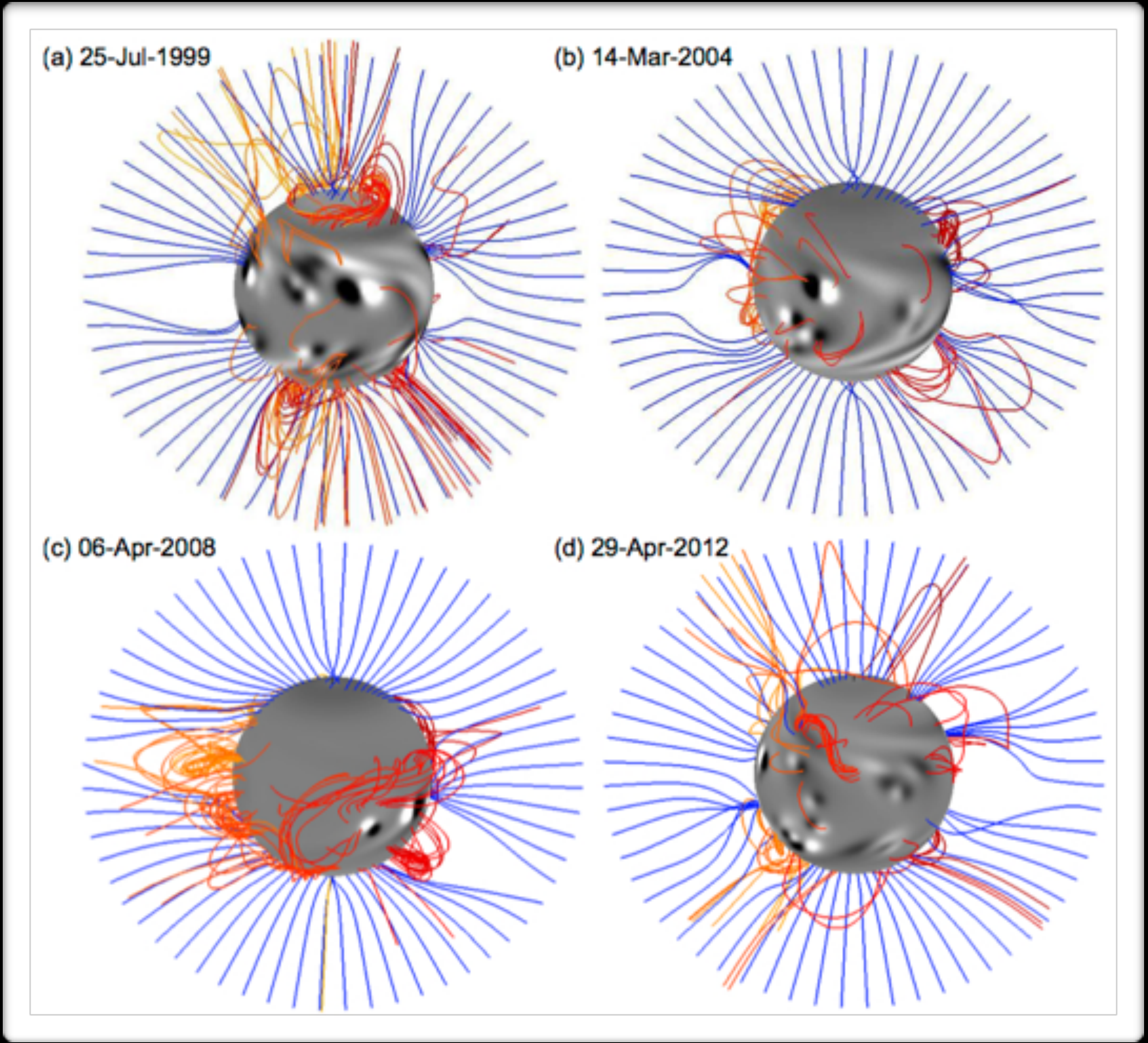
- Magnetofriction: Balance of Lorentz force and fictitious frictional force (Yang, Sturrock & Antiochos, 1986; Craig & Sneyd 1986)
  - Plasma velocity proportional to Lorentz force: $\mathbf{v} = \nu^{-1}\, \mathbf{j} \times \mathbf{B}$ where ν is the frictional coefficient
  - Evolve magnetic field according to Induction Equation
- Total magnetic energy in volume monotonically decreasing (provided net Poynting flux through boundaries is zero).



Magnetic loops have endowed with proxy emissivity
based on the fieldline-averaged current density

Cartesian data-driven magnetofriction model of NOAA AR 11158 using SDO/HMI magnetograms (Fisher et al., Space Weather, 2015) using the code described in Cheung & DeRosa (2012) and Cheung et al. (2015).

Time-dependent Coronal Models



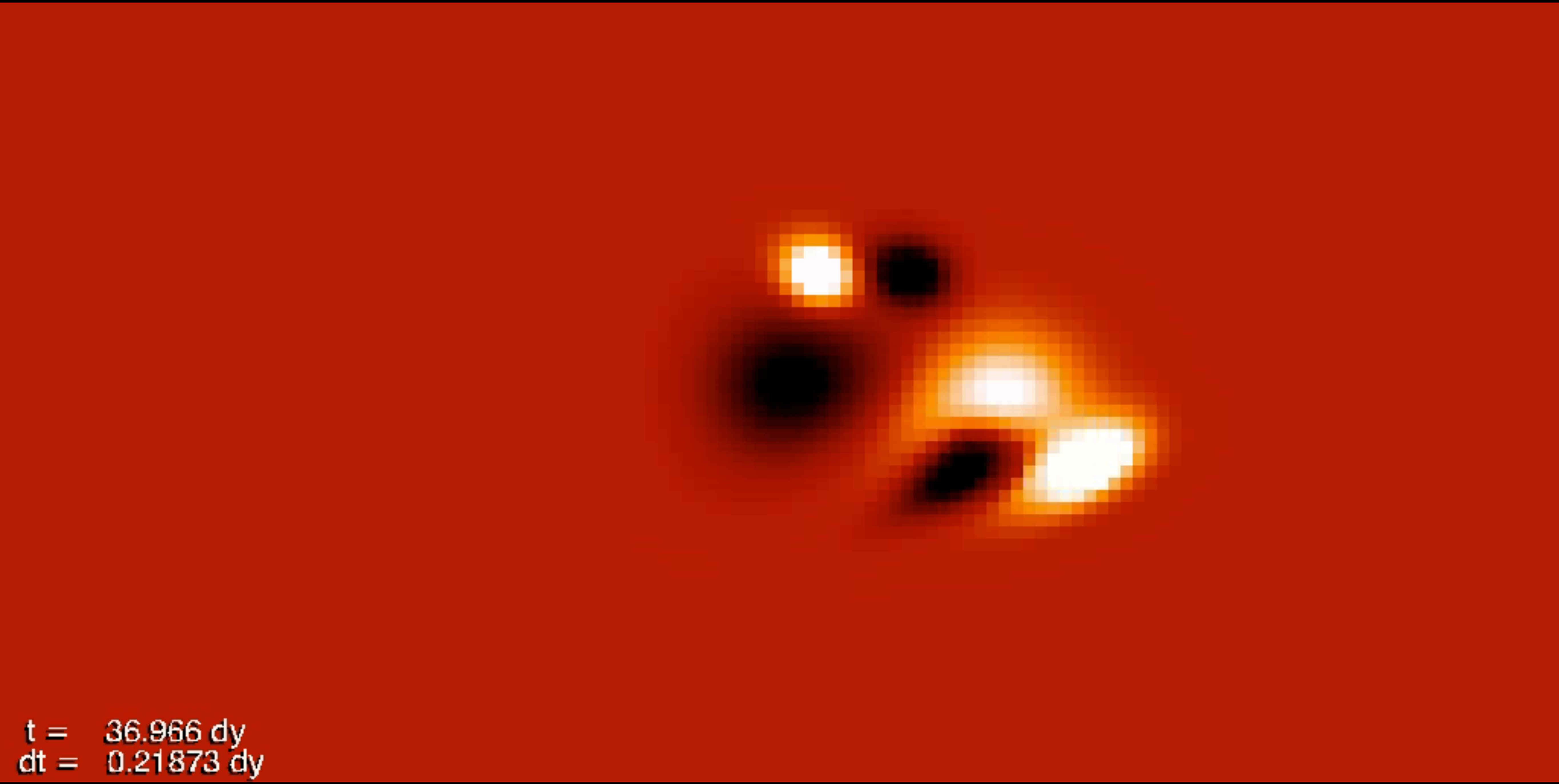
Data-driven models have time-dependent boundary conditions. The coronal B-field evolves in response to underlying driving at the photosphere from the following effects:

- Transverse (horizontal flows)
- Magnetic flux emergence and submergence
- (Turbulent) diffusion

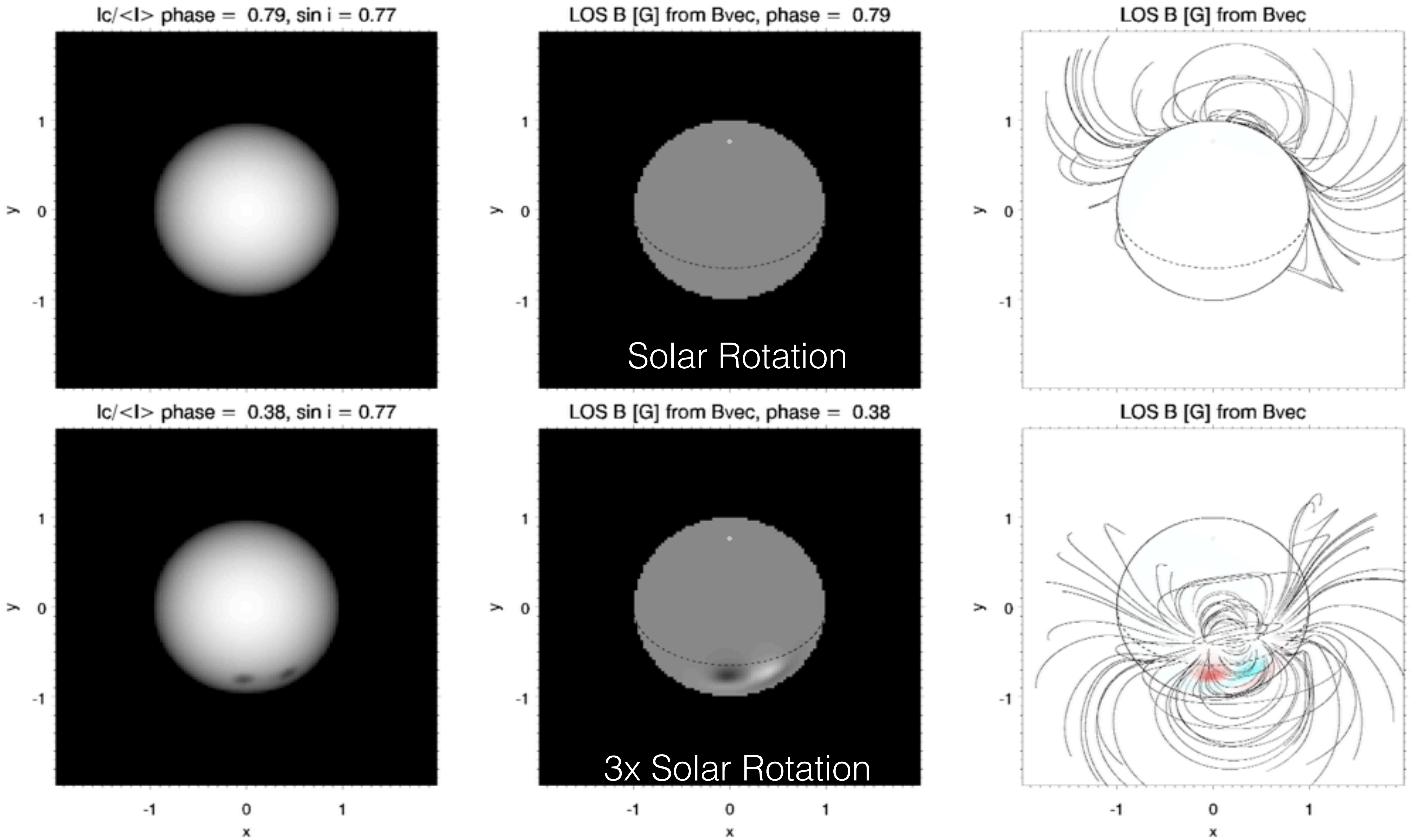
These models have memory.

Above: Non-potential models of the global solar coronal field from 1996 to 2012 (Yeates, 2014, Sol Phys, 289, 631).
See also models by D. Mackay @ St. Andrews

Example: 3 Active Regions



Solar-like differential rotation, meridional circulation and supergranular diffusion switched off for this run.

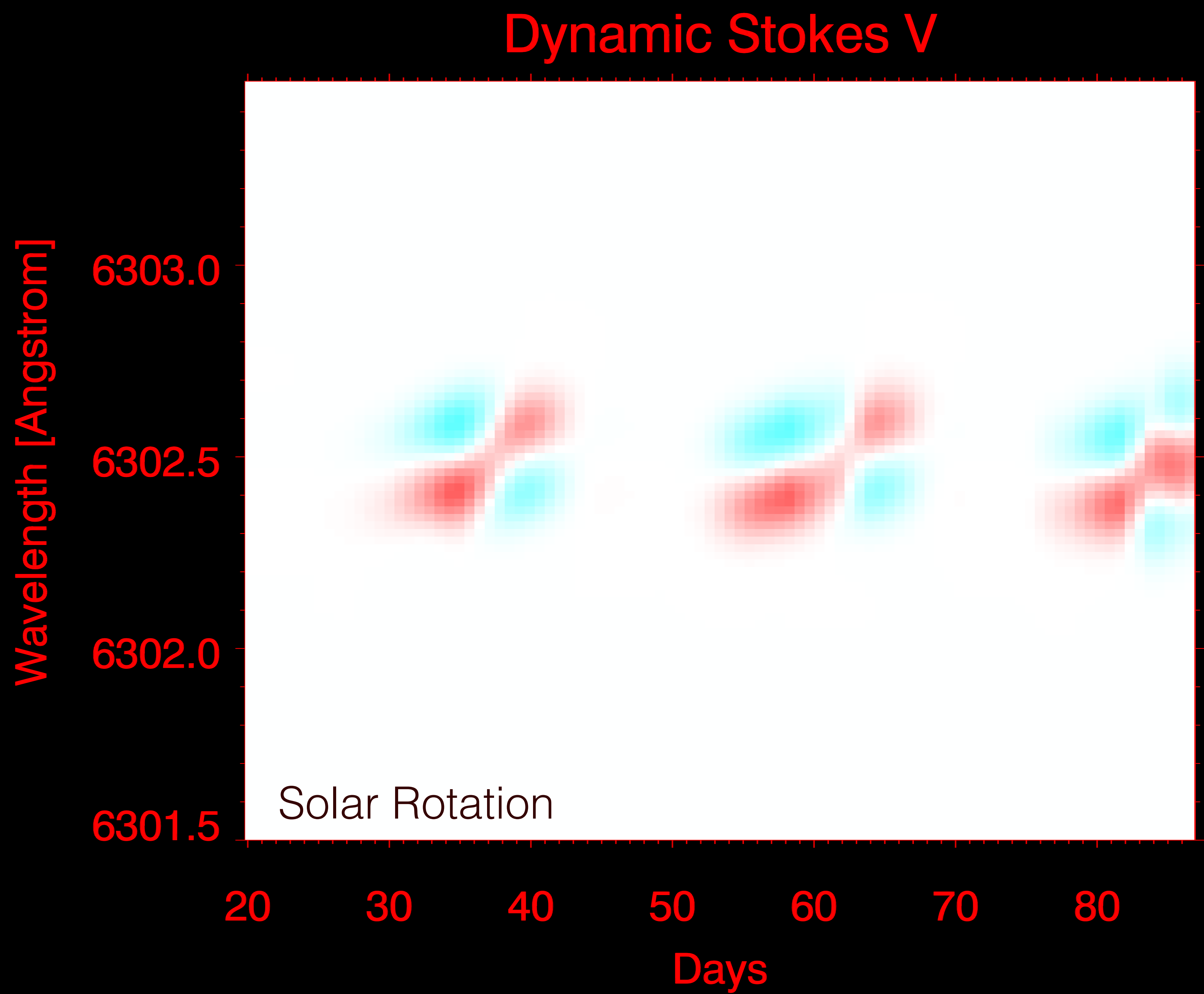


Synthetic white light image including
(1) limb darkening,
(2) Umbral darkening, but <u>excluding</u> plage / faculae brightening.

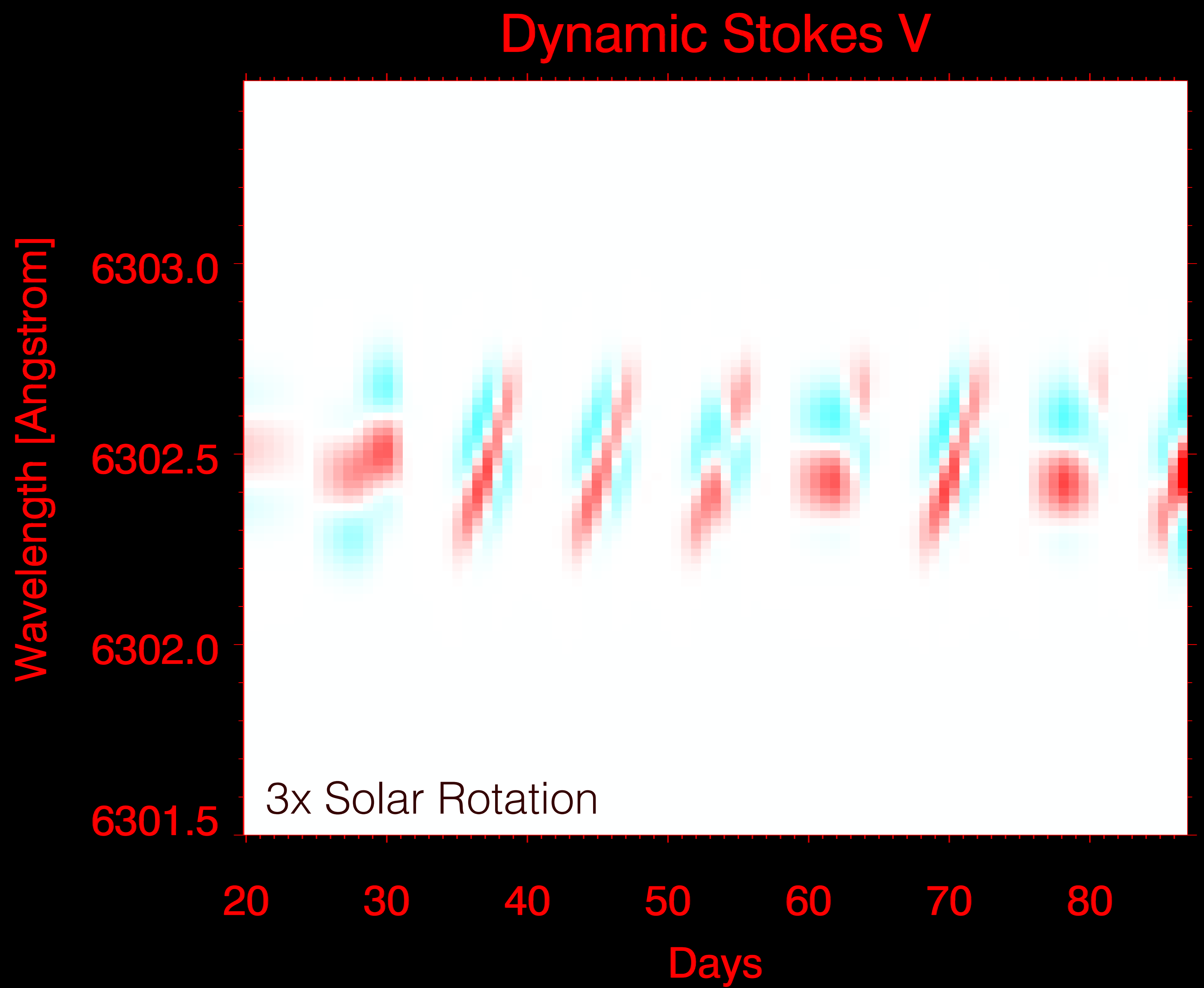
Line-of-sight component of the surface magnetic field.

Magnetofriction model of the stellar coronal field.

Stokes parameters (Milne-Eddington)



Zeeman Doppler Imaging data such as shown above (with appropriate noise) will be used to test inversions.



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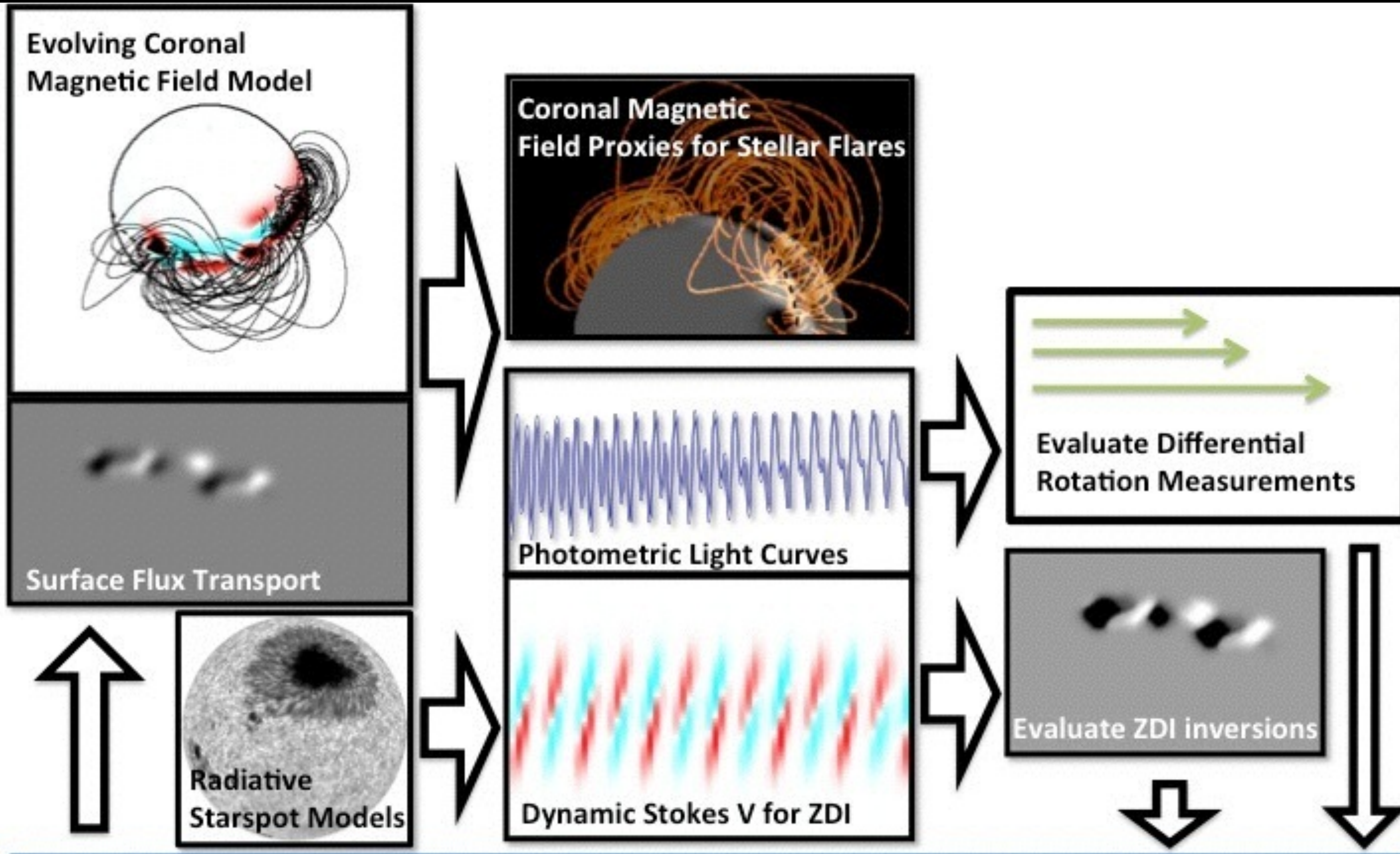

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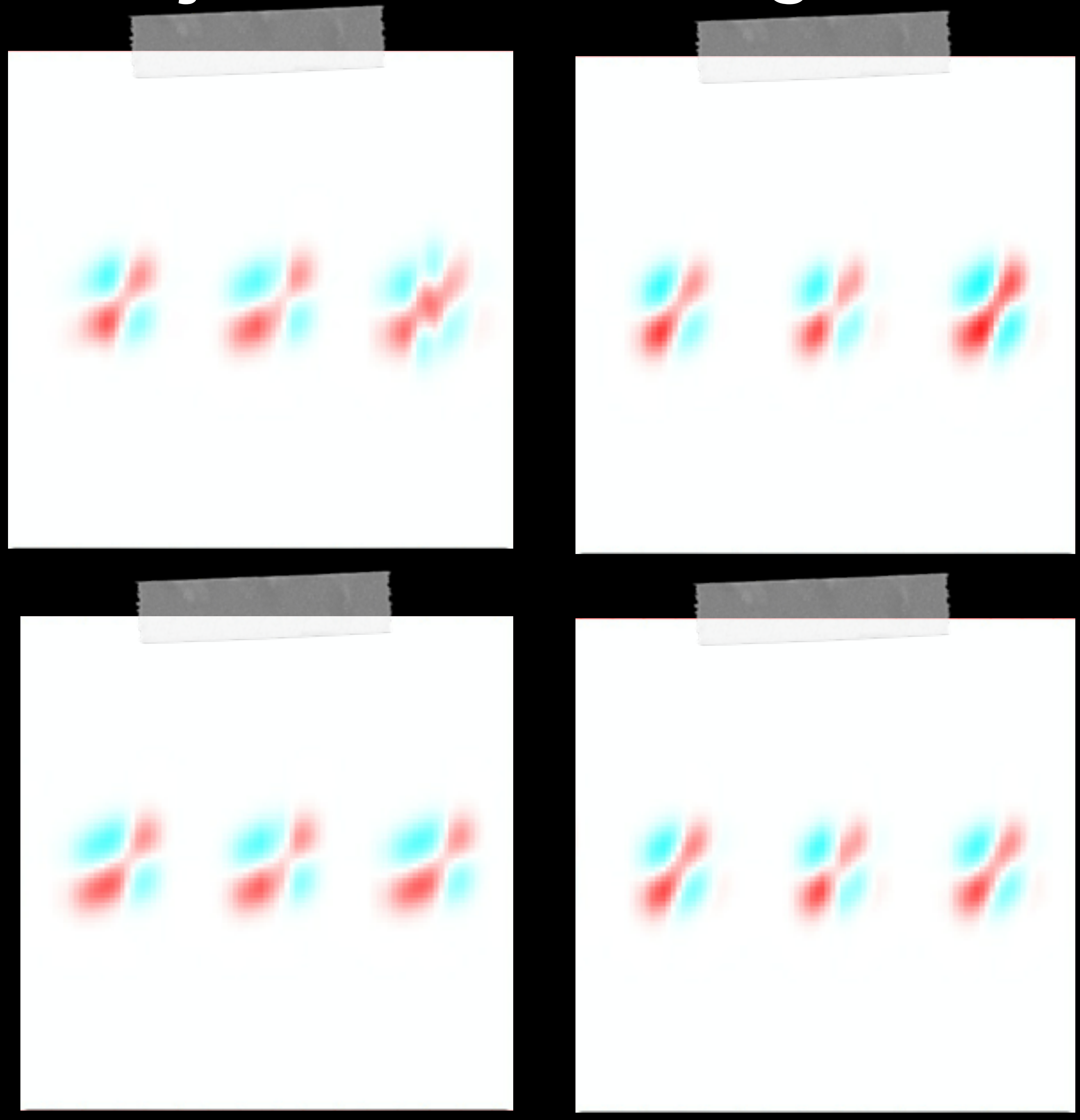
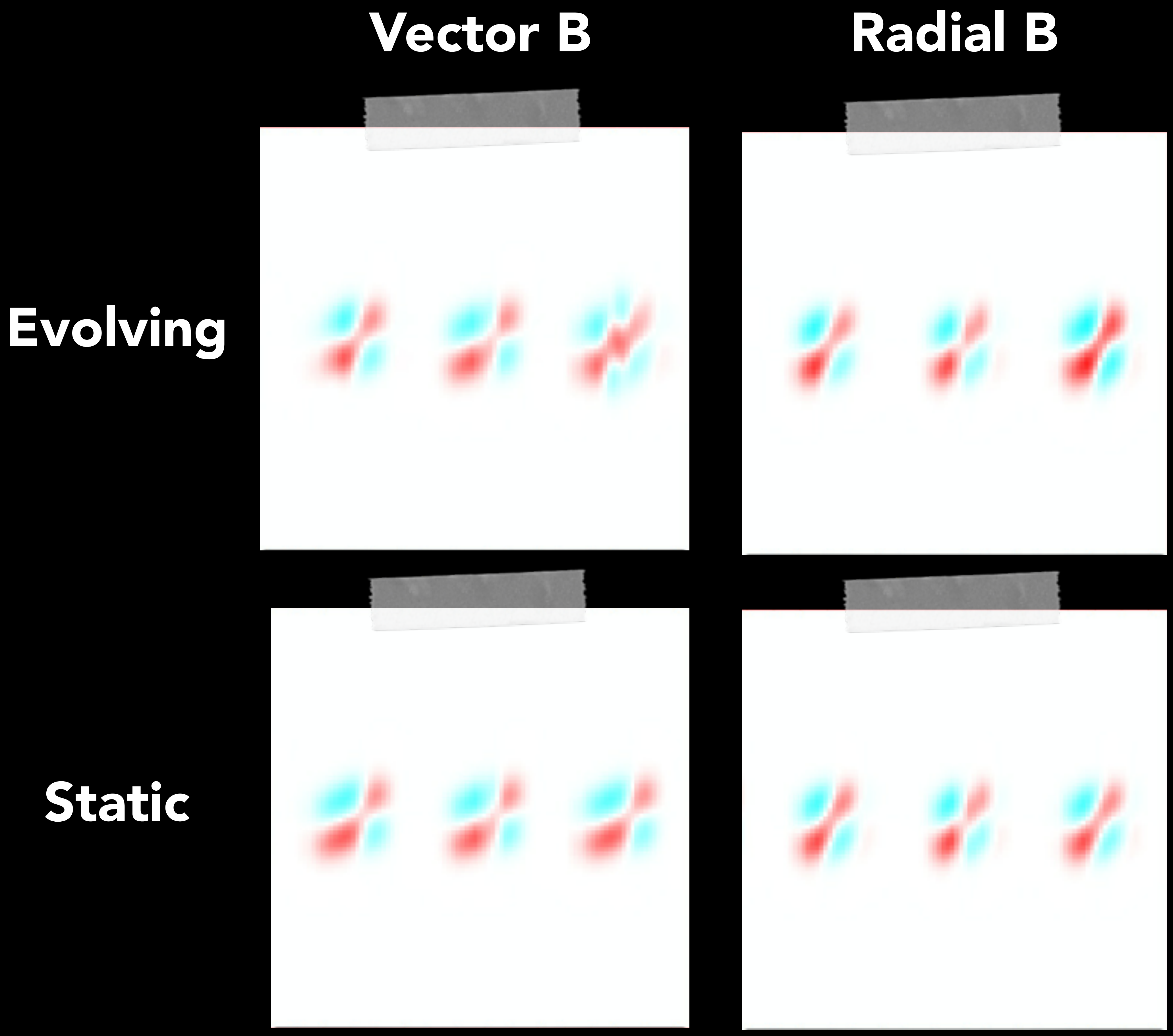
What's the difference between the following four dynamics Stokes V signals?

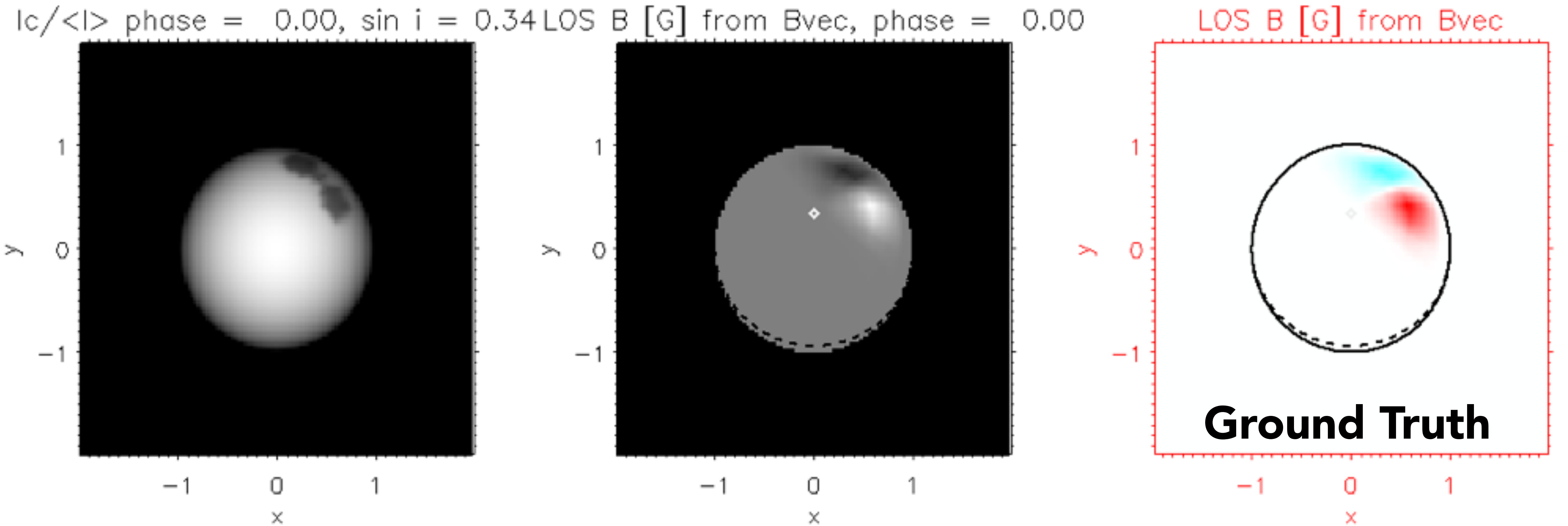



Vector B
Radial B
Evolving
Static

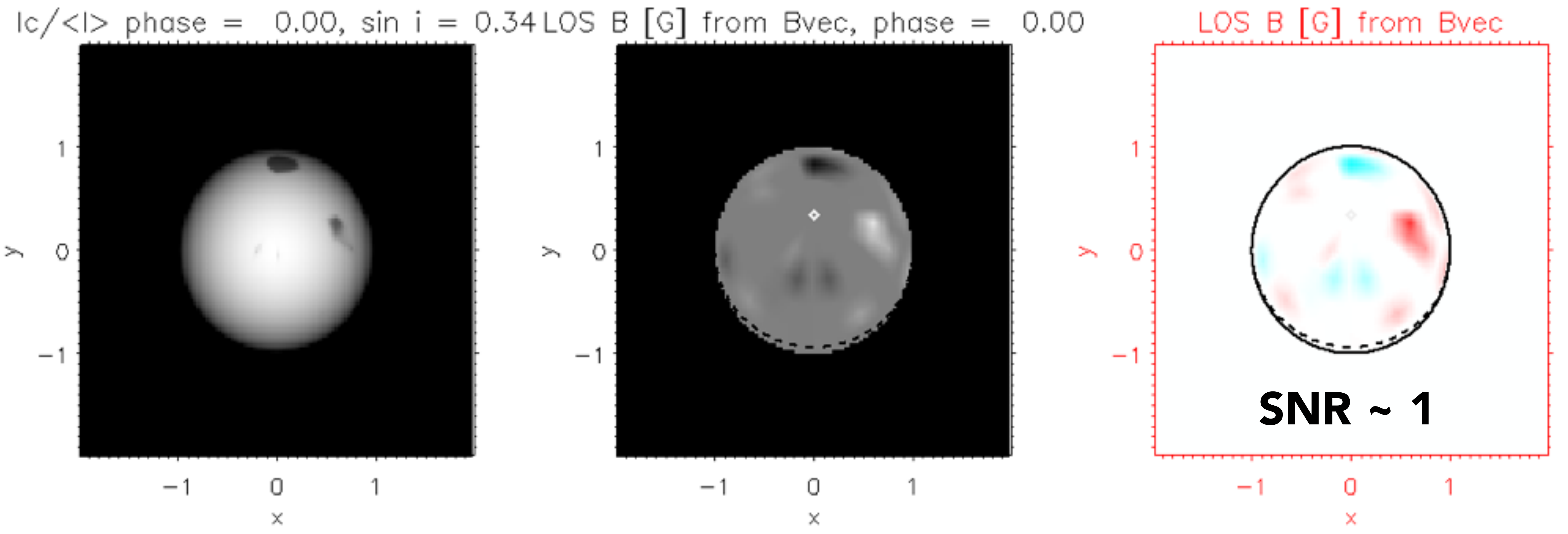
Experimental Inversion

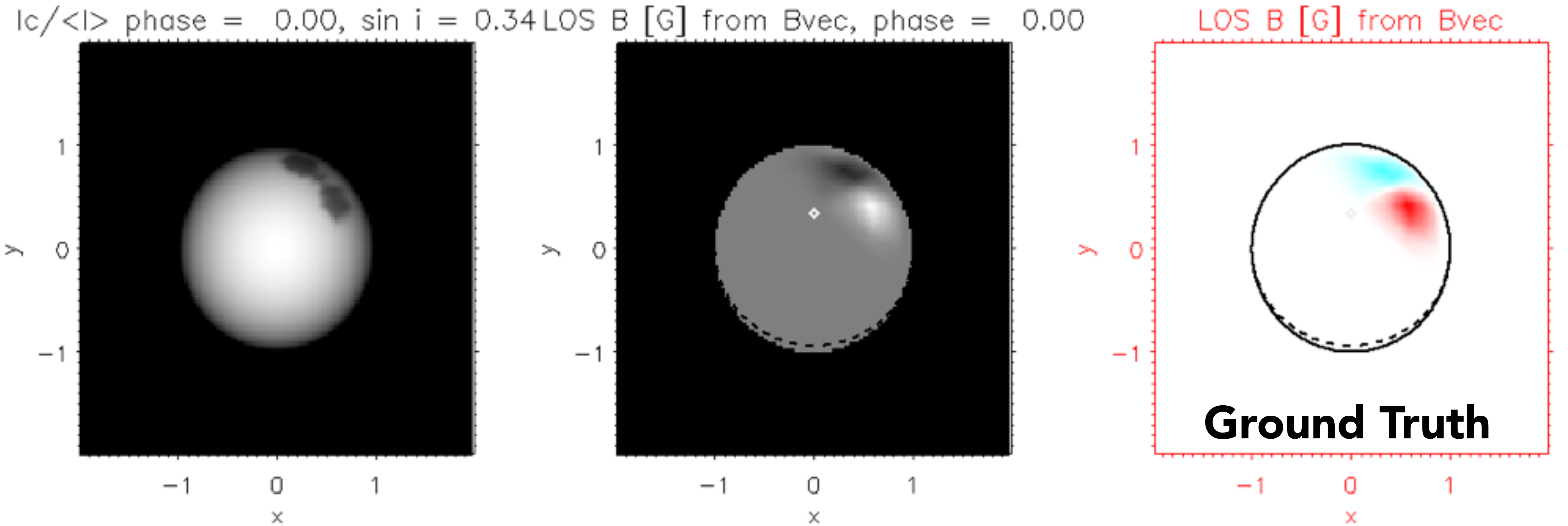
- A simple ZDI inversion code currently* in development.
- Calculate the response of the dynamic Stokes V signal (lambda/Δv, phase) for Dirac delta functions of the azimuthal, meriodional and radial components, assuming a Milne-Eddington atmosphere.
- Longitude-Latitude grid spanned by [24,12] grid points; 24 phase angles
- Not LSD (yet): only one line (Fe I 6302.5 Å)
- Inversion: Regularization with the L1-norm (sum of |B| over 3 components over the stellar surface). α is a chosen regularization parameter giving the importance of the L1-norm w.r.t. $\chi 2$. α is adjusted based on signal-to-noise (larger α for noisy data).
- Can be generalized to use other basis functions (e.g. spherical harmonics).

*i.e. this week…



Example: Two starspots with straddling azimuthal field





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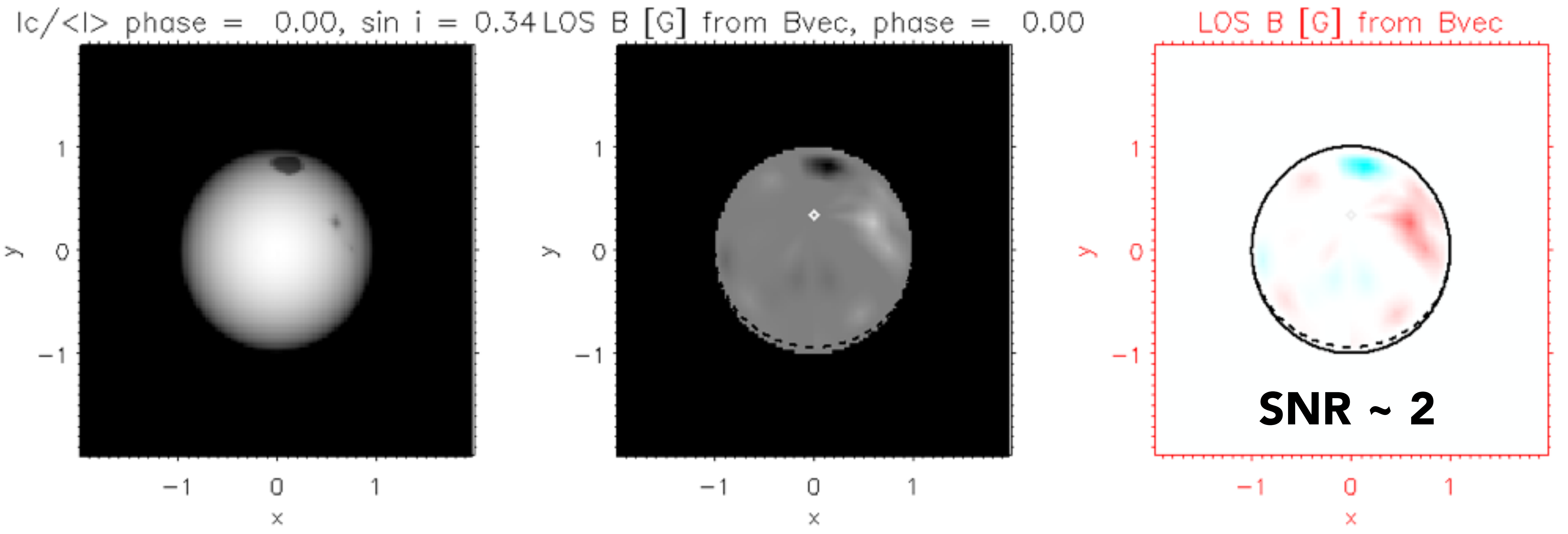

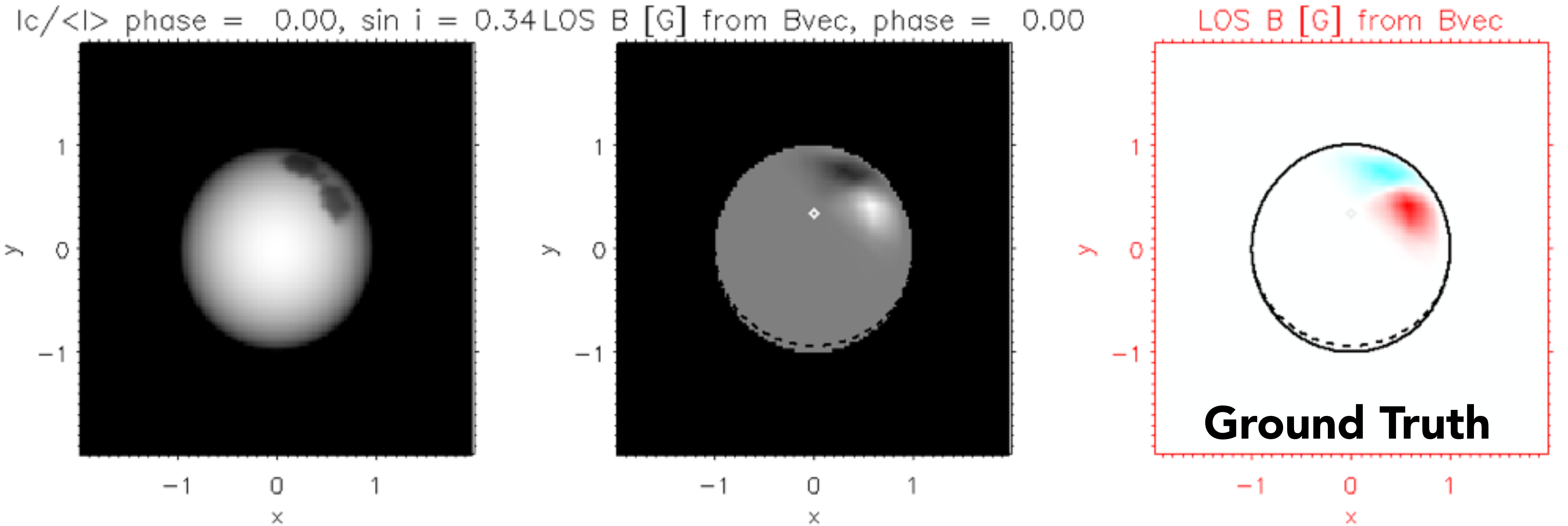

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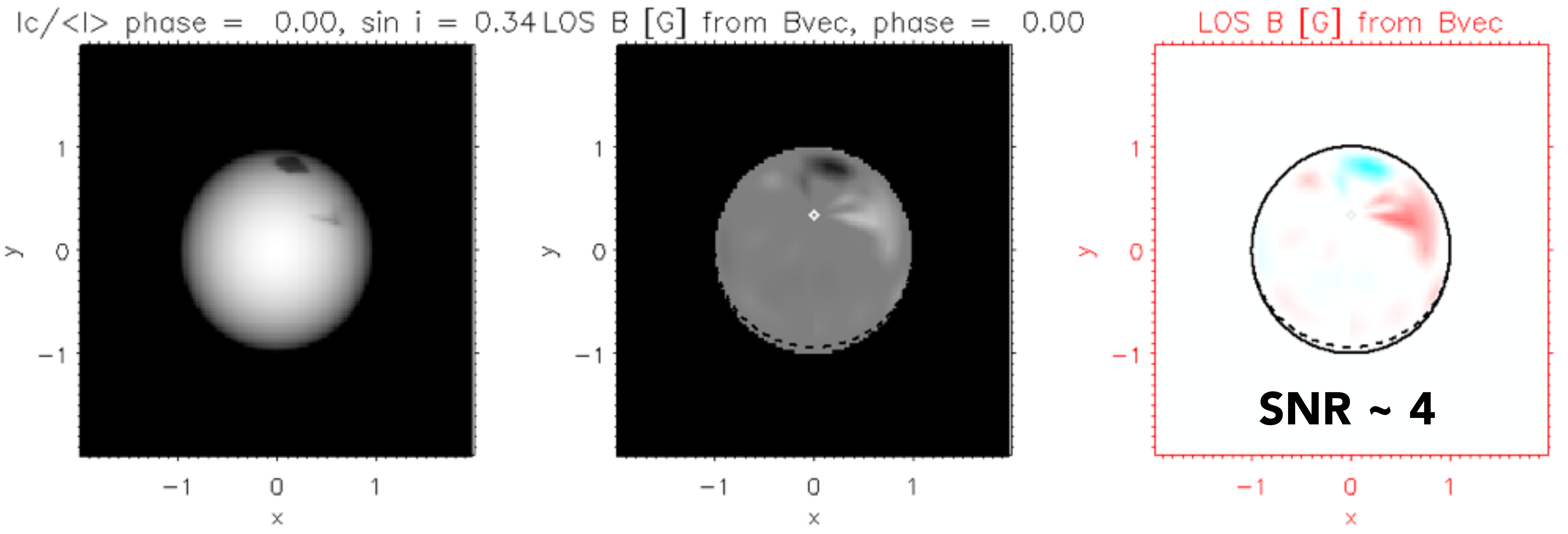

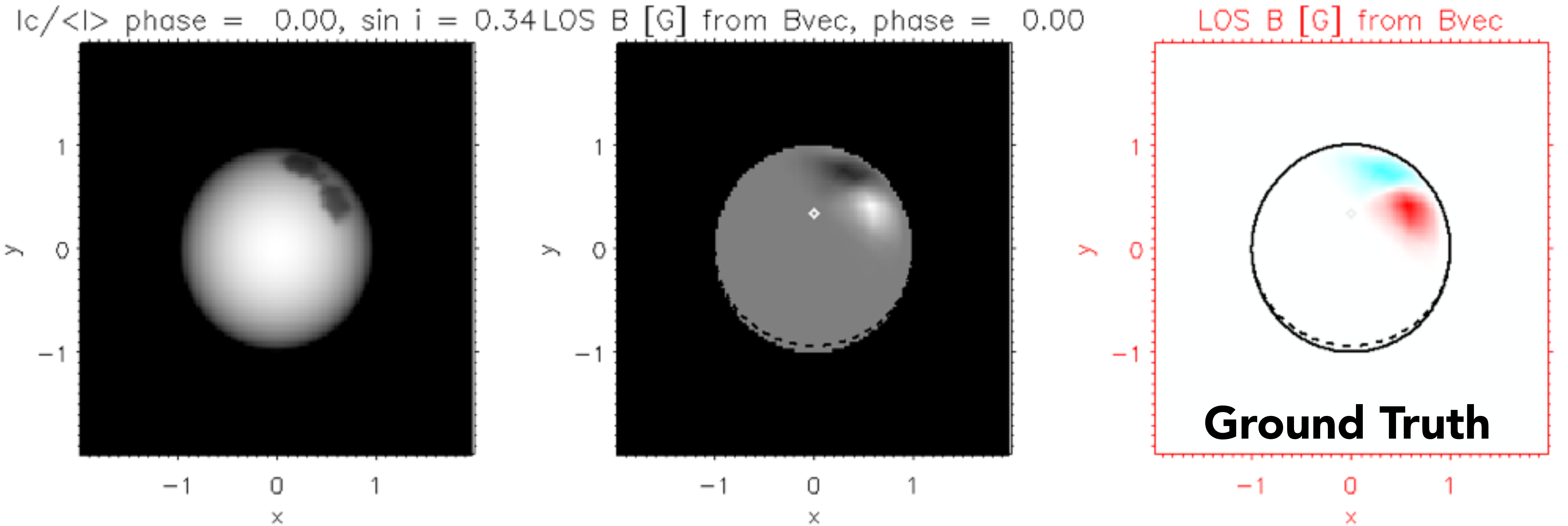

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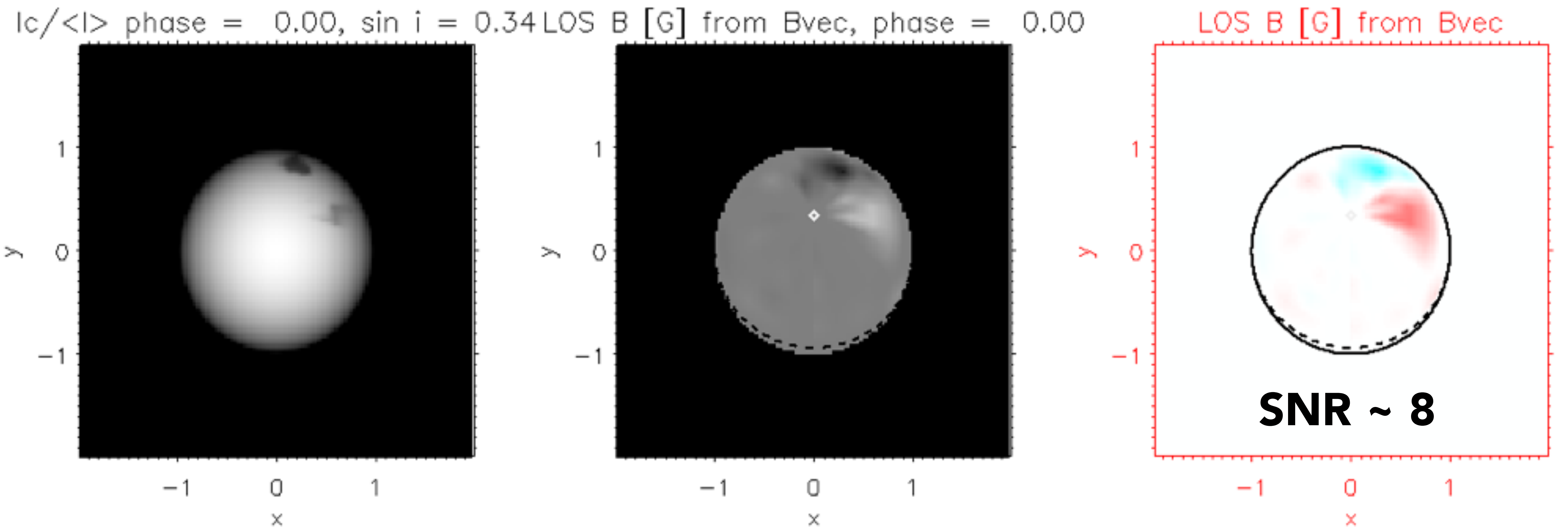

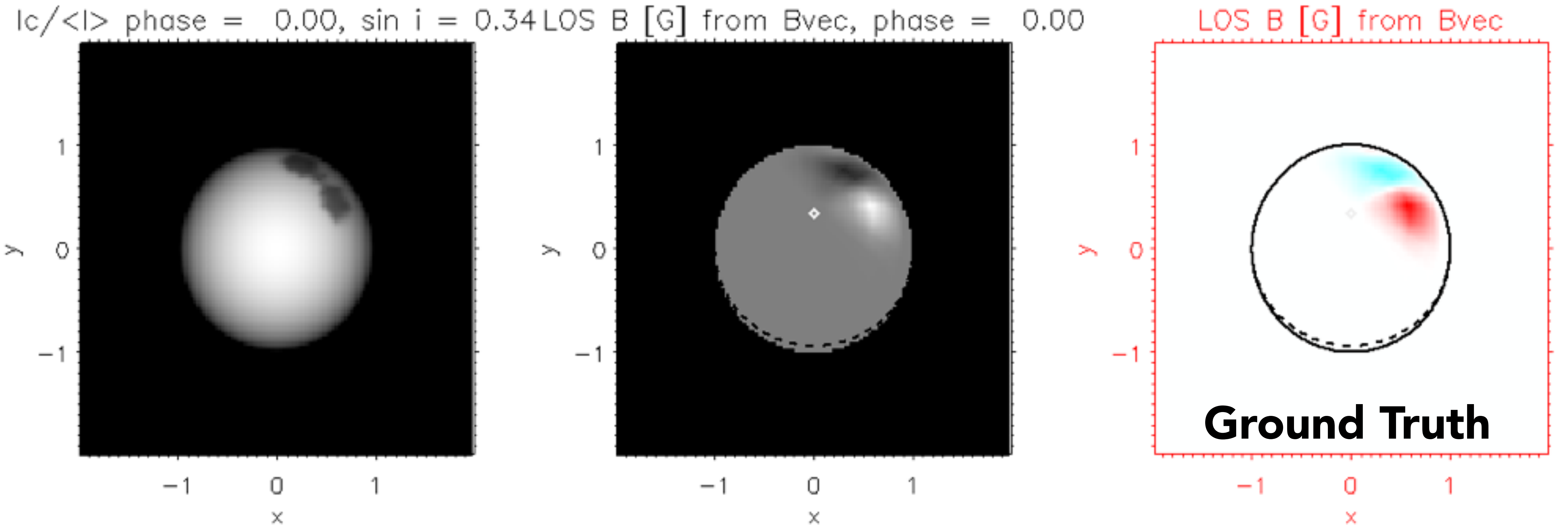

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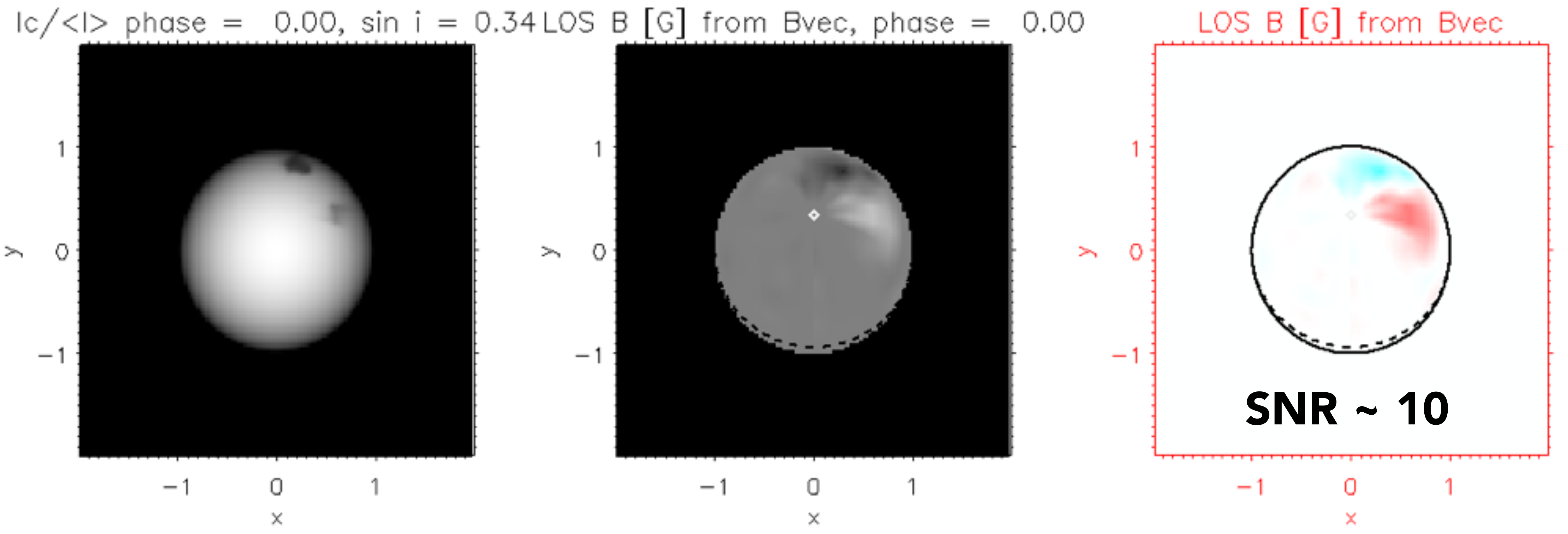
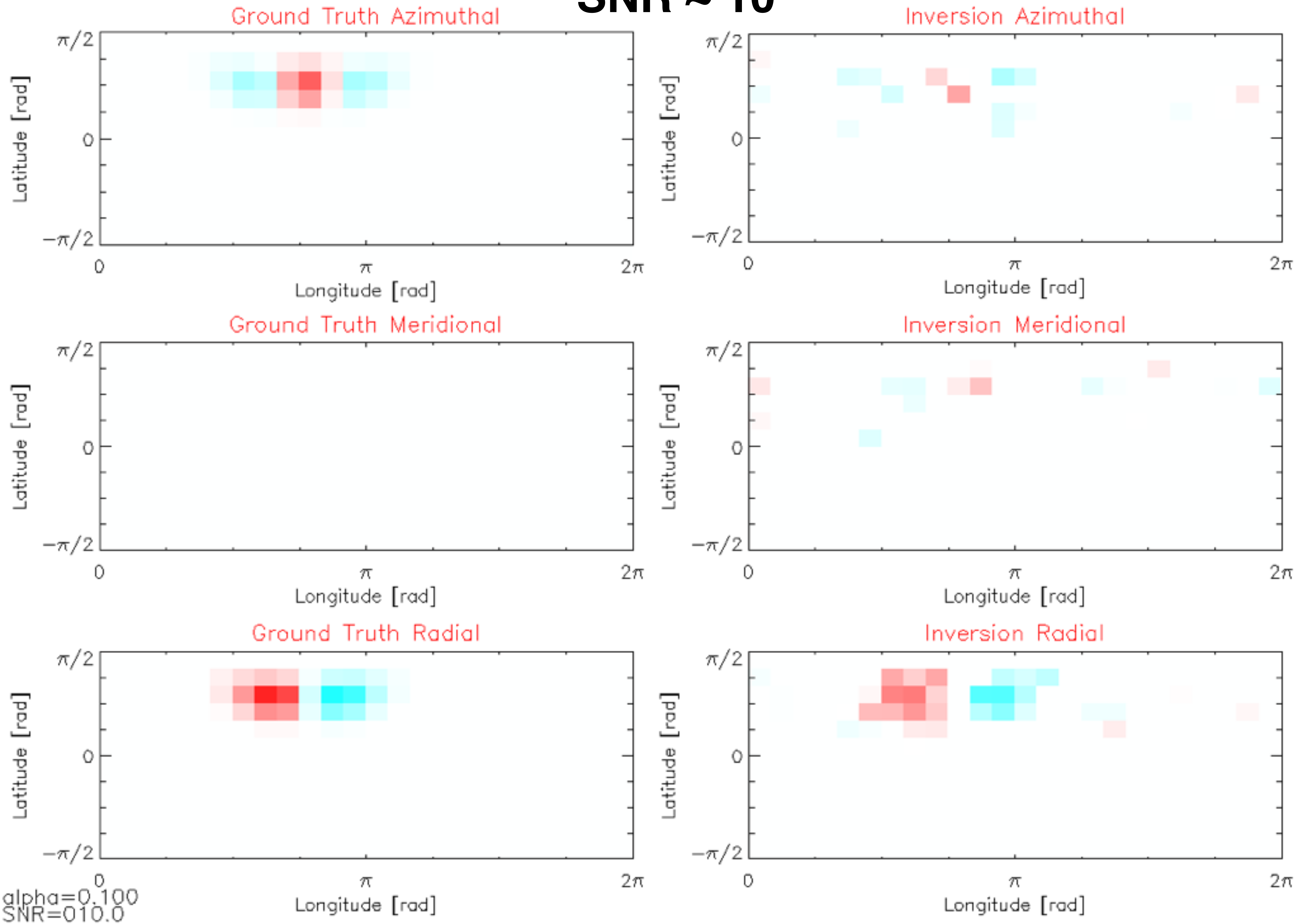
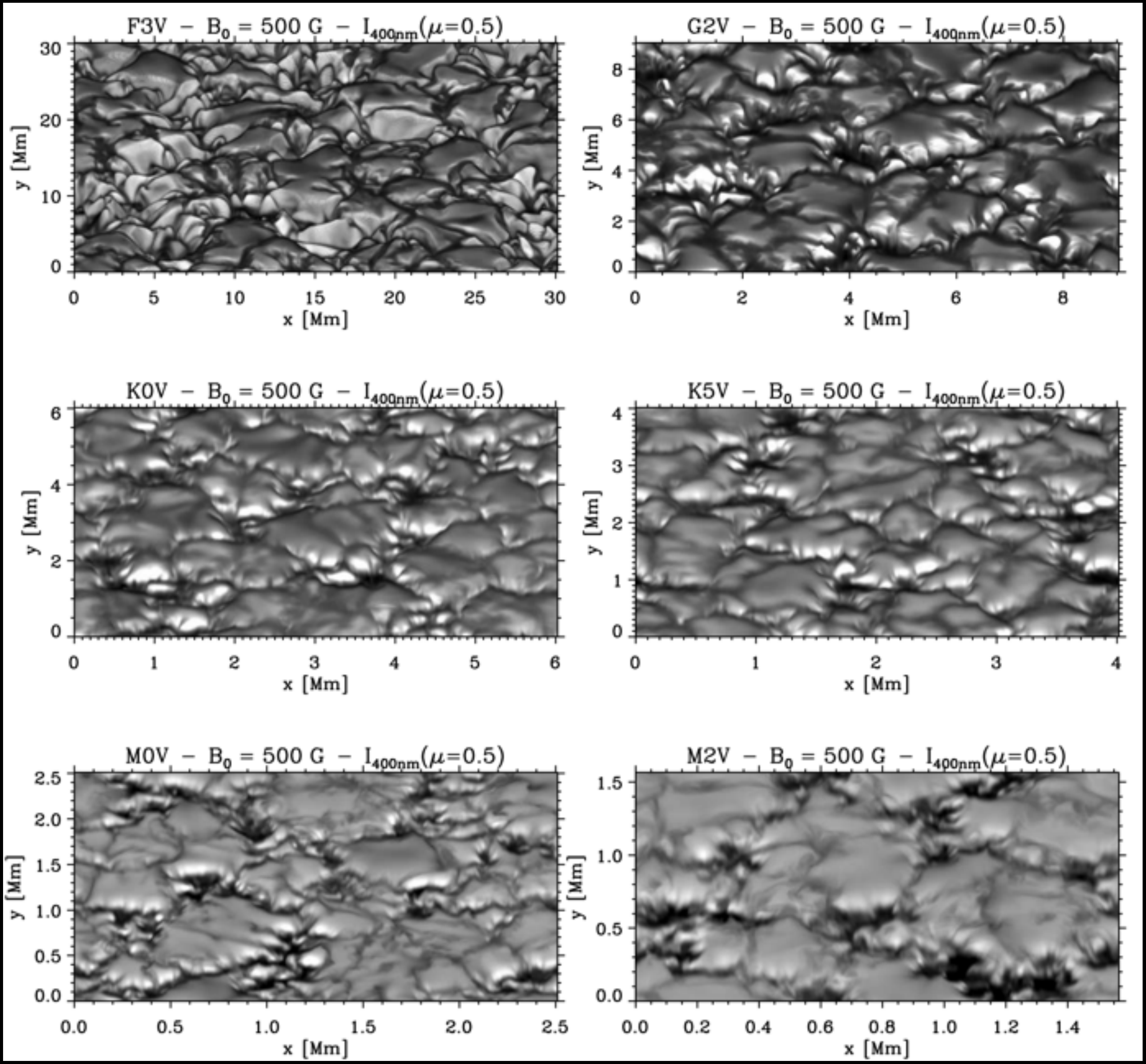


SNR ~ 10



Ground Truth Azimuthal
Inversion Azimuthal
Ground Truth Meridional
Inversion Meridional
Ground Truth Radial
Inversion Radial
Latitude [rad]
Longitude [rad]
π/2
0
−π/2
π
2π
alpha=0.100
SNR=010.0

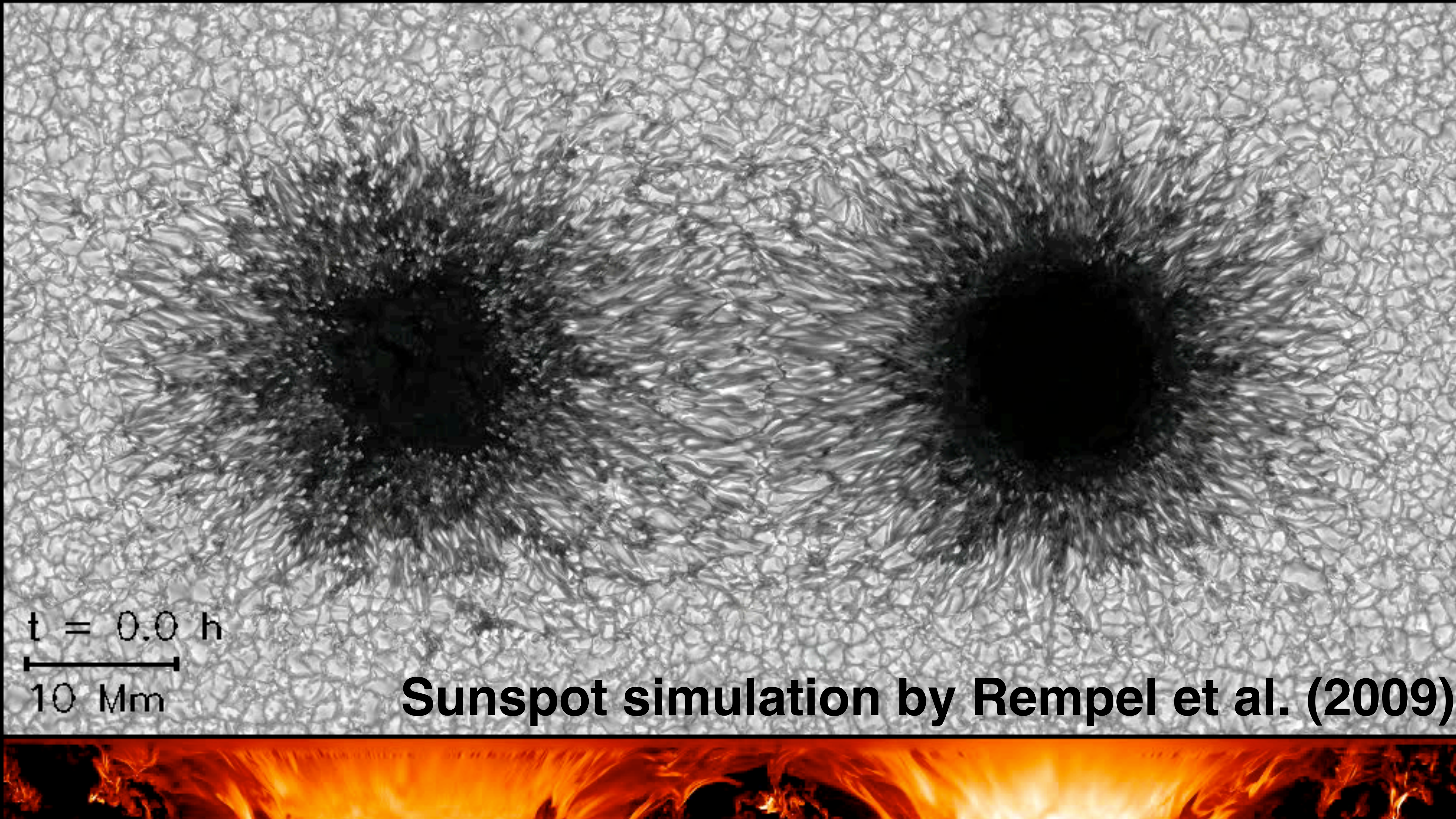
The role of MHD models



Beeck et al. (2015): Radiative MHD models of magnetoconvection in cool main sequence stars. Left: Synthetic intensity images in the wavelength band (400-410 nm) for μ = 0.5.

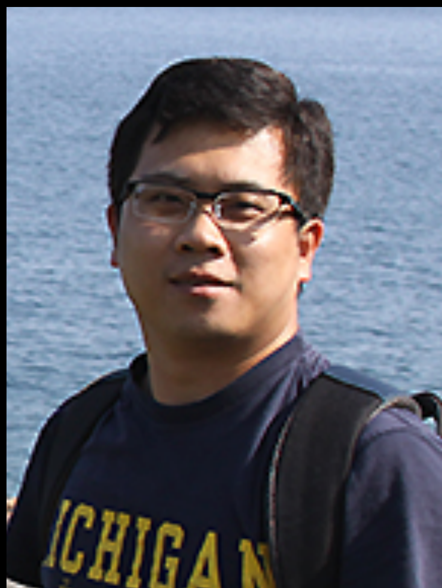
The M-type stars have no faculae.

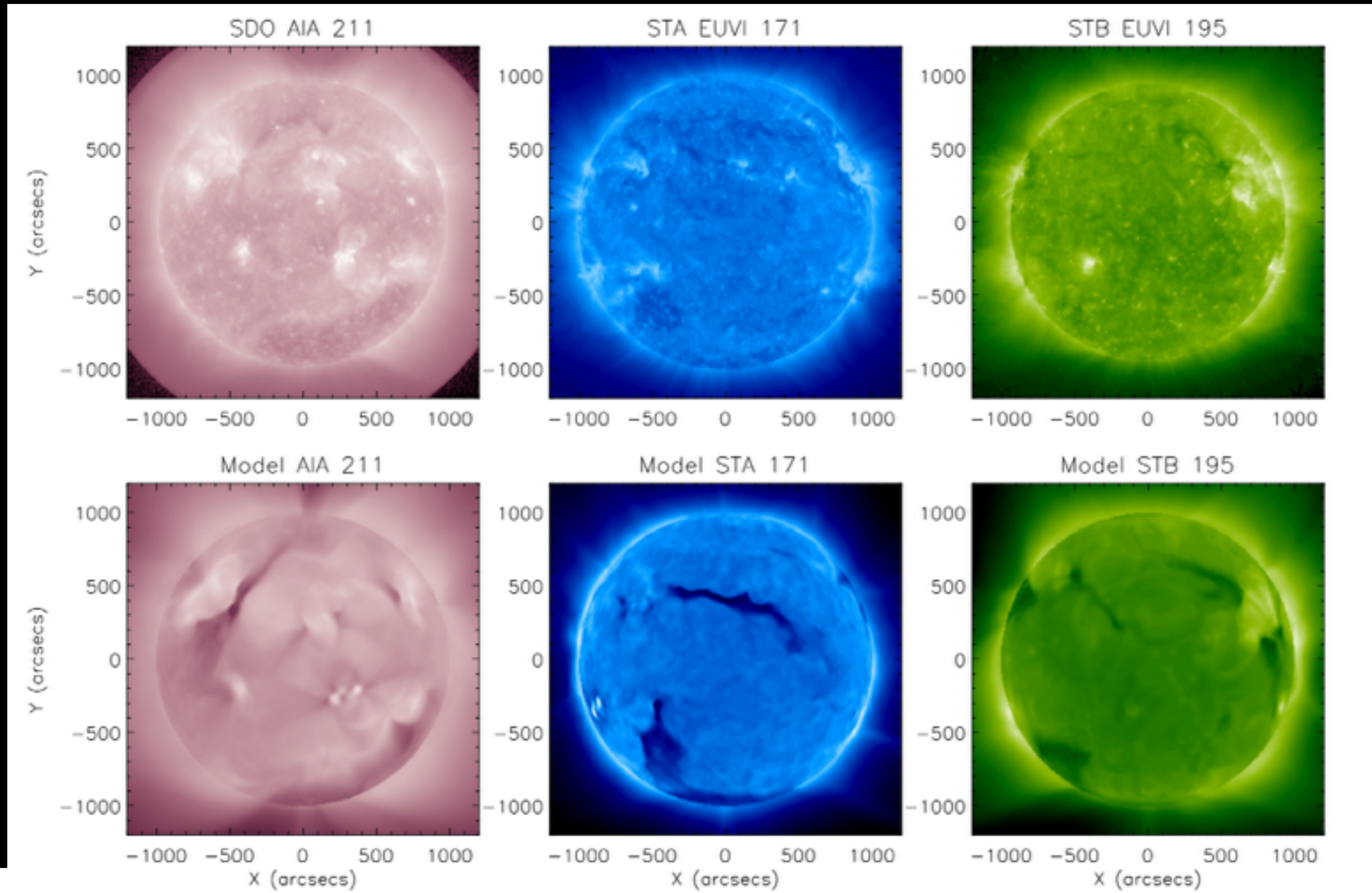
The role of MHD models



Desirable: starspot simulations with MURaM.

The role of MHD models





Meng Jin
postdoc
@ LMSAL

Alfvén Wave Solar Model (AWSoM)

of the Feb 15th 2011 solar eruption starting from a Gibson-Low flux rope to study global coronal impacts and possible eruption sympathy (Jin et al., ApJ, 2016).

Summary

- We are developing a simplified model of evolving stellar photospheric and coronal magnetic fields based on a constrained surface flux transport model and a magnetofrictional model.
    - Parameter studies to be performed for solar-like stars (but can be extended to other types).
- Forward synthesis of disk-integrated observables allows us to test
    - Zeeman Doppler Image inversions on evolving fields,
    - Properties derived from photometric light curves.
- Radiative MHD models needed for increasing the realism of synthetic observables, in particular for the center-to-limb variation and dependence on IBI.
- Feedback is very much appreciated. E.g. “Your model is two simplistic, you need to use more lines, different bases etc.”