

Modeling the solar corona with FORWARD

Sarah Gibson

The screenshot shows the website for the High Altitude Observatory (HAO) and its 'sun • earth • connections' project. The navigation bar includes links for 'About HAO', 'Research', 'Modeling', 'Data & Observations', 'News & Events', 'Partnerships', 'Education', 'For Staff', and 'Home'. The HAO logo is prominently displayed, along with the 'sun • earth • connections' branding. A search bar is located in the top right corner.

The main content area features a breadcrumb trail: 'Home » Data & Movies'. The primary heading is 'FORWARD: A TOOLSET FOR MODEL-DATA COMPARISON'. Below this, a paragraph explains the toolset's purpose: 'This set of codes is intended to be used for forward modeling of various coronal observables, and for accessing and comparing to existing data. Given a coronal model, many different synthetic observables (including [MLSO/CoMP Stokes profiles](#)) may be produced, as well as plots of model plasma properties (density, magnetic field, etc.)'.

Two sub-sections describe the toolset's capabilities:

- 'FORWARD enables "forward-fitting" of specific observations, and helps to build intuition into how physical properties of coronal plasma translate to observable properties.'
- 'FORWARD includes several analytic models in its distribution, and it is straightforward to expand it to incorporate others. It works with user-inputted numerical simulation datacubes, and automatically interfaces with the Solar Soft IDL "PFSS SolarSoft package" and "Magnetohydrodynamics on a Sphere (MAS)-corona datacubes".'

A central figure titled '"FORWARD" SolarSoft IDL Codes' displays various model outputs:

- 'Cavmorph' morphological density model: AIA 193, AIA 335, and pB (Carrington map @ 1.05 Rsun).
- Gibson&Low MHD flux rope model: XRT Al-mesh, Bx, linear polarization, and circular polarization.

A red handwritten-style text at the bottom of the figure reads 'NOW WITH WIDGETS!'.

On the right side, a blue sidebar titled 'FORWARD CODES' contains a list of links:

- Home
- Install FORWARD
- Running Instructions
- Customize
- Compile Fortran
- Trouble Shooting
- FORWARD Paper

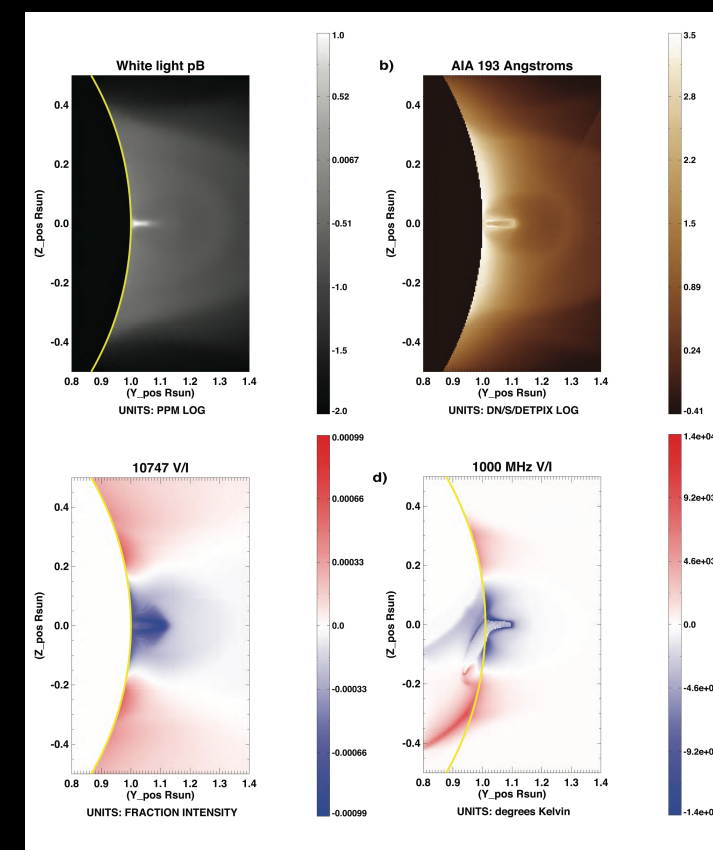
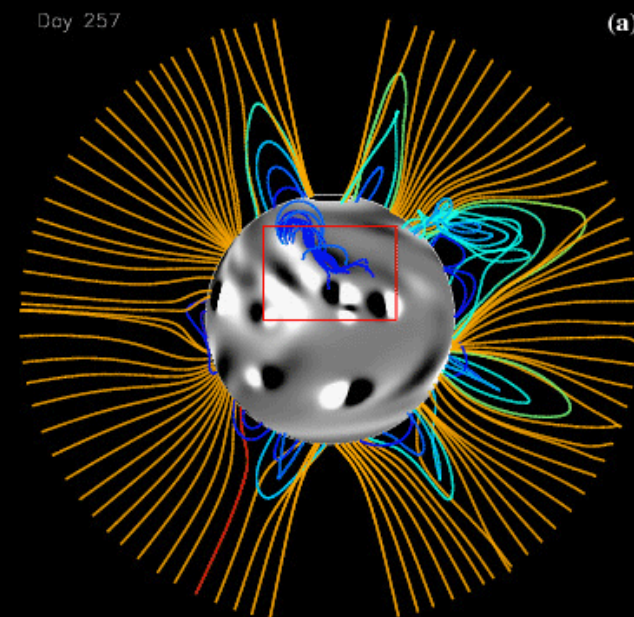
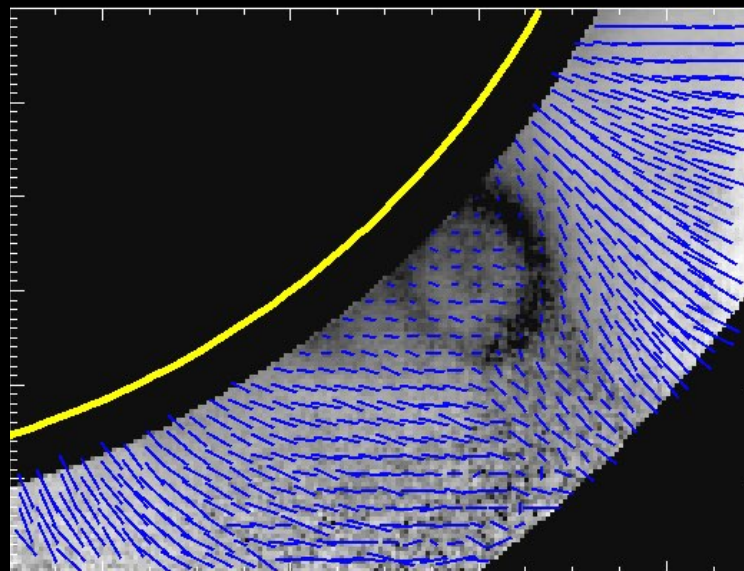
<https://www2.hao.ucar.edu/modeling/FORWARD-home>

Observations meet models

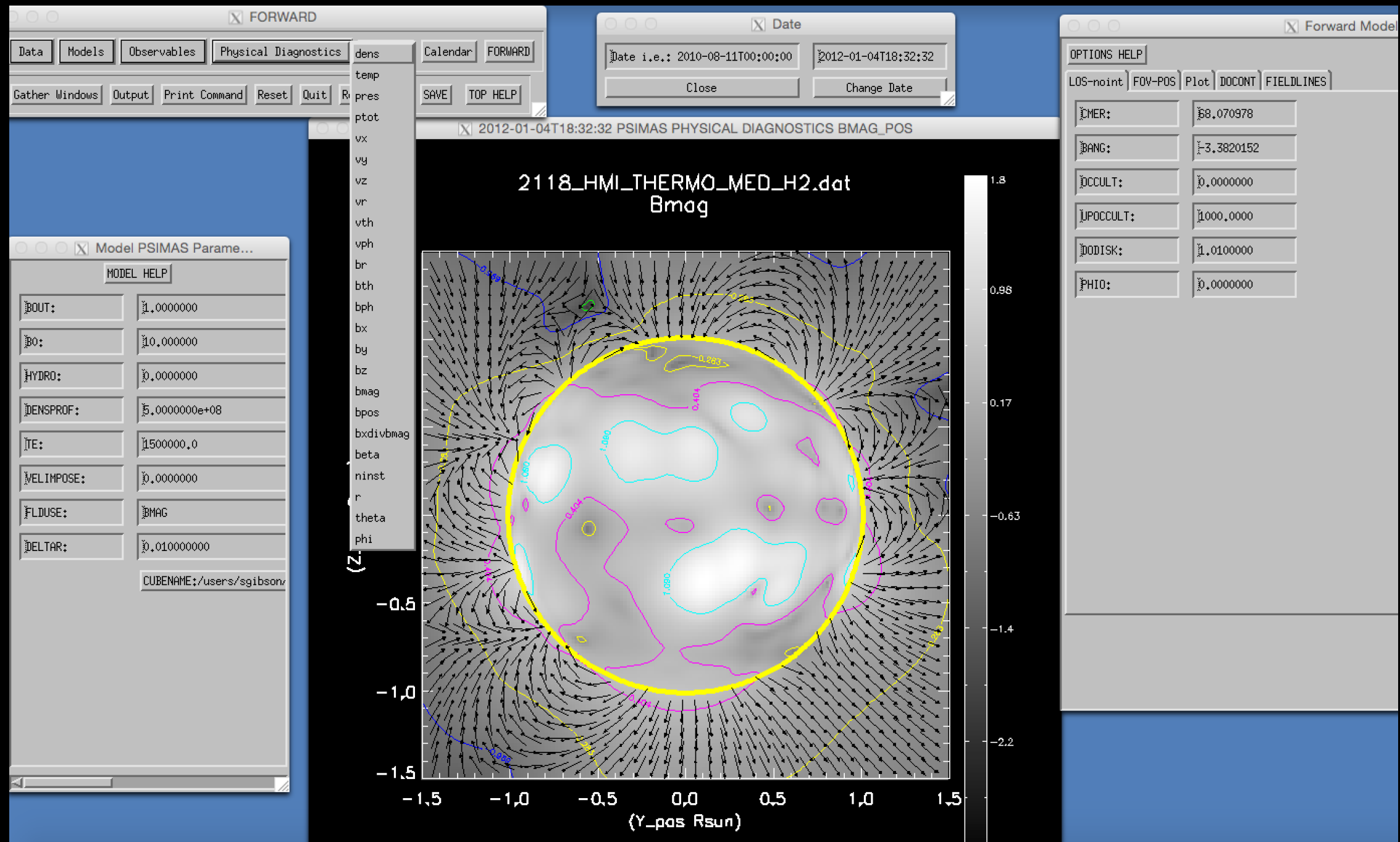
Solving an inverse problem requires three things:

- a means of specifying the **physical state** (e.g., the distribution of density, temperature, velocity, and magnetic field)
- a well-defined forward calculation (i.e., the **physical process** relating the physical state and the observations)
- the **observations** themselves.

The **FORWARD**
SolarSoft package
incorporates all three

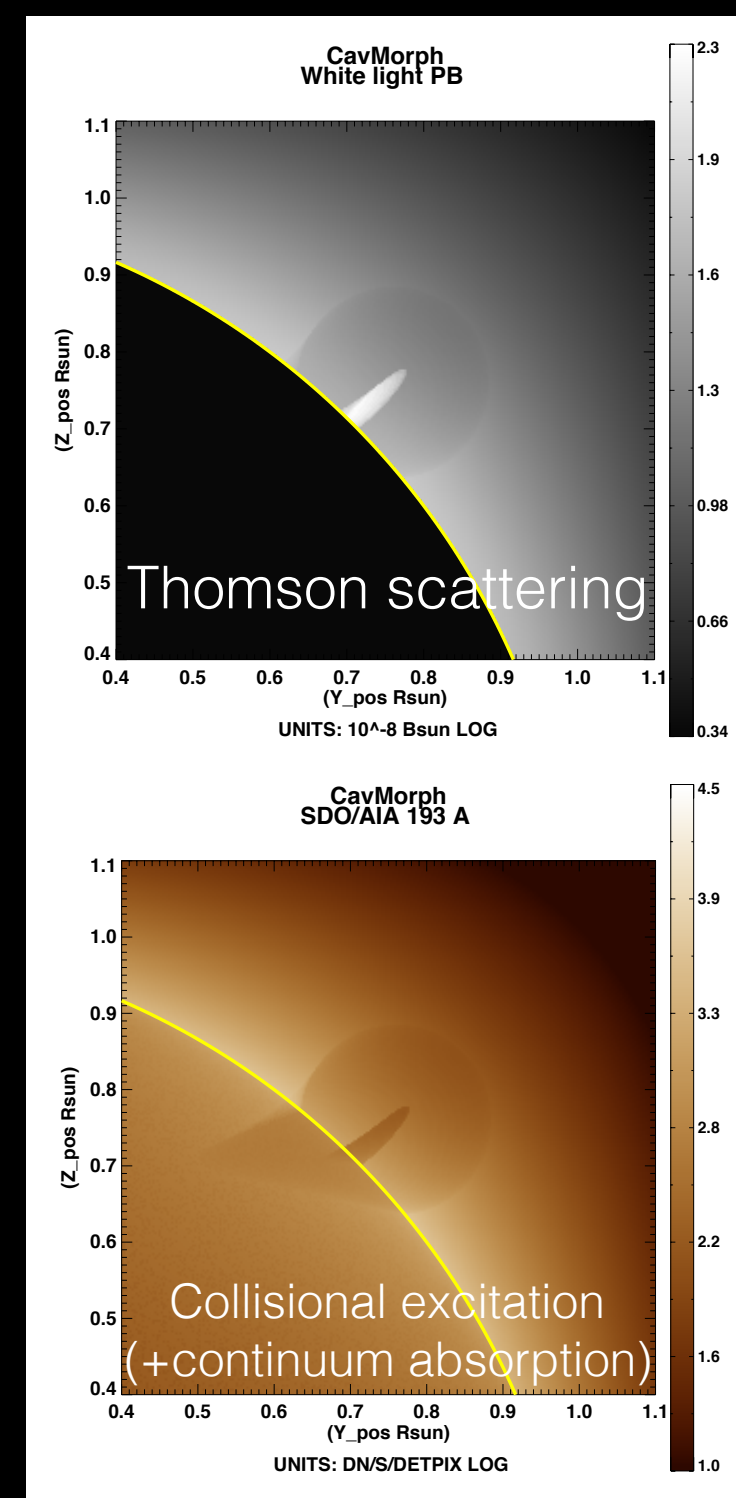
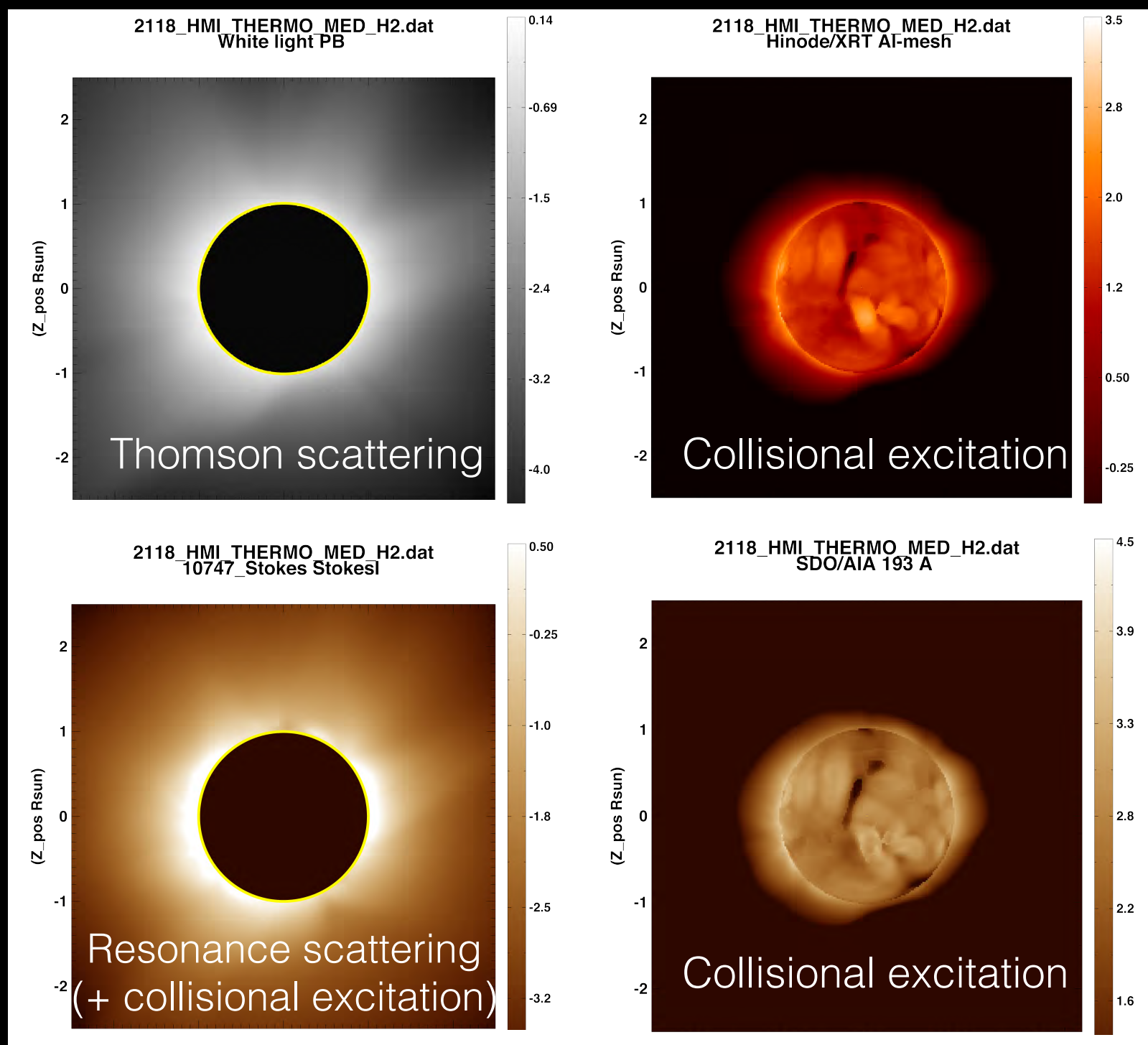


Physical State

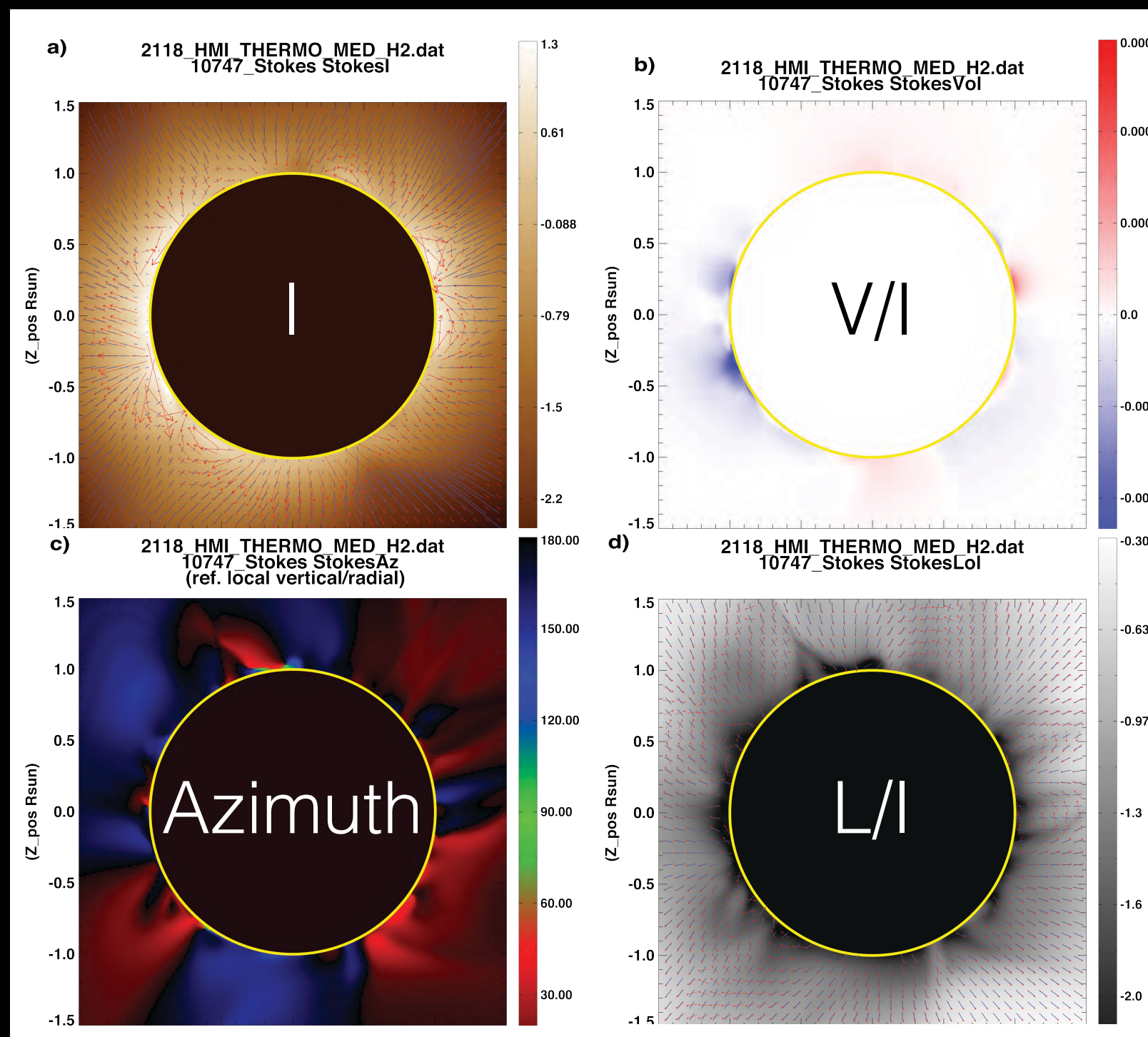


Works with any analytic or numerical model, but automatically interfaces with PFSS extrapolation and PSI MAS MHD simulation (given date)

Physical processes

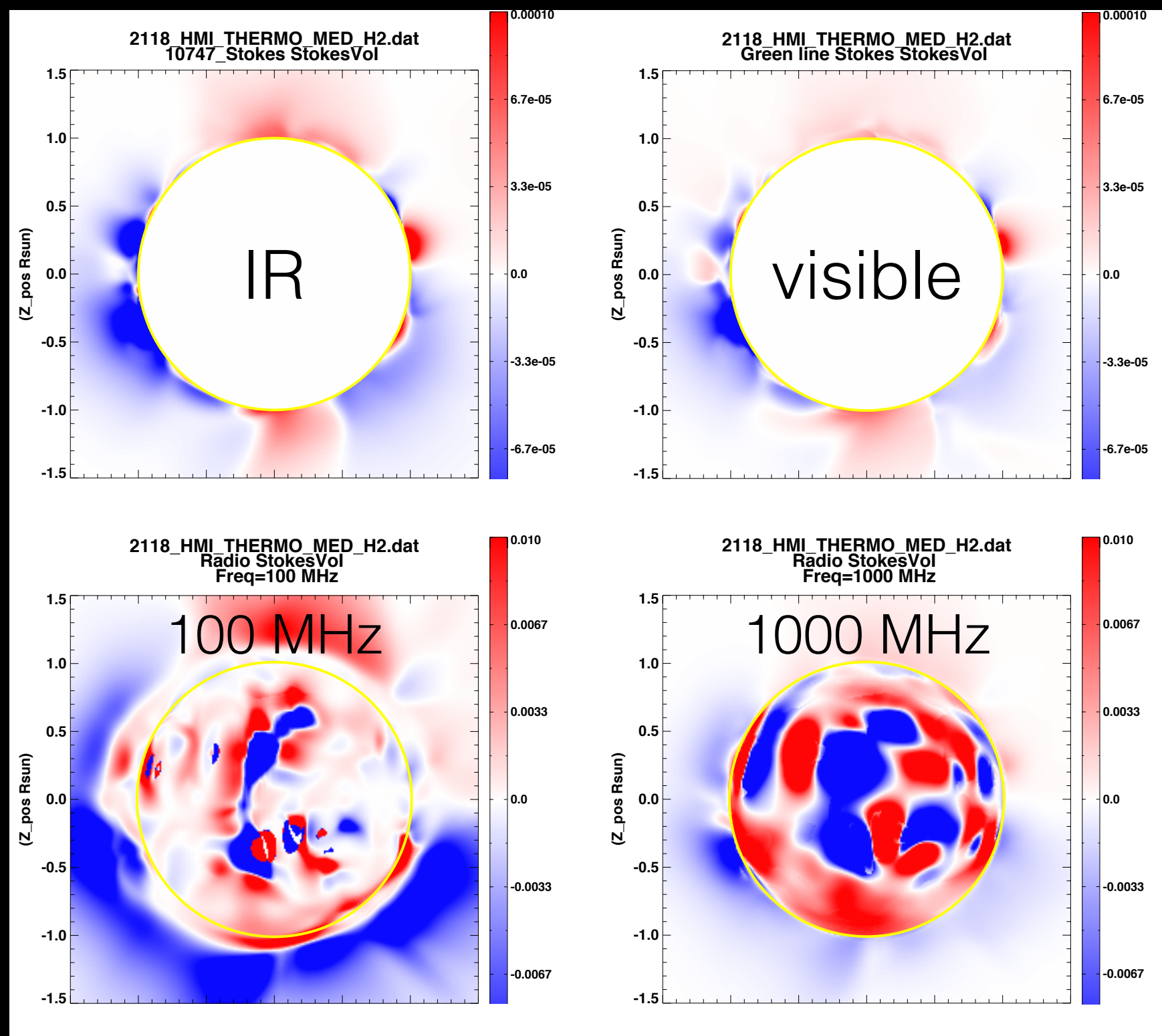


Physical processes



Polarization (Zeeman, saturated Hanle)

Physical processes



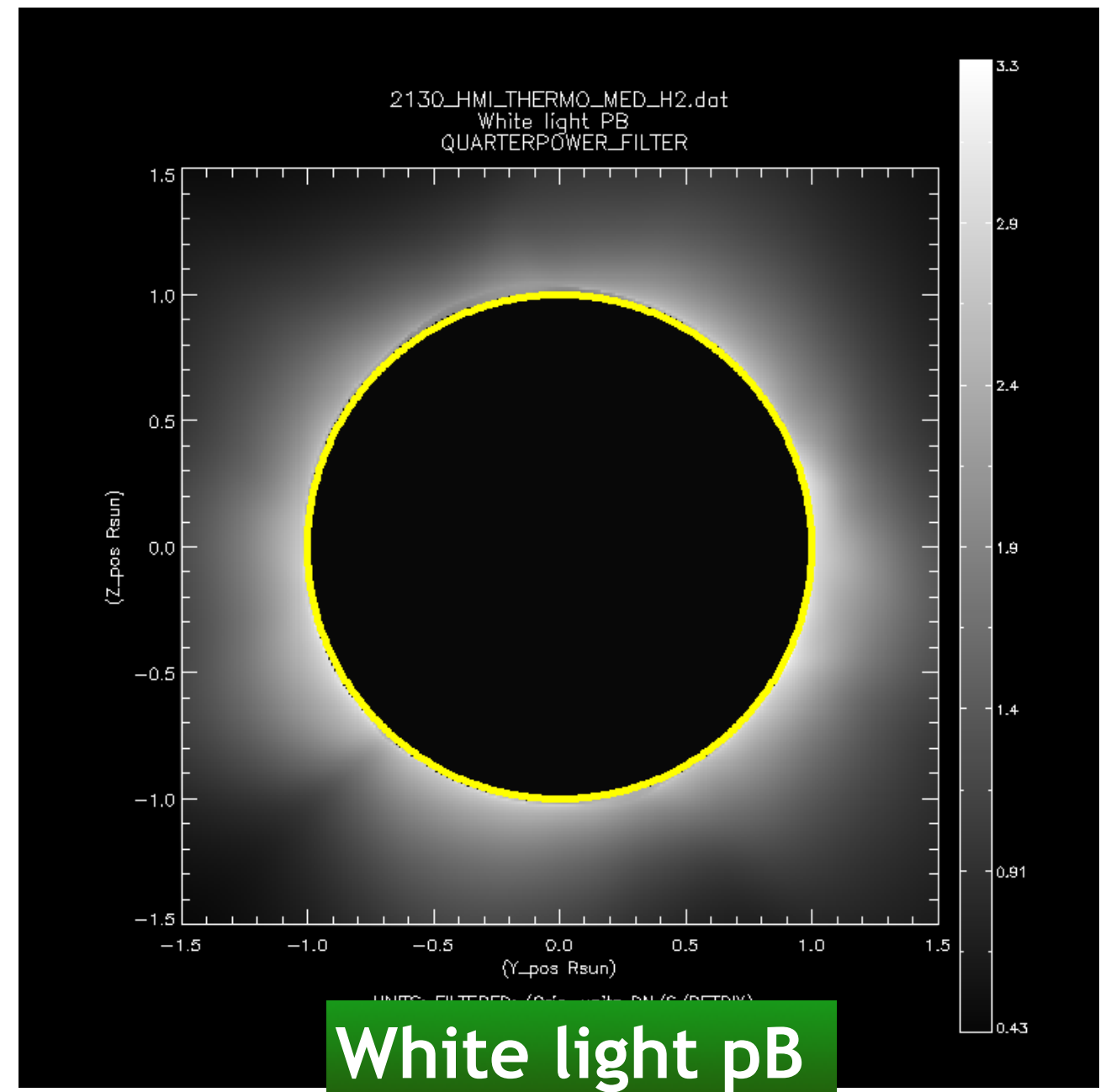
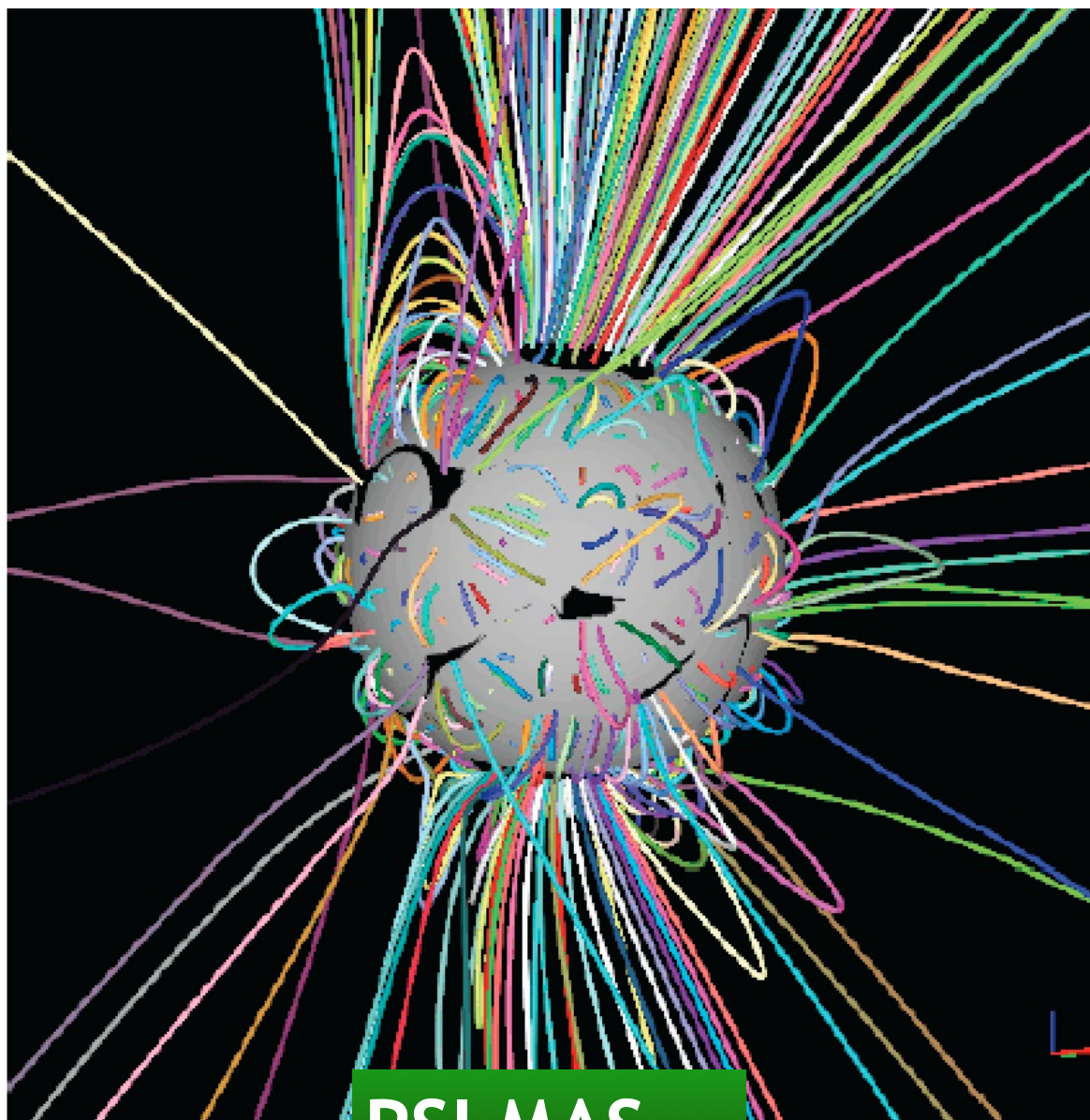
**Circular polarization at different wavelengths:
different dependencies on plasma along the line of sight**

Physical processes

Process	Physical-state dependency	Observation	Magnetic quantity probed
Thomson scattering	electron density	White-light pB, TB	Plasma structured by field (e.g. closed vs. open field boundaries, flux surfaces)
Collisional excitation	electron density, temperature	IR/Visible/EUV/SXR emission	Plasma structured by field (incl. loops, closed/open boundaries, flux surfaces)
Continuum absorption	chromospheric population density, electron density, temperature	EUV absorption features	Can indicate magnetic geometry suitable for prominence formation
Resonance scattering; polarization	electron density, temperature, vector magnetic field	Visible/IR spectra	B_{los} from Stokes V; Magnetic field direction from Stokes Q, U
Doppler shift	electron density, temperature, velocity	Visible/IR spectra	B_{pos} and field line direction from waves; flux surfaces from bulk flows
Thermal bremsstrahlung	electron density, temperature, vector magnetic field	Radio emission (intensity and circular polarization) as a function of frequency	B_{los} from Stokes V
Gyroresonance	electron density, temperature, vector magnetic field	Radio emission (intensity and circular polarization) as a function of frequency	Surfaces of constant magnetic field strength at each frequency
Faraday rotation	electron density, temperature, vector magnetic field	Rotation of plane of polarization	B_{los} from rotation measure

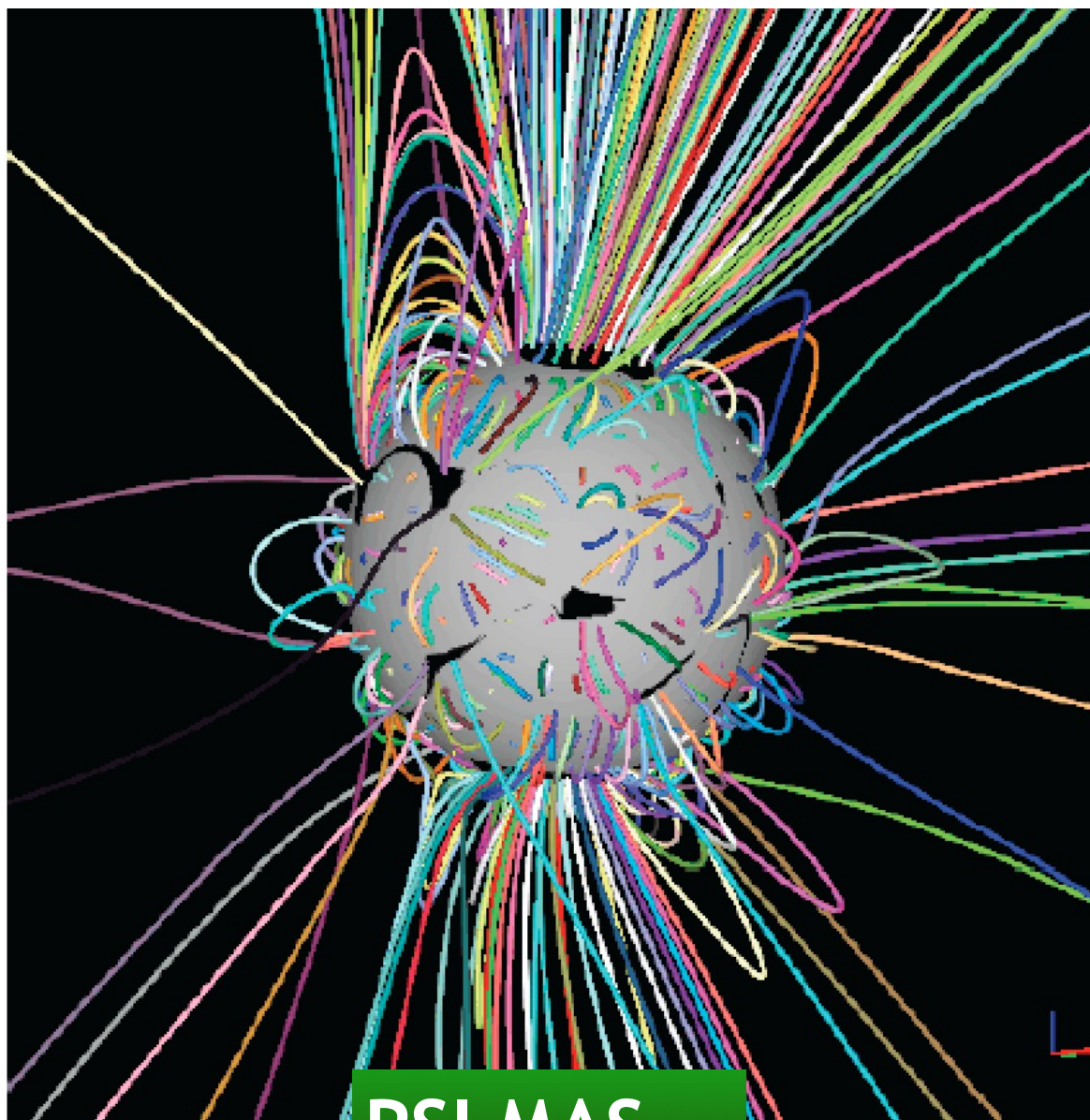
FORWARD SolarSoft IDL package

- Given plasma/magnetic fields synthesizes multi- λ observables
- Works with any analytic or numerical model
- Applies CLE code of Judge & Casini for visible/IR polarimetry

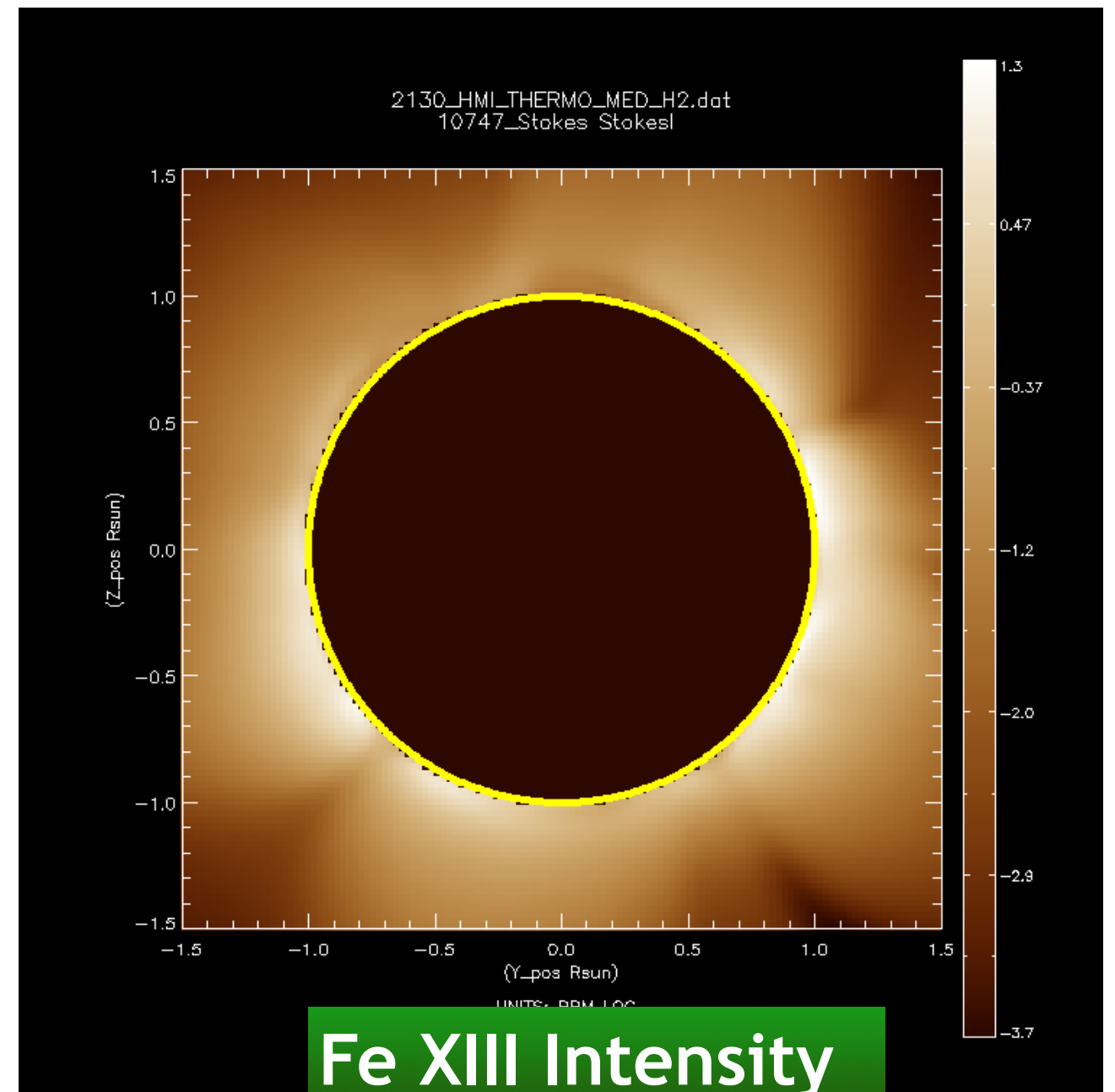


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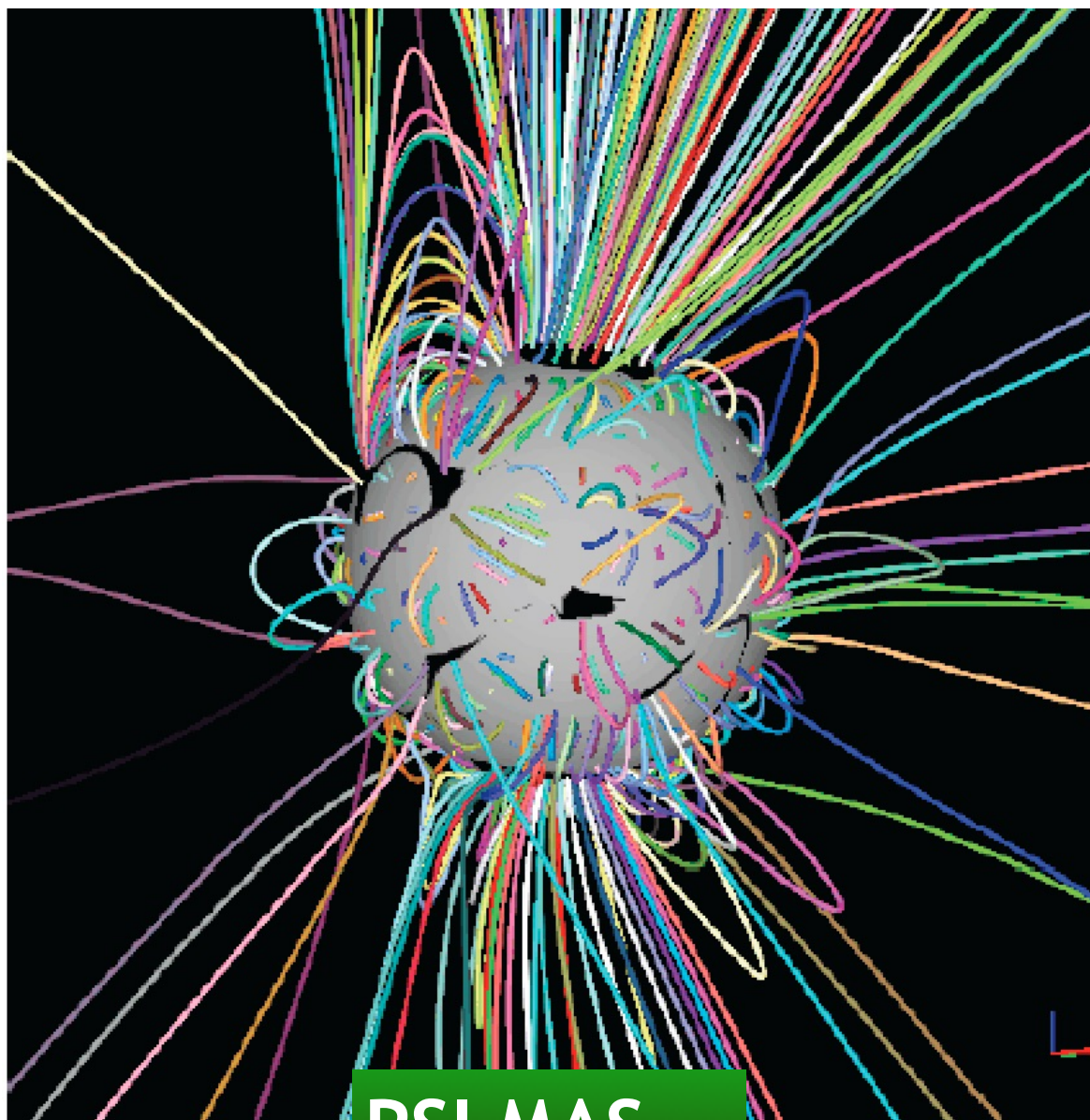
PSI MAS



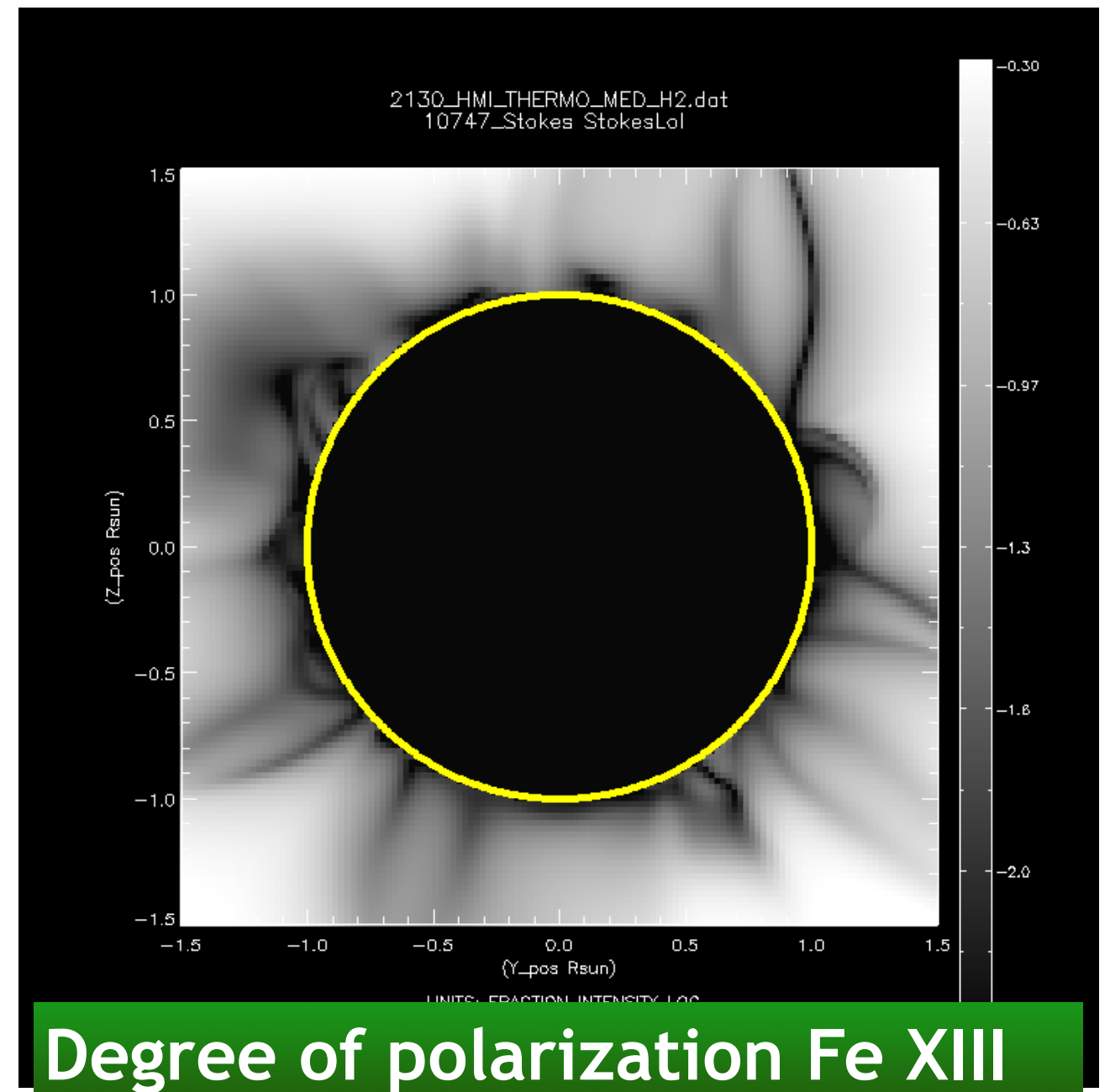
Fe XIII Intensity

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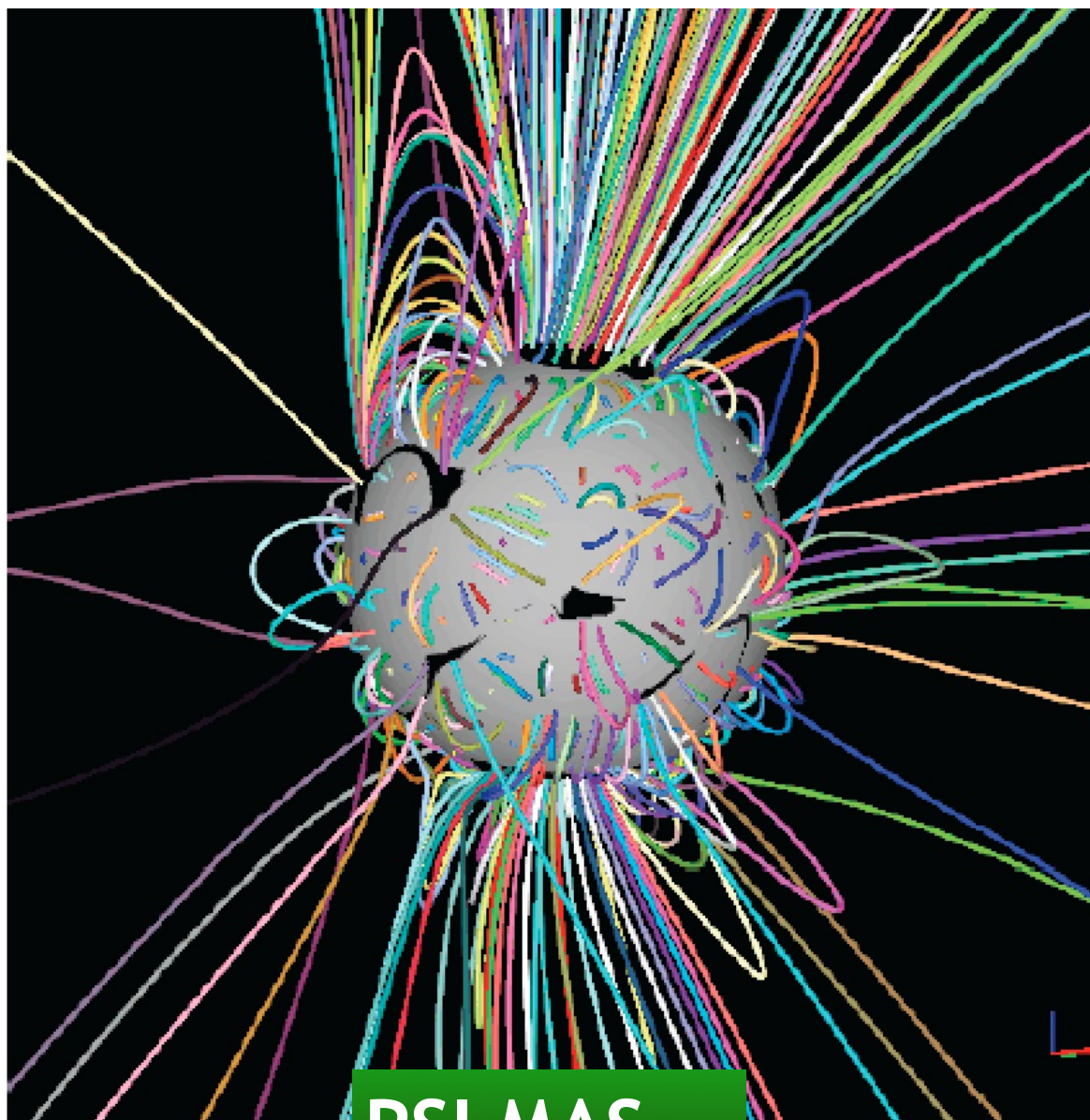
PSI MAS



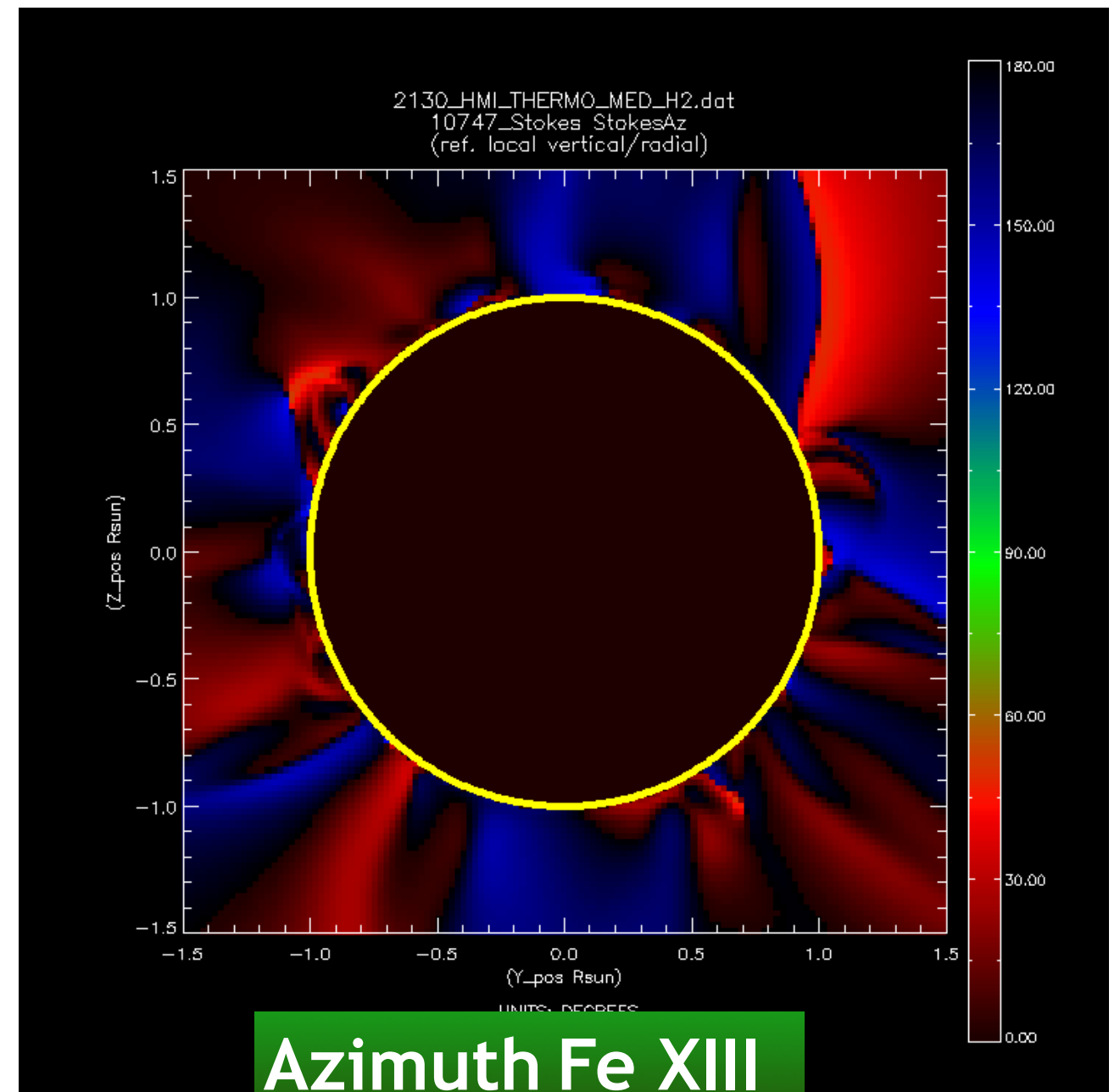
Degree of polarization Fe XIII

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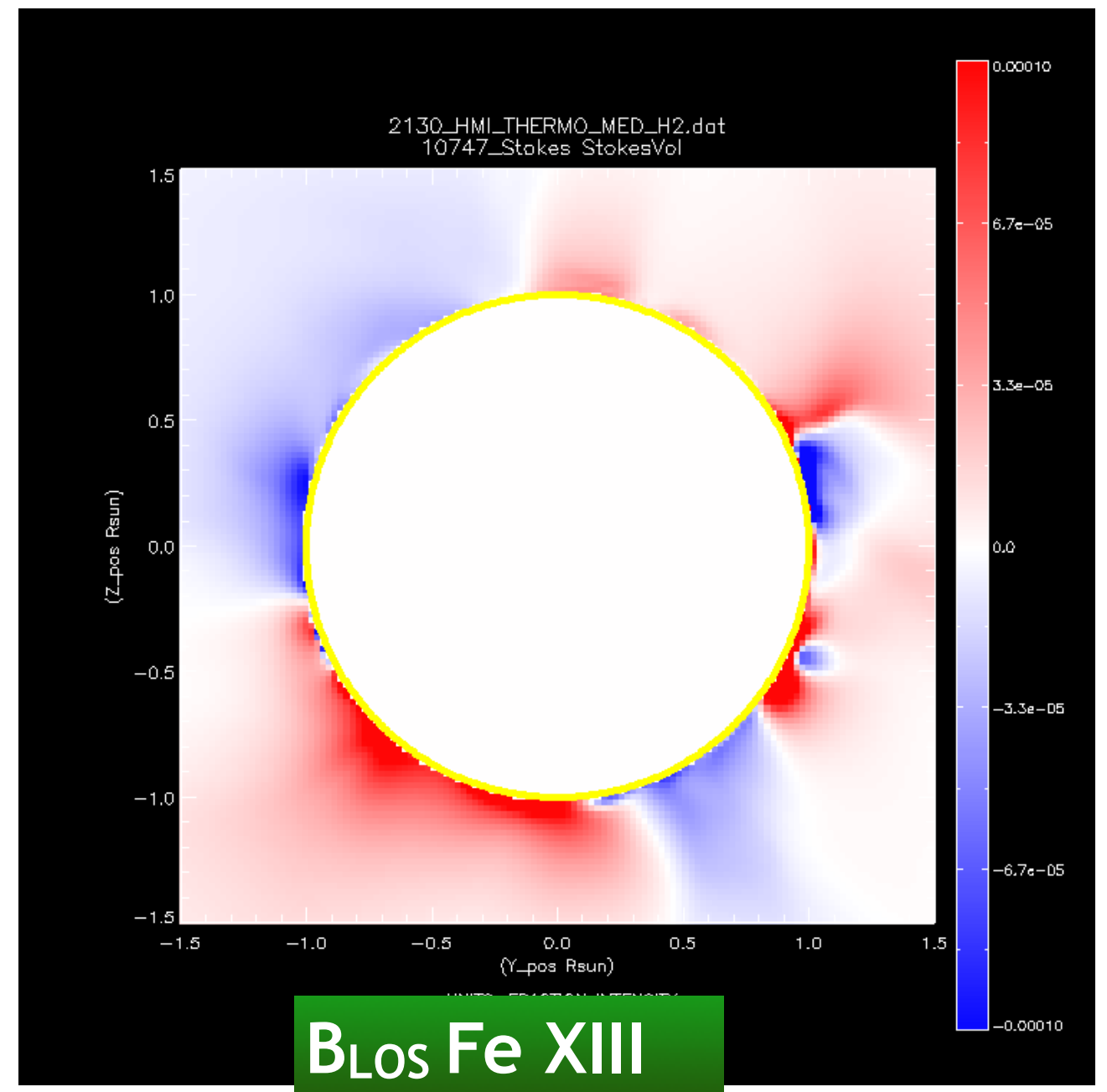
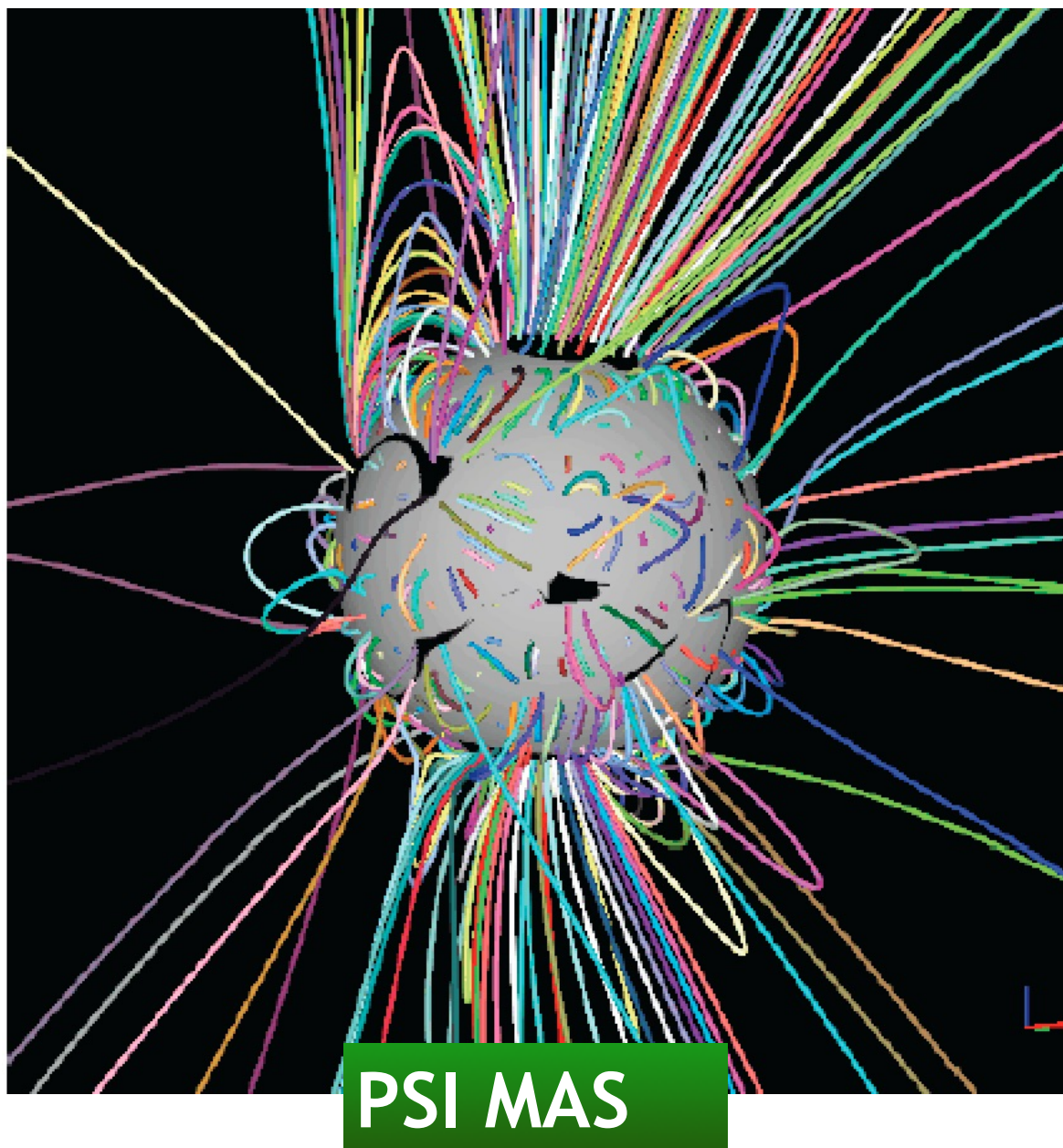
PSI MAS



Azimuth Fe XIII

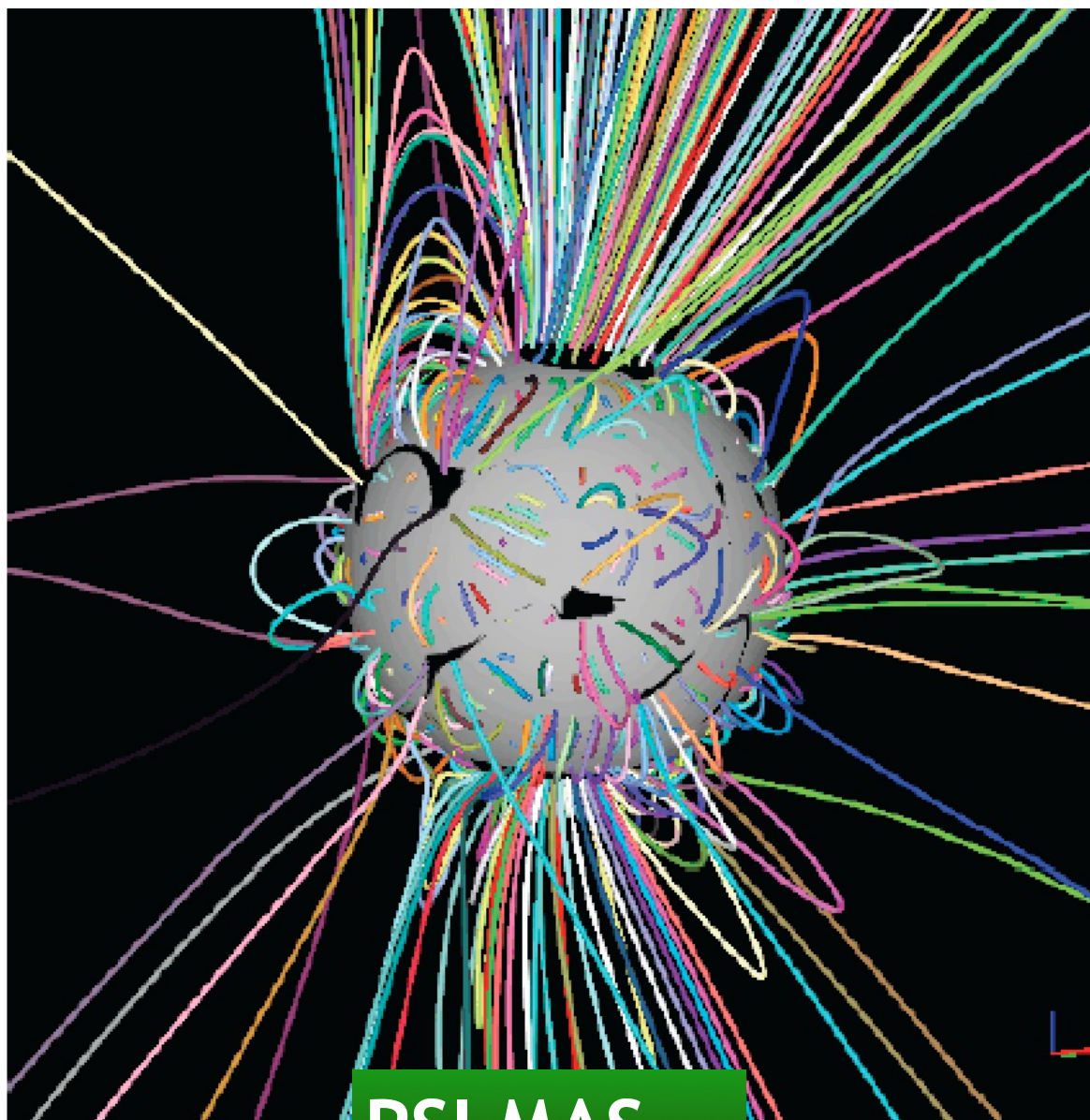
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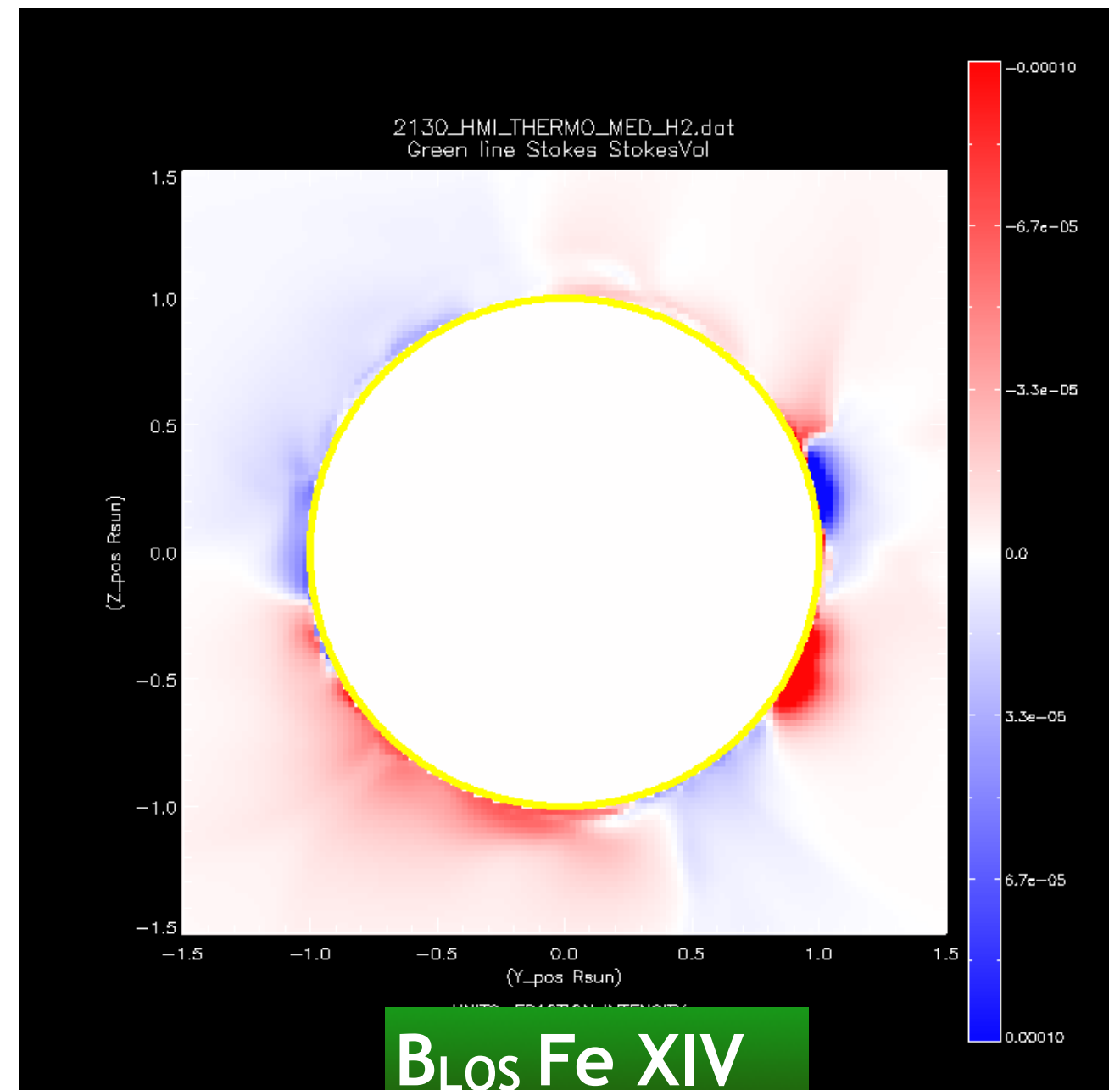


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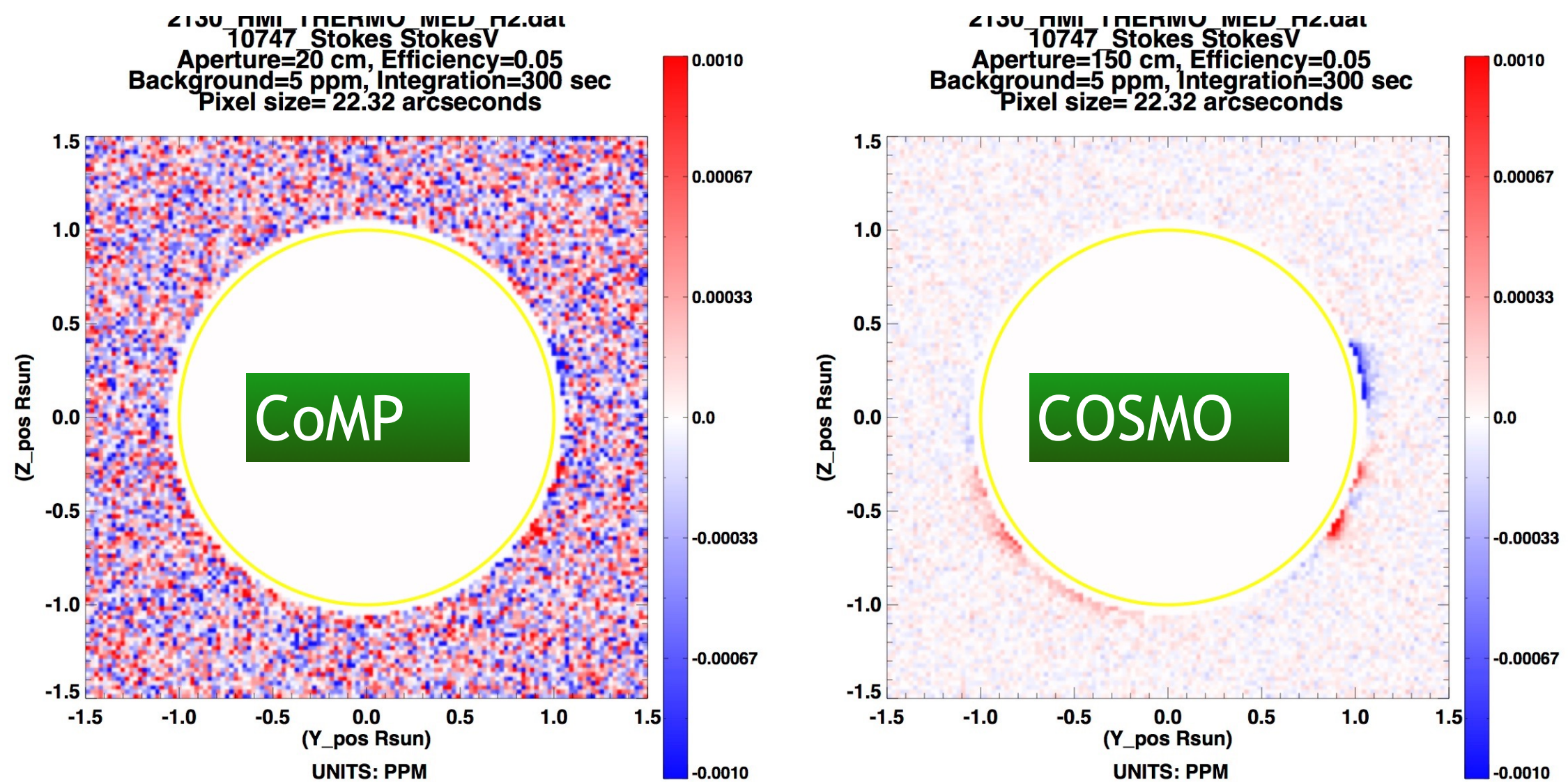
PSI MAS



B_{LoS} Fe XIV

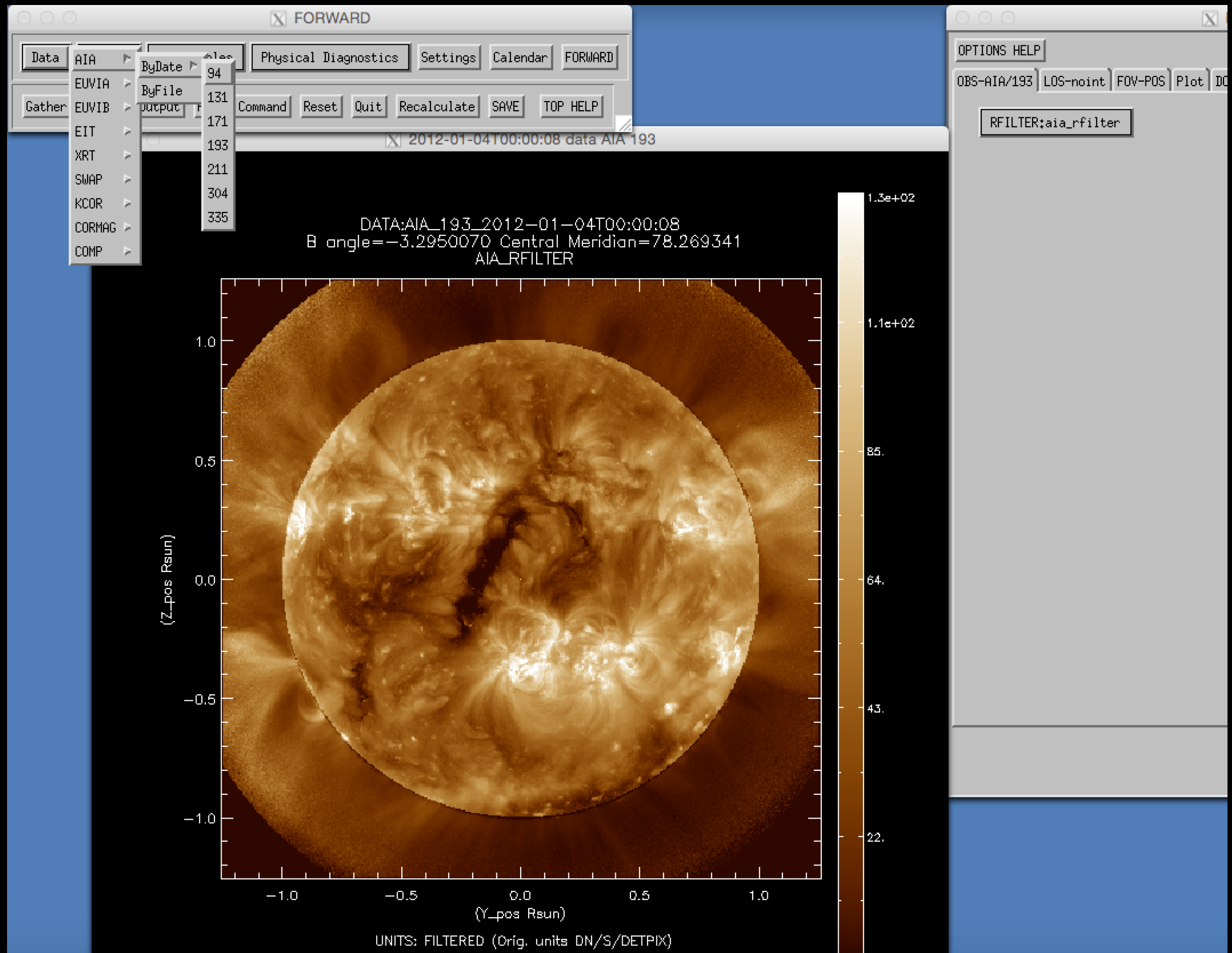
FORWARD SolarSoft IDL package

- Can add photon noise to telescope specifications

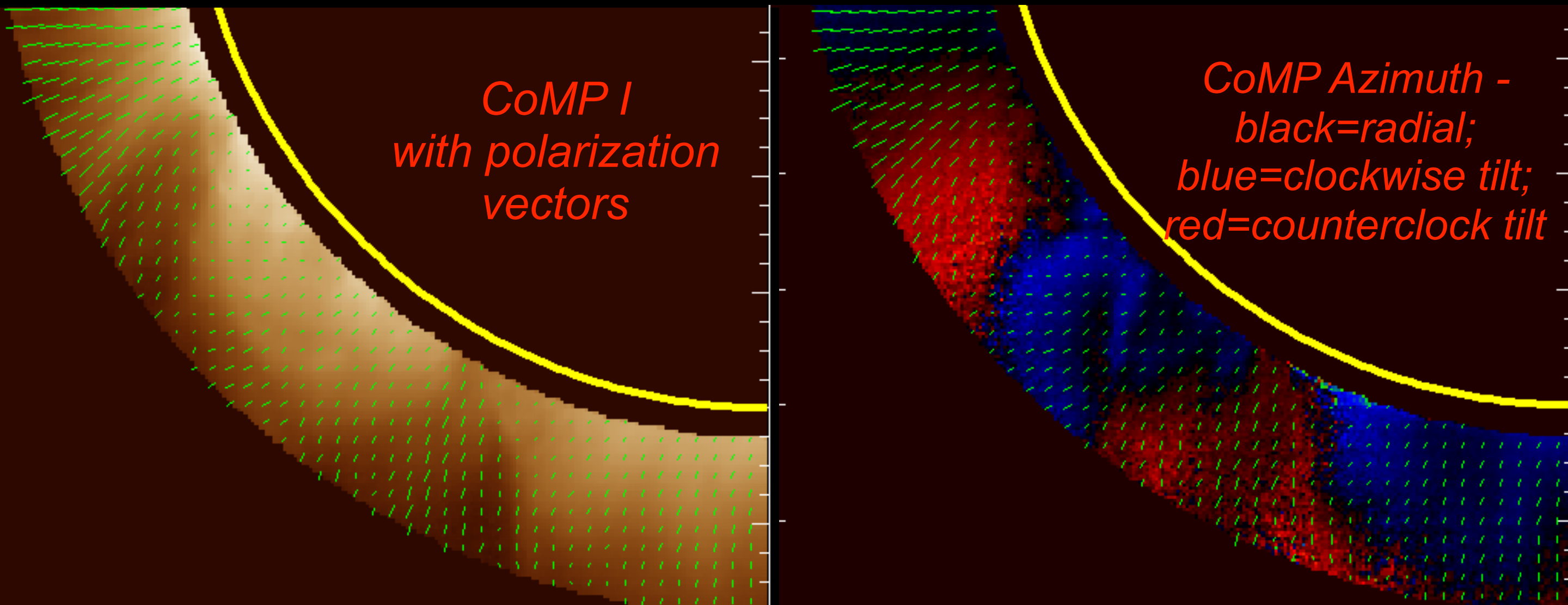


5 minute integration of circular polarization for Fe XIII

Observations



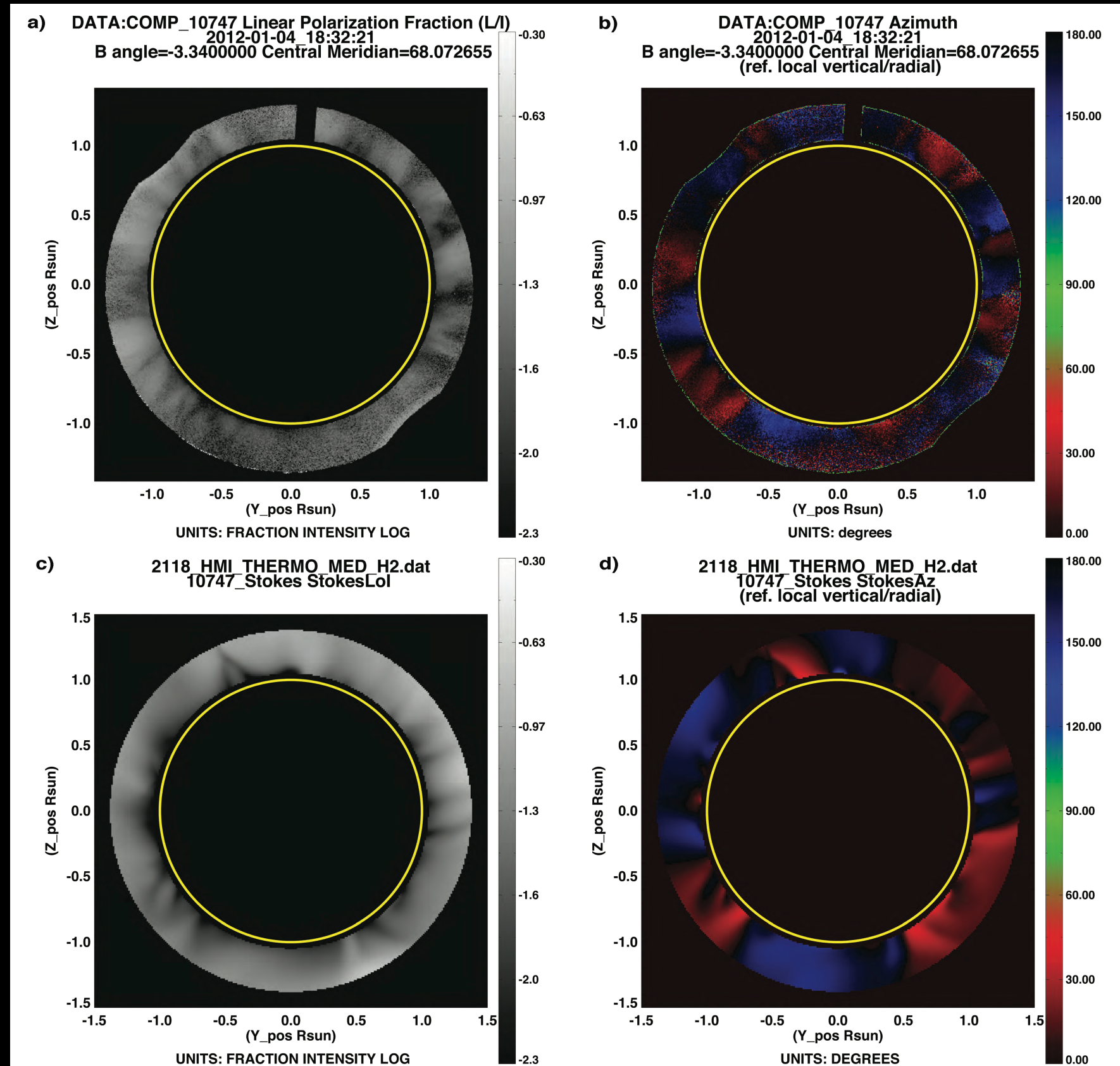
Observations



- Measures POS magnetic direction (with 90 degree flip when crosses V. Vleck angle)
- Quantifies expansion of flux tubes (significant to solar wind acceleration)

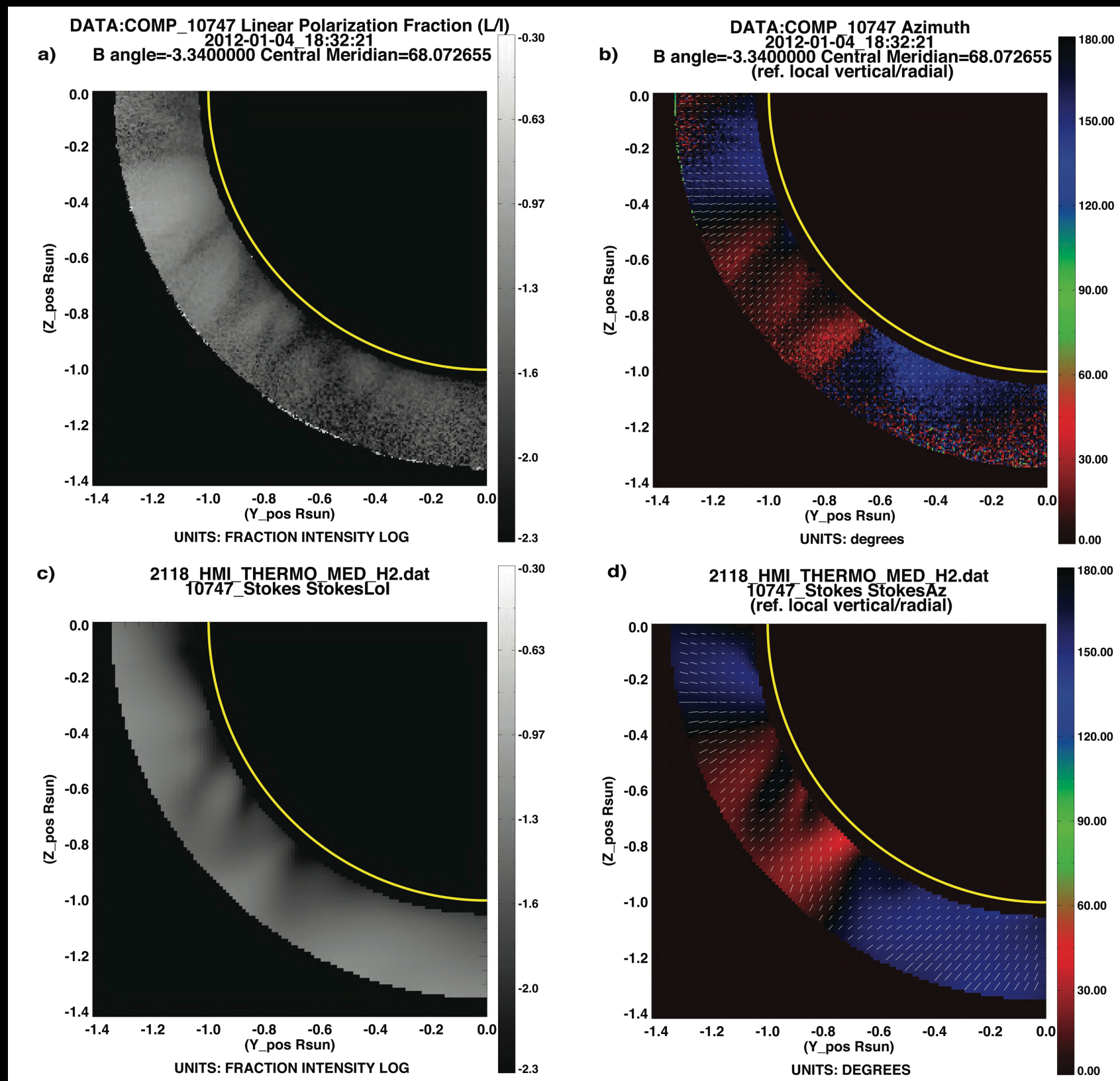
Model-data comparison

Model validation



Model-data comparison

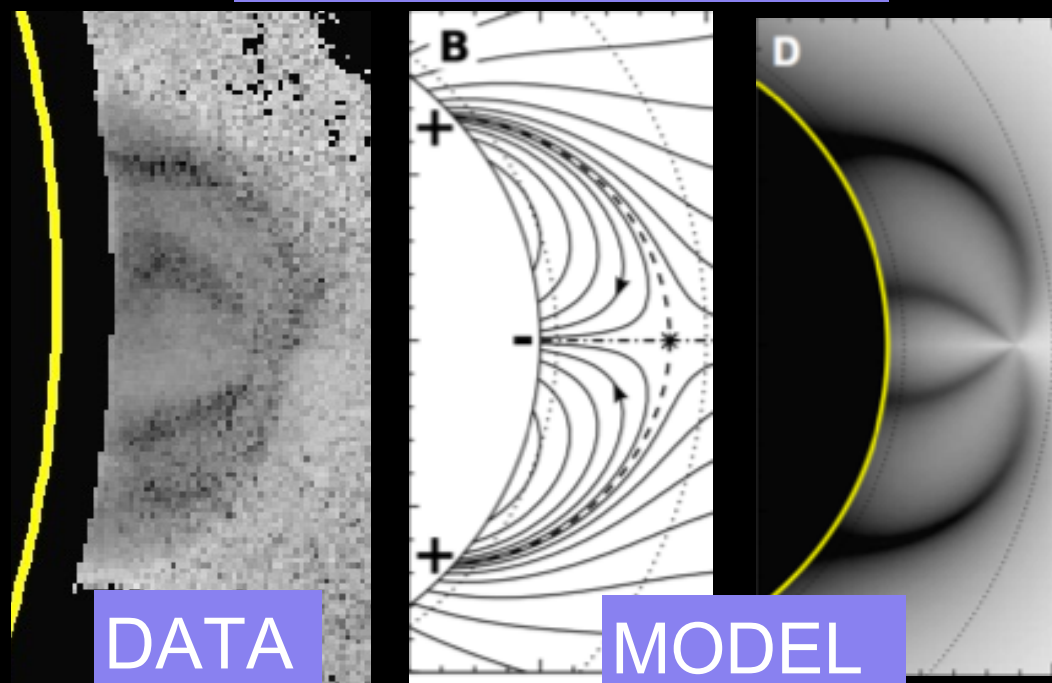
Model validation



Model-data comparison

Building intuition

Magnetic nulls



$$L/I = \frac{(\text{Stokes } Q^2 + \text{Stokes } U^2)^{1/2}}{\text{Stokes } I}$$

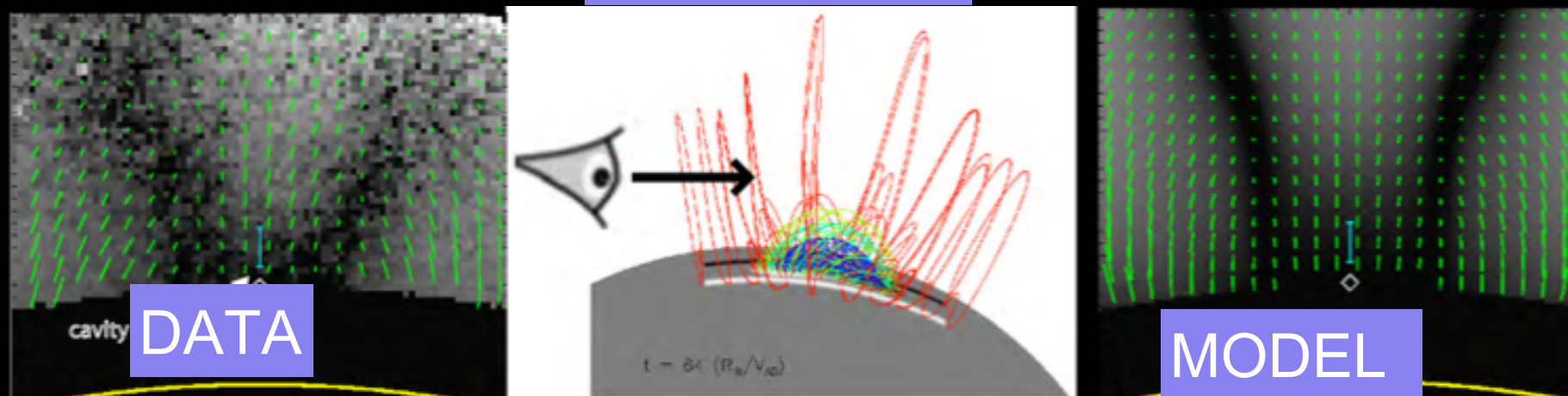
(Saturated) Hanle effect: depolarization

- Strong L/I signal: **B** in plane of sky
- zero: **B** along line of sight
- zero: Van Vleck angle (between **B** and radial) = 54.74

Gibson et al., 2017

Diagnostic of magnetic topology
(significant for predicting eruptions)

Flux ropes



Model-data comparison

Building intuition

$$Az = 0.5 \tan^{-1} \left(\frac{\text{Stokes } U}{\text{Stokes } Q} \right)$$

*CoMP Azimuth -
black=radial;
blue=clockwise tilt;
red=counterclockwise tilt*

diverging
fields

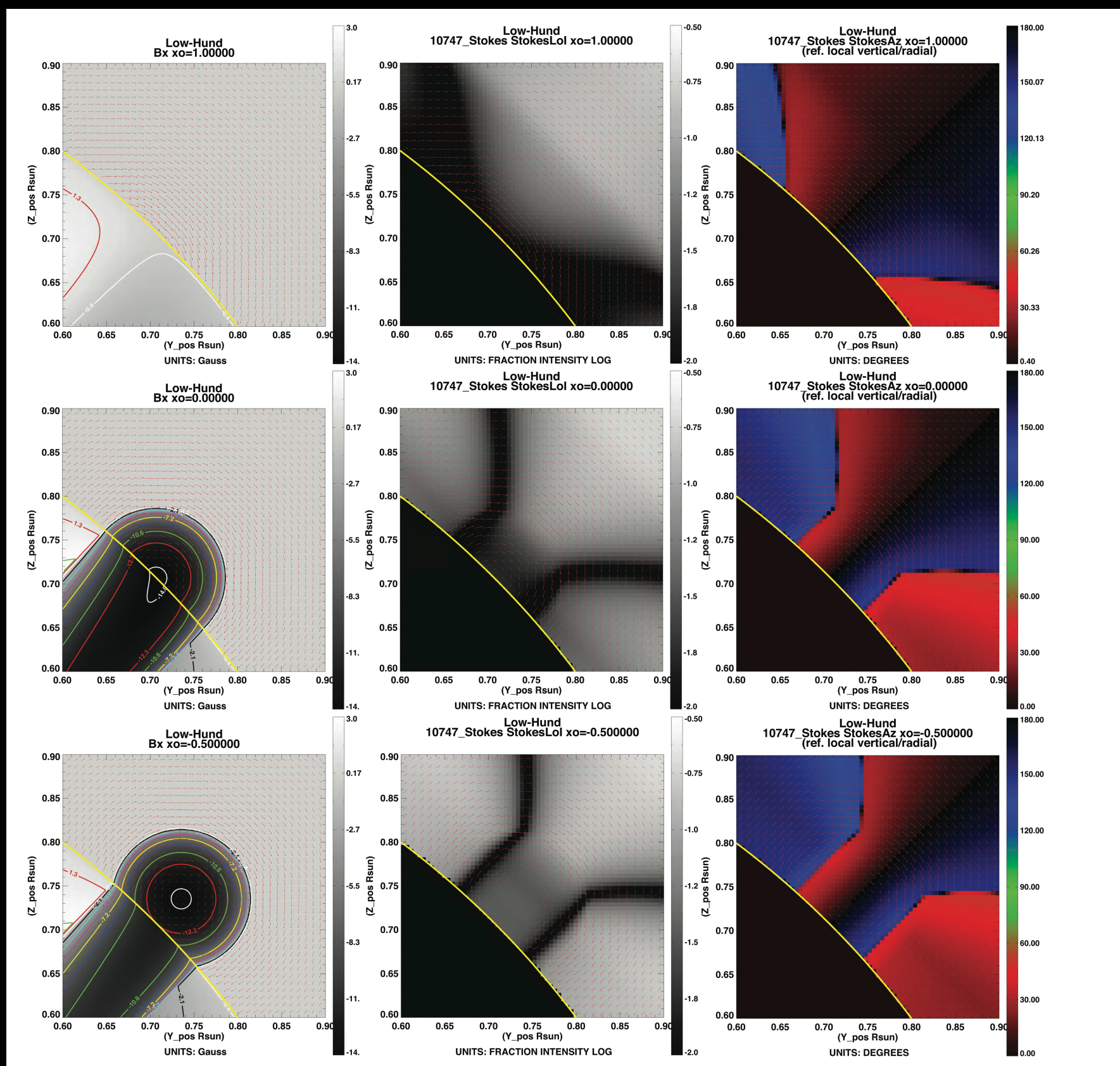
converging
fields

Linear polarization azimuth
= direction of POS vector
(but rotates 90 degrees at
V. Vleck angle!)

Diagnostic of non-radial expansion

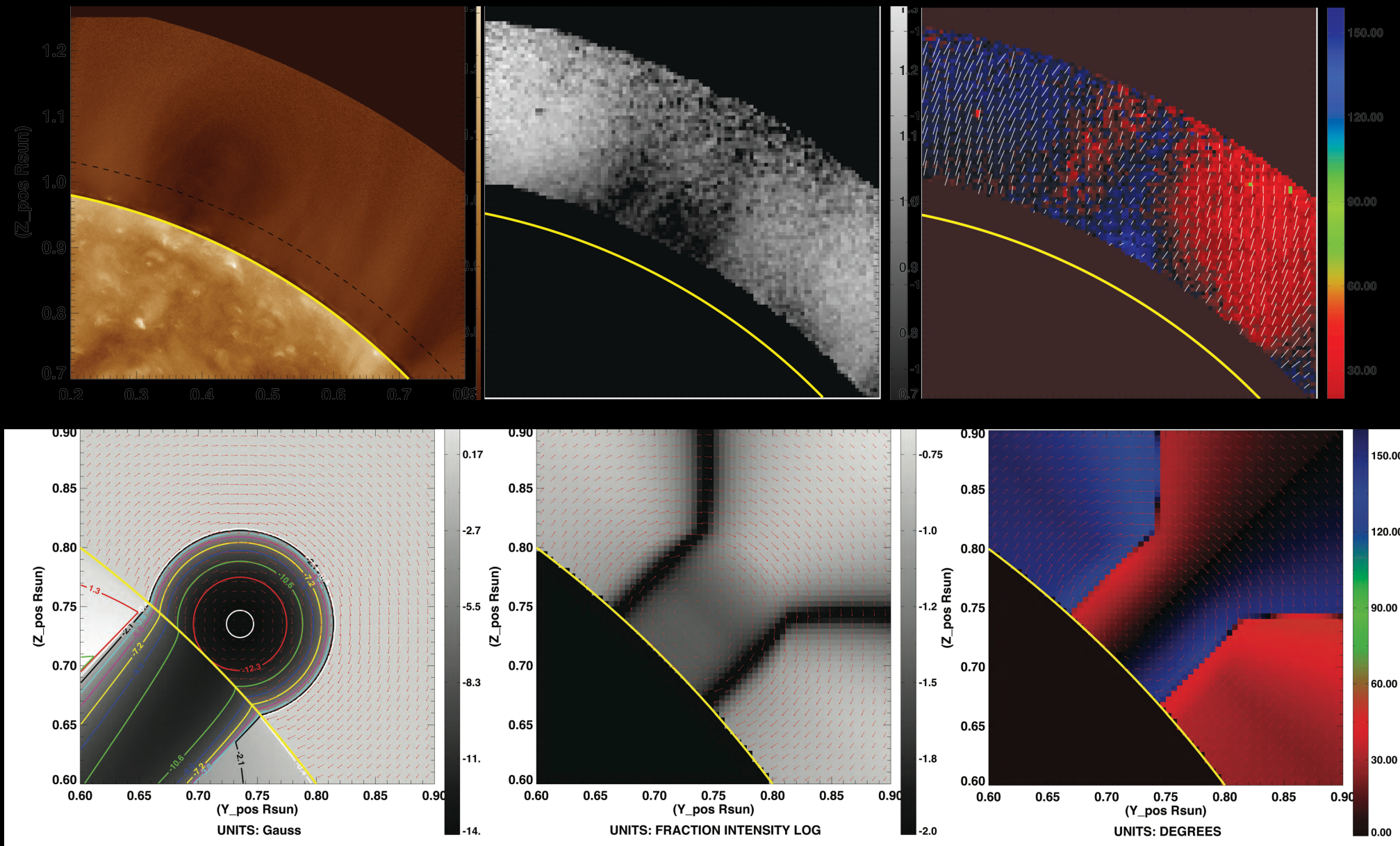
Model-data comparison

Forward fitting

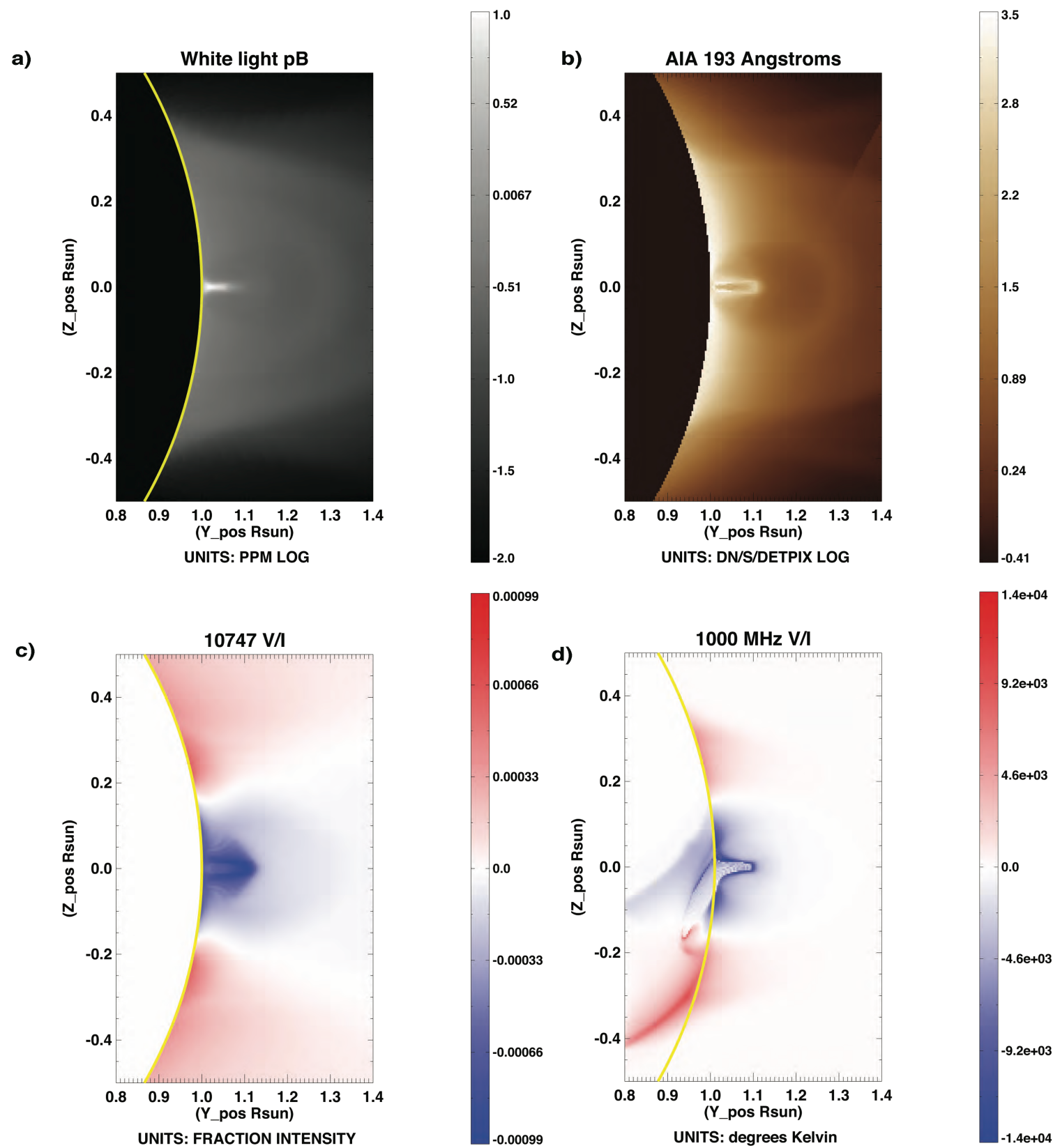


Model-data comparison

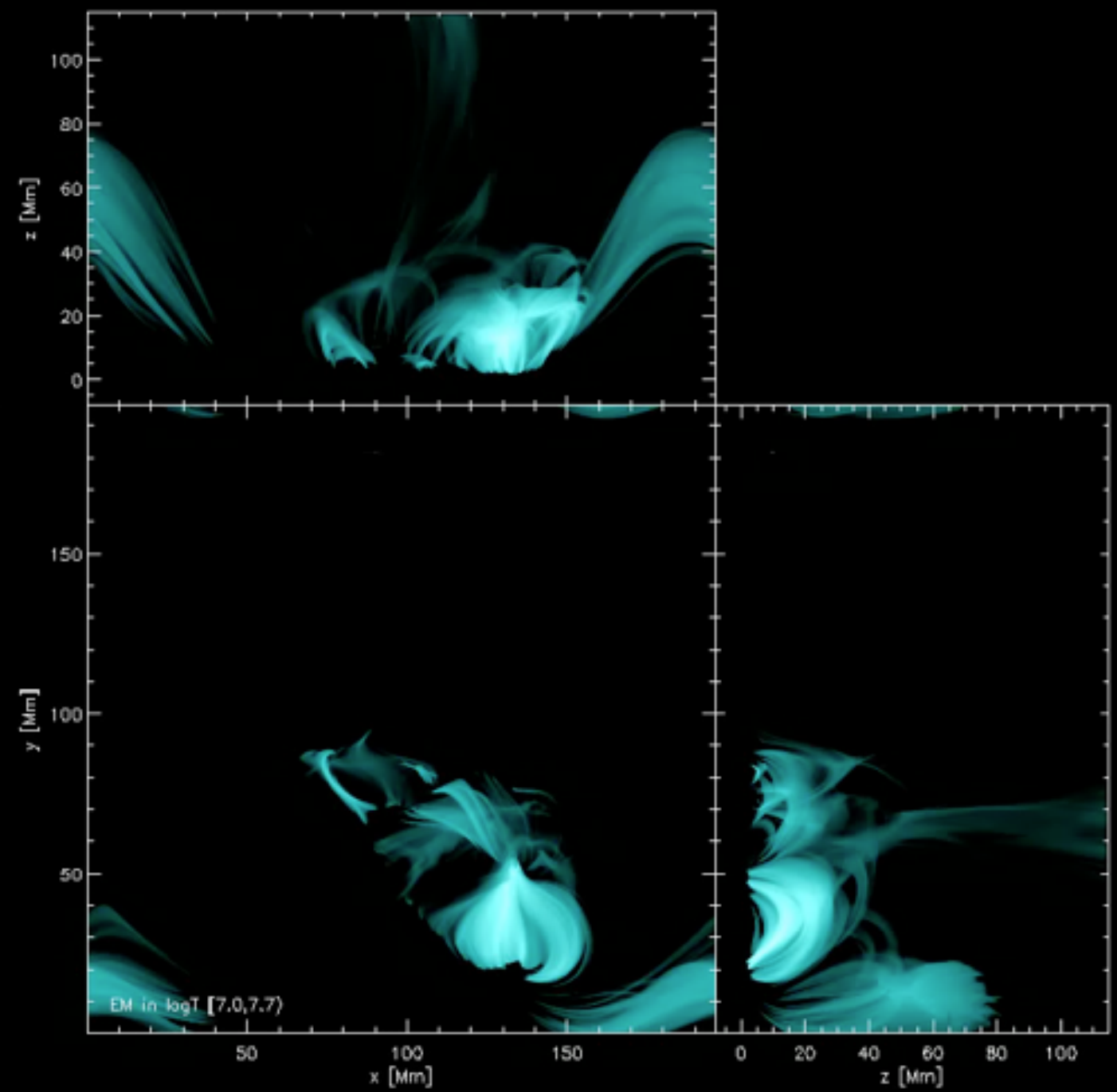
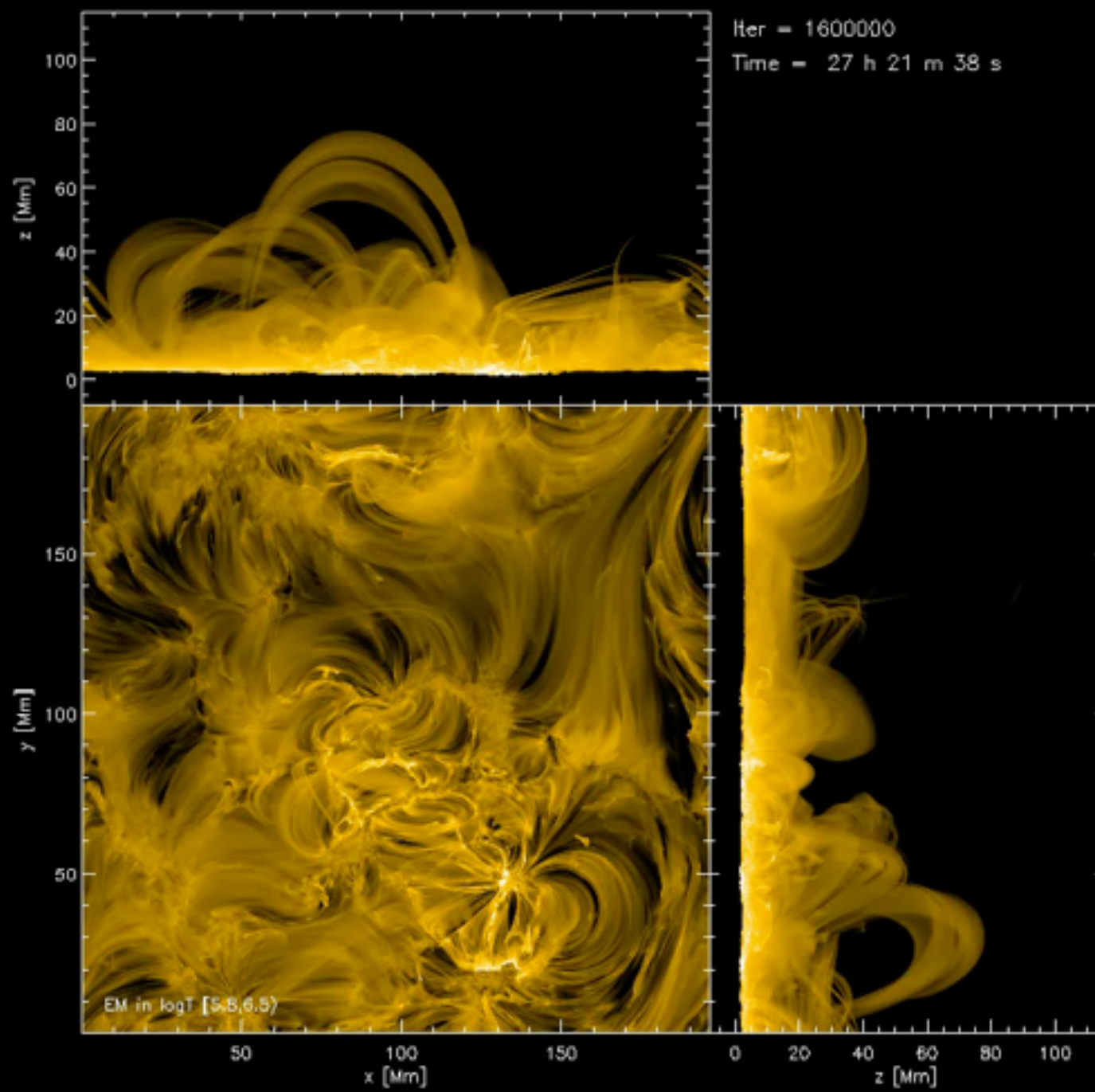
Forward fitting



Synthetic test beds

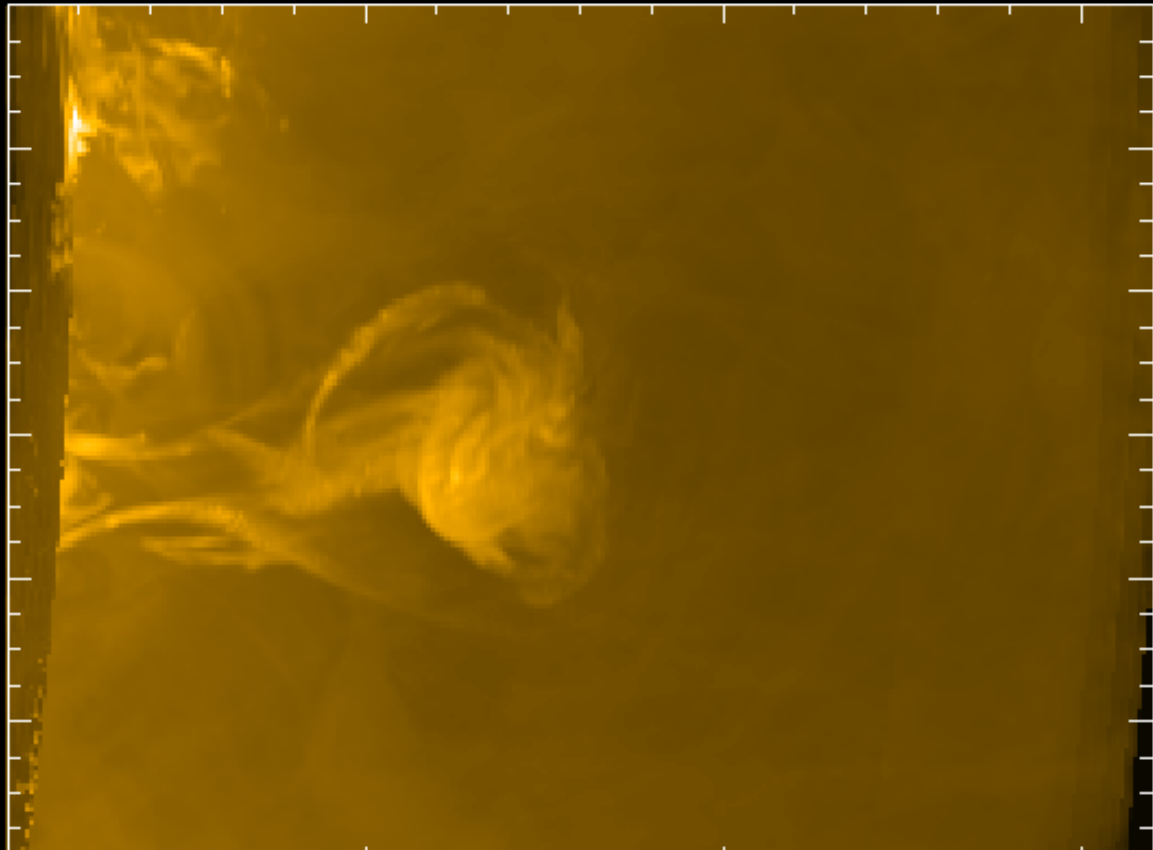


Fan, 2015
flux rope
simulation -
included with
FORWARD
distribution

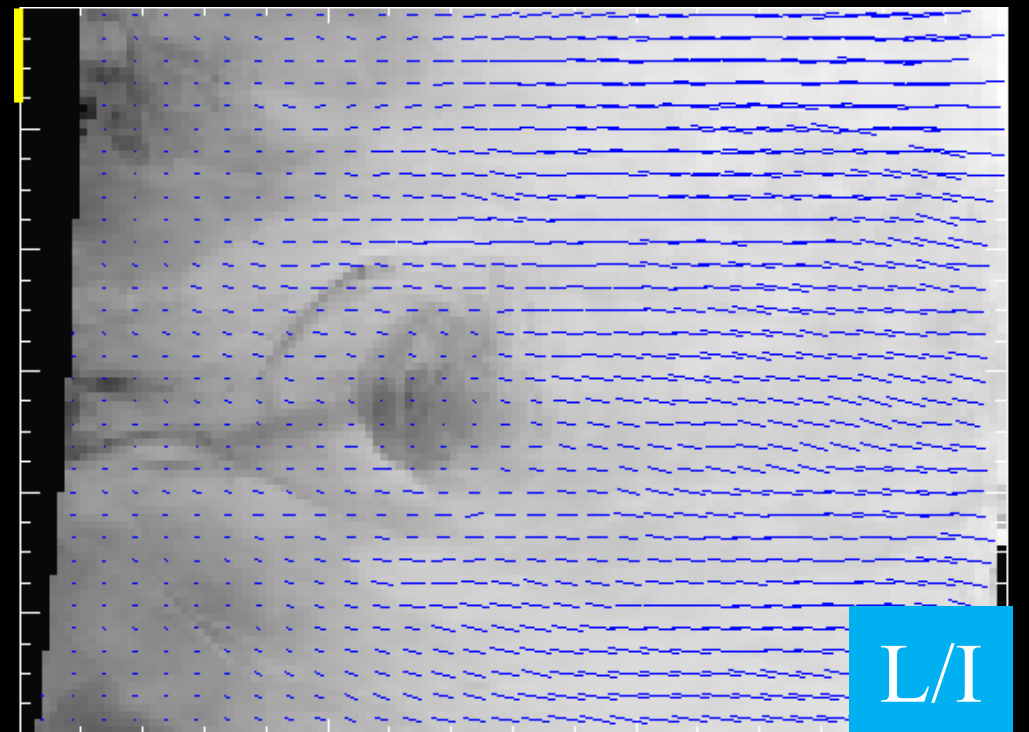
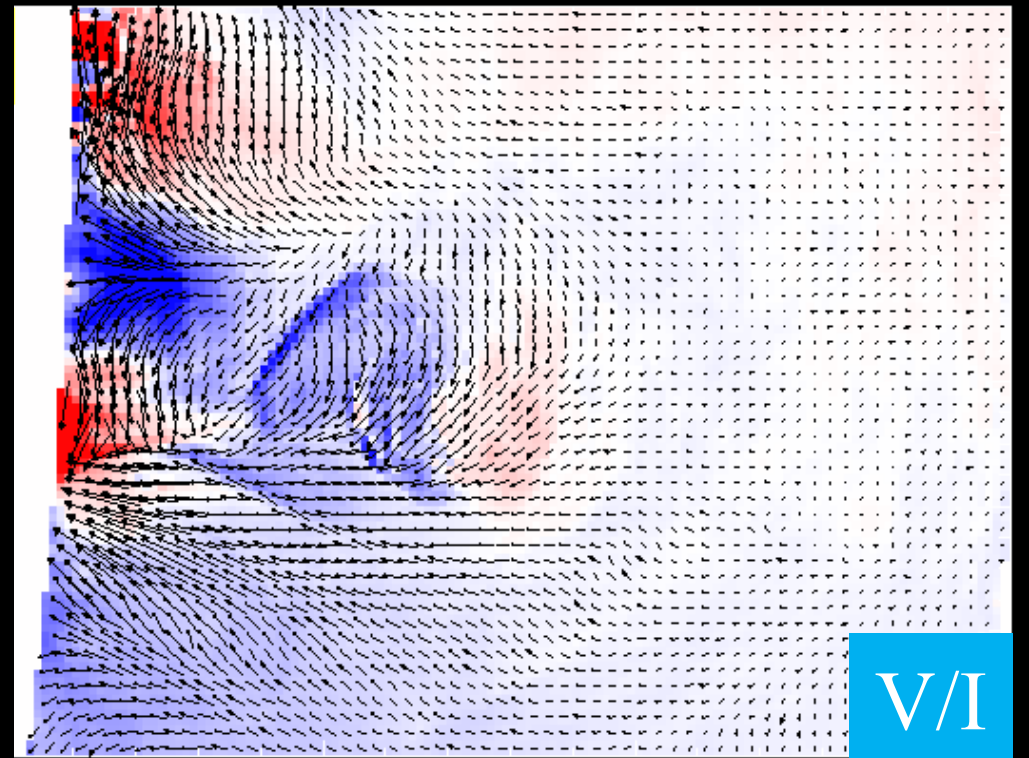


Emerging active region: Rempel, 2017

Synthetic test beds



**Exposes sensitivities of
polarimetric data to high
densities, temperatures,
and velocities**



Conclusions

- A range of magnetically sensitive physical processes have observational signatures **in the corona** at wavelengths from radio to soft Xray
- FORWARD is a community toolset for model-data comparison, enabling model validation, building intuition for coronal magnetic signatures, and forward fitting/inversion applications
- Synthetic testbeds provide a “ground truth” against which to test new methodologies for multi wavelength coronal magnetometry