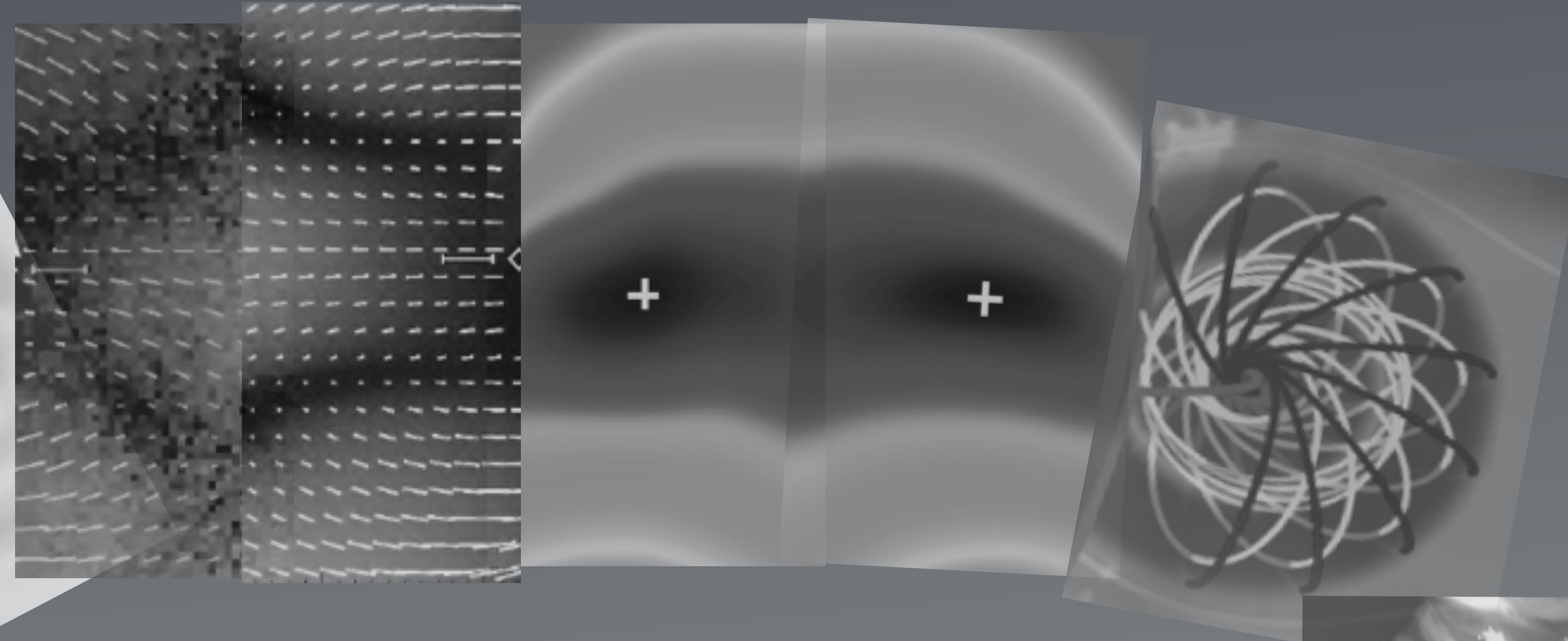
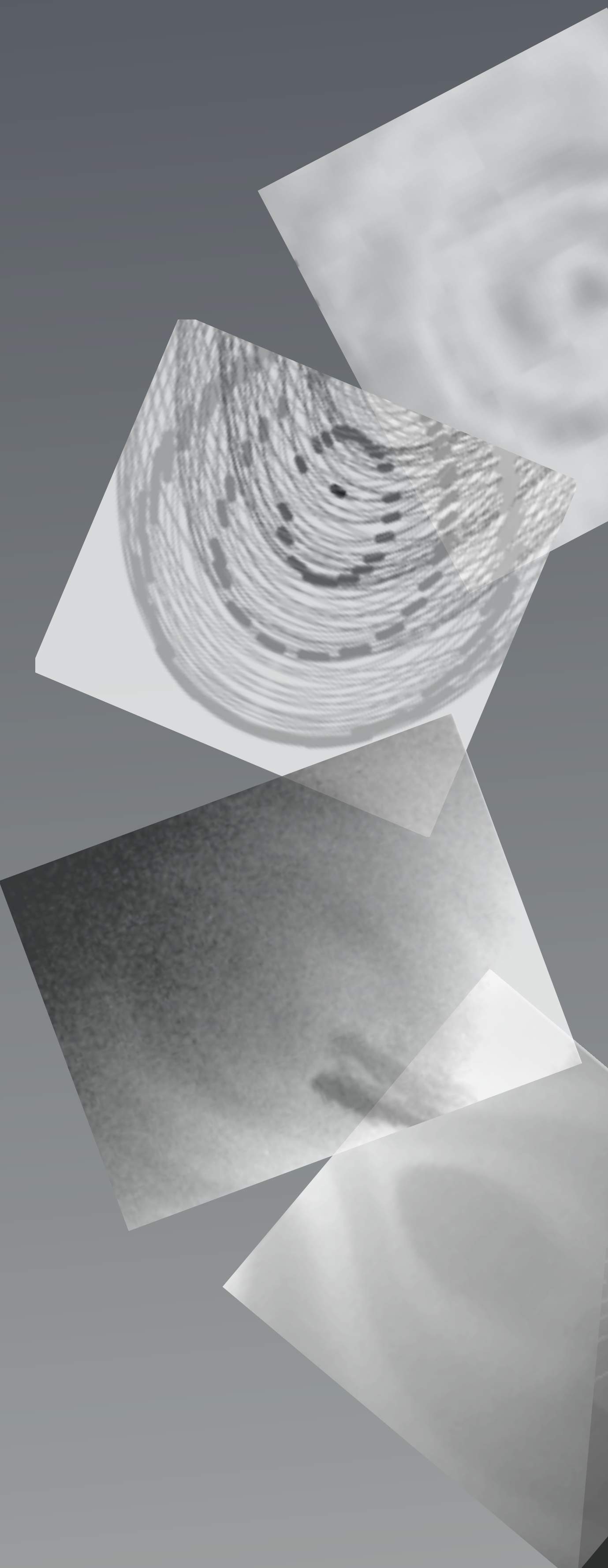
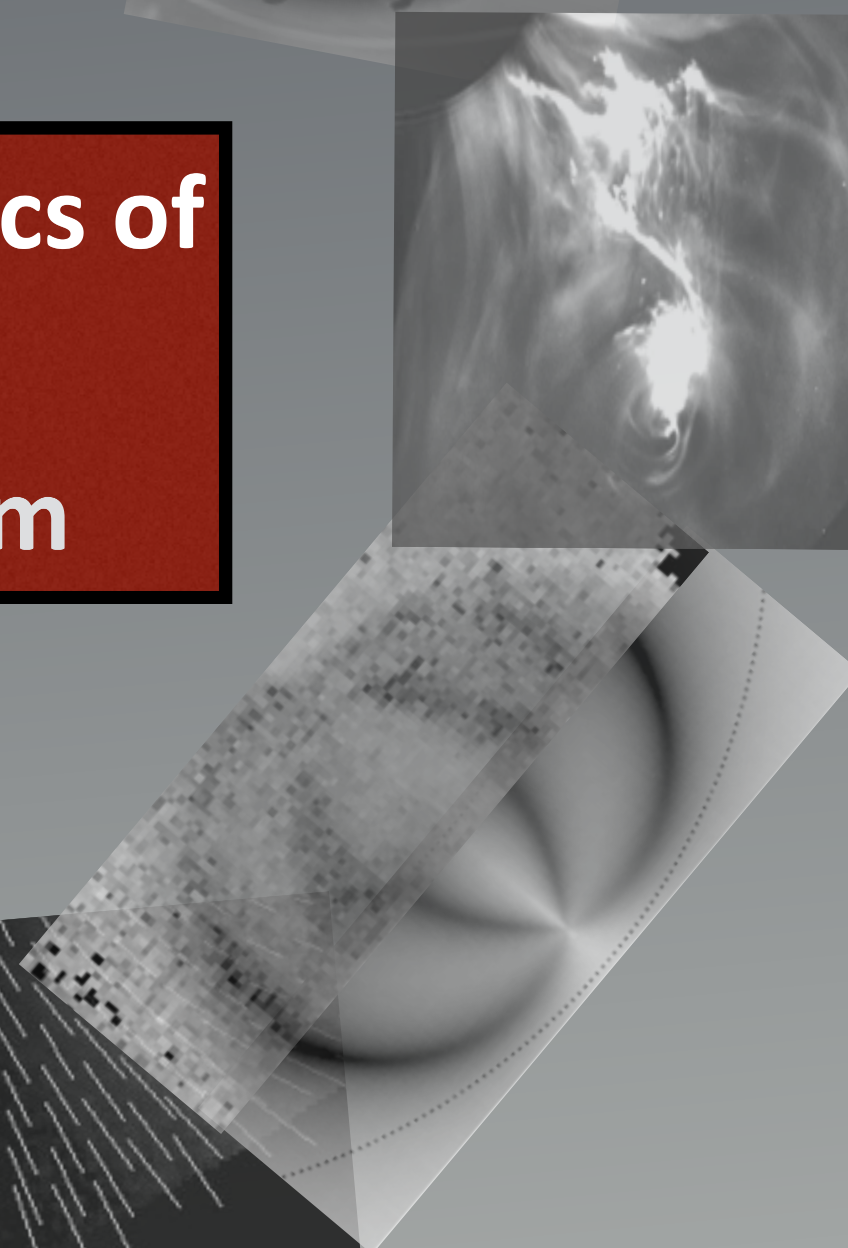
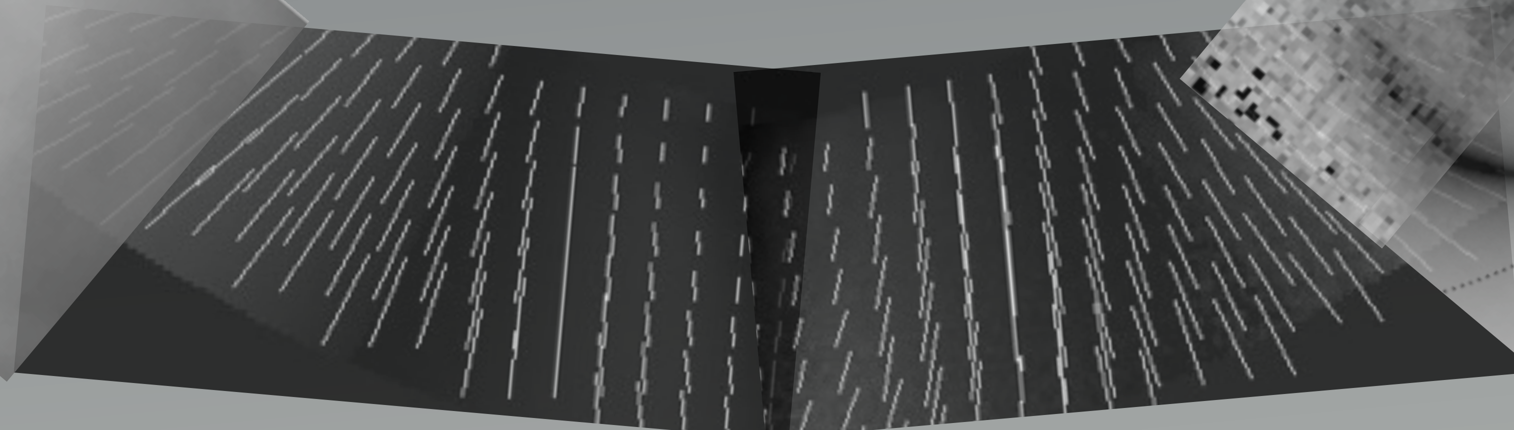



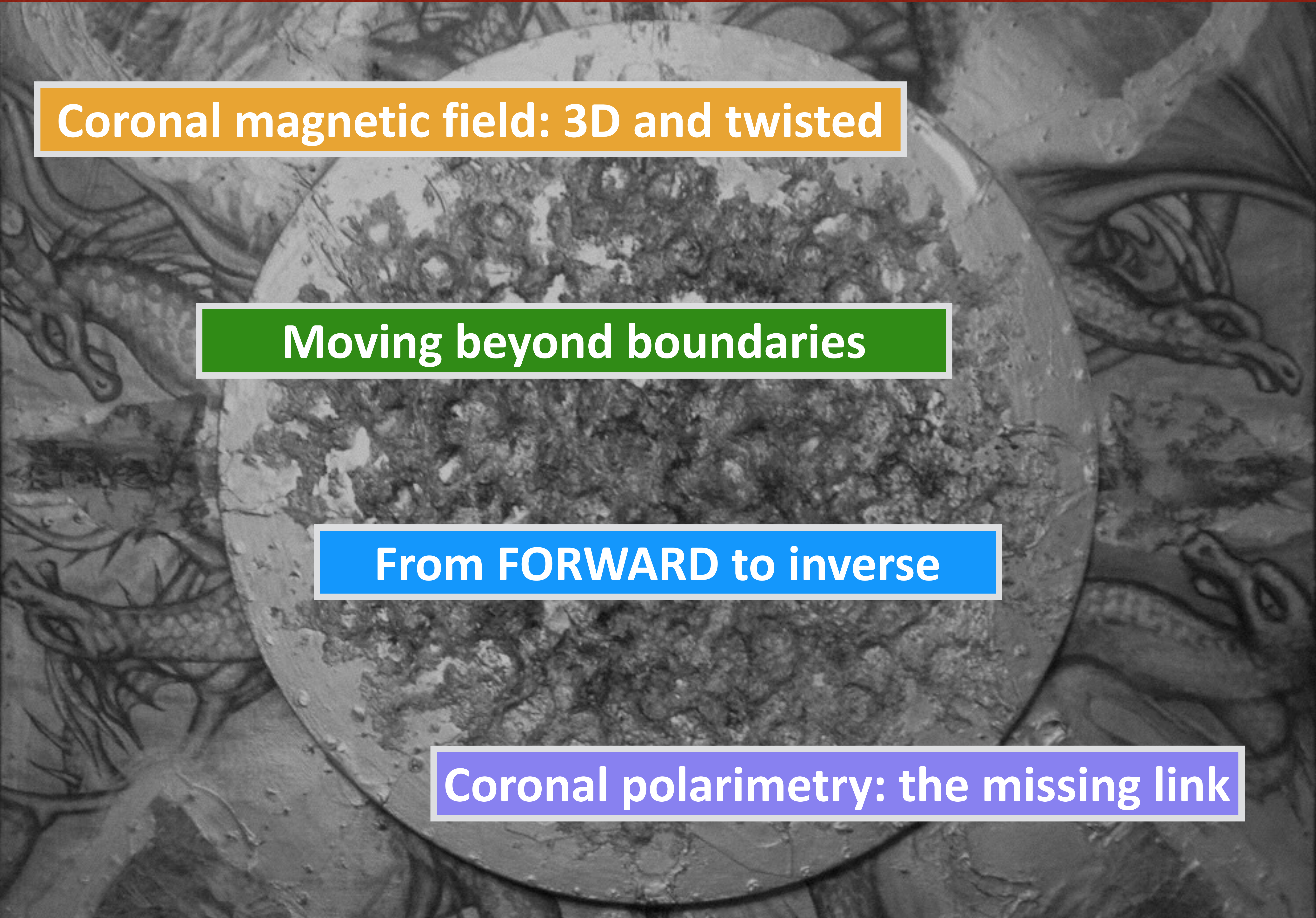
Dynamics and diagnostics of the solar corona:

Unchained magnetism

Sarah Gibson

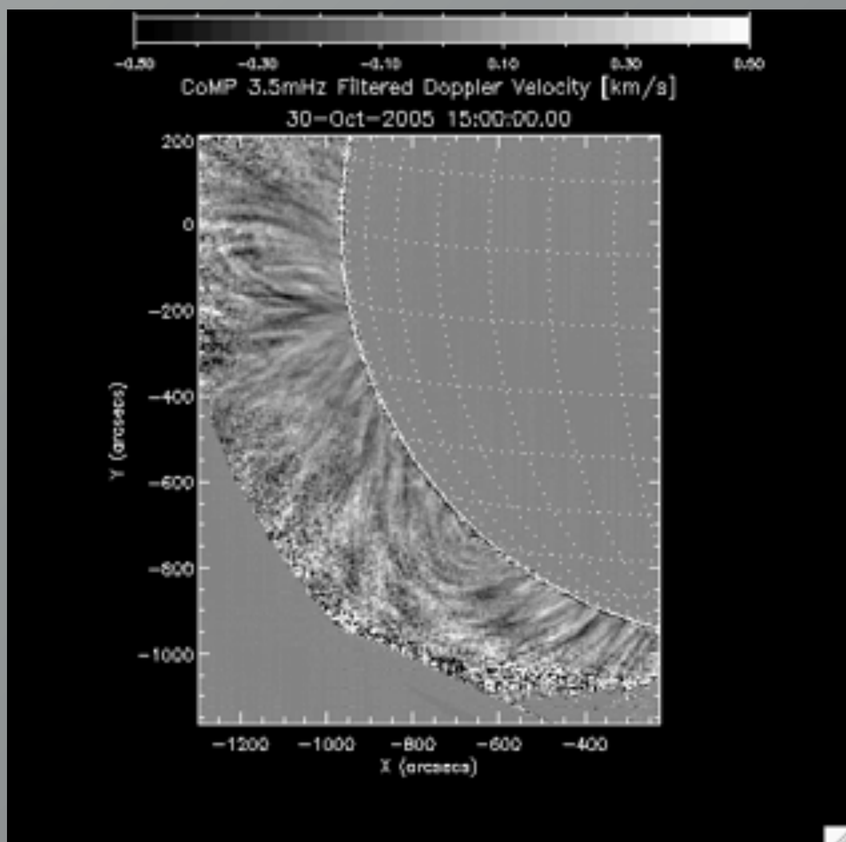
Outline



- Coronal magnetic field: 3D and twisted
- Moving beyond boundaries
- From FORWARD to inverse
- Coronal polarimetry: the missing link

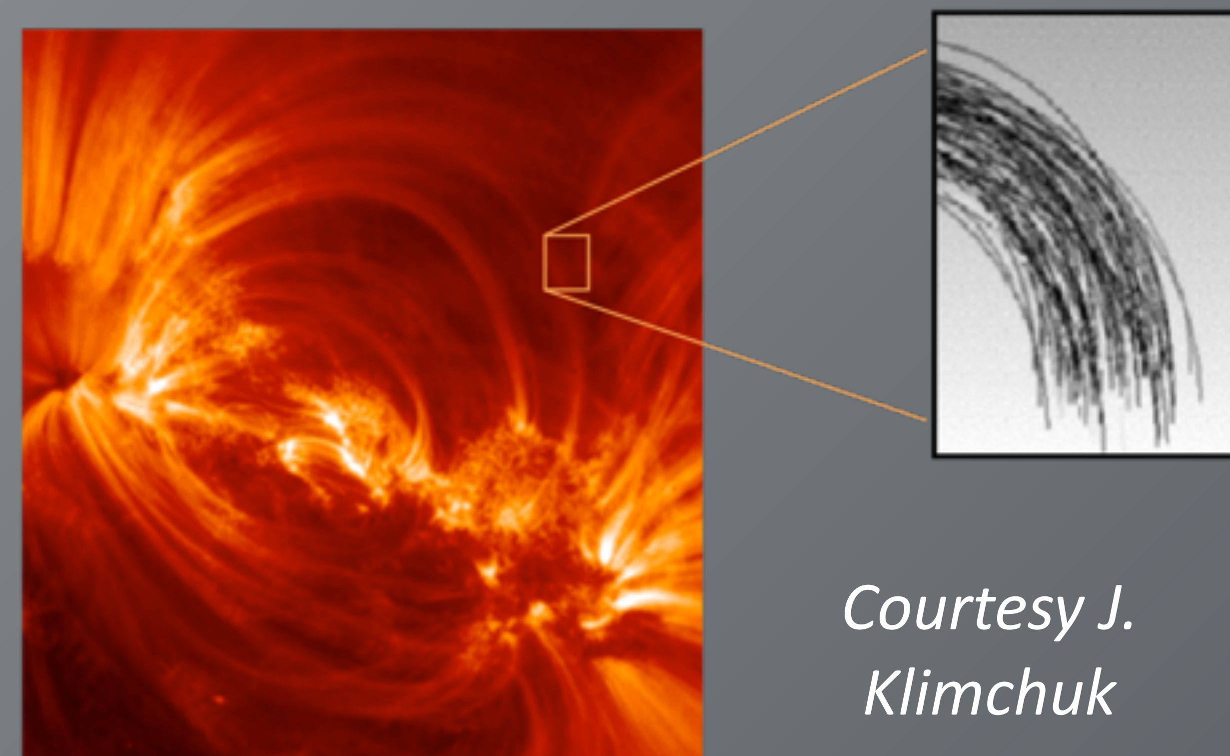
Coronal magnetic fields: 3D and twisted

Why we care about the coronal magnetic field



Tomczyk et al 2006

Waves



Courtesy J. Klimchuk

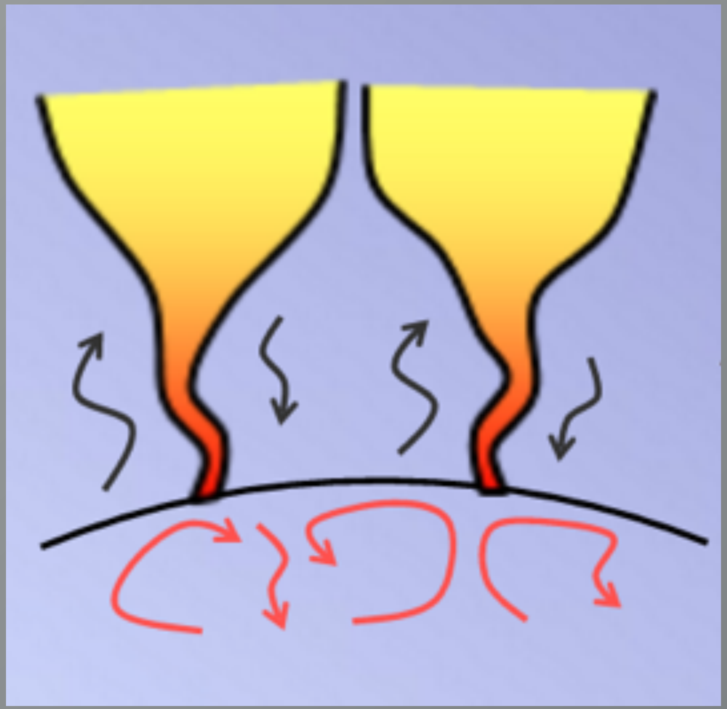
Nanoflares (reconnection-driven)

Important for coronal heating

Parker, 1972; Levine, 1974; Klimchuk 2006; 2015; Parnell & de Moortel, 2012; de Moortel & Browning 2015 (and references therein)

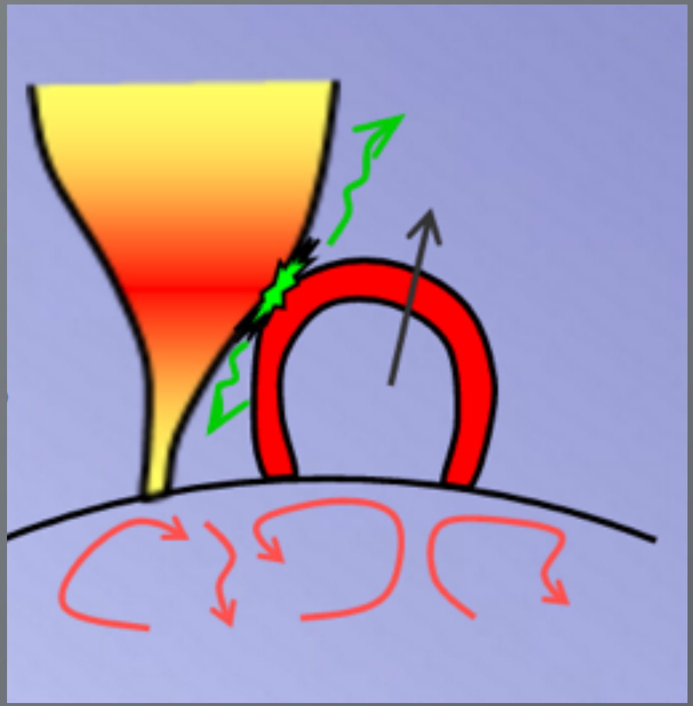
Coronal magnetic fields: 3D and twisted

Why we care about the coronal magnetic field



Waves/turbulence (magnetic flux-tube expansion)

Courtesy S. Cranmer



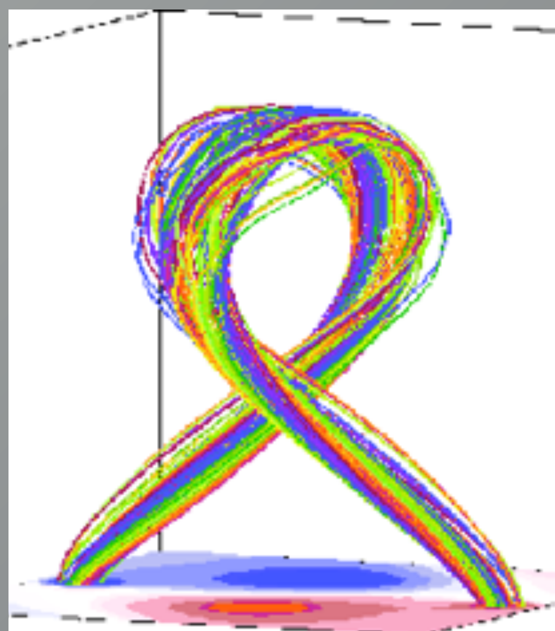
Reconnection-driven

Important for solar wind acceleration

Leer & Holzer, 1980; Pneuman, 1980; Wang & Sheeley, 1990; Suess et al. 1998; Fisk 2003; Wood, 2004; Cranmer, 2009; 2012; Ofman, 2010 (and references therein)

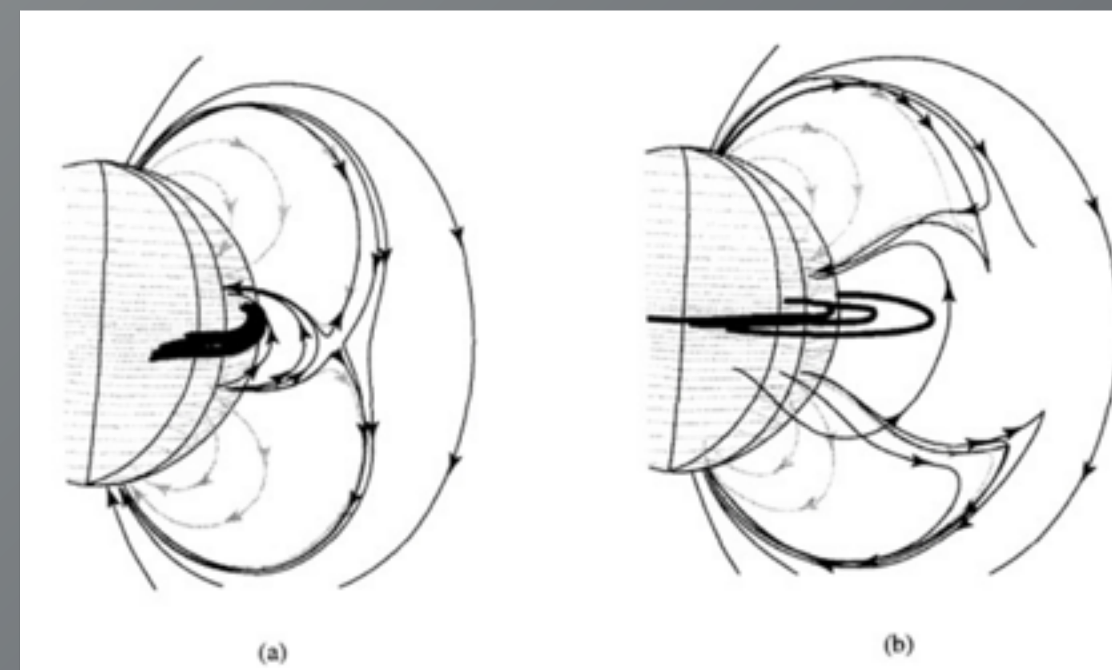
Coronal magnetic fields: 3D and twisted

Why we care about the coronal magnetic field



Toeroek et al., 2008

Ideal instability



Antiochos et al. 1999

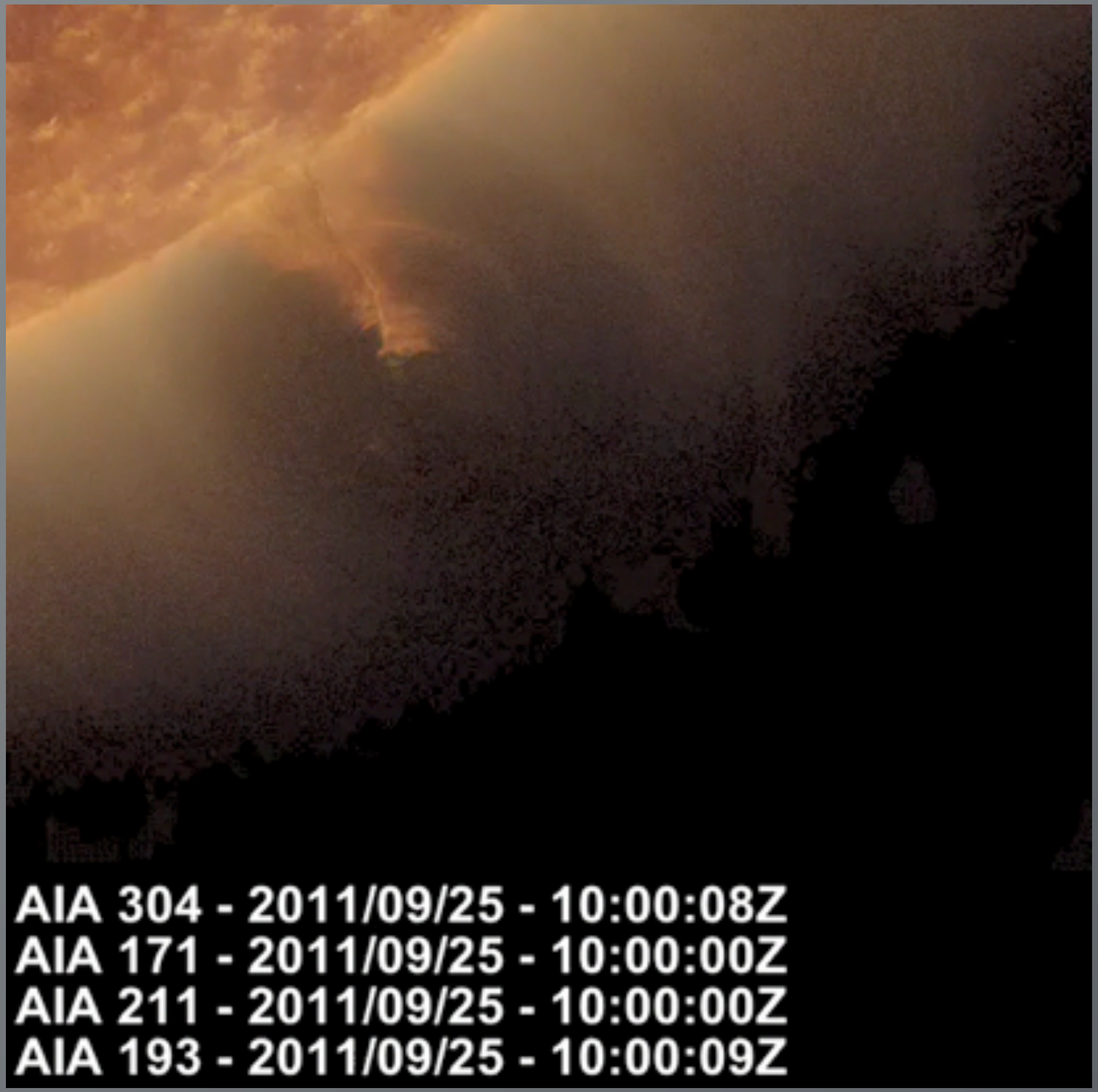
Reconnection-driven

Important for flares/CMEs/ space weather

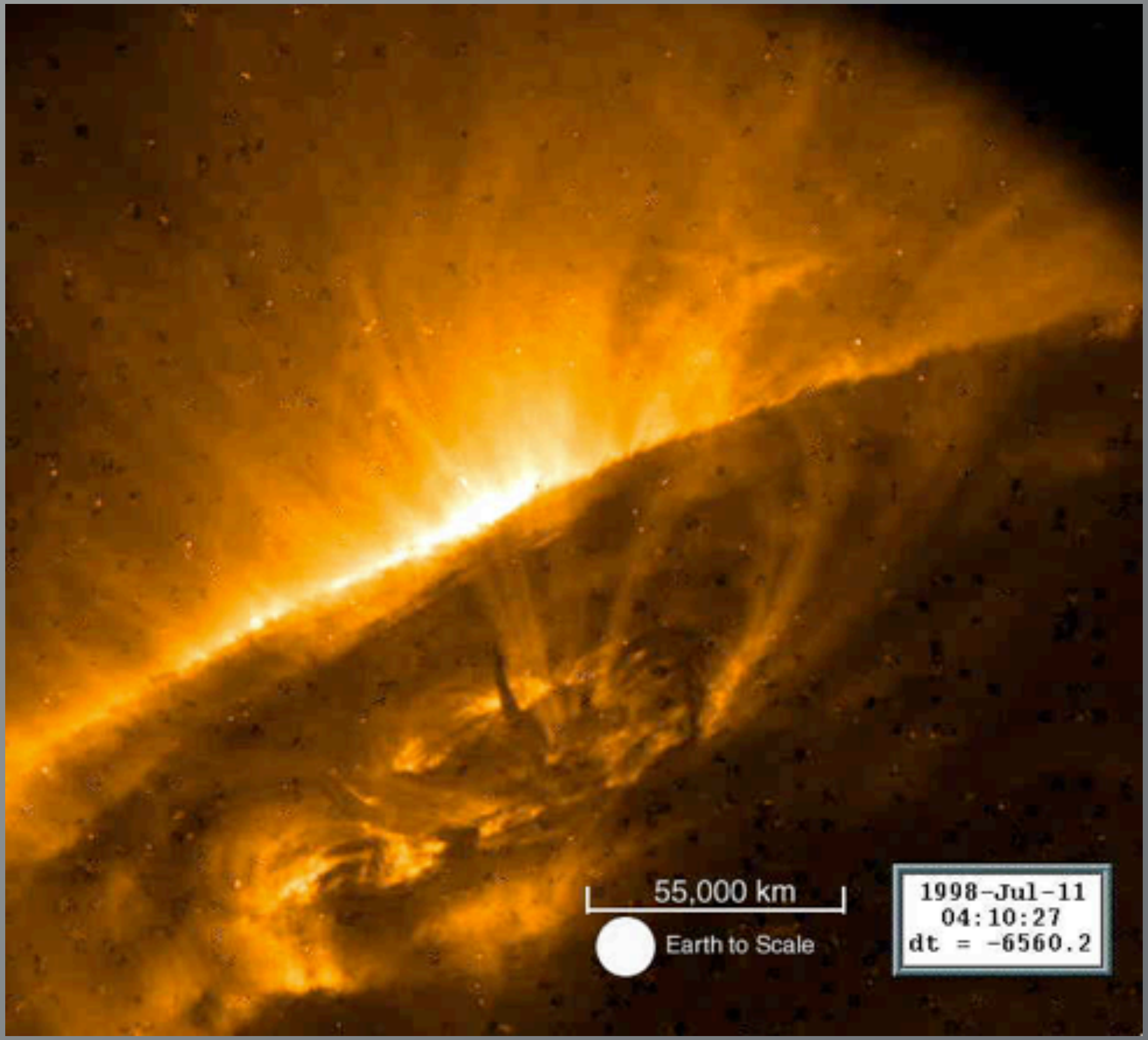
Sakurai, 1976; Hood & Priest, 1979; Moore & Labonte, 1980; van Ballegoiijen & Martens; Low, 1998; Antiochos 1999; Forbes 2000; Fan 2005; Toeroek & Kliem 2005; Chen, 2011 (and references therein)

Coronal magnetic fields: 3D and twisted

Coronal dynamics and magnetism are intrinsically linked



Li et al., 2012

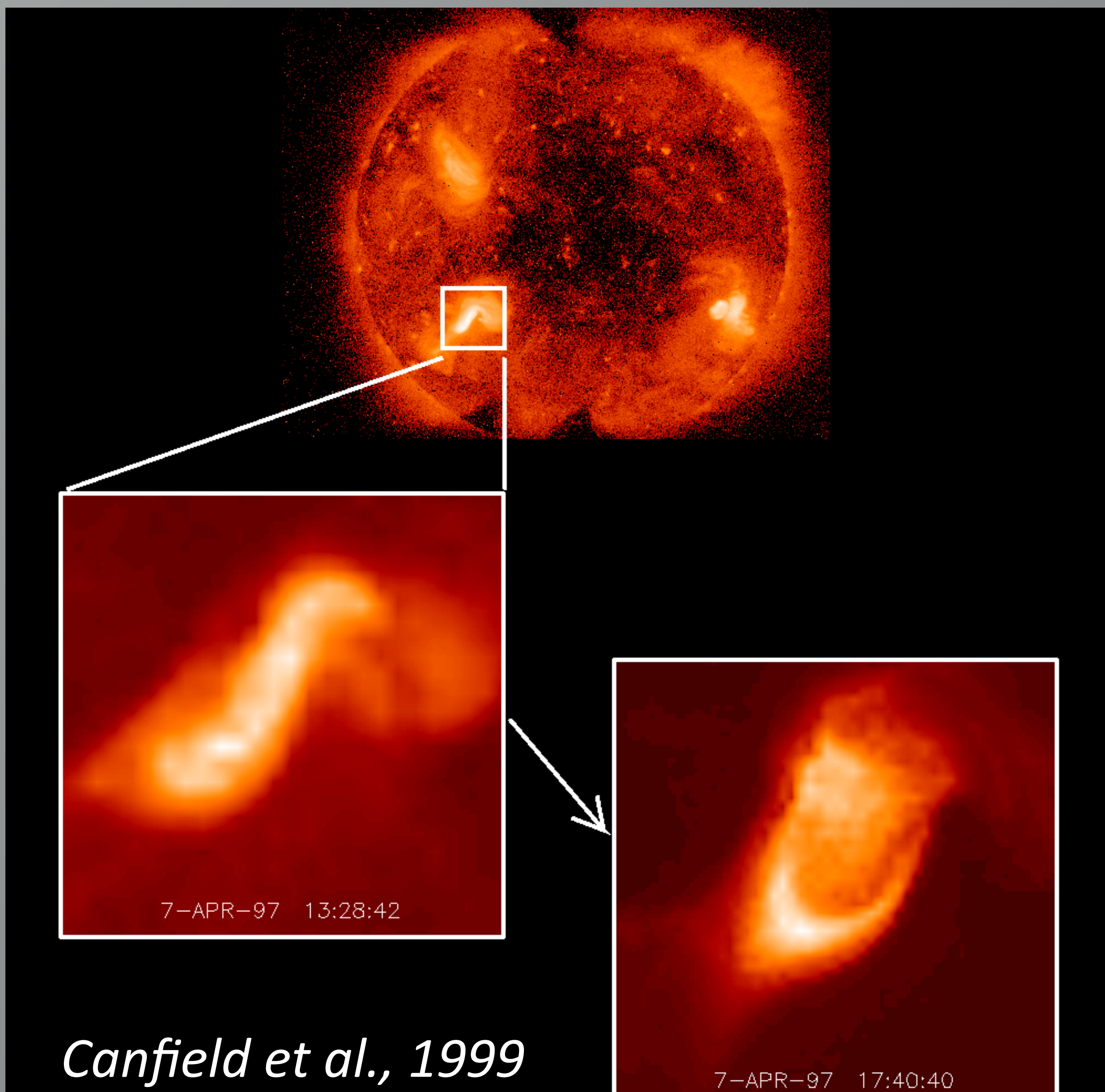


Hinode/SOT

Energy stored in twisted magnetic fields

Coronal magnetic fields: 3D and twisted

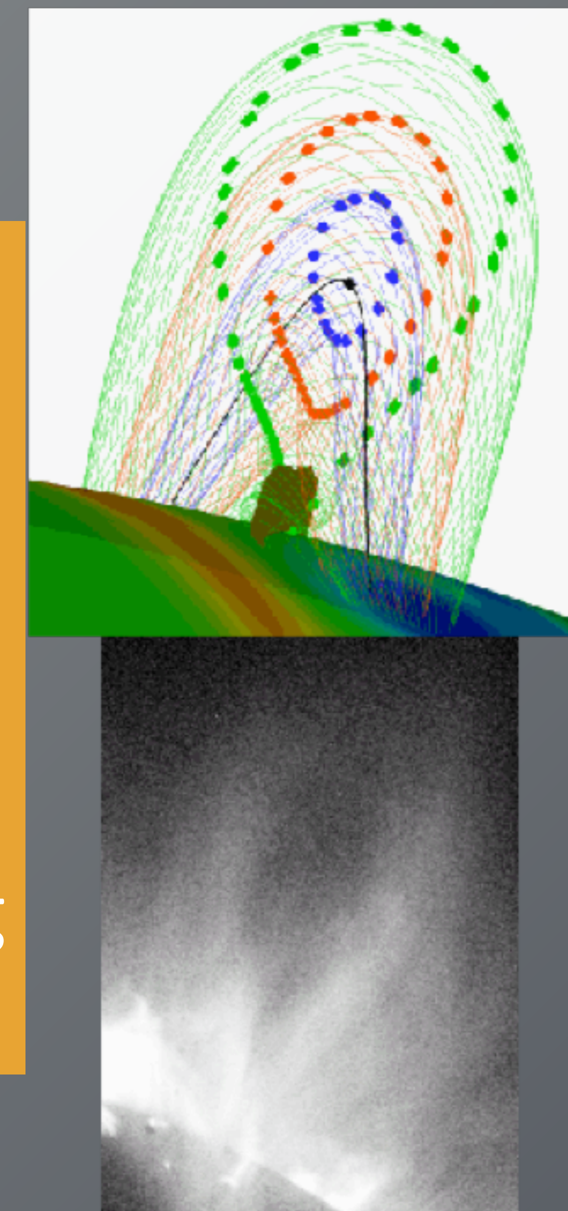
Twisted/sheared fields associated with CME source regions



Canfield et al., 1999

Sigmoidal active regions more likely to erupt than non-sigmoidal regions

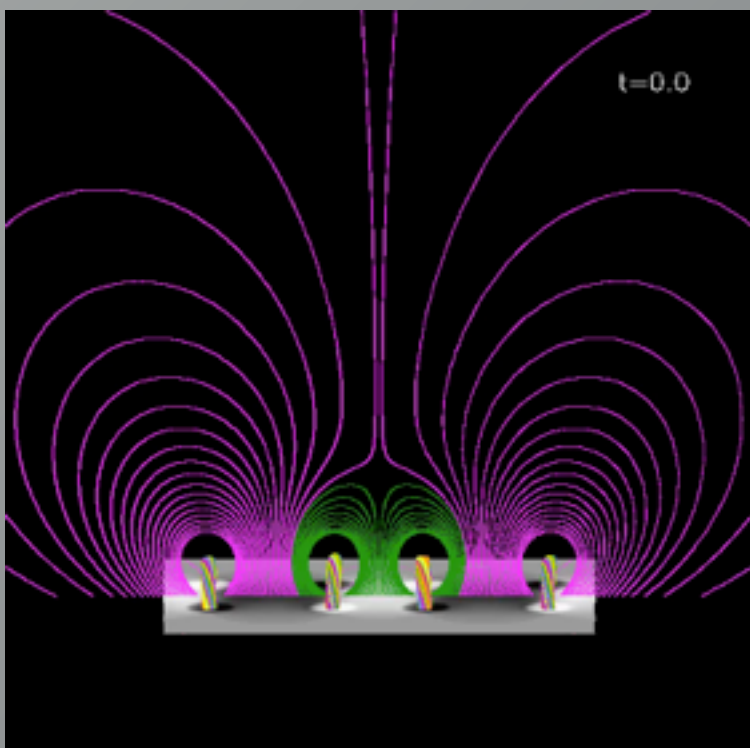
Cavity eruption predicted by slow change of morphology, consistent with current sheet forming below rising flux rope

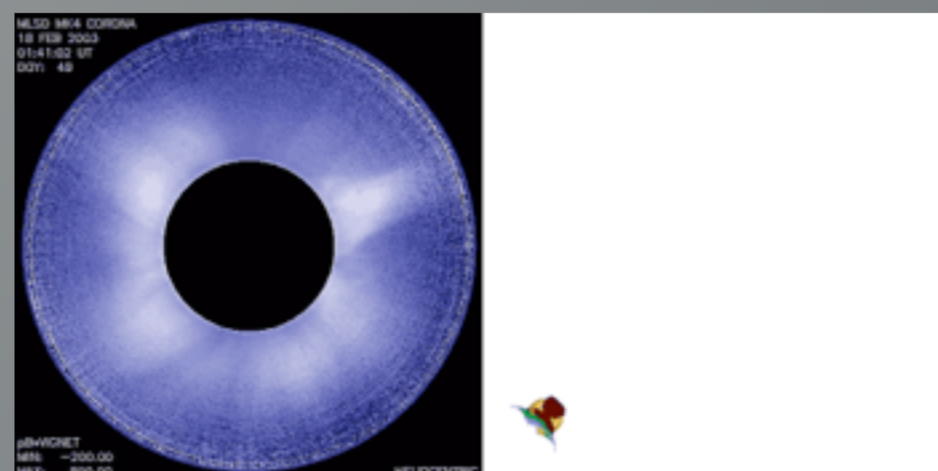


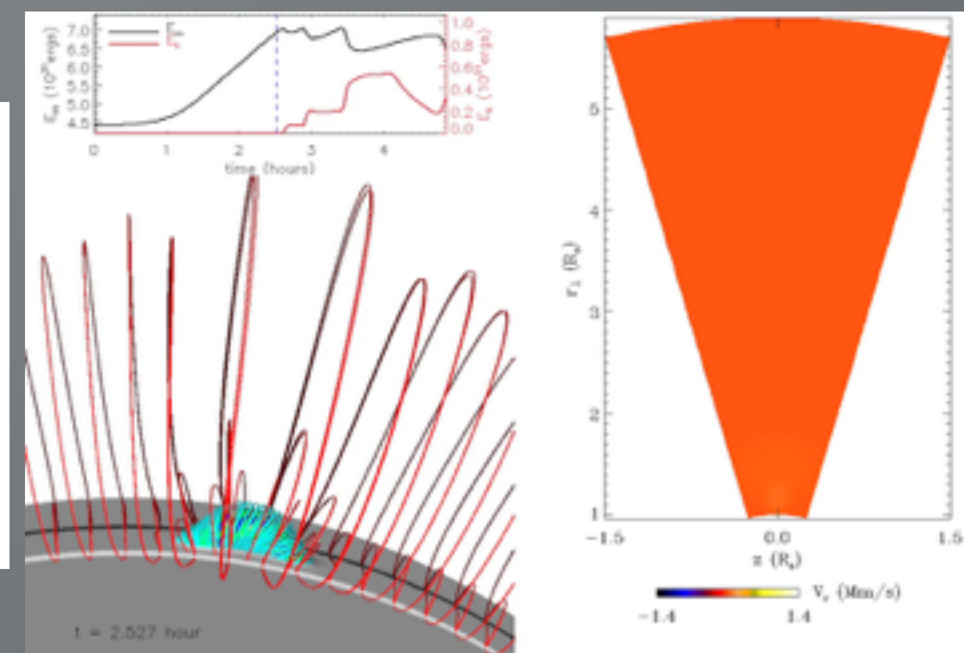
Forland et al., 2013; See also Aulanier et al., 2010; Savcheva et al., 2012

Coronal magnetic fields: 3D and twisted

Complication: the context surrounding an erupting source matters, in time and space







Changes to surrounding magnetic fields may trigger an eruption: "Sympathetic CMEs"

Biesecker & Thompson, 2000; Schrijver & Title, 2011; Torok et al., 2011; Lynch & Edmondson, 2013

Rotation and reconnection may change connectivity and topology

Green et al., 2007; Roussev et al. 2007; Gibson & Fan, 2008; Jacobs et al. 2009; Shiota et al., 2010; Kliem et al., 2012

Multiple eruptions from the same region may interact: "Cannibal CMEs"

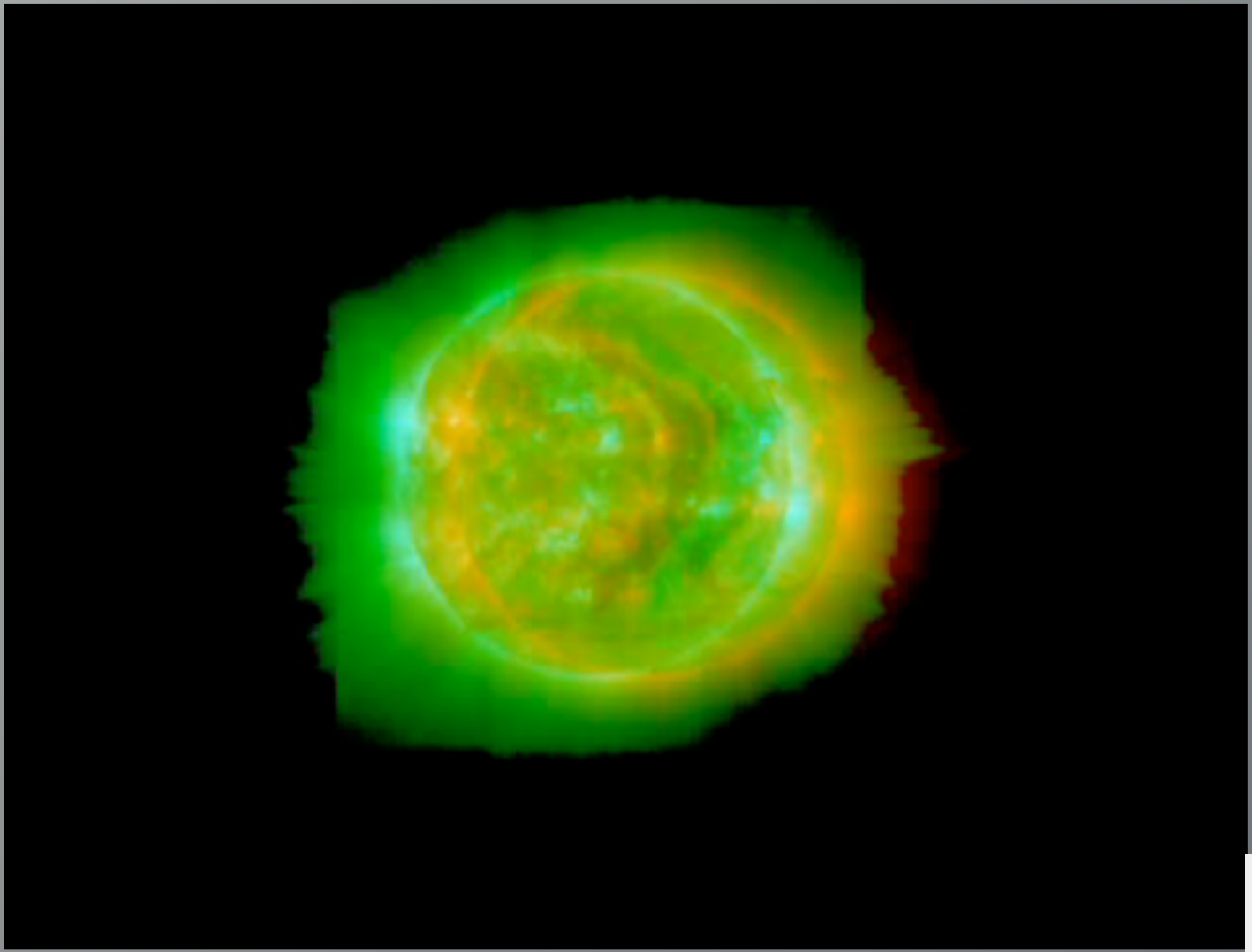
Gopalswamy et al., 2001; 2002; Richardson et al., 2003; Liu et al., 2012; Temmer et al., 2012; Lugaz et al., 2013; Chatterjee & Fan, 2014; Lugaz et al., 2016

Coronal magnetic fields: 3D and twisted

Take-home message #1

Ideally, we want to quantify the global coronal magnetic field

Boundaries and beyond



Potential-field source-surface global model

$$\mathbf{B} = -\nabla\Psi,$$

Solenoidal $\nabla \cdot \mathbf{B} = 0$

Laplace's equation

$$\nabla^2\Psi = 0,$$

$$B_r(r,\theta,\phi) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} b_{lm}c_l(r)P_l^m(\cos\theta)e^{im\phi},$$

$$B_\theta(r,\theta,\phi) = -\sum_{l=0}^{\infty}\sum_{m=-l}^{l} b_{lm}d_l(r)\frac{dP_l^m(\cos\theta)}{d\theta}e^{im\phi},$$

$$B_\phi(r,\theta,\phi) = -\sum_{l=0}^{\infty}\sum_{m=-l}^{l} \frac{im}{\sin\theta}b_{lm}d_l(r)P_l^m(\cos\theta)e^{im\phi},$$

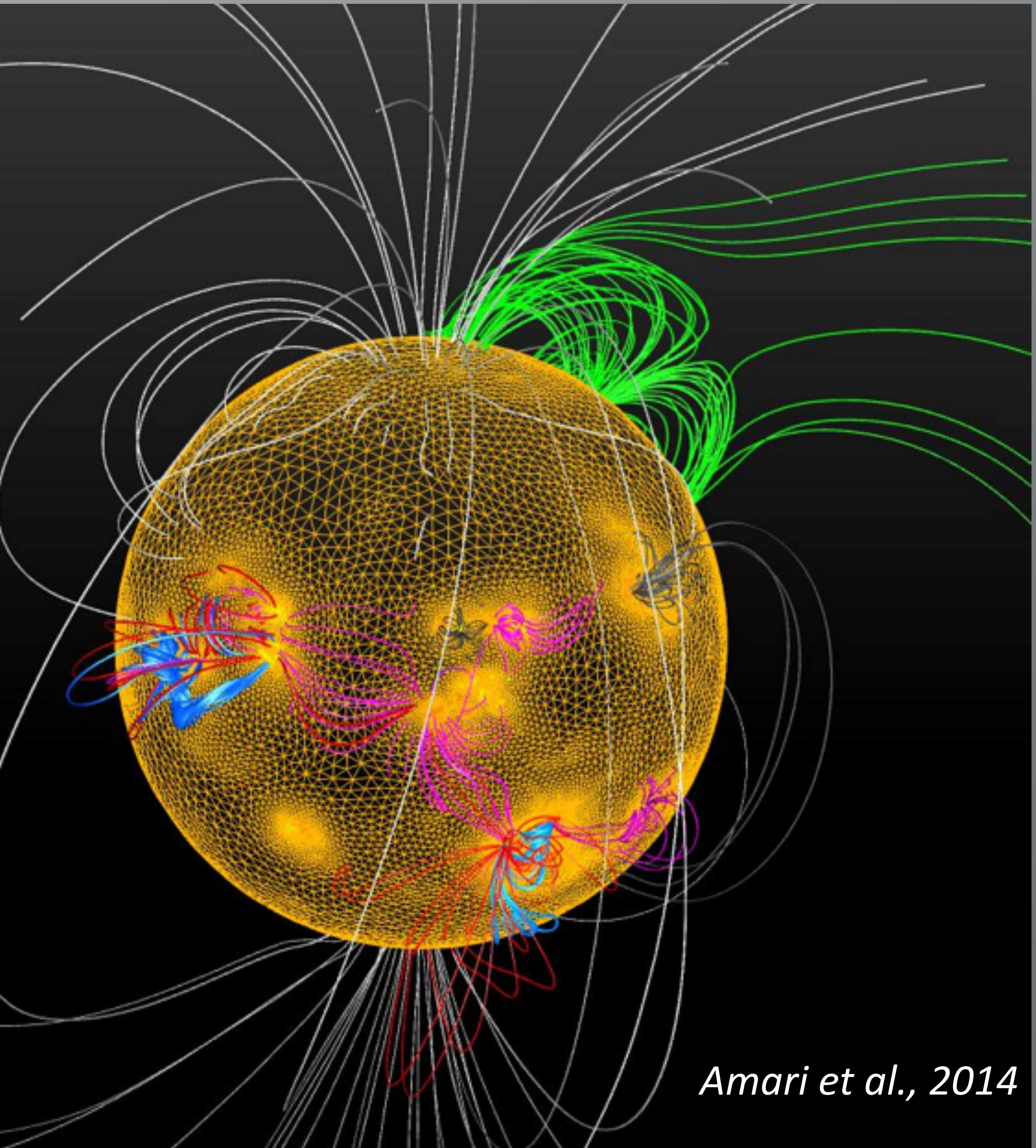
Depends only on specification of magnetic fields at lower boundary (photosphere) and assumption of radial field upper boundary

No information about free energy stored in coronal currents

$$\nabla \times \mathbf{B} = 0,$$

Boundaries and beyond

Non-linear force-free field (NLFFF) methods



Amari et al., 2014

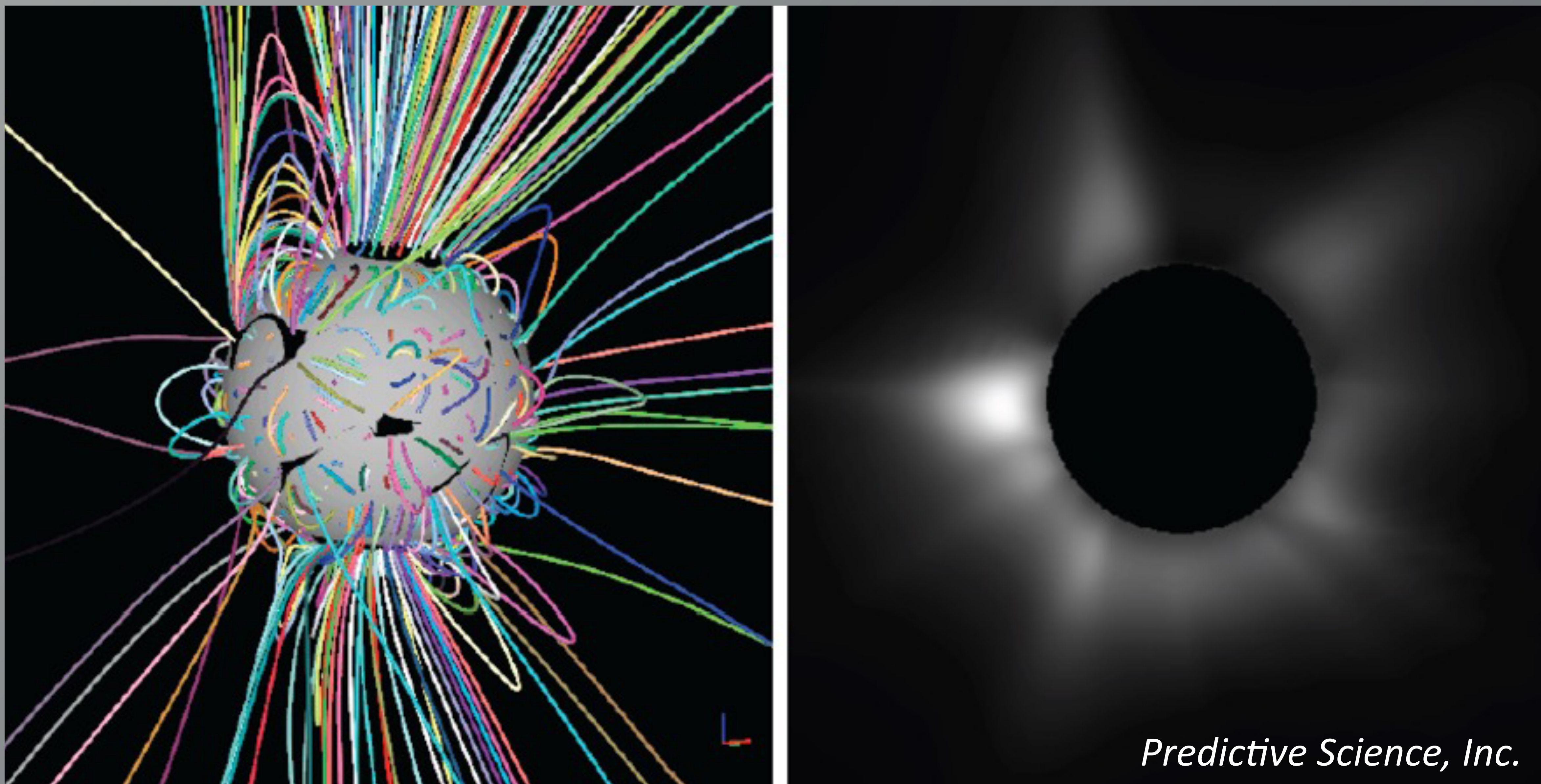
Extrapolate coronal field from vector field at lower boundary

Boundary condition constrains both coronal magnetic field and currents.

Results are sensitive to measurement uncertainties, model volume, large currents, and departures from force-free: **inconsistencies between methods**

Boundaries and beyond

Global magnetohydrodynamic MHD model

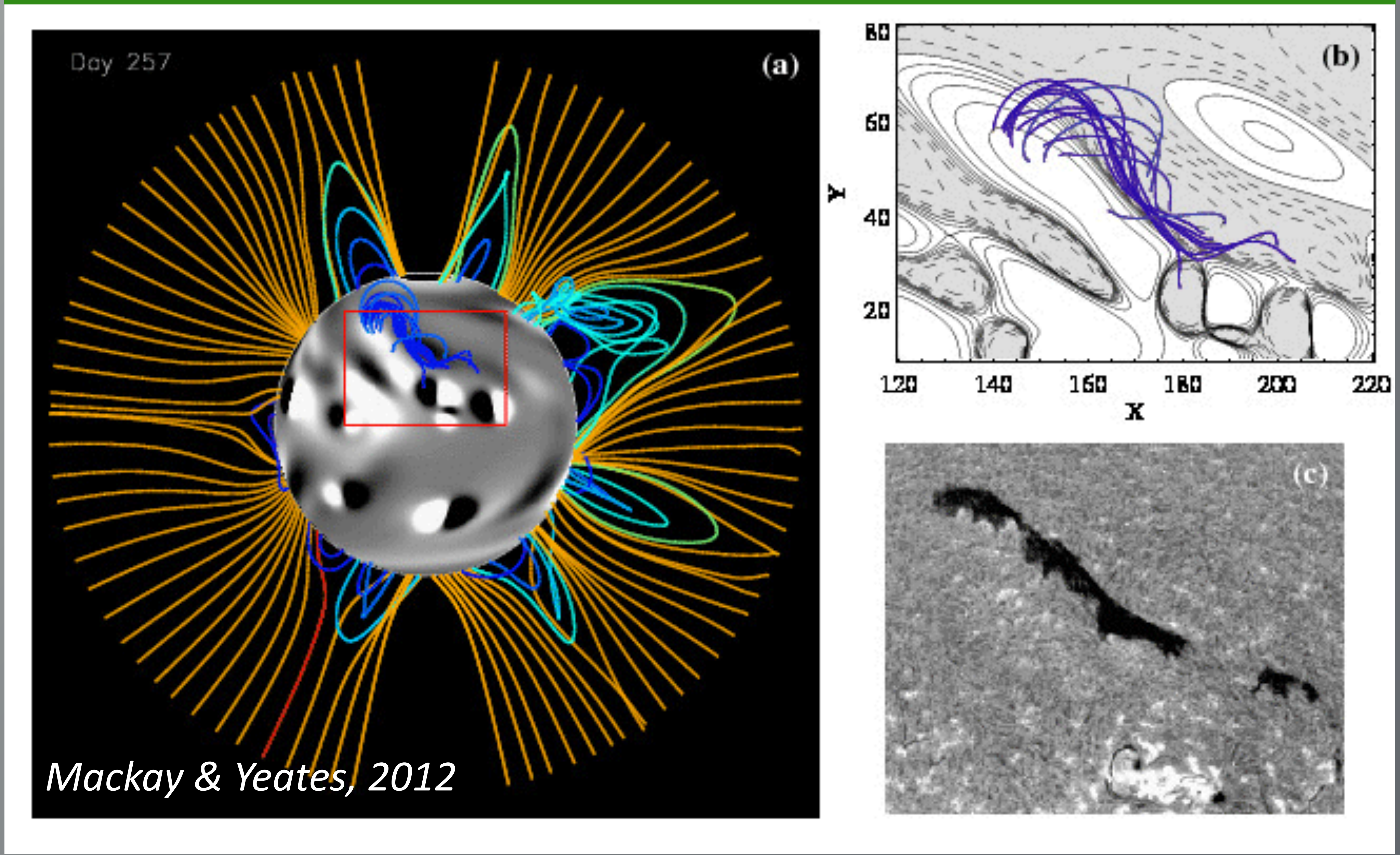


Dynamically relaxes to force-free equilibrium of plasma and field consistent with photospheric boundary and assumed thermodynamics.

Boundary condition is line-of-sight and static—> **missing key currents**

Boundaries and beyond

Global Flux-Transport Magnetofrictional Model



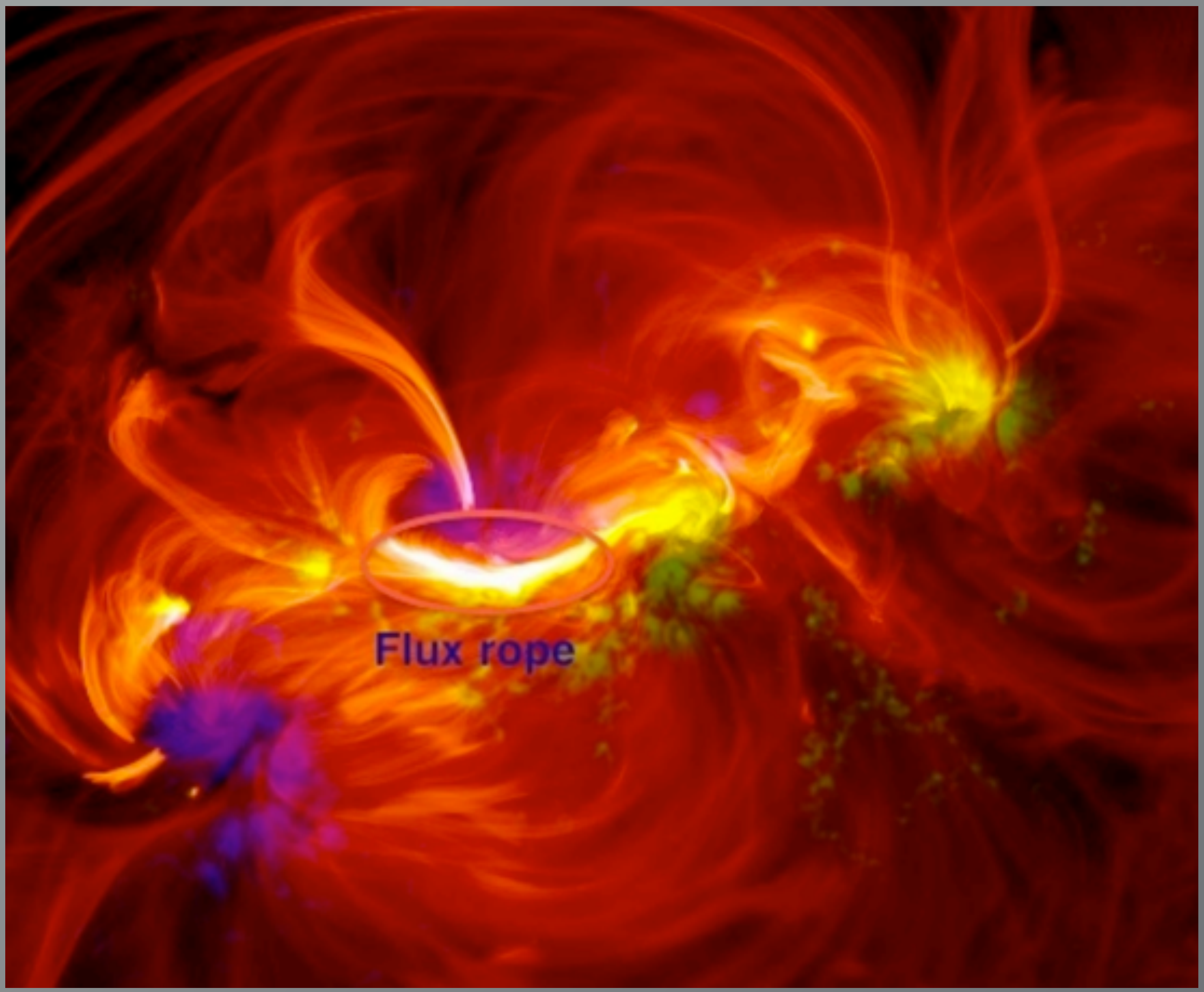
Magnetic energy buildup via time-varying photospheric fields

Quasi static evolution of field only (plasma distribution not solved)

Idealized active-region emergence

Boundaries and beyond

Coronal Global Evolutionary Model



Fisher et al., 2015

Time-varying, vector magnetic field and velocity at photospheric boundary used to model electric field

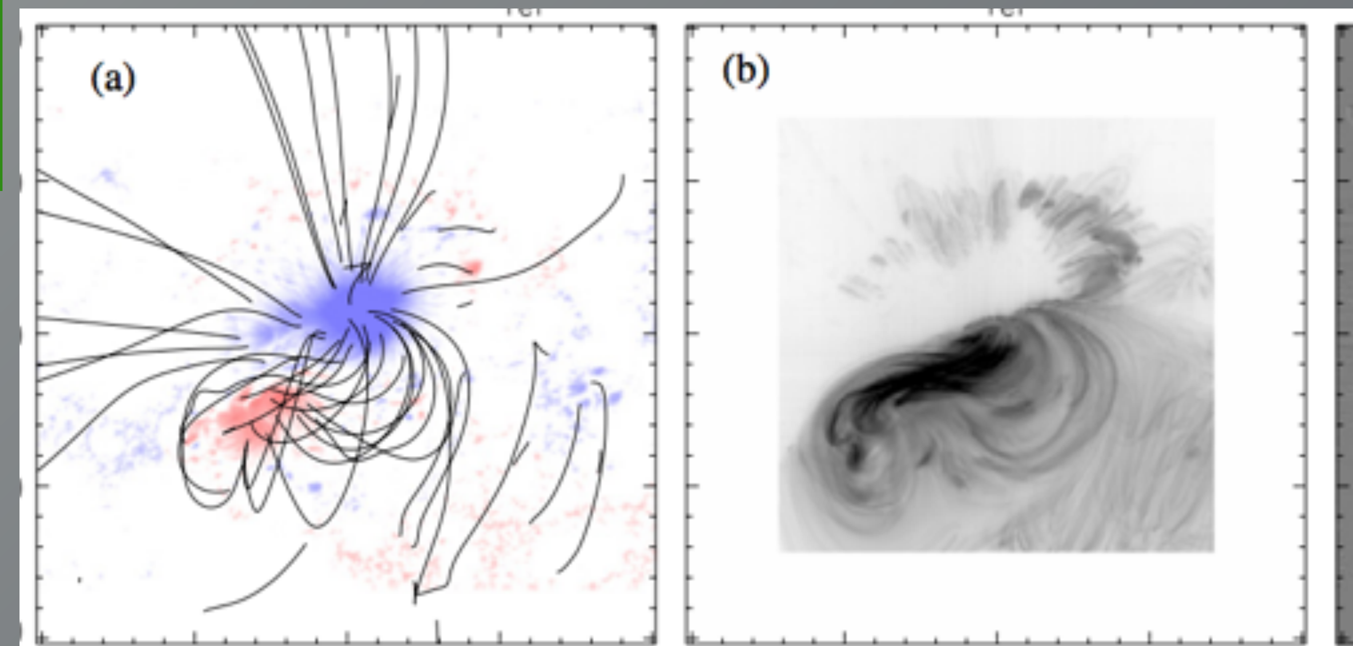
Evolve the overlying coronal magnetic field using a magneto frictional model

Plan to merge lower resolution global model with higher-resolution active-region model

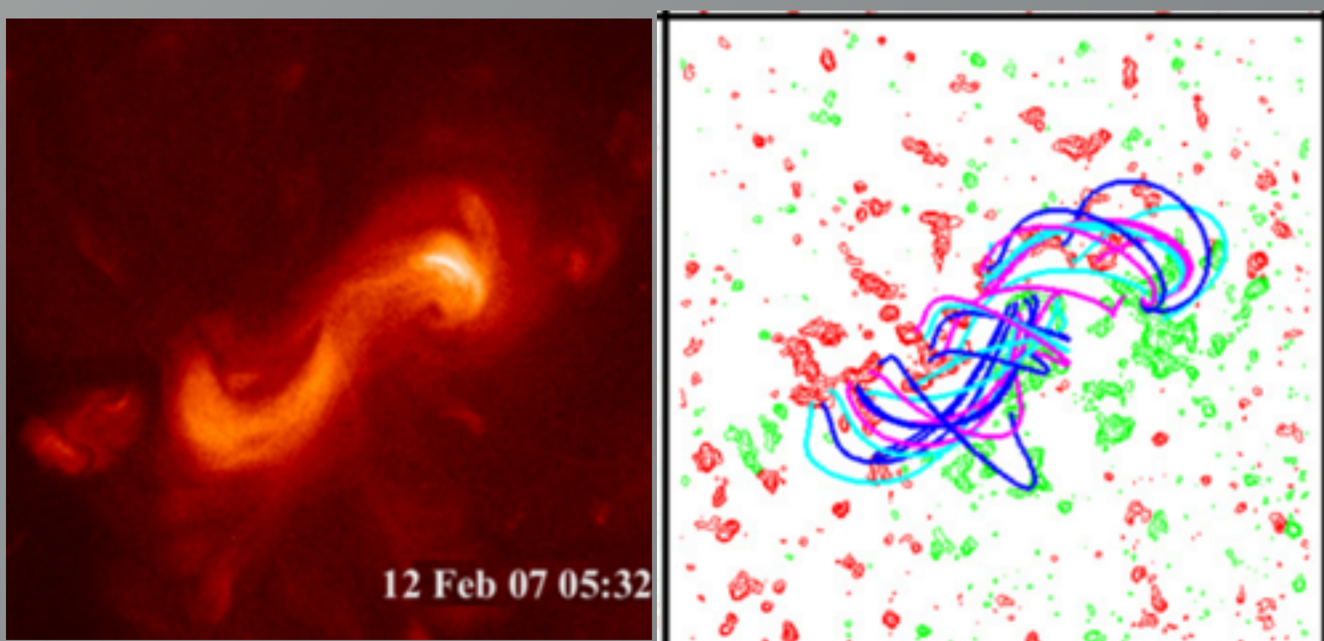
Determining electric field at boundary remains challenging

Boundaries and beyond

Non-linear force-free field with direct coronal constraints



Malanushenko et al., 2012



Savcheva & Ballegooijen, 2009

Flux-rope insertion method uses filament/sigmoid path to define volume, inserts flux rope with axial/poloidal flux as free parameters, and magneto frictionally relaxes

Quasi-Grad-Rubin method sets force-free parameter alpha to be constant along paths defined by coronal loops, then interpolates between loops

See also Chifu et al. 2015

Boundaries and beyond

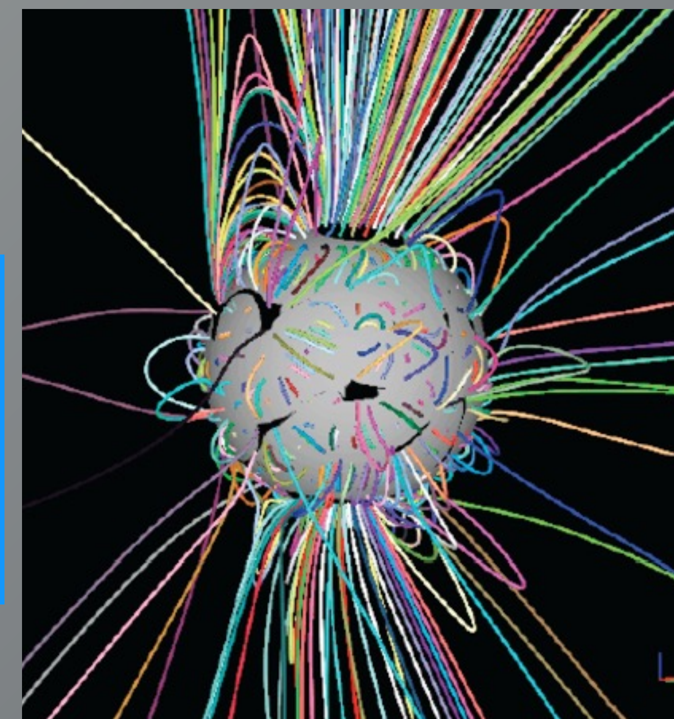
Take-home message #2

Photospheric boundary limitations motivate the (additional) incorporation of coronal observations into magnetic models.

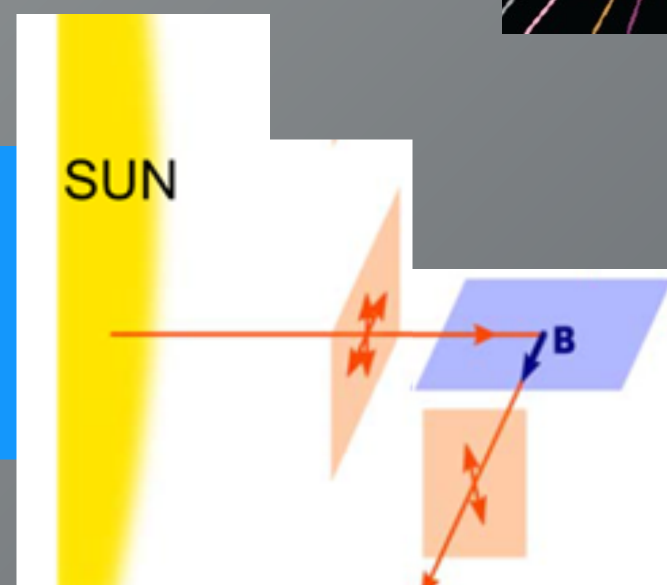
From FORWARD to inverse

Deconstructing the inverse problem

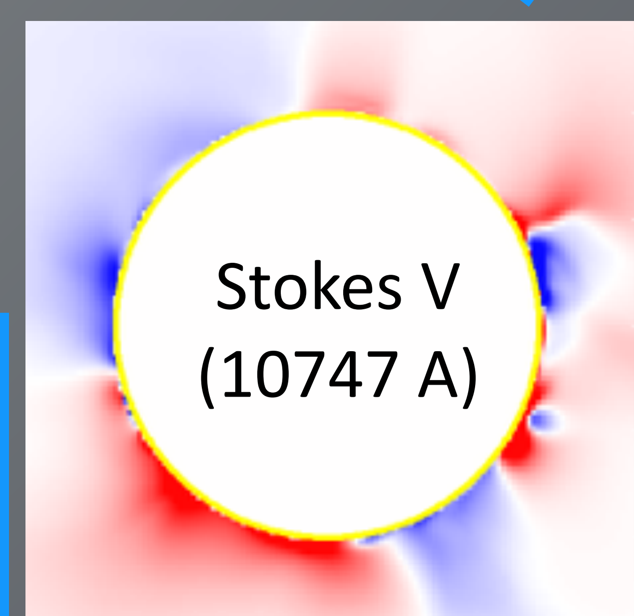
1) given a model for the **physical state** (e.g., the distribution of density, temperature, velocity, and magnetic field…)



2) and a representation of a physical process relating the physical state to observations



3) create synthetic data that is directly comparable to observations (**establish cost function**)

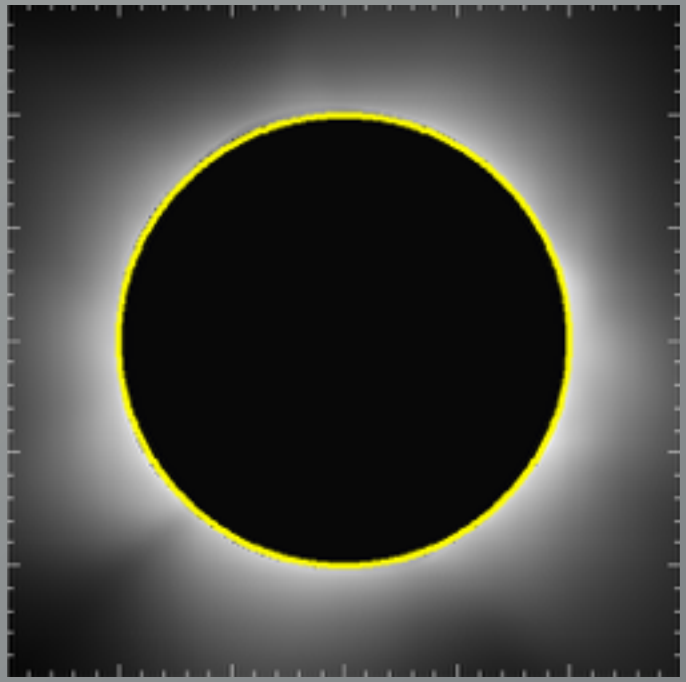


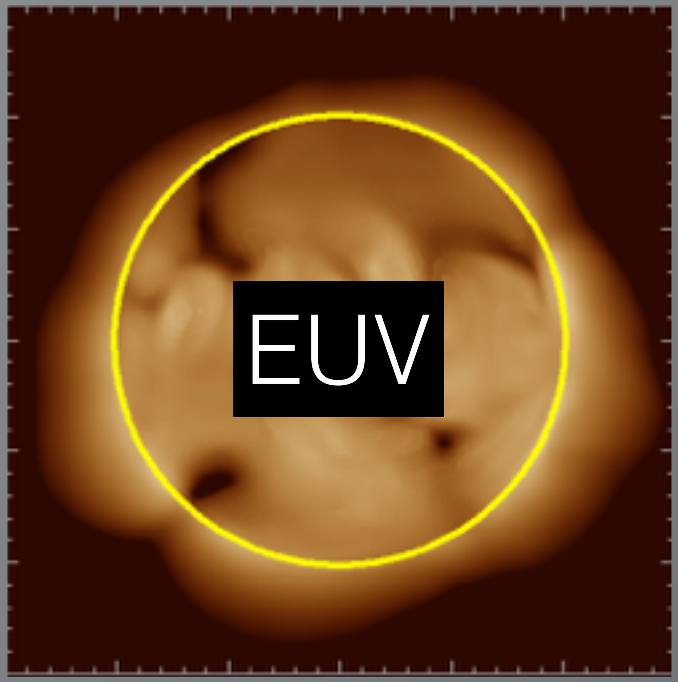
4) invert data: **change/ optimize model**

From FORWARD to inverse

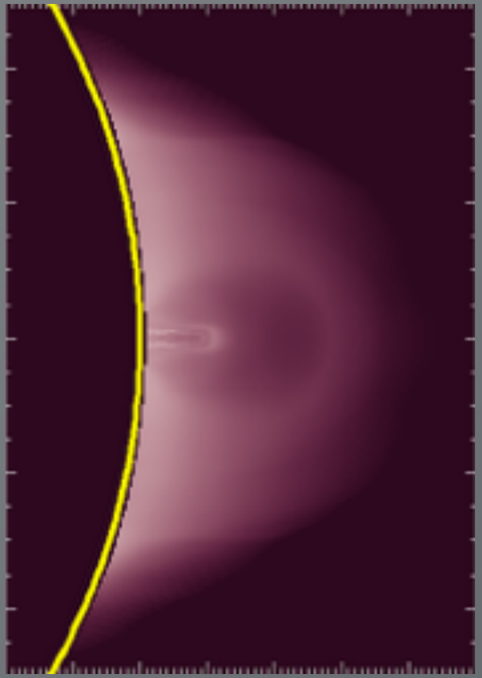
What should go into a cost function?

Multi-wavelength imaging





PSI MAS model and FORWARD (Gibson et al. 2016)



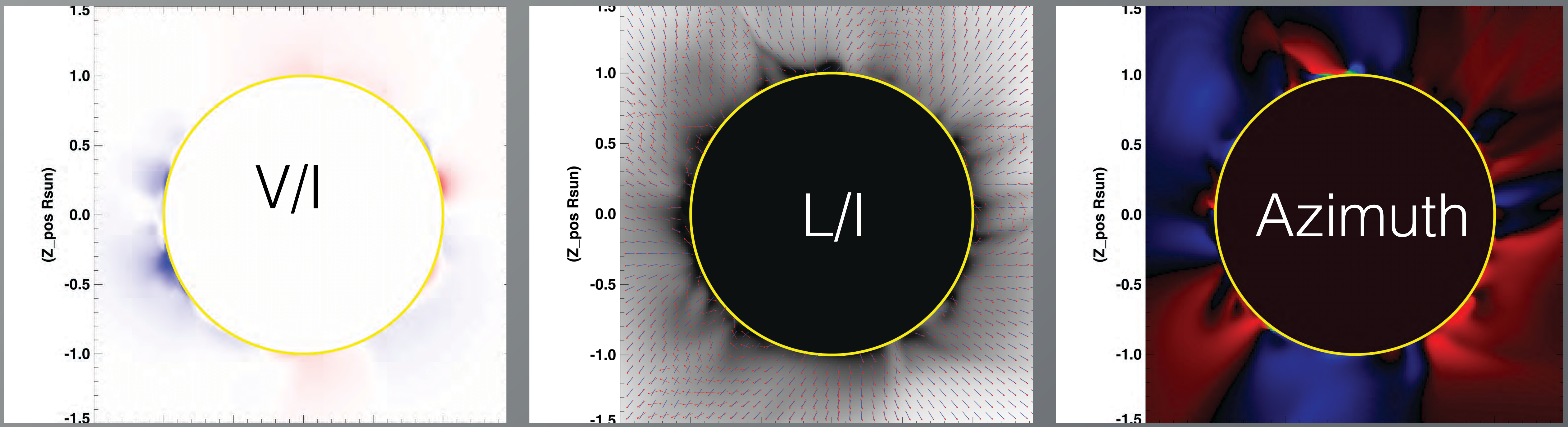
Fan model and FORWARD

Magnetic morphology (open vs. closed field; loop geometry; presence of dipped magnetic field) from intensities (Thomson scattering, collisional excitation/continuum absorption, resonance scattering)

From FORWARD to inverse

What should go into a cost function?

Coronal visible/IR spectropolarimetry
10747 A



PSI MAS model and FORWARD (Gibson et al. 2016)

Sensitive to B_{los} via circular polarization (Zeeman effect)

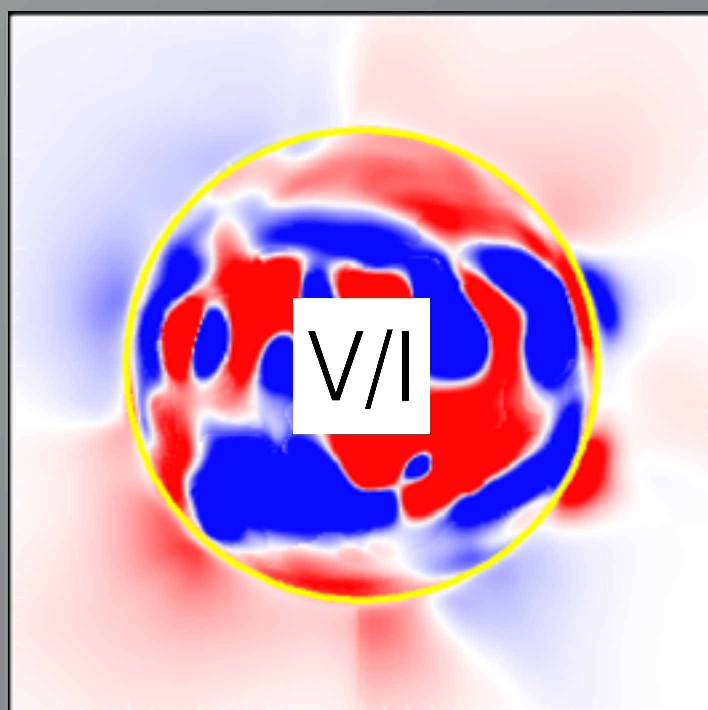
Sensitive to B_{pos} direction via linear polarization (Saturated Hanle effect)

Querfeld 1982; Casini & Judge 1999; Habbal 2001; Lin et al. 2004; Tomzyk et al. 2008

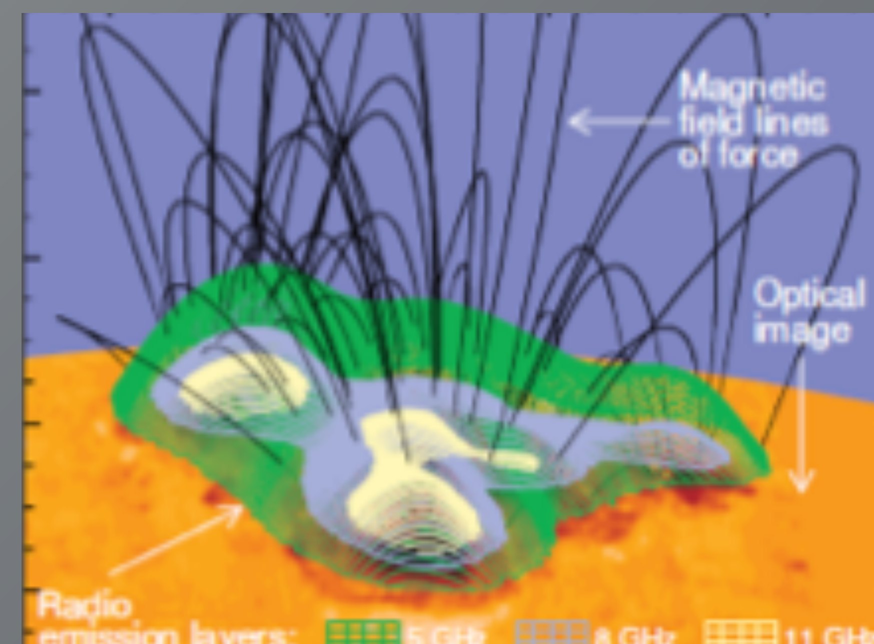
From FORWARD to inverse

What should go into a cost function?

Radio polarimetry



PSI MAS model and FORWARD



Lee et al 2007

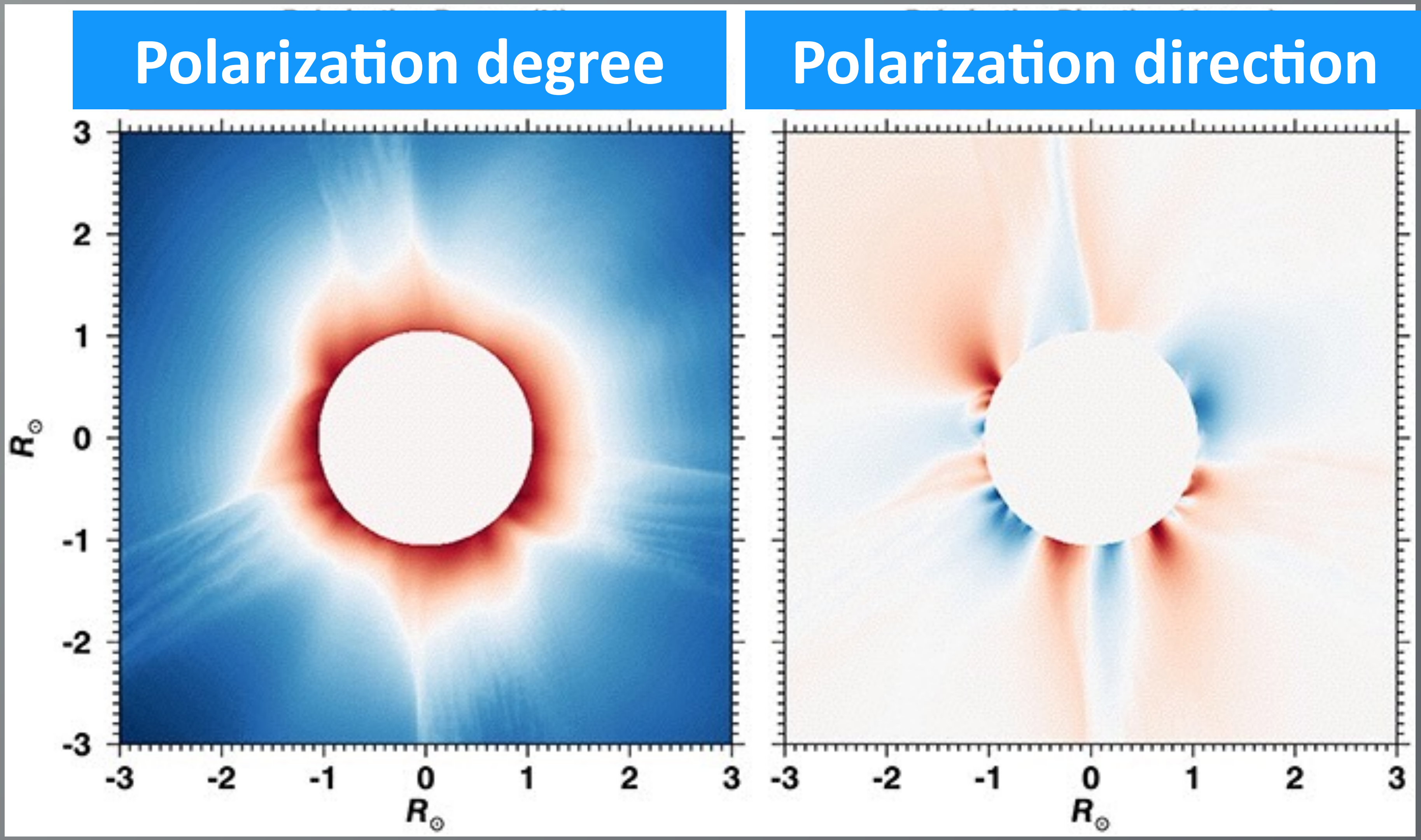
B_{los} from circular polarization (Thermal Bremstrahllung)
Isosurfaces of |B| as a function of frequency/height (Gyroresonance)

Dulk 1985; White & Kundu 1997; White 2000; Gelfreikh 2004

From FORWARD to inverse

What should go into a cost function?

Coronal visible/IR spectropolarimetry
10830 A

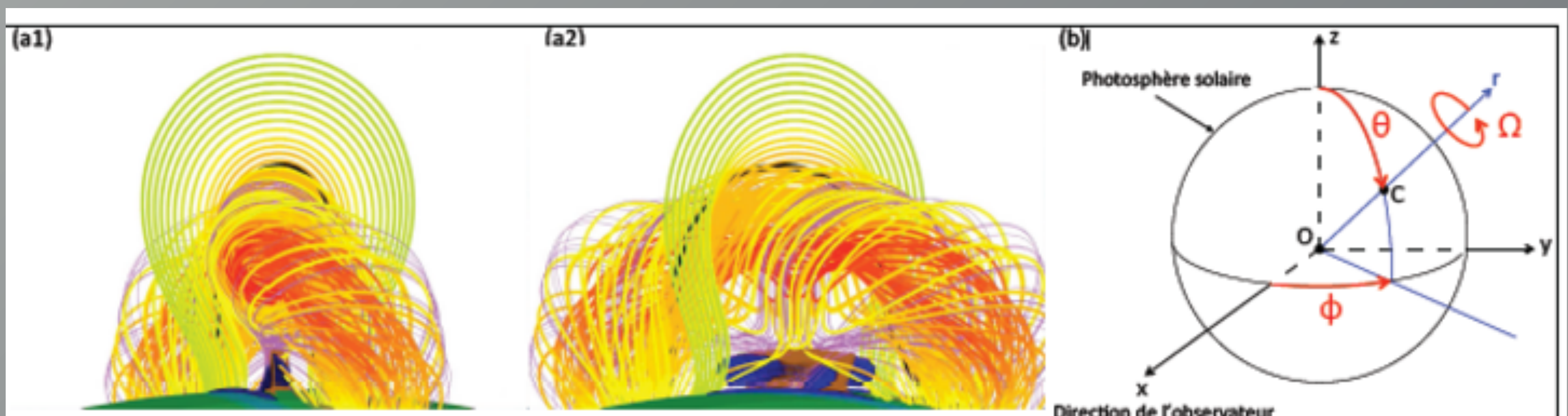


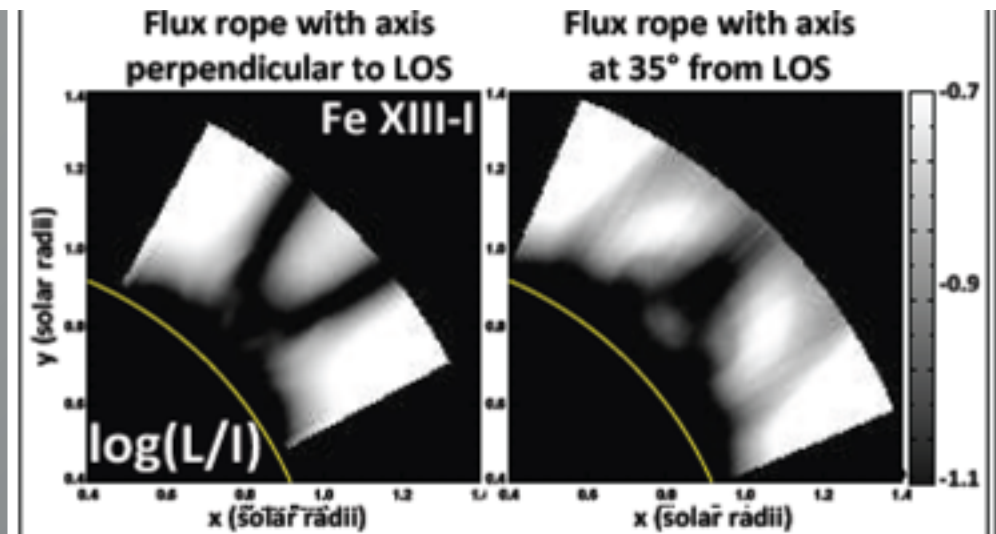
Rouafi et al. 2016; see also Fineschi et al. 1991, Kuhn et al. 2007; Dima et al. 2016

Sensitive to B strength and direction via linear polarization

From FORWARD to inverse

How should the model be changed/optimized

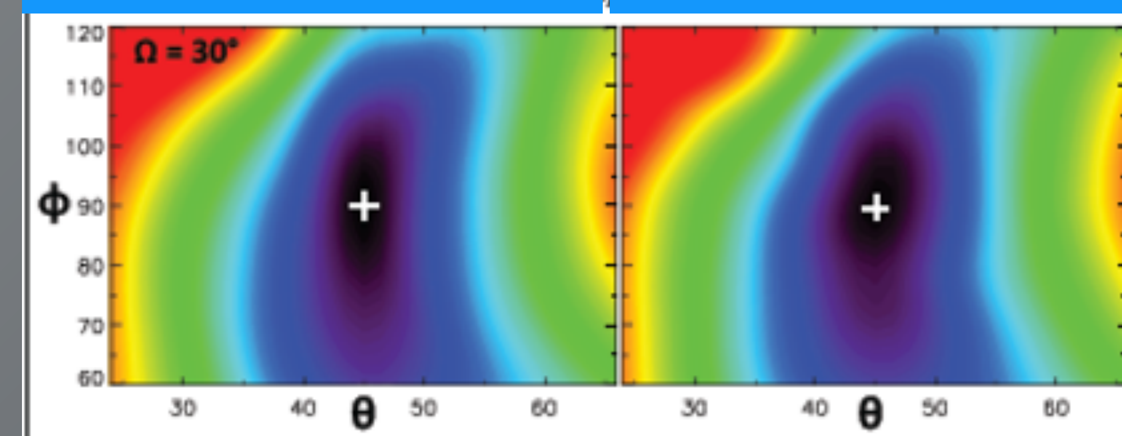


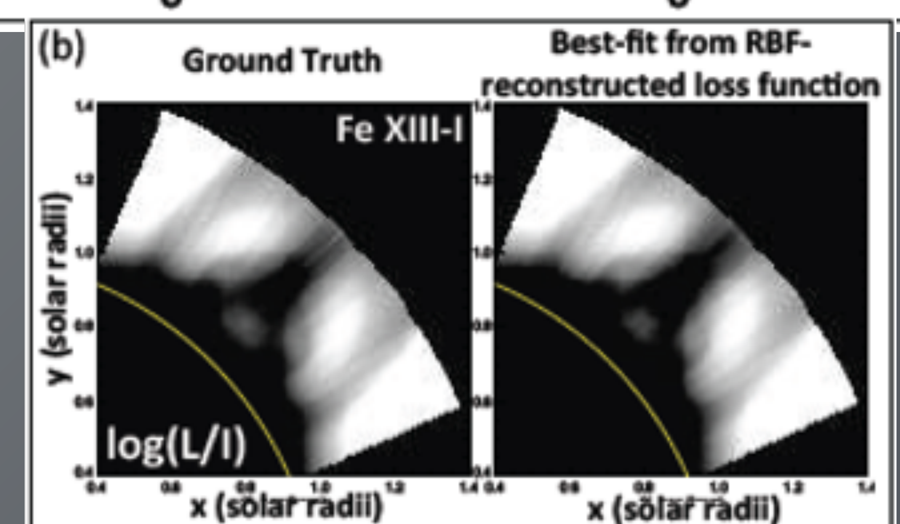


ROAM: Radial-basis-function Optimization Approximation Method

Dalmasse et al. 2016

Exact cost function | RBF cost function





Using parameterized model, seek to regain "ground truth"

Sparsely-sampled interpolate (n points from set of n^p points)

Example: 100 times faster than grid search

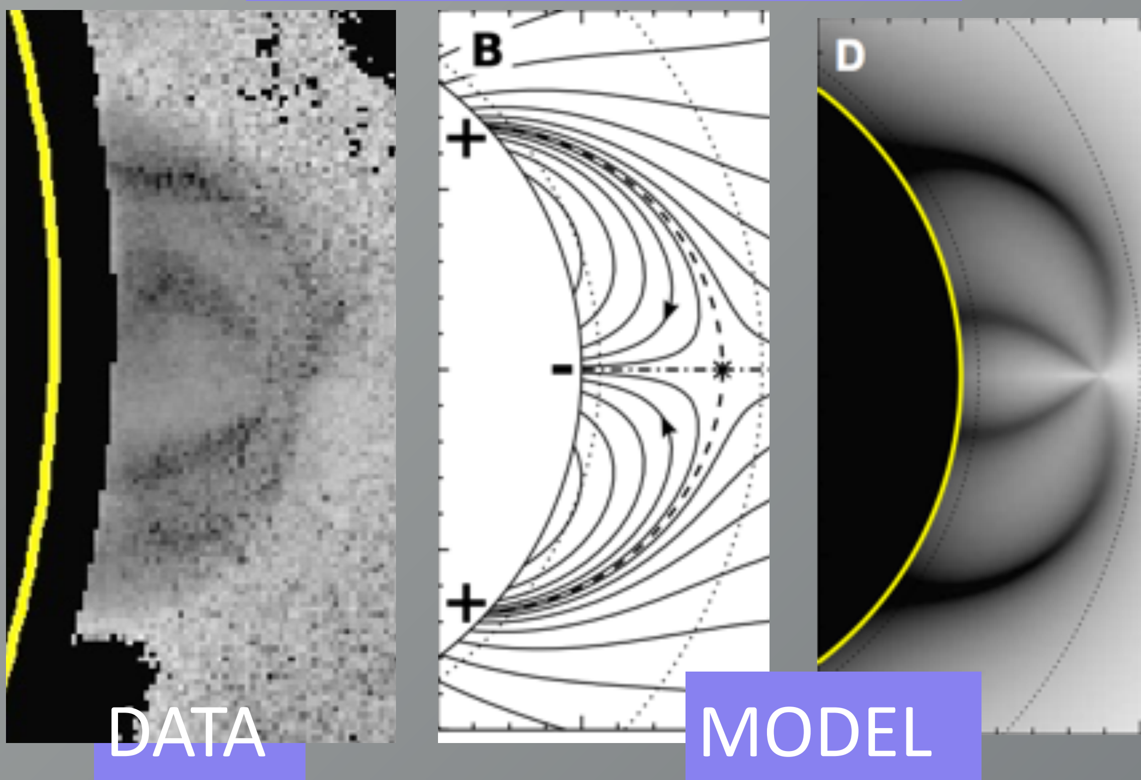
From FORWARD to inverse

Take-home message #3

Inversion technique needs to be capable of incorporating a range of observations (helps pin down line-of-sight ambiguity)

Coronal polarimetry: the missing link

Pseudostreamers



Rachmeler et al., 2014

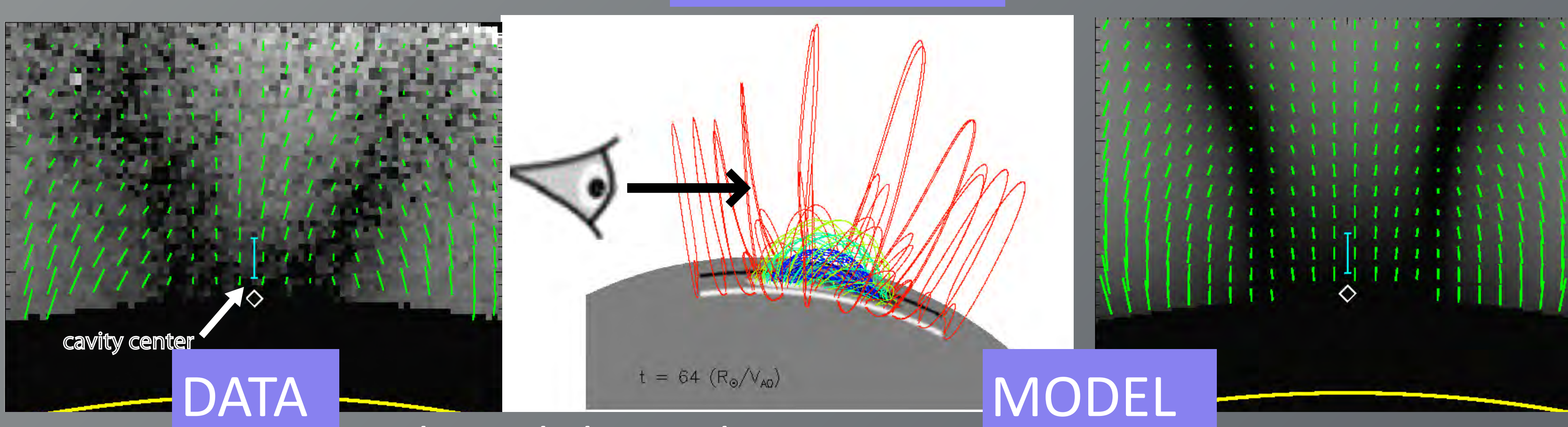
$$L/I = \frac{(\text{Stokes } Q^2 + \text{Stokes } U^2)^{1/2}}{\text{Stokes } I}$$

(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

Diagnostic of magnetic topology (significant for predicting eruptions)

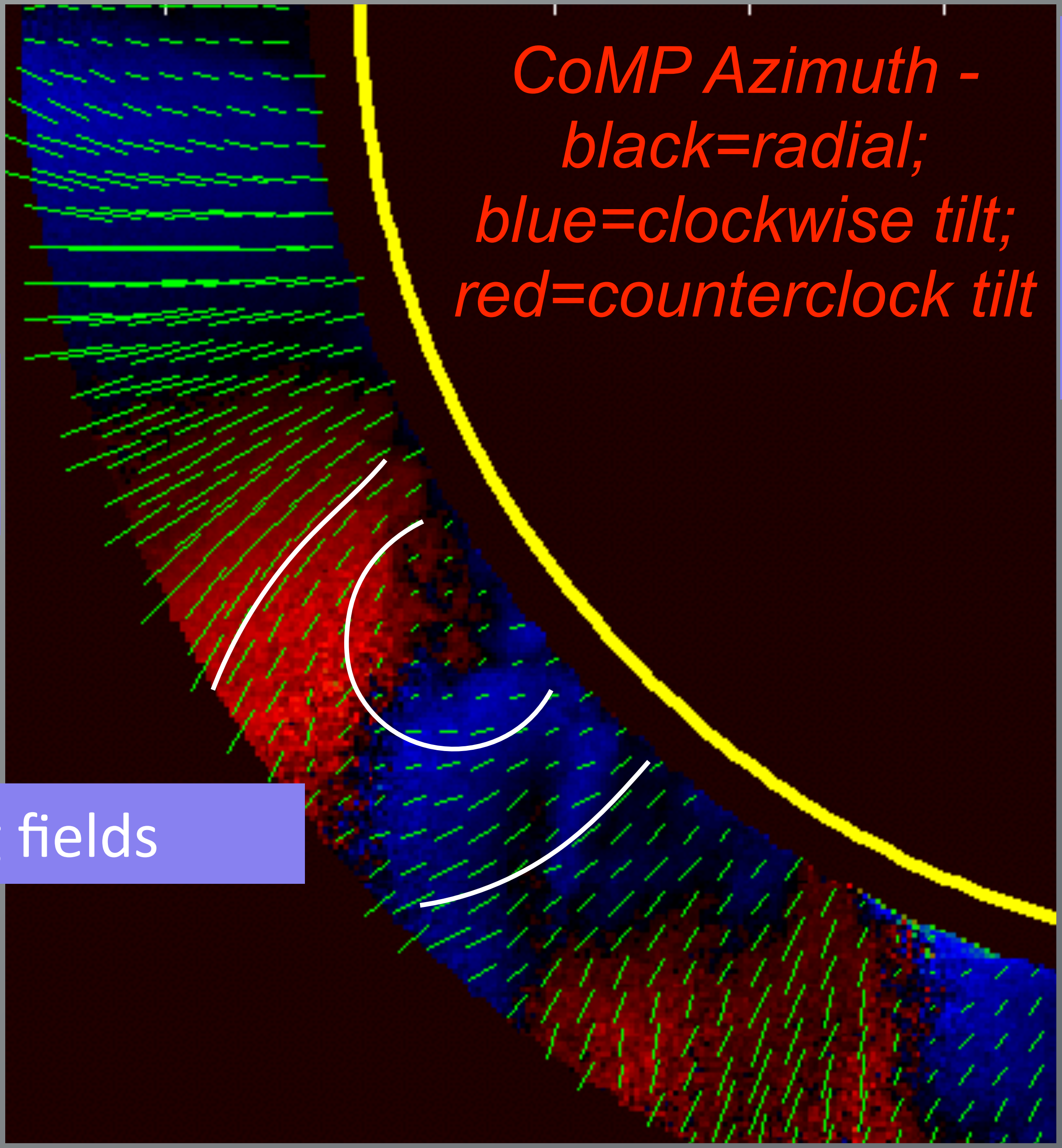
Flux ropes



Bak-Steslicka et al. 2013

Coronal polarimetry: the missing link

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



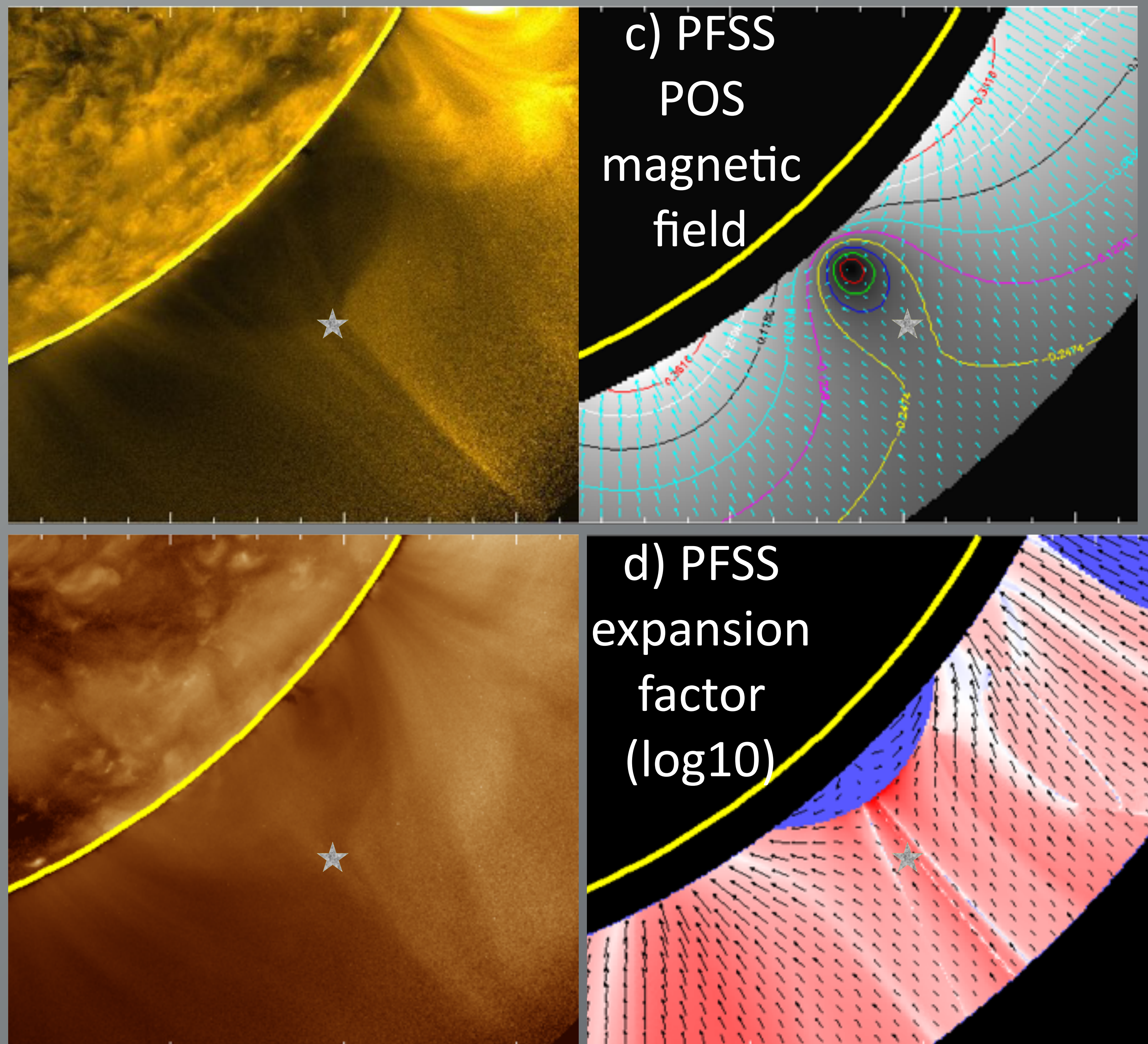
Linear polarization azimuth = direction of POS vector (but rotates 90 degrees at V. Vleck angle!)

diverging fields

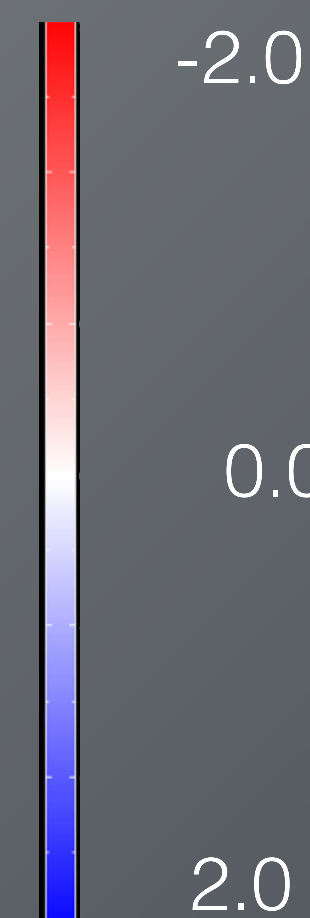
converging fields

Coronal polarimetry: the missing link

Pseudostreamer: PFSS and AIA observations

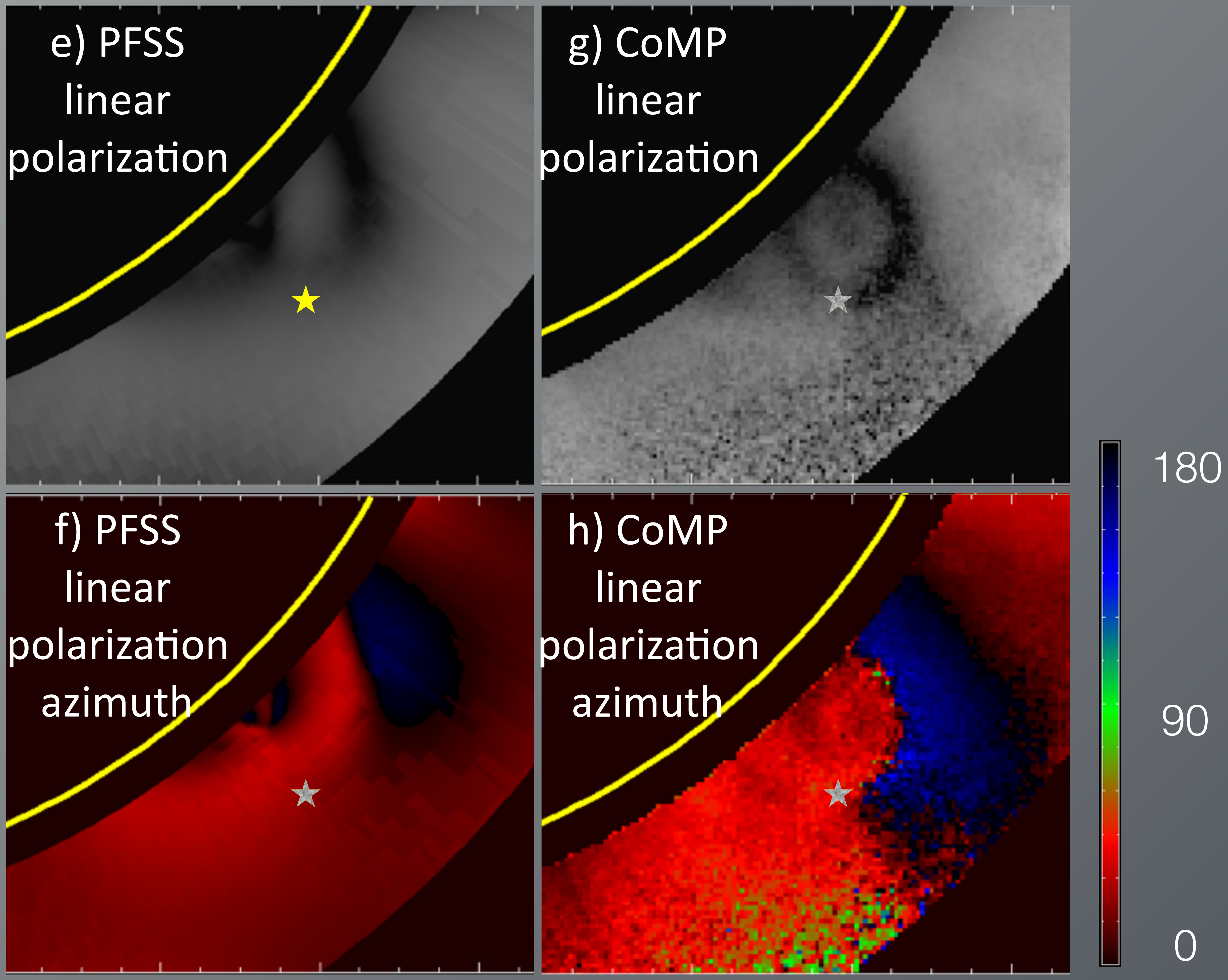


Null too low in PFSS



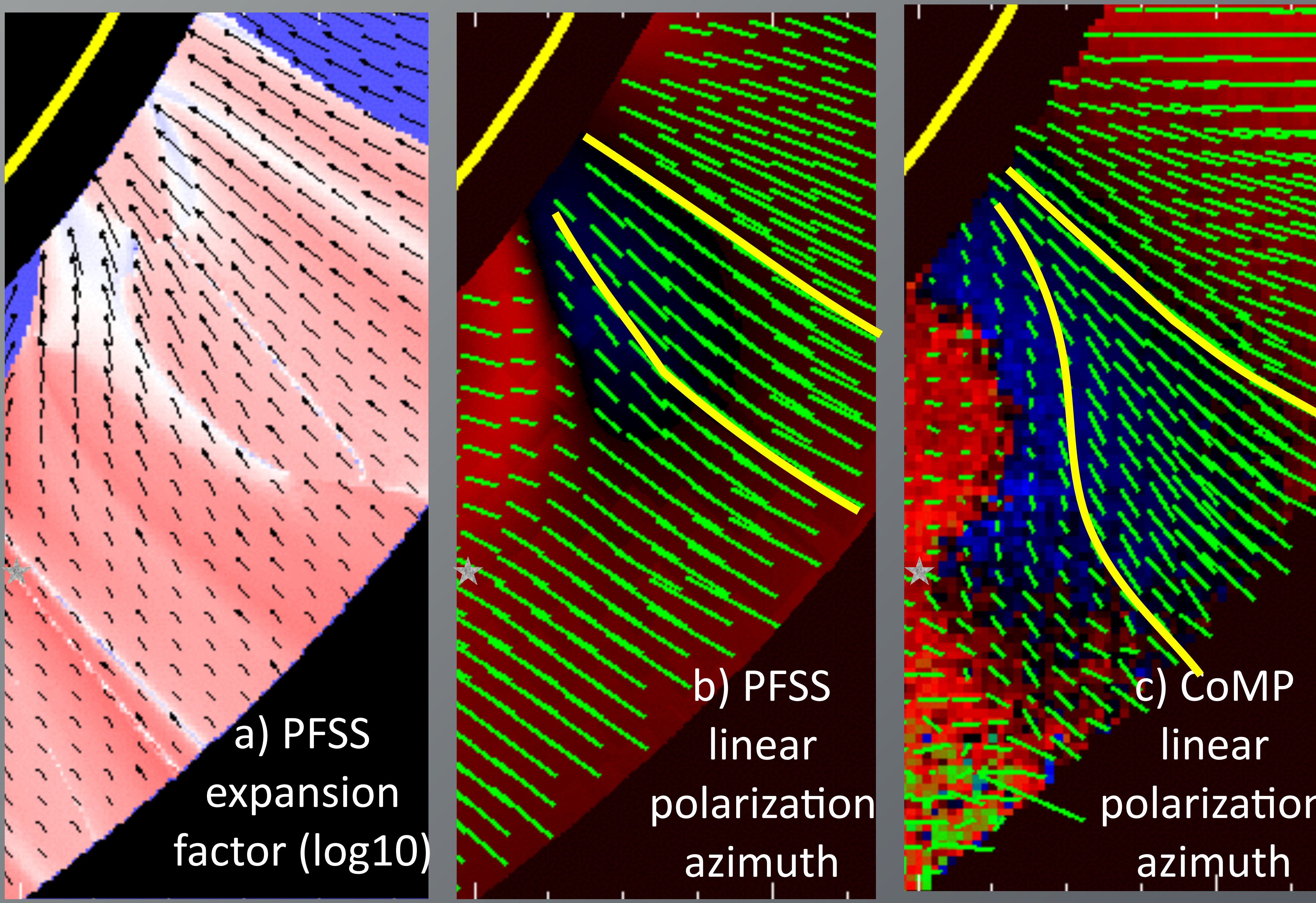
Coronal polarimetry: the missing link

Pseudostreamer: PFSS and CoMP observations



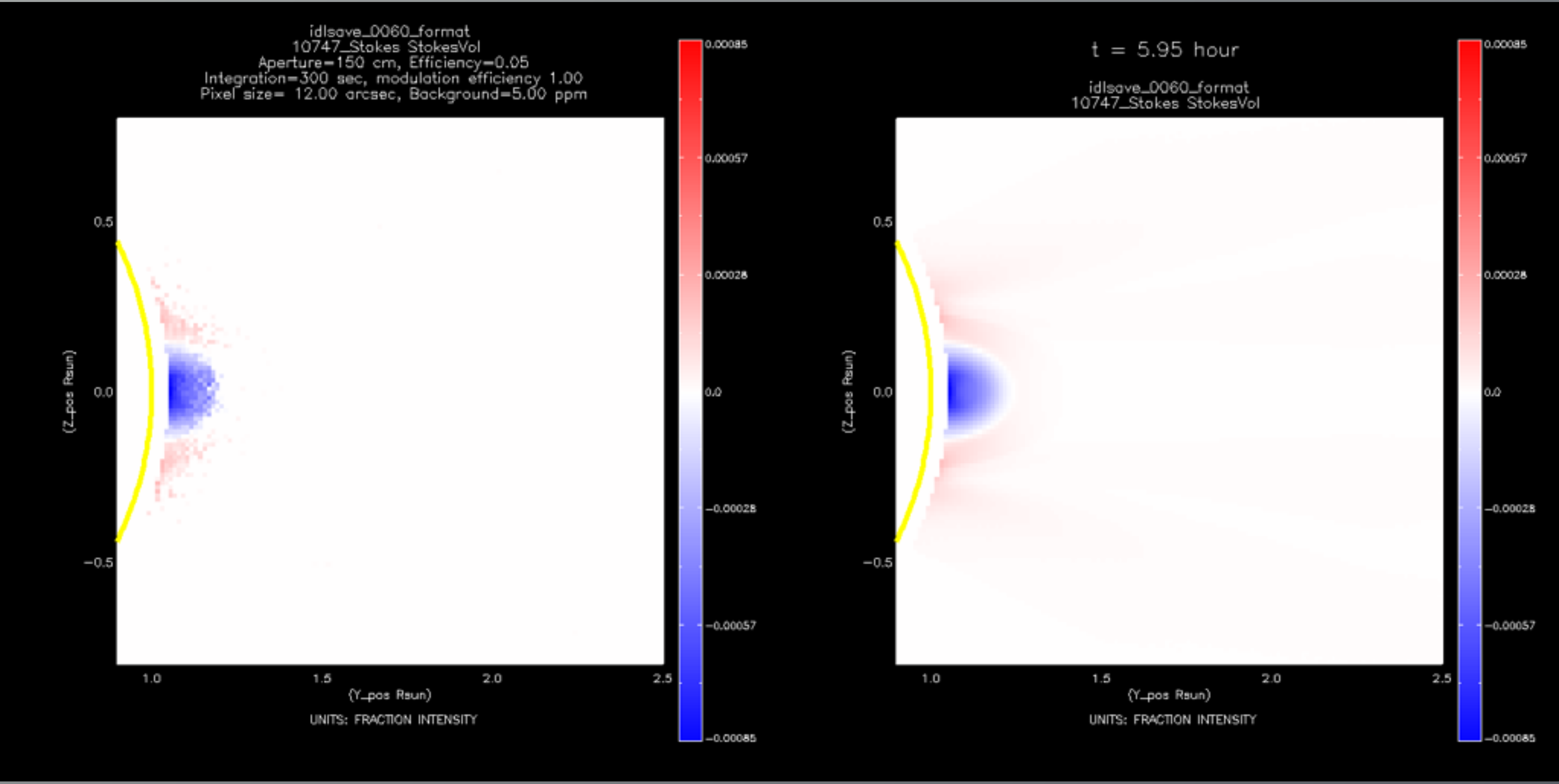
Coronal polarimetry: the missing link

Expansion factor associated with pseudo streamers may be underestimated? Significant for solar wind acceleration models
(*Wang et al. 2007; Riley & Luhmann, 2012; Wang et al. 2012*)



Coronal polarimetry: the missing link

Future diagnostics: Circular polarization (~B_{los})



Fan 2017 magnetic erupting flux rope simulation

Photon noise: 1.5 m telescope, 5 minute integration

Coronal polarimetry: the missing link

Take-home message #4:

Coronal polarimetry has great potential for constraining the coronal magnetic field

Conclusions

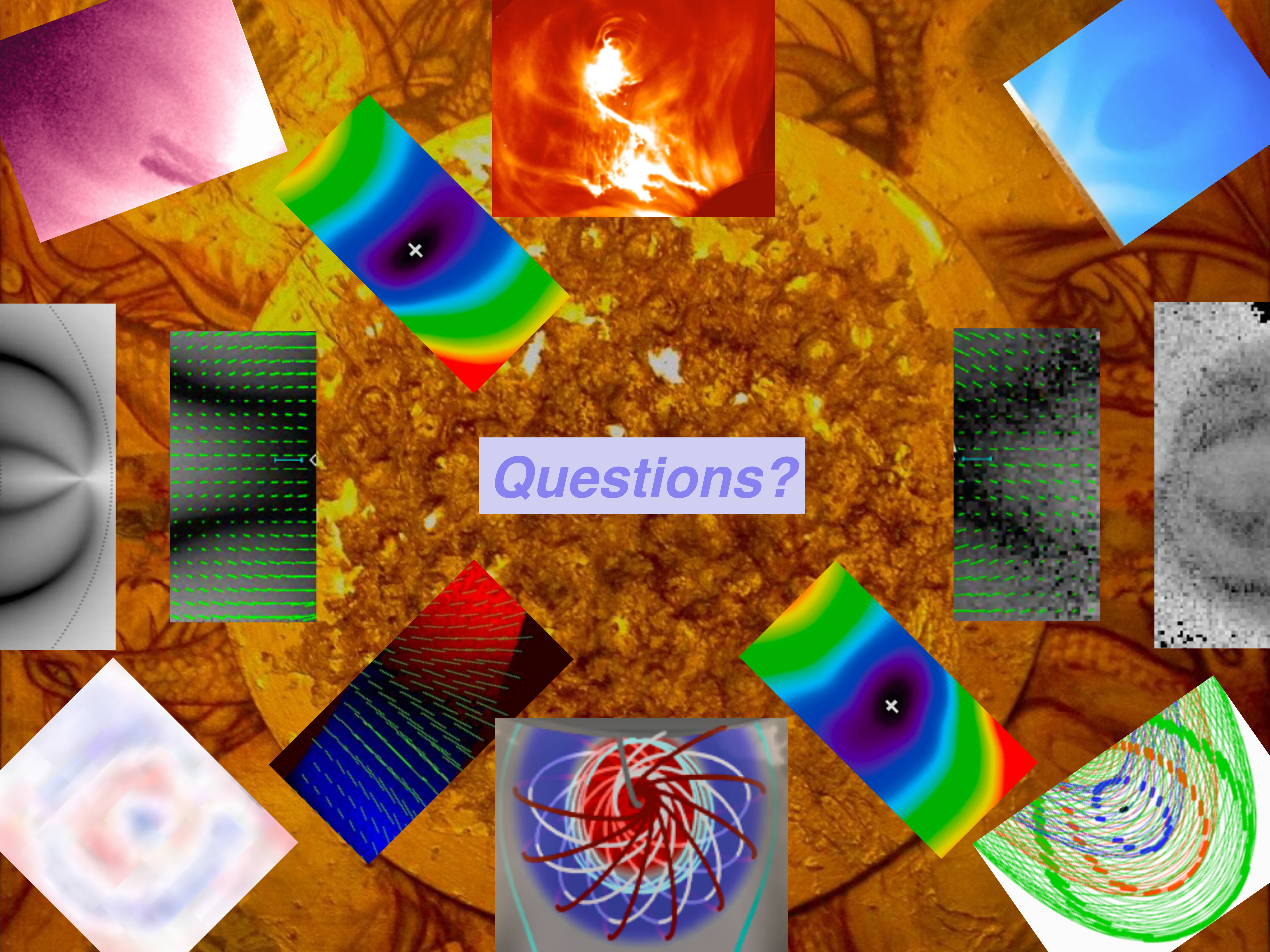
Coronal **magnetism is of broad importance** to solar physics

A range of observations yield clues to the coronal field;
Polarimetric data provide the most direct information.

Actually **quantifying the 3D global field** from these data is not easy.

Need to develop inversion methods that optimize use of observations from **all heights in solar atmosphere**

Leave no data behind!


Questions?