Nonlinear Force-Free Magnetic Field Modeling of the Solar Corona: A Critical Assessment

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on behalf of the *NLFFF working group**

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Rationale

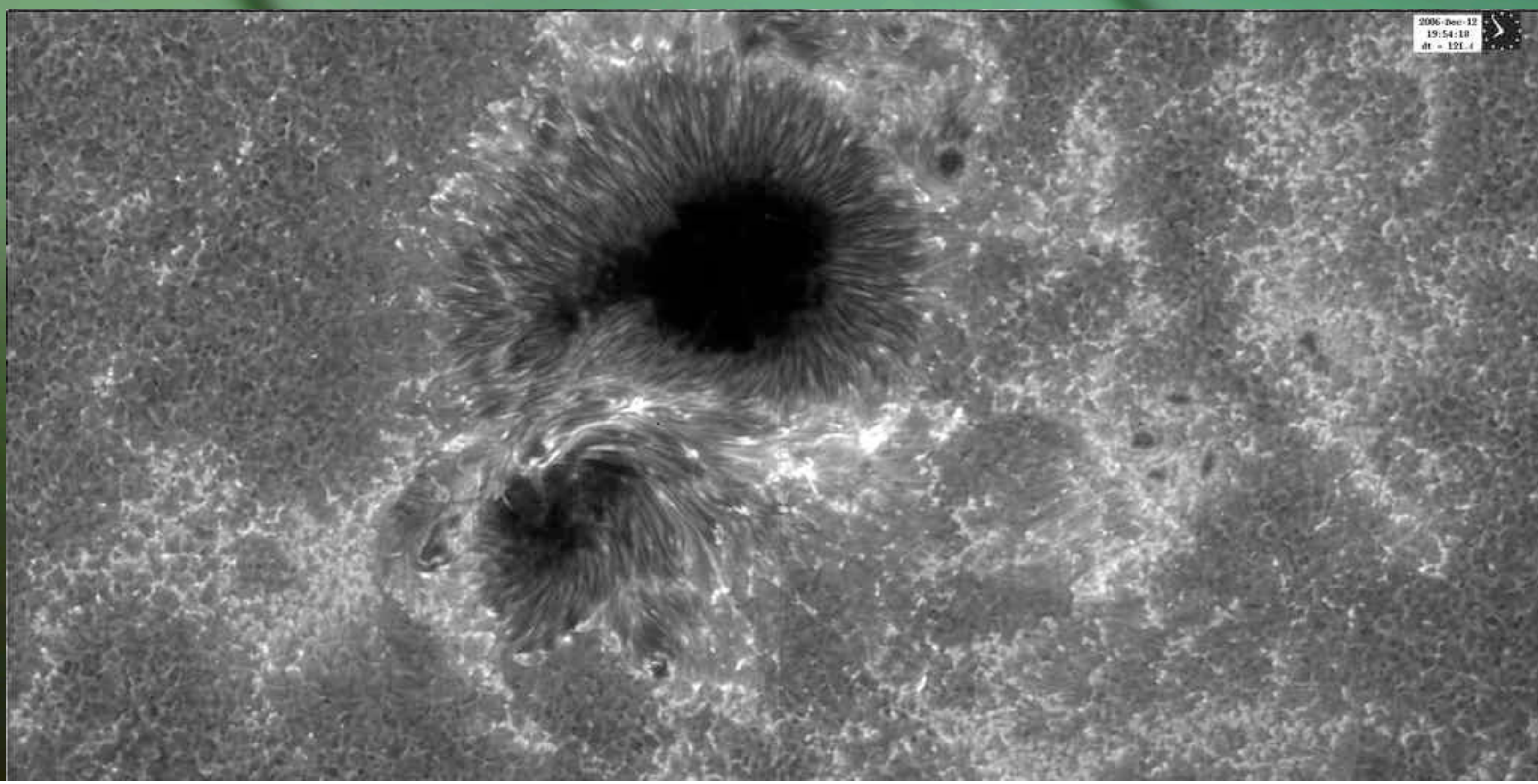
- Understanding the dynamical structure and evolution of the solar corona requires a *quantitative understanding of the coronal magnetic field and its currents*.
- *Nonlinear force-free fields (NLFFFs) provide a useful model*. The magnetic field is determined inside a computational volume, subject to $(\nabla \times \mathbf{B}) \times \mathbf{B} = 0$, or $\mathbf{J} = \alpha\, \mathbf{B}$.
- The scalar α is invariant along fieldlines of $\mathbf{B}$.
- In general, α varies spatially, making the problem of solving for $\mathbf{B}$ nonlinear.

Algorithms

- Three popular algorithms:
  - *Optimization* [minimize a metric containing $(\nabla \times \boldsymbol{B}) \times \boldsymbol{B}$ and $\nabla \cdot \boldsymbol{B}$]
  - *Current-field iteration* [initialize field, apply currents based on surface α, recompute field, iterate…, stop when a fixed point is (hopefully) reached]
  - *Magneto-frictional* [solve a MHD-like system of equations, including an ad-hoc friction term that drives the system toward a force-free state]

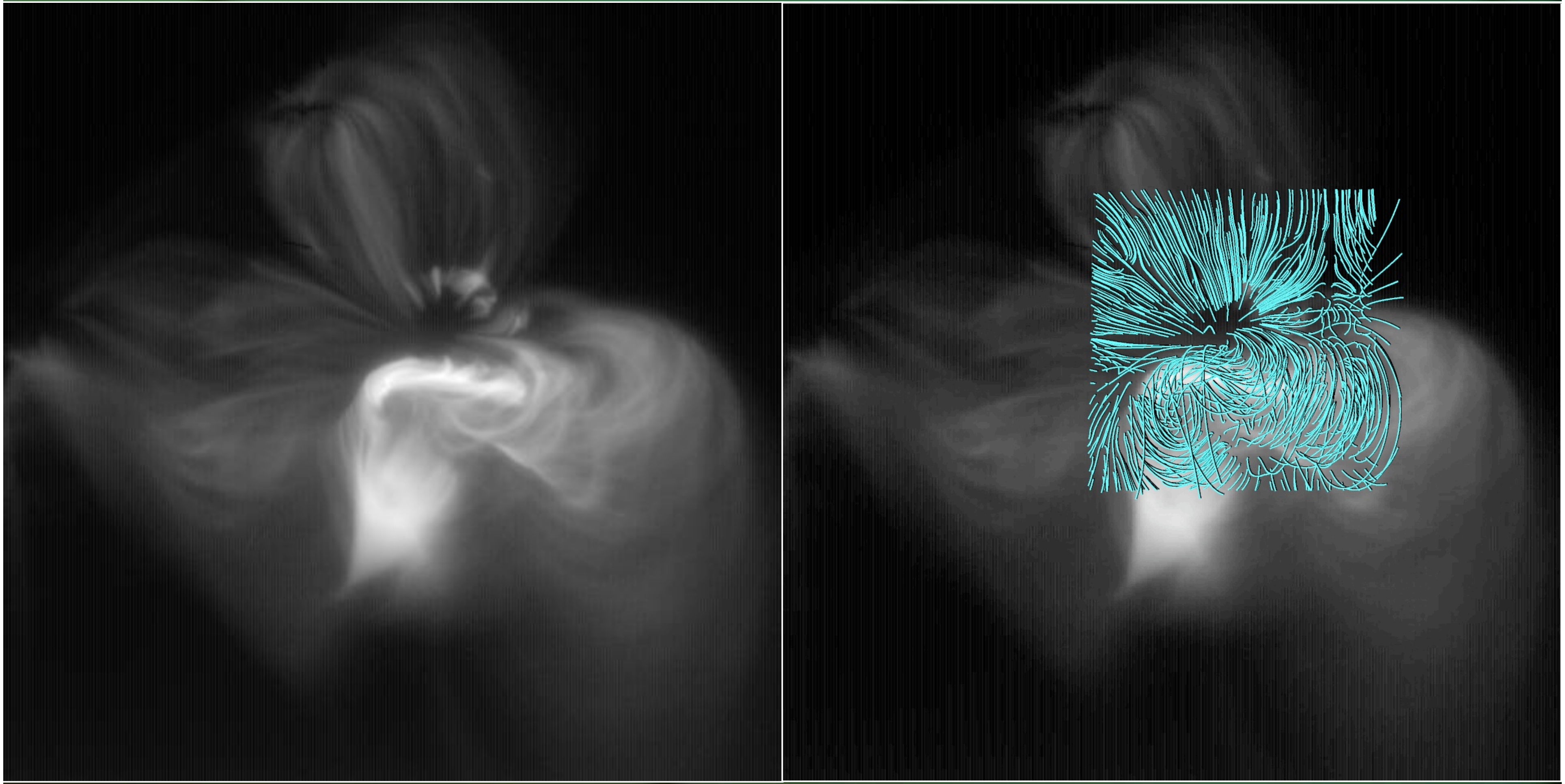
Previously…

- We performed 14 extrapolations for each of two Hinode/SOT-SP vector magnetogram scans bracketing the X flare that occurred on 13 Dec 2006 in AR 10930.



Ca II H from Hinode/SOT-BFI

Hinode/XRT overlay - preflare



fieldlines contained within a 320×320×128-pixel volume

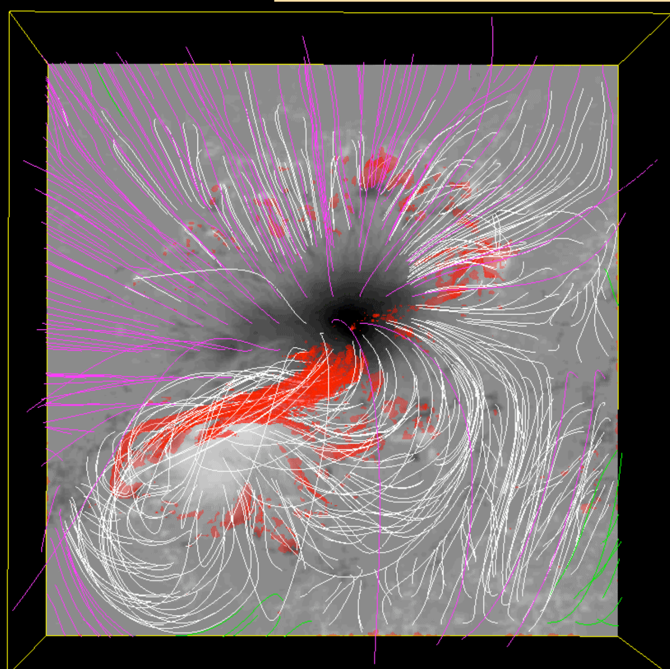
2006.12.12_2030

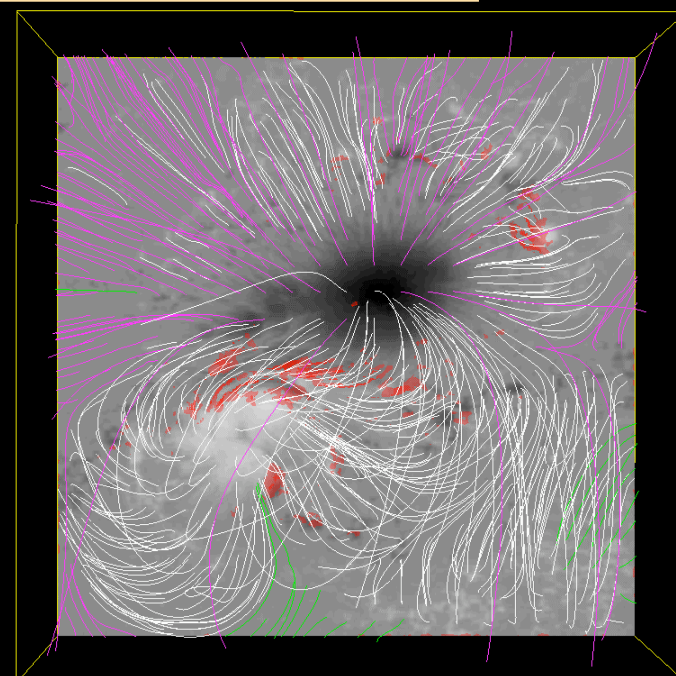
Volume renderings of current density

pre-flare

post-flare

difference in free energy = 3 × 10^{32} erg





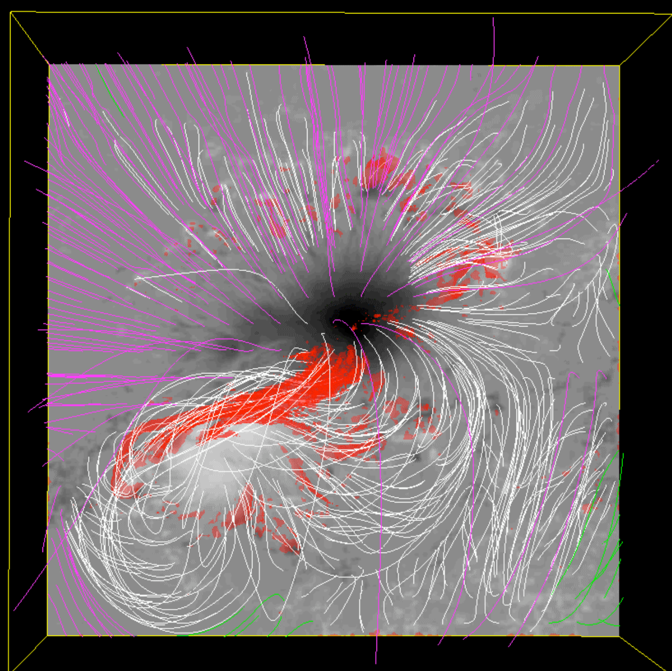
isosurface of |***J***| shown in red

$E/E_{pot}=1.32$

$E/E_{pot}=1.14$

Free energies for AR 10930

pre-flare



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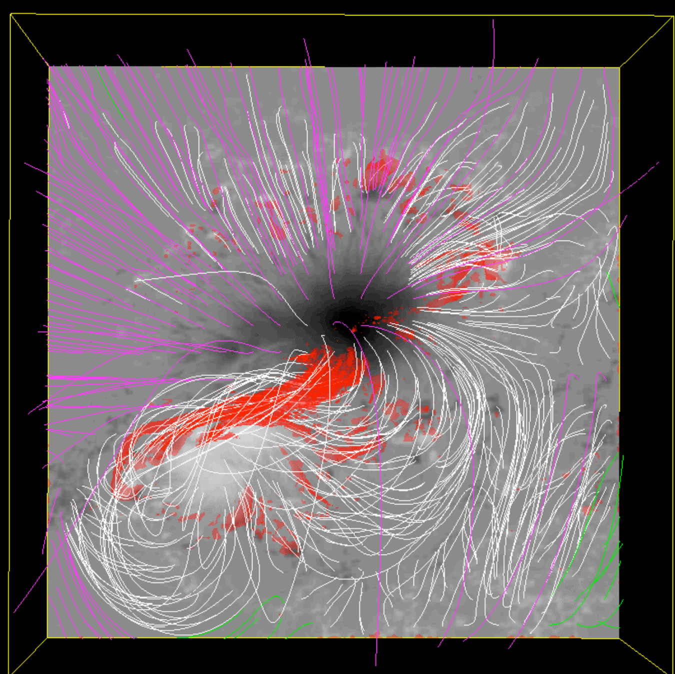
E/E_{pot}=1.32

Model	pre-flare E/E_{pot}
Wh^{+}_{pp}	1.32
Wh^{+}_{np}	1.10
Wie_{wp}	1.09
Val_{pp}	1.10
Wh^{0}_{pp}	1.04
Wie_{ns}	1.04
Val_{np}	0.88
Wie_{np}	0.95
Wie_{pp}	1.05
McT_{pp}	1.01
Wh^{0}_{np}	1.03
Wh^{-}_{np}	1.04
Wh^{-}_{pp}	1.05
McT_{np}	0.95
Potential	1.00

From Table 1 of Schrijver et al. (2008)

Free energies for AR 10930

pre-flare



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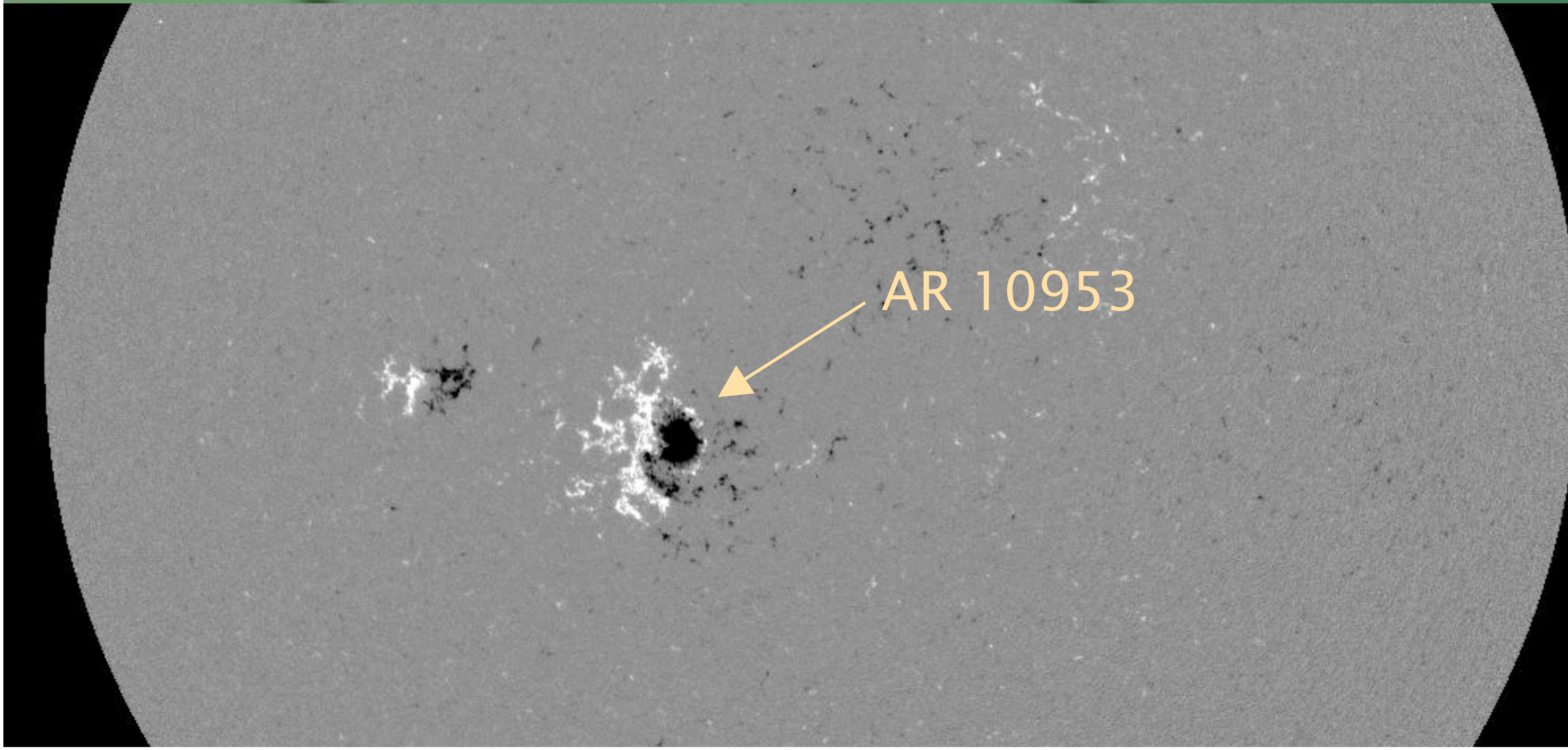
Now…

- We performed extrapolations based on Hinode/SOT-SP vector magnetogram scan of AR 10953 on 30 Apr 2007.



FDMG from SOHO/MDI

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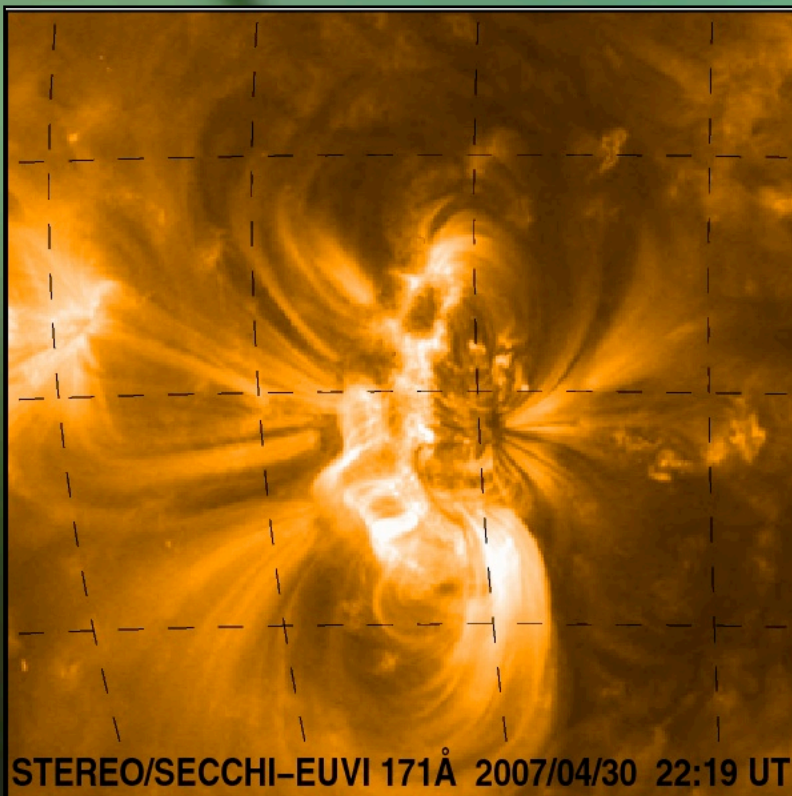

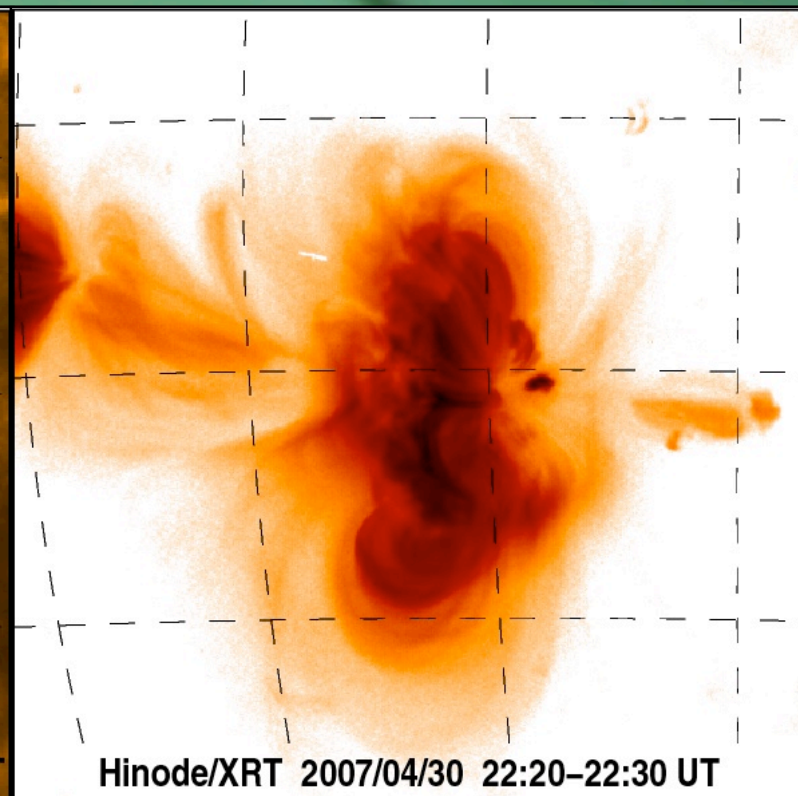

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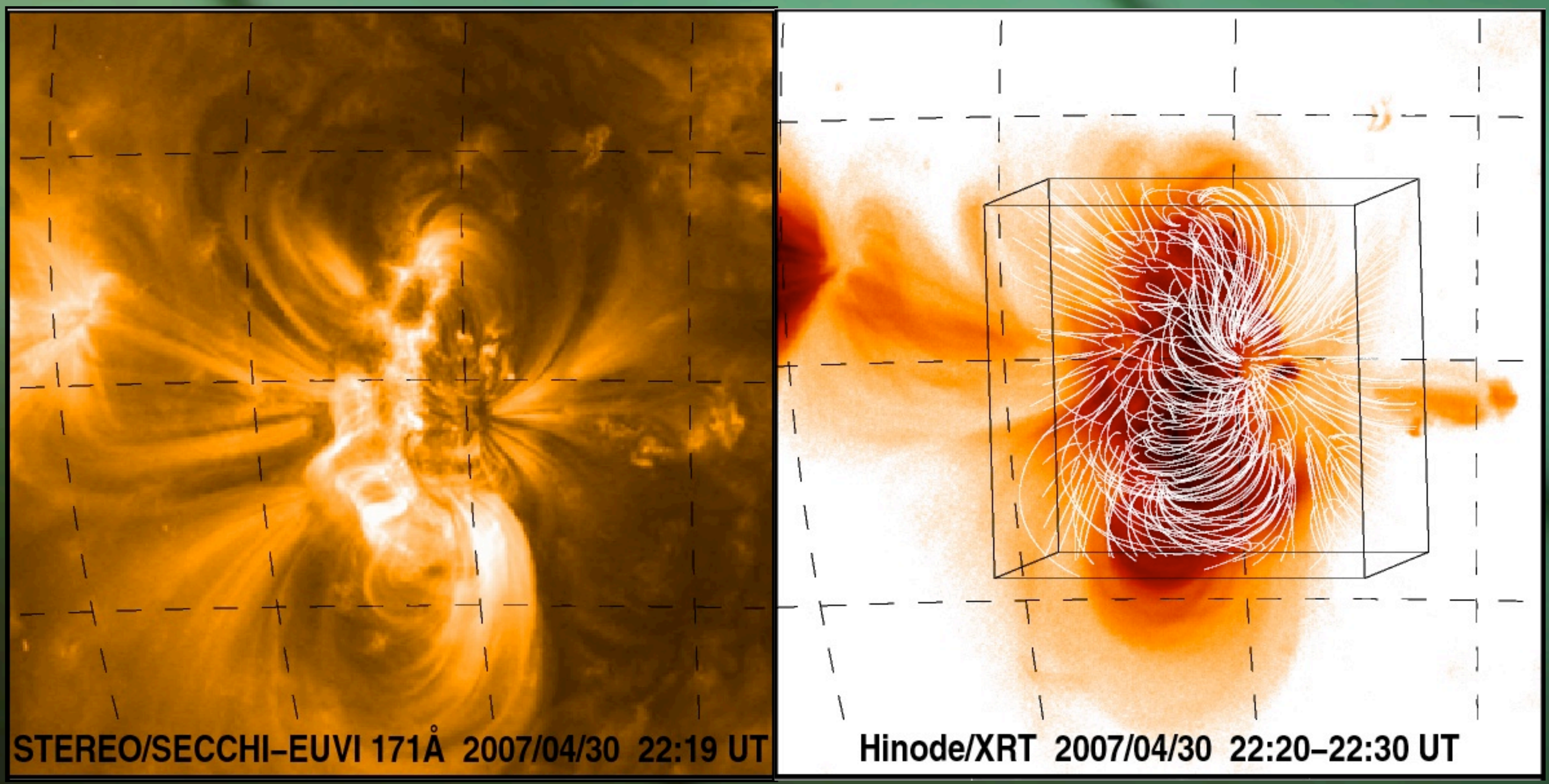
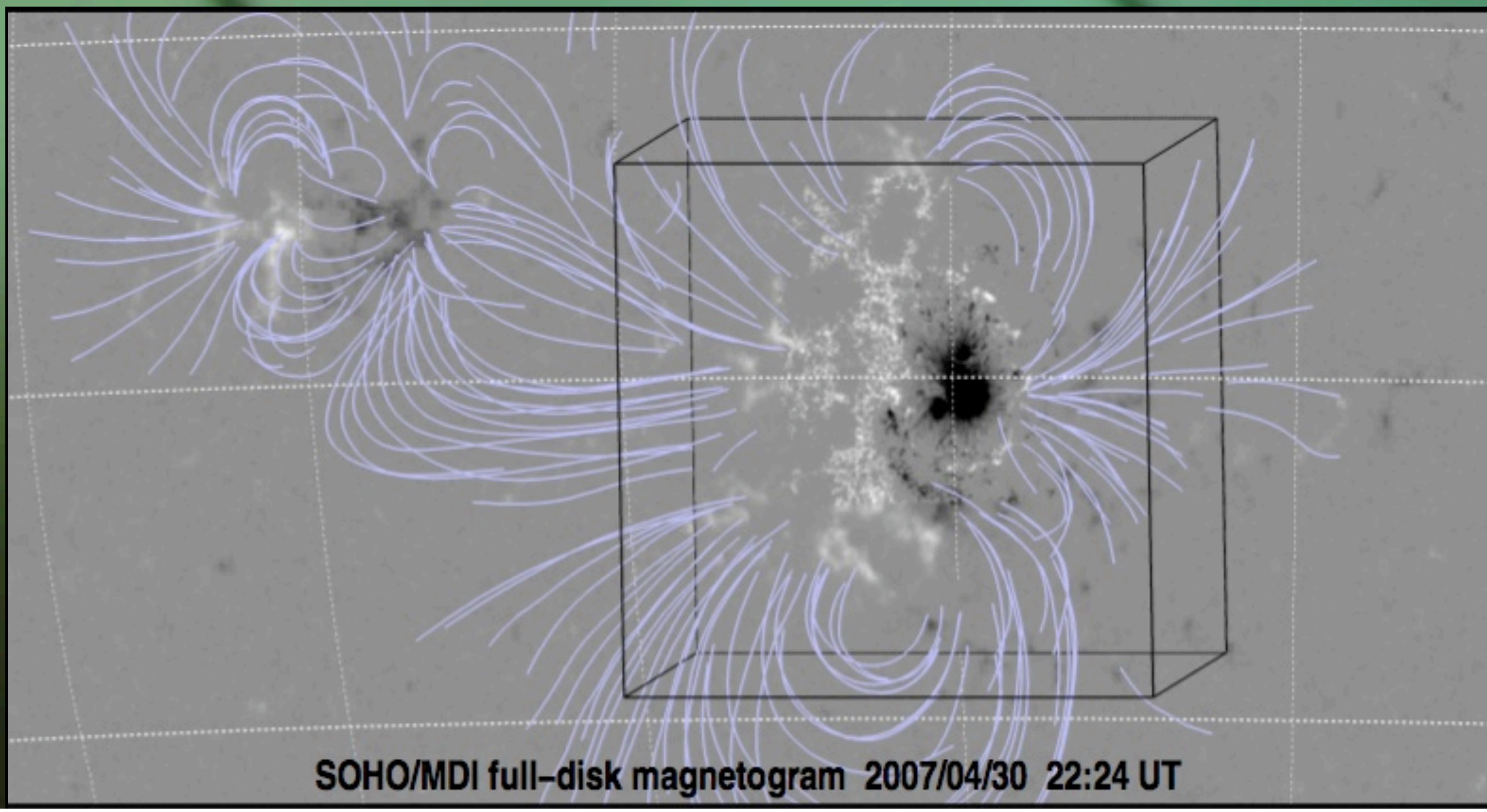


Comparison with STEREO

- We compared model fieldlines to three-dimensional loop trajectories determined using stereoscopy (applied to STEREO/SECCHI-EUVI).



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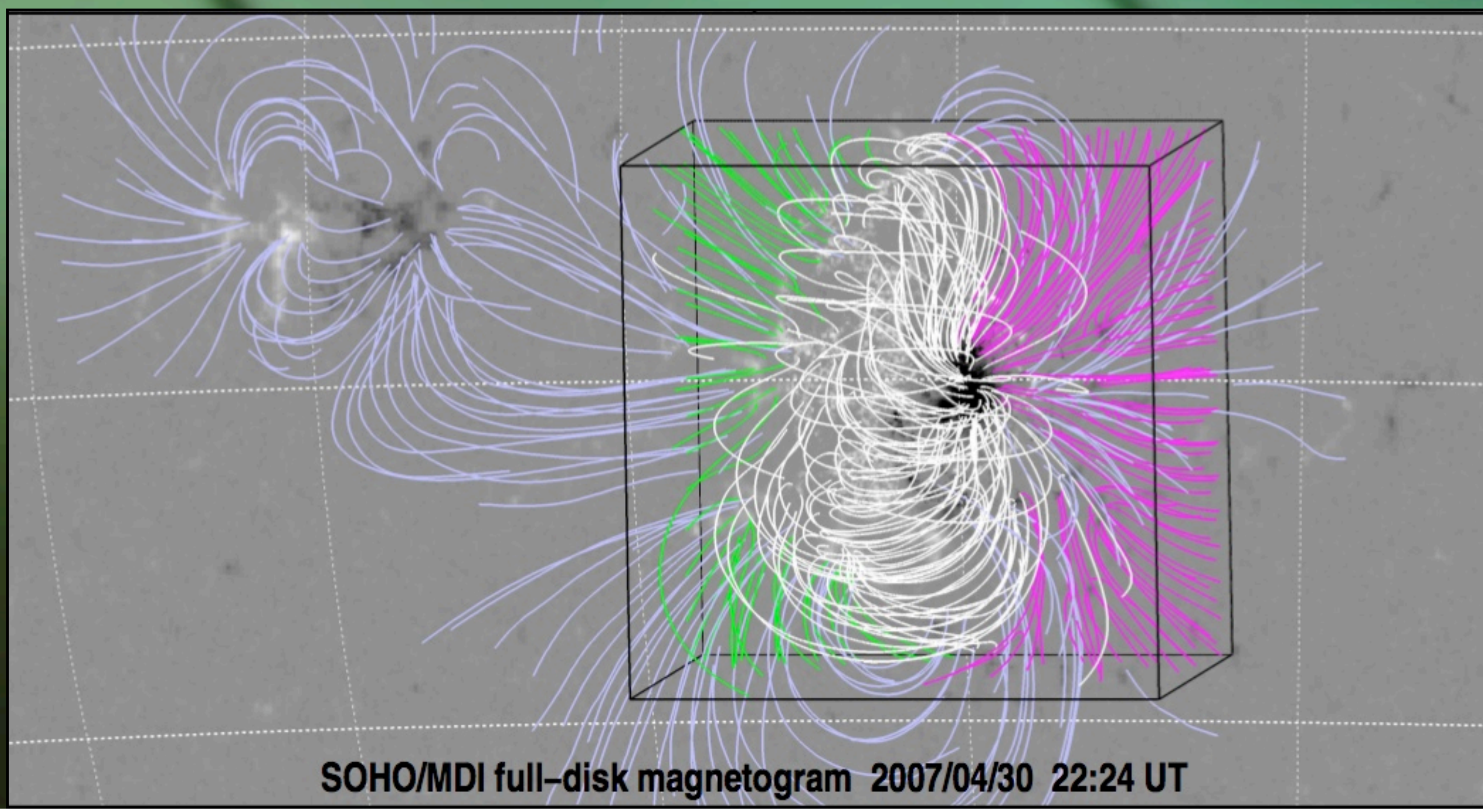

Comparison with STEREO

- We compared model fieldlines to three-dimensional loop trajectories determined using stereoscopy (applied to STEREO/SECCHI-EUVI).
- Alignment: $\phi < 5^\circ$ (yellow), $\phi > 45^\circ$ (red)

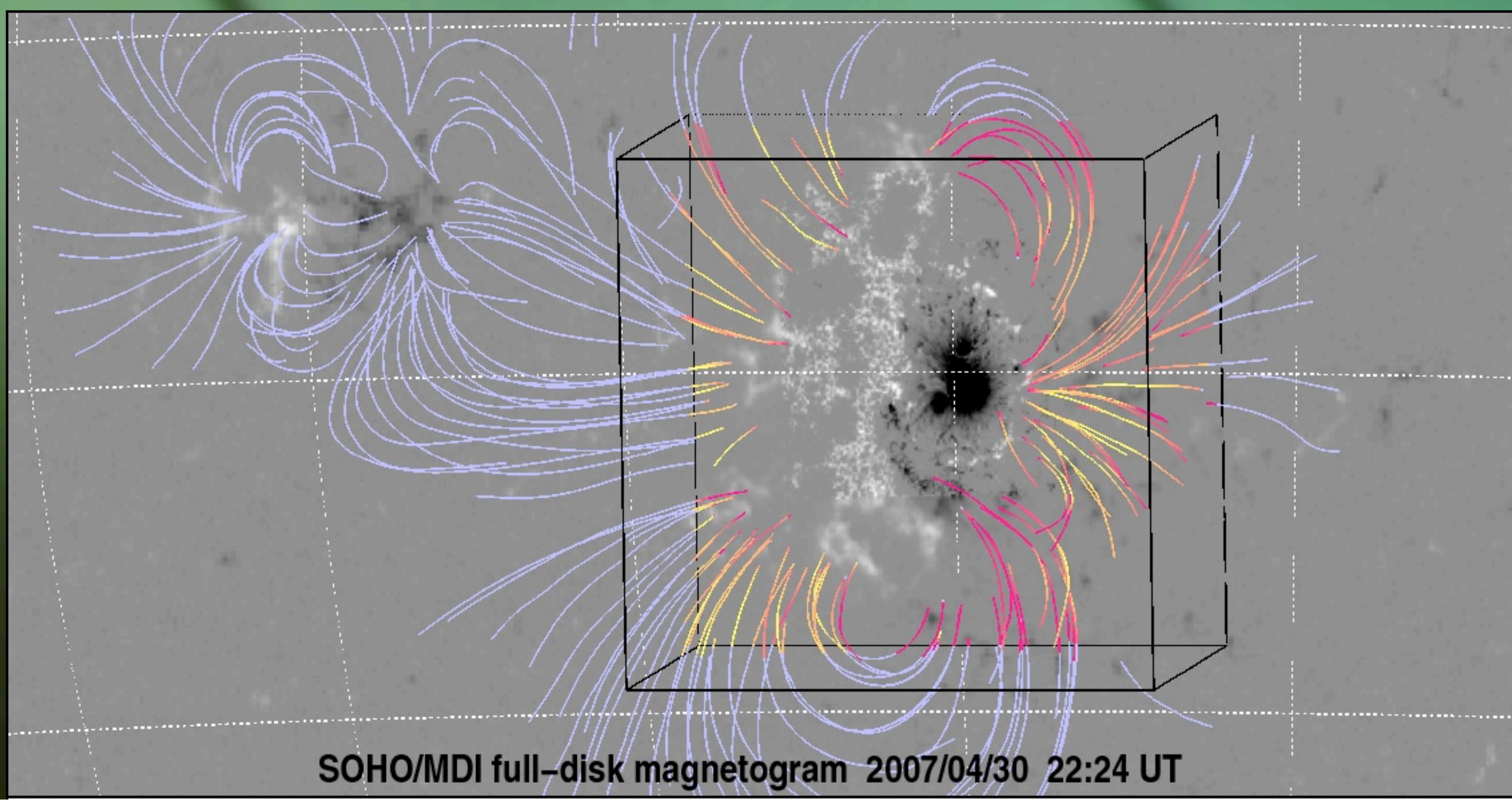

Table of metrics for AR 10953

FIELD EXTRAPOLATION METRICS[a] FOR AR 10953

Model[b]	E/E_{pot} [c]	$\langle \mathrm{CW} \sin\theta \rangle$ [d]	$\langle \lvert f_i \rvert \rangle$ [e] ($\times 10^8$)	$\langle \phi \rangle$ [f]
Wh^-	1.18	0.16	1.9	27°
McT	1.15	0.37	15.	38°
Val	1.12	0.19	99.	59°
Wie	1.08	0.46	20.	32°
Tha	1.04	0.52	34.	25°
Wh^+	1.03	0.24	7.4	24°
Rég	0.85	0.42	6.3	44°
Pot	1.00	—	0.02	24°

What is going on?

- Photosphere has Lorentz and buoyancy forces.
  - Data inconsistent with model assumption.
  - Codes have trouble converging/optimizing when applied to forced boundary data.
  - Codes did perform well when applied to force-free cases with known solutions.
- Preprocessing is an attempt to mitigate this.
  - Boundary data altered to reduce net forces and torques.
  - Laplacian smoothing also applied.
  - Results are better with preprocessing than without.

Conclusions

- NLFFF models should not inherently be trusted.
- A more physically realistic method is needed to capture the photosphere-to-corona interface to better transform the forced photospheric boundary data to (an approximation of) the force-free field in the low corona.
- Smaller problems:
  - Fields of view often too small (not all currents captured, edge effects cause issues).
  - Codes need some way to take into account uncertainties in the boundary data.