Partially Open Fields and the Energy of Solar Eruptions

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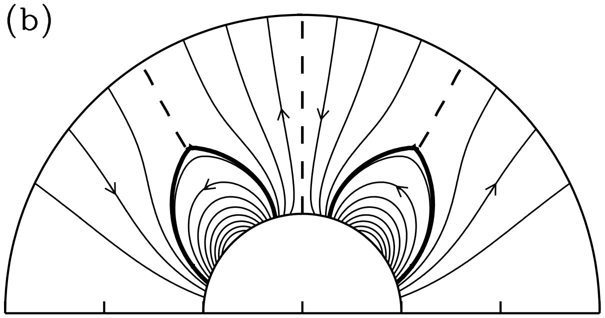
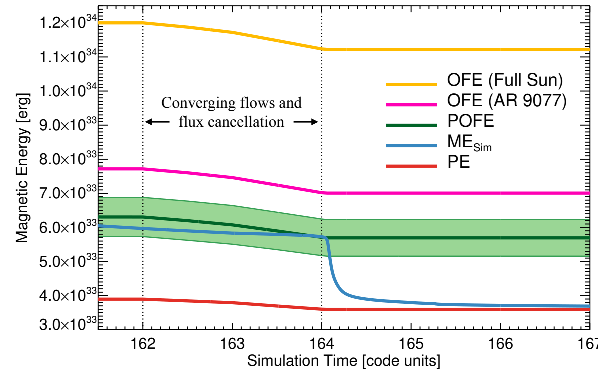
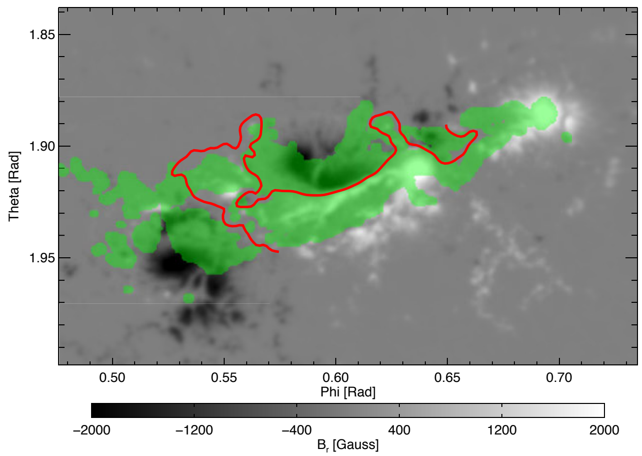
Abstract

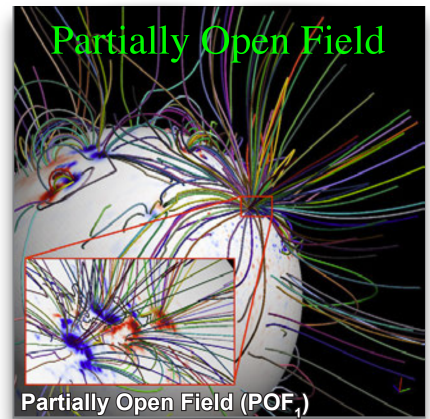
It has long been recognized that the energy source for major solar flares and coronal mass ejections (CMEs) is the solar magnetic field within active regions. Specifically, it is believed to be the release of the free magnetic energy (energy above the potential field state) stored in the field prior to eruption. For estimates of the free energy to provide a prognostic for future eruptions, we must know how much energy an active region can store – Is there a bound to this energy? The Aly-Sturrock theorem shows that the energy of a fully force-free field cannot exceed the energy of the so-called open field. If the theorem holds, this places an upper limit on the amount of free energy that can be stored. In recent simulations, we have found that the energy of a closely related field, the partially open field (POF), can place a useful bound on the energy of an eruption from real active regions, a much tighter constraint than the energy of the fully open field. A database of flare ribbons (Kazachenko et al., ApJ 845, 2017) offers us an opportunity to test this idea observationally. A flare ribbon mask is defined as the area swept out by the ribbons during the flare. It can serve as a proxy for the region of the field that opened during the eruption. In this preliminary study, we use the ribbon masks to define the POF for several large events originating in solar cycle 24 active regions, and compute the energy of the POF. We compare these energies with the X-ray fluxes and CME energies for these events. Work supported by NSF, NASA, and AFOSR.

Partially Open Fields as the Energy Bounds for Solar Eruptions*









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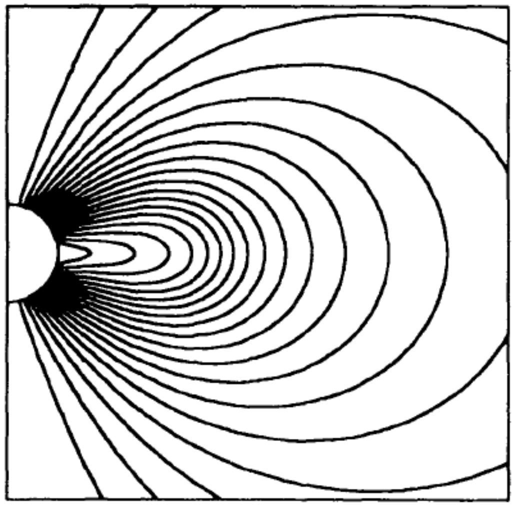
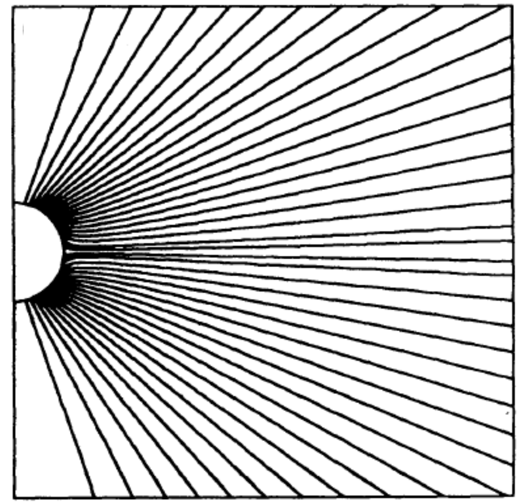
Introduction

- Major solar eruptions such as X-class flares and very fast coronal mass ejections (CMEs) usually originate in active regions on the Sun.
- The energy that powers these events is believed to be stored as free magnetic energy in active region (AR) fields prior to eruption
  - Free Magnetic Energy = Total Magnetic Energy - Potential Magnetic Energy
  - Amount of free energy stored is thus an important indicator of a possible eruption
- Solar active regions can store widely varying amounts of energy - so free energy alone does not tell you if an eruption is imminent
- We need to know how much energy can be stored (the "bound")
- In simulation studies, we have found that the energy of a particular field, the Partially Open Field (POF), can provide this bound (POFE).
- First, let's review open fields and their importance.

Aly-Sturrock "Theorem:"
How Much Energy can be Stored in the Coronal Magnetic Field?



A closed magnetic field;
Magnetic Energy = E



The open magnetic field
(field lines go to infinity);
Magnetic Energy = E_{open}

Aly (1984,1991) and Sturrock (1991) showed that
for force-free magnetic fields $E < E_{open}$

- Coronal magnetic fields not generally force-free
- In strong active regions, plasma ß very low, effectively force-free
- In MHD simulations, eruption can occur when this limit is reached

OFE is Not a Useful Upper Bound

- In an axisymmetric calculation, the entire field has to be opened in order to get a CME, so the OFE is the relevant upper bound
- For the real Sun, the OFE is huge - no CME opens all of the closed fields on the Sun

Partially Open Fields

- In a CME, a portion of the Sun's field is opened, while surrounding fields remain closed.
- Consider a field that is potential everywhere, except on a subdomain S_O where it is open: A Partially Open Field (POF).
- POFs discussed previously (e.g. Wolfson & Low 1992; Hu 2004; Aly &Amari 2007).
- In idealized simulations, we found that approaching the energy of this field (POFE) led to eruption (Amari et al. 2007, 2010, 2011).

Implications and Observational Tests

- If one can practically compute POFs for solar ARs, there are important space weather implications:
  - The maximum severity of a flare/CME from a given region could be known *prior* to the event
  - If the free magnetic energy in the AR can be reliably measured/deduced, major eruptions could be *predicted* if/when the AR free energy approaches the energy bound (POFE)
  - Concept applies to eruptive flares/CMEs - confined flares should release less than POFE
- How can we test this idea with observations?
  - A major component of computing POFs and their energy is identifying the region that opens (S_O)
  - We employ a data base of flare ribbons (Kazachenko et al. ApJ 2017) as a proxy for where the field opens
  - We compute POFs and their energies (POFE) for these regions
  - We will compare the results to actual energy release in the real eruptions

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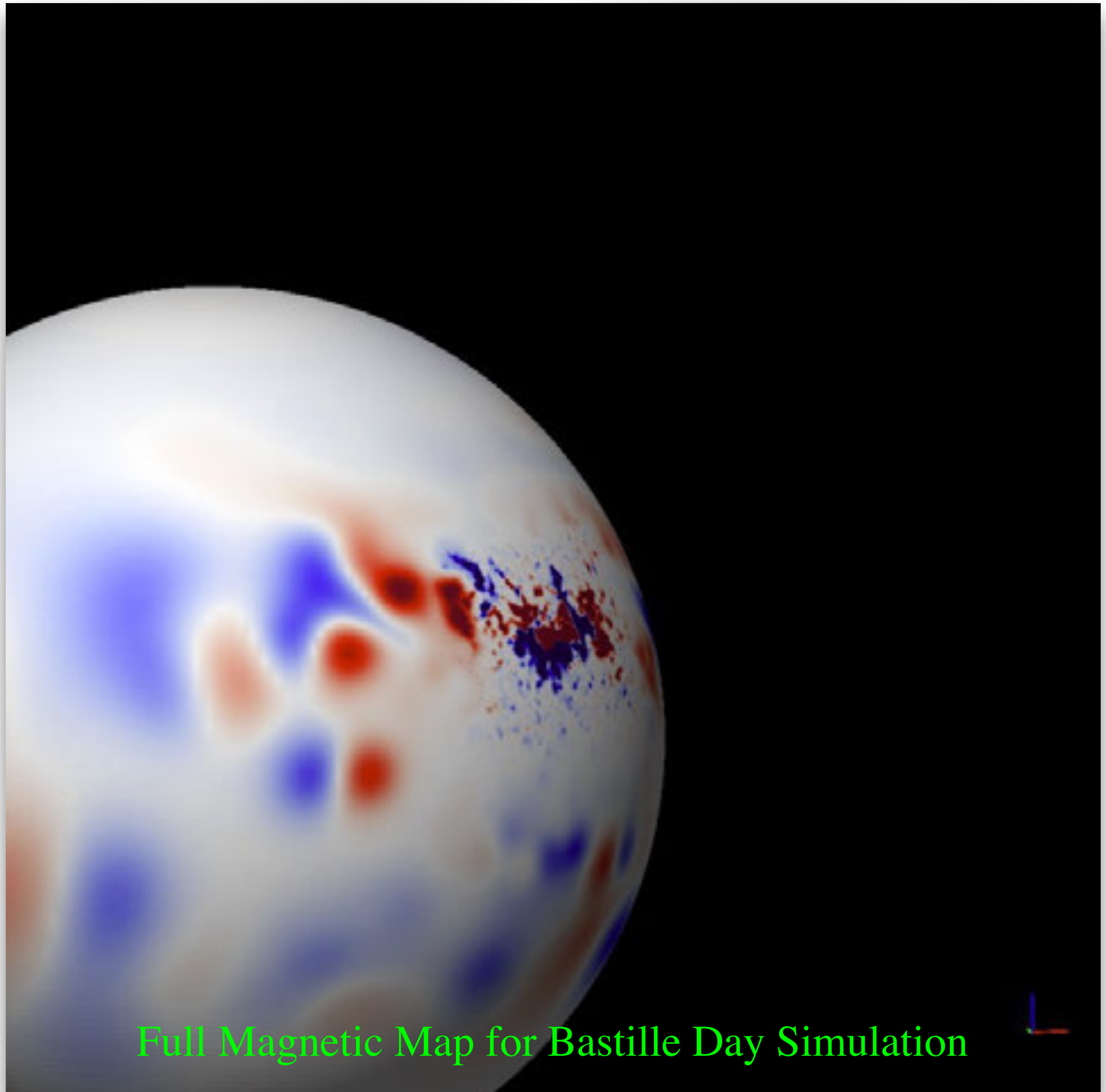
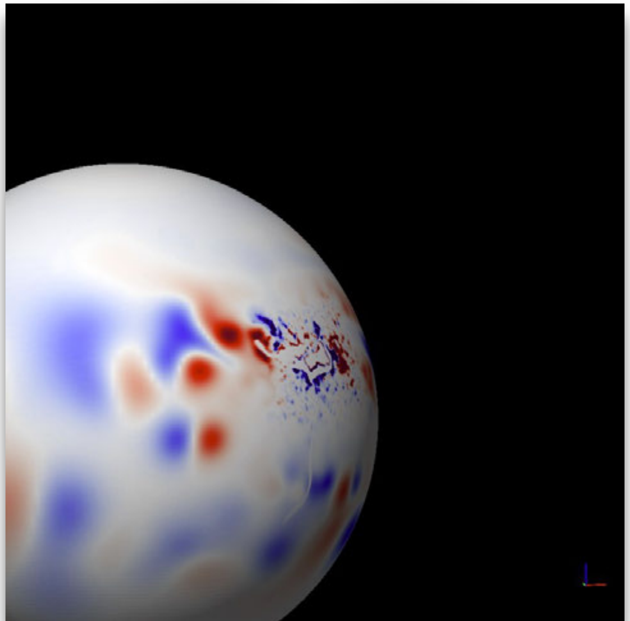
Calculating the Partially Open Field

- In general, this is a very difficult calculation to do exactly.
- First, we estimate S_O: this can be done topologically, here we use the ribbon masks.
- We develop two estimates of the POF for S_O - one a likely lower bound to the energy, the other a likely upper bound.
- These estimates involve solution of potential fields (Laplace's equation) and field line tracing.
- We have developed fast routines for accomplishing these tasks (PFSS solutions on multicore/GPU systems)
- We have calculated POFs for the 263 M & X class flares in the ribbon database. There are issues with some of the calculations, that we are working through.

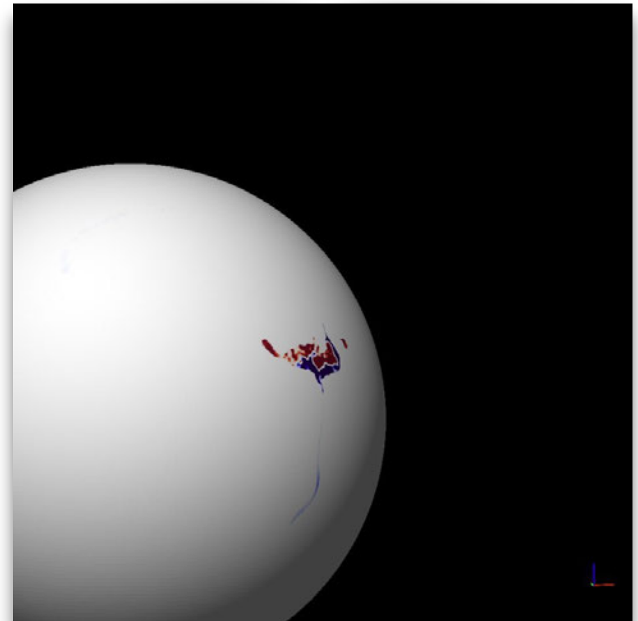
Partially Open Field Estimation: Method 1:

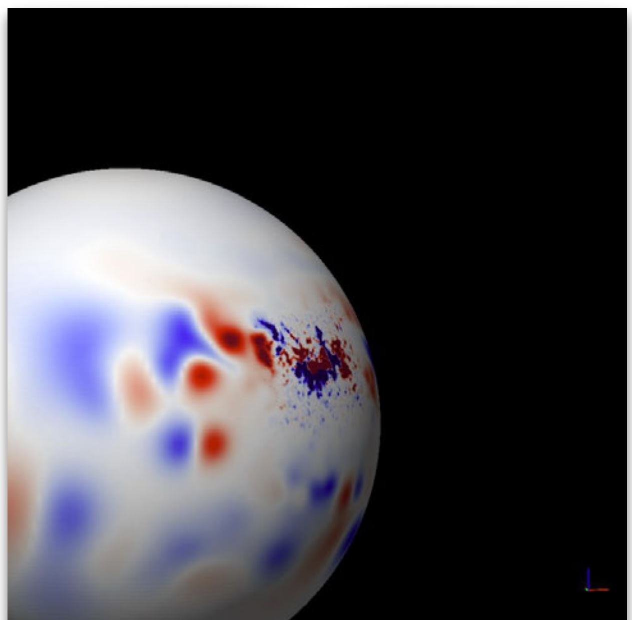


Partially Open Field Estimation: Method 1:



Consider S_O and region outside S_O separately





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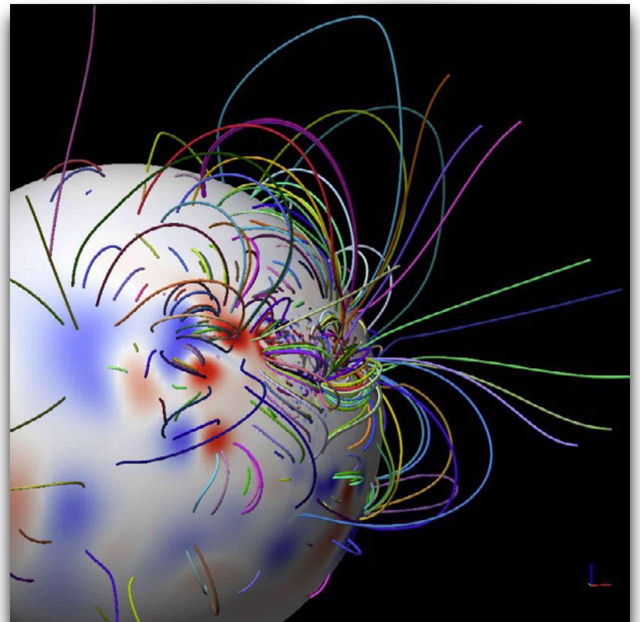
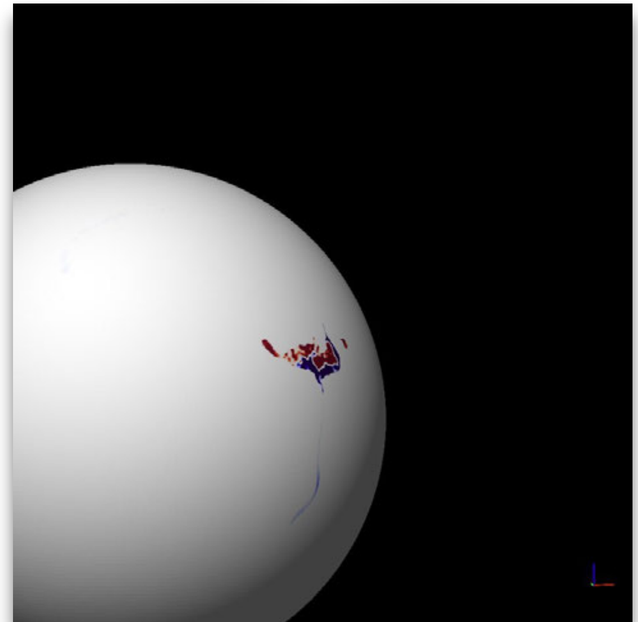
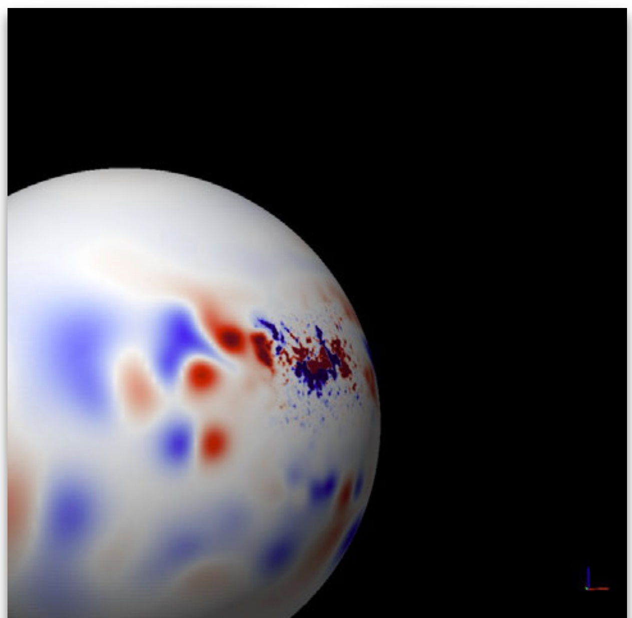


Compute PFSS
Outside S_O





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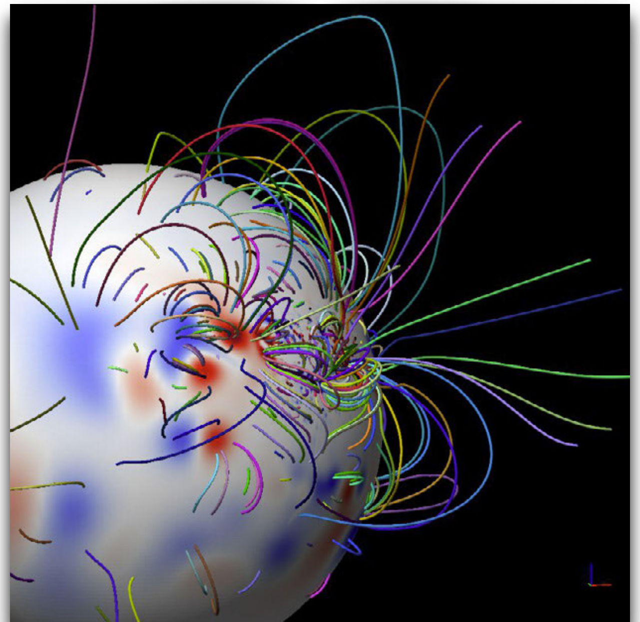
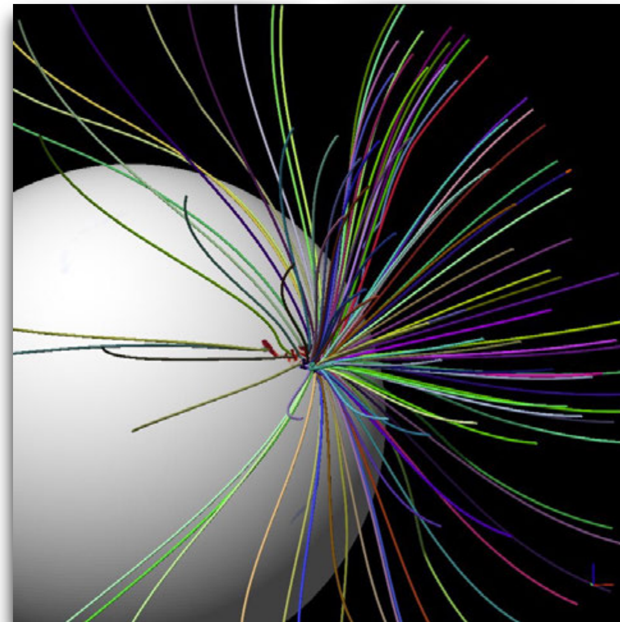
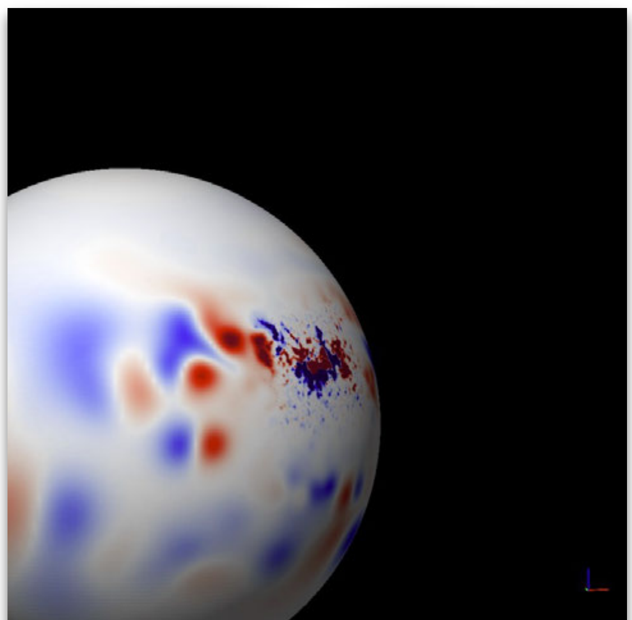


Compute PFSS
Outside S_O

Compute Open Field
Inside S_O





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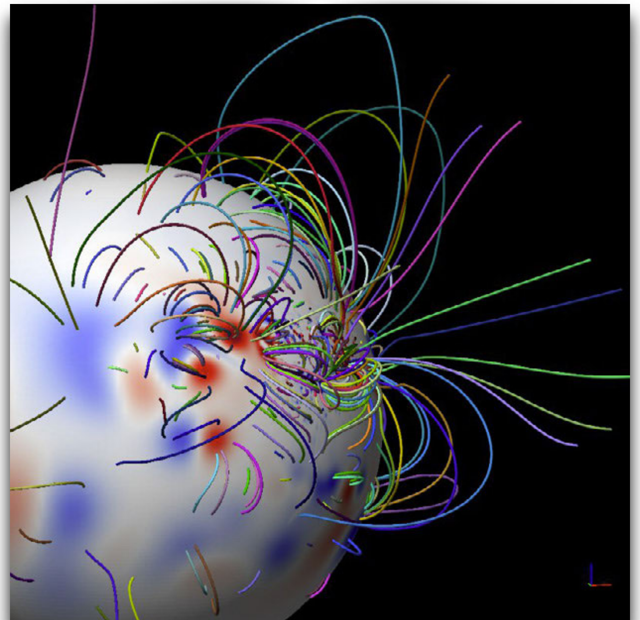
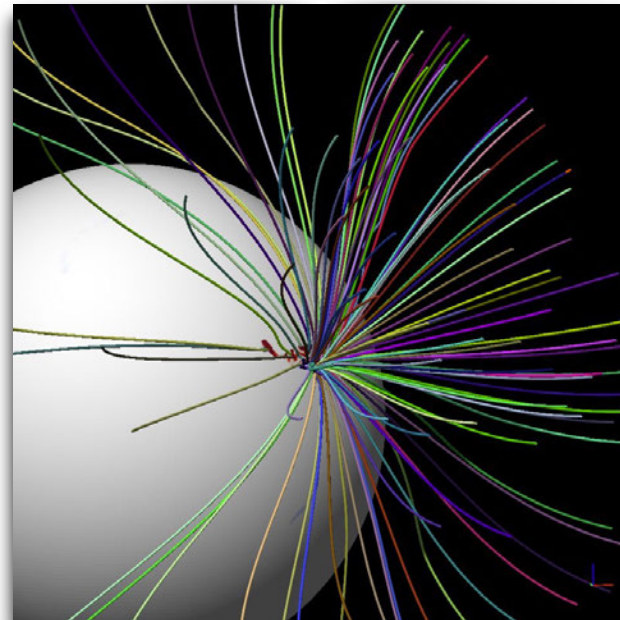
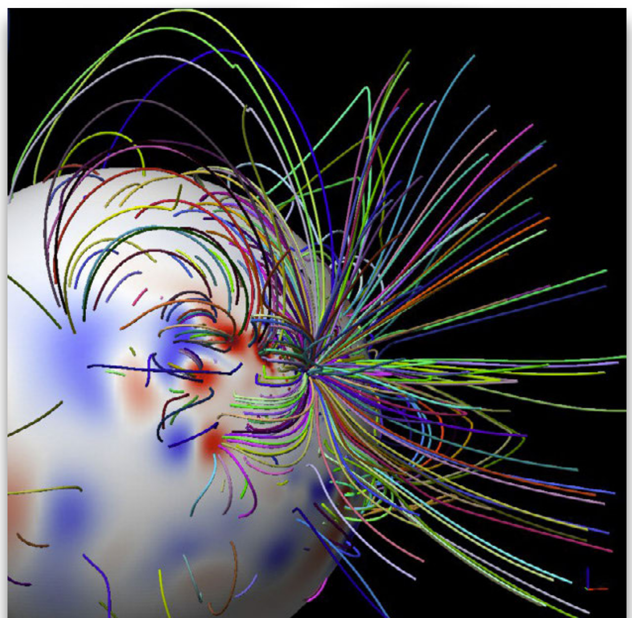
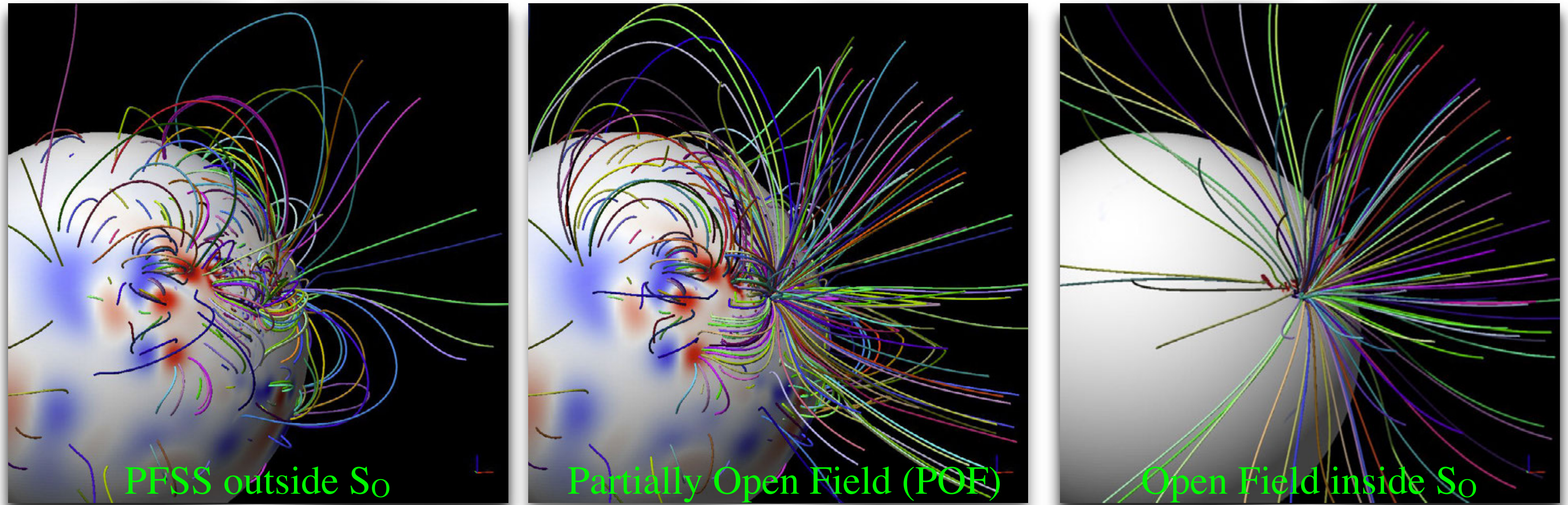


Sum these fields to obtain POF





Partially Open Field Estimation: Method 1:



- This POF actually has closed field lines originating in SO (from summing the fields).
- We think the energy of this field is a lower bound to the POFE.

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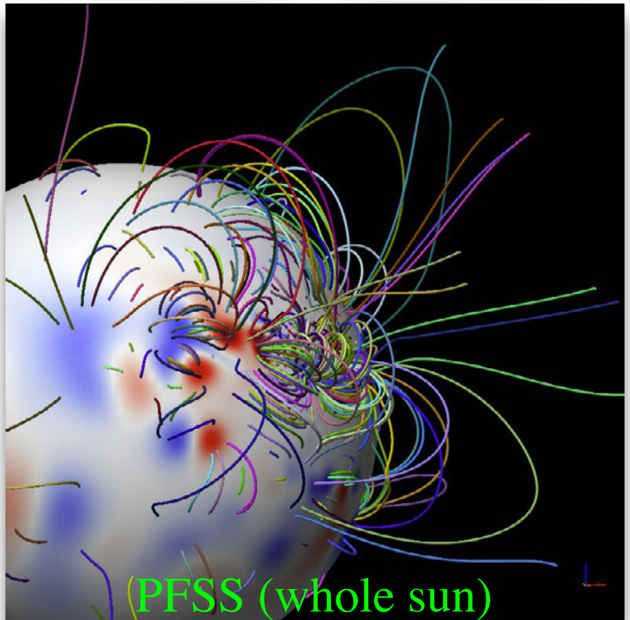
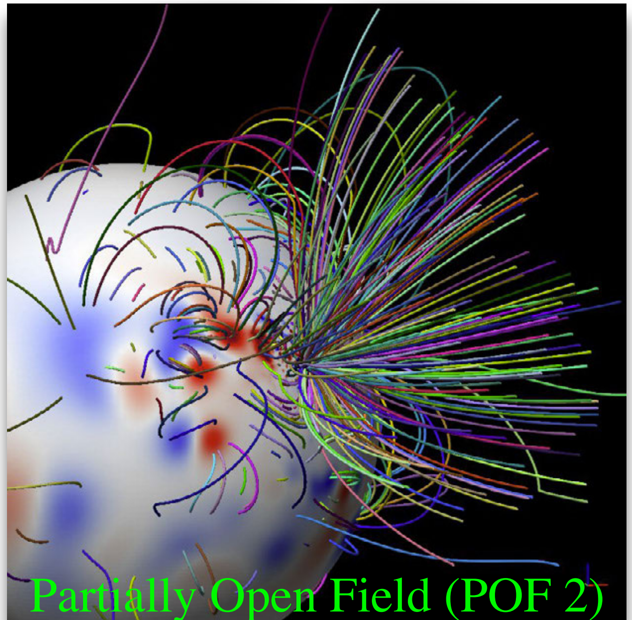
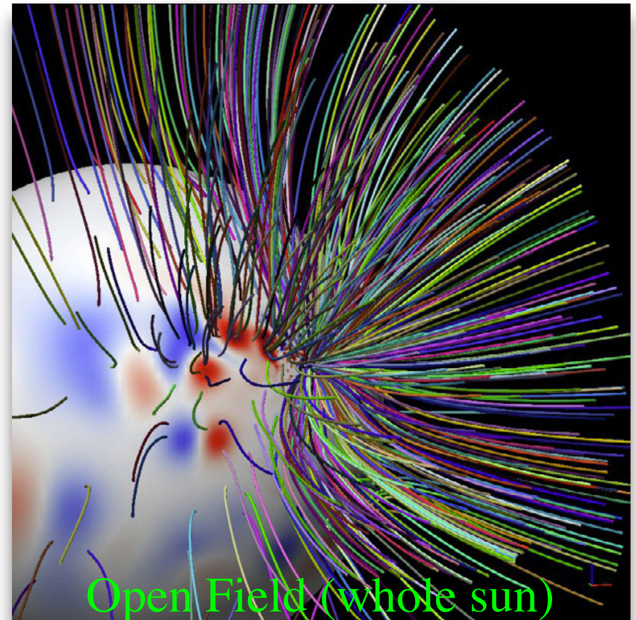
Partially Open Field Estimation: Method 2:



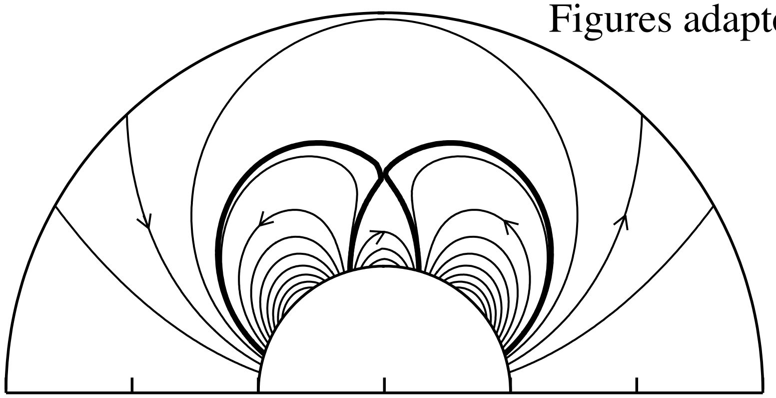




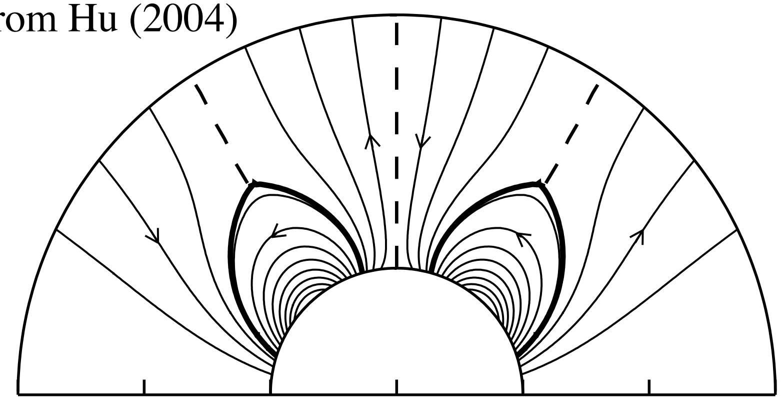
- This 2nd estimate for the POF combines the open and closed field solutions discontinuously, implying current sheets
- We think the energy of this field is an upper bound to the POFE.

How Well Does Our Estimate Work for a Known Case?

Figures adapted from Hu (2004)



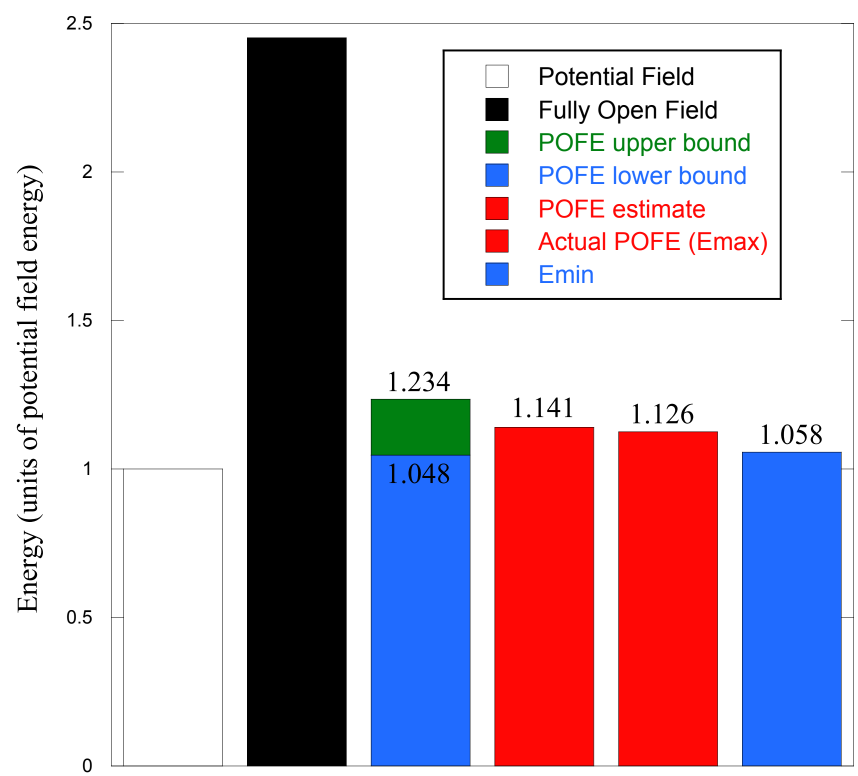
Multipolar Potential Field



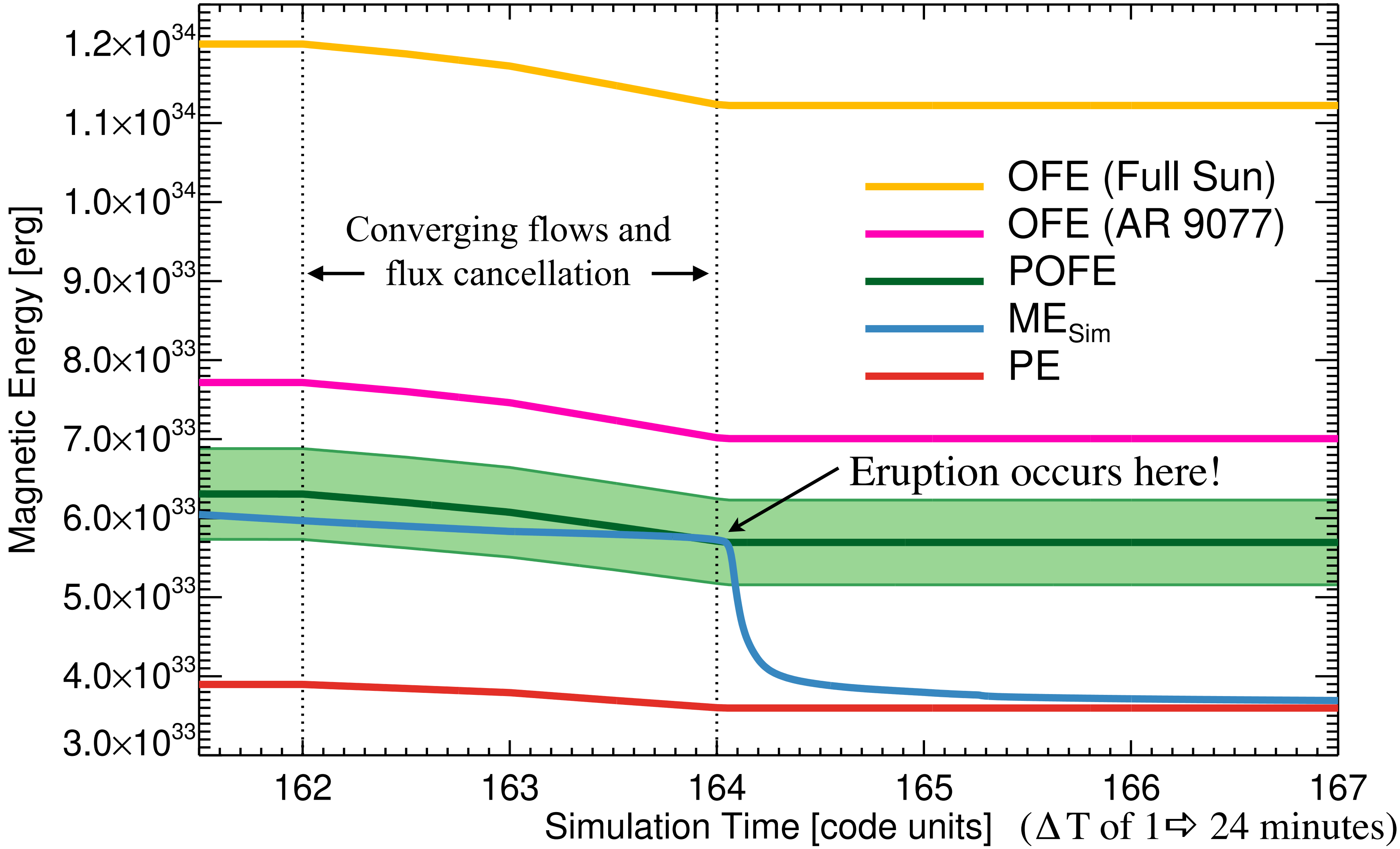
The Partially Open Field
(E_{MAX} identified by Antiochos et al. 1999)

- We apply our technique to the mutipolar field used to illustrate the Breakout model (Antiochos et al. 1999).
- They identified E_{MAX} as the energy of field where all of the central arcade field lines are open - This is the POFE.
- Hu (2004) calculated the energy of this field: 1.126 referenced to the potential field.
- Our technique provides a POFE estimate of 1.141, about 1.3% higher than the “true” value.
- The free energy of the POFE estimate (.141) is about 12% higher than the true value (.126).

Magnetic Energies - Multipolar Field



Torok et al. (2018): Energy Evolution in 7/14/2000 Simulation



- The average of the 2 POFEs predicts eruption onset
- Together, they give a narrow constraint for the energy required for a major eruption

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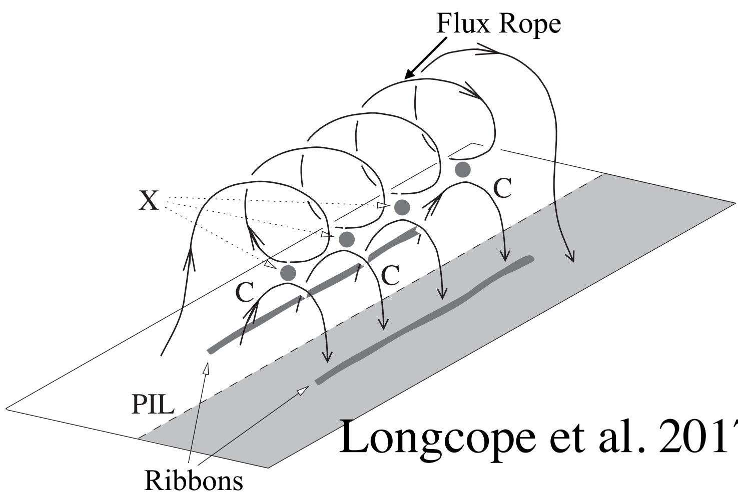
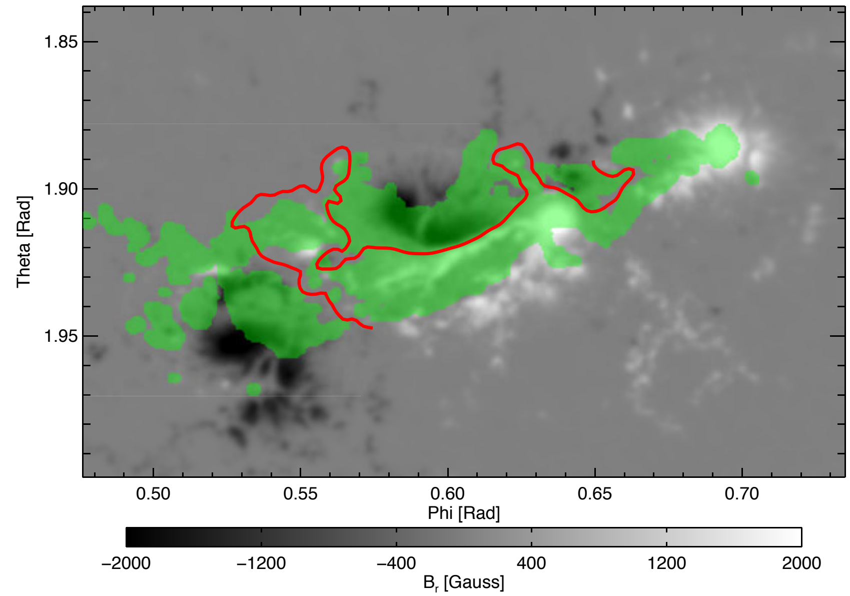
Flare Ribbon Masks Provide an Estimate of S_O (region of opening)

Example AR11158 (February 15, 2011)



Longcope et al. 2017)



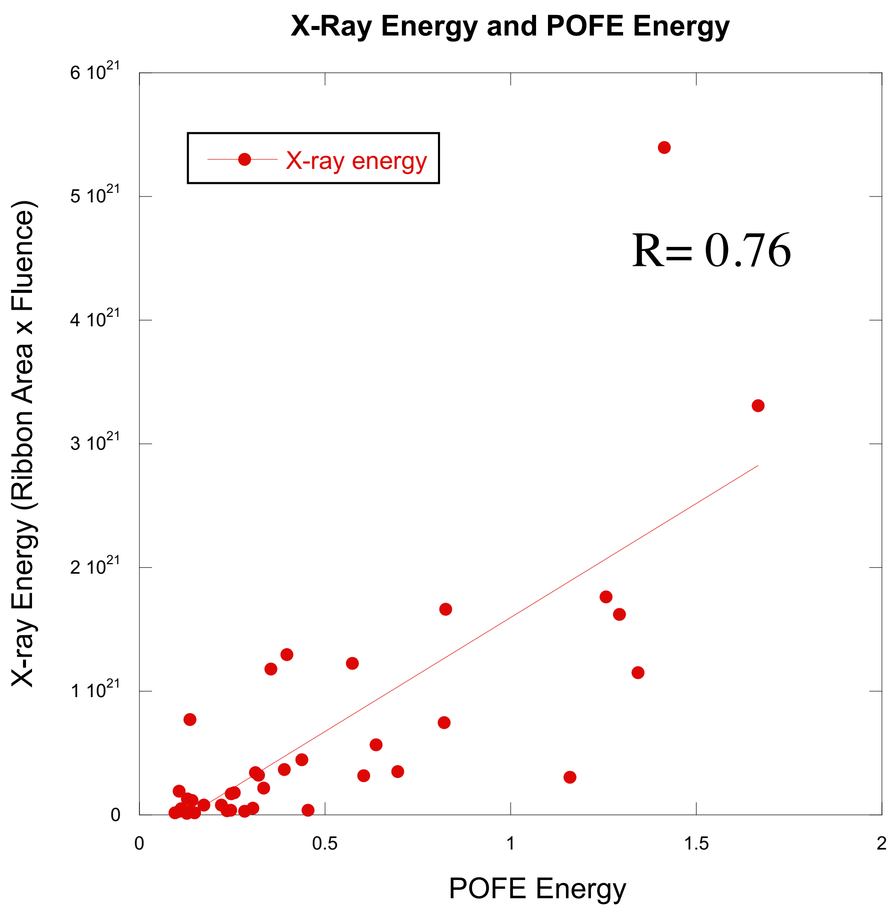
$$\Phi_{ribbon} = \int (\partial\Phi/\partial t)\, dt = \int B_r dS_{ribbon}$$

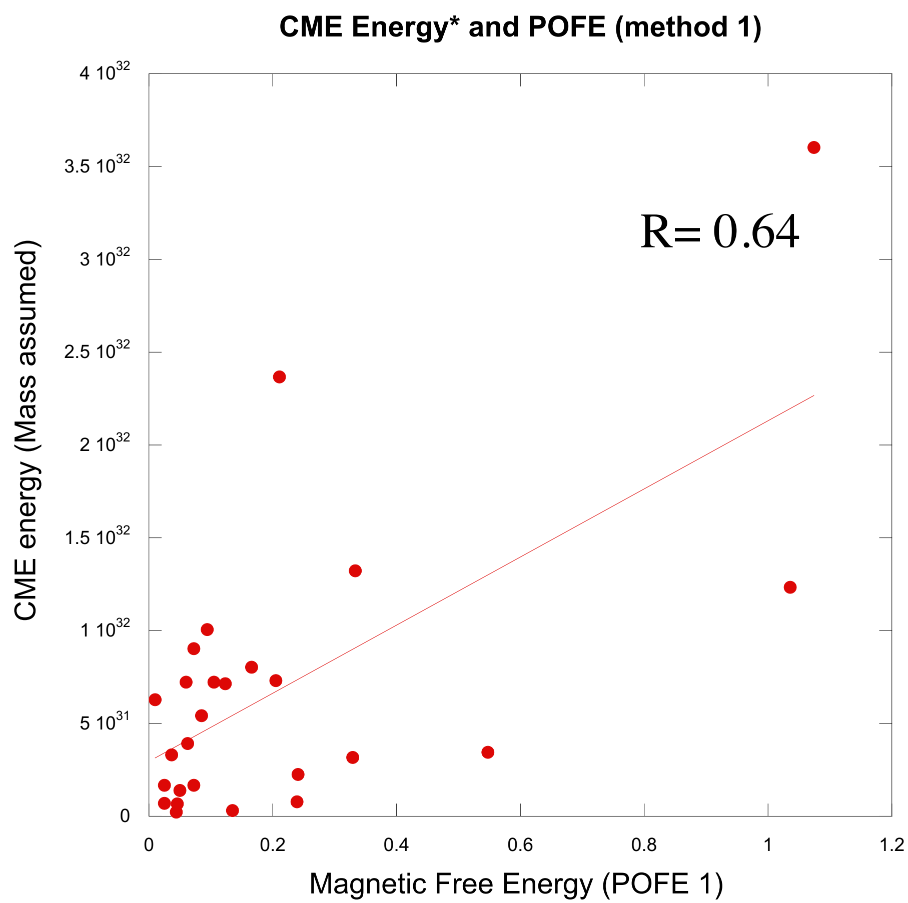
Cumulative Flare Ribbons (provided by Maria Kazachenko)

- We use the ribbon masks to put energy bounds on past events
- Masks available for 263 M & X class flares in Solar Cycle 24 (2010 - 2017)

Results: Observed Energy Release Correlates with POFE

- X-ray Energy (X-ray fluence ribbon mask area)
- CME Energy (really v^2: mass of 10^{16} gm assumed)





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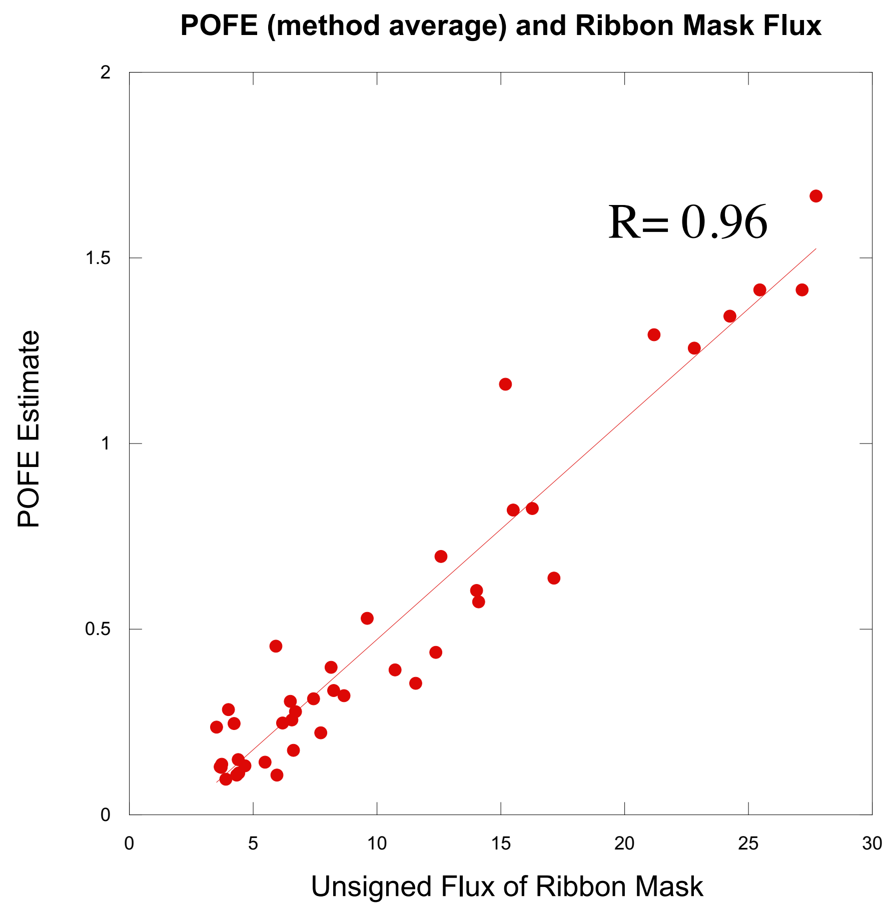
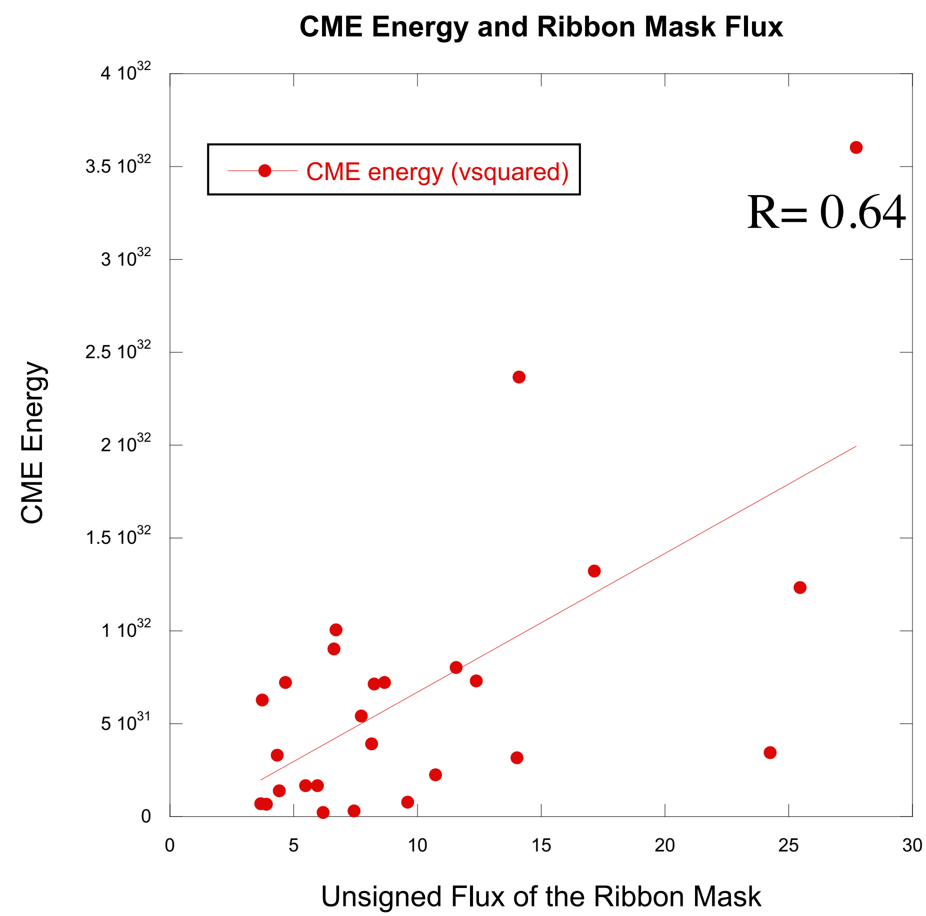
POFE Correlates Strongly with Ribbon Mask Flux

- So what new information does POFE provide?
  - POFE provides actual number for energy, not just a correlation





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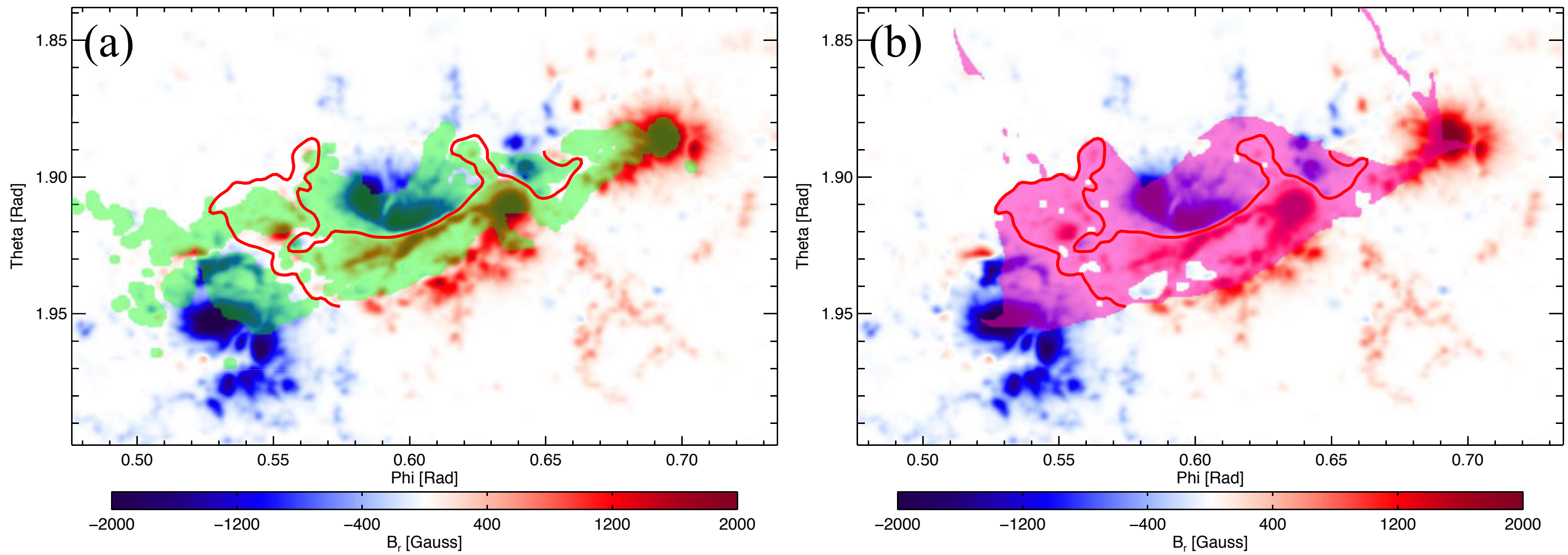
We Can Calculate Open Field Masks Prior to Eruption



S_O: Ribbon Mask (Green) S_O: Topogical Calculation with PFSS (Magenta)

- POFE for ribbon mask and pre-eruptive calculation similar (4.7×10^{32} vs 5.6×10^{32} ergs)

Next Steps in this Project:

- Improve calculation pipeline (e.g. balance magnetic flux in ribbon masks)
- Are there databases with total energy release for events?
- Calculate region of opening (S_O) topologically - see if correlations hold