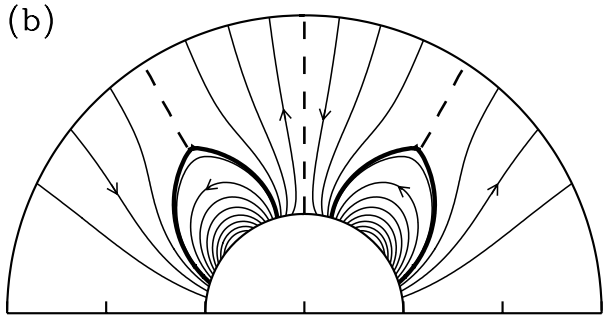
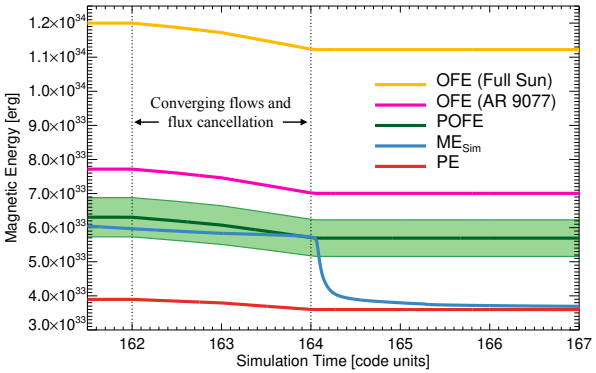
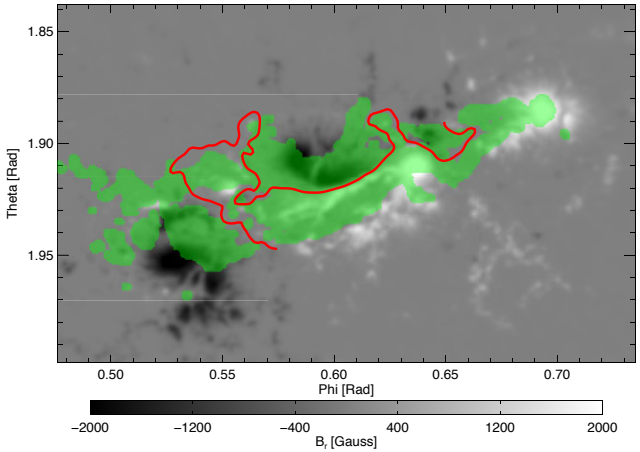
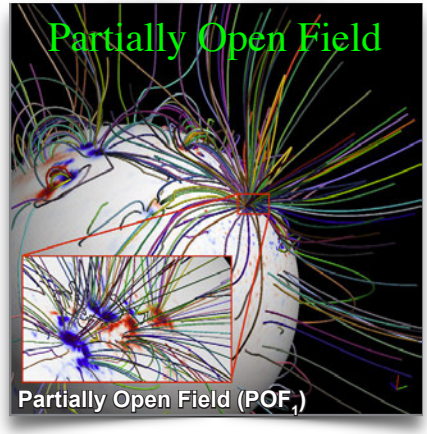
Partially Open Fields as the Energy Bounds for Solar Eruptions*









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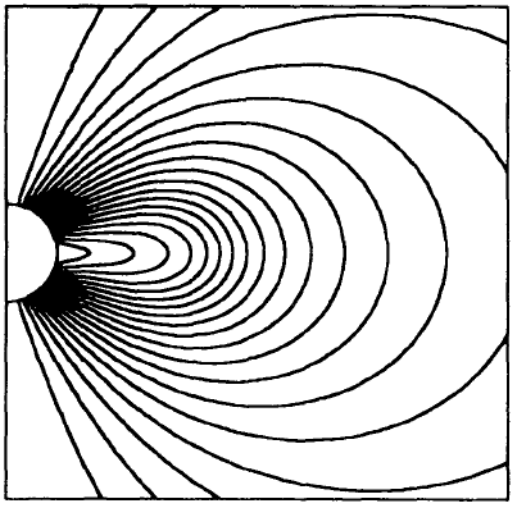
Predictive Science Inc.

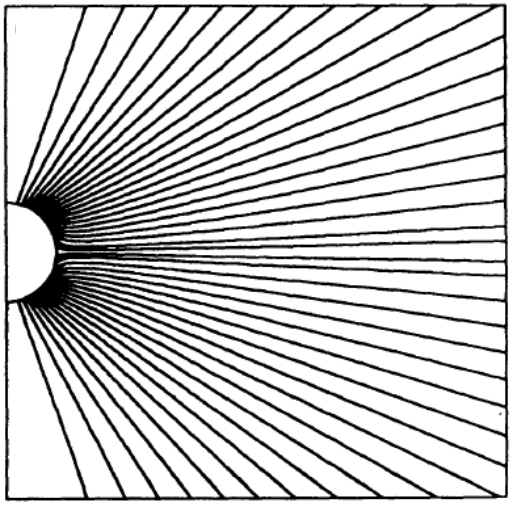
Introduction

- 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).

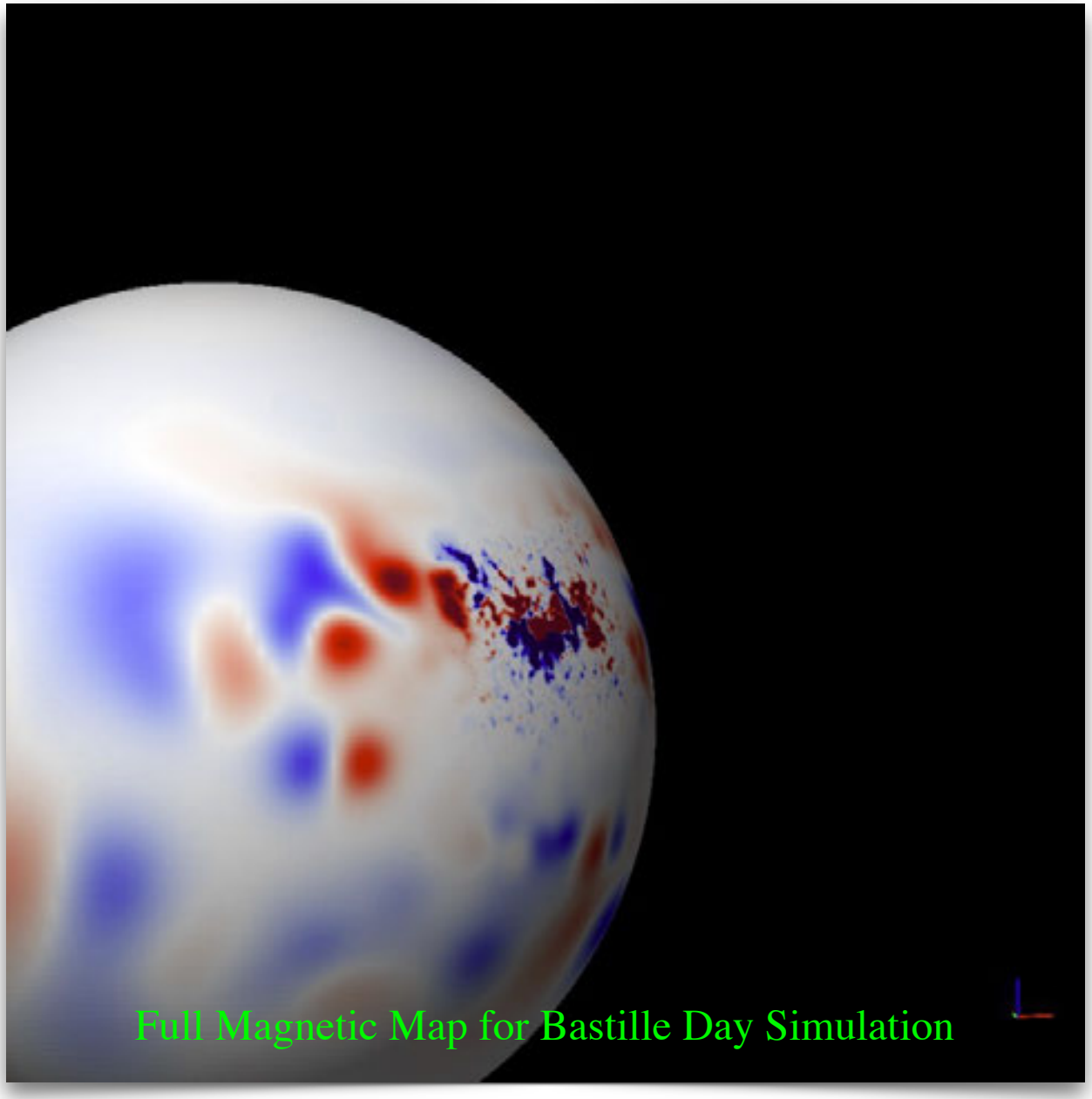
Implications and Observational Tests

- 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

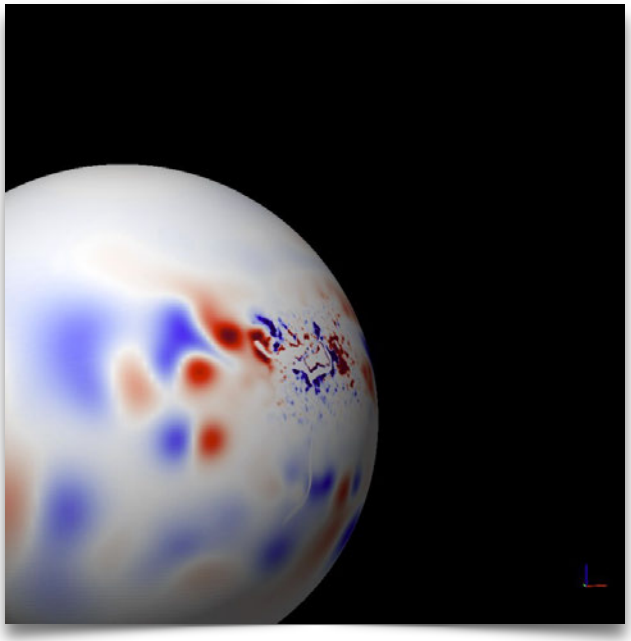
Calculating the Partially Open Field

- 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.

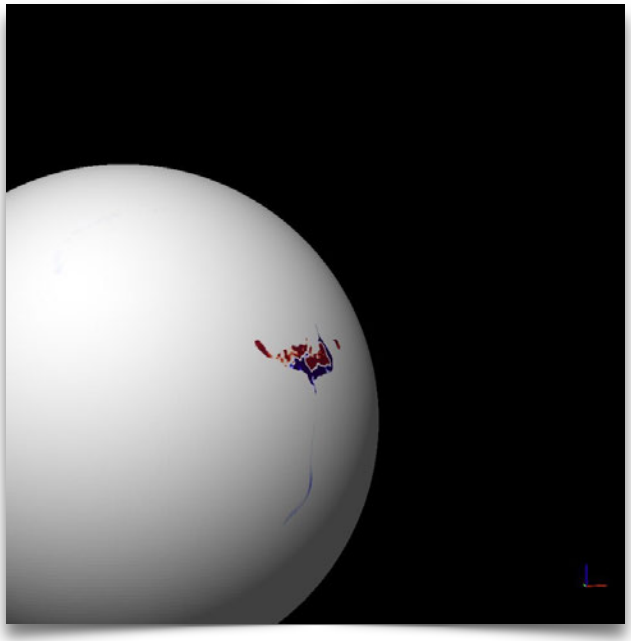
Partially Open Field Estimation: Method 1:

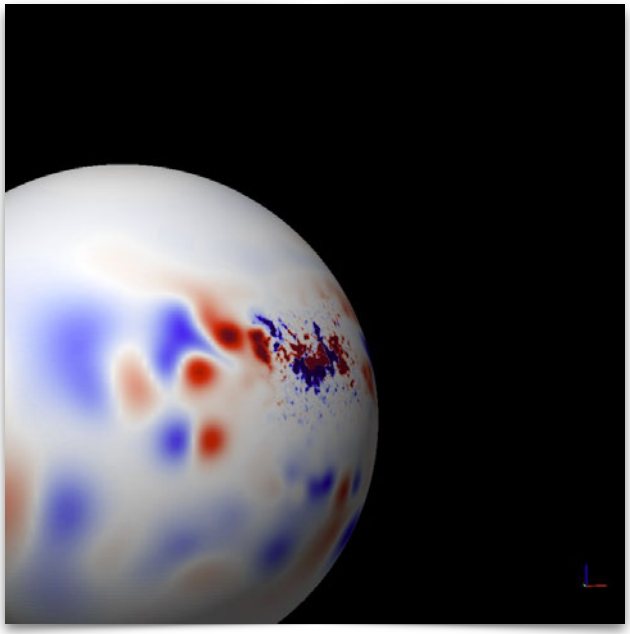


Partially Open Field Estimation: Method 1:



Consider S_O and region outside S_O separately





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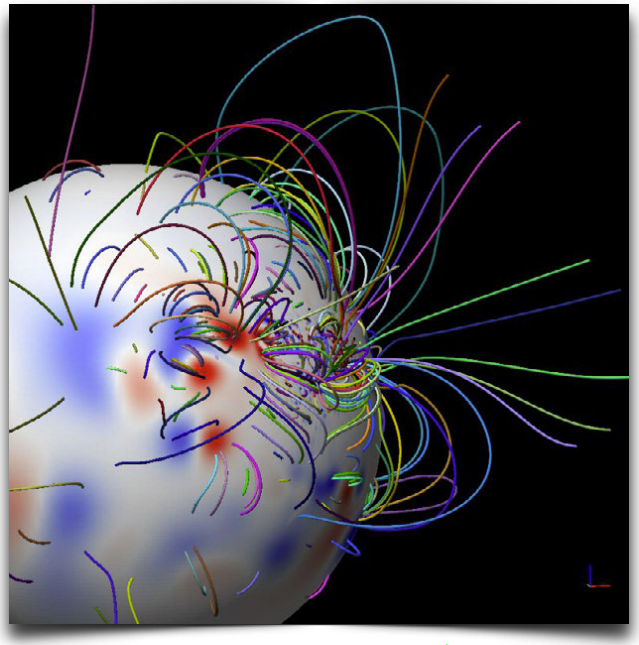
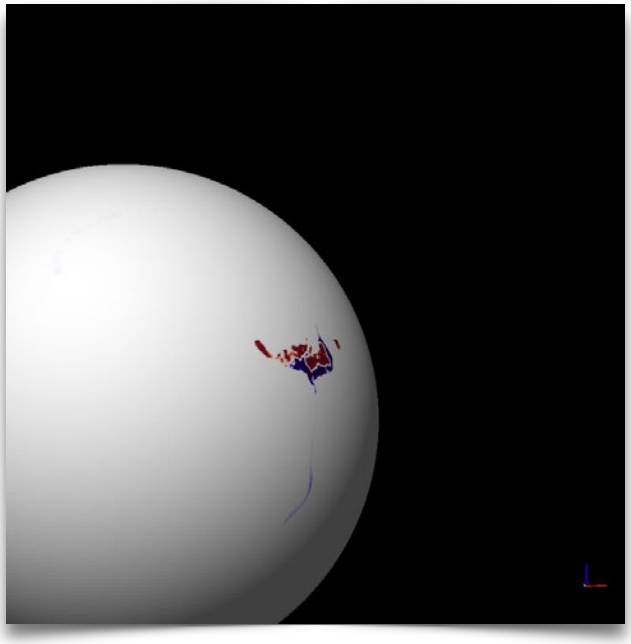
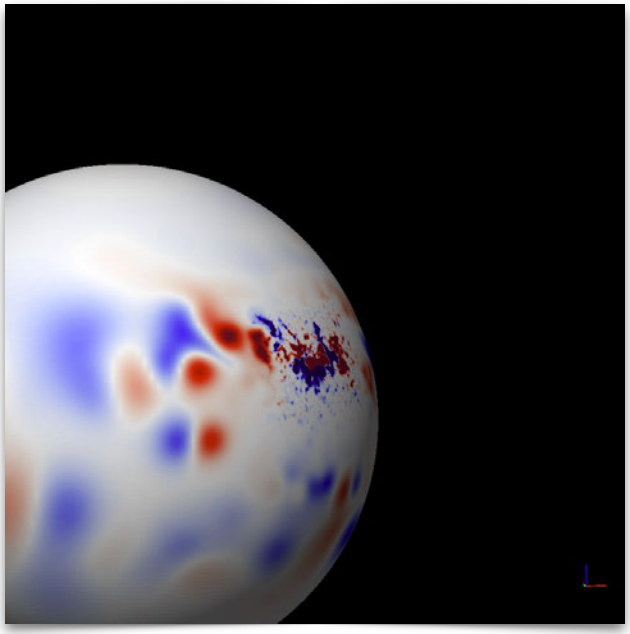


Compute PFSS
Outside S_O





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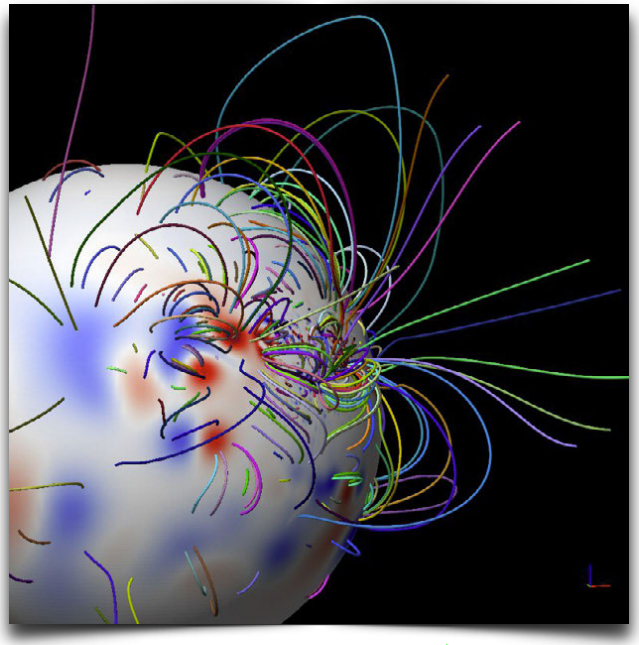
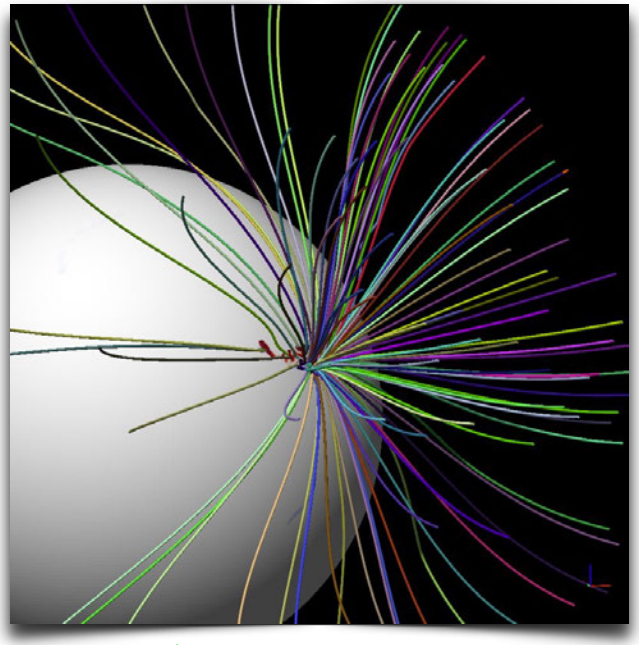
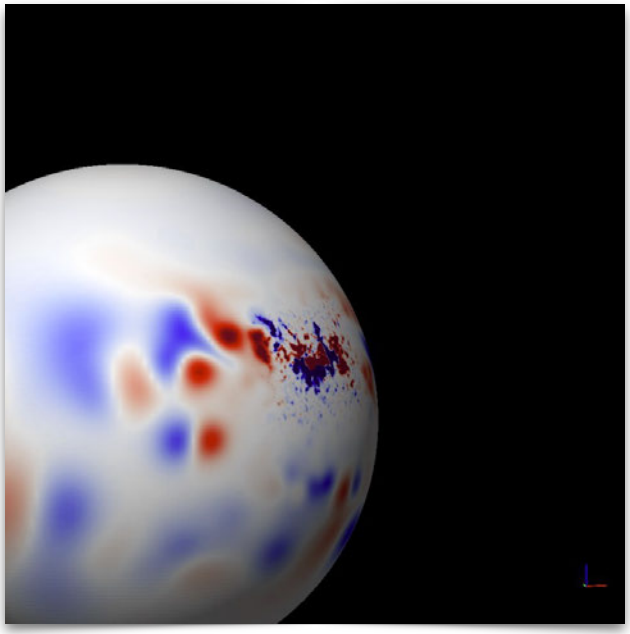


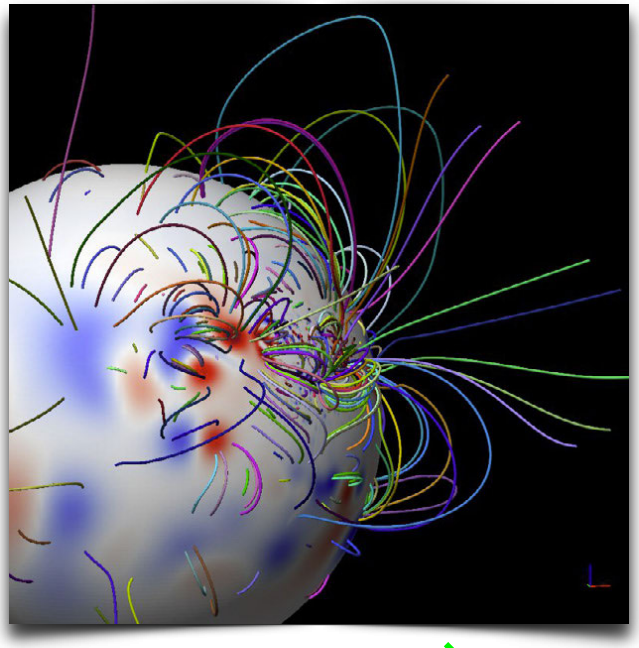
Compute PFSS
Outside S_O



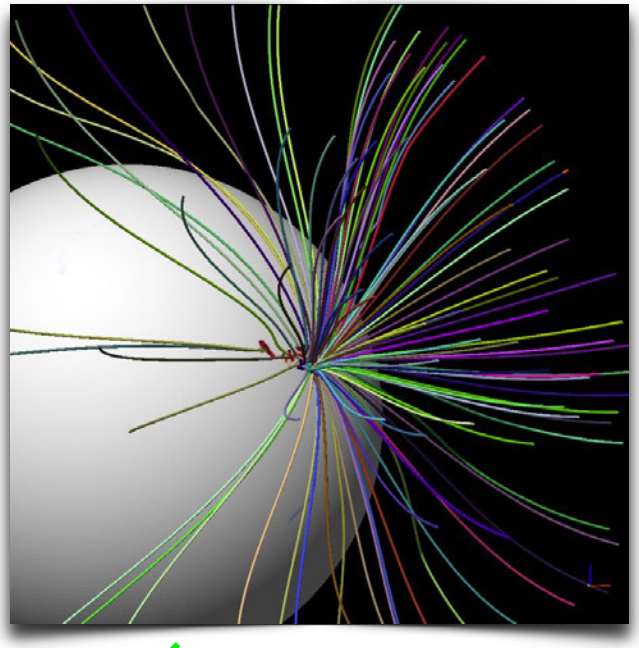
Compute Open Field
Inside S_O

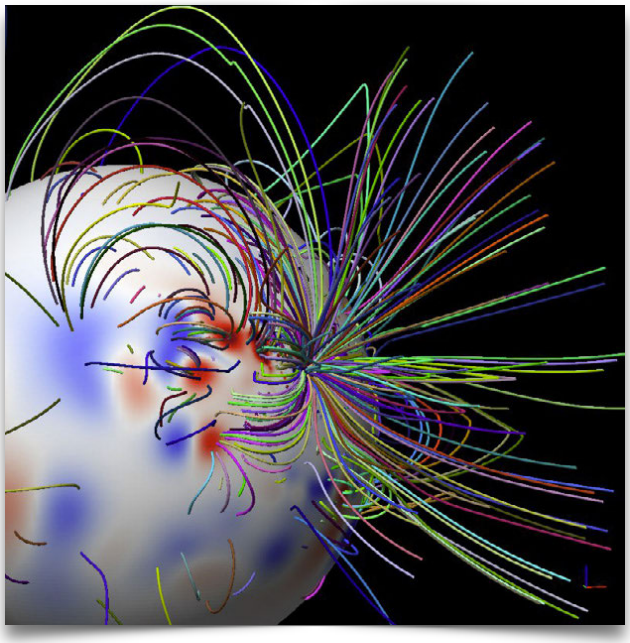


Partially Open Field Estimation: Method 1:

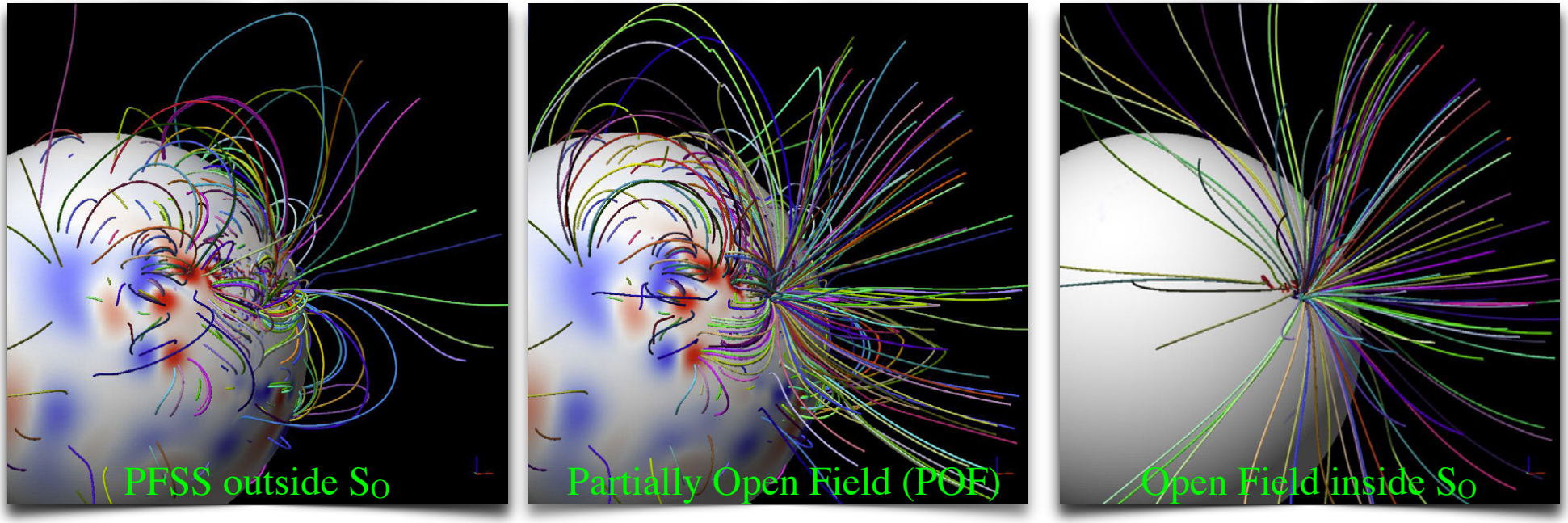


Sum these fields to obtain POF



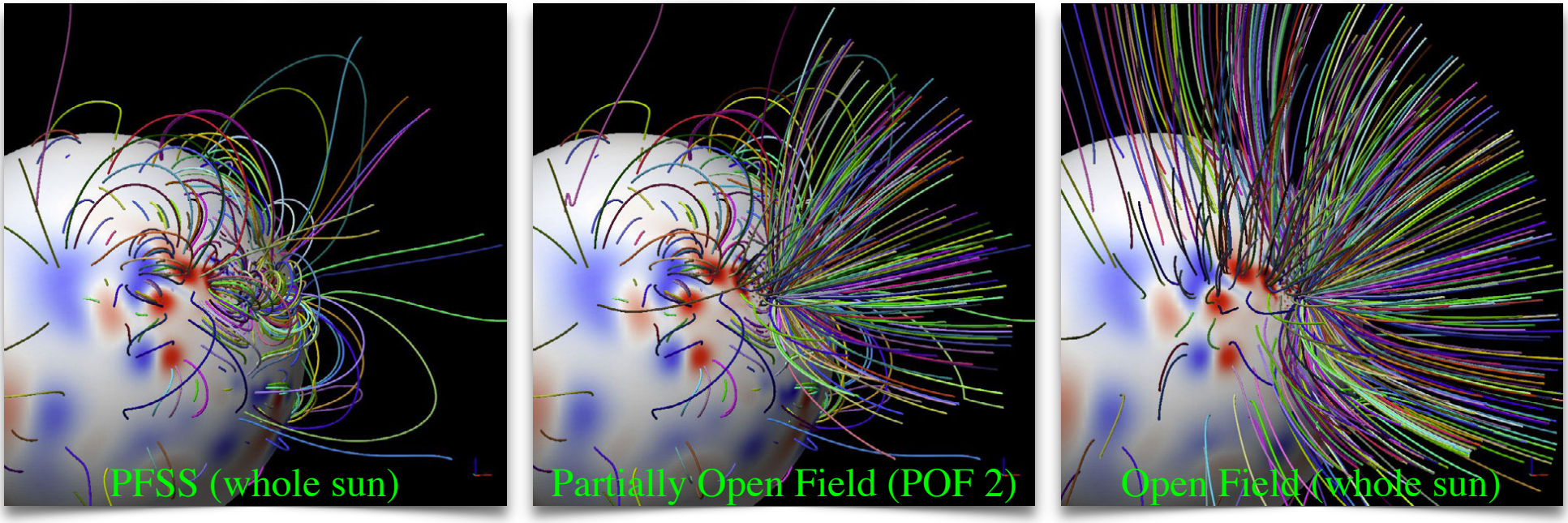


Partially Open Field Estimation: Method 1:



- 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.

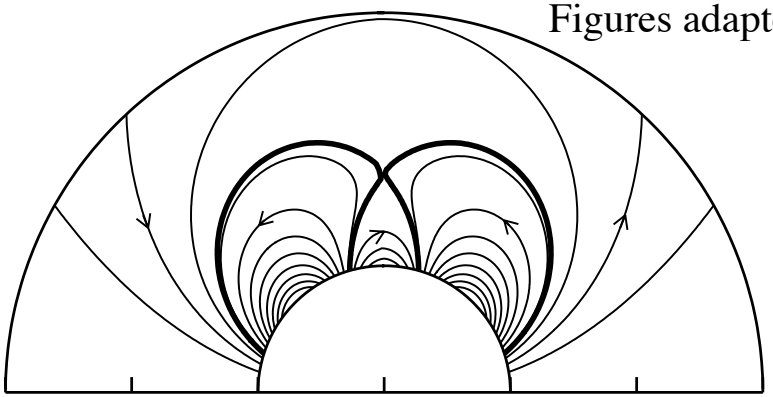
Partially Open Field Estimation: Method 2:



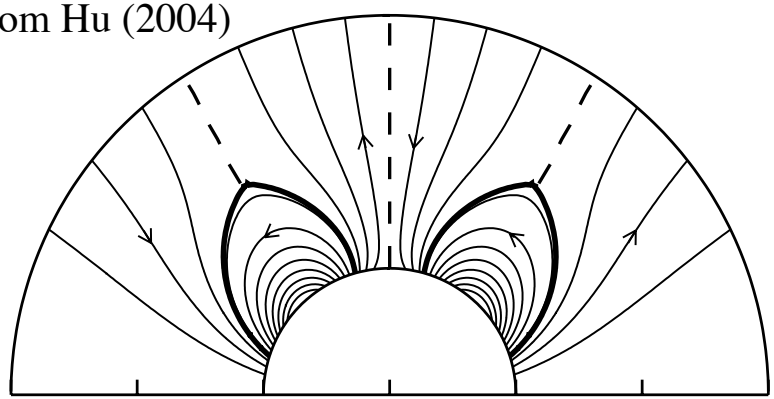
- This 2nd estimate for the POF combines the open and closed field solutions discontinuously, implying current sheets
- We think the energy of this field is an upper bound to the POFE.

How Well Does Our Estimate Work for a Known Case?

Figures adapted from Hu (2004)

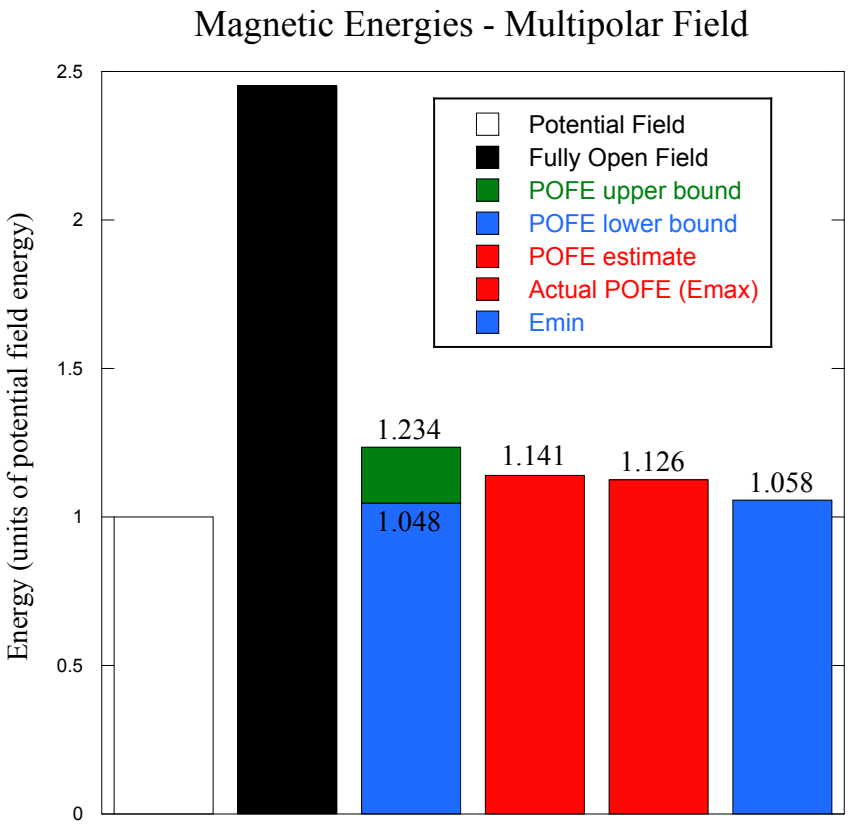


Multipolar Potential Field

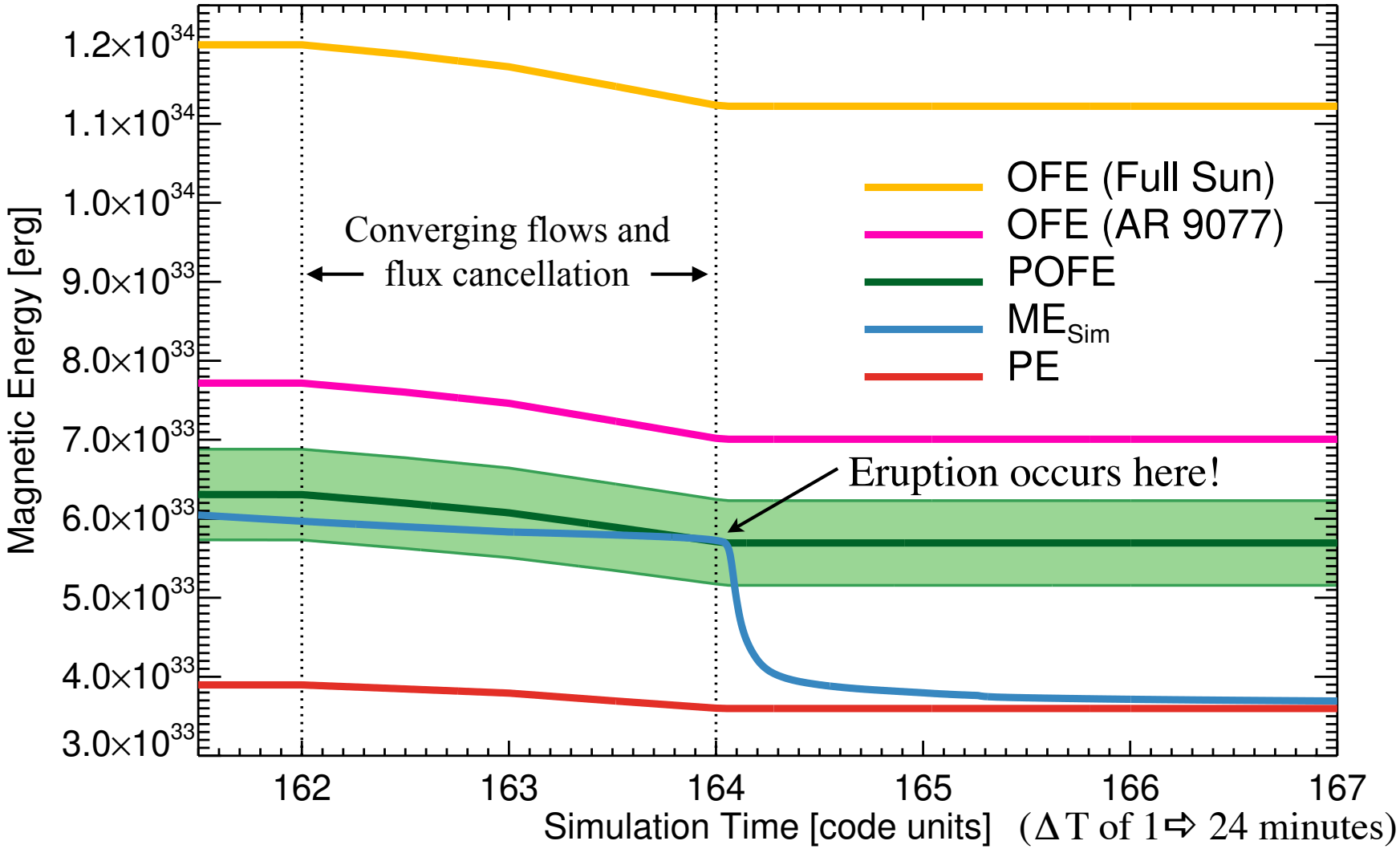


The Partially Open Field
(E_{MAX} identified by Antiochos et al. 1999)

- 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).



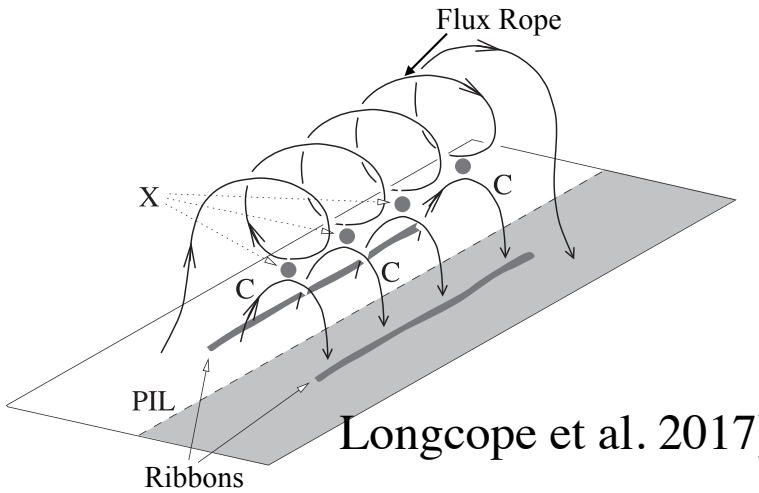
Torok et al. (2018): Energy Evolution in 7/14/2000 Simulation



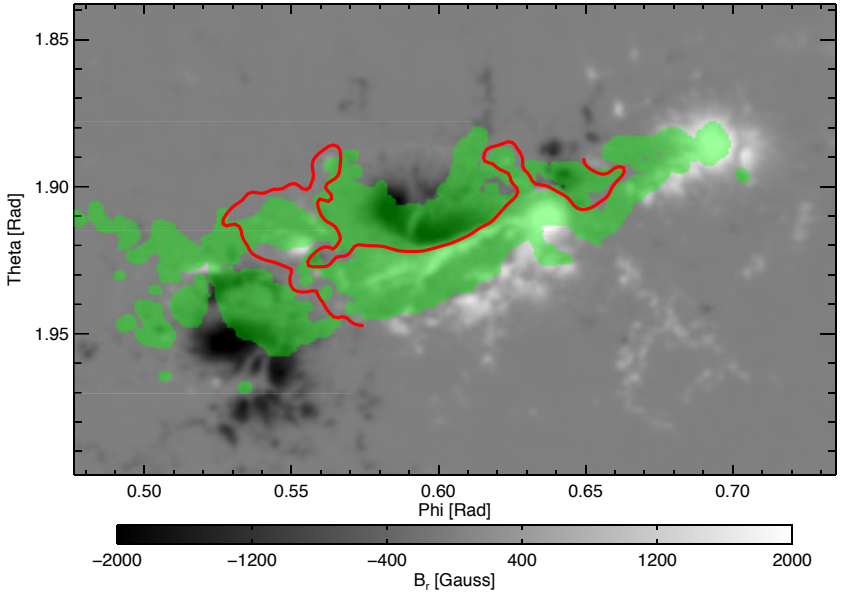
- The average of the 2 POFEs predicts eruption onset
- Together, they give a narrow constraint for the energy required for a major eruption

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

Example AR11158 (February 15, 2011)



Longcope et al. 2017)



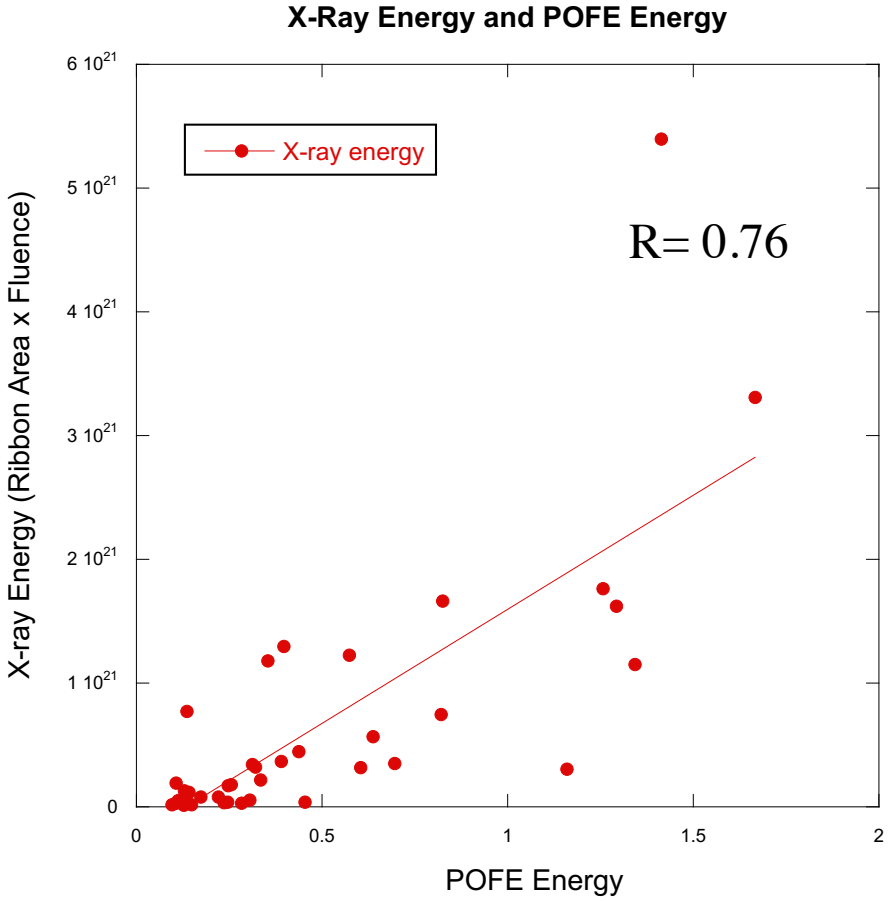
$$\Phi_{ribbon} = \int (\partial\Phi/\partial t)\, dt = \int B_r dS_{ribbon}$$

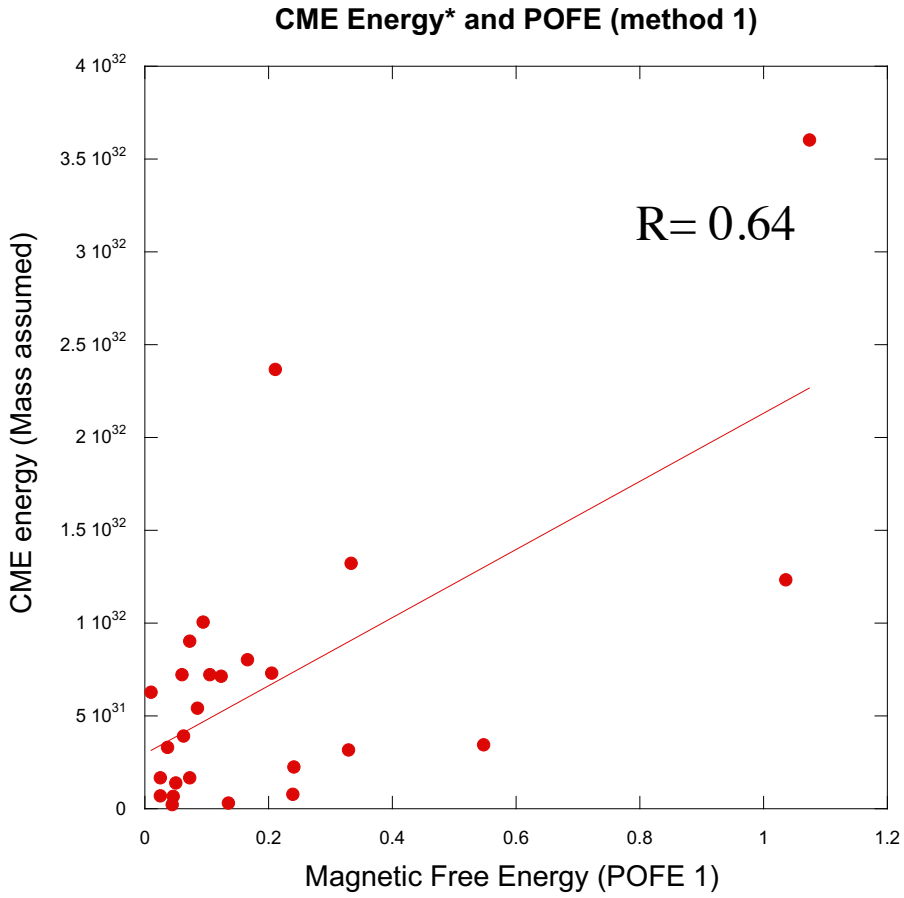
Cumulative Flare Ribbons
(provided by Maria Kazachenko)

- 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

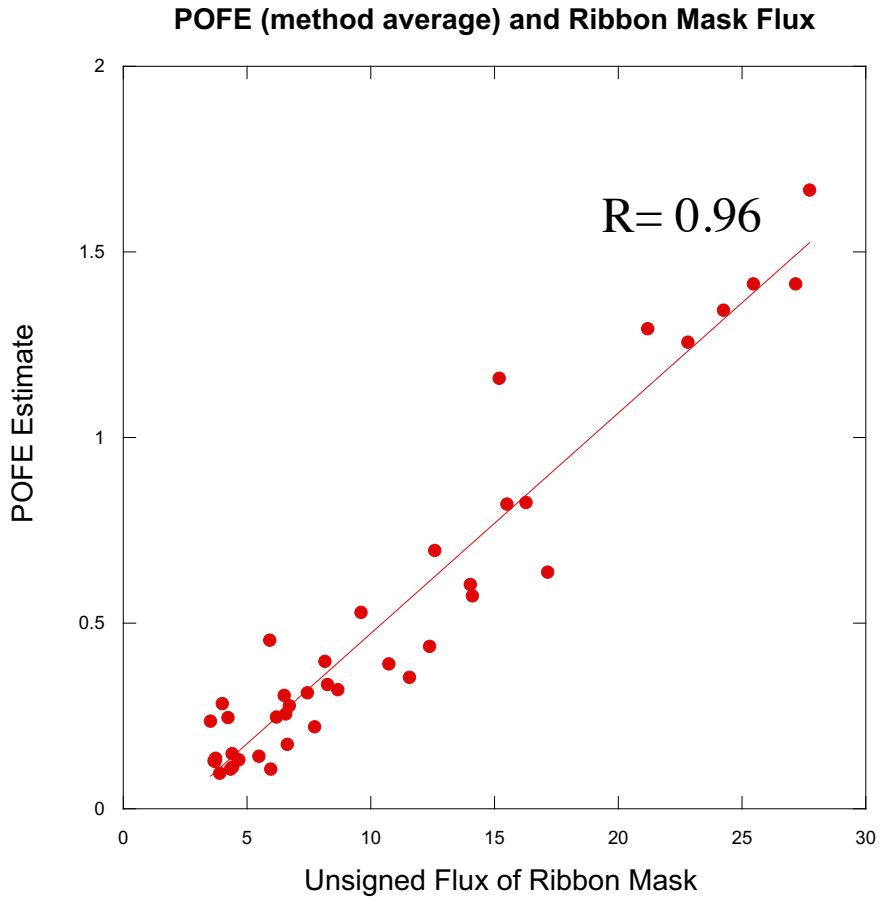
- X-ray Energy (X-ray fluence ribbon mask area)
- CME Energy (really v^2: mass of 10^{16} gm assumed)

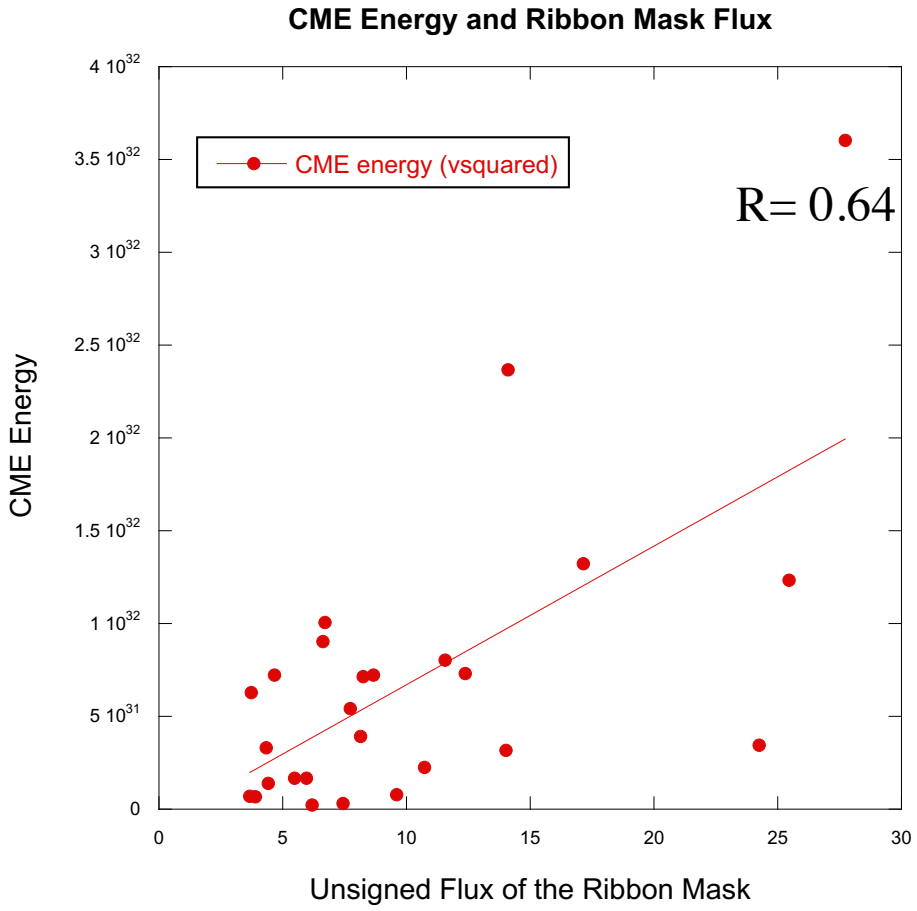




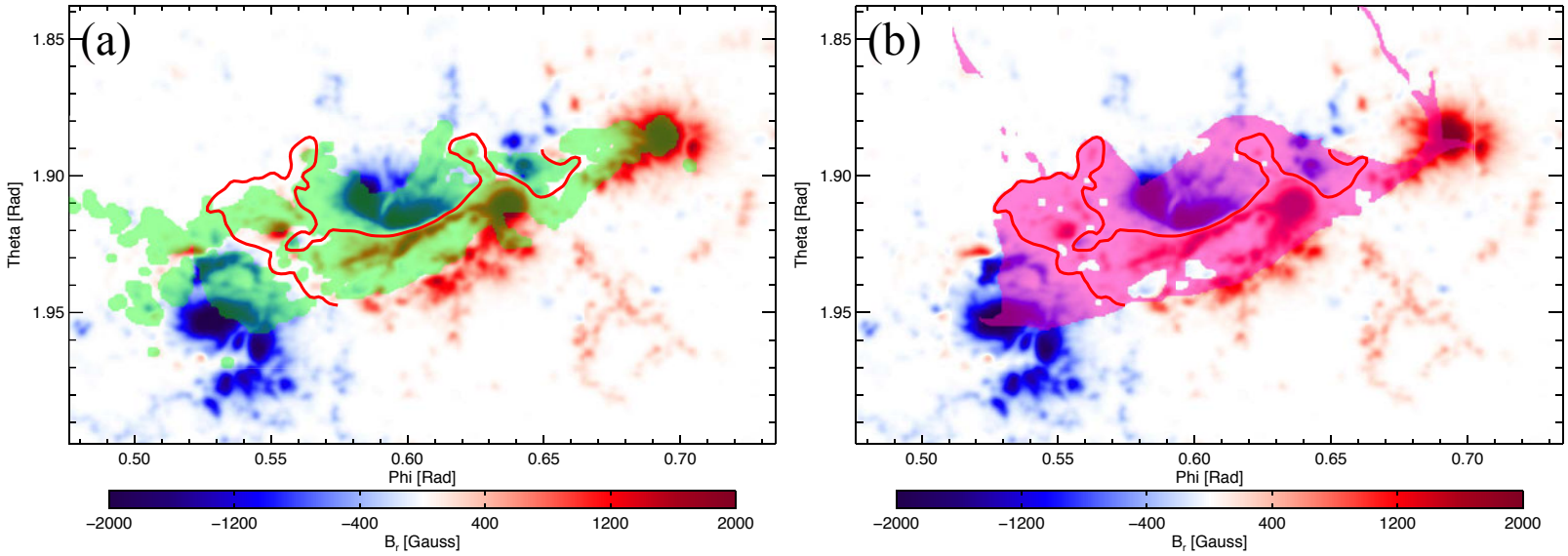
POFE Correlates Strongly with Ribbon Mask Flux

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





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