Data-driven time-dependent modelling scheme for determining the magnetic structure of CMEs

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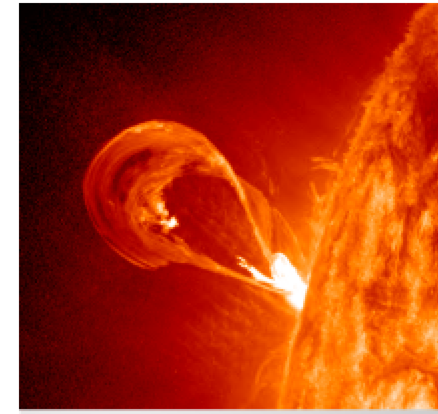
Introduction

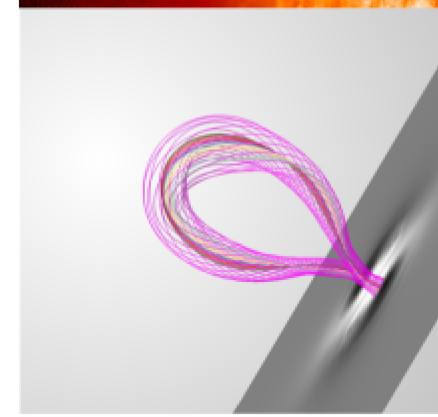
- Our goal is to determine the magnetic structure of Earth-impacting CMEs using a computationally efficient modelling scheme that spans from the lower corona up to the orbit of the Earth
- The scheme consists of three components:

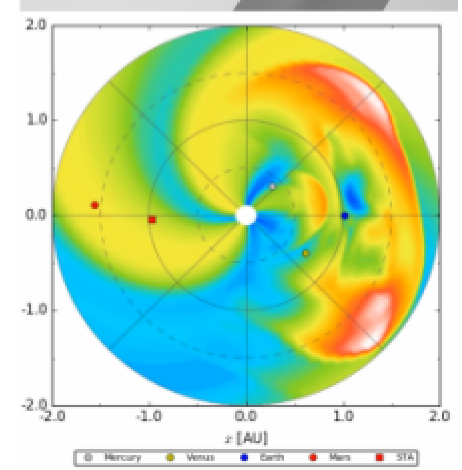
  A) A data-driven non-potential model of the coronal magnetic field up to 2.5 R_Sun for determining the magnetic structure of erupting CMEs

  B) A versatile flux rope model for fitting the kinematic properties of the CME (magnetic properties are determined in part A) and feeding it to the solar wind

  C) A three-dimensional MHD model, EUHFORIA, that computes self-consistently the dynamics of the inner heliosphere from 0.1 AU until the orbit of Mars







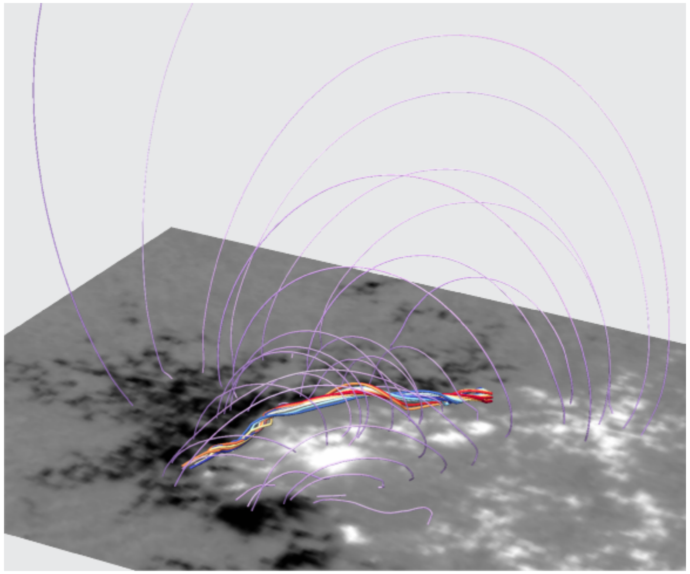
Upper image courtesy: SDO/AIA.
Lower images: Jens Pomoell

A) Data-driven non-potential model of the lower corona

- The goal of part A is to constrain the magnetic parameters of the CME flux rope (the magnetic flux, field direction and chirality) at the time of the eruption
- We model the magnetic field evolution in the lower corona at the time of the CME eruption using two alternative approaches:

  1) time sequence of non-linear force-free field (NLFFF) extrapolations
  2) **time-dependent magnetofrictional modelling,**

  both implemented in COROnal MAgnetics (CORMA) software package by Jens Pomoell
- E. Palmerio does also complementary work in our group to constrain the magnetic properties of CMEs using a variety of observational proxies (Palmerio et al., 2017, accepted)



Non-linear force-free extrapolation for NOAA AR 11226 by Jens Pomoell

Force-free approximation

- To keep our modelling methods computationally efficient we employ the *force-free field approximation*:
  - plasma beta is small in the low corona (R < ~2.5 R_Sun)
  - plasma dynamics is dominated by magnetic forces: plasma pressure and gravity can be neglected
  - Moreover, since the evolution is in large scales quasi-static, the MHD momentum equation transforms into the force-free equation:

$$\rho_m \frac{d\mathbf{V}}{dt} = -\nabla p - \rho_m \nabla \Psi + \mathbf{J} \times \mathbf{B}$$

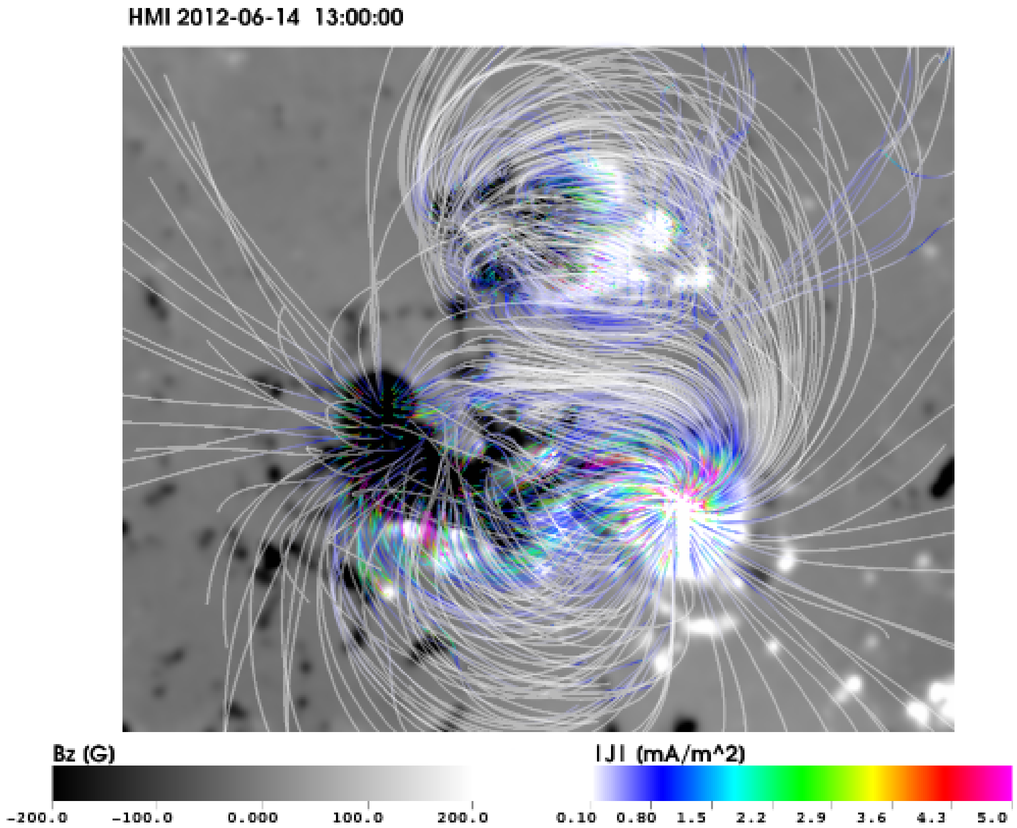
$$\Rightarrow \mathbf{J} \times \mathbf{B} = 0$$

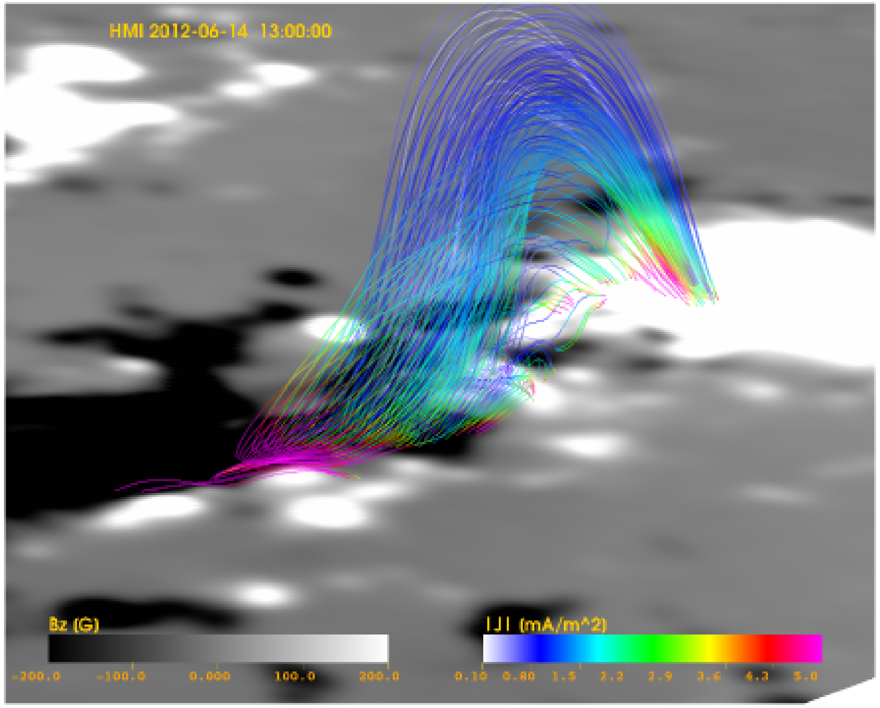
Force-free extrapolations

- When the force-free equation is solved with a fixed photospheric boundary condition one gets a static snapshot of the coronal magnetic field: *a Non-Linear Force-Free Field (NLFFF) extrapolation*
- Low-coronal boundary condition given by a vector magnetogram
- Several numerical methods to solve the force-free equation in the corona (e.g. Wiegelmann & Sakurai, 2012)

$$\begin{cases} (\nabla \times \mathbf{B}) \times \mathbf{B} = 0 \\ \nabla \cdot \mathbf{B} = 0 \\ \mathbf{B}(r = R_\odot) = \mathbf{B}_{magnetogram} \end{cases}$$

Force-free extrapolations using CORMA





Non-linear force free extrapolation for NOAA AR 11504 created using **the optimization method** (Wheatland et al., 2000) by Jens Pomoell.

Magnetofrictional (MF) method

- Magnetofrictional (MF) method is one option for solving the force-free equation (Yang et al. 1986)
- In MF method an ad hoc friction term is added to the MHD momentum equation, which in the force-free and quasi-static case transforms as:

$$\rho_m \frac{d\mathbf{V}}{dt} = -\nabla p - \rho_m \nabla \Psi + \mathbf{J} \times \mathbf{B} - \nu \mathbf{V} \Rightarrow \mathbf{V} = \frac{1}{\nu} \mathbf{J} \times \mathbf{B}$$

- Velocity **V** is now artificial and always proportional to the Lorentz force. Evolving the magnetic field according to the induction equation relaxes the configuration towards minimum energy force-free state (**V** → 0):

$$\begin{cases} \mathbf{V} = \frac{1}{\nu}\mathbf{J} \times \mathbf{B} = \frac{1}{\nu\mu_0}(\nabla \times \mathbf{B}) \times \mathbf{B} \\ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{V} \times \mathbf{B} - \eta(\nabla \times \mathbf{B})] \\ \mathbf{B}(r = R_\odot) = \mathbf{B}_{magnetogram} \end{cases}$$

Time-dependent magnetofrictional method

- MF method can be expanded to a time-dependent dynamic model by letting the photospheric boundary condition (**B**_magnetogram) change in time (van Ballegooijen et al., 2000; Cheung & DeRosa, 2012)

$$\begin{cases} \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B} - \eta(\nabla \times \mathbf{B})) \\ \frac{\partial \mathbf{B}}{\partial t}\Big|_{r=R_\odot} = -\nabla \times \mathbf{E}^{measured}\Big|_{r=R_\odot} \end{cases} \Leftrightarrow \begin{cases} \frac{\partial \mathbf{A}}{\partial t} = \mathbf{V} \times \mathbf{B} - \eta(\nabla \times \mathbf{B}) \\ \frac{\partial \mathbf{A}_h}{\partial t}\Big|_{r=R_\odot} = -\mathbf{E}_h^{measured}\Big|_{r=R_\odot} \end{cases}$$

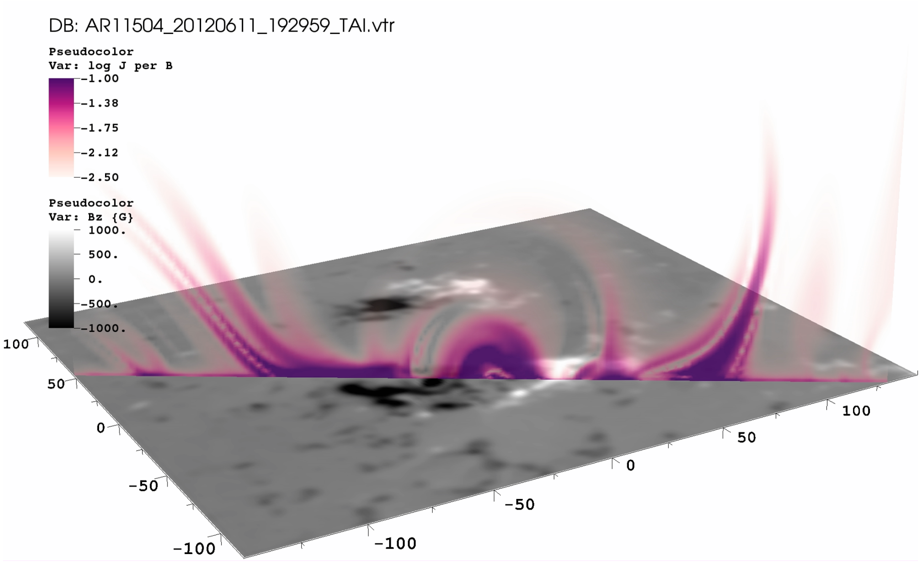
- This time-dependent magnetofrictional (TMF) method describes a dynamical balance between coronal relaxation towards a force-free state and photospheric driving (i.e. the non-zero horizontal electric field)

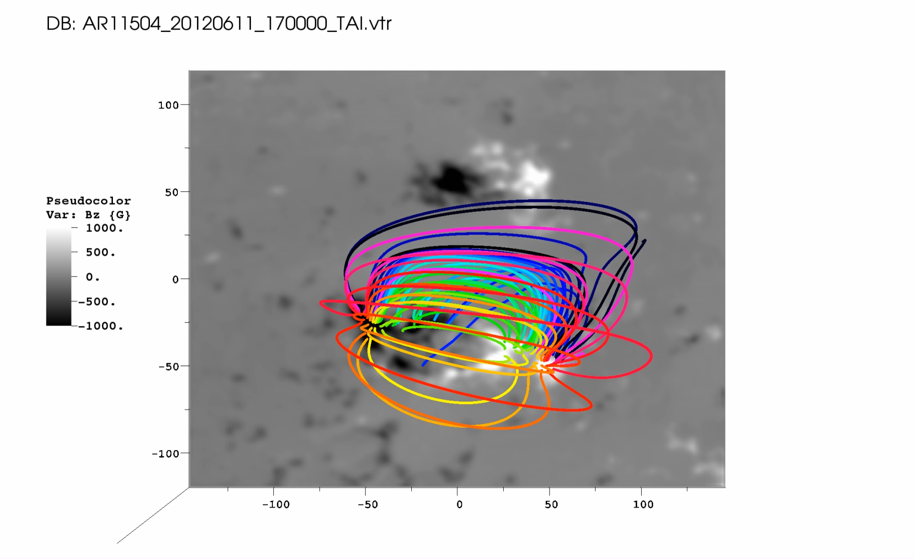
- The method has successfully modelled formation of flux ropes and their ejections (e.g. Cheung & DeRosa, 2012; Gibb et al., 2014; Weinzierl et al., 2016)

- The approach is not equivalent to time-dependent MHD (force-free assumption is still applied), but enables modelling the slow coronal energy build-up at several orders of magnitude lower computational cost

TMF simulations at the University of Helsinki

- Example run for NOAA AR 11504 driven by driven by photospheric electric field inverted from a sequence of HMI vector magnetograms





Photospheric driving: determination of the electric field

- The realism of the TMF method is dependent on the accuracy of the photospheric boundary condition, the electric field
- Determination of the photospheric electric field is not trivial
- The available input data consists of vector magnetograms (**B**) and (uncalibrated) Dopplergrams (**V**_LOS)
- Assumptions: ideal MHD + Faraday's law/ideal induction eq

$$\begin{cases} \mathbf{E} = -\mathbf{V} \times \mathbf{B} \\ \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} = \nabla \times (\mathbf{V} \times \mathbf{B}) \end{cases}$$

PDFI method

- State-of-the-art method to determine the photospheric electric field (Kazachenko et al., 2014) that employs all available input data
- Decomposes the electric field into inductive (**$\mathbf{E}_I$**) and non-inductive ($-\nabla\psi$) components:

$$\begin{cases} \mathbf{E} = \mathbf{E}_I - \nabla\psi \\ \nabla \times \mathbf{E}_I = -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla^2\psi = -\nabla \cdot \mathbf{E} = \nabla \cdot (\mathbf{V} \times \mathbf{B}) \end{cases}$$

- The inductive component can be determined from Faraday's law and a time series of vector magnetograms. The non-inductive component requires additional constraints:
  - **PDFI method uses a combination of Dopplergram and optical flow (FLCT) velocities with the ideal constraint (E • B = 0) to determine $-\nabla\psi$ (PDFI = PTD-Doppler-FLCT-Ideal)**
  - alternatives: differential rotation profile (Weinzierl et al., 2016), or ad hoc assumptions...

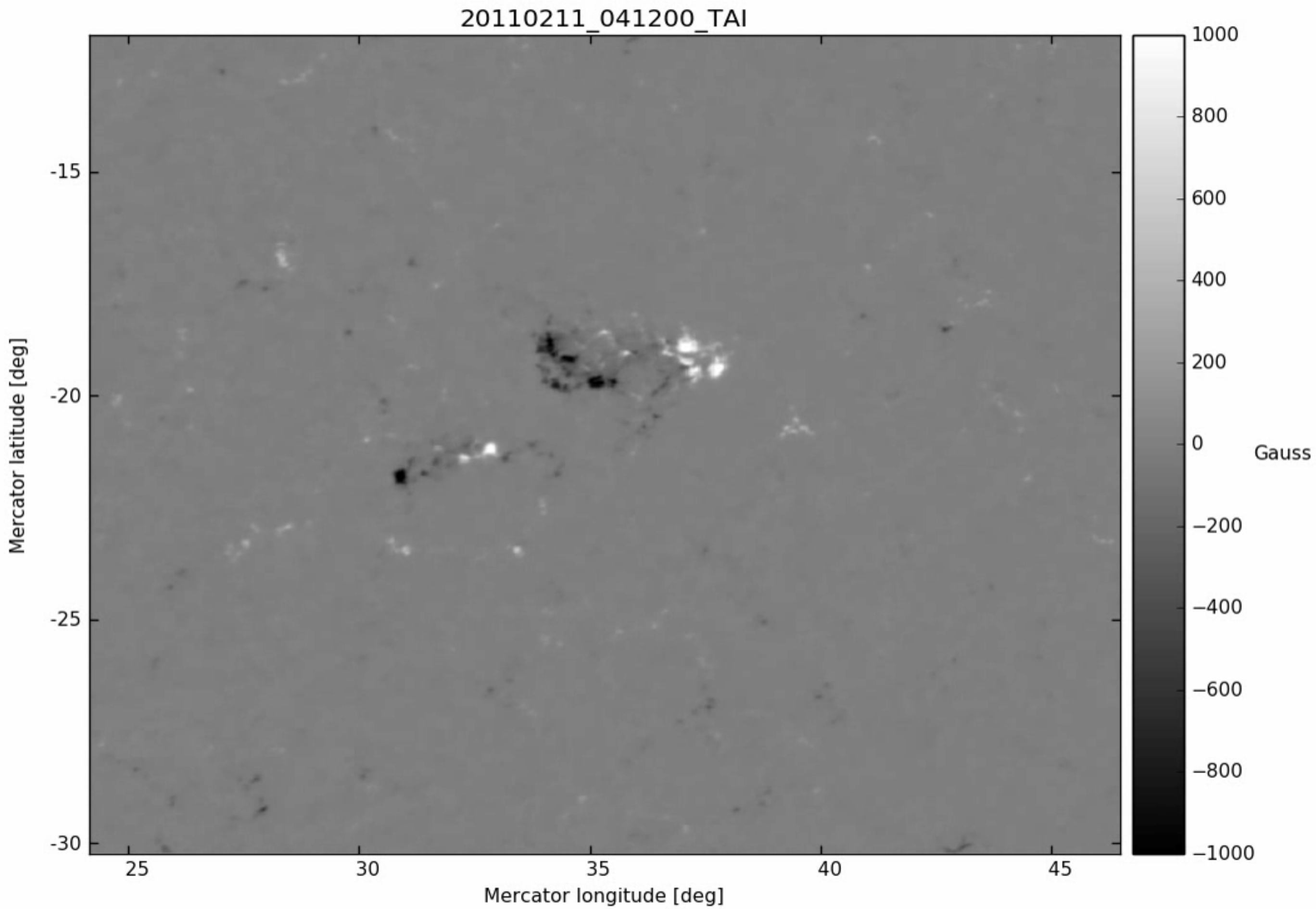
ELECTRICIT – a practical toolkit for photospheric electric field inversion

- Python software toolkit for routine electric field inversion developed in our group
- Partly based on SunPy package (Mumford et al., 2015) and will be joined to it in the future
- The toolkit is able to:
  - Download SDO/HMI vector magnetograms and Dopplergrams from Joint Science Operations Center, JSOC (http://jsoc.stanford.edu/)
  - Create cutouts from fulldisk LOS or vector magnetograms so that the cutout tracks a given region on the Sun (e.g. an active region) similarly to Space-weather HMI Active Region Patches, SHARPs (Bobra et al., 2014; Sun, 2013).
  - Determine the electric field from a time series of processed magnetogram (and Dopplergram) data

ELECTRICIT – a practical toolkit for photospheric electric field inversion

- Data processing functionality includes also data enhancing procedures such as removal of bad pixels and spurious flips in the azimuth of the magnetic field (Welsch et al., 2013)
- Processed magnetogram data series can be used in many applications: e.g. for creating time series of NLFFF extrapolations
- Velocity processing/determination (Dopplergrams, optical flow) not included yet
- Electric field inversion is based on PDFI-method (with limitations)
- Currently the toolkit works on local active region scales, but ultimately we aim at global electric field estimates over the entire solar surface

ELECTRICIT: an example cutout



Current state of the electric field inversion

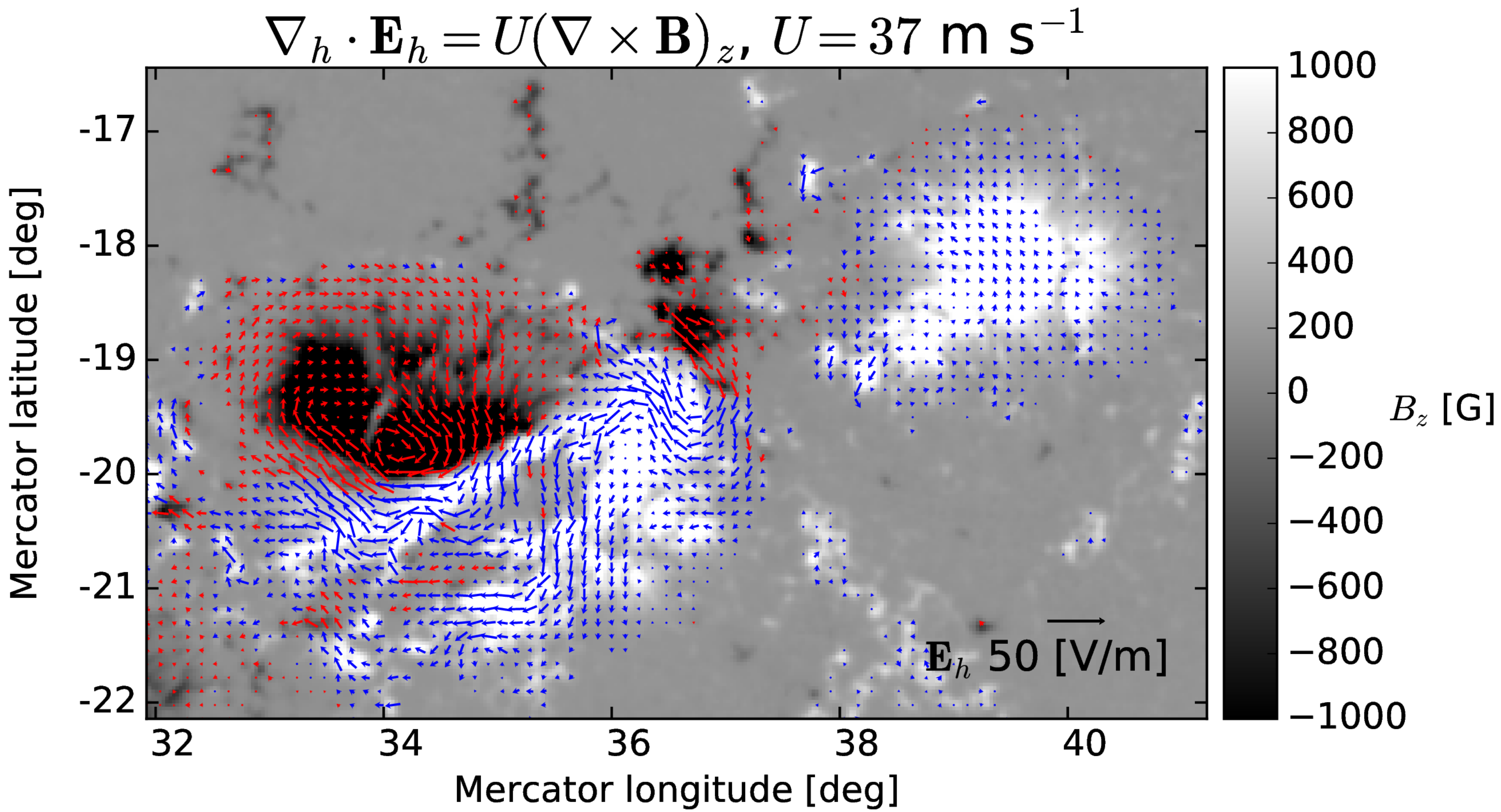
- Inversion currently based only on vector magnetograms. The use of velocity estimates will be added soon.
- Without velocity estimates PDFI-method is not complete and we are forced to use one of the following ad hoc assumptions to constrain the non-inductive component of the electric field:

$$\begin{cases} \nabla\psi = 0 & (0) \\ \nabla_h \cdot \mathbf{E}_h = -\nabla_h^2\psi = \Omega B_z & (1) \\ \nabla_h \cdot \mathbf{E}_h = -\nabla_h^2\psi = U(\nabla \times \mathbf{B}) \cdot \hat{\mathbf{z}} & (2) \end{cases}$$

$$\mathbf{E} = \mathbf{E}_I - \nabla\psi$$

- Assumption (0) sets the non-inductive component to zero, (1) imposes uniform vertical component of plasma vorticity (-Ω) at the photosphere (Cheung & DeRosa, 2012) and (2) imposes uniform vertical velocity (U) at the photosphere (Cheung et al., 2015)

Example electric field inversion



Example plot of the inverted horizontal photospheric electric field and the vertical magnetic field B_z for a subregion of NOAA AR 11158 on March 15, 2011 at 01:48:00 TAI.

Recent results for NOAA AR 11158

- We have created times series of photospheric electric field estimates for NOAA AR 11158 using ELECTRICIT and four (3+1) different methods:
  - PDFI method with each of the three ad hoc assumptions for the non-inductive electric field:

$$\begin{cases} \mathbf{E} = \mathbf{E}_I - \nabla\psi \\ \nabla \times \mathbf{E}_I = -\frac{\partial \mathbf{B}}{\partial t} \end{cases} + \begin{cases} \nabla\psi = 0 & (0) \\ \nabla_h \cdot \mathbf{E}_h = -\nabla_h^2 \psi = \Omega B_z & (1) \\ \nabla_h \cdot \mathbf{E}_h = -\nabla_h^2 \psi = U(\nabla \times \mathbf{B}) \cdot \hat{\mathbf{z}} & (2) \end{cases}$$

  - Optical flow based DAVE4VM method (Schuck, 2008) fed by the same magnetograms as above: $\mathbf{E} = -\mathbf{V} \times \mathbf{B}$

Optimization of the free parameters

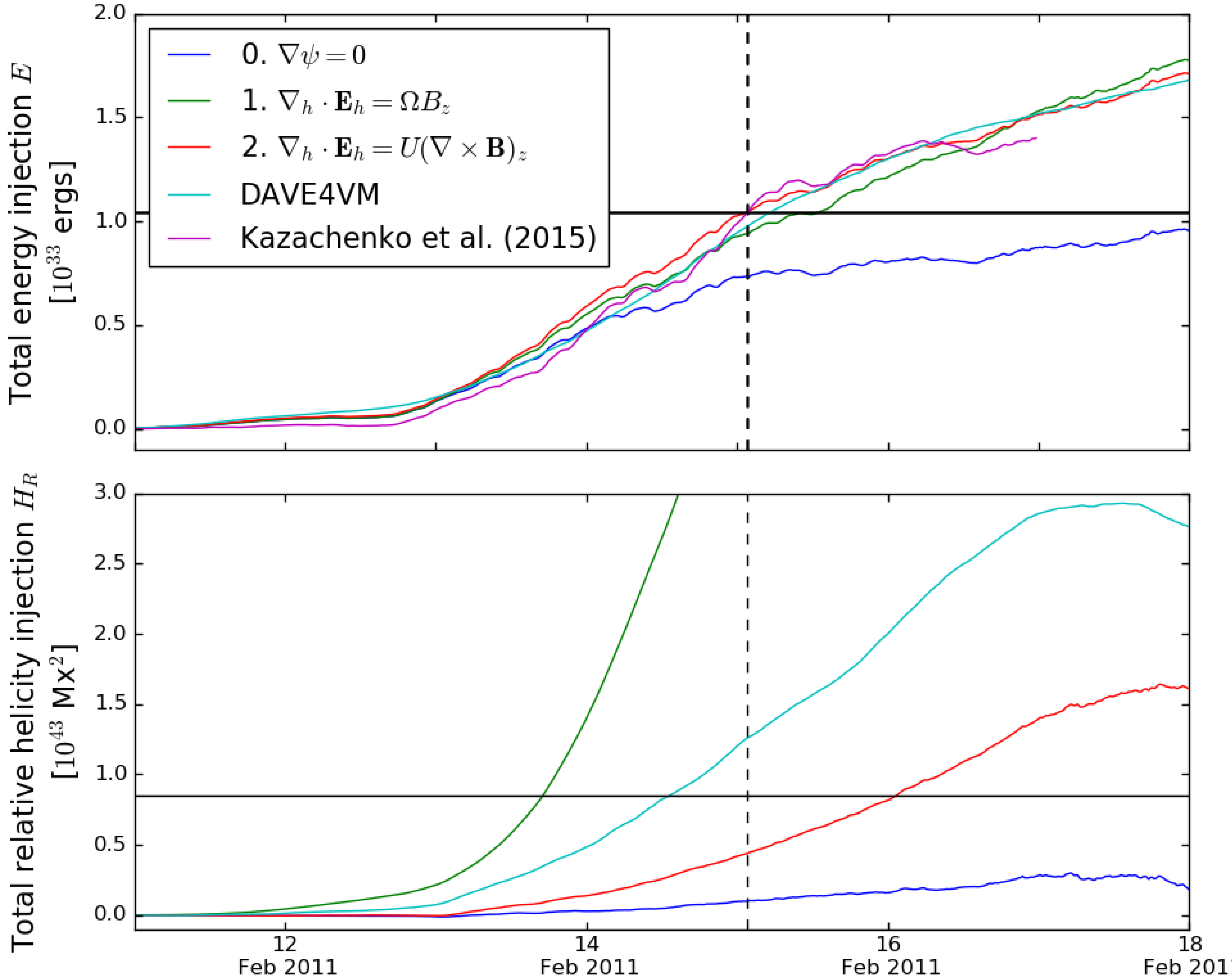
- Free parameters U and Ω are optimized using the time-integrated Poynting flux, which gives the total injection of magnetic energy from the photosphere to the corona:

$$E(t) = \int_0^t dt' \, \frac{dE}{dt'} = \int_0^t dt' \int_A dA \; S_z = \int_0^t dt' \int_A dA \; \frac{1}{\mu_0} (\mathbf{E} \times \mathbf{B}) \cdot \hat{\mathbf{z}}$$

- The optimal values were chosen so that they reproduce consistent time evolution for E(t) (between themselves and previous studies, e.g. by Kazachenko et al., 2015, who used the PDFI method)
- The optimal values are: U = 37 m/s and Ω = 9/128 rotations per day.
- We also studied the injection of relative magnetic helicity from the photosphere to the corona:

$$H_R(t) = \int_0^t dt' \, \frac{dH_R}{dt'} = -2 \int_0^t dt' \int_A dA \; (\mathbf{A}_P \times \mathbf{E}) \cdot \hat{\mathbf{z}}$$

Energy and helicity injections



Injected magnetic energy and relative helicity for NOAA AR 11158. Black solid lines mark the reference values of E and H_R from Kazachenko et al. (2015) at the time of the strongest flare of the active region (dashed line).

Discussion and conclusions

- The time evolution of the magnetic energy injection to the corona can be reproduced quite faithfully even if electric field estimates partly based on ad hoc assumptions are used
- Injection of relative helicity is not reproduced equally well; particularly the assumption (1) $\nabla_h \cdot \mathbf{E}_h = -\nabla_h^2 \psi = \Omega B_z$ (imposing constant plasma vorticity) clearly overestimates the helicity input
- Setting the non-inductive component to zero clearly underestimates both energy and helicity injections
- Next we will study the sensitivity of TMF simulation output to the different electric fields: particularly the feedback to the differences in the helicity injection is studied

Our requirements for synoptic magnetograms

- TMF simulations and electric field inversion in global scales require high cadence (~limiting cadence of 6 h, Weinzierl et al., 2016):
  - flux transport simulations with high resolution
  - flux transport simulations for the entire magnetic field vector (?)
  - SDO/HMI daily synchronic frames
- TMF simulations are sensitive to strong temporal discontinuities that can appear at the west limb of ADAPT maps (Weinzierl et al., 2016); they may even cause spurious flux rope ejections
- Our MHD model of the solar wind (EUHFORIA) is strongly dependent on the synoptic map which is used to create the lower boundary condition of the model

Thank you!