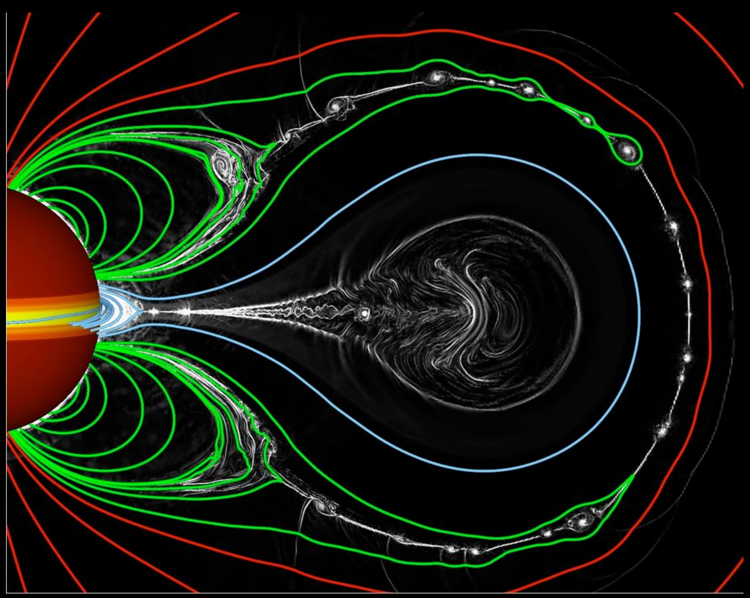
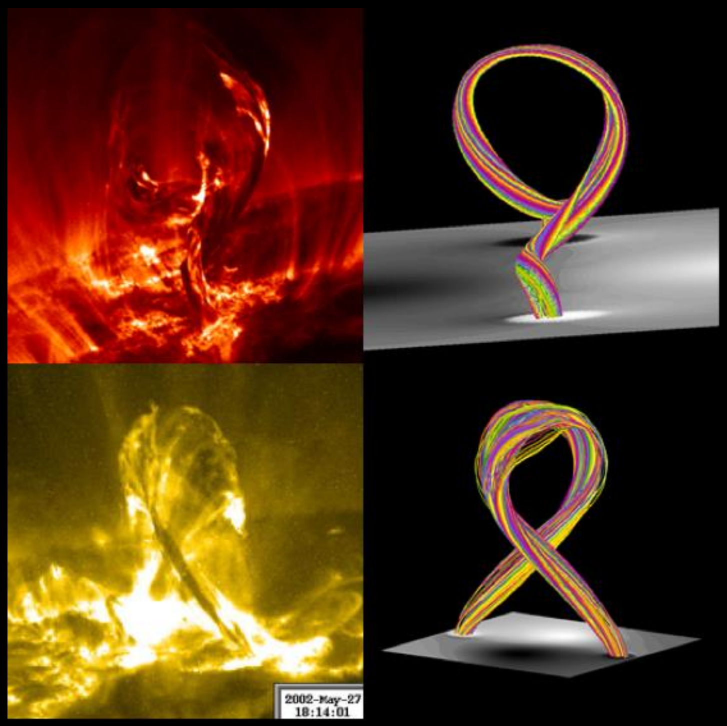
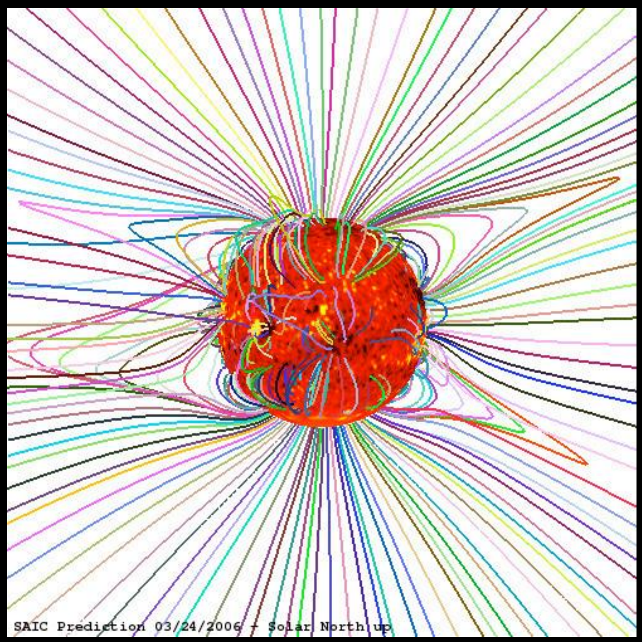
Numerical Modeling of Coronal Mass Ejections

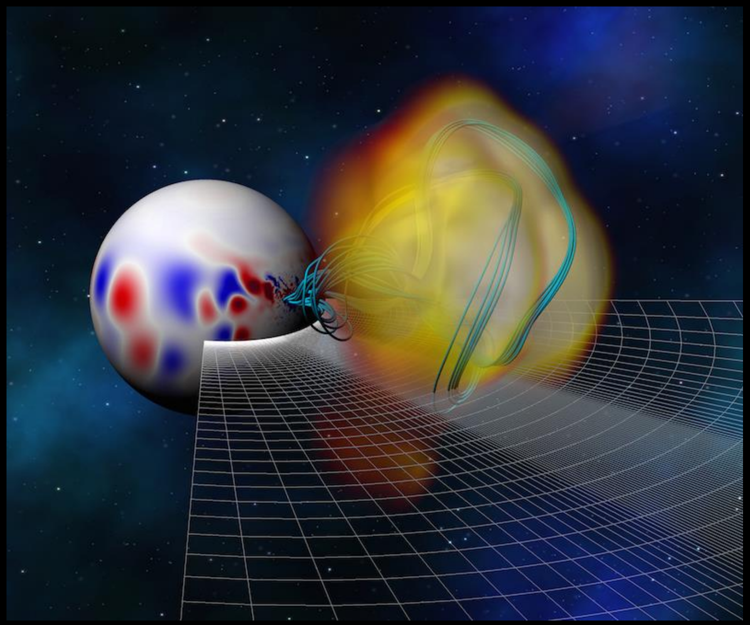
Tibor Török

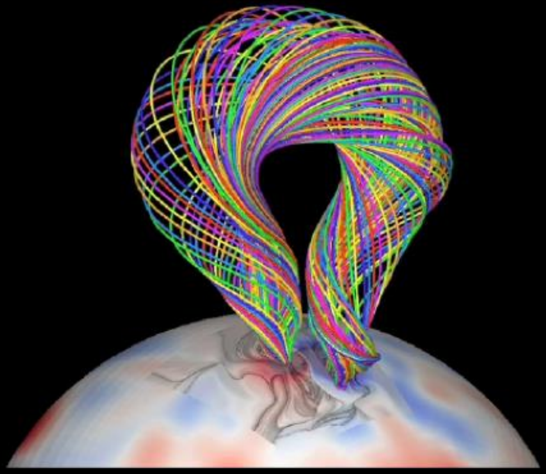
Predictive Science, Inc.

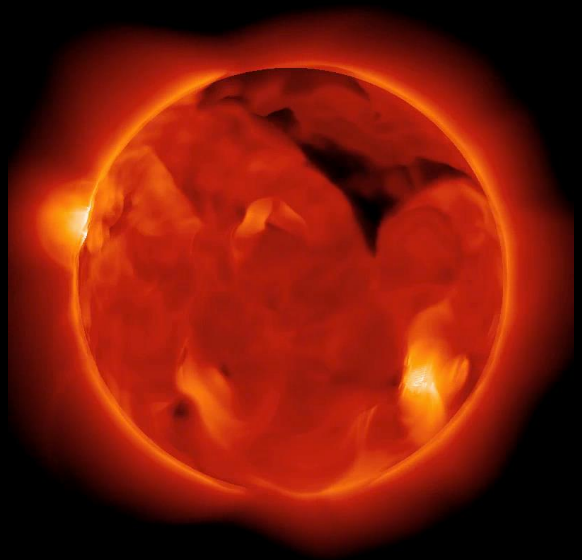












UNOOSA / ISWI Workshop 2024, June 10-14, Neustrelitz, Germany

OUTLINE:

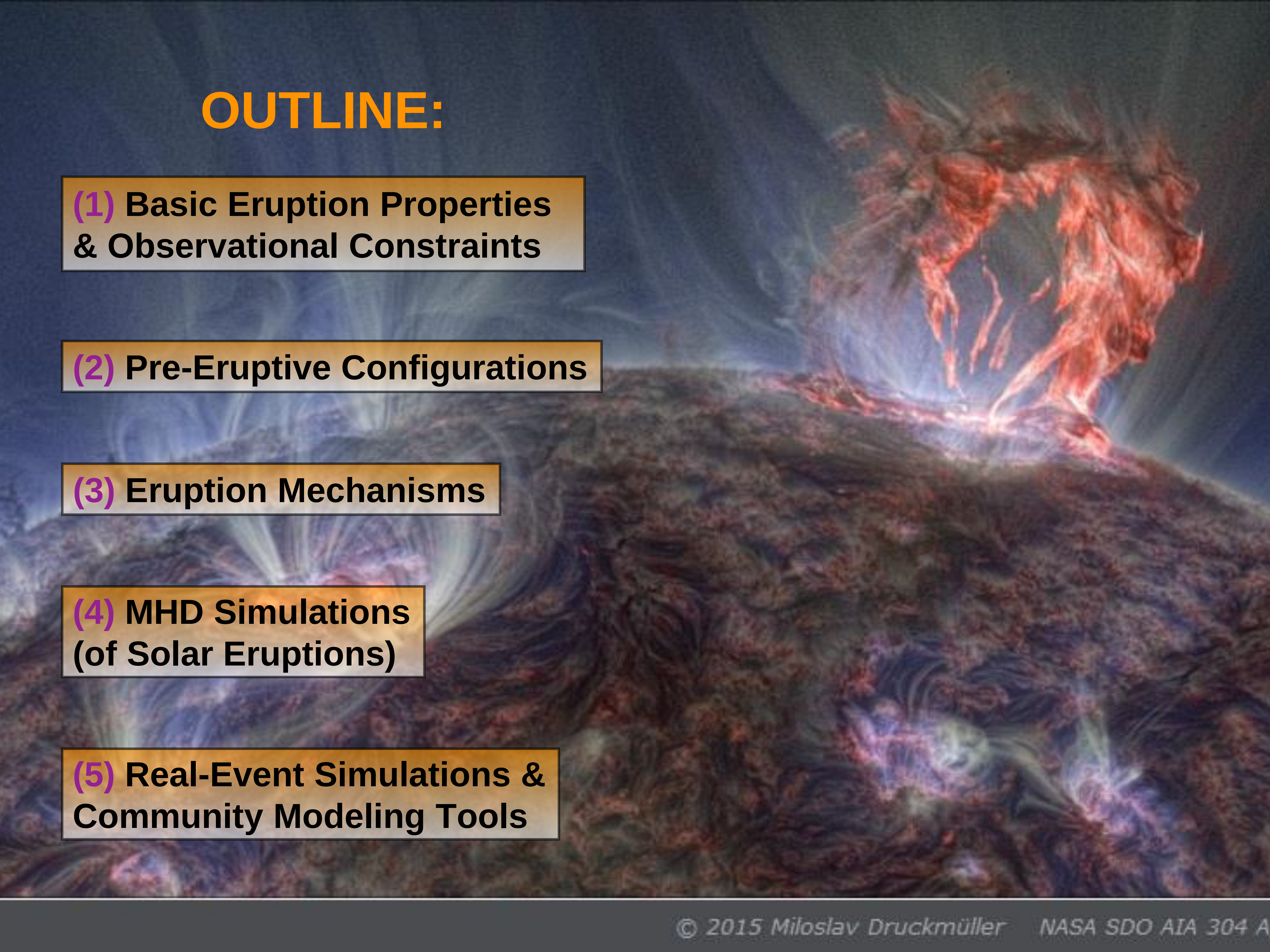
(1) Basic Eruption Properties & Observational Constraints

(2) Pre-Eruptive Configurations

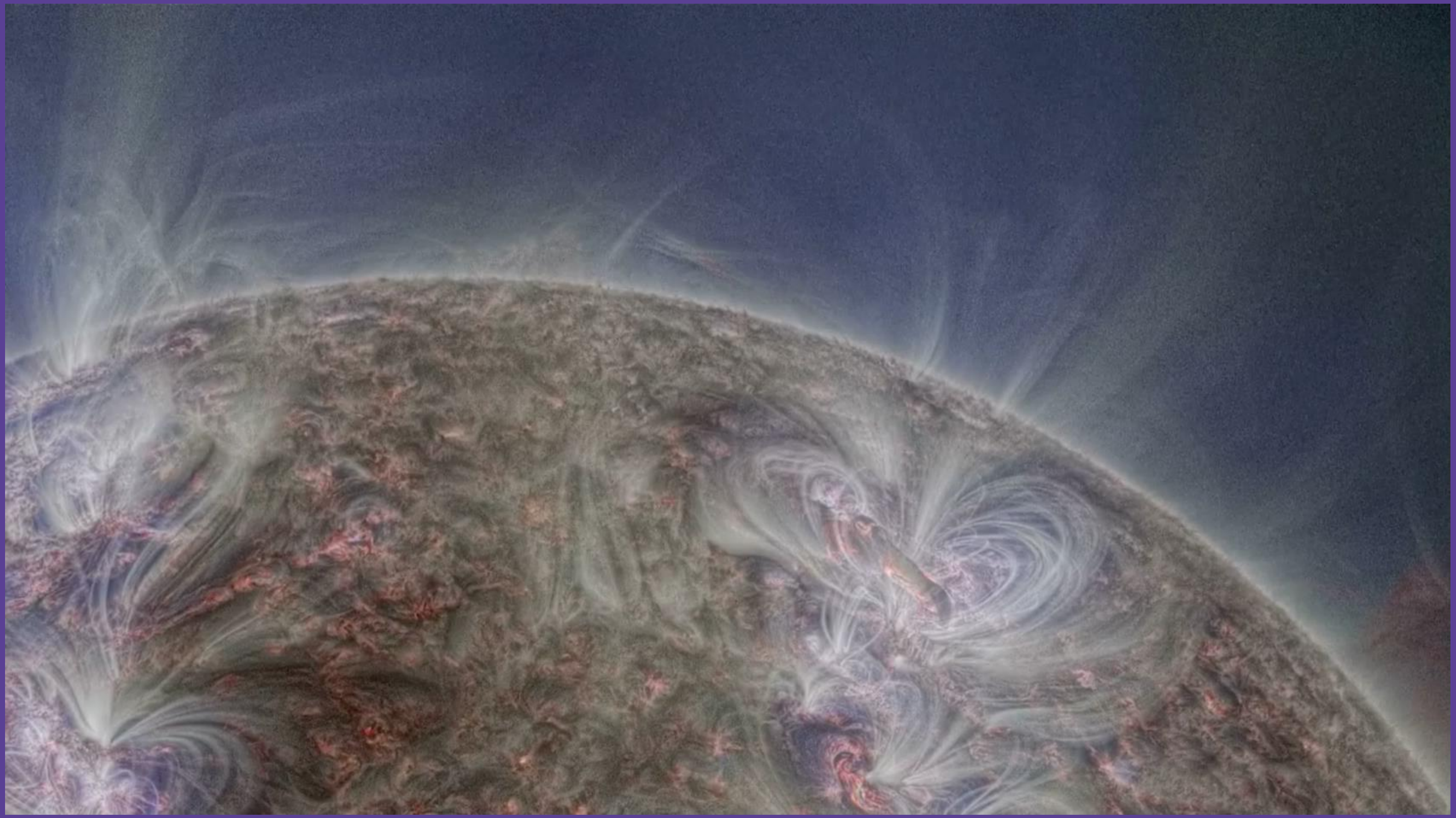
(3) Eruption Mechanisms

(4) MHD Simulations (of Solar Eruptions)

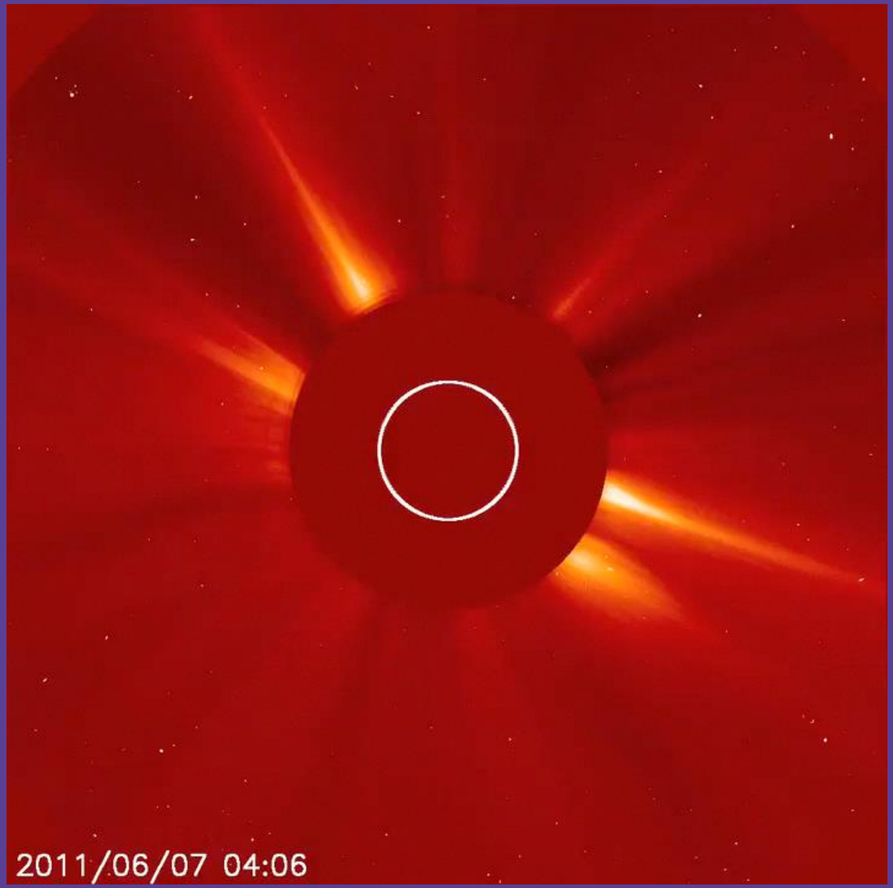
(5) Real-Event Simulations & Community Modeling Tools



(1) Solar Eruptions: Basic Properties



eruption on 7 June 2011 (SDO/AIA; courtesy M. Druckmüller)



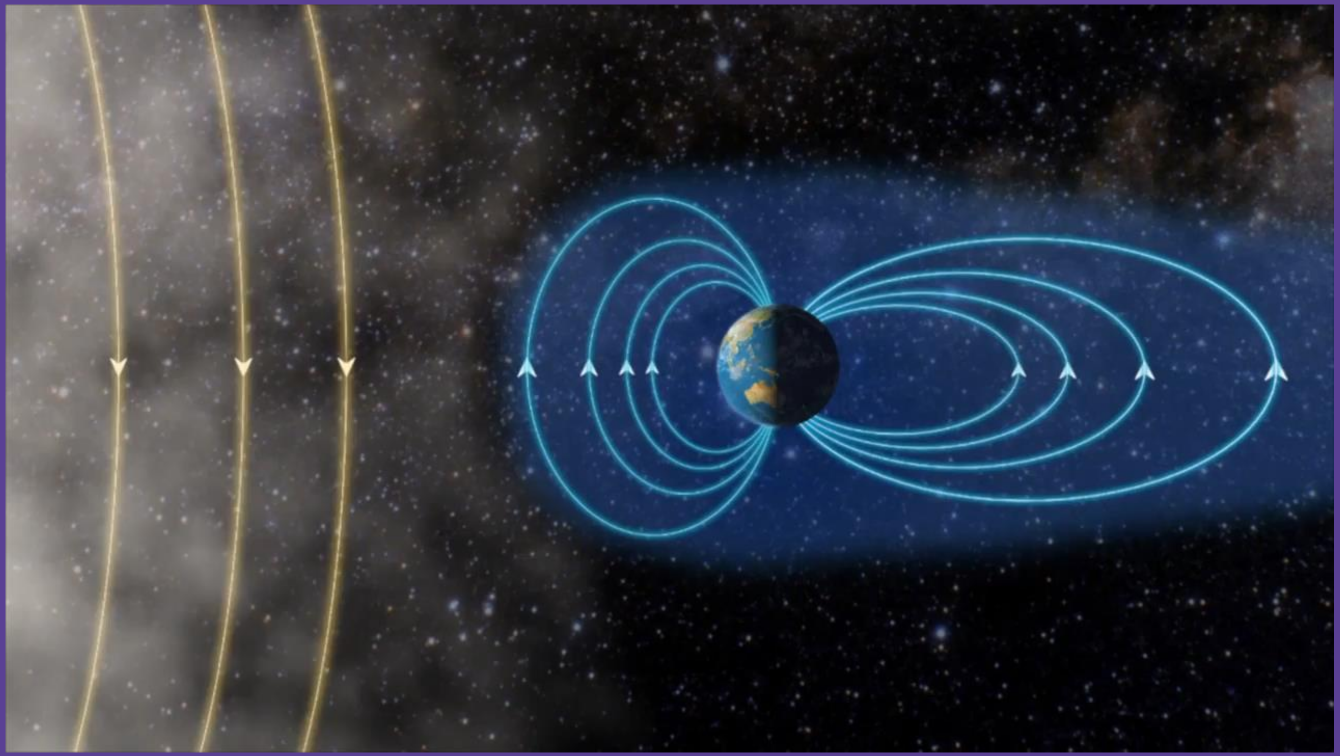
(SOHO/LASCO C2)

- Observed as flares, prominence eruptions, and CMEs (often coupled)

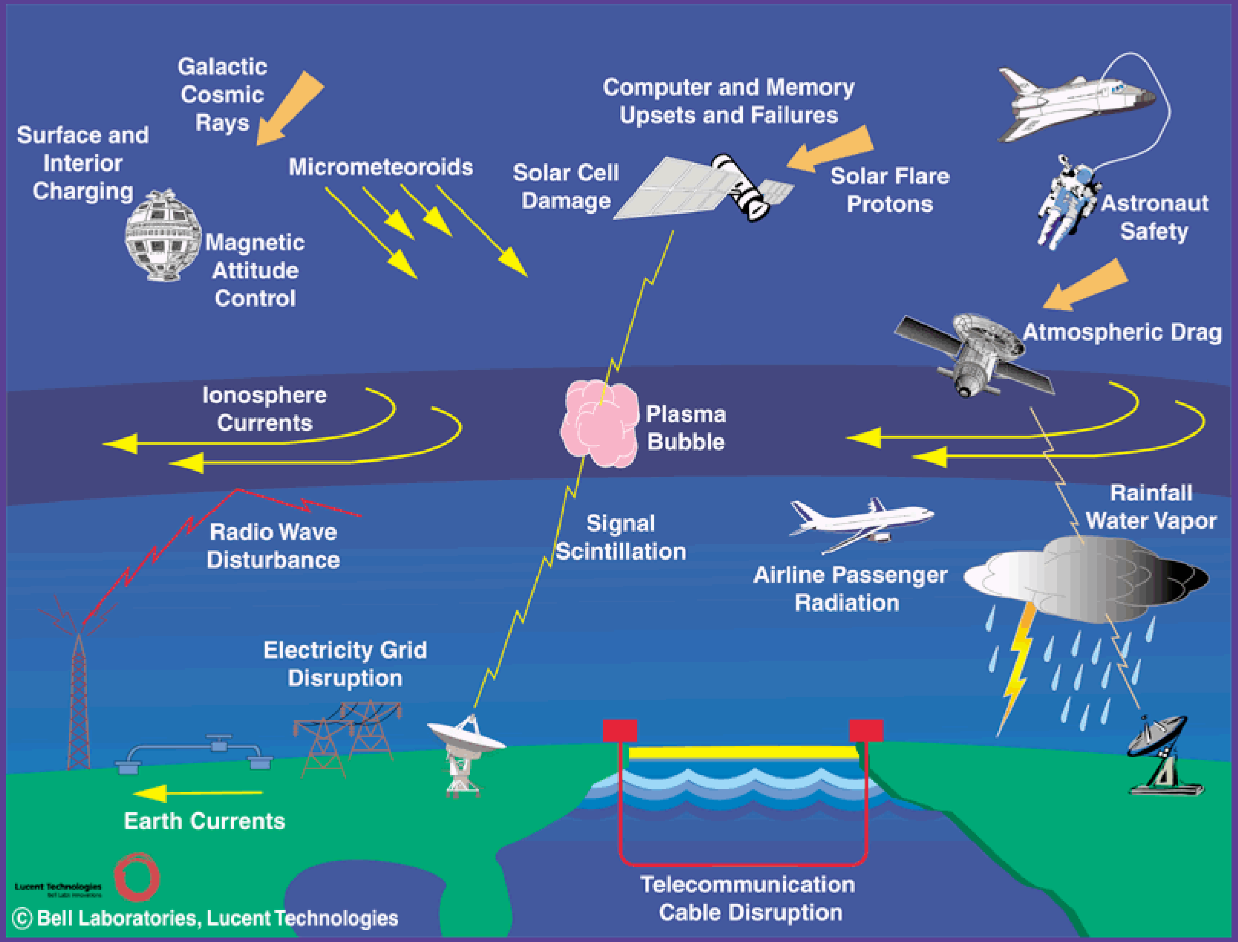
  → different manifestations of a single underlying process: a sudden and violent reconfiguration of a portion of the solar corona

- Largest energy release events in the solar system: up to several 10^{25} J
  (annual world energy consumption in 2023: 5.8 x 10^{20} J)

Practical Application: Space Weather



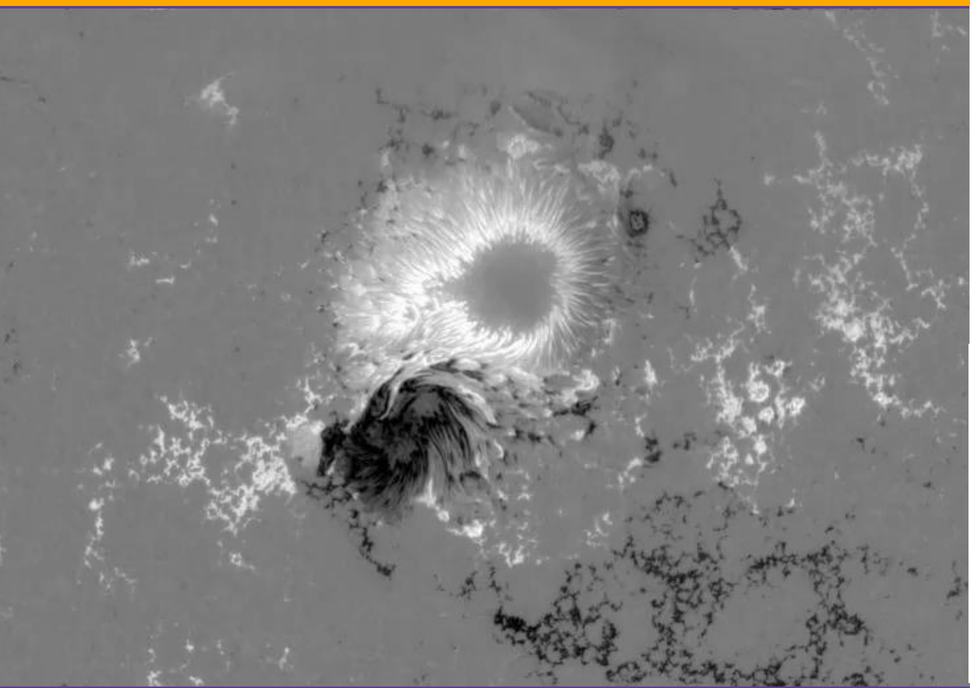
courtesy of University of Oslo (forskning.no)



space weather effects

- CMEs can interact with Earth's magnetosphere and cause geomagnetic storms
- CMEs, flares, and SEPs can destroy satellites, power grids, harm astronauts...
- One main goal: develop methods to forecast occurrence and impact of eruptions

Observational Constraints for Modeling



surface magnetic field around
X2.2 flare & CME on 13 Dec. 2006
(Hinode/SOT)

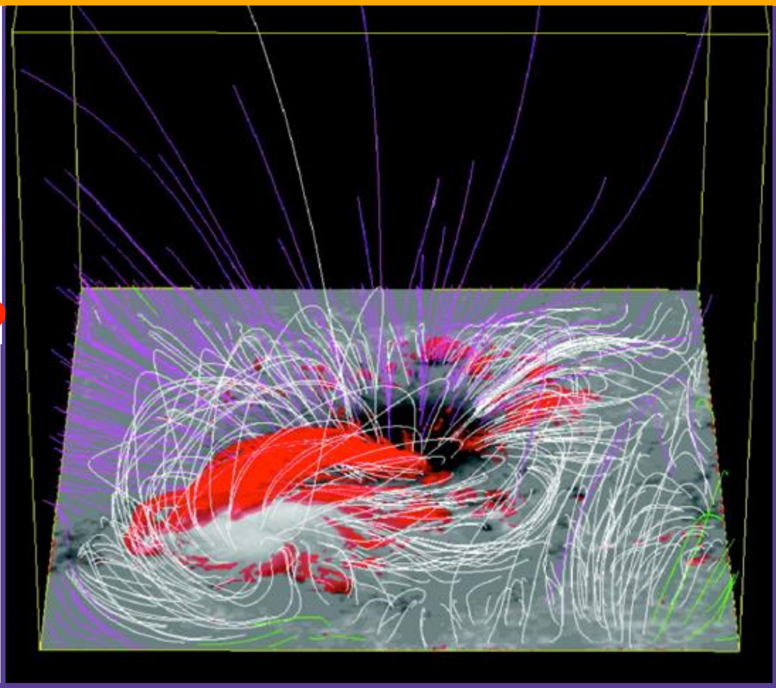
Table 1. Energy Requirements for a Moderately Large CME

Parameter	Value
Kinetic energy (CME, prominence, and shock)	10^{32} ergs
Heating and radiation	10^{32} ergs
Work done against gravity	10^{31} ergs
Volume involved	10^{30} cm^3
Energy density	100 ergs cm^{-3}

Table 2. Estimates of Coronal Energy Sources

Form of Energy	Observed Average Values	Energy Density ergs cm^{-3}
Kinetic ($(m_p n V^2)/2$)	$n = 10^9$ cm^{-3}, $V = 1$ km s^{-1}	10^{-5}
Thermal (nkT)	$T = 10^6$ K	0.1
Gravitational ($m_p ngh$)	$h = 10^5$ km	0.5
Magnetic ($B^2/8\pi$)	$B = 100$ G	400

Forbes (2000)



magnetic field extrapolation
of active region (13 Dec. 2006)
Schrijver *et al.* (2008)

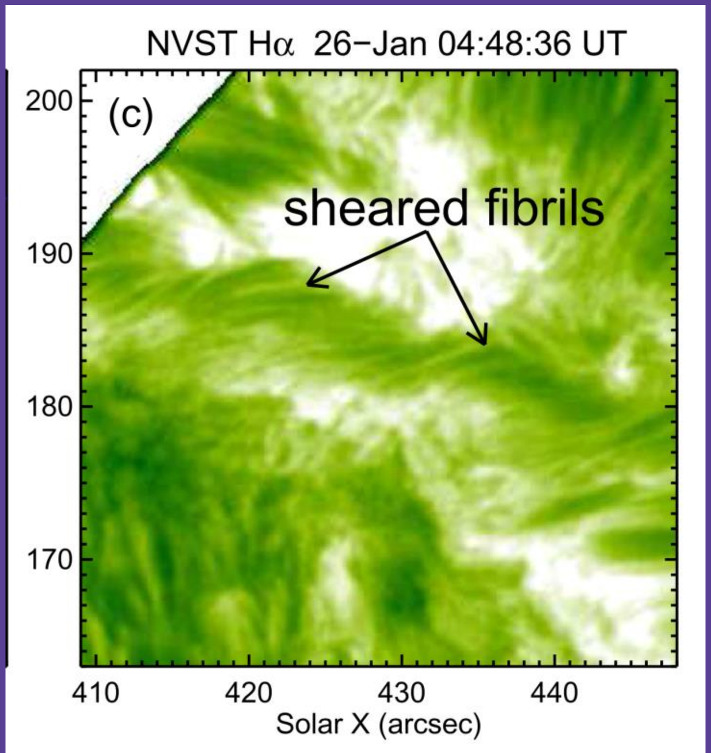
- Originate in low corona ($\beta \ll 1$) always above polarity inversion lines of the surface magnetic field; strongest events occur in active regions

- Eruptions are magnetically driven (non-magnetic mechanisms are ruled out)

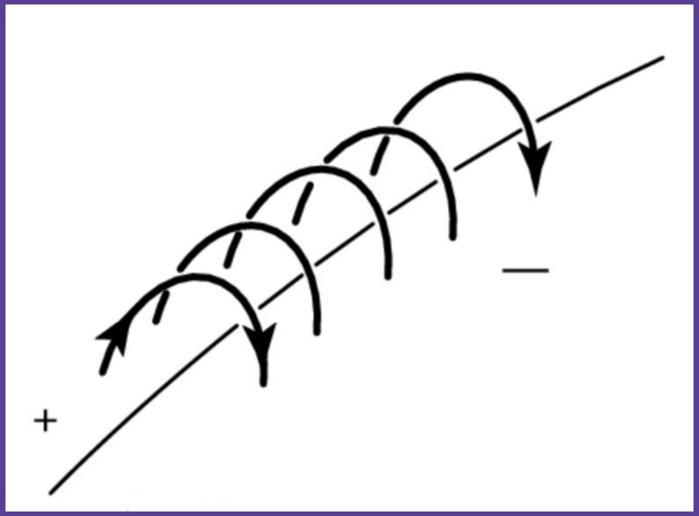
- Required ("free") magnetic energy slowly accumulated via flux emergence or surface flows & stored in current-carrying, sheared/twisted core field

- Currents in core field not stable → stabilized by ambient "strapping field"

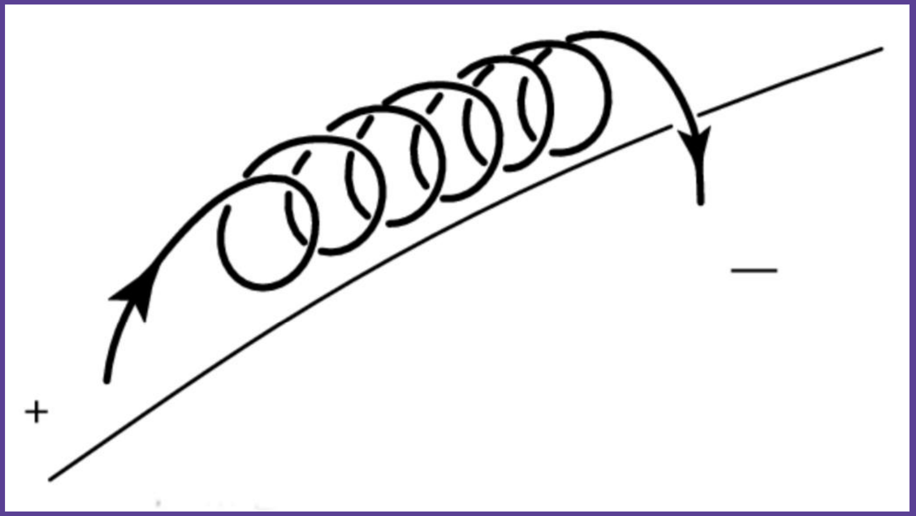
(2) Pre-Eruptive Configurations (PECs)



S. Yang *et al.* (2019)



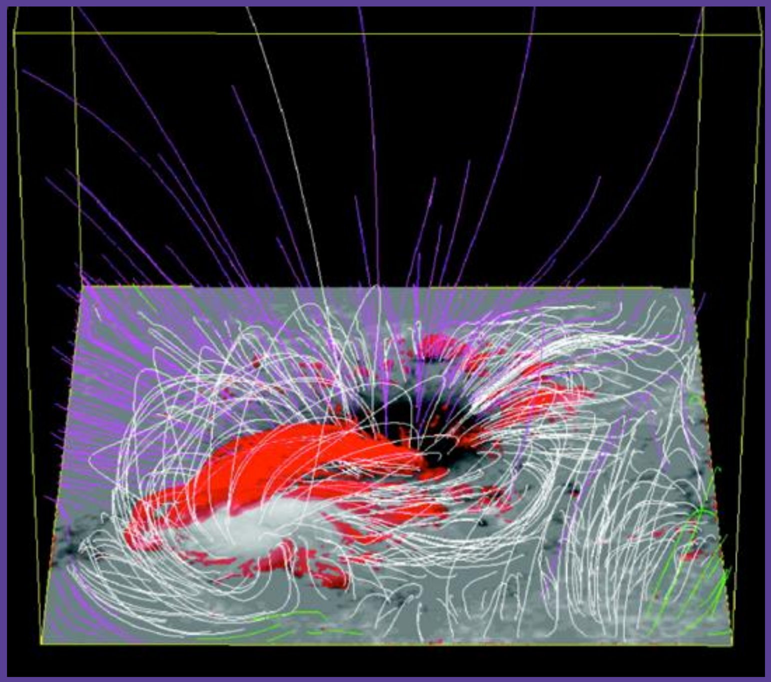
sheared magnetic arcade
(SMA)



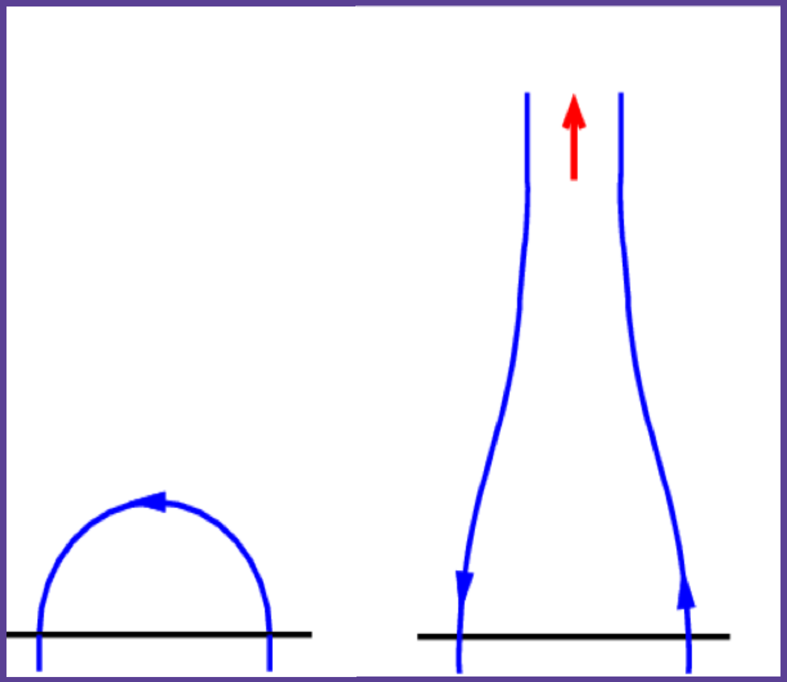
magnetic flux rope
(MFR)

- Pre-eruptive core field observed as (sheared) "filament channel" (FC)
- Long-lasting debate: is the (current-carrying) core field an SMA or an MFR?
- Why important? CME initiation mechanism (some require an MFR)
- Problem: no coronal $\boldsymbol{B}$ measurements & very few observations of FC formation
- Reality: hybrid configurations; SMA-to-MFR transition; … (Patsourakos+ 2020)

(3) Eruption Mechanisms



magnetic field extrapolation
of active region (13 Dec. 2006)
Schrijver *et al.* (2008)

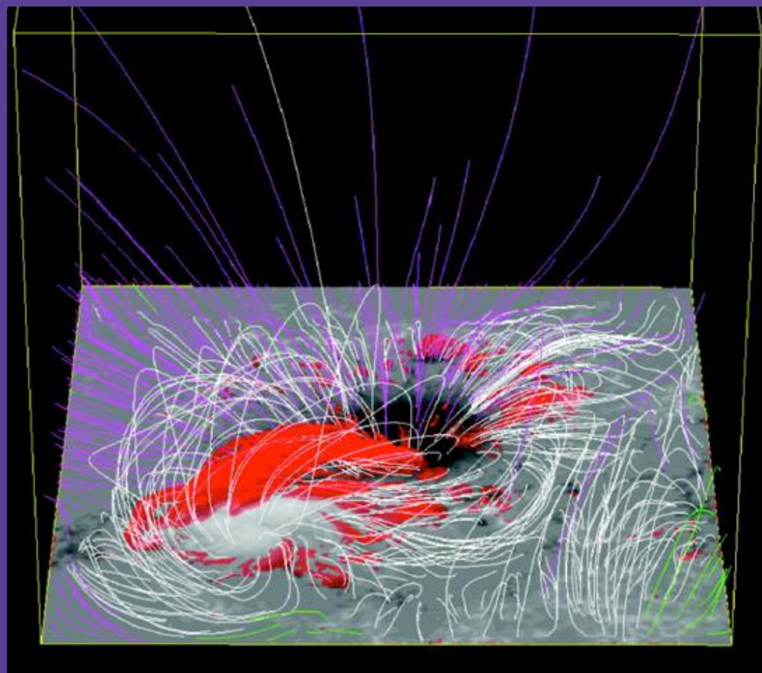


pre-eruption   initiation

Pre-eruption phase: closed current-carrying (I) core field stabilized by strapping field (SF)

Initiation phase: force balance destroyed (increase I or decrease SF) → closed field opens

(3) Eruption Mechanisms



magnetic field extrapolation
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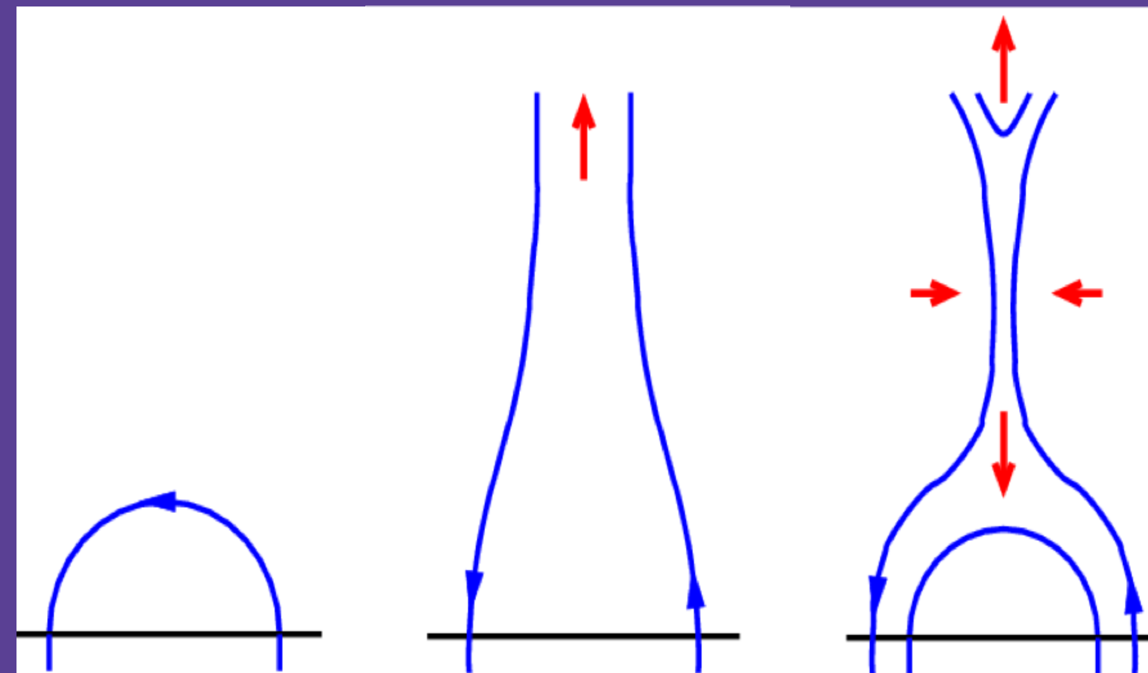
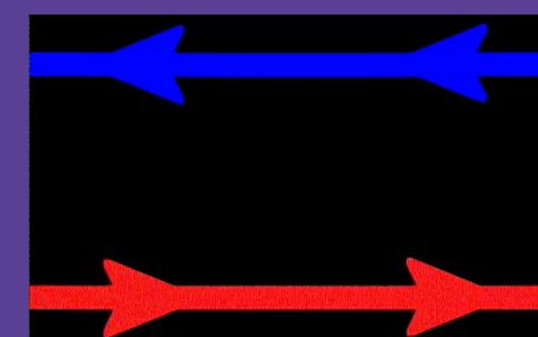
Schrijver *et al.* (2008)



pre-eruption initiation main phase

Yokoyama *et al.* (2001)



magnetic reconnection

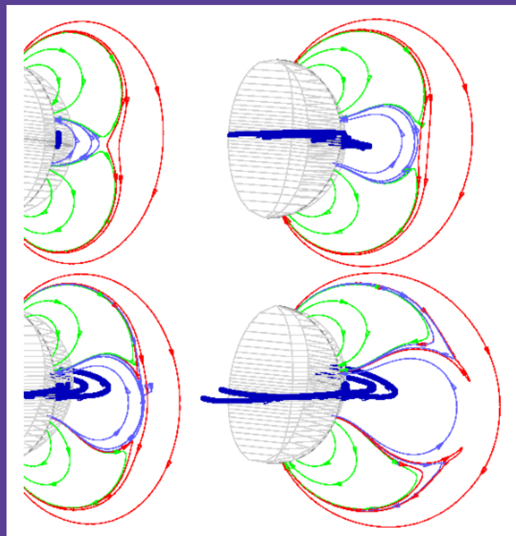
pre-eruption phase: current-carrying (I) core field stabilized by strapping field (SF)

initiation phase: force balance destroyed (increase I or decrease SF) → closed field opens

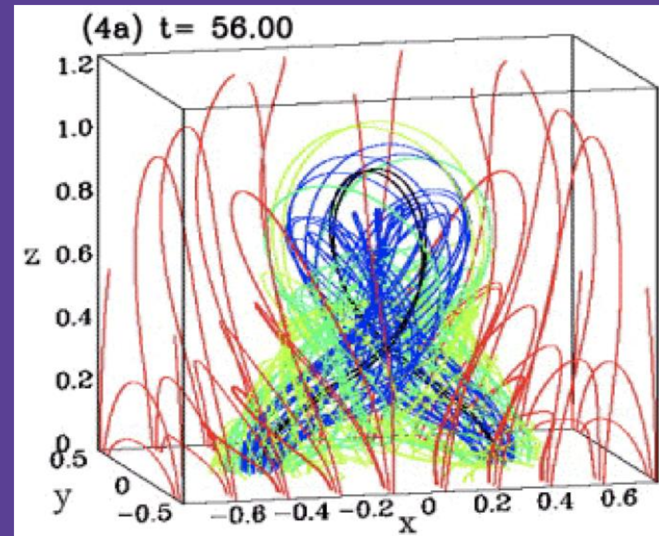
Main phase: - CME + formation of vertical current sheet below eruption

- re-configuration of coronal field by magnetic reconnection → flare

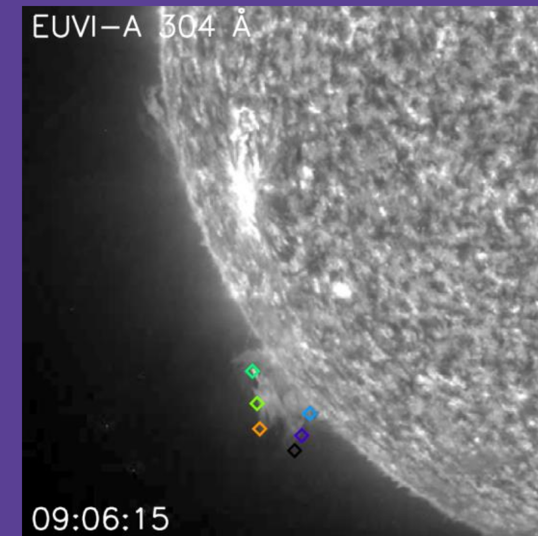
Initiation Phase: What *Triggers* an Eruption?



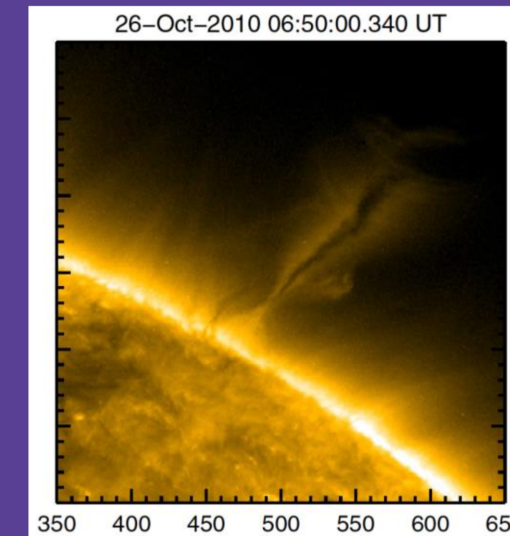
magnetic breakout
Antiochos *et al.* (1999)



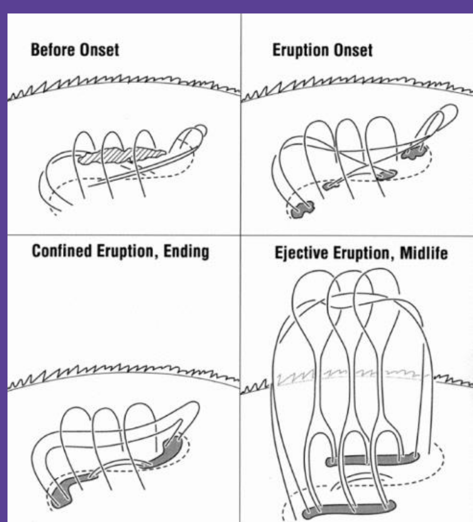
kink instability
Fan & Gibson (2003)



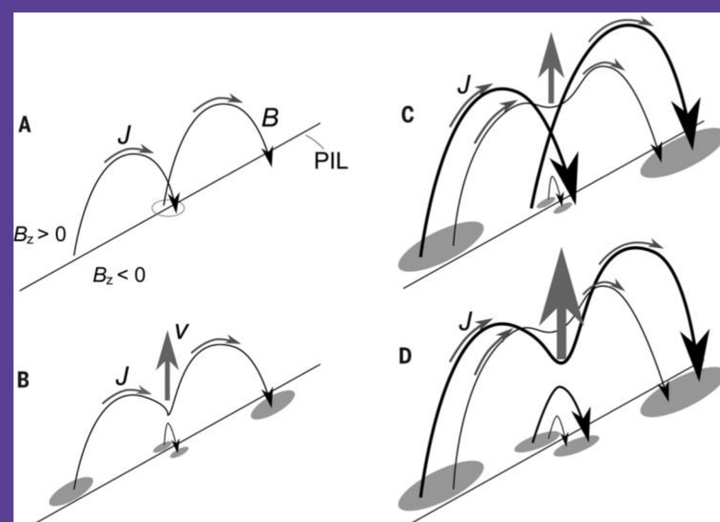
mass (un-)loading
Seaton *et al.* (2011)



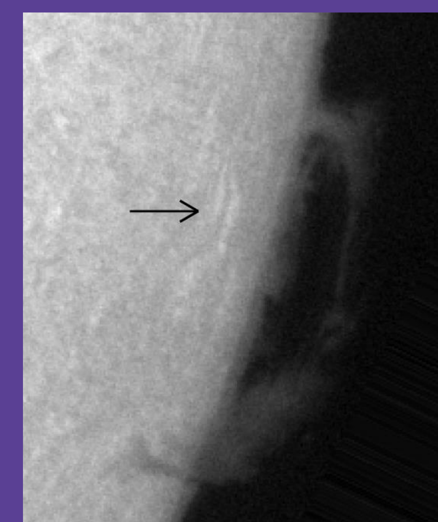
solar tornados
Su *et al.* (2012)



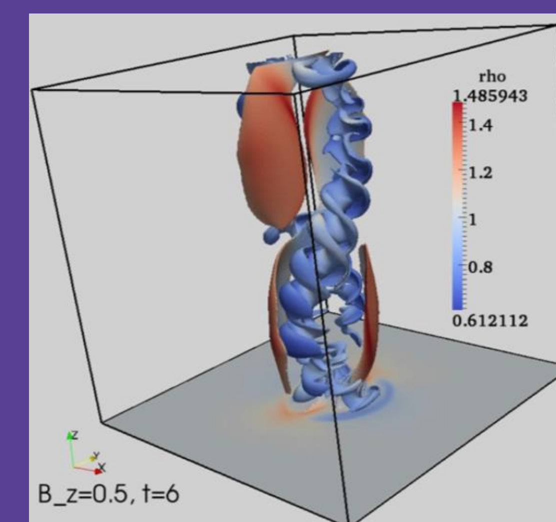
(slow) tether-cutting
Moore *et al.* (2001)



double-arc instability
Kusano *et al.* (2020)



flux feeding
Zhang *et al.* (2014)



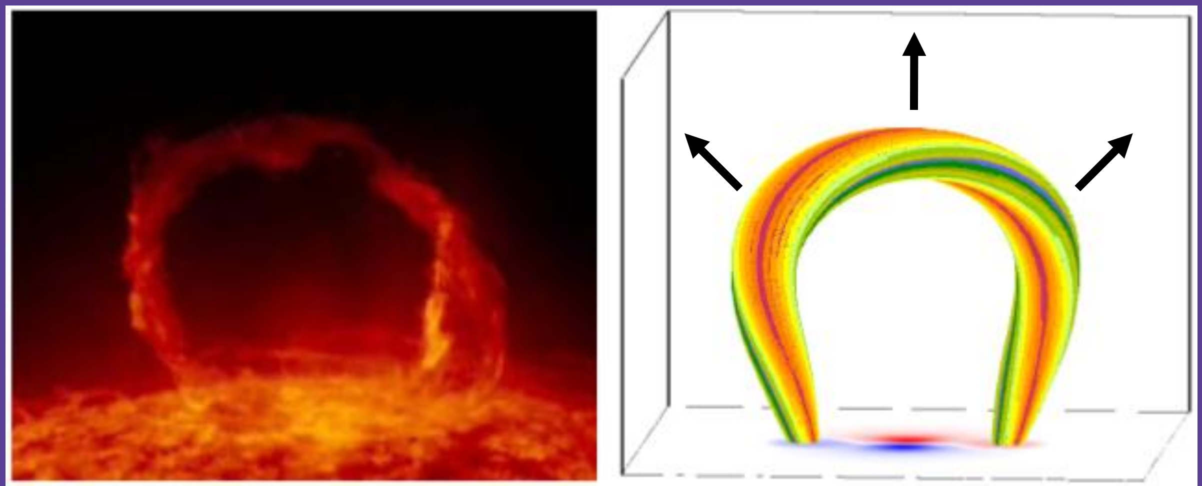
tilt instability
Keppens *et al.* (2014)

- Trigger: mechanism that prepares/supports eruption, but is not the main driver
- Many mechanisms have been suggested & new ideas still emerge (Green *et al.* 2018)
- Problem: quantitative properties/thresholds hardly known → need more studies!

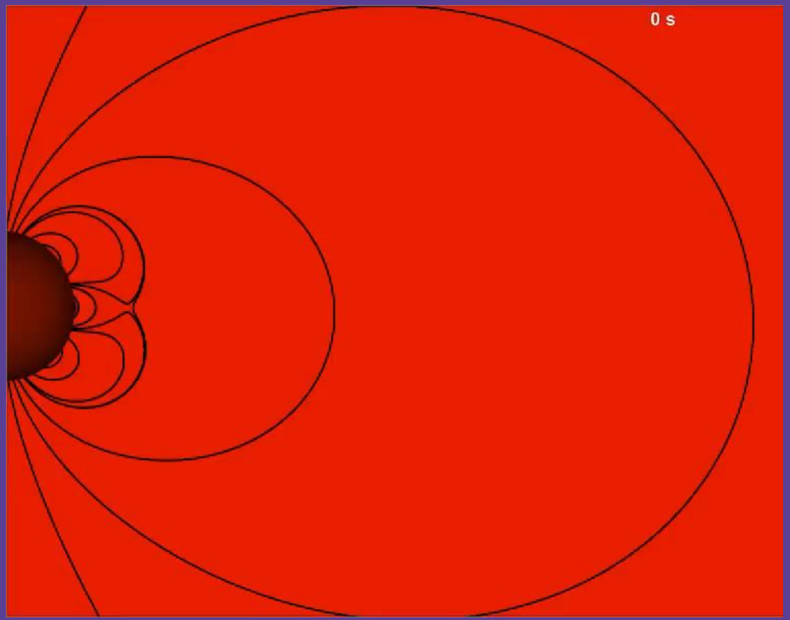
Main Phase: What *Drives* an Eruption?

- Driver: mechanism responsible for rapid acceleration & huge expansion of eruptive flux

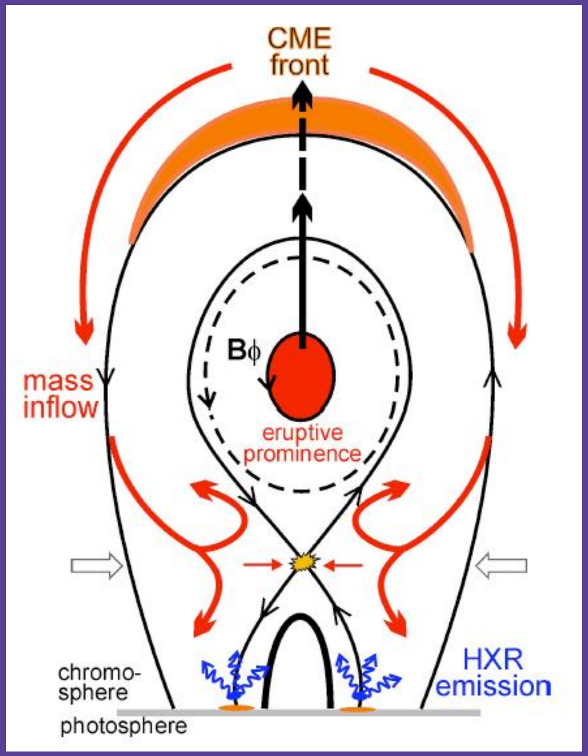
Main Phase: What *Drives* an Eruption?



torus instability
Kliem & Török (2006)



flare reconnection
Karpen *et al.* (2012)



CME-flare feedback

∉ Driver: mechanism responsible for rapid acceleration & huge expansion of eruptive flux

∉ Two main candidates identified (debated!):

- ideal MHD torus instability (driven by "hoop force")
- flare reconnection (more precisely: its ideal MHD consequences)

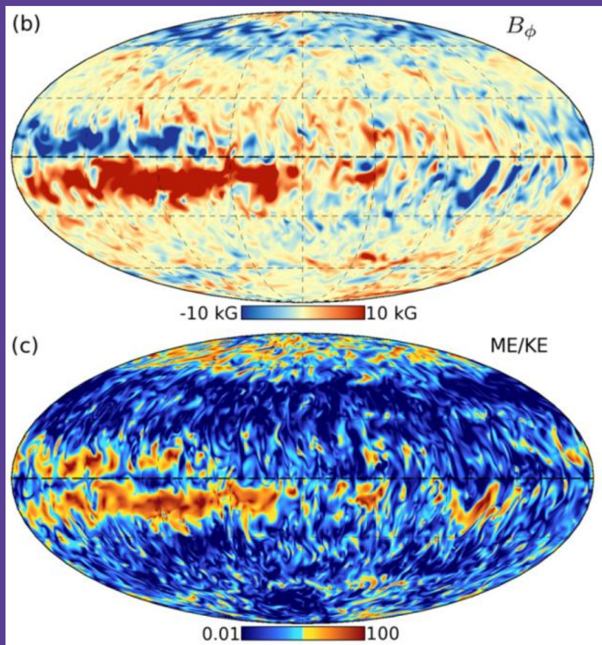
∉ Open question: which one is dominant under which circumstances?

- respective contributions difficult to separate (closely coupled; pos. feedback)

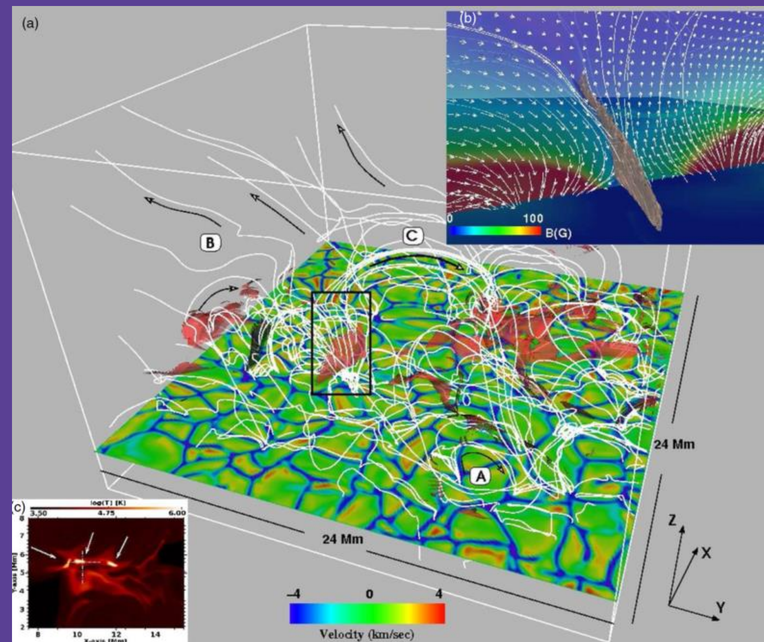
(4) Numerical (MHD) Simulations

- Cannot do experiments in astronomy use numerical simulations as a substitute
- Physics (solar applications) often well described by magnetohydrodynamics (MHD):
  - hydrodynamics + magnetic field (particles described as single fluid)
  - main assumption: macroscopic plasma velocity $v \ll c$
- Full MHD equations difficult to solve → typically only a reduced set is used
- Simulations formulated as initial boundary-value problem:
  - system of differential equations (typically single-fluid MHD)
  - set of boundary conditions (sometimes well constrained by observations)
  - initial state (typically less well constrained) often ad-hoc
- System discretized in space/time & evolved by numerical scheme (e.g., Lax-Wendroff)

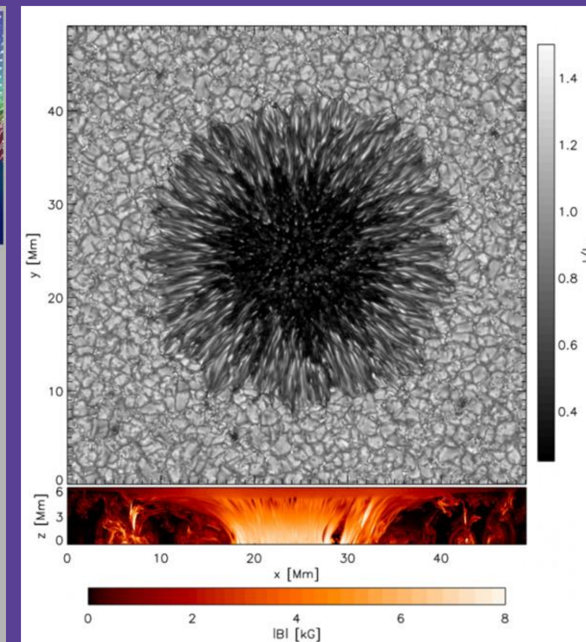
MHD Simulations: Solar Applications



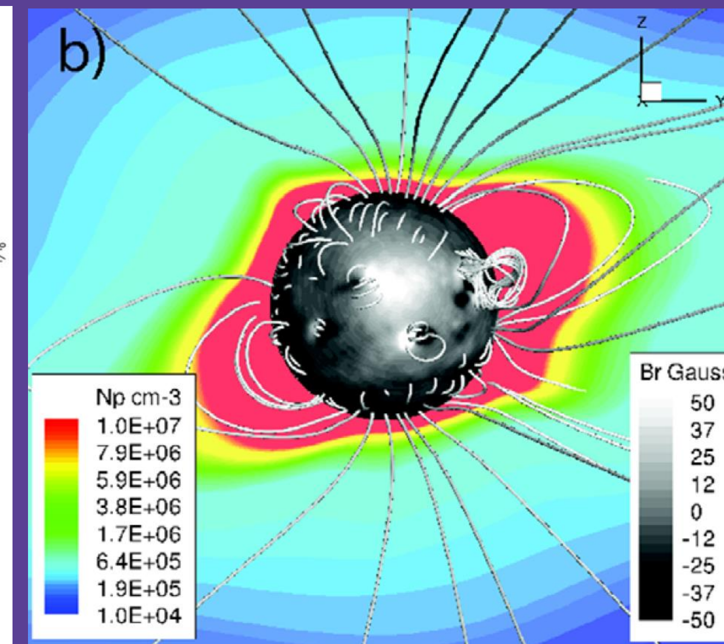
interior / CZ
Nelson & Miesch (2014)



quiet sun / chromosphere
Archontis & Hansteen (2014)



sunspots / ARs
Rempel (2012)



corona / heliosphere
Manchester *et al.* (2014)

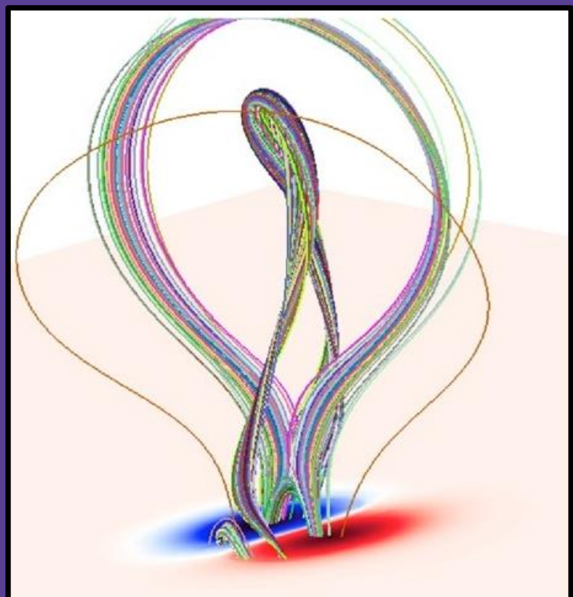
∉ Much progress in past decades (resolution, complexity of physics, observed data, ...)

∉ Still far from real solar complexity & enormous range of temporal/spatial scales

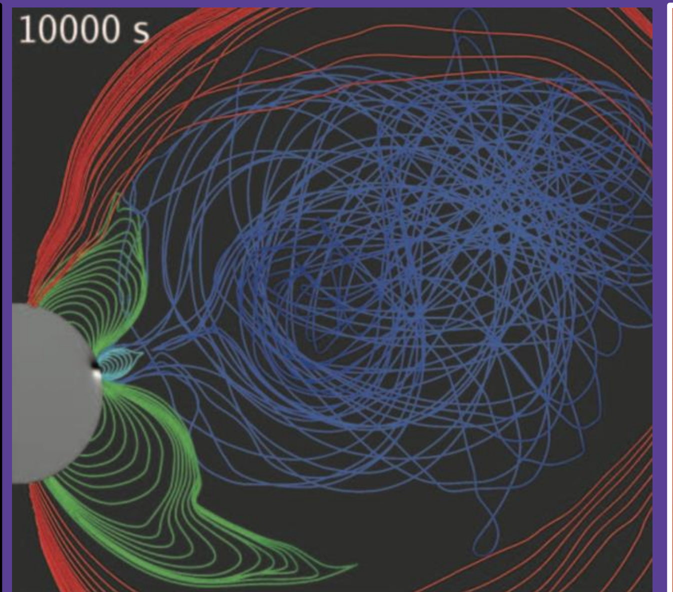
→ no <u>self-consistent model</u> that includes all relevant layers of the Sun

→ little inclusion of <u>microphysics</u> yet (reconnection, particle acceleration)

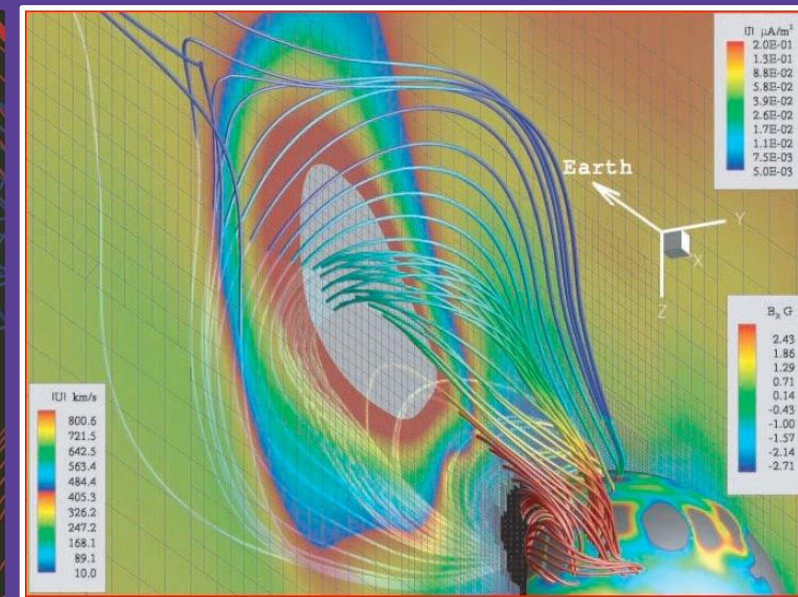
MHD Simulations of Solar Eruptions



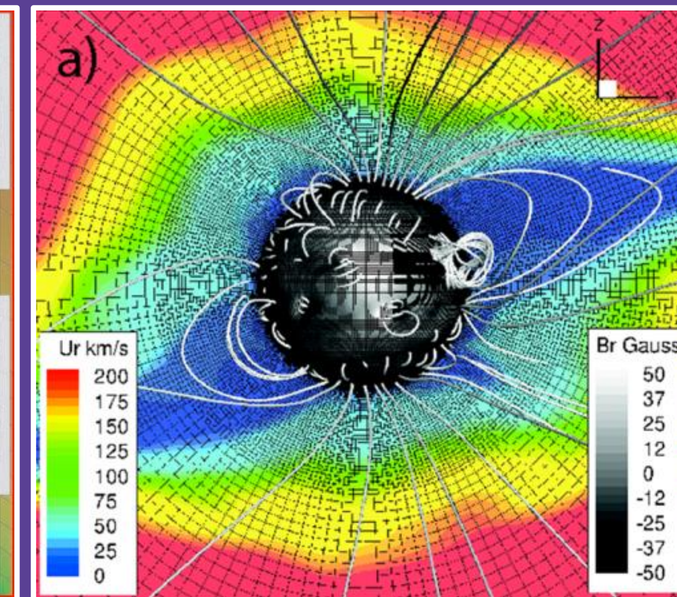
Amari *et al.* (2003)



Lynch *et al.* (2008)



Roussev *et al.* (2004)



Manchester *et al.* (2014)

- Can be (roughly) divided into two groups:

  idealized: limited 2D/3D domain; idealized fields; simple or no energy equation

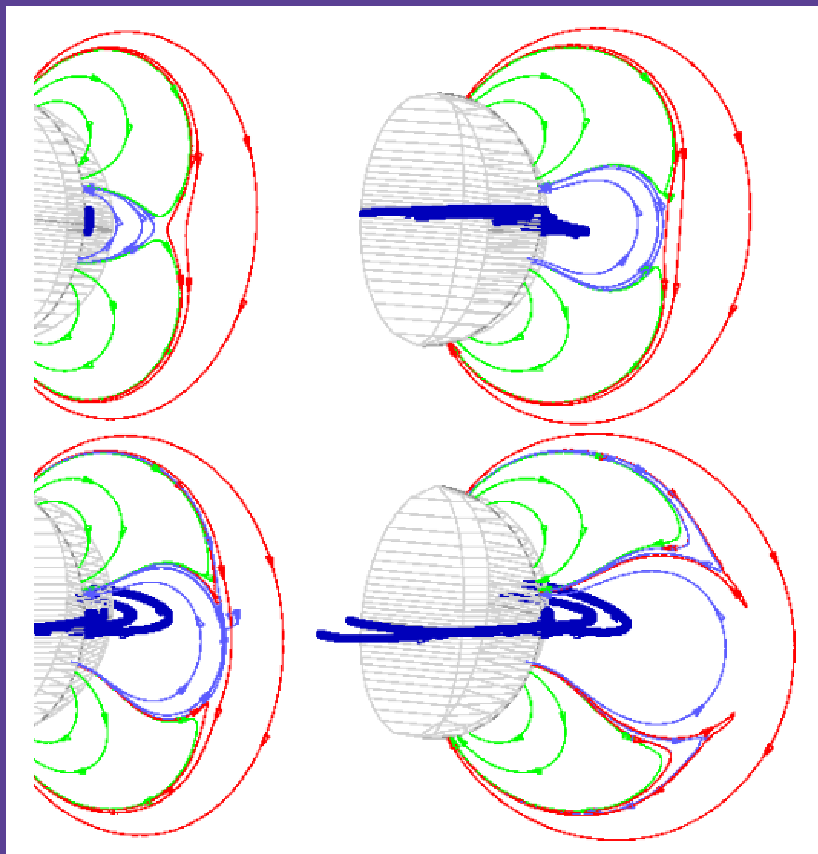
  "realistic": full corona; real magnetograms; thermodynamic MHD; solar wind

- Both approaches have <u>pros and cons</u>:

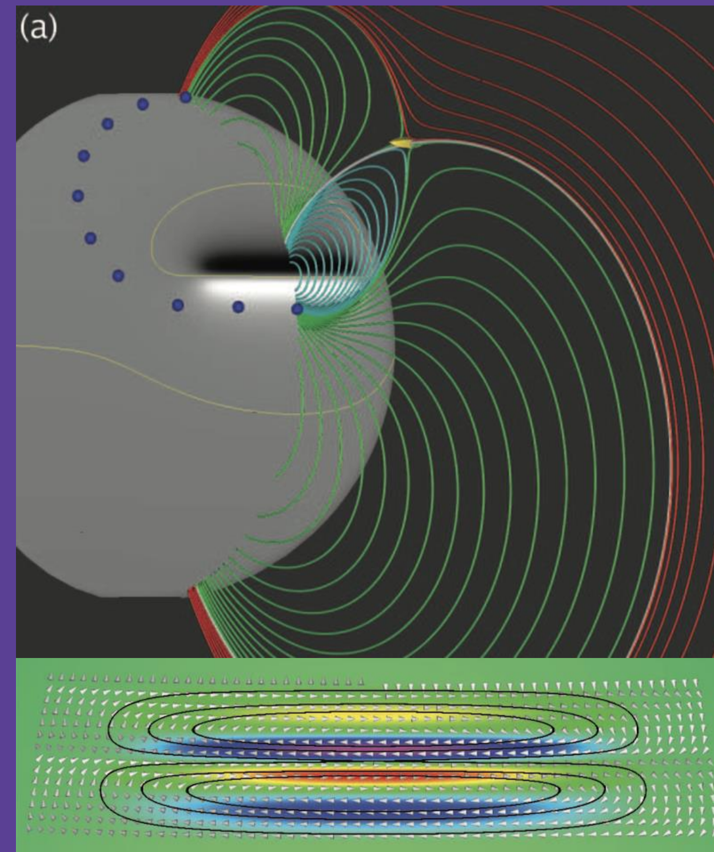
  idealized: simplified setups/physics; limited comparison with observations
  but: allow one to isolate physical mechanisms; fast □ parametric studies;

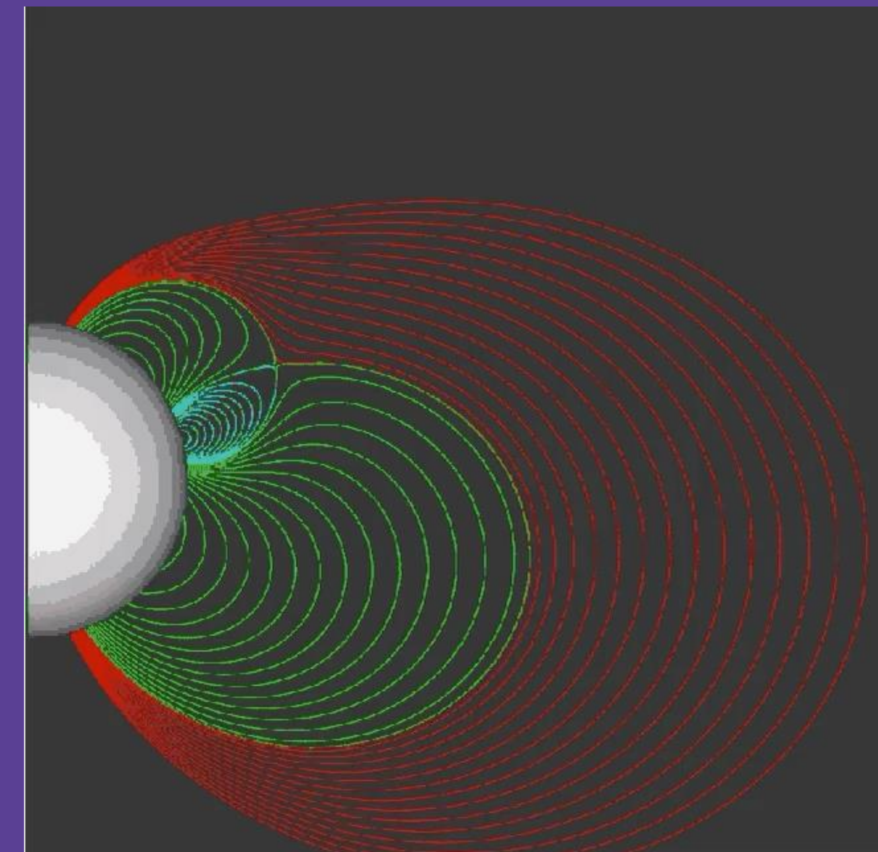
  "realistic": complex; time-consuming to develop; computationally expensive
  but: direct comparison with observations; more physics; potentially predictive

Idealized Simulations: Magnetic Breakout



Antiochos *et al.* (1999)



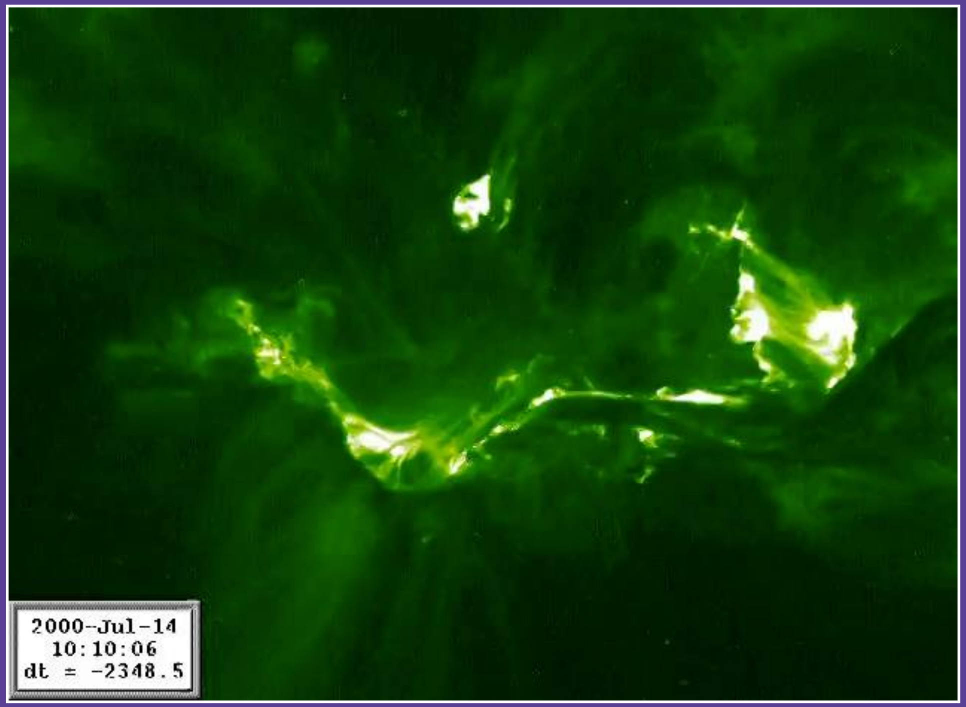


Lynch *et al.* (2008)

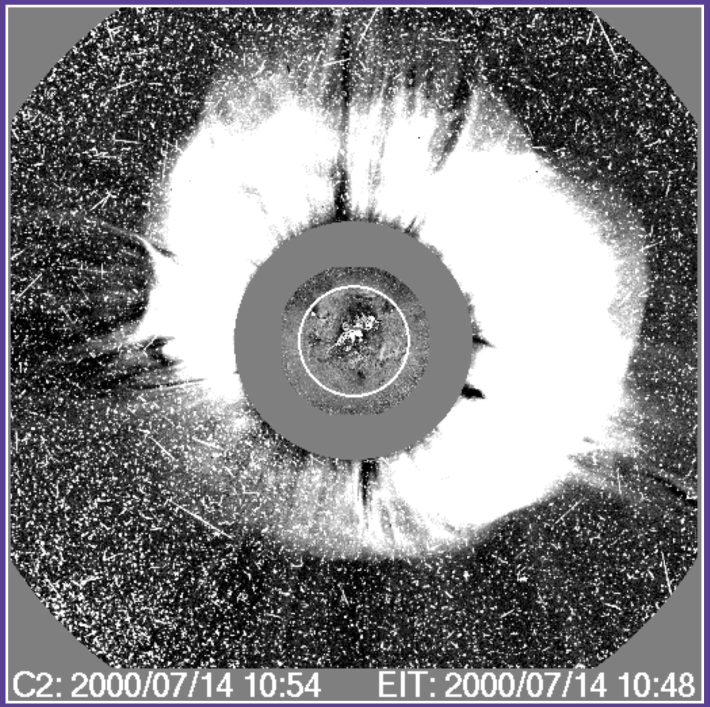
- Motivation: eruptions often originate in quadrupolar source regions
- Initial condition: three-dimensional potential field with overlying null point/line
- Flux in central arcade is continuously sheared via surface flows:
  - □ expansion of arcade + formation of SMA and (flare) current sheet
  - □ current sheet formation/steepening at null point □ “breakout” reconnection
- Requires fast flare reconnection (MFR formation) to produce CME

(5) Real-Event Simulations & Community Tools

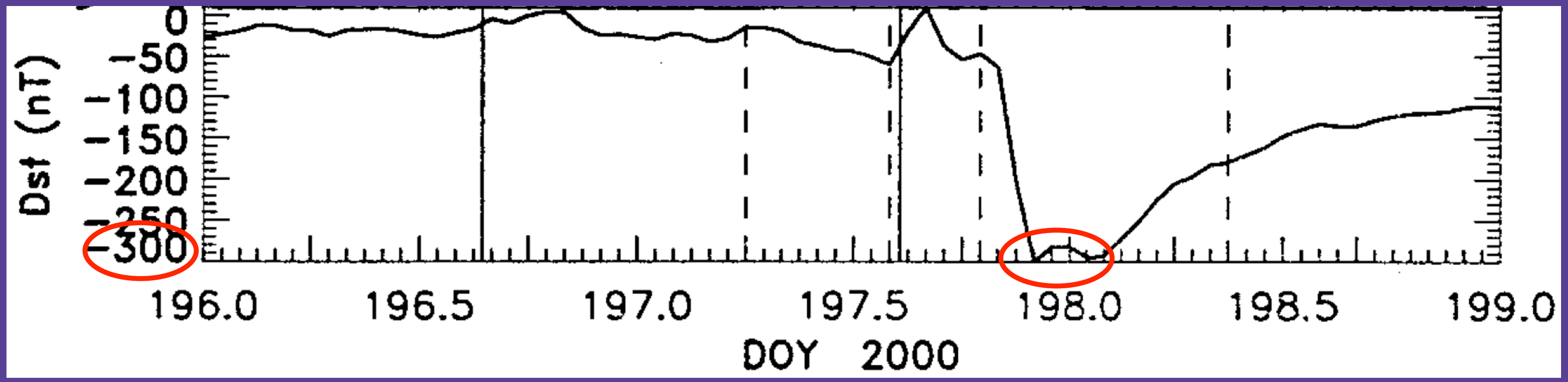
"Bastille Day" event:
X5.7 flare & halo CME (1700 km/s)
strong geomagnetic storm (-300 Dst)



TRACE 195 Å
(July 14, 2000)

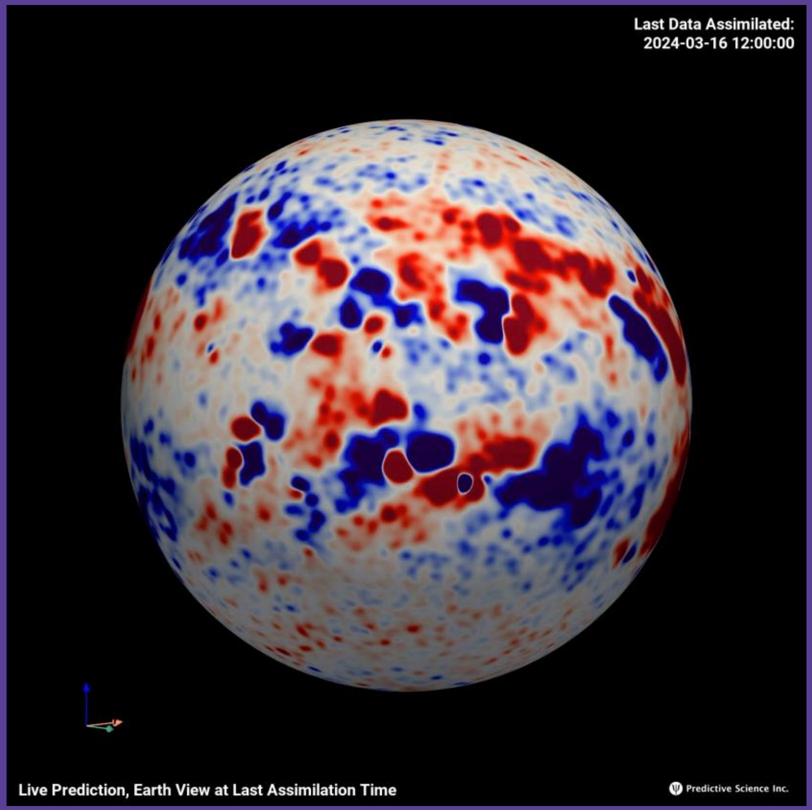


SOHO/LASCO C2

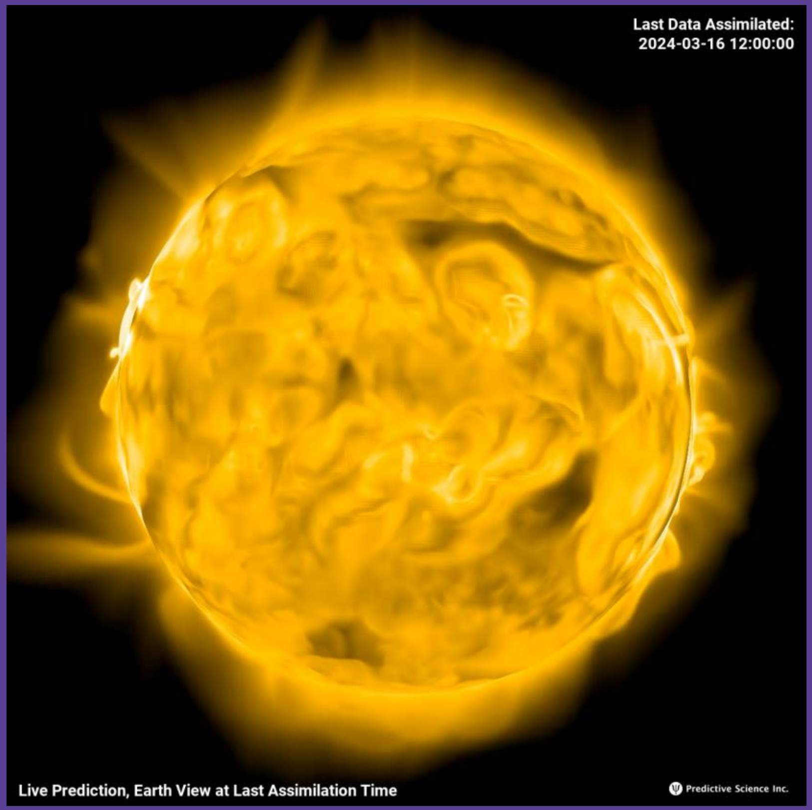


Lepping *et al.* (2001)

“Thermodynamic MHD” Model of Global Corona



const. updated magnetogram



SDO/AIA 171 Å

squashing factor

April 8, 2024 total solar eclipse: https://www.predsci.com/corona/apr2024eclipse/home.php

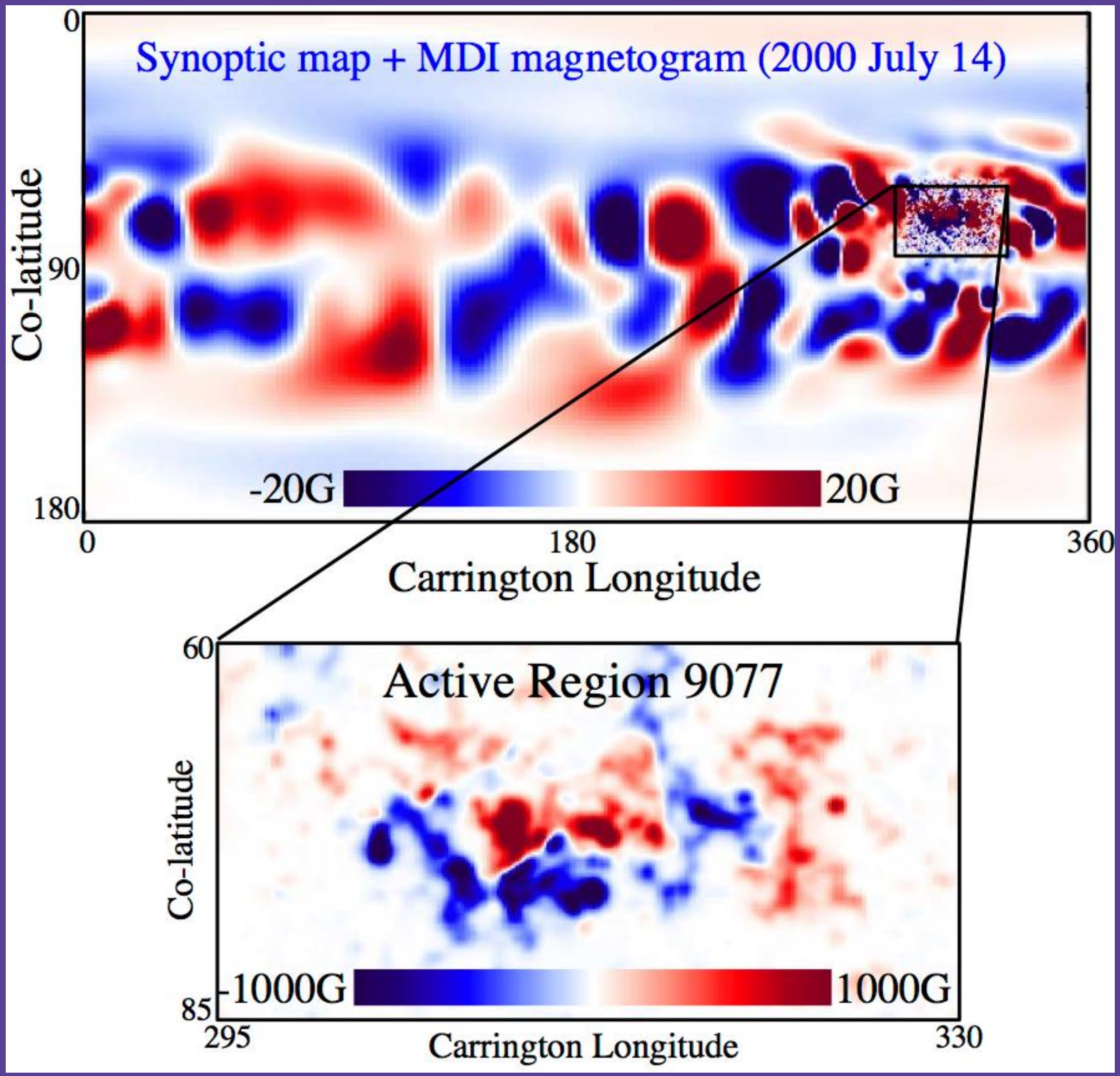
(1) Start with full-Sun (synoptic) magnetogram and calculate potential field

(2) Perform MHD relaxation with advanced energy transfer towards steady state
(include thermal conduction, radiative cooling, [empirical or WTD] coronal heating)

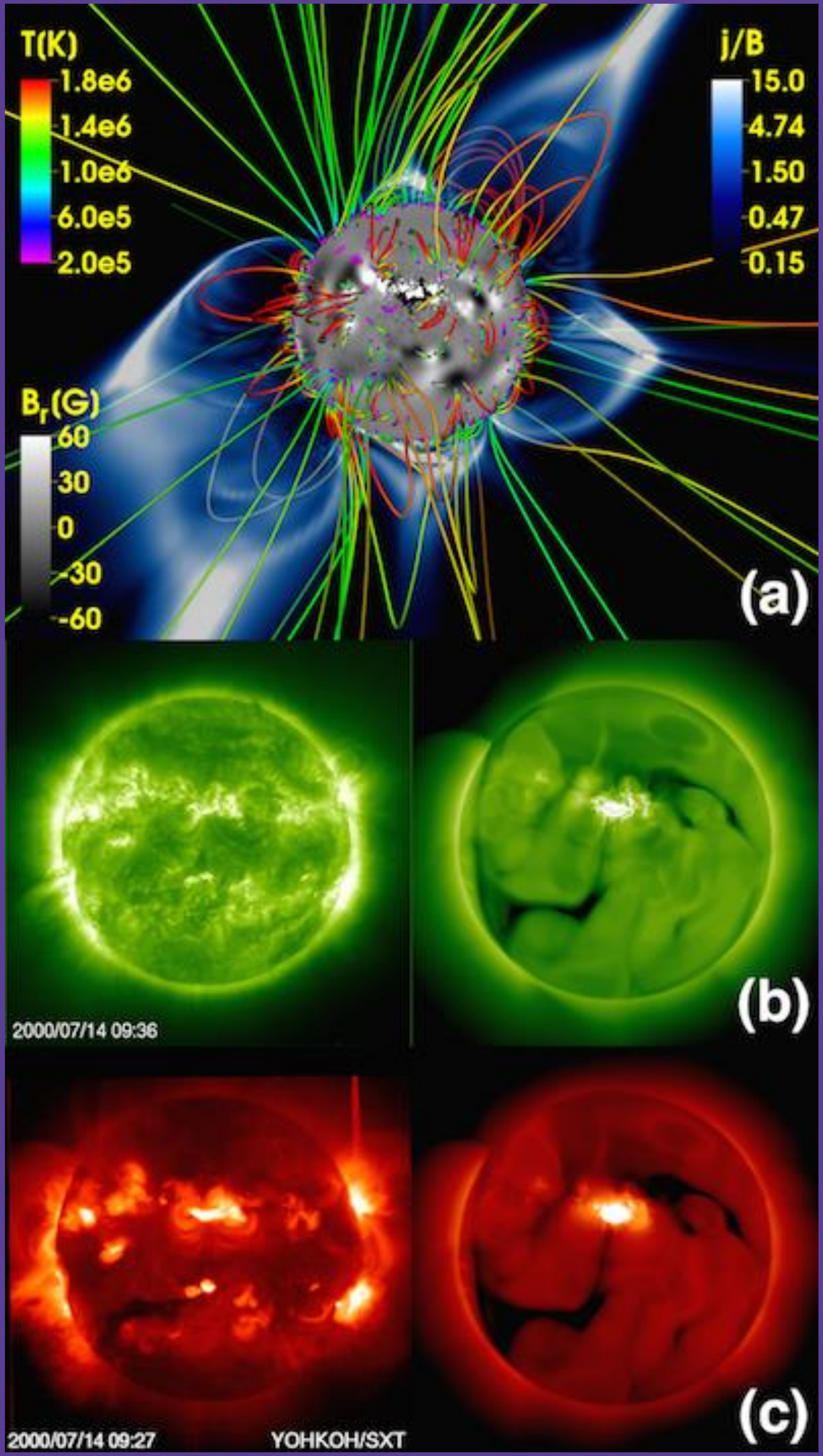
(3) New: evolve system via const. updated magnetic data & flux transport model

(semi-)realistic coronal magnetic field & plasma environment

"Bastille Day": Background Corona (1-20 R☉)

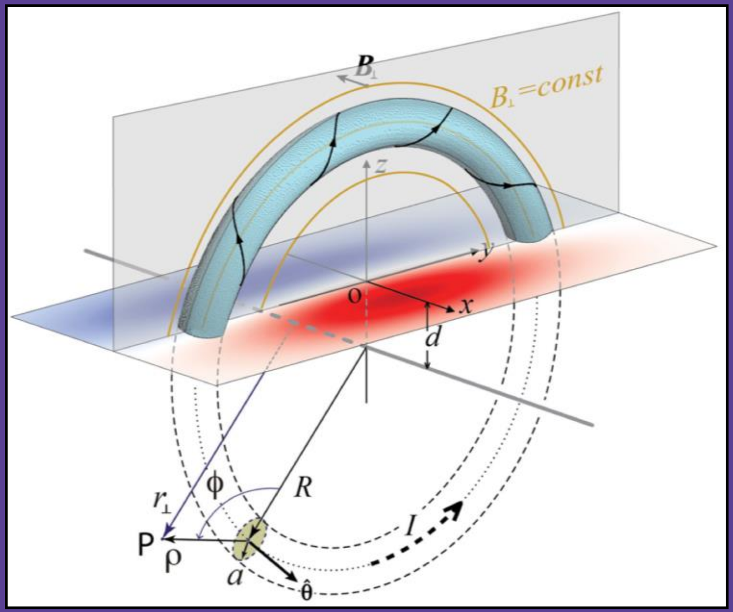


MDI synoptic map + LOS magnetogram

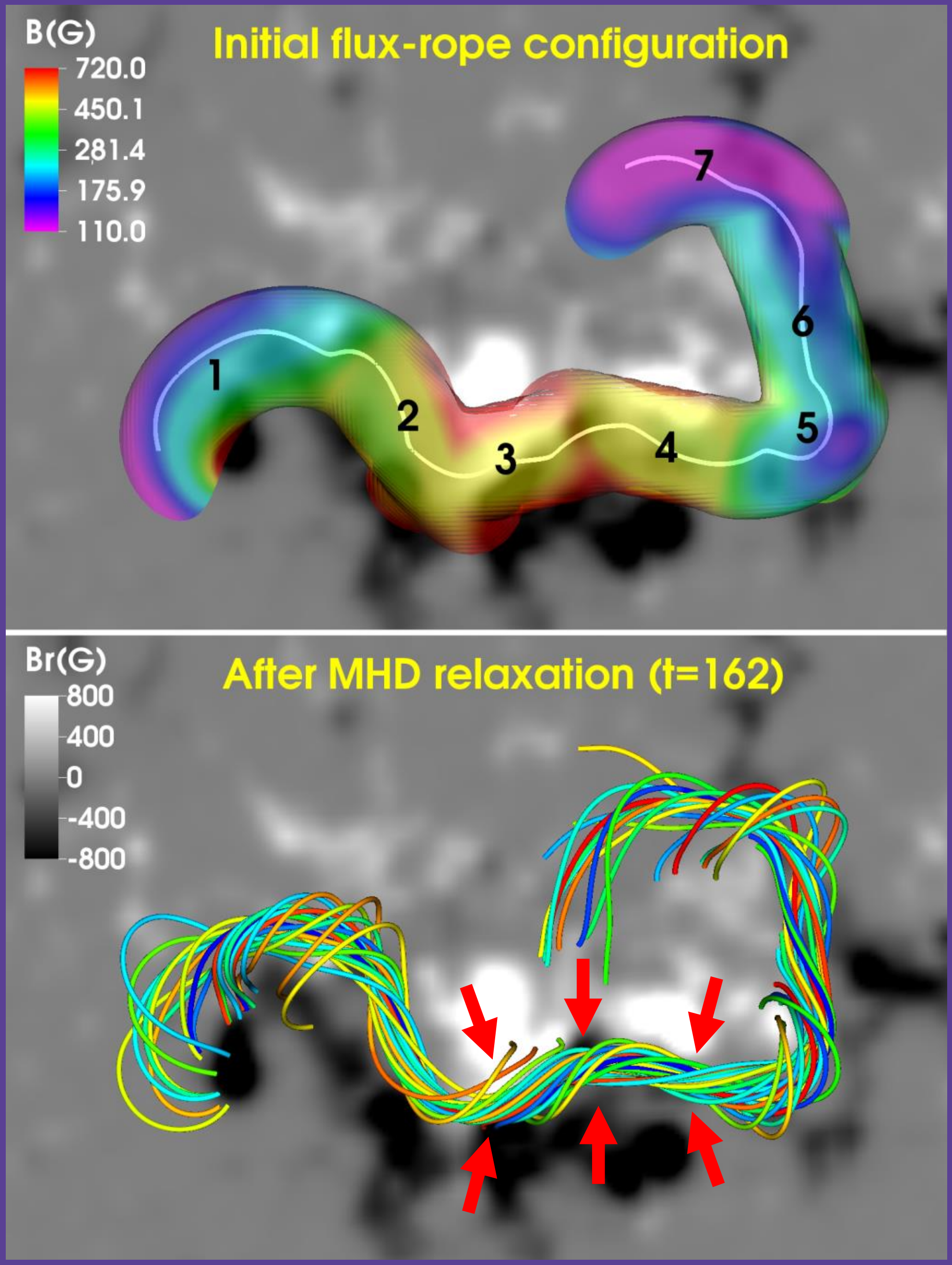


- Prepare magnetogram (boundary condition)
- Calculate global potential field
- Thermodynamic MHD relaxation
  - Steady-state solution of corona & SW

Source-Region Energization & Eruption Initiation



Titov *et al.* (2014)

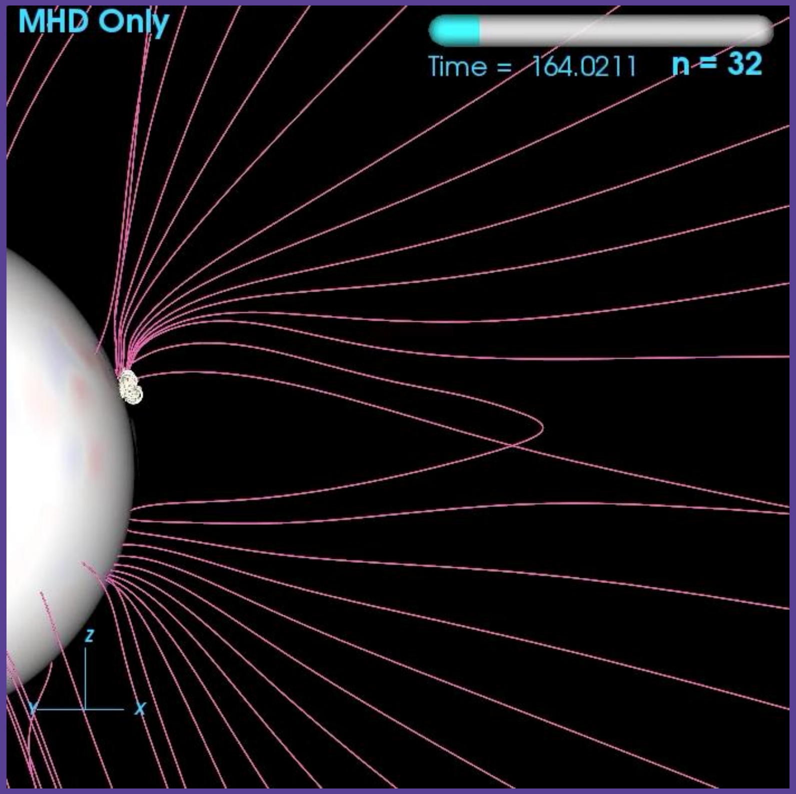


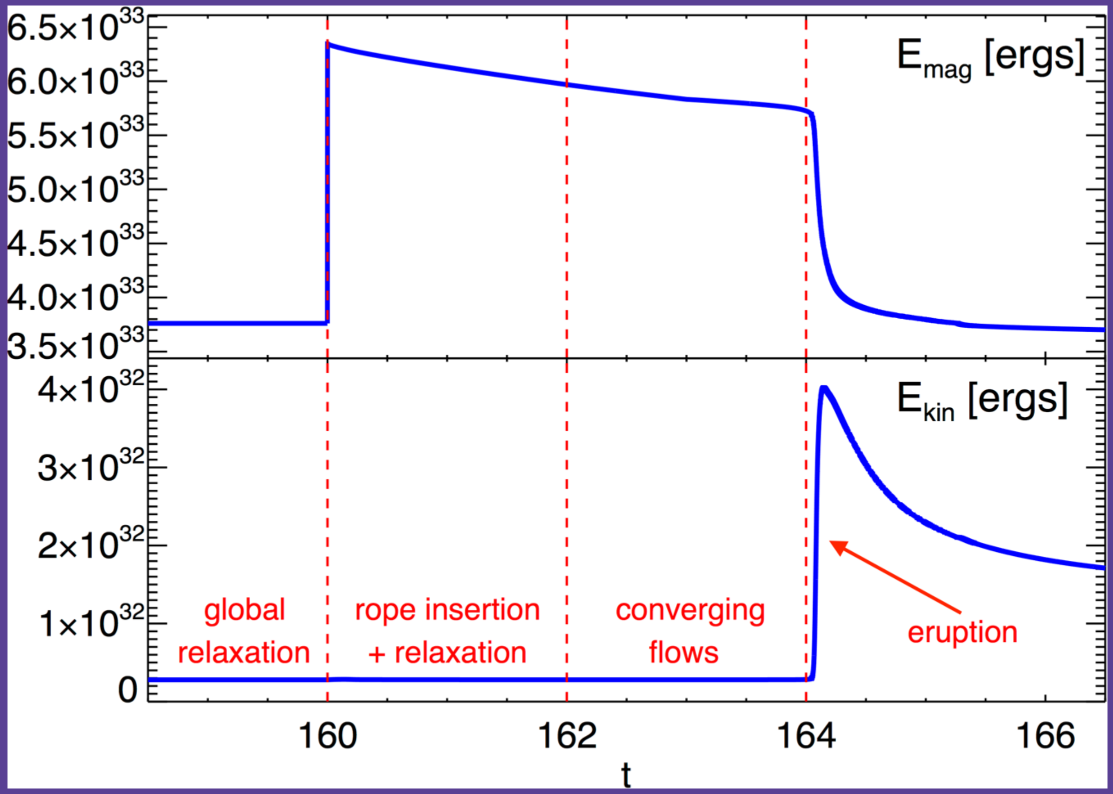
- Modified Titov-Démoulin (TDm) model: can construct a force-free MFR in an arbitrary (locally bipolar) ambient field.

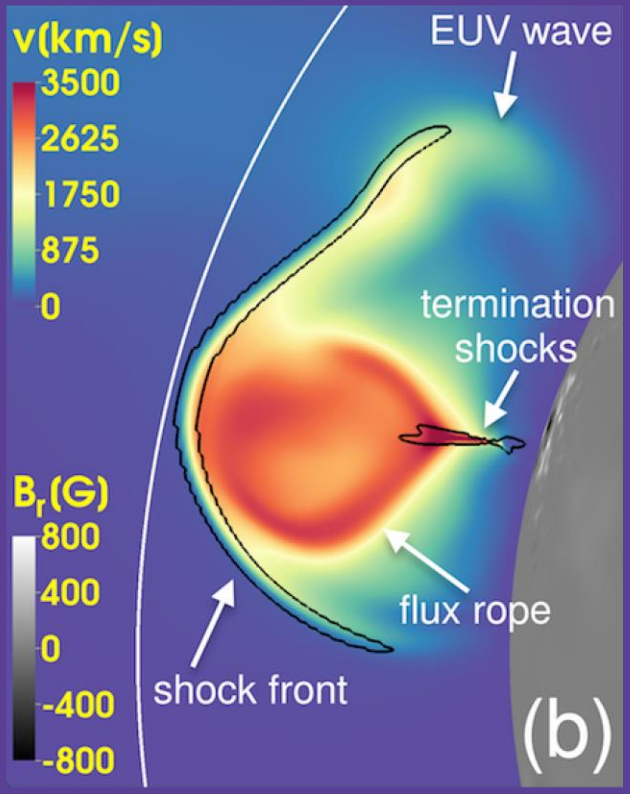
- Use 7 overlapping TDm ropes to build elongated, curved stable MFR inserted into background corona (would now use RBSL model; Titov *et al.*, 2018+21)

- Impose converging flows to trigger eruption (lift MFR to unstable height range)

Eruption







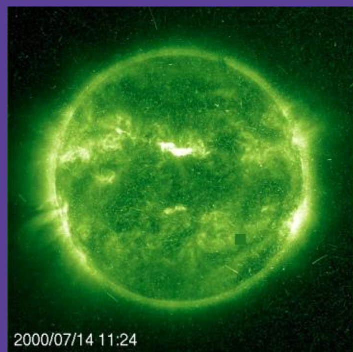
- Energy release: ≈ 1.3 x 10^{33} ergs in about 4 min (very impulsive release possible with stable-equilibrium MFR approach)

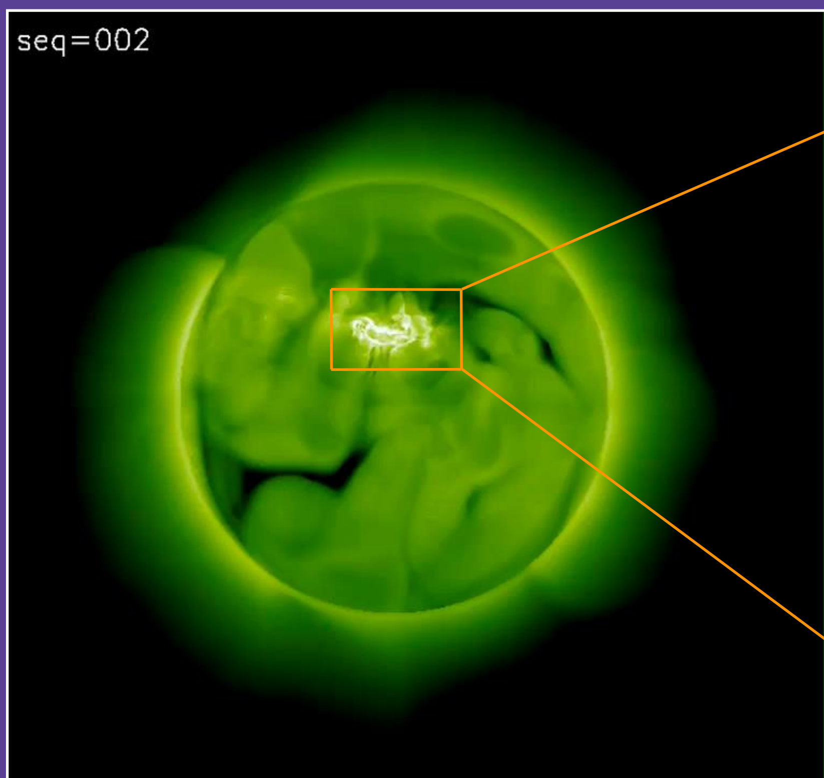
- CME speed ≈ 2,500 km/s in low corona and ≈ 1,500 km/s in outer corona: (real event: ≈ 1,700 km/s)

- Produces many features associated with CMEs: EUV wave, dimmings, shocks,…

(see Török *et al.* 2018 for a detailed description)

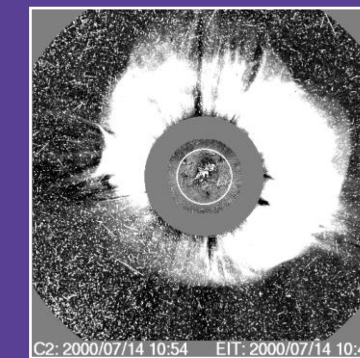
Synthetic Observations

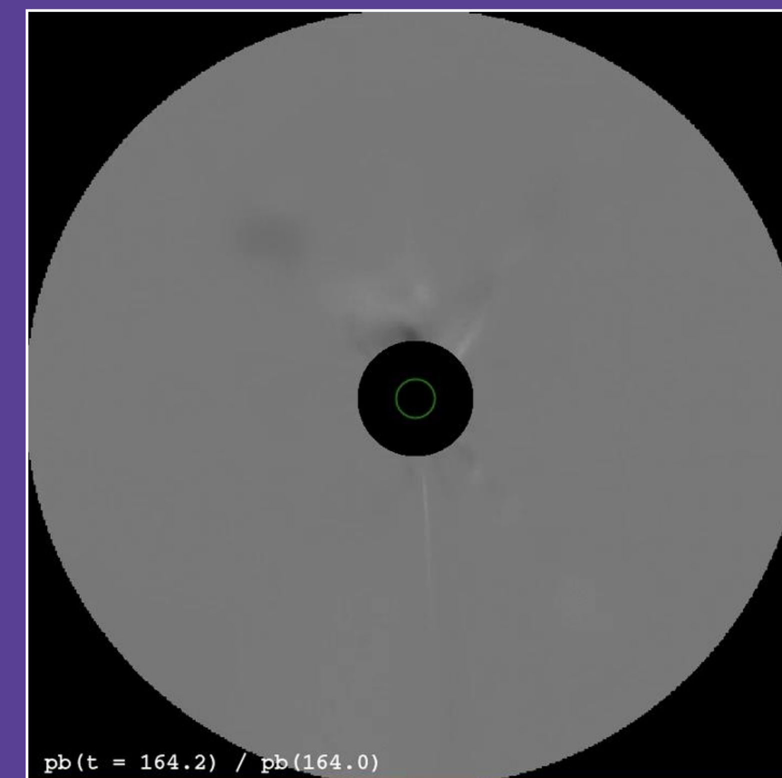




SOHO/EIT 195 Å
(synthetic emission;
full-disk view)

SOHO/EIT 195 Å
(active region)



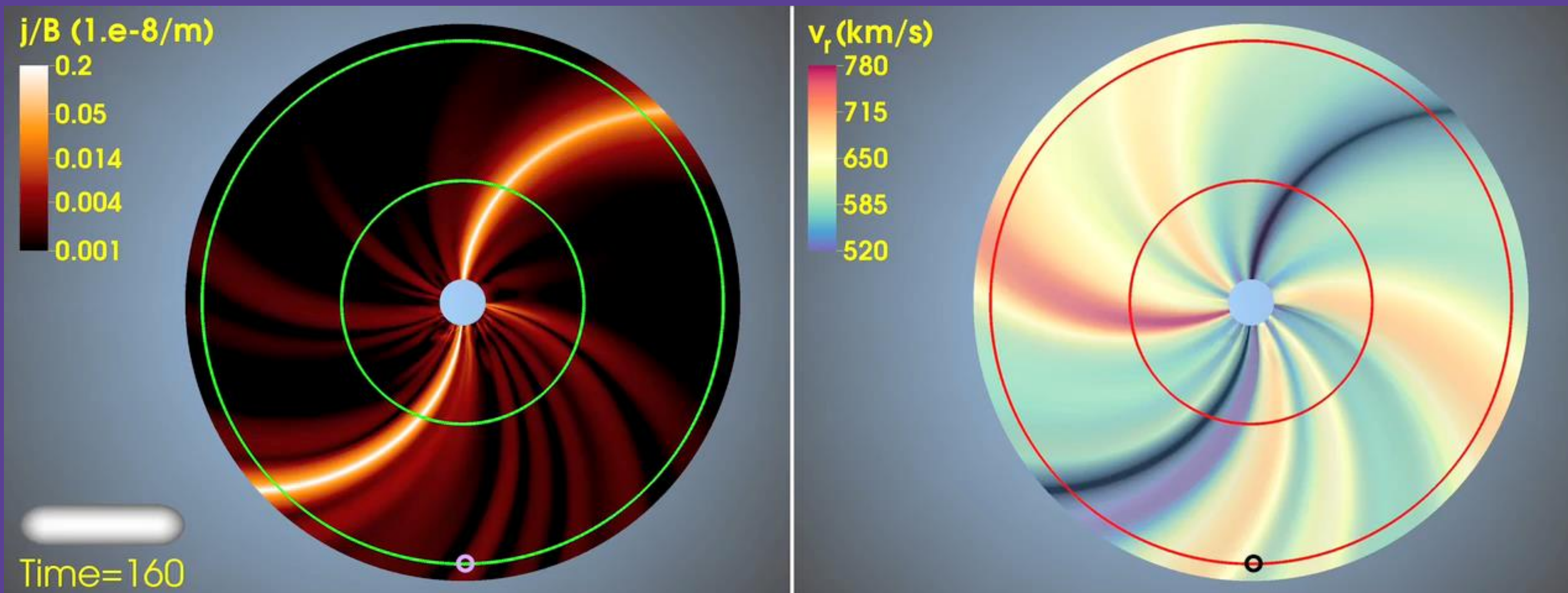


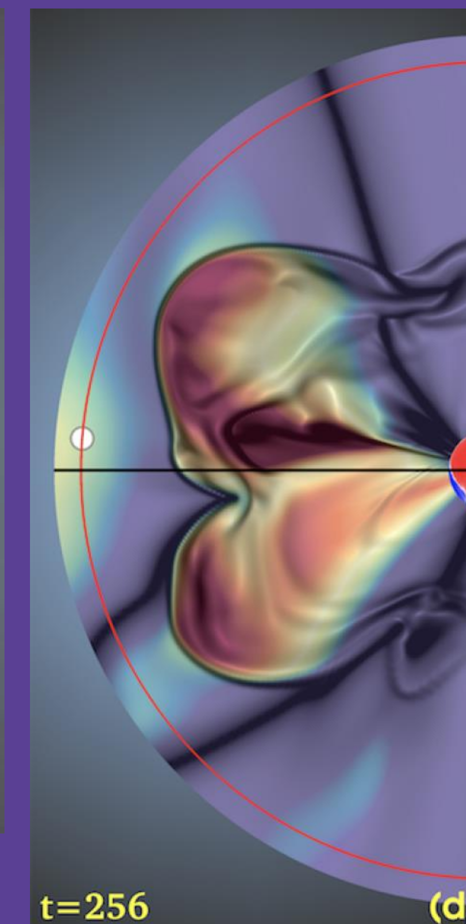
polarization brightness
running ratio
(synthetic emission; 3-
20 solar radii)

∉ synthetic satellite images allow direct comparison with observations

∉ flare arcade and halo-CME morphologies qualitatively reproduced

Heliospheric Simulation of ICME (20-235 R⊙)



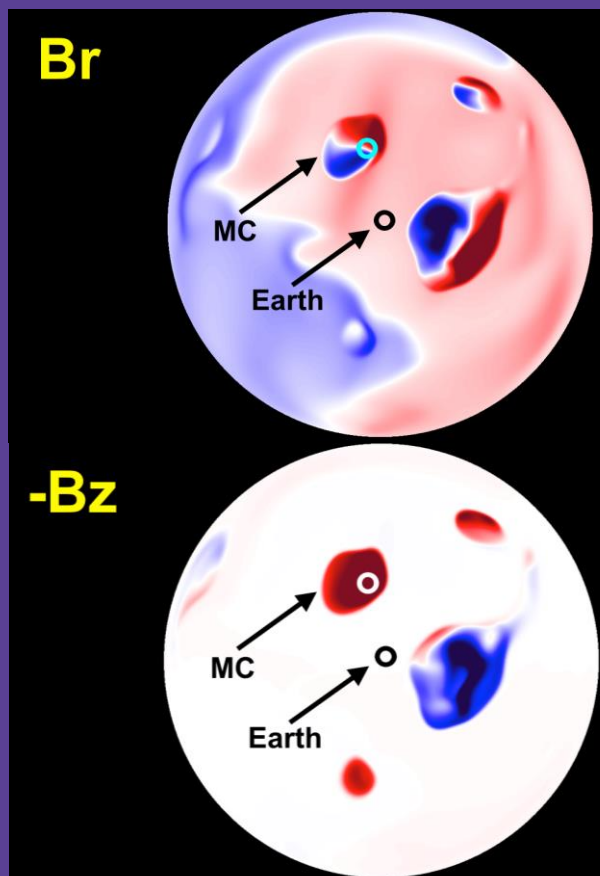


ICME propagation in equatorial plane (inner boundary at 20 Rs)

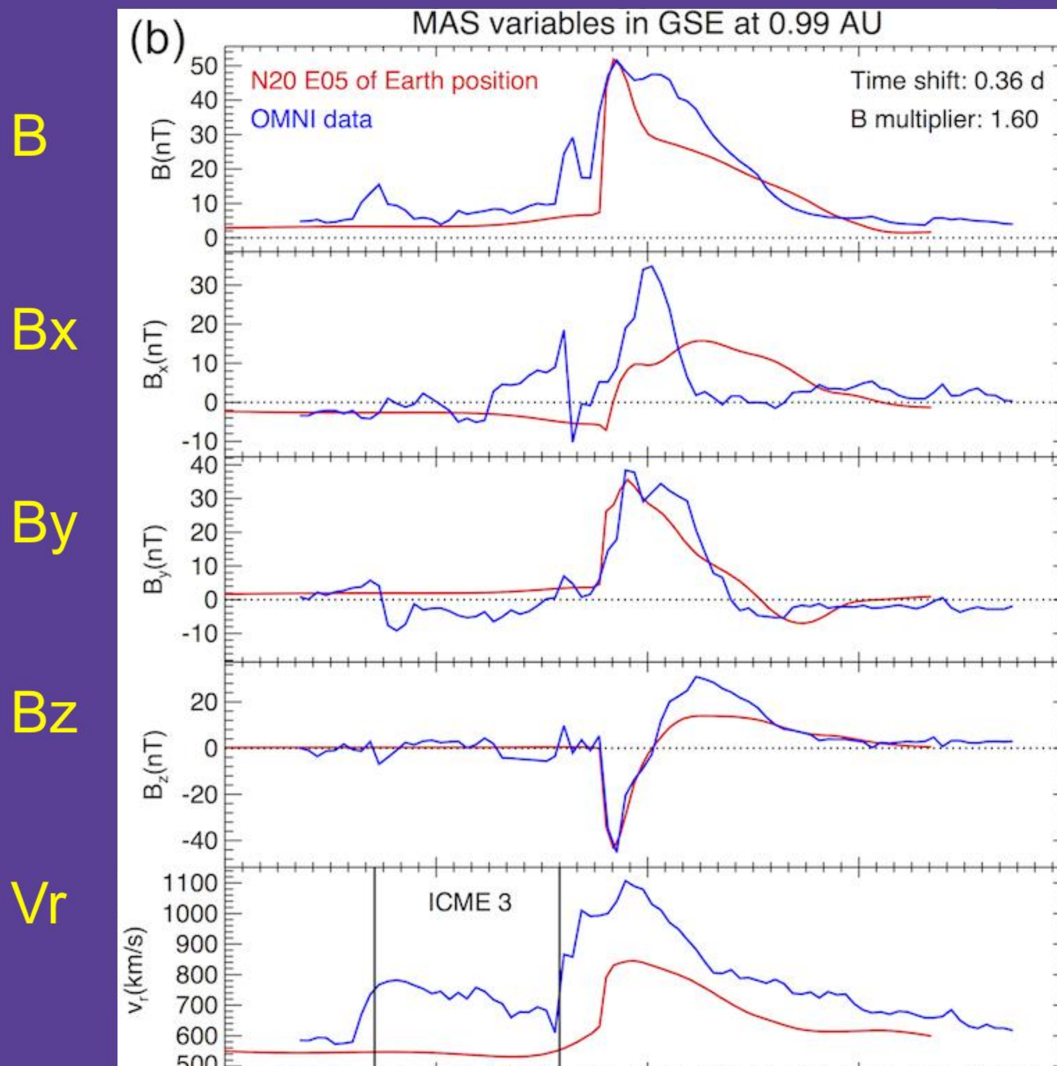
Propagate CME to 1 AU: coupling coronal to heliospheric domain (Lionello *et al*. 2013)

∉ ICME shape distorted by nonuniform solar wind (e.g., Owens 2006)

ICME Pattern at 1 AU & In-Situ Comparison

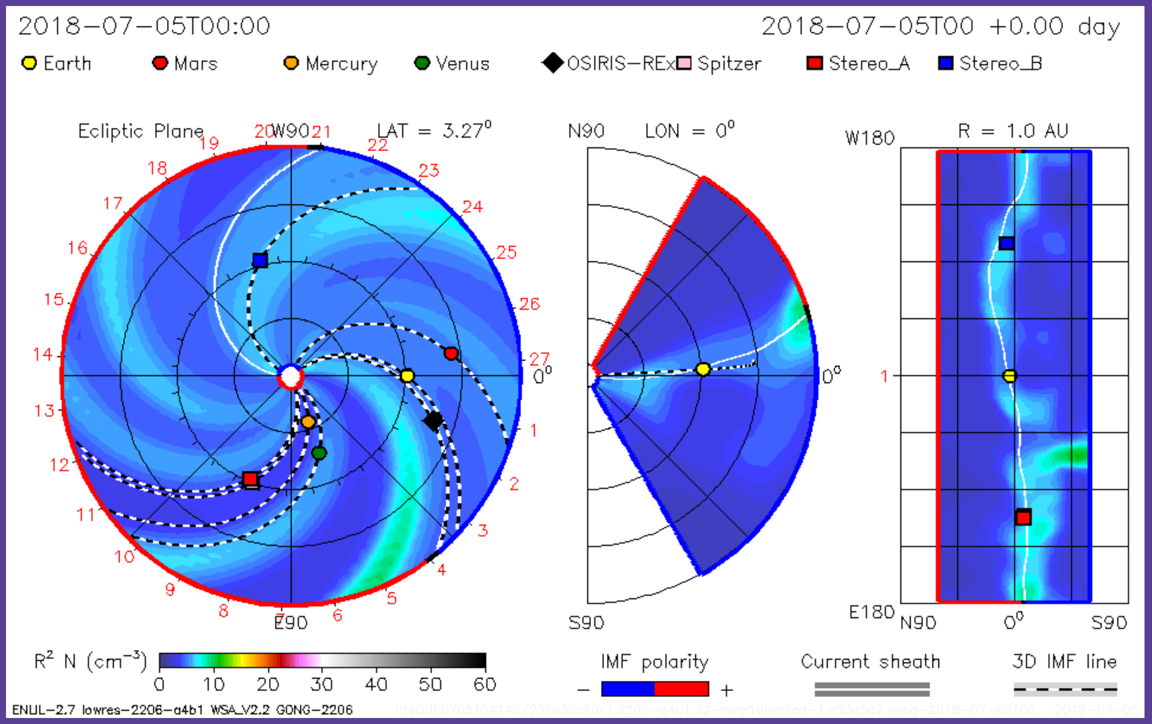


Br, -Bz at 1 AU sphere

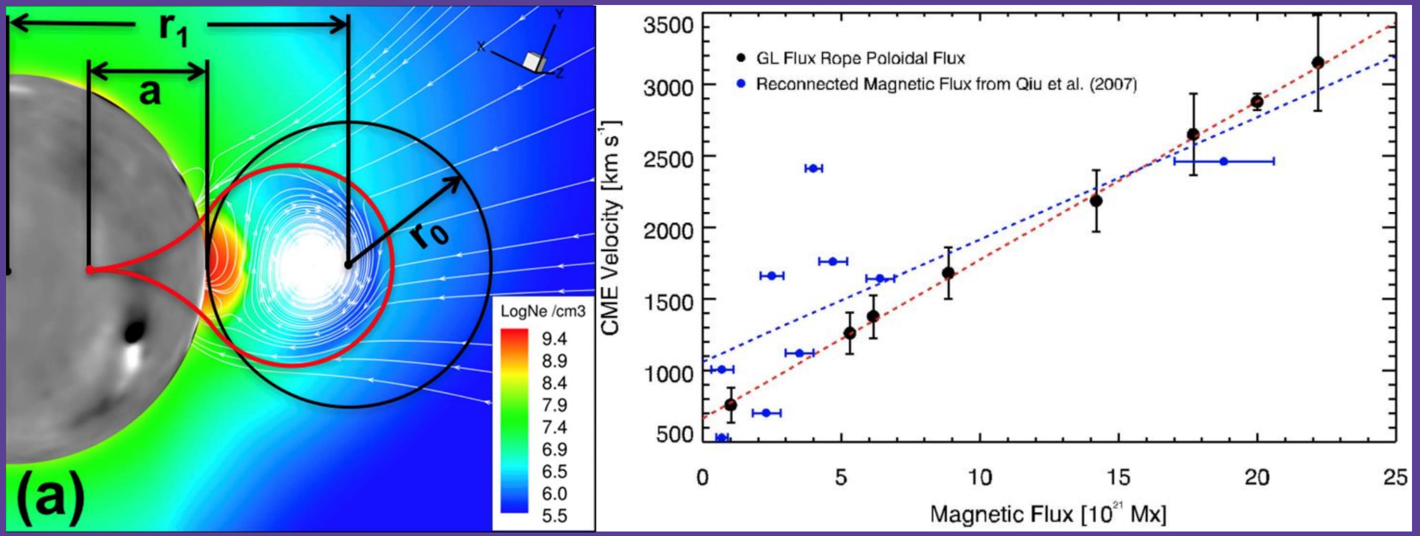


- ICME arrives "scattered" at 1 AU with varying B_z sign (due to distortion by SW)
- simulated MC: correct B_z, but too weak (by 1.6) and about 15° too much to north
- MC too slow by about 250 km/s; delayed by about 8.5 hours
- "correct" information is present in the simulation (encouraging!)

Community CME Modeling Tools



WAS-ENLIL (e.g., Odstrcil 2005)



EEGGL (Jin *et al.* 2017)

- operational (at NOAA)
- ignores coronal evolution
- CME set up as velocity cone (no internal B)
- requires observed CME speed
- cannot predict Bz

- not yet operational (available at CCMC)
- includes coronal evolution
- CME set up as out-of-equilibrium MFR
- requires observed CME speed
- will be able (in principle) to predict Bz

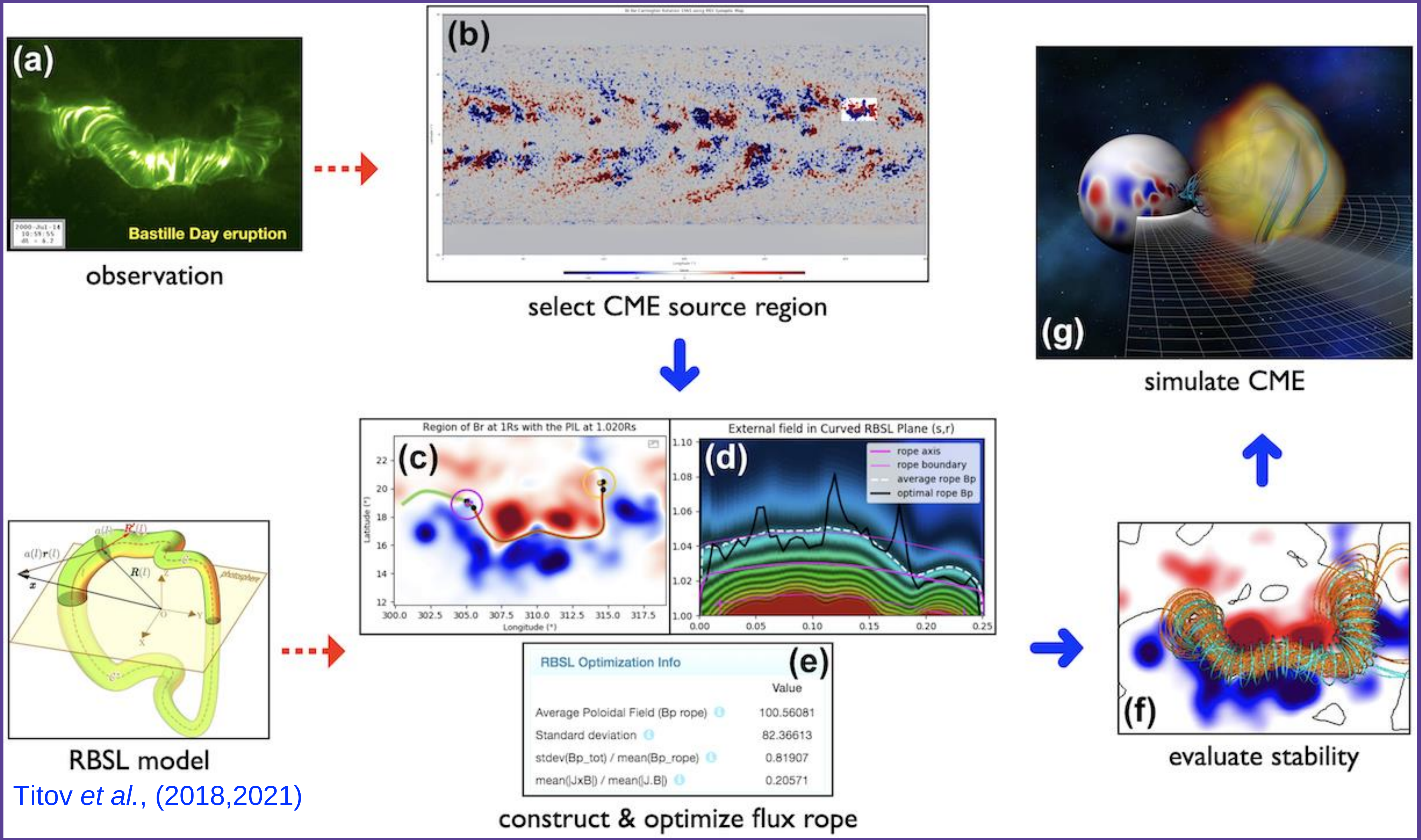
 see also EUHFORIA (https://euhforia.com/) & PSTEP (Kusano *et al.*, 2021)

CORHEL-CME (PSI product; Available at CCMC)

(see Linker *et al.* 2024 for a detailed description)

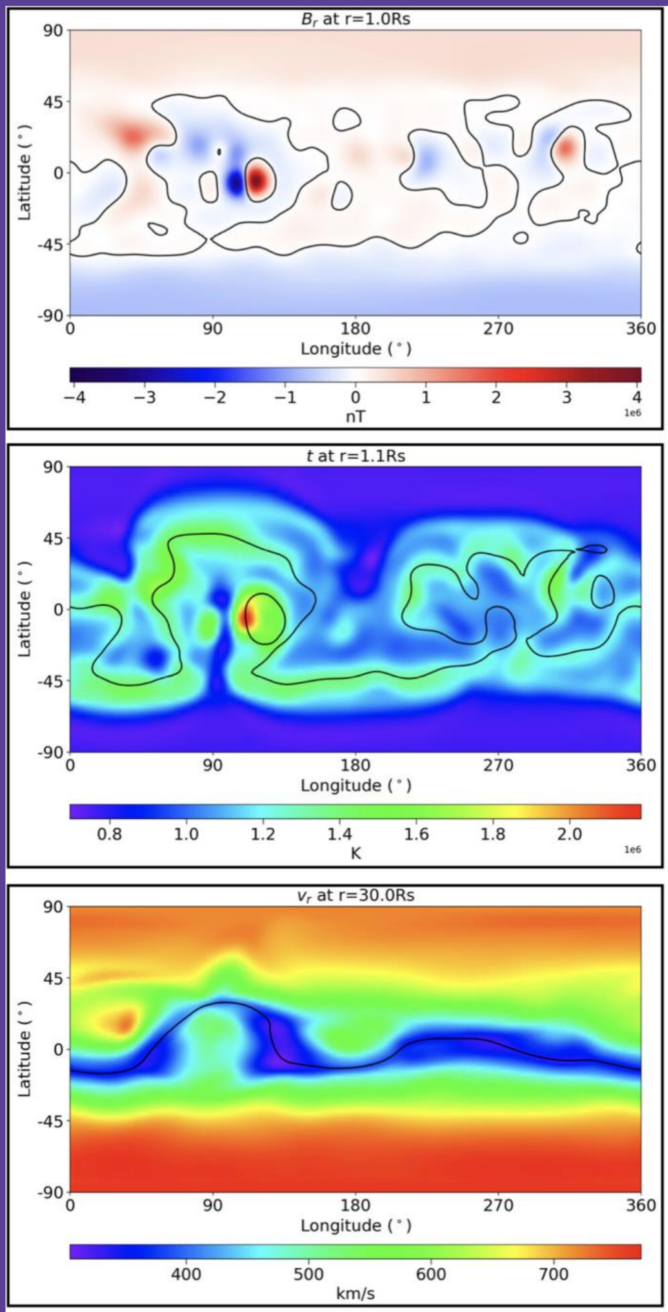
- Allows non-expert users to run Sun-to-Earth simulations of multiple observed CMEs
- Communication via interactive GUI-based web interface (no local installation)
- Highly automated: abstracts away many details of CME modeling from the user
- Capability to produce stable MFRs in complex CME source regions (RBSL model)

CORHEL-CME: Basic Steps

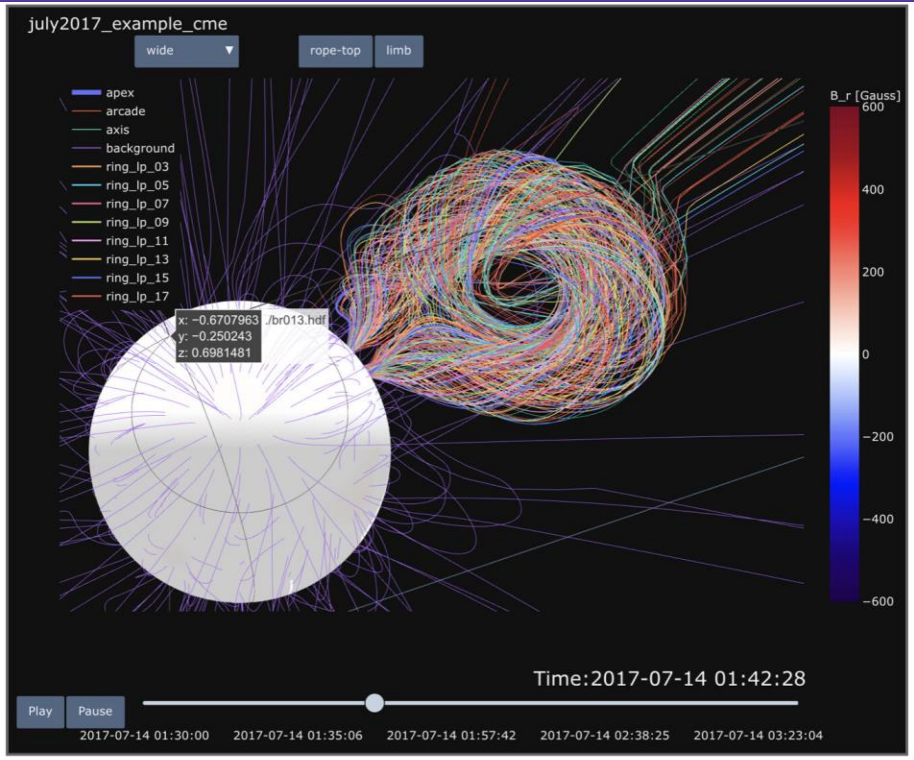


- User prepares simulation parameters with web interface (tar file produced)
- Simulation started with a single CORHEL command (on supercomputer)

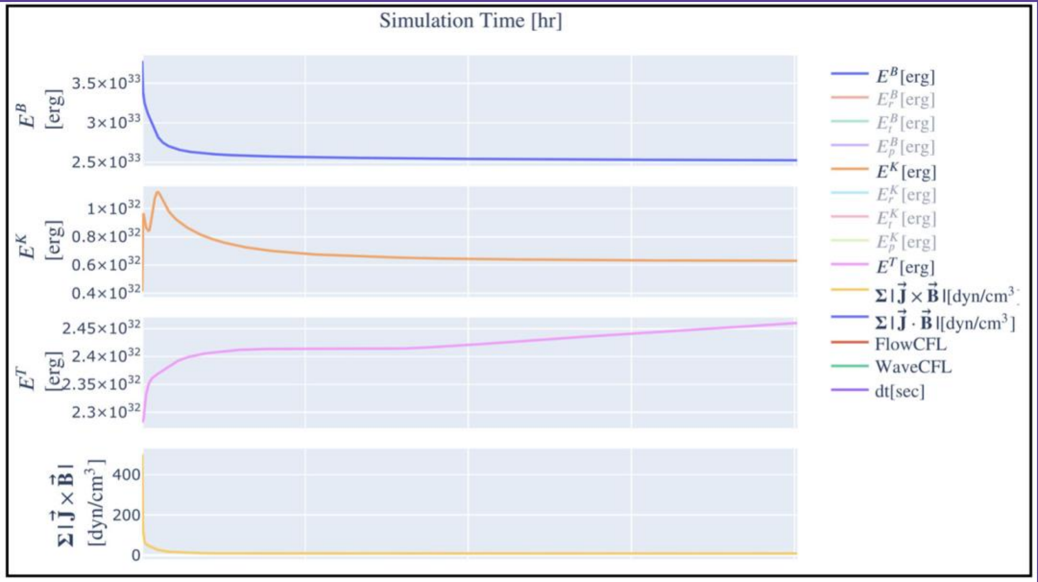
CORHEL-CME: Run Report



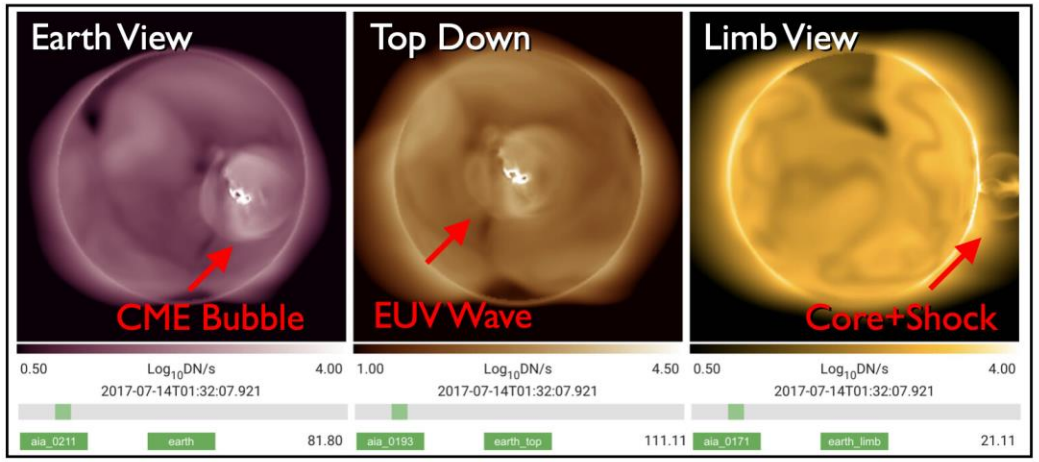
2D slices of physical variables



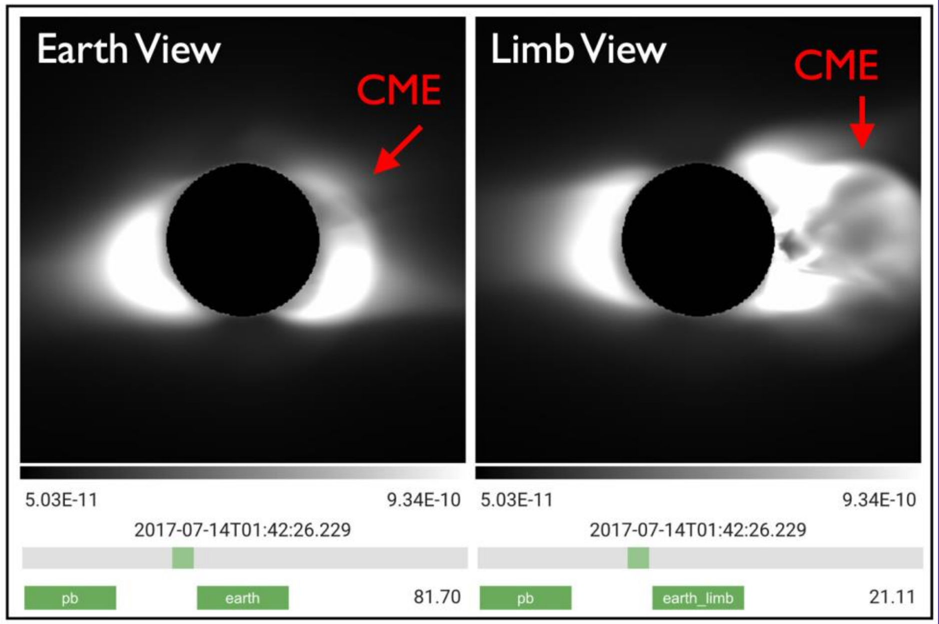
Interactive 3D Field-Line Explorer



Time series of physical/numerical variables



Interactive synthetic EUV emission



Interactive white light emission

- Upon completion of the simulation, user receives a detailed report
- User can perform deeper analysis using the simulation output data

Some Takeaways

- **Pre-eruptive configuration:** "MFR vs. SMA" picture too strict; real configurations likely hybrids; probably slow transition from SMA-like to MFR-like prior to eruptions

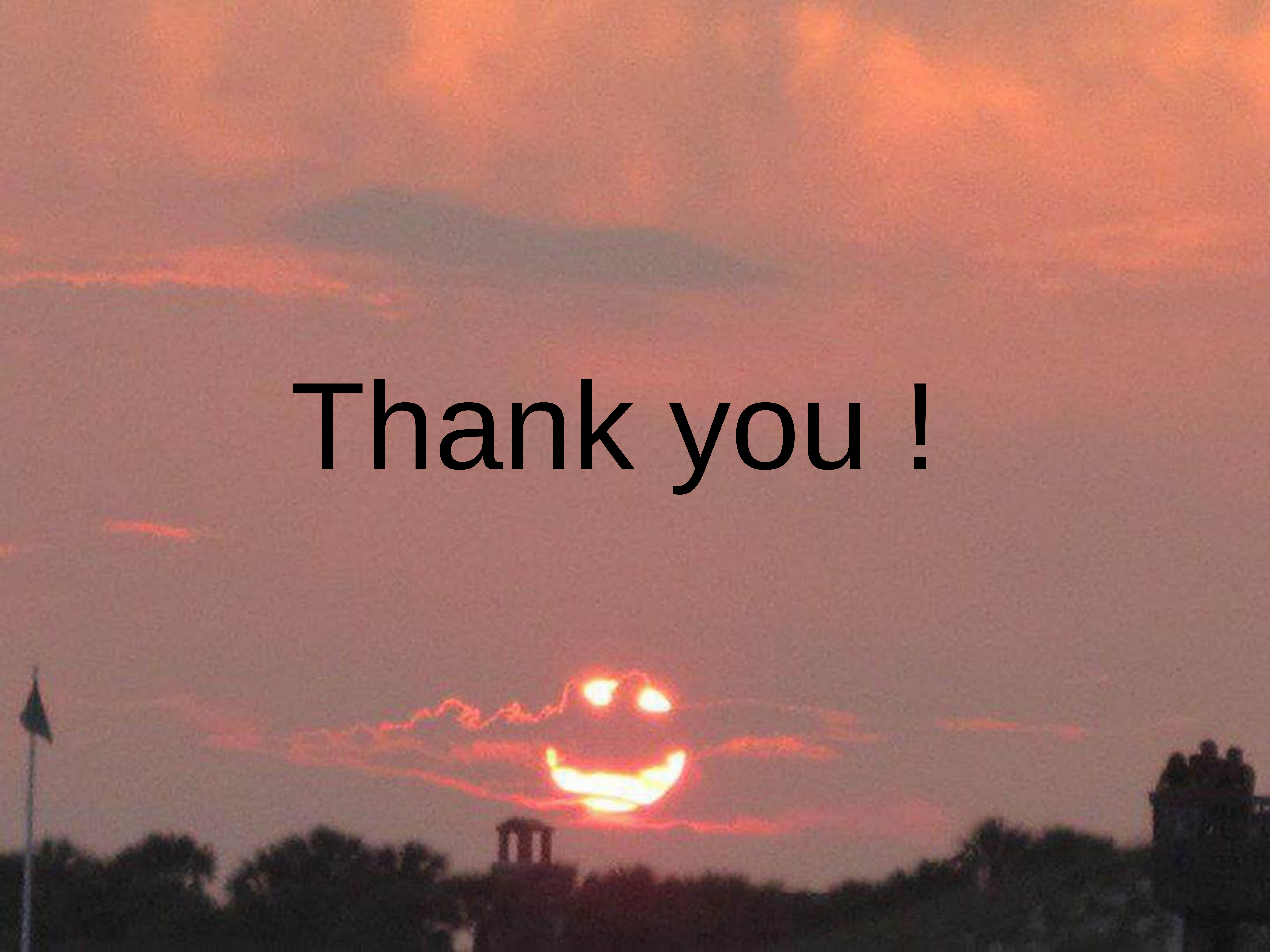
- **CME "triggering":** Many suggested mechanisms; quantitative properties/thresholds that can be checked against observations or real-event simulations are hardly known

- **CME "driving":** Two main mechanisms (TI + flare reconnection); their respective contributions & dependence on magnetic configuration/evolution not known

- **MHD simulations:** valuable substitute for experiments; provide quantities currently not available to observations; allow to study underlying physics & parameter space

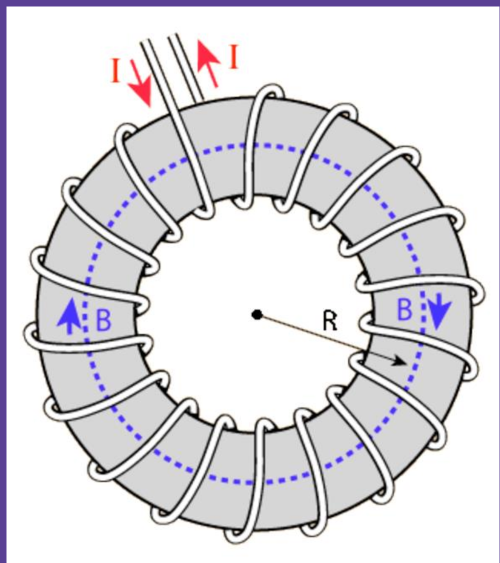
- **Real-event simulations:** significant progress made; scientifically valuable but not yet ready for space-weather forecast; further development needed (e.g. data-driven)

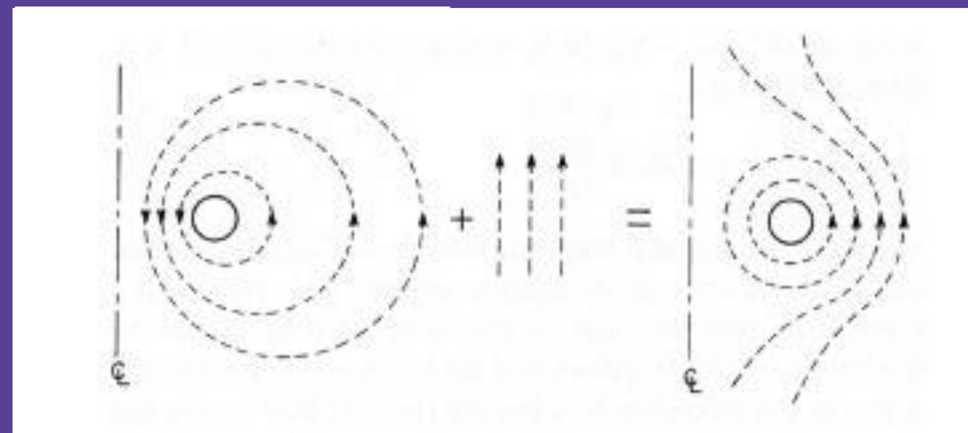
- **Community models:** tools are being developed; allow non-experts to model CMEs; may transition to operational space weather forecast tools in the future

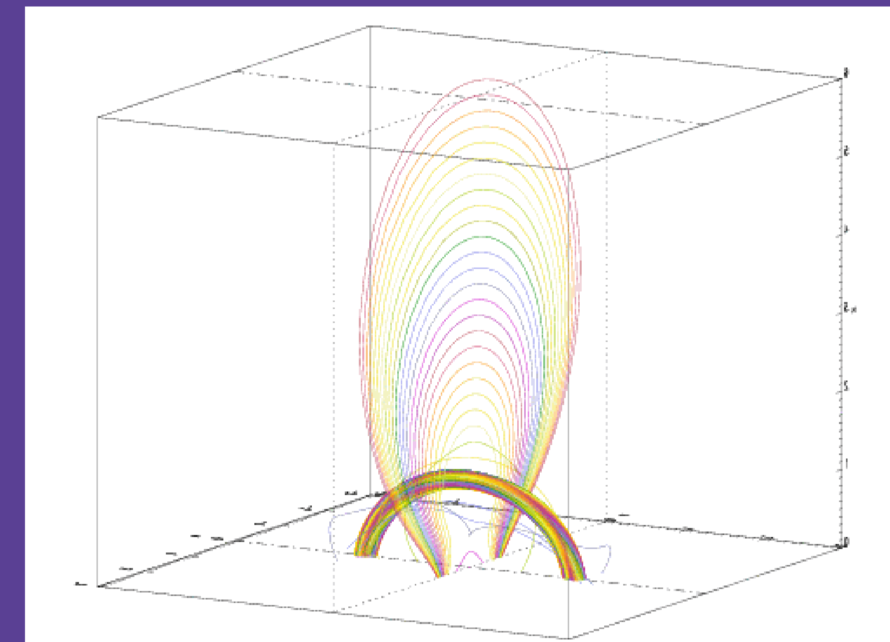

Thank you !

Backup Slides

Torus instability (TI)







Török & Kliem (2007)

- Current ring + external poloidal field:

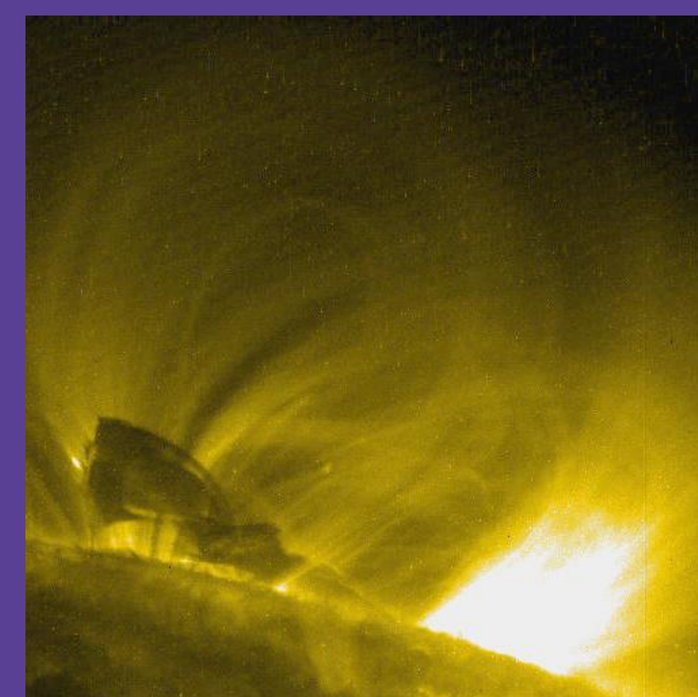
$$f_I = \frac{I^2}{4\pi^2 a^2 R^2}(L + \mu_0 R/2) \longleftrightarrow f_B = -\frac{I\, B_{ex}}{\pi\, a^2}$$

"hoop force" restoring force

- TI occurs if restoring force drops faster than hoop force during expansion of the ring after perturbation in *R*

$$B_{ext}(R) = B_0 R^{-n} \rightarrow n_{crit} \approx 3/2$$

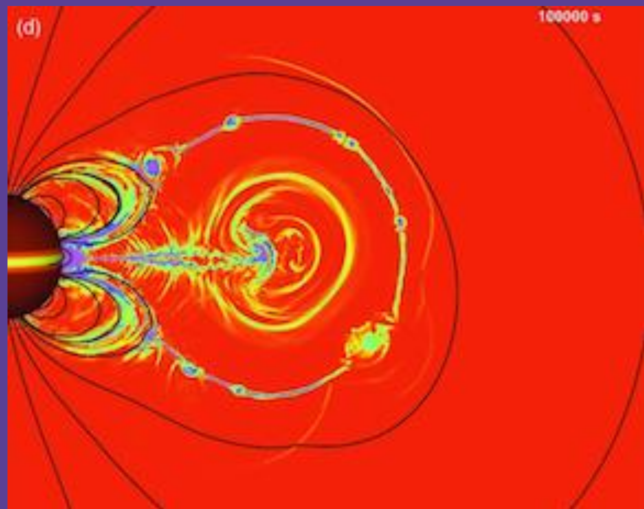
Osovets 59; Bateman 78; Kliem & Török 06; Démoulin & Aulanier 10; Kliem+ 14



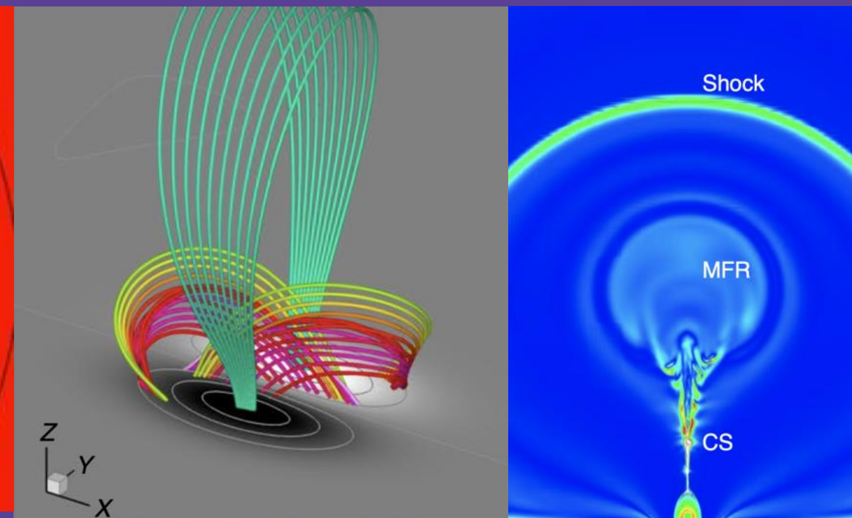
filament eruption on July 27, 2005

- On the sun: slowly rising MFR (filament) has to reach height at which $n > n_{crit}$ (role of trigger mechanism: lift MFR to critical height)

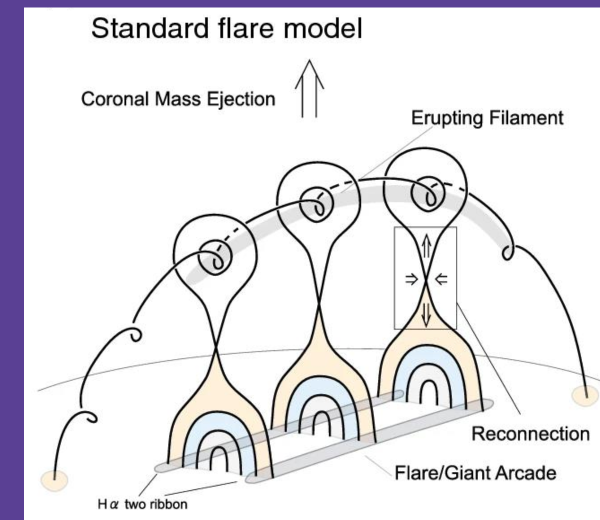
(Flare) Reconnection

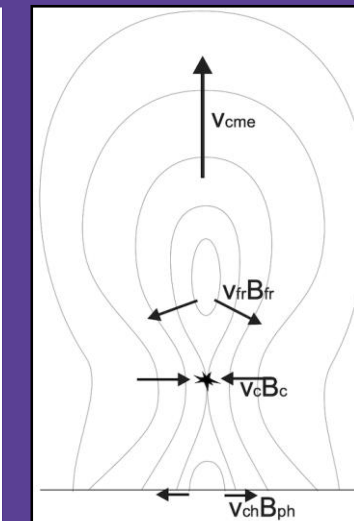


Karpen *et al.* (2012)



Jiang et al. (2021)





Vršnak (2016)

- Occurs in relatively small area within current sheet, so cannot drive eruption *directly*

- However, field reconfigurations due to reconnection have several (ideal) effects:
  - → reduce tension off overlying field above rising MFR
  - → add poloidal flux to the MFR, increasing hoop force
  - → reconnection jet may push MFR upward (at least initially)

Feedback: MFR rise enhances reco & reco sustains hoop force (e.g. Vršnak & Skender 05)

- Core field has to be lifted for current sheet to form (no distinguishing criterium to TI)

(4) Numerical (MHD) Simulations

$$
\begin{aligned}
\mathbf{J} &= \frac{1}{\mu}\nabla \times \mathbf{B} \\
\mathbf{E} &= \mathbf{J}/\sigma - \mathbf{v} \times \mathbf{B} \\
p_{tot} &= p + \frac{\mathbf{B}^2}{2\mu} \\
e &= \frac{p}{\gamma - 1} + \frac{\rho v^2}{2} + \frac{\mathbf{B}^2}{2\mu}
\end{aligned}
$$

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) &= 0 \\
\frac{\partial \rho\mathbf{v}}{\partial t} + \nabla\cdot(\mathbf{v}\rho\mathbf{v} - \mathbf{B}\mathbf{B}) + \nabla p_{tot} &= 0 \\
\frac{\partial e}{\partial t} + \nabla\cdot(\mathbf{v}e + \mathbf{v}p_{tot} - \mathbf{B}\mathbf{B}\cdot\mathbf{v} - \mathbf{B}\times\eta\mathbf{J}) &= 0 \\
\frac{\partial \mathbf{B}}{\partial t} + \nabla\cdot(\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) + \nabla\times(\eta\mathbf{J}) &= 0
\end{aligned}
$$

∉ Cannot do experiments in astronomy □ use numerical simulations as a substitute

∉ Physics (solar applications) often well described by magnetohydrodynamics (MHD):

– hydrodynamics + magnetic field (particles described as single fluid)

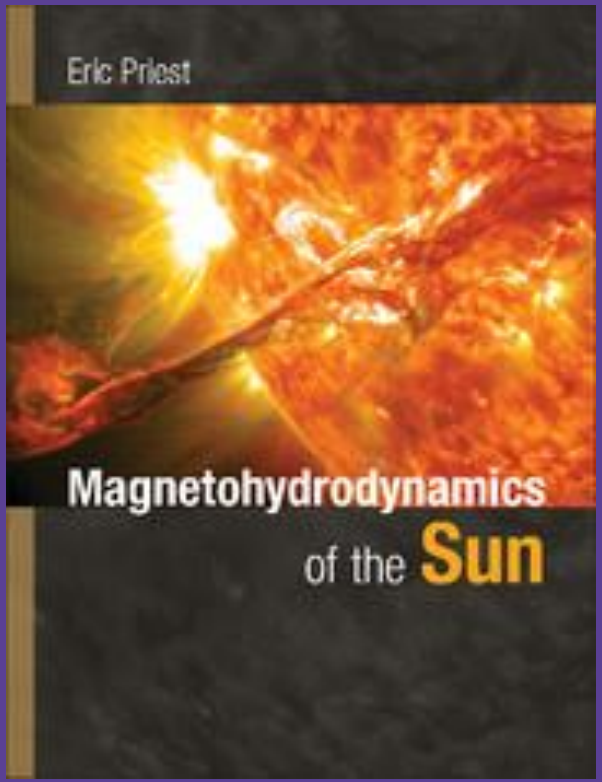
– main assumption: macroscopic plasma velocity $v \ll c$

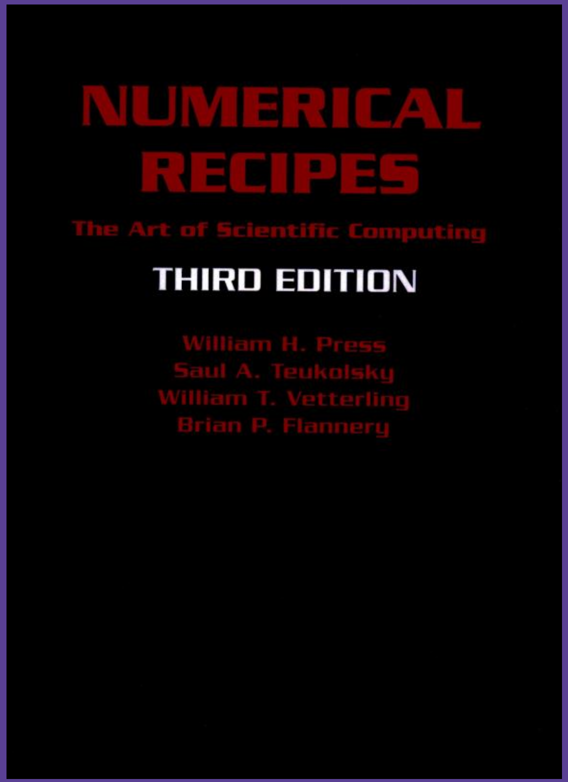
∉ Full MHD equations difficult to solve → typically only reduced set used

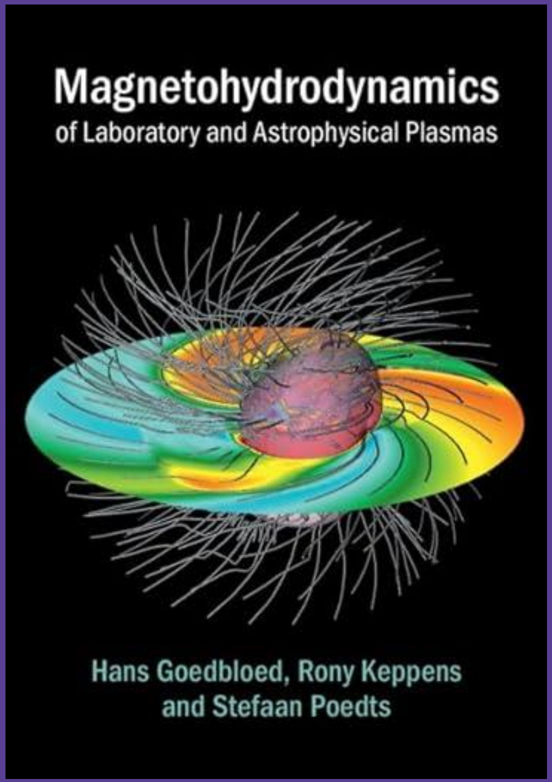
∉ For simulations: conservative form of MHD equations more convenient

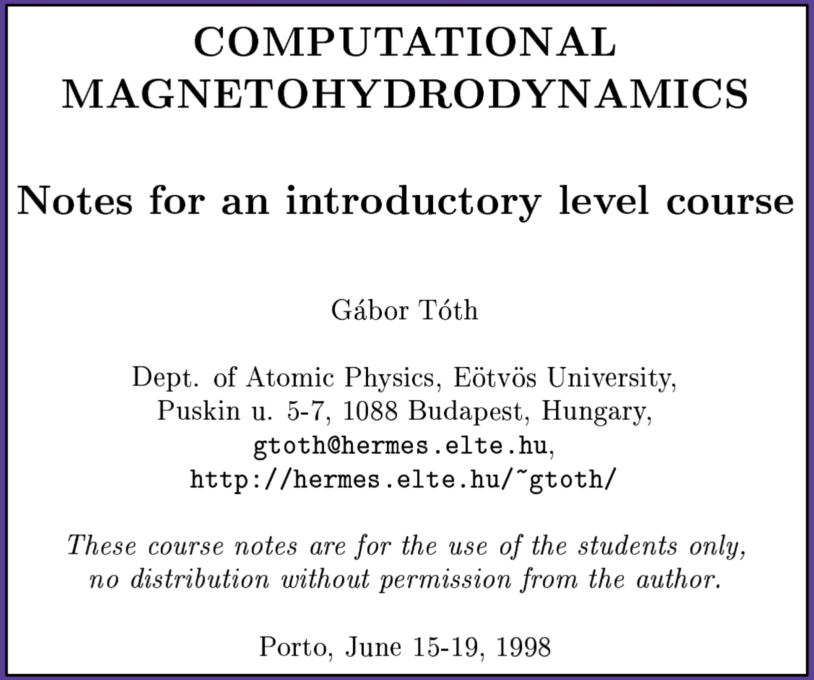
∉ Equations discretized & evolved by some numerical scheme (e.g., Lax-Wendroff)

A Few Useful Sources/Links









COMPUTATIONAL MAGNETOHYDRODYNAMICS

Notes for an introductory level course

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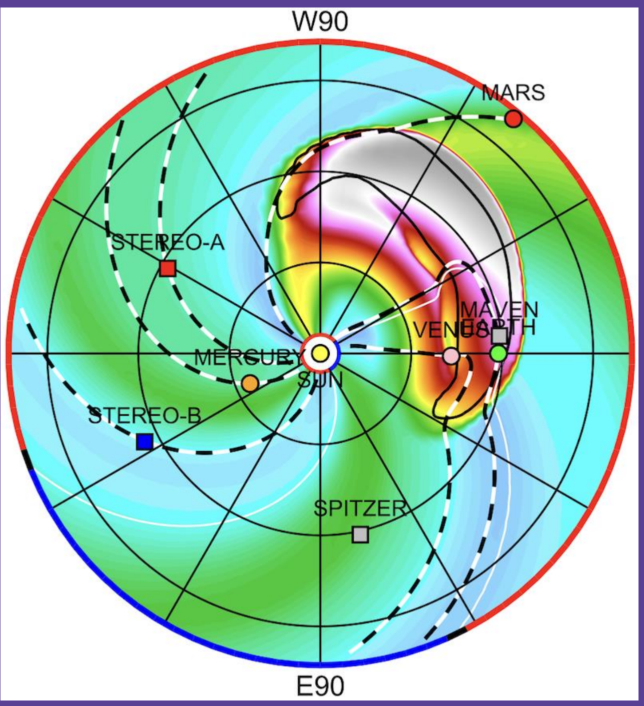
These course notes are for the use of the students only, no distribution without permission from the author.

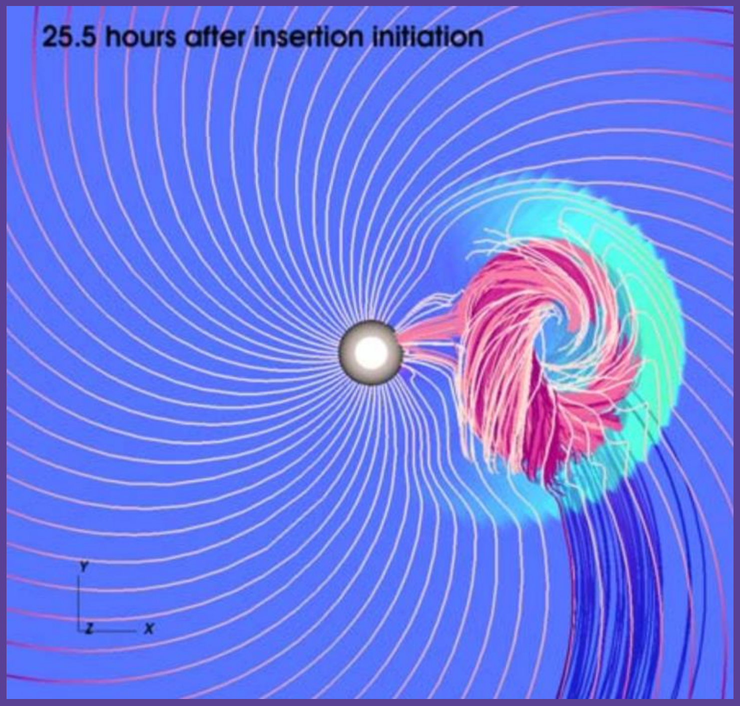
Porto, June 15-19, 1998

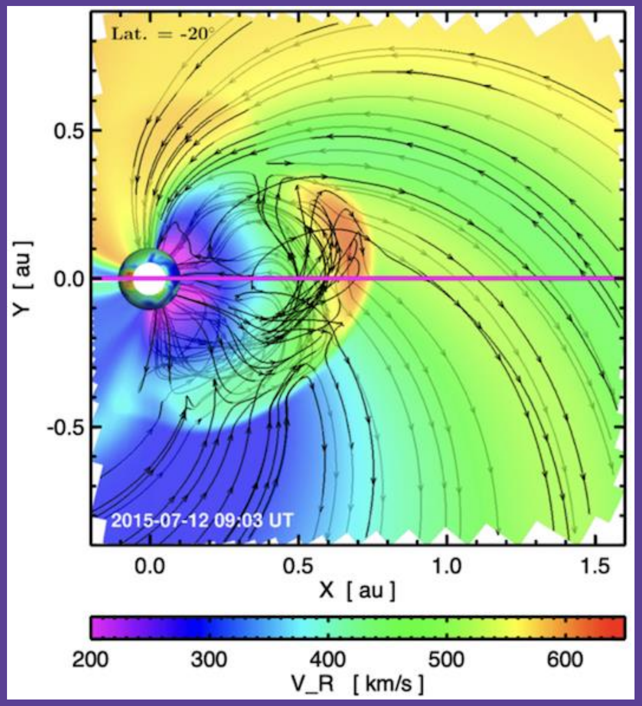
- Priest: leading textbook on solar MHD (theory + state-of-the-art research till 2014)
- Numerical Recipes: standard textbook on scientific computing (https://numerical.recipes/)
- Goedbloed *et al.*: includes a chapter on computational MHD
- Tóth: lecture on computational MHD (https://websites.umich.edu/~gtoth/Teach/porto_course.pdf)

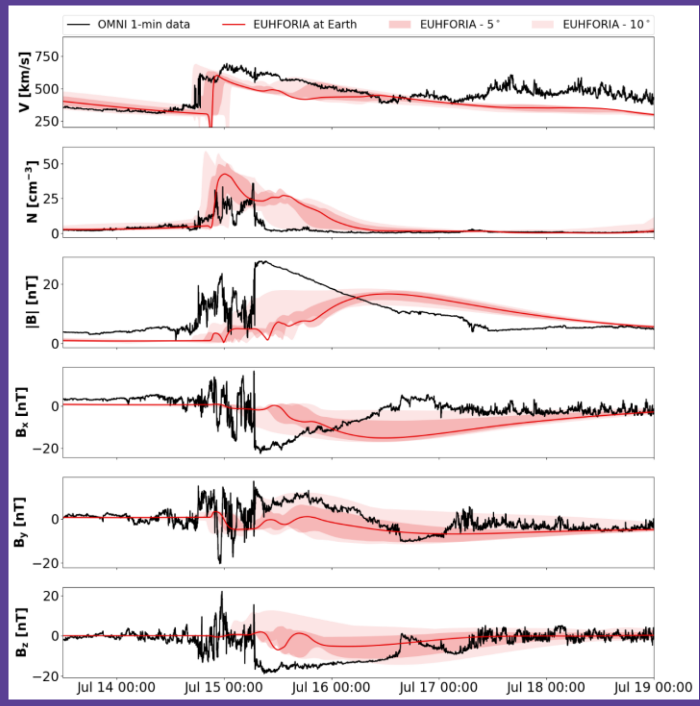
… and there are many more…

Idealized Simulations: ICME Propagation









Mays *et al.* (2015) velocity pulse

Asvestari *et al.* (2022) spheromak

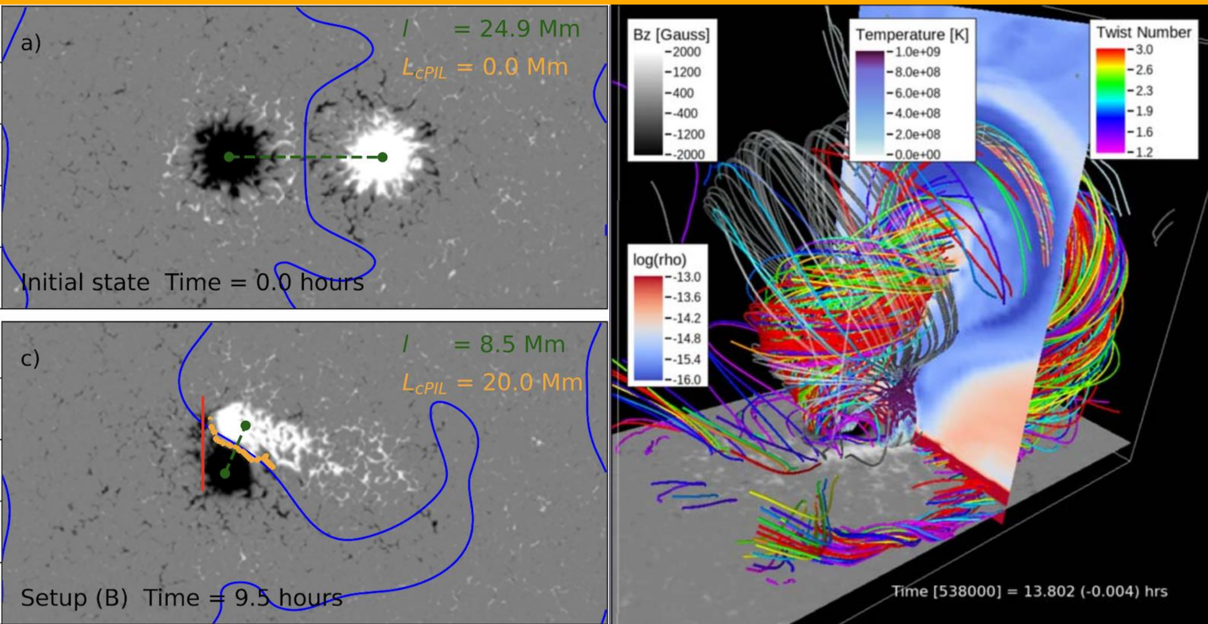
Palmerio *et al.* (2023) MFR

Scolini *et al.* (2019) 1 AU comparison

- Models of (I)CME propagation typically ignore initiation and early evolution
- Inner simulation boundary often at ~ 0.1 astronomical unit
- Initial condition: background interplanetary field + solar wind
- CME "initiation": velocity pulse (no CME field) or inserted spheromak/MFR
- Spheromak/MFR parameters constrained by CME observations (e.g. speed, width)

  □ allows comparison with in-situ satellite data

(5) Real-Event Simulations

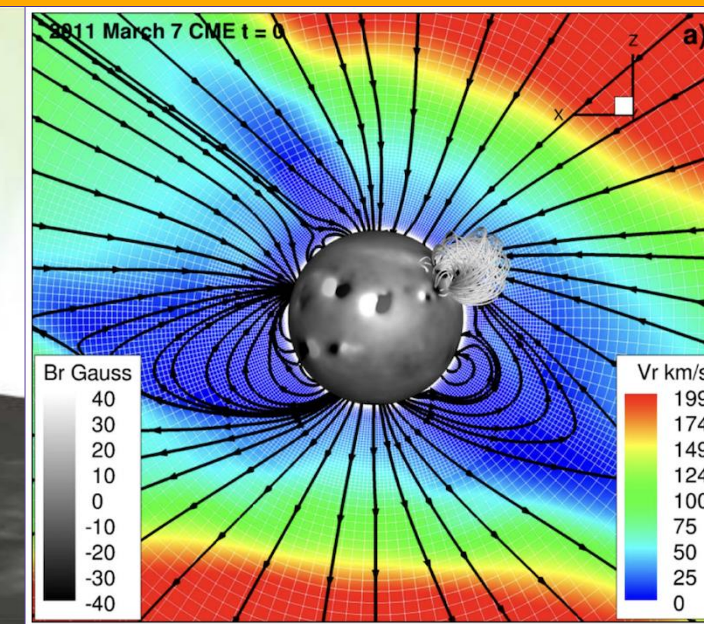


Rempel *et al.* (2023)

idealized/realistic hybrid (cartesian domain)

Guo *et al.* (2024)

data-driven (MHD; cartesian)



Jin *et al.* (2017)

global (thermodyn. MHD)

Several approaches have been pursued, e.g.:

- "Hybrid": no observed data but very sophisticated physics (thermodynamics, convection, radiative transfer); so far restricted to (very) low corona

- "Data-driven": observed photospheric fields and flows to drive configuration; often magnetofriction, recently also MHD; so far restricted to low/middle corona

- "Global": include full corona + inner heliosphere; observed B_r as boundary condition; "thermodynamic MHD"; can propagate CMEs to 1 AU or beyond

Global & "thermodynamic" simulations

MHD Equations
(Improved Energy Equation Model)

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\,\mathbf{J}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

$$\mathbf{E} + \frac{1}{c}\,\mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) = \frac{1}{c}\,\mathbf{J} \times \mathbf{B} - \nabla p - \nabla p_w + \rho \mathbf{g} + \nabla \cdot (\nu \rho \nabla \mathbf{v})$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (p \mathbf{v}) = (\gamma - 1)\left(-p \nabla \cdot \mathbf{v} - \nabla \cdot \mathbf{q} - n_e n_p Q(T) + H\right)$$

$$\gamma = 5/3$$

Mok et al. (2008, 2011)

- Idealized models inexpensive and well suited to study & test basic physical mechanisms

- State-of-the-art models aim for more realism by using:
    - large spherical domains to model extended corona & solar wind
    - observed photospheric magnetic fields as boundary condition
    - empirical coronal heating, thermal conduction, radiation losses

Summary

- Idealized MHD simulations improve our understanding of physical mechanisms at work in solar eruptions → e.g initiation & driving of eruptions and coupling between eruptions

- Global models using real data & improved coronal plasma descriptions now available → deeper insight & semi-realistic modeling of observed eruptions

- Coupling of coronal & heliospheric models will allow us soon to simulate observed events from Sun to Earth → important for understanding and predicting space weather

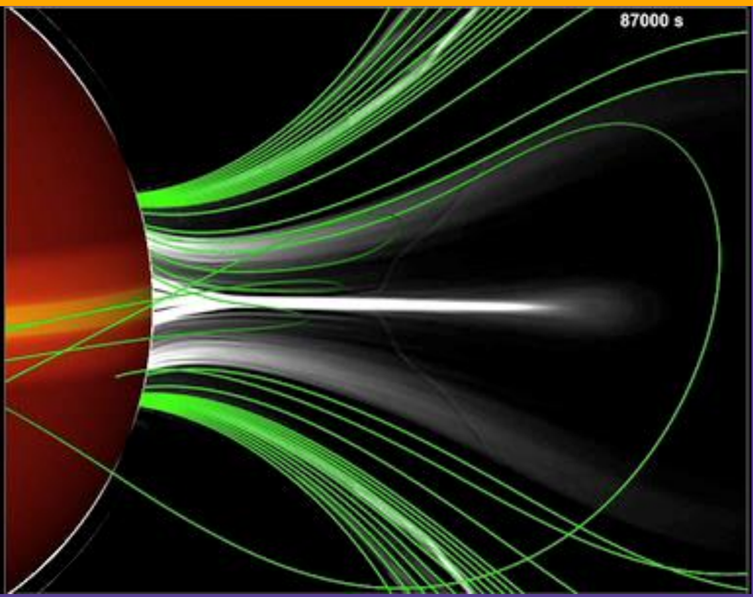
- Still, it will be many years before we have models that:

  – resolve the enormous range of length scales present in solar eruptions

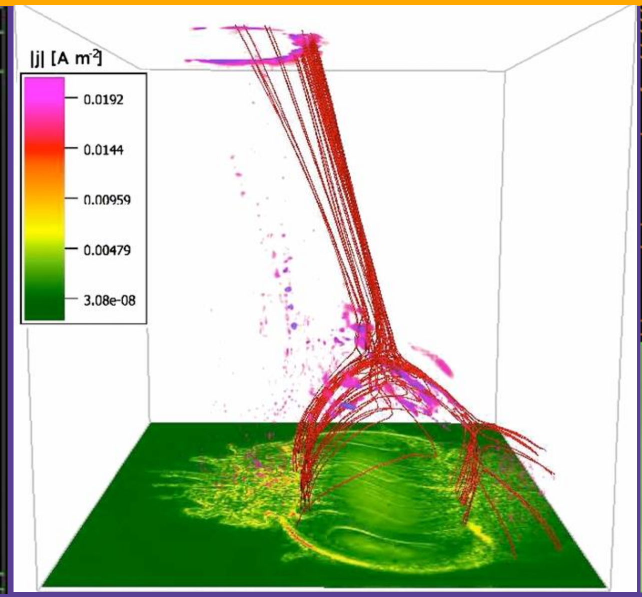
  – solve the complete set of plasma equations

  – use boundary & initial conditions that match reality

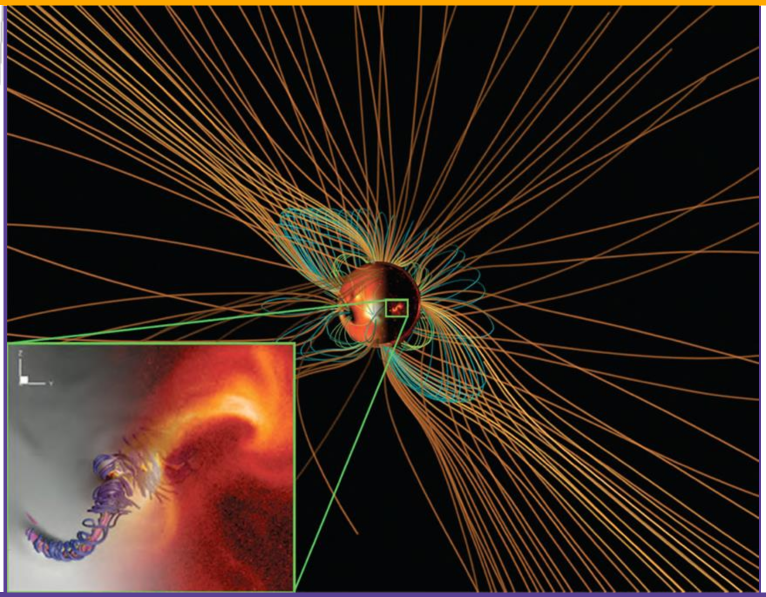
Outlook (Some Next Steps for MHD Modeling)



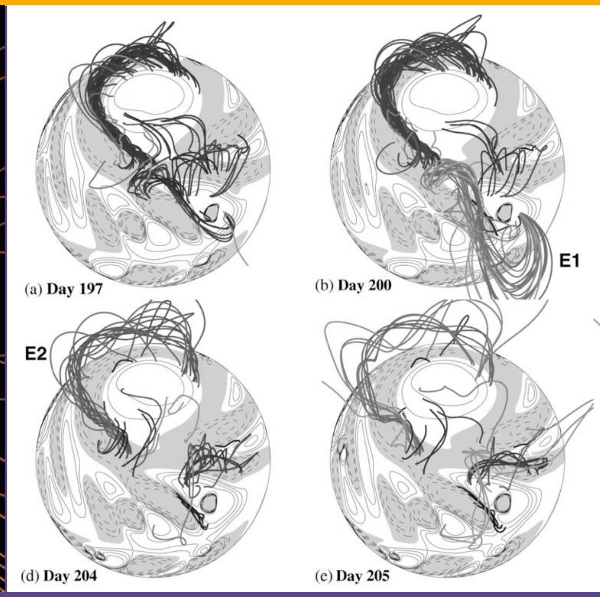
Karpen et al. (2012)



Baumann & Nordlund (2012)



Roussev et al. (2012)



Yeates & Mackay (2009)

- adaptive mesh refinement → improve modeling of reconnection (flare)
- couple MHD and PIC (kinetic) codes → modeling of particle acceleration
- couple flux emergence & CME models → more realistic pre-eruption configurations
- develop evolutionary MHD models → overcome present static modeling of corona