Numerical simulations of dynamic phenomena in the solar corona

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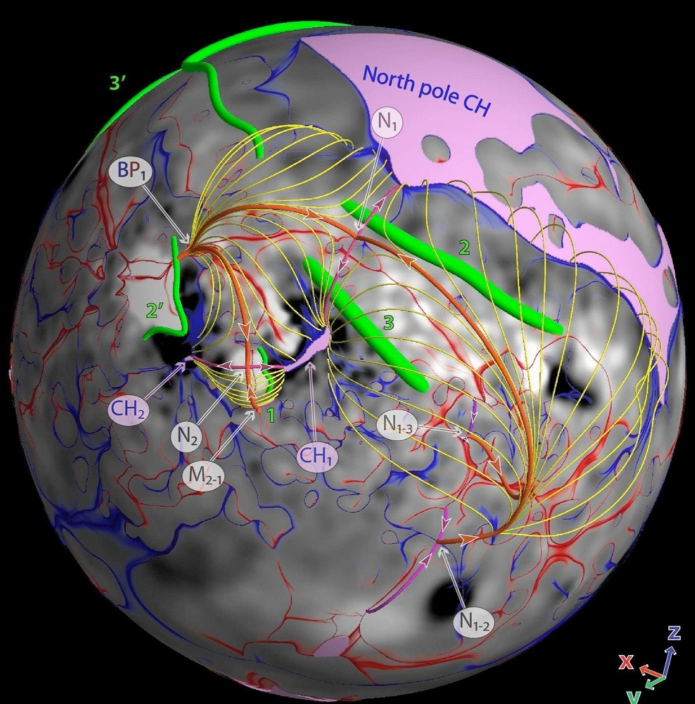
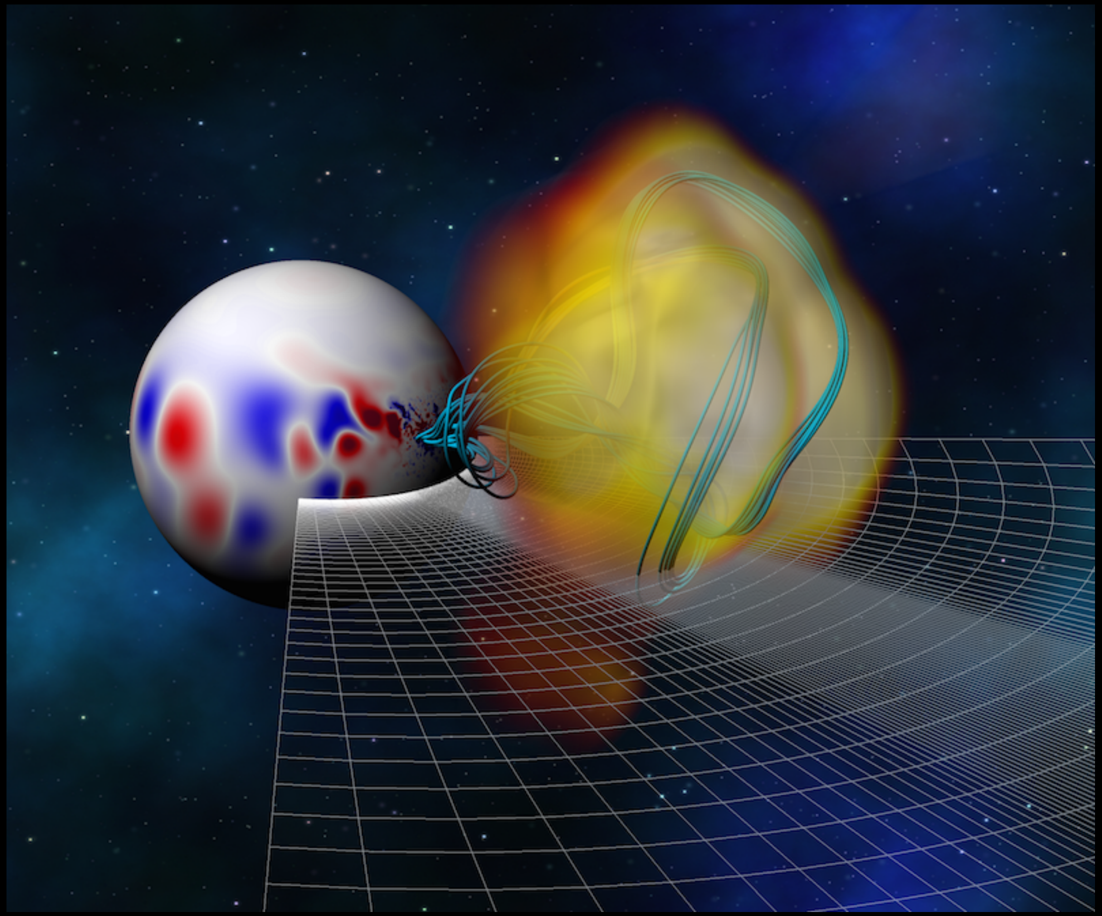
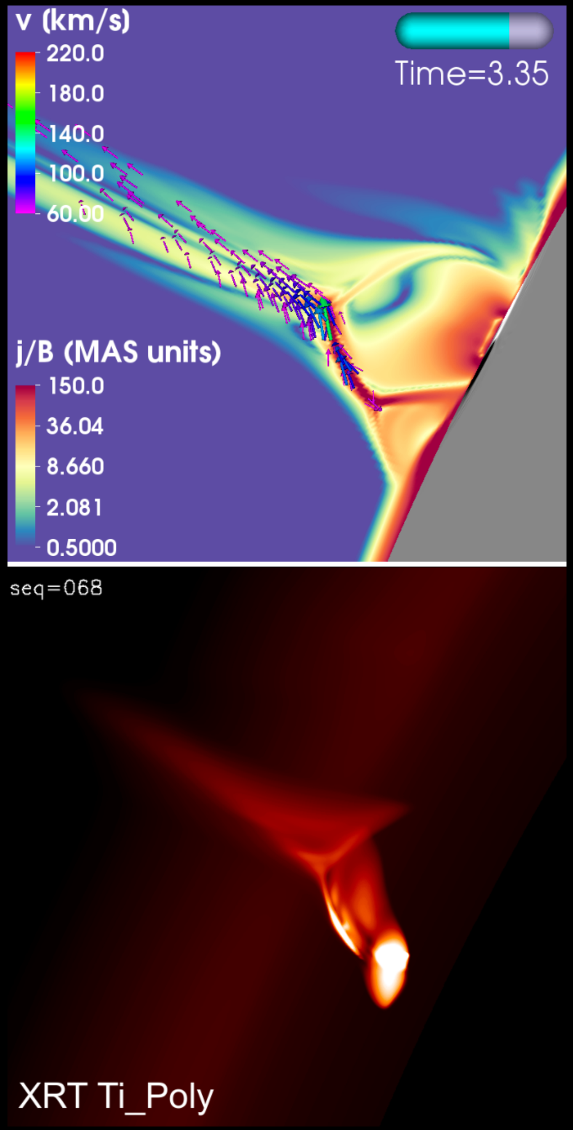
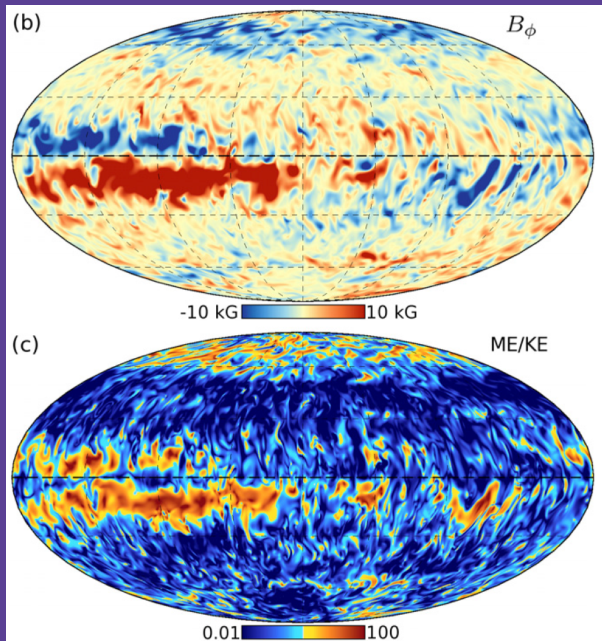






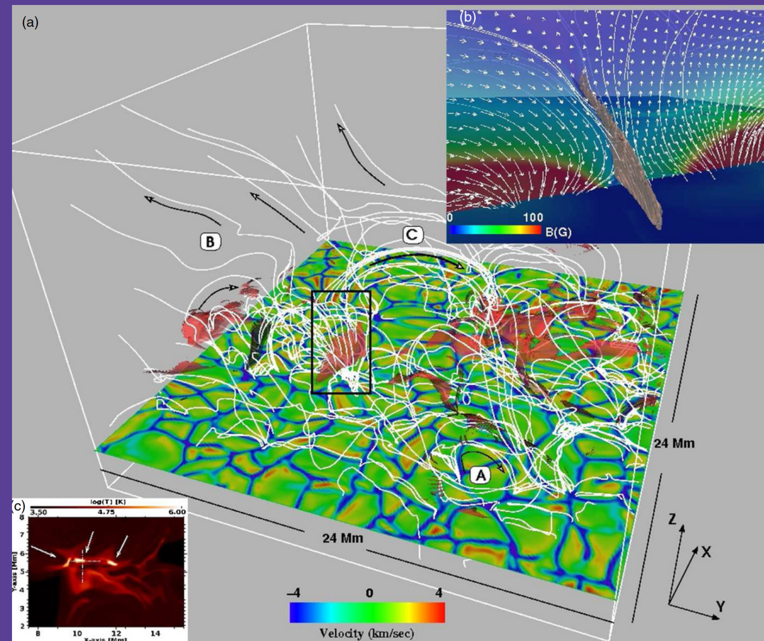
CSPM, 2015 October 5-9, Coimbra, Portugal

MHD simulations



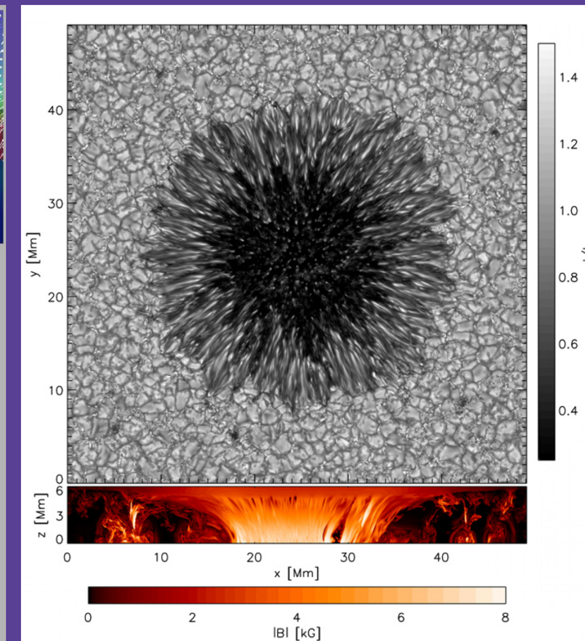
interior / CZ

Nelson & Miesch (2014)



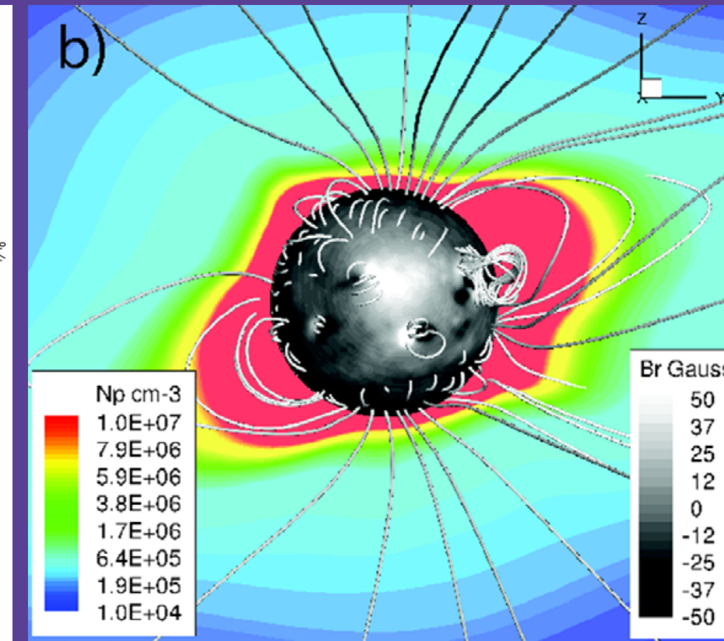
quiet sun / chromosphere

Archontis & Hansteen (2014)



sunspots / ARs

Rempel (2012)



corona / heliosphere

Manchester *et al.* (2014)

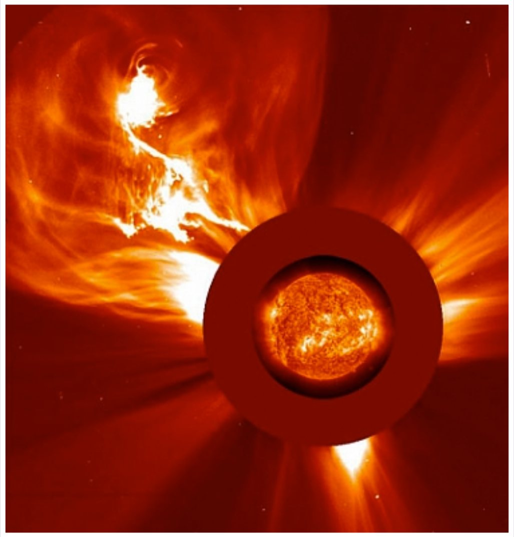
- formulated as initial boundary-value problem:
  - system of differential equations (single-fluid MHD)
  - set of boundary conditions (sometimes well constrained by observations)
  - initial state (less well constrained) → often ad-hoc
- have been evolving significantly in recent years

  (resolution, complexity of physics included, use of observed data, etc.)
- still far from covering real complexity & enormous range of length scales

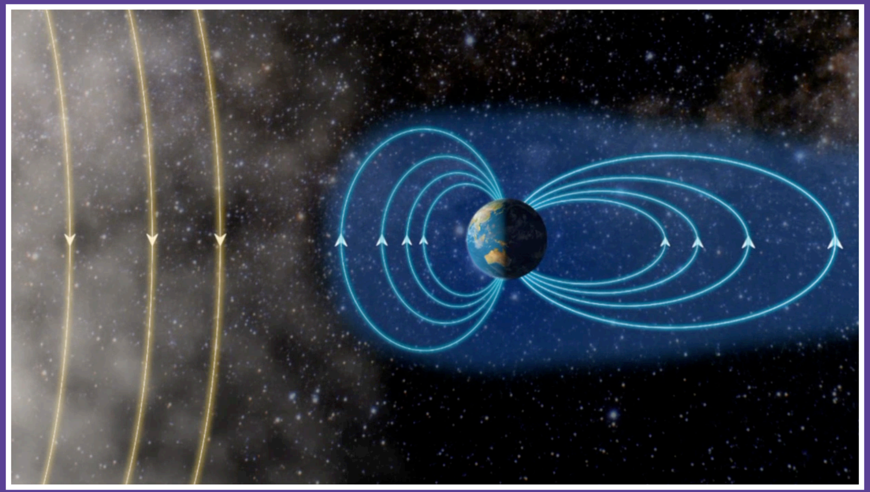
  → no self-consistent model that includes all relevant layers of the sun

  → no inclusion of microphysics yet (reconnection, particle acceleration)

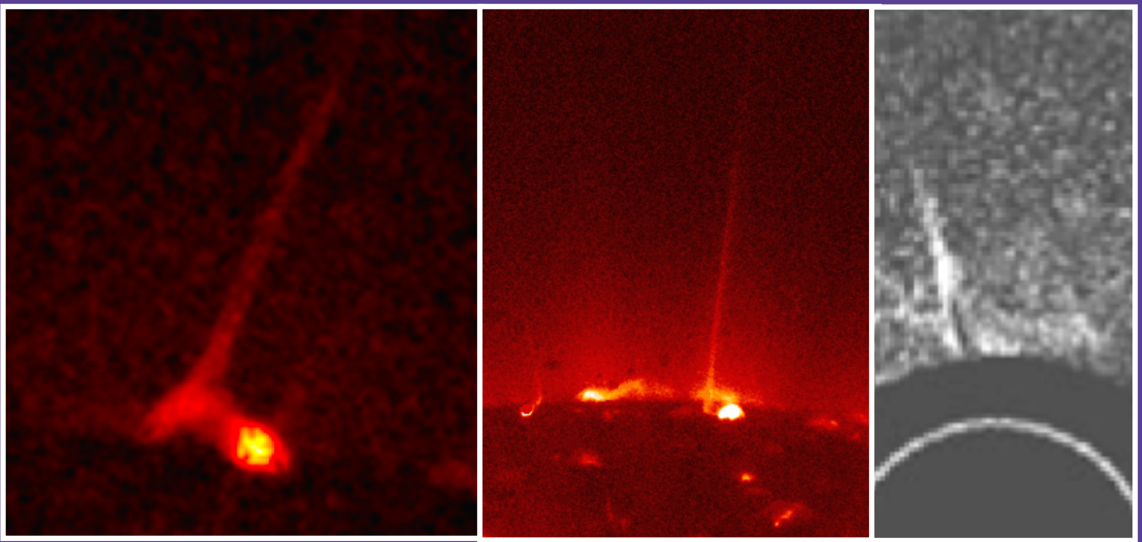
Large-scale transient events in the corona



CME



CME impact at Earth



Coronal jets

- solar corona exhibits a variety of transient dynamic phenomena
- two examples: coronal mass ejections (CMEs) and coronal jets
- some (still) open questions:

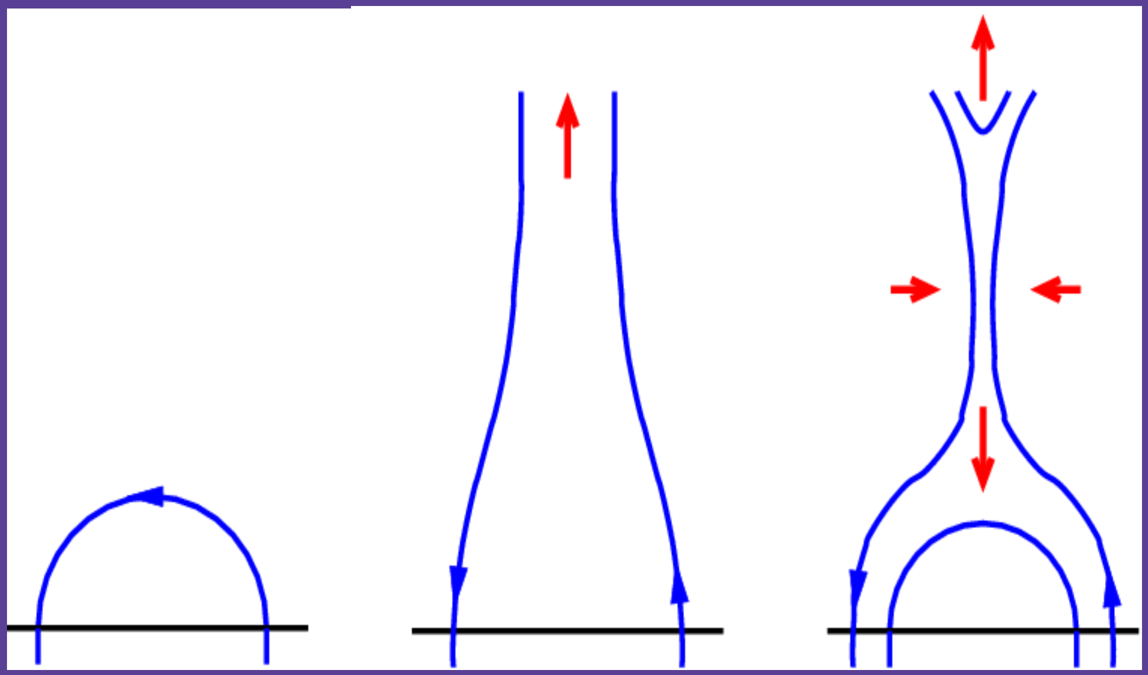
  (1) how are CMEs initiated and driven?

  (2) how can we predict their onset and impact at Earth?

  (3) how do jets form & how do they contribute to the solar wind?

MHD simulations can help us to answer these questions

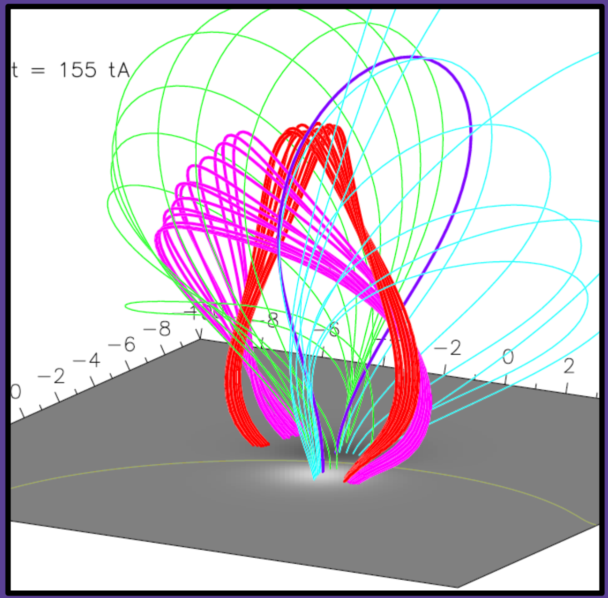
CMEs (solar eruptions)



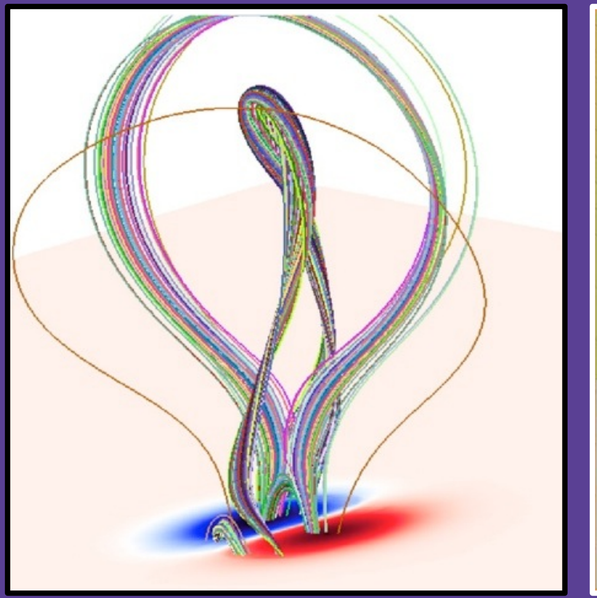
Yokoyama *et al.* (2001)

- CMEs are one observational manifestation of large-scale solar eruptions (together with flares and prominence/filament eruptions)
- they are the main driver of space weather disturbances at Earth
- basic eruption-scenario ("magnetic explosion") well established, but:
  - initiation, driving, and interplanetary evolution not yet well known
  - reliable predictions of onset and impact not yet possible

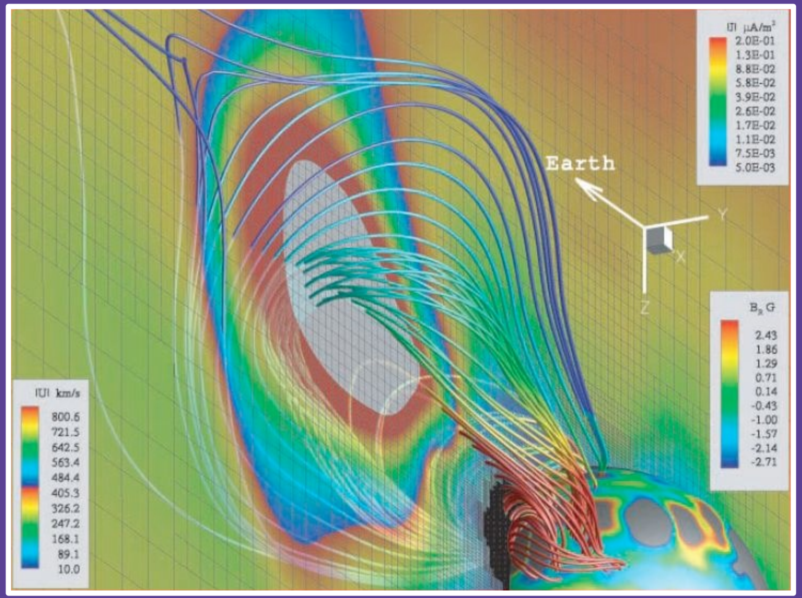
Numerical (MHD) simulations of solar eruptions



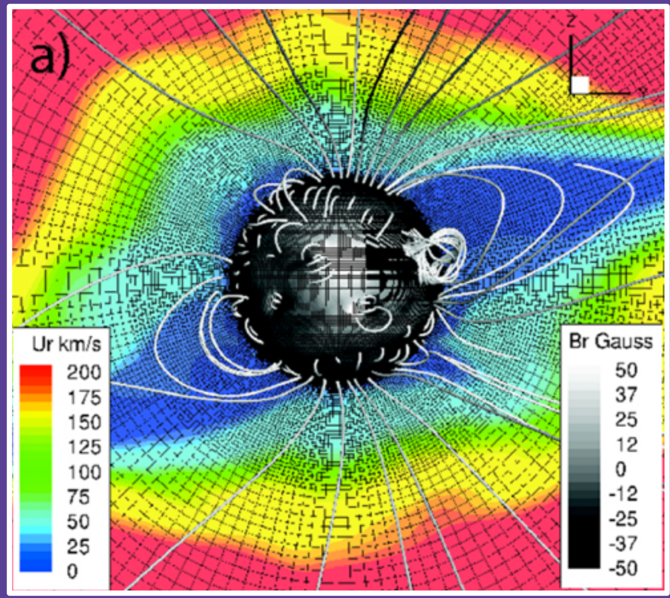
Aulanier *et al.* (2010)



Amari *et al.* (2003)



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

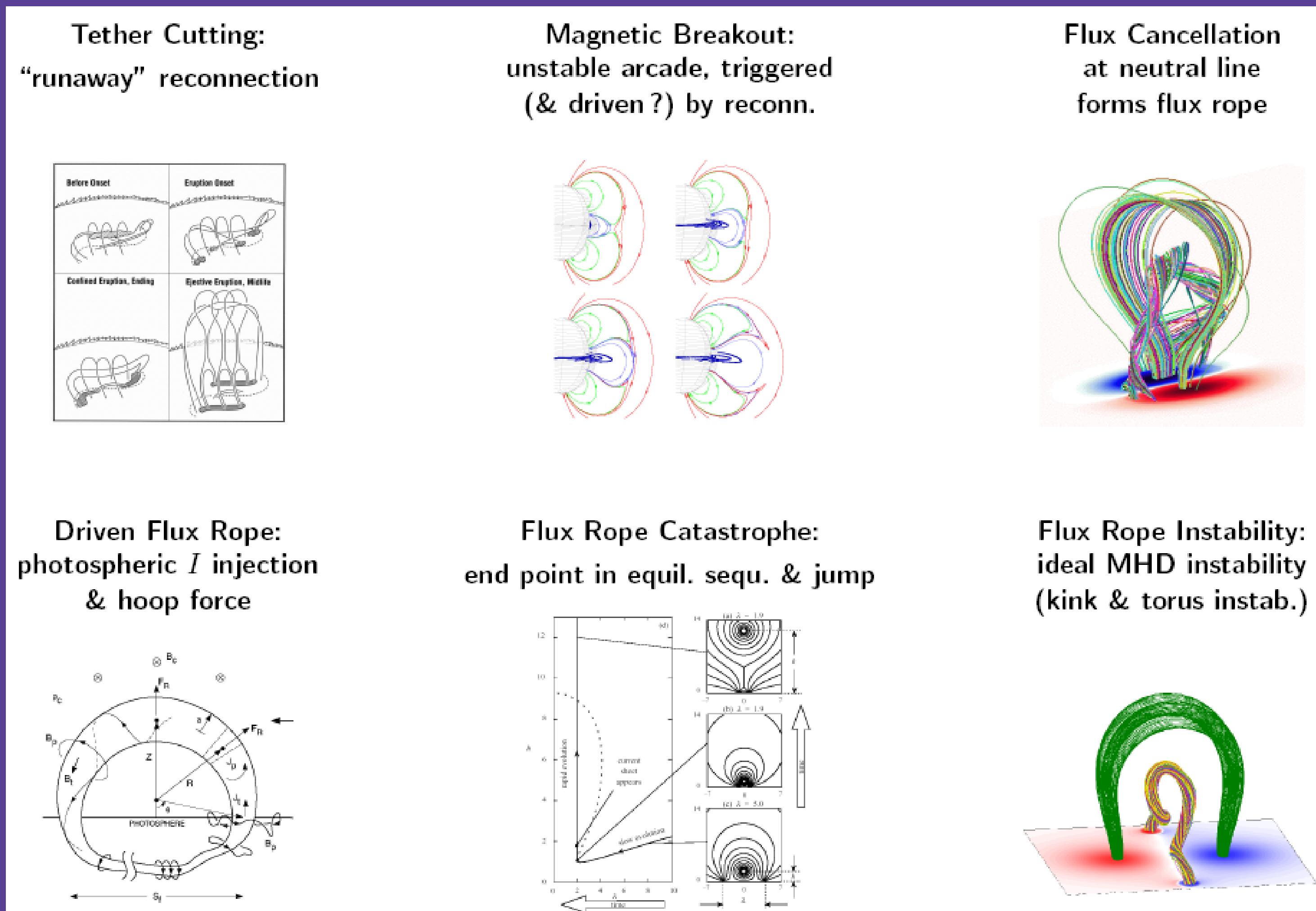
  "realistic": full corona; real magnetograms; thermodynamic MHD; solar wind

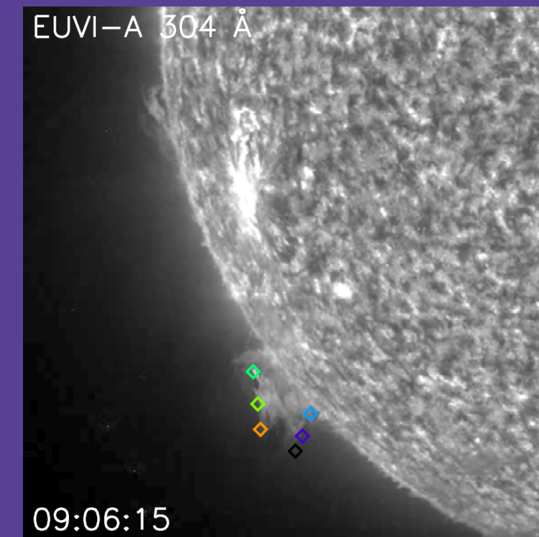
- both approaches have pros and cons:

  idealized: simplified configurations; limited direct comparison with observations
  but: fast → parametric studies; isolate physical mechanisms

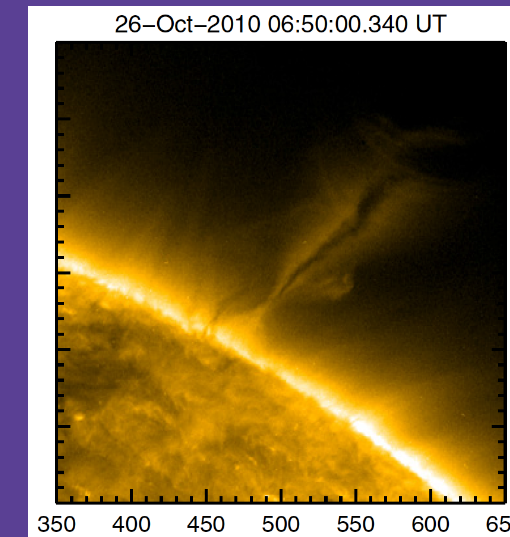
  "realistic": complex; time-consuming; expensive
  but: comparable to observations; more complete physics; potentially predictive

What **triggers** the onset of an eruption ?

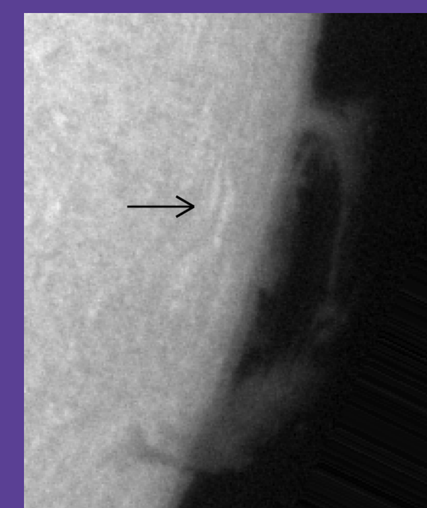




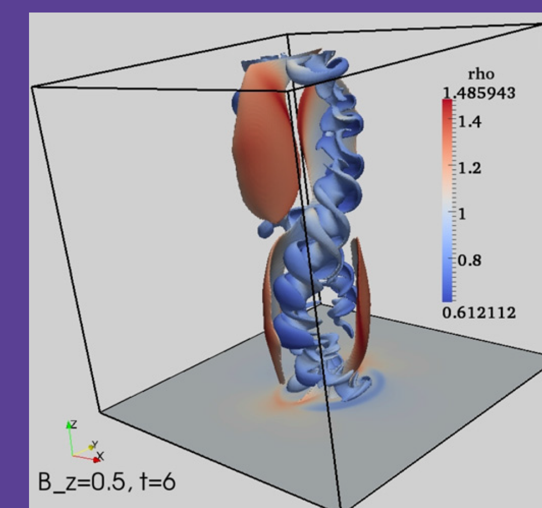
mass loading
Seaton *et al.*(2011)



solar tornados
Su *et al.*(2012)



flux feeding
Zhang *et al.*(2014)

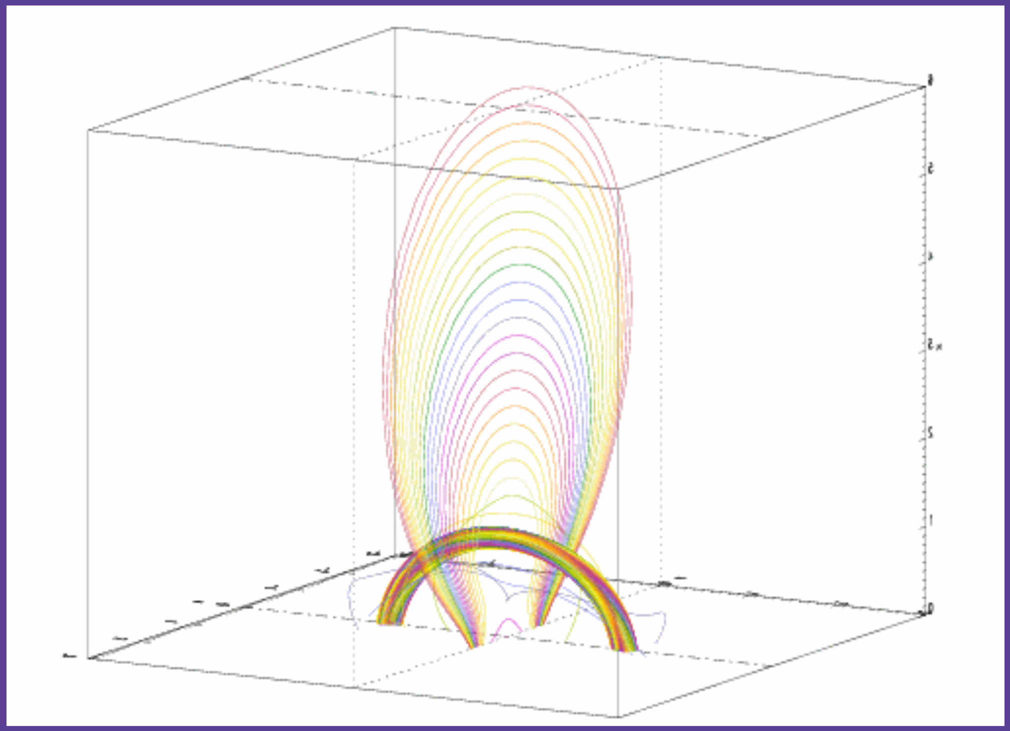


tilt instability
Keppens *et al.*(2014)

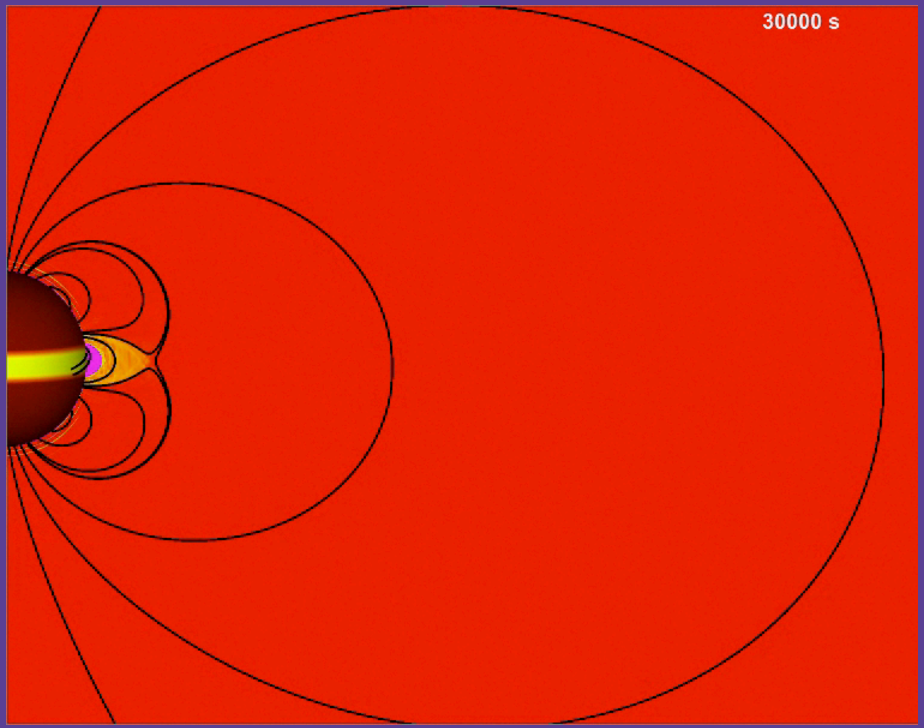
- idealized MHD simulations helped to substantiate suggested onset mechanisms
- but: quantitative onset criteria still not well known & new ideas still emerge

we need: more parametric studies using simple, idealized models

What **drives** an eruption (instability vs. reconnection) ?



Kliem & Török (2006)



Karpen *et al.* (2012)

- numerical simulations helped us to pin down the main <u>acceleration</u> mechanisms:

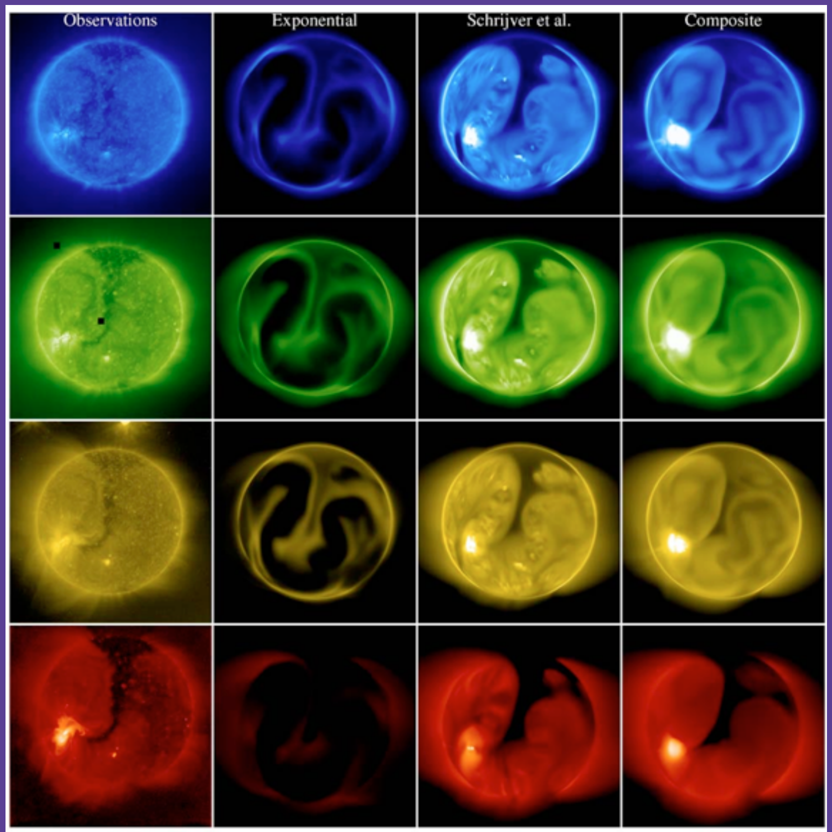
torus instability + flare reconnection

- <u>open question</u>: which one is dominant under which circumstances ?

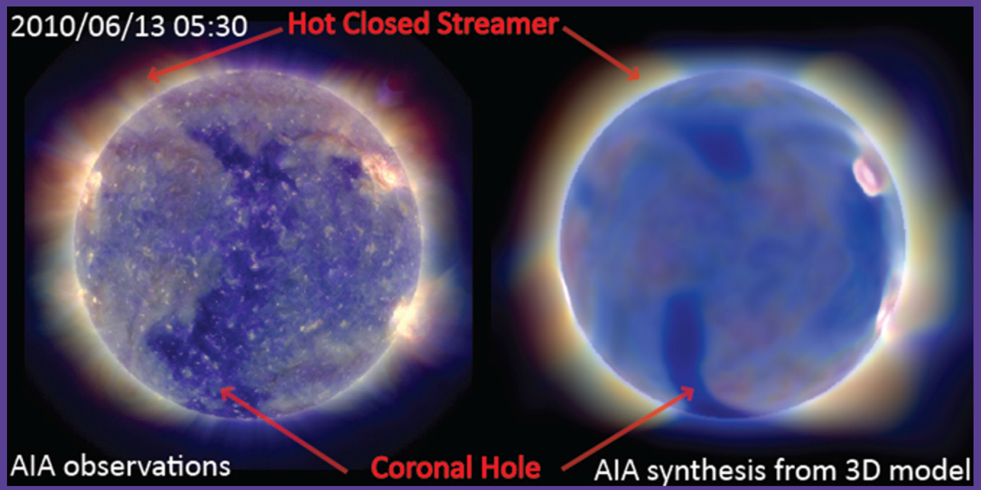
  - difficult to separate (mechanisms closely coupled)

  - timing & respective contribution likely depends on initial magnetic configuration

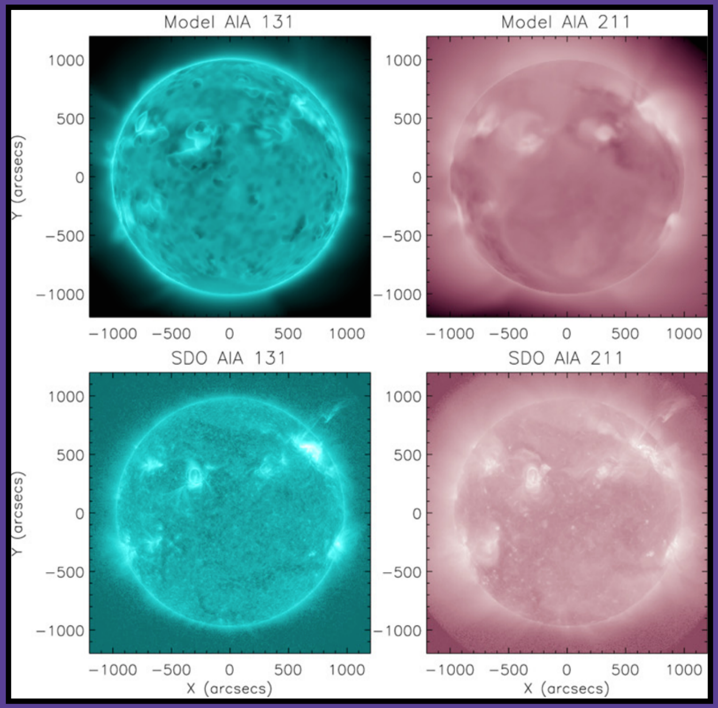
Thermodynamic MHD modeling of the corona



Lionello *et al.* (2009)



Downs *et al.* (2012)

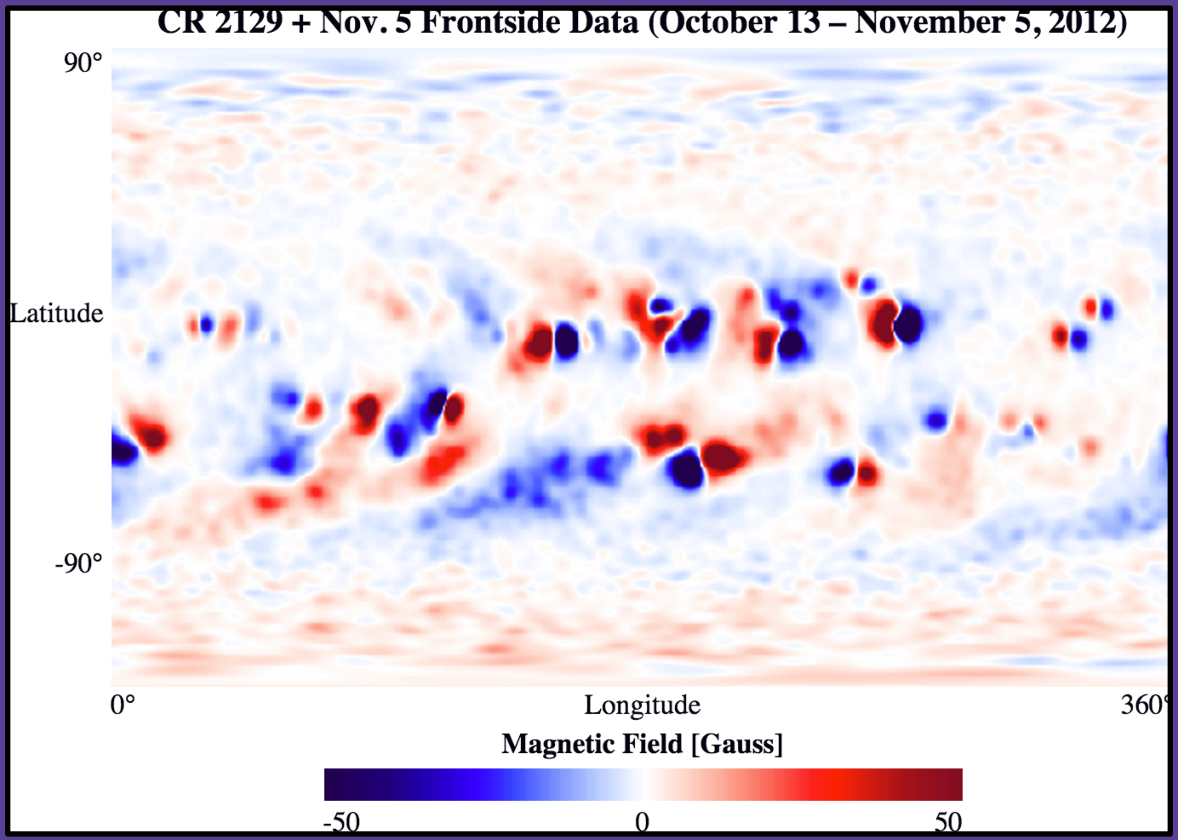


van der Holst *et al.* (2014)

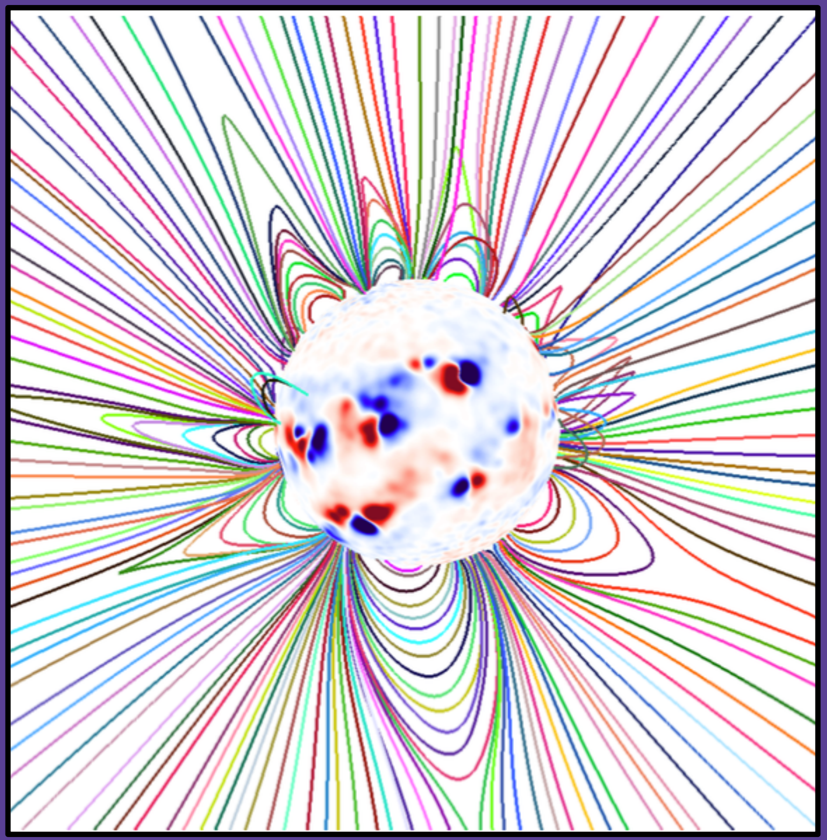
- calculate potential field from (filtered) synoptic map
- MHD relaxation to steady-state including <u>solar wind</u>
- advanced <u>energy transfer</u>: parallel TC, radiative losses, (empirical) coronal heating
  - → required to model CHs, quiet sun, and ARs simultaneously
- latest improvements: wave-turbulence & two-temperature models

→ **(semi-)realistic coronal magnetic field & plasma distributions**

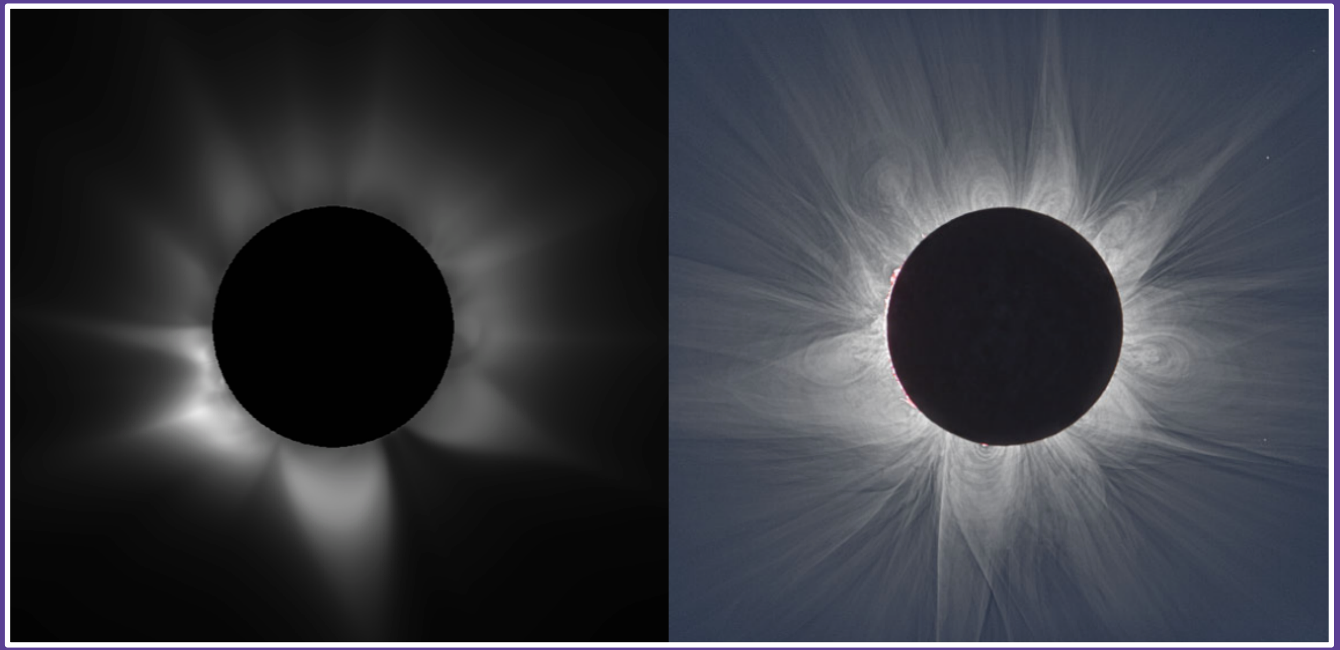
Example: solar corona during November 13, 2012 eclipse



daily updated HMI synoptic map



relaxed magnetic field

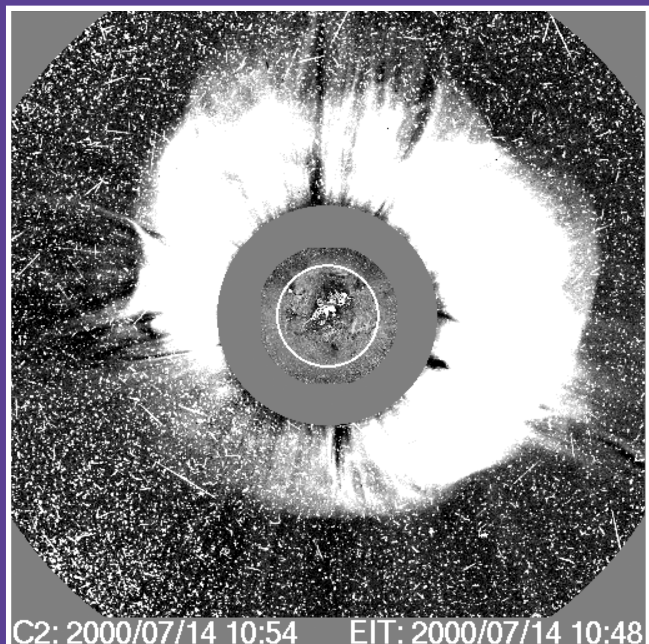


synthetic polarization brightness image
(Queensland, Australia - C. Emmanoulidis & M. Druckmüller)

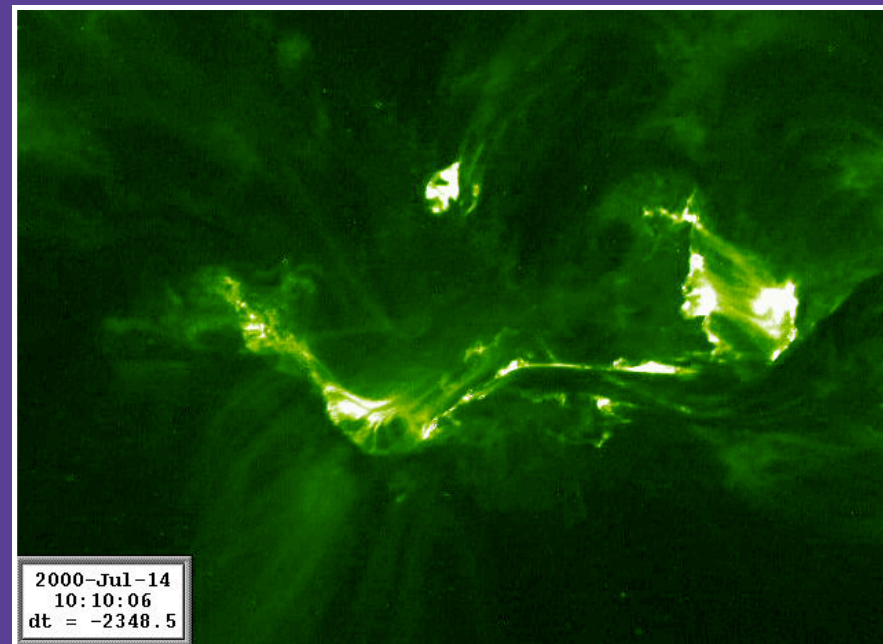
limitations:

- magnetic field changes rapidly
  → include flux evolution models
- streamers less inflated in model
  → energize source regions

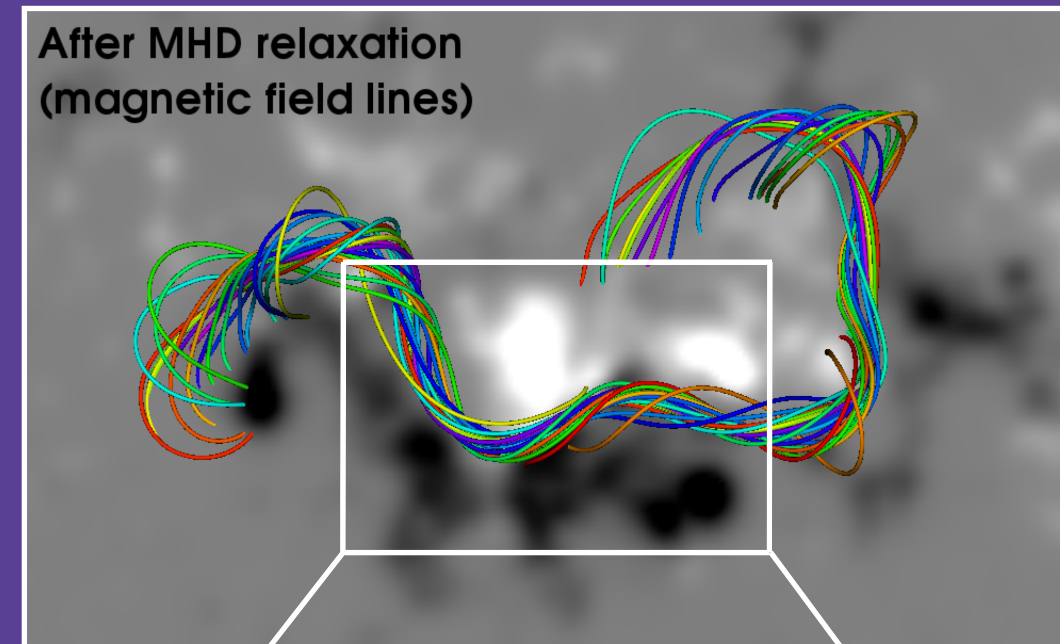
Thermodynamic MHD simulation of the Bastille Day event



SOHO/LASCO C2



TRACE 195 Å



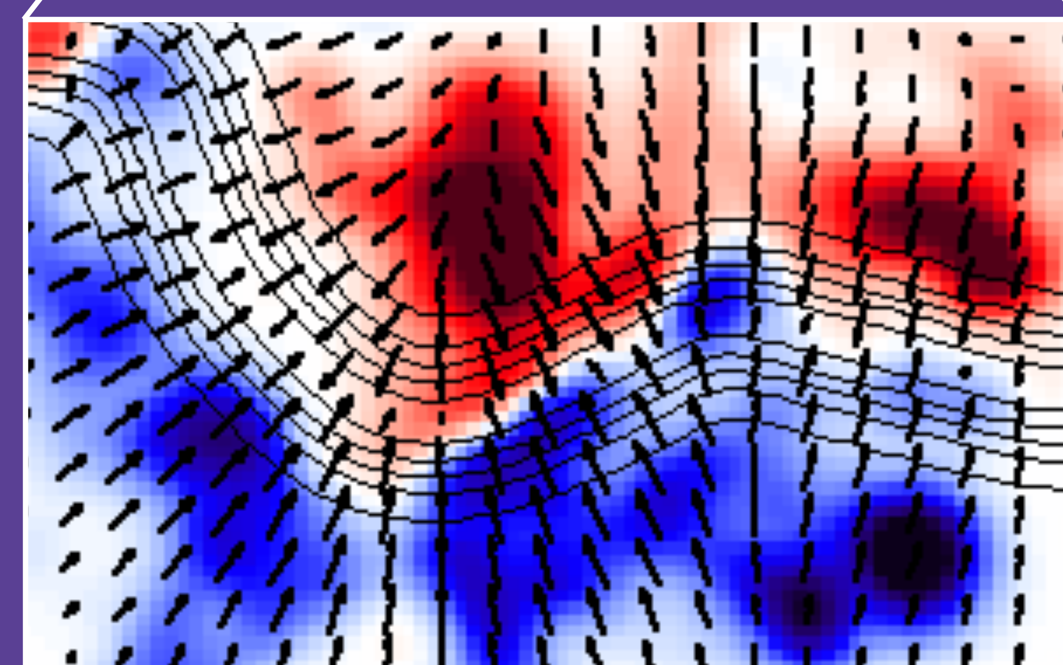
inserted flux rope

X5.7 flare & geo-effective halo CME on 2000 July 14

1.) calculate steady-state corona & solar wind

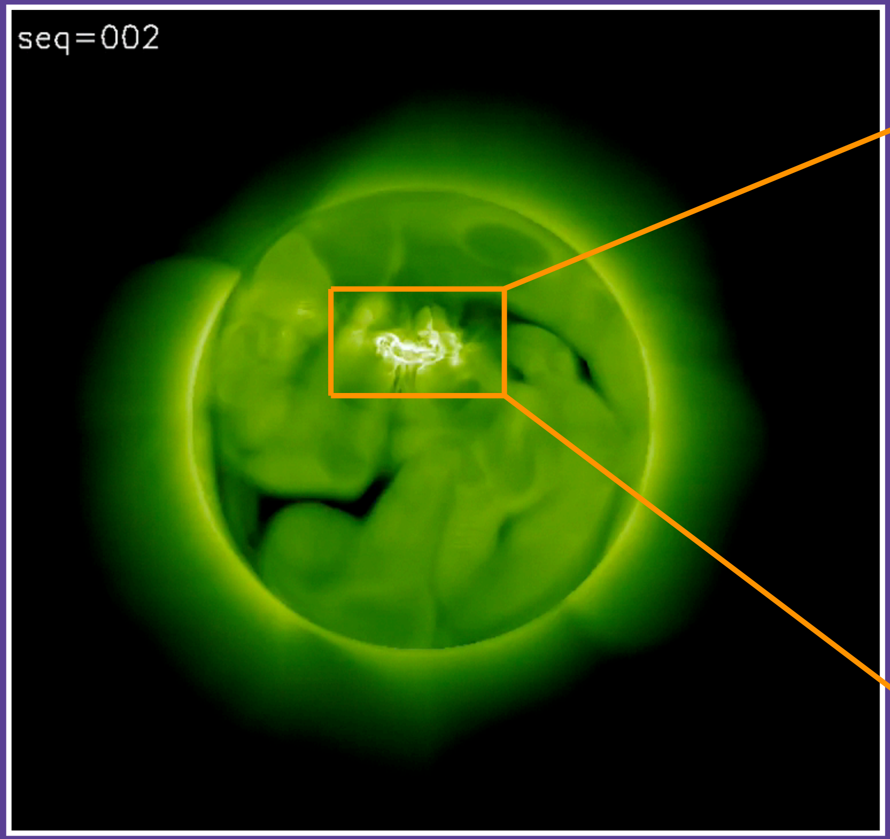
2.) construct <u>stable</u> flux rope in active region

3.) trigger eruption by ad-hoc converging flows

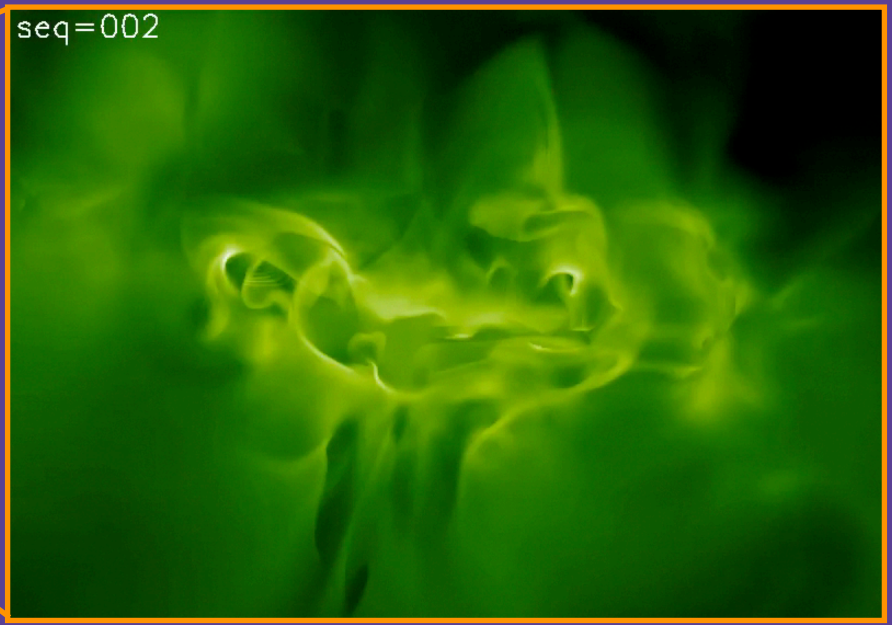


converging flows

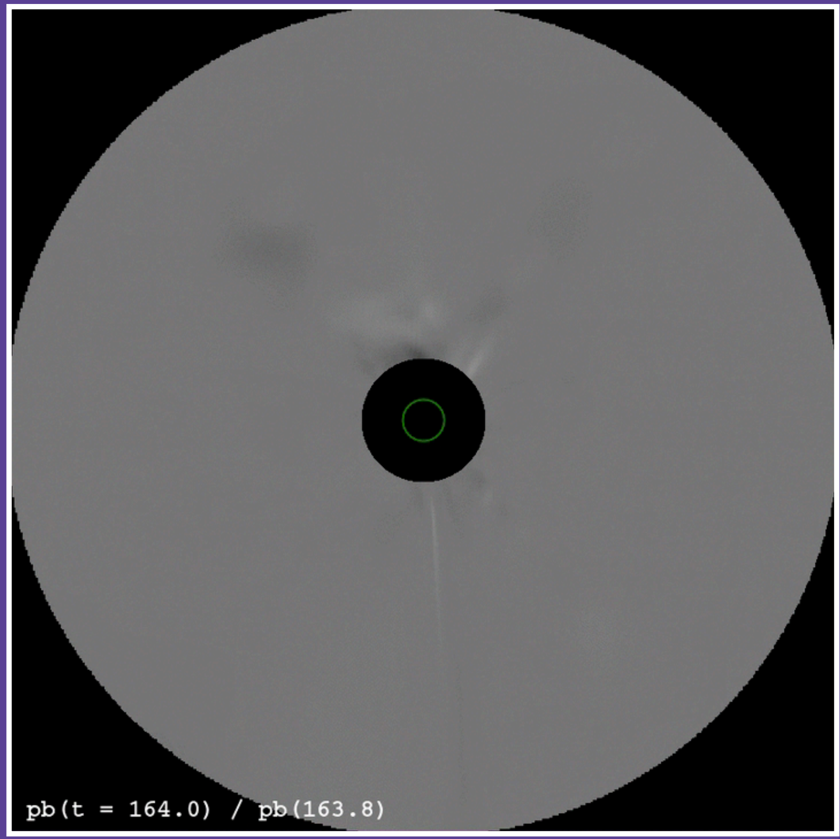
Thermodynamic MHD simulation of the Bastille Day event



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



SOHO/EIT 195 Å
(active region)

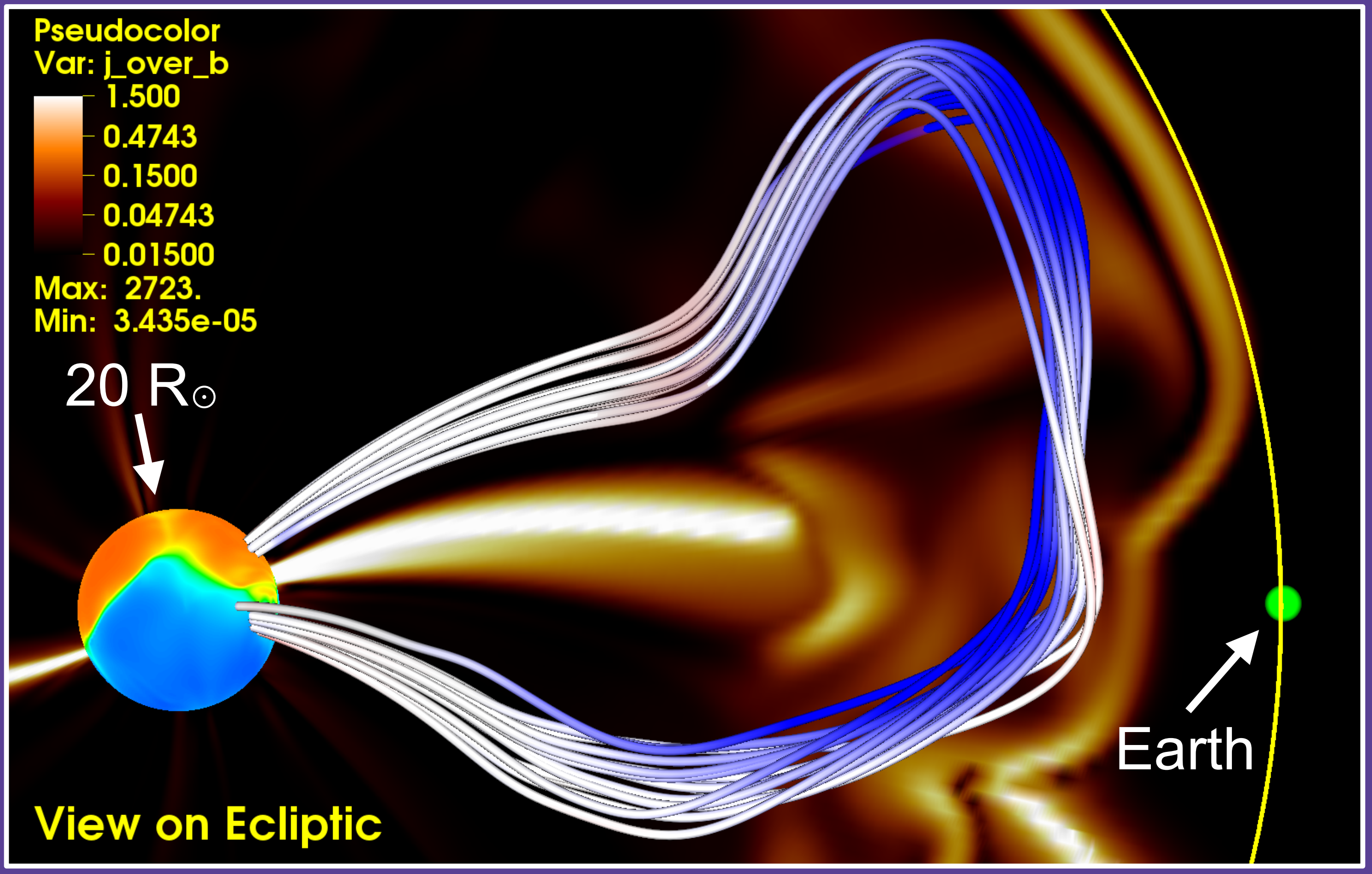


polarization brightness
running ratio
(synthetic emission;
3-20 solar radii)

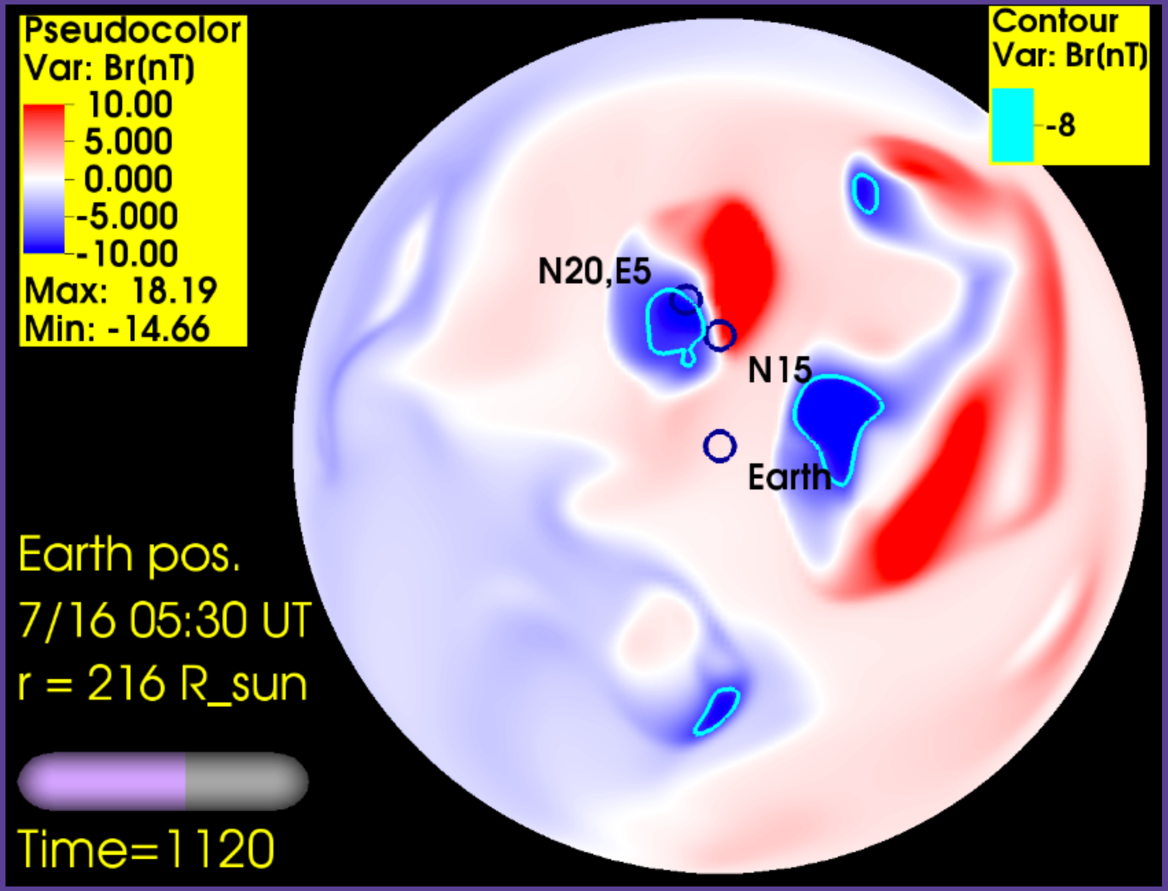
- synthetic satellite images allow direct comparison with observations
- flare arcade and halo-CME morphologies qualitatively reproduced
- CME speed ≈ 1500 km/s & kinetic energy ≈ 4 x 10^{32} ergs

provides quantities that cannot be observed directly (e.g. 3D magnetic field)

Heliospheric simulation of the Bastille Day event



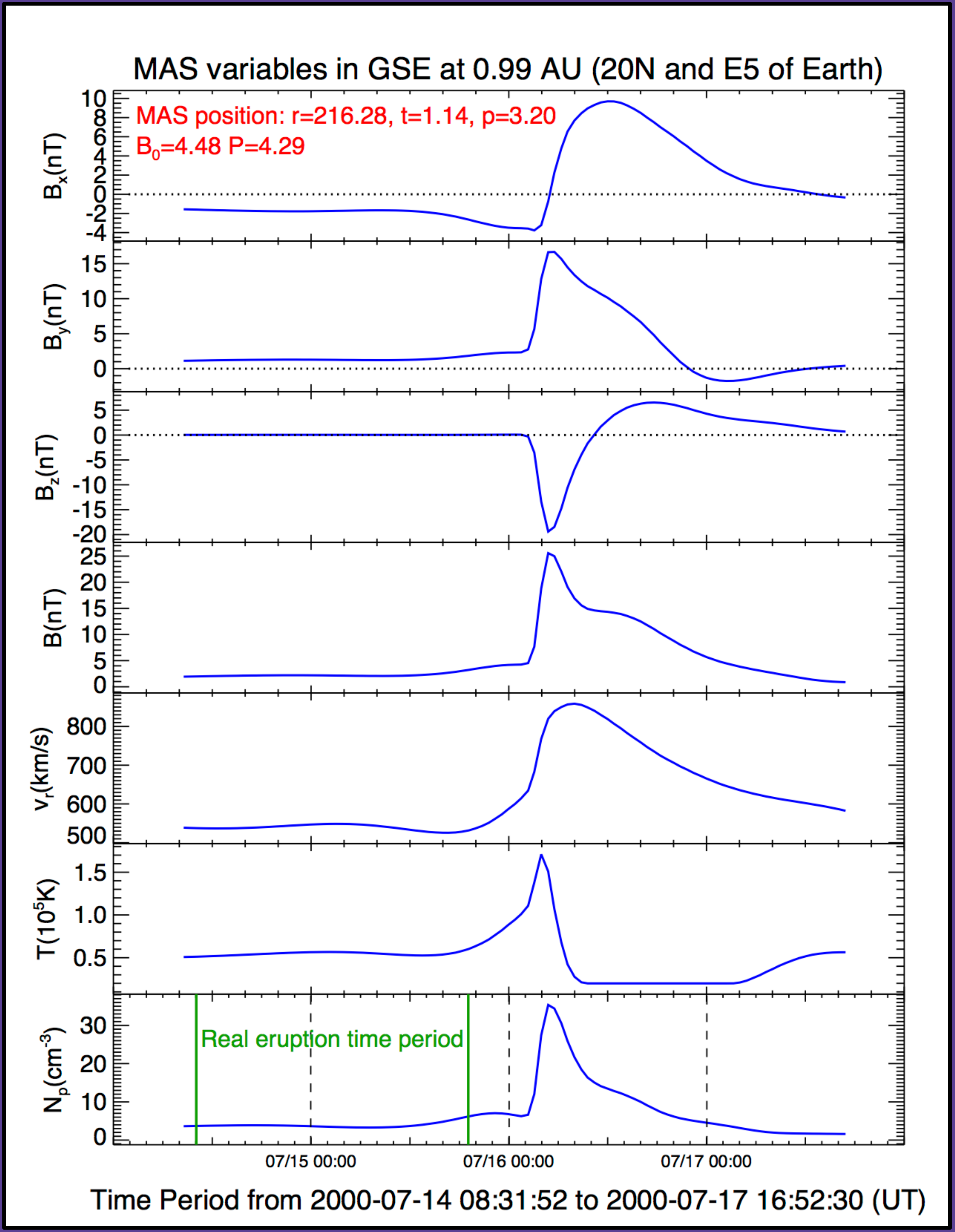
model ICME core & electric currents in ecliptic plane



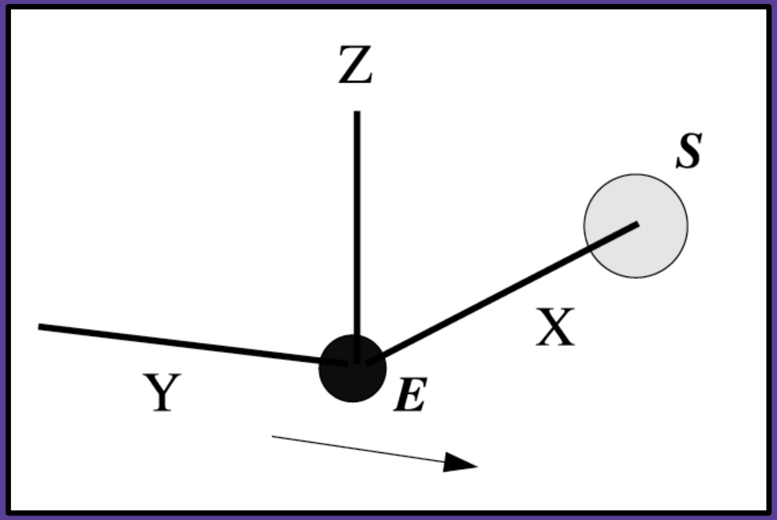
radial magnetic field at 1 AU

- flux-rope core structure preserved at 1 AU (still connected to surface)
- ICME arrives with rather scattered shape (non-synchronous eruption?)
- area of -Bz relatively small → difficult to match/predict

Heliospheric simulation of the Bastille Day event



simulation data at 1 AU



GSE coordinate system

- flux rope qualitatively reproduced (but: 15-20 degrees north of Earth!)
- B field strength too low (≈ factor 2)
- ICME too slow (≈ 6-8 h delay)

quantities at Earth very difficult to match with present models?

Solar X-ray jets in polar coronal hole

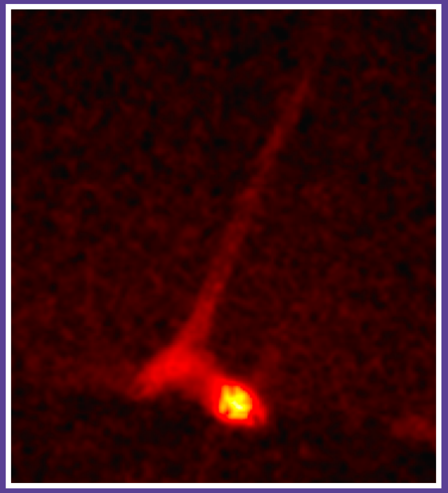
Cirtain *et al.* (2007)

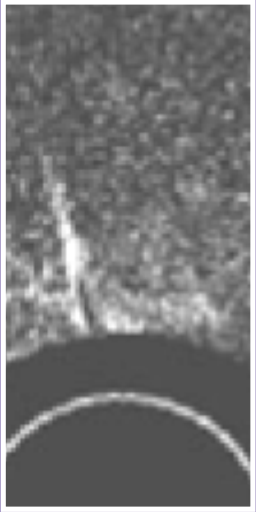
Solar jets

Jet property	Instrument SXT[1]	XRT[2]	EUVI[3]	COR1[4]	AIA[5]
Source region	Active region	Polar CH	Polar/Equat. CH	——	Polar/Equat. CH
Occurrence	~ 17/month	~ 60/day	—-	~ 15/day	—-
Duration [min]	2 – 600	5 – 40 (10)	20 – 40	$<$ 20 – 120	21 – 46
Velocity [km/s]	10 – 1000 (200)	80 – 500 (160)	270 – 400	100 – 560 (270)	94 – 760
Length [Mm]	30 – 400 (150)	10 – 120 (18)	100 (one event)	—-	63 – 188
Width [Mm]	5 – 100 (17)	3 – 12 (7)	25 (one event)	—-	—-

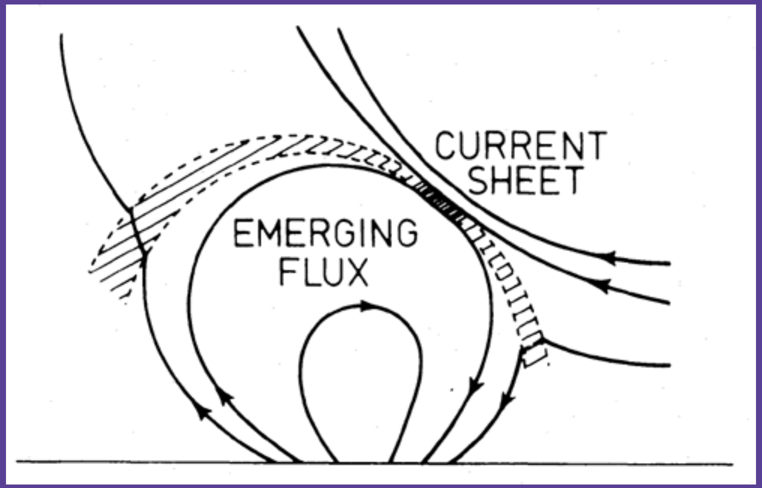
Shimojo *et al.* (1996); Savcheva *et al.* (2007); Nistico *et al.* (2009, 2010); Paraschiv *et al.* (2010); Moschou *et al.* (2013)

- transient collimated eruptions (bright point + stalk)
- occur in open or semi-open magnetic field regions
- occur at different heights (chromosphere, TR, corona)
- often show signatures of twist (helical rotation)
- can produce signatures in white-light coronagraphs

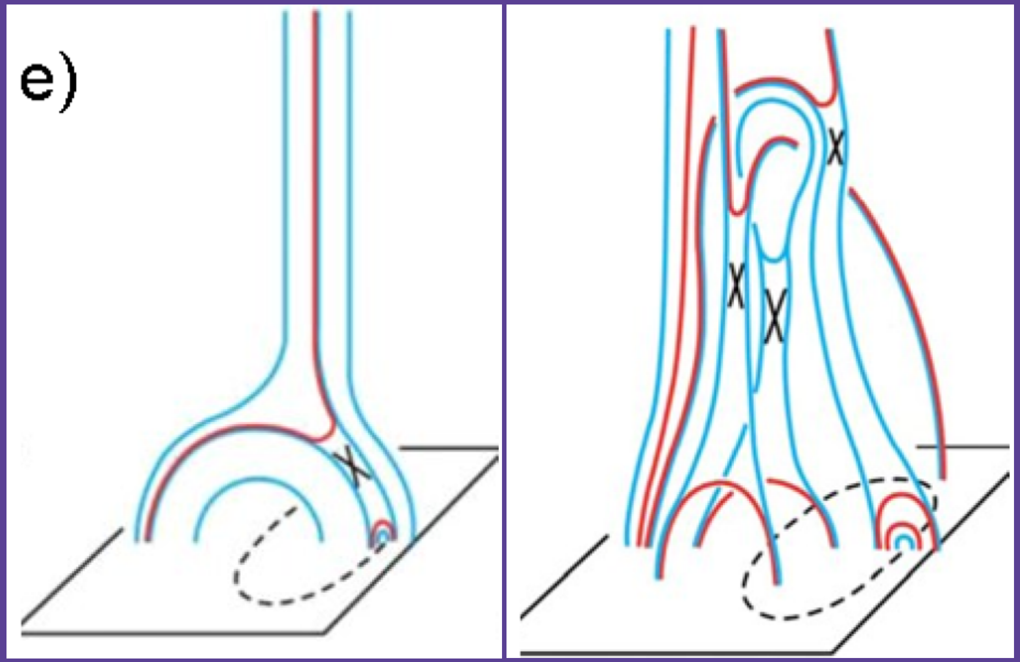




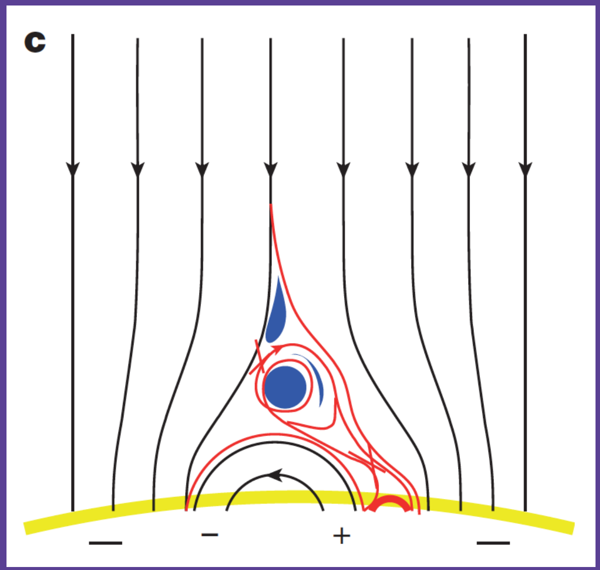
Theoretical ideas



Heyvaerts & Priest (1977)



Moore *et al.* (2010)



Sterling *et al.* (2015)

- basic scenario:

  flux emergence into (semi-) open coronal field

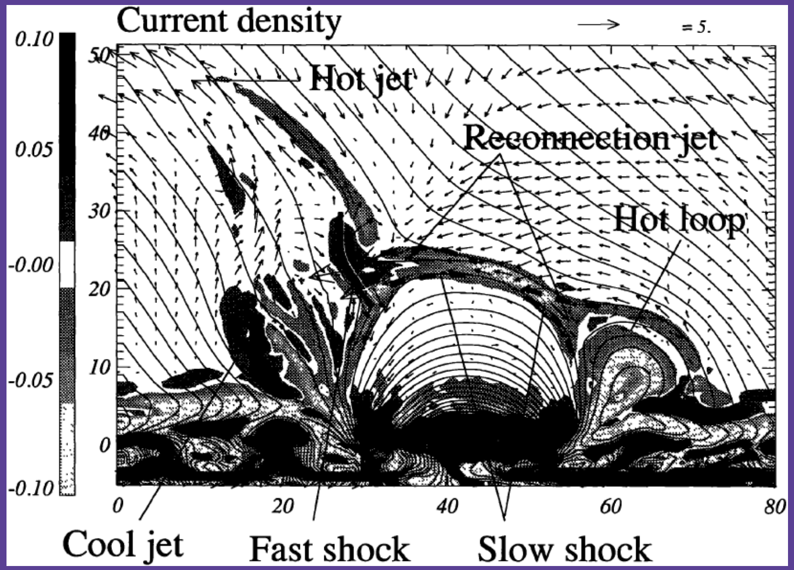
  → current sheet formation → reconnection causes jet

- variations: “standard” and “blowout” jet (emerging flux rope erupts)

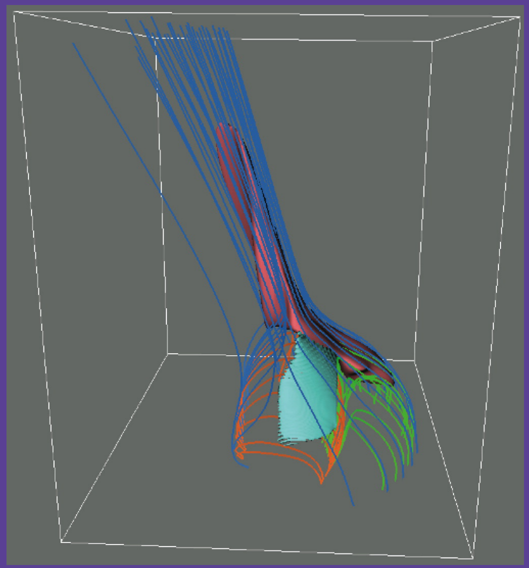
- recent ideas:

  jets due to flux cancellation and/or “mini-eruptions” rather than emergence
  (e.g., Young & Muglach 2013; Sterling *et al.* 2015)

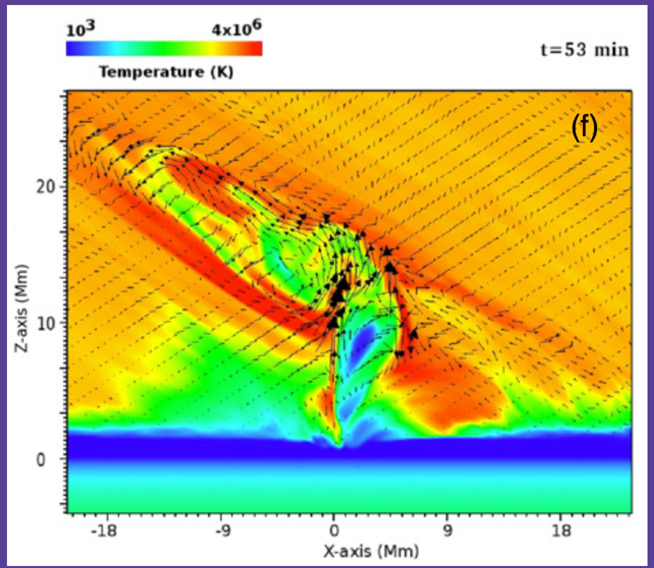
Numerical simulations



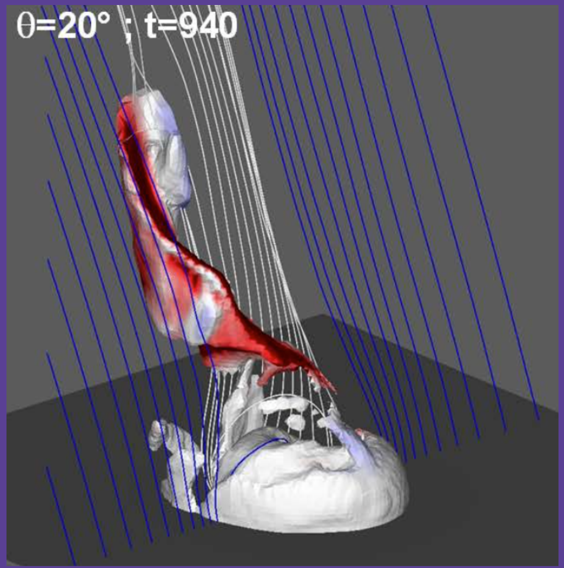
2D standard jet
Yokoyama & Shibata (1996)



3D standard jet
Moreno-Insertis *et al.* (2008)



3D blowout jet
Archontis *et al.* (2013)



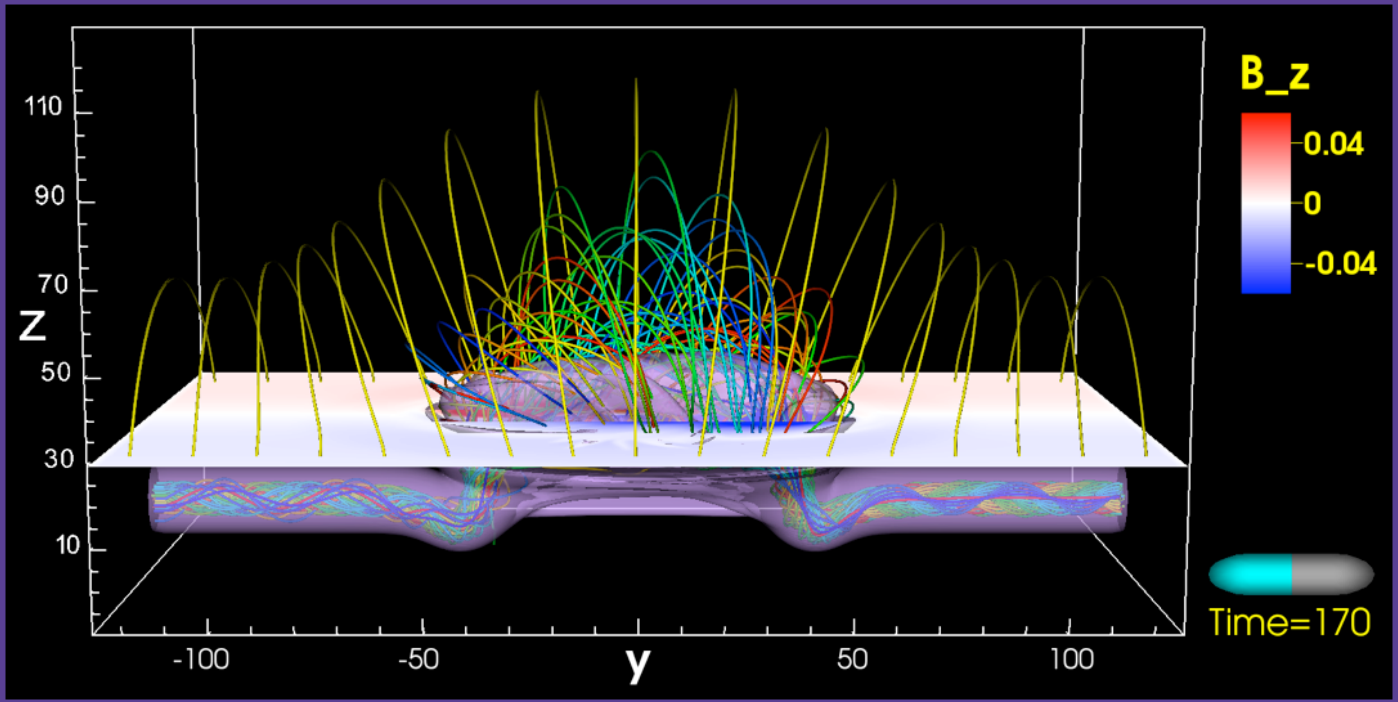
3D helical jet
Pariat *et al.* (2015)

- most simulations consider flux-emergence scenario (except Pariat *et al.*)
- standard + blowout jets & rotation (helical jets) successfully modeled
- recently thermal conduction has been included (Fang *et al.*, 2014)

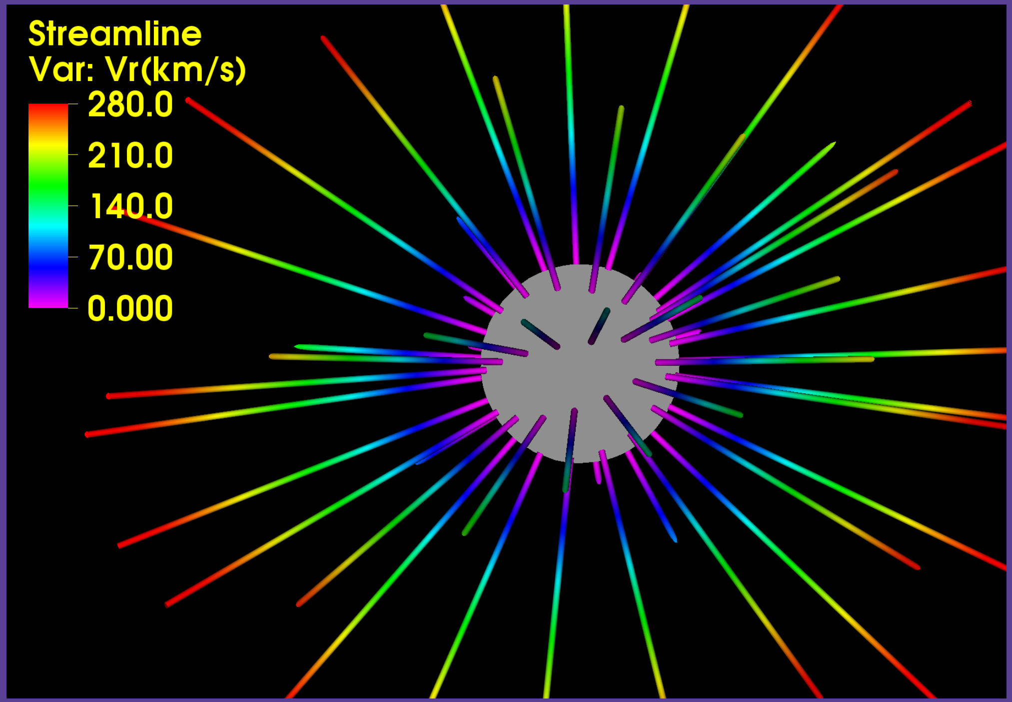
<u>not addressed yet:</u>

- full thermodynamic modeling (conduction, radiation, coronal heating)
- possible contribution to solar wind (so far only small boxes considered)
- MHD modeling of observed events

Thermodynamic MHD modeling of jets including the solar wind

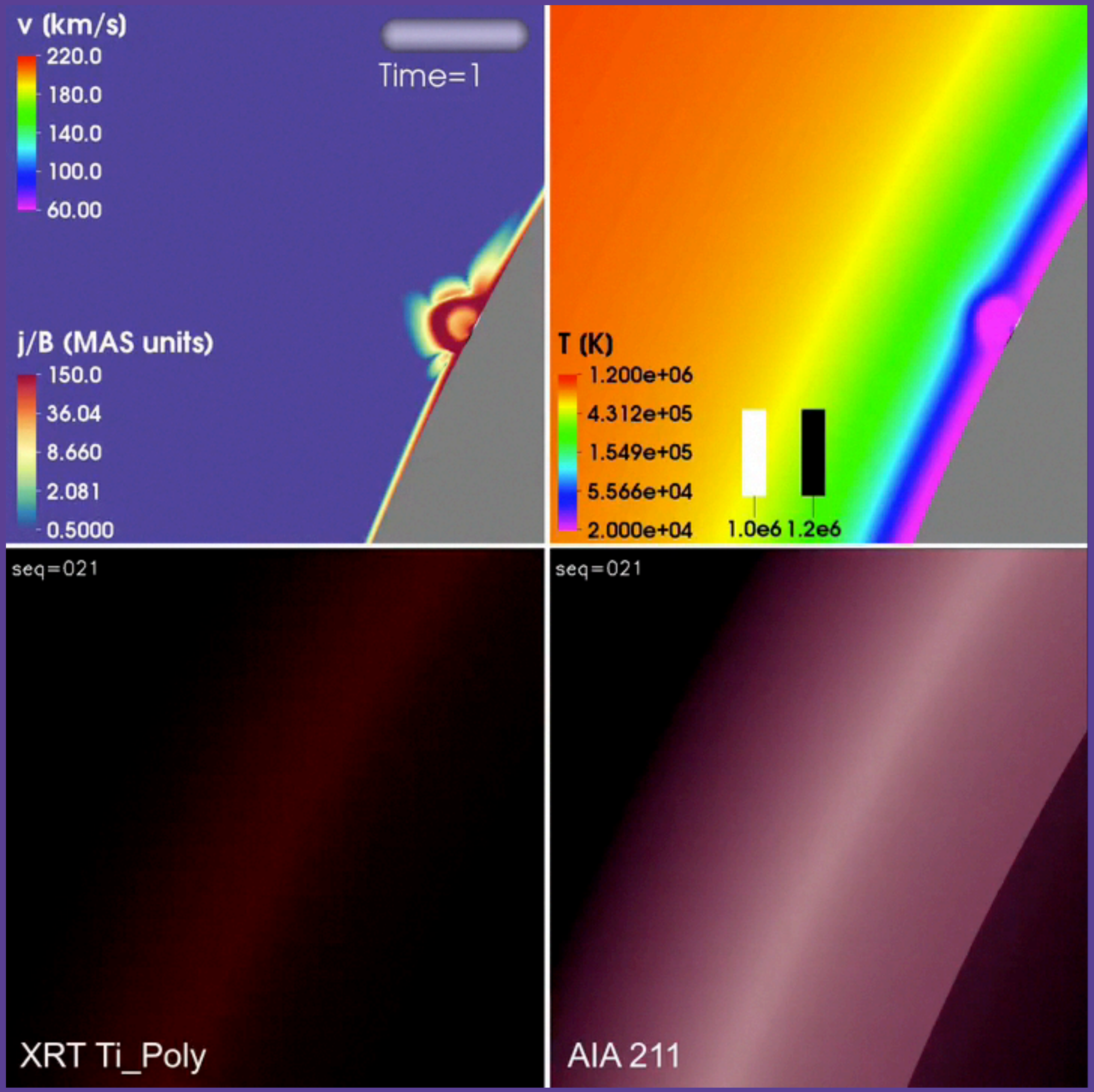


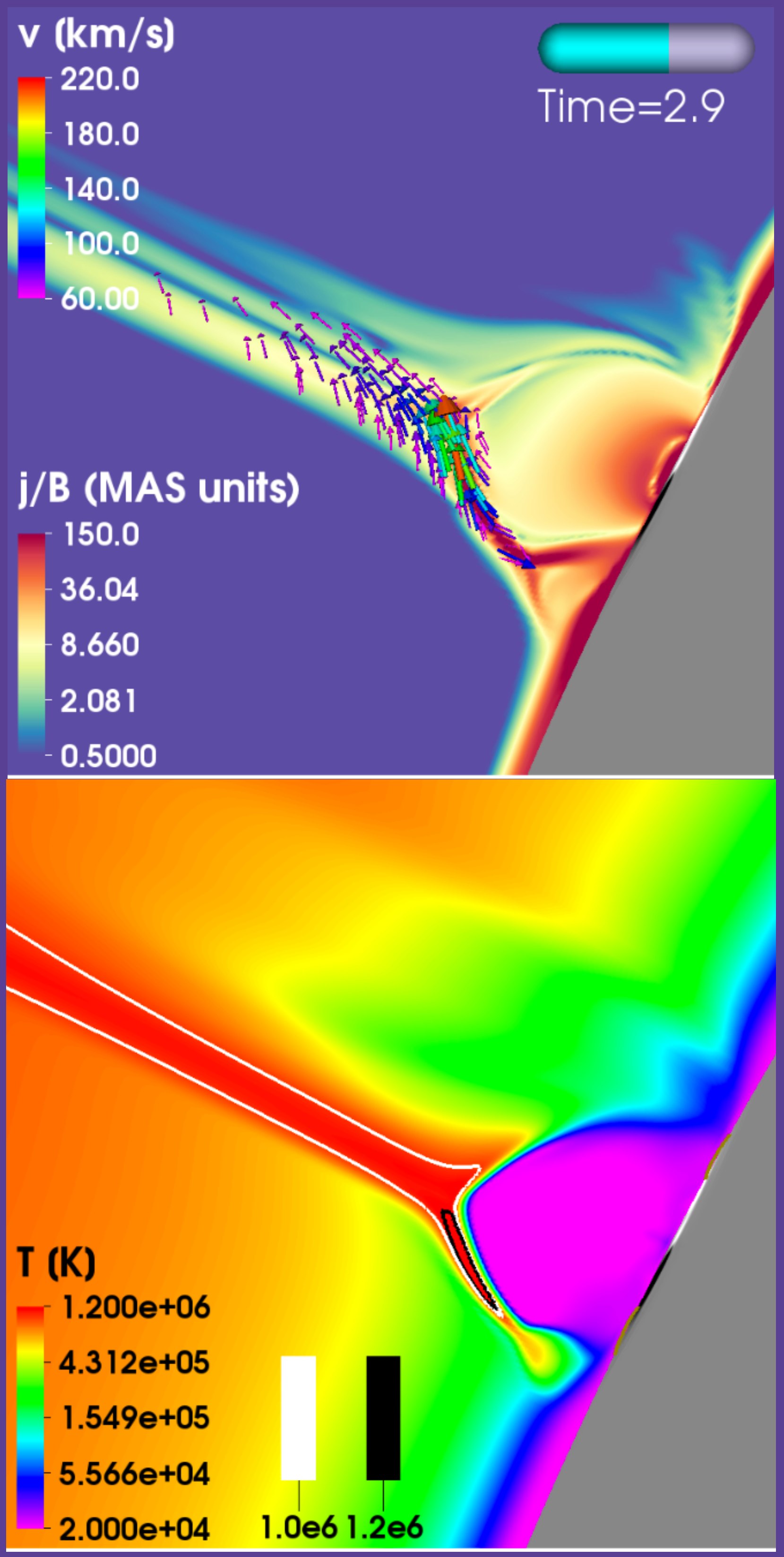
Leake *et al.* (2013)



- coronal domain: spherical grid spanning over 1-20 solar radii
- purely radial background magnetic field (6 G at surface) + solar wind
- simple (exponential) coronal heating + thermal conduction + radiative losses
- boundary-driven (coupling with flux-emergence simulation via electric fields)

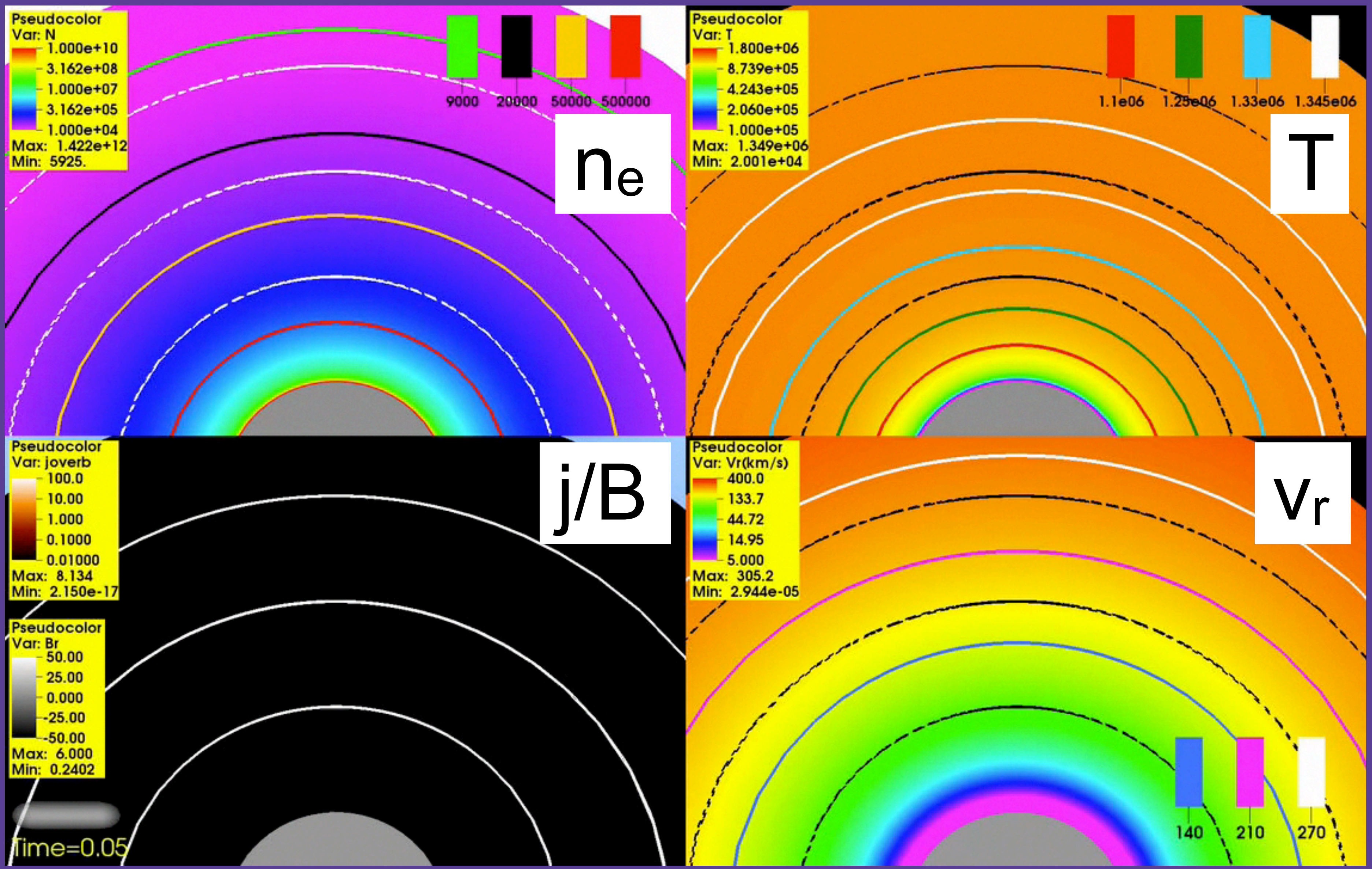
First results (low corona)

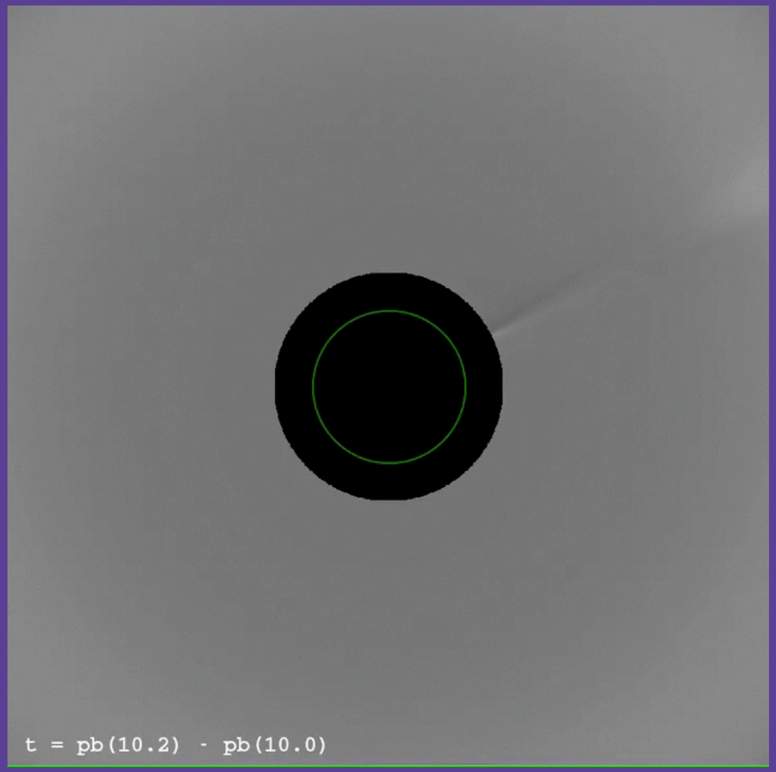




- “standard” jet produced (no “blowout” jet yet)
- peak jet temperature about 1.1 MK
- emission: bright point above surface & CS visible

First results (higher corona)

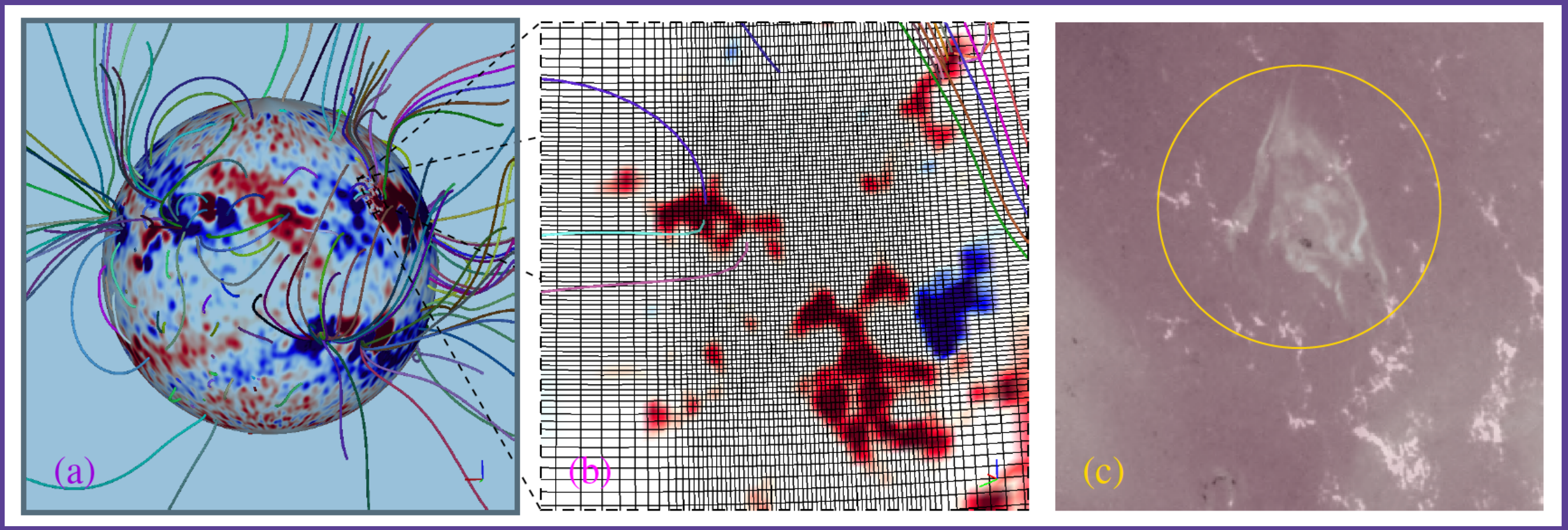




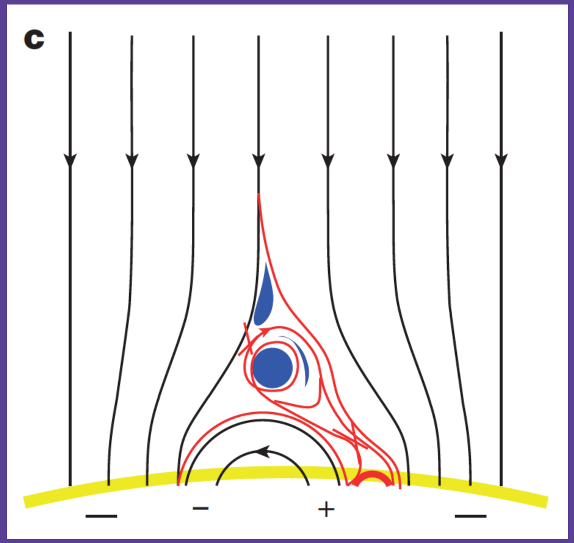
- “standard” jet effects corona at least up to several solar radii (yet to be quantified)
- jet-stalk signatures visible in synthetic white-light images
- quantitative analysis yet to be done

(see also recent work by J. Karpen, R. de Vore *et al.*)

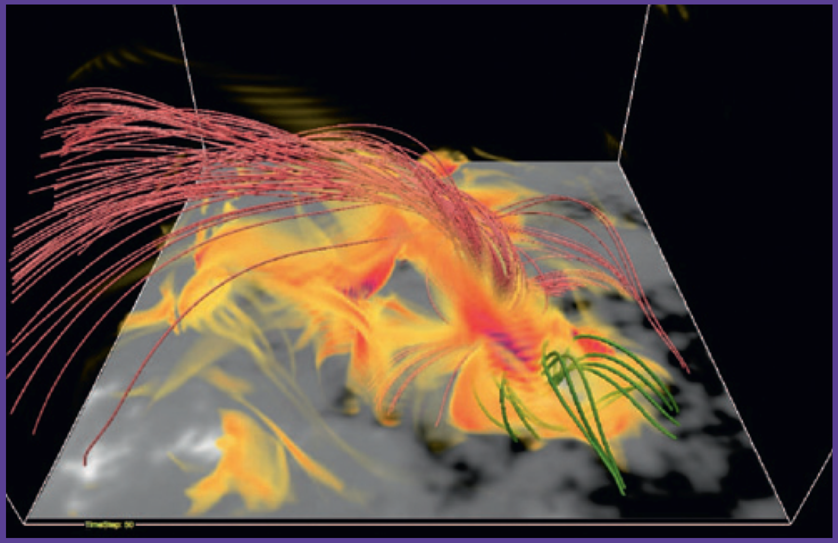
Next steps



blowout jet on 22 July 2011 (Shen *et al.* 2012)



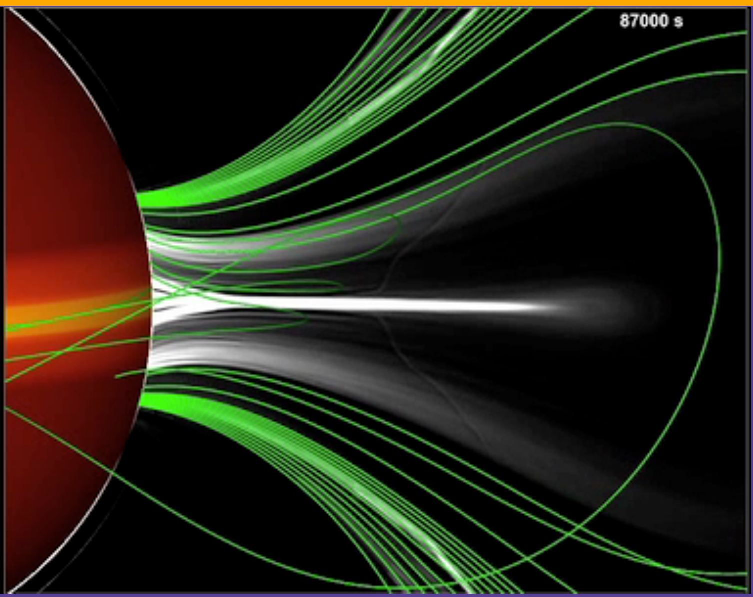
Sterling *et al.* (2015)



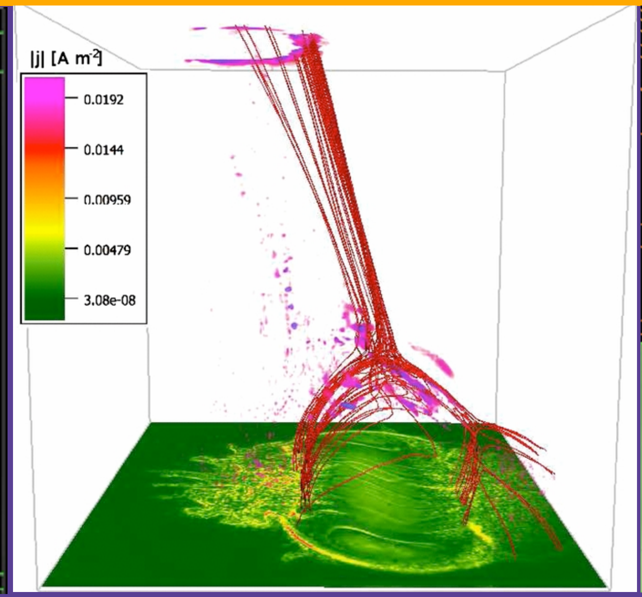
Cheung *et al.* (2015)

- investigate effects of, e.g., thermal conduction and field inclination
- simulate jet formation by flux cancellation & “mini-eruptions”
- modeling of observed events (so far only magneto-frictional simulation)

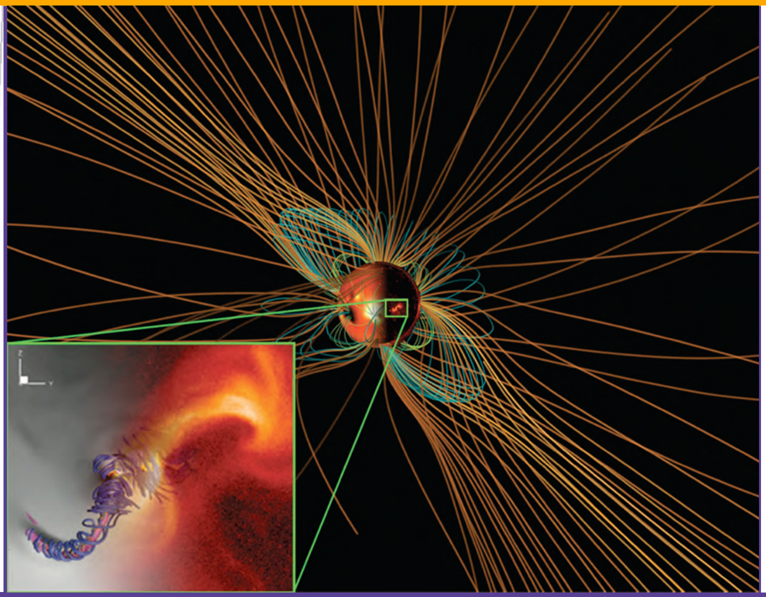
Outlook (some current & next steps)



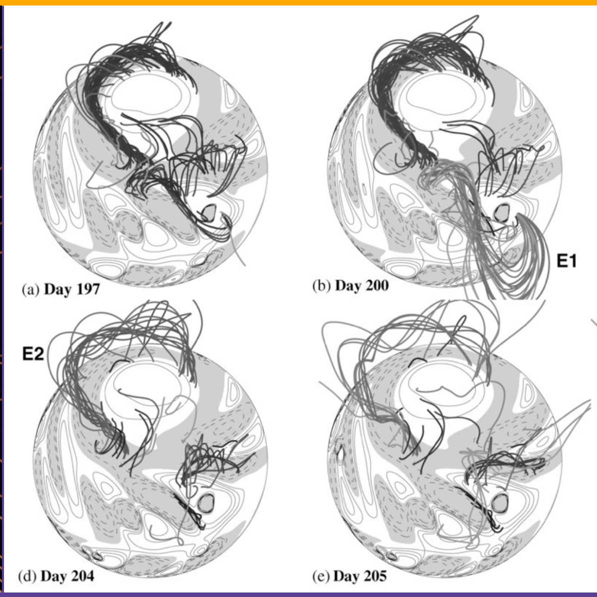
Karpen *et al.* (2012)



Baumann & Nordlund (2012)



Roussev *et al.* (2012)



Yeates & Mackay (2009)

- Adaptive mesh refinement → improve modeling of reconnection, shocks, etc.
- Couple MHD and PIC (kinetic) codes → modeling of particle acceleration
- Couple FE or NLFFF & CME models → more realistic pre-eruption configurations
- Develop evolutionary MHD models → overcome present “static” modeling of corona

  → simulate CMEs in real time

Summary

- MHD simulations are a powerful tool to model solar eruptions, but:
    - initiation, coupling & evolution of eruptions still not well understood
    - we cannot yet use simulations to predict eruption onset, interaction & impact

→ more idealized simulation studies needed to:

- better understand initiation and driving mechanisms
- derive quantitative onset (instability) thresholds

→ improve realistic simulations

- need to become more efficient & accurate
- extend models by, e.g., including observed flows & flux evolution

- other improvements: e.g. produce more realistic initial configurations by coupling to flux emergence simulations or NLFFF extrapolations