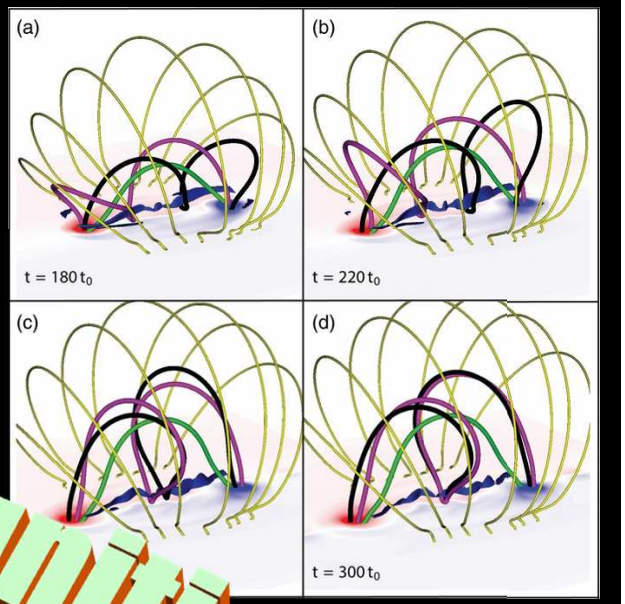
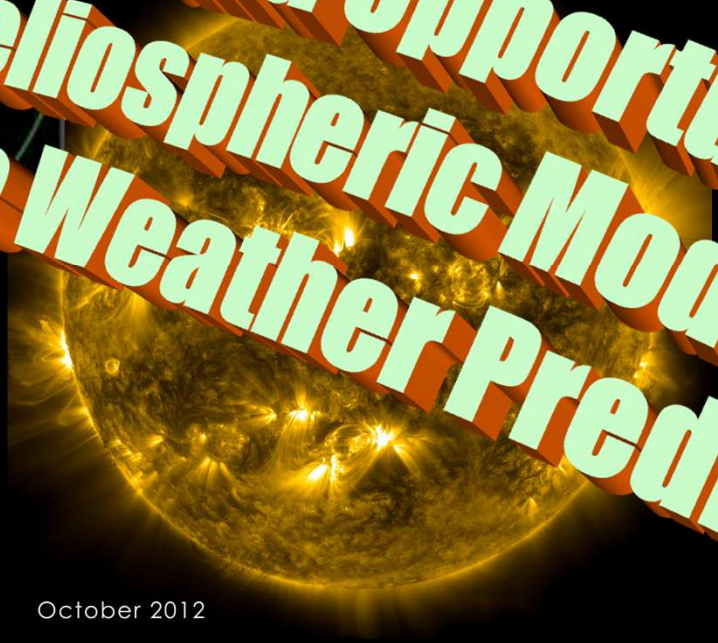
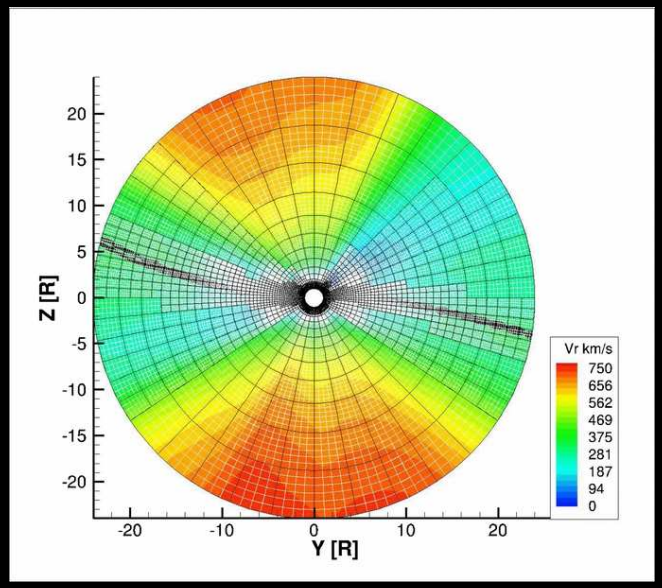


Challenges and Opportunities in Solar-Heliospheric Modeling For Space Weather Prediction





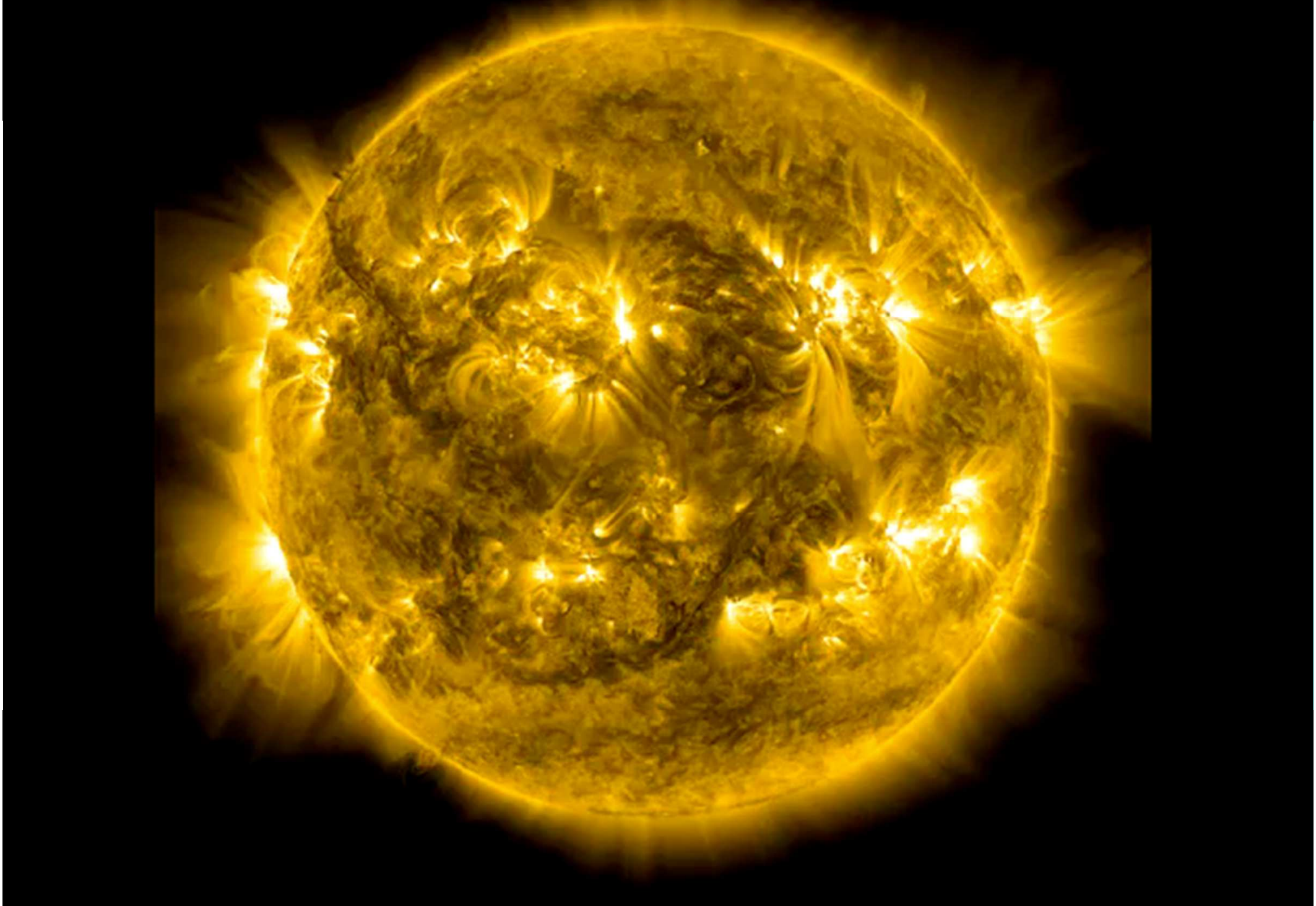
Judy Karpen
NASA GSFC

HSD

ISWI 2017
3 August 2017

- The Sun: origin of all space weather
- Why is modeling important?
- Modeling for understanding
- Modeling for forecasting
- Challenges to solar-heliospheric modeling
- The way forward

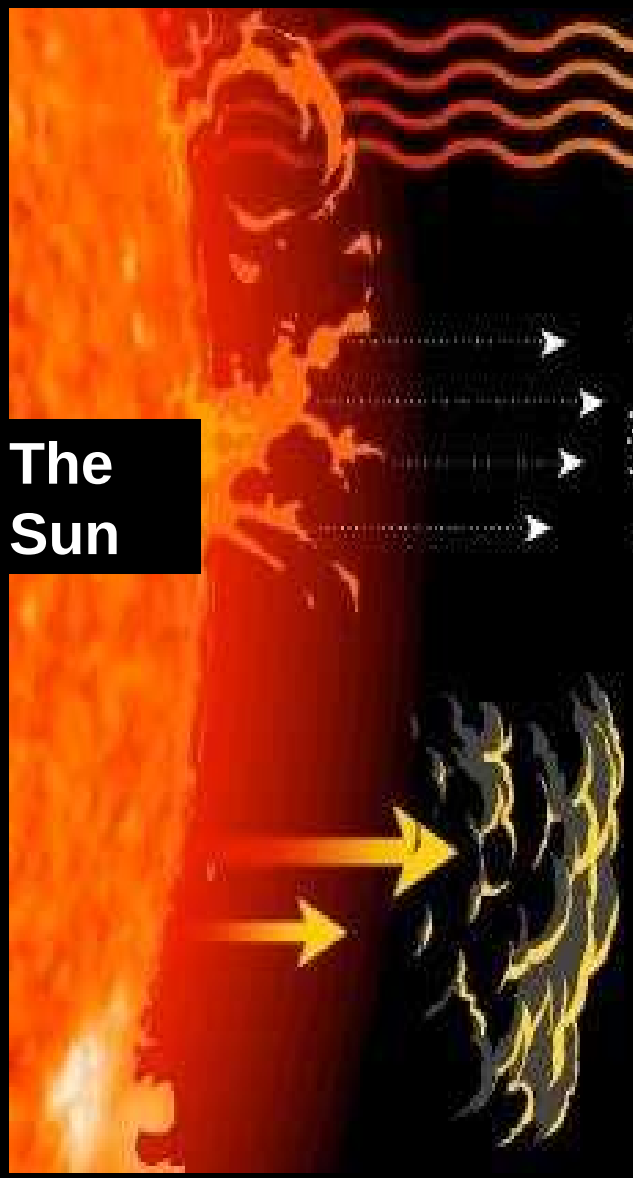
The Sun: Origin of All Space Weather



The Sun: Origin of All Space Weather

- **“Quiet” Sun affects space weather**
  - Active regions around sunspots emit strongly in UV/EUV
  - Weak vs strong solar cycle
- **Solar wind affects space weather**
  - Fast wind comes from open fields (coronal holes)
  - Slow wind comes from open-closed boundary (?)
  - Any point in or near the ecliptic plane can be bathed in fast or slow wind, at a given time.
  - Strong fast wind can cause geomagnetic storms!

Solar eruptions REALLY affect space weather



1) X-rays/EUV

Flares emits X-rays and EUV radiation. Reaches Earth in 8 min

2) Solar Energetic Particles (SEPs)

Particles are accelerated to extremely high energies from shocks driven by solar eruptions. Reach Earth in 15-60 min

3) Coronal Mass Ejection (CME)

Cloud of charged particles and magnetic fields ejected into space.

Reaches Earth in 1-3 days

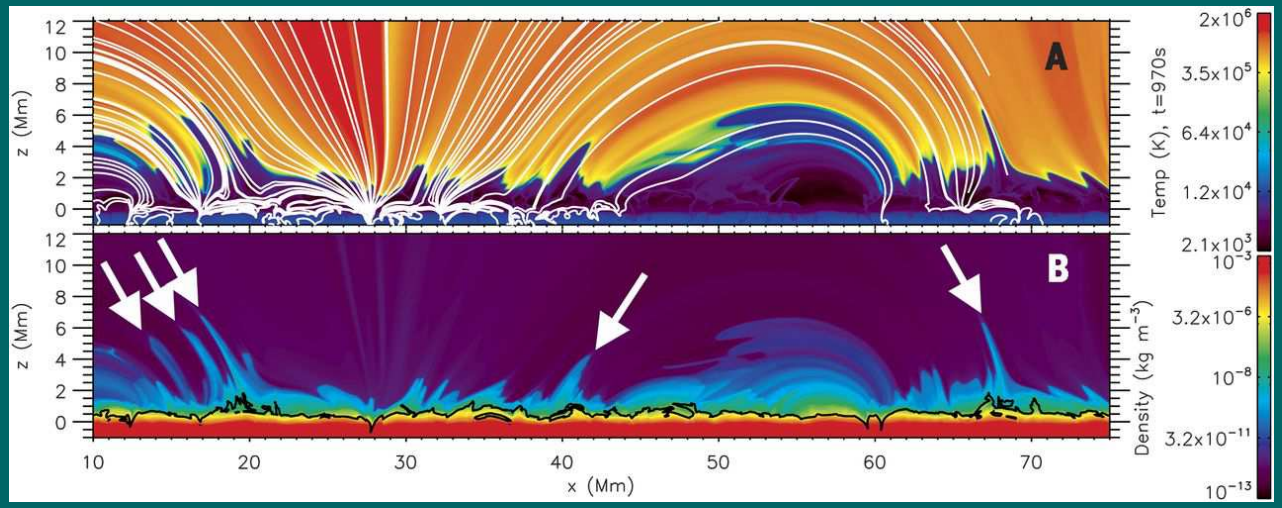
Why is modeling important?

- **To understand solar origins of space weather**
  - Solar dynamo/cycle
  - Solar eruptions (flares and CMEs)
  - Solar wind (fast and slow)
- **To predict conditions from Sun to heliosphere**
  - When and where will an eruption occur?
  - When will an eruption + shock arrive?
  - What is the orientation of the eruption's magnetic field?
  - What is the likely impact of the eruption on geospace?
  - Environmental conditions in the IPM and at other planets

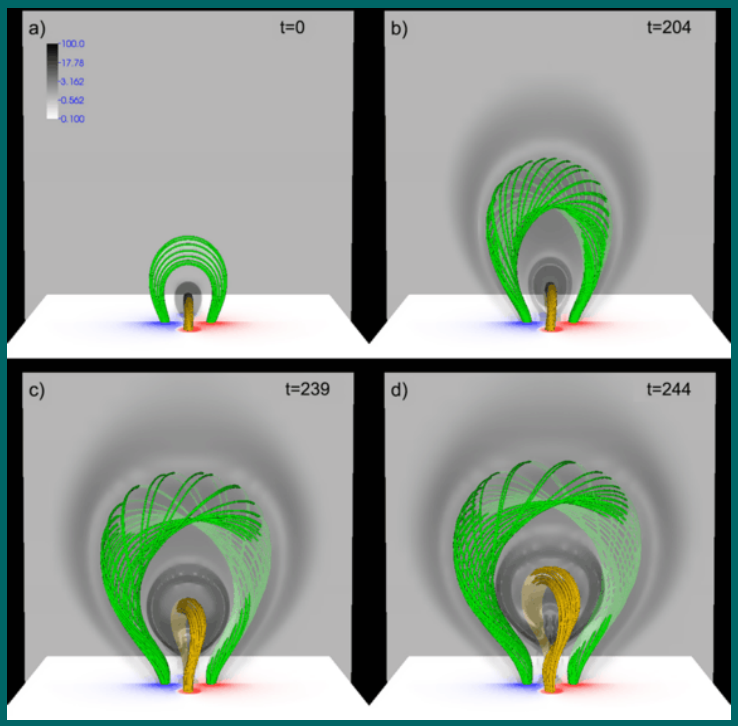
Modeling for Understanding: Current State of the Art

- **Magnetohydrodynamic (MHD) simulations of large-scale plasma + magnetic field**
  - 2D-3D, adaptive grids, divergence-free or cleaned
  - Gravitational stratification, thermodynamics (conduction, radiation, wave heating), partial ionization, ion-neutral coupling, multifluid, viscosity, resistivity, ambipolar diffusion, non-LTE, radiative transport
  - Data assimilation / driving
- **Kinetic simulations of particle dynamics and energetics in magnetic and electric fields**
  - 2D-3D, particle in cell (PIC), gyrokinetic, hybrid (MHD+PIC)
  - Multi-species, high mass ratio (p/e)

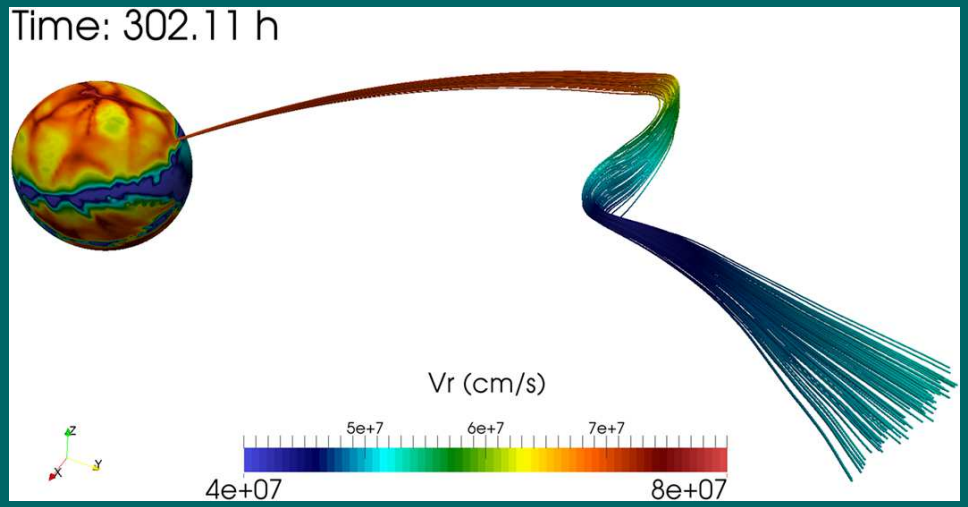
Examples



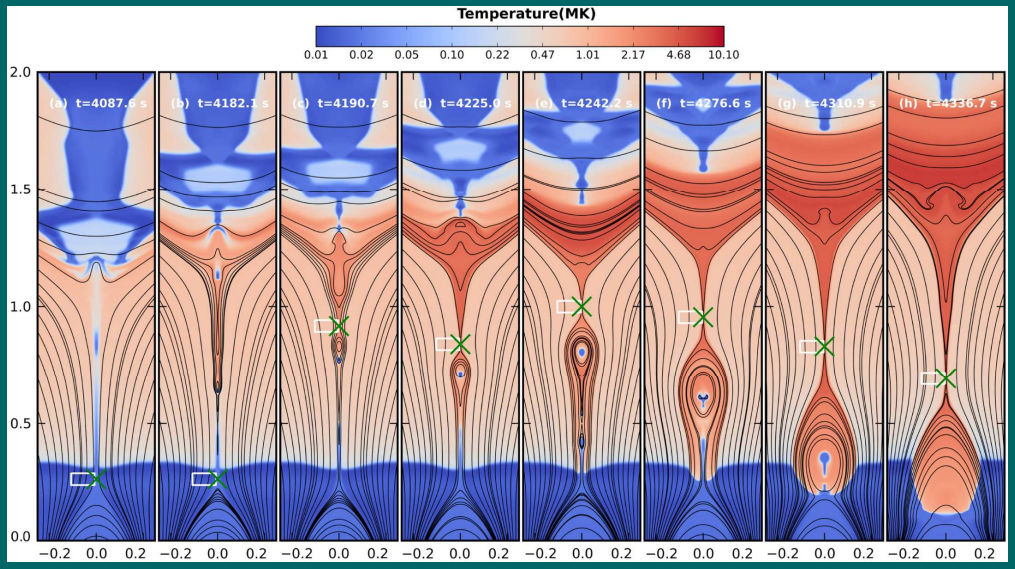
Bifrost



Torok-Kliem

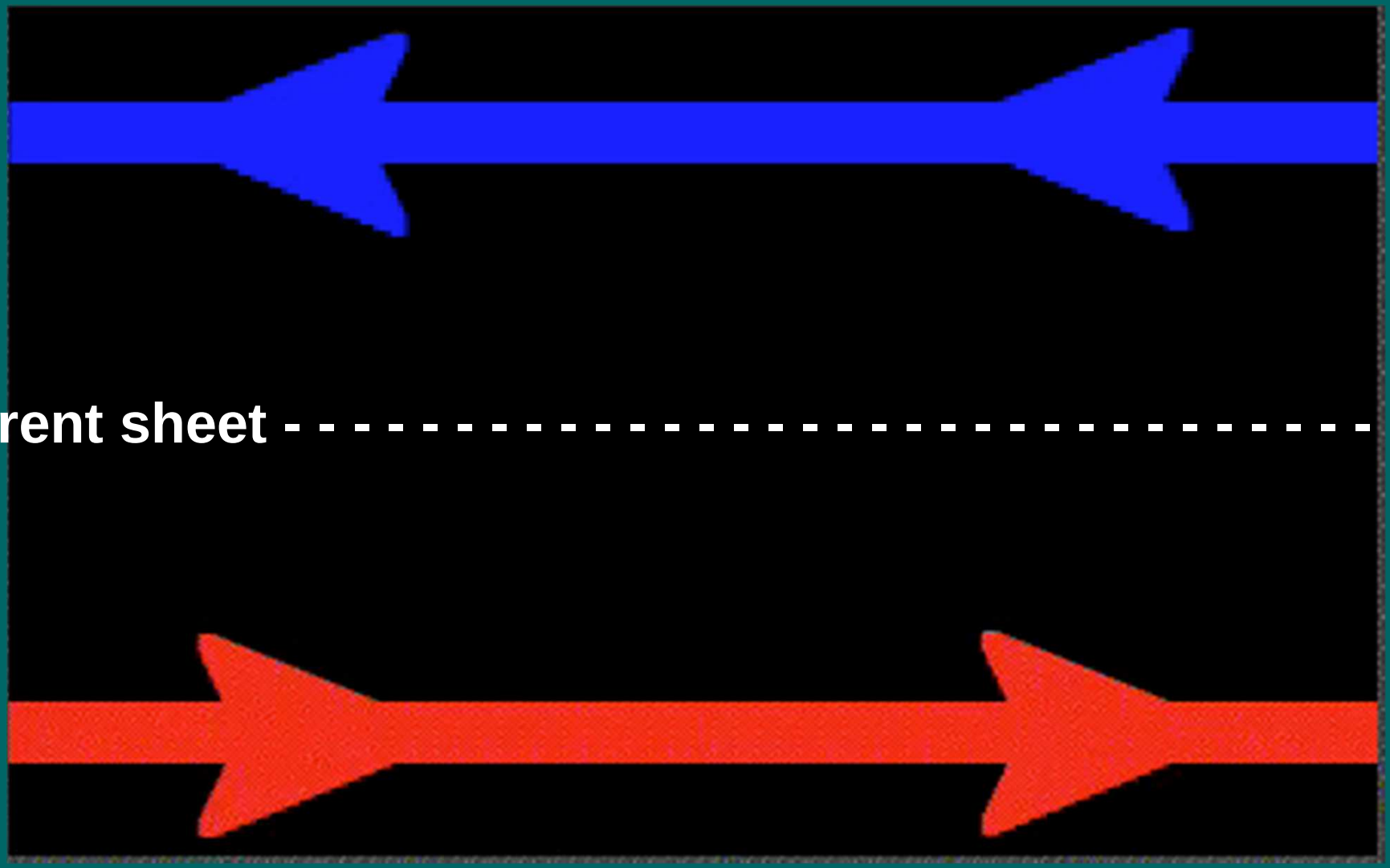


MAS + LFM-helio



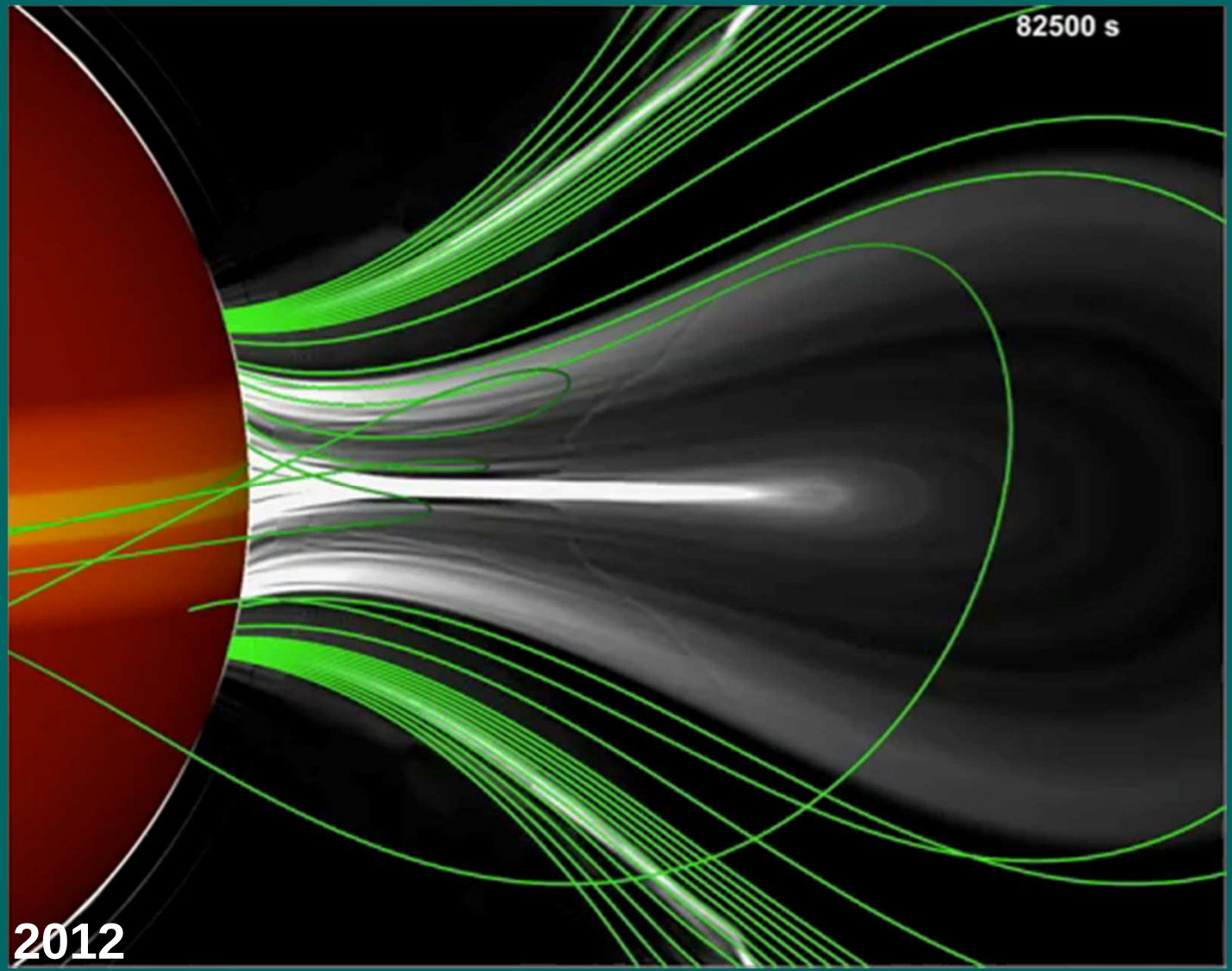
MPI-AMRVAC

Magnetic Reconnection 101



ARMS: CME/Flare Simulation

- Current sheet forms and thins
- Reconnection causes explosive dynamics
- Magnetic energy converted to motions, heating, **etc.**

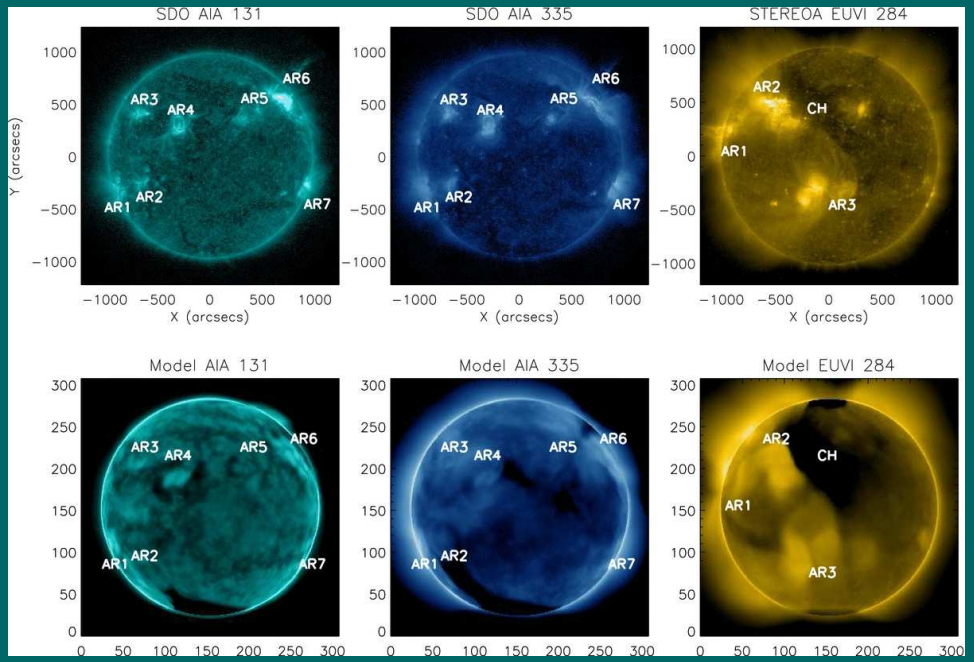


Karpen et al. 2012

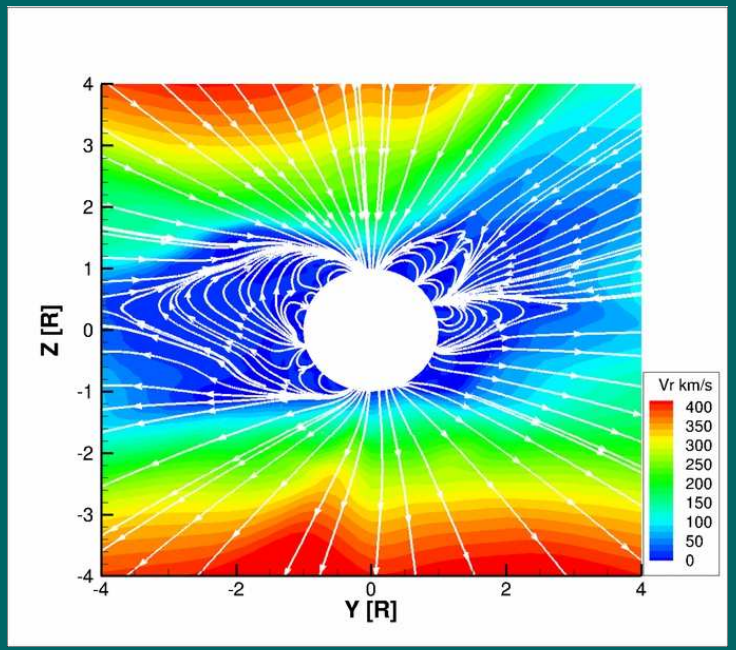
Modeling for Forecasting: Current State of the Art

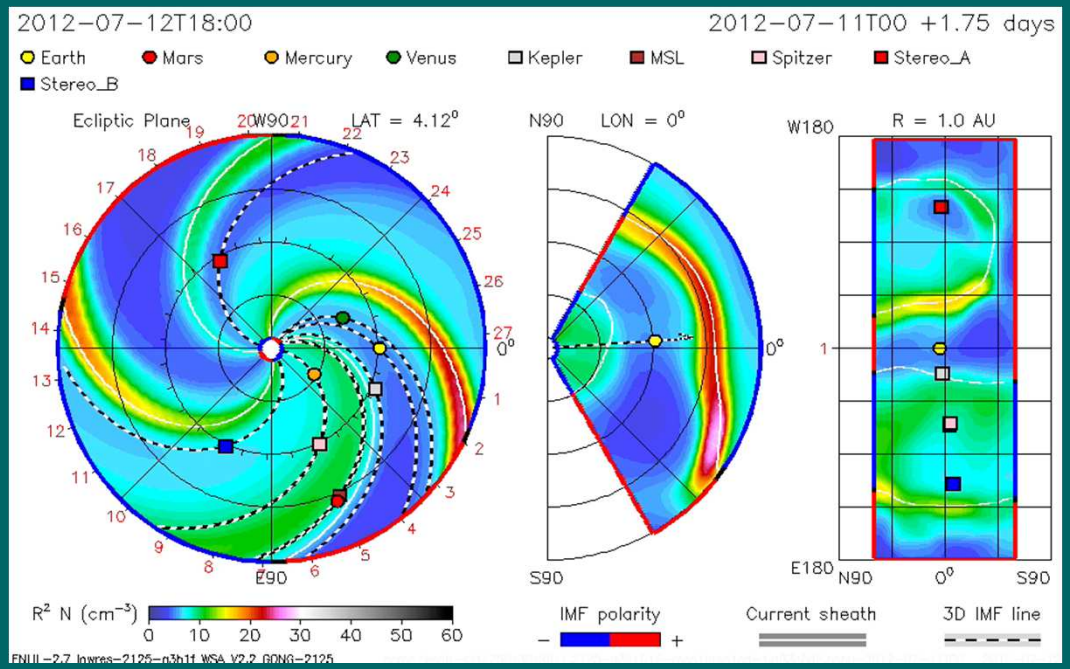
- **Semi-empirical models of solar wind**
- **MHD simulations of quiet solar corona & wind**
  - 3D magnetic field and plasma with thermodynamics
  - Data assimilation / data driven (from magnetograms)
- **MHD simulations of outer corona/heliosphere**
  - 3D magnetic field and plasma from >20 R_{sun} with solar wind, CME insertion at inner boundary (pressure pulse, magnetic flux rope)
  - Ensemble of multiple runs to establish uncertainties
- **Particle acceleration & transport in heliosphere**

Examples

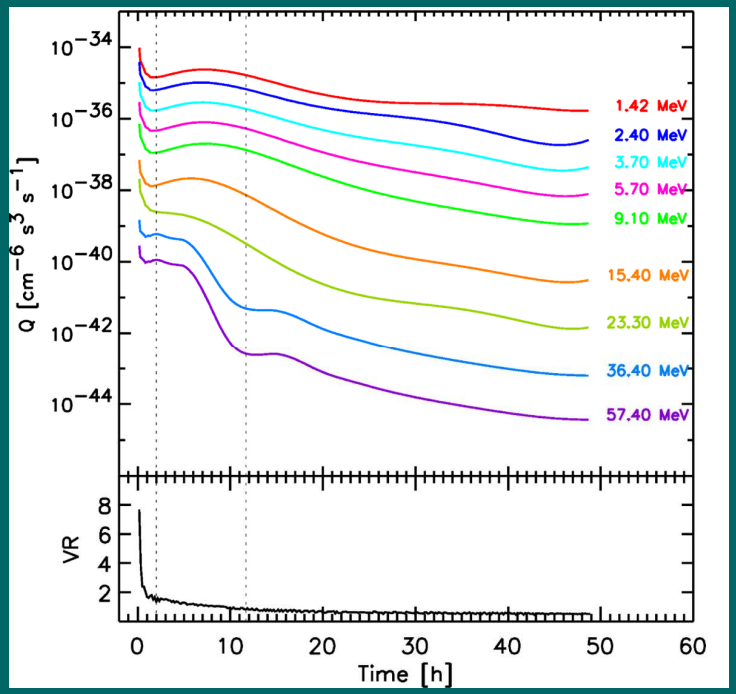


SWMF-AWSOM





ENLIL



SAP+SOLPENCO2+SEPEM

Challenges to Solar-Heliospheric Modeling

- **Trade-off: resolution vs system size/transit time**
- **Realistic treatment of inner boundary**
  - Steep gradients between photosphere and corona
  - Evolving photospheric or coronal magnetic field
- **Faster than real-time forecasting**
  - Code optimization and hardware limitations, reliability
- **Which physical processes must be included?**
  - Depends on phenomena being predicted
- **Can one model do it all?**

The Way Forward

- **Combination of observations, theory, and numerical modeling is needed to make progress on the key issues**
- **International cooperation is essential – 24 hr monitoring, huge data downloads, massive code development, modeling centers, and expensive space missions require multinational teamwork.**
- **Urgent need to attract and train the next generation of model builders – current generation is about to retire!**