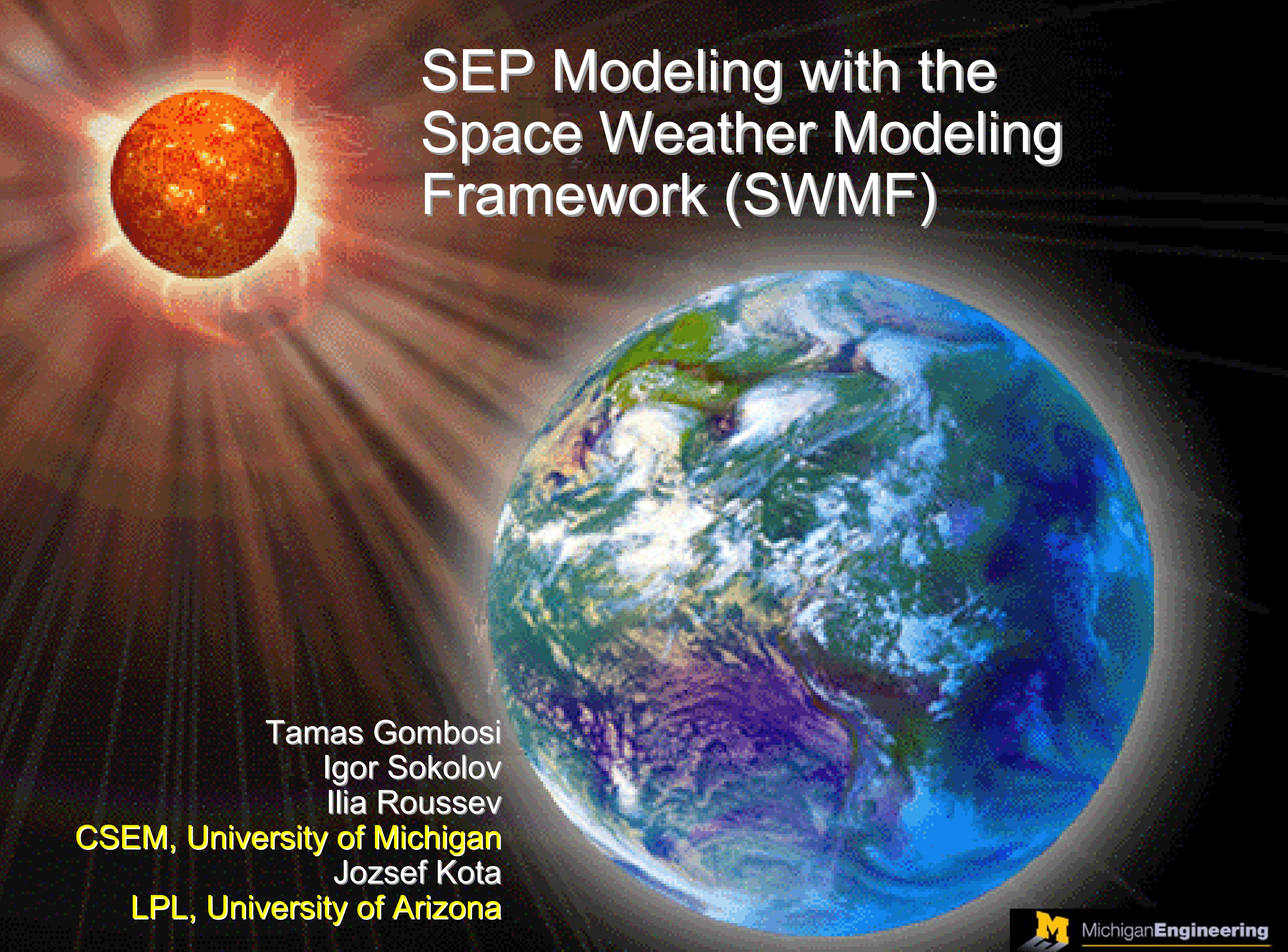
SEP Modeling with the Space Weather Modeling Framework (SWMF)



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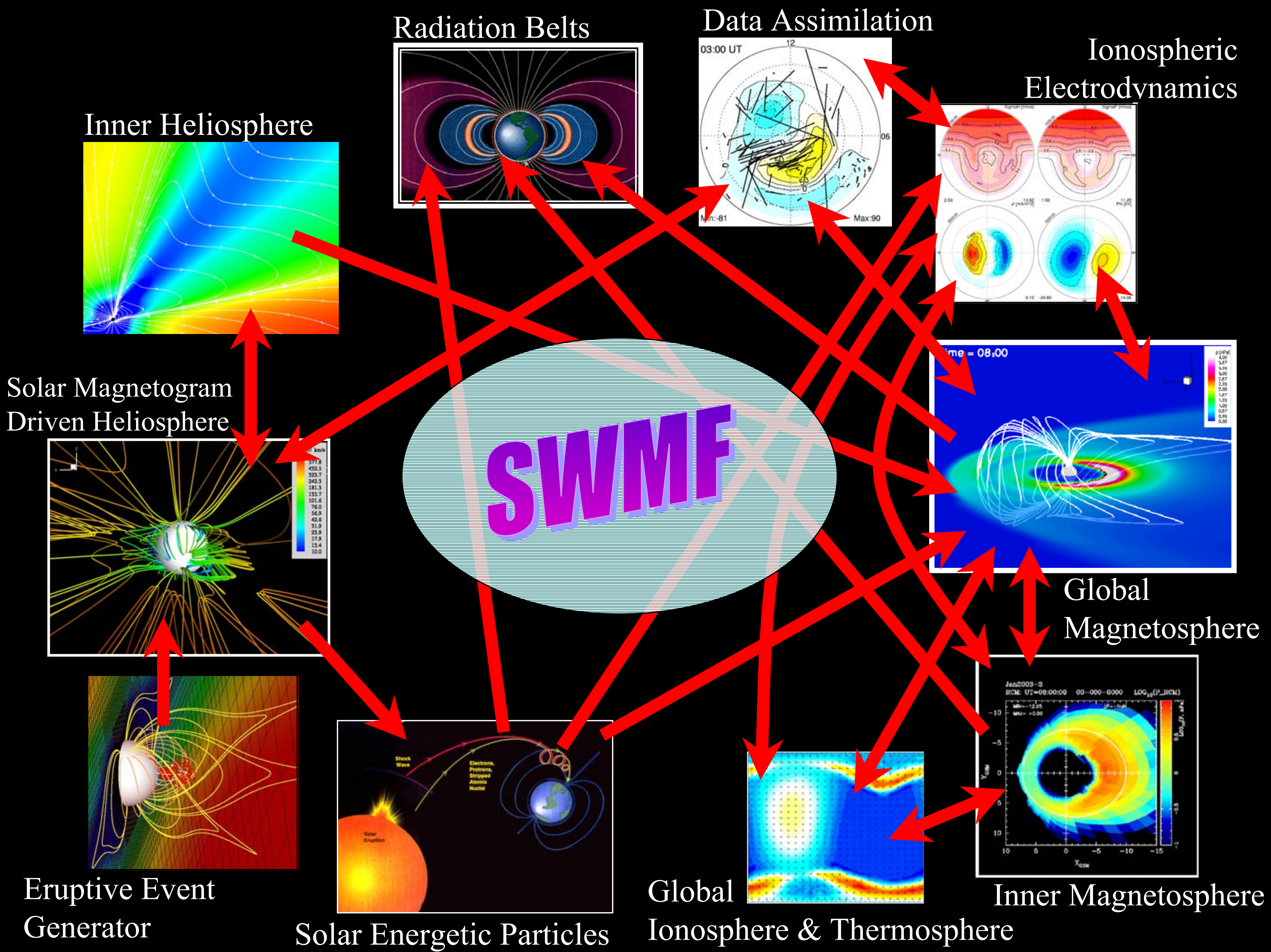
Outline

- The Space Weather Modeling Framework
  - Code coupling
  - BATS-R-US
  - SEP model
- The May 2, 1998 halo CME
  - Magnetogram driven CME generation
  - Shock analysis
  - Analytic SEP model
- Coupled CME-SEP simulation
  - CME from 1 Rs to 1 1 AU
  - Field line extraction
  - SEP time profiles and spectra
- Summary and future work



Radiation Belts
Data Assimilation
Ionospheric Electrodynamics
Inner Heliosphere
Solar Magnetogram Driven Heliosphere
SWMF
Global Magnetosphere
Eruptive Event Generator
Solar Energetic Particles
Global Ionosphere & Thermosphere
Inner Magnetosphere

BATS-R-US

- Physics
  - Semi-relativistic MHD (Alfvén speed is limited by c)
  - Four $\nabla \cdot B$ control methods (8 wave, projection, diffusion, CT)
  - Conservative, tightly coupled formulation
- Finite volume scheme
- High-resolution upwind scheme
  - Upwind differencing
  - Limited linear reconstruction
  - Approximate Riemann solver (Roe, Rusanov/Lax-Friedrichs, Linde, AW)
- Explicit, implicit and explicit/implicit time-stepping
- AMR & data structure
  - Adaptive self-similar blocks
  - Octree data structure
- Parallel implementation
  - Fortran-90 with MPI
  - Near-perfect parallel scaling to >1500 PEs

SEP Model

- Field-aligned Fokker-Planck equation
  - Distribution function function, f(x,p,μ,t), depends on position, energy-spectrum, pitch-angle distribution, time-profile.
  - Physical processes: convection, focusing, acceleration/cooling, pitch-angle scattering, injection
- Finite-difference ADI numerical method
- Grid follows field line as CME evolves. Quantities r,V,n,B taken from CME simulation. Can handle realistic CME.
- CME simulation (Manchester et al., 2004) indicates that shock is not a simple parallel shock. Efficient acceleration occurs at quasi-perpendicular compression as B drapes around CME.

Field-aligned Fokker-Planck Equation

Fluid frame: $\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla$

scattering

F-P eq: $$\frac{Df}{Dt} + w\mu\frac{\partial f}{\partial s} + \left\langle \frac{\Delta\mu}{\Delta t} \right\rangle \frac{\partial f}{\partial \mu} + \left\langle \frac{\Delta w}{\Delta t} \right\rangle \frac{\partial f}{\partial w} = \frac{\partial}{\partial \mu}\left(\frac{1}{2}D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) + q$$

Injection

Focusing $$\left\langle \frac{\Delta\mu}{\Delta t} \right\rangle = \frac{1-\mu^2}{2}\left[\frac{w}{L} - \frac{2}{w}b_i\frac{DV_i}{Dt} + \mu\frac{D\ln\left(n^2/B^3\right)}{Dt}\right]$$

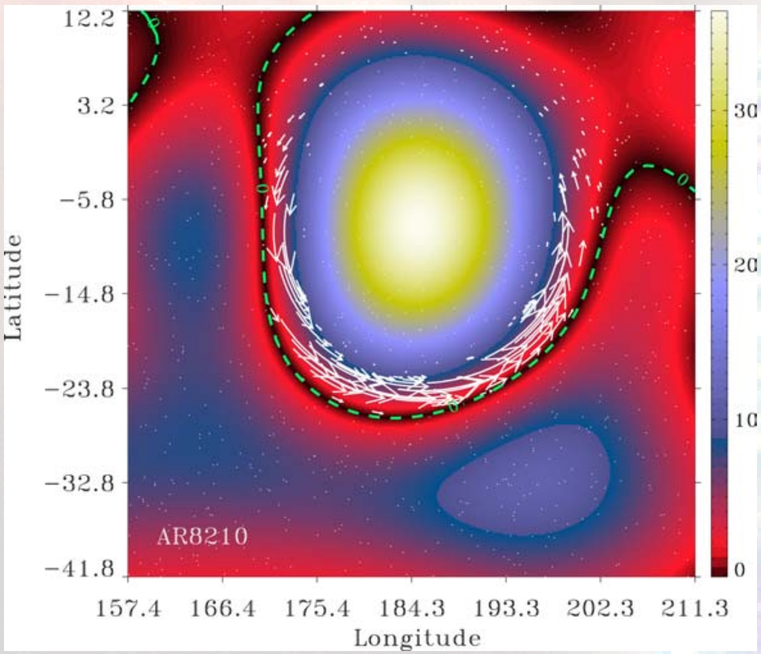
Acceleration: $$\left\langle \frac{\Delta w}{\Delta t} \right\rangle = -\mu b_i\frac{DV_i}{Dt} + w\mu^2\frac{D\ln\left(n/B\right)}{Dt} + \frac{w\left(1-\mu^2\right)}{2}\frac{D\ln B}{Dt}$$

Parallel

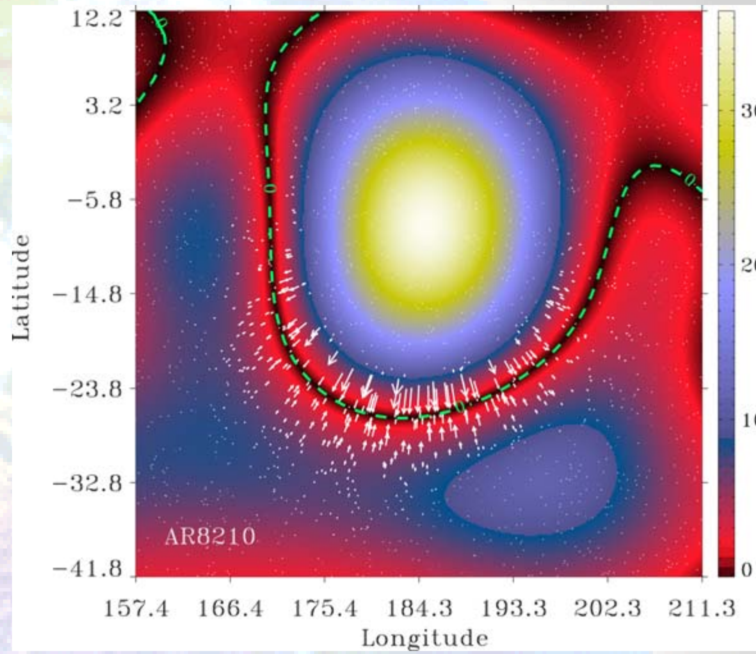
perpendicular

Boundary Motions

Map of the radial magnetic field strength (in units of Gauss), and structure of the boundary motions near the polarity inversion line (dashed line in green) of AR810



Shear motions representing sunspot rotation

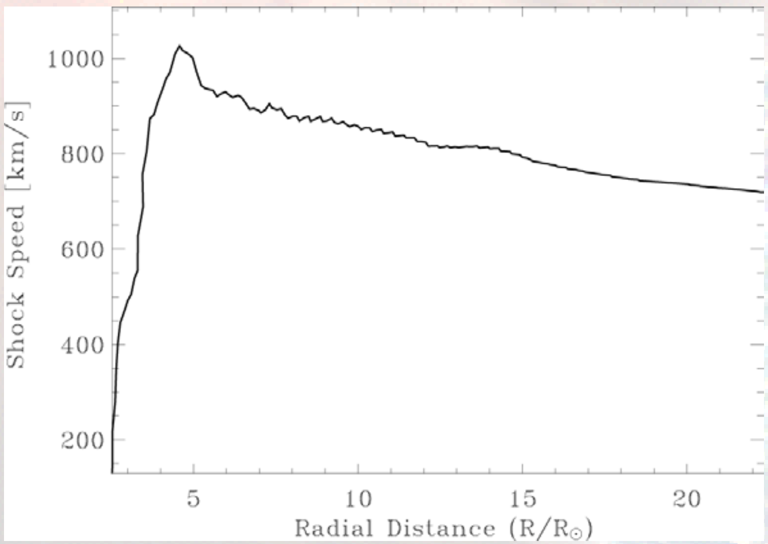


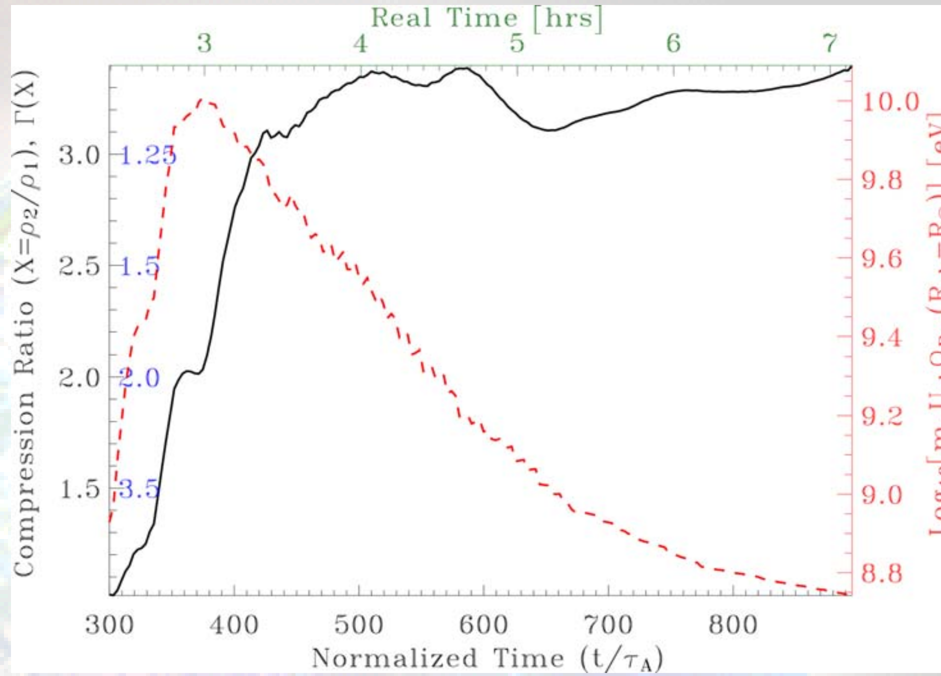
Converging motions resembling emergence of new magnetic flux

QuickTime™ and a
BMP decompressor
are needed to see this picture.

QuickTime™ and a
PNG decompressor
are needed to see this picture.

Acceleration of Solar Protons at CME-driven Shock





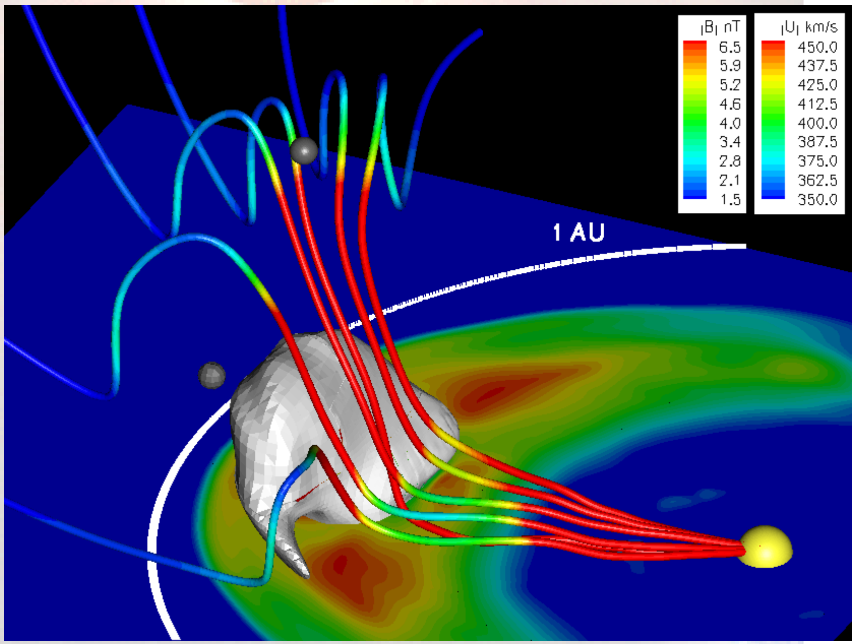
Compression ratio of the shock and the proton cut-off energy predicted by diffusive-shock-acceleration theory. Interior labels along left axis indicate the spectral index for the non-relativistic particle flux used in the theory: Γ=0.5(X+2)/(X-1).

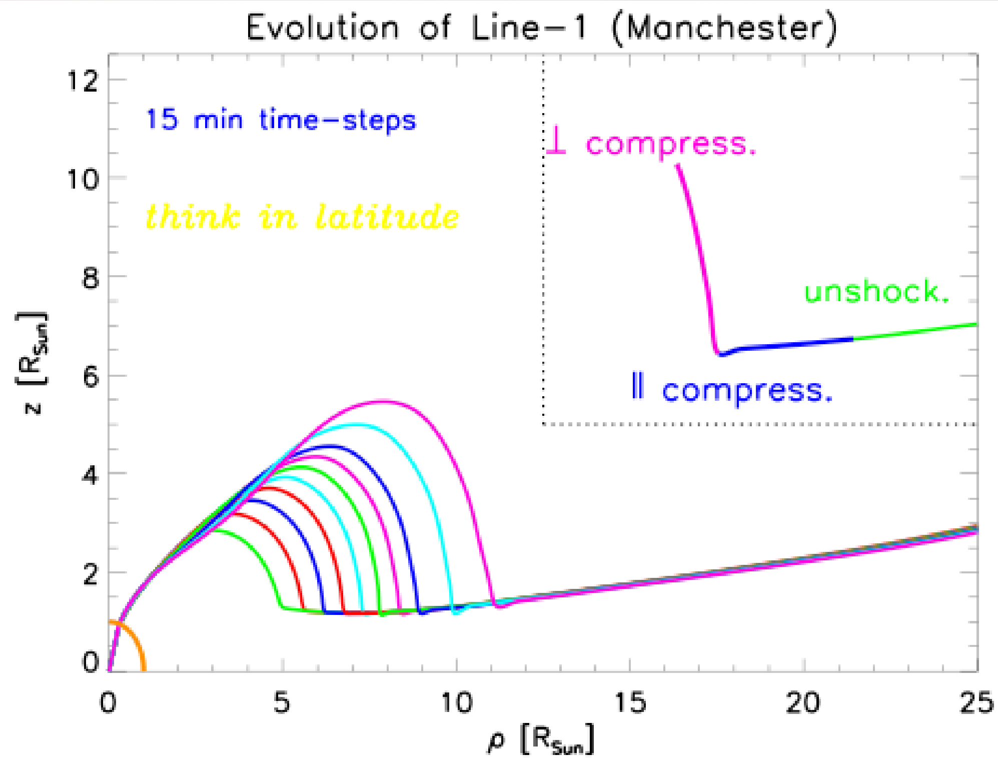
Eruption of a Gibson-Low Flux Rope (Manchester et al.)

QuickTime™ and a
PNG decompressor
are needed to see this picture.

- The movie shows a 2D cut through the center of the CME showing the expansion and propagation of the CME from 1 Rs to Earth.
- The leading edge of the CME arrives to Earth at t=68 hours. At this point time freezes and the movie shows a 200-fold zoom of the view.
- The initial frame at this point of time is about 1 AU wide, the final frame at the end of the zoom is 0.75 Rs = 80 Re wide.
- At the end of the zoom the leading shock arrives and compresses the magnetosphere. This is a good representation of the scales in the heliosphere and it also shows the computational challenge.

CME at 1 AU

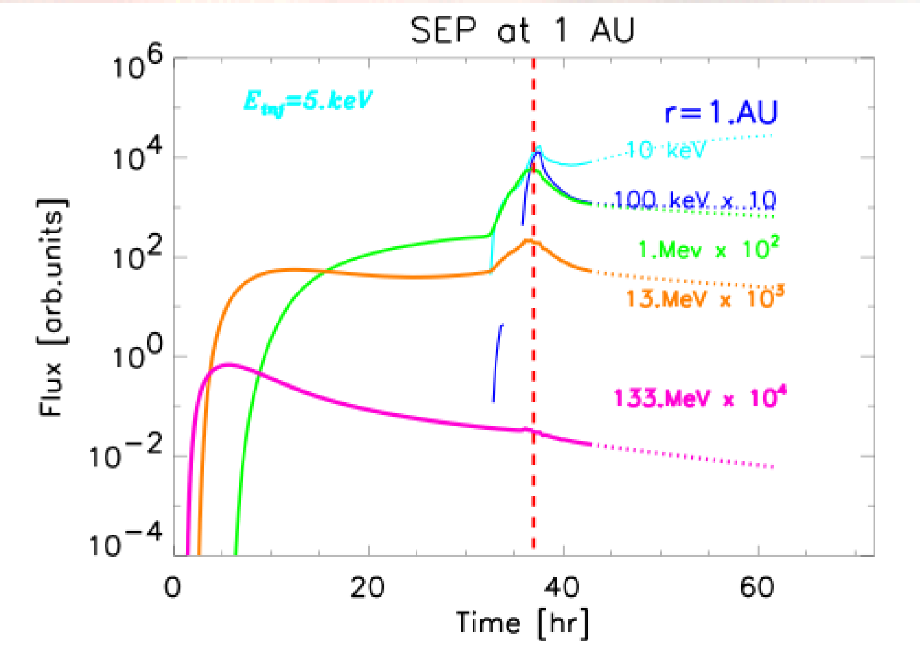


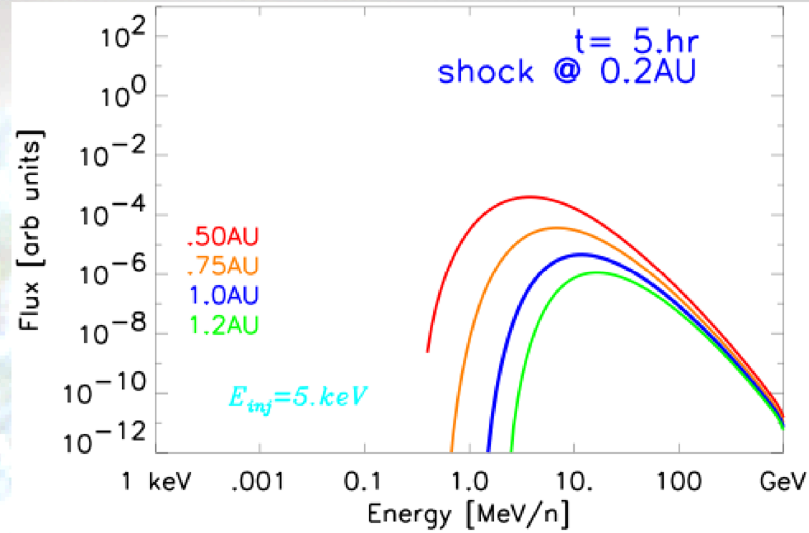


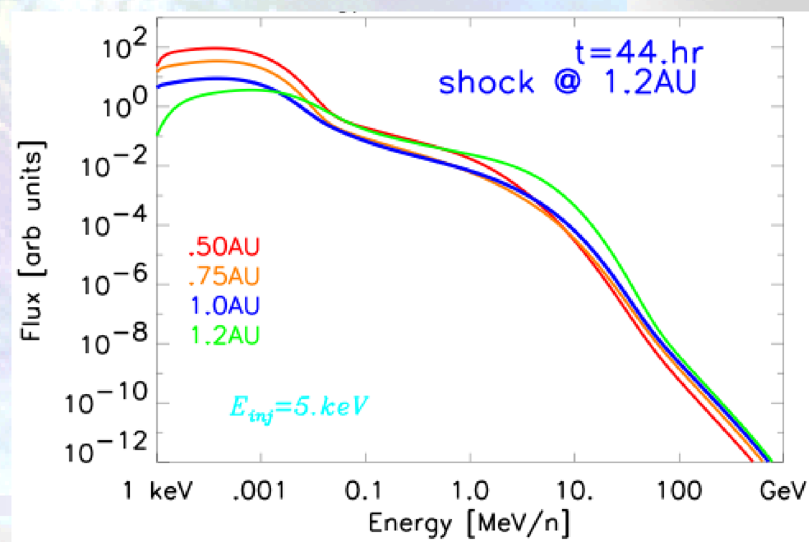
- Note the stronger magnetic field at the deflection.
- We get more acceleration than with a simple parallel shock.

Time-Profile at 1 AU for Different Energies

For space weather purposes we estimate the penetrating component of the SEP population (~20 MeV/n can penetrate 2 mm Al)







- Particles are injected at about 5 keV.
- The important part of the time profile is the evolution before the arrival of the shock

Summary and Future Work

- Space Weather Modeling Framework is working
  - High-resolution MHD simulation is coupled with kinetic equation for SEP transport along magnetic field lines.
  - Motion of magnetic field lines is traced.
- Physical requirements to numerical models of solar eruption:
  - Initial conditions should not produce shock wave as result of strong initial non-equilibrium;
  - However, solar eruption should be sufficiently energetic, rather violent, to form strong shock wave in Sun’s proximity.
- Prototype is working
  - Investigate flexibility and robustness
  - Predictive capability
  - User friendly GUI