3D Modeling of Coronal Acceleration and Transport of Solar Energetic Protons

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Motivation

- In situ SEP fluxes a convolution between changes at acceleration region and inteplanetary propagation conditions.
- 1 AU particle observations of early stages – little information about acceleration region dynamics, efficiency, location, etc.
- No in situ observations near the Sun yet, so need models to explore coronal SEP acceleration, especially since improved CME observations (STEREO, AIA)
- SEP acceleration and transport lower in the corona has been studied by e.g., Vainio & Laitinen (2008), Kocharov et al. (2011)
- Few studies of particle acceleration in realistic CME models (Sokolov et al., 2004; Kota et al., 2005)
- We investigate proton acceleration by combining a global 3D MHD CME model with a global particle acceleration and transport model – can probe the 3D aspect of acceleration and effects of CME dynamics on protons
- We modeled the May 13, 2005 CME and SEP event.

Models and Coupling

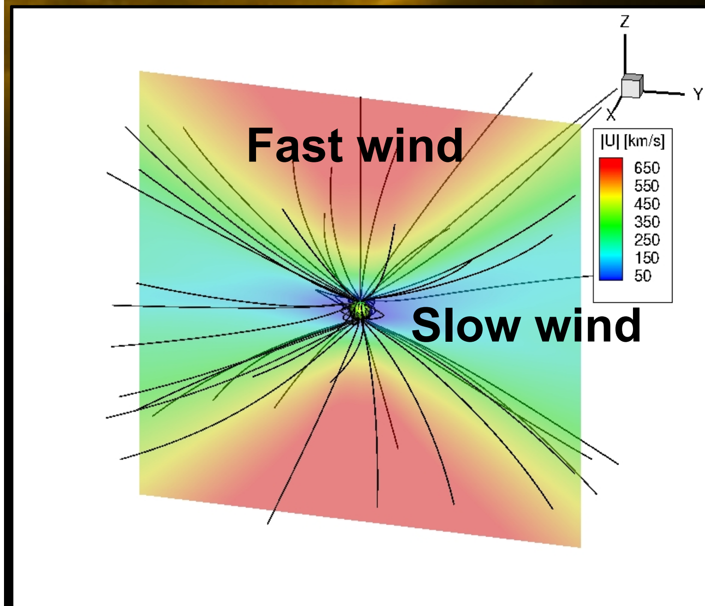
<u>3D MHD coronal model:</u> Block Adaptive Tree Solar-Wind Roe Upwind Scheme code (BATSRUS; Toth et al., 2011)

- Parallelized code with adaptive mesh refinement; developed at U Michigan

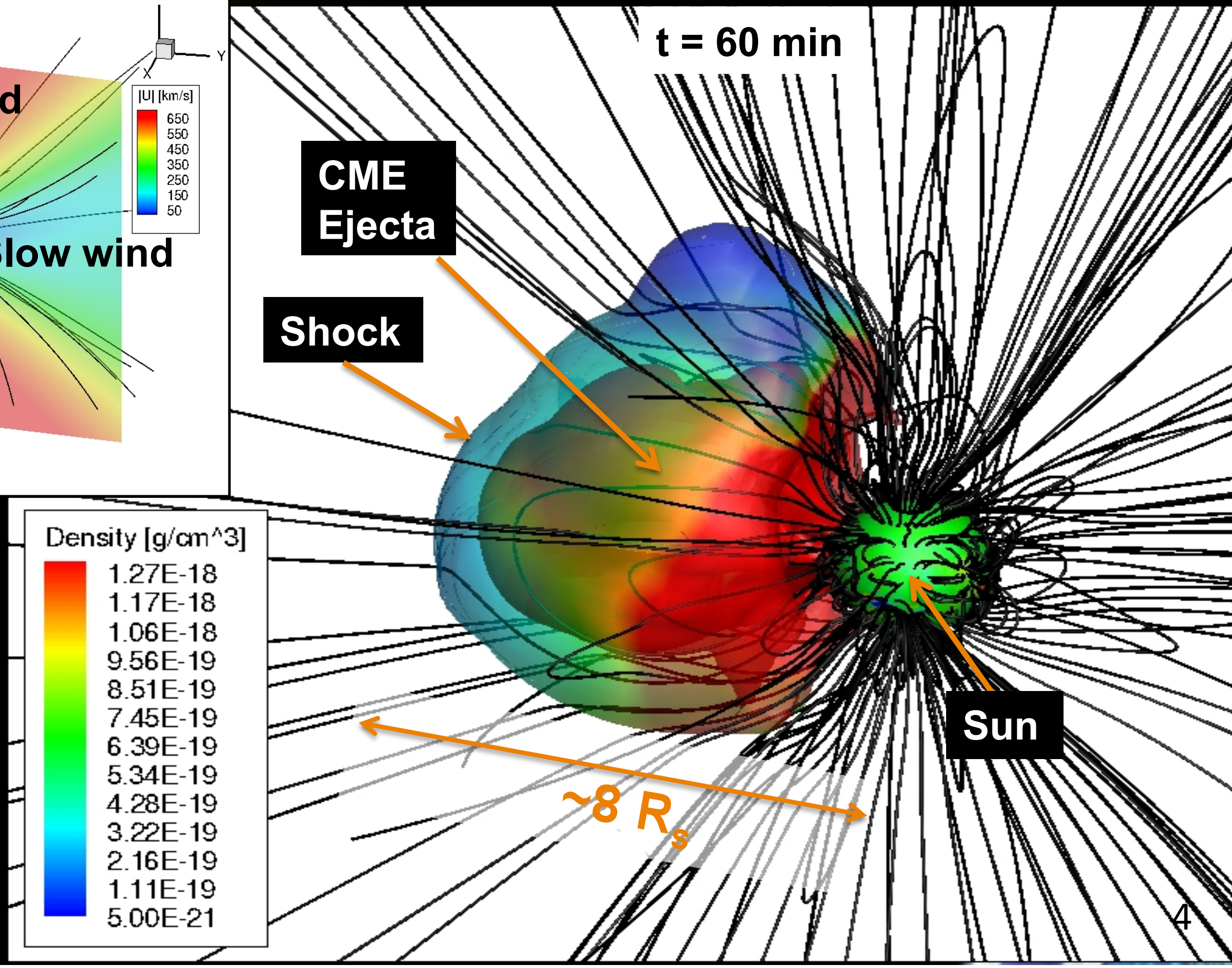
- Solar wind acceleration via surface Alfven wave damping (van der Holst et al., 2010; Evans et al., 2012)

- CME modeled by a Titov-Demoulin out-of-equilibrium flux rope (Titov & Demoulin, 1999)

BATSRUS Simulation



Results from the MHD simulation of May 13, 2005 CME



Models and Coupling

3D kinetic particle model: Energetic Particle Radiation Environment Module (EPREM; Schwadron et al., 2010)

• Global numerical particle acceleration and transport model; developed at Boston University and University of New Hampshire

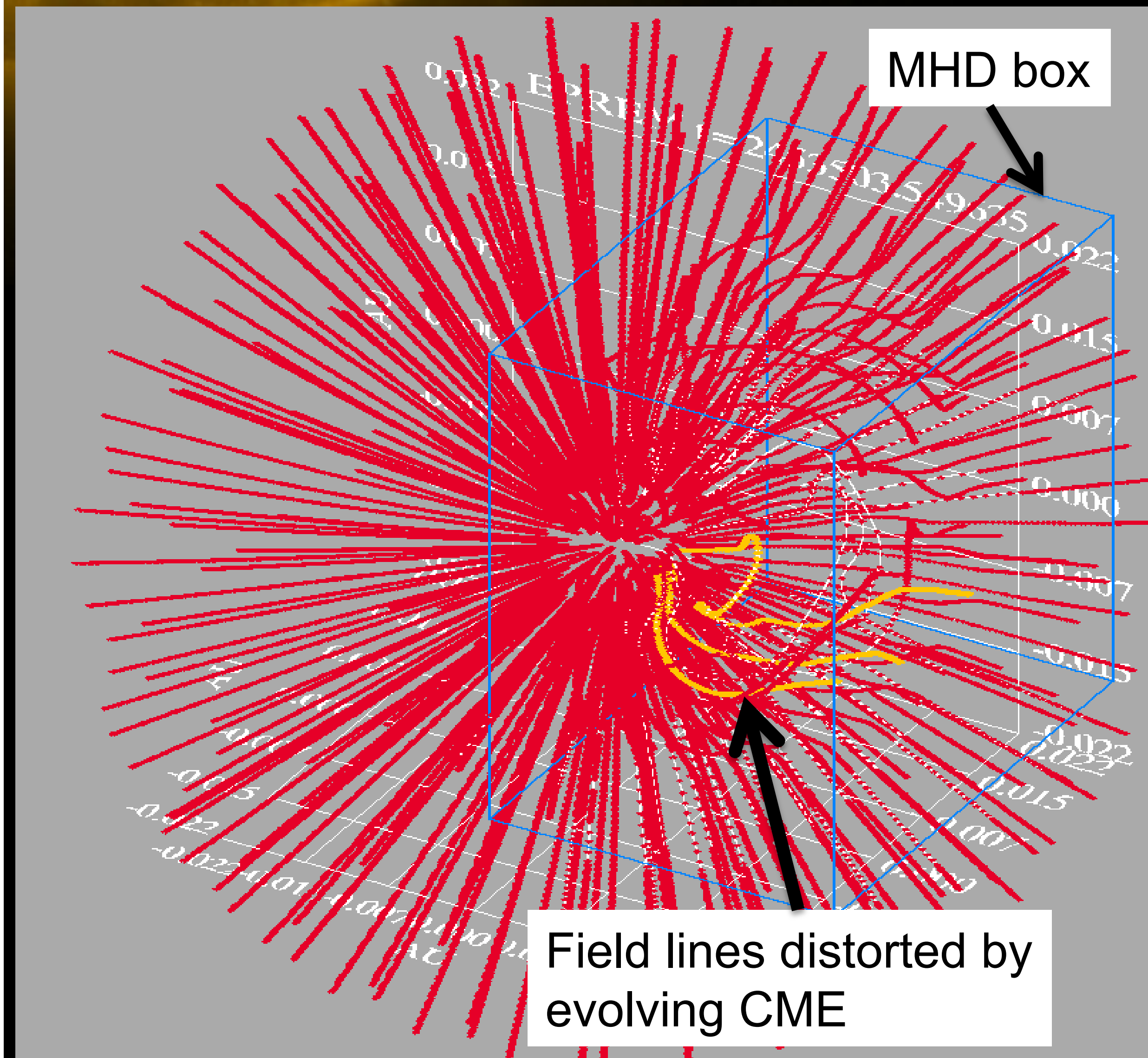
• Employs the transport equation recast in the solar wind frame (Kota et al., 2005)

• Considers effects of streaming, convection with the solar wind, adiabatic cooling and heating, pitch-angle focusing and scattering, and stochastic acceleration

• 3D Lagrangian grid of nodes embedded in solar wind flow simplifies computation

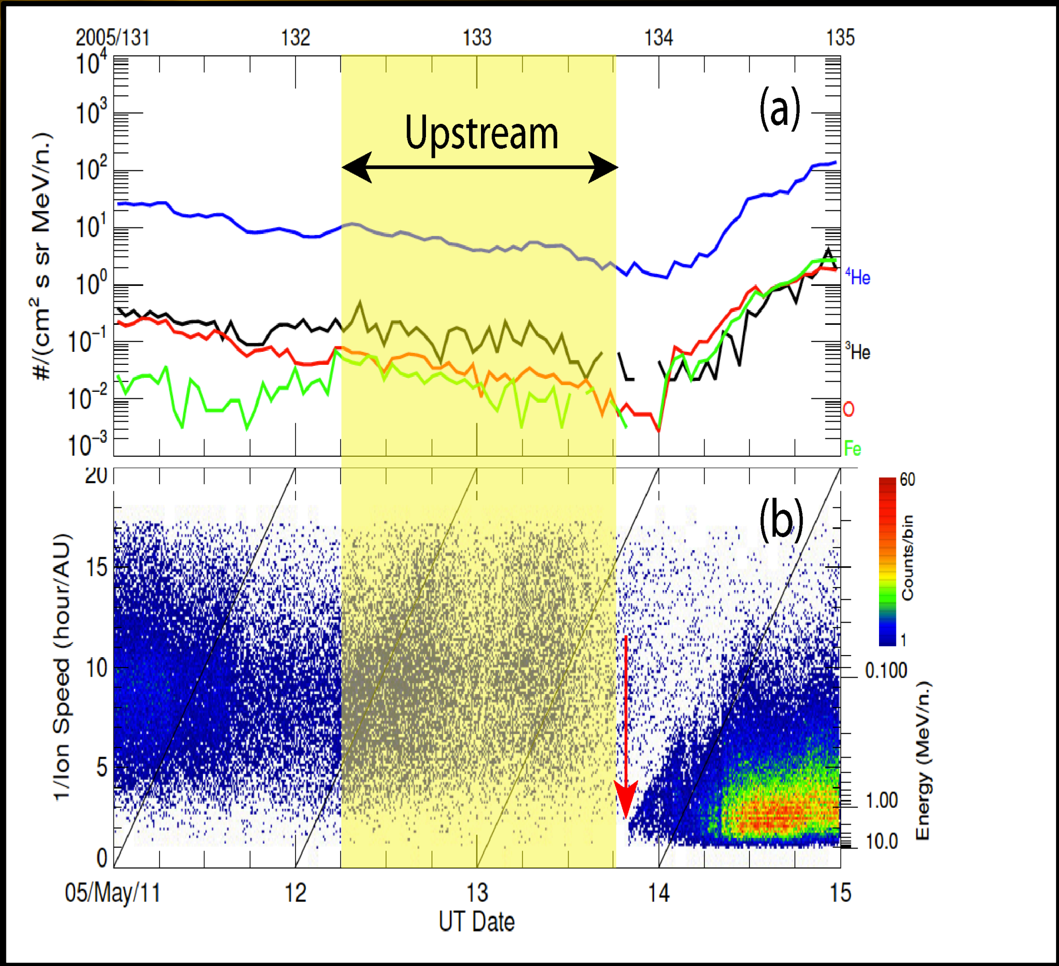
• Parallel mean free path scales with radial distance and rigidity (Li et al., 2003)

Coupling EPREM to BATSRUS



- Time-dependent one-way coupling
- Every ~2 min extract a box of regularly gridded MHD cells surrounding the CME.
- Grid cell is 0.092 R_s
- MHD information at EPREM nodes updated by interpolation in 3D

Suprathermal source population



-Used quiet time Helium observations at 1 AU 1.5 days before May 13 event

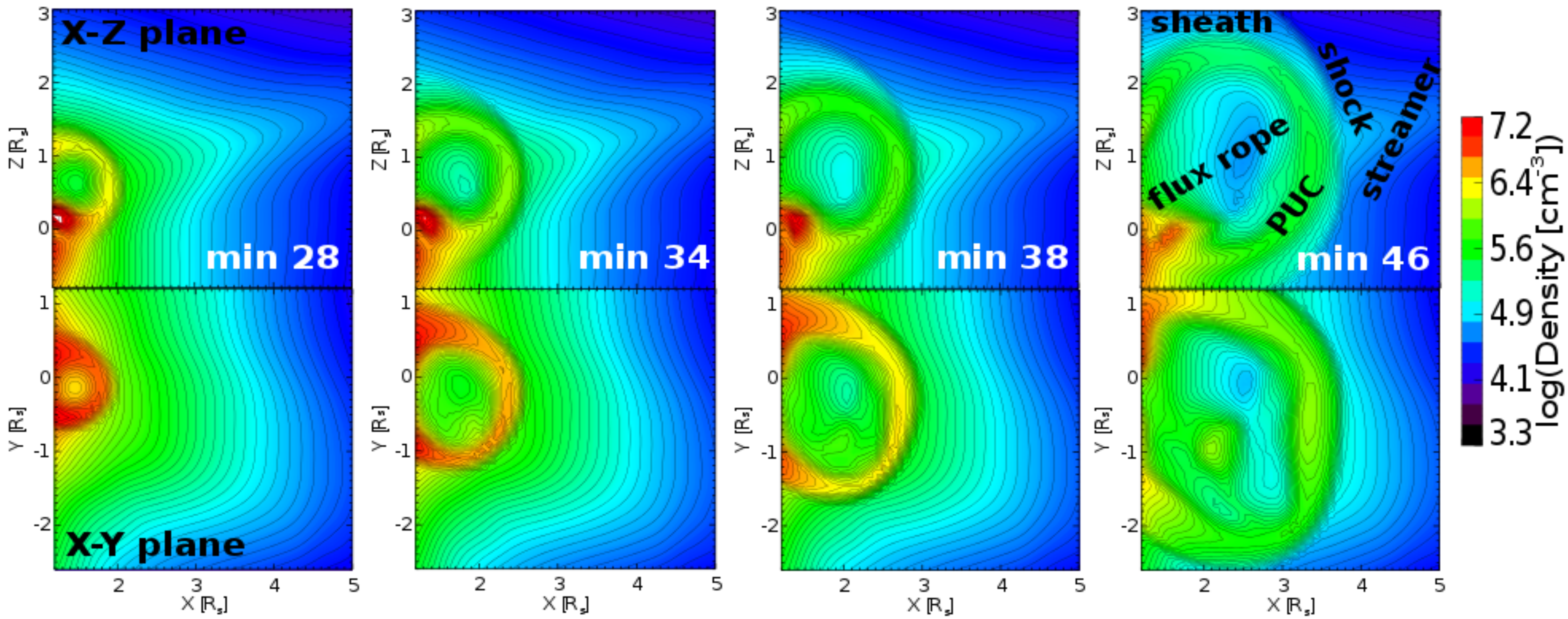
-Obtained spectrum between 0.1 and 1.0 MeV/nuc

-Scaled to 1.5 R_s assuming $1/r^2$ flux dependence

-Scaled to hydrogen spectrum assuming 10% He abundance

-Beyond 1.0 MeV assumed exponential rollover of spectrum (very steep decay of the fluxes)

Coronal and CME Density: **Inner Region**

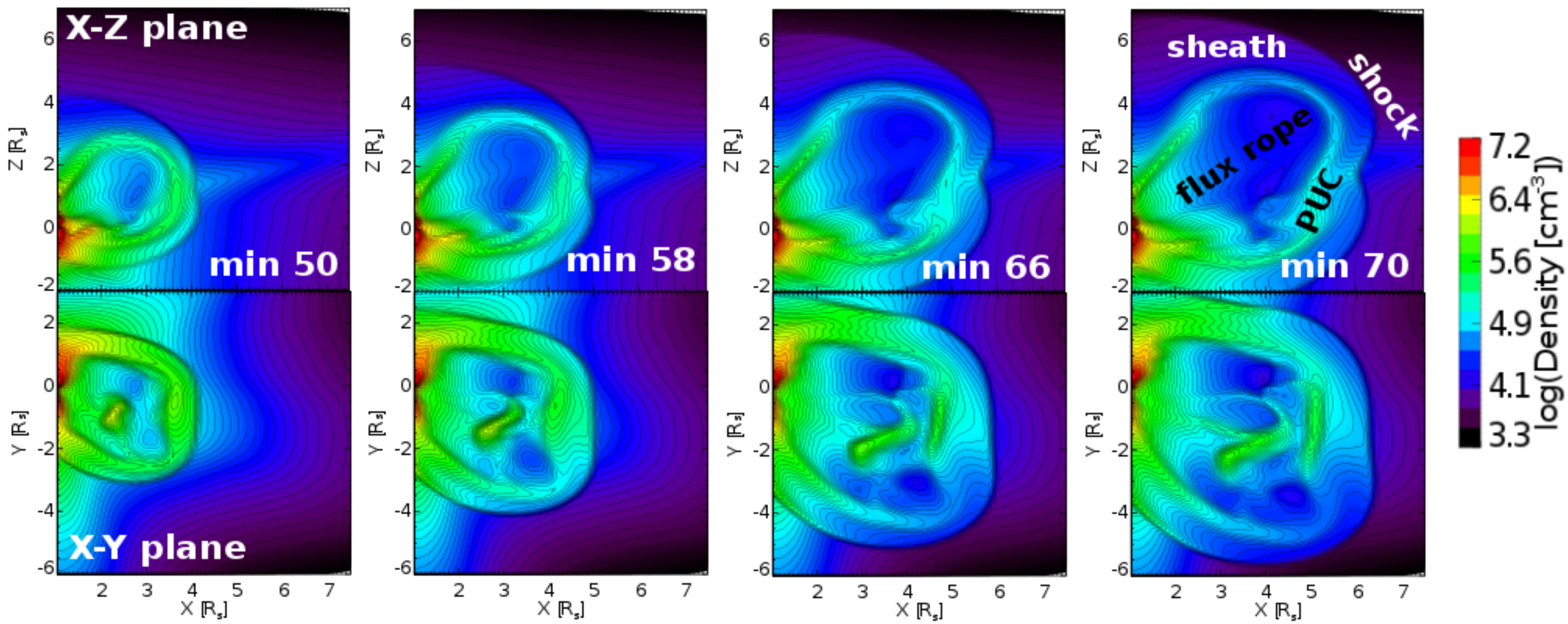


-X-Z and X-Y plane **density contours** over 18 minutes in inner region

-CME mostly inside a coronal streamer (a magnetically confined region of dense coronal plasma)

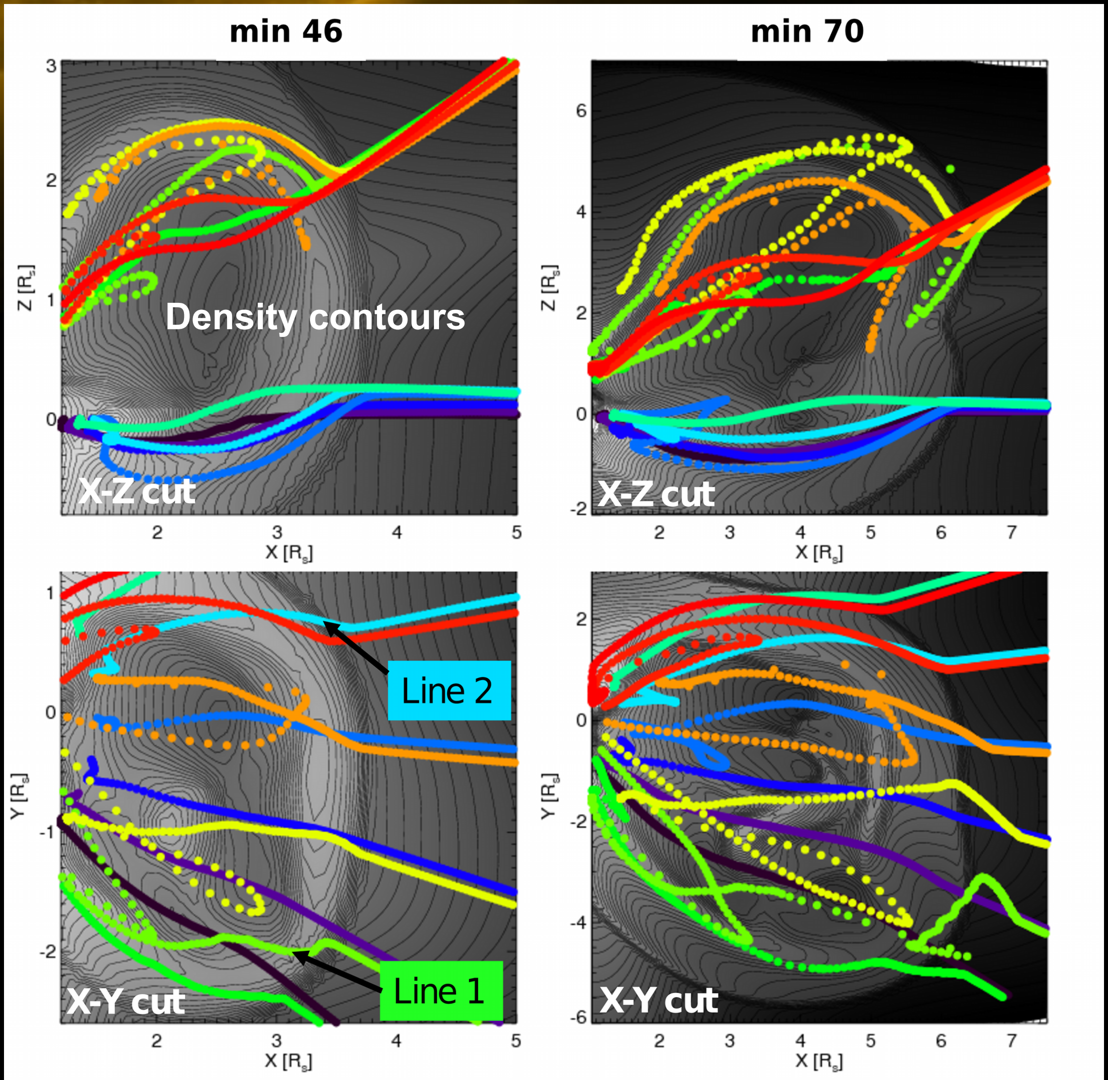
-CME retained original shape most of the time
-In last snapshot, CME exits dense part of streamer; overexpands in –Y direction
-Pile Up Compression (PUC) region separates from shock sheath

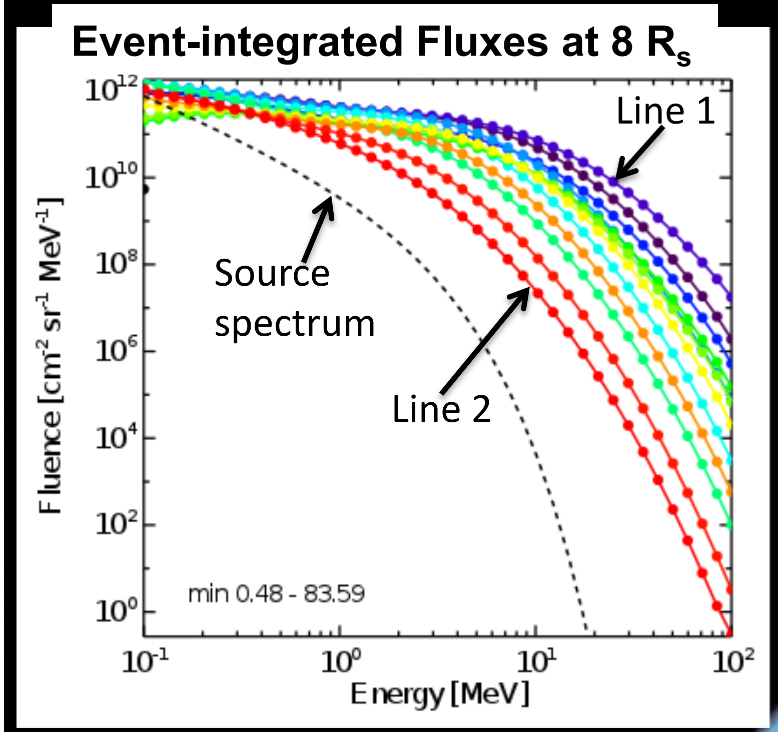
Coronal and CME Density: **Outer Region**



- X-Z and X-Y slices of density evolution over 20 minutes in outer region
- Expansion continues preferentially in +Z and –Y directions
- Sheath is distinct from PUC
- PUC wrapped closely around flux rope.

Look at EPREM field lines distorted by CME

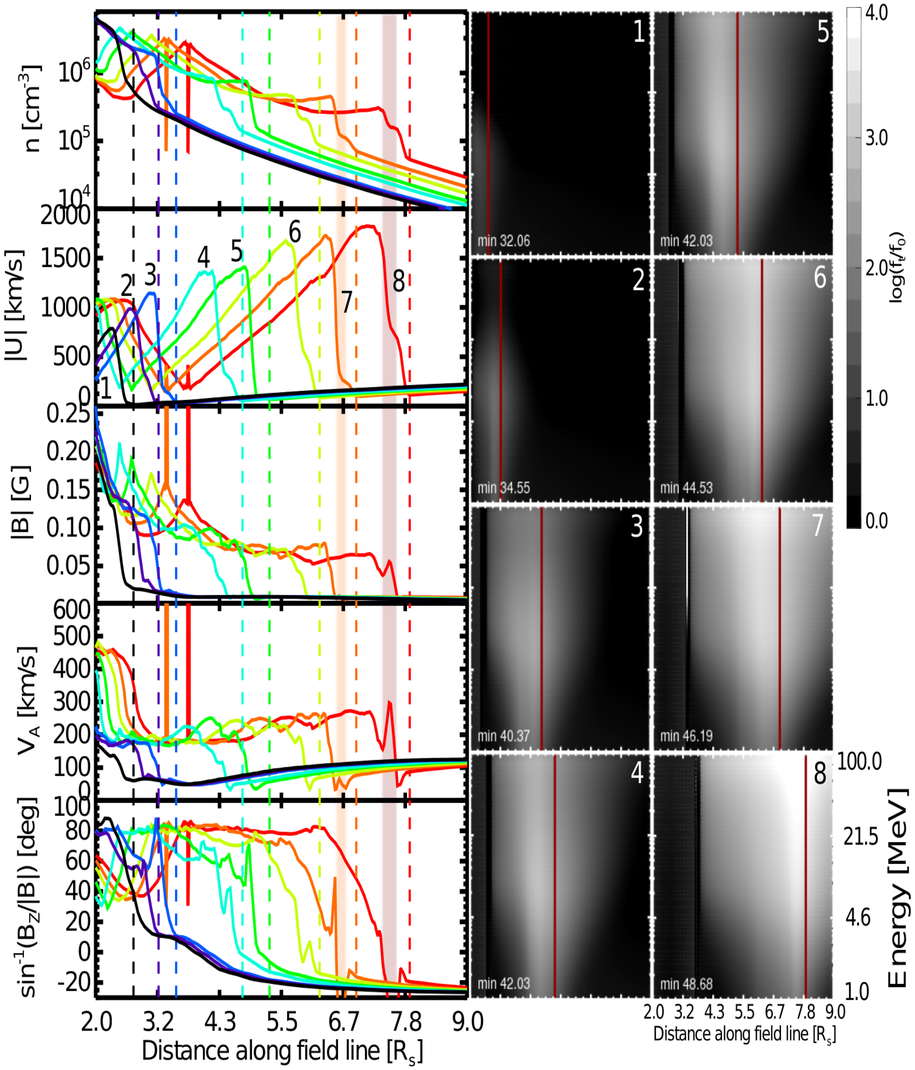




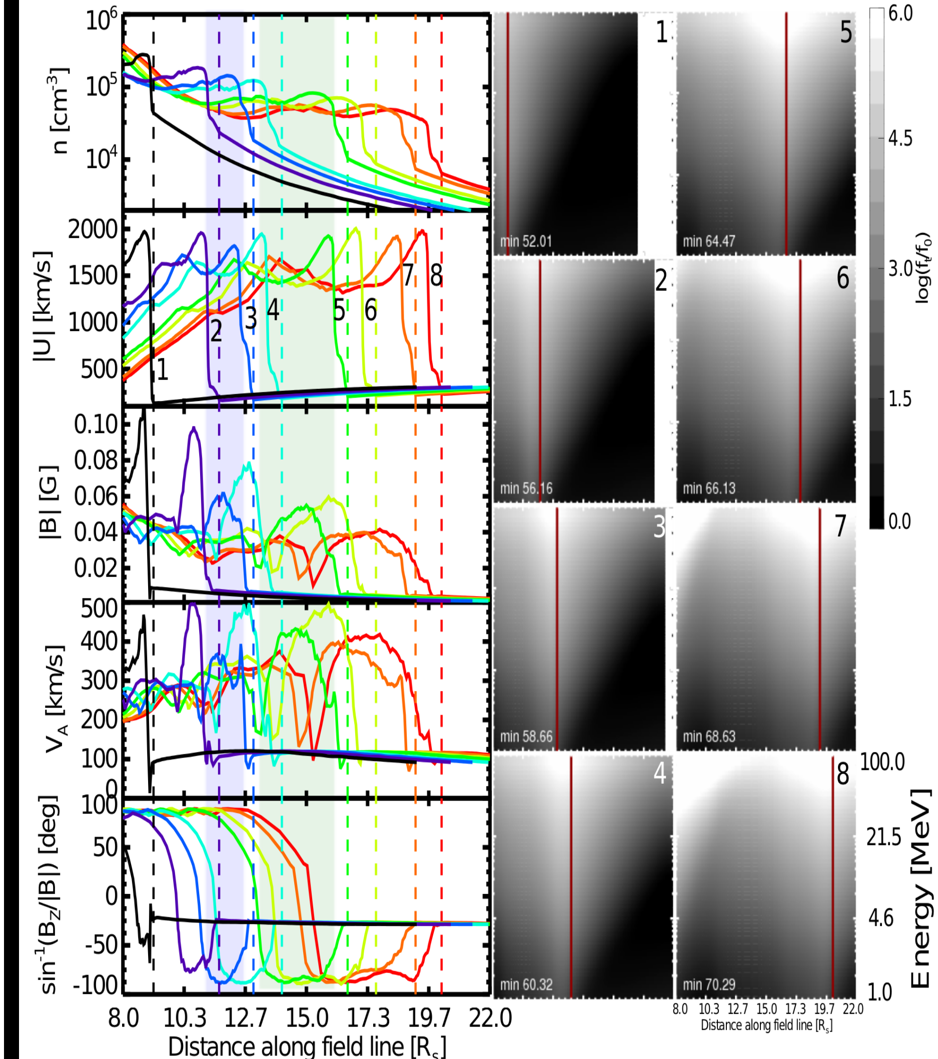
- Great difference in flux enhancements
- Look at two lines: one with most acceleration, one with least

Proton behavior along Line 1

Line 1 INNER REGION

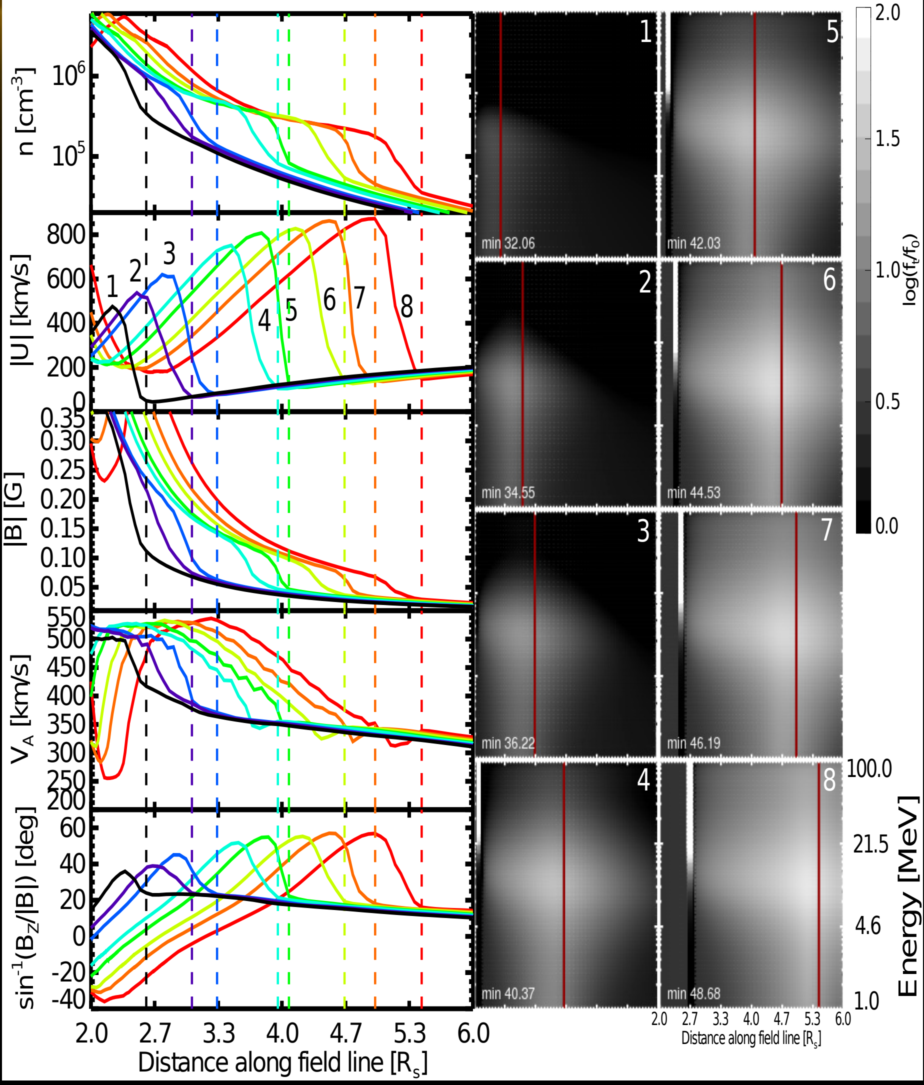


Line 1 OUTER REGION

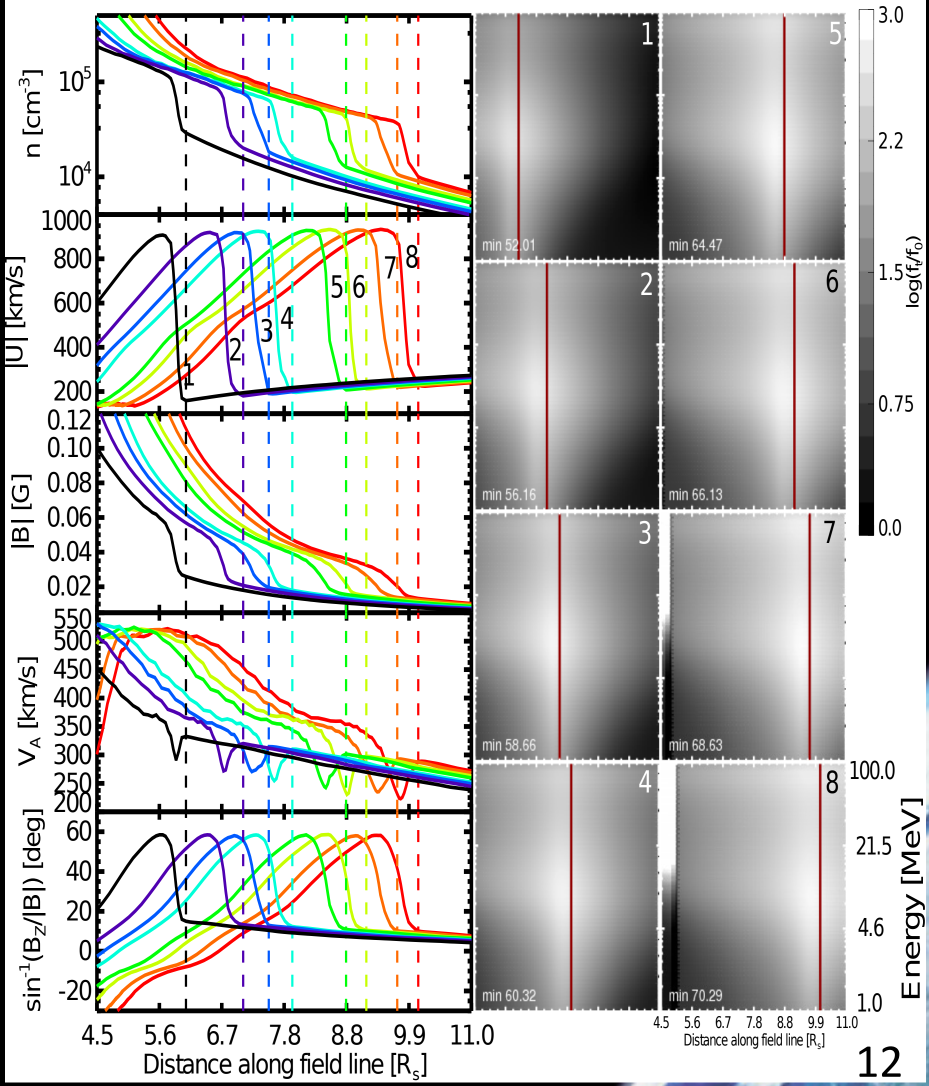


Proton behavior along Line 2

Line 2 INNER REGION

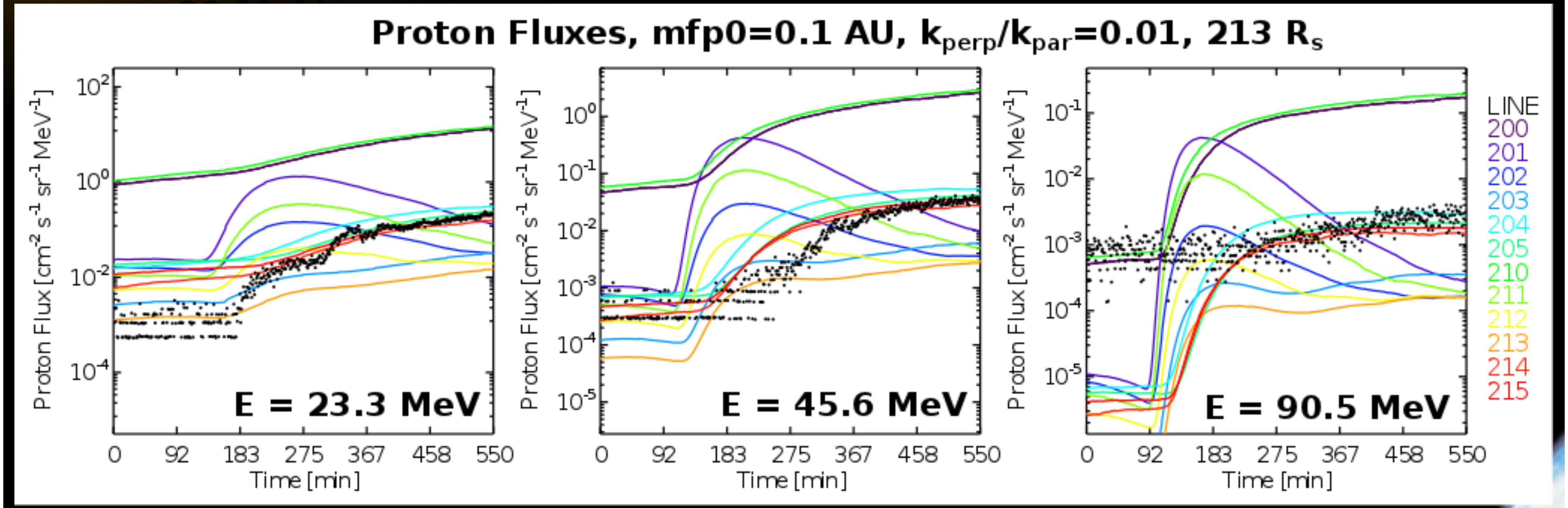


Line 2 OUTER REGION



Propagating coronal proton fluxes to 1 AU

-Used steady state solar wind model (U=400 km/s, B and n ~ $1/r^2$)
-Compared output to 5 min flux averages from SOHO/ERNE



Results:
- Large variations in coronal fluxes retained!
- Reasonable agreement to in situ observations
- Observations correspond to lines with least acceleration

Conclusions

- Detailed modeling study of proton acceleration in a realistic 3D CME in low to middle solar corona
- Shape and dynamics of CME governed by coronal conditions
- Strong acceleration due to compression regions and shock
- Orders of magnitude difference in acceleration between field lines probing different parts of the CME!
- Simulated fluxes near 1 AU correspond to observations
- Large differences in time profiles retained in 1 AU interplanetary fluxes

Extra Slides

EPREM Transport Equation

Based on Kota et al., 2005

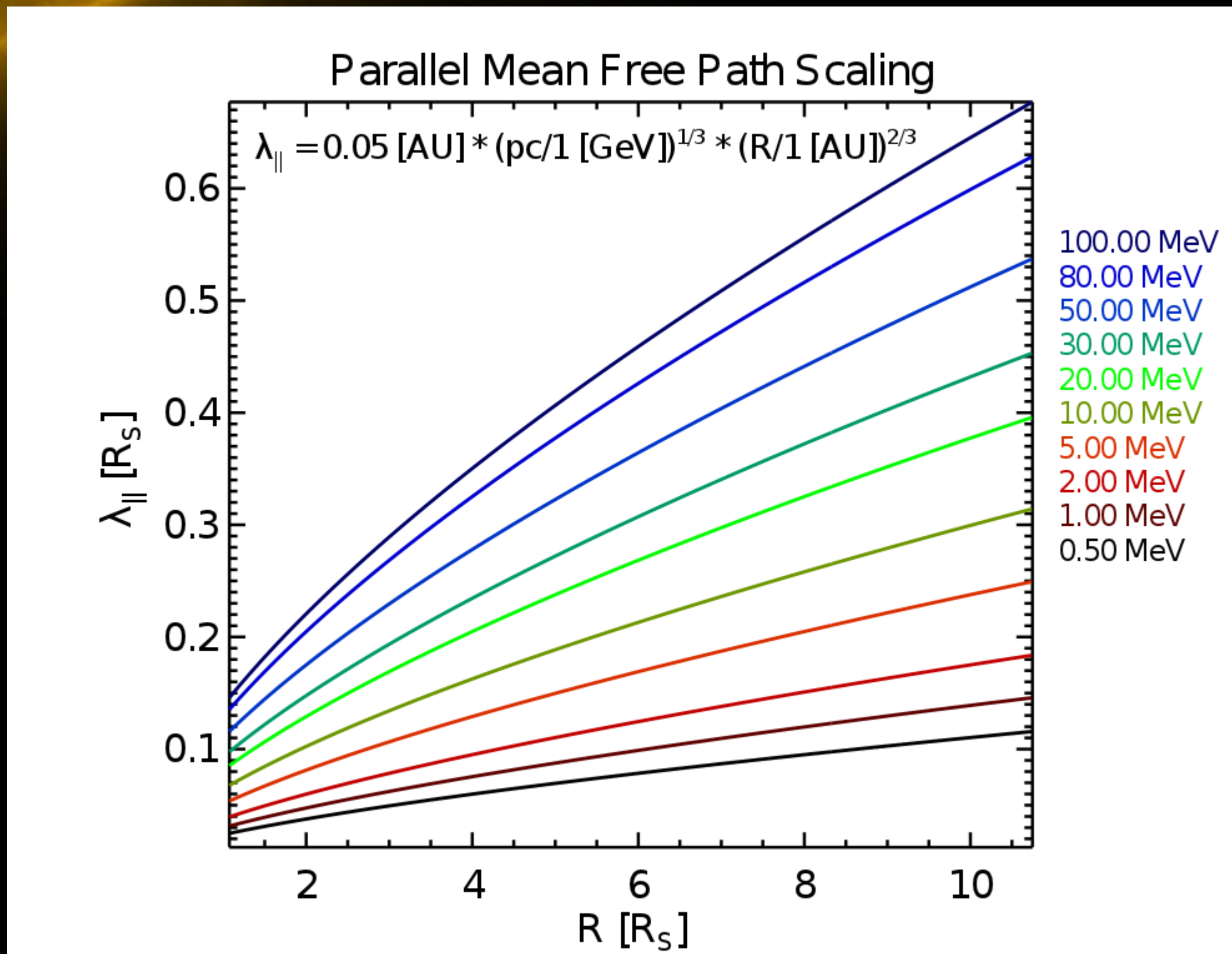
$$
\begin{aligned}
&\left(1 - \frac{\mathbf{V}\cdot\hat{e}_b v\mu}{c^2}\right)\frac{df}{dt} && \text{(convection)}\\
&+ v\mu\hat{e}_b\cdot\nabla f && \text{(streaming)}\\
&+ \frac{(1-\mu^2)}{2}\left[v\hat{e}_b\cdot\nabla\ln B - \frac{2}{v}\hat{e}_b\cdot\frac{d\mathbf{V}}{dt} + \mu\frac{d\ln(nr/B^3)}{dt}\right]\frac{\partial f}{\partial\mu} && \text{(focusing)}\\
&+ \left[-\frac{\mu\hat{e}_b}{v}\cdot\frac{d\mathbf{V}}{dt} + \mu^2\frac{d\ln(n/B)}{dt} + \frac{1-\mu^2}{2}\frac{d\ln B}{dt}\right]\frac{\partial f}{\partial\ln p} && \text{(adiabatic change)}\\
&= \frac{\partial}{\partial\mu}\left(\frac{D_{\mu\mu}}{2}\frac{\partial f}{\partial\mu}\right) && \text{(pitch-angle scattering)}\\
&- \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f_0}{\partial p}\right) && \text{(stochastic acceleration)}
\end{aligned}
$$

Schwadron et al., 2010

$$\frac{D_{pp}}{p^2} = \eta^2 D_0 w$$

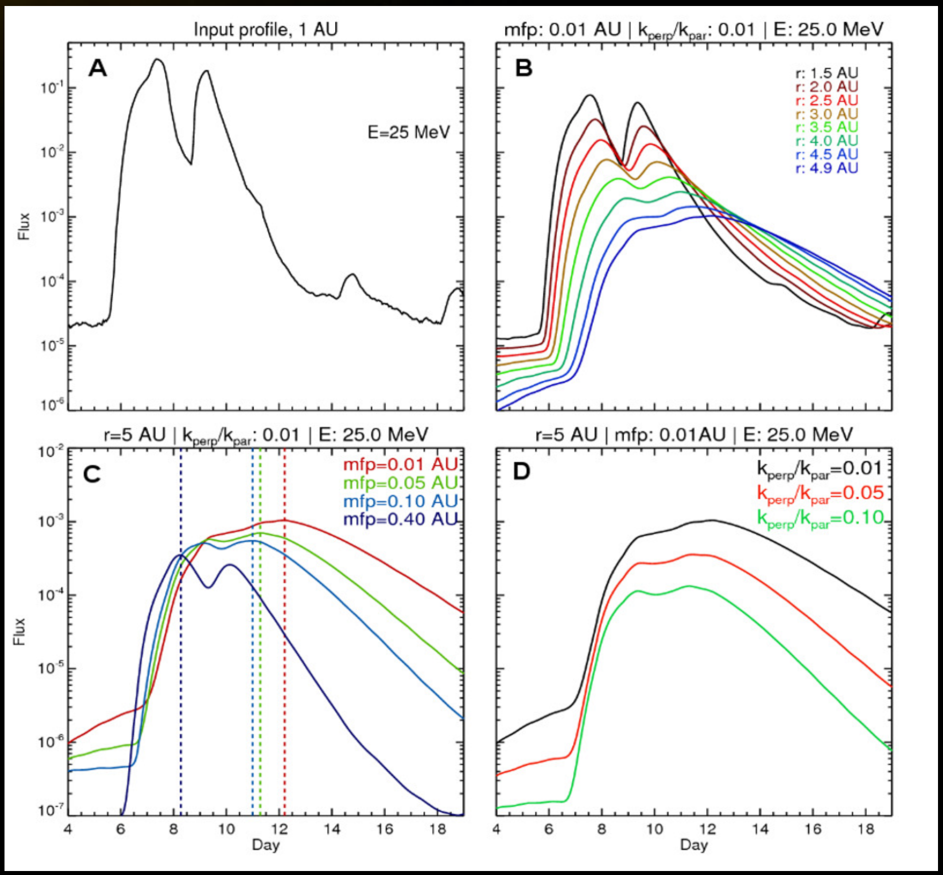
$$D_{\mu\mu} = \left(\frac{R_1}{r}\right)^{3/2}\frac{(1-\mu^2)v}{2\lambda_0}$$

The proton mean free path



MFP expression after Li et al. (2003) and Verkhoglyadova et al. (2008)

Illustrating Transport Effects



A. Source profile at 1 AU

B. Larger radial distance = more spread, lower max fluxes

C. Longer mean free path (less scattering) = earlier onset, faster decay

D. More perpendicular diffusion = lower fluxes