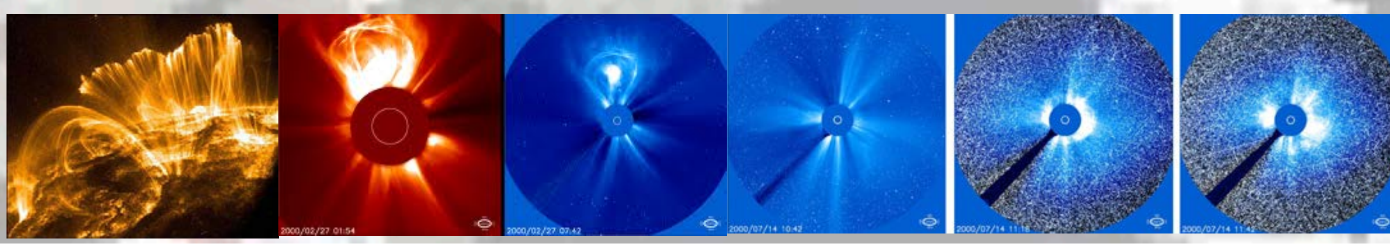
Coronal-Solar Wind Energetic Particle Acceleration Modules (C-SWEPA)

N. A. Schwadron, K. Kozarev, N. Lugaz, J. Linker, M. Gorby, Pete Riley, Z. Mikic, R. Lionello, T. Torok, V. Titov, B. Chandran, J. Cooper, M. Desai, K. Germaschewki, J. Giacalone, P. Isenberg, J. Kasper, K. Korreck, M. Lee, P. MacNeice, H. Spence, S. Smith, M. Stevens, P. Quinn, C. Joyce, R. Winslow, J. Chen, F. Rahmanifard

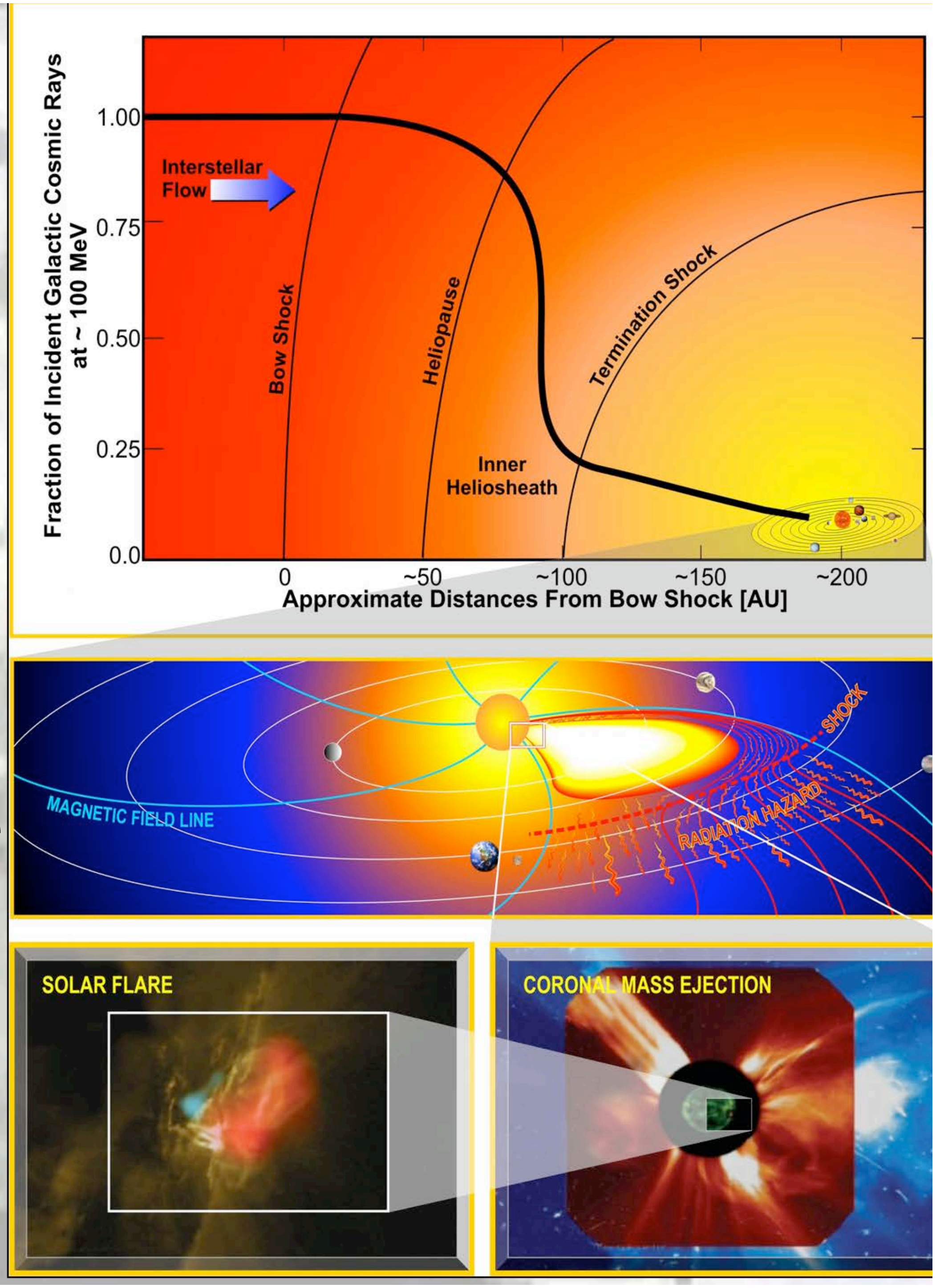


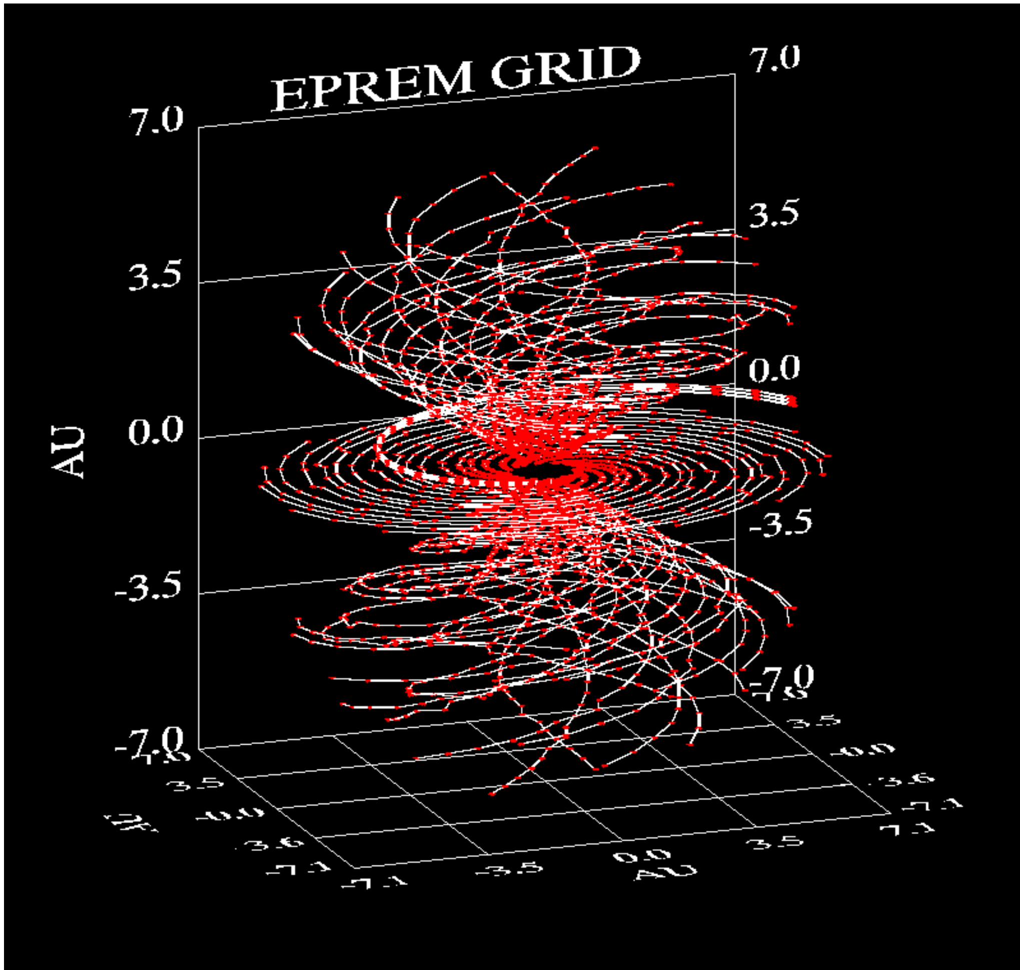
Institutions

- UNH
  - Energetic Particles Acceleration/EMMREM
  - Corona, CMEs and ICMEs
- PSI
  - Corona, CMEs and ICMEs
- SwRI
  - Seed particles
- Goddard & CCMC
  - Energetic particle acceleration
  - Community access

Radiation Hazards

- Galactic Cosmic Rays (GCRs)
  - Steady Background
  - Career limit in ~ 3 years
- **Solar Energetic Particles (SEPs)**
  - **Acute Sources**
  - **ESPs versus impulsive component**
  - **Time-dependent response**





Focused Transport in Lagrangian Frame (Kota, 2005)

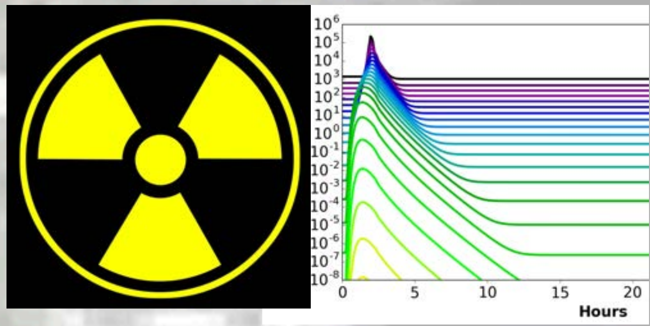
$$\left(1-\frac{(\vec{u}\cdot e_b)v\mu}{c^2}\right)\frac{df}{dt}+v\mu\frac{\partial f}{\partial z}+\frac{(1-\mu^2)}{2}\left[v\frac{\partial \ln B}{\partial z}-\frac{2}{v}e_b\cdot\frac{d\vec{u}}{dt}+\mu\frac{d\ln(n^2/B^3)}{dt}\right]\frac{\partial f}{\partial \mu}+$$
$$\left[-\frac{\mu e_b}{v}\cdot\frac{d\vec{u}}{dt}+\mu^2\frac{d\ln(n/B)}{dt}+\frac{(1-\mu^2)}{2}\frac{d\ln B}{dt}\right]\frac{\partial f}{\partial \ln p}=\frac{\partial}{\partial \mu}\left(\frac{D_{\mu\mu}}{2}\frac{\partial f}{\partial \mu}\right)+S$$

- Cross-field Diffusion
- Drift

Wargo Axiom

Science enables Exploration and Exploration enables Science

The Radiation Environment affects Human Systems



(Human-made) Radiation Instruments Probe Radiation and Its Effects

C-SWEPA Team Interactions

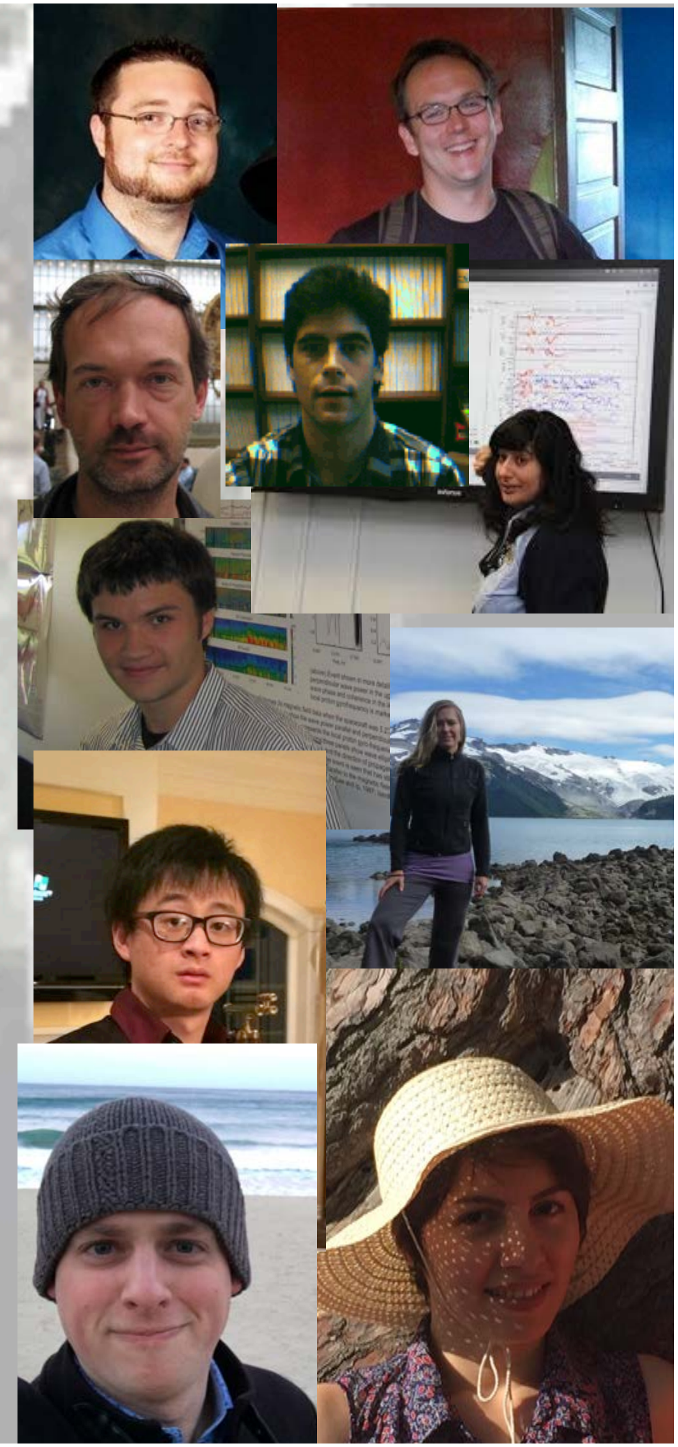
- LRO/CRaTER
- DREAM/ DREAM2
- Sun-2-Ice
- SPP
- International Team on Radiation Interactions

Goals

- **Goal 1:** Scientifically explore the seed populations and acceleration of energetic particles in the low corona, through interplanetary space, and over broad longitudinal regions
- **Goal 2:** Couple the energetic particle acceleration model (EPREM, the energetic particle radiation environment model) with MHD models that describe the propagation of coronal mass ejections from the low coronal plasma environment through the interplanetary medium.
- **Goal 3:** Validate results the coupled EPREM and EMMREM models with observations at distributed observers near 1 AU and out beyond Mars. Validation extends across our understanding of radiation induced hazards from solar energetic particles and galactic cosmic rays at Earth down to atmospheric levels, out into deep space and to Mars and beyond.
- **Goal 4**: Extend key data sets useful for the project: shock parameters at 1 AU, CME propagation data, and radiation environment data through the inner heliosphere.

Investigator Highlights

- Matt Gorby, Jon Linker, Ron Caplan, Tibor Torok, Jon Linker, UNH, PSI
  - Fantastic work on development, coordination, coupling
  - Work with PSI and CCMC
- Leila Mays, CCMC
  - Excellent partner at the CCMC
  - Currently leading a C-SWEPA publication
  - Invited talks at AGU, EGU, on C-SWEPA coupling
- Colin Joyce wins UNH Graduate Research Award
  - Should graduate soon
  - 1 award given each year at University of New Hampshire competed across all graduate students
  - Authored or Co-authored 14 publications, first-authored 5 publications in incredibly diverse areas
- Reka Winslow
  - New PostDoc at UNH
  - Several new discoveries about the evolution of Coronal Mass Ejections through *conjunction* events from Messenger to ACE, STEREO and LRO
- Junhong Chen
  - Recently received PhD
  - Work on suprathermal ions and PUI acceleration
- Philip Quinn
  - Graduate student
  - Leading three papers on pickup ions, suprathermal ions and radiation through the inner heliosphere
- Fatemeh Rahmanifard
  - Studying evolution of the solar cycle, possible development of grand minimum and implications for radiation



Report/ Development	LWS	C-SWEPA	Science	Deliverable	Ref Papers/ Presentations
Section 1: Radiation Environment Evolution	Radiation Hazards in Space and through atmospheres	Goal 3: Radiation interactions/ validation	Deep Solar min (23-24), min 24 max, evolution into gran min?	PREDICCS	10 Refereed Papers 9 talks (7 invited)
Section 2: Radiation Interactions + Event Modeling	“	Goal 2: Model coupling & radiation events	Energetic Particle Acceleration	PREDICCS	4 Refereed Papers 4 talks
Section 3: Radiation Modeling Through Atmospheres	“	Goal 3: EMMREM Validation	Radiation Interactions	EMMREM + PREDICCS	4 Refereed Papers 3 talkw
Section 4: Pickup Ions + Seed Populations	SEPs/Seed populations	Goal 1: Seed populations + SEP acceleration	Suprathermal Tails, Pickup Ions	EPREM	2 Refereed Publications 2 talks
Section 5: Modeling SEPs	Energetic Particle Acceleration	Goal 2: Model Coupling + SEP acceleration	Energetic Particle Accleeration	EPREM EPREM+Cone EPREM+ENLIL EPREM+MAS	17 Refeeed Papers 30 Presentations

Report/ Development	LWS	C-SWEPA	Science	Deliverable	Ref Papers/ Presentations
Section 6: Observed SEP Spectral Properties	Energetic Particle Acceleration/ Radiation	Goal 4: Extend key datasets	SEP properties – tests models of SEP acceleration	Data Products & Sharing	10 Refereed Papers 18 talks (many invited)
Section 7: Progress on Deliverables	Radiation, SEP acceleration	Goal 3: Model coupling	Energetic Particle Acceleration + Radiation Interactions	EMMREM PREDICCS EPREM EPREM+Cone EPREM+ENLIL EPREM+MAS	5 Refereed Papers 7 talks (many invited)
Section 8: ICME Evolution + Magnetic Complexity	ICMEs, energetic particle propagation	Goal 4: Extend key datasets	ICME evolution	Data Products and Sharing	3 Refereed Publications 2 talks
Section 9: Active Regions + Superflares	Flares + Acute Radiation Hazarda	Goal 3: Energetic Particle Acceleration	Superflares	EPREM+MAS	1 Refereed Publication
Section 10: Data Products + Sharing	Radiation, Energetic Particles	Goal 4: Extend Key Datasets	Energetic Particles	Data Products	12 Talks

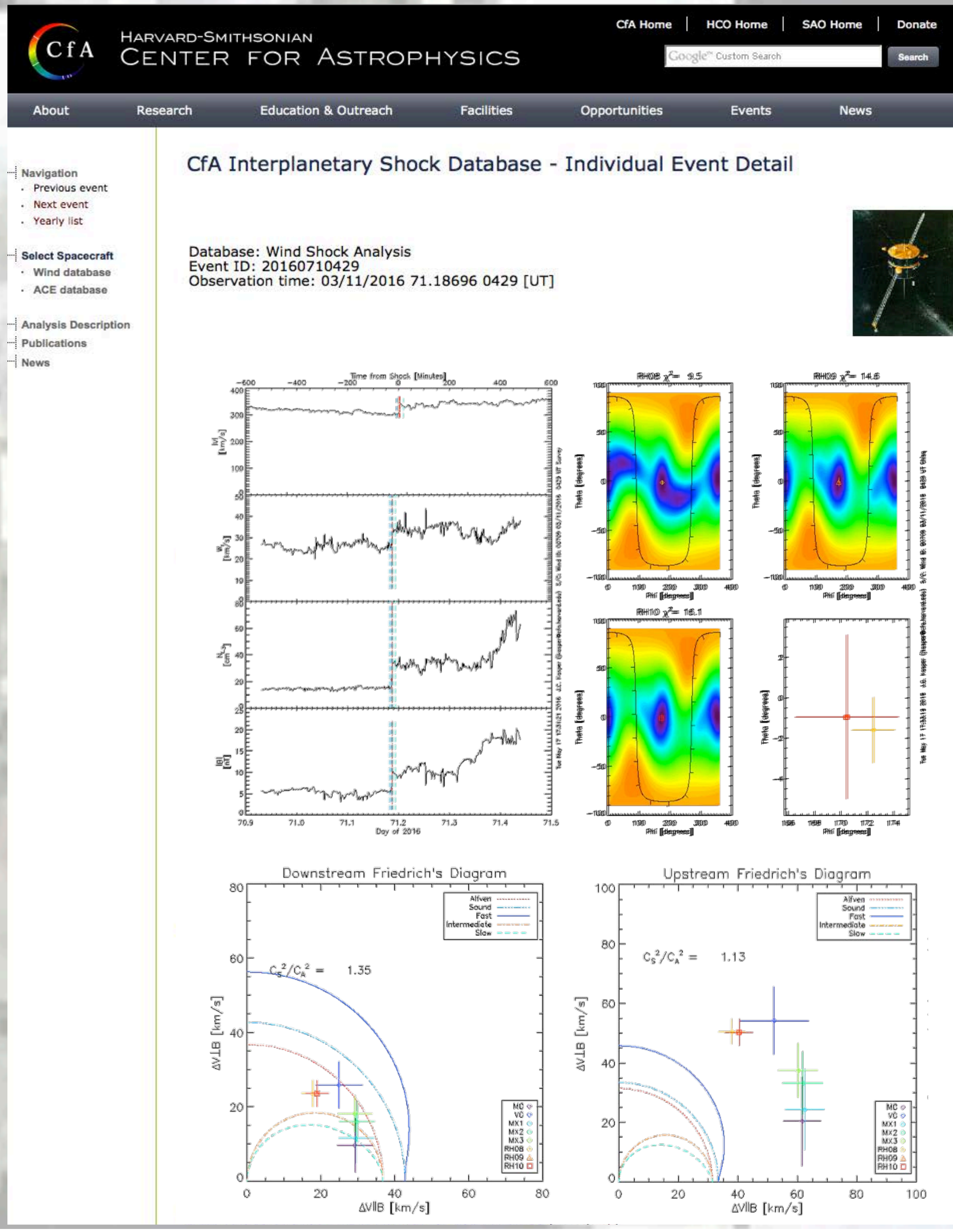
Overview of Deliverables

- *Deliverables outside CCMC*
  - **PREDICCS:** running in real-time radiation environment http://prediccs.sr.unh.edu
  - **EPREM – MAS**: model up and running, internal web interface working
- *Deliverables to the CCMC:*
  - **PREDICCS:** installed and running in real-time http://ccmc.gsfc.nasa.gov/ccmc-swan/prediccs.php
  - **EPREM:** installed, available for Runs on Request in work
  - **EPREM+cone:** installedavailable for Runs on Request in work
  - **Coupled WSA-ENLIL+EPREM:** installed, simulations are currently being tested, preliminary run results are listed at http://ccmc.gsfc.nasa.gov/community/LWS/lws_cswepa.php

Data Products - The CfA Interplanetary Shock Database

cfa.harvard.edu/shocks

- Observational summaries and MHD solutions derived for 600+ IP shocks
  - *Speed, orientation, morphology, type, magnitude*
- Integration with multiple spacecraft
  - **Wind** (1995-present)
  - **ACE** (through 2014)
  - **DSCOVR** (2015-present) pending lifting of data embargo
- Shock surface corrugation scaling
  - *James et al., 2015 (AAS)*
  - *Korreck et al. 2015 (AGU)*
- Scaling for minor ion heating
  - *Korreck et al. 2015 (AGU)*
- 1000+ page views per month, used by scientific, academic, and space weather communities



Data Sharing + Products (2/2)

- MESSENGER – 1 AU ICME Database
  - http://spdf.gsfc.nasa.gov/pub/data/messenger/
  - http://cswepa.sr.unh.edu/icmecatalogatmercury.html
- NASA's VEPO
  - http://vepo.gsfc.nasa.gov
- PREDICCS database
  - http://prediccs.sr.unh.edu/data/goesPlots/archive/

Agenda

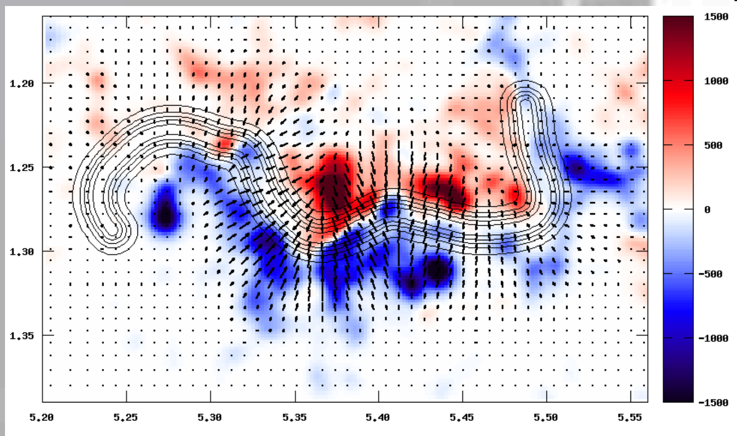
- **Overview**

- Modeling Formation of Solar Transients from the Low Corona (Jon Linker)
- Energetic Particle Propagation and Acceleration from the Low Corona and through the Solar System (Nathan Schwadron)
- Particle Radiation at Earth and Through the Inner Solar System (Phil Quinn and Colin Joyce)
  - Source Populations (Phil Quinn)
  - Propagation of CMEs (Reka Winslow)
- CSWEPA Tools and Methodology (Matthew Gorby)

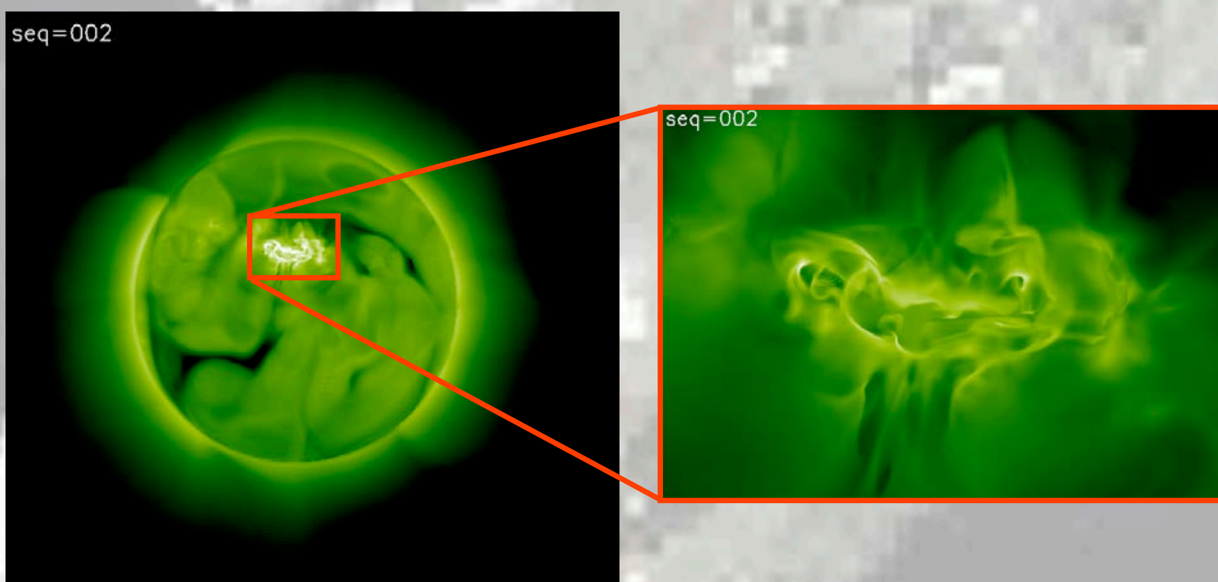
Energetic Particle Propagation and Acceleration from the Low Corona and through the Solar System

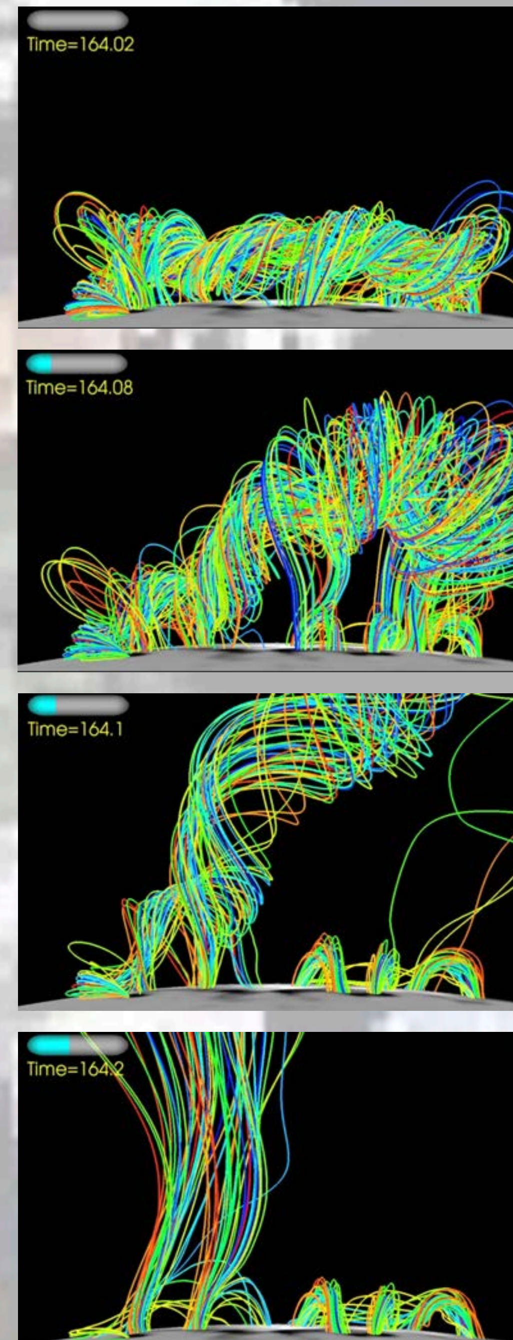
N. A. Schwadron, N. Lugaz, J. Linker, M. Gorby, Pete Riley, Z. Mikic, R. Lionello, T. Torok, V. Titov, B. Chandran, J. Cooper, M. Desai, K. Germaschewki, J. Giacalone, P. Isenberg, J. Kasper, K. Korreck, M. Lee, P. MacNeice, H. Spence, S. Smith, M. Stevens, P. Quinn, C. Joyce, R. Winslow, J. Chen, F. Rahmanifard

Eruption

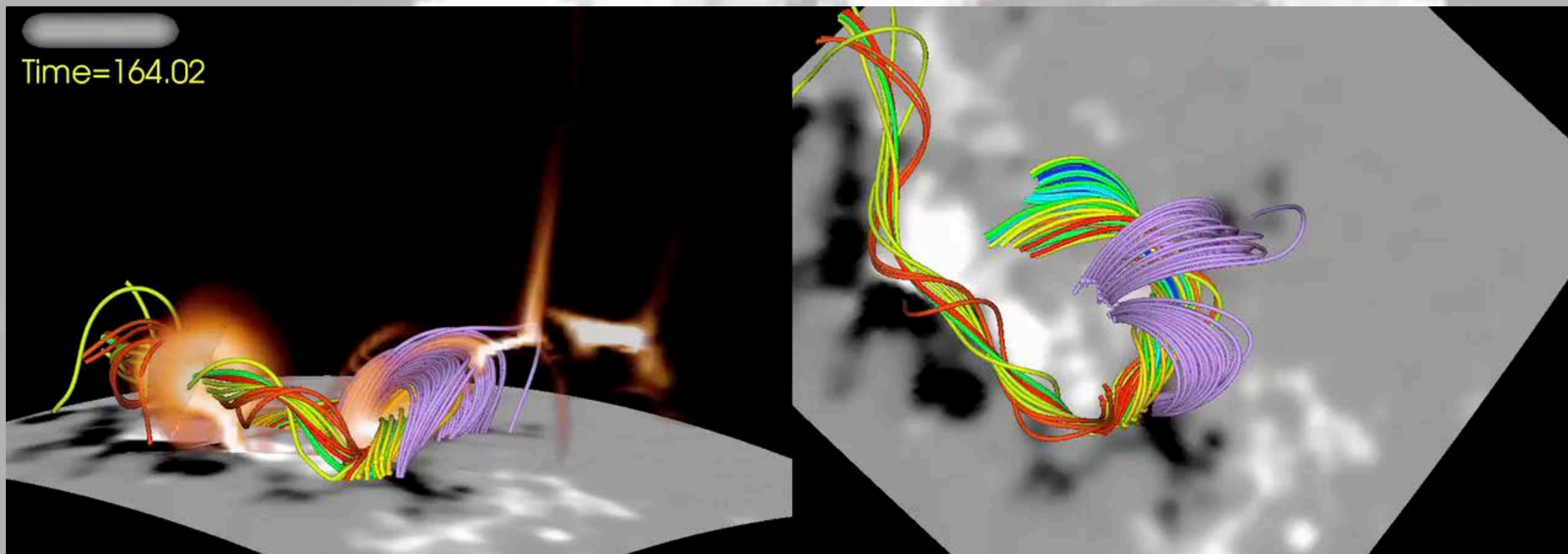


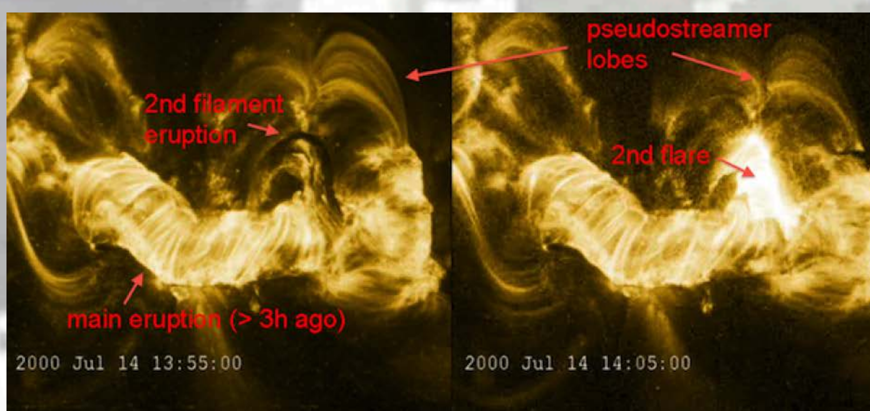
- *Flux rope eruption triggered by localized converging flows*
- *Eruption evolves west to east as was observed*





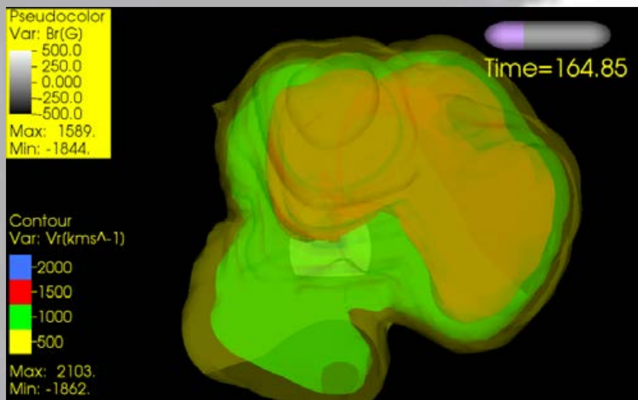
Sympathetic eruption

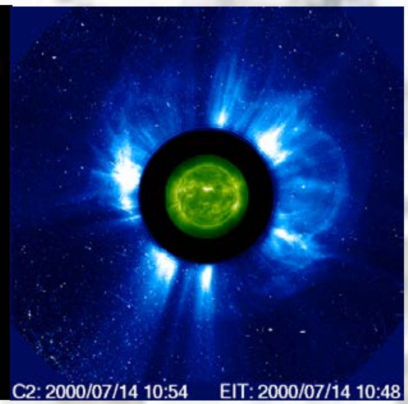


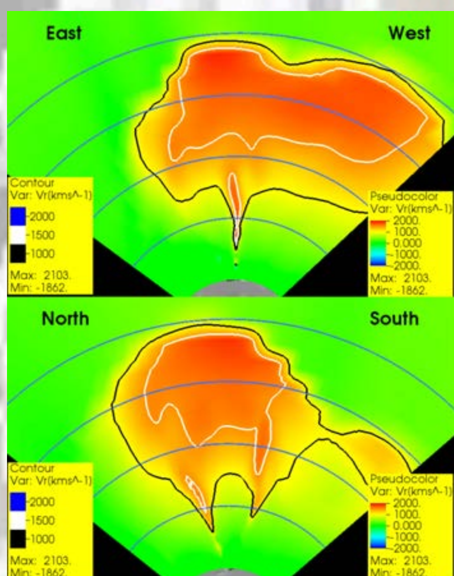


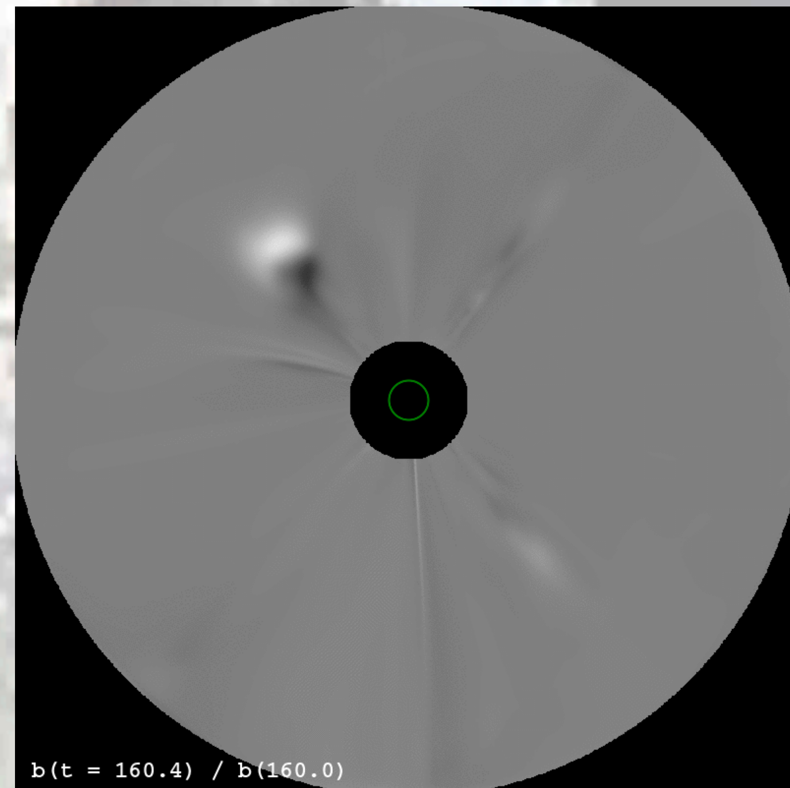
- *Second eruption qualitatively reproduced*

CME propagation





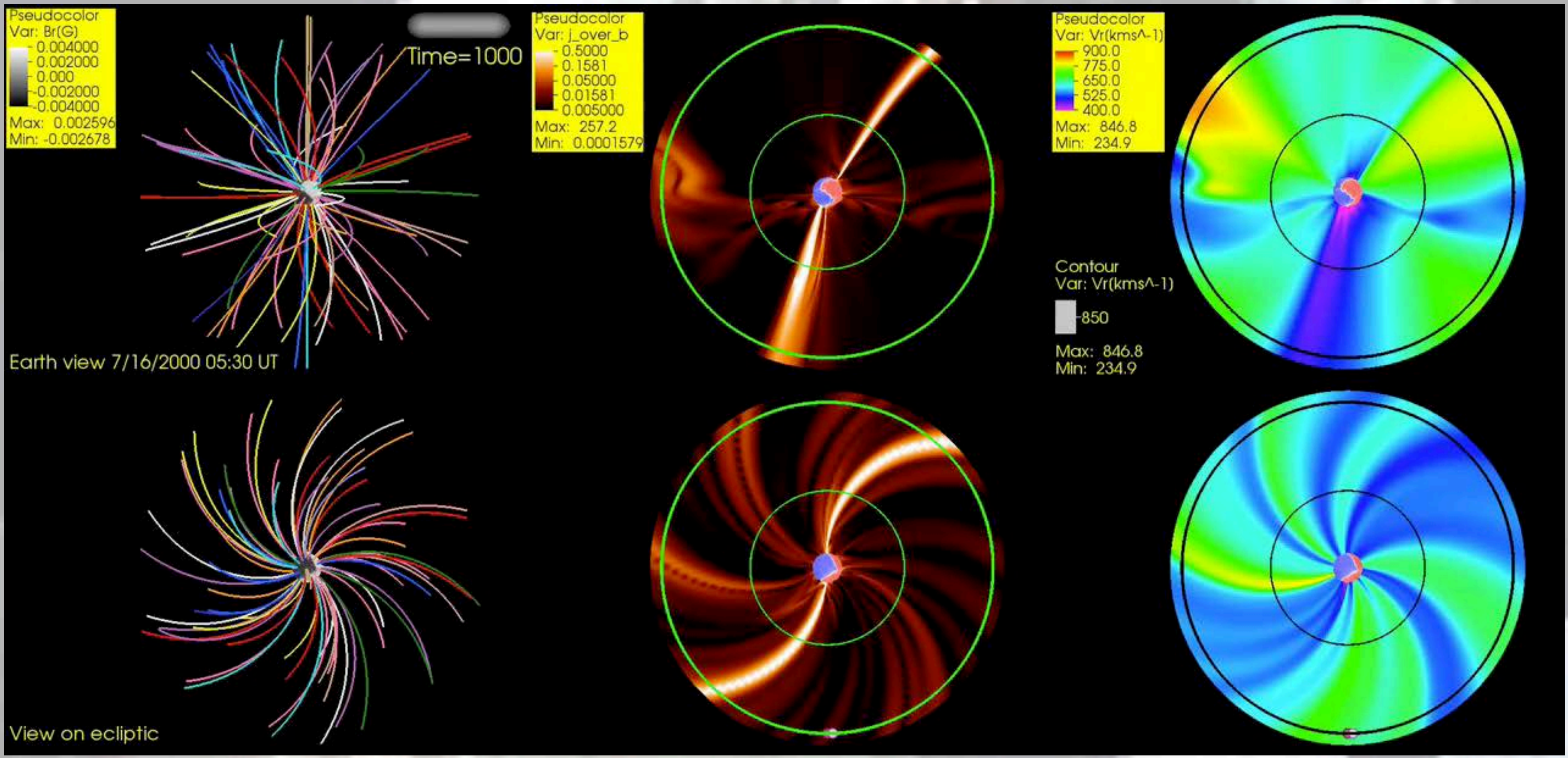




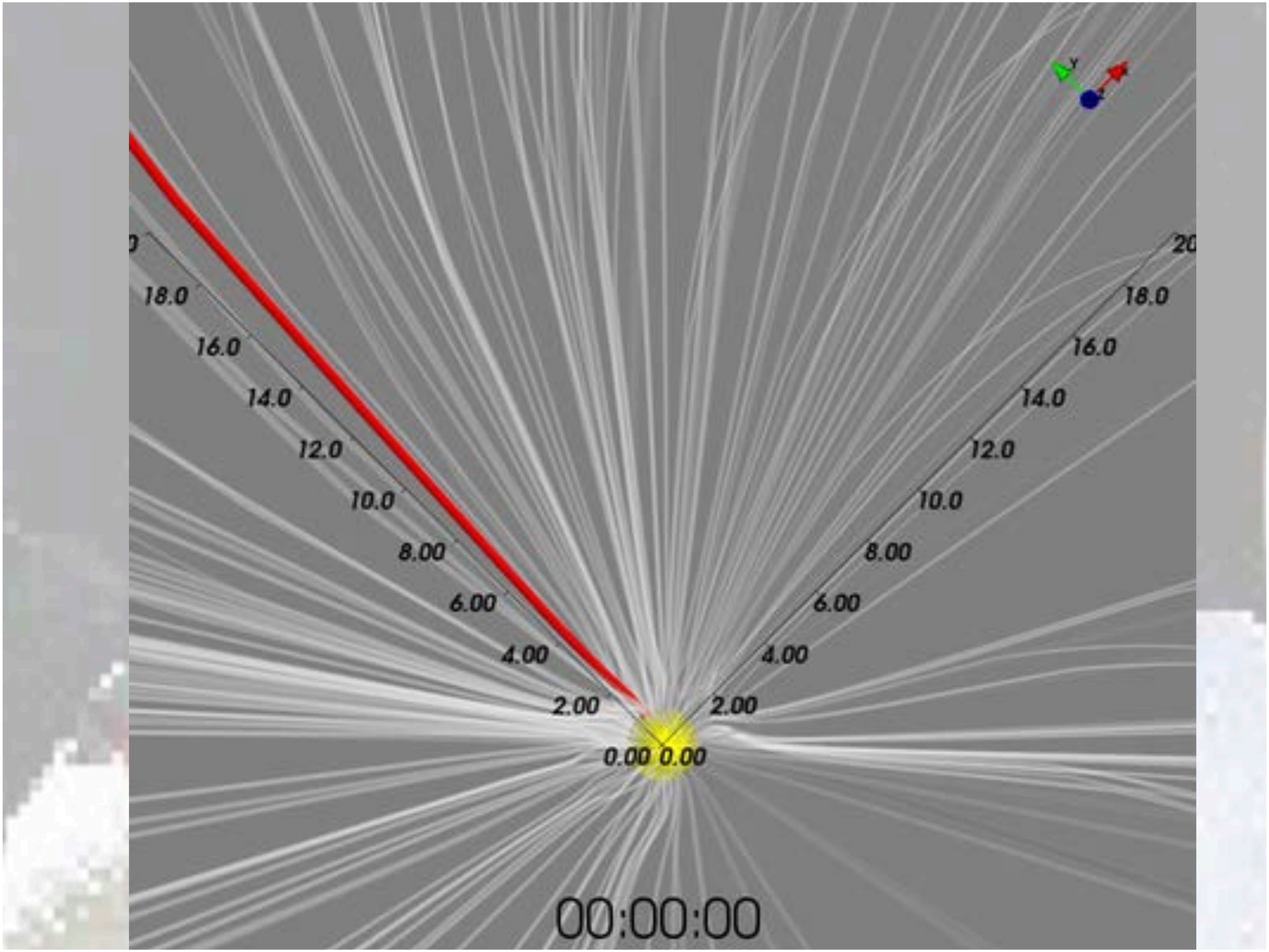
Halo CME
(Brightness as running ratio)

- *CME kinetic energy = 4×10^{32} ergs*
- *CME propagation speed $\gtrsim$ 1500 km/s*

Interplanetary propagation



- *Simulate the propagation of the CME to 1 AU*
- *Coupling to heliospheric code in rotating frame (Lionello et al. ApJ 2013)*



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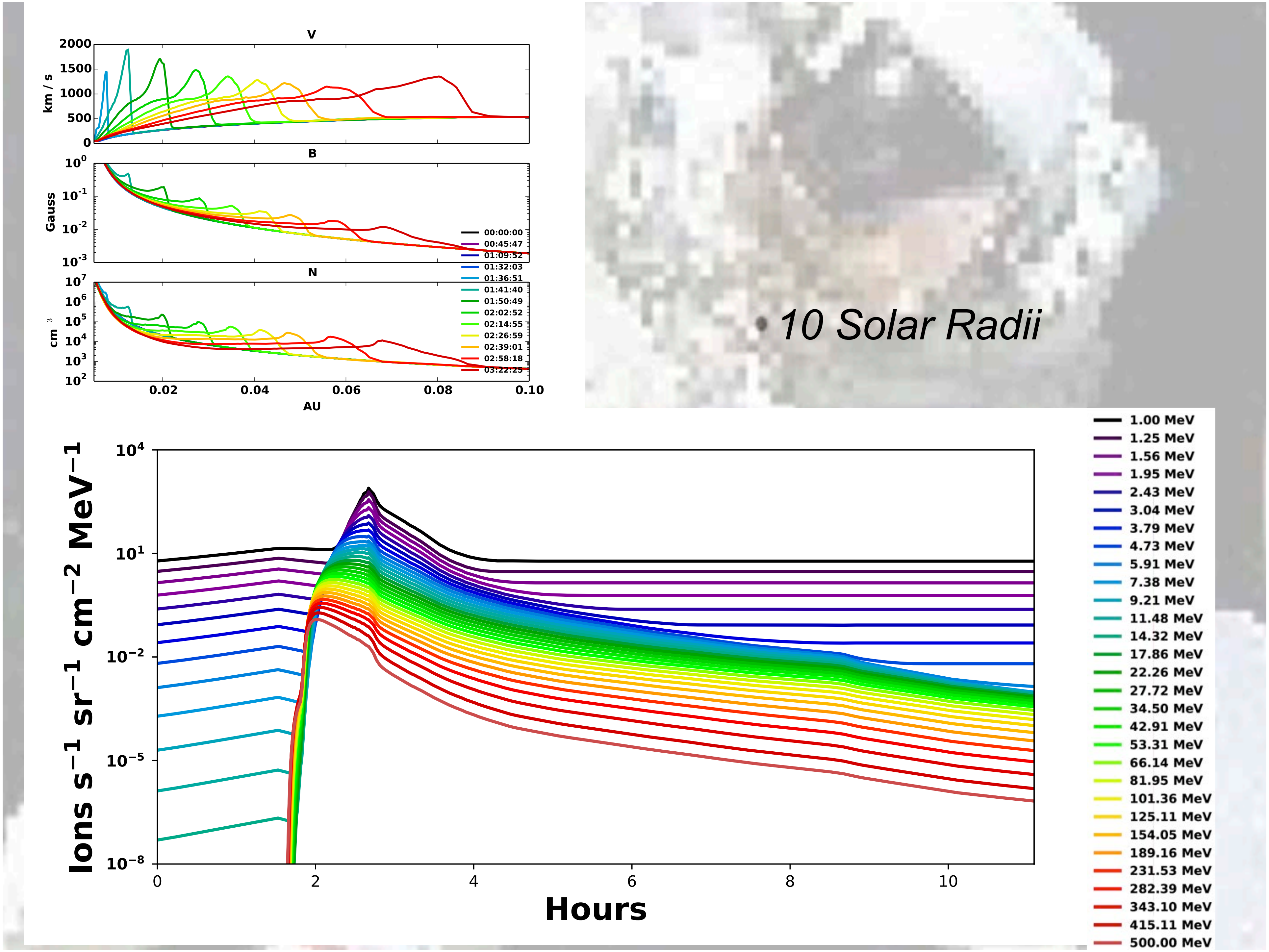
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02:14:55
02:26:59
02:39:01
02:58:18
03:22:25
10 Solar Radii
Ions s^{-1} sr^{-1} cm^{-2} MeV^{-1}
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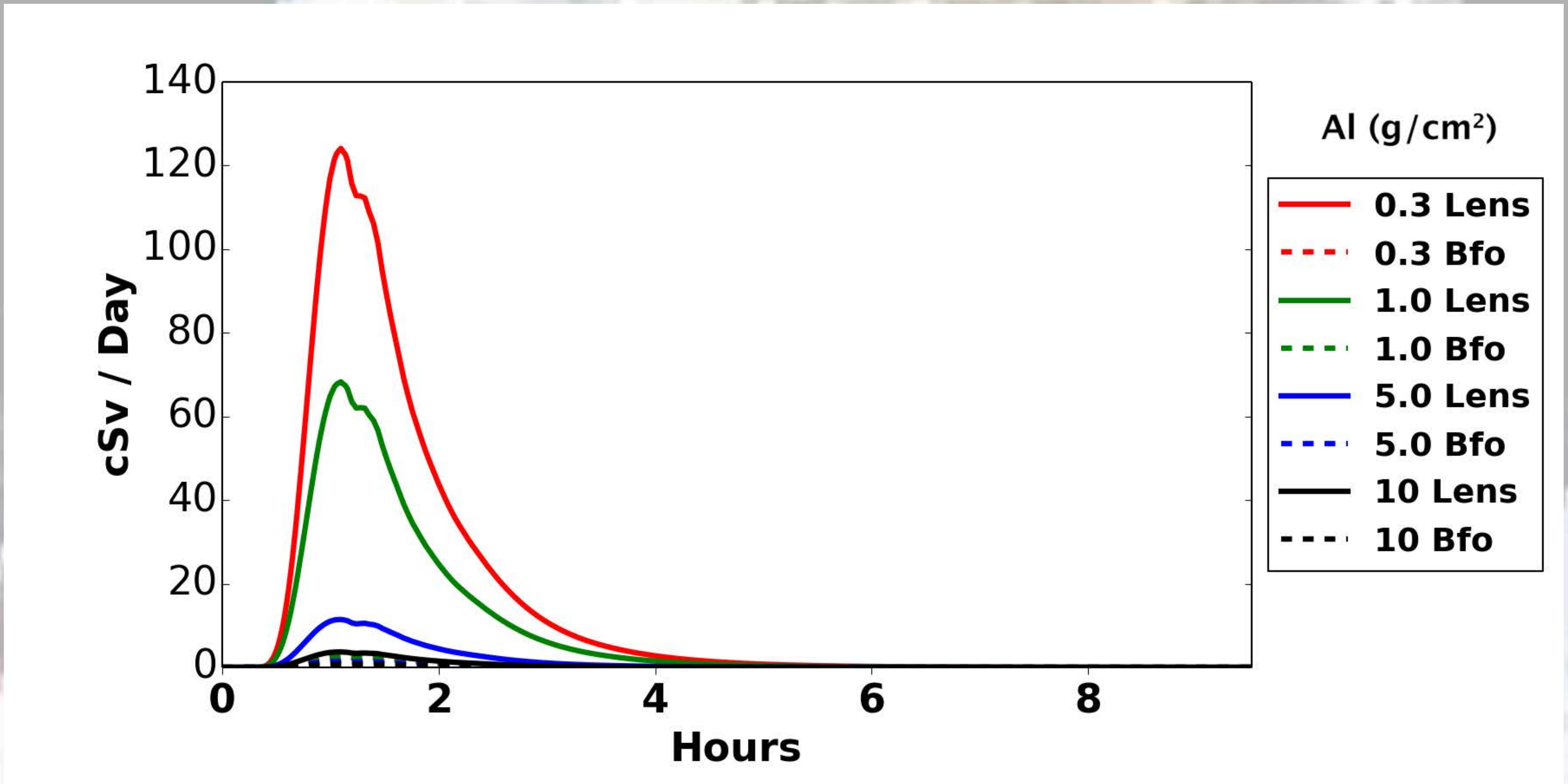
5.91 MeV
7.38 MeV
9.21 MeV
11.48 MeV
14.32 MeV
17.86 MeV
22.26 MeV
27.72 MeV
34.50 MeV
42.91 MeV
53.31 MeV
66.14 MeV
81.95 MeV
101.36 MeV
125.11 MeV
154.05 MeV
189.16 MeV
231.53 MeV
282.39 MeV
343.10 MeV
415.11 MeV
500.00 MeV

Dose Rates from Event

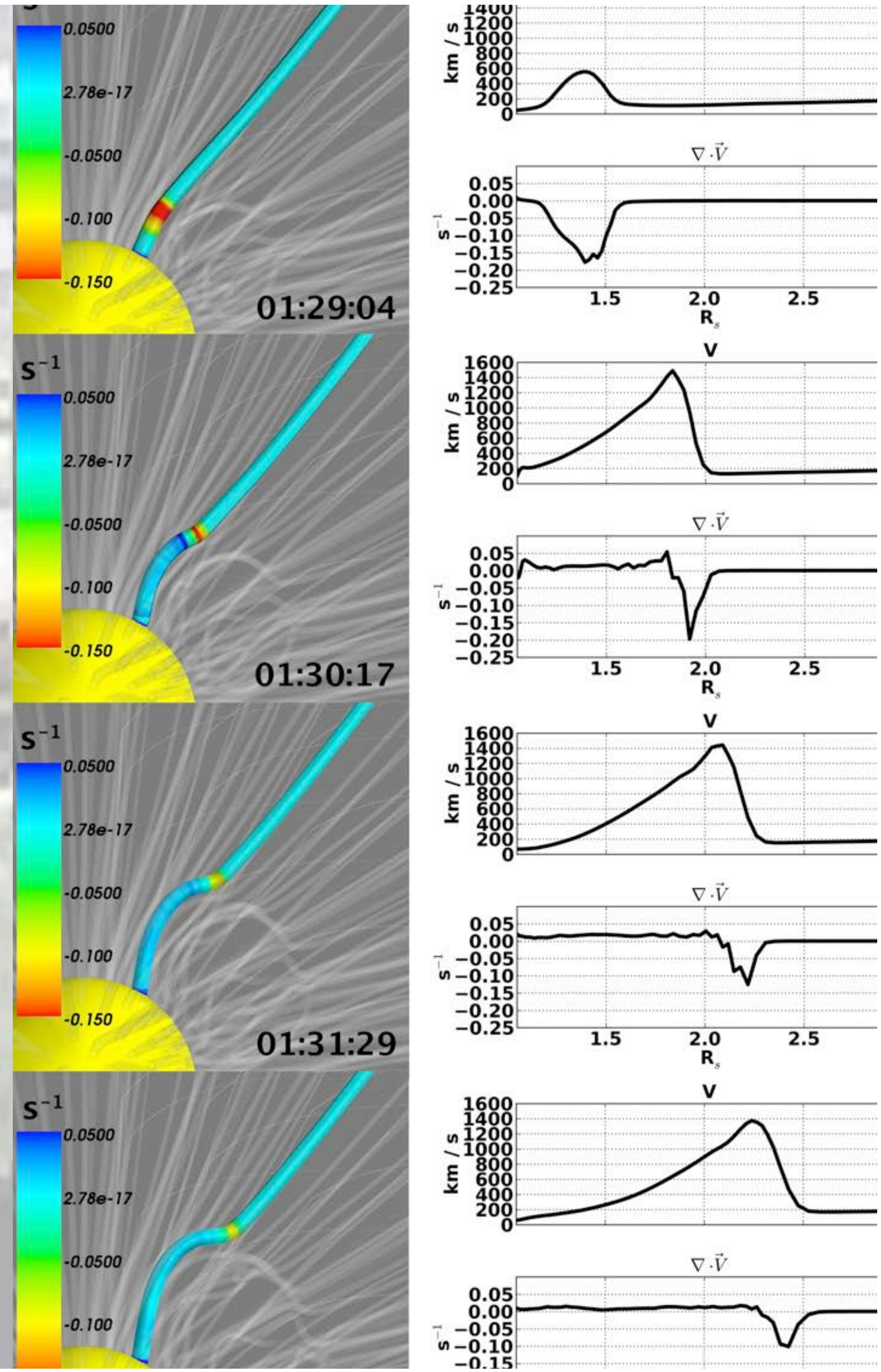


Localized acceleration in low corona

- In Parker-transport (assuming near isotropy), all particle acceleration arises from velocity divergence:

$$\frac{\partial f}{\partial t} + \boldsymbol{u} \cdot \nabla f - \nabla \cdot (\mathsf{K} \cdot \nabla f) - \frac{\nabla \cdot \boldsymbol{u}}{3} p \frac{\partial f}{\partial p} = Q_0 \delta(x) \delta(z) \delta(p - p_{\text{inj}}),$$

Schwadron et al., 2015



Diffusive solution with and without escape

- Assumes 70^o shock-normal

$$\lambda_{\|} = \lambda_{\|0}(R_g/R_{g0})^{\chi}$$

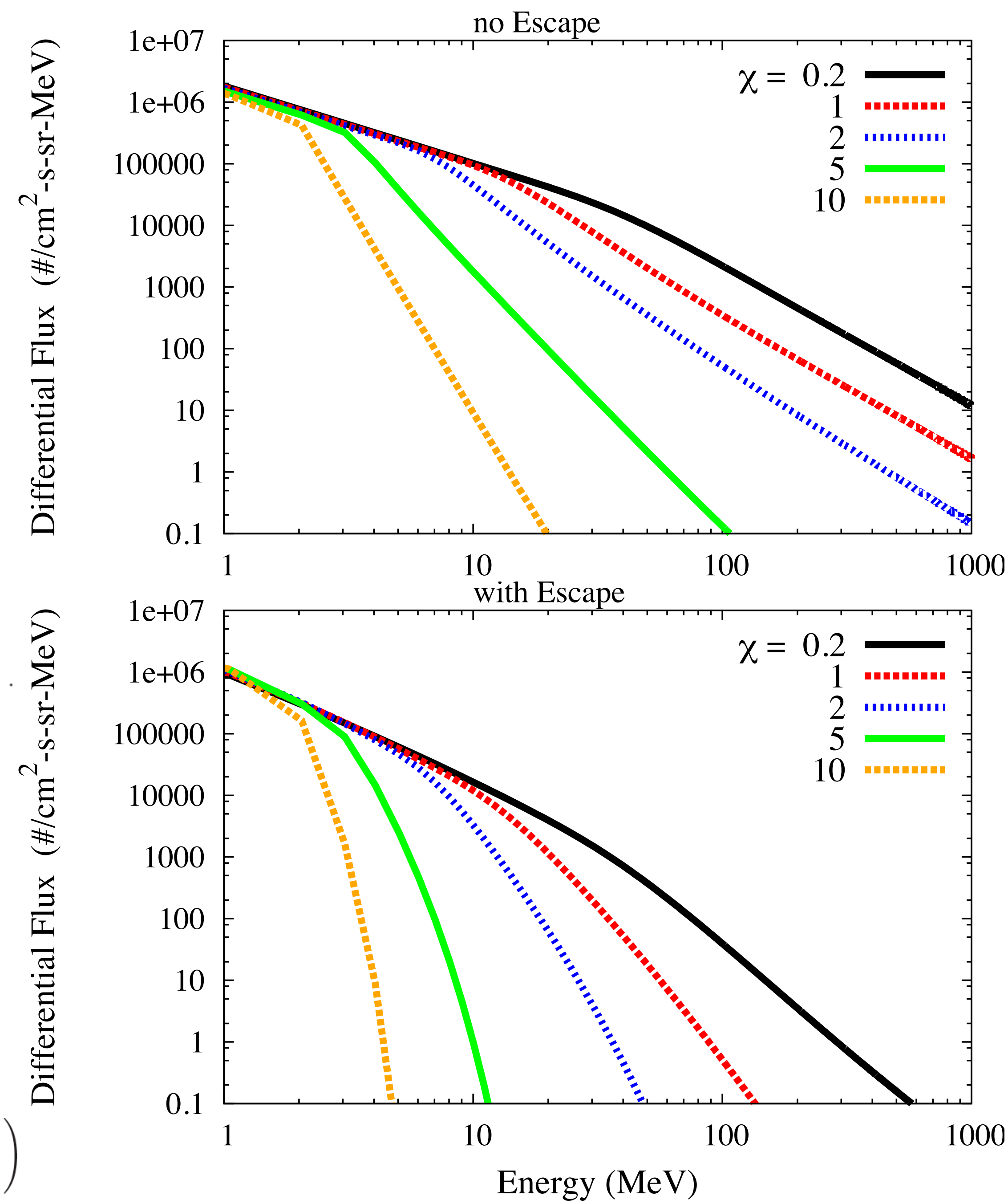
$$_L(z,p) = \frac{3u_1}{2\Delta u} f_{\text{inj}\epsilon}\left(\frac{p}{p_{inj}}\right)^{-\gamma}\left[\text{erf}\left(\frac{L+z_d+z}{2\sqrt{D_z}}\right) - \text{erf}\left(\frac{z_d+z}{2\sqrt{D_z}}\right)\right].$$

$$z_d = -\frac{3}{(\chi+1)\Delta u}(\kappa_{xz1}+\kappa_{xz2})$$

$$D_z = \frac{3}{2(\chi+1)\Delta u}\sum_{j=1}^{2}\left\{\frac{\kappa_{\|}\kappa_{\perp}}{u_{xj}} + \frac{(\kappa_{xzj})^2}{u_{xj}}\right\}$$

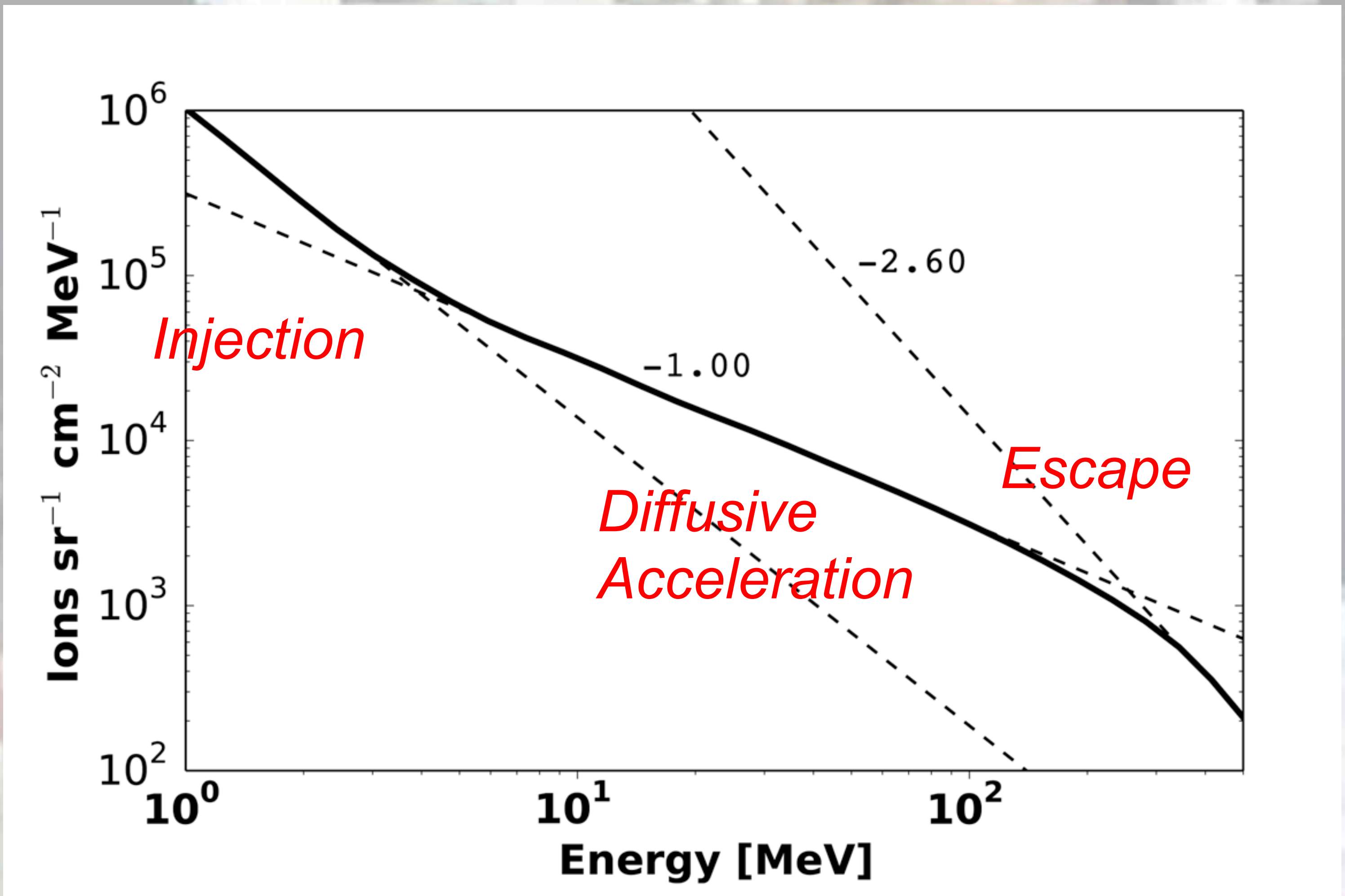
$$F_L^{\text{escape}}(z,p) = F_L(z,p)g^{\text{escape}}(p)$$

$$g^{\text{escape}}(p) \approx \exp\left(-\frac{6}{(\chi+1)\Delta u}\sum_{j=1}^{2}\sqrt{\frac{\kappa_{xxj}}{\tau}}\left[1-\left(\frac{v_{\text{inj}}}{v}\right)^{(\chi+1)/2}\right]\right)$$

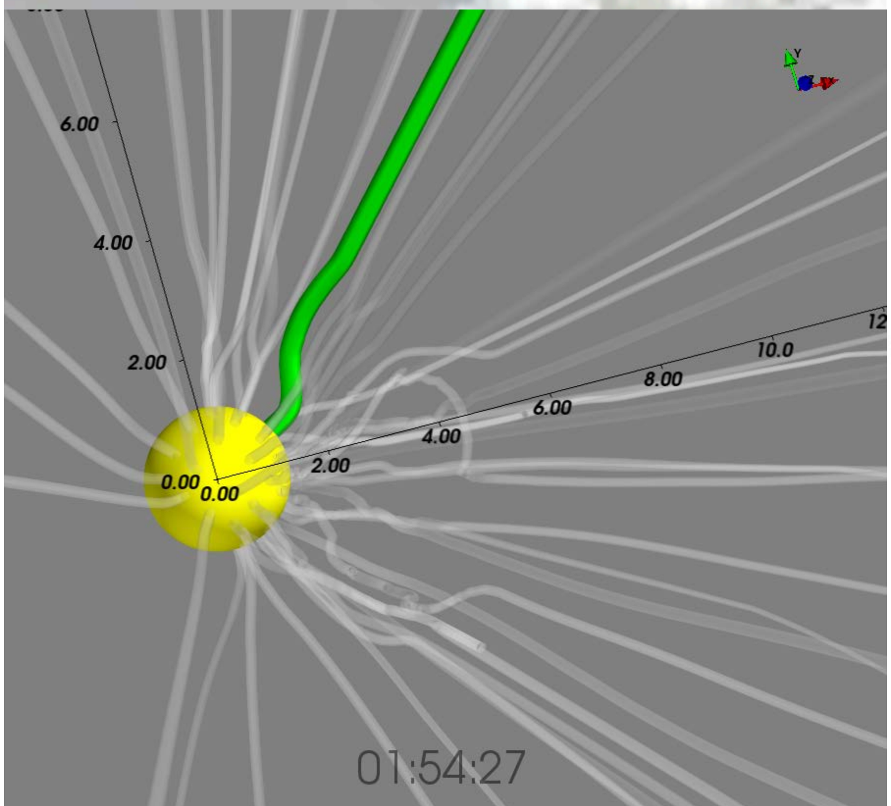


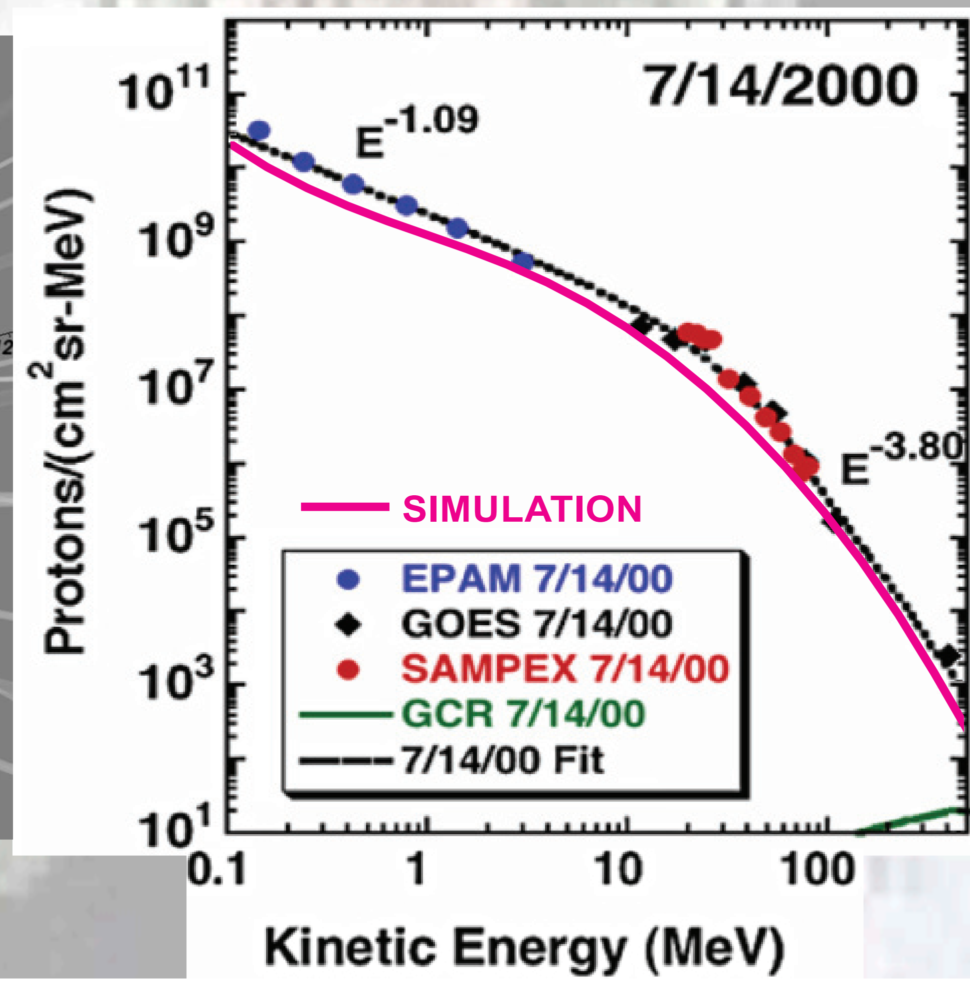
Schwadron et al., 2015

Decomposing Event

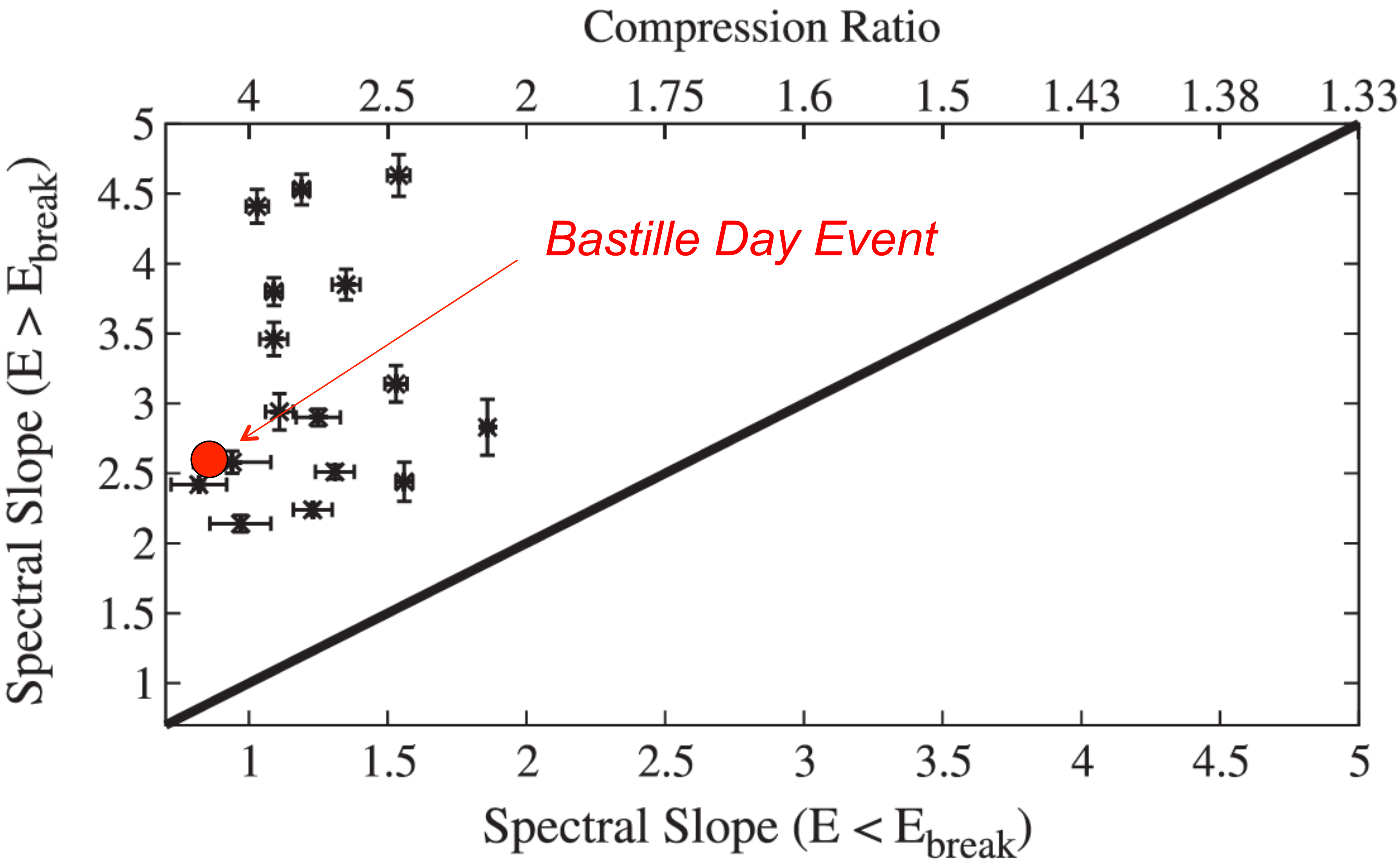


Flank Acceleration and Observational Comparison





Flank Acceleration GLEs

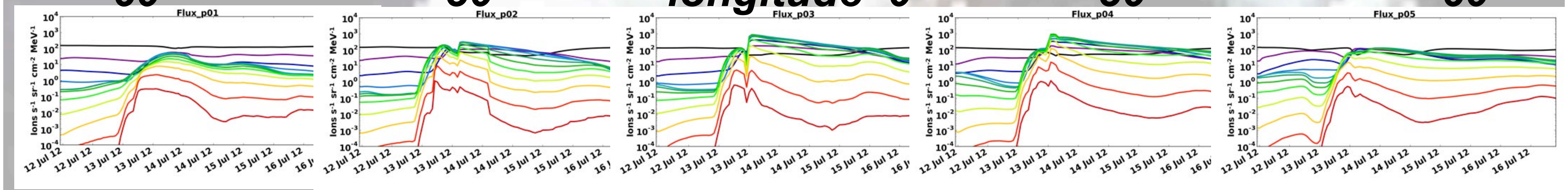


EPREM SEP profiles at different observers (latitude=0°)

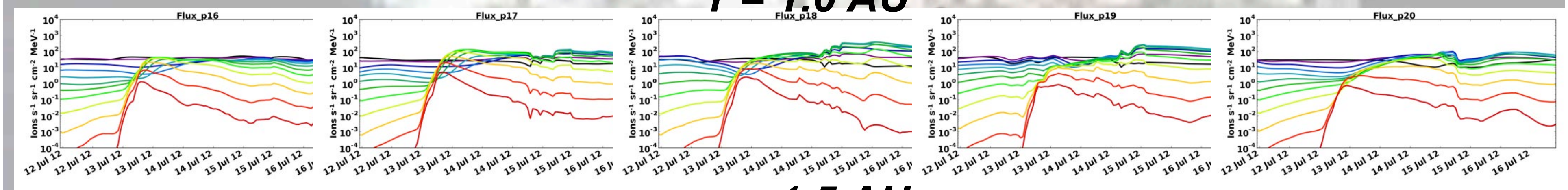
east | west

r = 0.5 AU

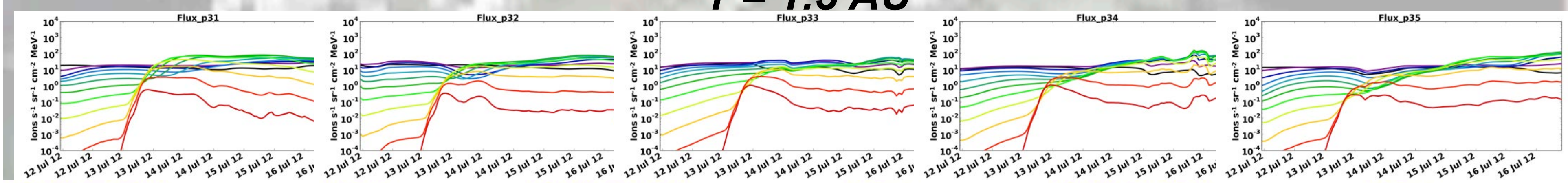
-60° | ***-30°*** | ***longitude=0°*** | ***30°*** | ***60°***

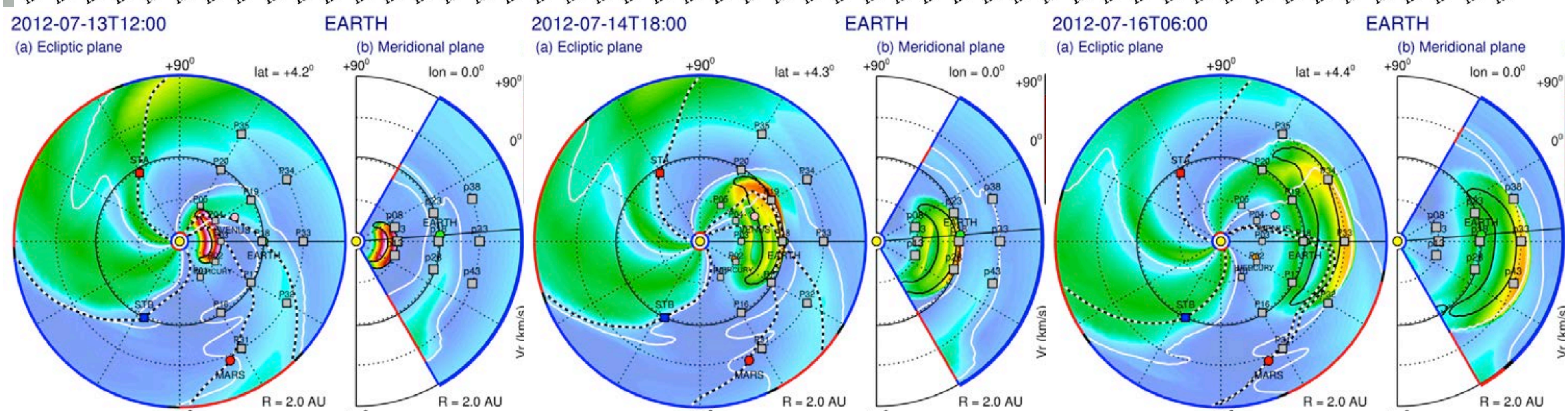


r = 1.0 AU



r = 1.5 AU





Conclusions

- Discovering roots of Energetic Particle Acceleration in Low Corona
- Significantly broadens longitudinal spread
- Characteristic spectrum showing
  - Injection
  - Diffusive flank acceleraion
  - Escape at high energies
- Validation both via time profiles and spectral shape of event

Backup

C-SWEPA Goals

- **Goal 1:** Scientifically explore the seed populations and acceleration of energetic particles in the low corona, through interplanetary space, and over broad longitudinal regions
- **Goal 2:** Couple the energetic particle acceleration model (EPREM, the energetic particle radiation environment model) with MHD models that describe the propagation of coronal mass ejections from the low coronal plasma environment through the interplanetary medium.
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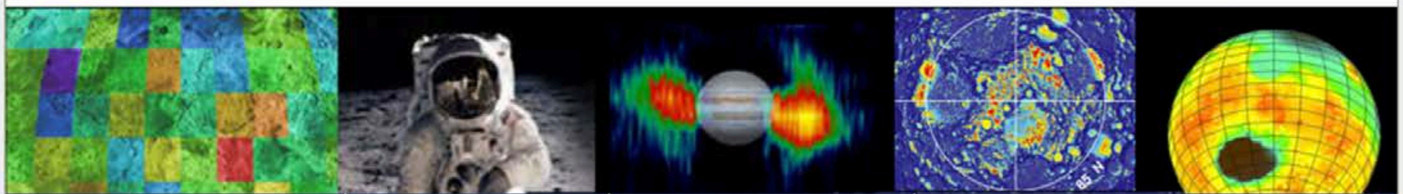
C-SWEPA Role – National & International Teams

- The Cosmic Ray Telescope the for the Effect of Radiation (CRaTER) team (http://crater.unh.edu)
- The Dynamic Response of the Environments at Asteroids, the Moon, and the Moons of Mars (DREAM and DREAM2 Projects, http://ssed.gsfc.nasa.gov/dream/)
- The Sun-2-Ice team (http://sun-2-ice.sr.unh.edu, NSF FESD)
- The Solar Probe Plus team *(http://solarprobe.jhuapl.edu)*
- The International Team on Radiation Interactions. (http://www.issibern.ch/teams/interactplanetbody/)

INTERNATIONAL SPACE SCIENCE INSTITUTE

ISSI Research Team:

Radiation Interactions at Planetary Bodies



The Internatioinal Space Science Institute (ISSI) is an Institute of Advanced Study, bringing together scientists from all over the world meet in a multi- and interdisciplinary setting to advance the understanding of results from space missions, ground based observations and laboratory experiments.

The international research teams are set up in response to an Annual Call by ISSI. Their goal is to carry out a resarch project leading to publications in scientific journals.

Proposal Abstract

Radiation Interactions at Planetary Bodies

SINCE THE LAUNCH of the Lunar Reconnaissance Orbiter (LRO) in 2009, the Comic Ray Telescope for the Effects of Radiation (CRaTER) has directly measured the Lunar radiation environment and mapped albedo protons (~100 MeV) coming from the Moon. Particle radiation has widespread effects on the lunar regolith ranging from chemical alteration of lunar volatiles to the formation of subsurface electric fields with the potential to cause dielectric breakdown that could modify the regolith in permanently shaded craters. LRO/CRaTER's direct measurements are transforming our understanding of the lunar radiation environment and its effects on the moon.

Similarly, the Radiation Assessment Detector (RAD) has been measuring the energetic particle radiation environment on the surface of Mars since the landing of the Curiosity rover in August 2012. The Martialn surface is protected by the atmosphere above; though only about 1% as thick as Earth's, its depth is sufficient to stop solar wind ions and the large majority of Solar Energetic Particles. RAD, like CRaTER, measures radiation dose, dose equivalent (related to human health risks), and particle spectra to enable rigorous tests of environment and transport models.

Recent measurements of galactic cosmic radiation and solar energetic particle radiation at other planetary objects (e.g., the moons of Mars) raise new fundamental questions about how radiation interacts at planetary bodies and what its long term impacts are.

This ISSI team will advance the study of radiation interactions.
Read more... (proposal and abstract, pdf)