Development of a Physics-Based Prototype Model Chain for Solar Energetic Particle Acceleration and Transport Forecasting for the Inner Heliosphere

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The Project **SPREAdFAST - "Solar Particle Radiation Environment Analysis and Forecasting – Acceleration and Scattering Transport"** (http://spreadfast.astro.bas.bg)

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Summary of Objectives

-Develop a prototype of a software framework for observation-driven, physics-based modelling of the coronal acceleration of SEPs, their heliospheric transport, and event forecasting;

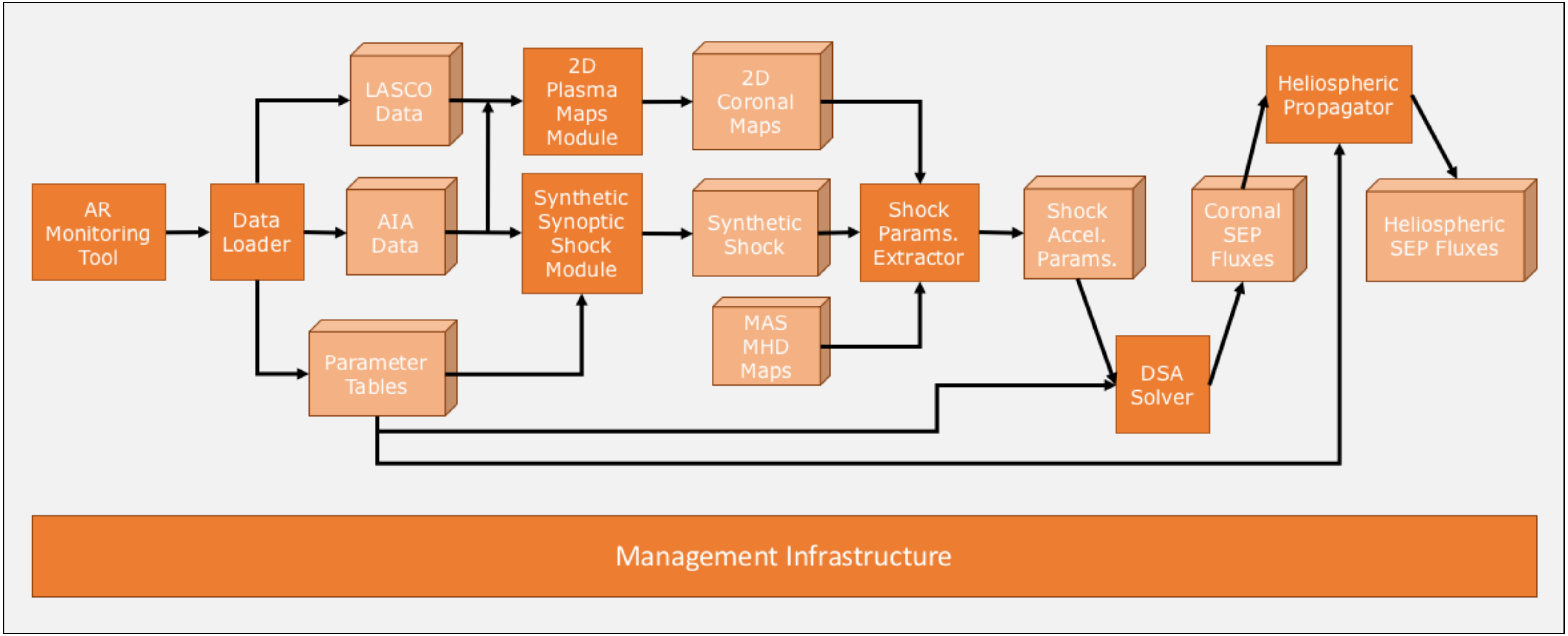
-Develop and test prototype of the software framework for the system by adapting existing models and developing new modules;

-Develop parameter tables for the data-driven sun-heliosphere modelling/forecasting chain, by modelling a number of historical events;

-Perform validation studies to assess the performance of the SPREAdFAST forecasting prototype;

-Ultimate goal is to help improve SEP event forecasting in the heliosphere

SPREAdFAST work flow



Technical Developments: AR Monitor

ARMonitor downloads real-time:
- ace_epam_5m
- solar_regions
- goes15_xray_1m
- goes15_protons_5m
- solar_probabilities

All of the above are in JSON format.

It also downloads synoptic AIA 1k images every 3 minutes, overwriting the previous images.

ARMonitor has been implemented on the SPREAdFAST dedicated machine.

Example from solar_regions


```
{
  "observed_date":"2019-09-10",
  "region":2748,
  "latitude":14,
  "longitude":-102,
  "location":"N14W0*",
  "carrington_longitude":210,
  "old_carrington_longitude":209,
  "area":null,
  "spot_class":null,
  "extent":null,
  "number_spots":null,
  "mag_class":null,
  "mag_string":null,
  "status":"d",
  "c_xray_events":0,
  "m_xray_events":0,
  "x_xray_events":0,
  "proton_events":null,
  "s_flares":0,
  "impulse_flares_1":0,
  "impulse_flares_2":0,
  "impulse_flares_3":0,
  "impulse_flares_4":0,
  "protons":null,
  "c_flare_probability":0,
  "m_flare_probability":0,
  "x_flare_probability":0,
  "proton_probability":0,
  "first_date":"2019-09-01T08:44:00"
}
```


Example from ace_epam_5m


```
{
  "time_tag":"2019-09-17T02:50:00",
  "dsflag_de1":0,
  "dsflag_de4":0,
  "dsflag_p1":0,
  "dsflag_p3":0,
  "dsflag_p5":0,
  "dsflag_p7":0,
  "dsflag_fp6p":0,
  "numpts_de1":46,
  "numpts_de4":46,
  "numpts_p1":182,
  "numpts_p3":182,
  "numpts_p5":182,
  "numpts_p7":91,
  "numpts_fp6p":91,
  "de1":7.5587604e+002,
  "de4":3.0894909e+001,
  "p1":2.2197253e+003,
  "p3":1.8815151e+001,
  "p5":2.6814399e+000,
  "p7":1.2990458e-001,
  "fp6p":6.3571823e-001,
  "fp6p_ratio":null,
  "dsflag_p2":0,
  "dsflag_p4":0,
  "dsflag_p6":0,
  "dsflag_p8":0,
  "numpts_p2":182,
  "numpts_p4":182,
  "numpts_p6":91,
  "numpts_p8":91,
  "p2":3.2913498e+001,
  "p4":8.3164396e+000,
  "p6":6.1349666e-001,
  "p8":5.0077826e-002,
  "dsflag_p1_30":0,
  "dsflag_p2_30":0,
  "dsflag_p4_30":0,
  "dsflag_p3_30":0,
  "dsflag_p5_30":0,
  "dsflag_p6_30":0,
  "dsflag_p7_30":0,
  "dsflag_p8_30":0,
  "numpts_p1_30":45,
  "numpts_p2_30":45,
  "numpts_p3_30":45,
  "numpts_p4_30":45,
  "numpts_p5_30":20,
  "numpts_p6_30":18,
  "numpts_p7_30":14,
  "numpts_p8_30":12,
  "p1_30":1.6289267e+004,
  "p2_30":4.3438720e+006,
  "p3_30":4.0454850e+005,
  "p4_30":7.8594836e+002,
  "p5_30":3.4253490e+000,
  "p6_30":1.0913471e+000,
  "p7_30":2.8682745e-001,
  "p8_30":1.1080042e-001
}
```


Example from solar_probabilities


```
{
  "date":"2019-09-16T00:00:00",
  "c_class_1_day":1,
  "c_class_2_day":1,
  "c_class_3_day":1,
  "m_class_1_day":1,
  "m_class_2_day":1,
  "m_class_3_day":1,
  "x_class_1_day":1,
  "x_class_2_day":1,
  "x_class_3_day":1,
  "10mev_protons_1_day":1,
  "10mev_protons_2_day":1,
  "10mev_protons_3_day":1,
  "100mev_protons_1_day":1,
  "100mev_protons_2_day":1,
  "100mev_protons_3_day":1,
  "polar_cap_absorption":"green"
}
```


Example from goes15_protons_5m


```
{
  "time_tag":"2019-09-17T02:50:00",
  "p1_flux":3.537900161743164e+001,
  "p2_flux":1.935729980468750e-001,
  "p3_flux":4.690429940819740e-002,
  "p4_flux":1.642660051584244e-002,
  "p5_flux":2.734070084989071e-002,
  "p6_flux":5.894309841096401e-003,
  "p7_flux":3.130079945549369e-003,
  "p8_flux":3.1617000e-003,
  "p9_flux":1.4905100e-003,
  "p10_flux":6.7750702e-004,
  "p11_flux":2.1818699e-004
}
```

Technical Developments: MongoDB database

Used technologies:

- Python 3.6,
- MongoDB 4.0
- JSON interface

Reasons to choose MongoDB:

- very fast
- data is stored natively in JSON documents, thus we don't need most of input data
- strong support, excellent python libraries for manipulating data
- good and very flexible document design: No need to alter table design
- indexing is very flexible too, doesn't depend on documents structure
- Really scalable solution, easy parallelizing if needed.

Implementation

- a bash script is responsible for regular download of appropriate JSON files with data and parameters for recent solar regions
- the downloaded files are processed by python script which inserts each JSON document in DB.
- each collection has Primary Key to make sure we don't duplicate data (see DB model)

Technical Developments: Data Loader

- A module to download necessary data based on the results from ARMonitor;
- Optimizes obtaining data for all modules of SPREAdFAST;
- Useful for both historical events, and for real-time/forecasting version of the system;
- Downloading on-demand data from AIA, LASCO, MAS web-based model results

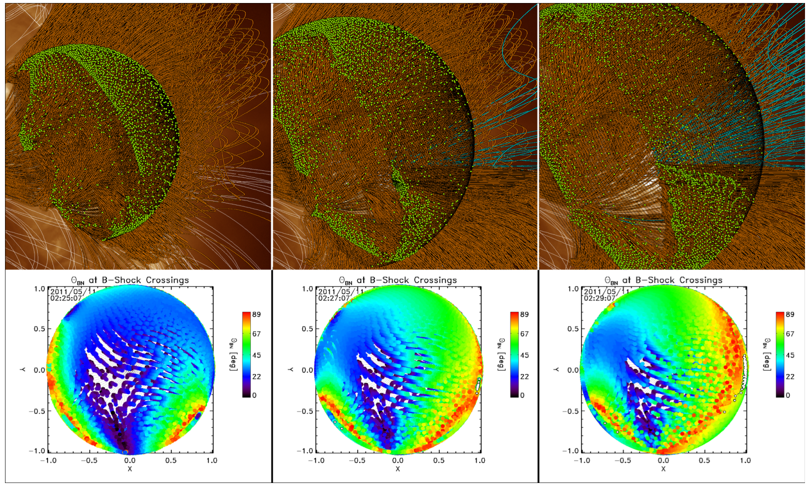
Technical Developments:
Synthetic Synoptic Shock Module (S3M)

- Extended existing CSGS geometric model (Kozarev et al. 2017) and CASHeW framework for shock/compression characterisation to 6 Rsun and beyond;

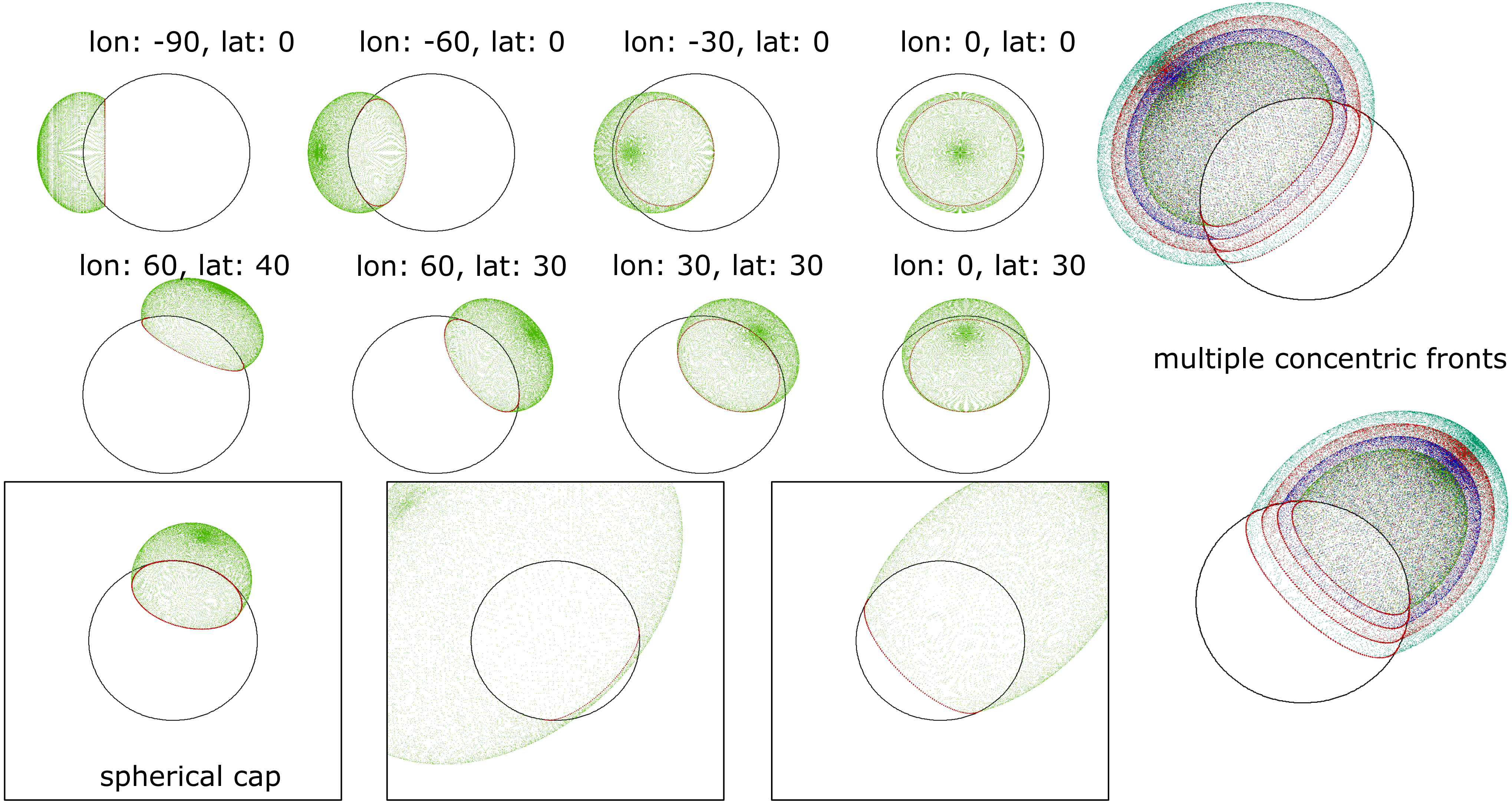
- Developed automated radial/lateral wave and driver kinematics measurements;

- Replaced spherical shock model with spheroid using radial and lateral kinematics measurements;

- Implemented differential emission measure model of Cheung et al. (2015)

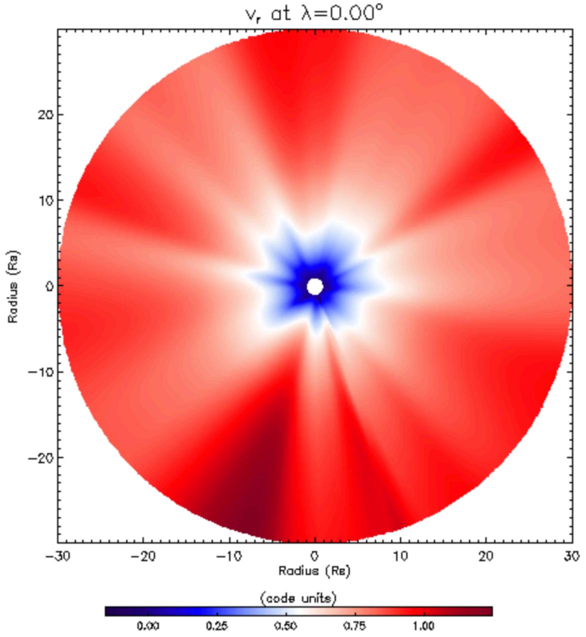


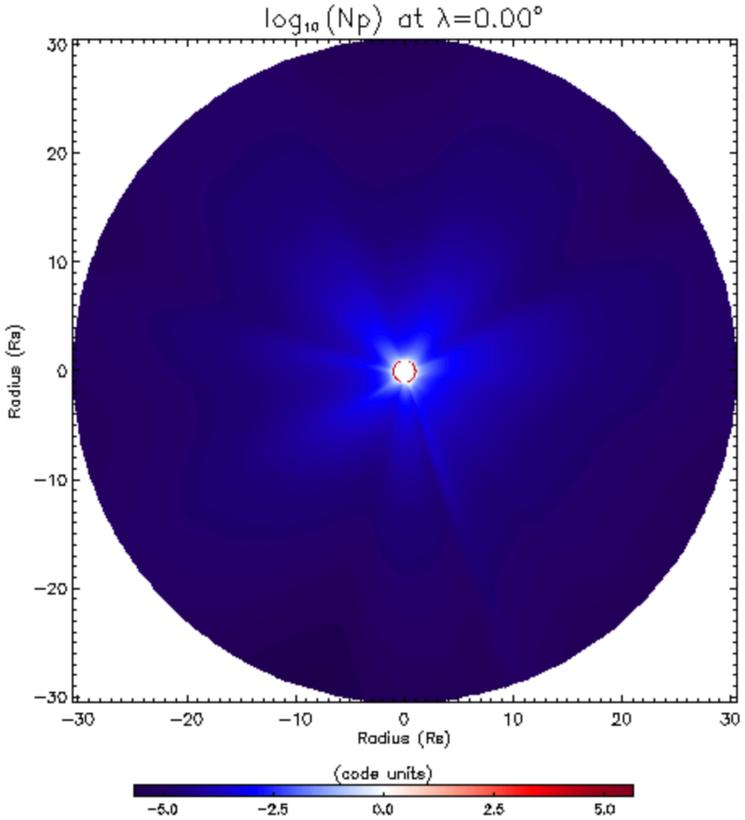
Technical Developments:
Developing a spheroid model for S3M

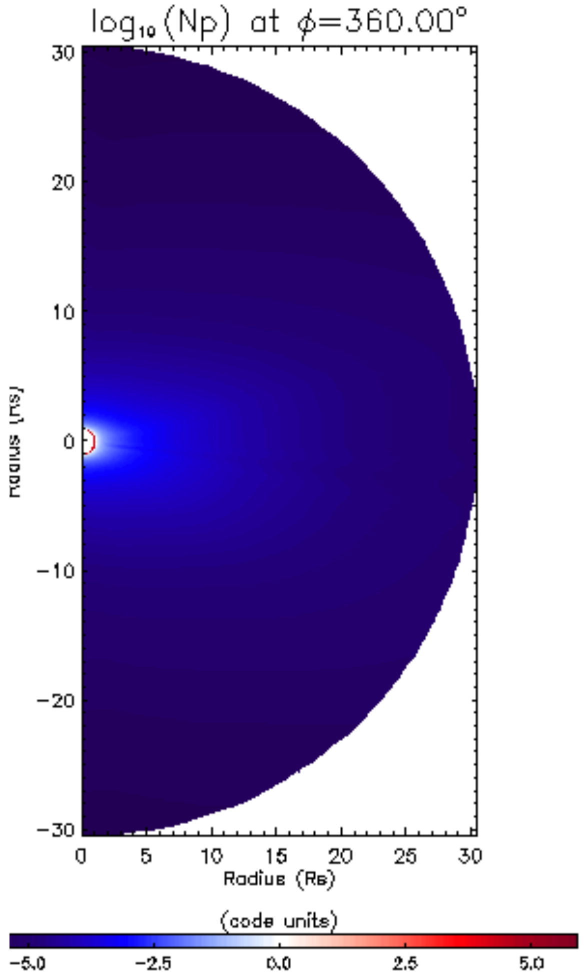


Technical Developments:
Using Predictive Science MAS MHD model results

- Developed interface for ingesting MAS MHD result datacubes
- Model provides plasma information up to 30 solar radii
- Developed trilinear interpolation of plasma quantities for each shock point
- Automated the download of datacubes

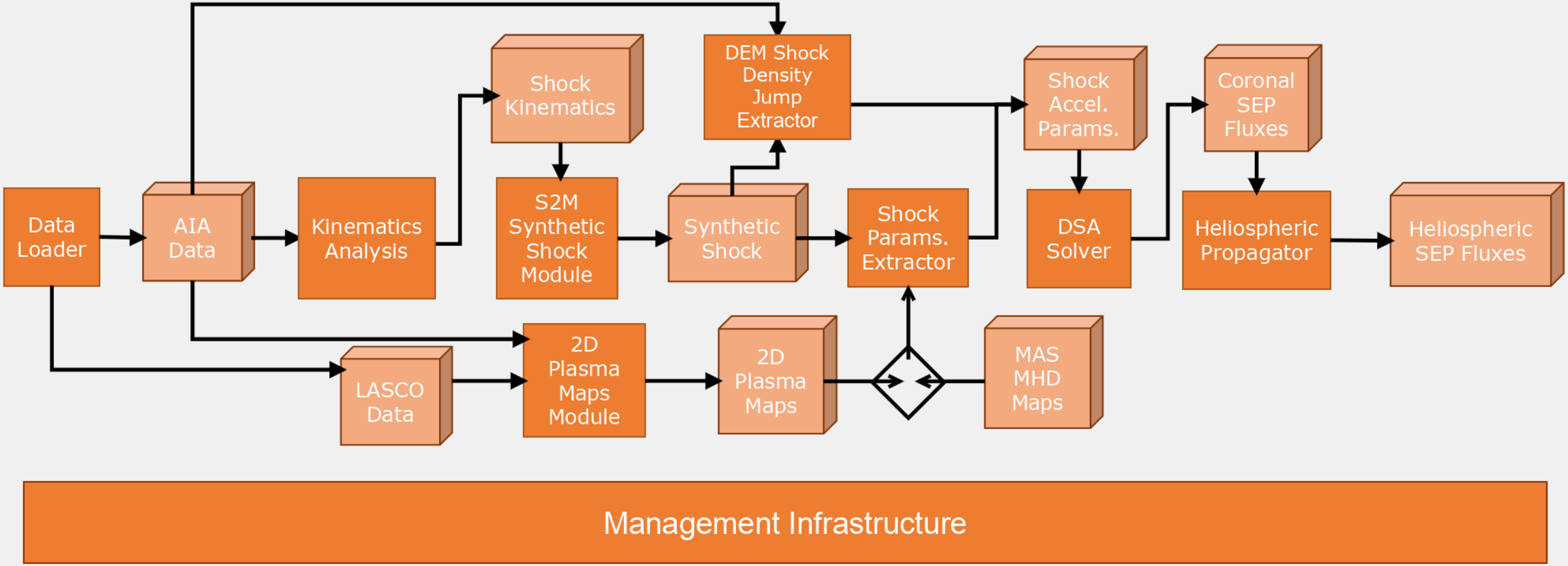




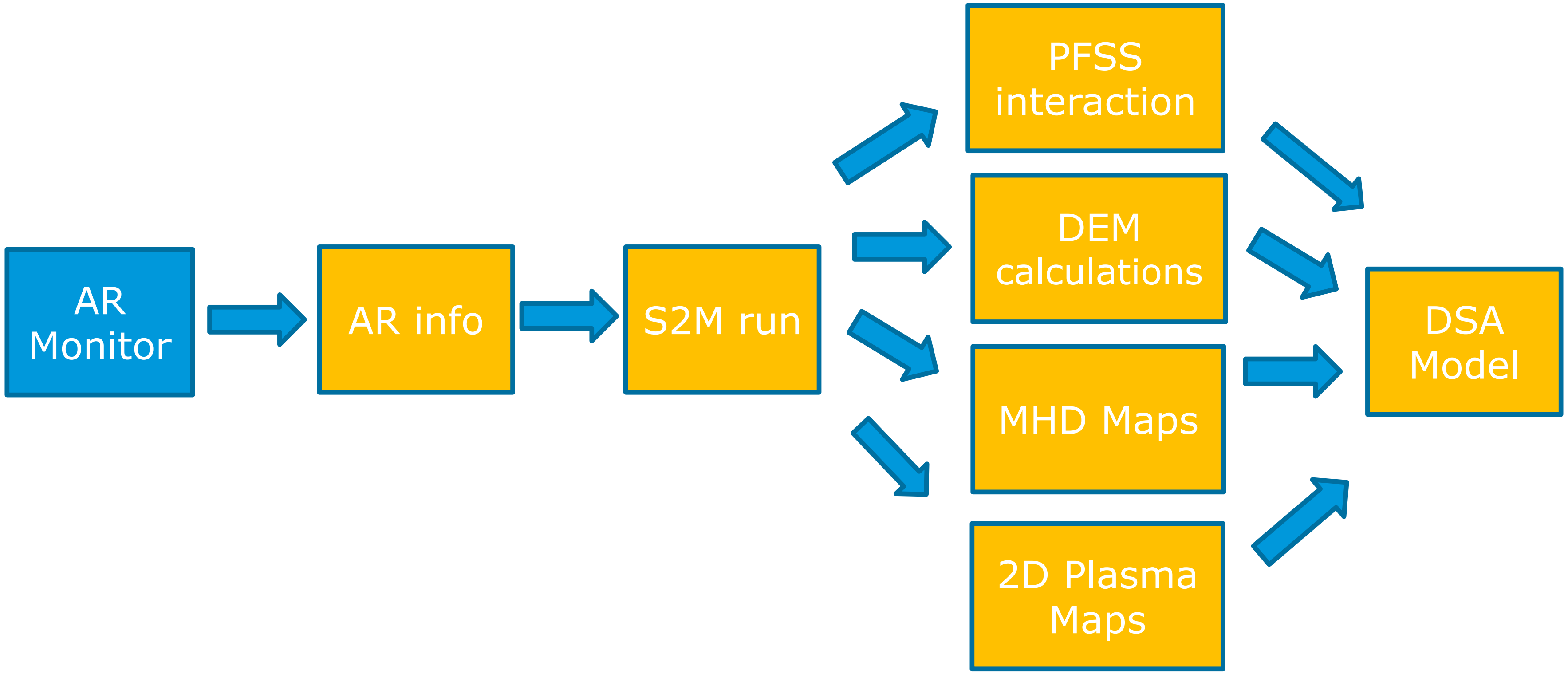


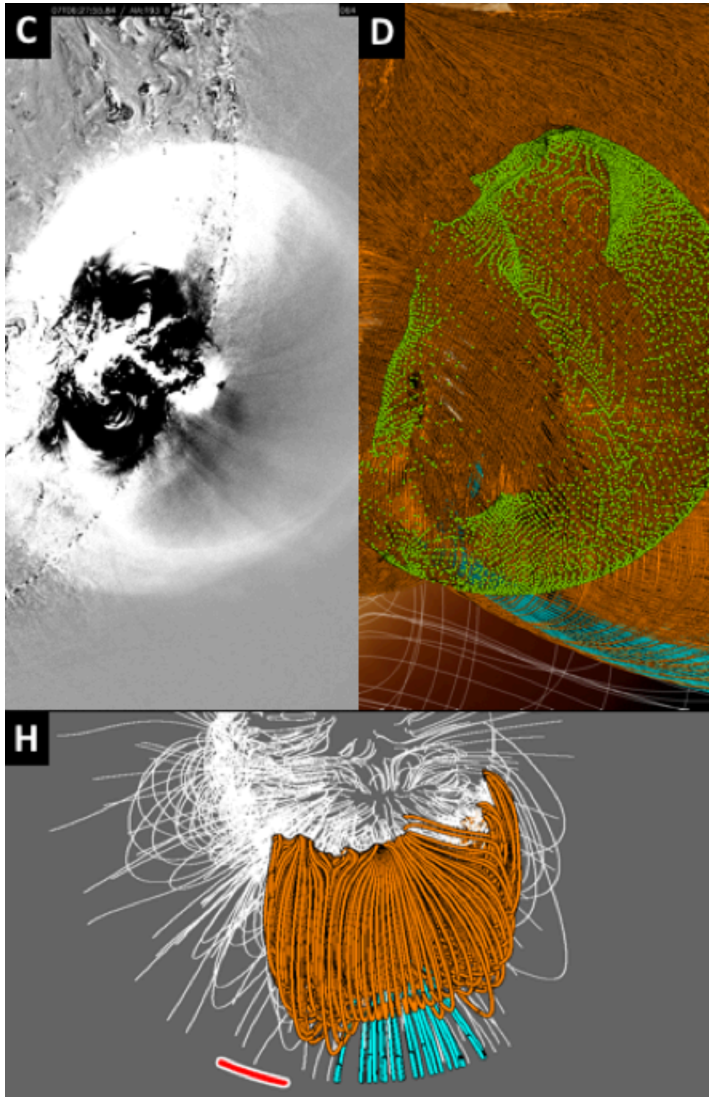
SPREAdFAST - Synthetic Shock Module (S2M) version

- A version of the system for studying historical events and developing tables of typical coronal plasma parameters

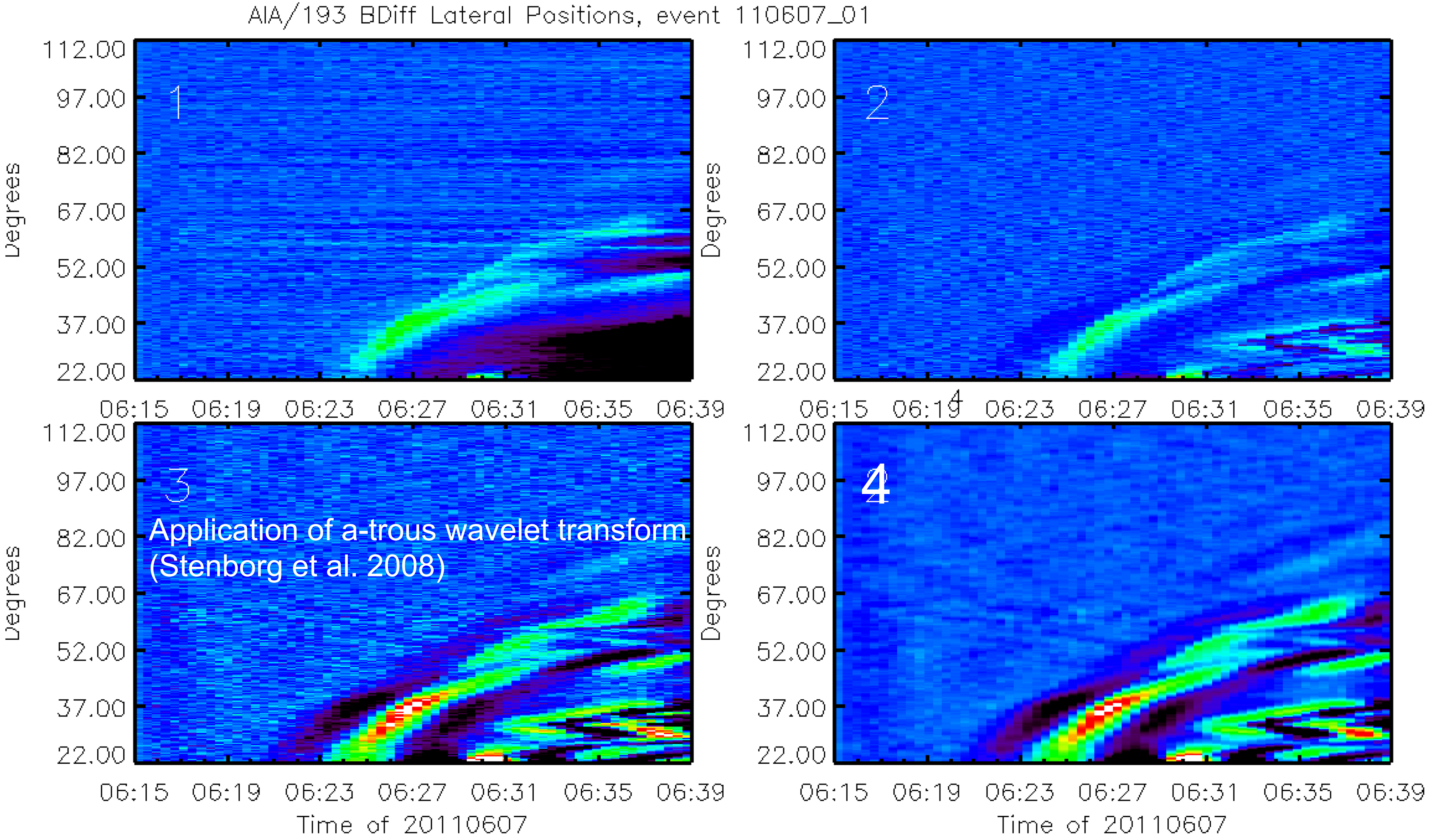


Synthetic Shock Module (S2M) Sub-Framework

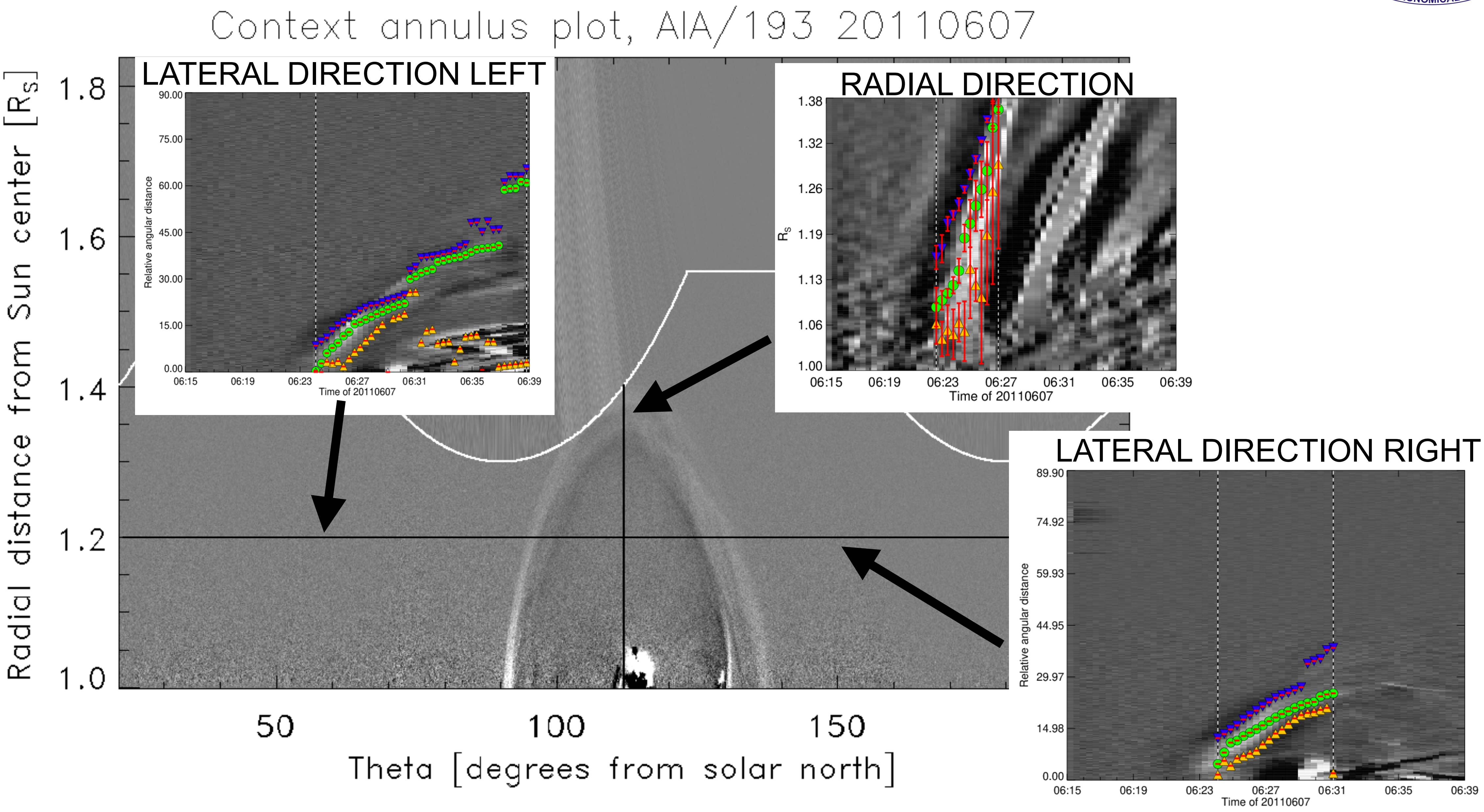




Preparation of J-Maps for Automated Kinematic Measurements

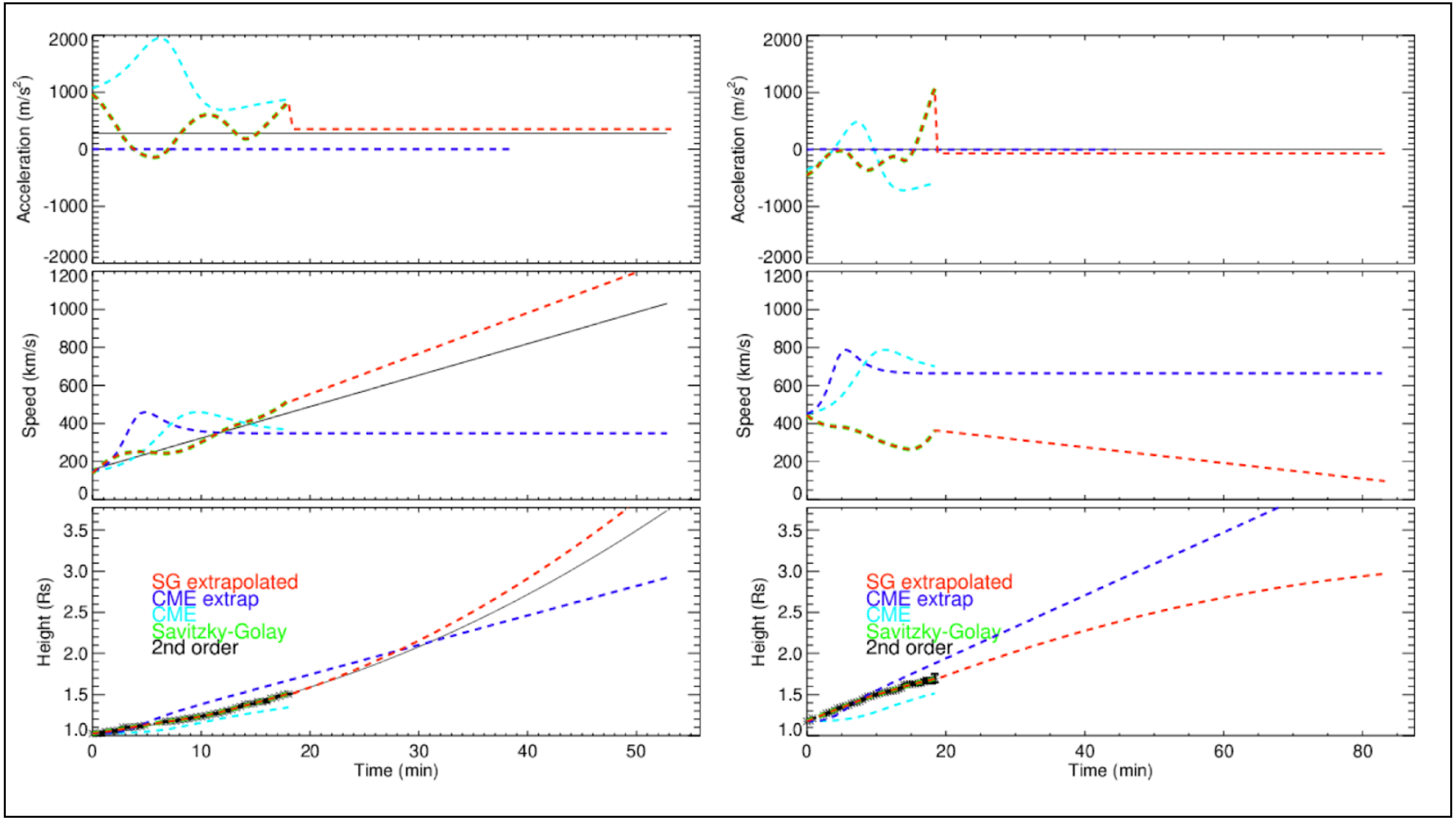


The Event of 07 June, 2011 - Kinematics from AIA



Radial and Lateral Kinematics, June 07, 2011

Radial (left) and lateral (right) **extrapolations** of CBF kinematics to 6 Rs for a single historical event.



S2M Instance and Spheroid Aspect Ratio

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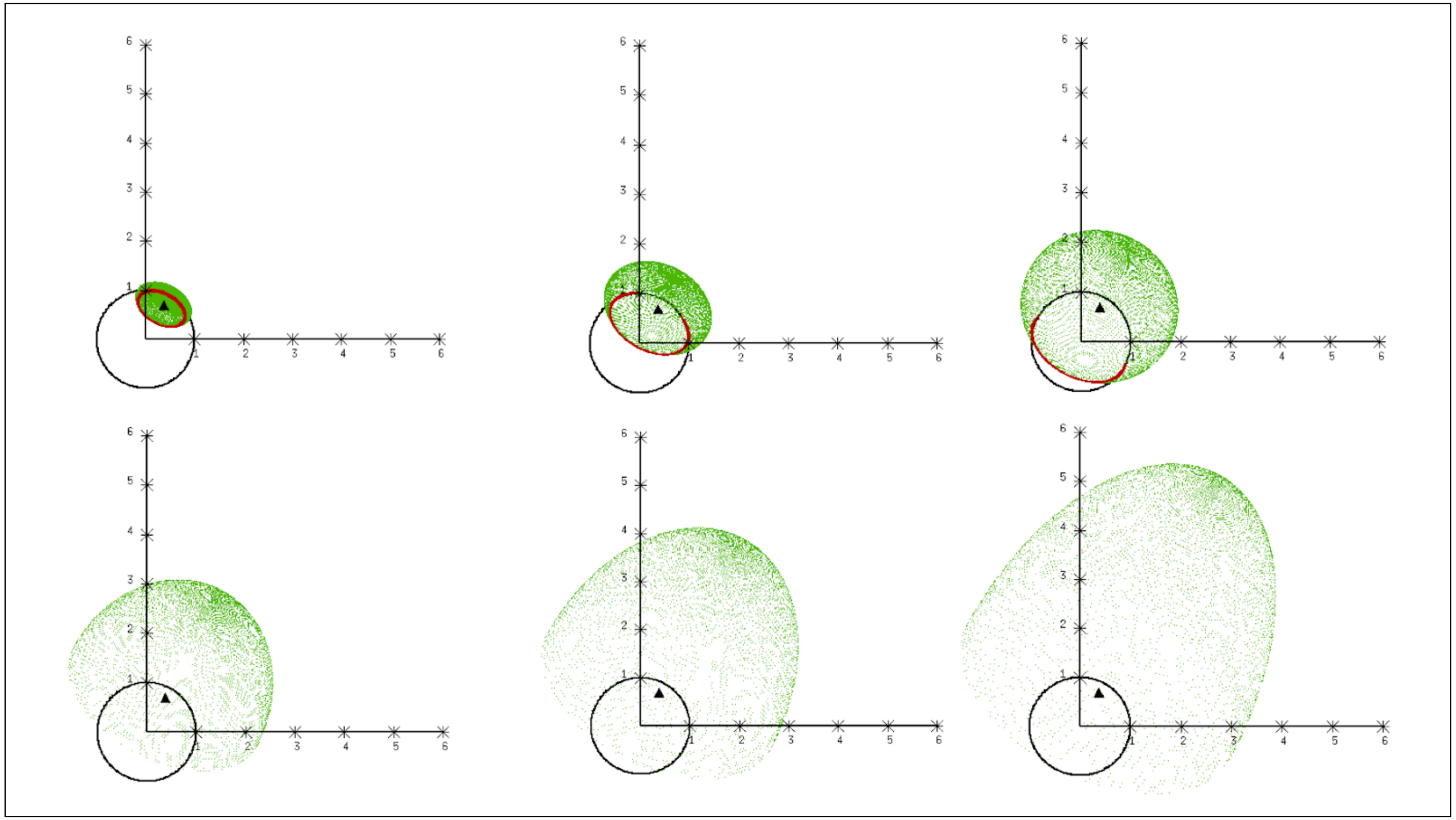
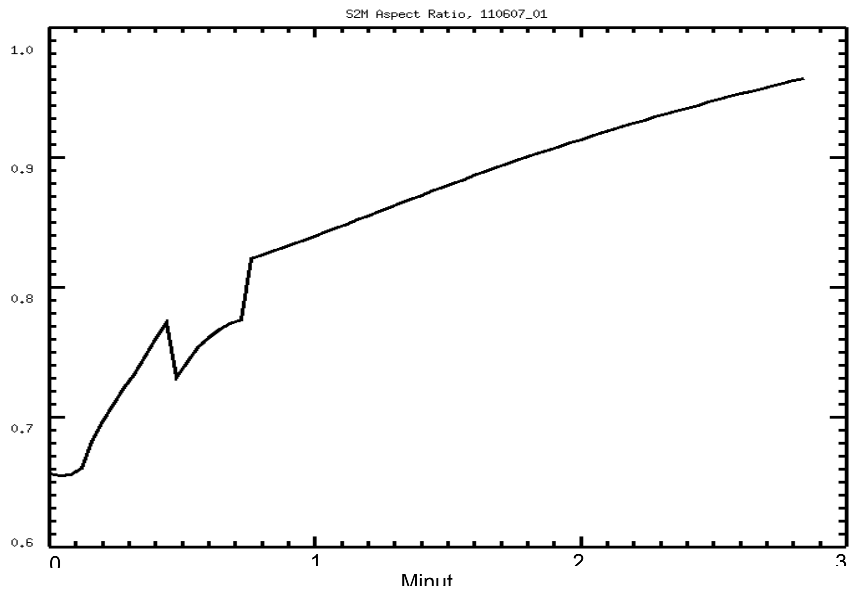
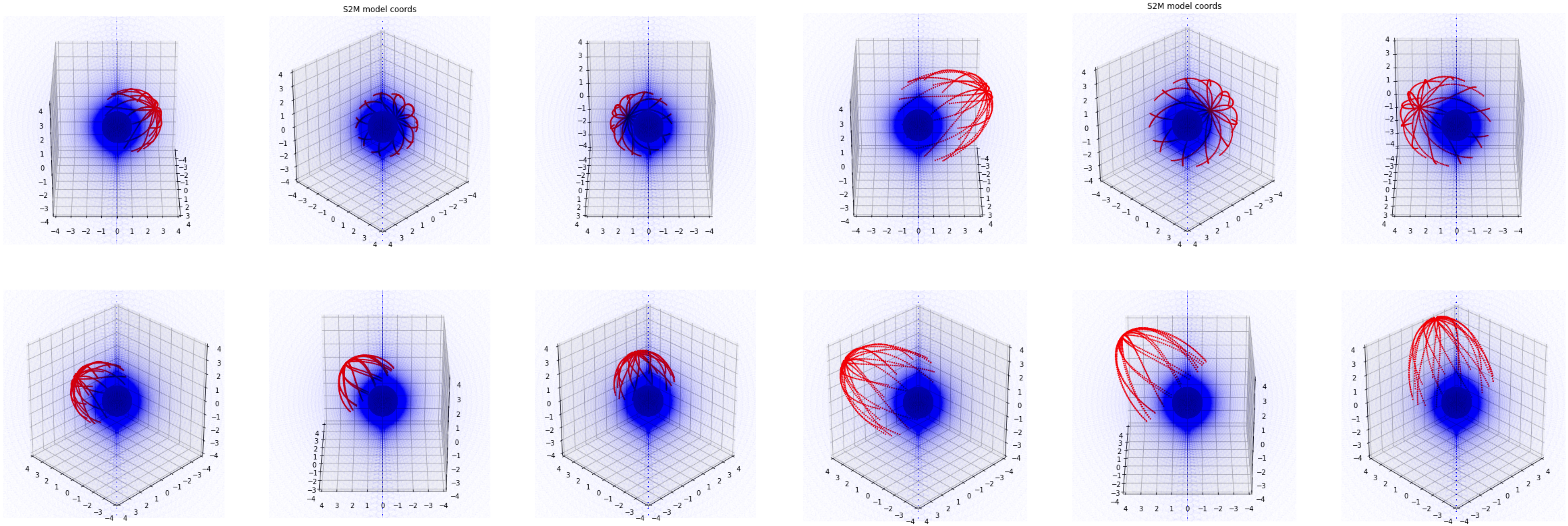
Evolution of an S2M surface with a changing aspect ratio, based on extrapolation of the CBF kinematics





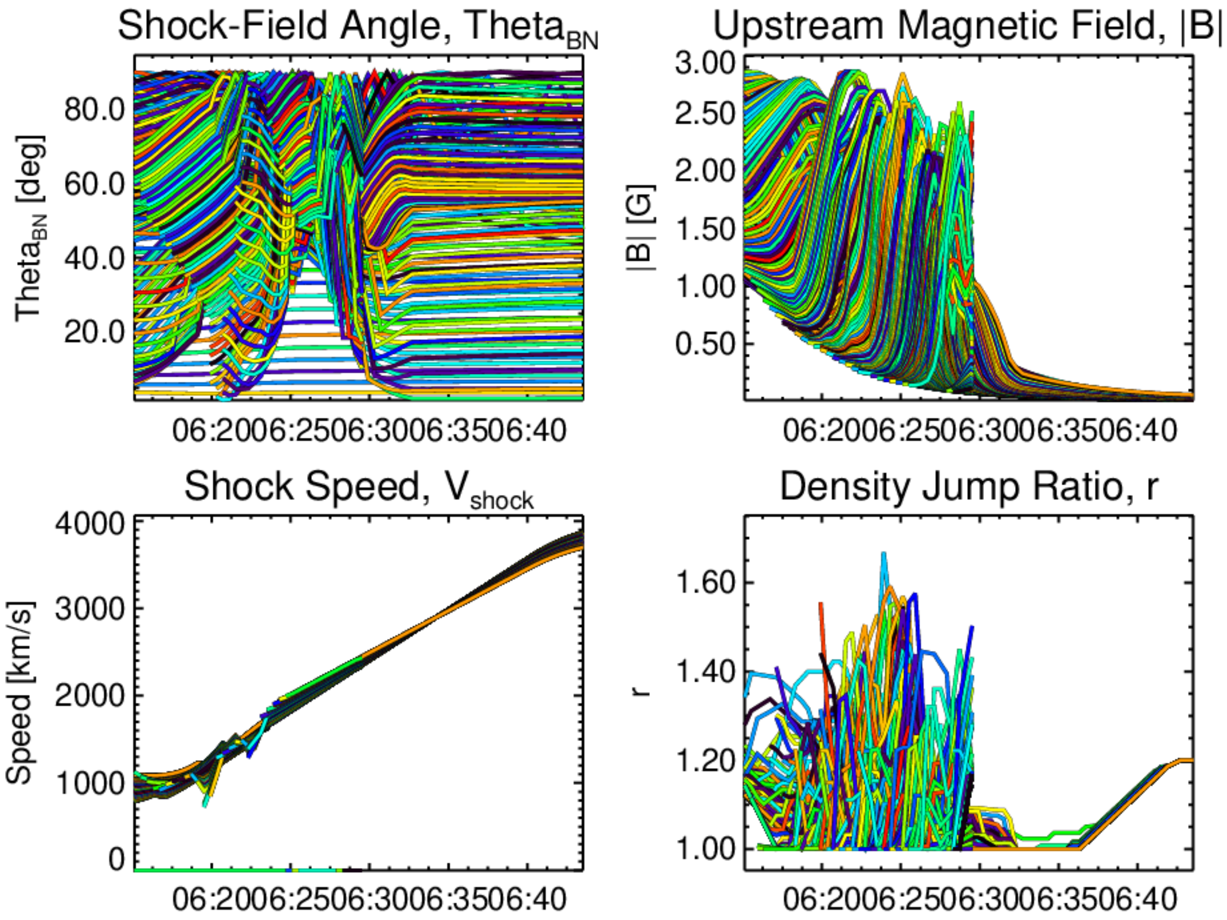
Shock Interaction with MAS Synoptic Model Result

A multi-angle view of the S2M model skeleton (red), overlaid on the MAS model nodes (light blue), for two different time steps.

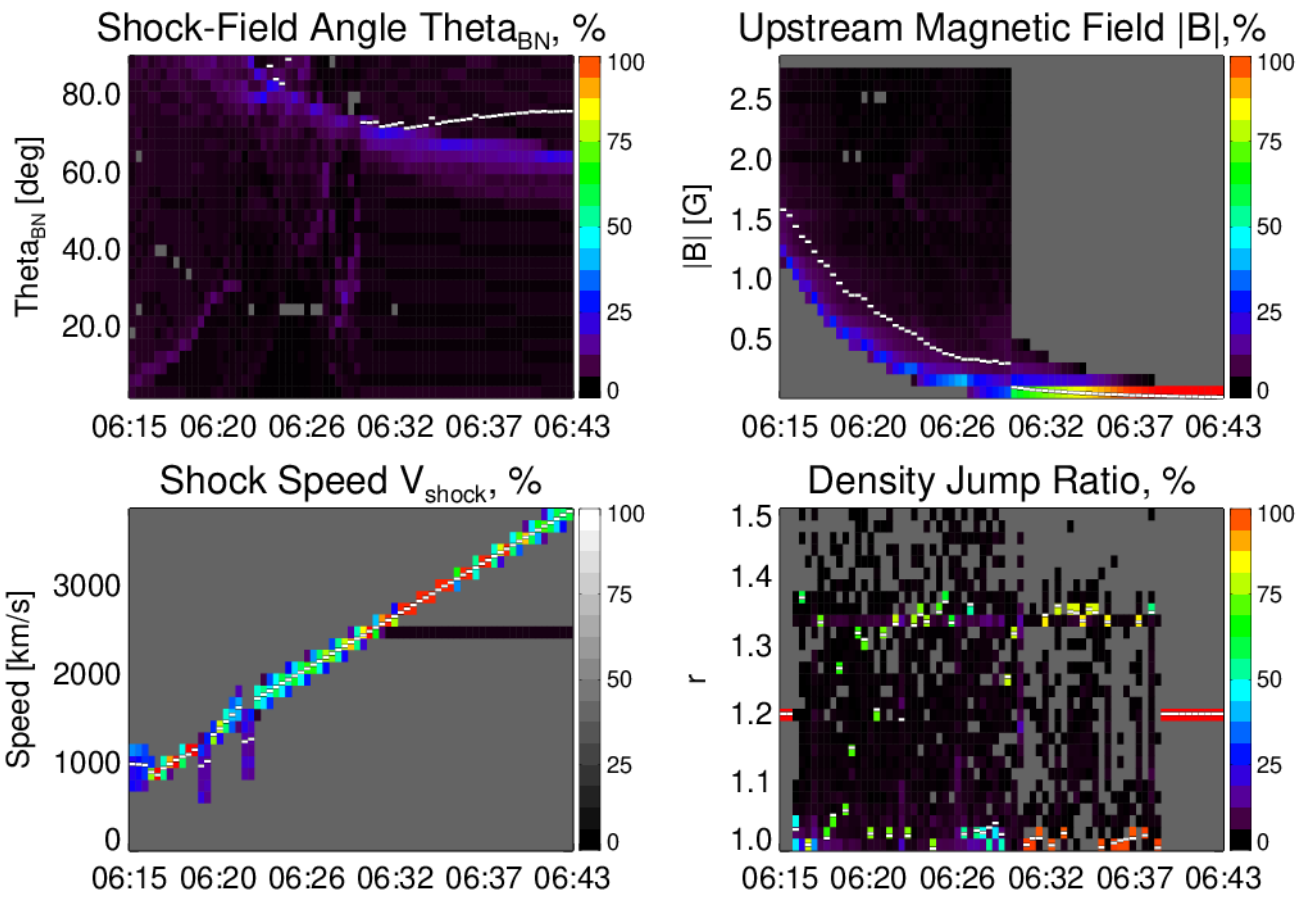


Shock Interaction with MAS Synoptic Model Result

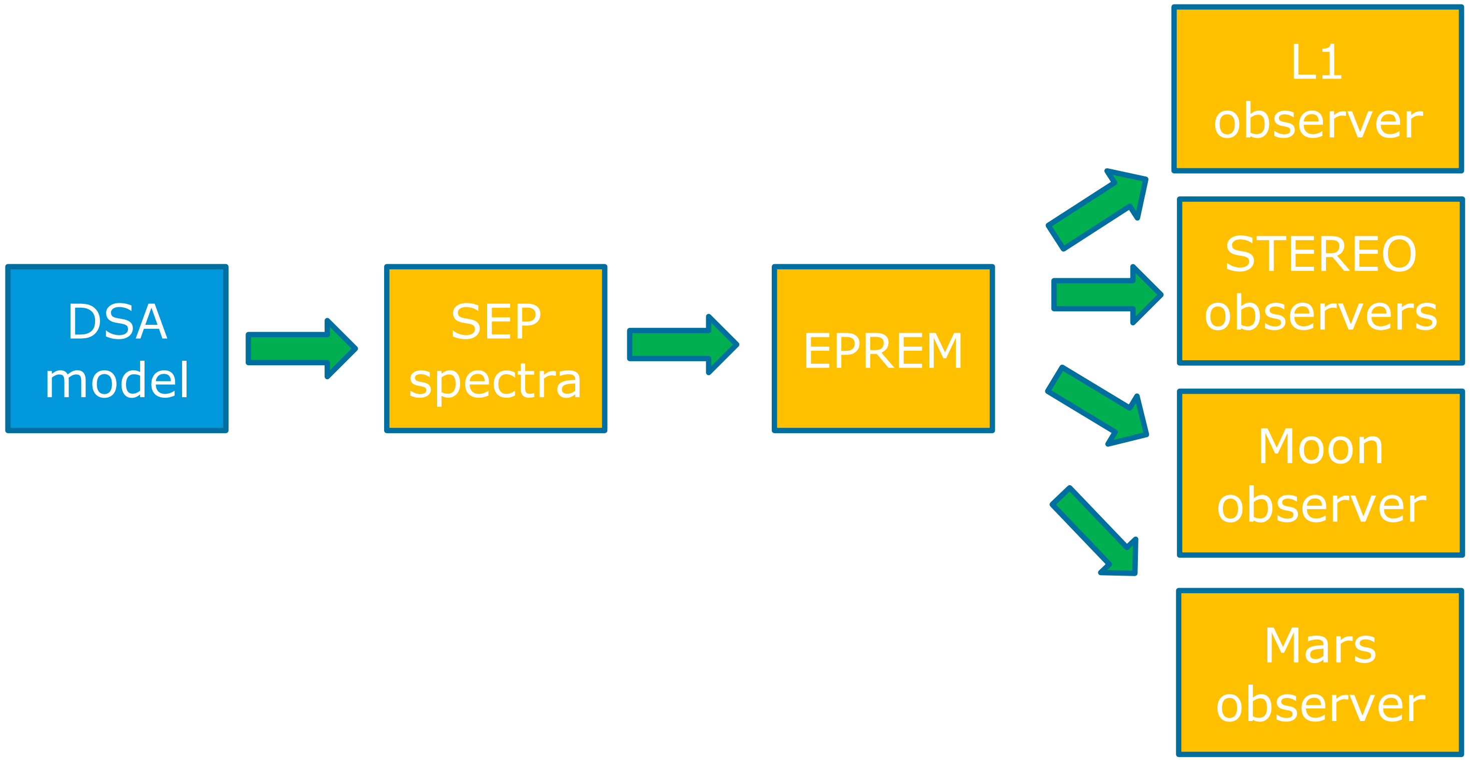
Timeseries of shock parameters at crossing points

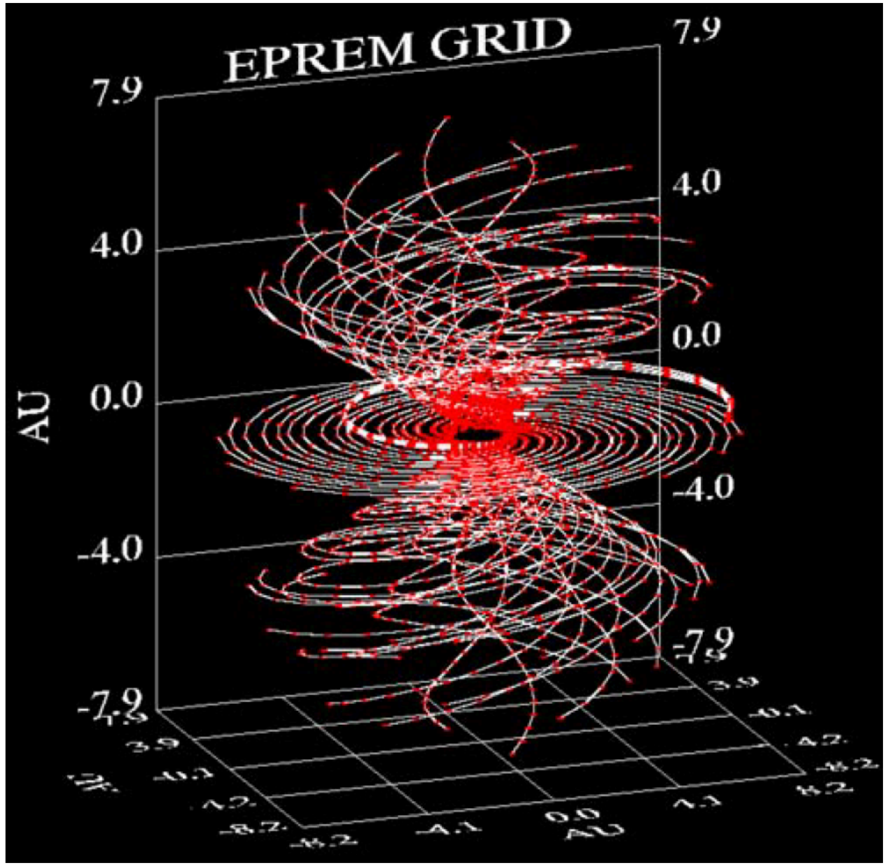


Timeseries histograms of shock parameters

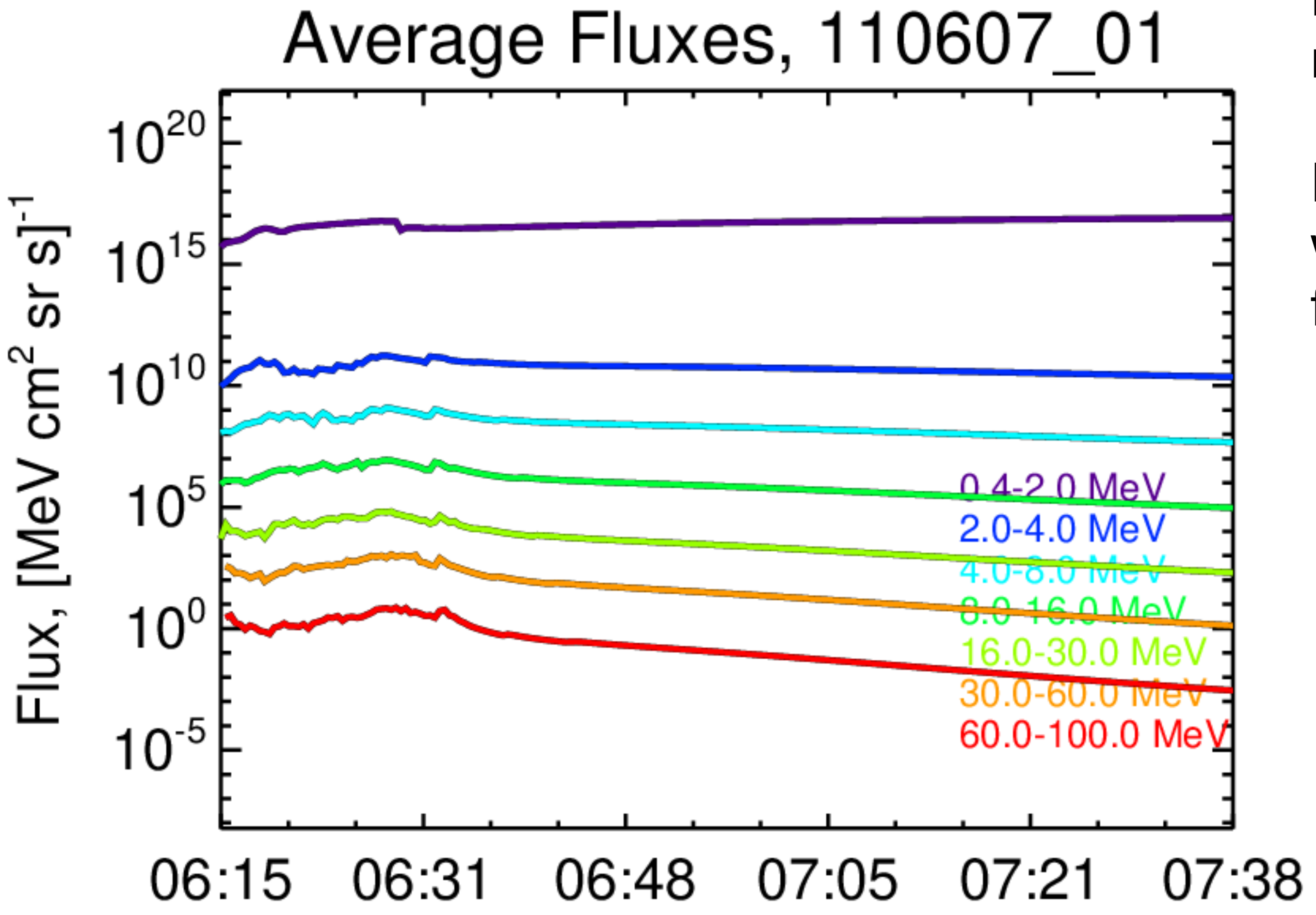


Heliospheric Propagator Module - Based on EPREM (Schwadron et al. 2010, Kozarev et al. 2010)



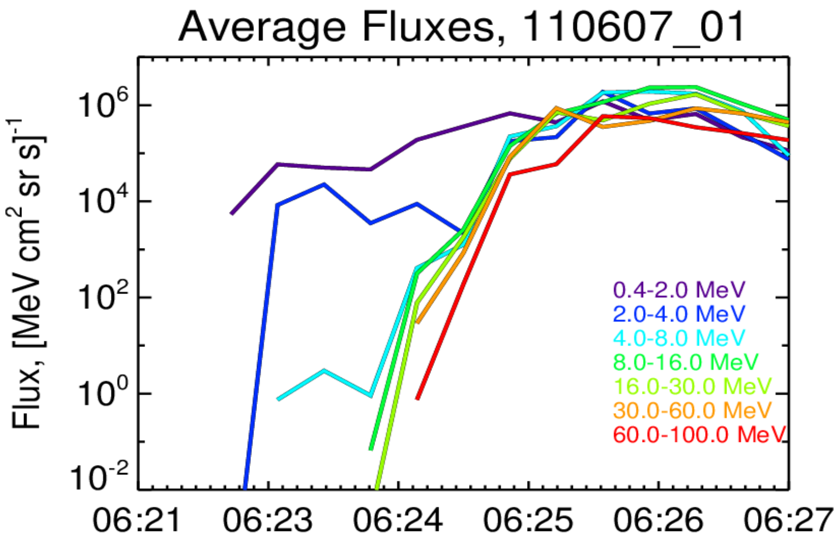


Fluxes from Coronal DSA Model



Left - Low-resolution coronal DSA model run results, used as input for EPREM.

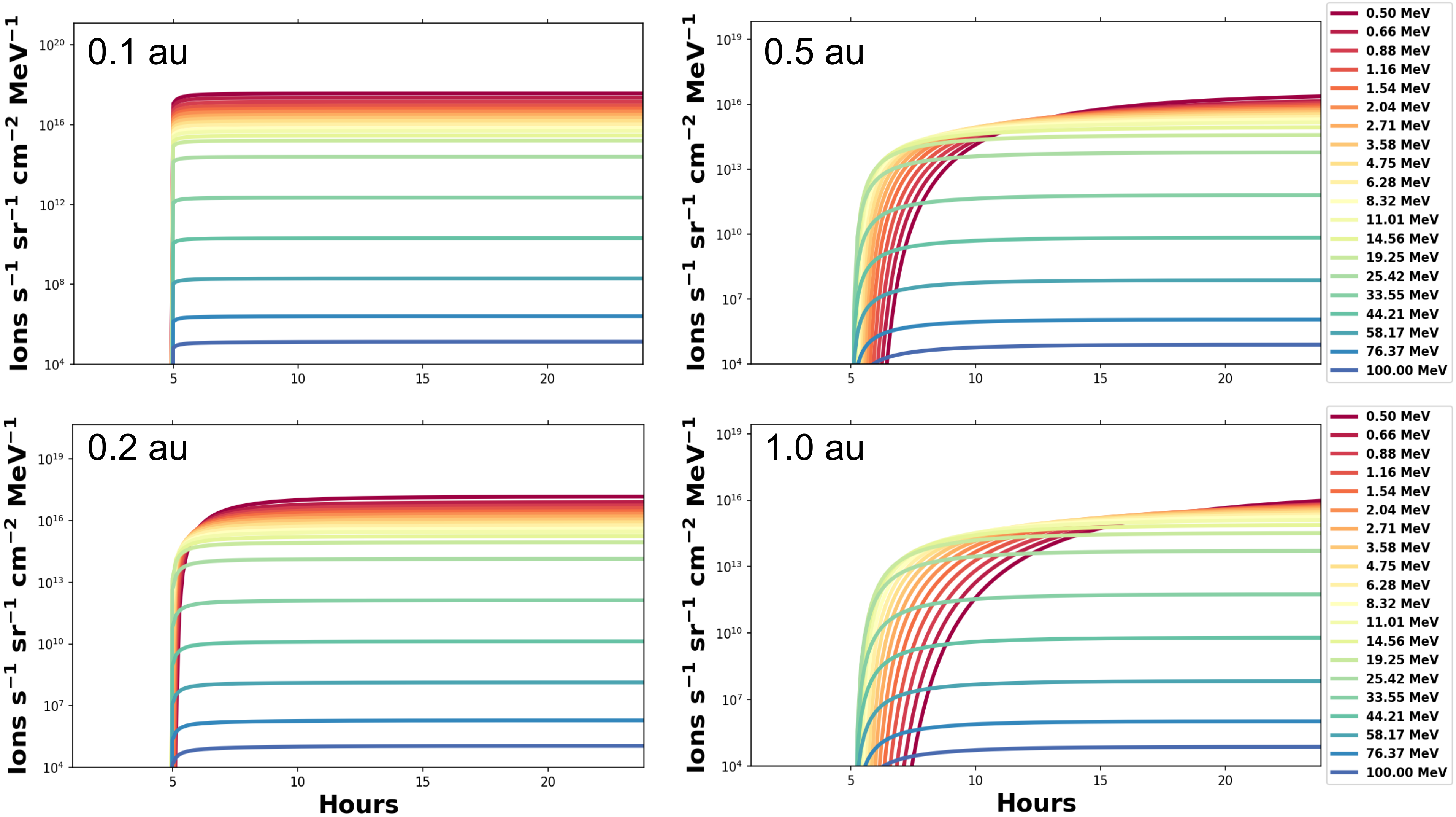
High-resolution runs are underway, and will likely show similar results as run from Kozarev et al. 2019 below.



Kozarev et al. (2019)

EPREM Output at 4 Radial Distances

This run used the output of the low-resolution coronal DSA model as time-dependent input to EPREM. Transport effects are easily observed



Technical Developments: Criteria for SEP event selection

➢Aim

To compile a list of proton events to study and compare with the forecasts of SPREAdFAST

➢Procedure

The time period covers SDO data availability: 2010-present day

➢SEP list

Based on SOHO/ERNE instrument with identified solar origin (flares and CMEs)

All SEP-producing CMEs in the above period (~200) inspected whether they propagate in a quiet IP environment: no wide CMEs (e.g. with angular width larger than 60 degrees)

no CMEs reported within a cone of +/- 45 degrees centered at the measurement position angle of the SEP-related CME

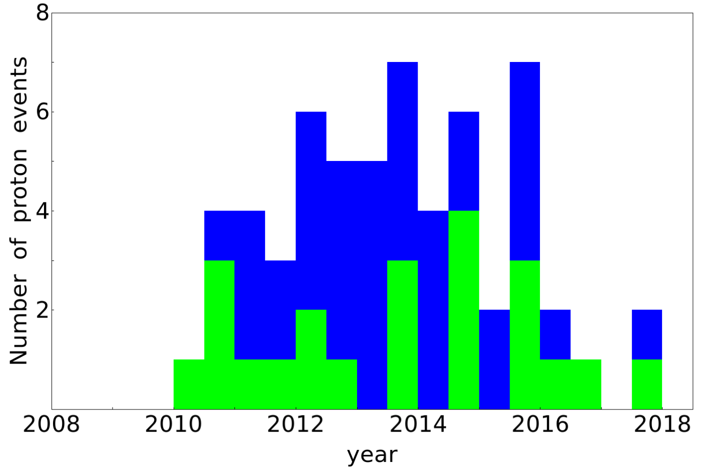
➢Resulted lists (59 proton events in total)

1. Extended event list (37 events): **Δt is 1 day**, i.e. no CMEs over a period of 1 day prior the SEP-producing CME
2. Short event list (22 events): **Δt is 3 days**, i.e. no CMEs over a period of 3 days prior the SEP-producing CME

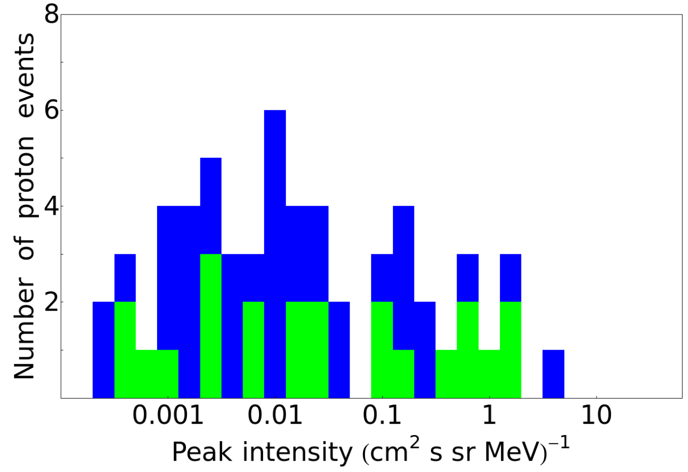
Technical Developments:
Criteria for SEP historical event selection

event date	Year	m	d	C-class	flare st	flare max	lat	long	CME on	speed	AW	onset UT	peak UT	Jp 20 MeV
ERNE20100612.phe	2010	6	12	20	00:30	00:57	43	23	01:32	486	119	2.530024	7.026509	0.020739
ERNE20100814.phe	2010	8	14	4.4	09:38	10:05	17	52	10:12	1205	360	10.874657	12.789826	0.62665
ERNE20100818.phe	2010	8	18	4.5	04:45	05:48	18	88	05:48	1471	184	7.302391	11.86549	0.116959
ERNE20100831.phe	2010	8	31	u	u	u	u	u	21:17	1304	360	23.462481	26.326908	0.019093
ERNE20100909.phe	2010	9	8	3.3	23:05	23:33	21	87	23:27	818	147	1.027806	4.624994	0.013464
ERNE20110307.phe	2011	3	7	19	13:45	14:30	10	-18	14:49	698	261	16.623395	19.154749	0.001349
ERNE20110329.phe	2011	3	29	u	u	u	u	u	20:36	1264	195	21.606675	25.720125	0.001111
ERNE20110511.phe	2011	5	11	0.81	02:23	02:43	17	85	02:48	745	225	3.647167	7.294316	0.013273
ERNE20110604.phe	2011	6	4	u	u	u	u	u	06:48	1407	360	11.857062	17.852375	0.009764
ERNE20110808.phe	2011	8	8	35	18:00	18:10	16	61	18:12	1343	237	18.81525	19.481396	0.180893
ERNE20110921.phe	2011	9	21	nr	nr	nr	nr	nr	22:12	1007	360	24.335288	26.683452	0.009076
ERNE20111103.phe	2011	11	3	21	23:28	23:36	19	-61	23:30	991	360	24.128569	27.792371	0.088392
ERNE20120330.phe	2012	3	29	0.62	23:19	23:23	23	43	23:36	753	36	6.964811	9.895853	0.015584
ERNE20120405.phe	2012	4	5	1.5	20:49	u	18	29	21:25	828	360	24.255371	29.151542	0.005529
ERNE20120409.phe	2012	4	9	3.9	12:12	12:44	20	65	12:36	921	360	15.08748	21.182714	0.002247
ERNE20120517.phe	2012	5	17	51	01:25	01:47	11	76	01:48	1582	360	3.477749	5.059845	0.967634
ERNE20120526.phe	2012	5	26	u	u	u	u	u	20:58	1966	360	22.410732	33.718557	0.238762
ERNE20120608.phe	2012	6	8	7.7	02:51	03:07	-19	21	03:47	353	119	7.245316	11.00904	0.000314
ERNE20120717.phe	2012	7	17	17	12:03	17:15	-28	65	13:48	958	176	15.827621	19.991033	3.34175
ERNE20120723.phe	2012	7	23	u	u	u	u	u	02:36	2003	360	7.971176	18.662817	0.322726
ERNE20120831.phe	2012	8	31	8.4	19:45	20:43	-19	-42	20:00	1442	360	23.14416	39.031738	0.22936
ERNE20120908.phe	2012	9	8	g	g	g	g	g	10:00	734	360	11.802911	15.583288	0.041935
ERNE20121007.phe	2012	10	7	u	u	u	u	u	07:36	663	149	16.388485	20.984891	0.001052
ERNE20130206.phe	2013	2	6	8.7	00:04	00:21	22	-19	00:24	1867	271	16.448596	40.496461	0.00414
ERNE20130226.phe	2013	2	26	u	u	u	u	u	09:12	987	360	13.292438	35.425134	0.025571
ERNE20130305.phe	2013	3	5	u	u	u	u	u	03:48	1316	360	14.027178	34.461202	0.009114
ERNE20130315.phe	2013	3	15	11	05:46	06:58	11	-12	07:12	1063	360	17.769939	21.800121	0.02193
ERNE20130502.phe	2013	5	2	11	04:58	05:10	10	26	05:24	671	99	9.109342	18.934993	0.001295
ERNE20130817.phe	2013	8	17	33	18:16	18:24	-7	30	19:12	1202	360	20.909526	28.886622	0.008773
ERNE20130830.phe	2013	8	30	8.3	02:04	02:46	13	-43	02:48	949	360	7.176324	15.503147	0.001257
ERNE20130925.phe	2013	9	24	nr	nr	nr	nr	nr	20:36	919	360	7.538161	21.810336	0.000478
ERNE20130930.phe	2013	9	29	1.2	21:43	23:39	10	43	22:12	1179	360	17.503214	18.119398	1.285614
ERNE20131207.phe	2013	12	7	12	07:17	07:29	-16	49	07:36	1085	360	11.964884	24.771538	0.000919
ERNE20131212.phe	2013	12	12	4.6	03:11	03:36	-23	46	03:36	1002	276	6.458699	16.500847	0.005279
ERNE20131214.phe	2013	12	13	u	u	u	u	u	21:24	518	360	5.088908	22.308777	0.037665
ERNE20140104.phe	2014	1	4	40	18:47	19:46	-11	-33	21:23	977	360	22.681096	29.559051	0.011054
ERNE20140214.phe	2014	2	14	u	u	u	u	u	08:48	1165	360	12.702881	[illegible]	[illegible]

Proton event distribution vs. year



Proton event distribution vs. their peak intensity



Summary of Developments

- Development of Sun active region monitoring tool: ARMonitor
- Development of synthetic synoptic shock module: S3M
- Adaptation of existing models (CASHeW, EPREM, 2D Plasma maps) for use in the system
- Augmenting the coronal 3D geometric shock model CSGS
- Development of interfaces to existing models (PFSS, MAS MHD)
- Integration of Cheung et al. (2015) DEM model for plasma characterization
- Development of list of historical events to characterize from Sun to 1 AU

Future Work

- Process list of historical events for ground truth
- Develop tables of typical parameters for historical events from runs output
- Finish forecasting version of the system
- Develop web interface for synoptic data, forecasts and historical events
- Forecasting system validation