Towards Visual Verification of Coronal Mass Ejections in ENLIL Ensemble Simulations through Optical Flow Analysis

Alexander Bock

Scientific Visualization Group, Linköping University

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DISCLAIMER

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Problem, Goal, Approach

PROBLEM

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- 4D evolution of CMEs is not fully understood

Problem

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MAR 2010 - JUL 2013 **Both ENLIL versions 2.6 and 2.7**	Hits	Average Error	RMSE	Average Absolute Error
Earth	71	-2.94	10.51	**9.51**
STEREO A	47	-1.92	11.10	**9.13**
STEREO B	37	1.64	13.67	**11.18**
All Locations	155	-1.06	10.18	**9.14**

Romano *et al.*, AGU Fall 2013 Meeting

PROBLEM

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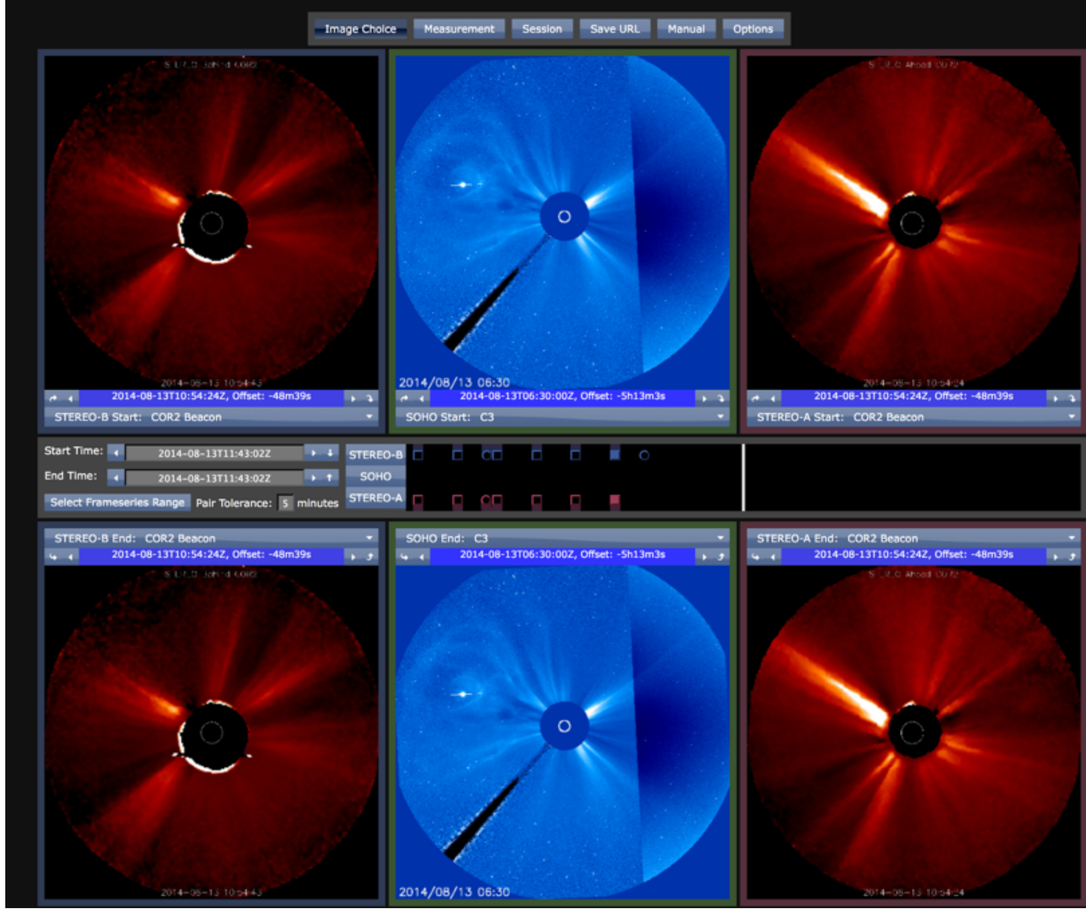
- Sources of uncertainty

Problem

- Sources of uncertainty
  - Manual input of boundary conditions



Problem

- Sources of uncertainty
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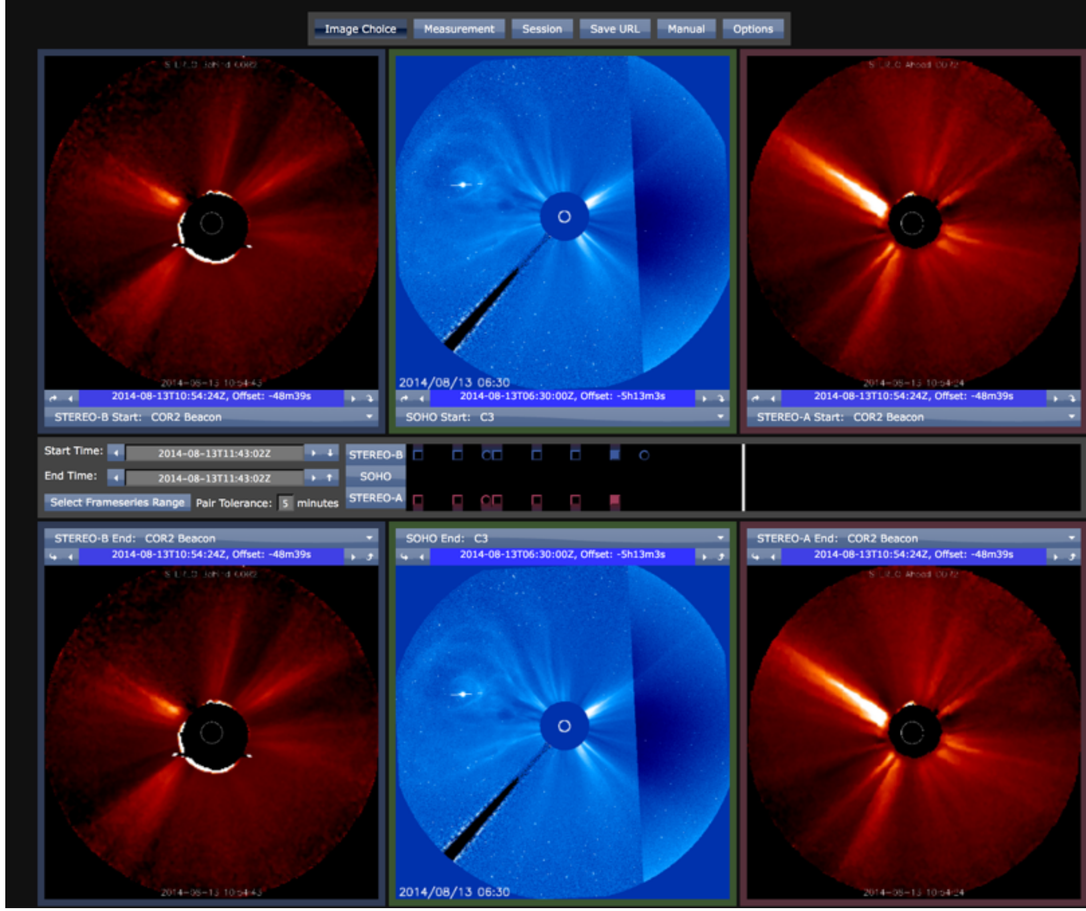
    - Longitude, Latitude, Velocity, Opening Angle



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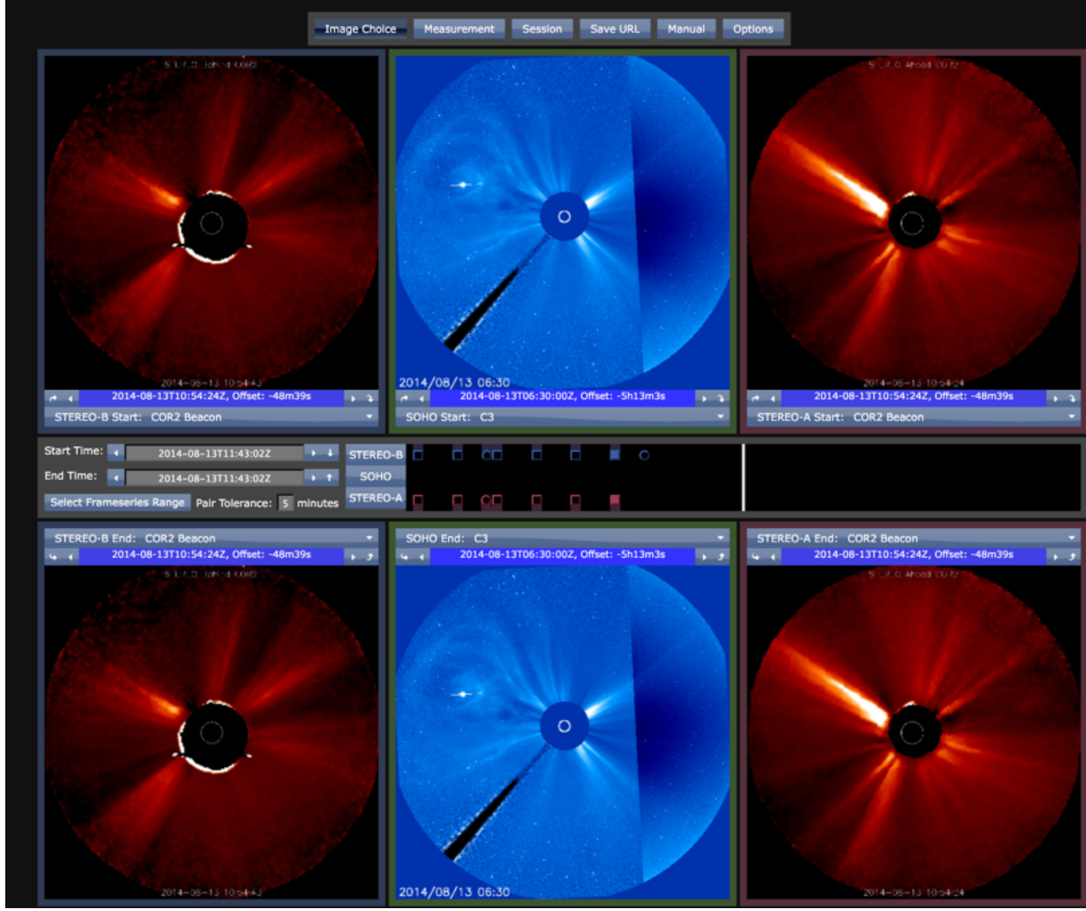
  - Assumptions (Cone structure of CME, Propagation, Interactions, …)



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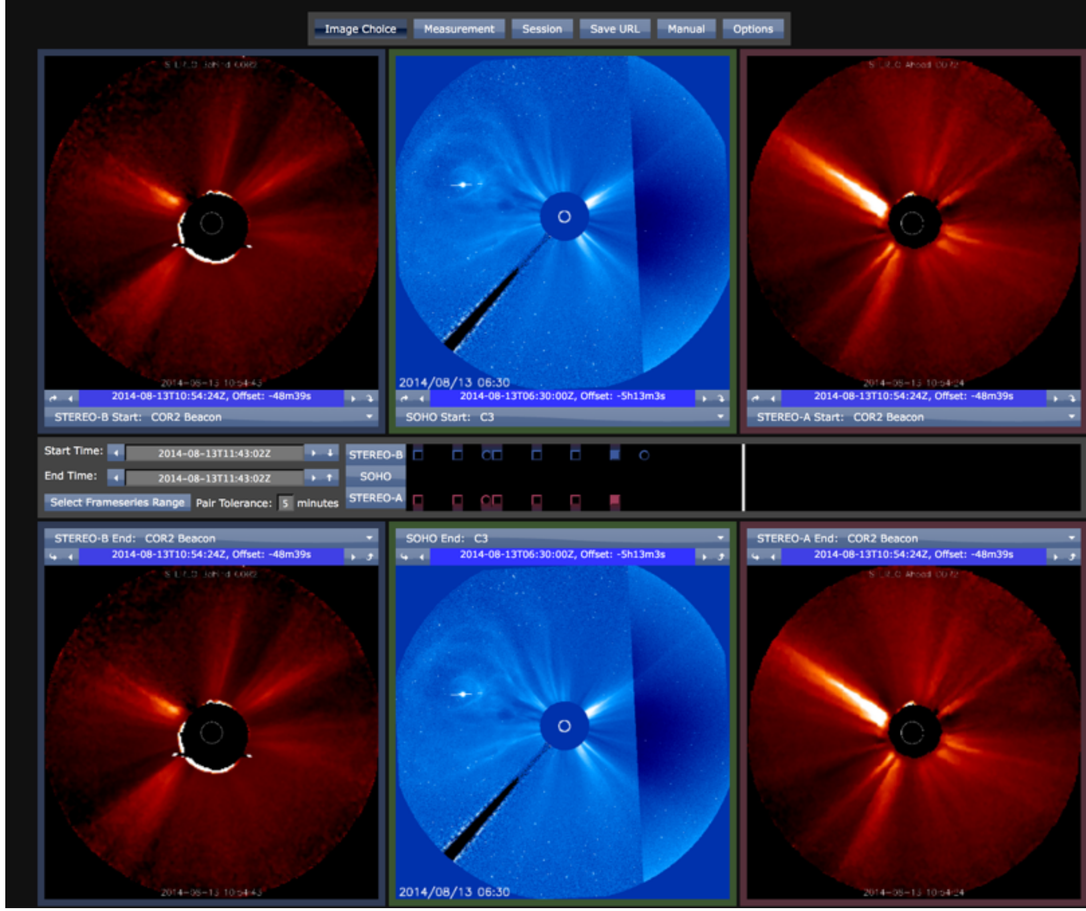

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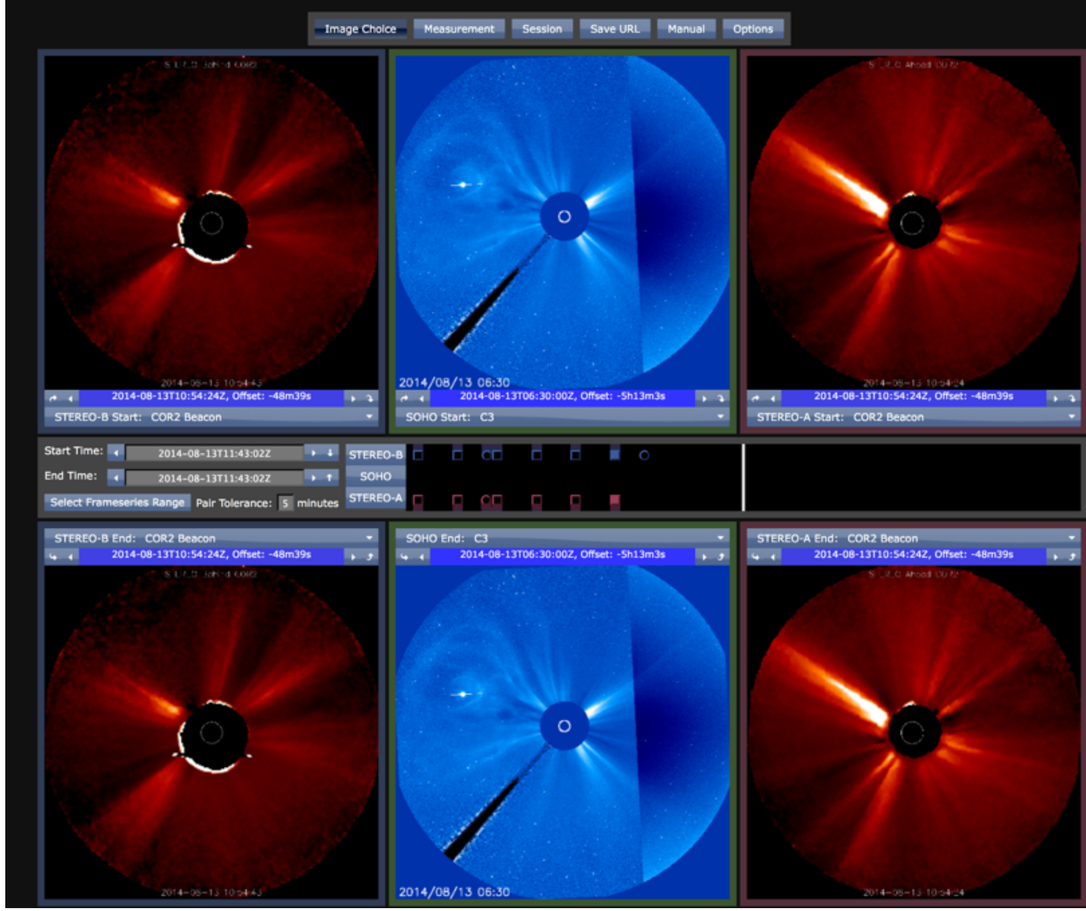

Goal

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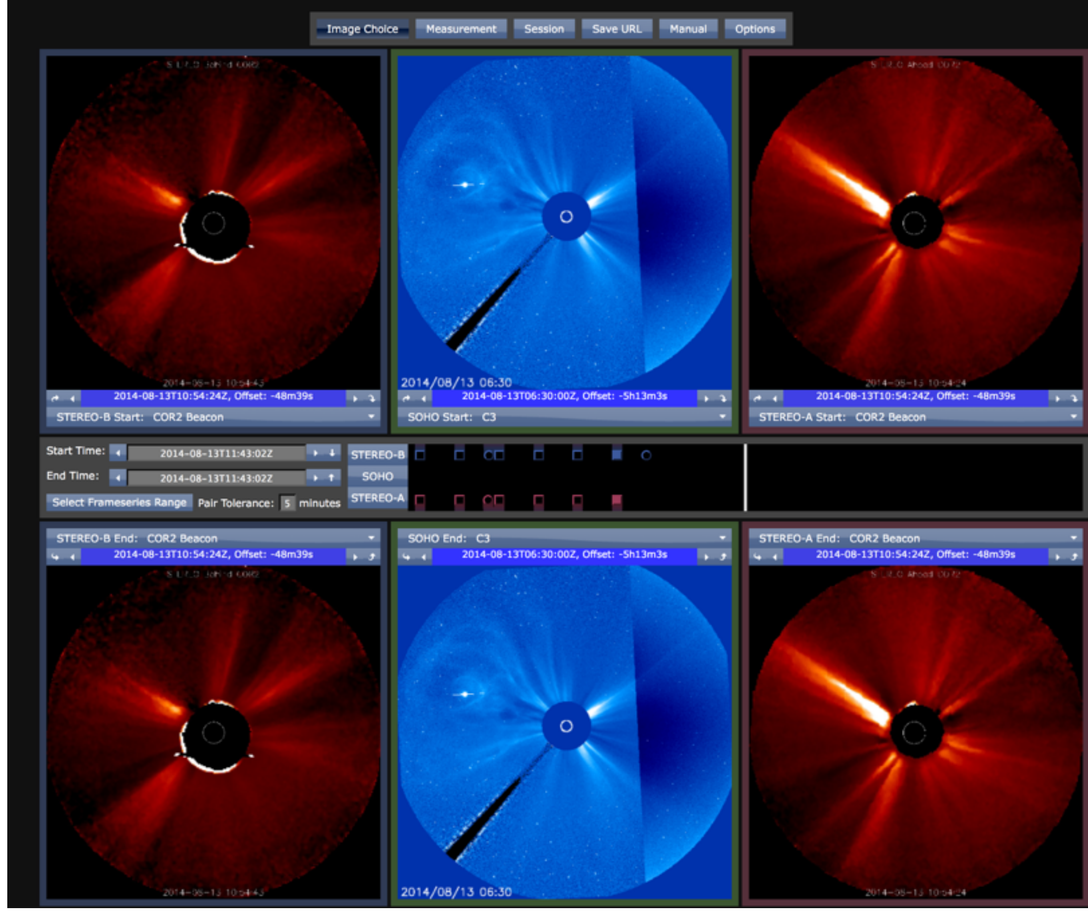

Goal

1. Decrease the prediction error (*Space Weather Analysts*)

Problem

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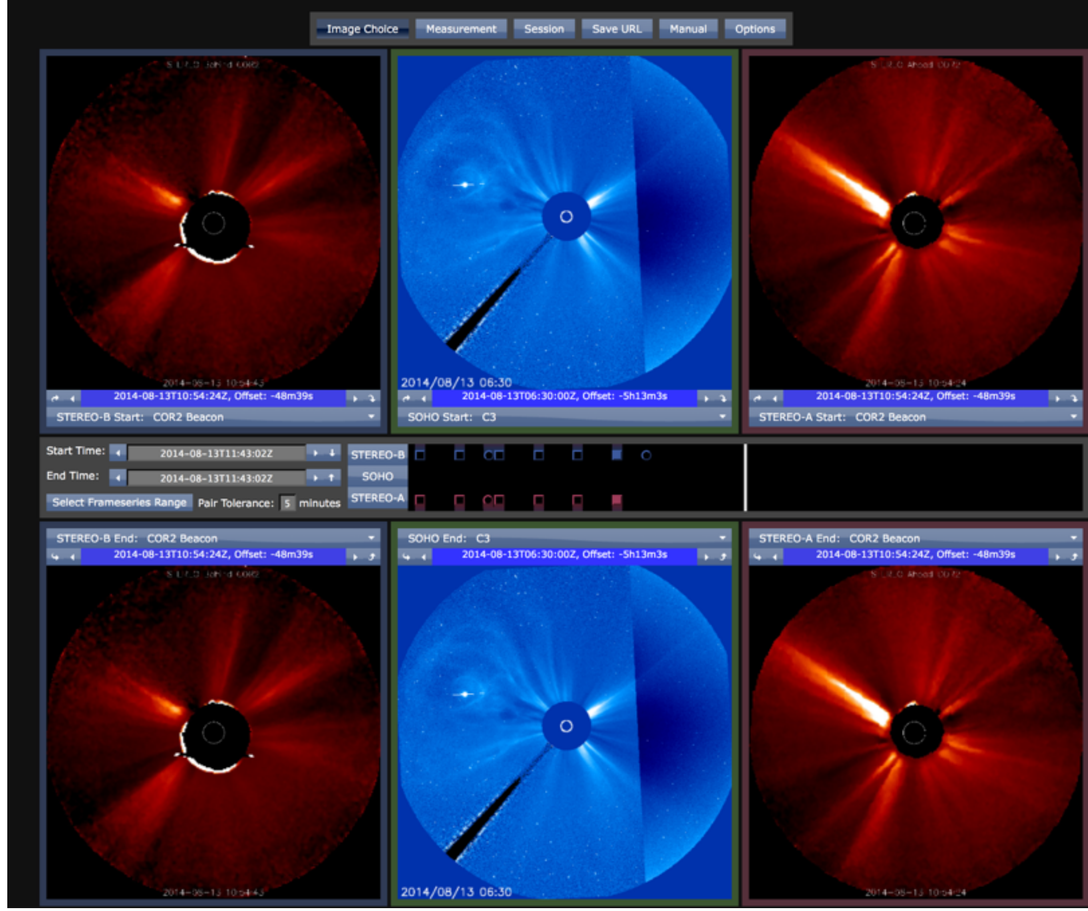

Goal

1. Decrease the prediction error (*Space Weather Analysts*)
2. Interactive exploration of 4D data (*Scientists*)

Approach

Approach

- Generating ensemble simulations
  - Small variations of boundary conditions
  - High probability that “correct” boundary conditions are covered in ensemble run

time (21.5Rs)	Lat	Lon	w/2	v	flag	Arrival time	maxKp(90,135,180)	Rmin(Re)	Duration (hrs)
2014-04-18T15:22	-34.	10.	45.	1402.	C	2014-04-20T05:00	5 7 7	5.4	25.0
2014-04-18T15:14	-33.	10.	41.	1540.	C	2014-04-20T03:31	5 7 7	5.5	26.3
2014-04-18T15:19	-37.	10.	48.	1477.	C	2014-04-20T03:28	5 7 7	5.3	25.3
2014-04-18T15:24	-35.	10.	42.	1382.	C	2014-04-20T06:27	5 6 7	5.6	26.0
2014-04-18T15:33	-37.	9.	48.	1312.	C	2014-04-20T06:48	5 7 7	5.4	24.6
2014-04-18T15:32	-36.	9.	44.	1316.	C	2014-04-20T07:25	5 6 7	5.5	25.4
2014-04-18T15:15	-32.	7.	46.	1449.	C	2014-04-20T03:28	5 7 8	5.2	24.5
2014-04-18T15:08	-31.	8.	41.	1590.	C	2014-04-20T02:11	5 7 7	5.4	25.5
2014-04-18T15:13	-35.	7.	40.	1521.	C	2014-04-20T04:25	5 6 7	5.6	26.7
2014-04-18T15:17	-33.	7.	46.	1429.	C	2014-04-20T03:57	5 7 7	5.3	24.6
2014-04-18T15:26	-35.	7.	41.	1357.	C	2014-04-20T07:07	5 6 7	5.6	25.6
2014-04-18T15:25	-34.	7.	42.	1362.	C	2014-04-20T06:35	5 6 7	5.5	25.2
2014-04-18T15:21	-37.	11.	45.	1400.	C	2014-04-20T05:42	5 6 7	5.5	26.0
2014-04-18T15:13	-36.	11.	49.	1536.	C	2014-04-20T02:00	5 7 8	5.2	24.9
2014-04-18T15:17	-40.	11.	53.	1478.	C	2014-04-20T02:54	5 7 8	5.2	24.7
2014-04-18T15:22	-38.	11.	40.	1382.	C	2014-04-20T08:06	4 6 6	5.8	27.3
2014-04-18T15:31	-40.	10.	40.	1313.	C	2014-04-20T10:13	4 5 6	6.0	27.9
2014-04-18T15:31	-39.	10.	53.	1317.	C	2014-04-20T05:59	5 7 8	5.2	24.0
2014-04-18T15:21	-33.	9.	42.	1381.	C	2014-04-20T05:59	5 6 7	5.5	25.4
2014-04-18T15:13	-31.	9.	49.	1522.	C	2014-04-20T01:37	6 7 8	5.0	24.0
2014-04-18T15:18	-36.	9.	46.	1454.	C	2014-04-20T04:10	5 7 7	5.4	25.4
2014-04-18T15:23	-34.	9.	46.	1361.	C	2014-04-20T05:31	5 7 7	5.3	24.6
2014-04-18T15:33	-35.	8.	51.	1289.	C	2014-04-20T06:21	5 7 8	5.2	23.8
2014-04-18T15:32	-35.	8.	59.	1294.	C	2014-04-20T05:20	6 8 8	4.9	22.3
2014-04-18T15:21	-33.	9.	47.	1371.	C	2014-04-20T04:58	5 7 7	5.3	24.4
2014-04-18T15:13	-32.	9.	44.	1512.	C	2014-04-20T02:52	5 7 7	5.3	25.1
2014-04-18T15:18	-36.	9.	51.	1444.	C	2014-04-20T03:15	6 7 8	5.1	24.3
2014-04-18T15:23	-34.	9.	43.	1351.	C	2014-04-20T06:29	5 6 7	5.5	25.2
2014-04-18T15:33	-36.	8.	46.	1279.	C	2014-04-20T07:45	5 7 7	5.5	24.4
2014-04-18T15:32	-35.	8.	35.	1284.	C	2014-04-20T11:15	4 5 6	6.0	26.9
2014-04-18T15:19	-34.	9.	47.	1405.	C	2014-04-20T04:28	5 7 7	5.3	24.6
2014-04-18T15:11	-32.	9.	50.	1545.	C	2014-04-20T01:05	6 8 8	5.0	23.9
2014-04-18T15:16	-36.	9.	55.	1479.	C	2014-04-20T02:00	6 8 8	5.0	23.6
2014-04-18T15:21	-34.	8.	47.	1385.	C	2014-04-20T04:50	5 7 7	5.3	24.6
2014-04-18T15:30	-36.	8.	51.	1314.	C	2014-04-20T05:57	5 7 8	5.2	24.0
2014-04-18T15:30	-35.	8.	52.	1319.	C	2014-04-20T05:32	6 7 8	5.1	23.6
2014-04-18T15:21	-35.	9.	46.	1384.	M	2014-04-20T05:16	5 7 7	5.4	24.8

Approach

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time (21.5Rs)	Lat	Lon	w/2	v	flag	Arrival time	maxKp(90,135,180)	Rmin(Re)	Duration (hrs)
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2014-04-18T15:21	-33.	9.	47.	1371.	C	2014-04-20T04:58	5 7 7	5.3	24.4
2014-04-18T15:13	-32.	9.	44.	1512.	C	2014-04-20T02:52	5 7 7	5.3	25.1
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2014-04-18T15:23	-34.	9.	43.	1351.	C	2014-04-20T06:29	5 6 7	5.5	25.2
2014-04-18T15:33	-36.	8.	46.	1279.	C	2014-04-20T07:45	5 7 7	5.5	24.4
2014-04-18T15:32	-35.	8.	35.	1284.	C	2014-04-20T11:15	4 5 6	6.0	26.9
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2014-04-18T15:18	-36.	9.	46.	1454.	C	2014-04-20T04:10	5 7 7	5.4	25.4
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2014-04-18T15:16	-36.	9.	55.	1479.	C	2014-04-20T02:00	6 8 8	5.0	23.6
2014-04-18T15:21	-34.	8.	47.	1385.	C	2014-04-20T04:50	5 7 7	5.3	24.6
2014-04-18T15:30	-36.	8.	51.	1314.	C	2014-04-20T05:57	5 7 8	5.2	24.0
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→ Score

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2014-04-18T15:25	-34.	7.	42.	1362.	C	2014-04-20T06:35	5 6 7	5.5	25.2
2014-04-18T15:21	-37.	11.	45.	1400.	C	2014-04-20T05:42	5 6 7	5.5	26.0
2014-04-18T15:13	-36.	11.	49.	1536.	C	2014-04-20T02:00	5 7 8	5.2	24.9
2014-04-18T15:17	-40.	11.	53.	1478.	C	2014-04-20T02:54	5 7 8	5.2	24.7
2014-04-18T15:22	-38.	11.	40.	1382.	C	2014-04-20T08:06	4 6 6	5.8	27.3
2014-04-18T15:31	-40.	10.	40.	1313.	C	2014-04-20T10:13	4 5 6	6.0	27.9
2014-04-18T15:31	-39.	10.	53.	1317.	C	2014-04-20T05:59	5 7 8	5.2	24.0
2014-04-18T15:21	-33.	9.	42.	1381.	C	2014-04-20T05:59	5 6 7	5.5	25.4
2014-04-18T15:13	-31.	9.	49.	1522.	C	2014-04-20T01:37	6 7 8	5.0	24.0
2014-04-18T15:18	-36.	9.	46.	1454.	C	2014-04-20T04:10	5 7 7	5.4	25.4
2014-04-18T15:23	-34.	9.	46.	1361.	C	2014-04-20T05:31	5 7 7	5.3	24.6
2014-04-18T15:33	-35.	8.	51.	1289.	C	2014-04-20T06:21	5 7 8	5.2	23.8
2014-04-18T15:32	-35.	8.	59.	1294.	C	2014-04-20T05:20	6 8 8	4.9	22.3
2014-04-18T15:21	-33.	9.	47.	1371.	C	2014-04-20T04:58	5 7 7	5.3	24.4
2014-04-18T15:13	-32.	9.	44.	1512.	C	2014-04-20T02:52	5 7 7	5.3	25.1
2014-04-18T15:18	-36.	9.	51.	1444.	C	2014-04-20T03:15	6 7 8	5.1	24.3
2014-04-18T15:23	-34.	9.	43.	1351.	C	2014-04-20T06:29	5 6 7	5.5	25.2
2014-04-18T15:33	-36.	8.	46.	1279.	C	2014-04-20T07:45	5 7 7	5.5	24.4
2014-04-18T15:32	-35.	8.	35.	1284.	C	2014-04-20T11:15	4 5 6	6.0	26.9
2014-04-18T15:19	-34.	9.	47.	1405.	C	2014-04-20T04:28	5 7 7	5.3	24.6
2014-04-18T15:11	-32.	9.	50.	1545.	C	2014-04-20T01:05	6 8 8	5.0	23.9
2014-04-18T15:16	-36.	9.	55.	1479.	C	2014-04-20T02:00	6 8 8	5.0	23.6
2014-04-18T15:21	-34.	8.	47.	1385.	C	2014-04-20T04:50	5 7 7	5.3	24.6
2014-04-18T15:30	-36.	8.	51.	1314.	C	2014-04-20T05:57	5 7 8	5.2	24.0
2014-04-18T15:30	-35.	8.	52.	1319.	C	2014-04-20T05:32	6 7 8	5.1	23.6
2014-04-18T15:21	-35.	9.	46.	1384.	M	2014-04-20T05:16	5 7 7	5.4	24.8

Approach

- Generating ensemble simulations
  - Small variations of boundary conditions
  - High probability that “correct” boundary conditions are covered in ensemble run
- What is “correct”?
  - In situ measurements (arrival time, KpIndex, R_{min})
  - Image-based comparisons of coronagraphs and renderings (Stereo A, Stereo B, SOHO)
  - …

→ Score

time (21.5Rs)	Lat	Lon	w/2	v	flag	Arrival time	maxKp(90,135,180)	Rmin(Re)	Duration (hrs)
2014-04-18T15:22	-34.	10.	45.	1402.	C	2014-04-20T05:00	5 7 7	5.4	25.0
2014-04-18T15:14	-33.	10.	41.	1540.	C	2014-04-20T03:31	5 7 7	5.5	26.3
2014-04-18T15:19	-37.	10.	48.	1477.	C	2014-04-20T03:28	5 7 7	5.3	25.3
2014-04-18T15:24	-35.	10.	42.	1382.	C	2014-04-20T06:27	5 6 7	5.6	26.0
2014-04-18T15:33	-37.	9.	48.	1312.	C	2014-04-20T06:48	5 7 7	5.4	24.6
2014-04-18T15:32	-36.	9.	44.	1316.	C	2014-04-20T07:25	5 6 7	5.5	25.4
2014-04-18T15:15	-32.	7.	46.	1449.	C	2014-04-20T03:28	5 7 8	5.2	24.5
2014-04-18T15:08	-31.	8.	41.	1590.	C	2014-04-20T02:11	5 7 7	5.4	25.5
2014-04-18T15:13	-35.	7.	40.	1521.	C	2014-04-20T04:25	5 6 7	5.6	26.7
2014-04-18T15:17	-33.	7.	46.	1429.	C	2014-04-20T03:57	5 7 7	5.3	24.6
2014-04-18T15:26	-35.	7.	41.	1357.	C	2014-04-20T07:07	5 6 7	5.6	25.6
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2014-04-18T15:13	-36.	11.	49.	1536.	C	2014-04-20T02:00	5 7 8	5.2	24.9
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2014-04-18T15:31	-39.	10.	53.	1317.	C	2014-04-20T05:59	5 7 8	5.2	24.0
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2014-04-18T15:23	-34.	9.	46.	1361.	C	2014-04-20T05:31	5 7 7	5.3	24.6
2014-04-18T15:33	-35.	8.	51.	1289.	C	2014-04-20T06:21	5 7 8	5.2	23.8
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Approach

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- Visualization deals with Ensemble techniques

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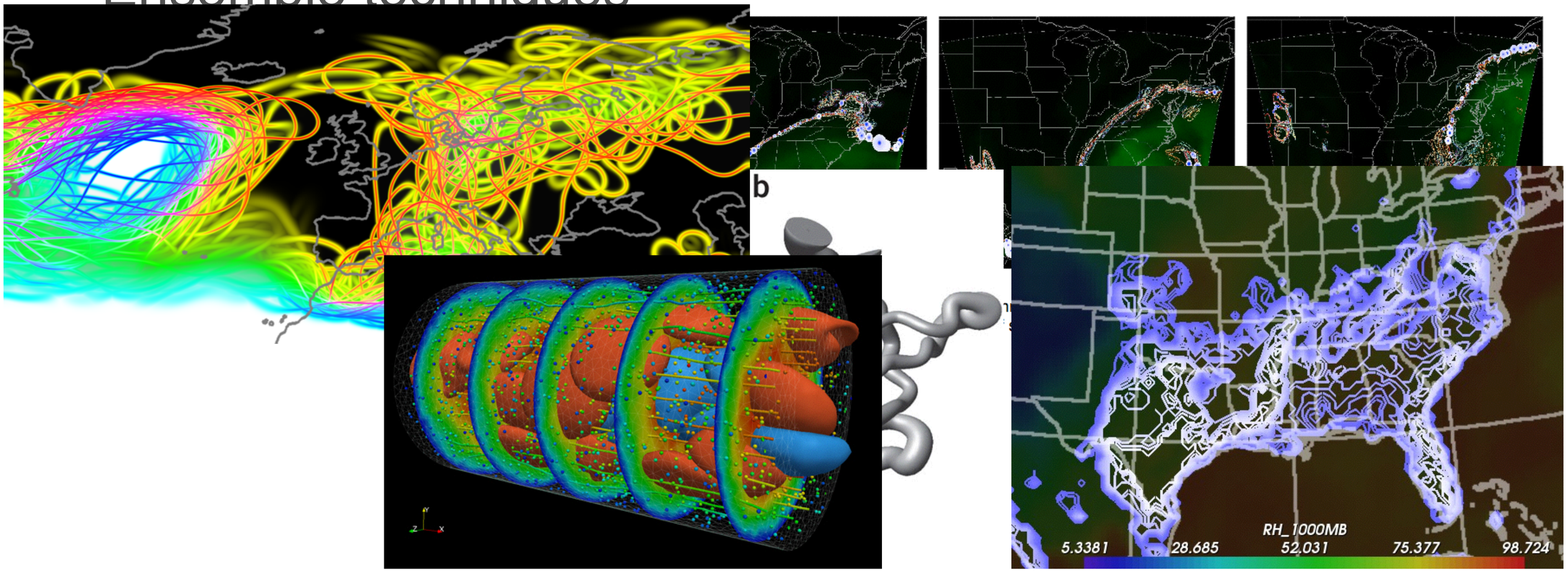

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  - Glyphs
- Interactive exploration techniques to gain insight into data

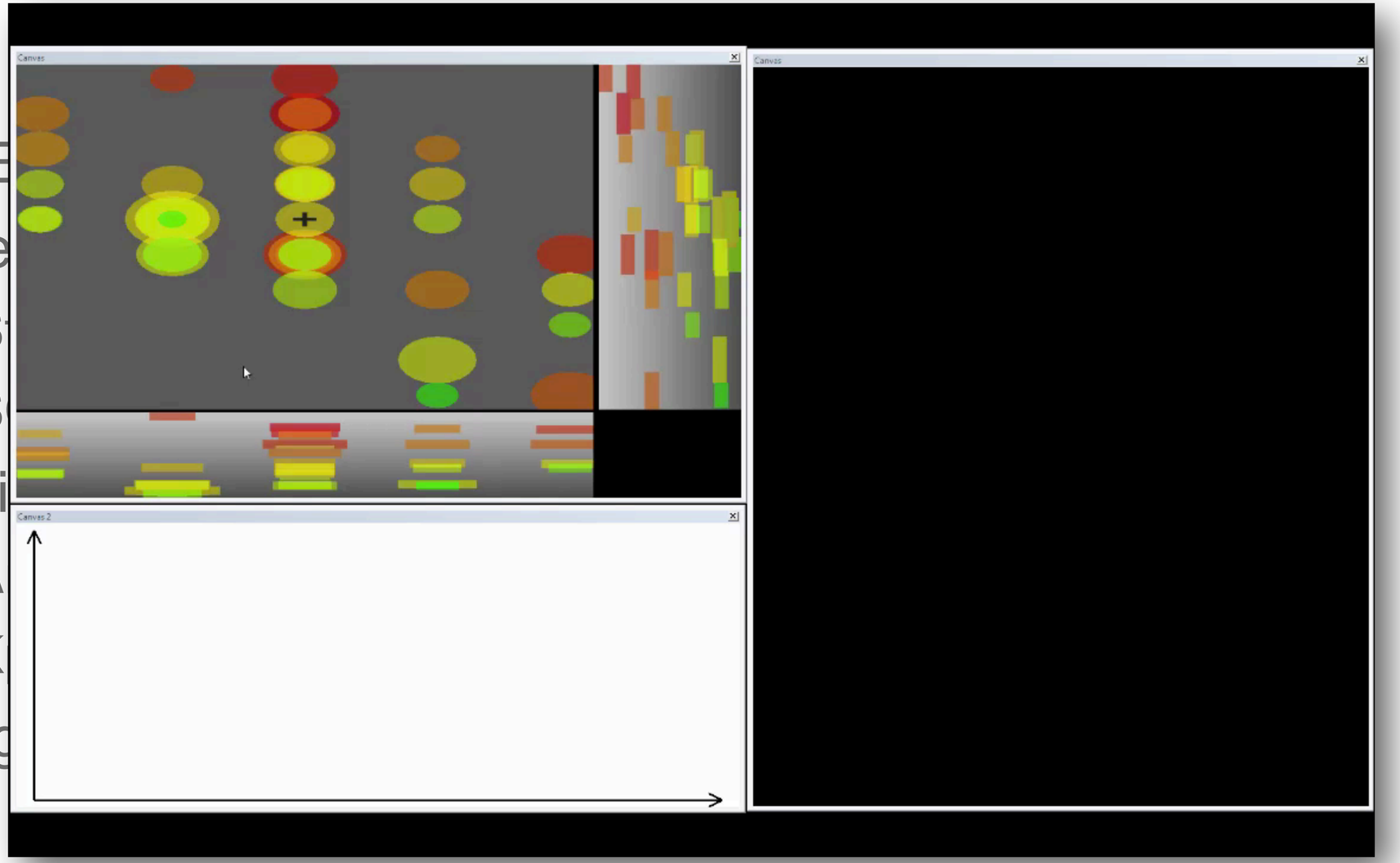
System Overview

System Overview

- Data
  - 4D ENLIL with Cone Model Ensemble simulations
  - Satellite imagery
    - Stereo A, B: Cor2, HI1, HI2
    - SOHO: LASCO C3
  - In Situ ground truth measurements
    - Arrival time
    - KpIndex (90, 135, 180 degrees)
  - Image-based measurements

System Overview

- Data
  - 4D E
  - Sate
    - S
    - S
  - In Si
    - A
    - K
  - Imag



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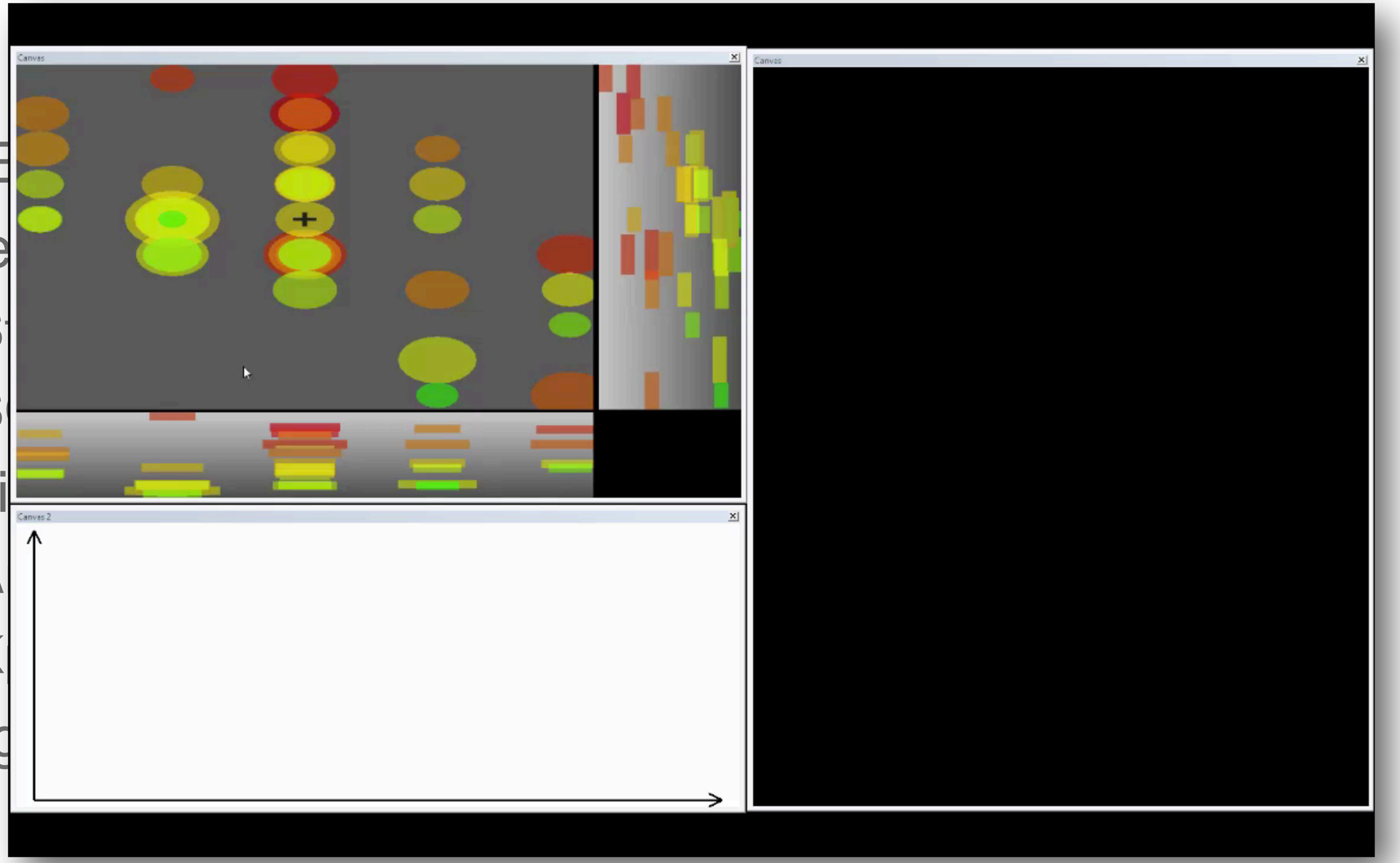
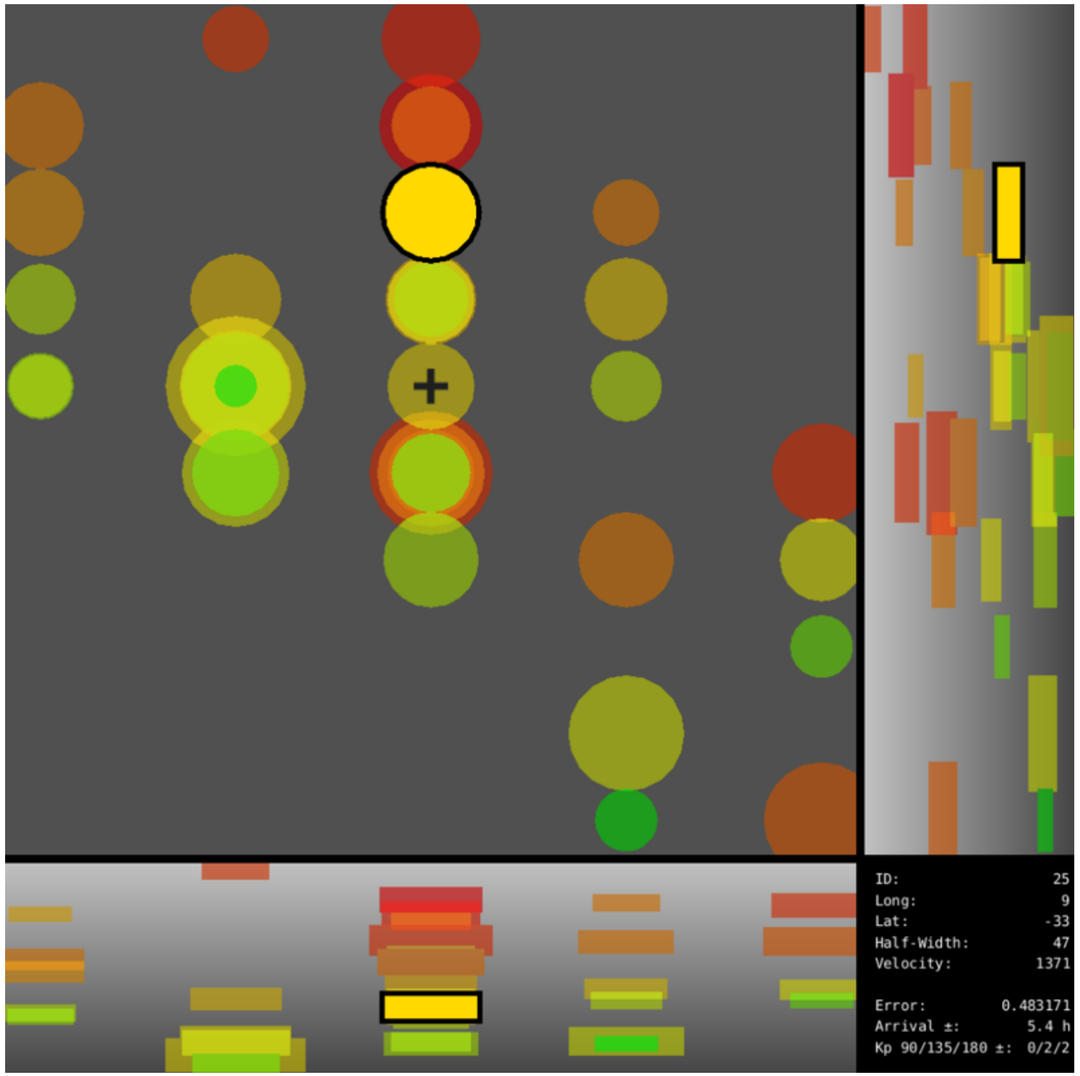


Ensemble Selection View

- Spatial context for Ensemble members
  - Selecting Ensemble member
  - Detect patterns
  - Switching between scores



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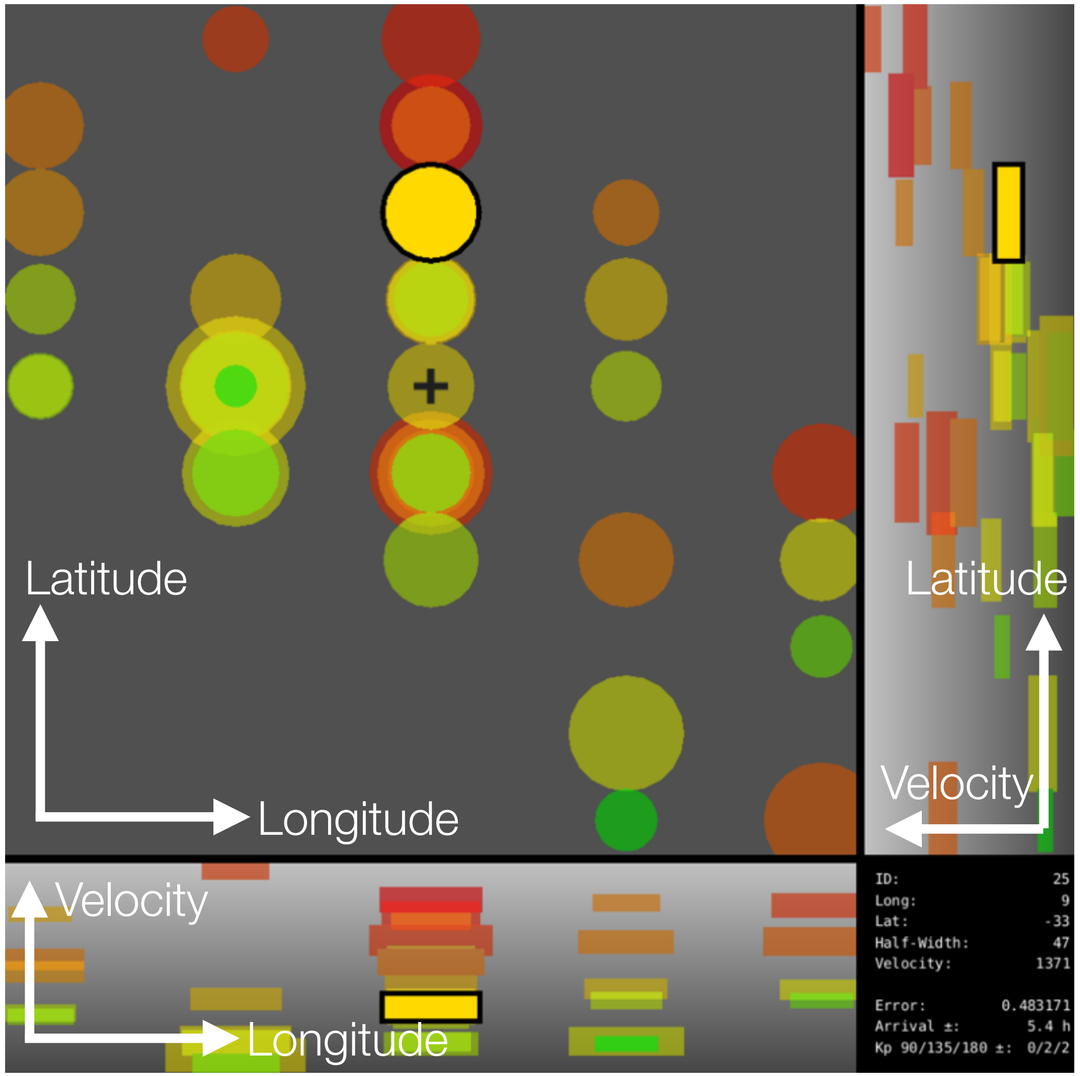

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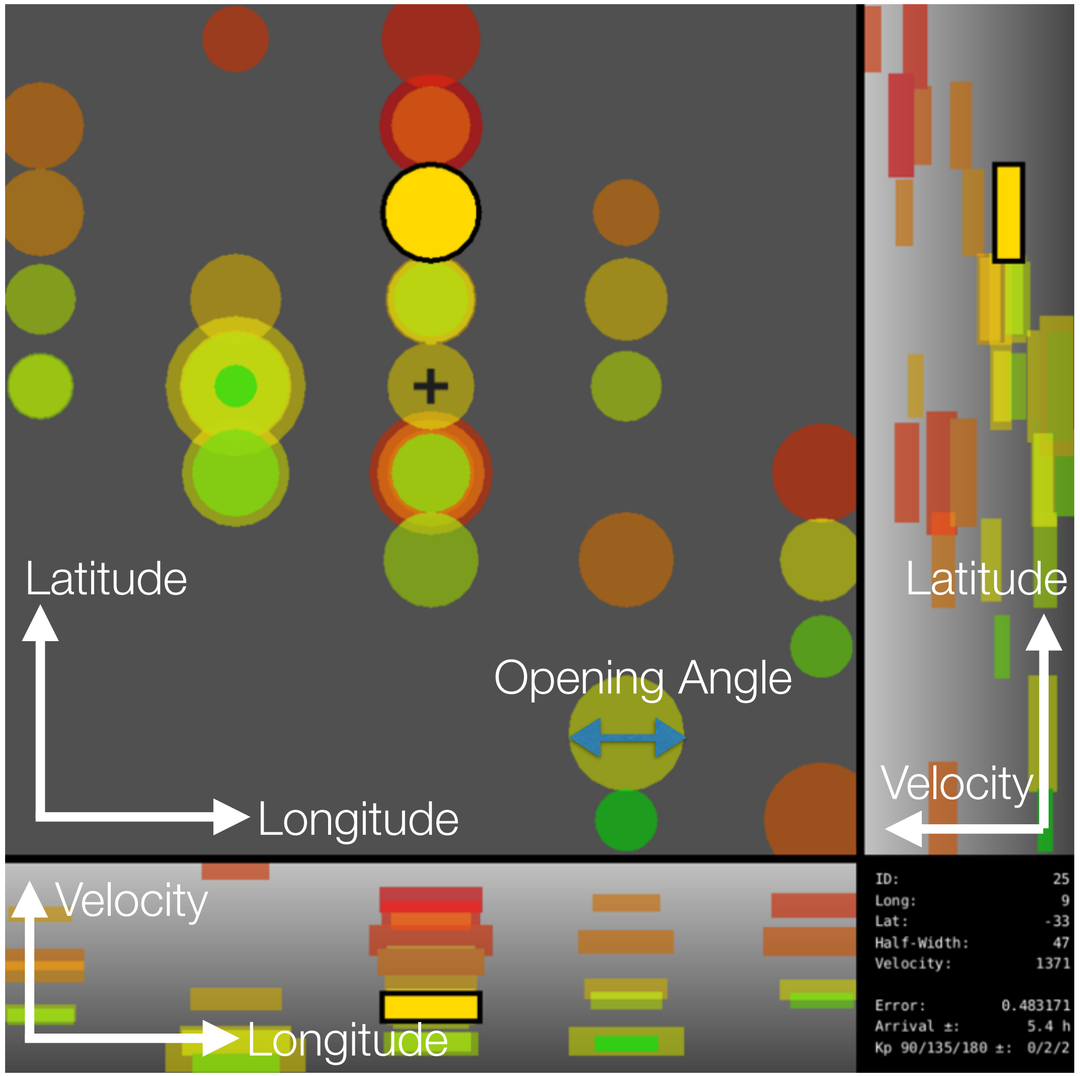

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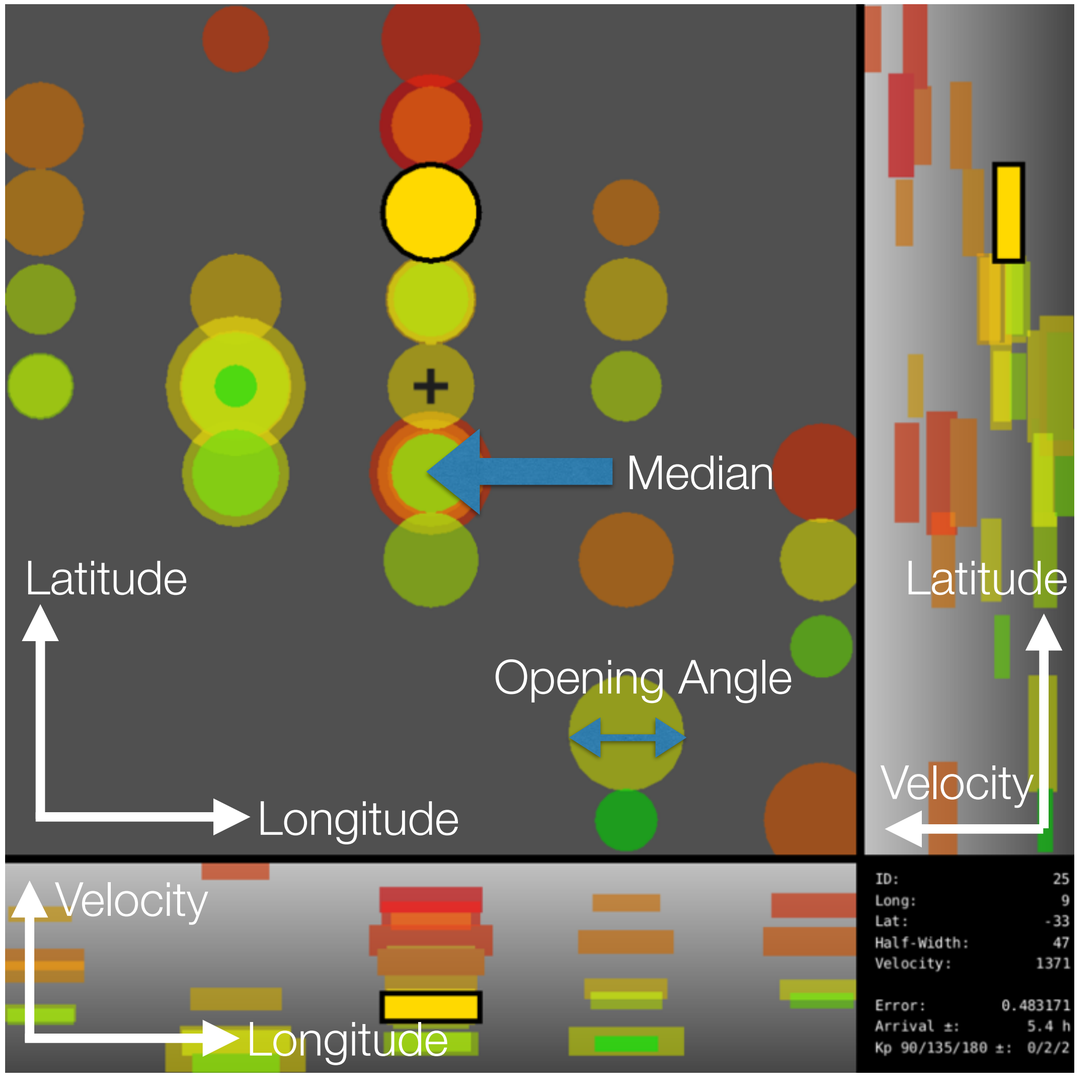

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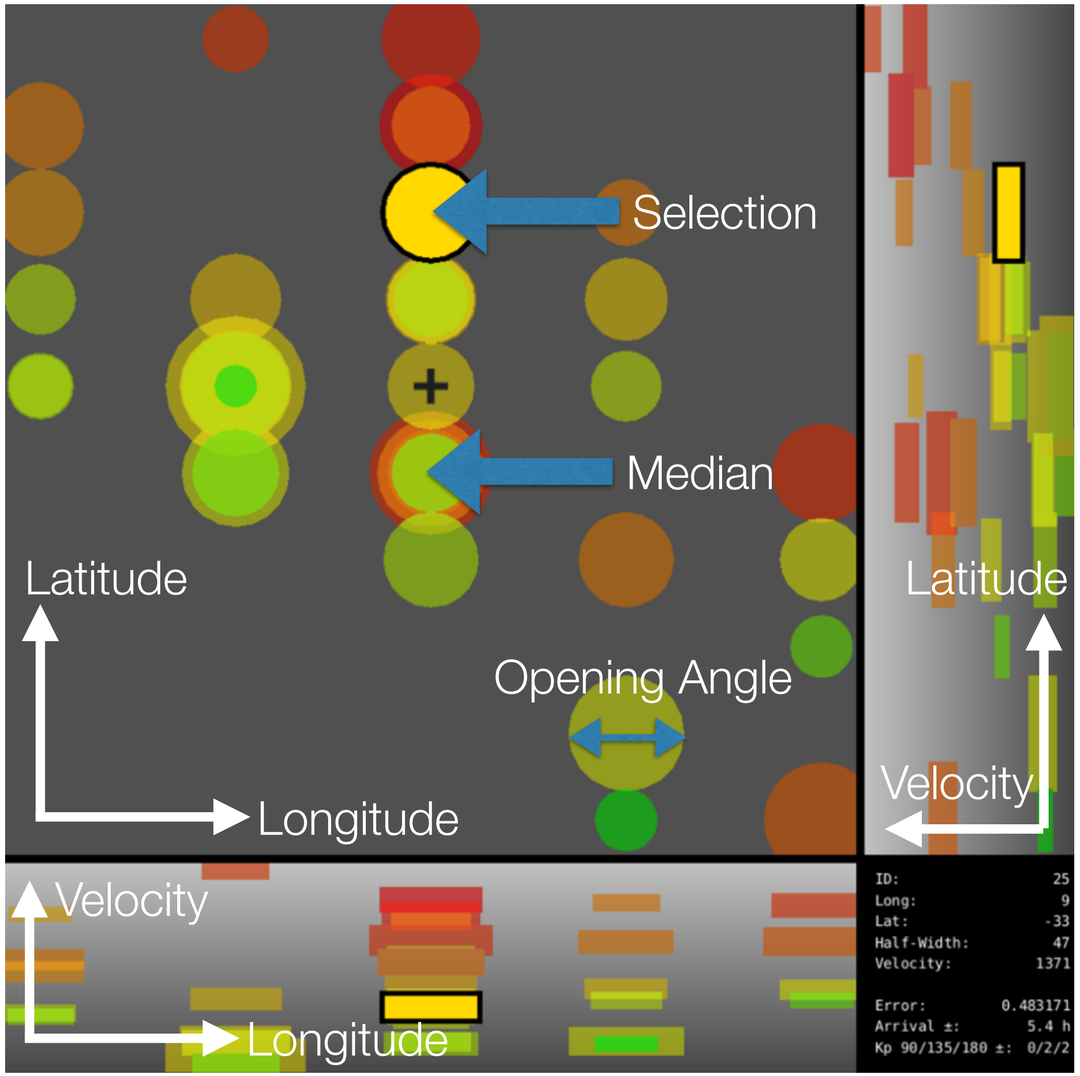

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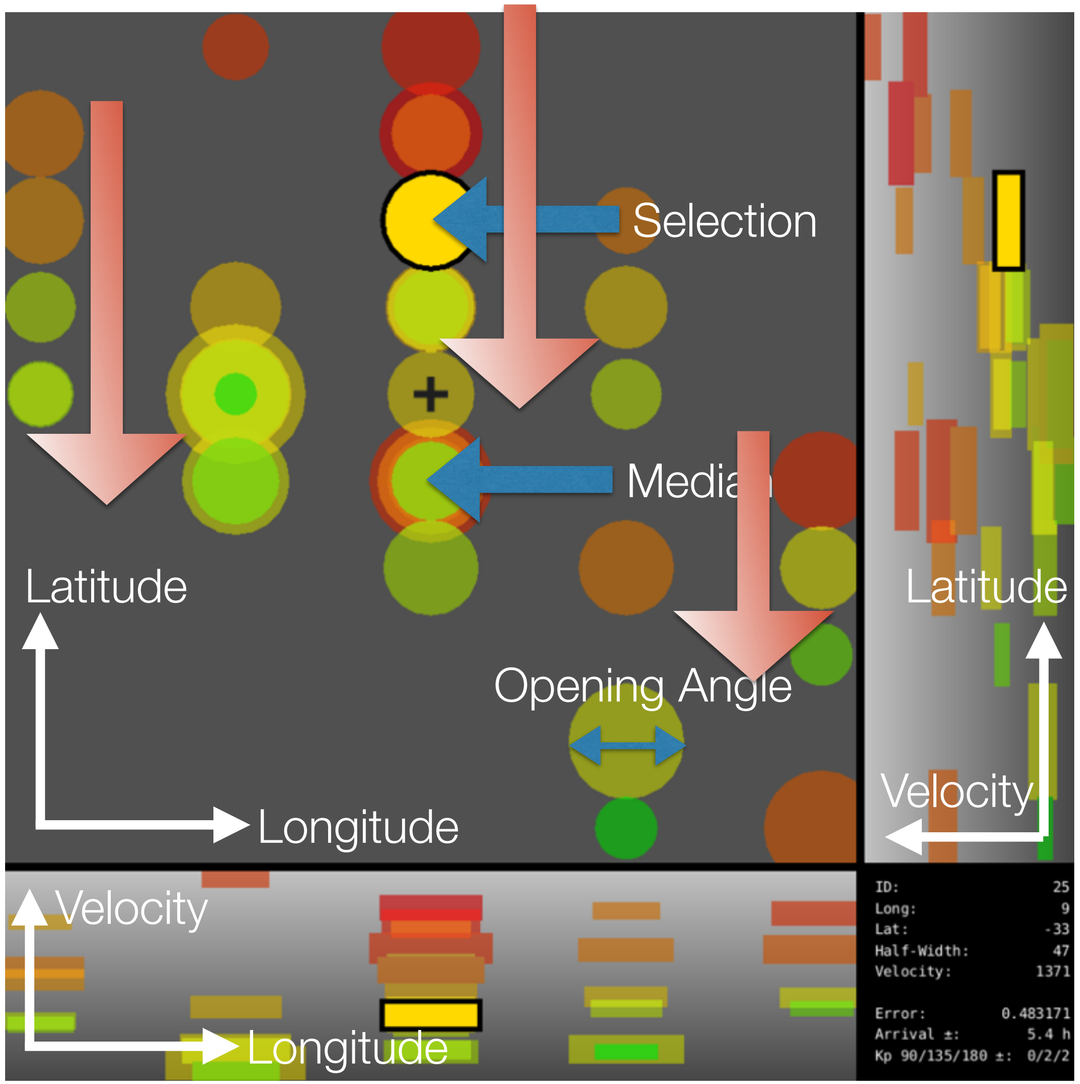

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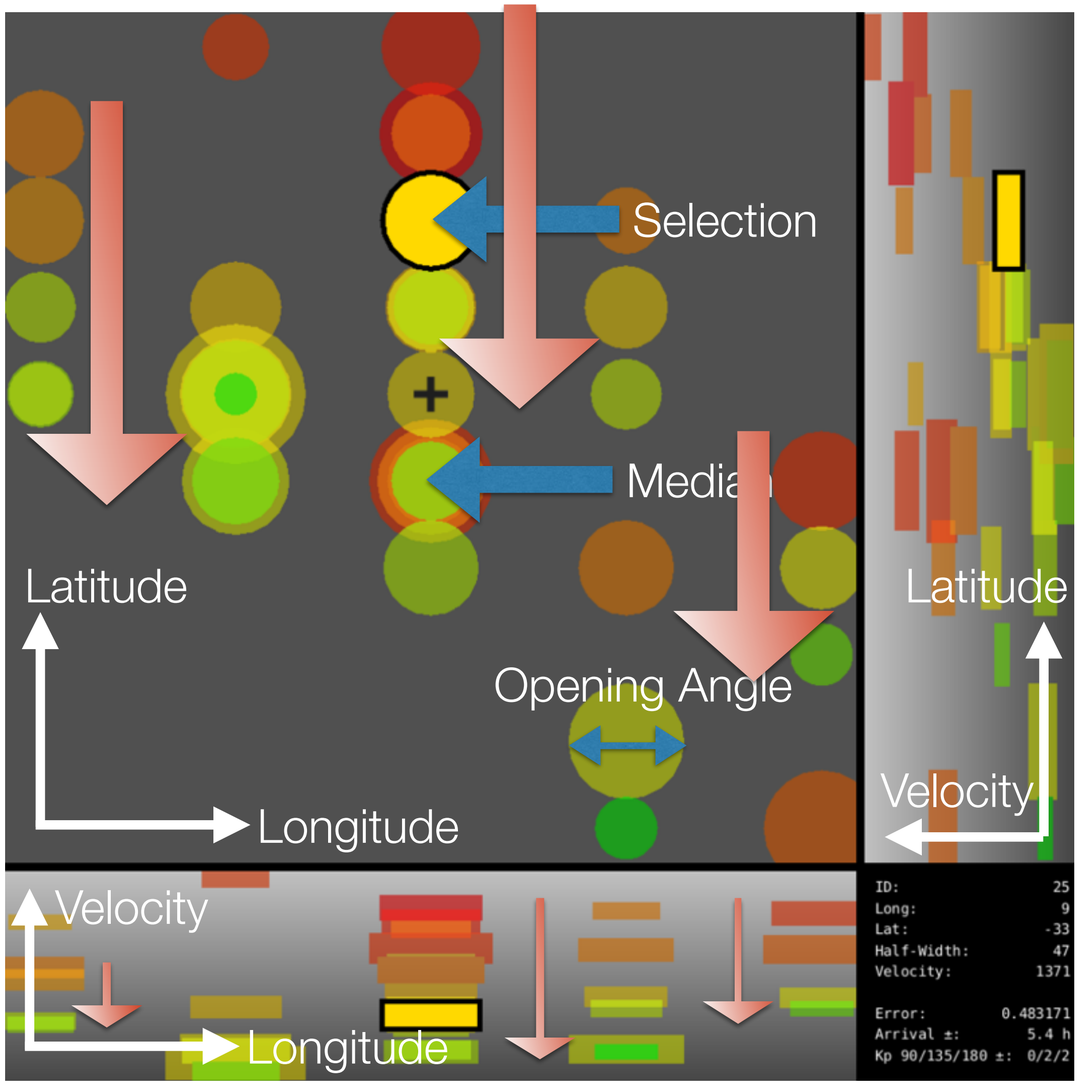

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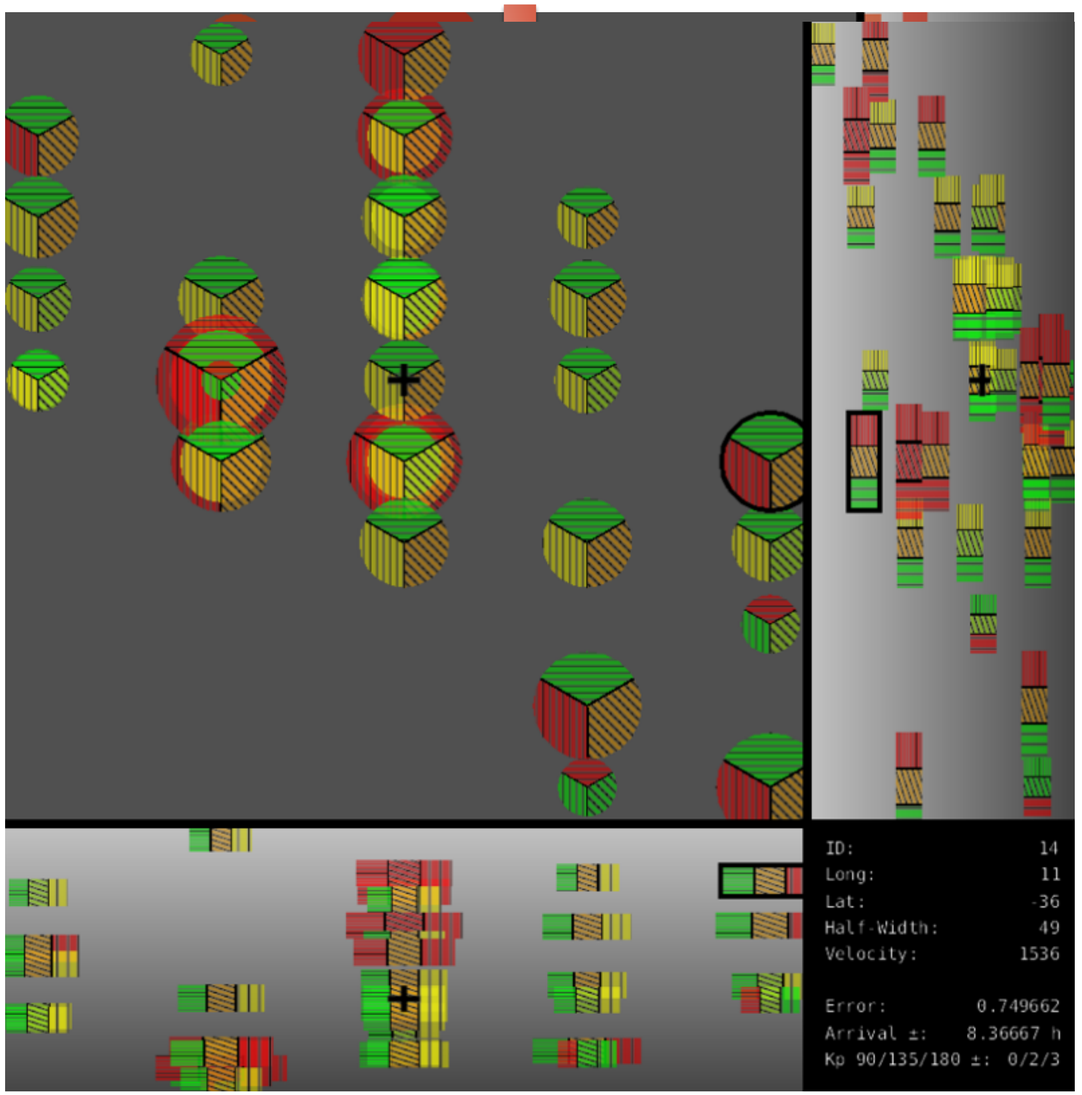

Timeline View

- Show time evolution of an error metric
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- Selection to load time step

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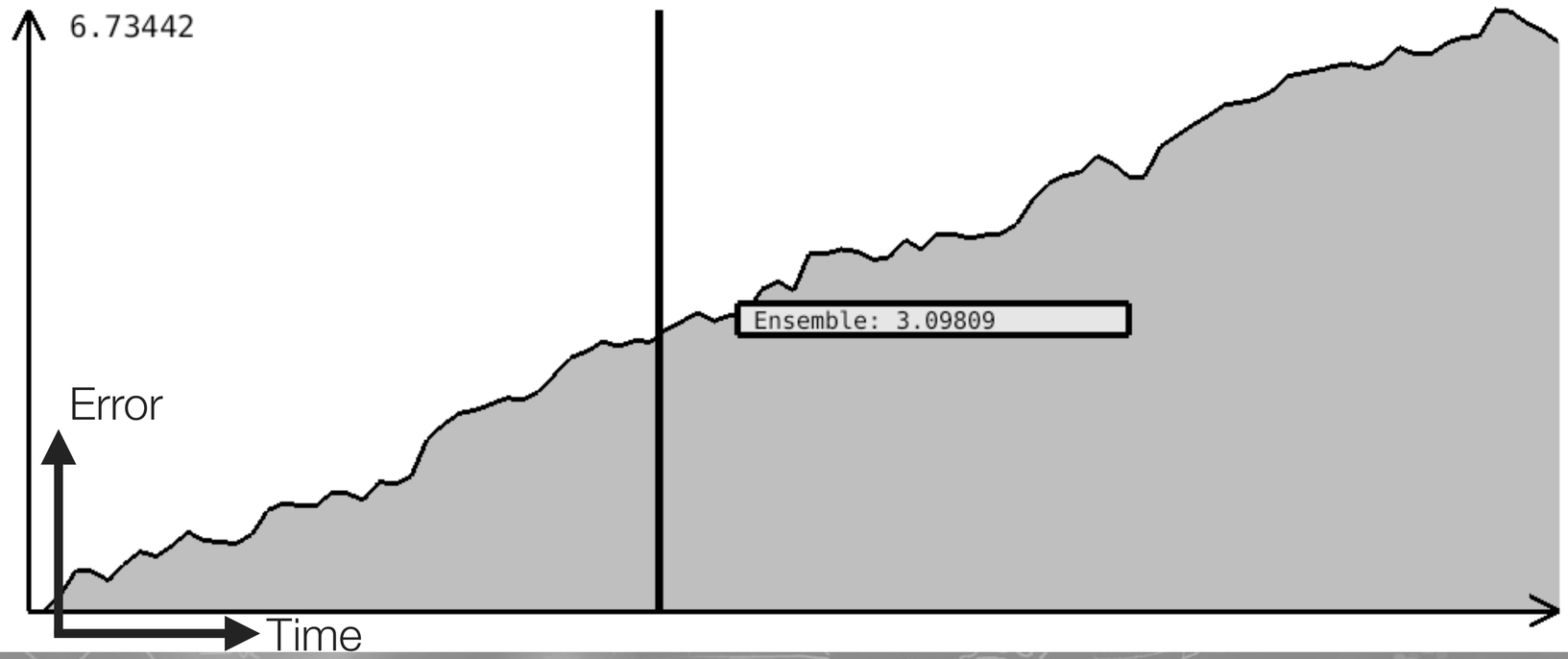

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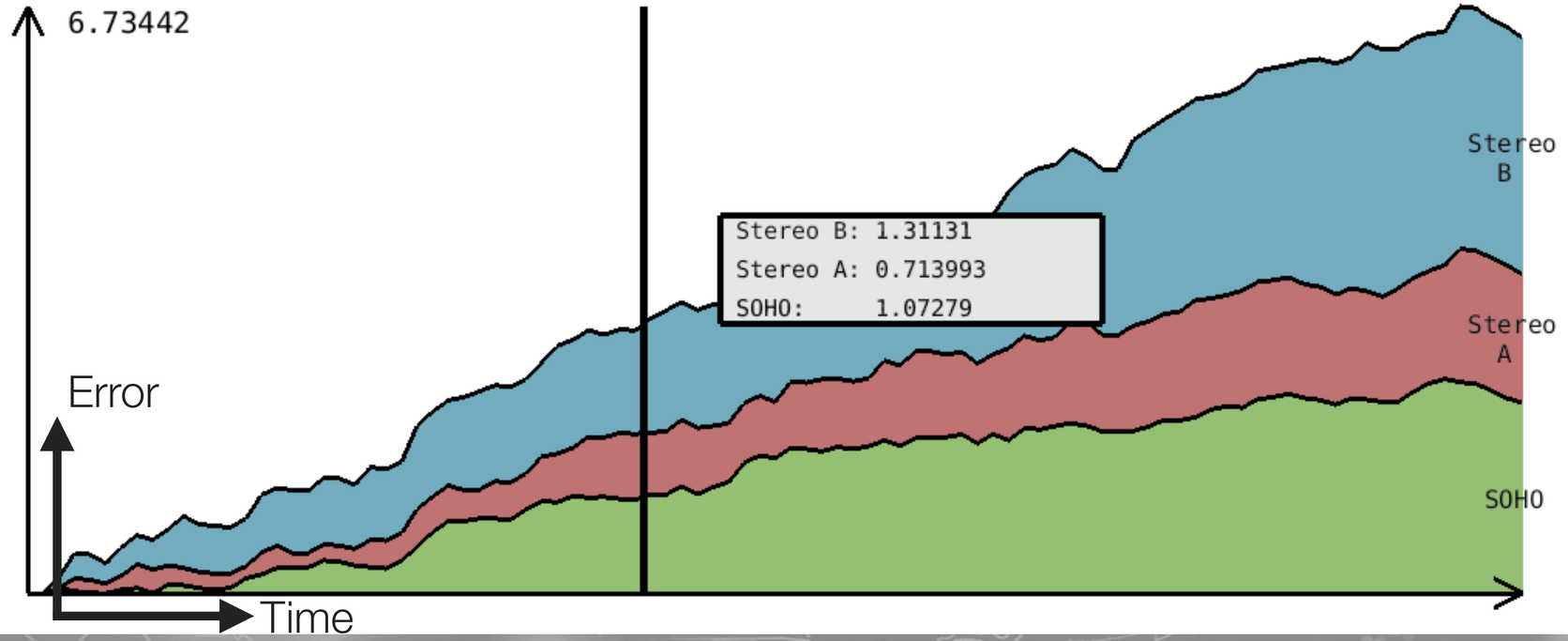

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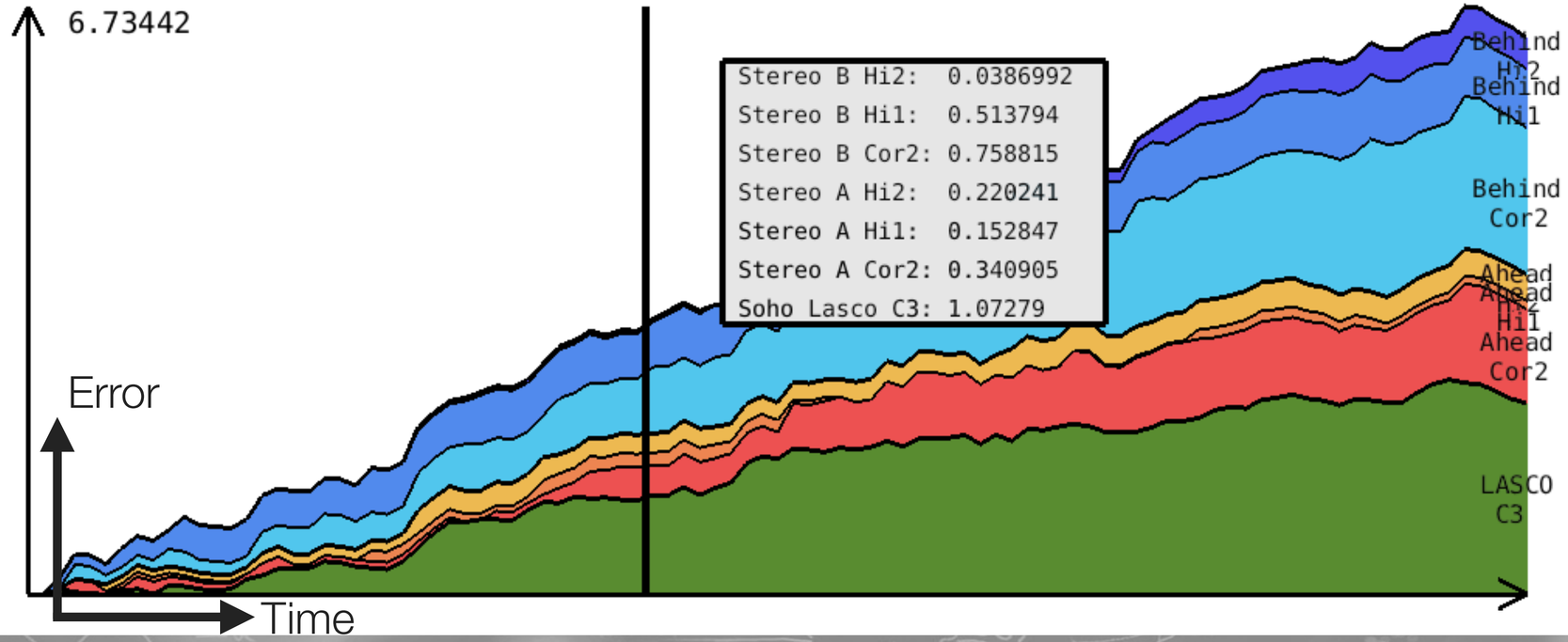
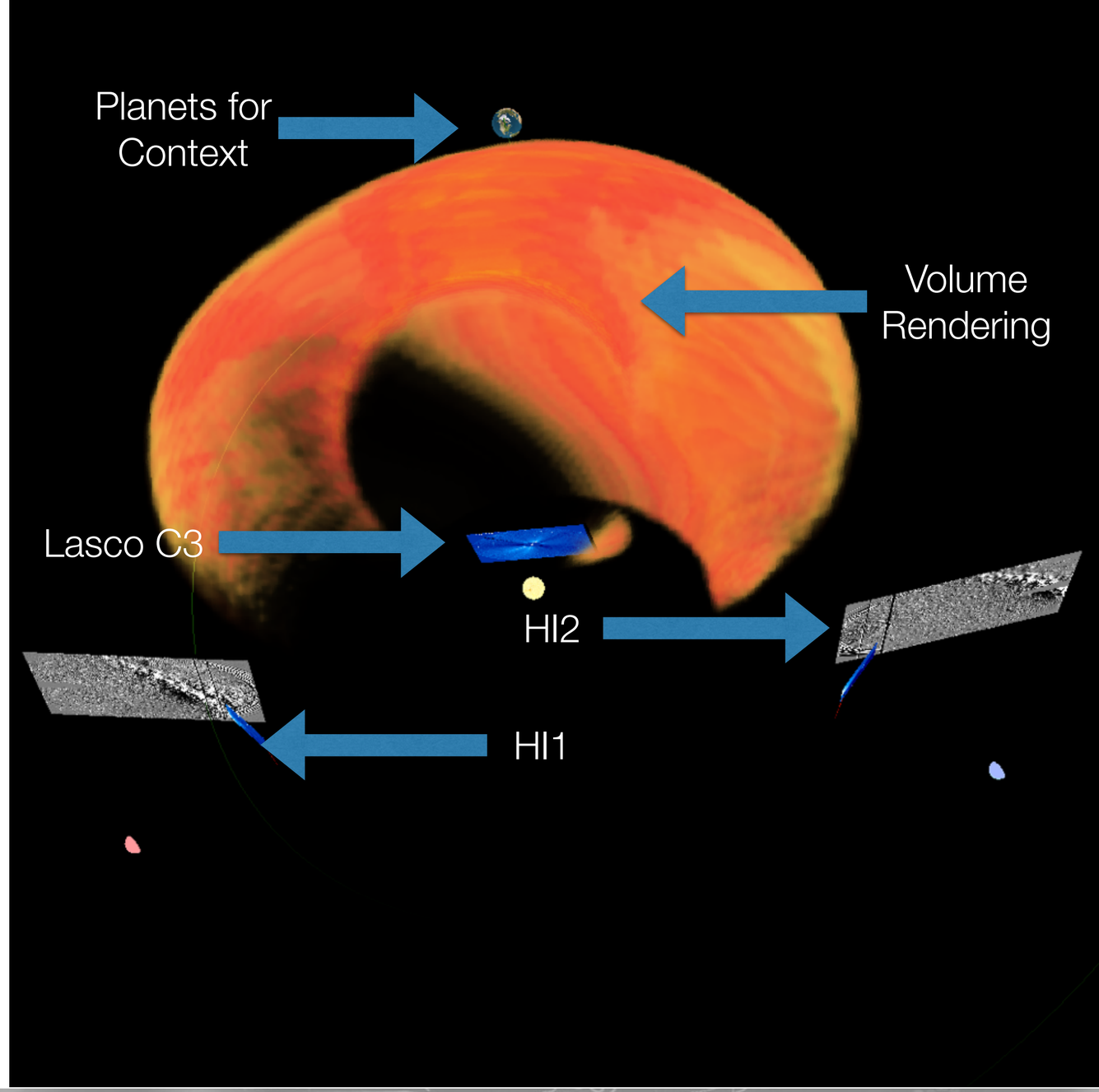
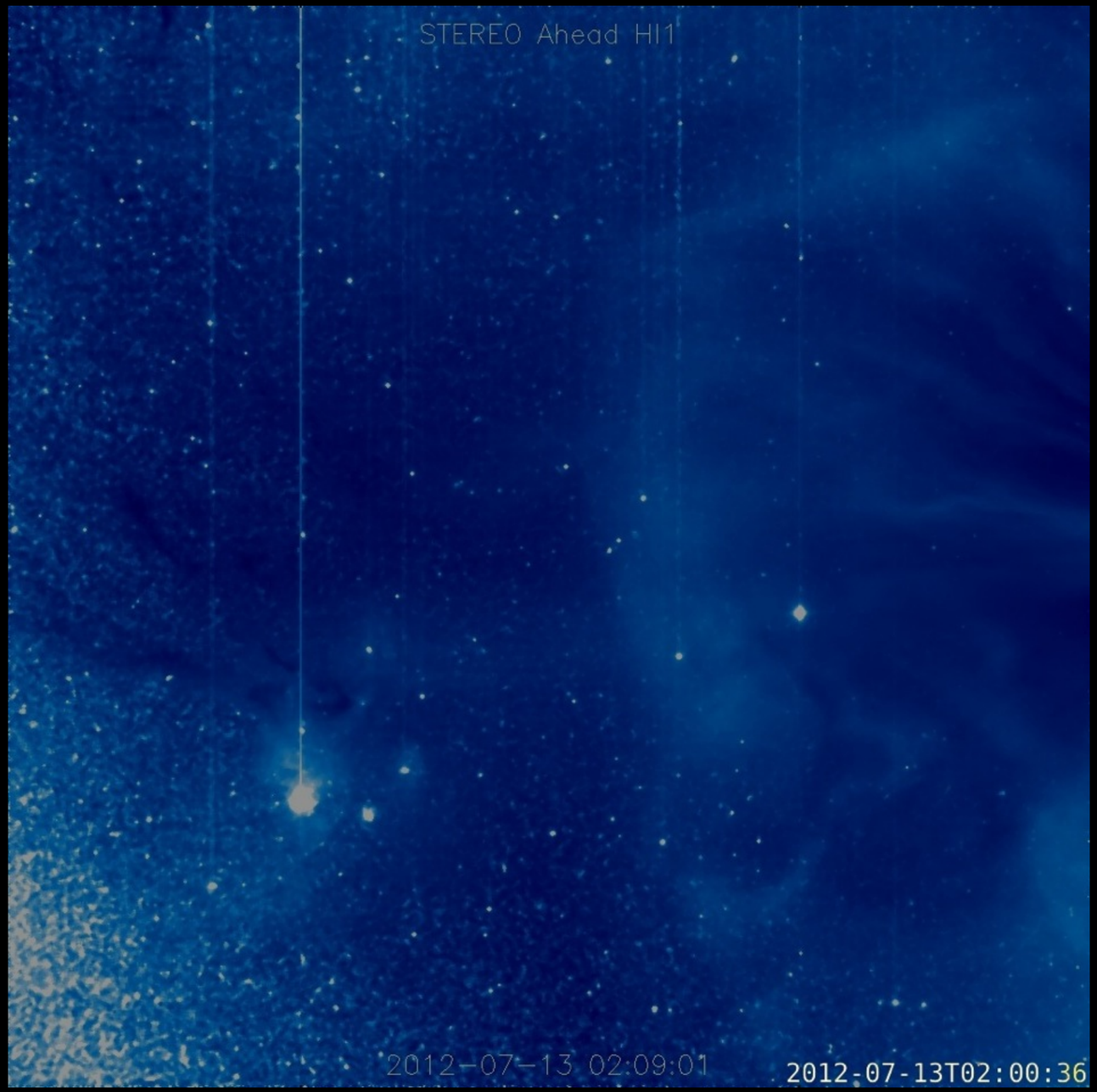
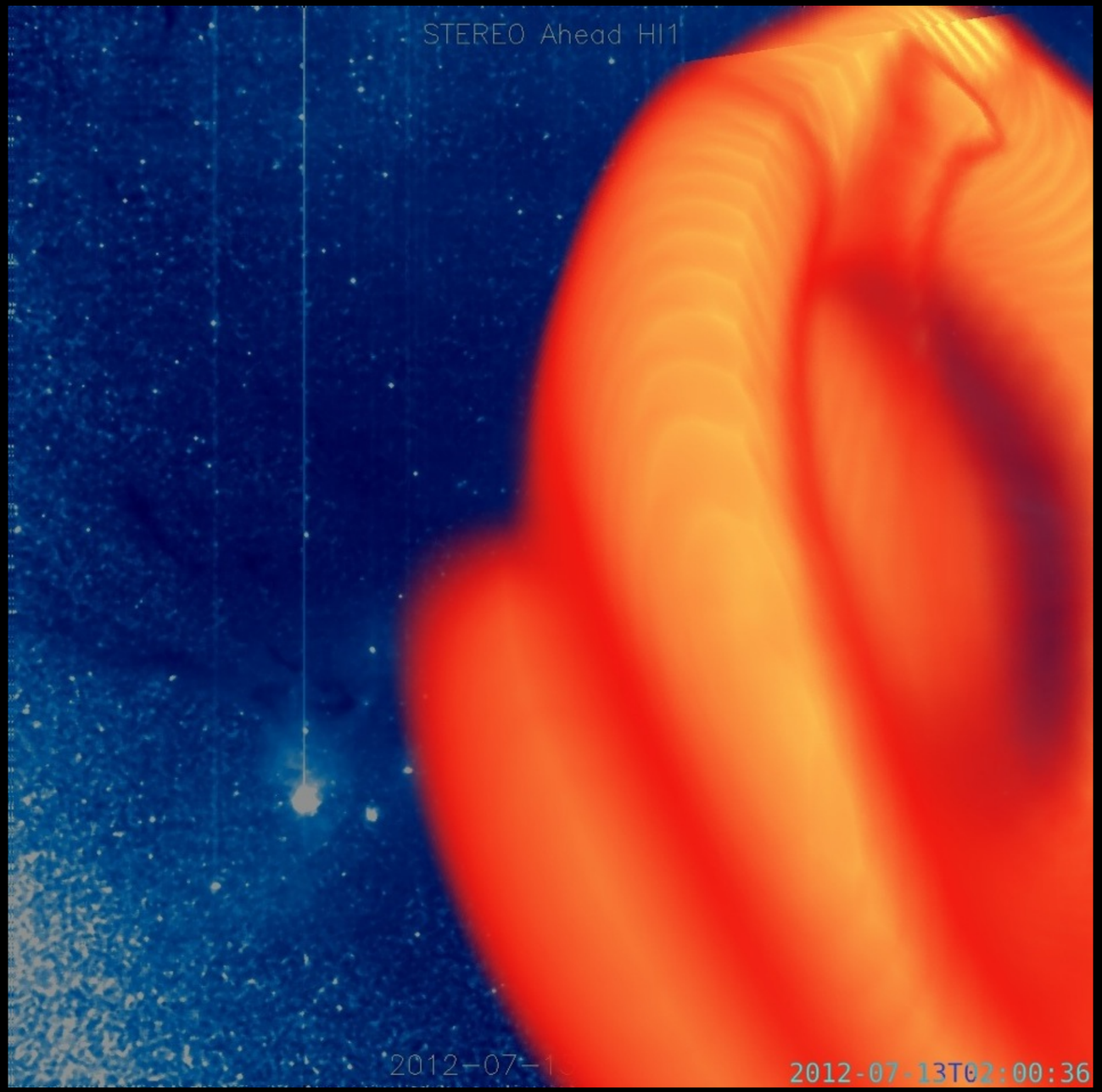


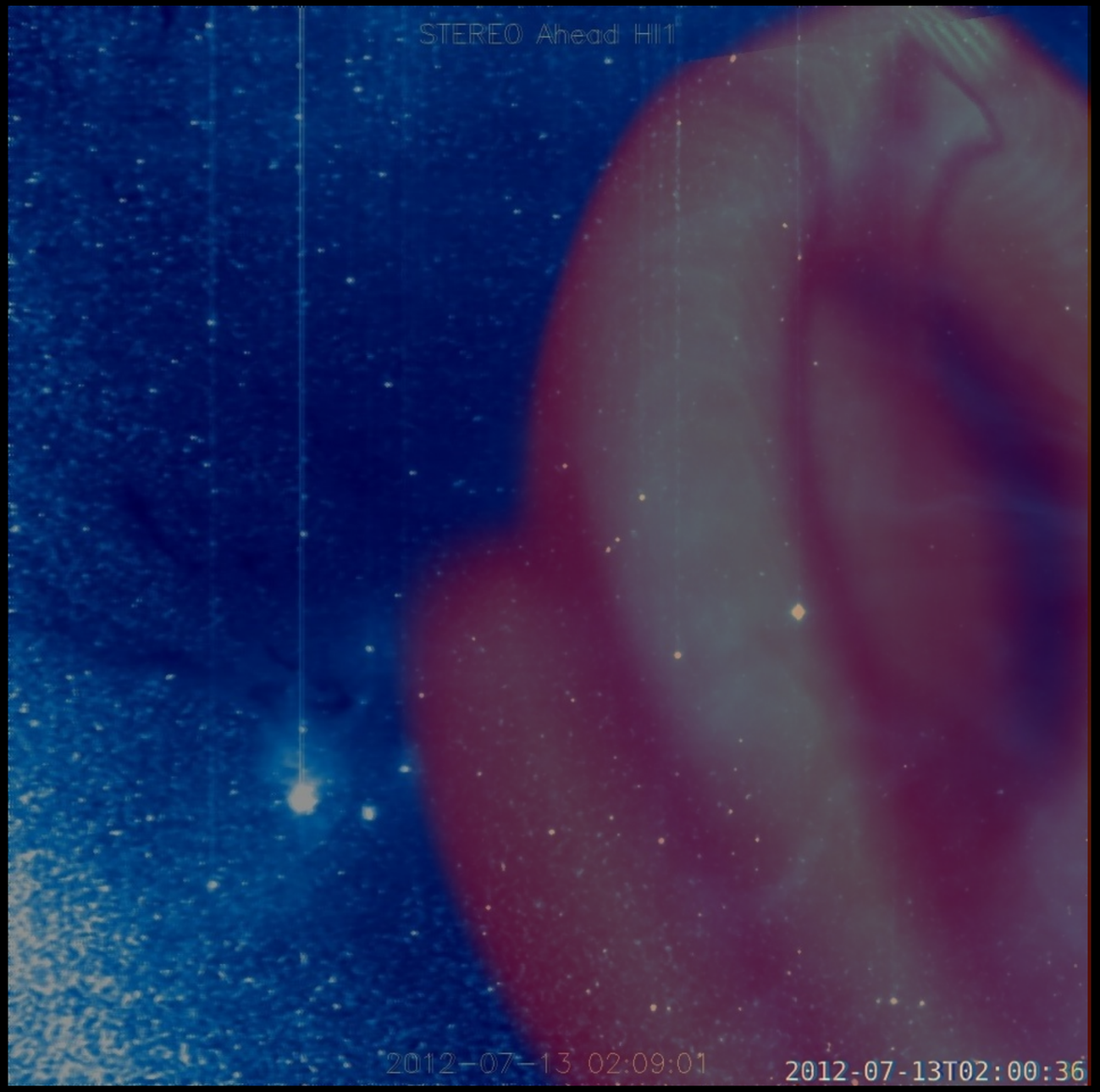
Rendering View

- Interactive volume rendering with geometry
- Integrated view of satellite images
- See-through capabilities




STEREO Ahead HI1
2012-07-13 02:09:01
2012-07-13T02:00:36


STEREO Ahead HI1
2012-07-1
2012-07-13T02:00:36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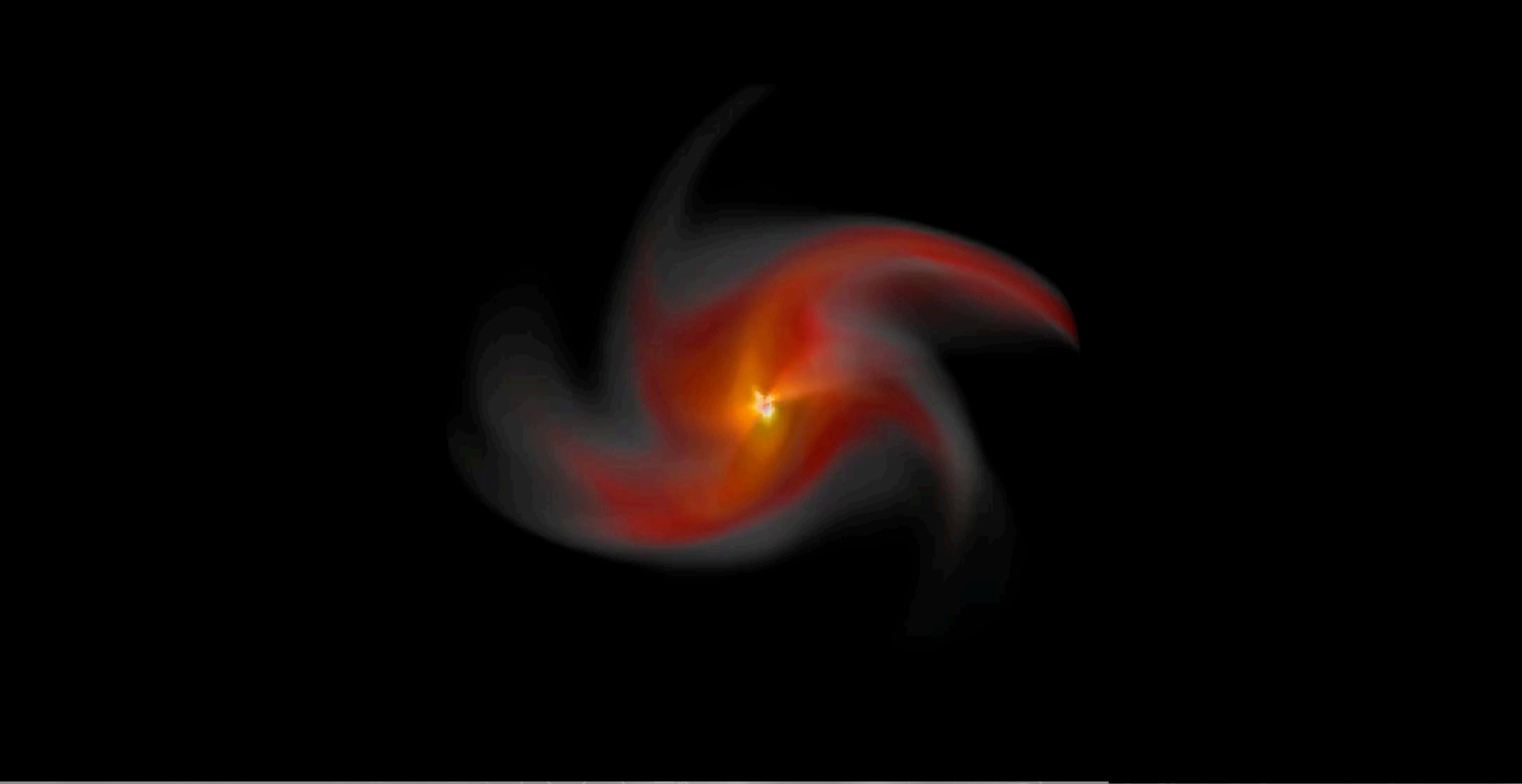

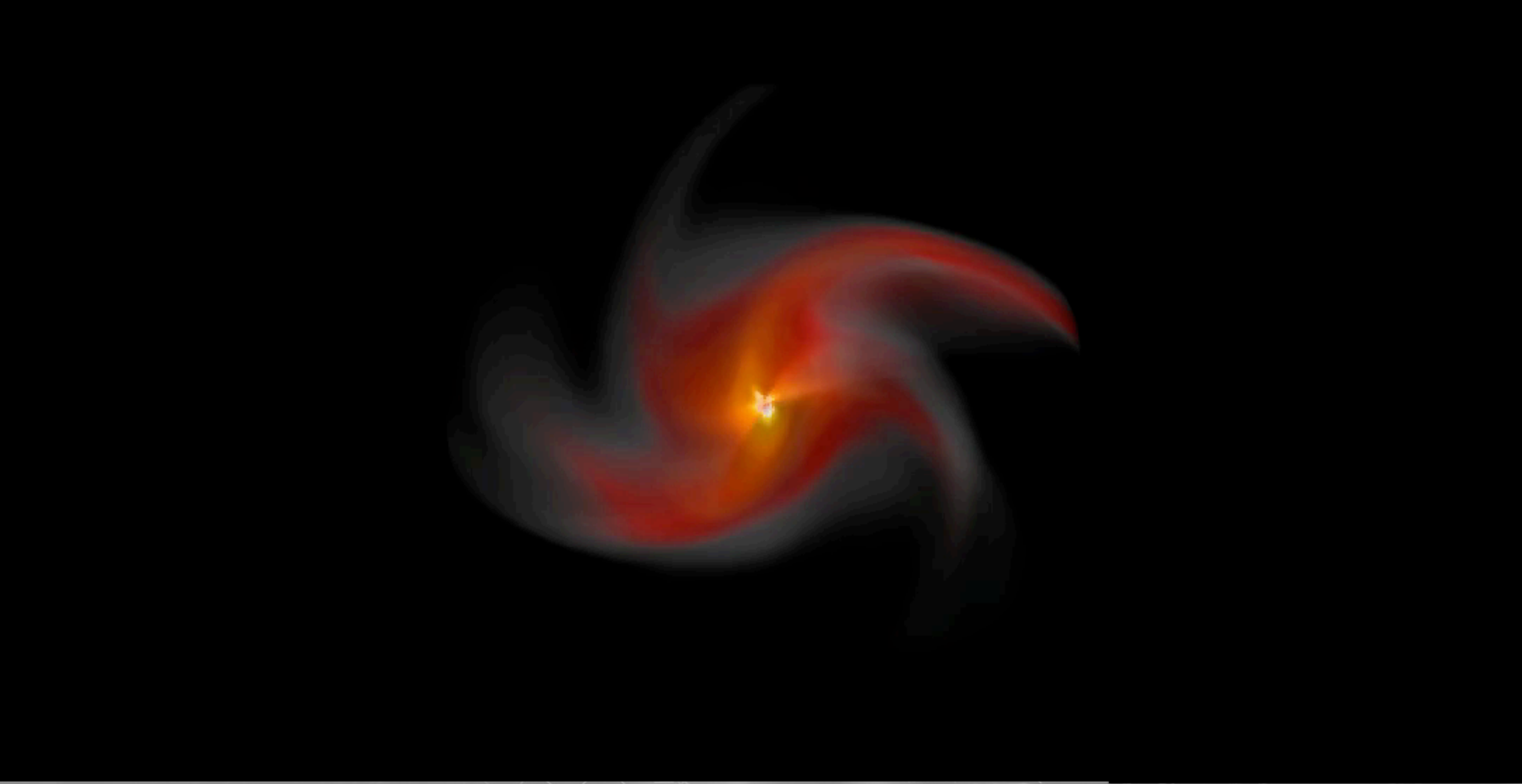

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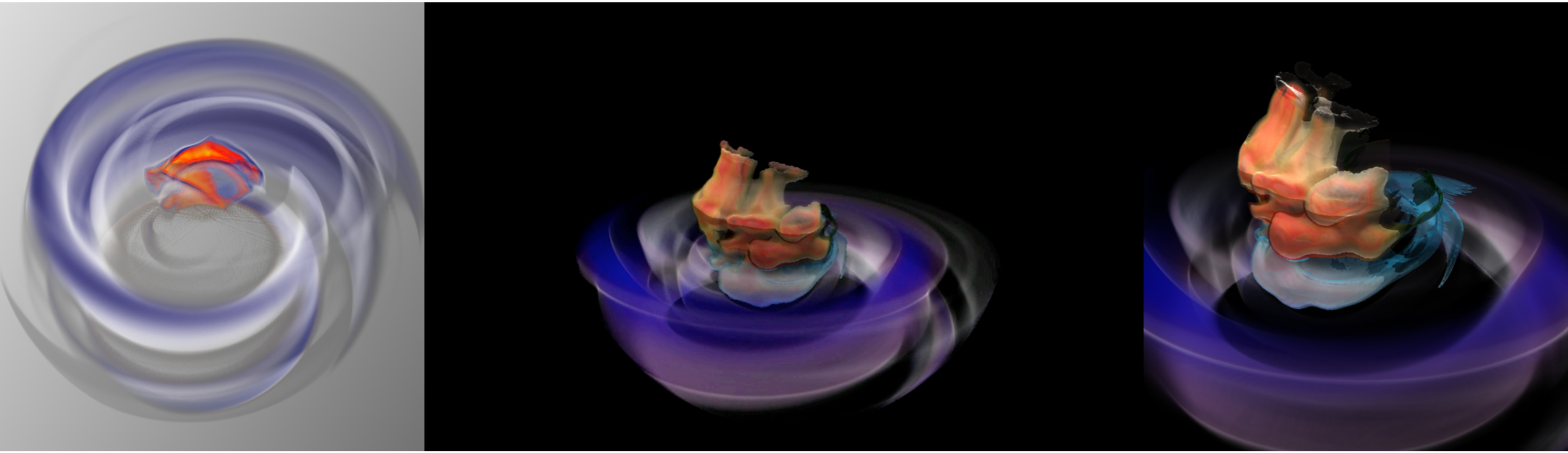

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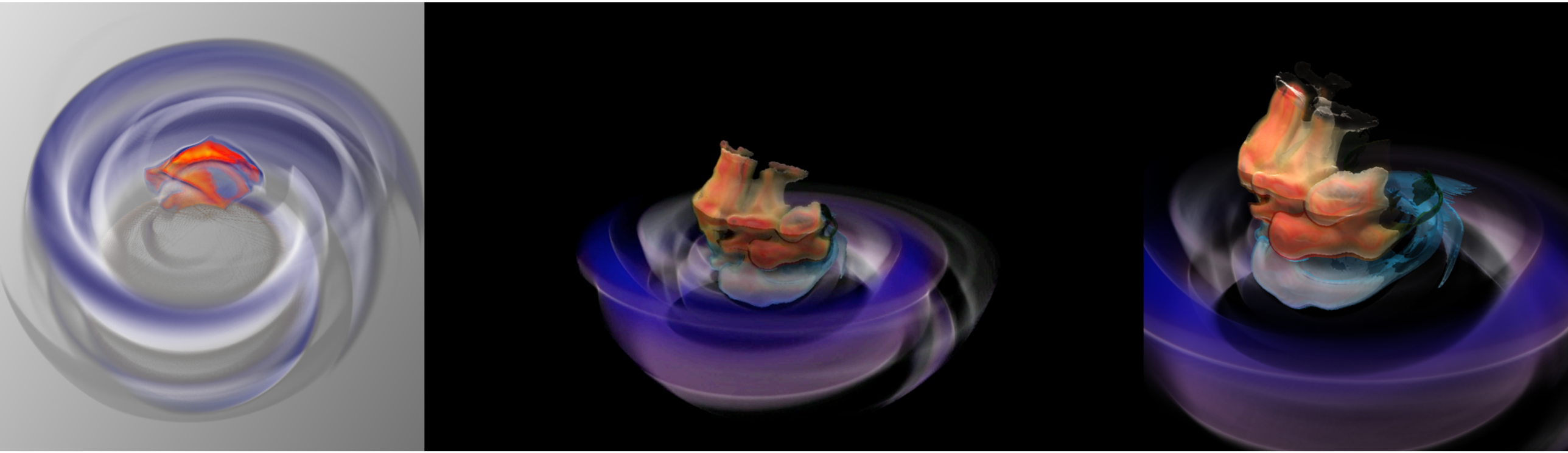

Comparisons of Rendering with Satellite Imagery

Comparisons with In Situ Imagery

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- Method of getting time-dependent data

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  - *Secrets of optical flow estimation and their principles*, Sun, Roth, Black, CVPR 2010

Optical Flow Analysis

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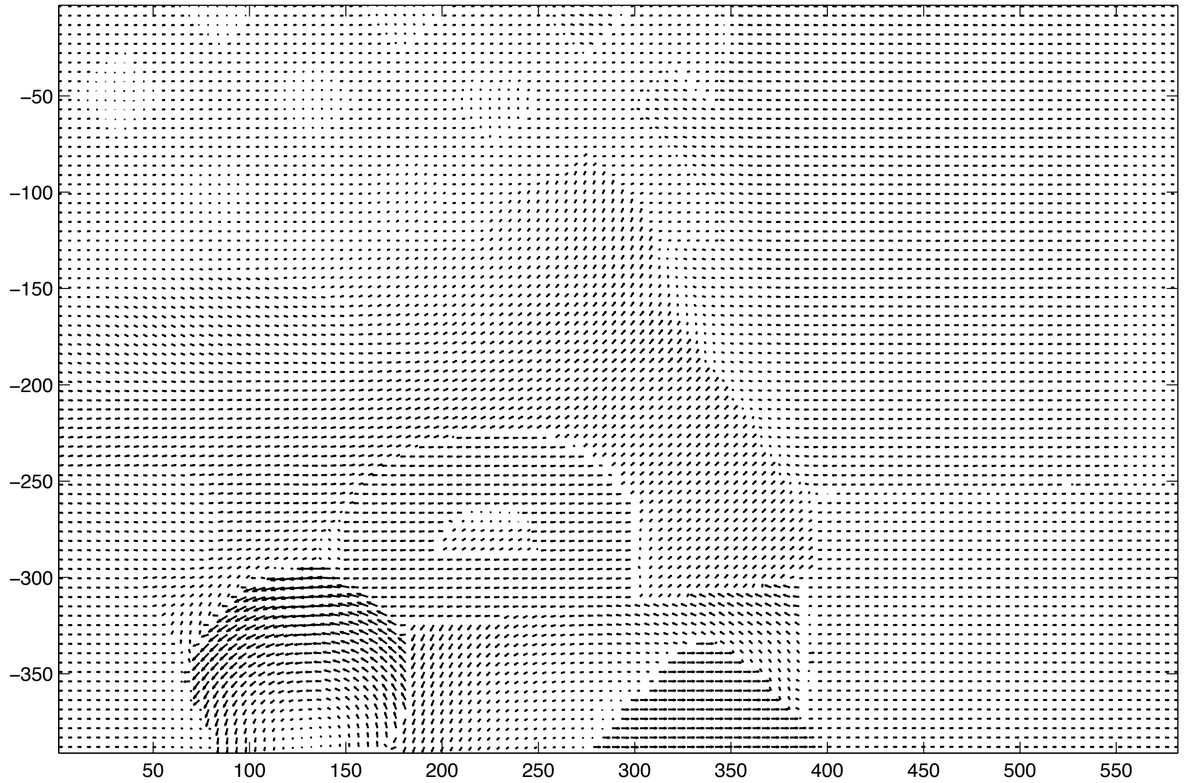

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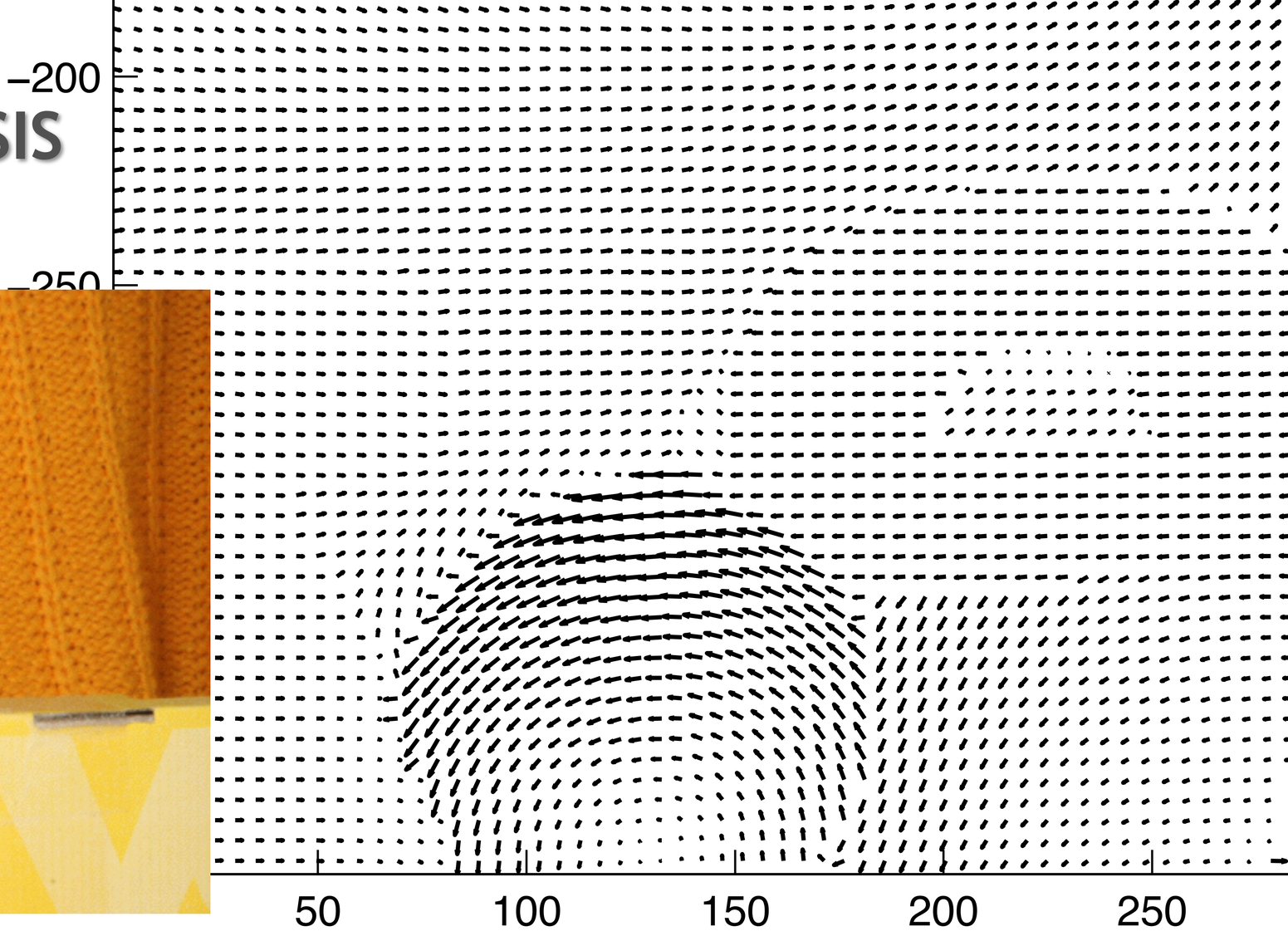
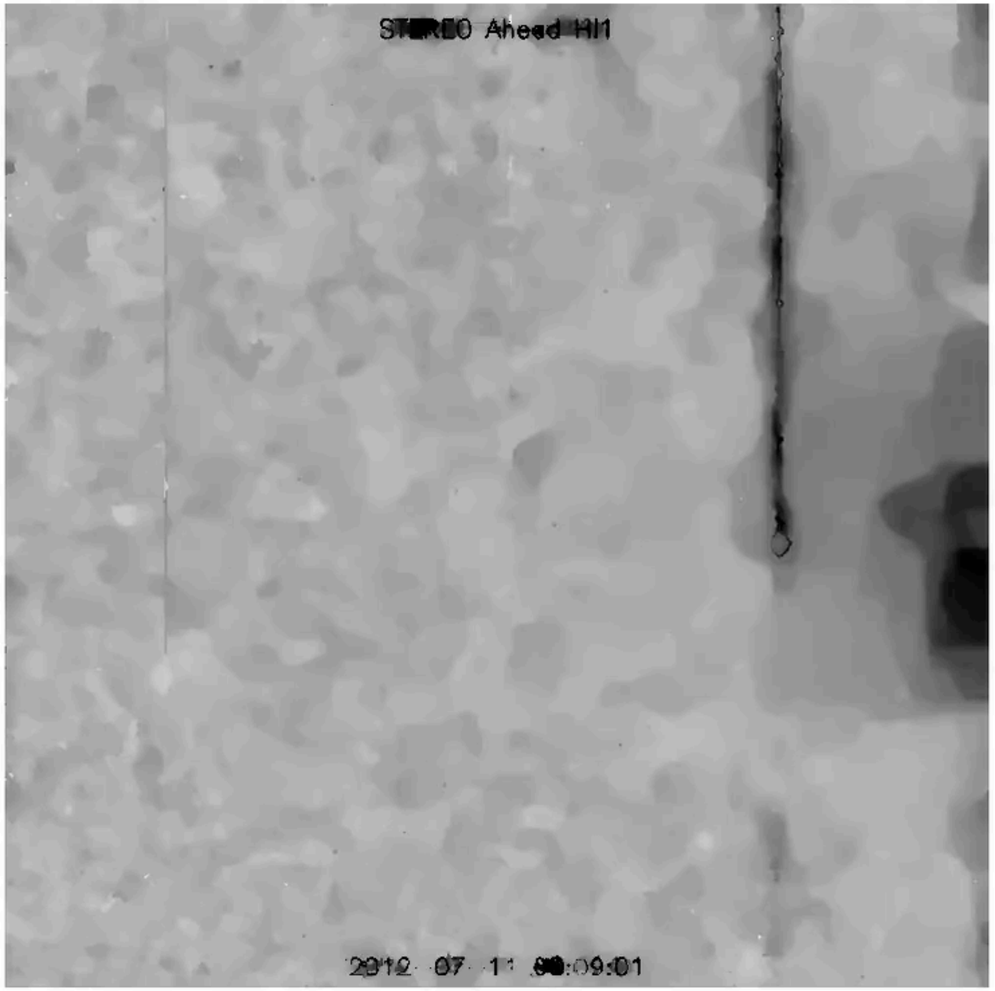
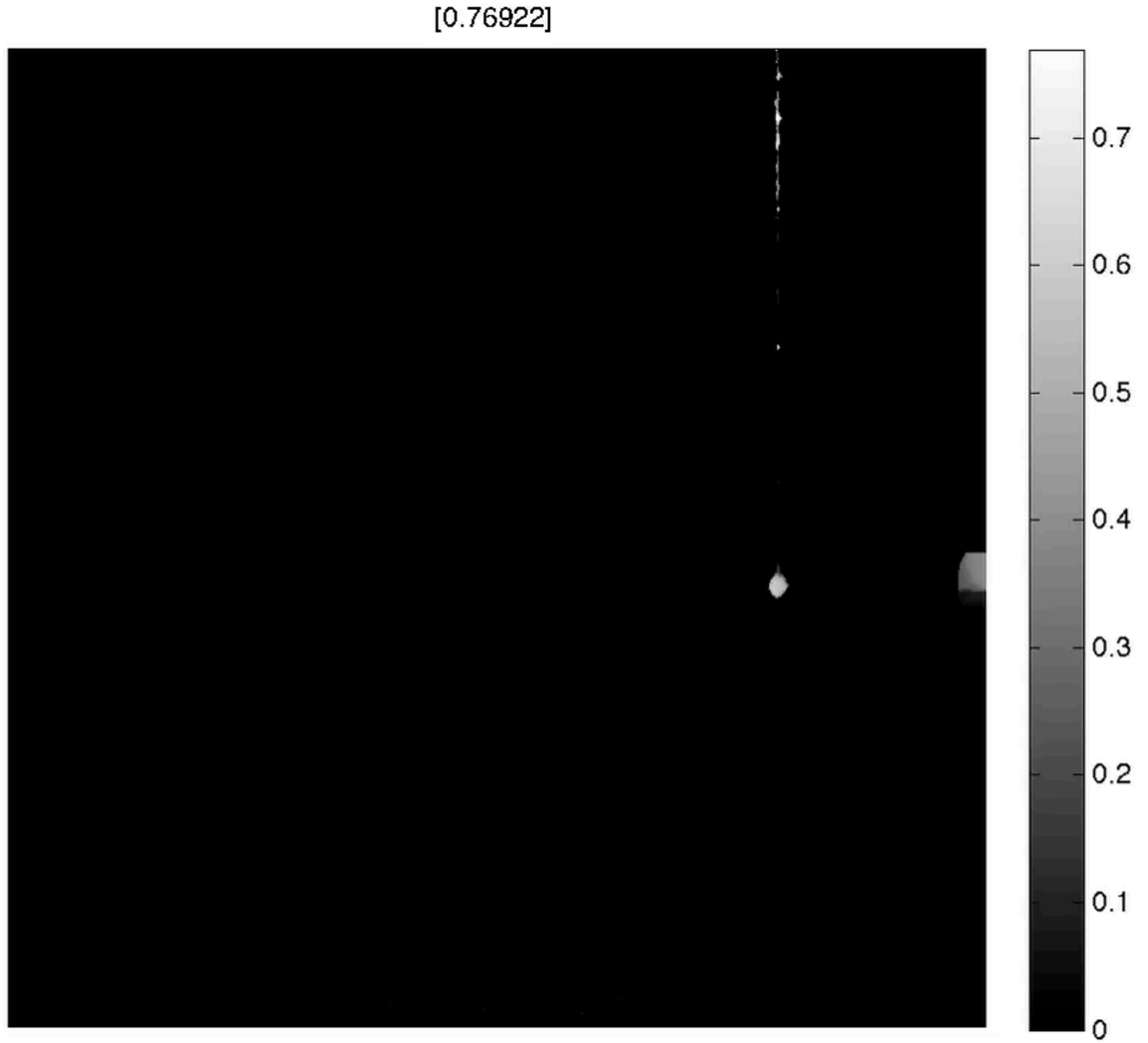
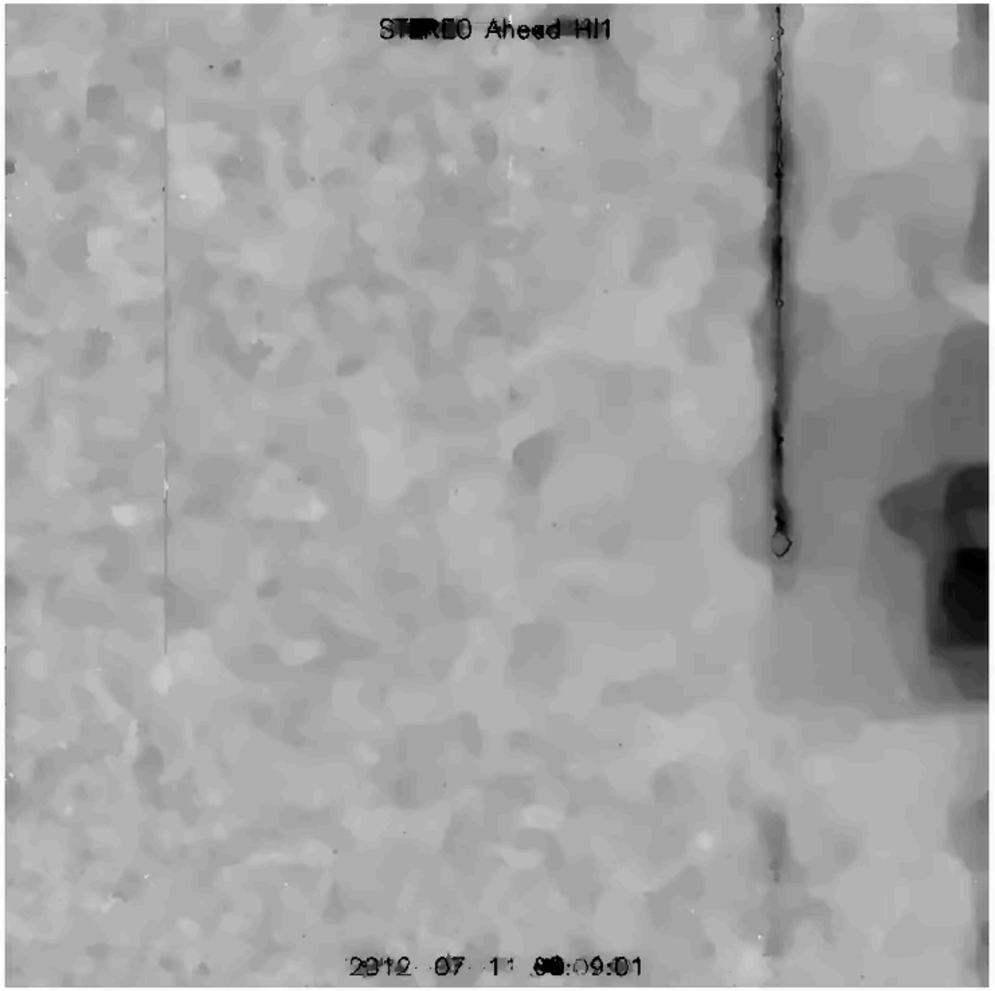


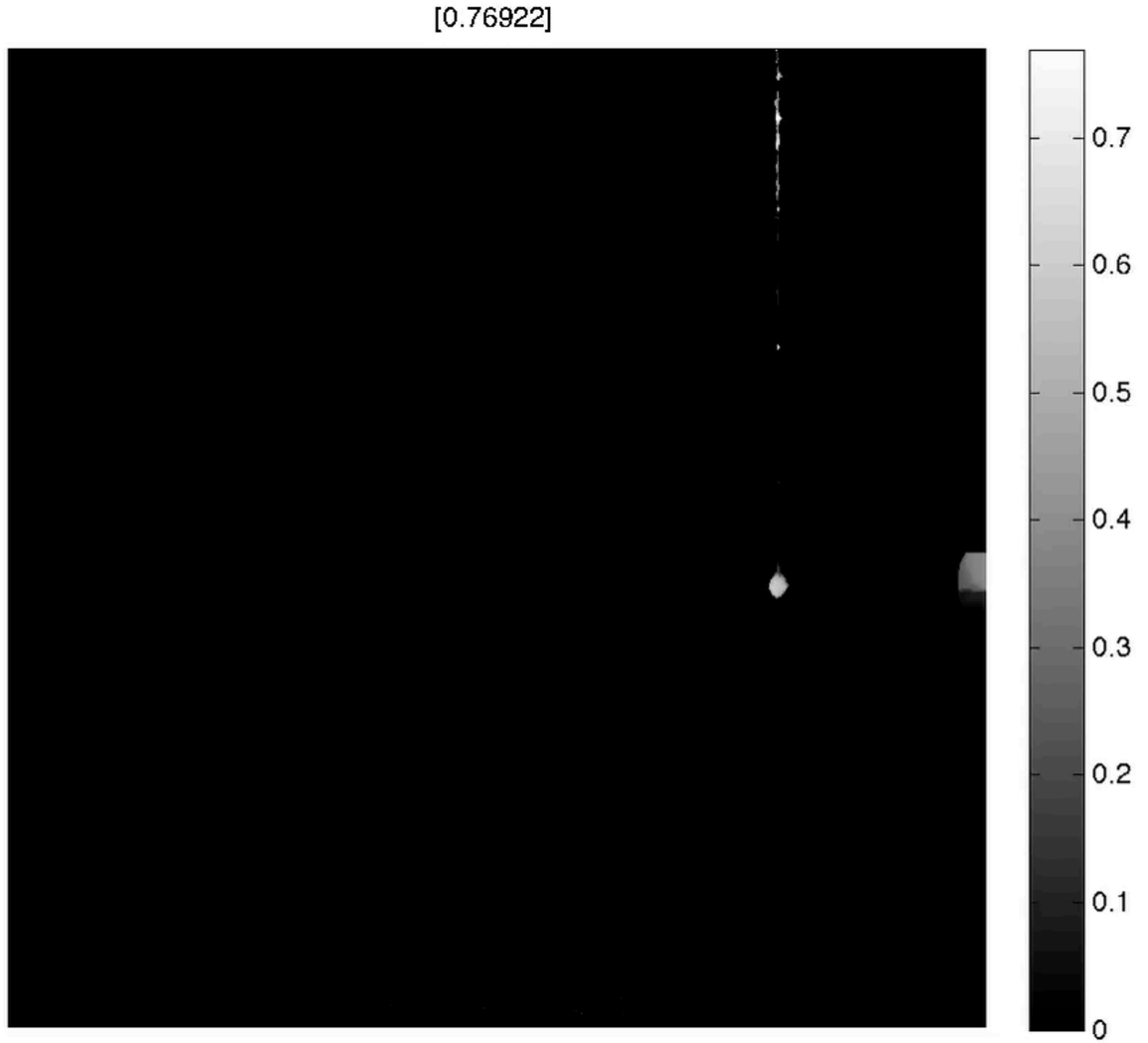
Optical Flow Applied To Satellite Images





Optical Flow Applied To Satellite Images





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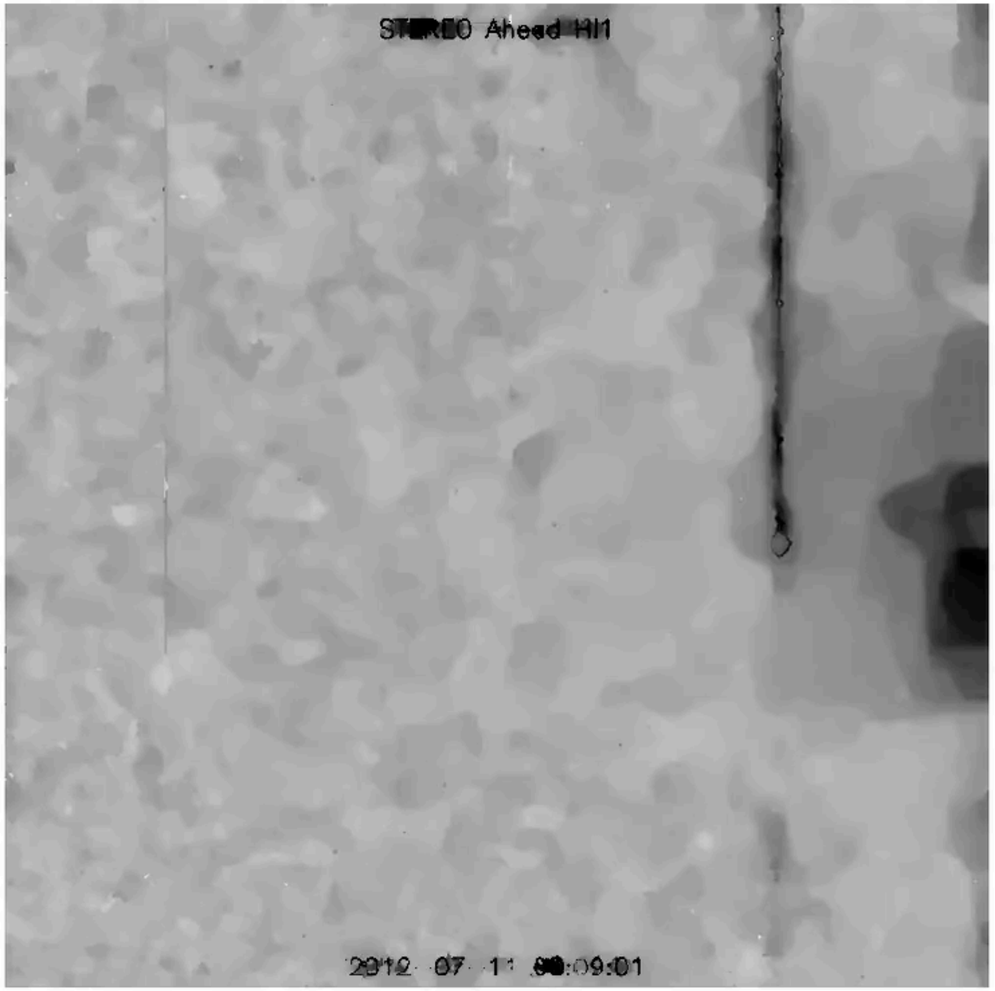

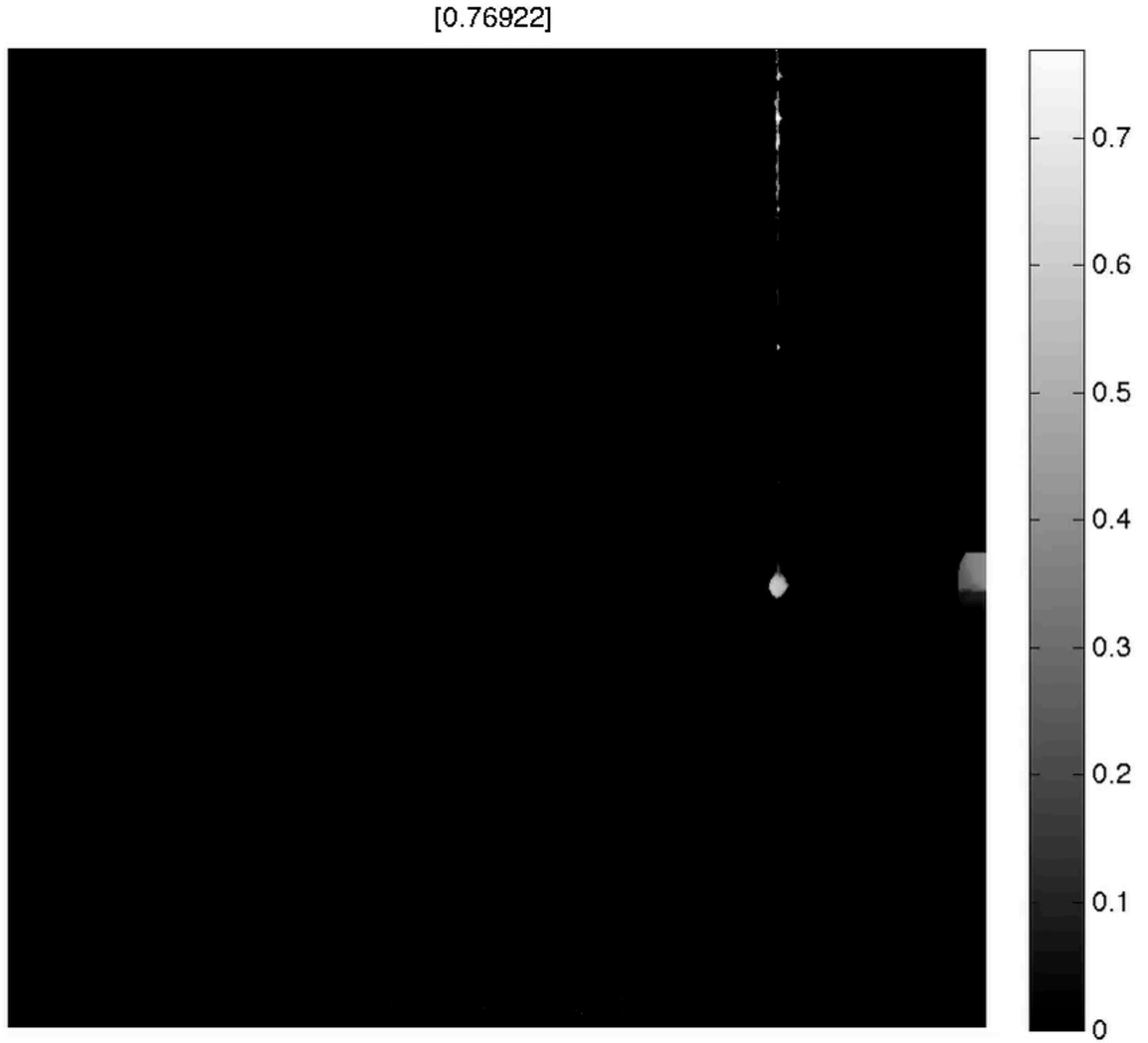

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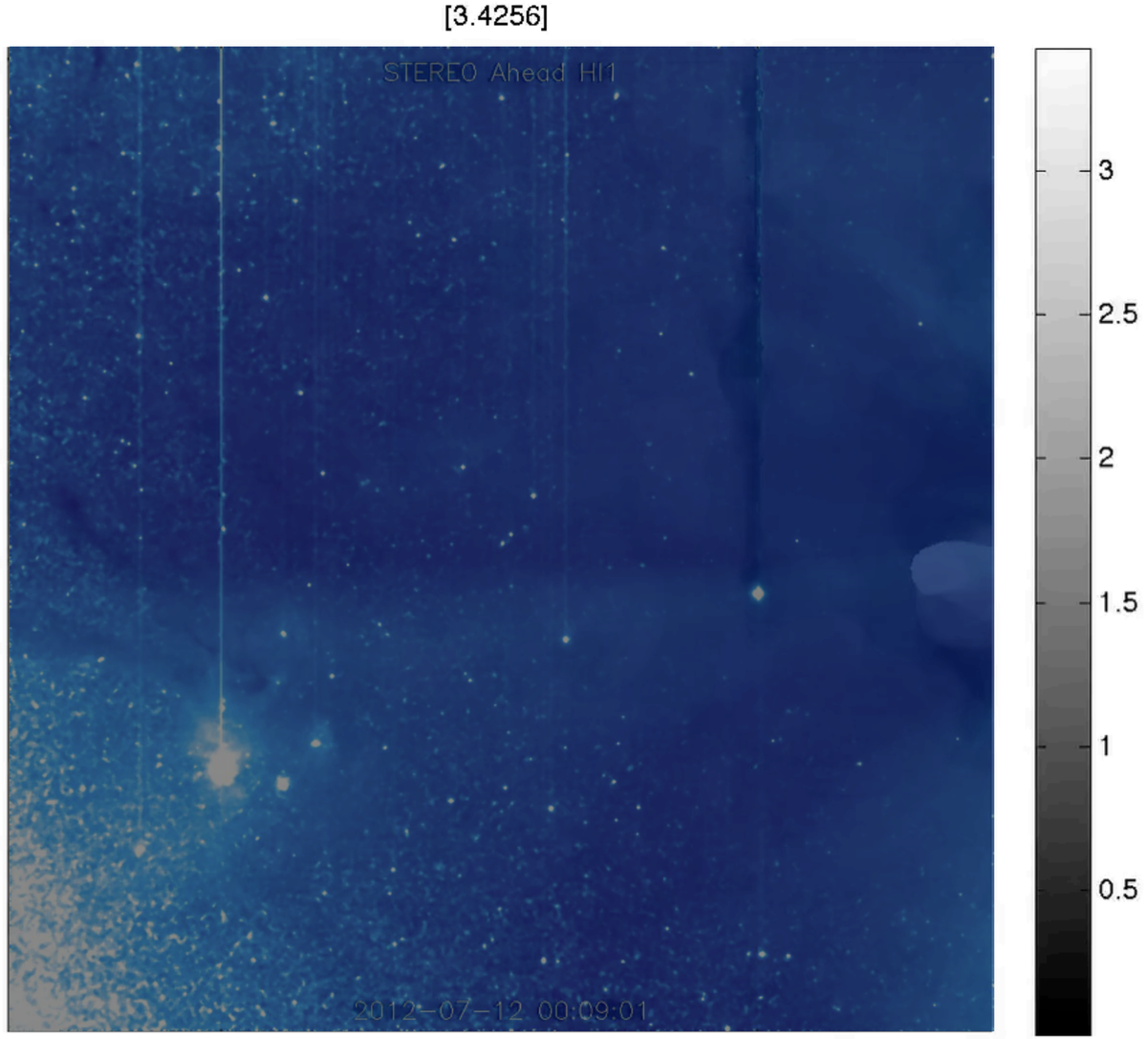

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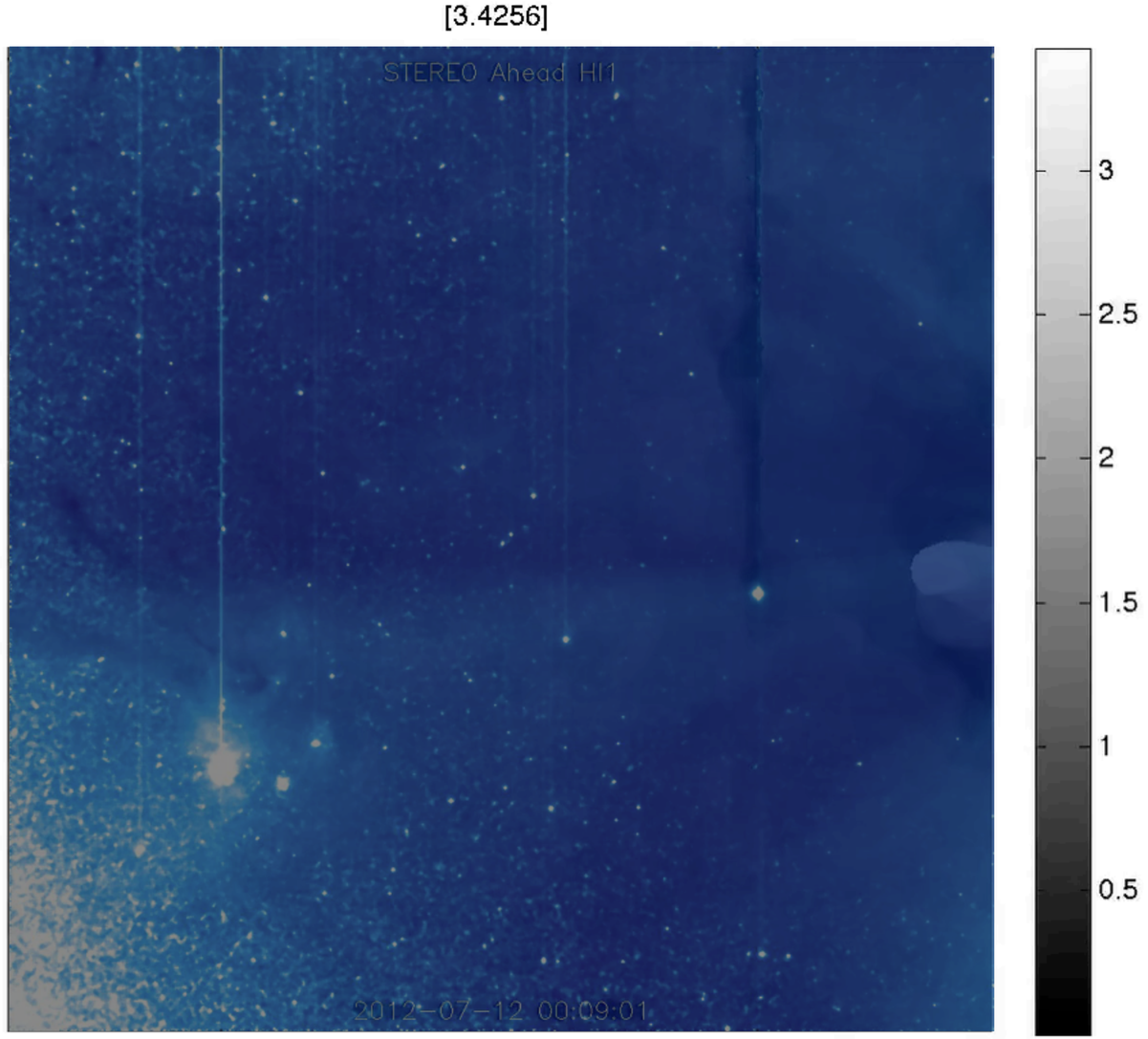
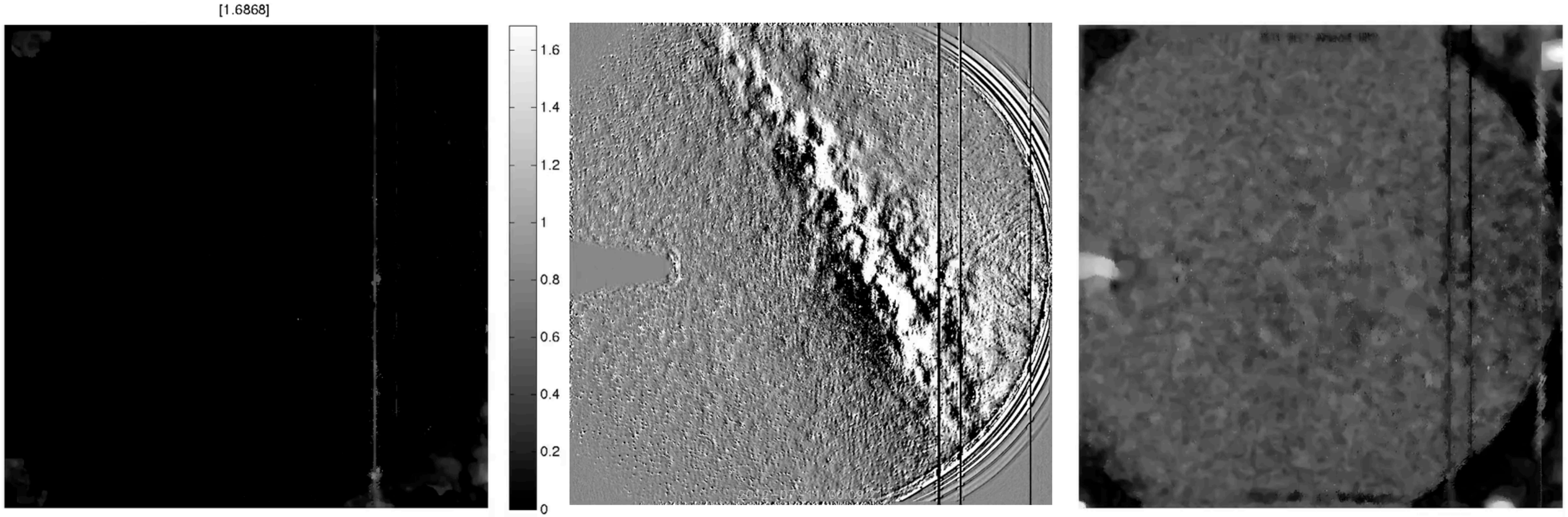


Open Questions and Call for Help

- Hi2 images are very noisy



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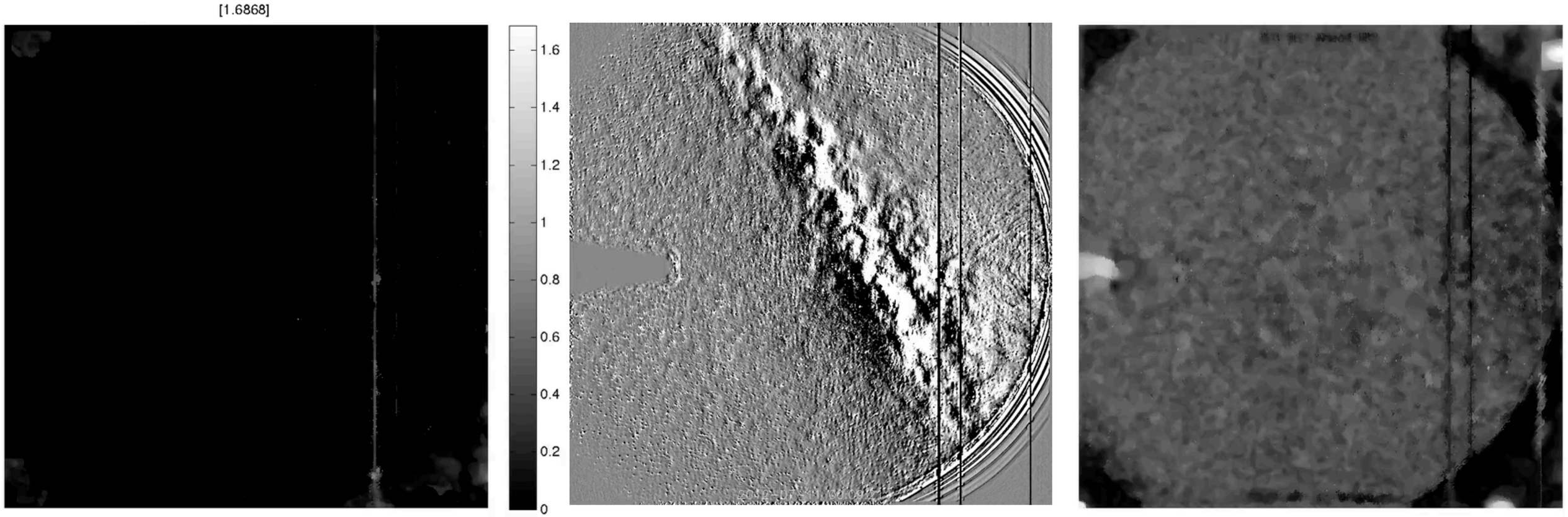

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- Foreseeable problems?

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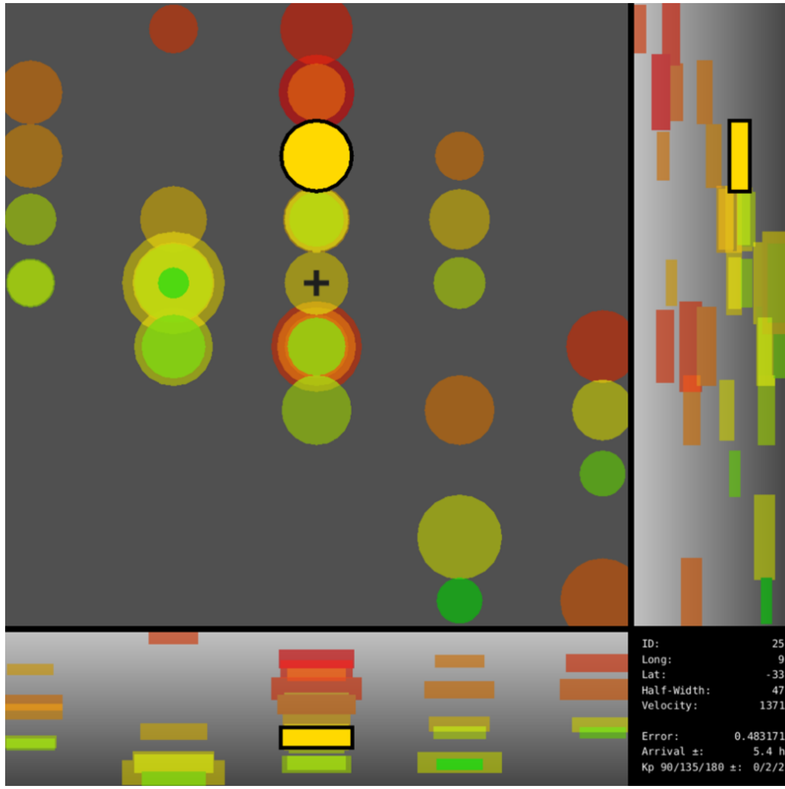
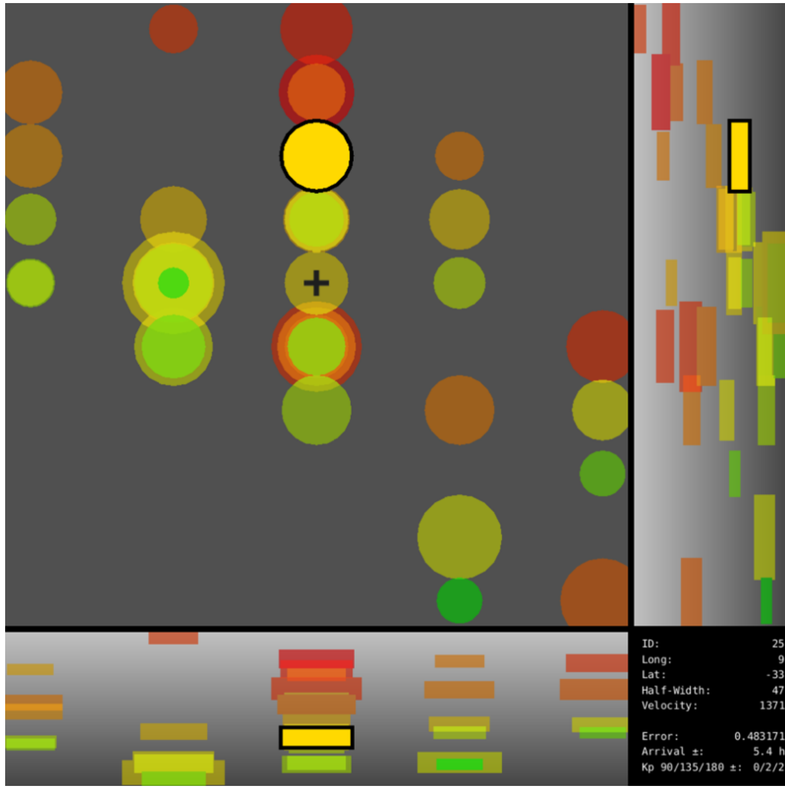


Open Questions and Call for Help

- Foreseeable problems?

- Usefulness of predicting potentially useful Ensemble members?



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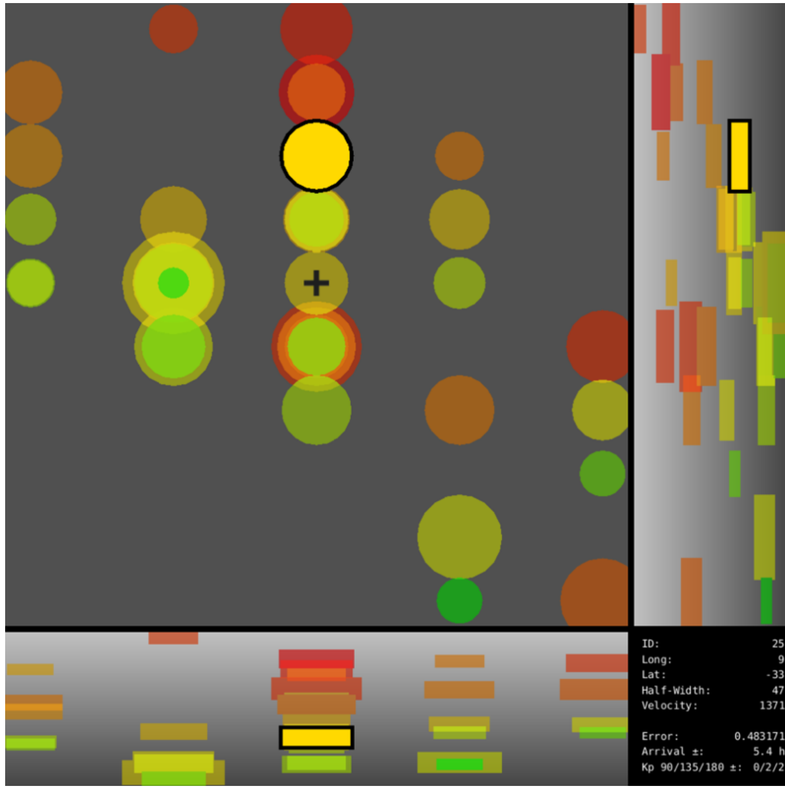
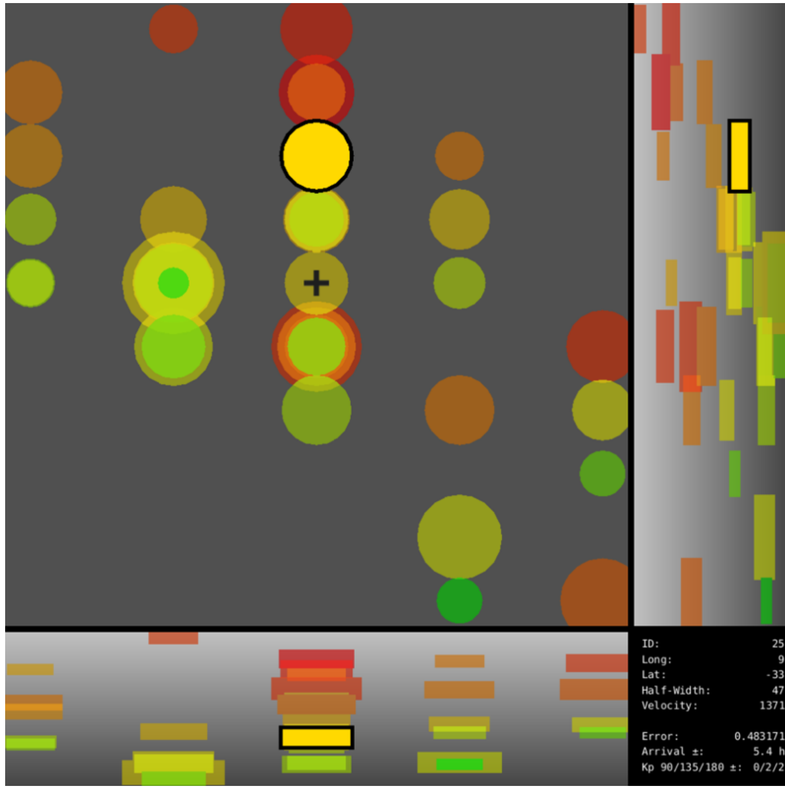


Open Questions and Call for Help

- Foreseeable problems?
- Usefulness of predicting potentially useful Ensemble members?
- Other time-dependent measures?



THANK YOU!

QUESTIONS?

Linköping University
expanding reality

NORRKÖPING
VISUALIZATION CENTER

CRESEARCH