Interactive Exploration of Plasmas in Magnetic Confinement Fusion

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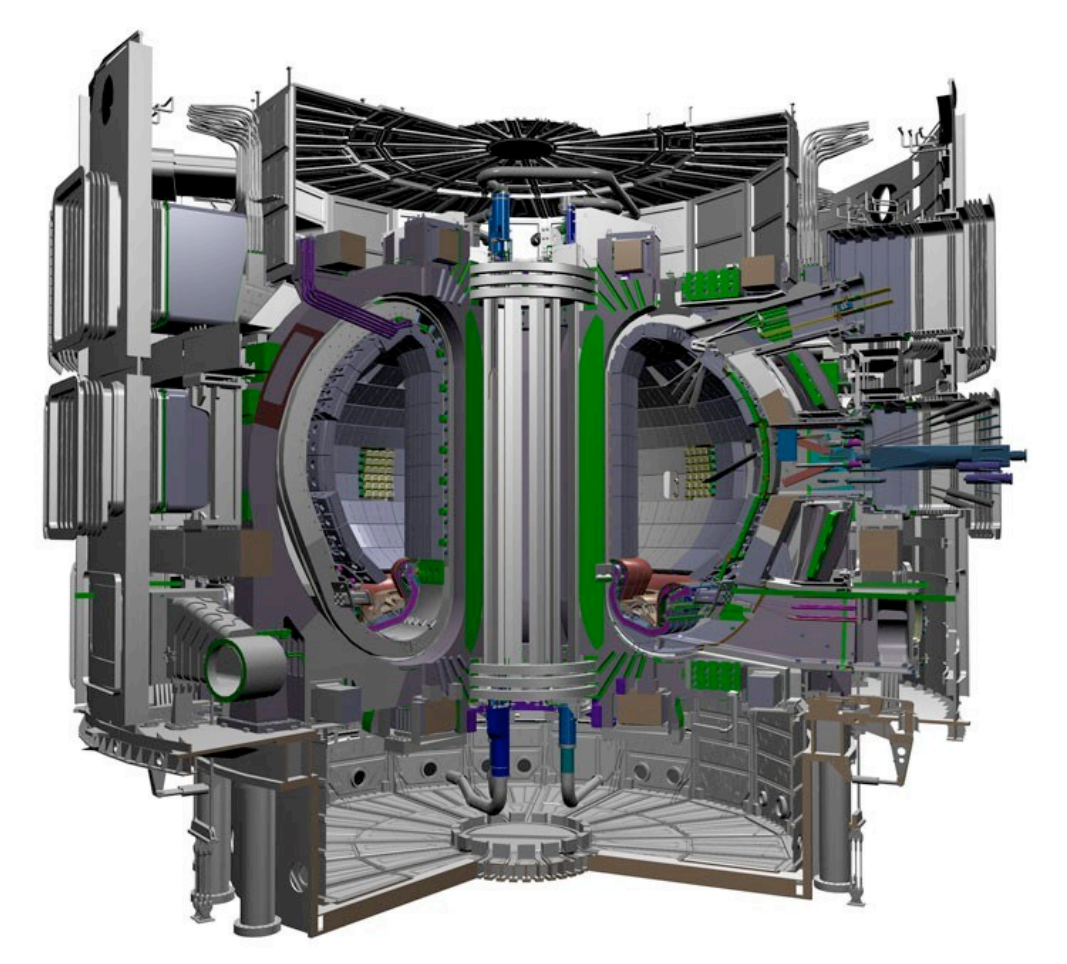
University of Utah

And many other members of the DOE SciDACs VACET, CEMM, CSWPI, SDM, GPS-TTBP, and FACETS, SWIM, and CPES FSP.



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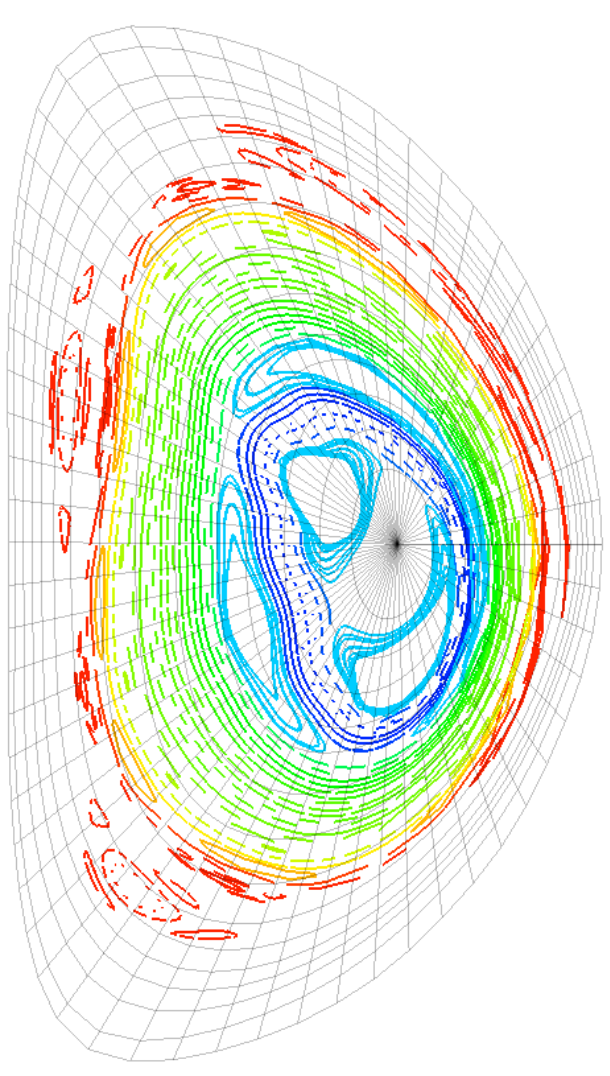
Toroidal Magnetic Fields

- Goal:

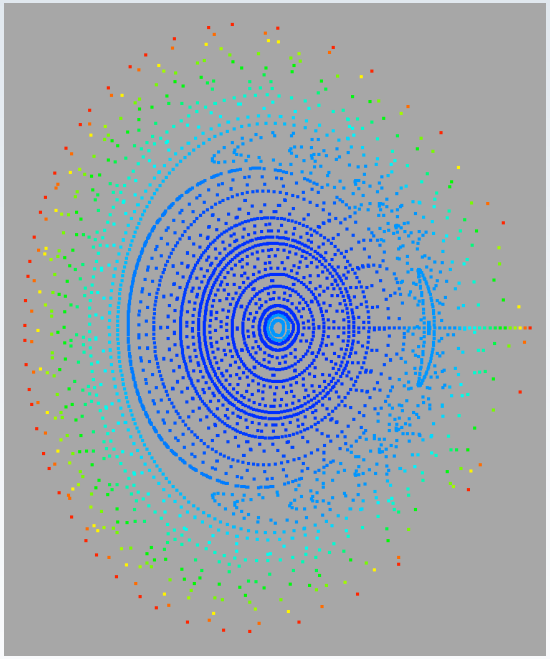
  Understanding Quasi Periodic Fieldlines and Their Topology in Toroidal Magnetic Fields

  Topology == identify island chains and their growth.



Toroidal Magnetic Fields

- View the traditional puncture plot not as series of discrete points on the magnetic surface but as series of points that when connected correctly encapsulates the surface.



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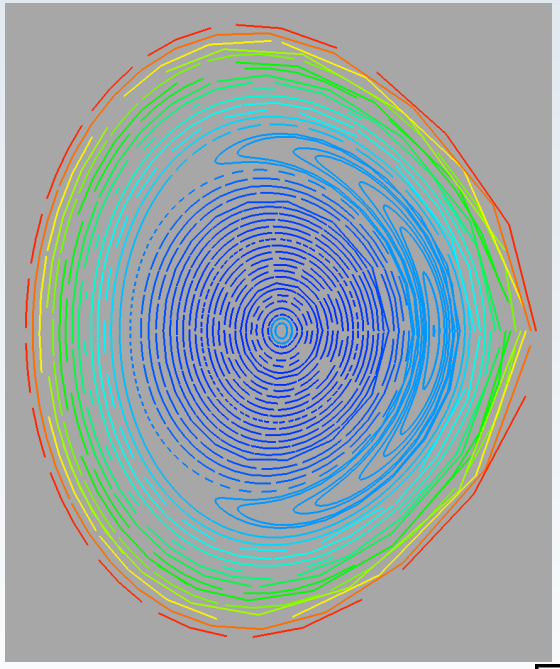
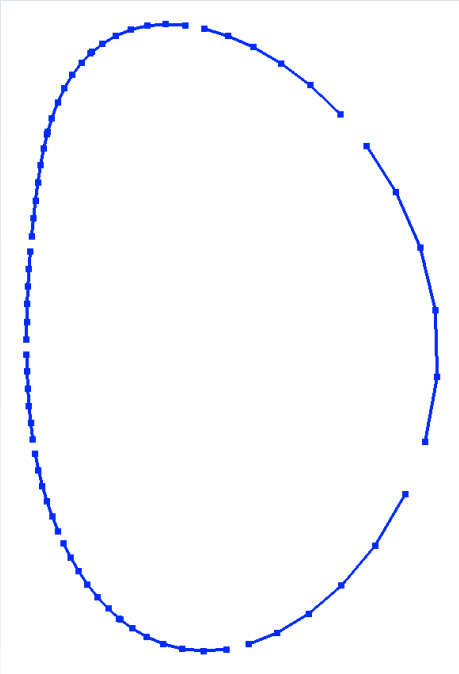
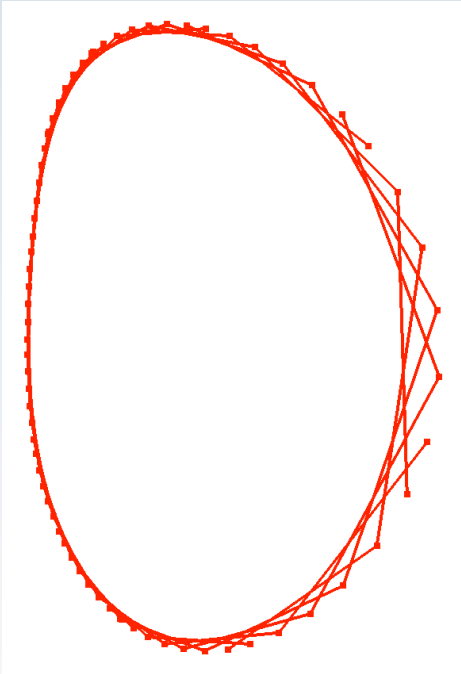


Minimum Spanning Trees

- Create a connection between every N^{th} point
- N represents a toroidal approximation
- Some approximations are better than others.



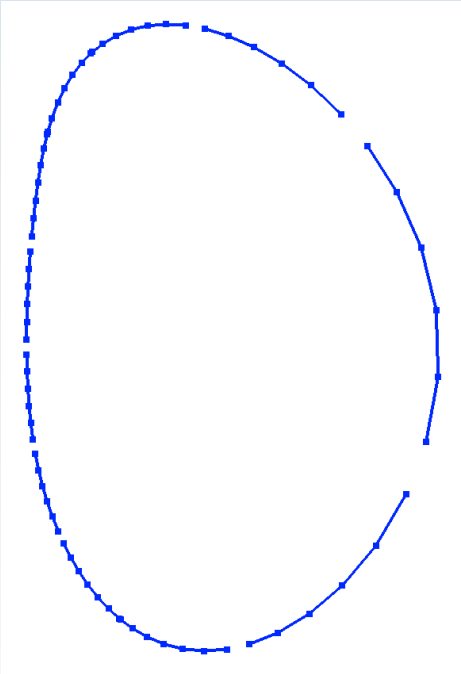
#T = 11



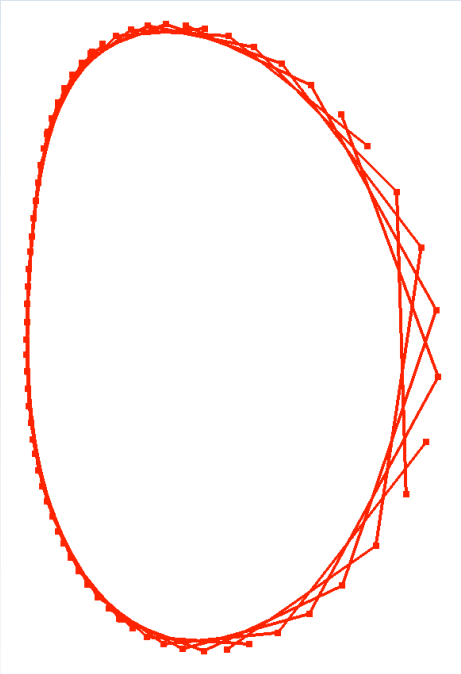
#T = 13

Minimum Spanning Trees

- Sum the distance between every Nth point



#T = 11



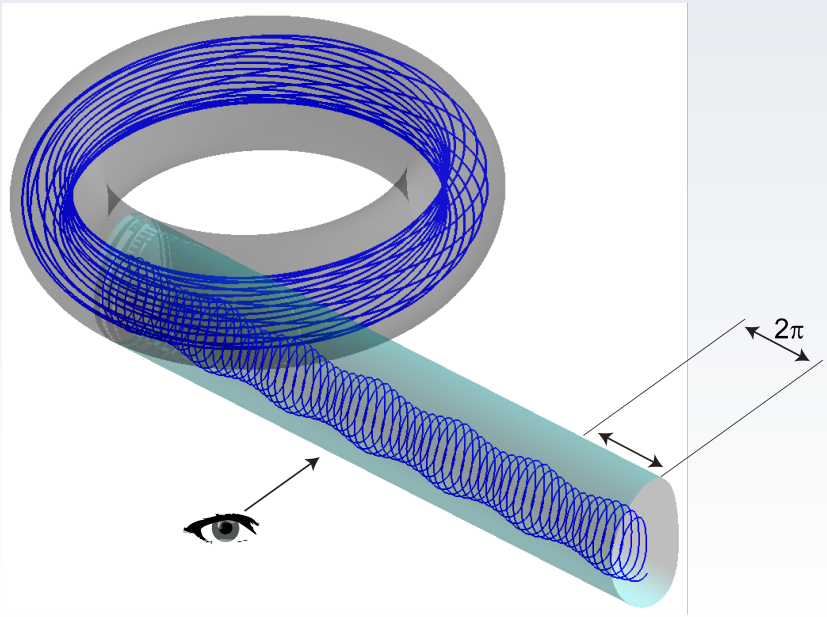
#T = 13

Toroidal Period	Distance Measure
11	2.48948
22	4.06558
35	4.13914
33	4.71994
24	7.2642
13	11.2266
31	13.9537
20	15.9752
2	16.0013

Ridgeline Analysis

- The oscillation of the ridgeline is due to an area preserving deformation of the magnetic surface.

- For an island chain the oscillation is further influenced by the rotation of the islands between each poloidal section.



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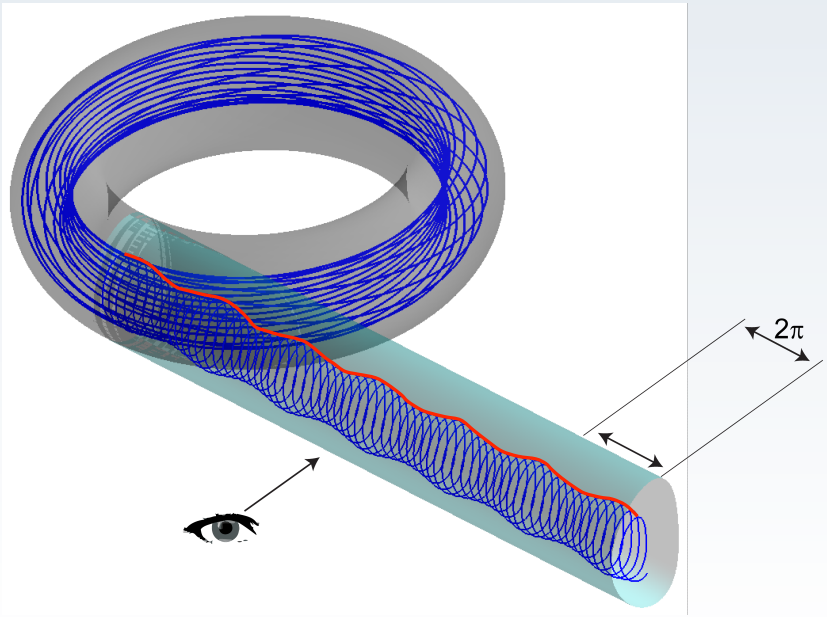

Ridgeline Analysis

- Period analysis to find the fundamental periods.
- Yin Estimator

$$\min_{f \in N}(\sigma) = \sum_{i=0} (r_i - r_{i+f})^2$$

- r is the ridge height

Poloidal Period	Period Variance
16	2.09995e-05
15	2.19973e-05
10	2.57625e-05
5	2.80012e-05
11	8.53558e-05
14	1.67688e-04
12	2.13748e-04
13	2.22252e-04
6	2.24051e-04

Combined measures

- Form *"winding pairs"* that are a rational approximation to the safety factor.

Toroidal/Poloidal Windings

Toroidal/Poloidal Winding Pair	Safety Factor
11, 5	2.20
35, 16	2.19
22, 10	2.20
24, 11	2.18
33, 15	2.20
13, 6	2.17
2, 1	2.00
9, 4	2.25

Minimum Spanning Tree

Toroidal Period	Distance Measure
11	2.48948
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Ridgeline Plot

Poloidal Period	Period Variance
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6	2.24051e-04

Combined the periods

- Ranking the winding pairs gives a best rational approximation and allows us to draw the cross section

Period Winding Pairs

Winding Pair	Euclidean Distance
35,16	2
22,10	2.23607
11,5	3
33,15	3.16228
24,11	5.65685
13,6	9.43398
9,4	15.6205
2,1	17

Minimum Spanning Tree

Toroidal Period	Distance Measure
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Ridgeline Plot

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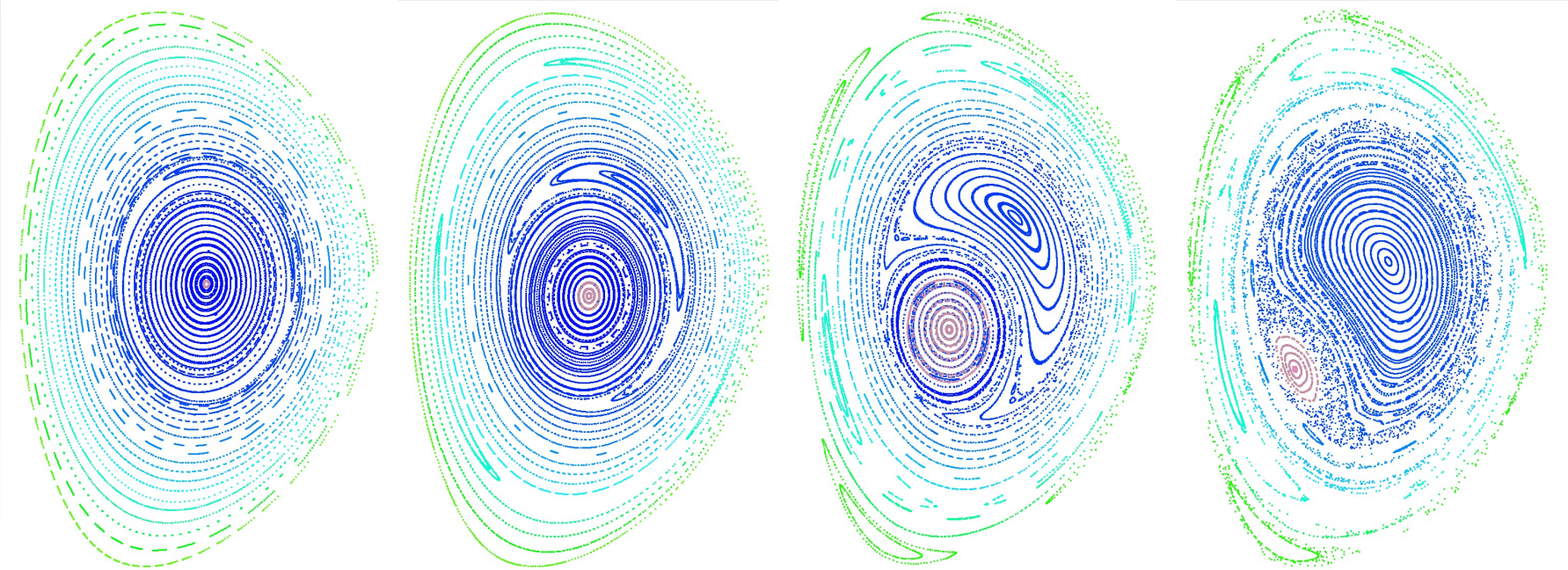
Sawtooth crash- visualization of the shift of the magnetic axis.

- M3D-C1 simulation of a sawtooth crash showing the growth of a large 1,1 magnetic island that shifts the magnetic axis from its original location in the center of the field to the island's center. During this shift the calculation of the safety factor (shown in pink) becomes ambiguous because of the dual state of magnetic axis.



Island identification via resonant period analysis

- Analysis is performed on the distance measures (minimum spanning trees) and ridgeline measures.
- If a primary resonance is present:
  - Topologically an island chain.
- If a secondary resonance is present:
  - Topologically an island chain around an island.
- Examples shown are for the distances only. But the same analysis is done on the ridgeline plots.

Resonances of an island chain

- Ranked distance measures for a 3, 1 surface:

period	12	distance	3.41531	period	47	distance	59.6037	period	19	distance	86.9769
period	24	distance	5.76941	period	46	distance	60.1588	period	22	distance	88.284
period	36	distance	6.98177	period	43	distance	60.7246	period	23	distance	88.3346
period	48	distance	7.24089	period	44	distance	61.5344	period	20	distance	88.5419
period	39	distance	15.818	period	41	distance	65.8694	period	17	distance	92.3583
period	27	distance	21.06	period	40	distance	66.7349	period	16	distance	92.3816
period	45	distance	21.251	period	38	distance	71.2354	period	14	distance	99.5046
period	33	distance	25.7002	period	37	distance	73.2272	period	7	distance	100.475
period	15	distance	26.5901	period	31	distance	73.6984	period	13	distance	100.638
period	42	distance	26.9074	period	35	distance	73.8232	period	8	distance	102.371
period	21	distance	28.9197	period	34	distance	74.2003	period	10	distance	102.427
period	9	distance	31.6031	period	32	distance	74.8913	period	11	distance	102.869
period	3	distance	31.7965	period	29	distance	79.1712	period	4	distance	105.441
period	30	distance	33.4714	period	28	distance	79.495	period	5	distance	105.532
period	18	distance	39.4377	period	26	distance	85.4789	period	2	distance	113.363
period	6	distance	44.9135	period	25	distance	86.9371	period	1	distance	114.325

No resonance for a flux surface

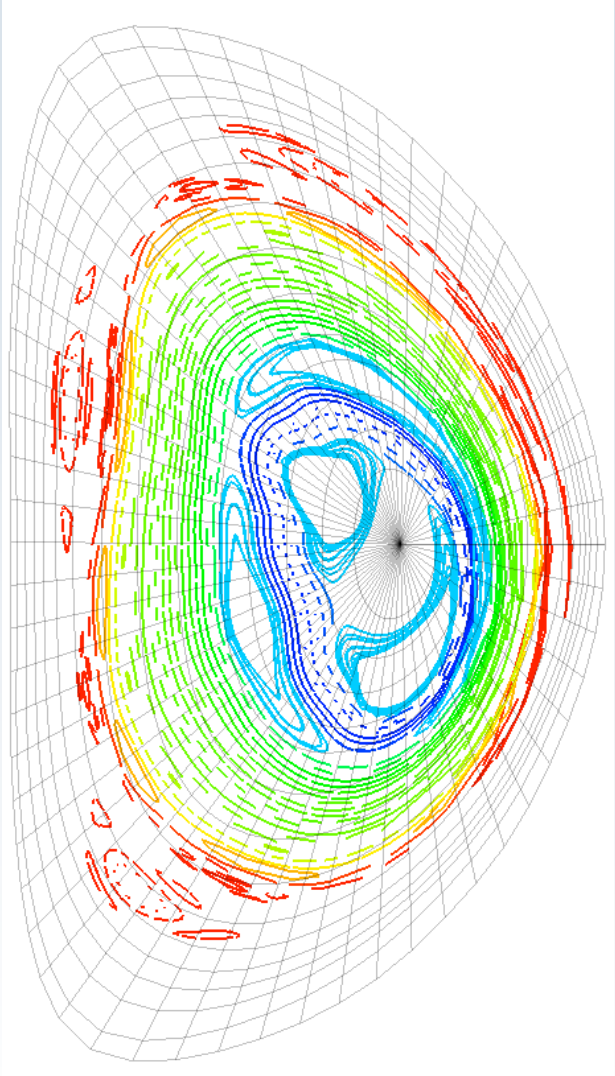
- The “best” winding pair gives a test resonance, #*T* and #*P* (31,14)
  - Divide the distance values into 31 groups.
  - GCD in the first group is 1
  - Not a resonance

Toroidal Period	Variance (Normalized)
31,14	98.5507
20,9	97.5
40,18	96.6667
11,5	95.5056
9,4	94.5055

period 31 distance 3.36685
period 20 distance 5.53997
period 40 distance 8.1705
period 42 distance 9.50776
period 11 distance 10.5374
period 49 distance 15.943
period 9 distance 16.9851
period 29 distance 17.862
period 22 distance 18.1704
period 33 distance 22.8725
period 44 distance 24.7281
period 38 distance 26.1876
period 2 distance 29.4314
period 18 distance 29.8071
period 47 distance 30.4791
period 13 distance 35.3297
period 46 distance 36.2263
period 27 distance 38.2784
period 24 distance 38.281
period 35 distance 38.5035
period 36 distance 42.397
period 45 distance 42.5566
period 48 distance 43.5138
period 7 distance 43.6269
period 37 distance 49.396
period 43 distance 51.0771
period 16 distance 51.7761
period 26 distance 53.2747
period 4 distance 53.8789
period 15 distance 54.872
period 34 distance 54.9104
period 39 distance 55.0839
period 25 distance 55.3703
period 41 distance 55.4419
period 28 distance 62.5092
period 32 distance 62.8183
period 30 distance 65.5705
period 5 distance 66.2904
period 23 distance 67.612
period 17 distance 68.1686
period 14 distance 69.0003
period 6 distance 71.7156
period 21 distance 74.2159
period 19 distance 74.6213
period 12 distance 80.2541
period 8 distance 82.1708
period 3 distance 82.9138
period 10 distance 84.8558

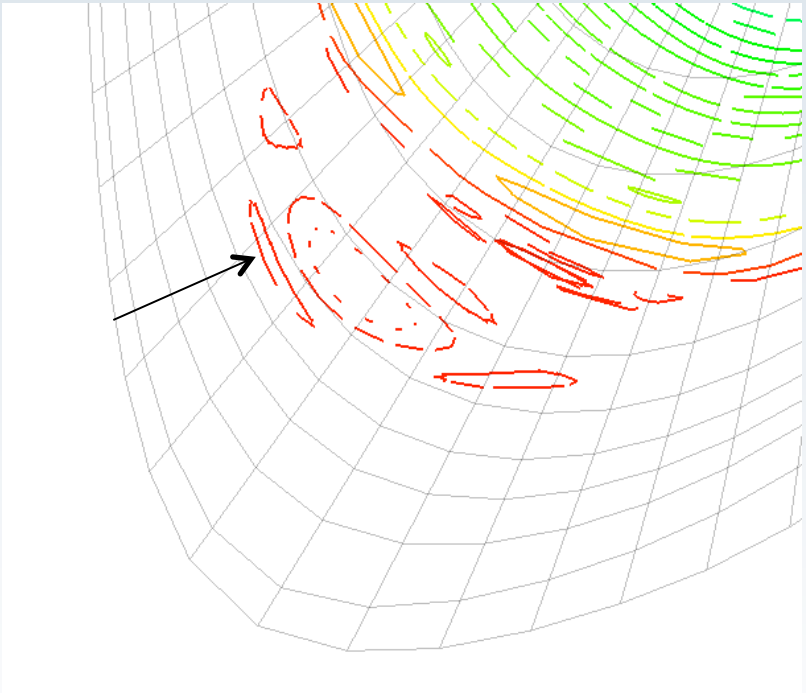
Resonance of an island chain

- Application:



Resonance of an island chain

- Significance of the integer multiple:
  - Number of secondary islands



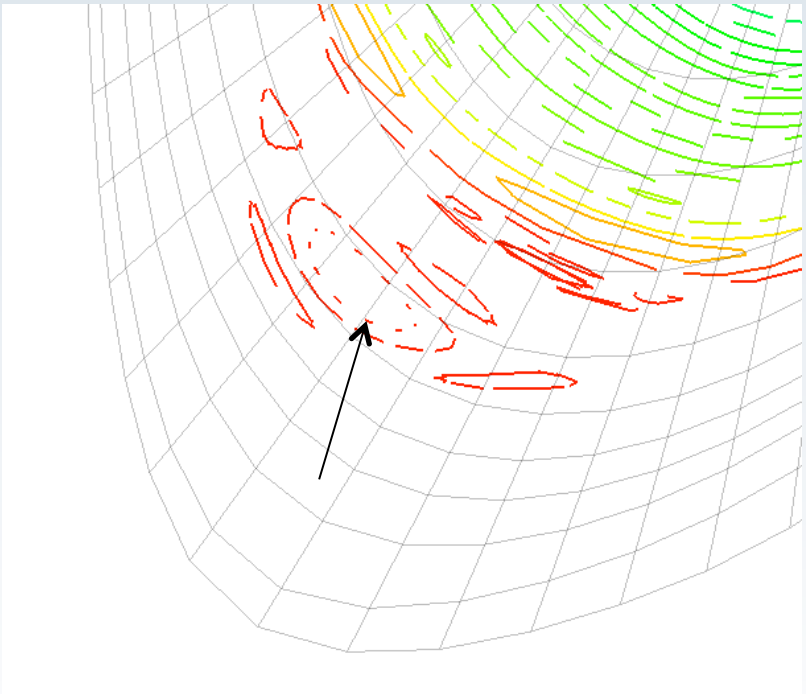
3,1 Island Chain

period	12	distance	3.41531
period	24	distance	5.76941
period	36	distance	6.98177
period	48	distance	7.24089
period	39	distance	15.818
period	27	distance	21.06
period	45	distance	21.251
period	33	distance	25.7002

GCD = 12
12/3 = 4
3 groups with 4 islands
in each group

Resonance of an island chain

- Significance of the integer multiple:
  - Number of secondary islands



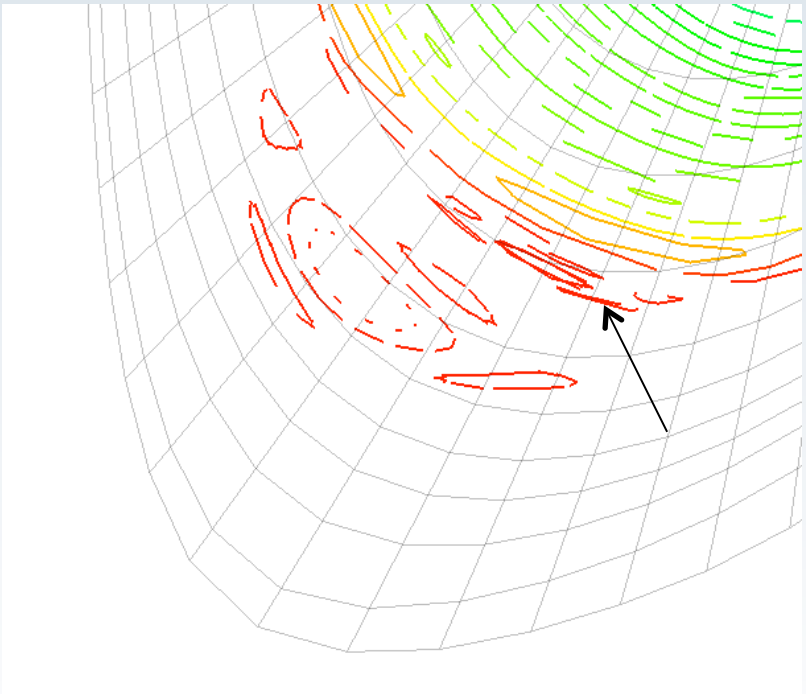
3,1 Island Chain

period 33 distance 0.420497
period 66 distance 0.743953
period 99 distance 0.972337
period 132 distance 1.11467
period 165 distance 1.17684
period 153 distance 8.45086
period 120 distance 10.1513
period 144 distance 11.076
period 87 distance 11.9256
period 111 distance 12.5772

GCD = 33
33/3 = 11
3 groups with 11 islands
in each group

Resonance of an island chain

- Significance of the integer multiple:
  - Number of secondary islands



5,2 Island Chain

period 25 distance 4.38164
period 75 distance 4.99118
period 50 distance 6.18796
period 70 distance 10.7297
period 55 distance 12.6121
period 45 distance 14.4465
period 30 distance 16.4711
period 20 distance 17.8002
period 65 distance 18.4483
period 60 distance 19.7733
period 5 distance 20.2321
period 40 distance 24.2429
period 35 distance 25.9114
period 15 distance 30.2585
period 10 distance 32.1881

GCD = 25
25/5= 5
5 groups with 5 islands in each groups

More details

- *Analysis of Recurrent Patterns in Toroidal Magnetic Fields*, IEEE, Transactions on Visualization and Computer Graphics, Vol 16, No. 6 Nov/Dec 2010

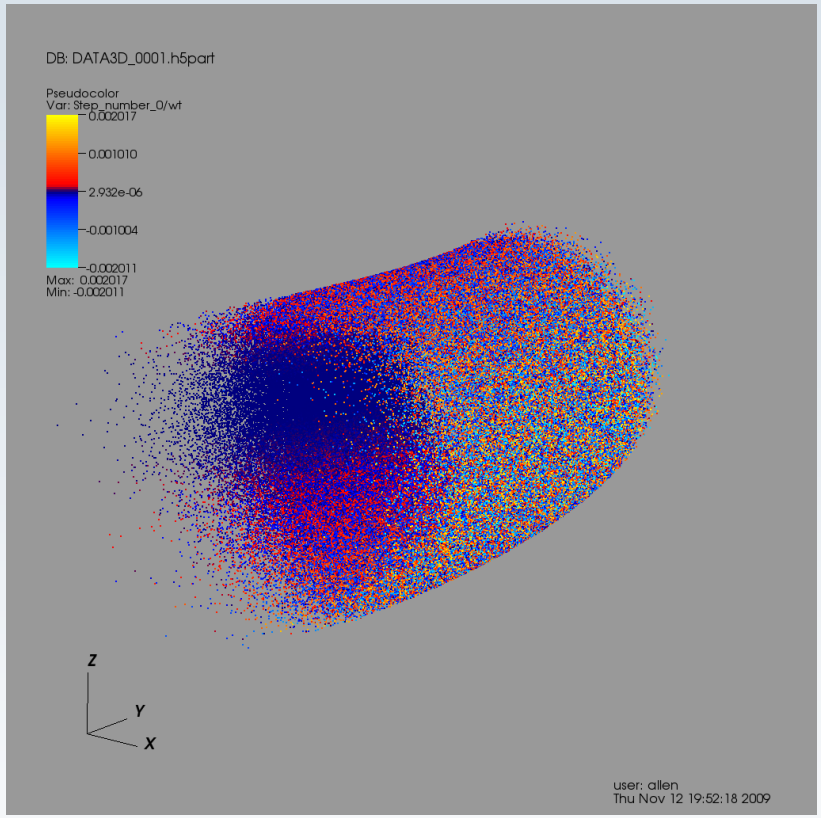
- *Understanding quasi-periodic fieldlines and their topology in toroidal magnetic fields*. Topological Methods in Data Analysis and Visualization II – Theory, Algorithms, and Applications, 2011.

Turbulence in Magnetic Fields

- Goal:

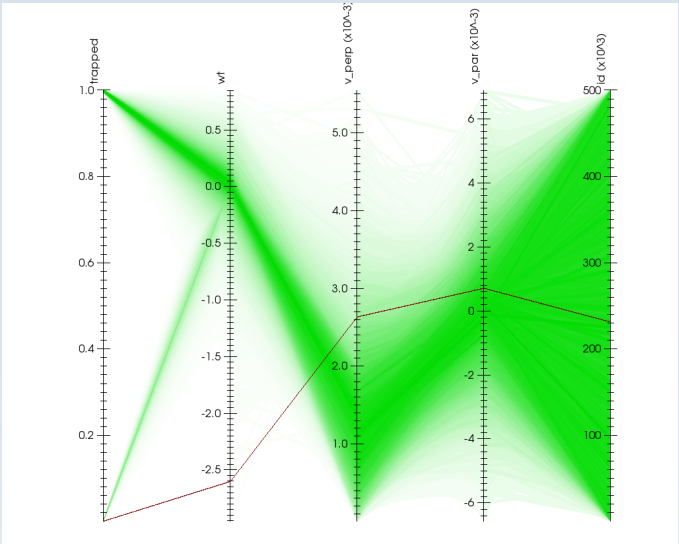
  Visualizing large number of particles while interesting from a graphics point of view yields little domain knowledge.

  More important is finding *"interesting"* particles and understanding the mechanism for their radial diffusion.

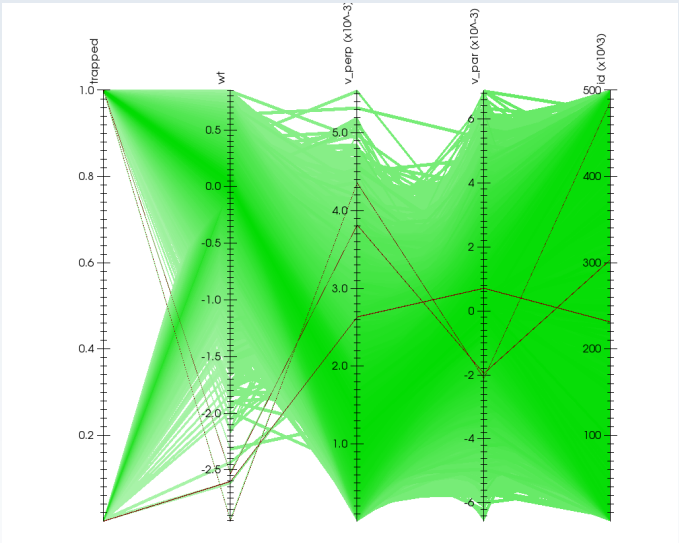


Range based queries in multidimensional space.

- Parallel Coordinates
- A parallel coordinate plot highlighting a single multivariate value (brown). In green are all of the particle multivariate values using opacity mapping.



- A parallel coordinate plot highlighting three multivariate values (brown). In green are all of the particle multivariate values without the opacity mapping

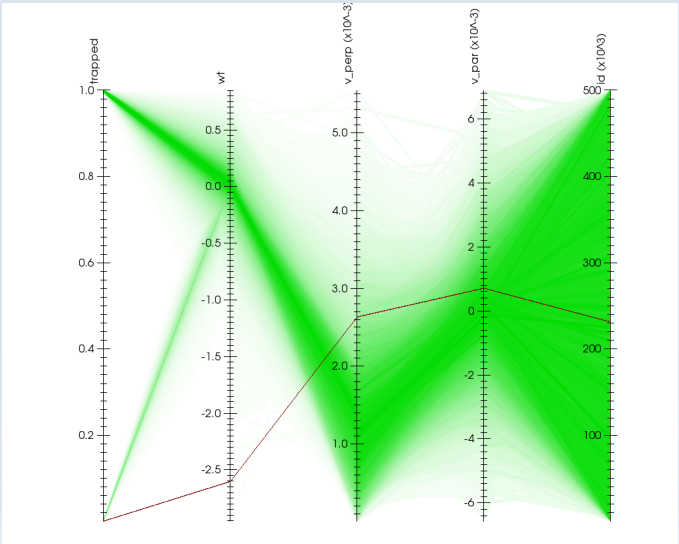


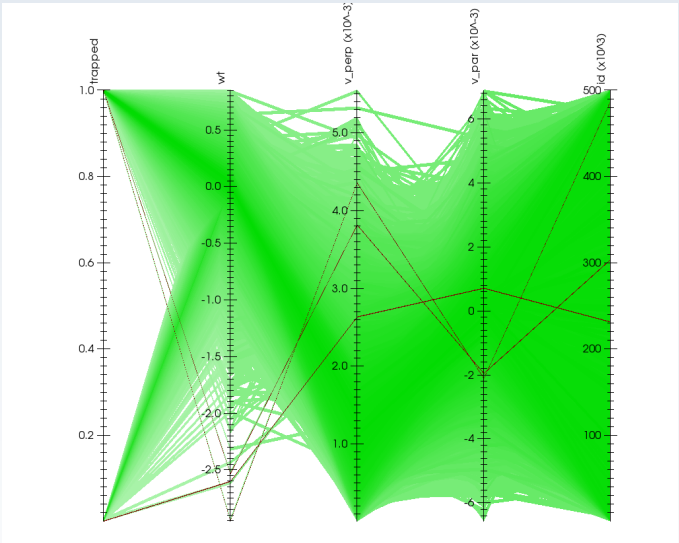
Range based queries in multidimensional space.

- Each of the particles have similar signatures with the exception of their passing/trapped state.

- The question for the scientist is: does this difference in state have any relevant meaning (i.e is there any correlation)?

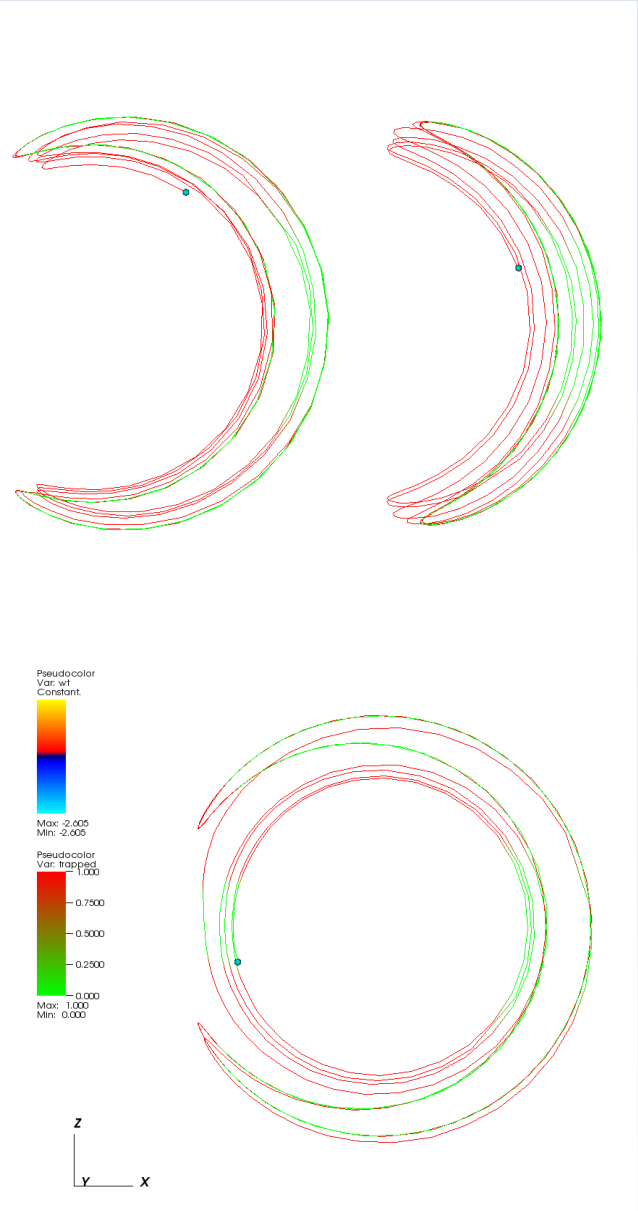
- In this case it does not seem to be, and as such the particles have a similar signature.





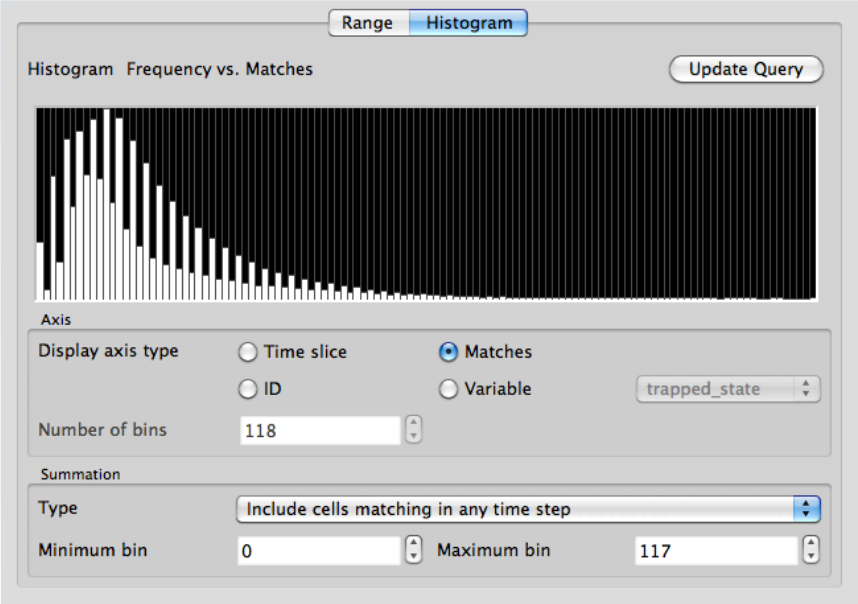
Range based queries in multidimensional space.

- The radial (R-Z) paths for the three particles selected previously.
- For two of the particles, though they have a large radial excursion, their paths follow a similar trajectory in that they have the characteristic ``banana-shaped'' orbit of magnetically-trapped particles.
- However one particle has been caught in the microturbulence eddies and in addition to having a large radial excursion it was pushed through multiple trapped and passing orbits as demonstrated by the path it followed during the simulation



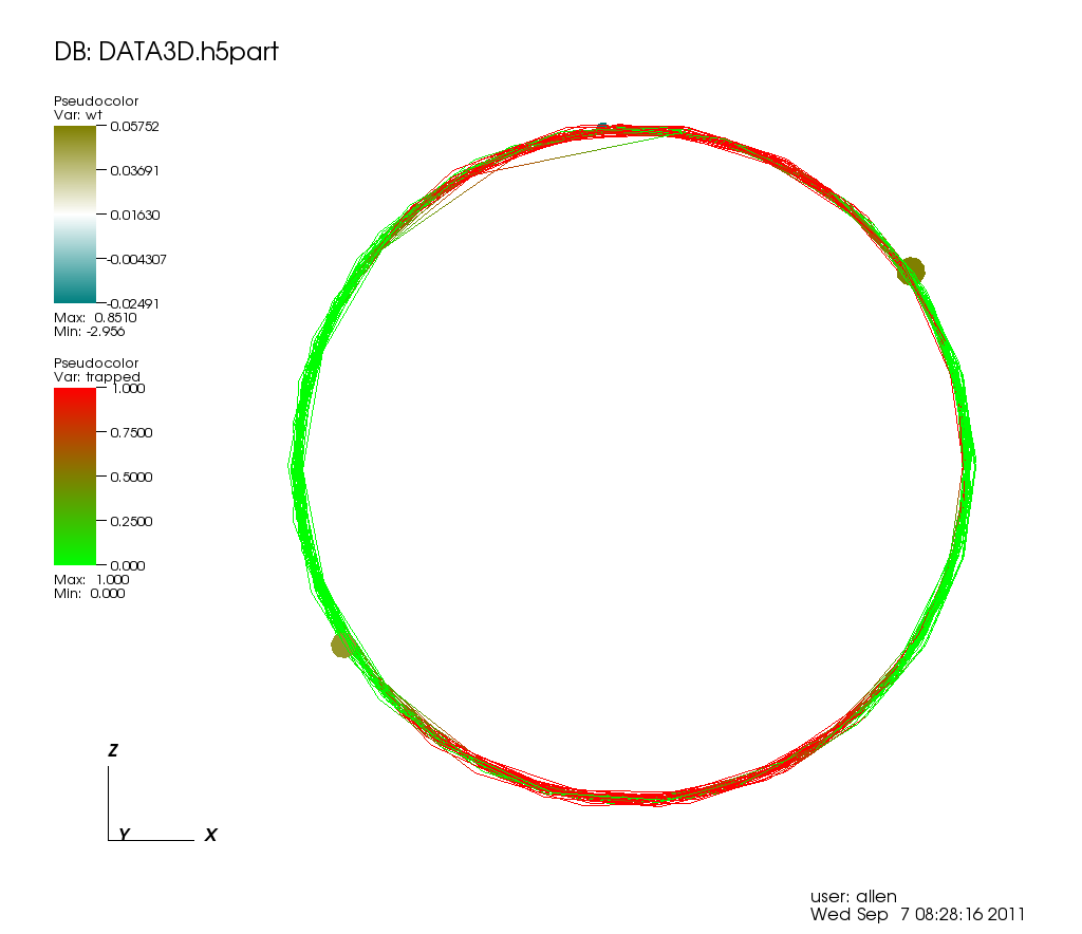
Range based queries in multidimensional space.

- Queries can be cumulative – look for *"state changes"* between multiple time slices or an "event" over all time slices.
- Trapped / untrapped state changes.
- Particles that hit the wall.



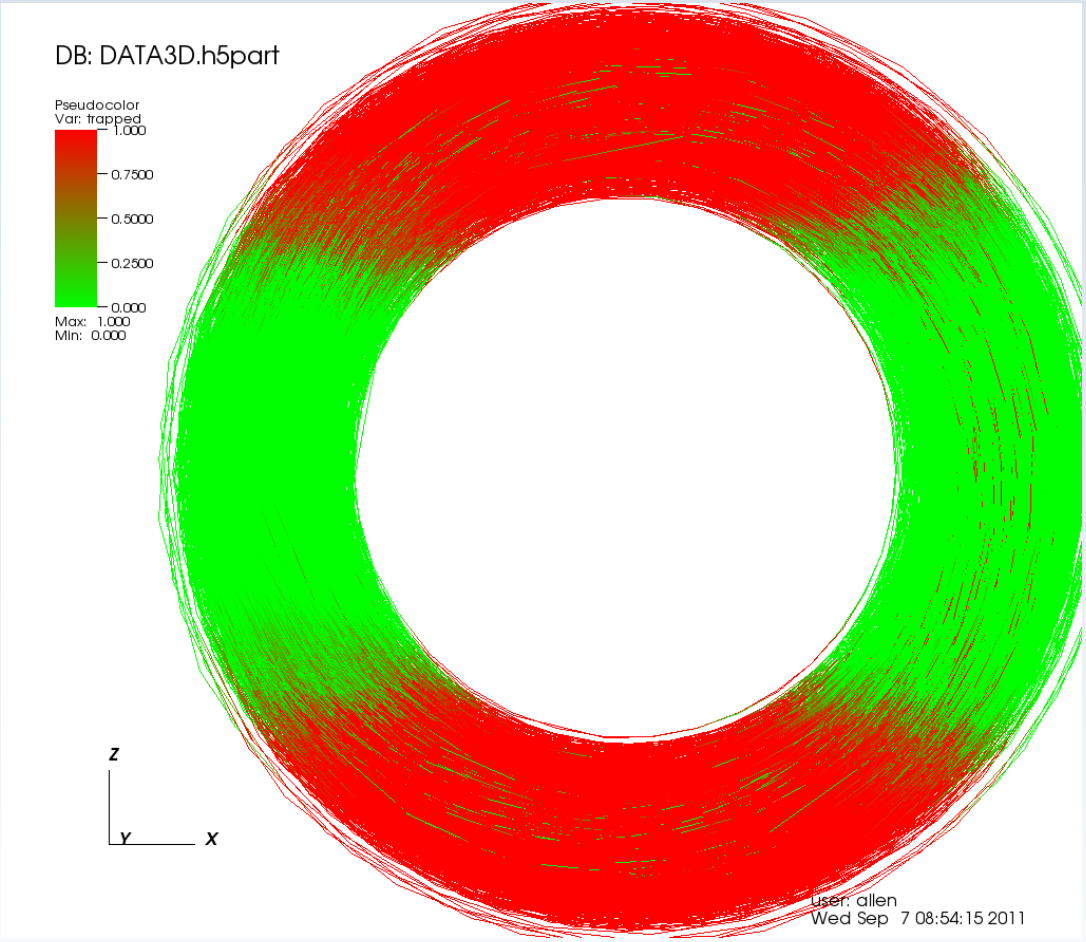
Cumulative range based queries.

- Three particles that changed from trapped to untrapped most frequently (111, 112, and 117 times out of 746 time steps) yet did not experience a large radial excursion.



Cumulative range based queries.

- 949 particles that changed from trapped to untrapped for 10% of the simulation.



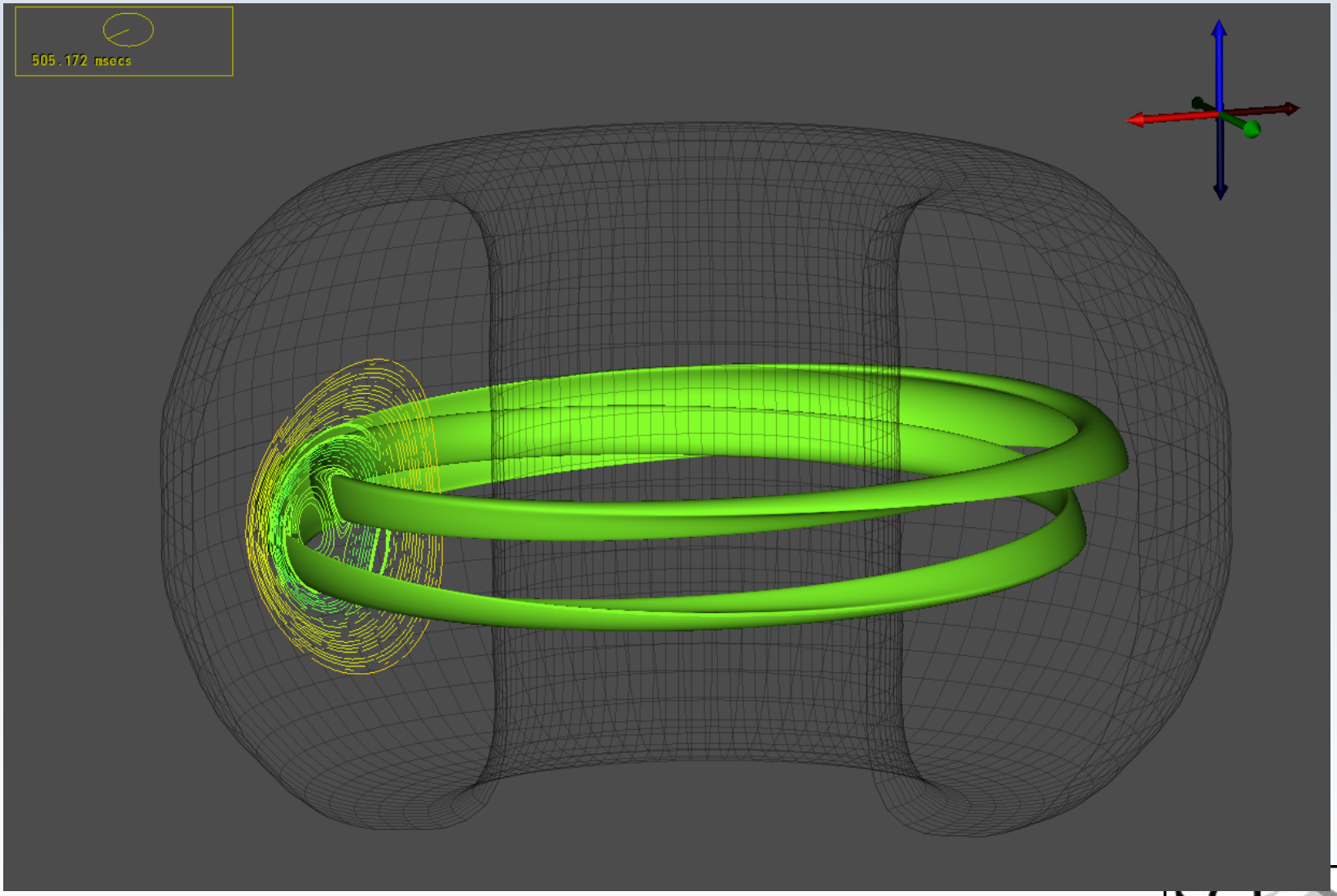
More details

- *High performance multivariate visual data exploration for extemely large data*. In SuperComputing 2008 (SC08), 2008.10
- *Fastbit: Interactively searching massive data*. In SciDAC 2009.
- Alfred Inselberg. Parallel Coordinates. Springer-Verlag, 2009.

Tools are deployed in the VisIt Toolkit

- VisIt Toolkit - https://wci.llnl.gov/codes/visit
- Poincaré Plot available since version 2.0
- Query based selections available in 2.3
- Cumulative queries to be release in 2.4 (later this fall).

- Complete map
- Scott Kruger, Tech-X, NIMROD



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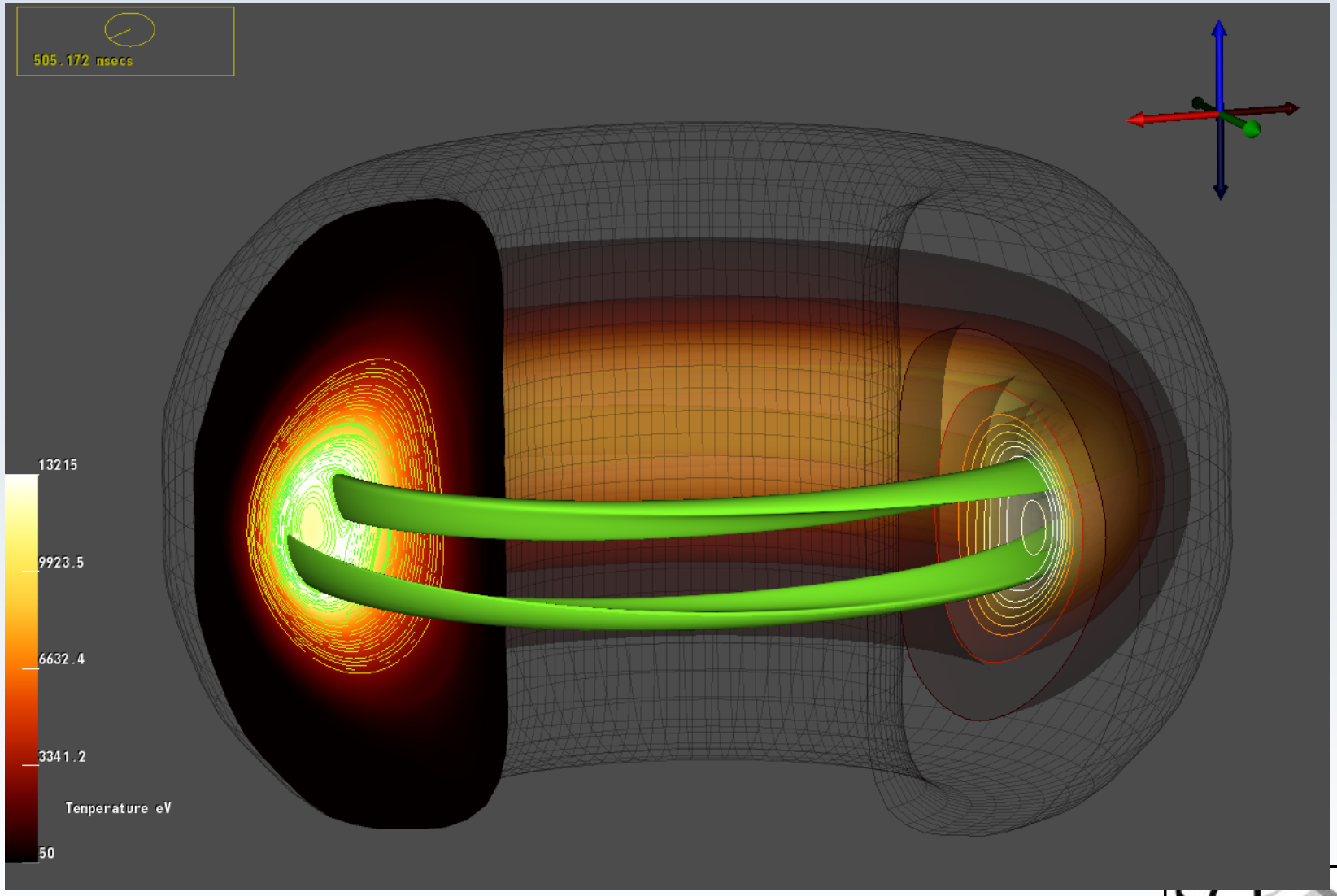

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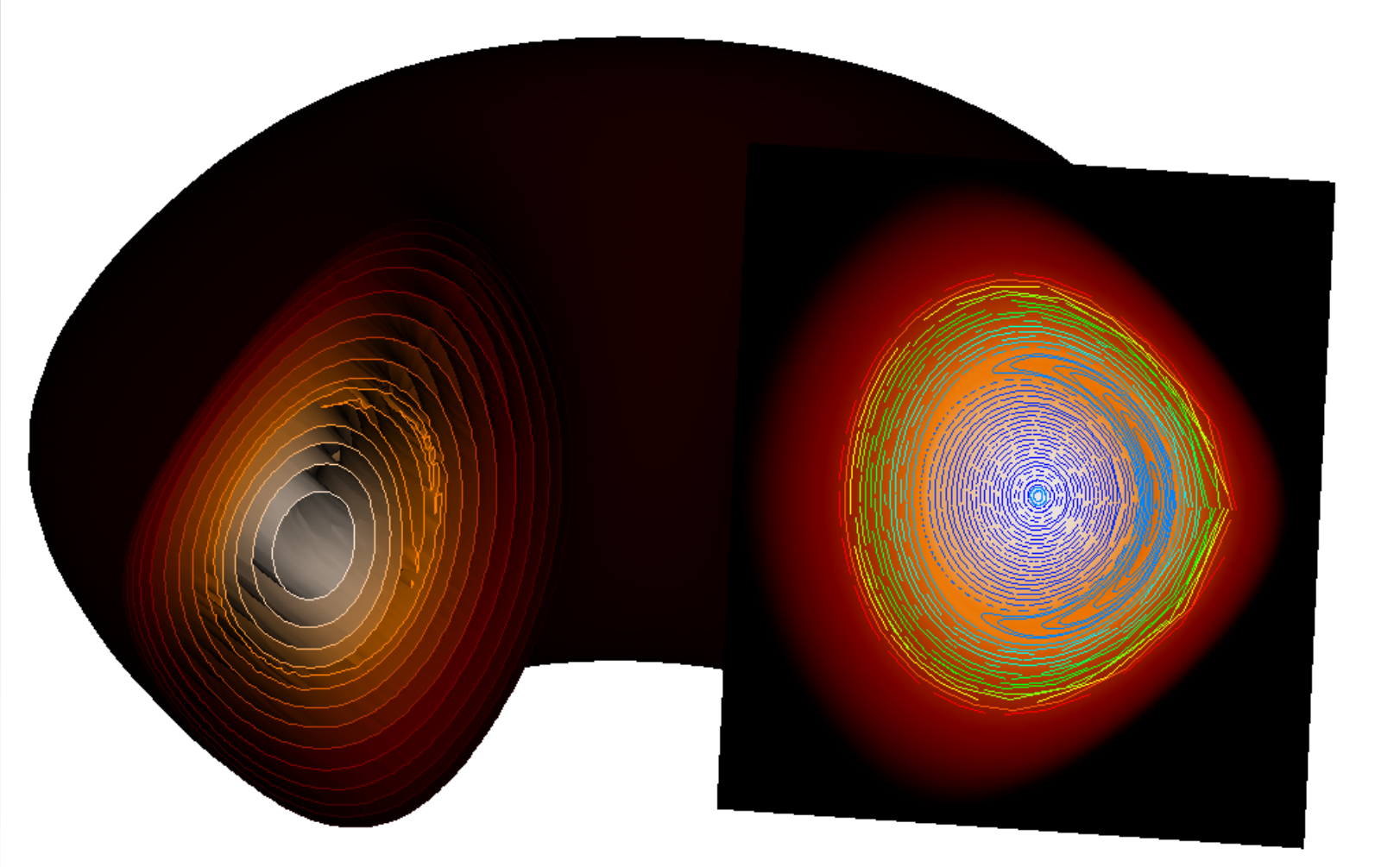

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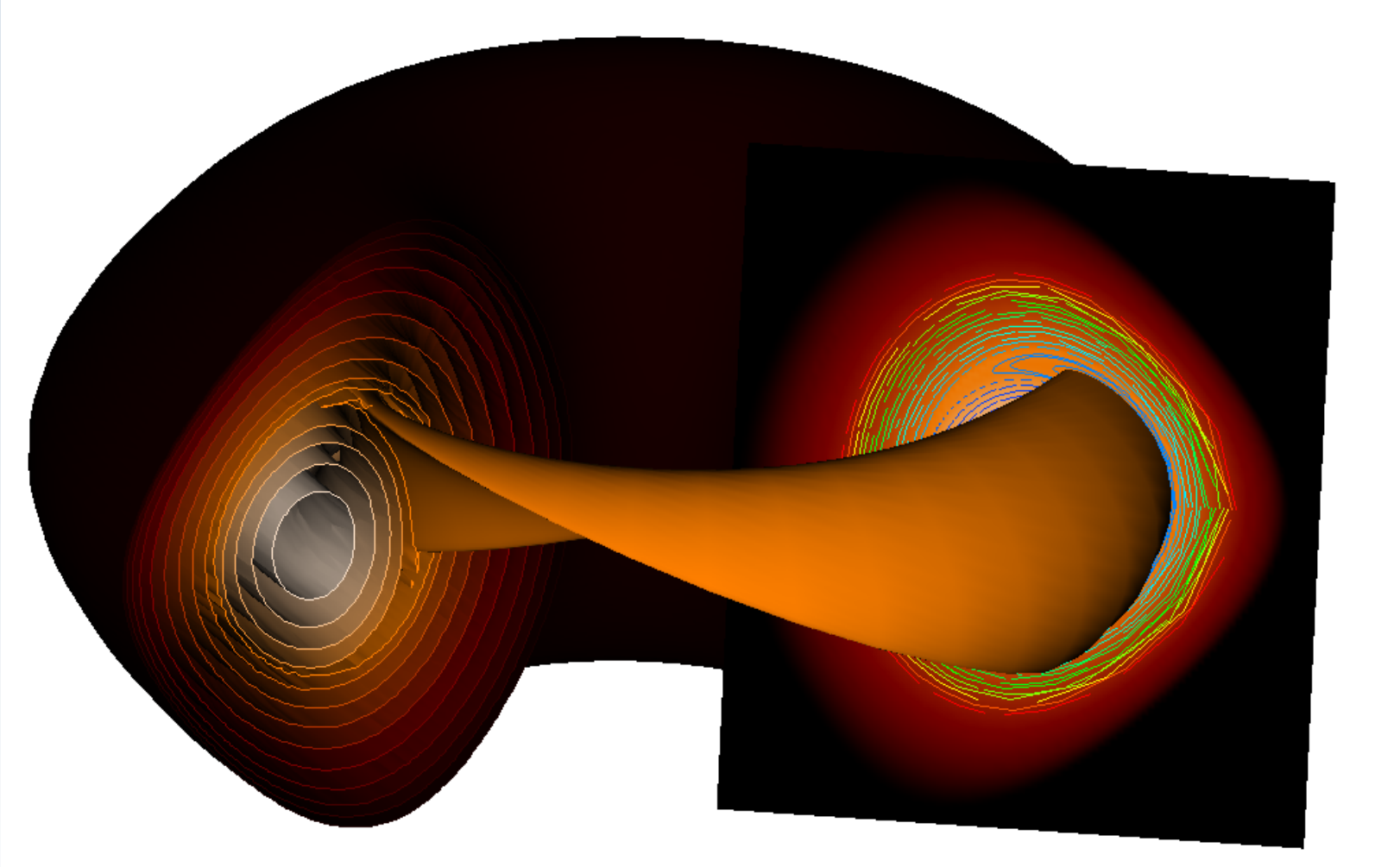
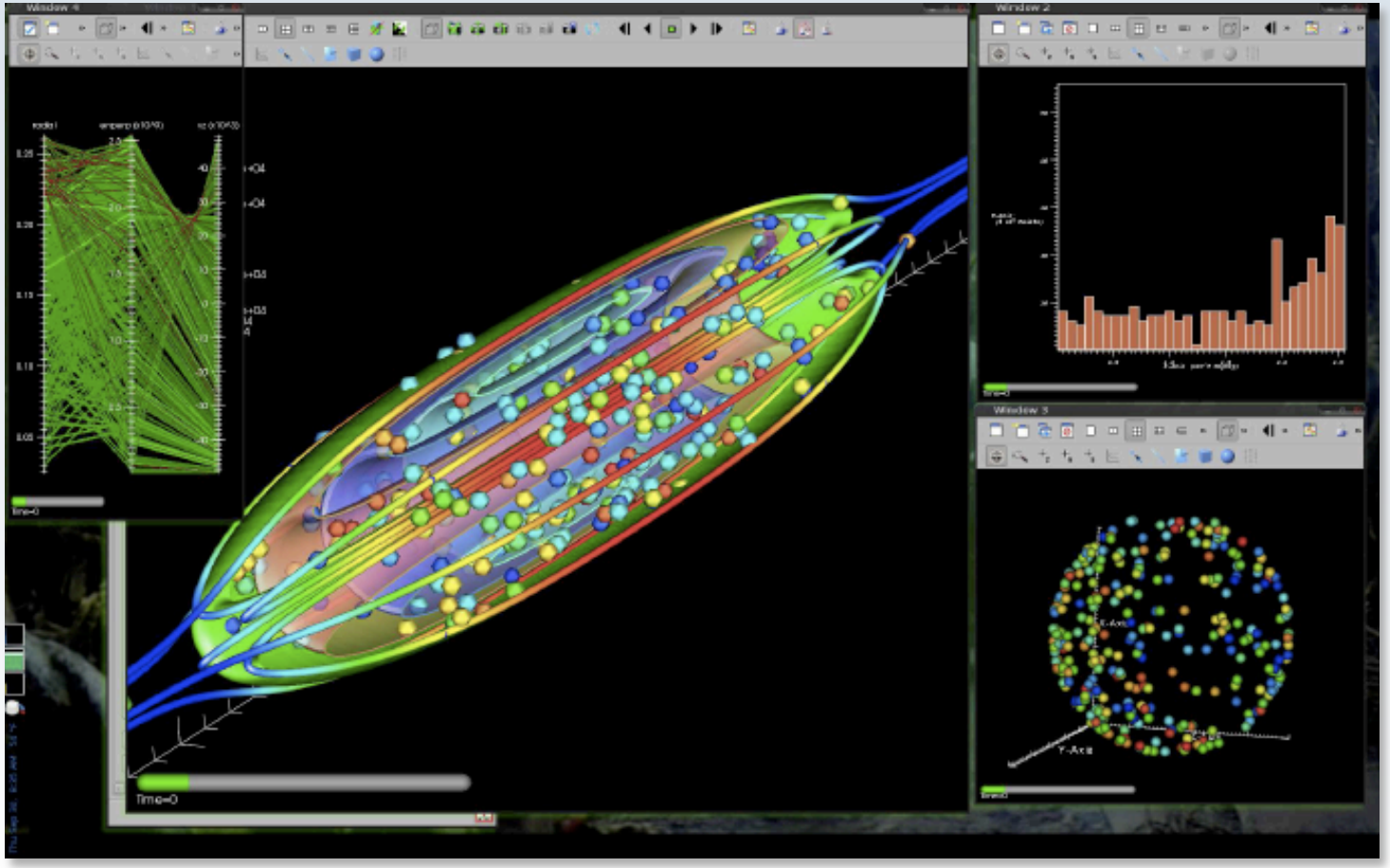


Hybird Kinetic MHD in NIMORD

- Charlson Kim, PSI Center, Univ. Washington.



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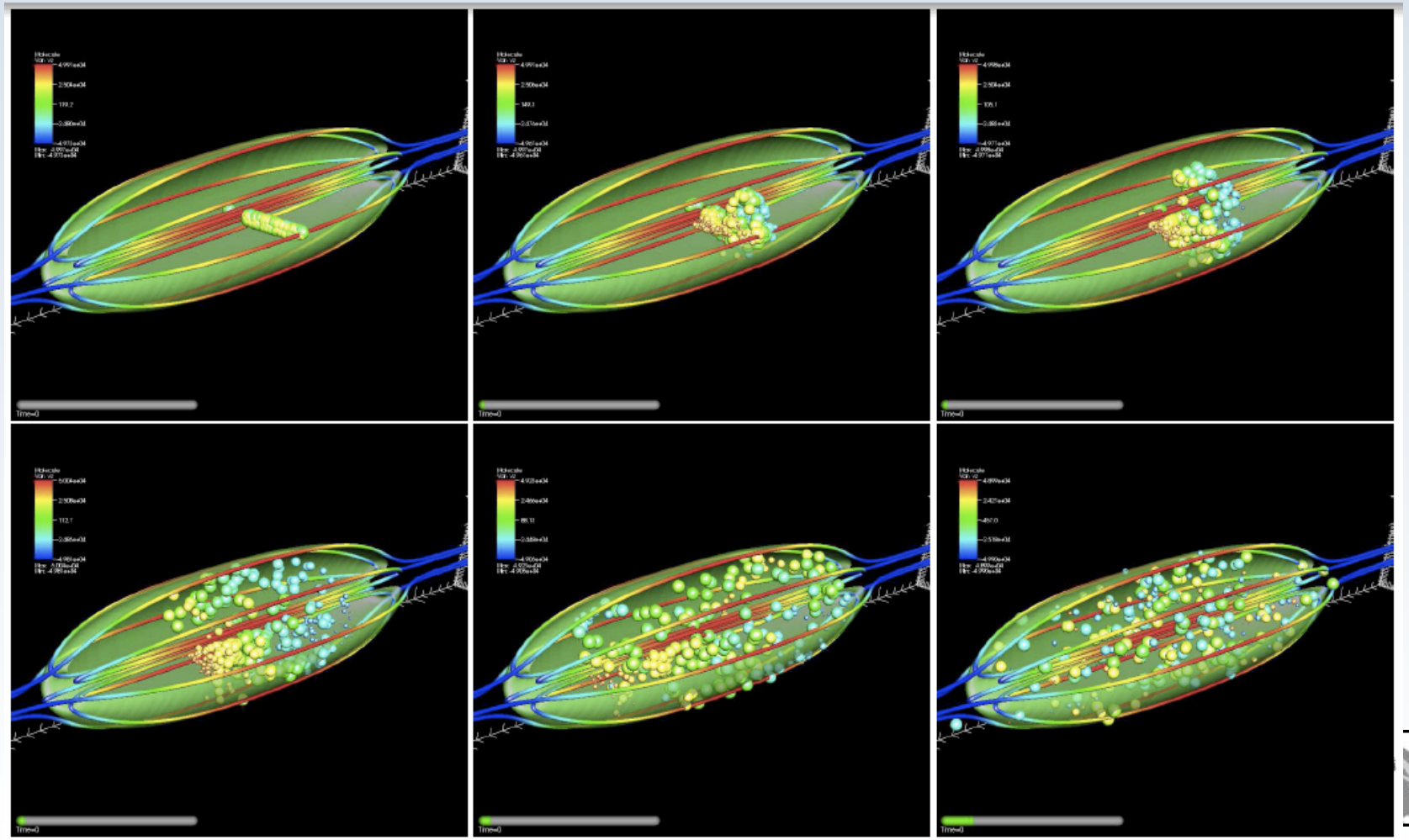

Acknowledgements

- VisIt Development

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- Fast-Bit

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- Physicists

  Scott Kruger, Josh Breslau, Nathan Ferraro, Steve Jardin, Stephane Ethier, Seung-Ho Ku, Raul Sanchez

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