Feature Tracking Using Reeb Graphs

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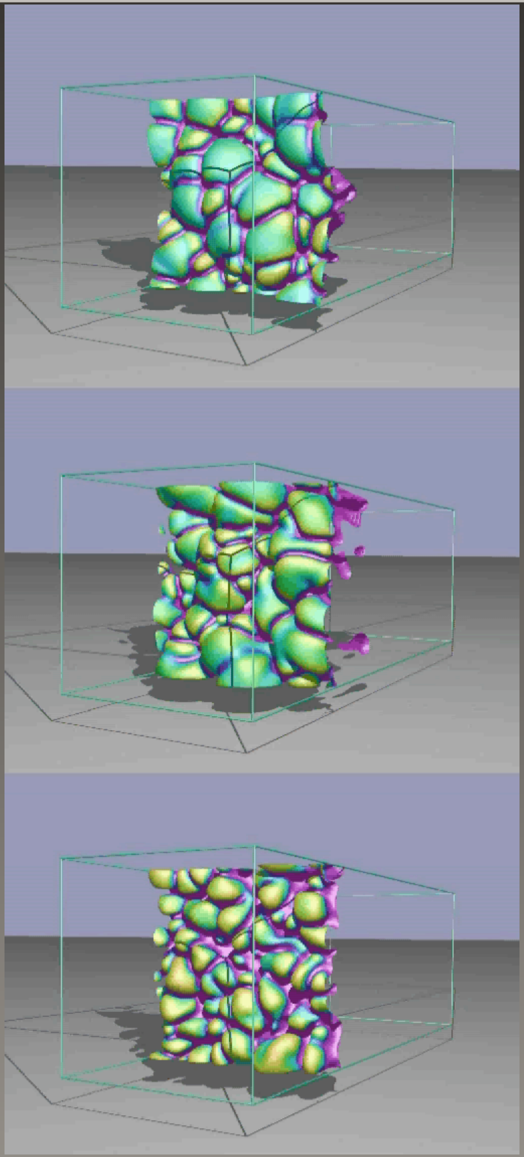
Feature Tracking in Combustion Simulations



- **Application:**
  - Simulation of premixed lean hydrogen flames under different levels of turbulence
  - Lean combustion reduces emissions
  - ➔ Important for engine and power plant design (among other areas)
  - Lean flames burn in cellular mode (non-uniform, time-dependent, difficult to characterize)
- **Scientific Goal:**
  - Understanding the temporal evolution of burning cells
  - Influence of turbulence

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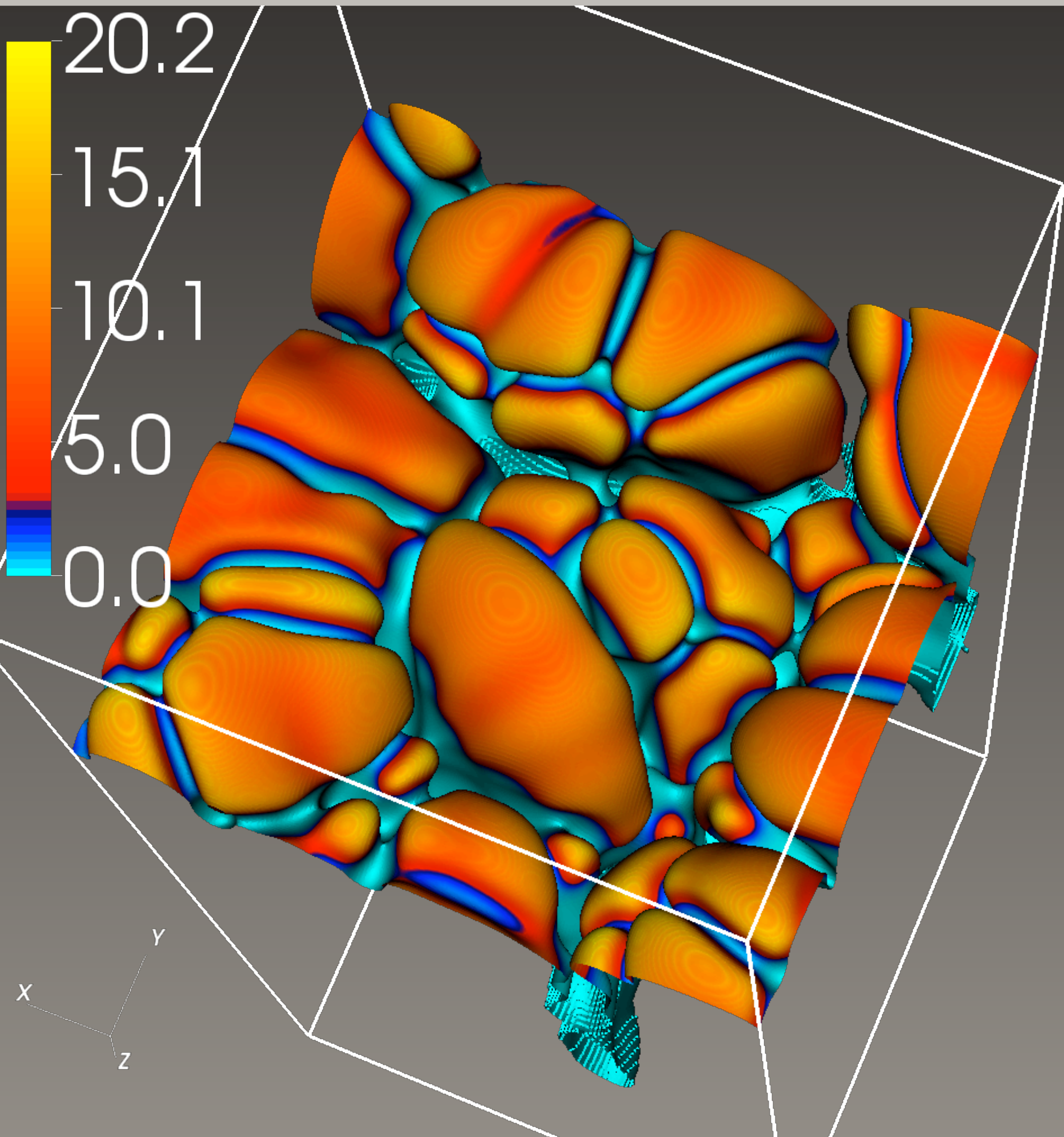
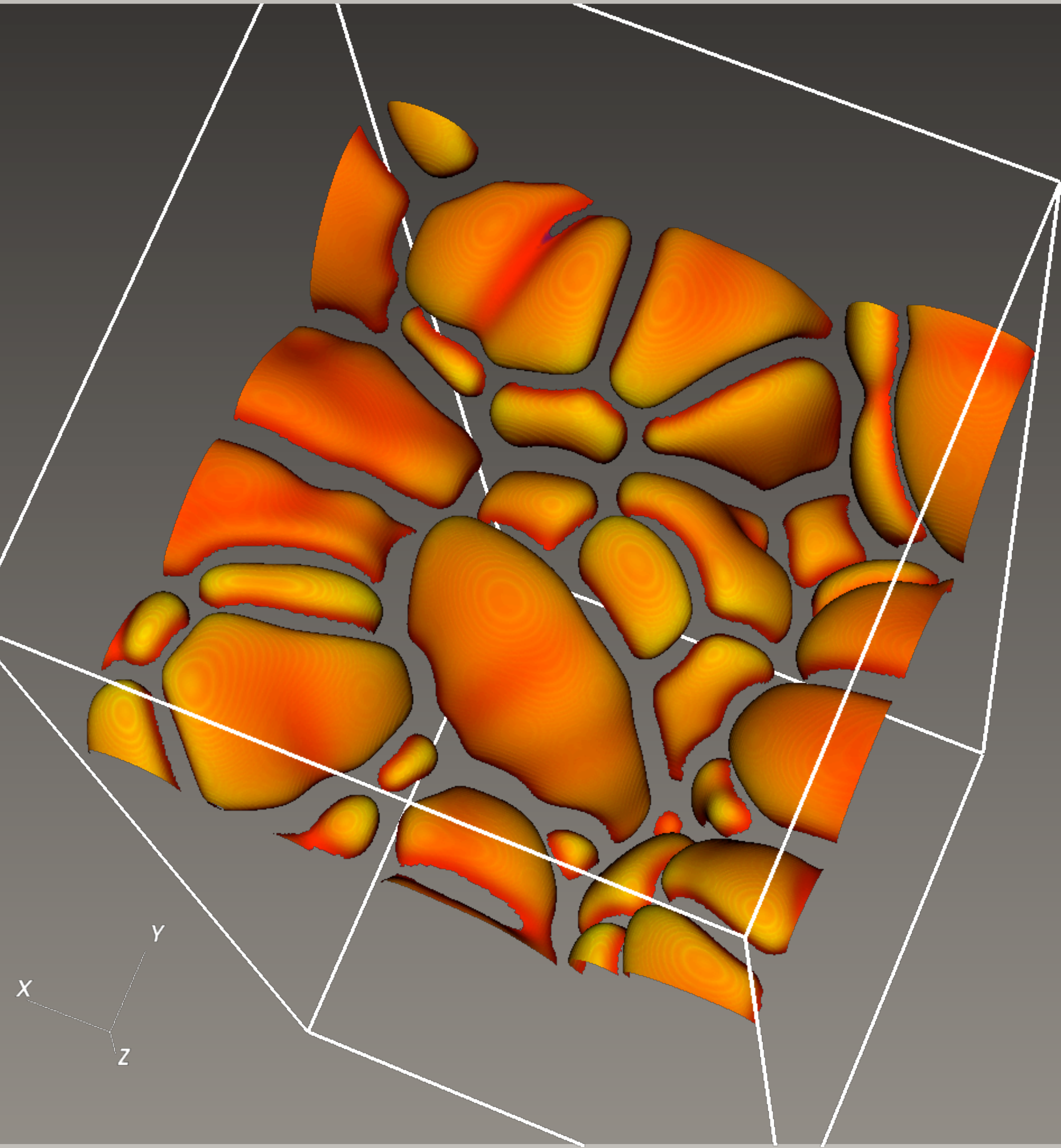


- Isotherm represents "flame surface"
- Fuel not evenly consumed: Burning cells separated by extinction regions

- **Interested in evolution of burning cells**

Individual Burning Regions



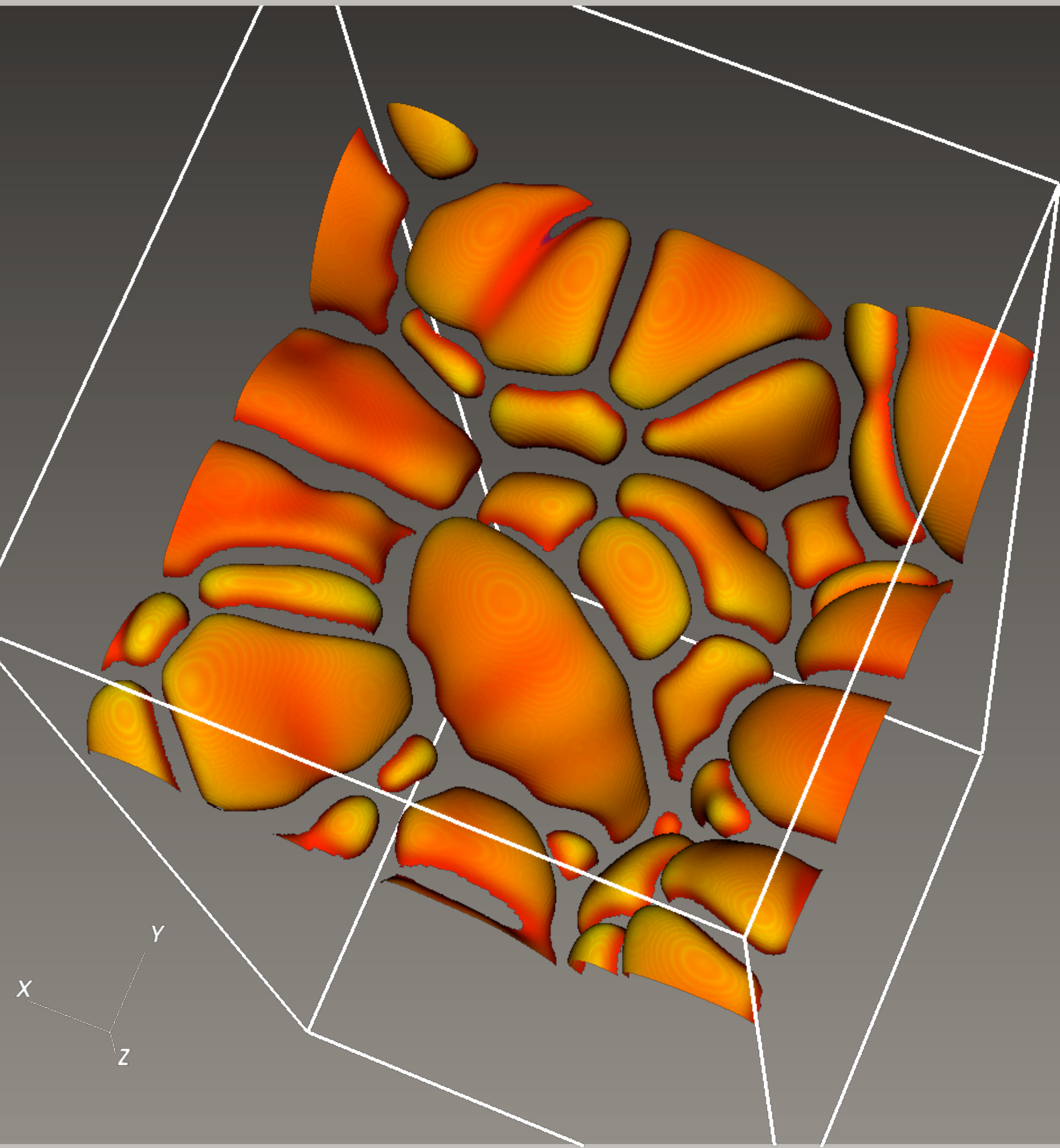
- Threshold isotherm by fuel consumption rate

➔ Burning regions (connected components)

- When do regions emerge, die, split, or merge?

➔ Tracking graph

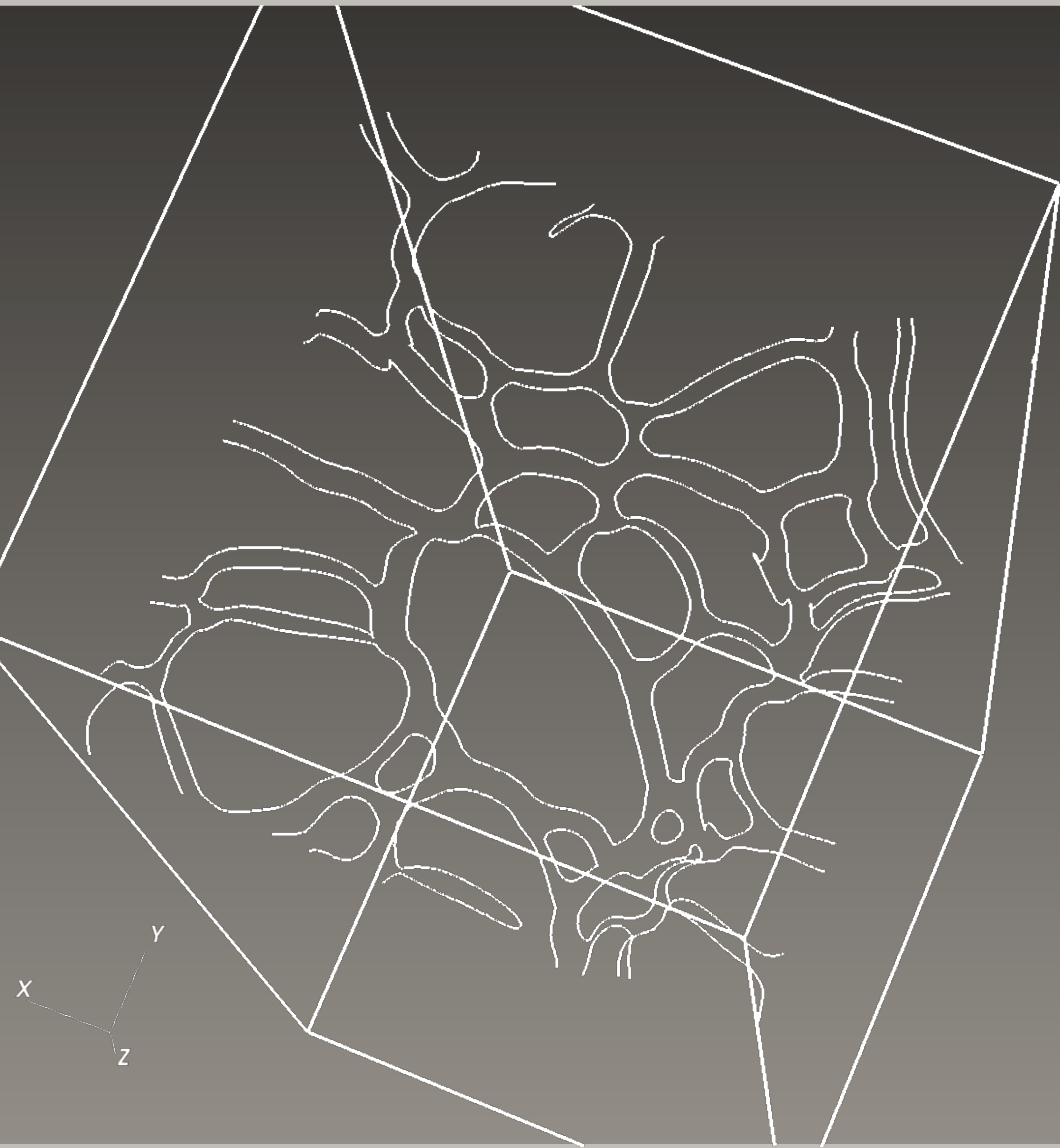
Individual Burning Regions



- Burning cells defined on isotherm
- Isotherm varies over time

➔ Tracking features defined over changing domain

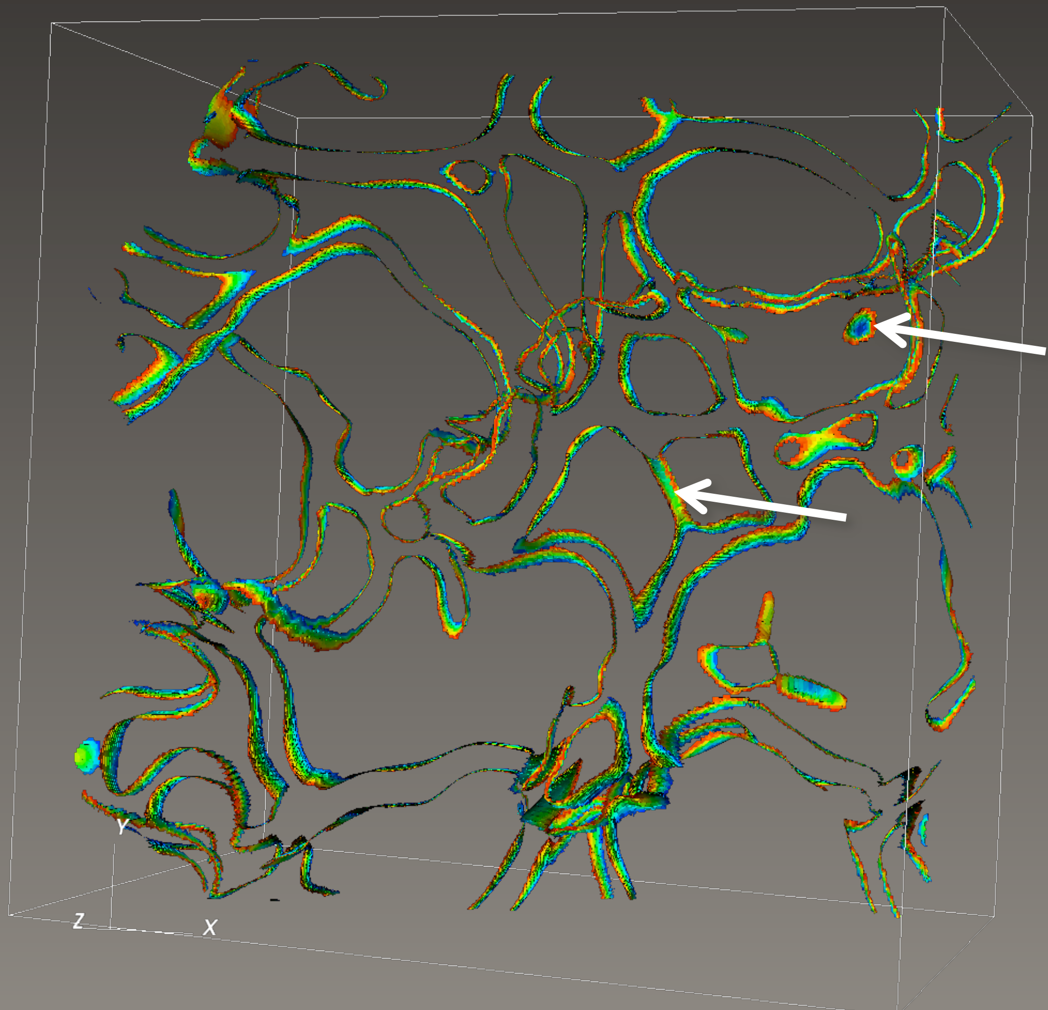
Burning Region Boundaries



- Track burning cells by considering their boundaries
- Obtained by two successive contouring operations

➔ Trace evolution of burning regions by considering contours

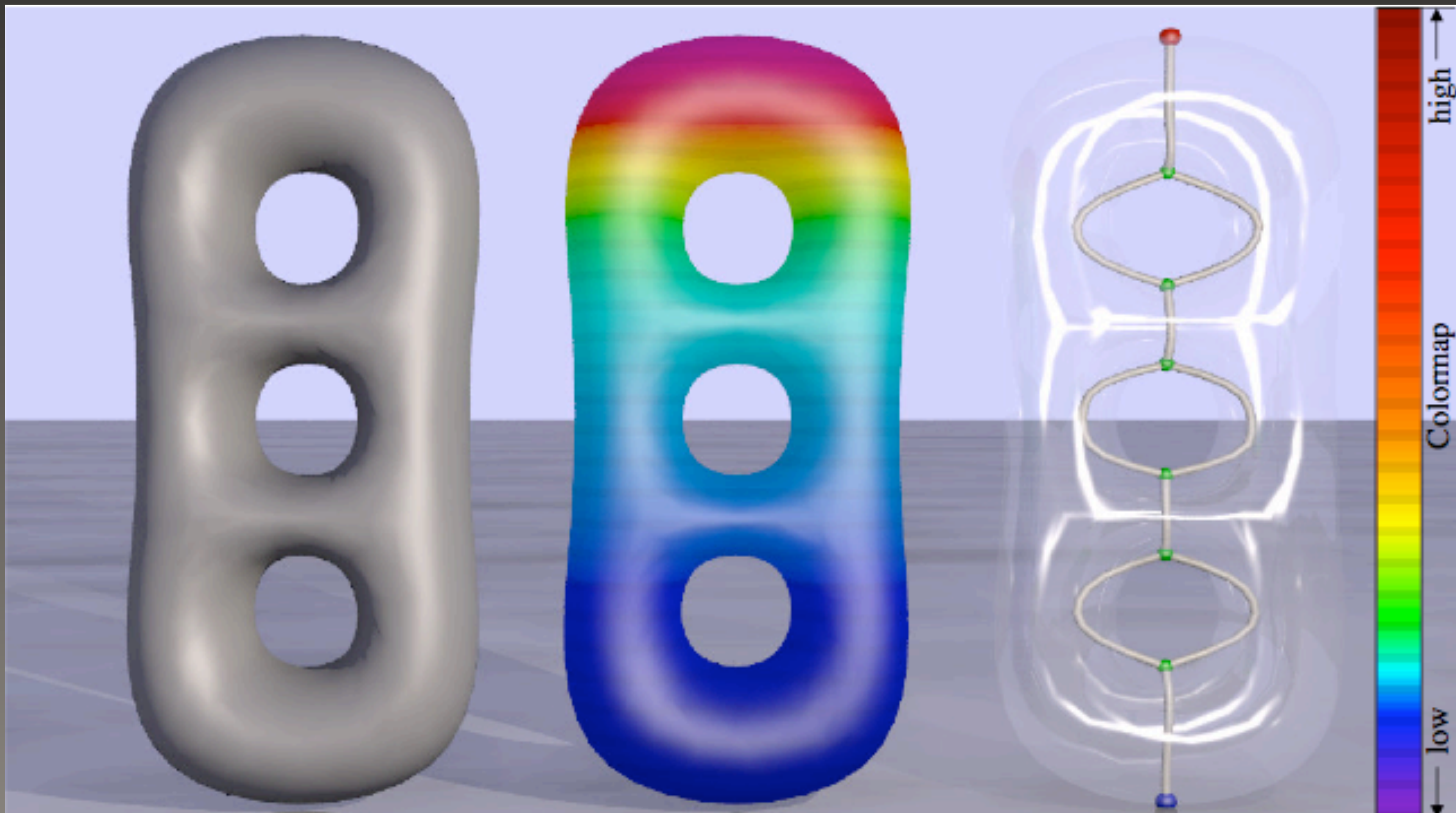
Burning Region Boundaries



- Over time, boundaries create sweep surfaces

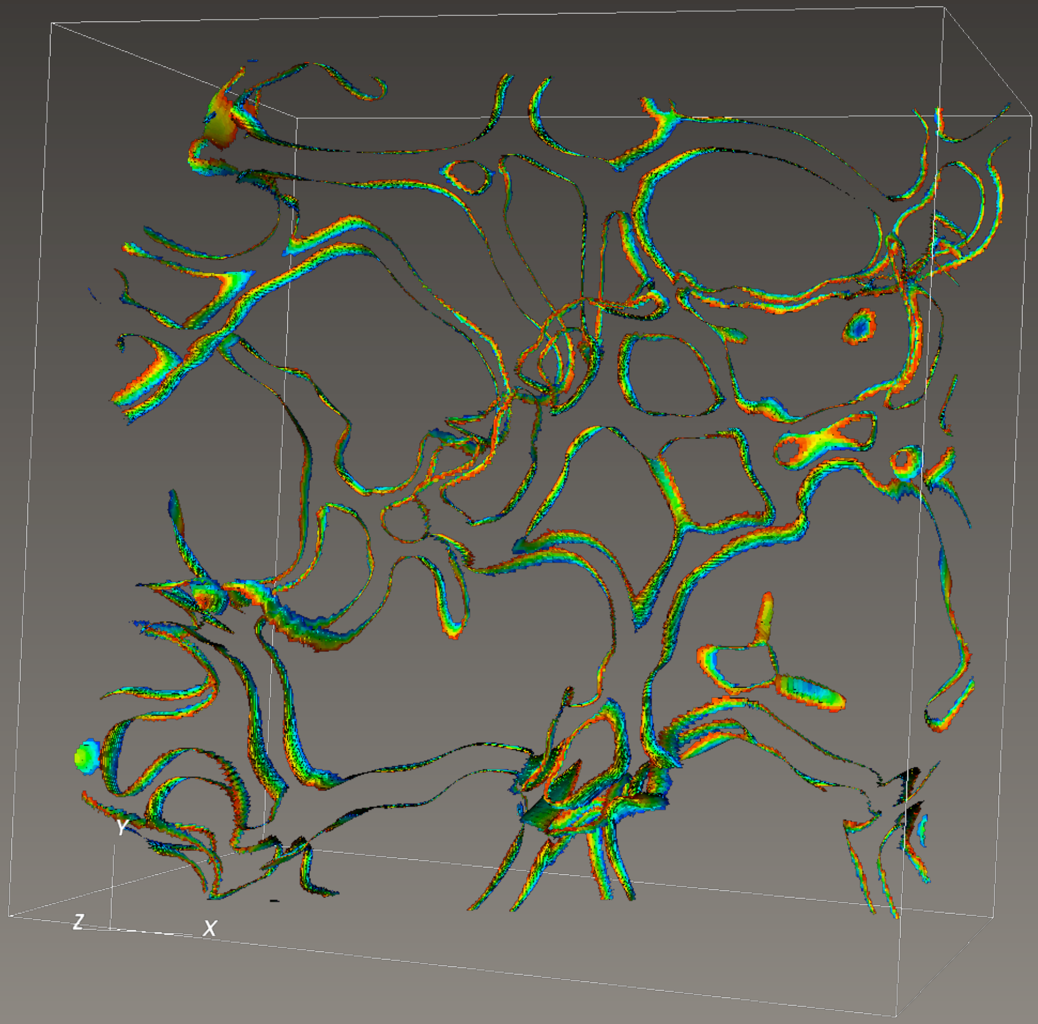
➔ Use Reeb graph (with time as Morse function)

Reeb Graph



[Reeb 1946, Sur les Points Singuliers d'une Forme de Pfaff Complétement Intégrable ou d'une Fonction Numérique]

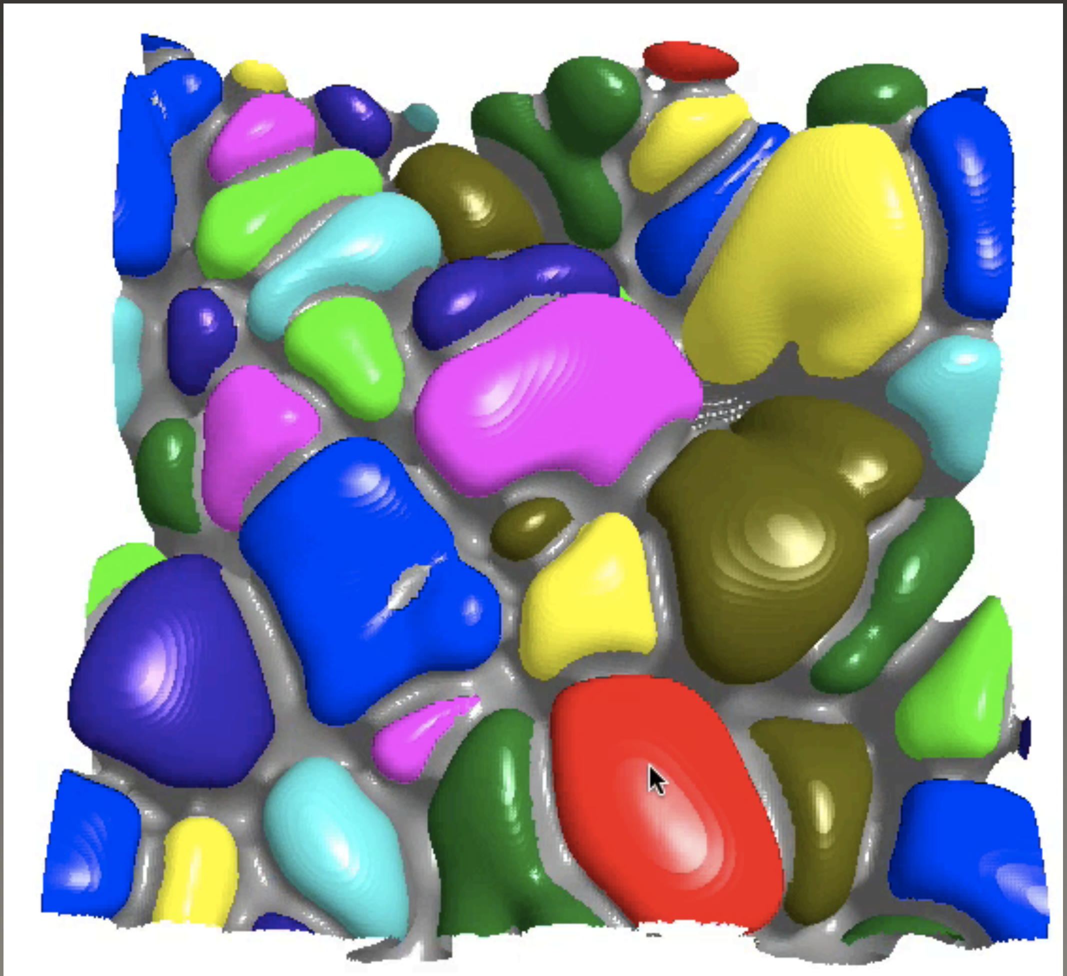
Burning Region Boundaries



- Over time, boundaries create sweep surfaces

➔ Use Reeb graph (with time as Morse function

Classification via Segmentation



[Bremer et al., submitted to IEEE TVCG, Analyzing and tracking burning structures in lean premixed hydrogen flames]

Tracking Graph Extraction Pipeline

1. Concatenate to obtain 4D mesh
2. Extract isotherm in 4D
3. Extract isotherm for original time steps
4. Segment vertices on 3D isosurface
5. Classify 4D isosurface vertices between time steps
6. Construct boundary surface
7. Extract Reeb-graph
8. Simplify Reeb-graph

1. Concatenate Time Steps

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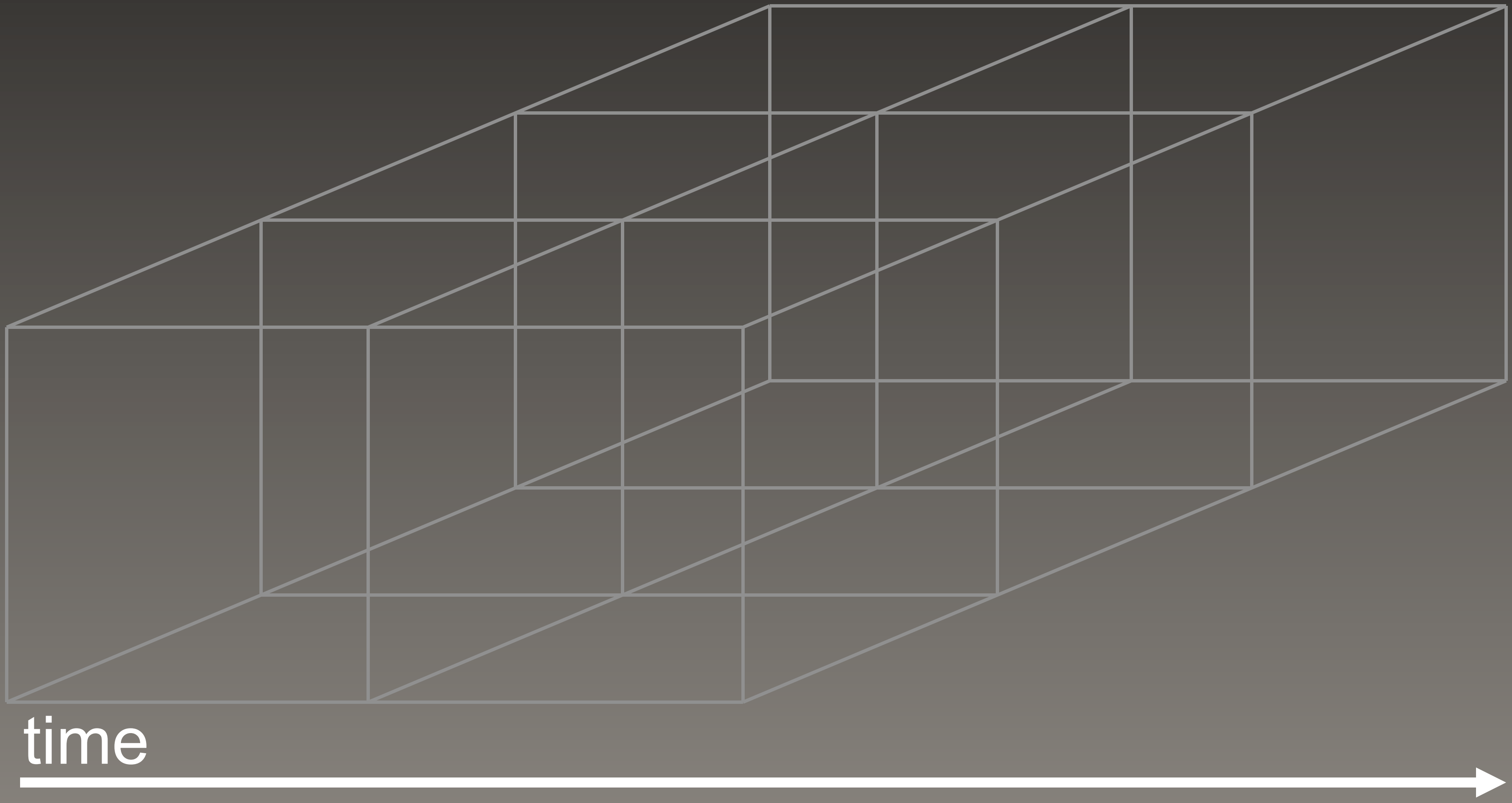
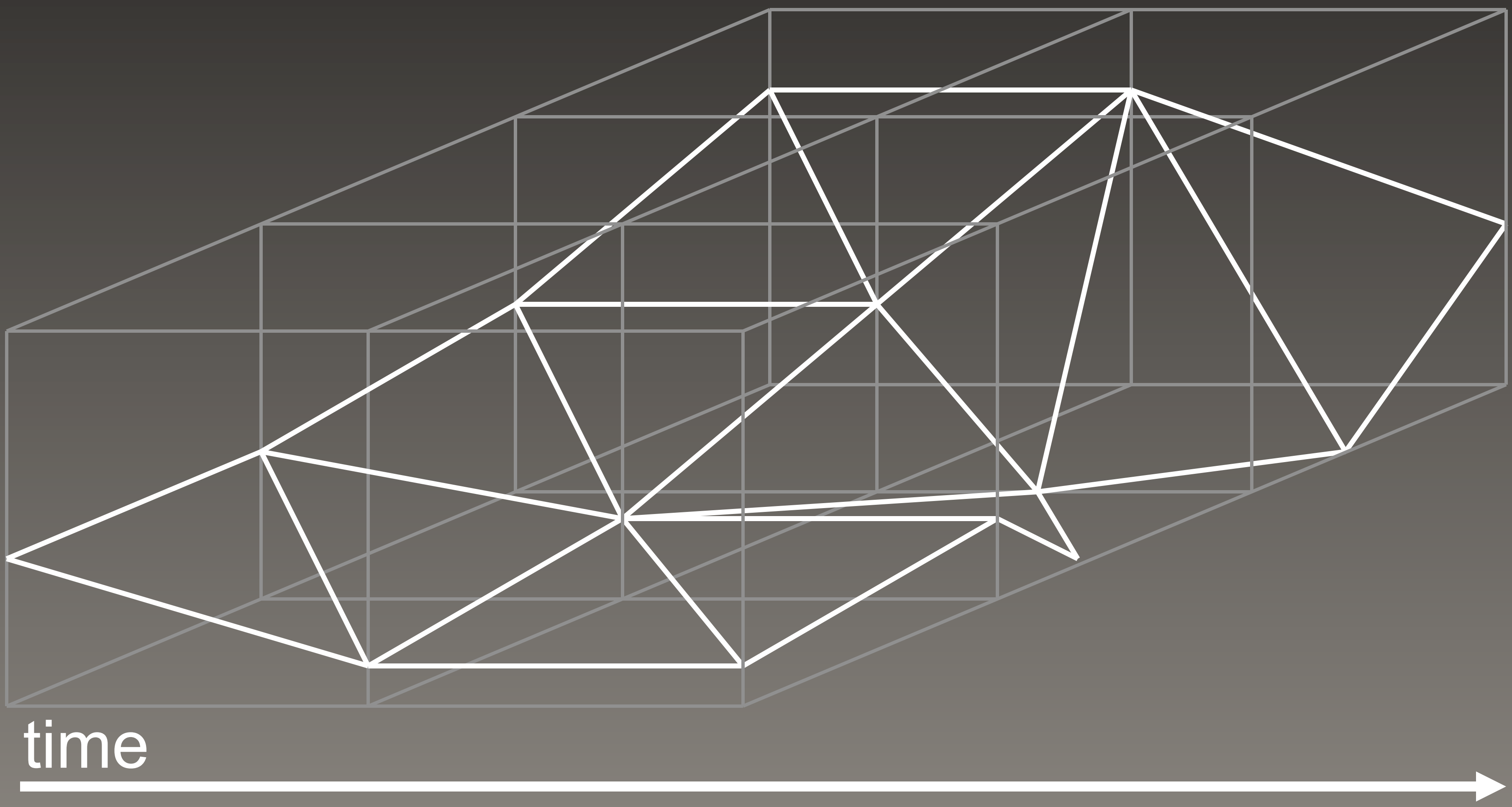
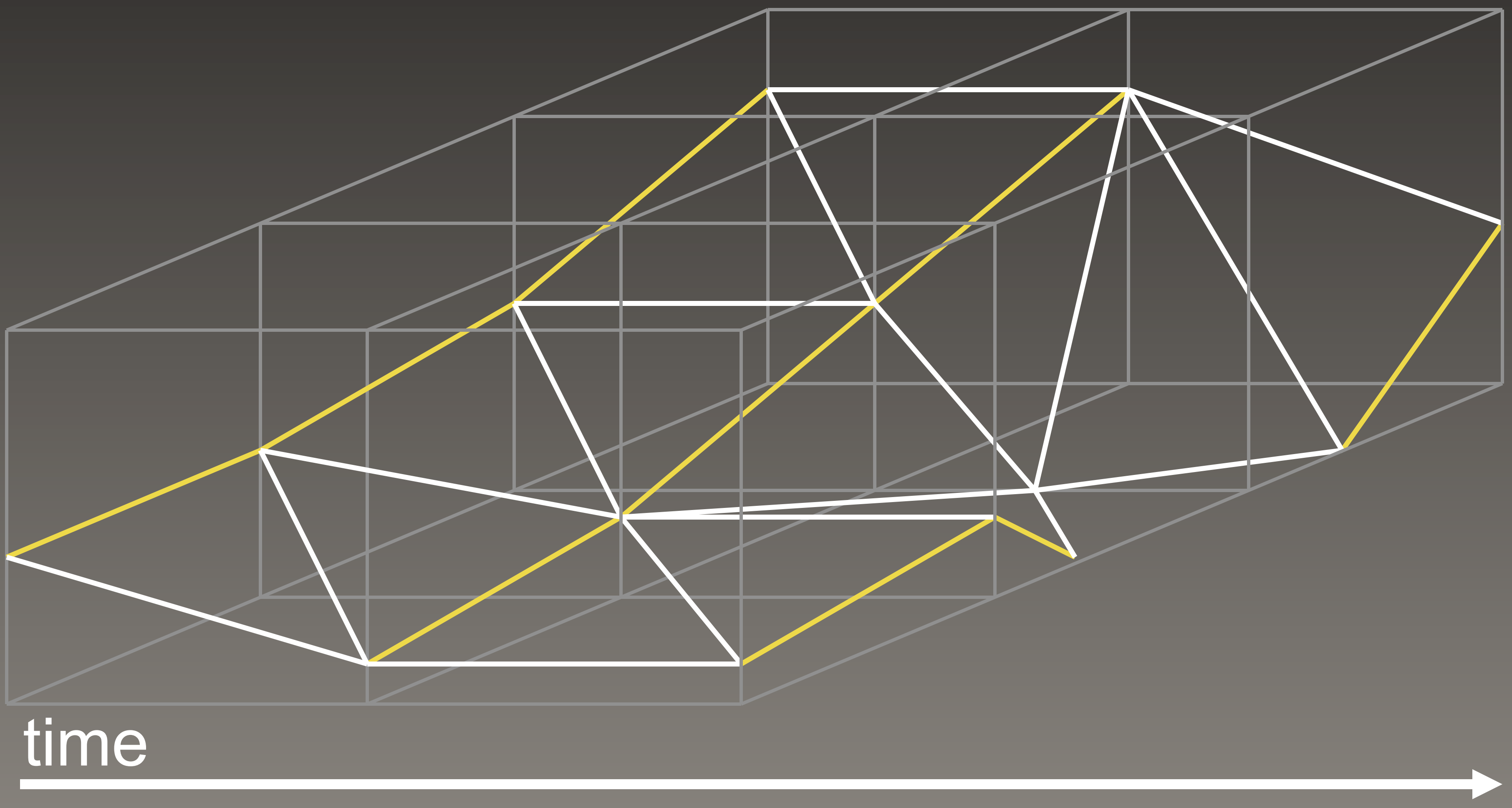


2. Extract Time Surface with Associated Fuel Consumption Values

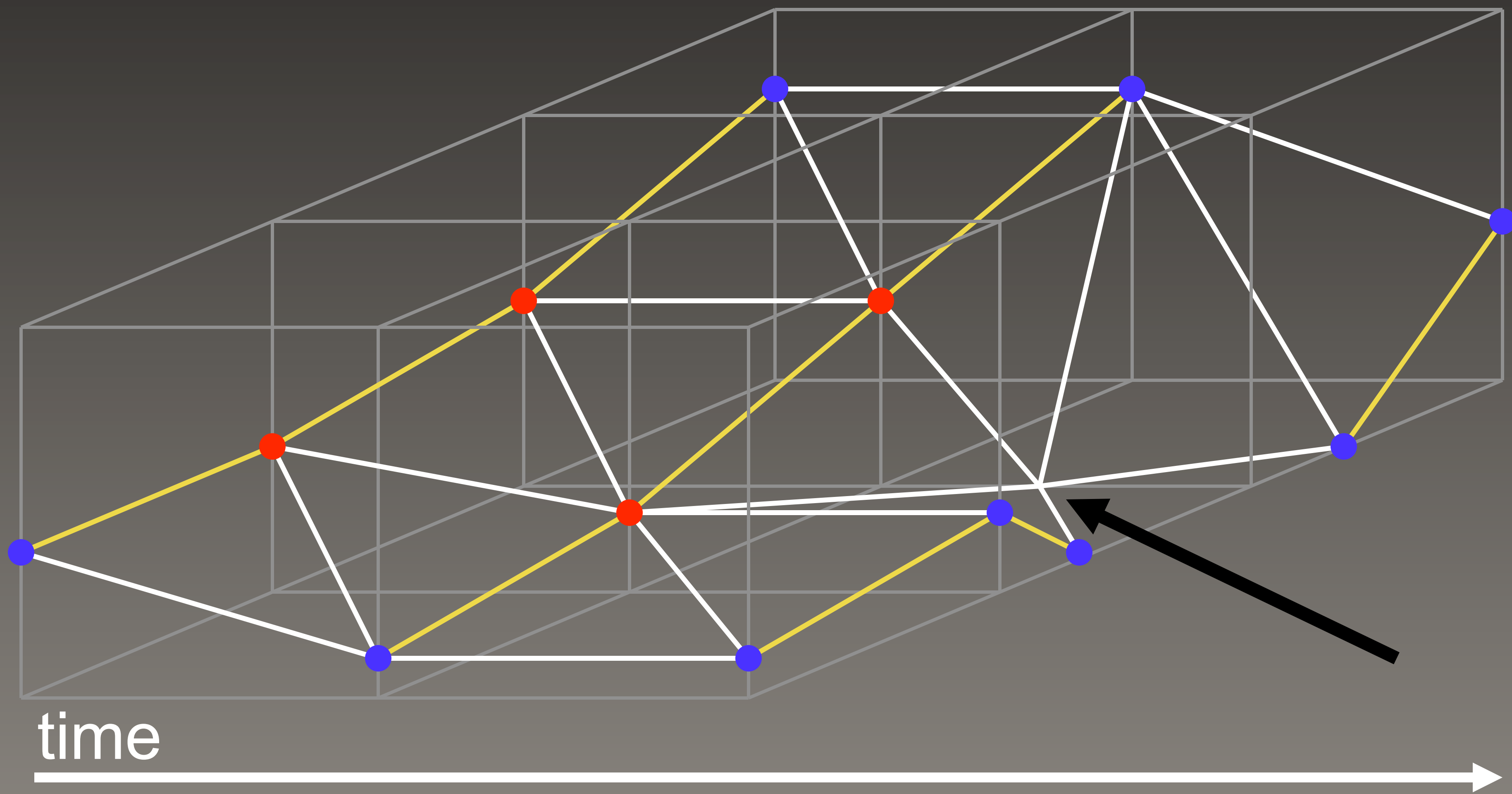


[Bhaniramka et al., IEEE TVCG 2004: Isosurface construction in any dimension using convex hulls]

3. Extract Isosurface in Original Time Steps – Filter Operation

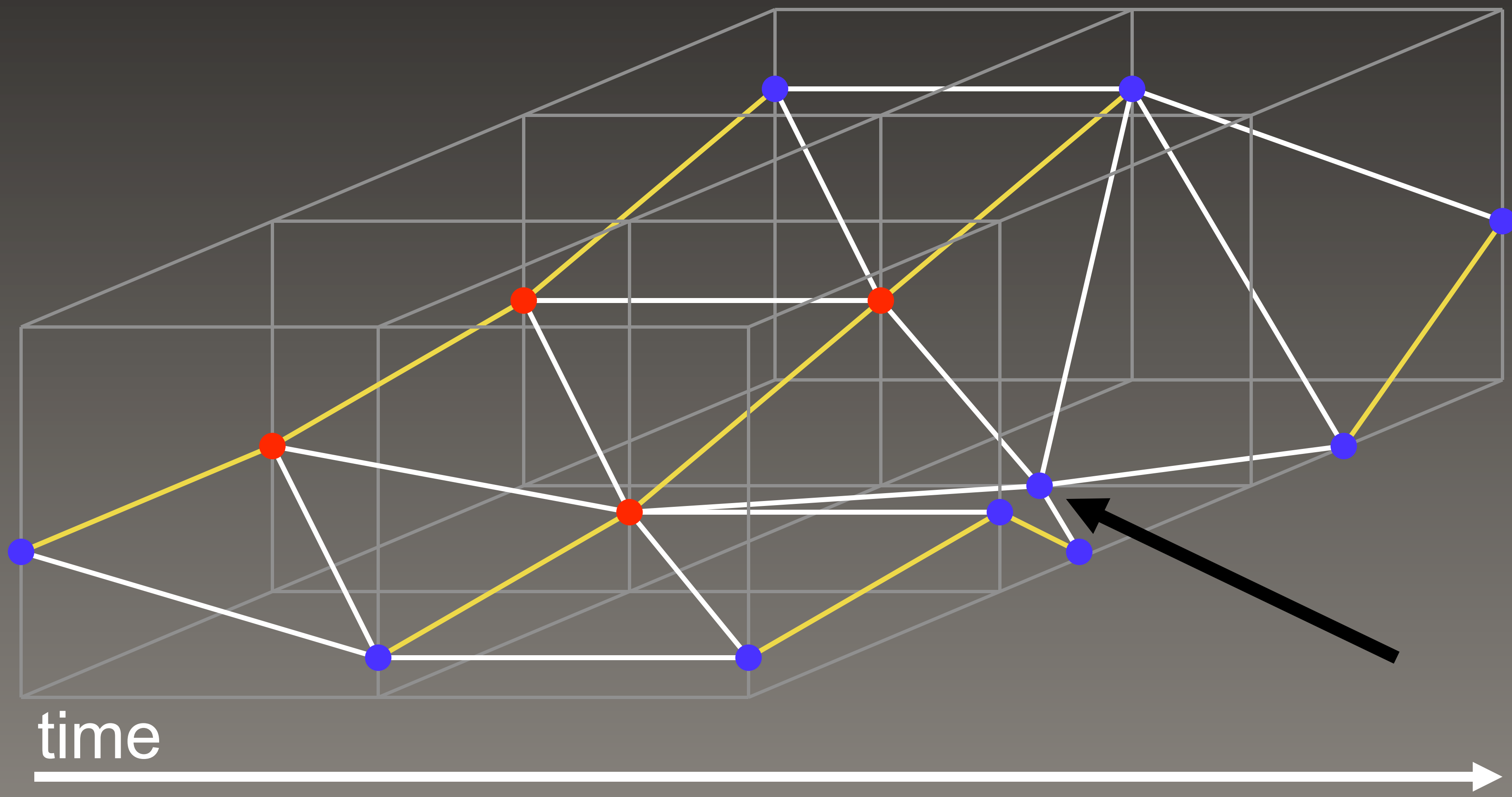


4. Classify 3D Isosurface Vertices – Compute Segmentation within Time Steps

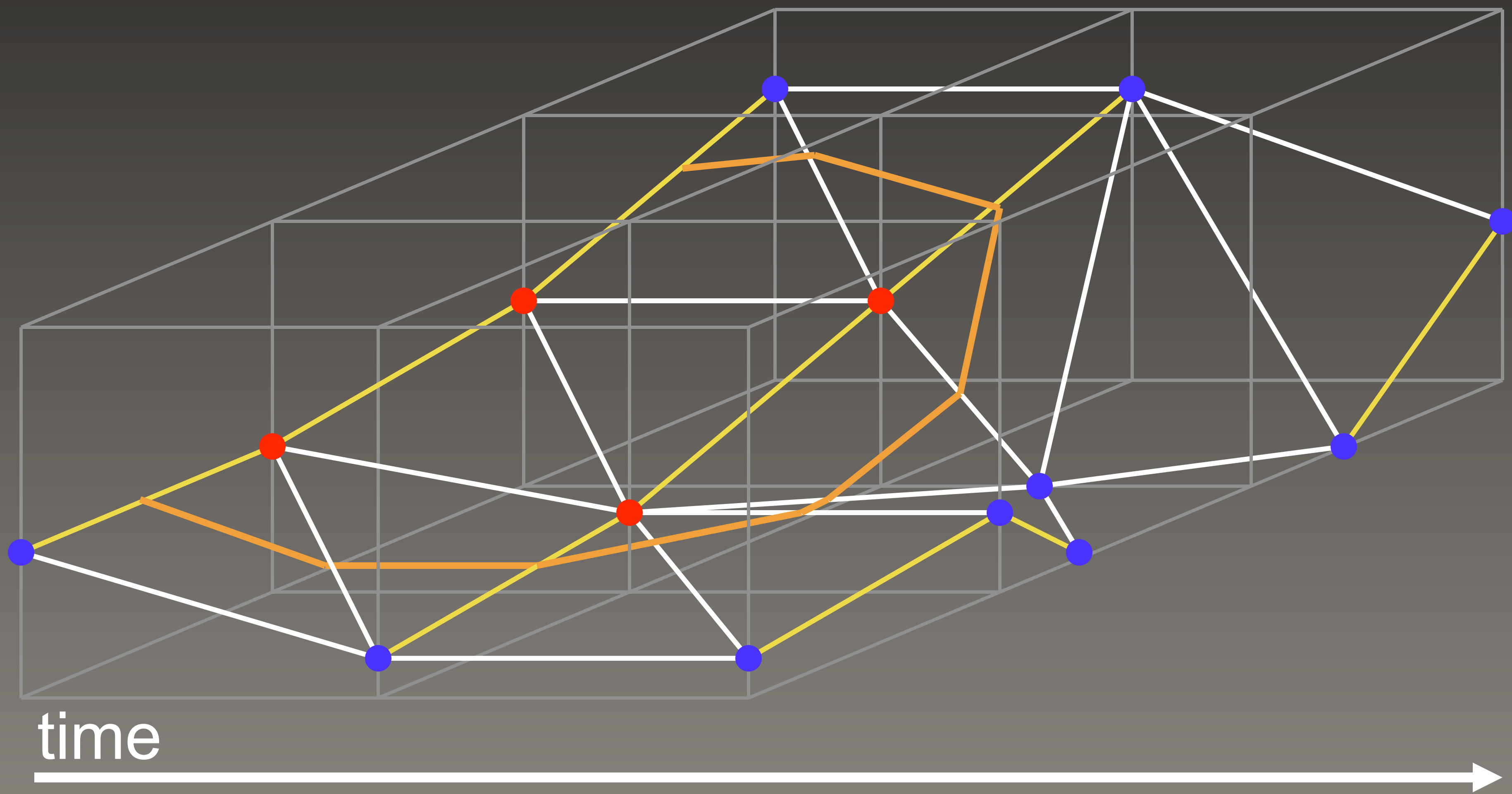


[Bremer et al., submitted to IEEE TVCG, Analyzing and tracking burning structures in lean premixed hydrogen flames]

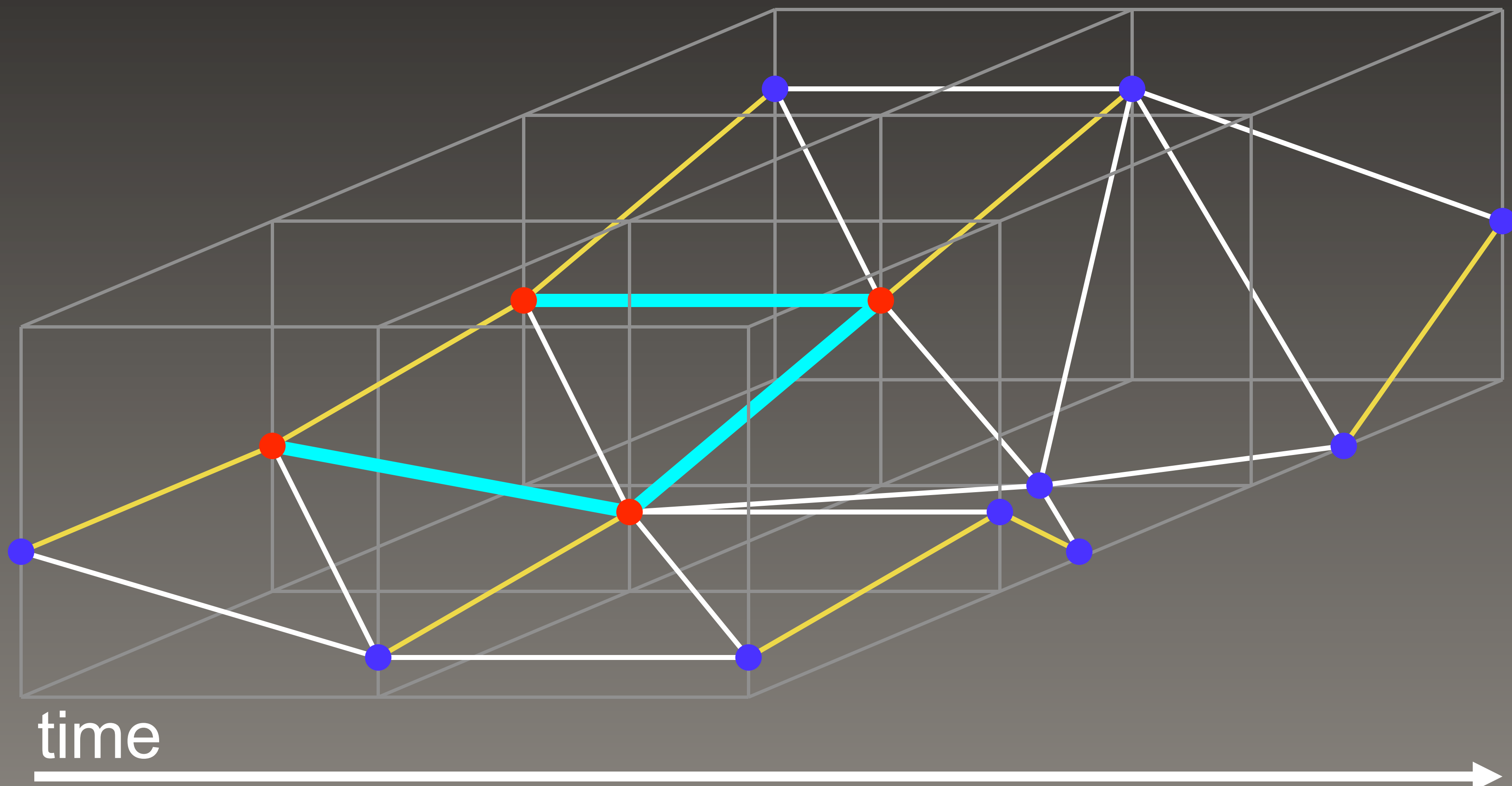
5. Classify 4D Time Surface Vertices Between Time Steps – Simple Thresholding



6. Construct Swept Boundary – "Correct"

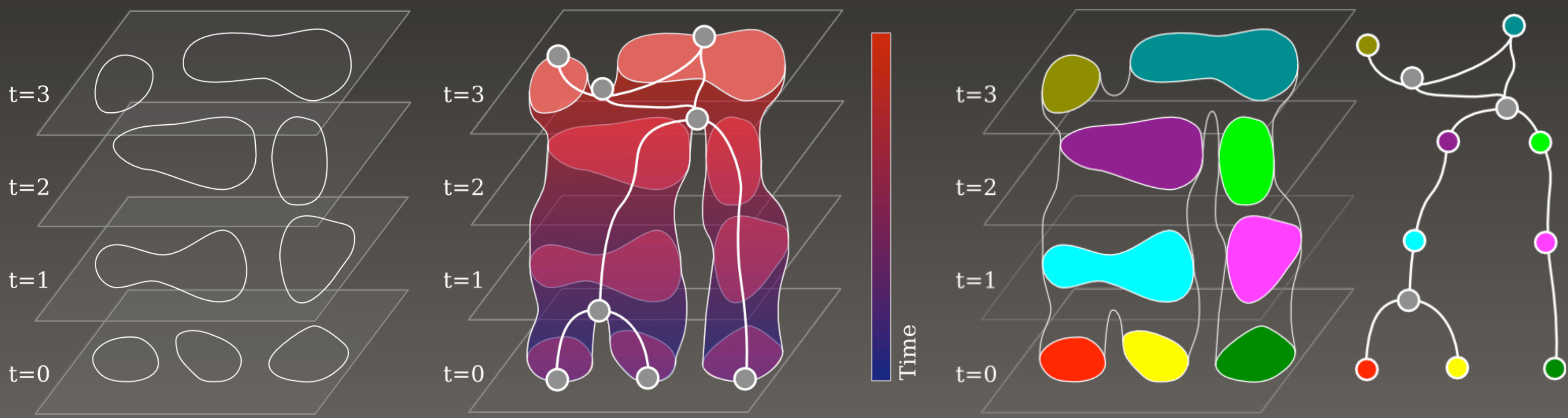


6. Construct Swept Boundary – Snapped to Vertices



- Preserve connectivity
- Simple case table
- Reuse isosurface vertices (intersection points along original grid edges)

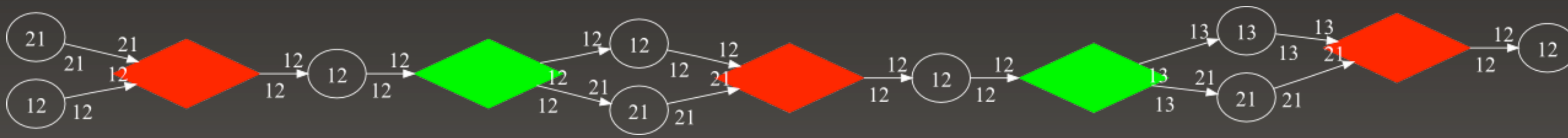
7. Compute Fully Augmented Reeb Graph



- Within each time step unique id per burning region
- Between time steps id not necessarily consistent
- Augment with degree two nodes to preserve correlation between graph and segmentation (and enable genus determination)

[Pascucci et al., ACM SIGGRAPH 2007: Robust On-line Computation of Reeb Graphs: Simplicity and Speed]

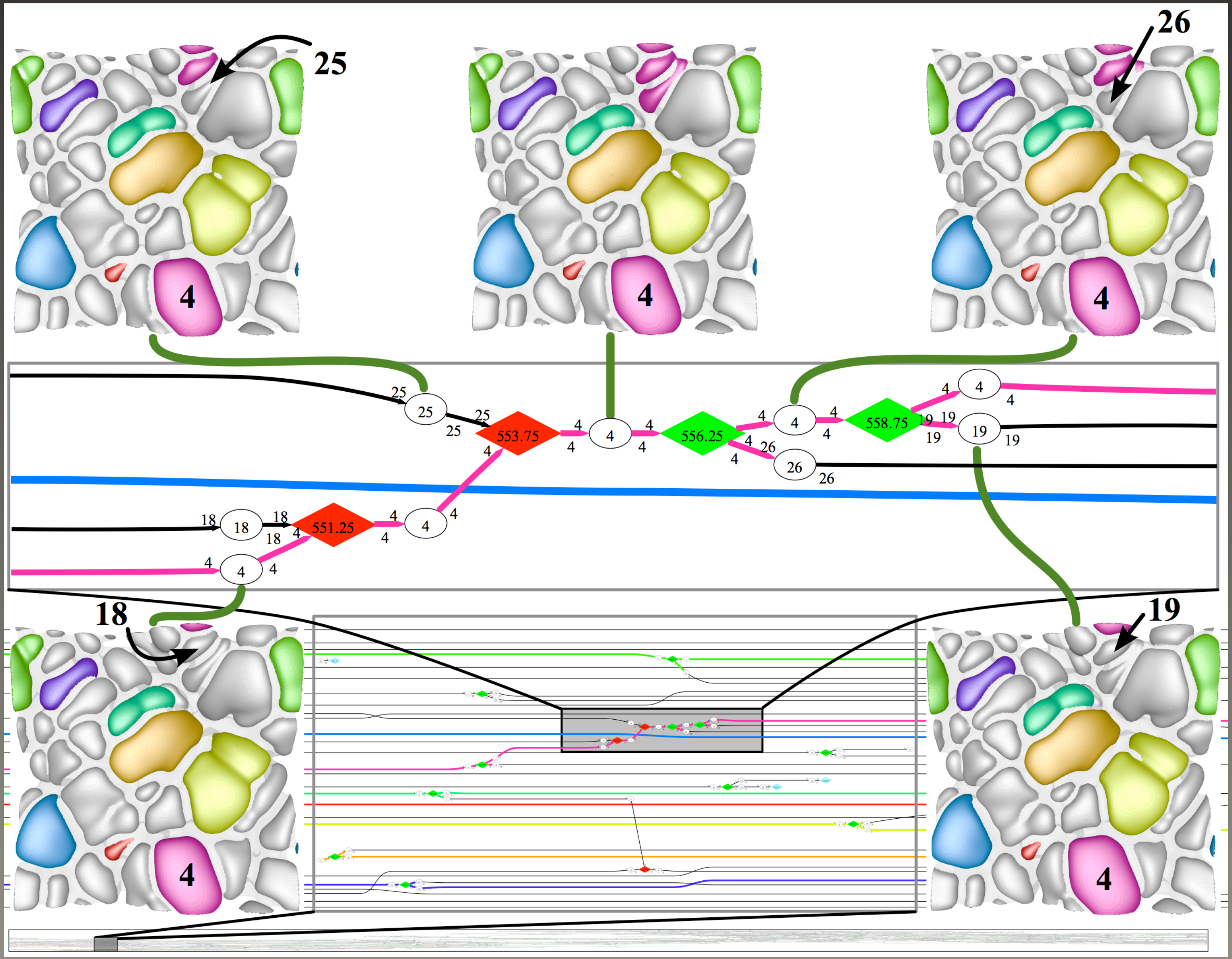
8. Simplify Reeb Graph



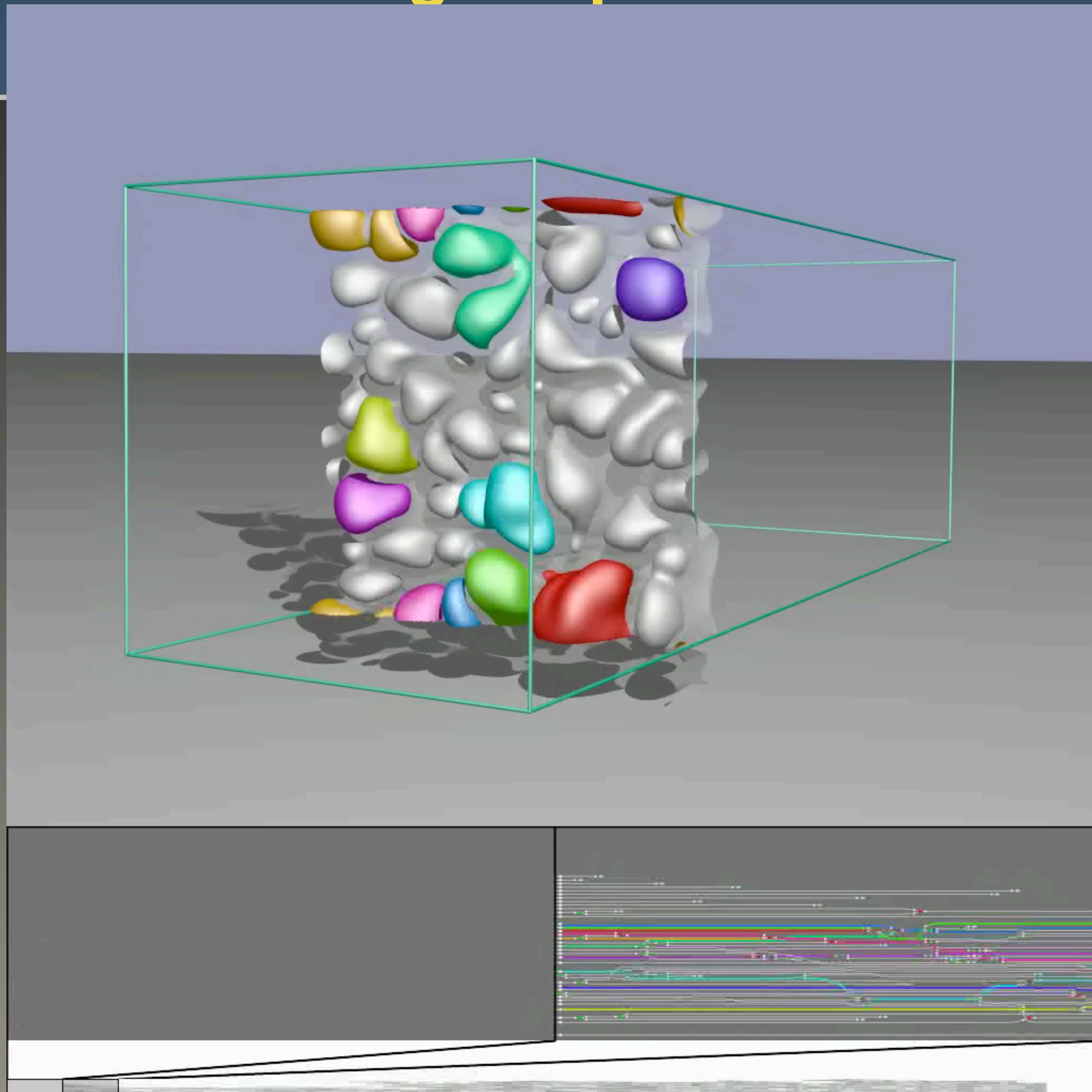
- Simplify loops that span less than one full time step
- Remove all loops spanning exactly one full time step
- Remove features with life span less than two time steps
- Construct simplified graph and layout using GraphViz

- Still “extended” merge/split events
  - Several split/merge events before “full” split/merge

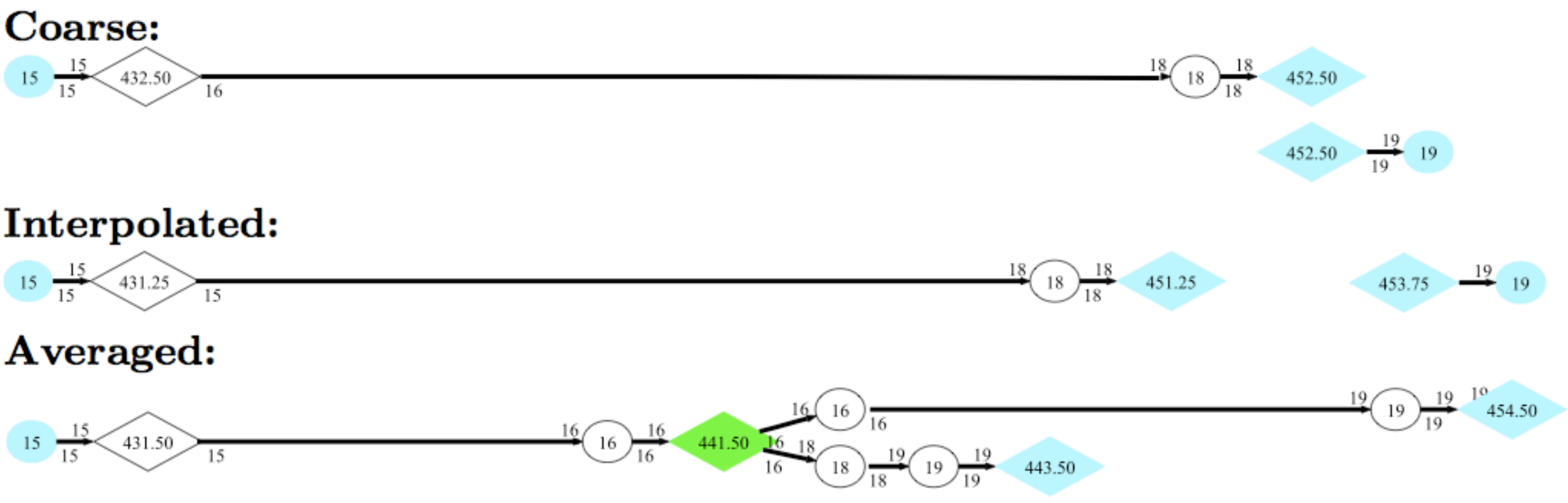
Tracking Graph Example



Tracking Graph – Movie

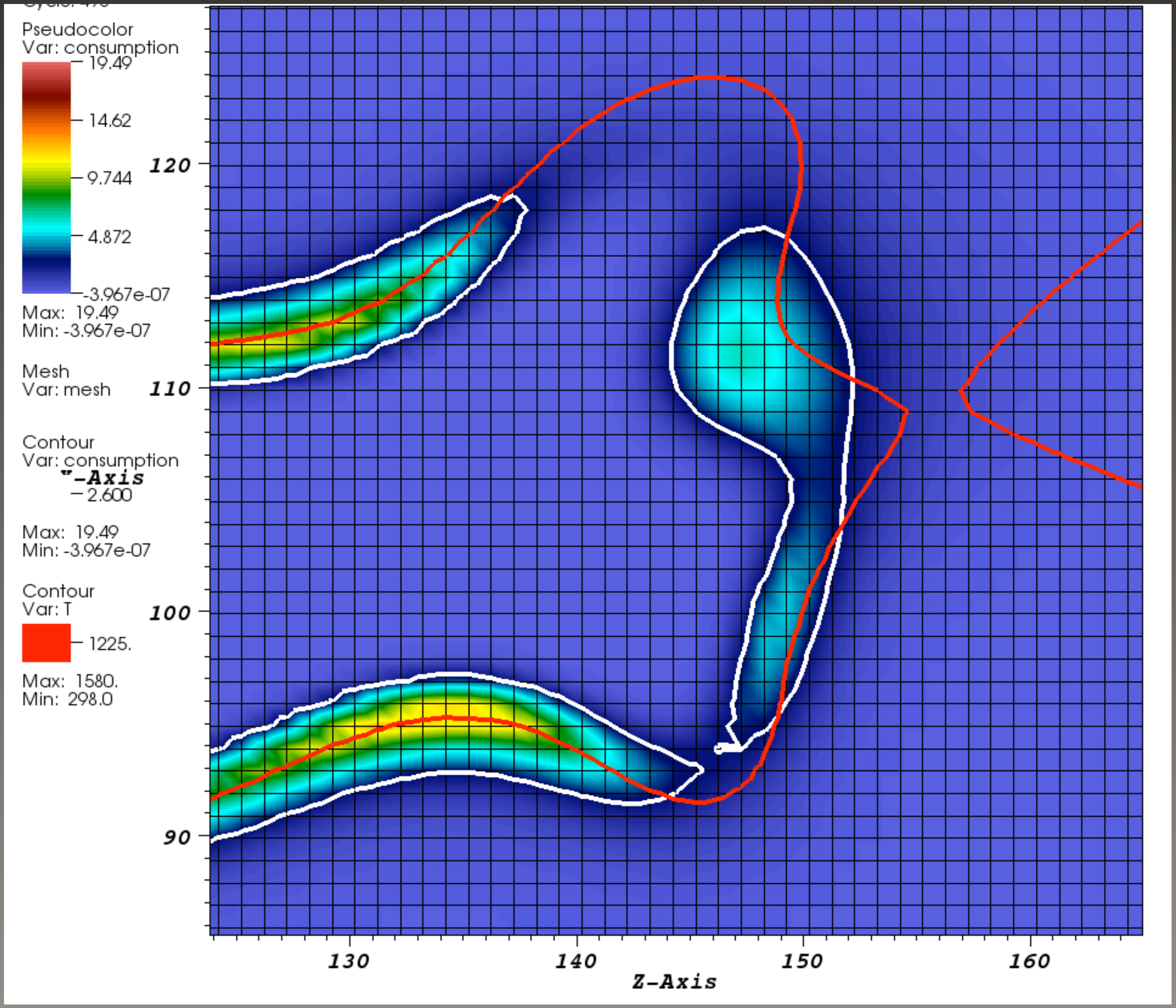


Tracking Graph Comparison – Example



- Coarse: Use original data set
- Interpolated: Create intermediate time steps using linear interpolation
- Averaged = "Ground Truth": Use finer simulation with more time steps and downsample

Lost Tracking Explained



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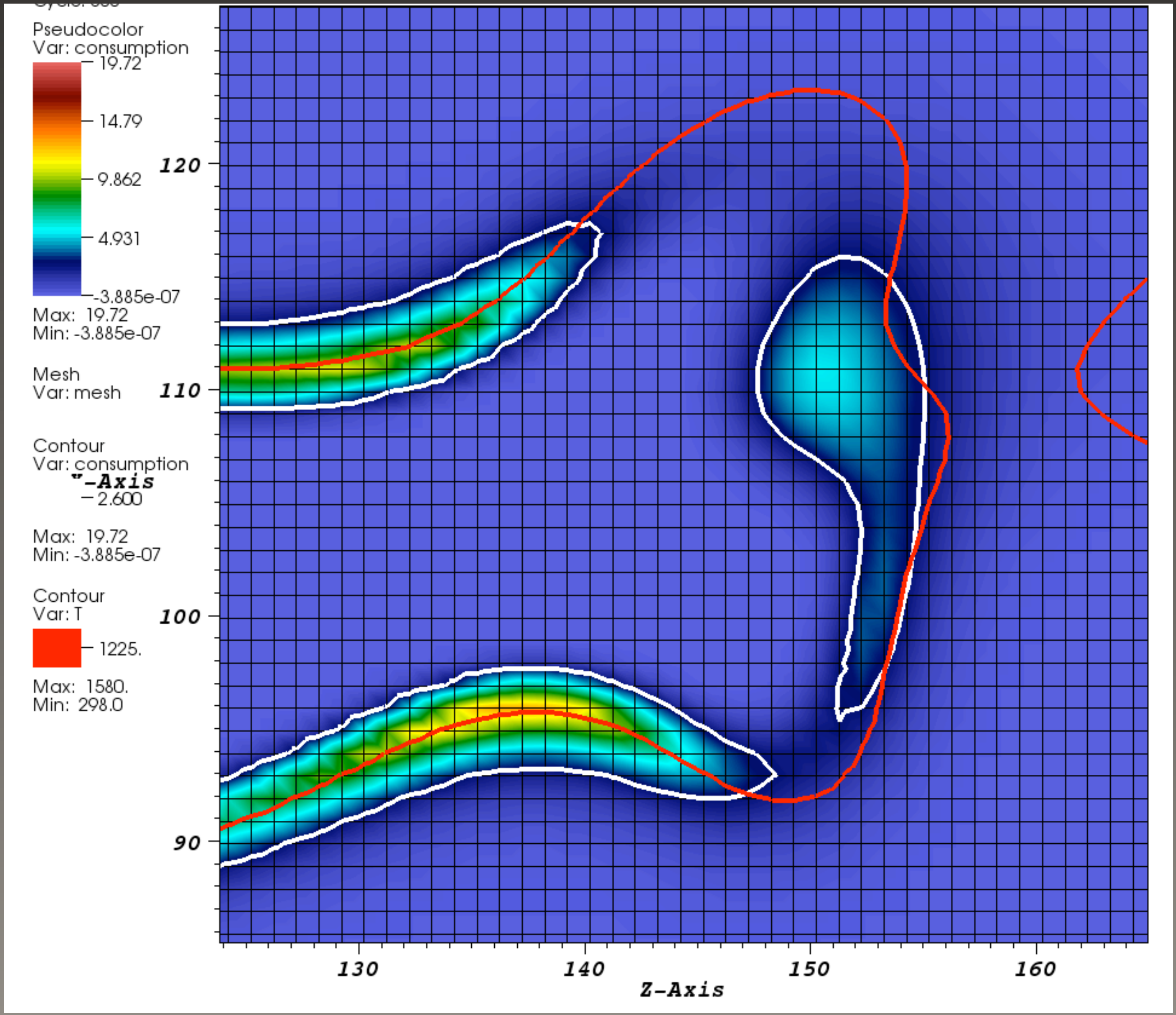

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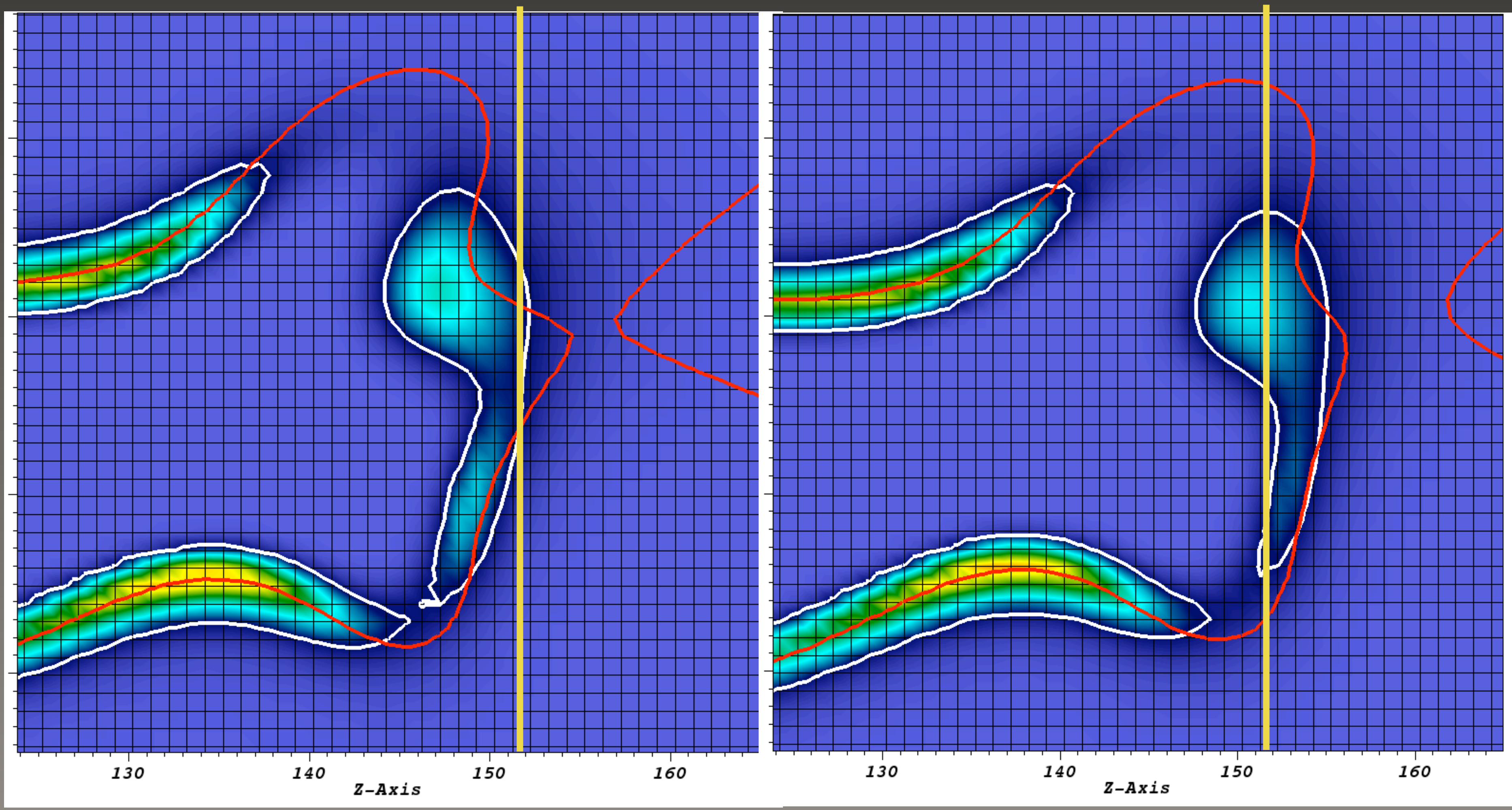

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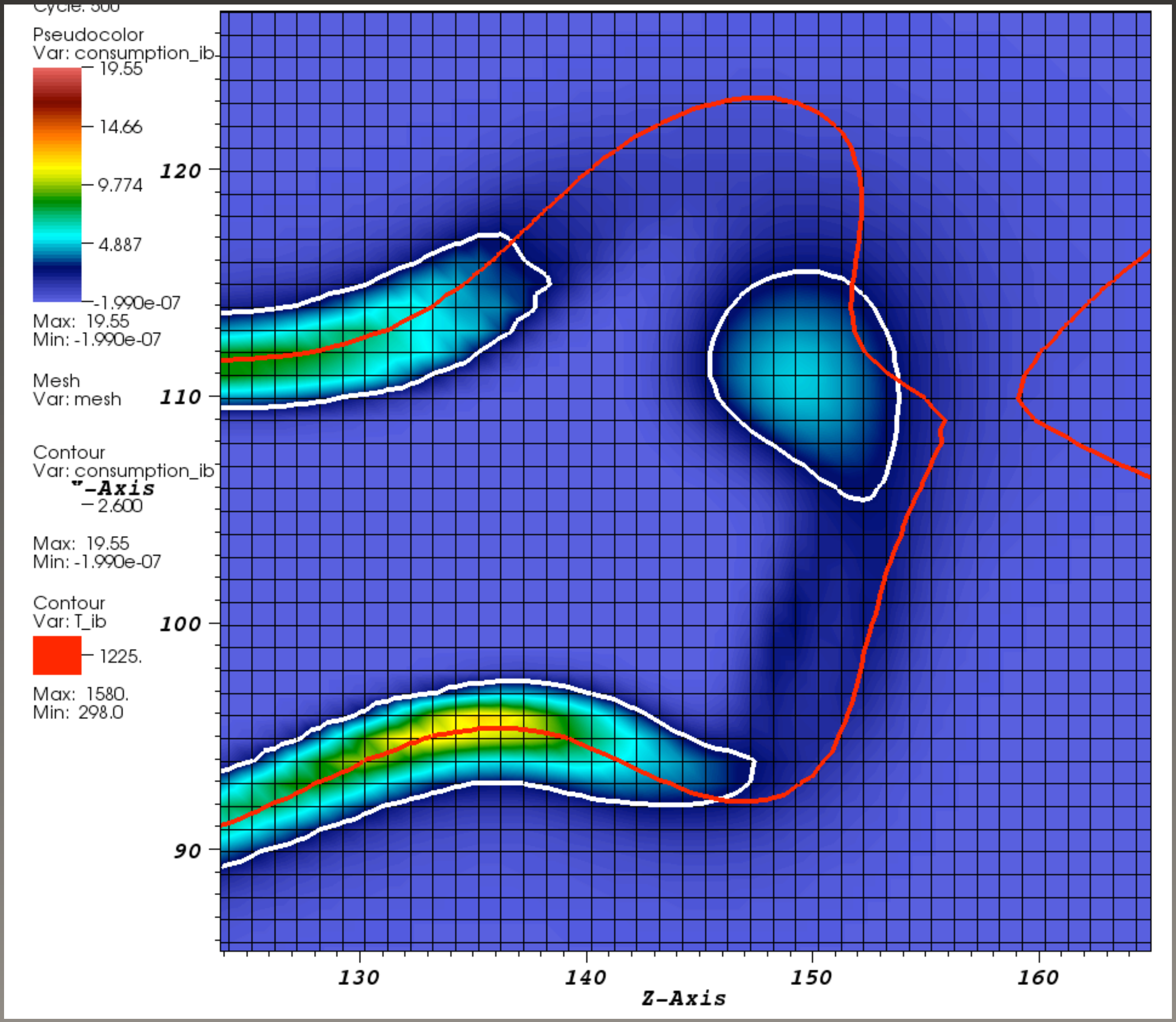

Tracking Graph Comparison – Summary

- During period where fine data available approximately 29 burning regions existed in the domain
- Tracking graphs for 16 of these 29 regions differed between various analysis approaches
  - 3 differences due to data differences between coarse and fine simulation
  - 2 differences due to merging and splitting between coarse time steps
  - 1 difference: region splitting of and dying between coarse time steps
- Discounting those: correct tracking for 19 out of 29 regions
- Other problems mainly due to lack of temporal resolution

Related Work in Feature Tracking

- [Mascarenhas & Snoeyink, 2008] Comprehensive overview of isosurface tracking
- [Samtaney et al., 1994] track thresholded regions with image processing techniques
- [Silver & Wang, 1997 & 1998] use volume for correspondence
- [Laney et al., 2006] use similar approach for tracking in turbulent mixing
- [Reinders et al., 2001] use motion prediction to improve tracking
- [Ji et al., 2003 & 2004] extract time surface and use its connected components to track features

Related Work in Feature Tracking

- [Edelsbrunner et al., 2004] compute time-varying Reeb graphs using Jacobi [Edelsbrunner et al., 2002] sets to correlate critical points
- [Szymczak, 2005] presents related techniques for contour trees
- [Sohn and Bajaj, 2006] use a hybrid approach also defining correspondences between contour trees using volume matching similar to Silver & Wang.
- Also related work in tracking critical points in vector field analysis [Tricoche et al, 2000; Theisel et al., 2003; Garth et al., 2004 ; Weinkauf et al., 2005]

Conclusions and Future Work

- **Conclusions**
  - Tracking works if temporal resolution sufficient
  - Artifacts due to insufficient temporal resolution easy to recognize
  - Analysis on isotherm aggravates tracking problems somewhat, but fast moving burning zones would also cause problem to full 3D analysis

- **Future Work**
  - Presentation
    - Layout of tracking graphs
    - Link graphs and physical segmentation views
  - Analysis
    - Integrate with simulation (access to more time steps)
    - Use graphs to compute derived quantities
    - Full 3D analysis eliminating need to restrict to isotherm (fewer varying parameter choices)

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Questions?