

Extracting Coherent Structures in Turbulent Flows

Bryce Angus & Dr. Tomasz Plewa

Department of Scientific Computing

Introduction

The consistent luminosity generated by the thermonuclear explosions known as Type Ia supernovae (remnants of which shown in Figure 1.) , makes them crucial cosmological distance markers, serving as a foundational tool for measuring the expansion rate of the universe. The turbulent flame fronts that drive these explosions contain organized, persistent vortical patterns embedded within turbulent flows, referred to as coherent structures. The behavior of these vortex tubes directly influences the combustion dynamics of the explosion. The identification and analysis of these coherent structures is essential to building physically accurate modules of turbulent combustion in extreme astrophysical environments like Type Ia supernovae. This work expands the existing data analytics tool LAVAflow, developed within the Department of Scientific Computing at Florida State University, with new modules designed to support the detection and extraction of coherent structures in turbulent flow fields, advancing our ability to study the Type Ia supernova explosion process quantitatively. Relevant portions of the LAVAflow code base shown in Figure 2.

Methods

Before new functionality could be developed, LAVAflow's existing codebase was ported from deprecated parallel processing plugins in C++ to their updated C equivalents. This modernization was a necessary prerequisite to ensure the stability and forward compatibility of LAVAflow as new modules are integrated.

Accurate computation of differential operators such as divergence and curl requires information about the cells surrounding every point in the mesh, including those at the edges of the domain. Meaning that operators applied near domain boundary would either lack sufficient information or would need to reduce the effective size of the domain, both of which would compromise accuracy. The BoundaryConditions module resolves this by accepting an existing uniform mesh and expanding it with a user-specified number of ghost cell layers in the x,y, and z dimensions. These ghost cells are then populated a variety of boundary conditions selected by the user. This provided the surrounding cell information that differential operators require across the entire domain. This extension is a fundamental requirement for all future operator-based analysis in LAVAflow.

The added Vorticity module takes in three velocity components V_x, V_y, V_z and applies the curl operator across the mesh to compute the vorticity of each cell. Vorticity can be computed along a specified dimension or in full 3D.

The added DBSCAN module accepts a mesh as input and returns a set of labels for each data point, indicating each point's cluster ID, if applicable. It does so by implementing the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) algorithm over a 3D mesh. As DBSCAN does not require a pre-defined number of clusters, and is capable of identifying structures of arbitrary shape while correctly distinguishing them from low-value background regions, the DBSCAN algorithm is a quality algorithm for this project.

Fig 2. Diagram of the relevant portions of LAVAflow codebase

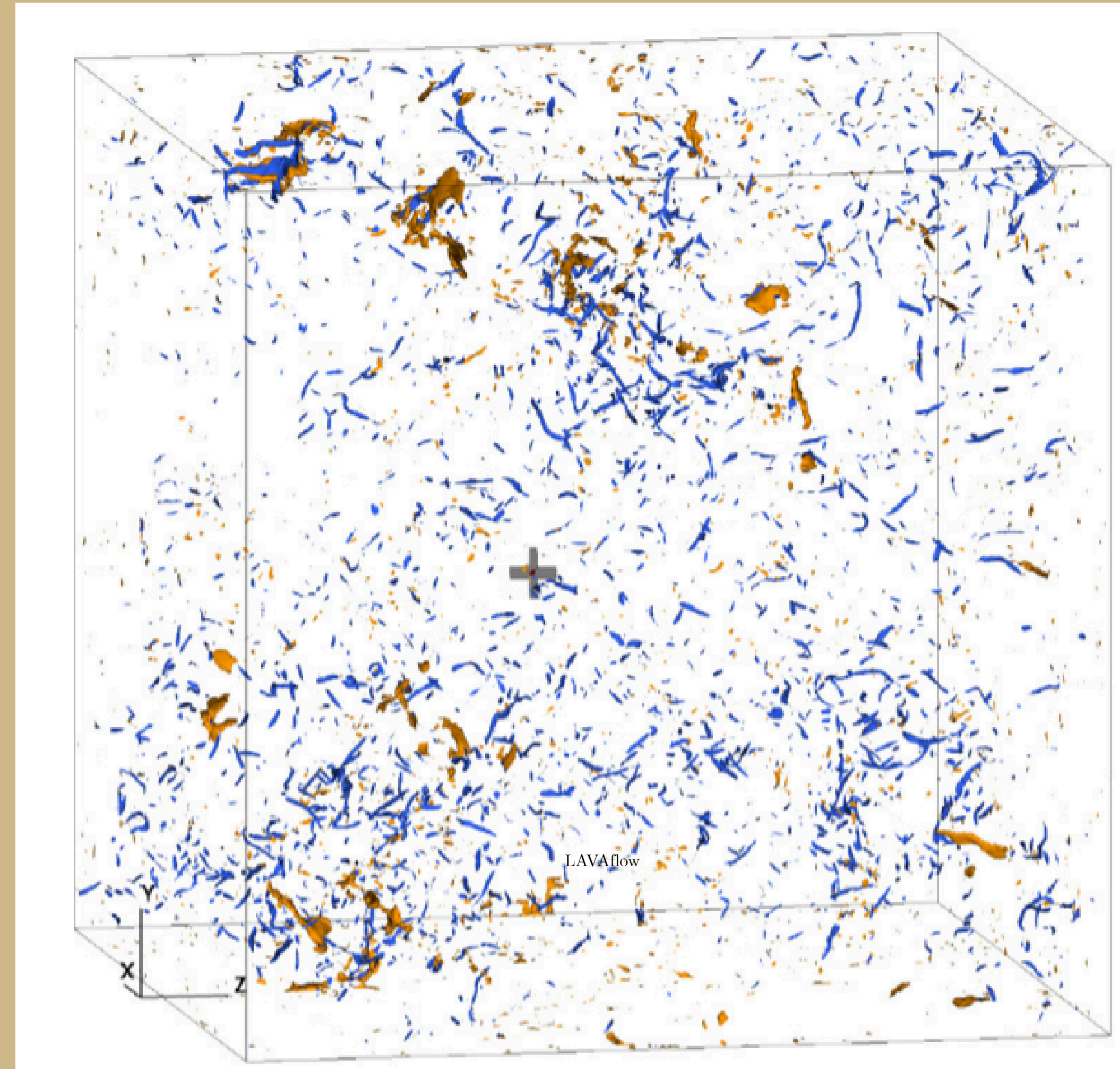
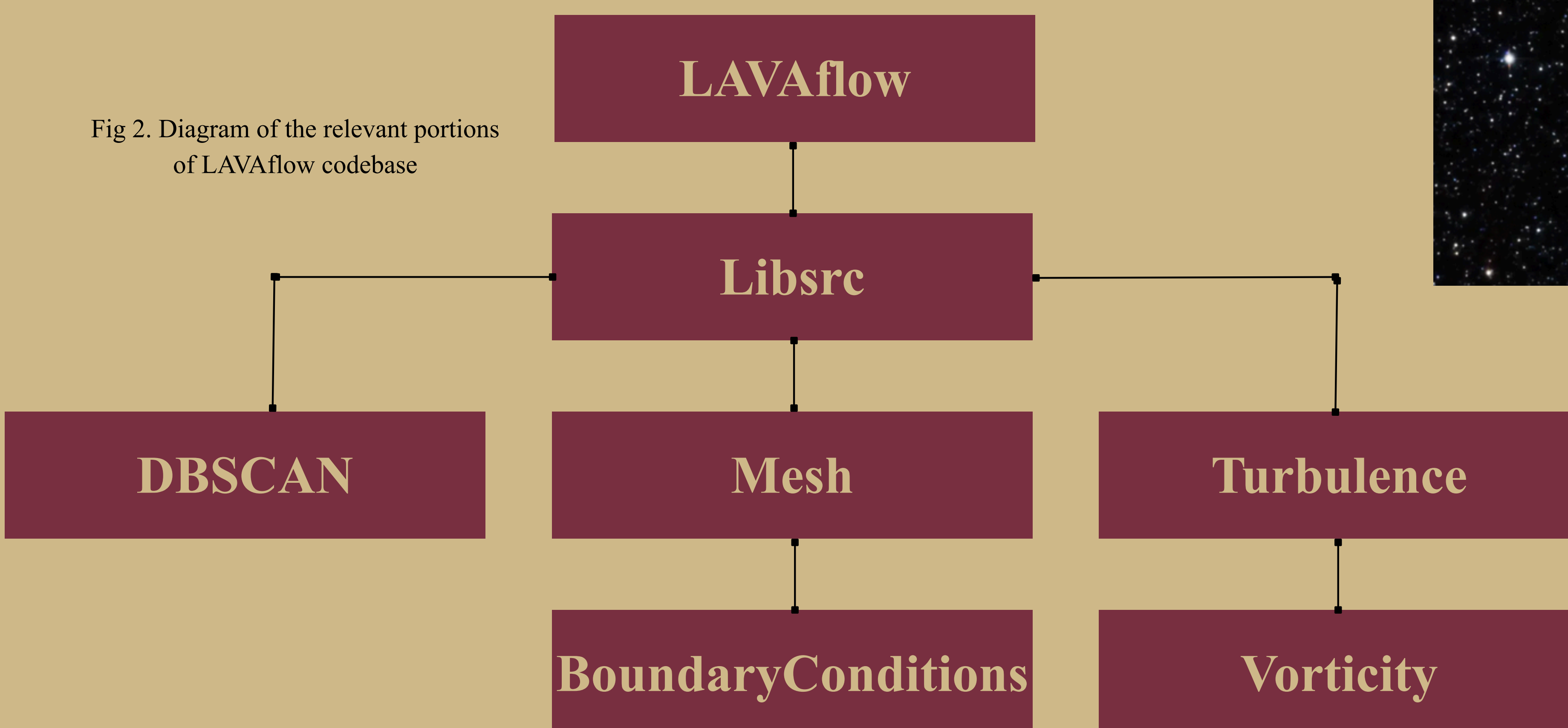


Fig 3. Coherent structures in turbulent flows. Apopted from E Brooker, T Plewa, D Fenn, Type Ia supernovae deflagration-to-detonation transition explosions powered by the Zel'dovich reactivity gradient mechanism, *Monthly Notices of the Royal Astronomical Society*



Fig 1. Type Ia Supernova Remnant 6299. Adopted from NASA

Results

The BoundaryConditions and Vorticity modules have been verified in tandem using a synthetic vector field with a known analytical solution, allowing the computed output to be directly compared against expected values at every position in the domain. The curl operator was first validated in 2D using a synthetic vortex field, confirming that the ghost cell expansion correctly populates boundary information and produces accurate numerical derivatives at a near domain boundaries. This verification was subsequently extended to 3D, where the same synthetic field approach was applied across all three dimensions simultaneously. The 3D results confirmed that the implementation scales correctly from 2D, maintaining numerical accuracy across the full mesh domain. Together these verification steps establish confidence in the correctness and reliability of the foundational pipeline.

Upcoming Results

The next stage of the project will apply the full LAVAflow pipeline, including the BoundaryConditions, Vorticity, and DBSCAN modules, to a realistic 3D turbulent velocity field from a Type Ia supernova simulation, as illustrated in Figure 1. The BoundaryConditions module will first be applied to the simulation's three-component velocity field, extending the domain is properly extended with ghost cells before any further operator-based analysis is performed. The extended velocity components will then be passed to the Vorticity module, computing the full 3D curl across the mesh domain. The resulting mesh will be passed to the DBSCAN module to identify and label regions of concentrated rotational motion corresponding to coherent vortical structures. Parameter tuning of DBSCAN's epsilon neighbor radius and minimum point threshold will be conducted iteratively, guided by the physical scale and density characteristics of the structures expected in supernova-relevant turbulence. The goal of this tuning processes is to achieve a configuring that consistently separates distinct coherent structures from another while correctly, classifying low-vorticity regions as background noise.

Discussion

The coherent structures targeted by this pipeline carry significant physical consequences within turbulent flows. In reactive flows such as the turbulent flame fronts present in Type Ia supernovae, coherent vortical structures correspond to stationary regions of low mixing rate. The persistence of these low-mixing rate regions directly affects how and where combustion proceeds, influencing the overall energy release profile of the explosion. A better understanding of these coherent structures has direct implications for the accuracy of supernova explosion models. Additionally, in magnetized flows, coherent vortical structures are closely associated with magnetic reconnection regions, sites where magnetic field lines rearrange topology and rapidly release stored energy. The ability to automate the location and characterization of these structures in 3D fields opens new paths for studying the interaction between turbulence and magnetic dynamics in astrophysical environments.

The methods developed here establish a generalized, physical-informed tool for coherent structure detection in 3D turbulent fields. LAVAflow has the potential to be applied across a range of turbulent flow problems where ever the identification and classification of organized structures within complex flows is of scientific value.

Selected References

- E Brooker, T Plewa, D Fenn, Type Ia supernovae deflagration-to-detonation transition explosions powered by the Zel'dovich reactivity gradient mechanism, *Monthly Notices of the Royal Astronomical Society: Letters*, Volume 501, Issue 1, February 2021, Pages L23–L27, <https://doi.org/10.1093/mnrasl/laaa141>
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