Title: New Perspectives on Star Formation and Protostellar Outflows. A Talk in 3 Acts

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Abstract: The role of outflows in global star formation processes has become hotly debated even as fundamental questions about the nature of these outflows continues to receive attention. In this talk I discuss both problems and new approaches to their resolution. Astrophysical outflows have always been a subject at the forefront of the numerical technologies and in the first act of the talk I introduce AstroBEAR, a new Adaptive Mesh Refinement MHD tool developed at Rochester for the study of star formation outflow issues. The question of \'feedback\', the mechanisms by which protostellar outflows can drive turbulence in either clouds or clusters, is then addressed via AstroBEAR simulations. In these studies we seek to understand the detailed mechanisms by which outflows can return energy to their environment and, perhaps, drive turbulent motions. Finally we turn to the MHD processes involved with the outflows themselves and focus on a new tool, High Energy Density Laboratory experiments. I will present results from a campaign of experiments carried out at Imperial Collage in London which directly address issues of magnetically dominated radiative outflows and jets.

Star Formation and Proto-stellar Outflows: Experiments Virtual and Actual

A talk in 3 Acts

Adam Frank
University of Rochester

A Cast of Many

AstroBEAR MHD / Young Stars

Sorin Mitran UNC

*Andrew Cunningham (UR)

Alexei Poludnenko (UR, UChicago)

Peggy Varniere (UR, Grenoble)

Kris Yirak (UR)

Sean Matt (UV)

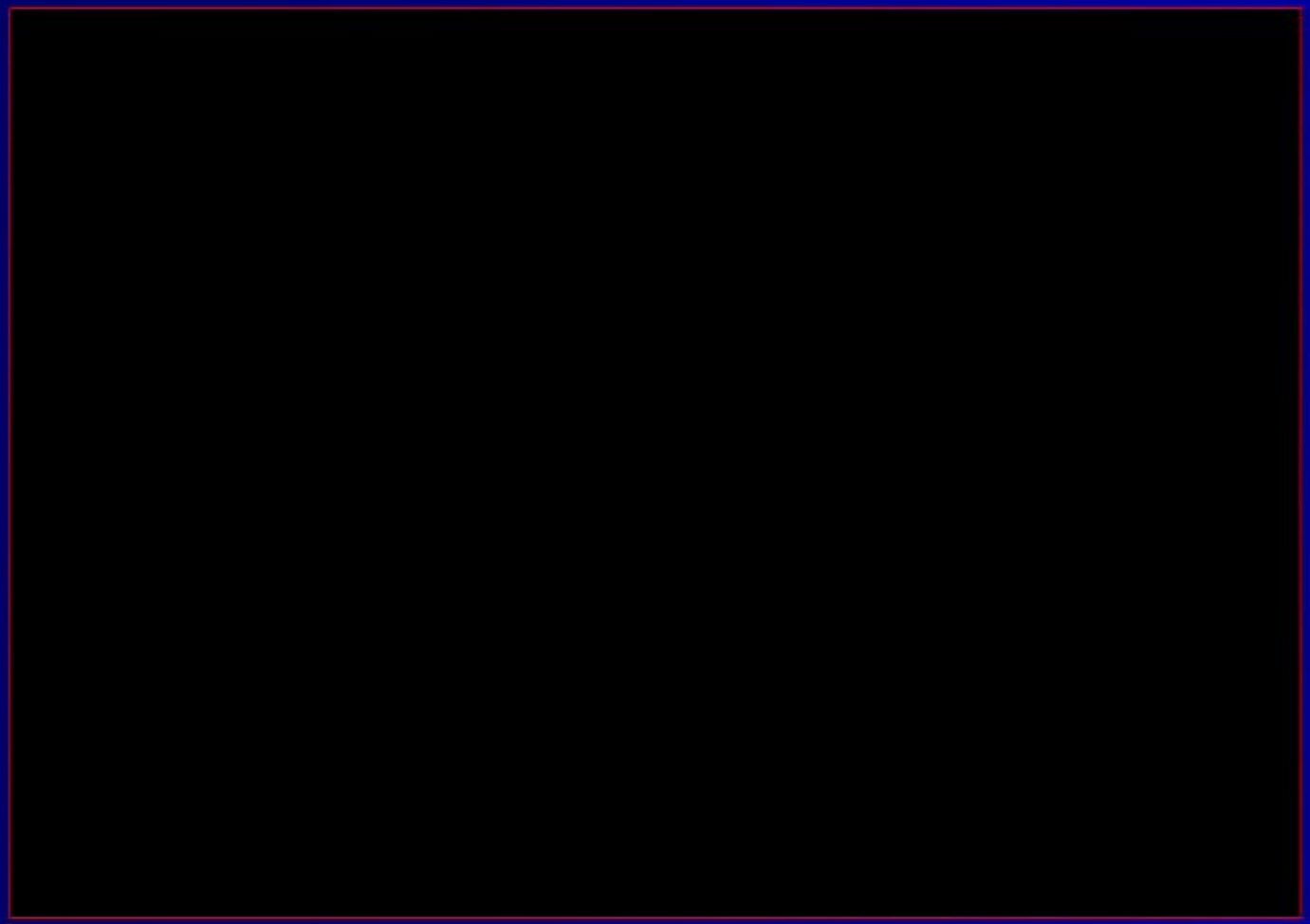
Lab Astro:

Sergey Lebedev (Imperial College, London)

A. Ciardi (Observatory Paris)

Thanks to: NSF, DOE, NASA, UR Laboratory for Laser Energetics

Star Formation: Collapse and Complexity



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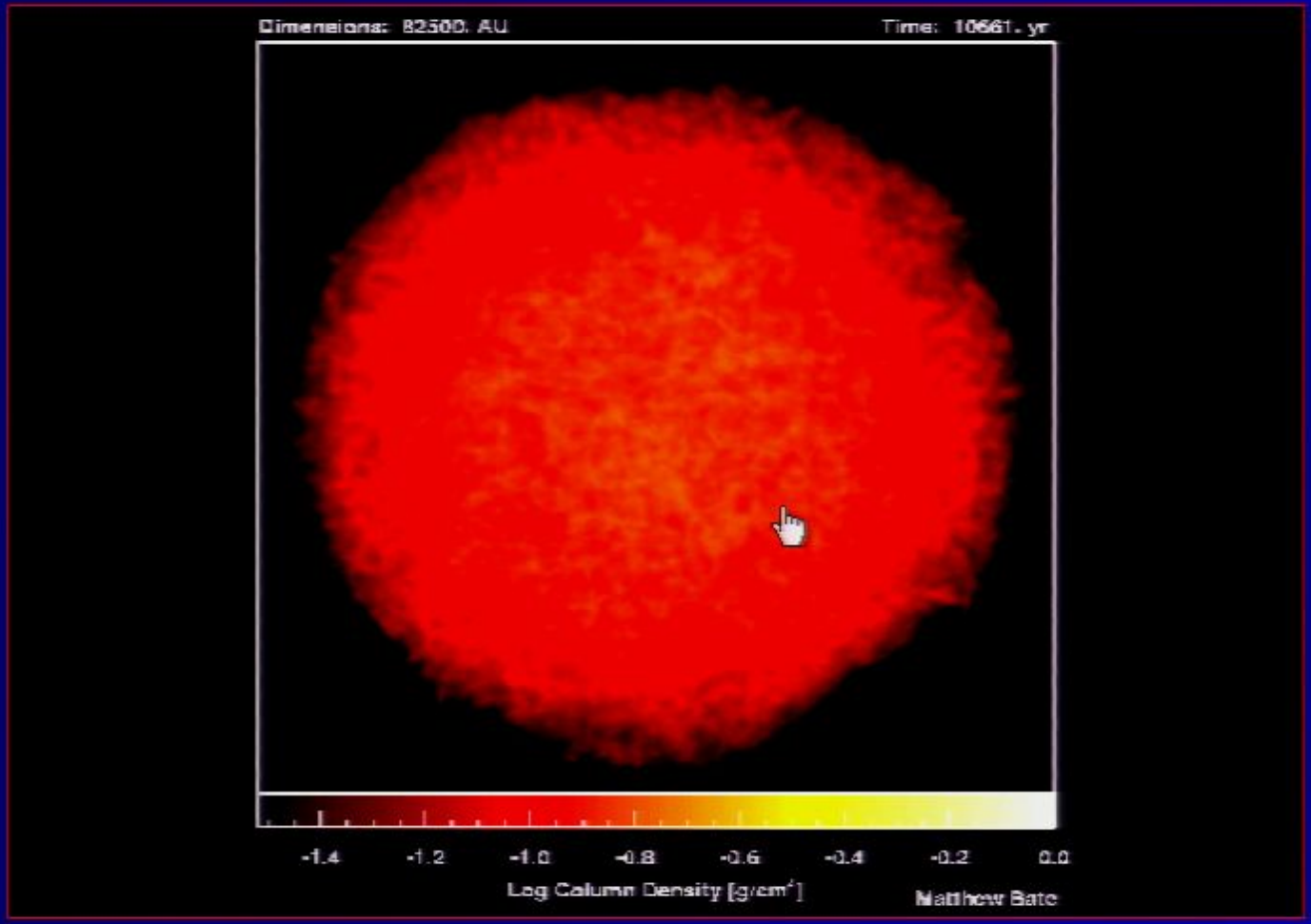

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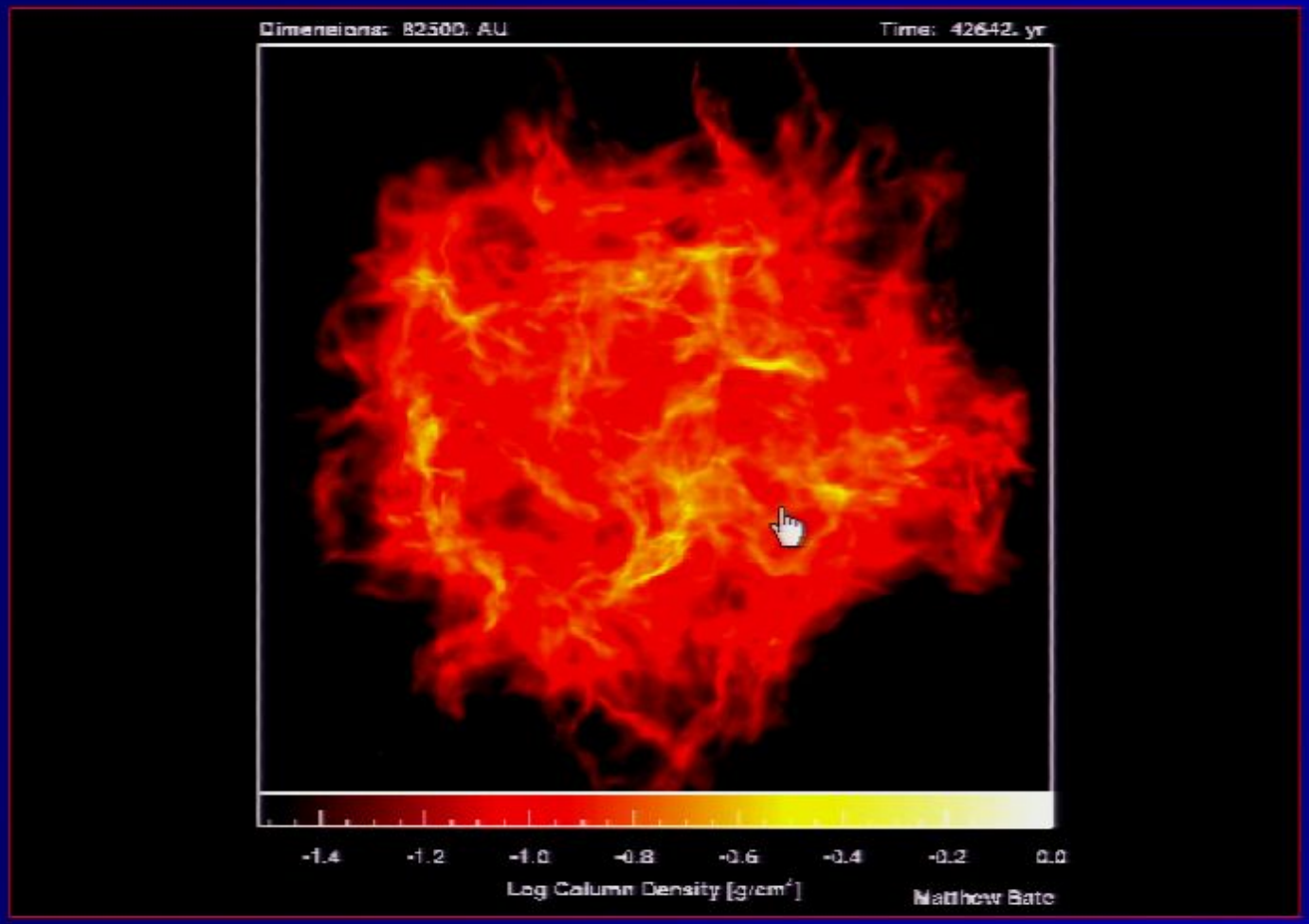

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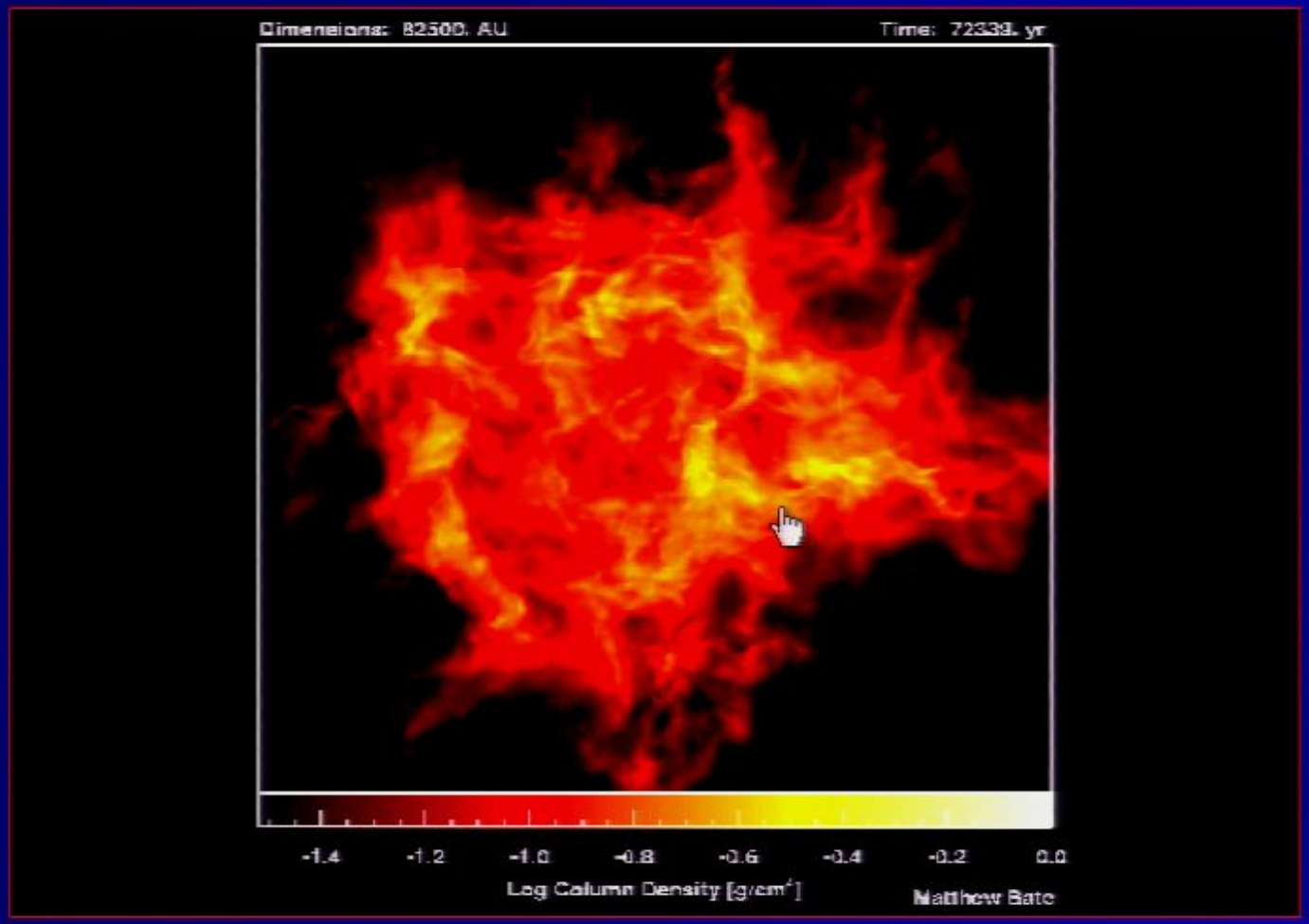

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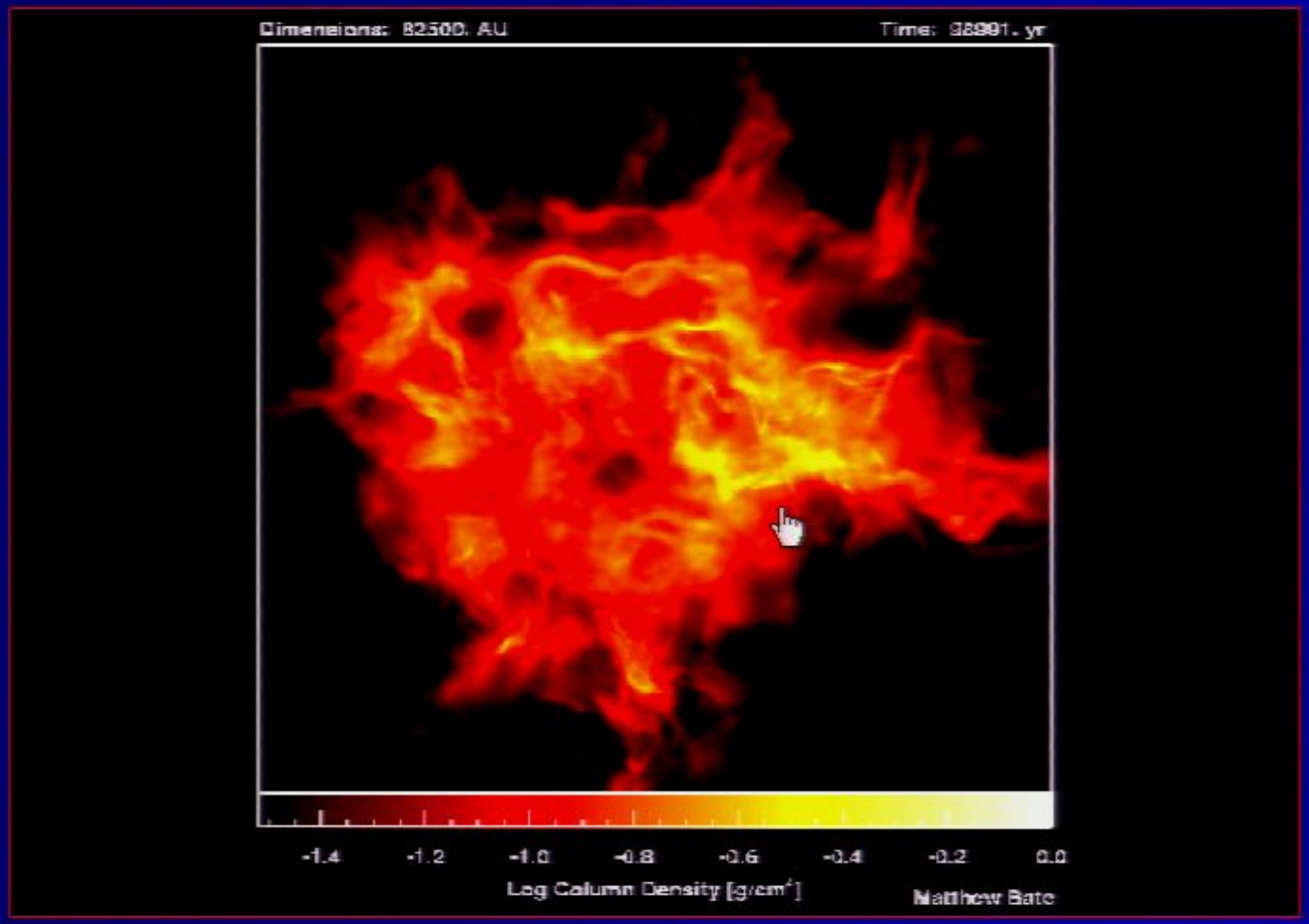

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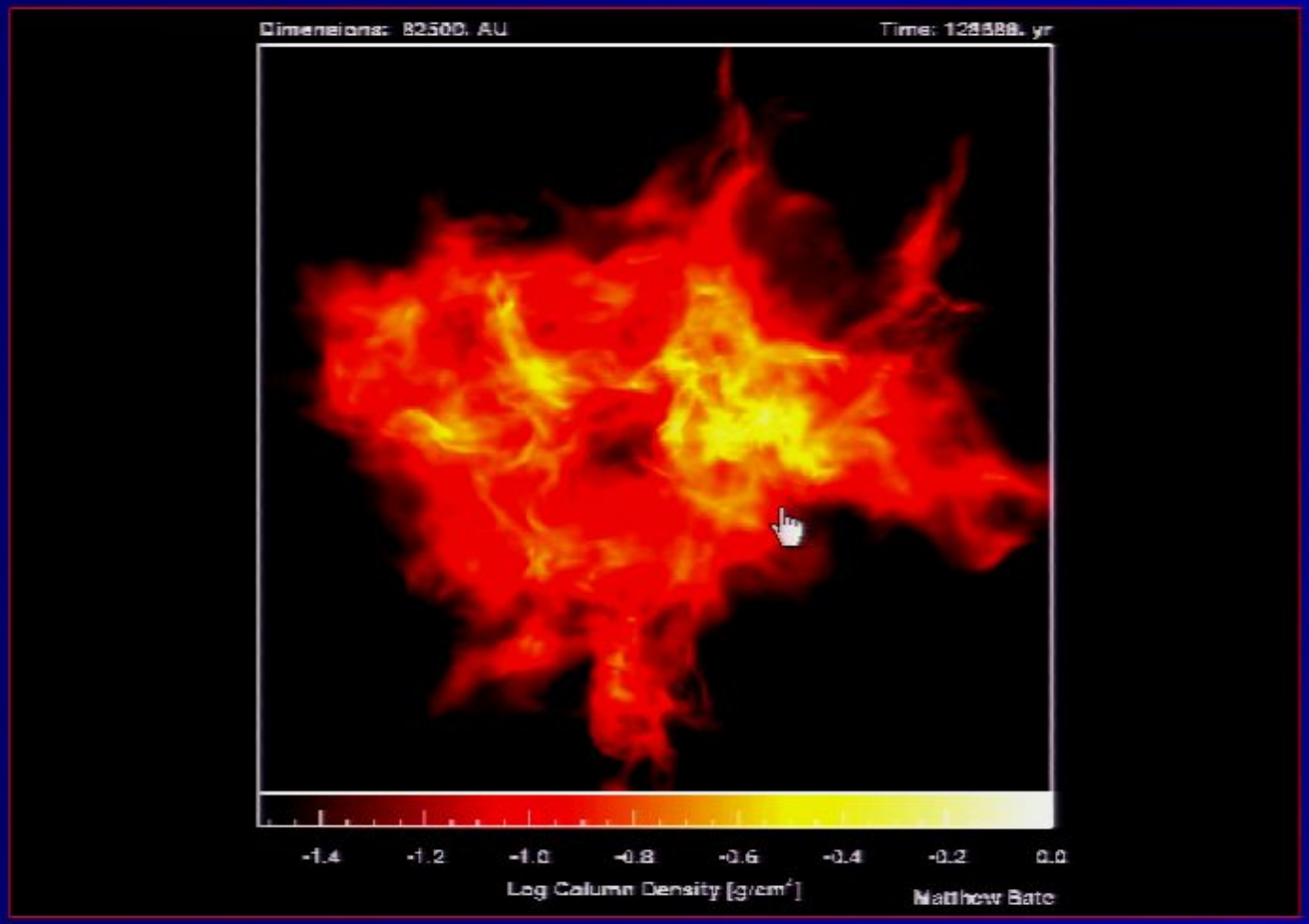

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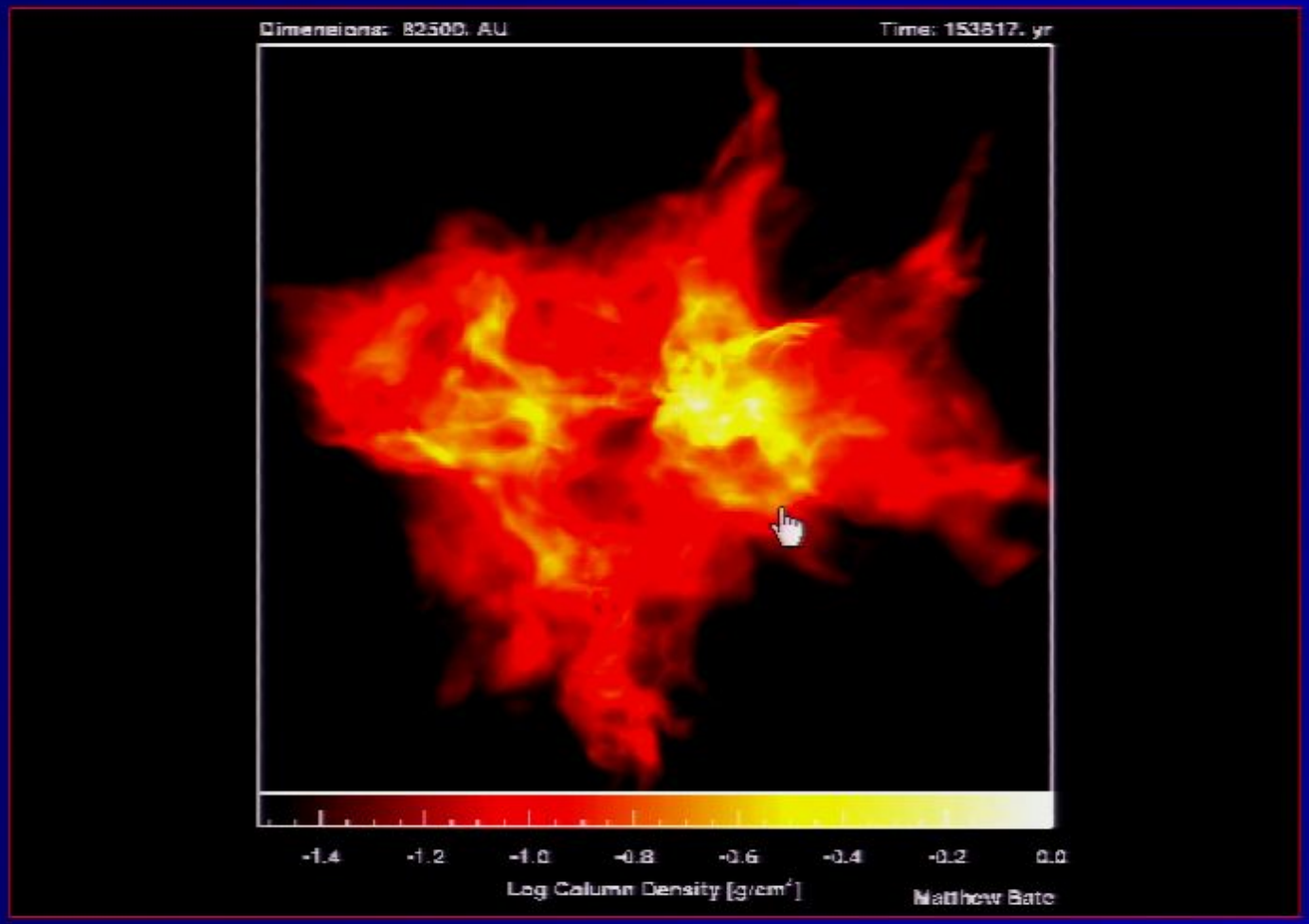

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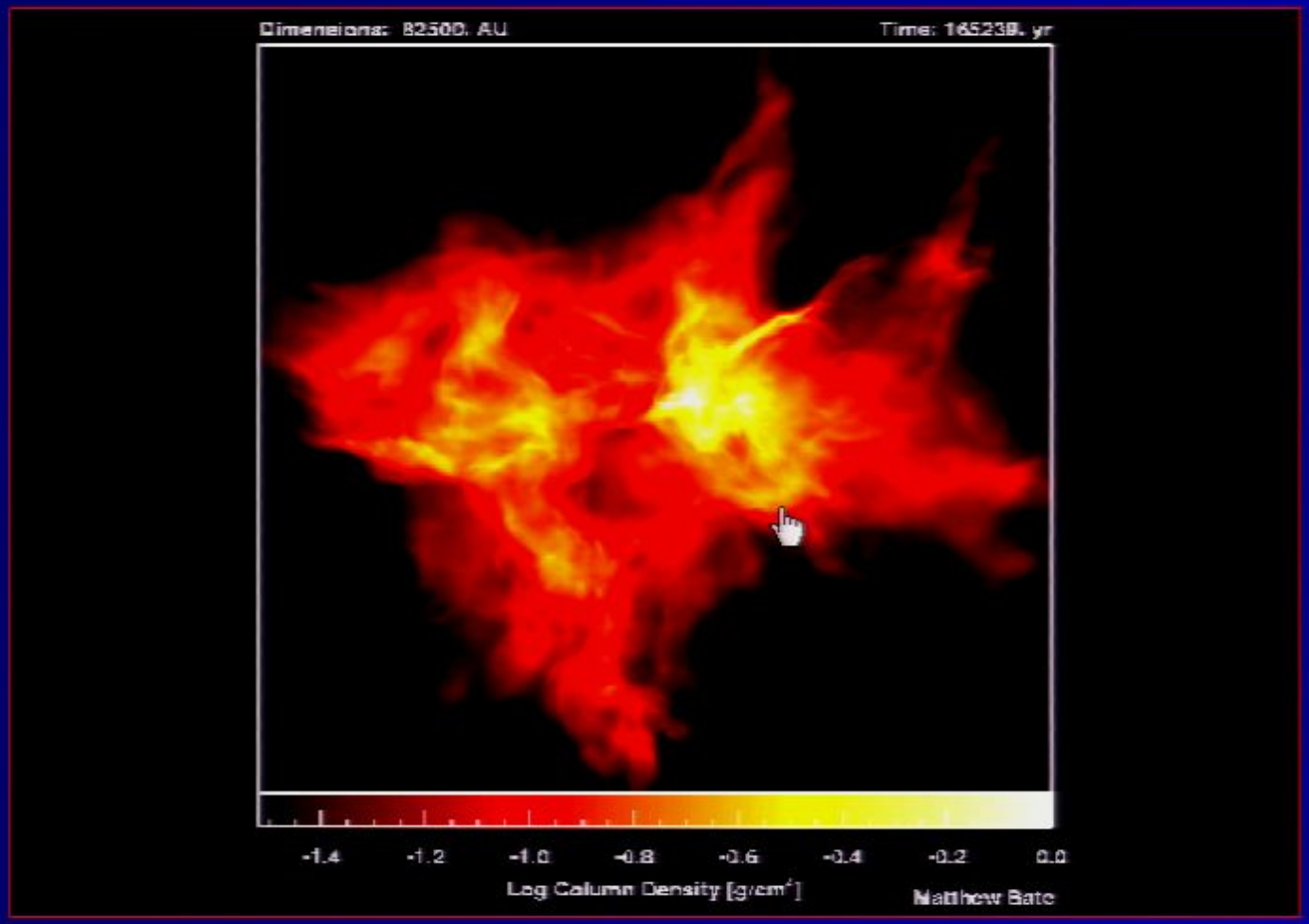

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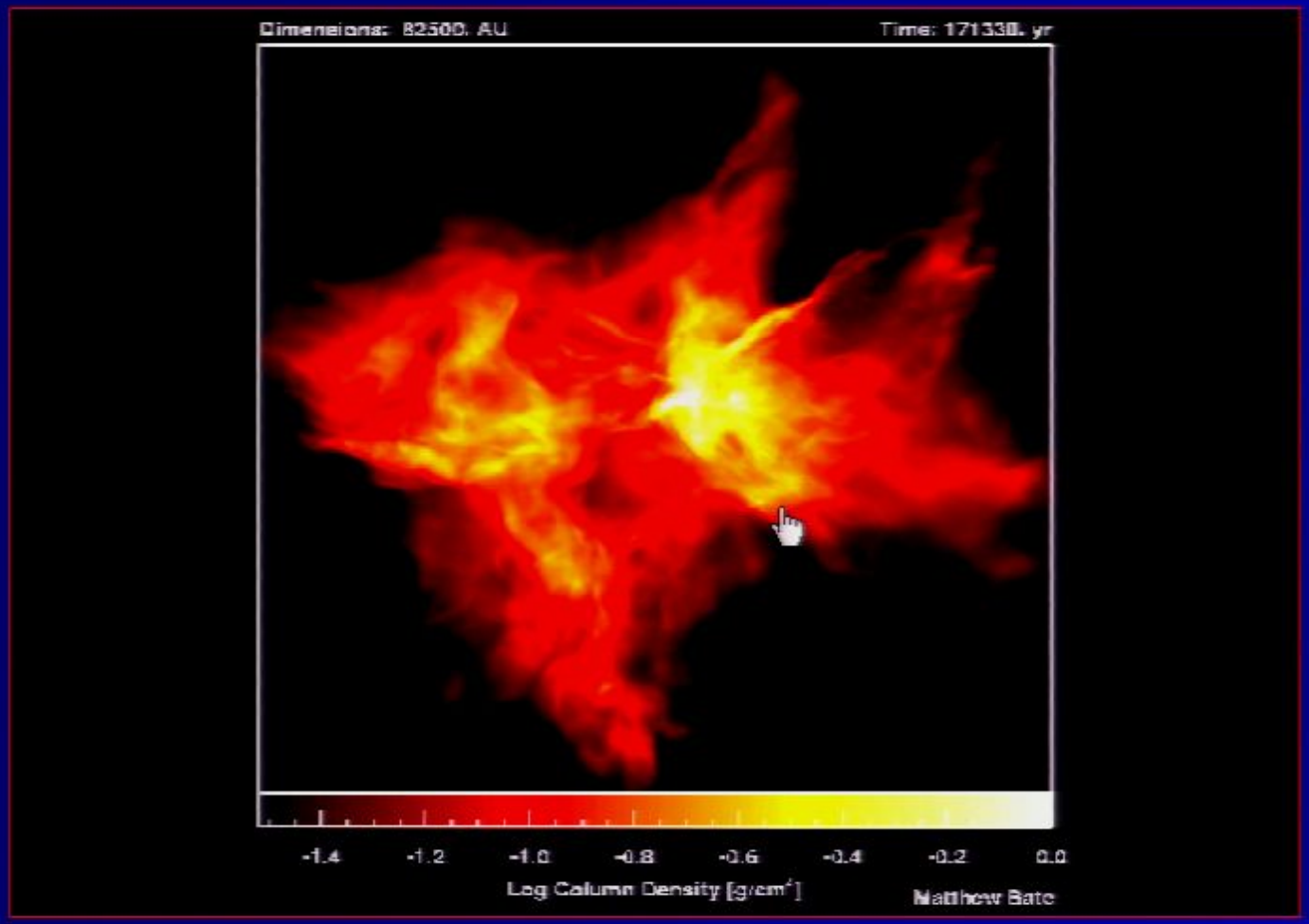

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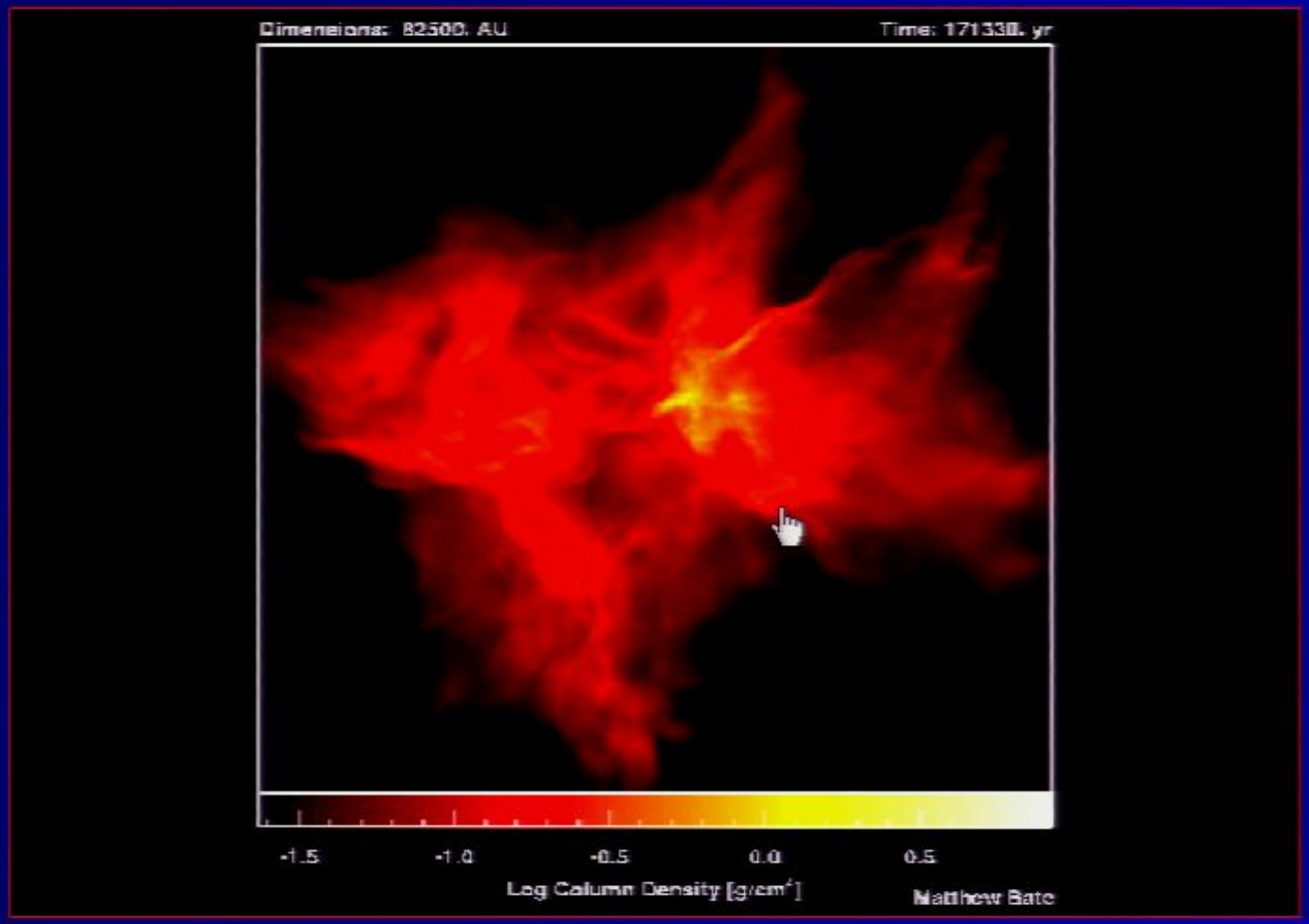

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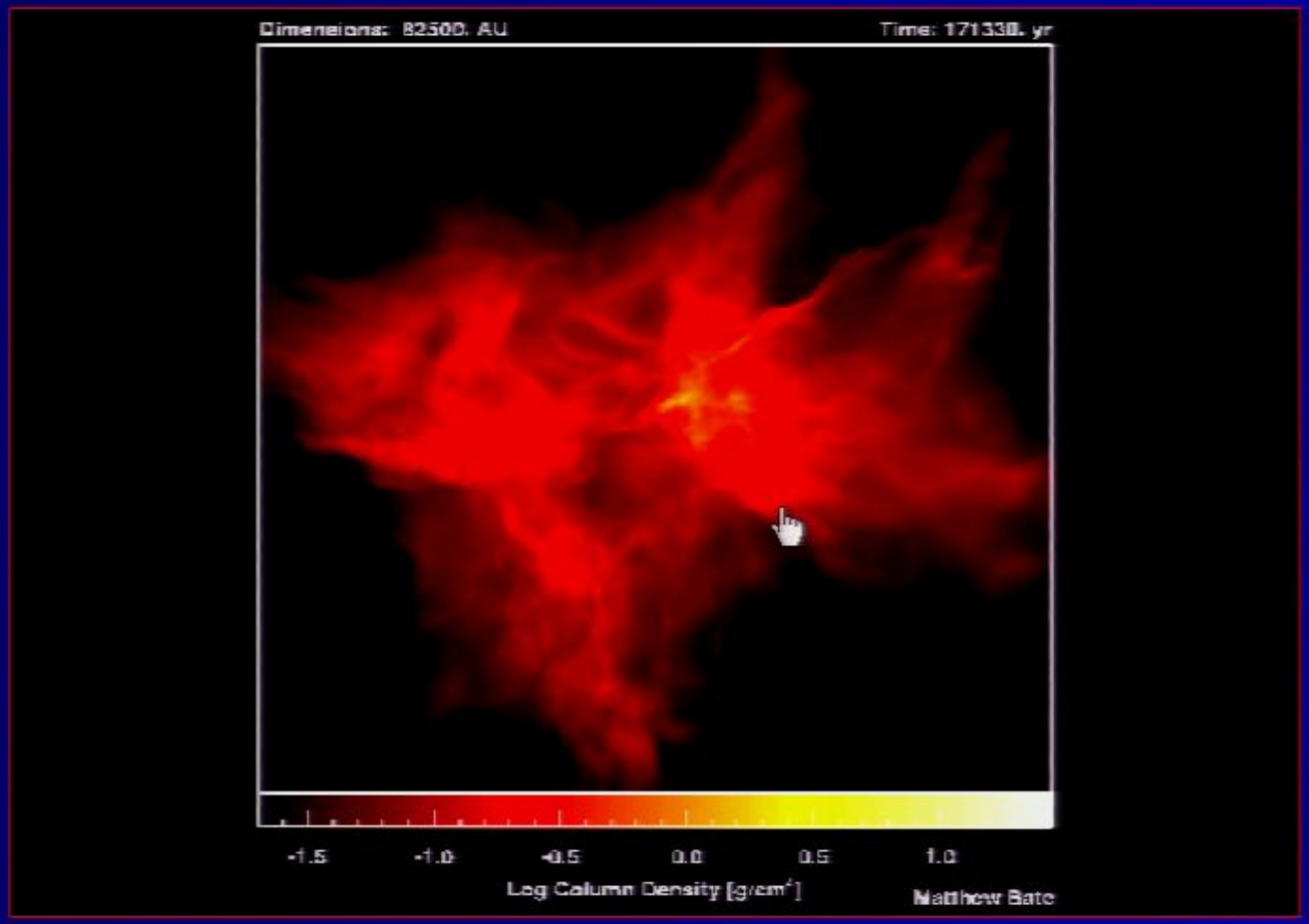

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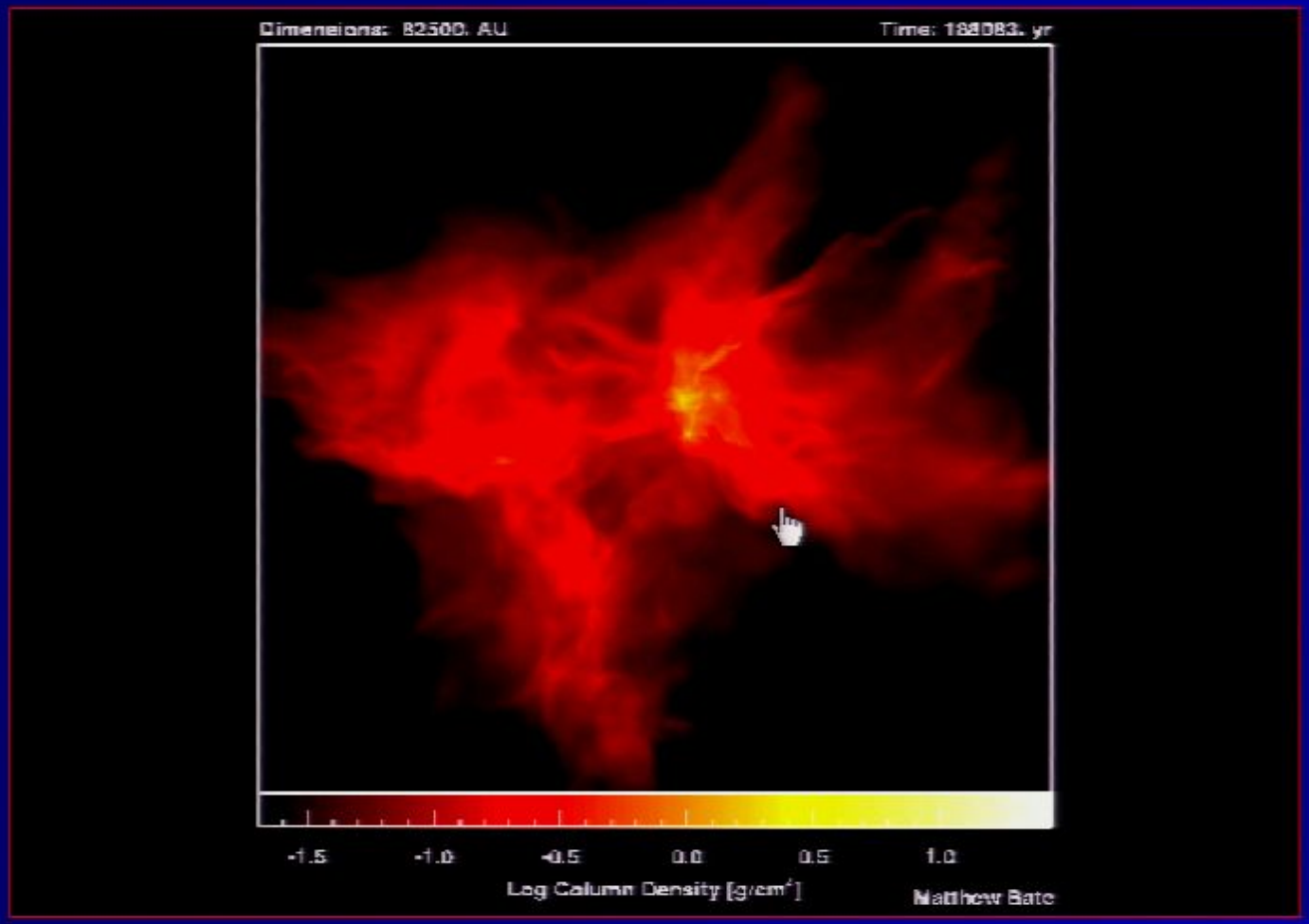

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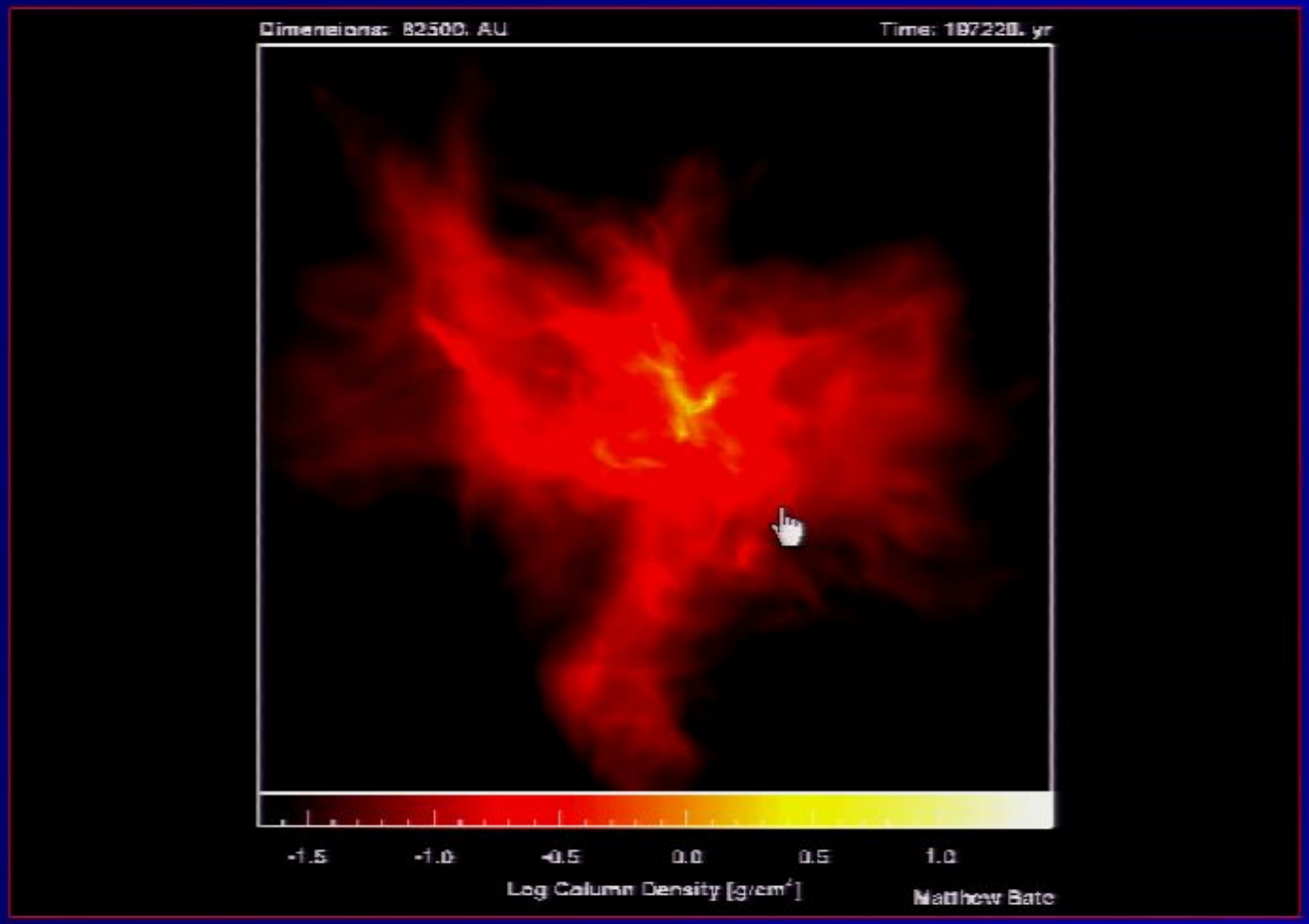

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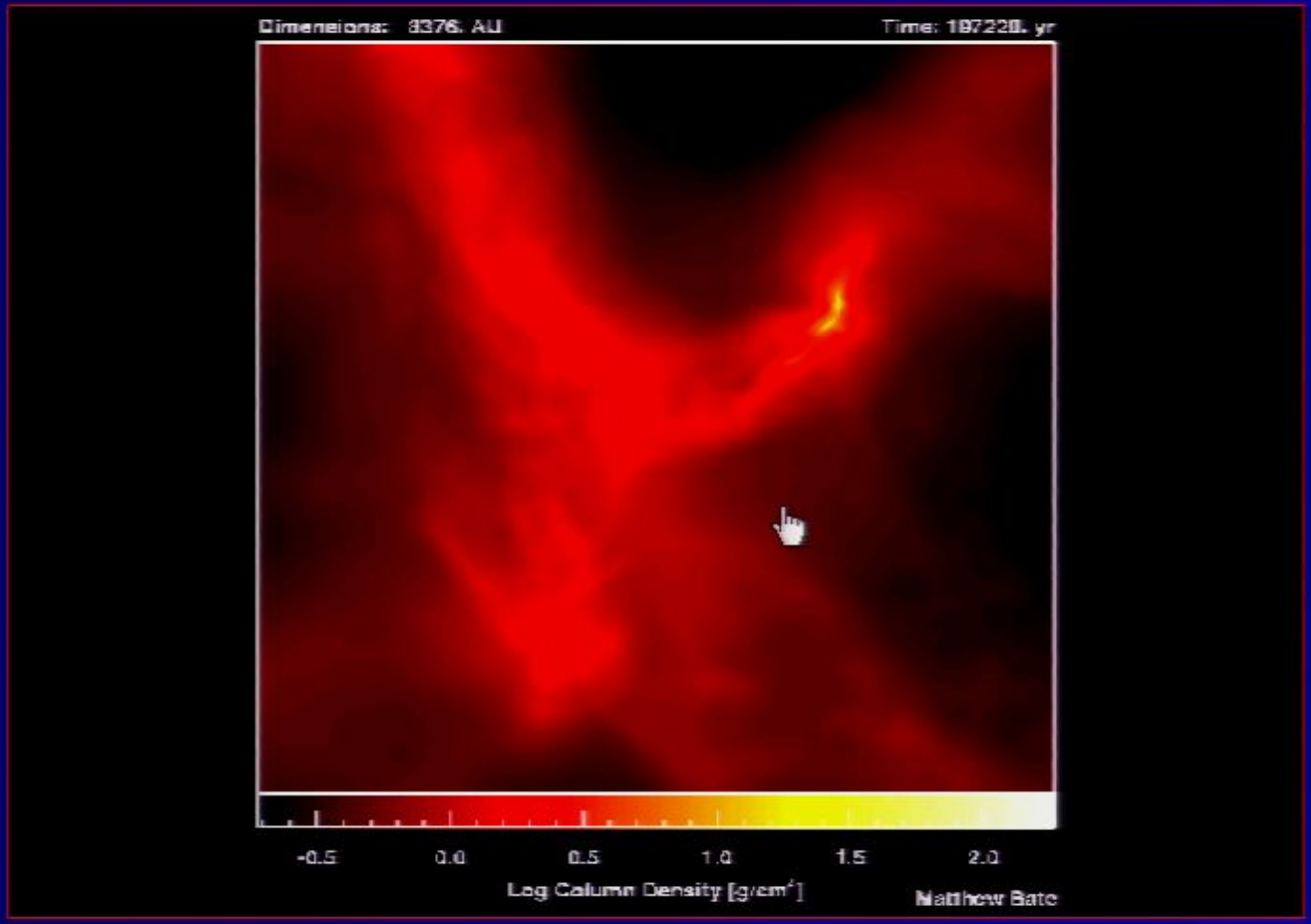

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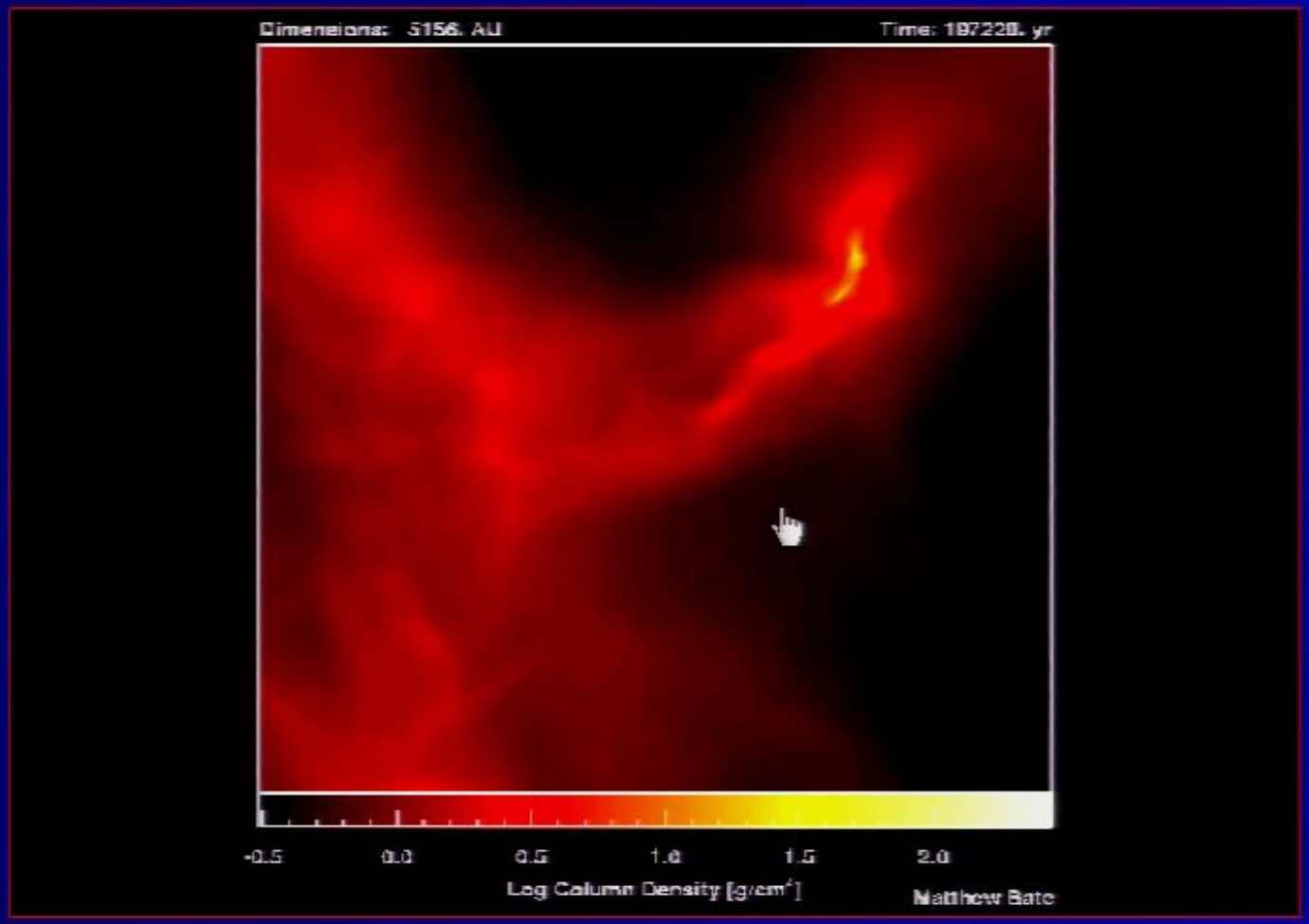

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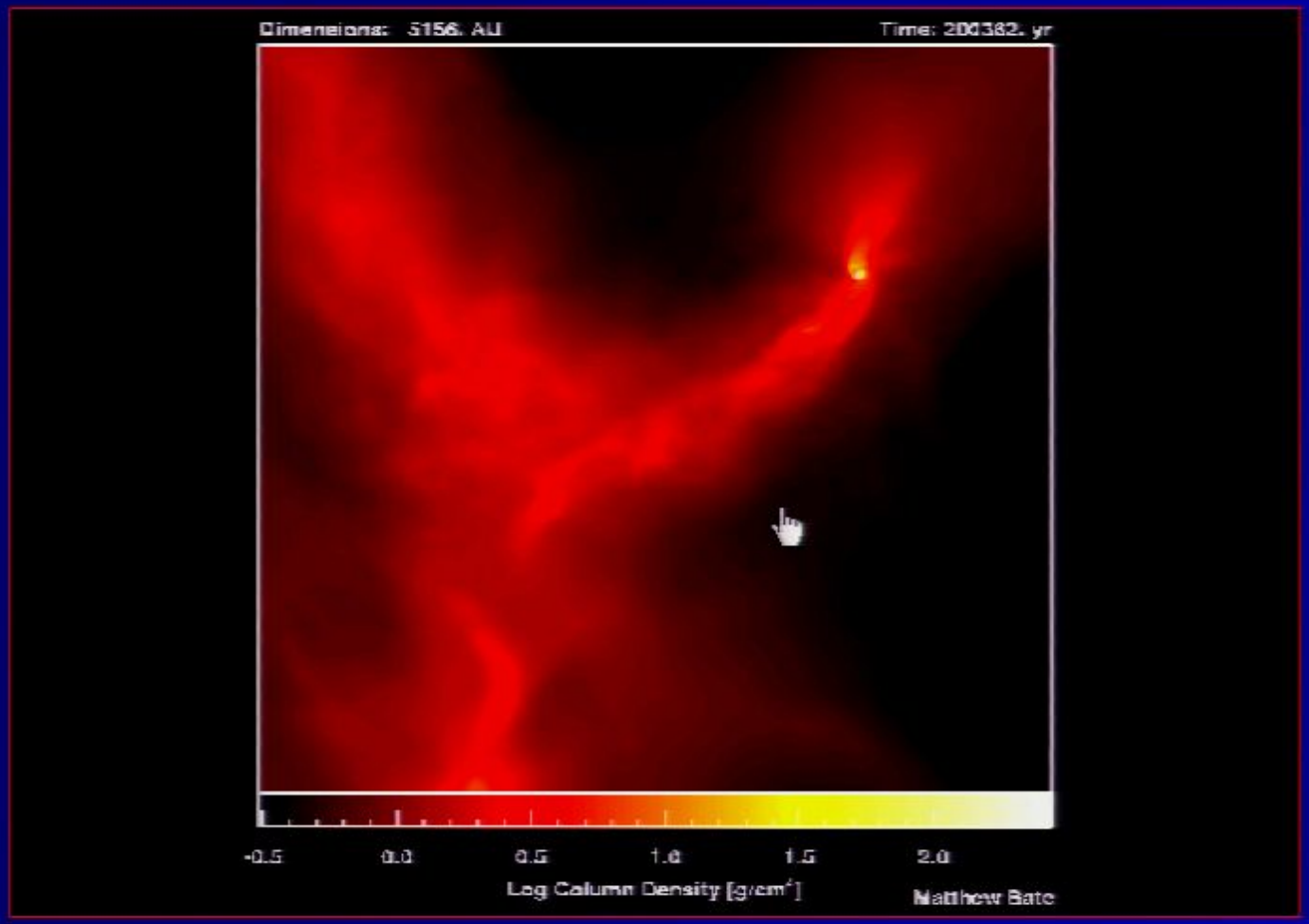

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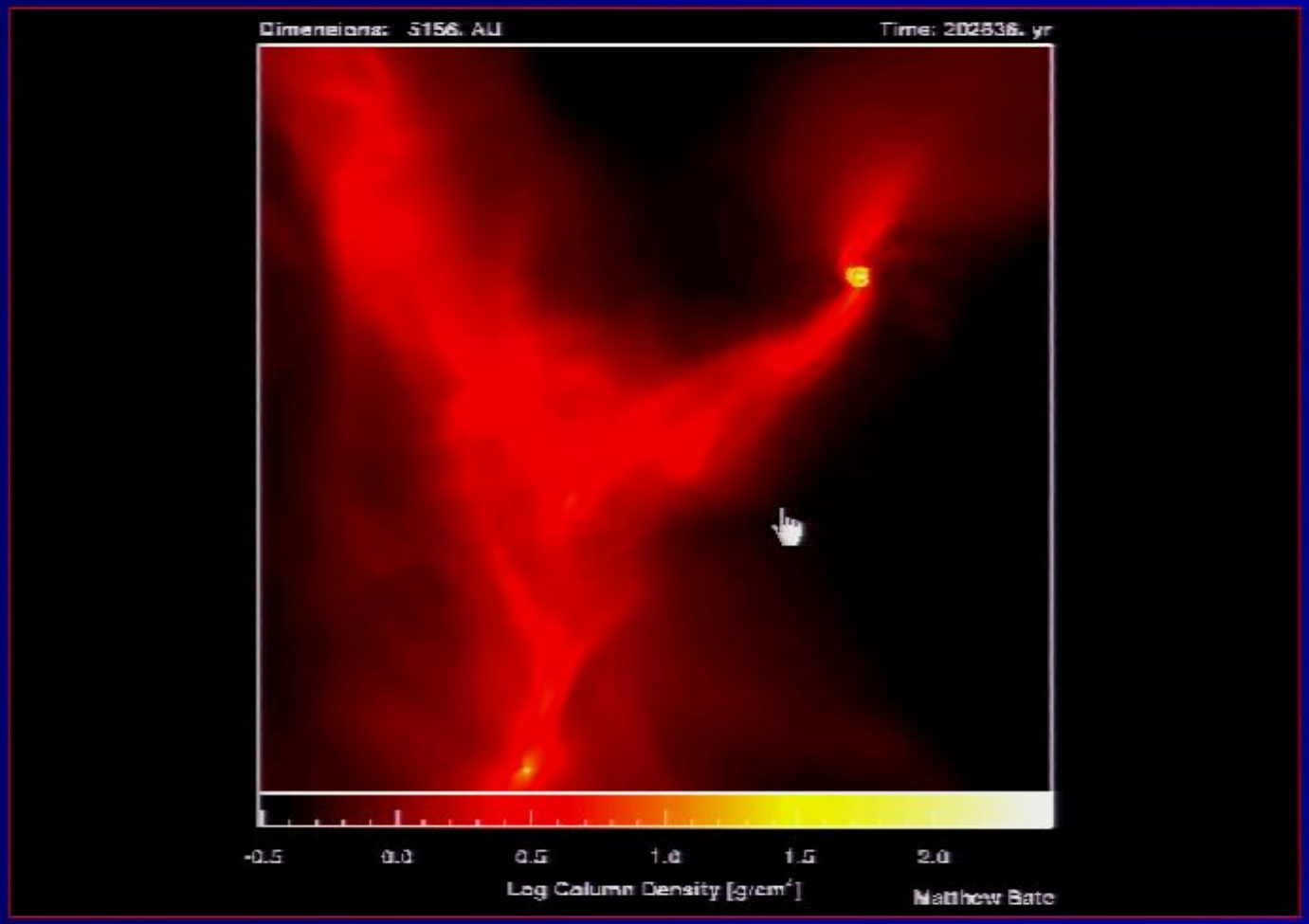

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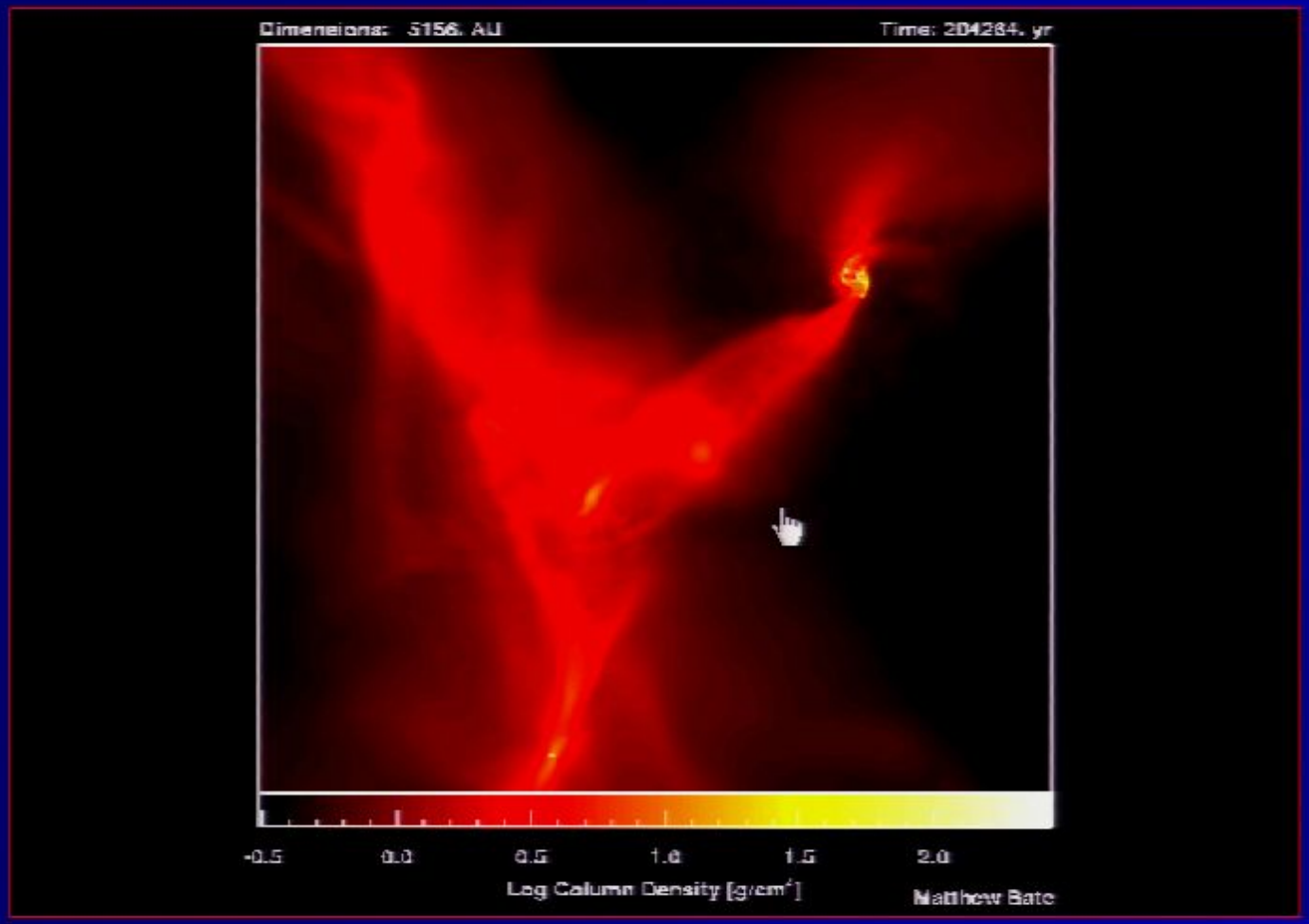

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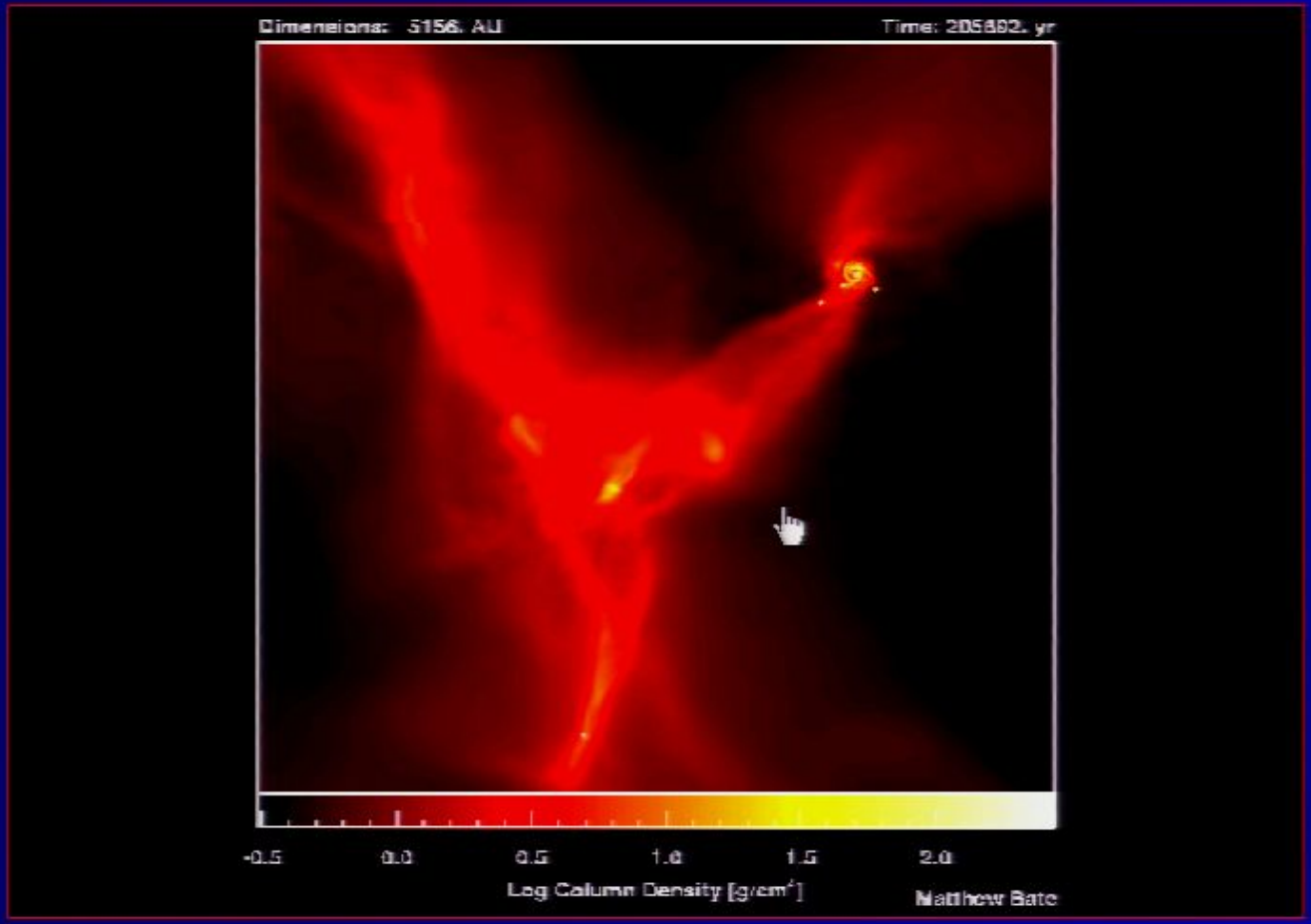

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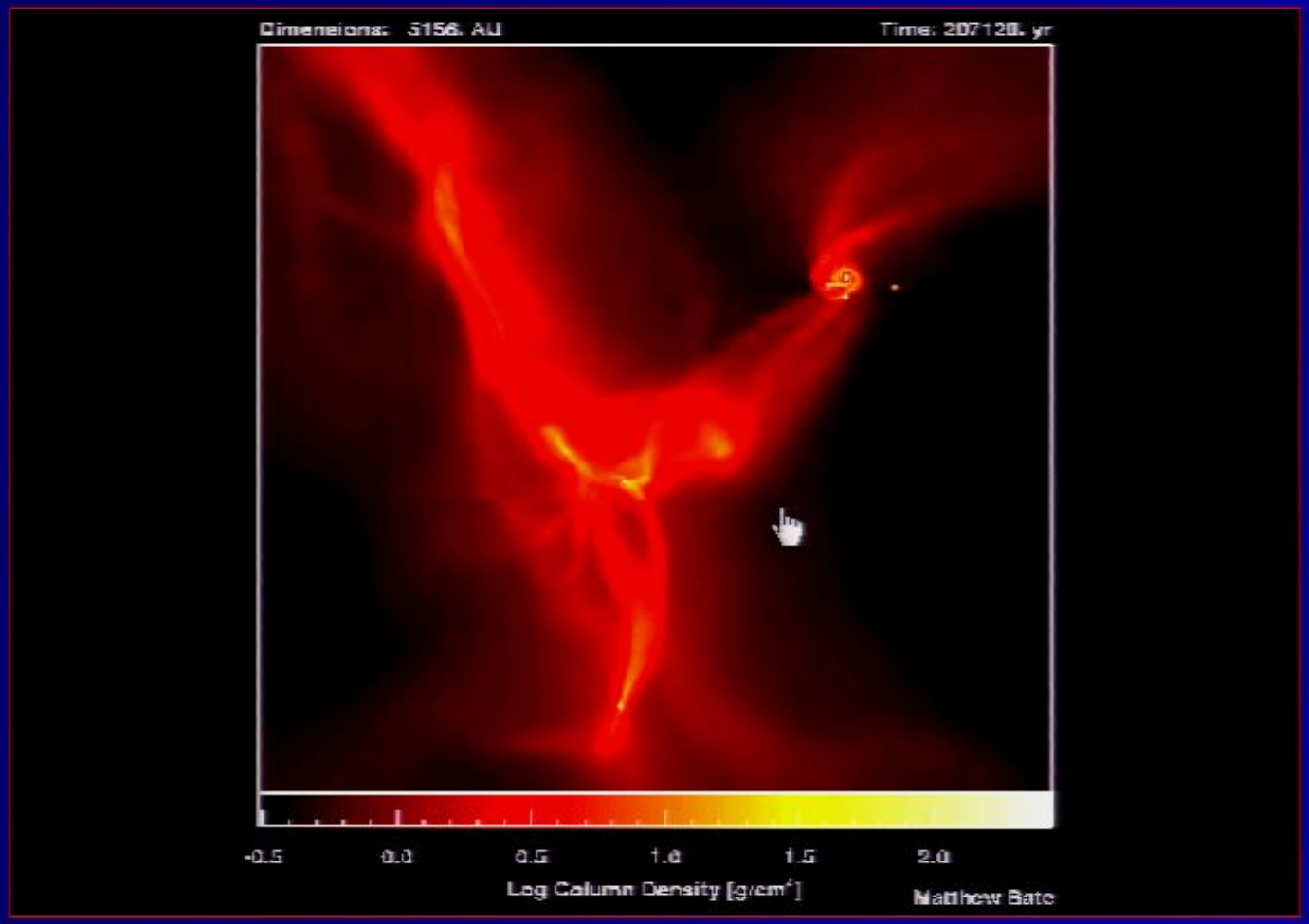

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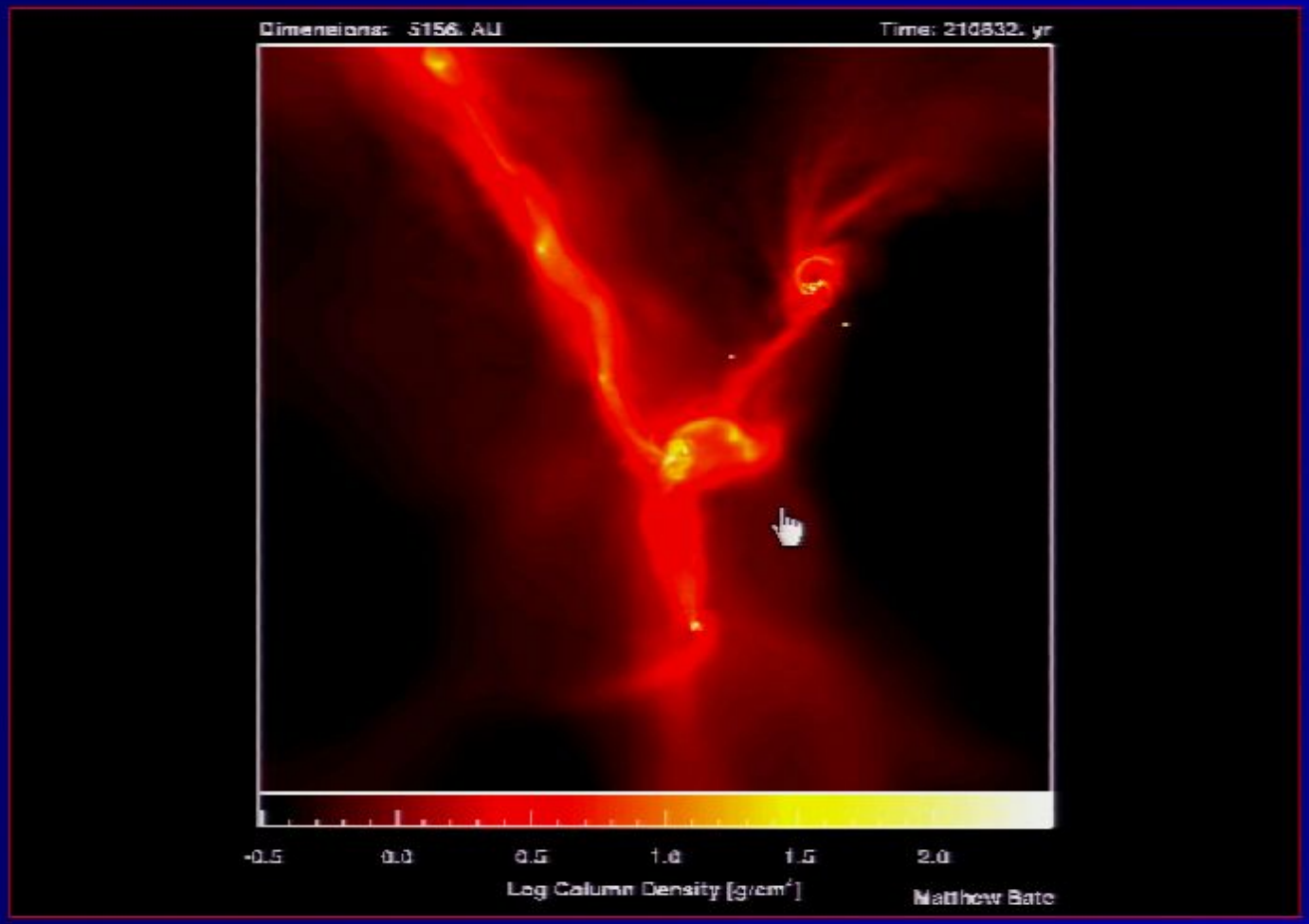

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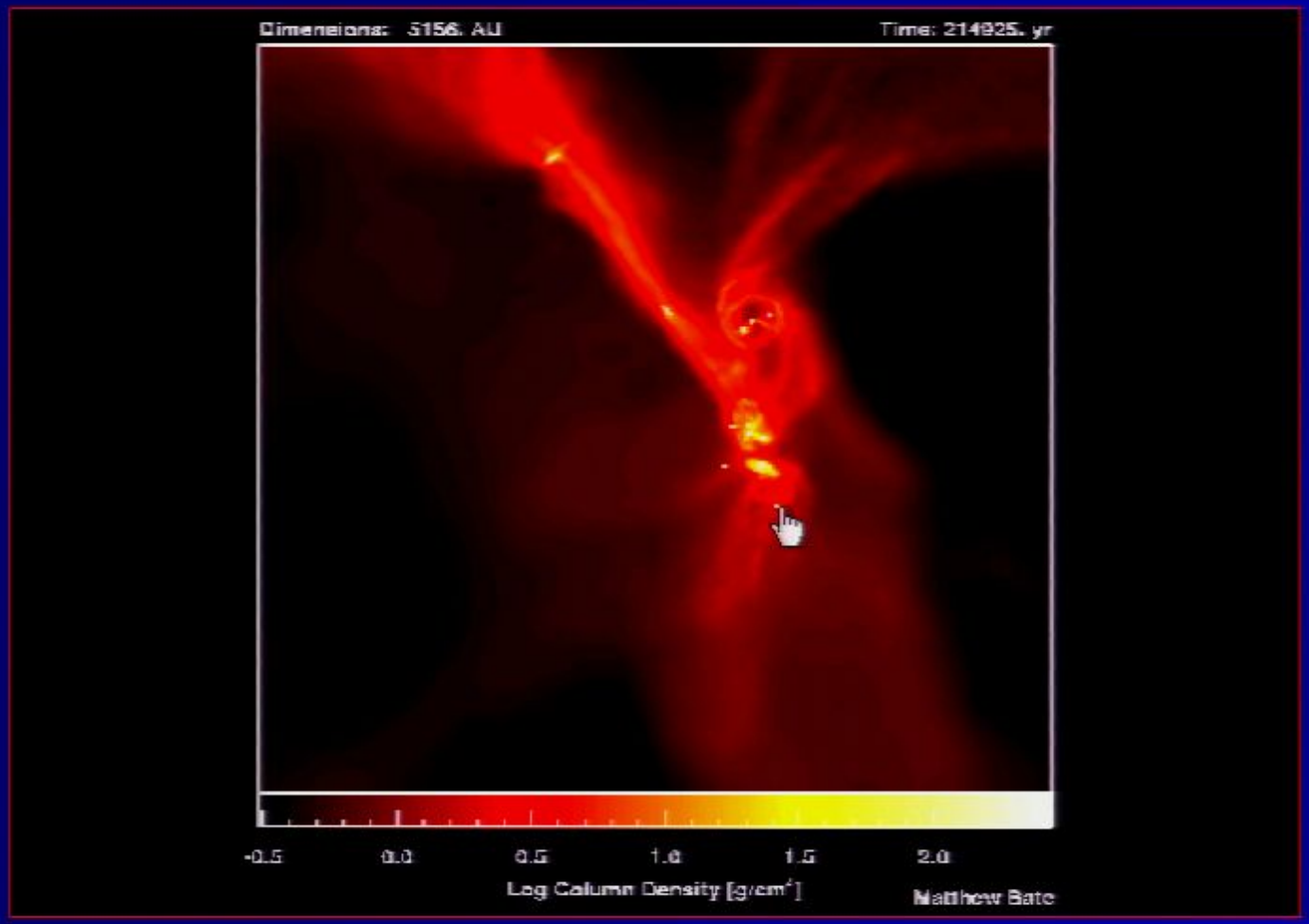

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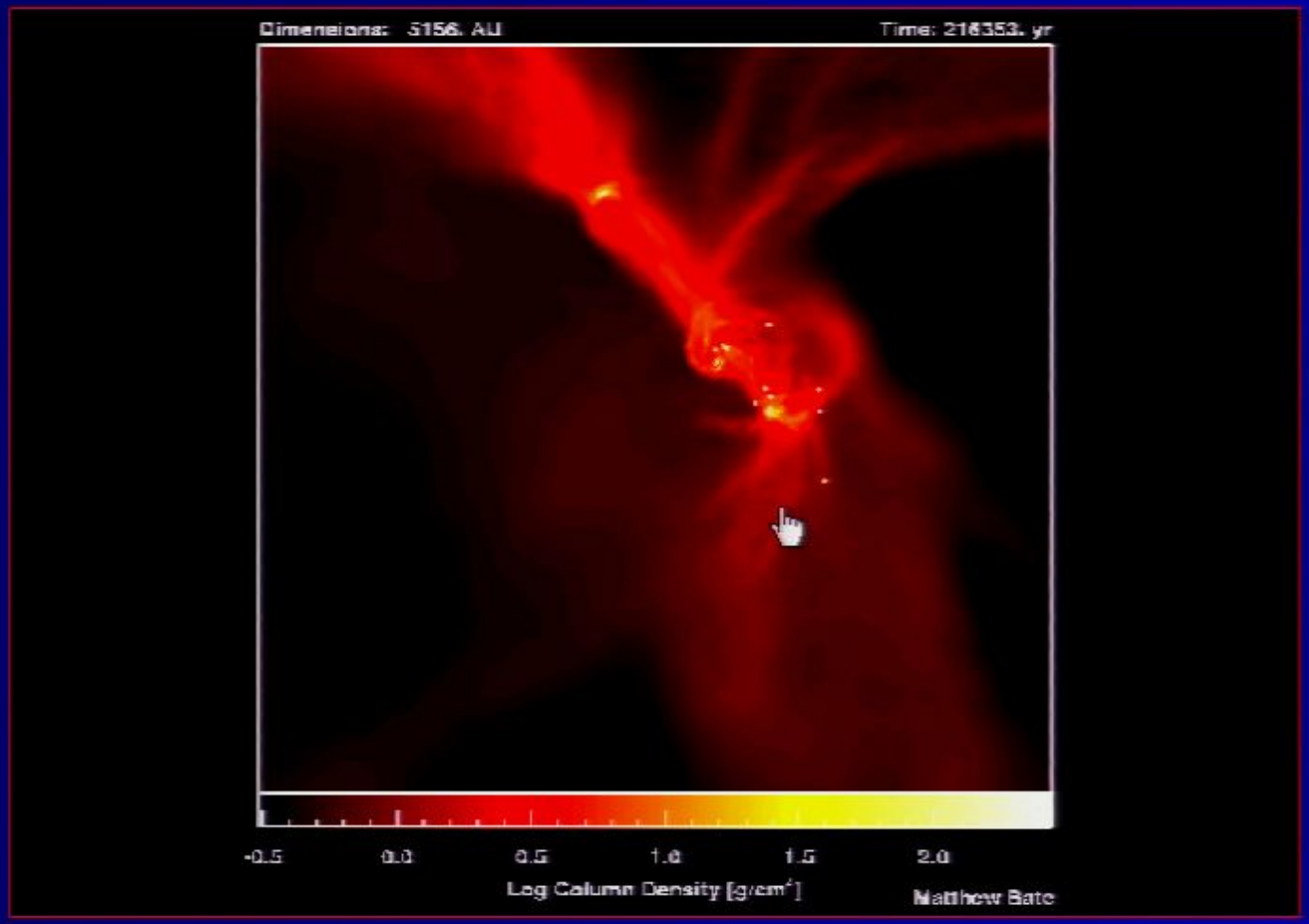

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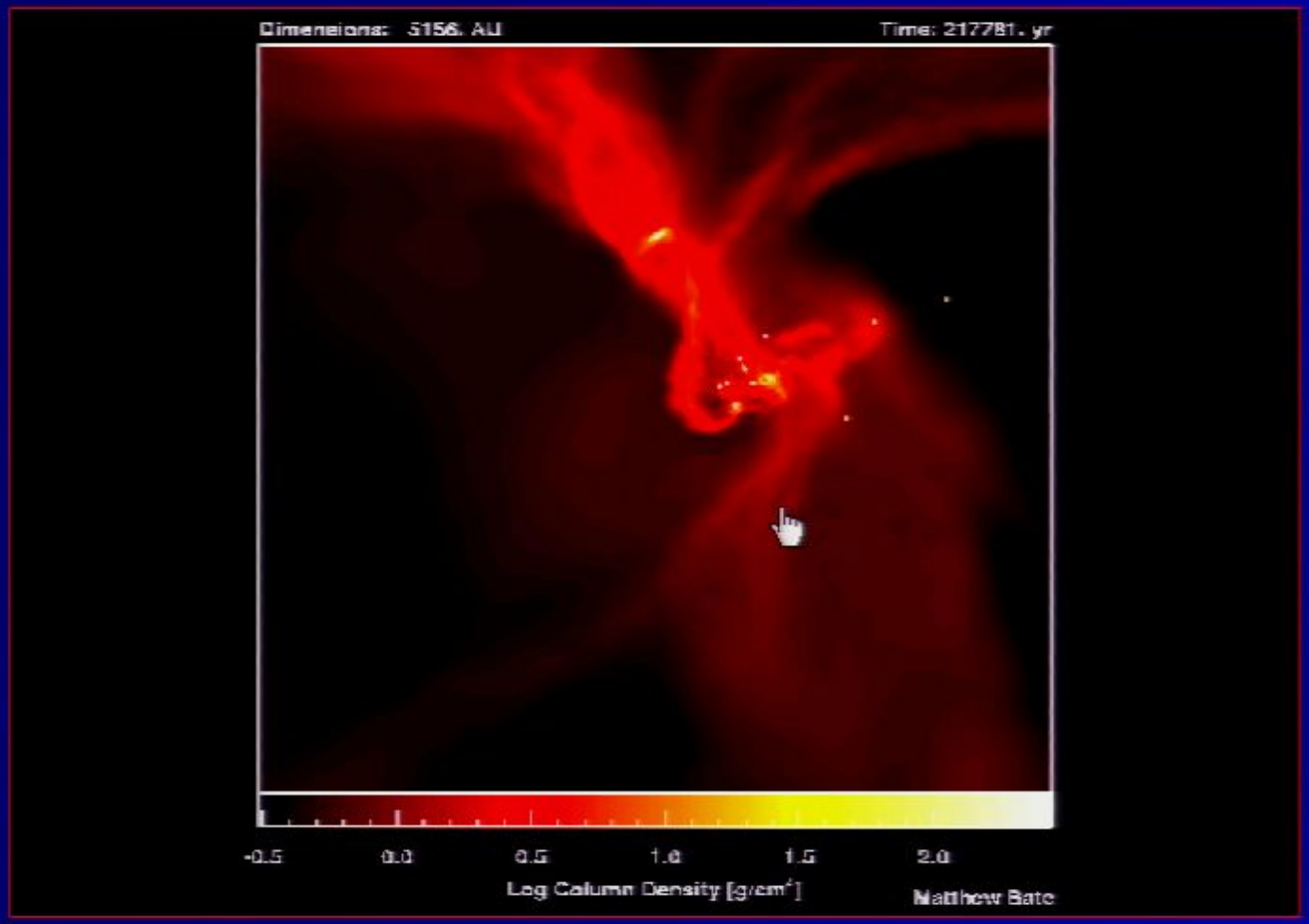

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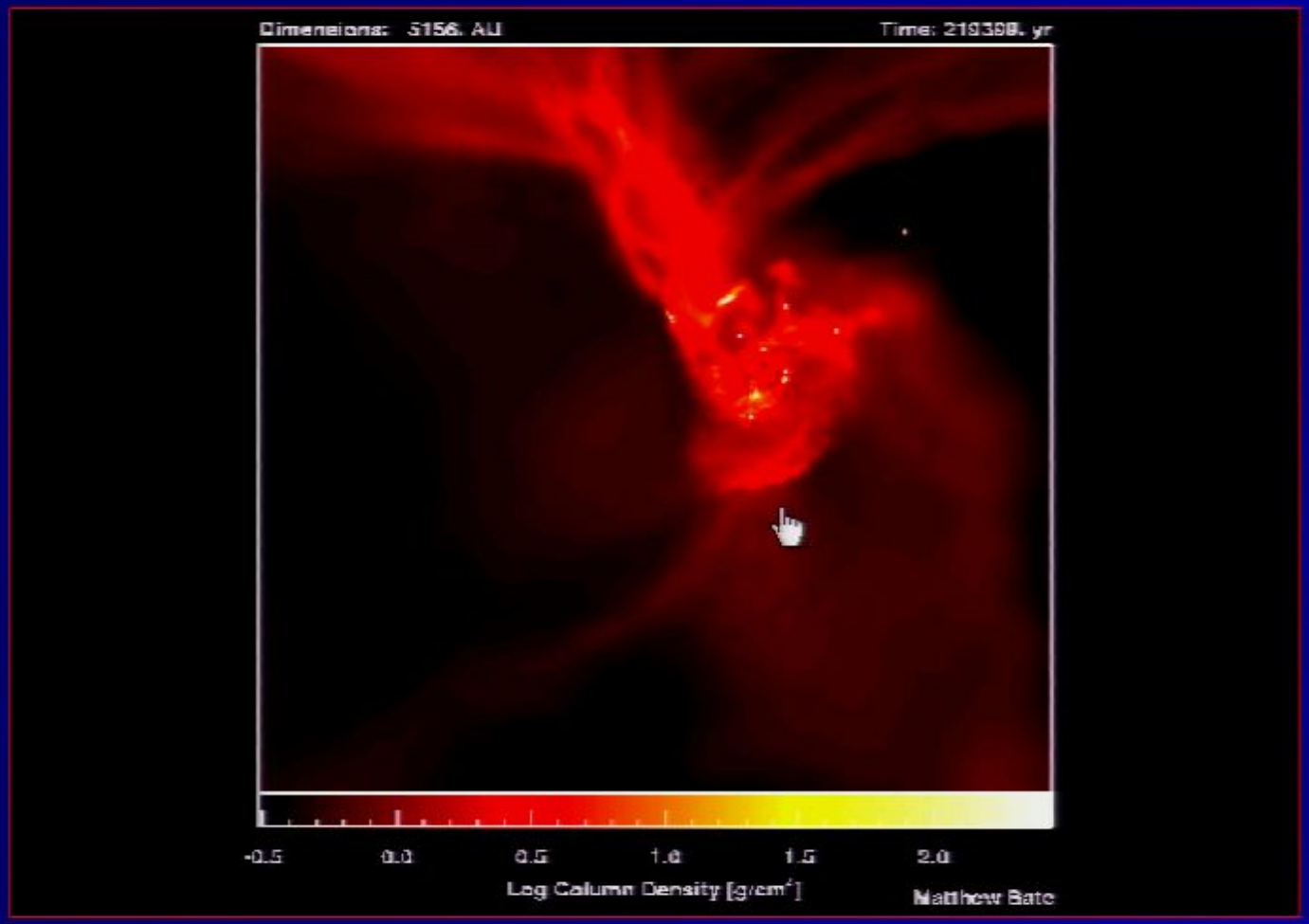

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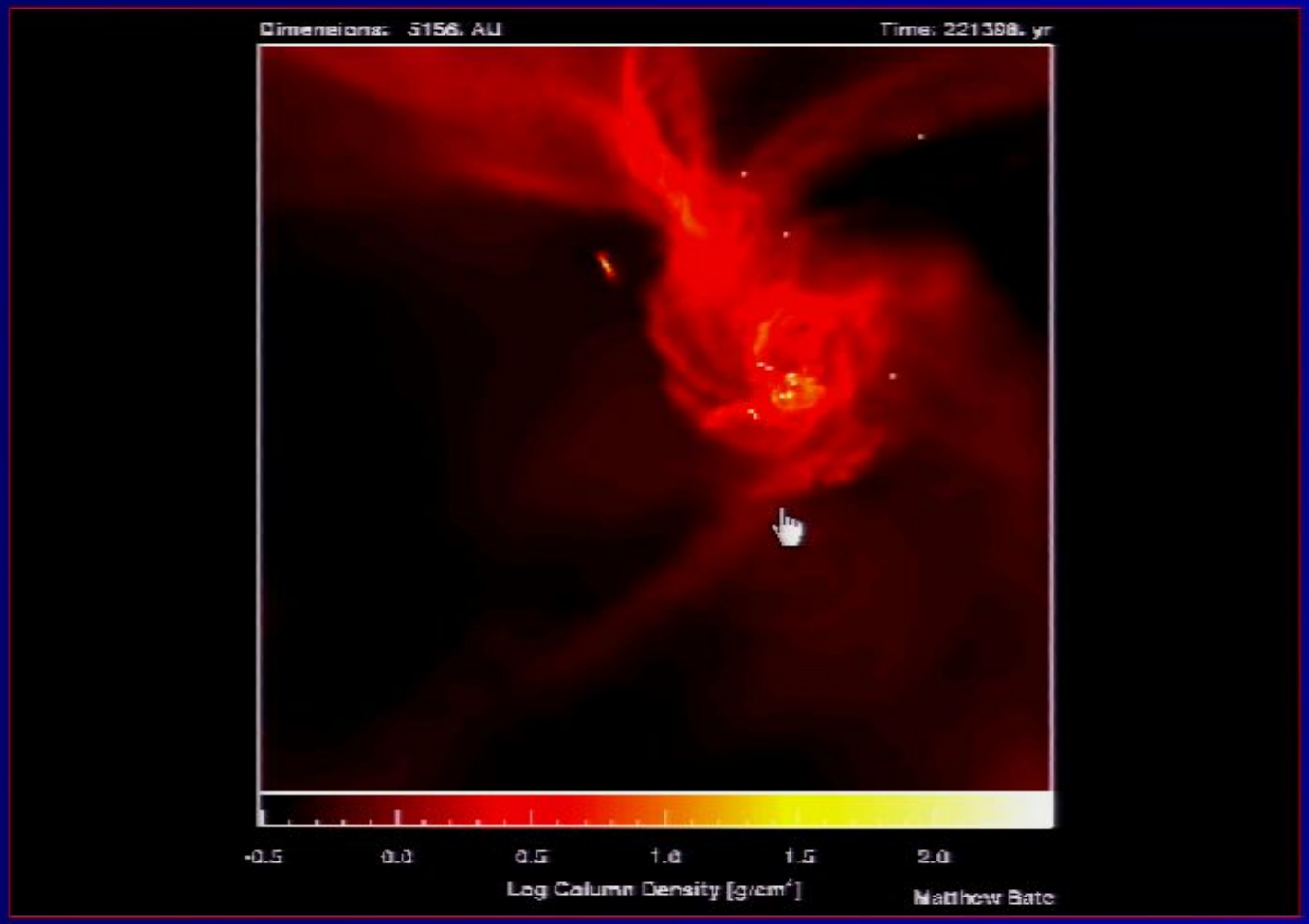

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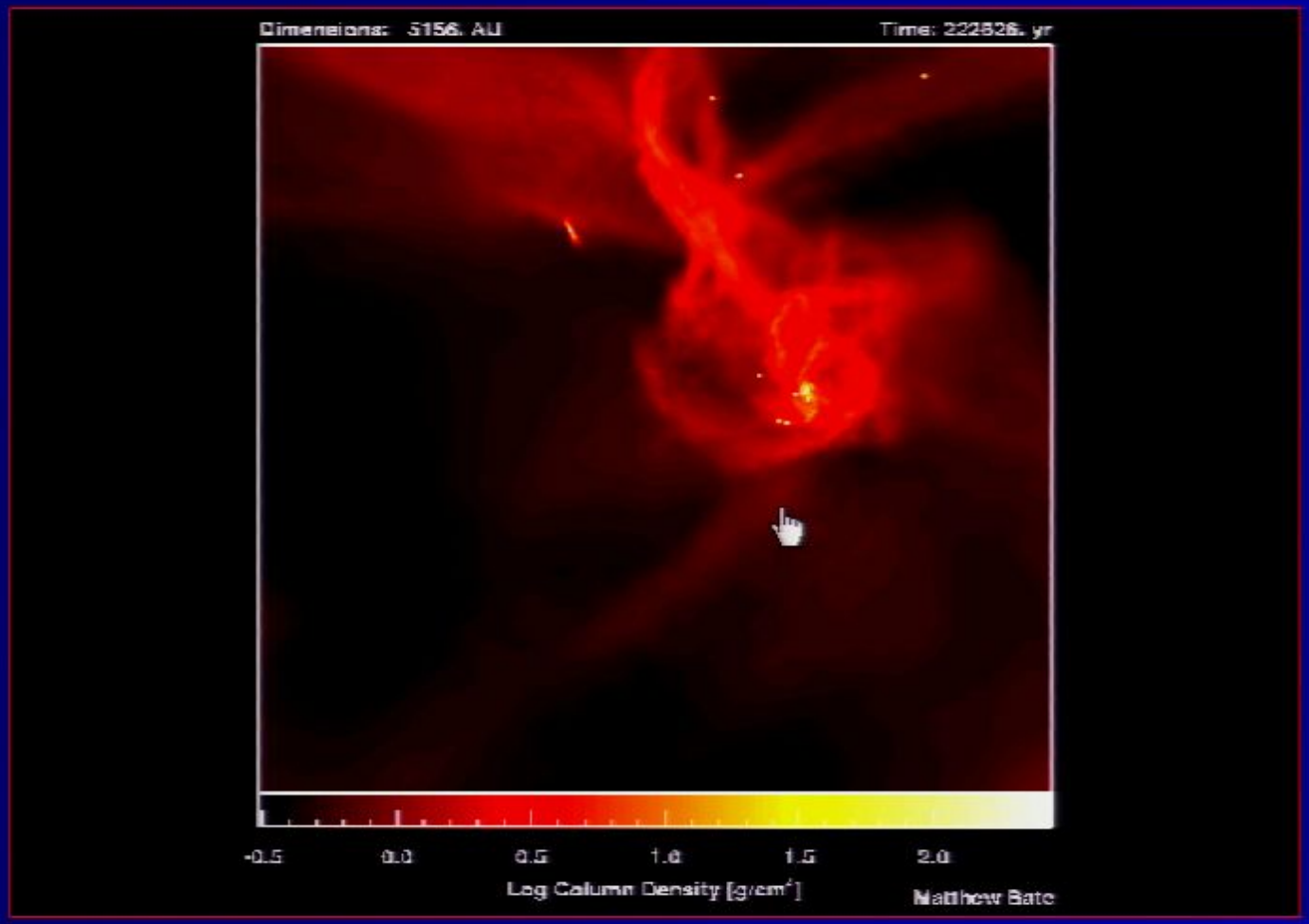

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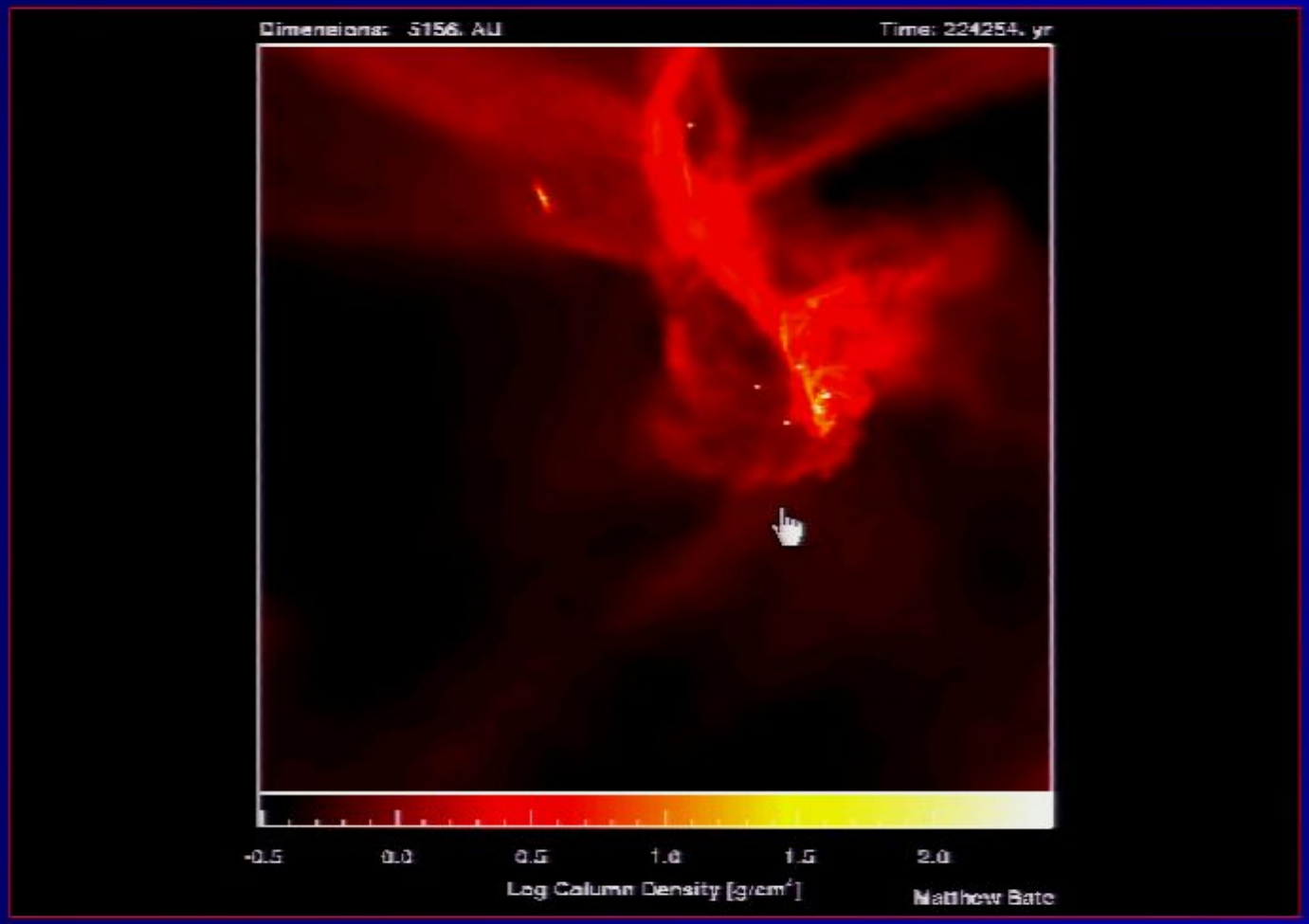

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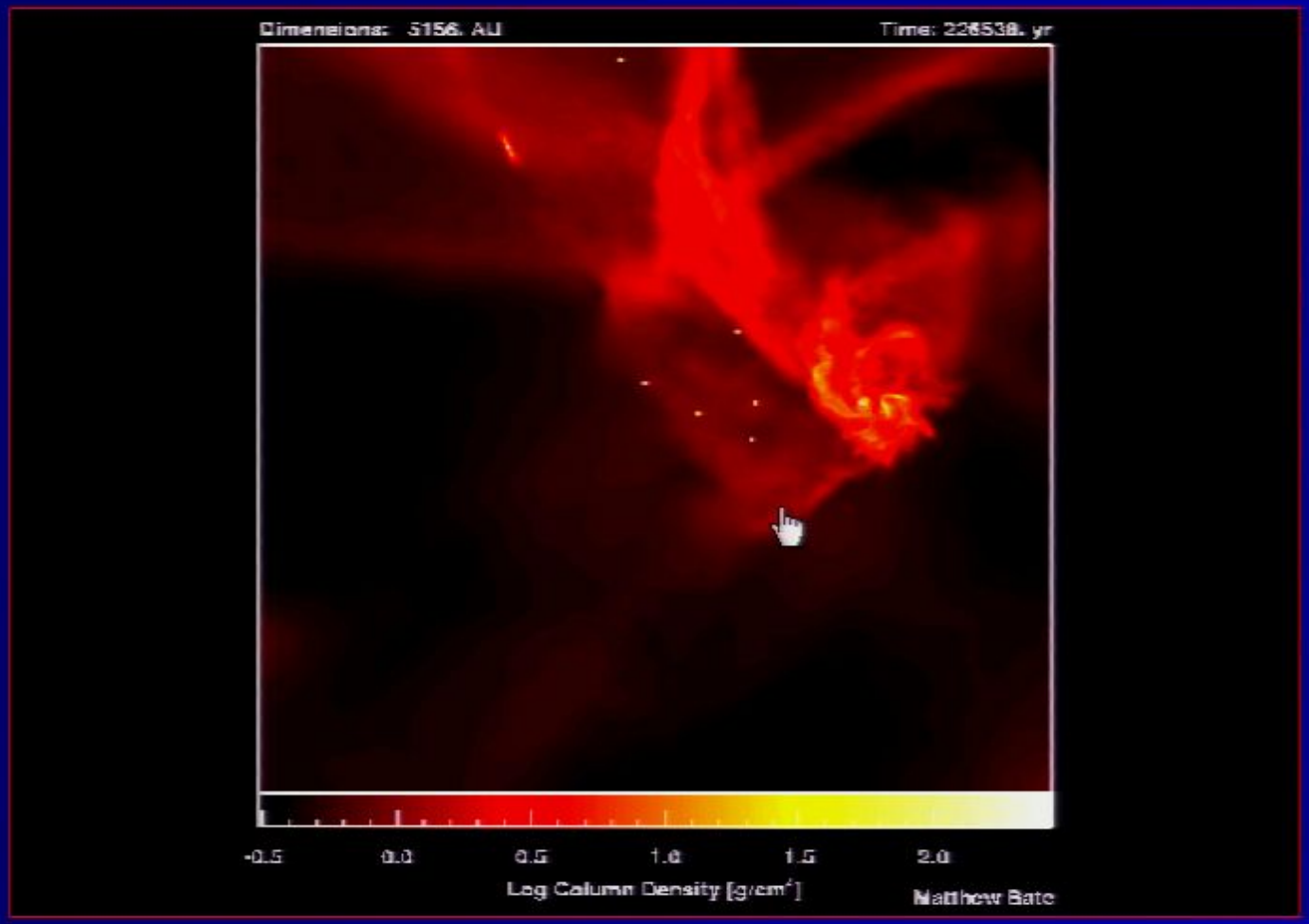

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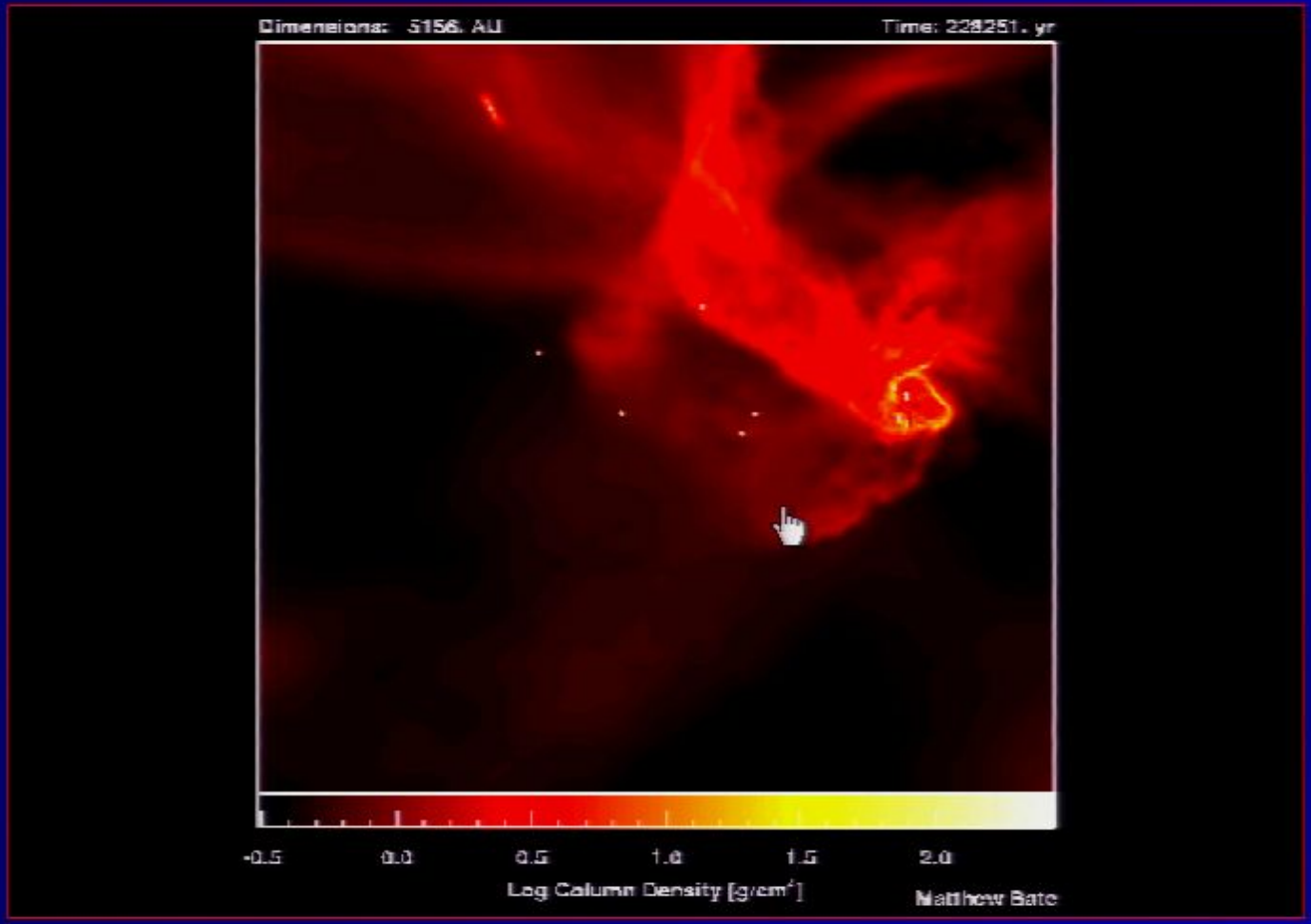

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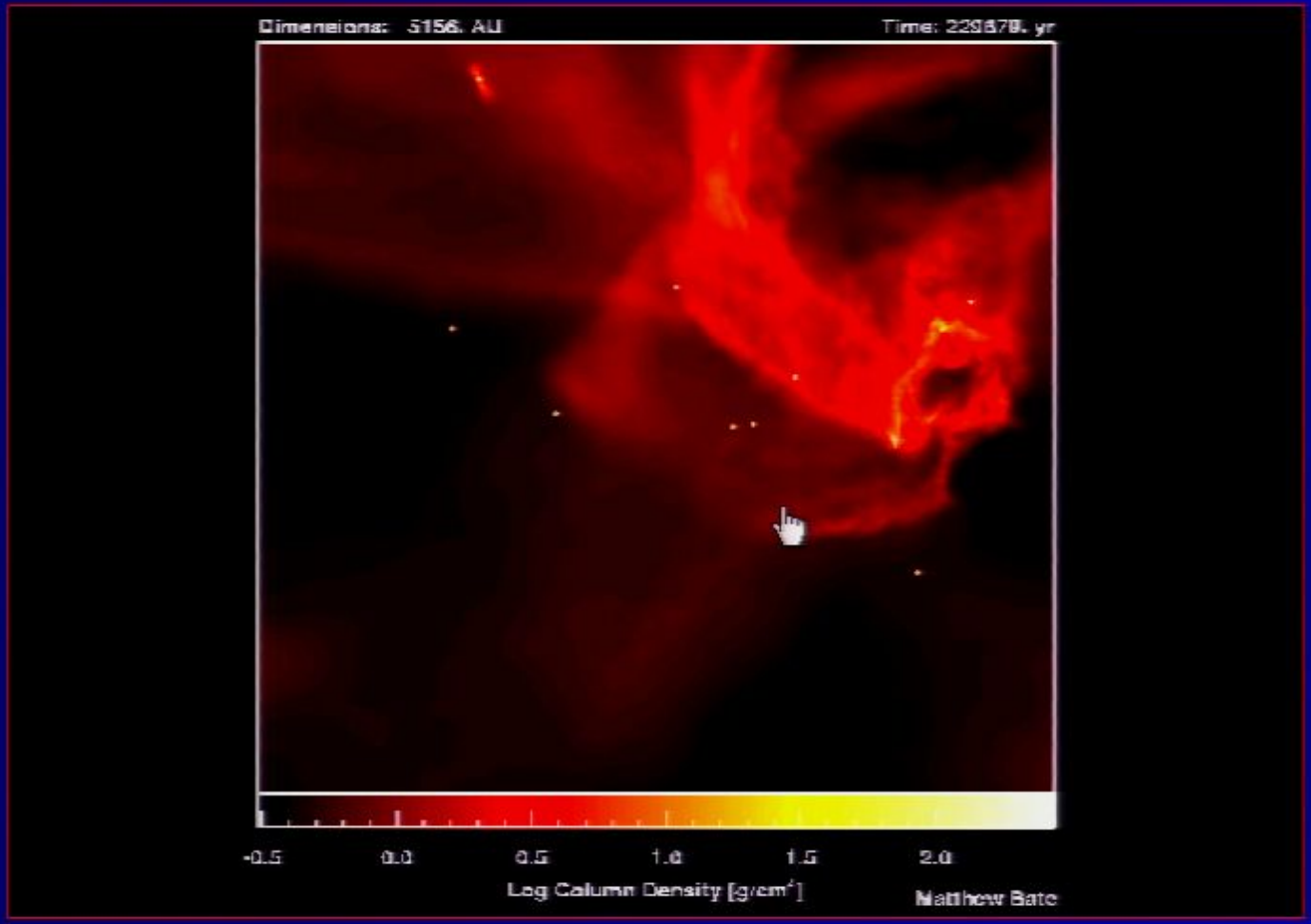

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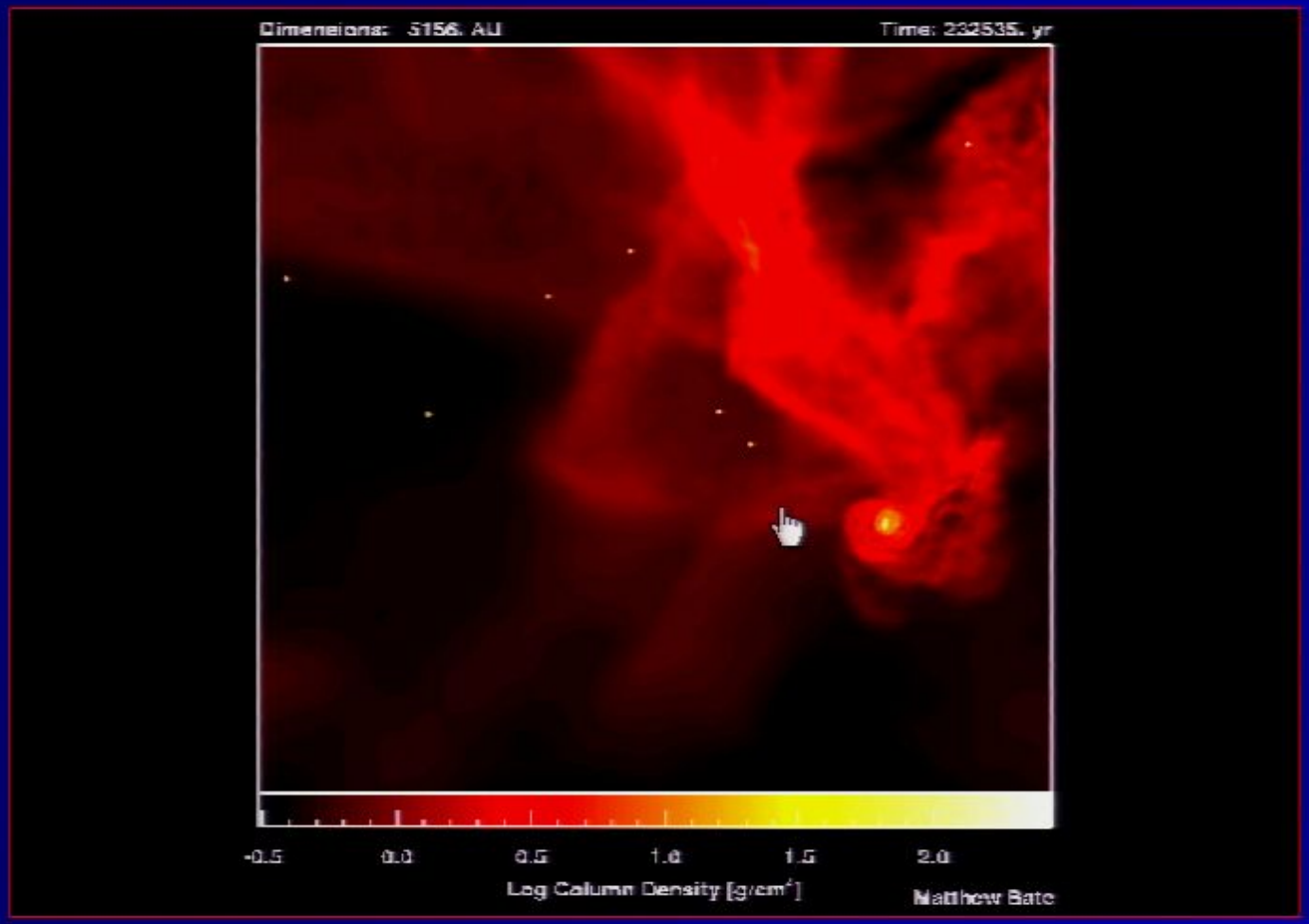

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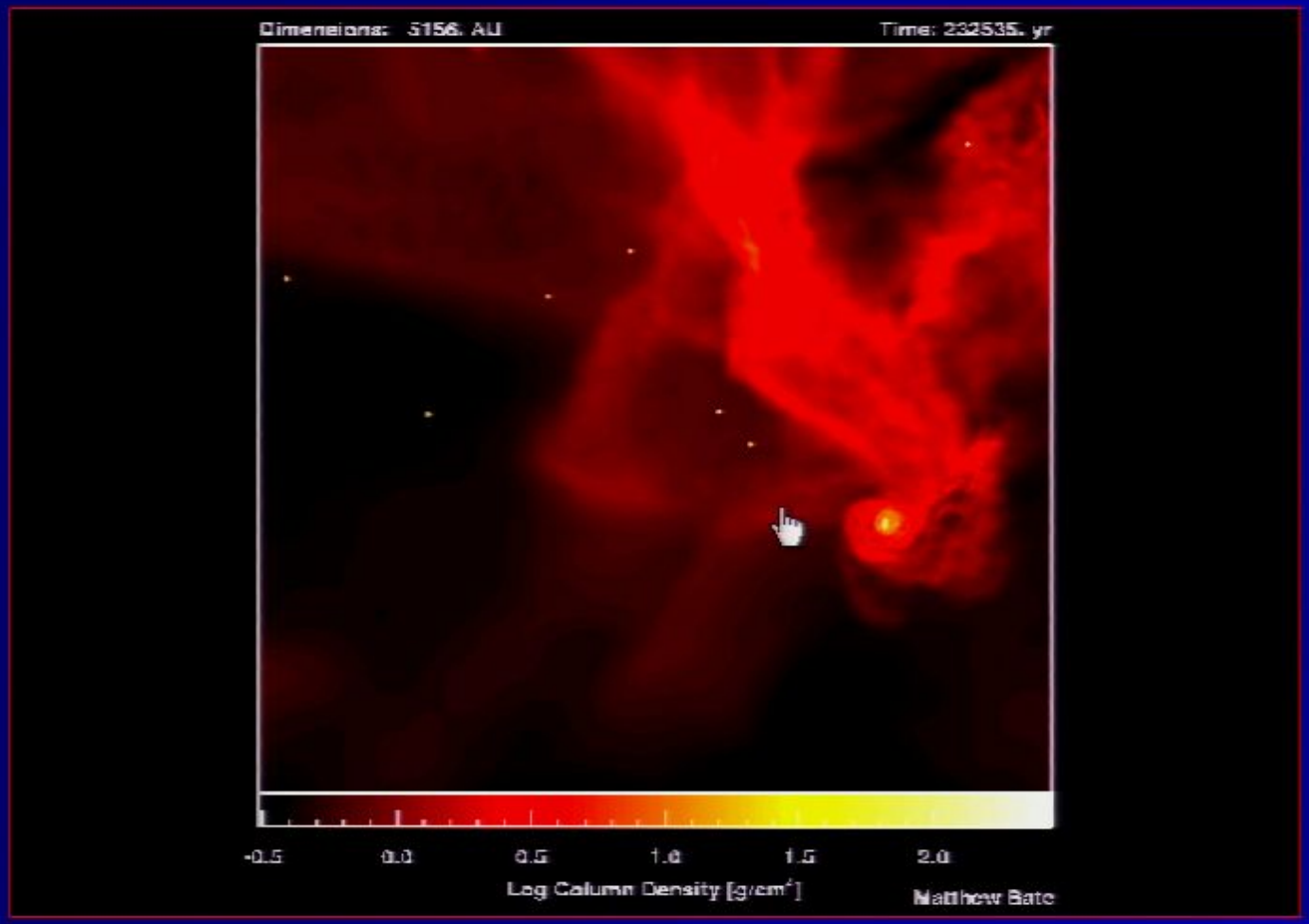

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Star Formation, Complexity and "Multi-physics"

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- Stars (planets) form via gravitational collapse of 'Molecular Clouds'
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- … dissipative processes, N-body processes, et

Some Outstanding Questions in Star Formation

- What controls Star Formation Efficiency?
  - $M > M_{jeans}$
  - SFE << 30%
- What is nature and global role star formation outflow
  - Nearly all young stellar object drives outflow
  - $t_{of} \sim .1\ t_{form}$
  - $L_{of} > 10\ L_{form}$
- Answers effect everything from Cosmology to Astrobiology

Talk in 3 Acts

- Act I: How to study these problems
  - Advances in Multi-physics AMR simulation studies
- Act II: Outflow Feedback and Cloud Turbulence
- Act III: MHD Processes in Outflows
  - Laboratory Astrophysics studies of Magnetized Episodic Jets.

Act 1

Frontiers of Algorithm Development

- Adaptive Mesh Refinement – code automatically places grid cells where needed.
- Multi-physics – code simulates many physical processes simultaneously
  - Magnetic Fields, gravity, radiation transport, chemistry, ionization dynamics.

Basic Equations (Magnetic fields only)

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MHD Equations

$$
\begin{aligned}
\partial_t \rho + \nabla \cdot (\rho \vec{u}) &= 0 \quad \text{(conservation of mass)} \\
\partial_t (\rho \vec{u}) + \nabla \cdot (\rho \vec{u}\vec{u}^t + \mathcal{P}) &= 0 \quad \text{(conservation of momentum)} \\
\partial_t \vec{B} + \nabla \cdot (\vec{u}\vec{B}^t - \vec{B}\vec{u}^t) &= 0 \quad \text{(induction equations)} \\
\partial_t (\rho e) + \nabla \cdot (\rho e \vec{u} + \mathcal{P}\vec{u}) &= 0 \quad \text{(conservation of energy)} \\
\nabla \cdot \vec{B} &= 0 \quad \text{(divergence constraint)}
\end{aligned}
$$

Here $\rho(\vec{x},t) > 0$ is the density, and $\vec{u}(\vec{x},t)$ and $\vec{B}(\vec{x},t) \in \mathbb{R}^3$ denote the velocity and the magnetic field, respectively. The matrix $\mathcal{P}(\vec{x},t) = (p_{ij}(\vec{x},t)) \in \mathbb{R}^{3\times 3}$ is given by

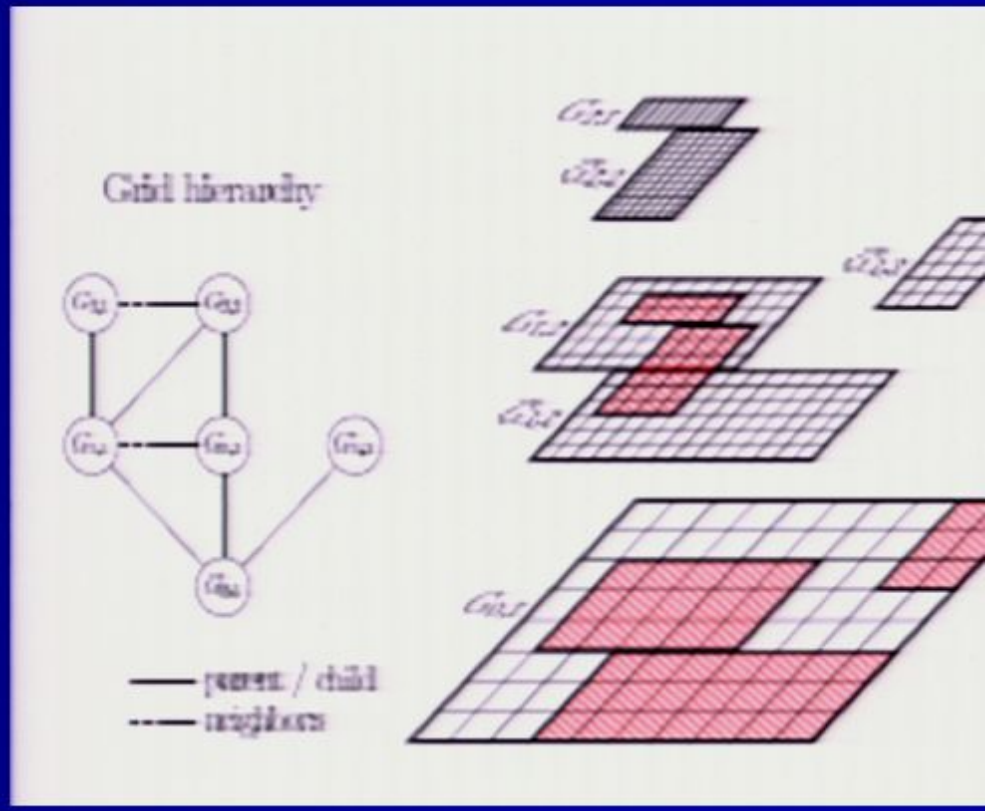
$$
\mathcal{P} := \left(p + \frac{1}{8\pi}\vec{B}^2\right)\mathcal{I} - \frac{1}{4\pi}\vec{B}\vec{B}^t = \left((p + \frac{1}{8\pi}\vec{B}^2)\delta_{ij} - \frac{1}{4\pi}B_i B_j\right)_{i,j=1}^{3}
$$

where $p(\vec{x},t) > 0$ is the pressure. With temperature $T(\vec{x},t)$ and internal energy $\varepsilon = \varepsilon(\rho, T)$ the total energy $e(\vec{x},t)$ satisfies

$$
e = \varepsilon + \tfrac{1}{2}\vec{u}^2 + \tfrac{1}{8\pi\rho}\left(B_x^2 + B_y^2 + B_z^2\right)
$$

Adaptive Mesh Refinement
AMR

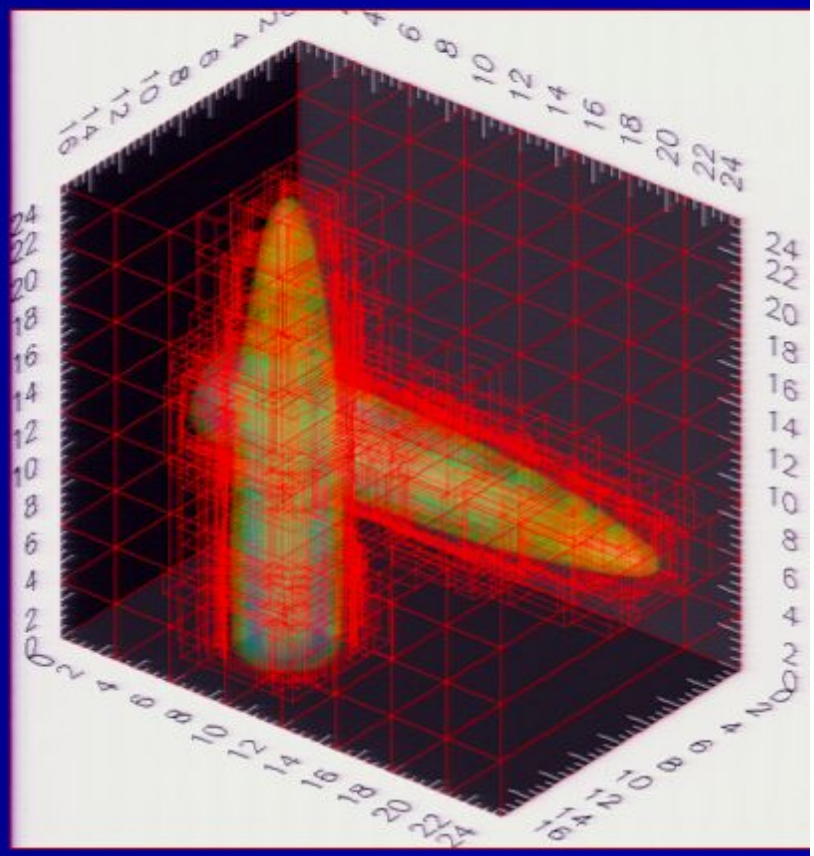
- Different AMR Methods:
  - Patch based regridding
  - Cell based regridding
- University of Rochester Code
  - *AstroBEAR: patch*
- Hierarchy of Grids
- Require *Prolongation/Restriction* Operators (MHD Balsara 2001)
  - Carry data from one grid level to another
- Prolongation (Corse to Fine)
- Restriction (Fine to Corse)



R. Deiterding

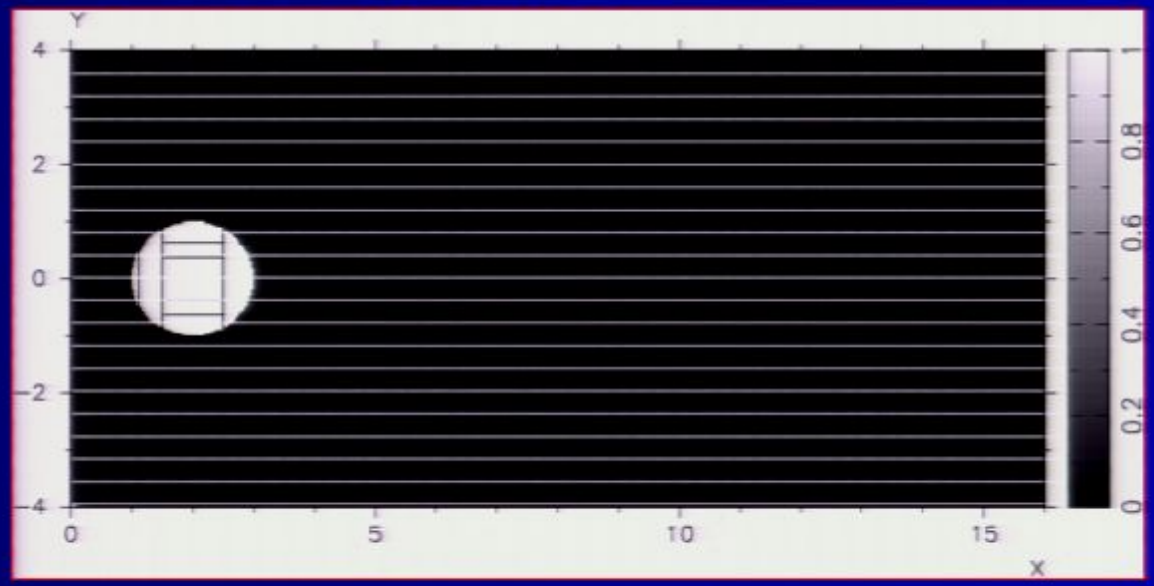
AstroBEAR MHD-AMR Code

- Set of Riemann solvers (Full, Roe, MHD).
- MHD divergence preserving: options for several forms of CT method.
- MHD DivB = 0 Prolongation-restriction.
- Built-in physics modules:
  - Time-dependent Ionization and H_2Chemistry
  - Radiation driving via Thomson scattering
  - Elliptic Multi-grid solver (diffusion, self-gravity etc)
- Parallel – load balance and domain decomposition



AMR MHD
Div B = 0

- Hydro: Need conservative prolongation/ restriction operators.
- MHD: Maintain solenoidal condition. Need divergence free operators



Cunningham, Varniere, Frank & Jones 2007

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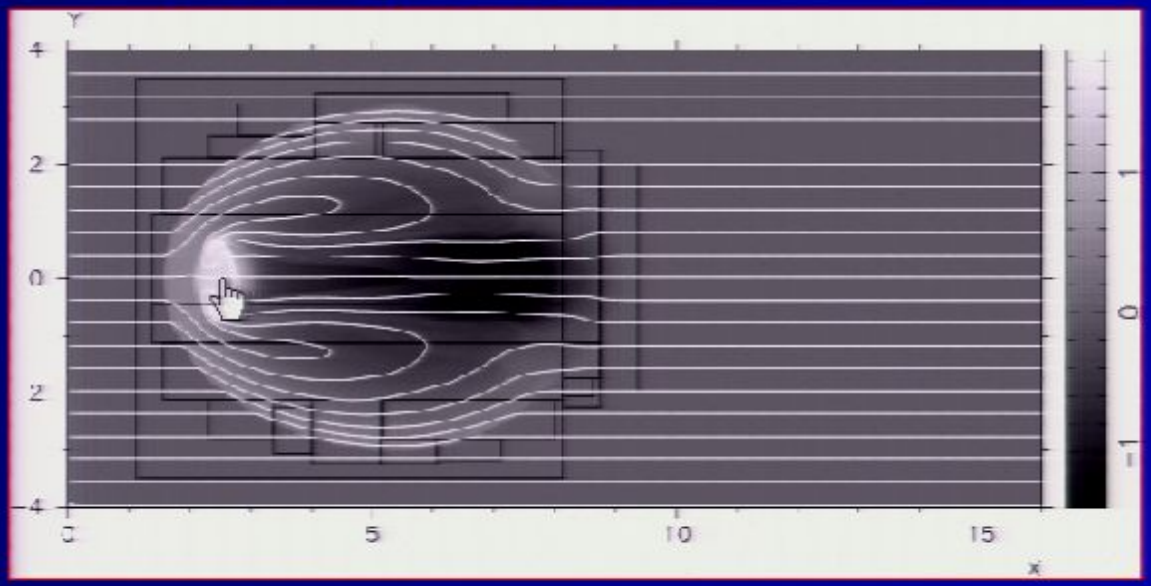

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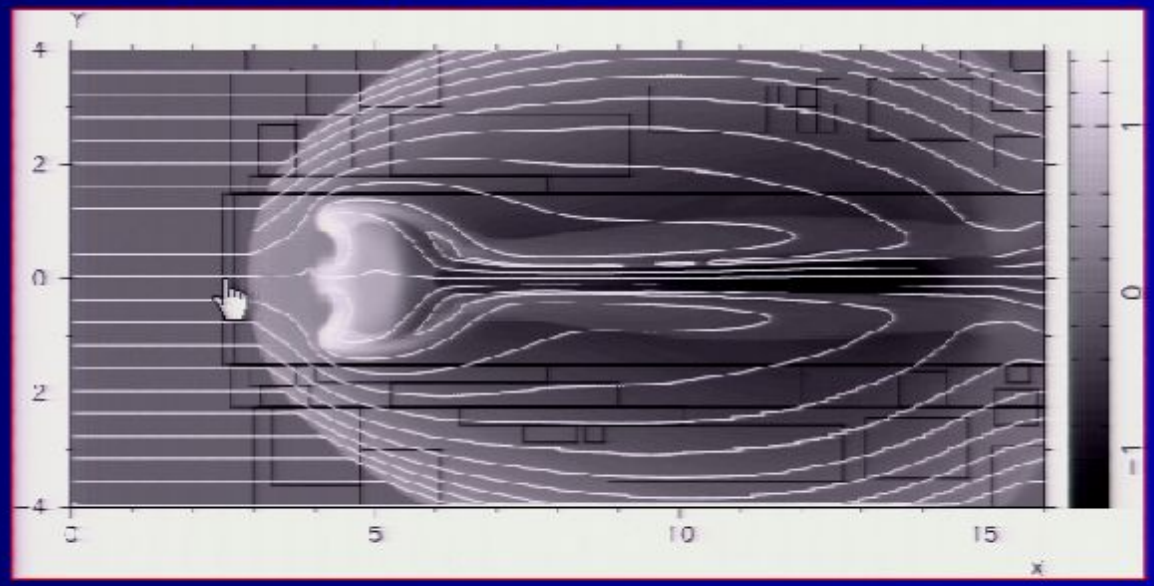

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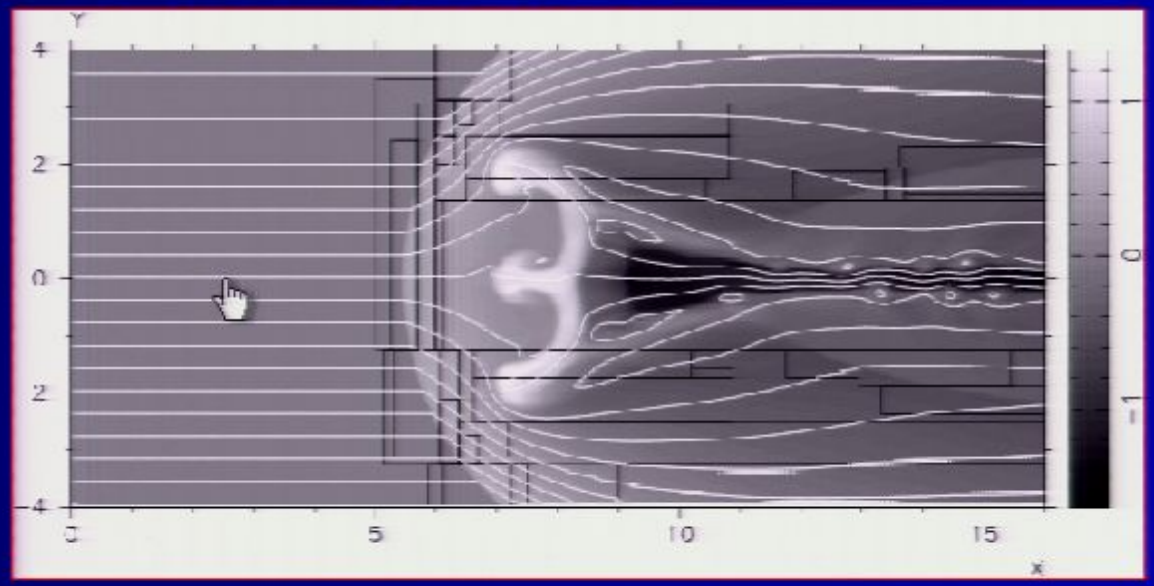

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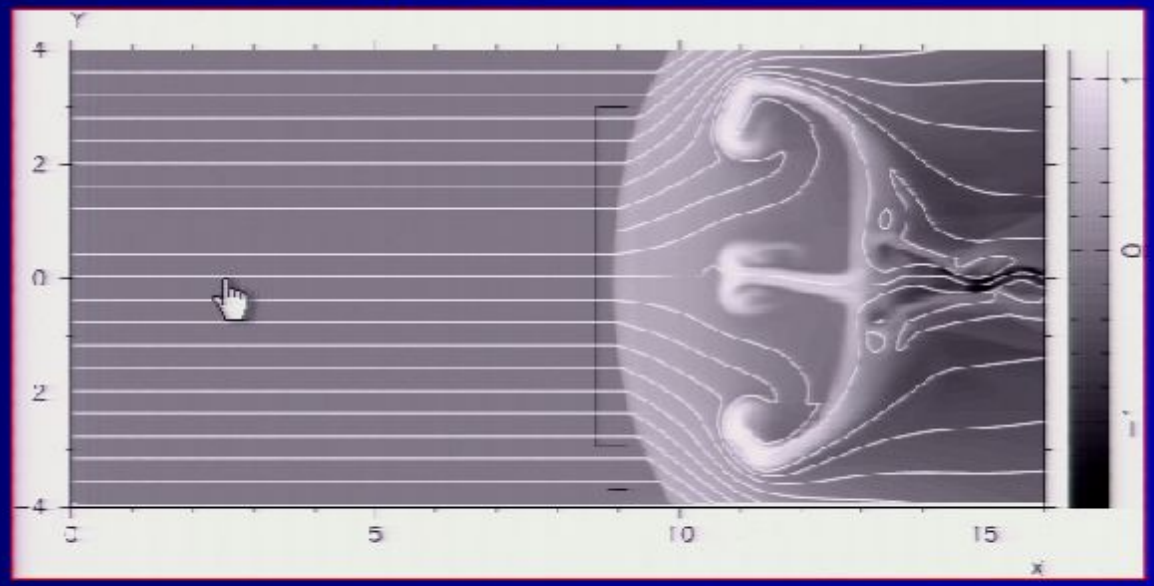

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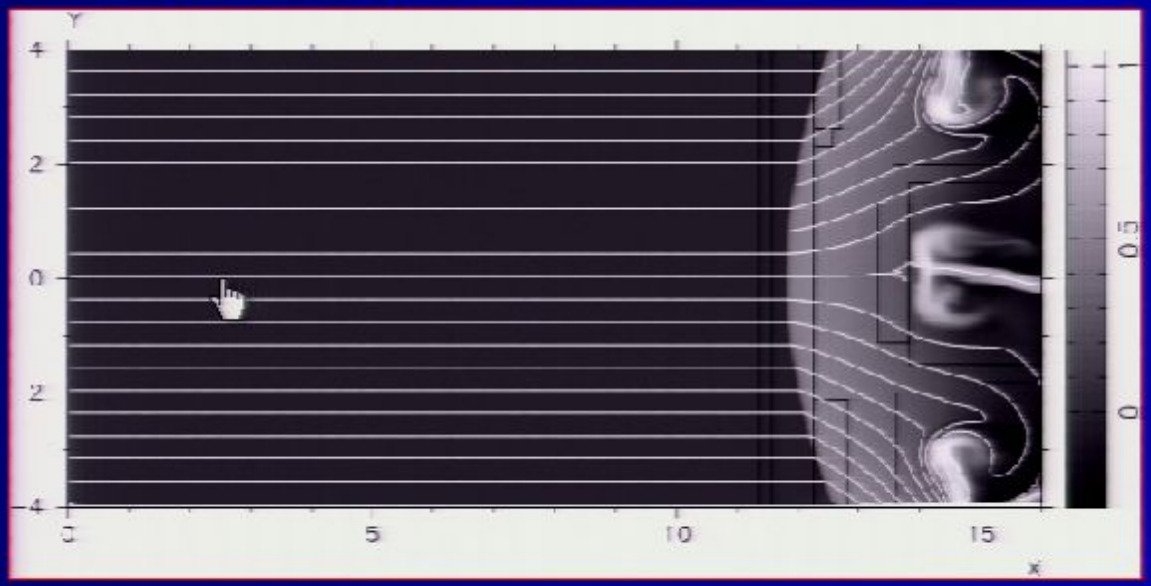

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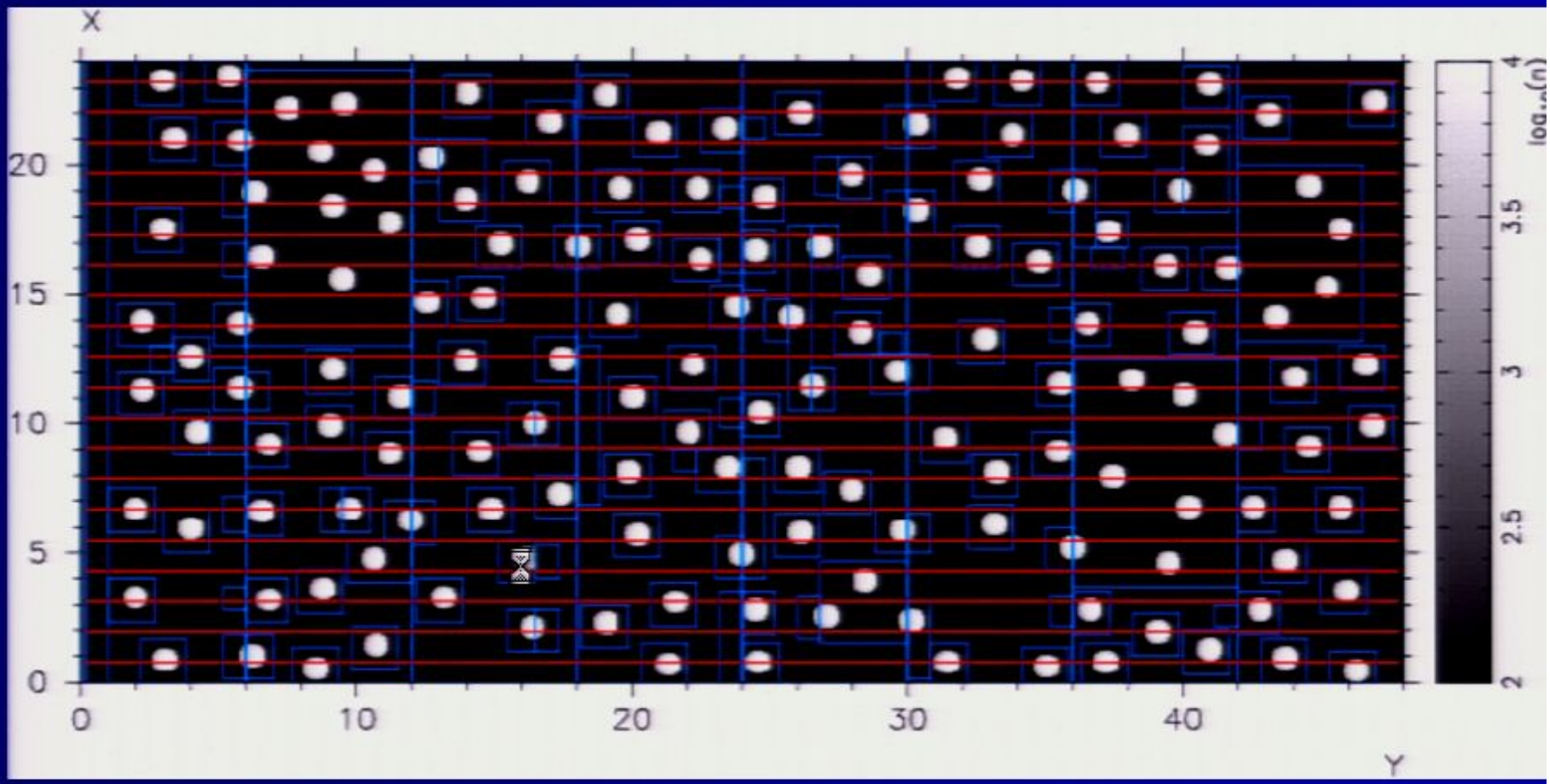
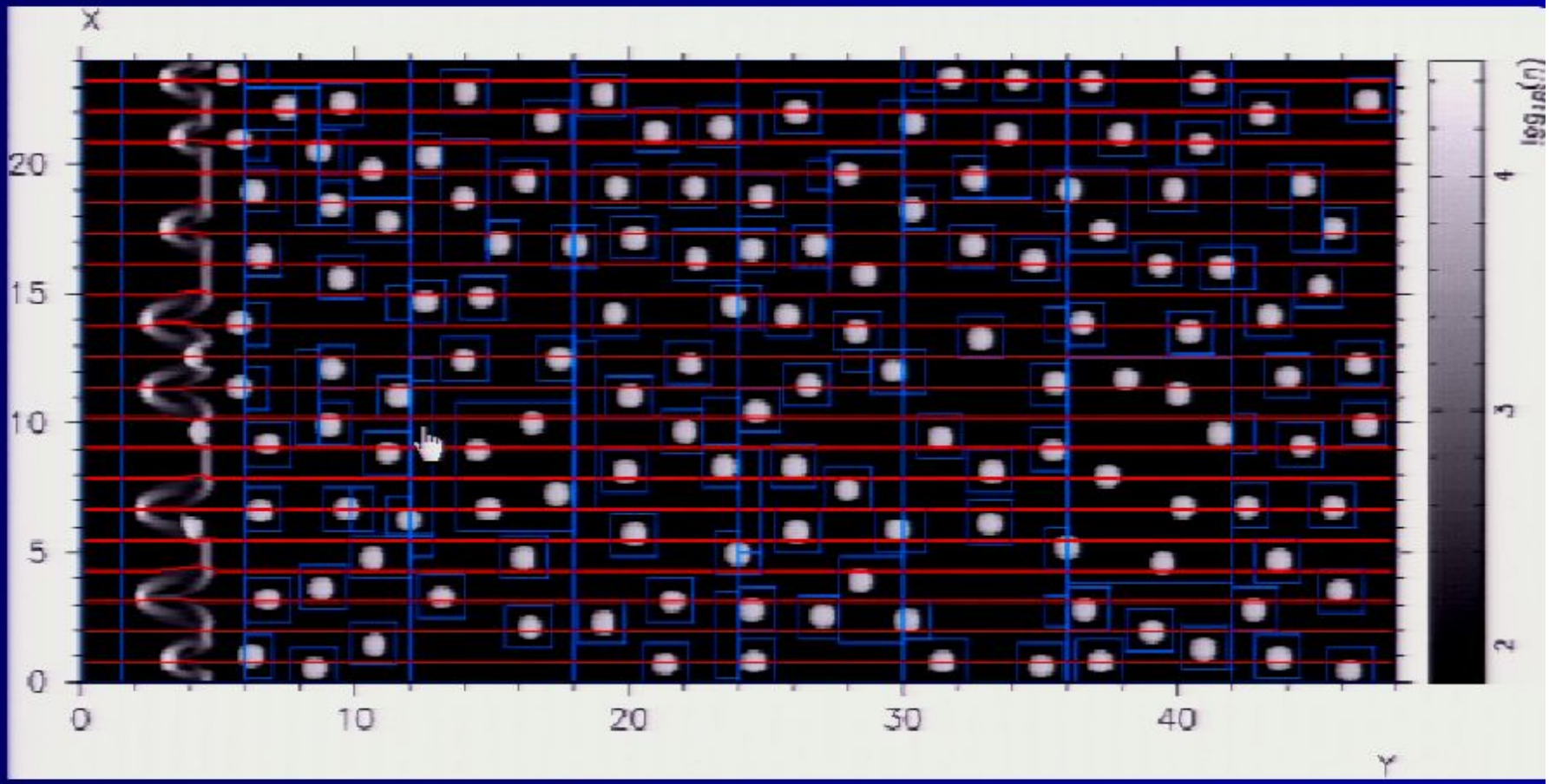
Radiative MHD Shocks in Heterogeneous Media

Cunningham, Frank, Varniere & Mitran 2007



Radiative MHD Shocks in Heterogeneous Media

Cunningham, Frank, Varniere & Mitran 2007



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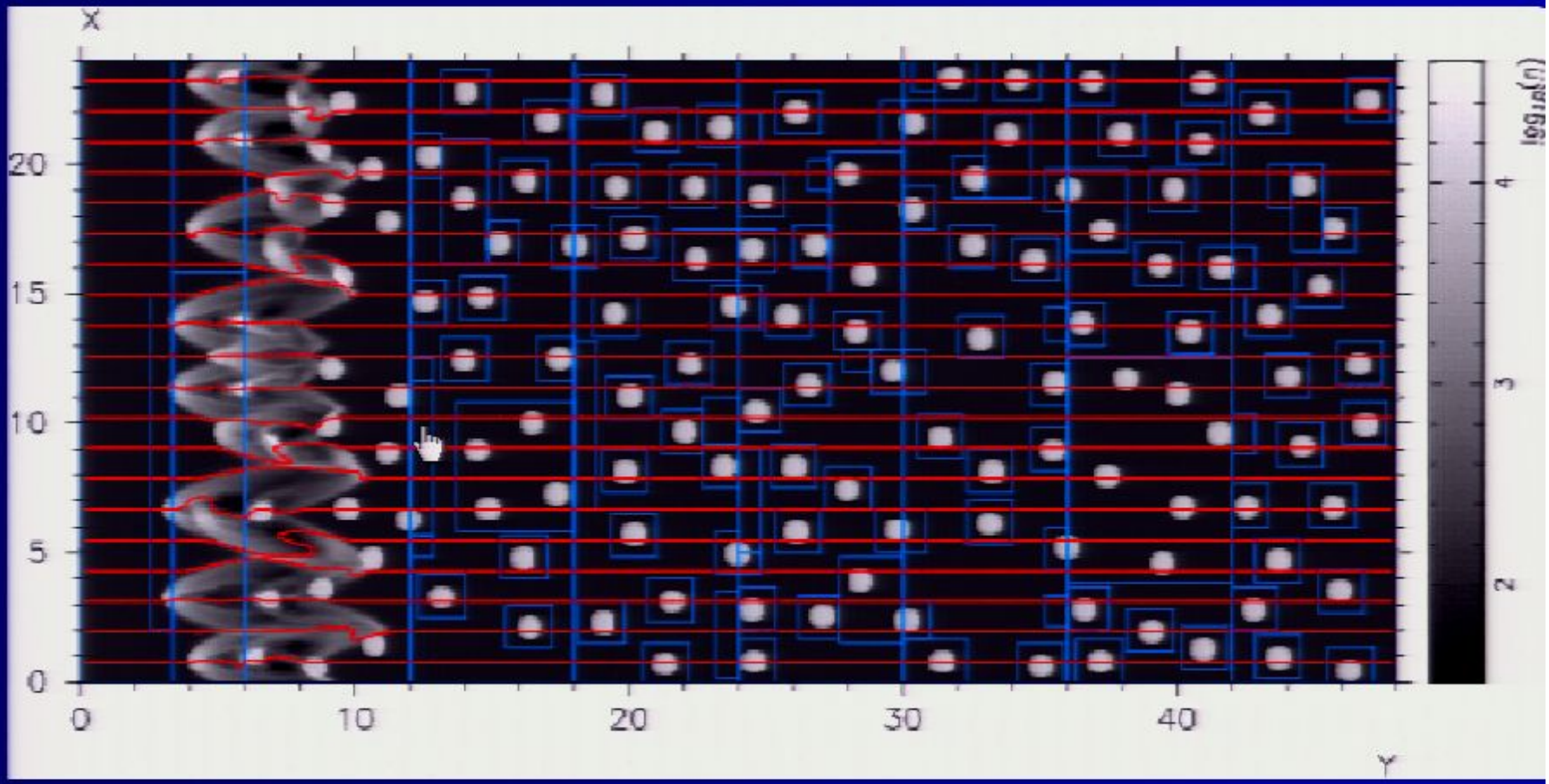

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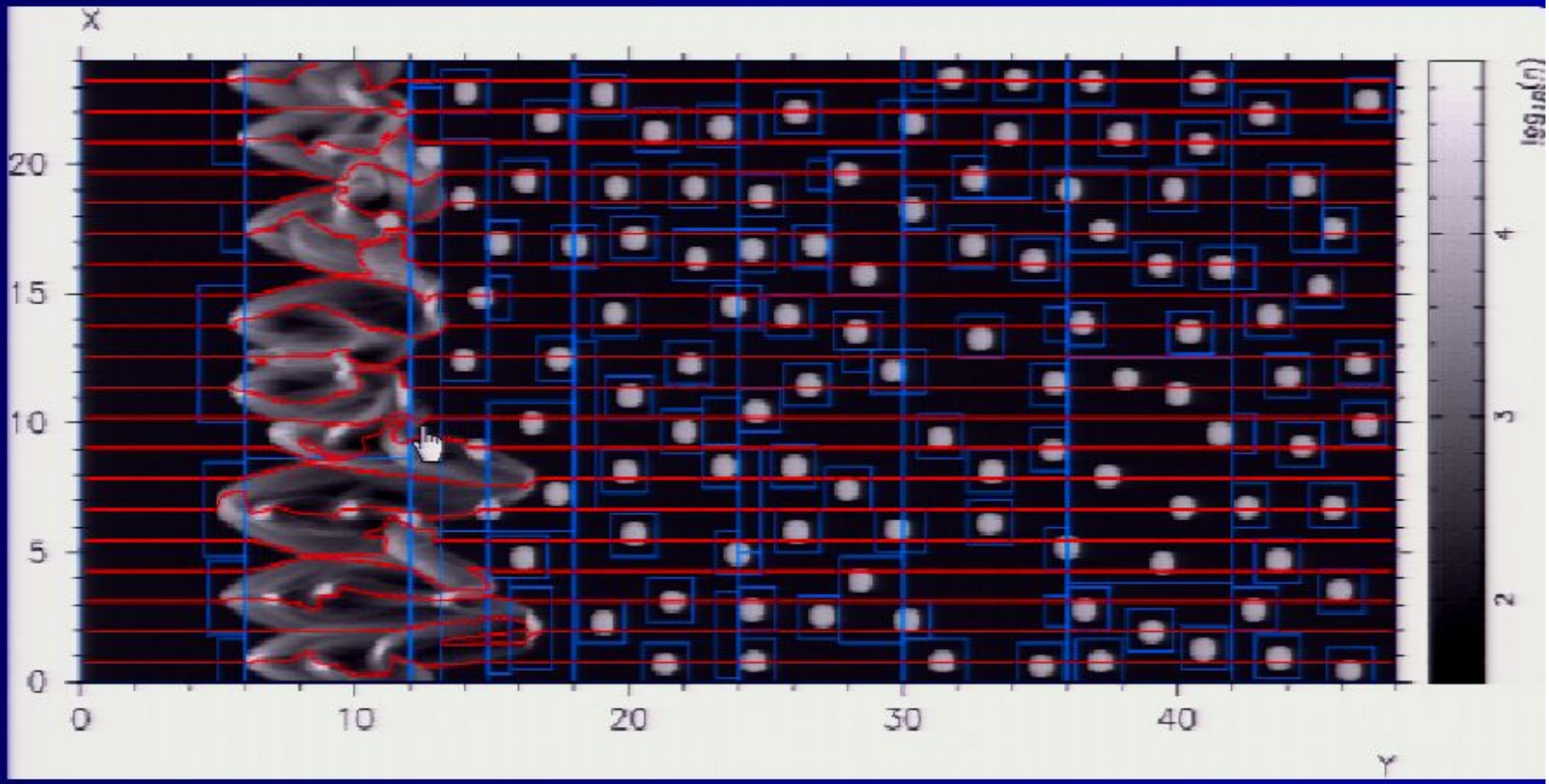

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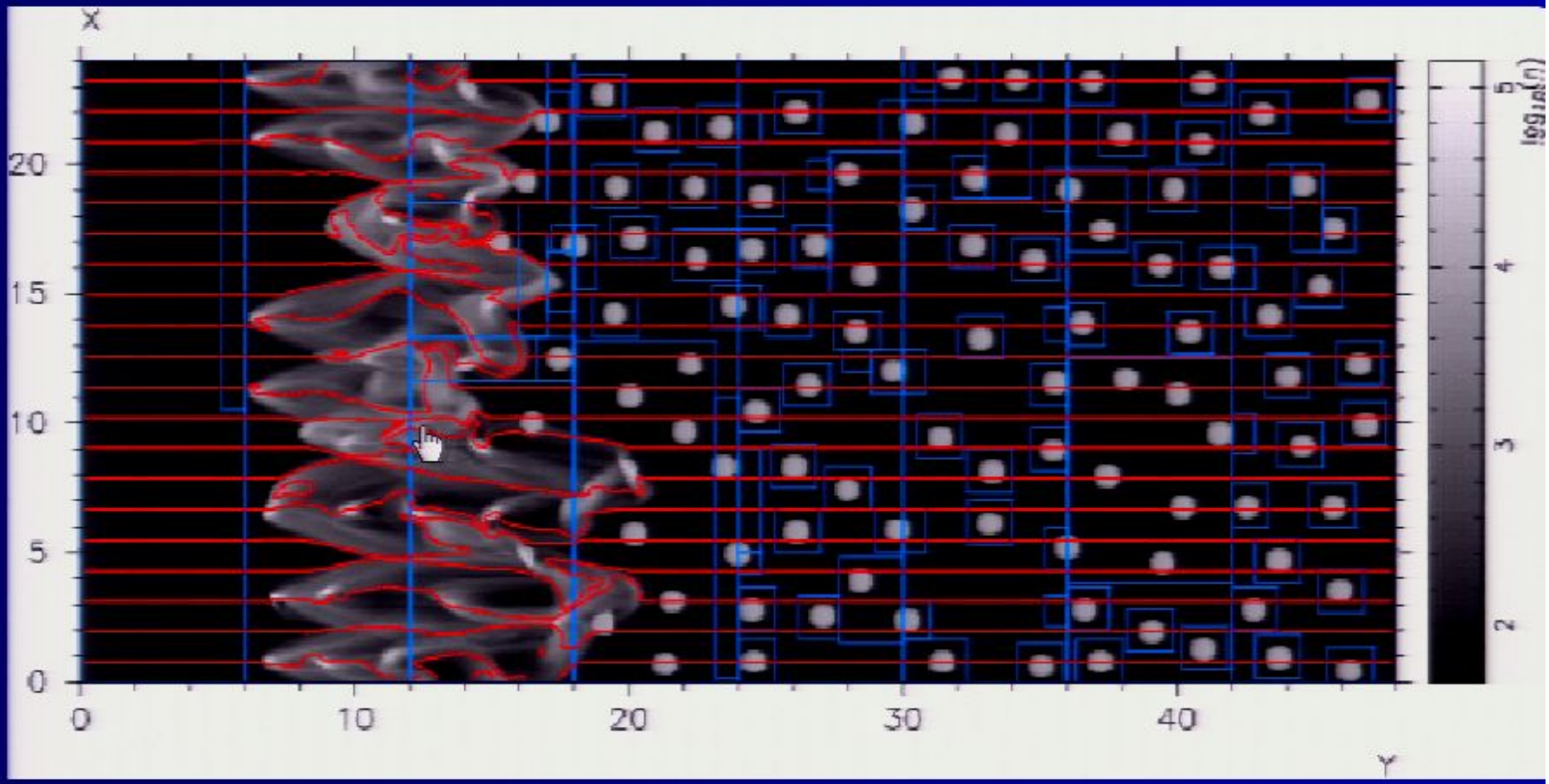

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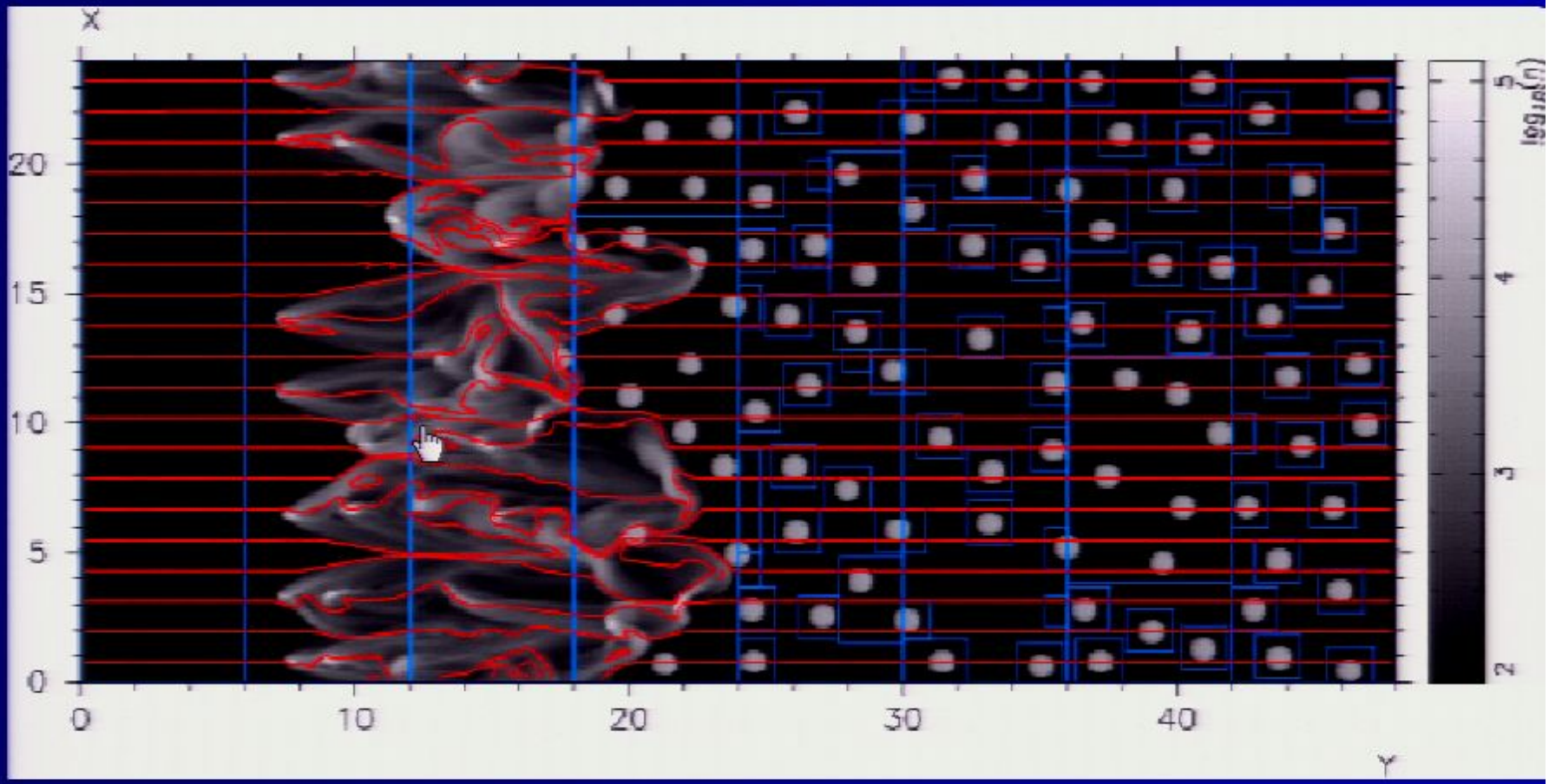

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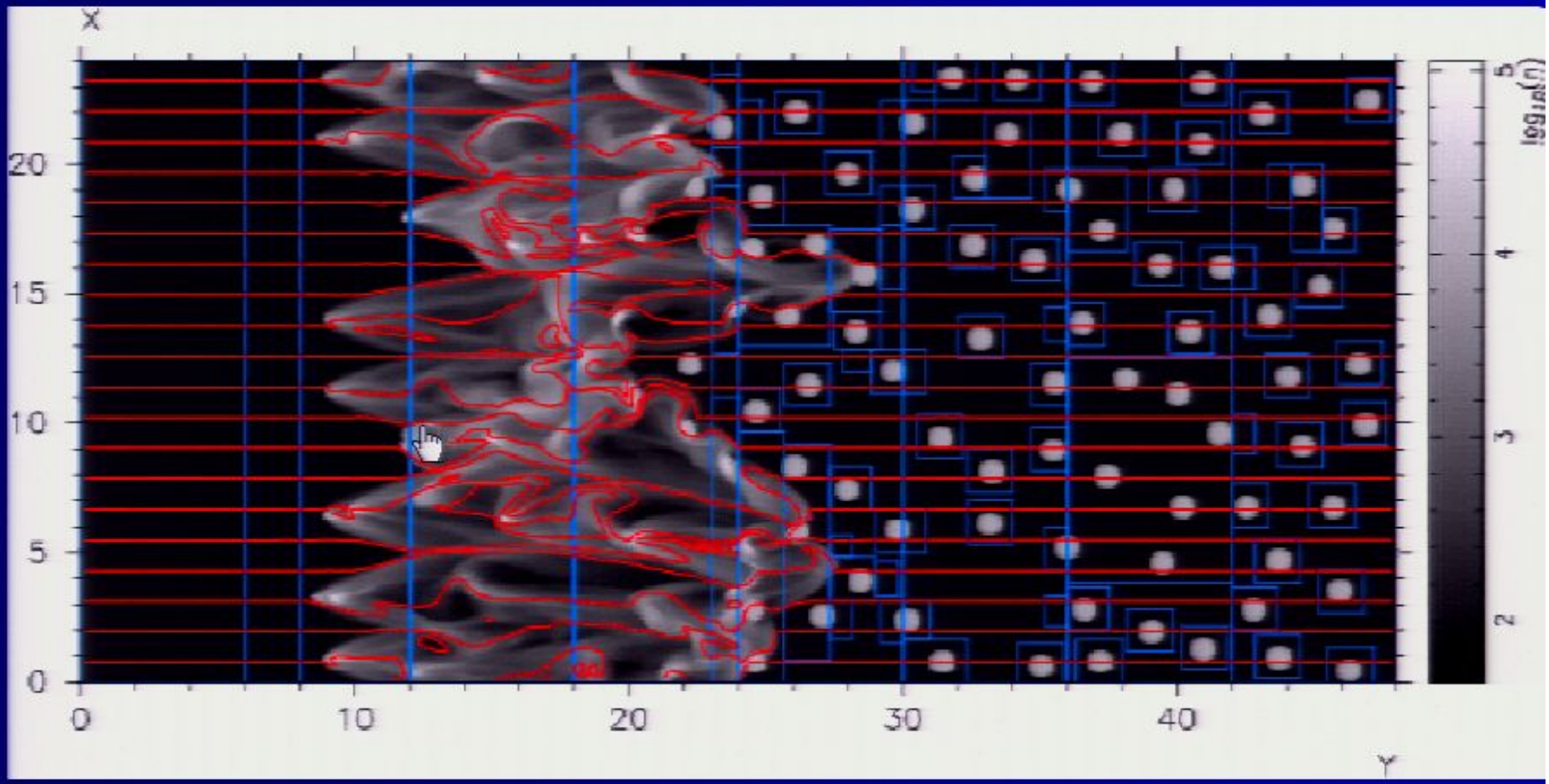

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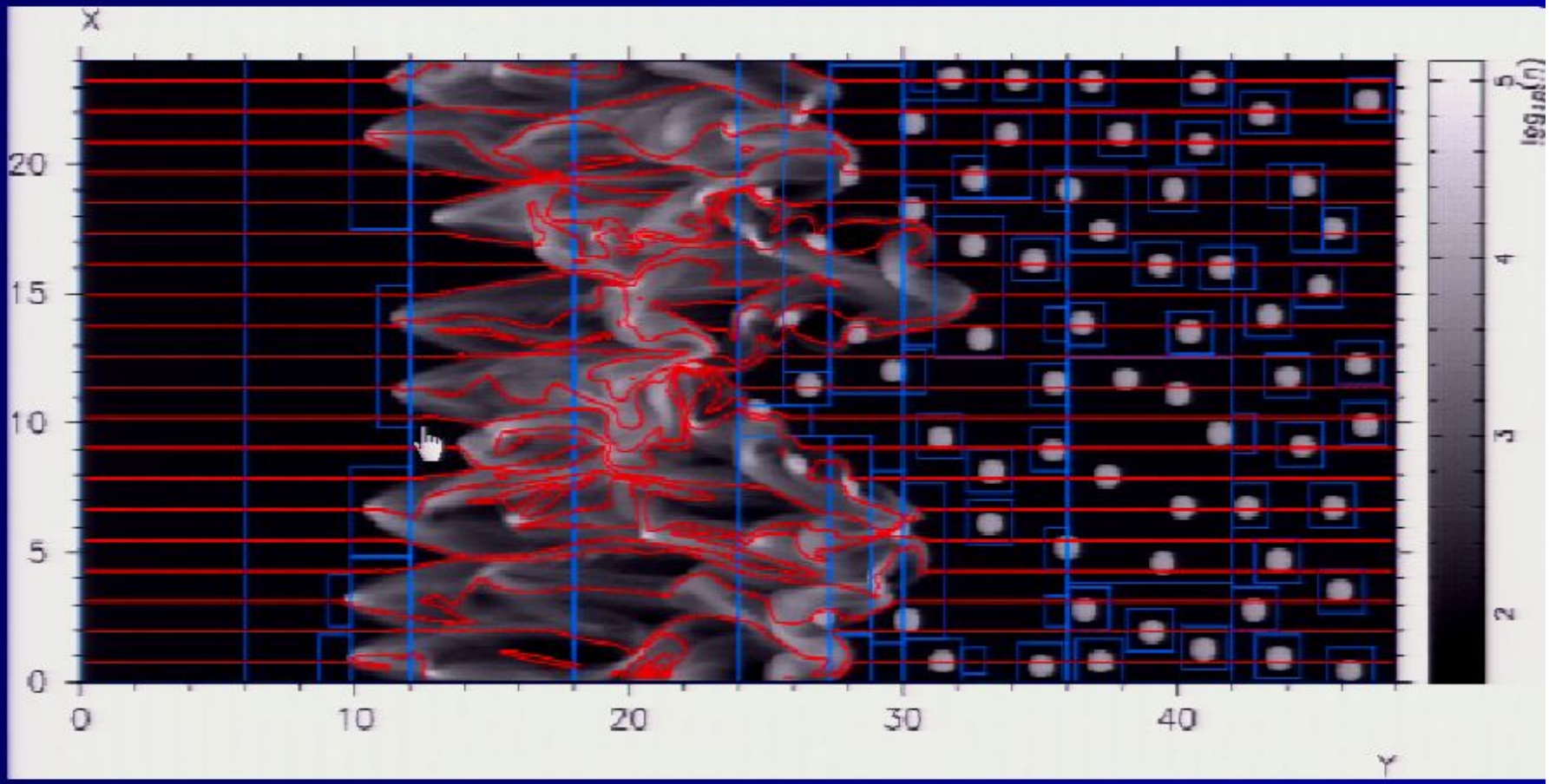

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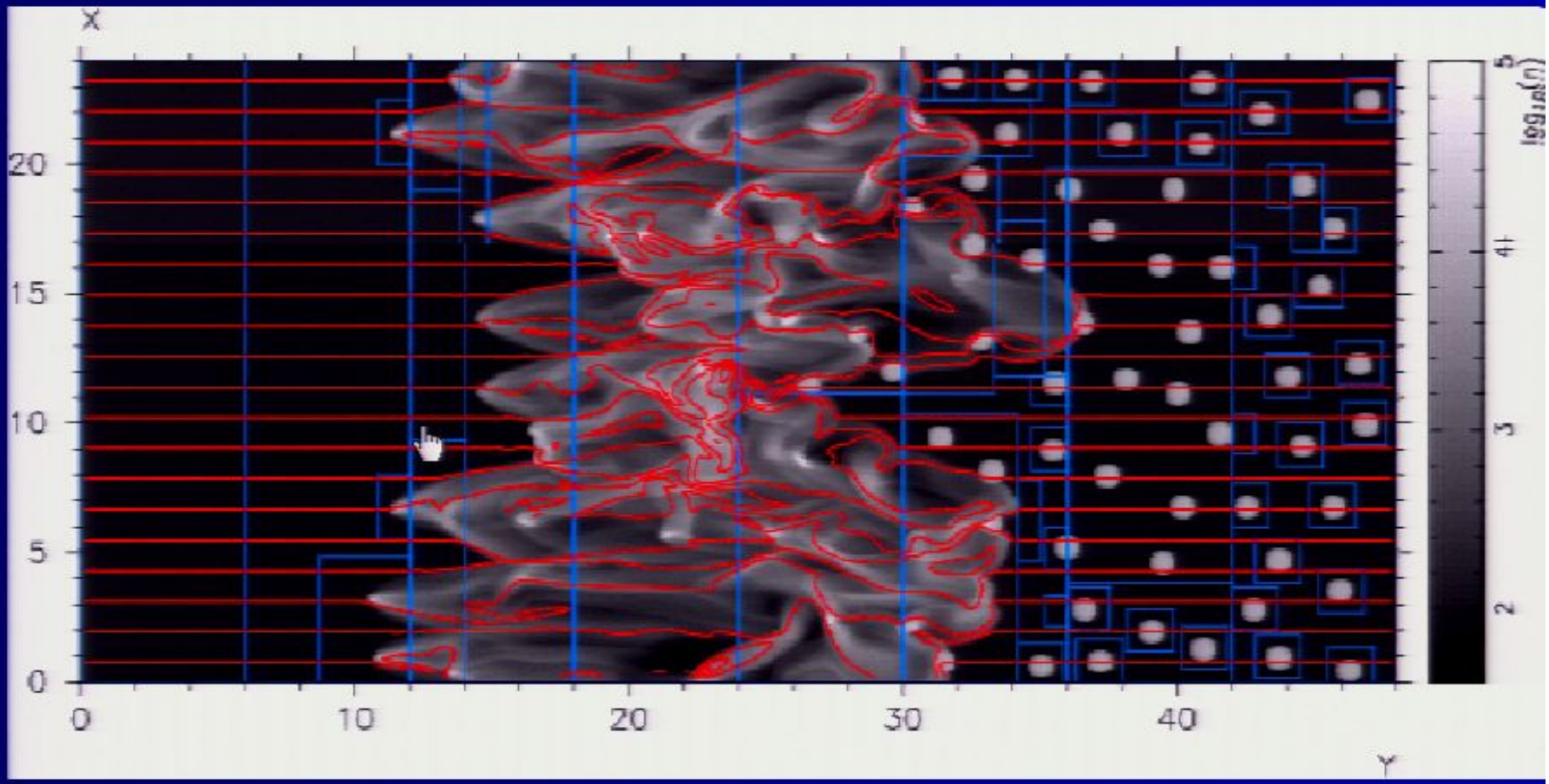

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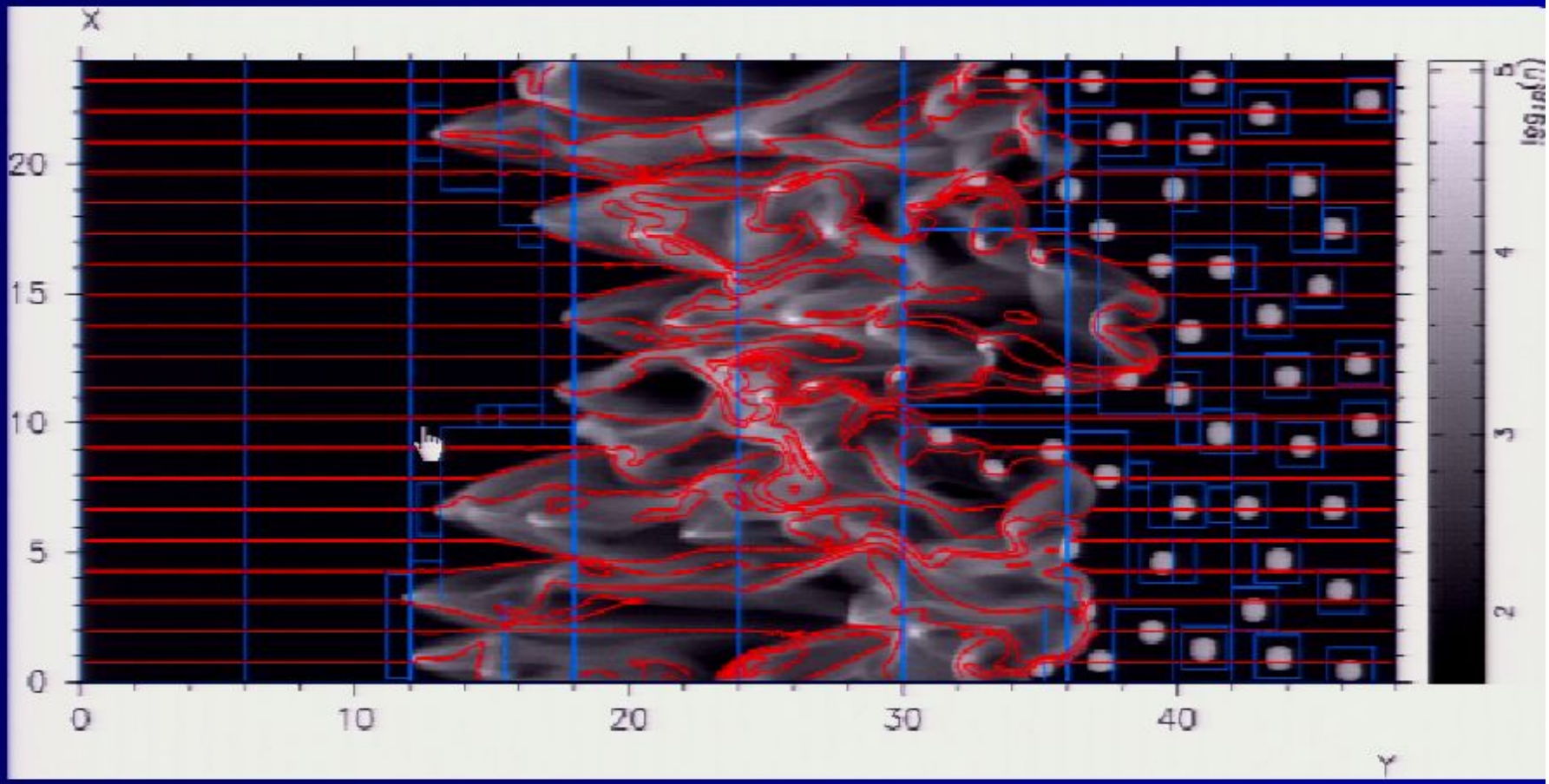

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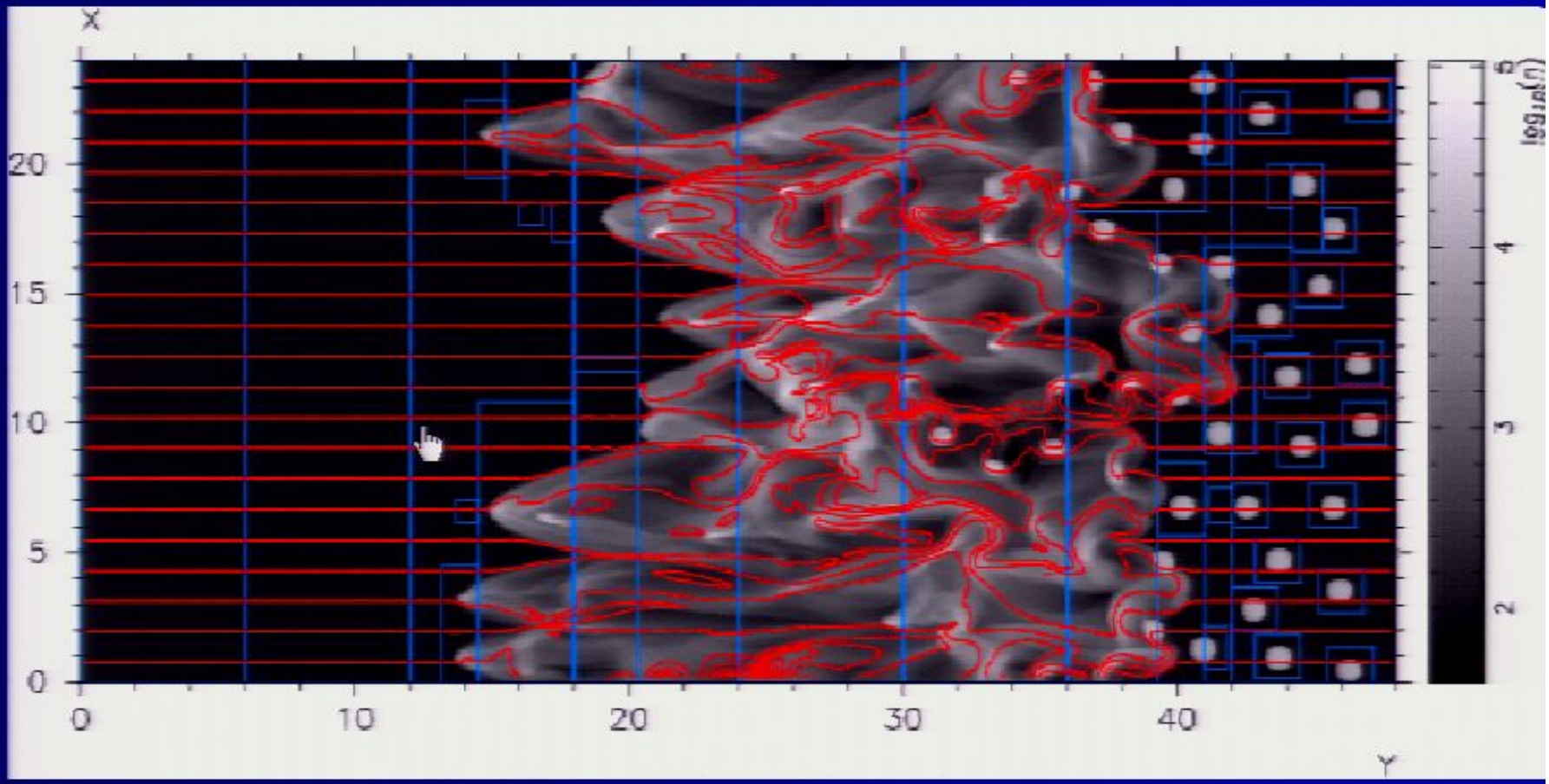

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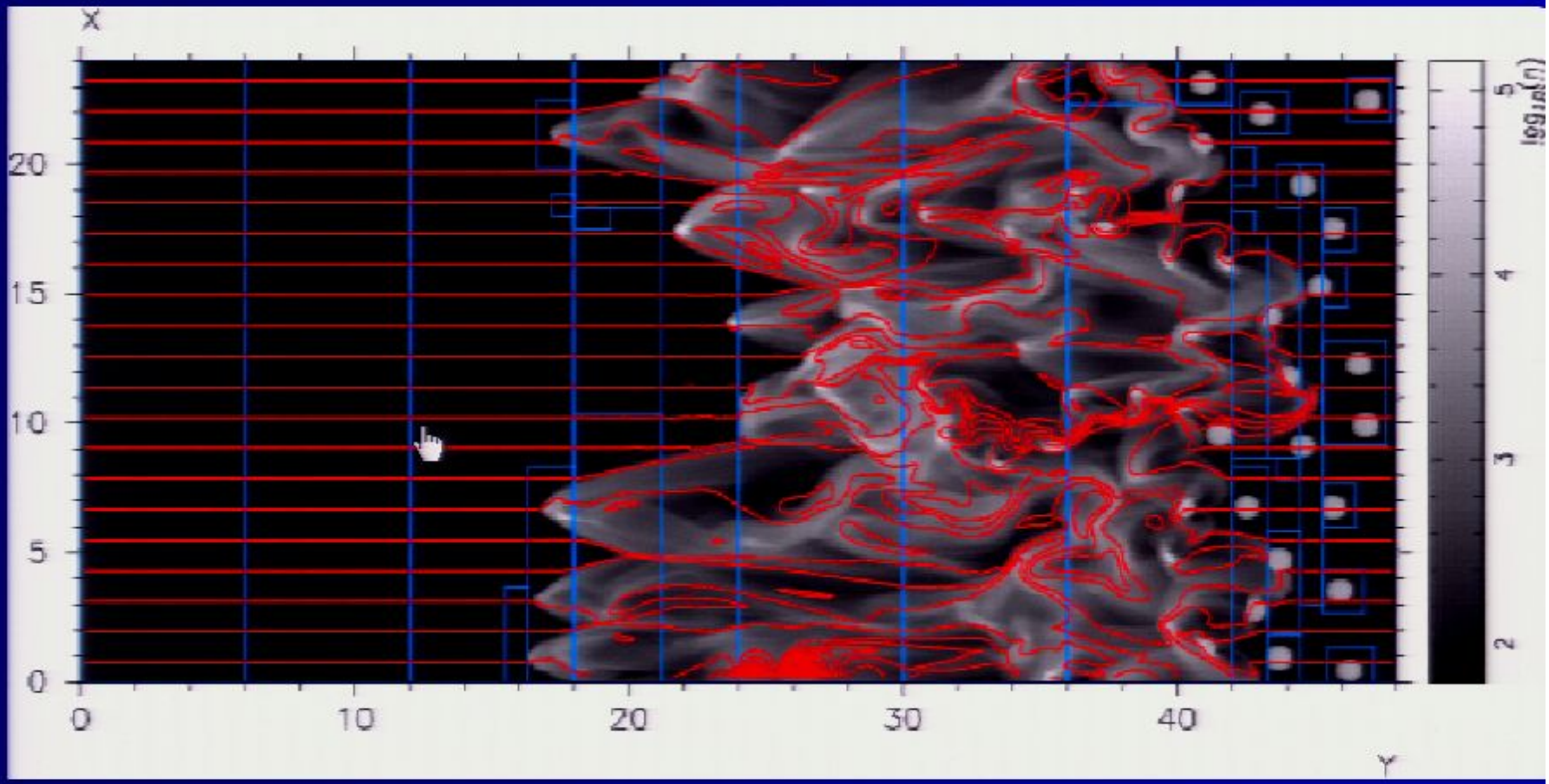

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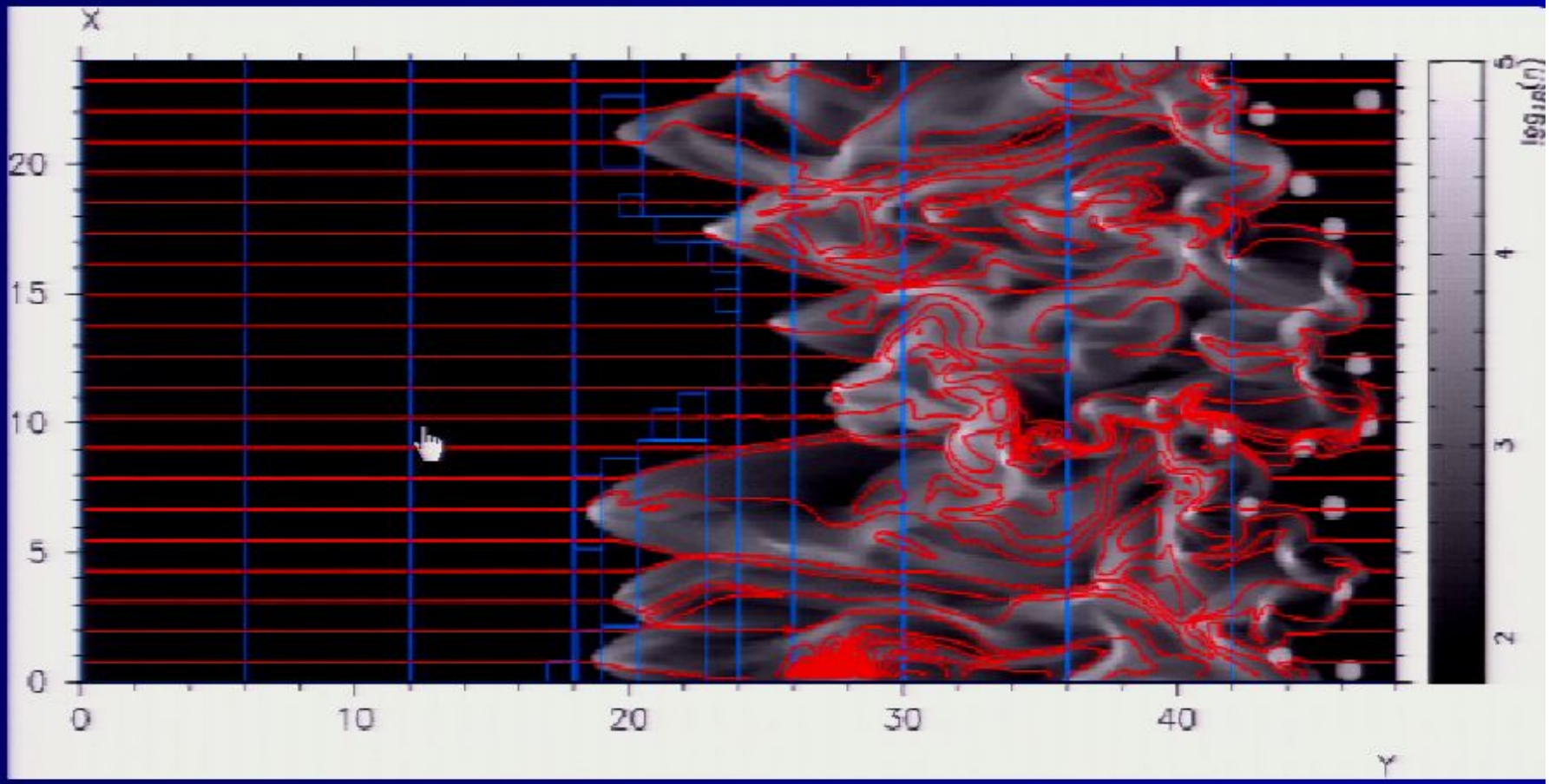

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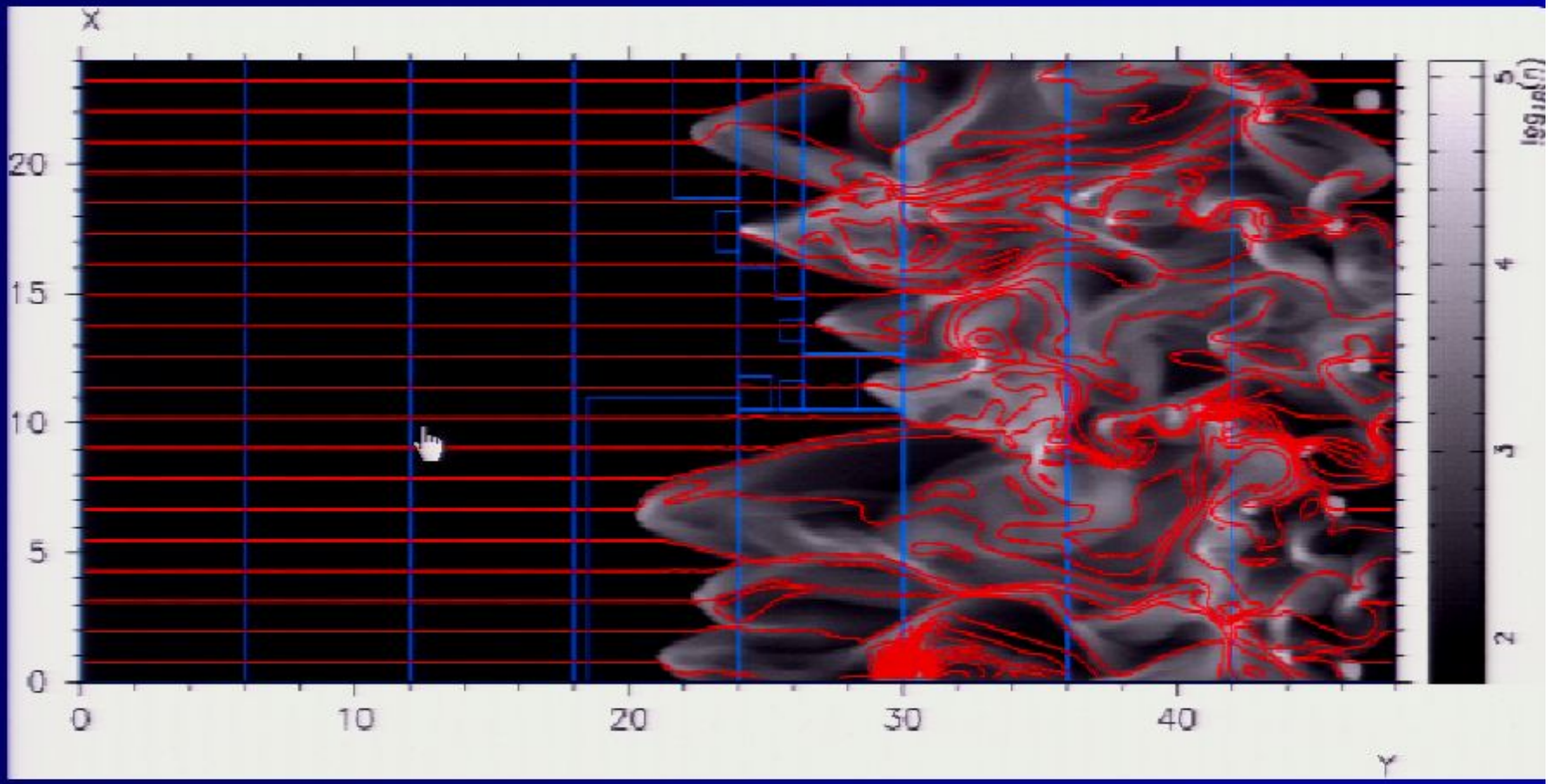

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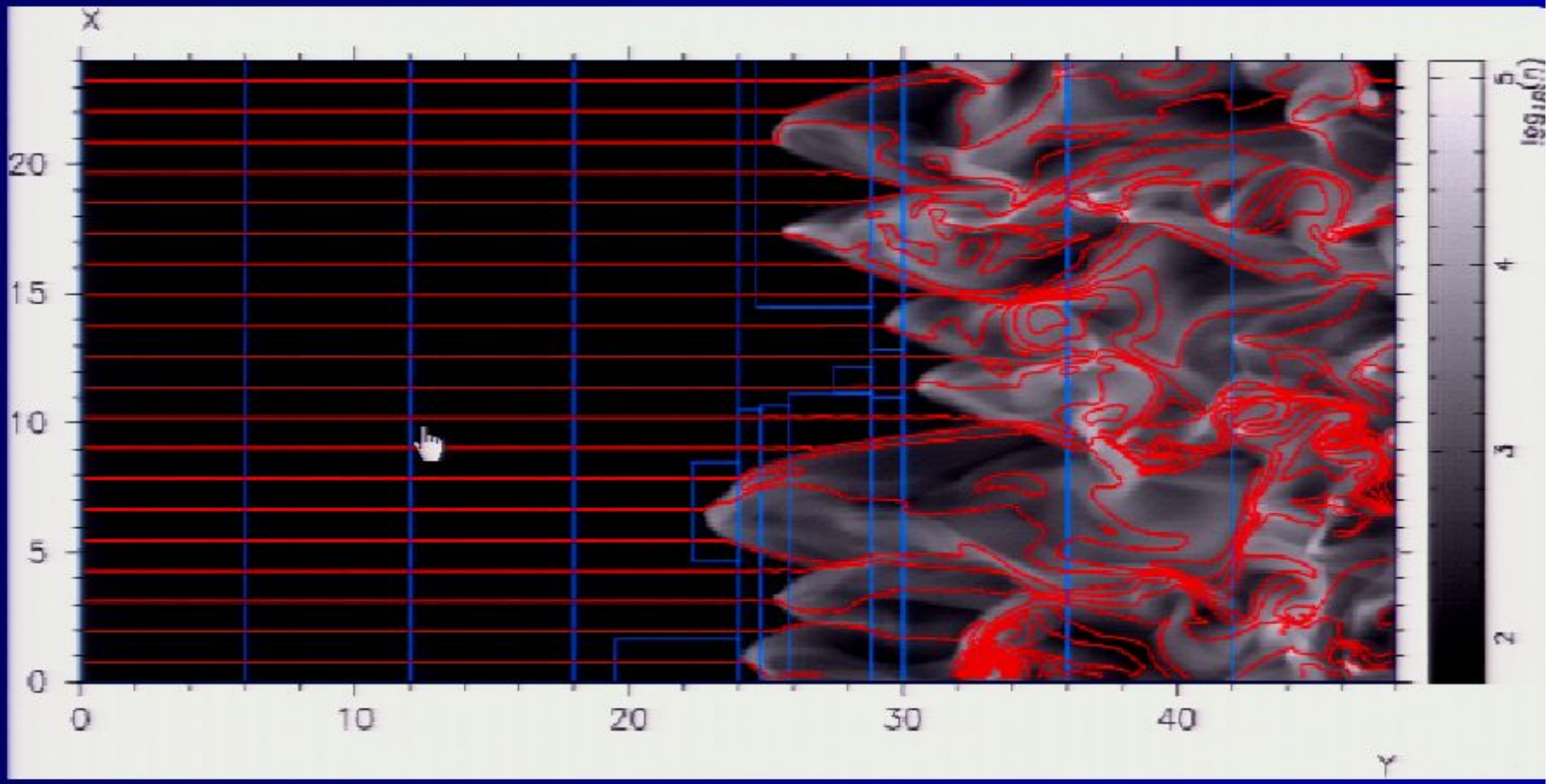

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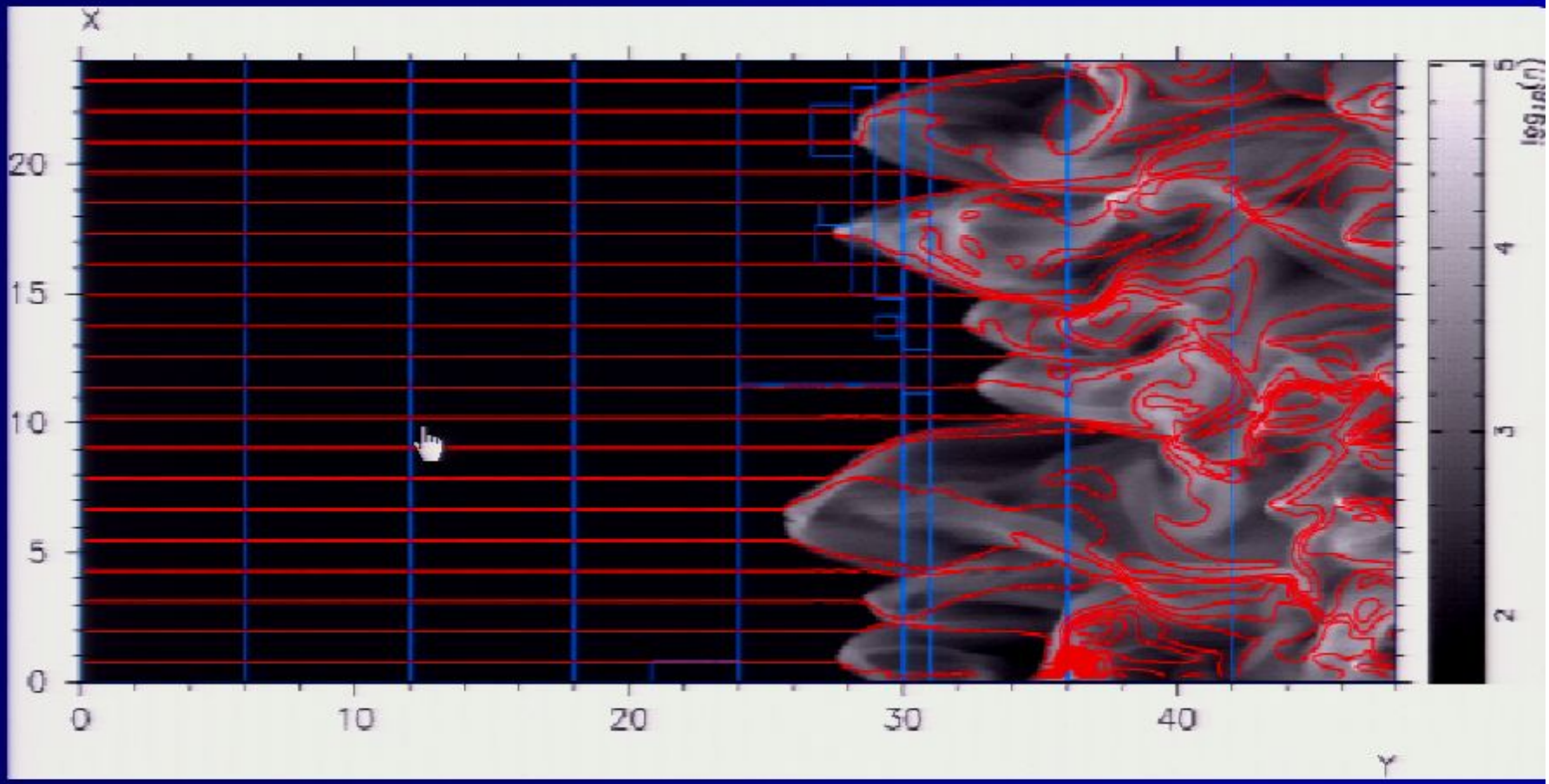

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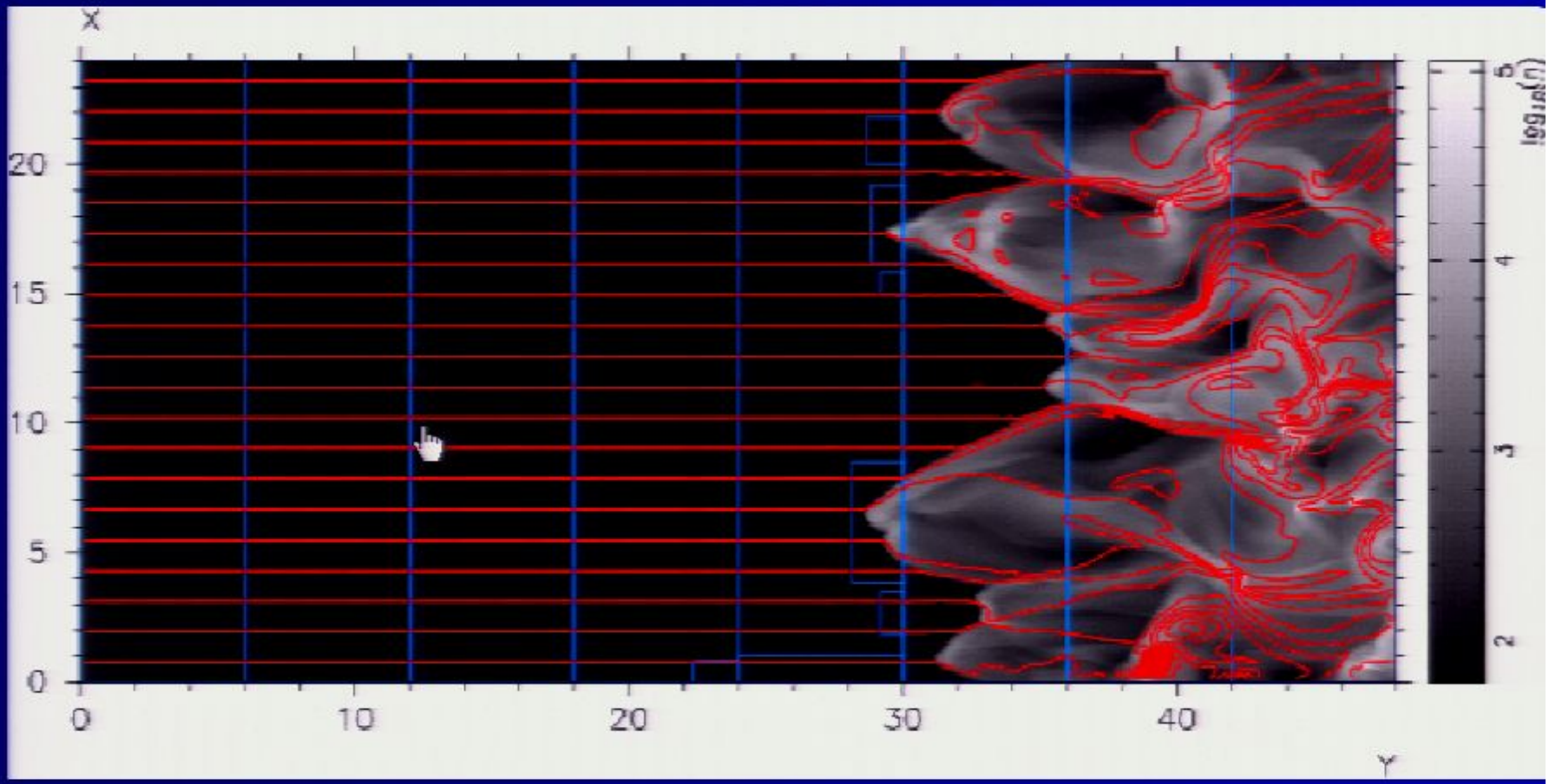

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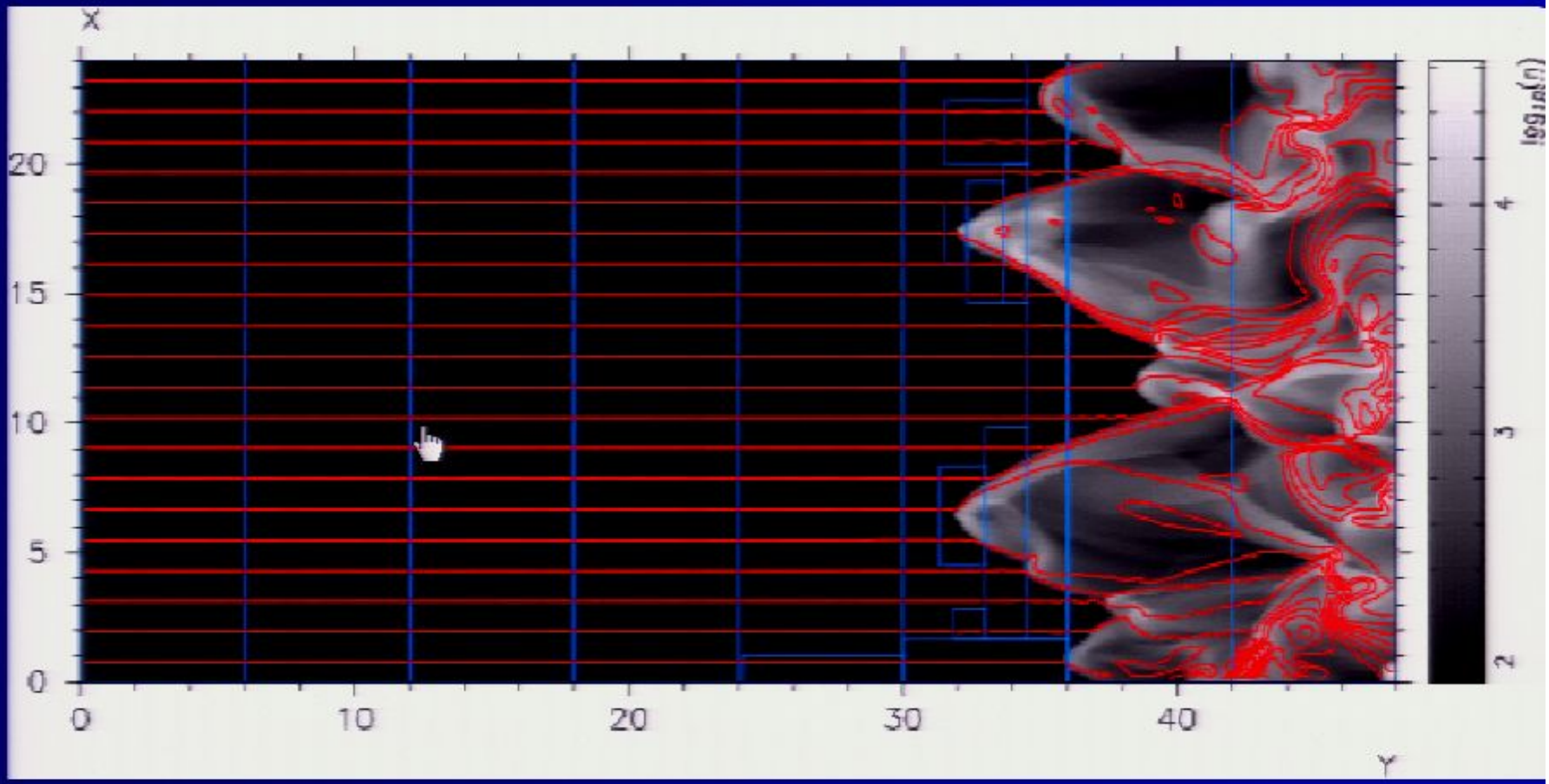

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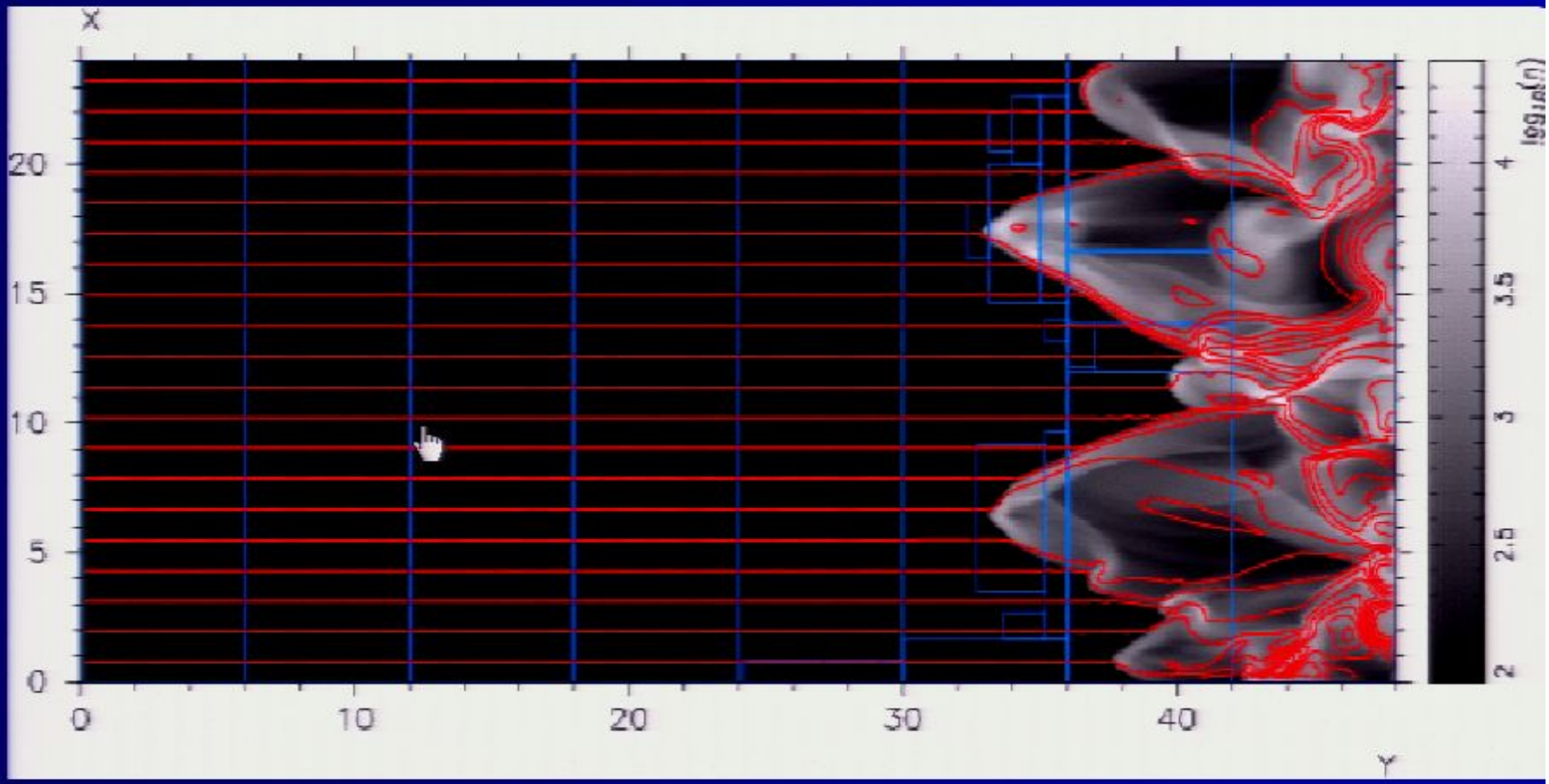
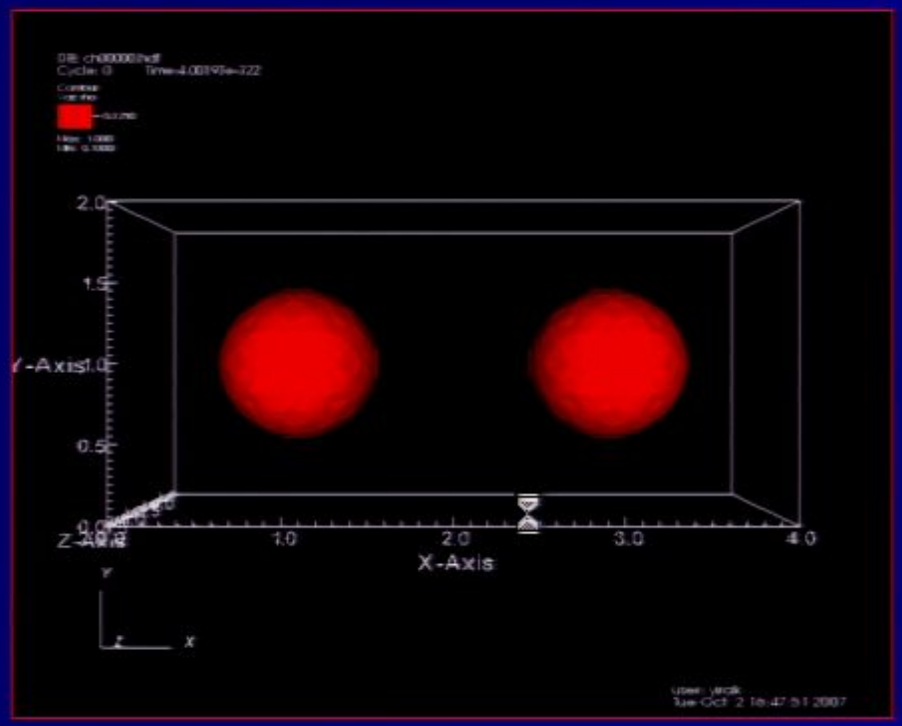
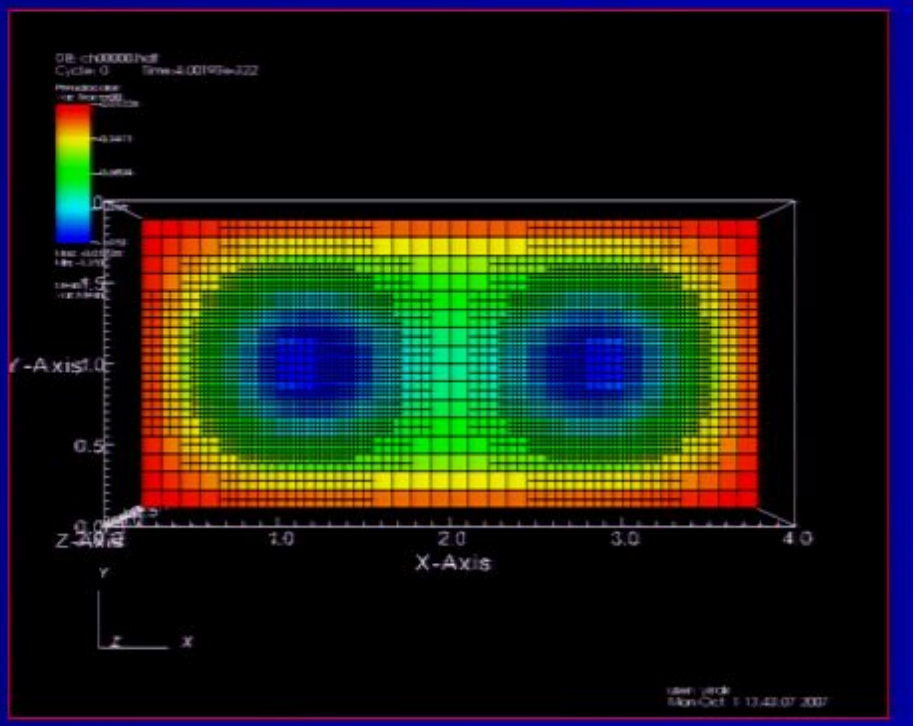


Self-Gravity and AMR

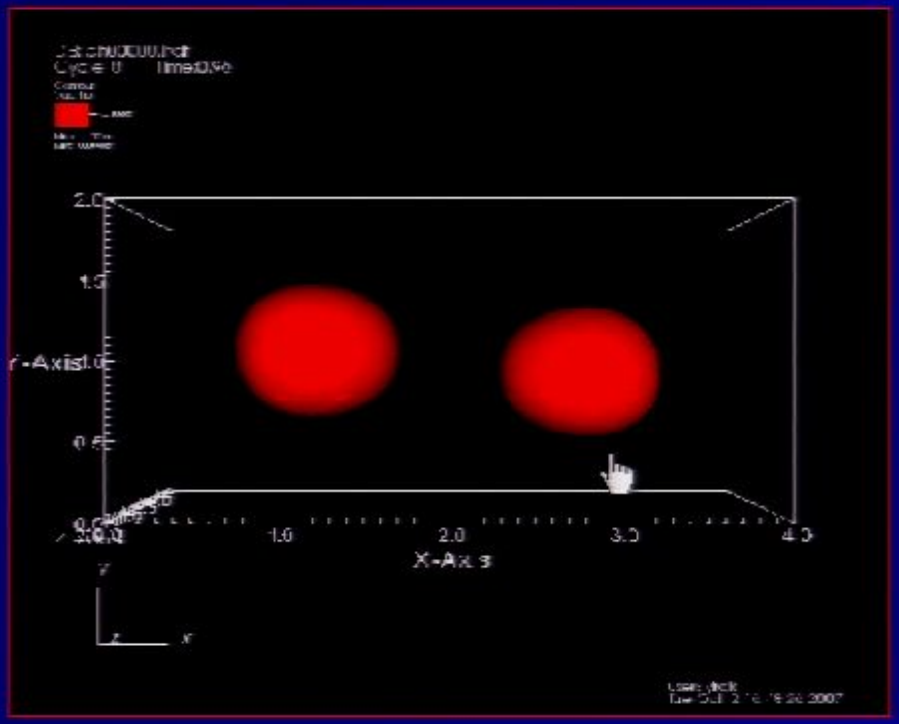


Density isosurface



AMR grid Structure

Self-Gravity and AMR



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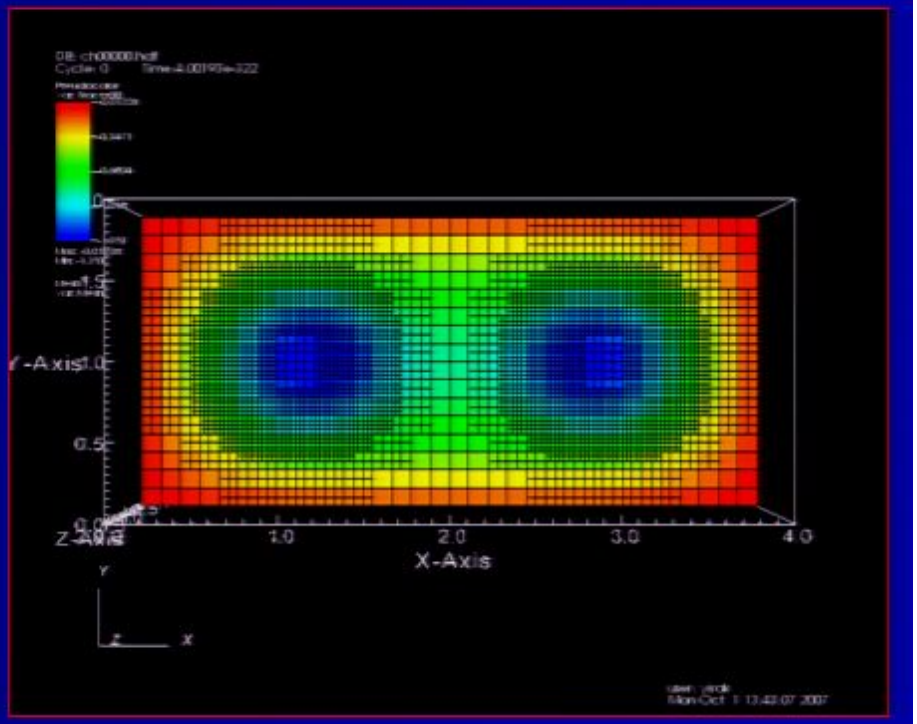
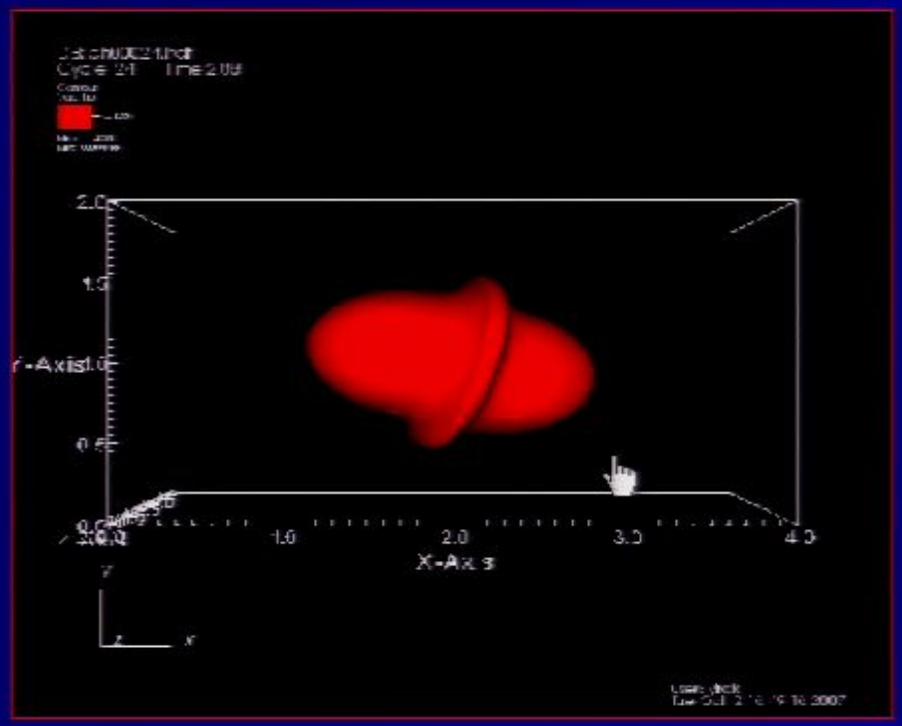


AMR grid Structure

Self-Gravity and AMR



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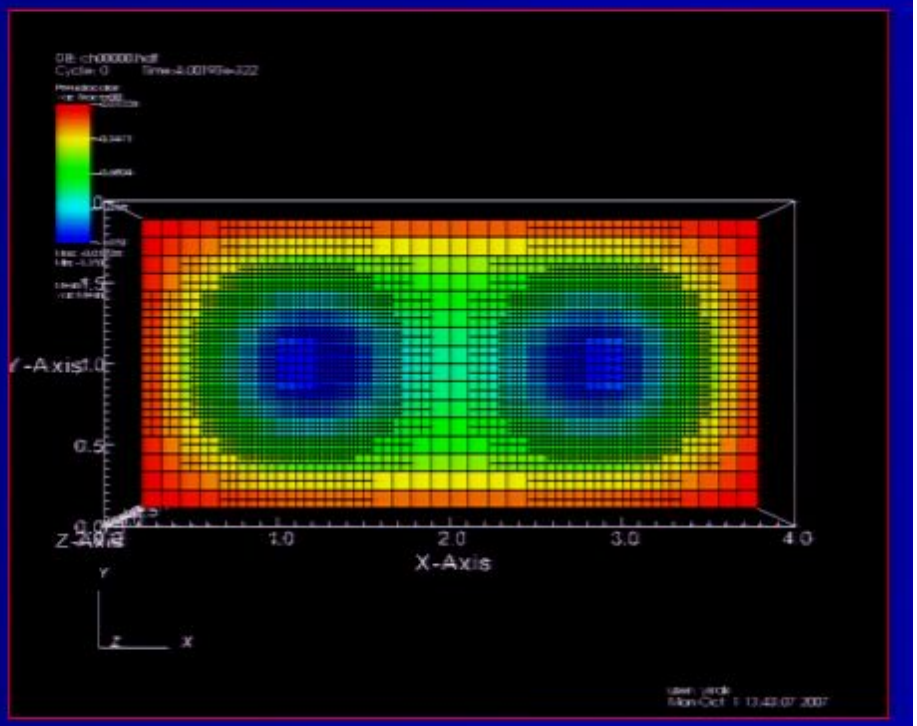
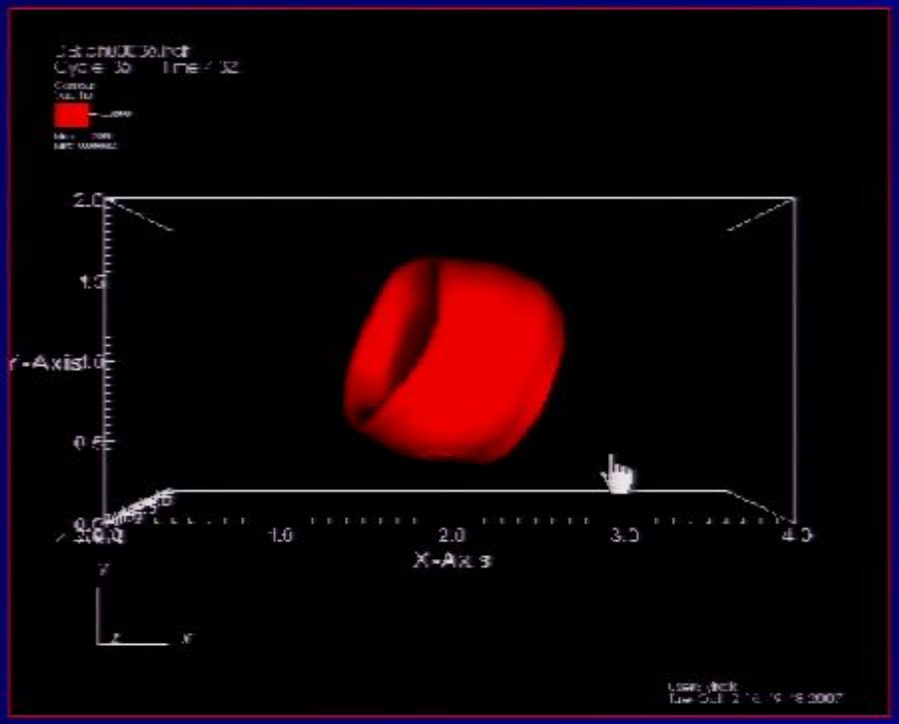


AMR grid Structure

Self-Gravity and AMR



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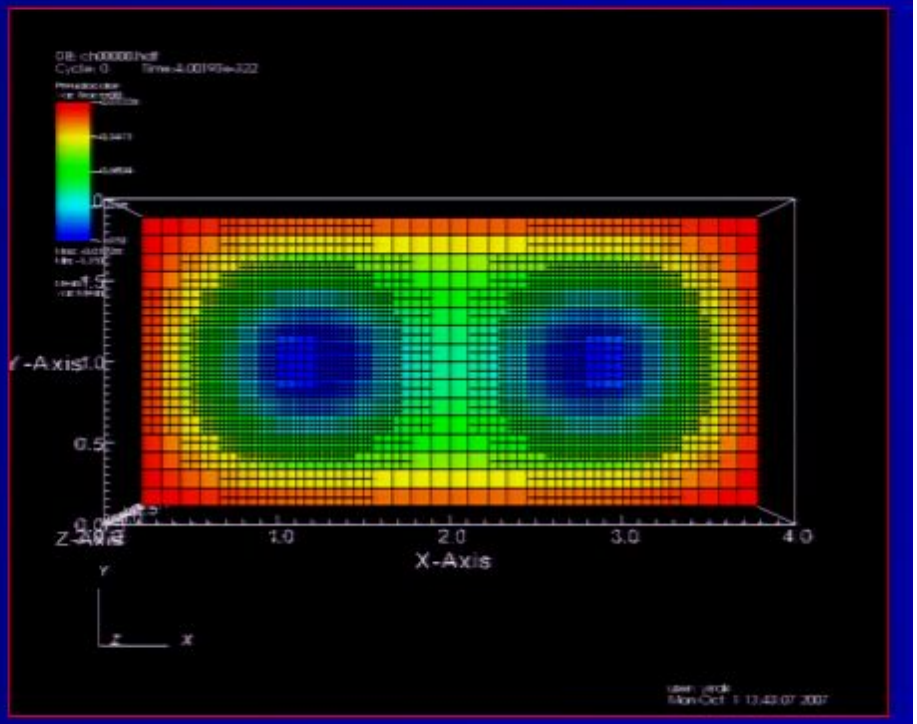
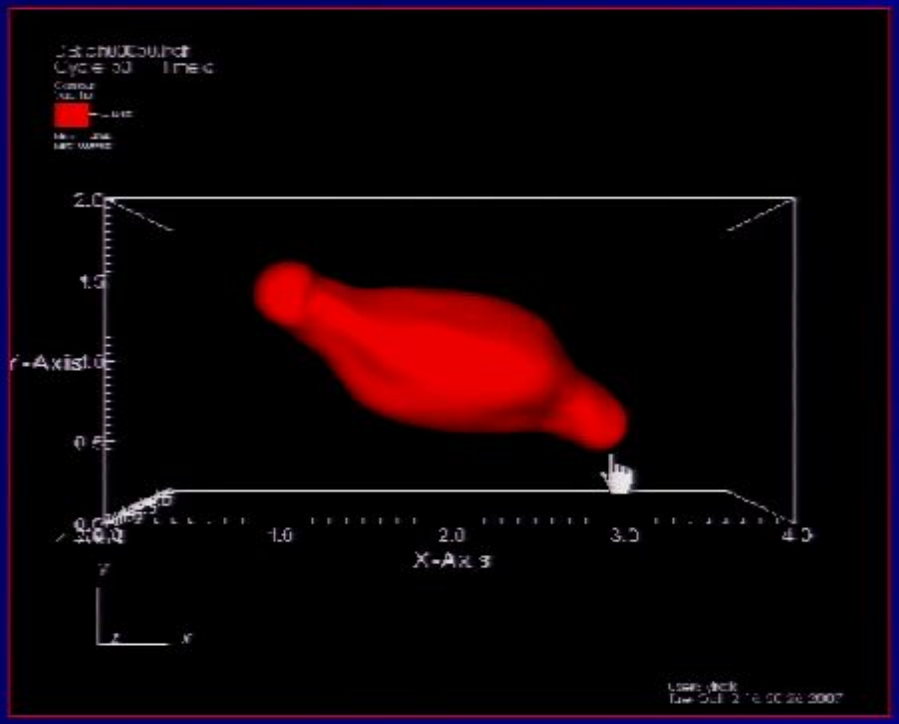


AMR grid Structure

Self-Gravity and AMR



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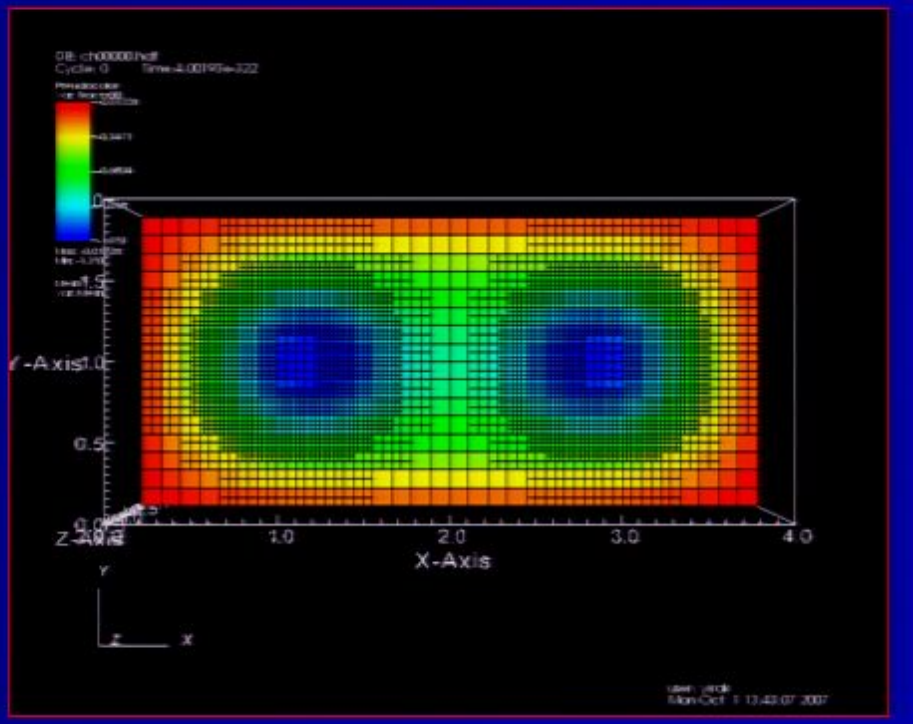
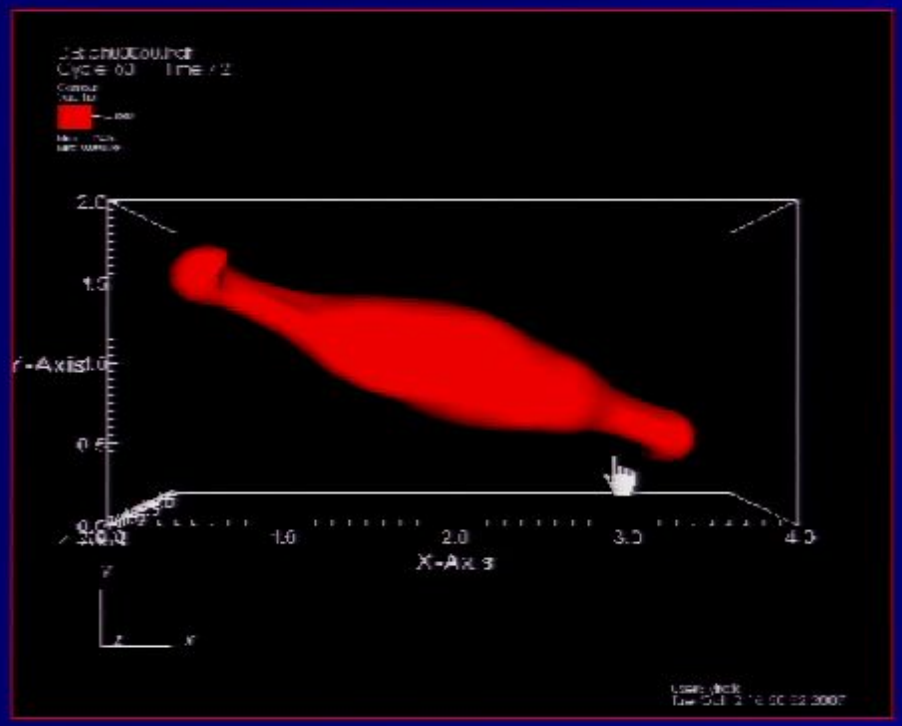


AMR grid Structure

Self-Gravity and AMR



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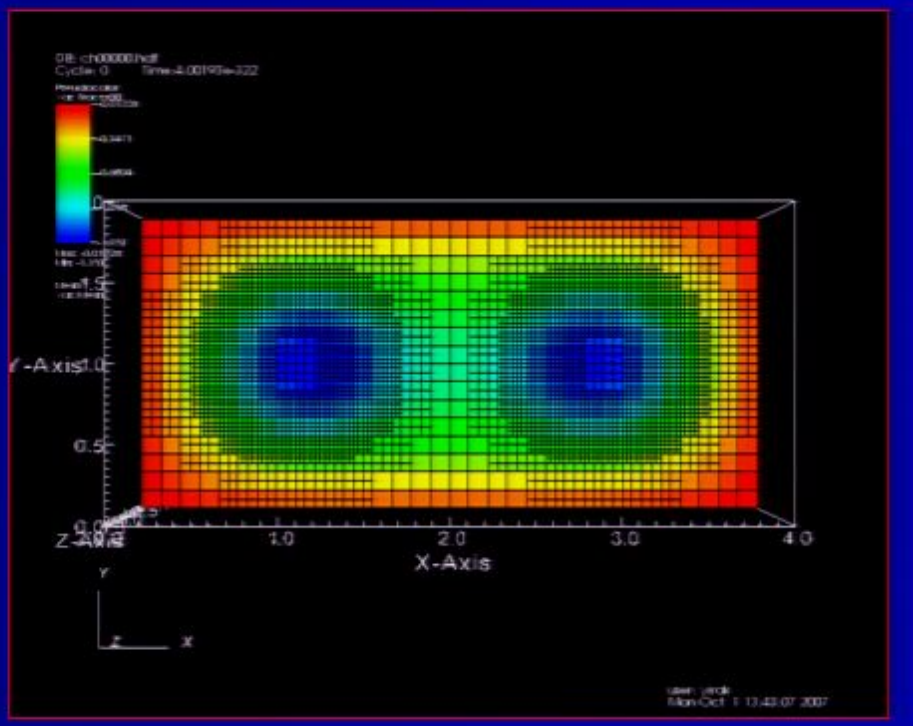
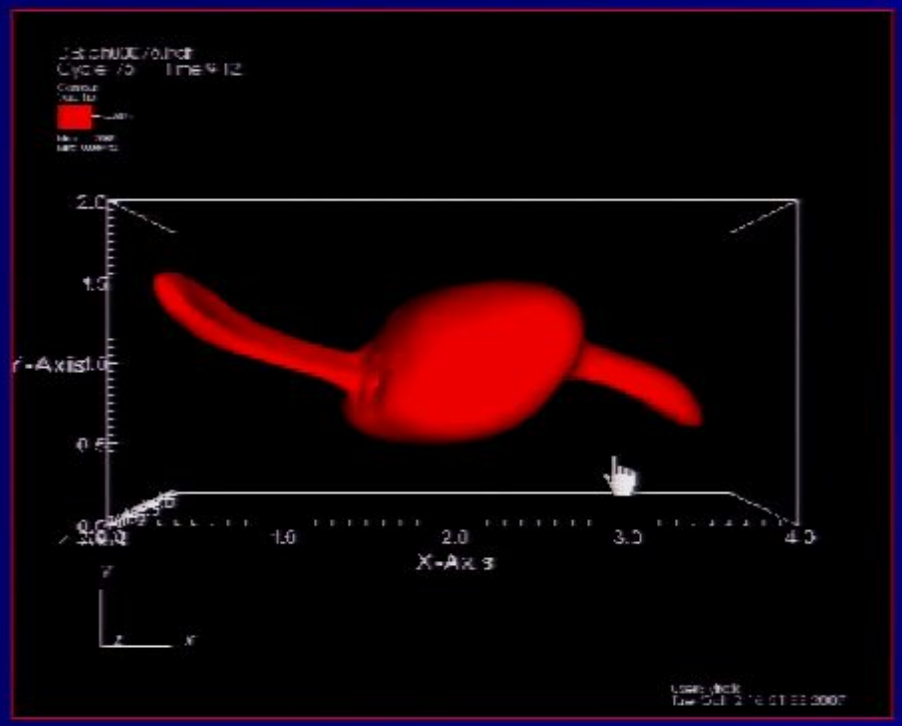


AMR grid Structure

Self-Gravity and AMR



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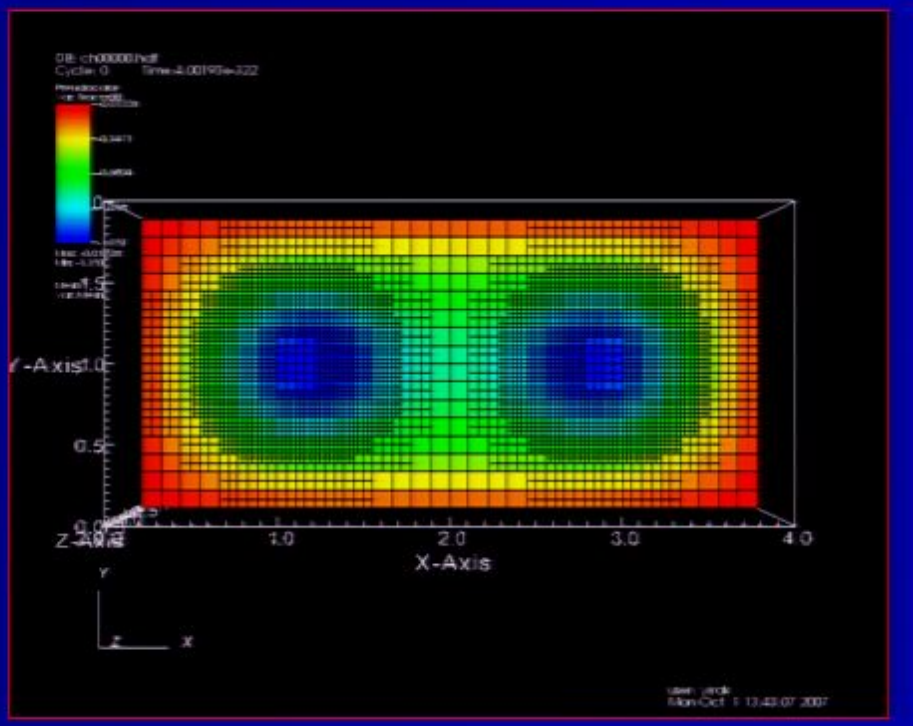
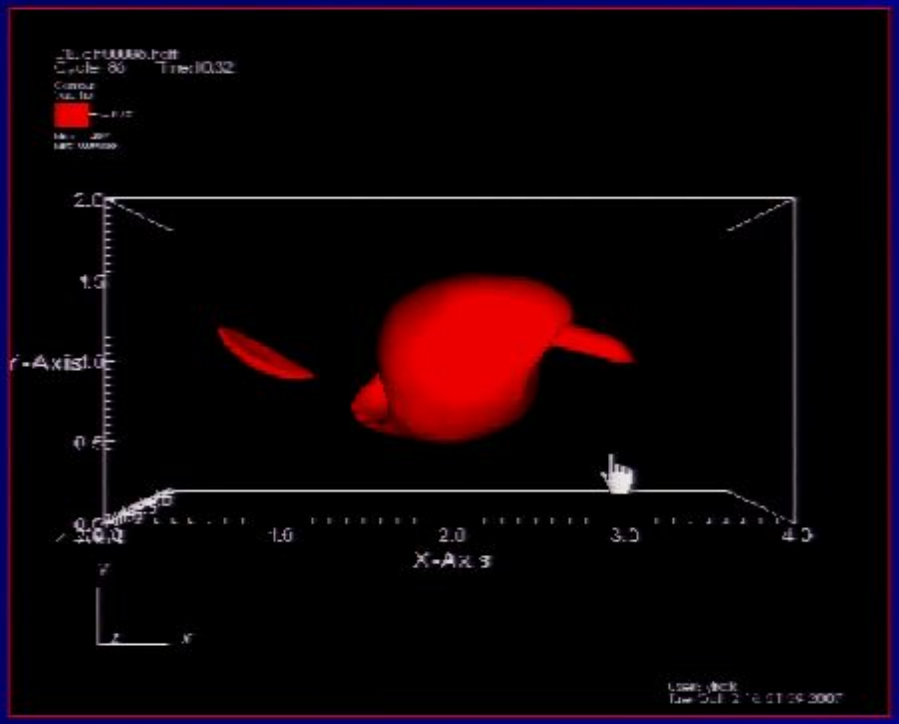


AMR grid Structure

Self-Gravity and AMR



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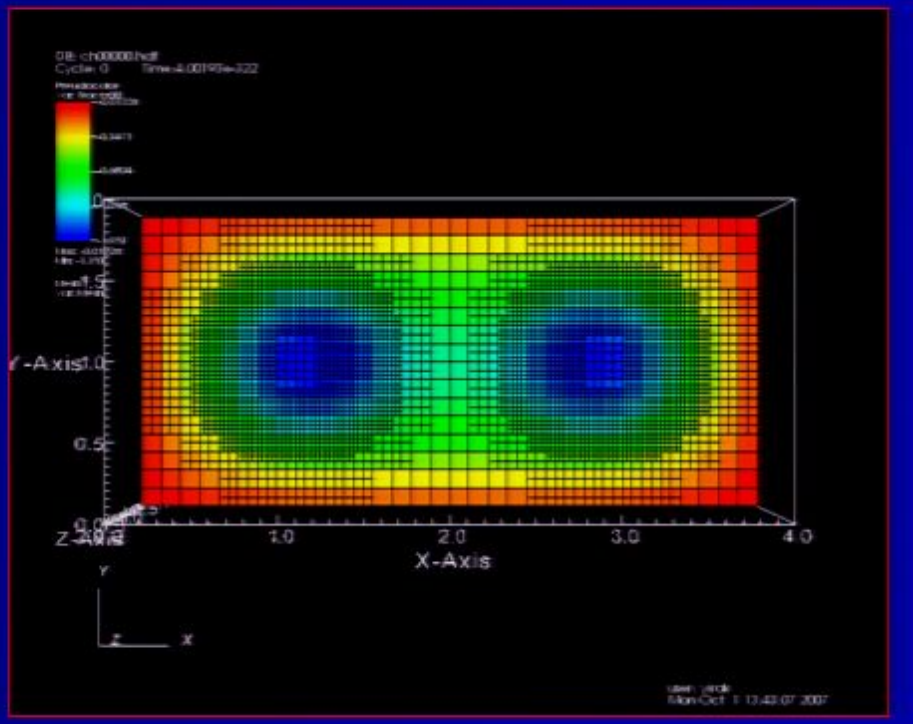
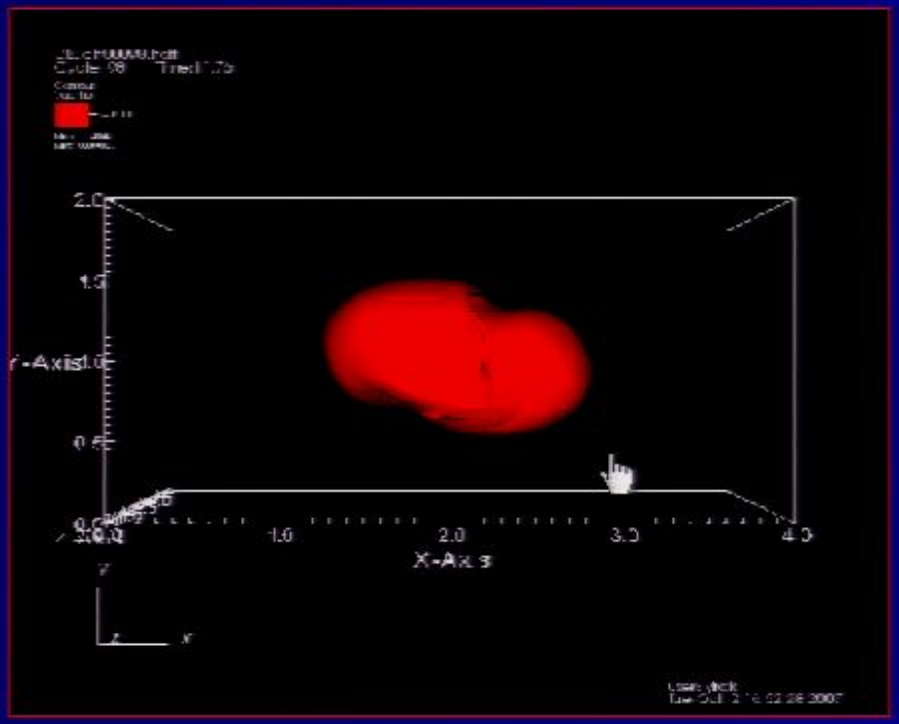


AMR grid Structure

Self-Gravity and AMR



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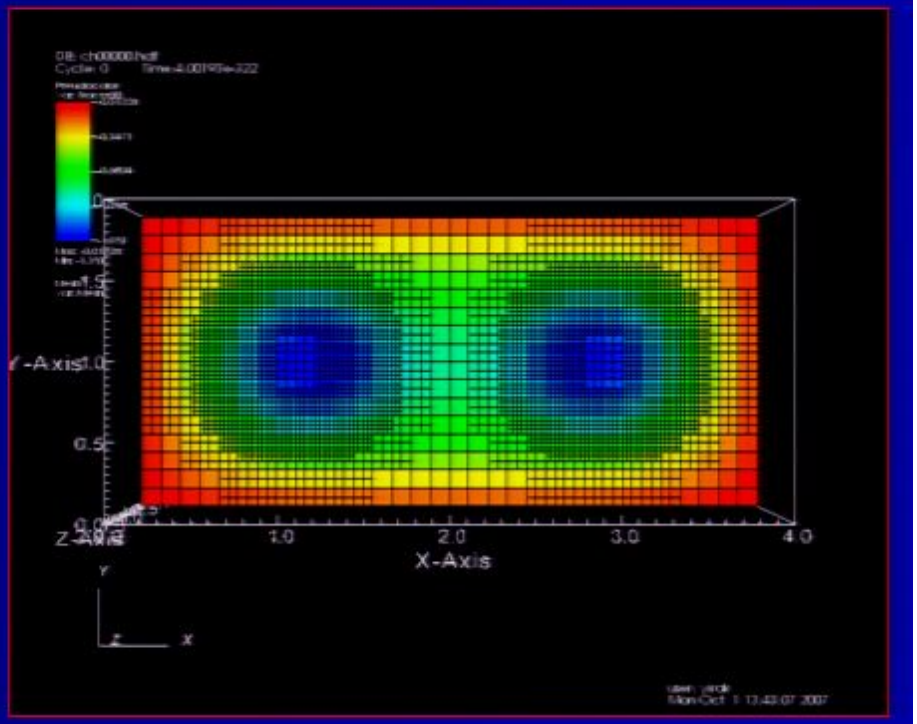
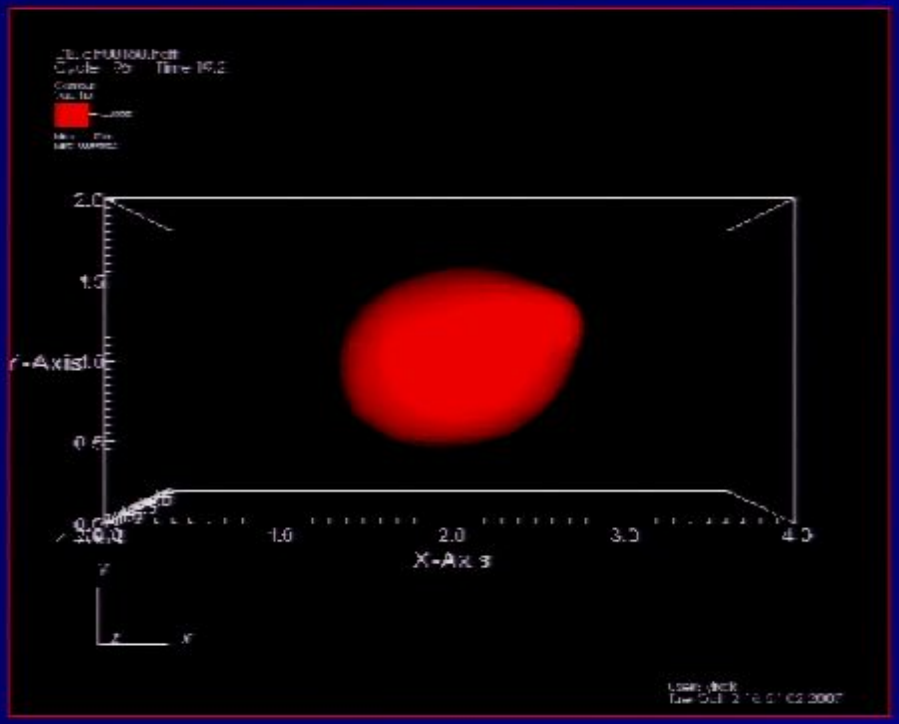


AMR grid Structure

Self-Gravity and AMR



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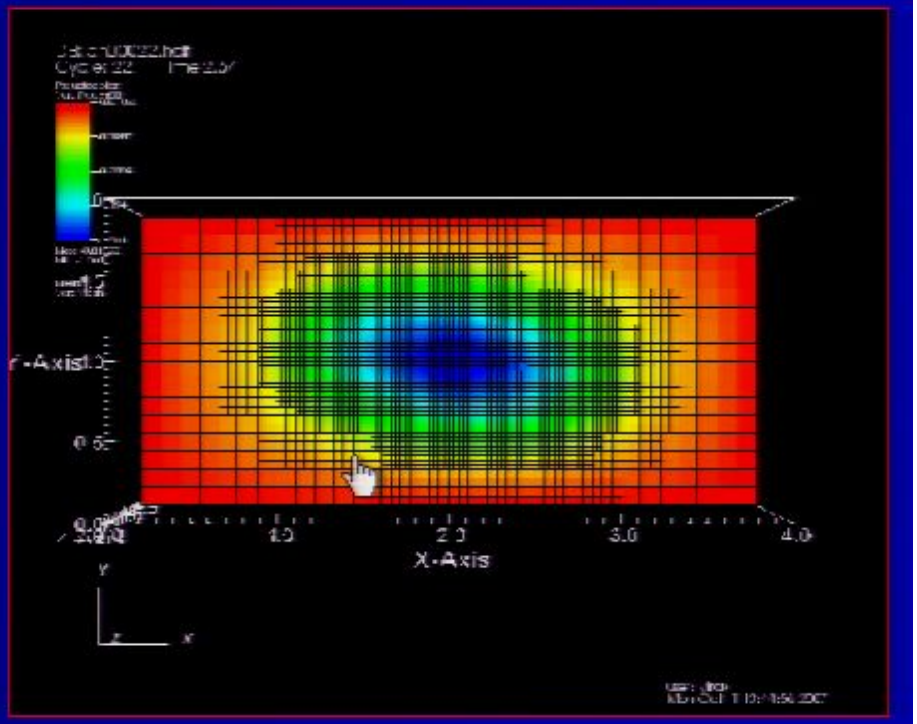
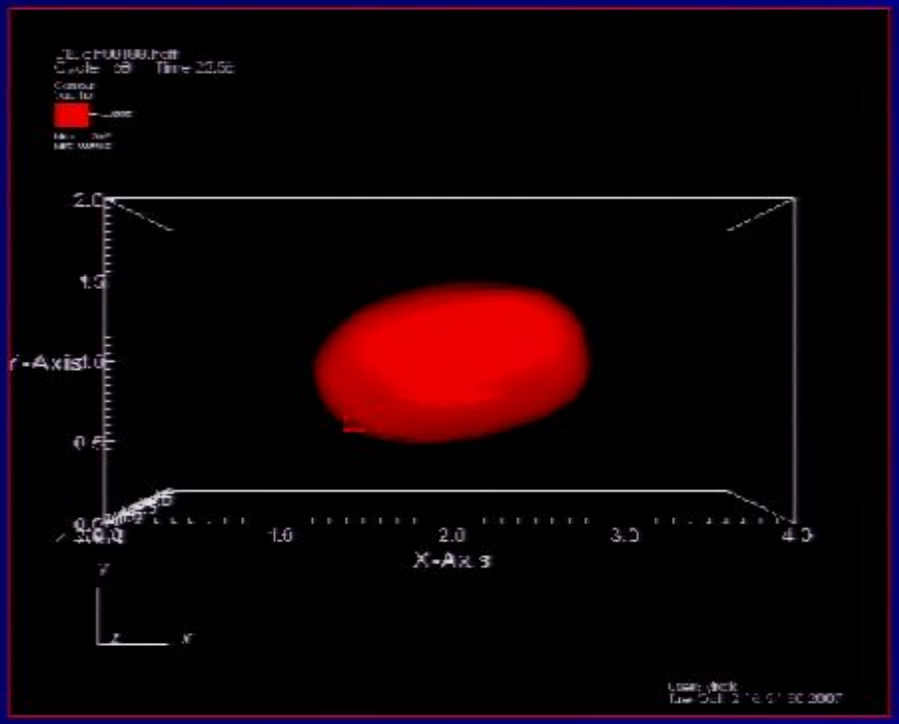


AMR grid Structure

Self-Gravity and AMR



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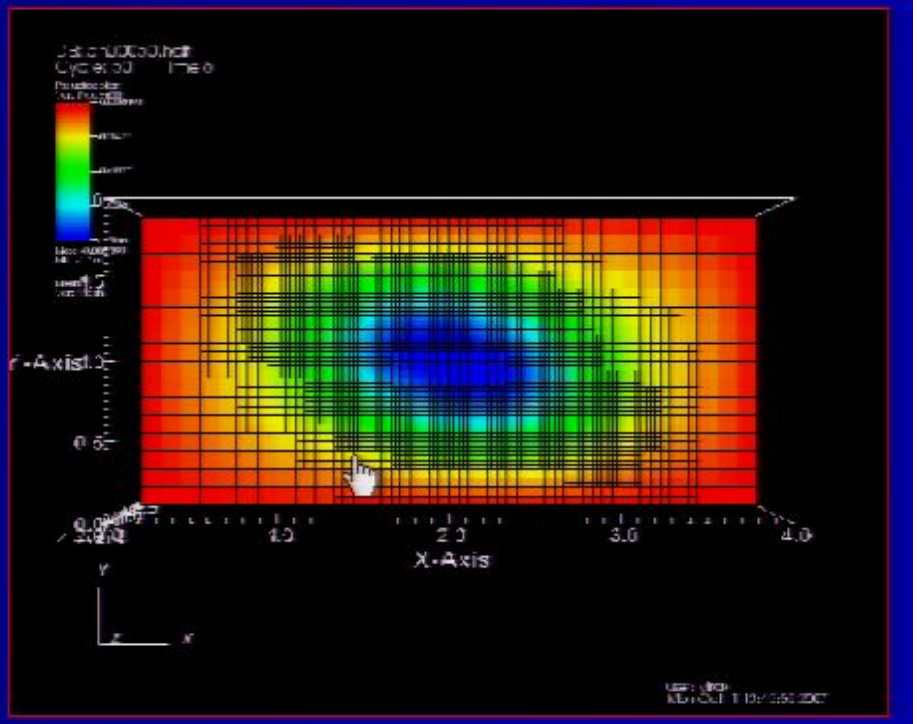
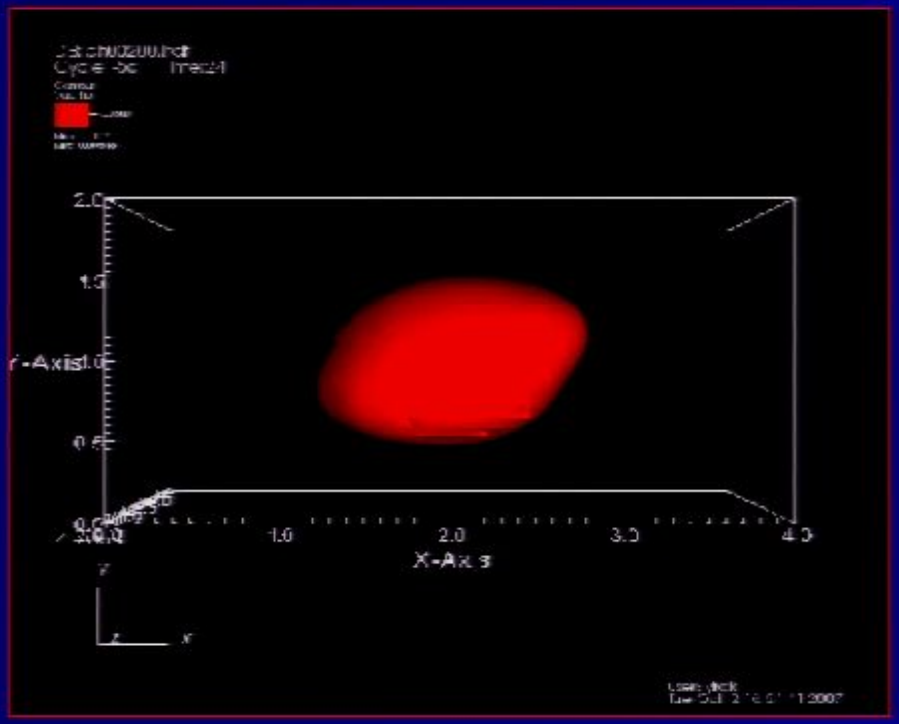


AMR grid Structure

Self-Gravity and AMR



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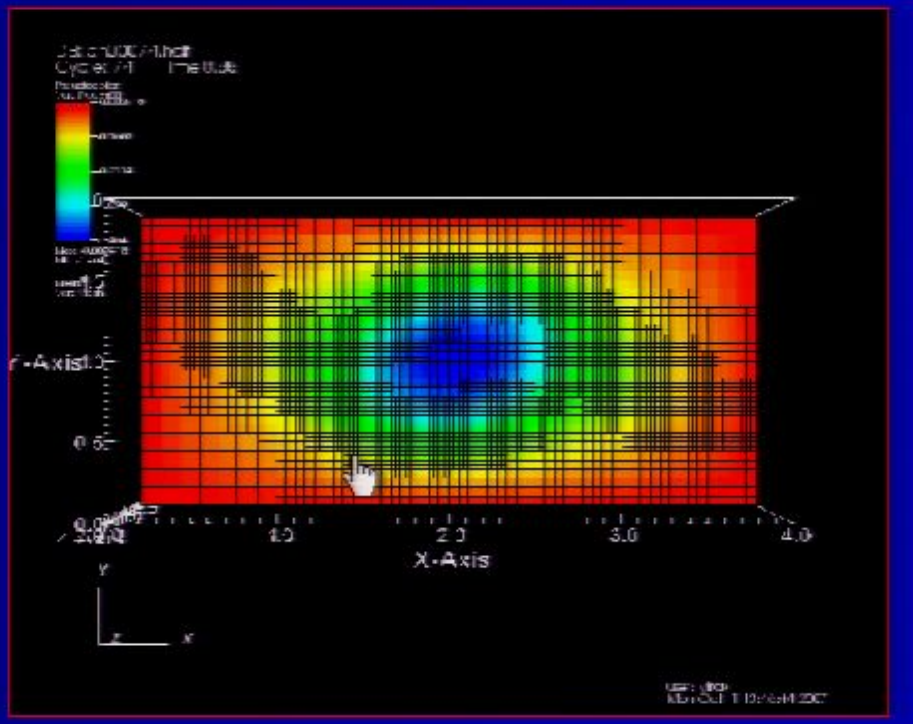
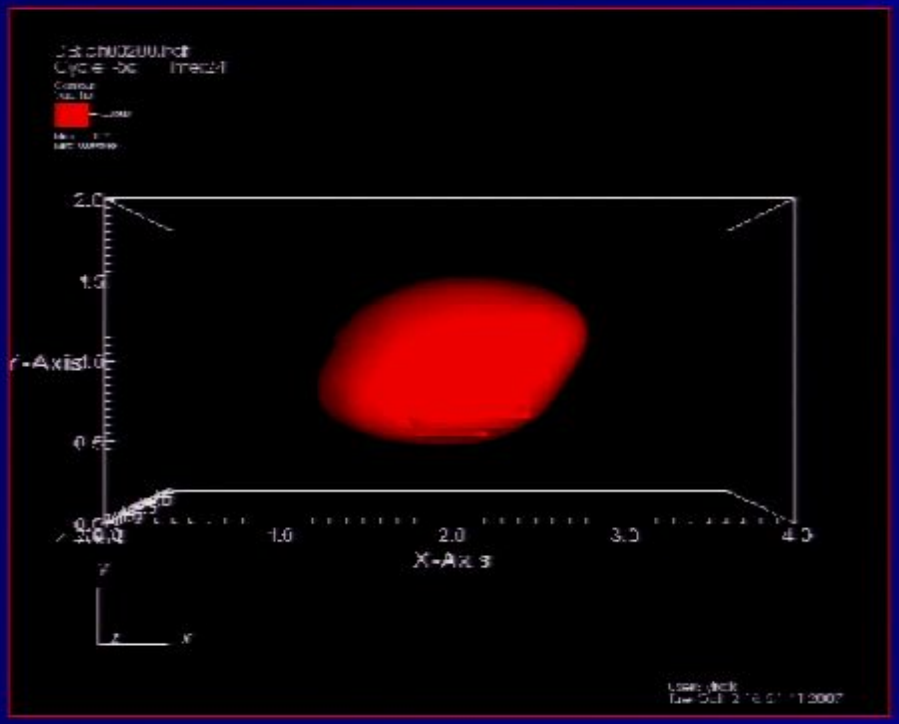


AMR grid Structure

Self-Gravity and AMR



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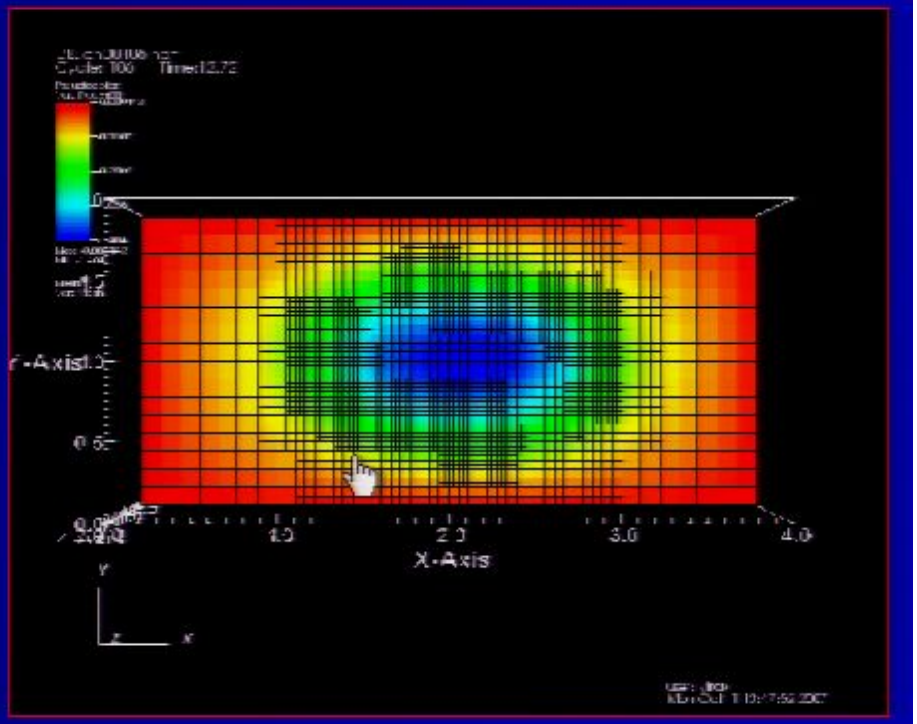

AMR grid Structure

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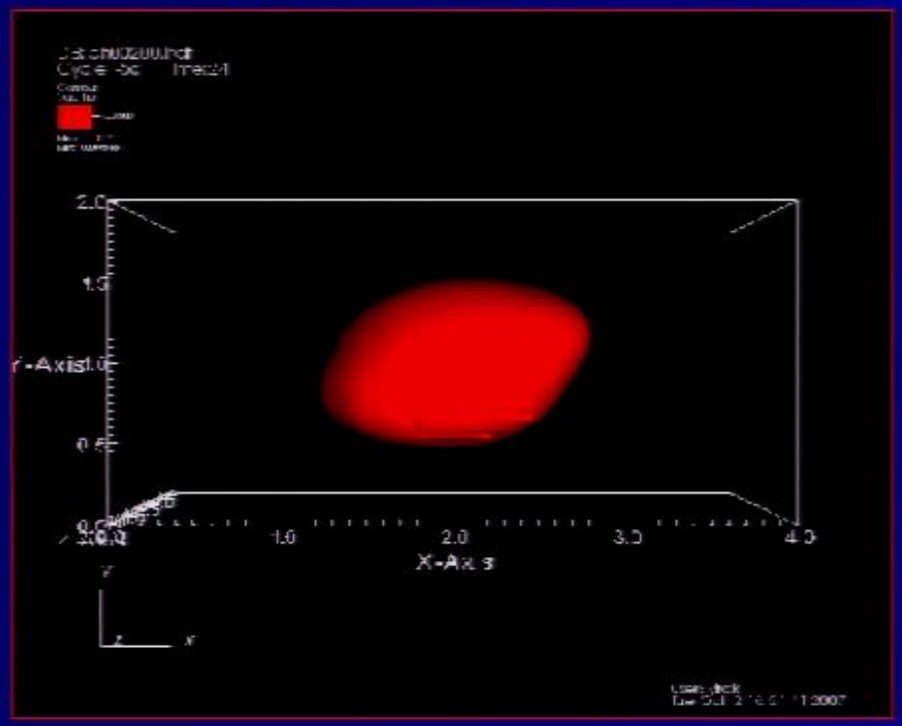

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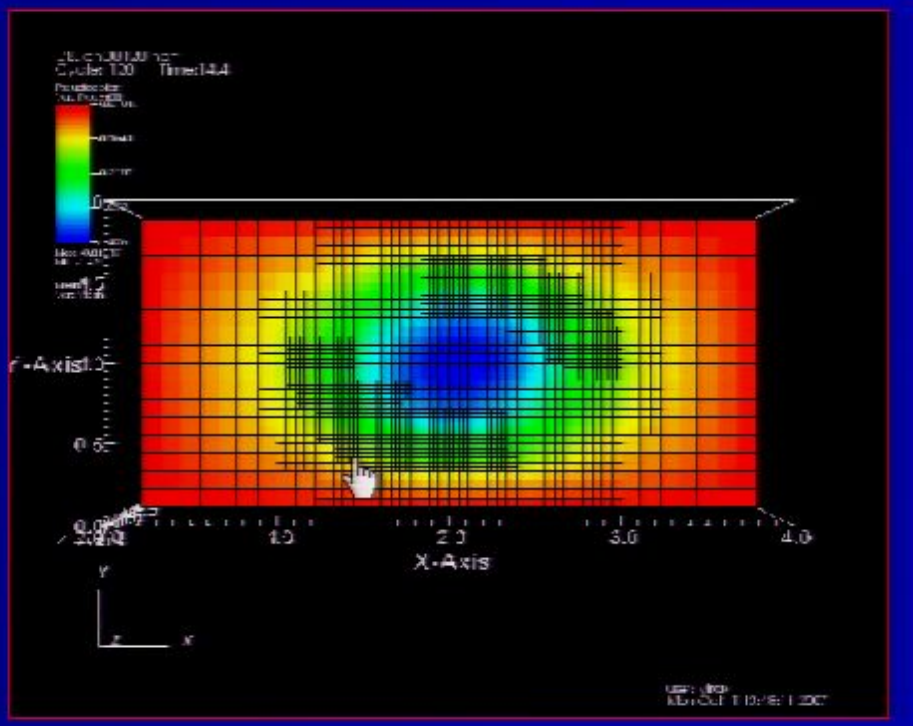
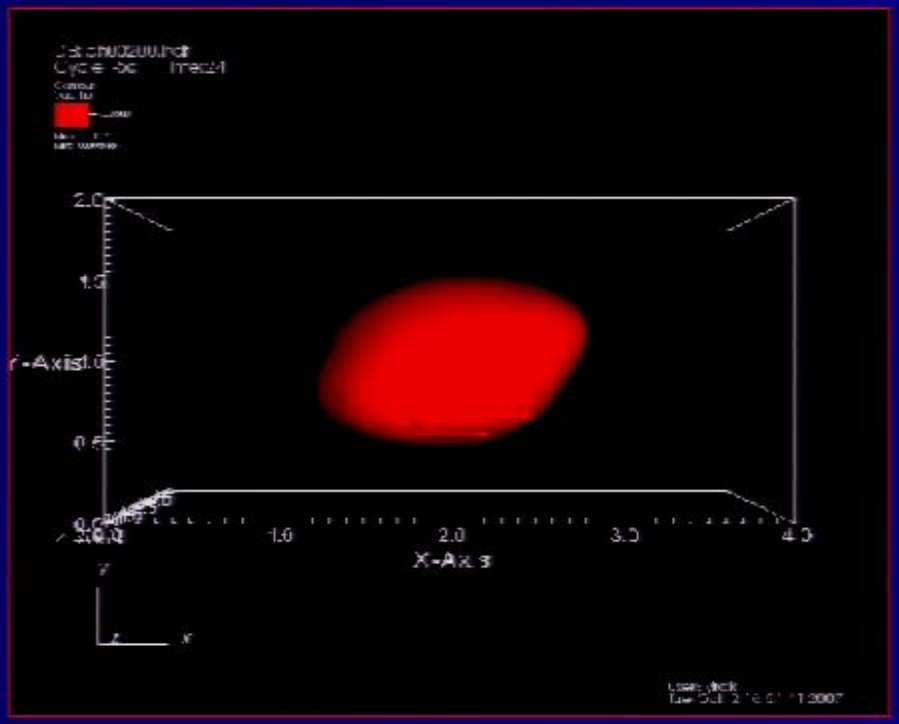


AMR grid Structure

Self-Gravity and AMR



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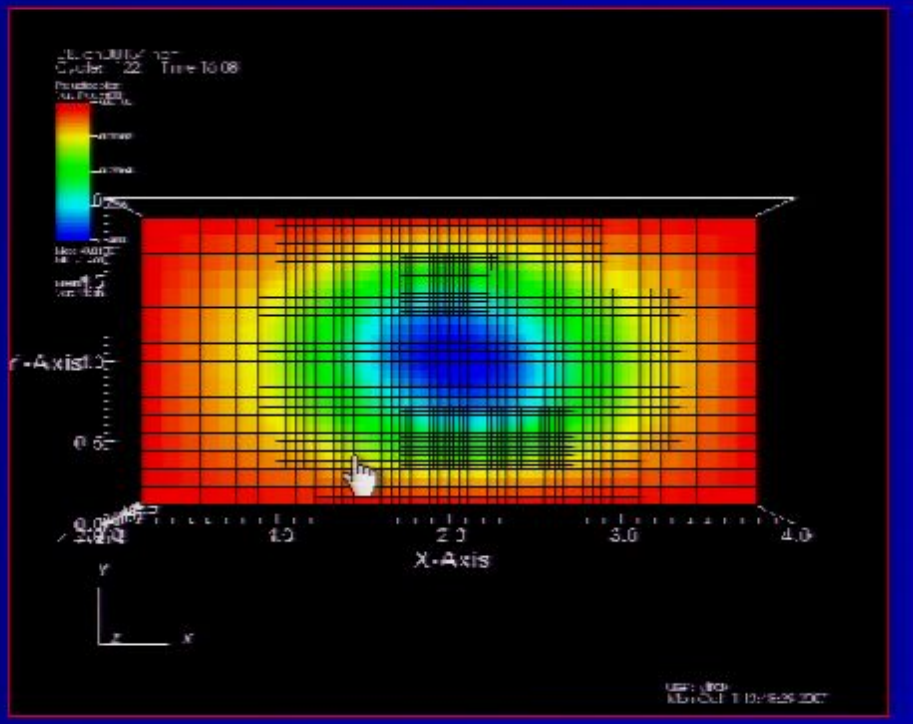
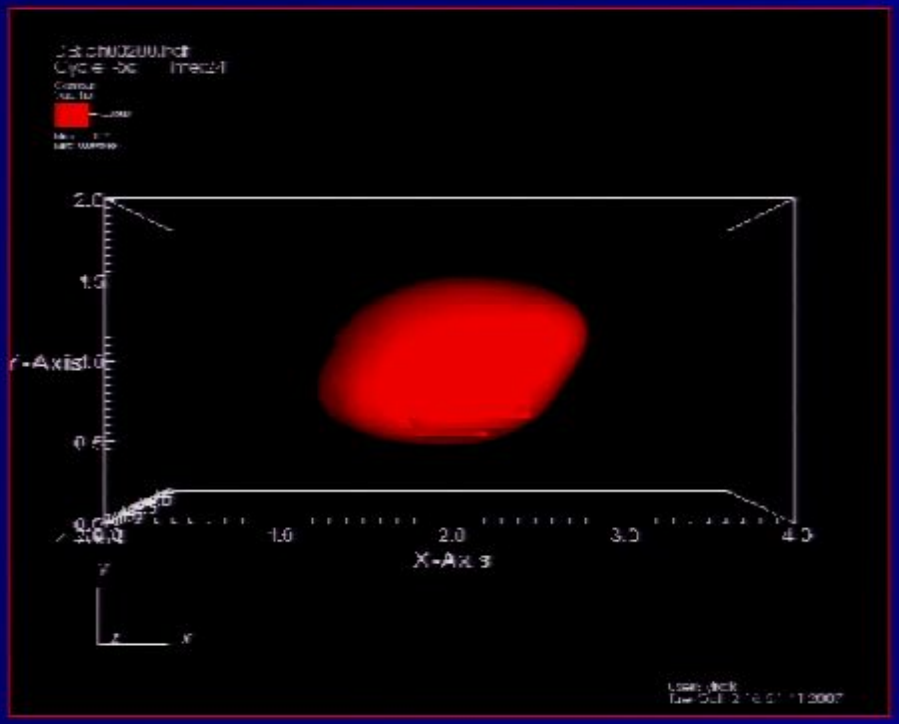


AMR grid Structure

Self-Gravity and AMR



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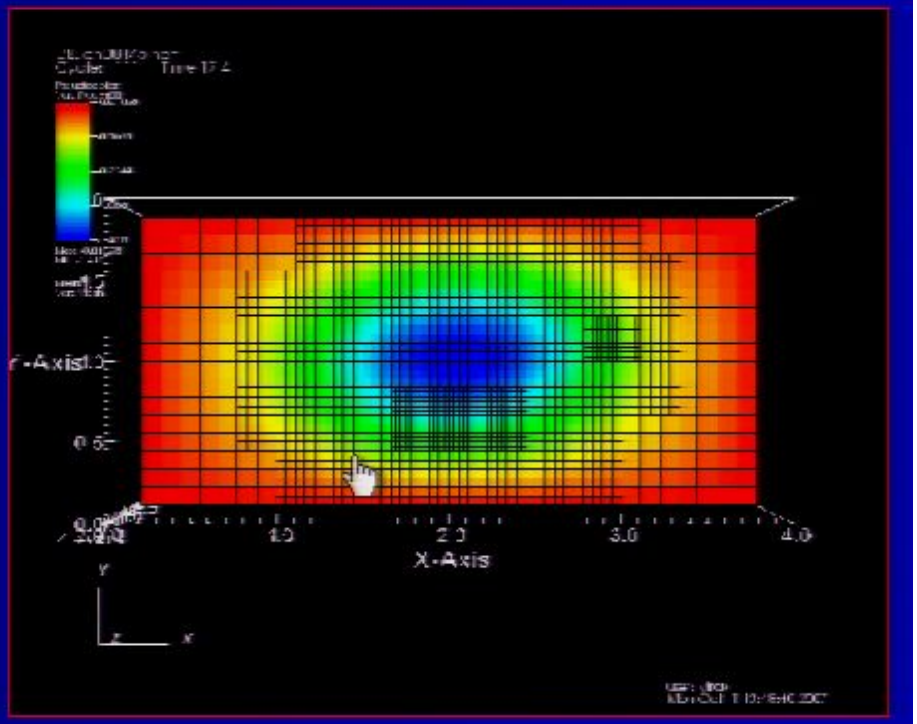
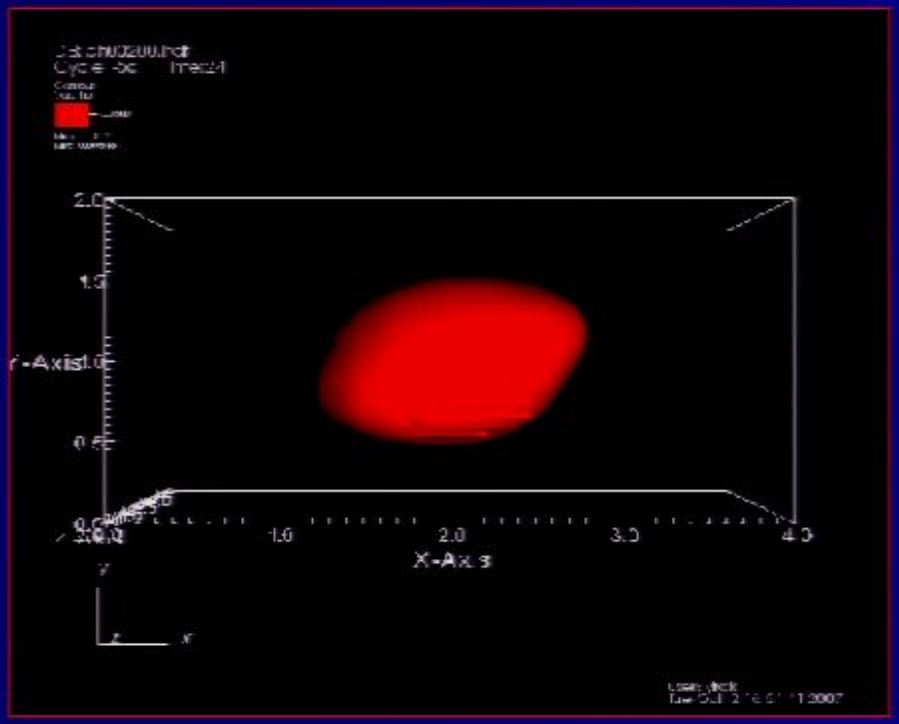


AMR grid Structure

Self-Gravity and AMR



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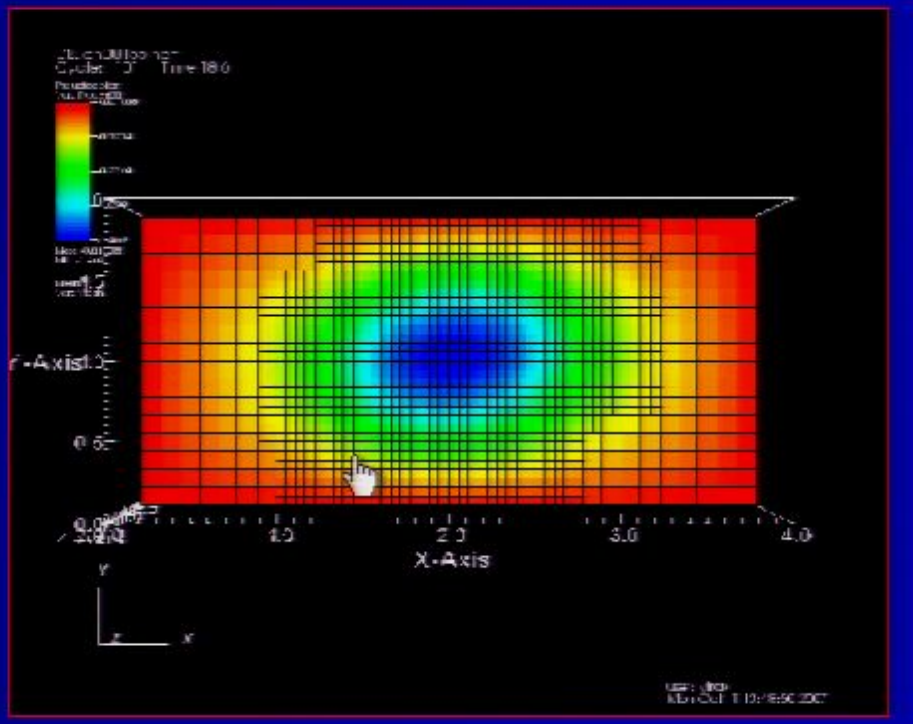
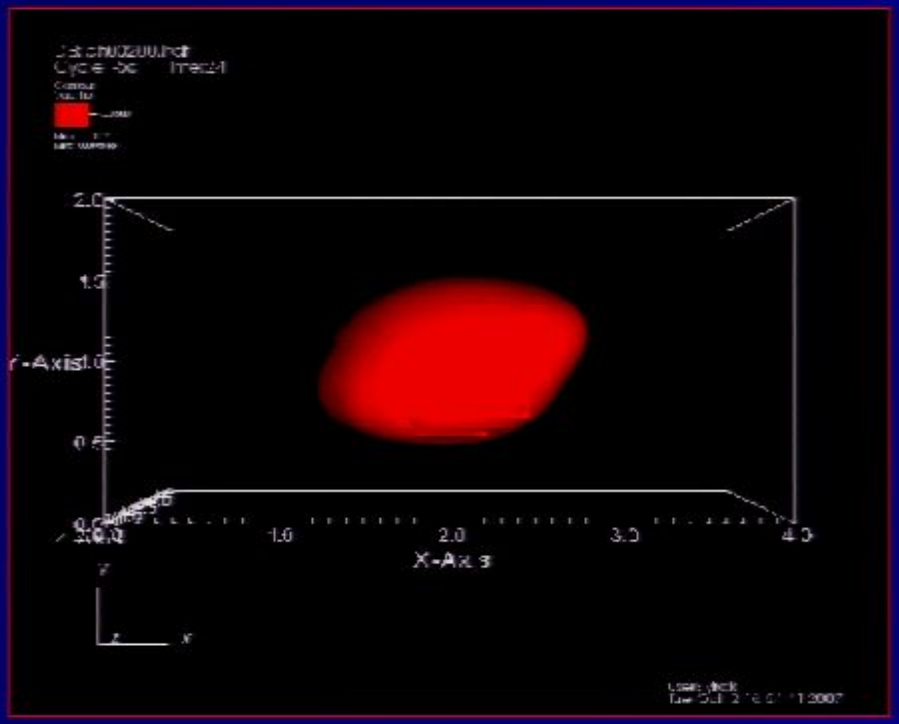


AMR grid Structure

Self-Gravity and AMR



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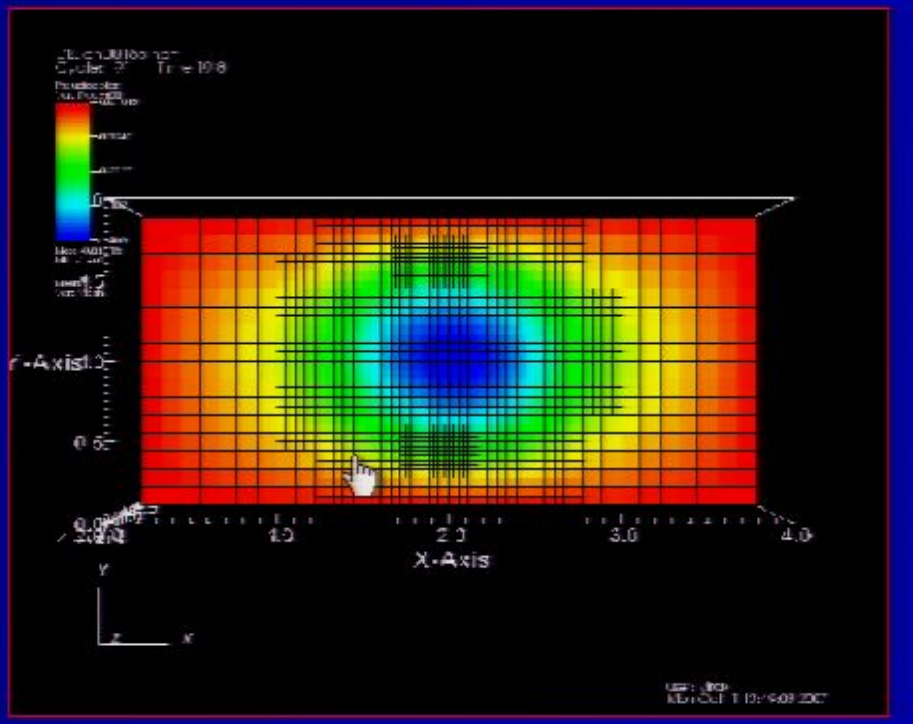
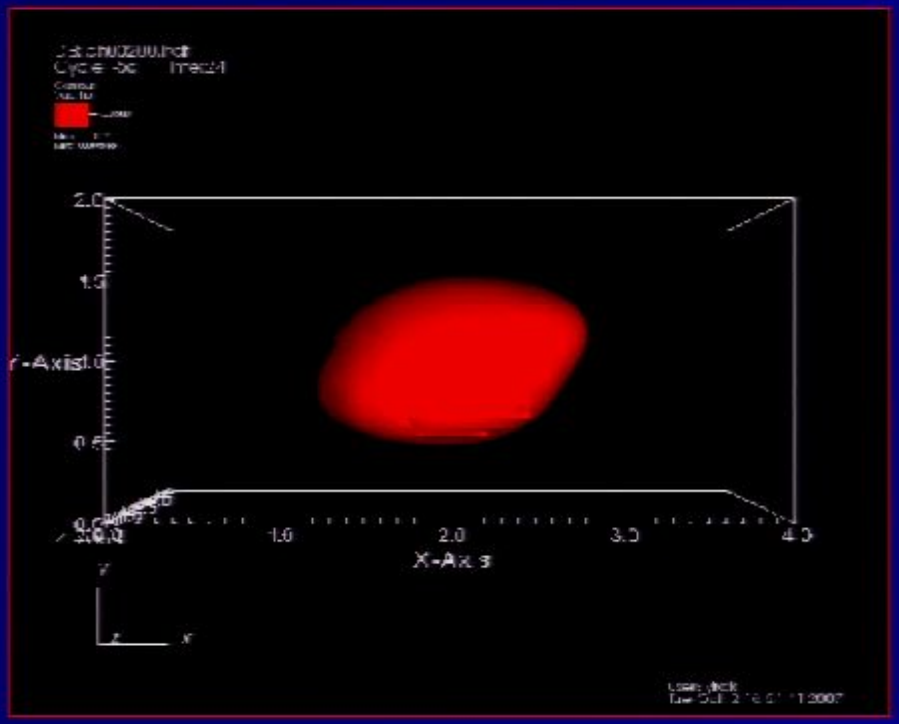


AMR grid Structure

Self-Gravity and AMR



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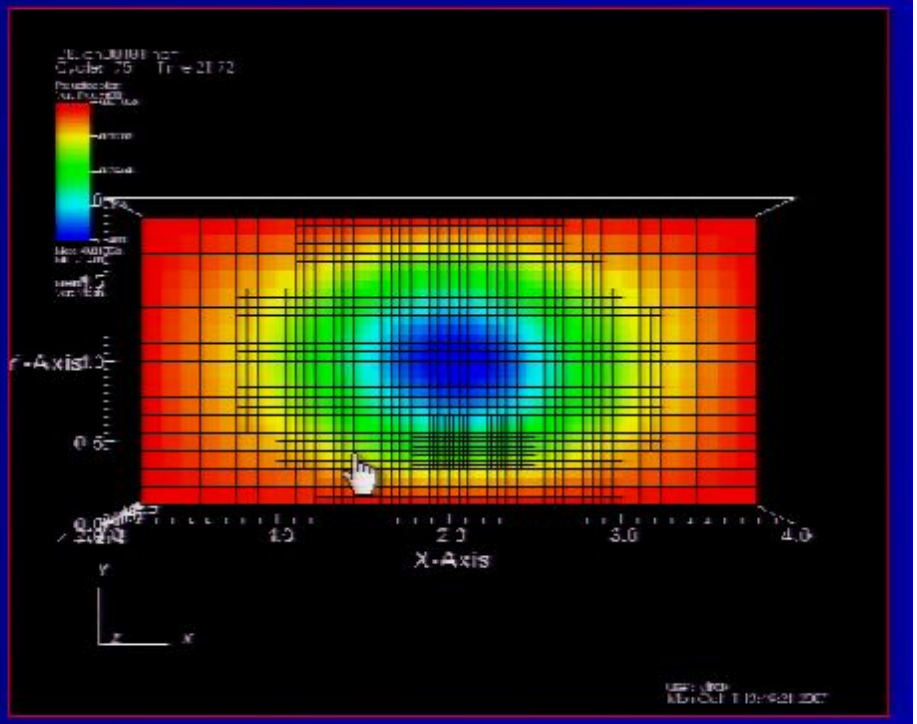
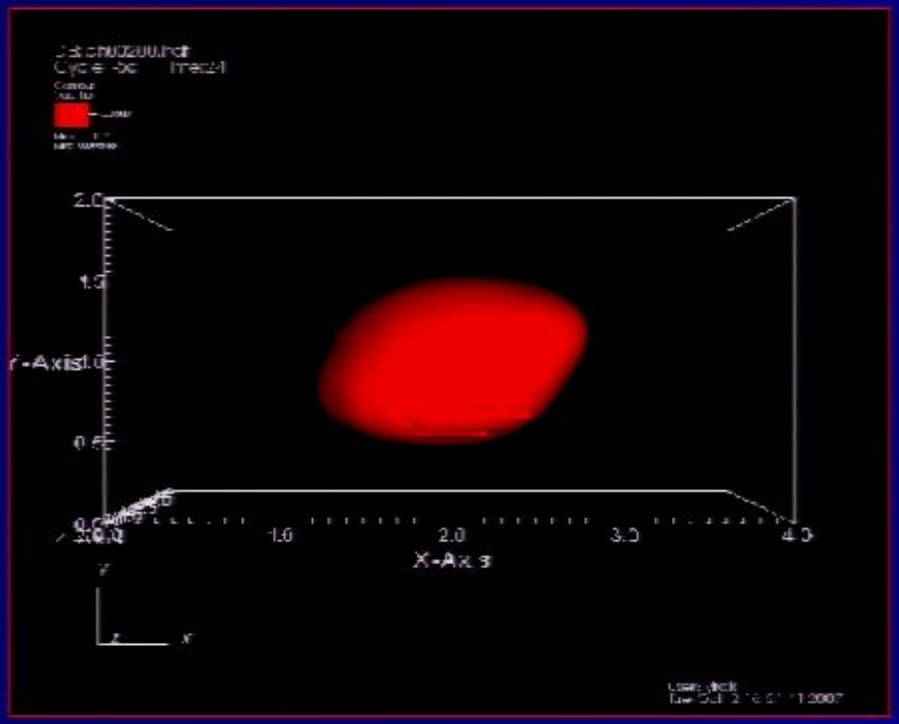
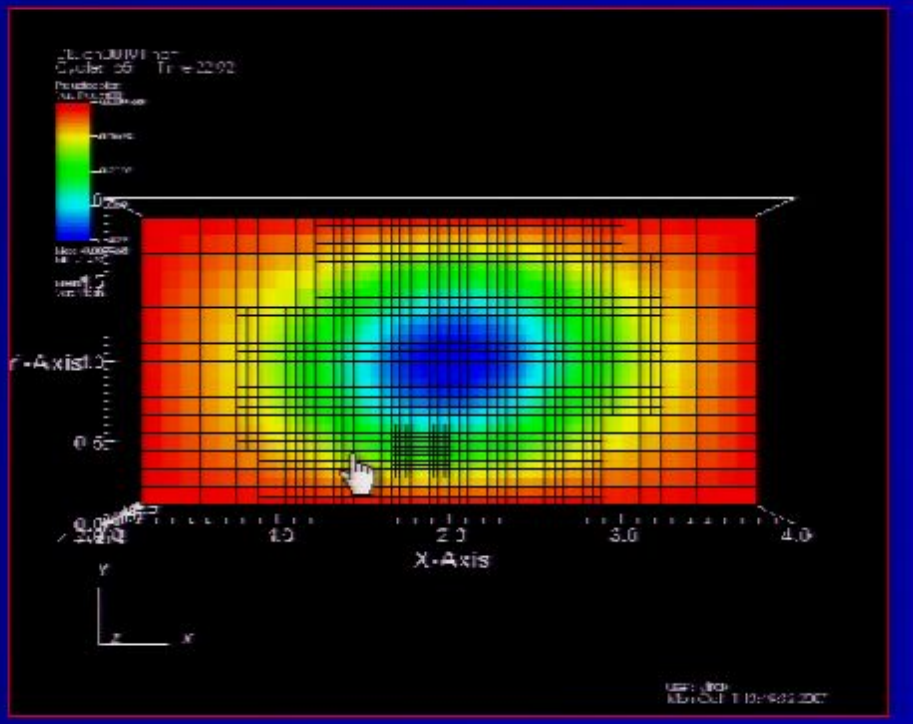


AMR grid Structure

Self-Gravity and AMR



Density isosurface



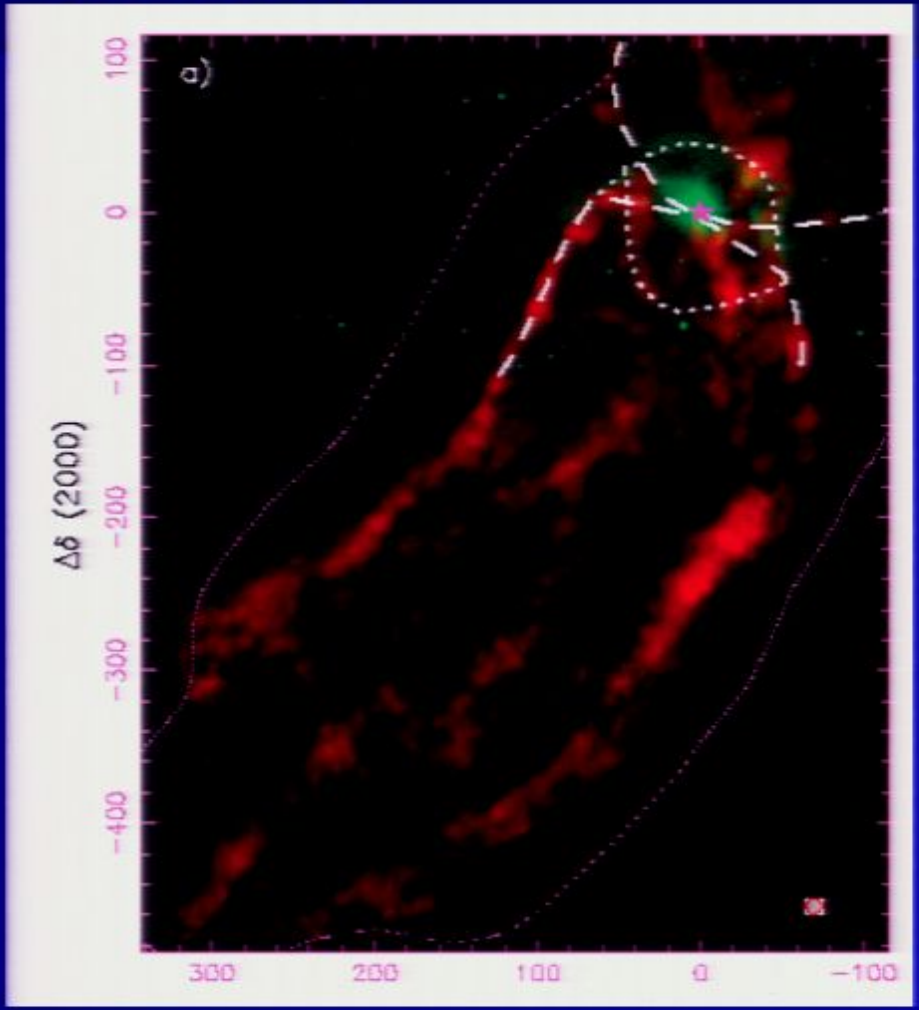
AMR grid Structure

Act 2
Turbulence and Protostellar Outflows

1. Turbulence supports clouds against self-gravity.
2. Turbulence decays ‘’’fast”.
3. What re-energizes turbulence?

Jets and Molecular Outflows

Ubiquitous Phenomena in Star Forming Environments



HH Jet
HH 111

Molecular Outflow
IRAS 16316

MHD and Outflows:
Magneto-Rotational Launching (MRL)

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  - MRL -> EVERY COLLIMATED OUTFLOW ENVIRONMENT!
    - YSOs, AGN, micro-Quasars: GRBs, SNe

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  - Theory/Simulation – "Fling" (B_p) vs. "Spring" (B_ϕ)

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- Mature Paradigm – Ex. HH jet rotation -> disk footpoints (Cabrit et al 2006)

MRL Basics

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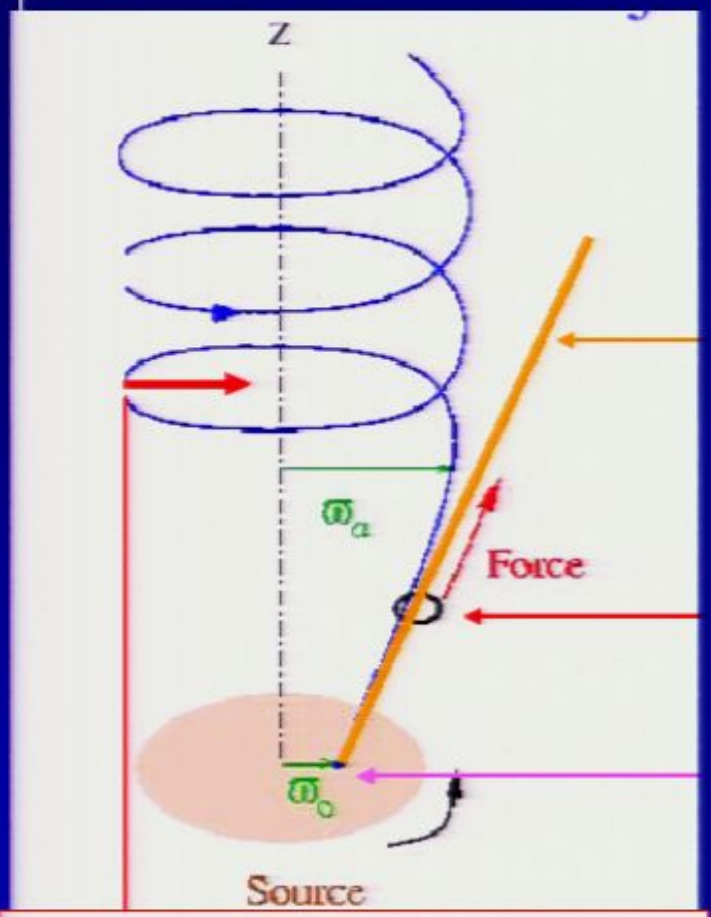

Magneto-centrifugal Models
"Fling" *(Tsinganos et al)*

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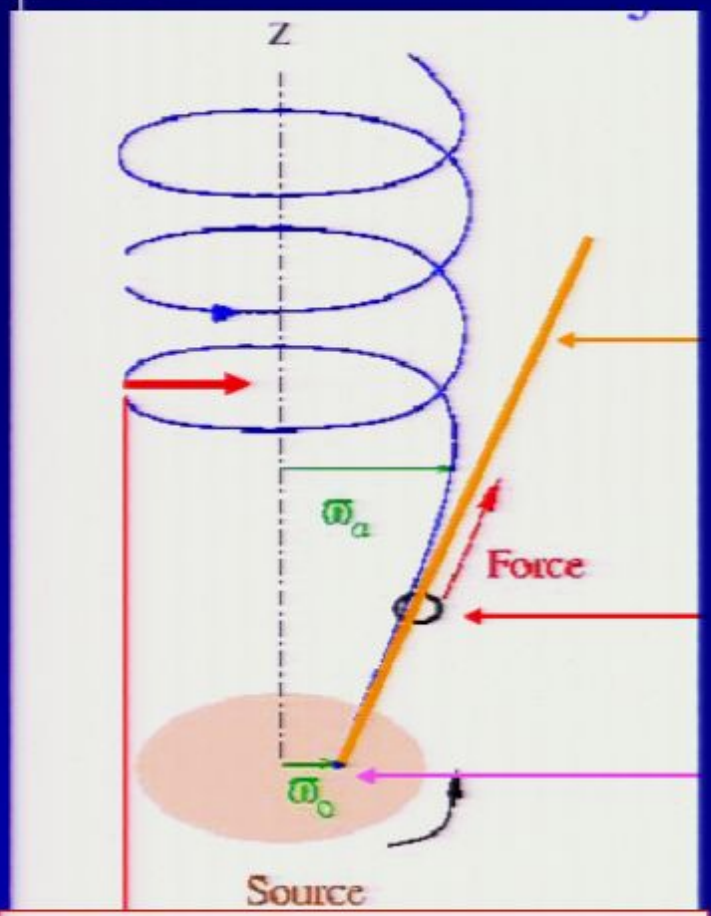

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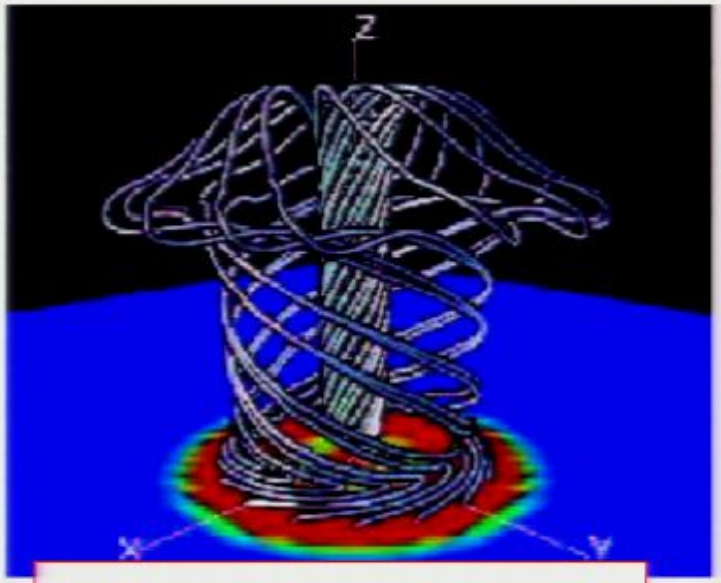

Magnetic Tower Models
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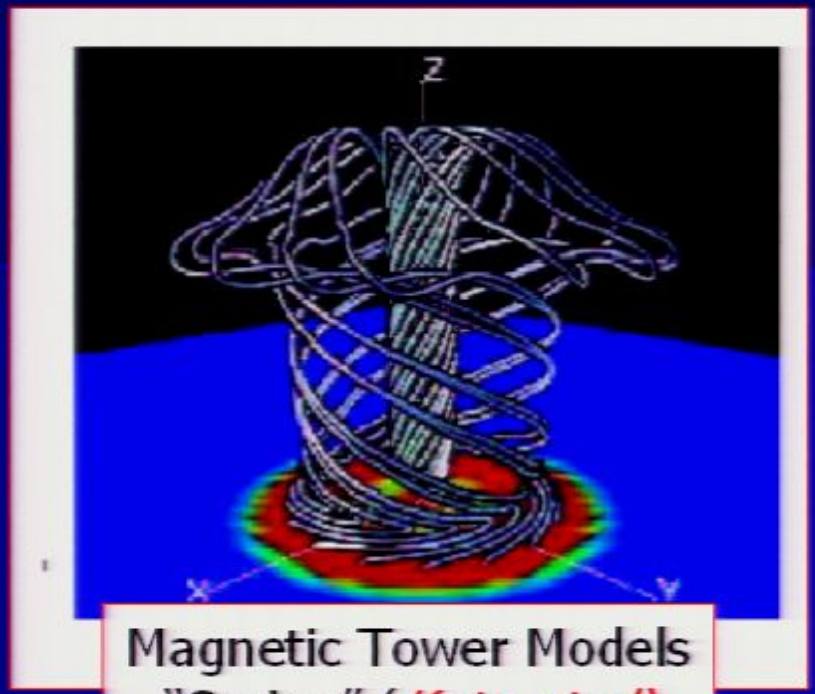

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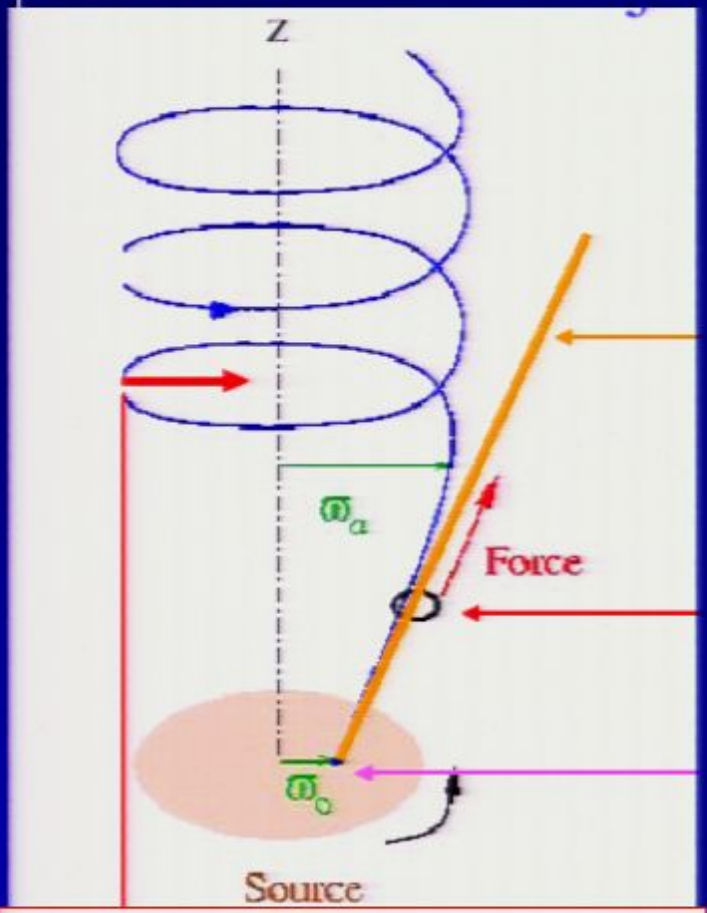

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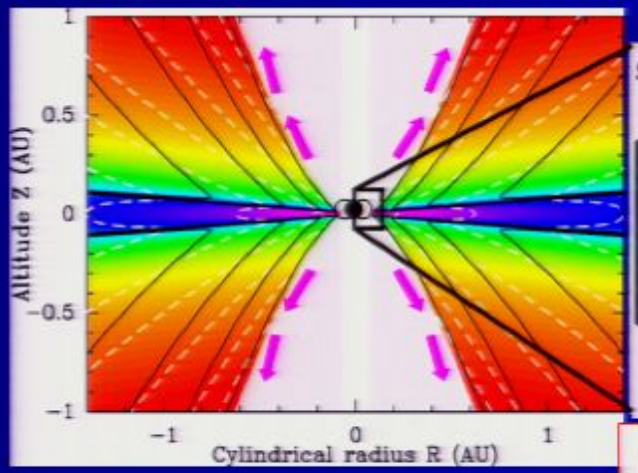
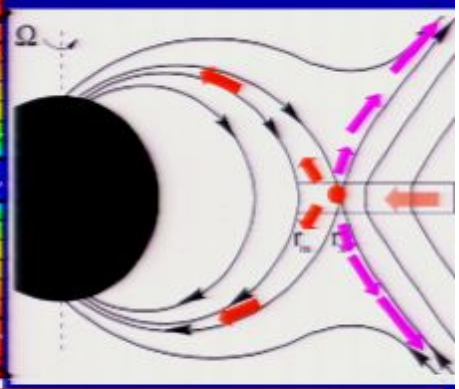
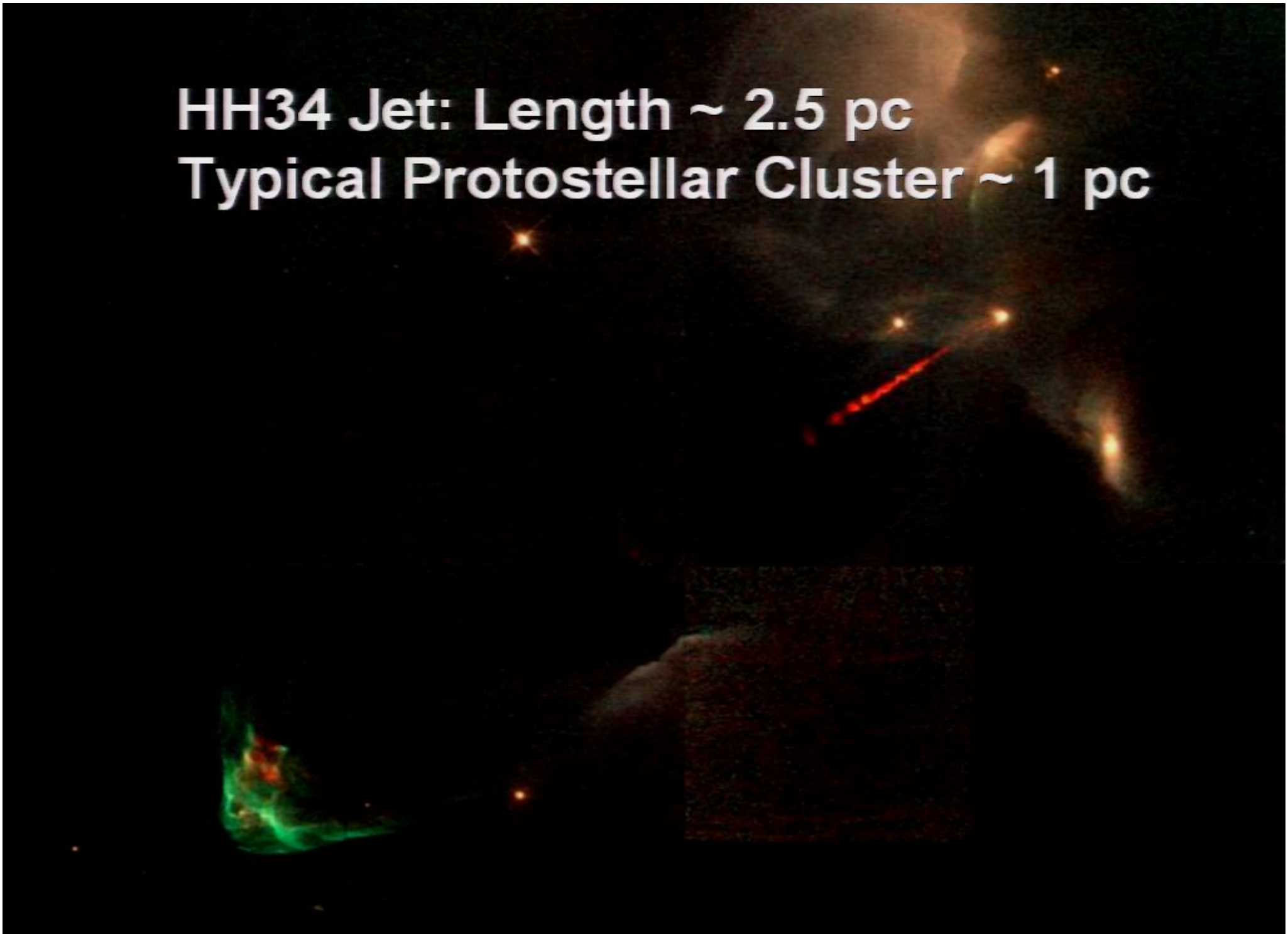
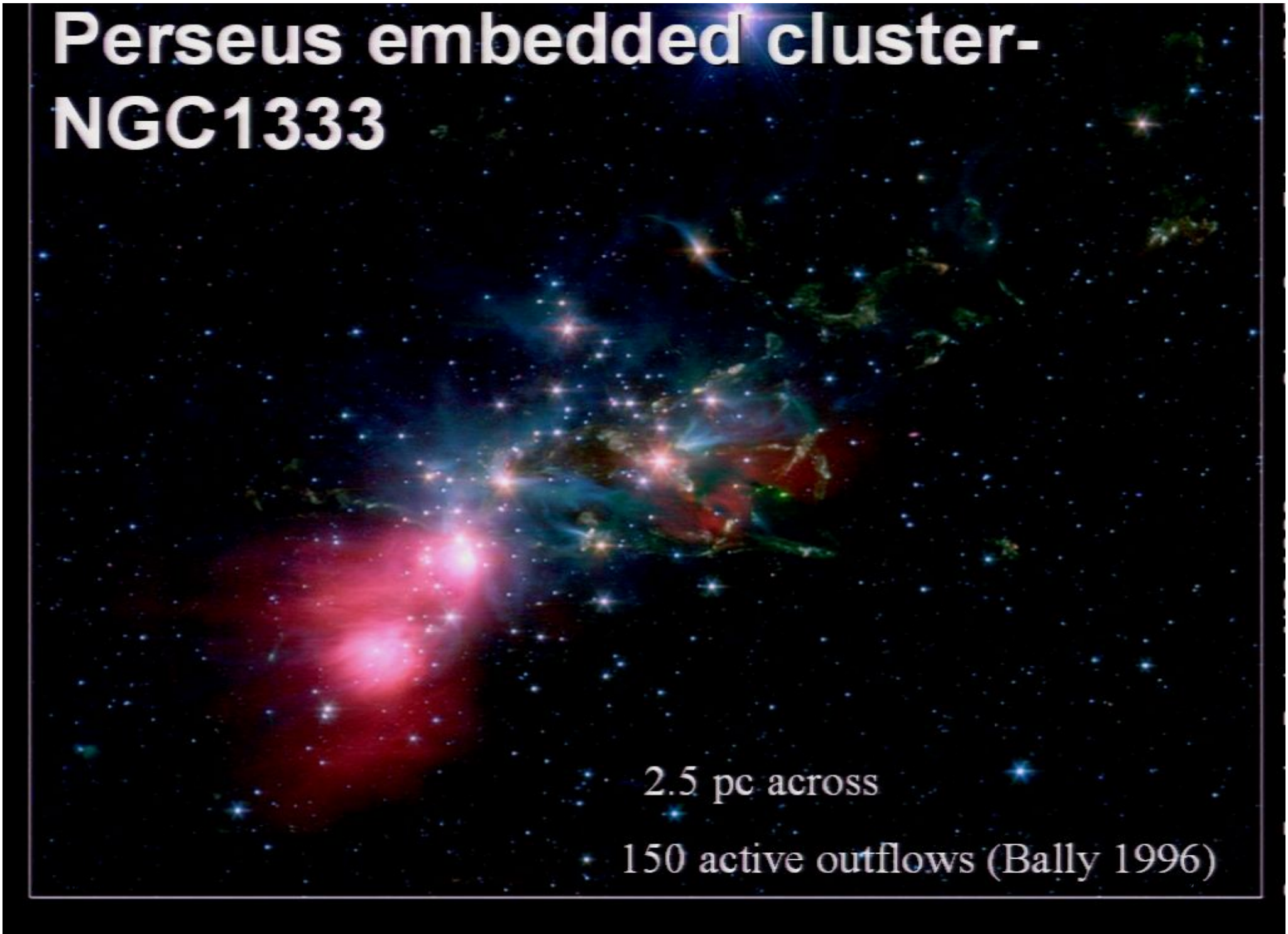




Disk-Star Models
(Ferreria et al)


HH34 Jet: Length ~ 2.5 pc
Typical Protostellar Cluster ~ 1 pc


Perseus embedded cluster-
NGC1333
2.5 pc across
150 active outflows (Bally 1996)

Macroscopic Scales: Outflow Feedback & Turbulence

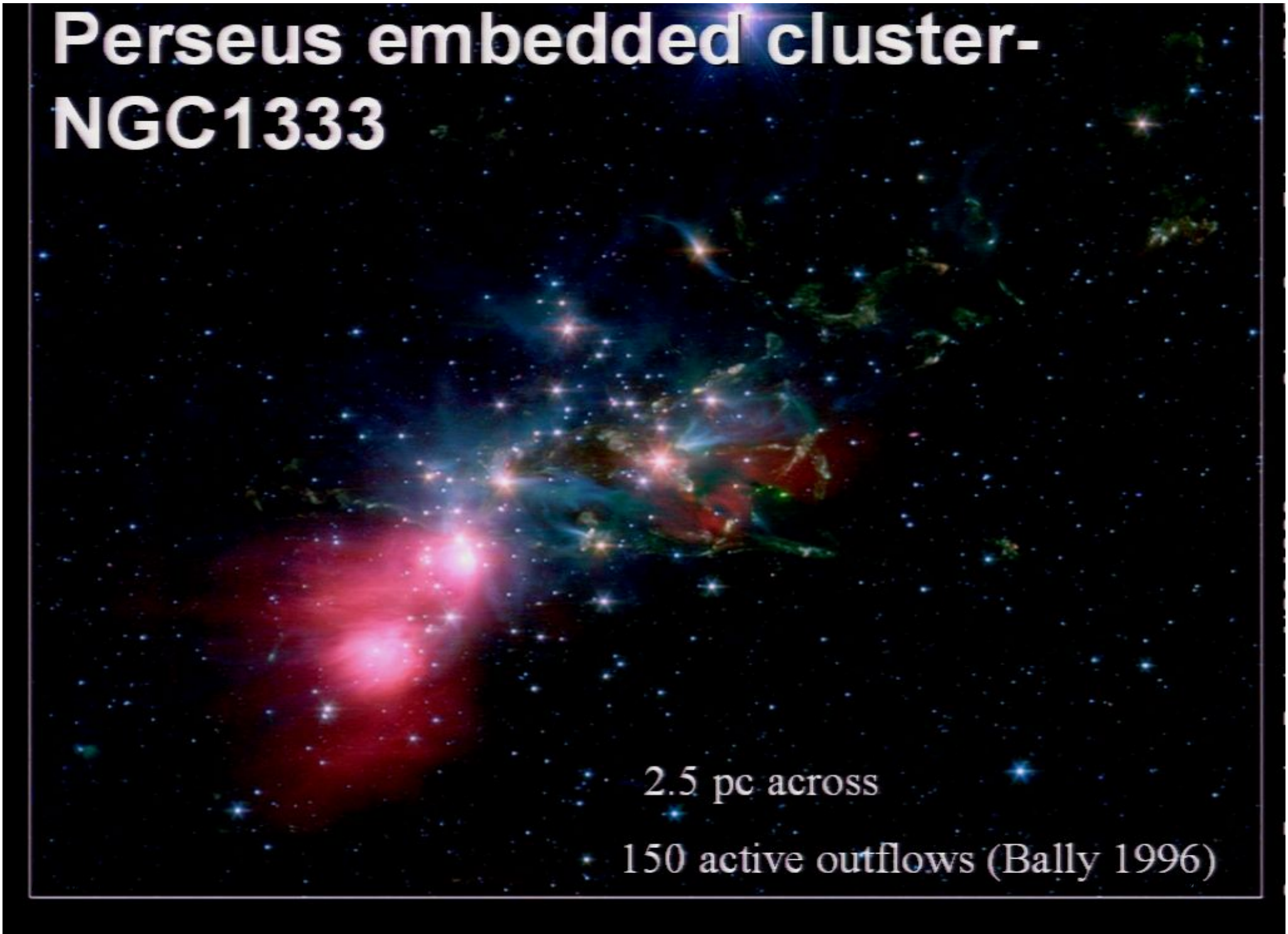
- ***Theory: MHD turbulence decays on timescales shorter than a cloud freefall time. Turbulence can not support clouds againts collapse.***

- ***Observation***: total outflow energy budgets = cloud/cluster turbulent energy (Walawender et al 2006, Sandell & Knee 2001).

- Typical cloud size/stellar density => whole cluster overrun by outflows.

$$\frac{V_{outflow}}{V} = 1$$

Tens/Hundreds proto-stars eject enough E_k replenish $E_{turb.}$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Macroscopic Scales: Outflow Feedback & Turbulence

- Can space-filling isotropic turbulence be driven by needles (jets), or balloons (outflows)?

- Explicate mechanisms.

- Connection with observational structures.

- Global Analytics – Matzner, Tan, Krumhotz, others
- Global sims – Maclow 2000, Nakamura & Li 2005, 2007
  - ISM-Supernova Balsara et al 2001, 2004,2005

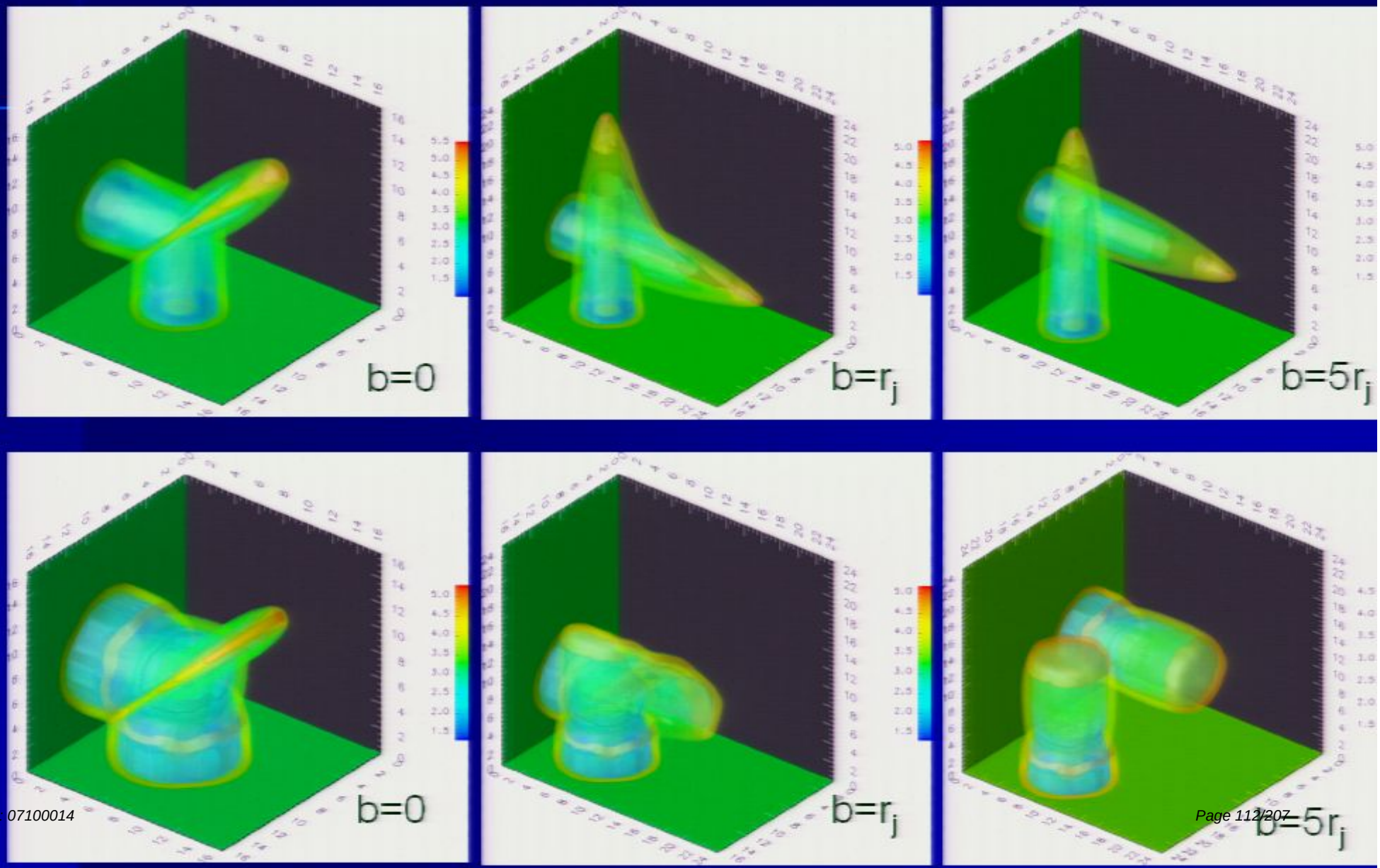
- Resolution critical for jet sims : $R_j \sim 20$ zones.

Question:
Outflow Collisions as a Route to Turbulence?

Explore effect of single collisions on accelerating ambient material. Vary impact parameter (*b*)

Cunningham, Frank & Blackman 2006

Simulations: Outflow Collisions
(Cunningham, Frank, Blackman 06)

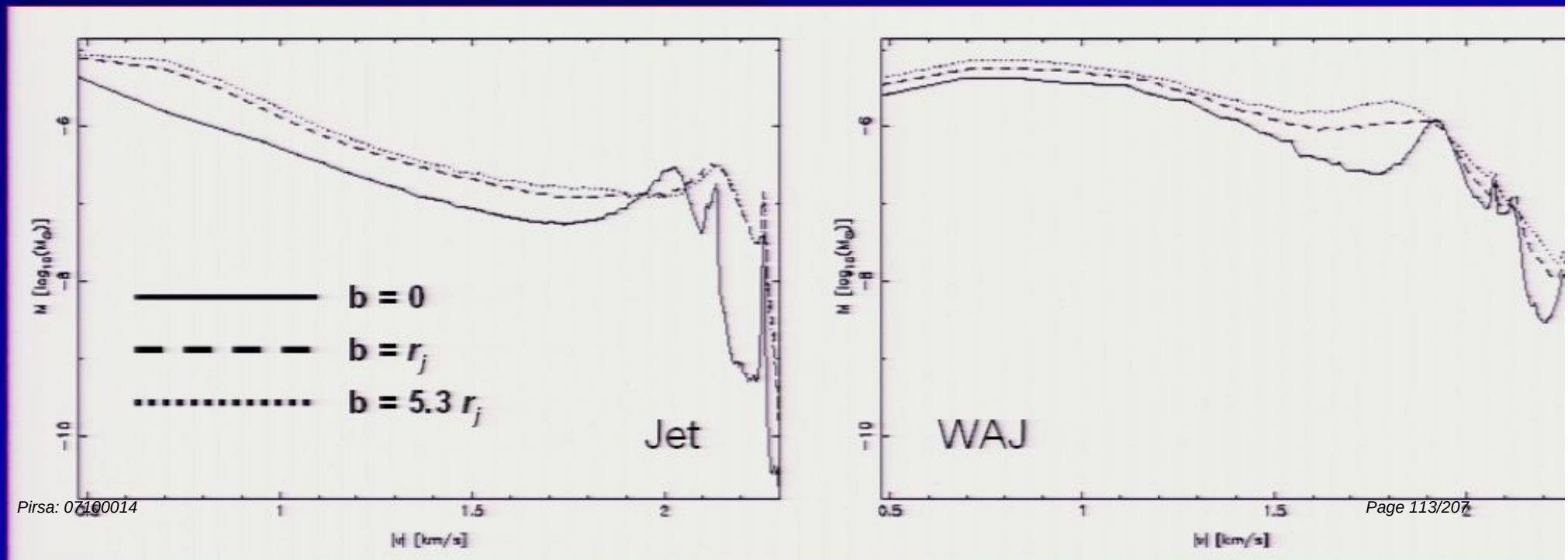


M vs V Plots

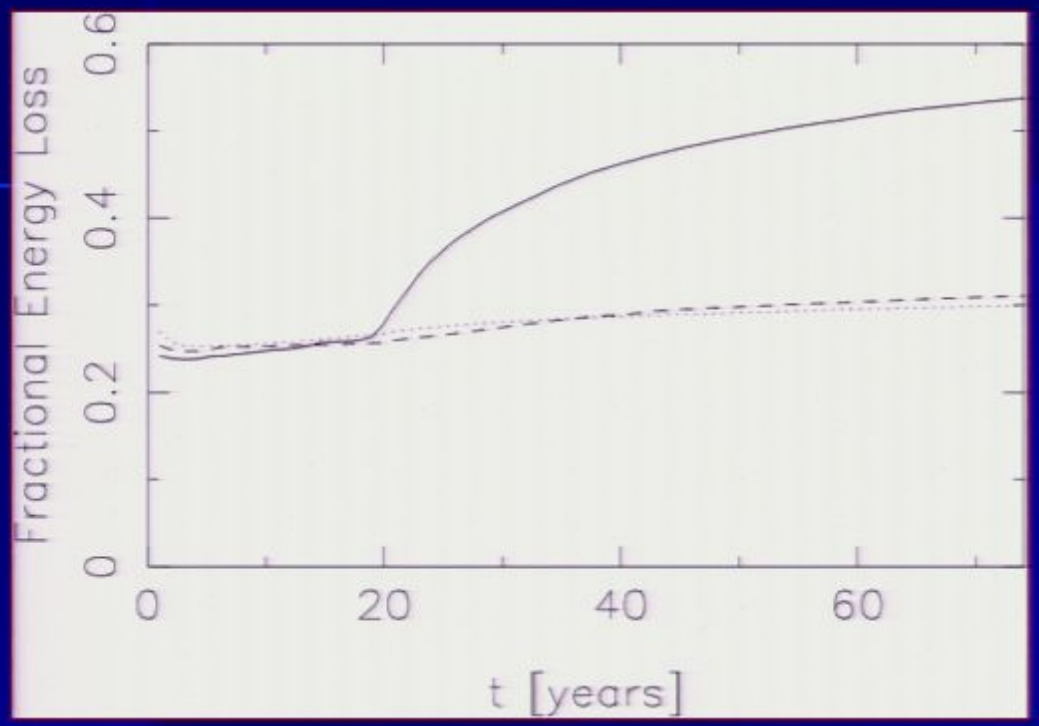
- M(v) or dP/dv diagnostic for molecular outflows
- Power law for low velocities.

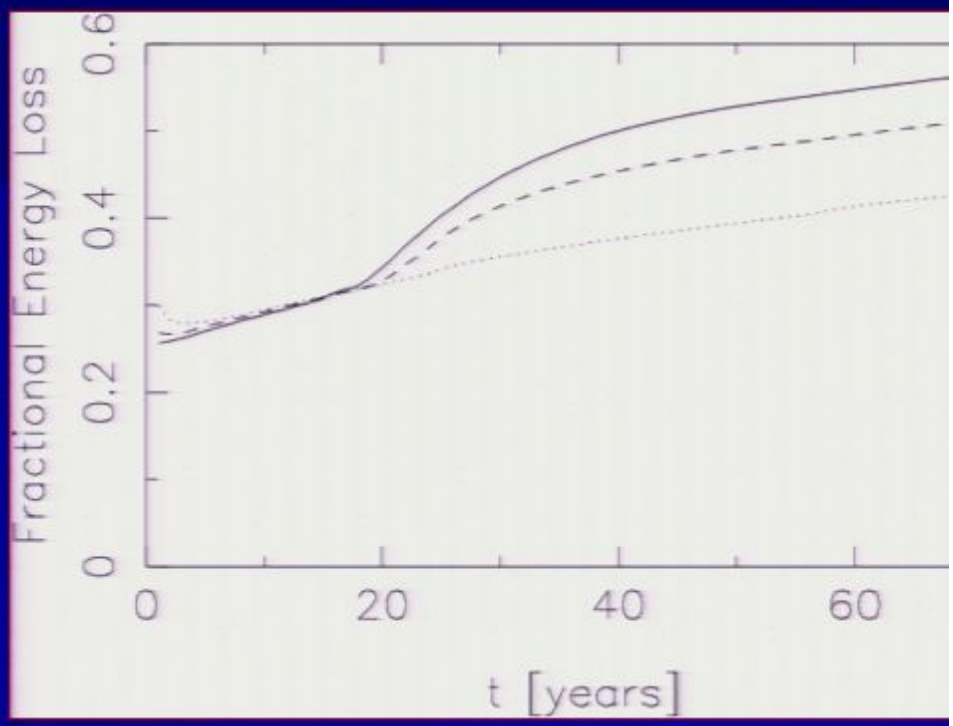
$$M(v) \propto V^{-n}$$
$$1.3 < n < 2.5$$

- **RESULTS**
- For jets we find n ~ 1.7
- *Little difference between interacting ($b = 0$, r_j) and non-interacting cases ($b >> r_j$)!*
- *Surface Area Effect – 2 jets become 1*



Results: Radiative Loss





- Shock jump relations - 20% of energy budget is radiated by ambient material after interception by mach disk (for a single jet).
- Collimated jet collisions ~ double radiative loss.
- Less energy available to drive turbulent motions once the driving source has ceased and the flow becomes subsumed into the cloud

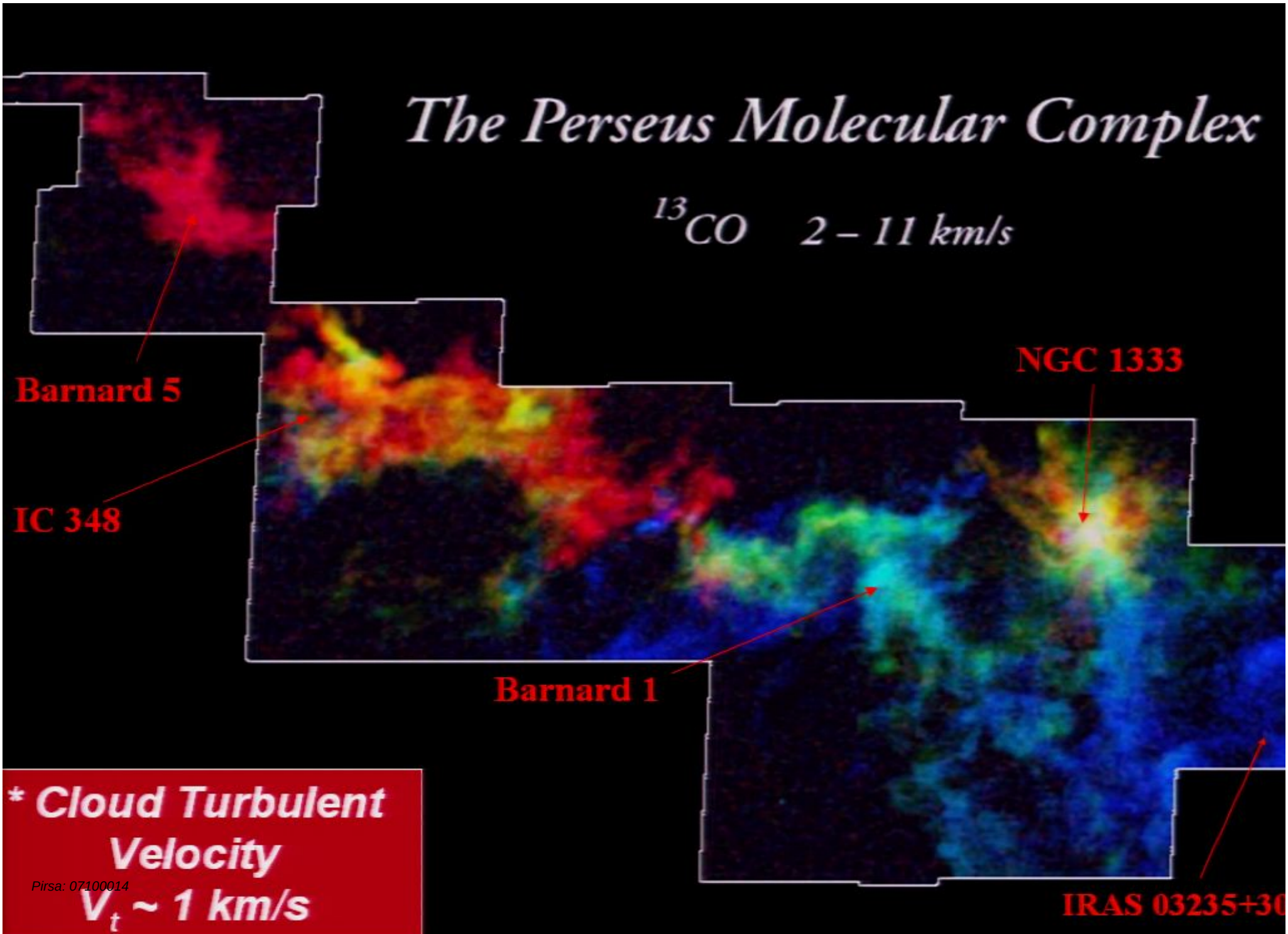
Question:
Fossil Cavities as Intermediaries to Protostellar Turbulence?

Observations of NGC 1333 :

Quillen et al 2005

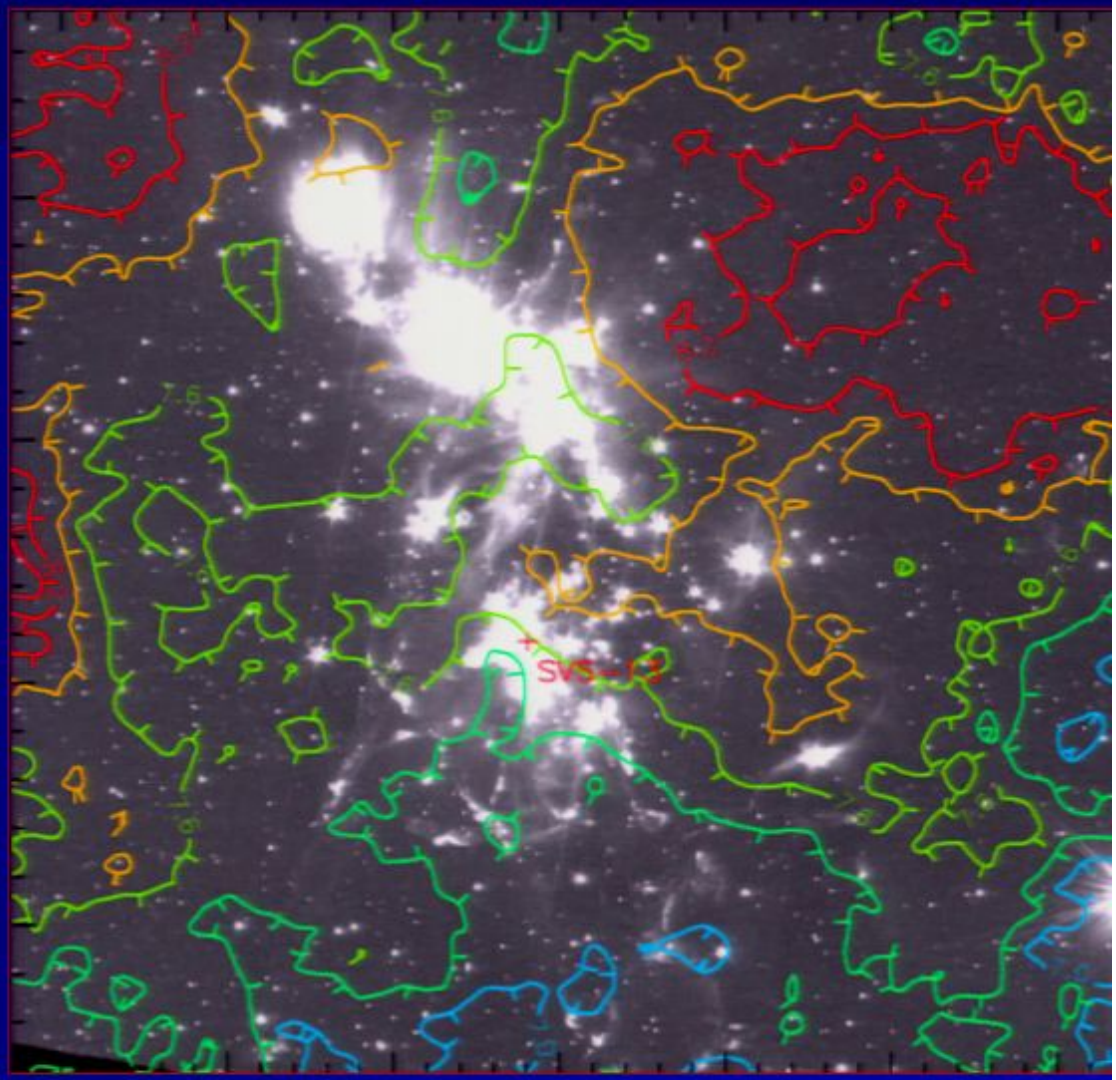
Simulations of Fossil Cavities

Cunningham et al 2006



NGC 1333 Data

- Explore High Rez ^{13}CO Data (Ridge et al 04)
- Correlate with Spitzer images + 2Mass data etc.



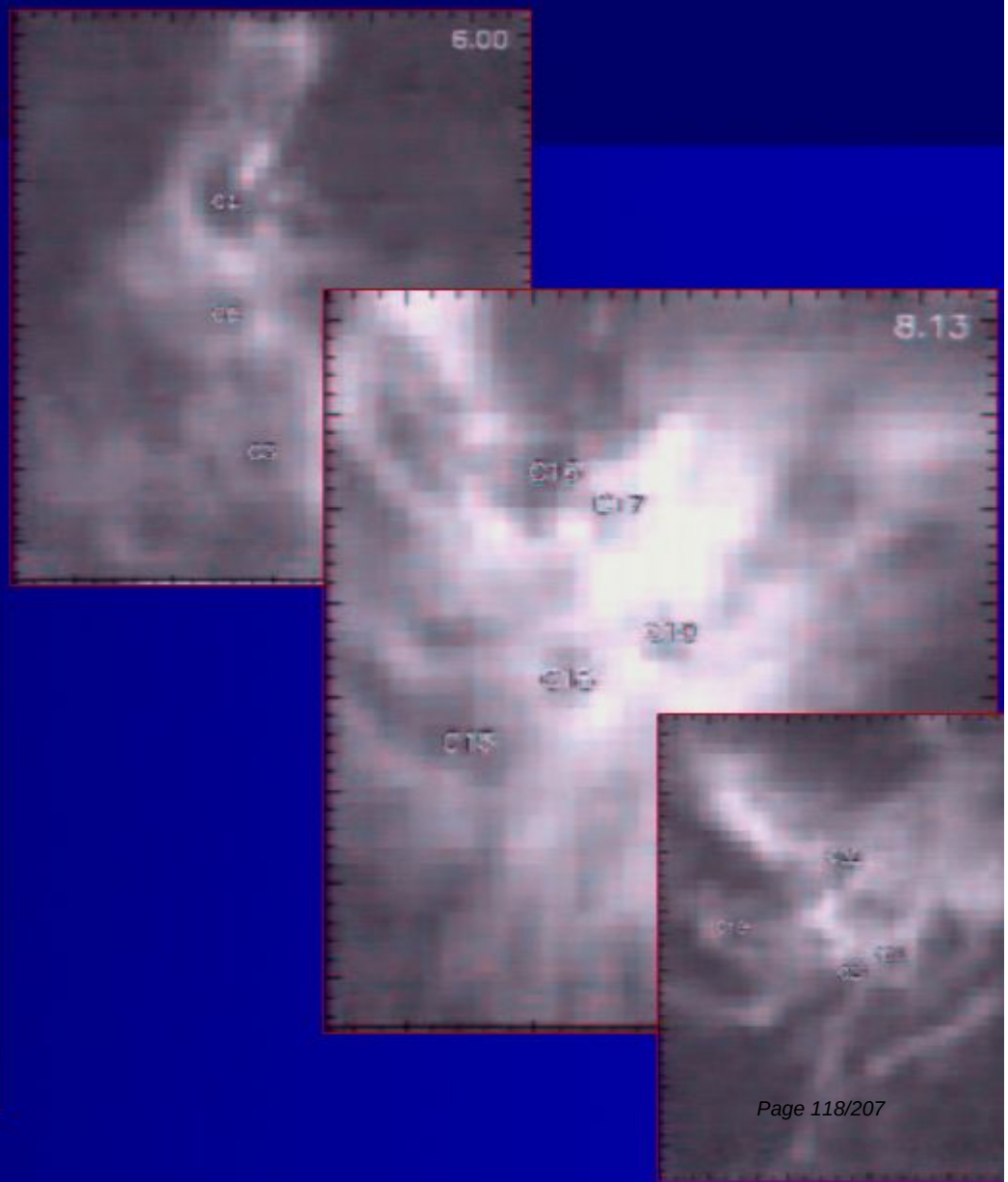
^{13}CO map + Spitzer 4.5 μ image

CO Data
.2 km/s contour spacing
.47 km/s gradient top to bottom

Spitzer data: SVS13 – center left
Many outflows visible

NGC 1333: Cavities

- No significant structure correlated with known outflows seen in ^{13}CO data (V_{disp} ~ 1 km/s)
- Bulk of cloud – no high V gas associated with active outflows
- But…numerous low V cavities.
  - Cavities appear in neighboring channels
  - Different cavities not in same channels.
- i.e. Cavities are real



Cavity Simulations

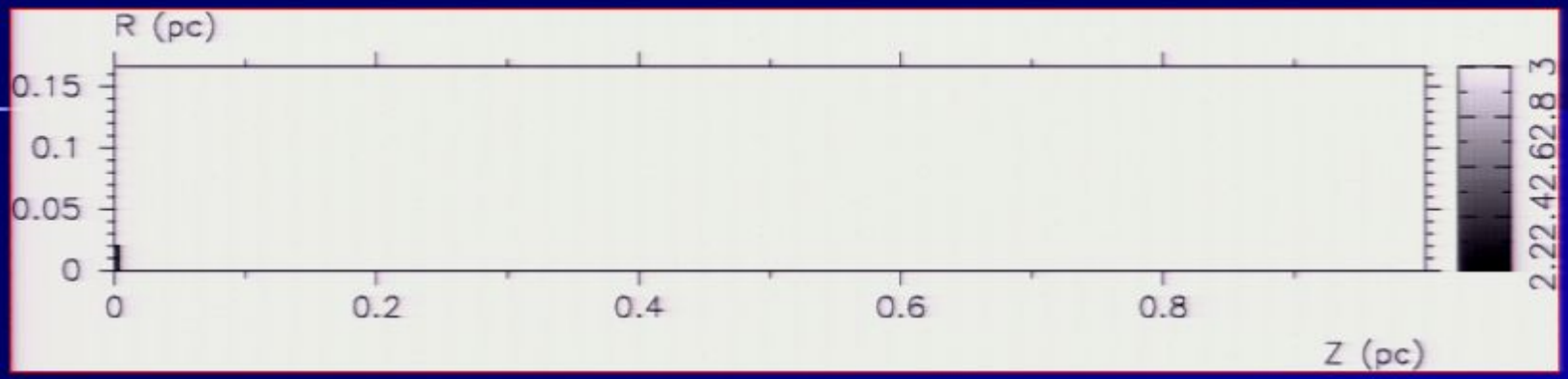
Cunningham, Frank, Blackman & Quillen 2006

- Explore time-decaying Jets/WAW outflow evolution (Bertout et al 96)

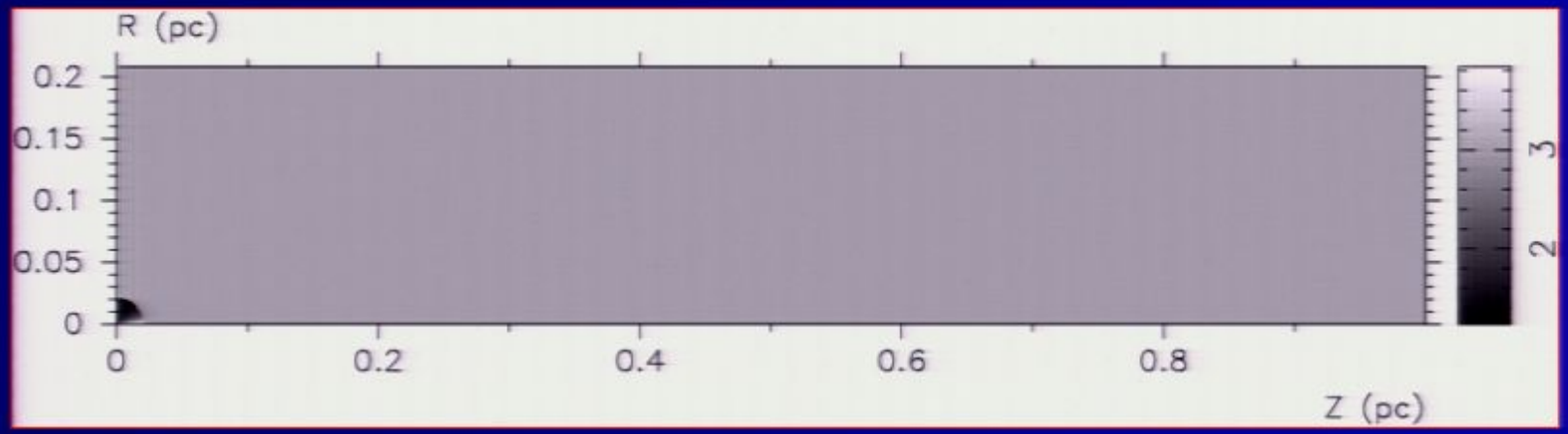
$$\dot{M} \approx \dot{M}_o e^{-\gamma t}$$

- Outflow power decays after 10^4 y.
- Simulation runs for 10^5 y
- Run to 0.5 pc scales
- Compare with scaling relations of *Quillen et al*
- Compare with PV diagrams

Fossil Cavity Sims: Jets and WAW



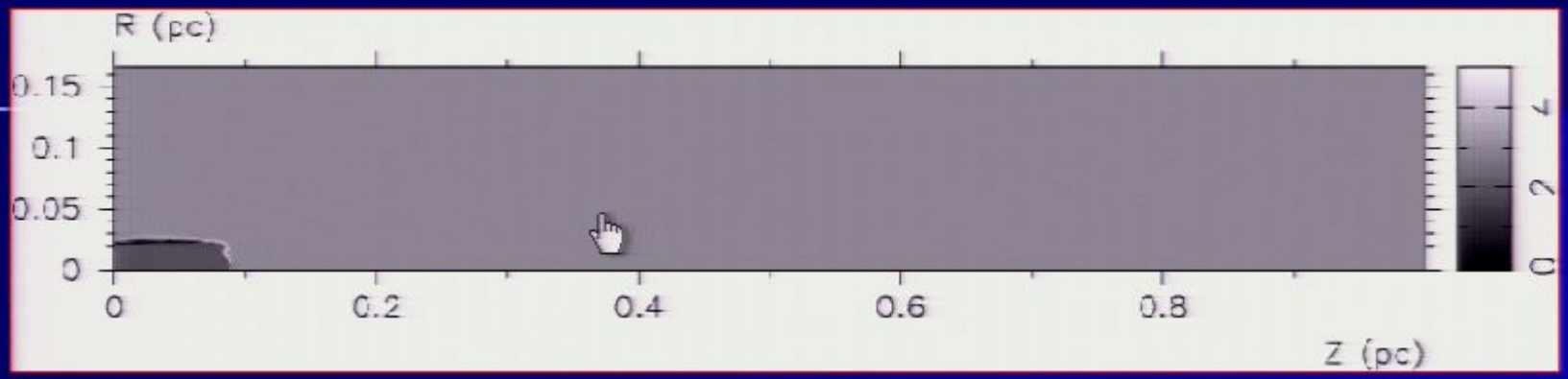
Collimated Jet



Wide Angle Wind (Matzner Class Sol)

- Strong deceleration
- Rarefactions backfill cavity

Fossil Cavity Sims: Jets and WAW



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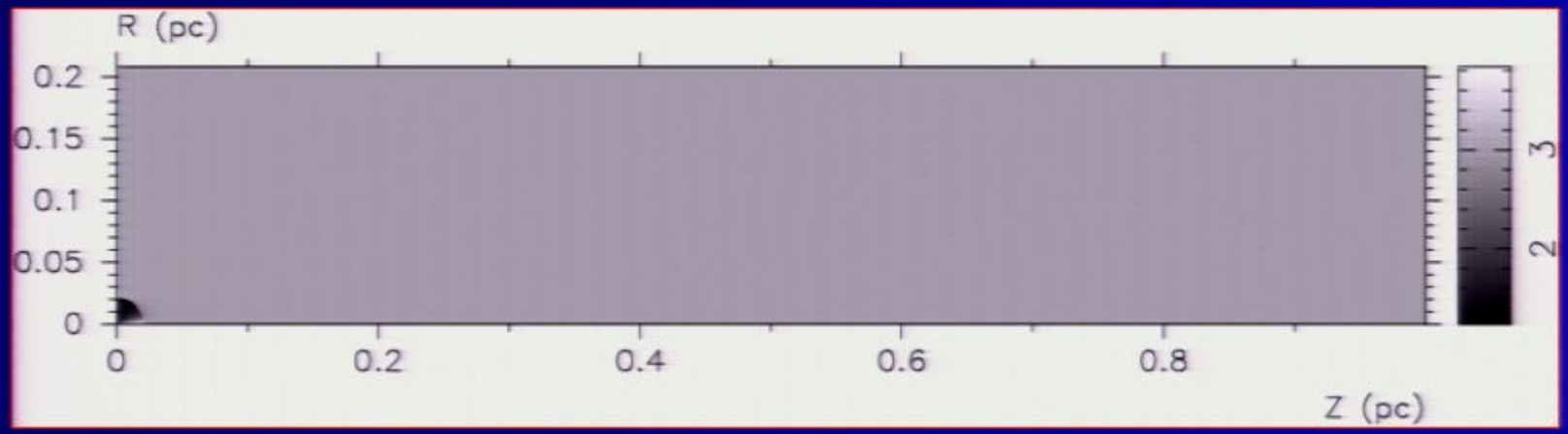

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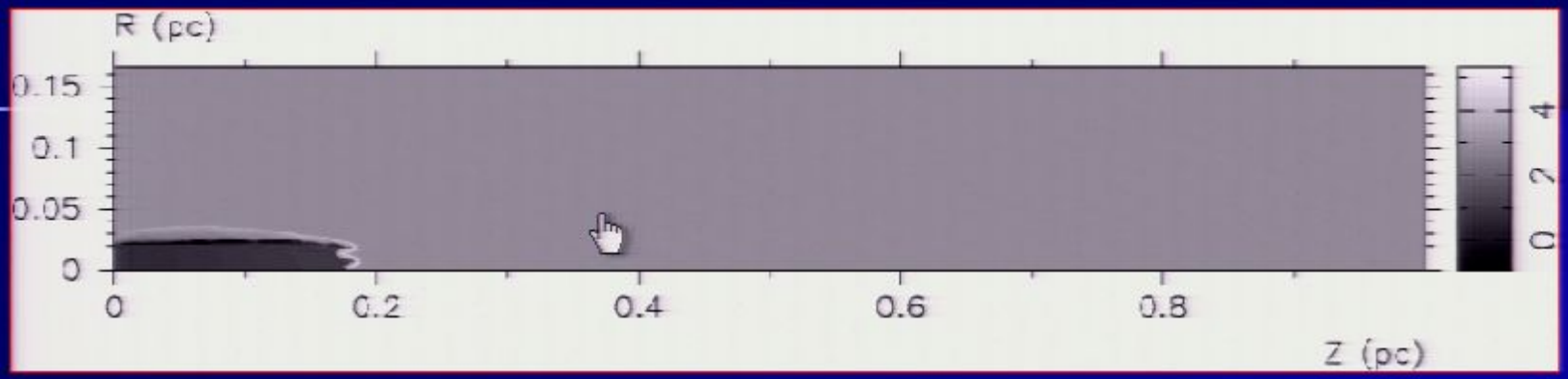

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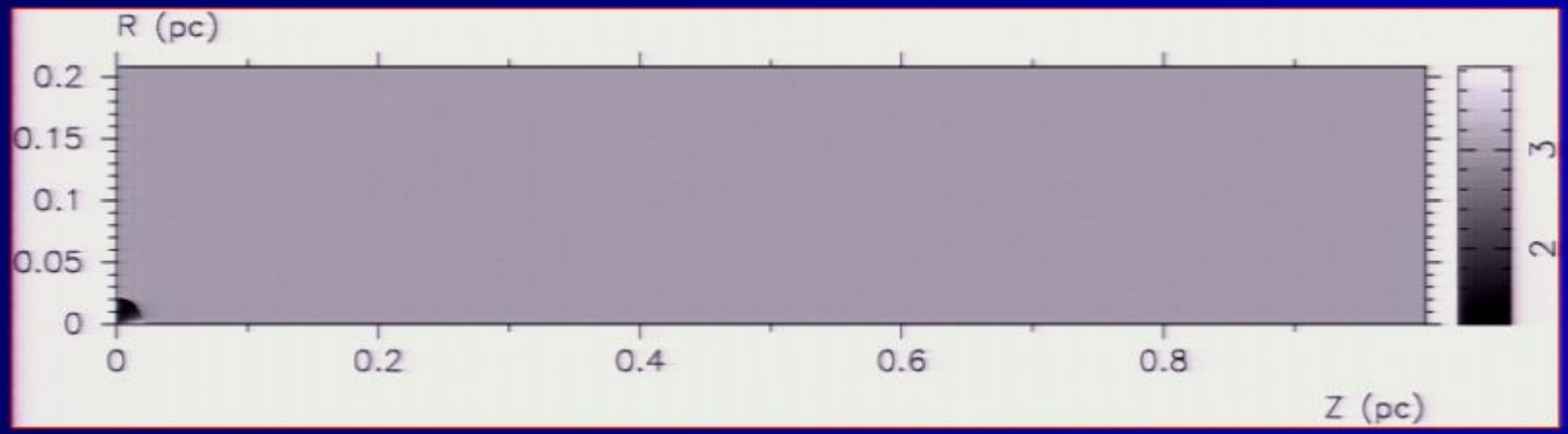

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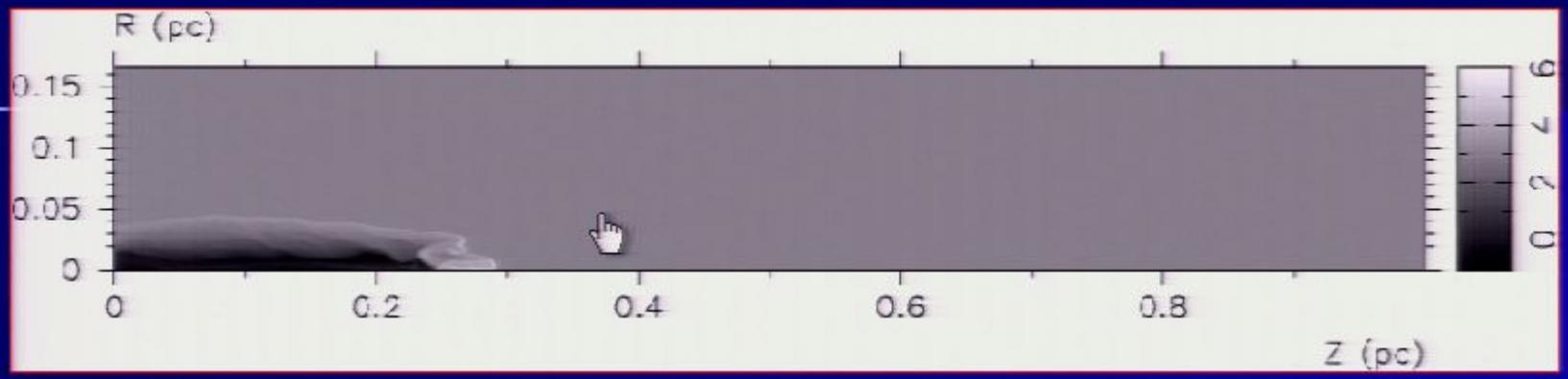

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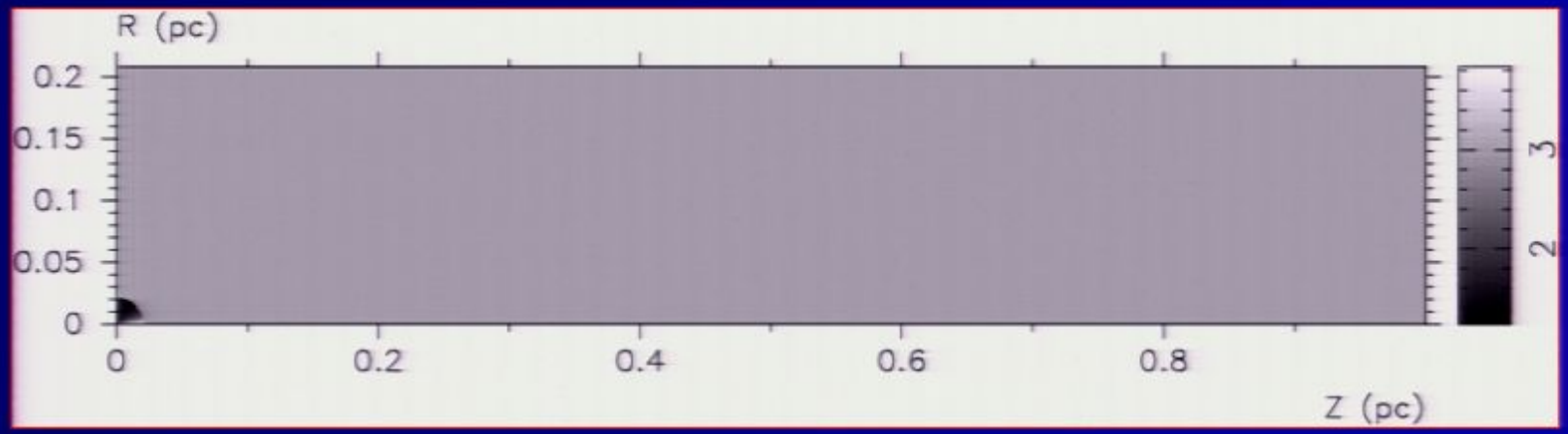

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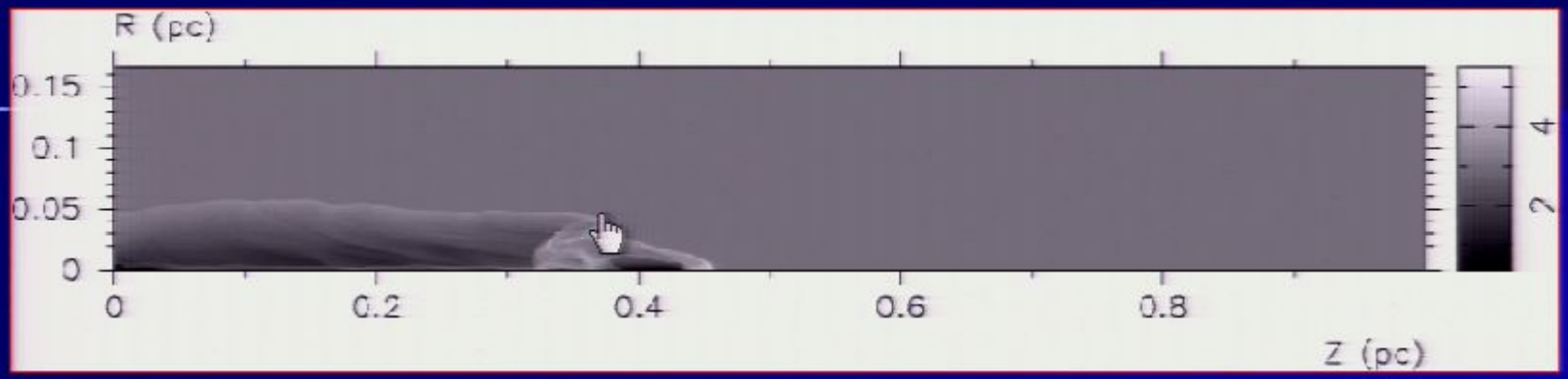

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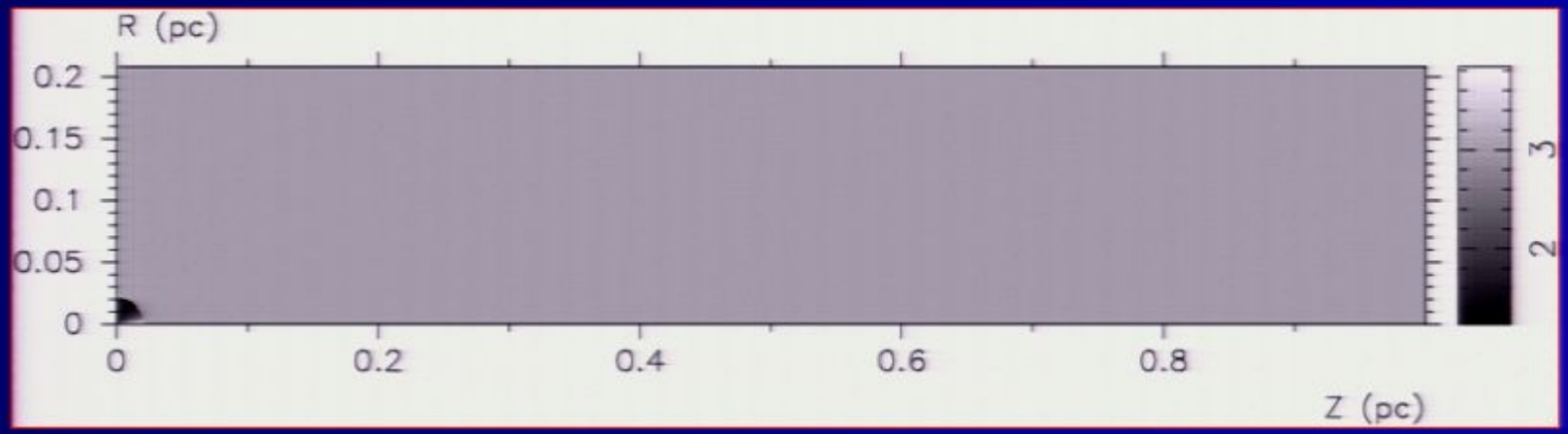

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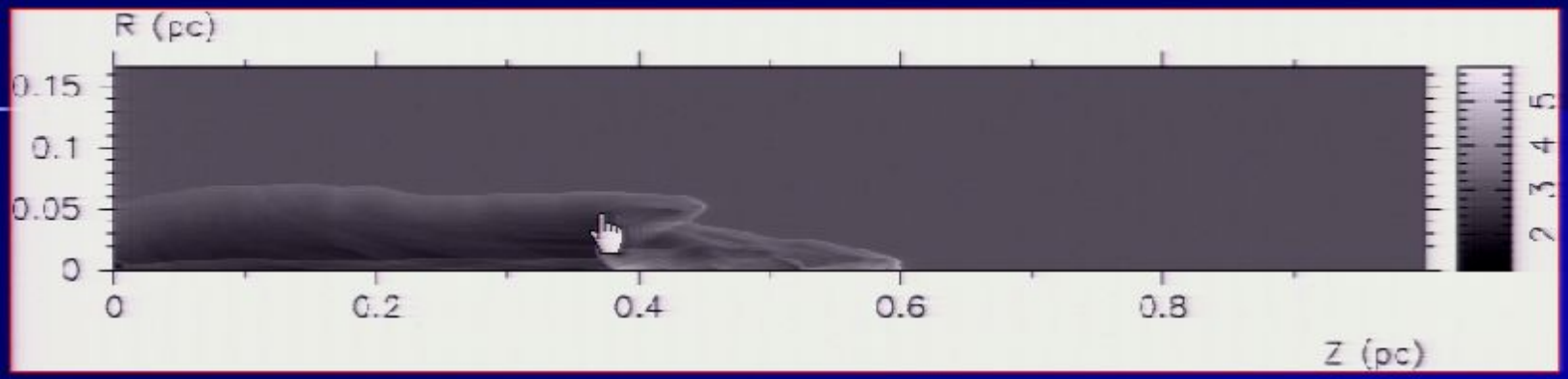

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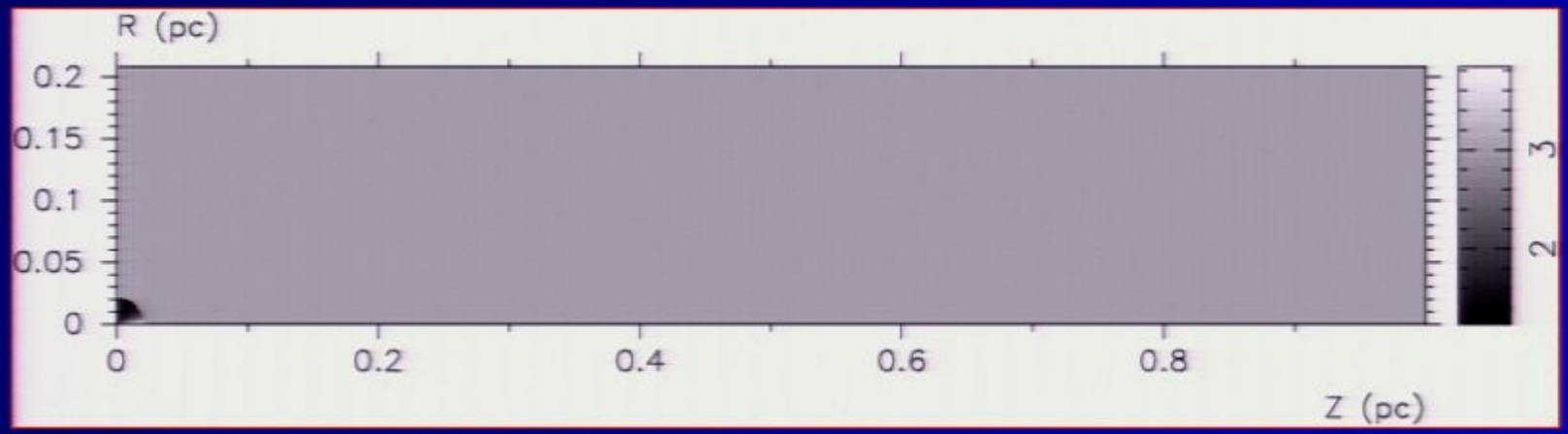

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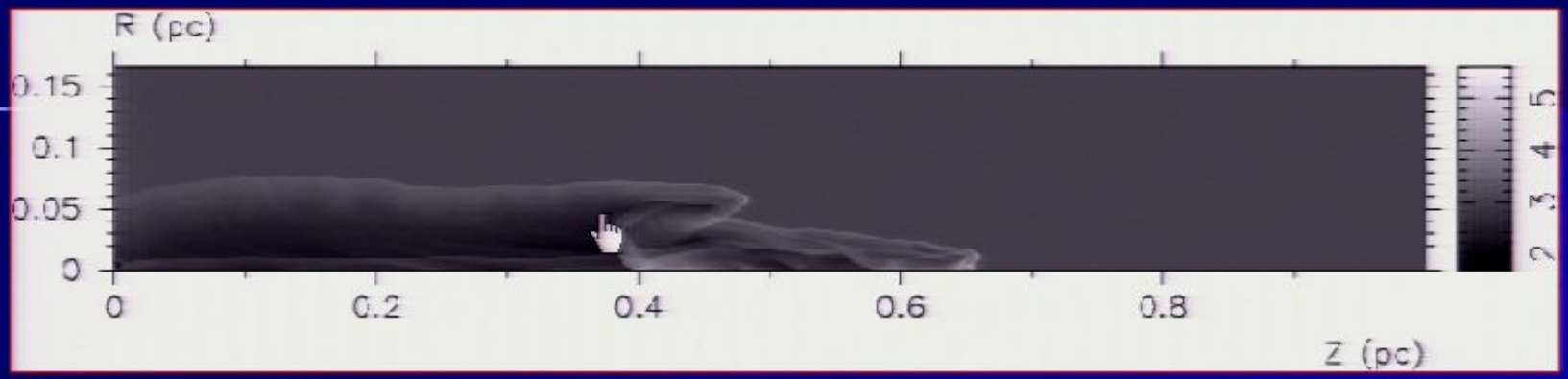

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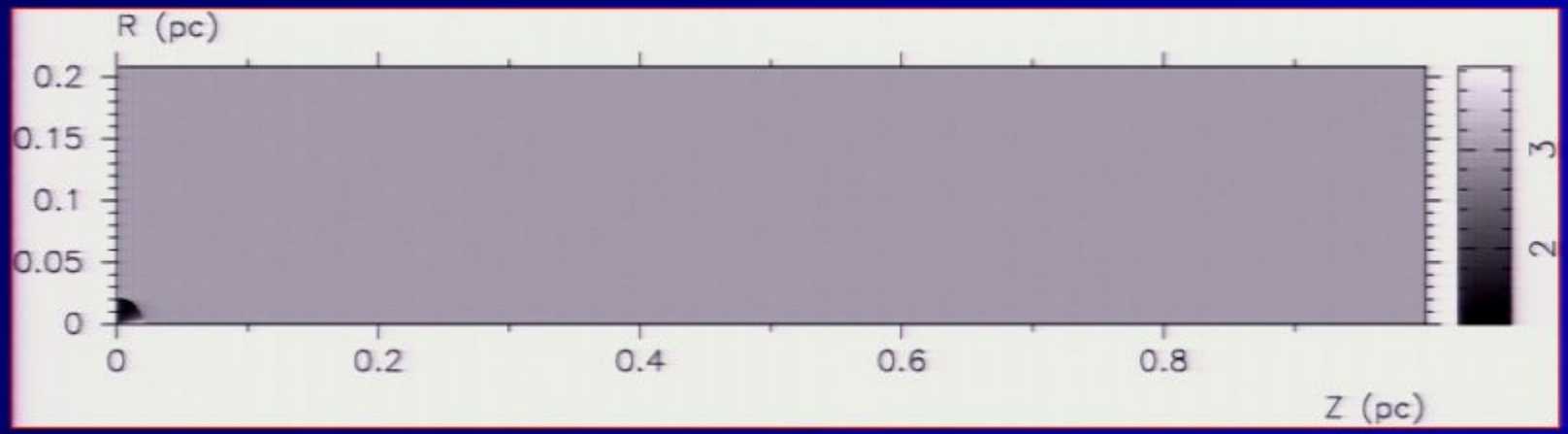

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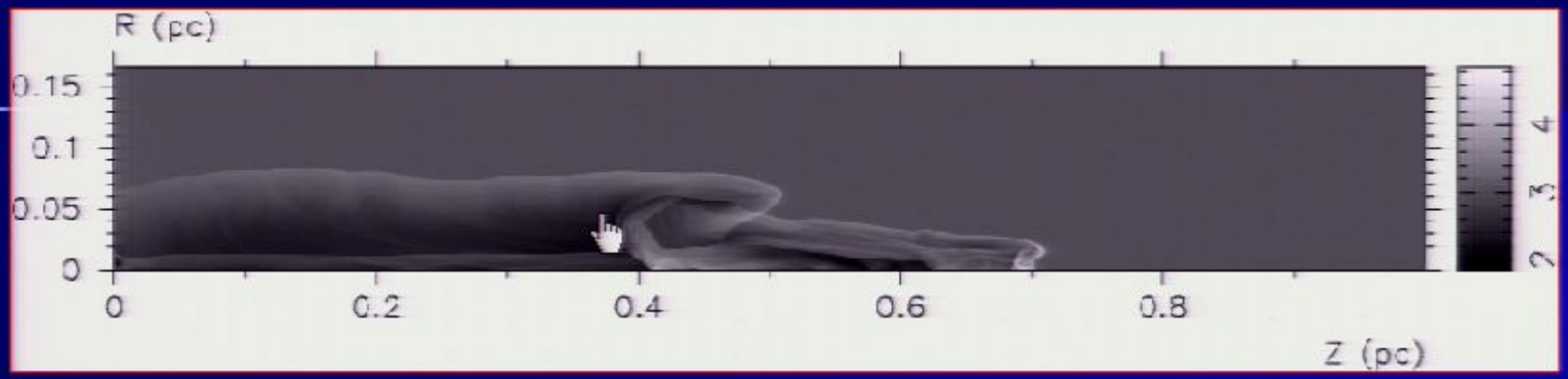

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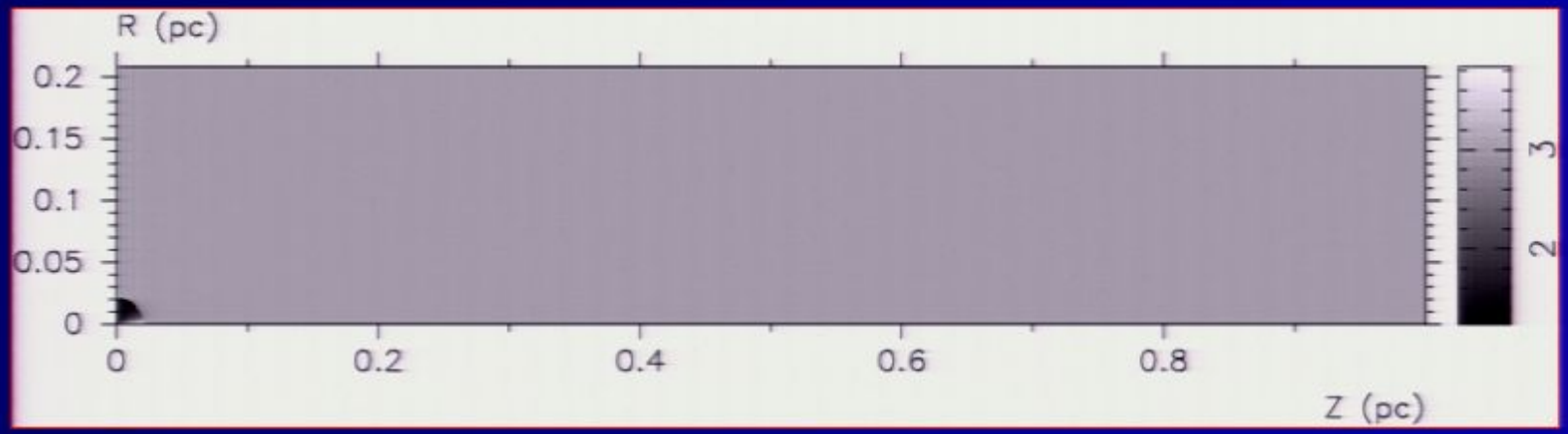

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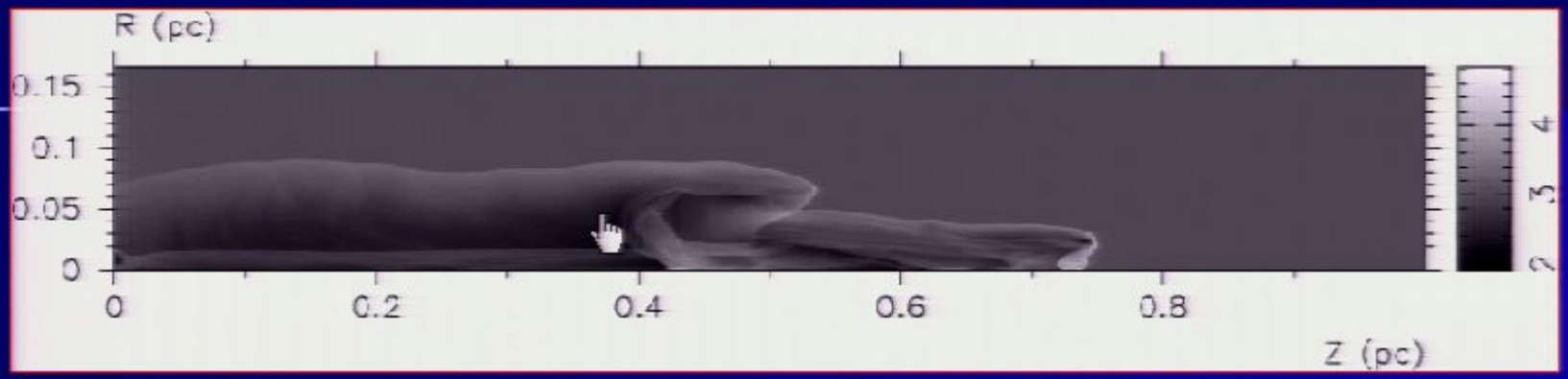

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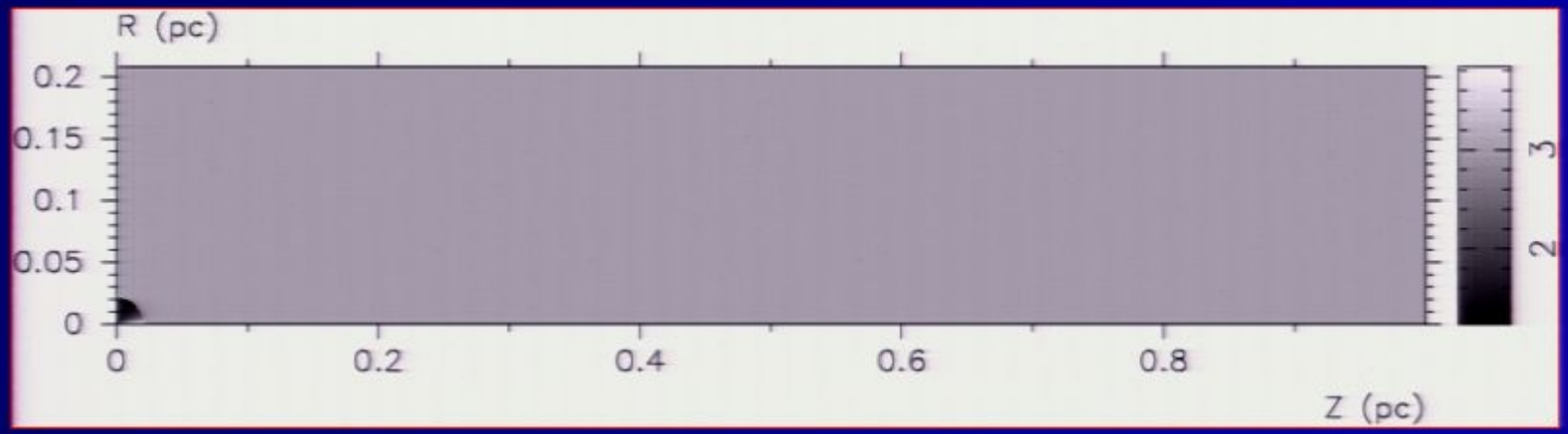

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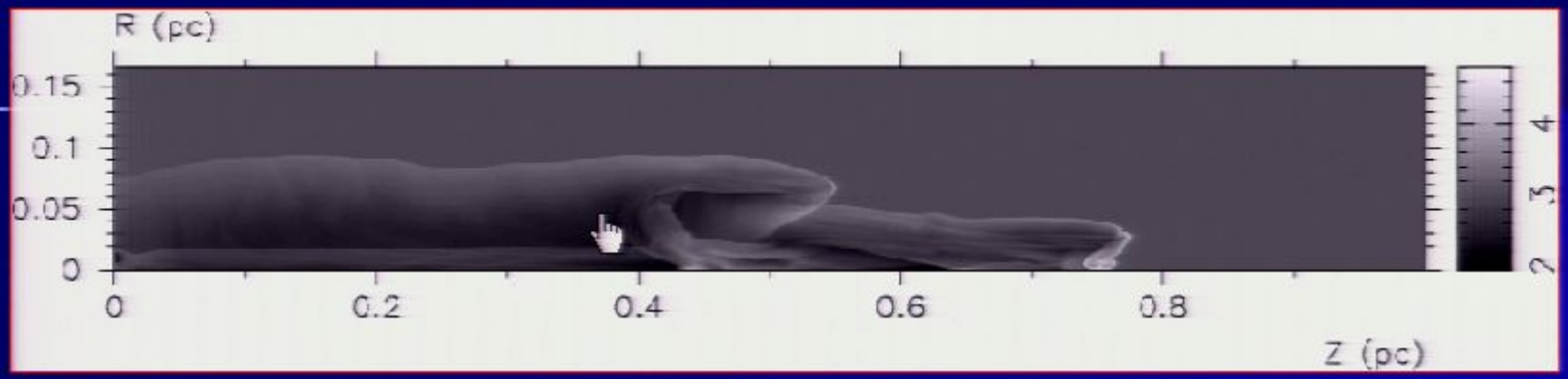

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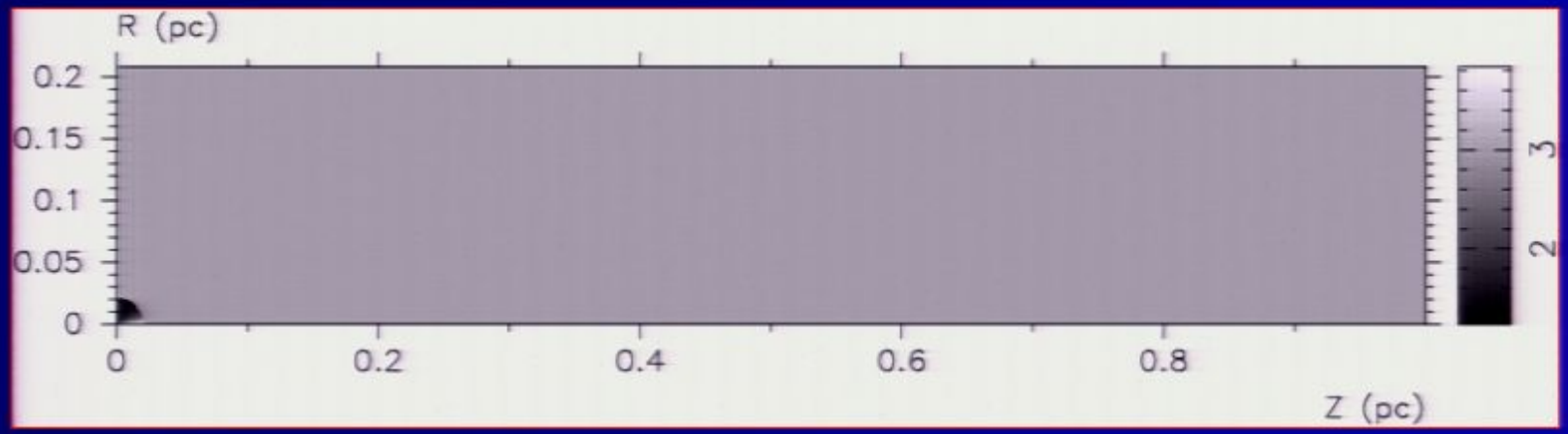

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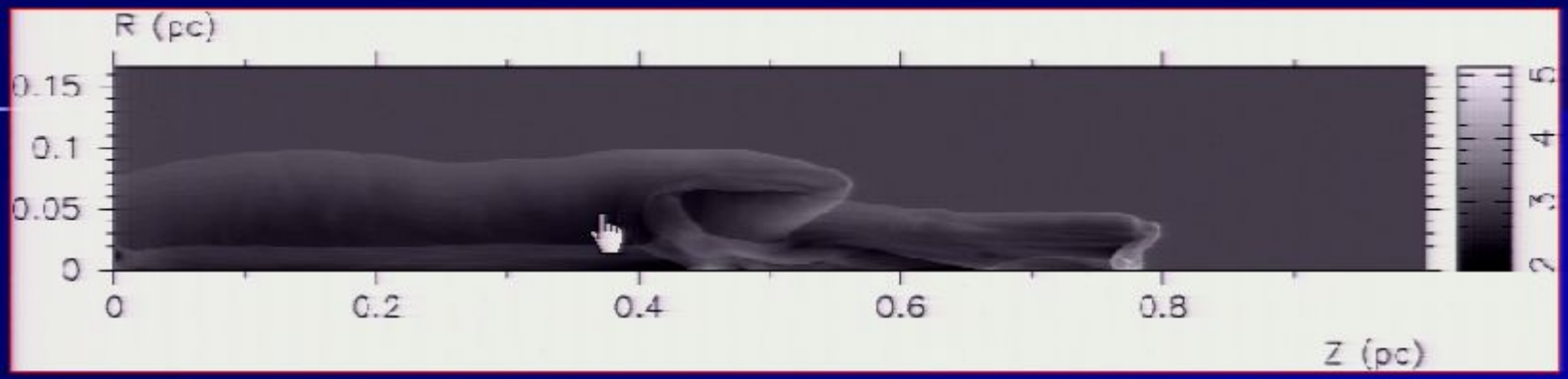

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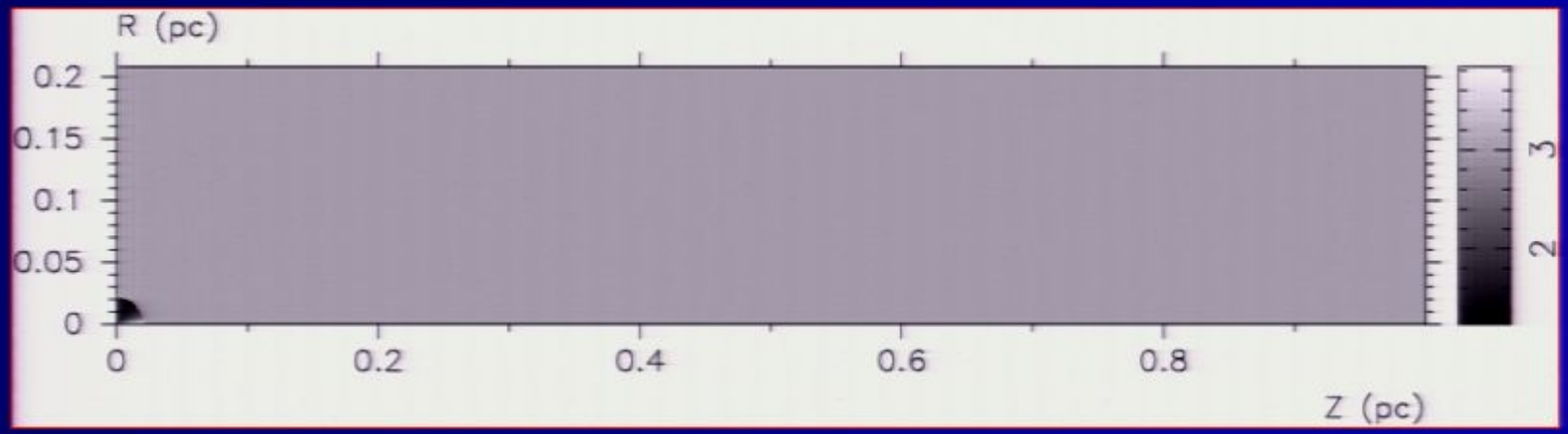

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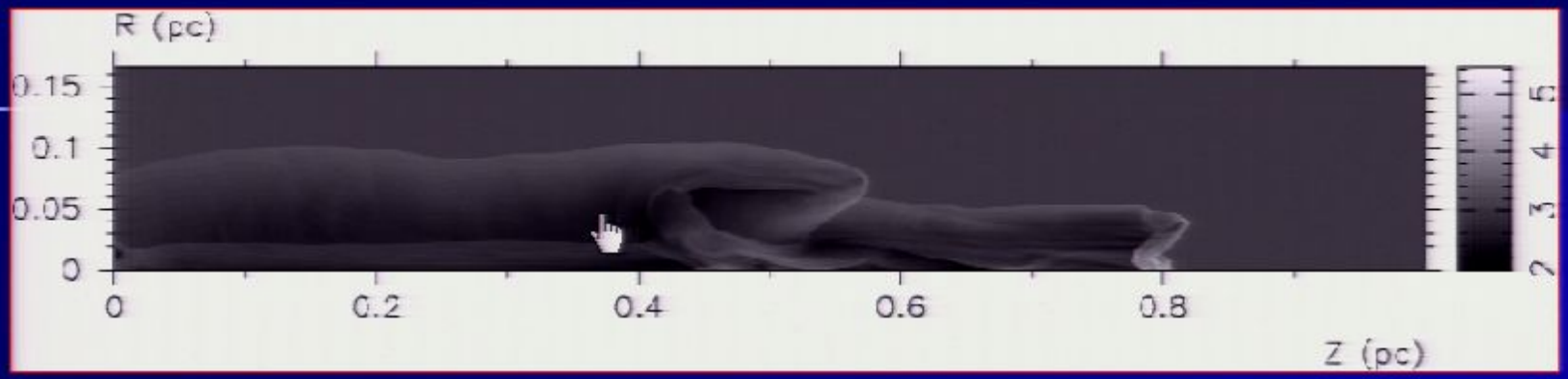

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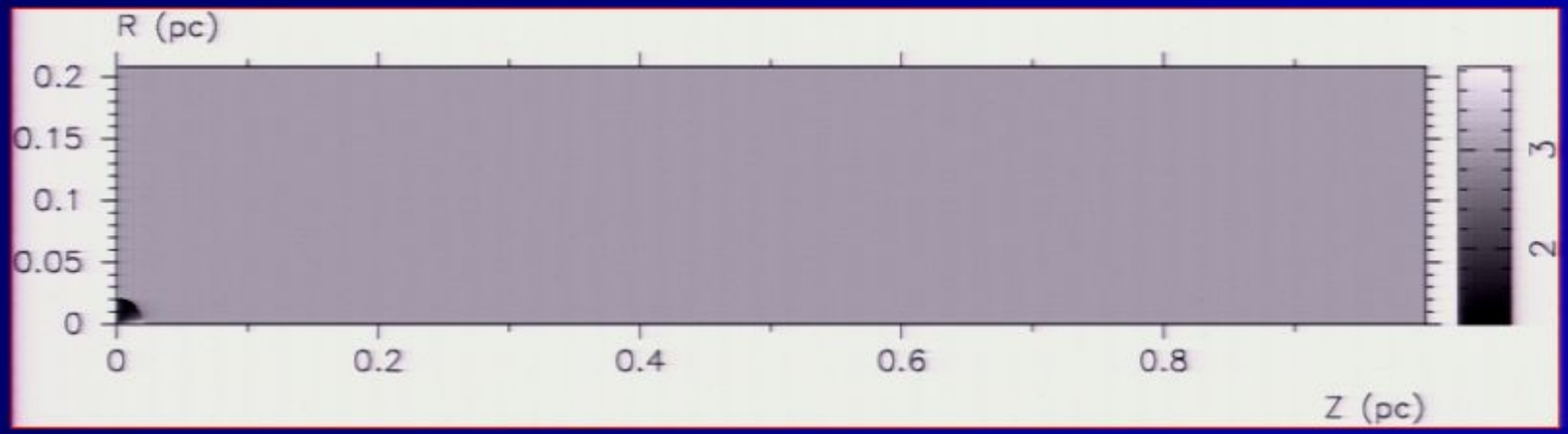

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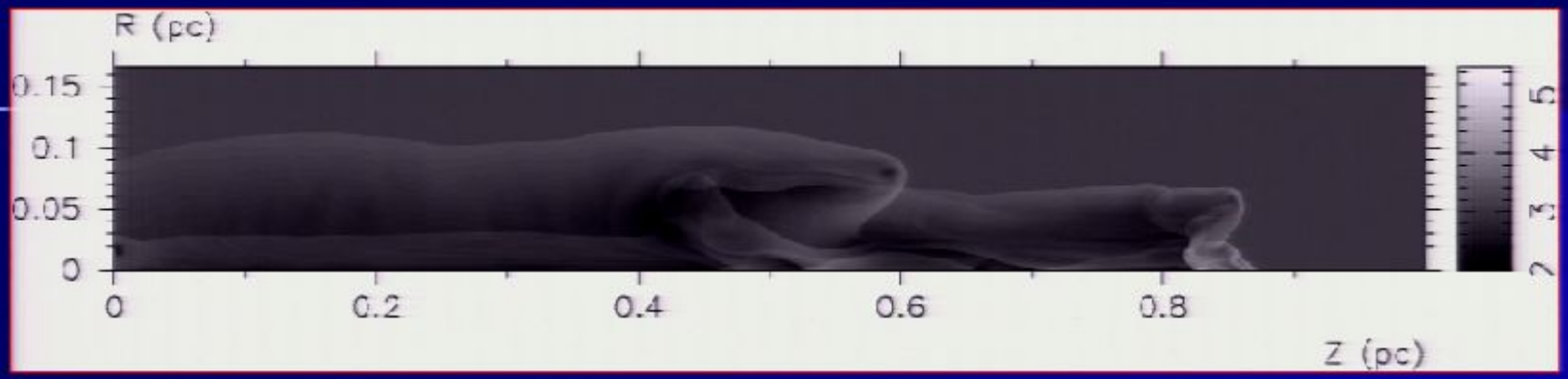
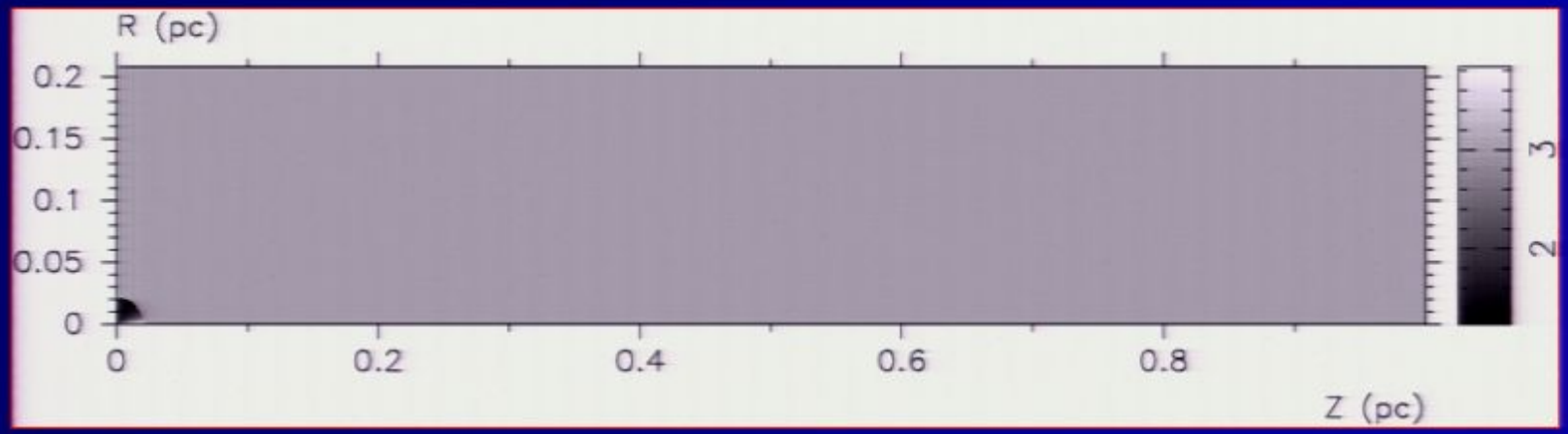


Collimated Jet



Wide Angle Wind (Matzner Class Sol)

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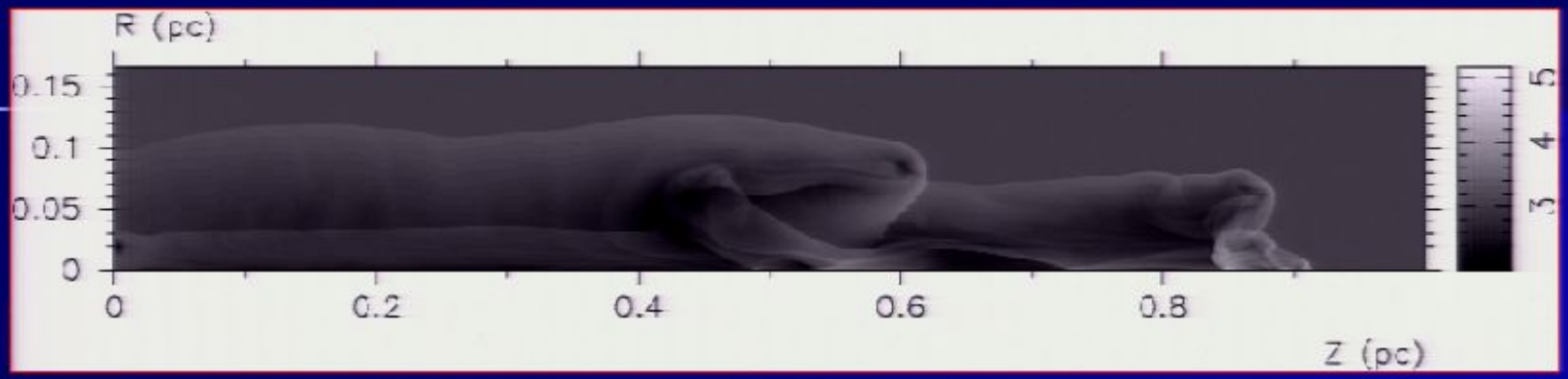

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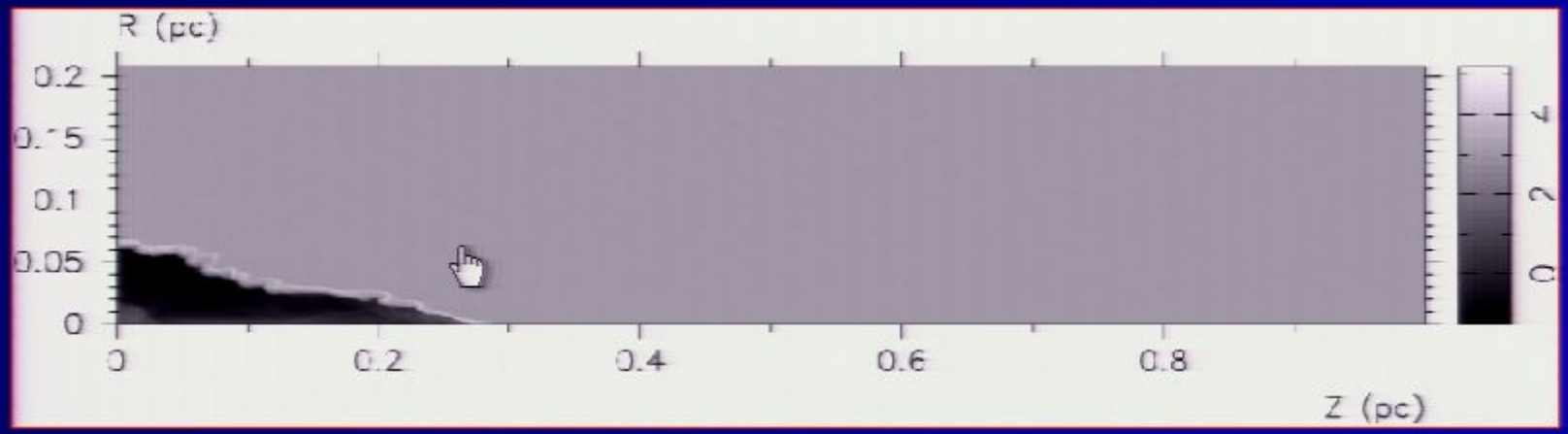

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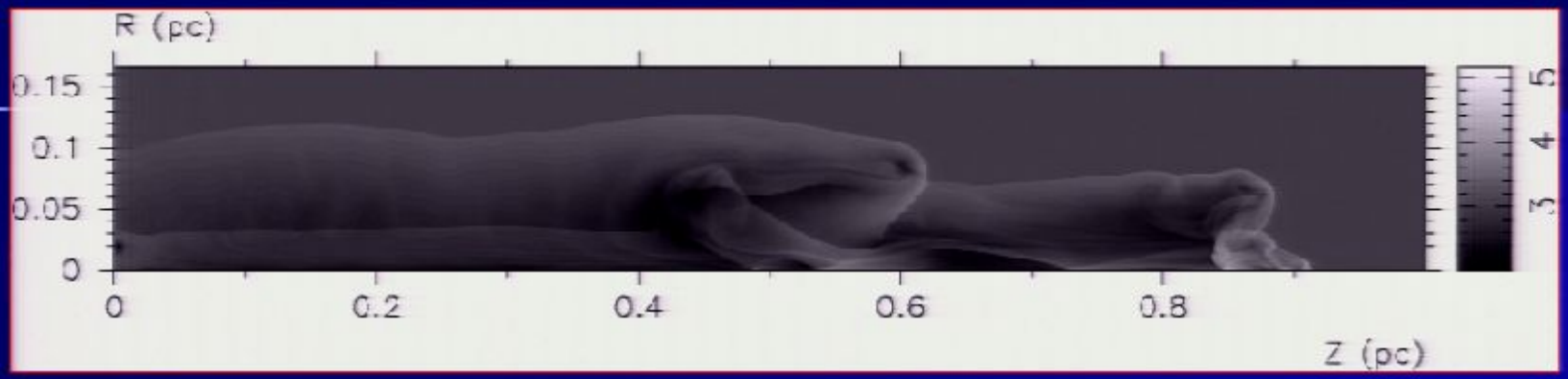

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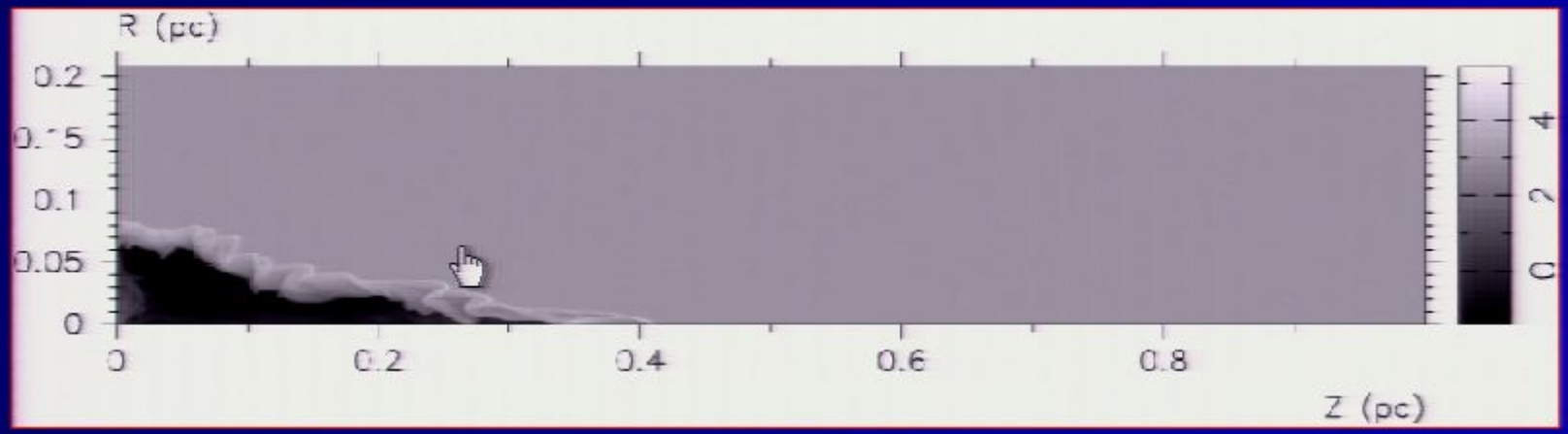

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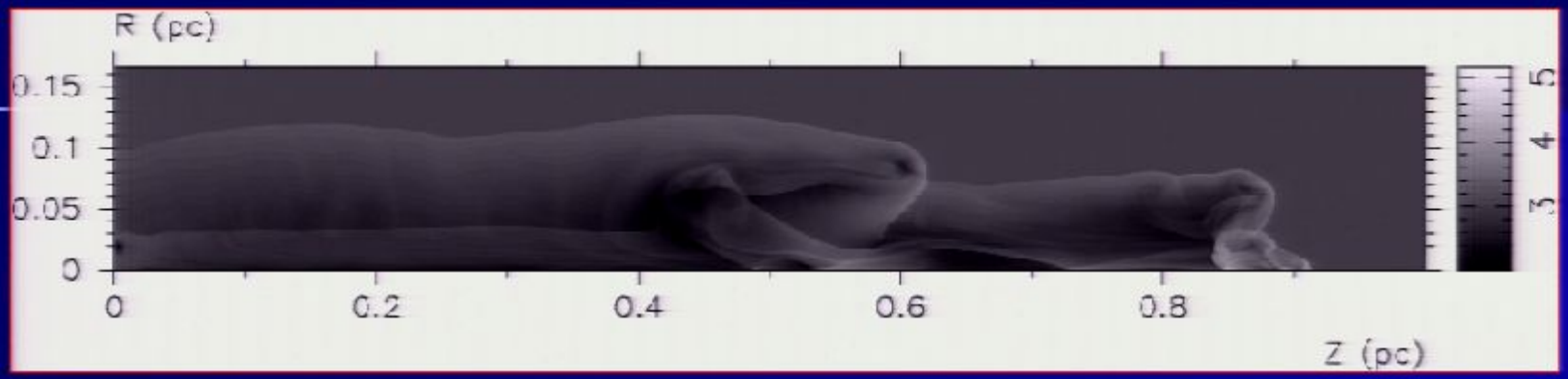

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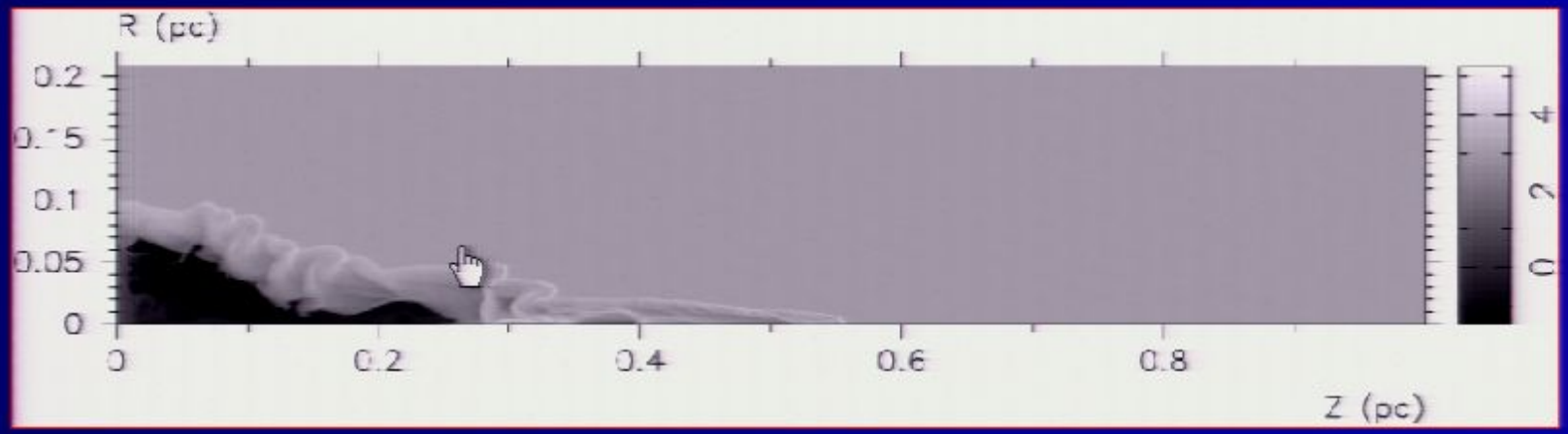

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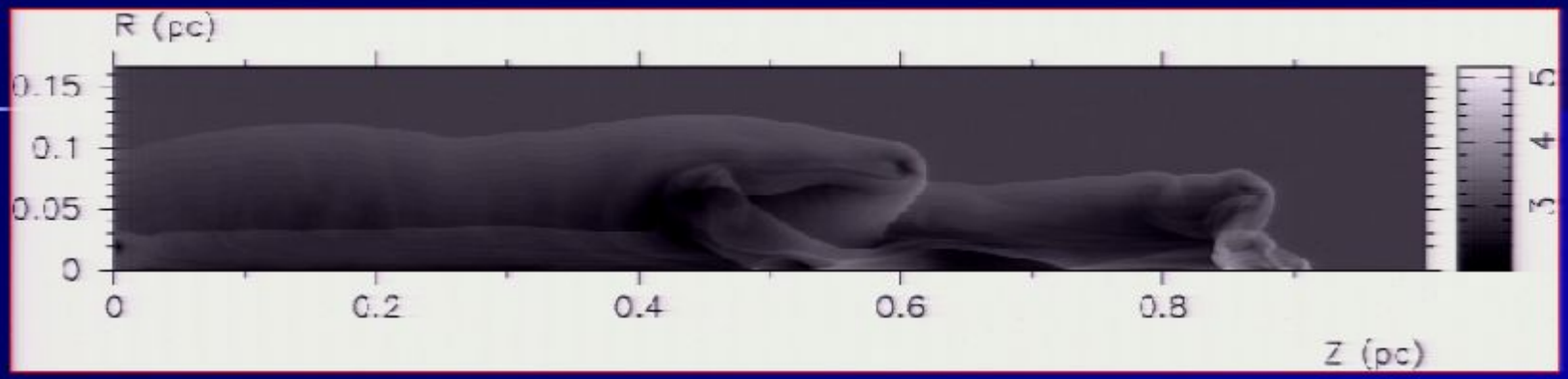

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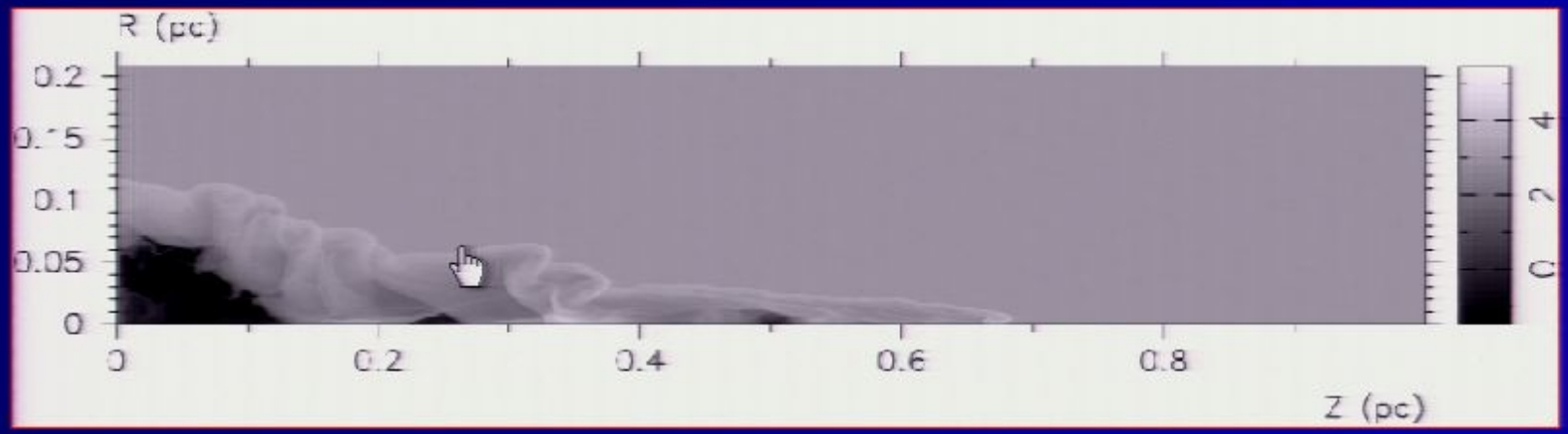

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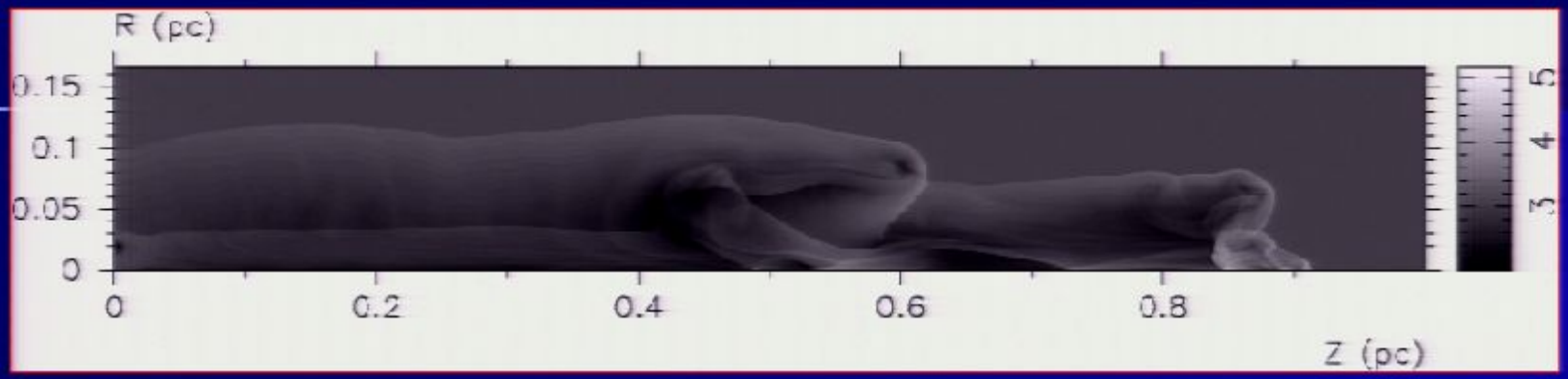

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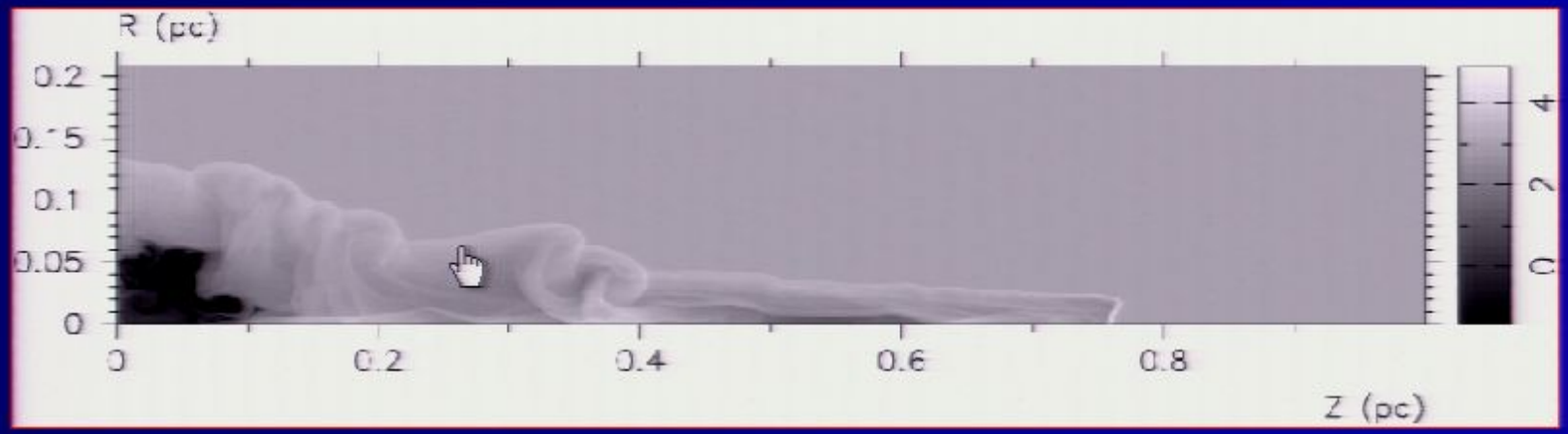

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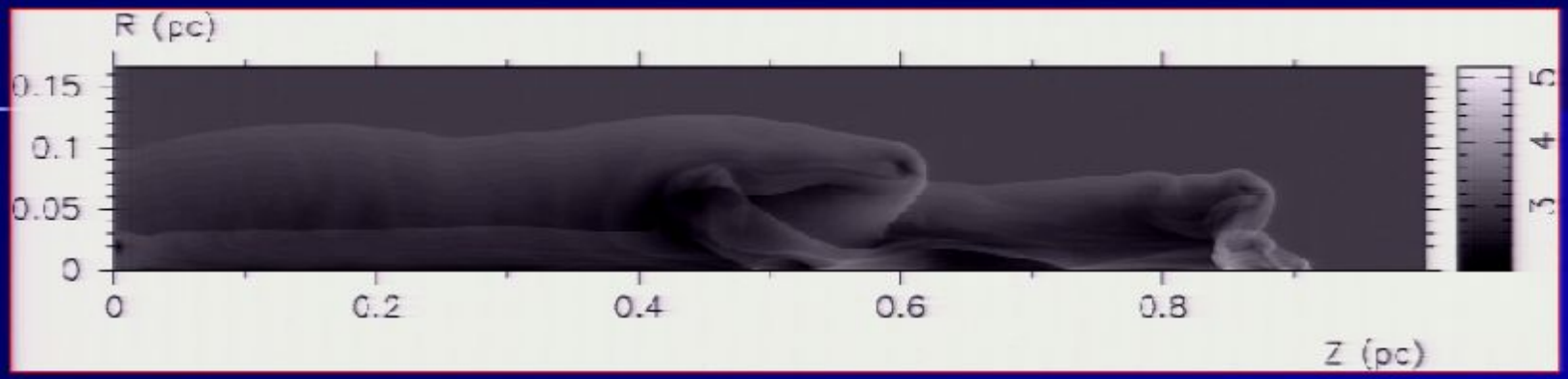

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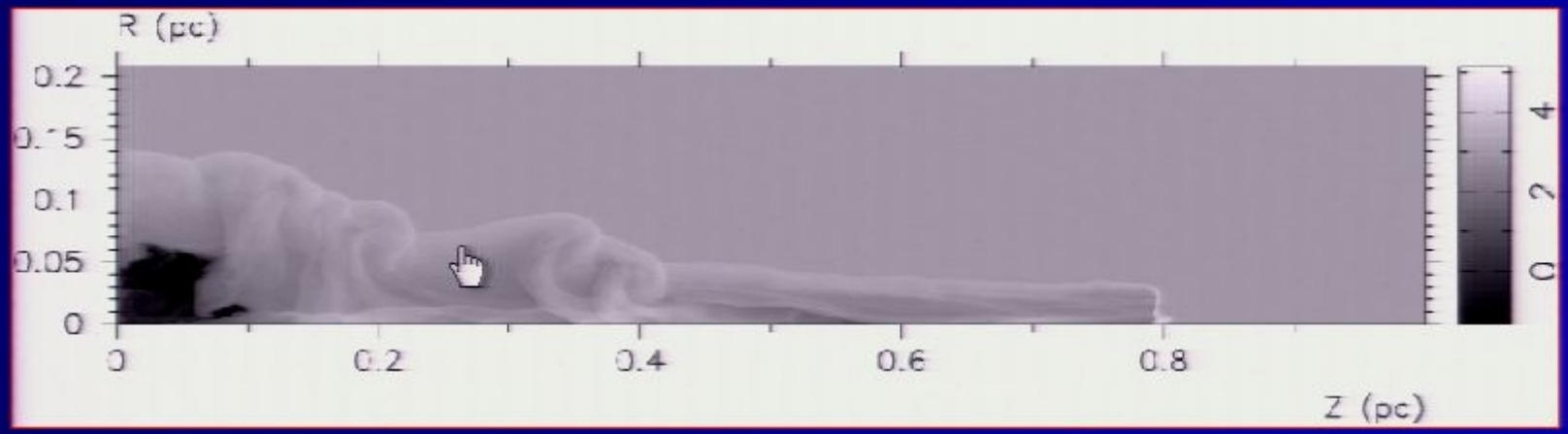

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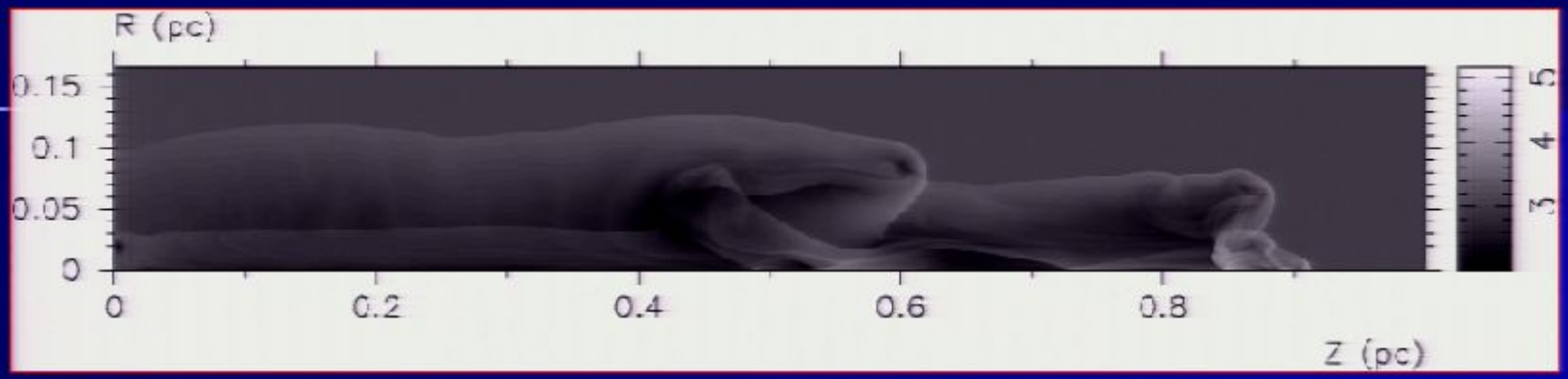

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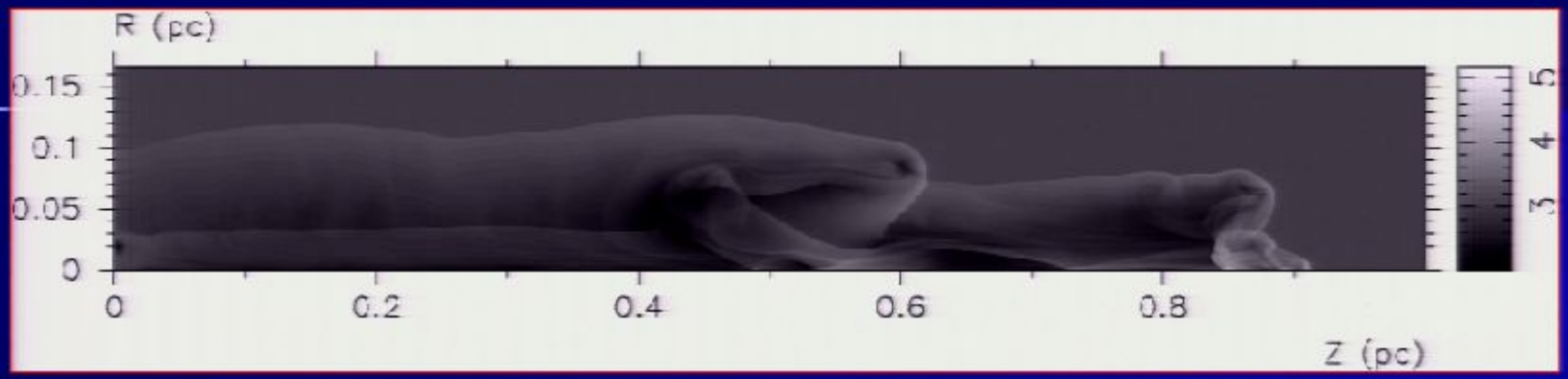

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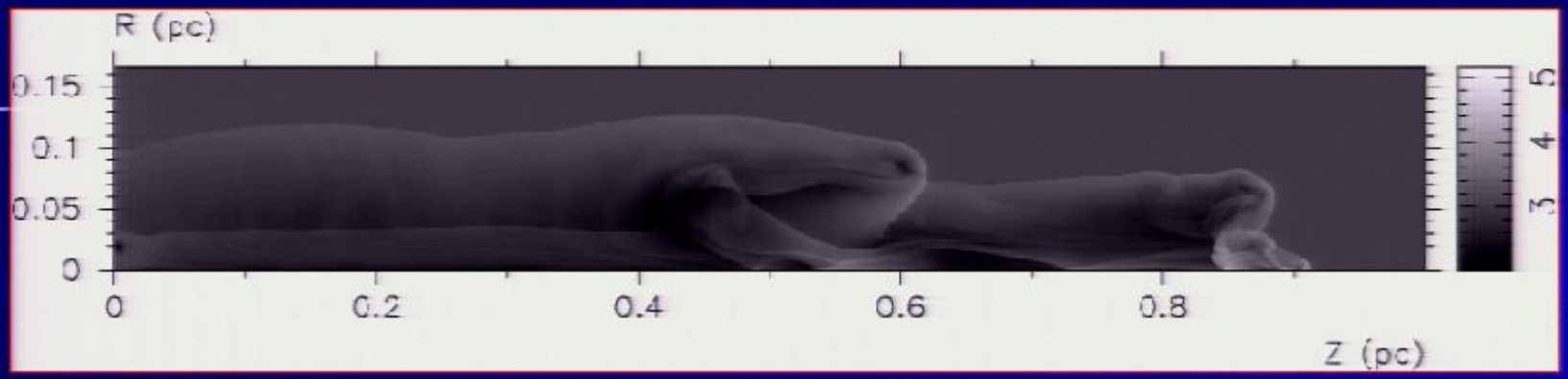

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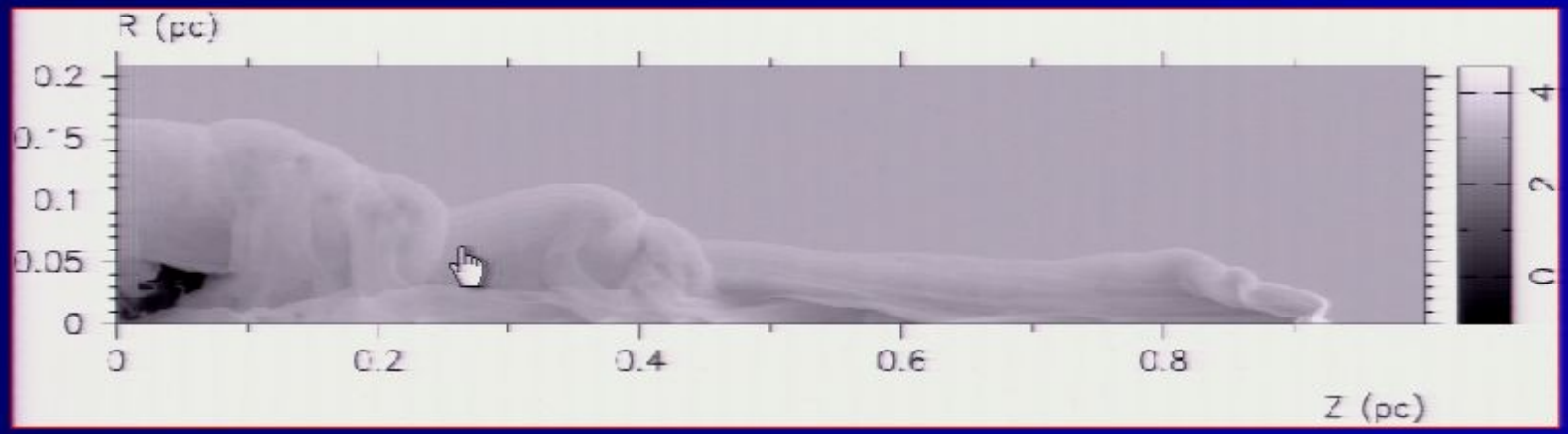

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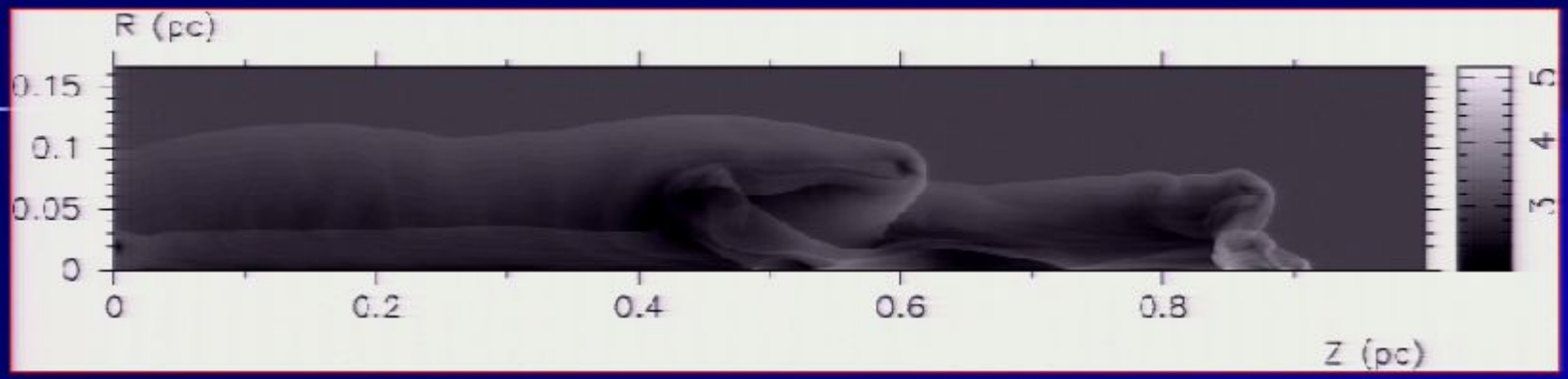

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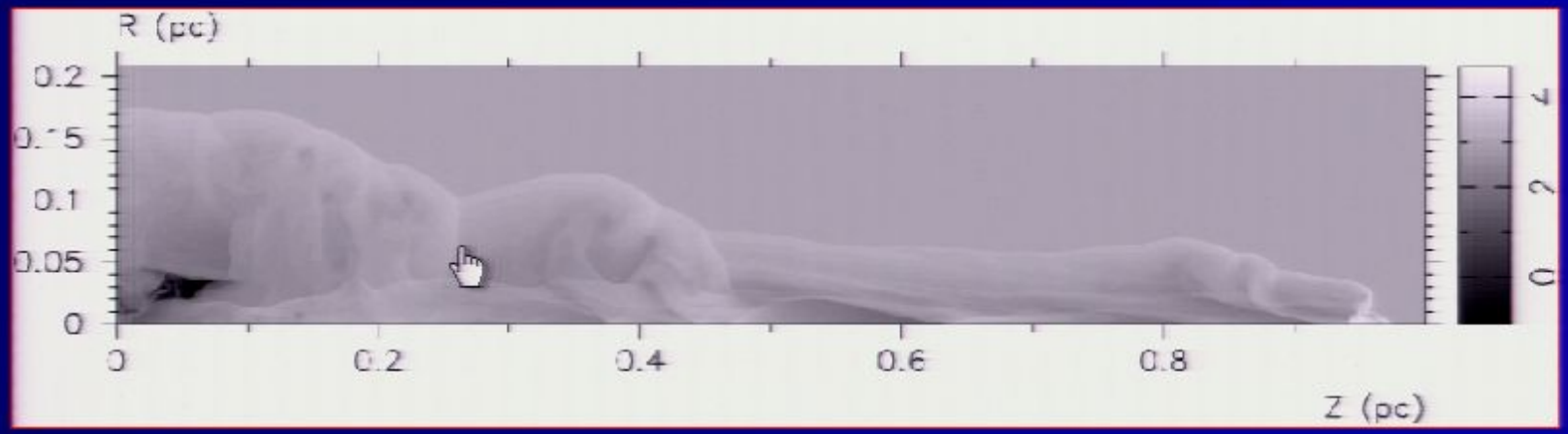

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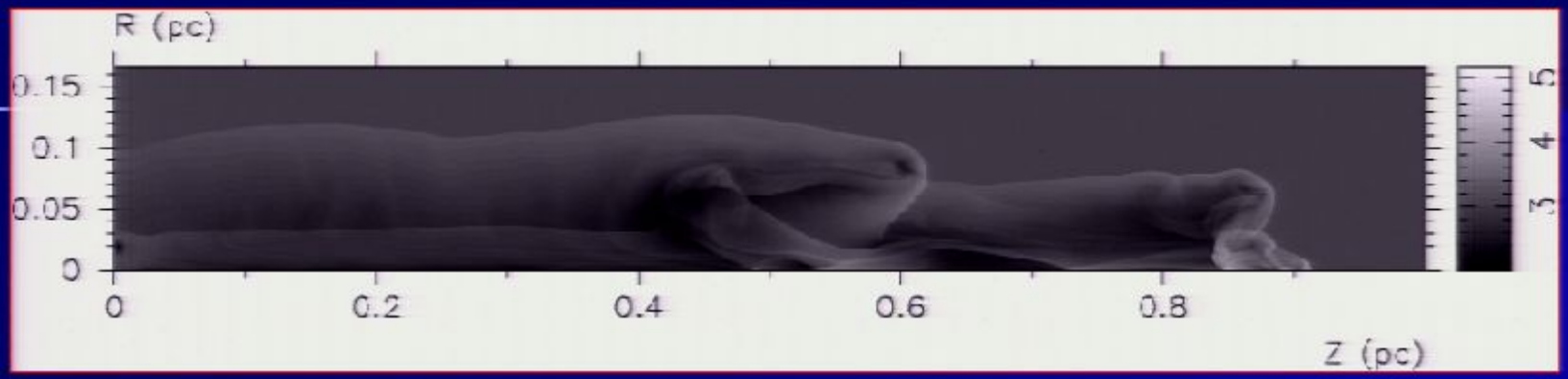

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Fossil Cavity Sims: Results

Quillen et al scaling relation for momentum

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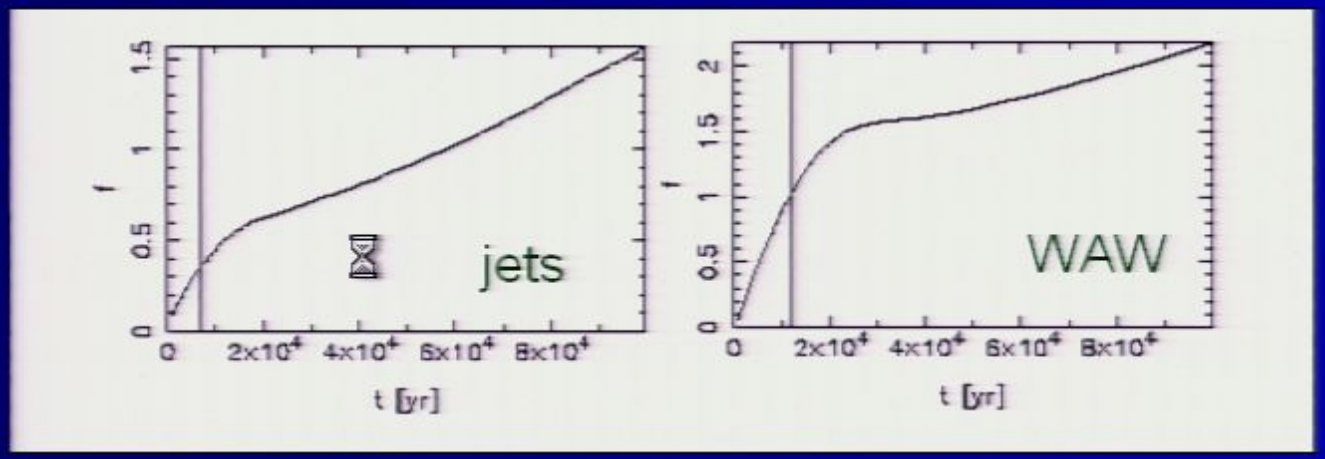
Simulation comparison: deviation from scaling relation small



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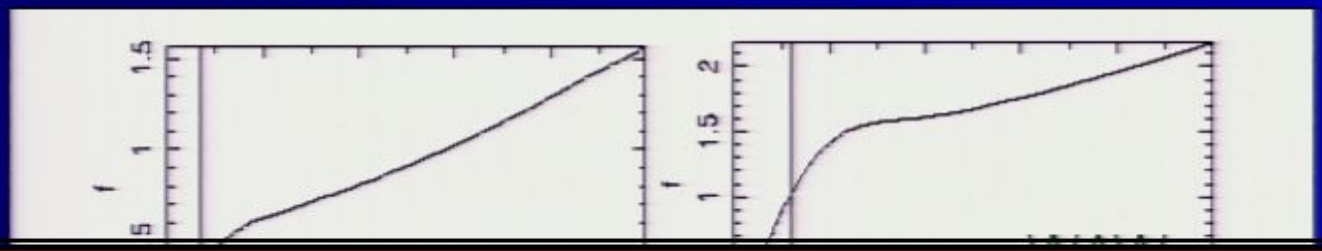

Time dependent jets/wind

= fossil cavities

= turbulent support

Question

Radiative Jets in Turbulent Media. Transfer Mechanisms for a single jet?

Cunningham et al. 2007

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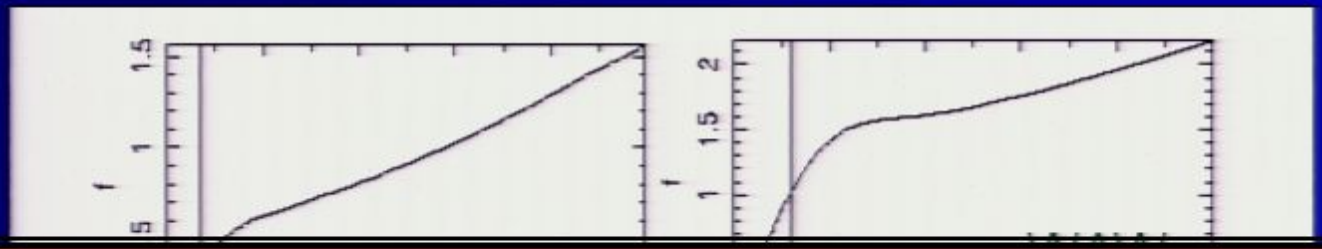

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Time-dependent Jets in Turbulent Environment

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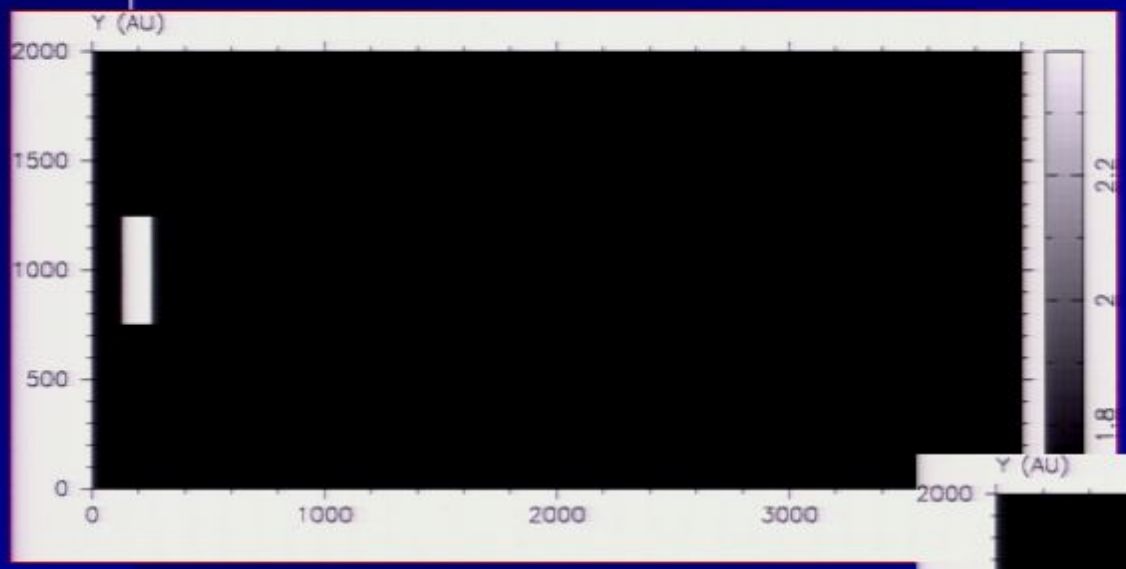

2-D slices of 3-D simulation

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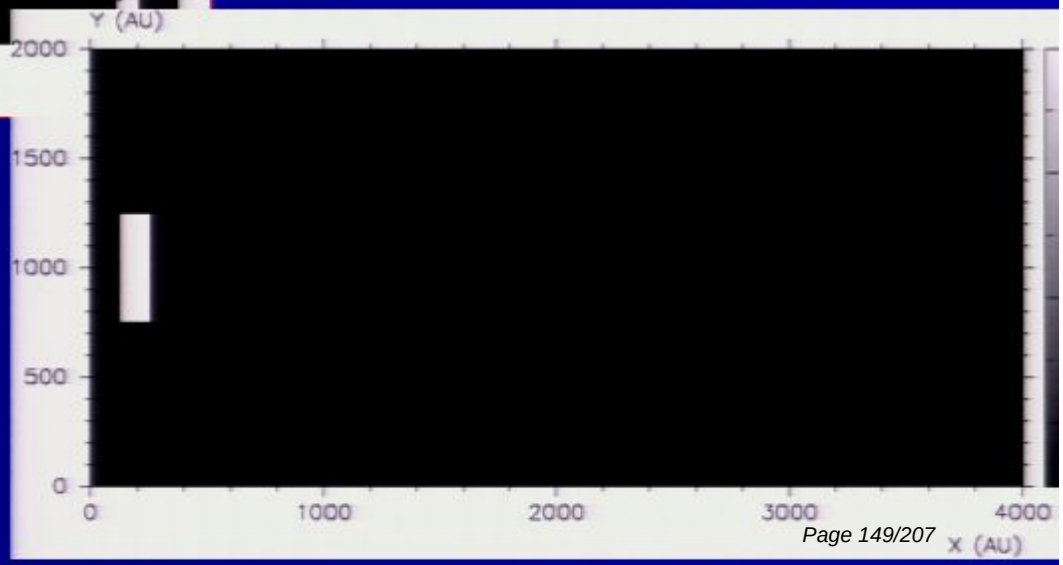

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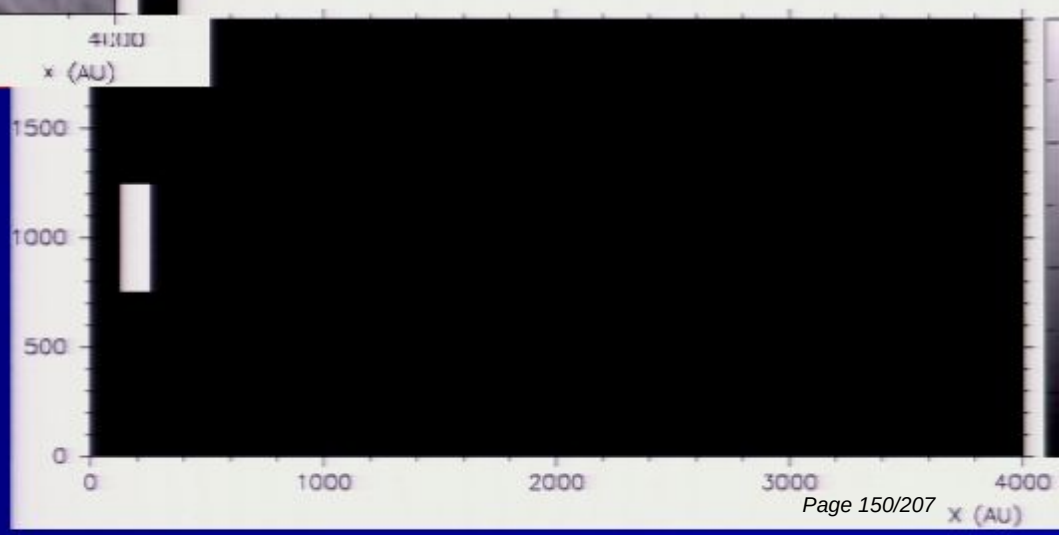

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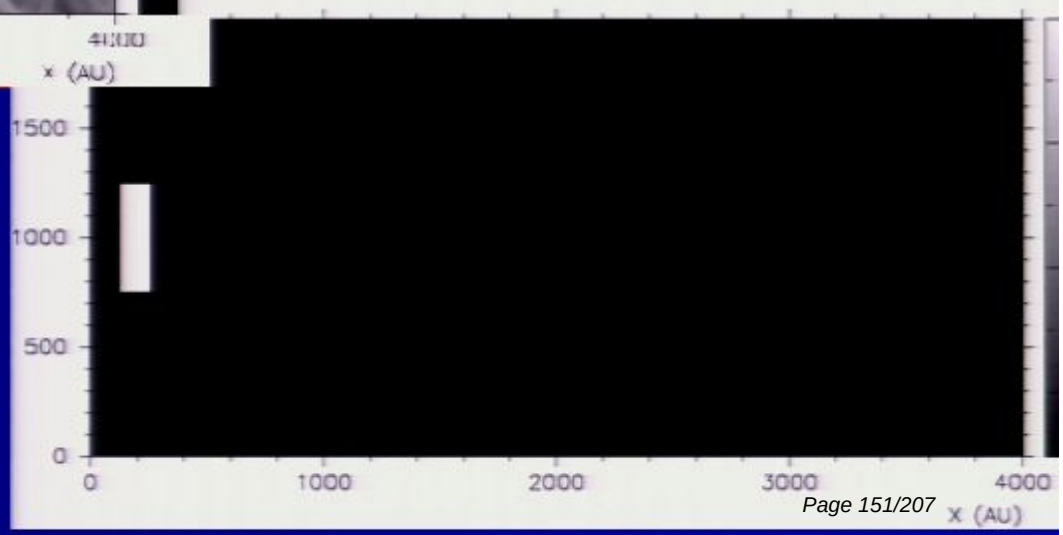

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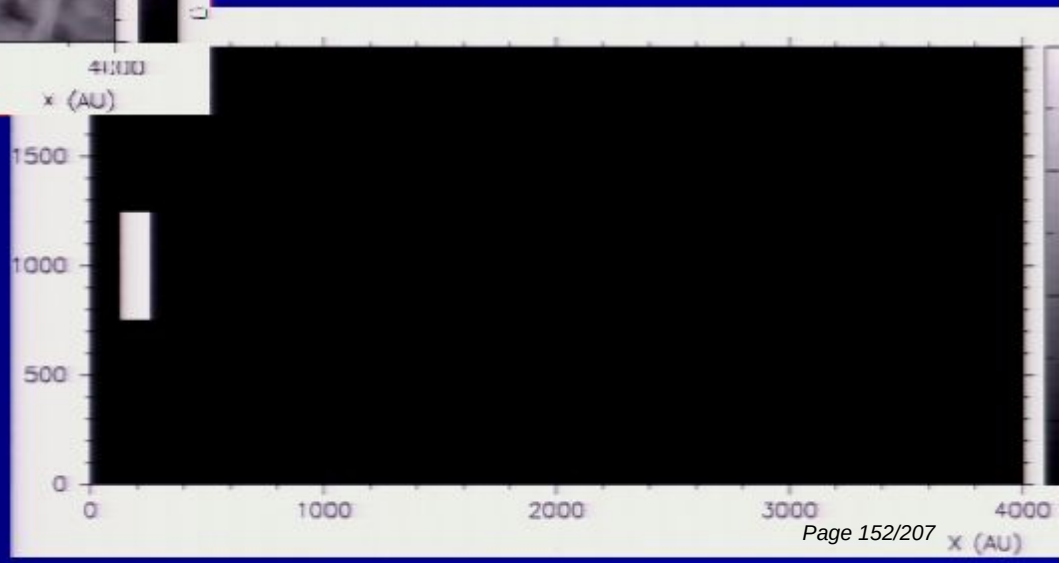

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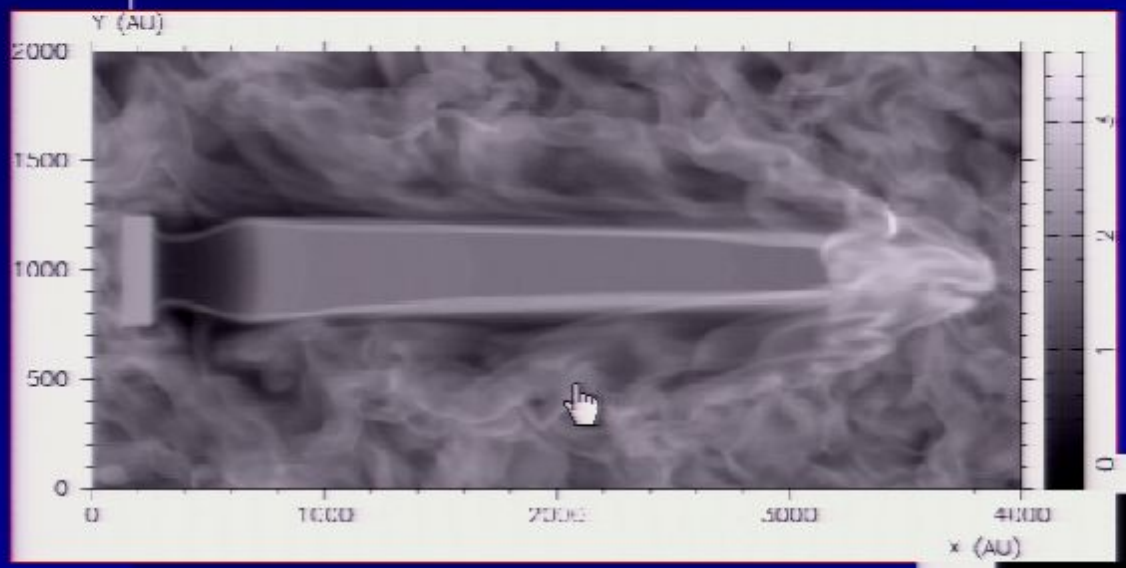

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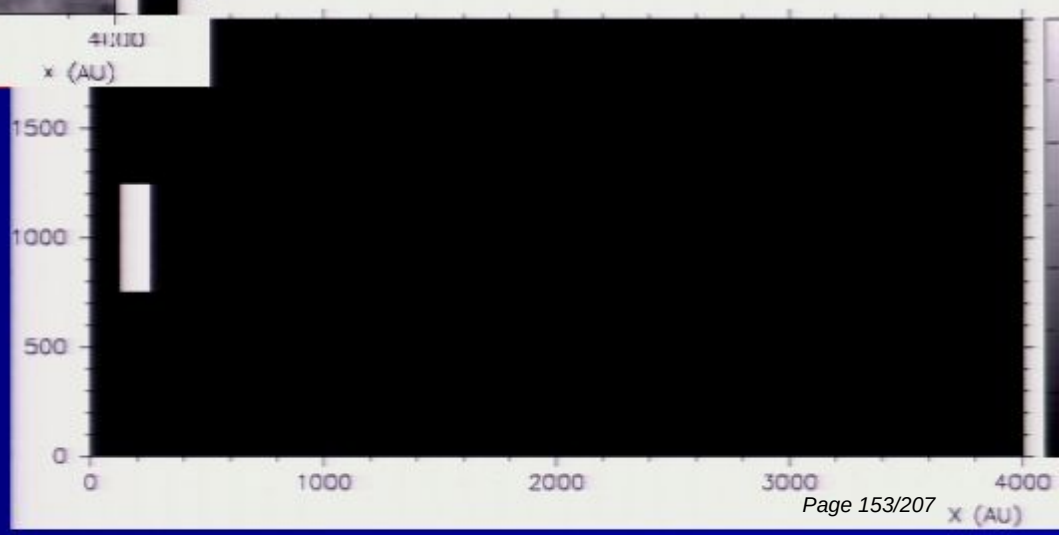

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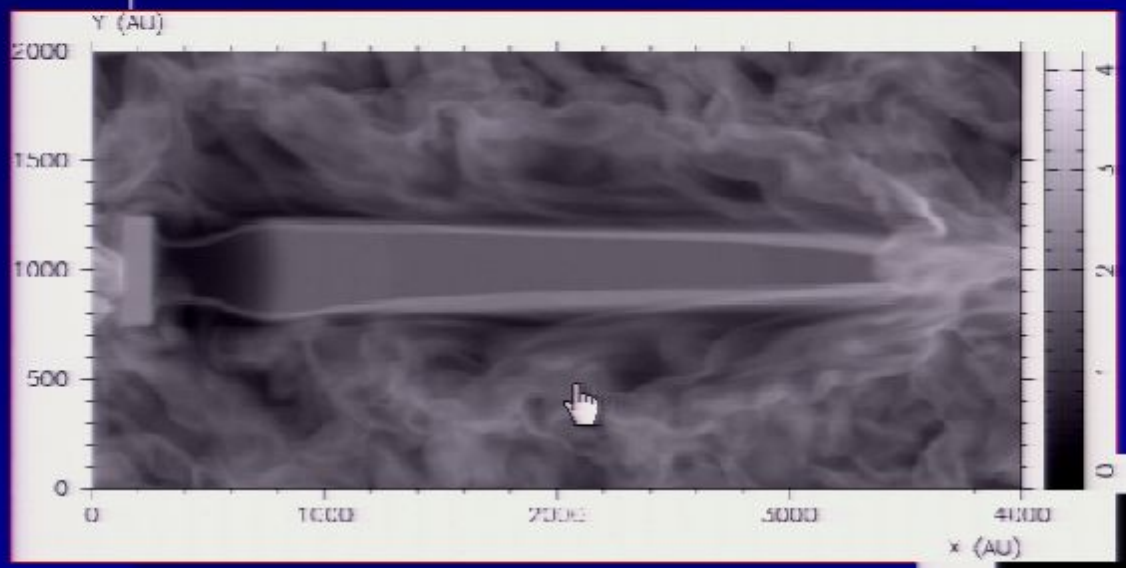

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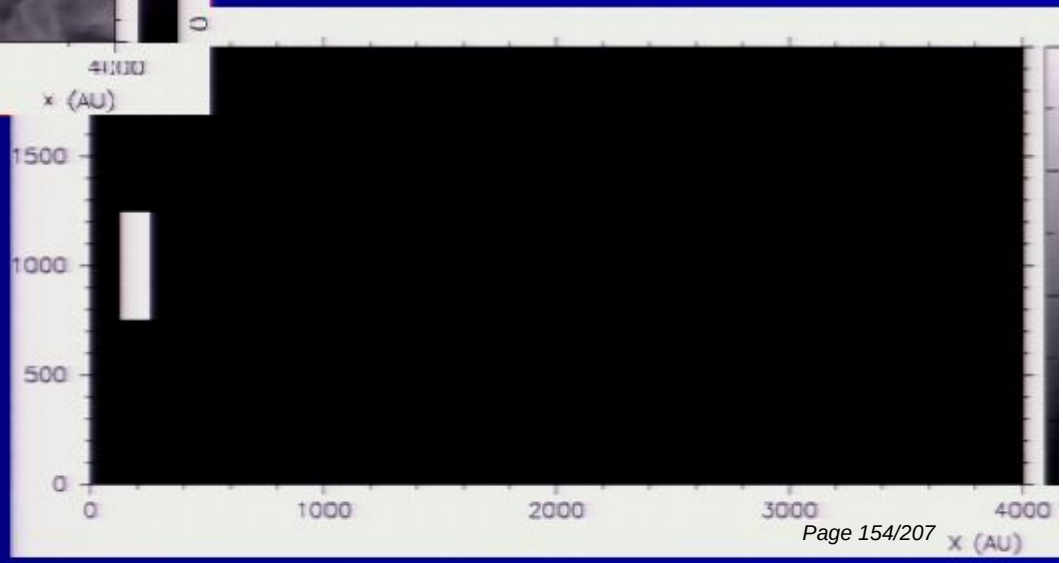

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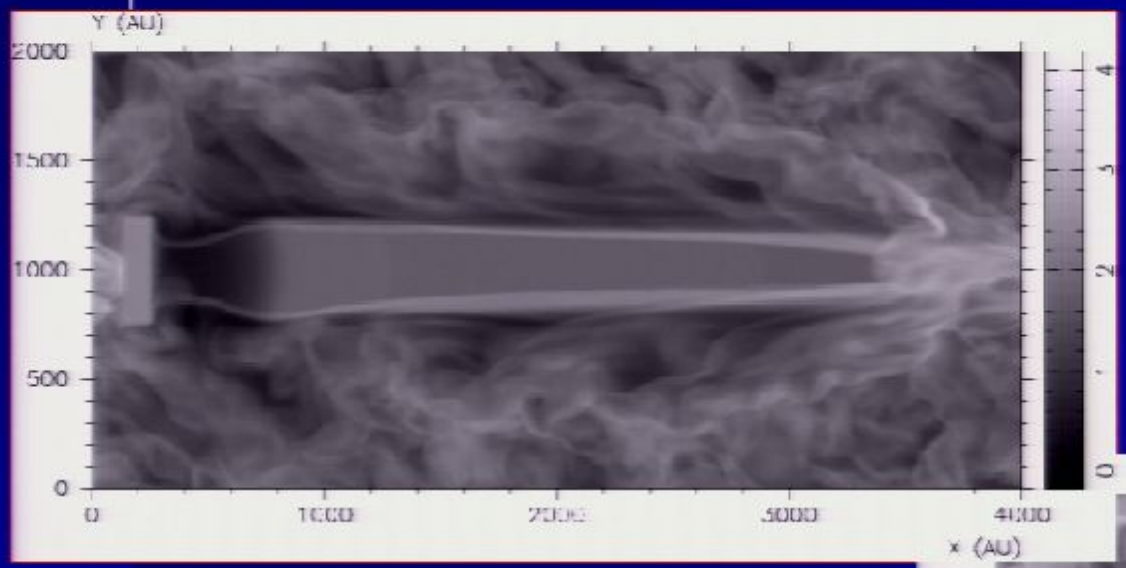

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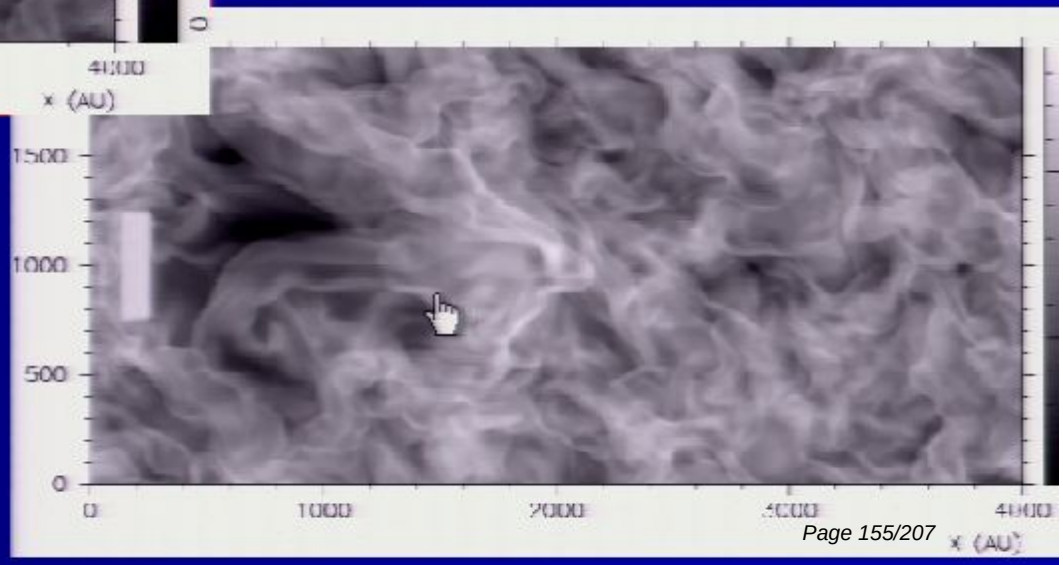

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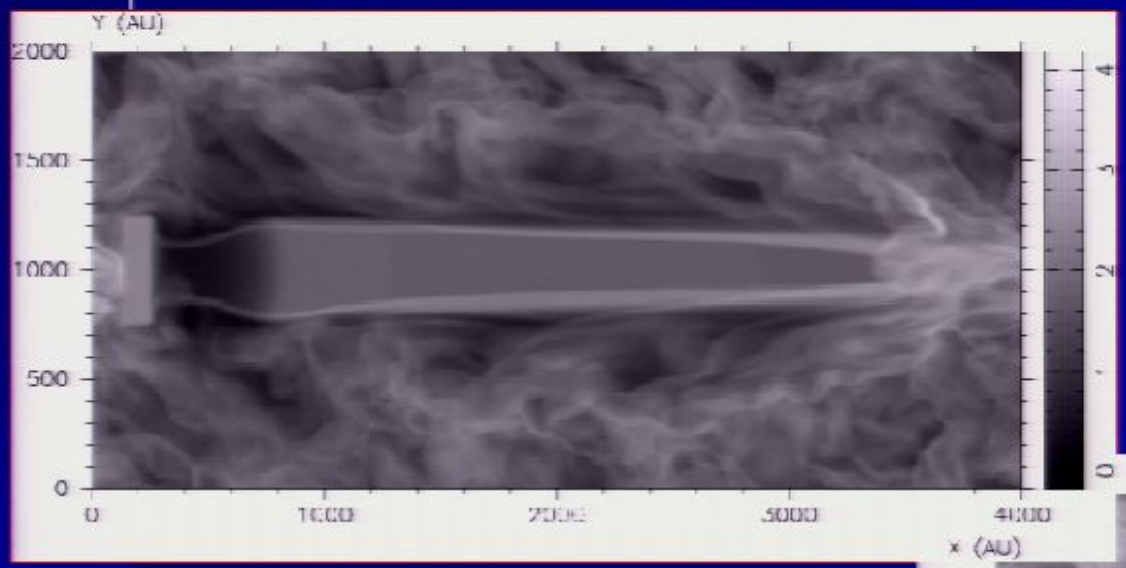

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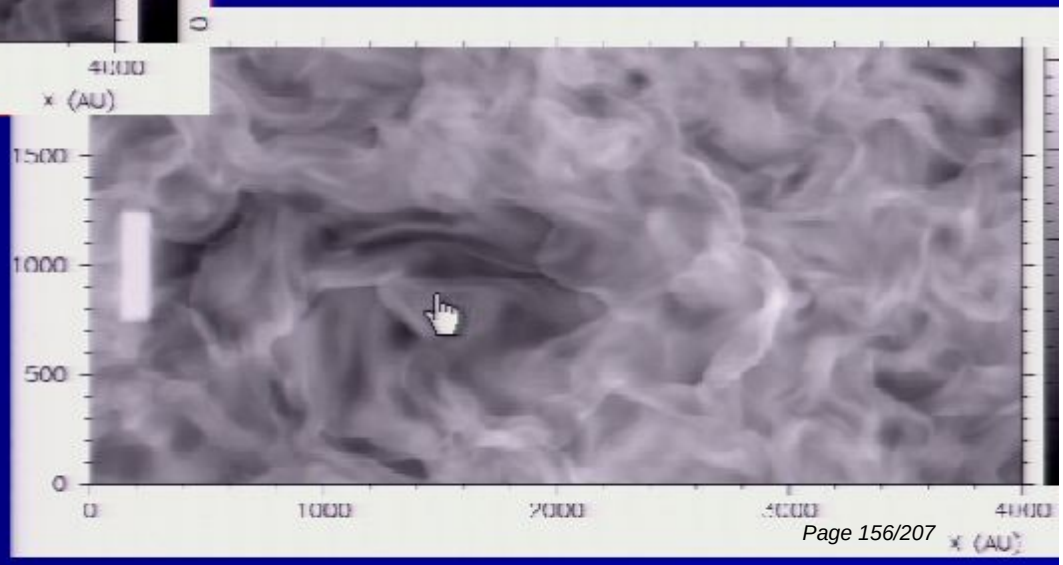

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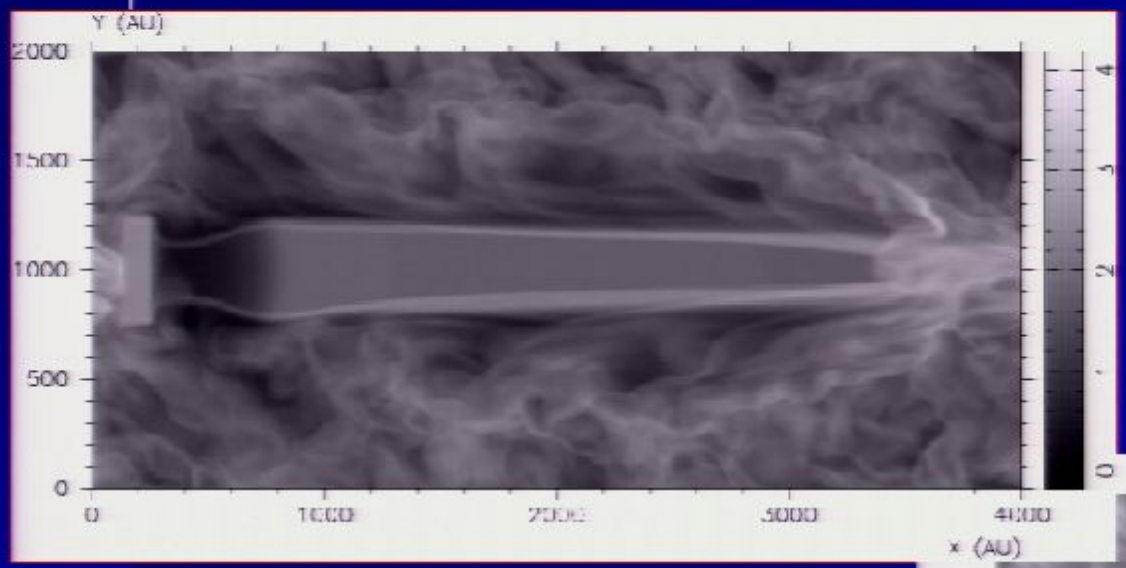

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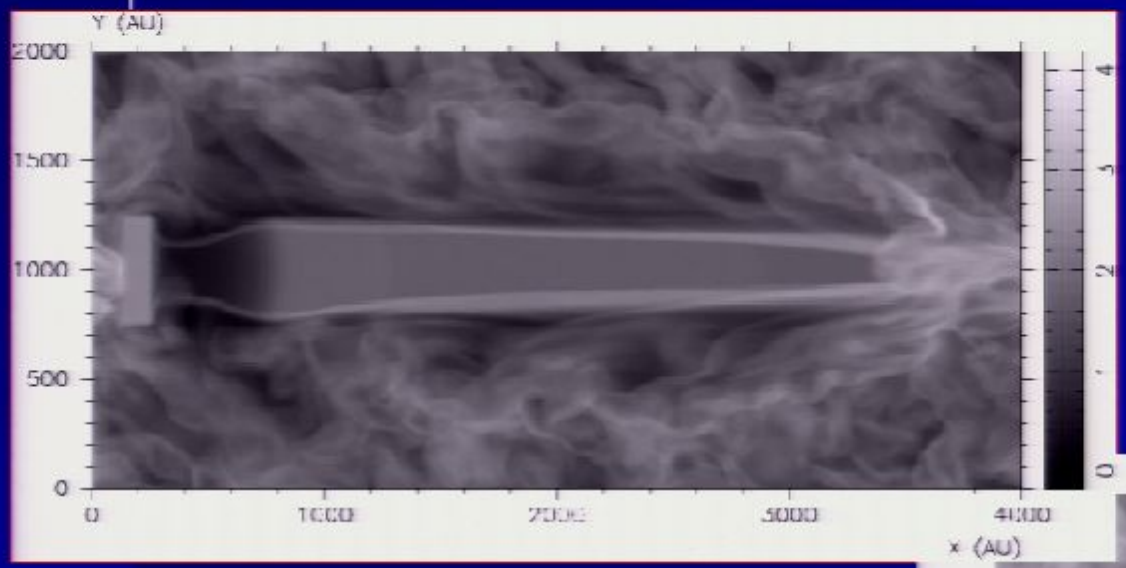

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Short Period

Turbulent Spectra

$[k] = 1/L$
$[\psi] = L^2/T^3$
$[\nu] = L^2/T$
$[E] = L^3/T^2$

- Classic Kolmogorov Result

$$E(k,\psi) = Ck^{-5/3}\psi^{2/3}$$

- Driving scale k_{min}
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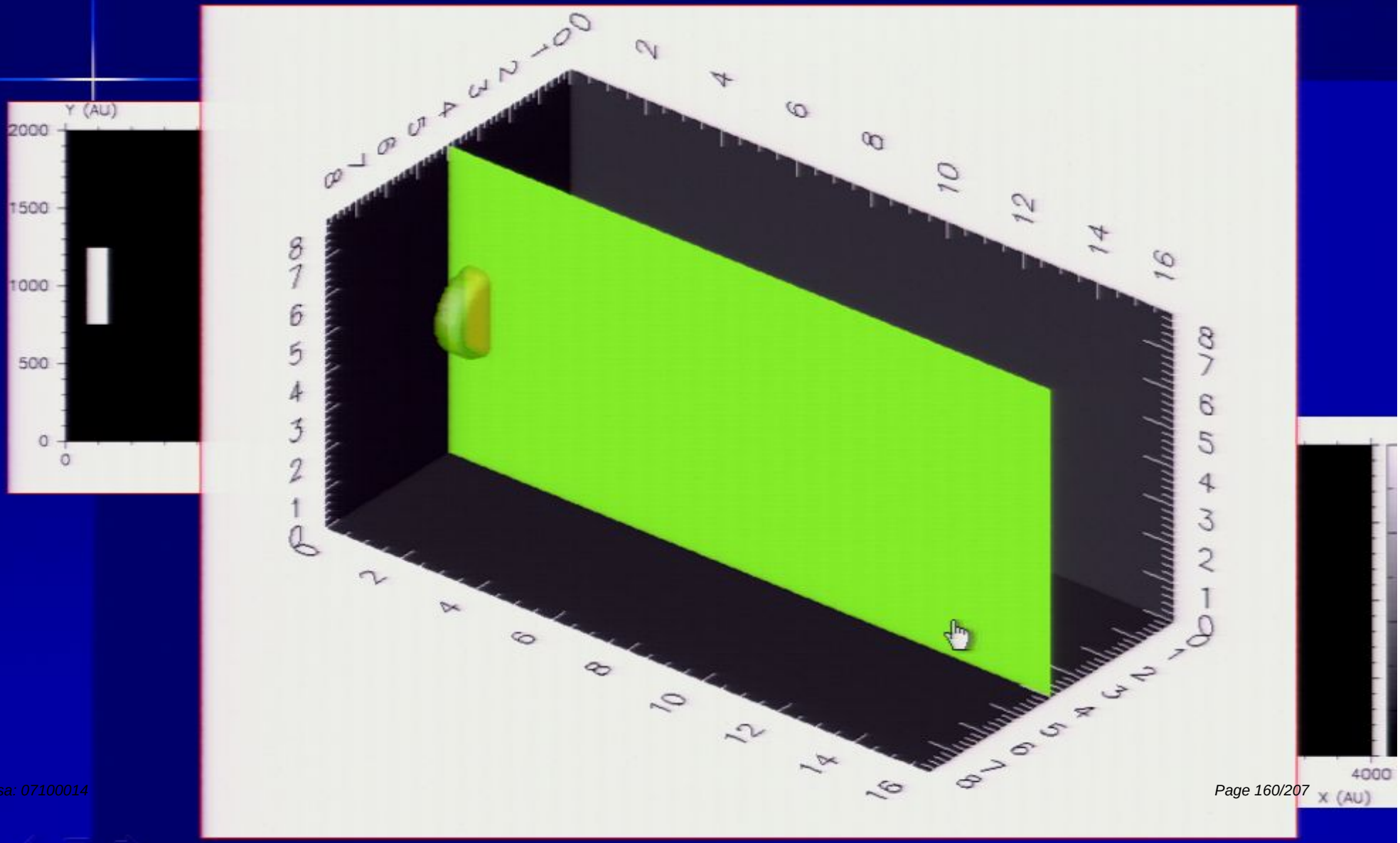
Time-dependent Jets in Turbulent Environment



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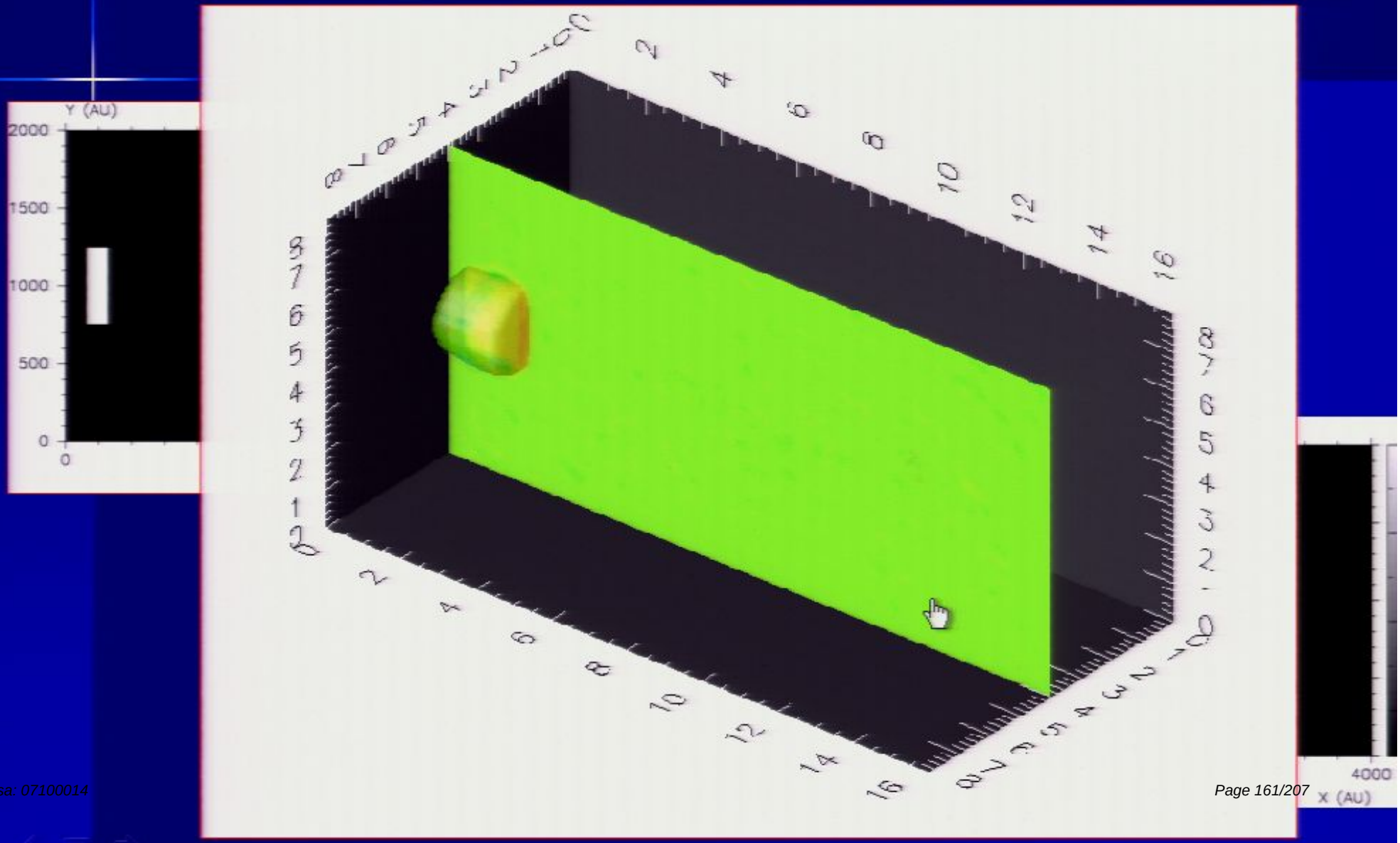

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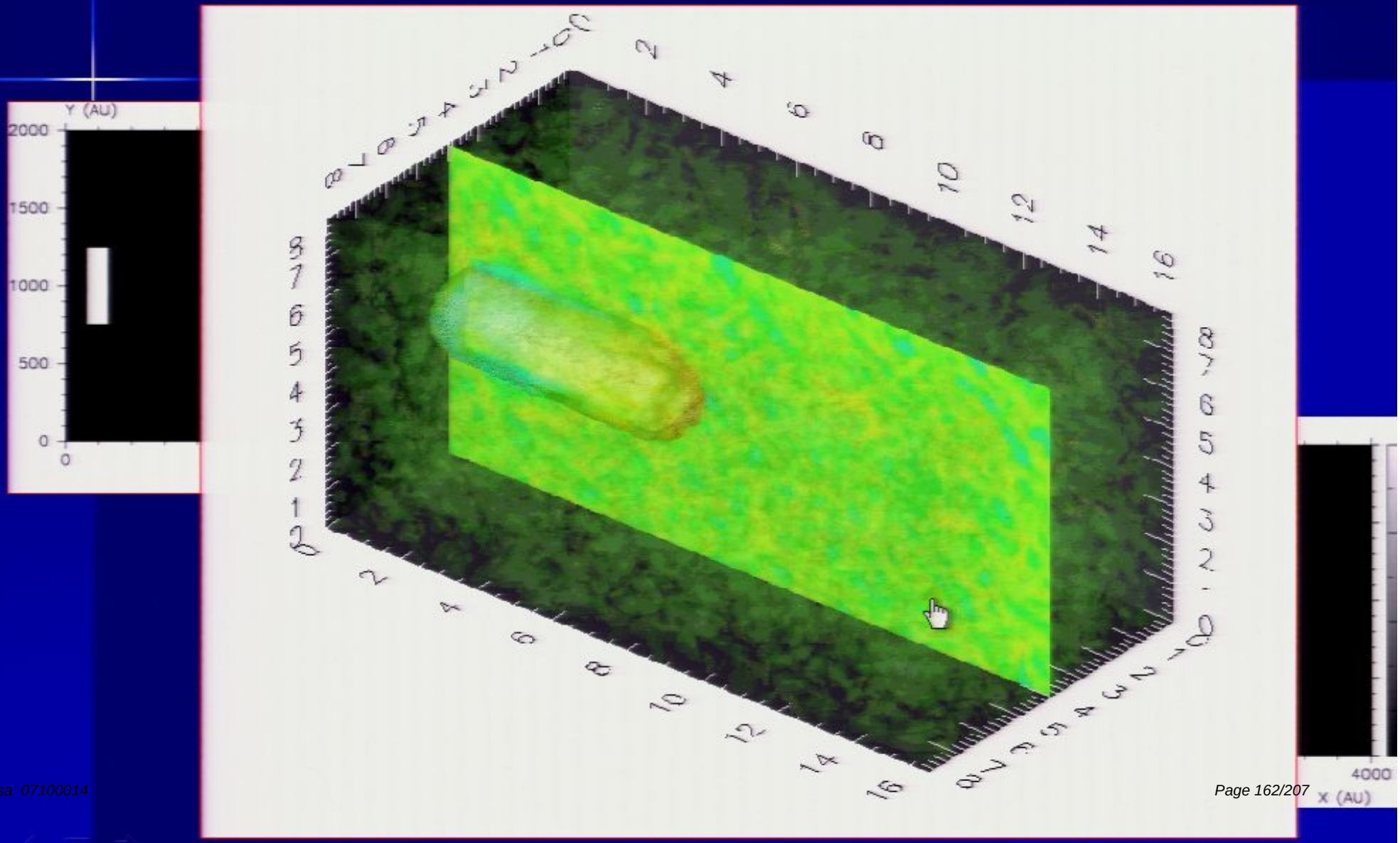

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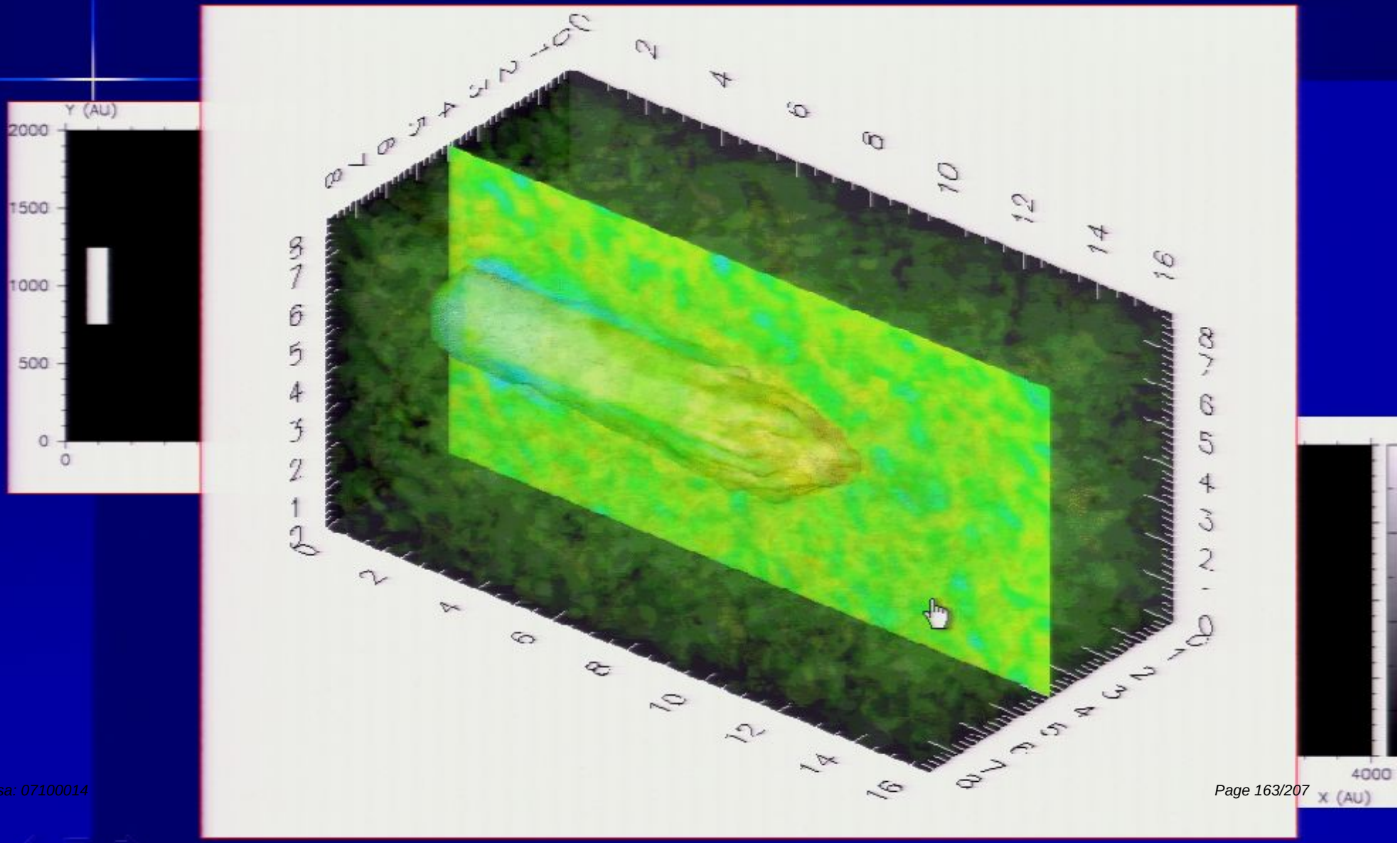

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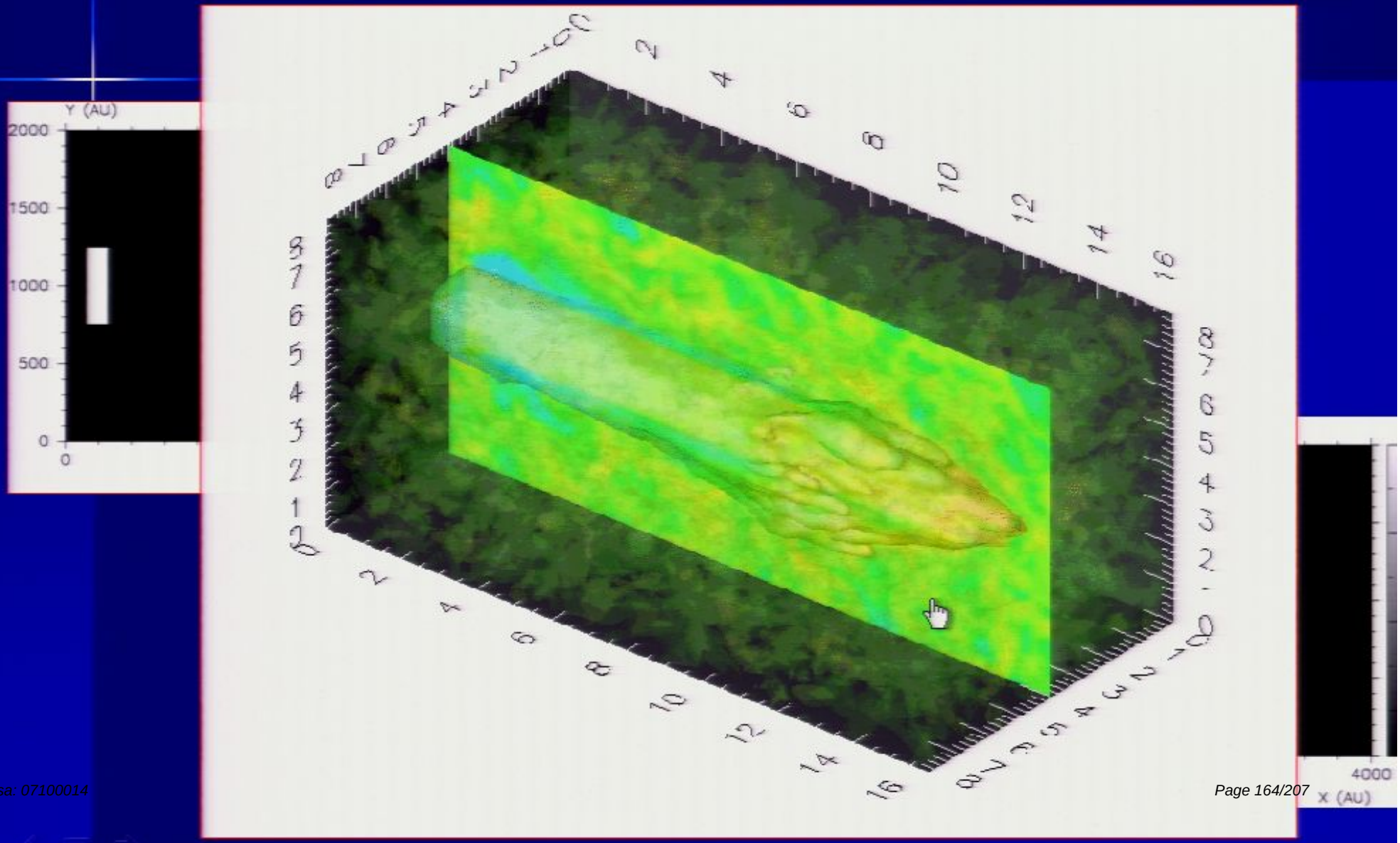

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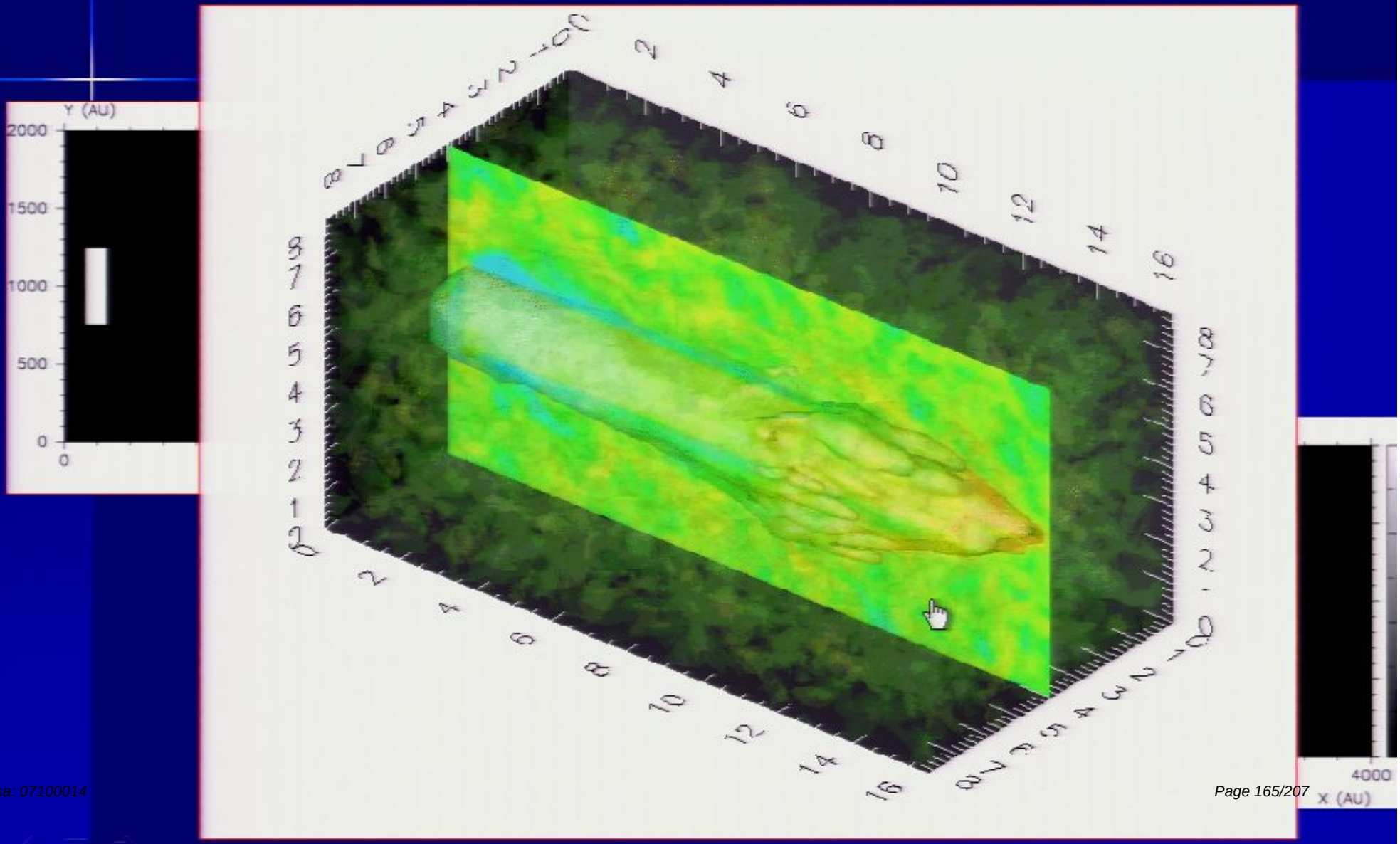

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⌛

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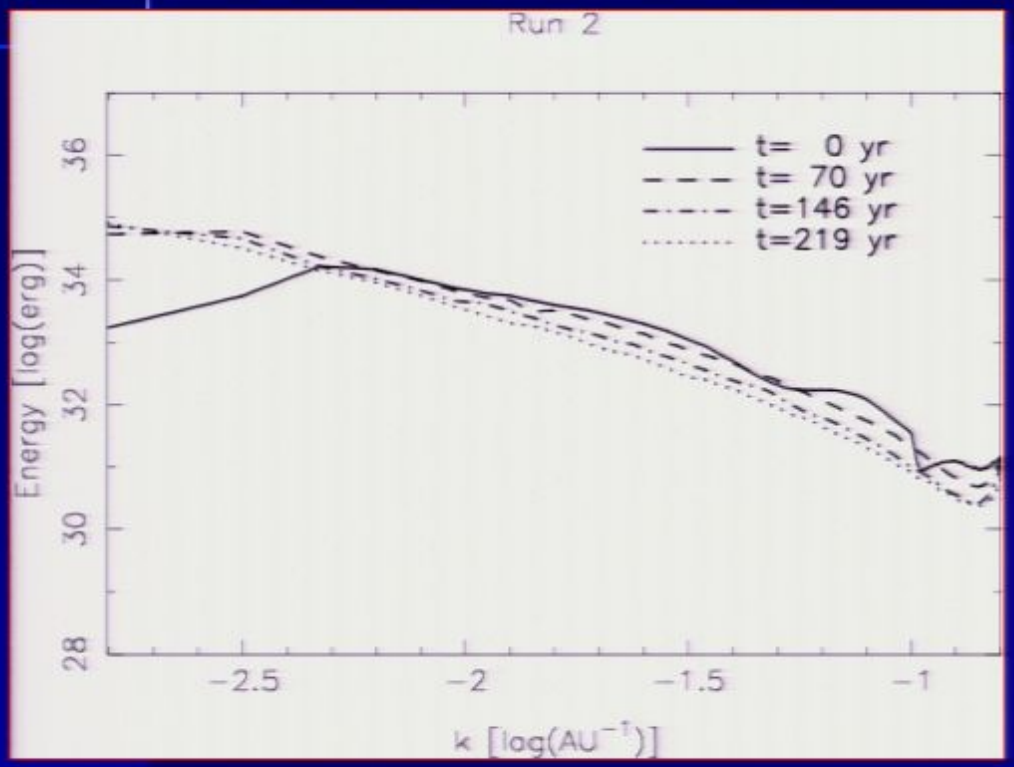
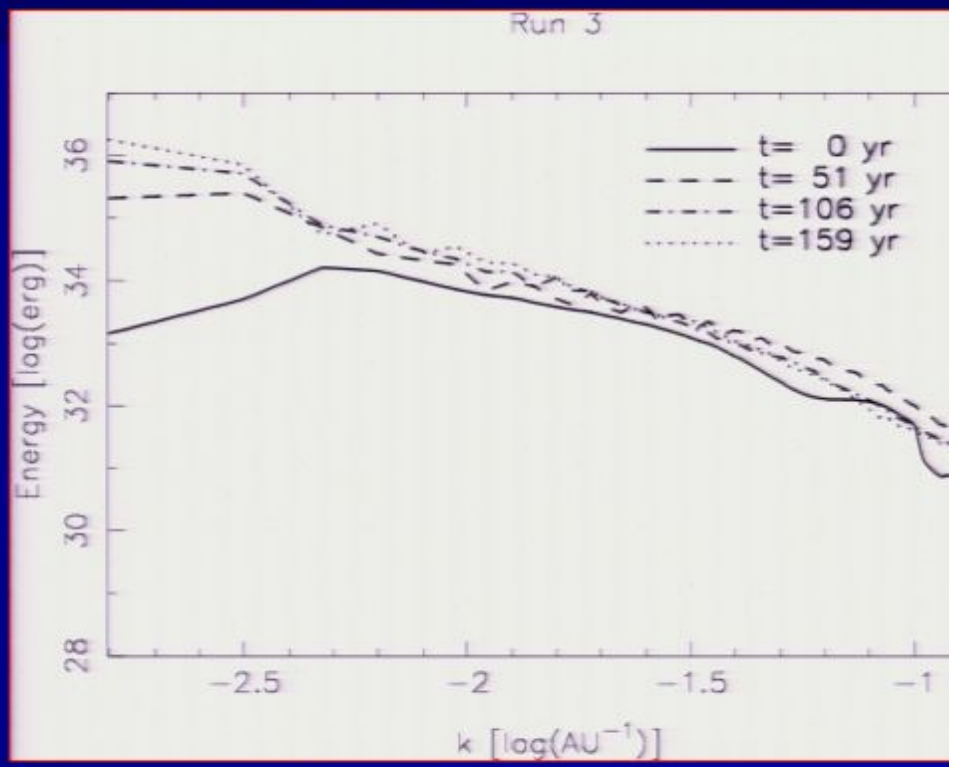
Time Dependent Jets in a Turbulent Environment

Intermediate pulse

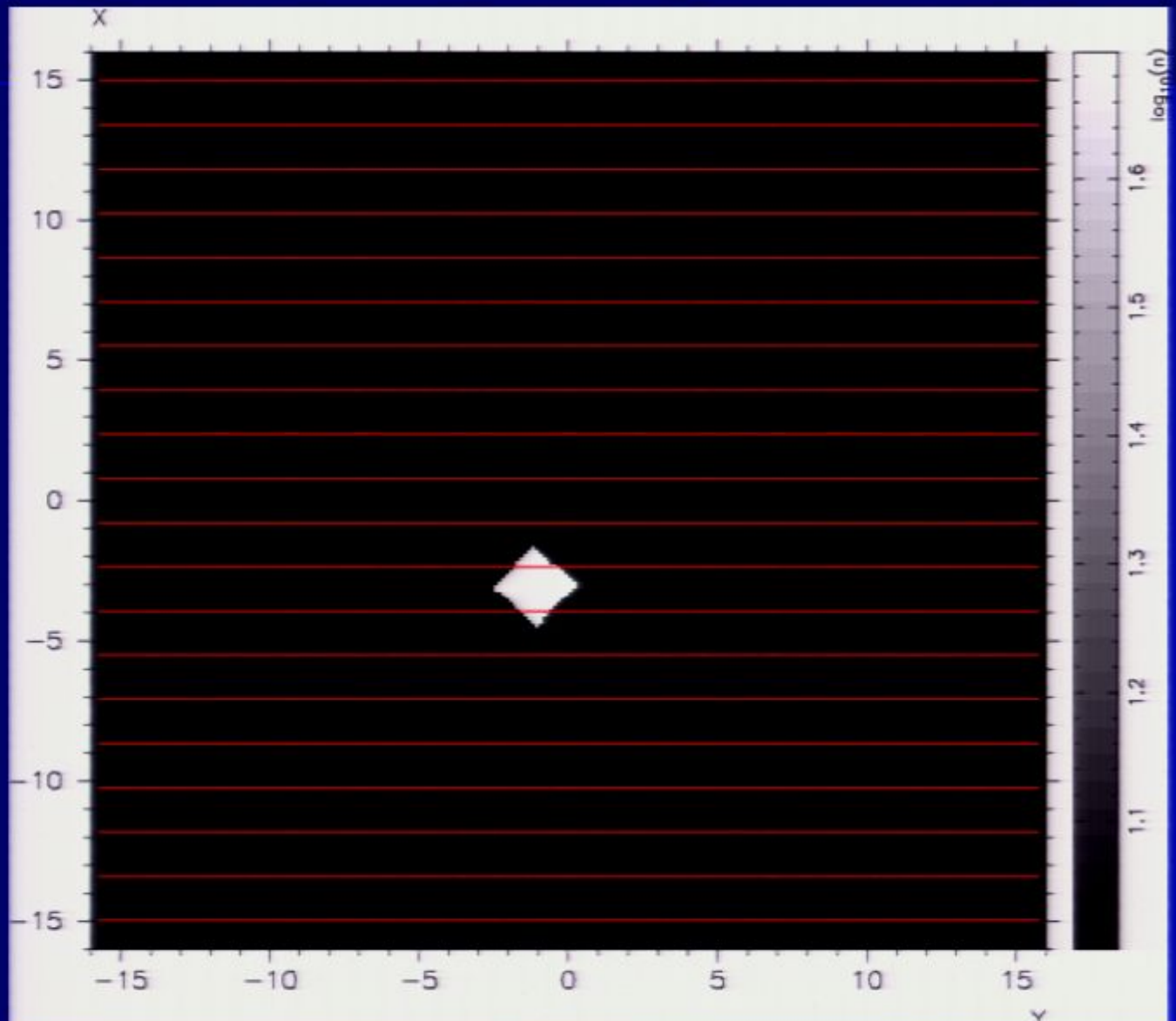


Long pulse



- Without jet, turbulence decays as expected.
- With jet, "turbulence" re-energized on all scales.
- With jet long "driving" scales energized which not previously present

Future: Focus on Individual Objects
L1551
Frank, Bally, Blackman, Hartigan 2008*



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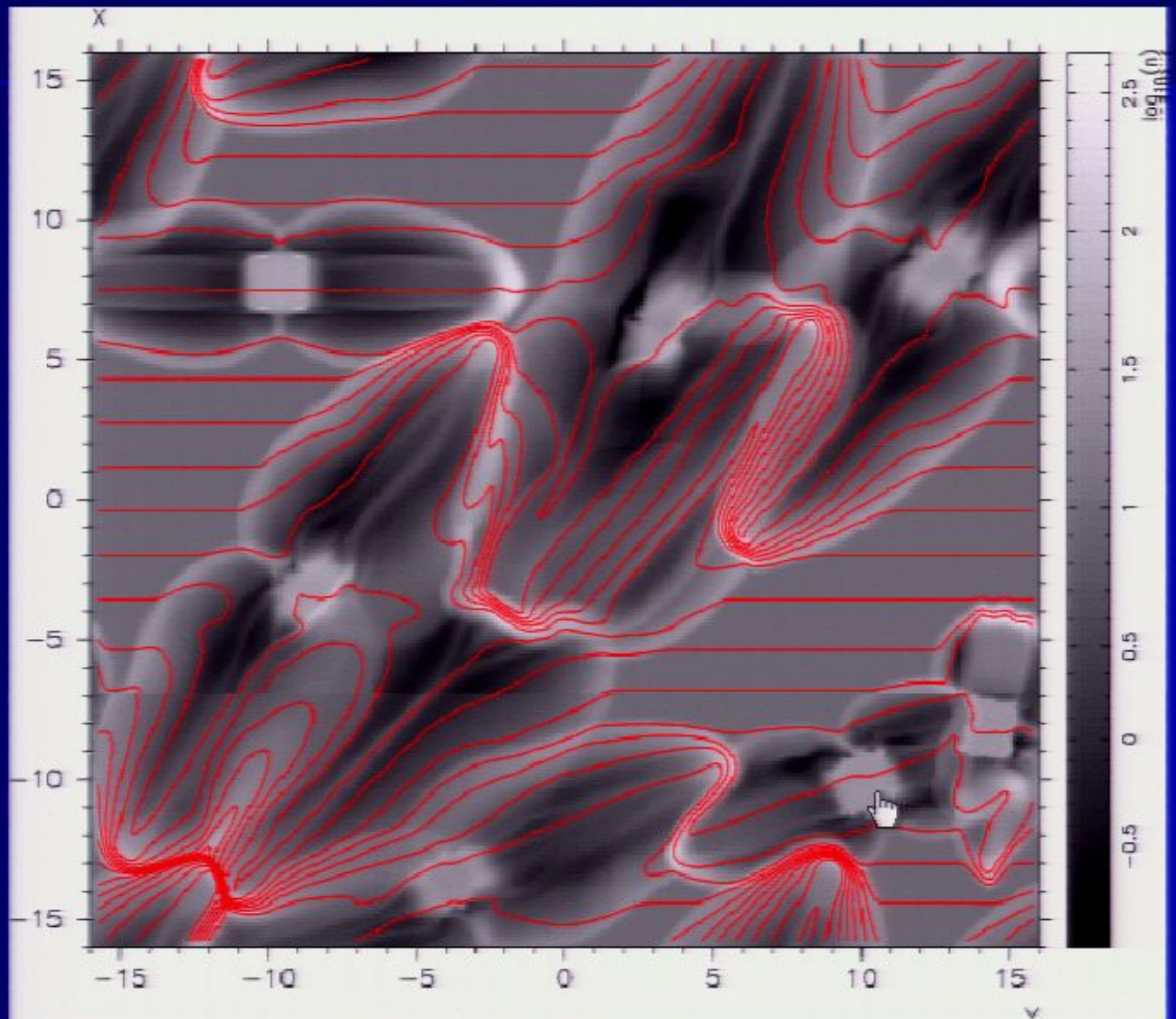

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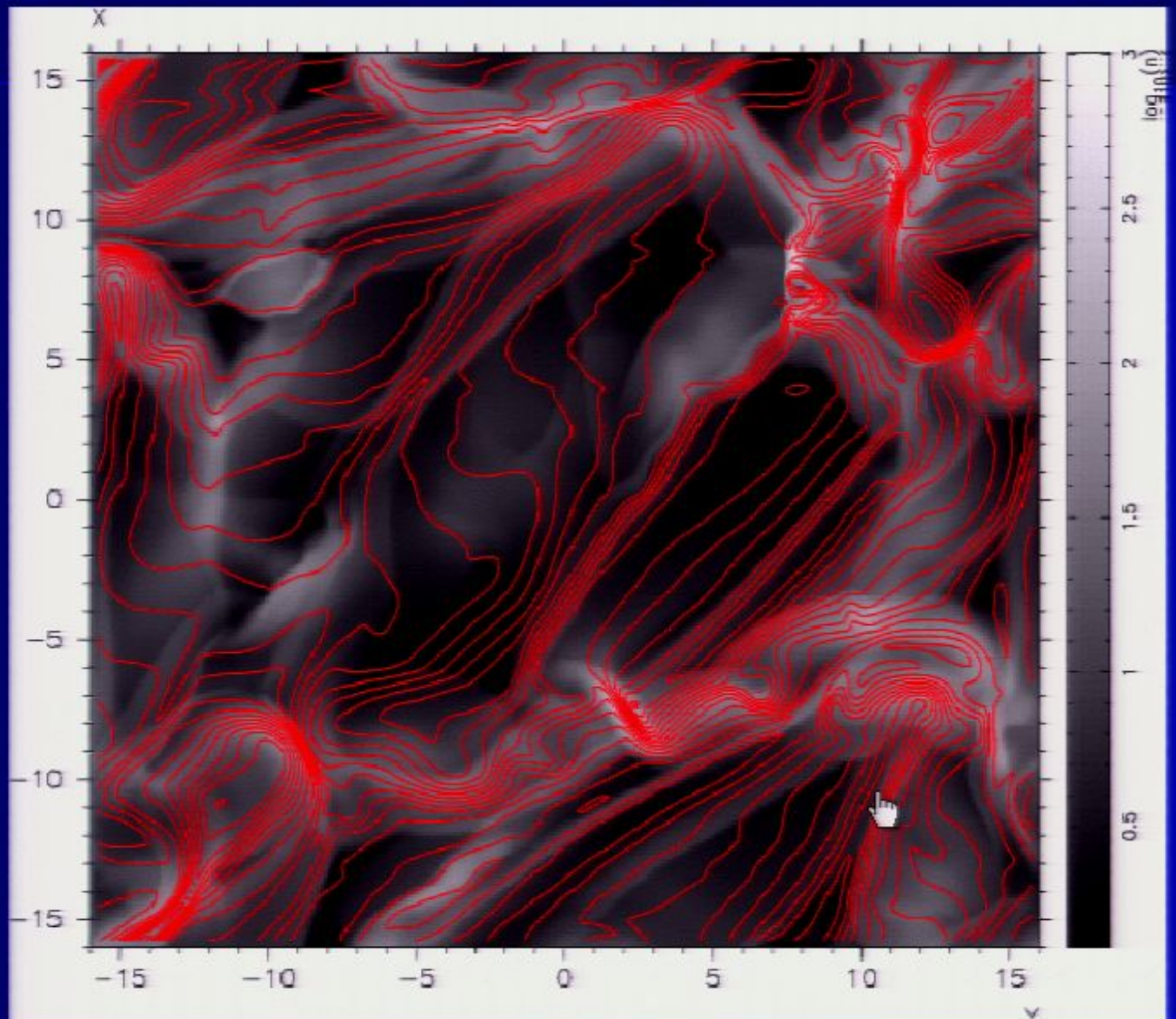
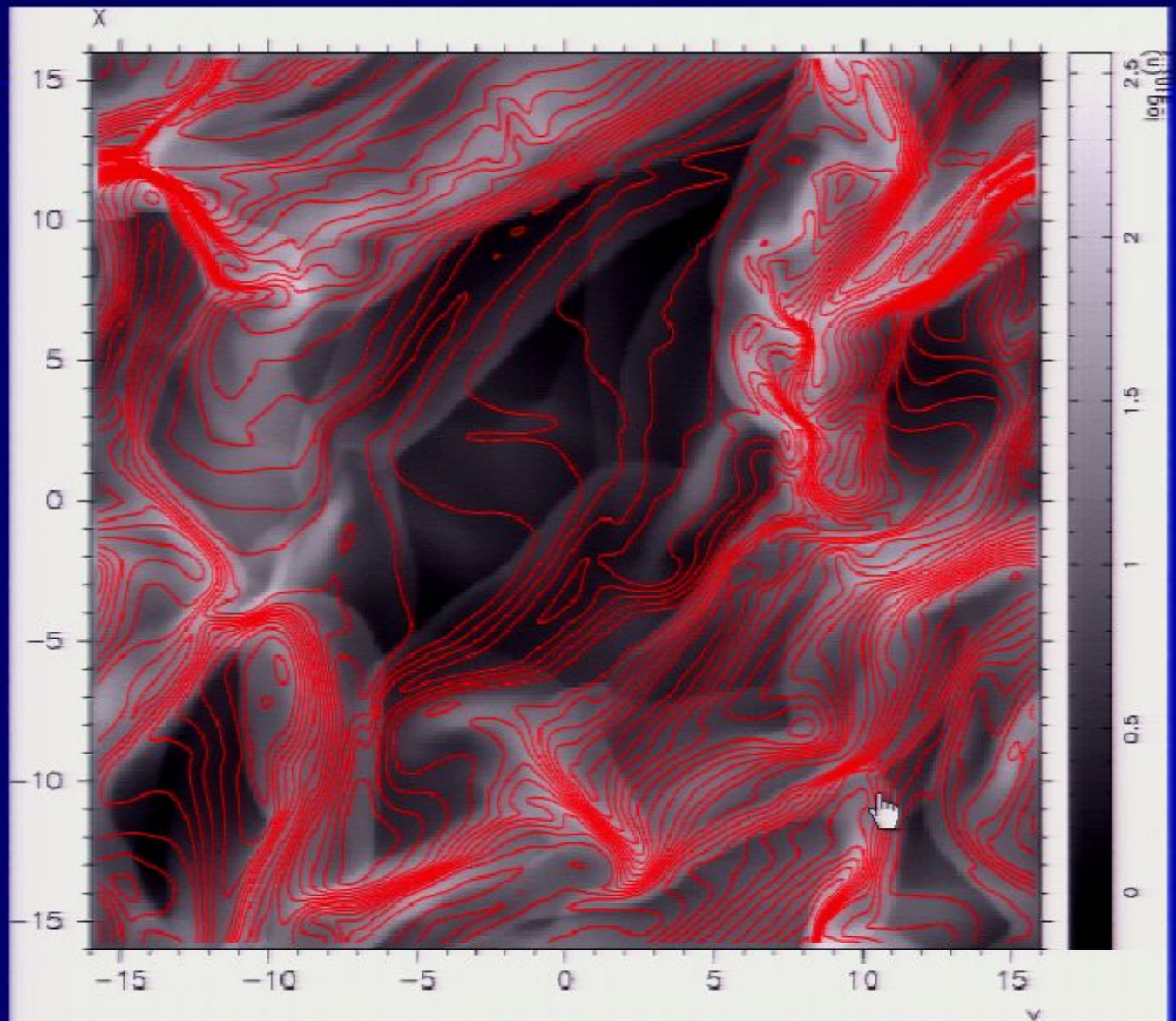


Future: Focus on Individual Objects
L1551
Frank, Bally, Blackman, Hartigan 2008*



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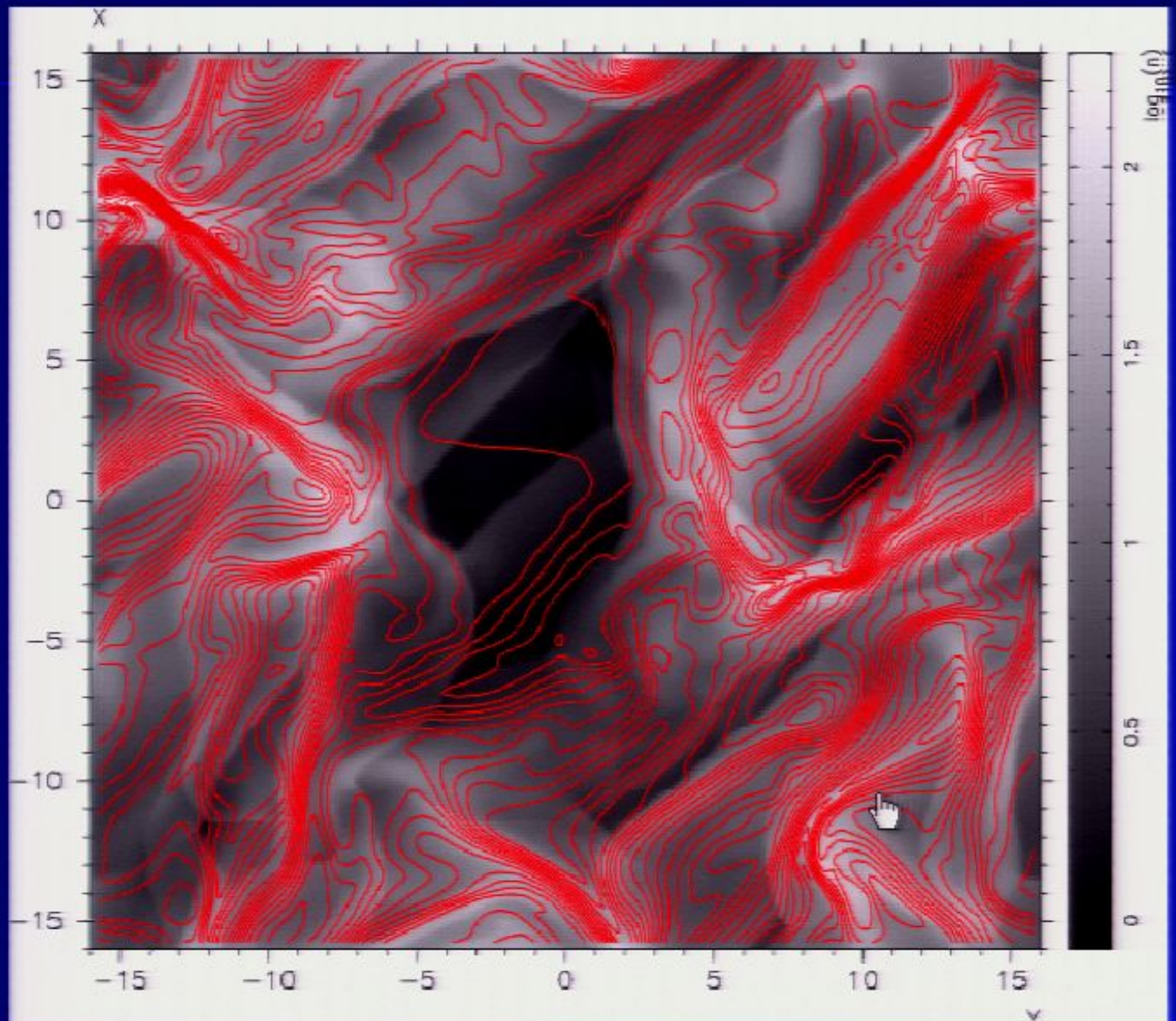

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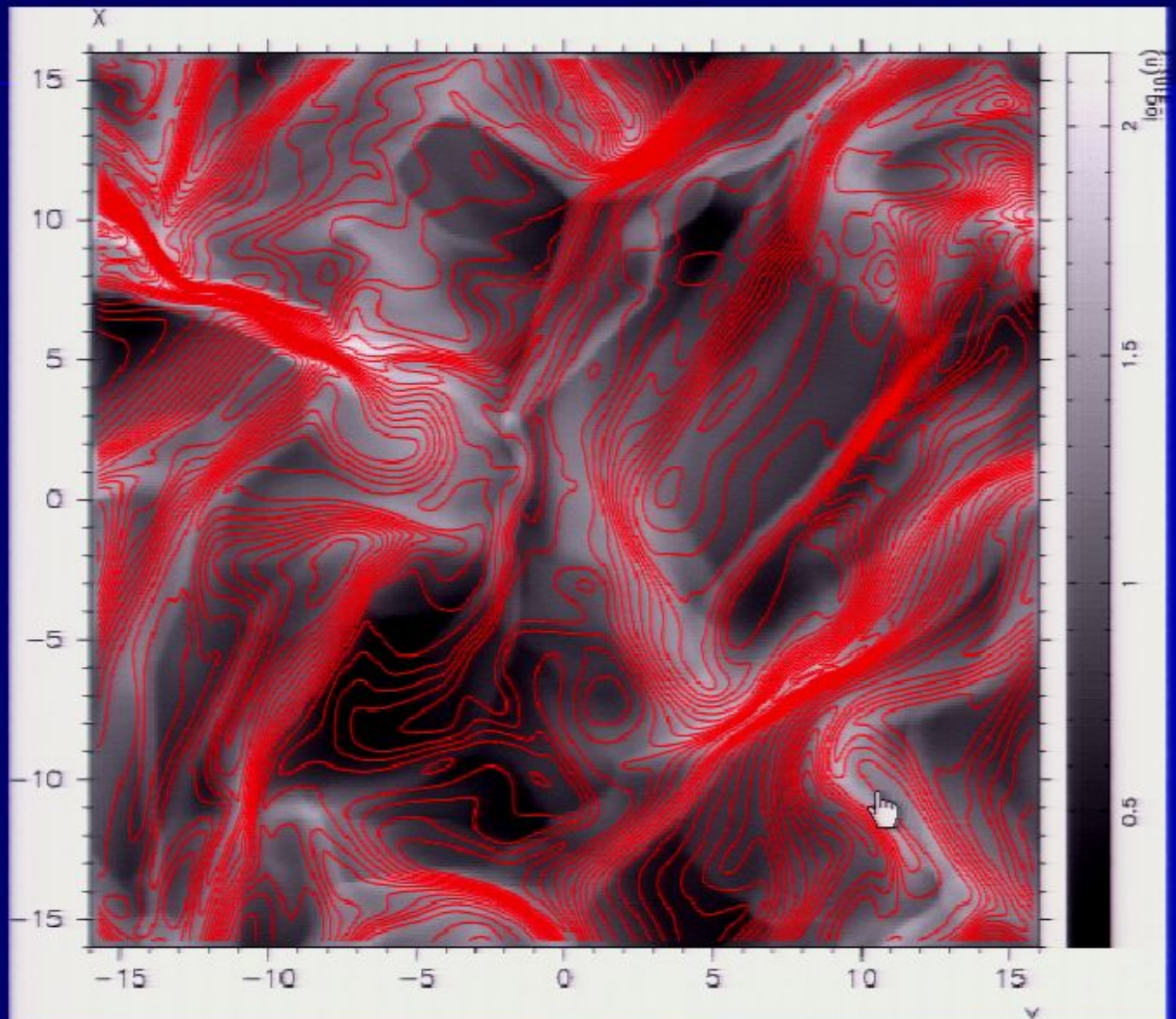

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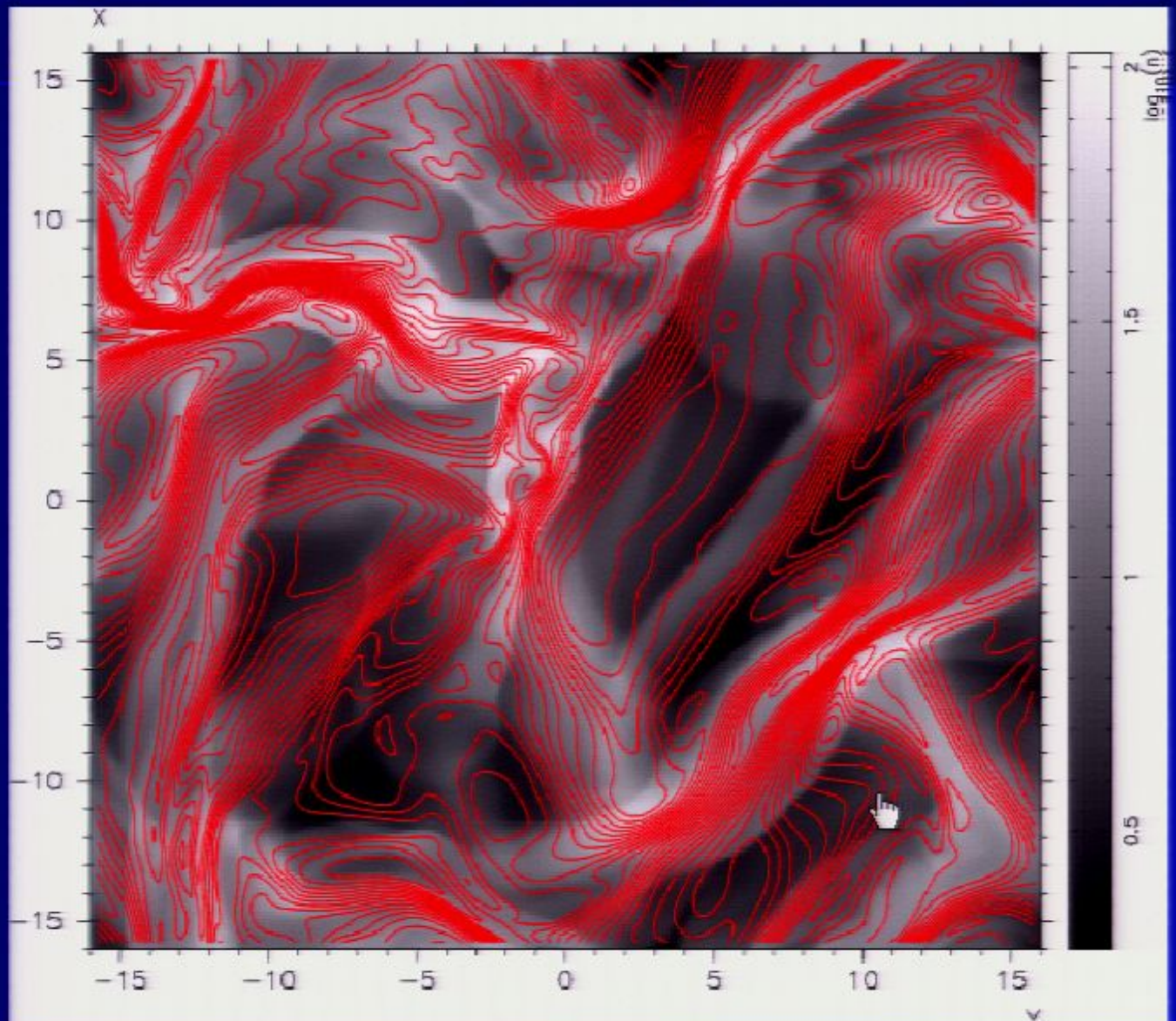

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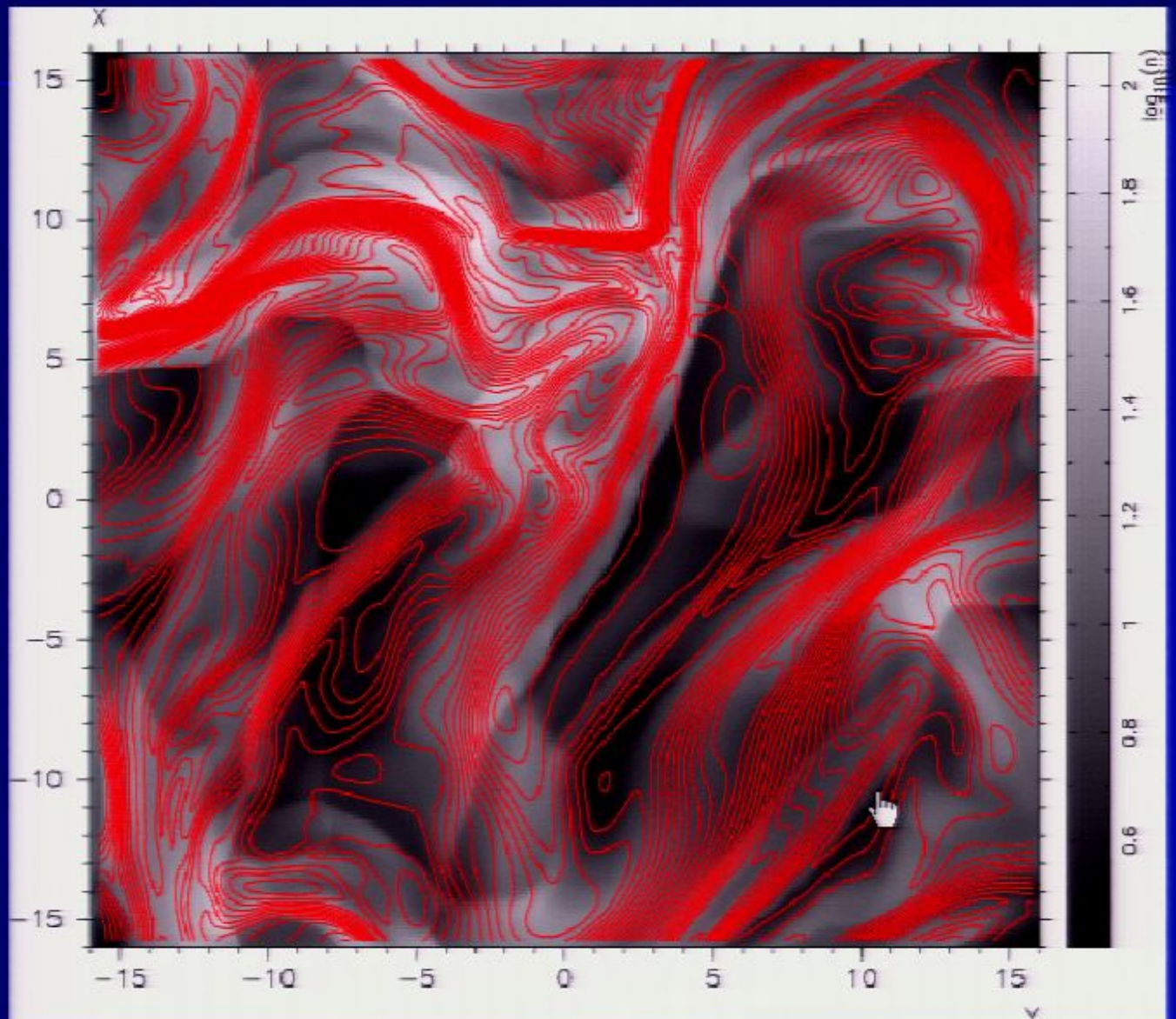

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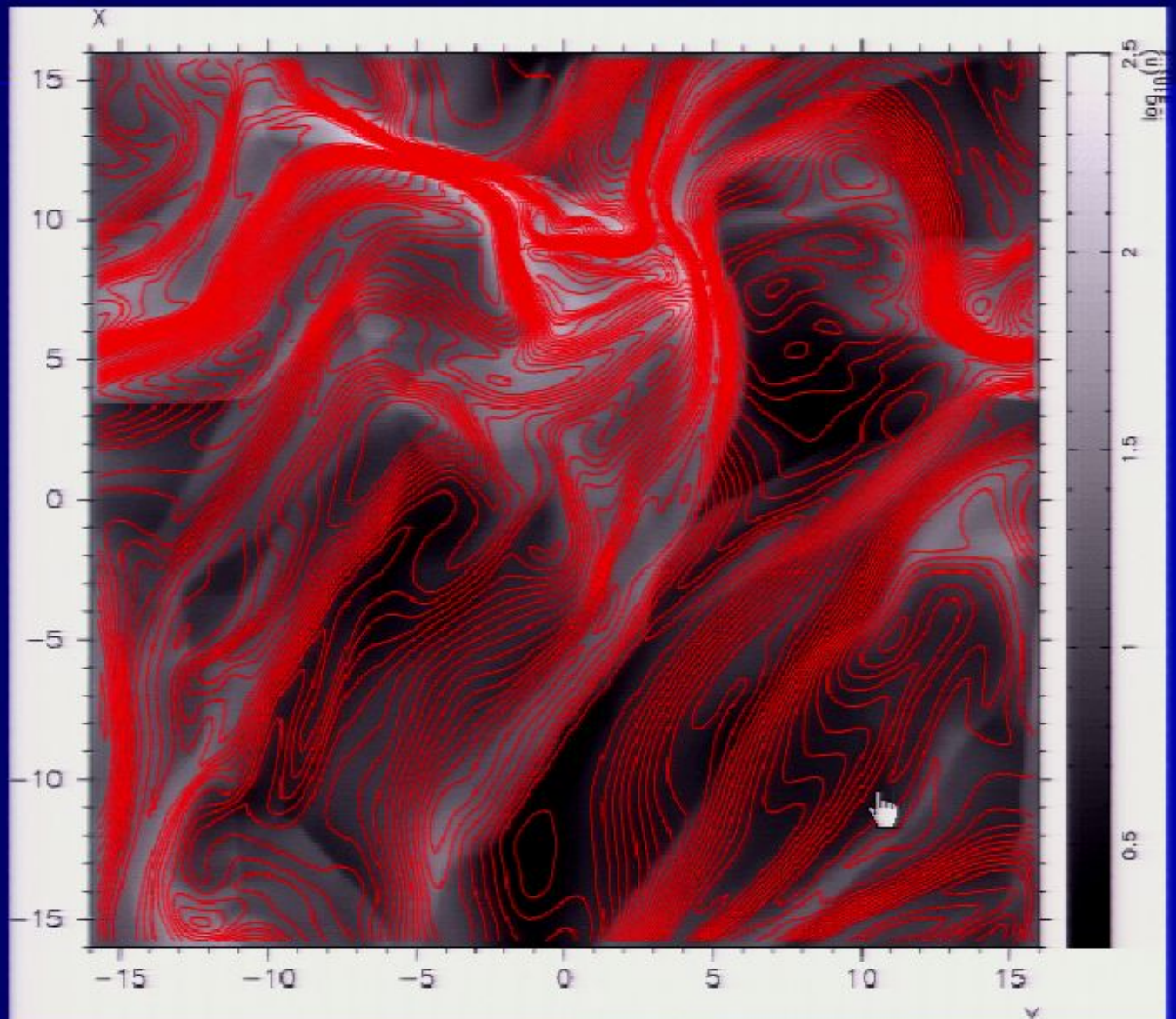

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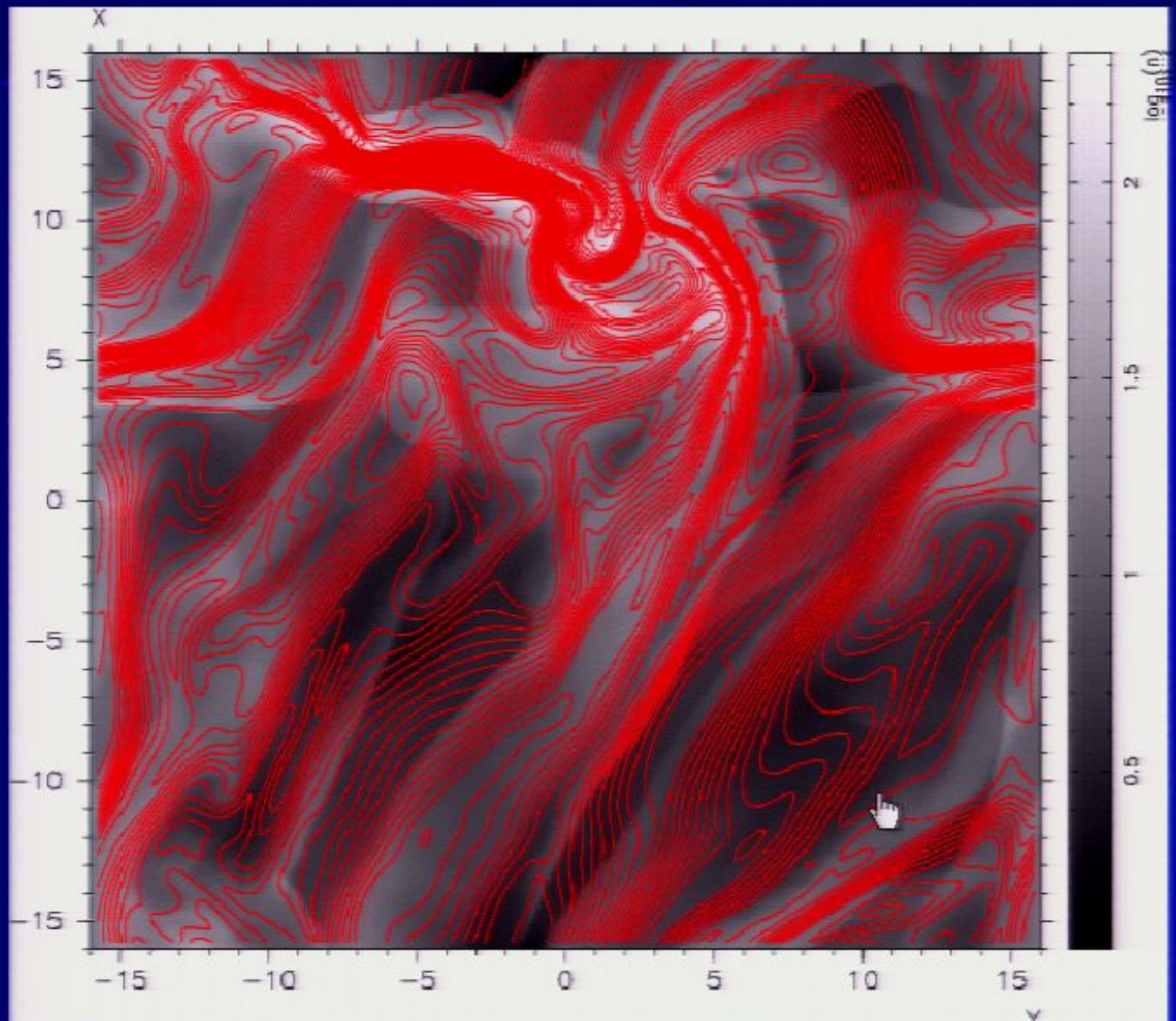
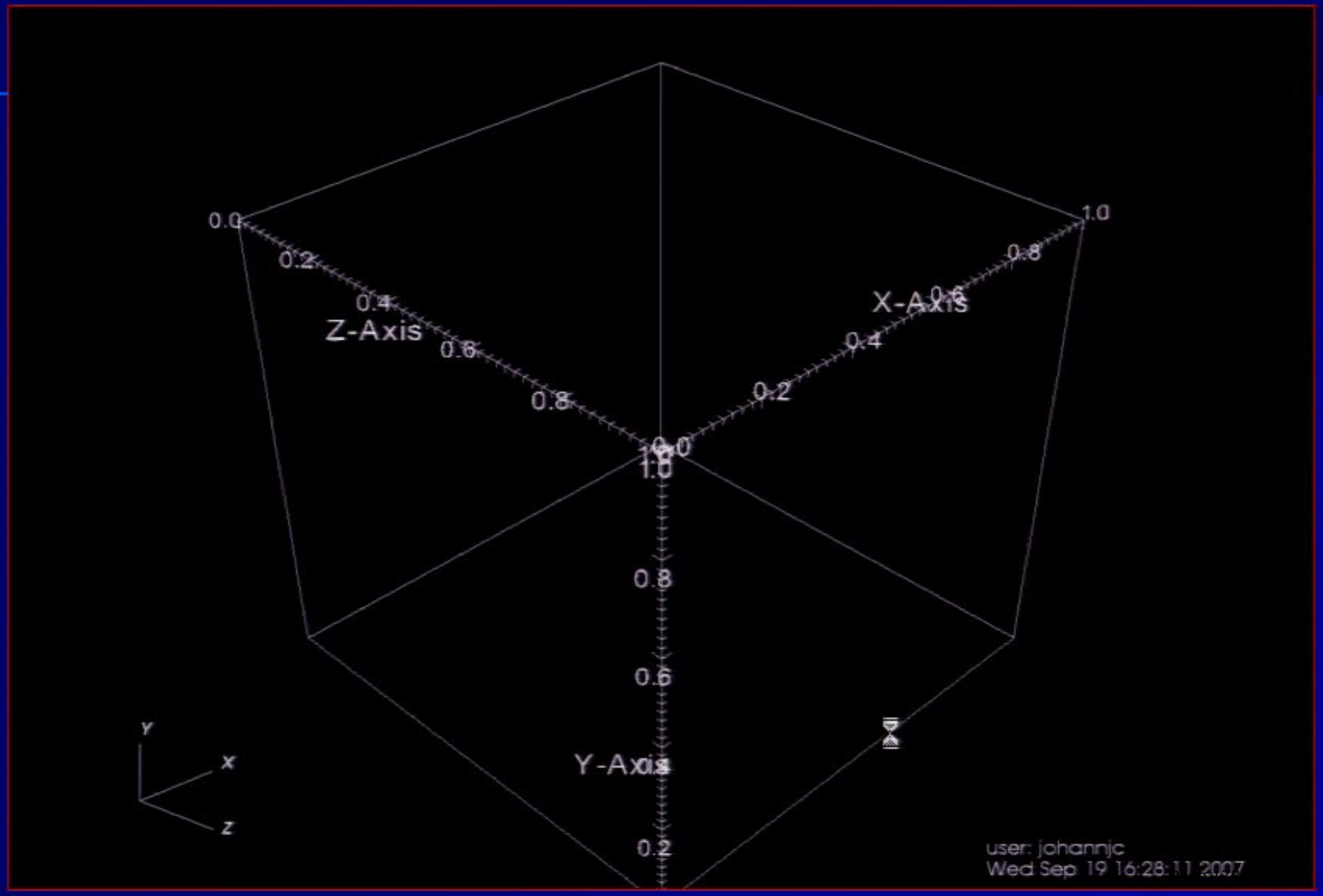


3-D Sims: AstroCUB

Jonathan Carroll



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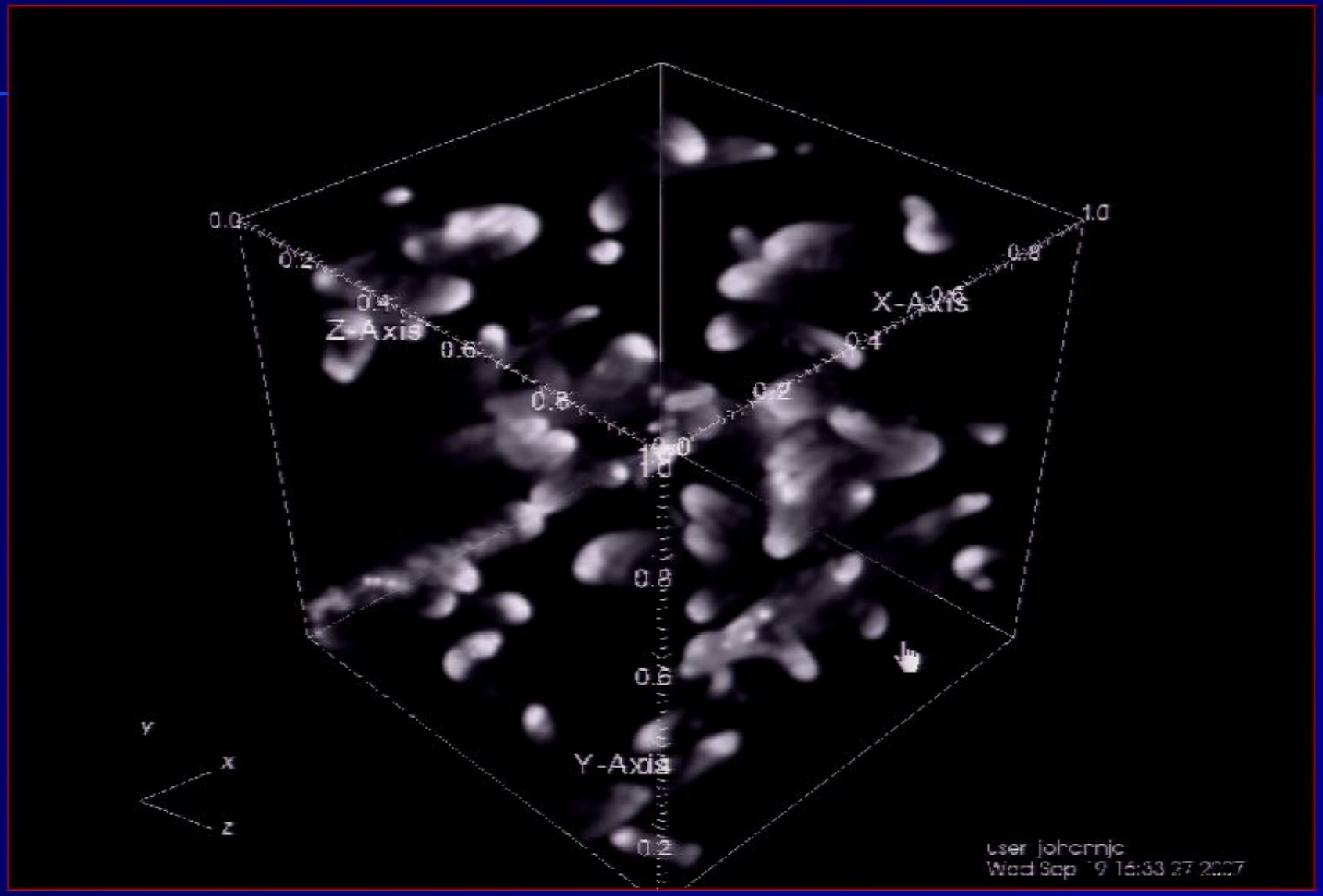

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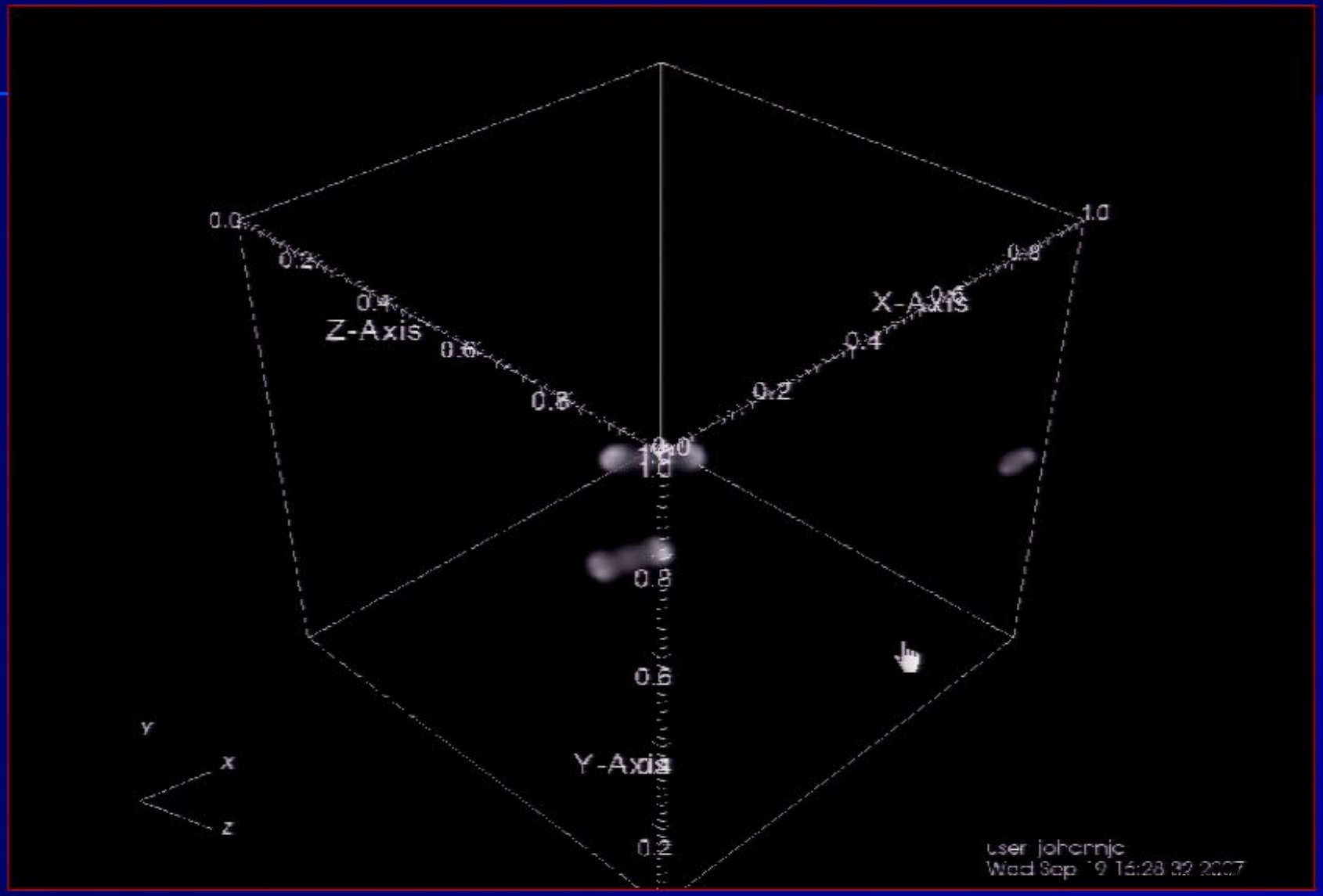

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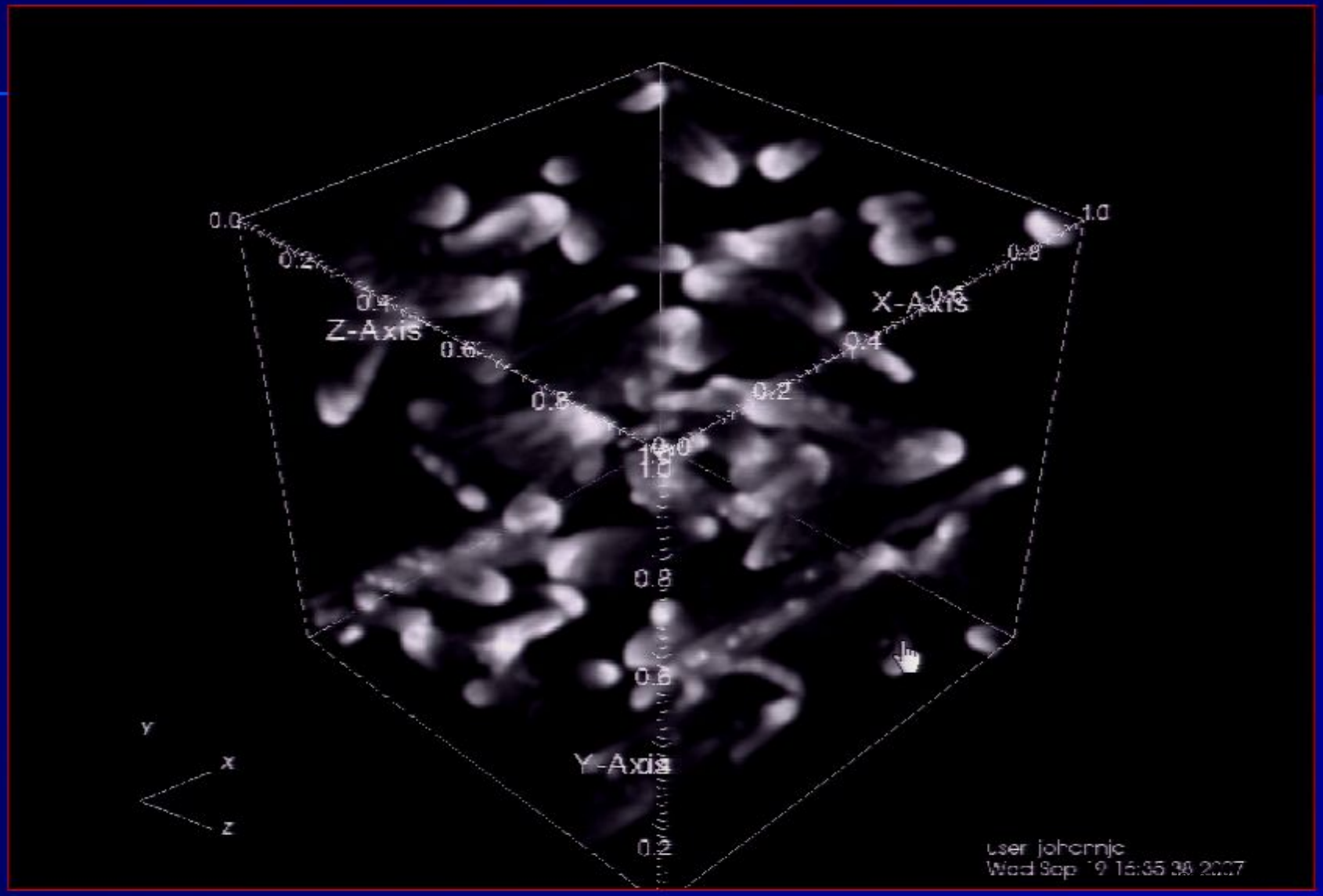

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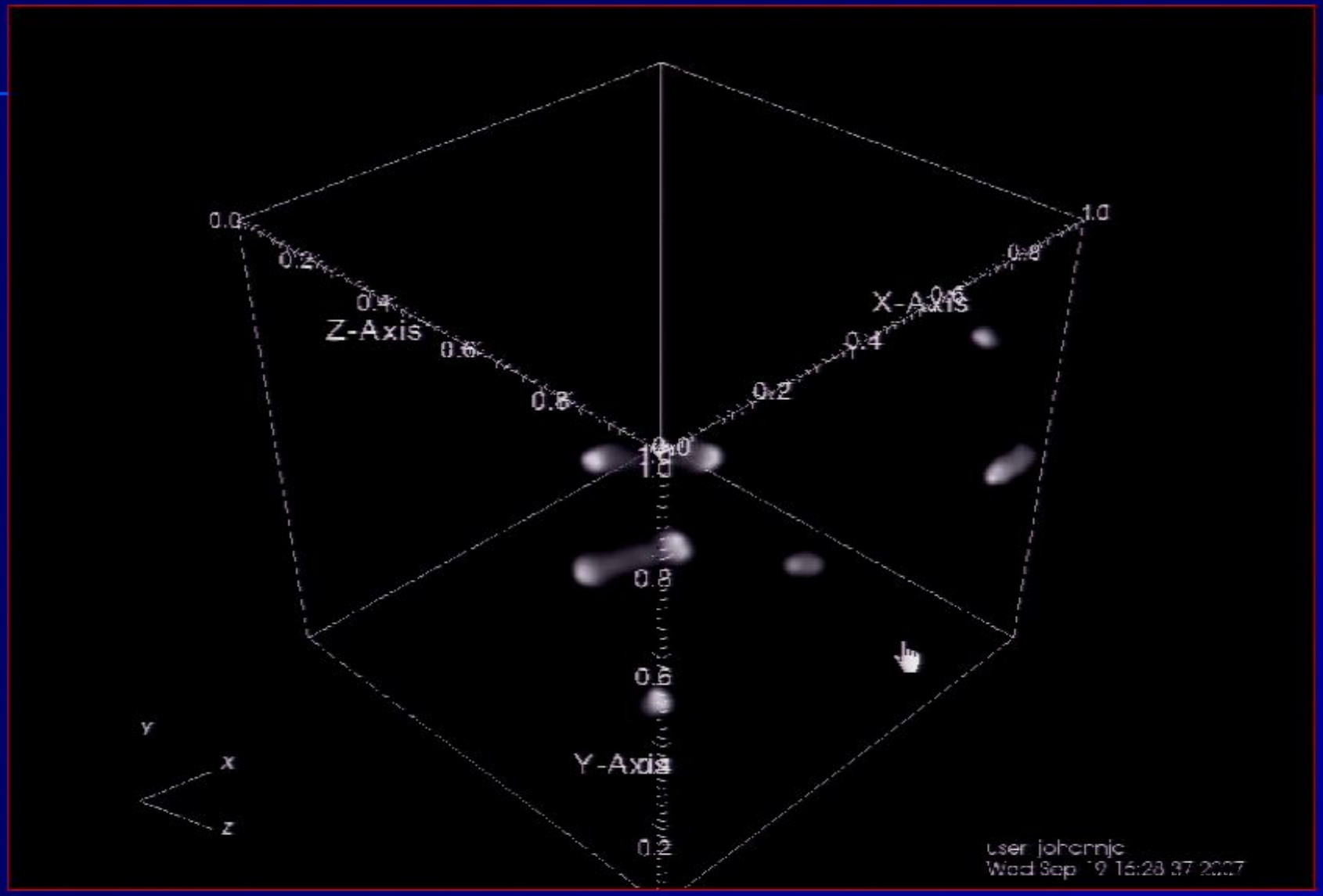

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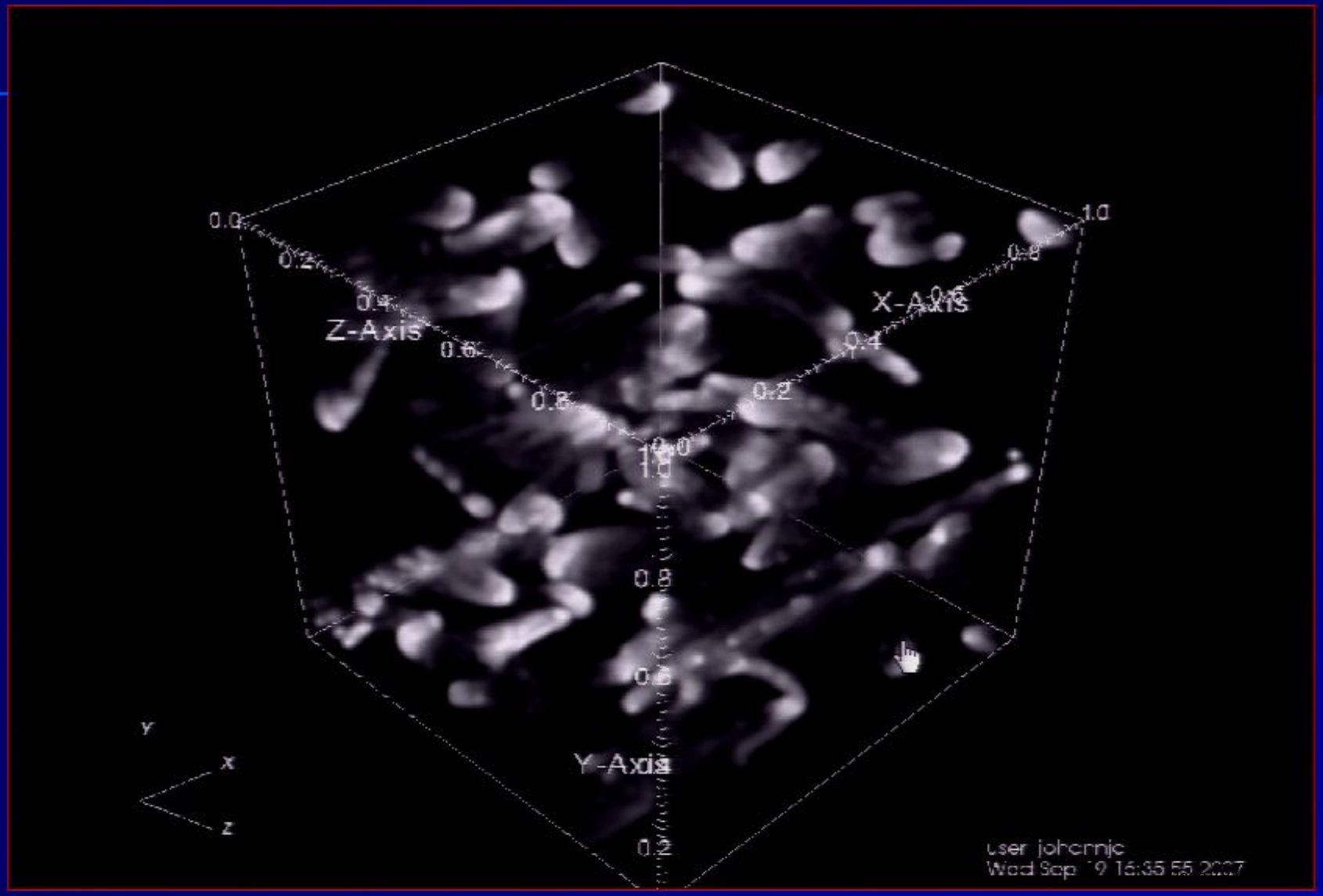

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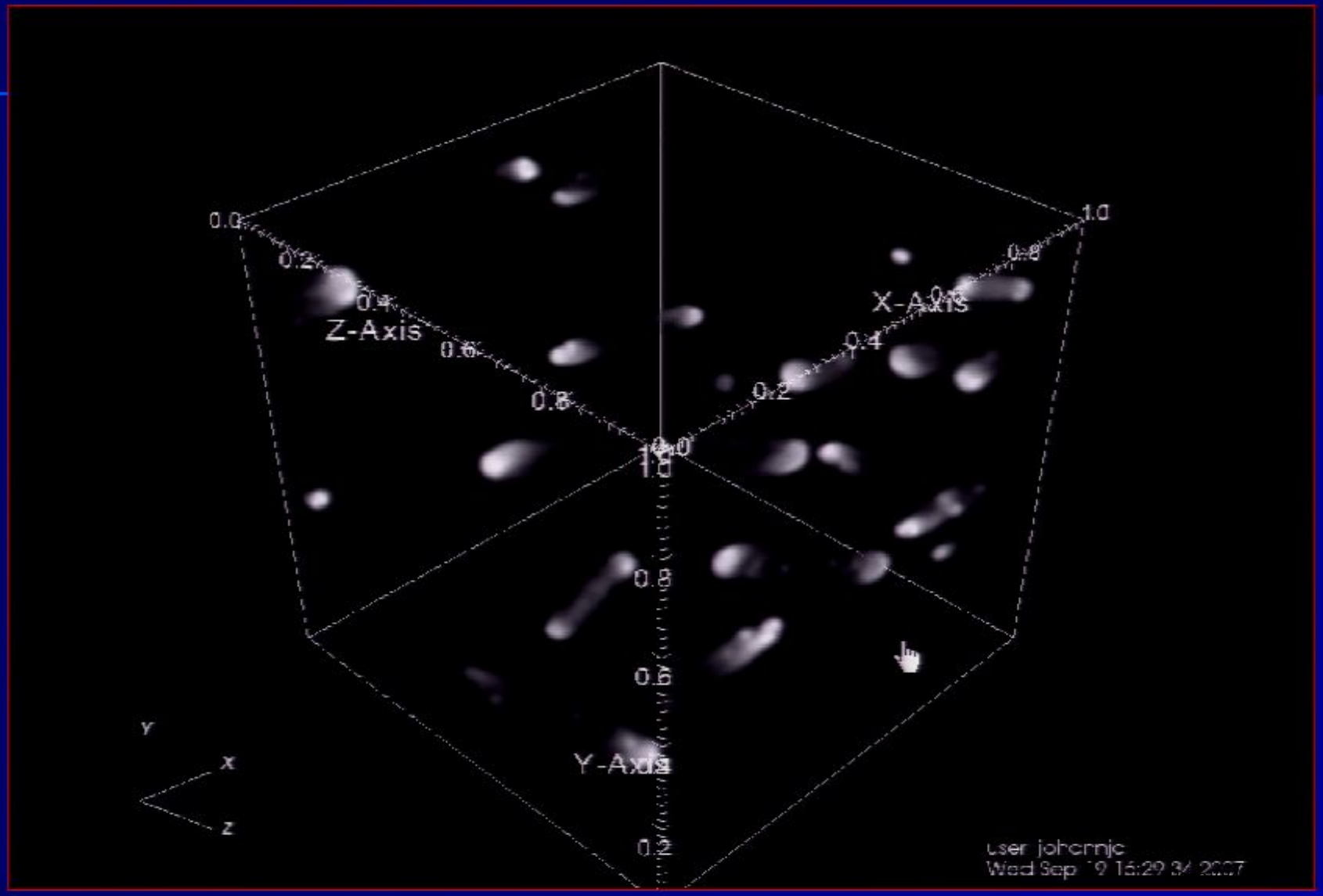

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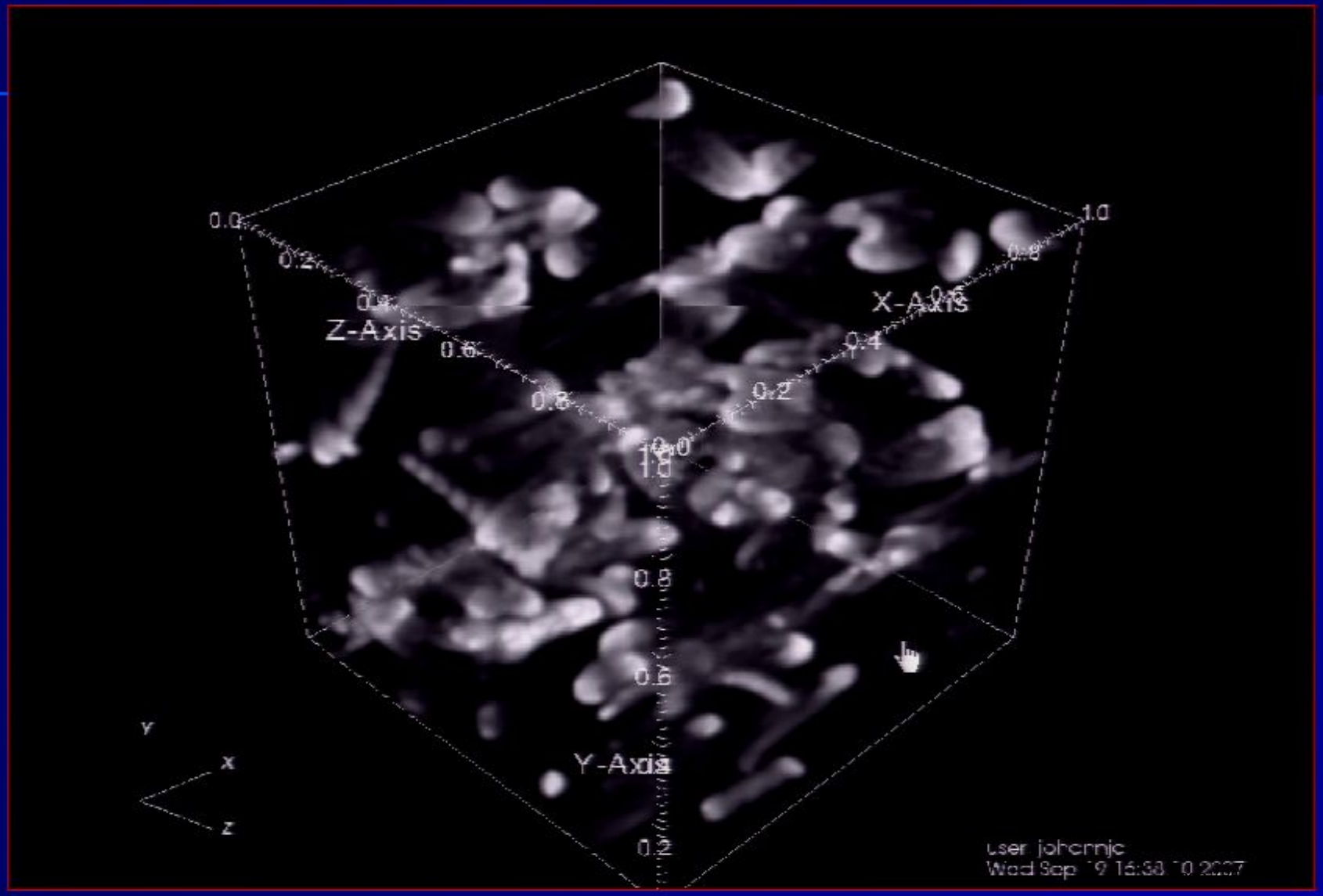

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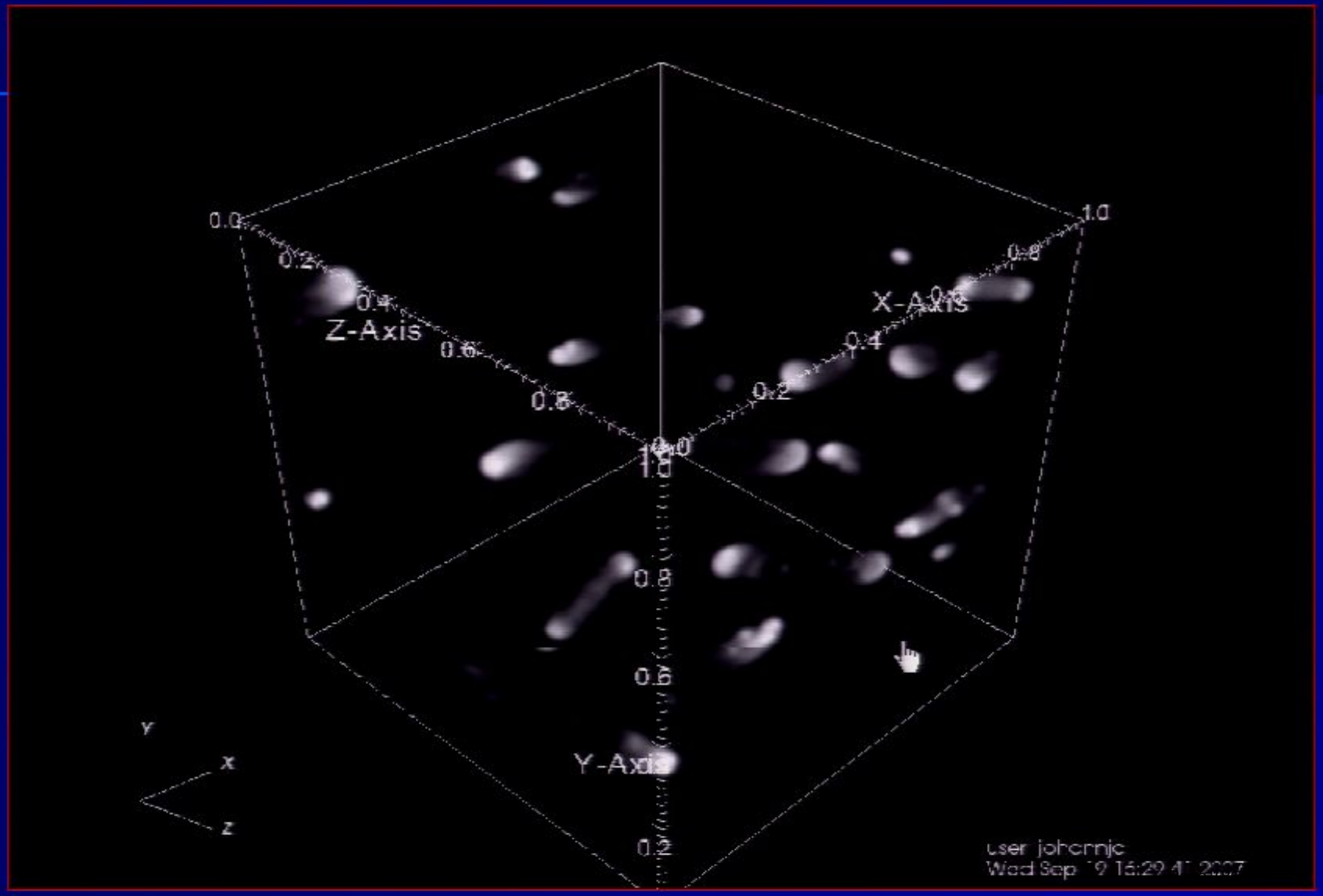

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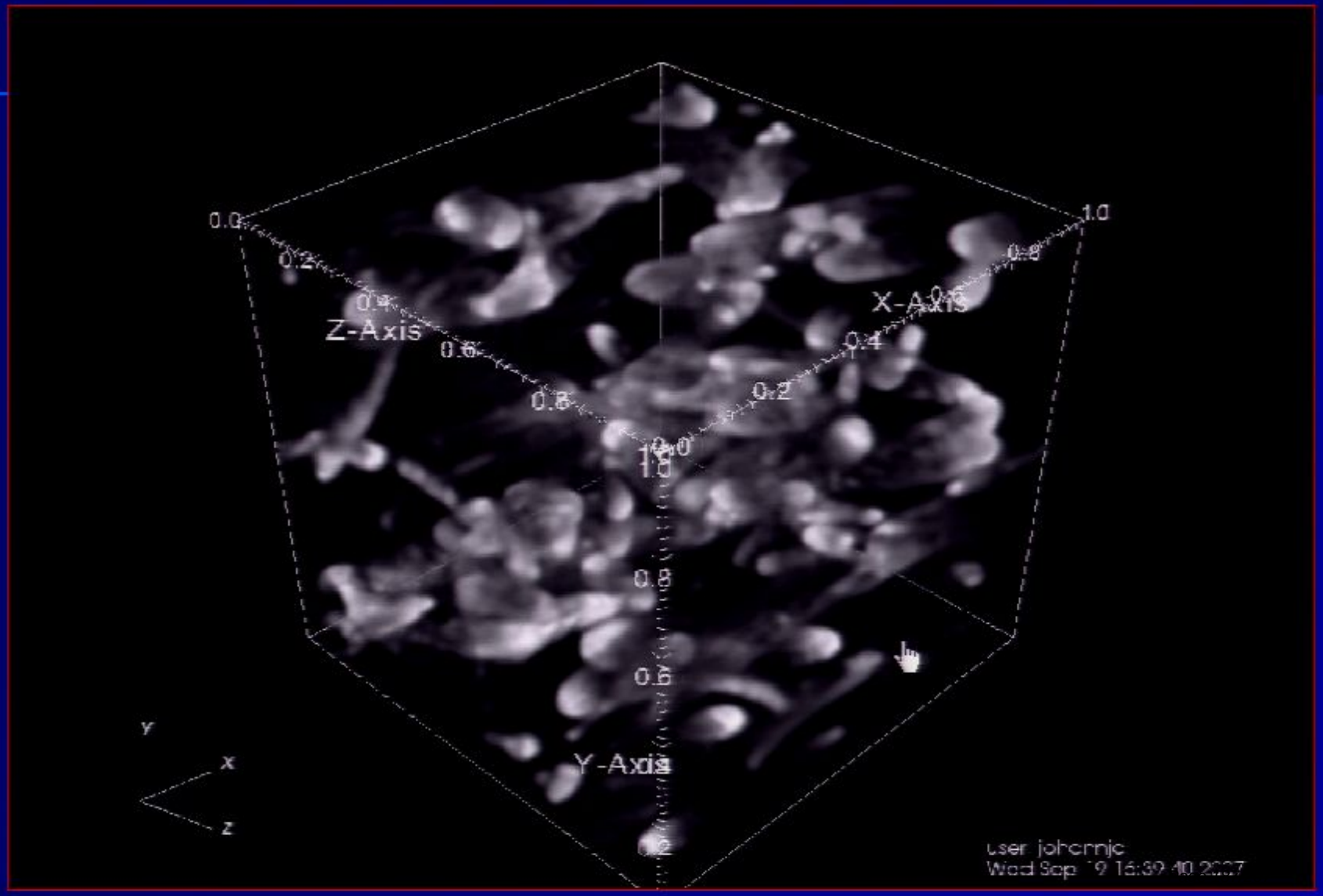

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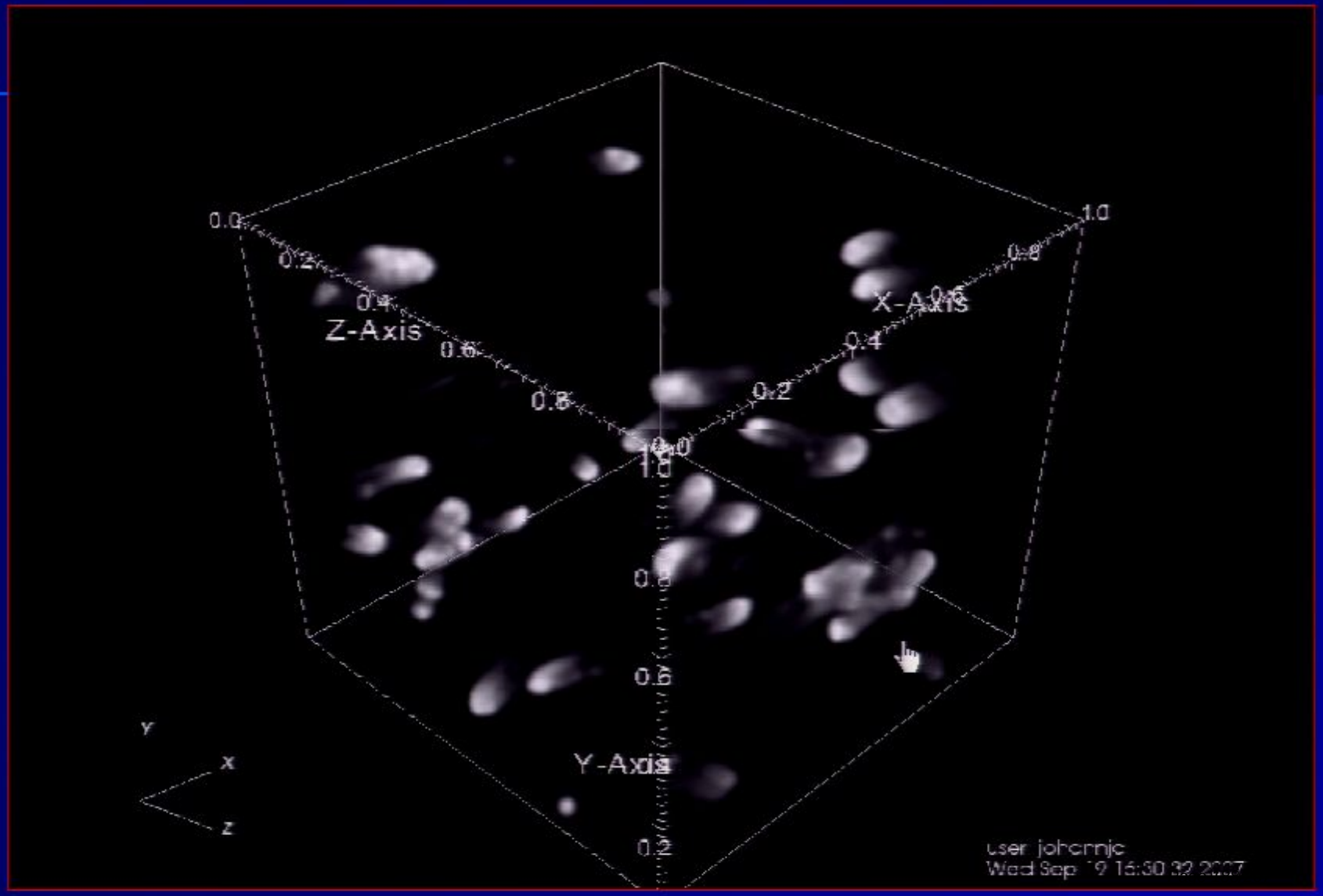

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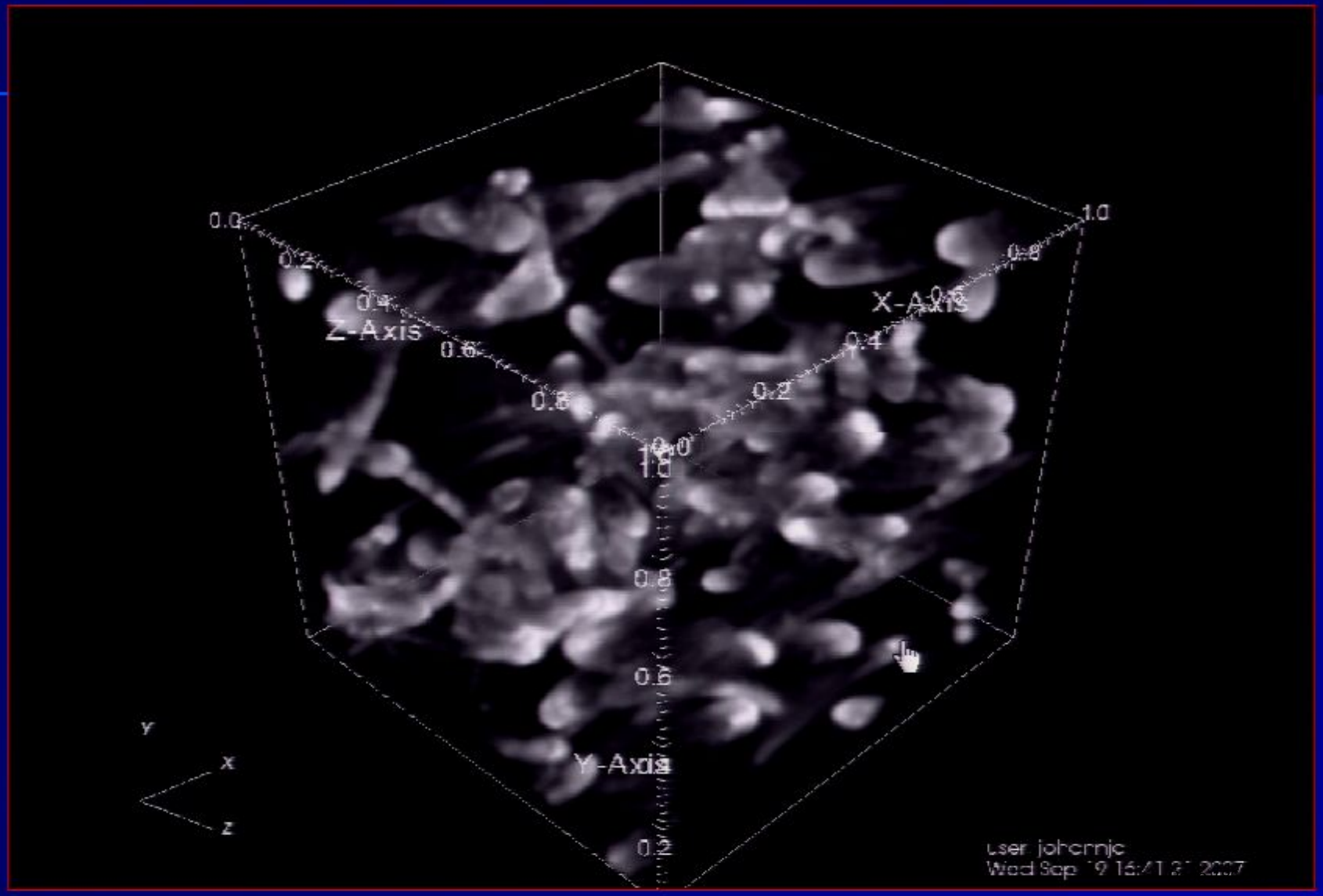

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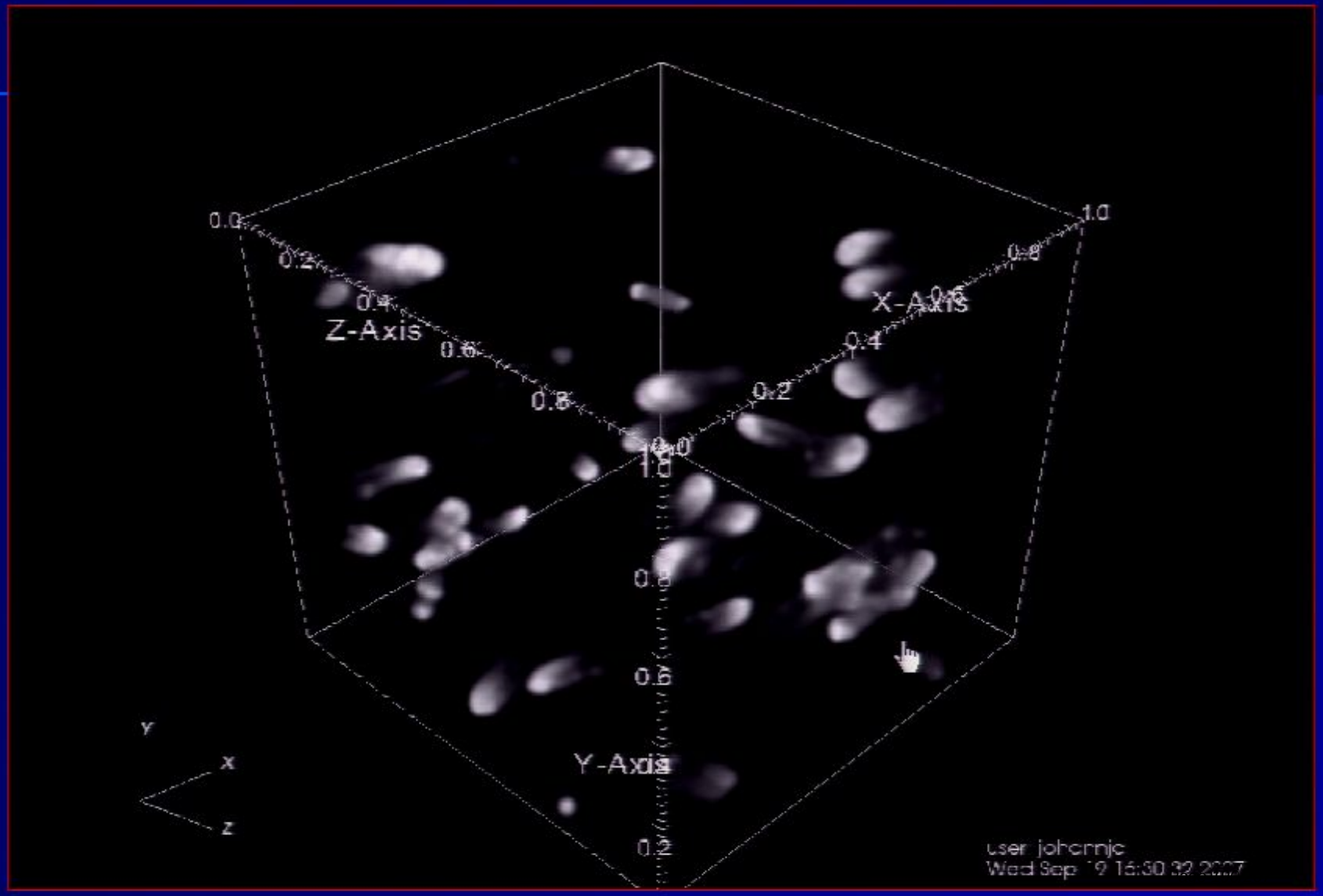

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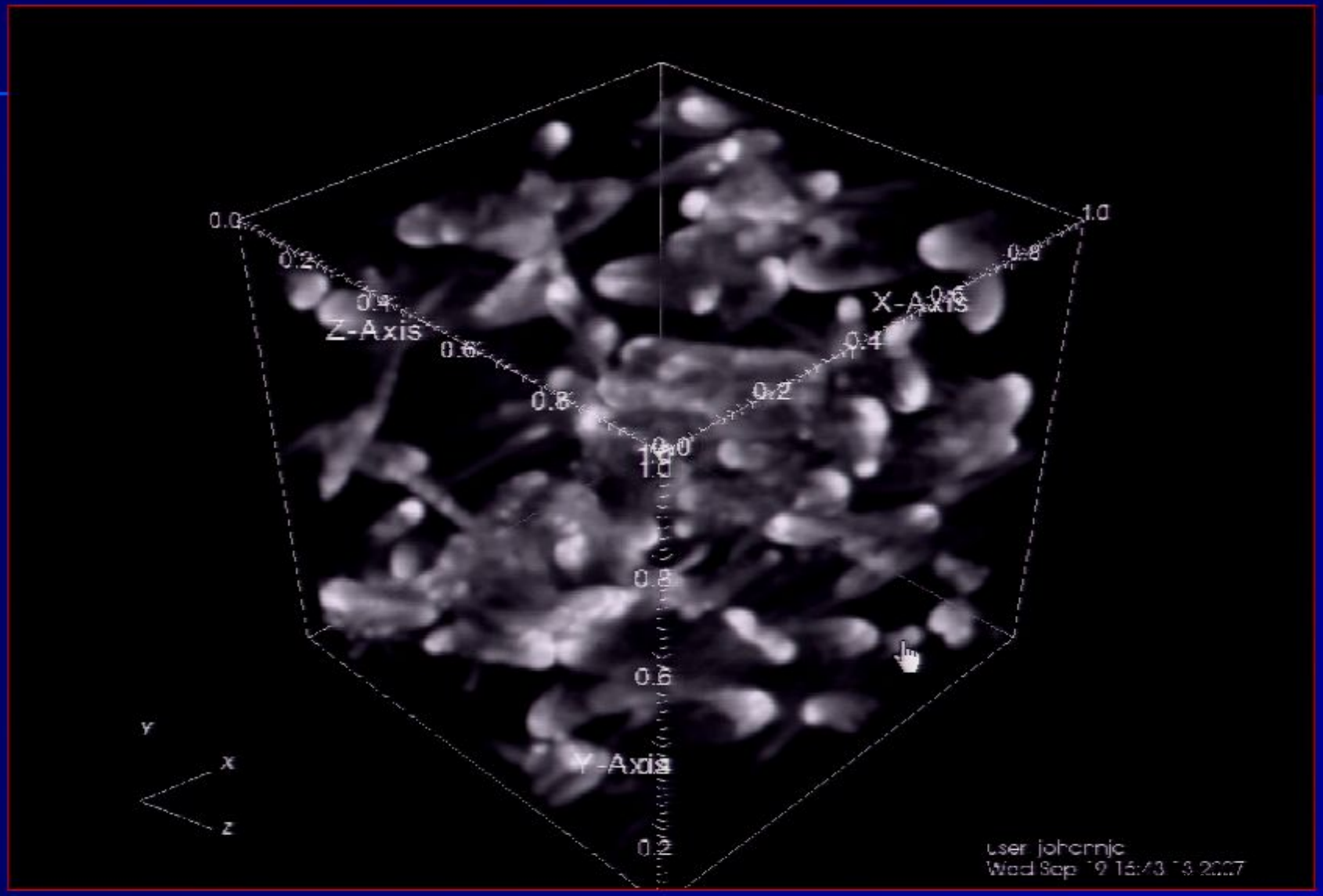

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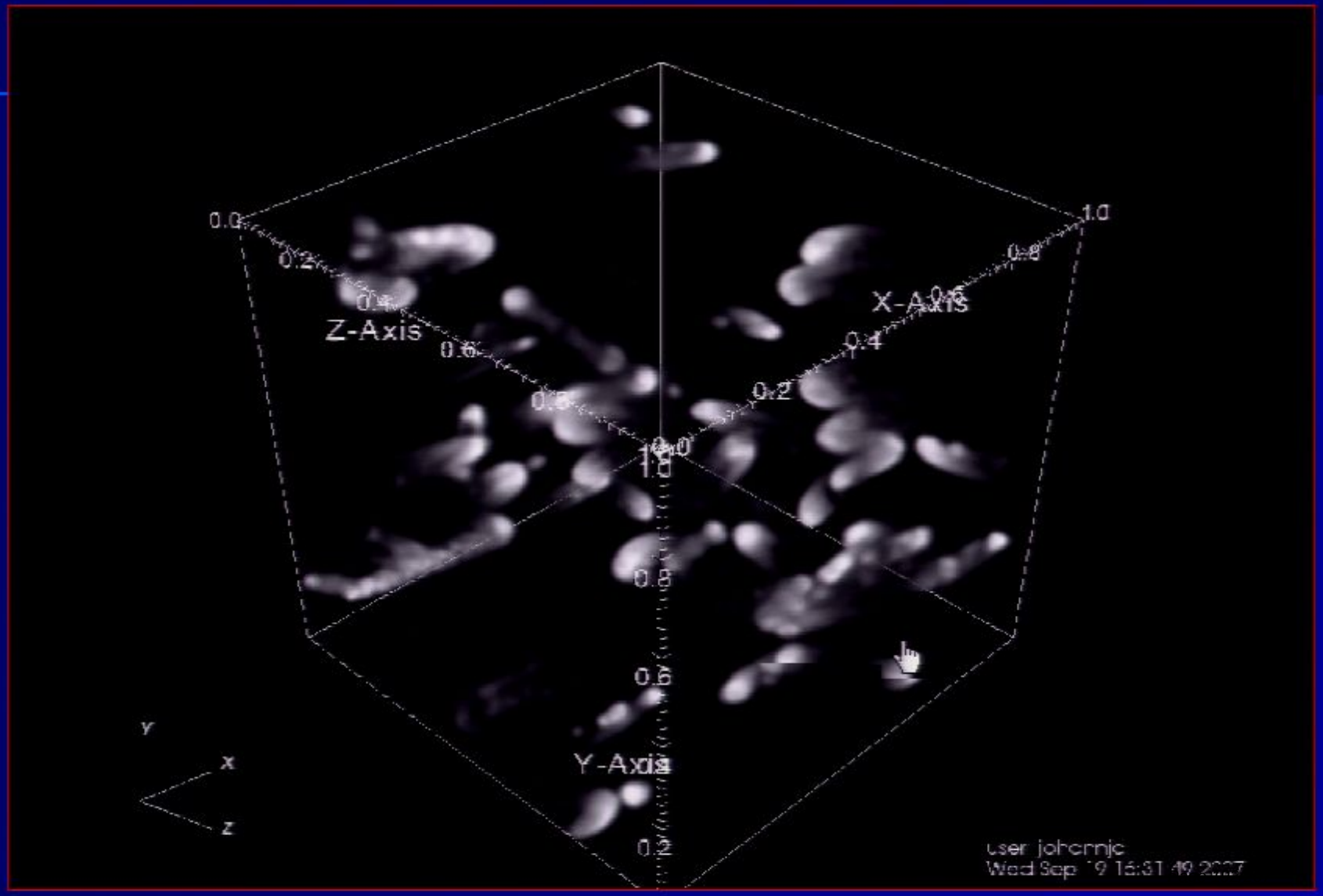

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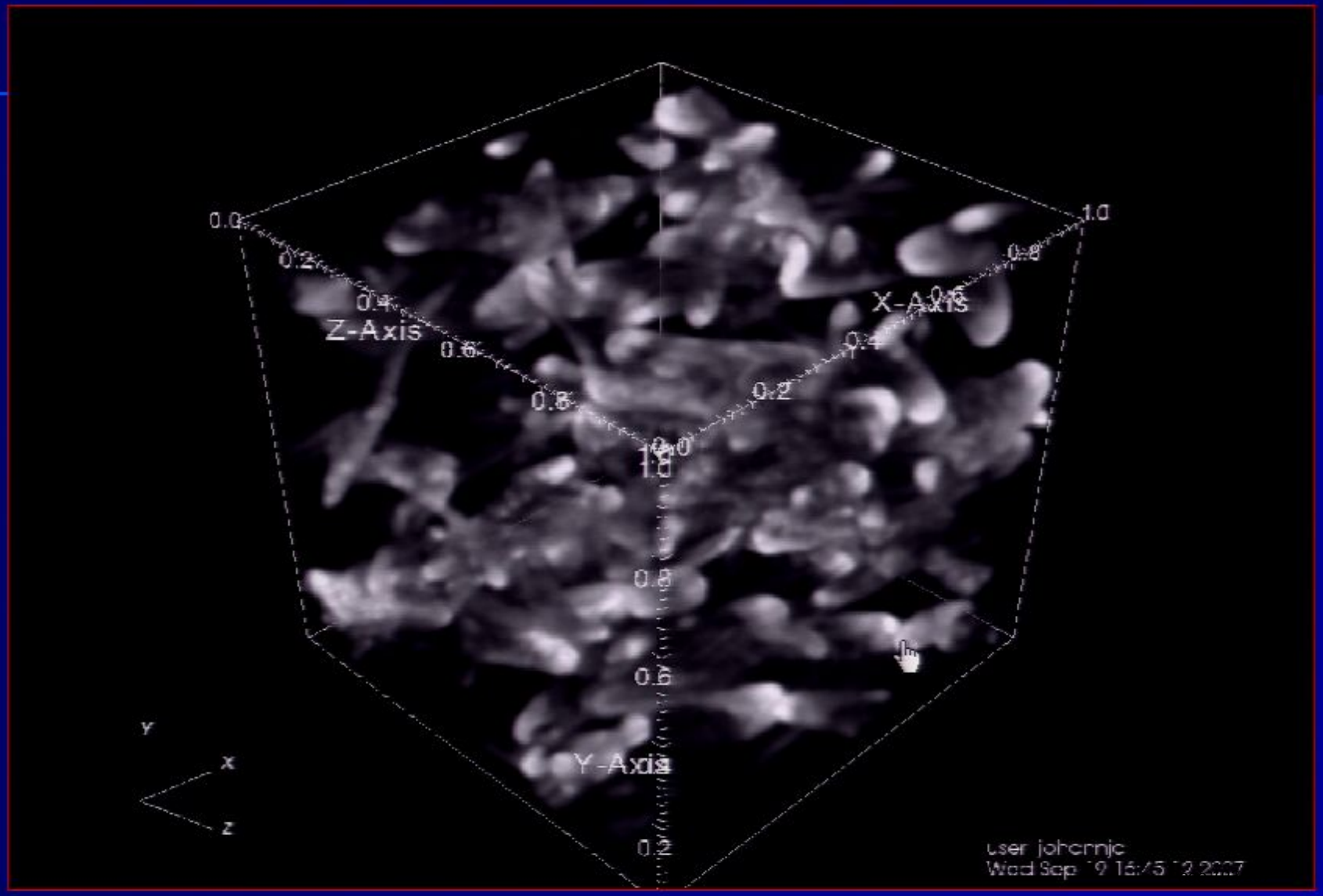

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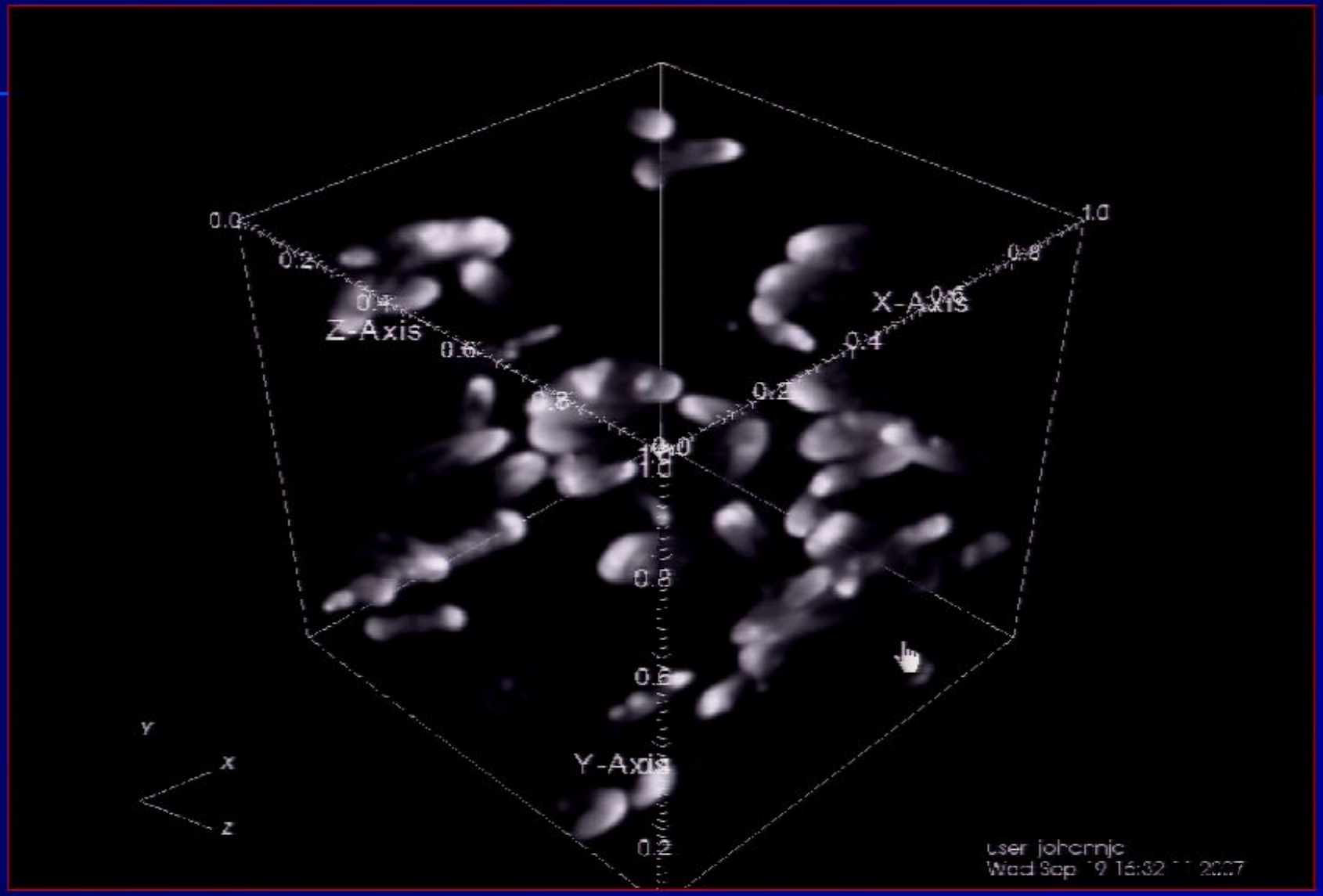

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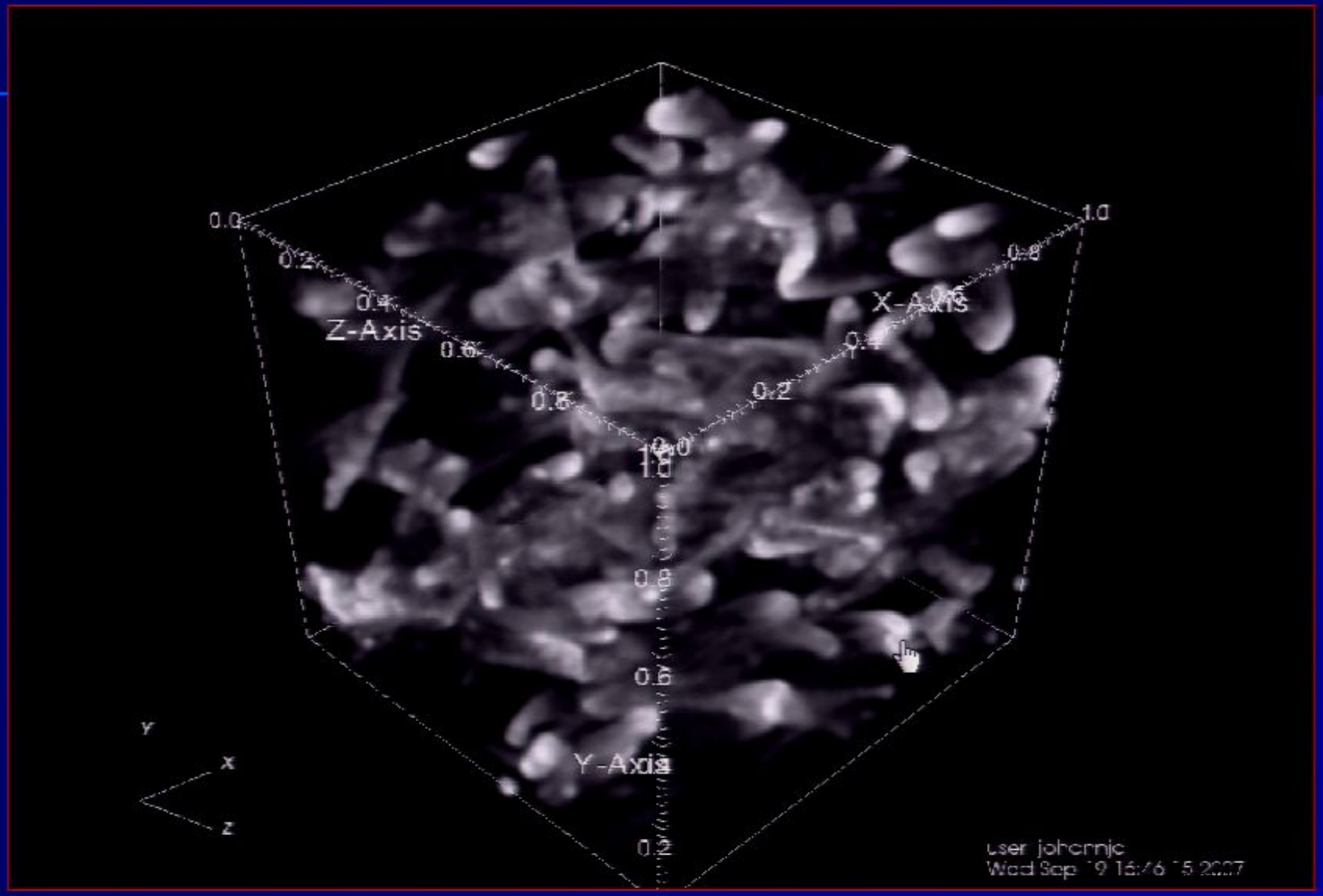
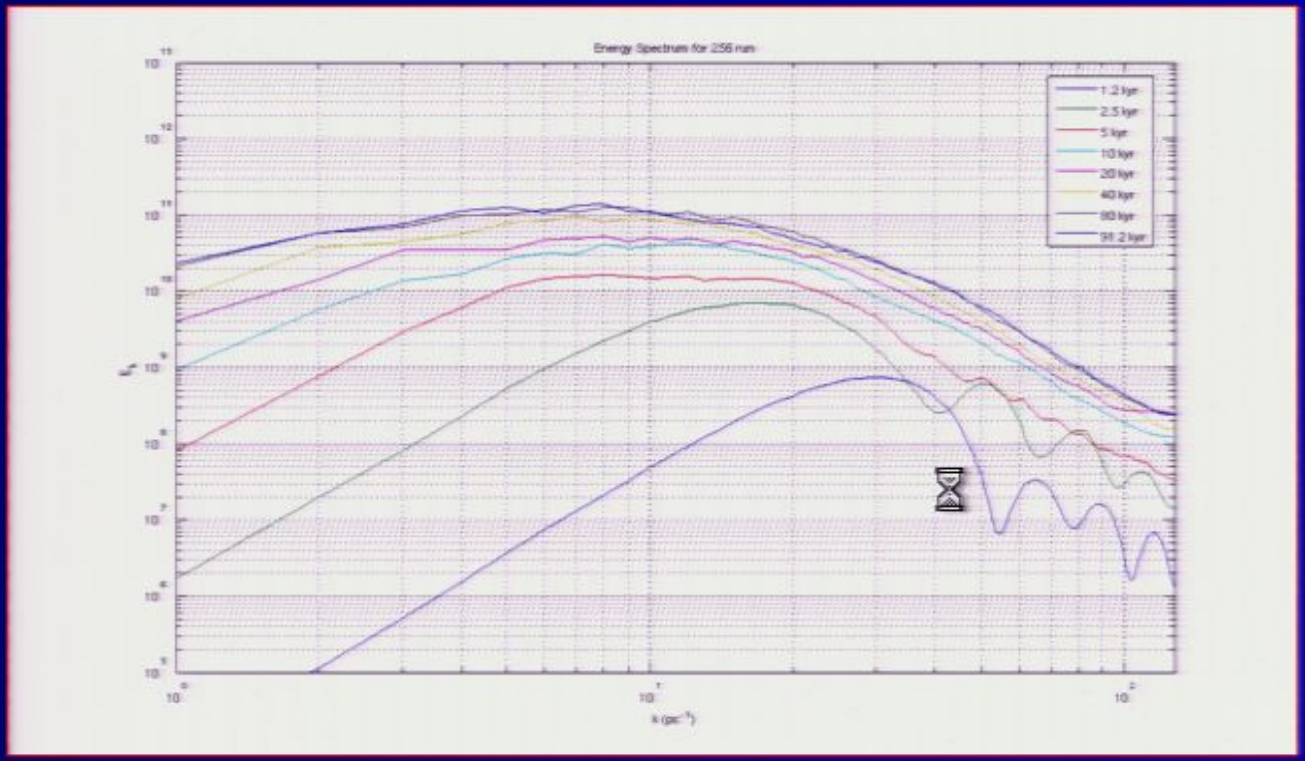


Power Spectra

- Break at k_{drive} shifts as jets grow



Conclusions Act II

- Colliding Jets
  - Interactions of active outflows not important.
- NGC 1333/Fossil Cavities
  - Fossil cavities "store" momentum.
  - Fossil cavities = transient jets/outflows
  - Momentum budgets match
- Outflows in Turbulent Media
  - Re-energize turbulence high k, energize low k

What do Real MHD Outflow Systems Show?

Micro-Mesoscales

Act 3
High Energy Laboratory Astrophysics

Validating Simulations and Beyond

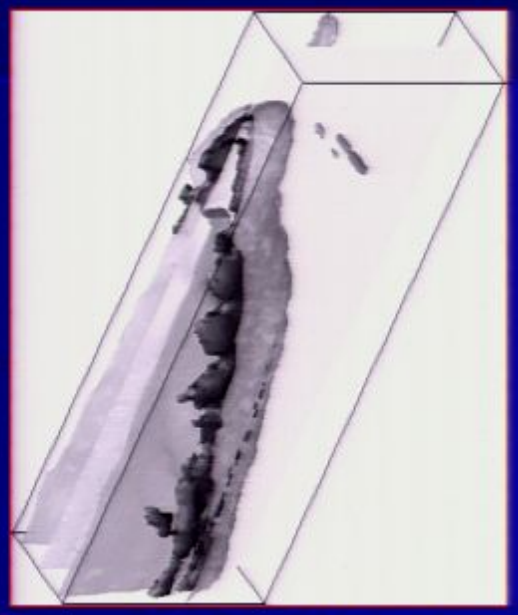
Omega Laser
University of Rochester, LLE

Z-pinch
Sandia National Labs

High Energy Density Lab Astro (HEDLA)

Observation – Simulation – Experiment …

HH505 Bally et al 04

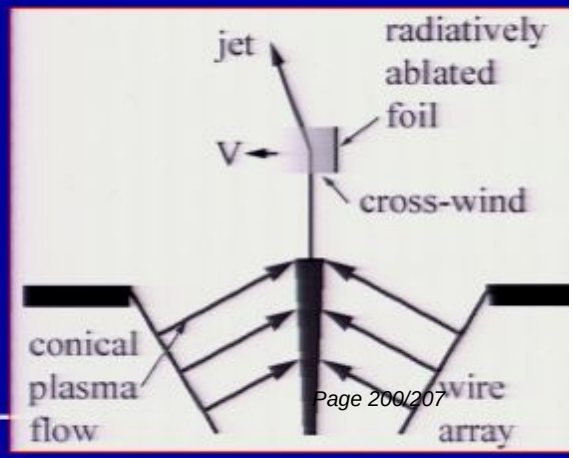


AstroBEAR AMR sim.

Excellent testbed for :

- code verification
- extension of analytical models

Example: Supersonic Jet-Wind Interaction

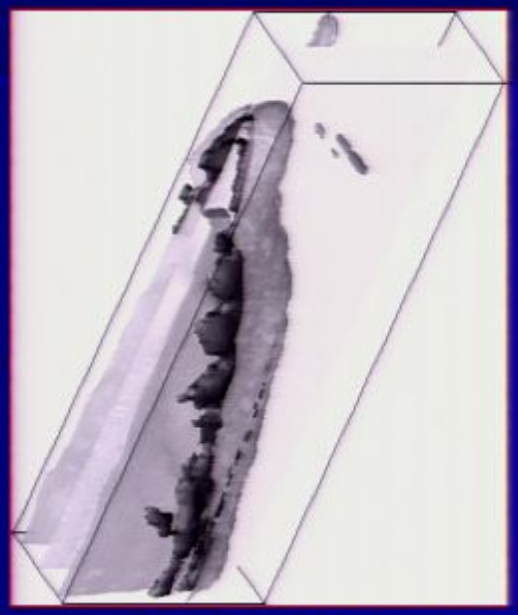


Lebedev, Frank, Blackman et al 2002, 2004, 2005, 2006

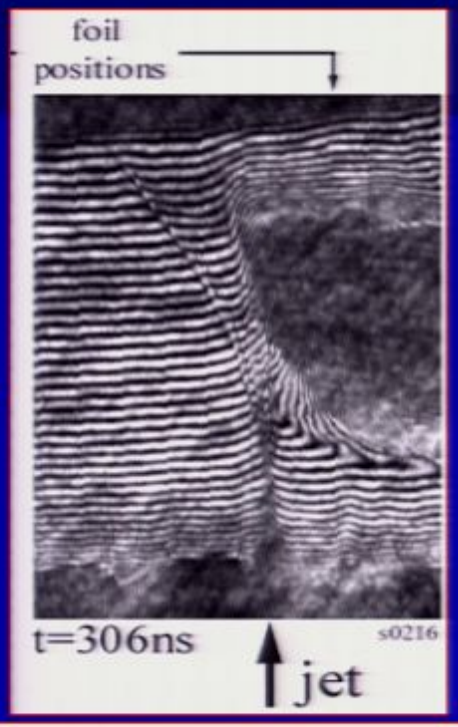
High Energy Density Lab Astro (HEDLA)

Observation – Simulation – Experiment …

HH505 Bally et al 04



AstroBEAR AMR sim.



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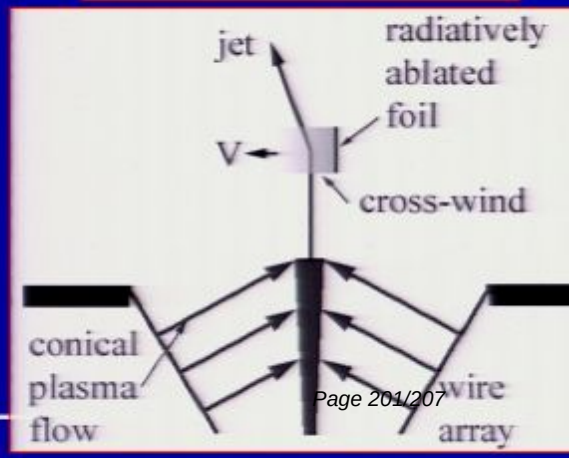


Lebedev, Frank, Blackman et al 2002, 2004, 2005, 2006

Lab Jet Experiments: Similarity

- The dynamics are described by Euler's Eqs. ("pure hydro"); viscous dissipation, heat transport can be neglected (Re >> 10^4, Pe >> 1)

Conservation of mass: $$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho v) = 0$$

Conservation of momentum: $$\frac{\partial v}{\partial t} + (v \bullet \nabla) v = -\frac{\nabla p}{\rho}$$

Energy $$\frac{\partial p}{\partial t} - \gamma_a \frac{p}{\rho}\frac{\partial \rho}{\partial t} + v \bullet \nabla p - \gamma_a \frac{p}{\rho} v \bullet \nabla \rho = 0$$

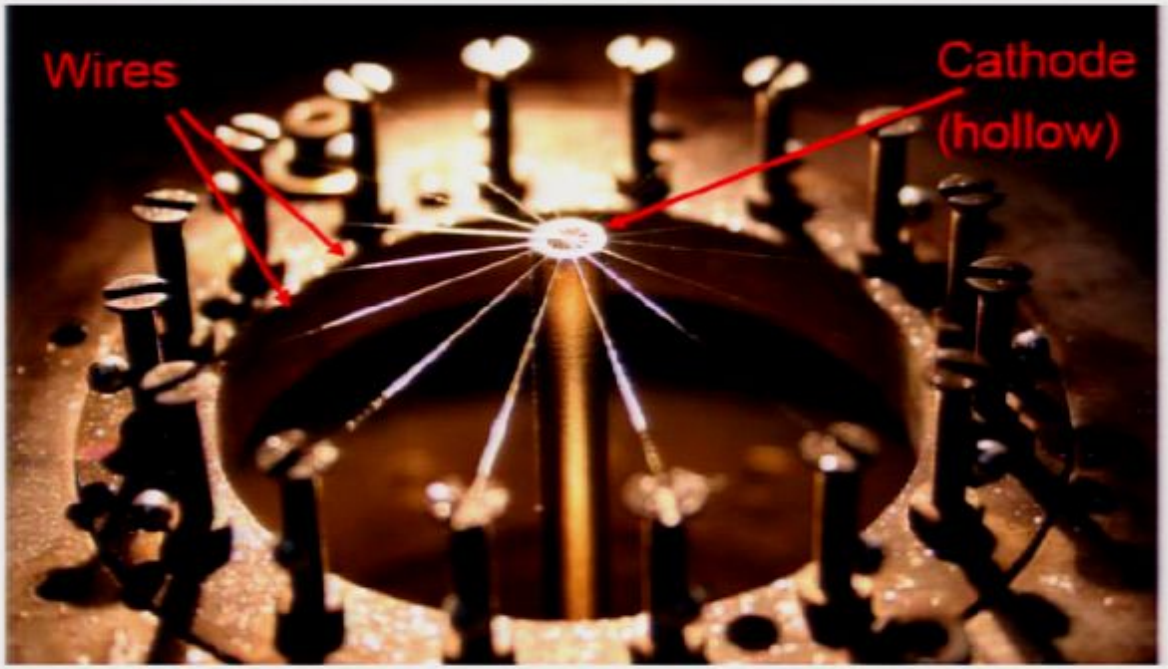
Equations are invariant under change of variables (scales)

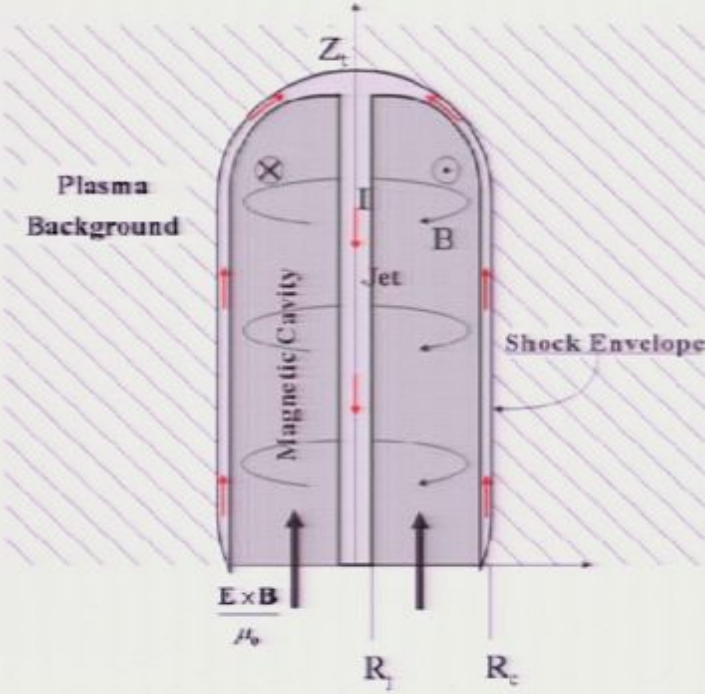
$$r_2 = a r_1, \quad \rho_2 = b \rho_1, \quad P_2 = c P_1$$

$$t_2 = a\sqrt{\frac{b}{c}}\, t_1, \quad V_2 = \sqrt{\frac{c}{b}}\, V_1$$

Schematic of the experiment

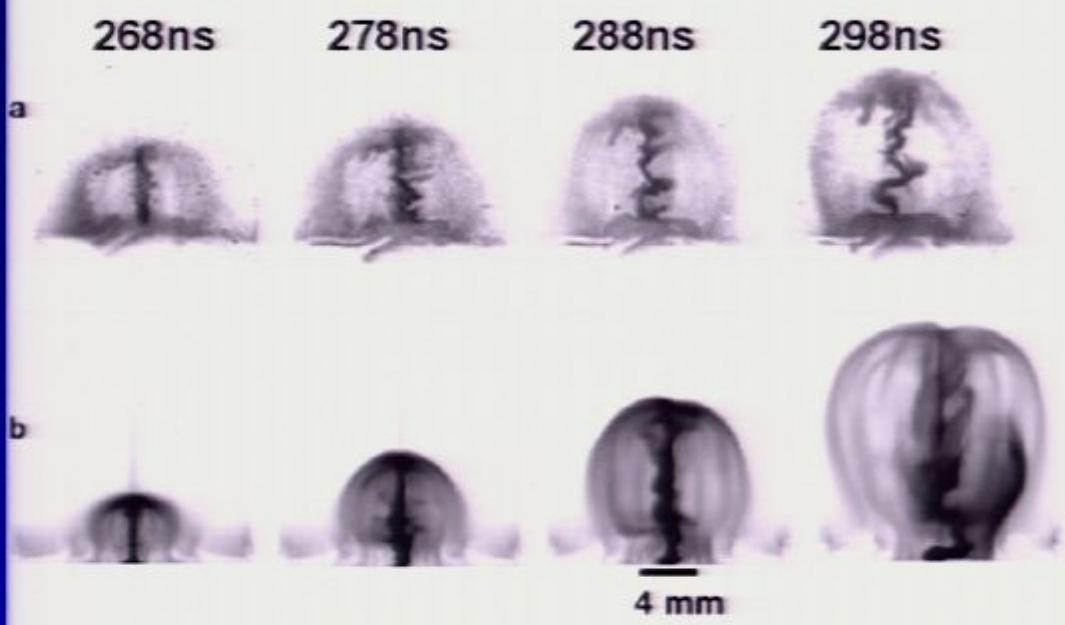
16 x 13μm W wires driven by 1MA, 250ns current pulse (~1 MG toroidal magnetic field)





Magnetic Tower jets in laboratory experiments

Experiment versus 3-D MHD



Jet driven by the pressure of the toroidal magnetic field

Collimation of the central jet by the hoop stress

Collimation of the magnetic bubble by the ambient medium

Instabilities do not destroy the jet but lead to variability of the flow

Variability of the jet emission

Two temporal scales for outflow variability:

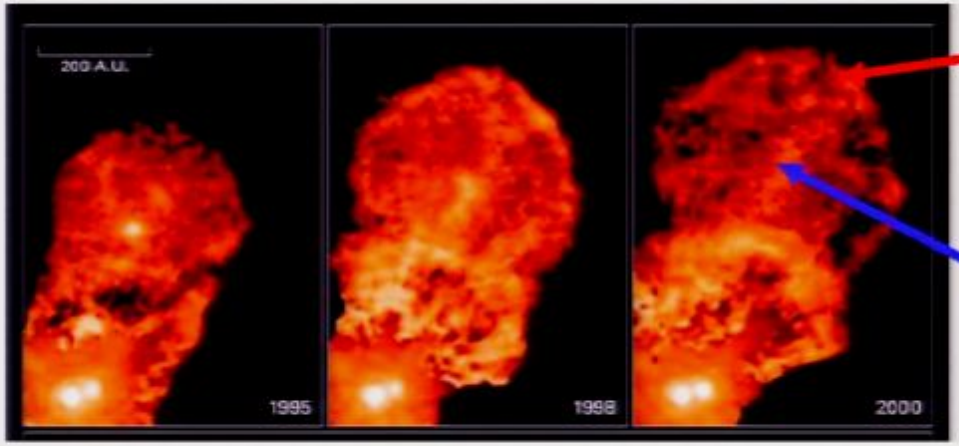
- fast – instability growth time
- slow – bubble growth time

Conclusions Act 1,2, 3

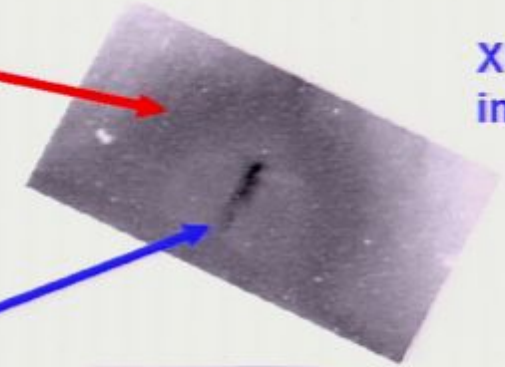
- Importance/difficulty of Multi-physics AMR codes.
- Protostellar jets – open questions on all scales.
- HEDLA – episodic magnetic tower experiments go beyond code validation.

Analogy with astrophysical objects: is this more than just a similar look?

XZ Tauri



Experiment

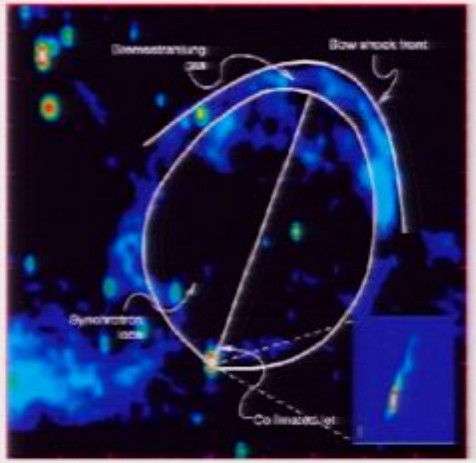


XUV image

X-ray image

Laser shadow

Cygnus X-1



Similarities:

Hot collimated jet (x-ray in experiment, optical in observations)

surrounded by a lower temperature bubble (XUV in experiment, IR in observations)

Lab Jet Experiments: Similarity

- The dynamics are described by Euler's Eqs. ("pure hydro"); viscous dissipation, heat transport can be neglected (Re >> 10^4, Pe >> 1)

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