

Title: Simulating the Big Bang

Date: Jul 29, 2008 02:00 PM

URL: <http://pirsa.org/08070048>

Abstract: At the end of inflation, dynamical instability can rapidly deposit the energy of homogeneous cold inflation into excitations of other fields. This process (known as preheating) essentially starts the hot big bang as we know it. I will present simulations of several preheating models using a new numerical solver DEFROST I developed. The results trace the evolution of the fields, which quickly become very inhomogeneous as the instability kicks in. Surprisingly, there appears to be a certain universality across preheating models with different decay channels. After initial transient, the field density distributions quickly become stationary and lognormal to high precision. I will discuss possible connection of this observation to scalar field turbulence.

SIMULATING THE BIG BANG

REHEATING AFTER INFLATION WITH DEFROST



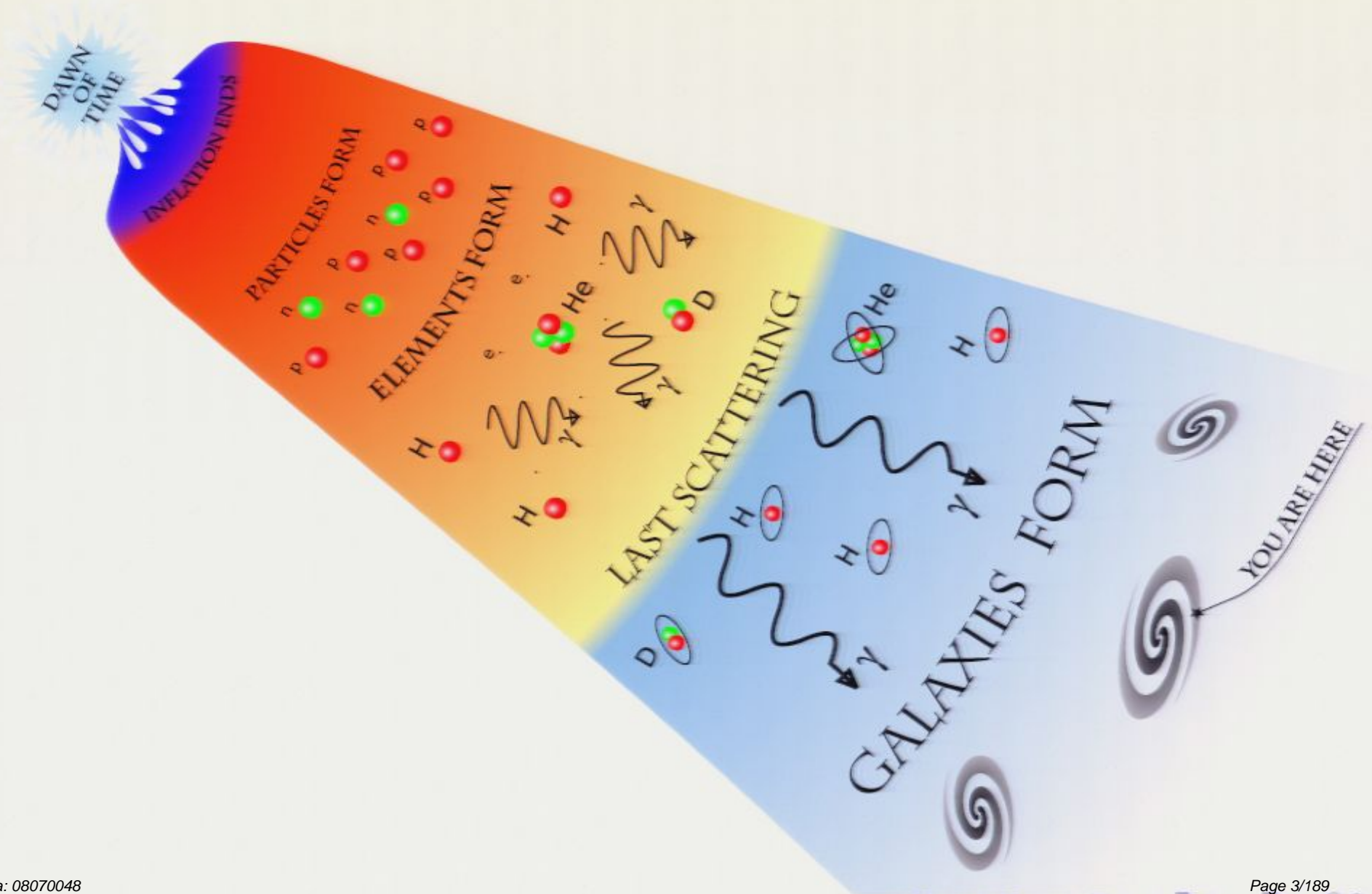
Andrei Frolov

Department of Physics
Simon Fraser University

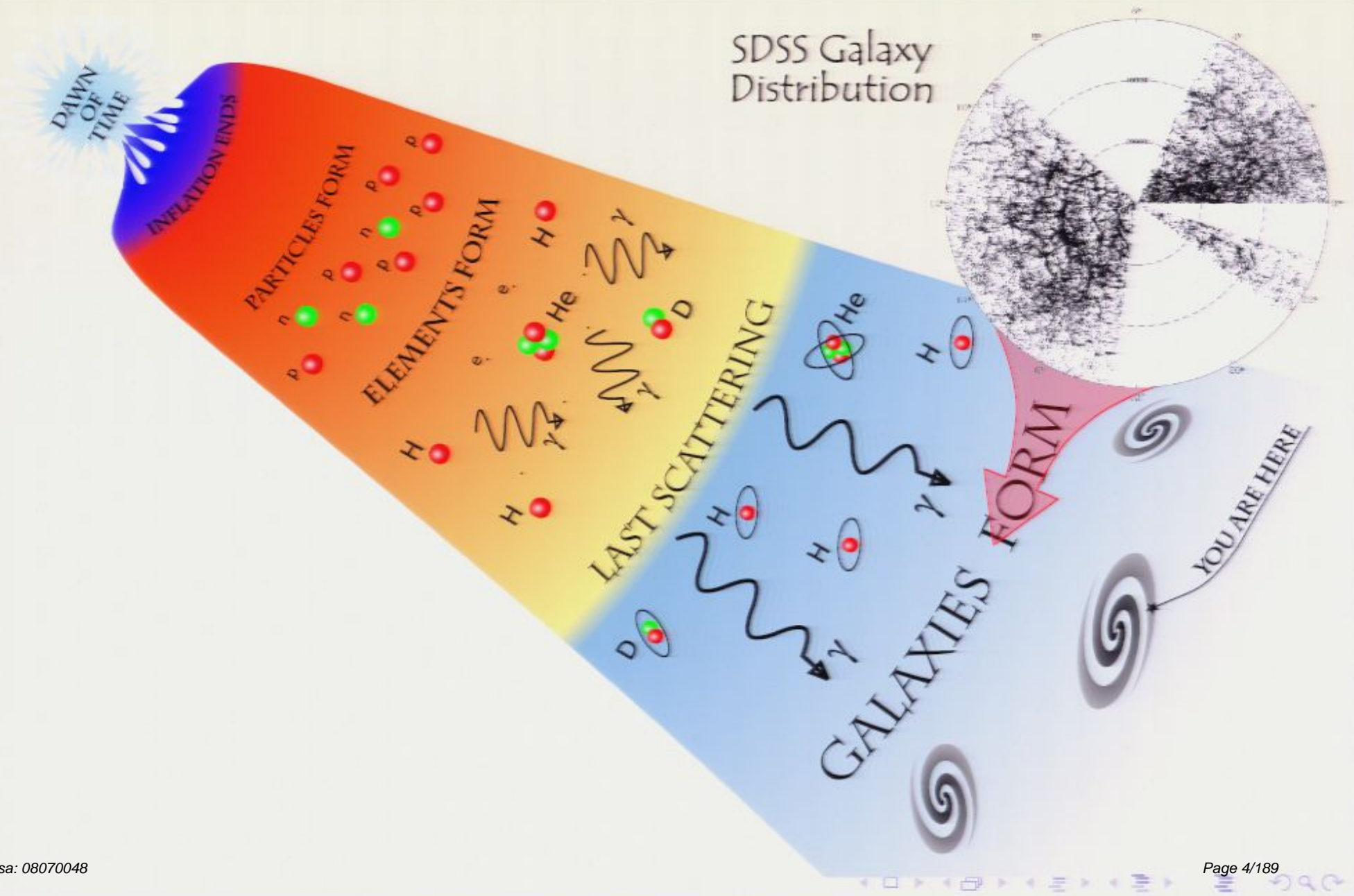


*Perimeter Institute
Waterloo ON Canada
29 July 2008*

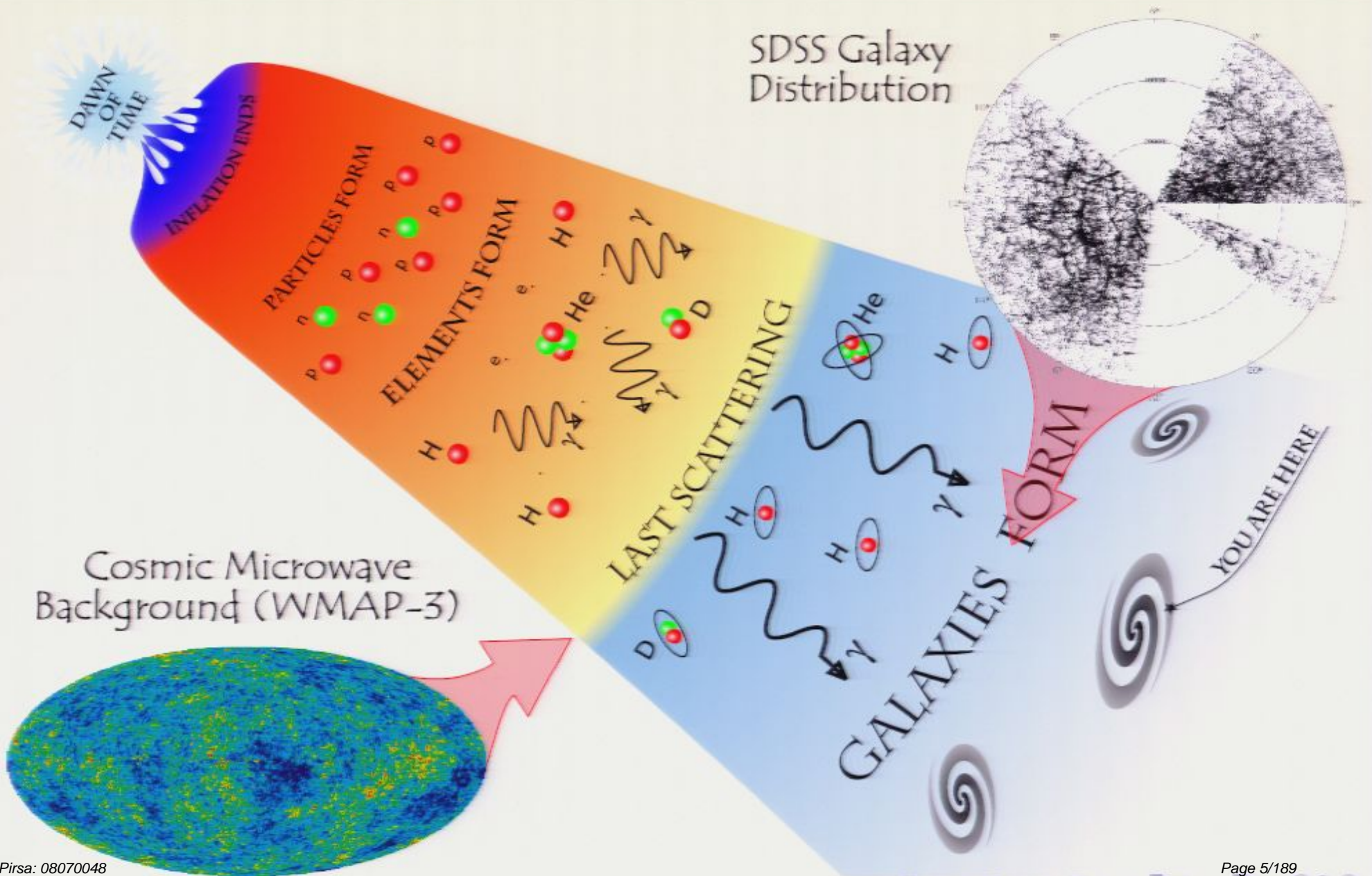
BRIEF HISTORY OF THE UNIVERSE



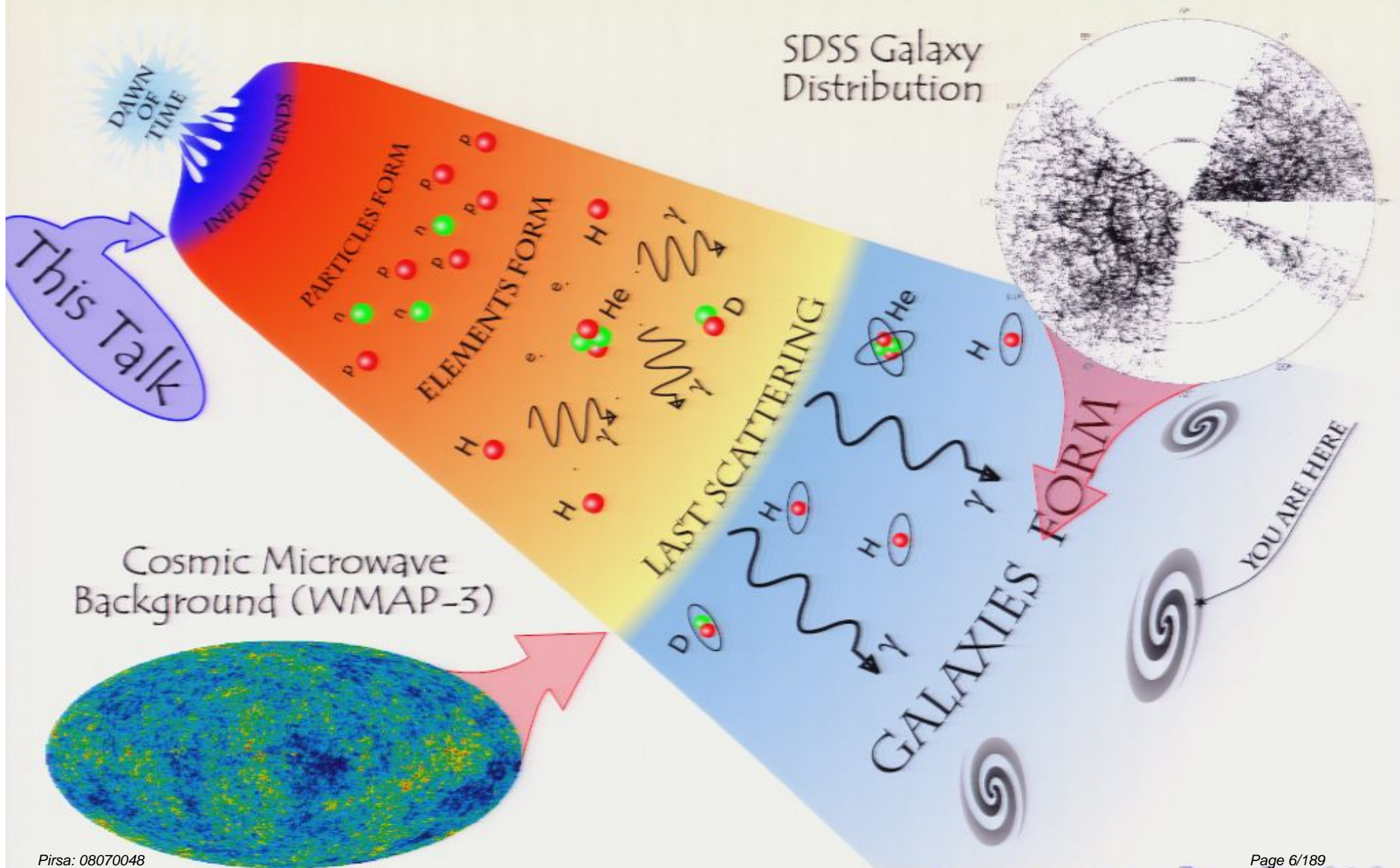
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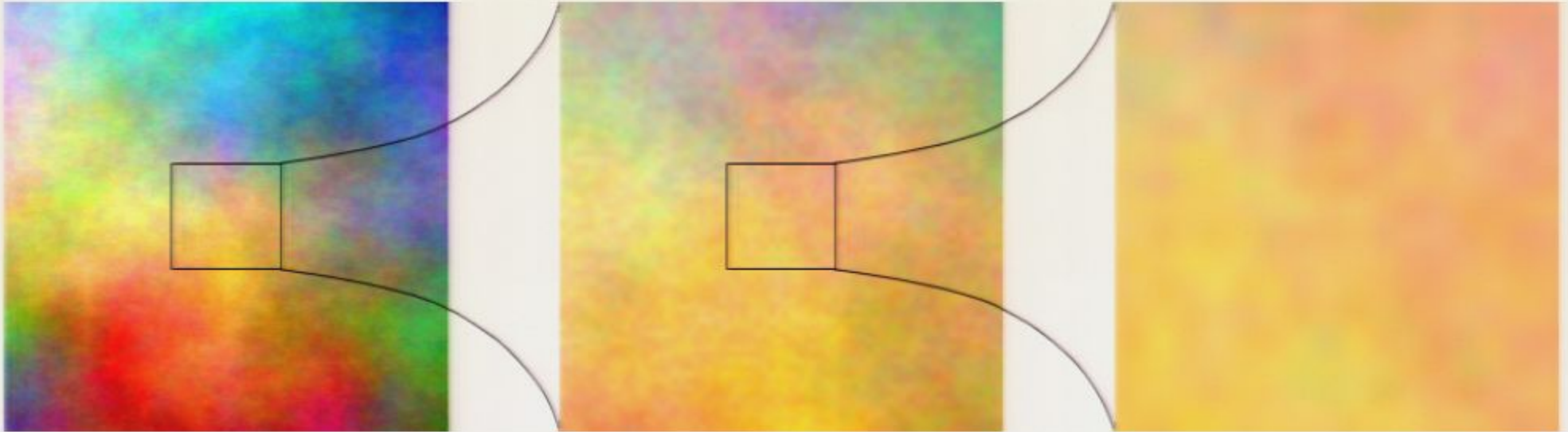
BRIEF HISTORY OF THE UNIVERSE



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INFLATION SOLVES MANY PROBLEMS, BUT...



inflation wipes the slate clean and re-seeds the structure

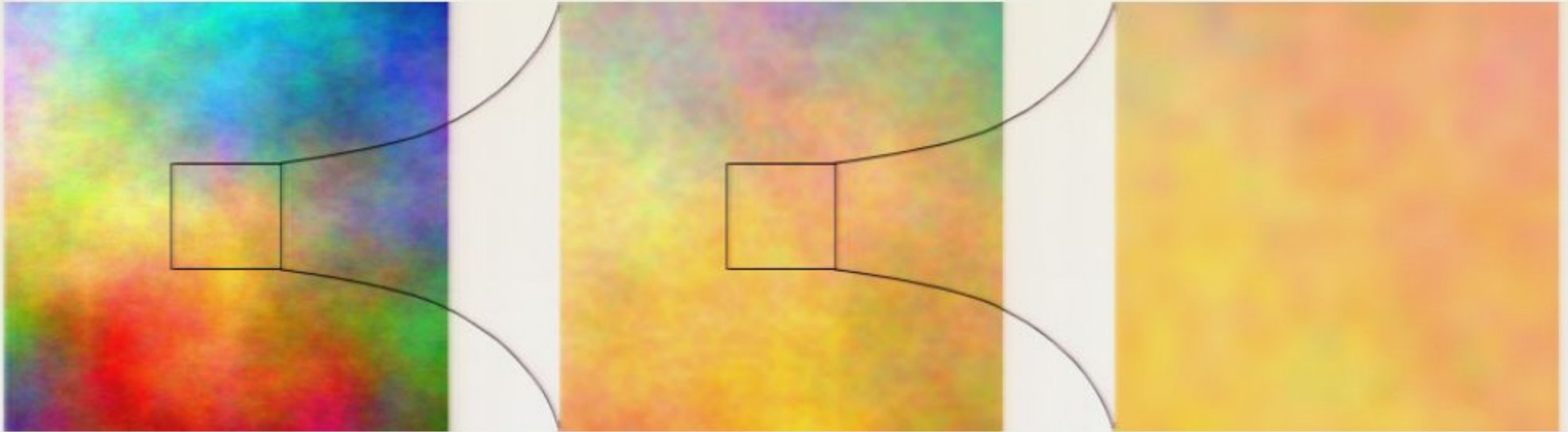
**Inflation
is cold**

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**Big Bang
is hot**

Inflation has to end! But how?...

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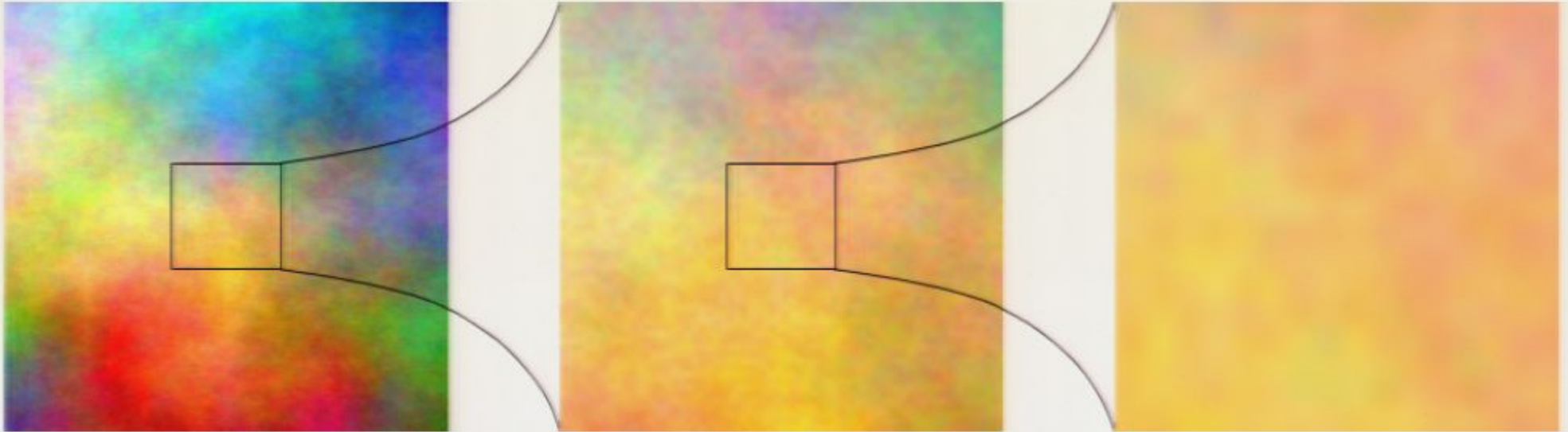
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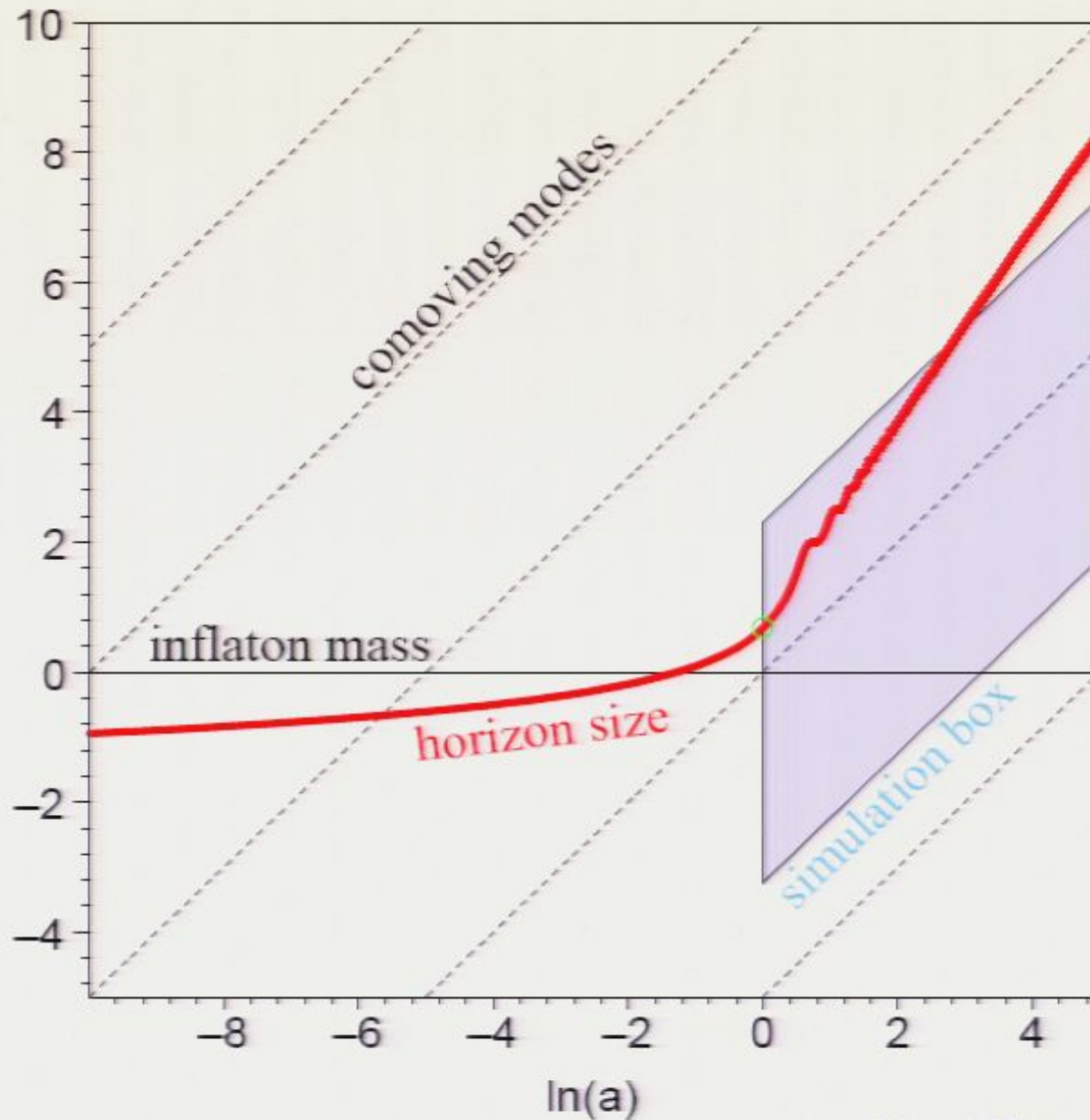
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WHEN DOES INFLATION END, ANYWAY?



CHAOTIC INFLATION AND PREHEATING

SIMPLE MODEL

inflaton field ϕ decays into a scalar field χ

$$V(\phi, \chi) = \frac{1}{2}m^2\phi^2 + \frac{1}{2}g^2\phi^2\chi^2$$

in an expanding (homogeneous) spacetime

$$ds^2 = -dt^2 + a^2(t)d\vec{x}^2$$

EQUATIONS OF MOTION

$$\ddot{\phi} + 3H\dot{\phi} + (m^2 + g^2\chi^2 - \frac{\Delta}{a^2})\phi = 0$$

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$$H^2 \equiv \frac{\dot{a}^2}{a^2} = \frac{\langle \rho \rangle}{3}, \quad \rho = \frac{\dot{\phi}^2}{2} + \frac{\dot{\chi}^2}{2} + \frac{(\nabla\phi)^2}{2a^2} + \frac{(\nabla\chi)^2}{2a^2} + V(\phi, \chi)$$

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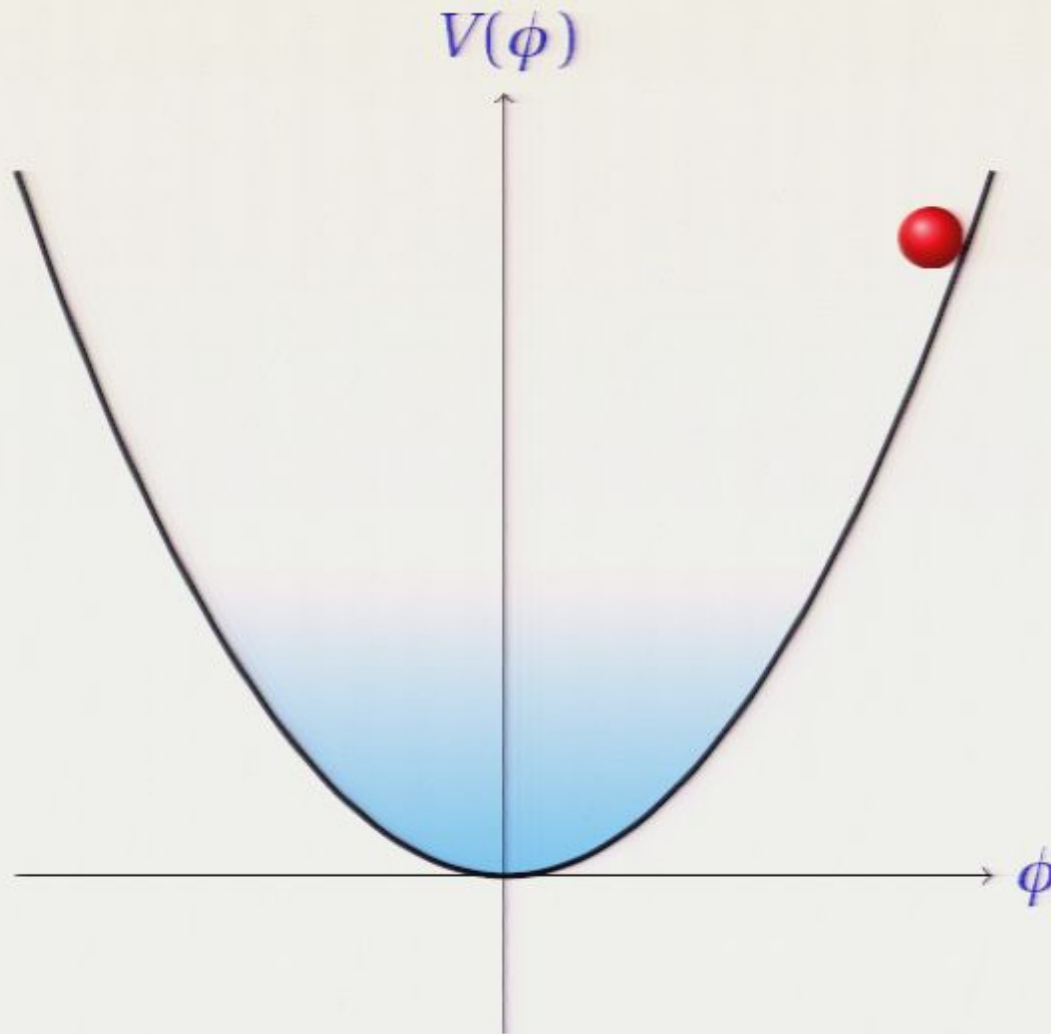
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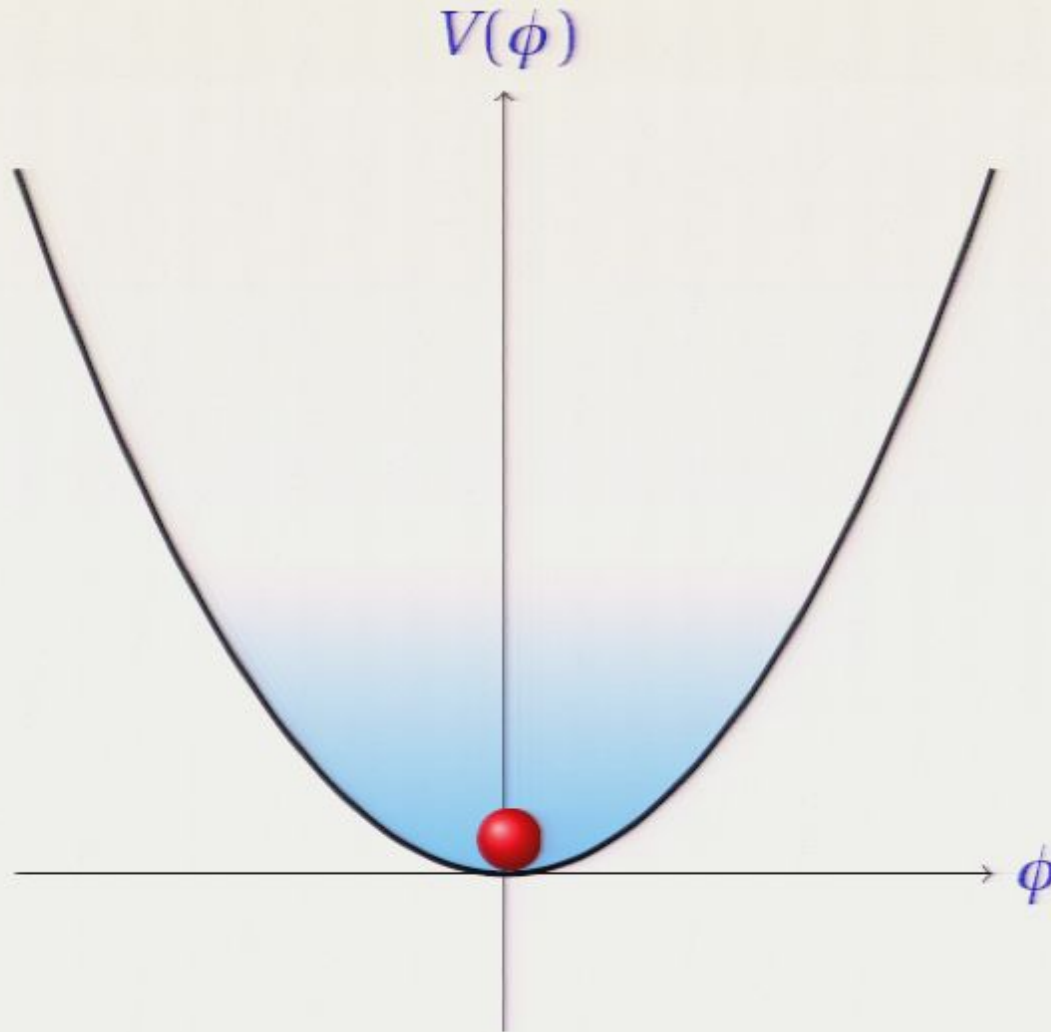
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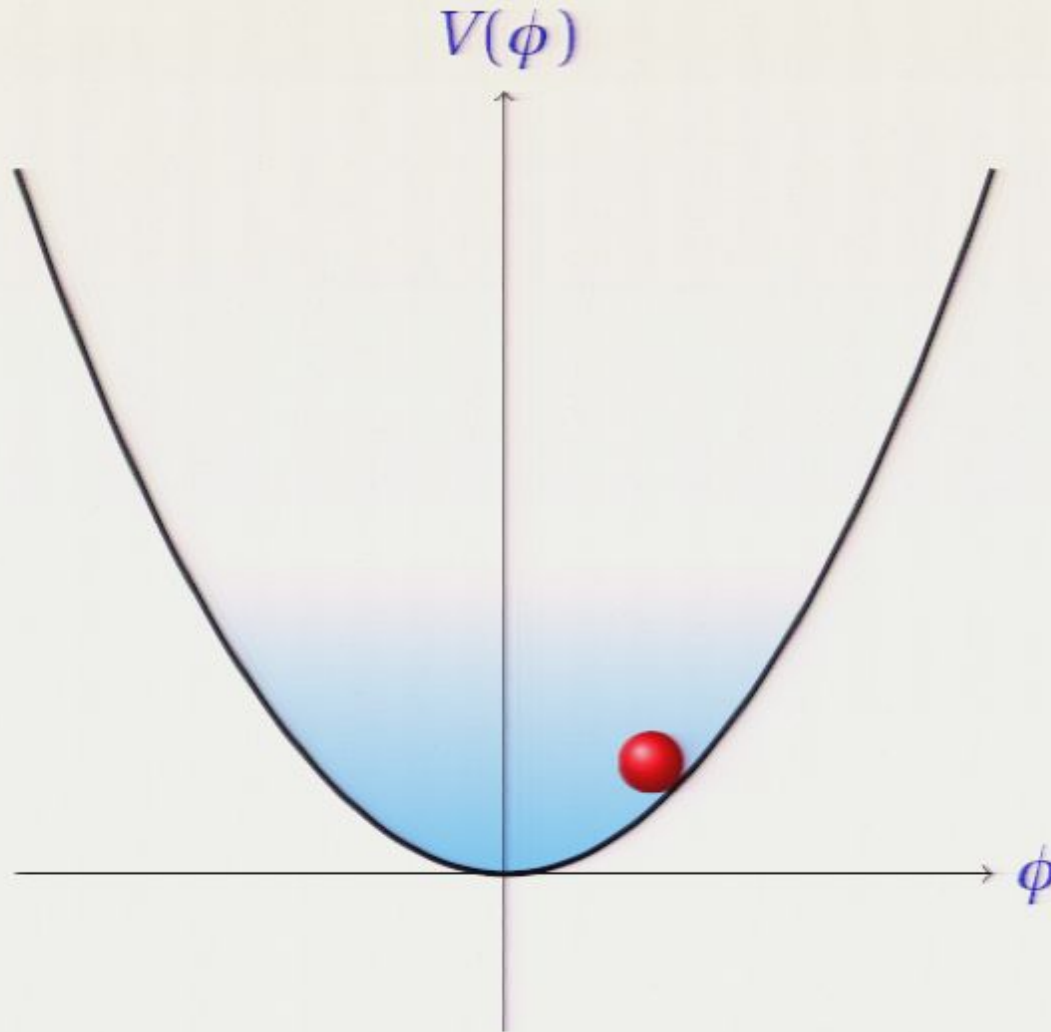
INFLATON DYNAMICS



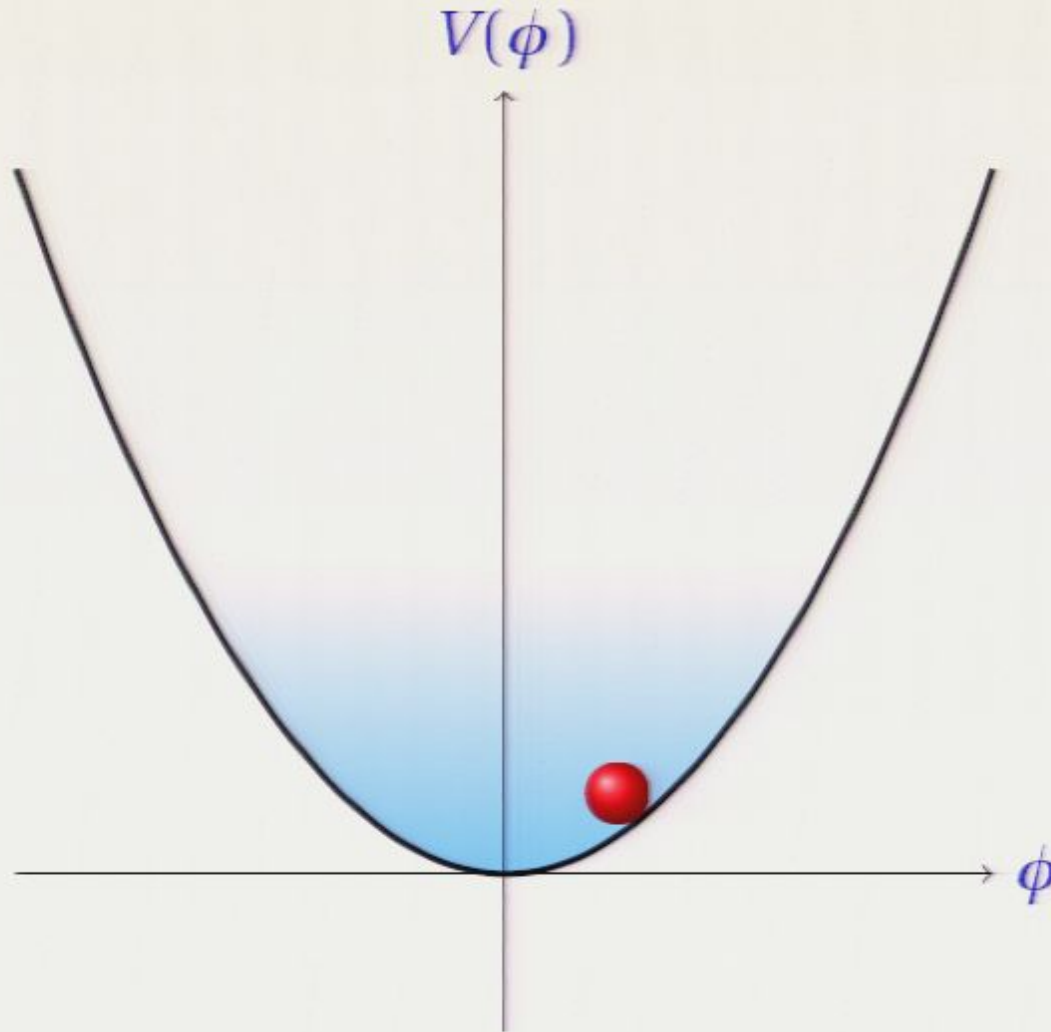
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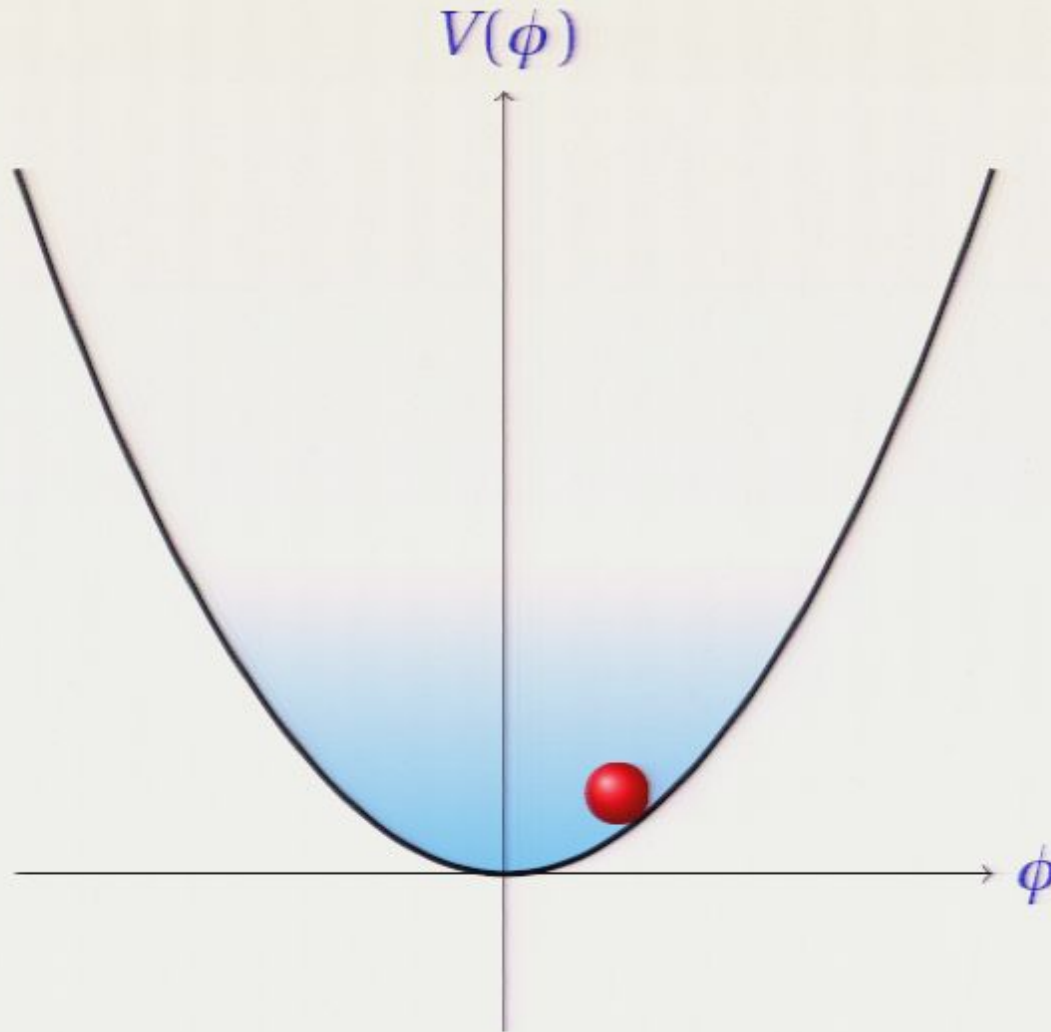
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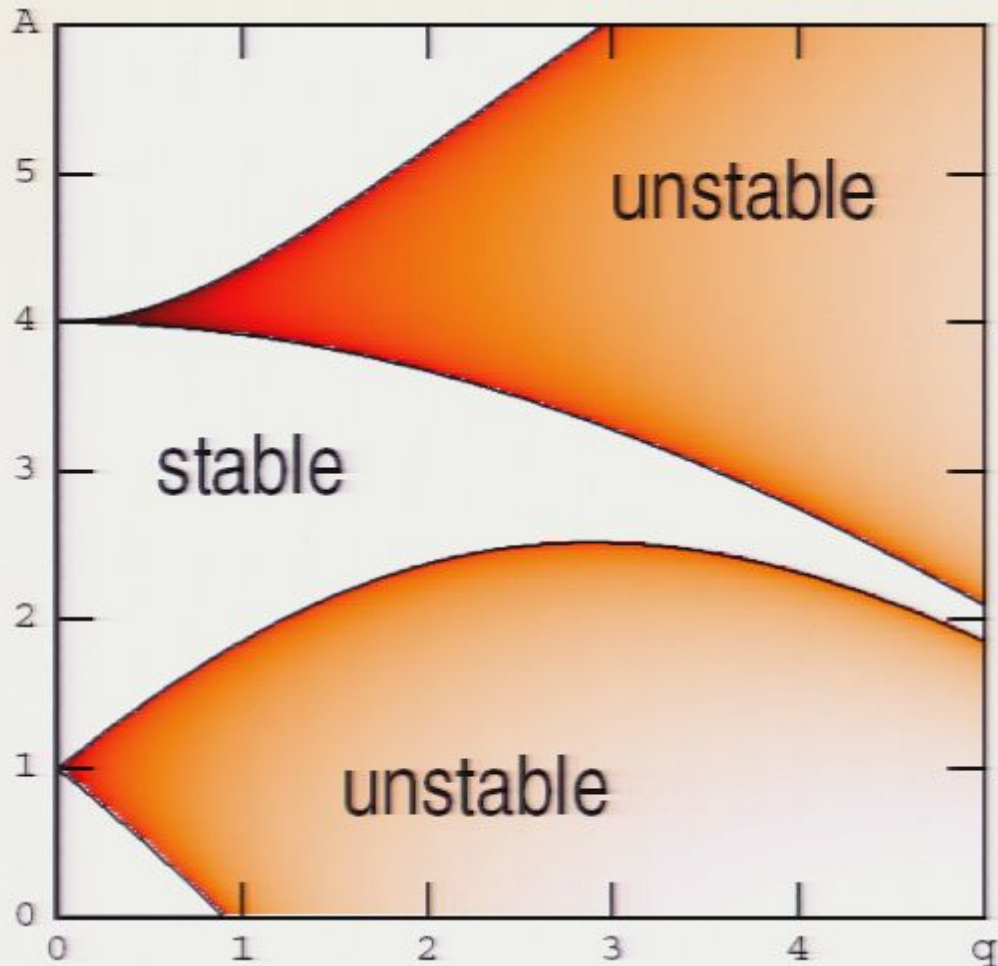
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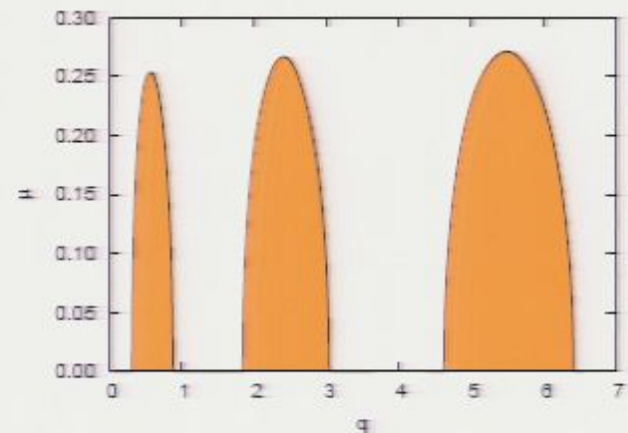
MATHIEU EQUATION



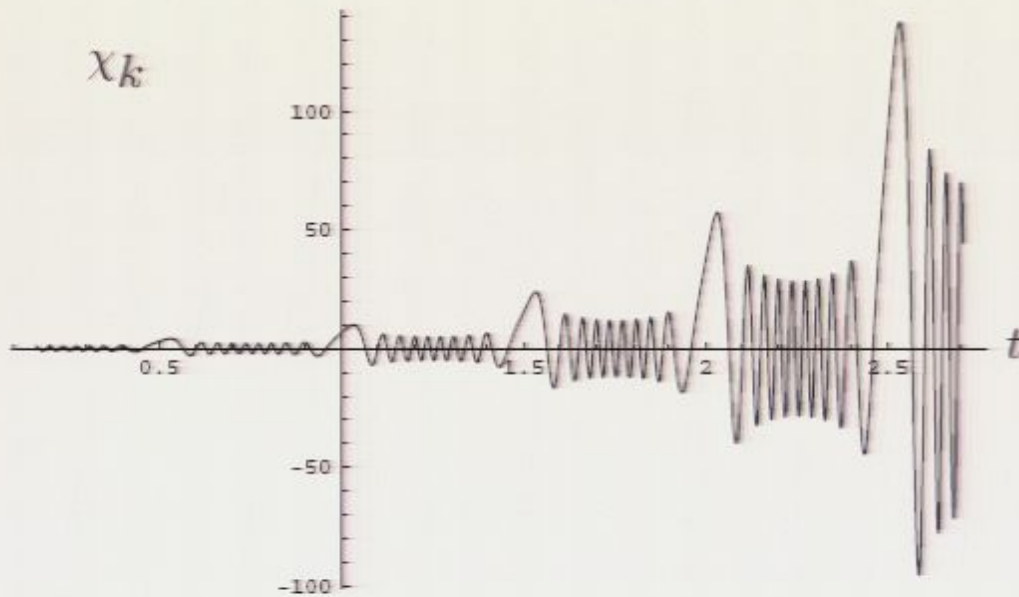
$$\chi'' + [A - 2q \cos 2z] \chi = 0$$

$$A = 2q + \frac{k^2}{m^2 a^2}, \quad q = \frac{g^2 \Phi^2}{4m^2}$$

in unstable region $\chi \propto e^{\mu z}$!



BROAD PARAMETRIC RESONANCE



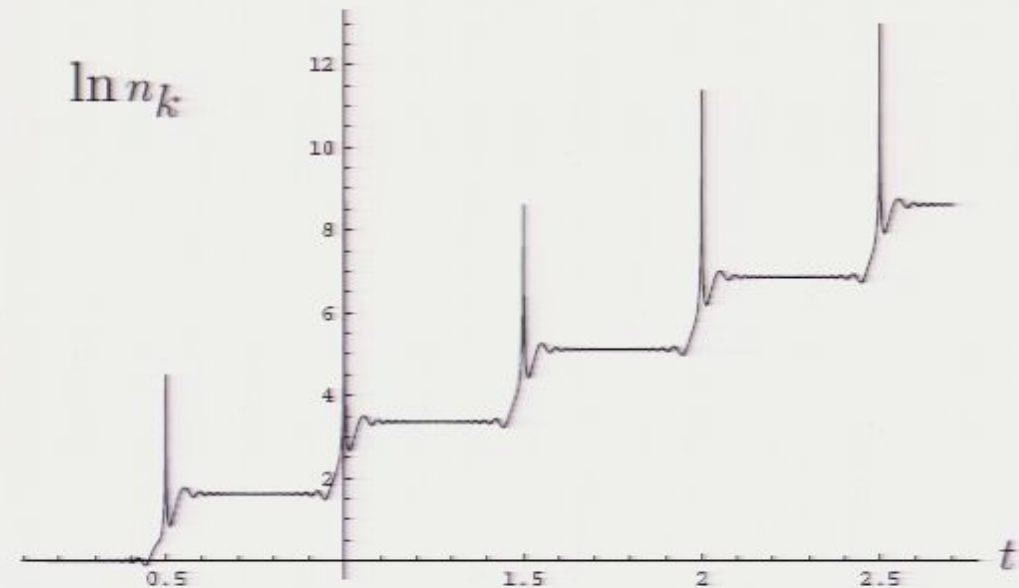
Kofman, Linde, & Starobinsky
[hep-th/9405187](https://arxiv.org/abs/hep-th/9405187),
[hep-ph/9704452](https://arxiv.org/abs/hep-ph/9704452)

For large q ($g\Phi \gg m$),
resonant bands are broad

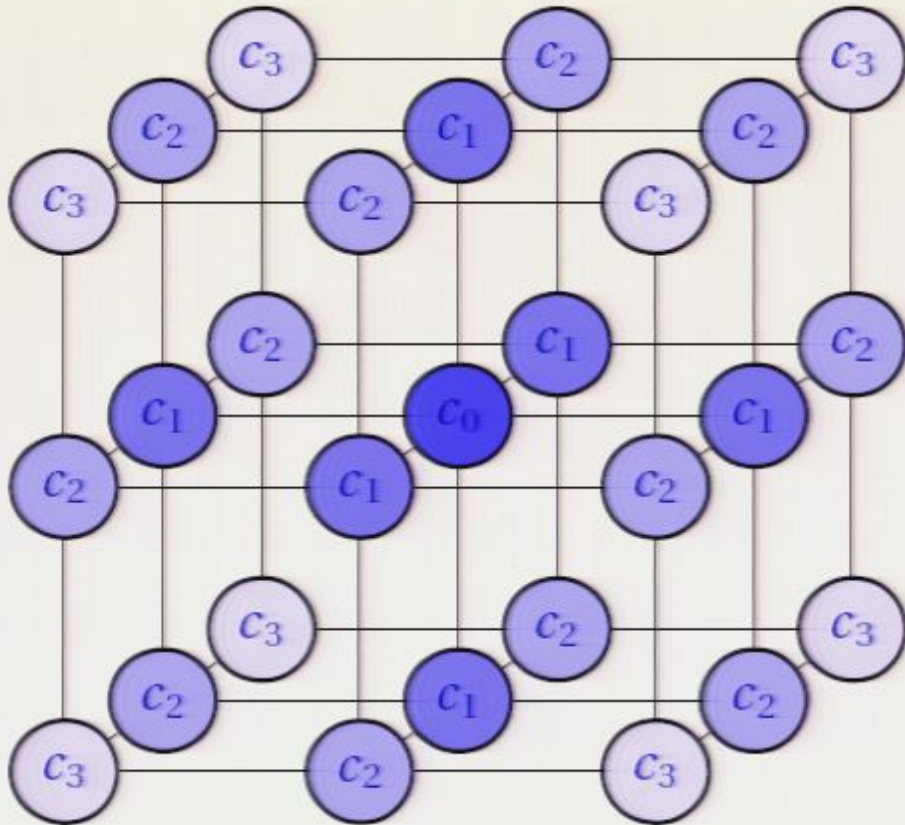
Particles are produced when
 $\phi(t) = 0$

Otherwise, χ is heavy, and n
is an adiabatic invariant

$(q \sim 200, \mu \sim 0.3)$



DEFROST: A NEW 3D NUMERICAL SOLVER

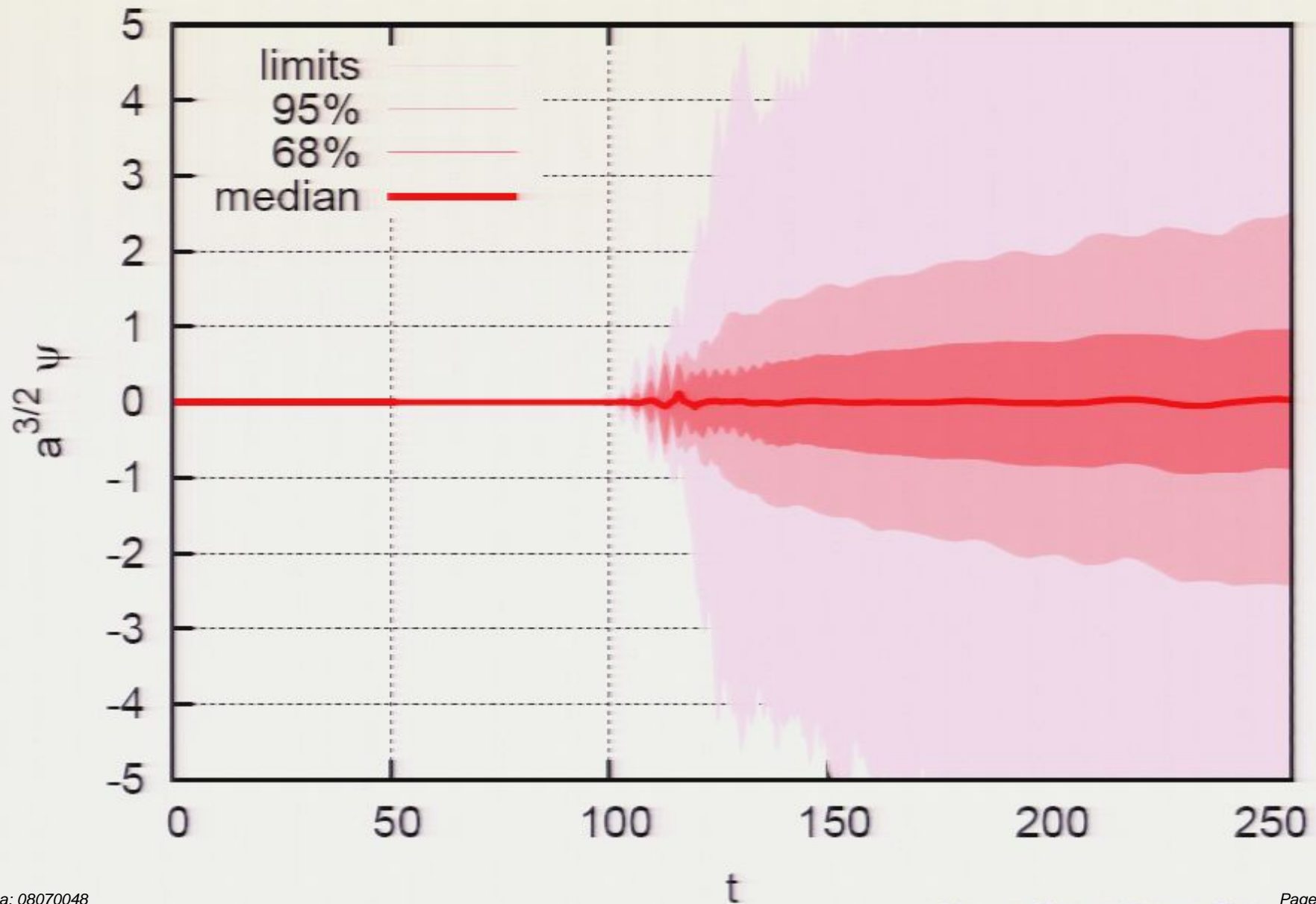


| | | | | |
|-------------|----------------|----------------|----------------|-----------------|
| coefficient | c_3 | c_2 | c_1 | $-c_0$ |
| degeneracy | 8 | 12 | 6 | 1 |
| standard | 0 | 0 | 1 | 6 |
| isotropic A | 0 | $\frac{1}{6}$ | $\frac{1}{3}$ | 4 |
| isotropic B | $\frac{1}{12}$ | 0 | $\frac{2}{3}$ | $\frac{14}{3}$ |
| isotropic C | $\frac{1}{30}$ | $\frac{1}{10}$ | $\frac{7}{15}$ | $\frac{64}{15}$ |

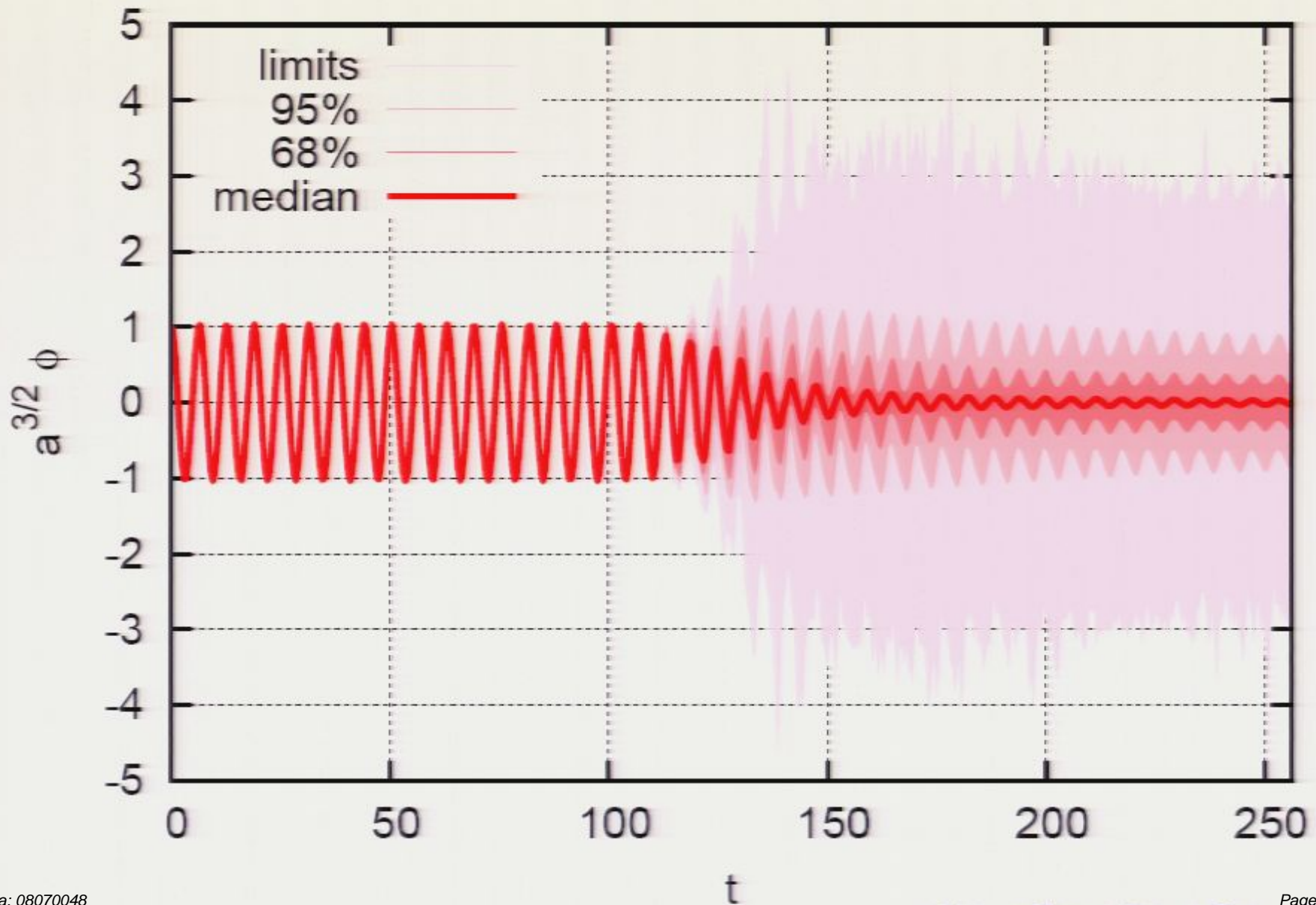
<http://www.sfu.ca/physics/cosmology/defrost>

[Fortran-90, 600 lines, very fast, instrumented for 3D]

DEVELOPMENT OF THE INSTABILITY

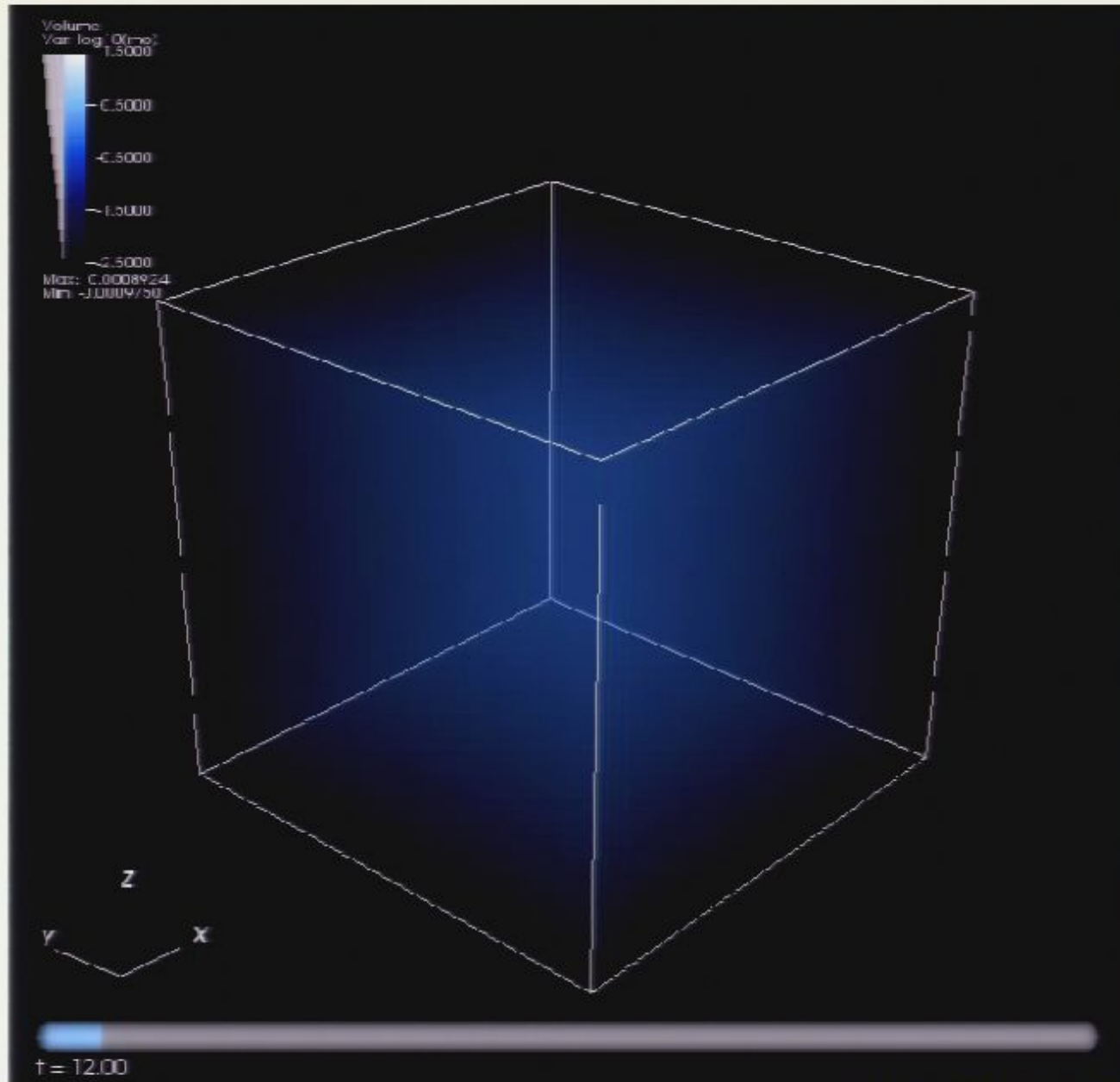


INFLATON DECAYS (BUT NOT FULLY)...

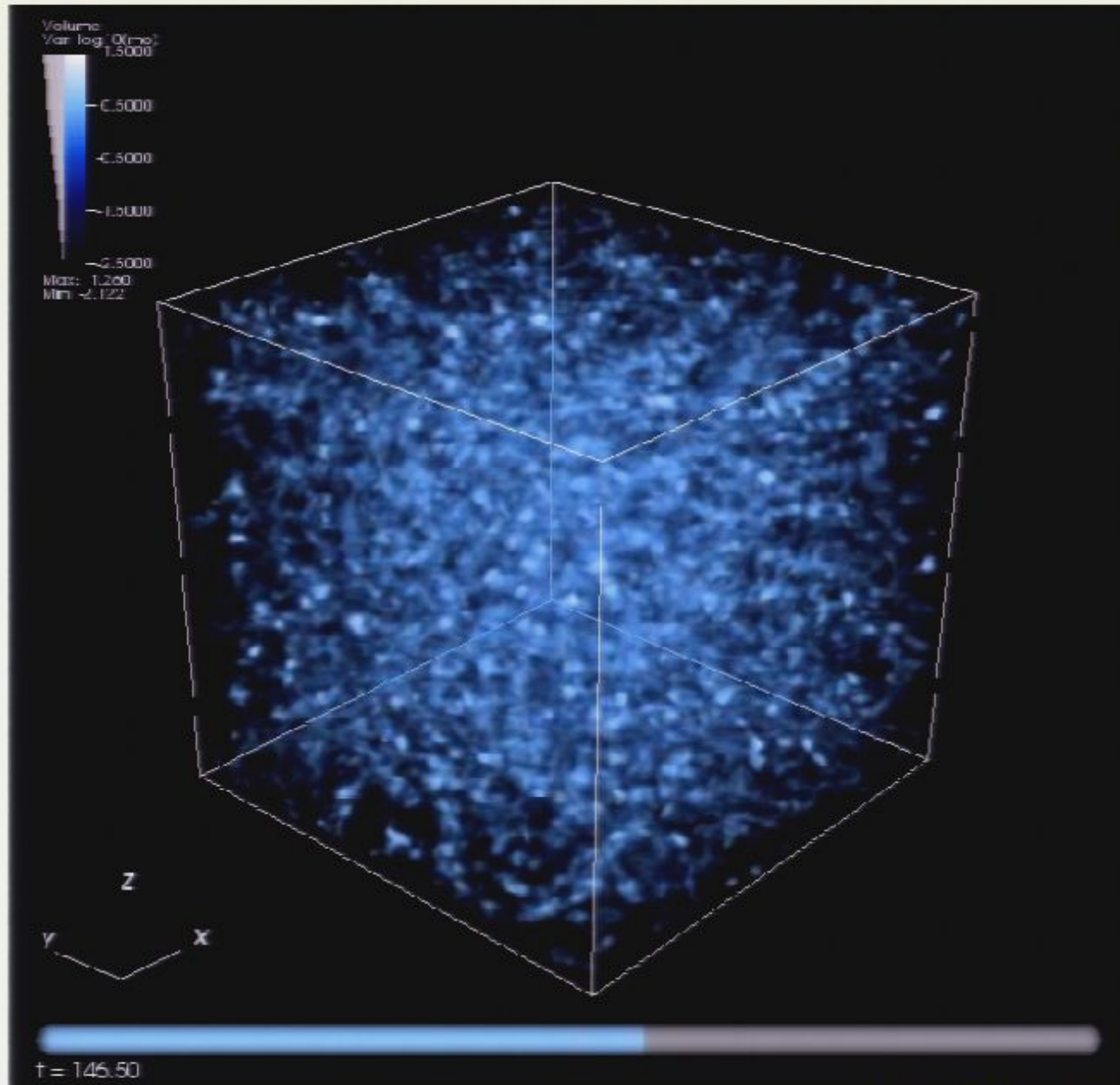


DENSITY EVOLUTION DURING PREHEATING

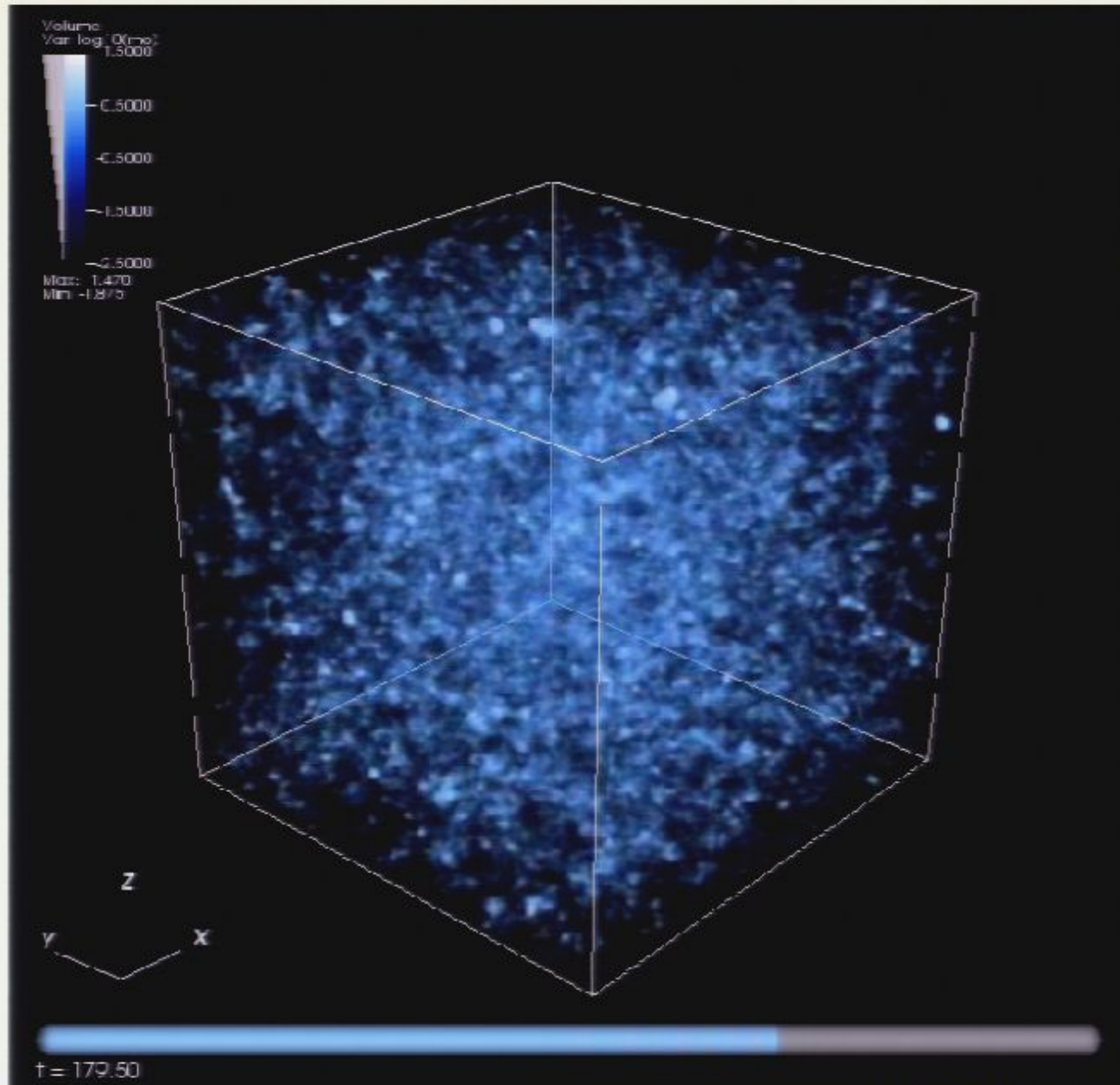
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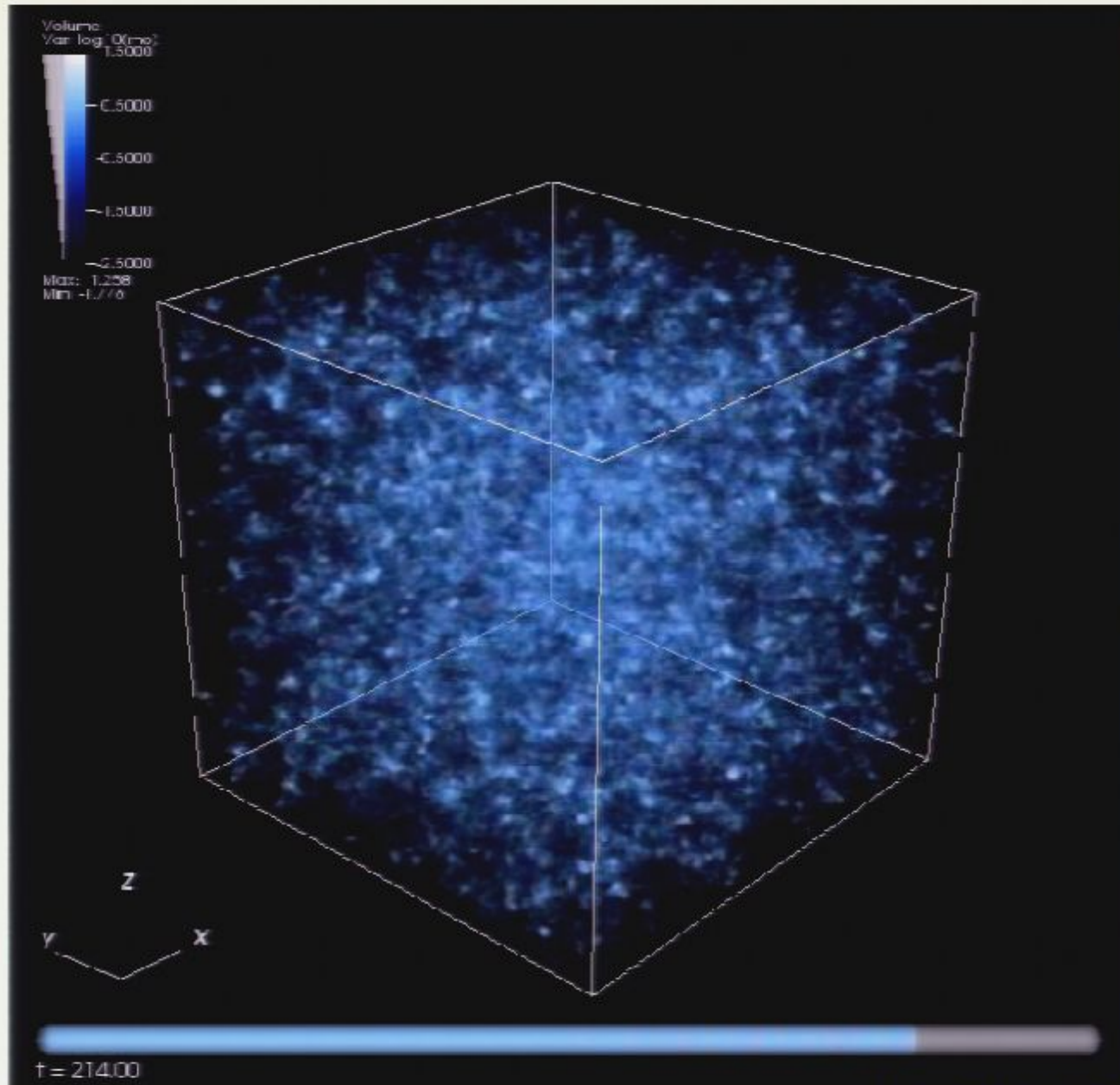
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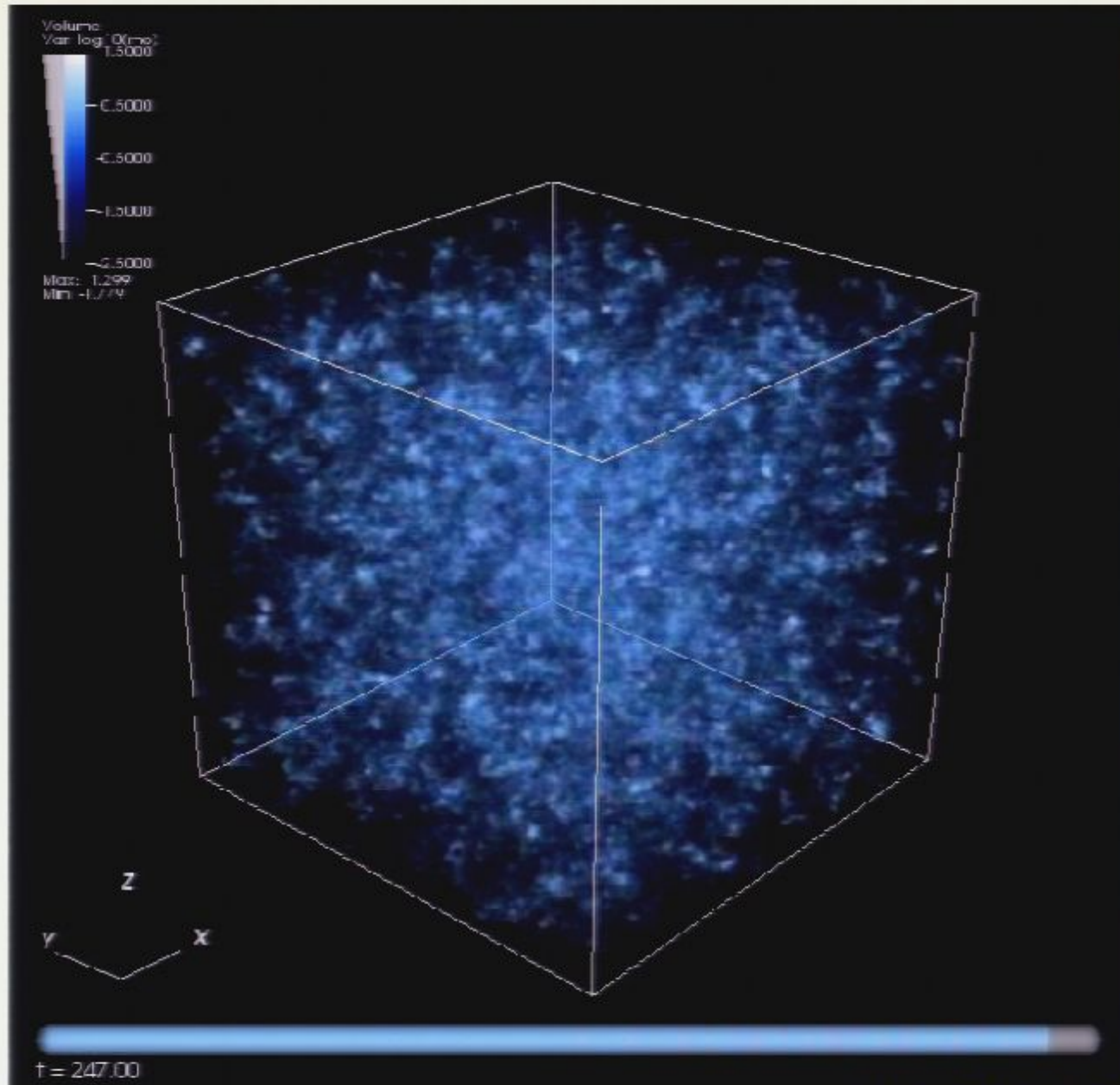
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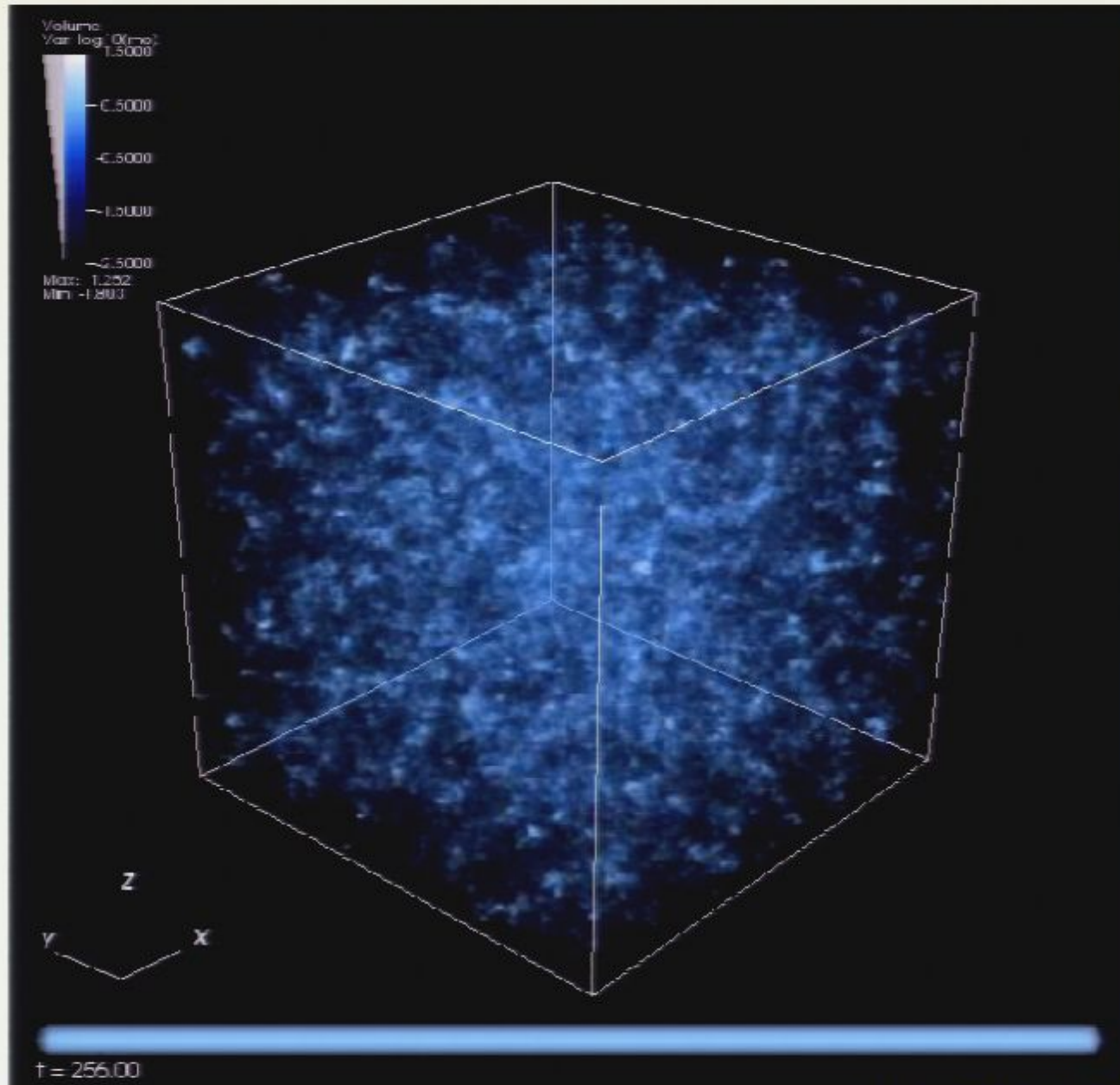
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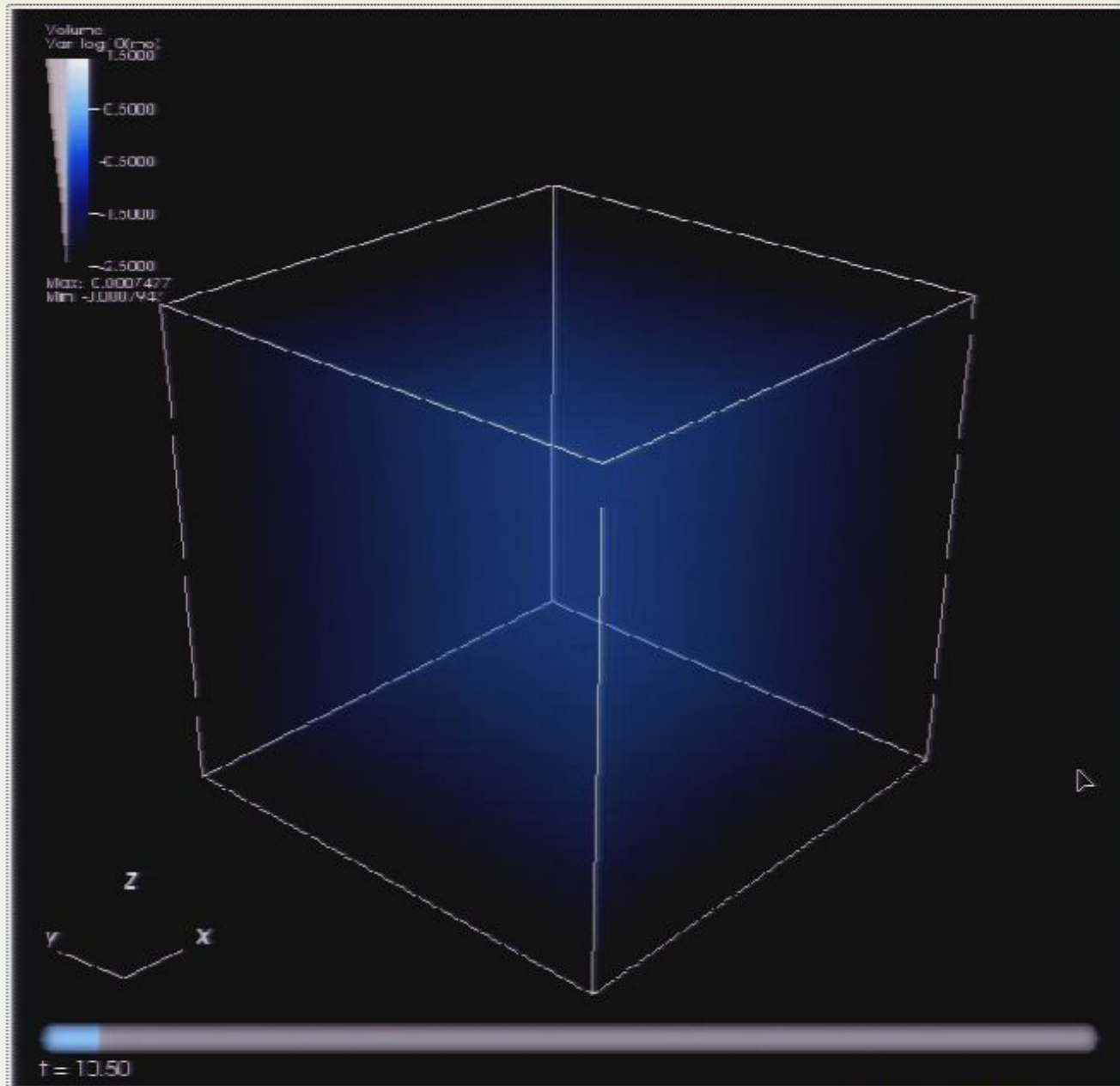
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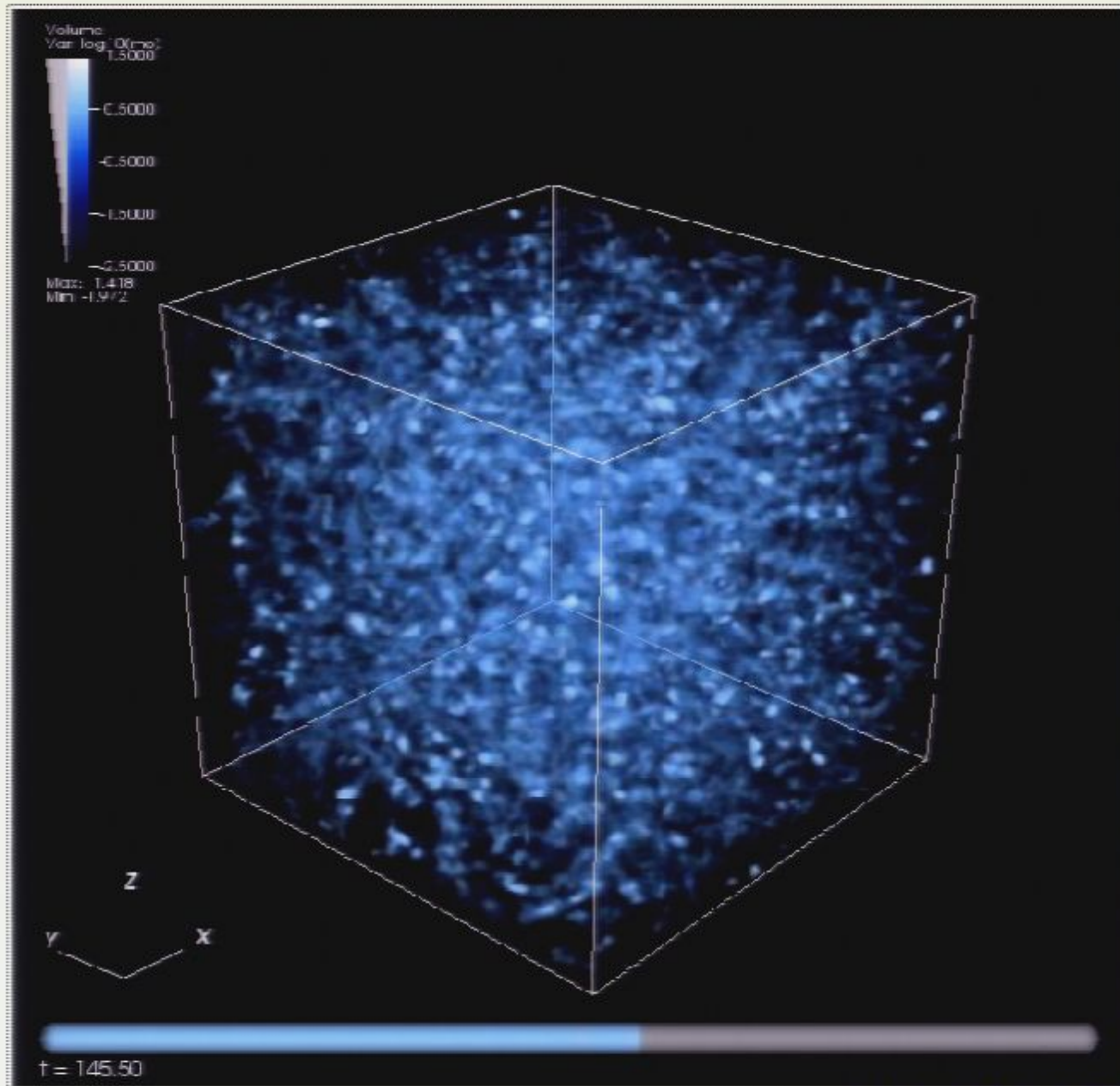
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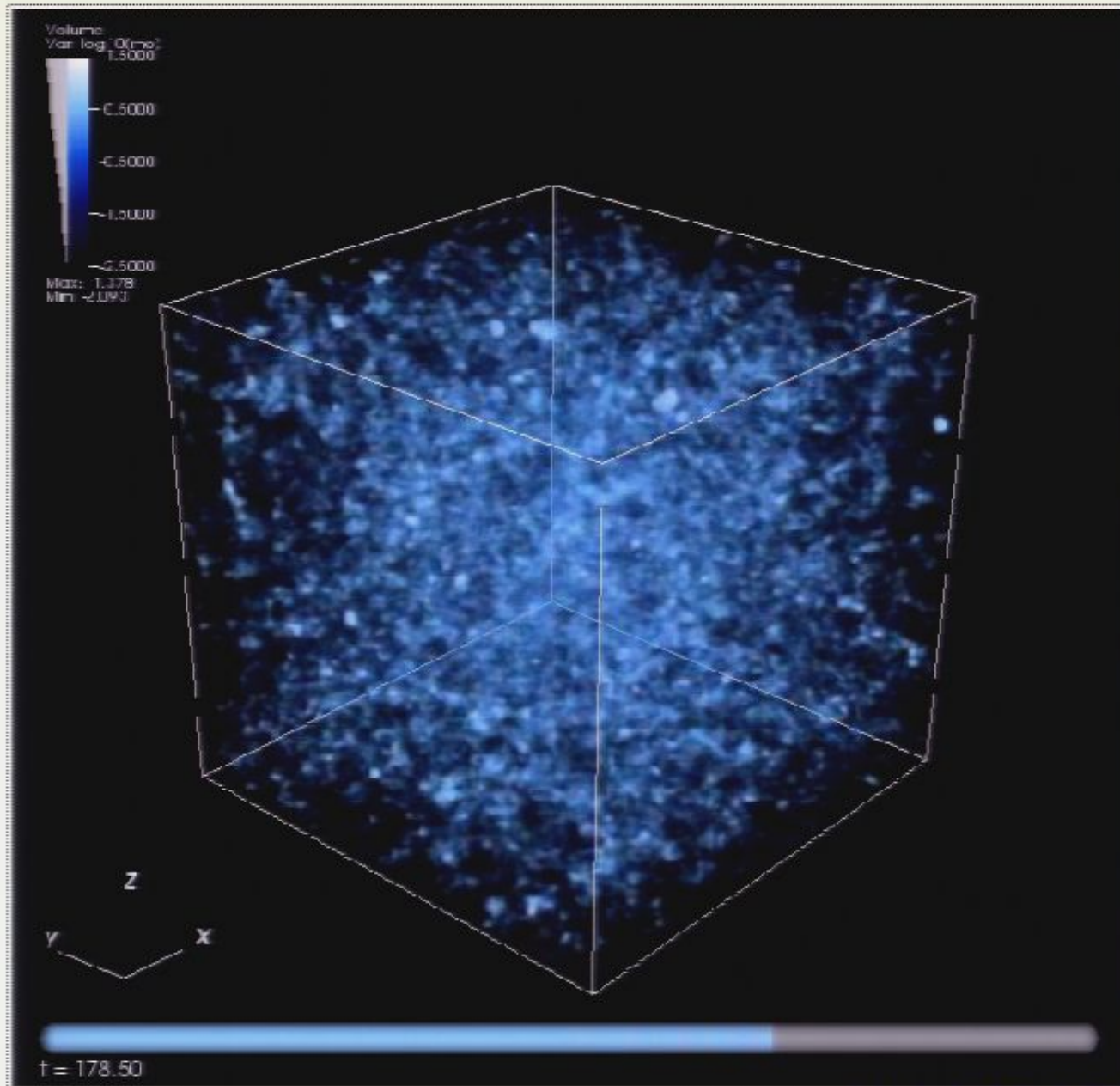
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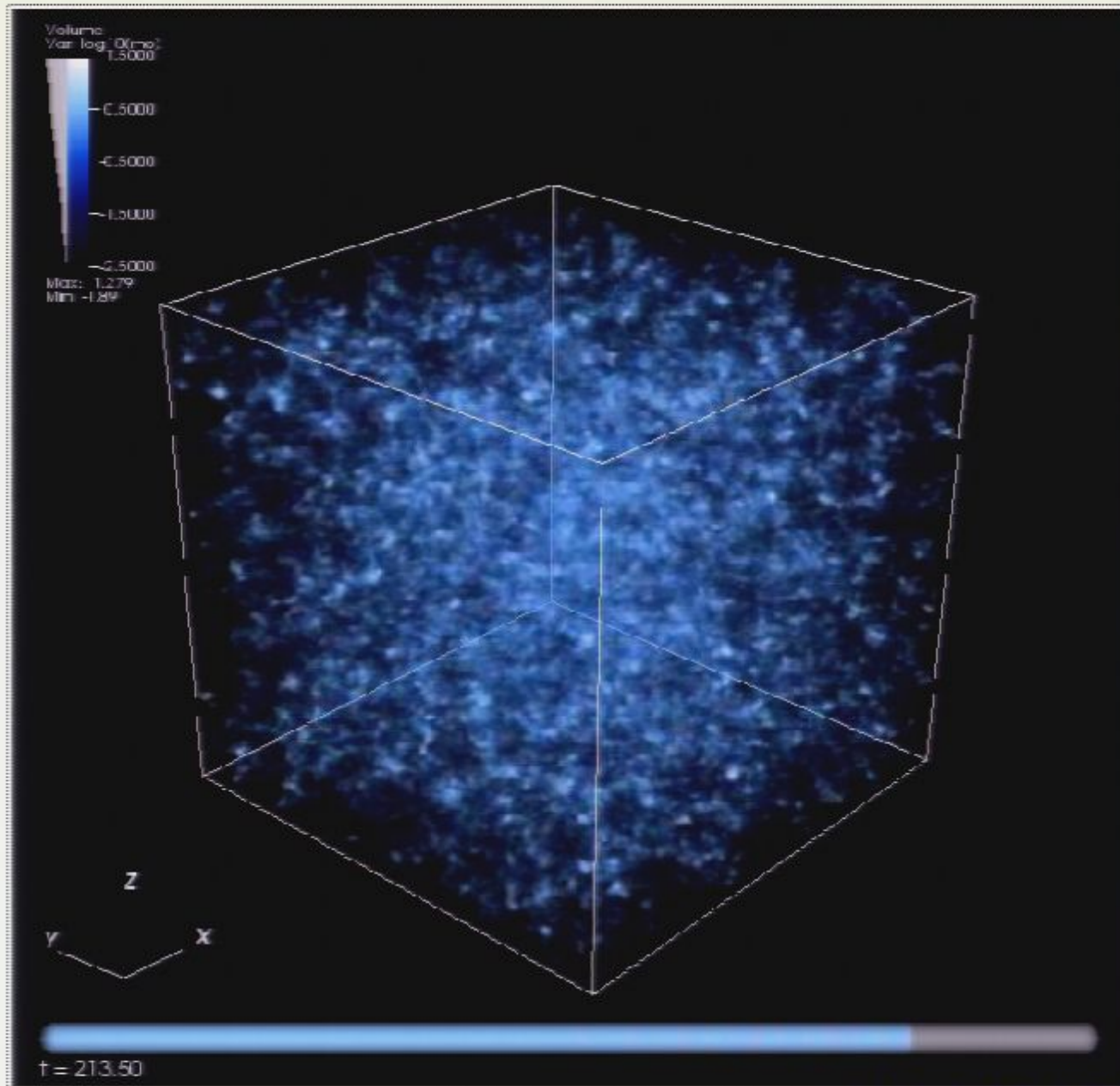
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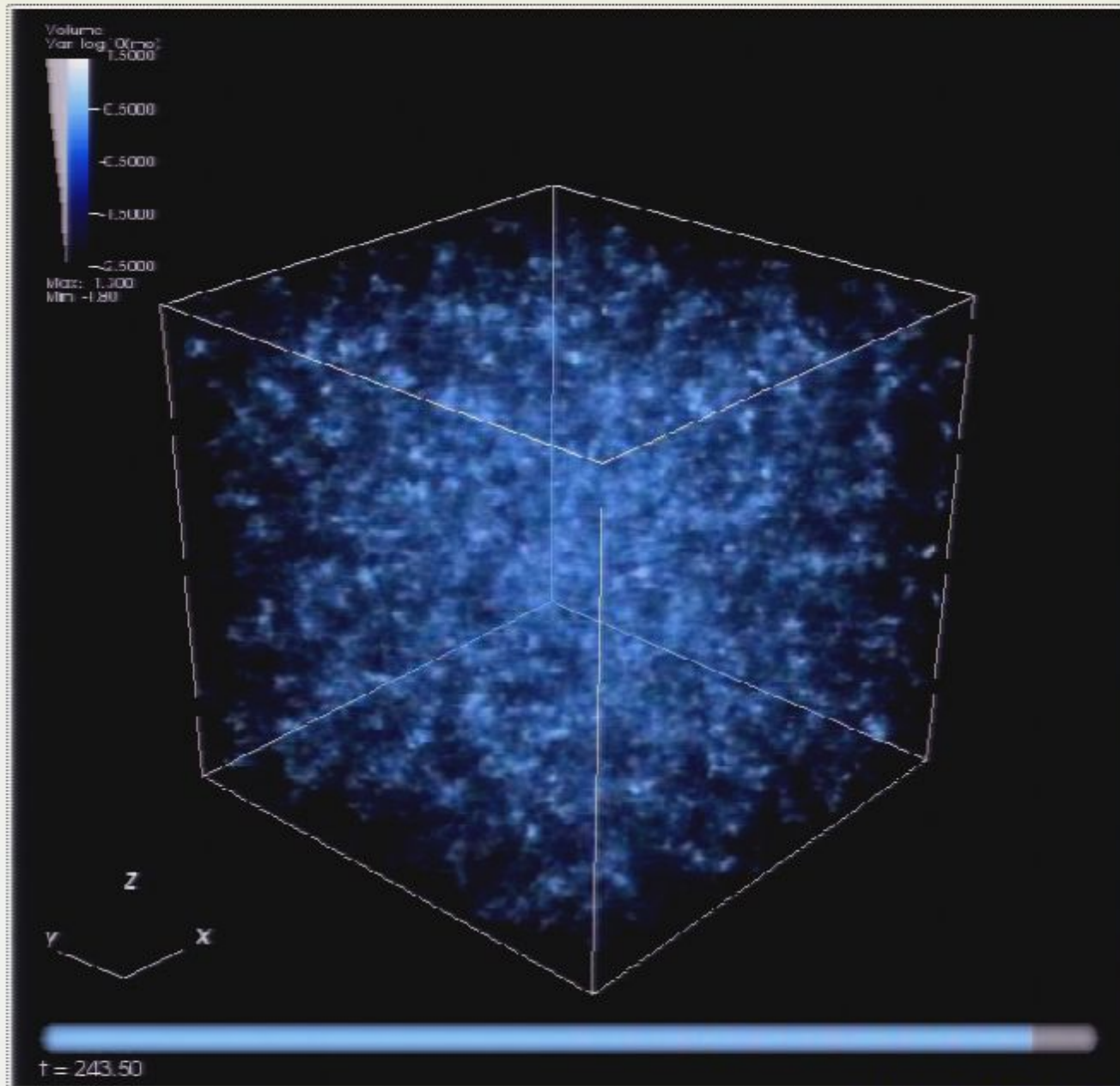
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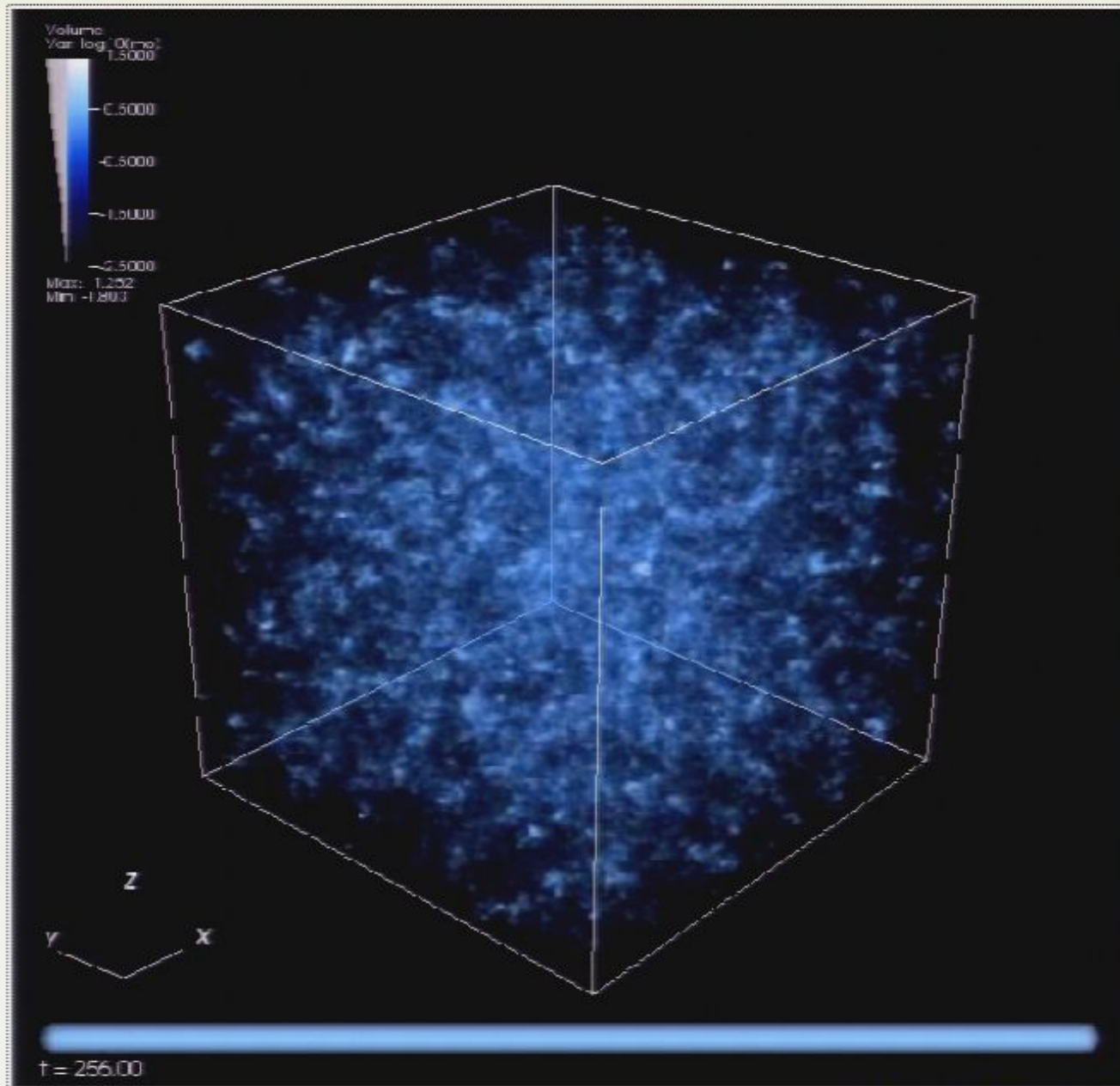
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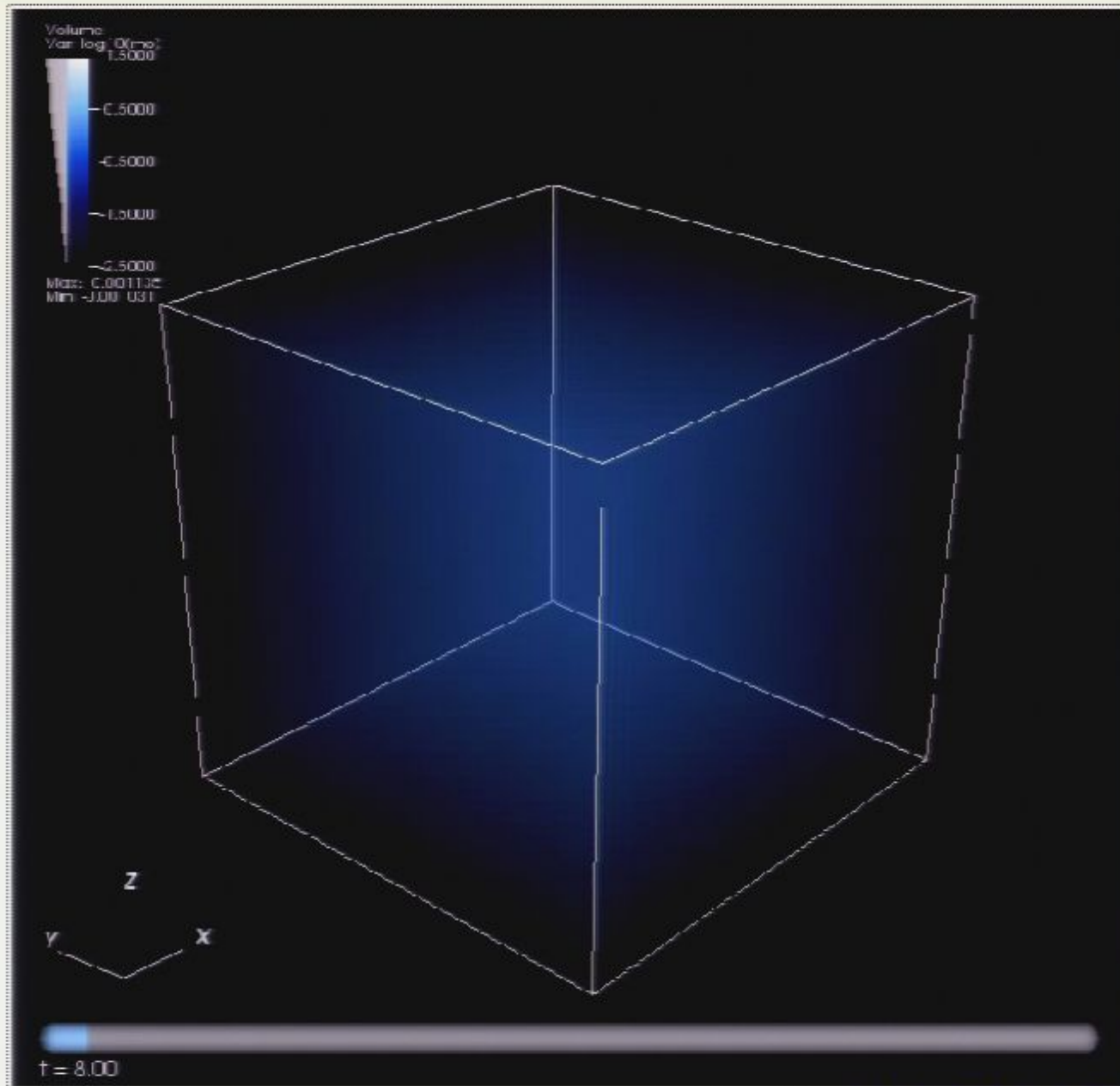
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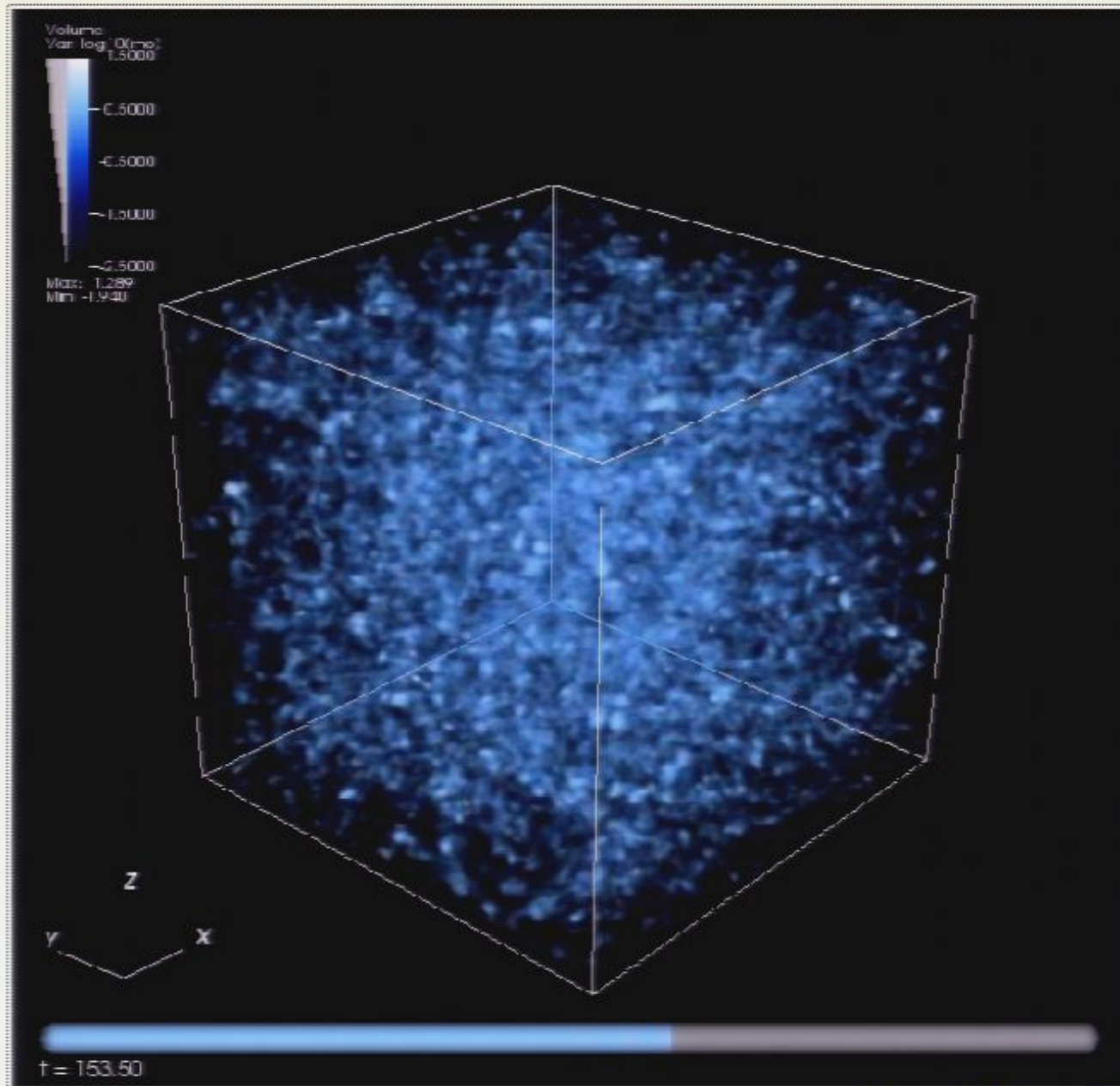
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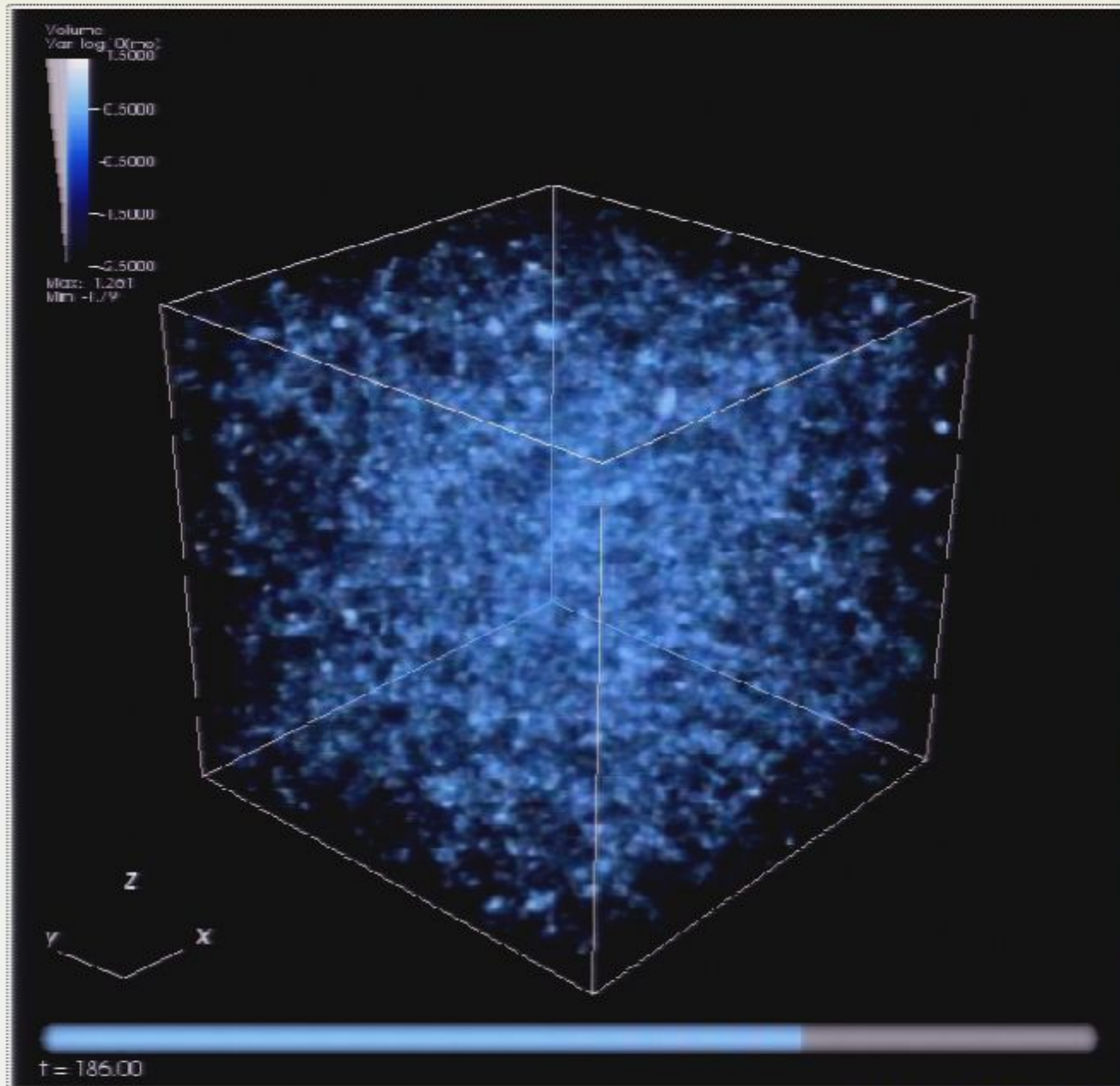
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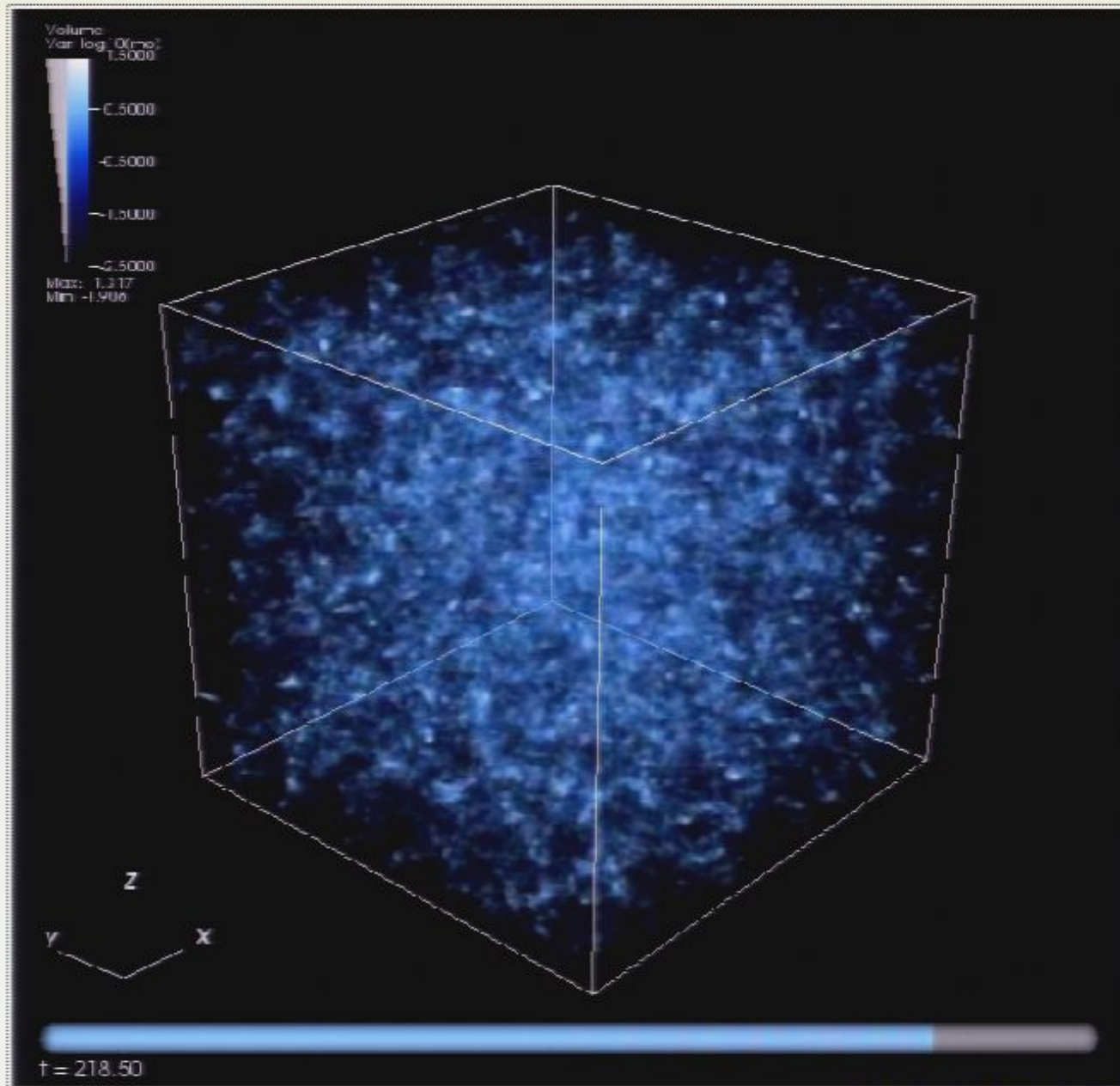
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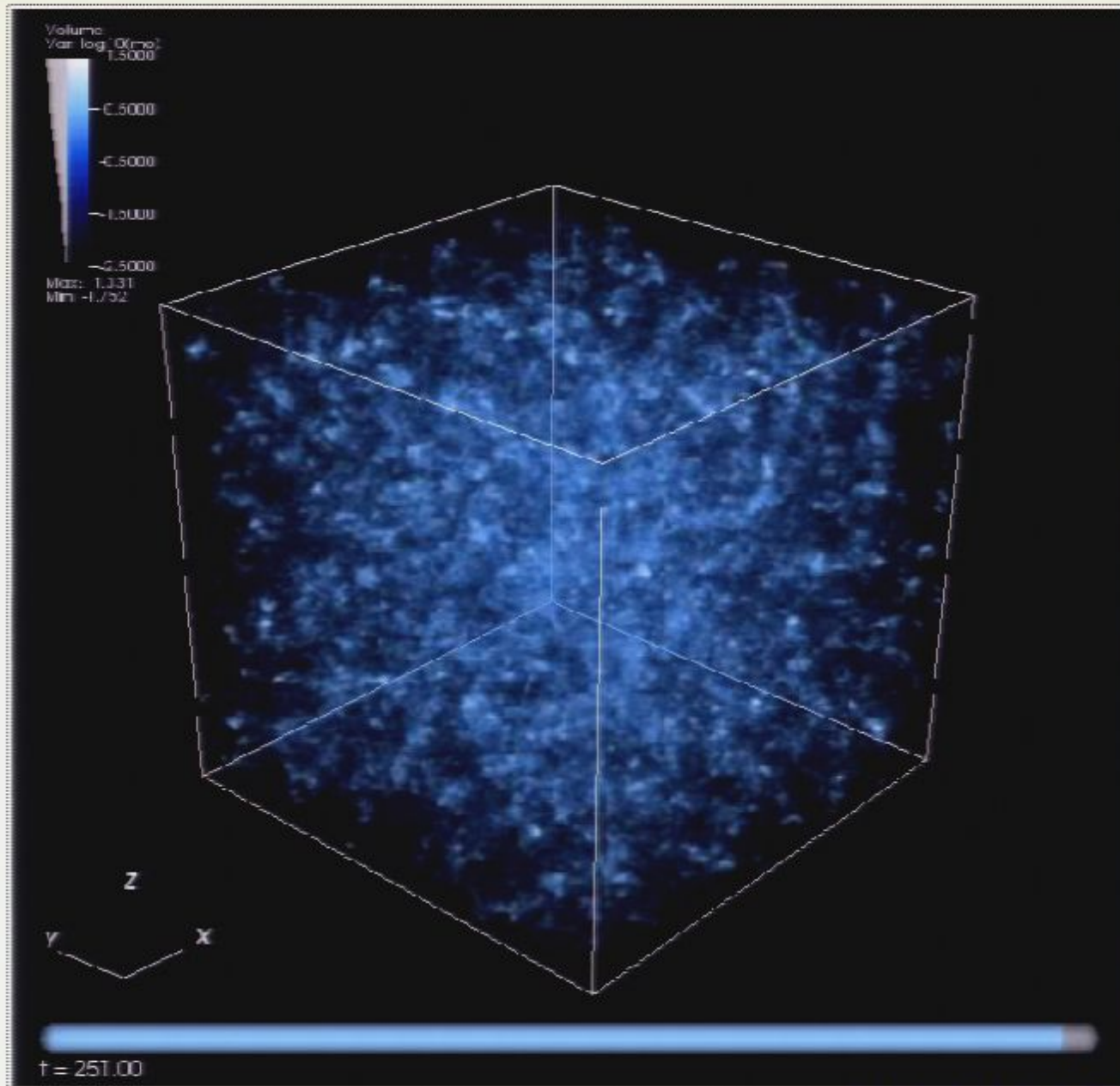
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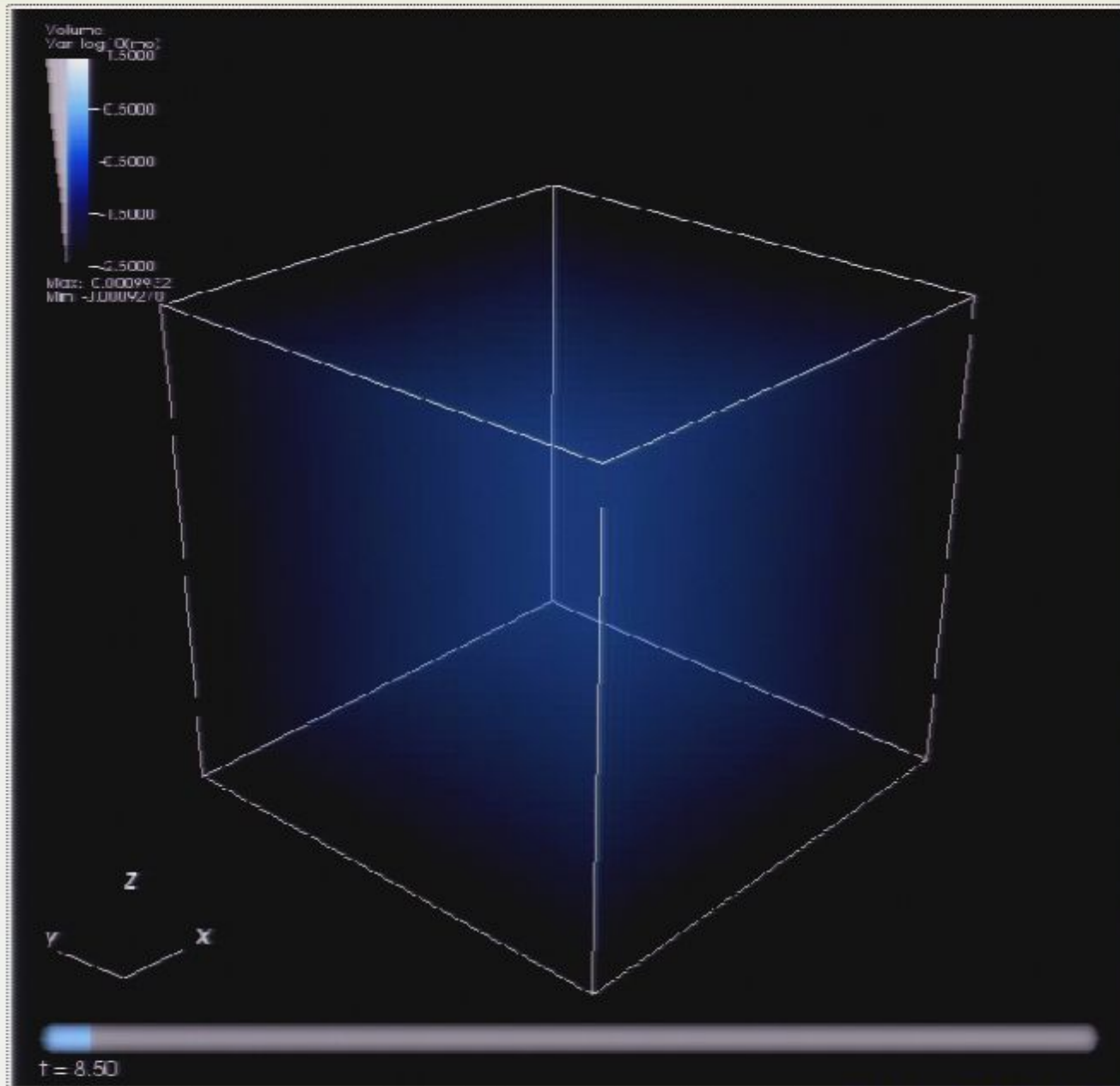
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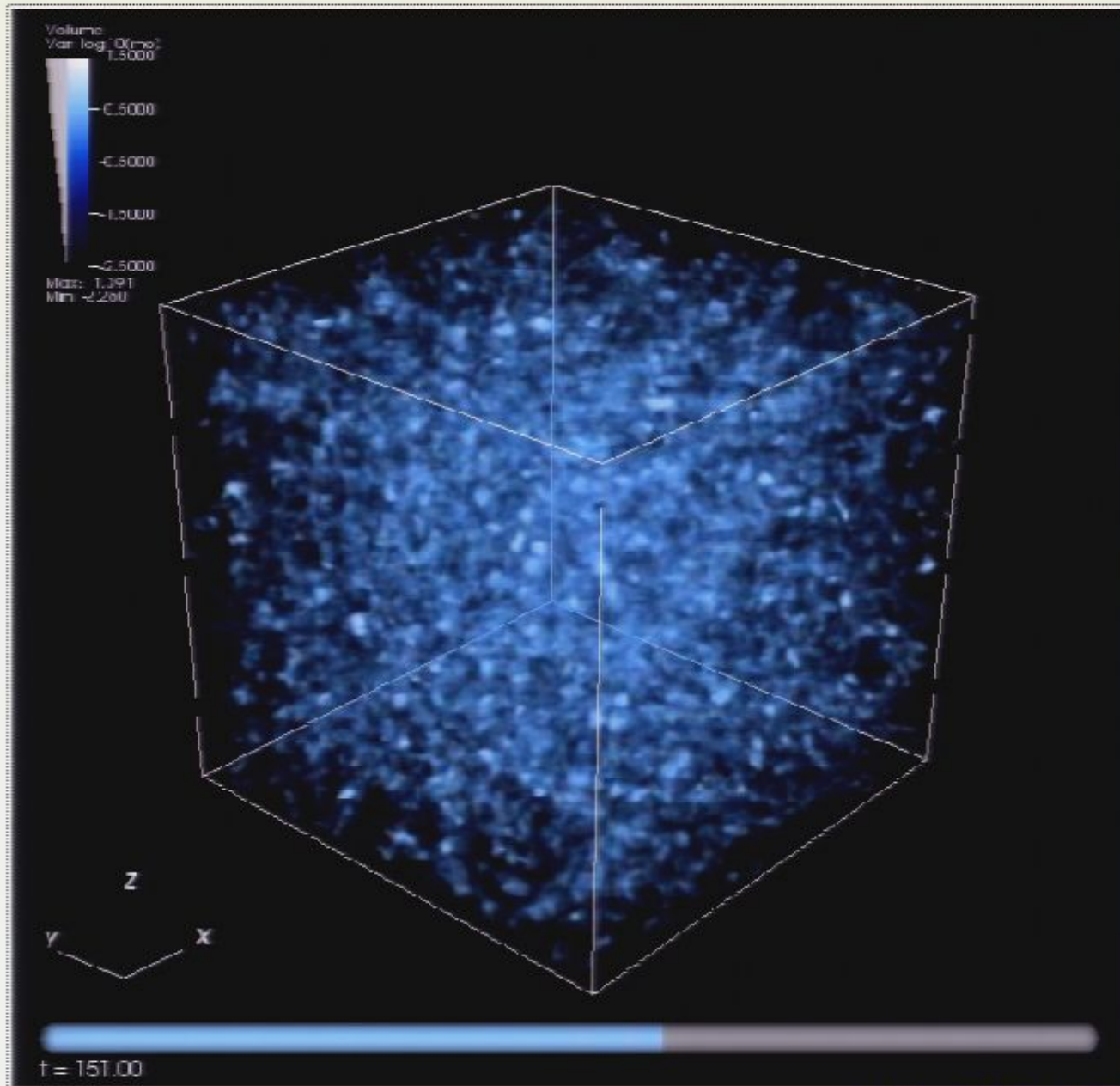
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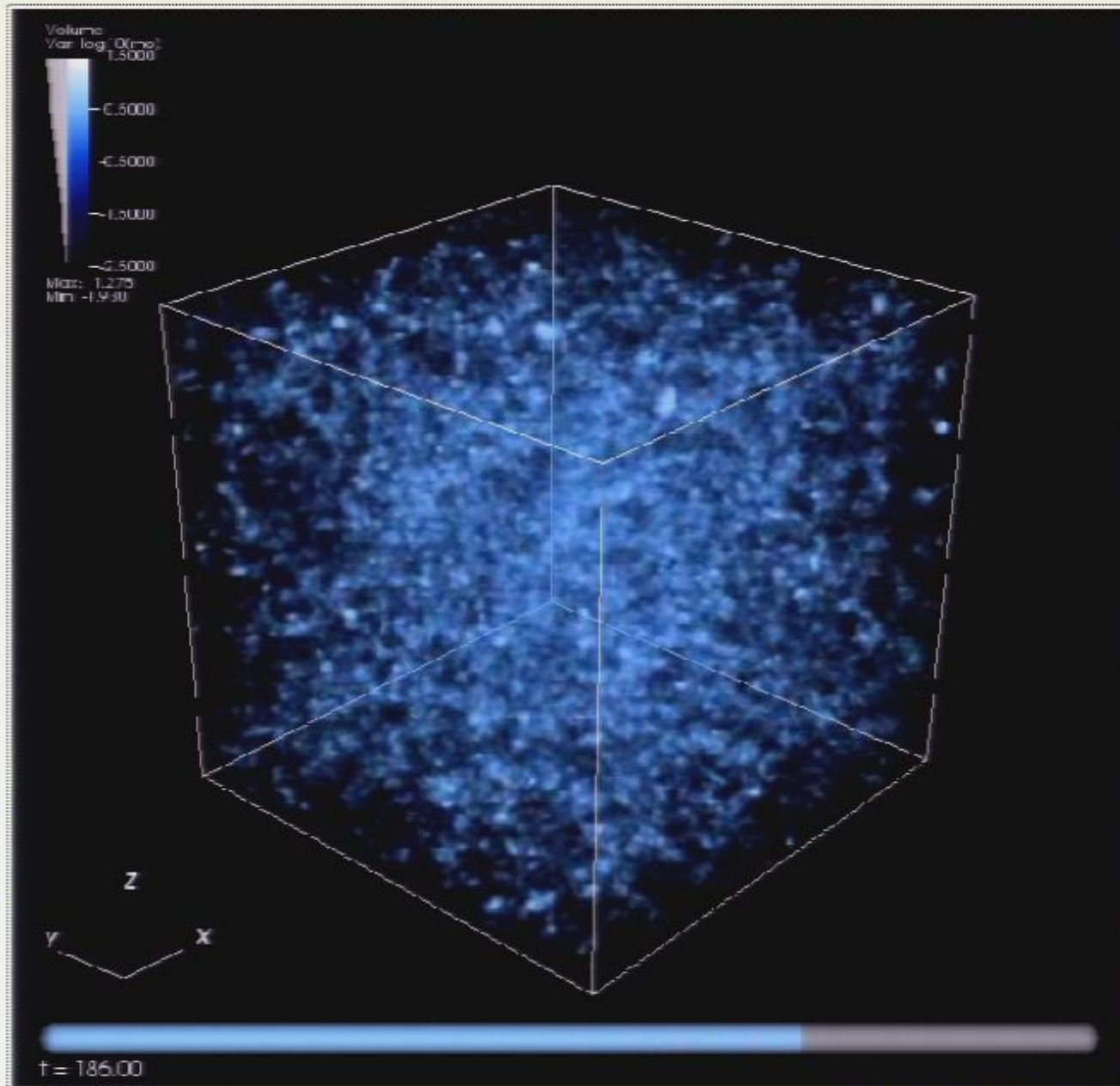
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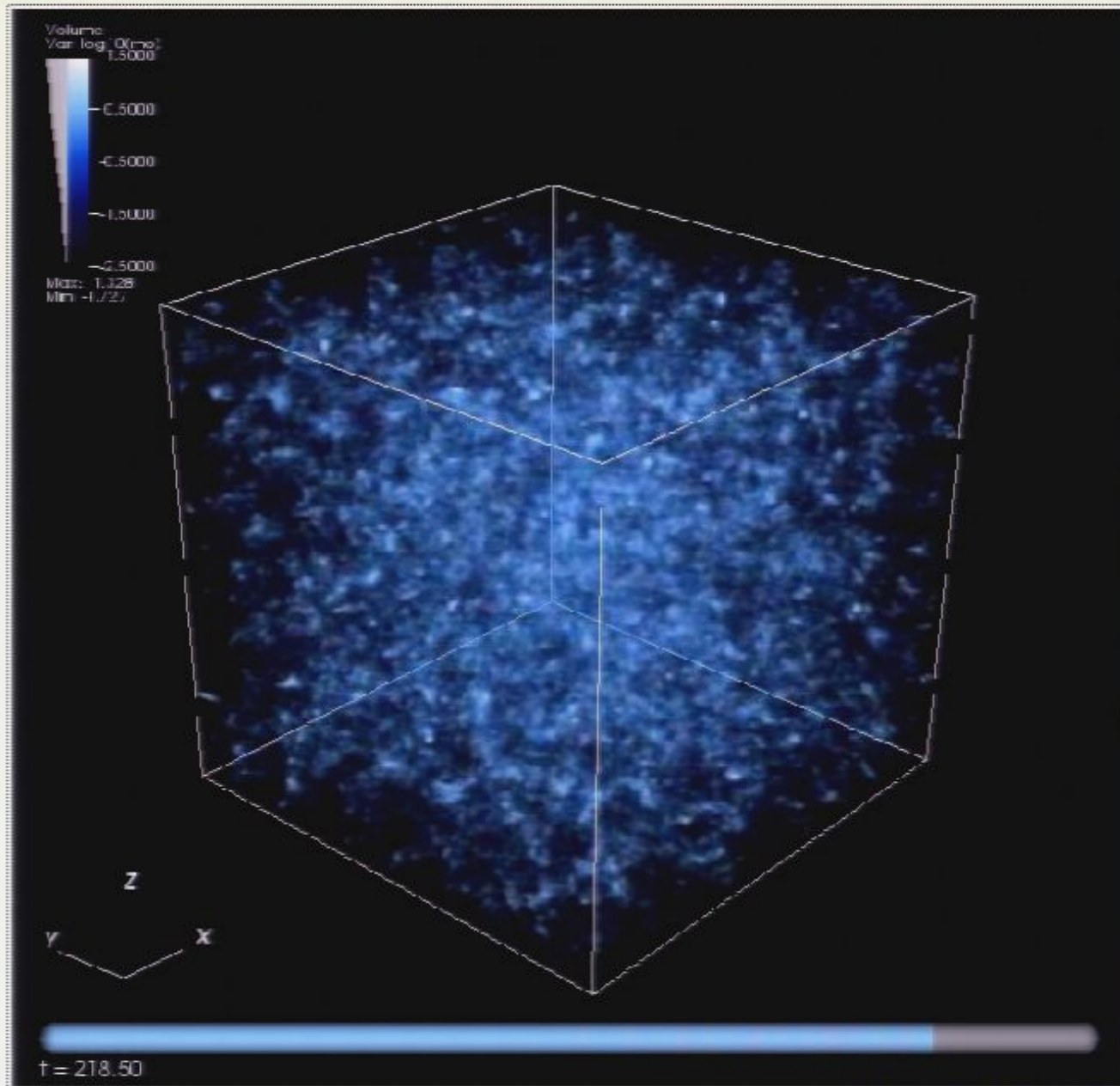
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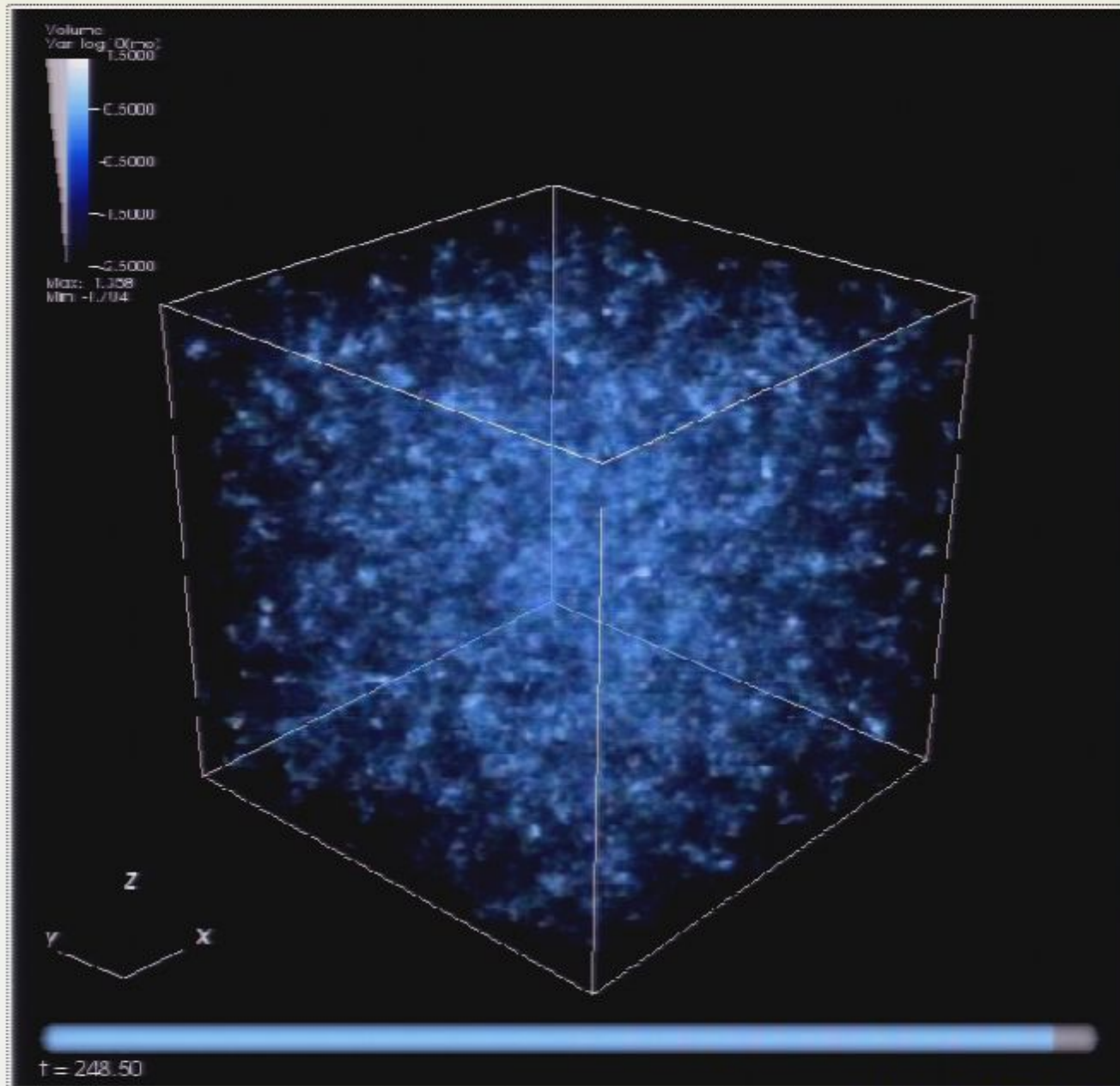
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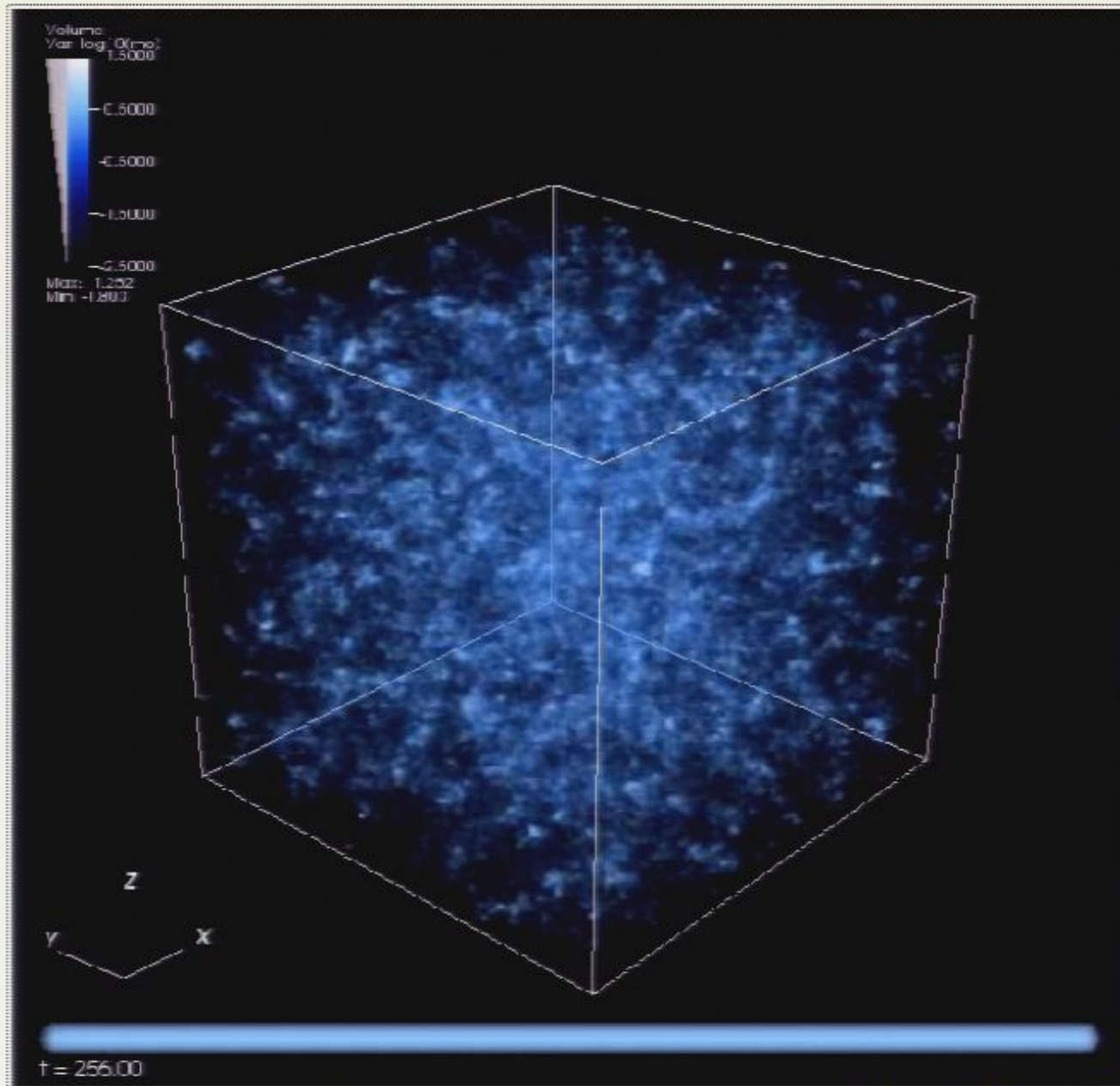
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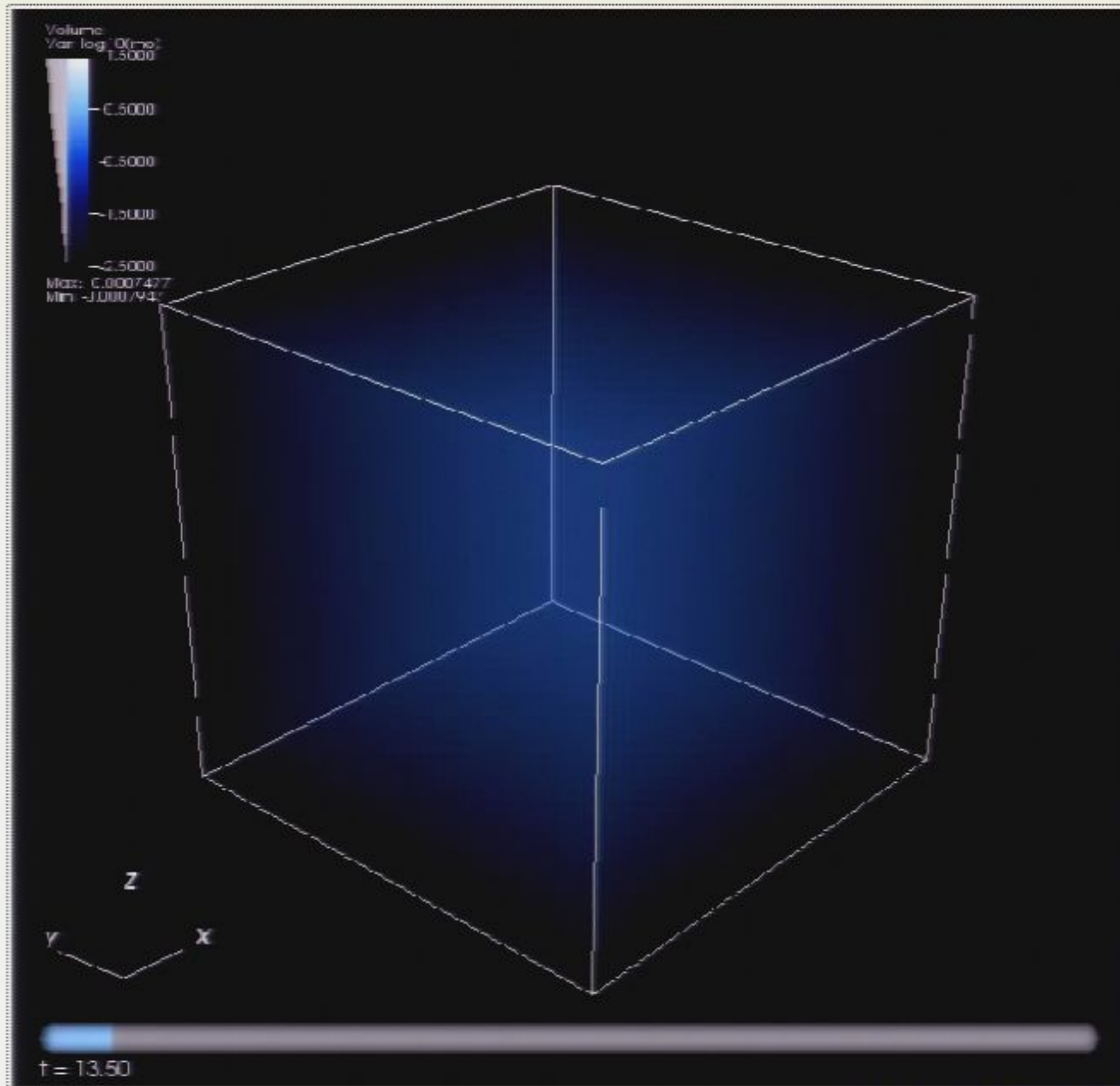
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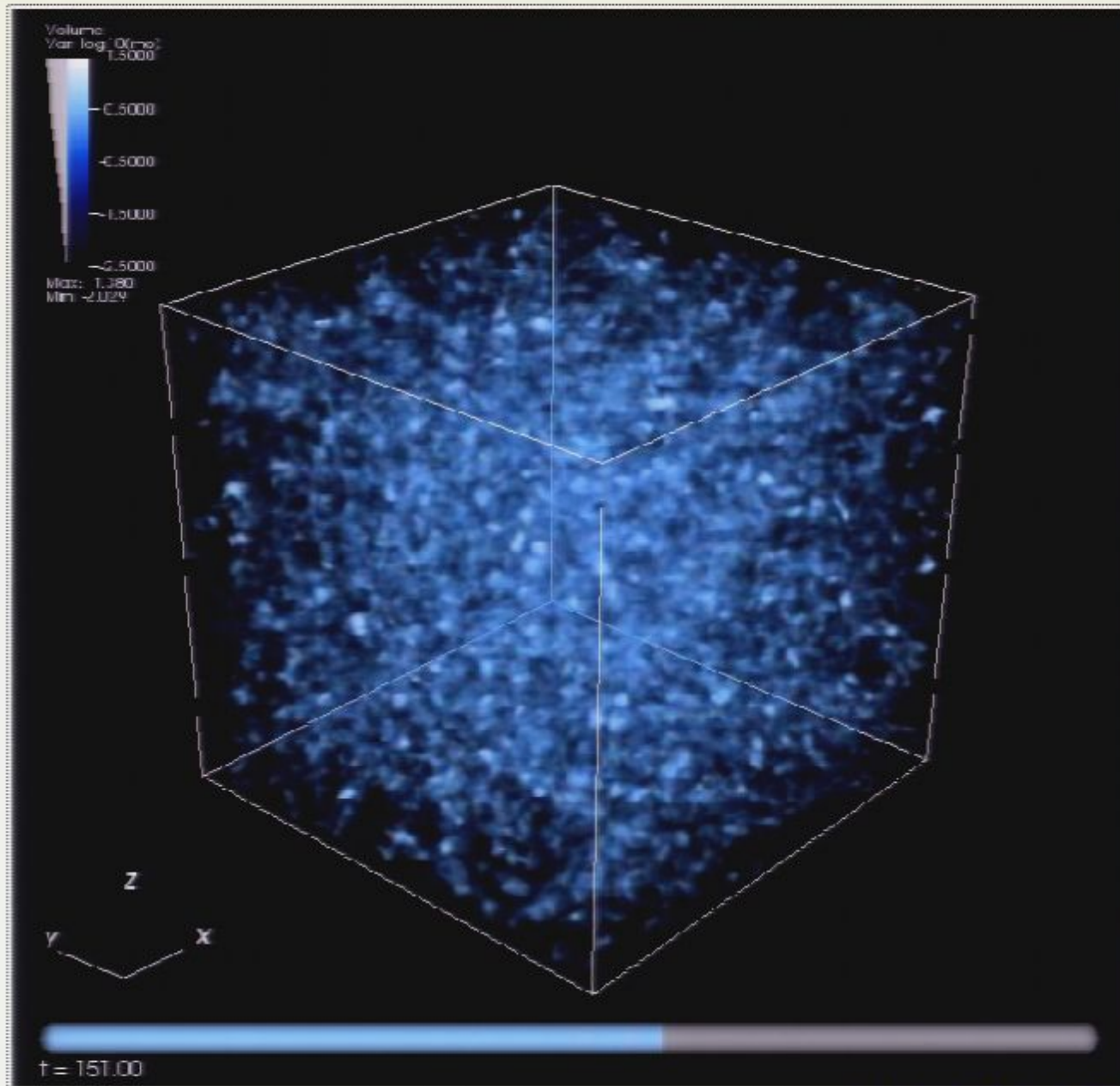
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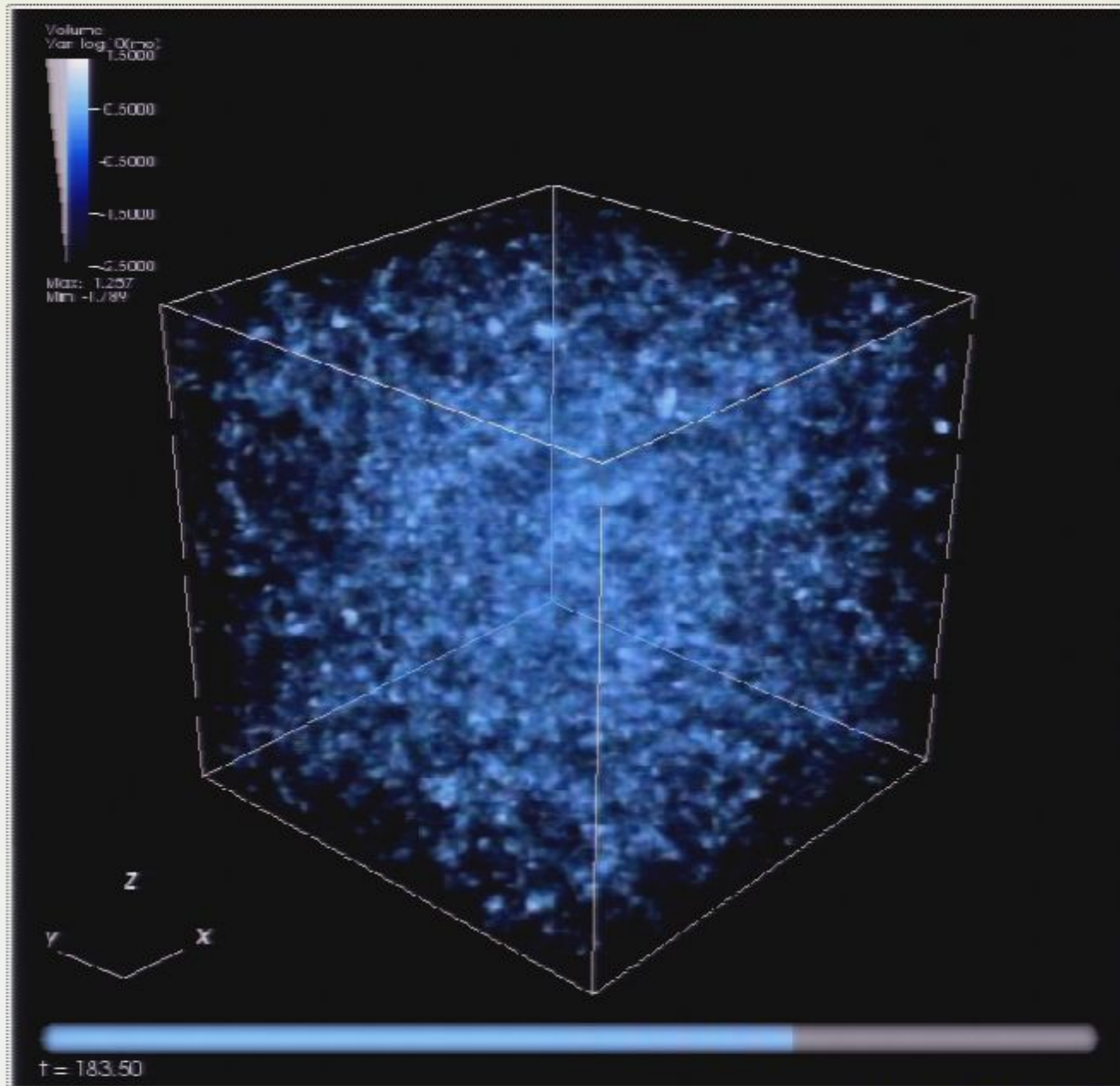
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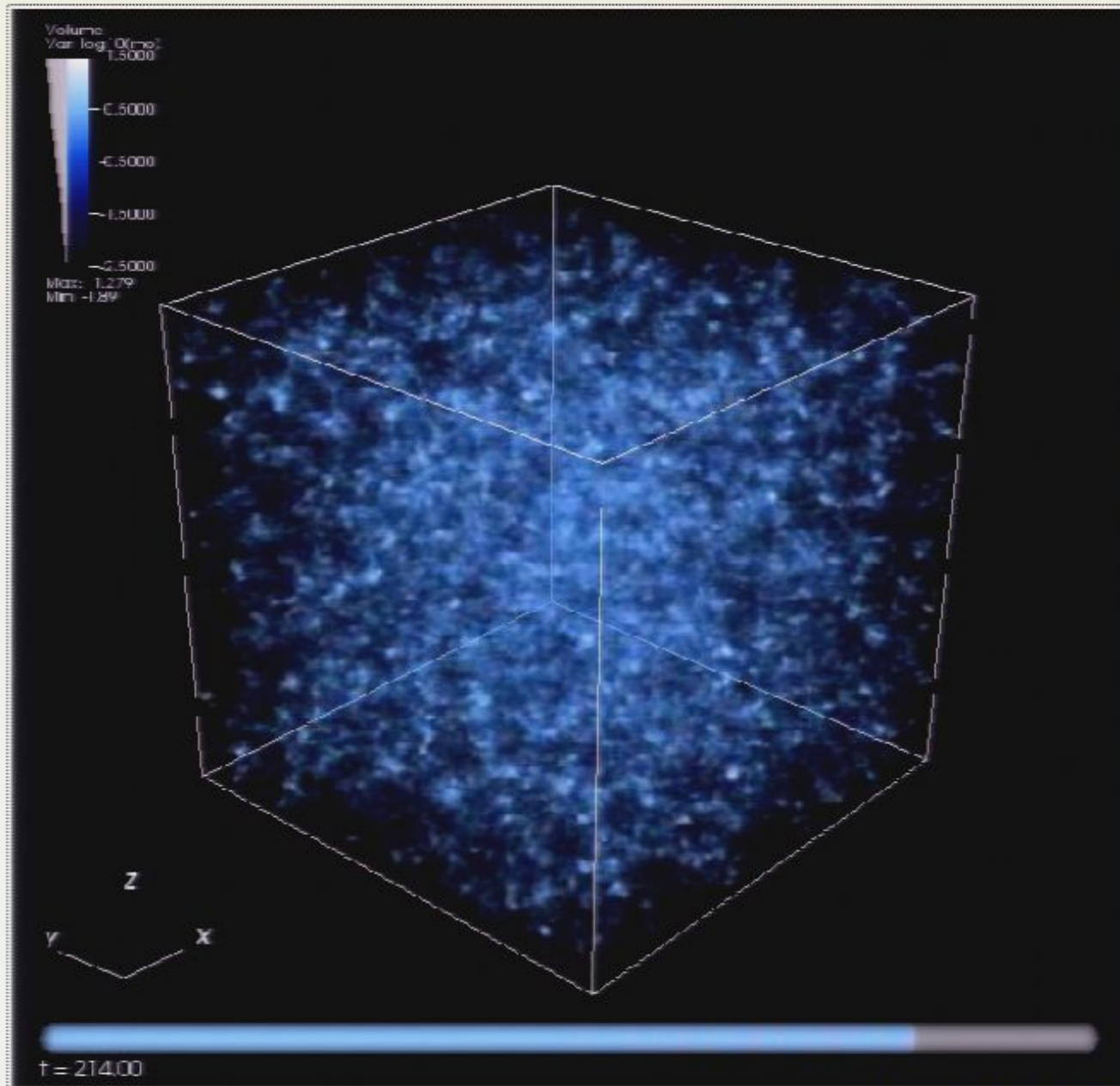
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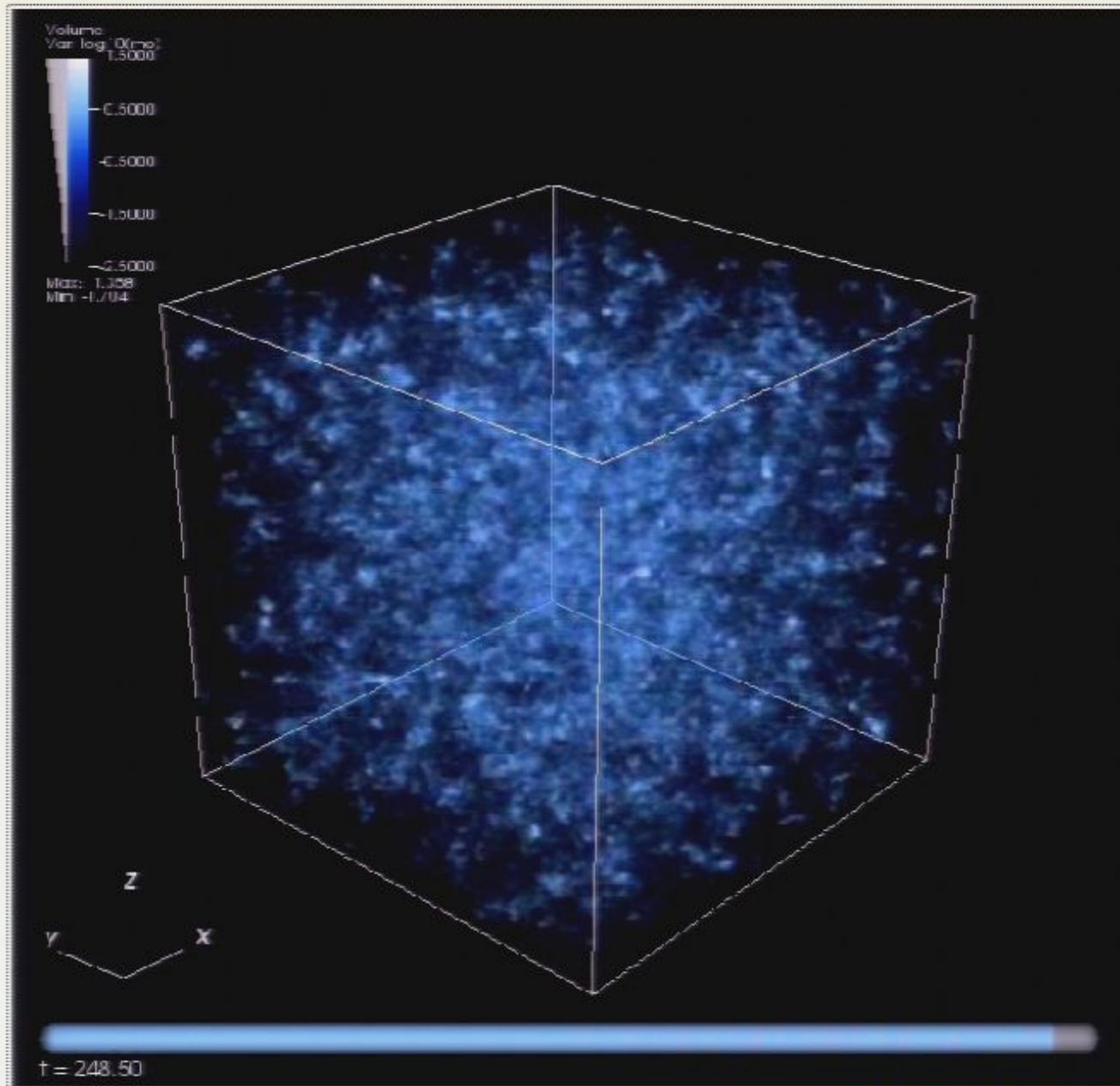
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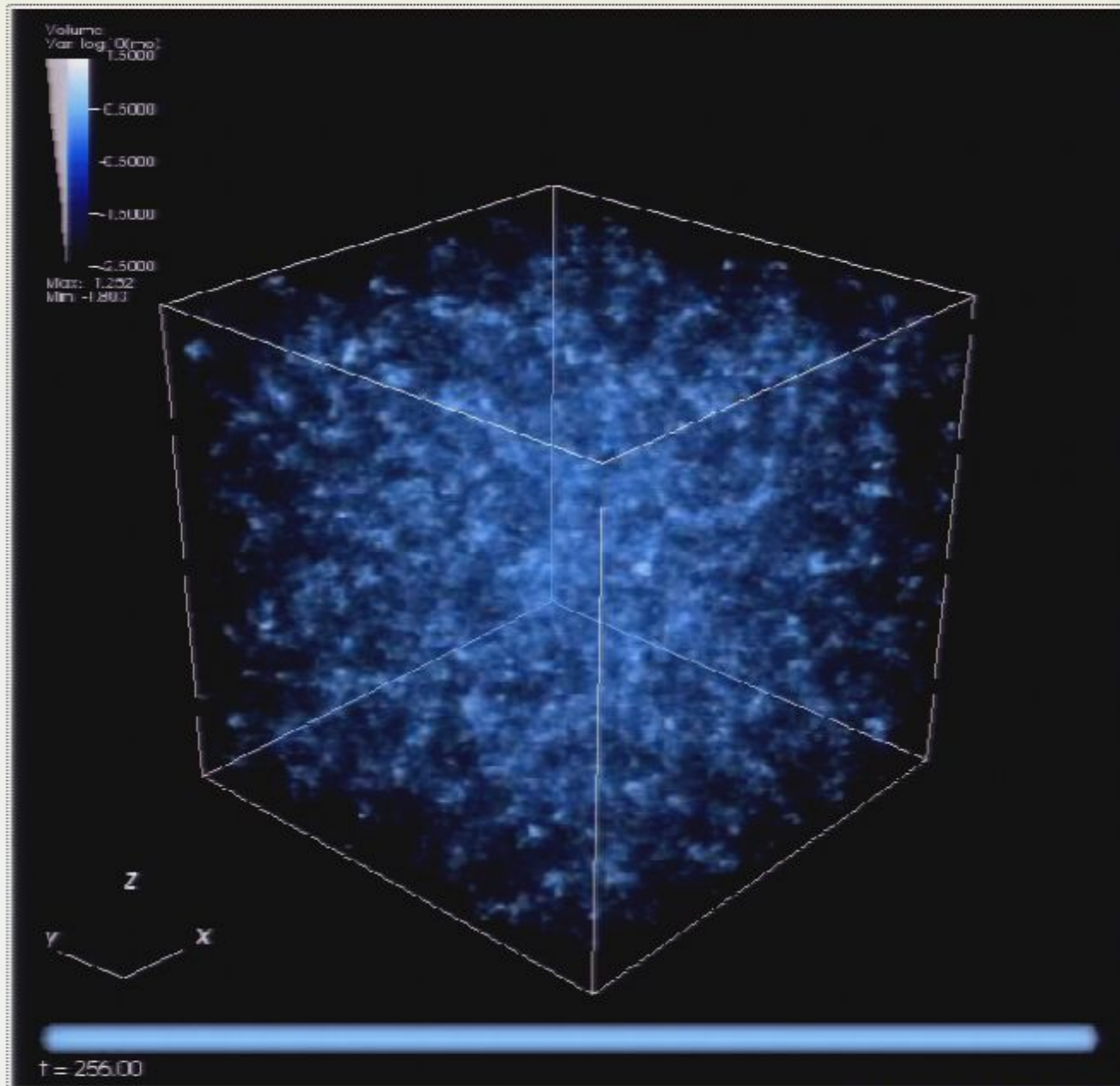
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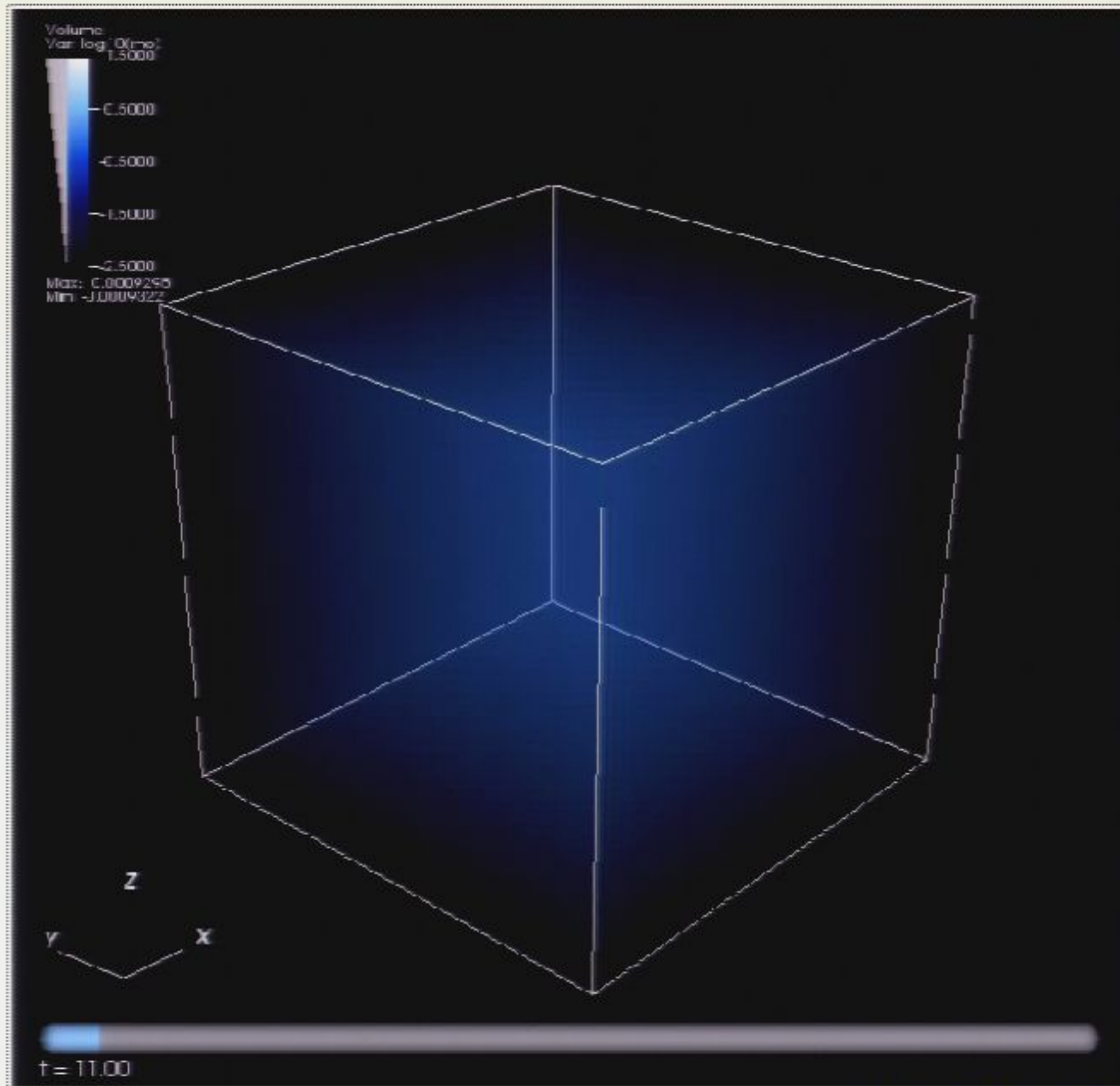
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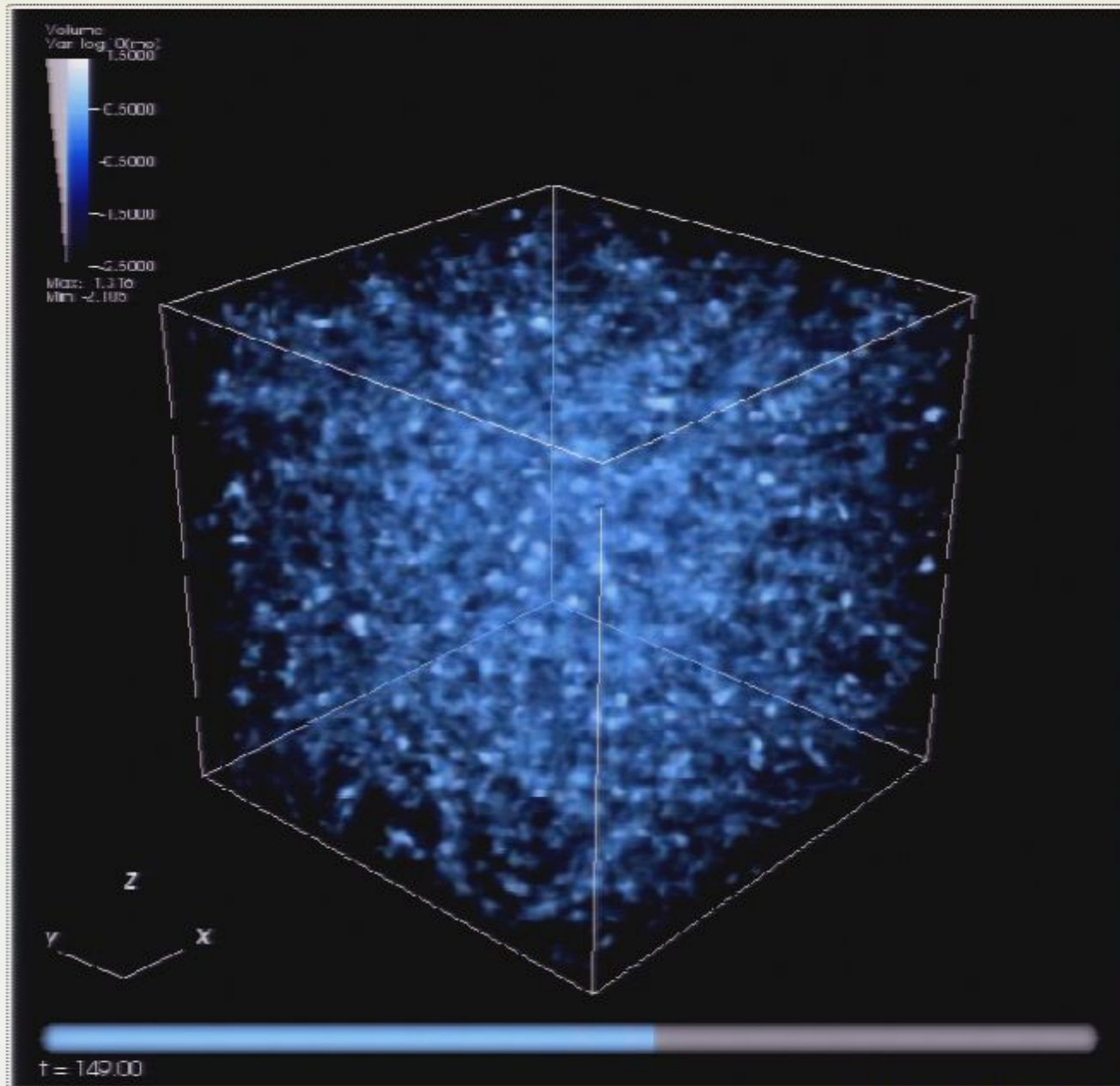
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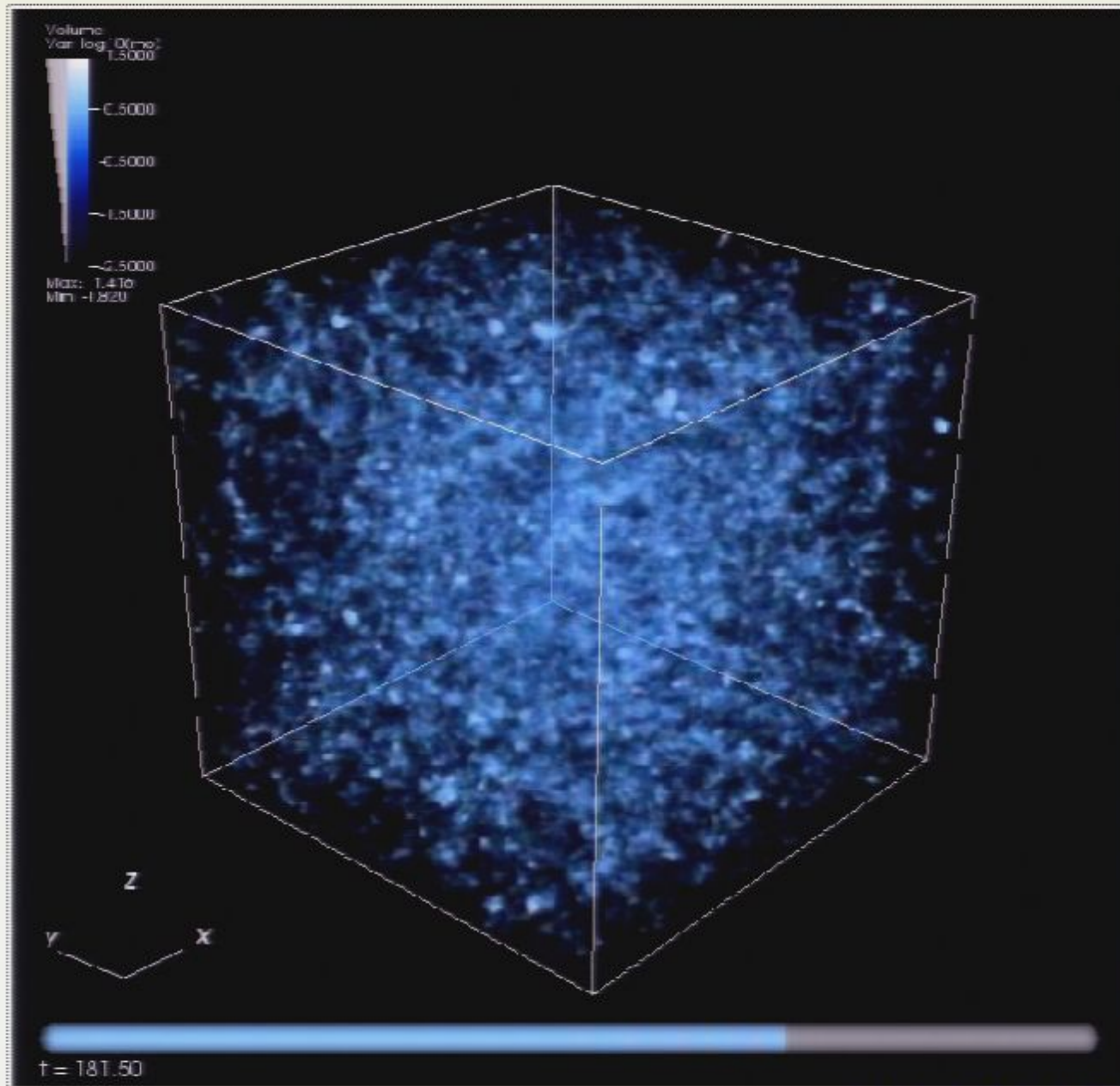
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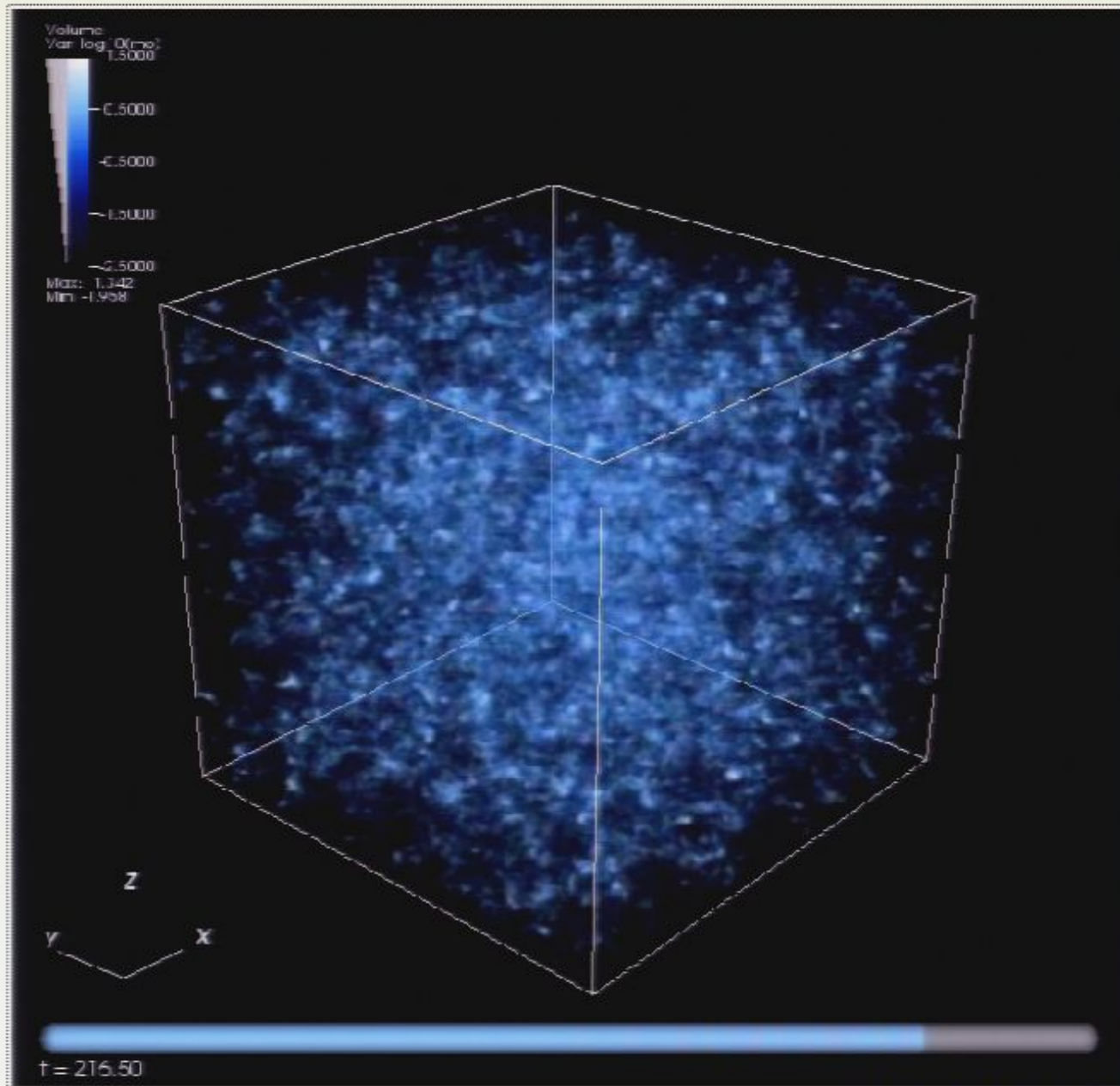
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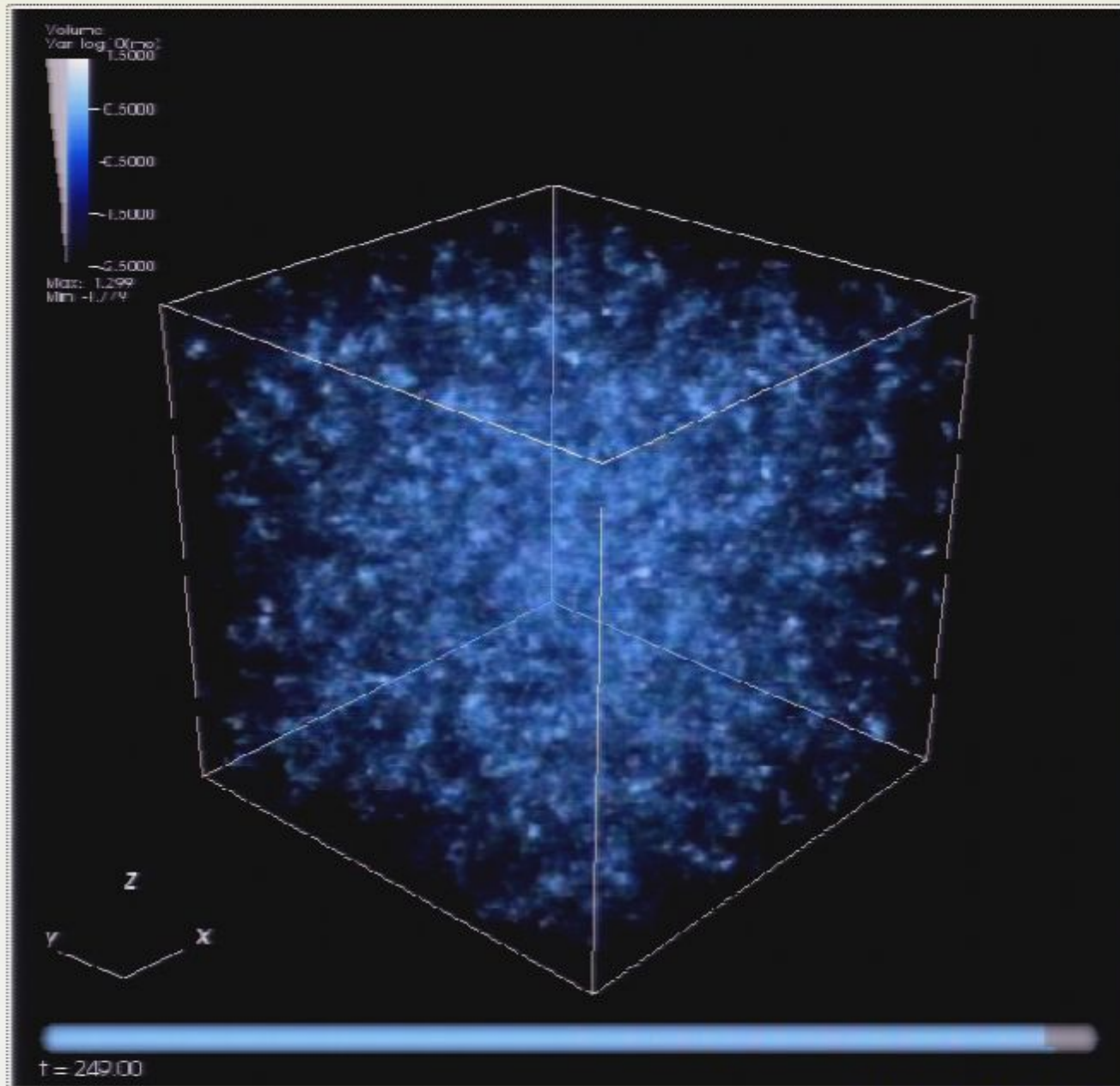
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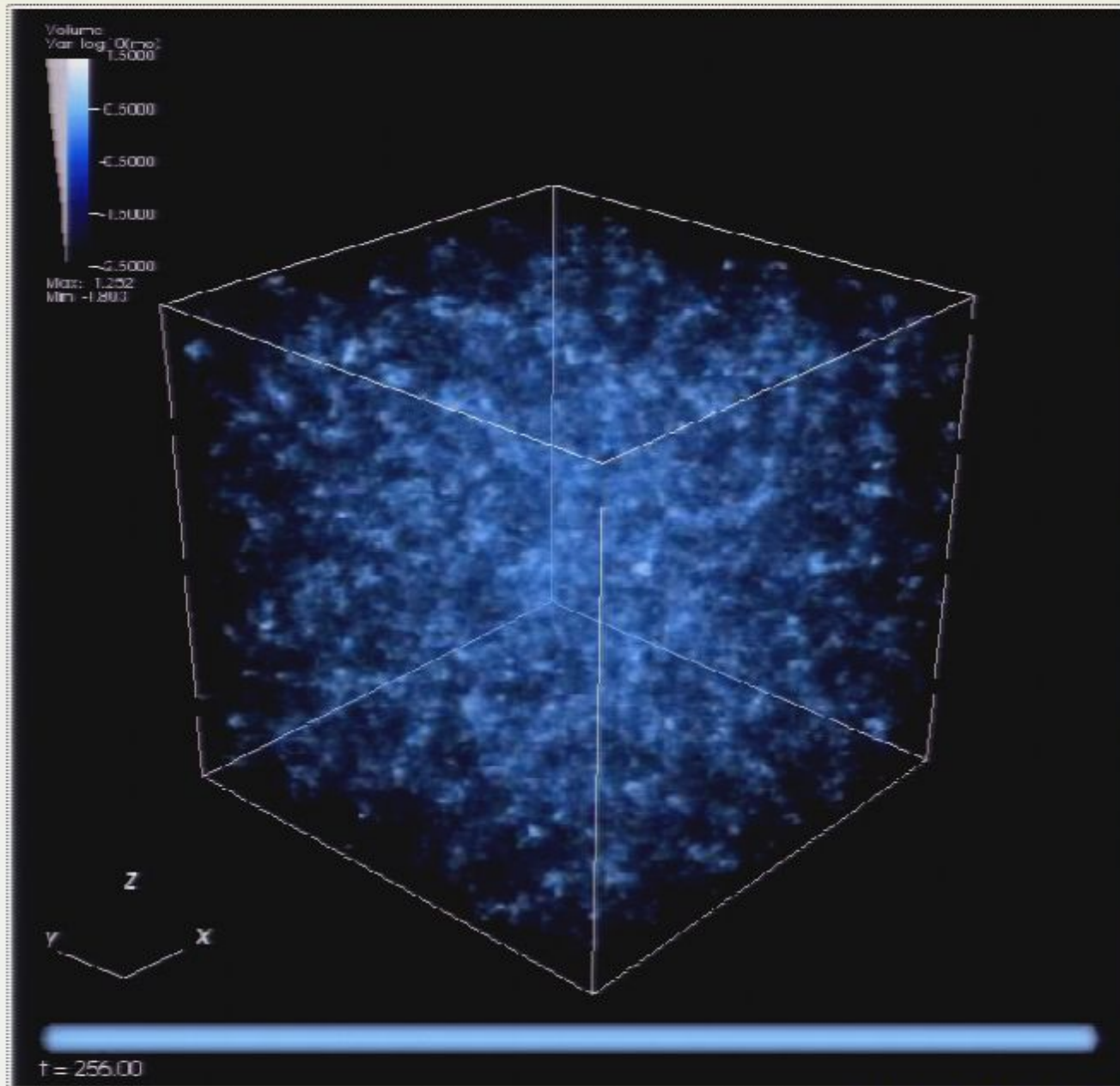
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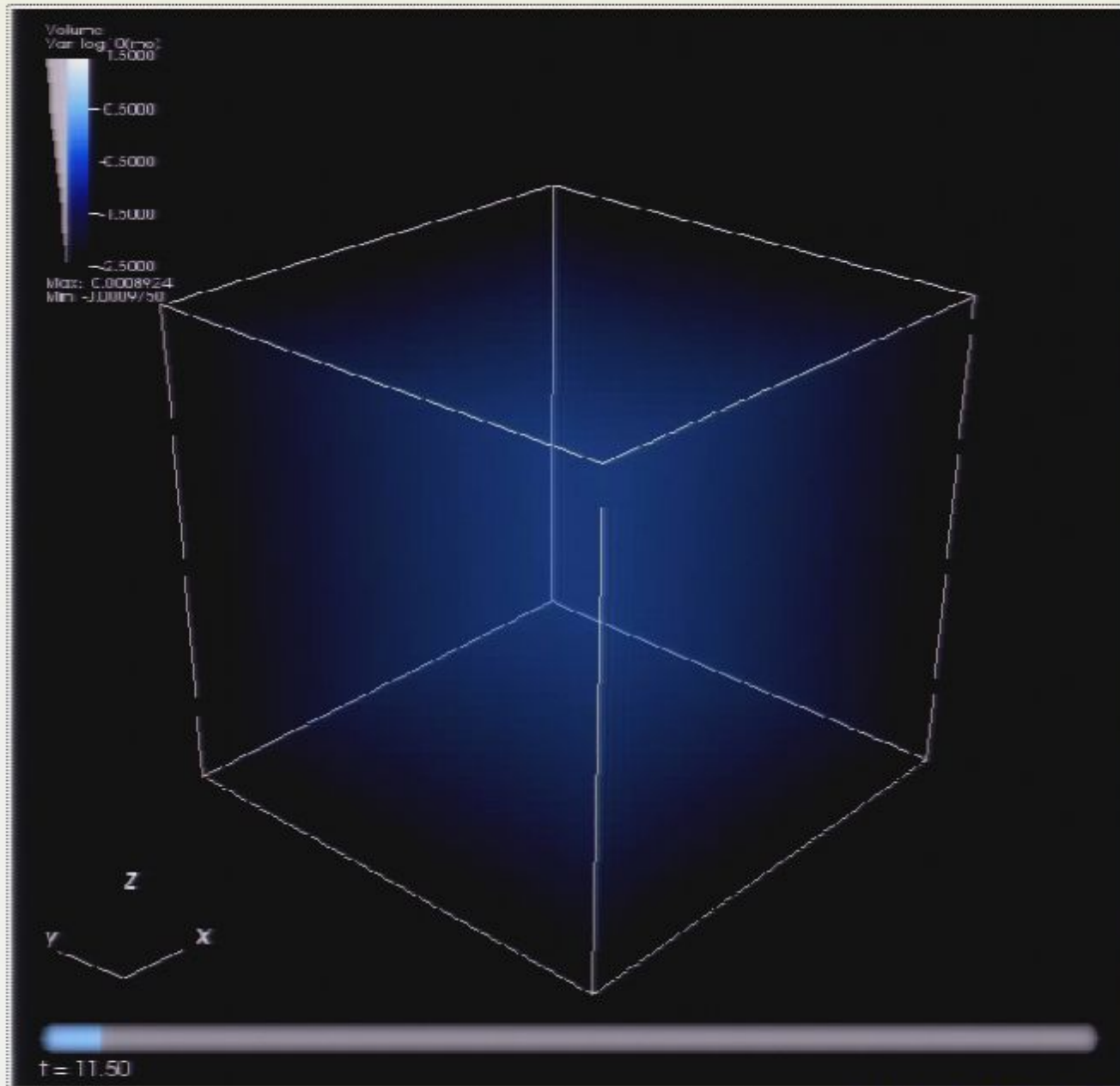
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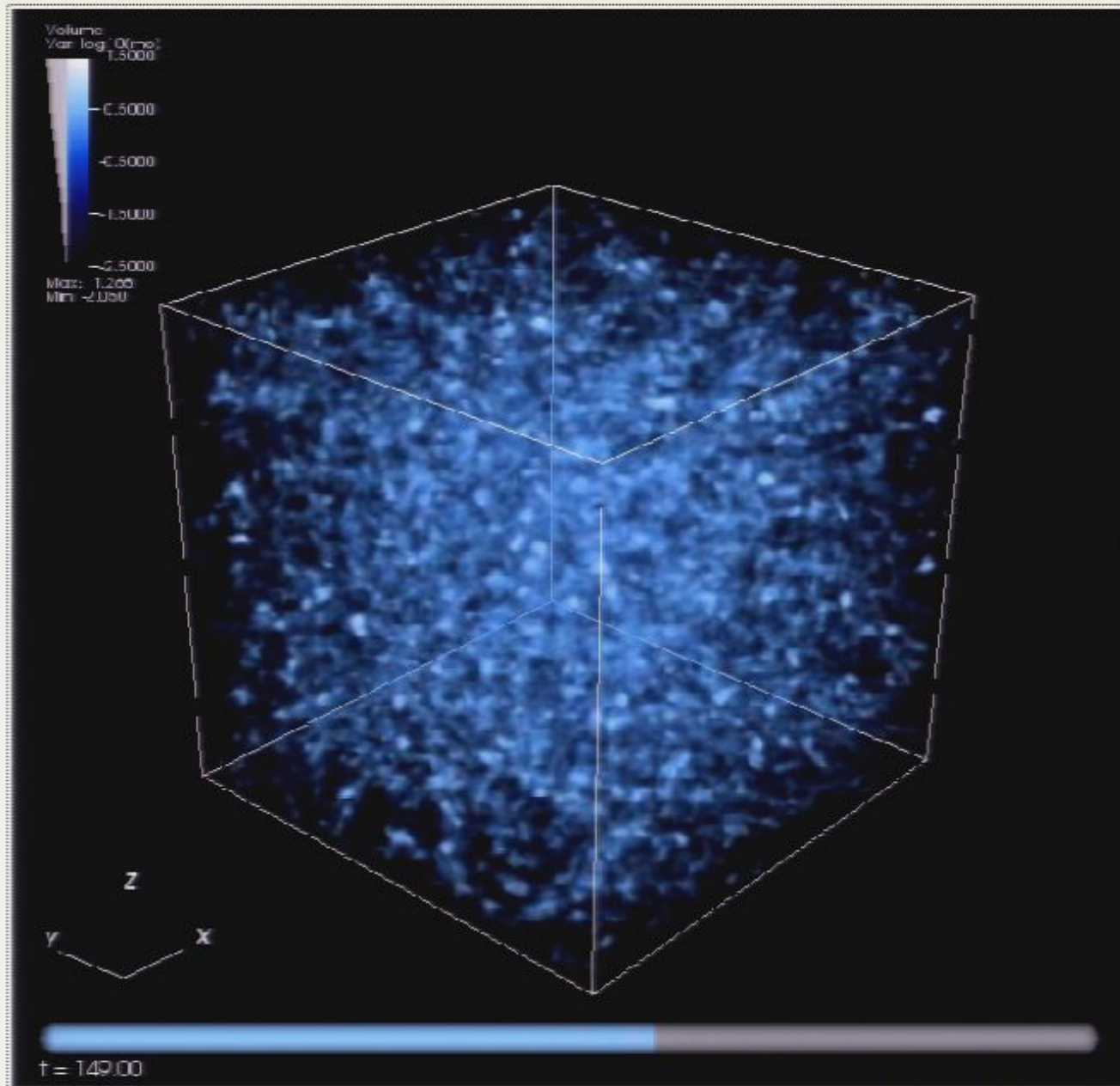
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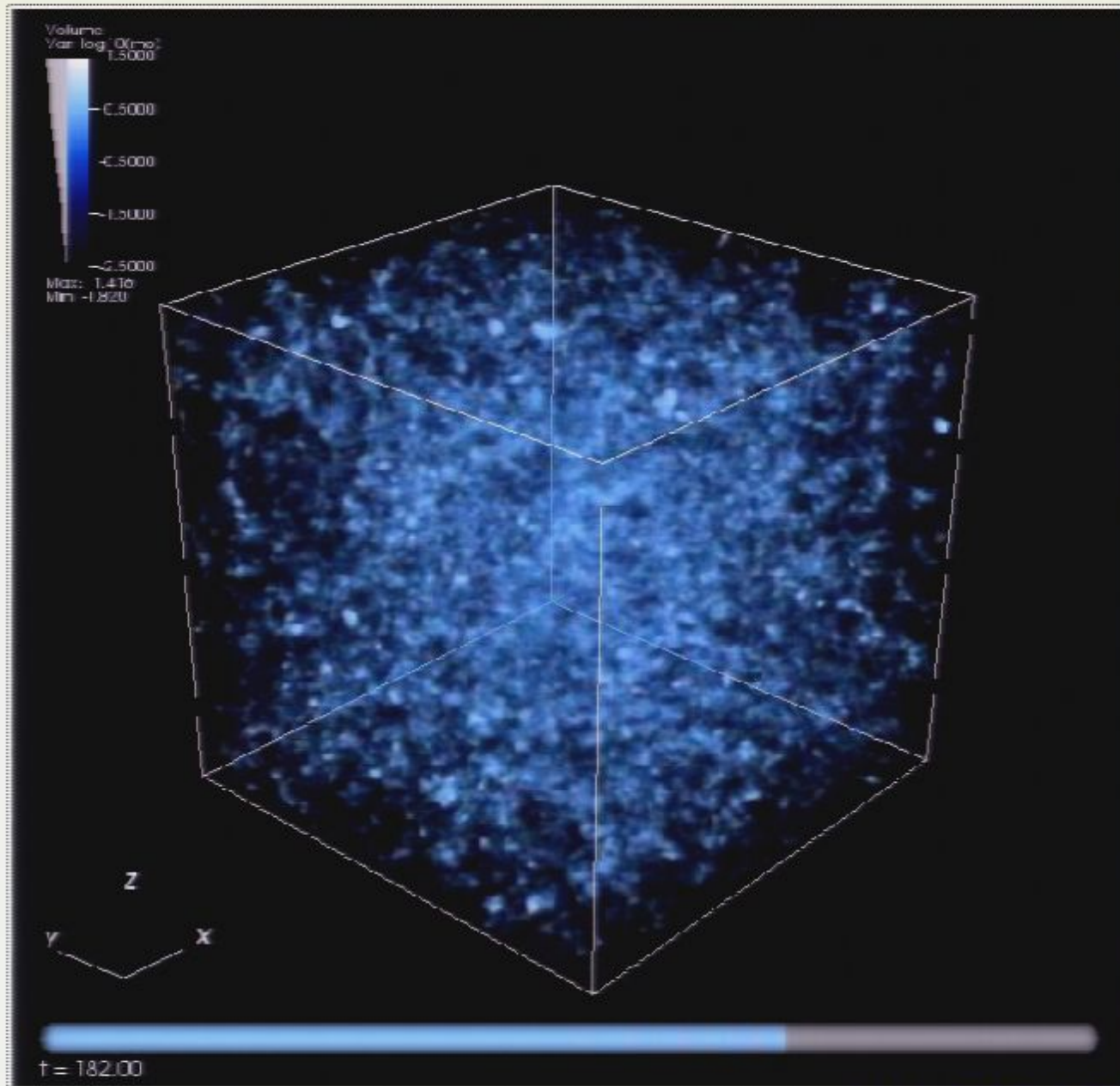
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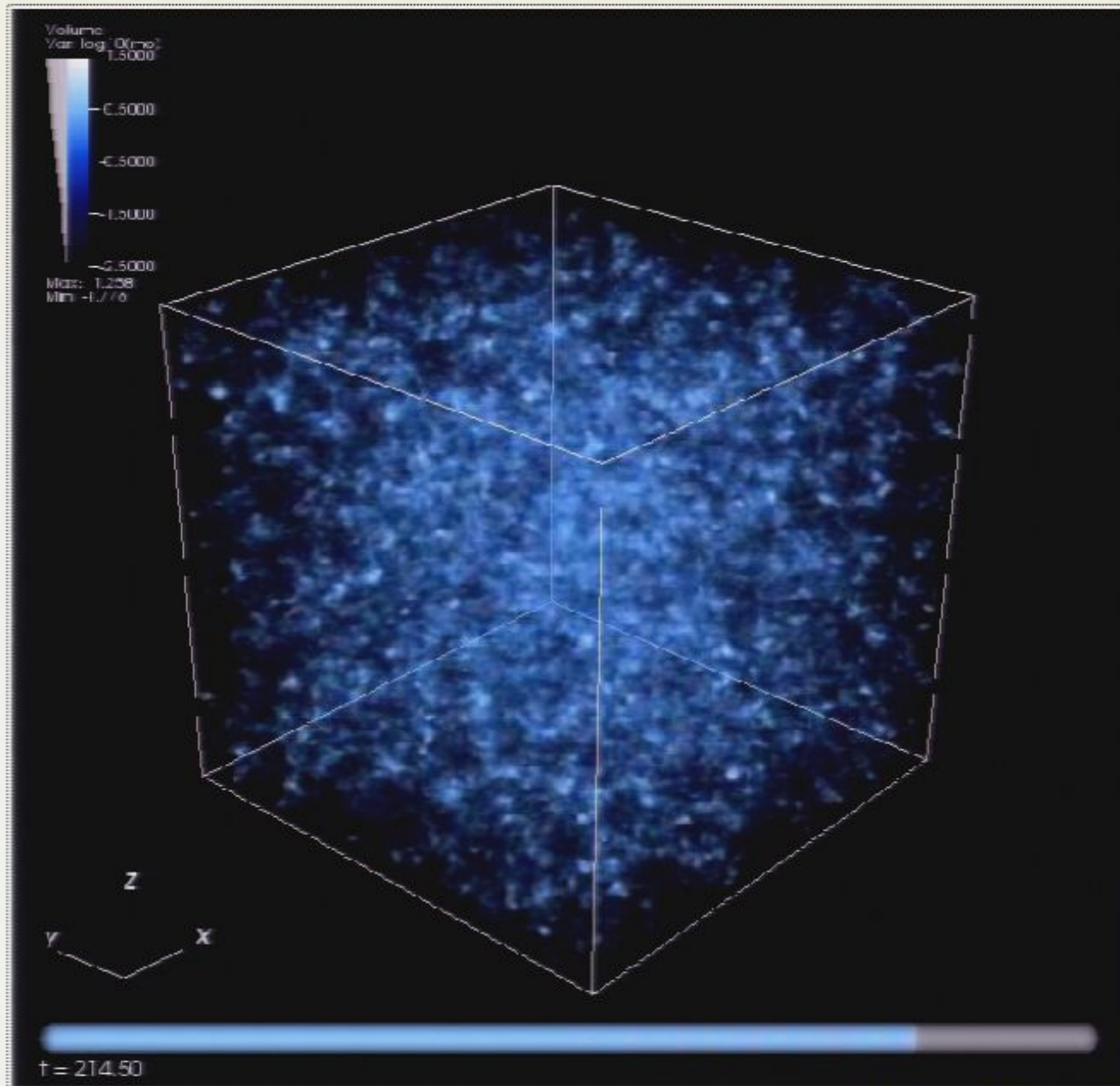
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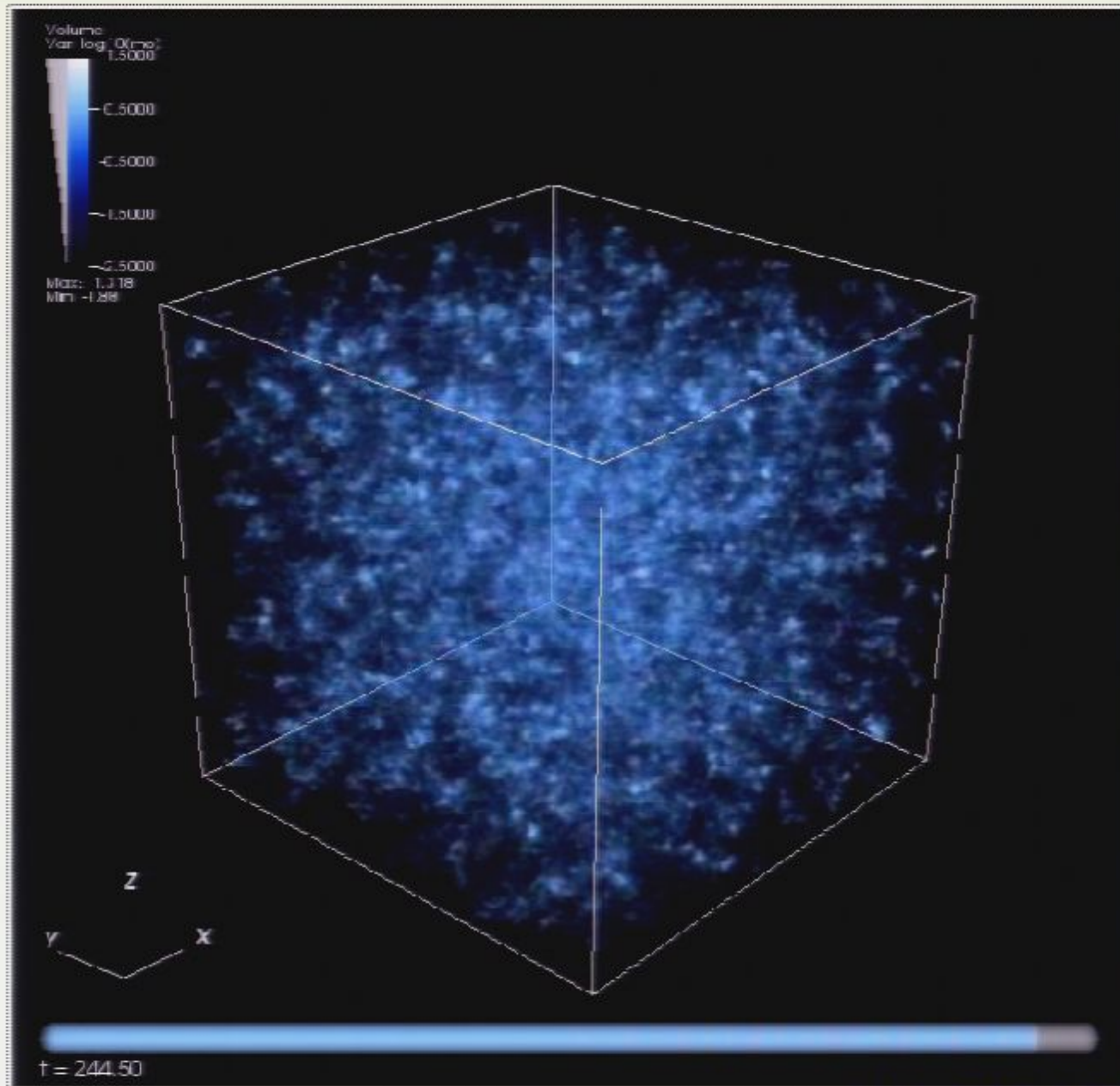
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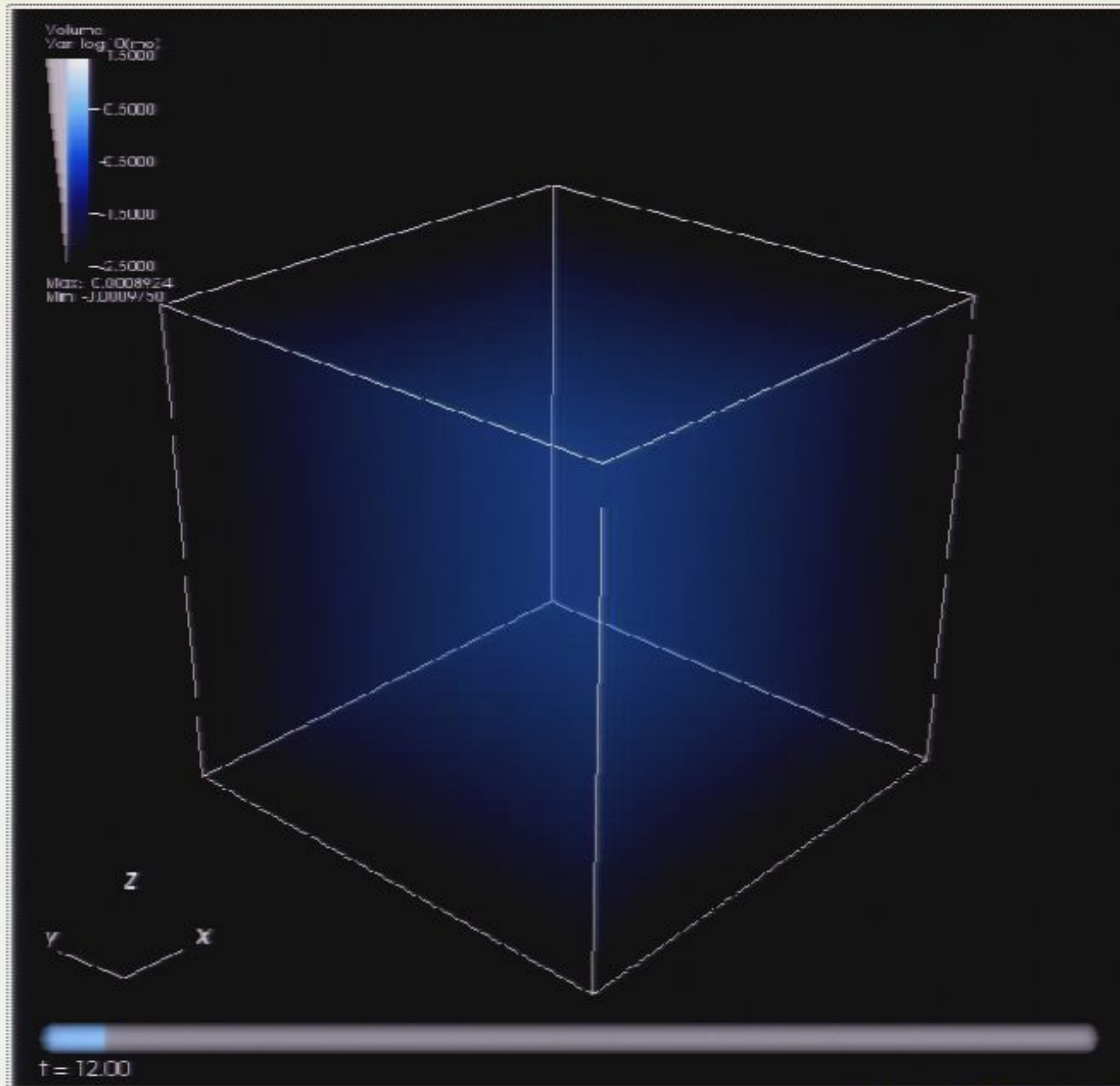
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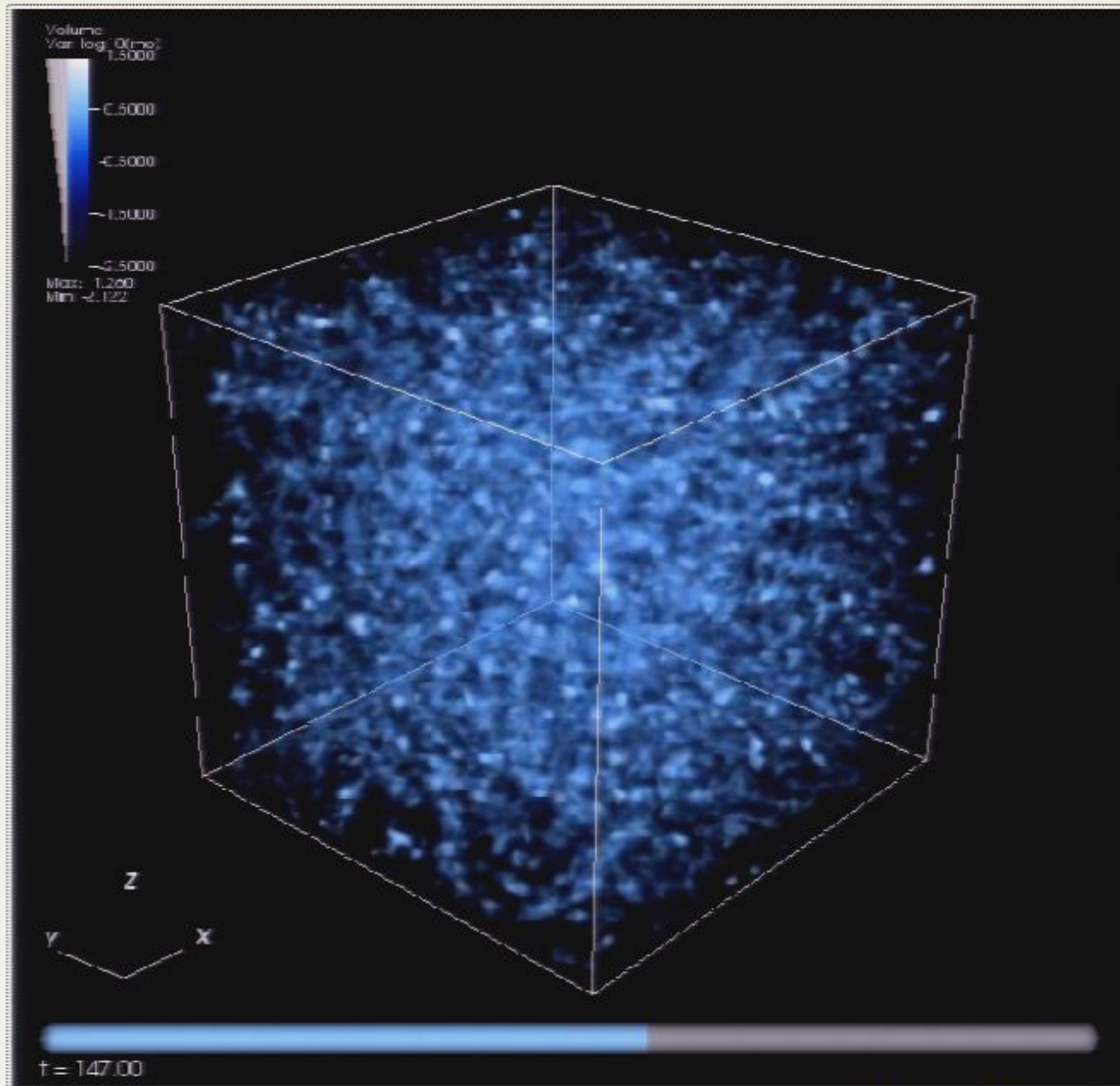
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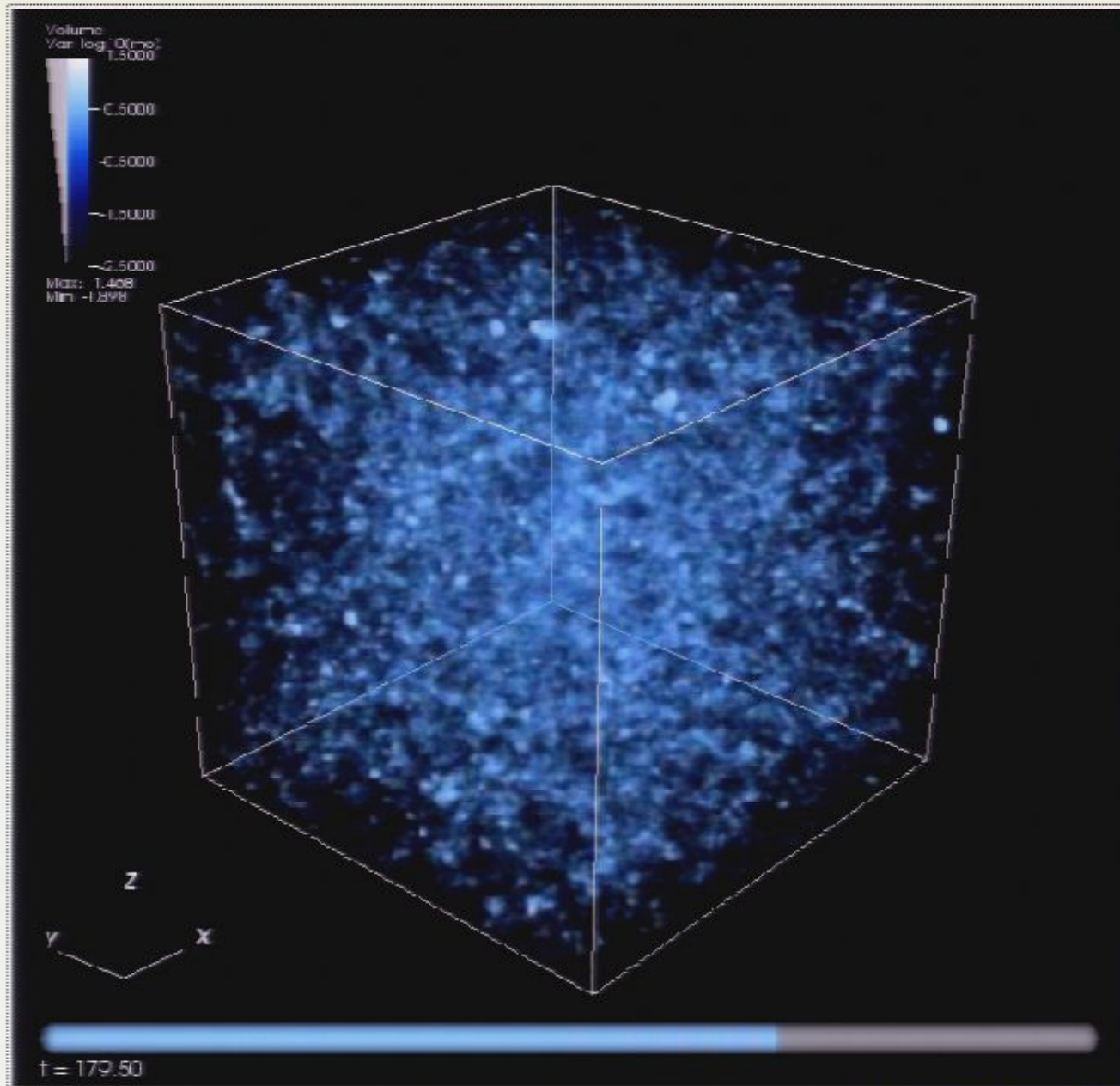
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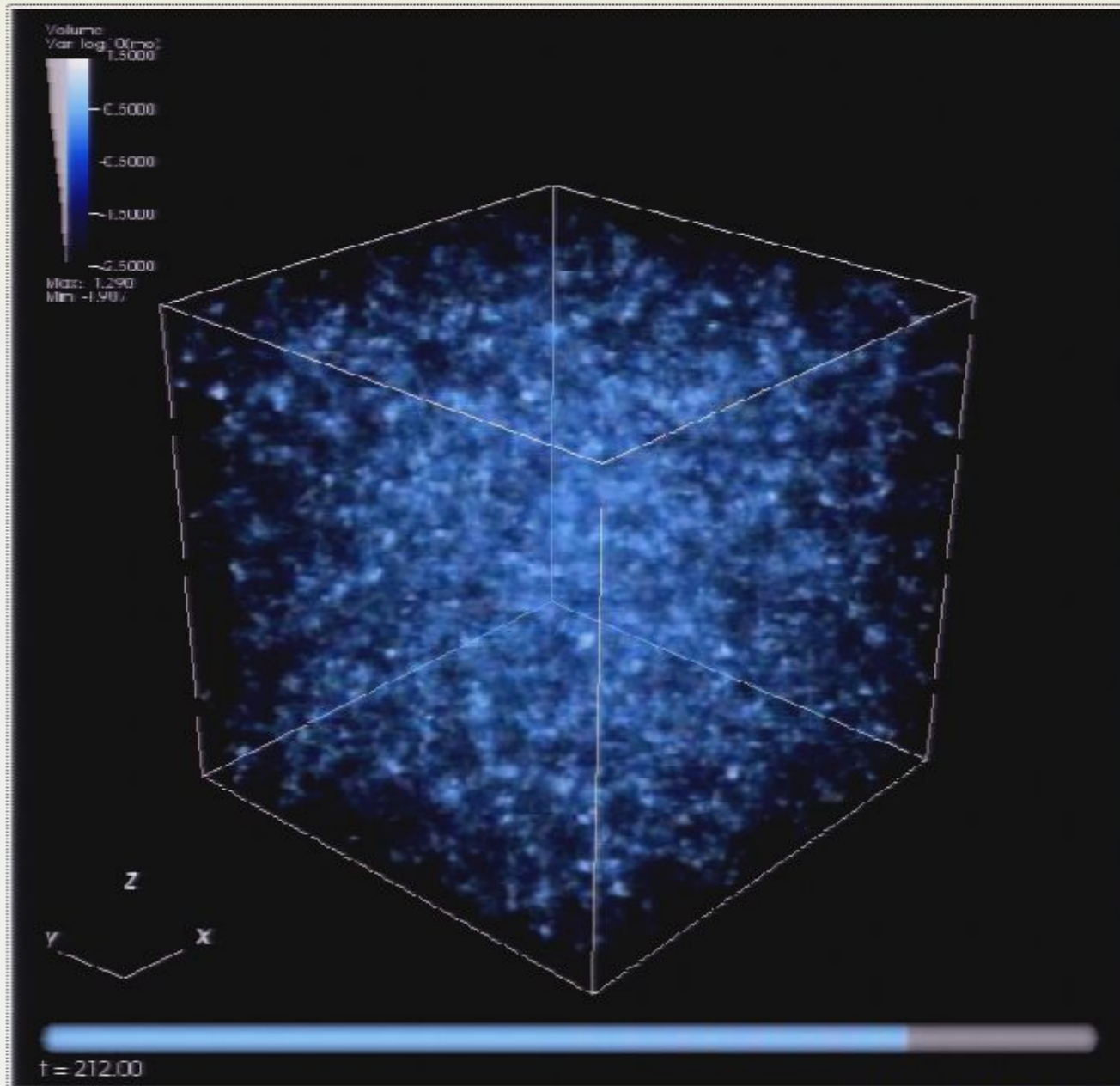
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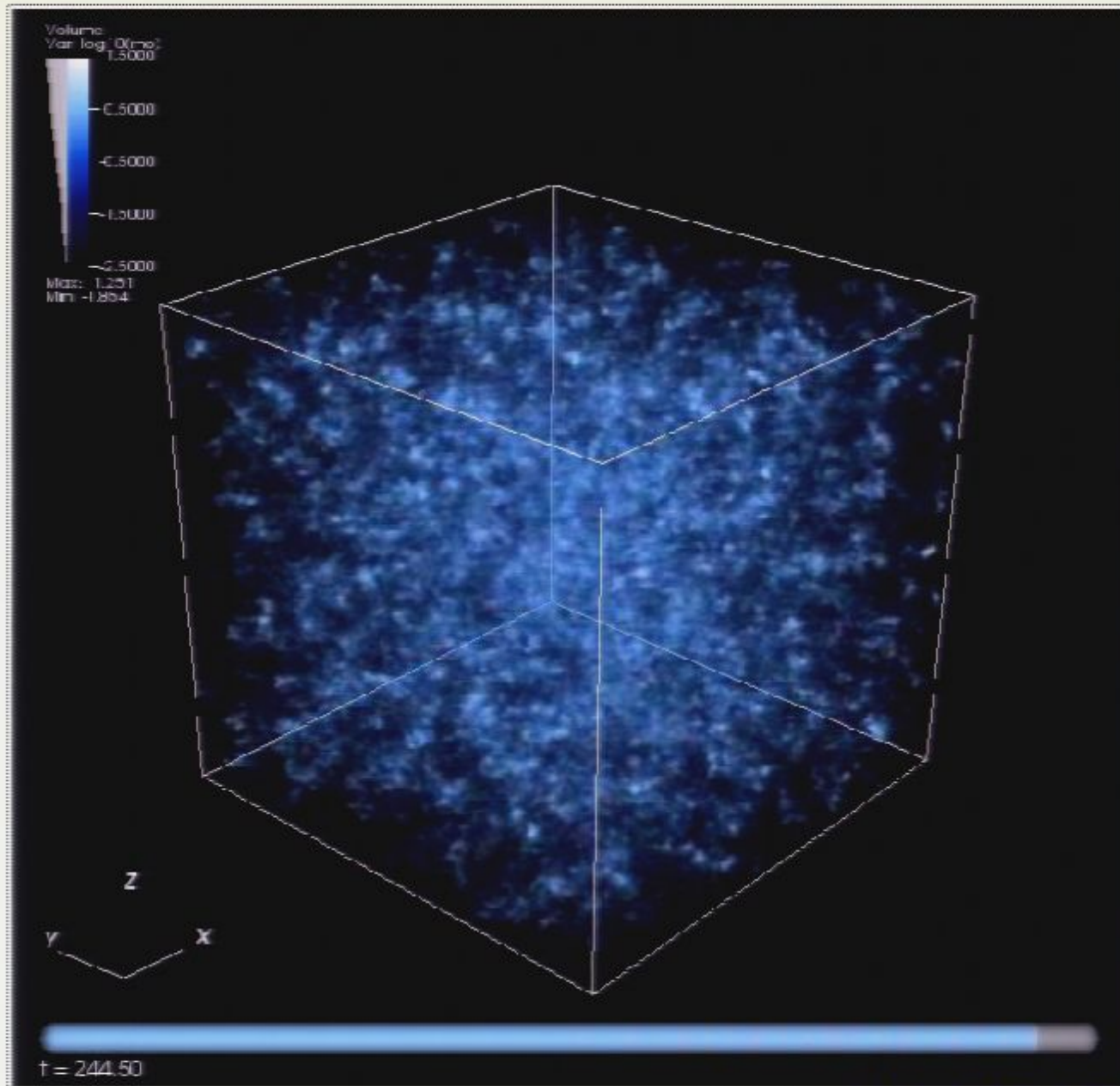
DENSITY EVOLUTION DURING PREHEATING



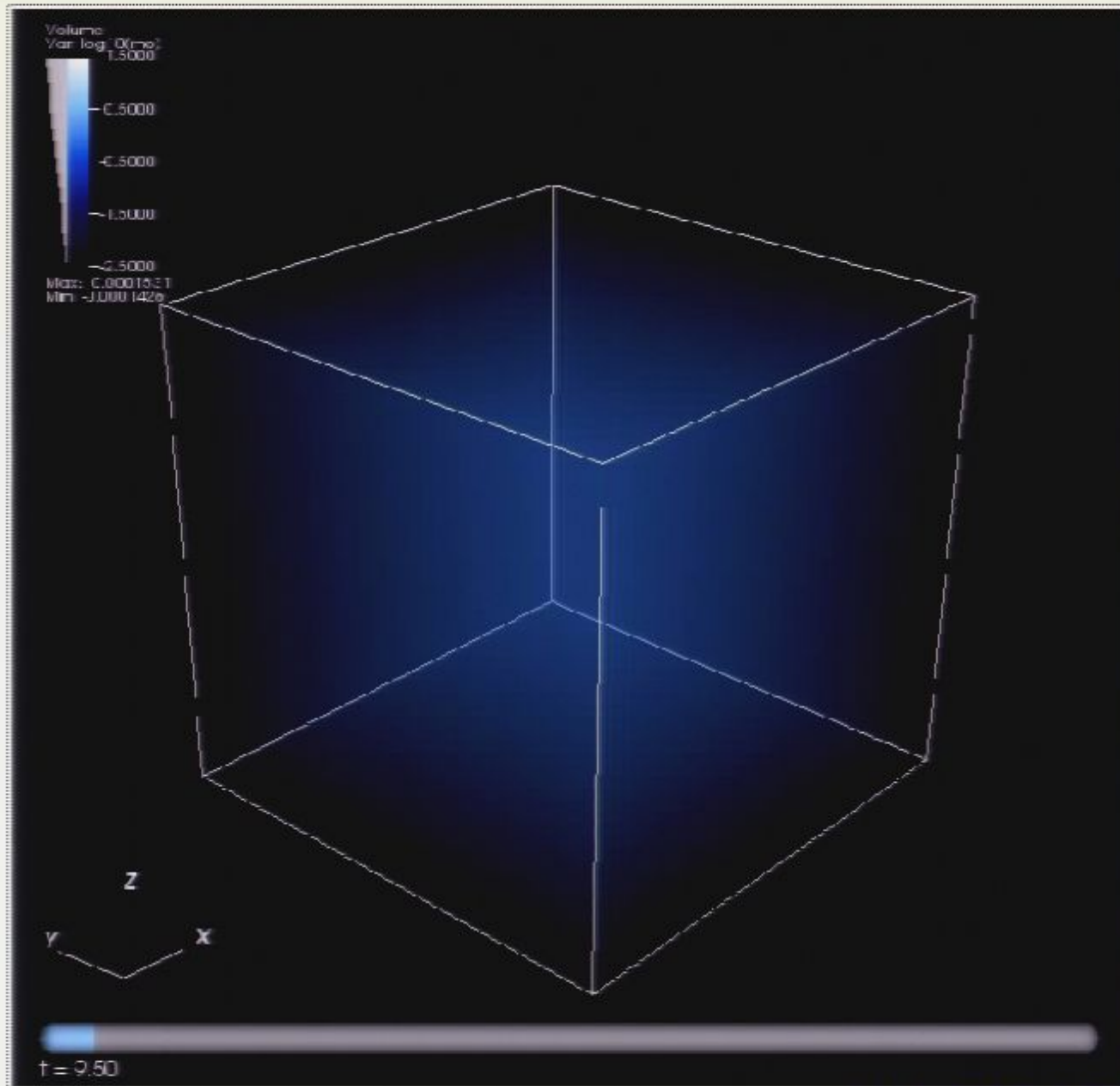
DENSITY EVOLUTION DURING PREHEATING



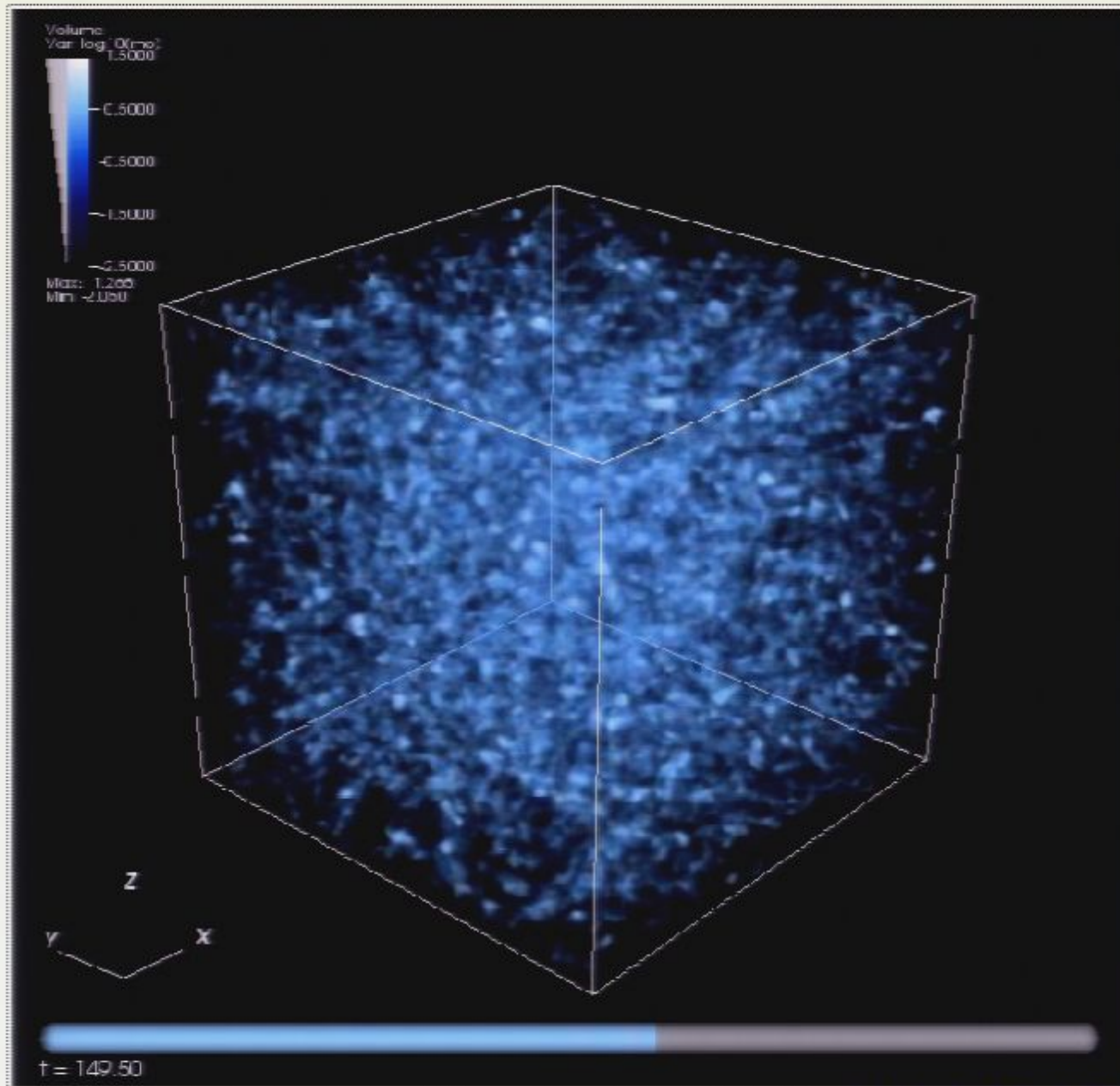
DENSITY EVOLUTION DURING PREHEATING



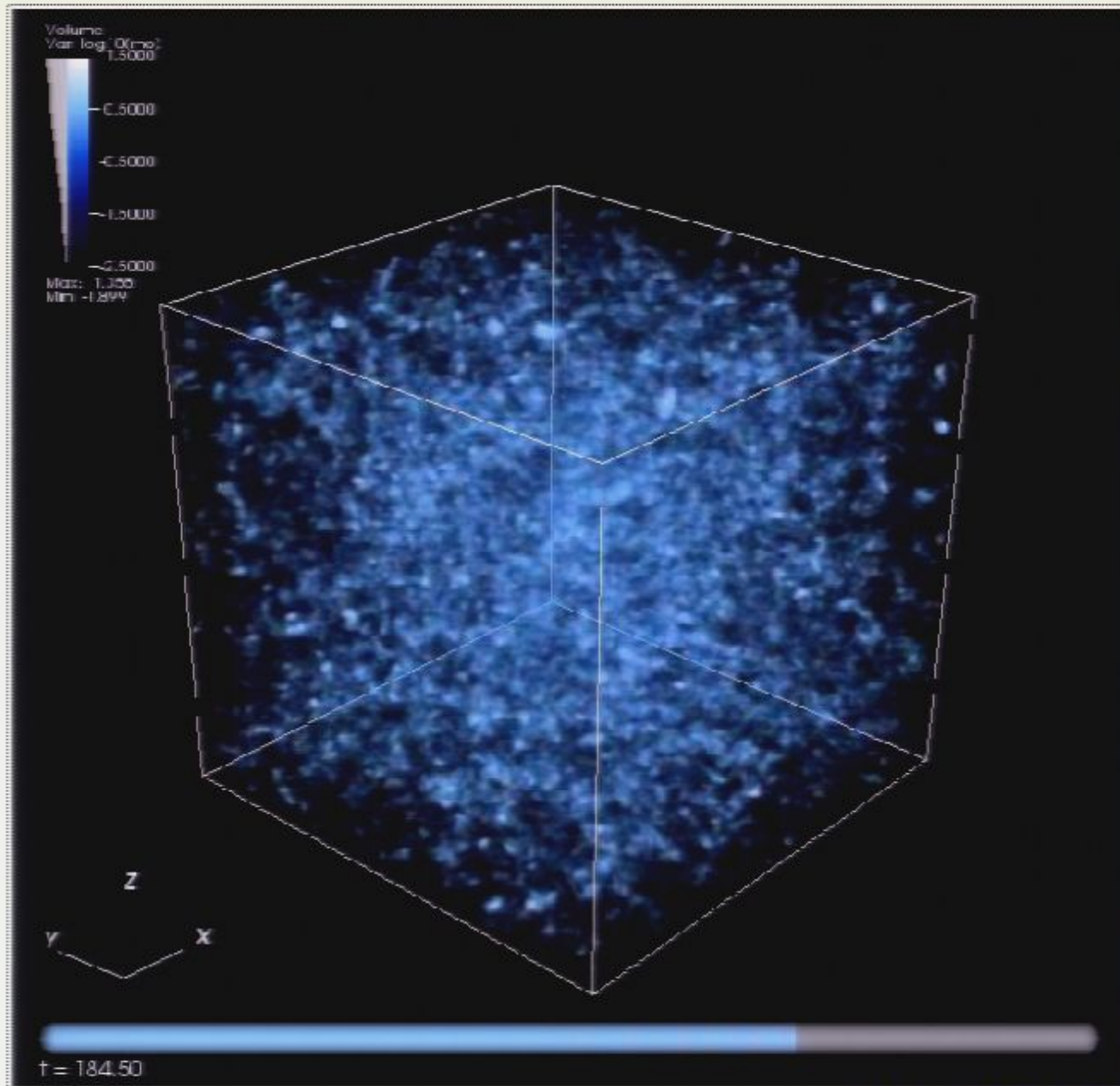
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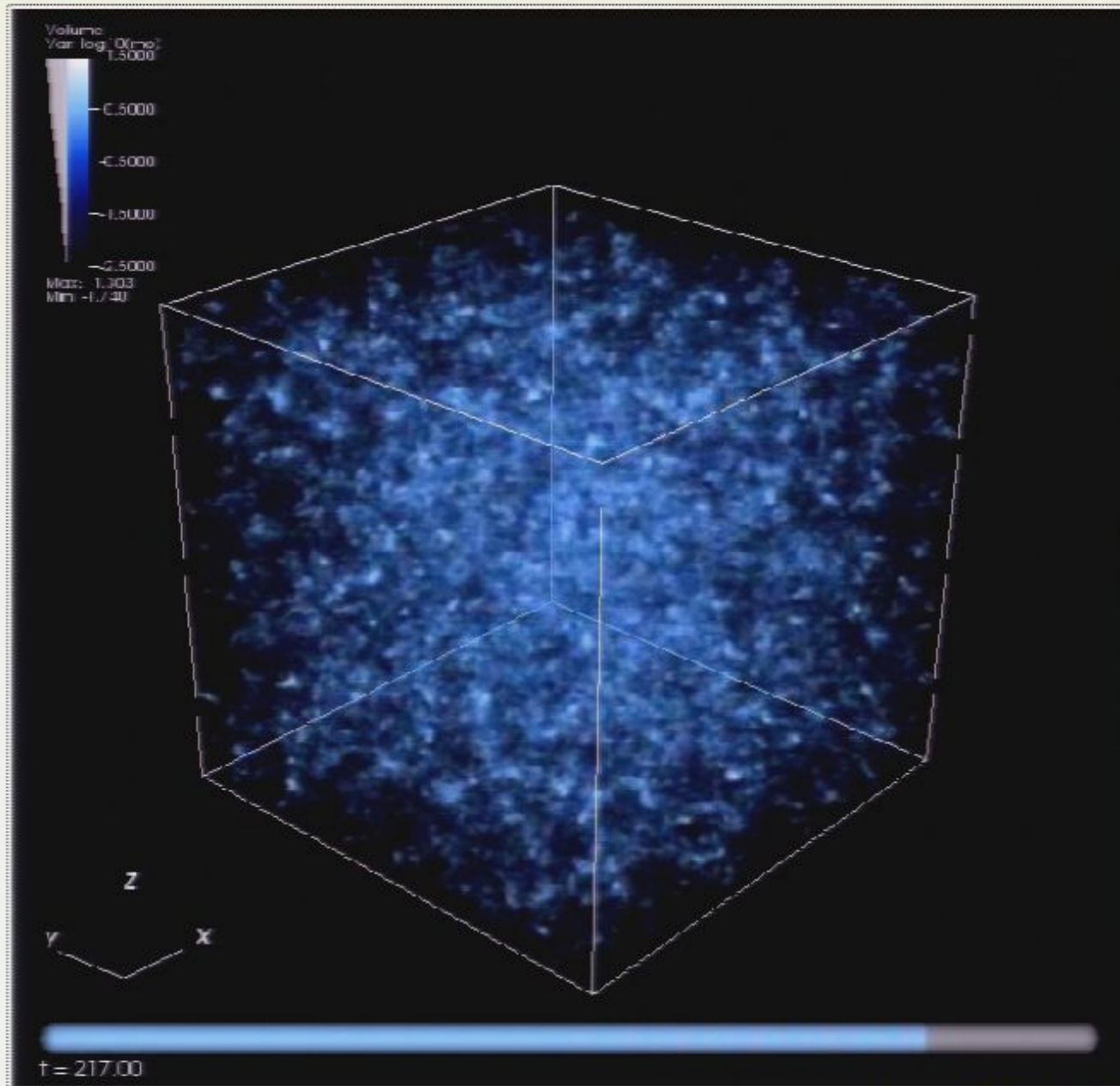
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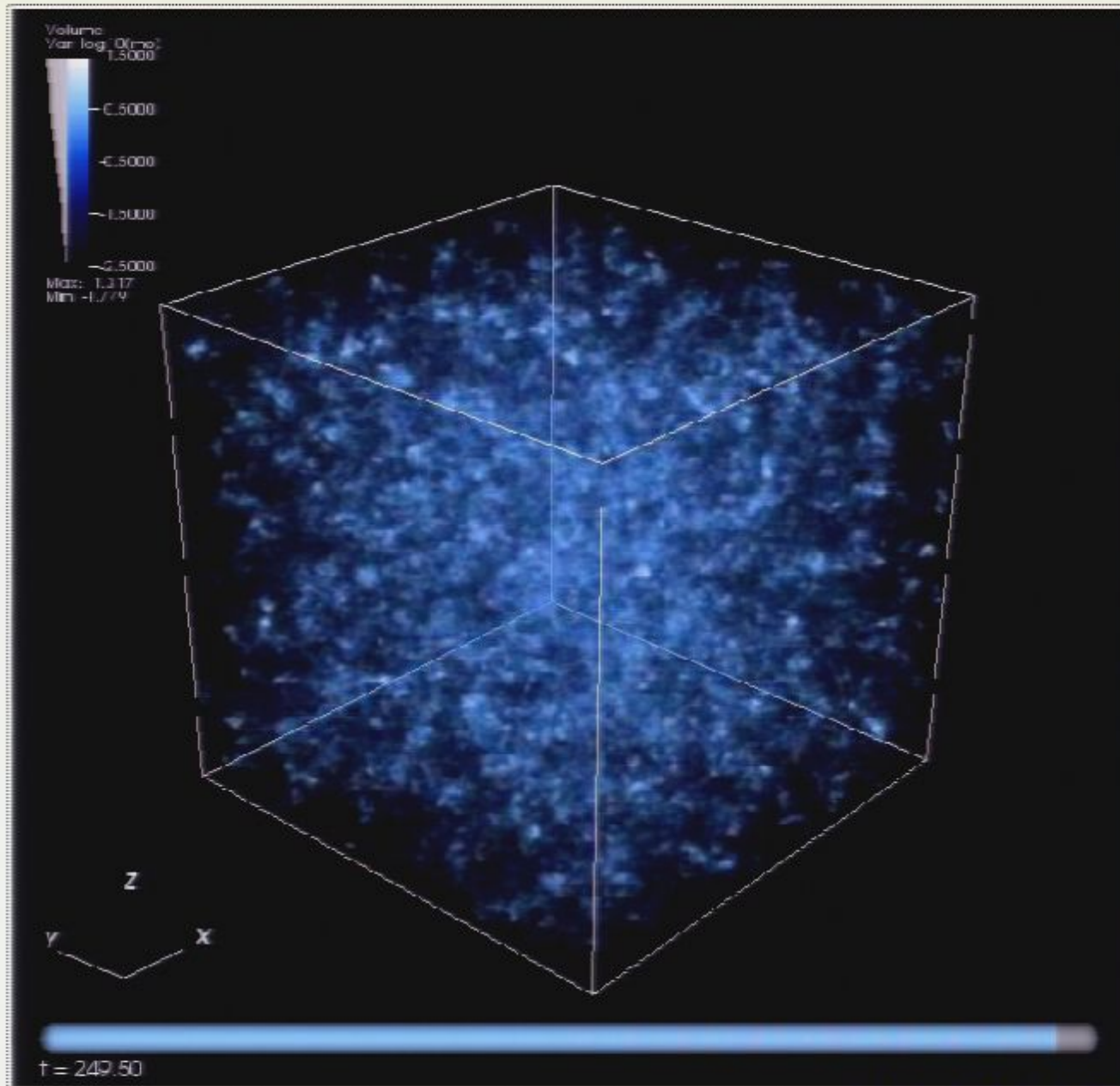
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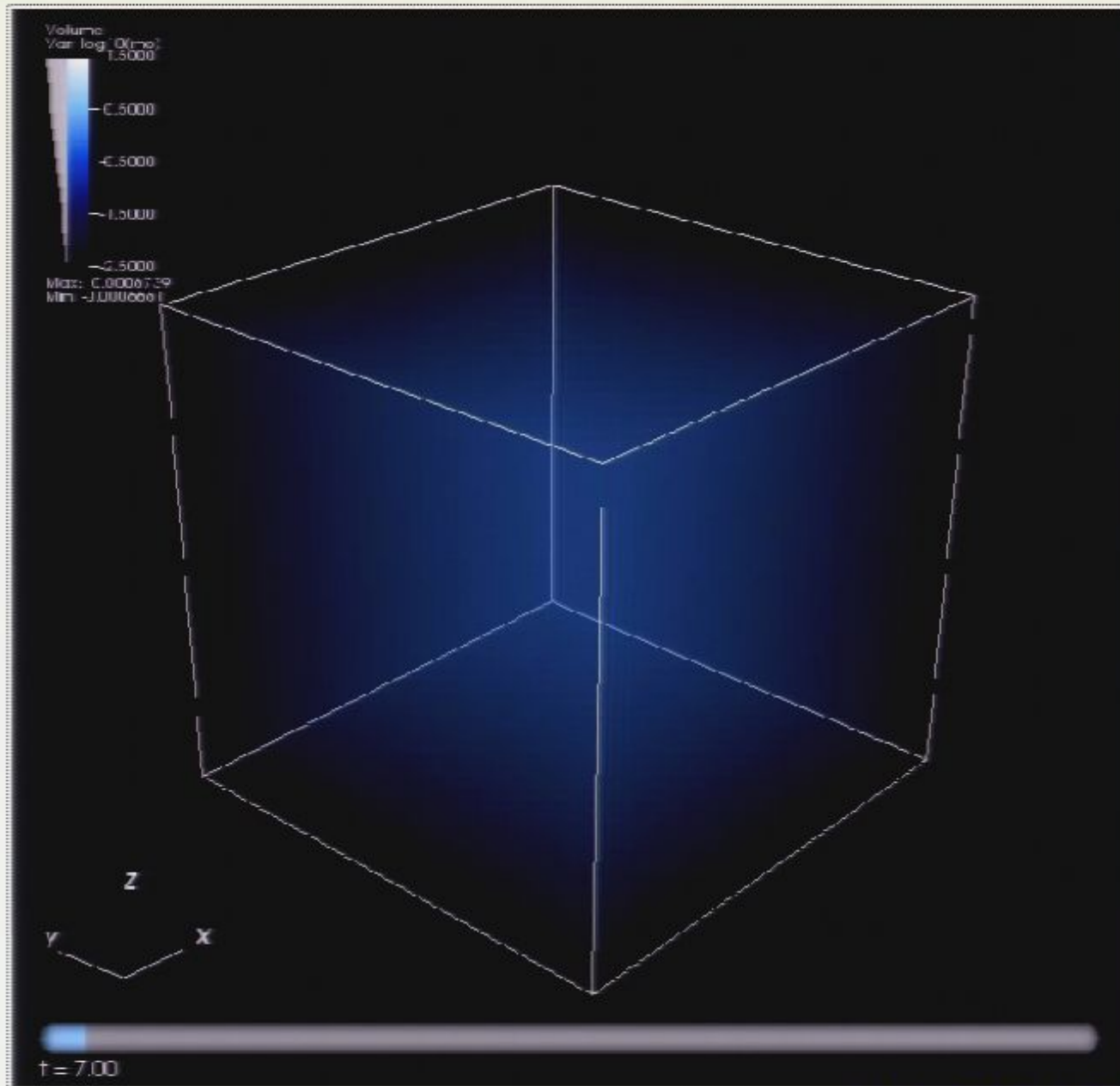
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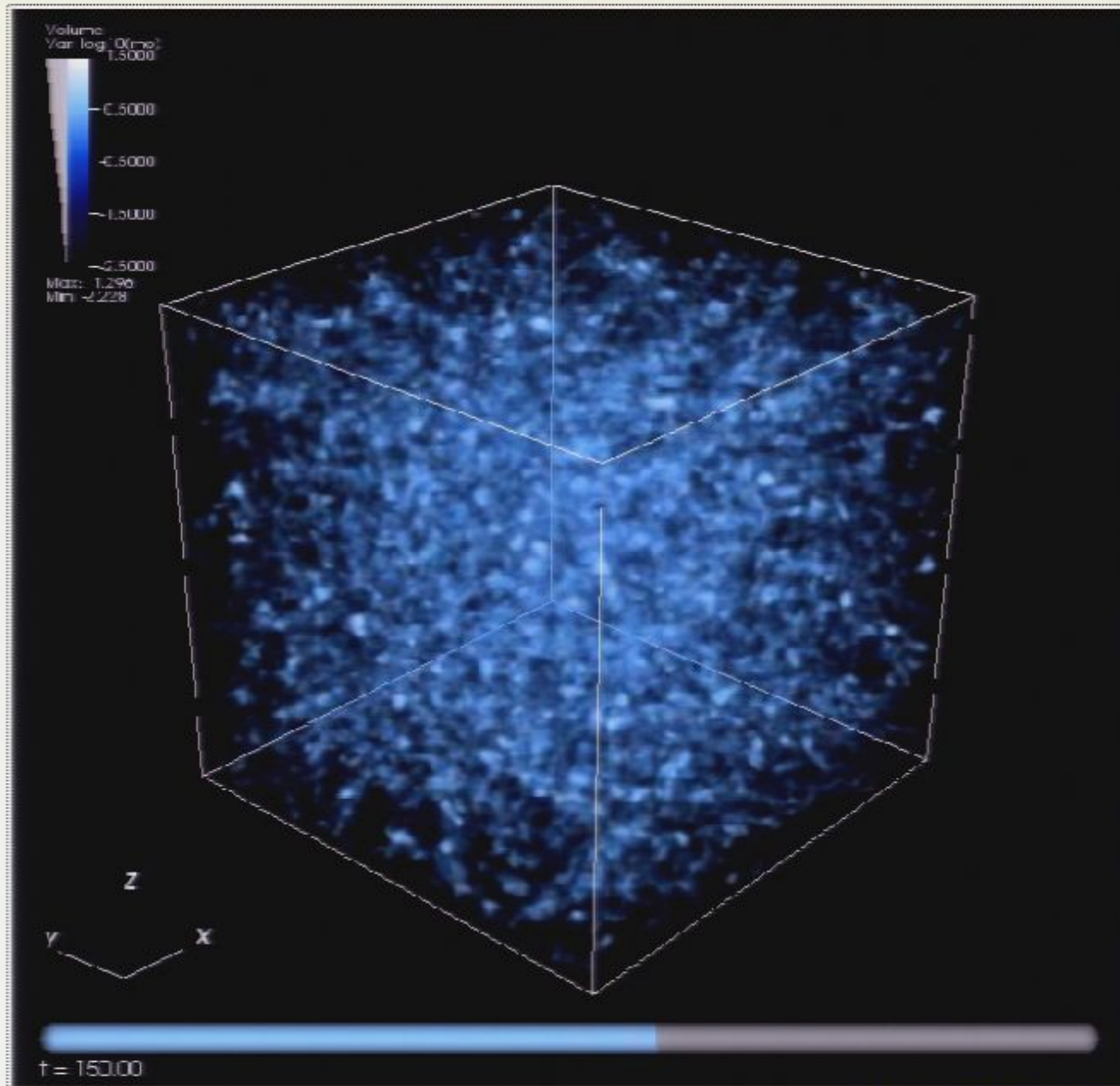
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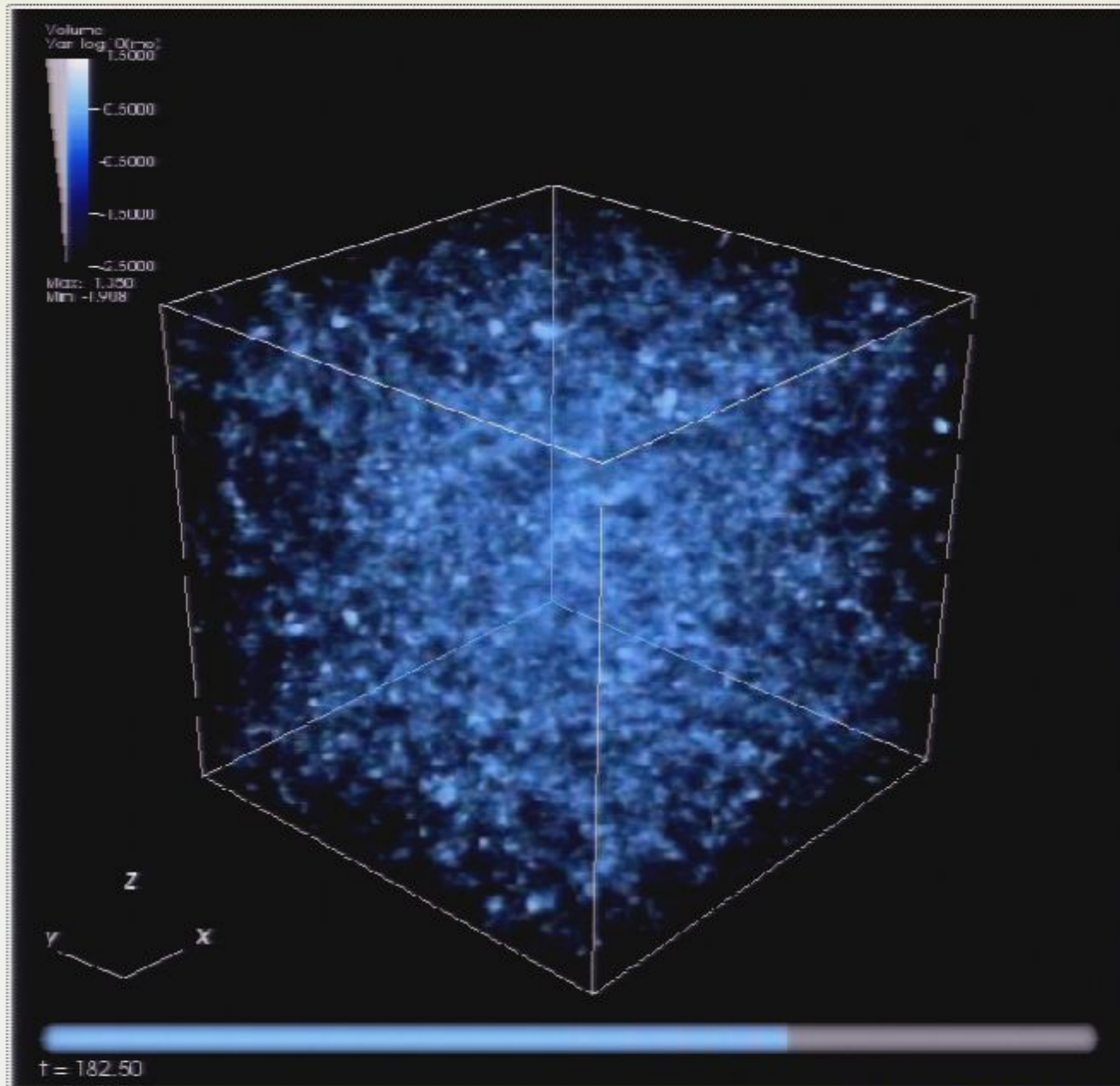
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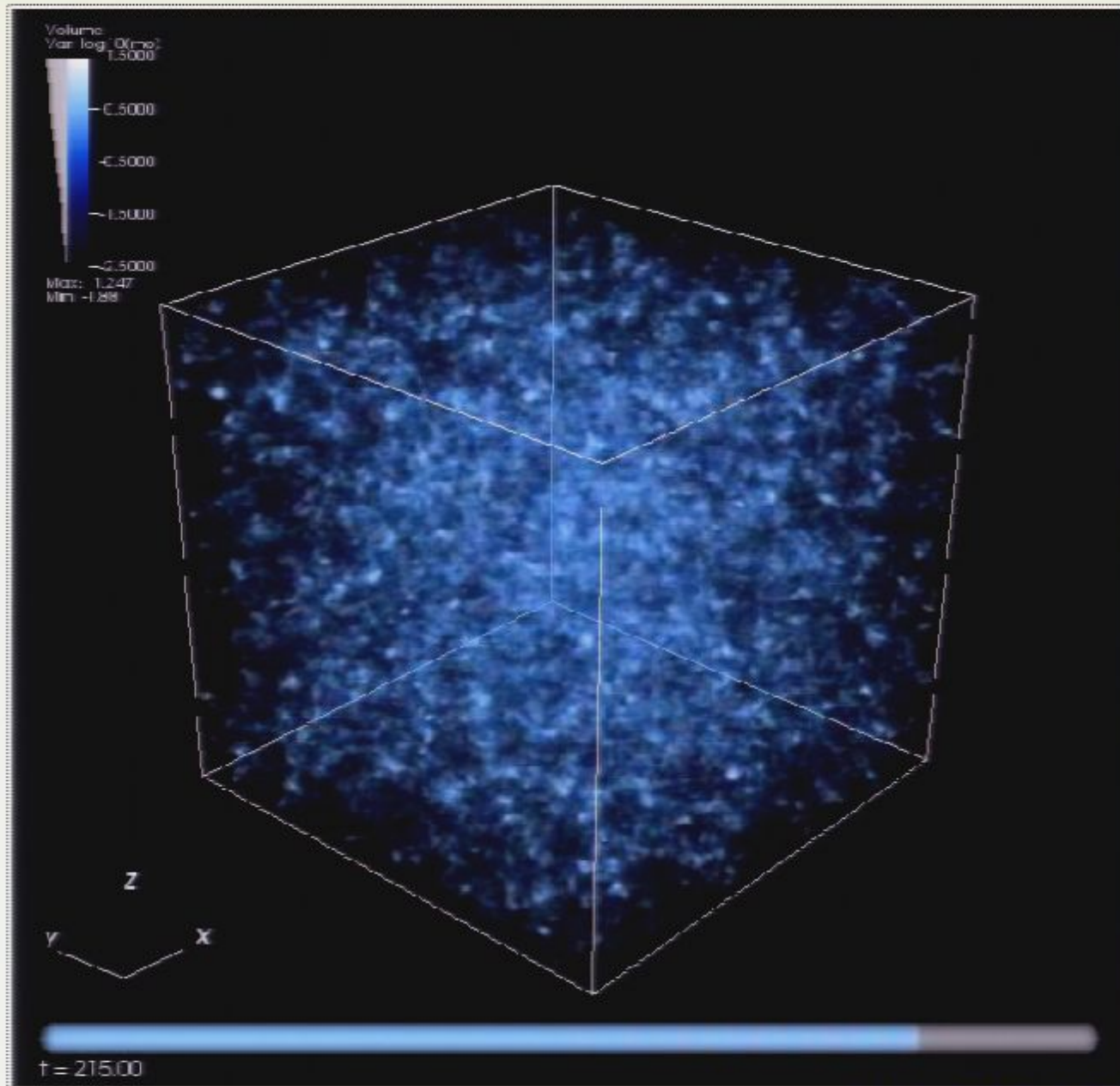
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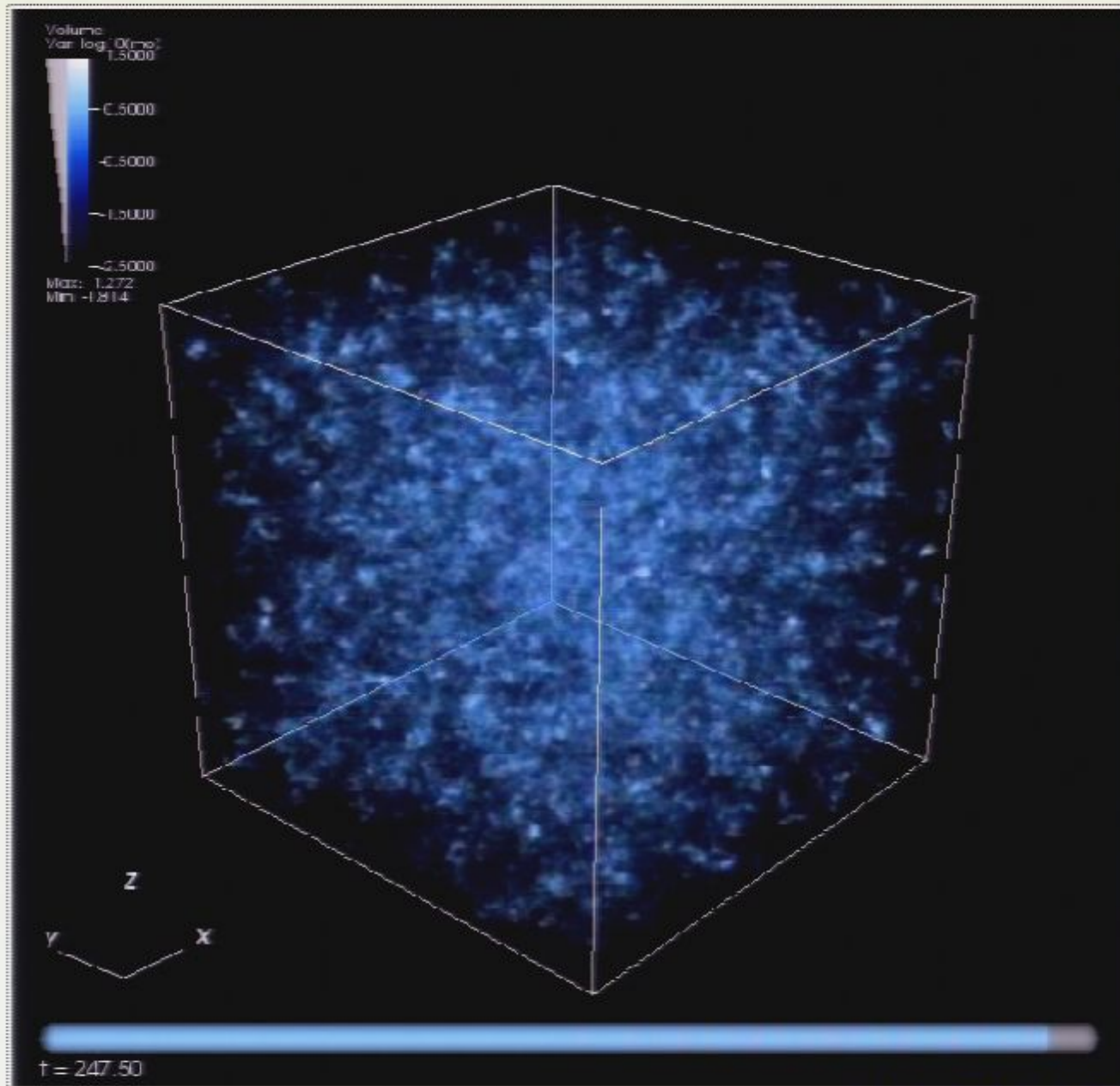
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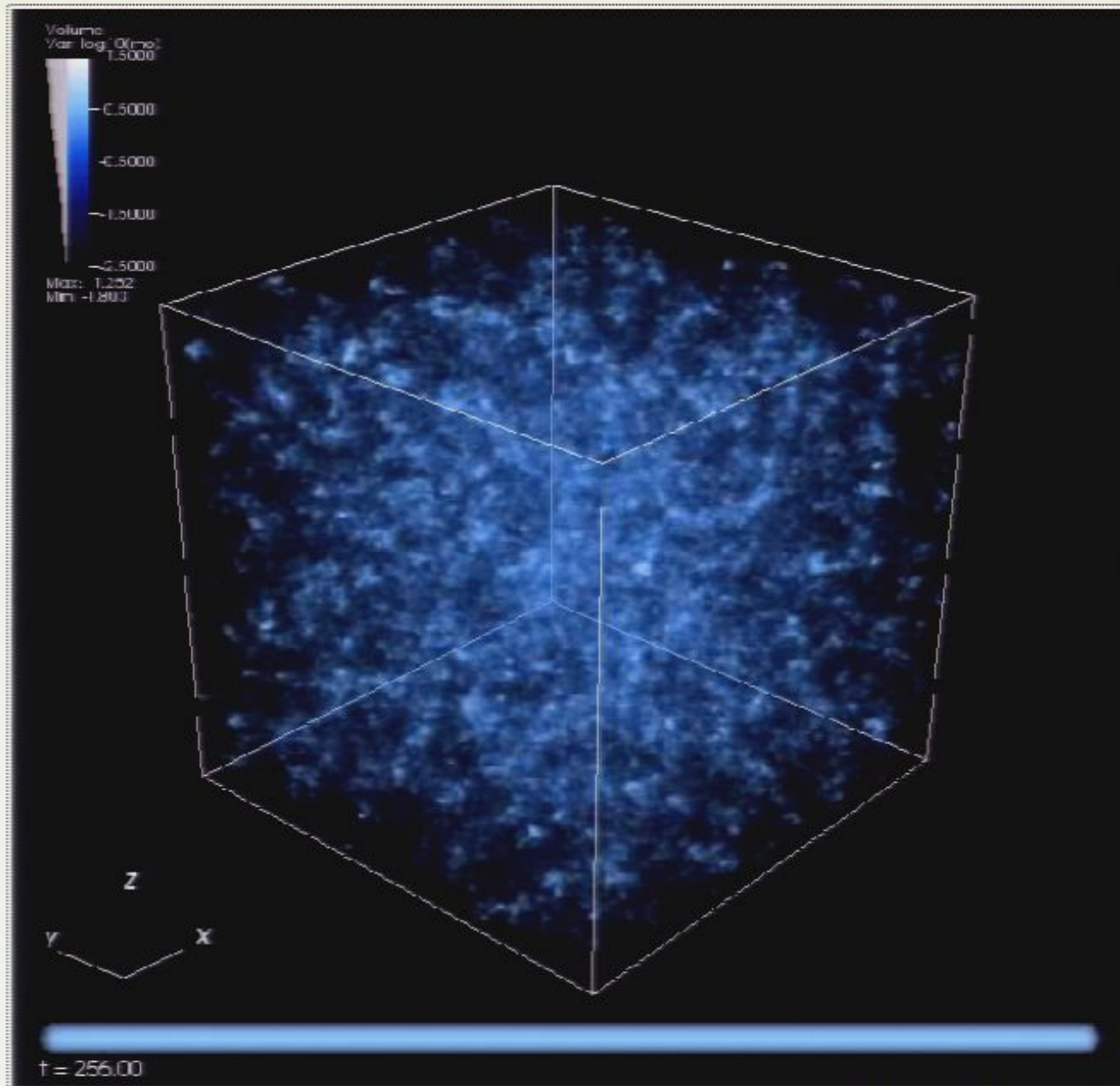
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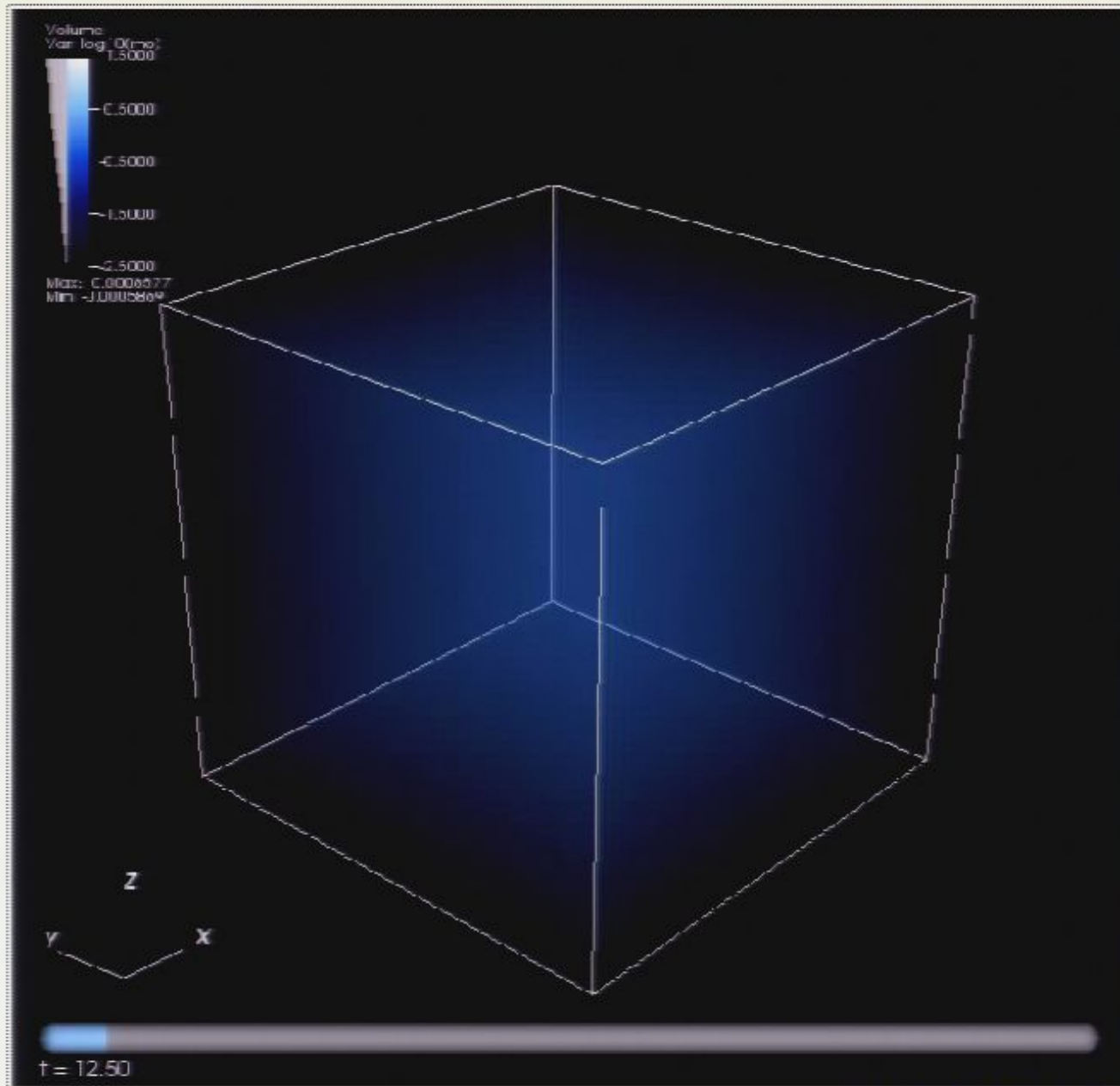
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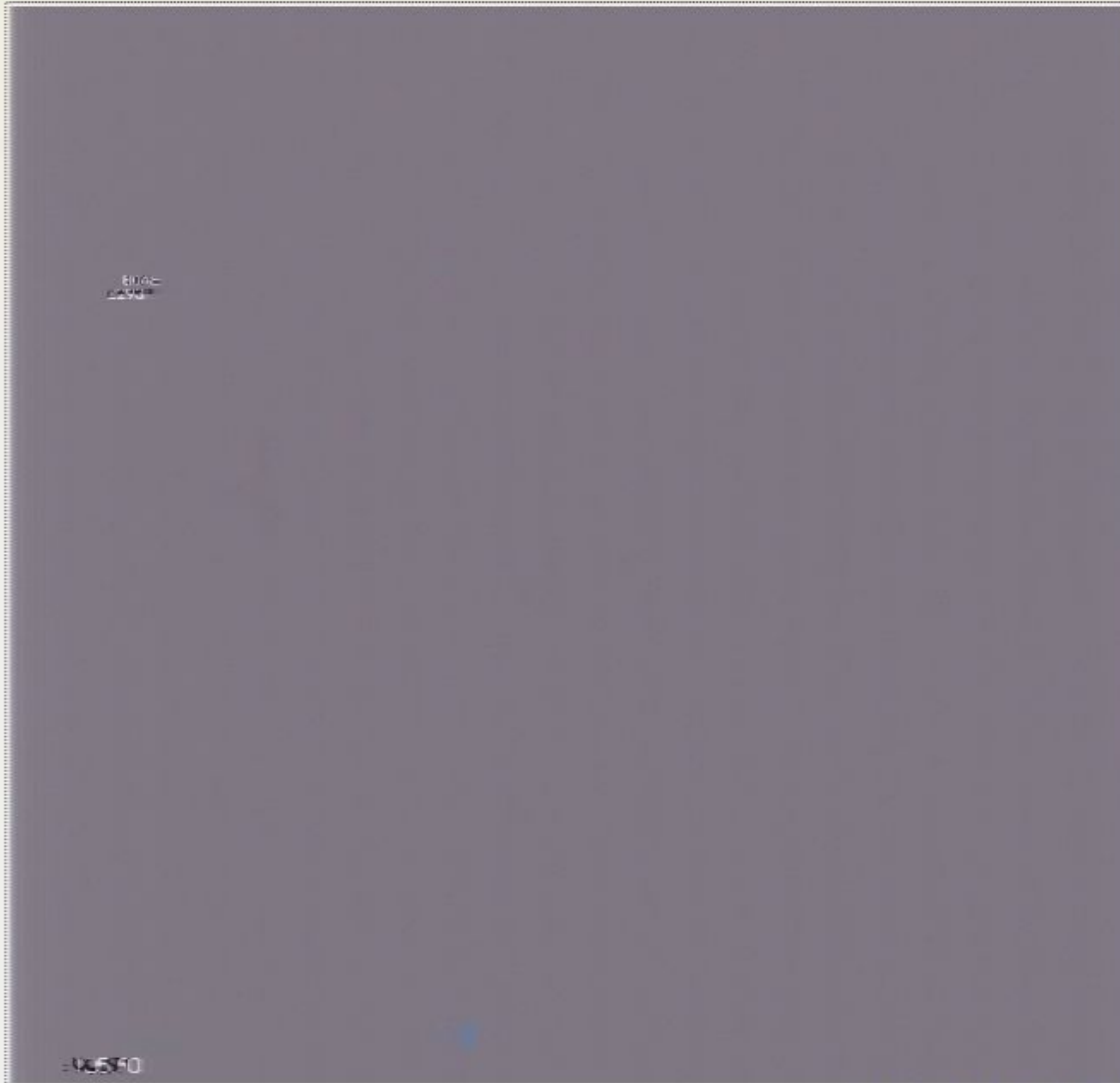
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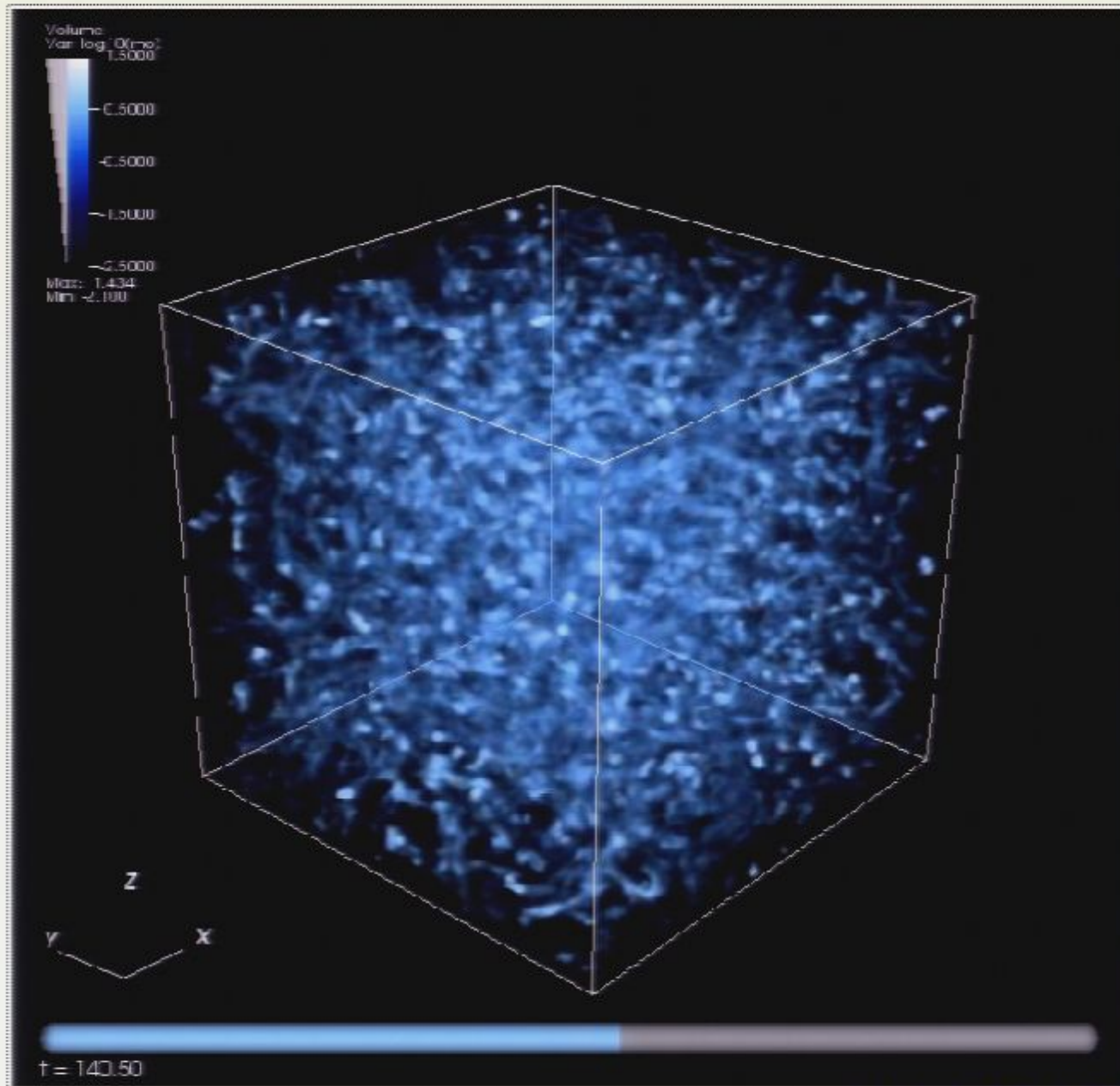
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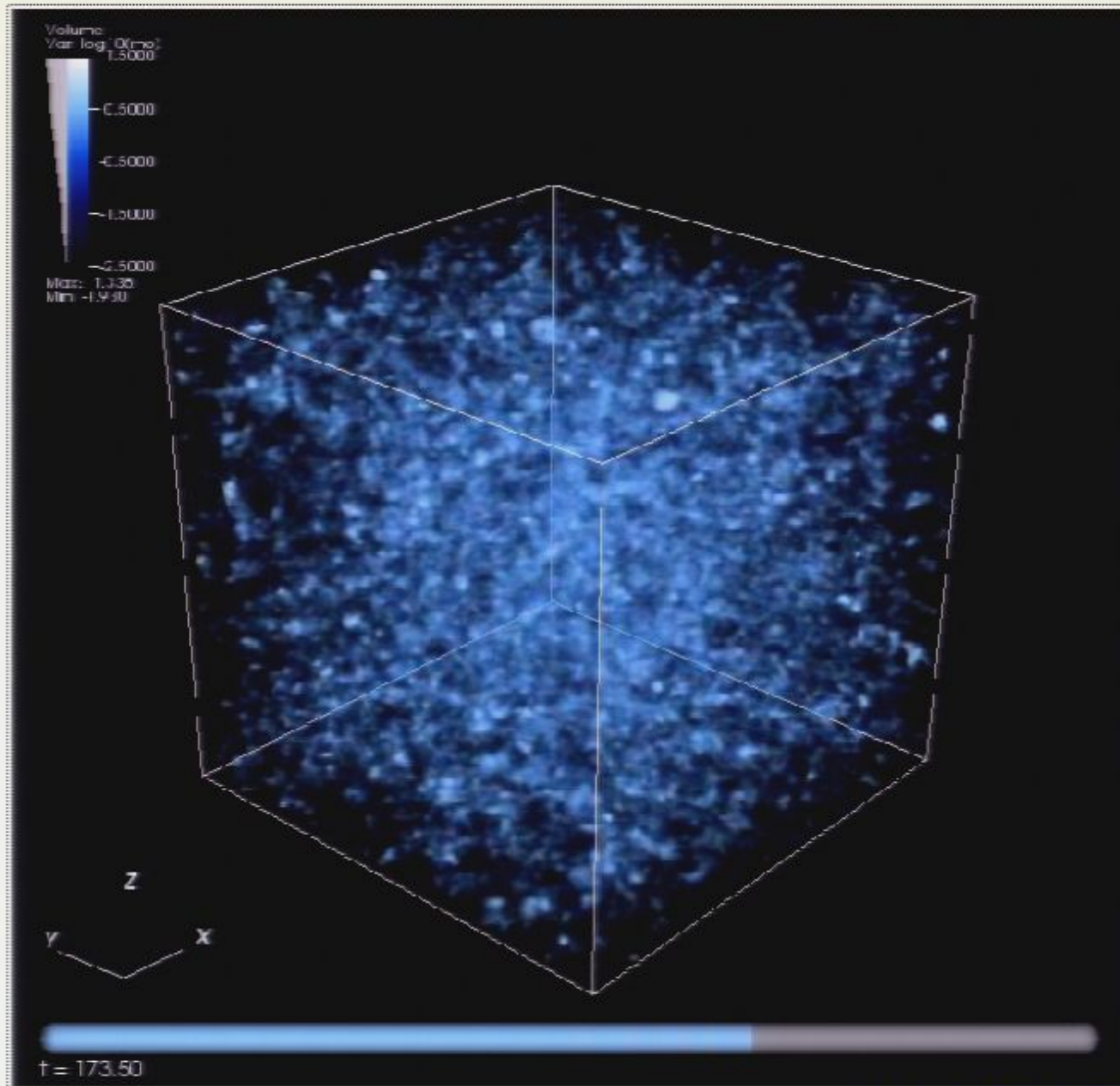
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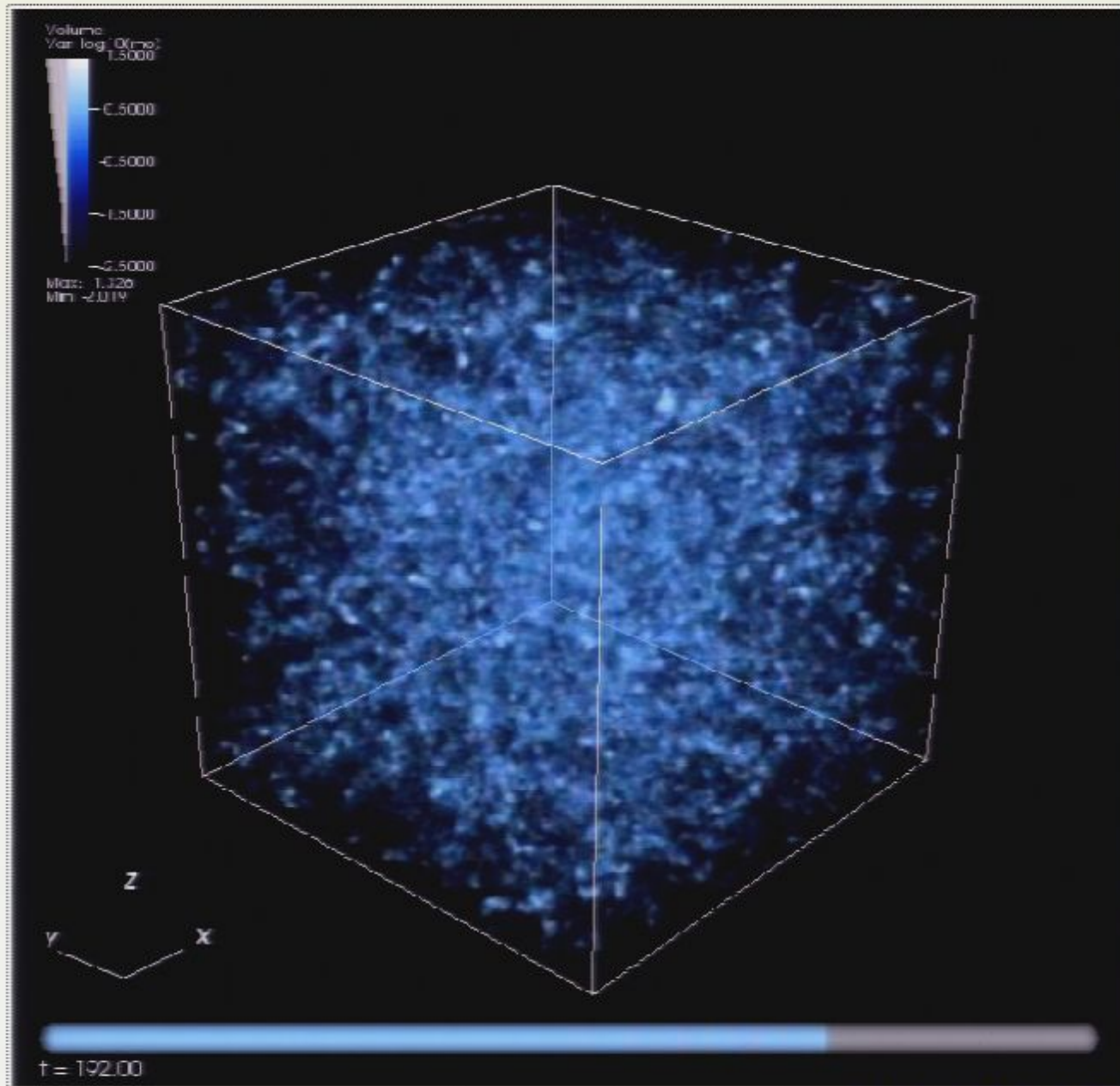
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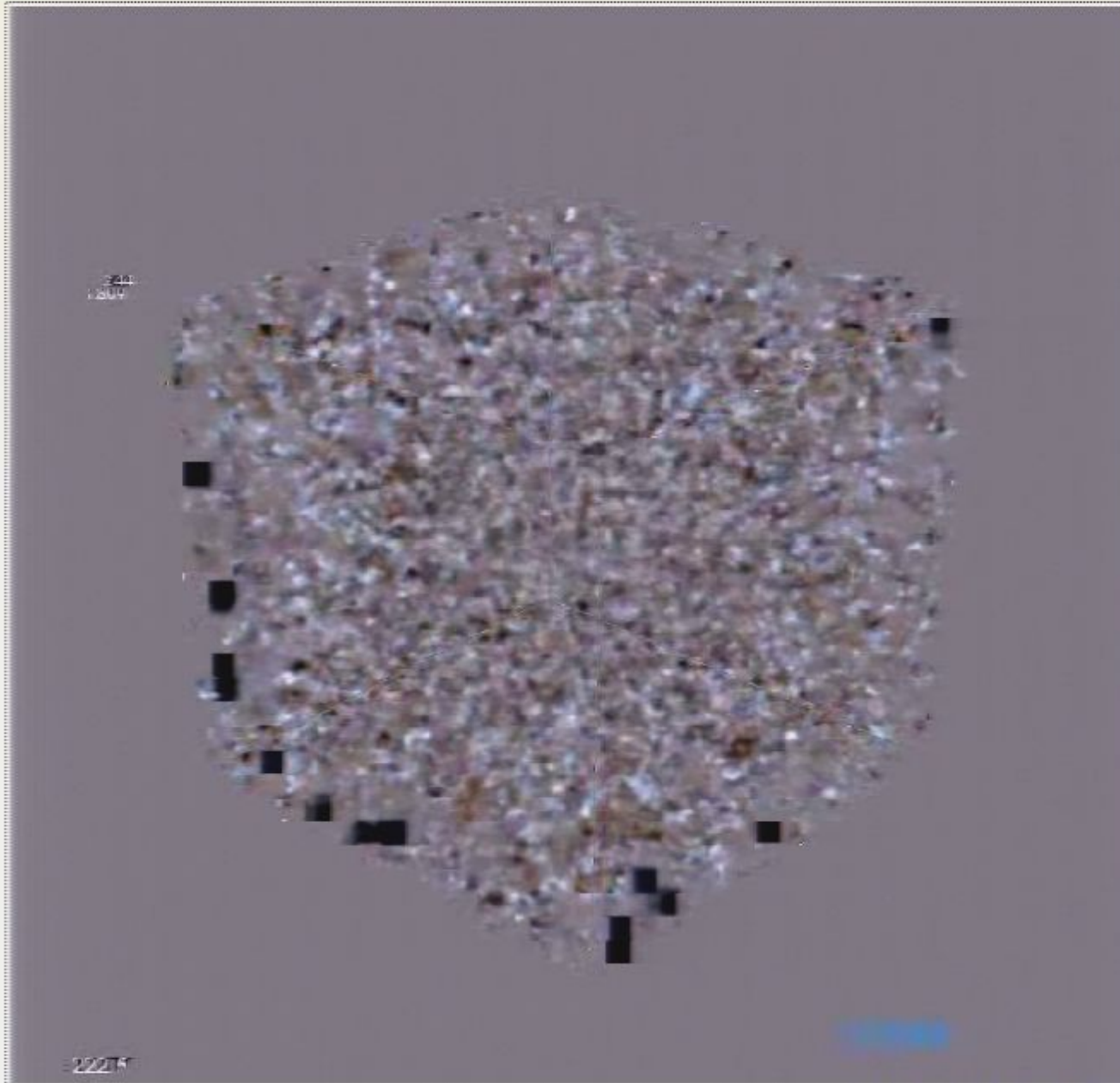
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DENSITY EVOLUTION DURING PREHEATING



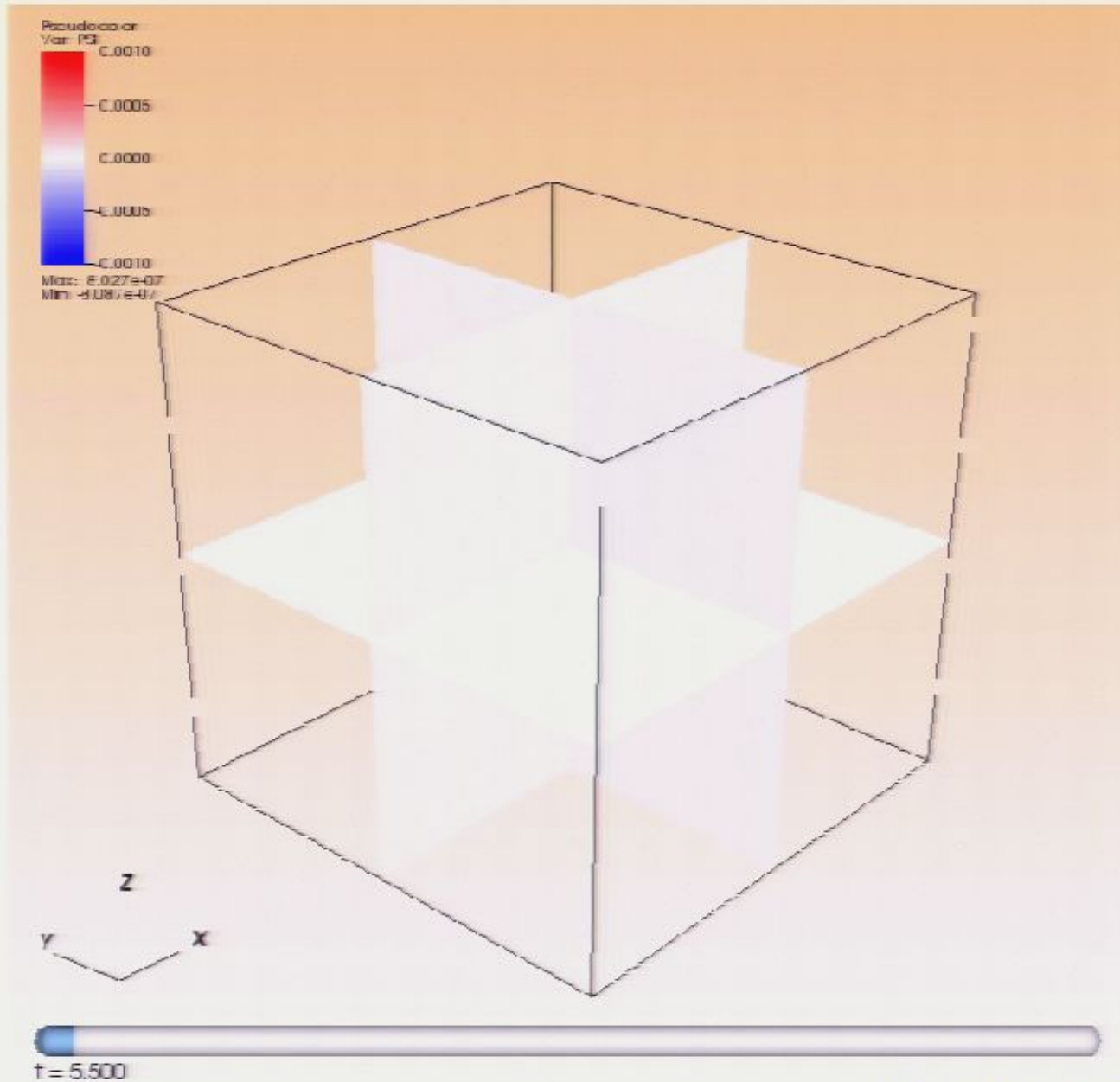
Pirsa: 08070048

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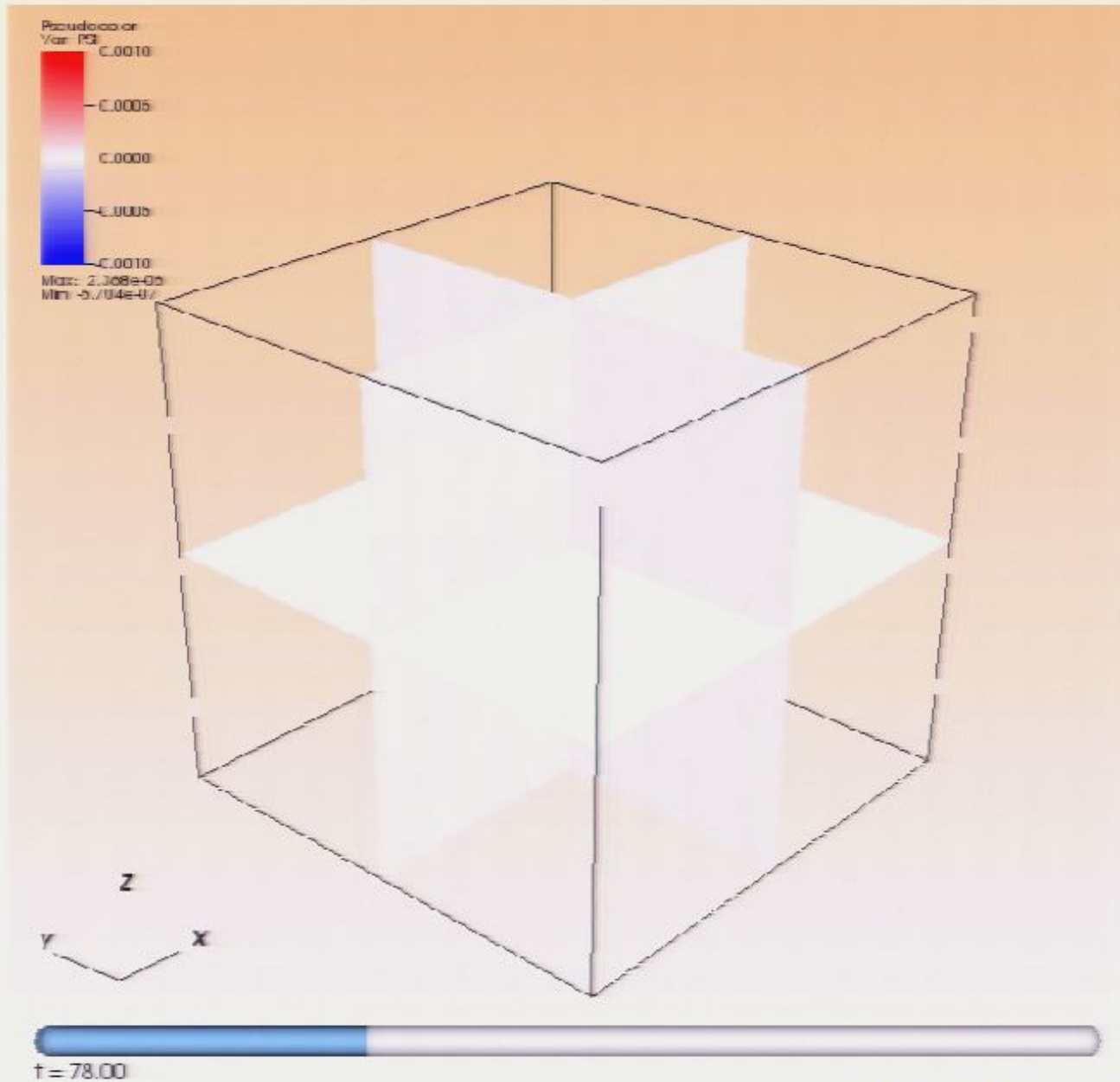
SMALL-SCALE STRUCTURE FORMATION



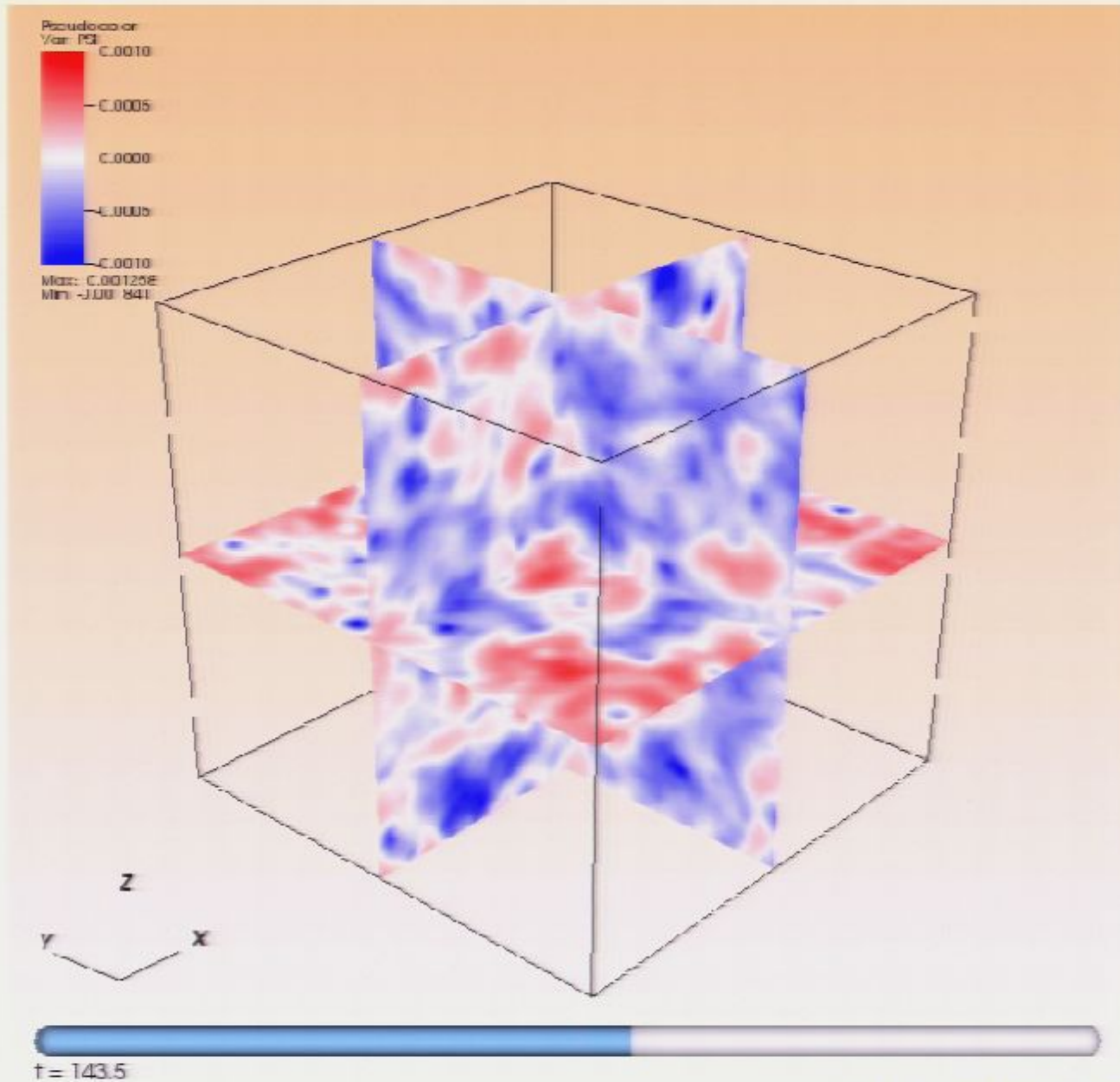
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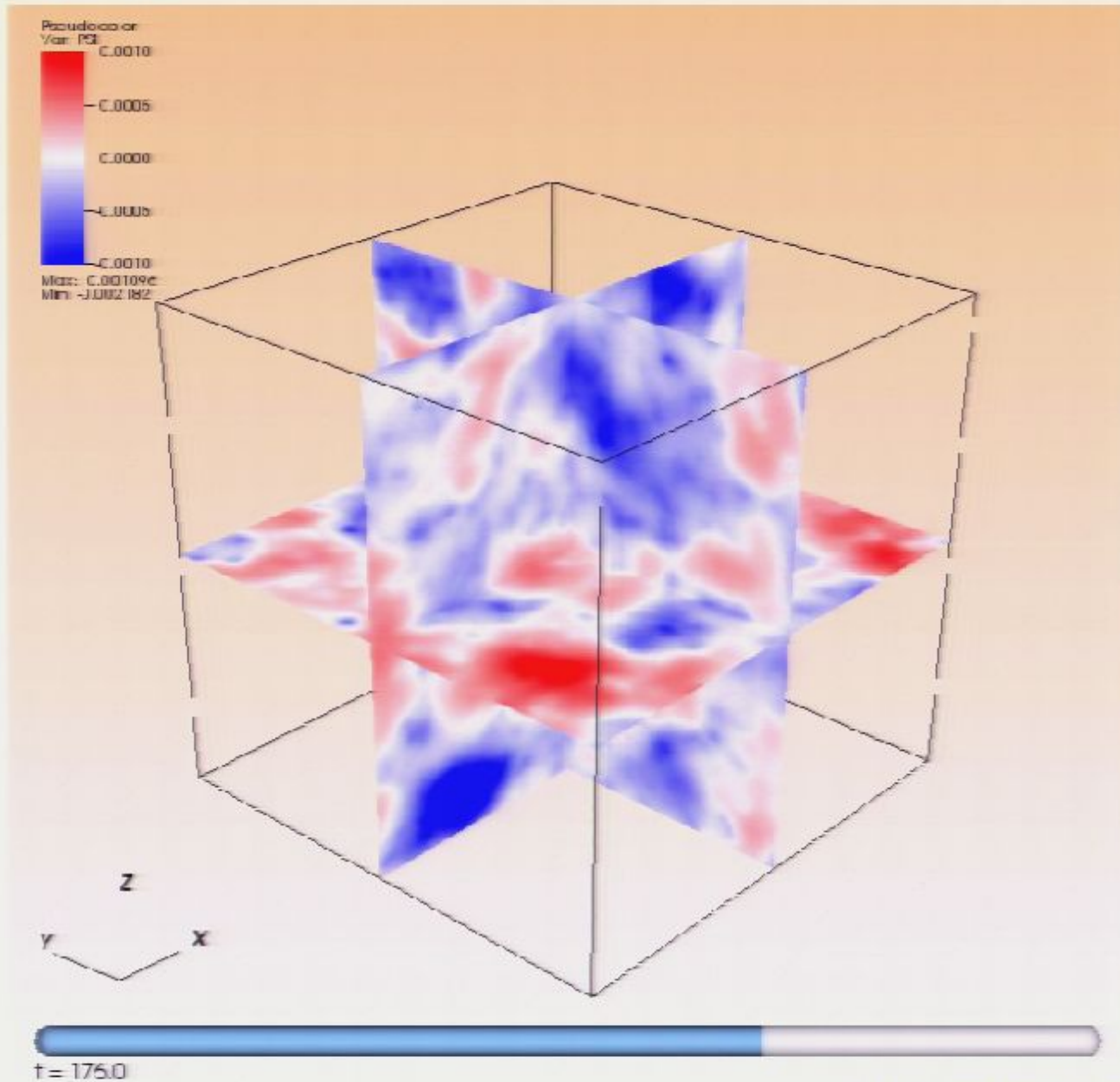
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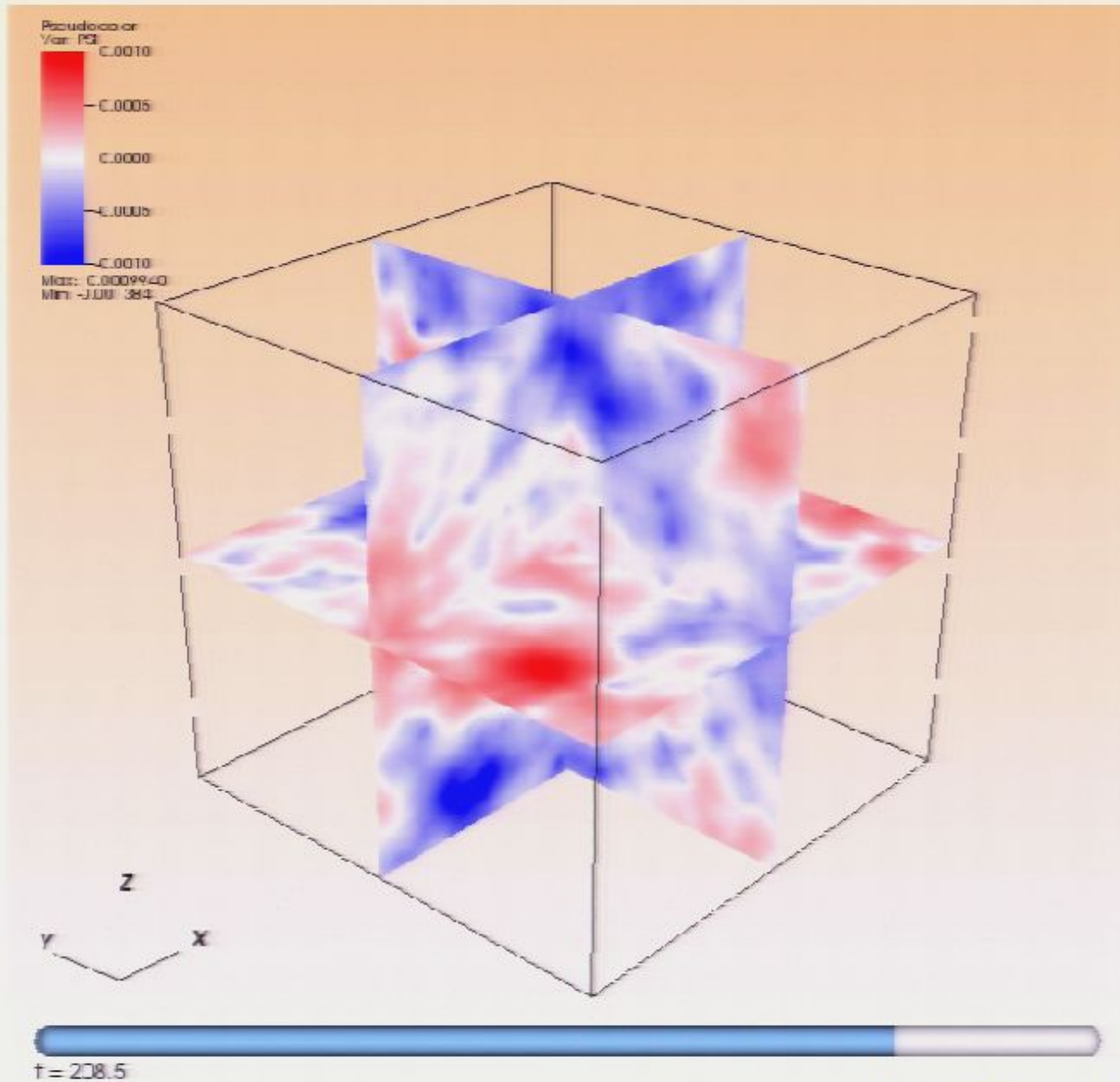
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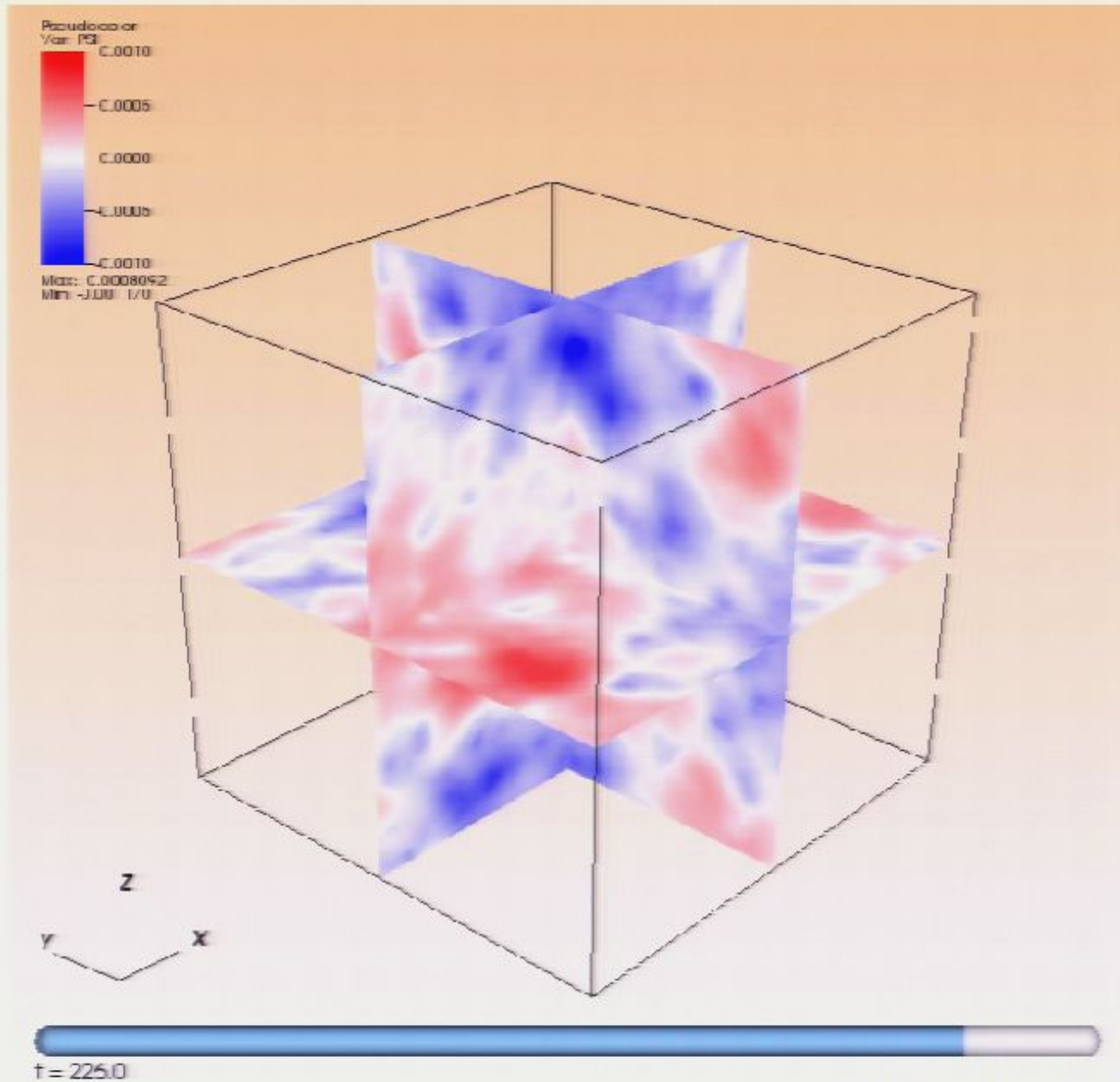
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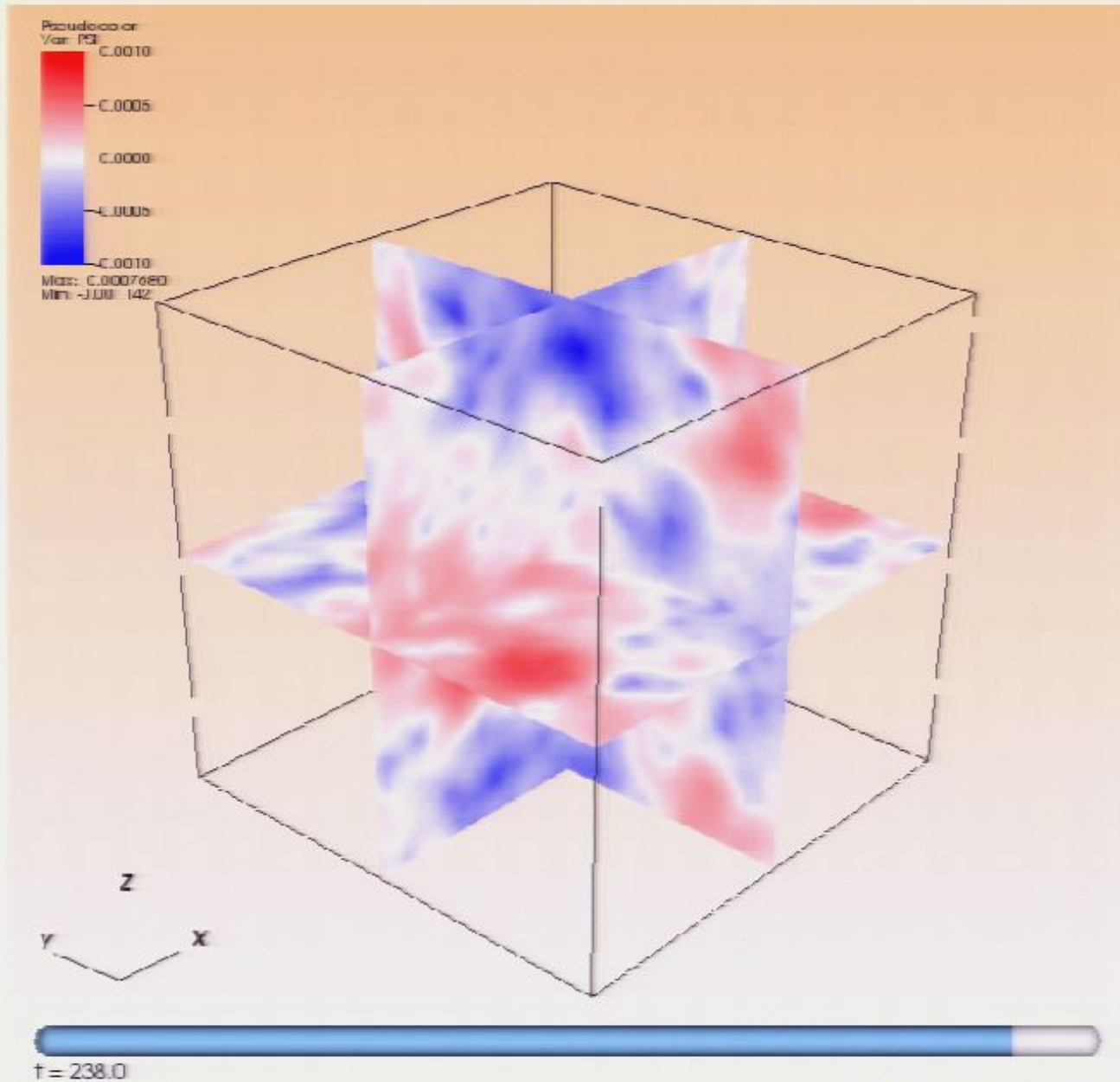
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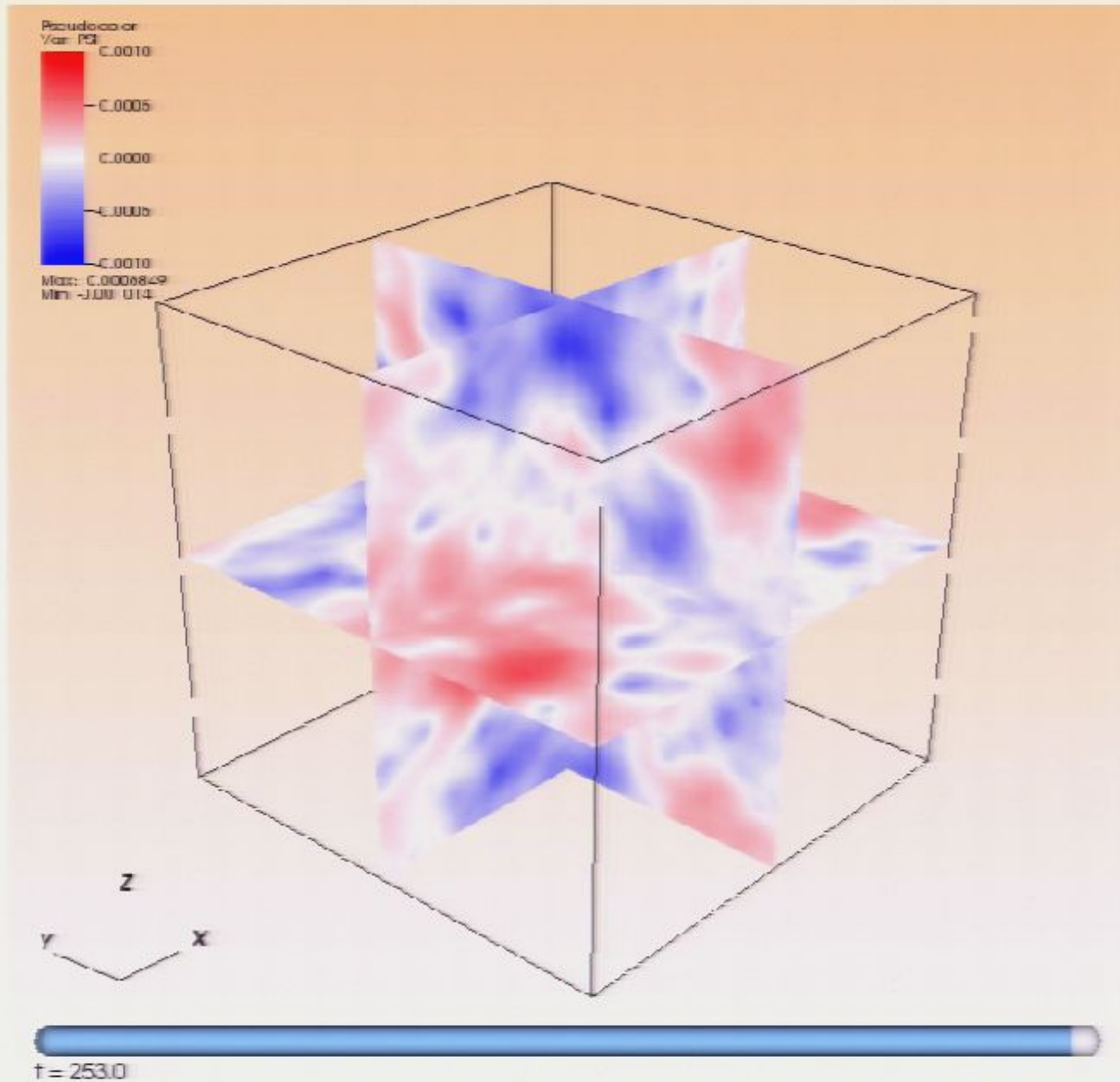
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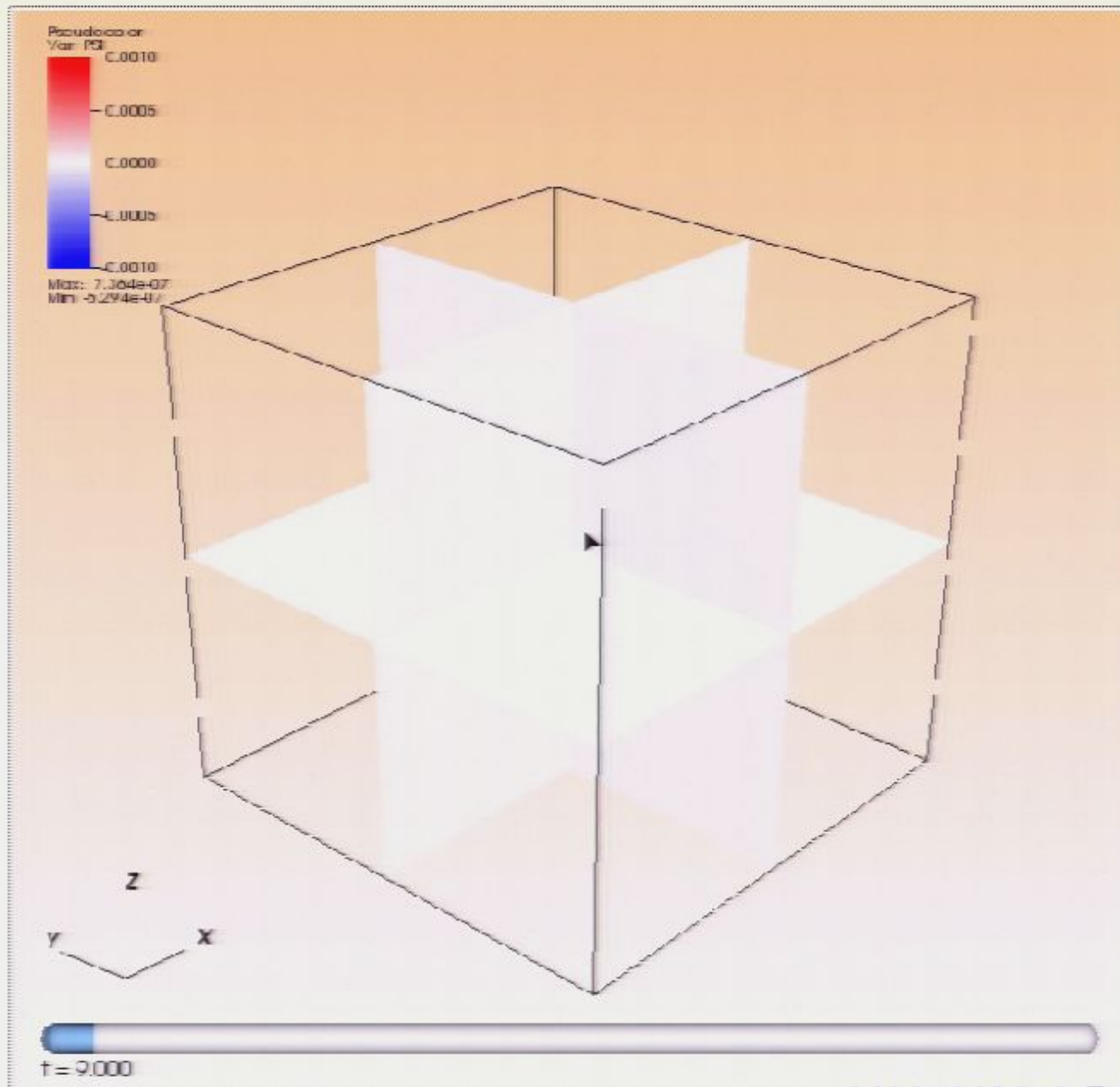
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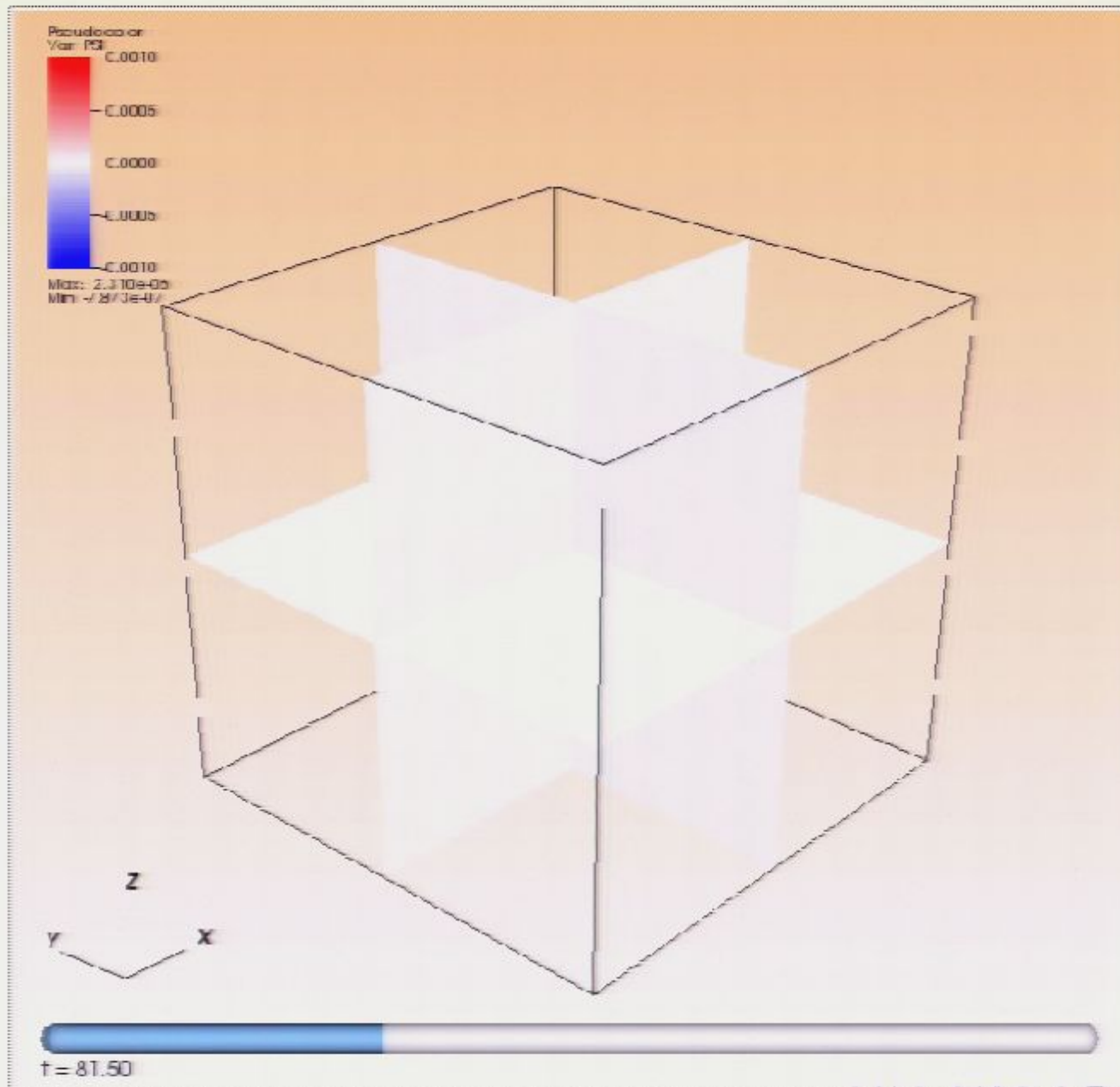
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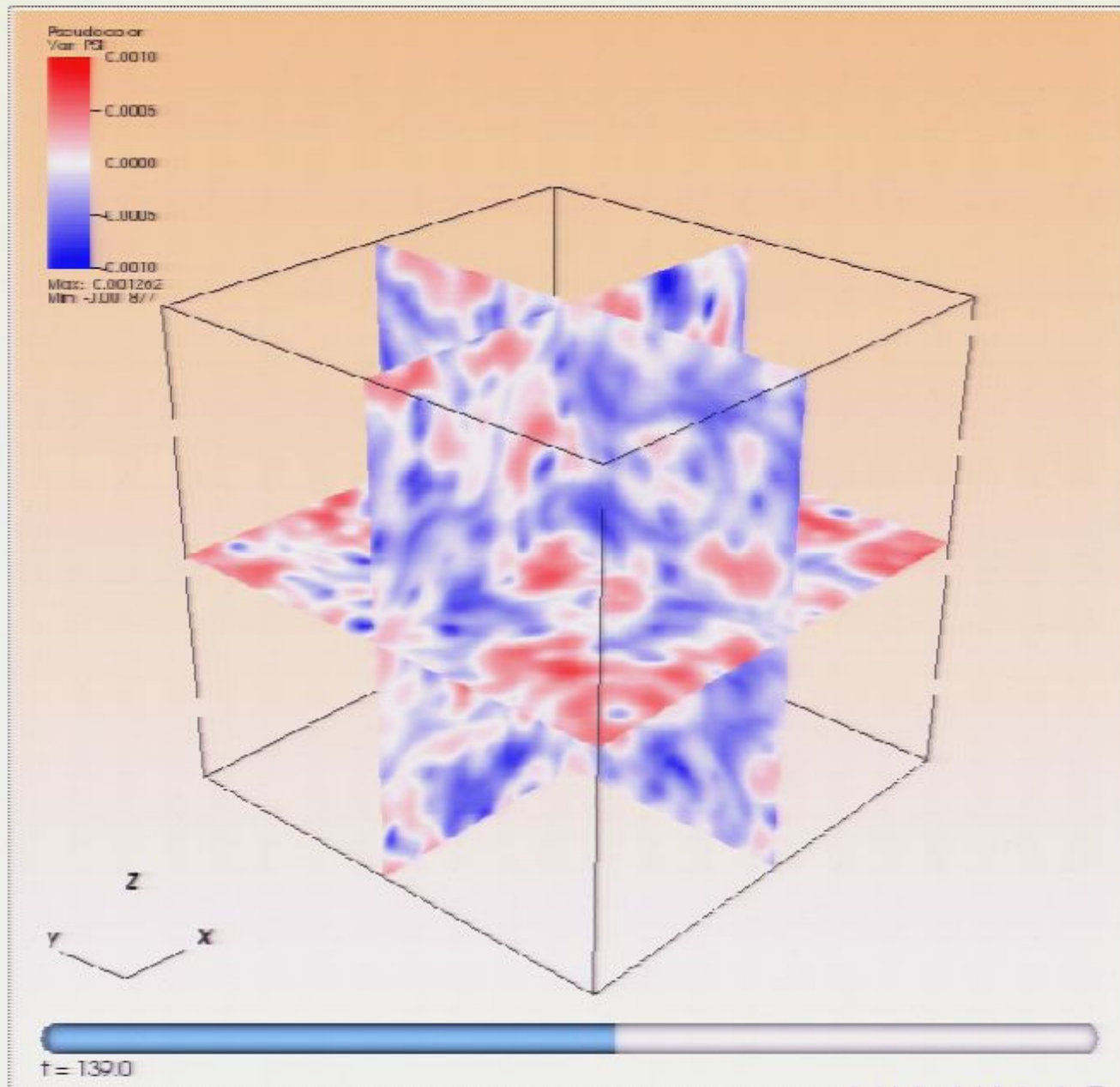
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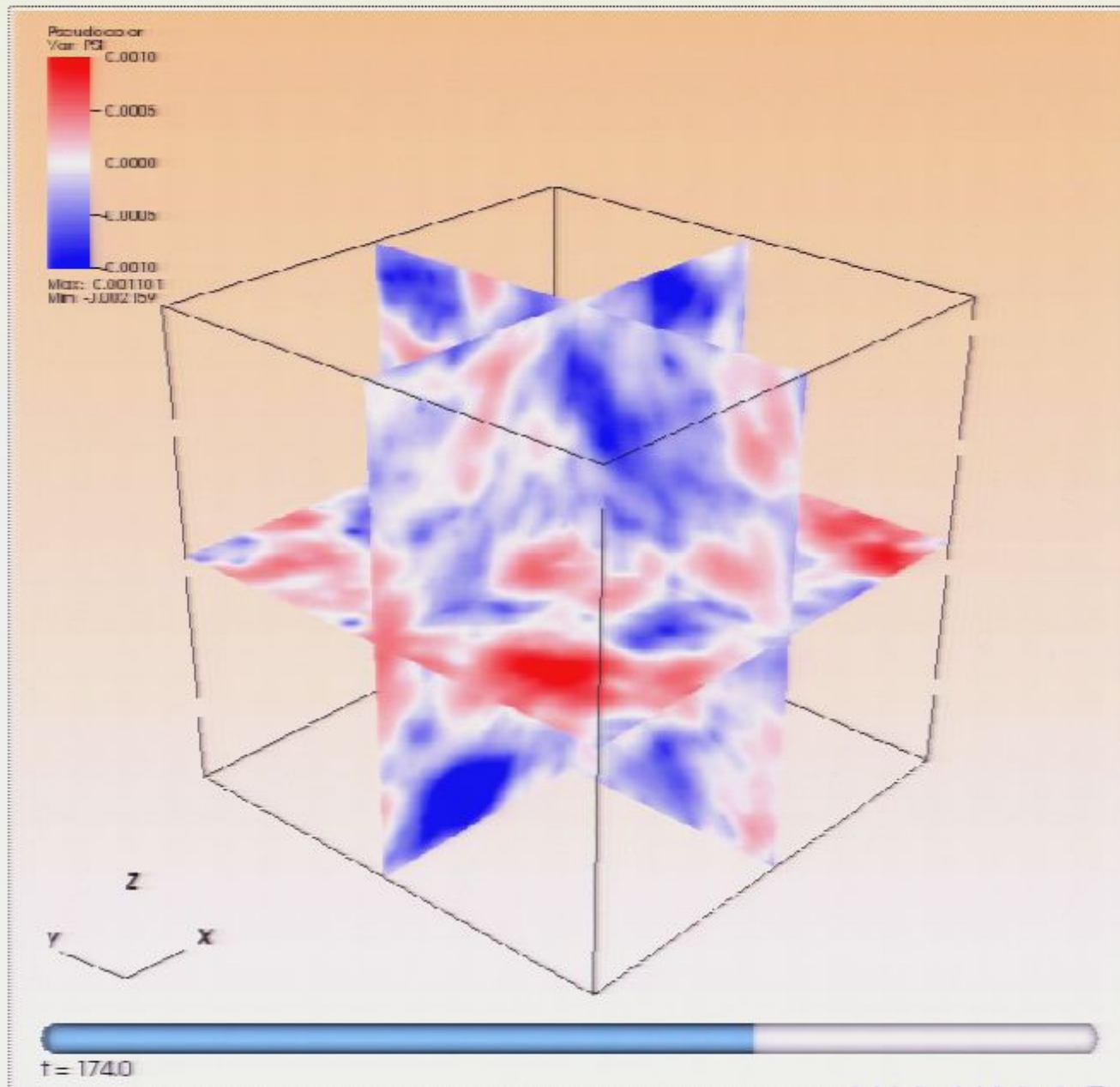
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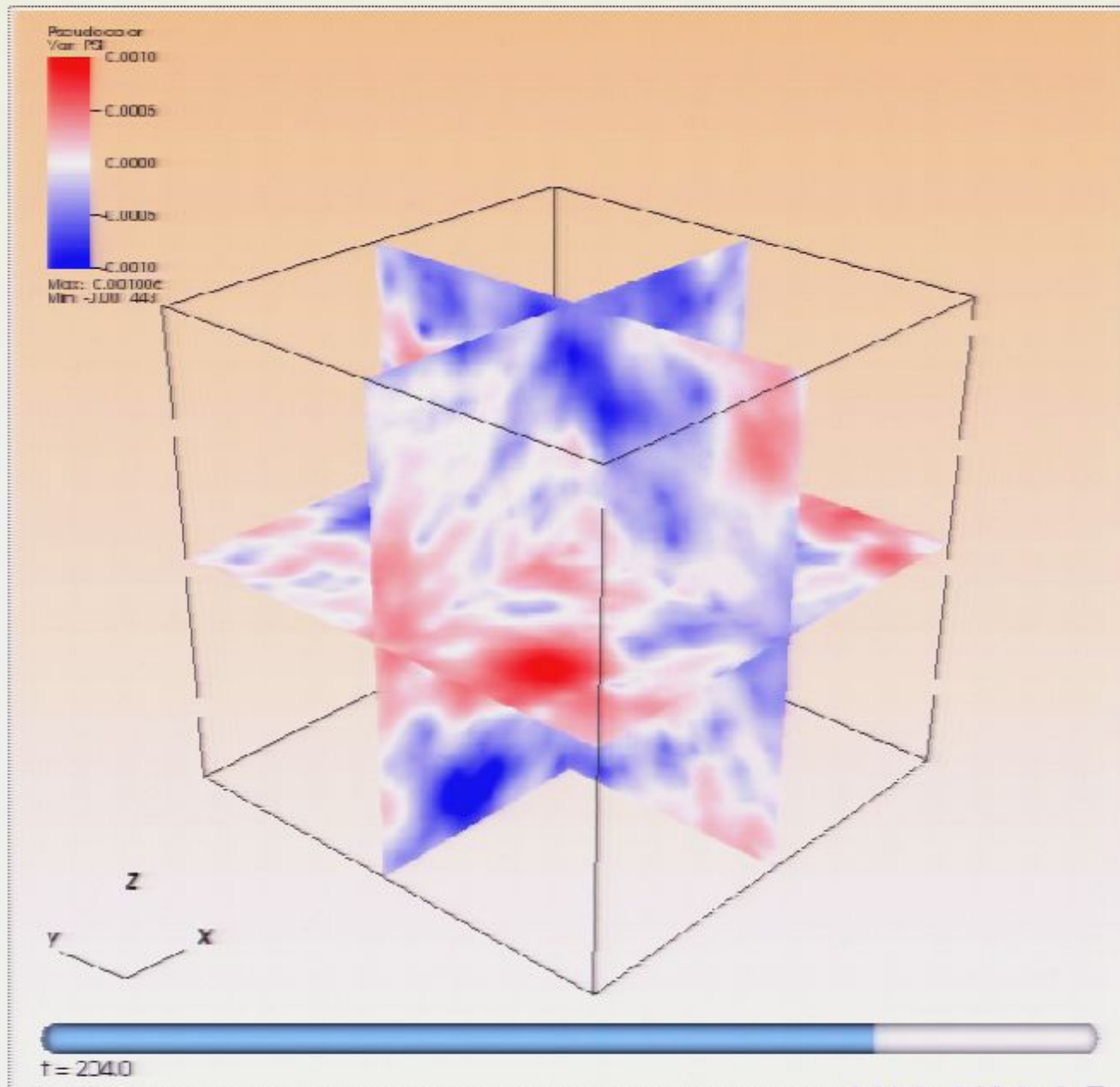
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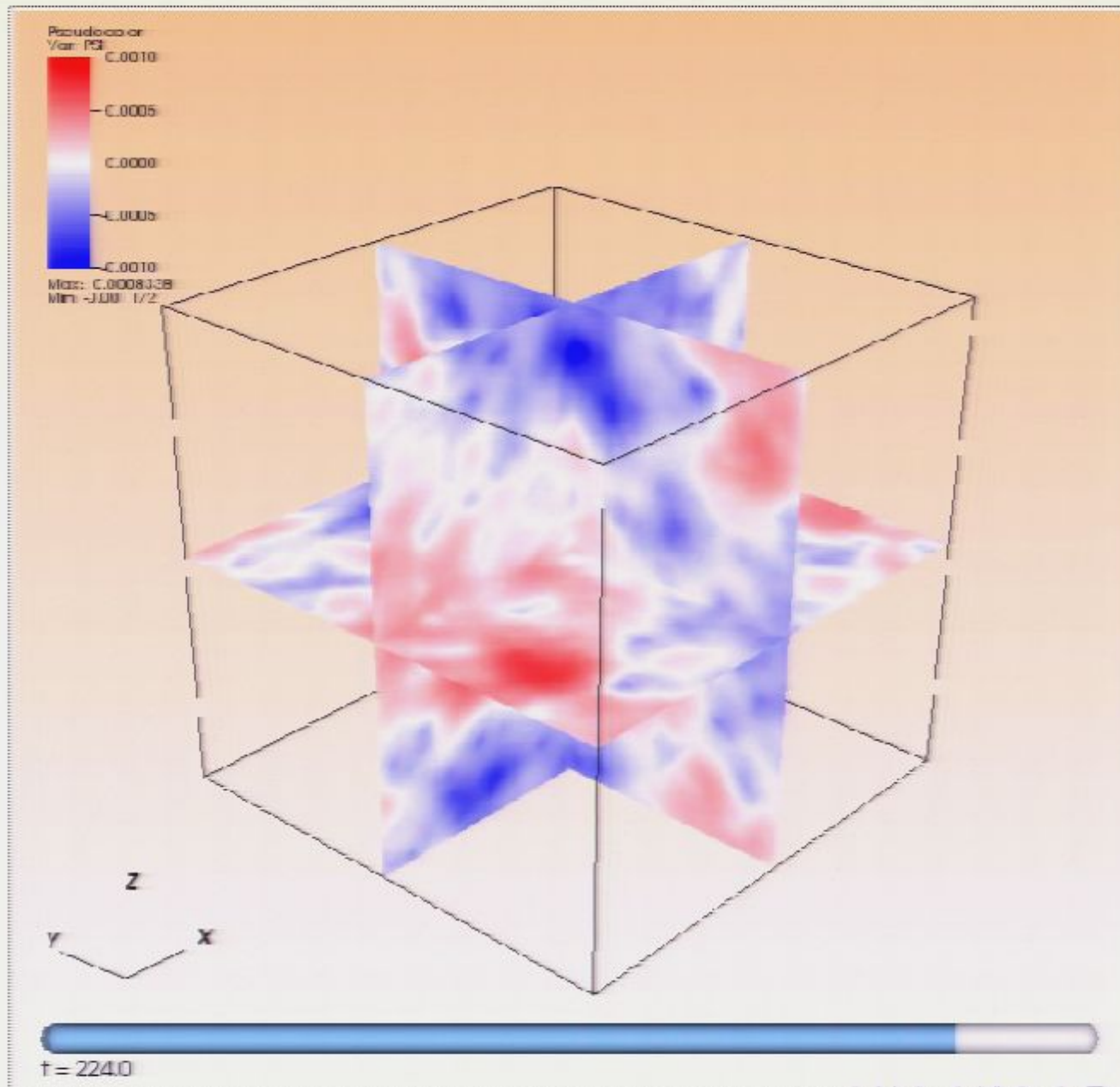
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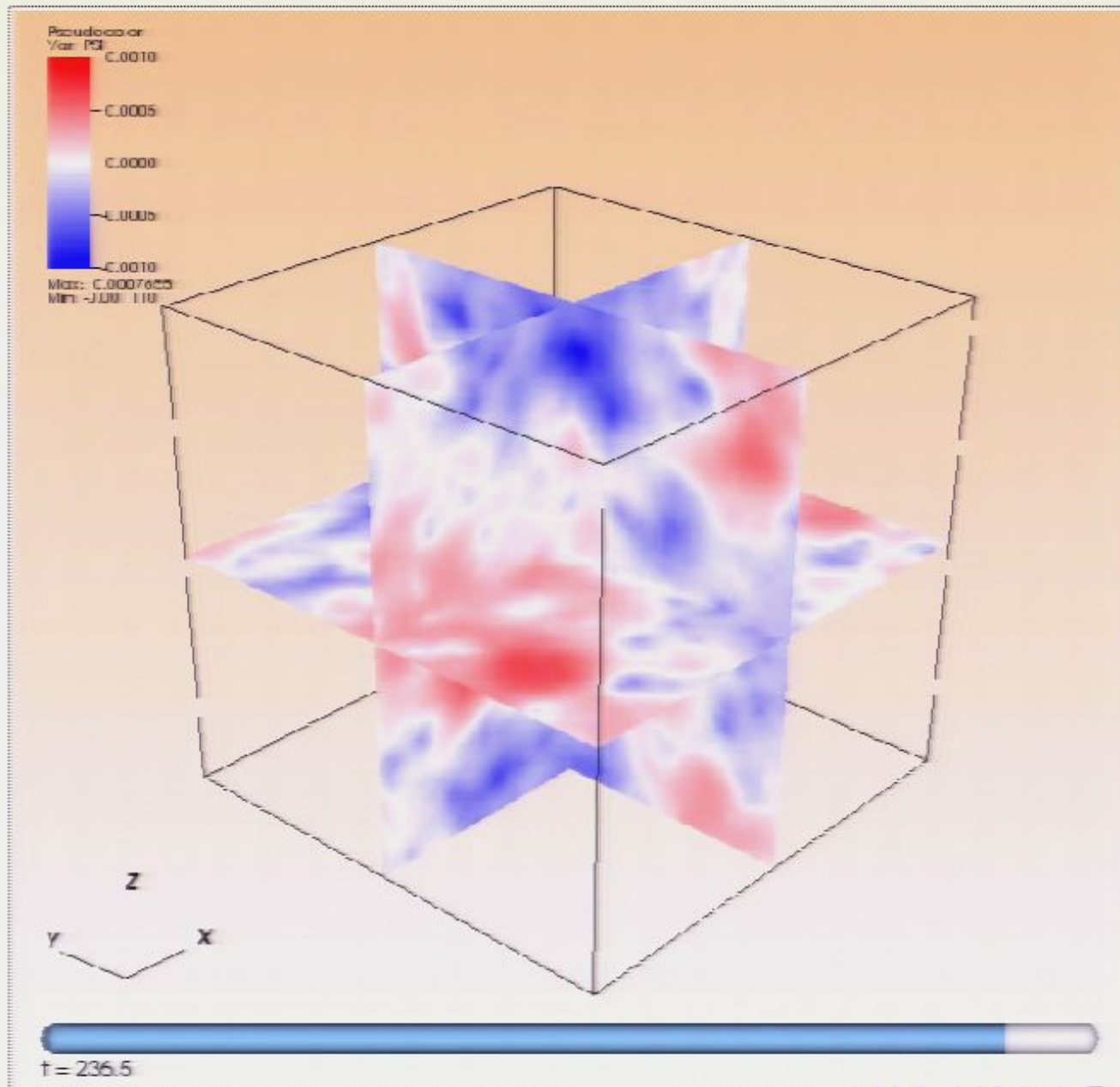
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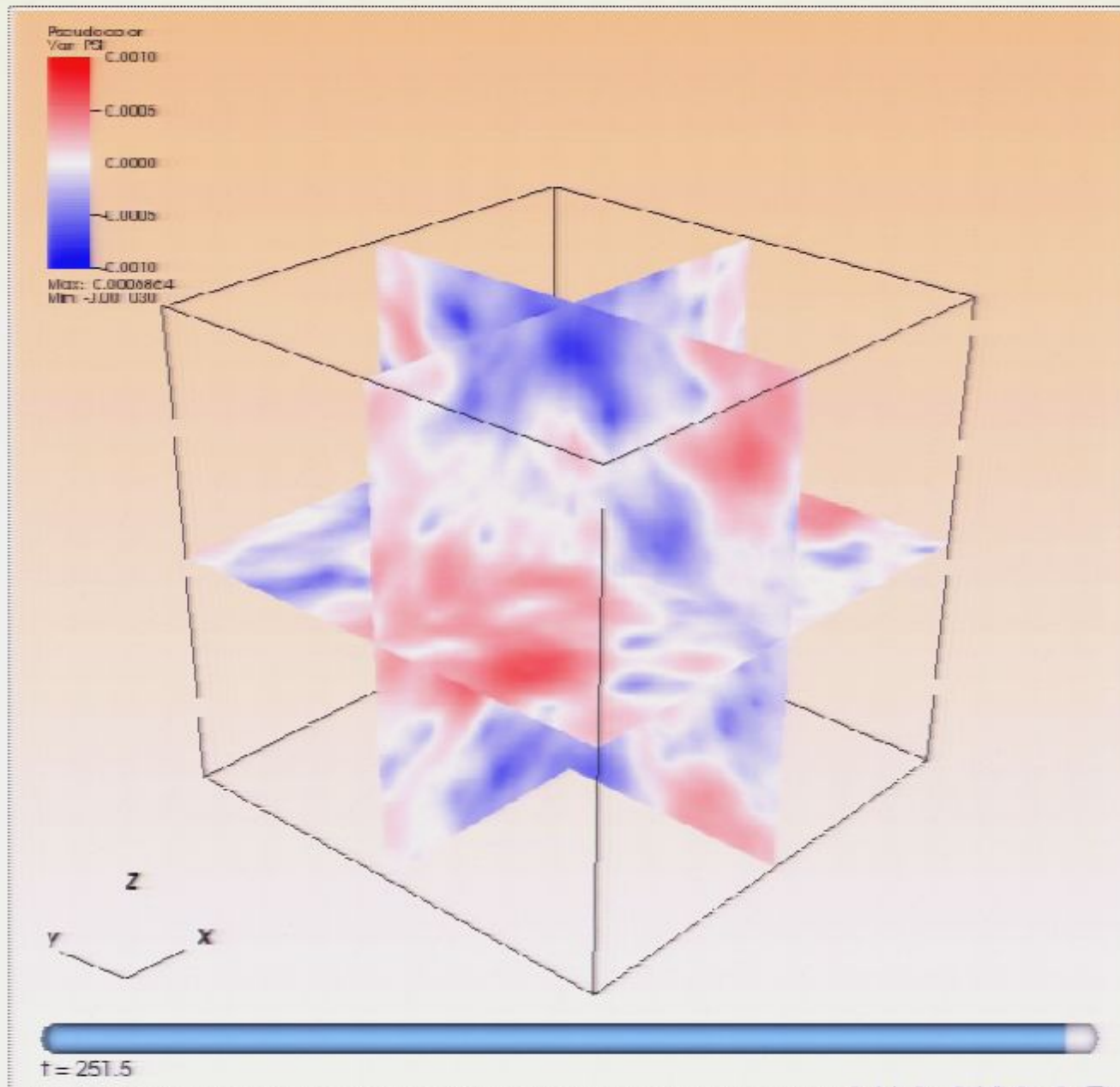
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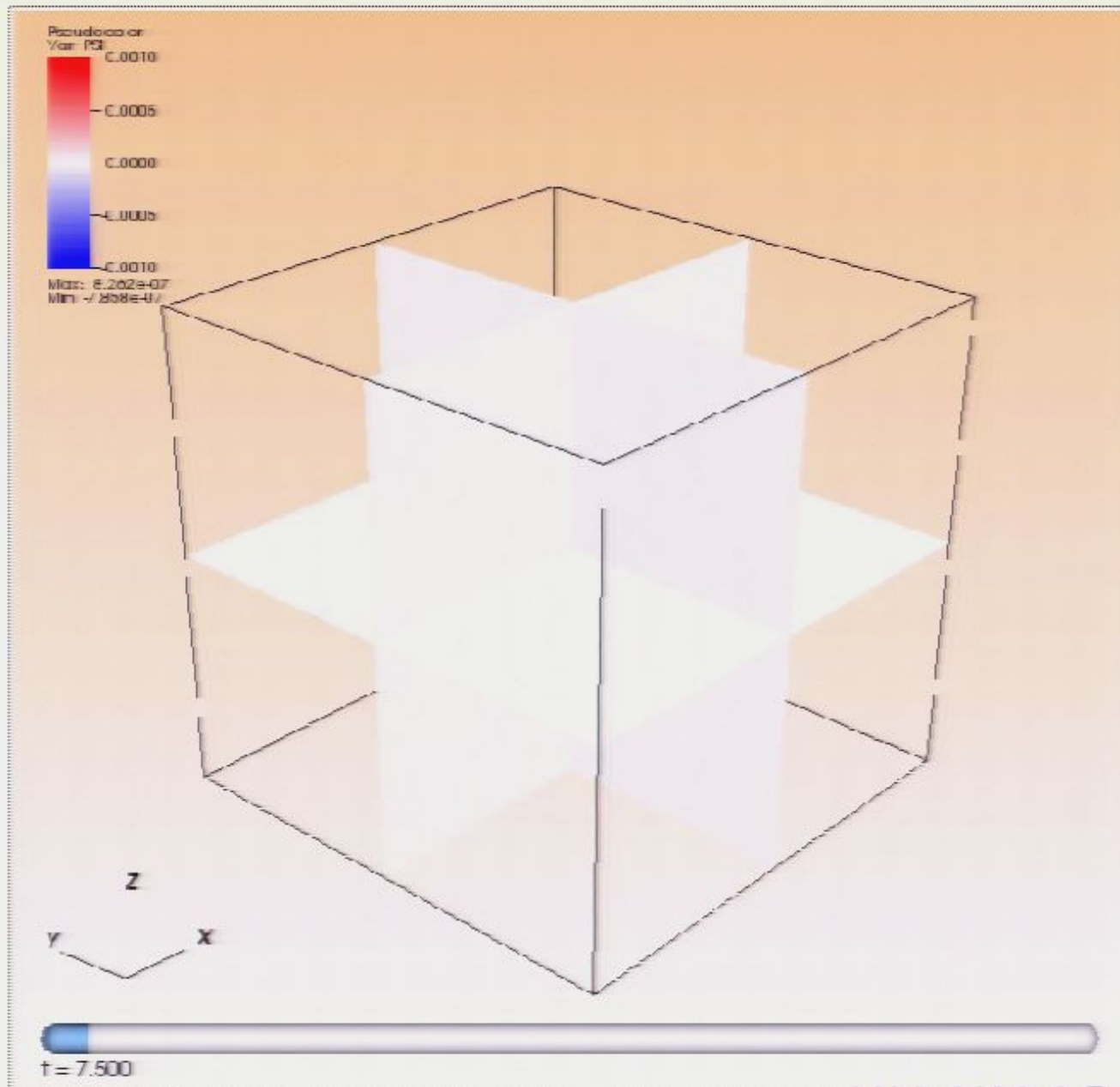
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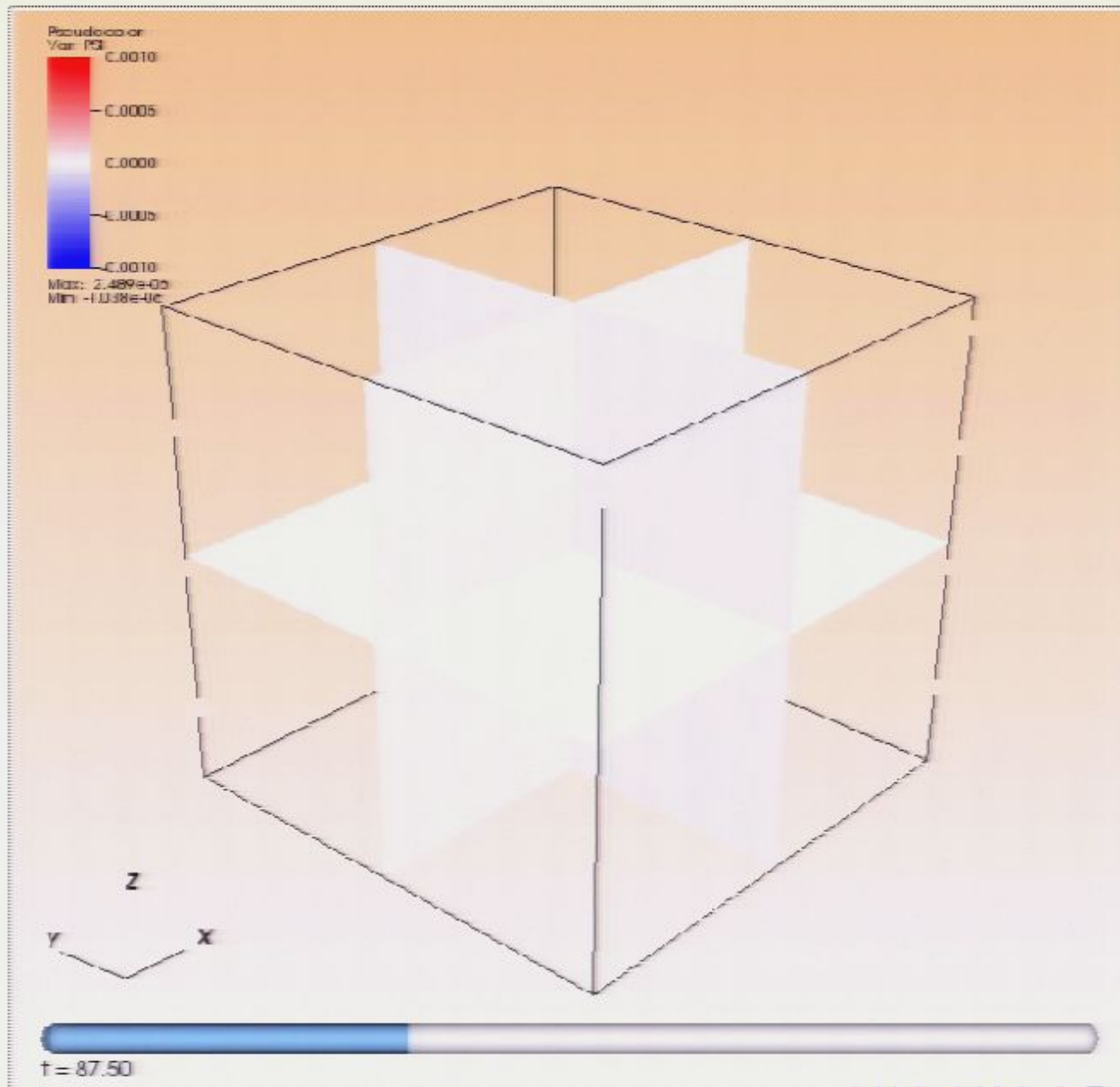
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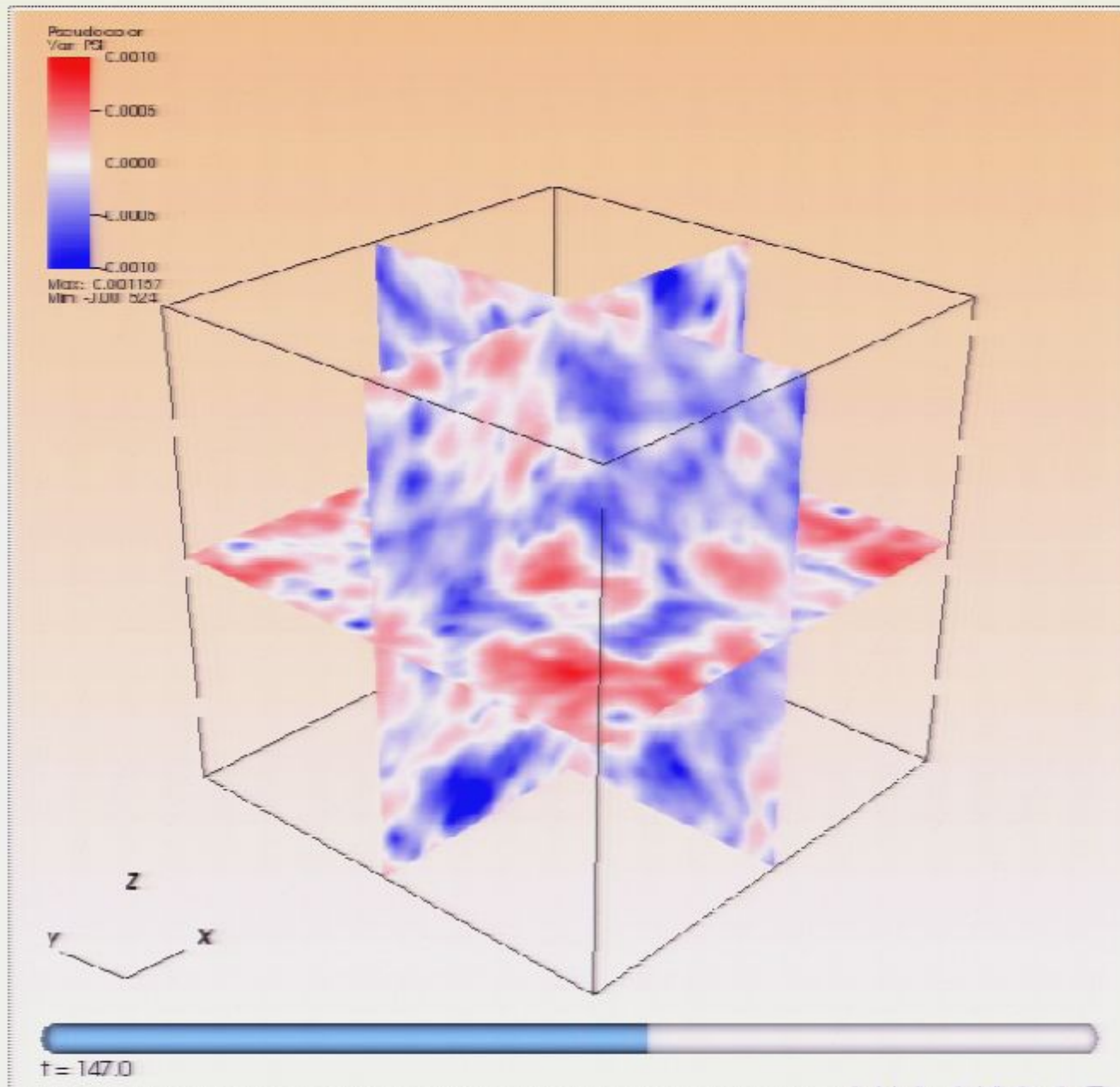
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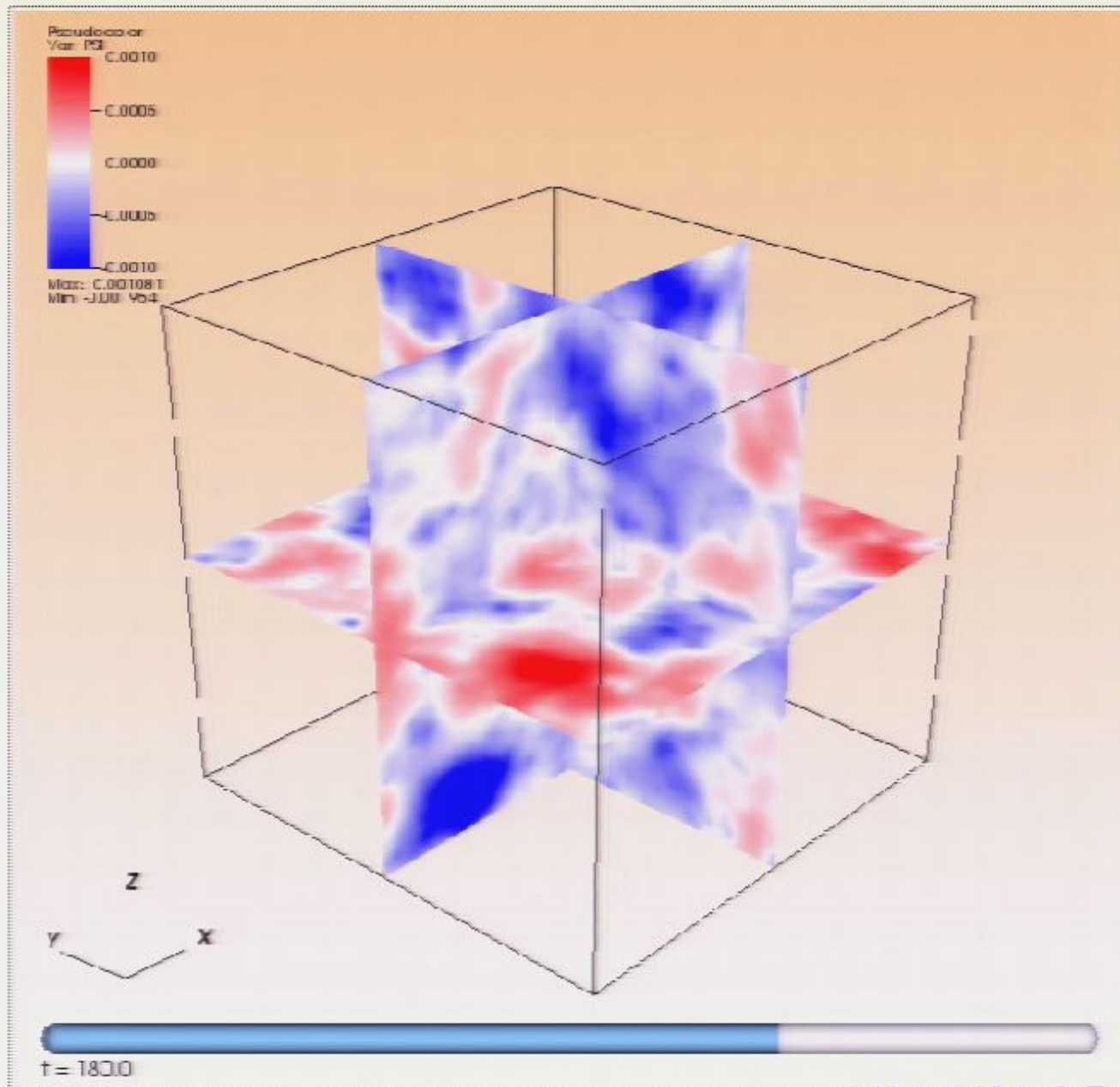
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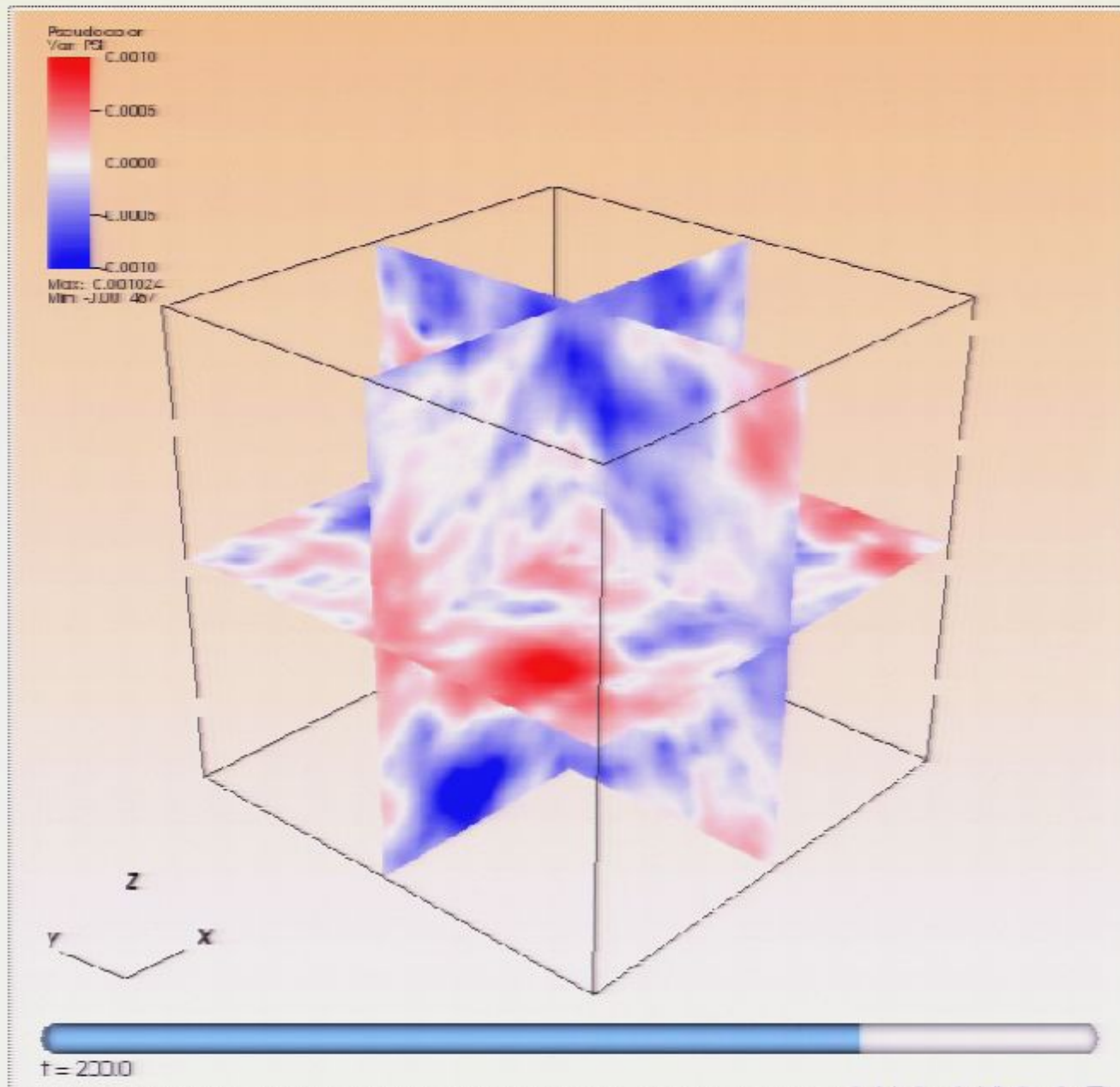
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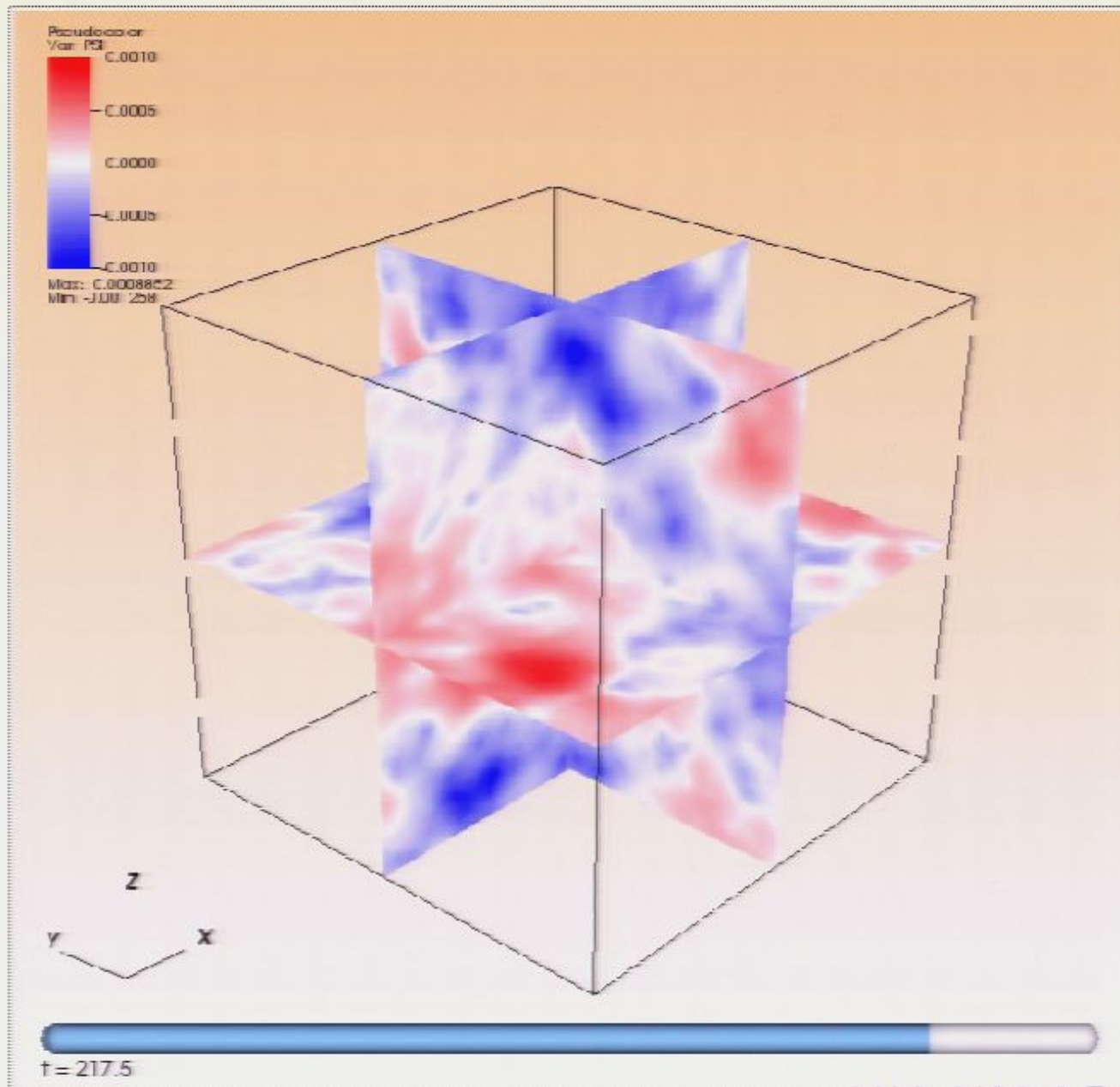
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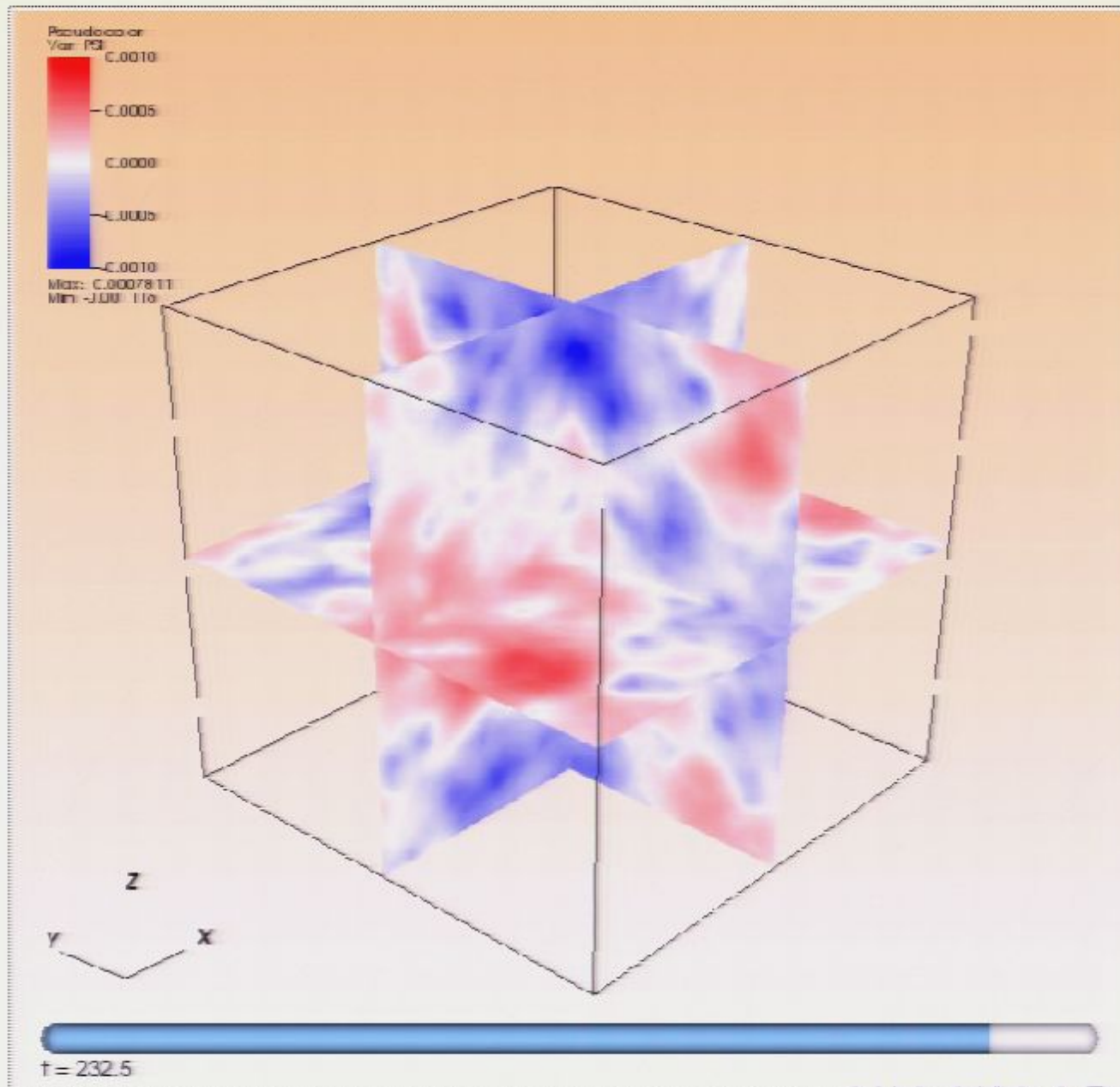
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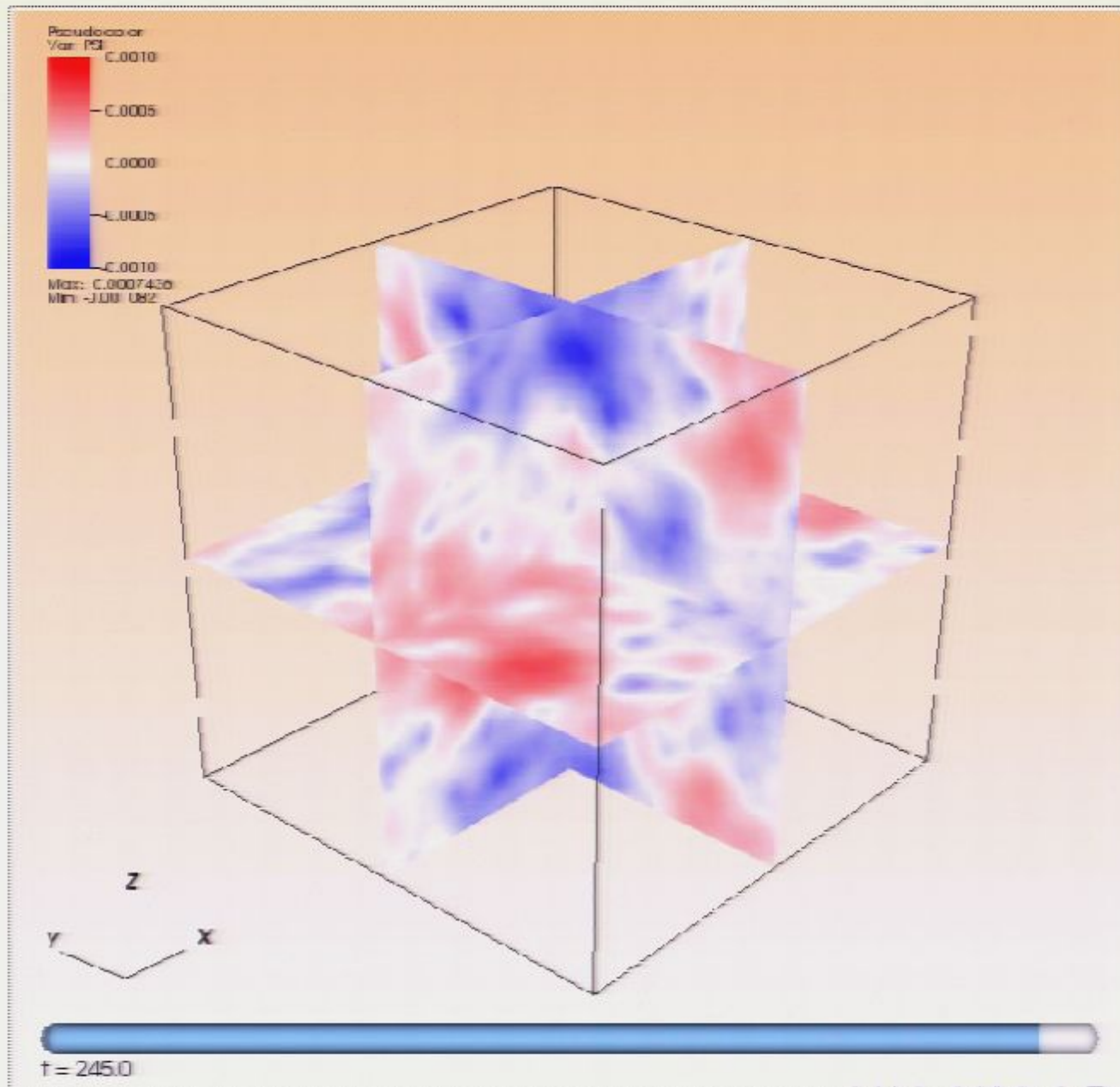
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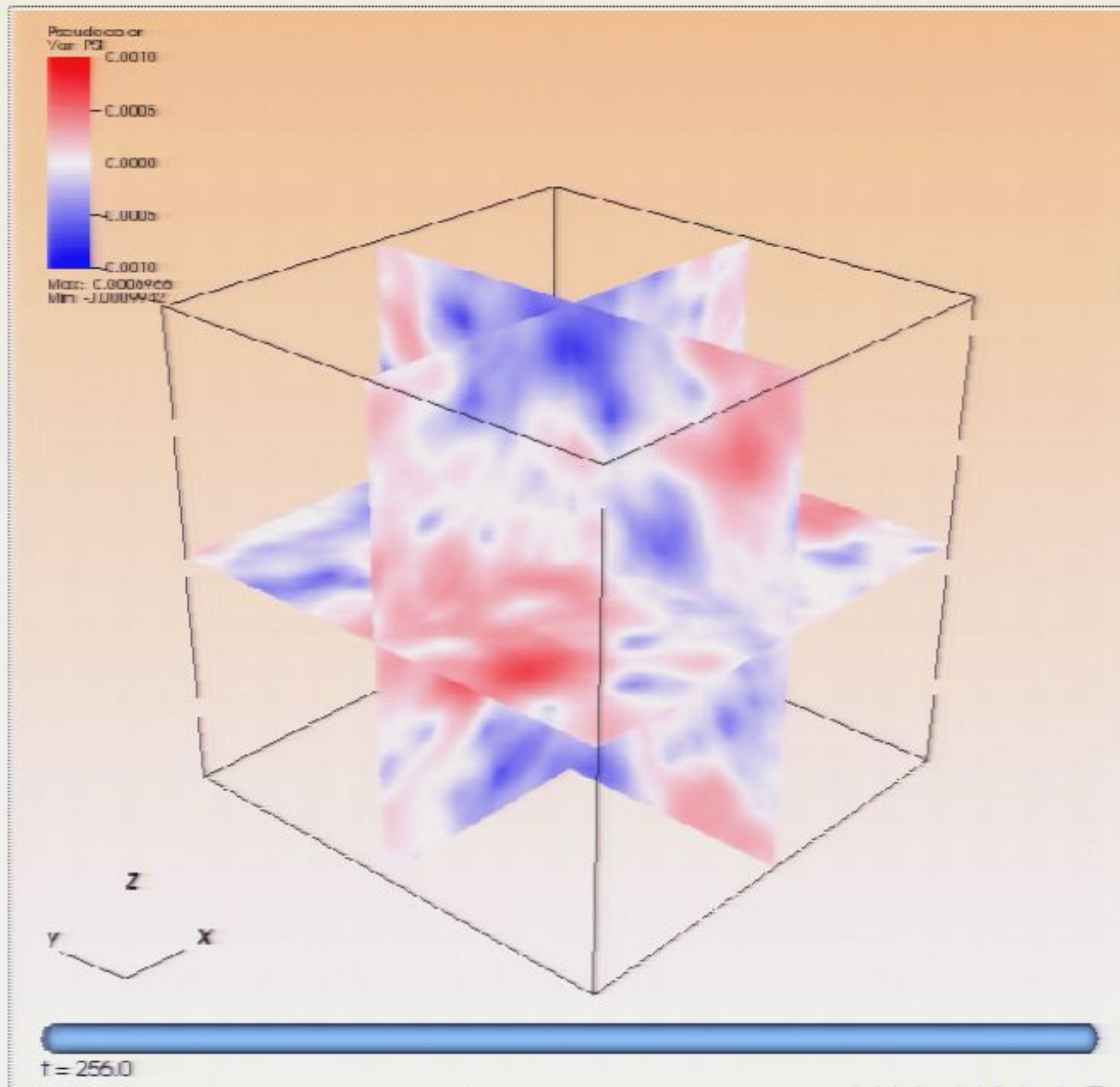
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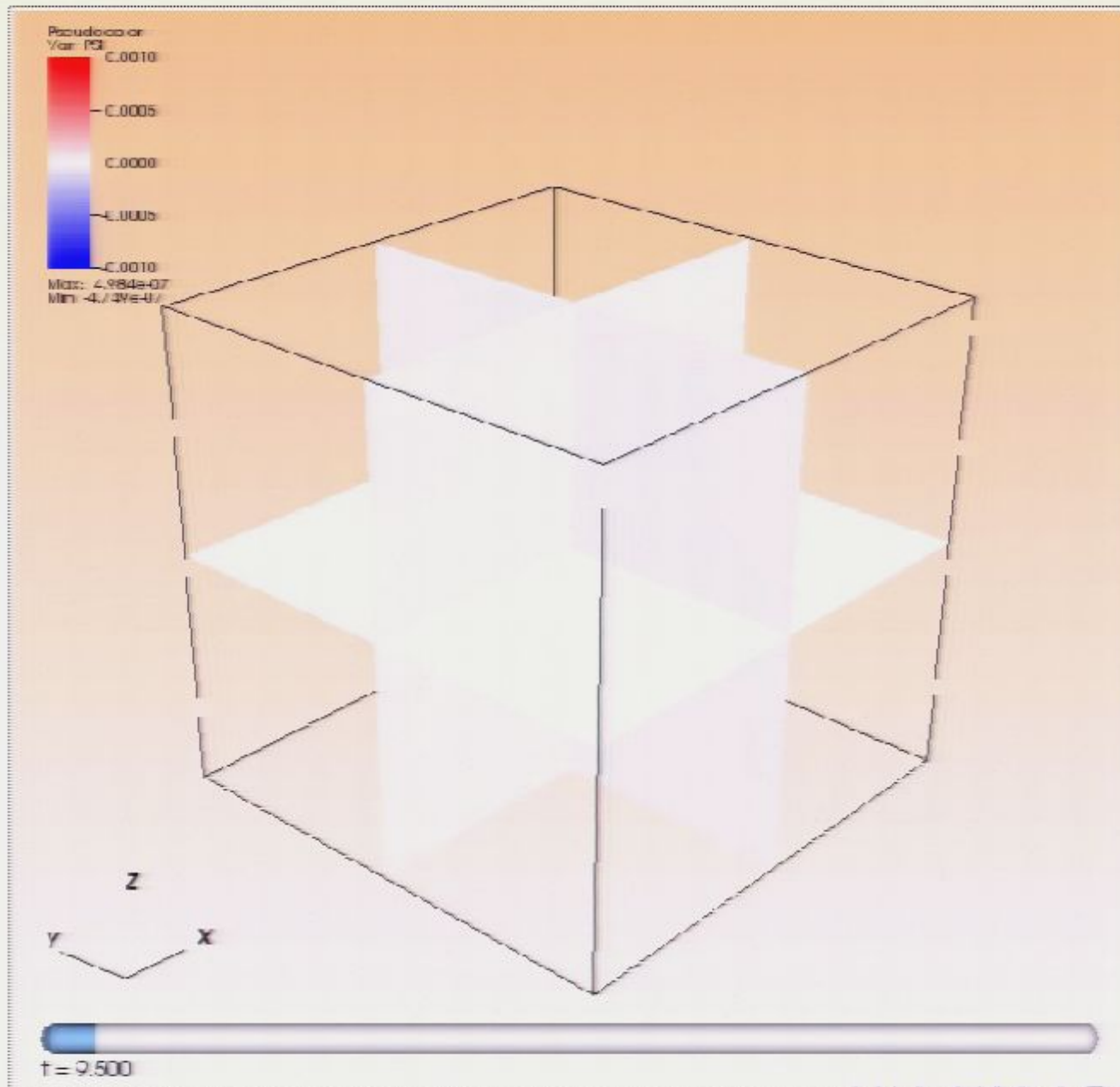
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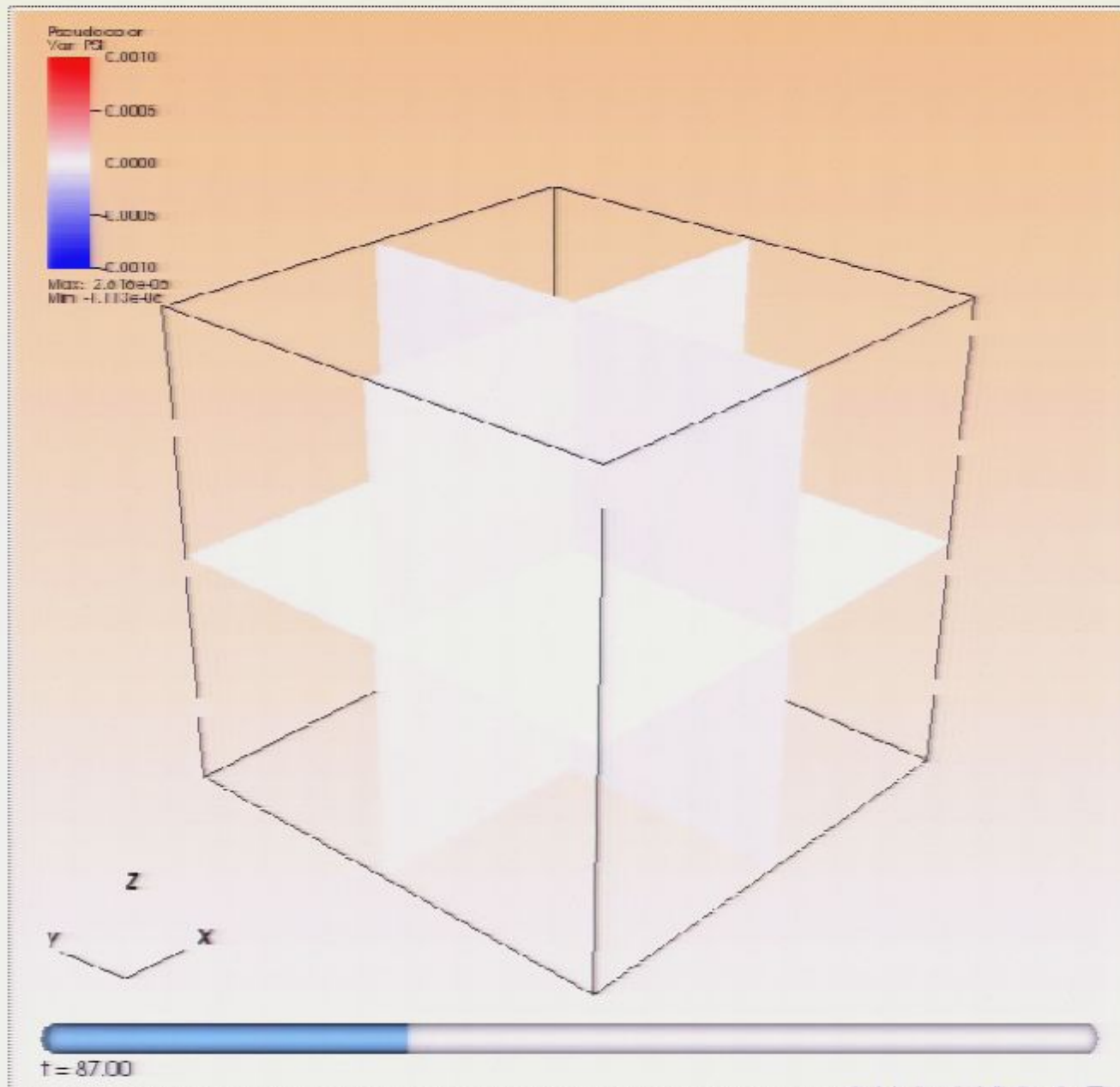
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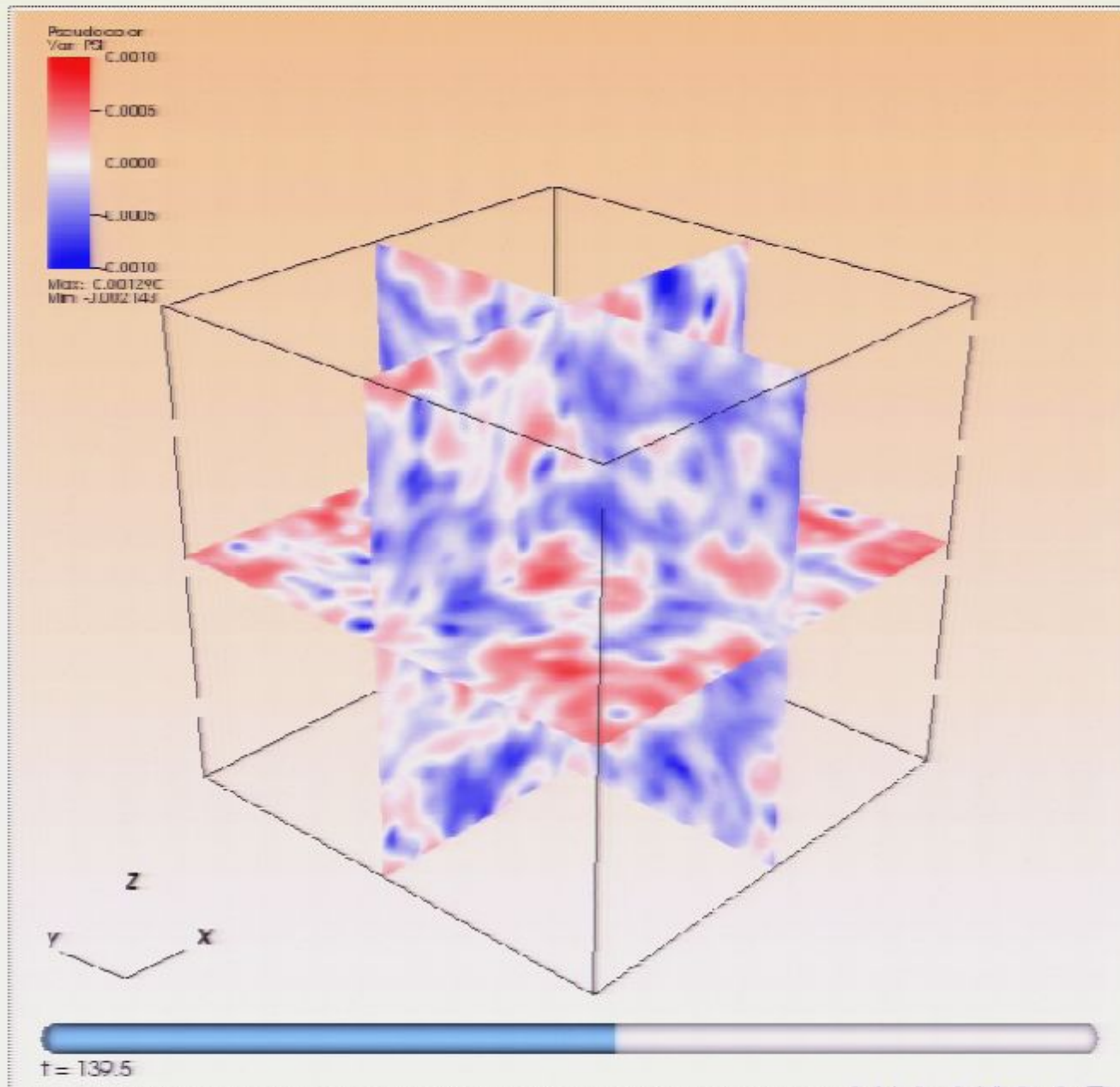
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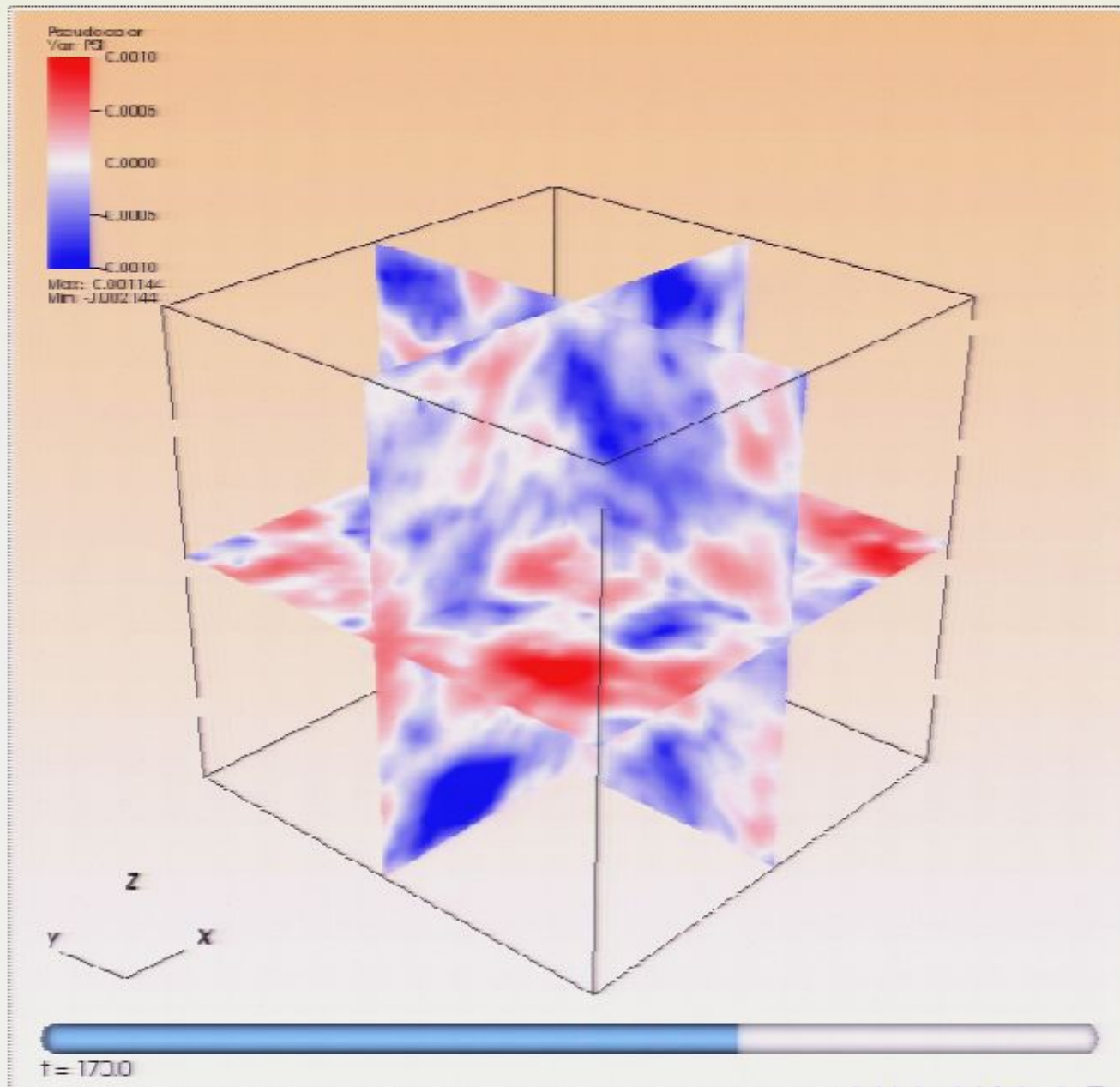
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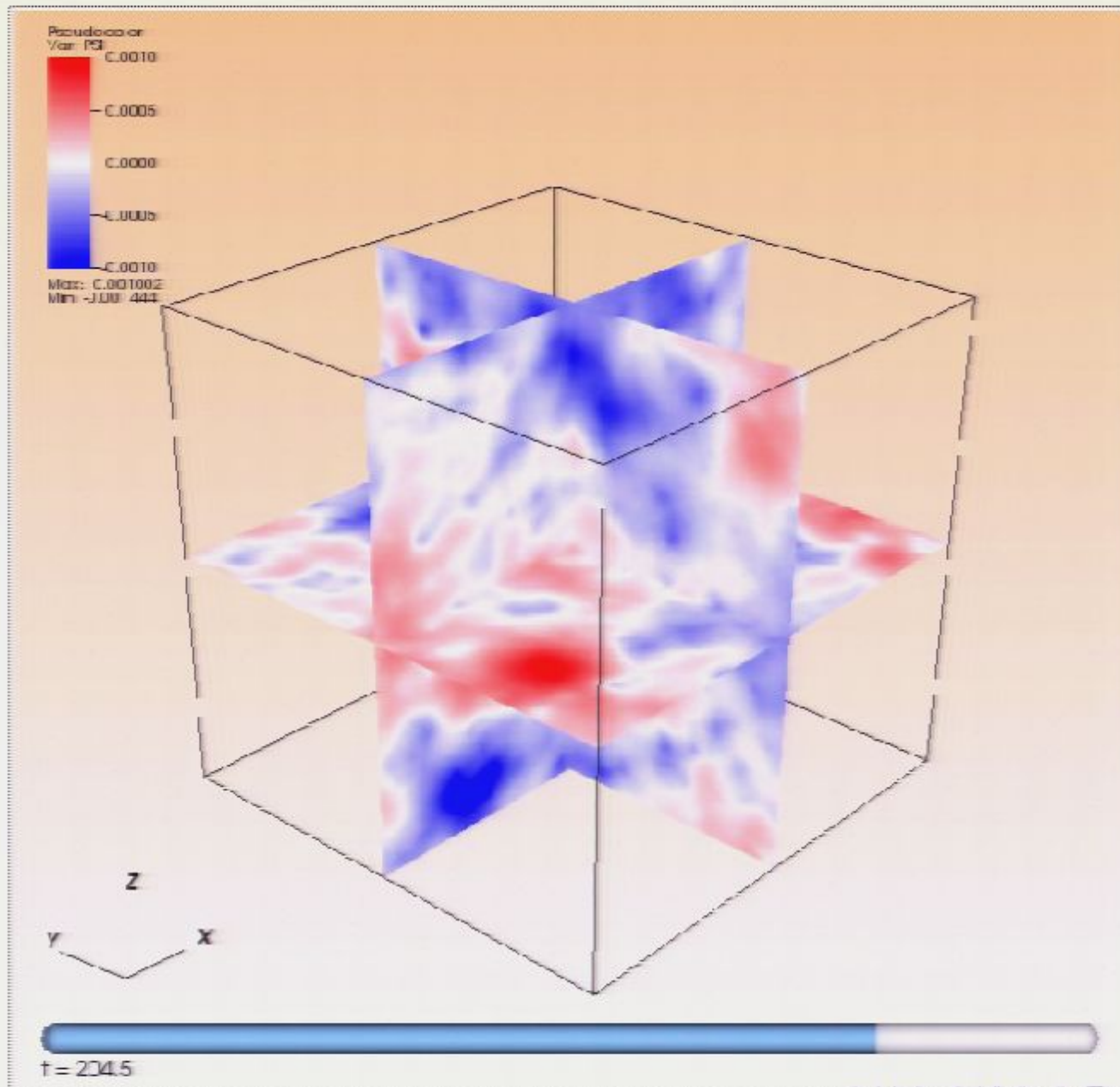
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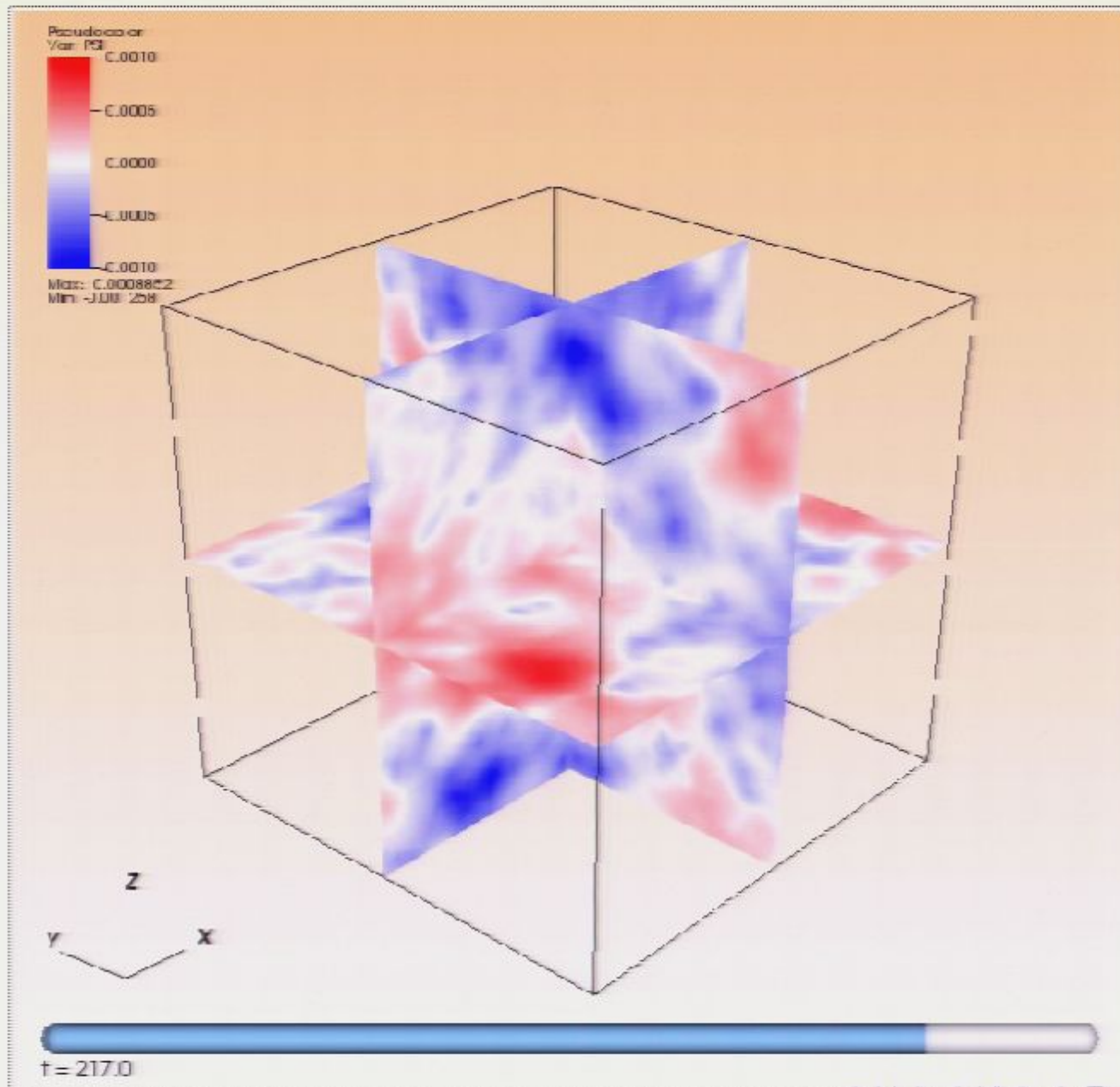
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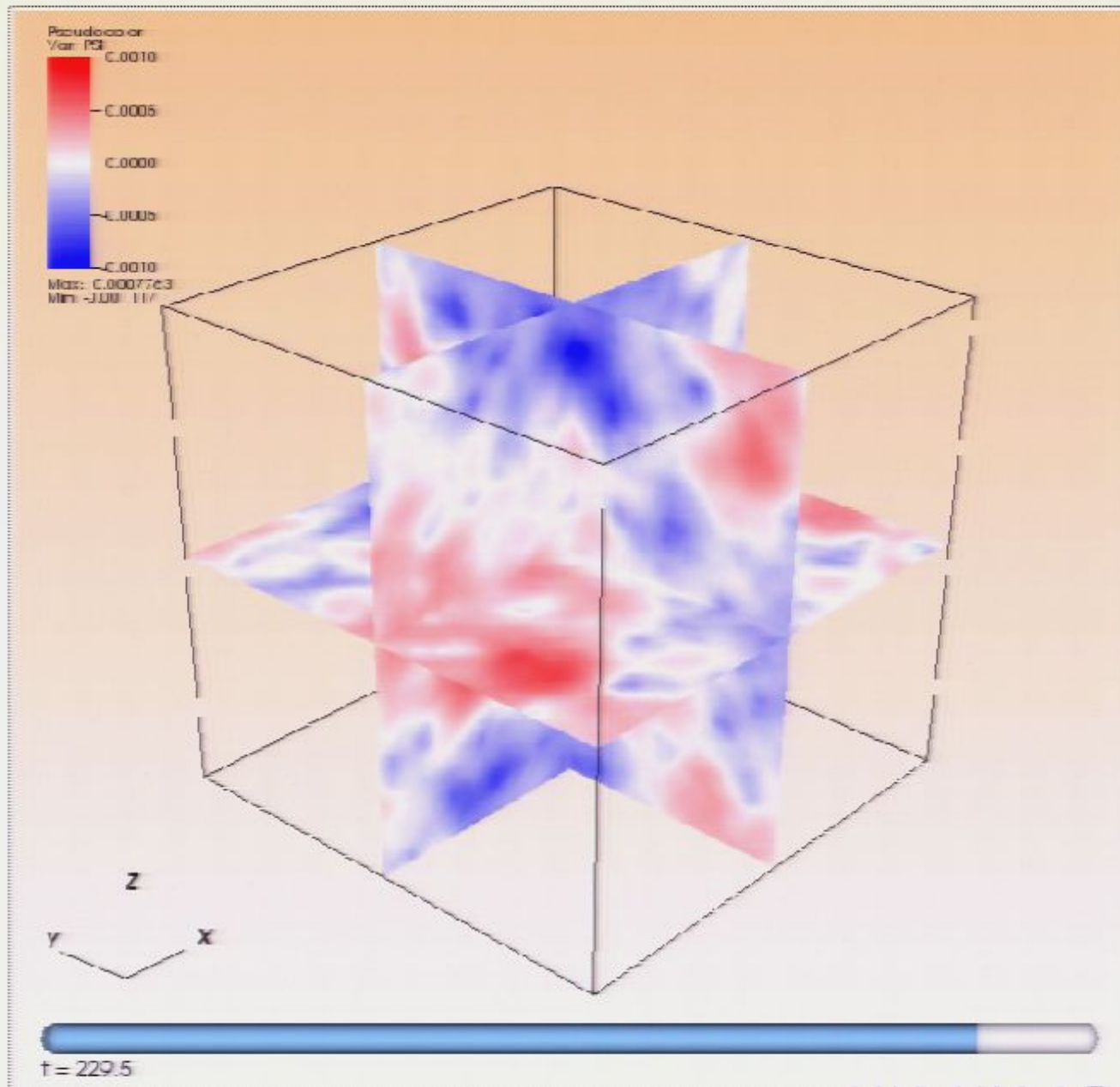
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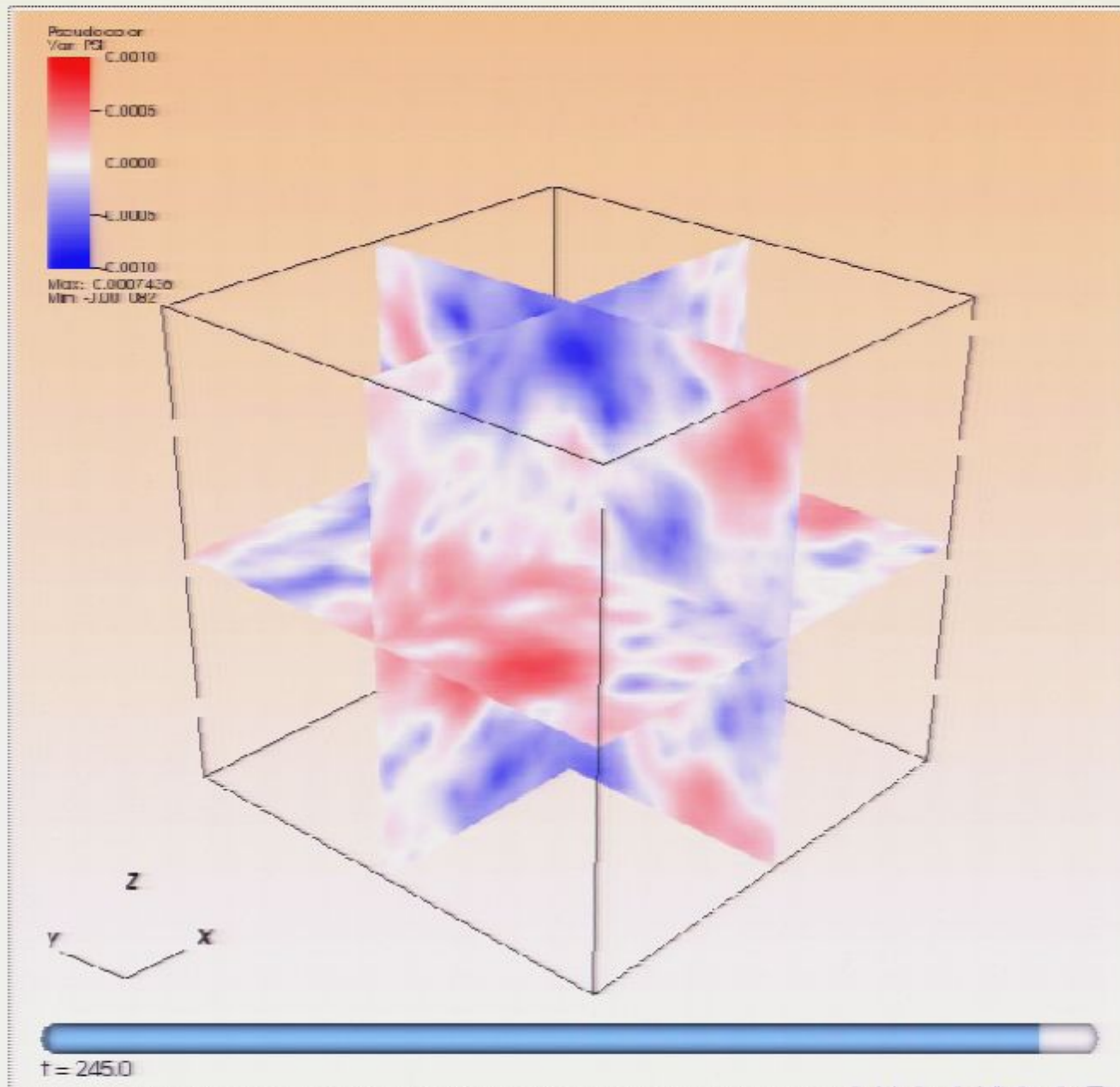
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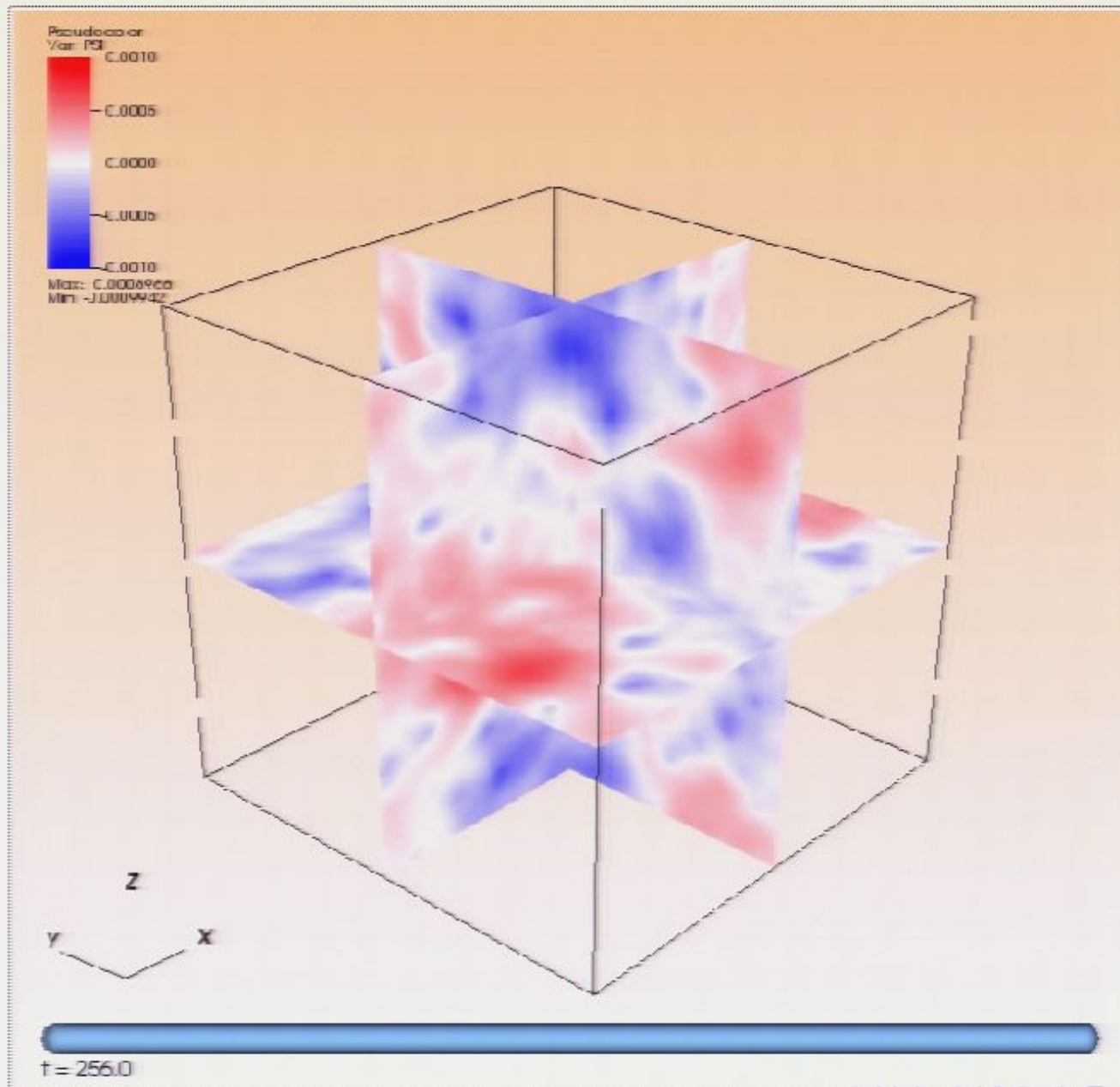
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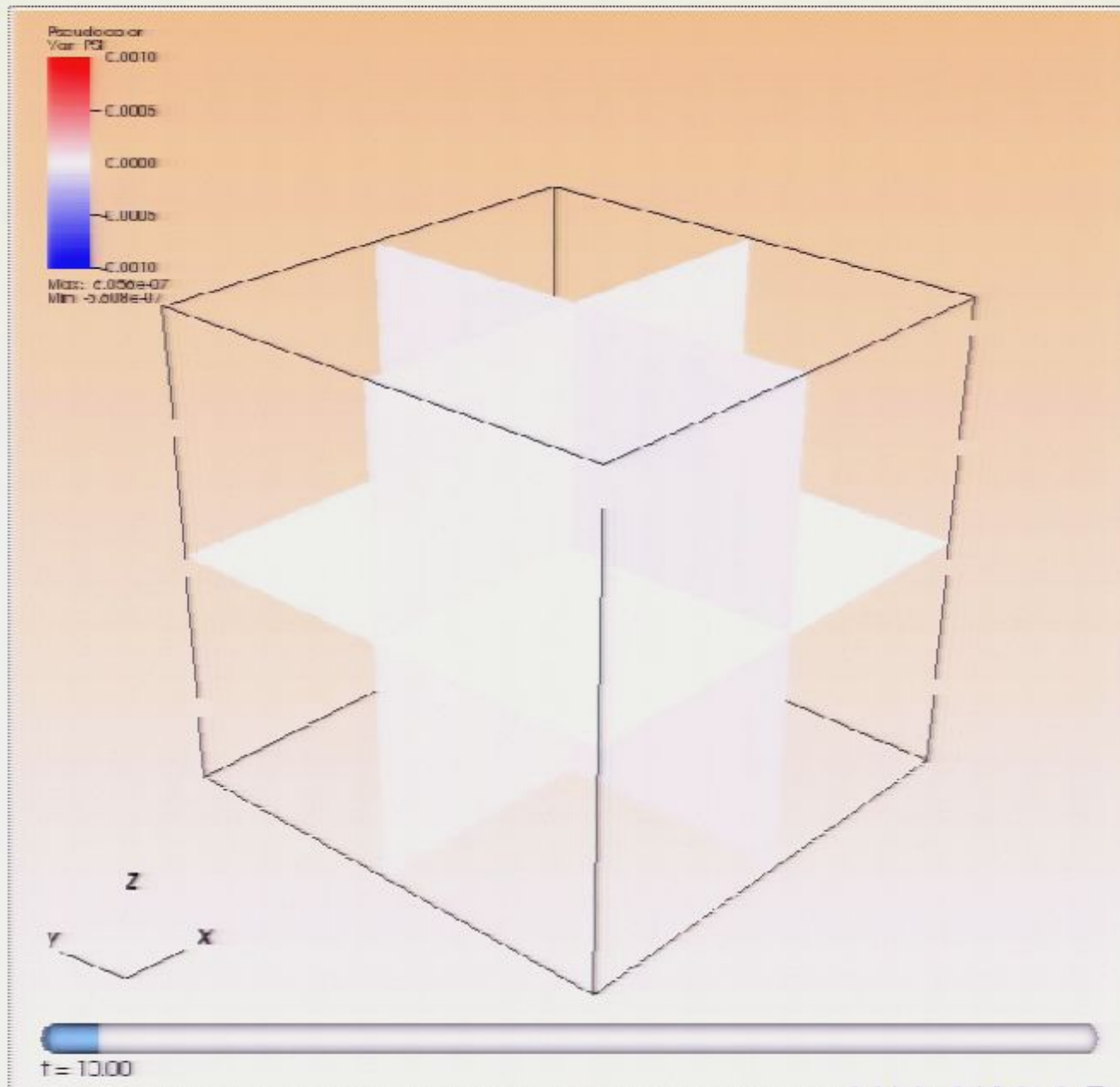
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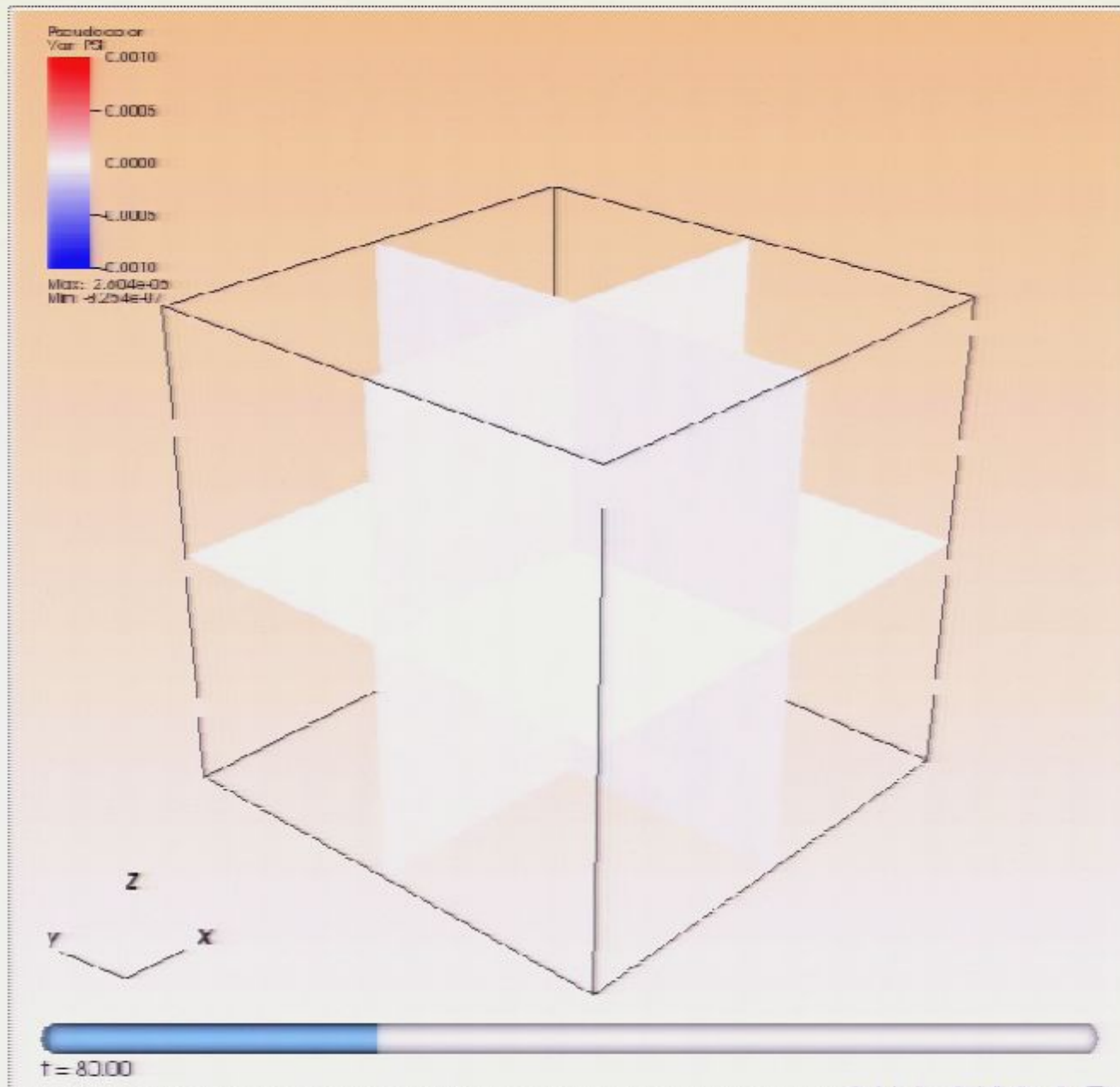
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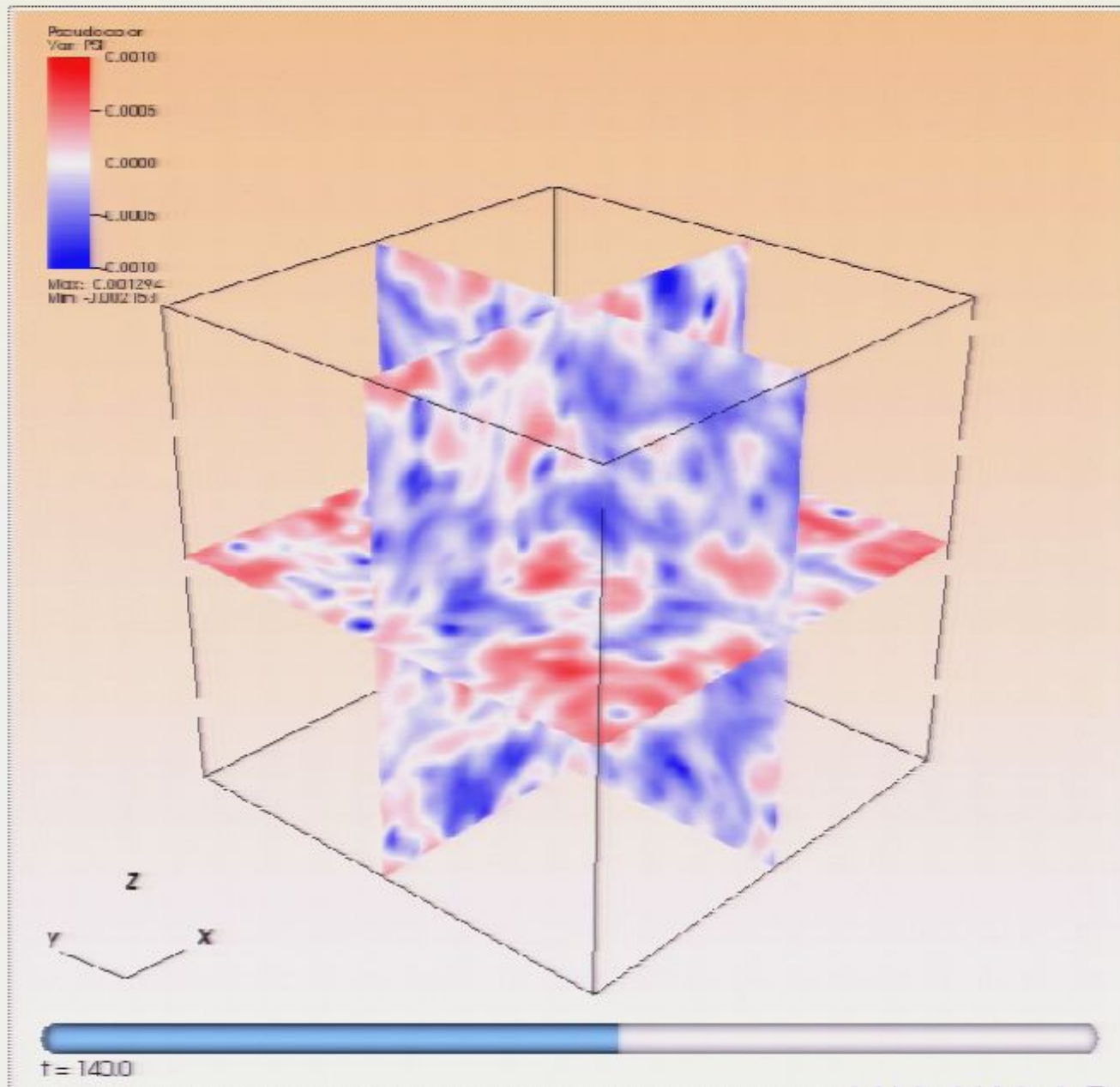
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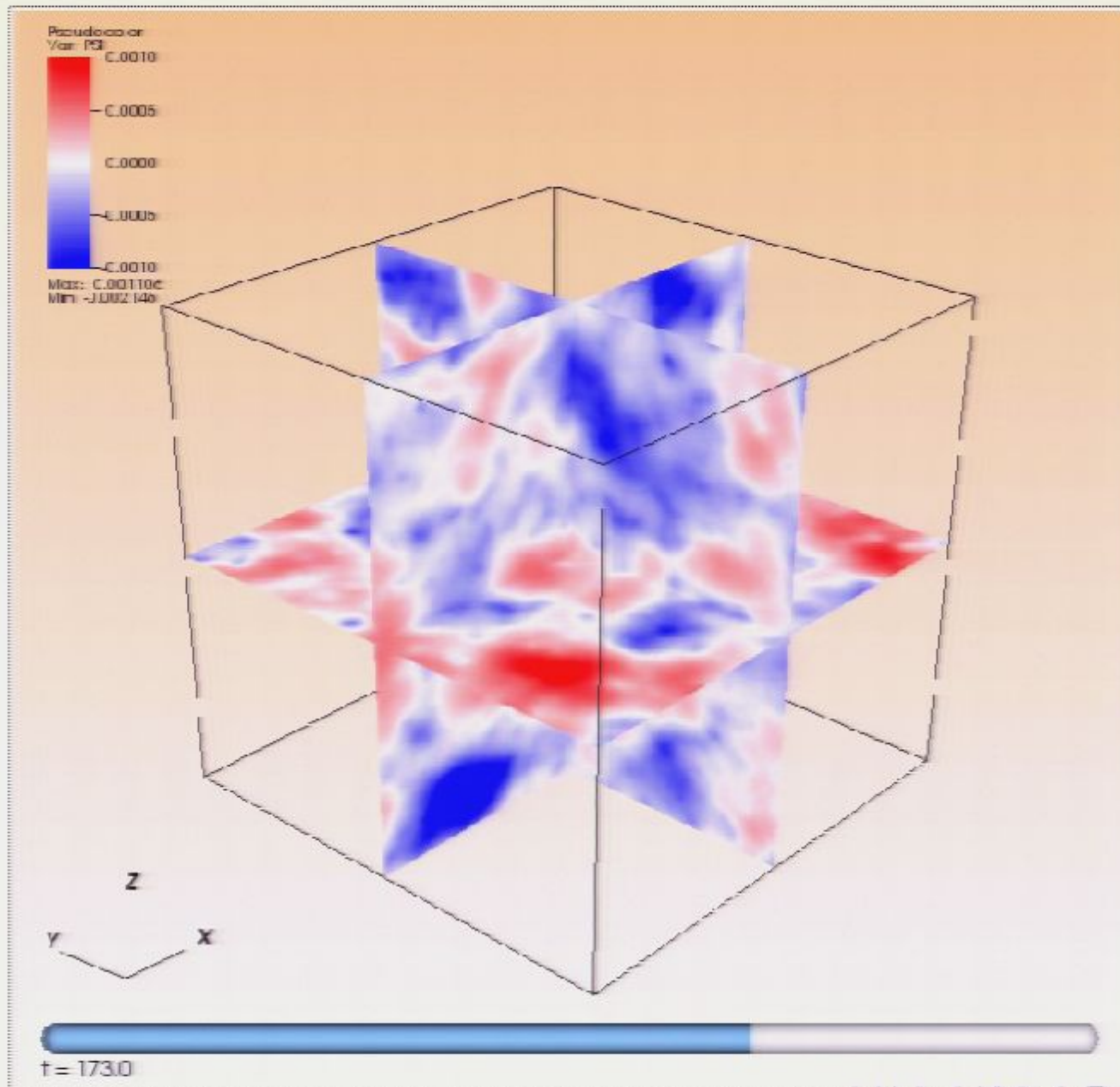
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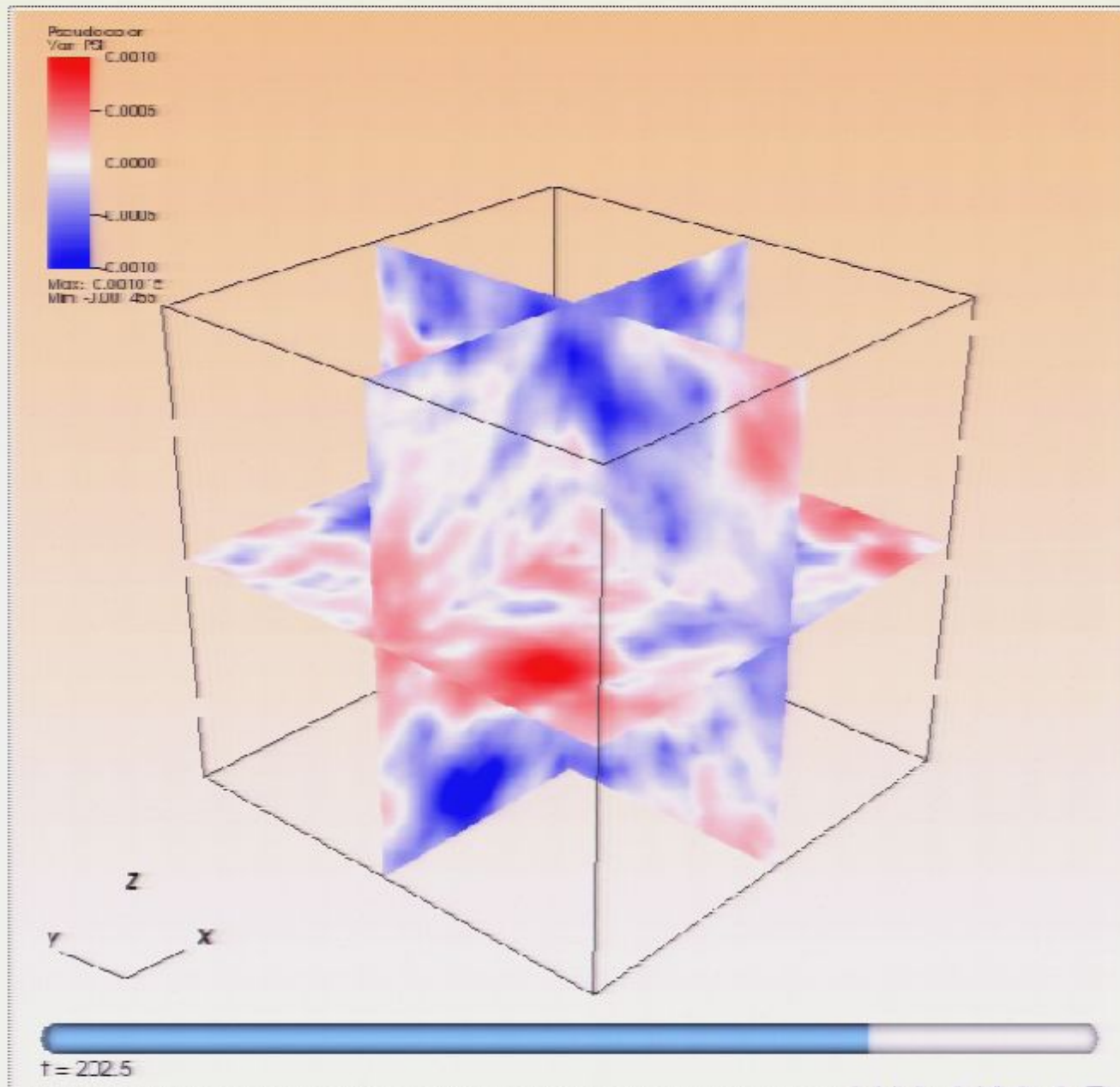
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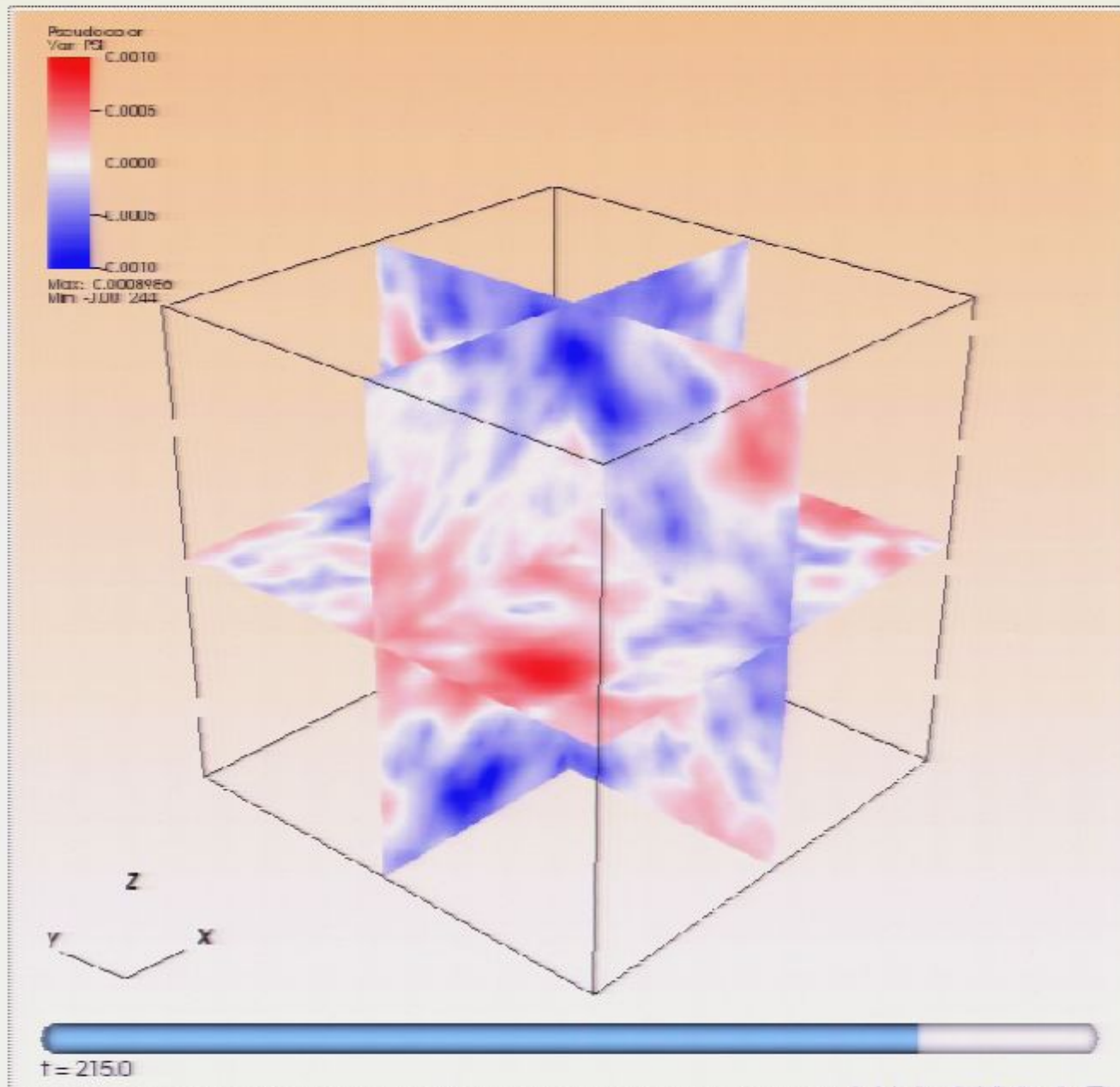
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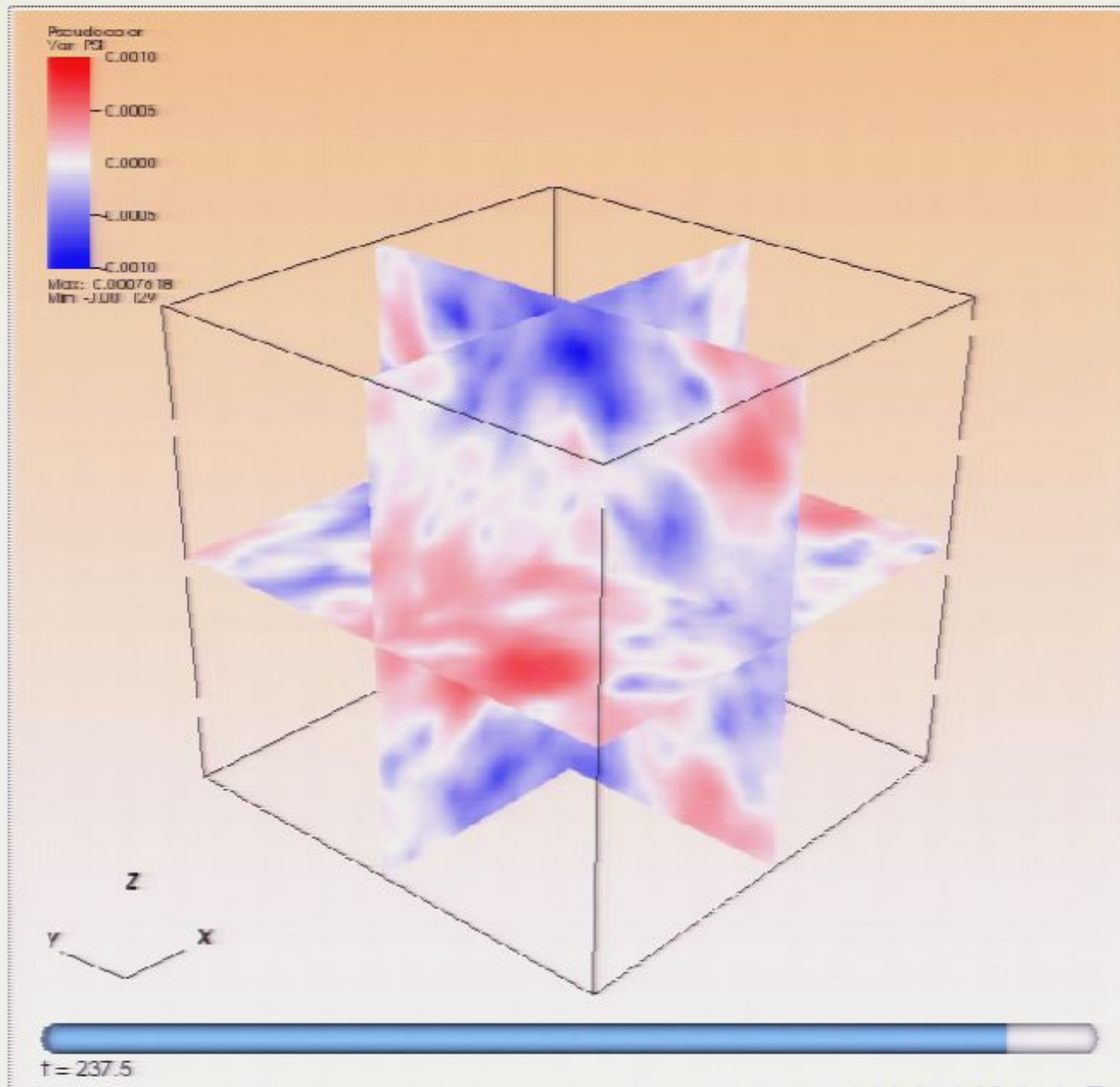
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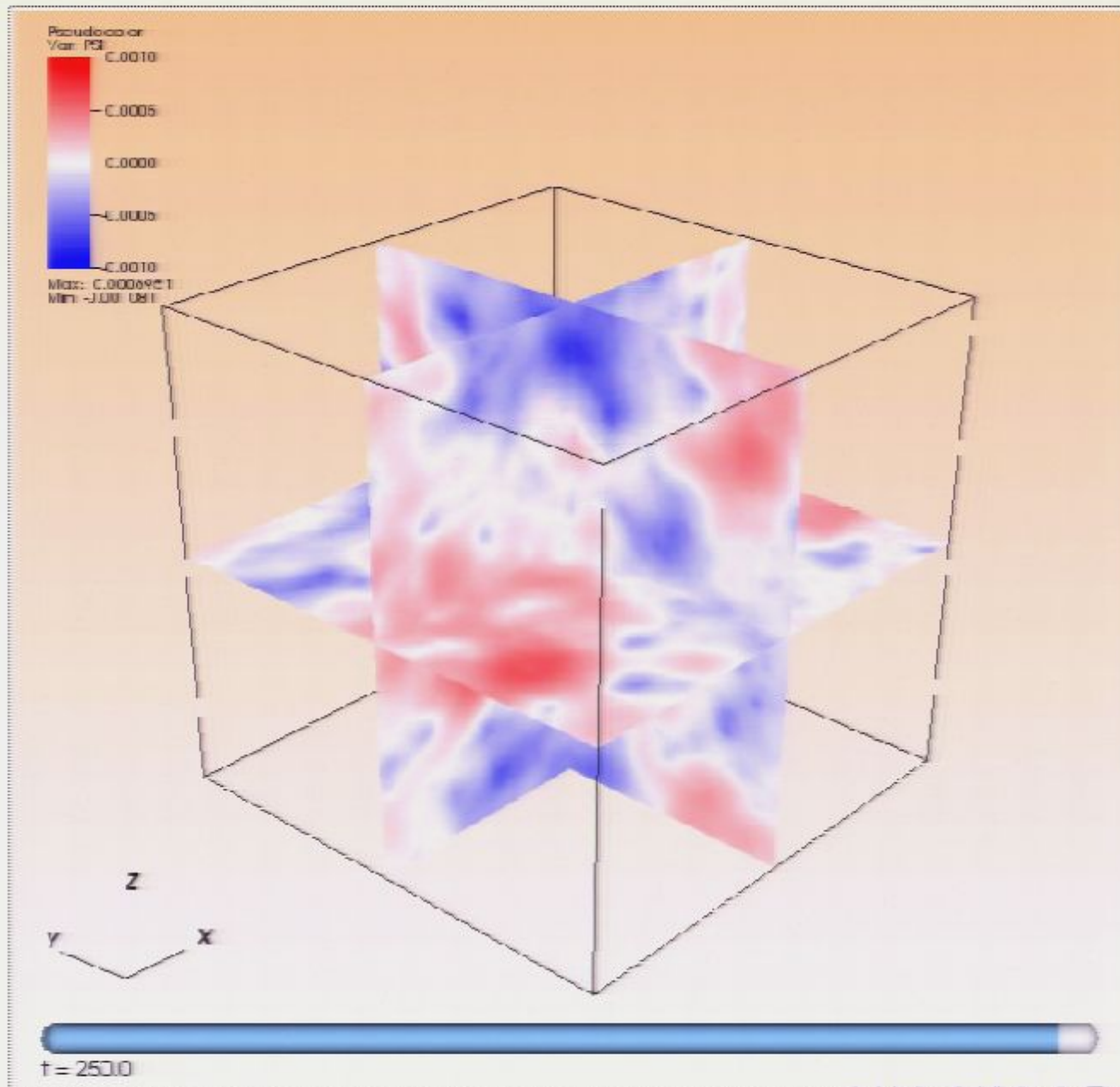
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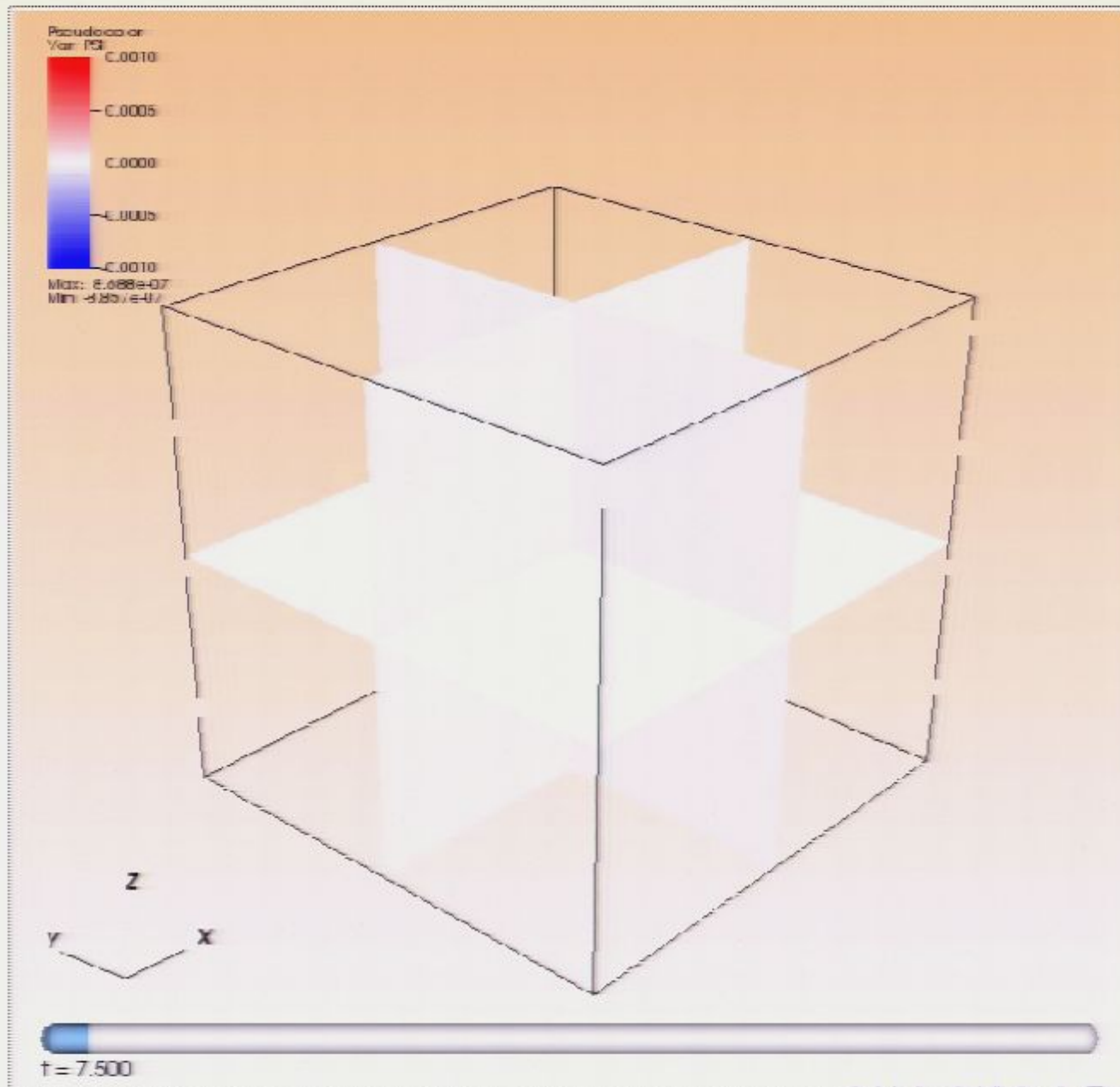
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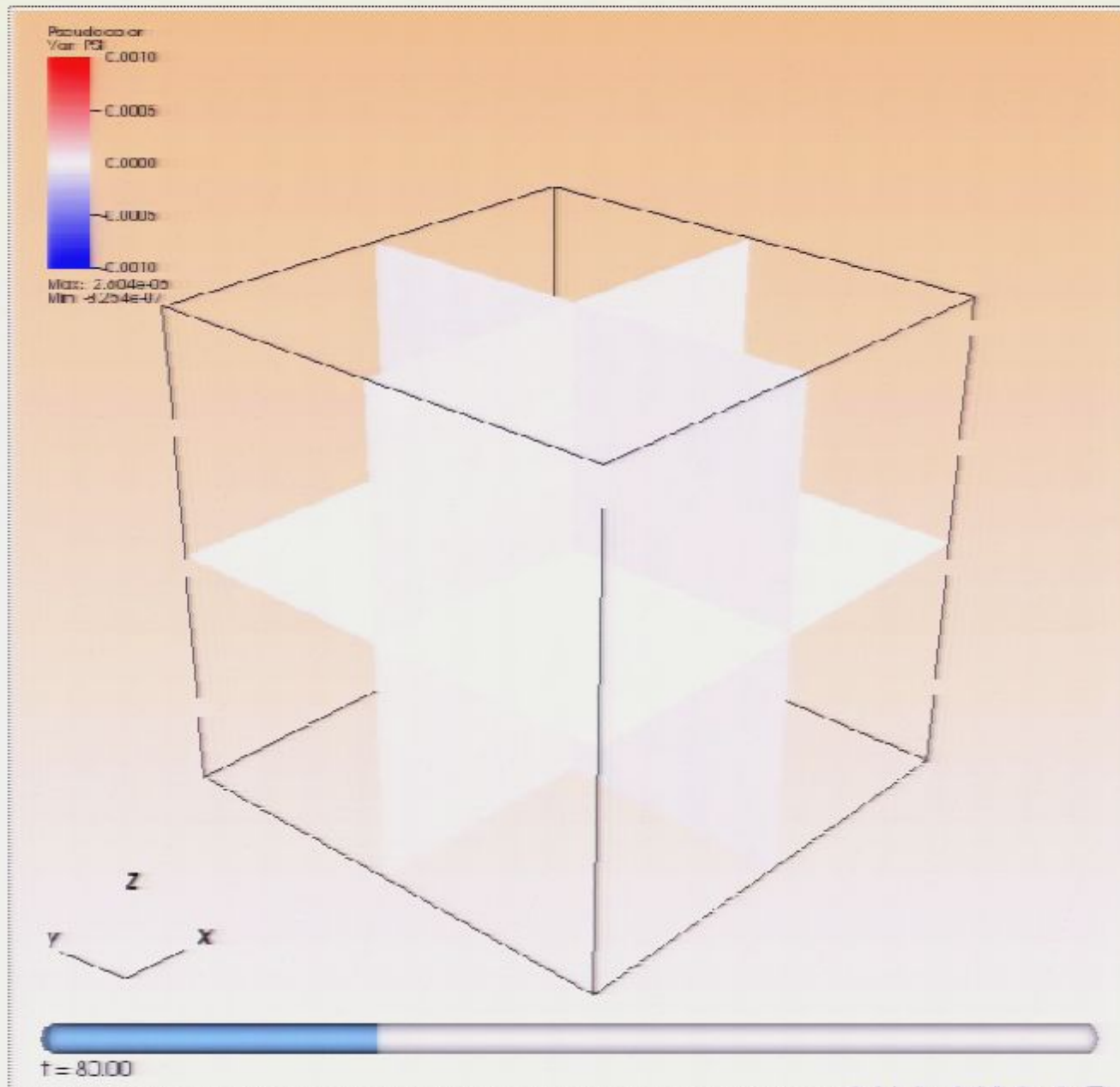
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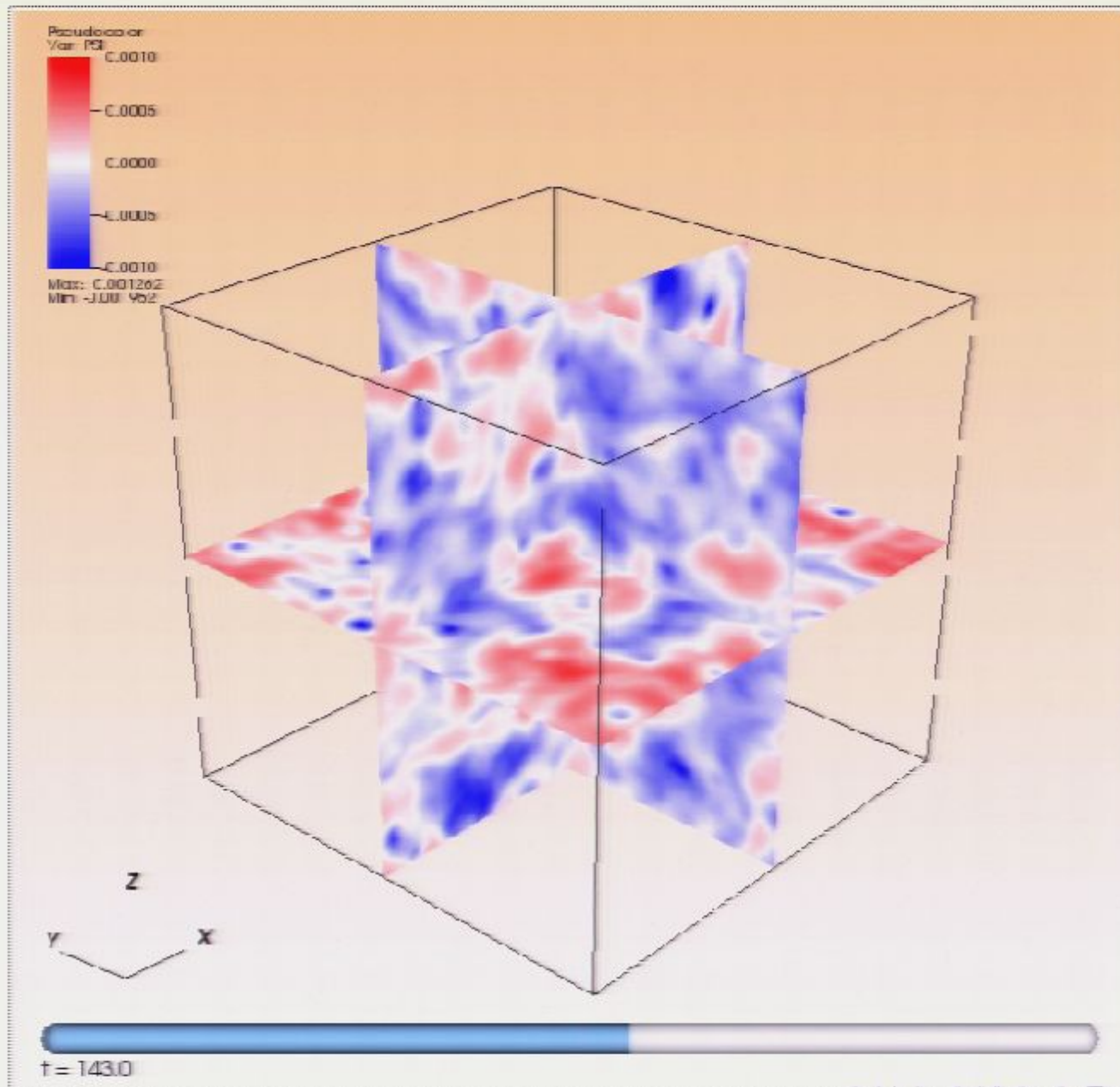
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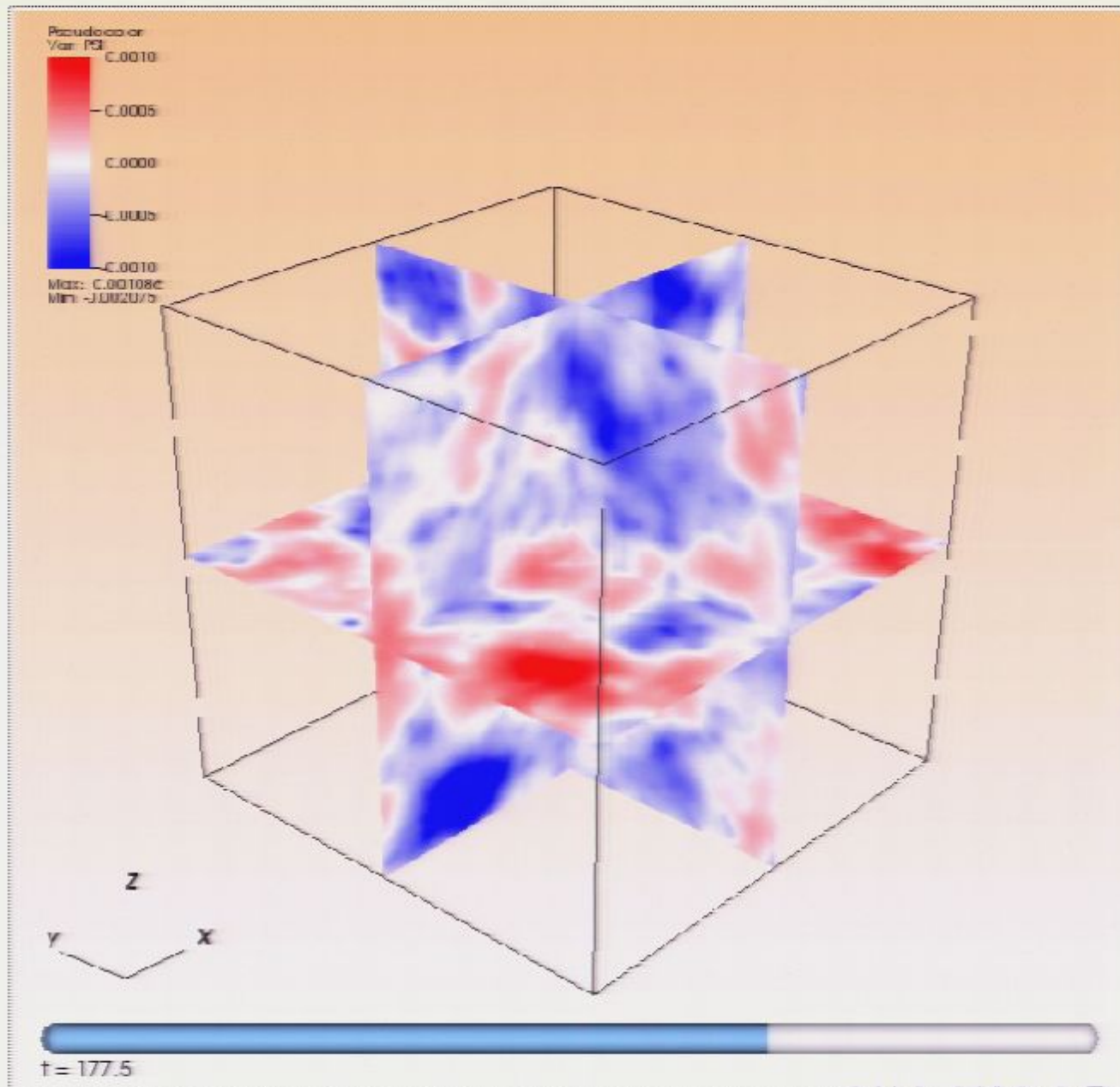
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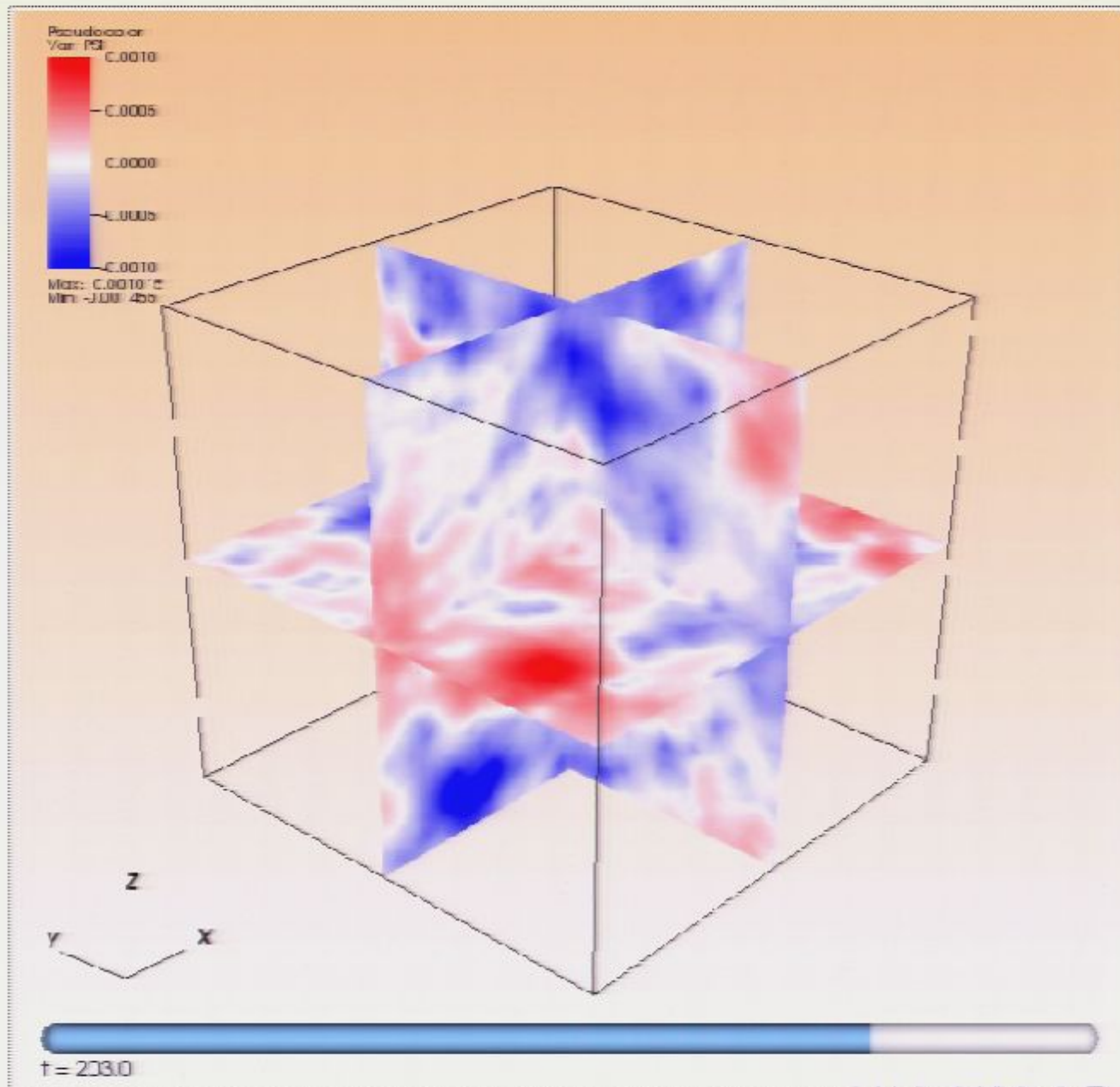
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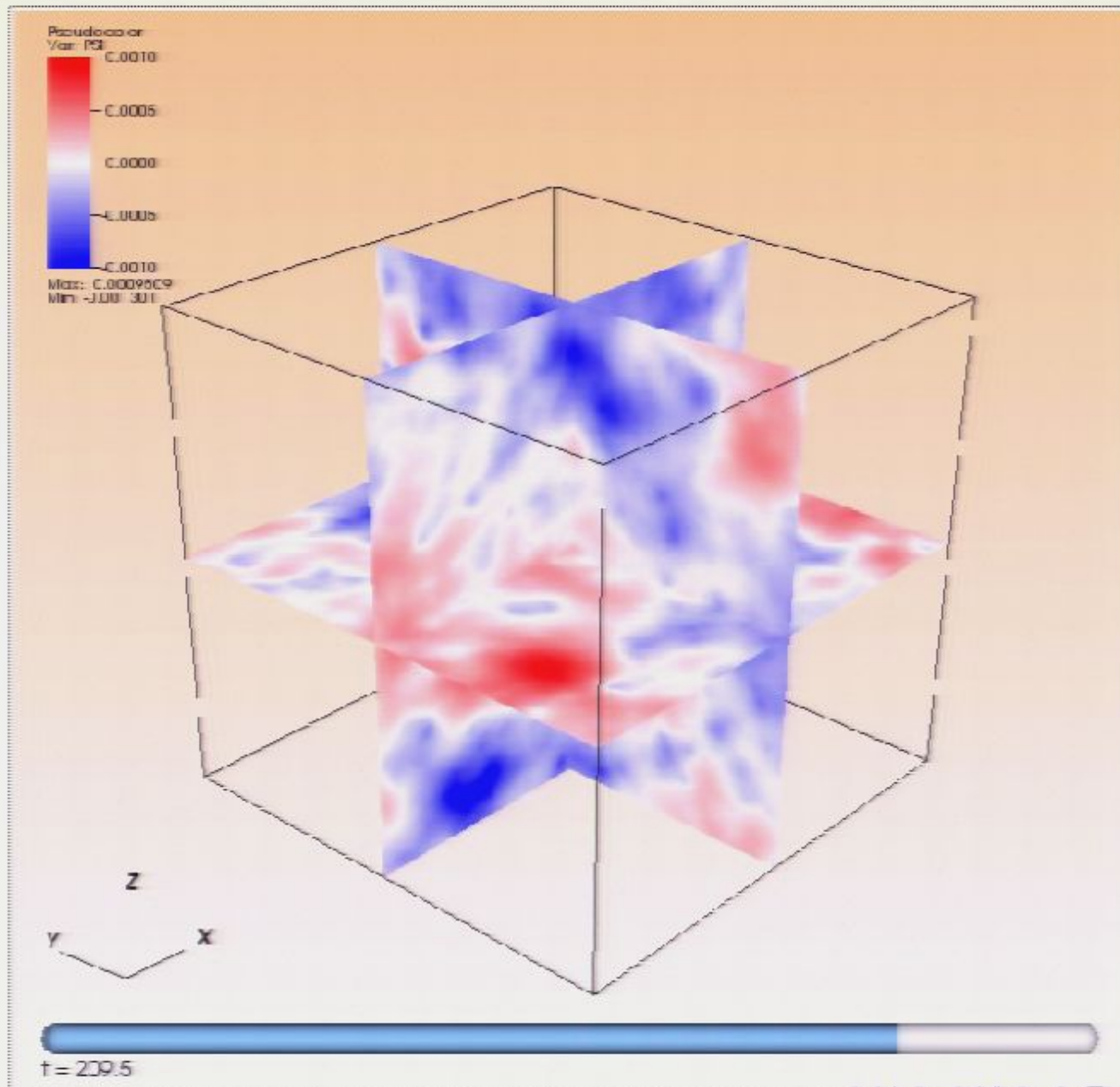
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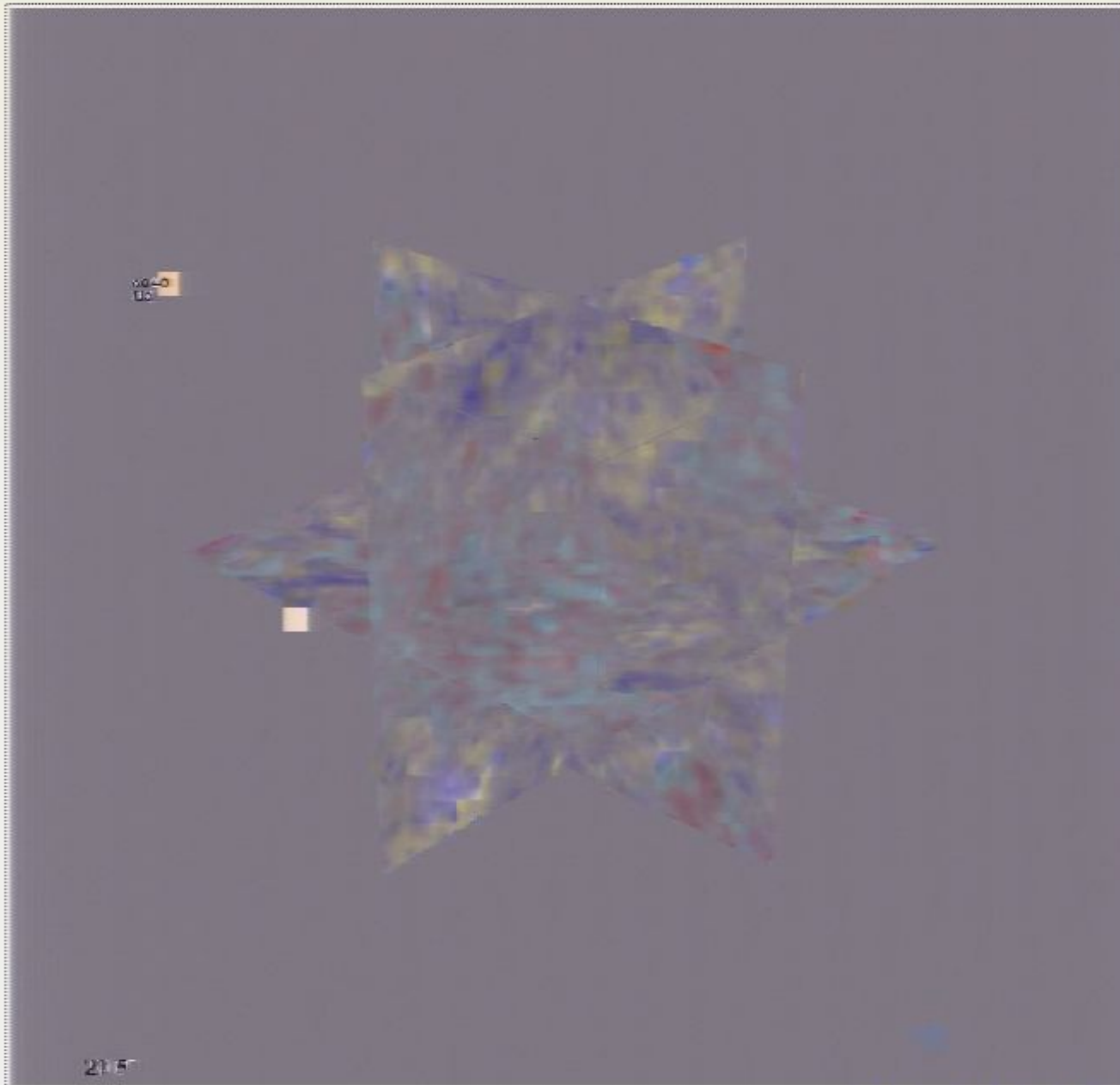
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SMALL-SCALE STRUCTURE FORMATION



SMALL-SCALE STRUCTURE FORMATION



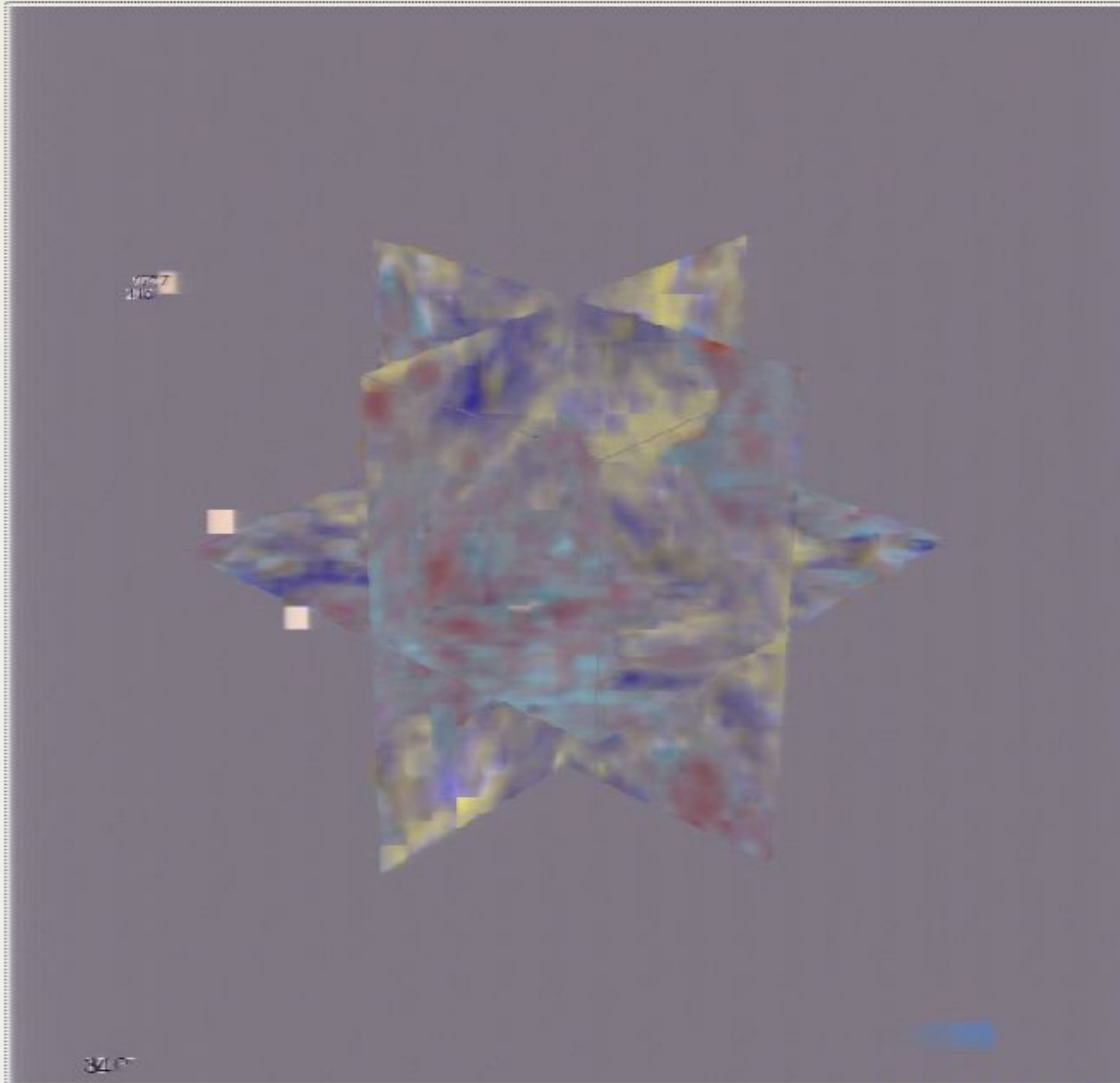
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21:57

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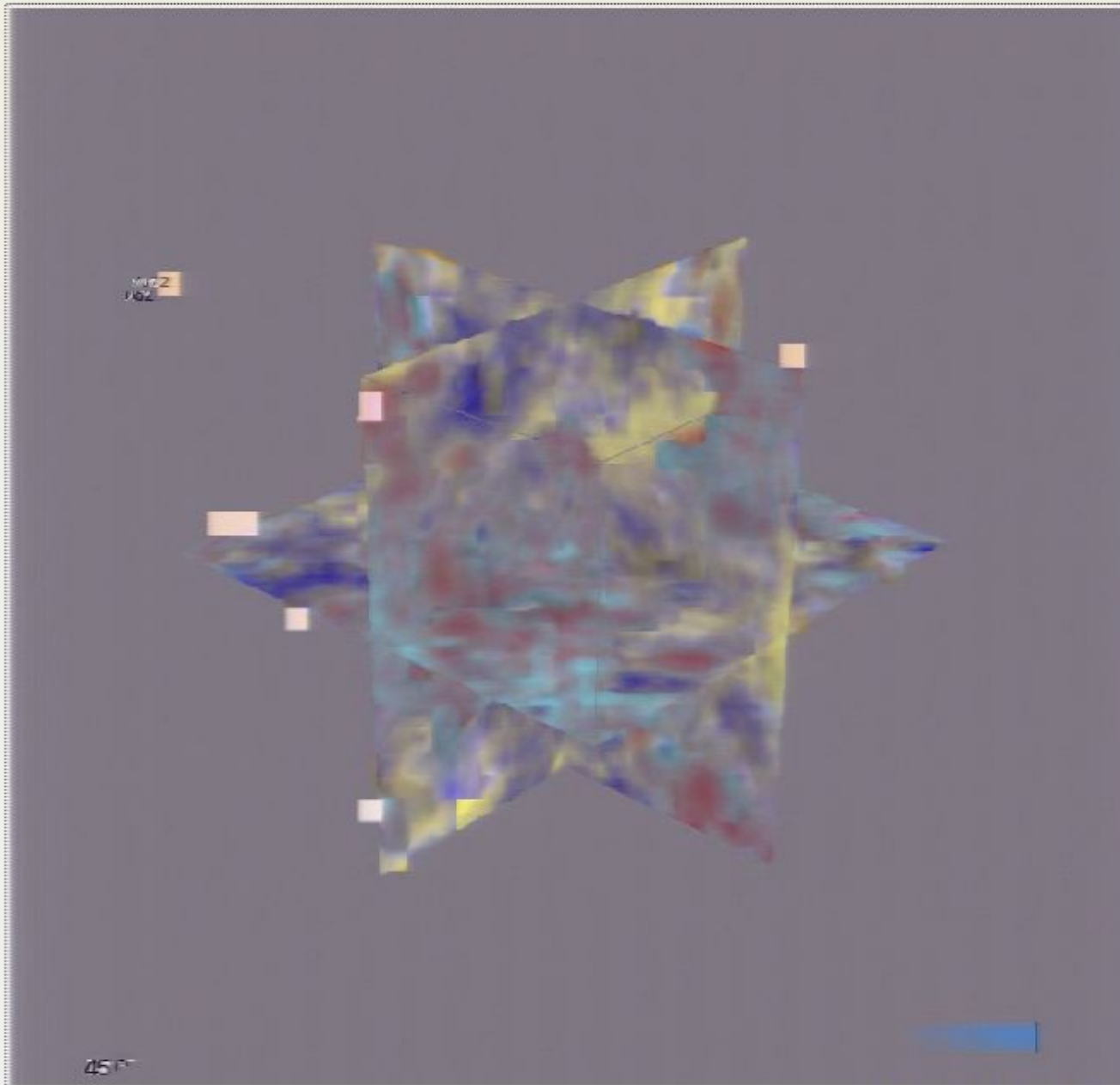
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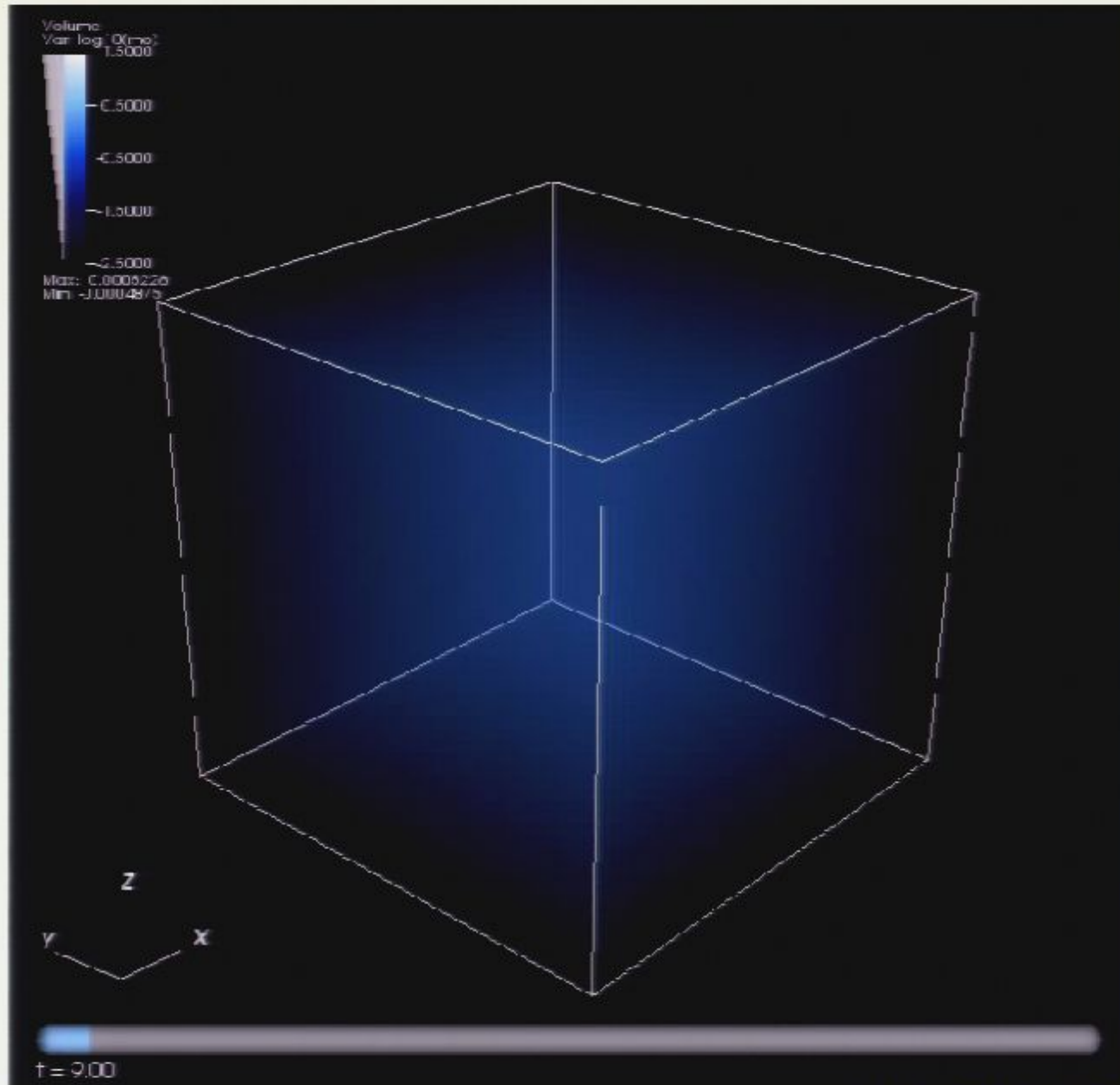
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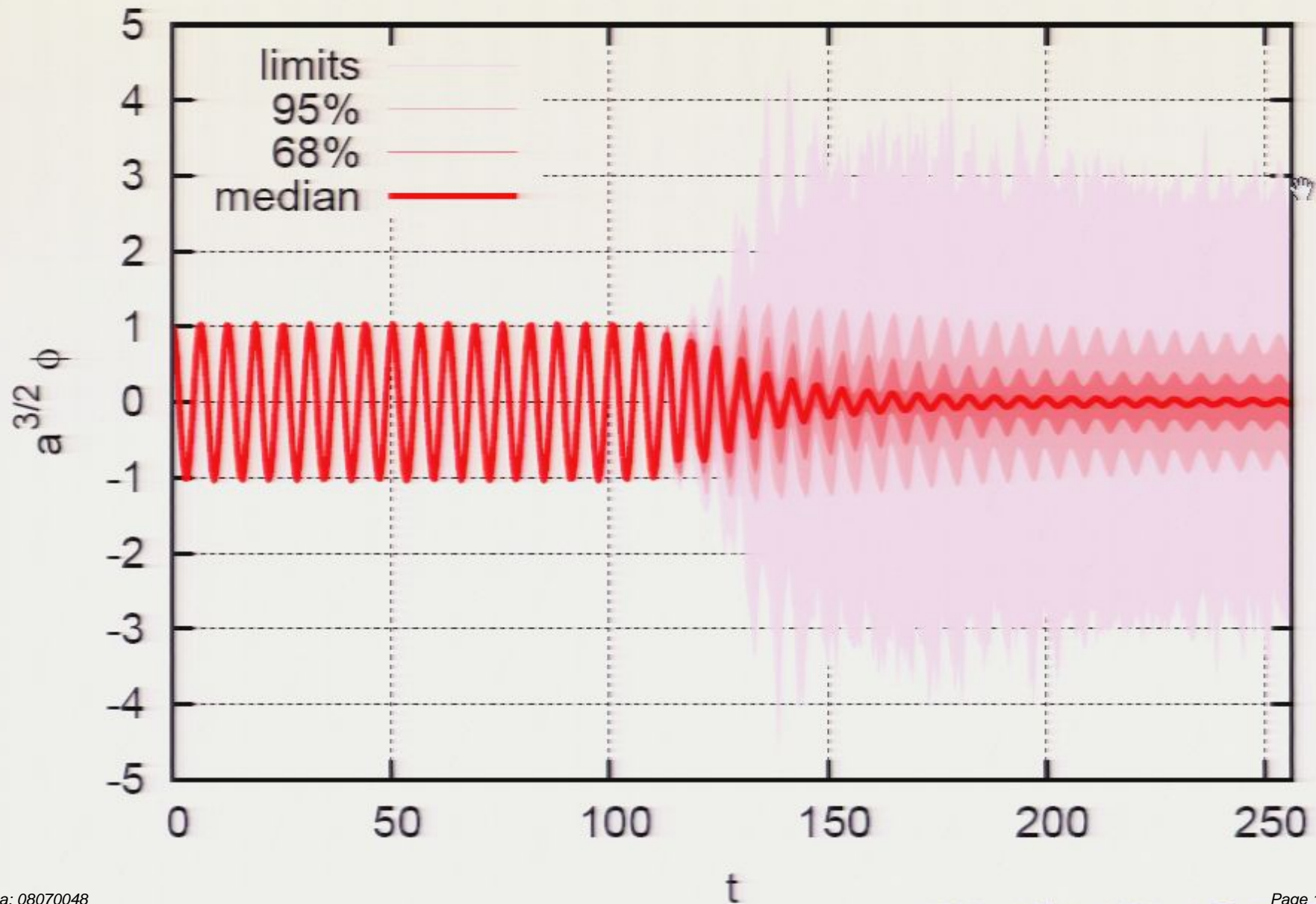
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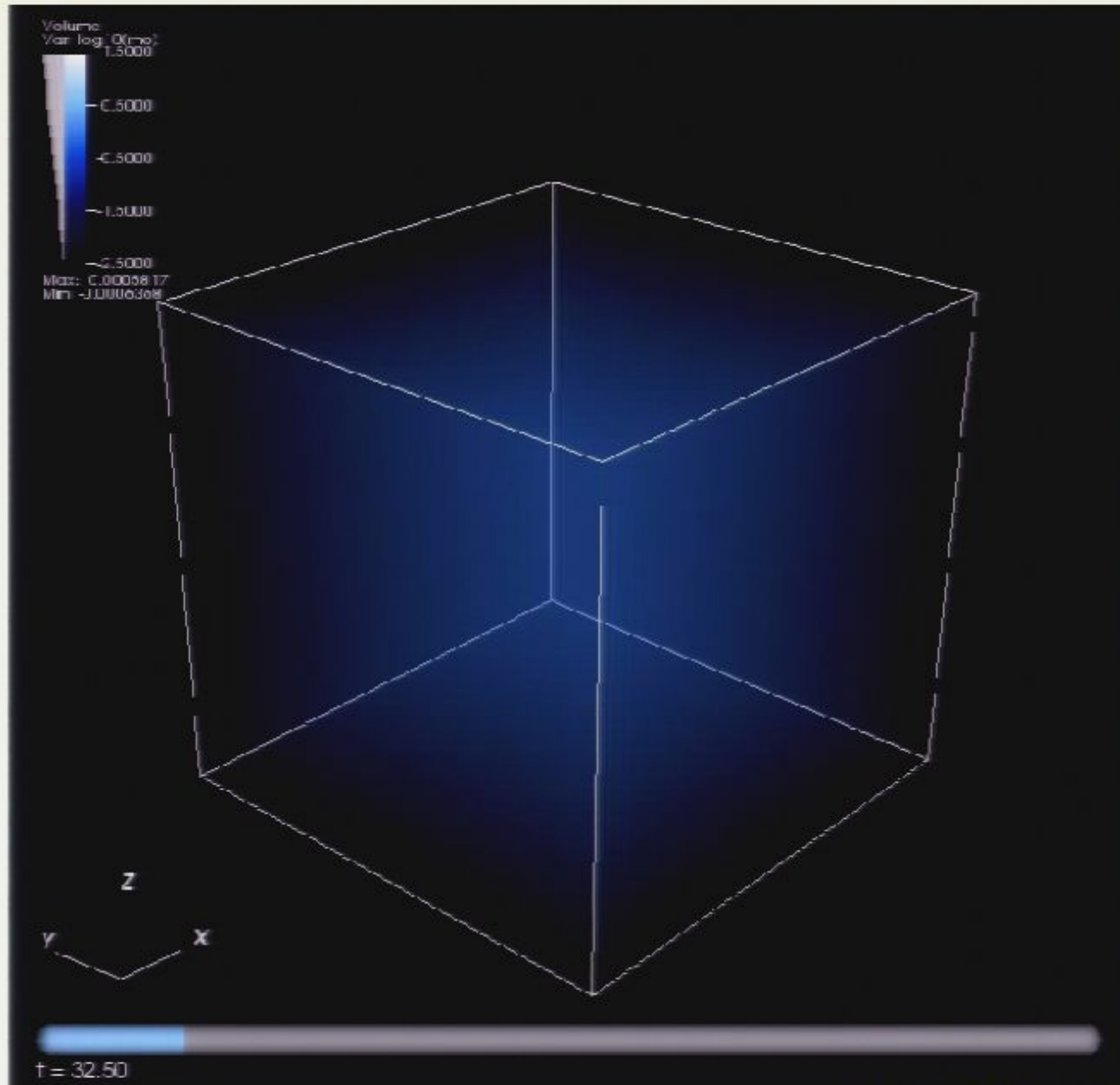
DENSITY EVOLUTION DURING PREHEATING



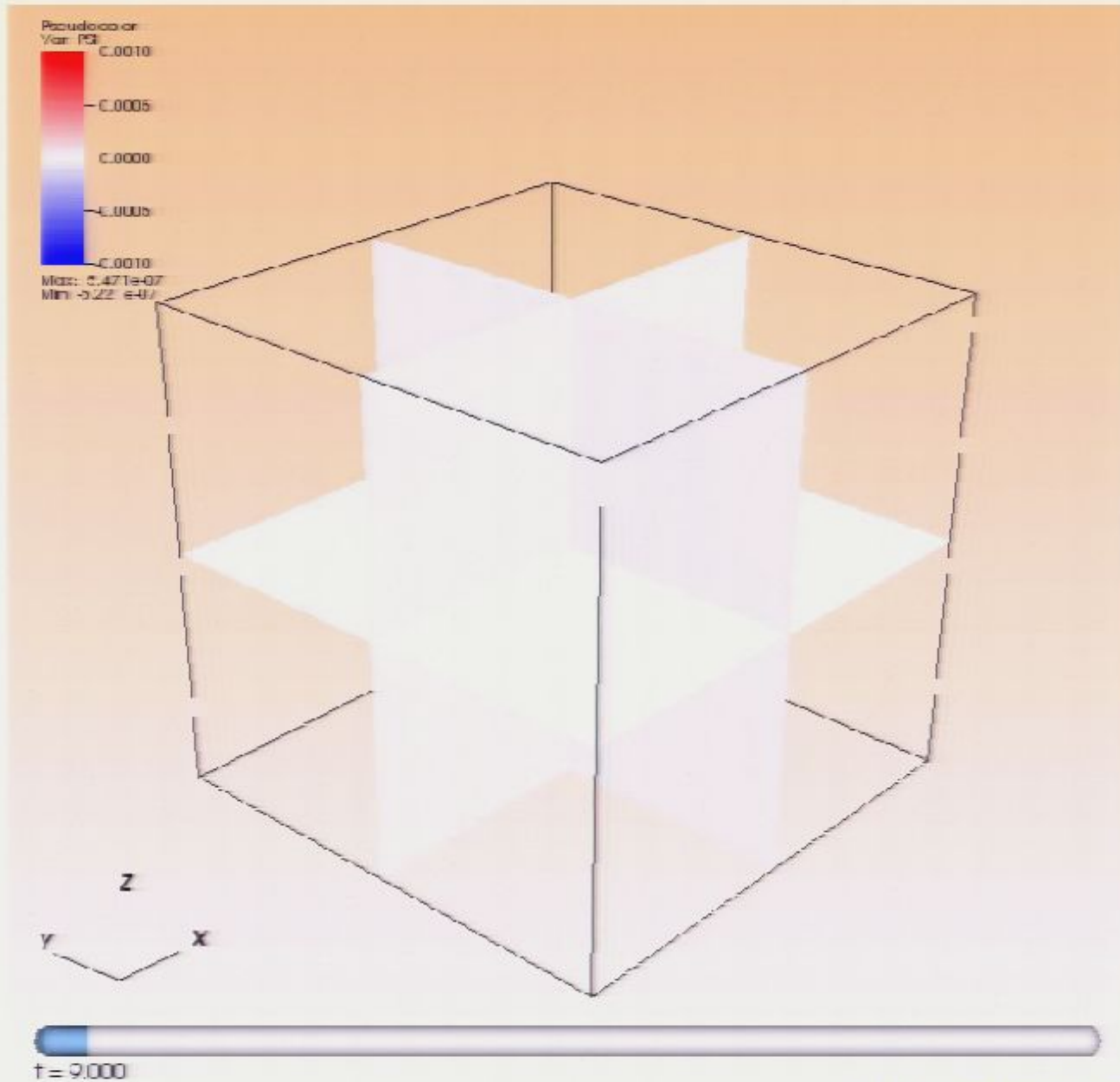
INFLATON DECAYS (BUT NOT FULLY)...



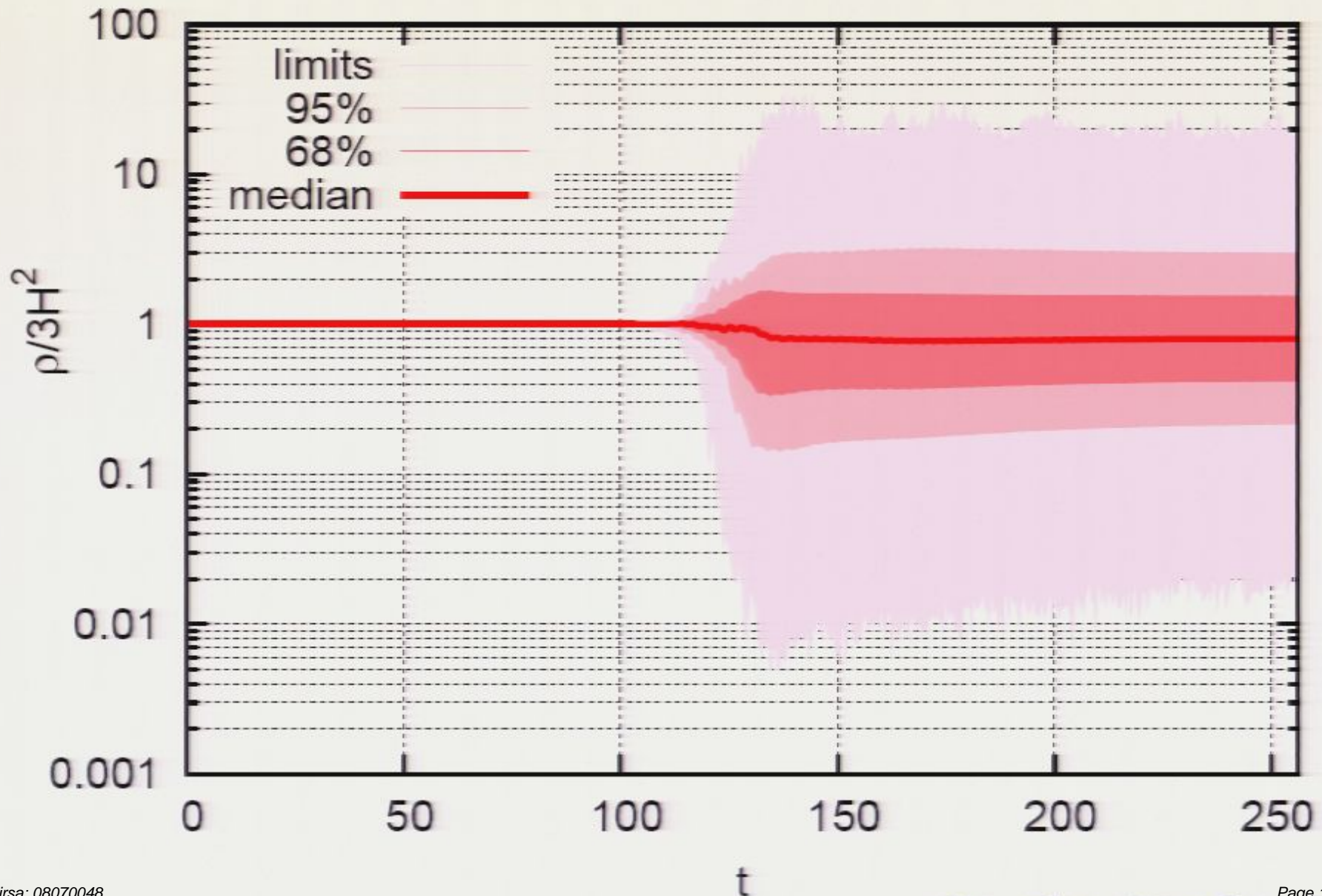
DENSITY EVOLUTION DURING PREHEATING



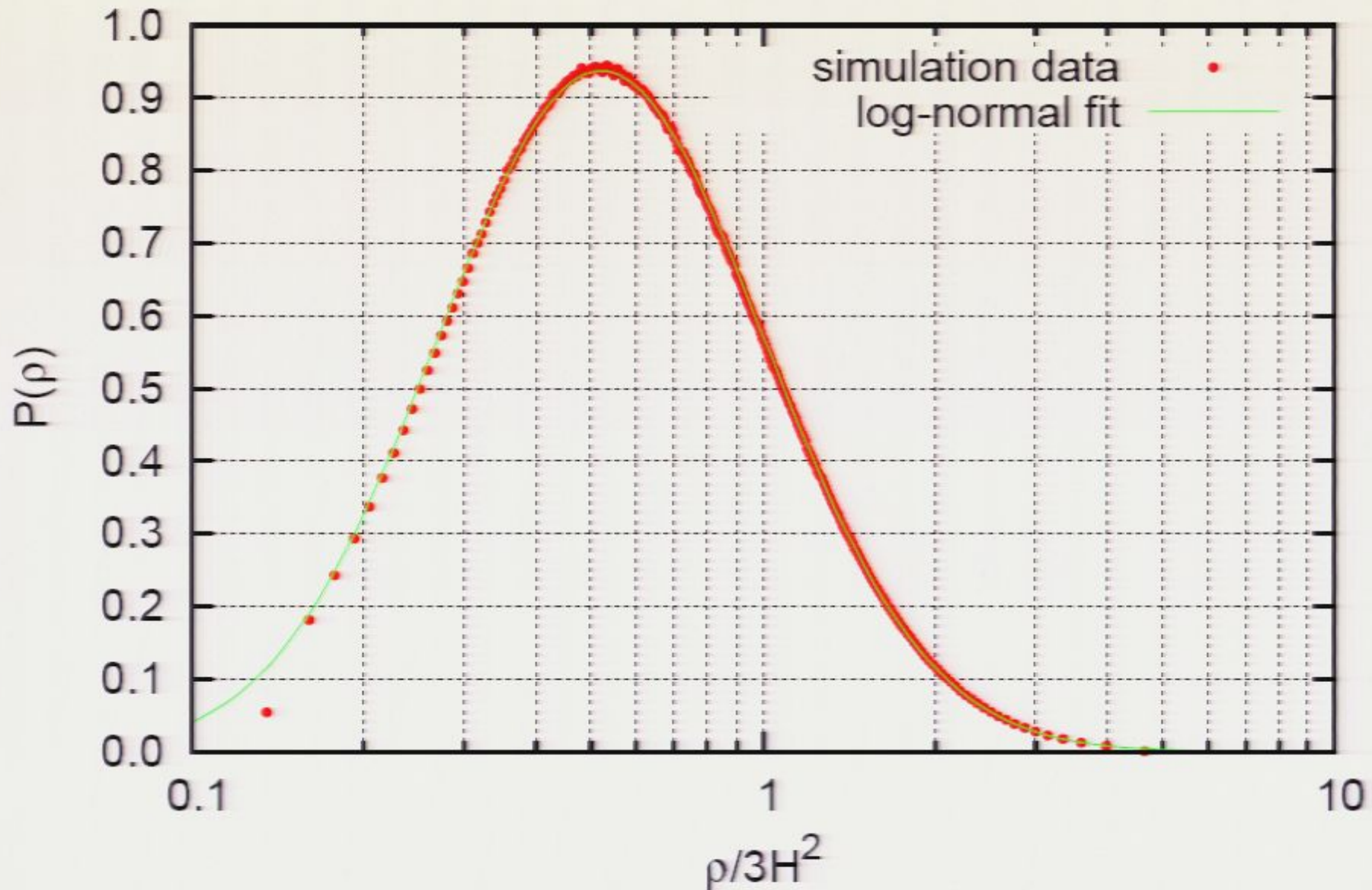
SMALL-SCALE STRUCTURE FORMATION



DENSITY CONTRAST IS VERY NON-GAUSSIAN!



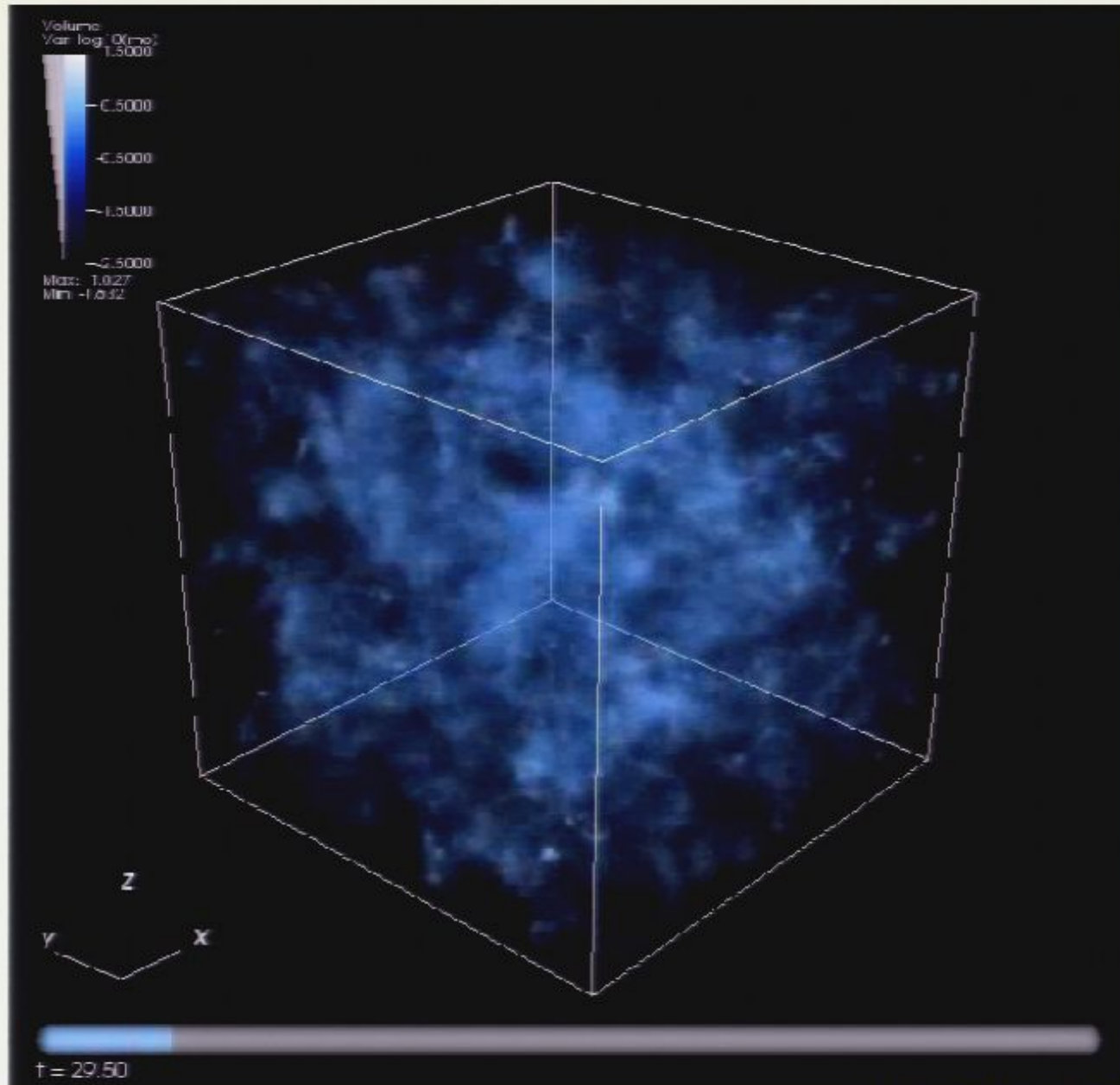
IN FACT, IT'S VERY LOG-NORMAL!



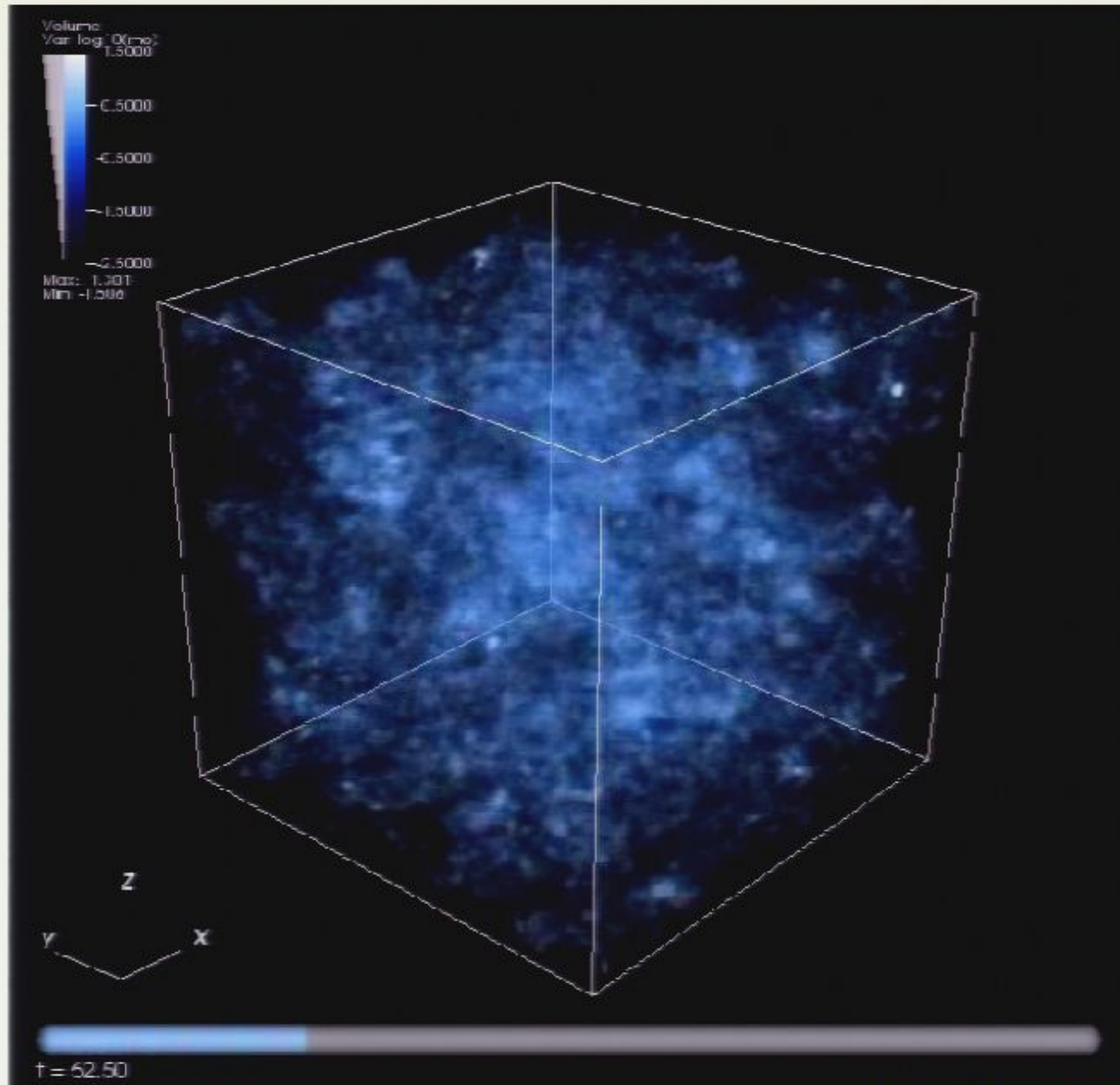
DENSITY EVOLUTION (TRILINEAR COUPLING)



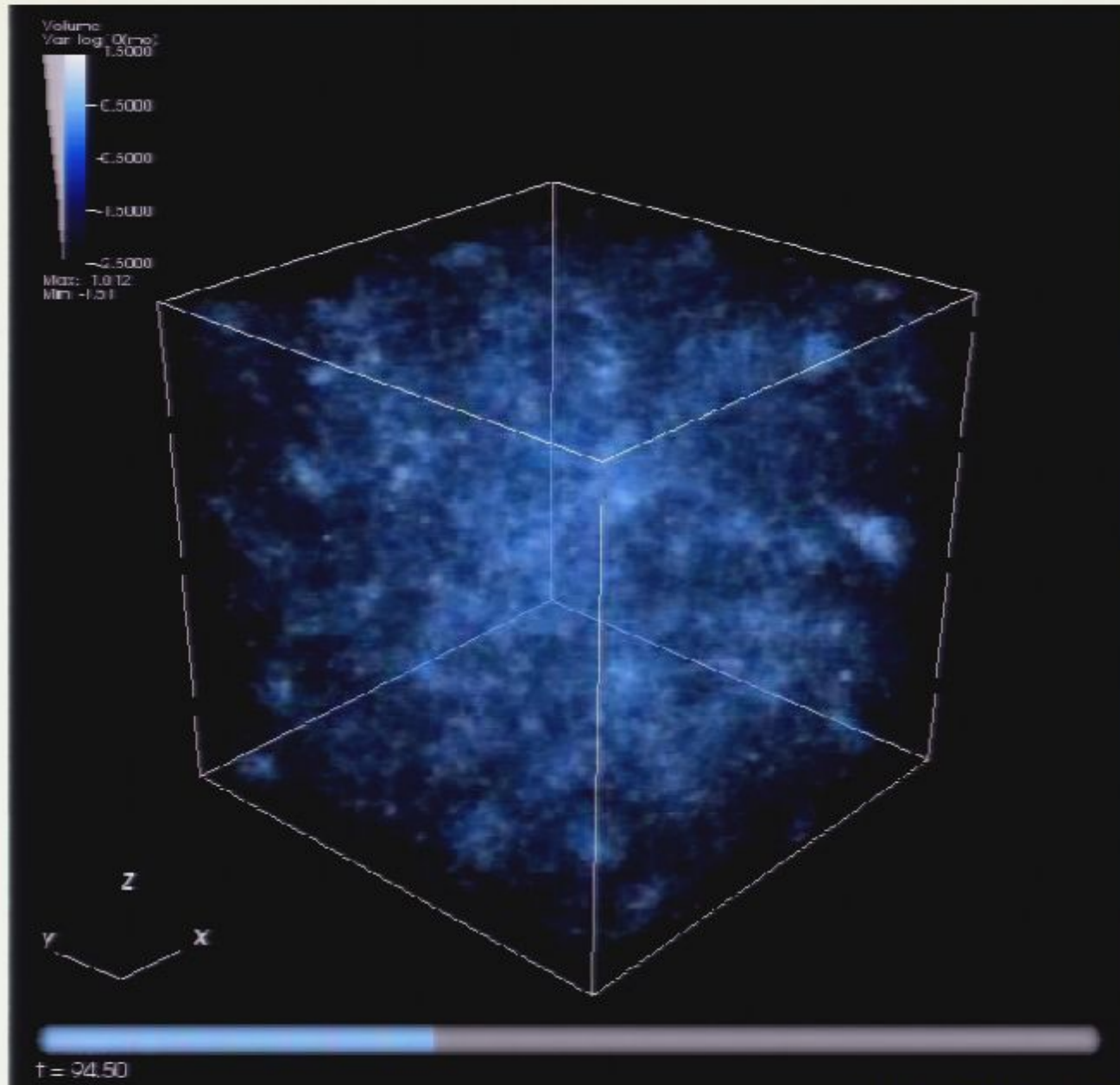
DENSITY EVOLUTION (TRILINEAR COUPLING)



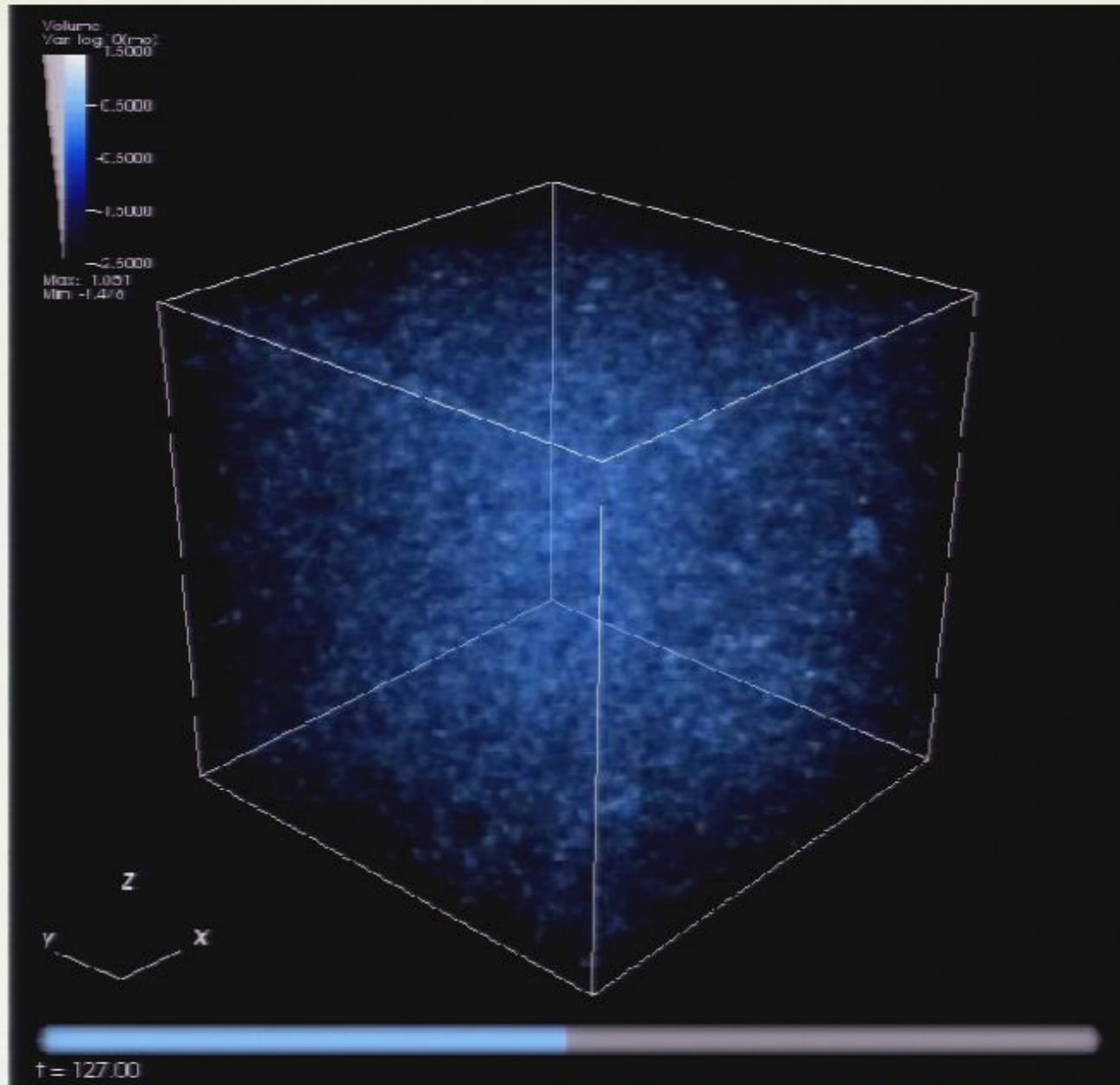
DENSITY EVOLUTION (TRILINEAR COUPLING)



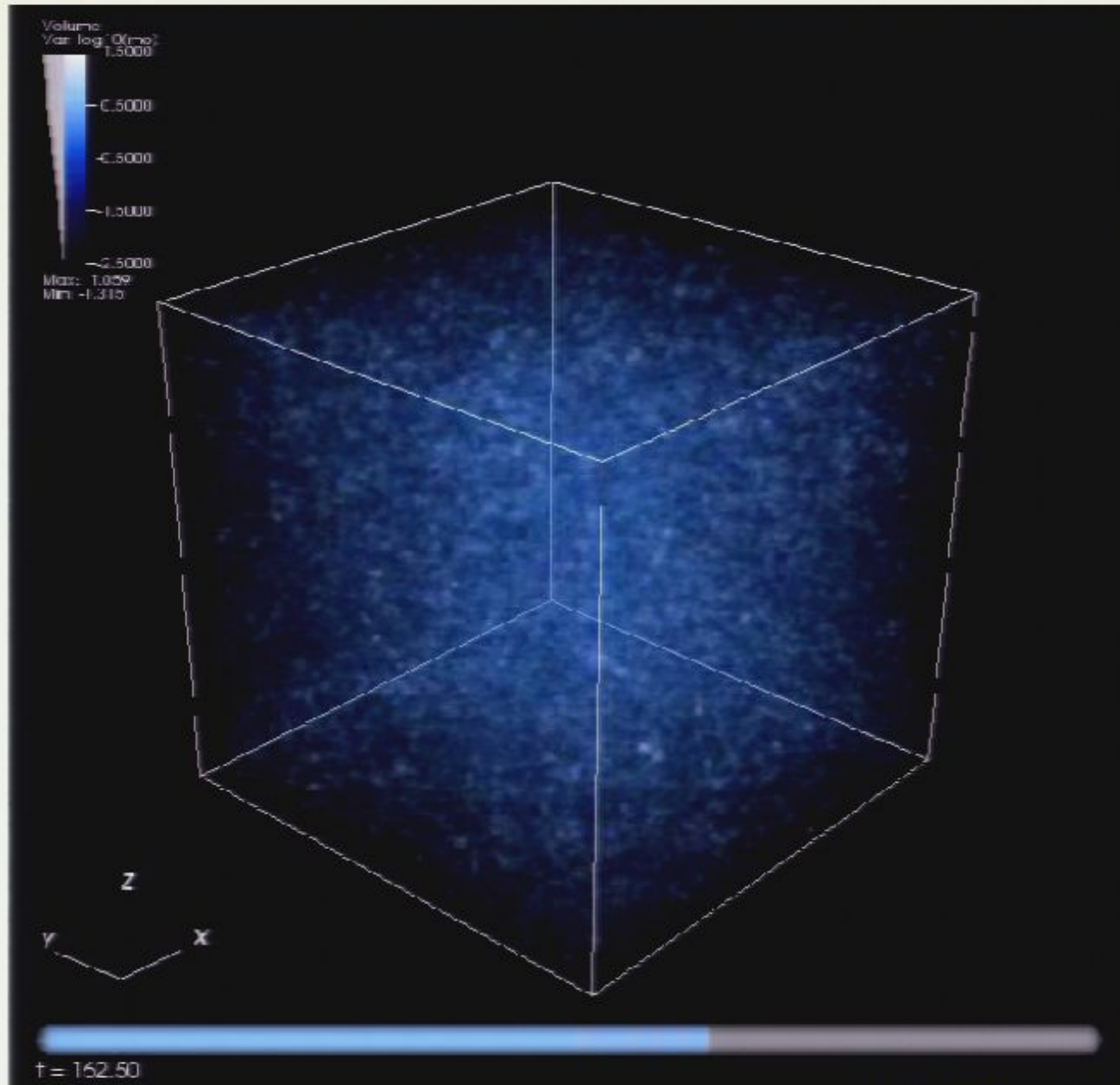
DENSITY EVOLUTION (TRILINEAR COUPLING)



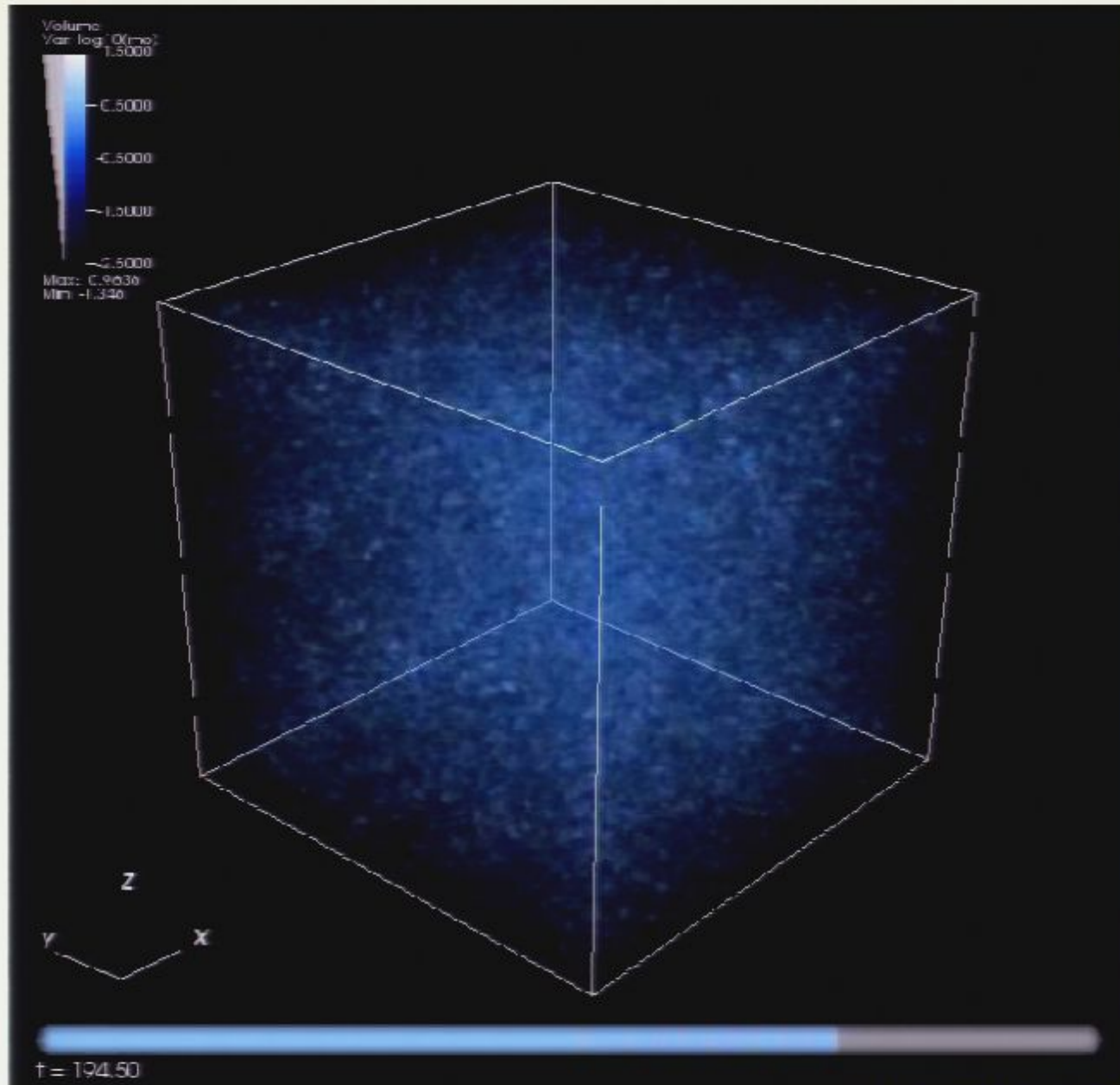
DENSITY EVOLUTION (TRILINEAR COUPLING)



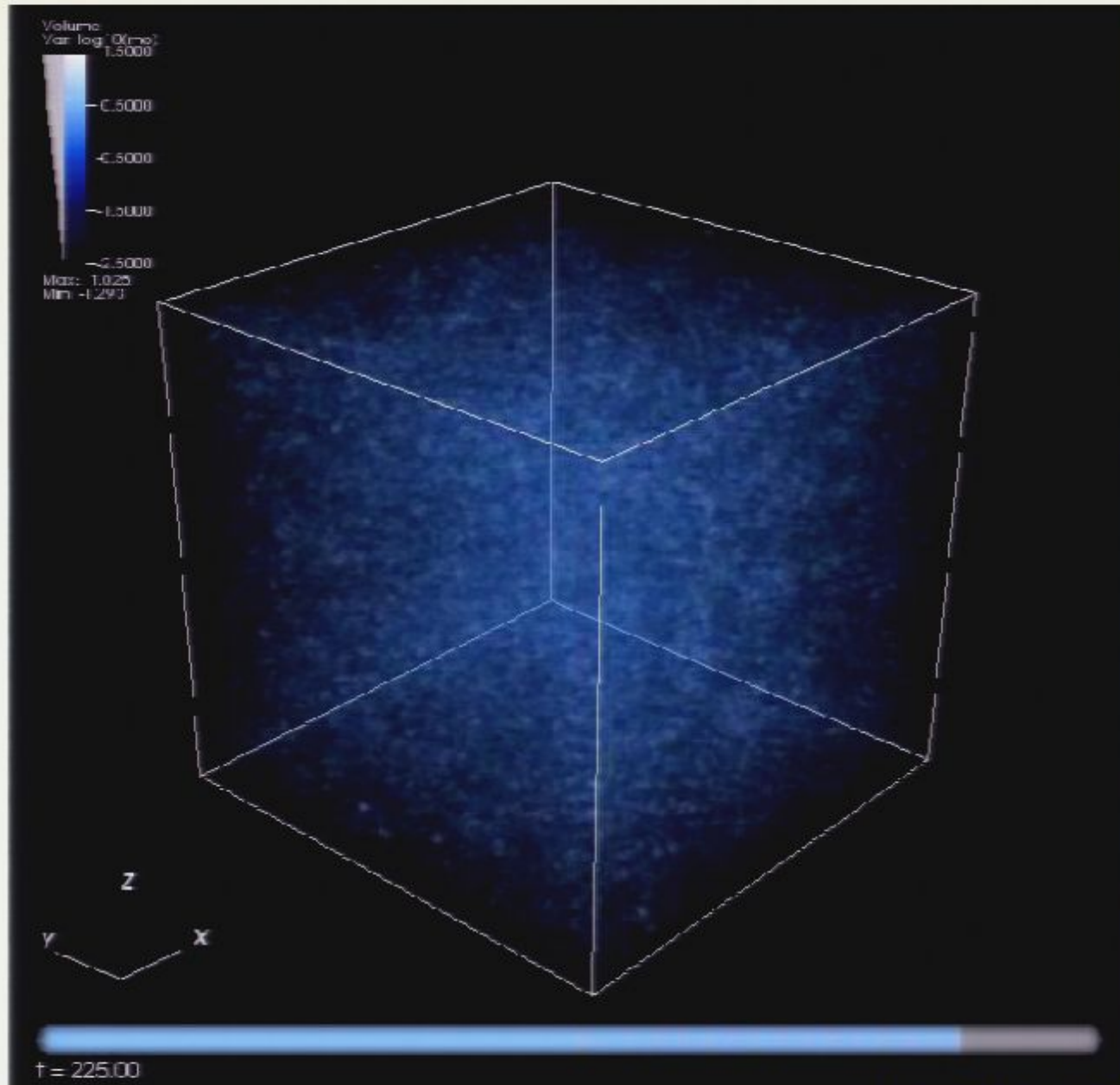
DENSITY EVOLUTION (TRILINEAR COUPLING)



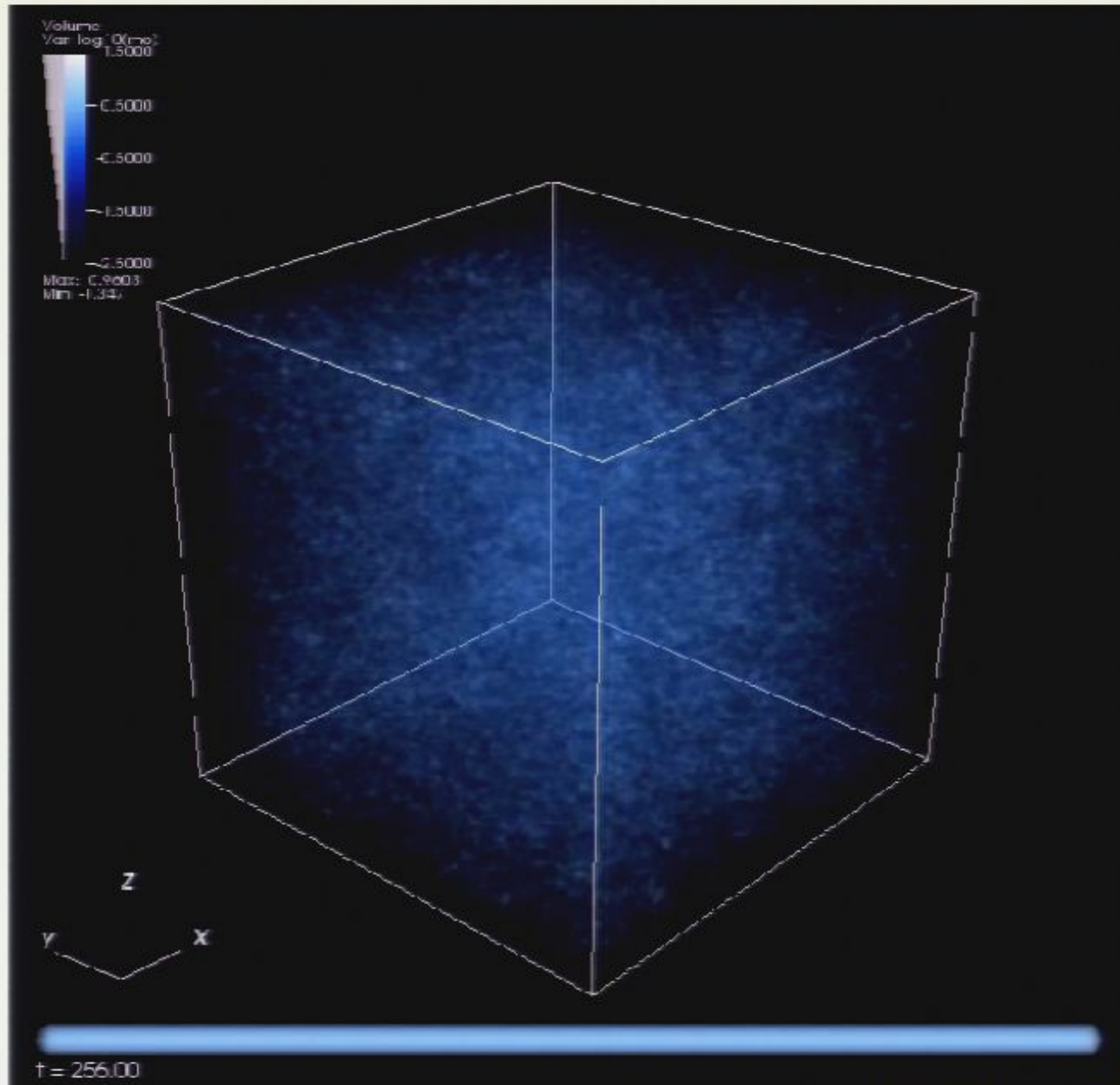
DENSITY EVOLUTION (TRILINEAR COUPLING)



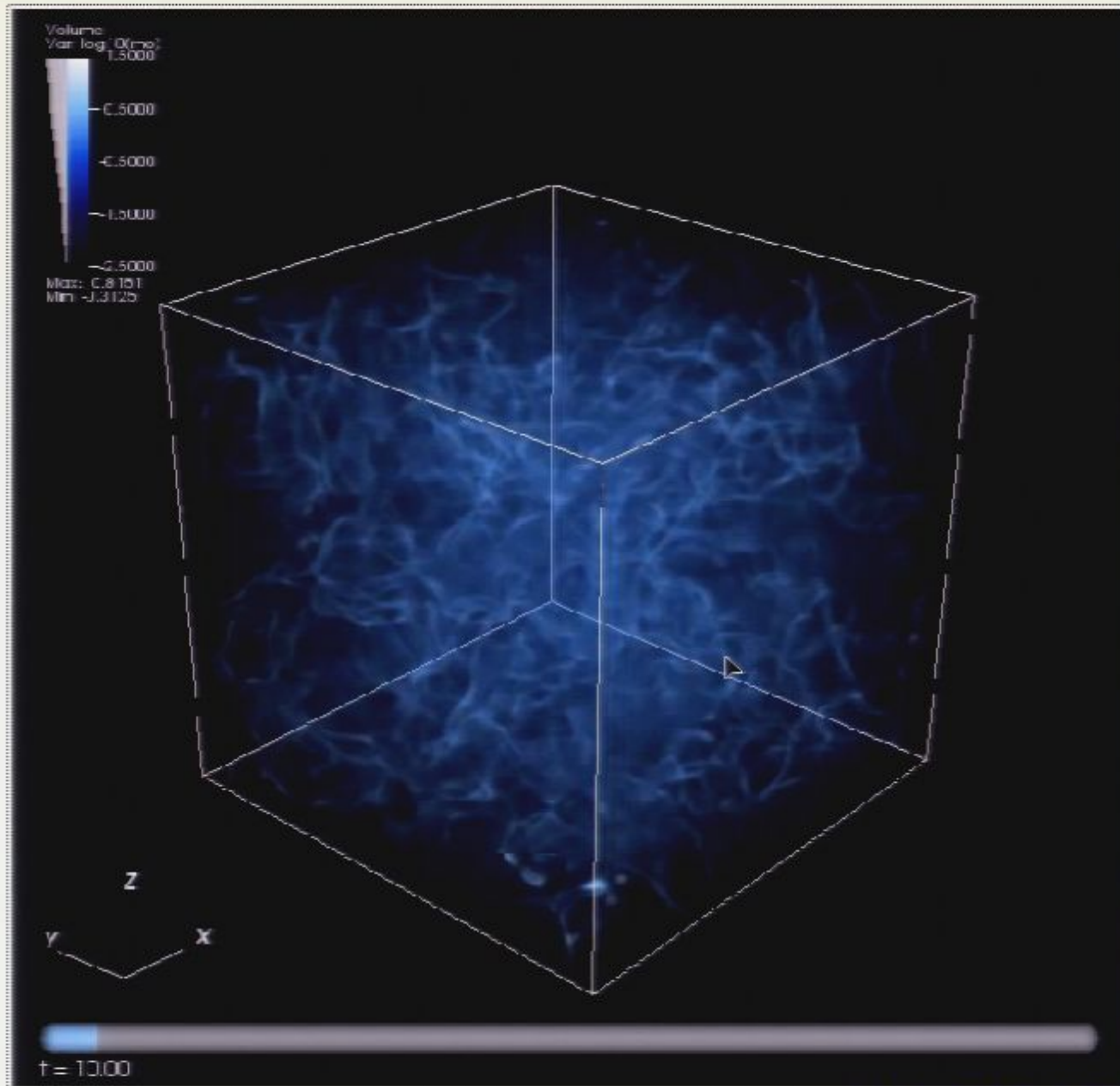
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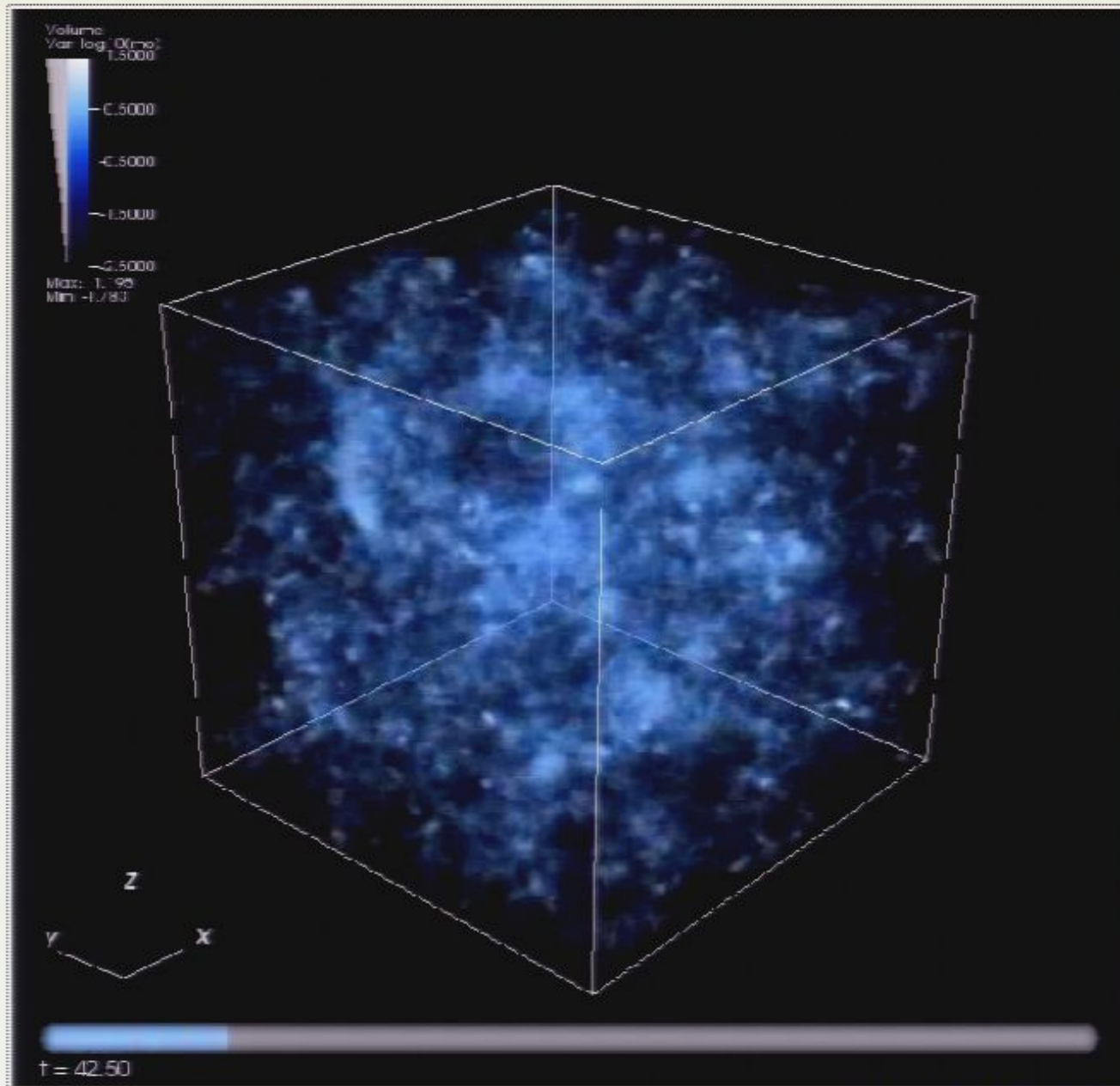
DENSITY EVOLUTION (TRILINEAR COUPLING)



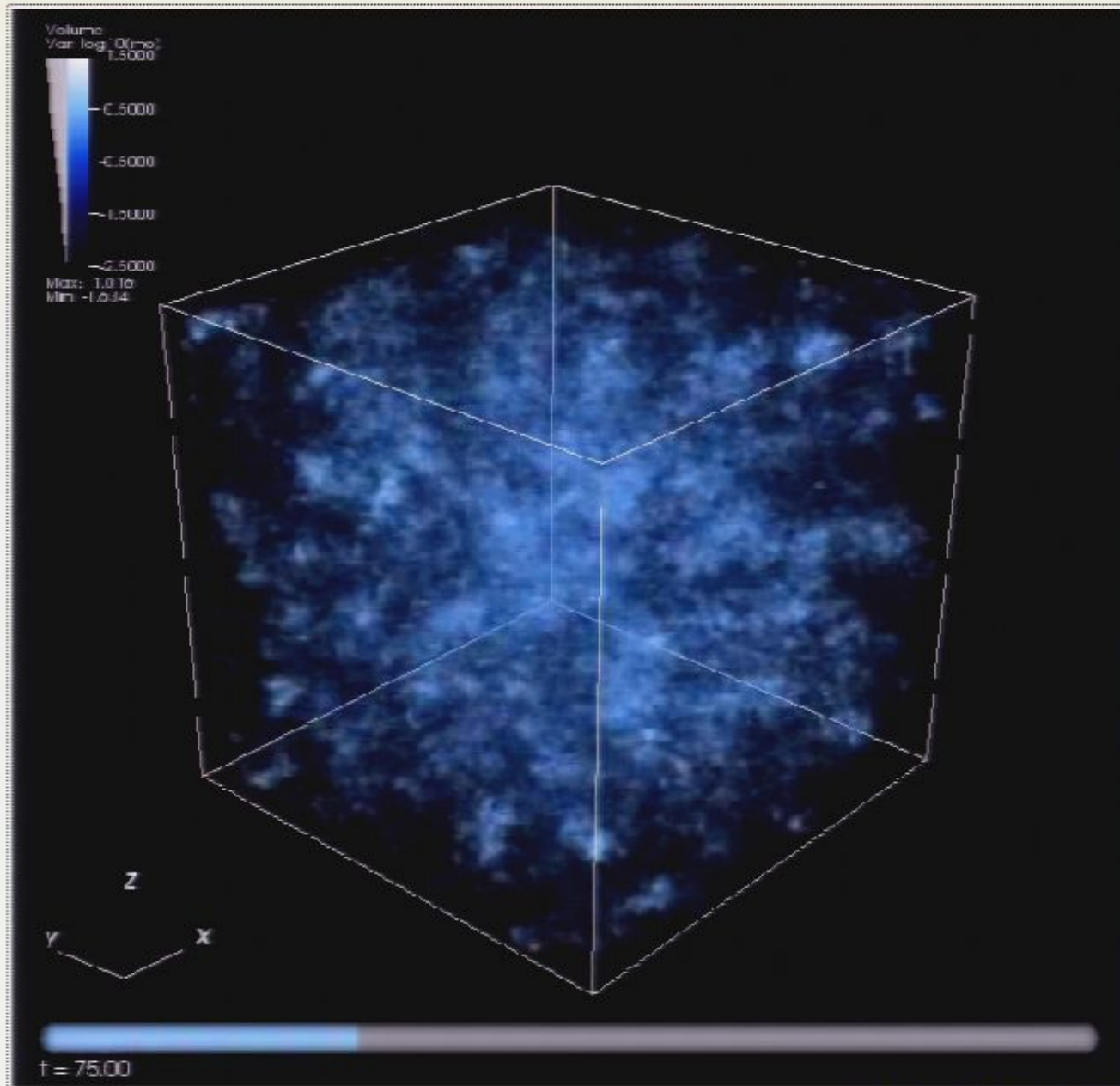
DENSITY EVOLUTION (TRILINEAR COUPLING)



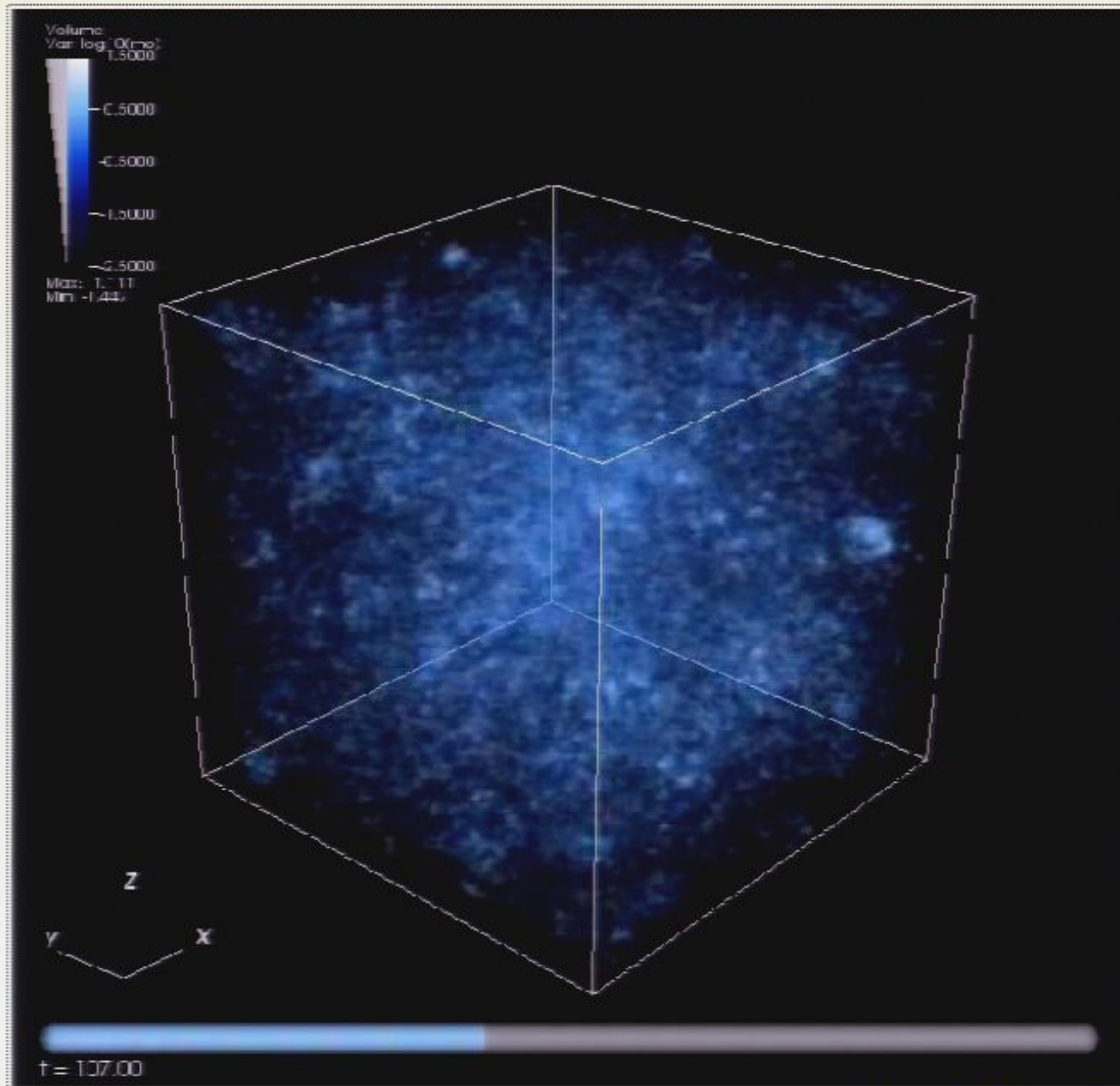
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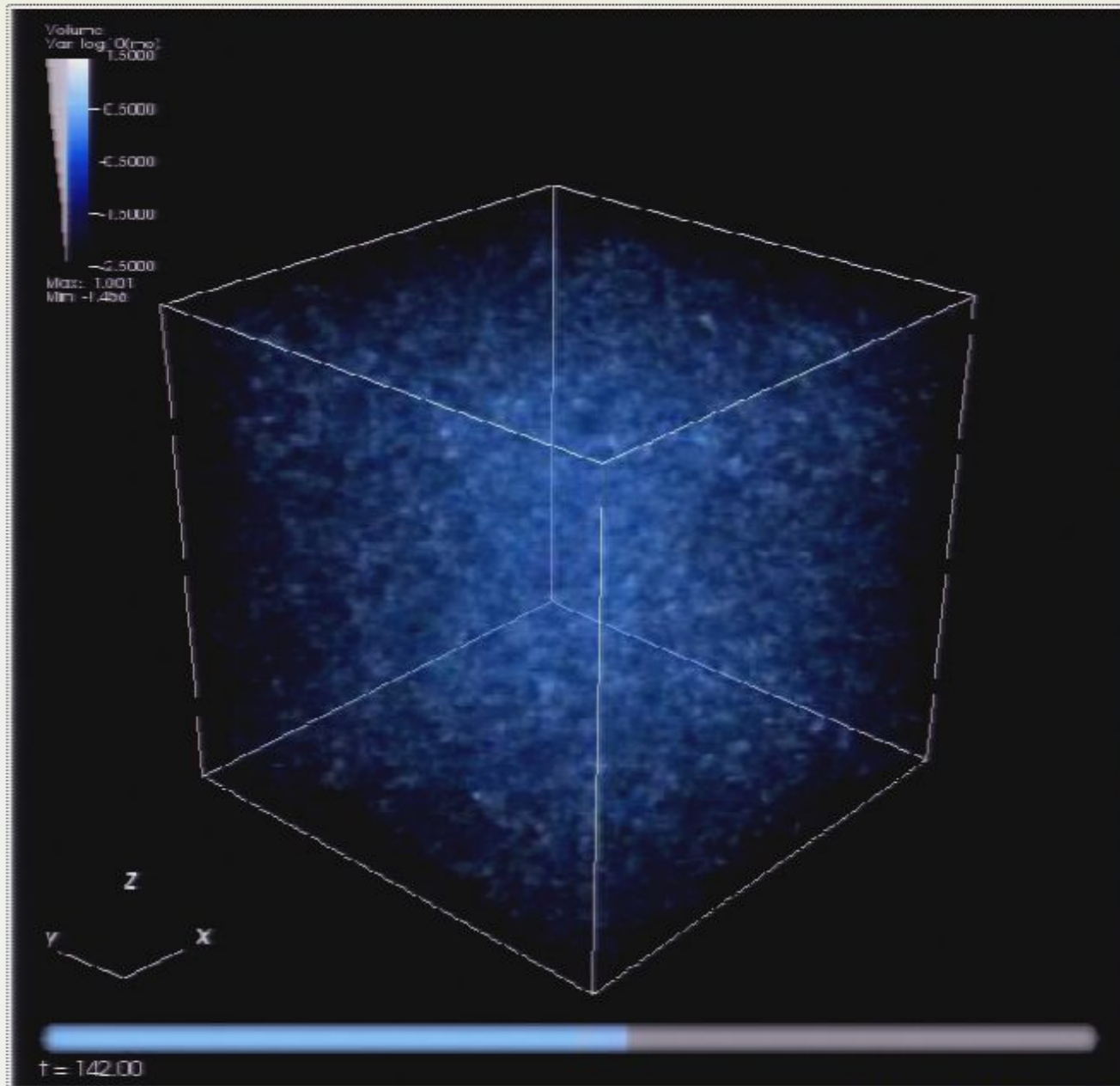
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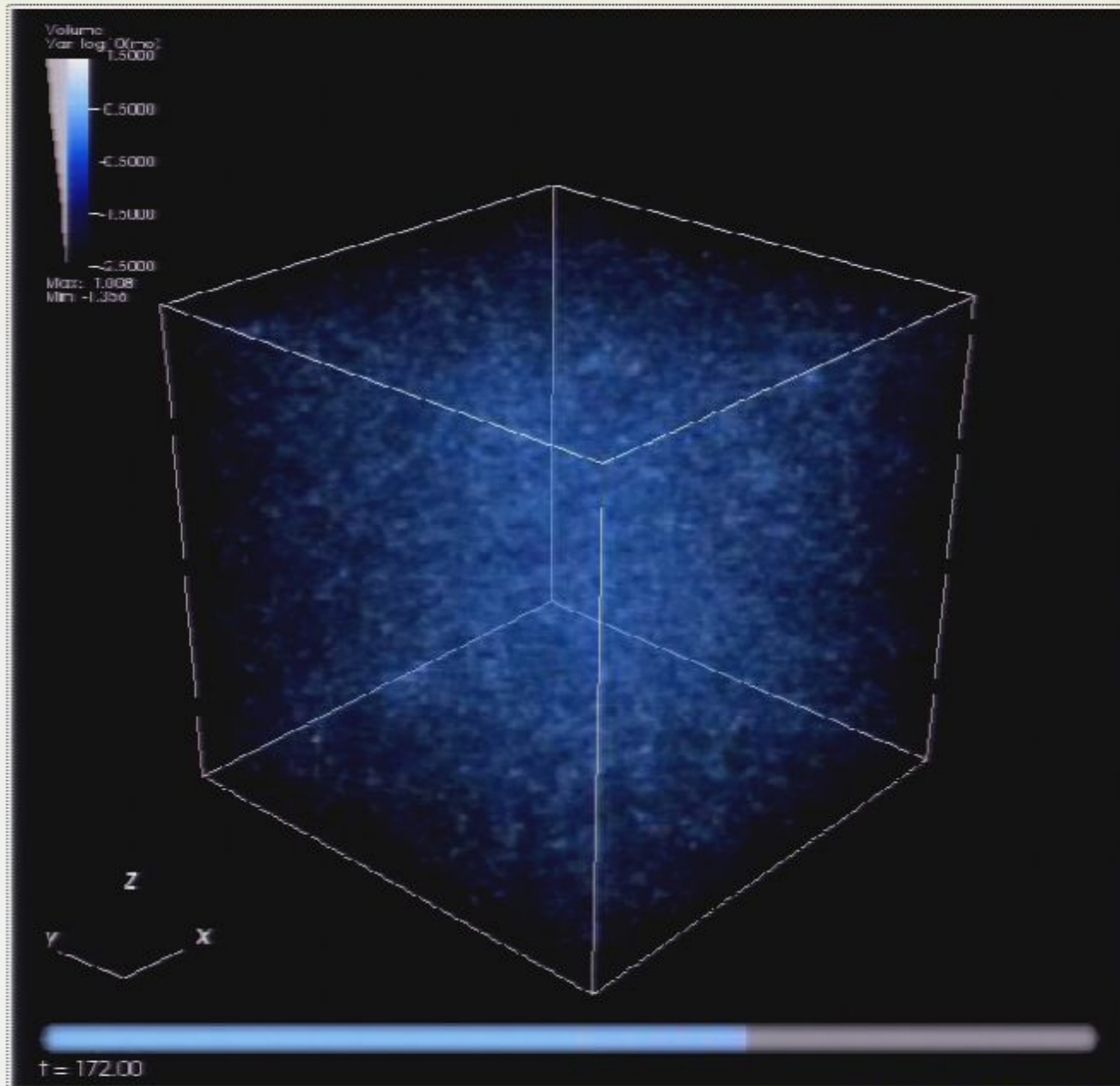
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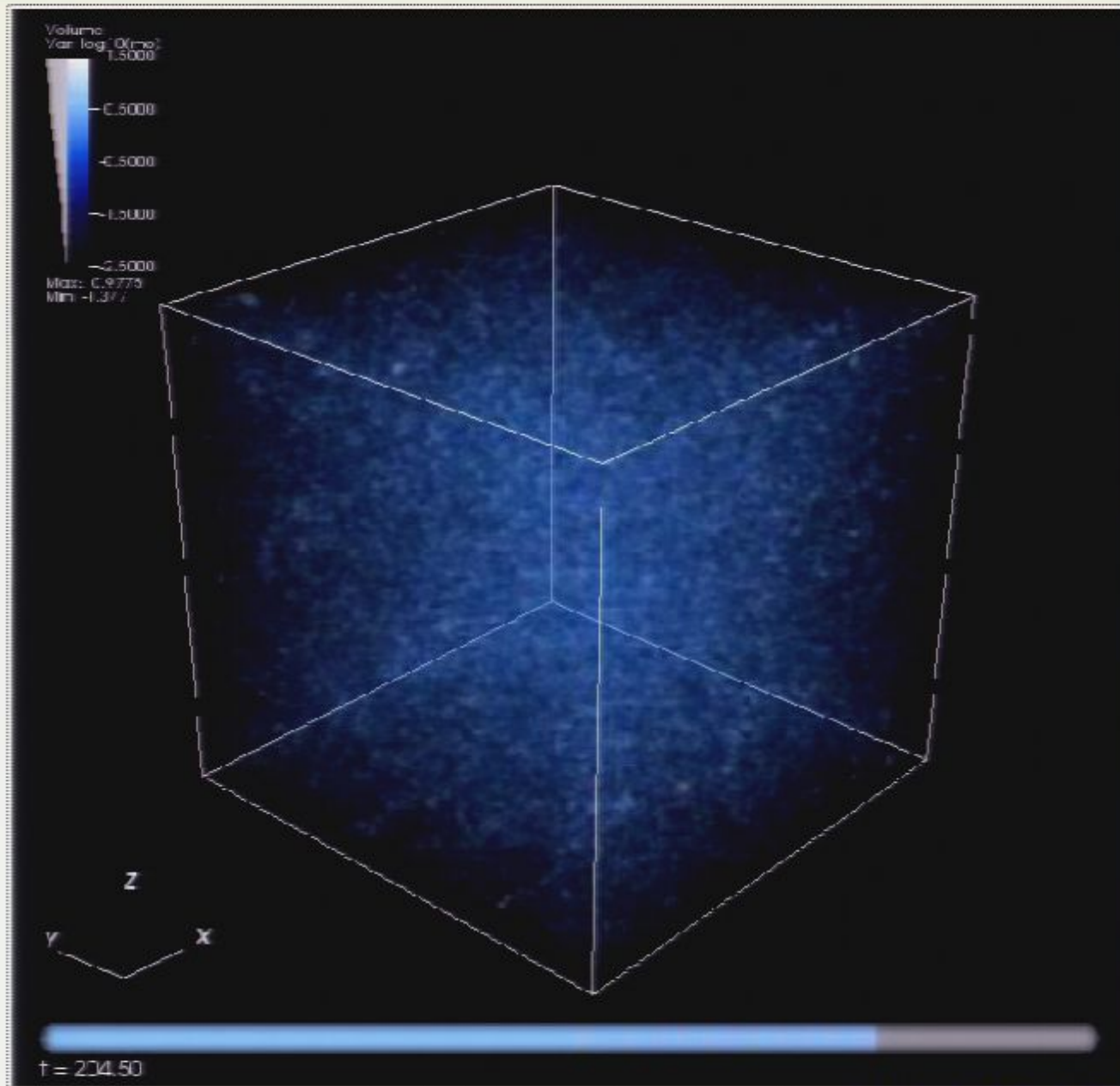
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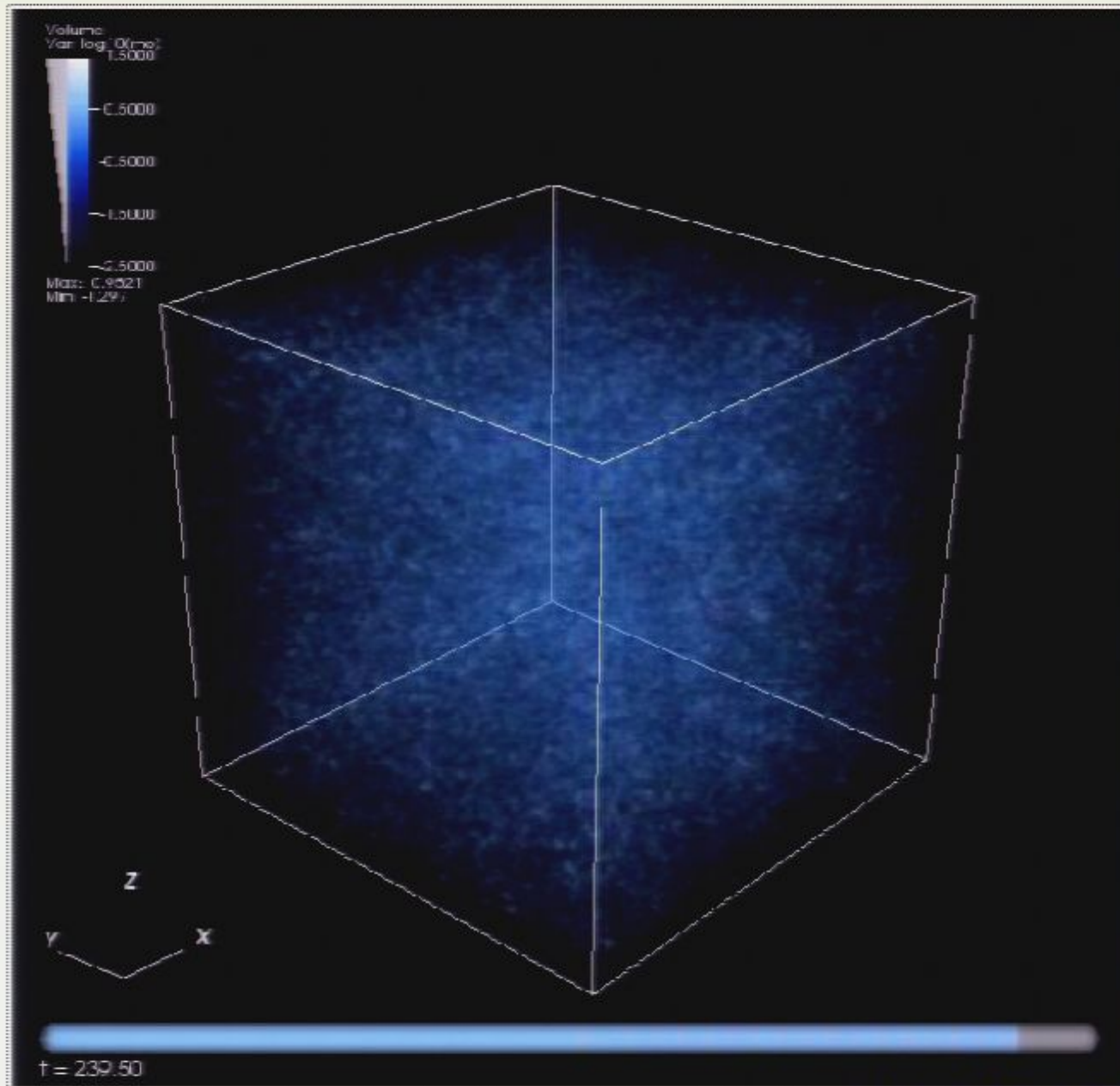
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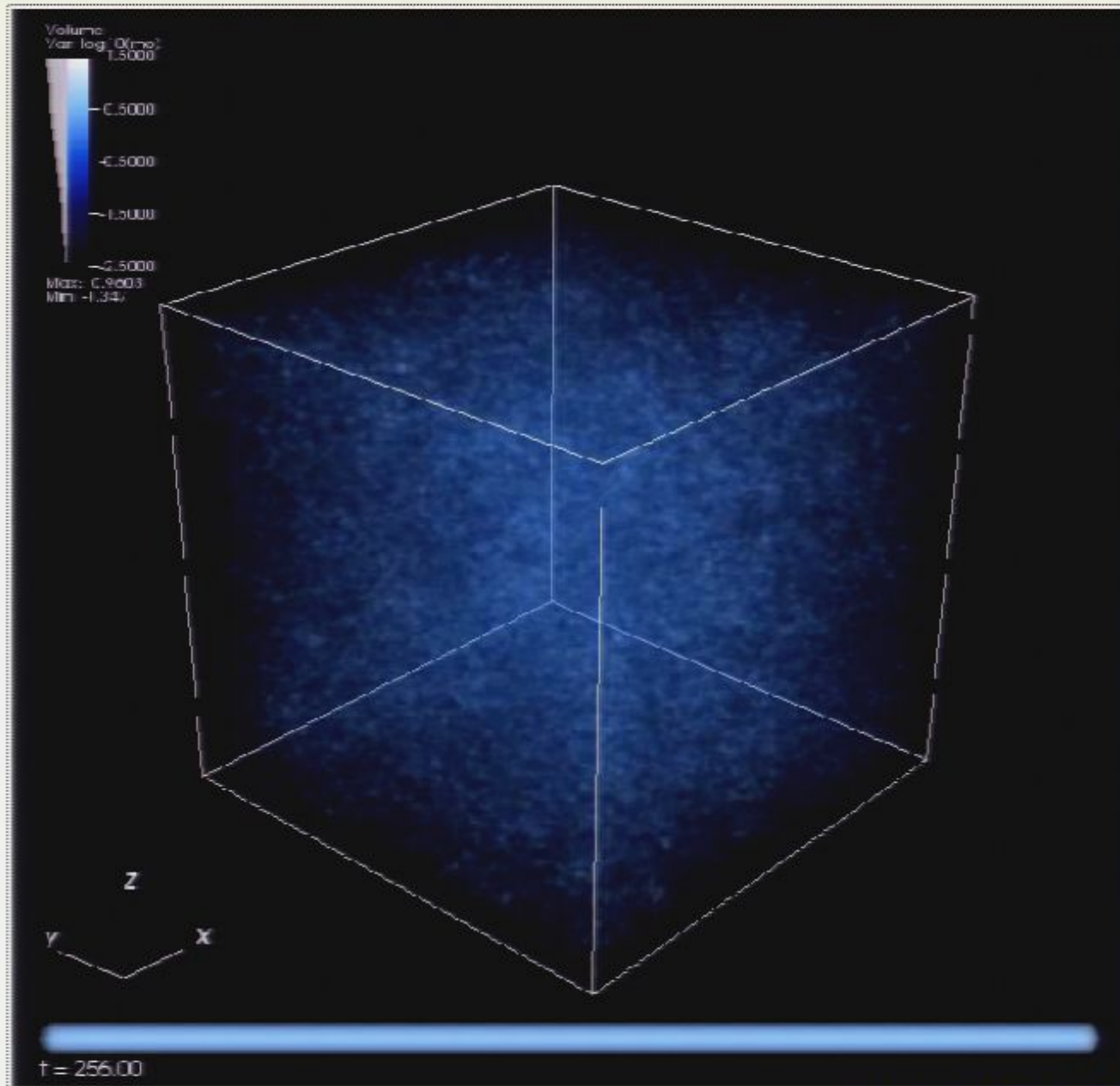
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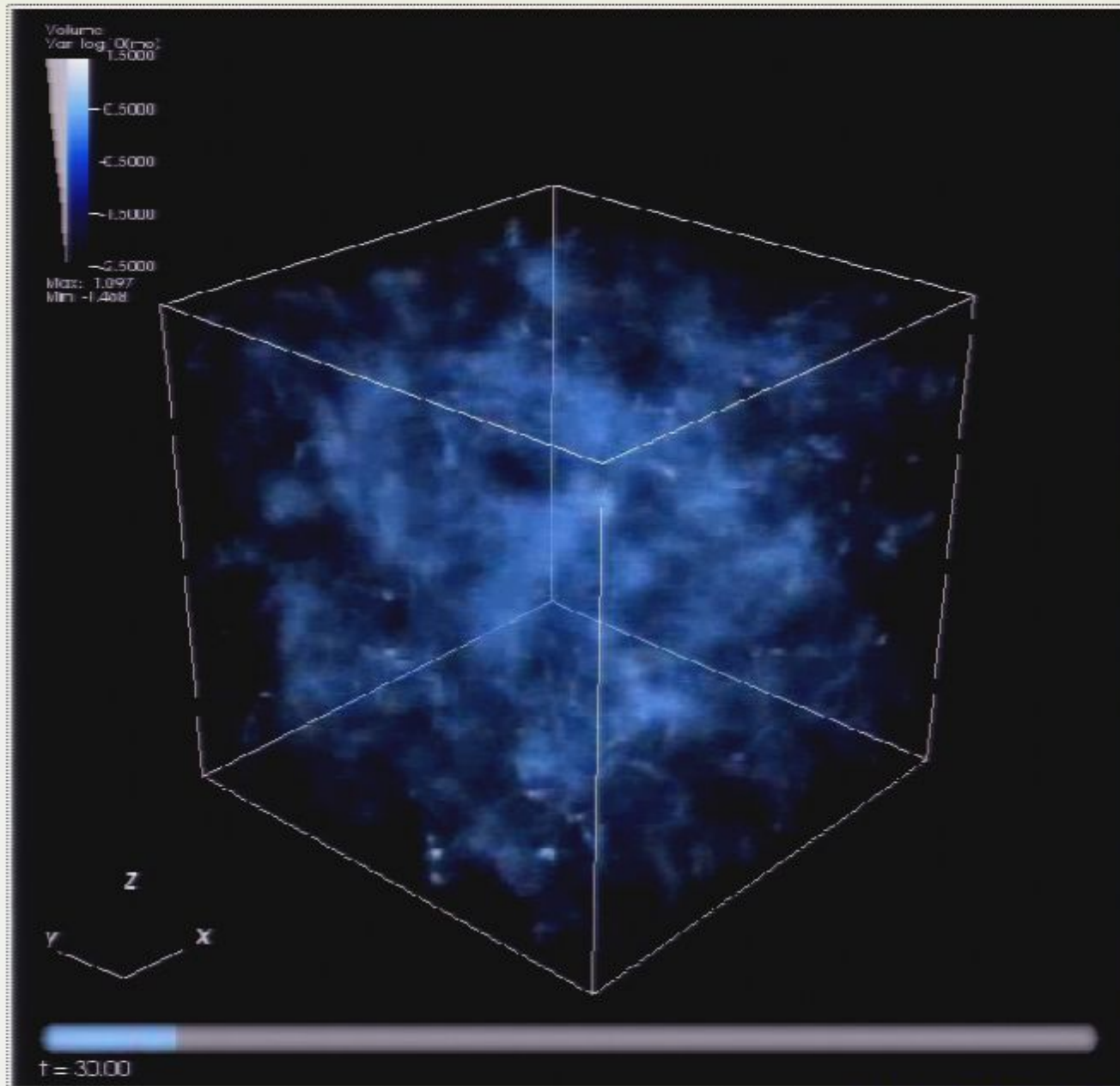
DENSITY EVOLUTION (TRILINEAR COUPLING)



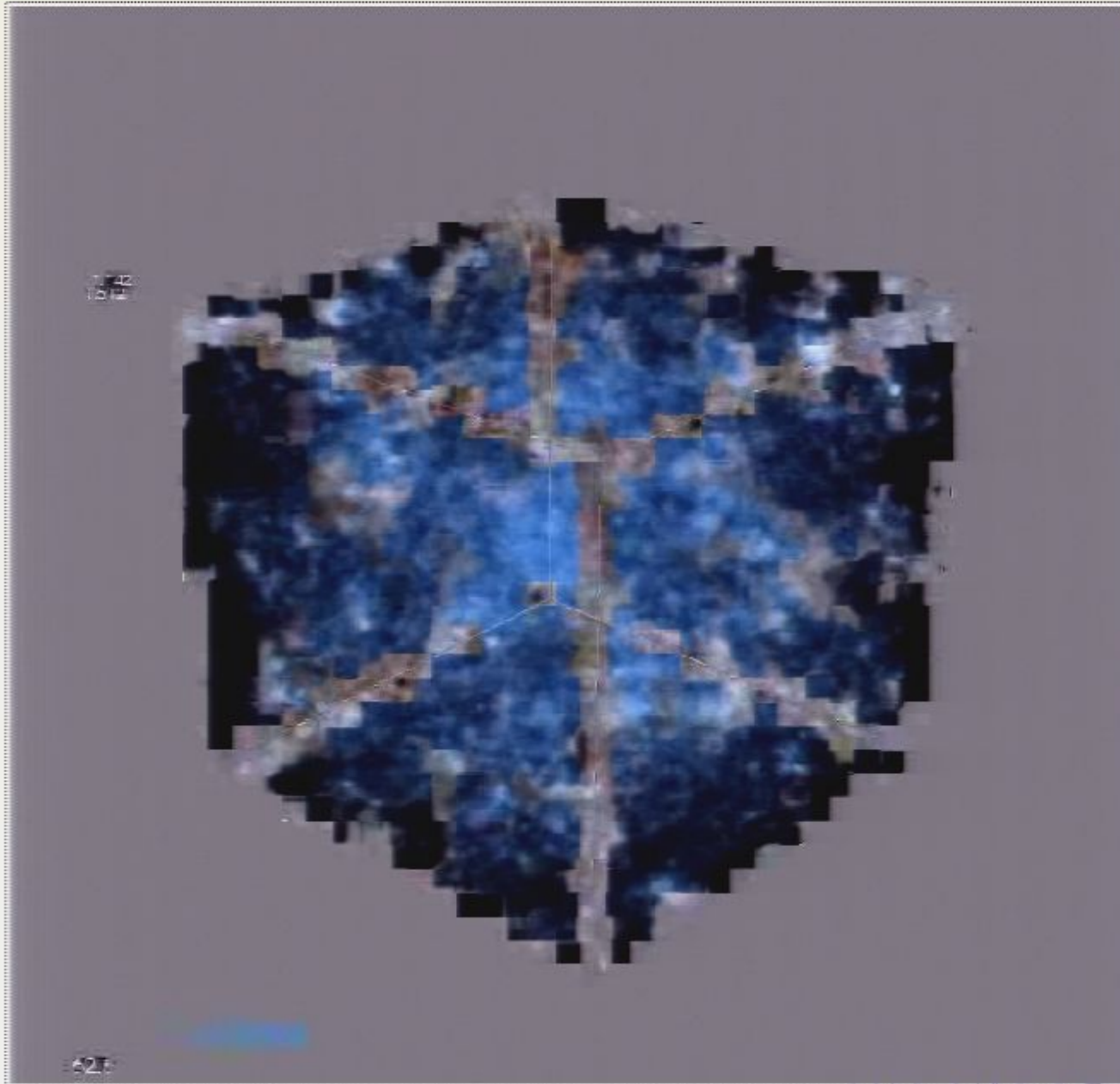
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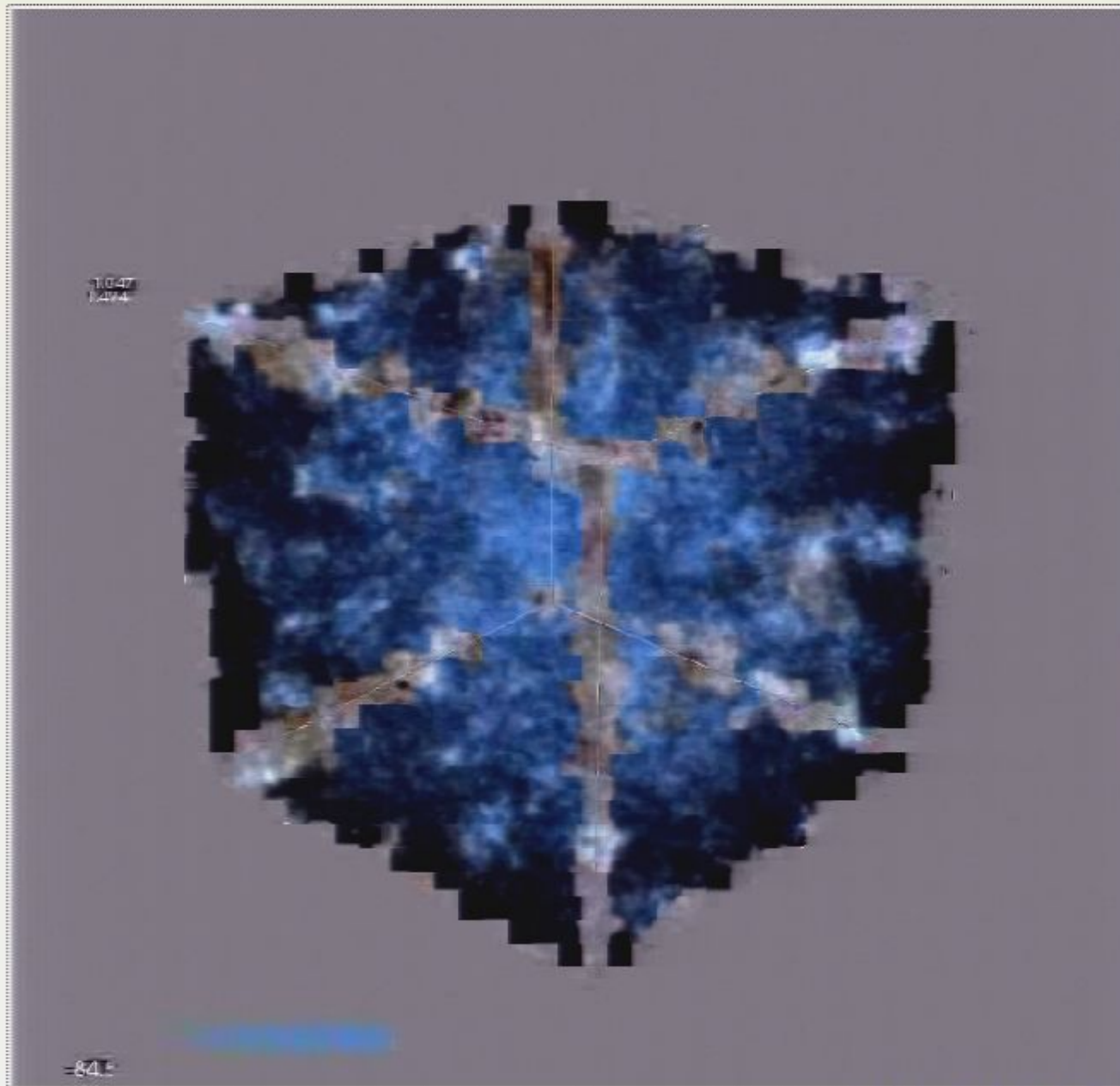
DENSITY EVOLUTION (TRILINEAR COUPLING)



Pirsa: 08070048

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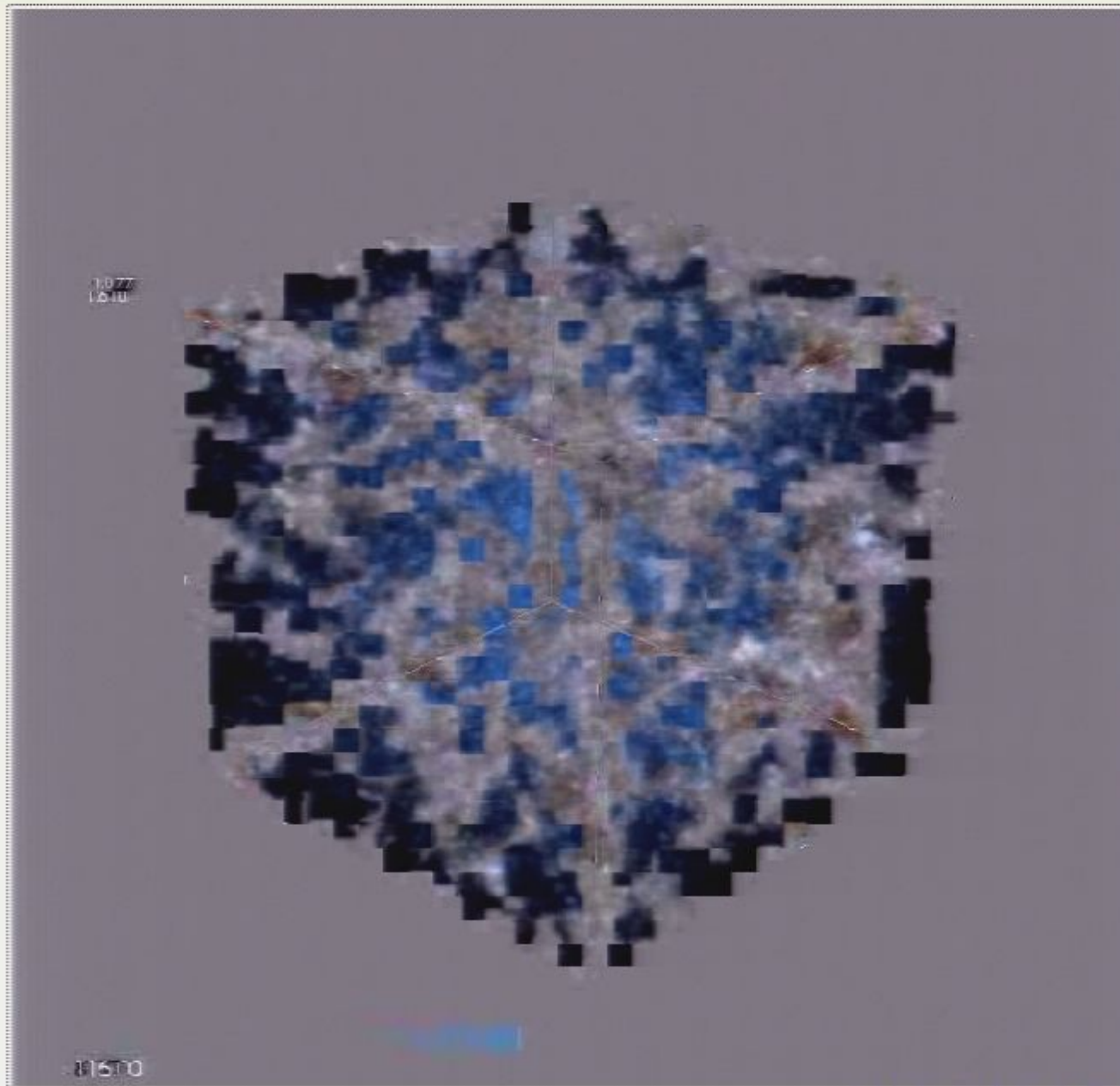
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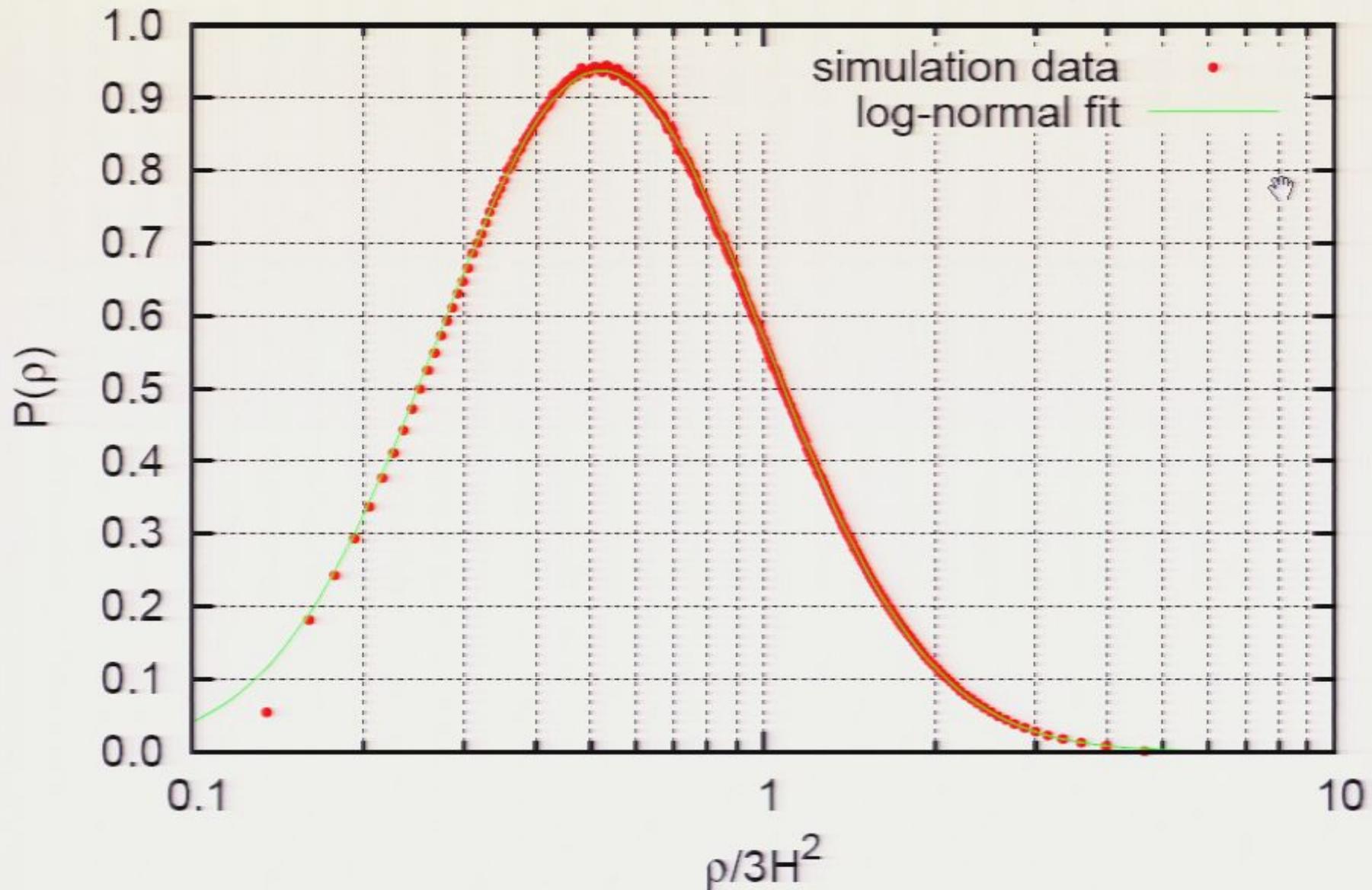
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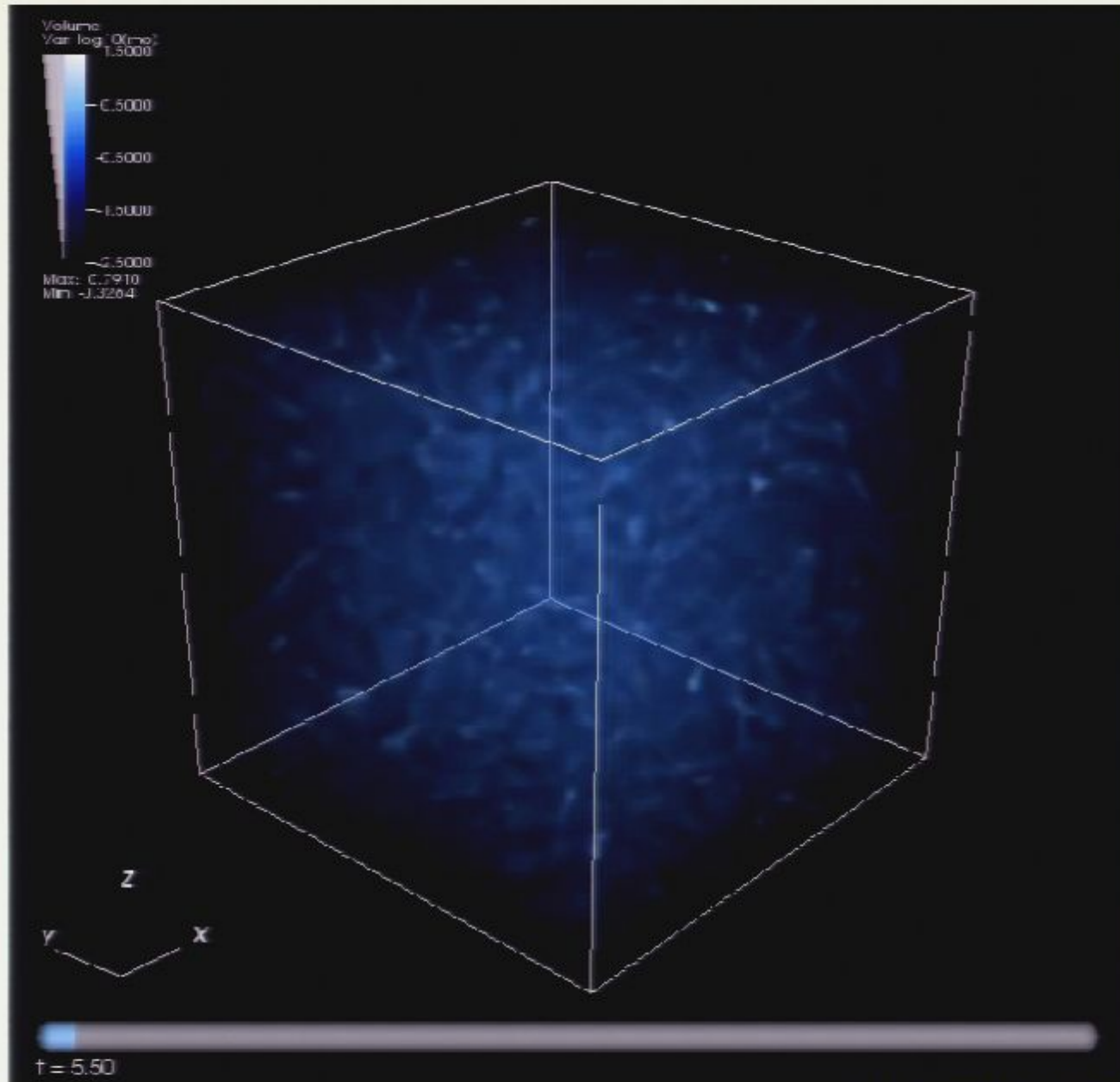
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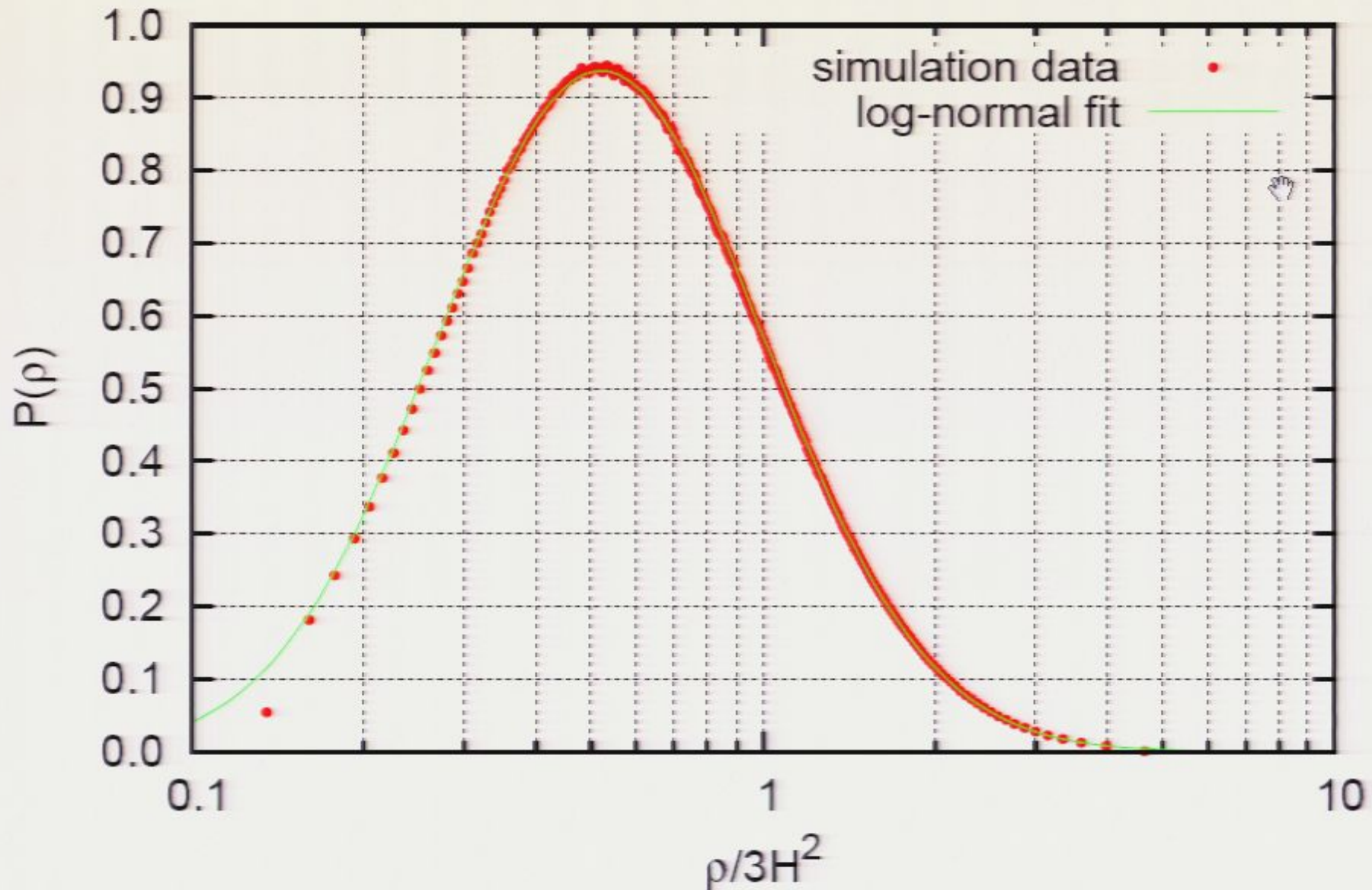
IN FACT, IT'S VERY LOG-NORMAL!



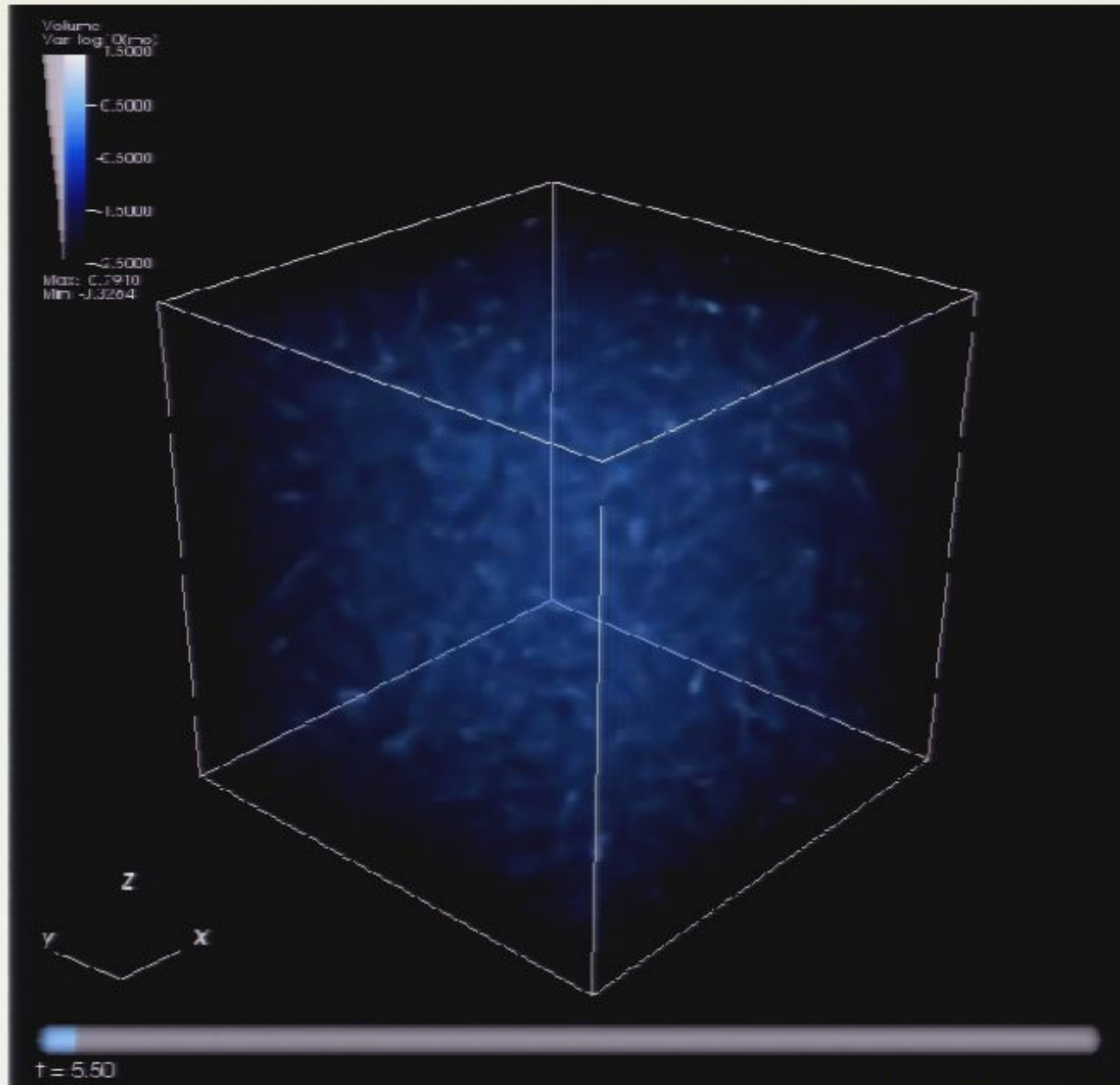
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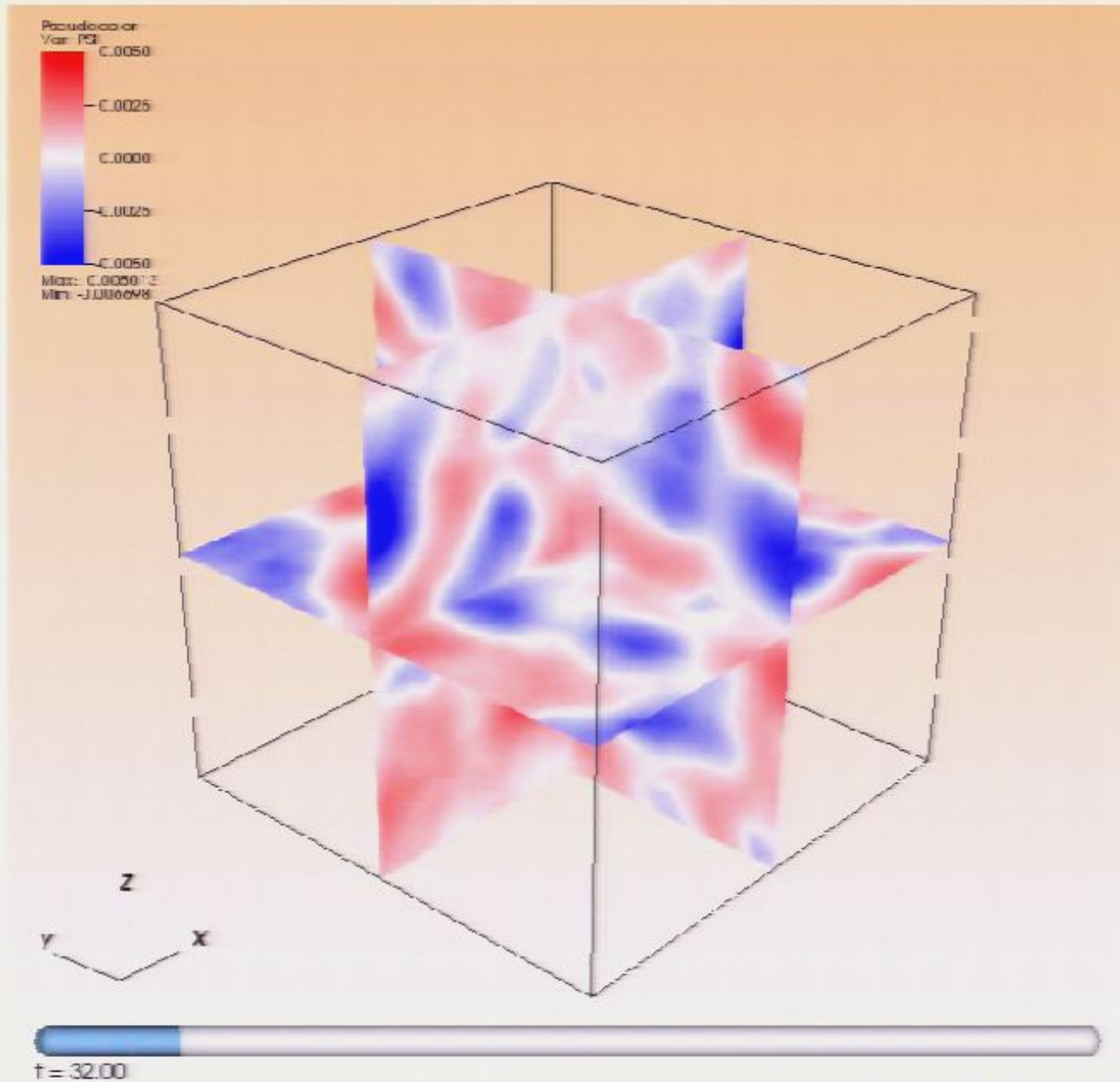
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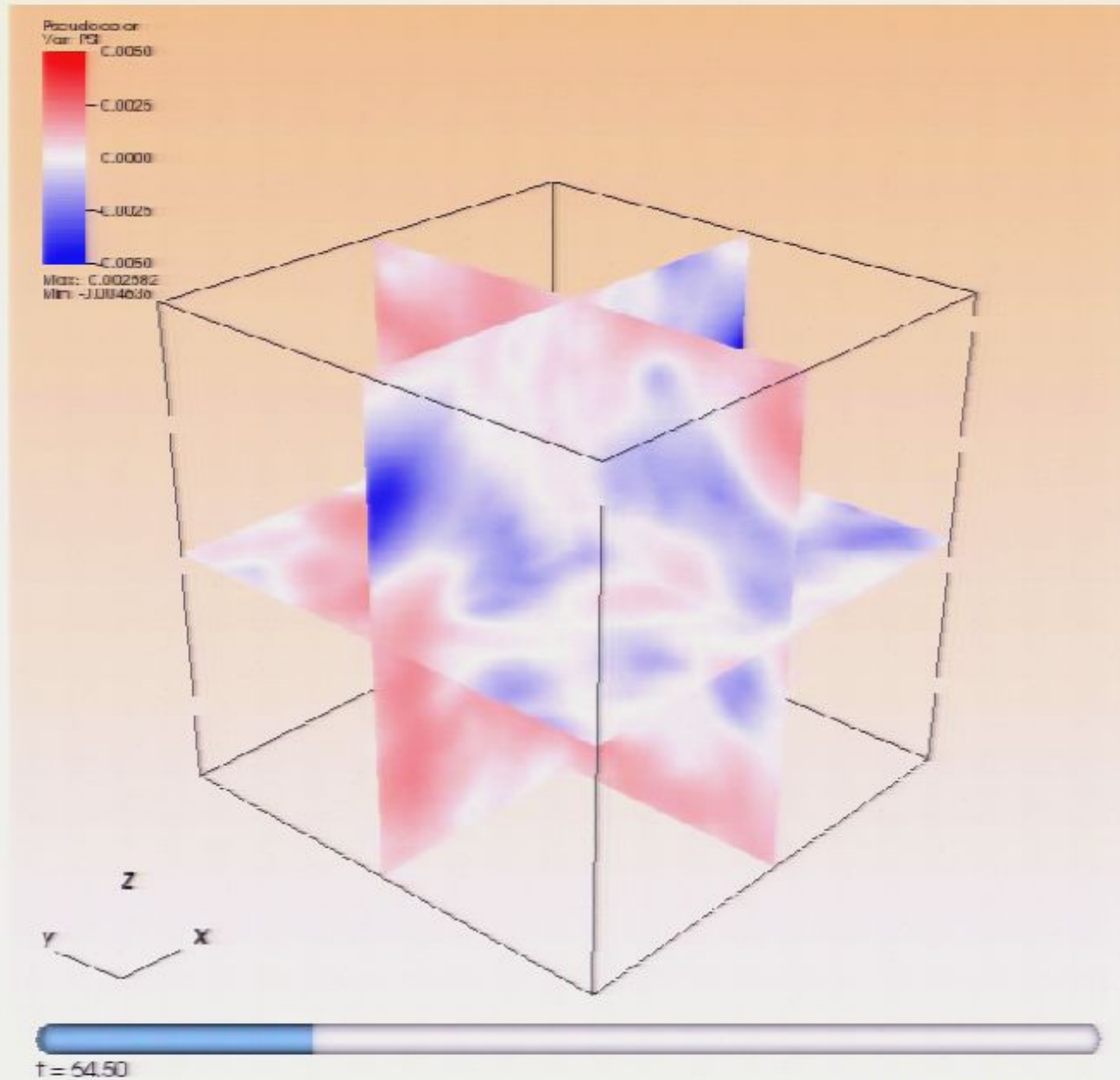
GRAVITATIONAL POTENTIAL (TRILINEAR COUPLING)



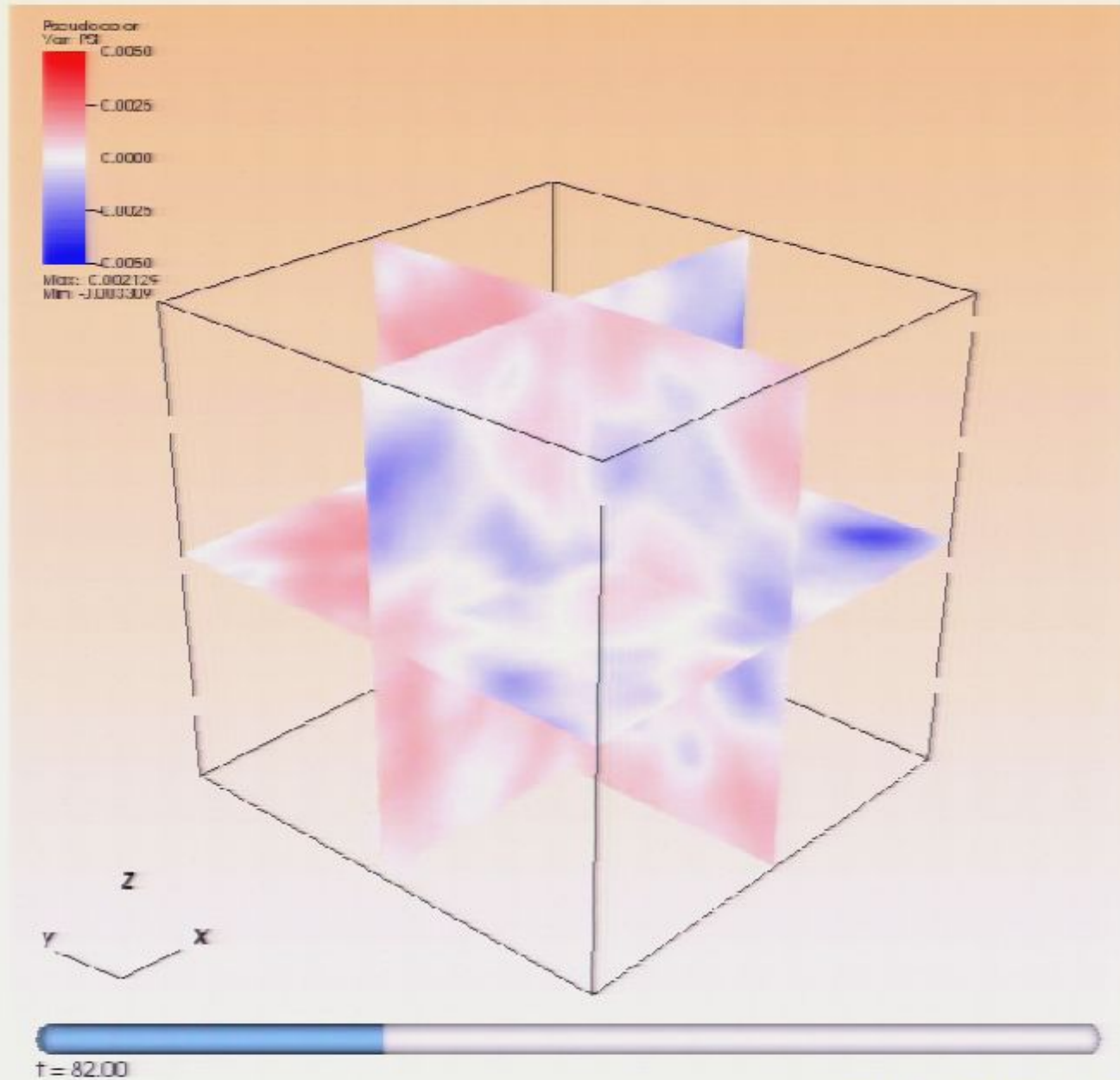
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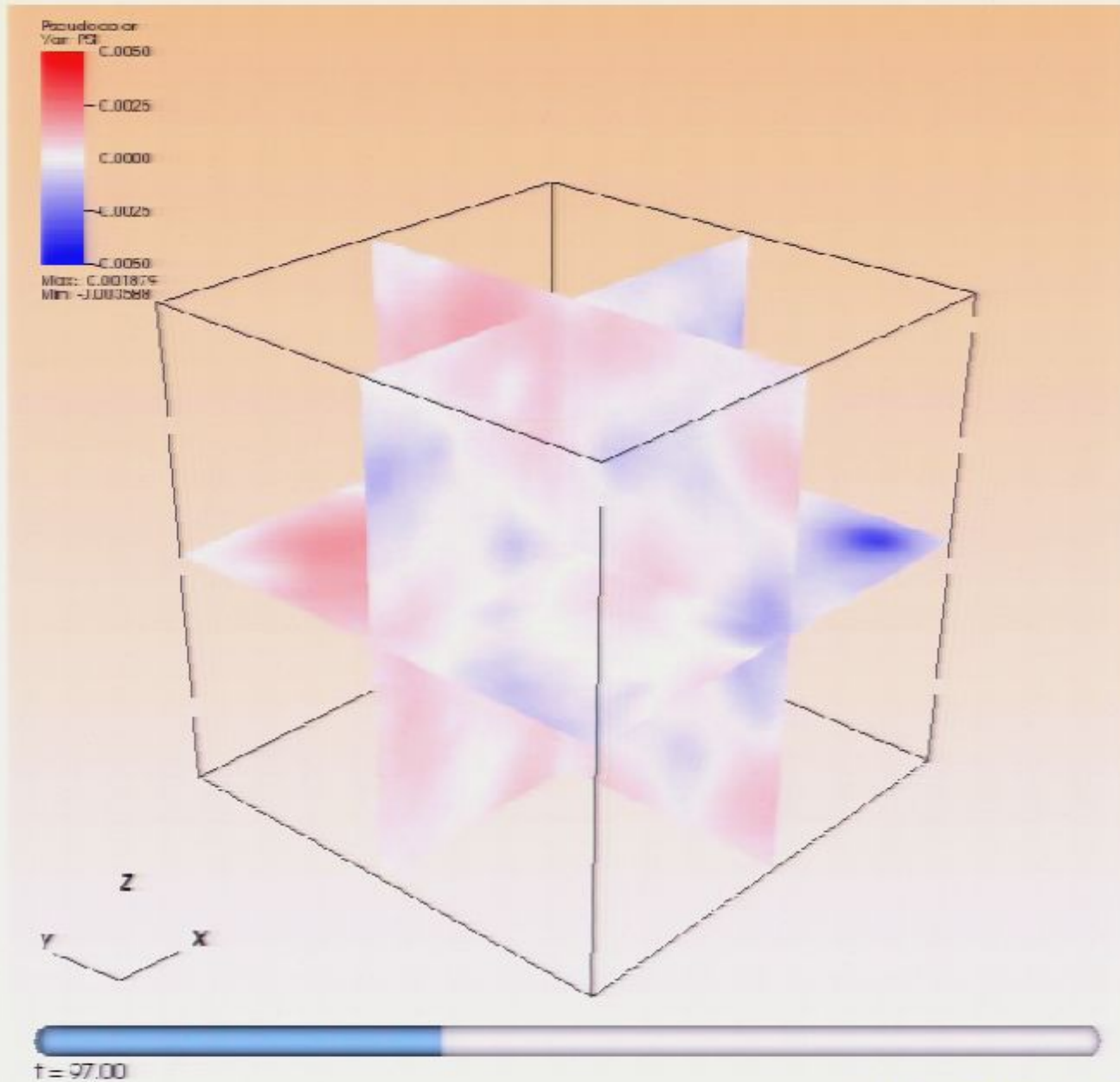
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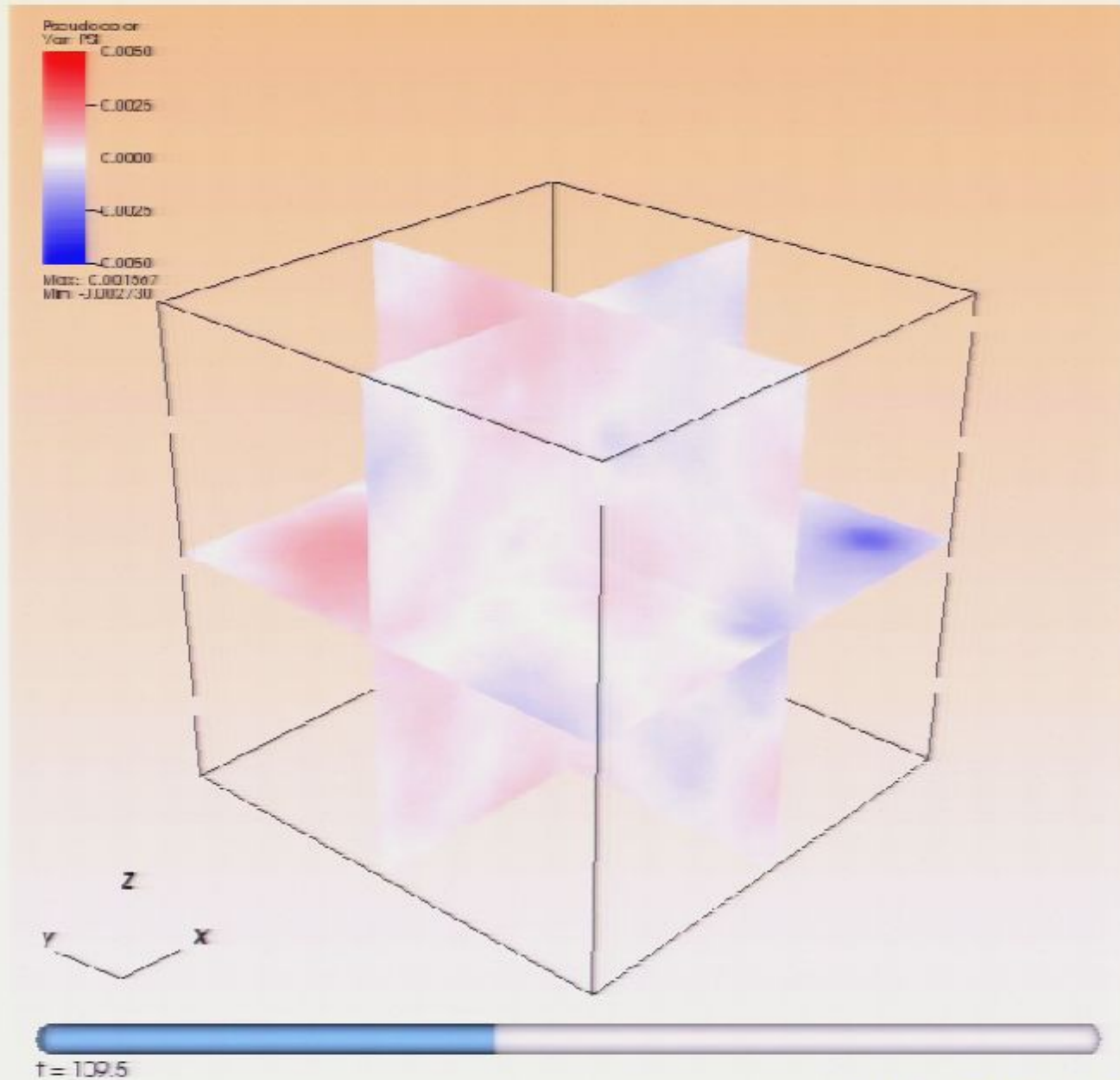
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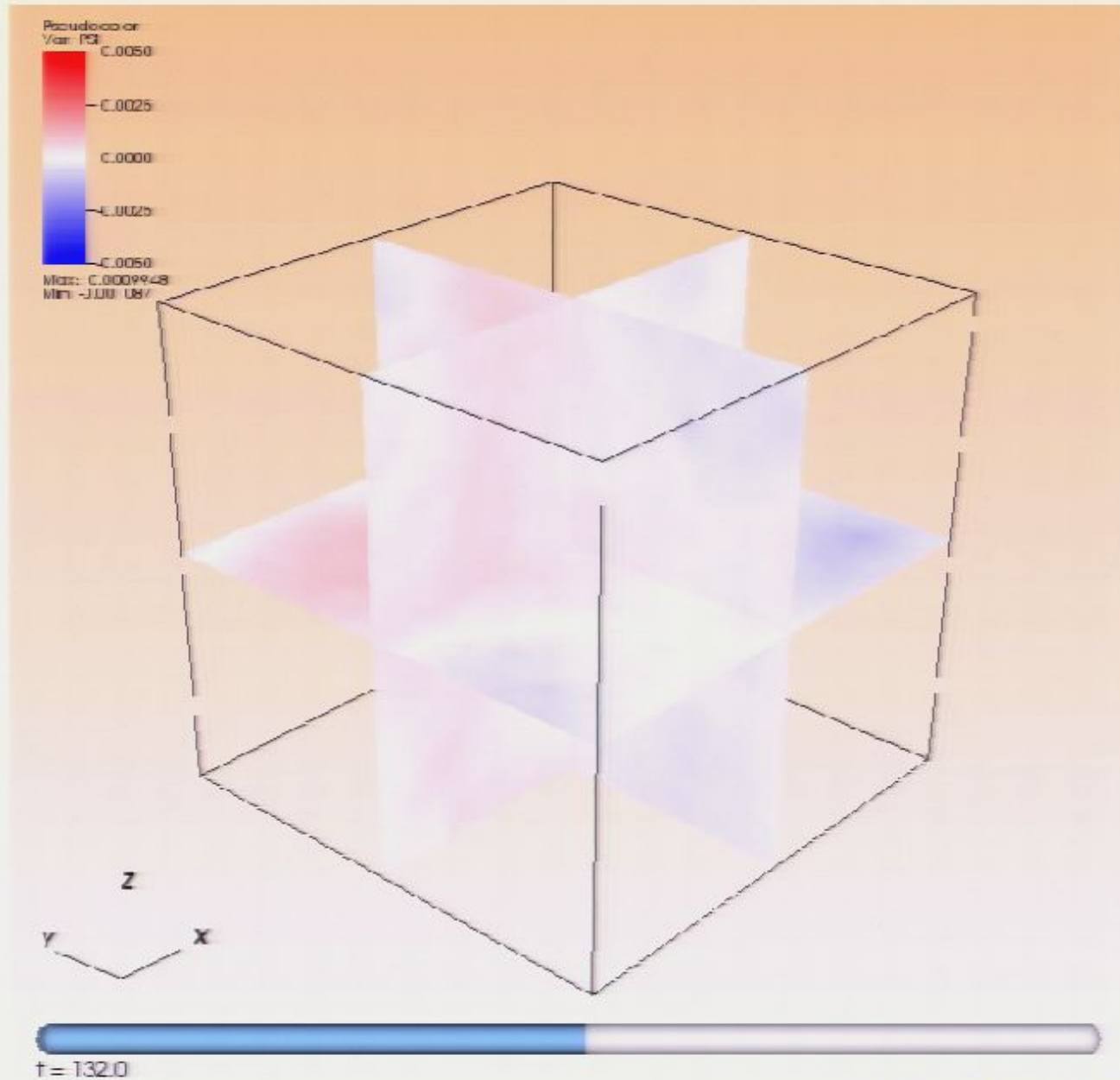
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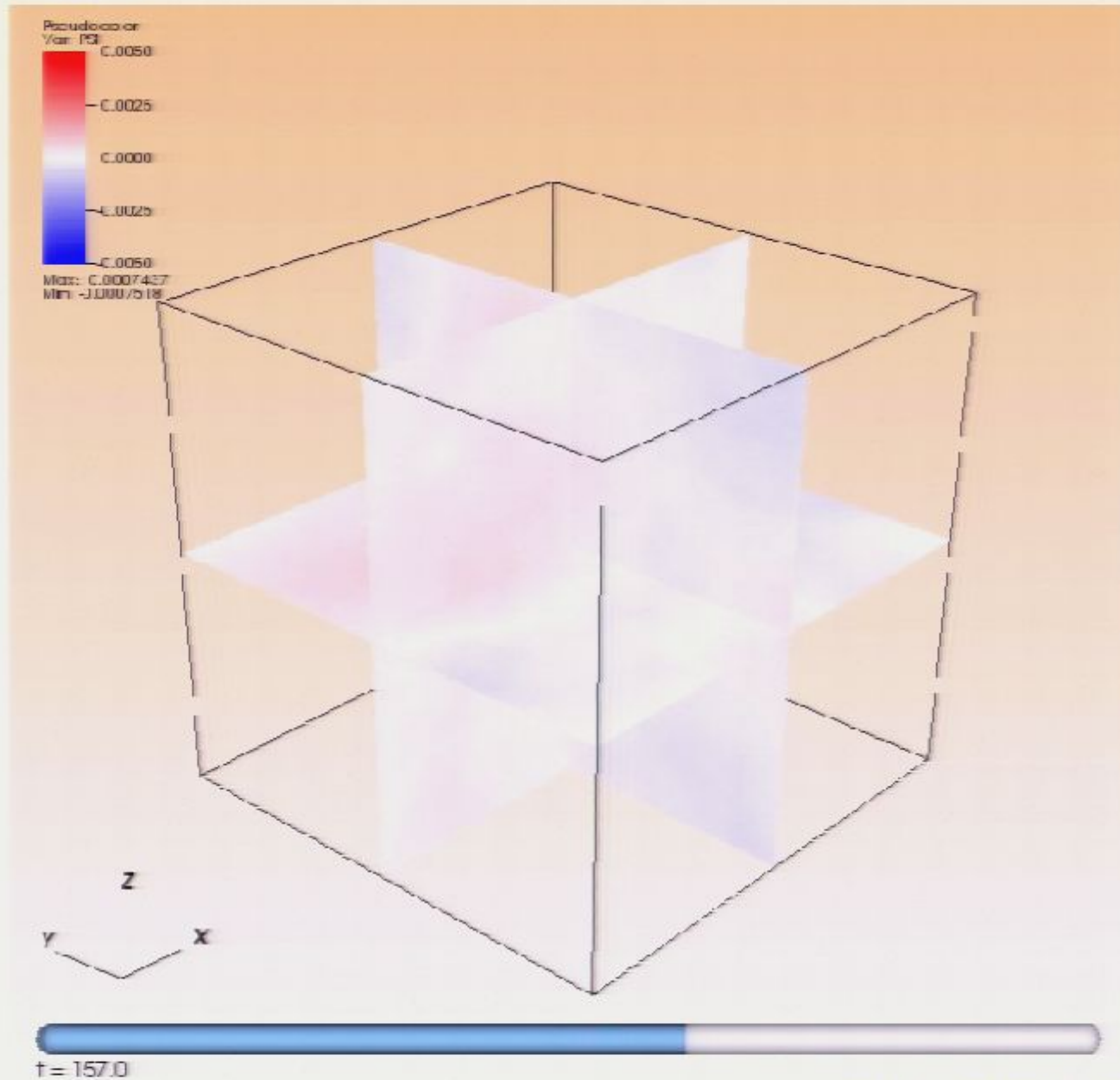
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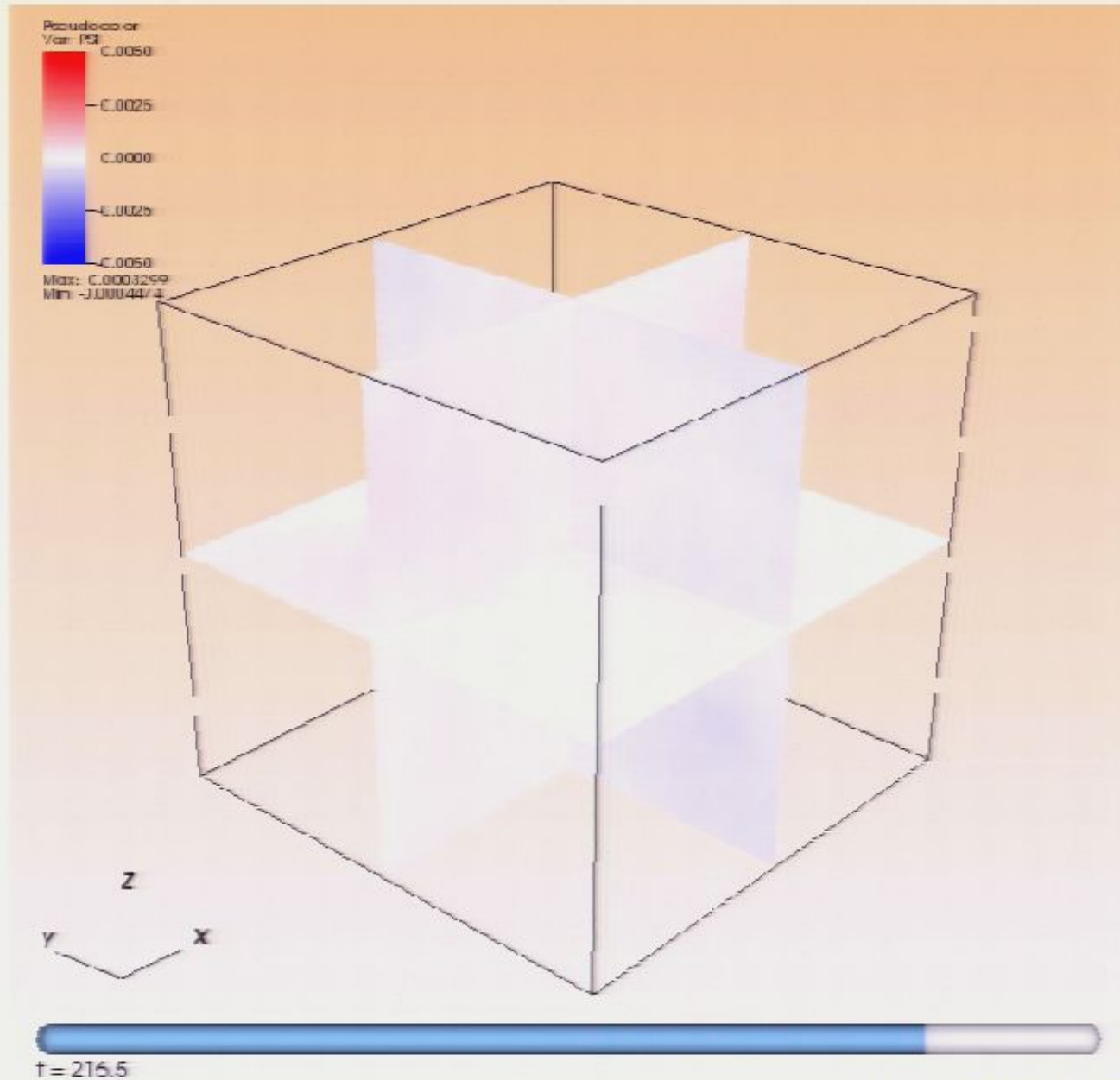
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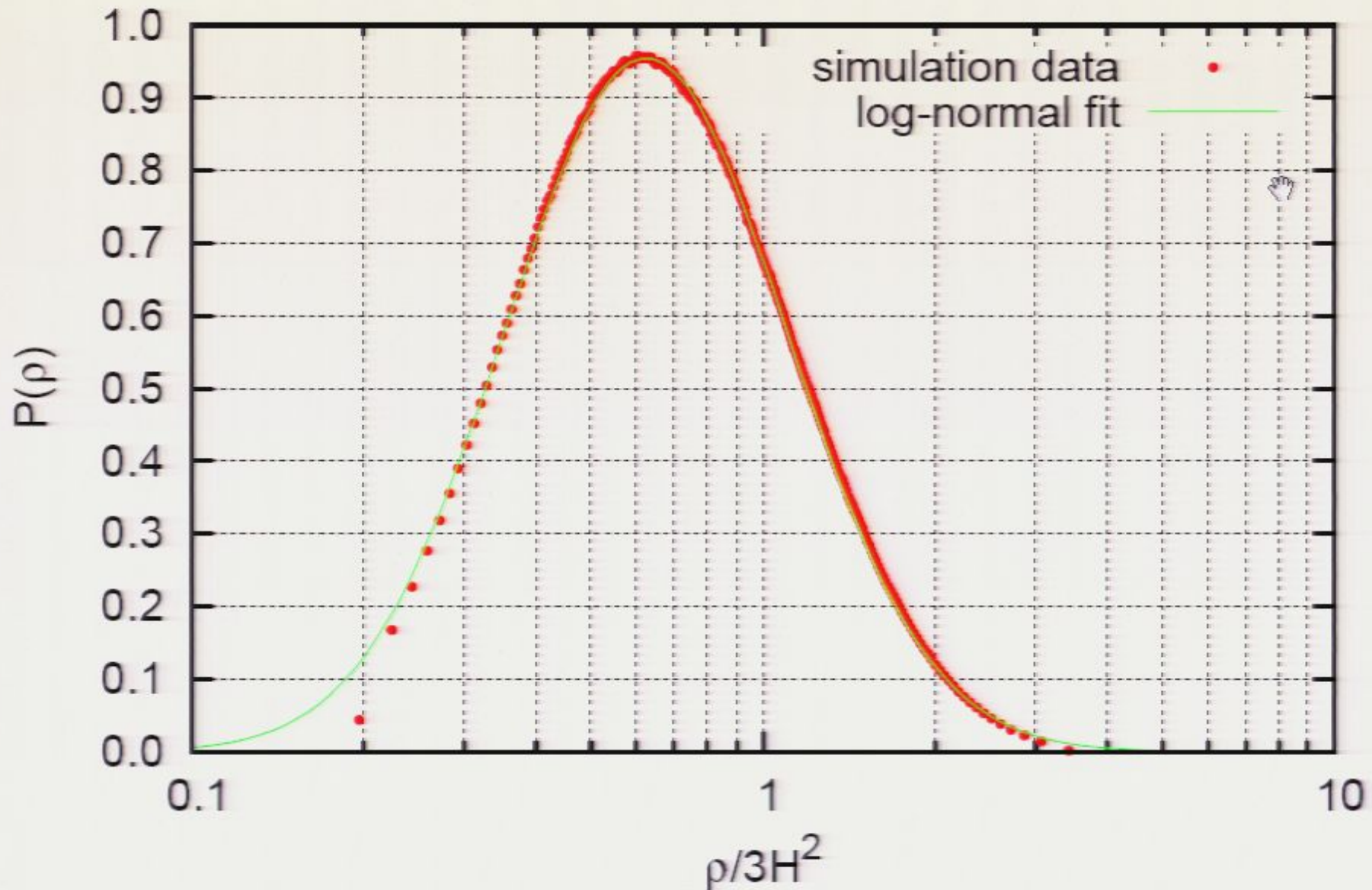
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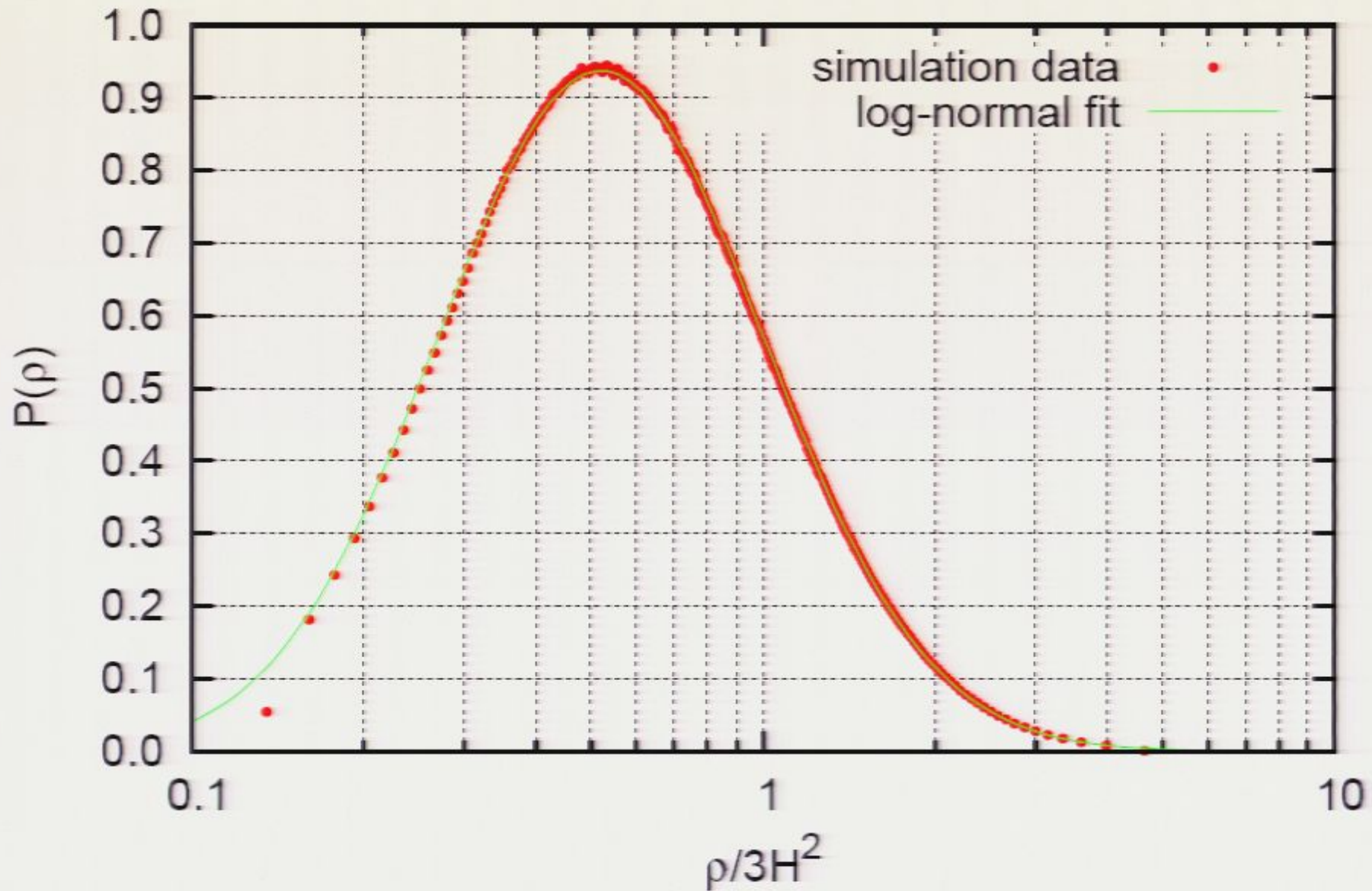
GRAVITATIONAL POTENTIAL (TRILINEAR COUPLING)



DENSITY PDF (TRILINEAR COUPLING)



DENSITY PDF (QUARTIC COUPLING)



THIS SIMPLY CAN'T BE JUST A COINCIDENCE!

What's Going On?

ISOTHERMAL SUPERSONIC TURBULENCE

Nordlund and Padoan (1998)

$$\frac{\partial \ln \rho}{\partial t} = -\vec{u} \cdot \nabla \ln \rho - \nabla \cdot \vec{u}$$

$$\frac{\partial \vec{u}}{\partial t} = -\vec{u} \cdot \nabla \vec{u} - \frac{p}{\rho} \nabla \left(\ln \rho + \ln \frac{p}{\rho} \right) + \vec{F}$$

For constant equation of state,
equations of motion
do not depend on mean density!

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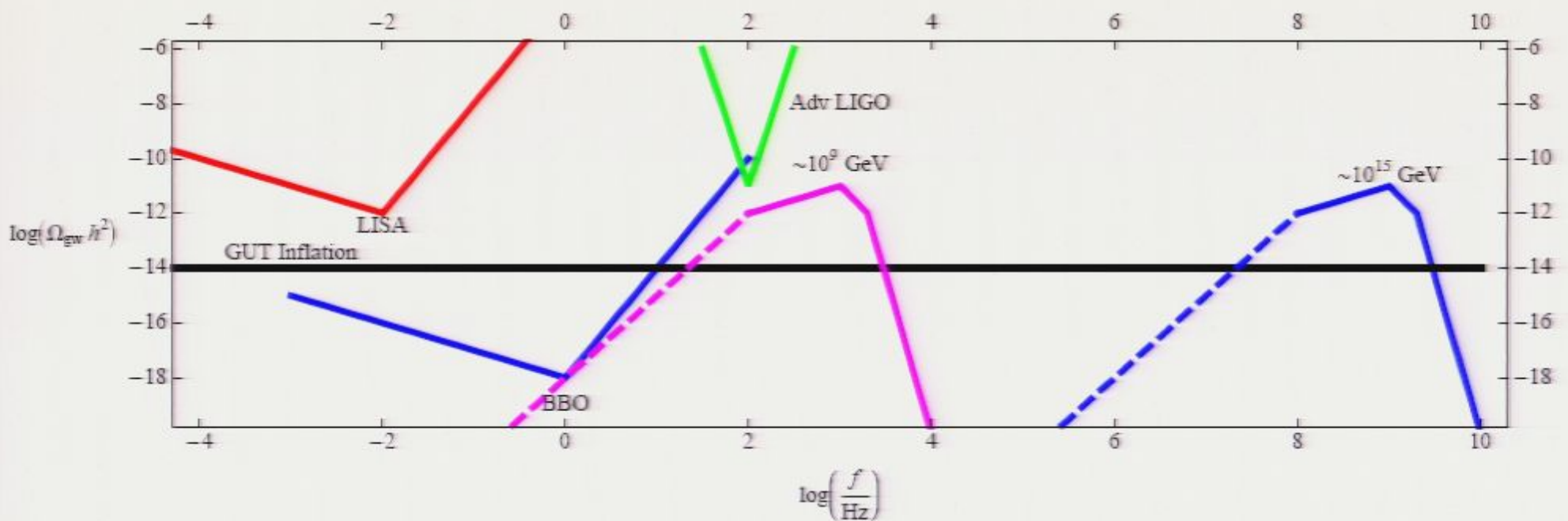
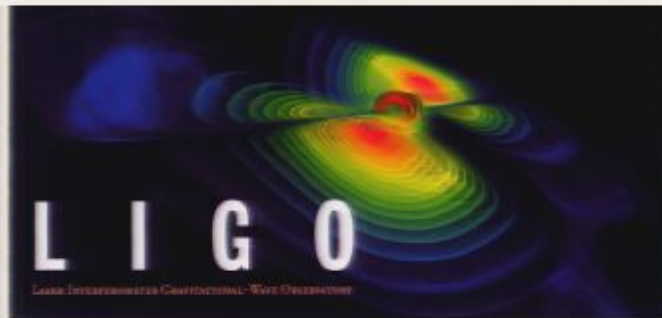
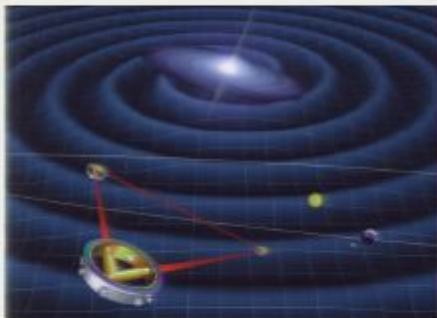
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GRAVITATIONAL WAVES FROM PREHEATING



Easter, Giblin, and Lim (2007)

OBSERVABLE SIGNATURES OF PREHEATING?

1 Primordial Black Holes (no!)

- gravitational potential of order 10^{-3}
- relativistic EOS does not help with growth

2 Non-Gaussianity (maybe?)

- very large at small scales...
- ... but supposedly gets wiped out by thermalization

3 Gravitational Waves (yes!)

- copious production (Ω_{gw} of order 10^{-6})...
- ... but wavelength is very short (hybrid models help!)
- stochastic background is difficult to observe

Definitely Worth Investigating!..

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