

Title: String Cosmology

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Abstract:

Cosmic string properties and detection

3rd Lecture on
Brane Inflation : From Superstrings to Cosmic Strings
Perimeter Institute, June 24, 2005

Cosmic string properties and detection

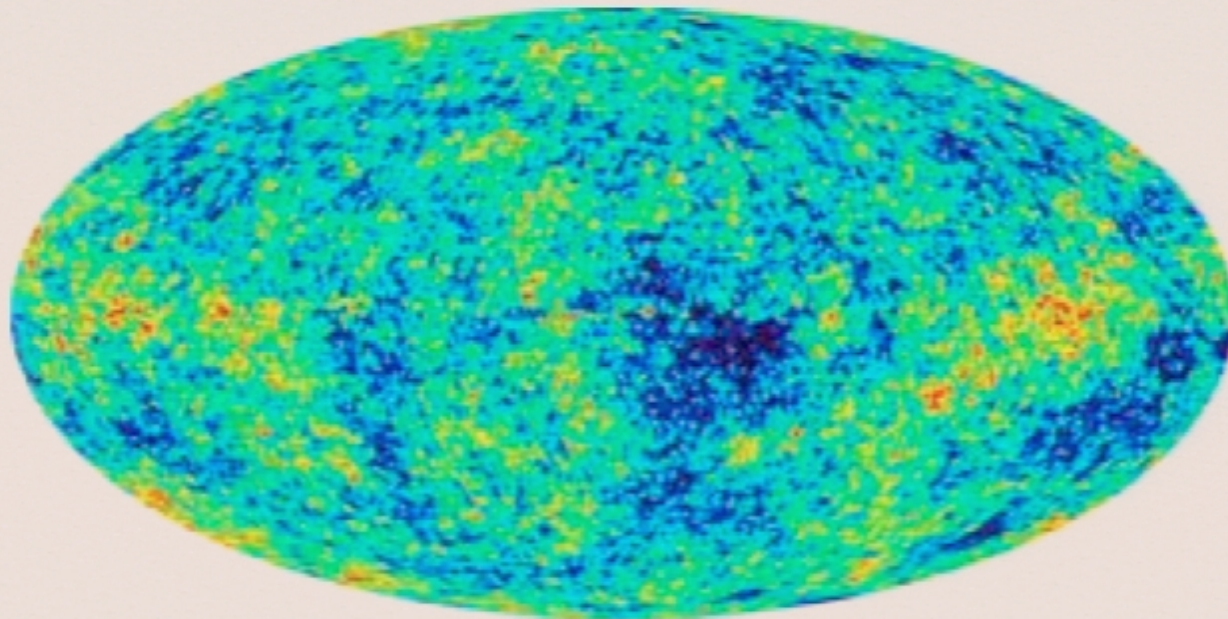
3rd Lecture on
Brane Inflation : From Superstrings to Cosmic Strings
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Inflationary Universe

$$10^{-30} \text{ m}$$

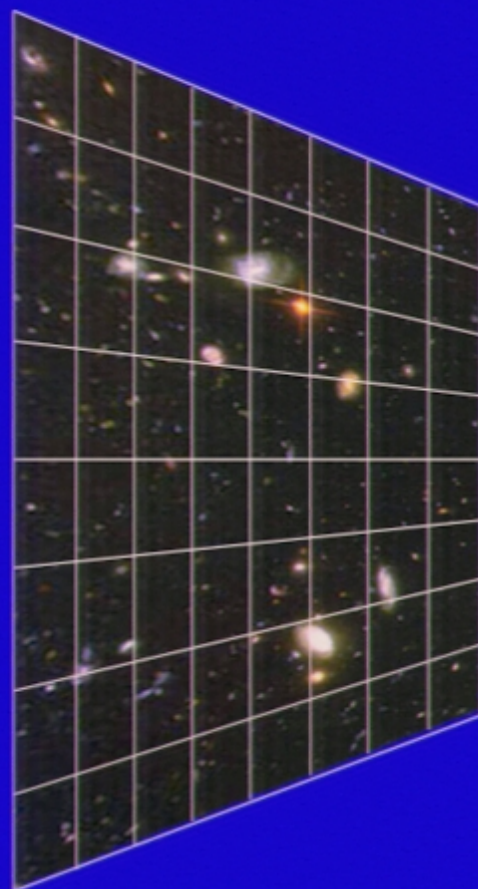
- Inflation : solves a number of outstanding cosmological problem: flatness, horizon, defects, angular momentum etc.
- generated all matter-energy in our universe from the inflaton potential.
- started the hot big bang.
- generated the density perturbation that seeded the structure formation.
- generated the temperature perturbation observed in WMAP.

WMAP 2003



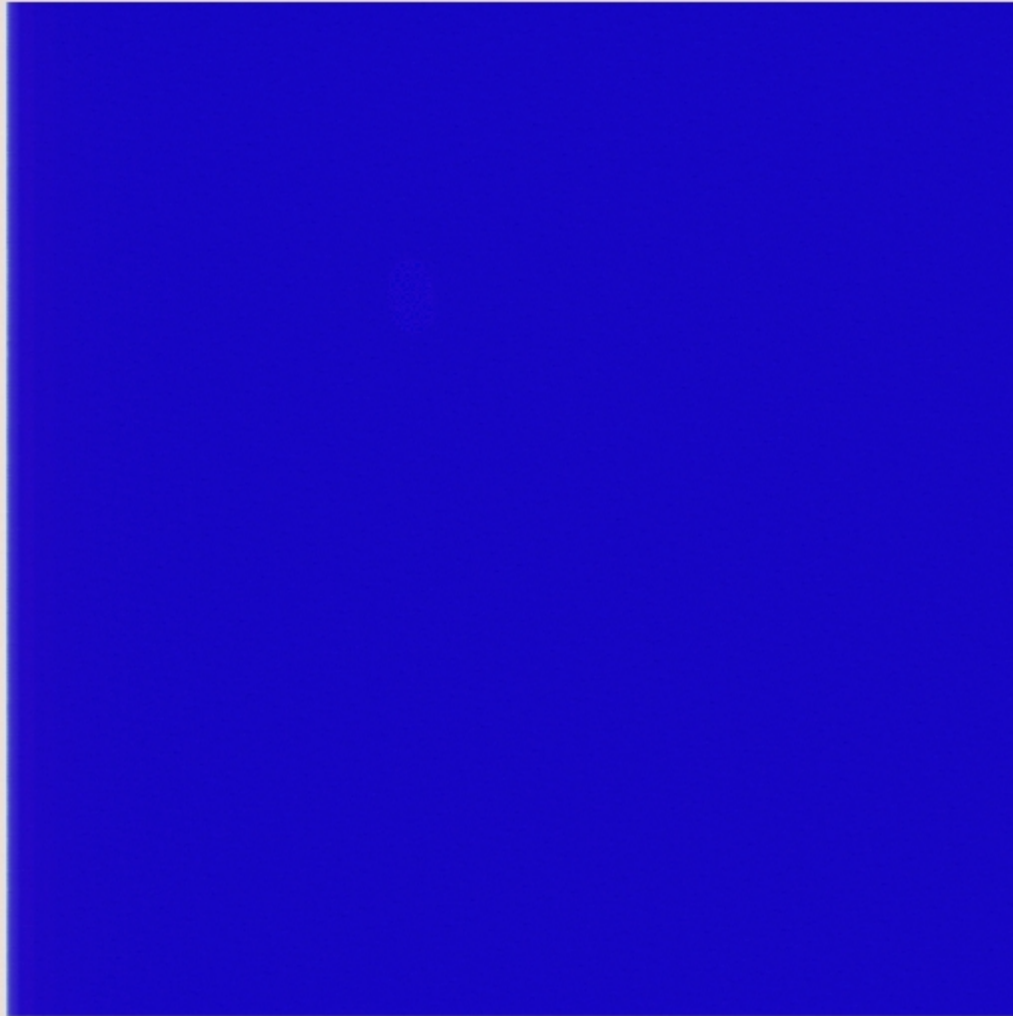
Data strongly supports inflation

Brane World



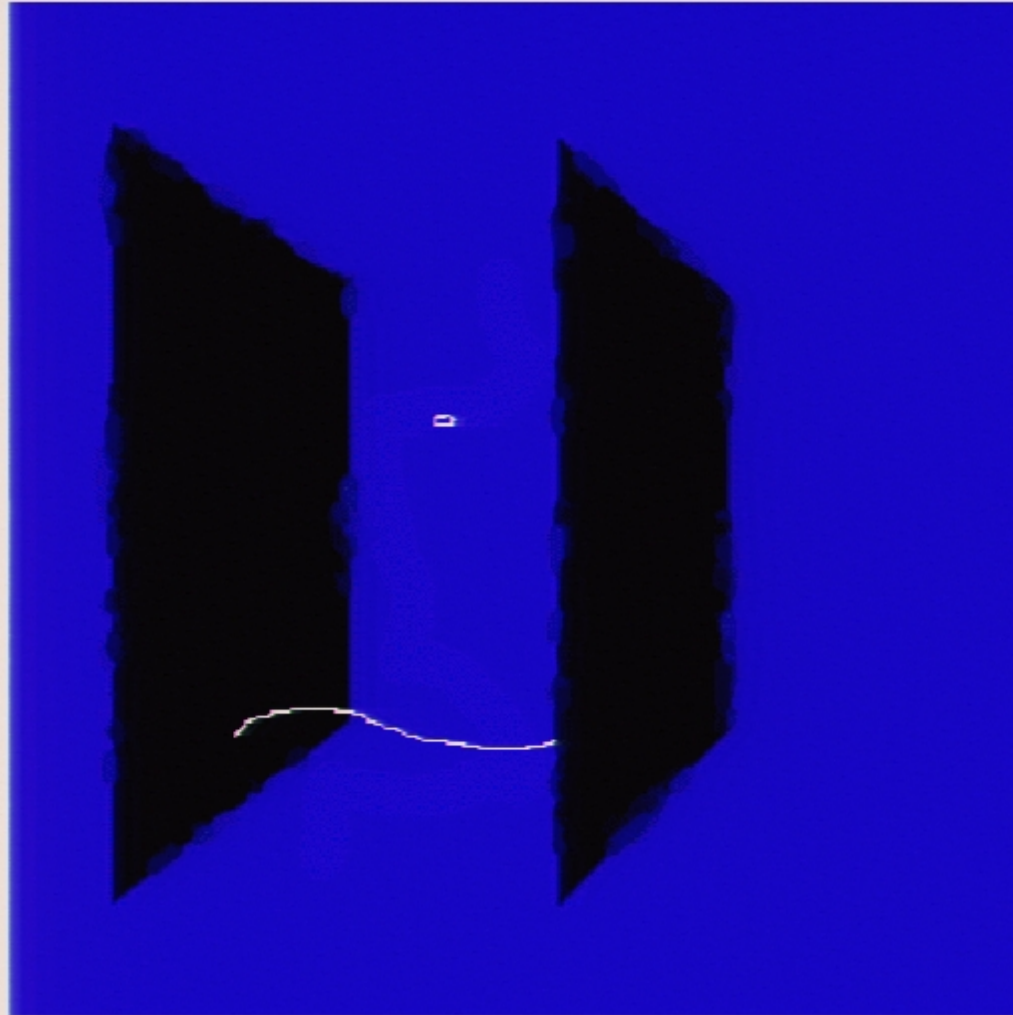
Aaron
Miller

Brane Inflation and Collision



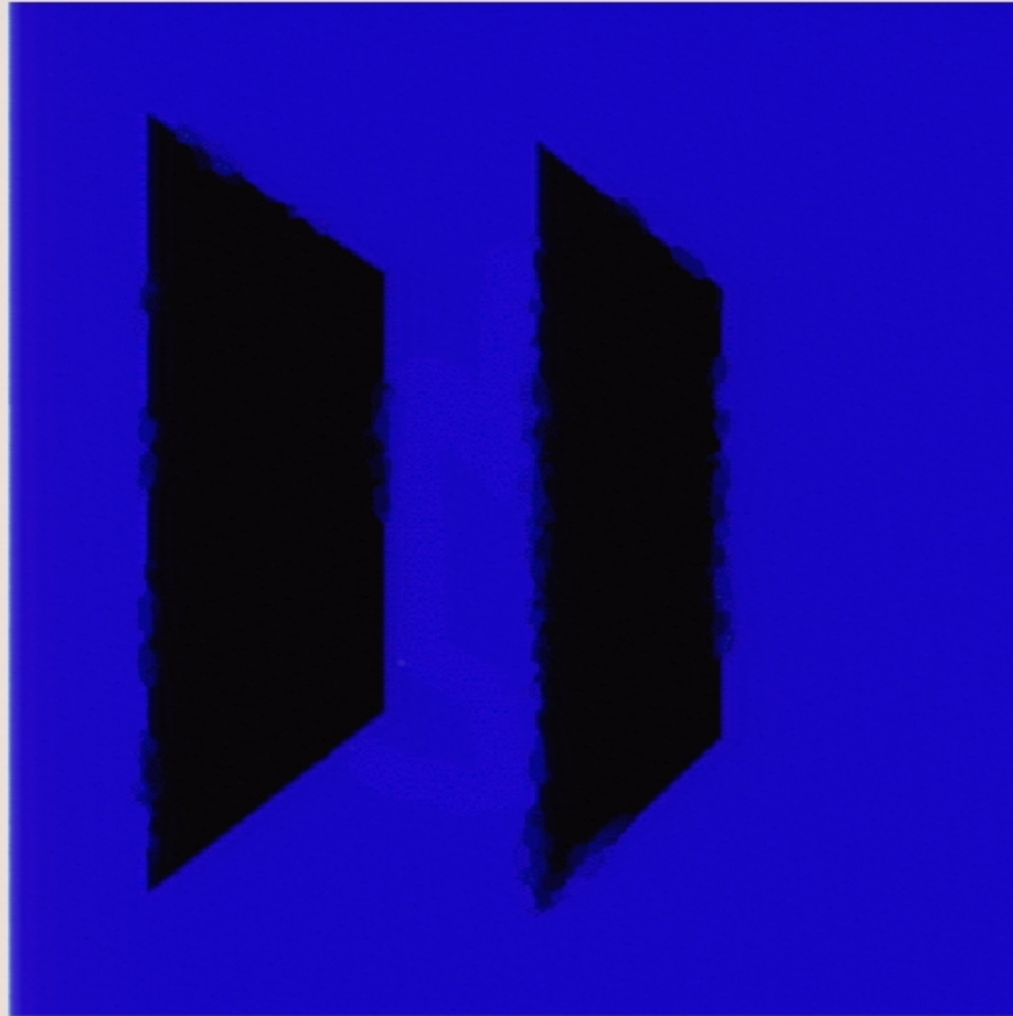
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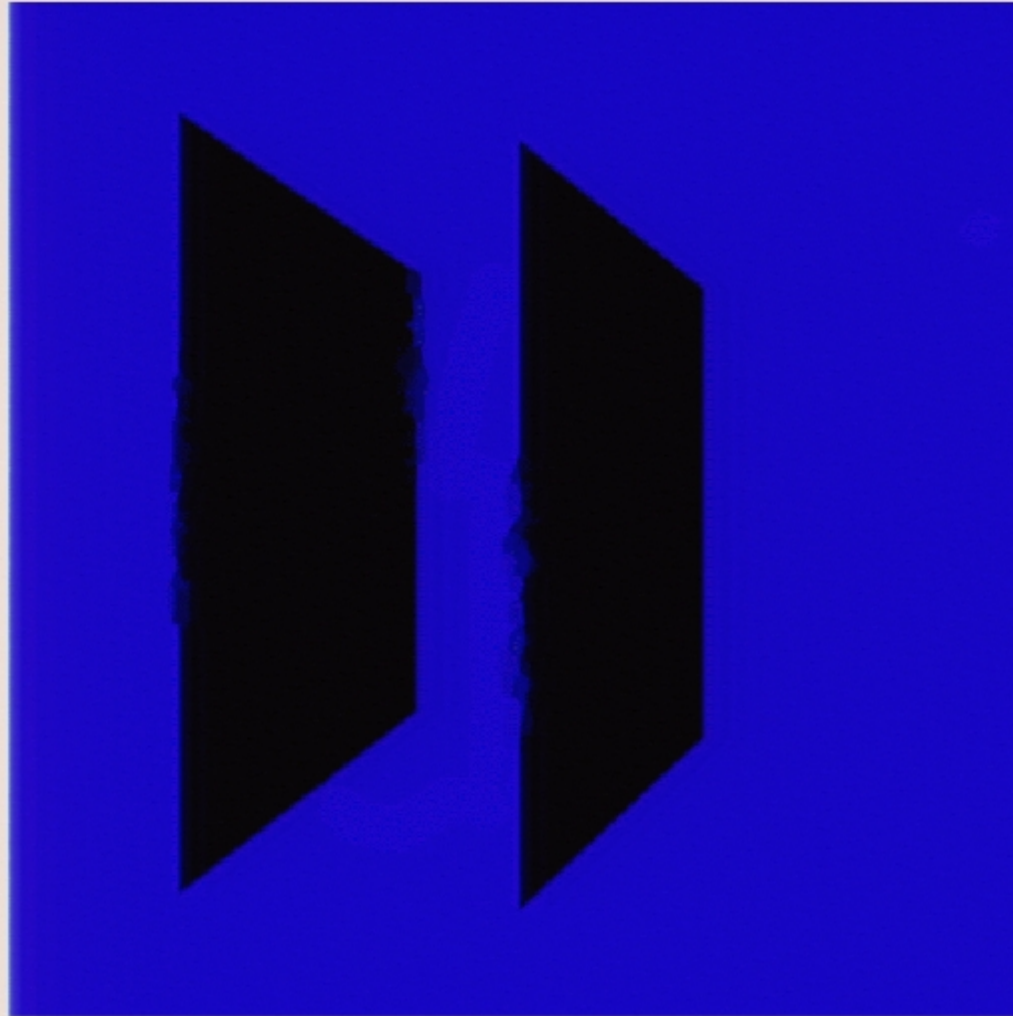
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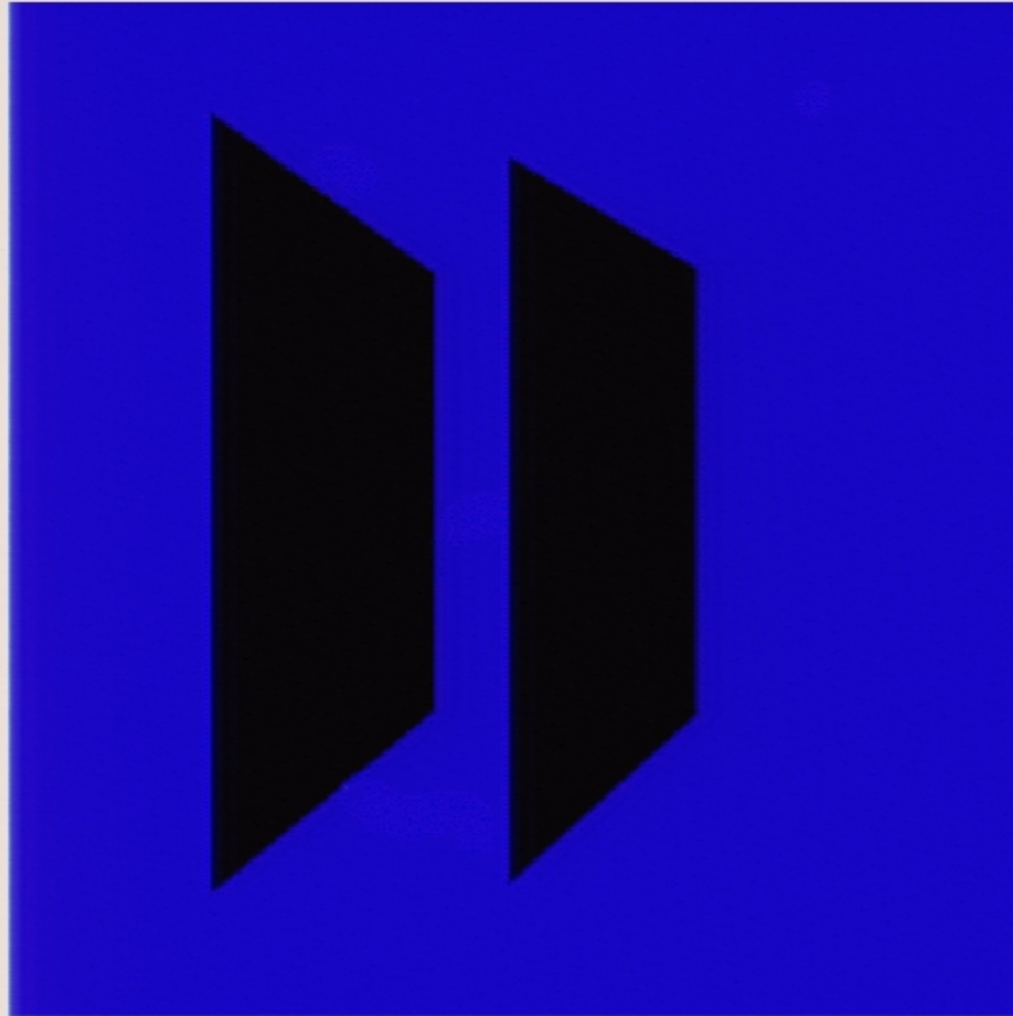
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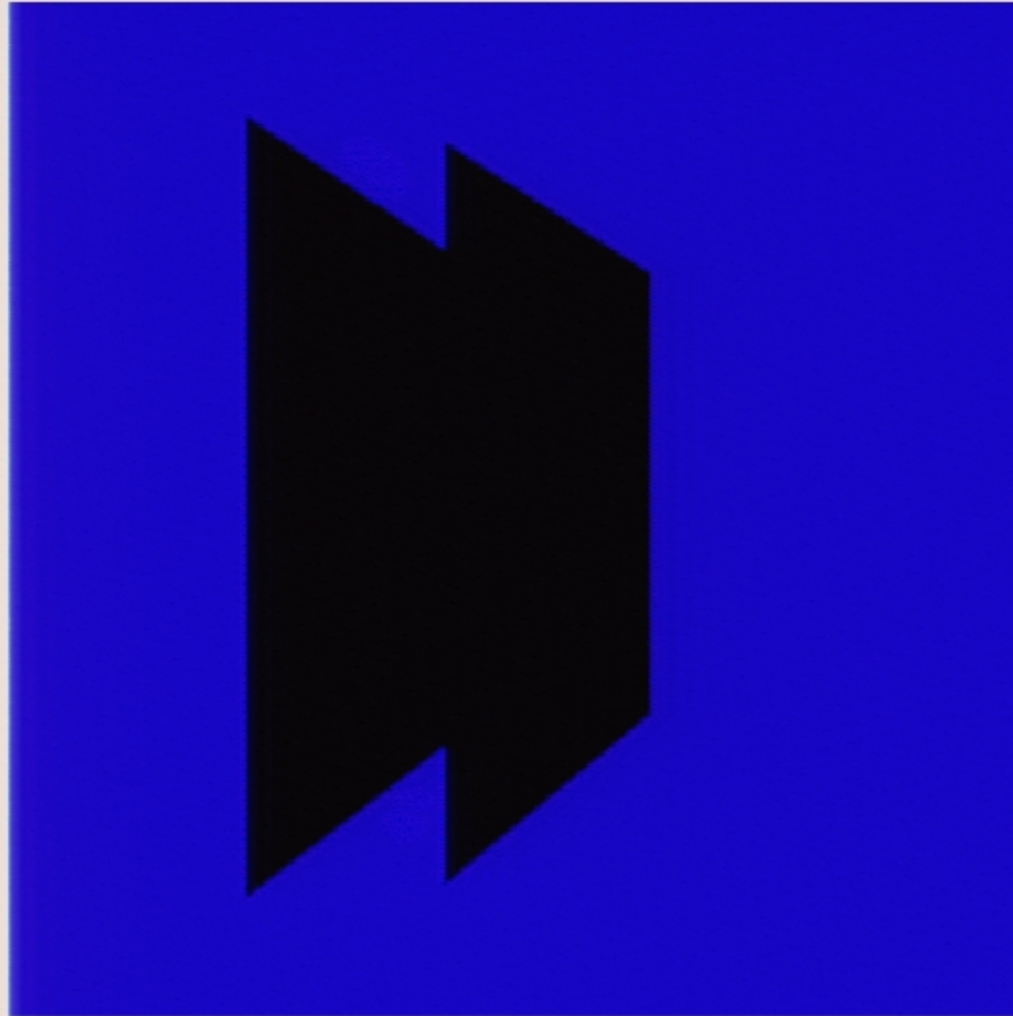
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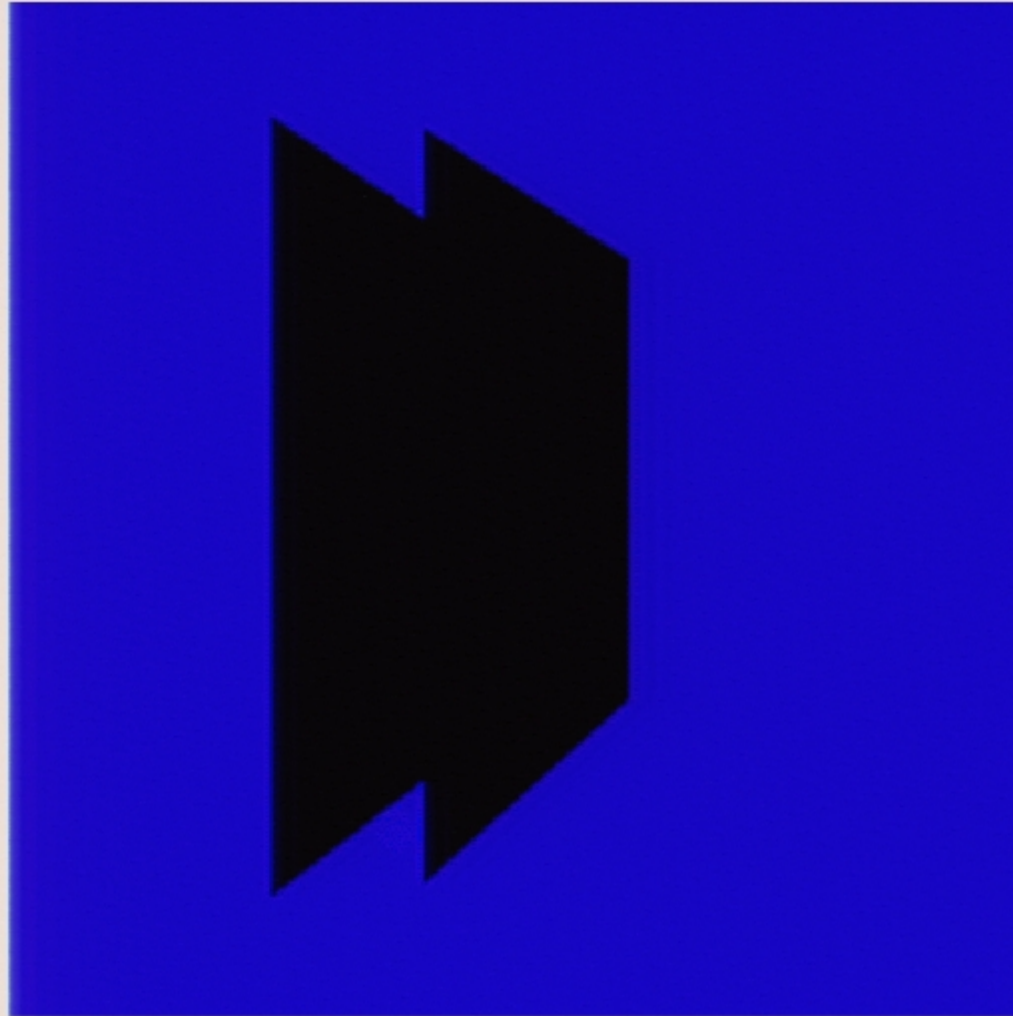
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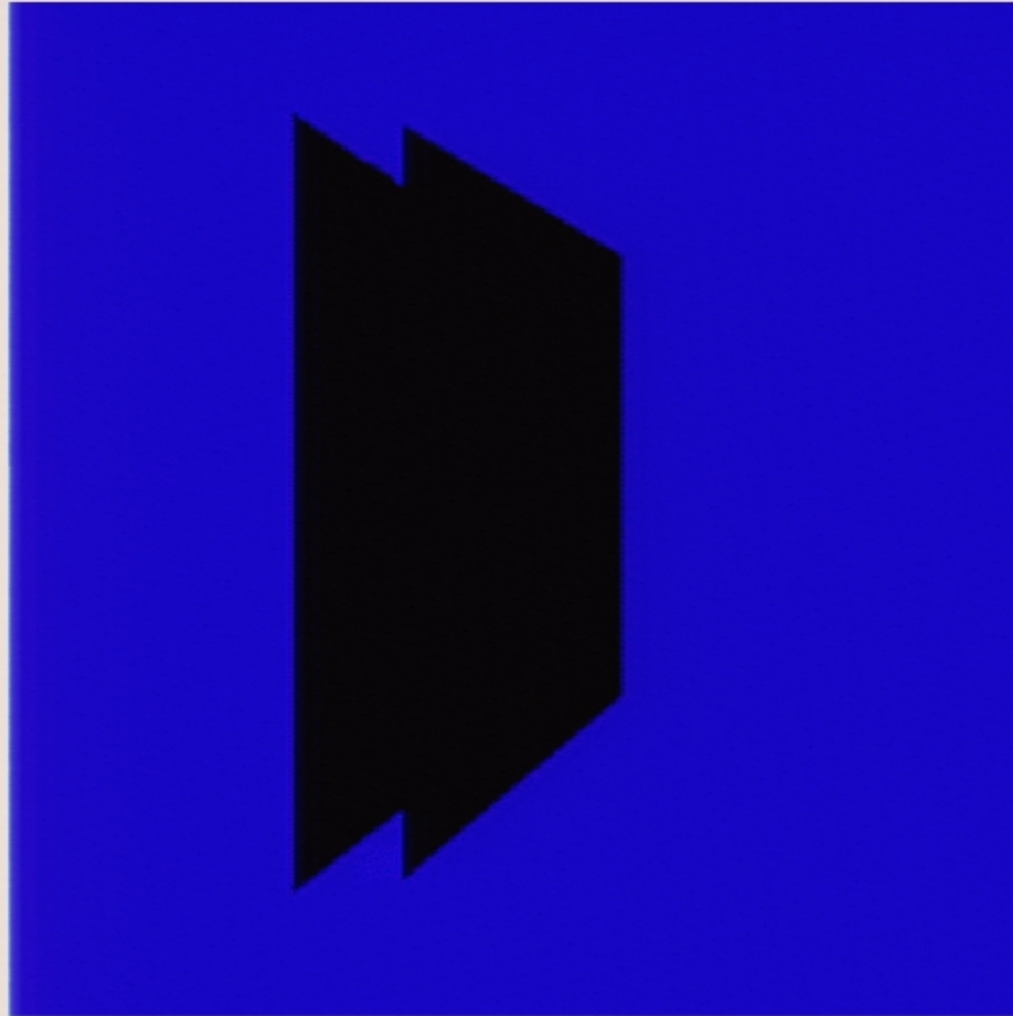
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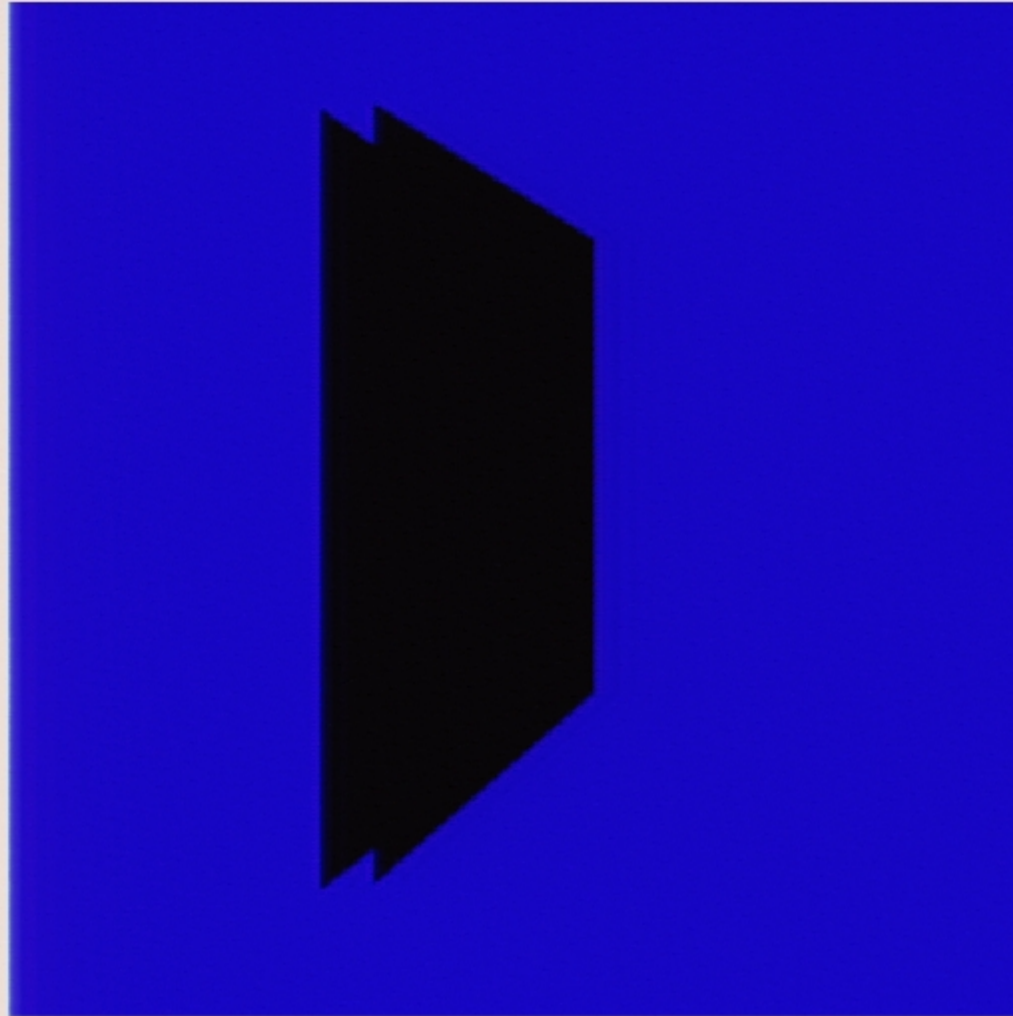
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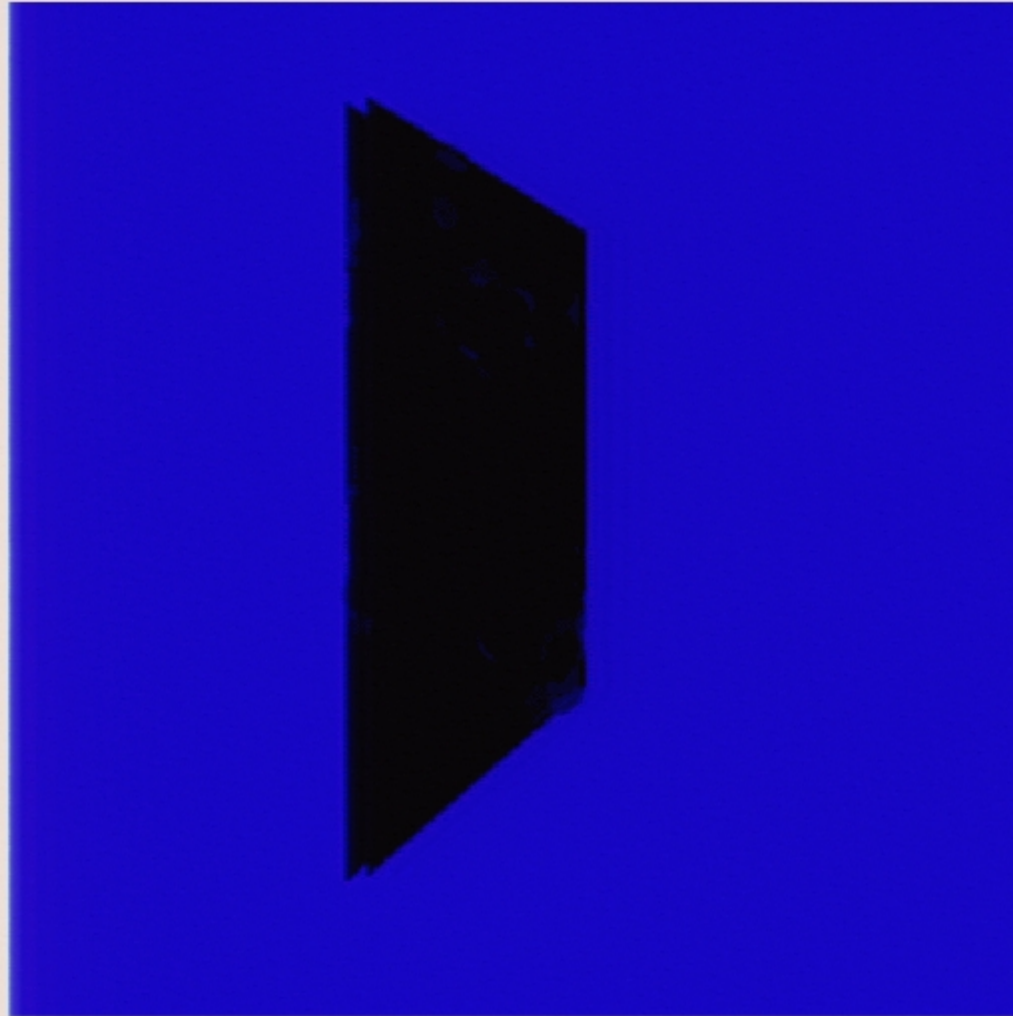
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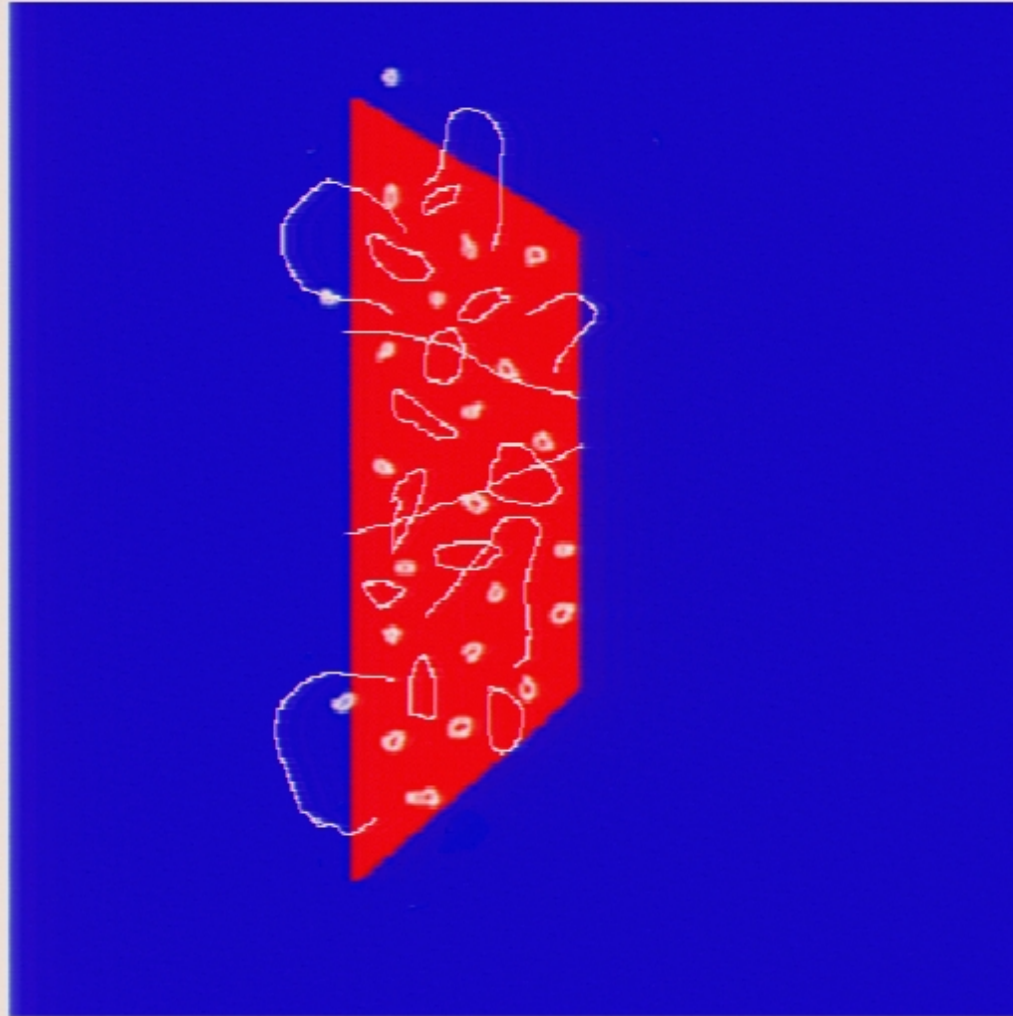
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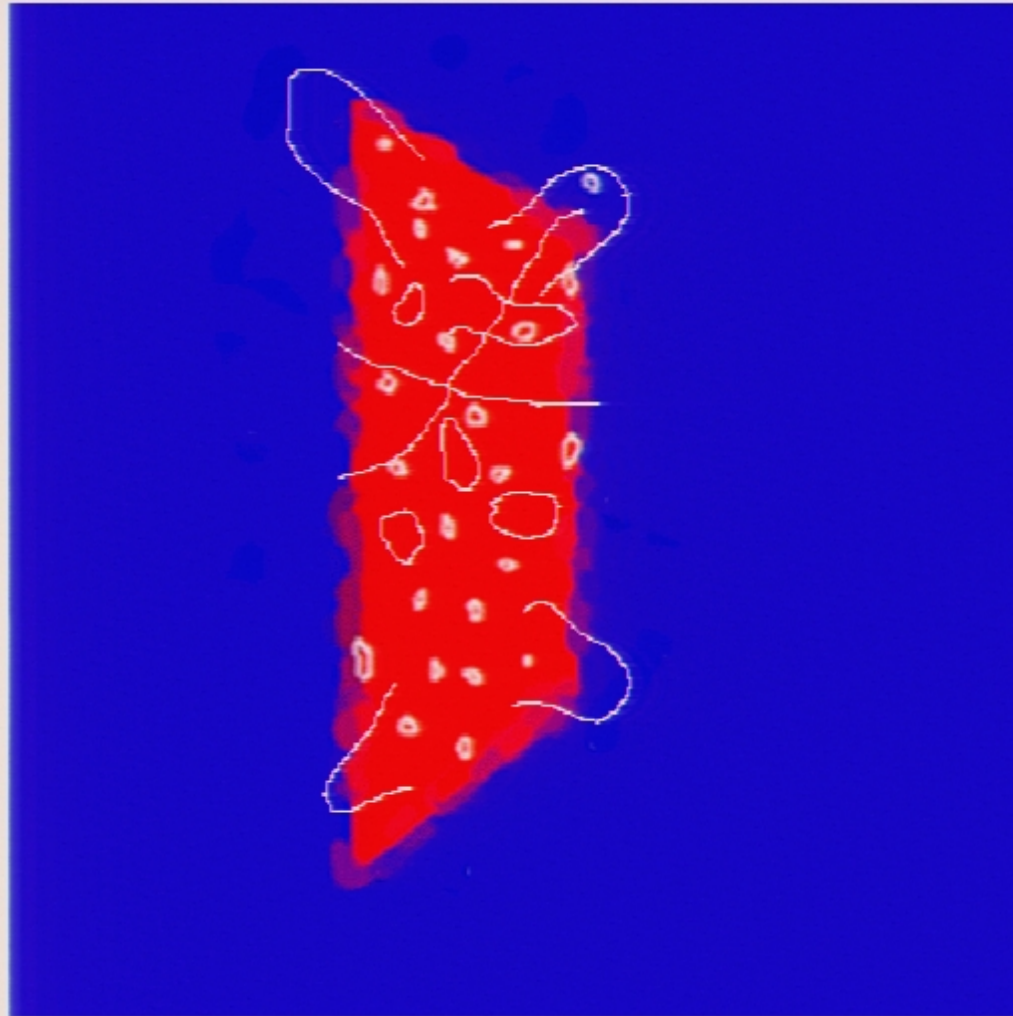
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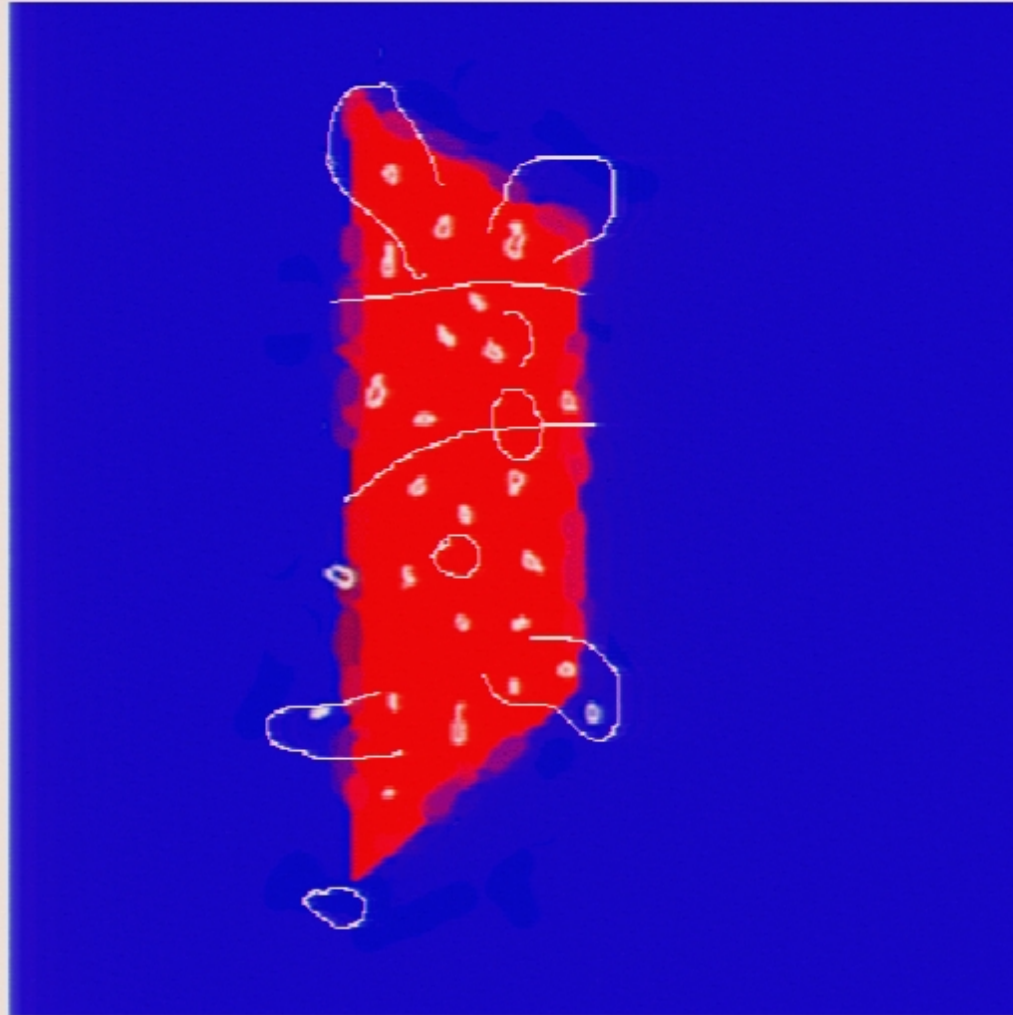
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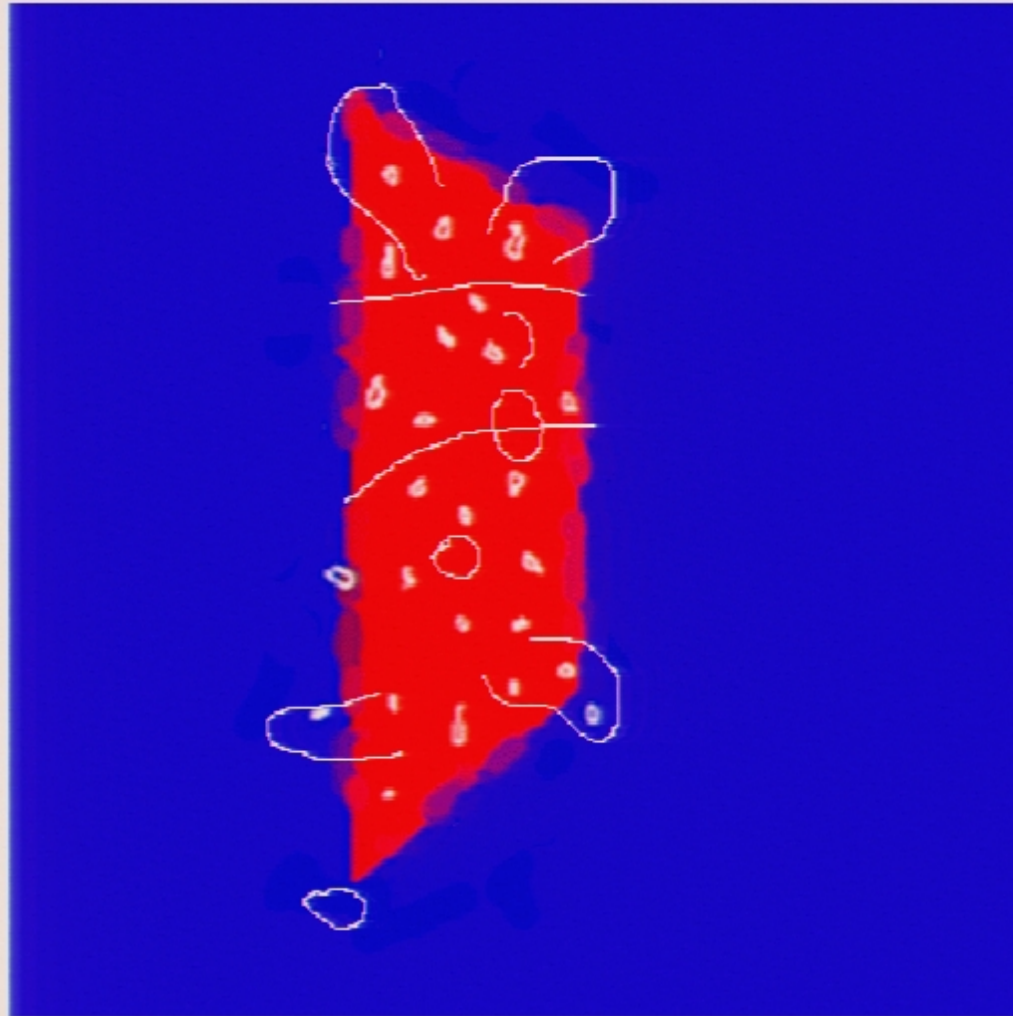
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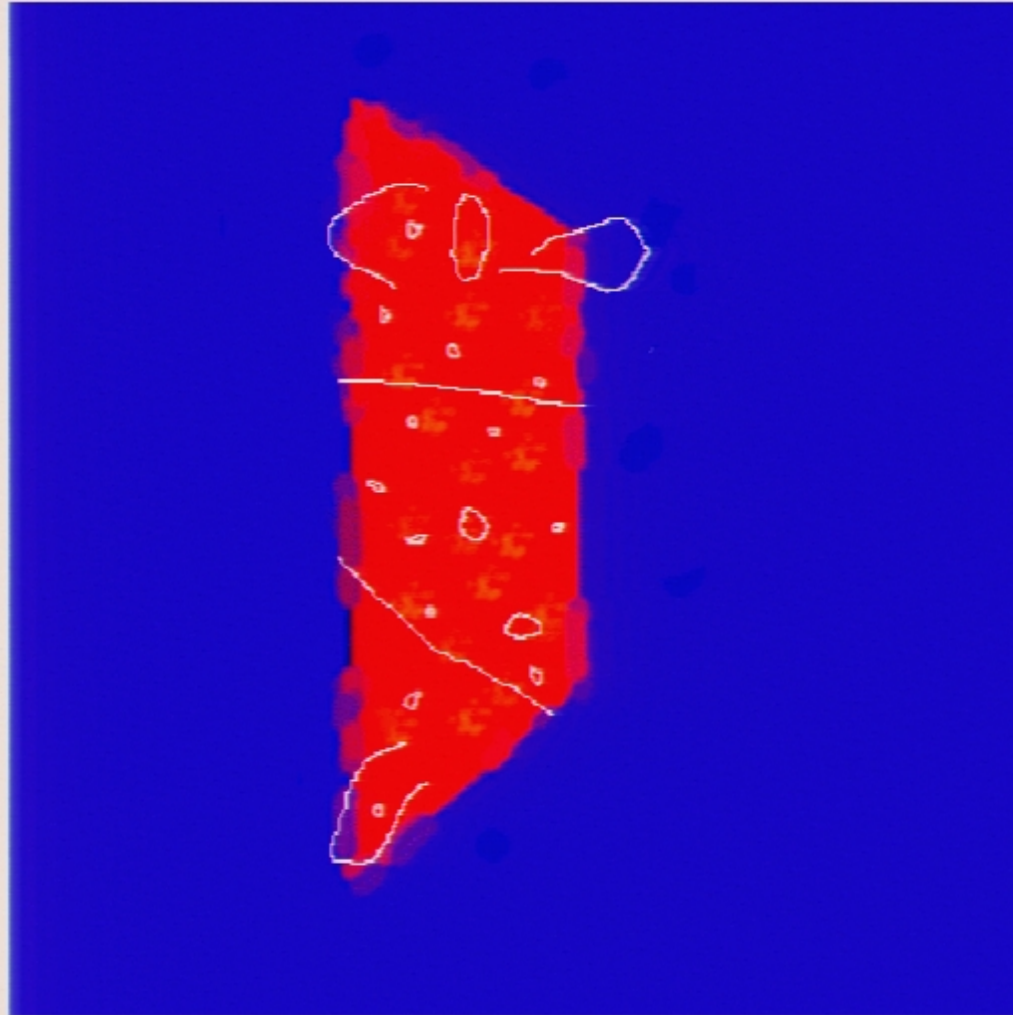
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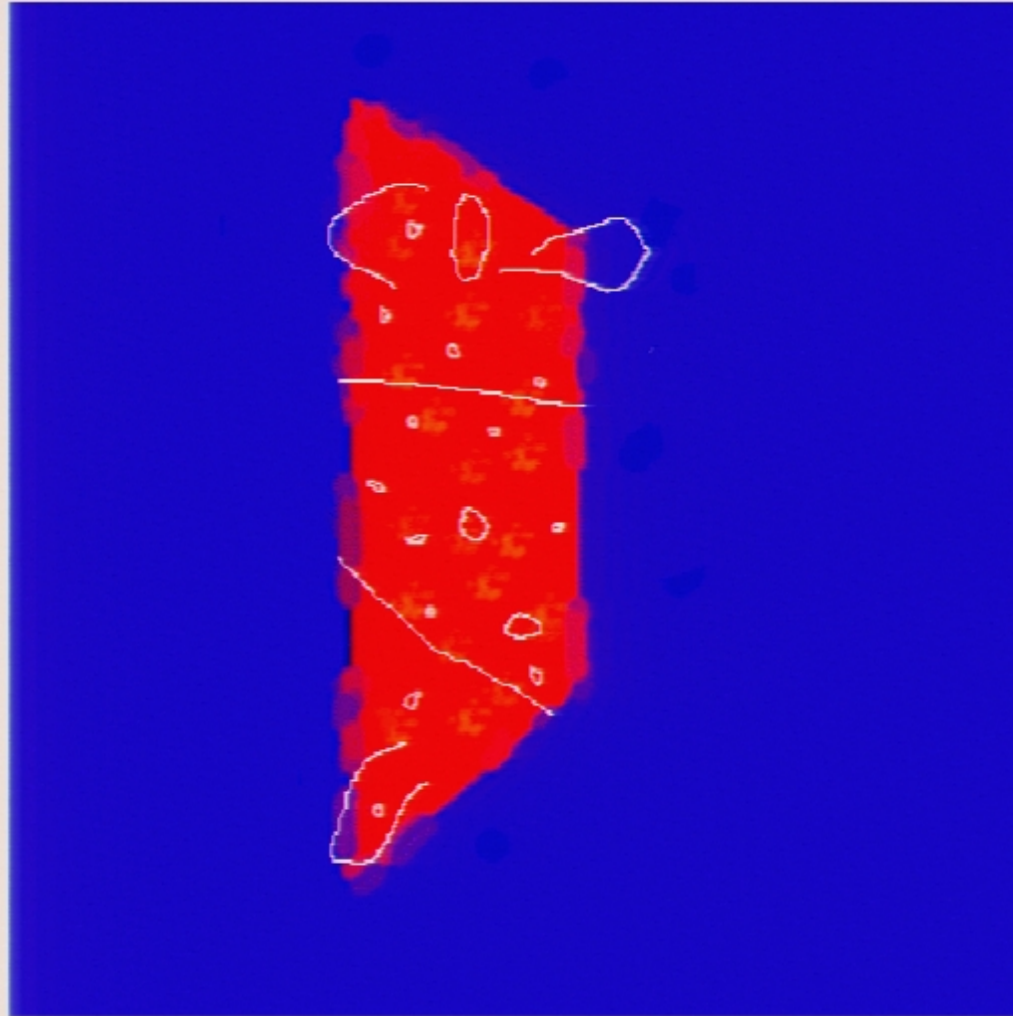
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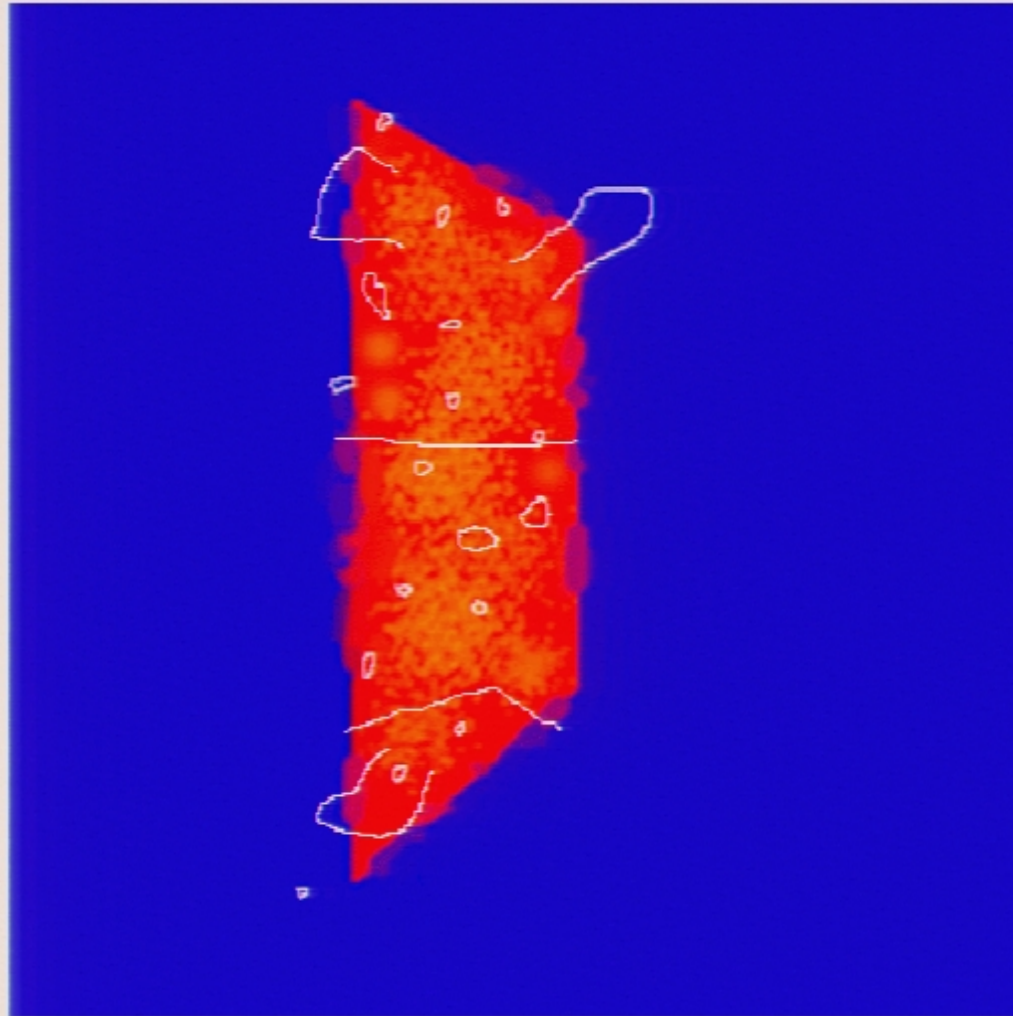
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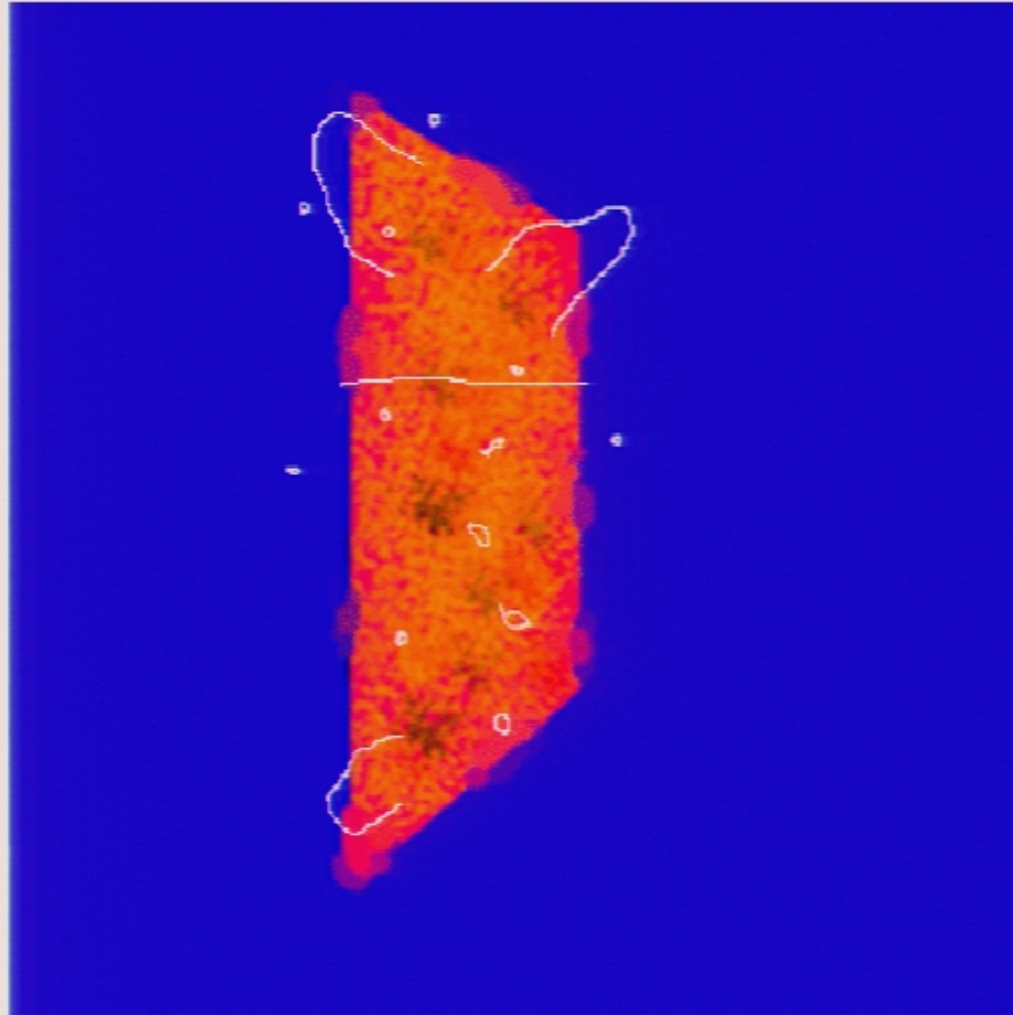
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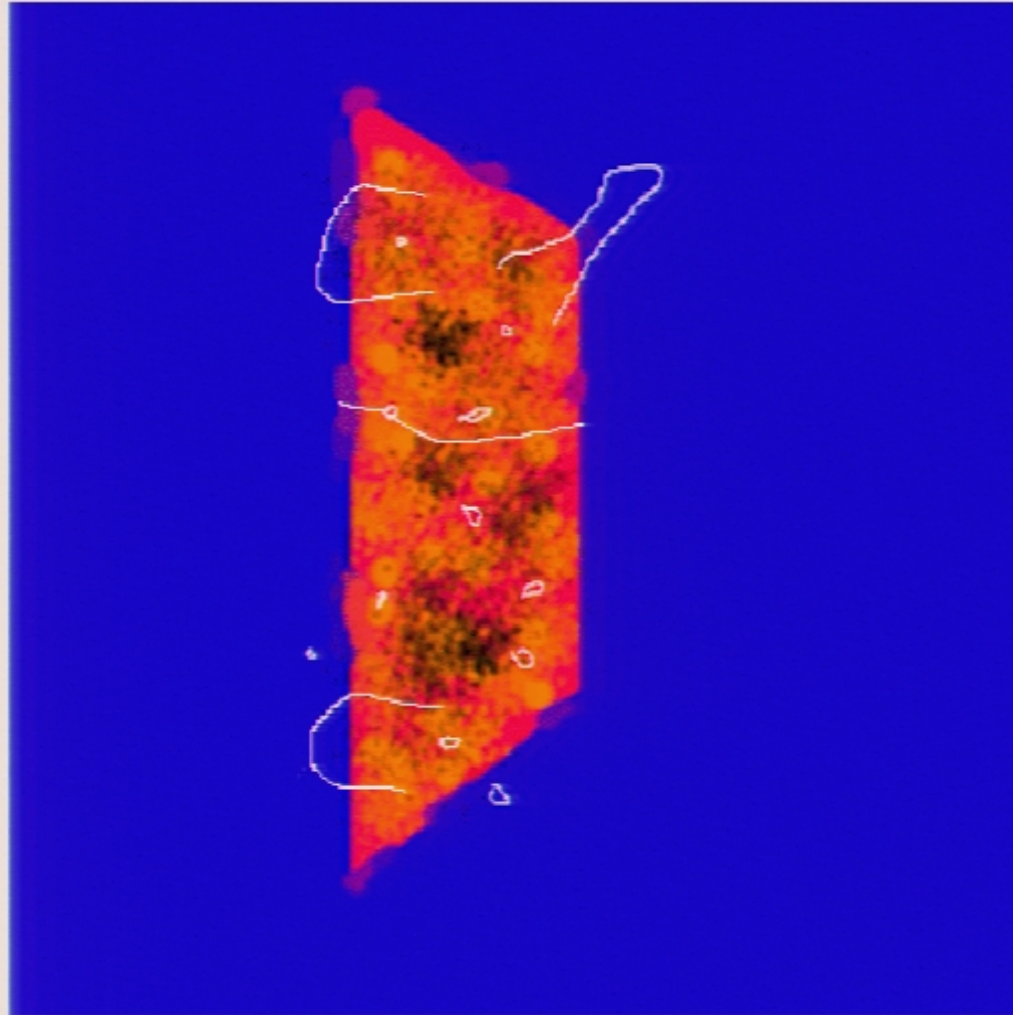
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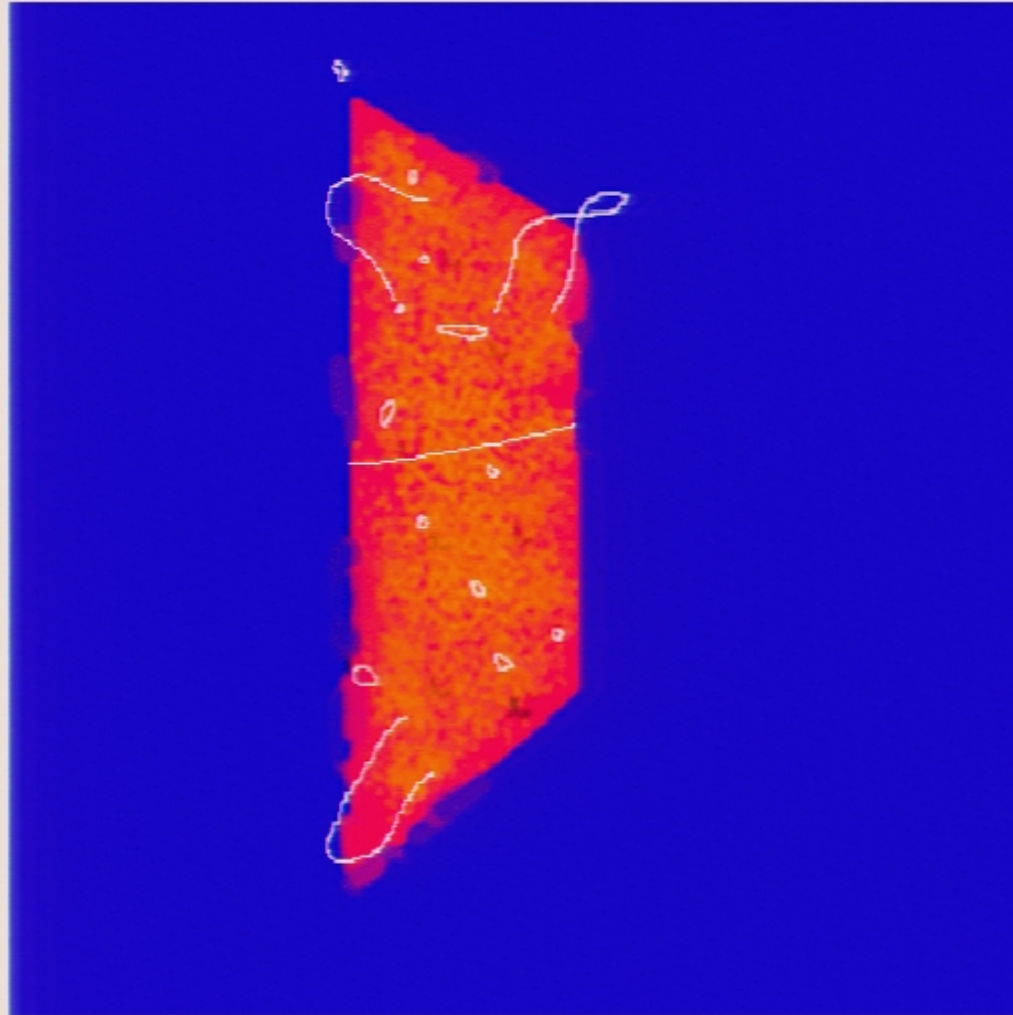
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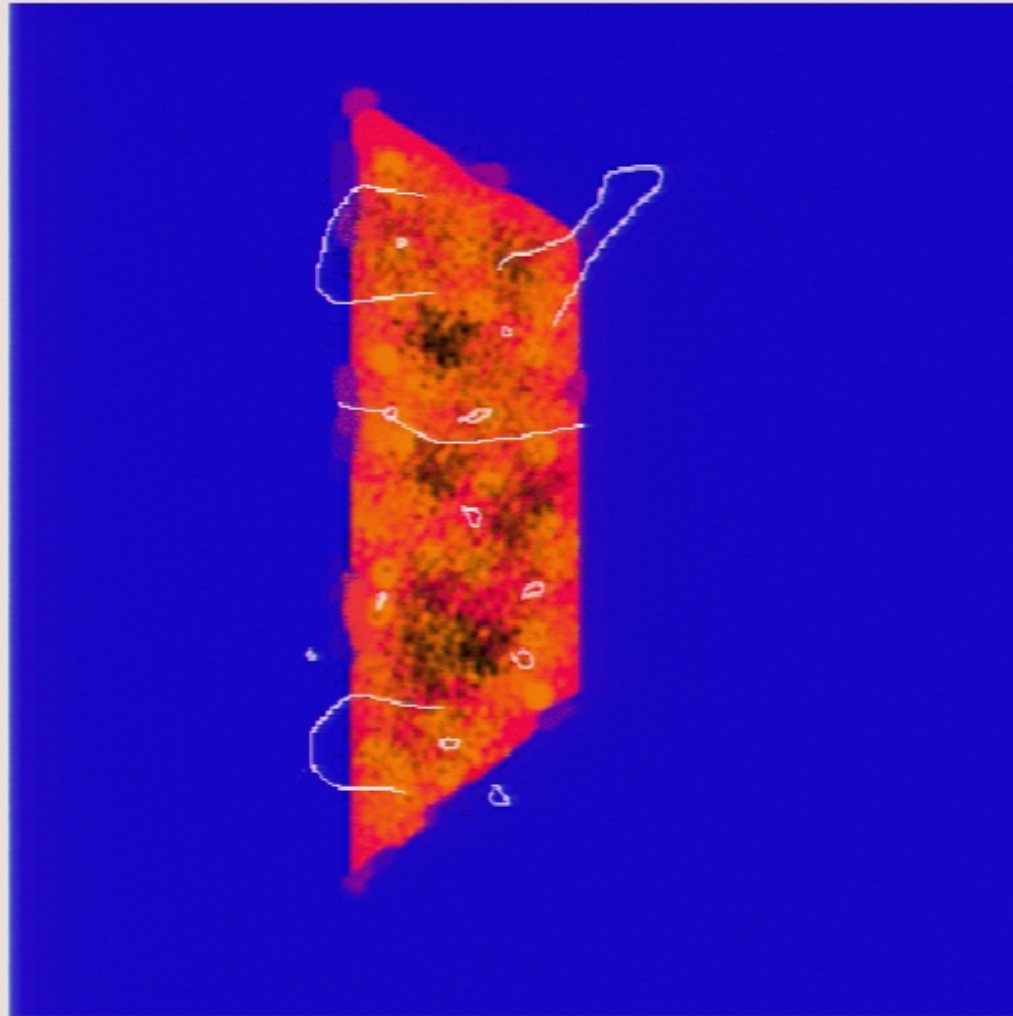
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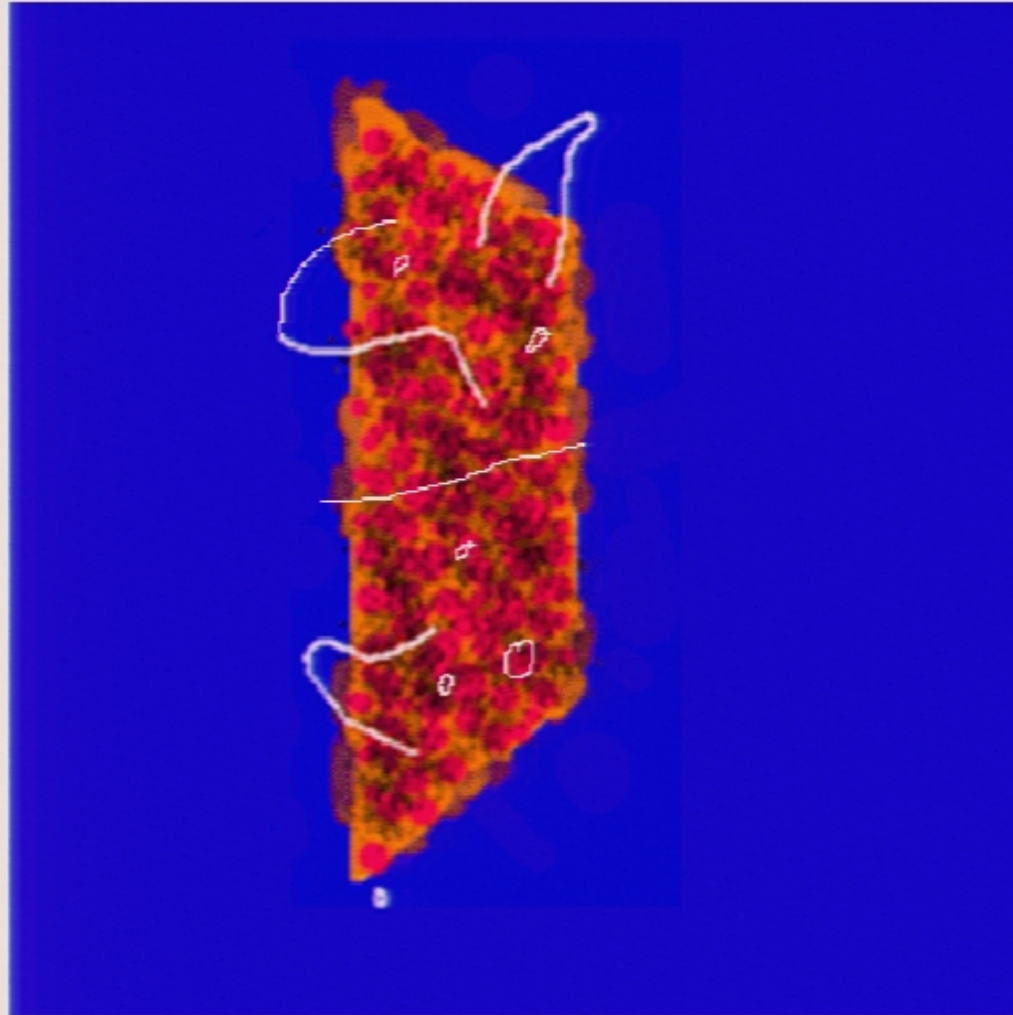
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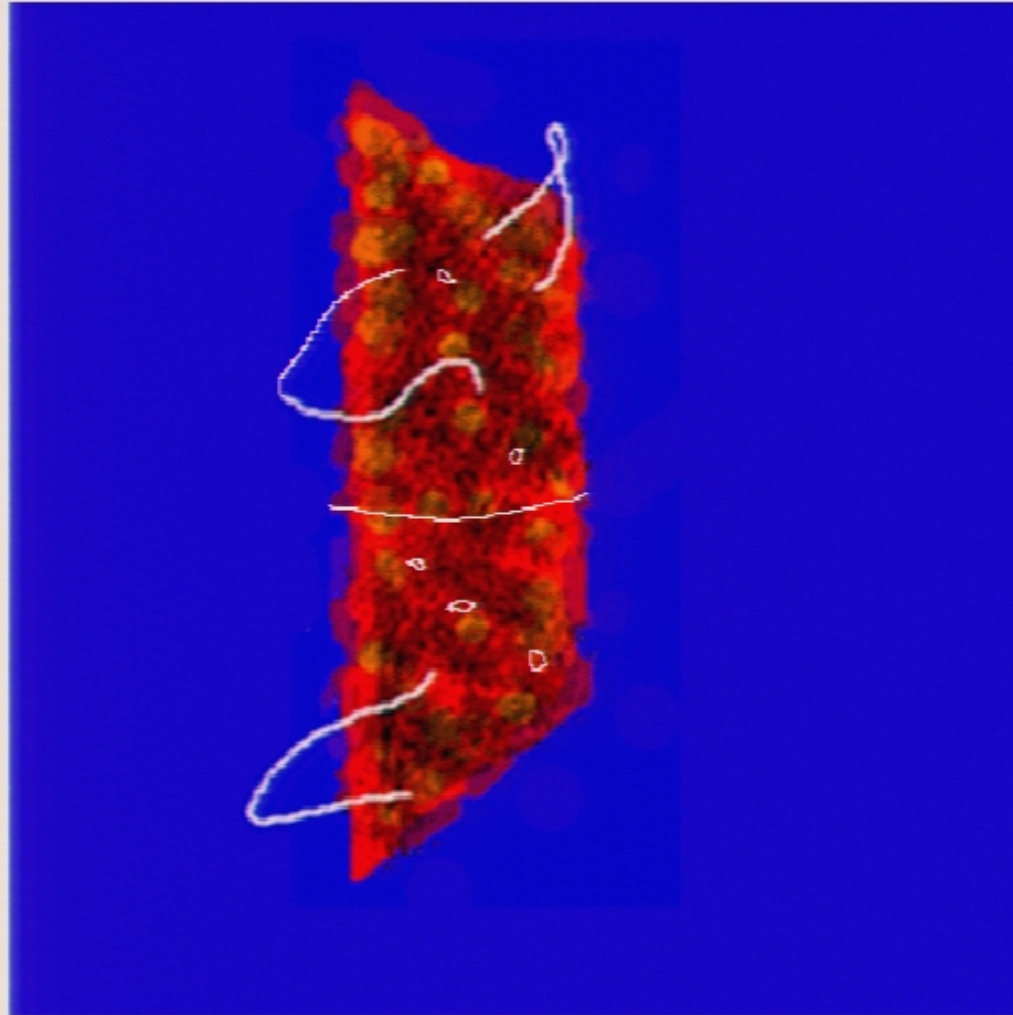
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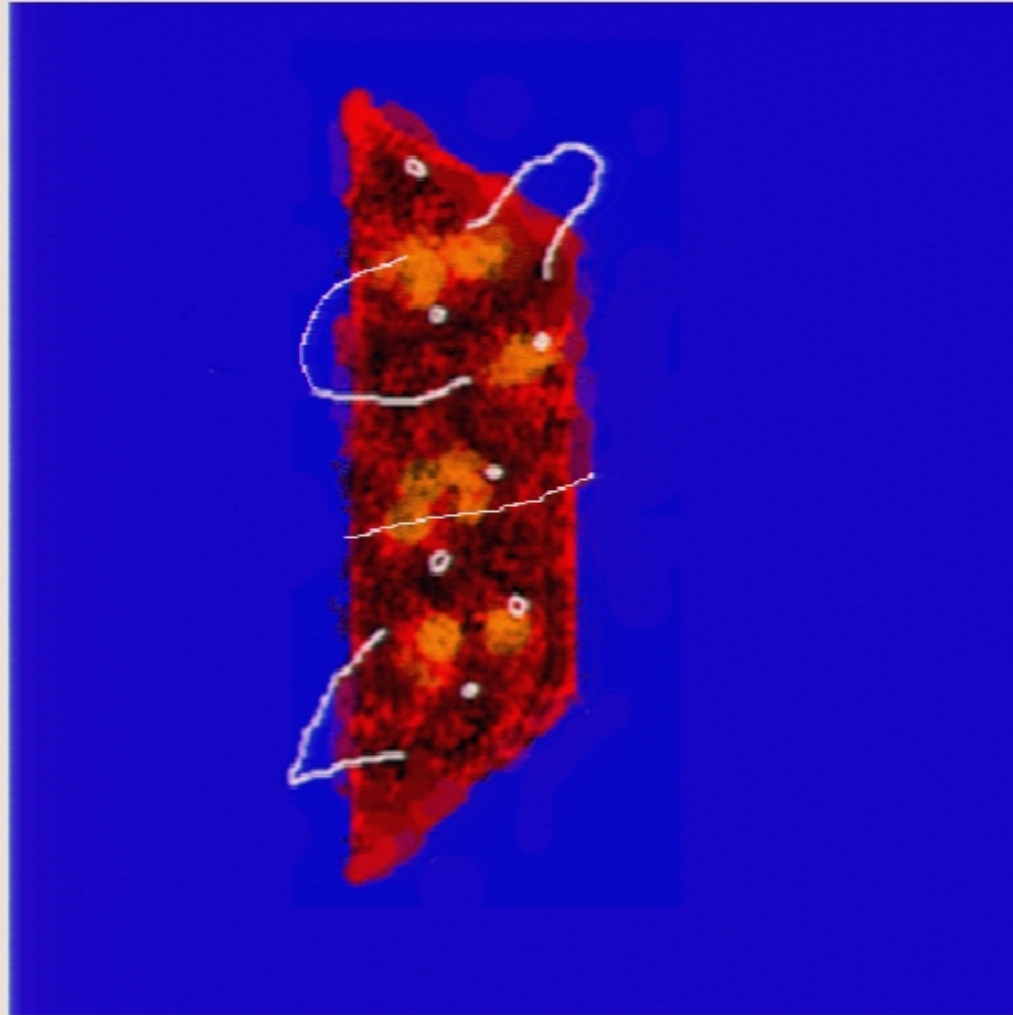
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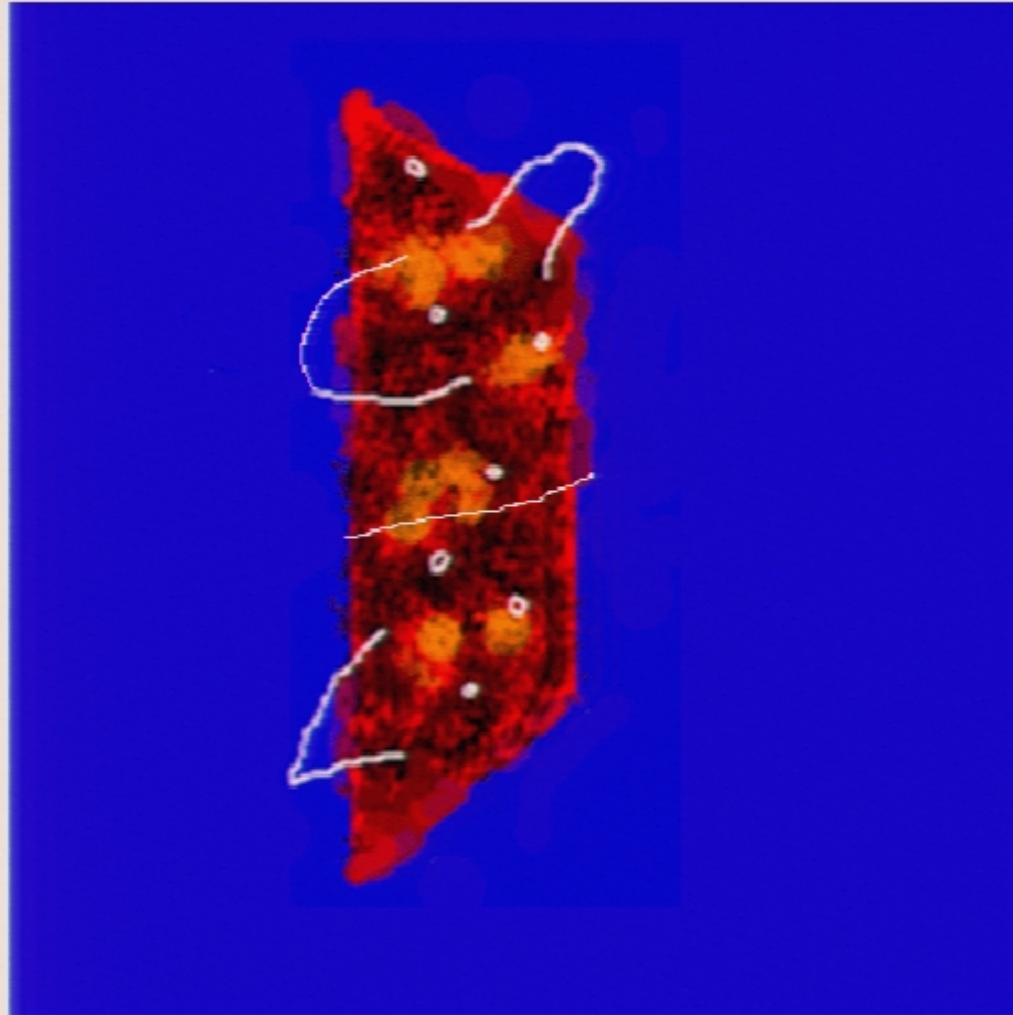
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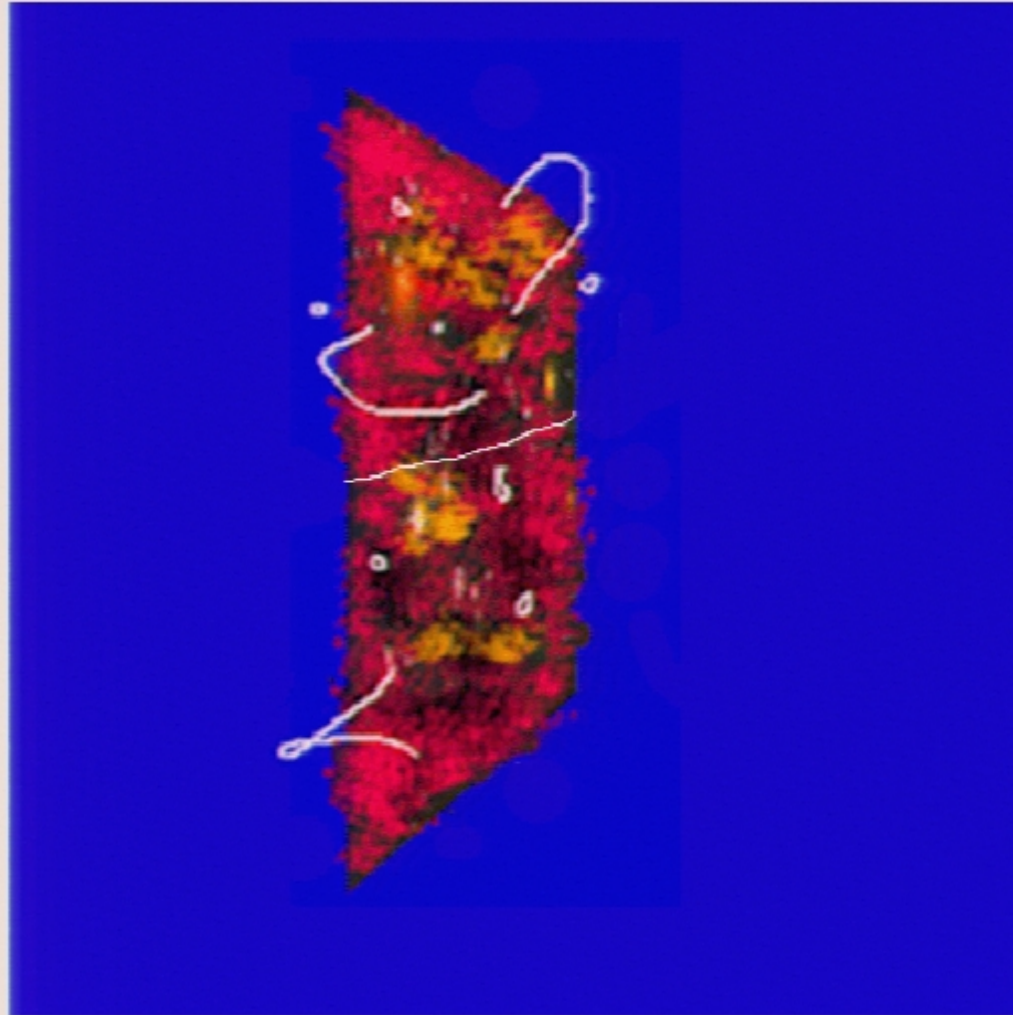
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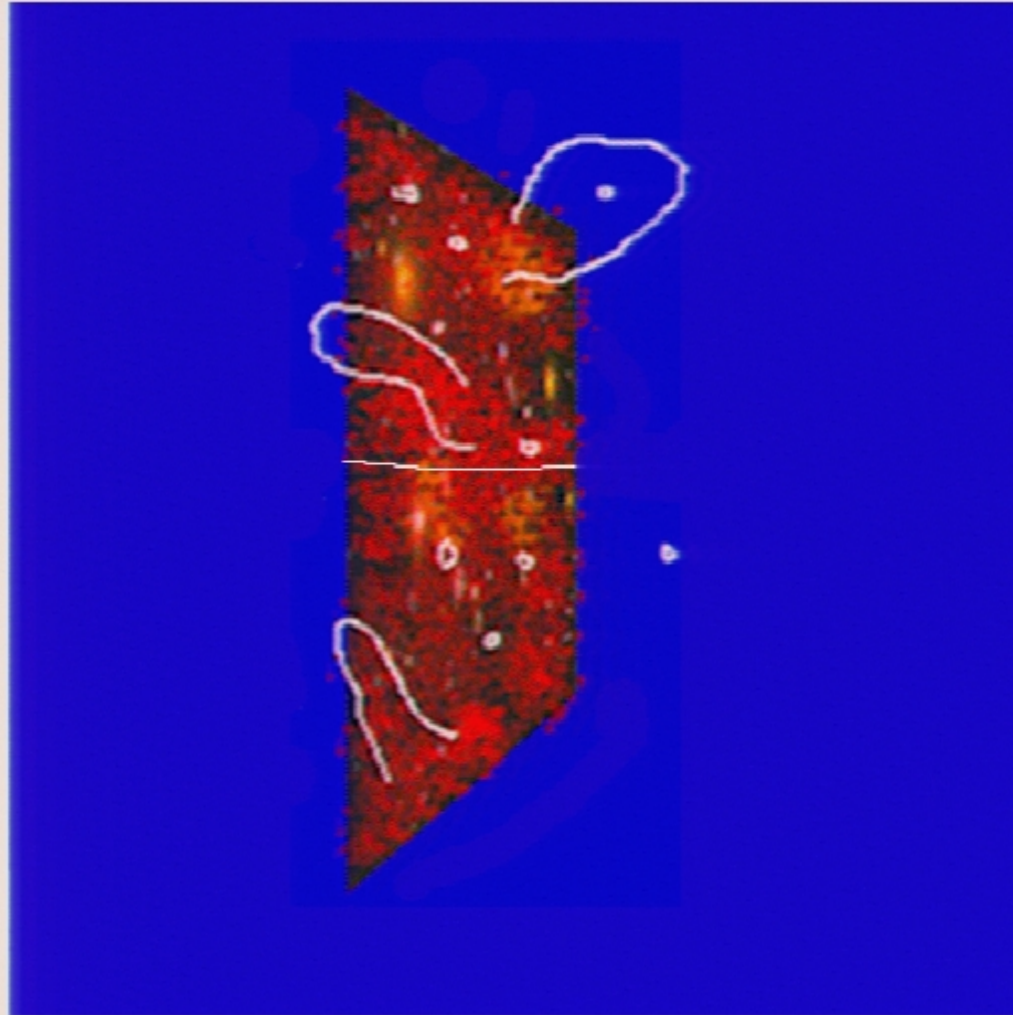
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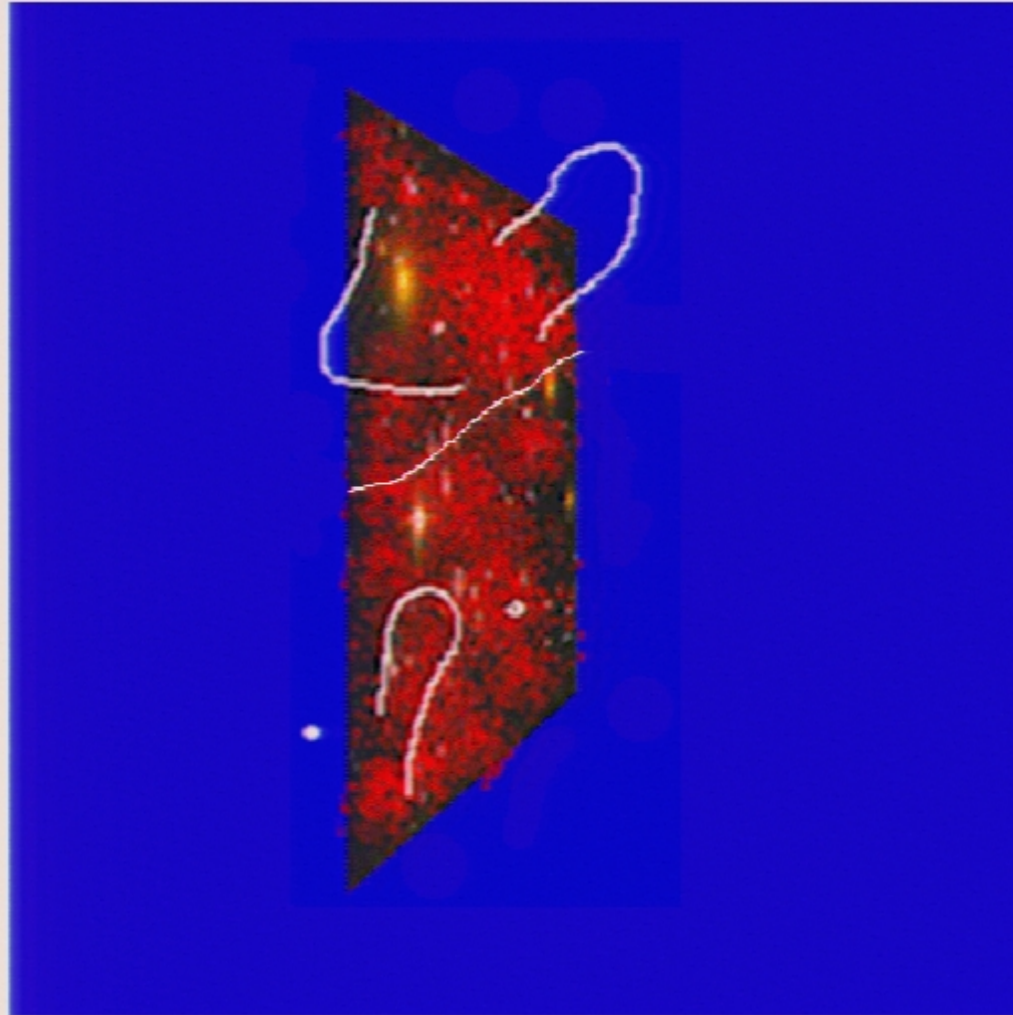
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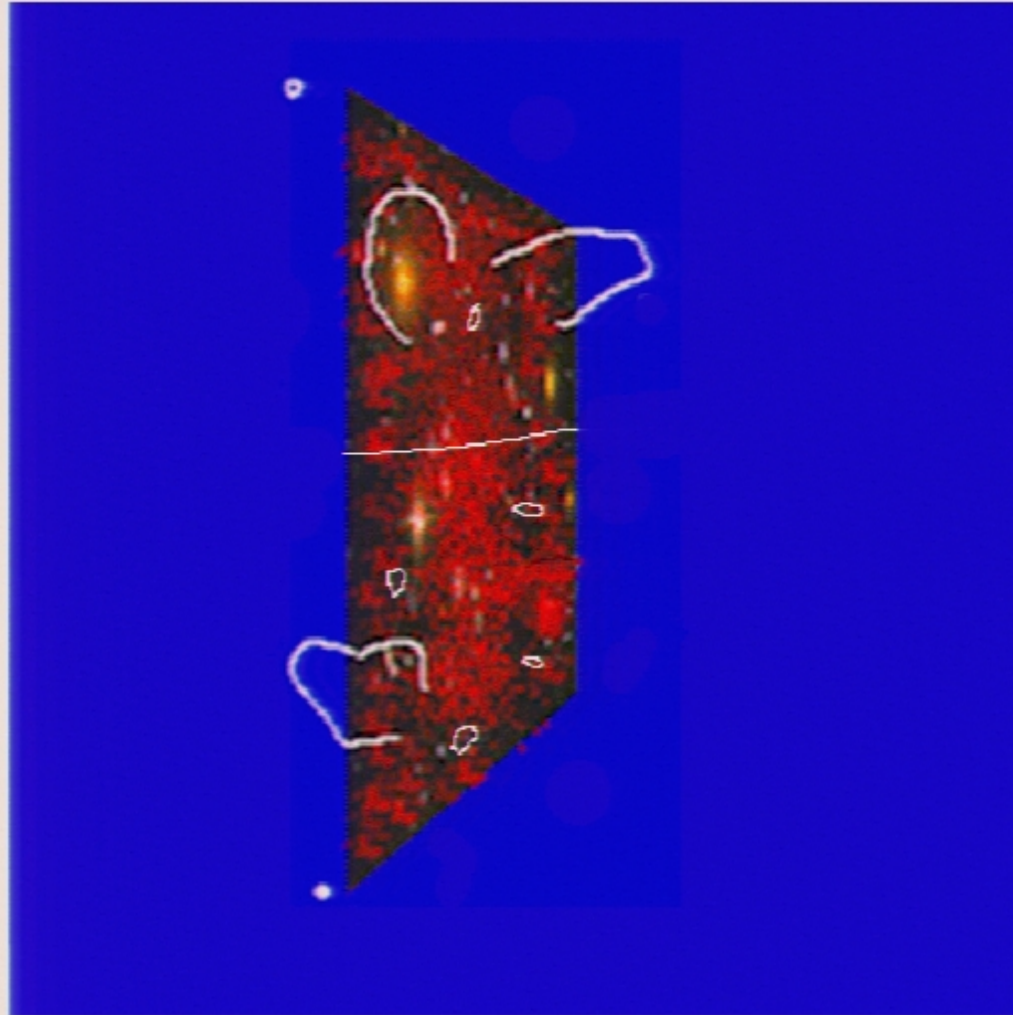
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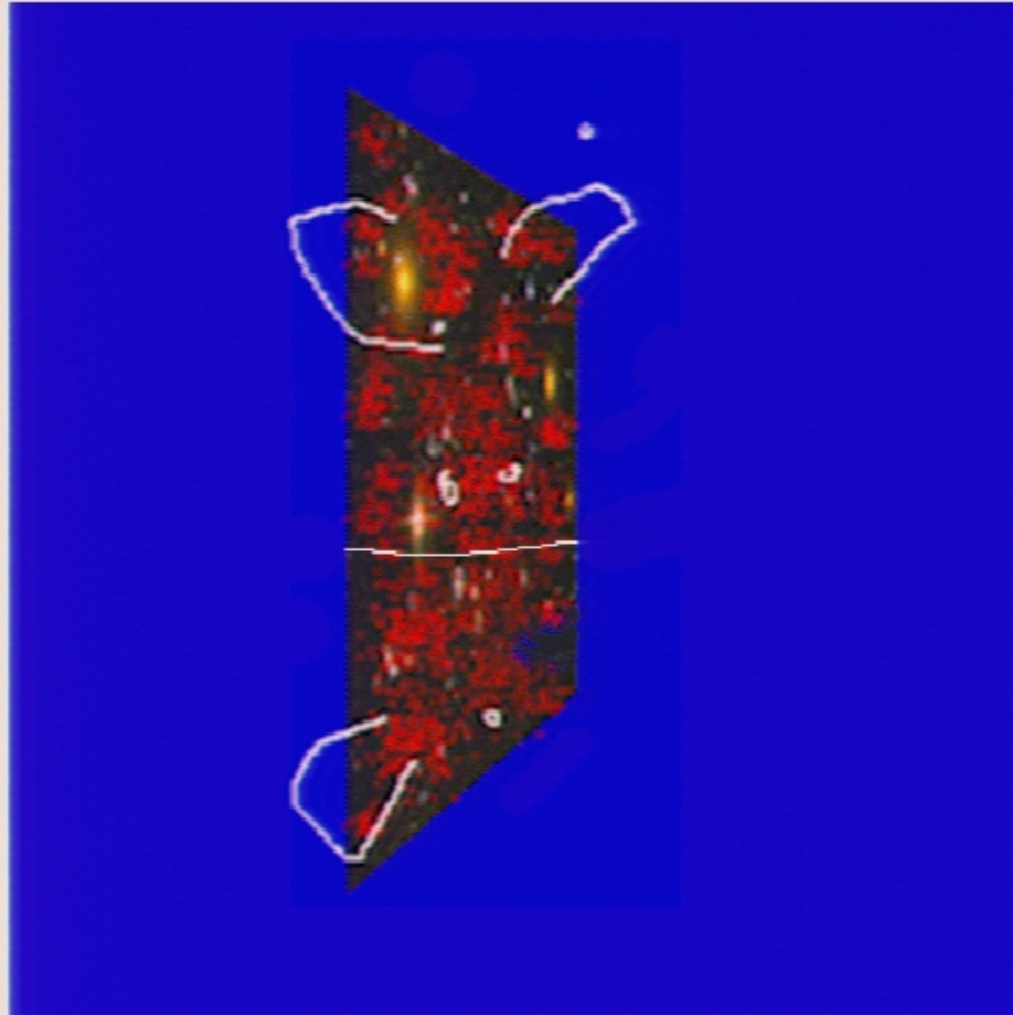
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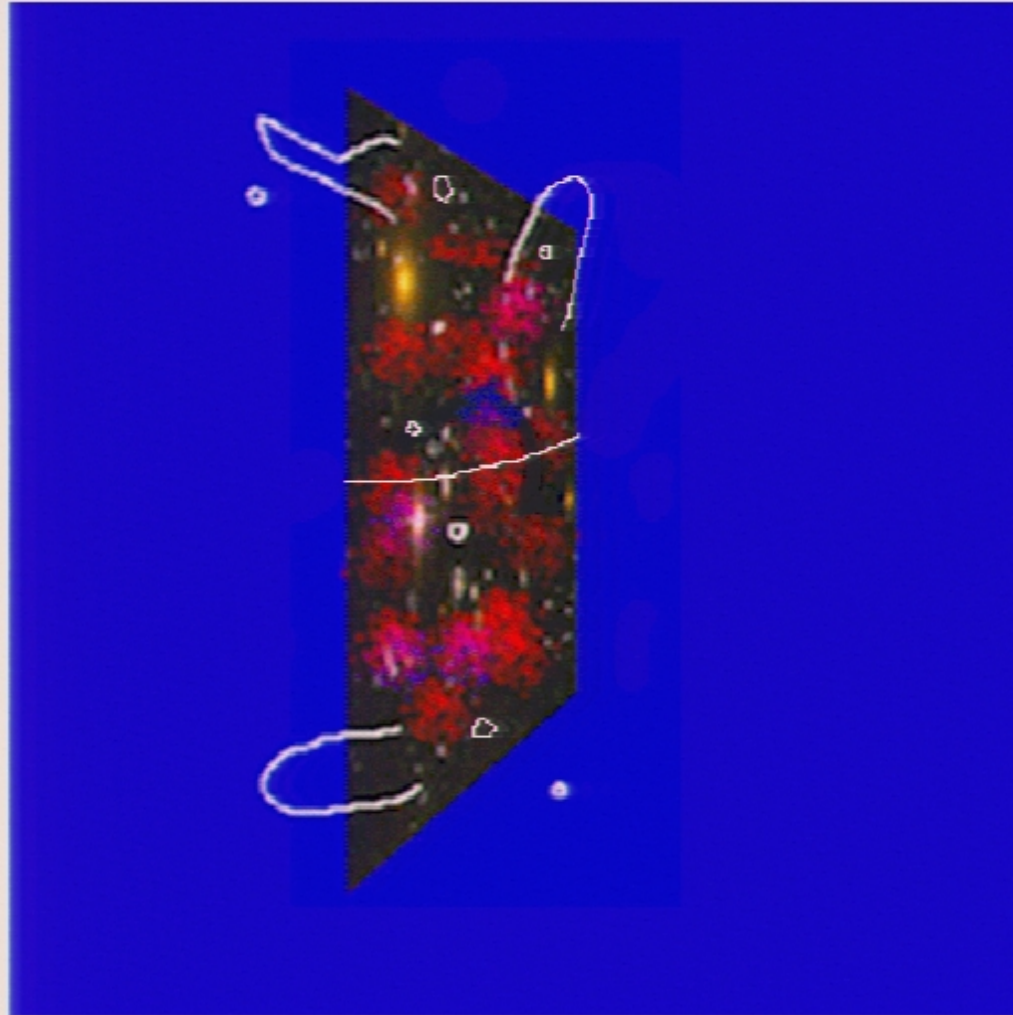
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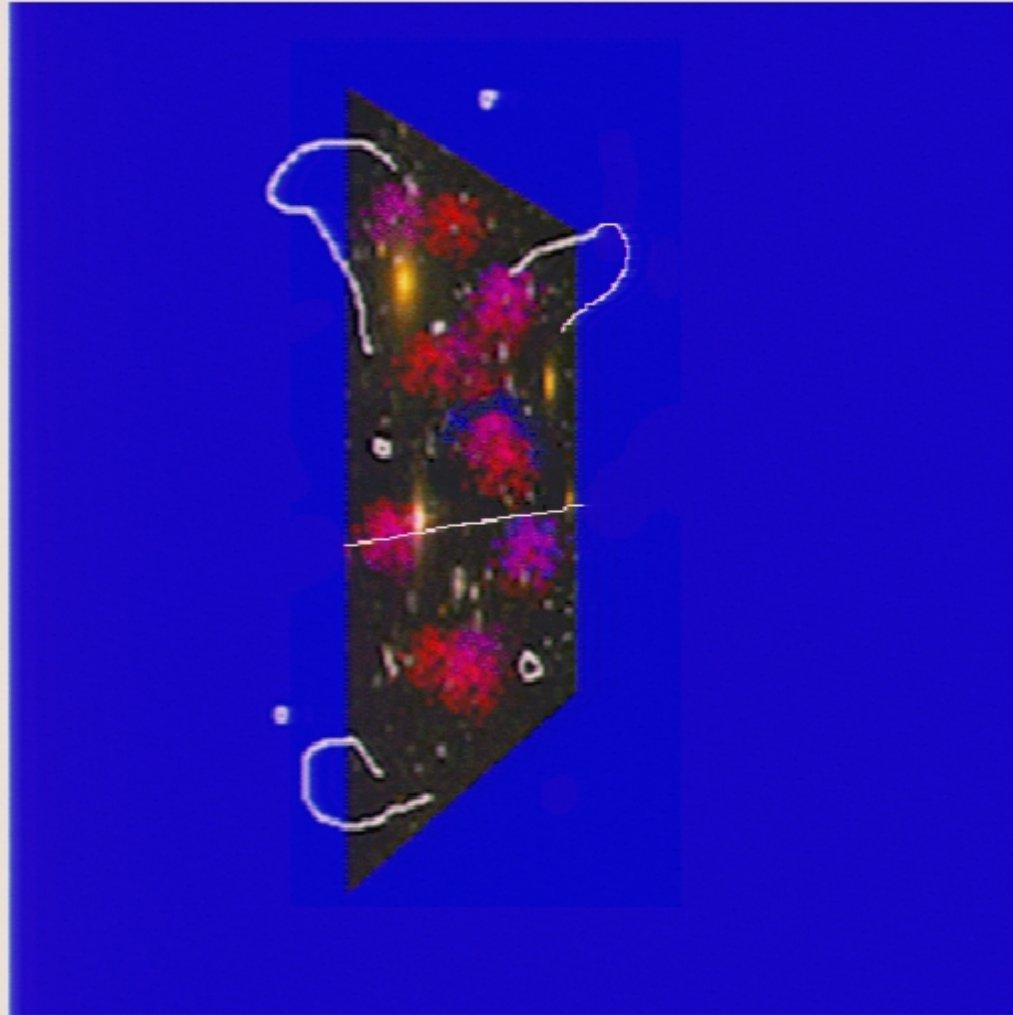
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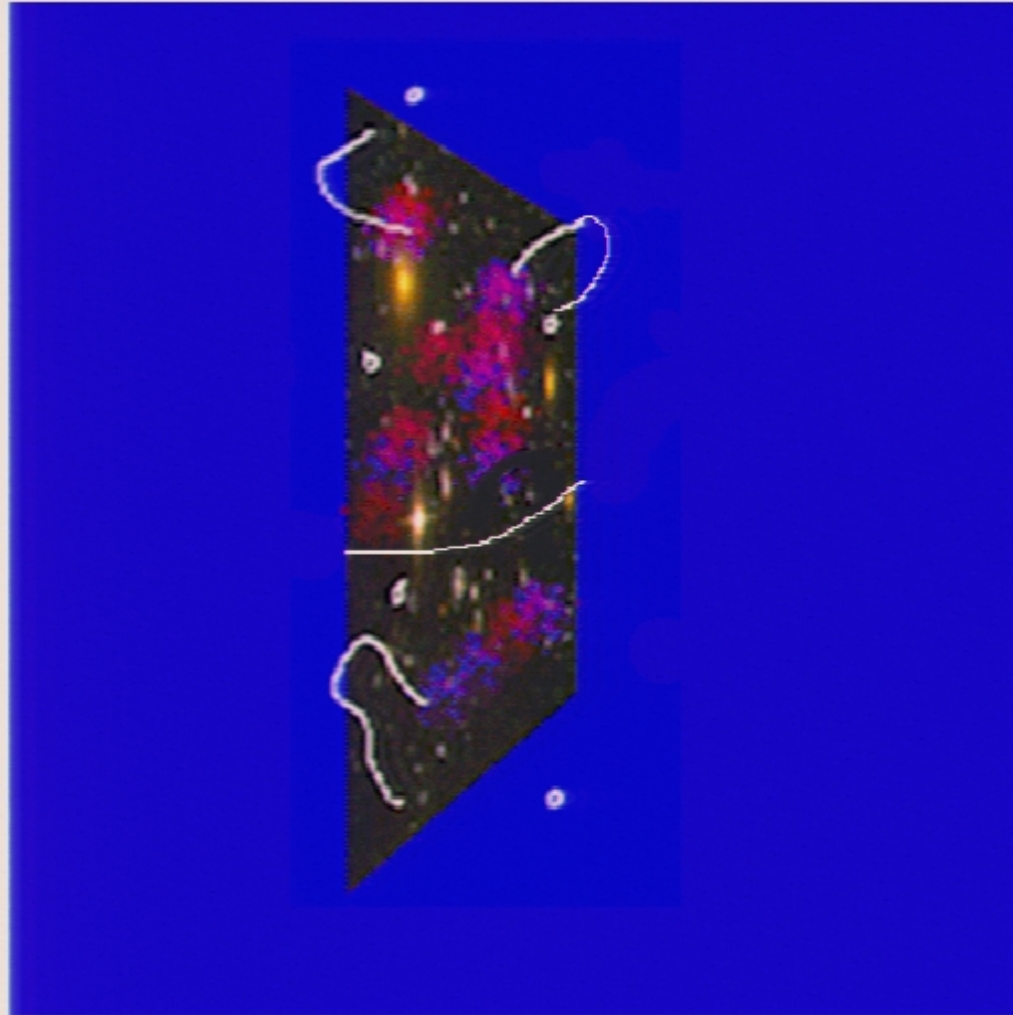
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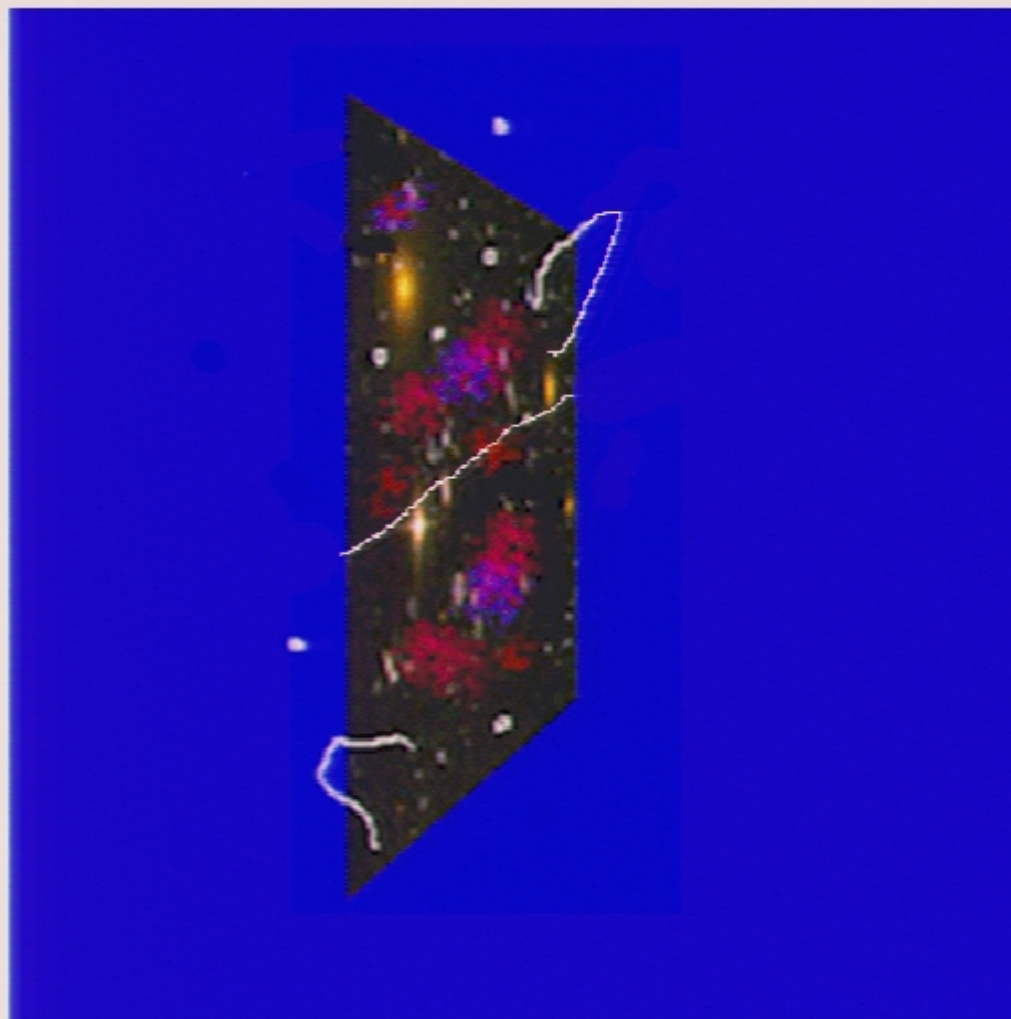
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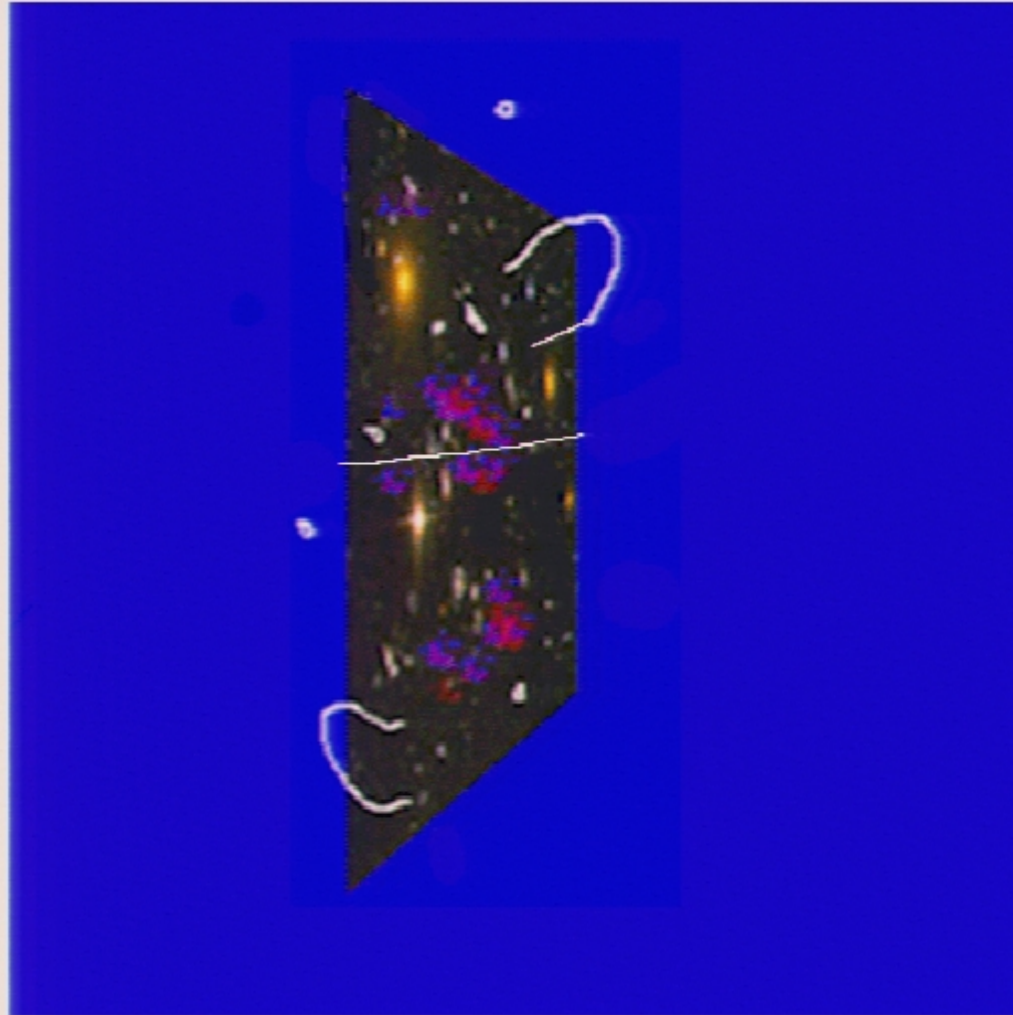
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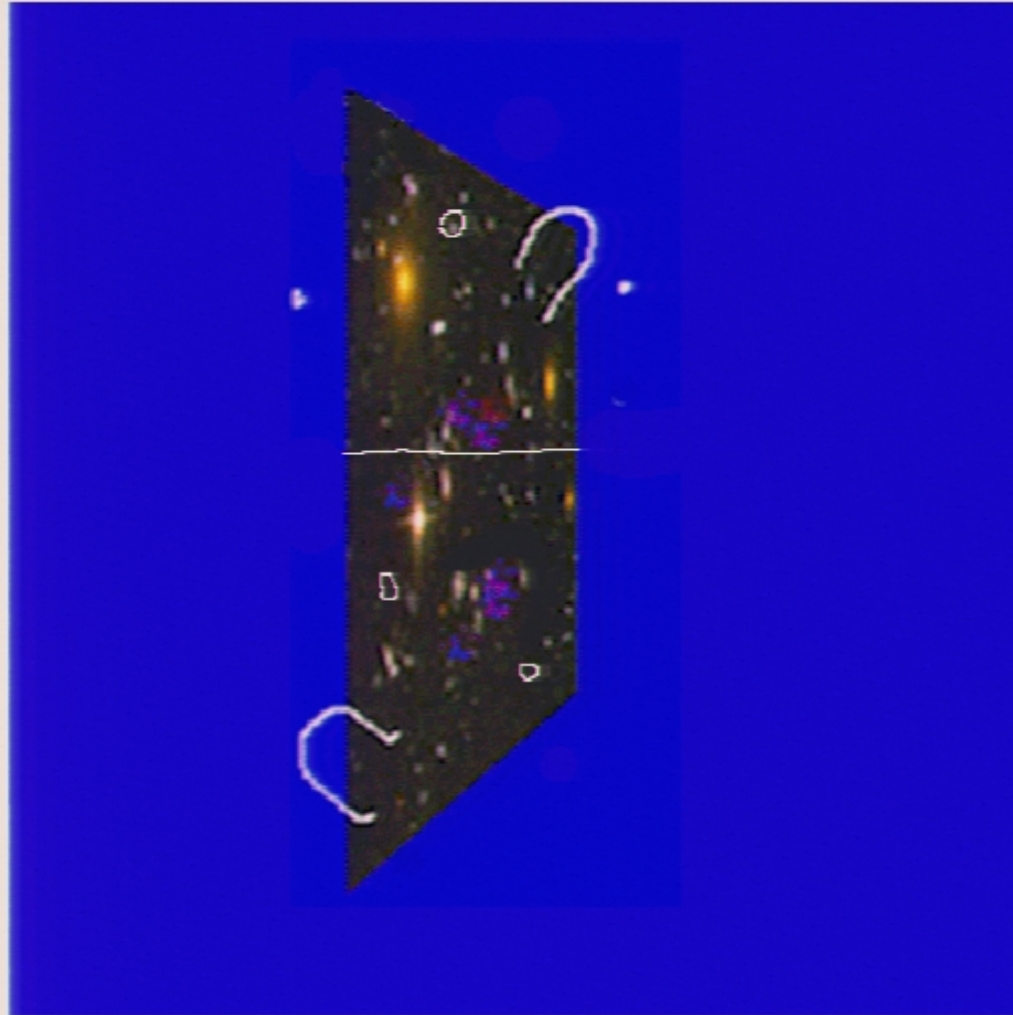
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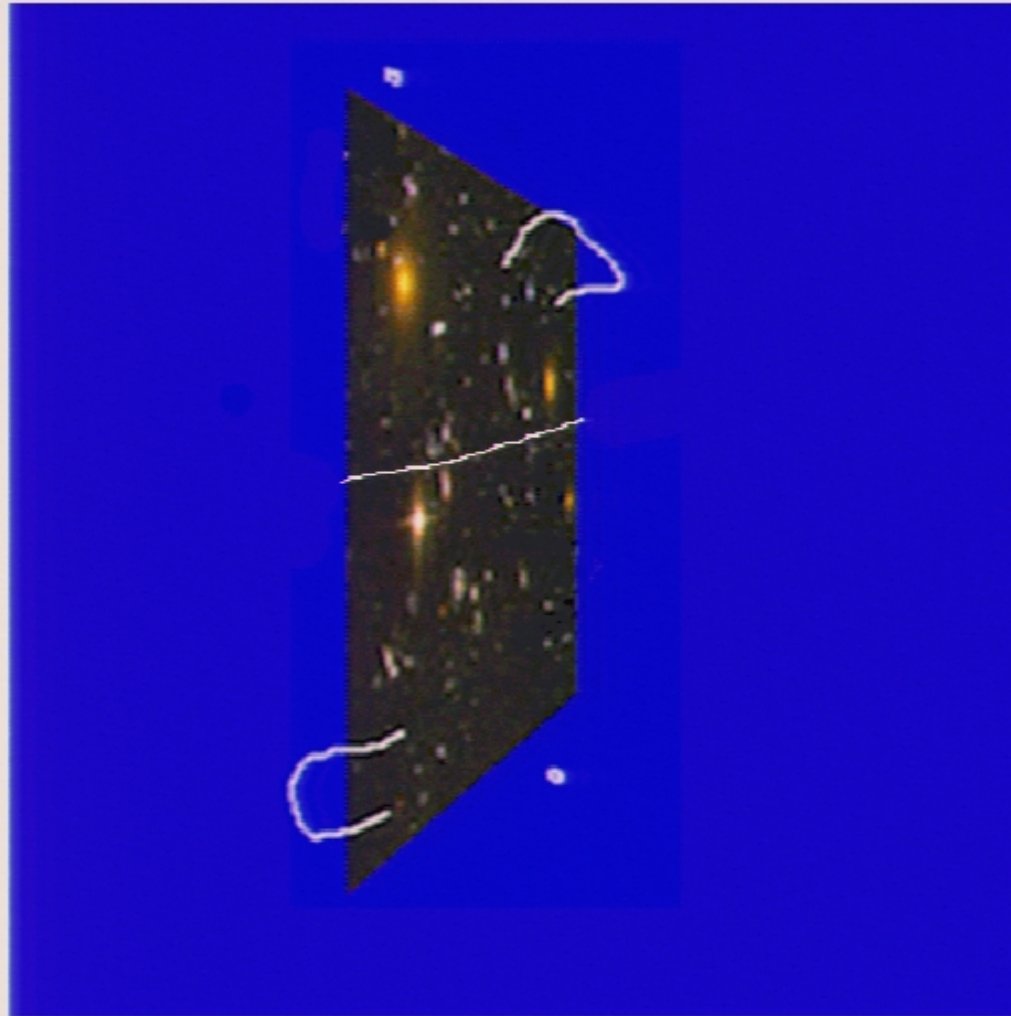
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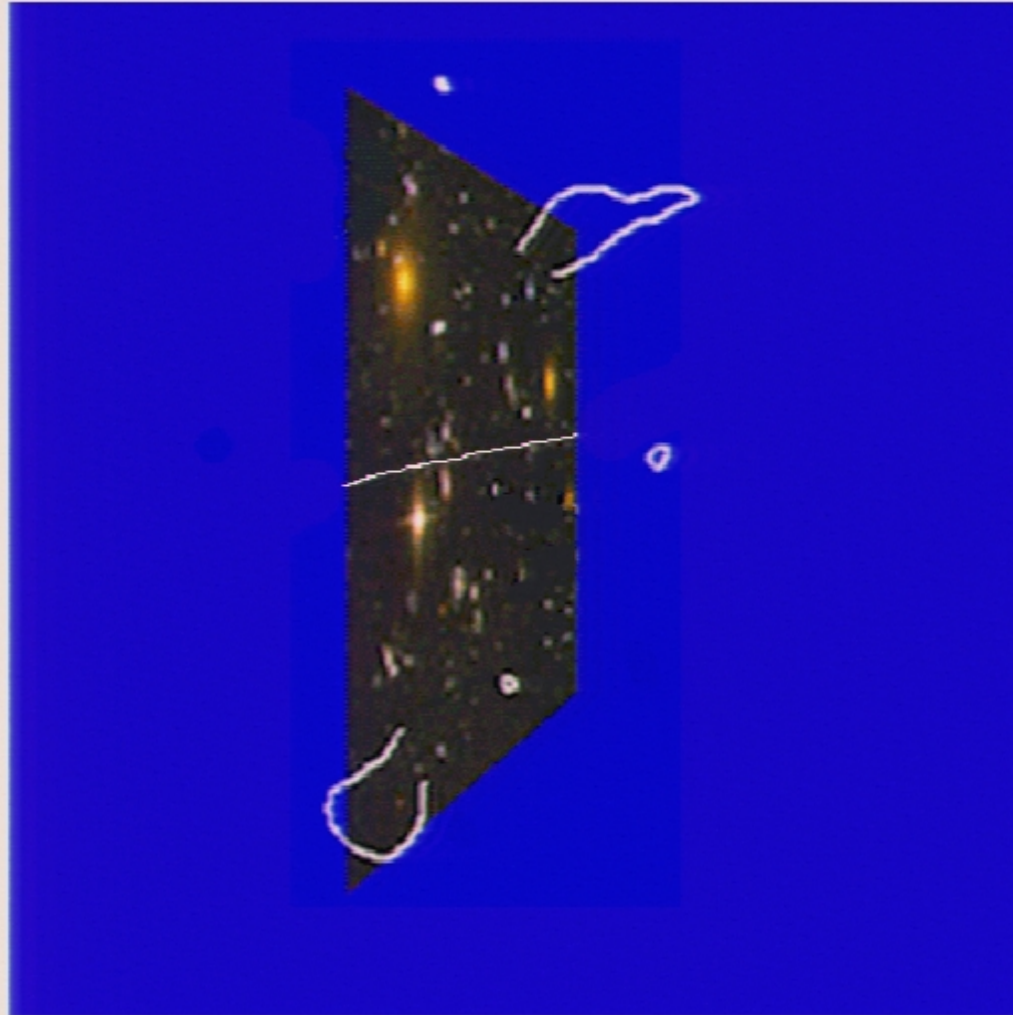
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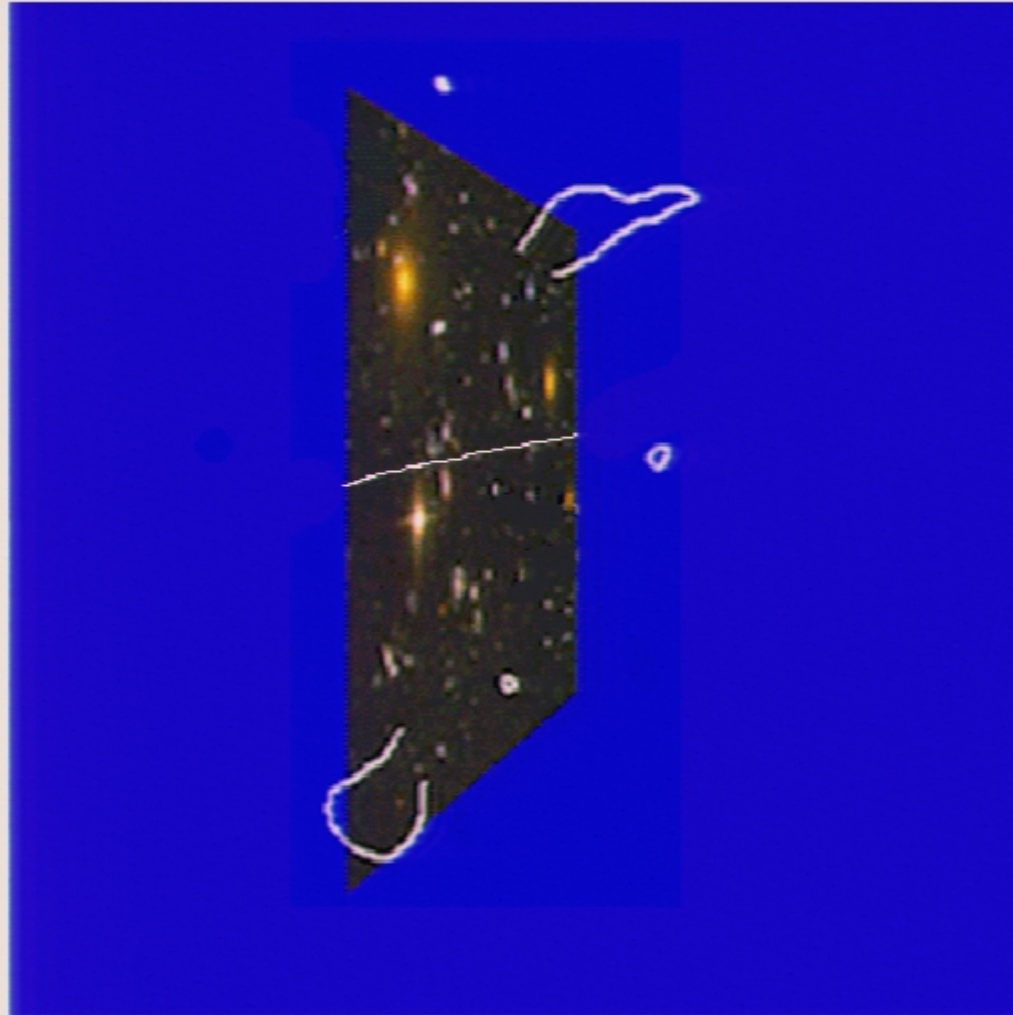
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Cosmic string production towards the end of brane inflation

this follows from superstring theory property
+ the cosmological condition

- Monopoles : density $\sim a^{-3}$ Disastrous
- Domain walls : density $\sim 1/a$ Disastrous
- cosmic strings : density $\sim a^{-2}$
interaction cuts it down to a^{-4} during radiation

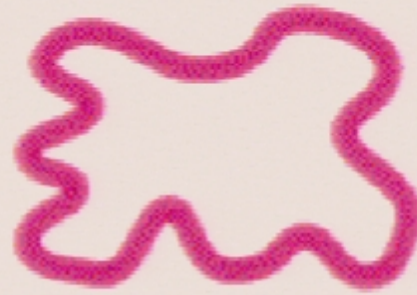
N. Jones, H. Stoica, H.T., hep-th/0203163

S. Sarangi, H.T., hep-th/0204074

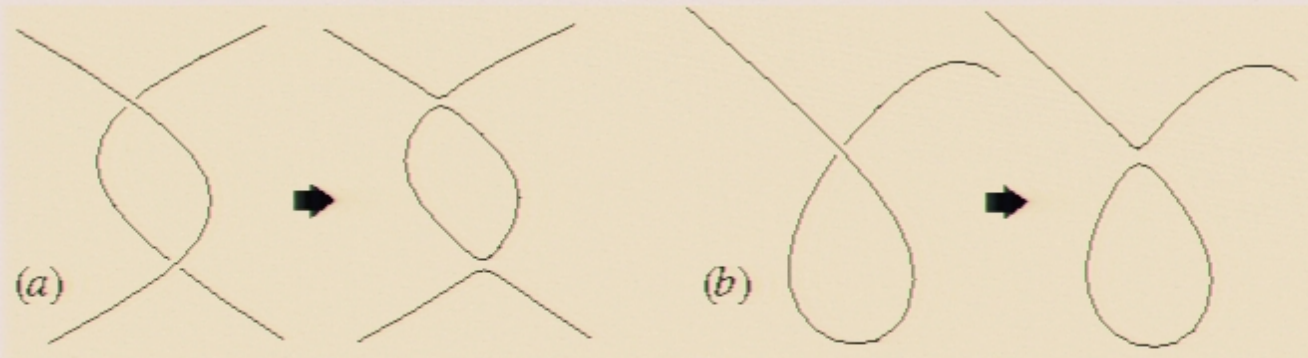
History of cosmic strings

- Early 1980s : proposed to generate density perturbation as seed for structure formation; as an alternative to inflation; Kibble, Zeldovich, Vilenkin, Turok, Shellard,
- In 1985, Witten attempted to identify the cosmic strings as fundamental strings in superstring (heterotic) theory. He pointed out a number of problems with this picture: tension too big, no production and stability.
- In early 1990s, COBE data disfavors cosmic strings.
- By late 1990s, CMB data supports inflation and ruled out cosmic string as an explanation to the density perturbation.
- In 1995, Polchinski and others pointed out the presence of D-branes in string theory.
- Brane world/brane inflation leads to a revival of cosmic strings. Realistic realization of brane world/inflation are known : KKLT and KKLMNT and other scenarios.

Cosmic strings

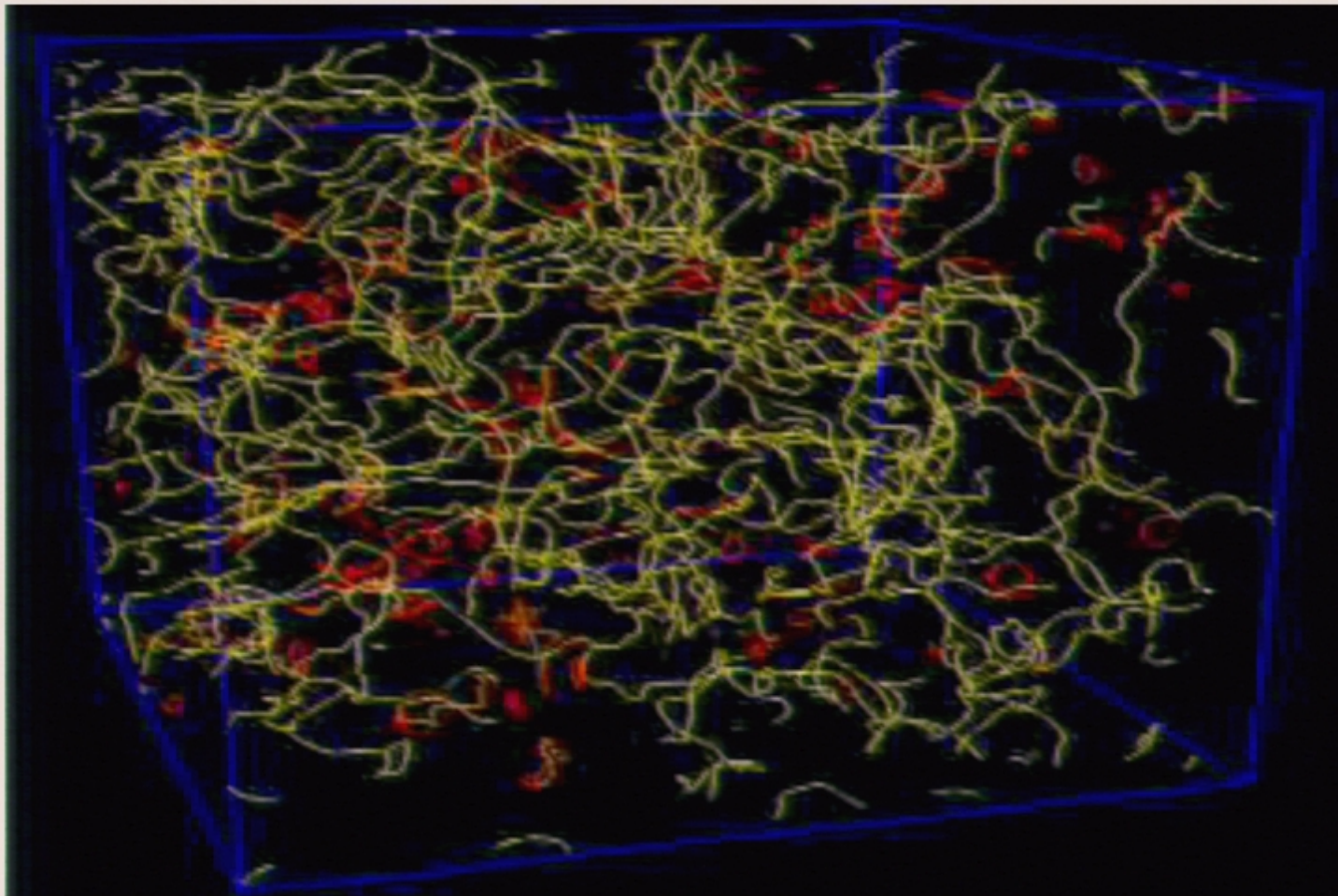


- Cosmic string interactions



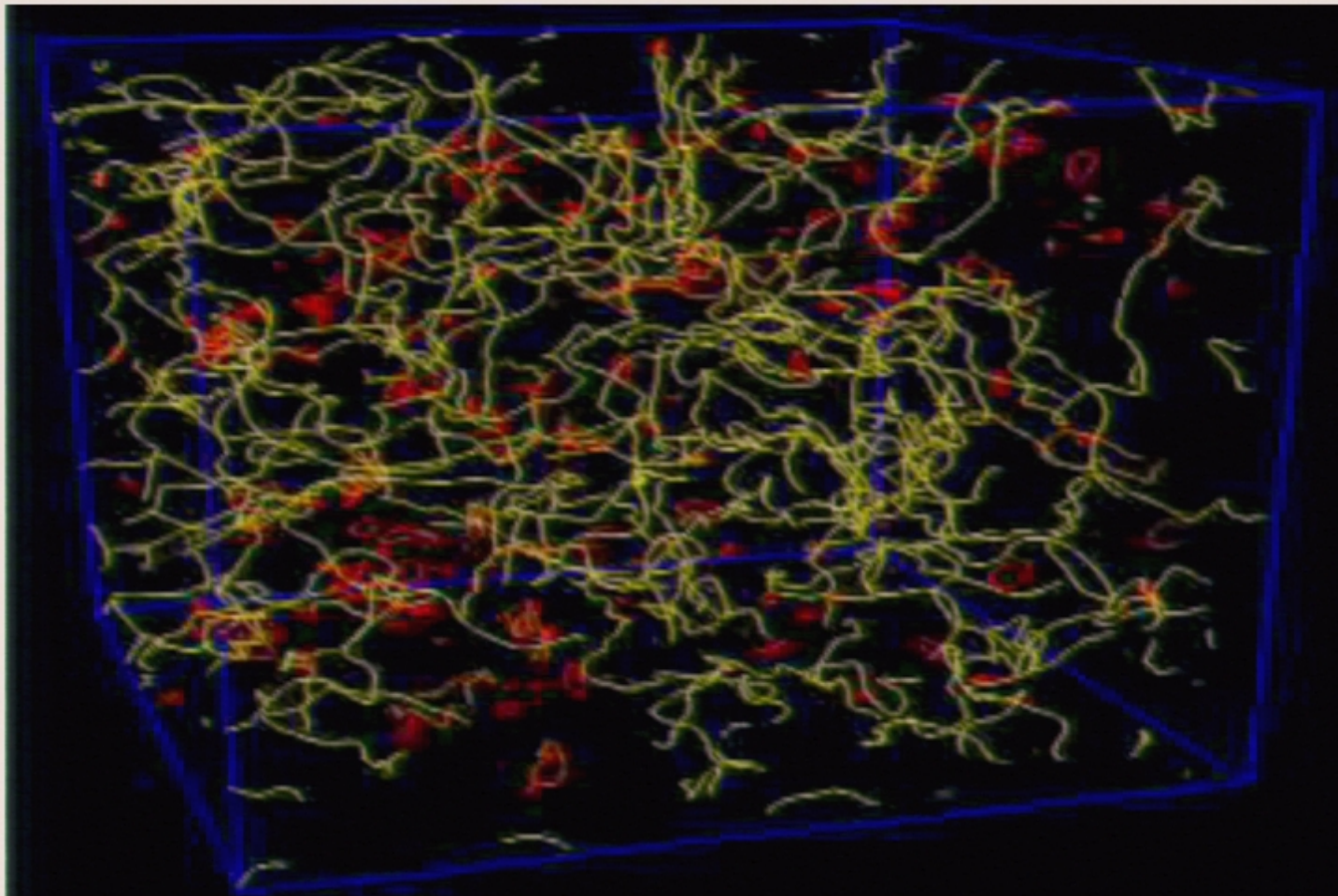
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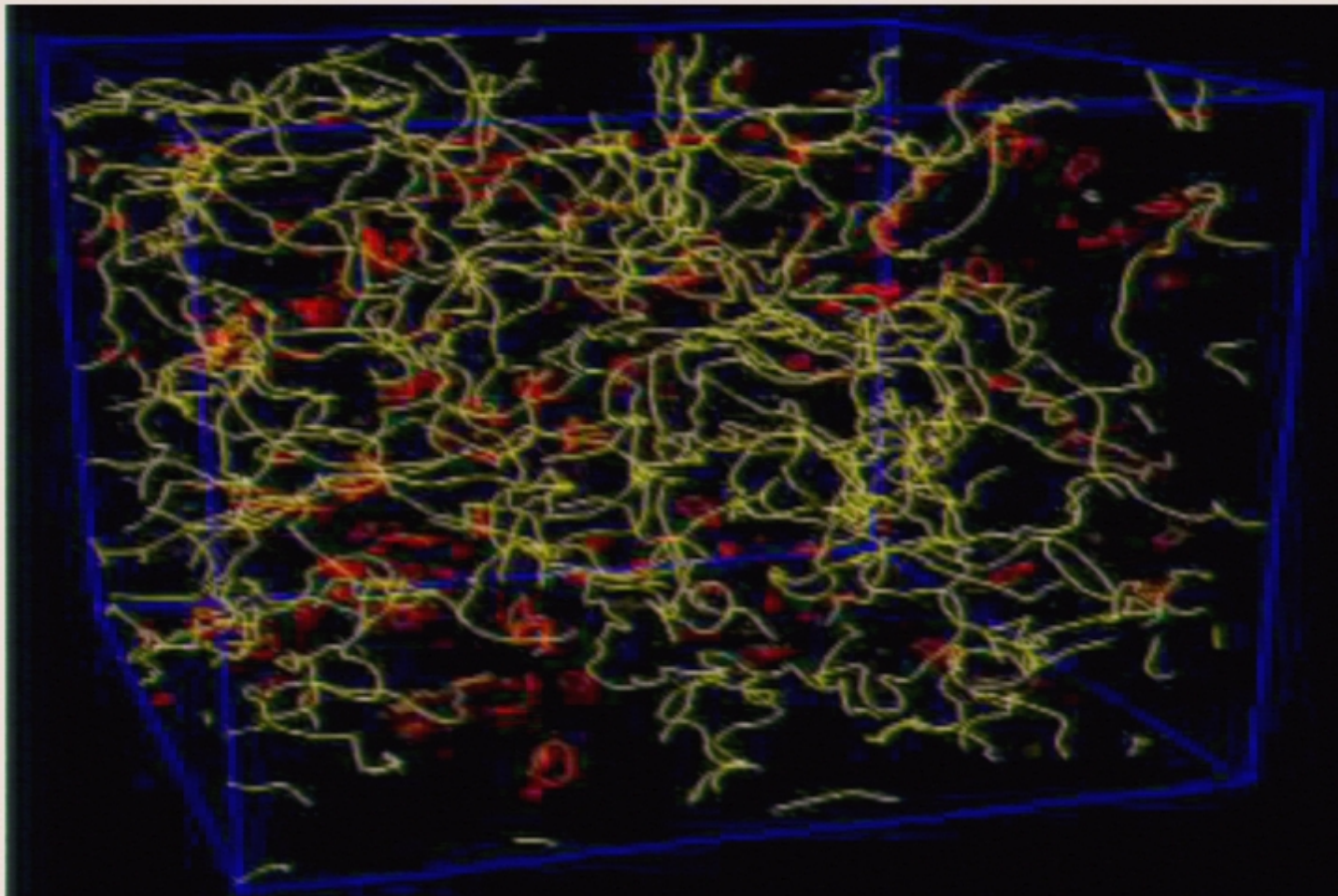
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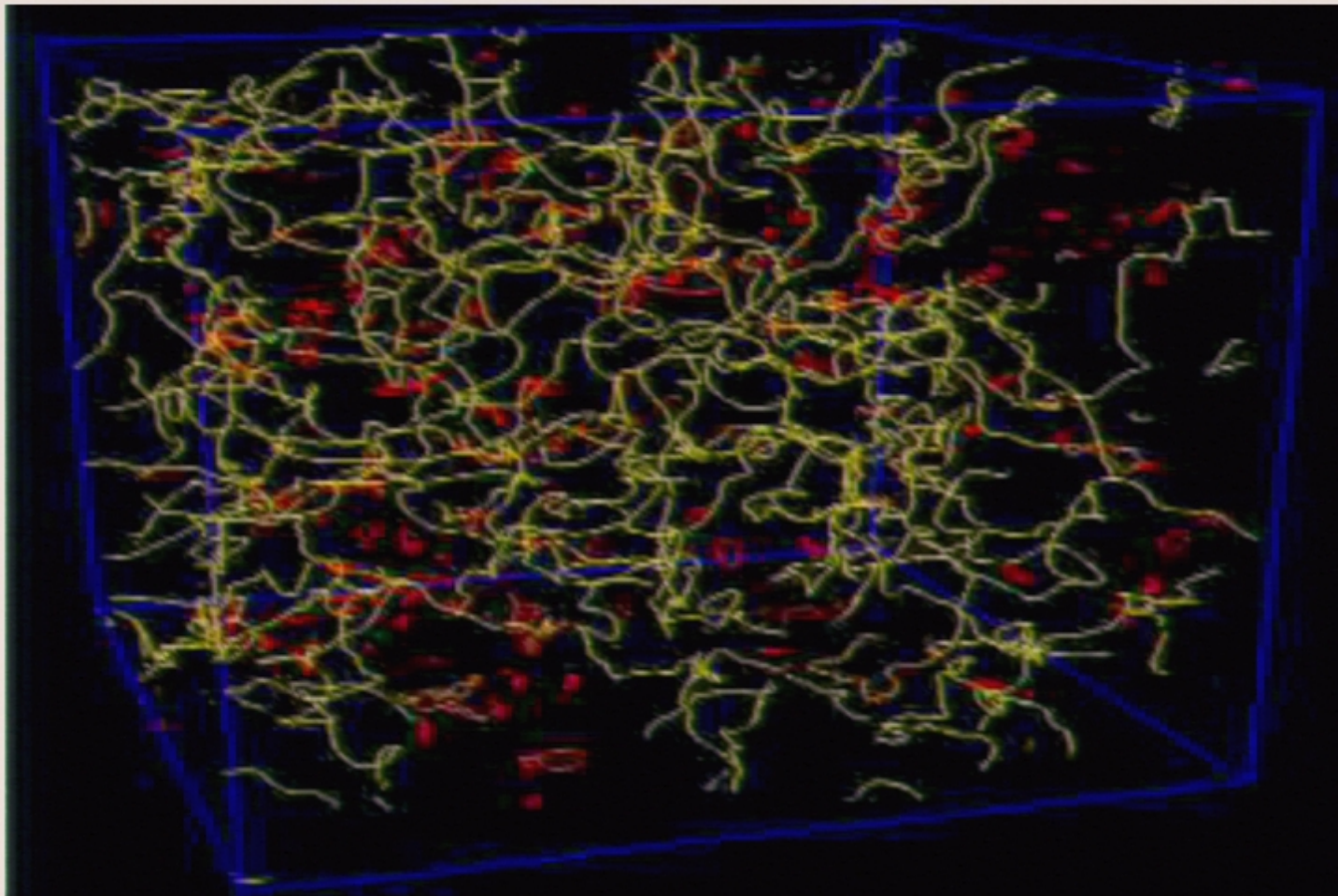
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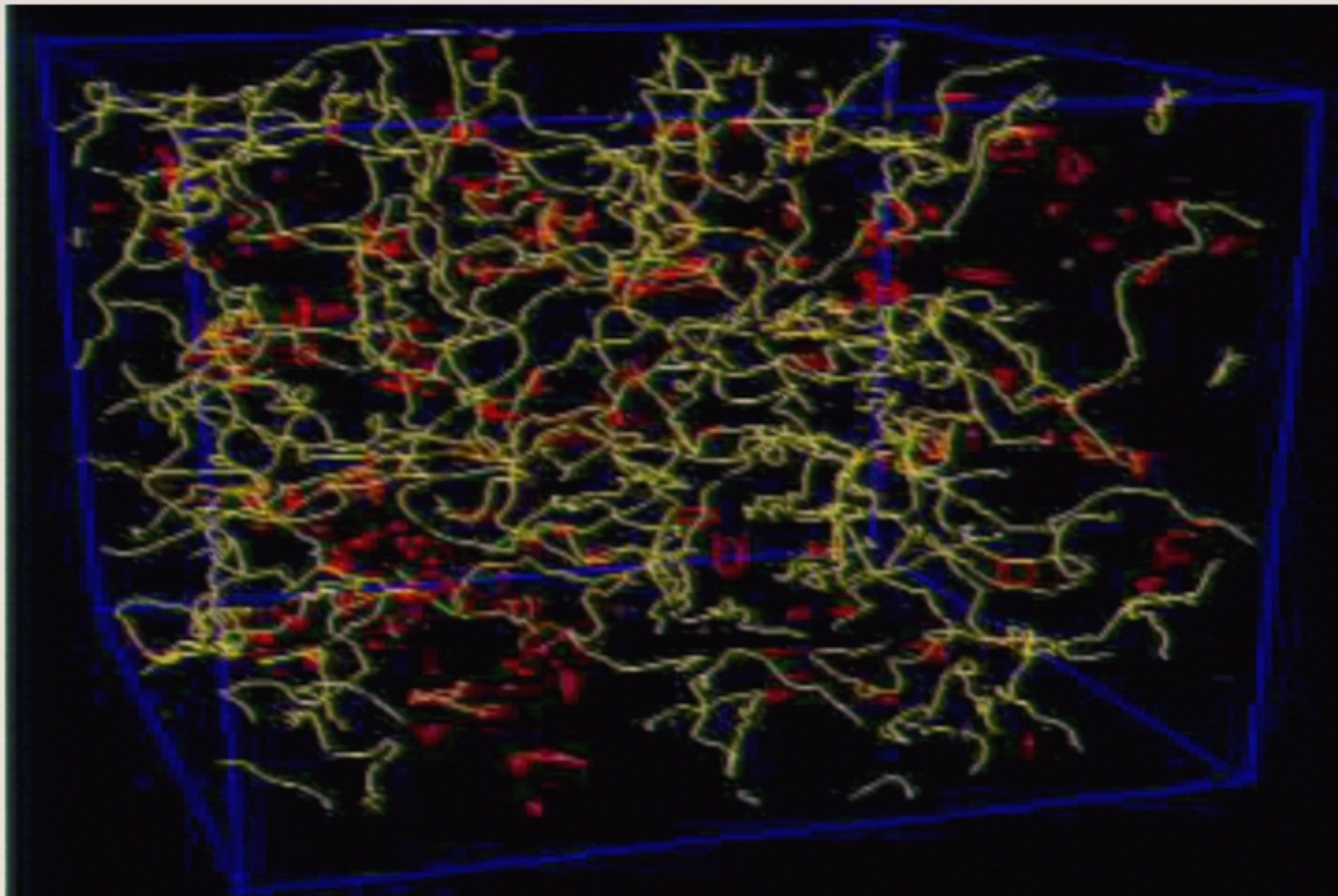
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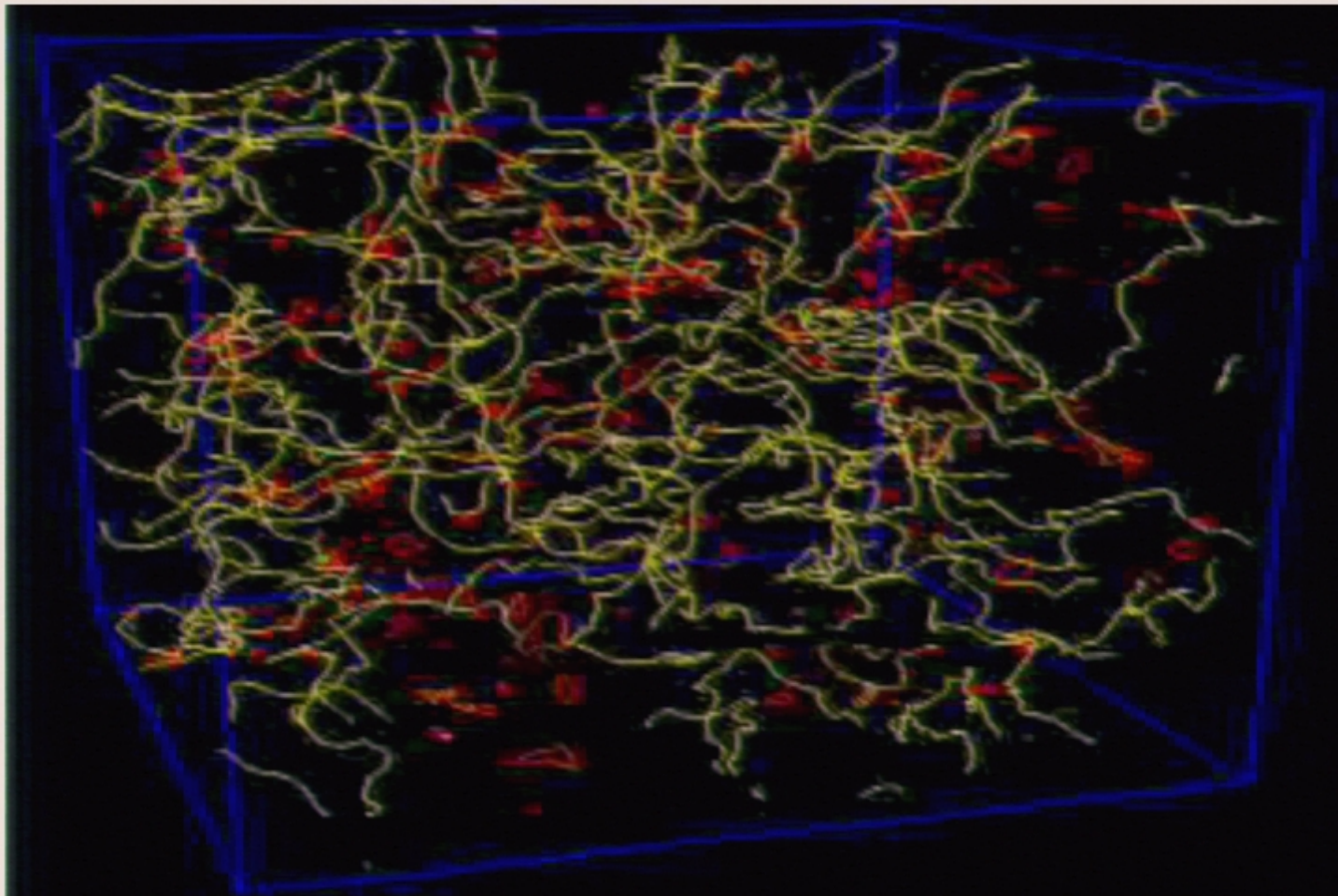
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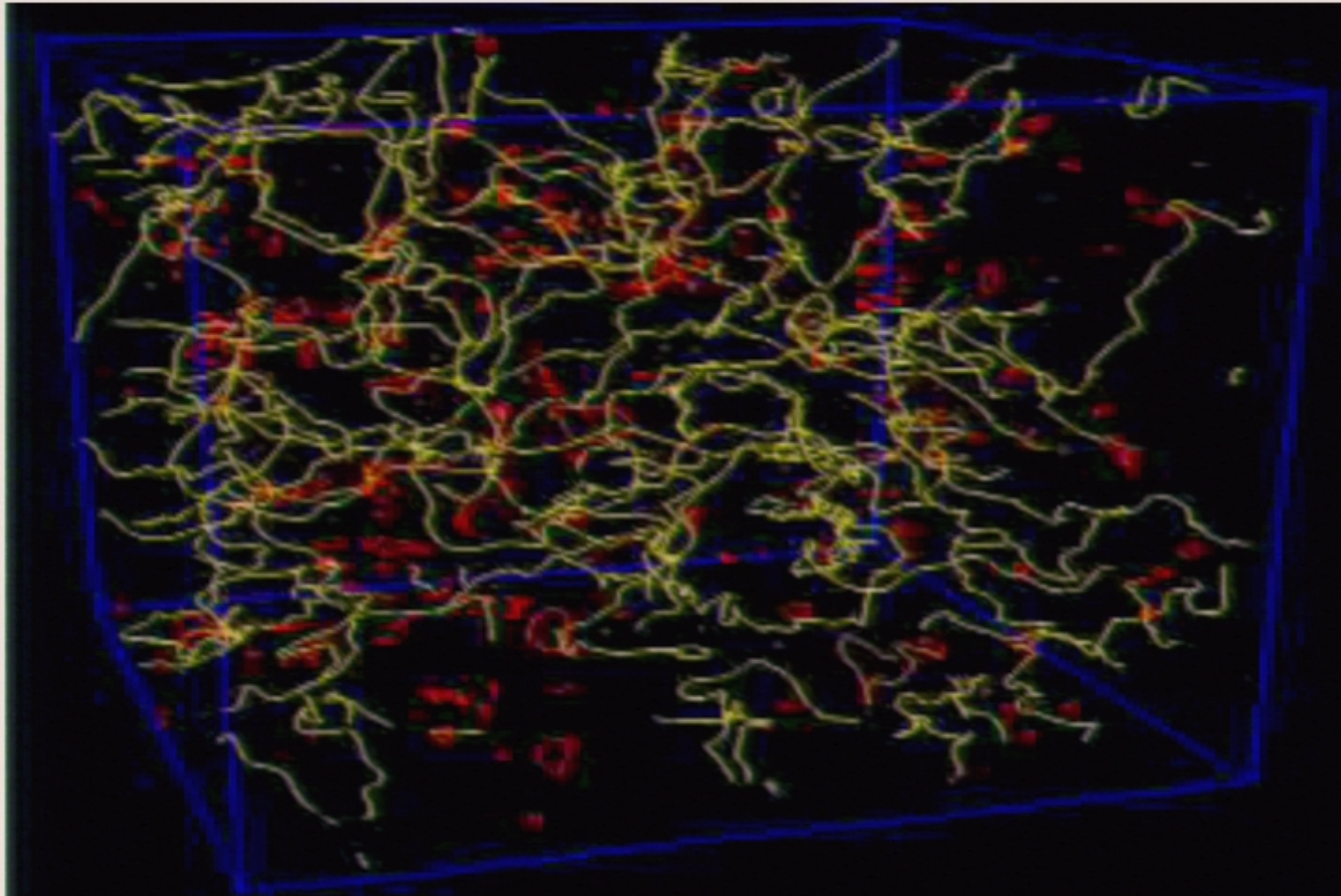
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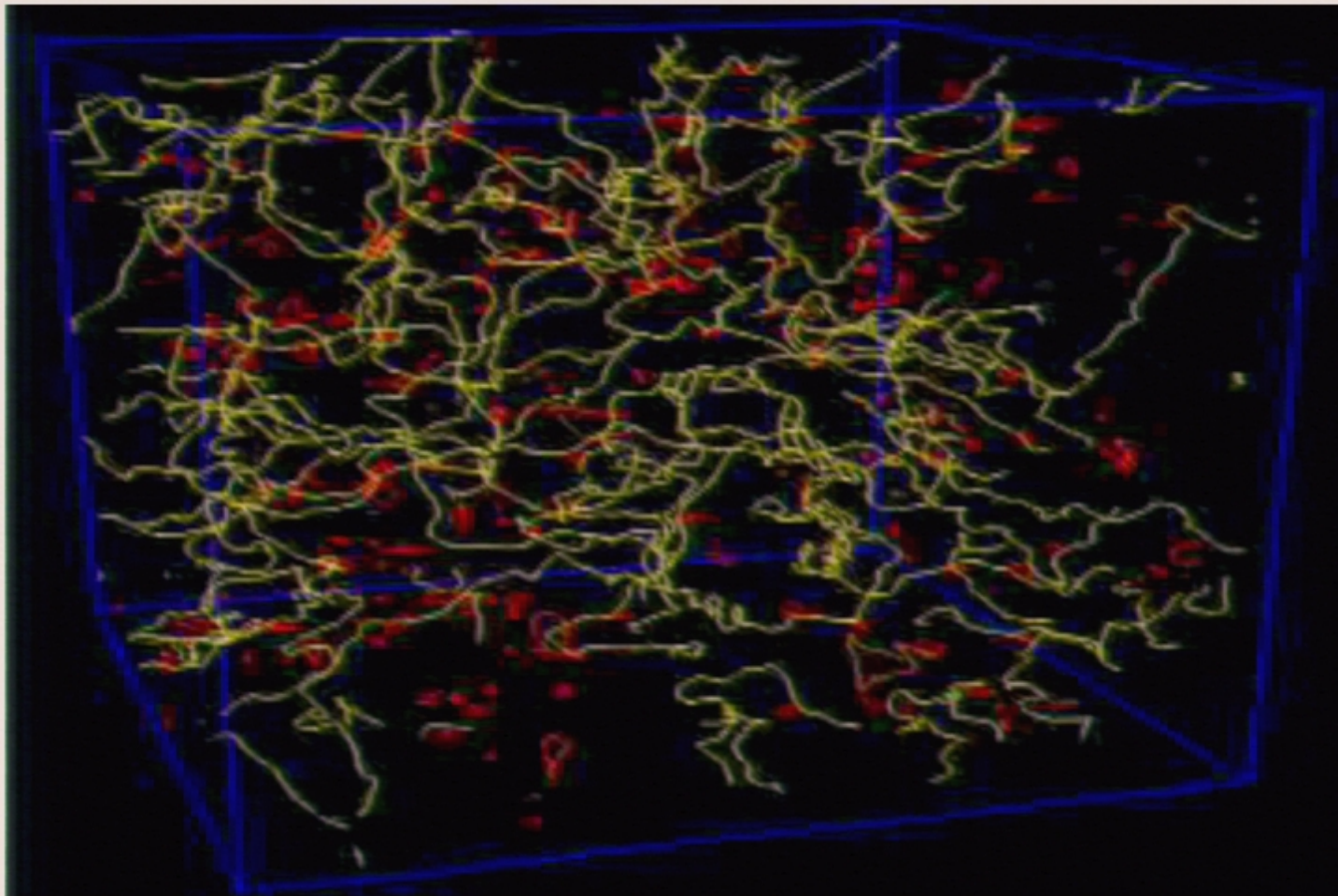
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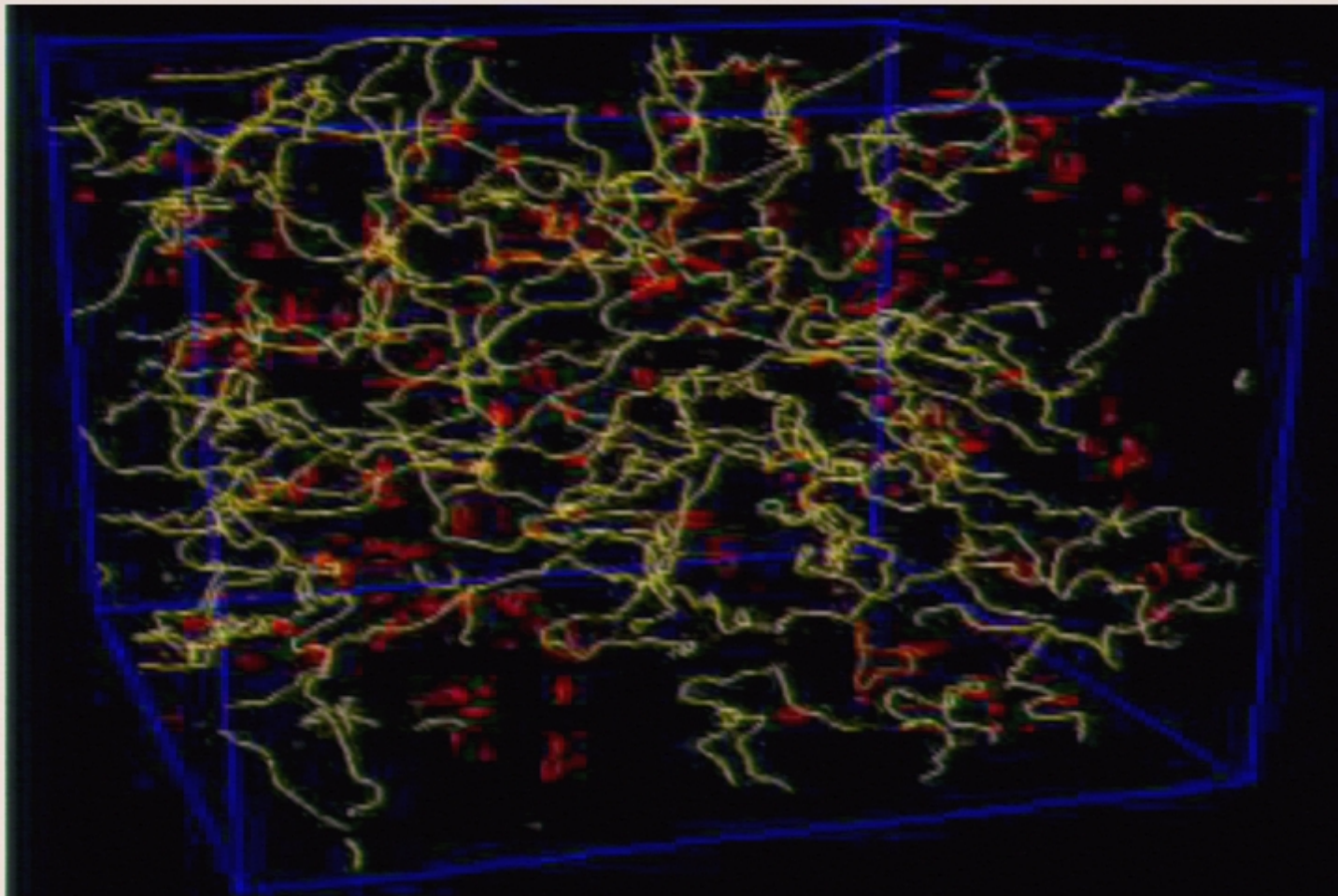
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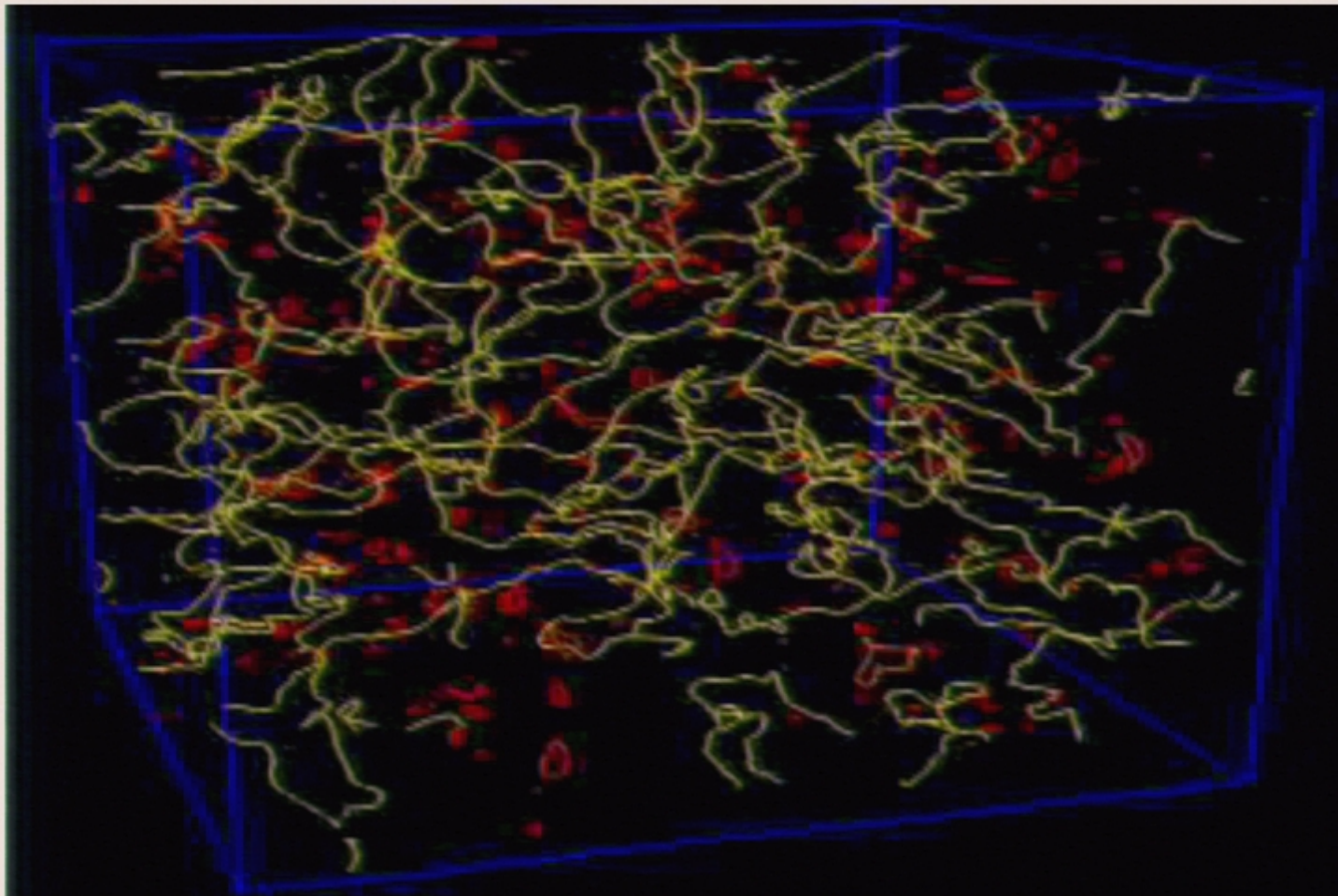
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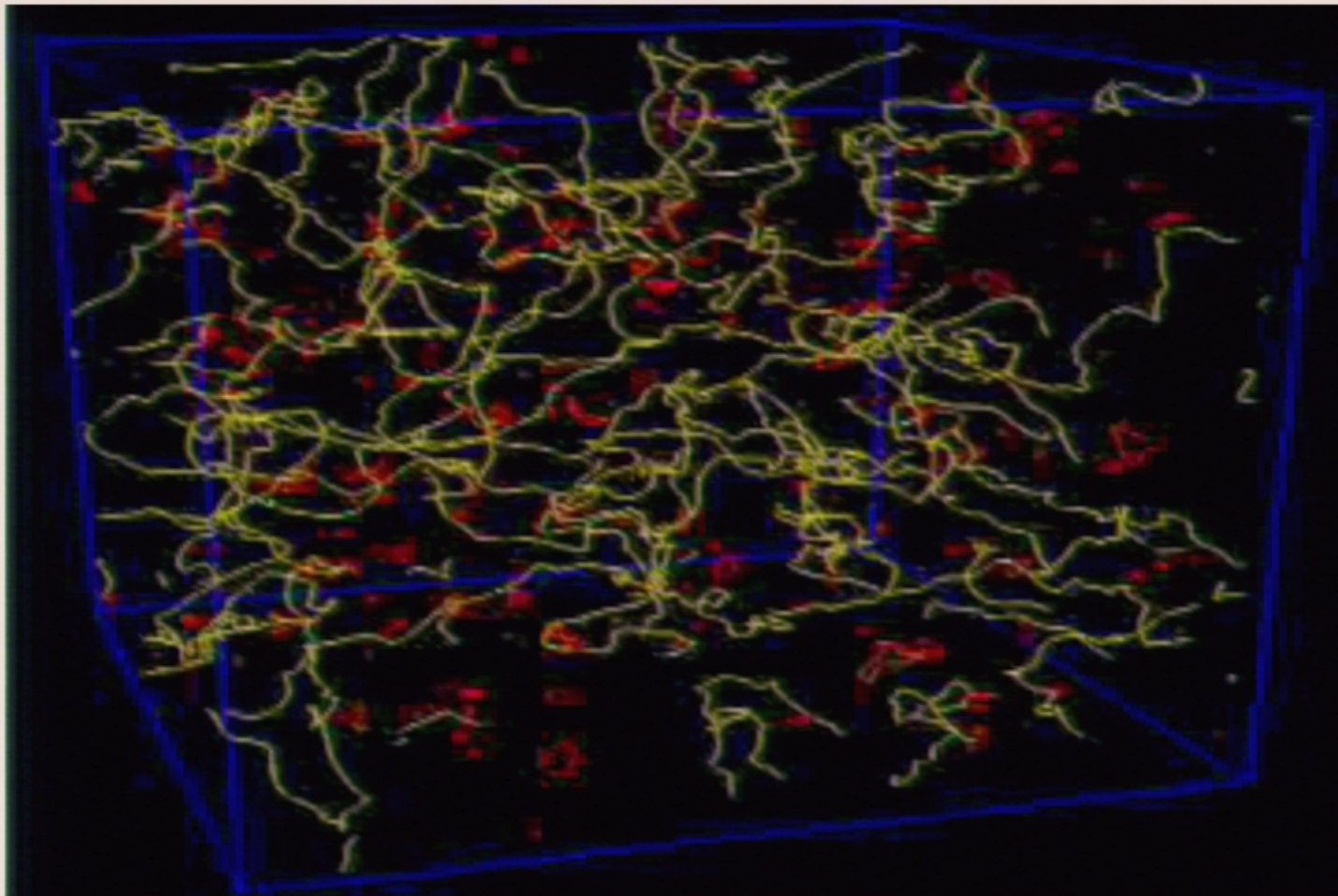
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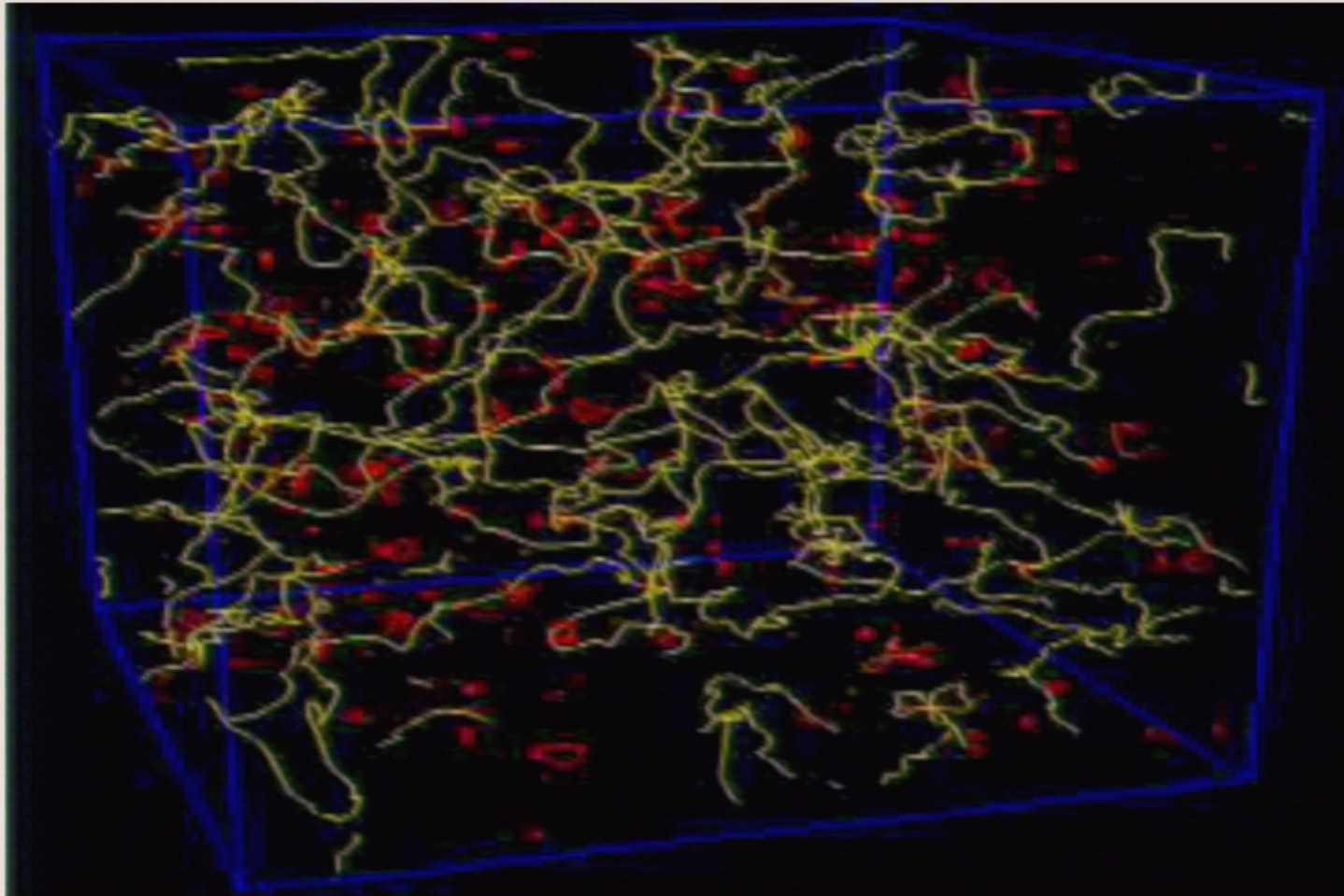
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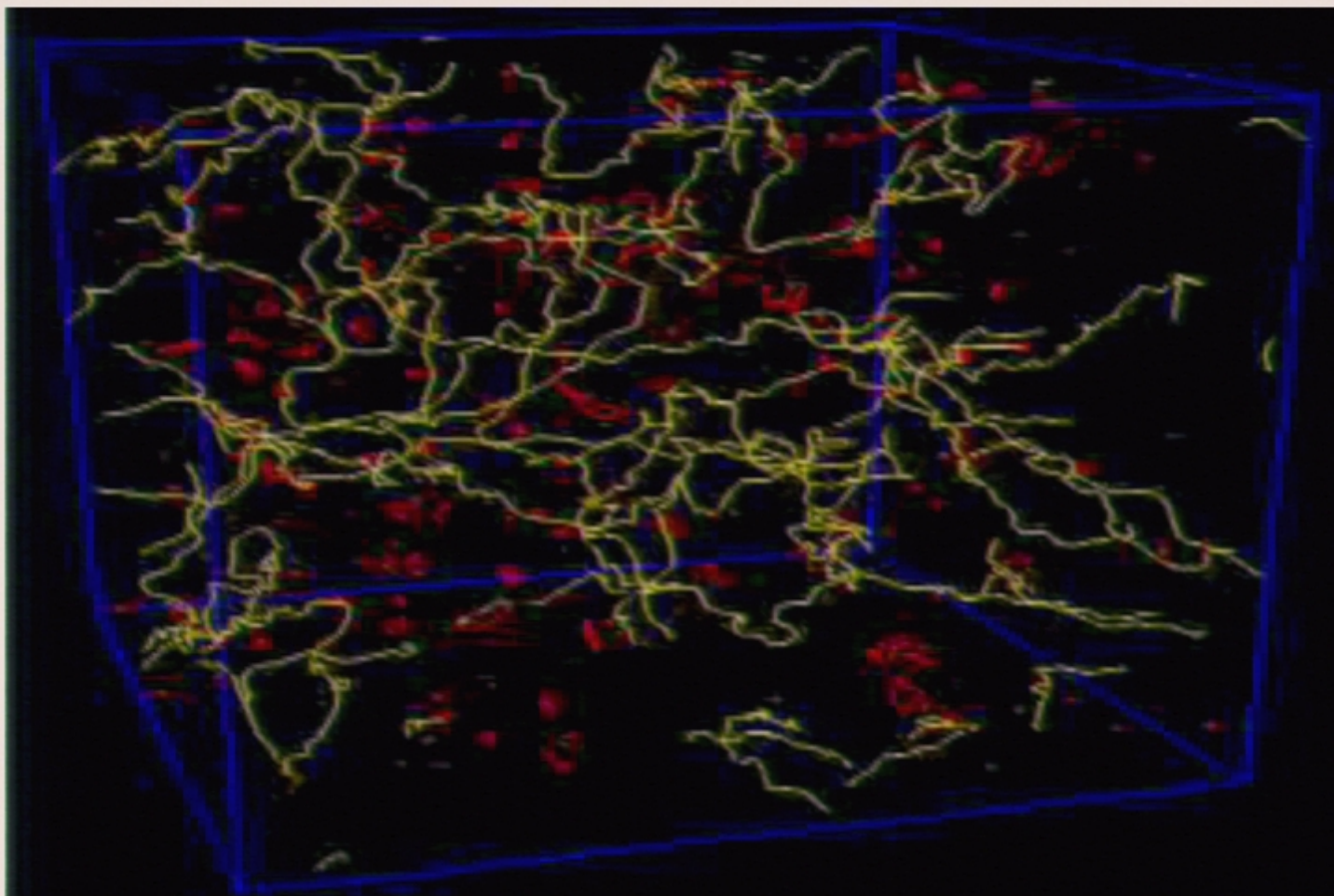
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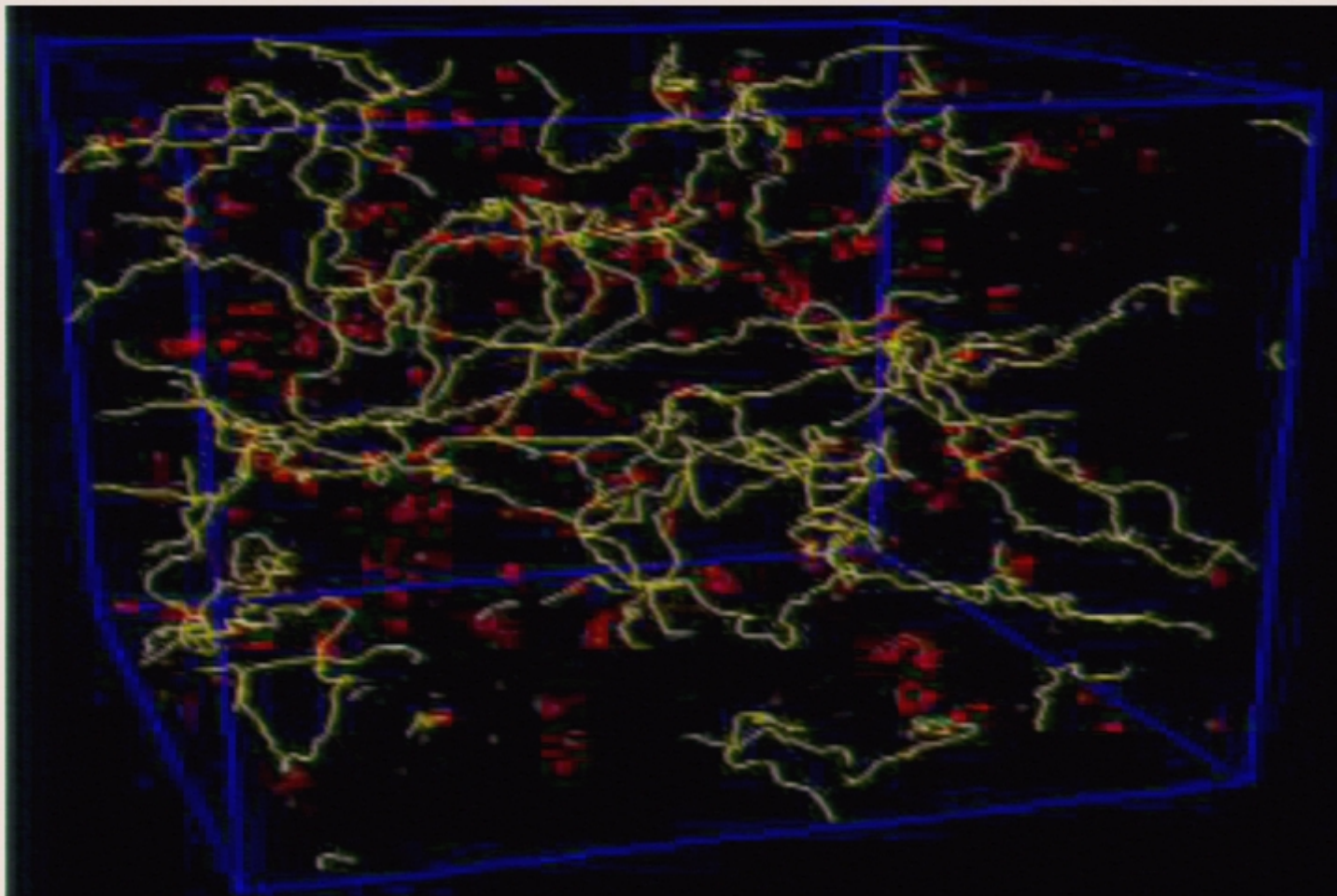
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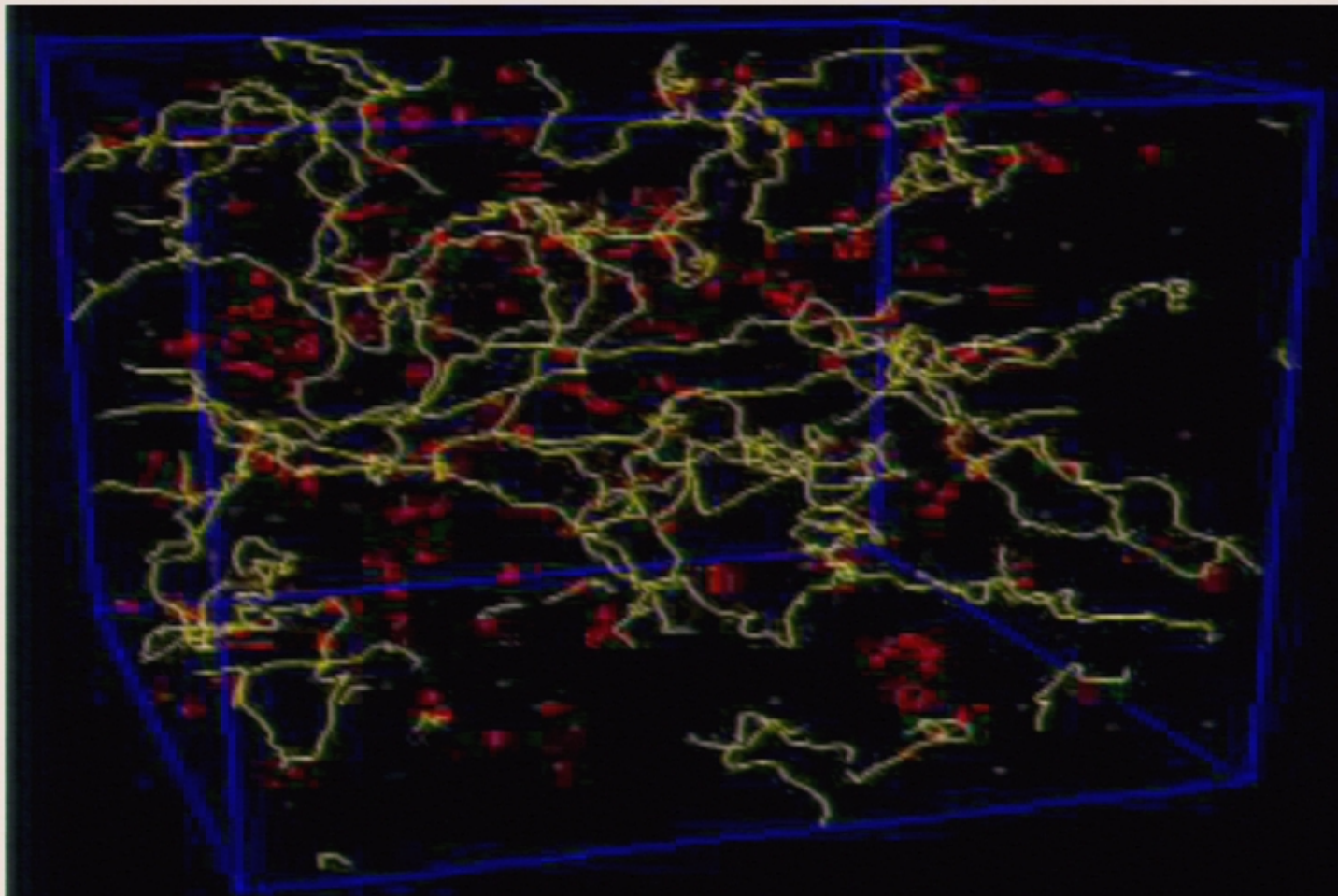
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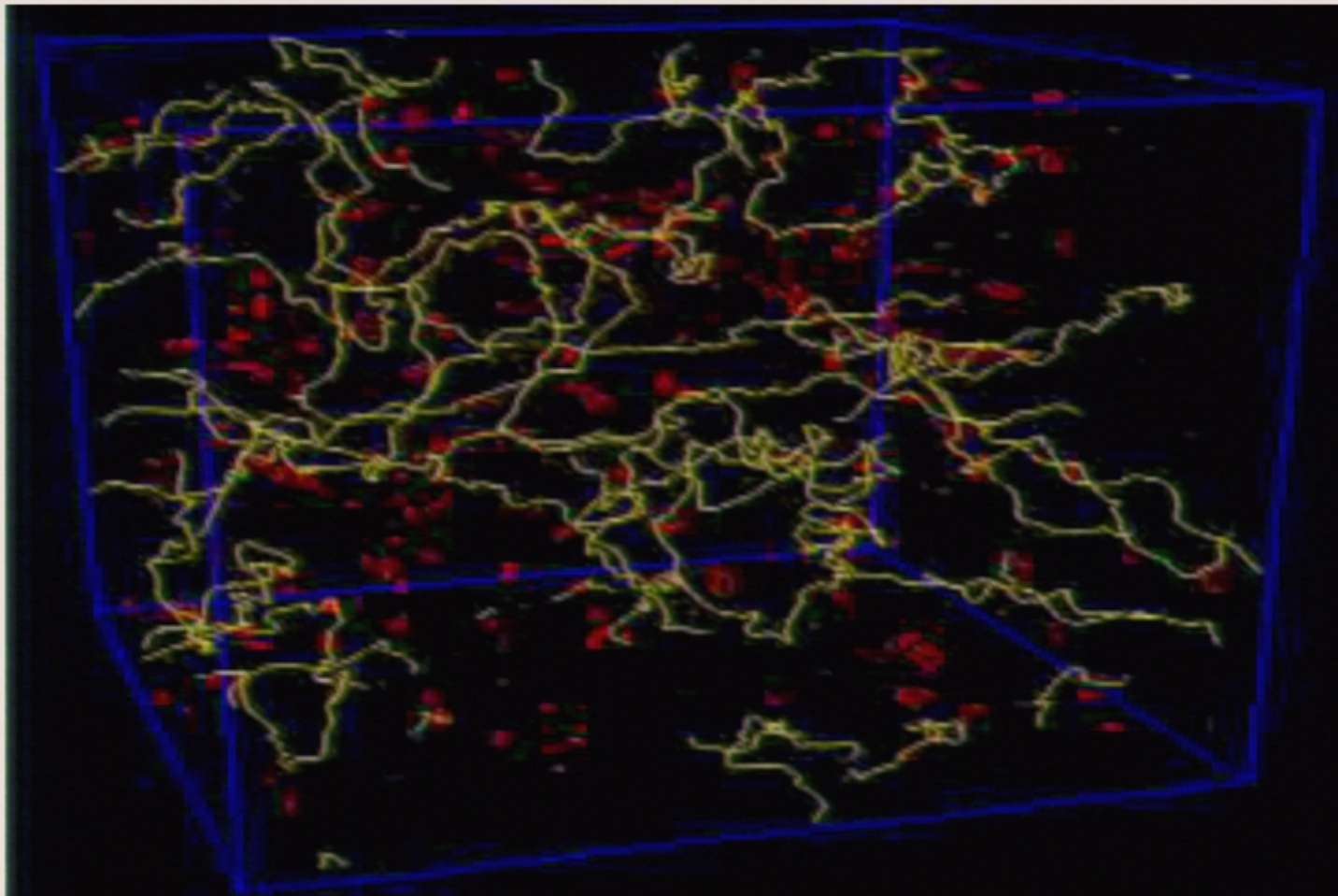
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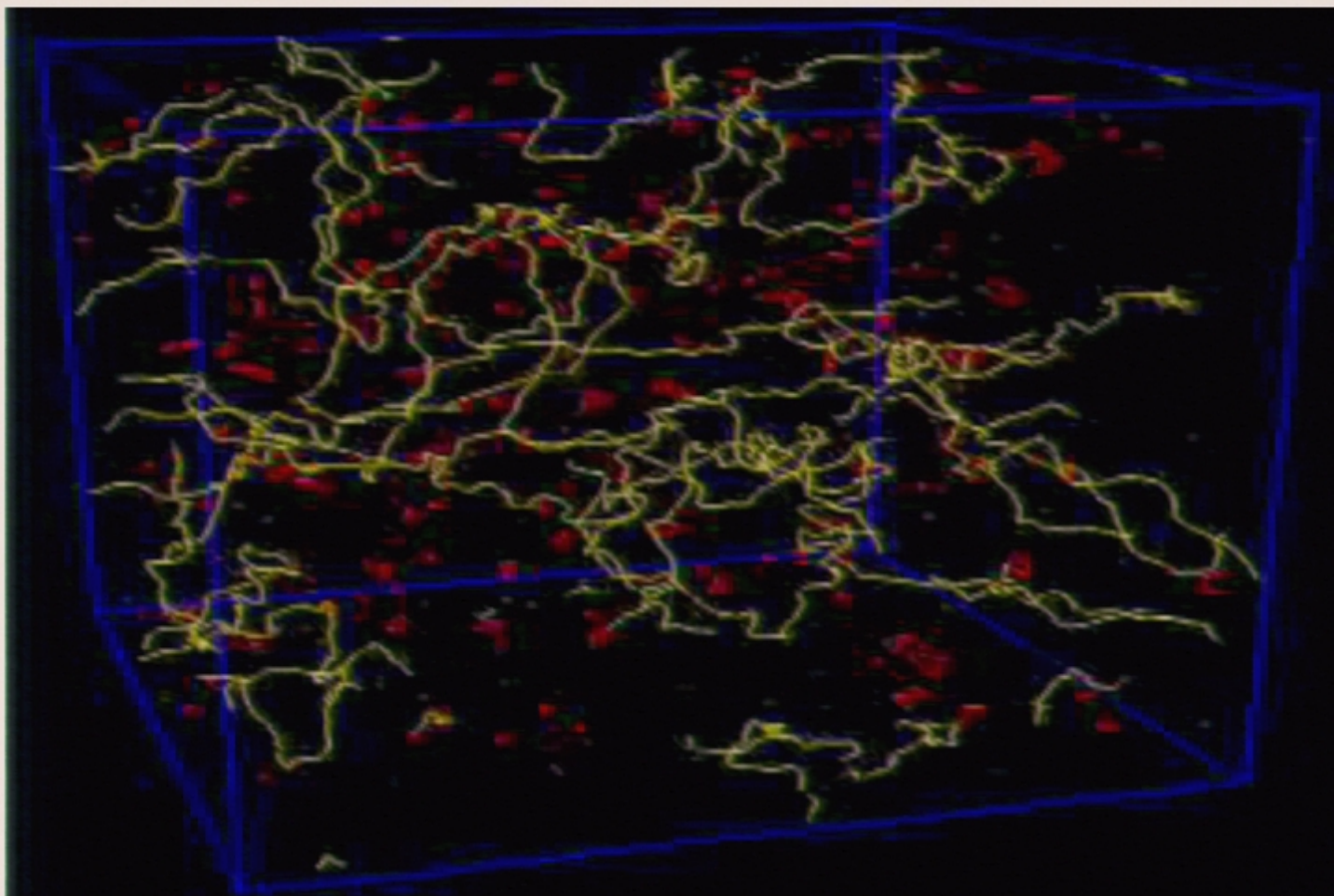
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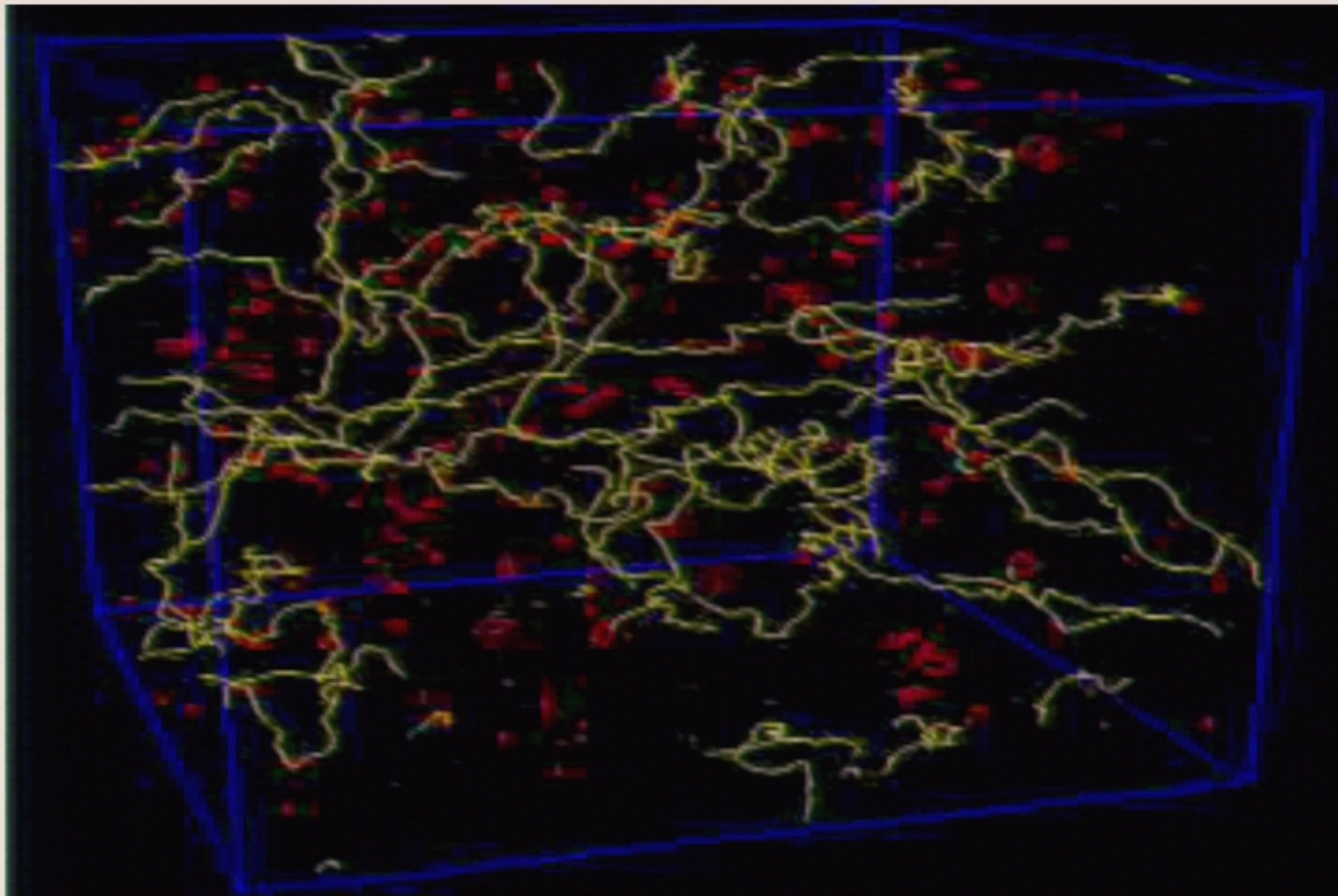
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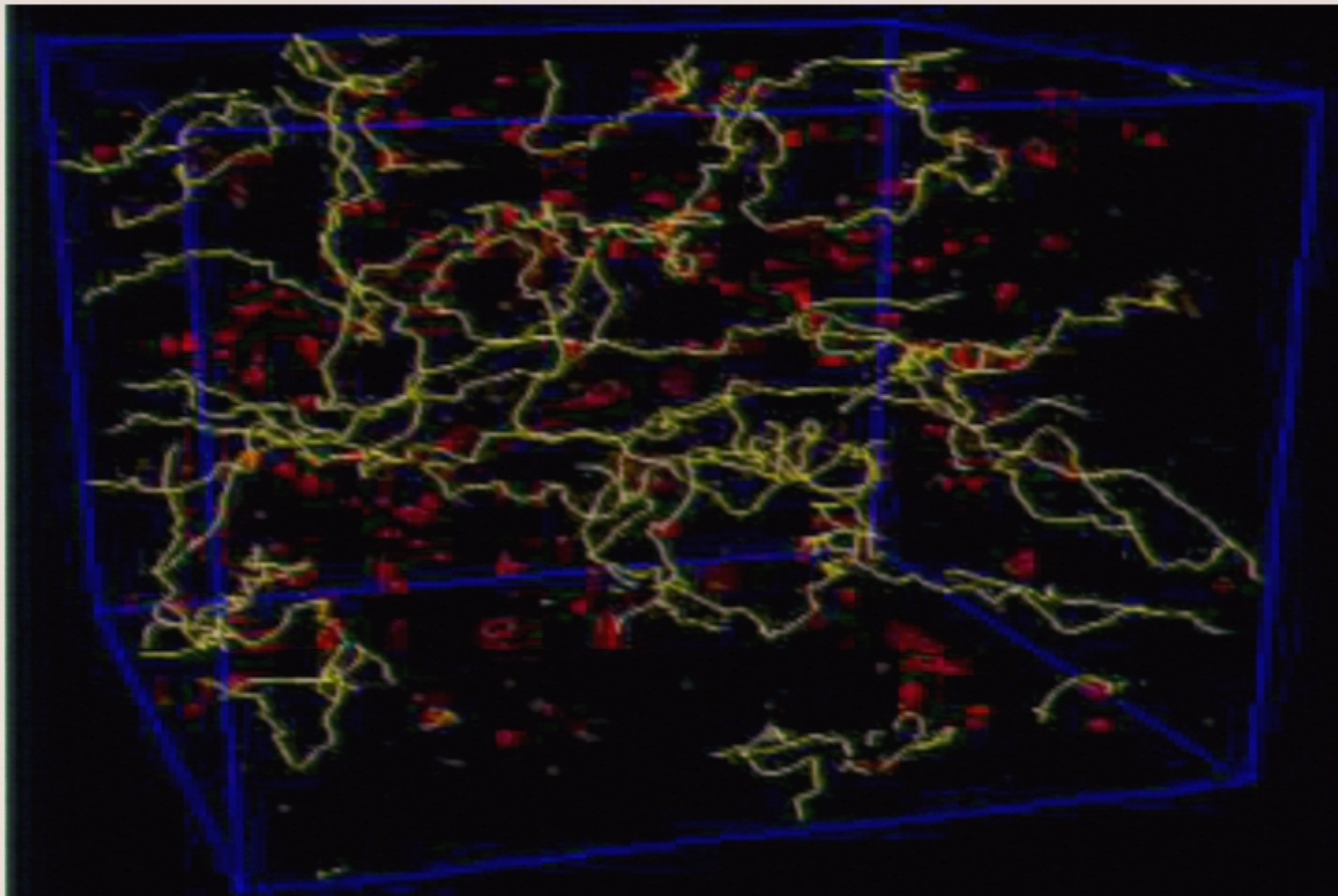
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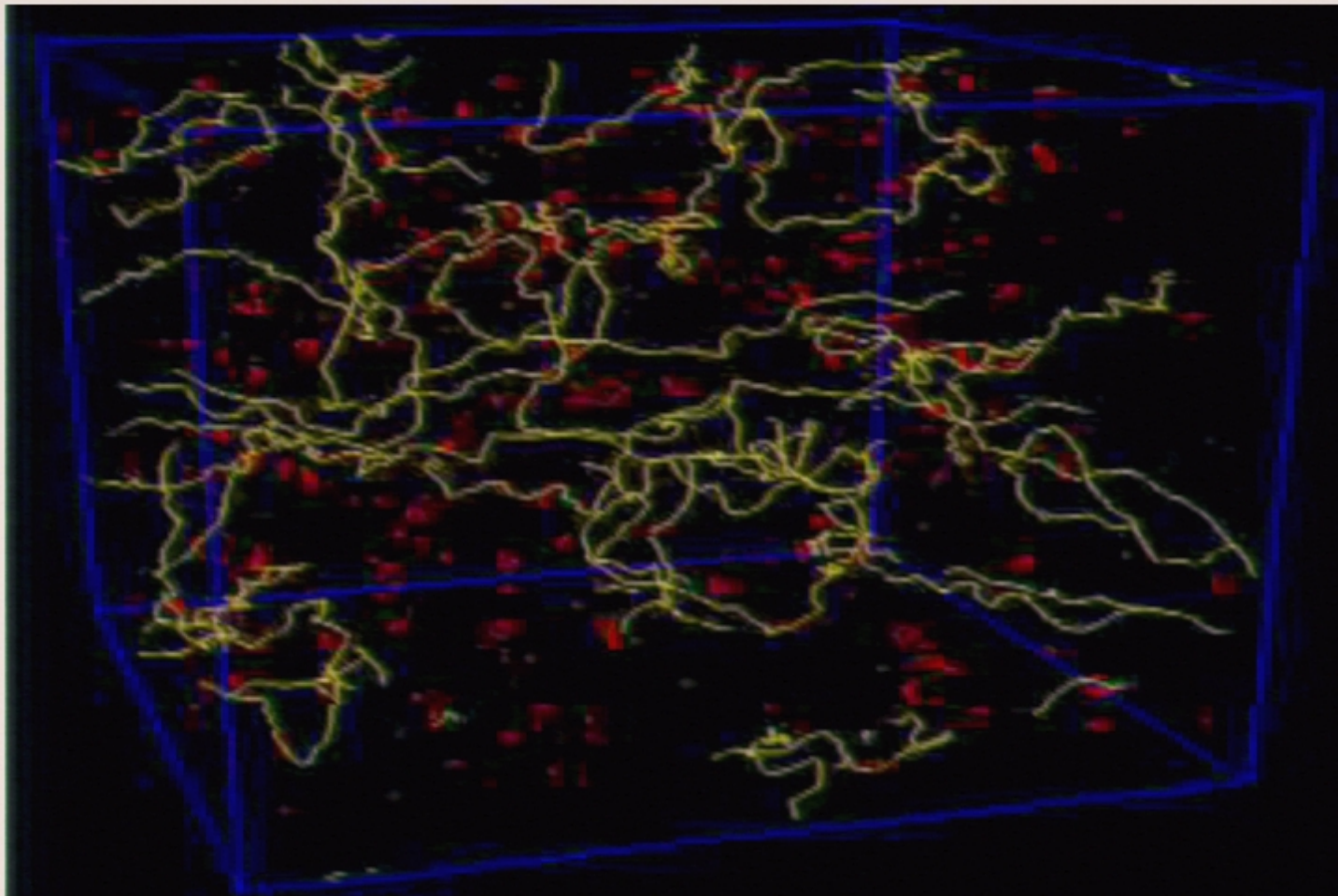
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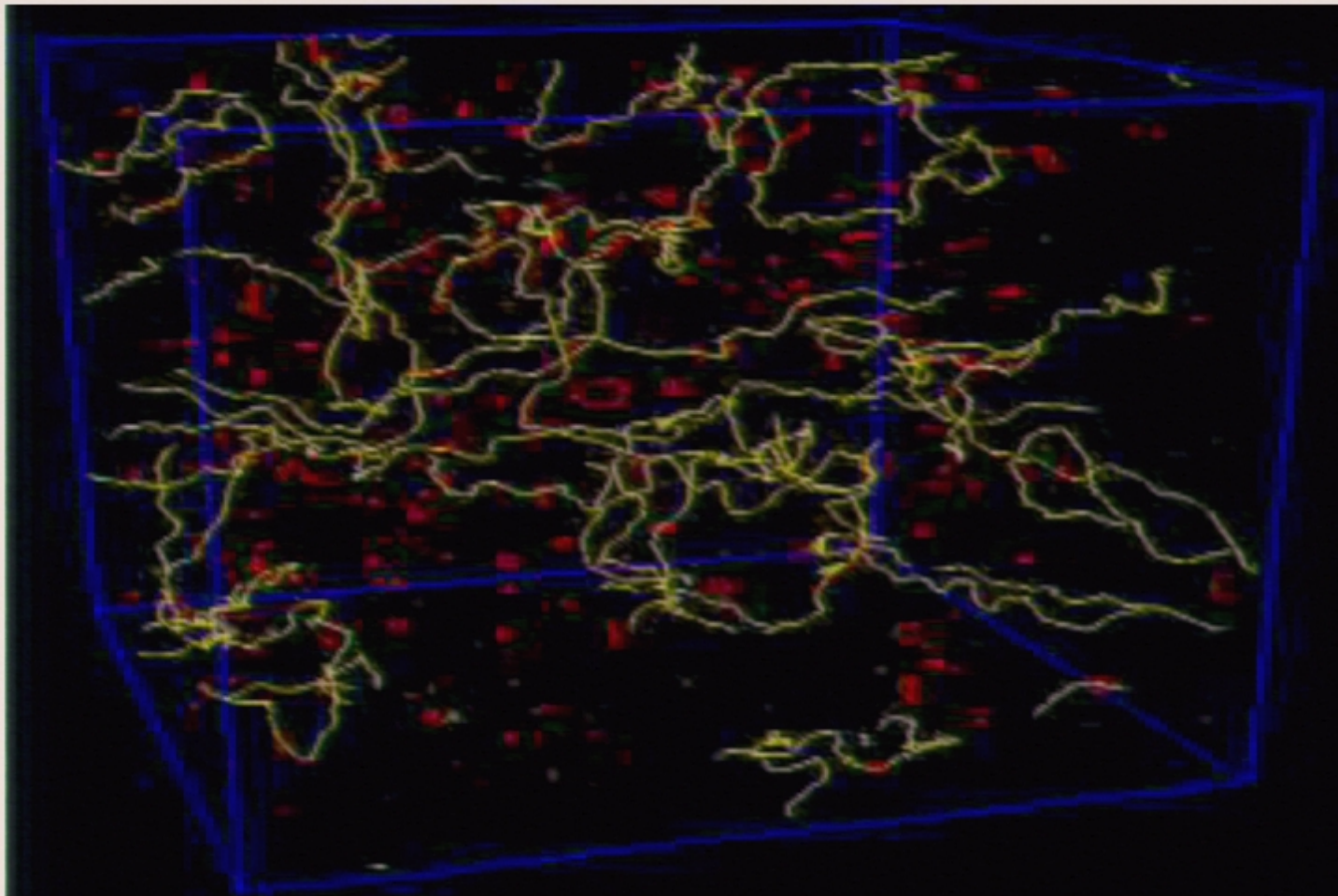
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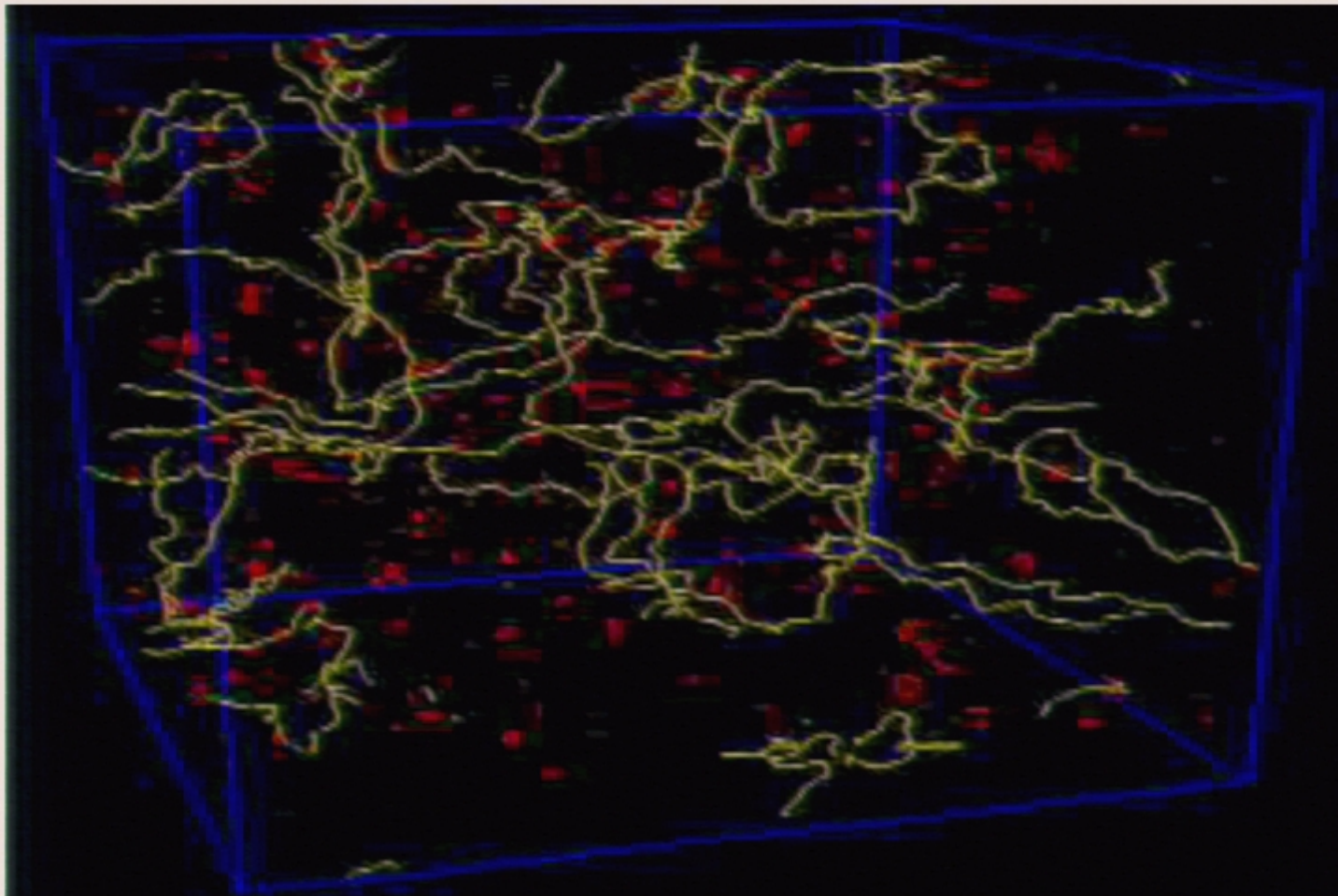
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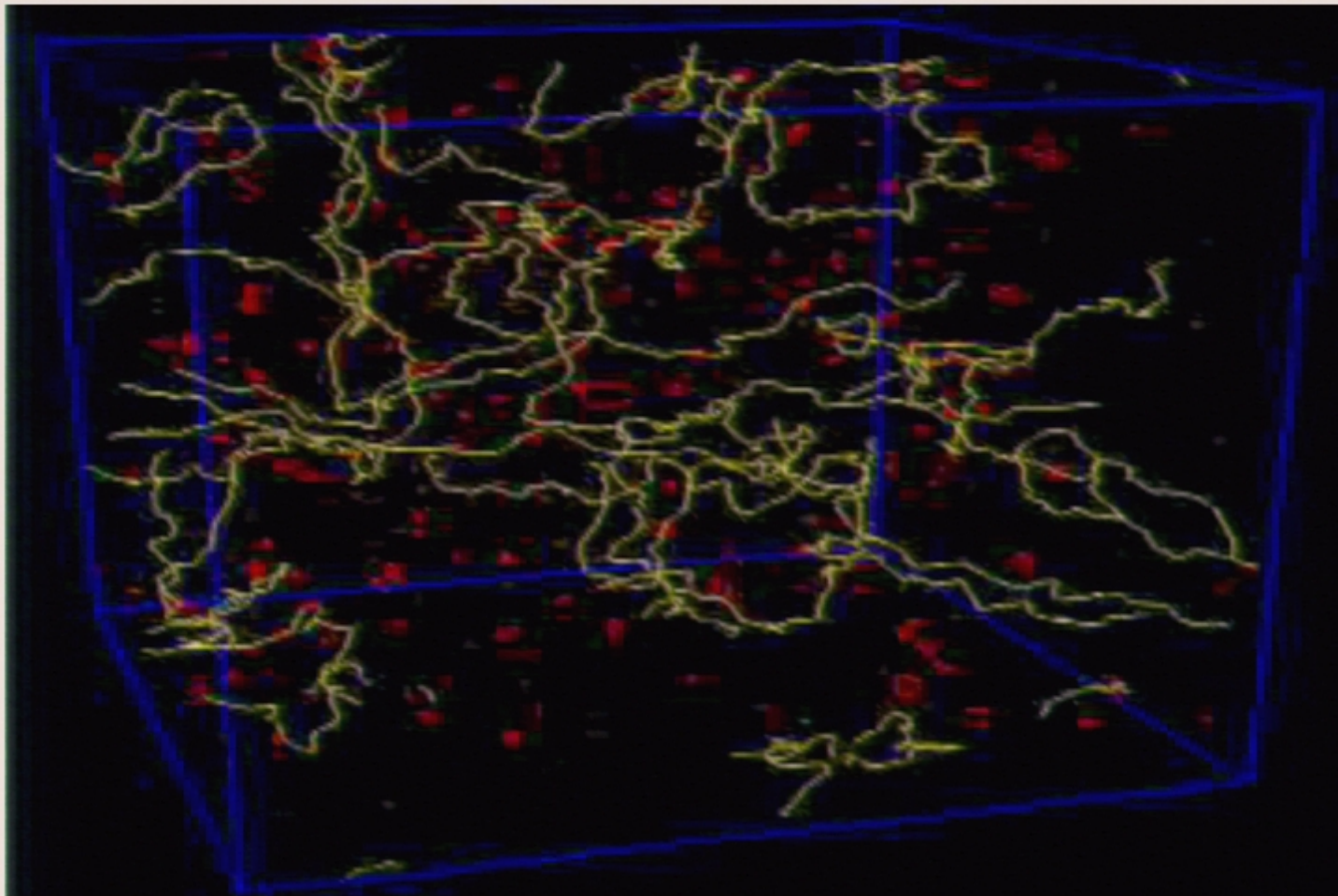
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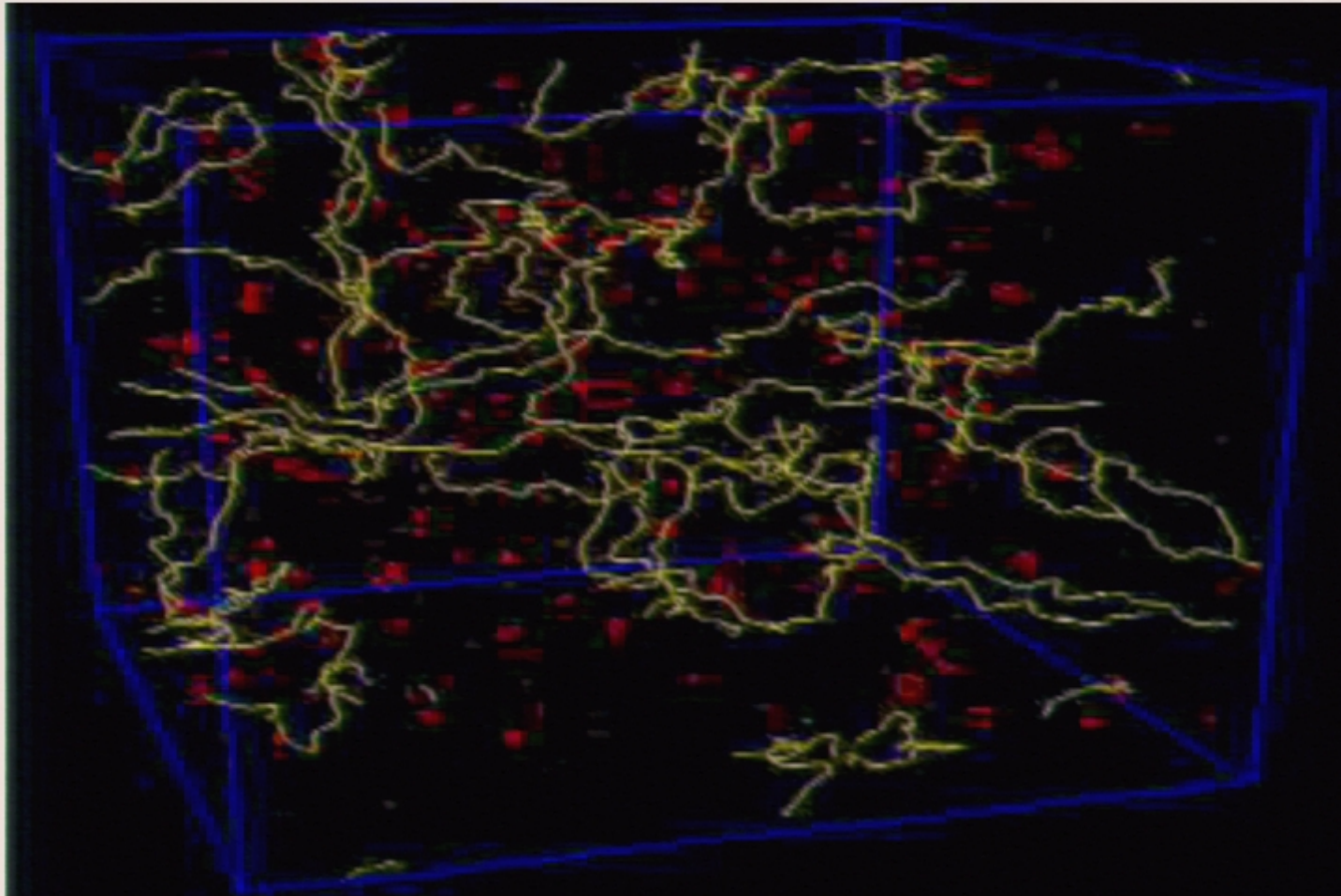
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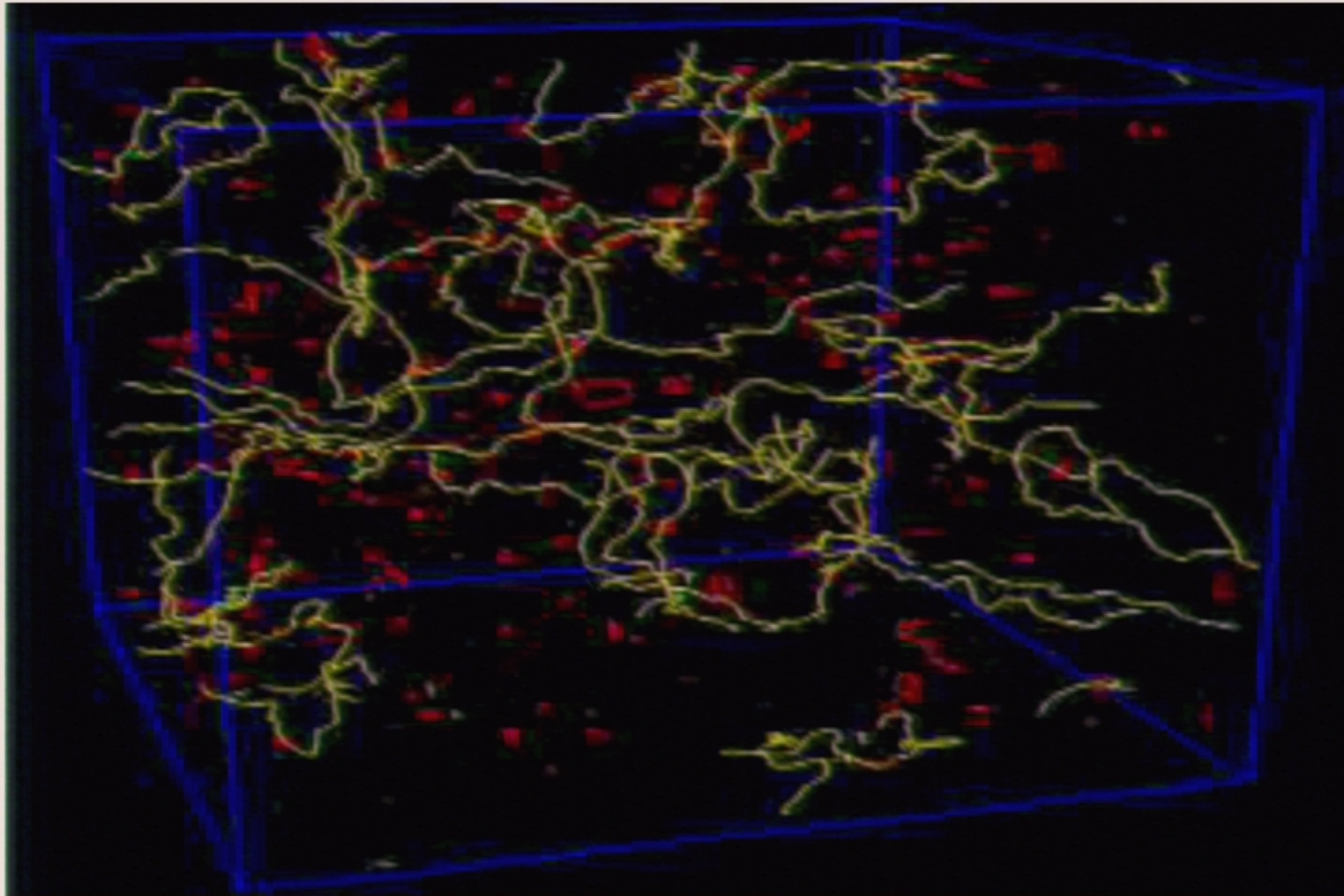
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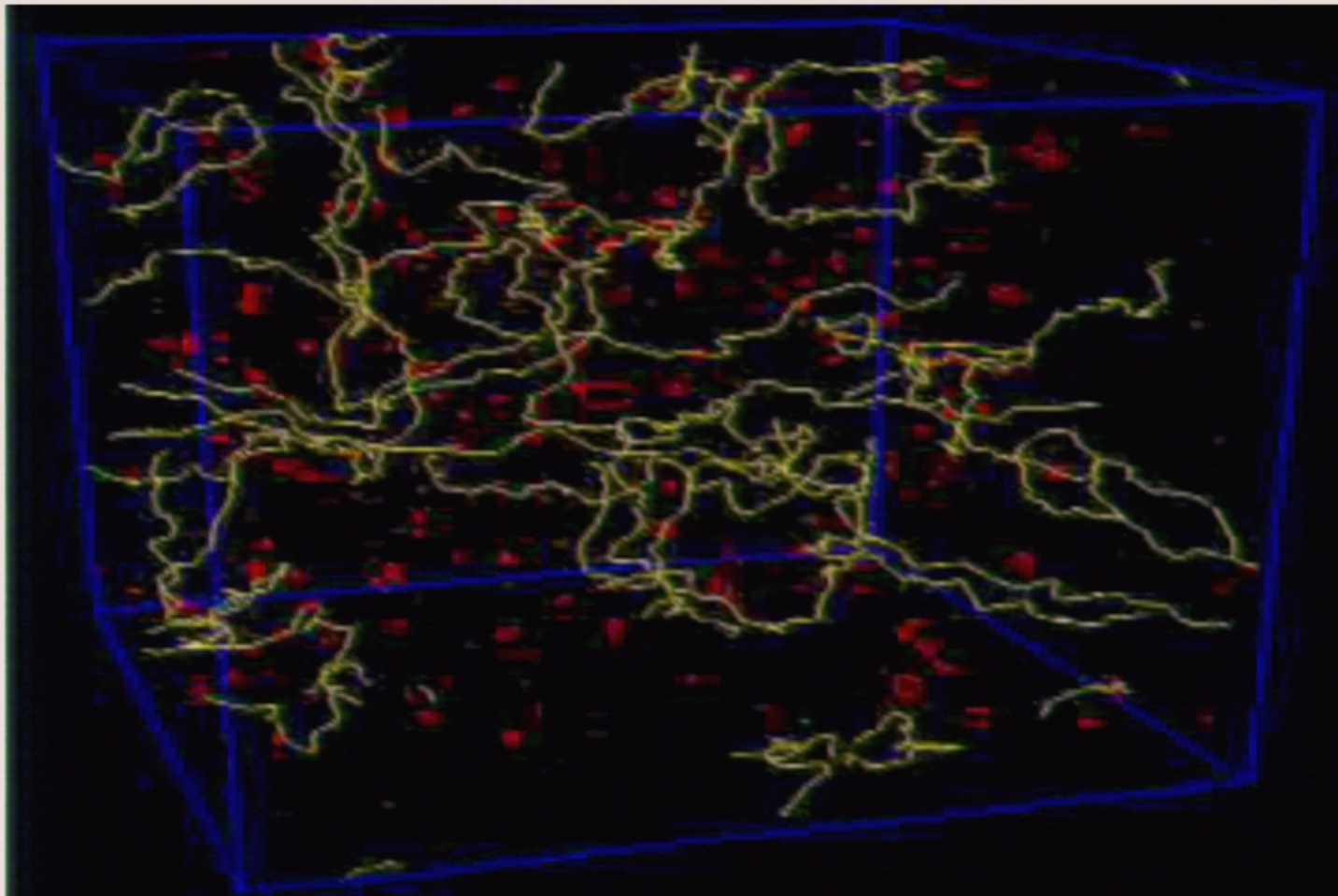
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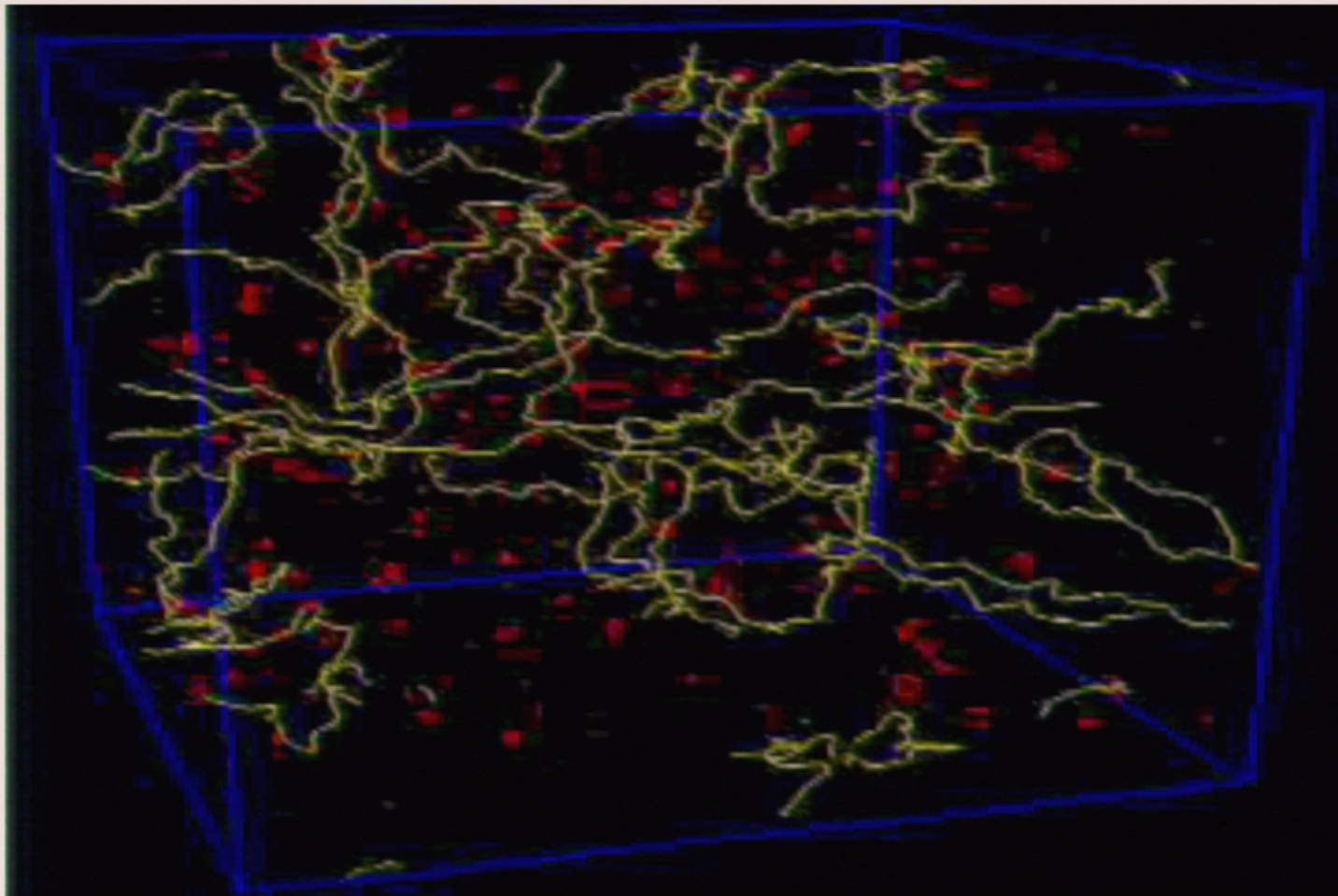
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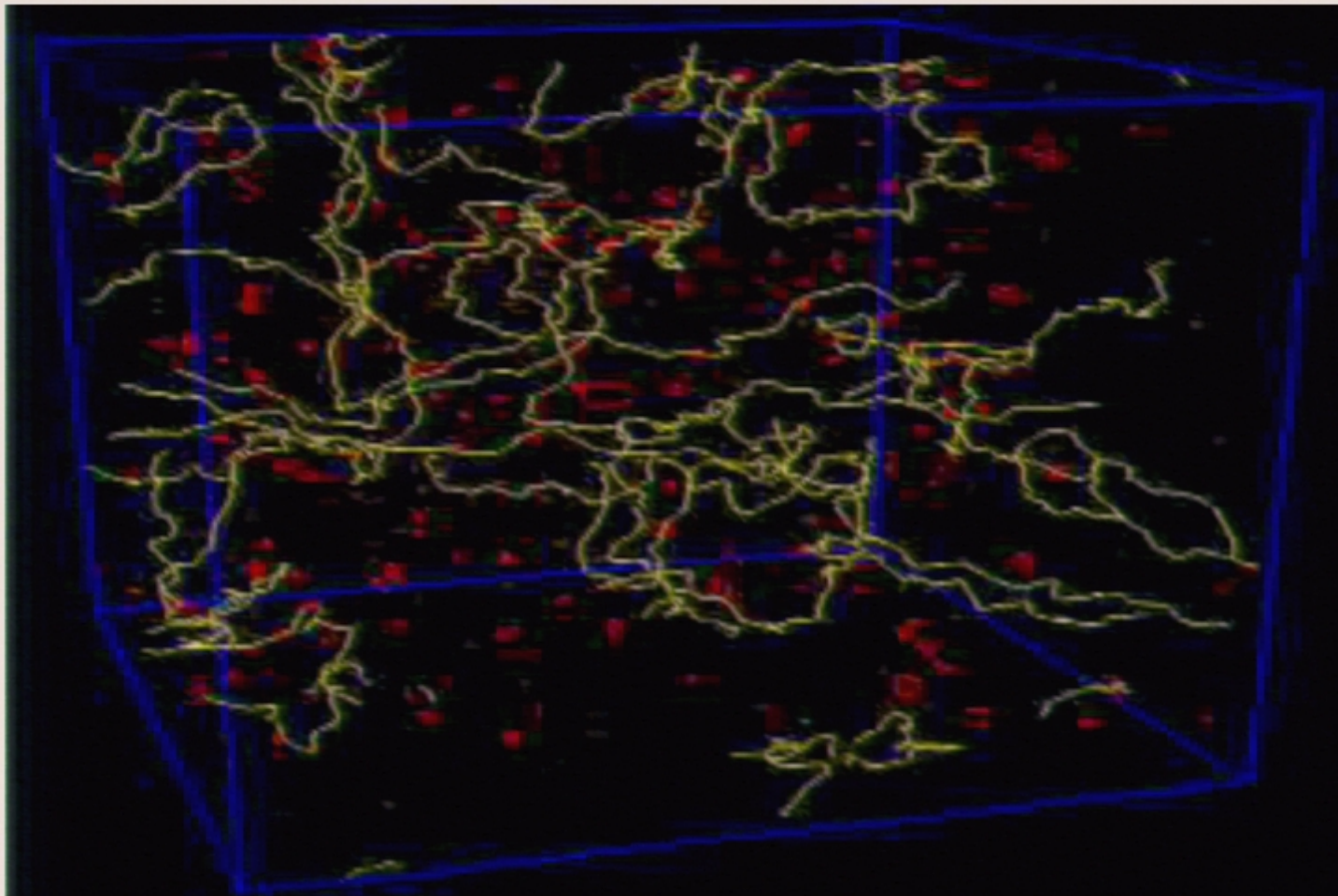
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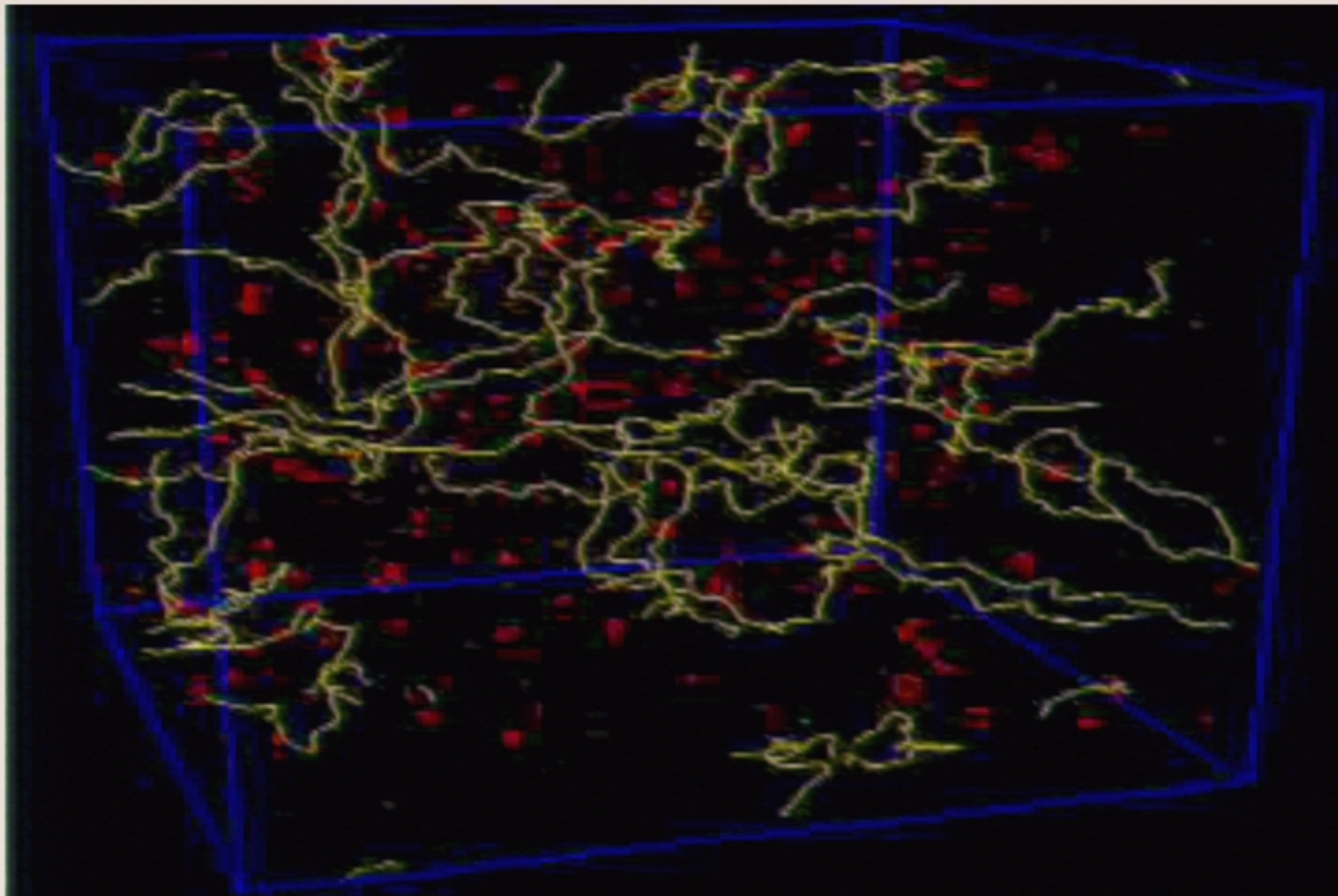
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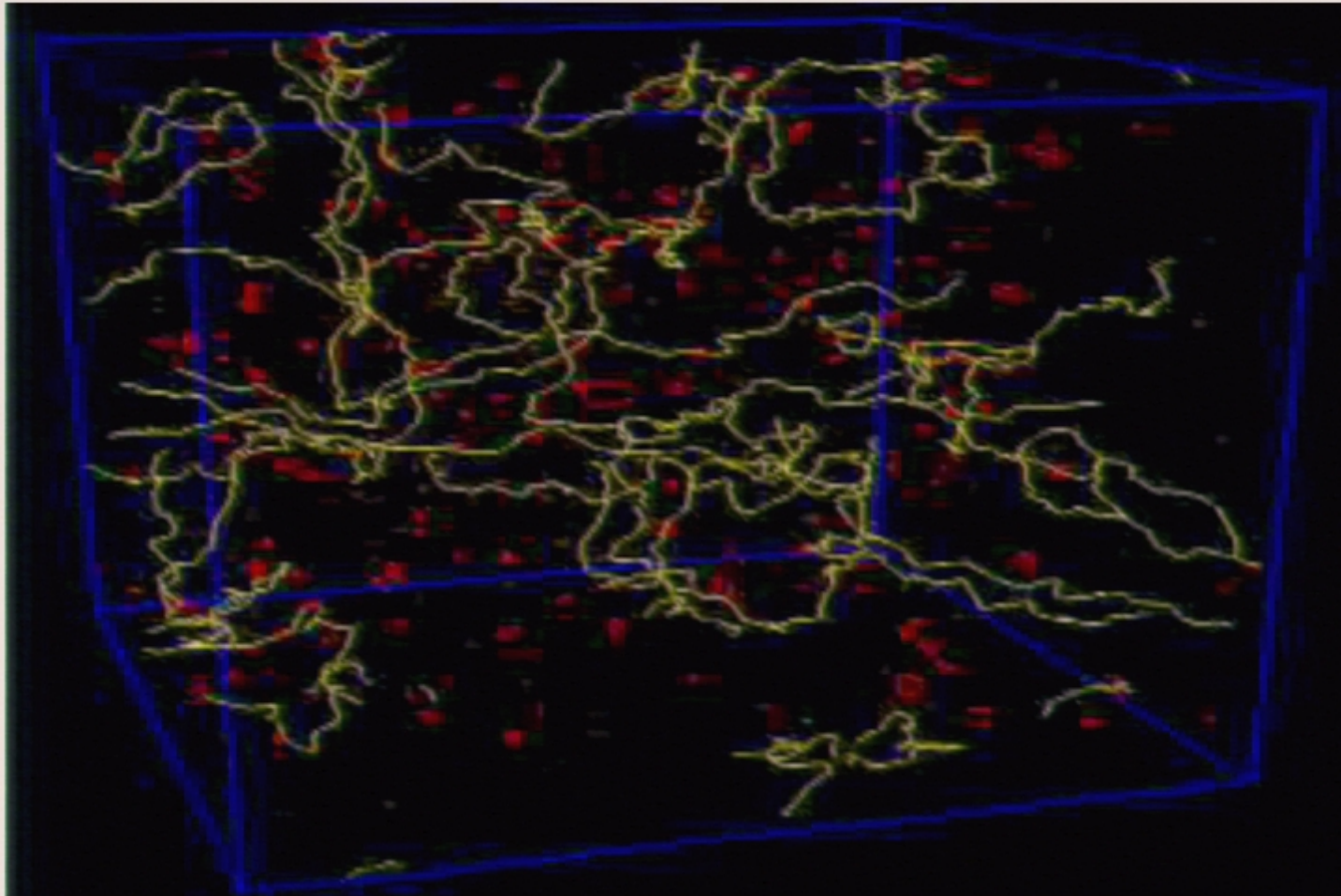
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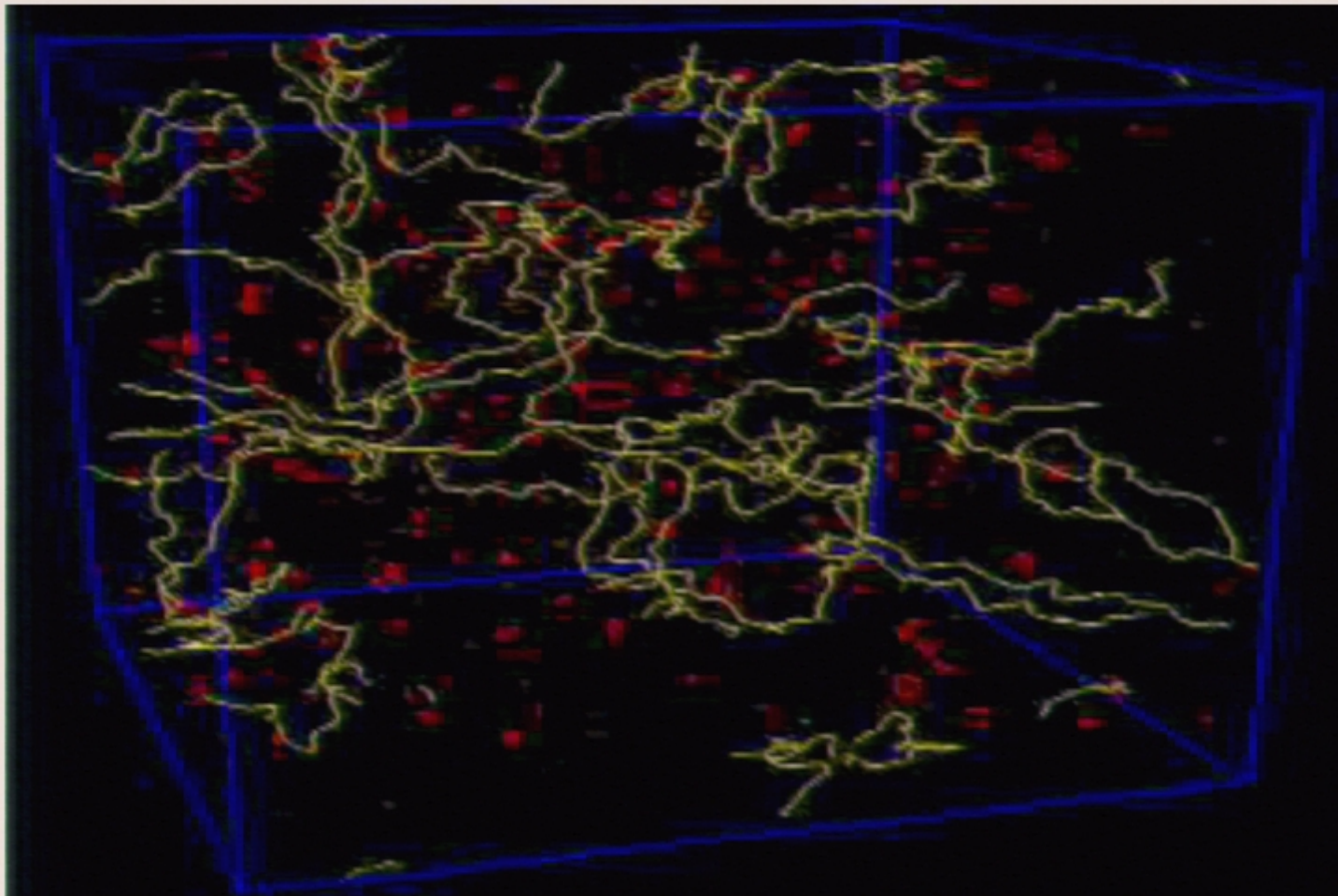
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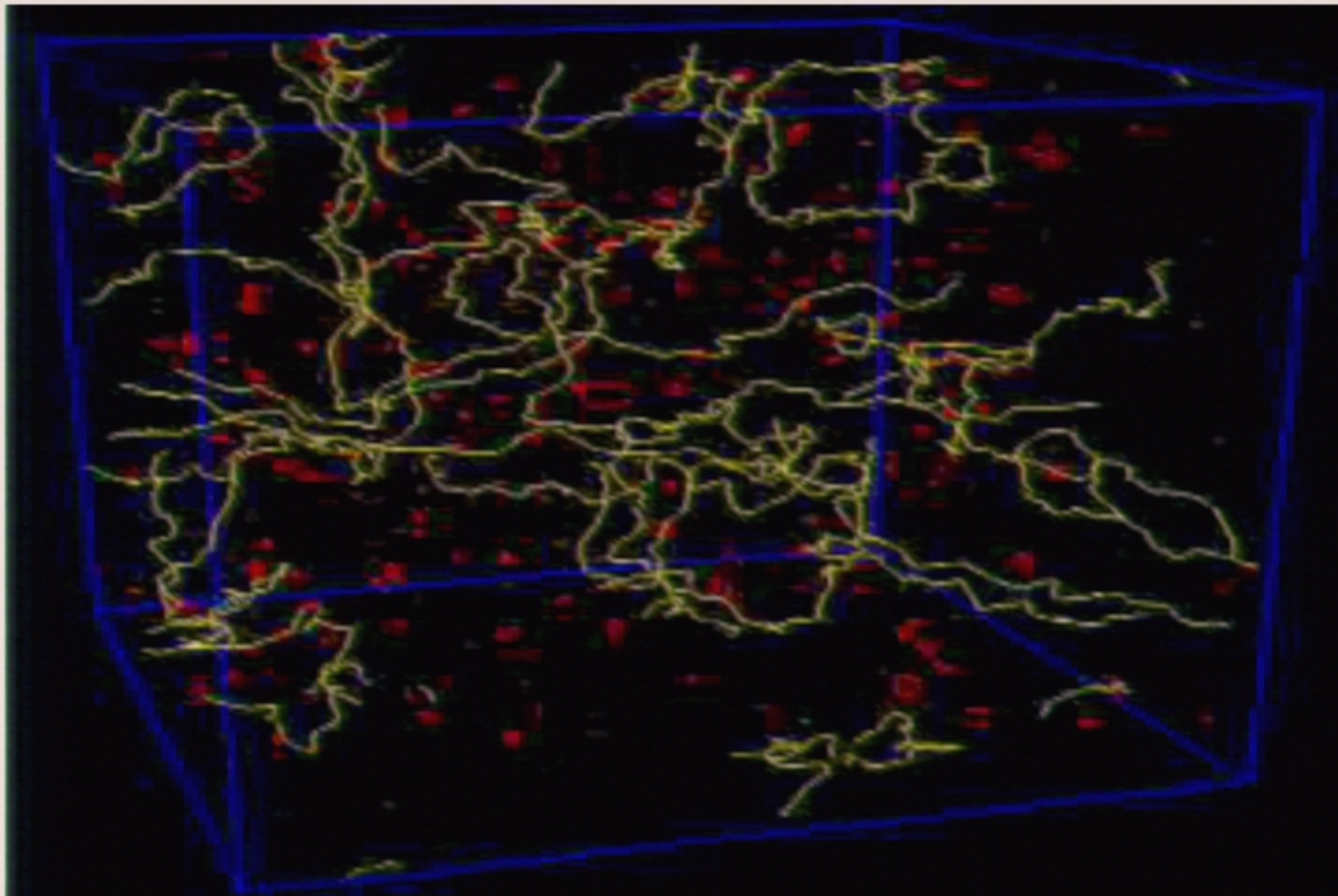
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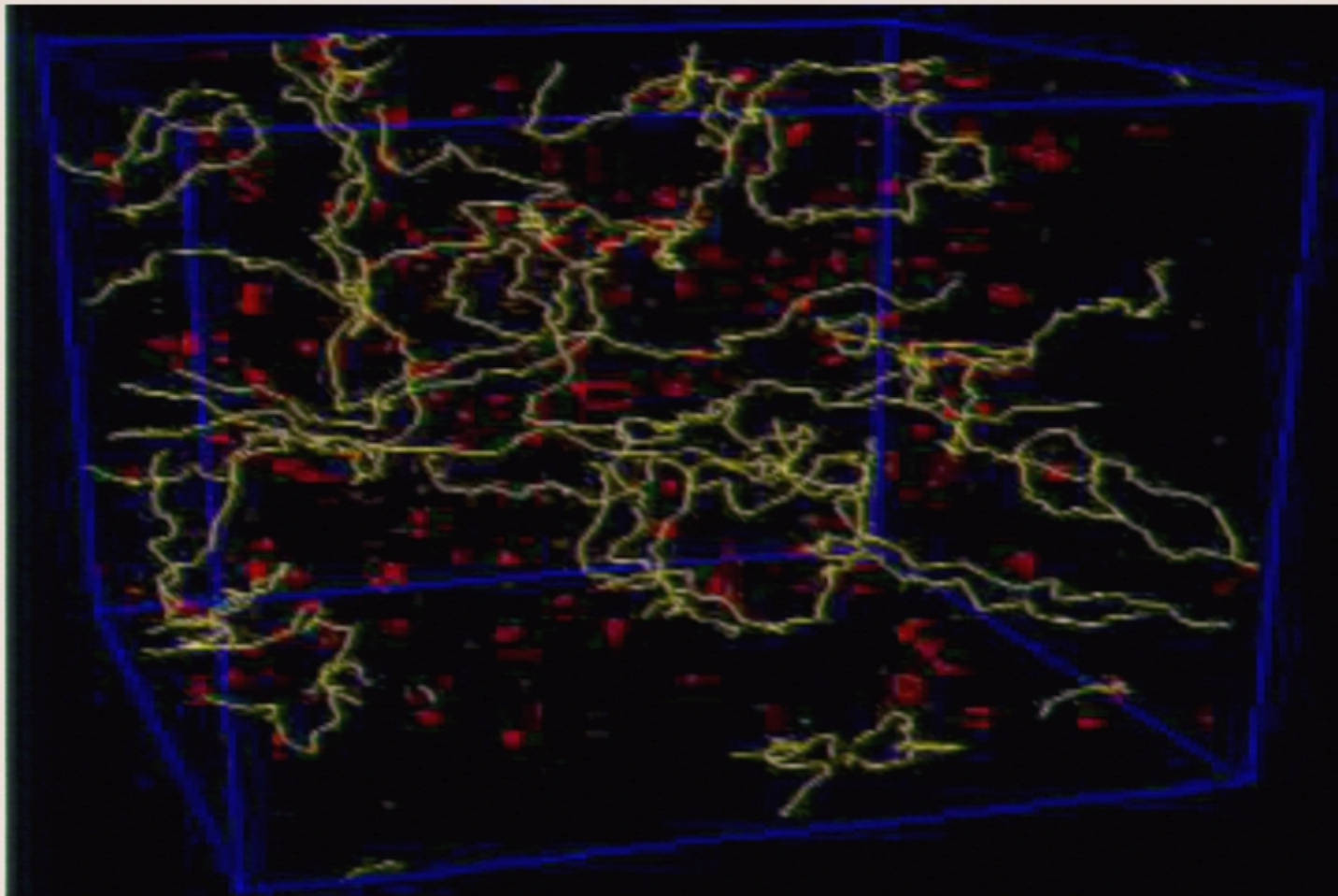
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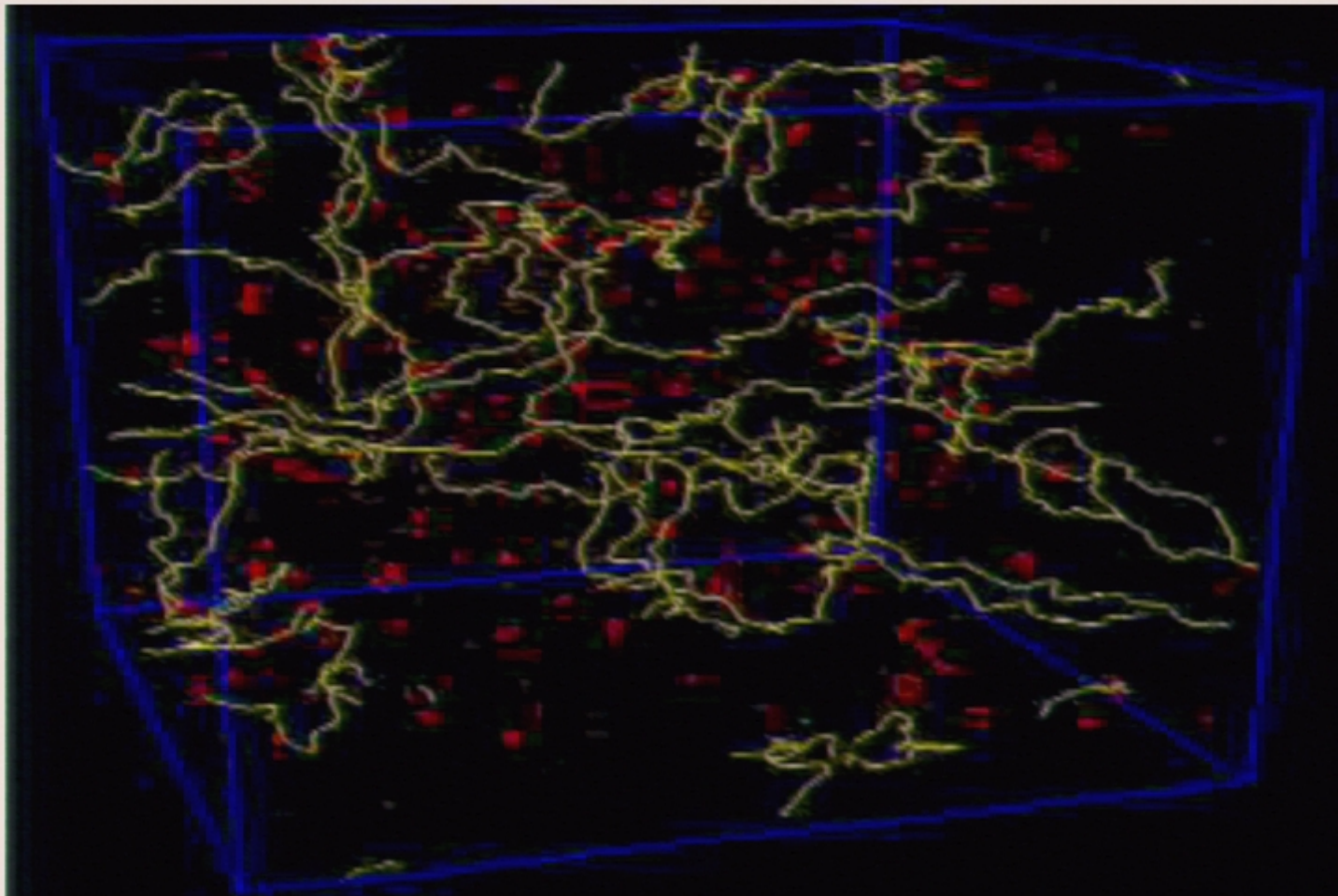
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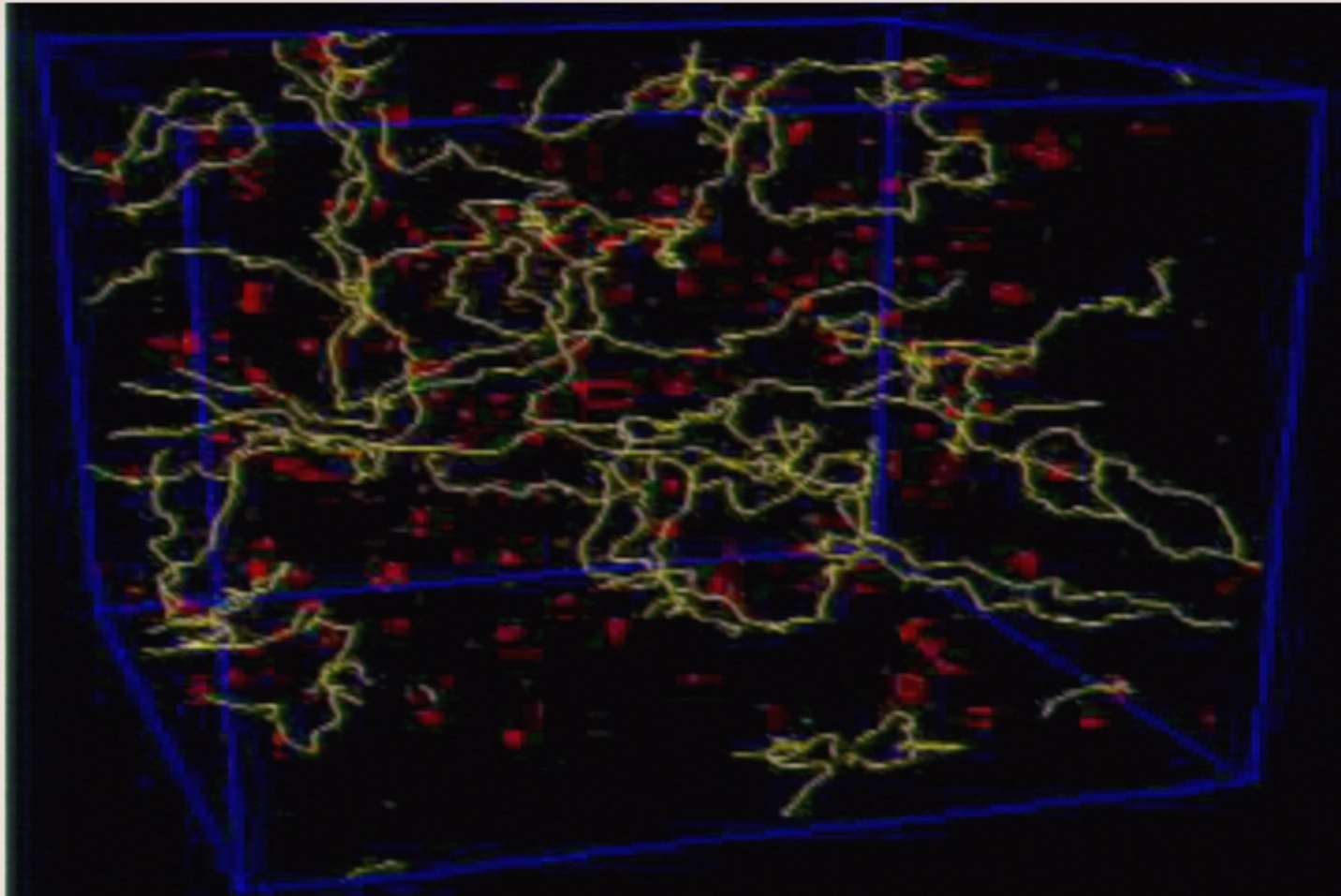
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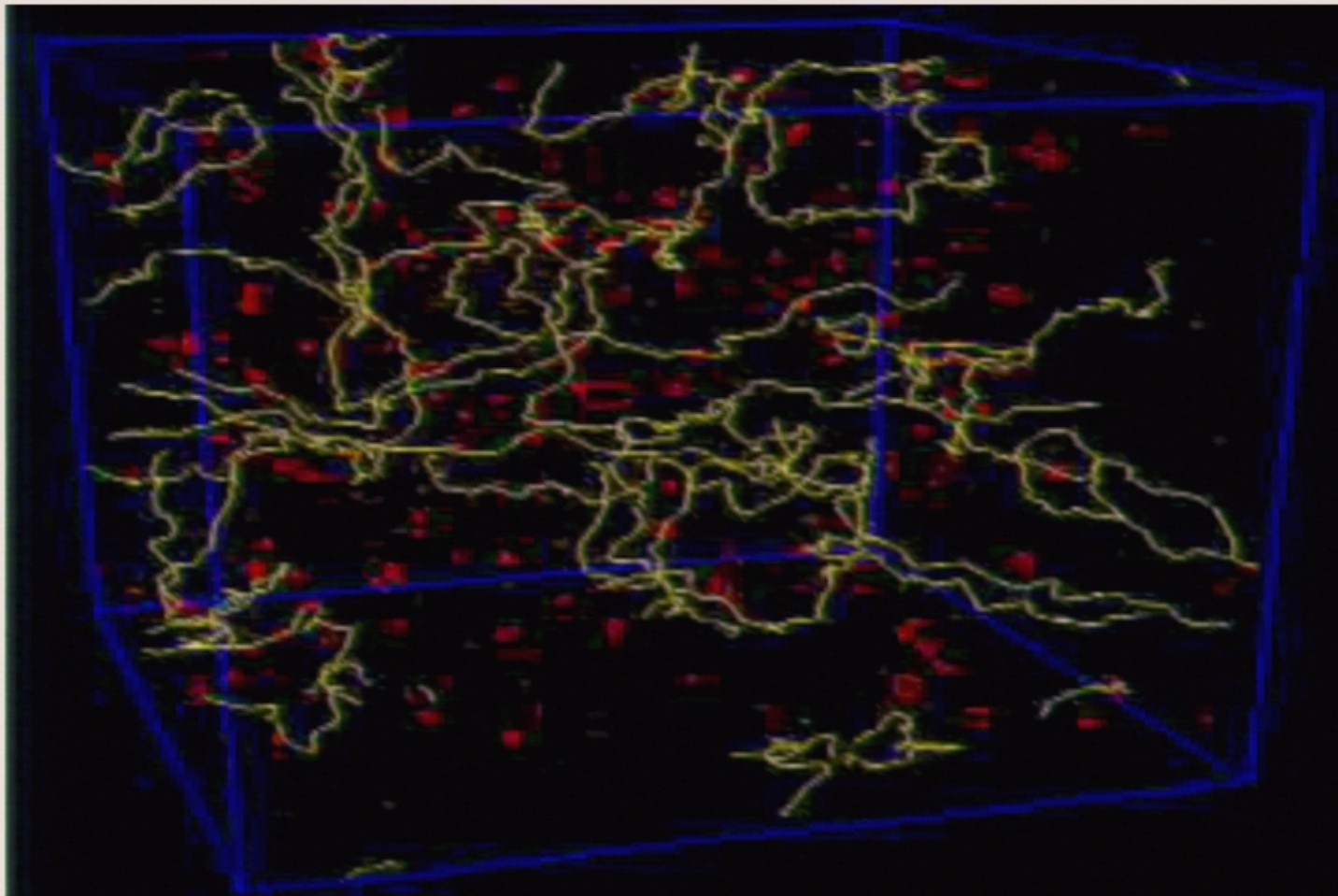
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Cosmic String Network Evolution

Allen, Martins & Shellard



Scaling of the cosmic string network

Velocity-dependent one-scale model

$$v = HL \left(\frac{1 + 3\omega}{2c} \right)$$

$$\frac{dn}{dt} + 2Hn = -\frac{cnv}{L} - Pn^2vL$$

$$\Omega_{cs} \sim 8\pi G\mu(10)$$

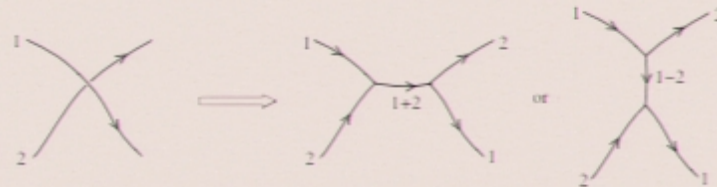
$$v \sim 0.65$$

Kibble, Martins, Shellard etc.

(p,q) Superstrings

- In contrast to vortices in Abelian Higgs model, cosmic strings from brane inflation should have a spectrum in tension.
- A simple example is the (p,q) strings, where p and q are coprime. (1,0) strings are fundamental strings while (0,1) strings are D1-strings.
- The spectrum depends on the particular brane inflationary scenario.

$$G\mu_{p,q} = \sqrt{p^2 g_s^2 + q^2} G\mu$$



They have non-trivial interactions.

N. Jones, H. Stoica, H.T., hep-th/0303269

G. Dvali and A. Vilenkin, hep-th/0312004

E. Copeland, R. Myers and J. Polchinski, hep-th/0312067

M. Jackson, N. Jones and J. Polchinski, hep-th/0405229

Evolution of the (p,q) Cosmic Superstring Network

$$\begin{aligned} & \frac{dn_\alpha}{dt} + 2Hn_\alpha \\ &= -\frac{cn_\alpha v}{L} - Pn_\alpha^2 vL + FvL \left(\frac{1}{2} \sum_{\beta,\gamma} P_{\alpha\beta\gamma} n_\beta n_\gamma - \sum_{\beta,\gamma} P_{\beta\gamma\alpha} n_\gamma n_\alpha \right) \end{aligned} \quad (1)$$

$$\alpha = (p, q)$$

$$\dot{v} = (1 - v^2) \left(-2Hv + \frac{c_2}{L} \right) \quad \dot{L} = HL + c_1 v$$

$$c_1 = 0.21 \quad c_2 = 0.18 \quad v = 0.655 \quad HL = 0.137$$

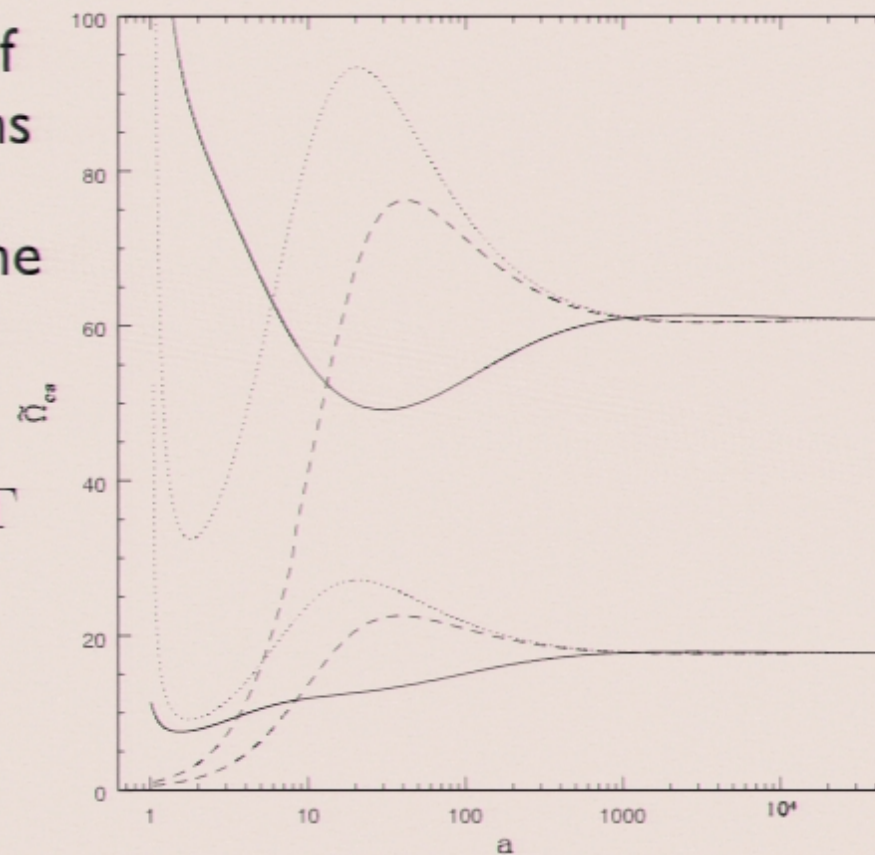
Scaling of the Cosmic Superstring Network

independent of
initial conditions

Insensitive to the
details of the
interactions

$$\Omega_{cs} = 8\pi G\mu\Gamma$$

$$\Gamma \sim 10$$

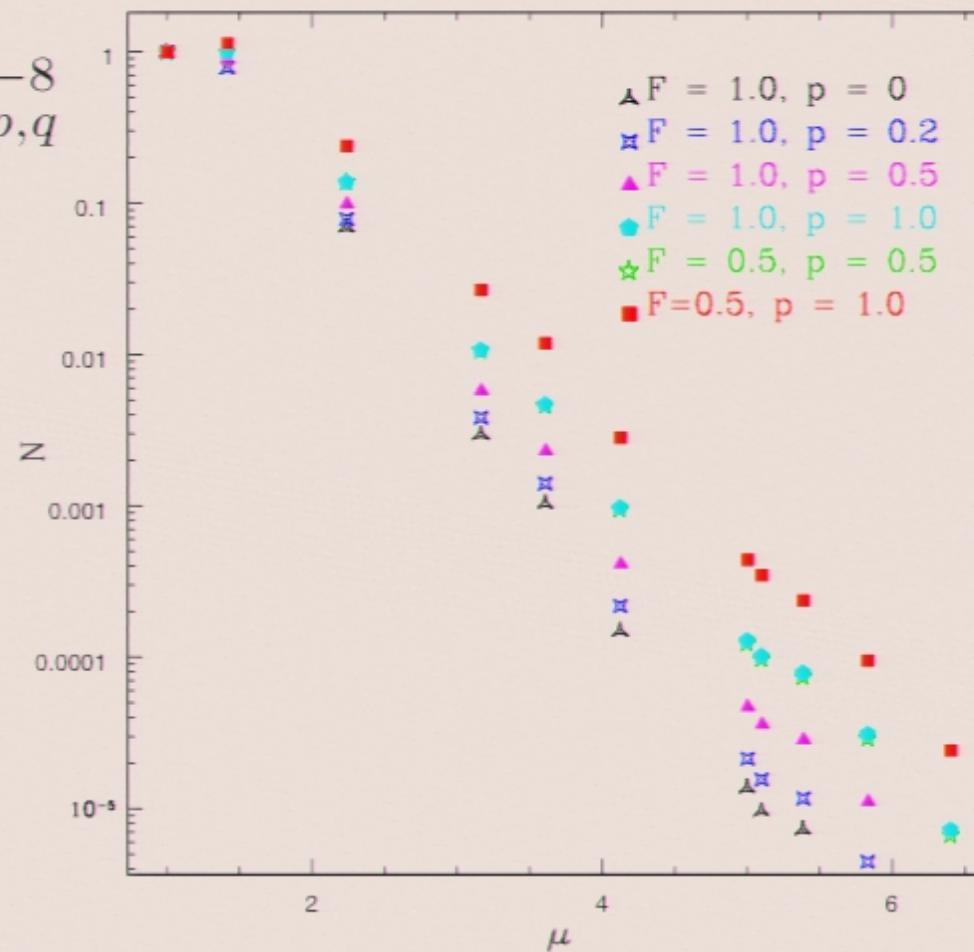


H.T., I. Wasserman, M. Wyman, [astro-ph/0503506](#)

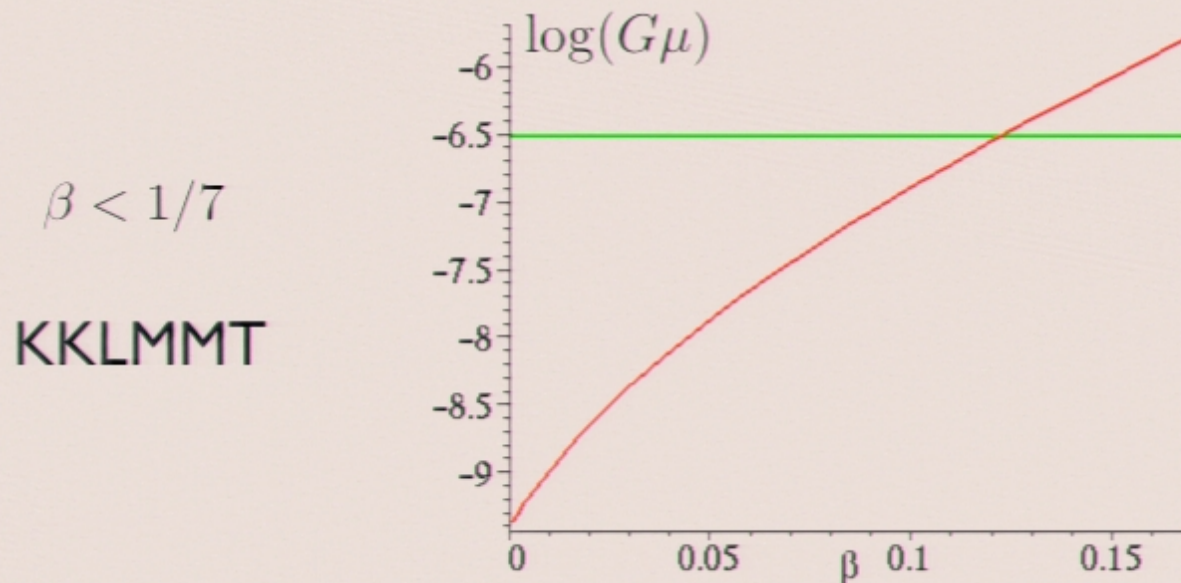
See also E. Copeland and P. Saffin, [hep-th/0505110](#)

Relative density of (p,q) strings

$$n_{p,q} \sim \mu_{p,q}^{-8}$$



Cosmic string tension



$$5 \times 10^{-7} > G\mu \geq 4 \times 10^{-10}$$

H. Firouzjahi, H.T.,
hep-th/0501099

Observational bound from WMAP :

$$5 \times 10^{-7} > G\mu$$

Pogosian, Wasserman, Wyman
Jeong, Smoot

Rich tension spectrum

In 6 dim. toroidal compactification:

$$(p, q) \rightarrow (p, q_1, q_2, q_3, q_4, q_5, q_6)$$

In a warped deformed conifold :

$$(p, n, j, l', m', l, m)$$

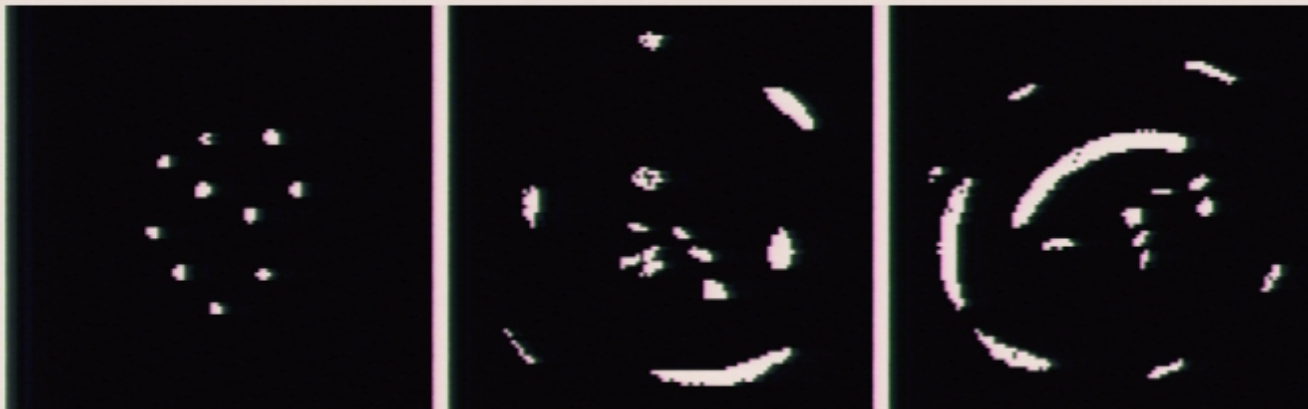
$$\tau(p, n, j - 1, l)$$

with strong enough binding energy

Search for Cosmic Strings

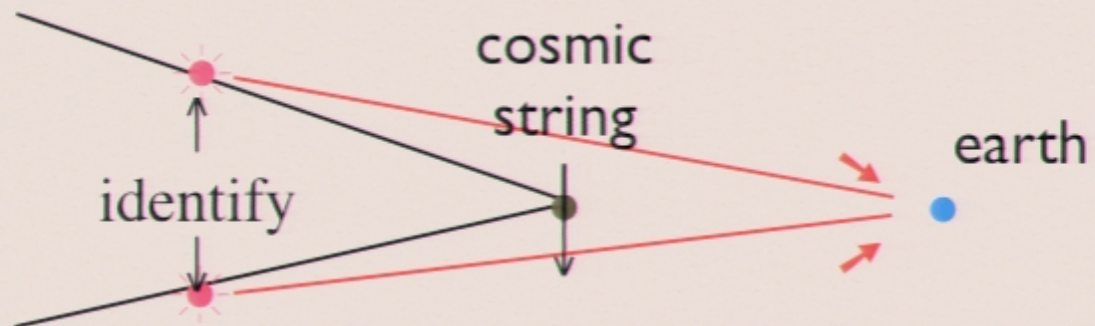
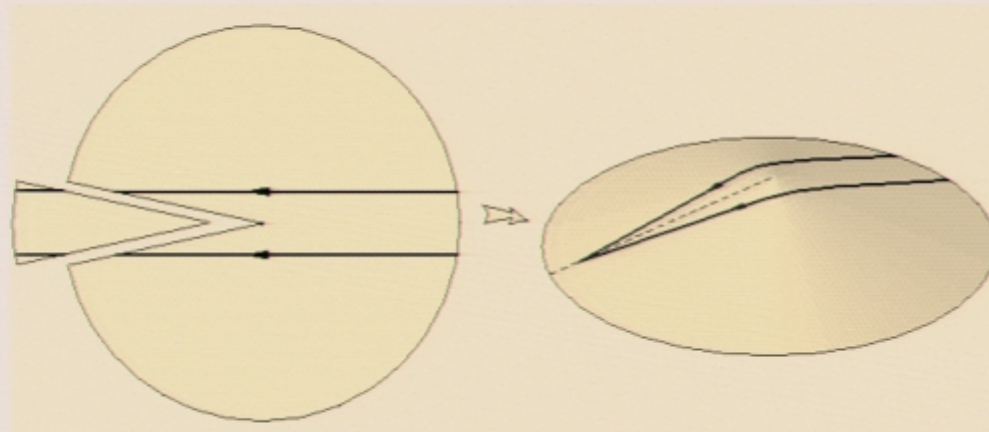
- Lensing
- Cosmic Microwave Background Radiation
- Gravitational Wave Burst
- $\Delta T/T$
- Pulsar Timing
- Stochastic Gravitation Radiation Background

typical gravitational lensing events



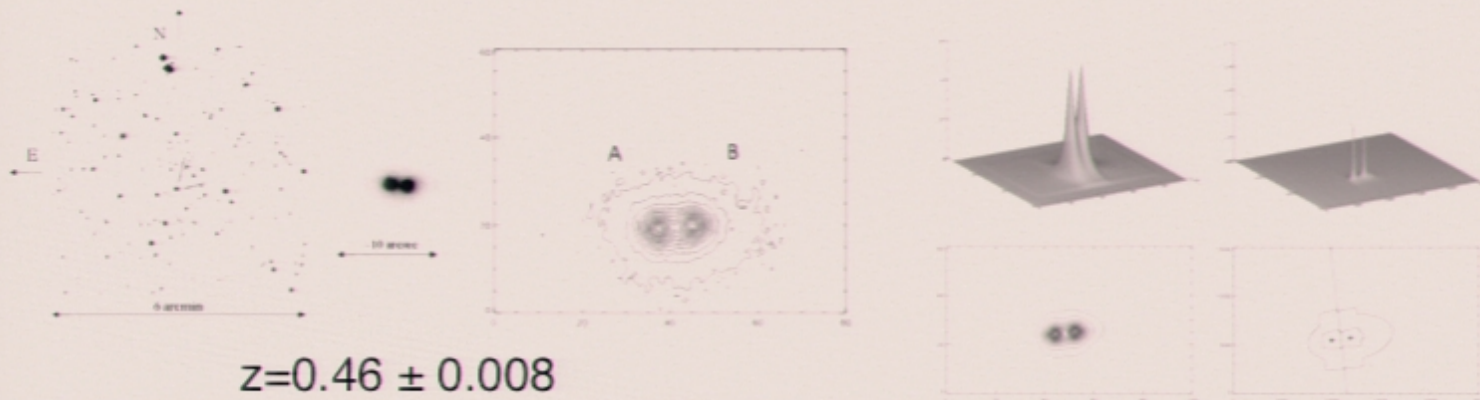
cosmic string lensing

cosmic string introduces a deficit angle

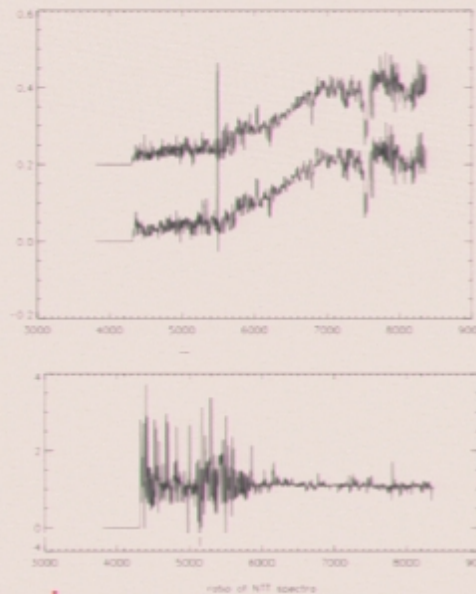
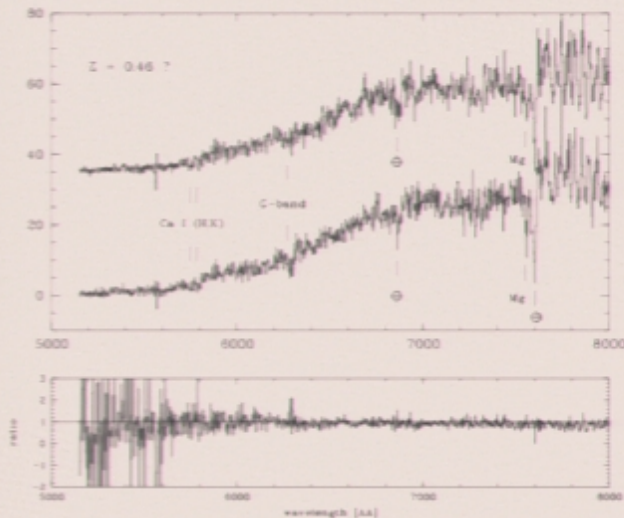


CSL 1

Sazhin etc. astro-ph/0302547



$z=0.46 \pm 0.008$



1.9 arc sec
 $\downarrow$
 $G_{\mu} \sim 4 \times 10^{-7}$

coordinates
 not given !

identical spectra with confidence level
 above 99.9%

More Data :

Sazhin etc, astro-ph/0506400

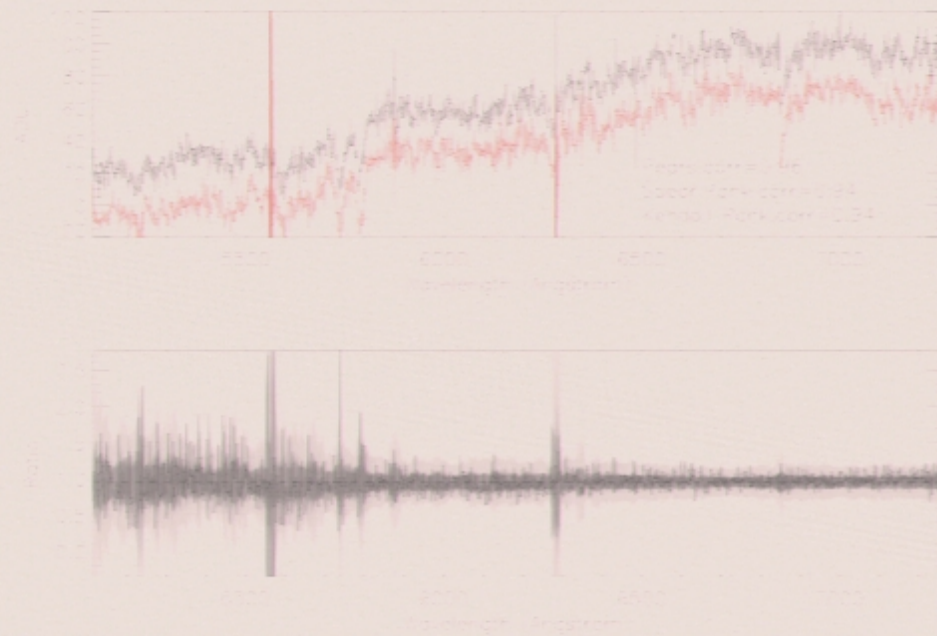
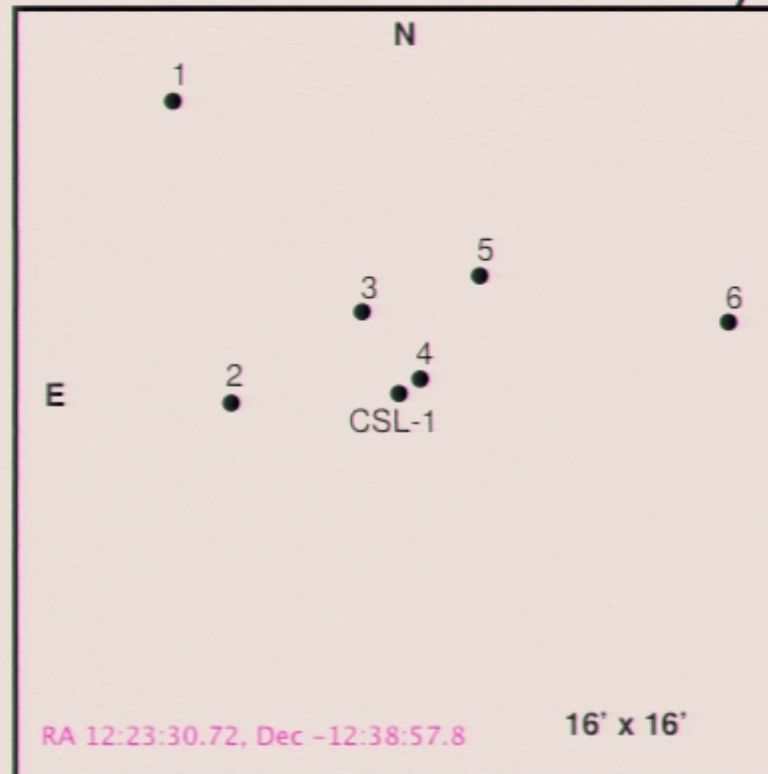


Fig. 3.— Upper panel: the spectra of the two components of CSL-1. Lower panel The ratio between the two spectra in the upper panel. The 1 and 3 σ limits are shown as dark and light grey shaded regions.

$$\text{R.A.}_{2000} = 12^h 23^m 30^s.5; \delta_{2000} = -12^\circ 38' 57''.0$$

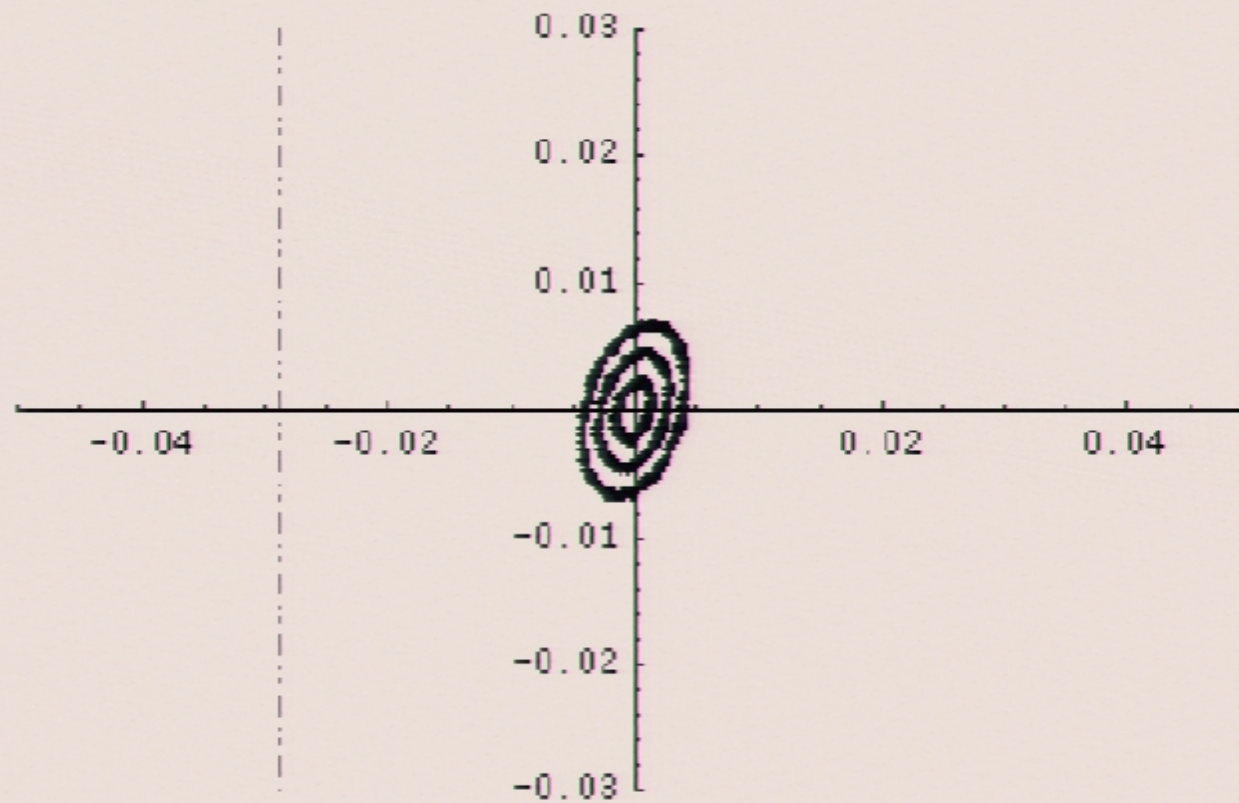
Additional candidates nearby



- Half a degree field with 50,000 sources
- This spring, a UW Seattle group's request for Hubble Space Telescope time was approved for the coming year.

Sazhin, M.V., Khovanskaya, O.S., Capaccioli, M. & Longo, G., 2004, Possible observation of a cosmic string, Talk at *Quarks 2004, 13th International Seminar on High Energy Physics*, Pushkinskie Gory, Russia, May 24-30, 2004.

cosmic string lensing



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cosmic string lensing



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cosmic string lensing



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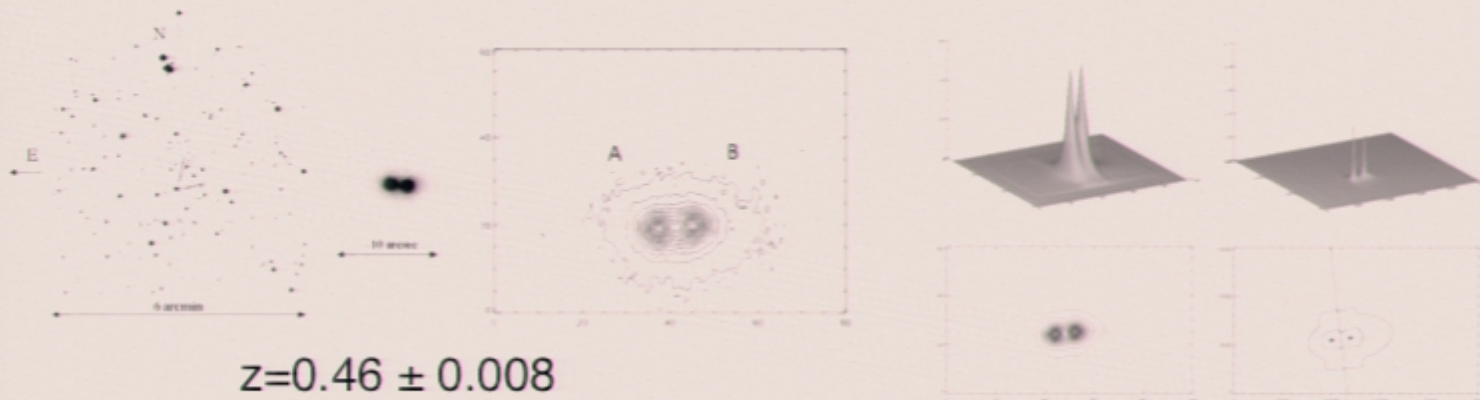
cosmic string lensing



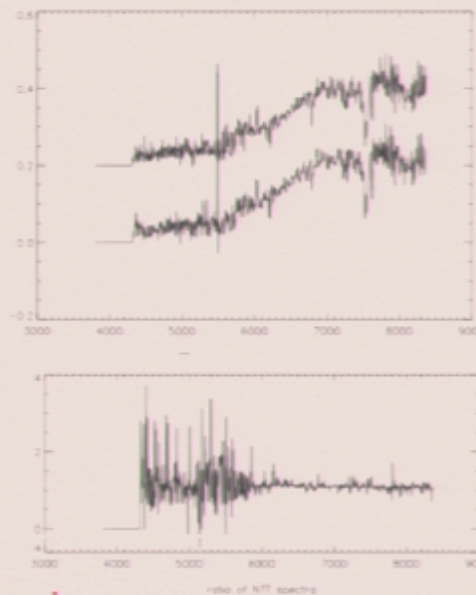
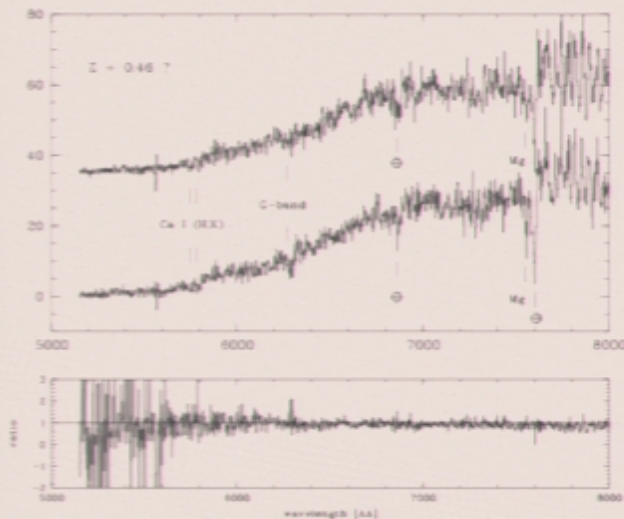
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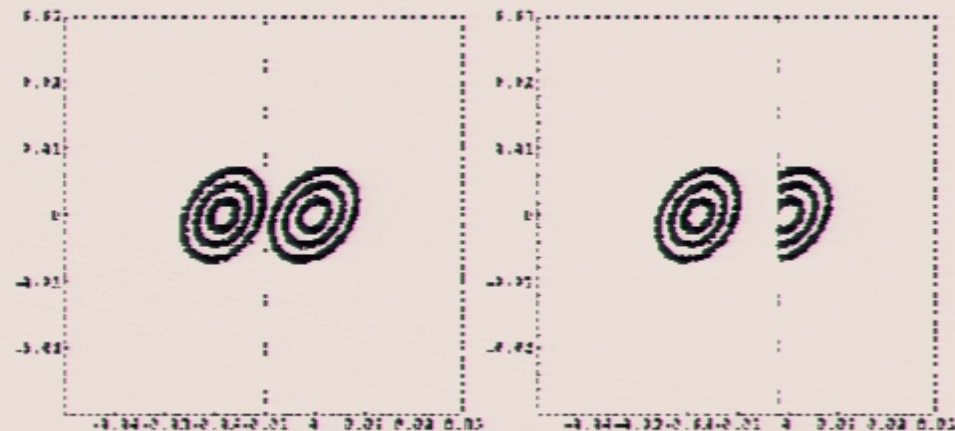


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Clean Signature

$$\delta = \frac{D_{S,CS}}{D_{S,O}} 8\pi G\mu\gamma(1 + \mathbf{n} \cdot \mathbf{v})$$

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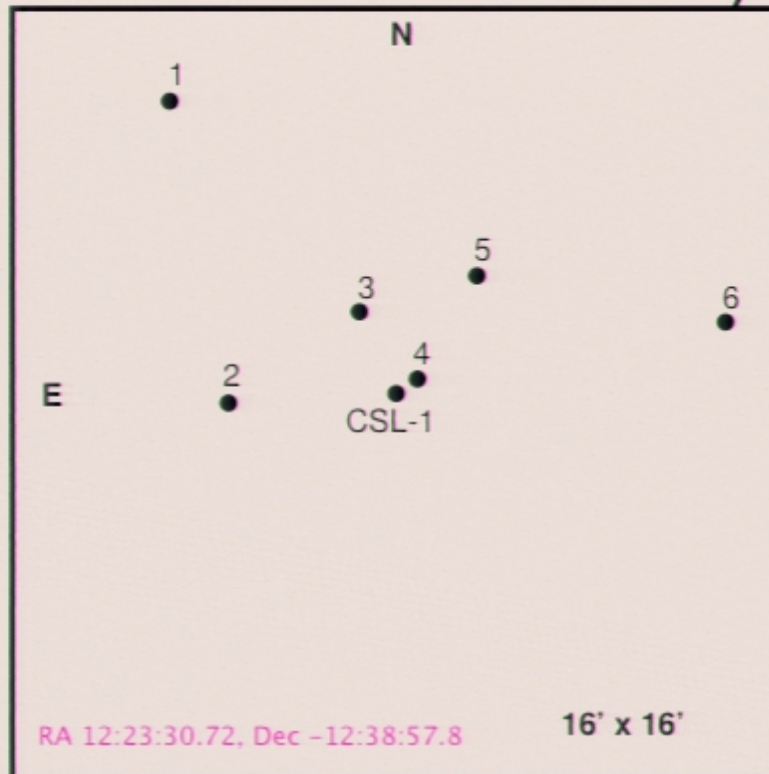


Oscillating string loop:

R. Schild, I Masnyak, B. Hnatyk, V. Zhdanov, [astro-ph/0406434](#)

?

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cosmic string lensing



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cosmic string lensing



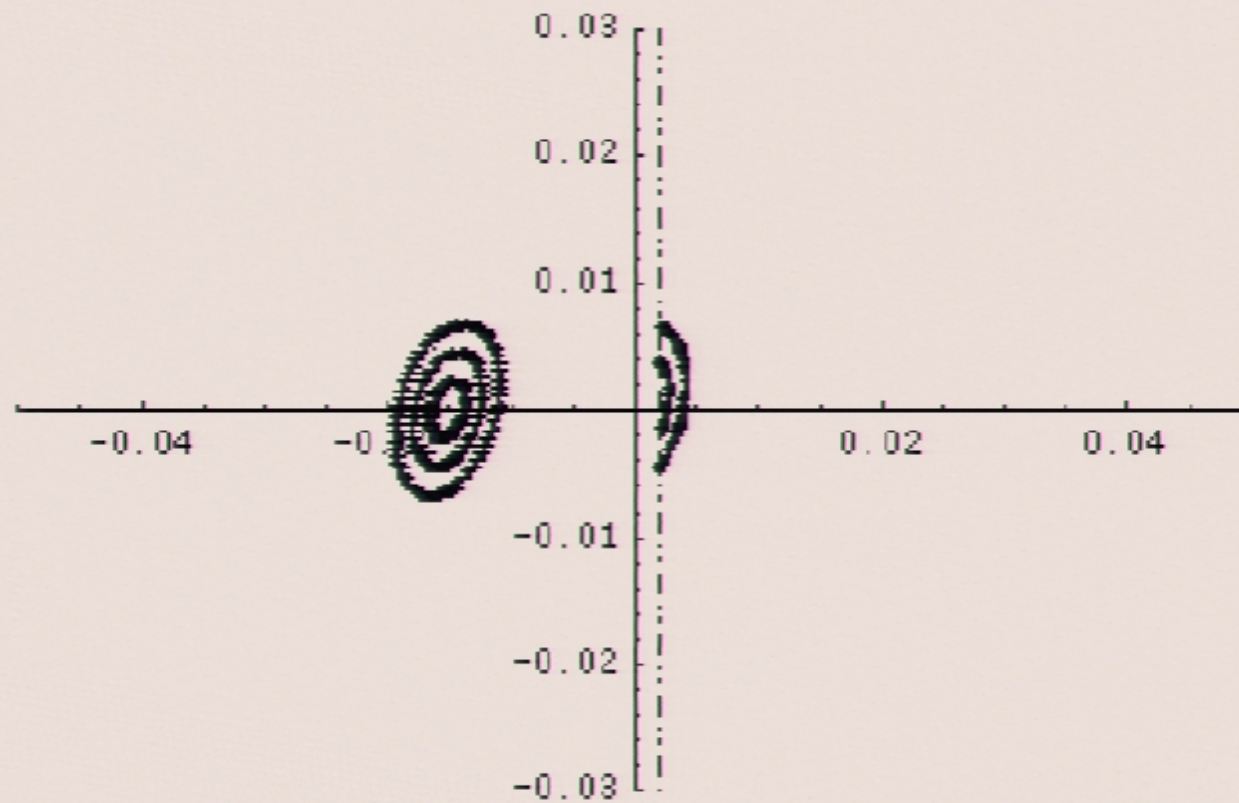
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cosmic string lensing



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cosmic string lensing

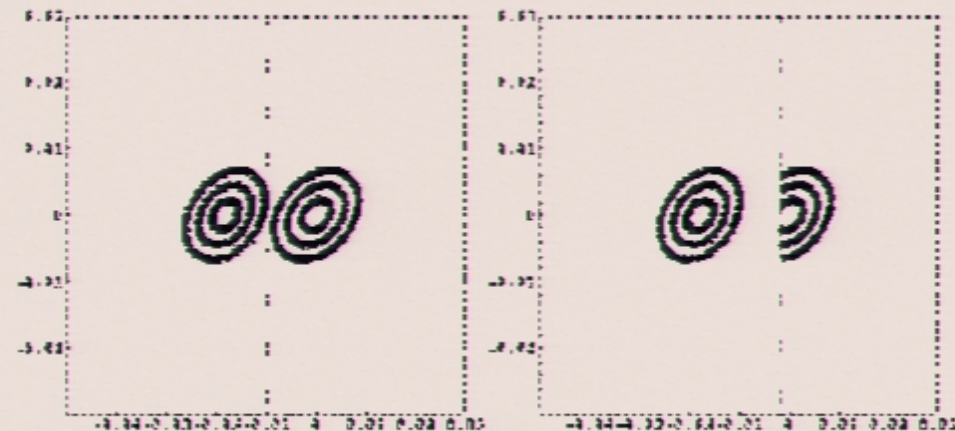


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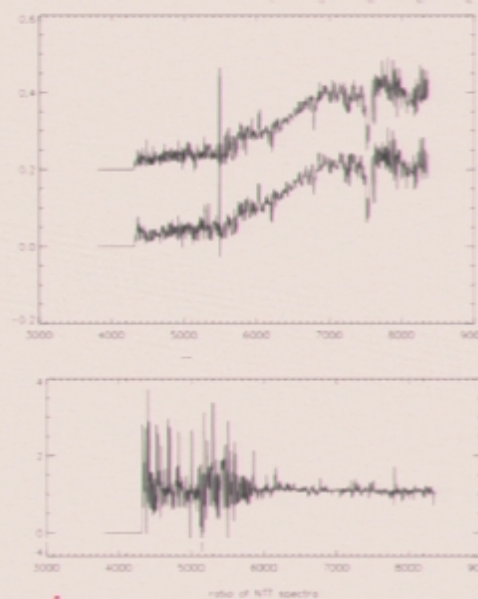
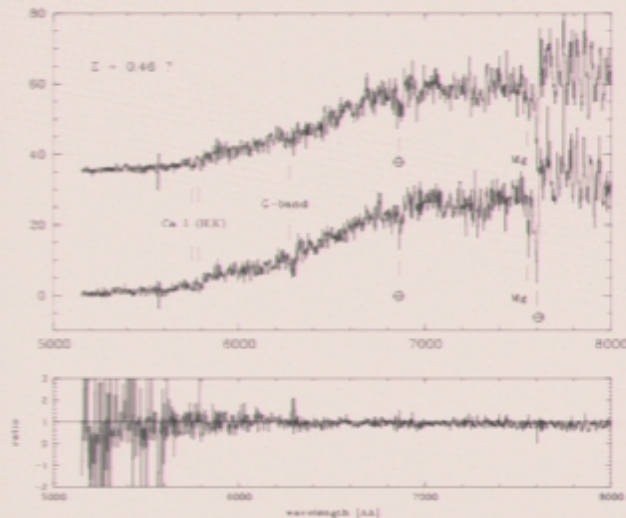
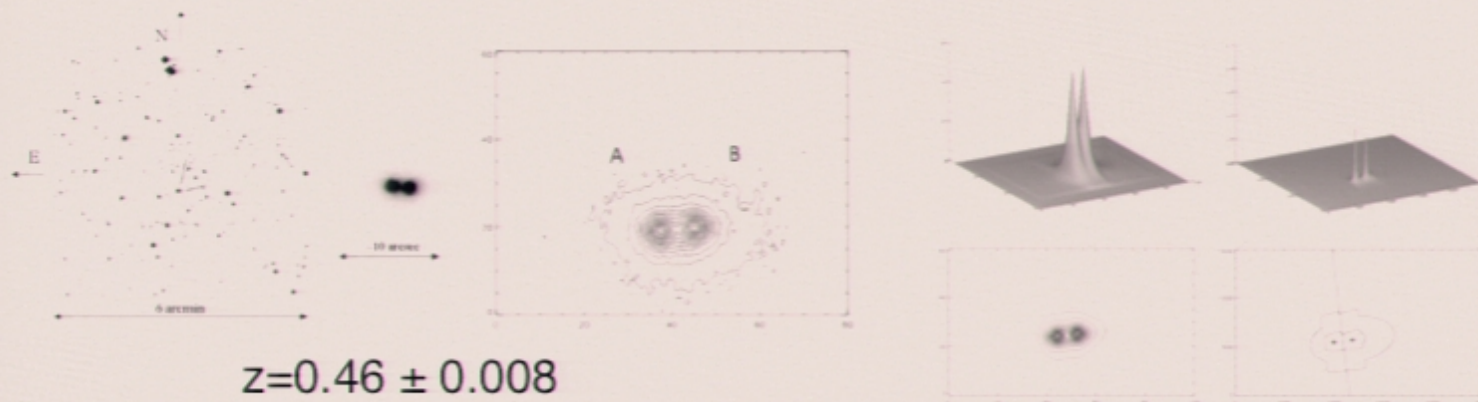
Oscillating string loop:

R. Schild, I Masnyak, B. Hnatyk, V. Zhdanov, [astro-ph/0406434](#)

?

CSL 1

Sazhin etc. astro-ph/0302547



1.9 arc sec
↓
 $G_{\mu} \sim 4 \times 10^{-7}$

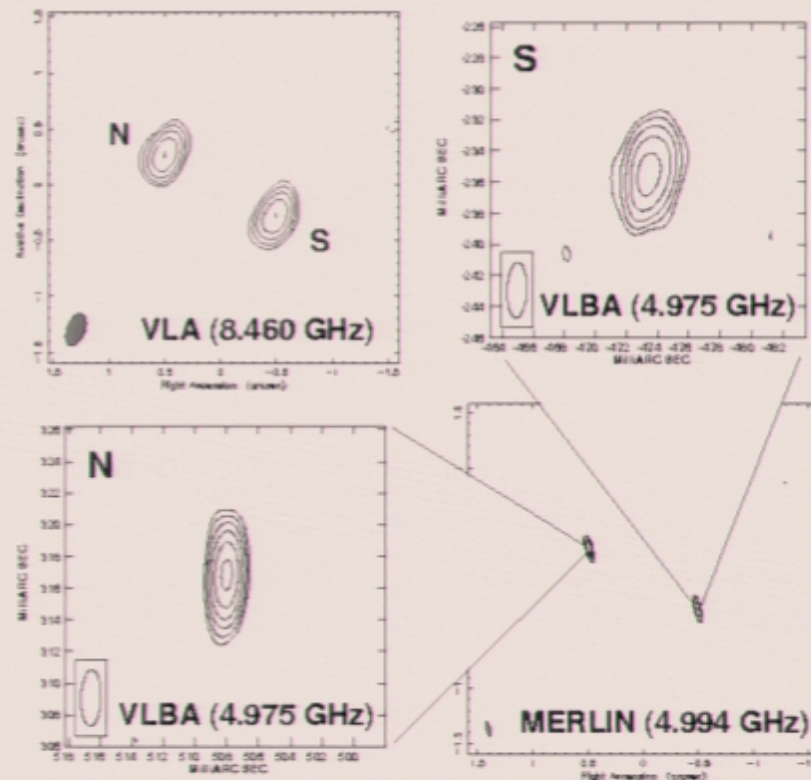
coordinates
not given !

identical spectra with confidence level
above 99.9%

A nearly
symmetric
double-image
gravitational
lens

Winn etc.
astro-ph/0009451

1.13 arc sec
↓
 $G\mu \sim 2 \times 10^{-7}$



$$\Delta T/T = 8\pi G\mu v\gamma$$

Kaiser and Stebbins

2σ effect



hot

cold

CSL-I
 $\Delta T \sim 30\mu\text{K}$

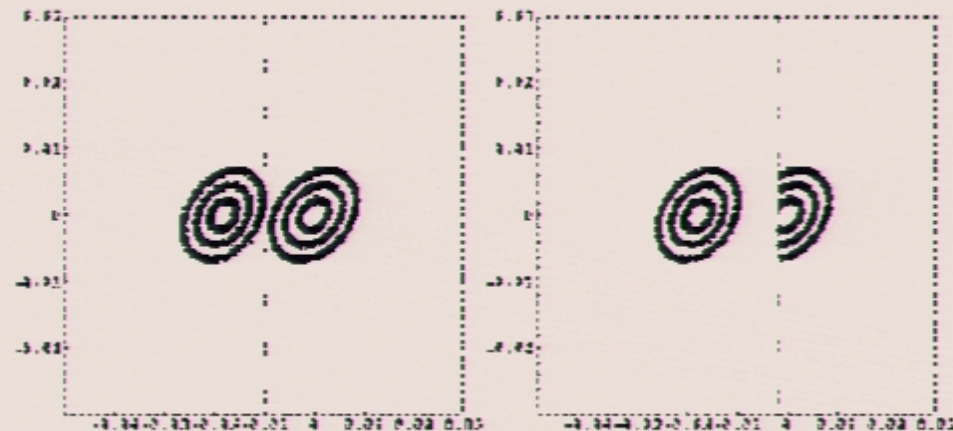
A.S. Lo and E.L. Wright, astro-ph/0503120

Signatures of Cosmic Strings in the Cosmic Microwave
Background

Clean Signature

$$\delta = \frac{D_{s,cs}}{D_{s,o}} 8\pi G\mu\gamma(1 + \mathbf{n} \cdot \mathbf{v})$$

Ben Shlaer



Oscillating string loop:

R. Schild, I Masnyak, B. Hnatyk, V. Zhdanov, [astro-ph/0406434](#)

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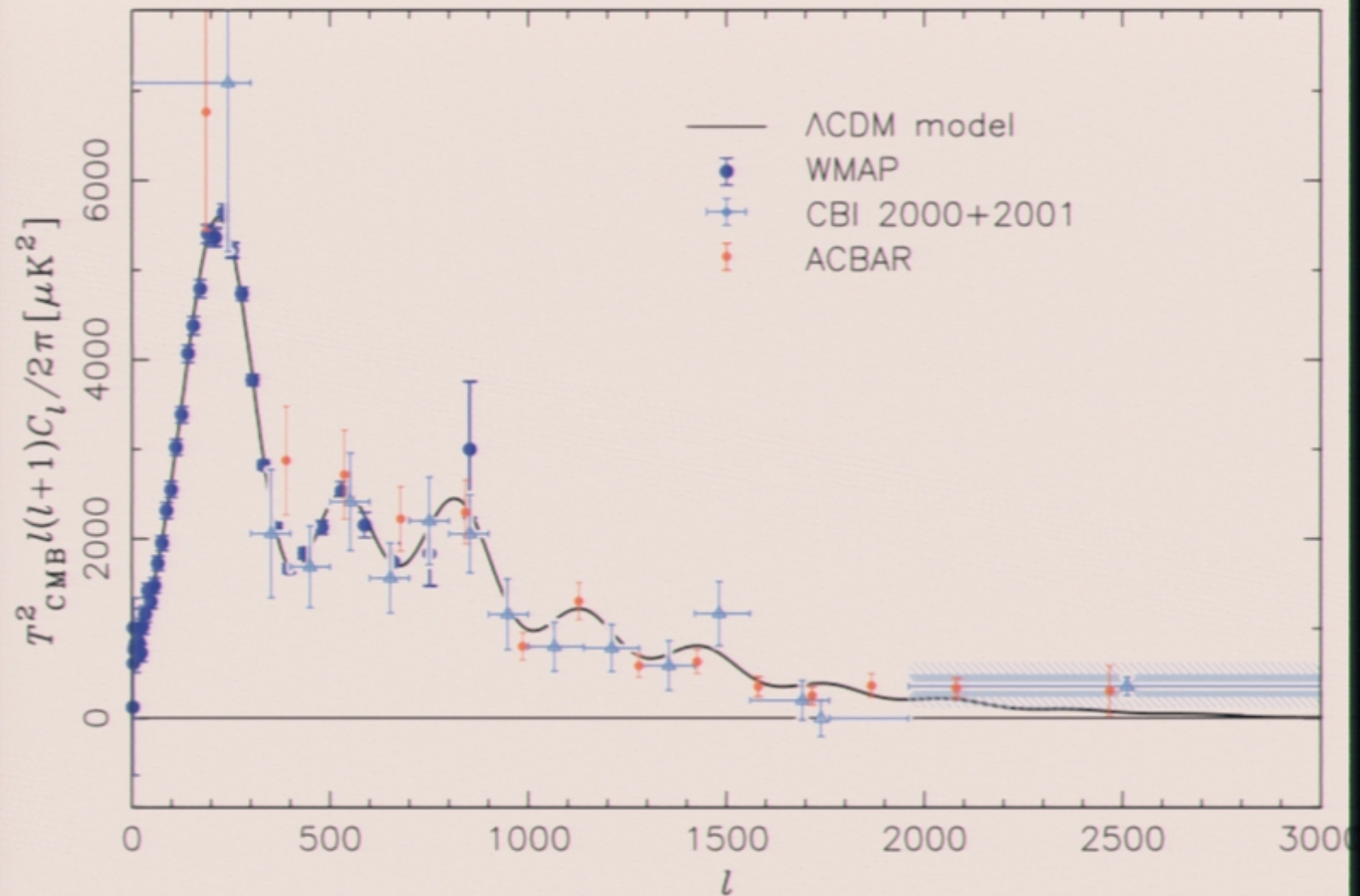
hot

cold

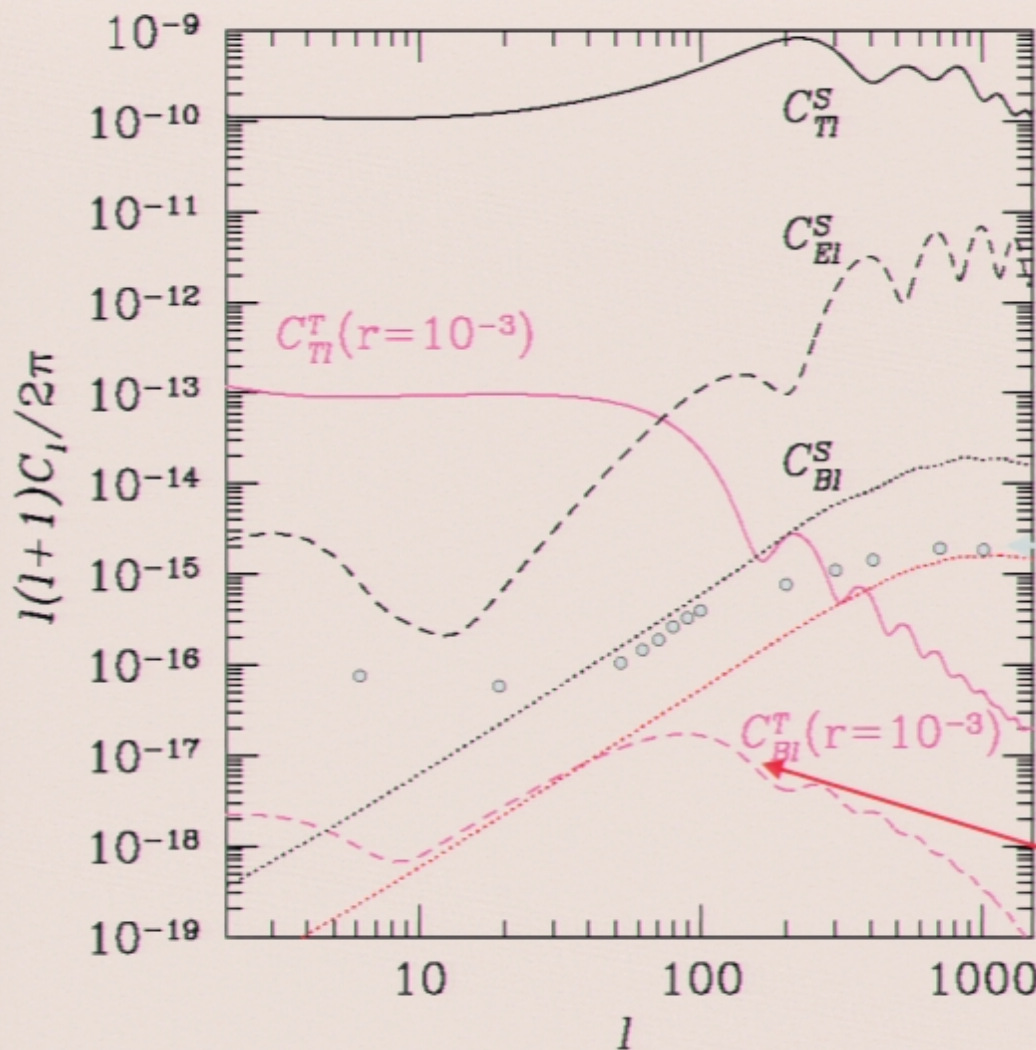
CSL-I
 $\Delta T \sim 30\mu\text{K}$

A.S. Lo and E.L. Wright, astro-ph/0503120

Signatures of Cosmic Strings in the Cosmic Microwave
Background



CBI+WMAP+ACBAR Spectrum. The solid black line is the WMAP Λ CDM model with a pure power-law primordial spectrum (written in `wpri_v1.txt`). The highest l ACBAR point has been displaced slightly to lower l for clarity. The blue shaded and hatched regions indicate confidence intervals on the high- l CBI measurement.



Science Targets:

Fine scale E-pol

Lensing: E → B

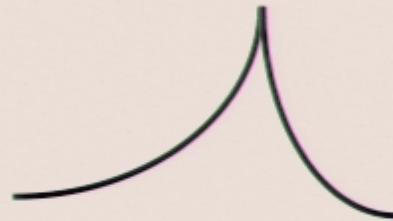
Cosmic Strings
(Brane Inflation)
Pogosian, Tye,
Wasserman,
Wyman:
Astro-ph:03041488

Grav. Waves
 $E_{\text{inf}} \sim 6 \times 10^{15} \text{ GeV}$
(slow-roll Inflation)

CMB B-mode polarization

B. Winstein

cusps and kinks
are quite common in string evolution



CUSP

$$h(t) \sim |t|^{1/3}$$



KINK

$$h(t) \sim |t|^{2/3}$$

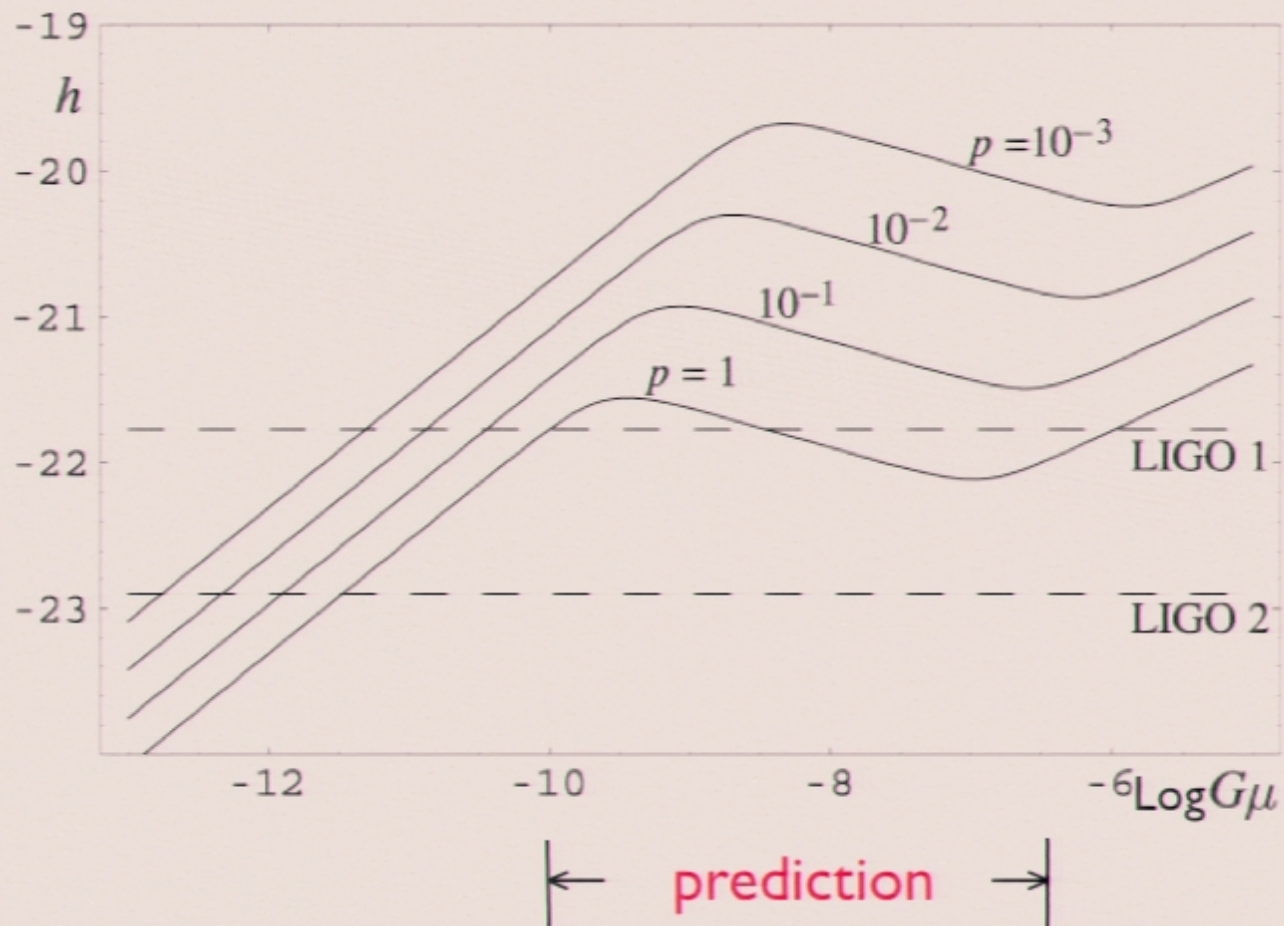


wave form of
gravitational wave bursts

Damour and Vilenkin

gravitational wave radiation from cusps

Damour and Vilenkin



Closed time-like curves

Gott time machine

$$\begin{array}{c} * \rightarrow \\ \leftarrow * \end{array}$$

$$8\pi G\mu\gamma > 2$$

Fortunately or unfortunately,
it is totally unstable

Ben Shlaer

Superstring Theory may be testable

- Instead of searching for tiny particles or signatures in accelerators, such strings may stretch across the universe.
- We still have to show that the string tensions have the right values (as given earlier) so they are compatible with all present observational bounds and yet can be detected in the near future.
- We shall also discuss more of their properties and see that they may have quite distinct signatures.

Open Problems

Stability of D-strings inside D3-branes

E. Copeland, R. Myers and J. Polchinski, hep-th/0312067

L. LeBlond and H.T. hep-th/0402072

J. Blanco-Pillado, G. Dvali, and M. Redi, hep-th/0505172

Reheating

Barnaby, Burgess, Cline, ...

Louis Leblond, N. Jones, ...

A more realistic string tension spectrum than (p,q) .

How natural is the KKLMMT scenario and its extension to fast roll with DBI action (Silverstein, Tong, Alishahiha, Chen,...) ? Sarah Shandera

Other inflationary scenarios in string theory :
branes-at-angle, D3/D7, racetrack, assisted, moduli,
topological,