Title: Searching for Cosmic Superstrings

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Abstract:

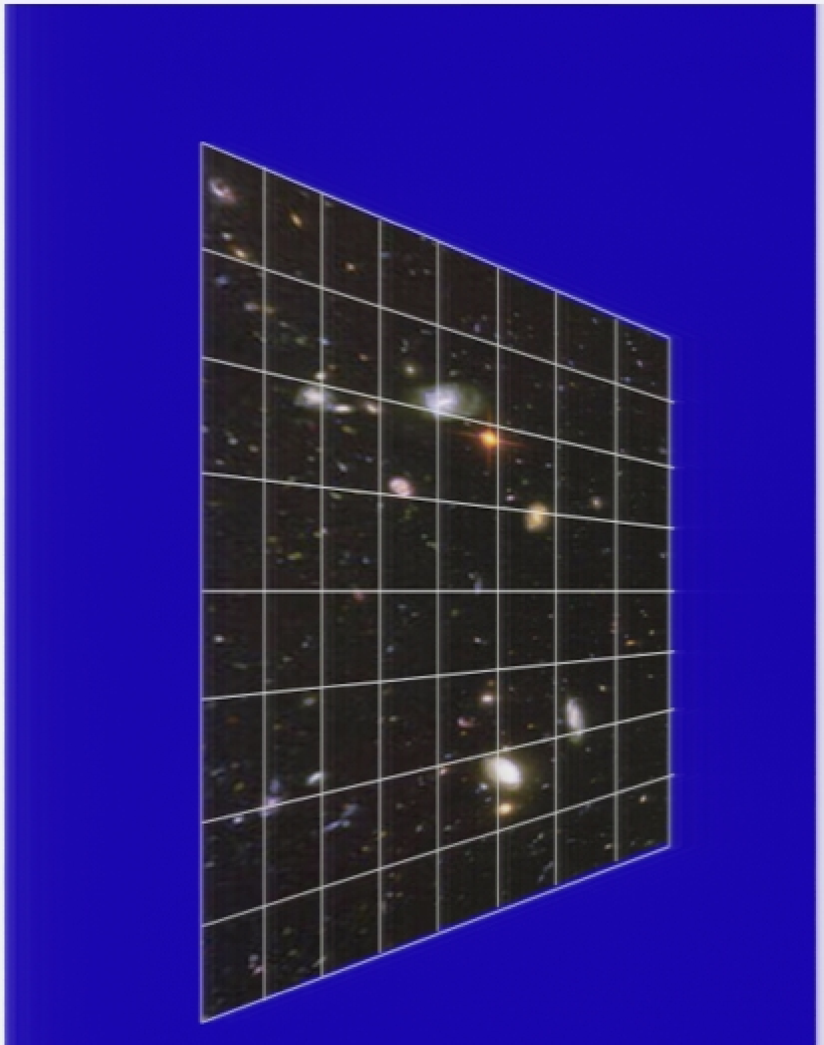
Searching for Cosmic Superstrings

Henry Tye

Gia Dvali, Nick Jones, Louis Leblond, Horace Stoica, Gary Shiu, Levon Pogosian, Sash Sarangi, Ira Wasserman, Mark Wyman, Sarah Shandera, Ben Shlaer, Hassan Firouzjahi

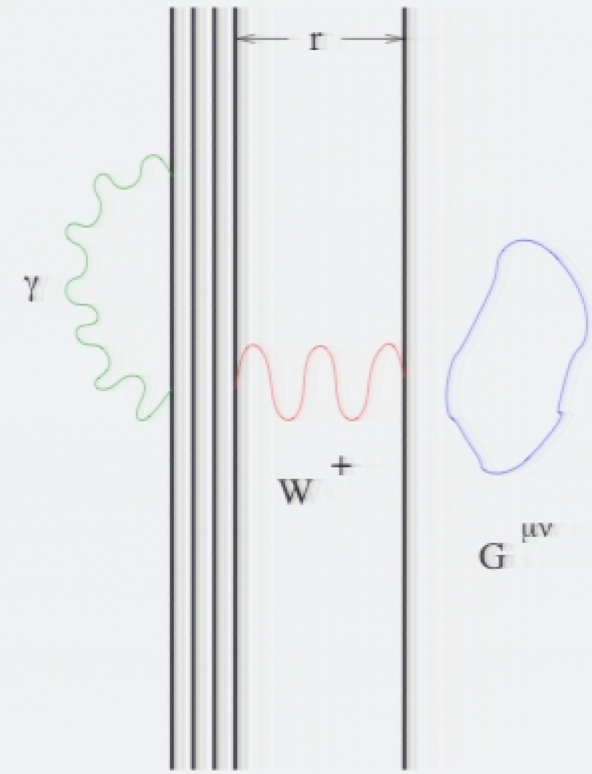
Perimeter Institute, March 29, 2005

Brane World



Aaron
Miller

Brane world



10^{-30} m

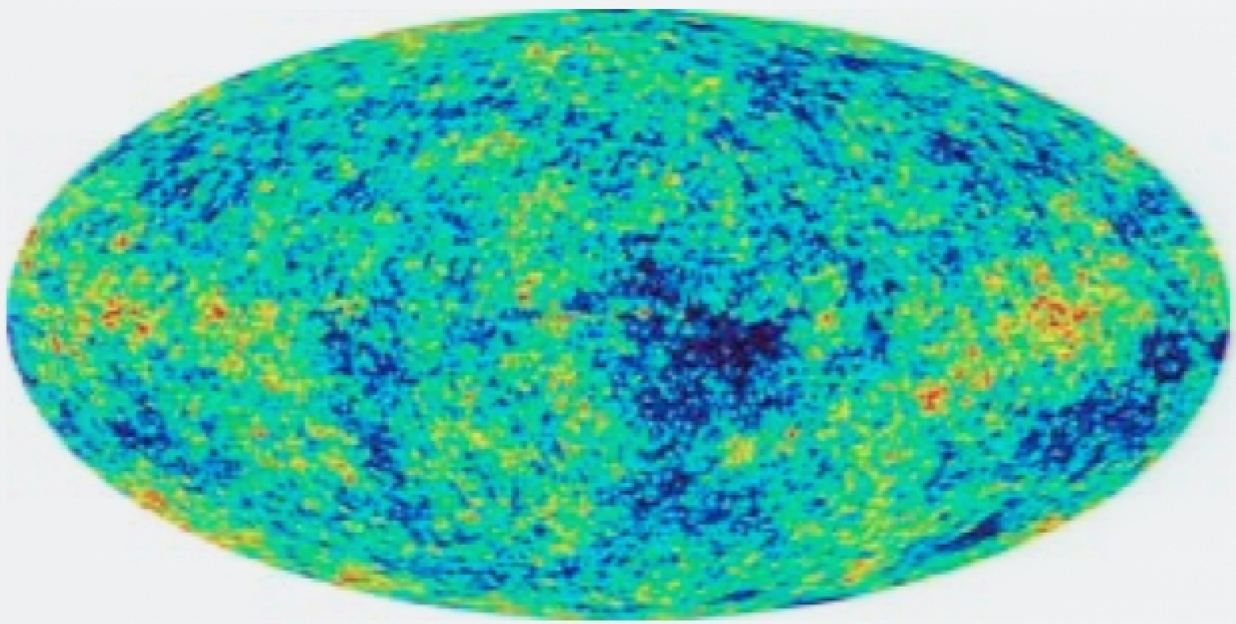
How to test this picture ?

Inflationary Universe

10^{-30} m

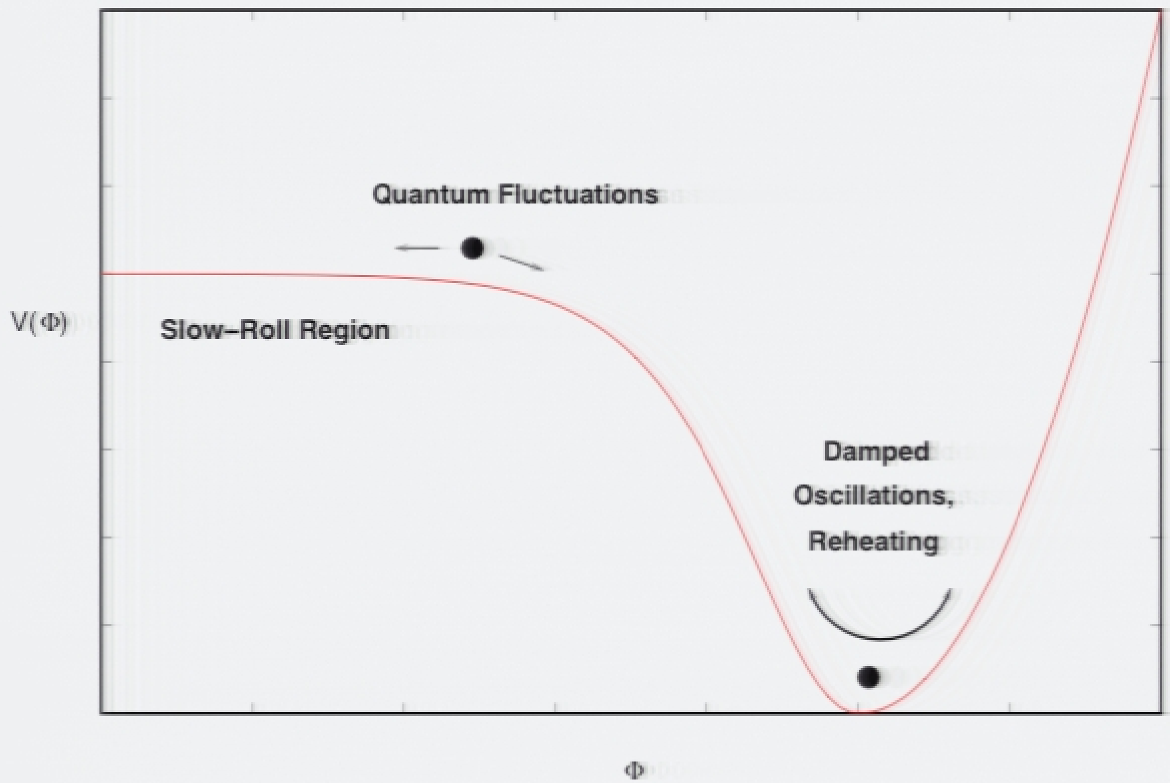
- Inflation : solves a number of outstanding cosmological problem: flatness, horizon, defects, angular momentum etc.
- generated all matter-energy from dark energy
- started the hot big bang
- generated the density perturbation that seeded the structure formation
- generated the temperature perturbation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

WMAP 2003



Data strongly supports inflation

inflaton potential

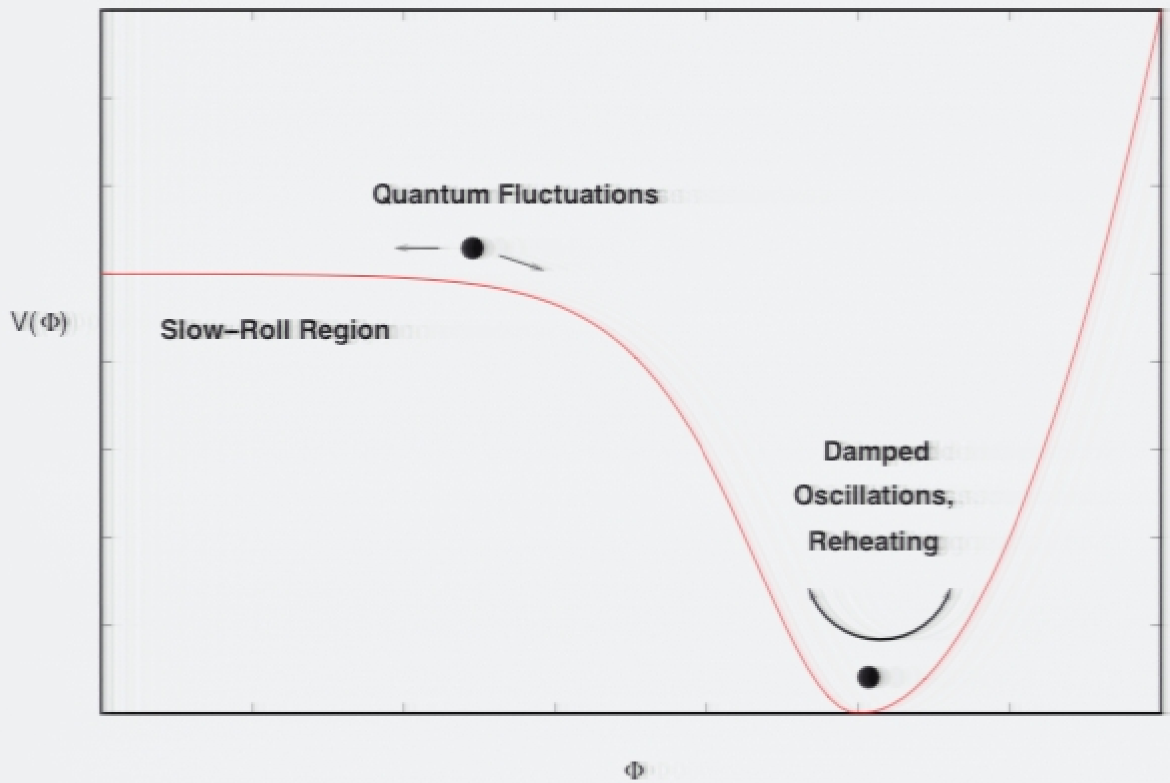


What is the inflaton field ?

Inflation

- $$H^2 = \Lambda + \frac{k}{a^2} + \frac{\rho_m}{a^3} + \frac{\rho_r}{a^4}$$
- a(t) = the cosmic scale factor ~ size of universe
- H = Hubble constant =(da/dt)/a
- Λ = dark energy = cosmological constant
- k = curvature
- ρ_m = matter density at initial time
- ρ_r = radiation density at initial time
- H = constant $\Rightarrow$ a = exp(Ht)

inflaton potential



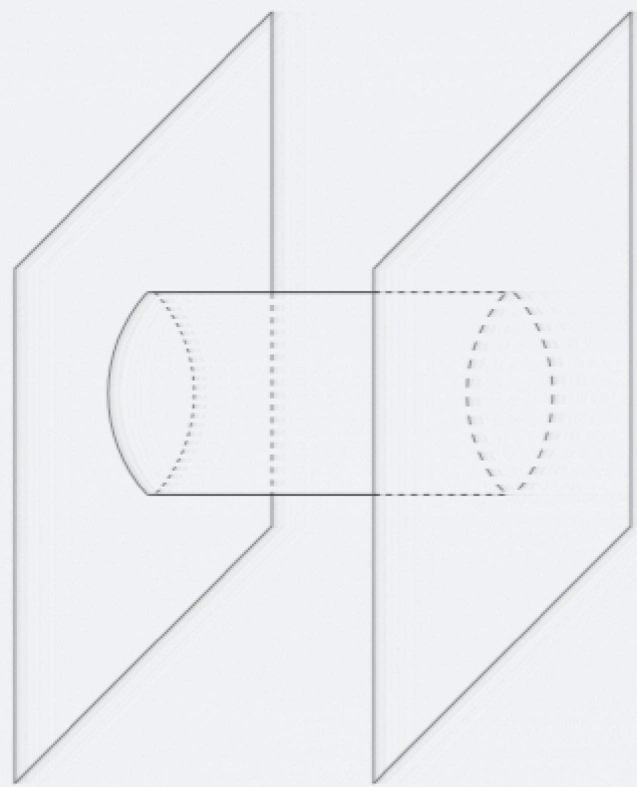
What is the inflaton field ?

How is inflation realized in brane world ?

Brane inflation

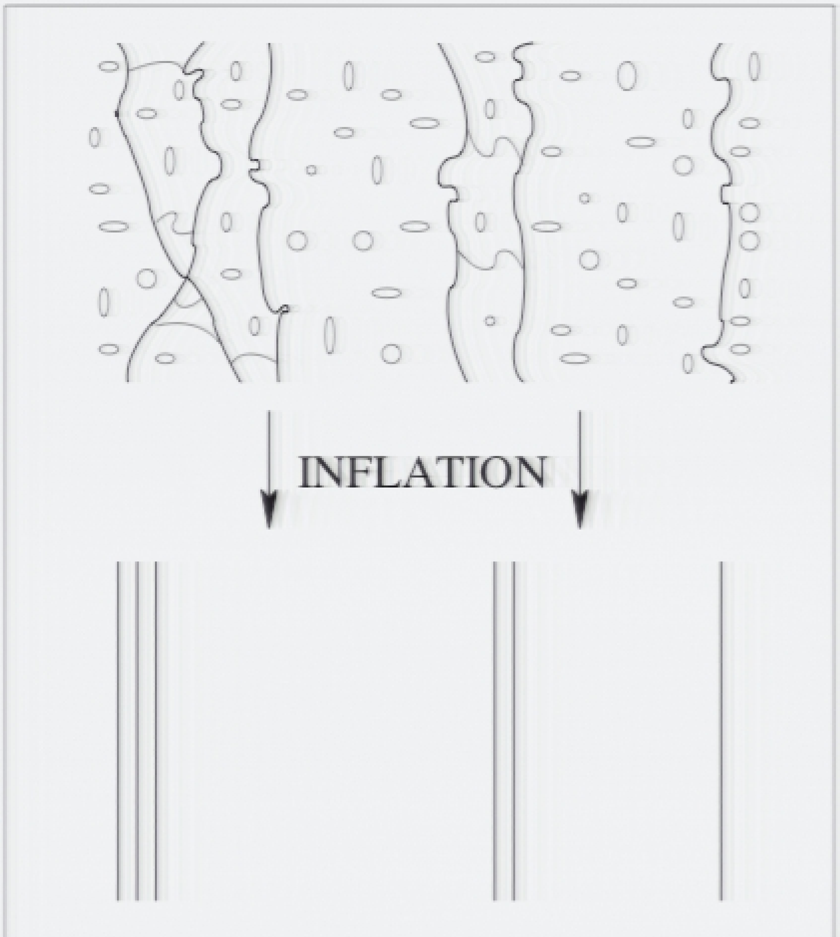
Dvali and H.T. hep-ph/9812483

Inflaton is an open string mode

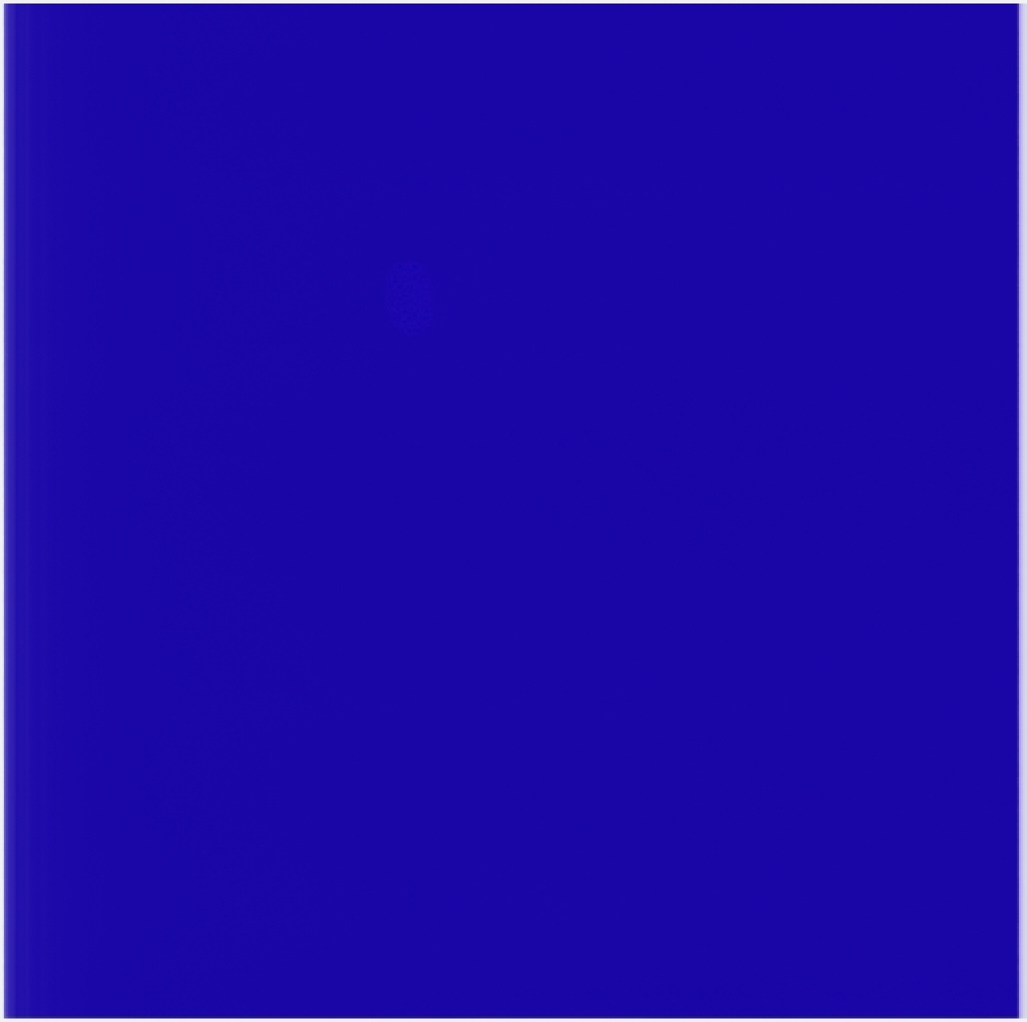


Inflaton potential comes from the closed string exchange

Brane inflation



Brane Inflation and Collision



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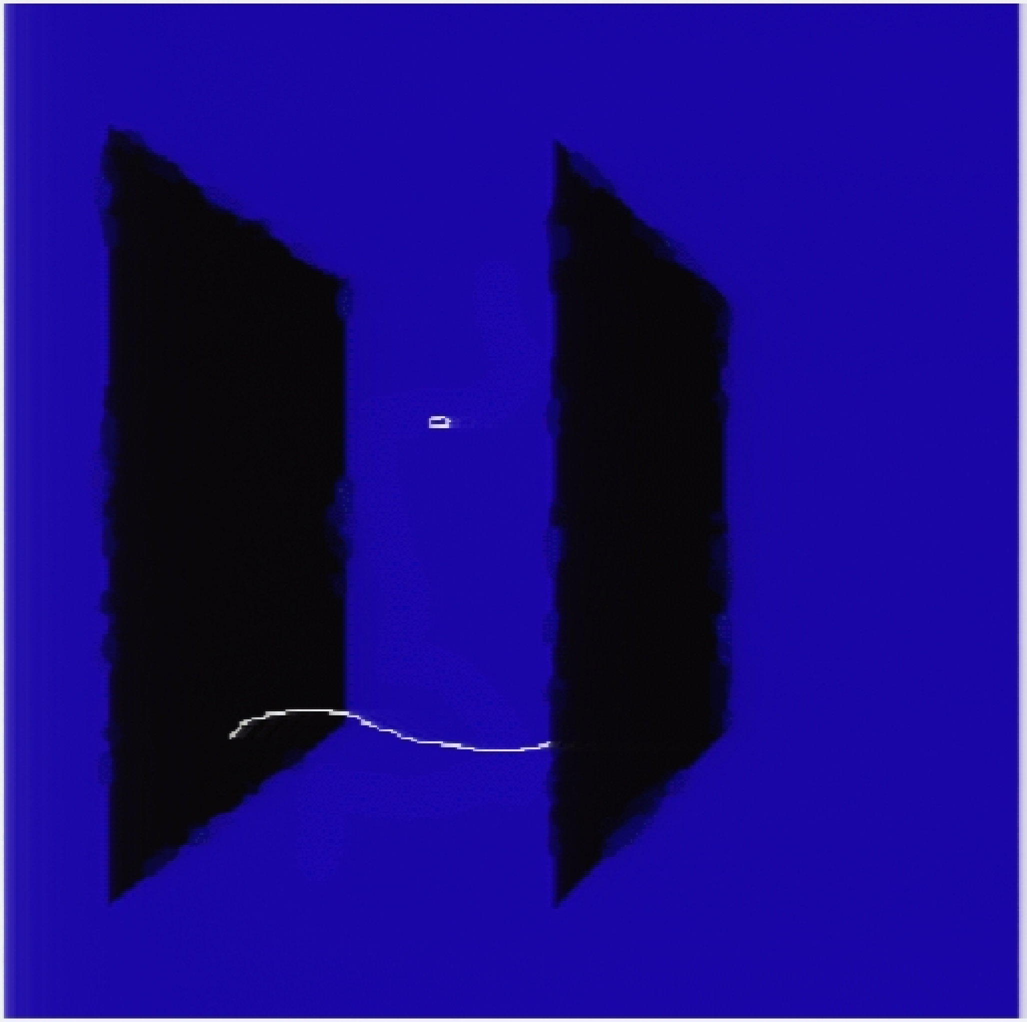

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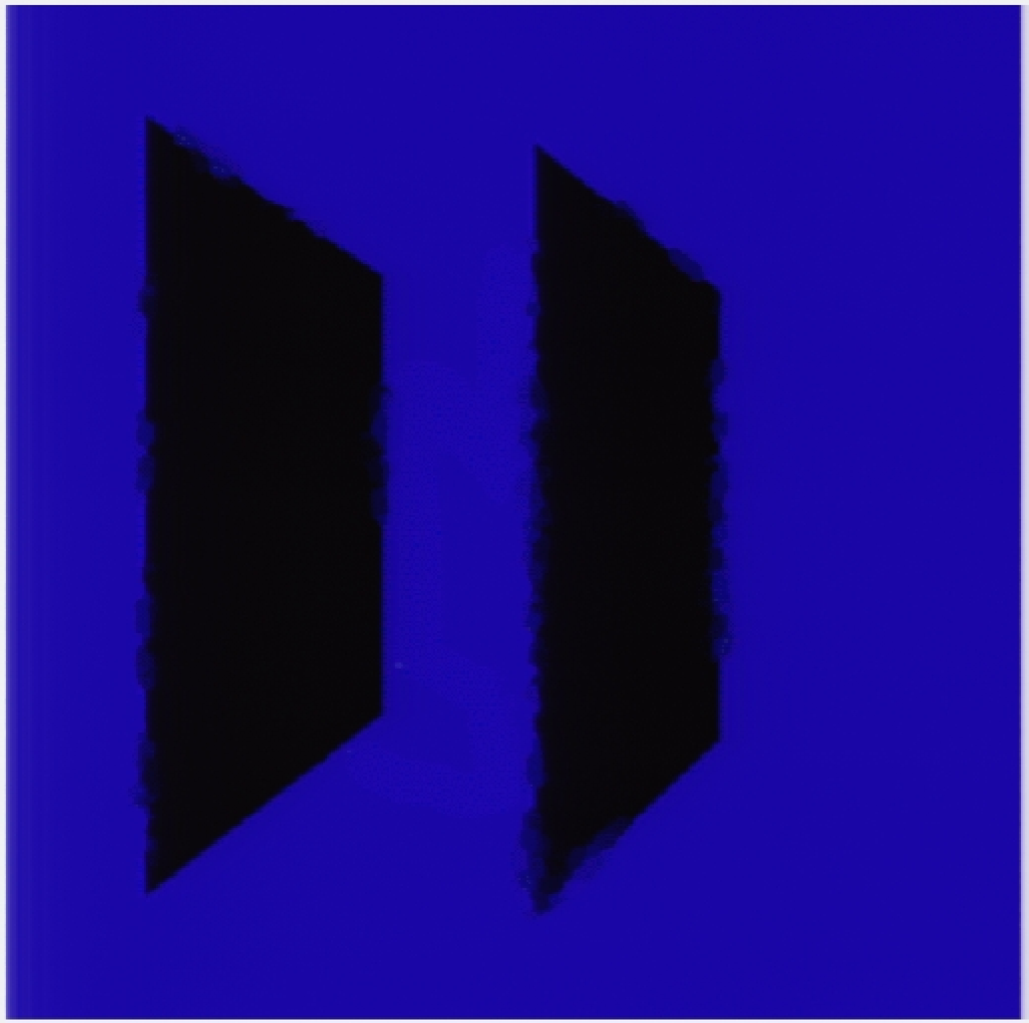

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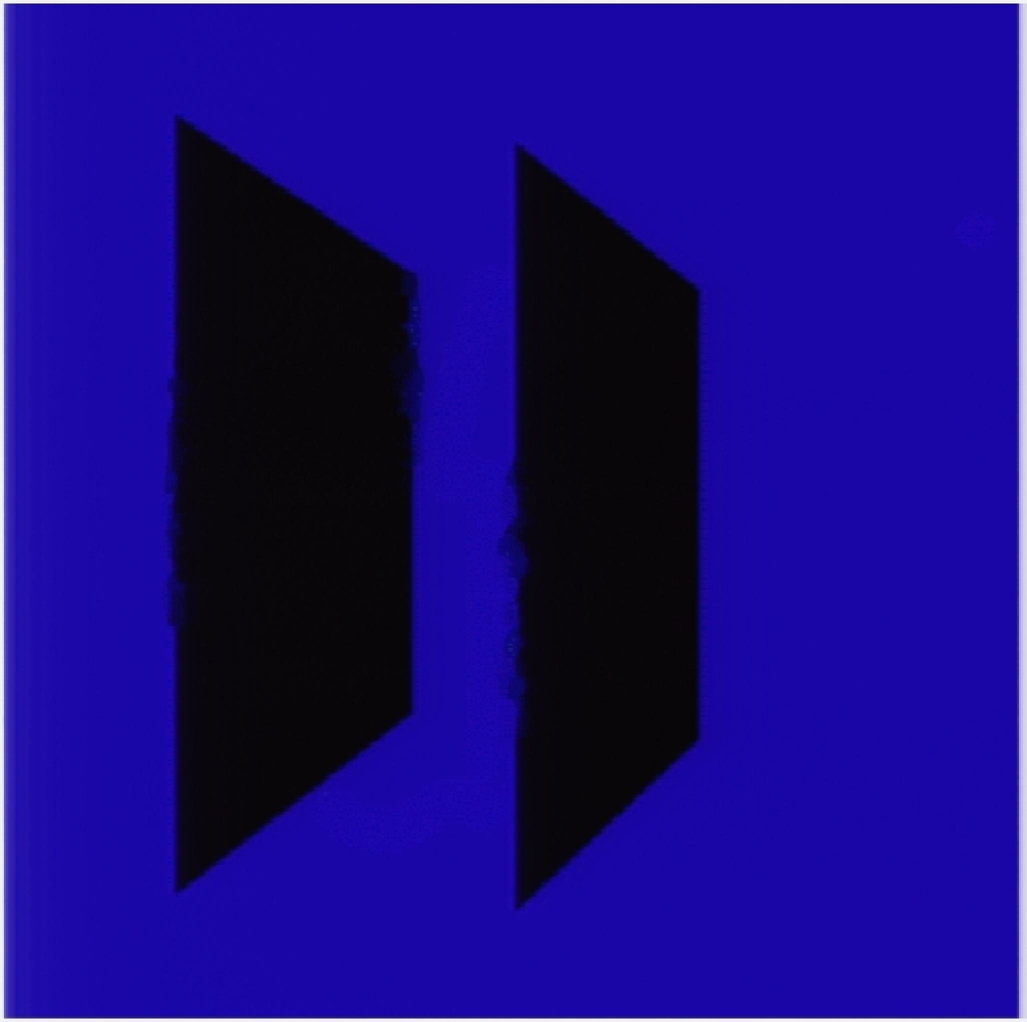

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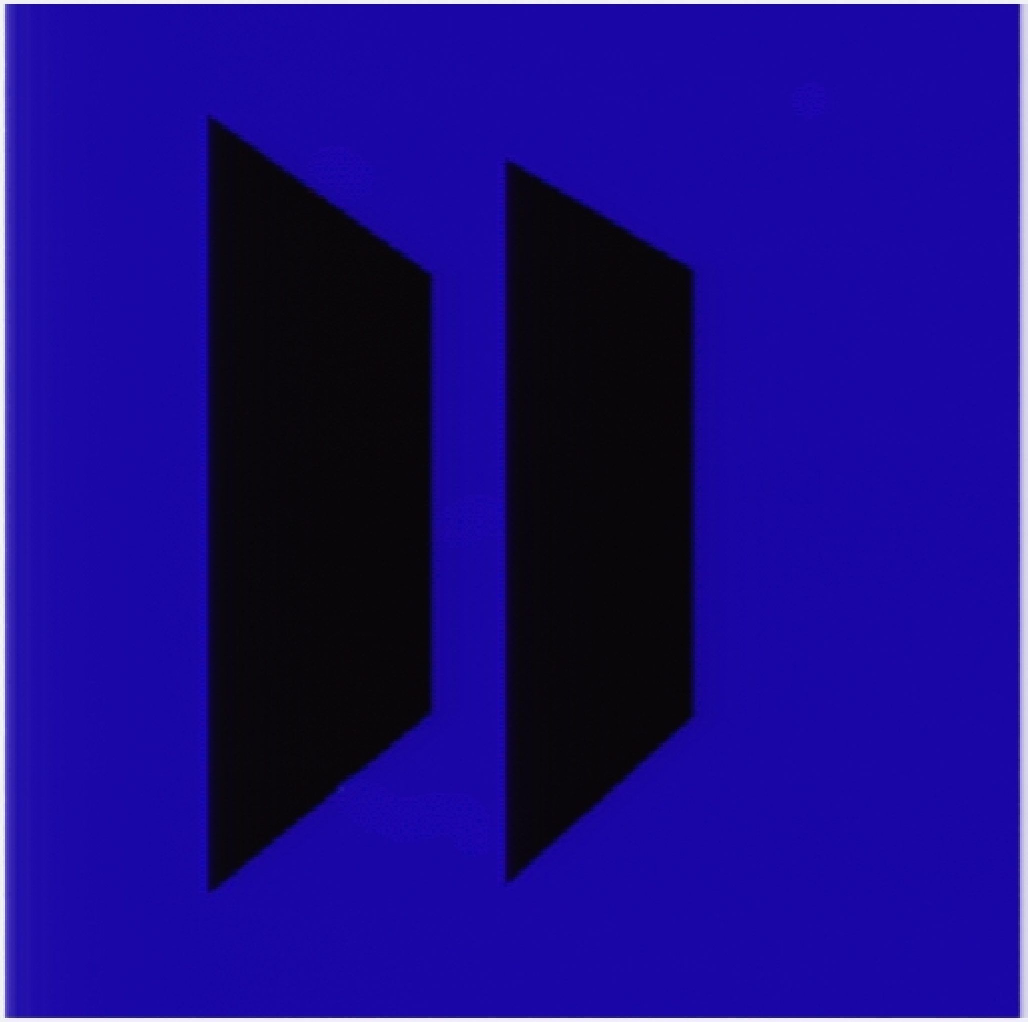

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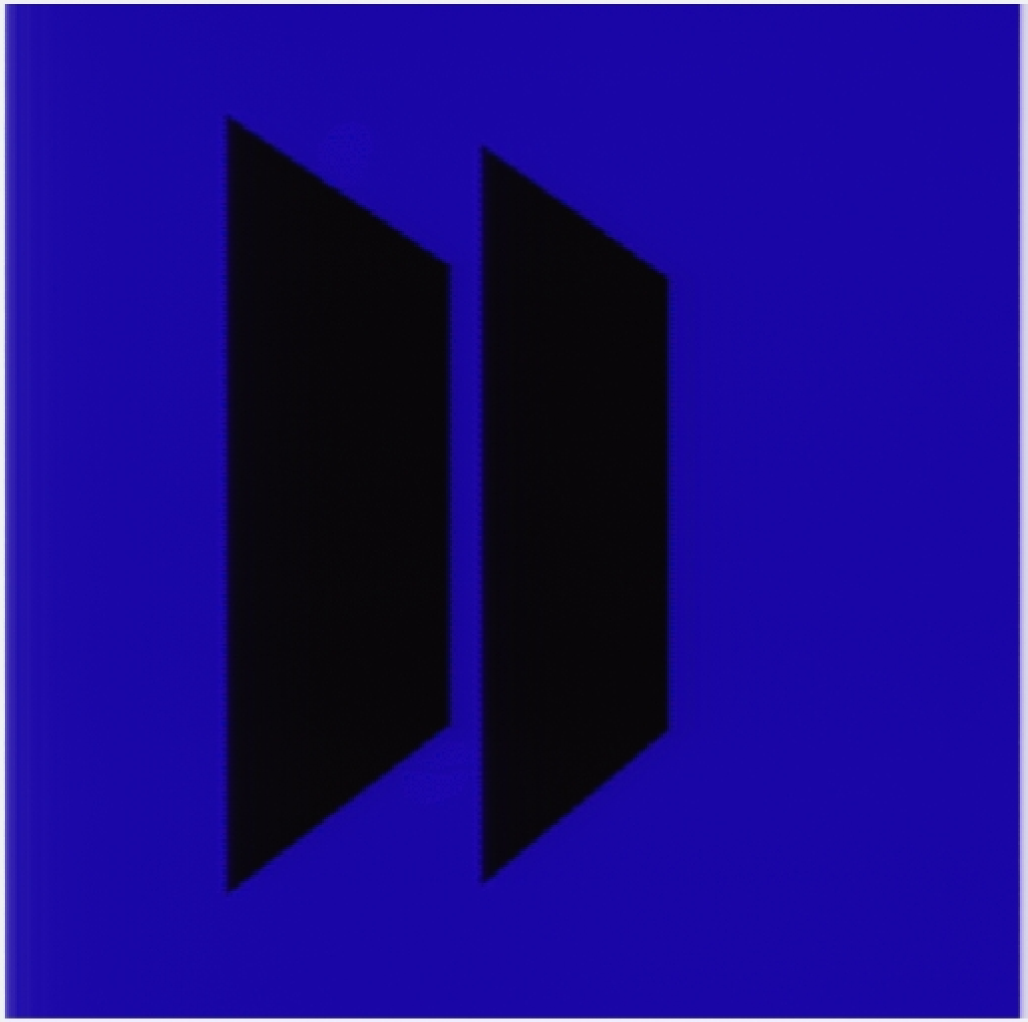

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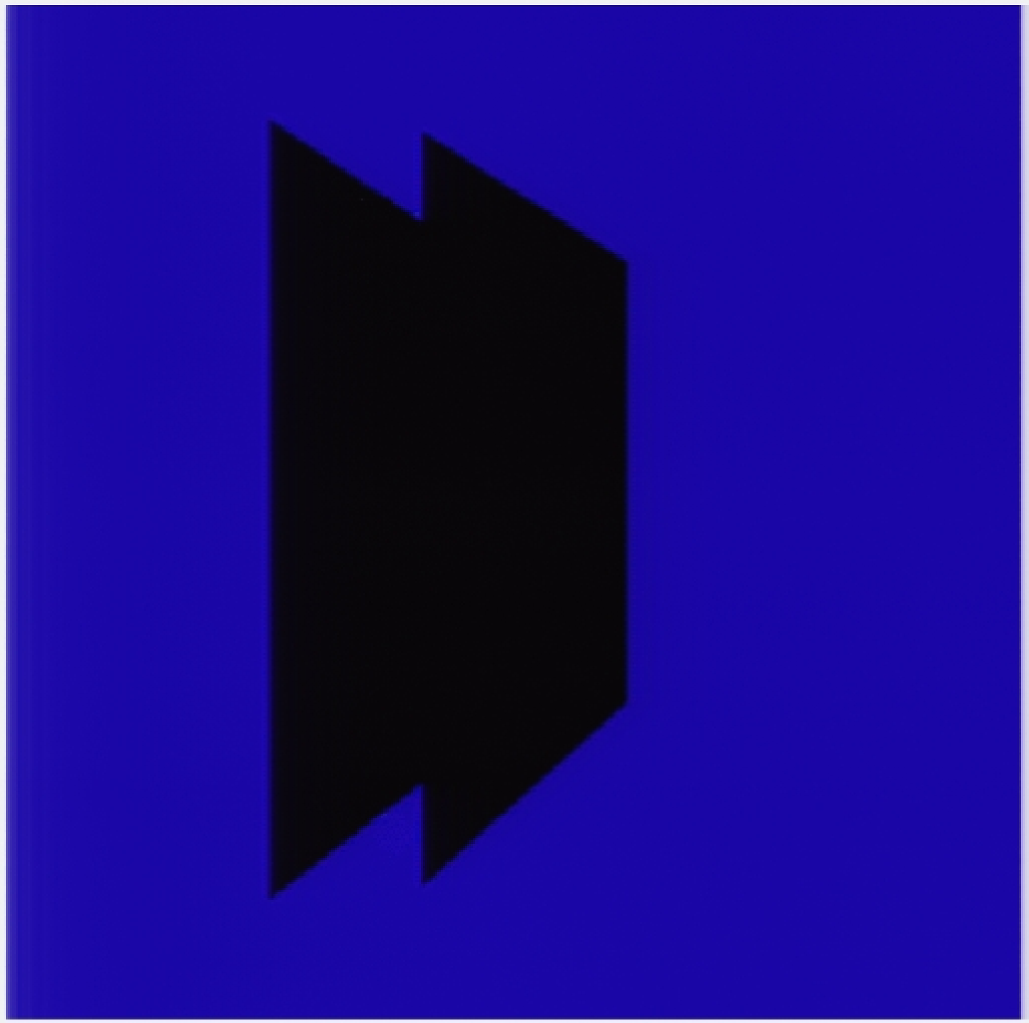

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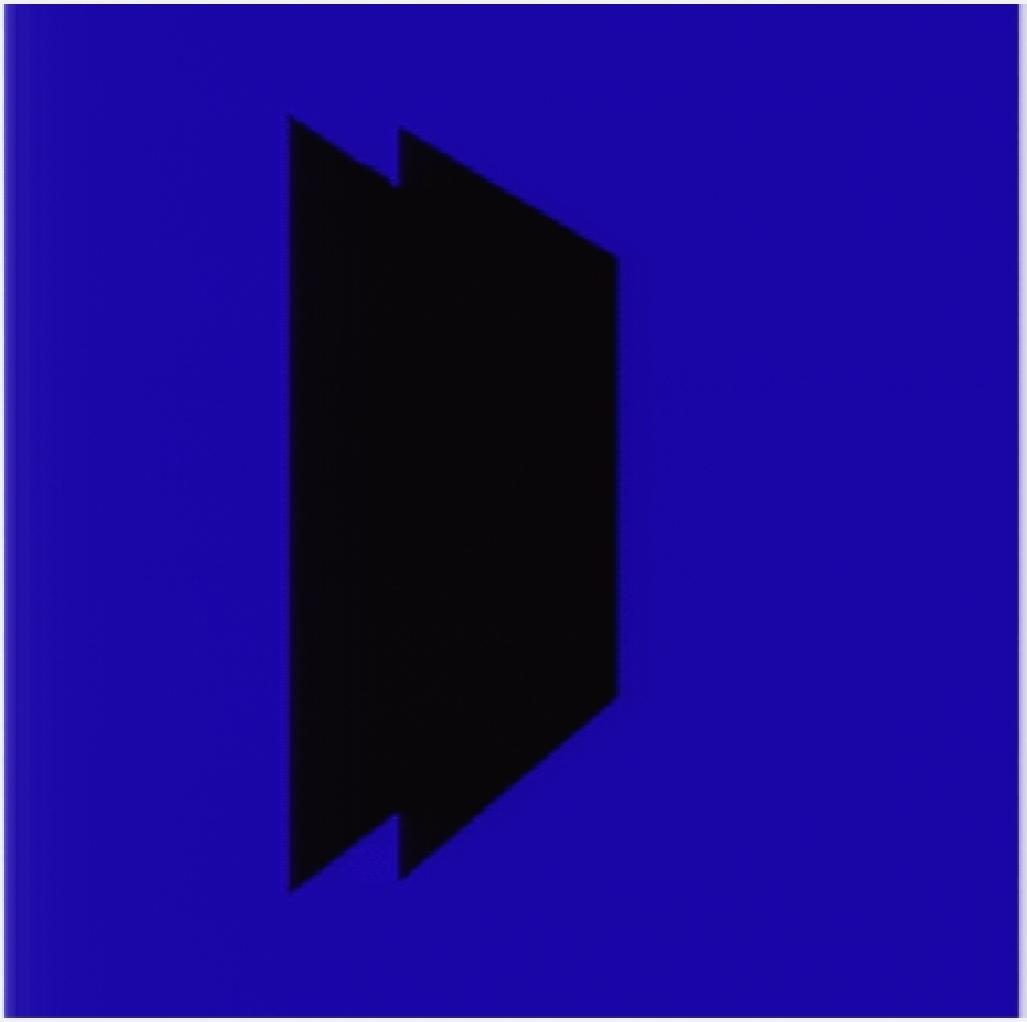

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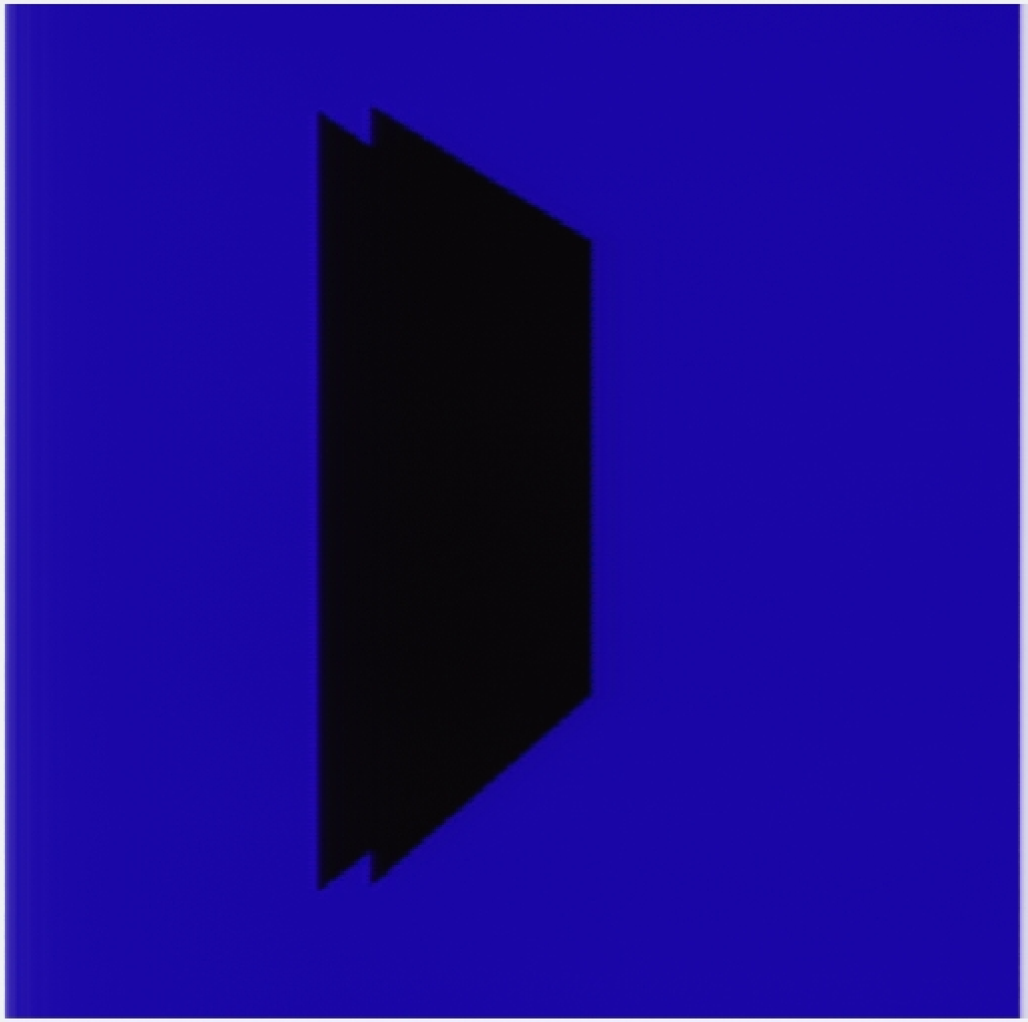

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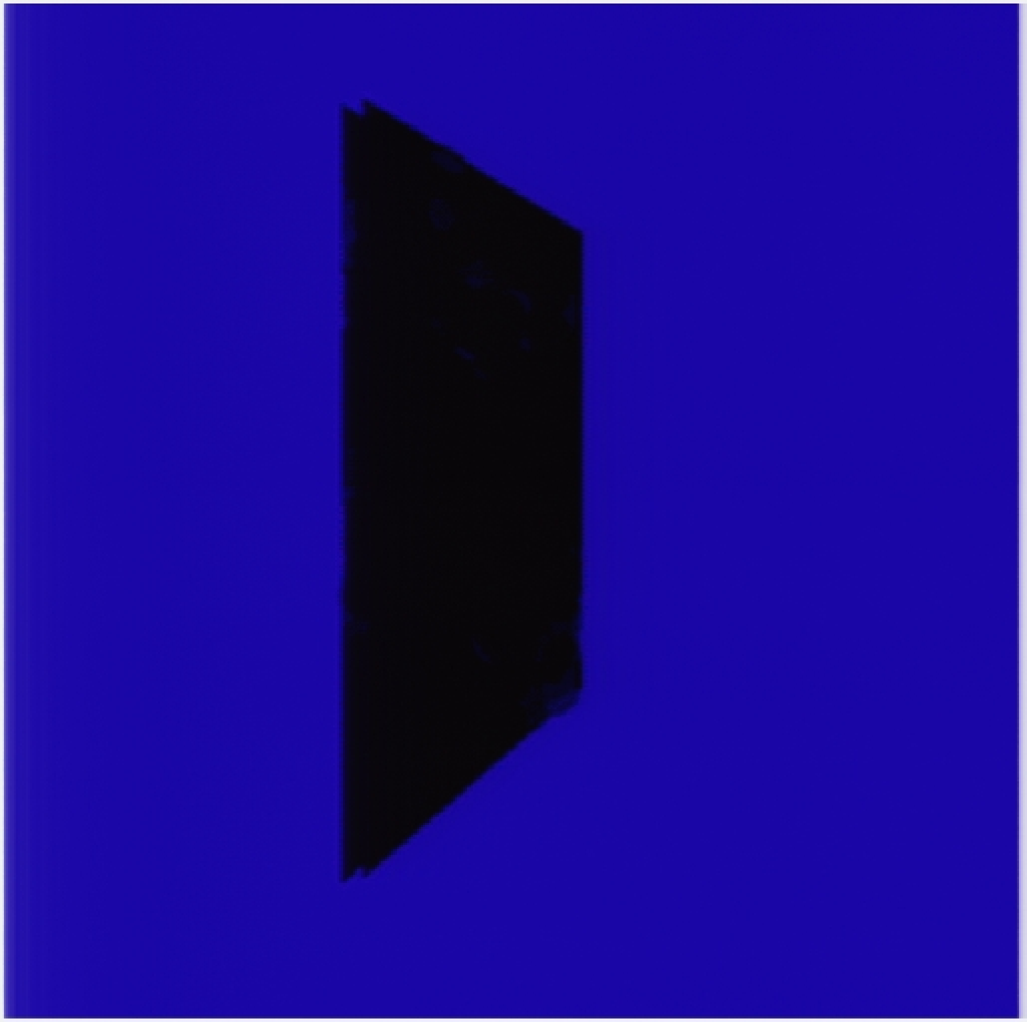

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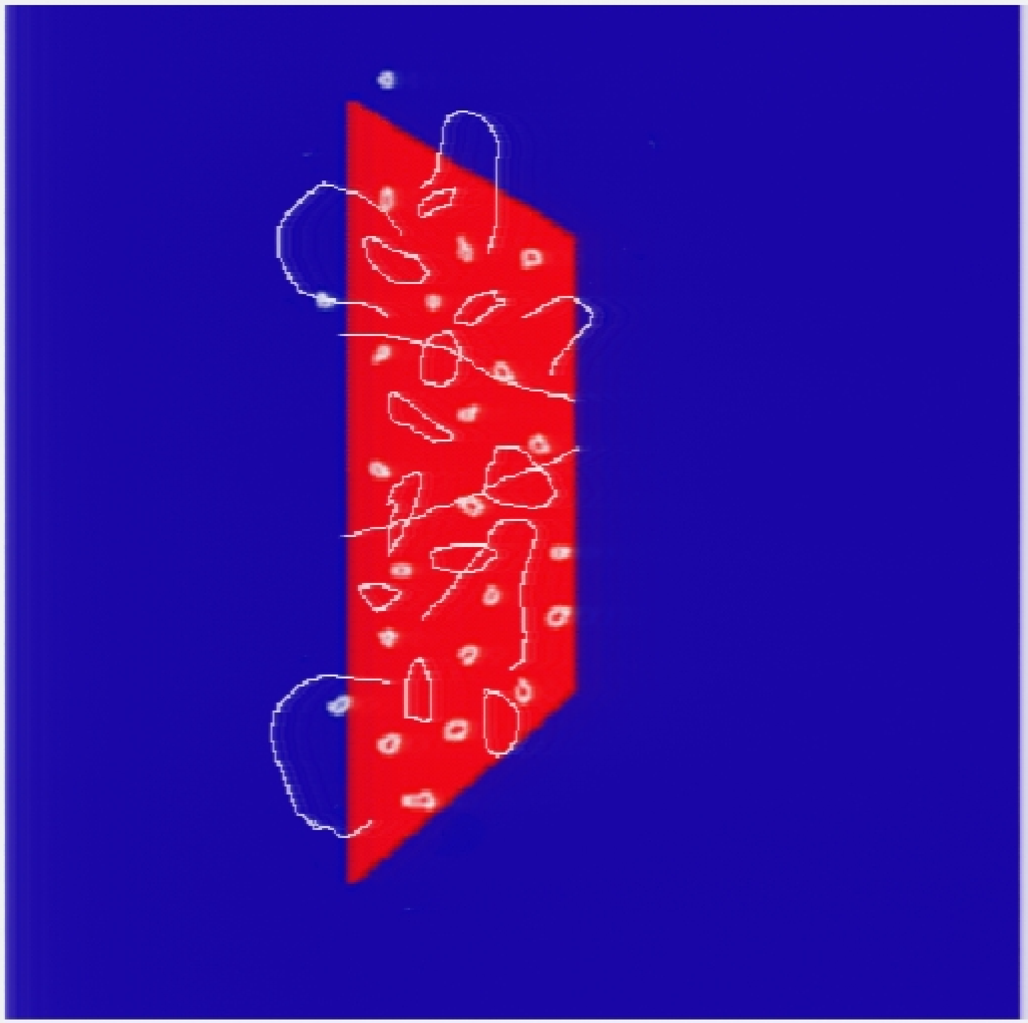

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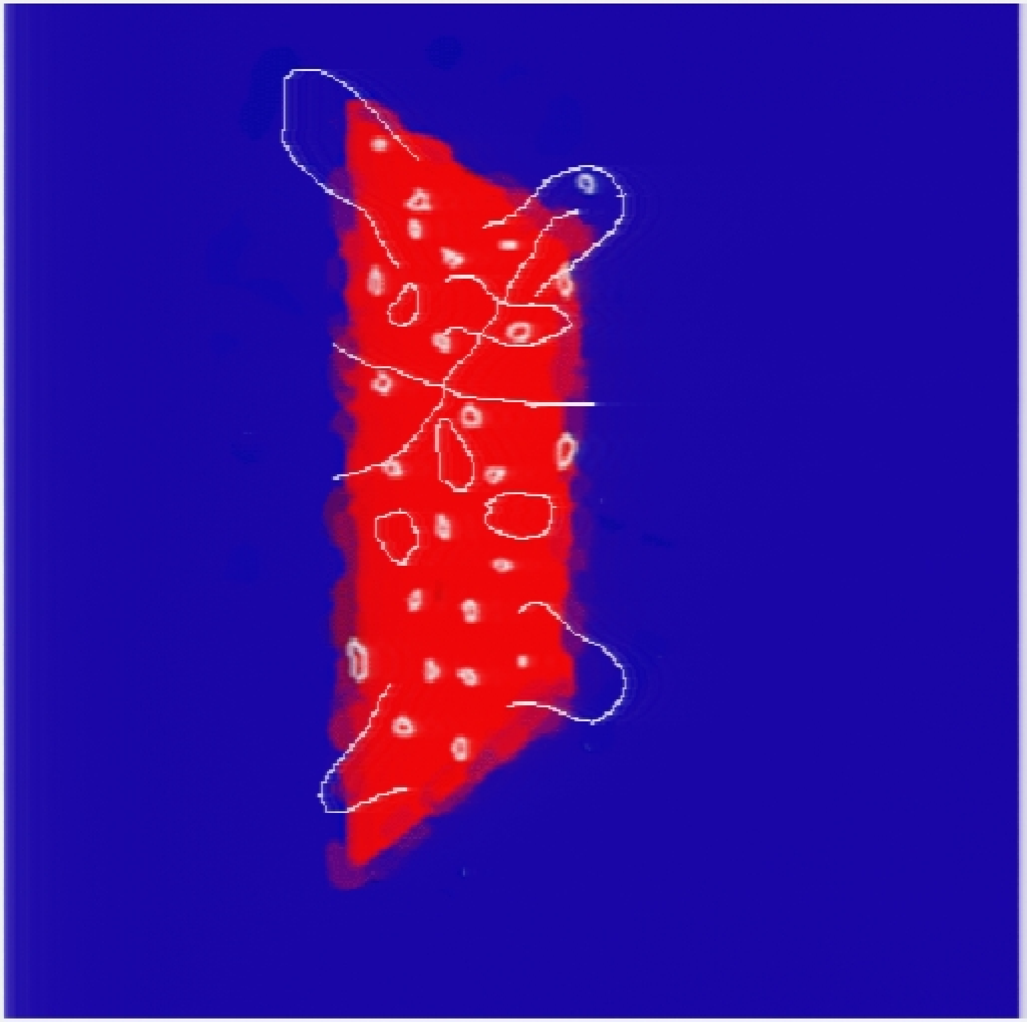

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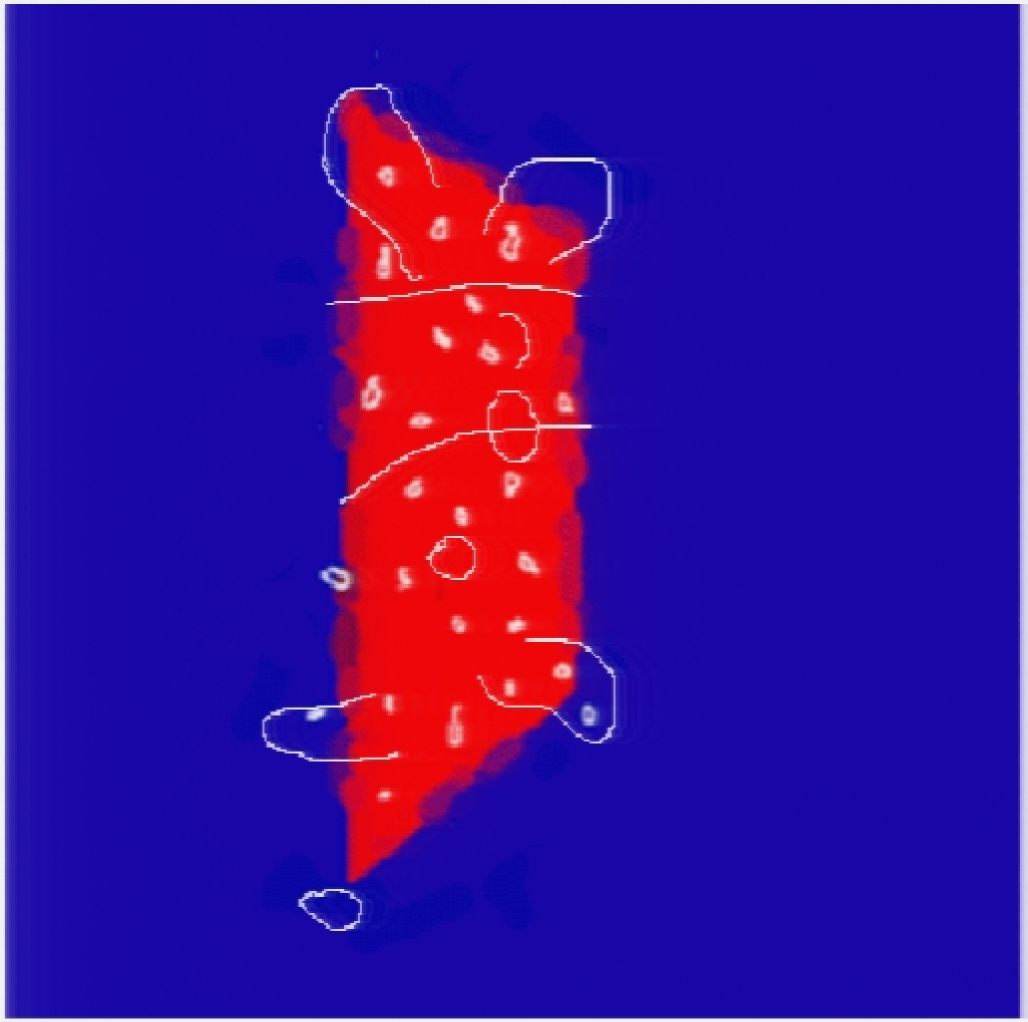

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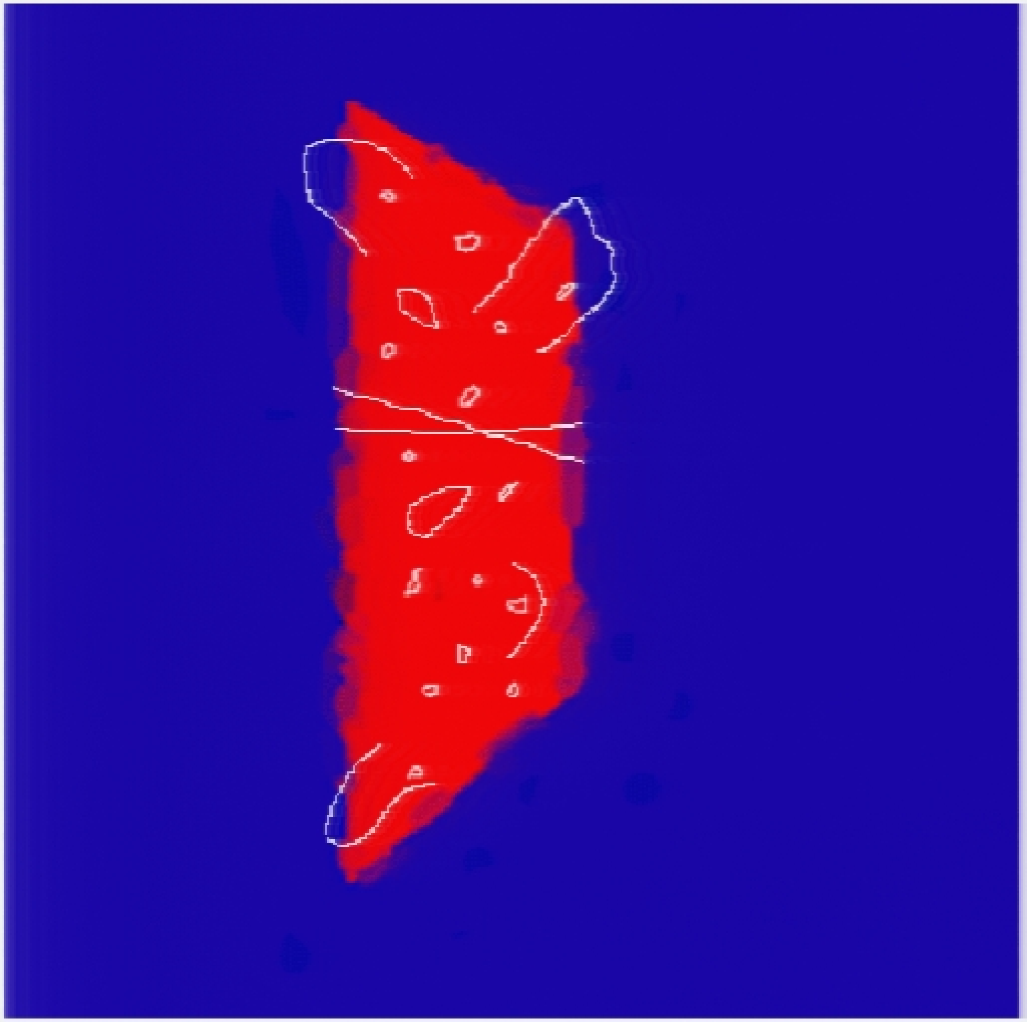

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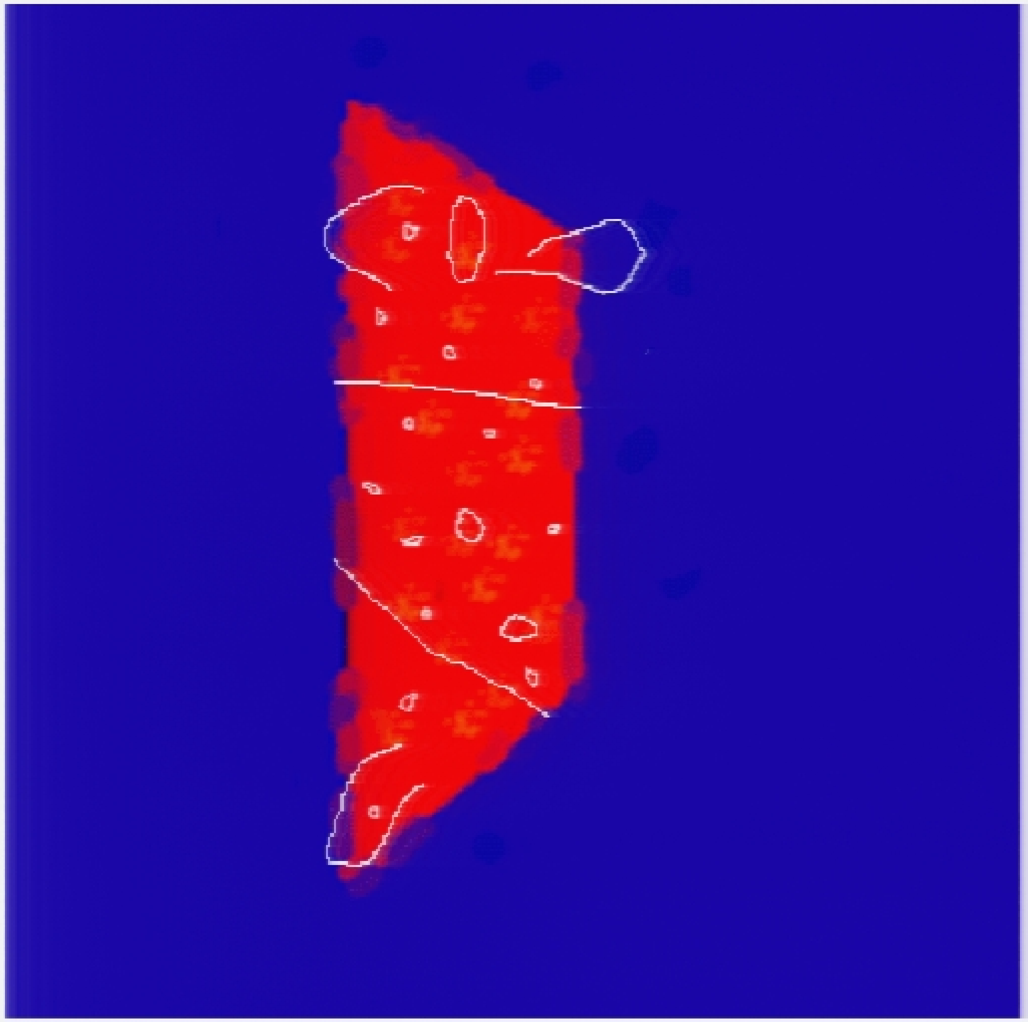

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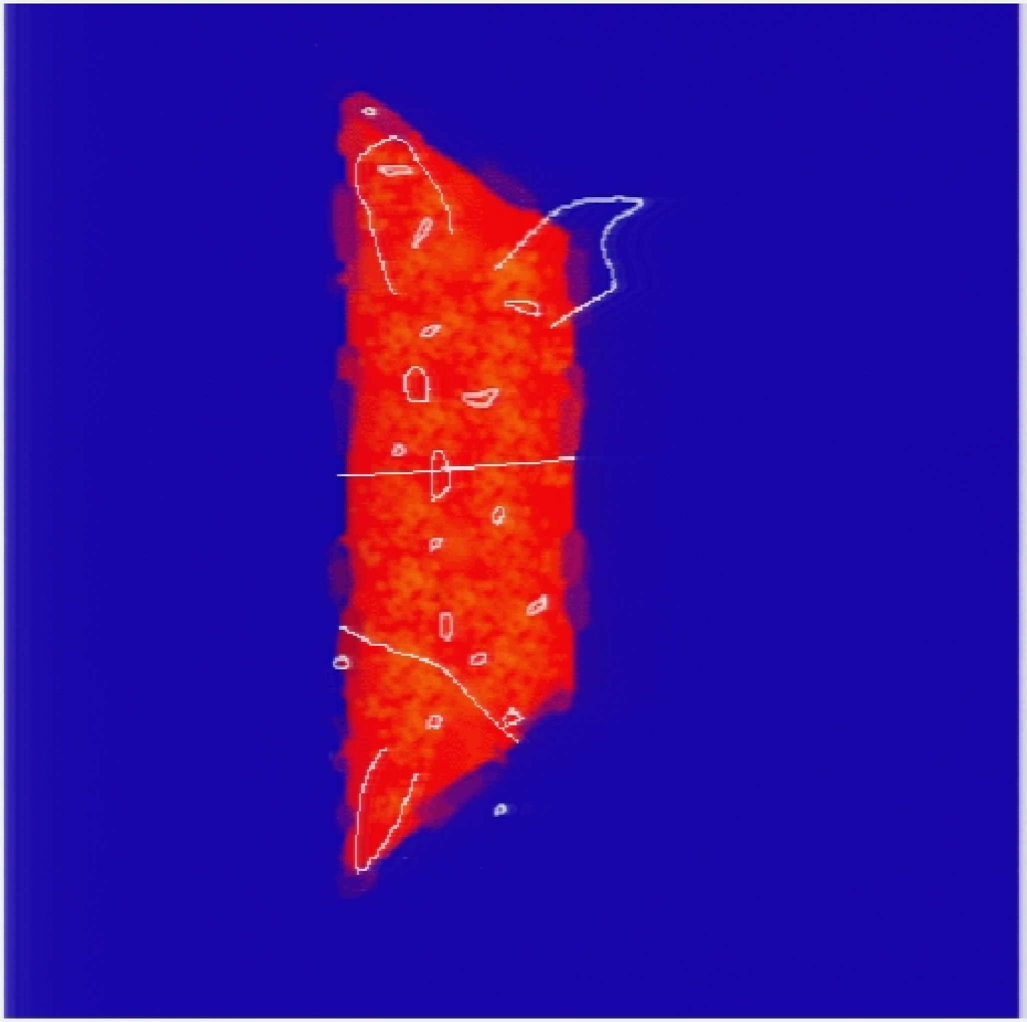

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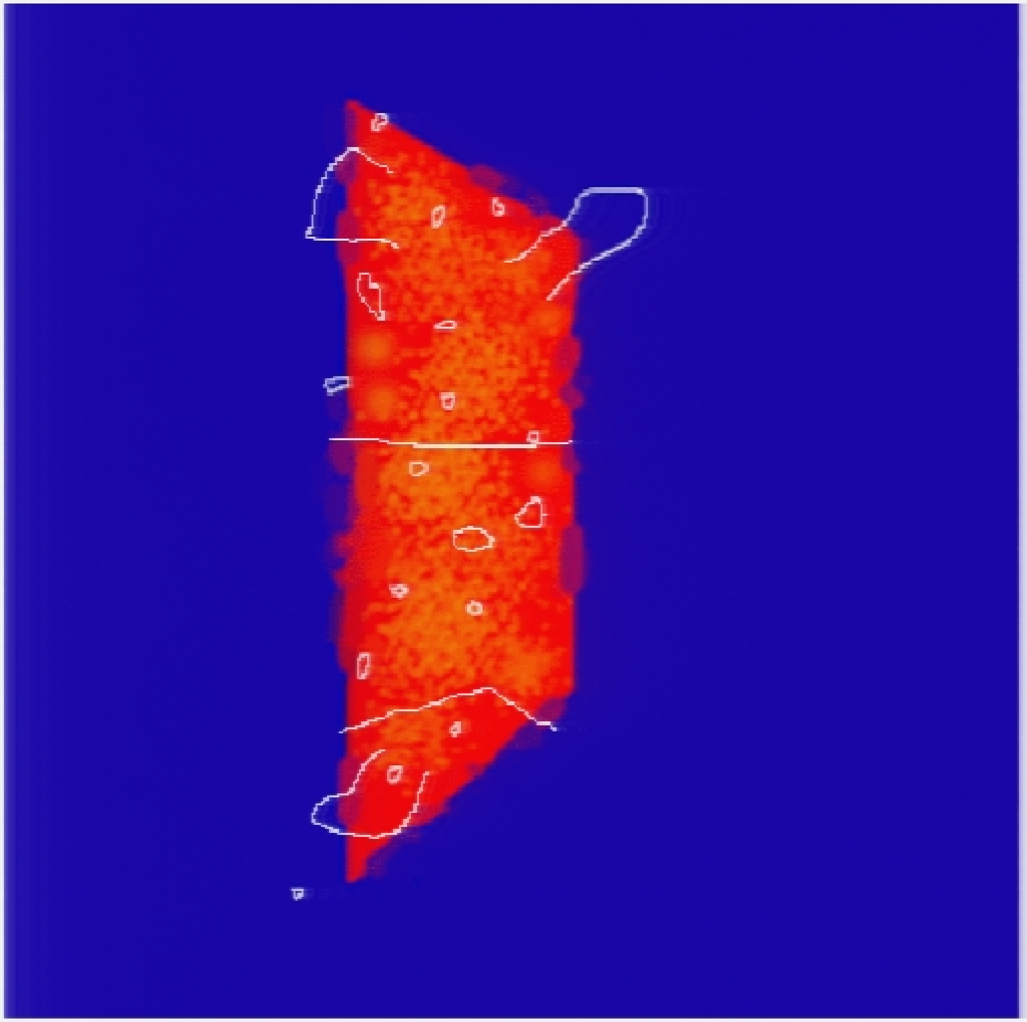

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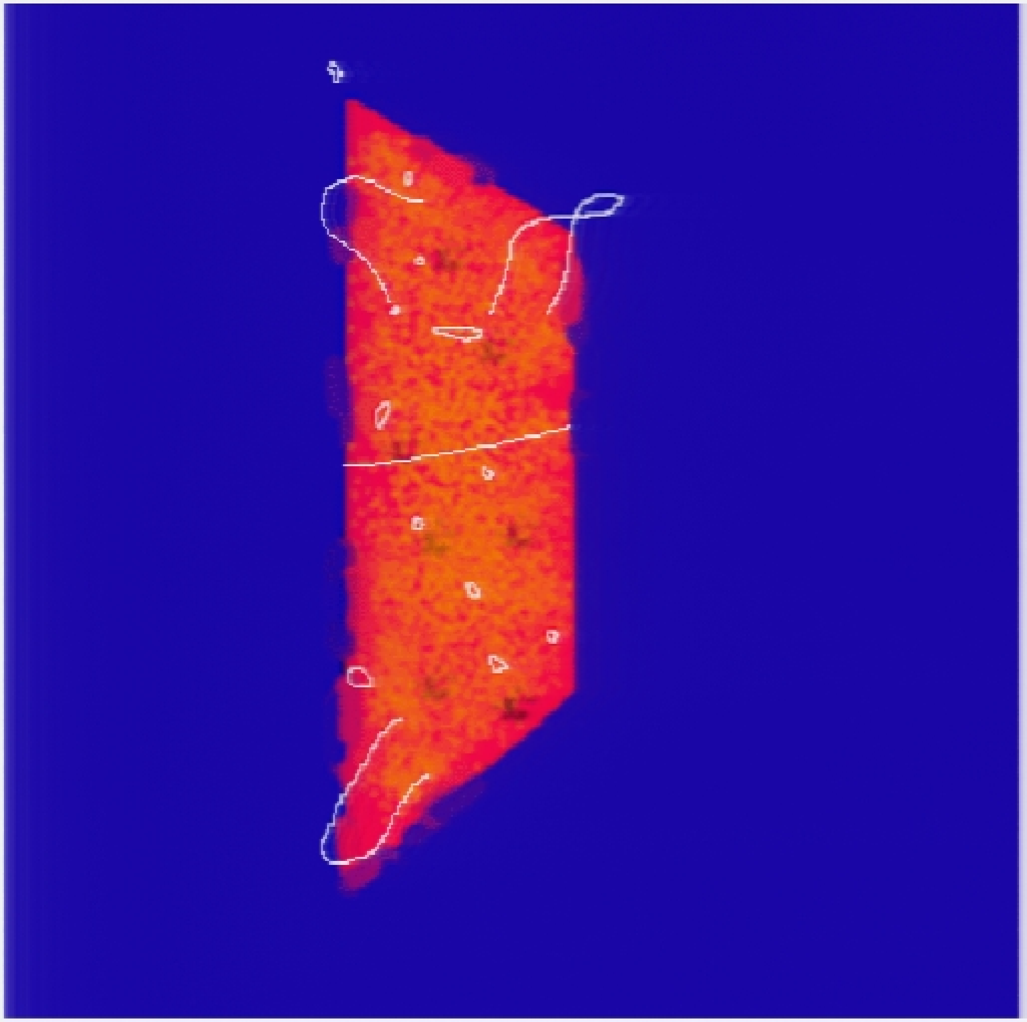

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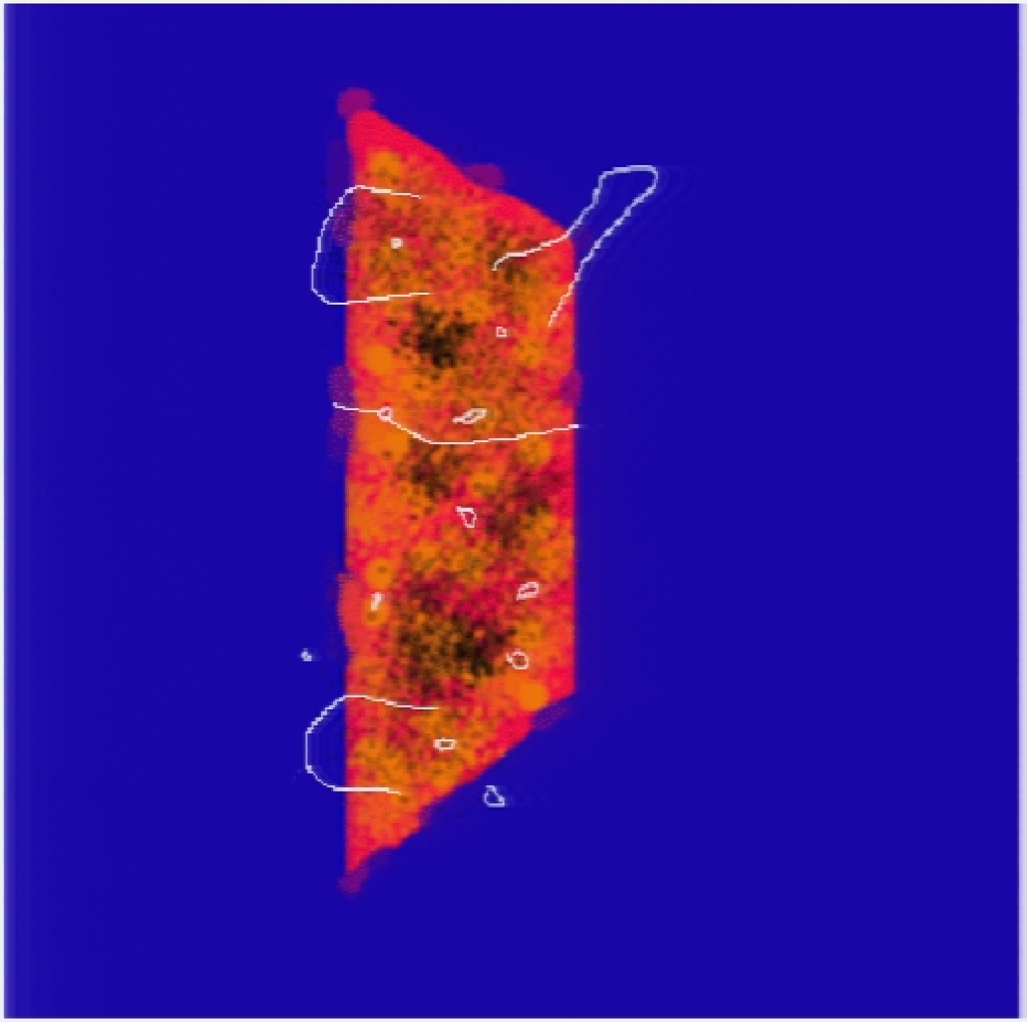

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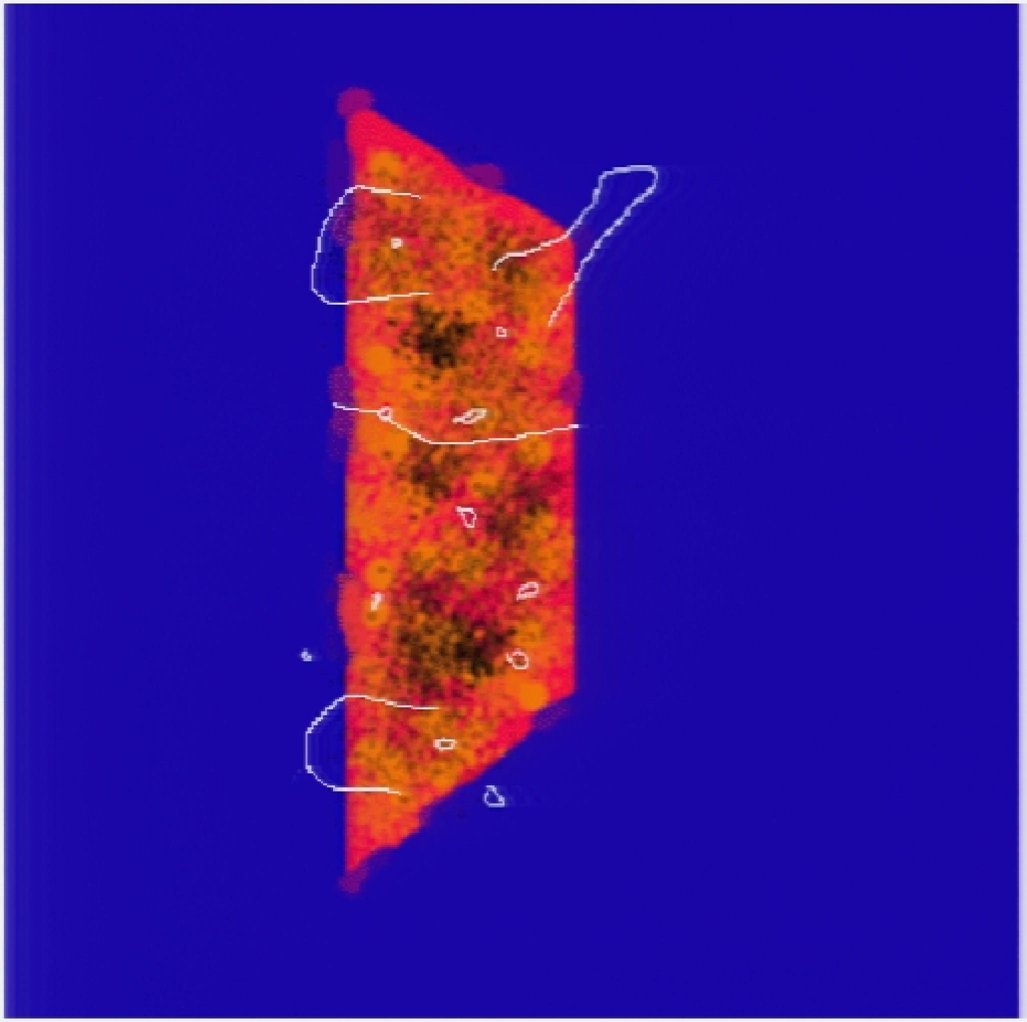

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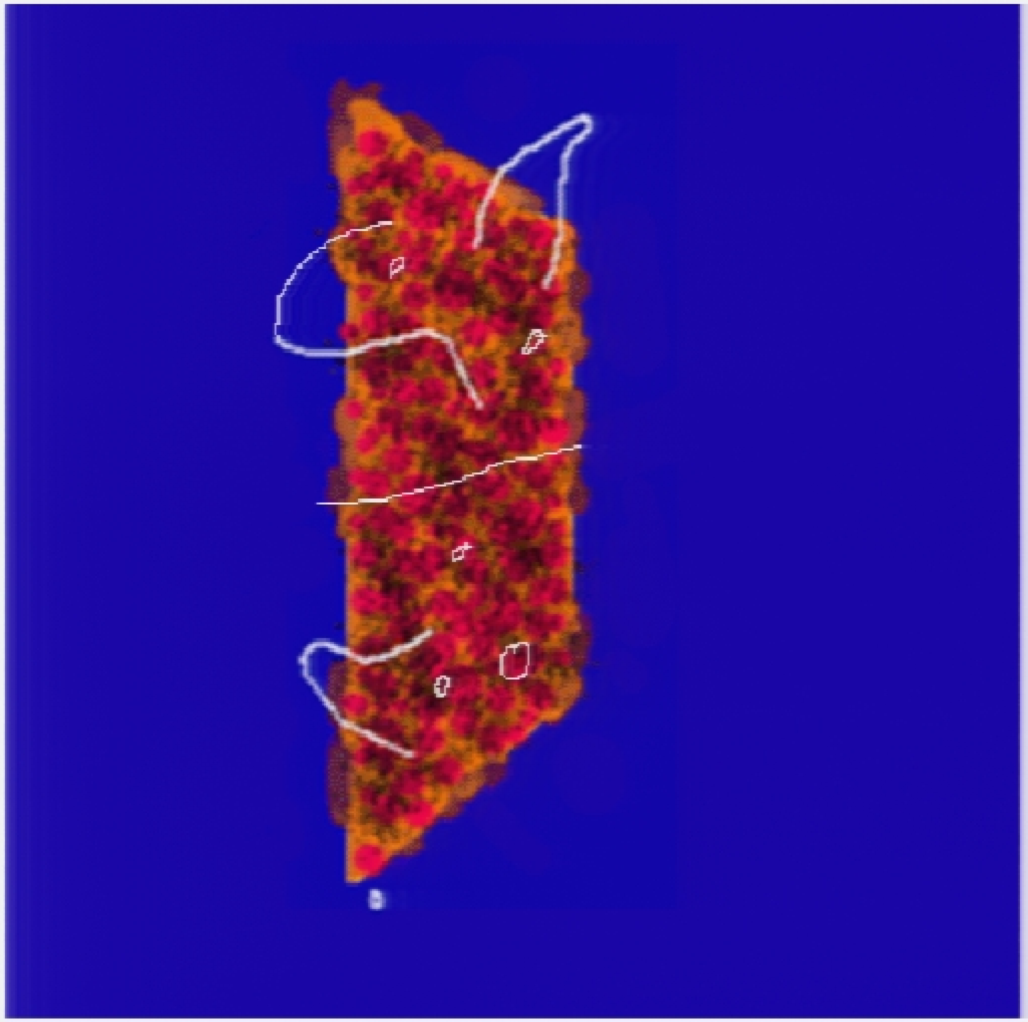

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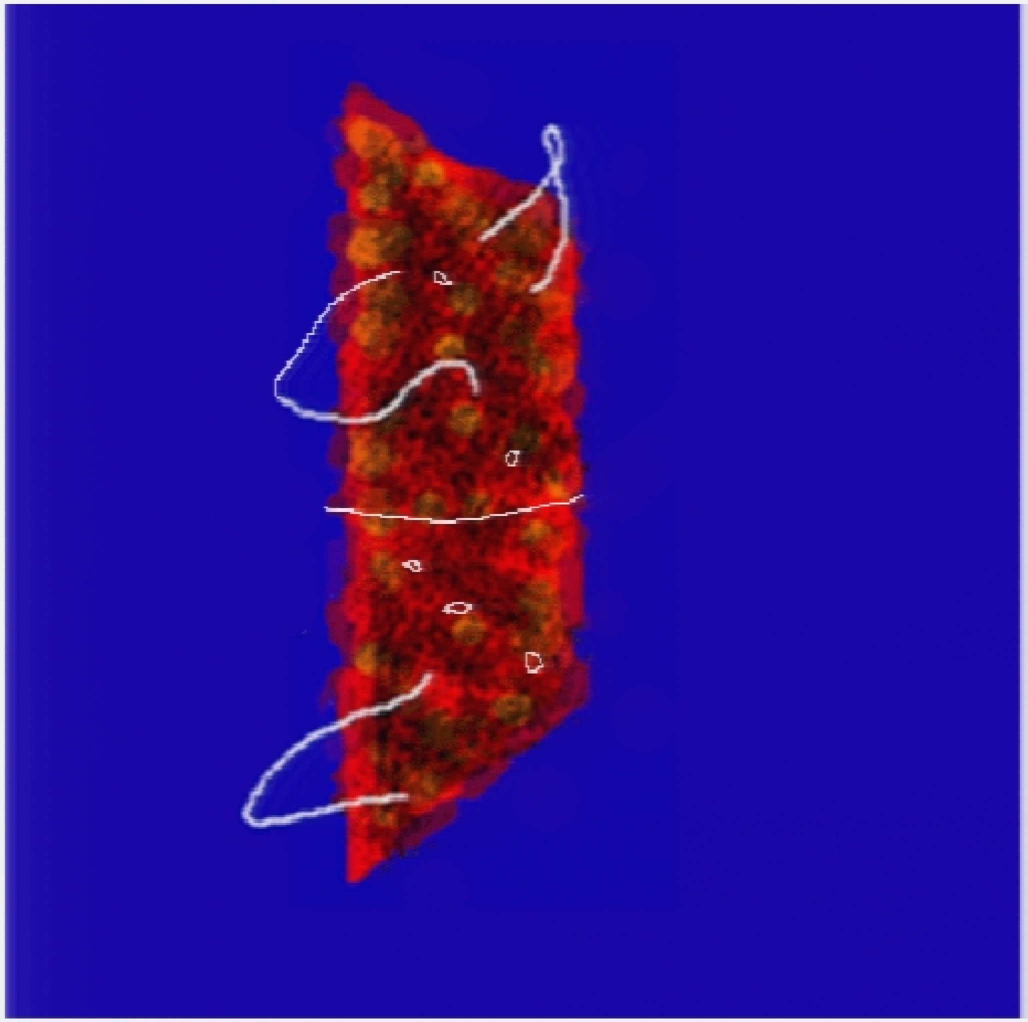

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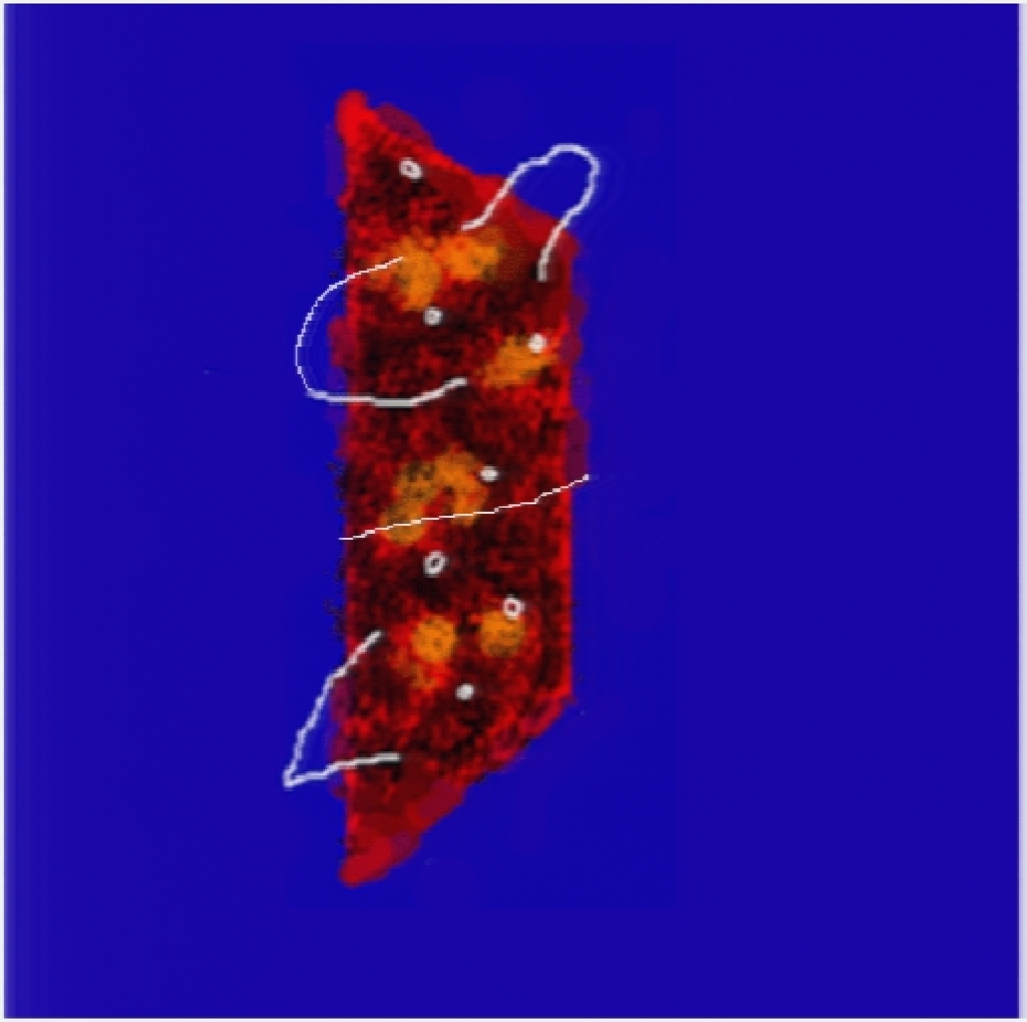

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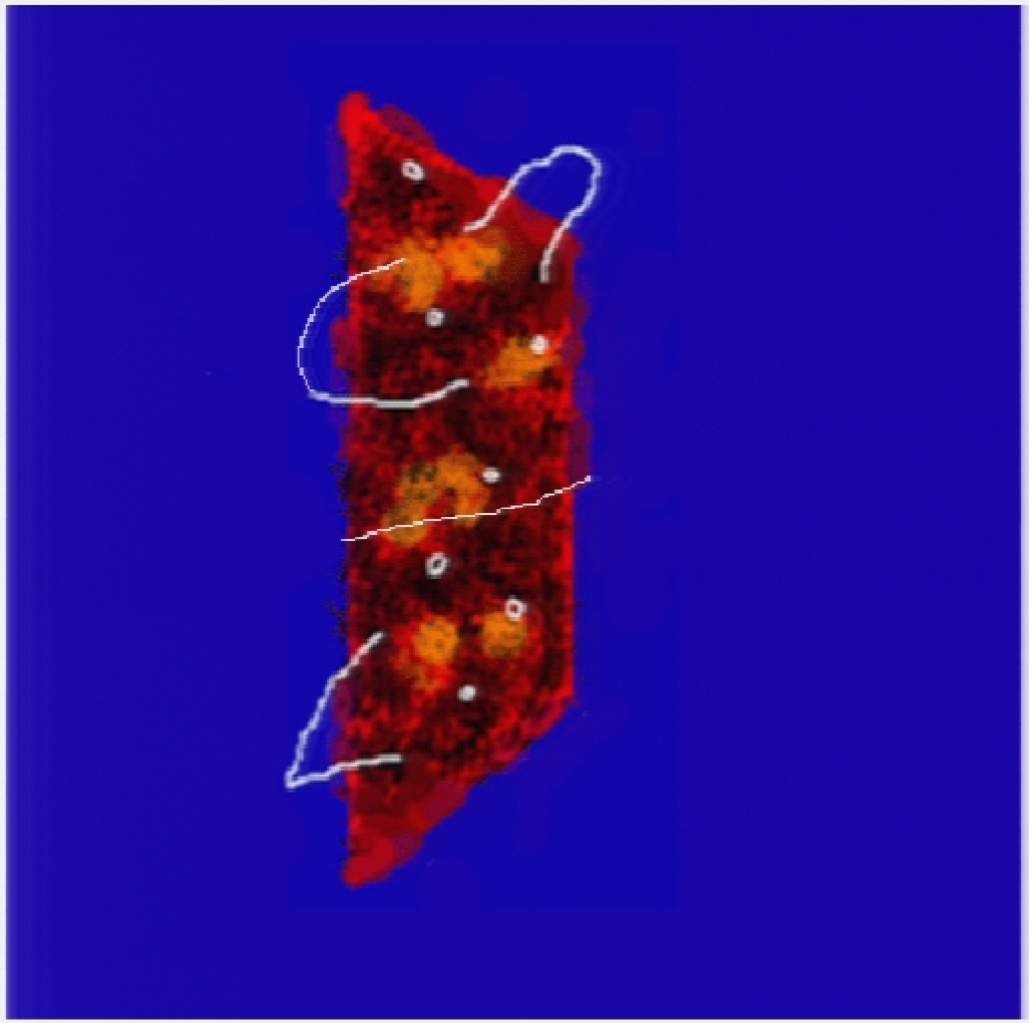

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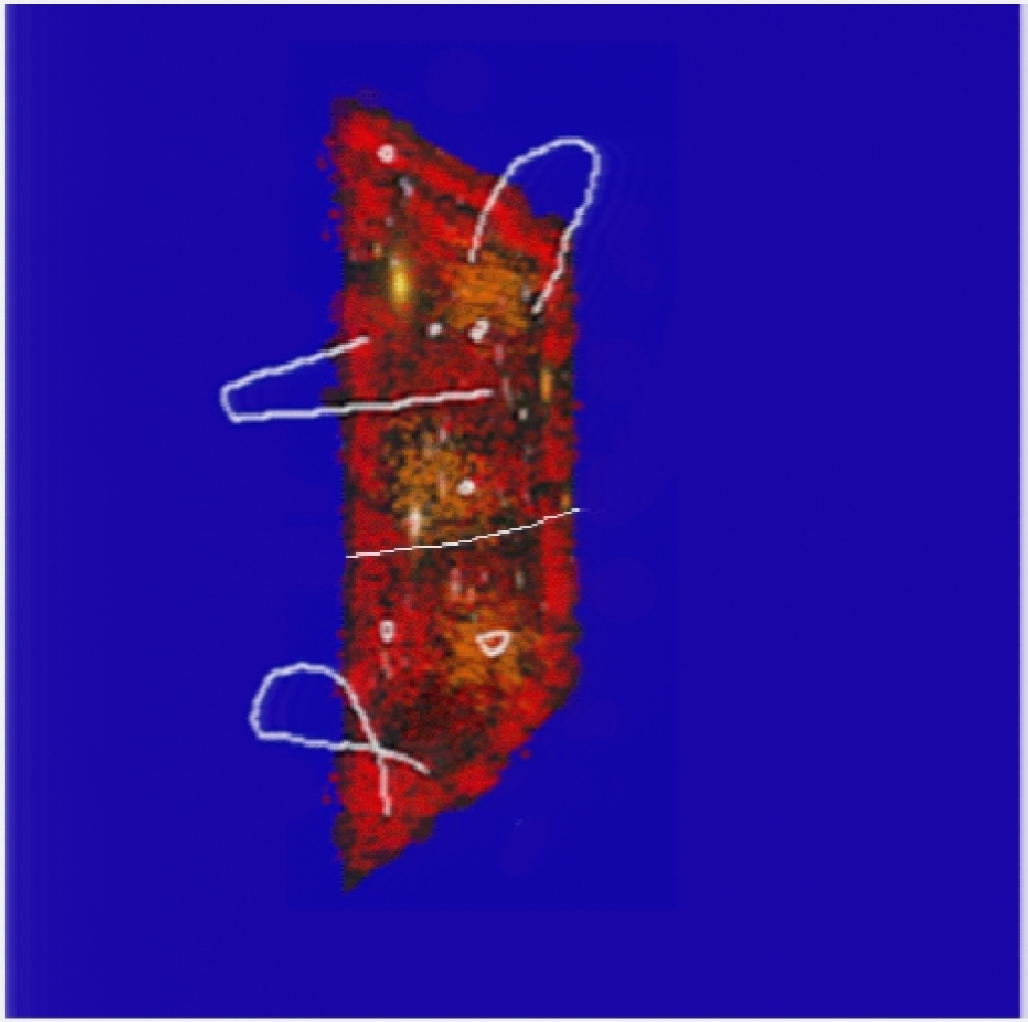

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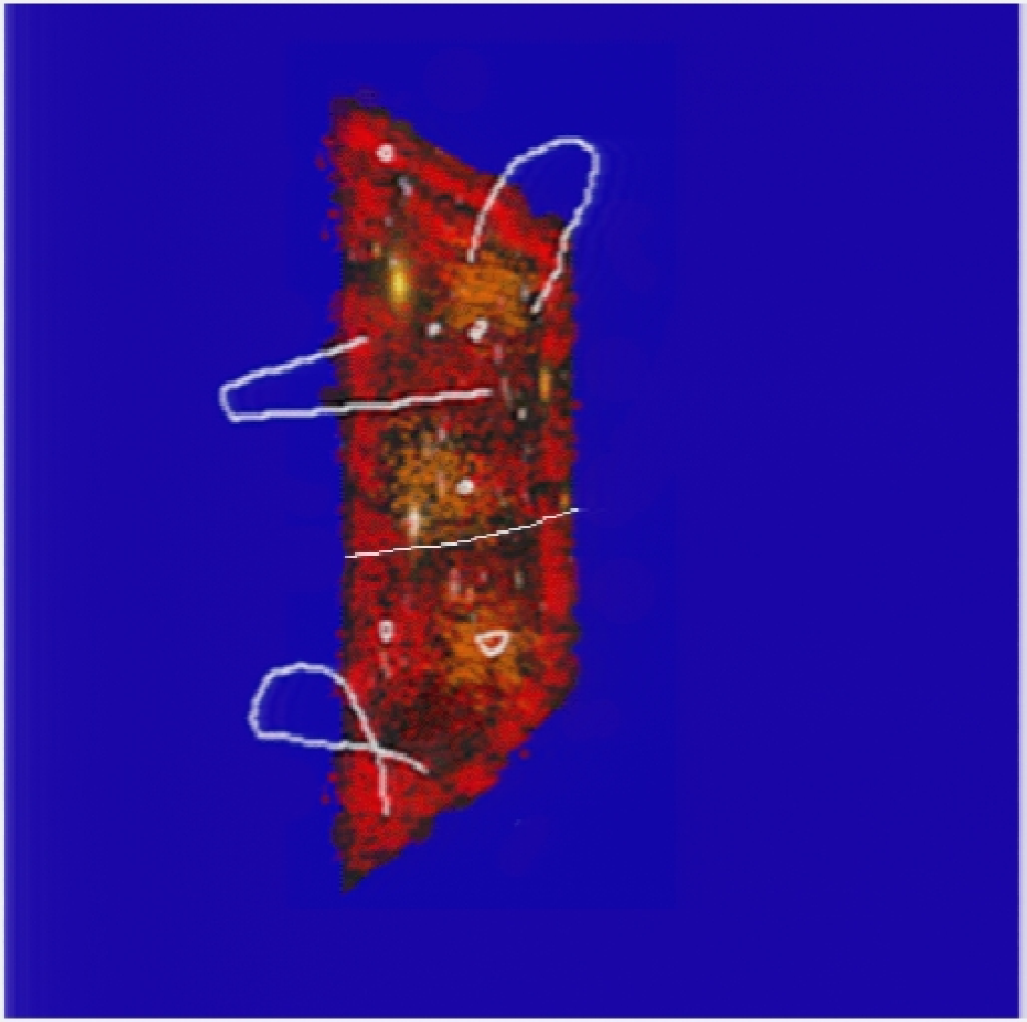

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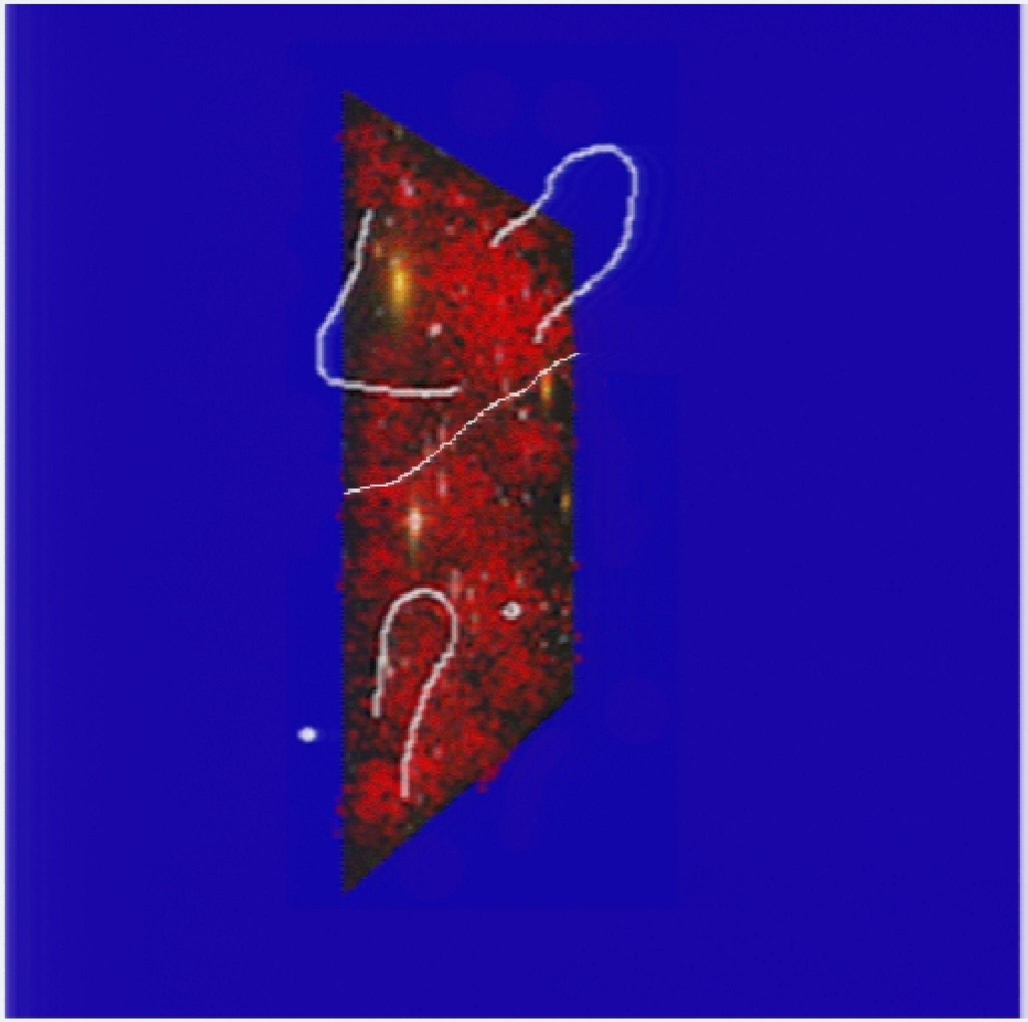

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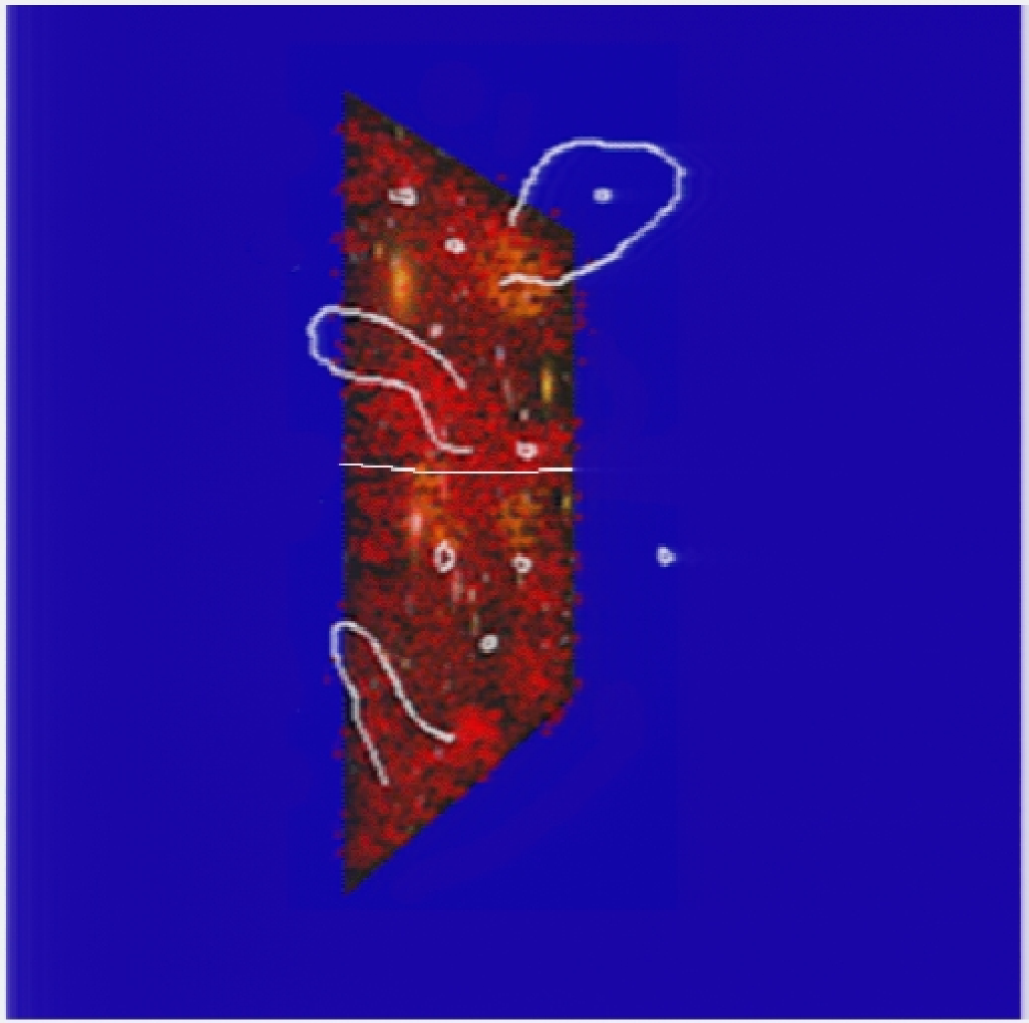

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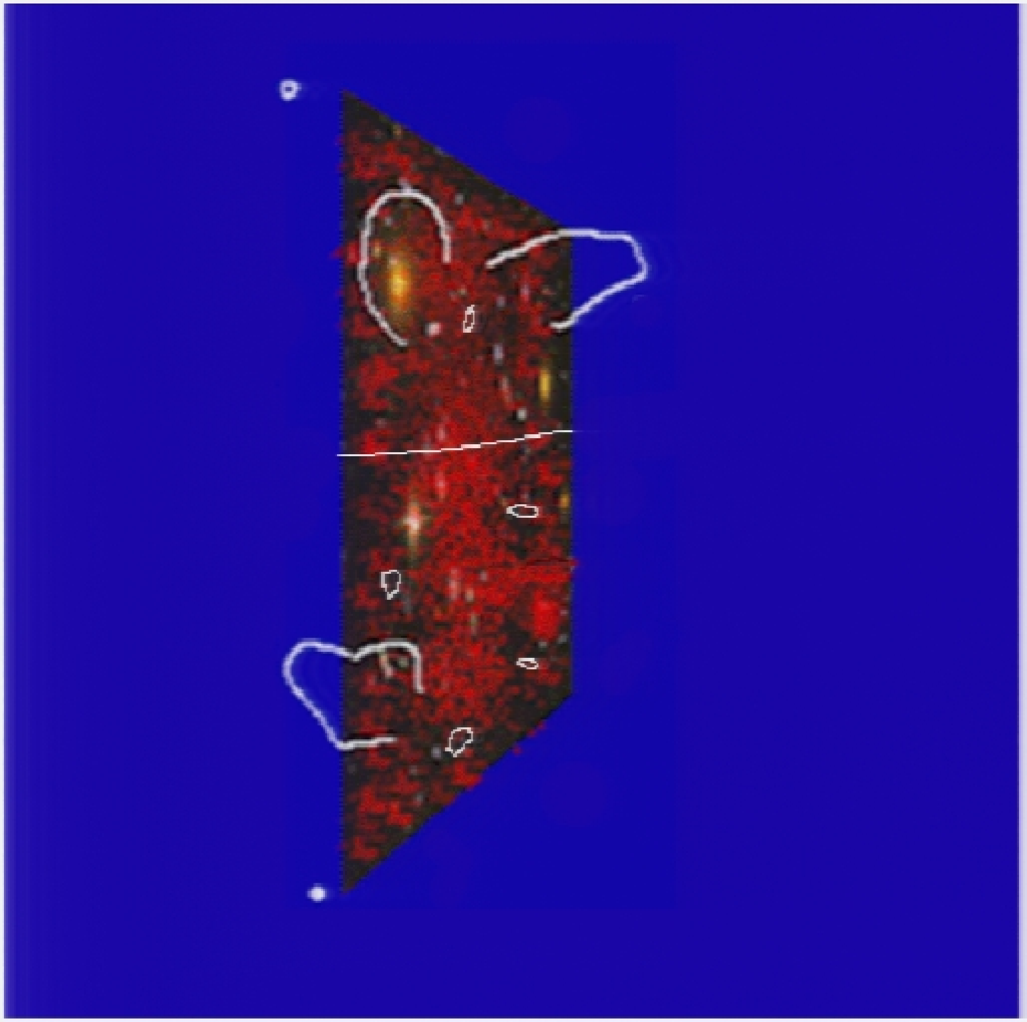

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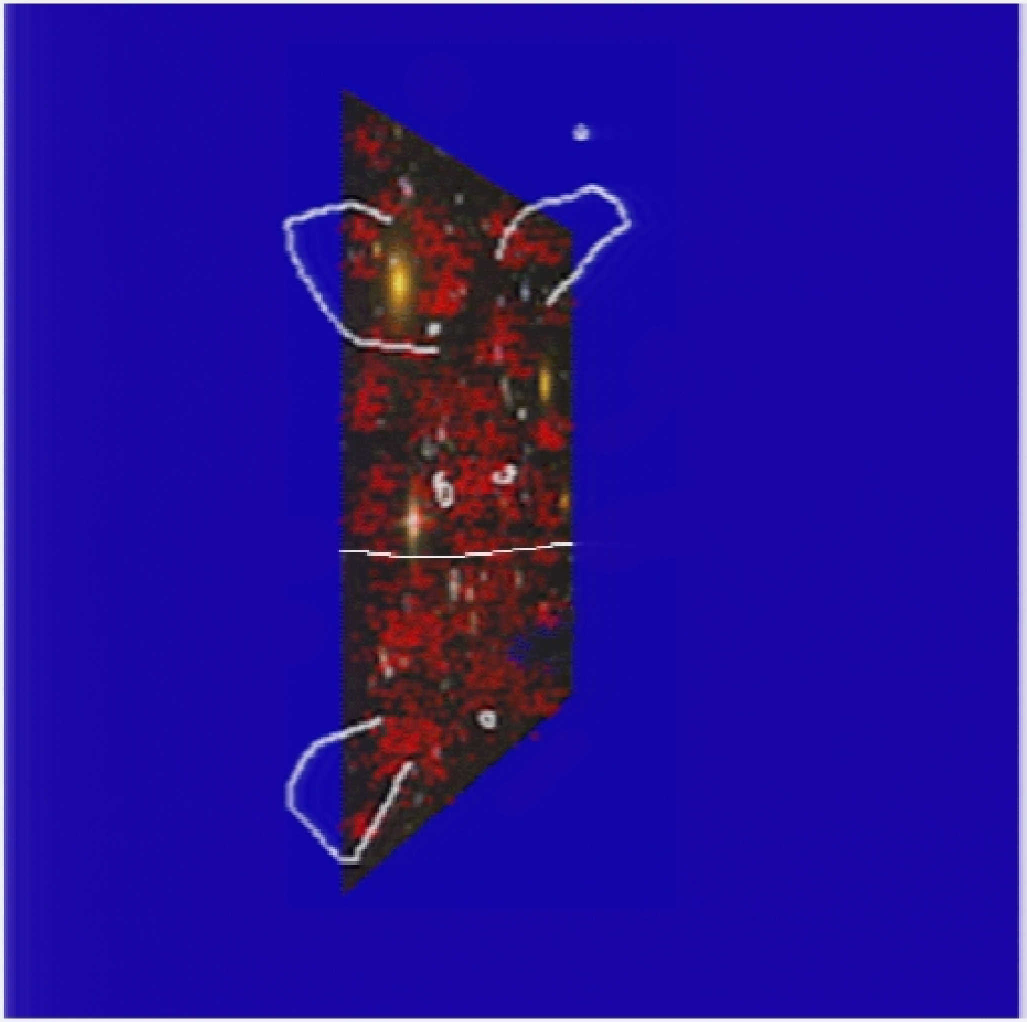

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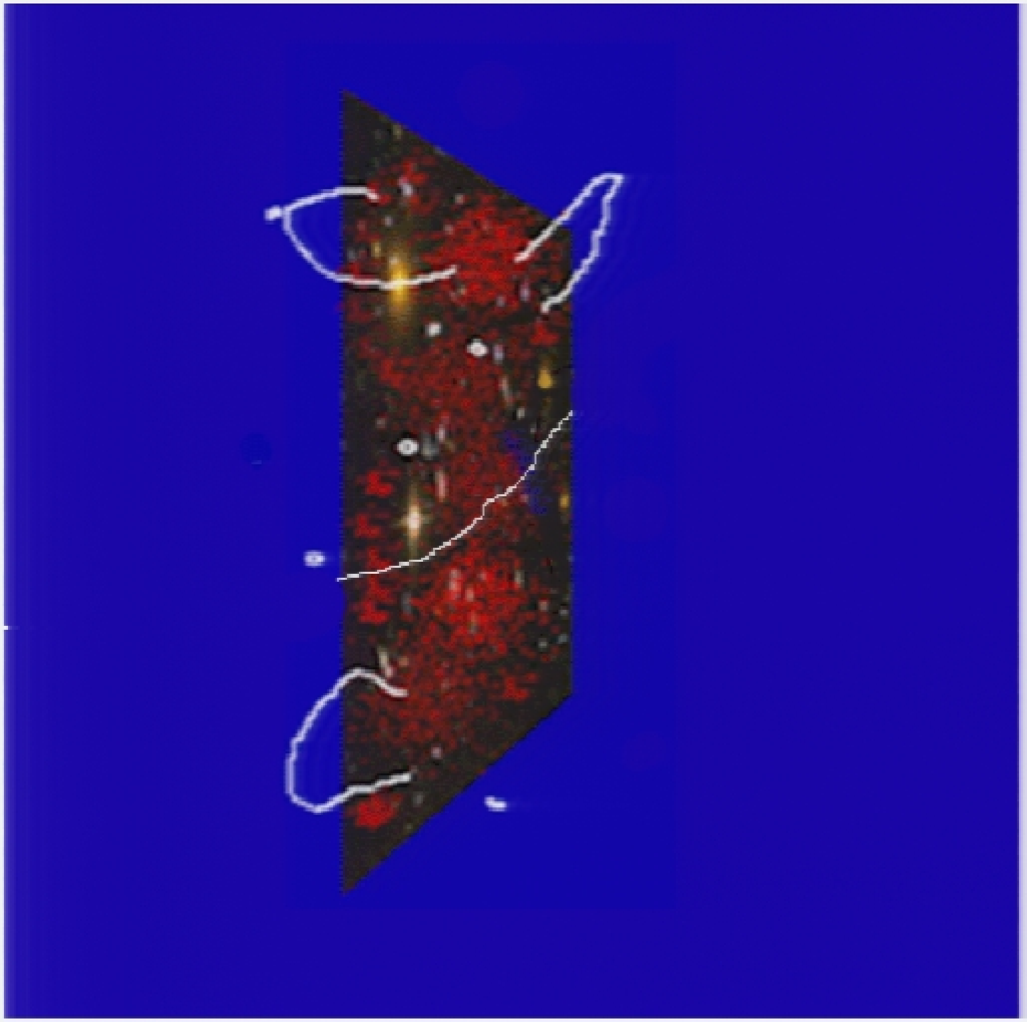

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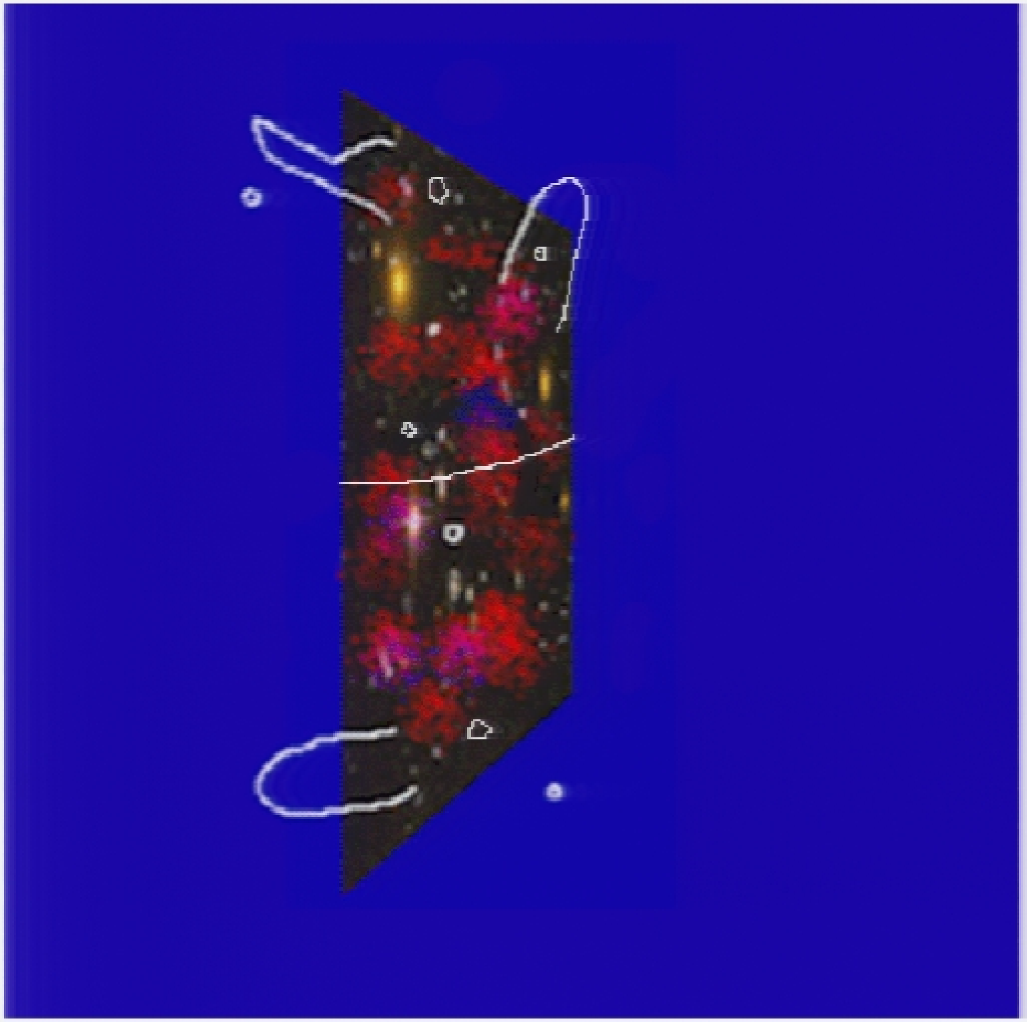

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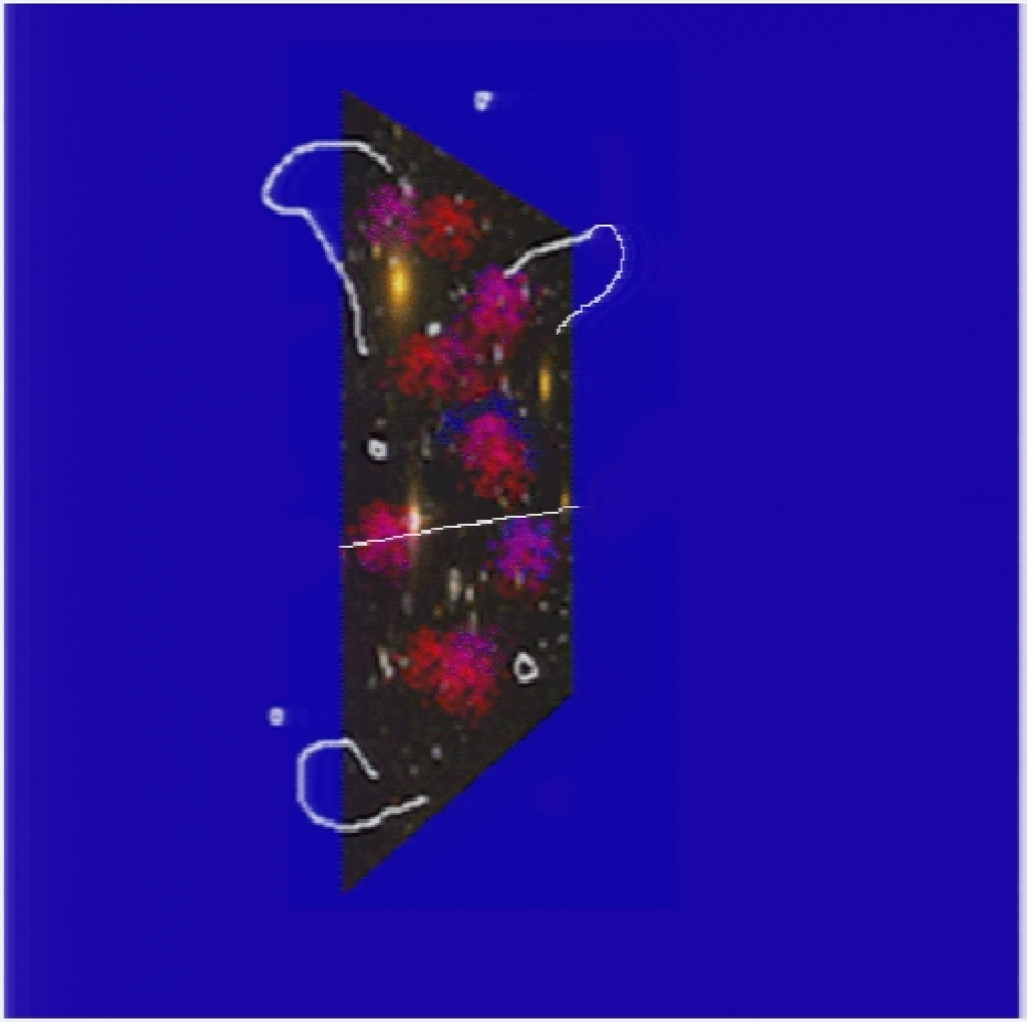

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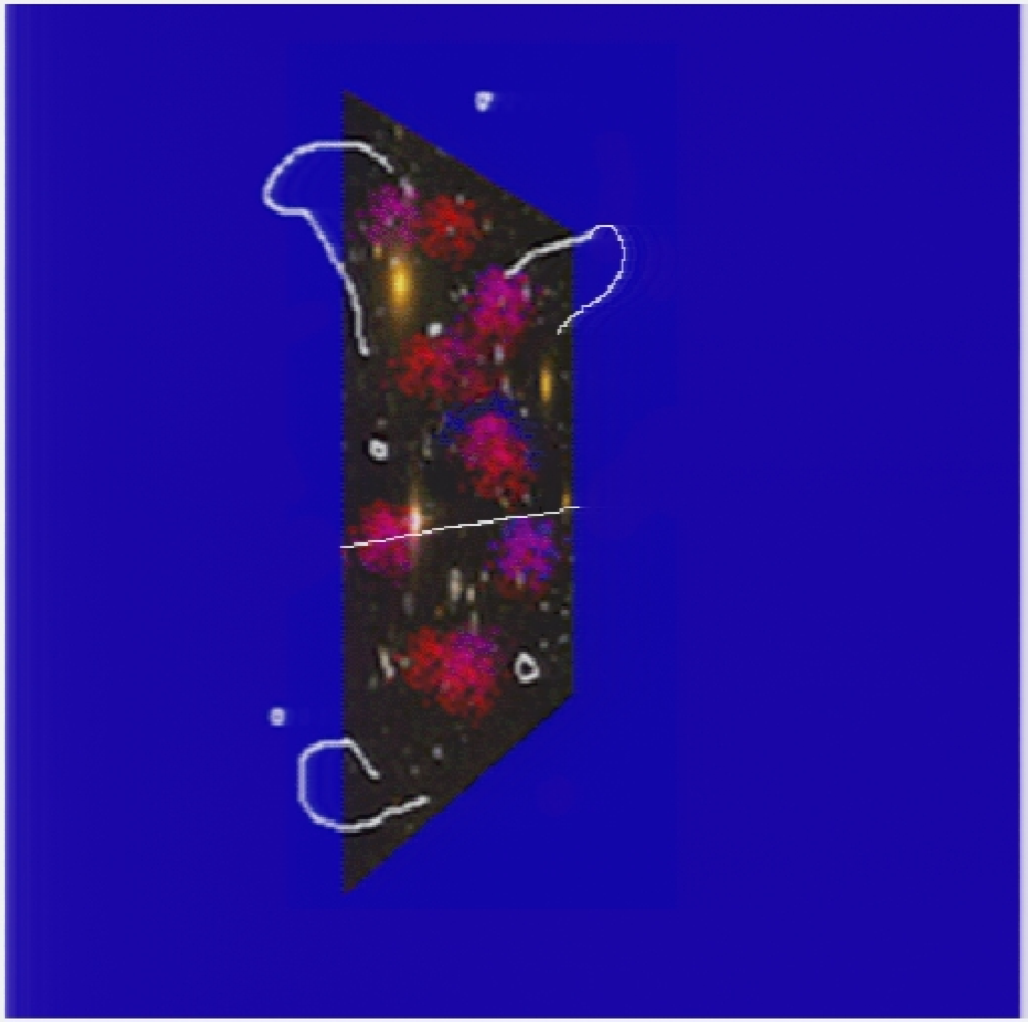

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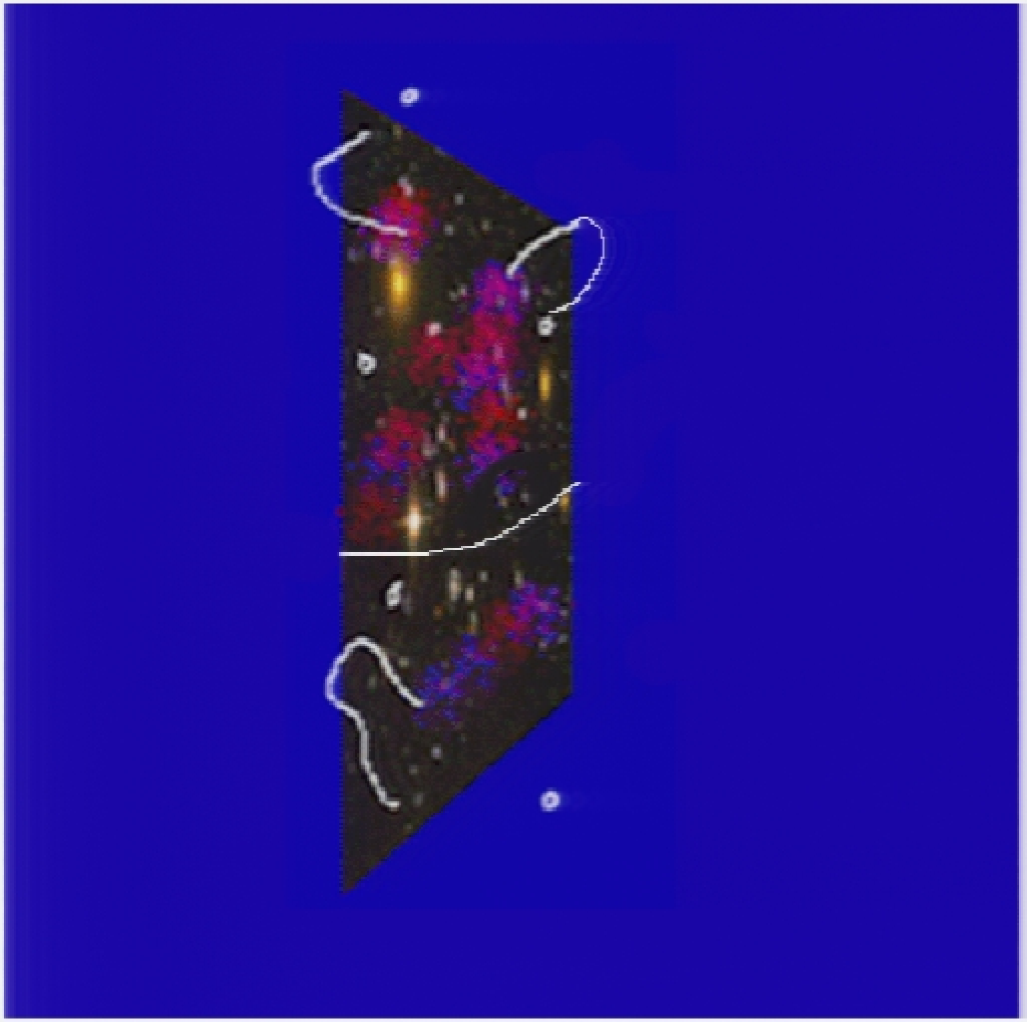

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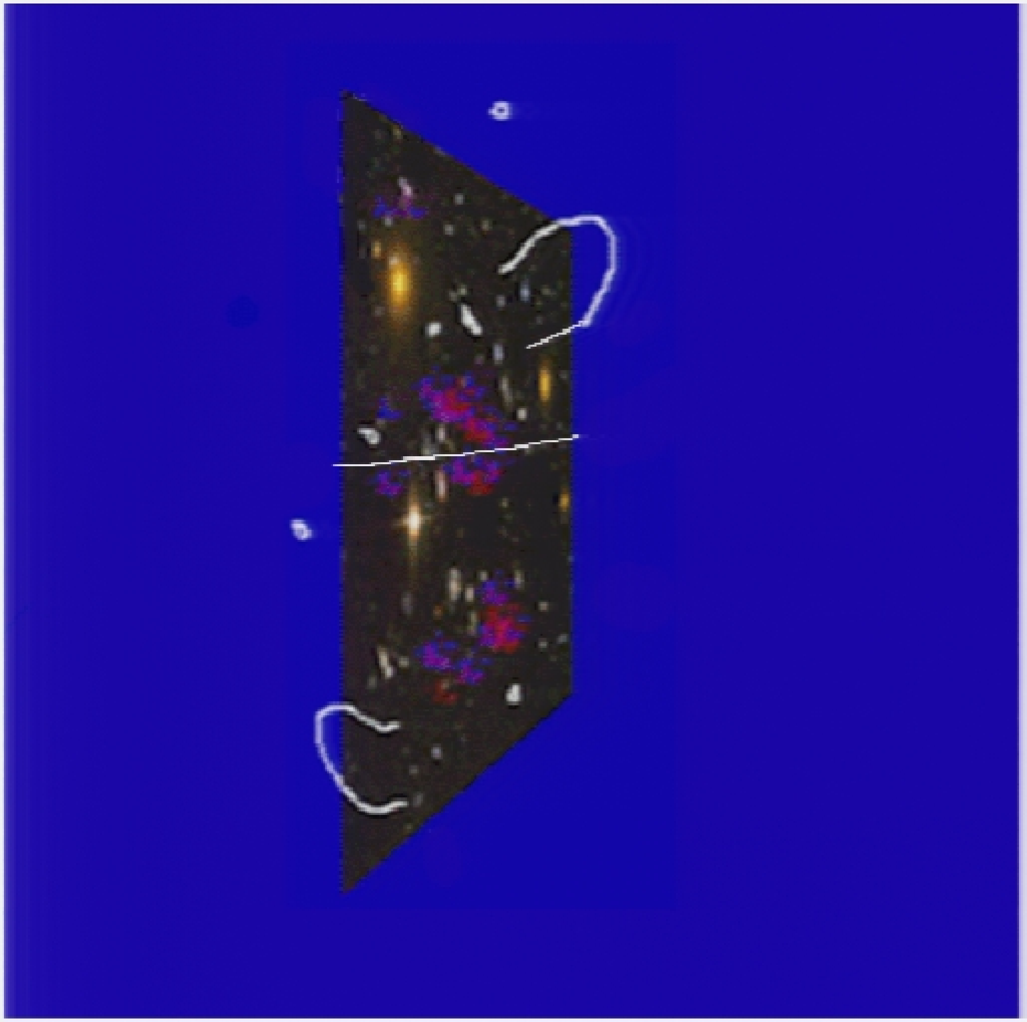

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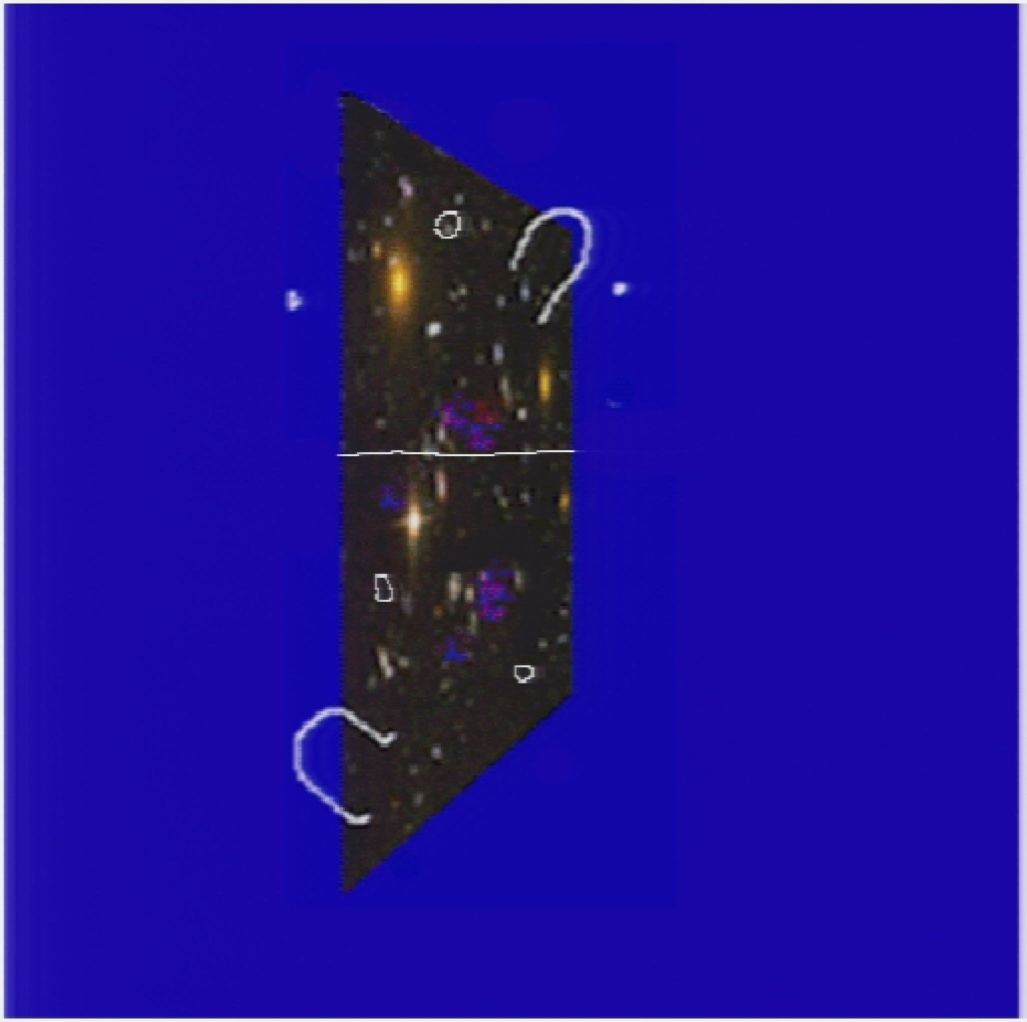

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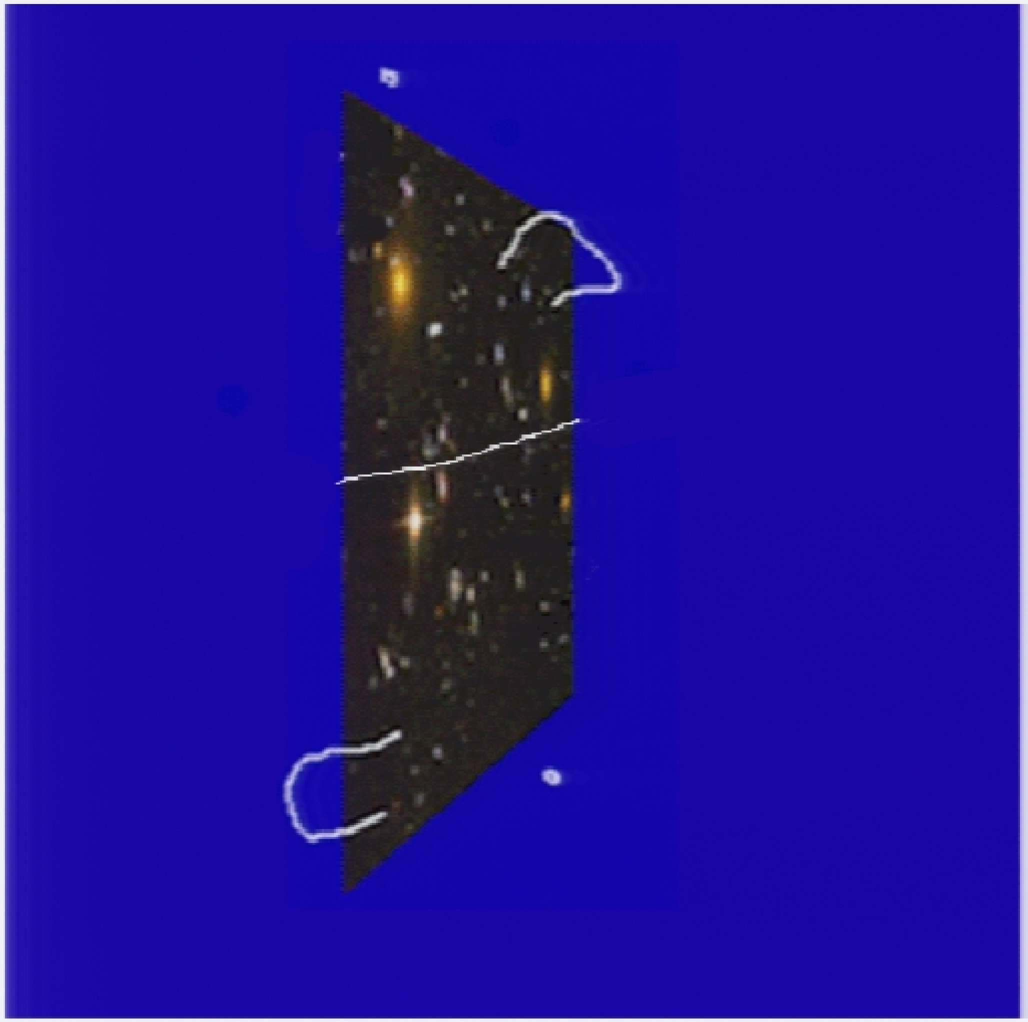

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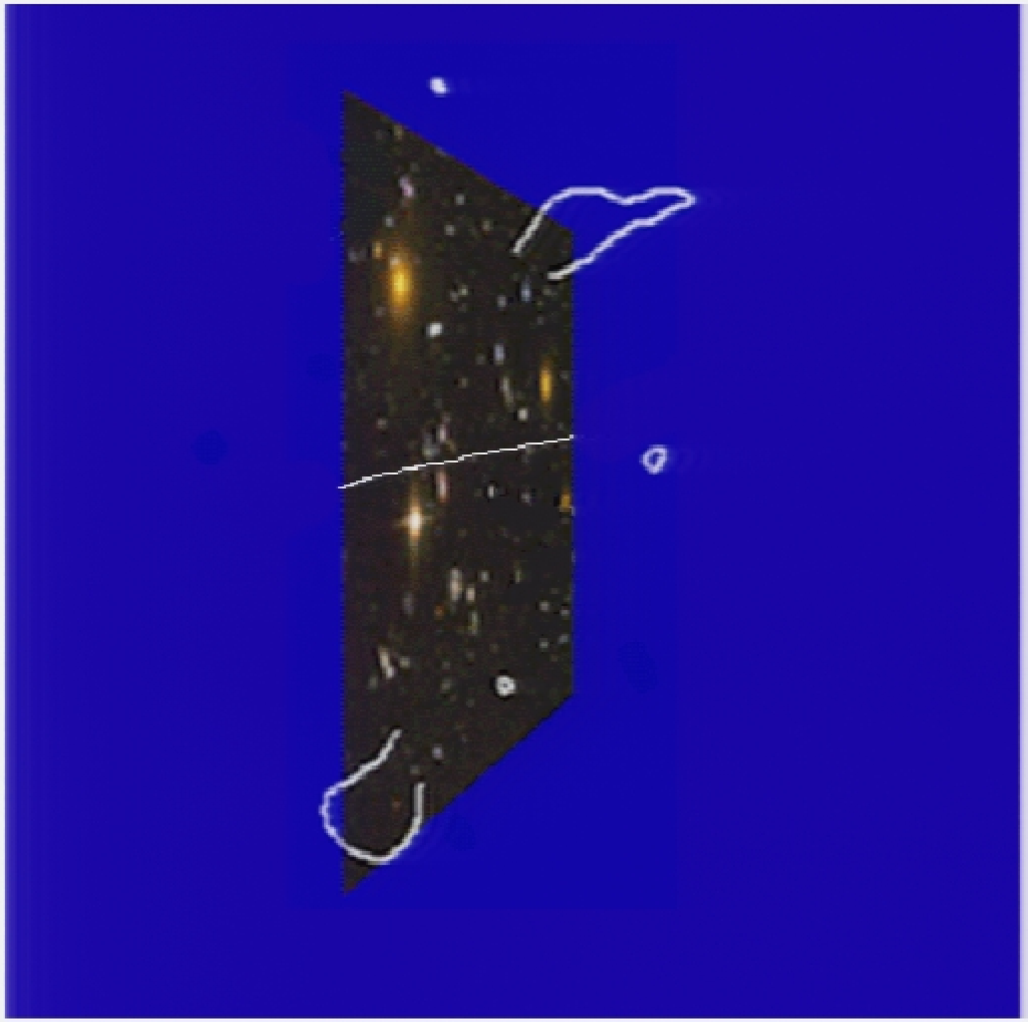

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Start with a realistic string vacuum : a KKLT state

Burgess, Quevedo, Dvali, ...

Add a pair of D3-antiD3-branes : the KKLMMT scenario

$$V(\phi) = \frac{\beta}{2} H^2 \phi^2 + 2T_3 h^4 \left(1 - \frac{1}{N}\frac{\phi_0^4}{\phi^4}\right)$$

For slow roll inflation : $\eta = \beta/3 < 1/100$

This is a fine-tuning on $\beta < 1/30$?

$\beta \simeq 0 \rightarrow \quad G\mu = 2 \times 10^{-10}$

S. Kachru, R. Kallosh, A. Linde, S. Trivedi, hep-th/0301240
KKLT + J. Maldacena, L. McAllister, hep-th/0308055

A Closer Look at KKLMMT

$$\eta = \frac{\beta}{3} - \frac{C}{\phi^6}$$

So there is a range when the slow-roll parameter is almost zero.

This implies that the constraint on fine-tuning should be relaxed.

$\beta < 1/7$

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

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Fast Roll Inflation

With DBI, fast roll inflation looks possible.

Alishahiha, Silverstein, Tong, hep-th/0404084

X. Chen, hep-th/0408084

With the potential from brane interaction, slow-roll combined with fast roll, brane inflation is quite generic.

Sarah Shandera

Inflationary predictions are sensitive to β, but not to the warping.

Cosmic string production towards the end of brane inflation

this follows from superstring theory property
+ the cosmological condition

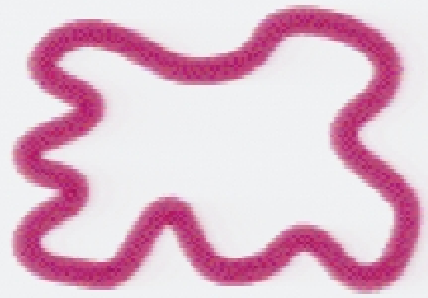
- Monopoles : density ~ a^{-3} Disastrous
- Domain walls : density ~ 1/a Disastrous
- cosmic strings : density ~ a^{-2}
  interaction cuts it down to a^{-4} during radiation

N. Jones, H. Stoica, H.T., hep-th/0203163
S. Sarangi , H.T., hep-th/0204074

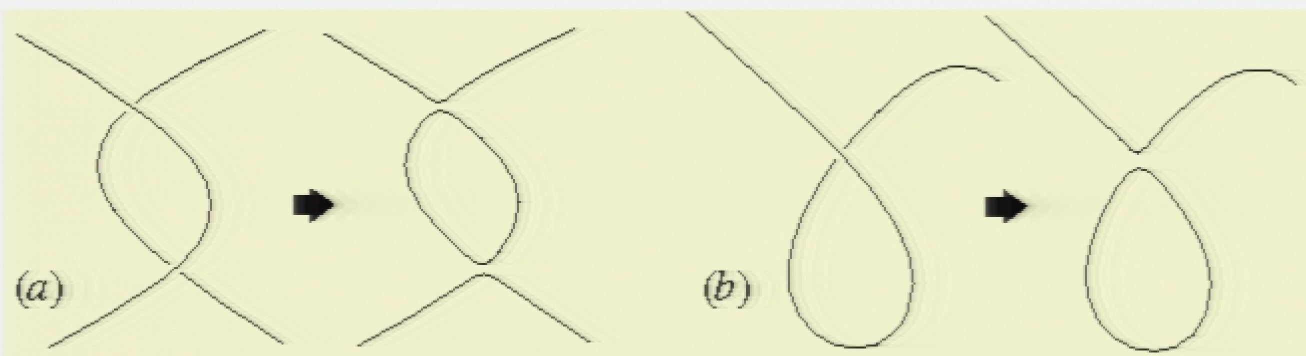
History of cosmic strings

- 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 theory. He pointed out a number of problems with this picture: tension, 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 density perturbation.
- In 1995, Polchinski and others pointed out the presence of 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 KKLMMT scenarios

Cosmic strings

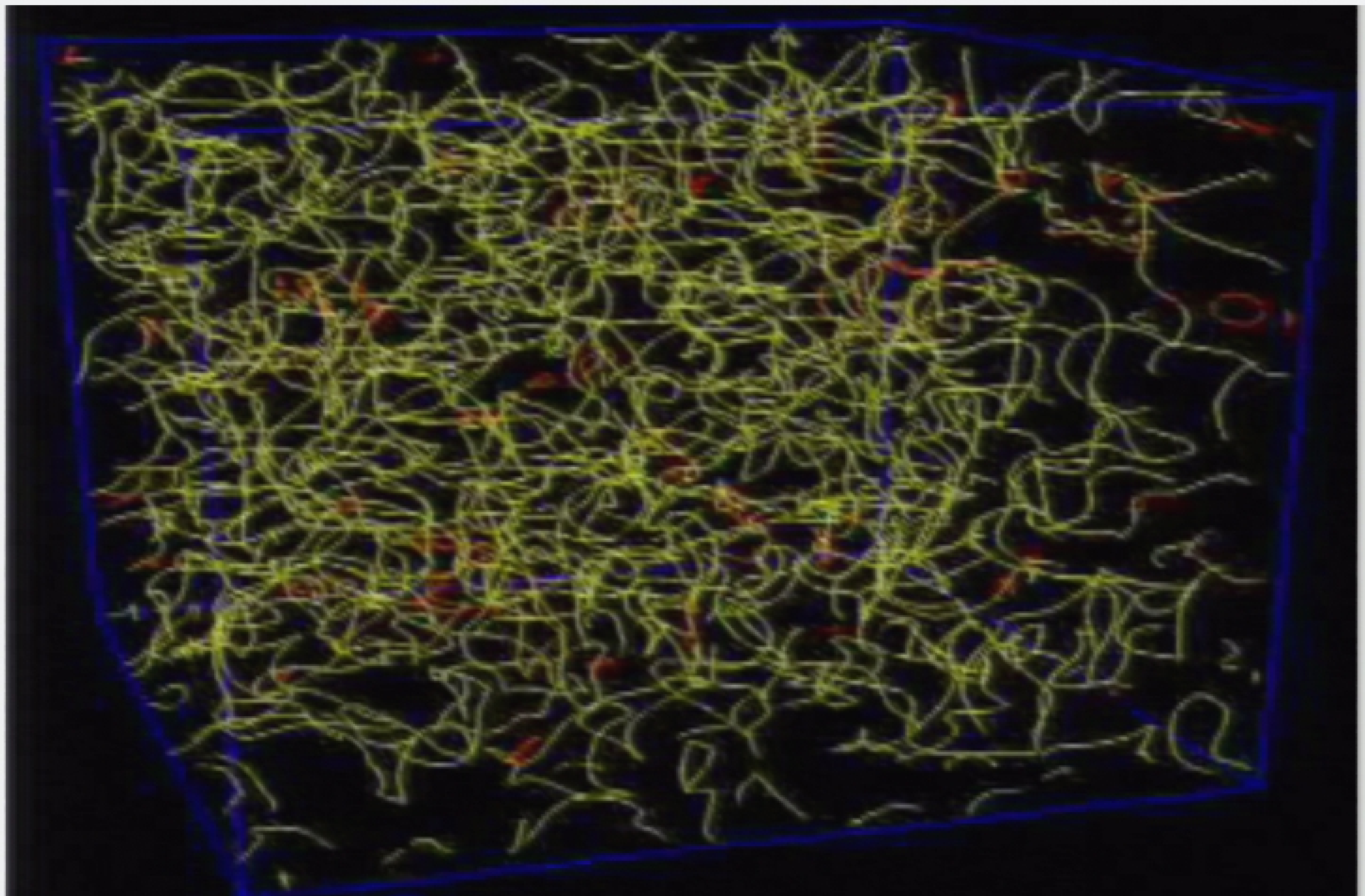


- Cosmic string interactions



Cosmic String Network Evolution

Allen, Martins & Shellard



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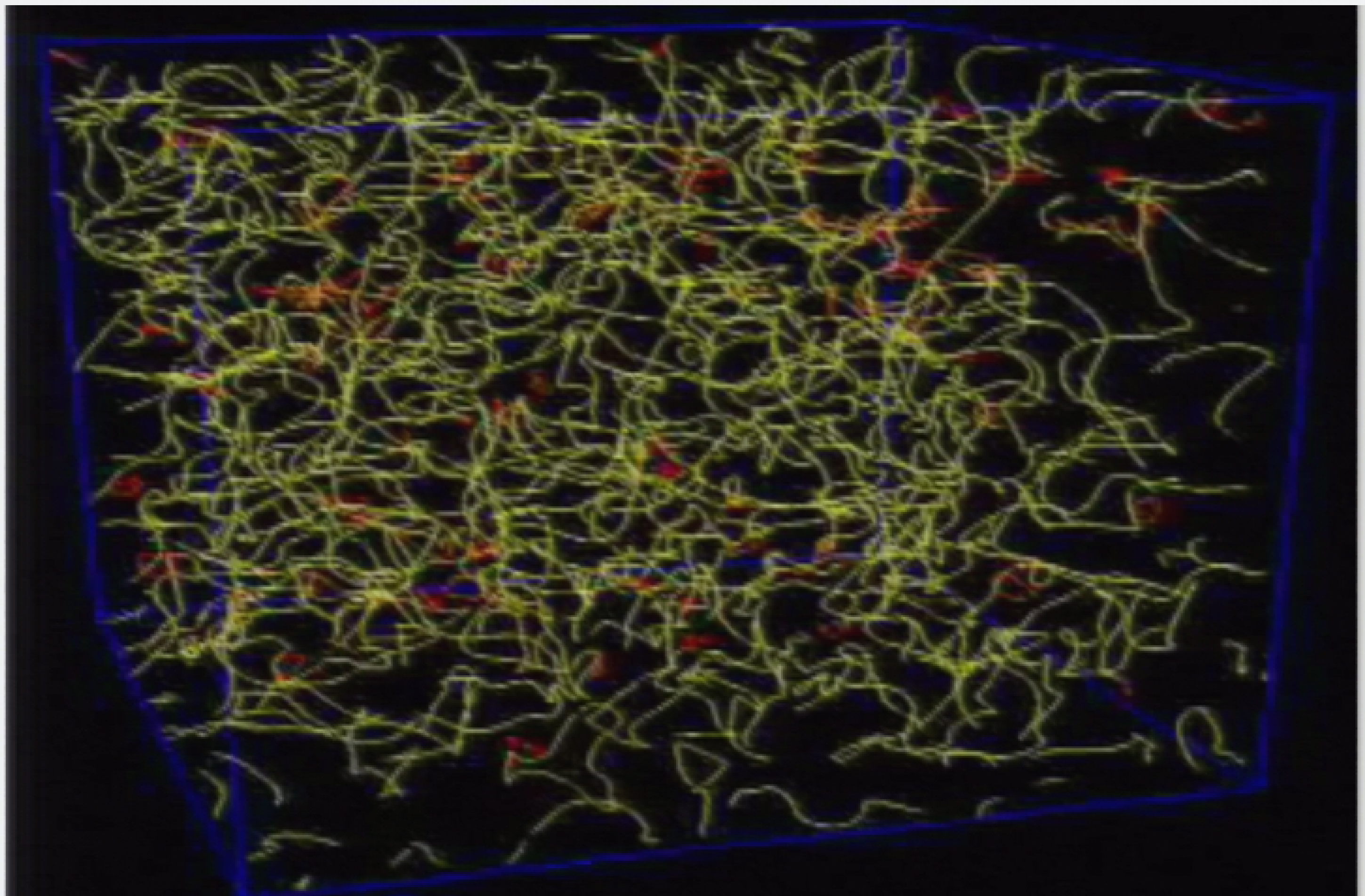

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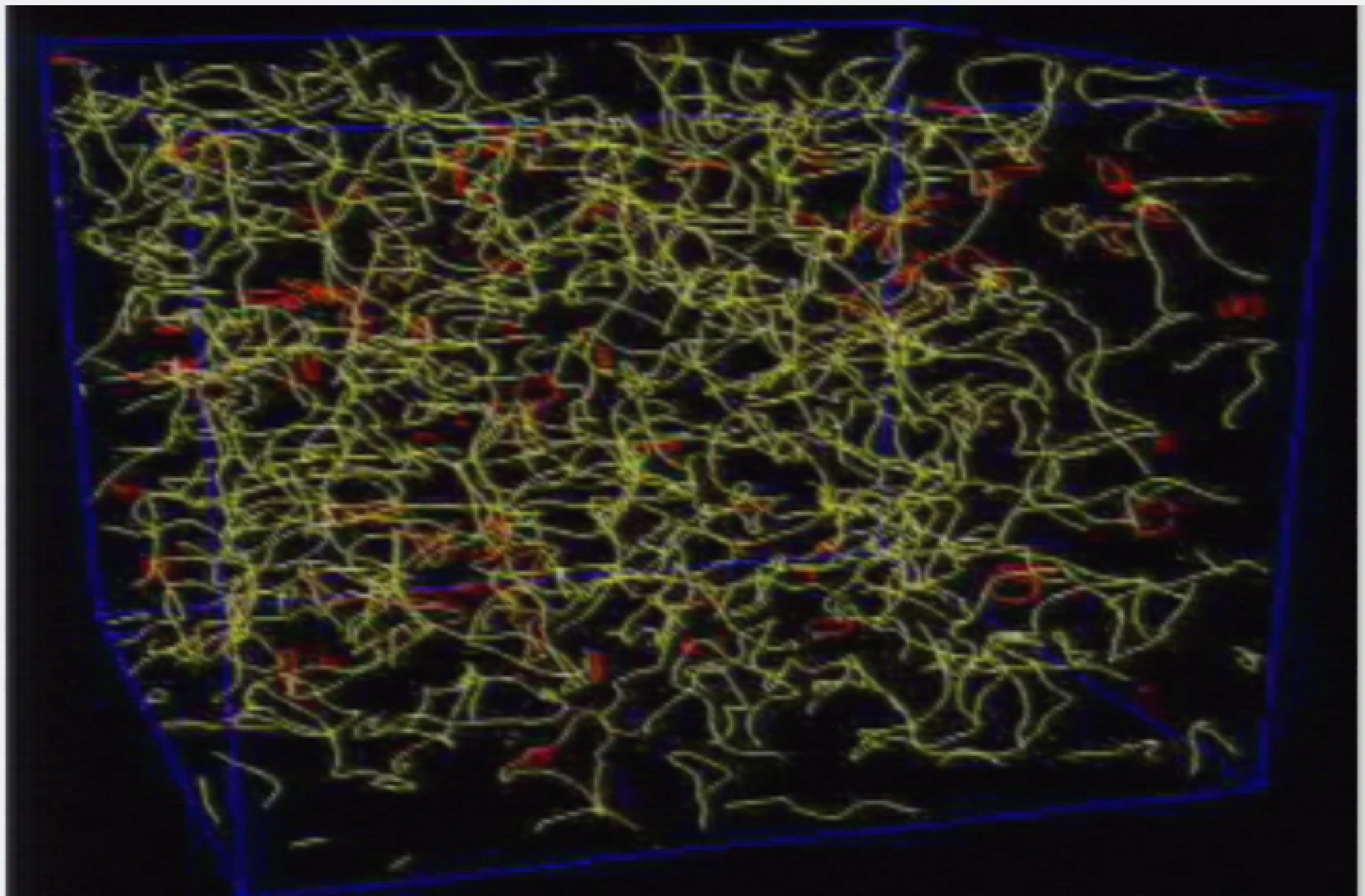

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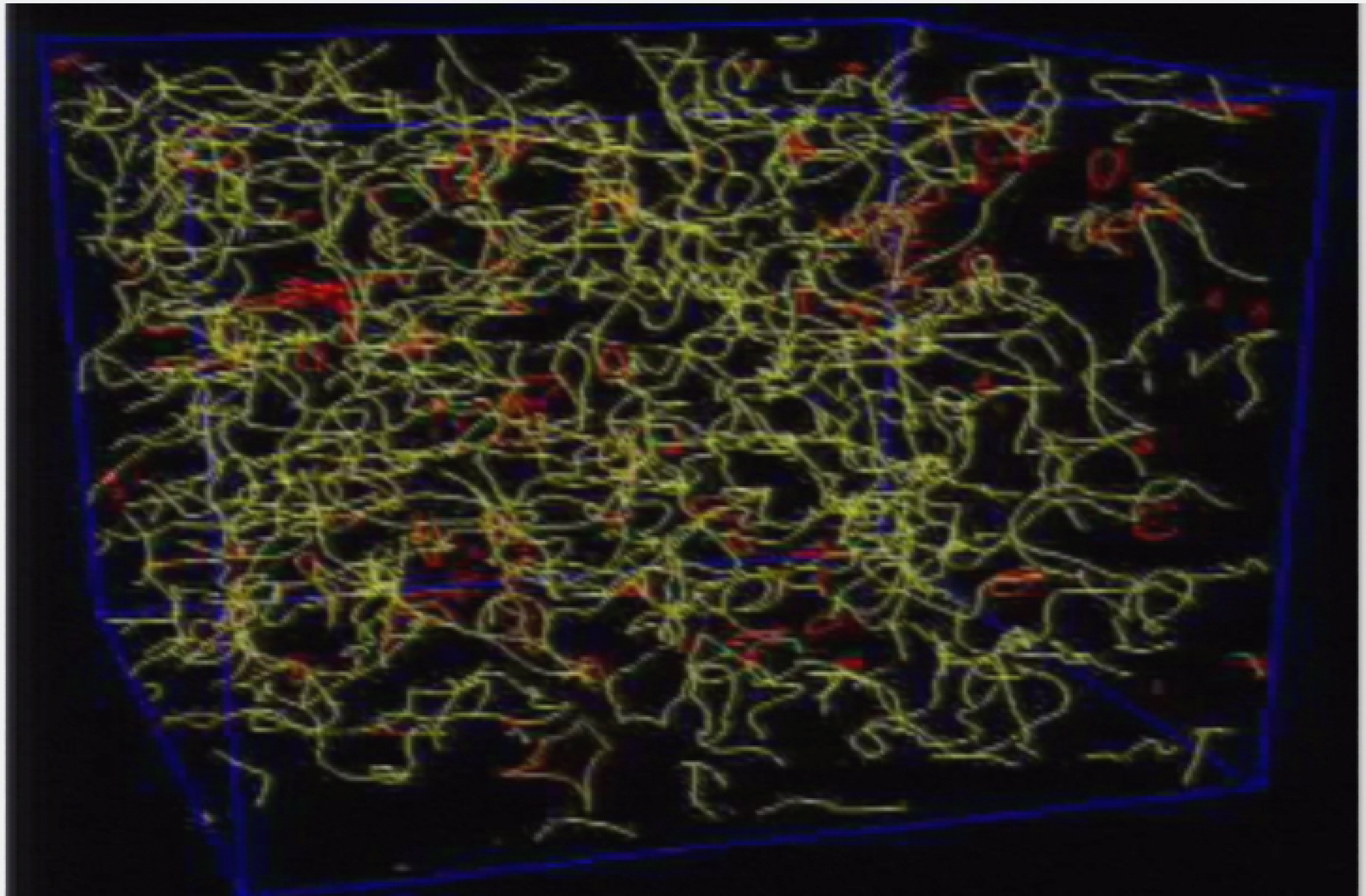

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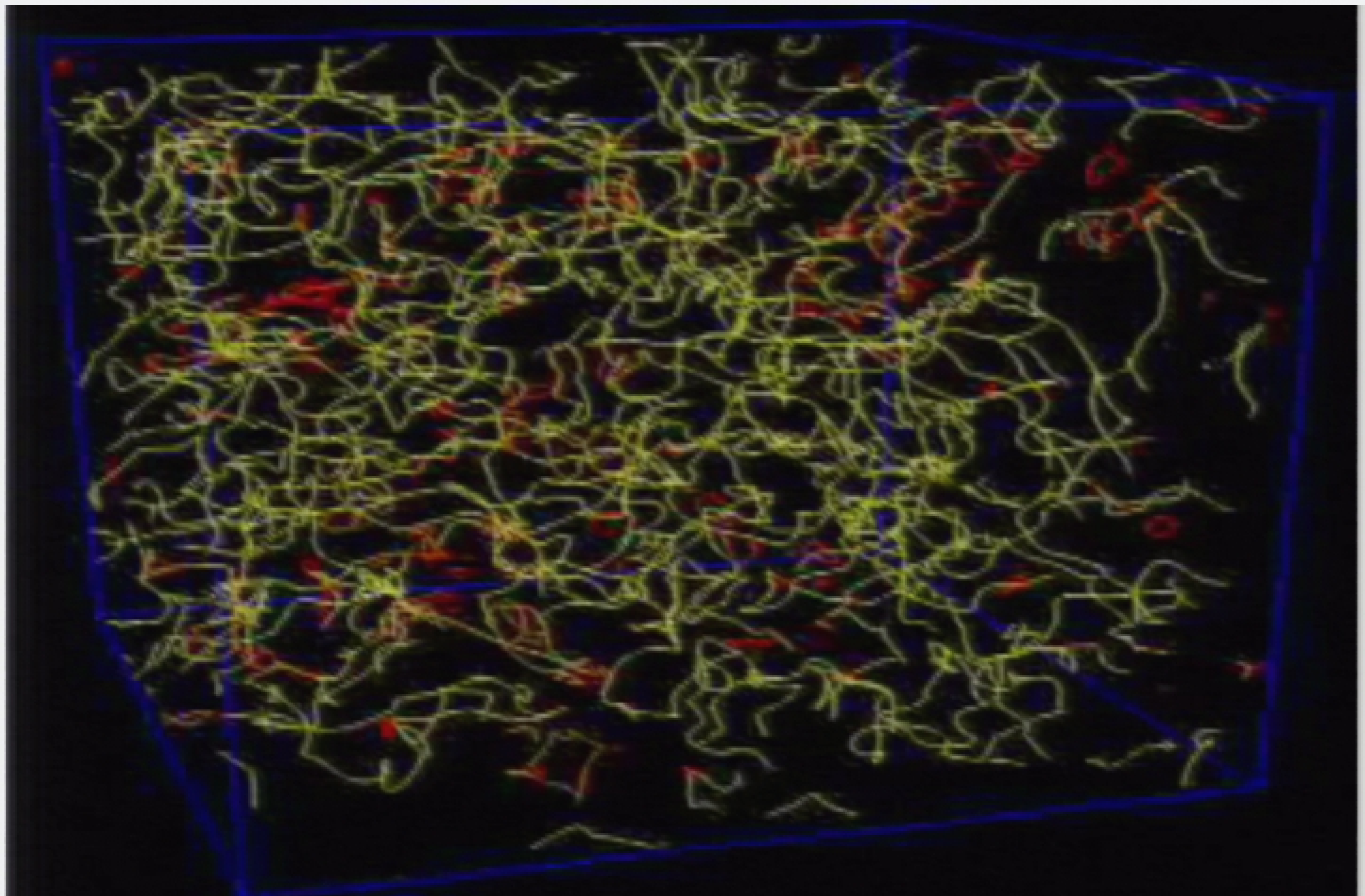

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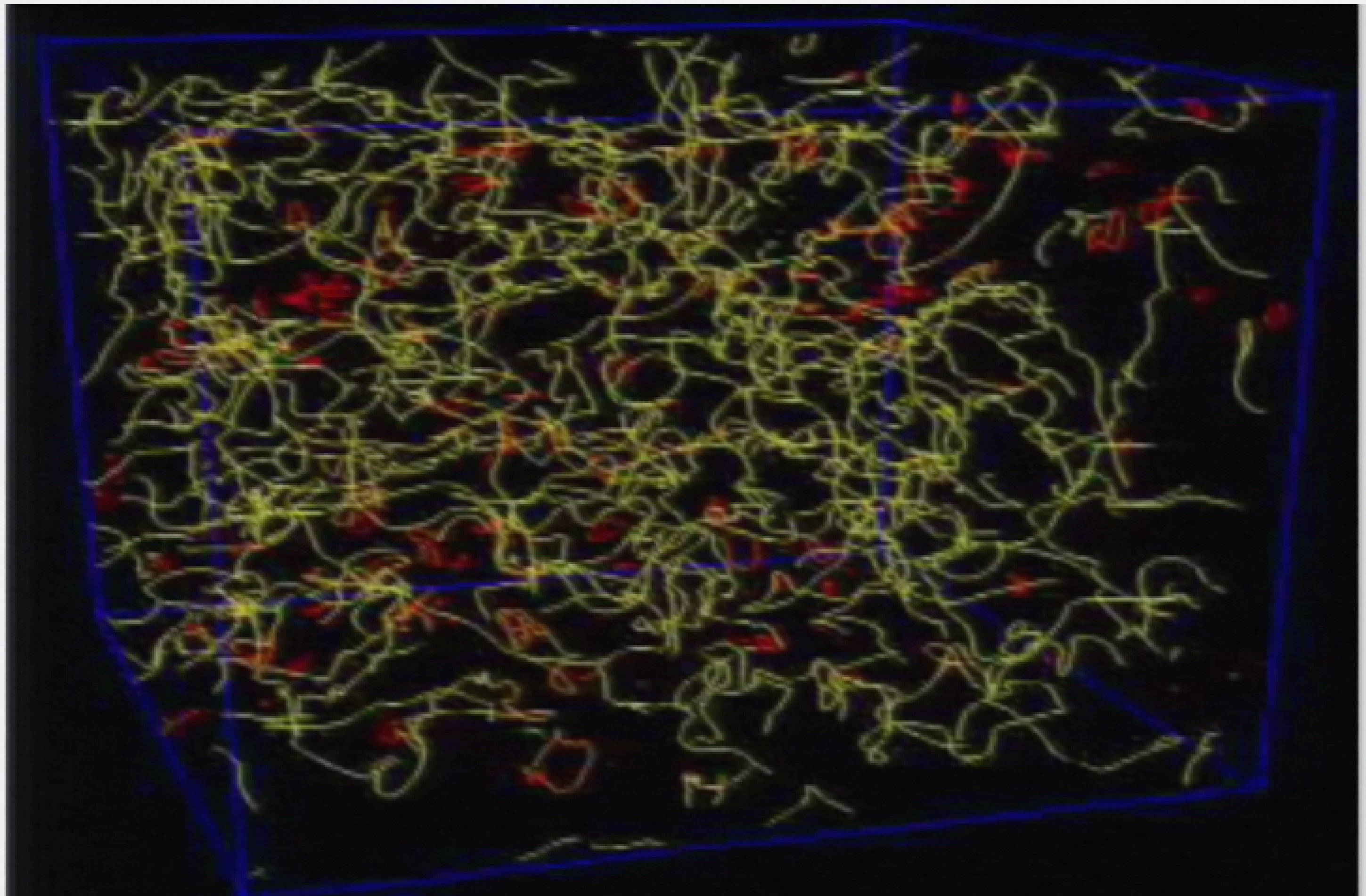

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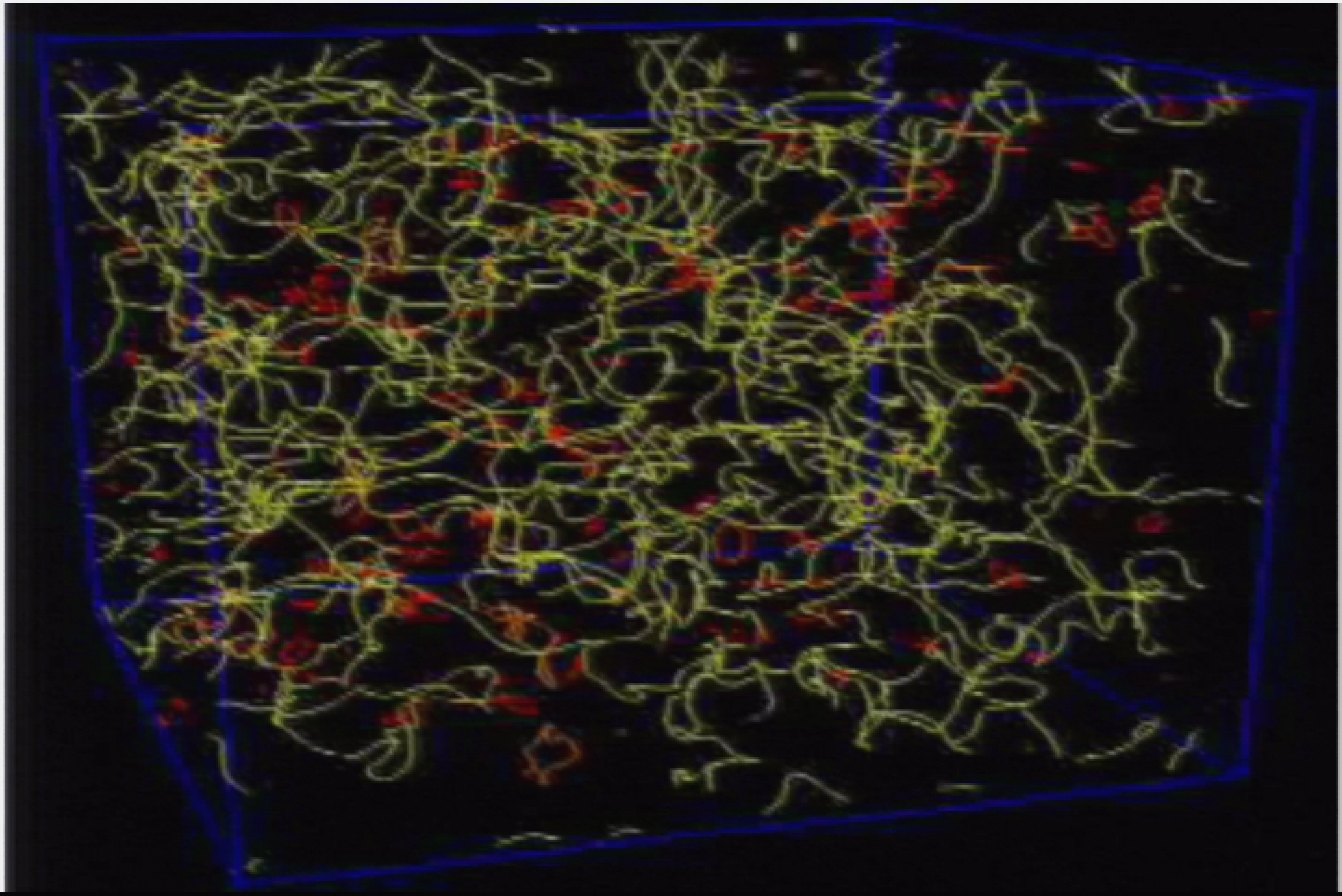

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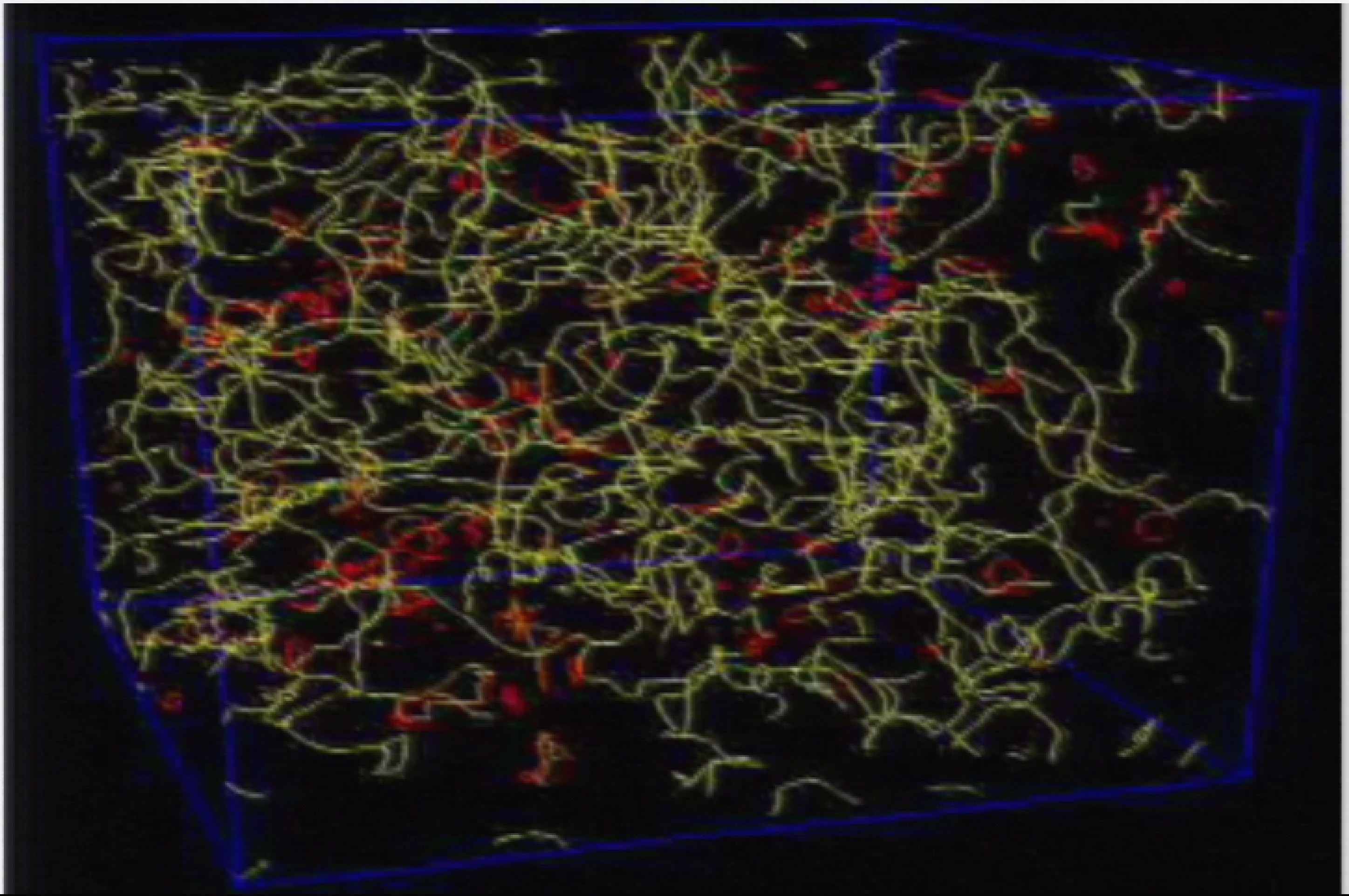

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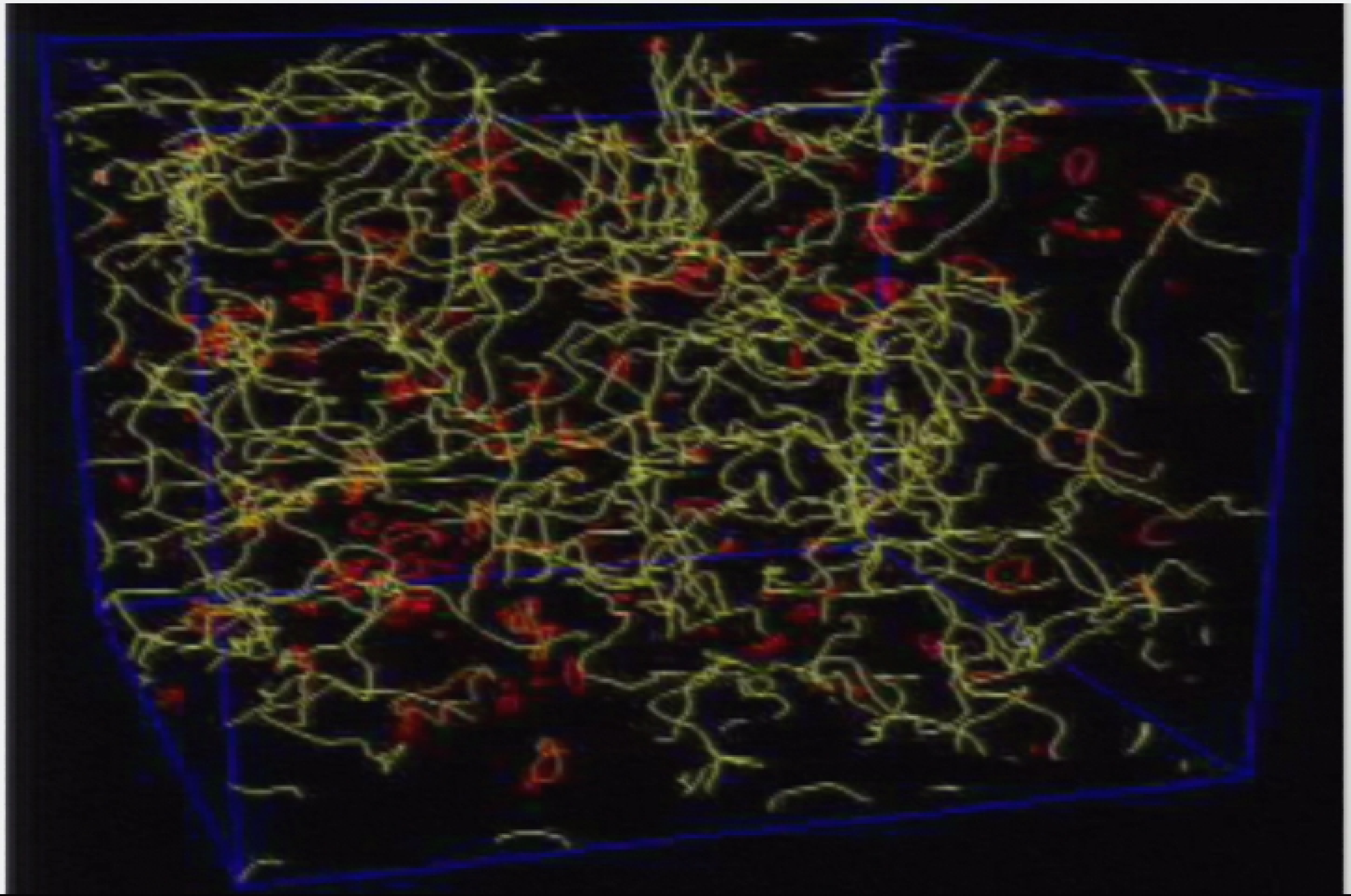
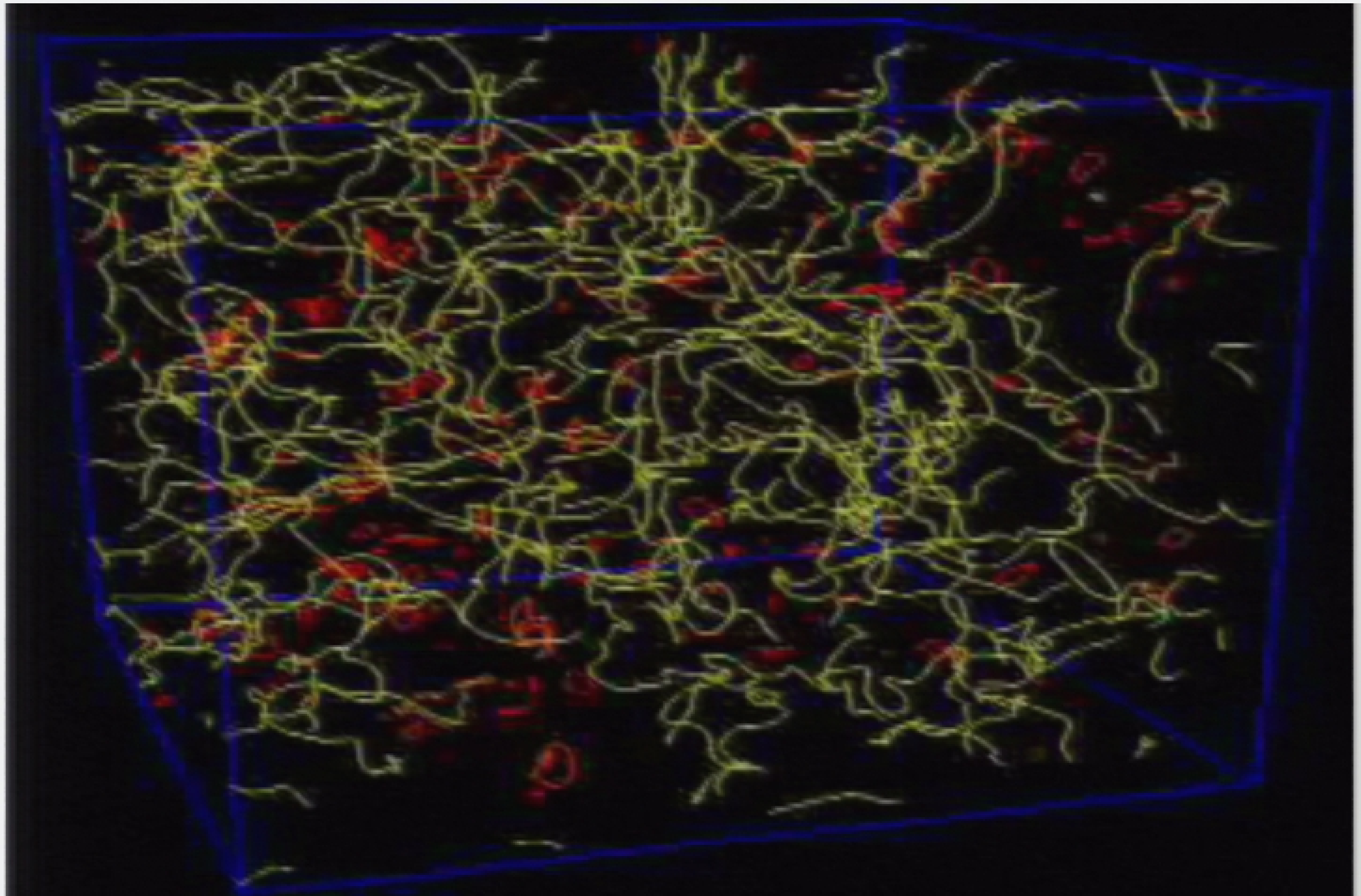


Cosmic String Network Evolution

Allen, Martins & Shellard



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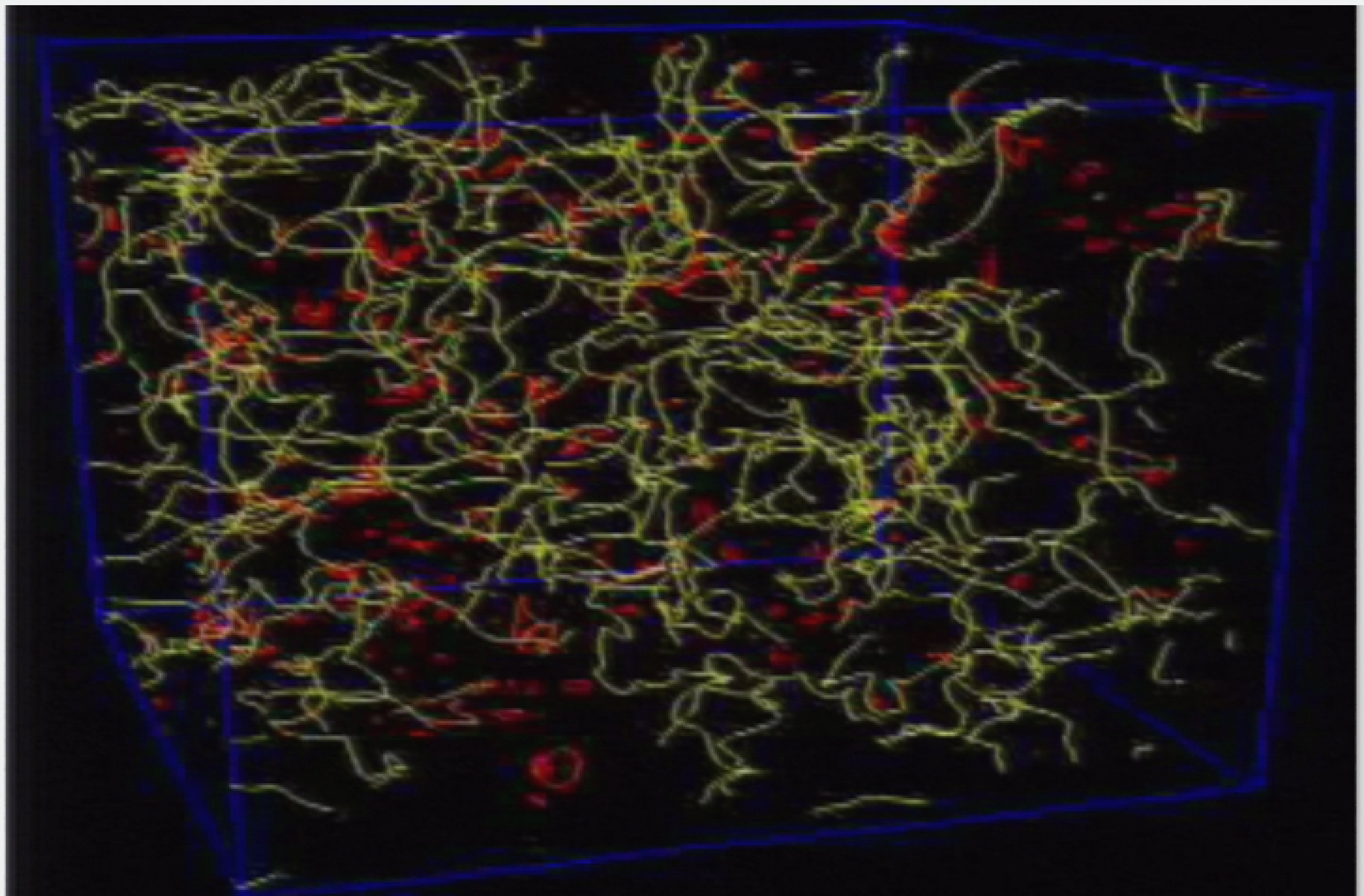

Cosmic String Network Evolution

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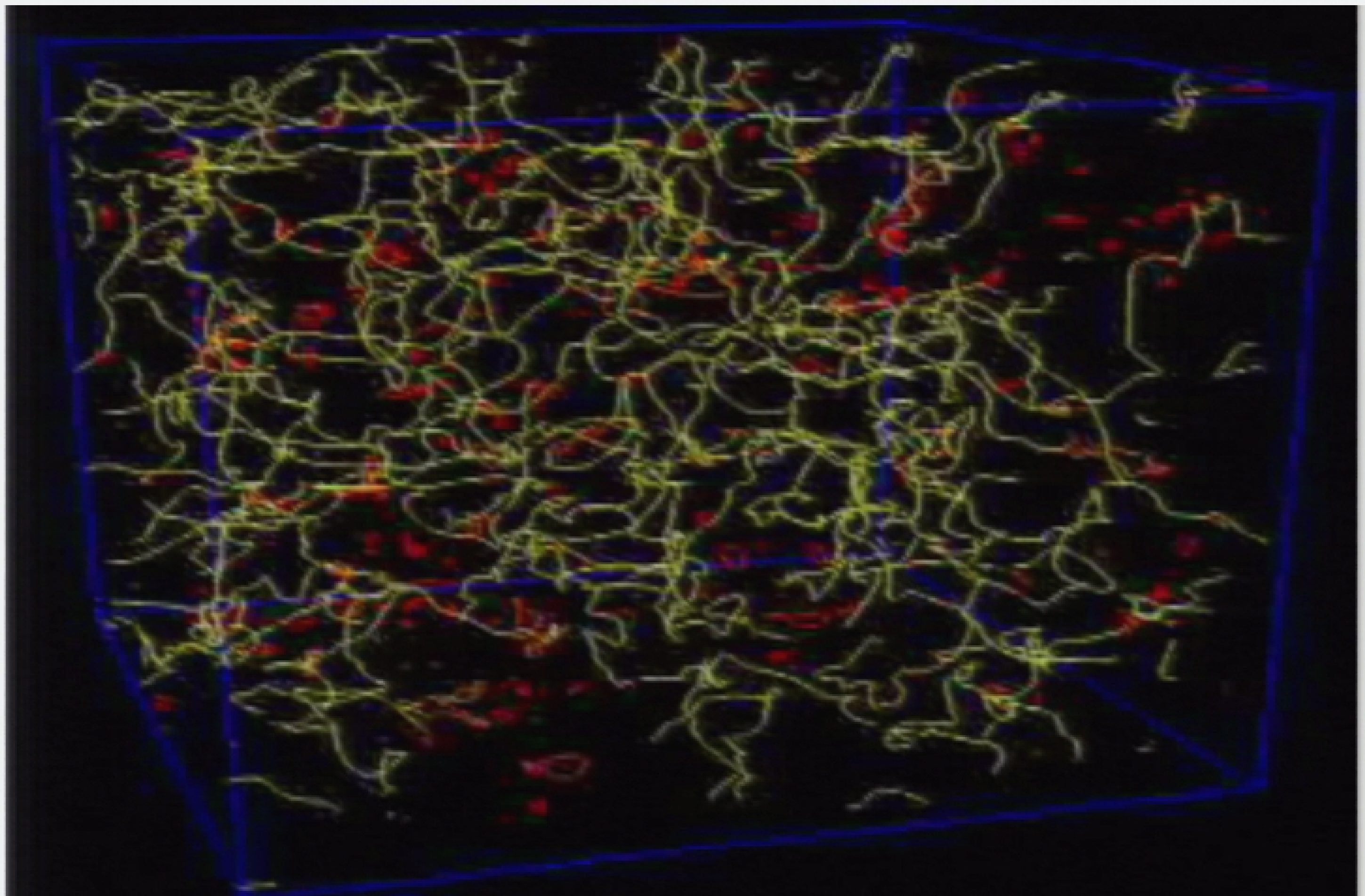

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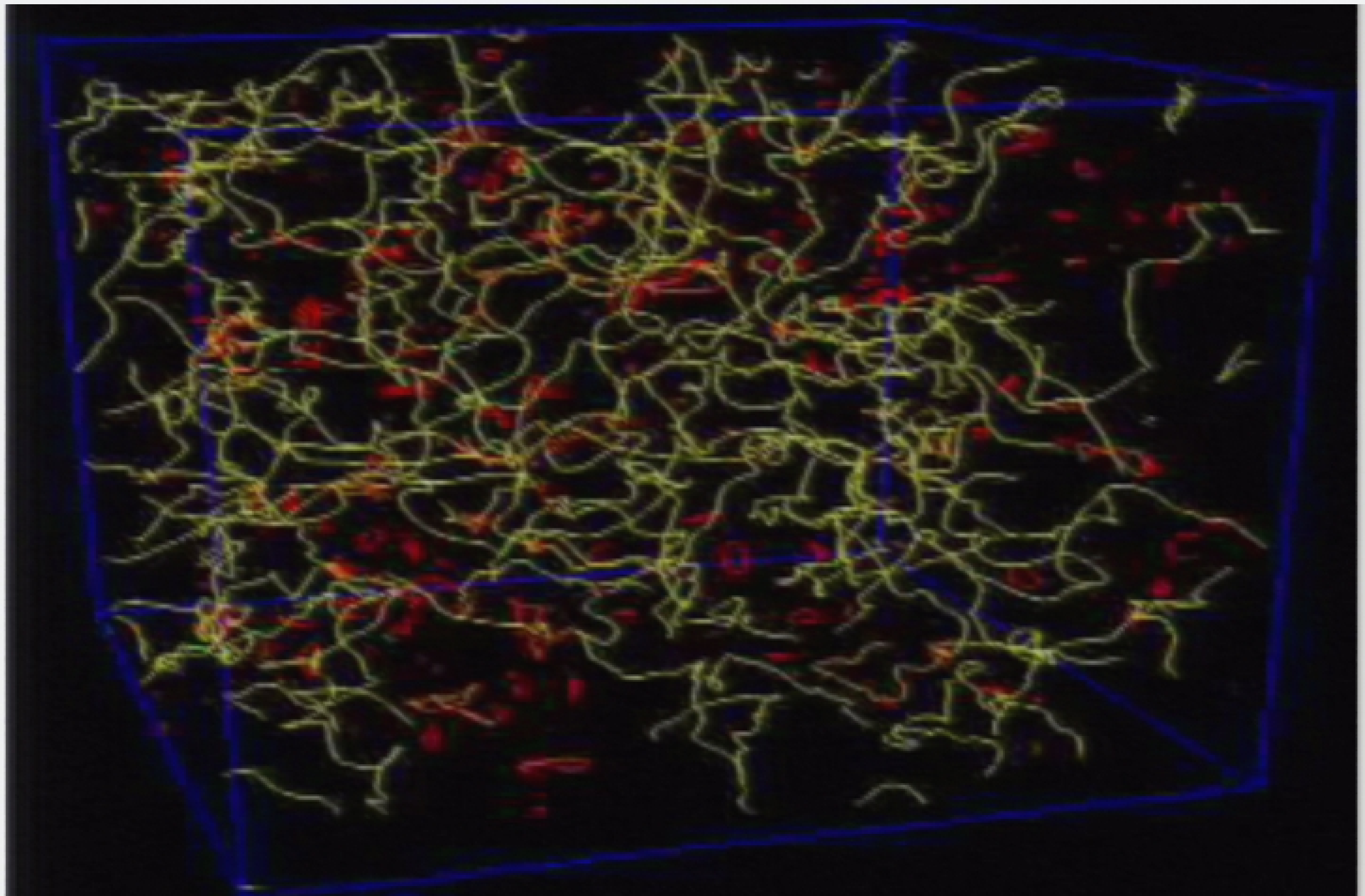

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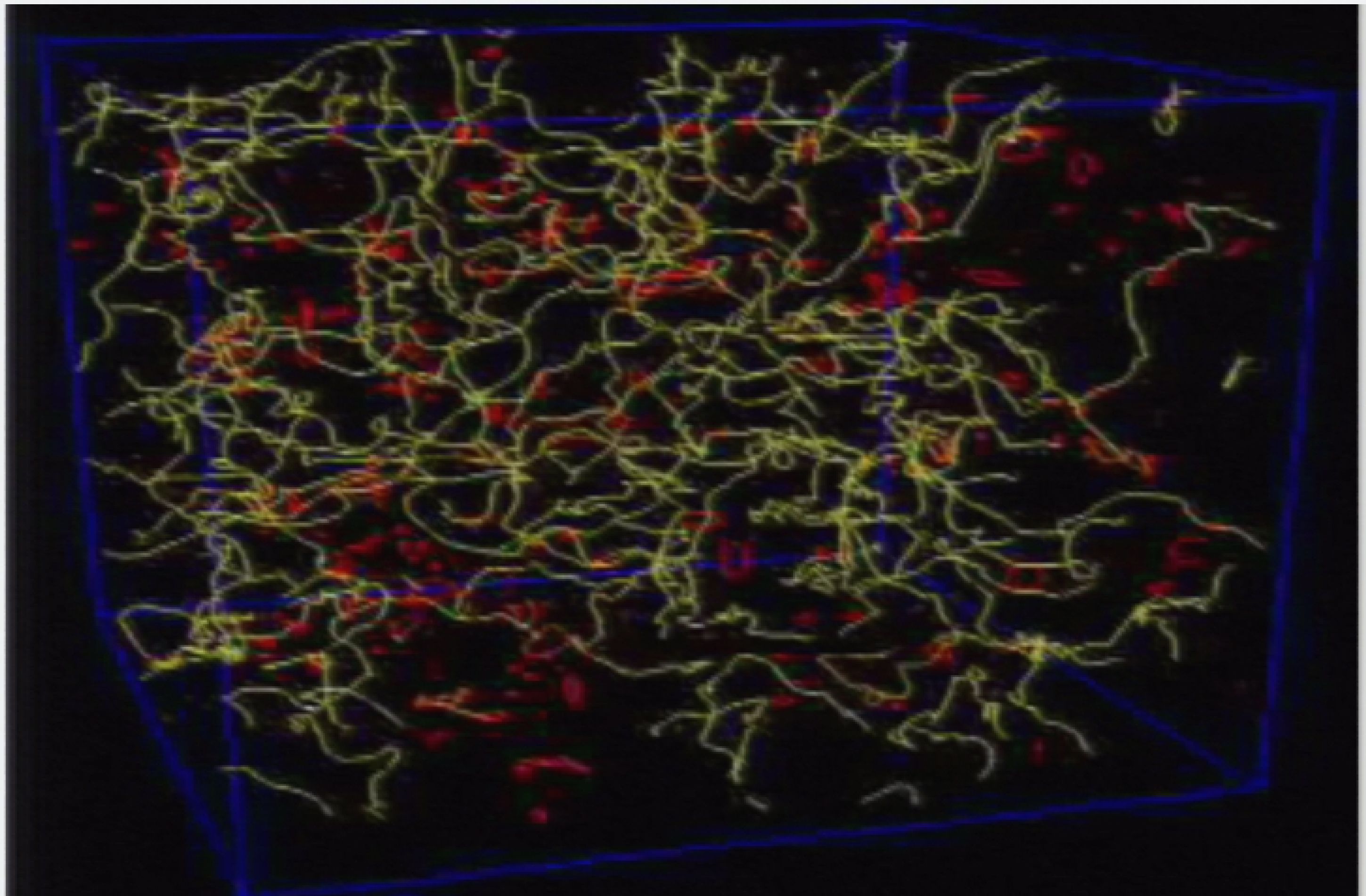

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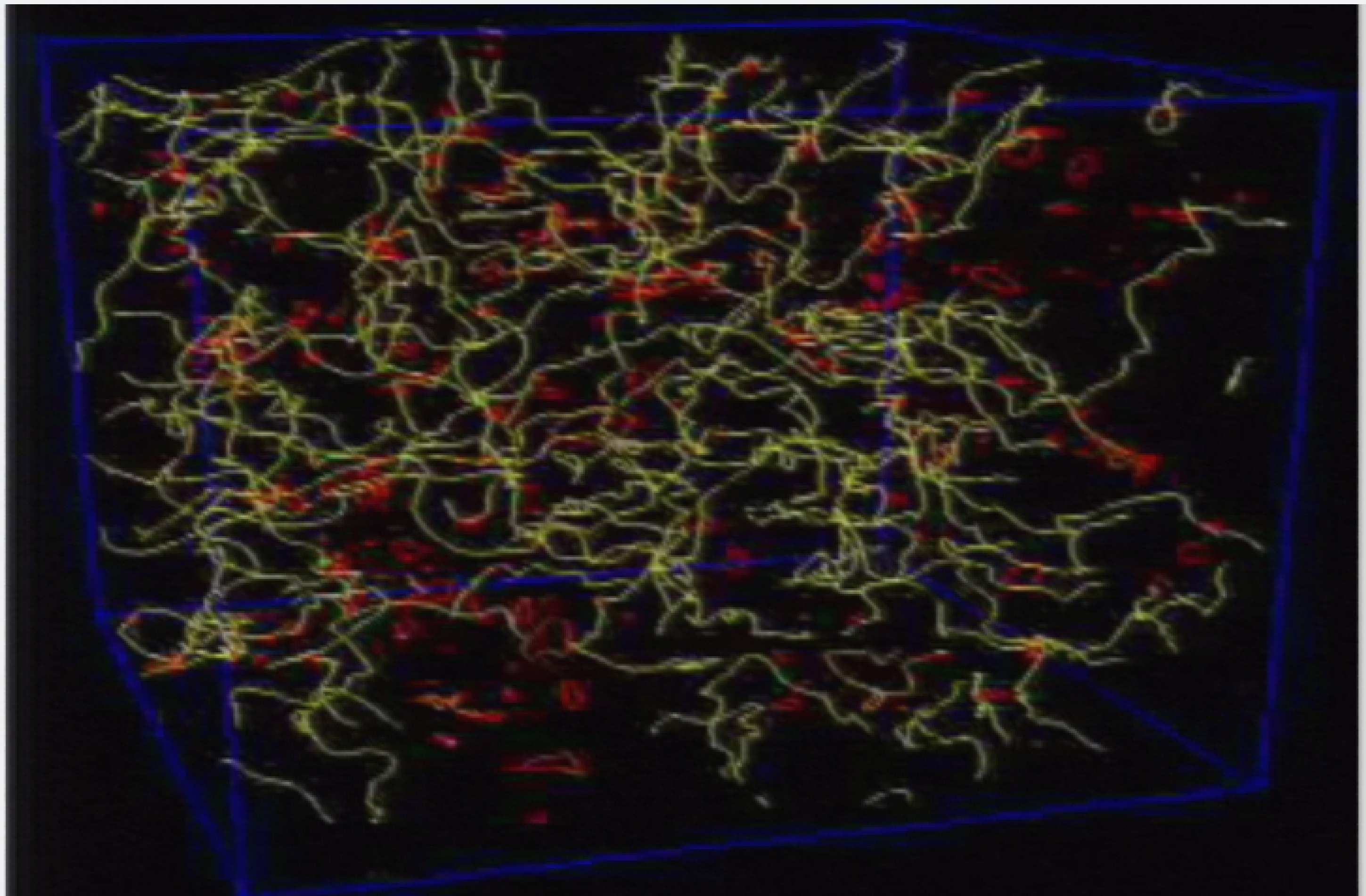
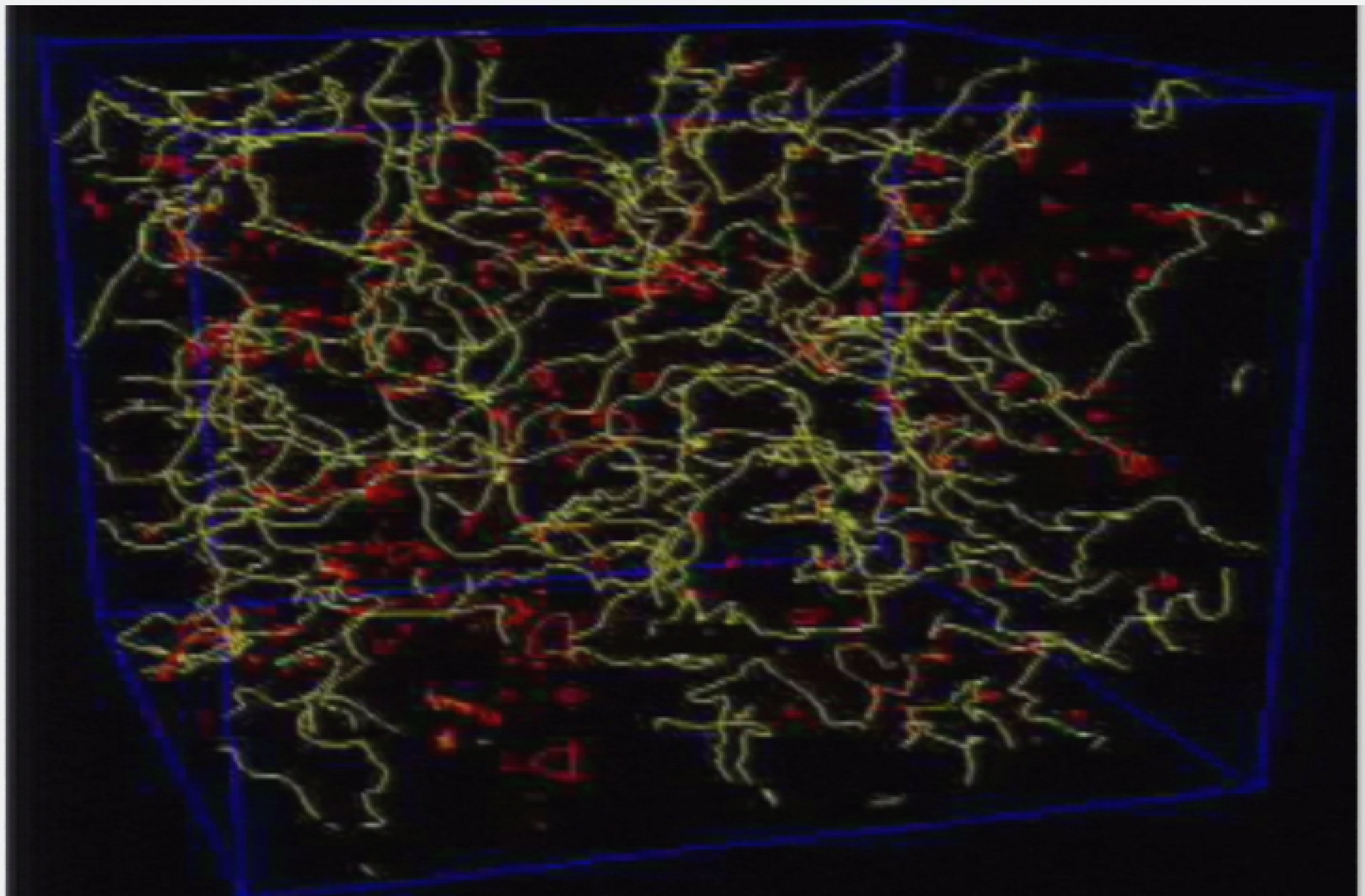


Cosmic String Network Evolution

Allen, Martins & Shellard



Cosmic String Network Evolution

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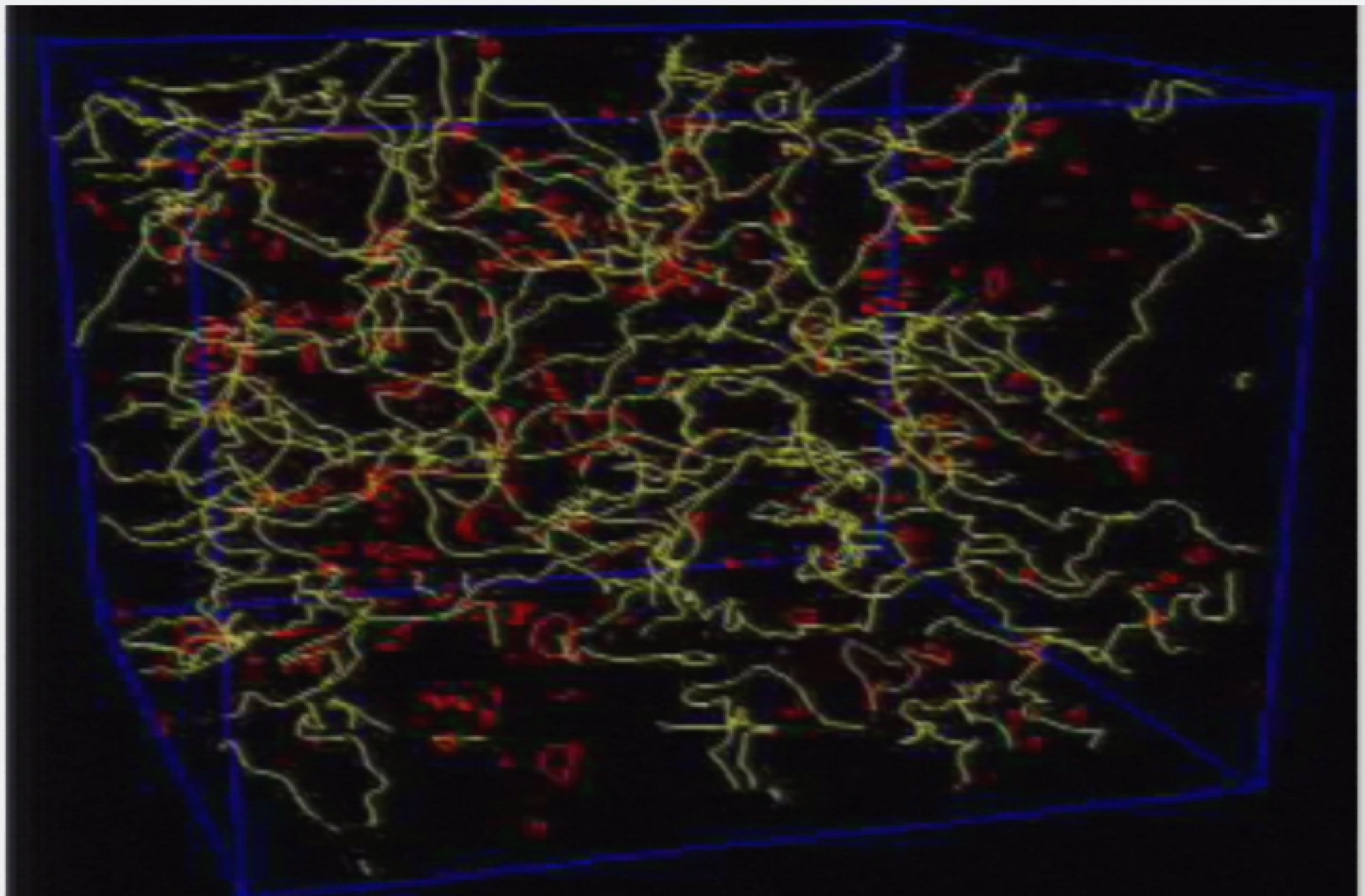
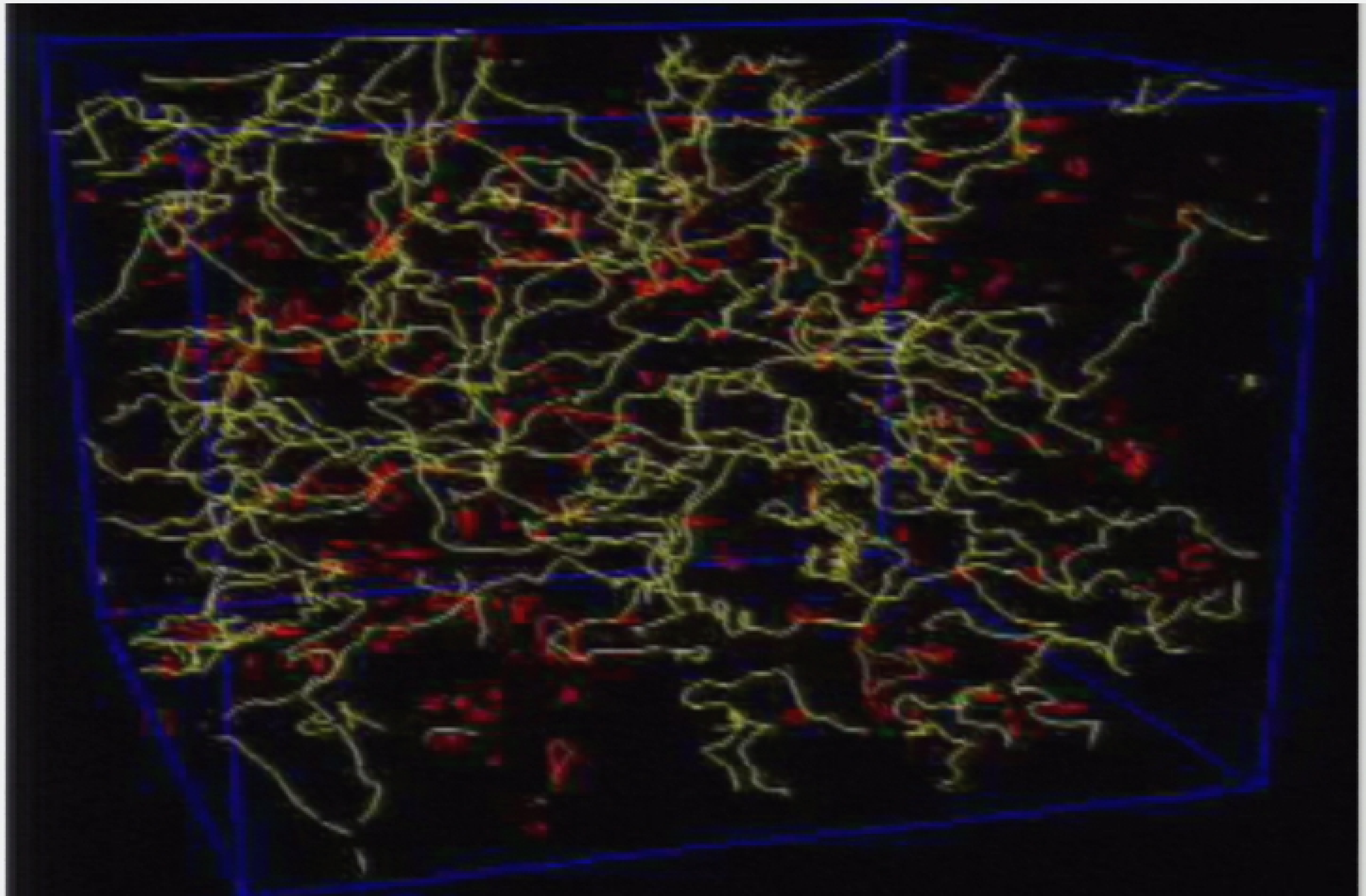


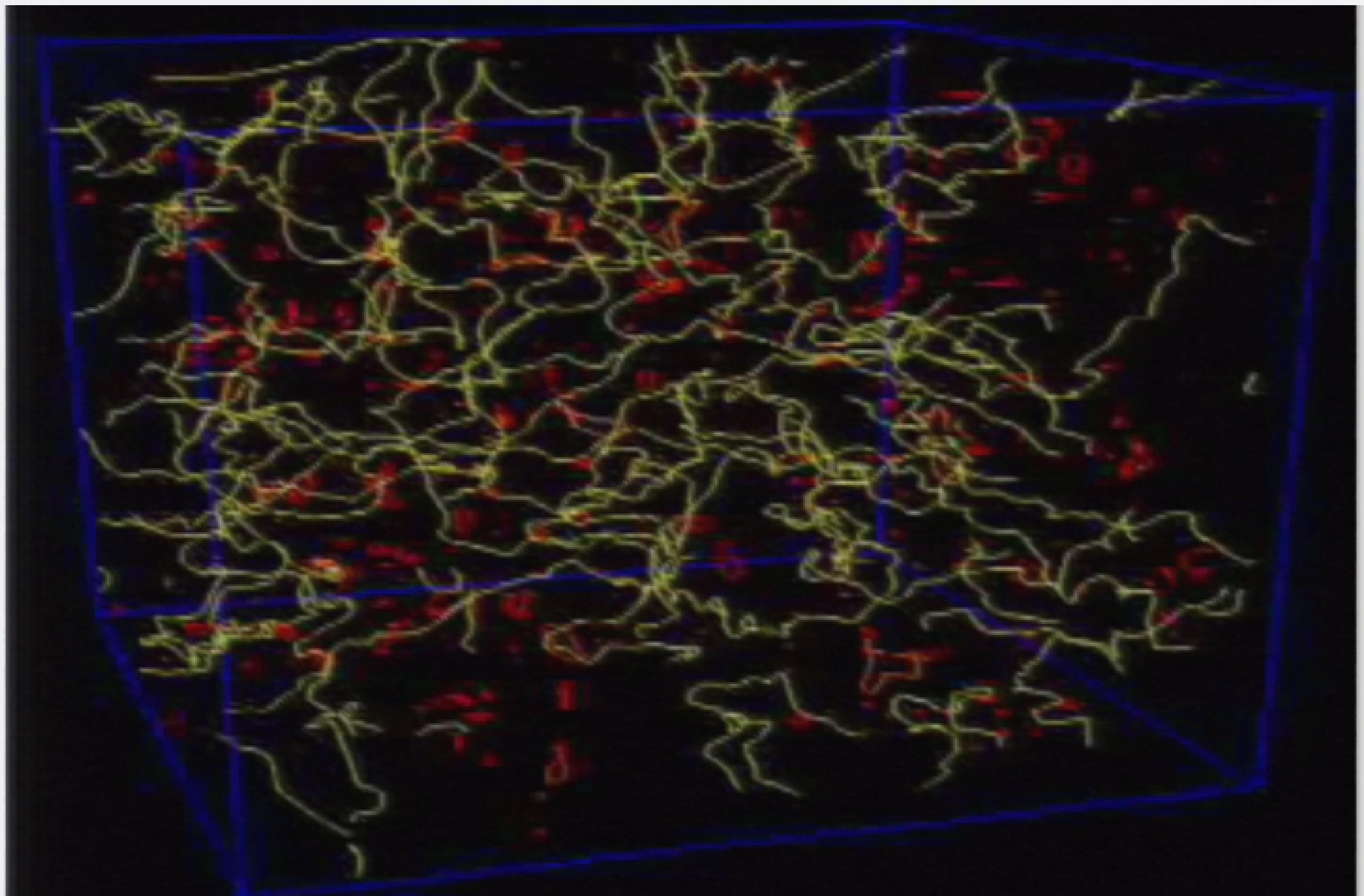
Cosmic String Network Evolution

Allen, Martins & Shellard



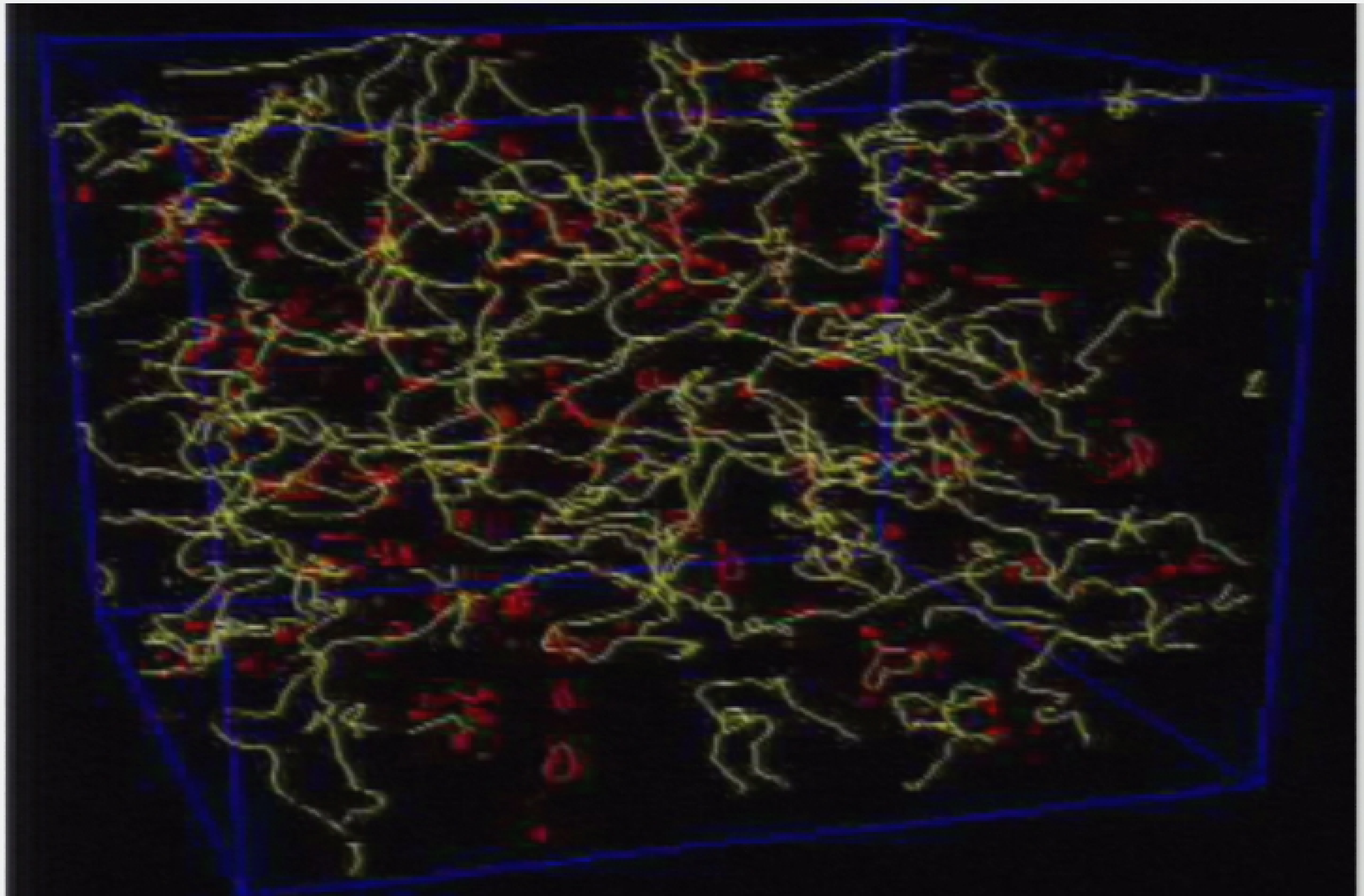
Cosmic String Network Evolution

Allen, Martins & Shellard



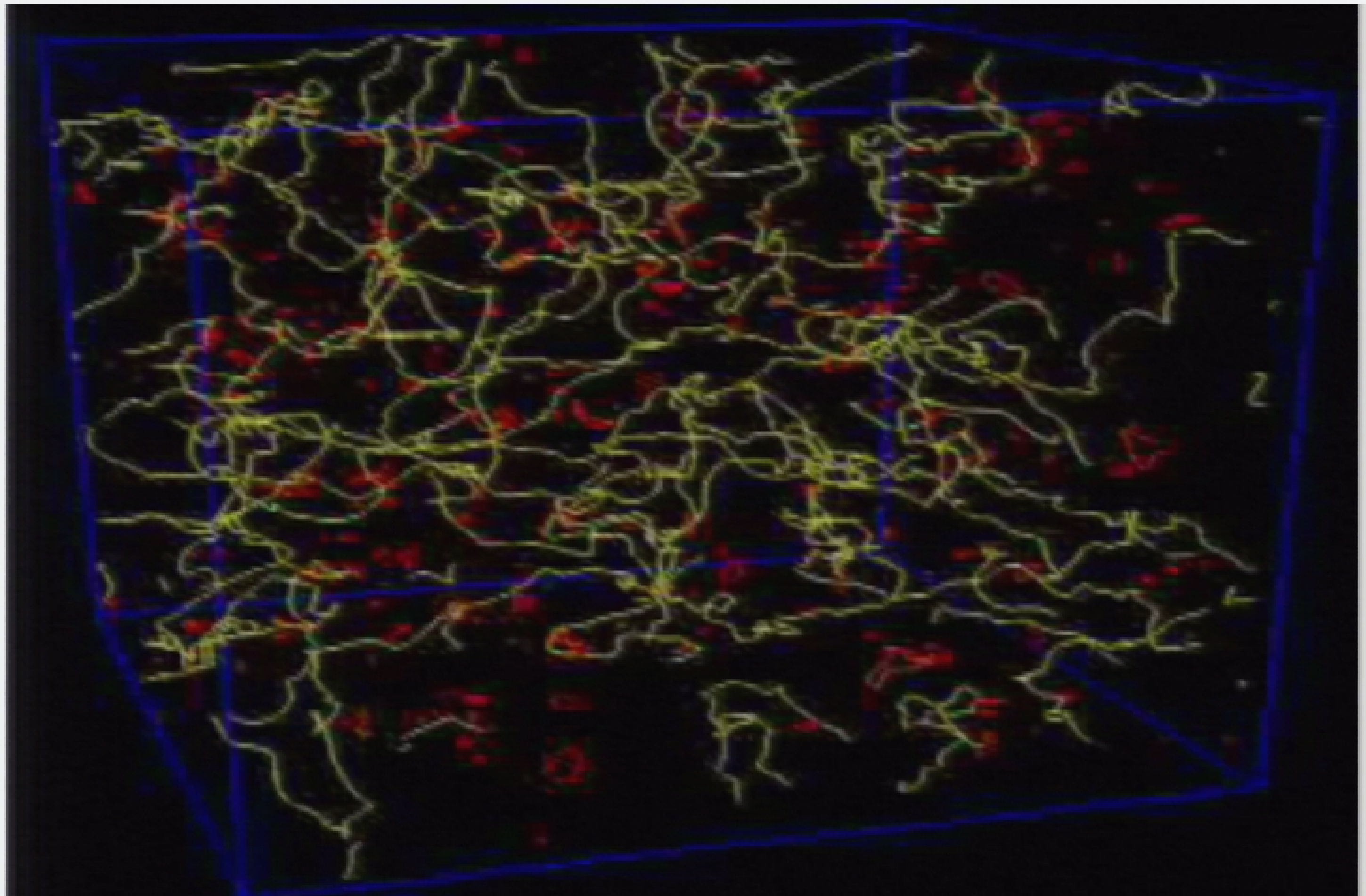
Cosmic String Network Evolution

Allen, Martins & Shellard



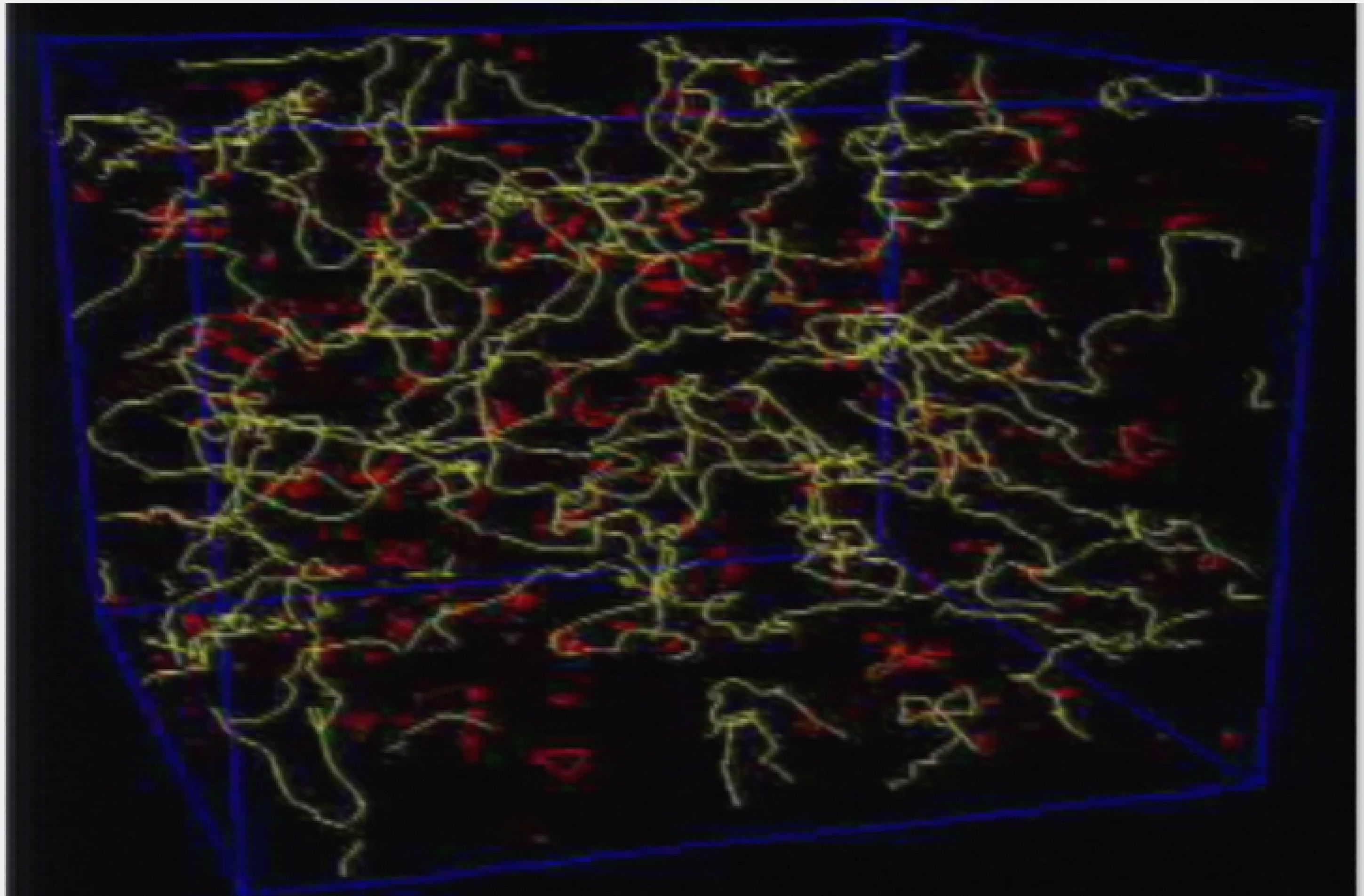
Cosmic String Network Evolution

Allen, Martins & Shellard



Cosmic String Network Evolution

Allen, Martins & Shellard



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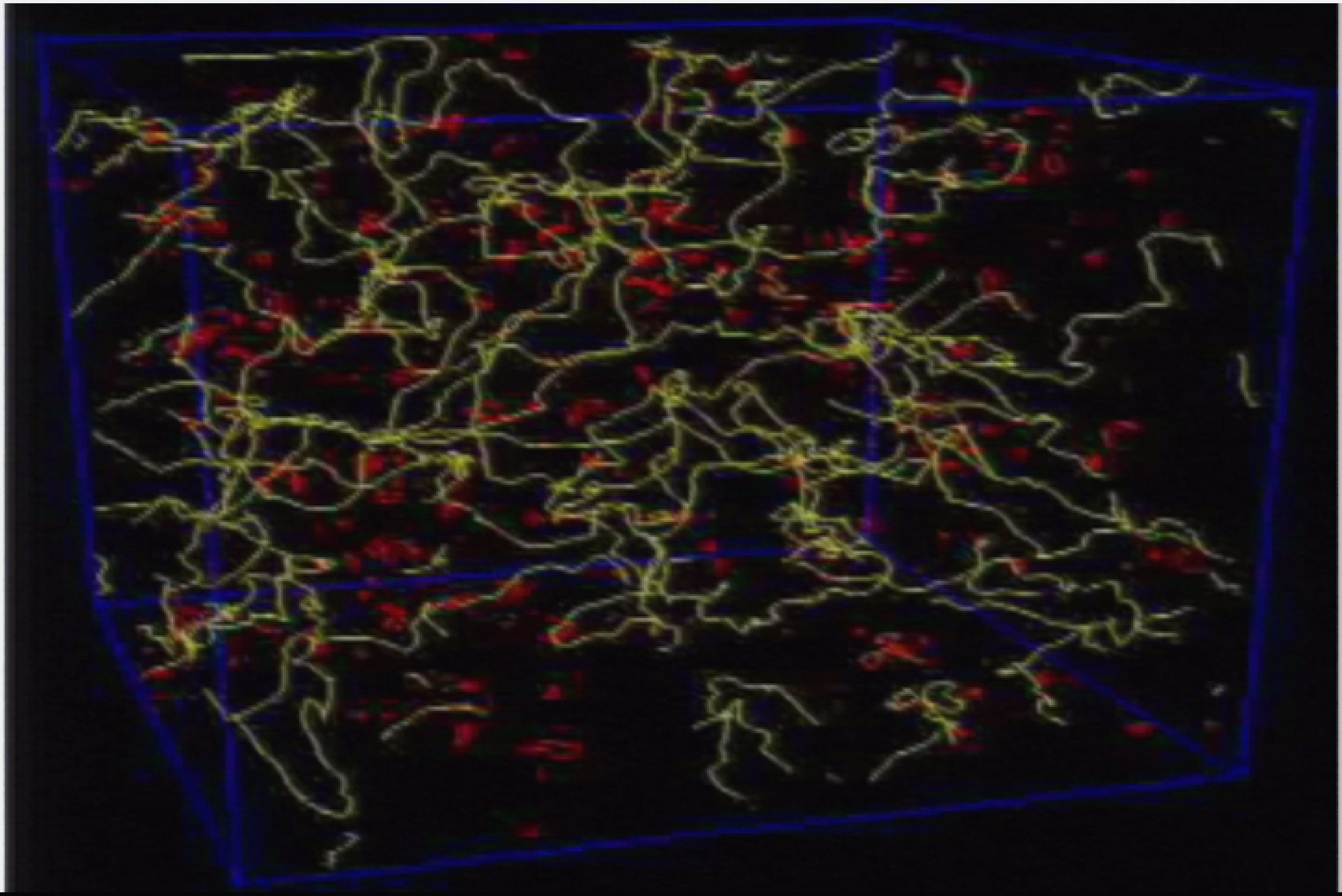
Allen, Martins & Shellard



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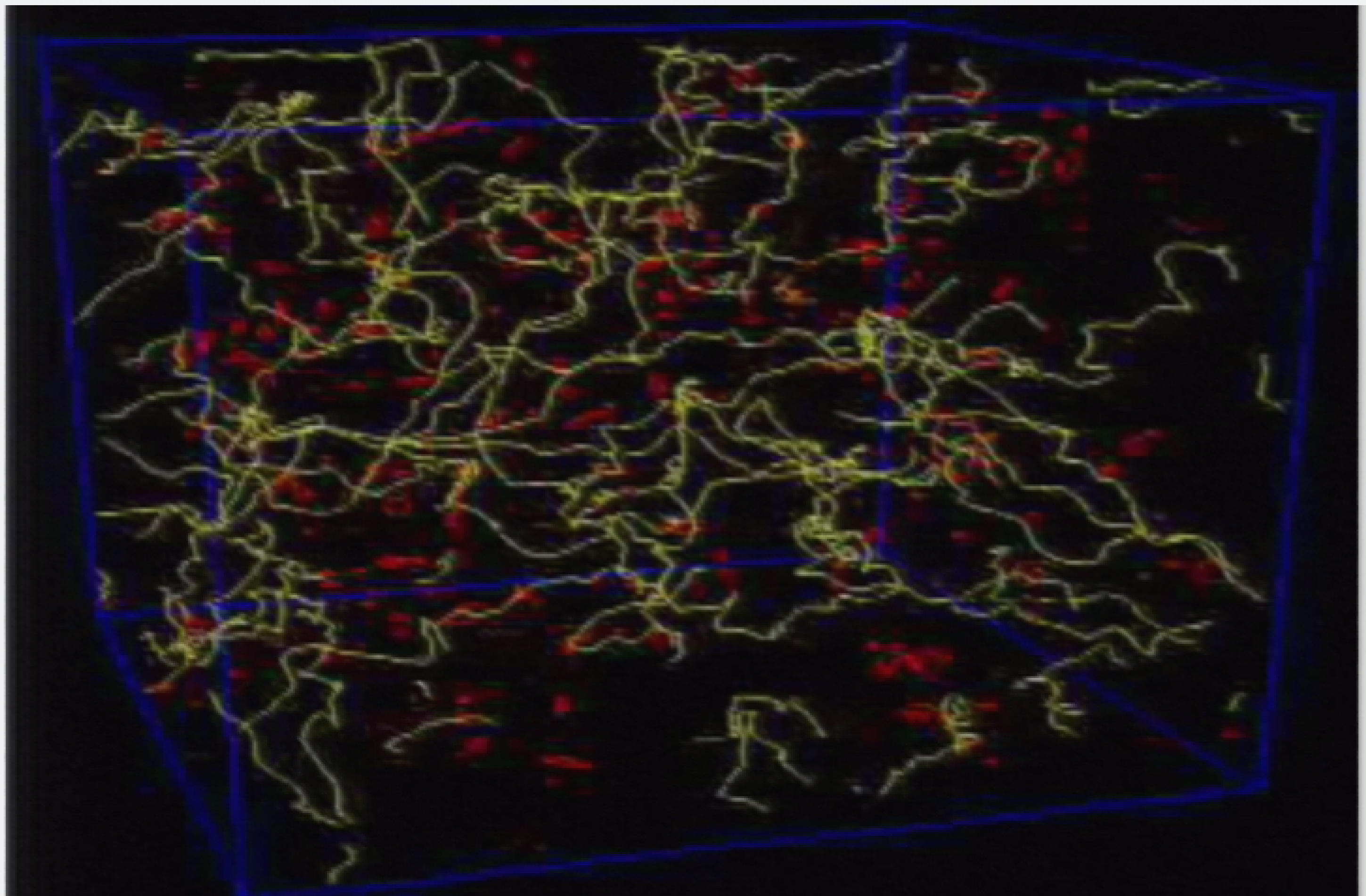
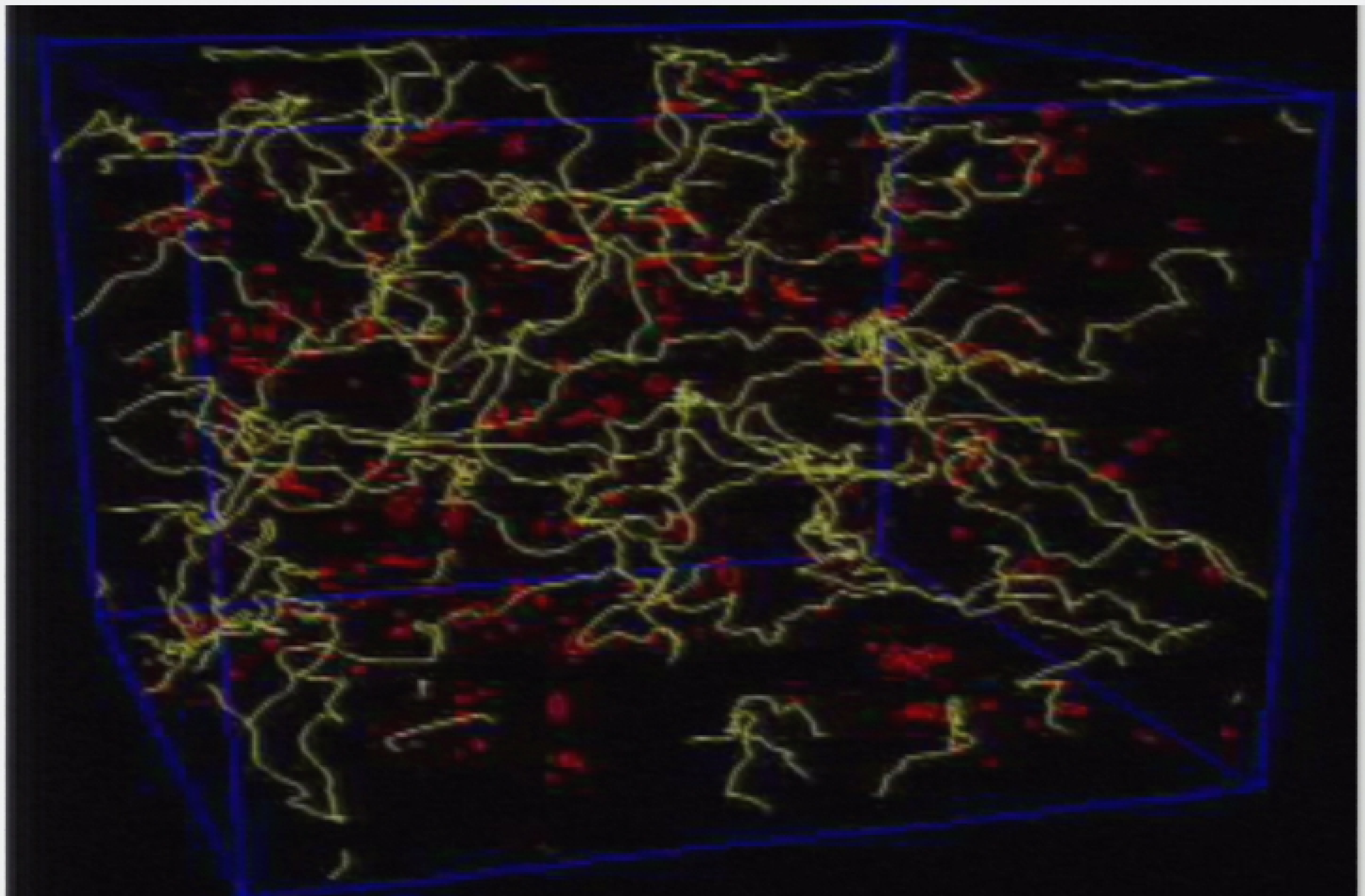


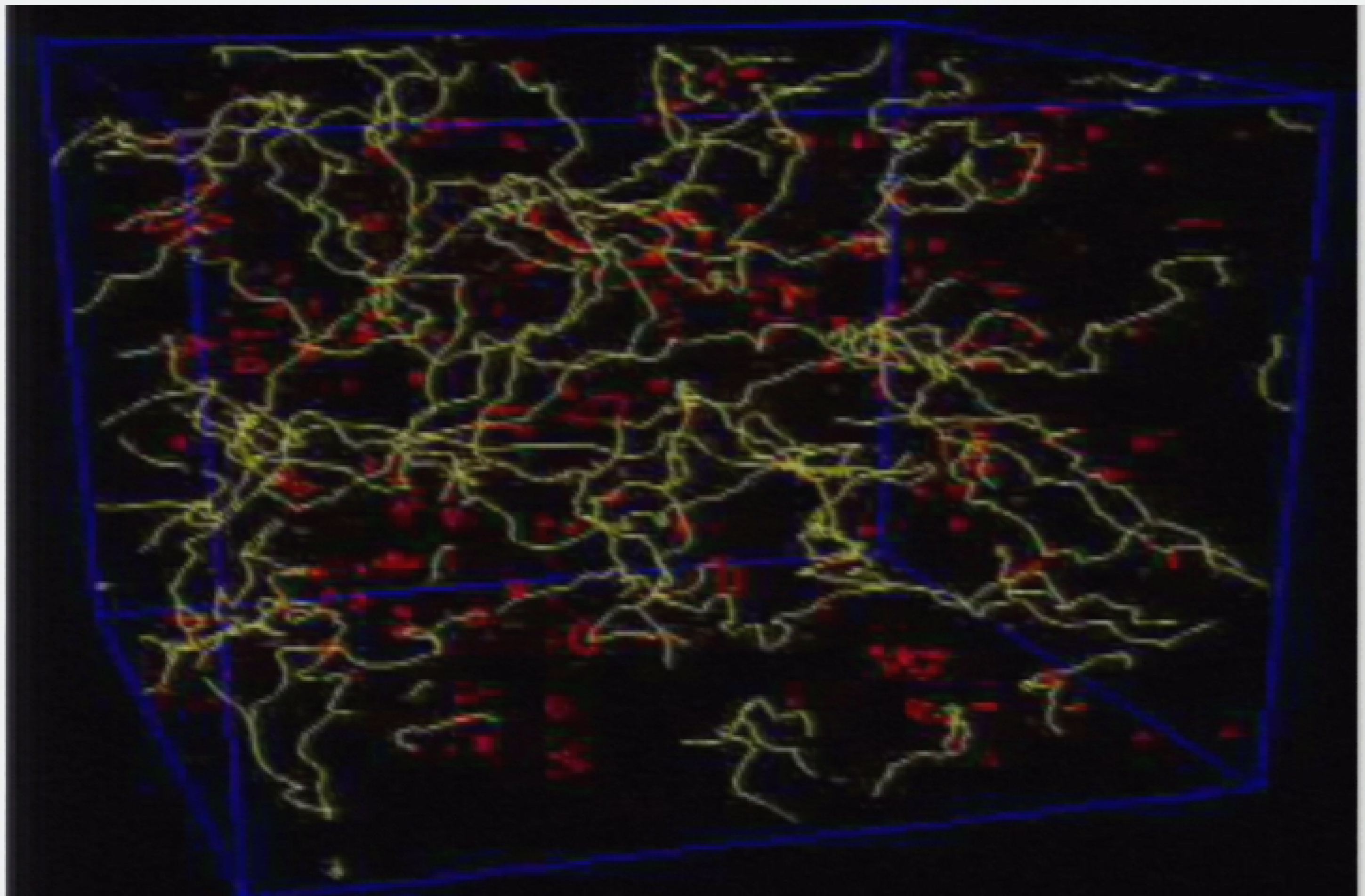
Cosmic String Network Evolution

Allen, Martins & Shellard



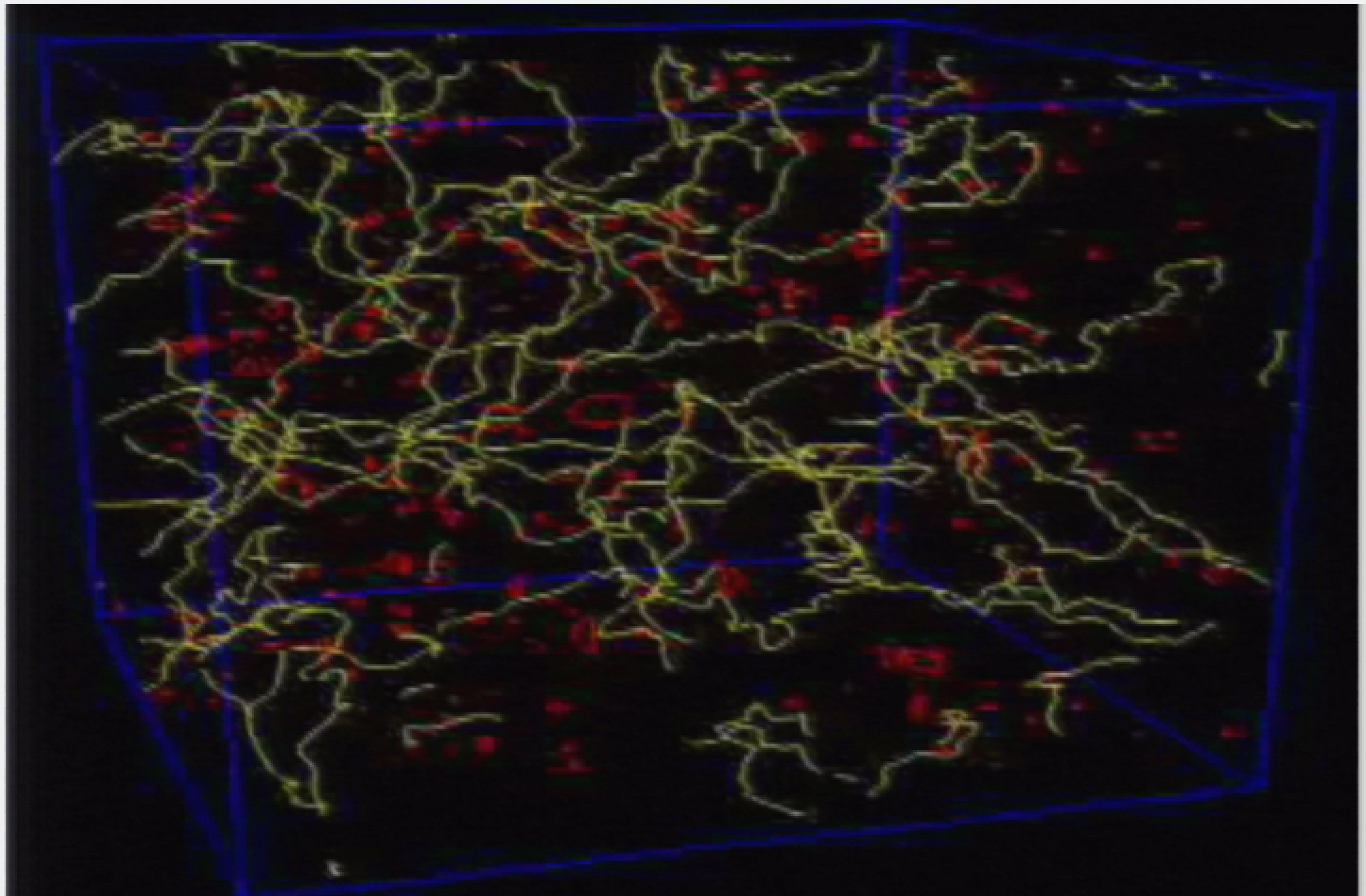
Cosmic String Network Evolution

Allen, Martins & Shellard



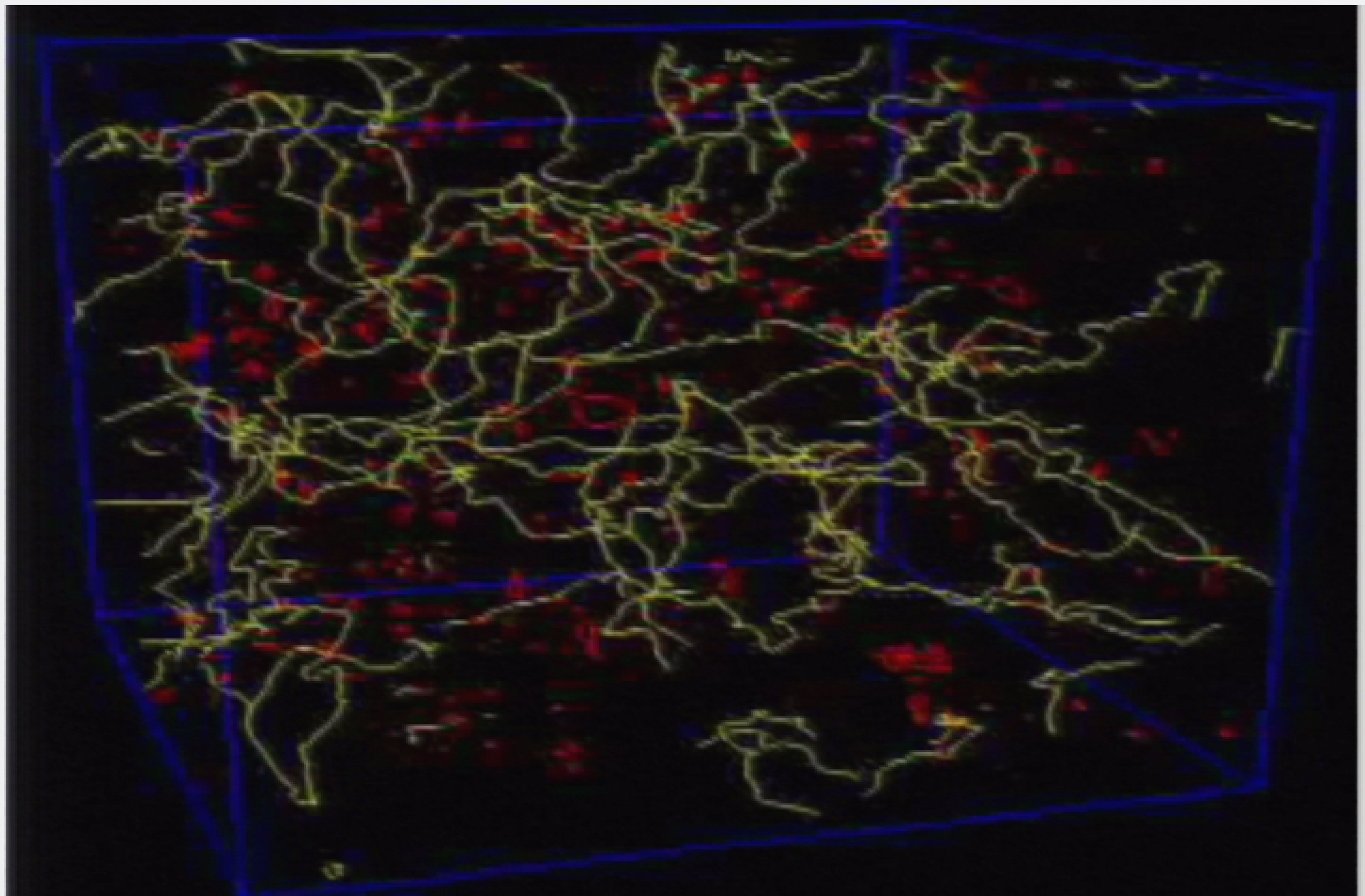
Cosmic String Network Evolution

Allen, Martins & Shellard



Cosmic String Network Evolution

Allen, Martins & Shellard



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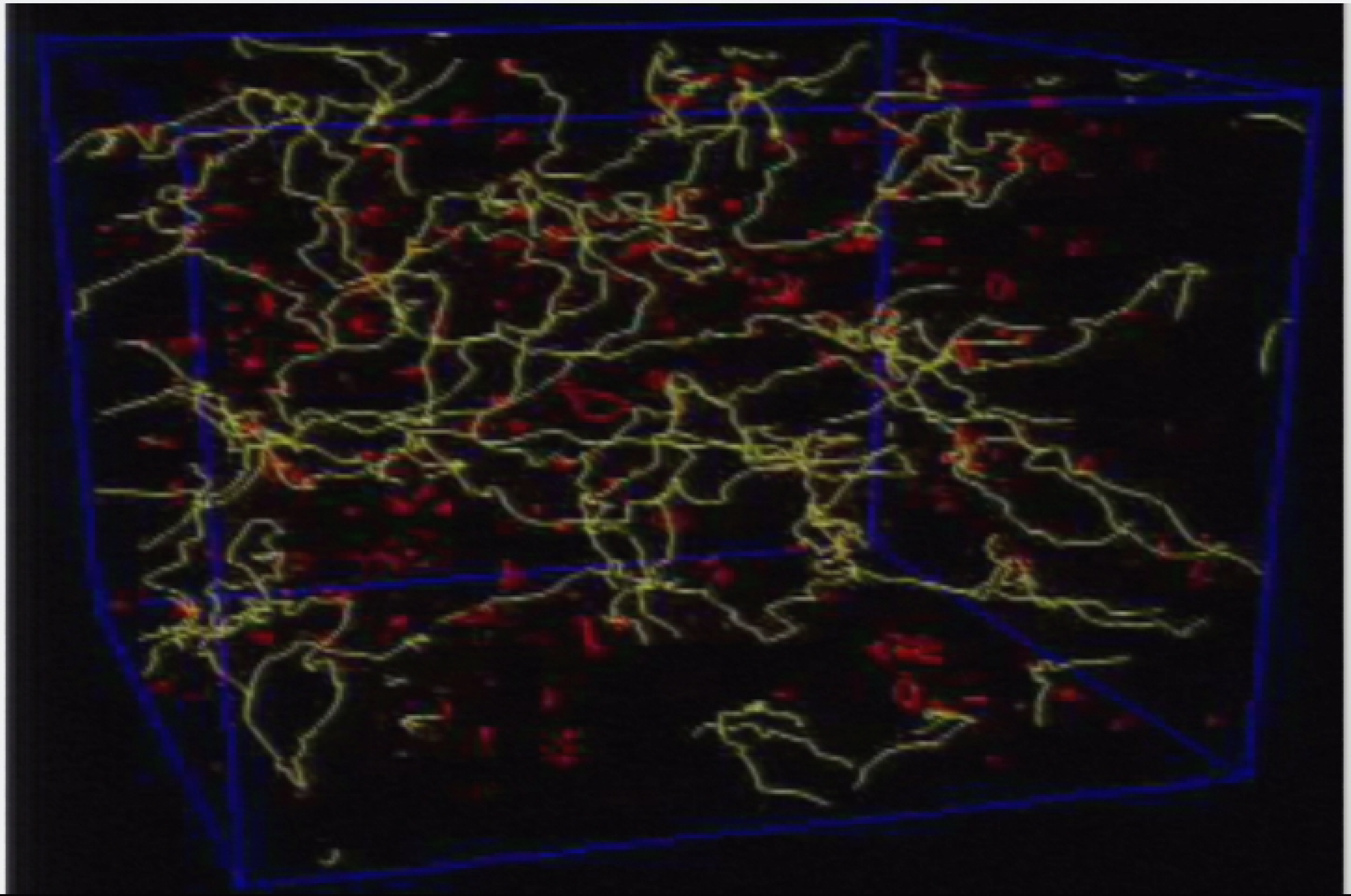
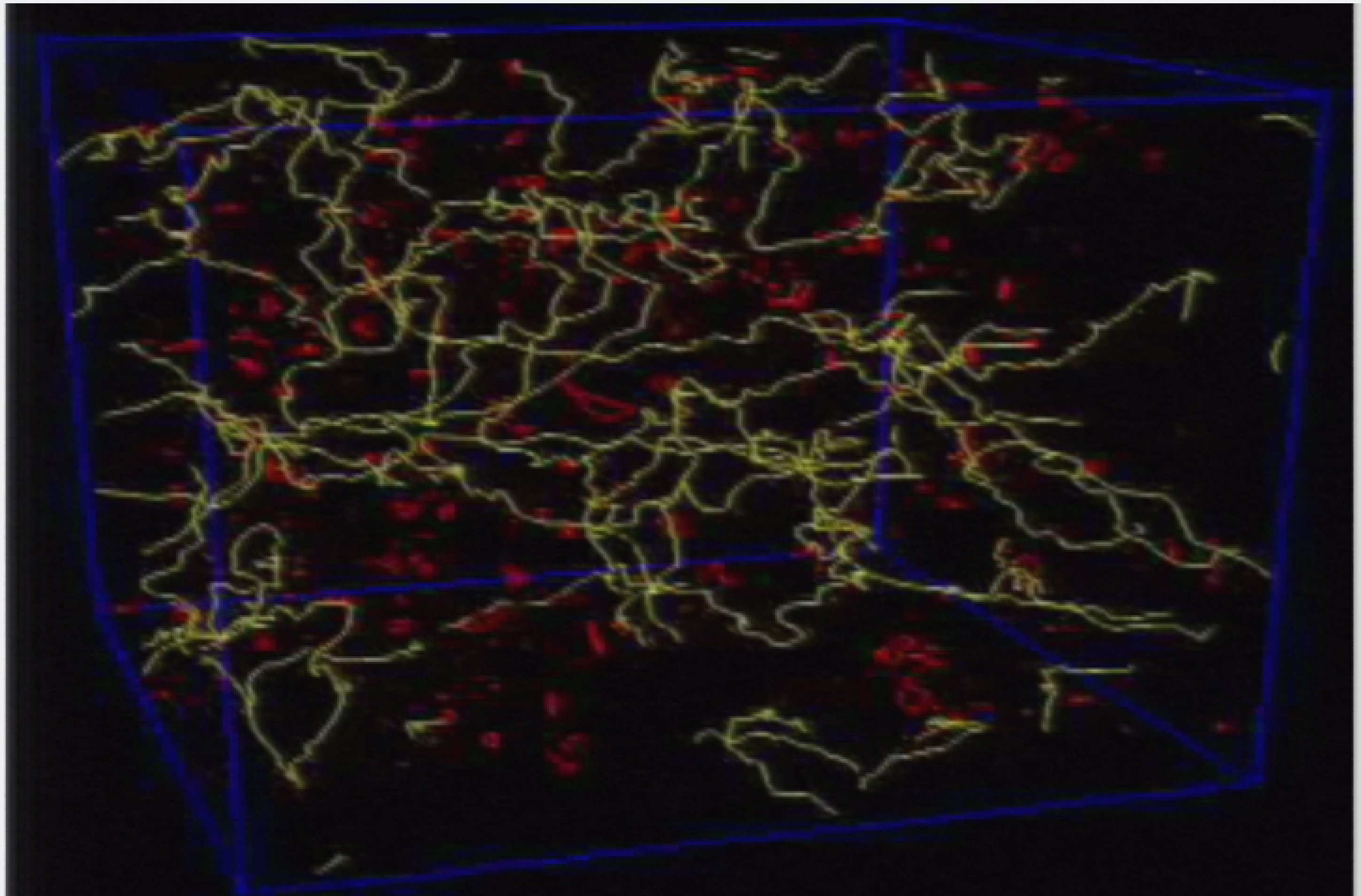
Allen, Martins & Shellard



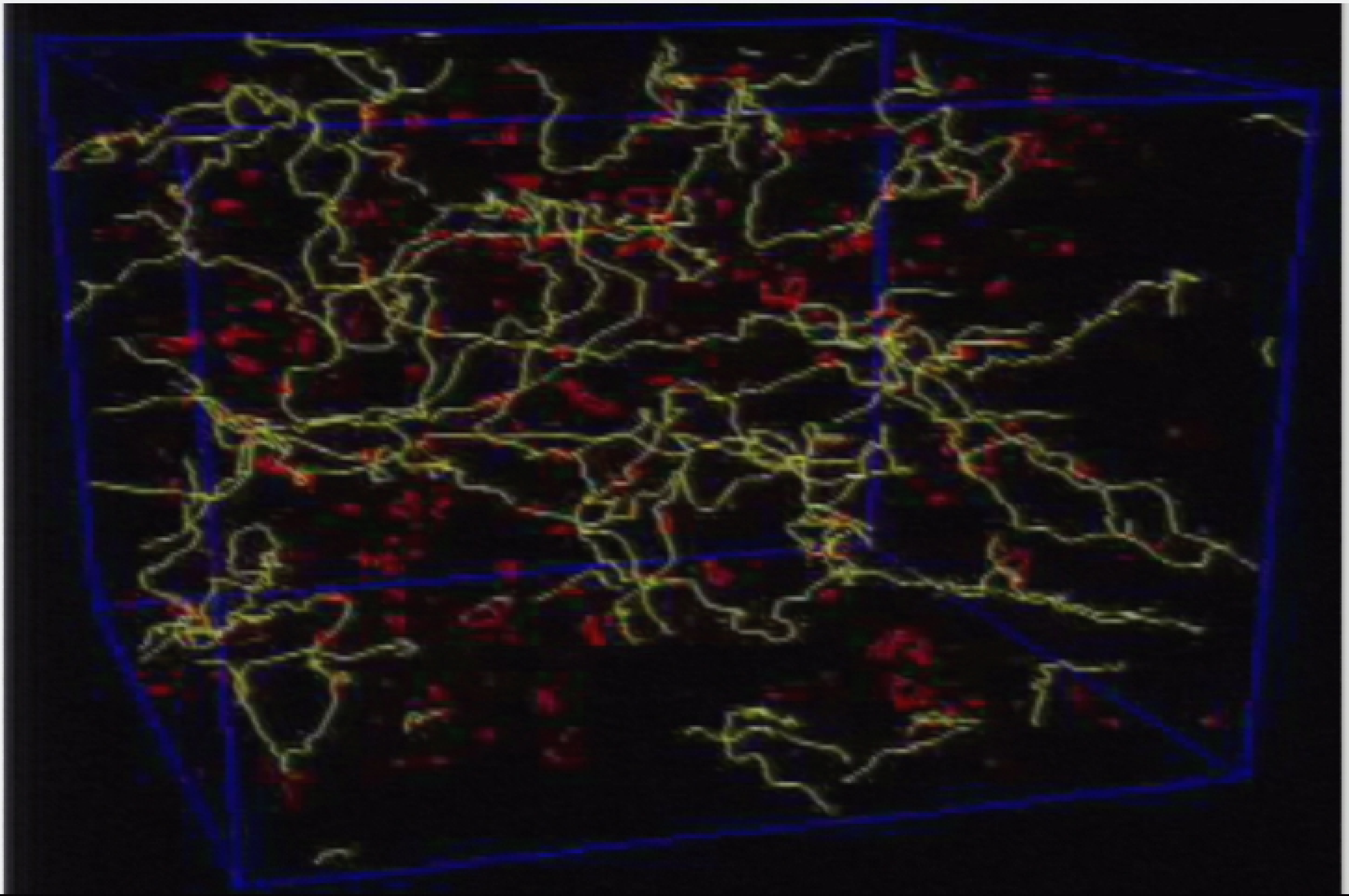
Cosmic String Network Evolution

Allen, Martins & Shellard



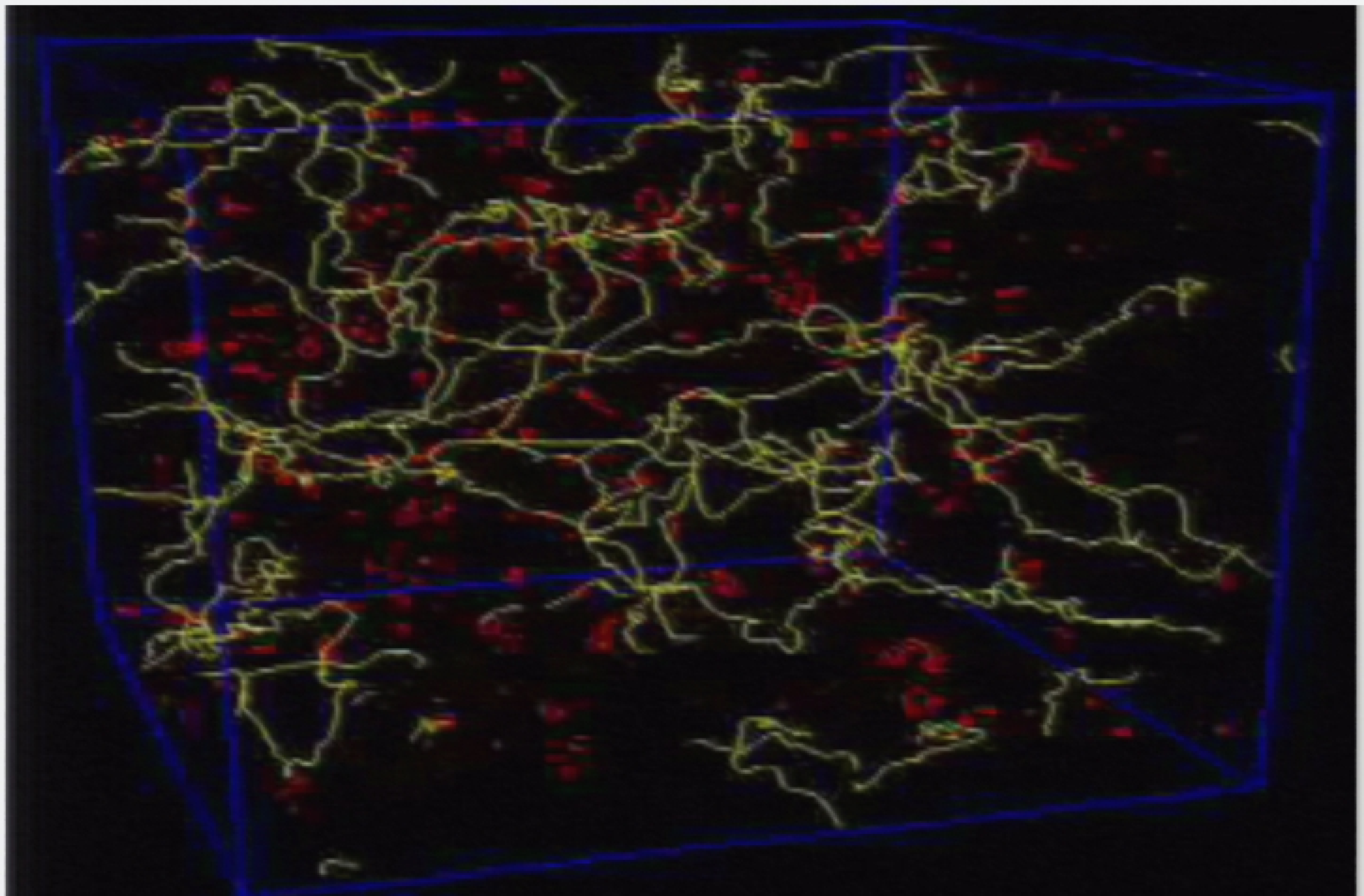
Cosmic String Network Evolution

Allen, Martins & Shellard



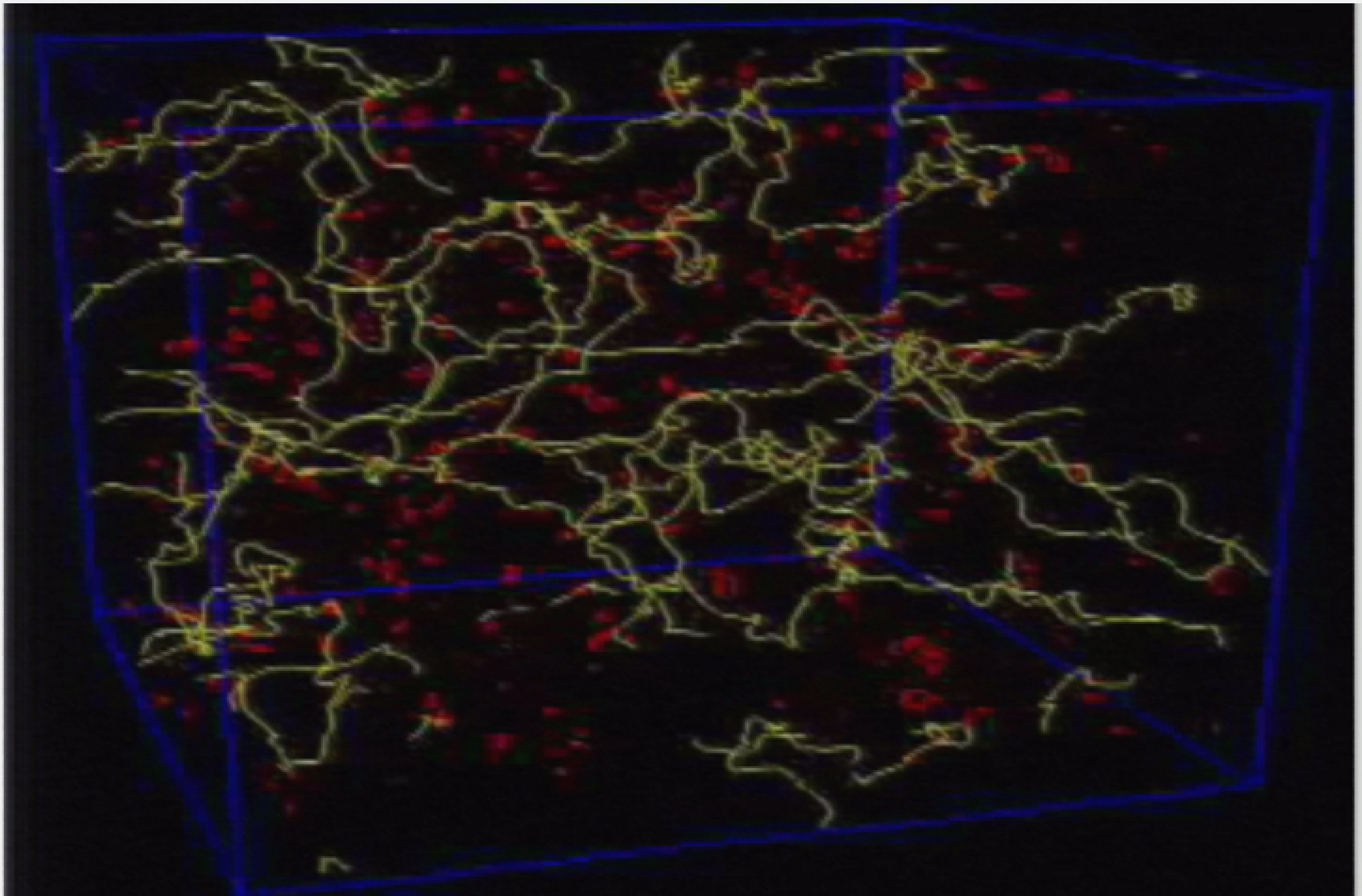
Cosmic String Network Evolution

Allen, Martins & Shellard



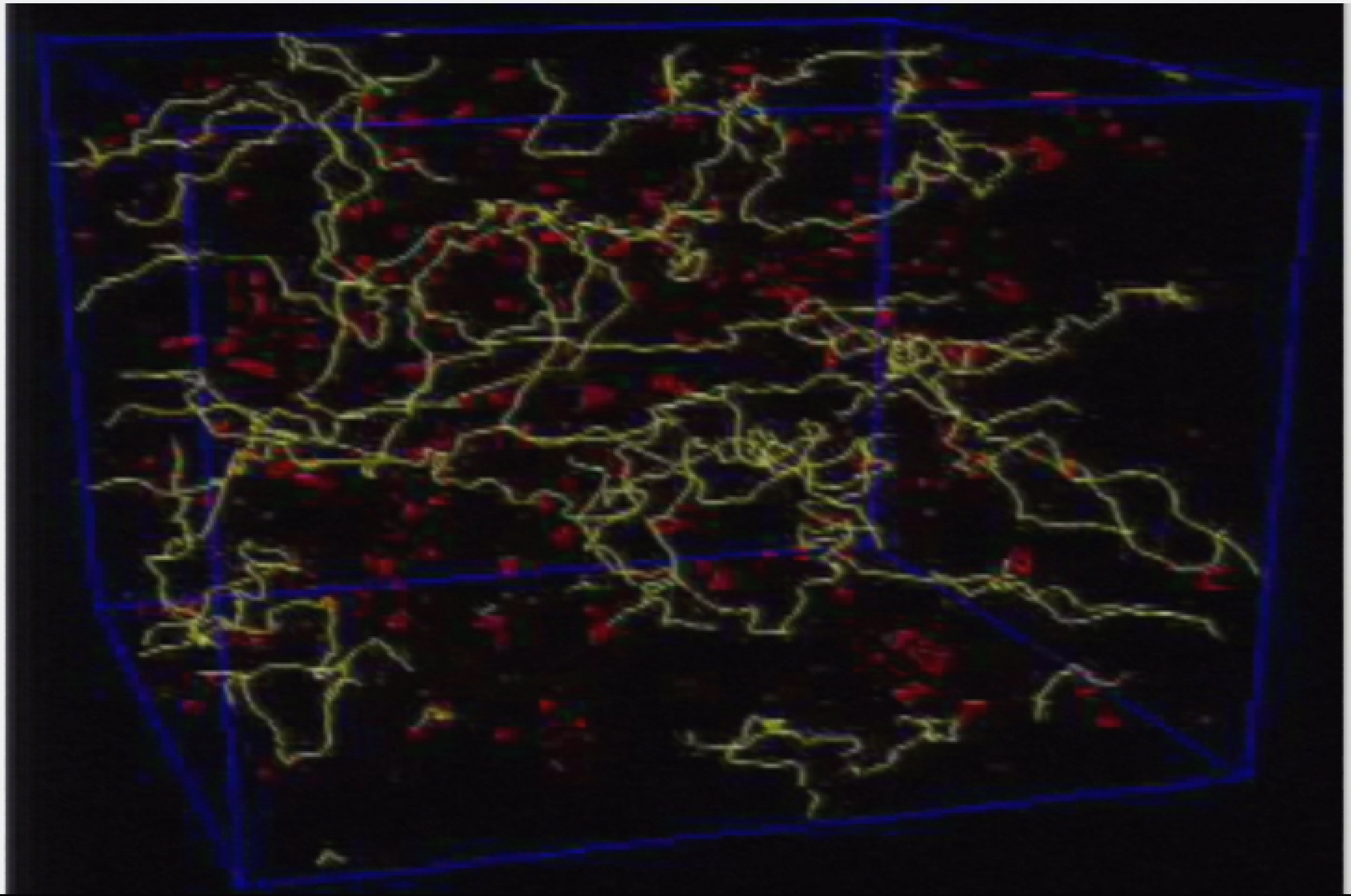
Cosmic String Network Evolution

Allen, Martins & Shellard



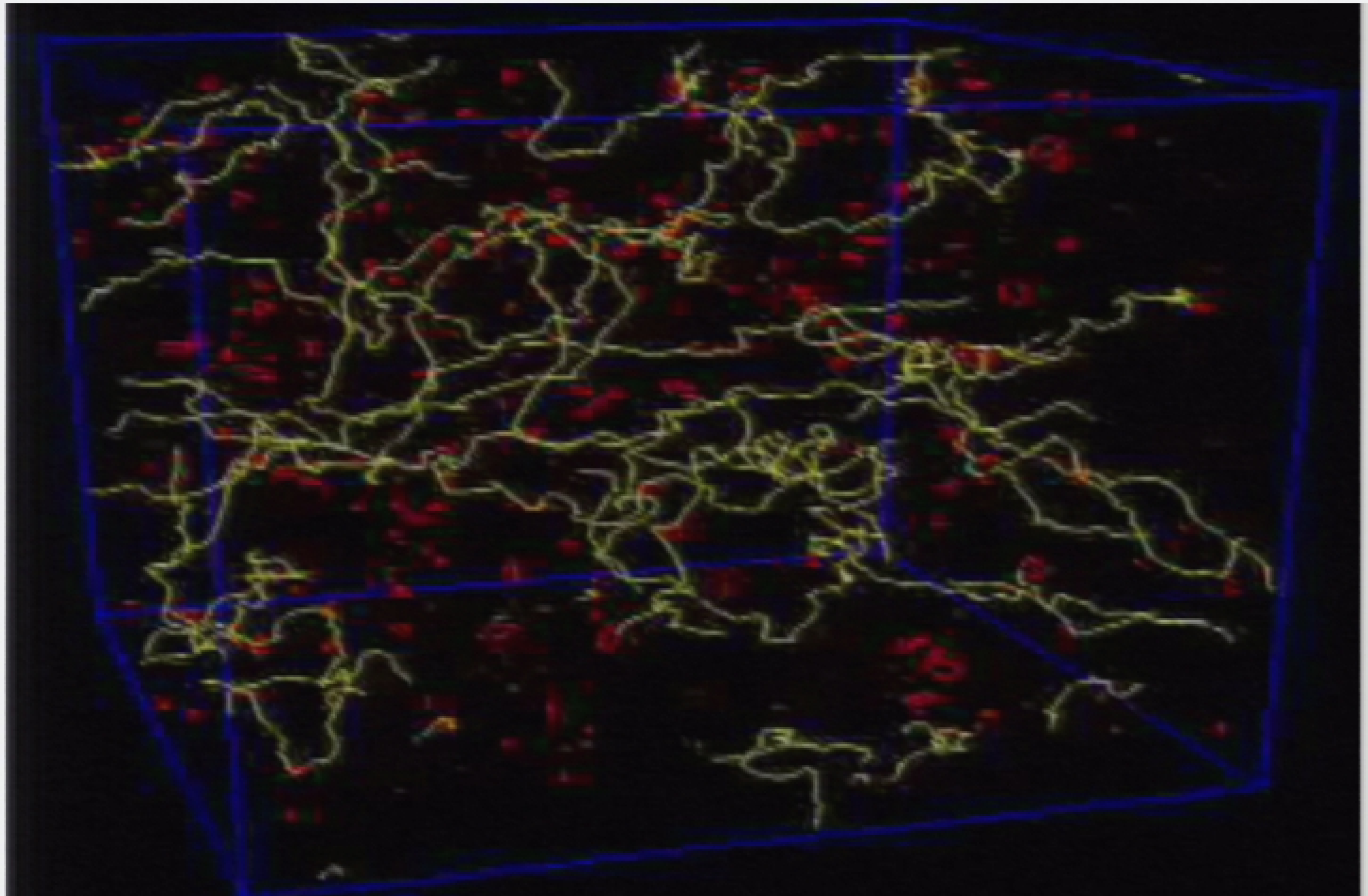
Cosmic String Network Evolution

Allen, Martins & Shellard



Cosmic String Network Evolution

Allen, Martins & Shellard



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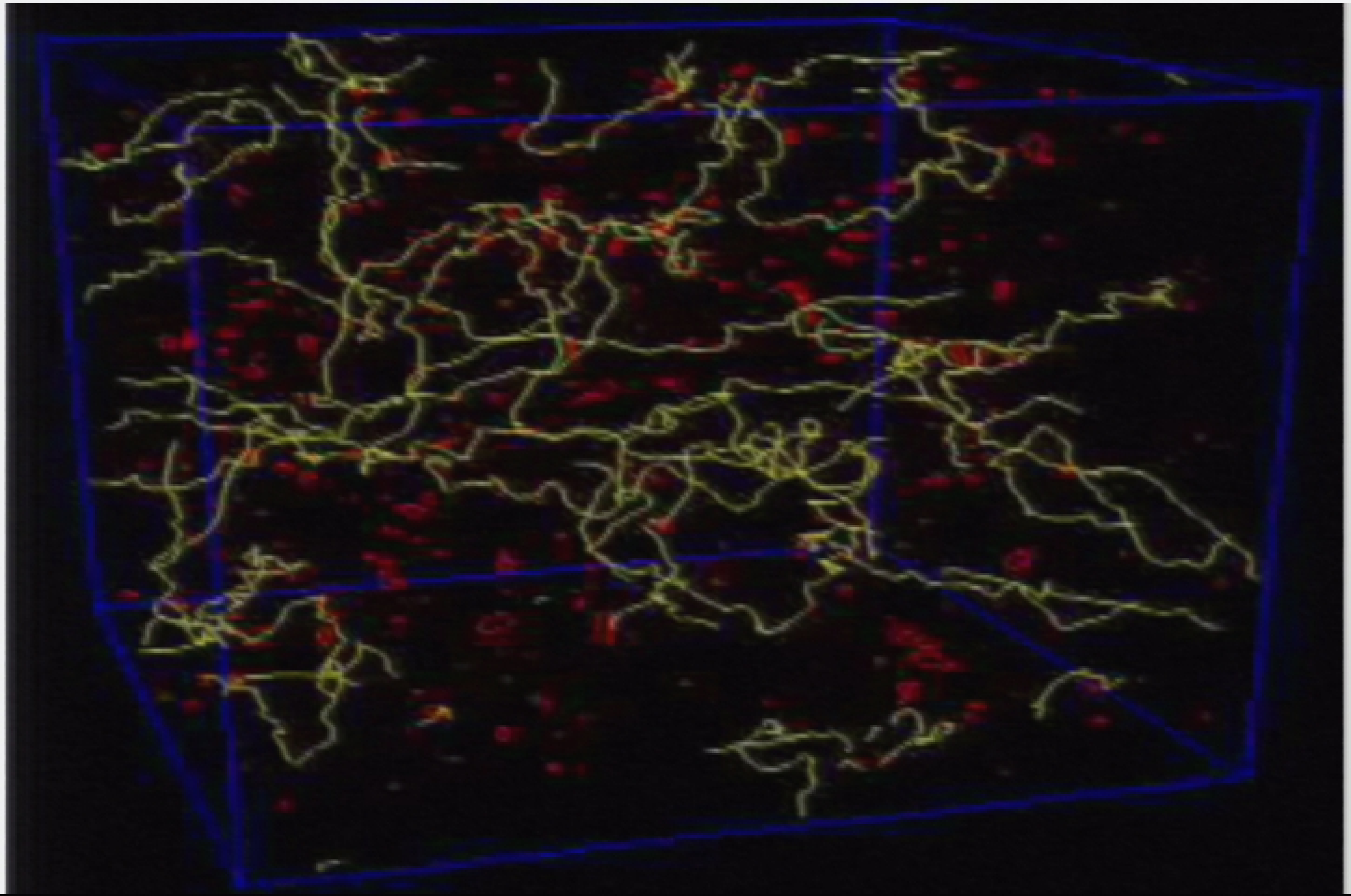

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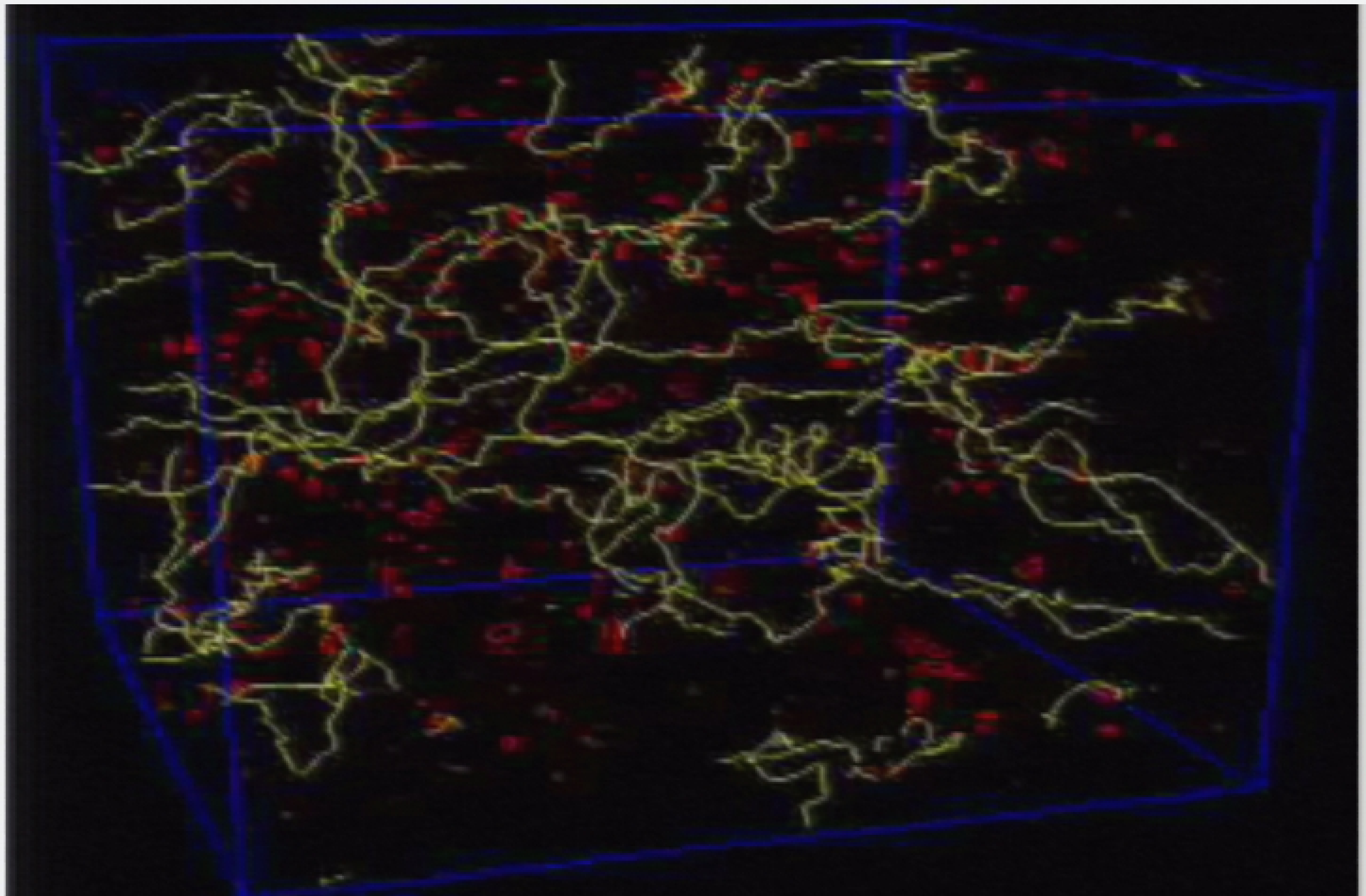

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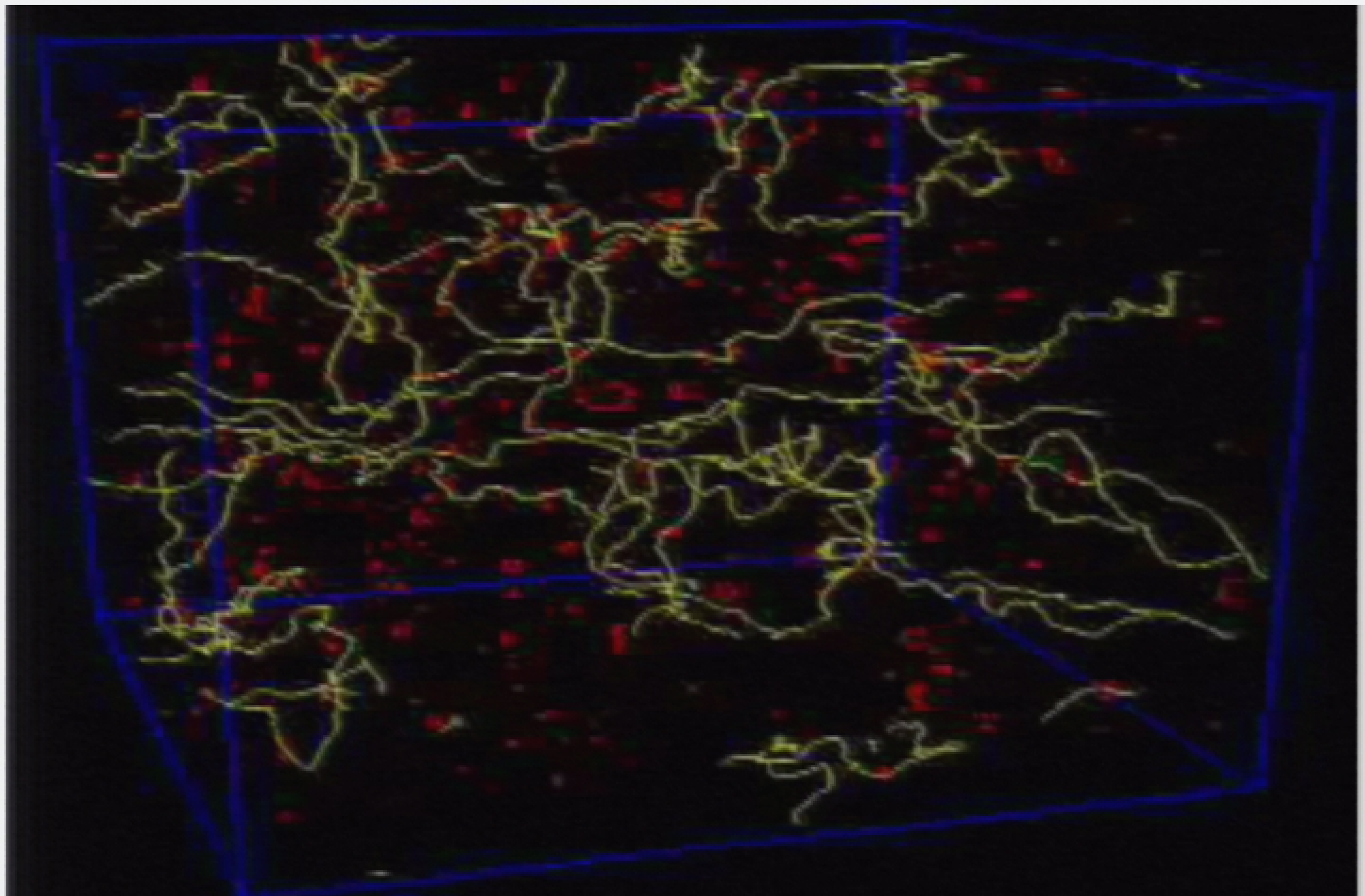

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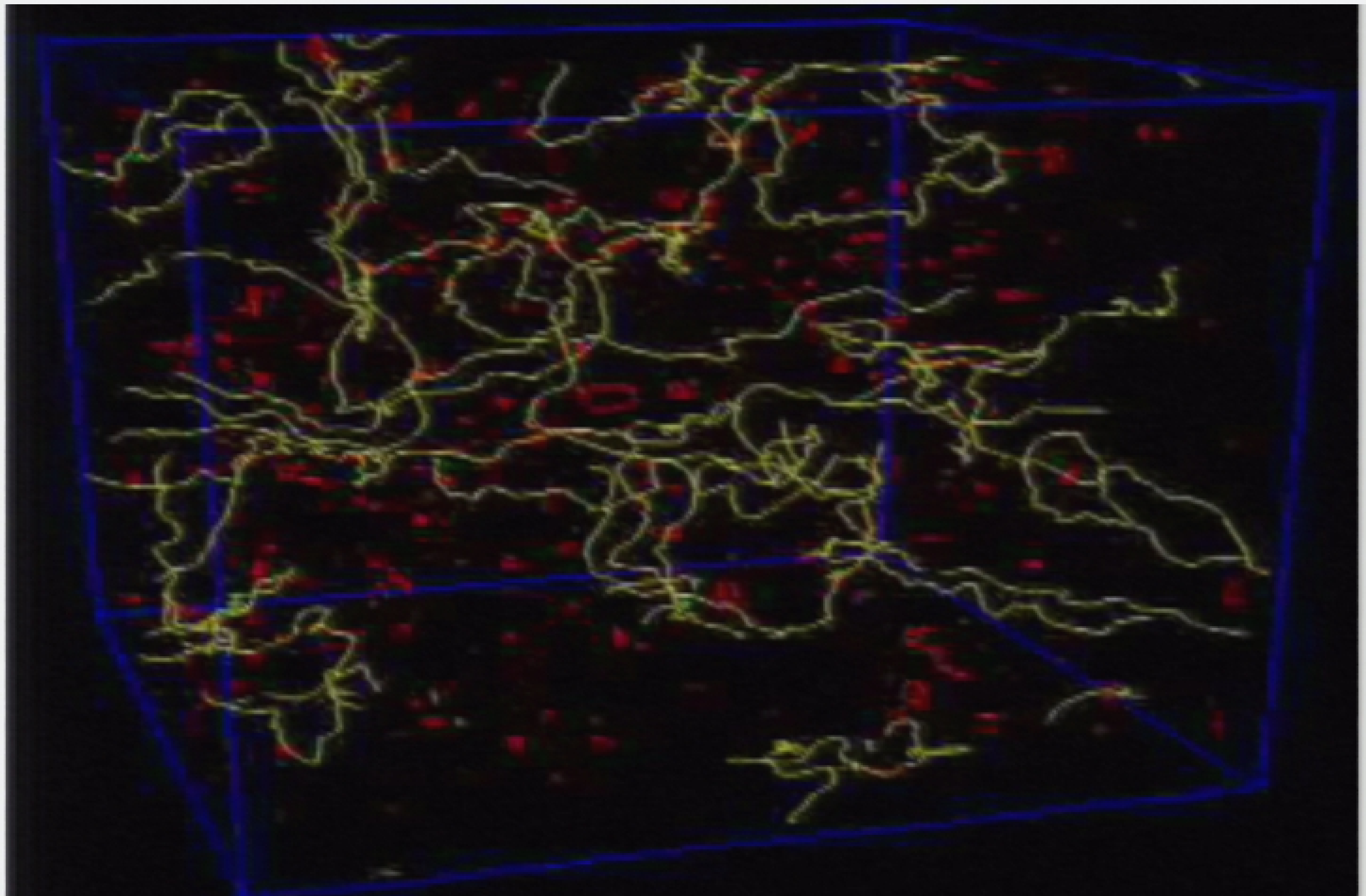

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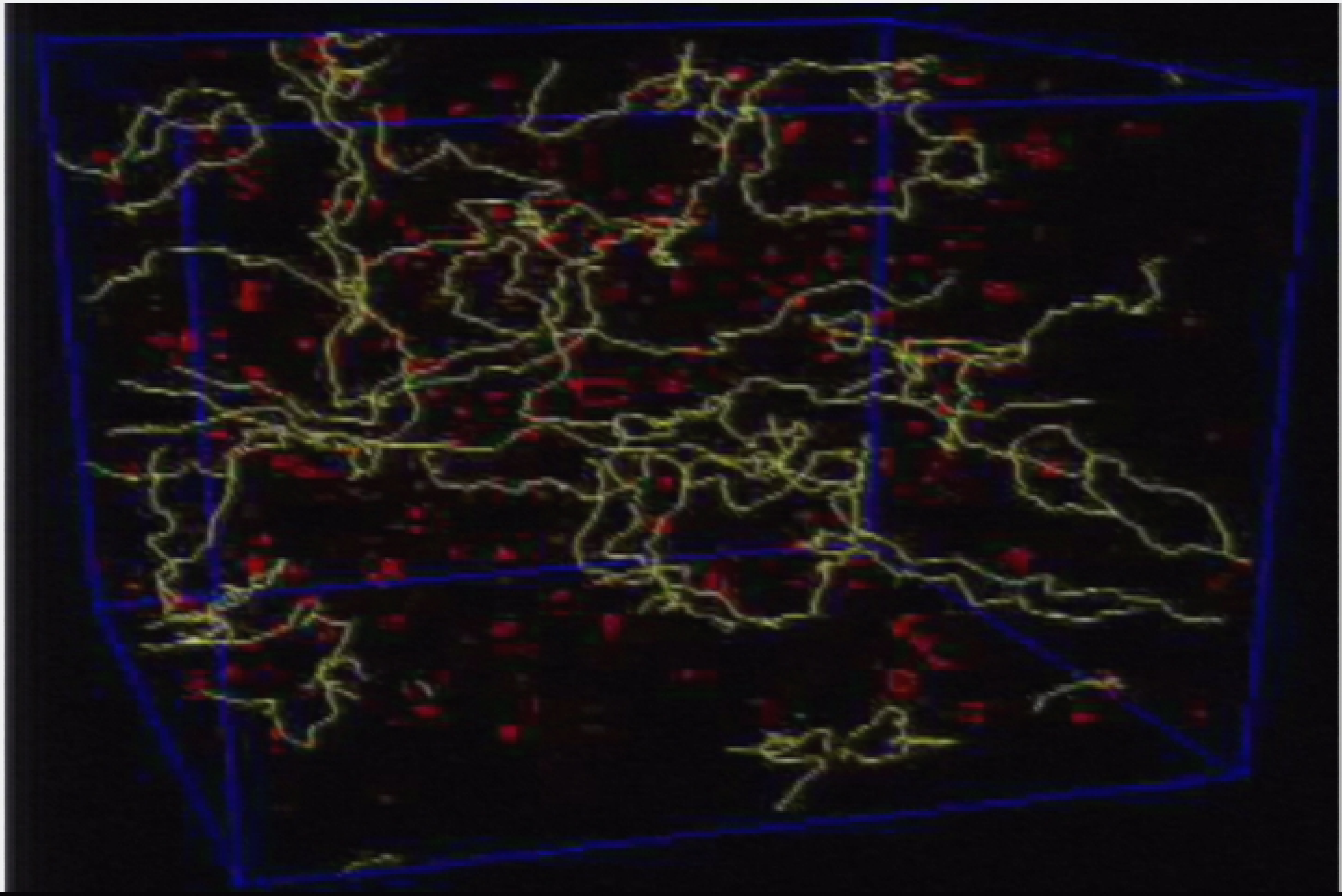

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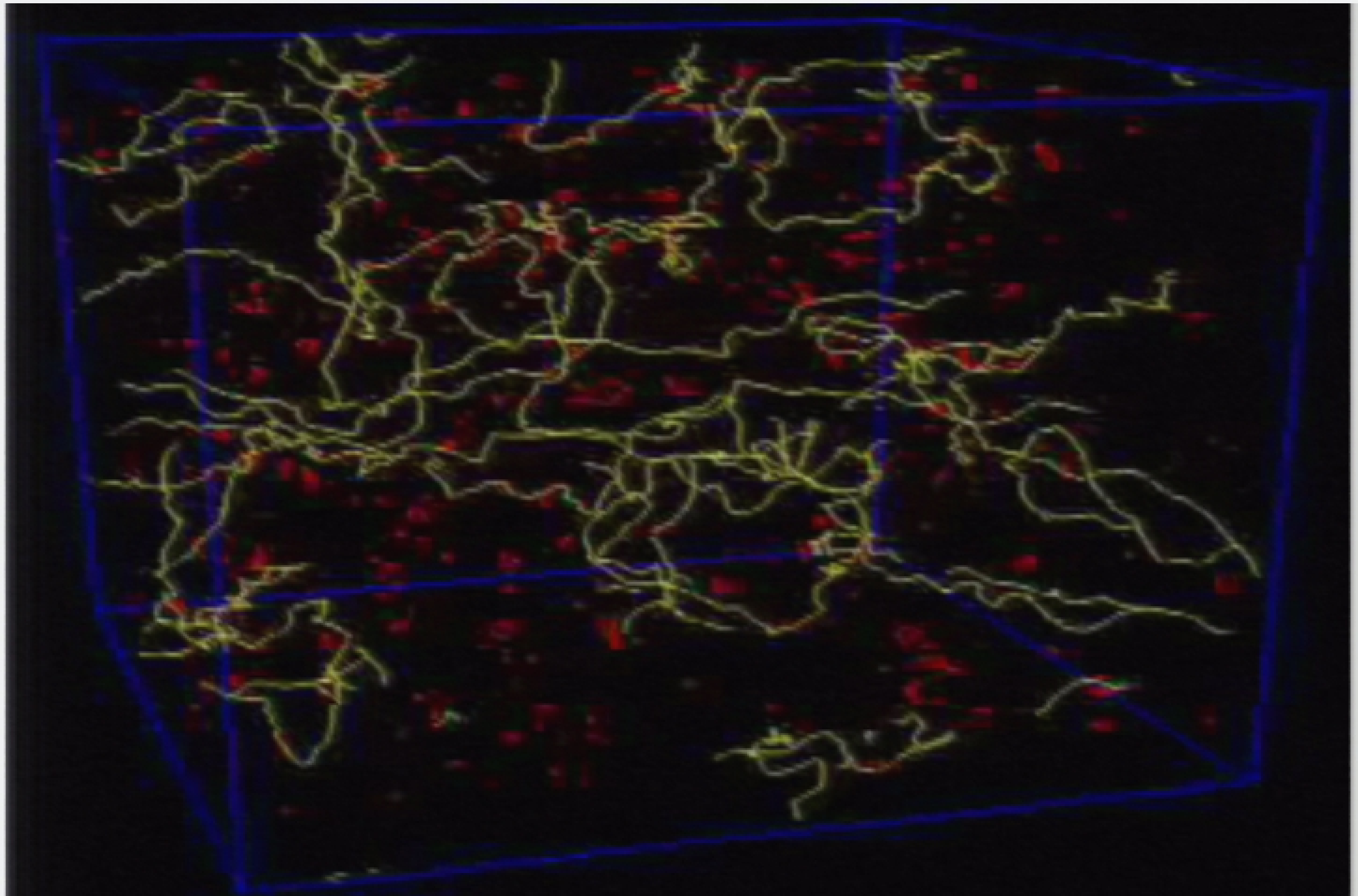

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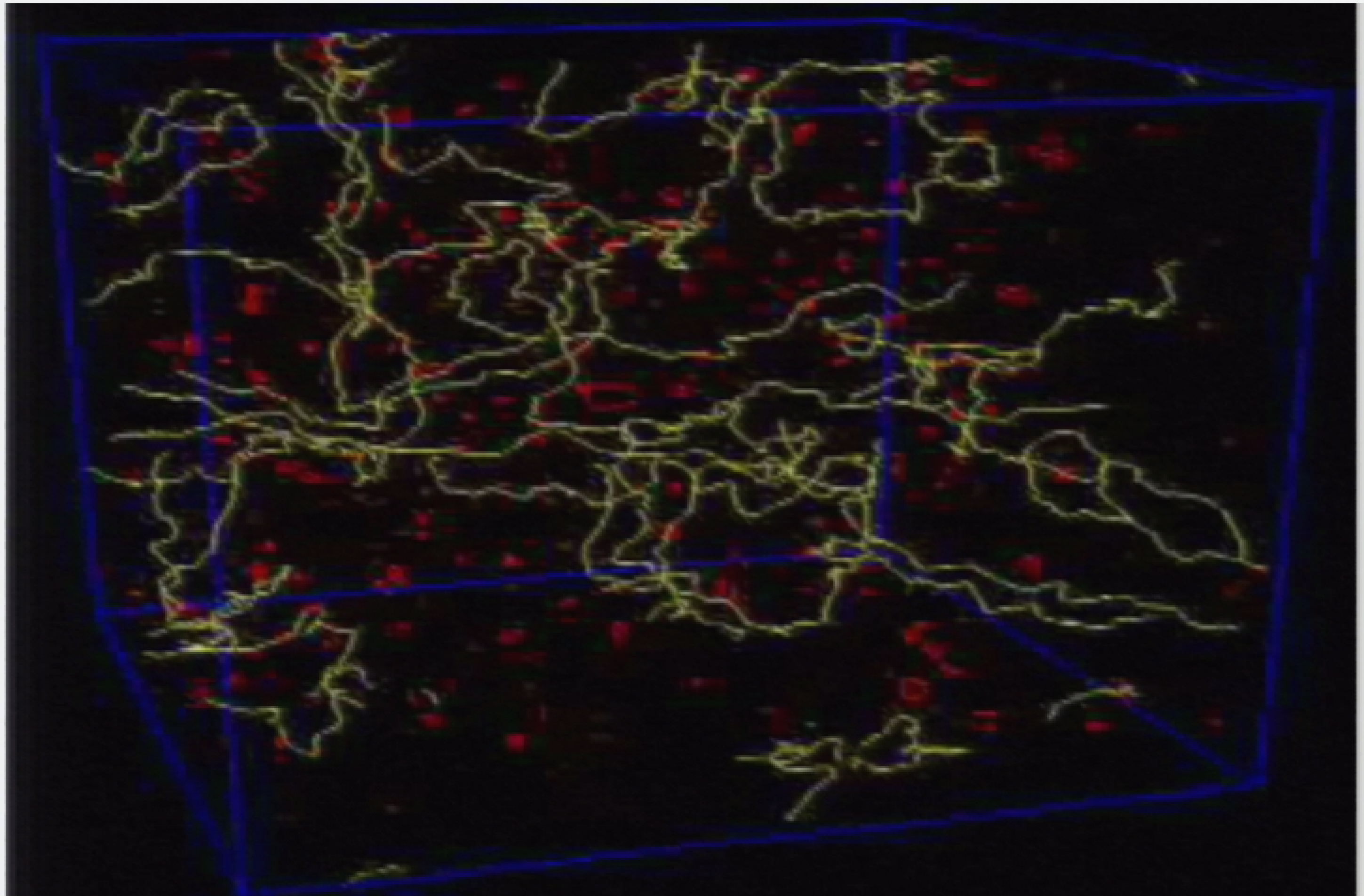

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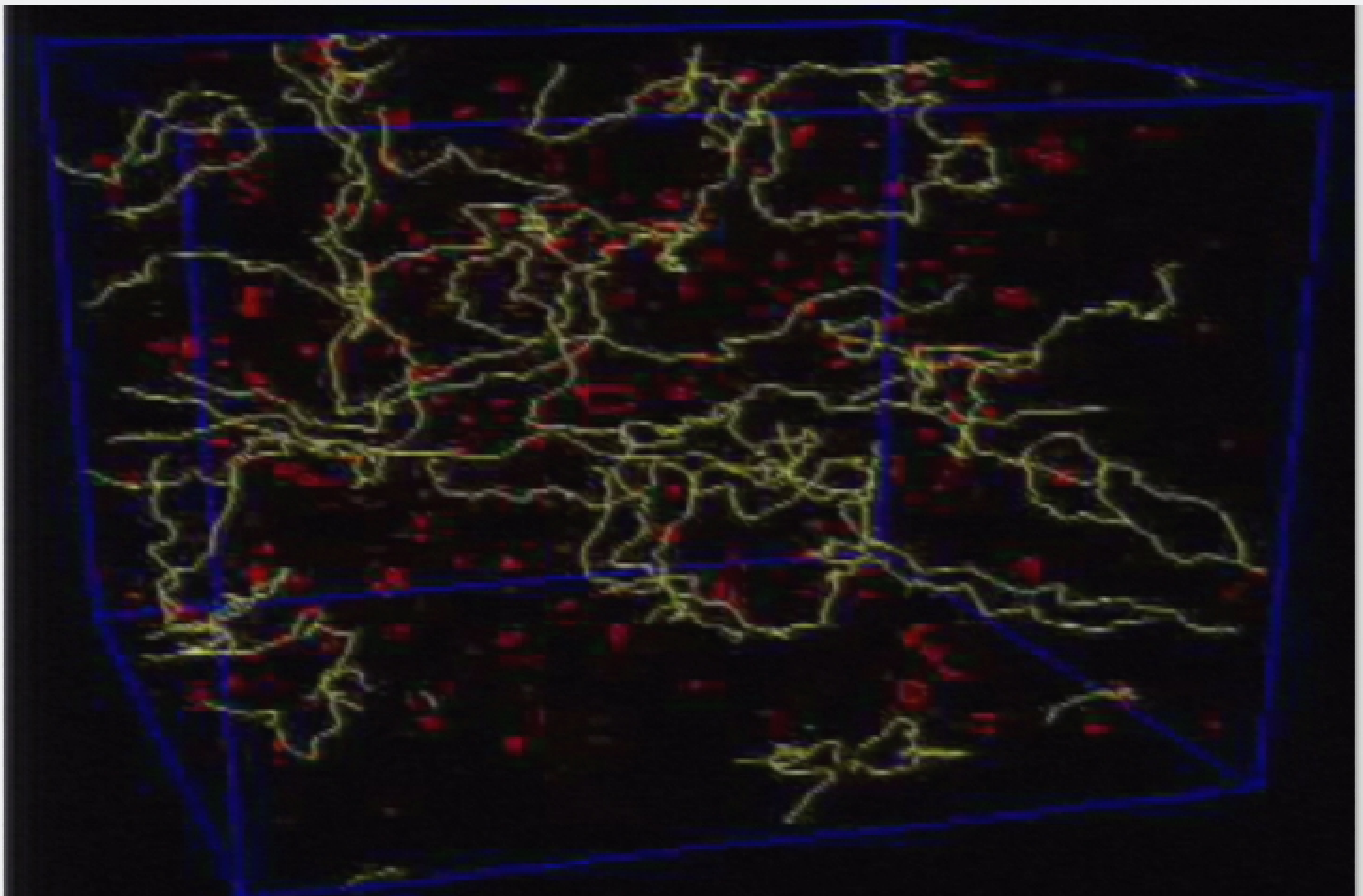
Allen, Martins & Shellard



Scaling of the cosmic string network

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

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

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

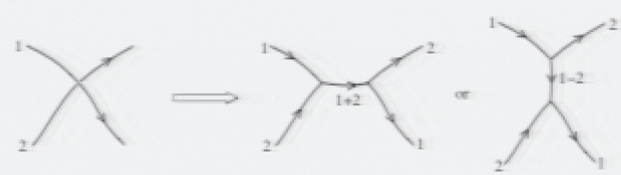
$$v \sim 0.65$$

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
E. Copeland, R. Myers and J. Polchinski, hep-th/0312067
M. Jackson, N. Jones and J. Polchinski, hep-th/0405229

Evolution of the Cosmic Superstring Network

$$\frac{dn_\alpha}{dt} + 2Hn_\alpha$$

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

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

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

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

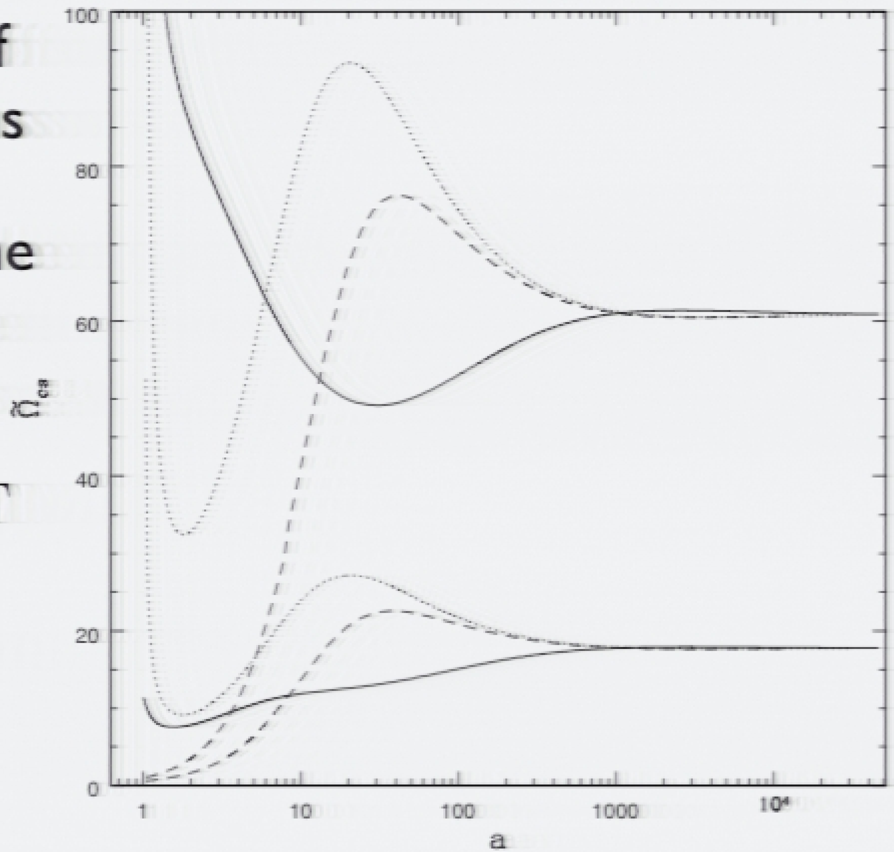
Scaling of the Cosmic Superstring Network

independent of initial conditions

Insensitive to the details of the interactions

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

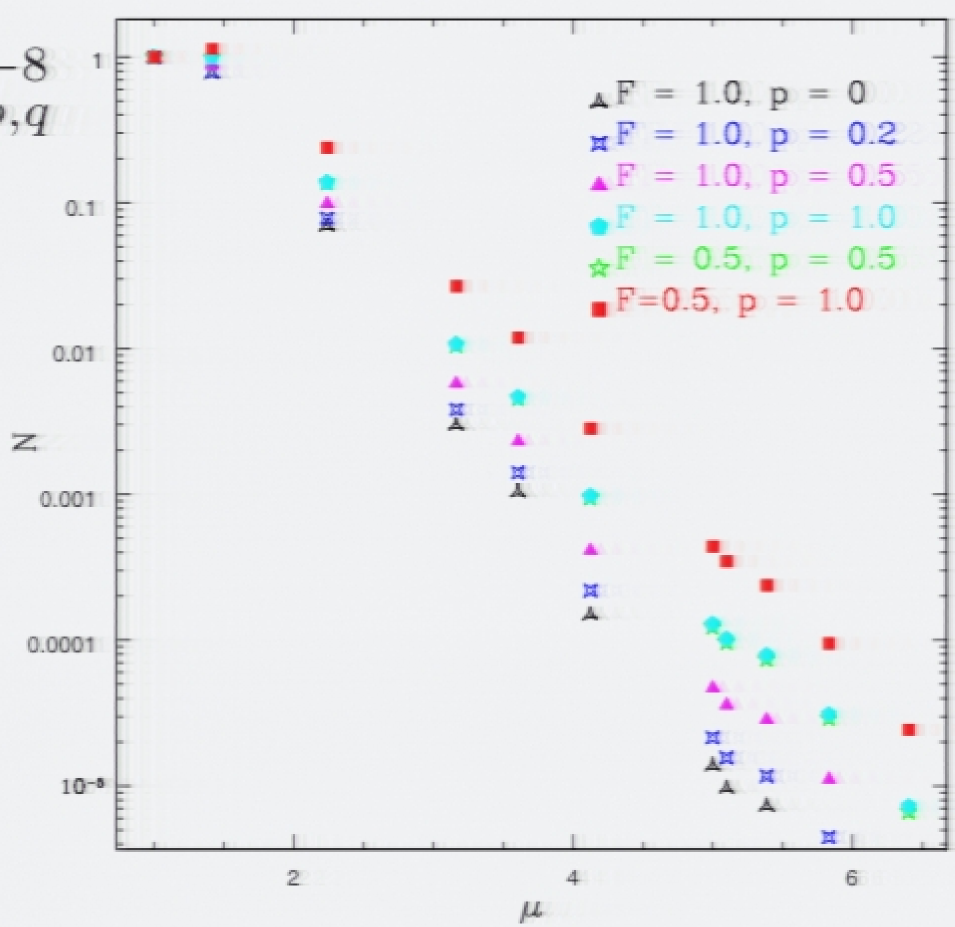
$$\Gamma \sim 10$$



H.T., I. Wasserman, M. Wyman, astro-ph/0503506

Relative density of (p,q) strings

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



cosmic string tension

Use the CMB/COBE data:

$$10^{-6} > G\mu > 10^{11}$$

Sarangi, H.T.

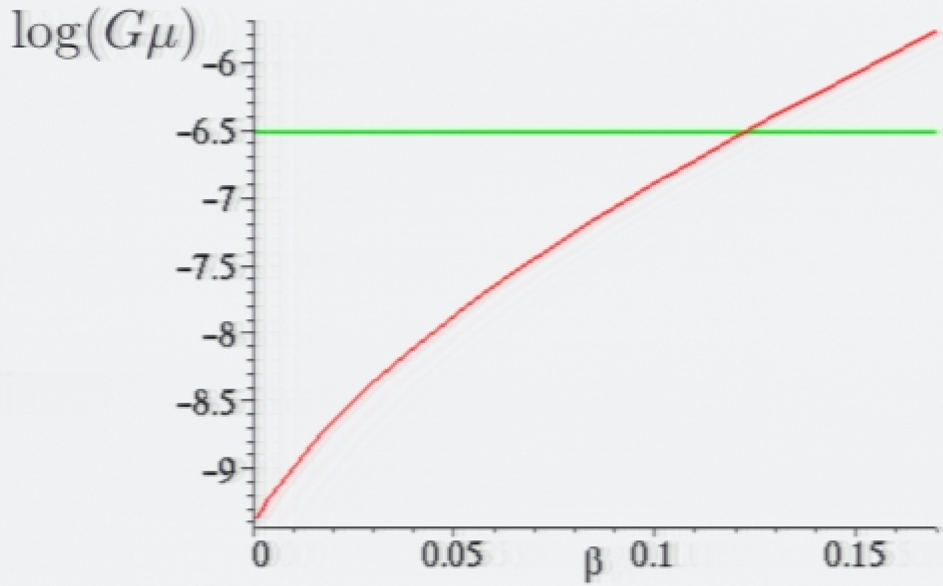
brane-anti-brane : $G\mu \sim 10^{-10}$ to 10^{-9}

angled branes : $G\mu \sim 10^{-7}$

Observational bound from WMAP :

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

Pogosian, Wasserman, Wyman
Jeong, Smoot



$\beta < 1/7$

KKLMMT

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

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

Observational bound from WMAP :

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

Pogosian, Wasserman, Wyman
Jeong, Smoot

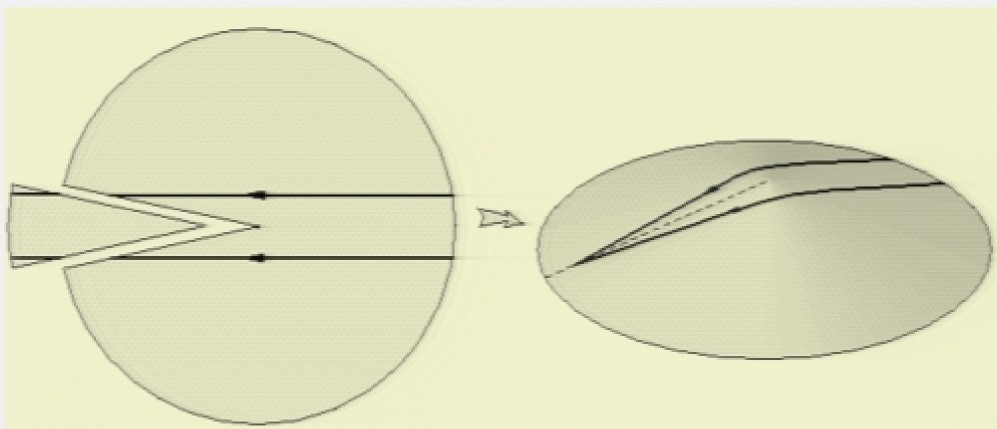
Search for Cosmic Strings

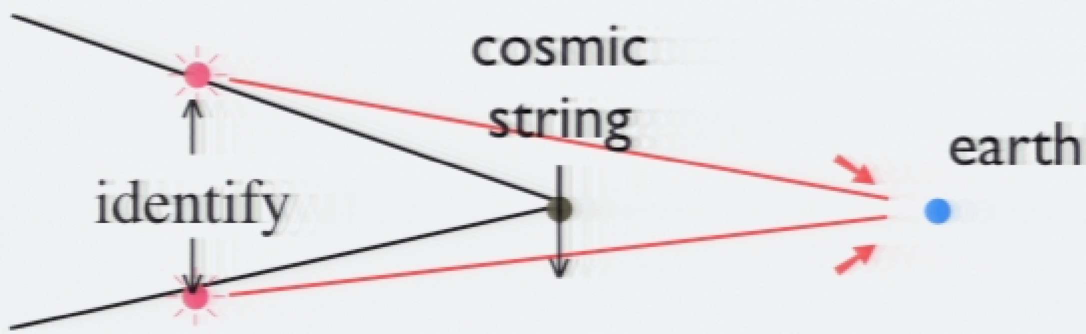
- Lensing
- Cosmic Microwave Background Radiation
- Gravitational Wave Burst
- $\Delta T/T$
- Pulsar Timing
- Stochastic Gravitation Radiation Background

typical gravitational lensing events

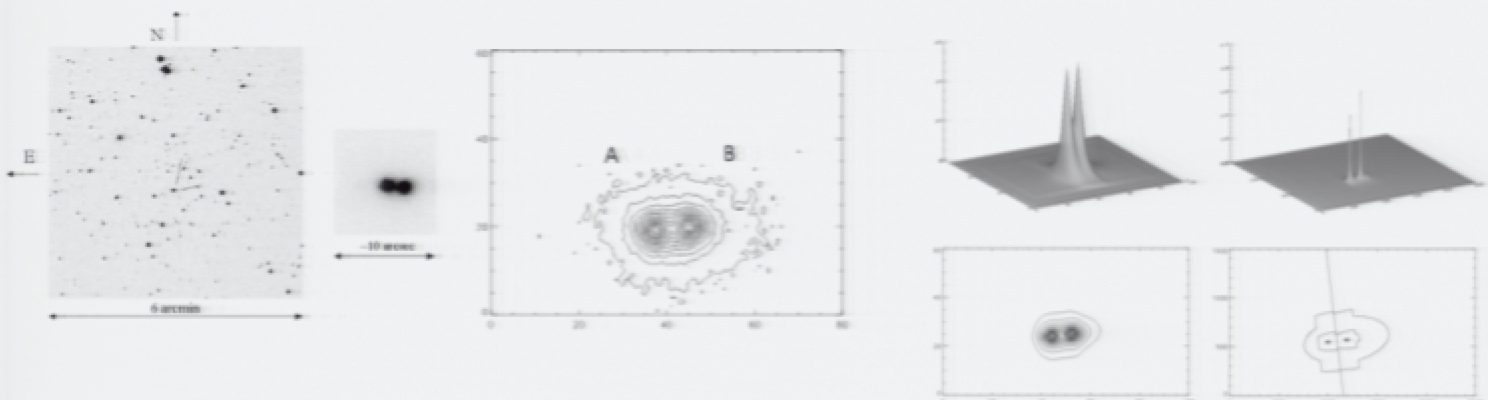
cosmic string lensing

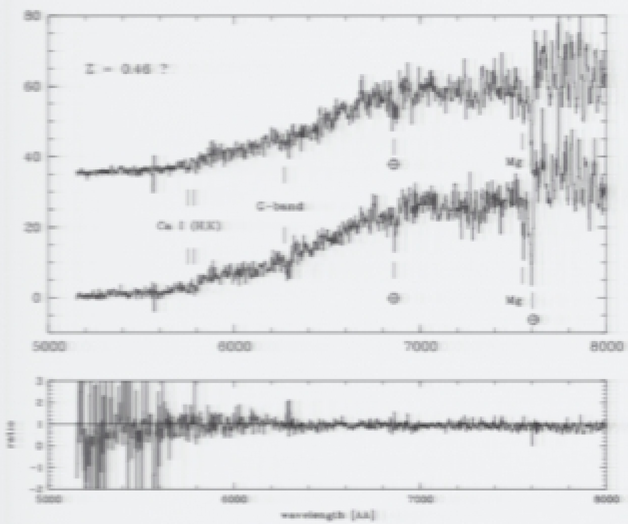
cosmic string introduces a deficit angle

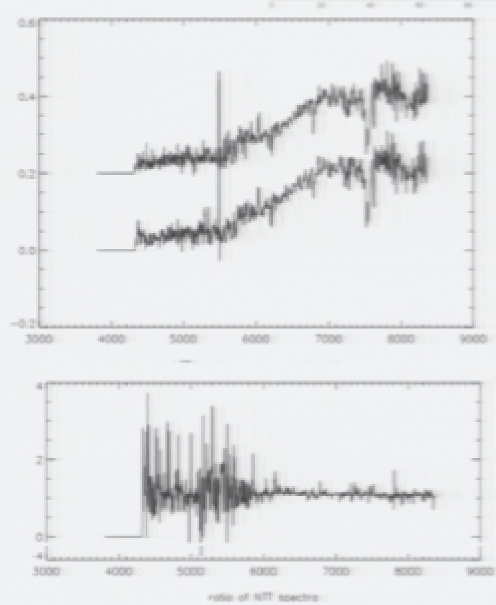




CSL 1 Sazhin etc. astro-ph/0302547







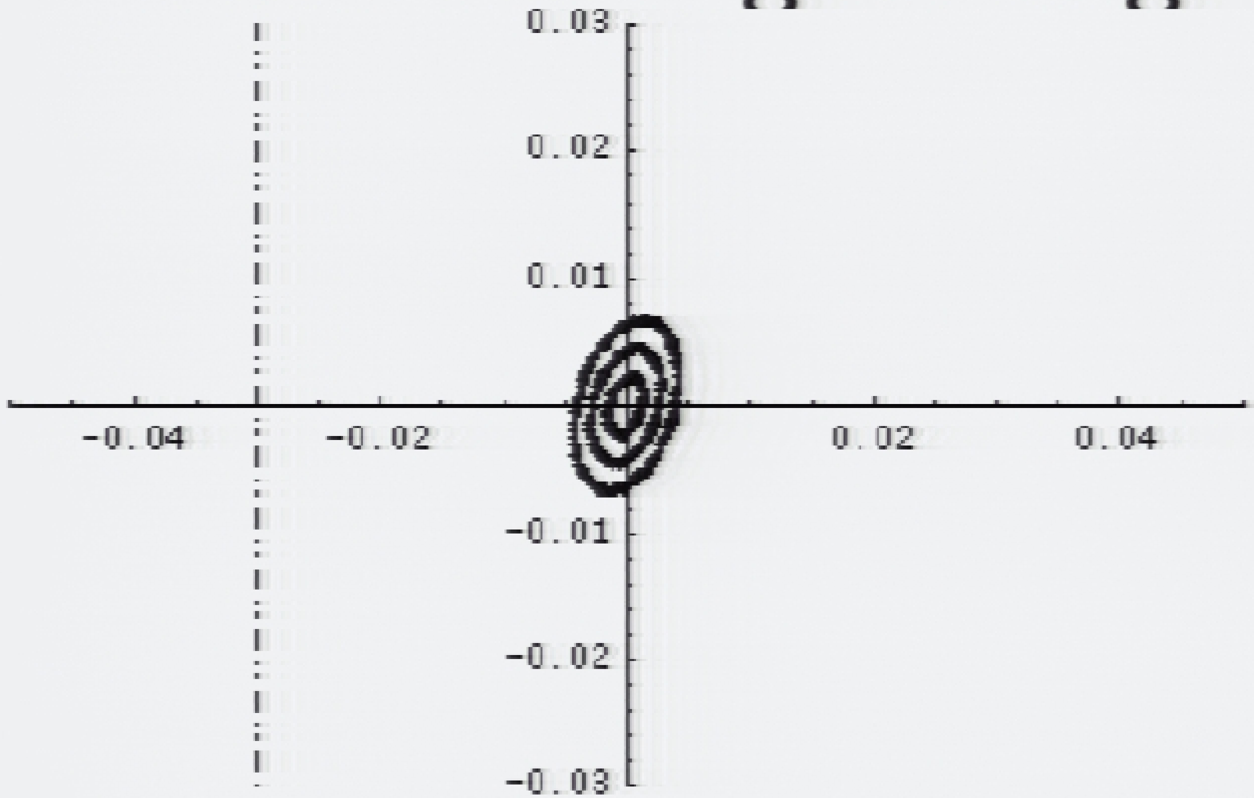
2 arc sec

⇓

$G\mu \sim 4 \times 10^{-7}$

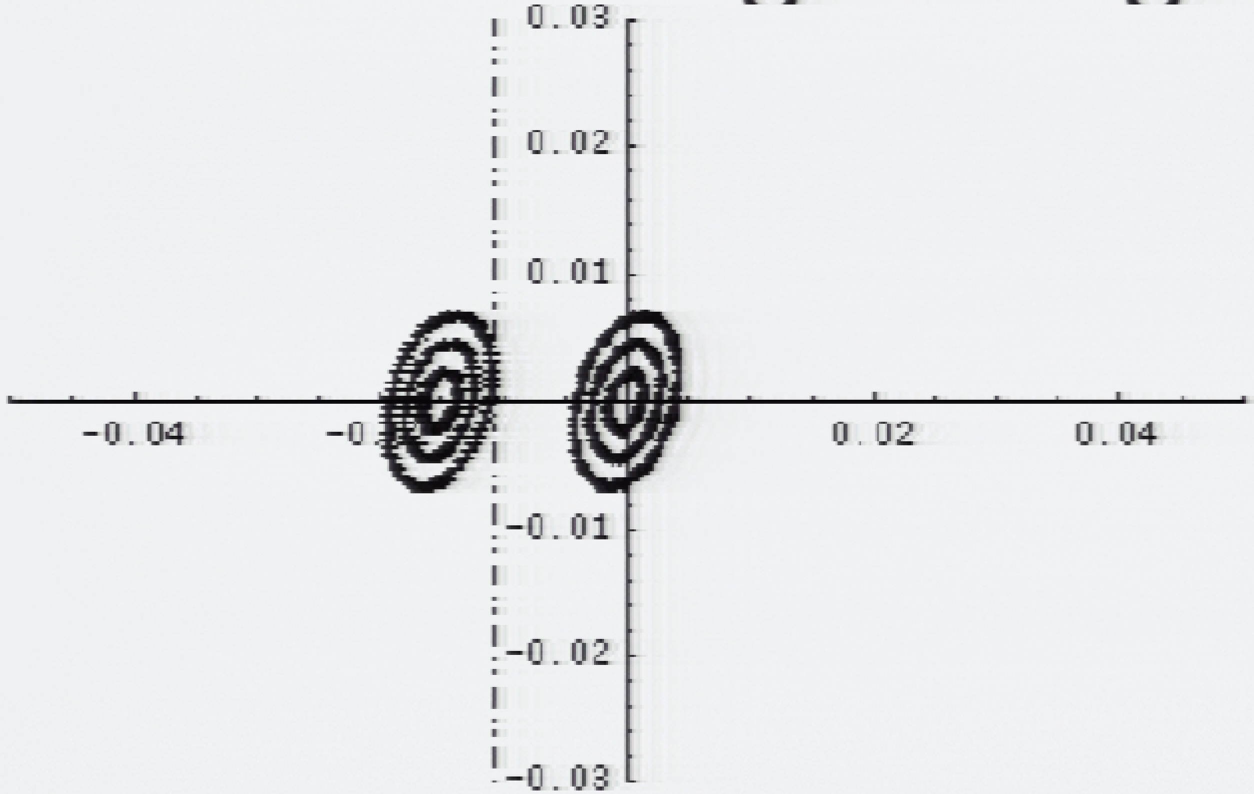
coordinates not given !

cosmic string lensing



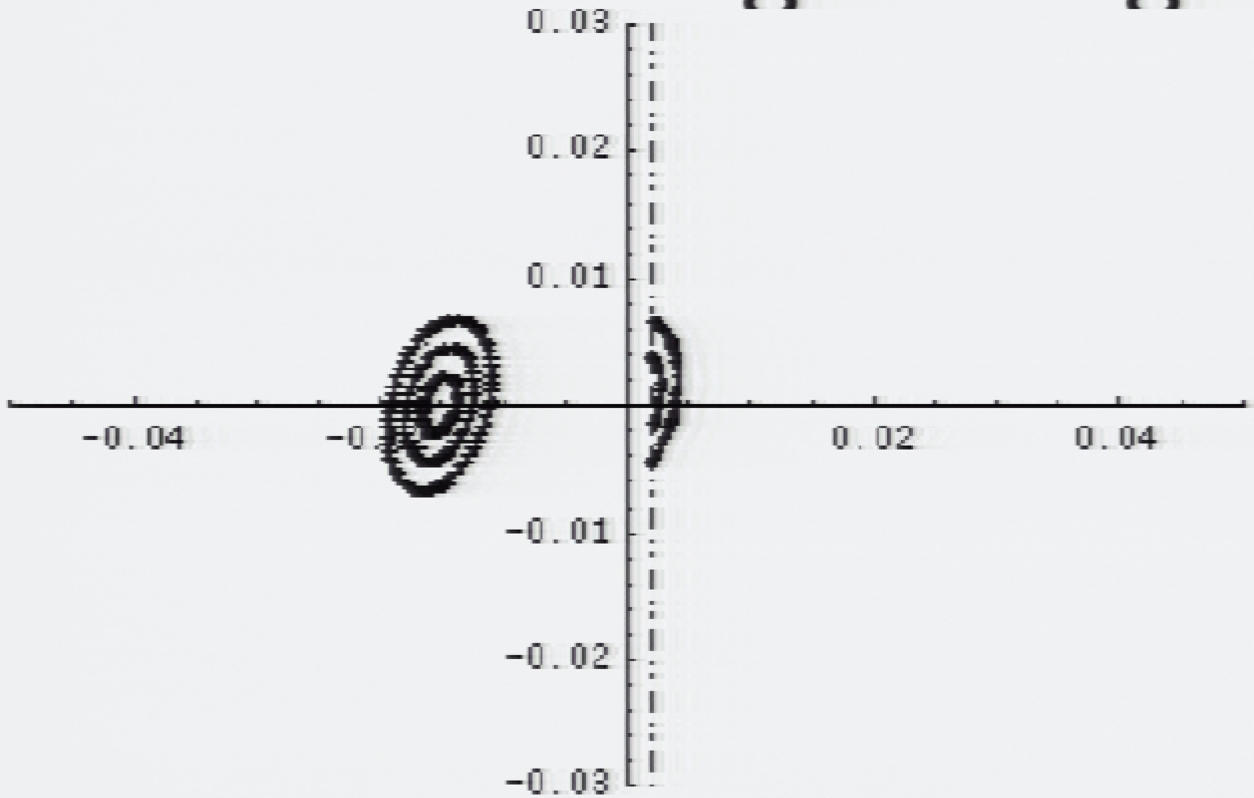
Ben Shlaer

cosmic string lensing



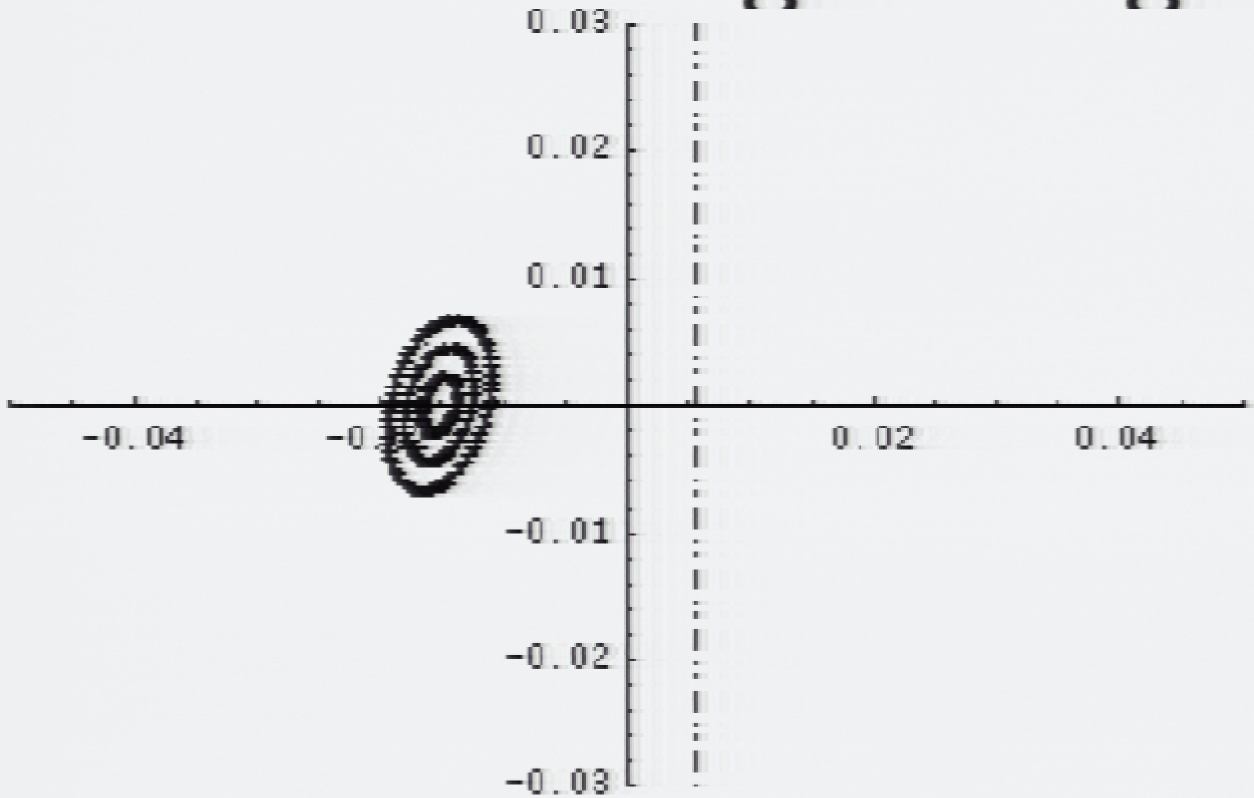
Ben Shlaer

cosmic string lensing



Ben Shlaer

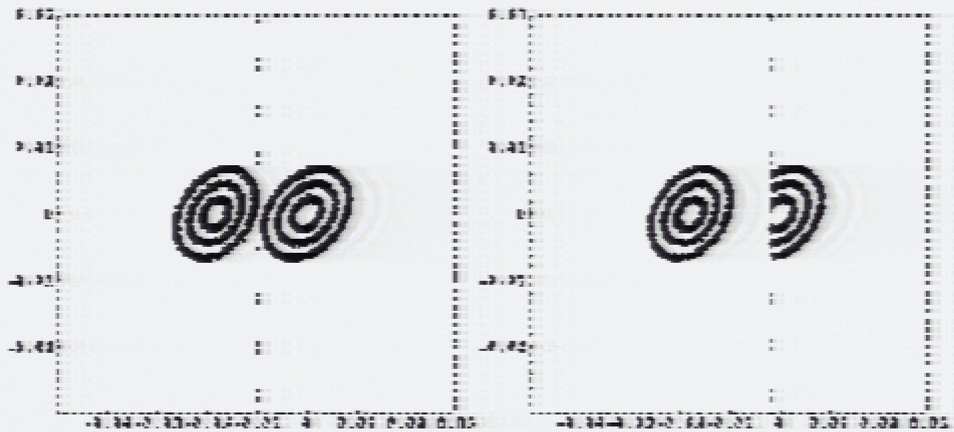
cosmic string lensing



Ben Shlaer

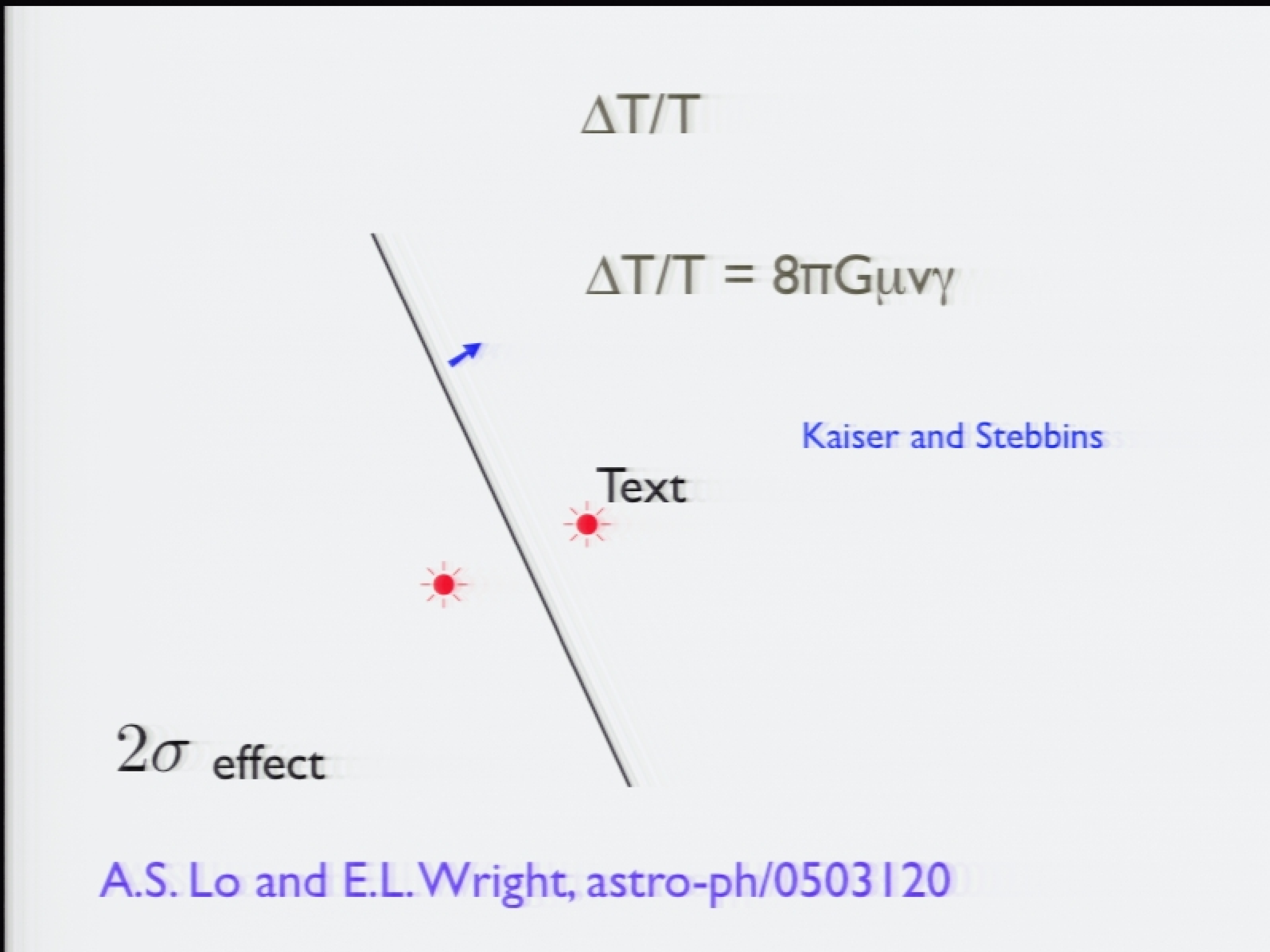
Clean Signature

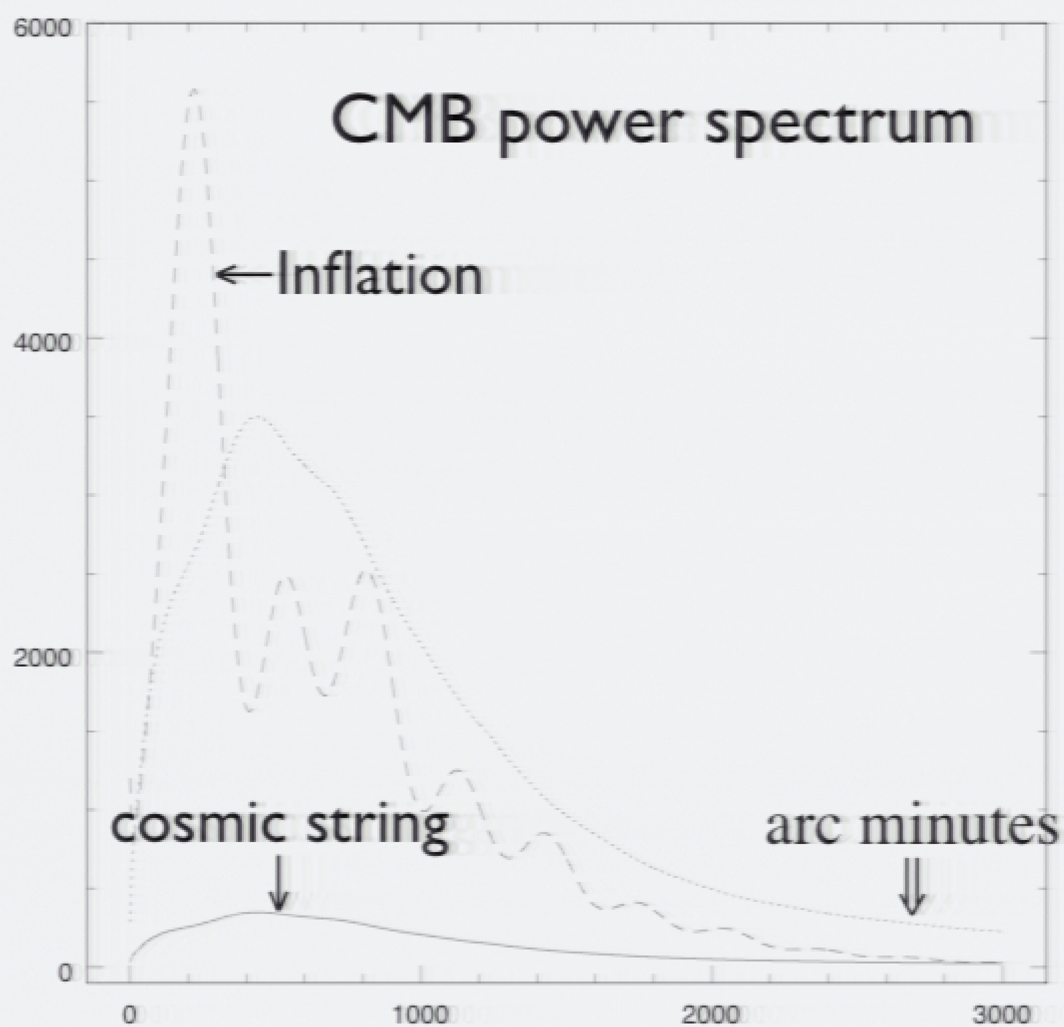
$$\delta = \frac{D_{s,cs}}{D_{s,O}} 8\pi G\mu\gamma$$



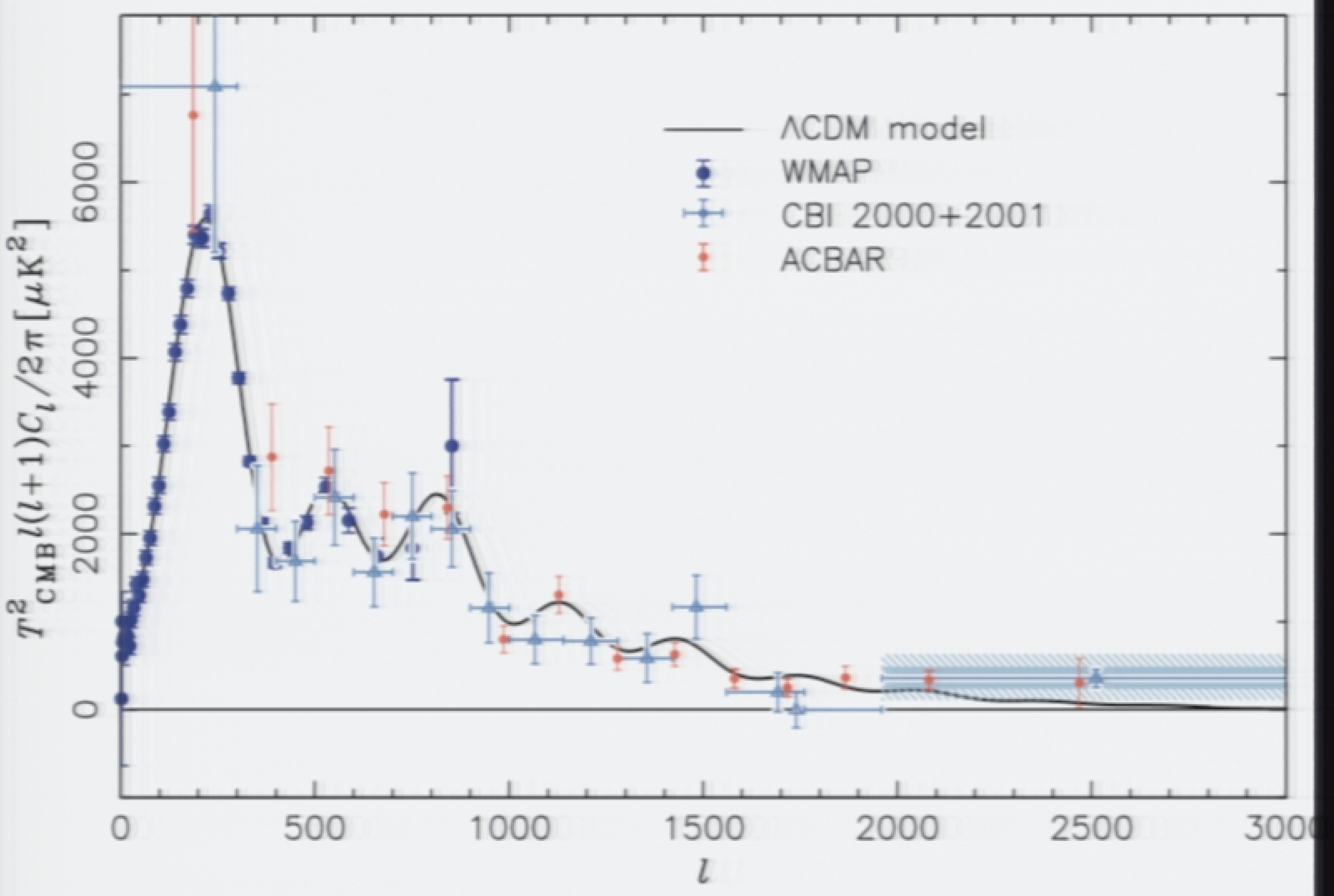
Oscillating string loop:

R. Schild, I Masnyak, B. Hnatyk, V. Zhdanov, **astro-ph/0406434**

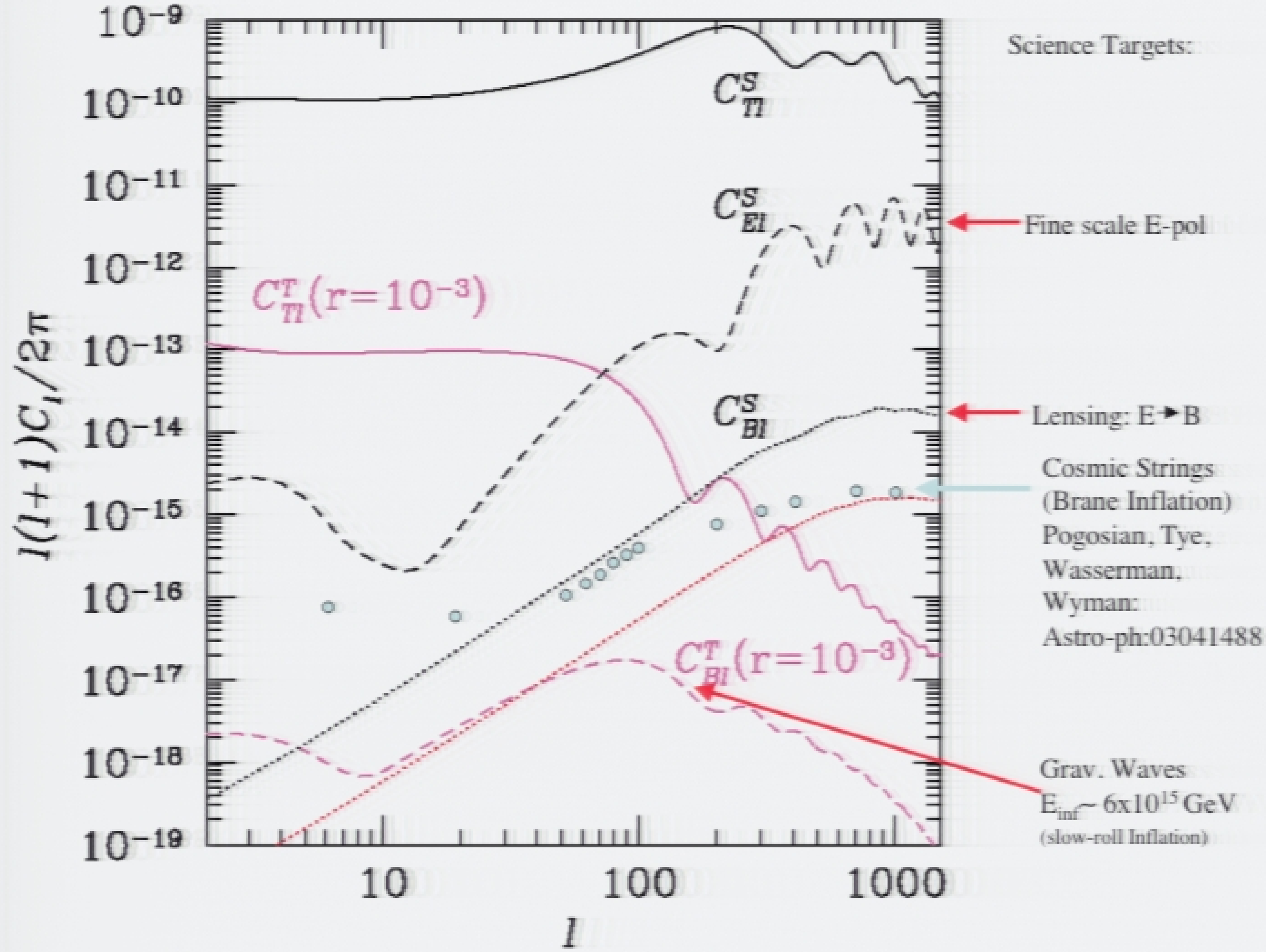

ΔT/T
ΔT/T = 8πGμvγ
Kaiser and Stebbins
Text
2σ effect
A.S. Lo and E.L. Wright, astro-ph/0503120


CMB power spectrum
←Inflation
cosmic string
arc minutes
6000
4000
2000
0
0
1000
2000
3000

L. Pogosian



—CBI+*WMAP*+ACBAR Spectrum. The solid black line is the *WMAP* ΛCDM model with a pure power-law primordial spectrum (wm
_v1.txt). The highest l ACBAR point has been displaced slightly to lower l for clarity. The blue shaded and hatched regions indicate

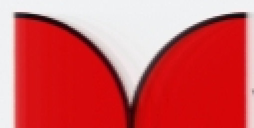


CMB B-mode polarization B.Winstein

cusps and kinks in string evolution
are quite commonin string evolution

CUSP

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



wave form of gravitational wave bursts

KINK

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

Damour and Vilenkin

Cusp in Cosmic String Evolution

KITP press release 2004

Cusp in Cosmic String Evolution

KITP press release 2004

Cusp in Cosmic String Evolution

KITP press release 2004

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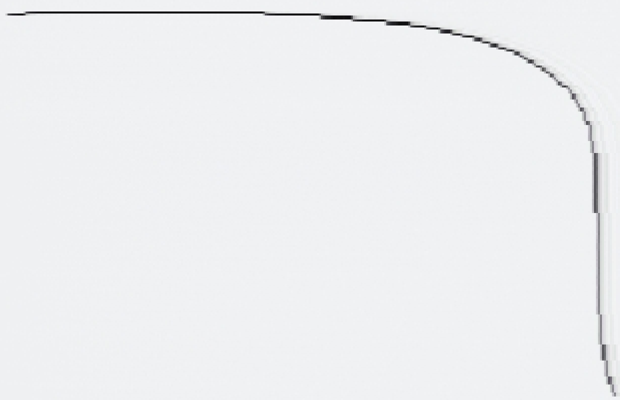
Cusp in Cosmic String Evolution



KITP press release 2004

Cusp in Cosmic String Evolution

KITP press release 2004

Cusp in Cosmic String Evolution

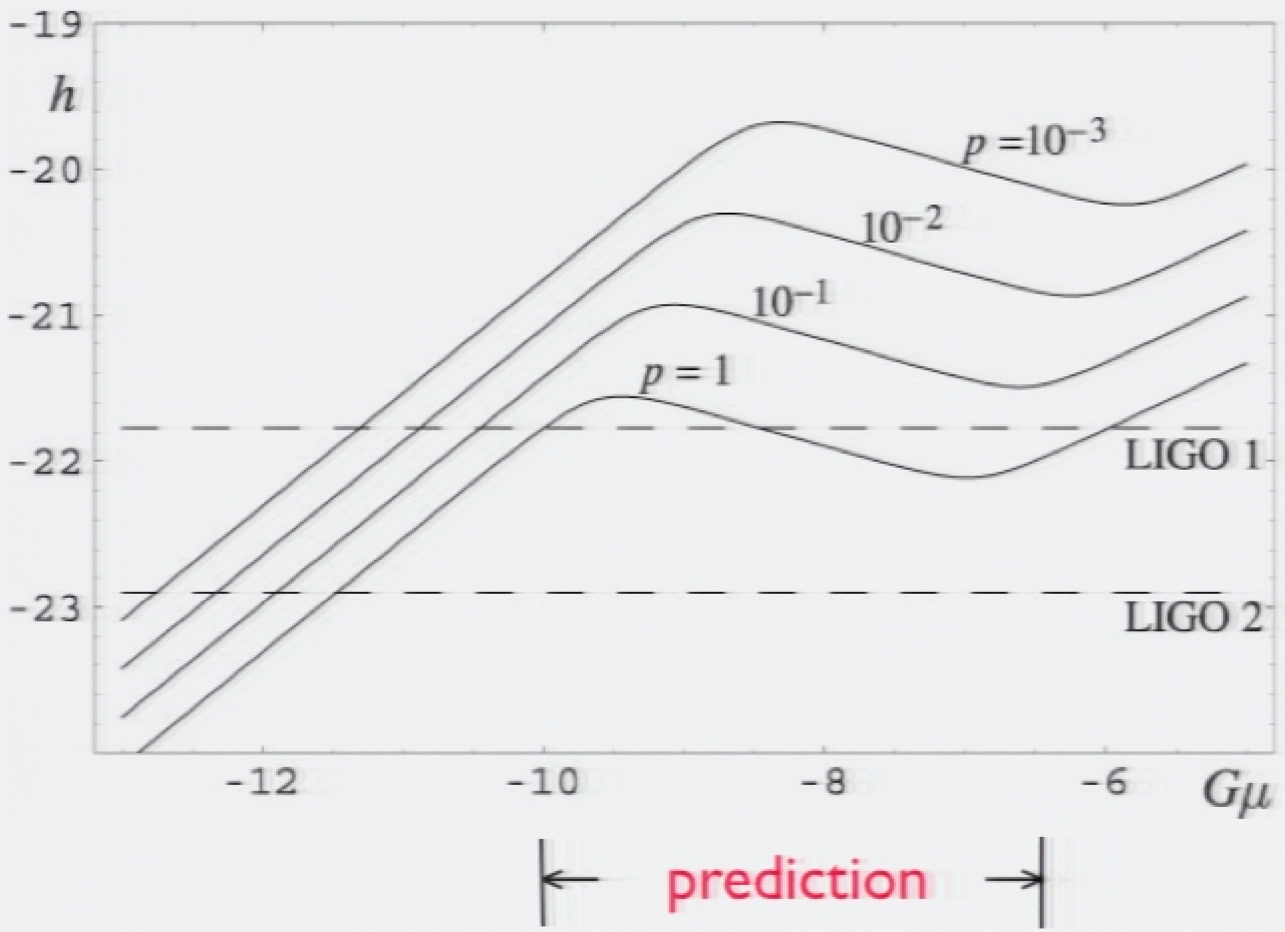
KITP press release 2004

Cusp in Cosmic String Evolution

KITP press release 2004

gravitational wave radiation from cusps

Damour and Vilenkin



Closed time-like curves

Gott time machine

$$* \rightarrow$$

$$\leftarrow *$$

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

Ben Shlaer

Summary and Remarks

To describe our universe in superstring theory, brane world merges naturally.

Brane interactions provide a natural geometric picture of inflation.

Graceful exit from inflation starts the hot big bang epoch.

Cosmic strings are copiously produced at the end of inflation.

The cosmic string should be tested in the near future.
Search for cosmic strings is going on right now.

Cosmic superstrings provide a window to the superstring theory.

Many outstanding and challenging questions remain:

Open Problems

Stability of D-strings inside D3-branes

E. Copeland, R. Myers an J. Polchinski, hep-th/0312067
L.LeBlond and H.T. hep-th/0402072

Reheating — Barnaby, Burgess, Cline,..
Louis Leblond

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

Other brane inflationary scenarios in string theory, such as D3/D7 — Zagerman

Other inflationary scenarios in string theory: racetrack, assisted, ...

C. Burgess etc., A. Mazumdar, ...