Title: Warped Brane Inflation

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Abstract:

Outline

- Motivation for String Cosmology
- Moduli Stabilization(GKP,KKLT)
- Warped Brane Inflation
- Cosmic Strings Spectrum
- dS Vacua Without Anti-brane
- Conclusion

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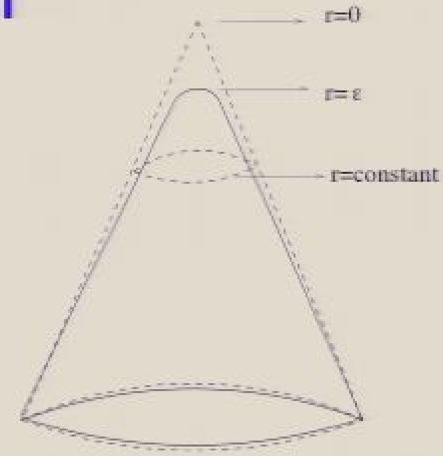
Motivation for String Cosmology

- Recent observations strongly support inflation as the origin of big bang and the structure formation in universe.
- However, the origin of the inflation is not known from a fundamental theory point of view.
- String theory, on the other hand, is a consistent theory of gravity. So far it has evaded observations.
- Since the scale of inflation is very high, possibly GUT scale, it is natural to expect that string theory was relevant in driving inflation.
- This would provide a unique chance to test the relevance of string theory to the real world.

Moduli In String Theory

- String theory is a higher dimensional theory. After compactification to four dimensions one gets many scalar fields, moduli, depending on details of compactifications.
- Good News: Due to large number of moduli, it is possible that some of them play the role of inflaton field. Examples are: Tachyon Inflation, Racetrack Inflation, DBI-Inflation, D3-D7 Inflation, Brane Inflation, Warped Brane Inflation.
- Bad News: These moduli may couple to the inflaton field and interfere with the slow roll conditions. Furthermore, If they are not stabilized they will destroy the success of late time big bang cosmology, like big bang nucleosynthesis.
- The first task in string cosmology is the understanding of moduli and their stabilization mechanism.

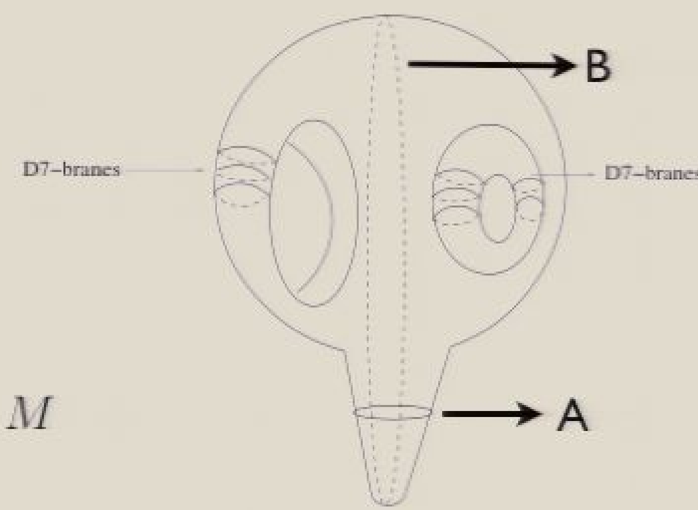
Complex Structure Stabilization



- Particular example studied carefully is a deformed conifold in IIB string theory(Kelebanov and Sttrassler, hep-th/0007191).

- A deformed conifold is defined by $\sum_{i=1}^{4} w_i^2 = \epsilon^2$

- There are two 3-cycles, called A and B. One can turn on M units of RR 3 forms F3 on A cycle and K units of NSNS 3 forms H3 on B cycles:



$$\frac{1}{4\pi^2 l_s^2}\int_B H_3 \;=\; -K, \qquad \frac{1}{4\pi^2 l_s^2}\int_A F_3 = M$$

The Warped Deformed Conifold

- By turning these fluxes one can create a warped geometry like Randall-Sundrum(RS) scenario(Kachru, Giddings and Polchiski, hep-th/0105097).
- The metric inside the conifold is almost an AdS metric:

$$ds^2 = h(r)^2\left(-dt^2 + a(t)^2 d\vec{x}^2\right) + h(r)^{-2}dr^2 \qquad h(r) = \frac{r}{R}$$

- Where R is the characteristic length scale of the AdS geometry

$$R^4 = \frac{27}{4}\pi g_s N \alpha'^2 .$$

- N=MK is the effective background D3-brane charge. The warp factor at the end of the throat is given by

$$h_A = e^{-2\pi K/3g_s M}$$

Volume Modulus Stabilization

- In GKP, they could stabilize the complex structure like axion-dilaton field. However, the volume modulus can not be stabilized by flux compactifications.

- In supergravity limit the potential for moduli is

$$V_F = e^{\mathcal{K}} \sum_{a,b} \left(g^{\bar{a}b} \overline{D_a W} D_b W - 3|W|^2 \right) \to e^{\mathcal{K}} \sum_{i,j} \left(g^{\bar{i}j} \overline{D_i W} D_j W \right)$$

- Where the Kahler potential and the superpotential are

$$\mathcal{K} = -\ln[-i(\rho - \bar{\rho})] - \ln[-i(\tau - \bar{\tau})] \qquad W = W(\tau)$$

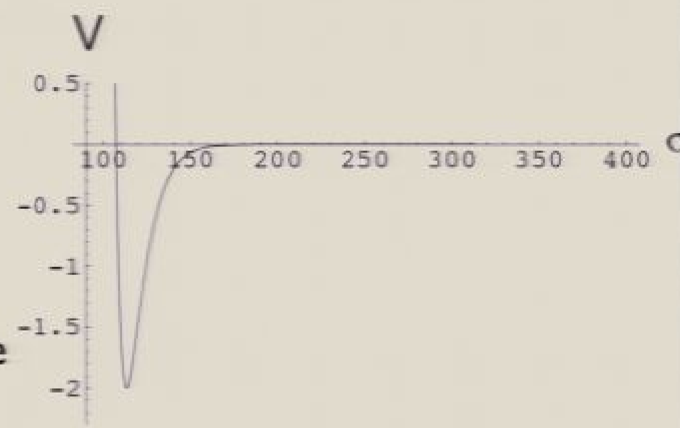
- Because W is independent of the volume modulus(Kahler modulus), the potential is independent of the volume modulus and it can not be stabilized in GKP.

KKLT

hep-th/0301240

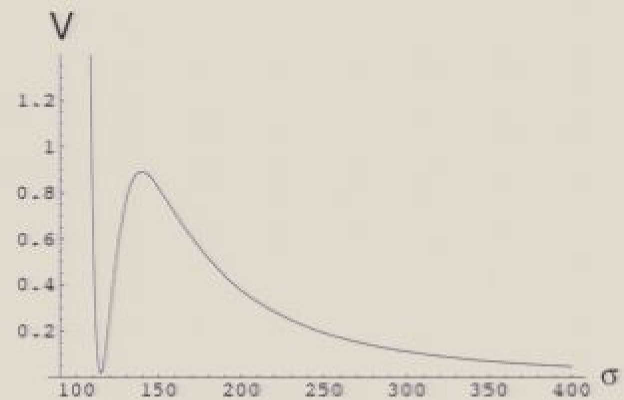
- Kachru and collaborators realized that non-perturbative effects on superpotential can create ρ dependence in W.

$$W = W_0 + Ae^{ia\rho}$$



- One can stabilize the volume modulus while the vacuum is a supersymmetric AdS minimum.

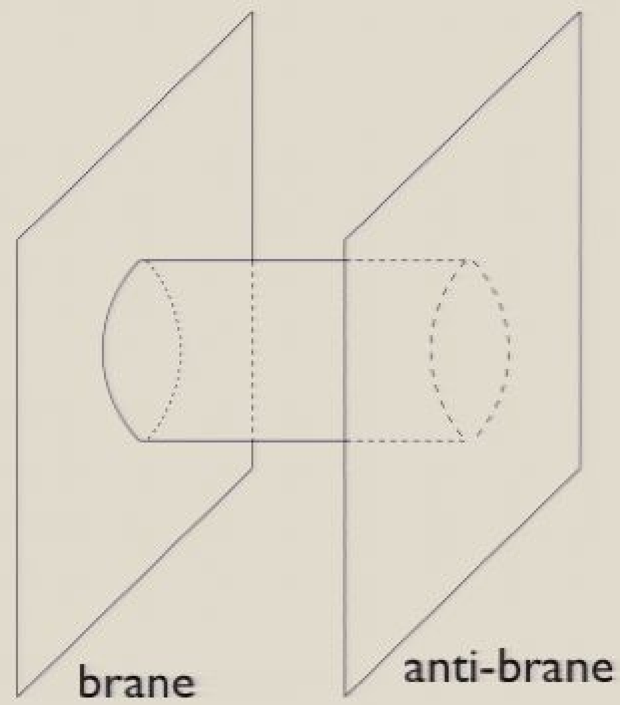
- To obtain a 4D theory with positive cosmological constant, they uplift the AdS vacuum by adding some anti-D3 brane at the bottom of the conifold.

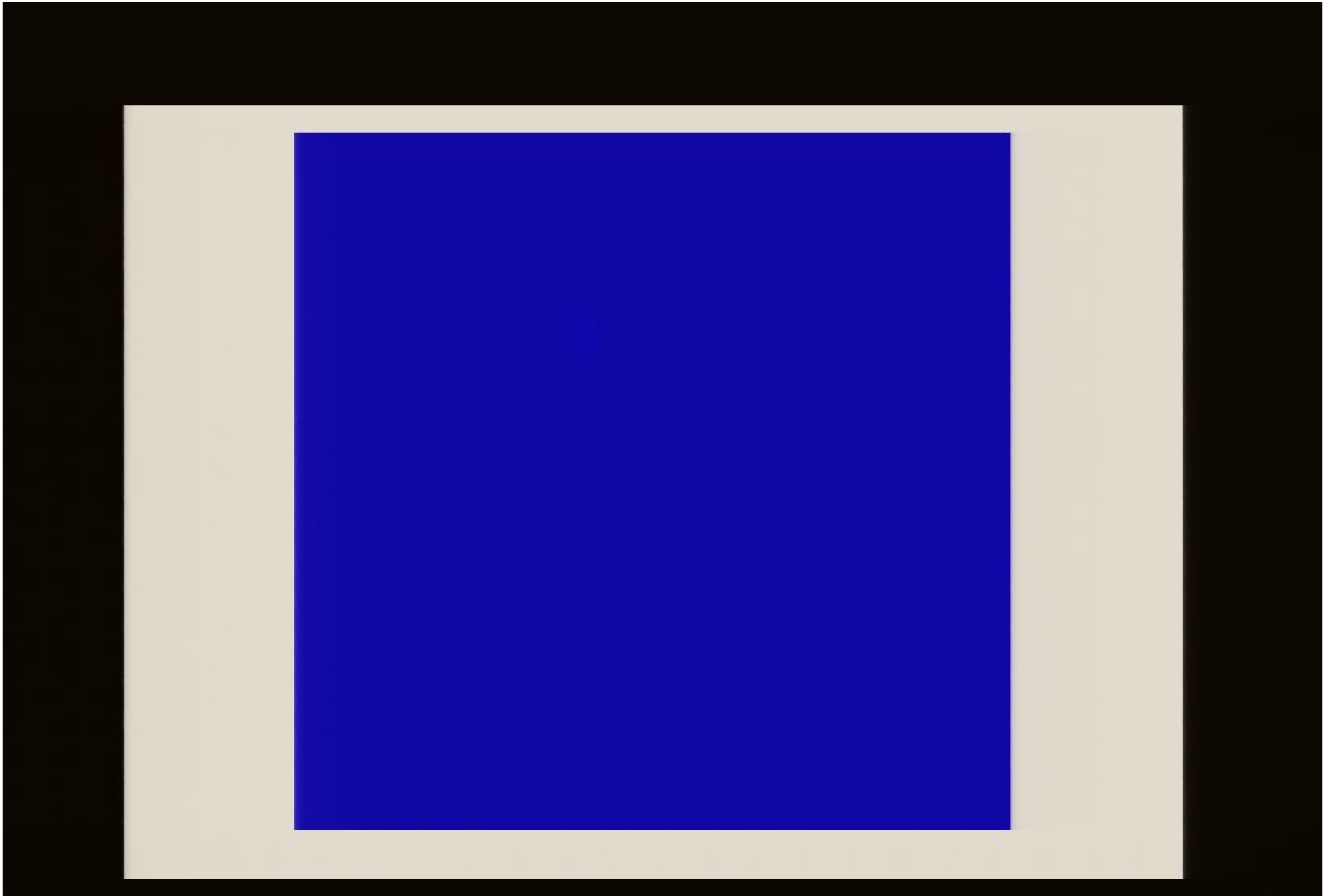


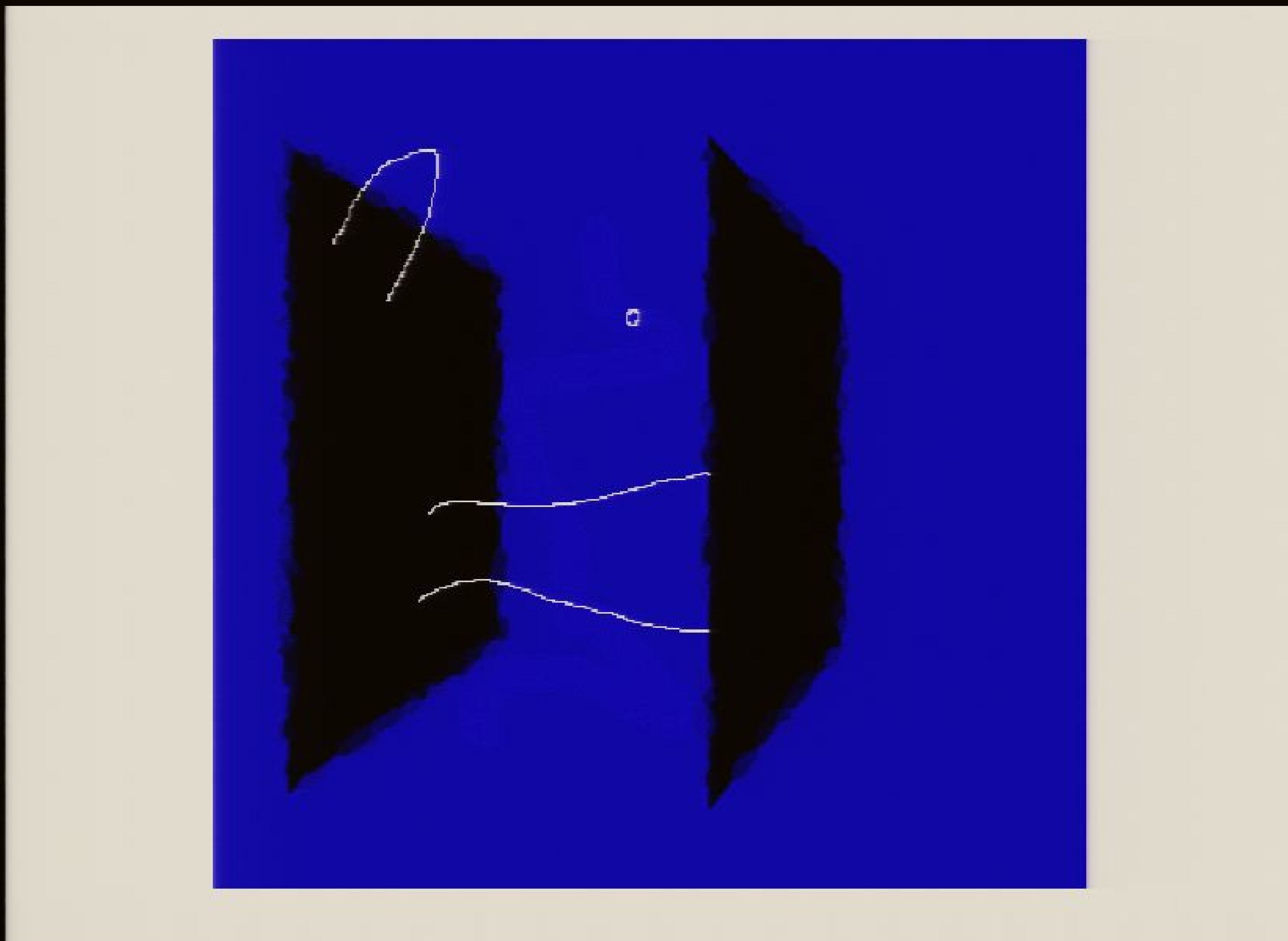
Brane Inflation

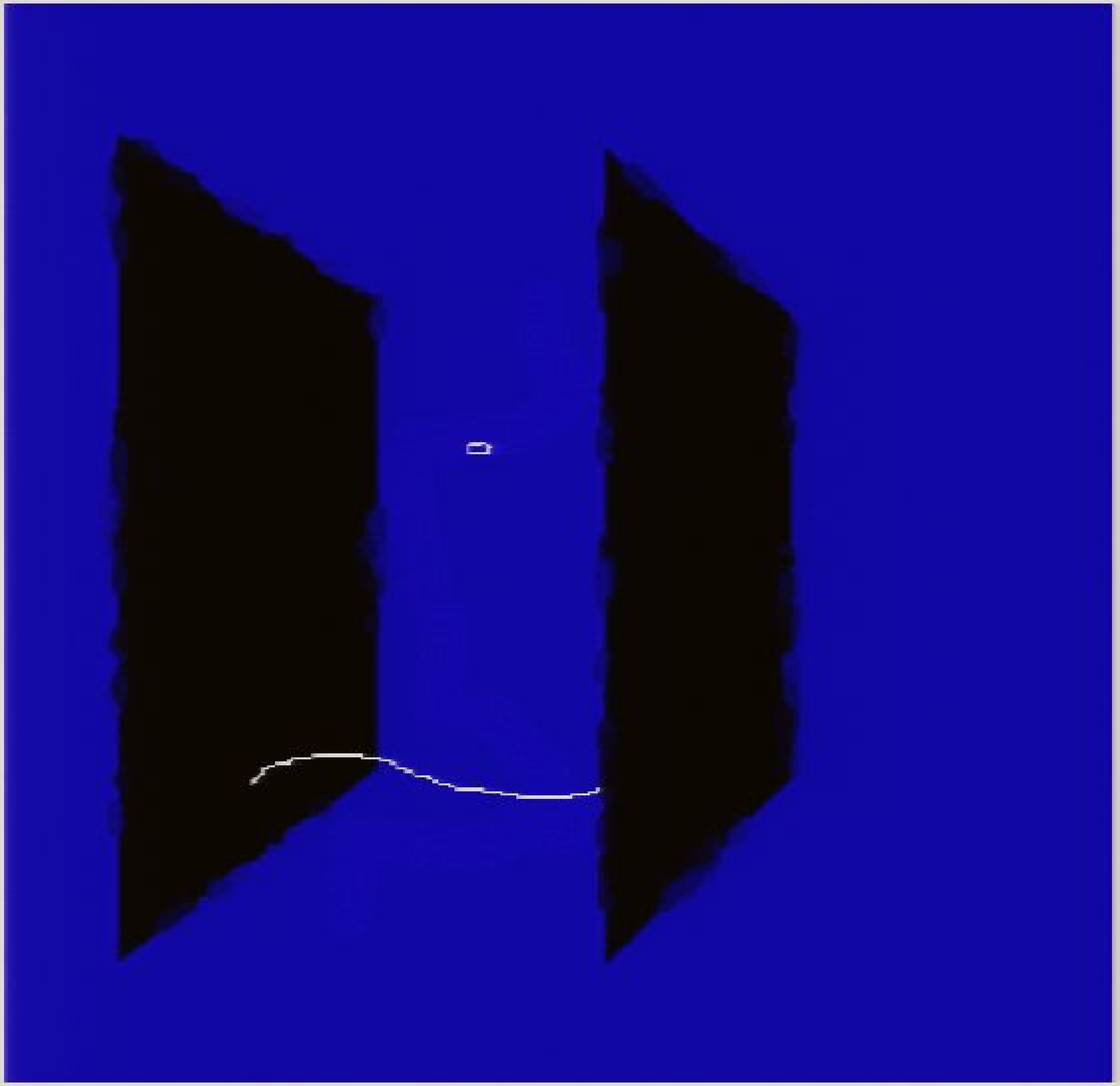
G. Dvali and H. Tye, hep-ph/9812483

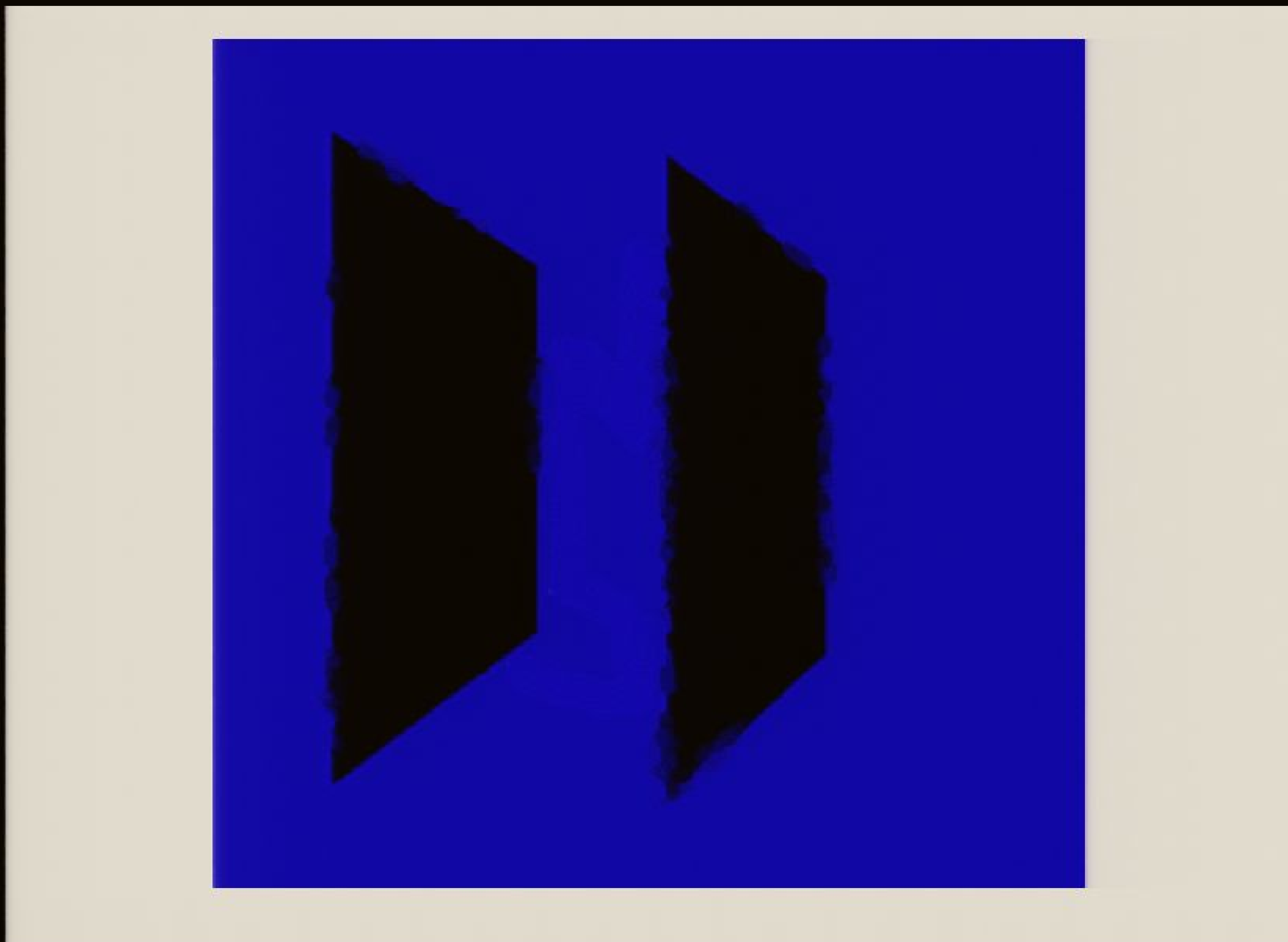
- In brane inflation the inflaton field is the distance between brane and anti-brane.
- There is an attractive force between brane and anti-brane. If the potential is flat enough one can get enough inflation.
- When the distance between brane and anti-brane is at the order of string scale, a tachyon develops. Inflation ends when brane and anti-brane collide.
- Problem: In flat CY, the potential is too strong to achieve the slow-roll conditions for inflation.

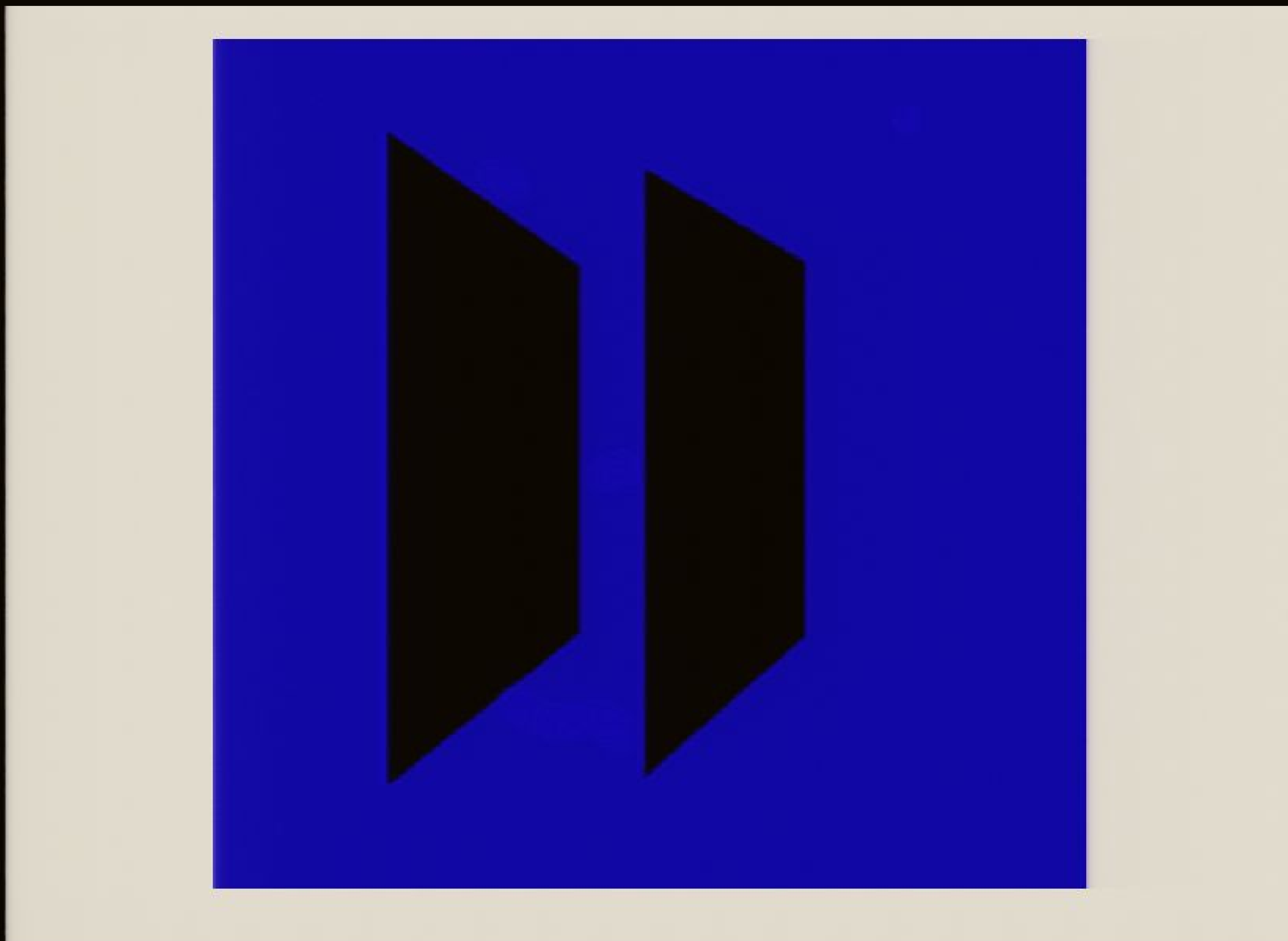


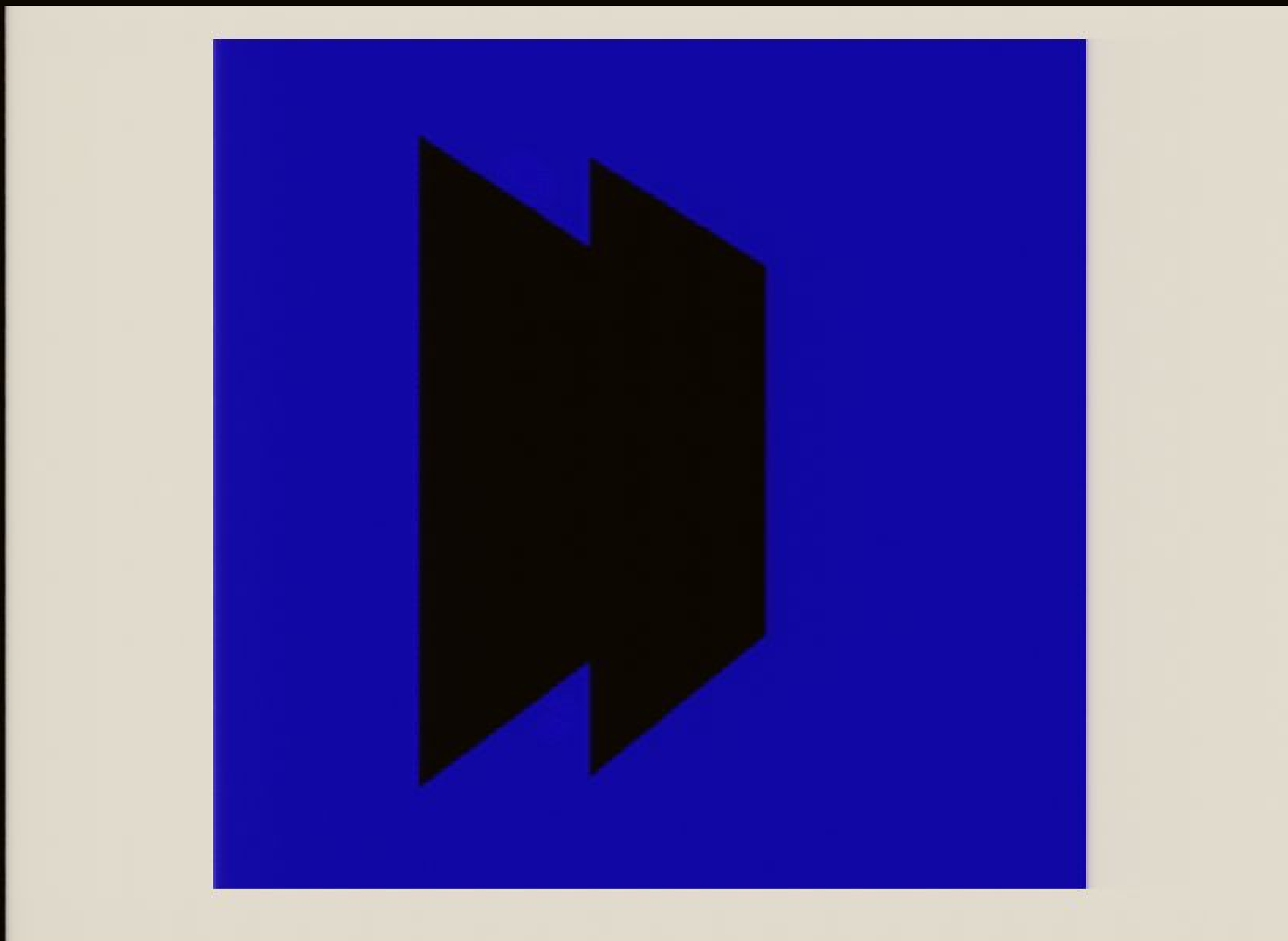


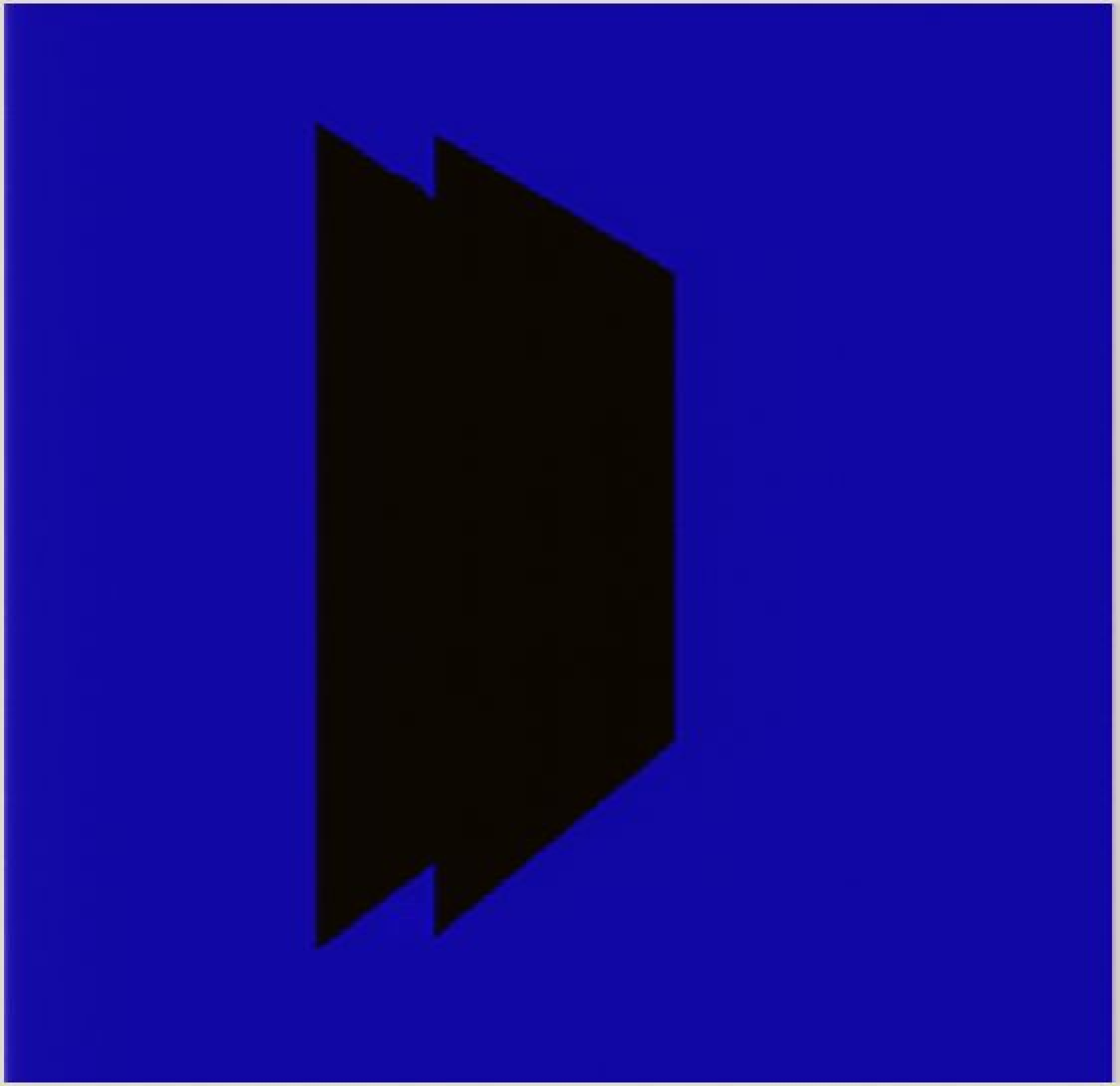


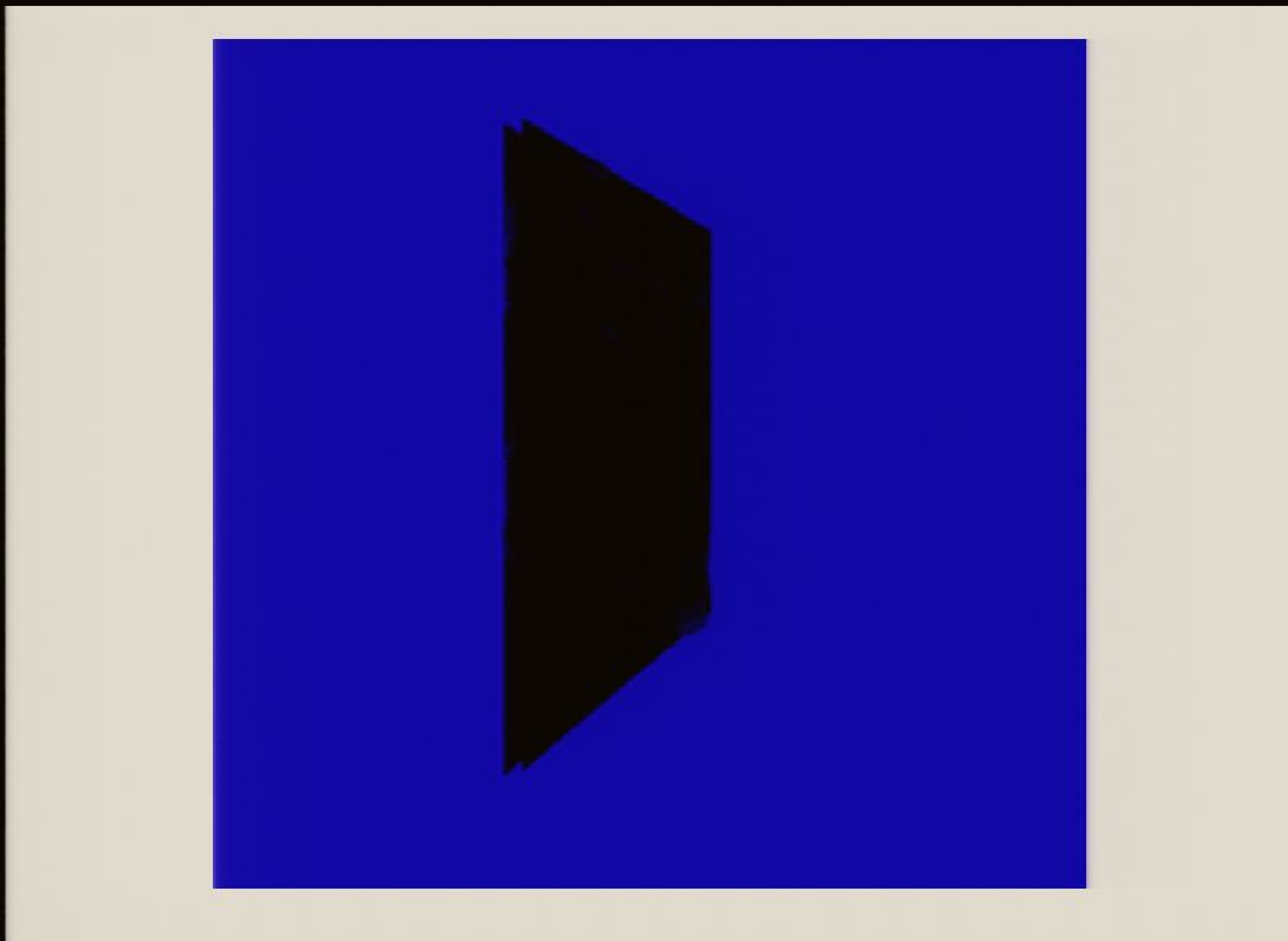


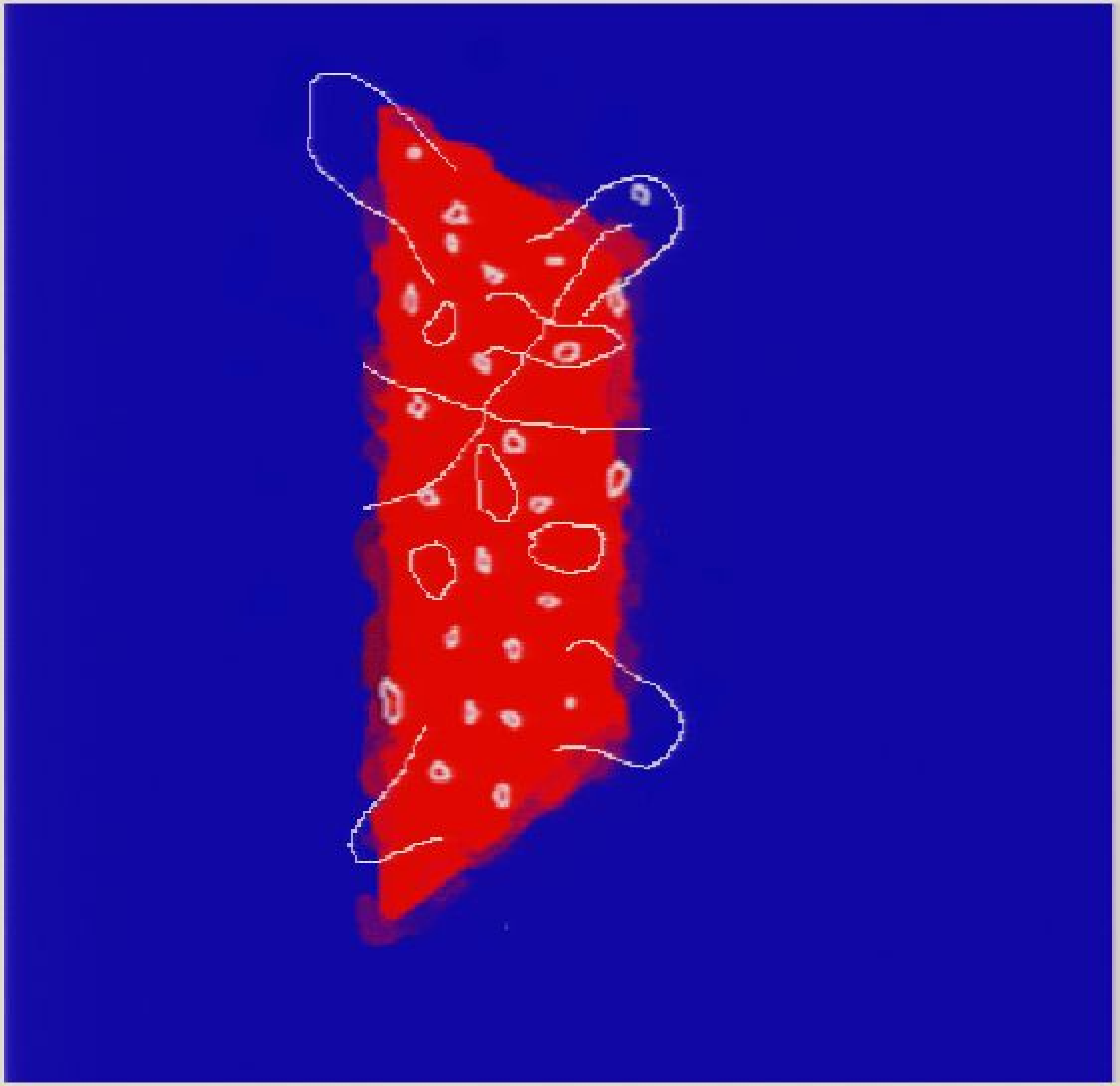


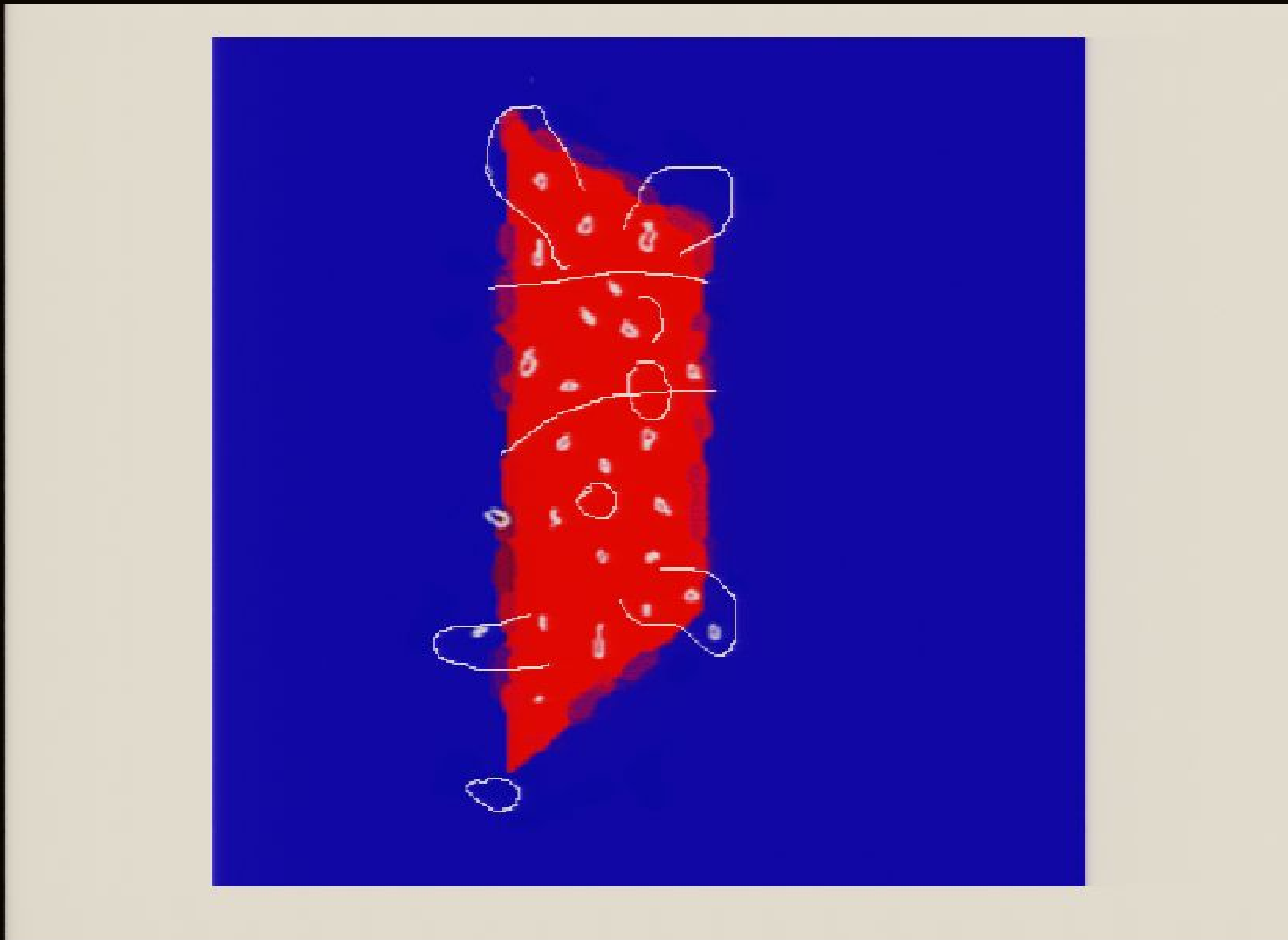


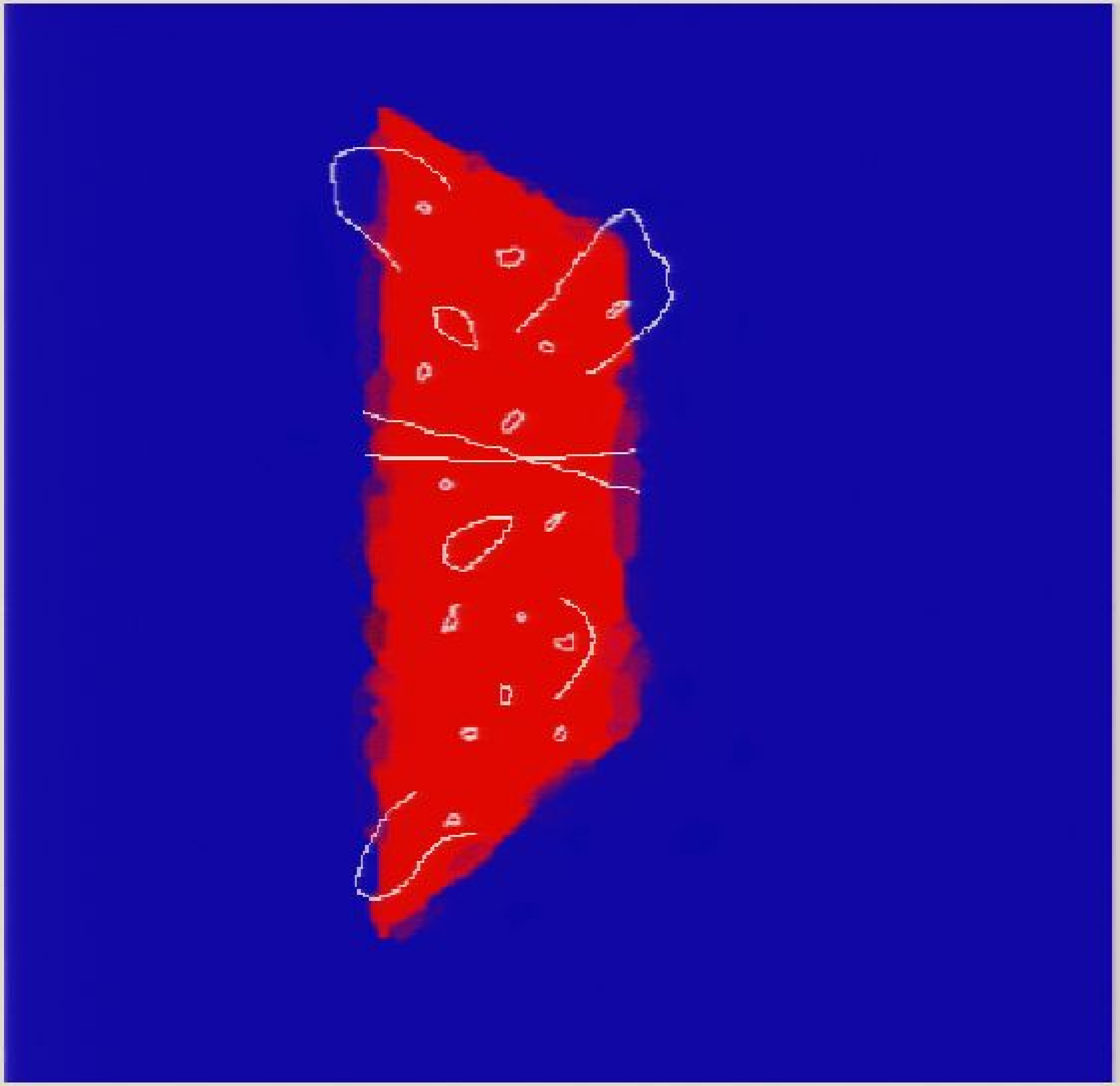


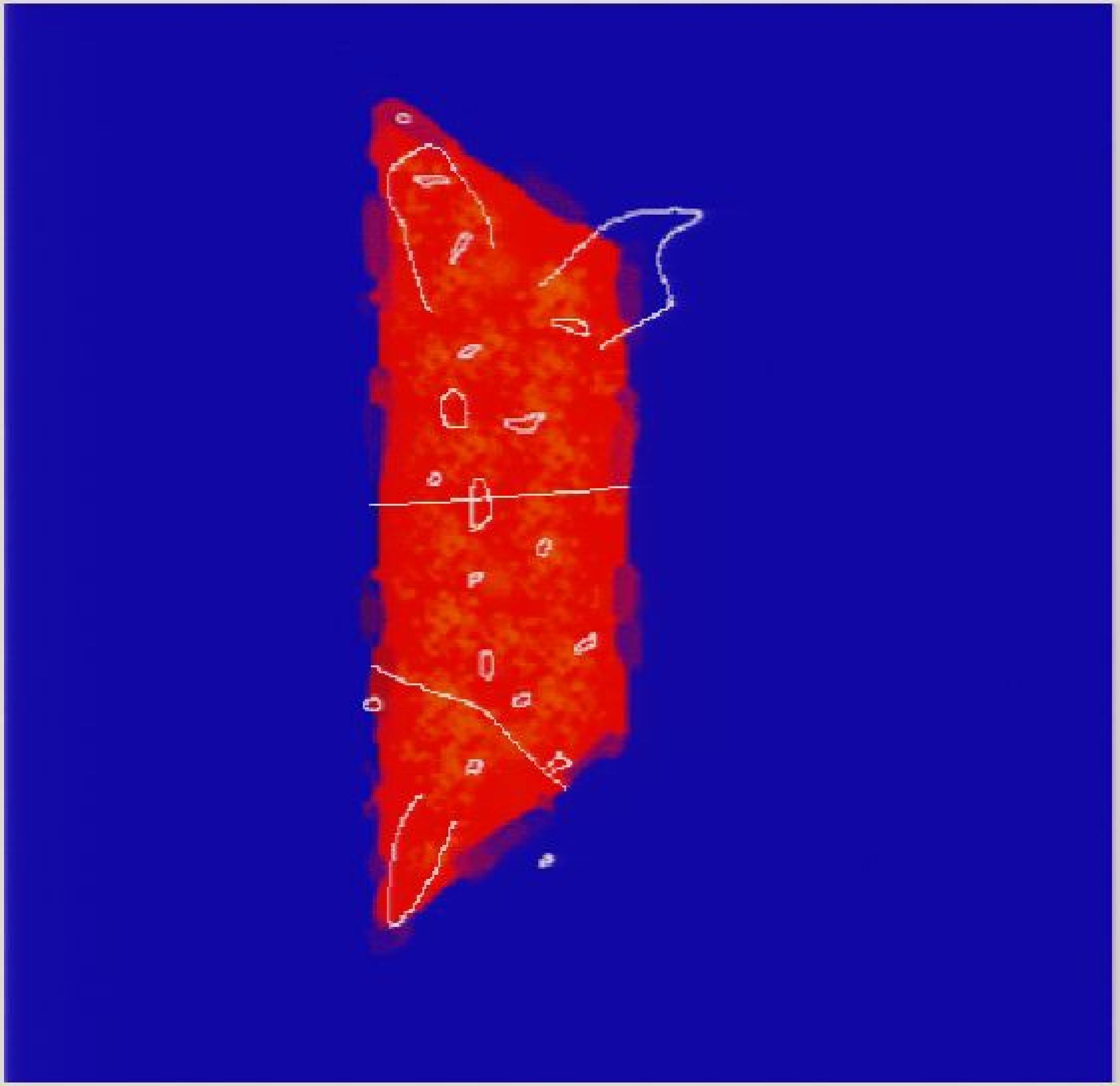


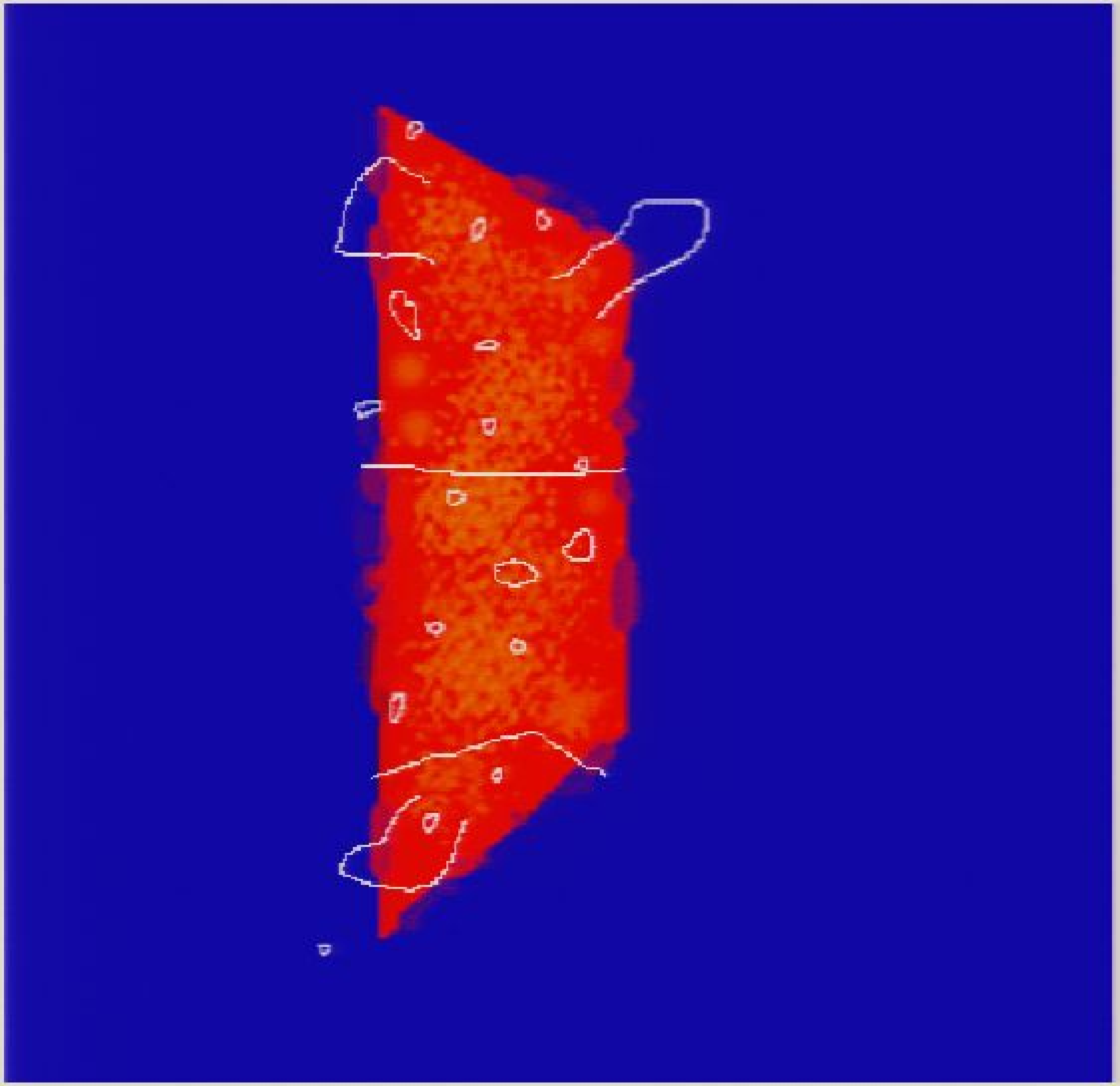


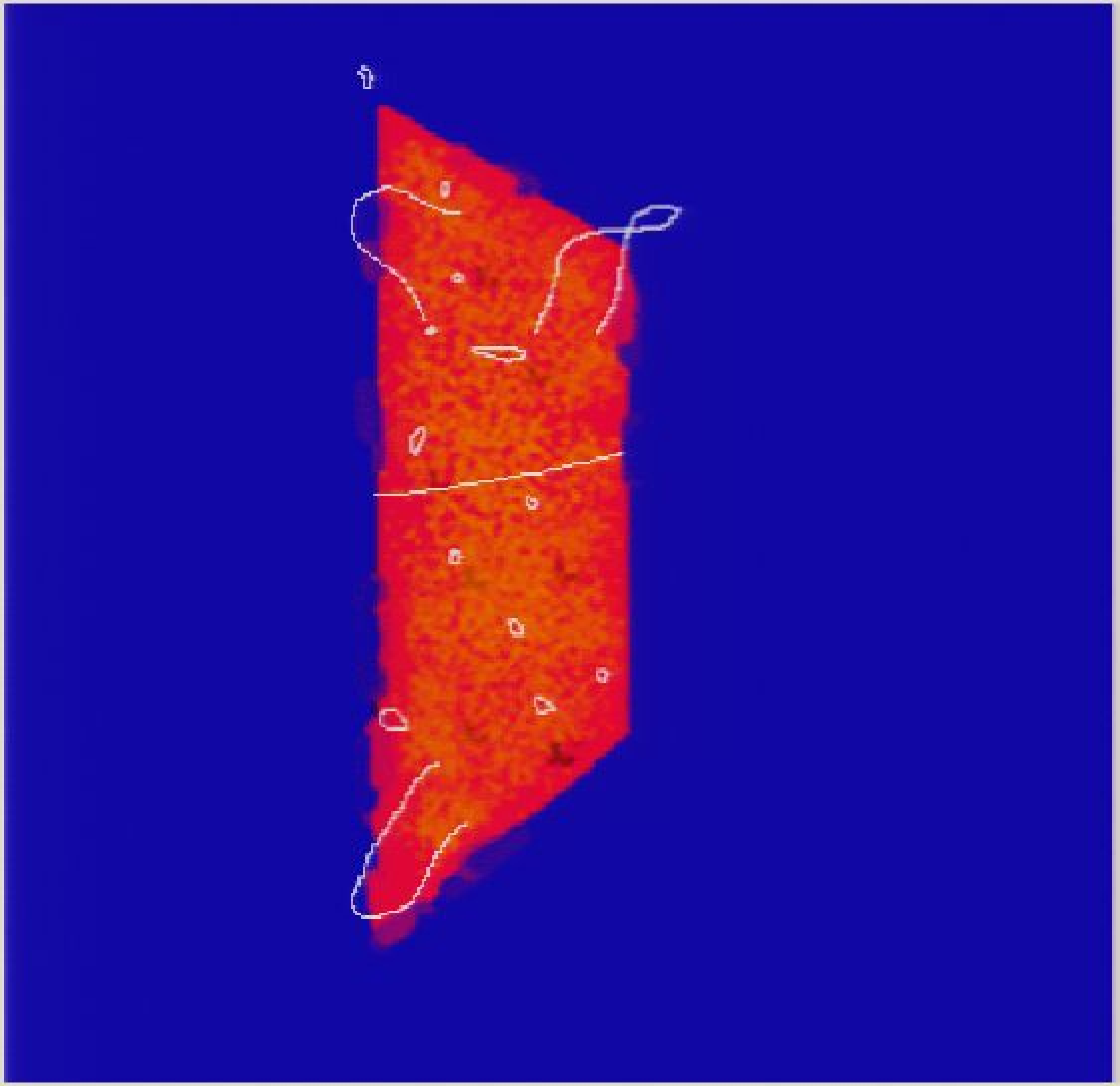


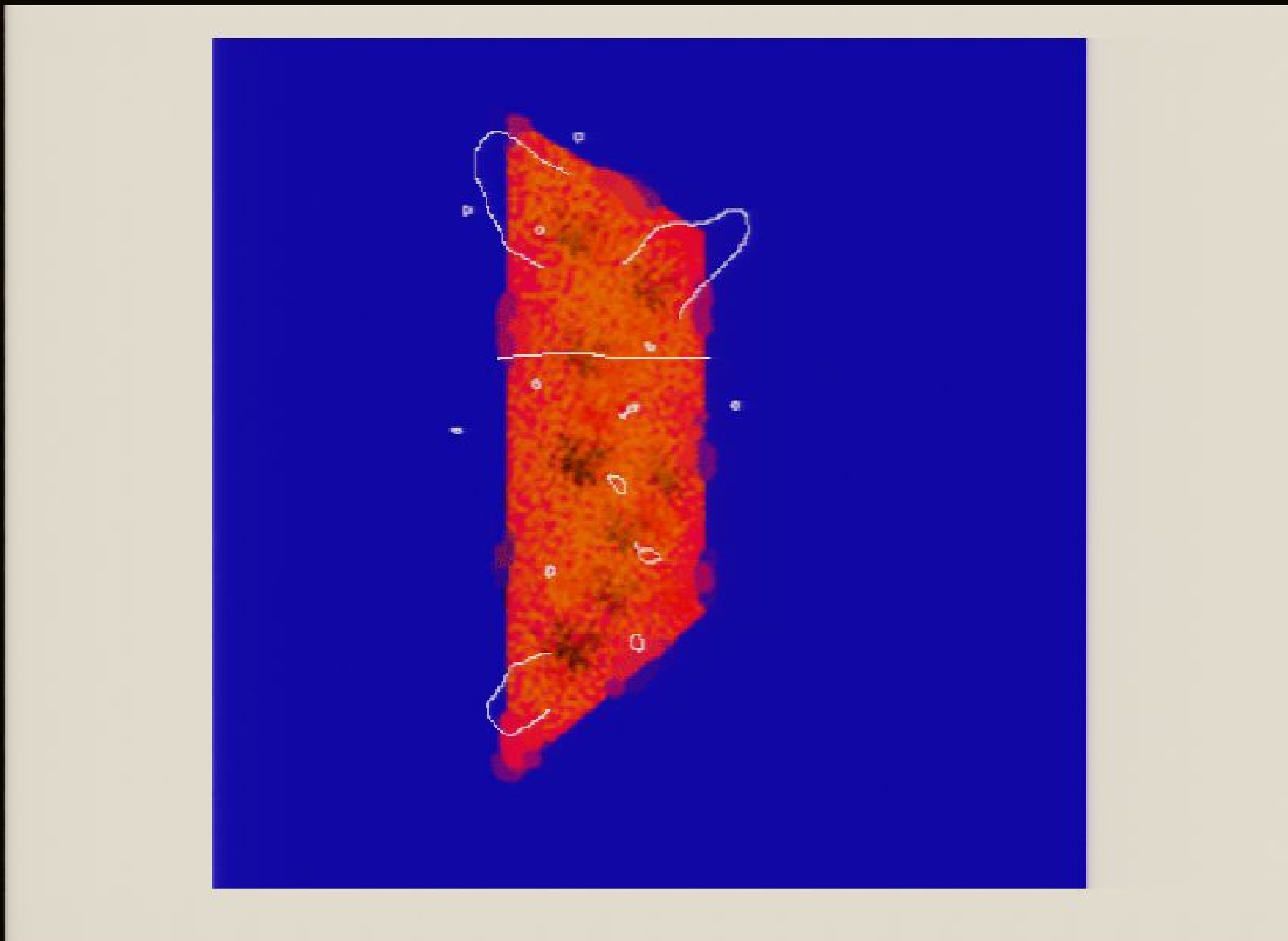


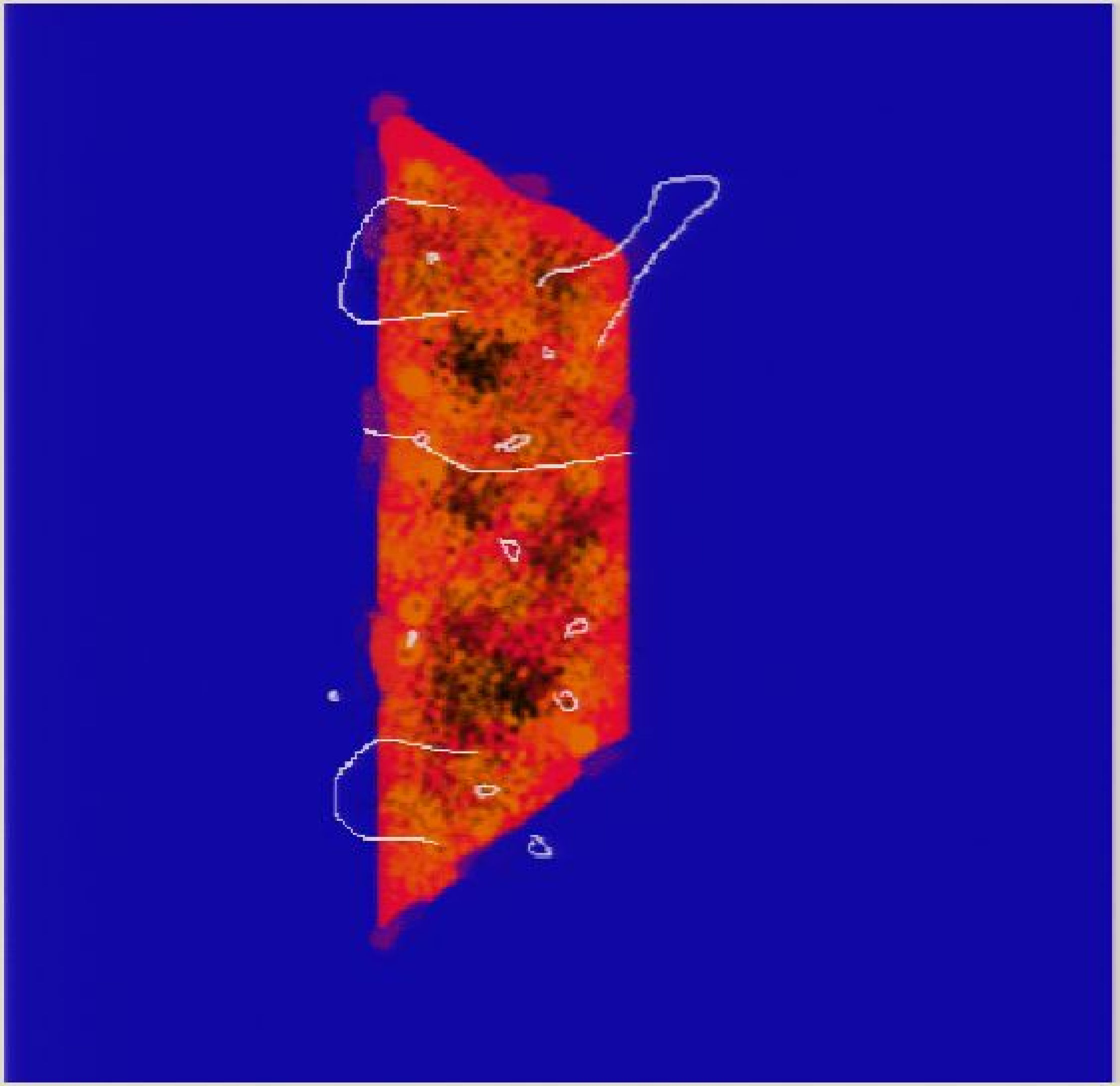


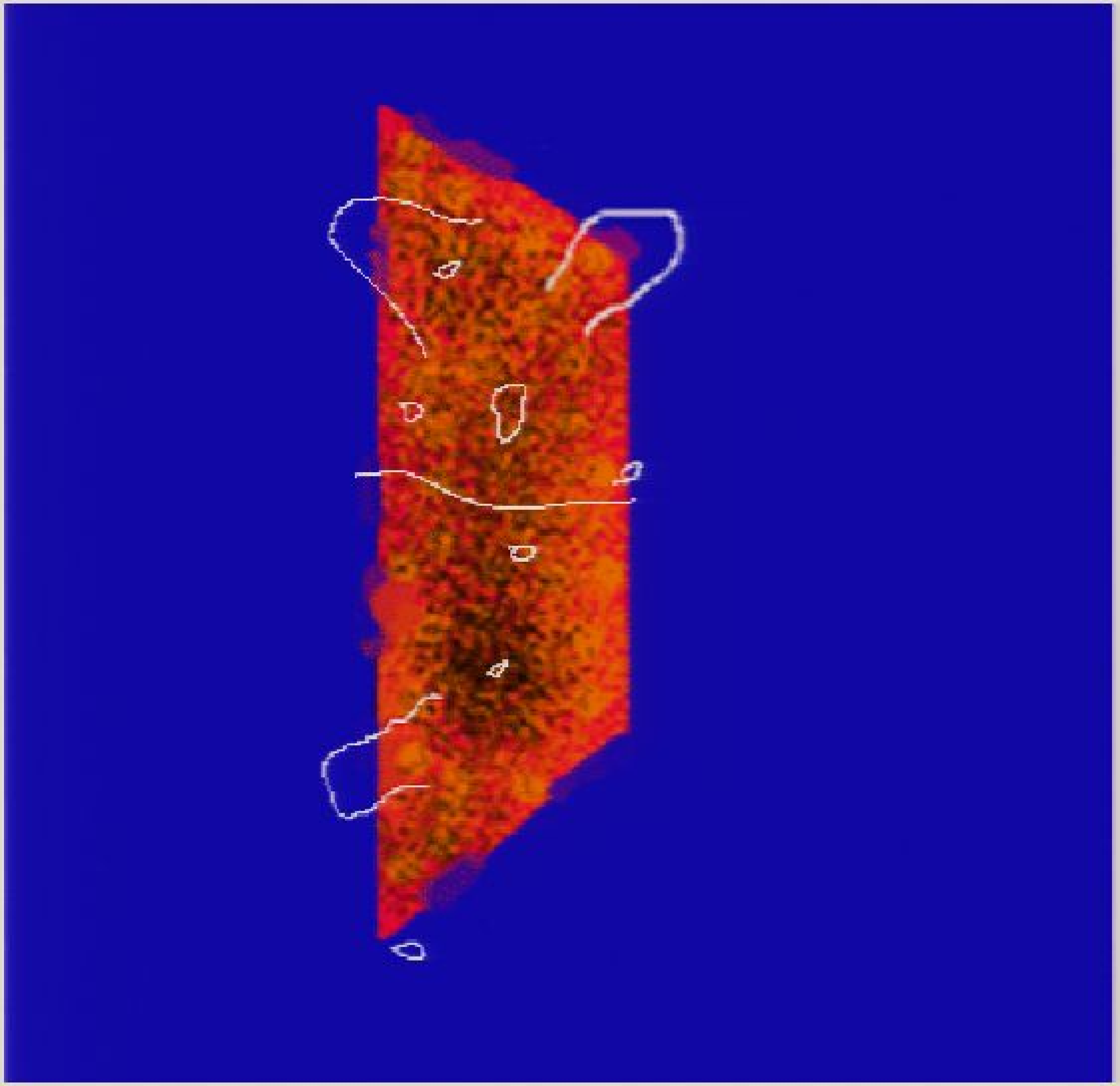


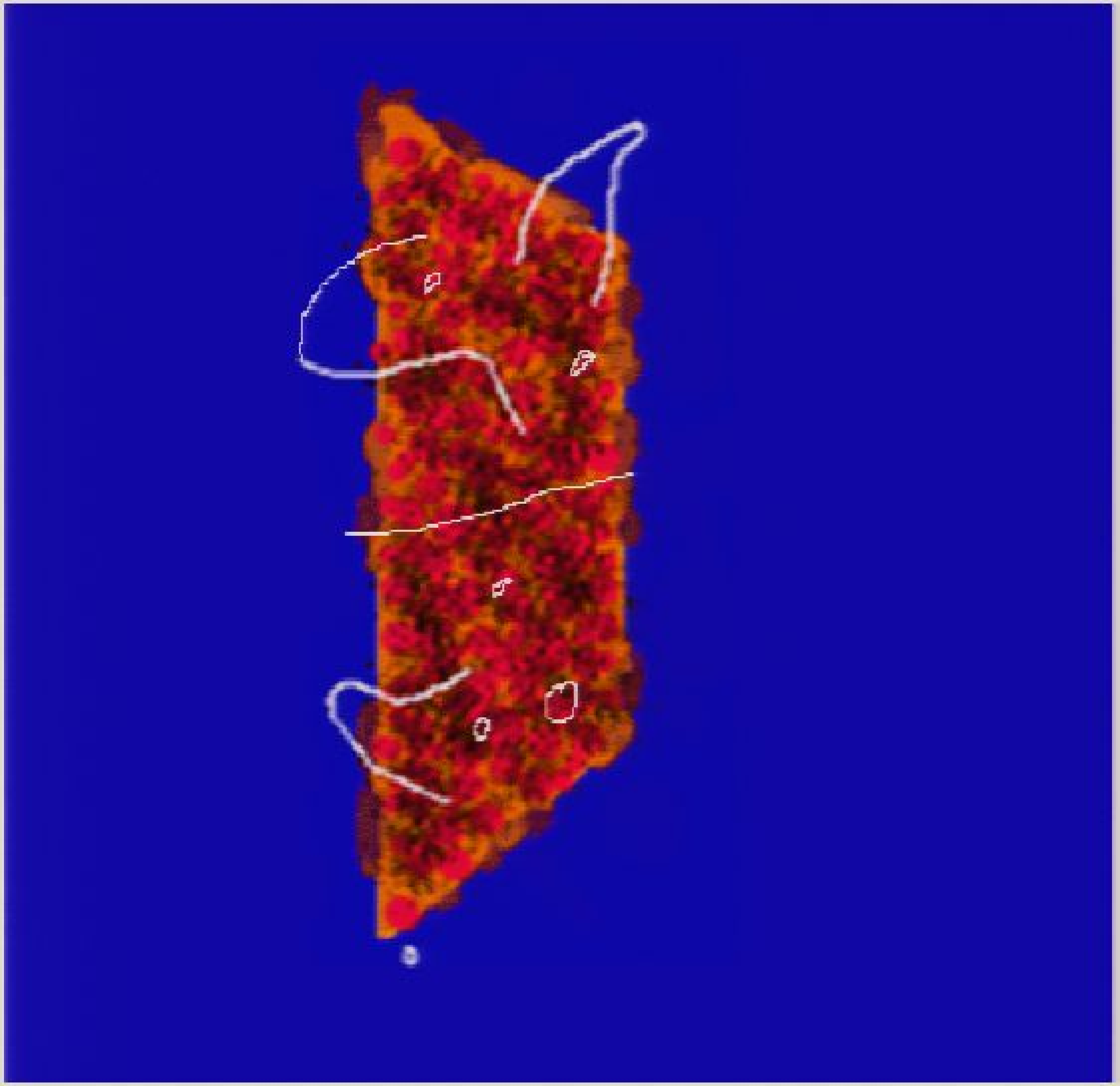


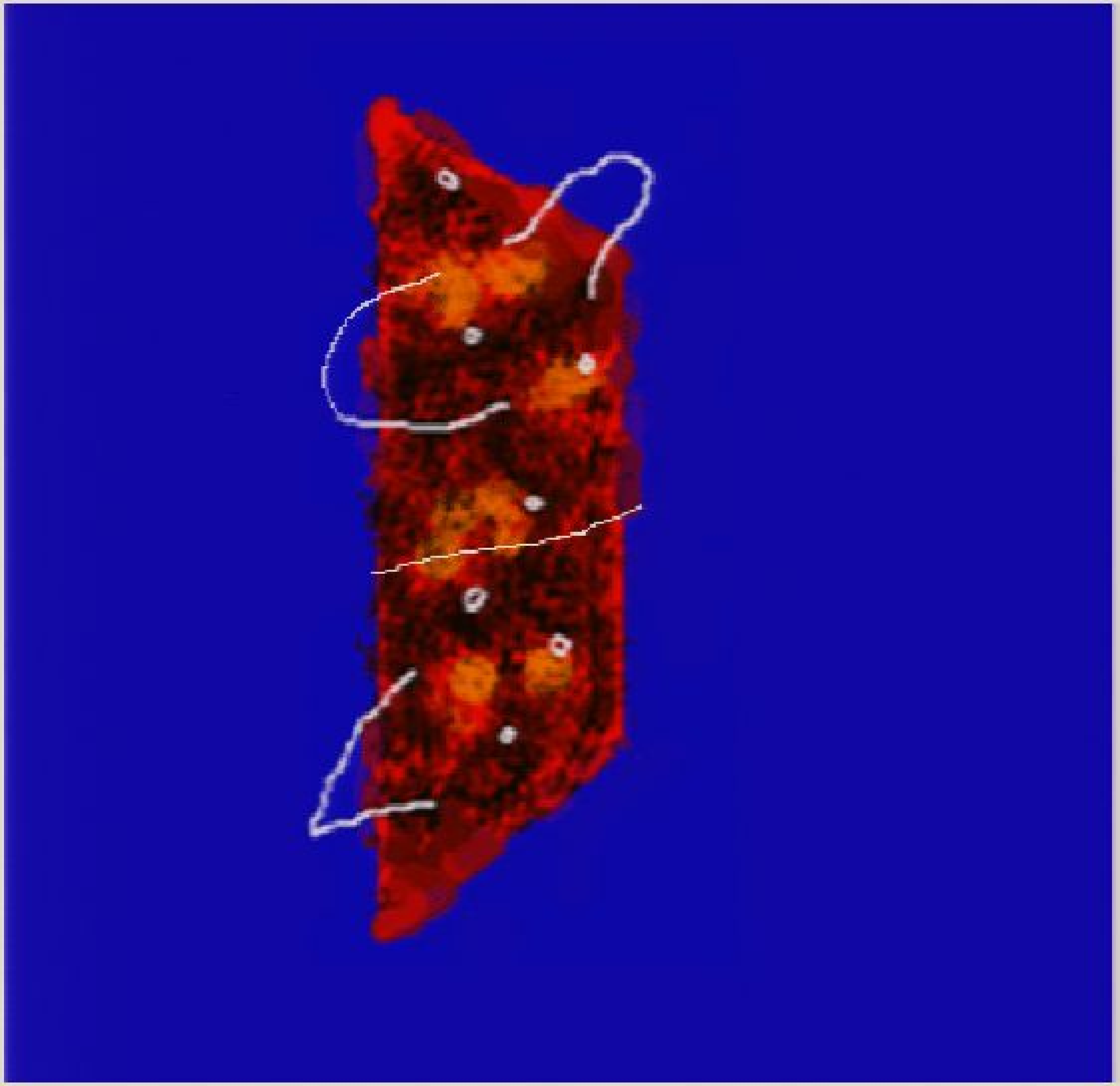


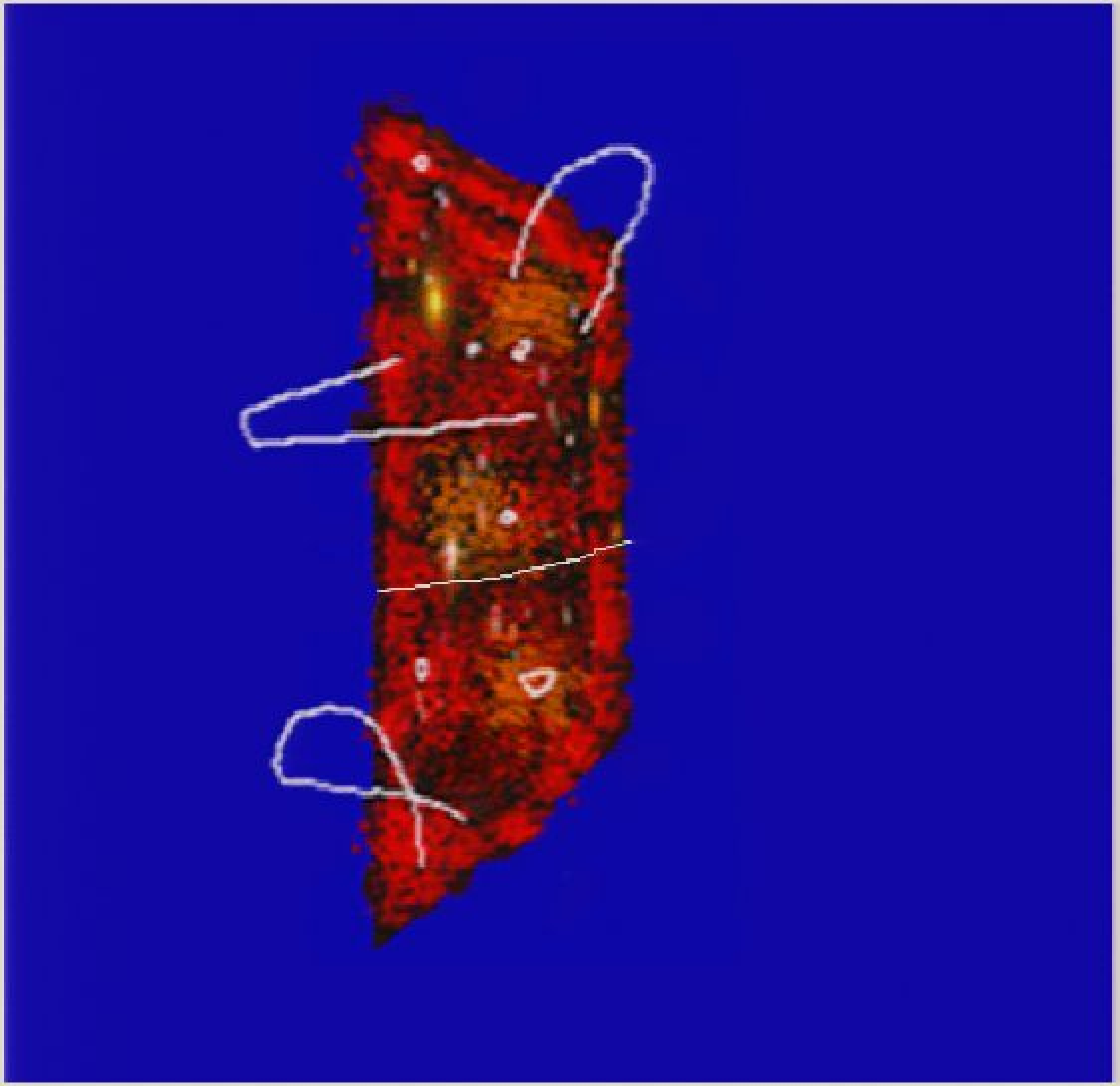


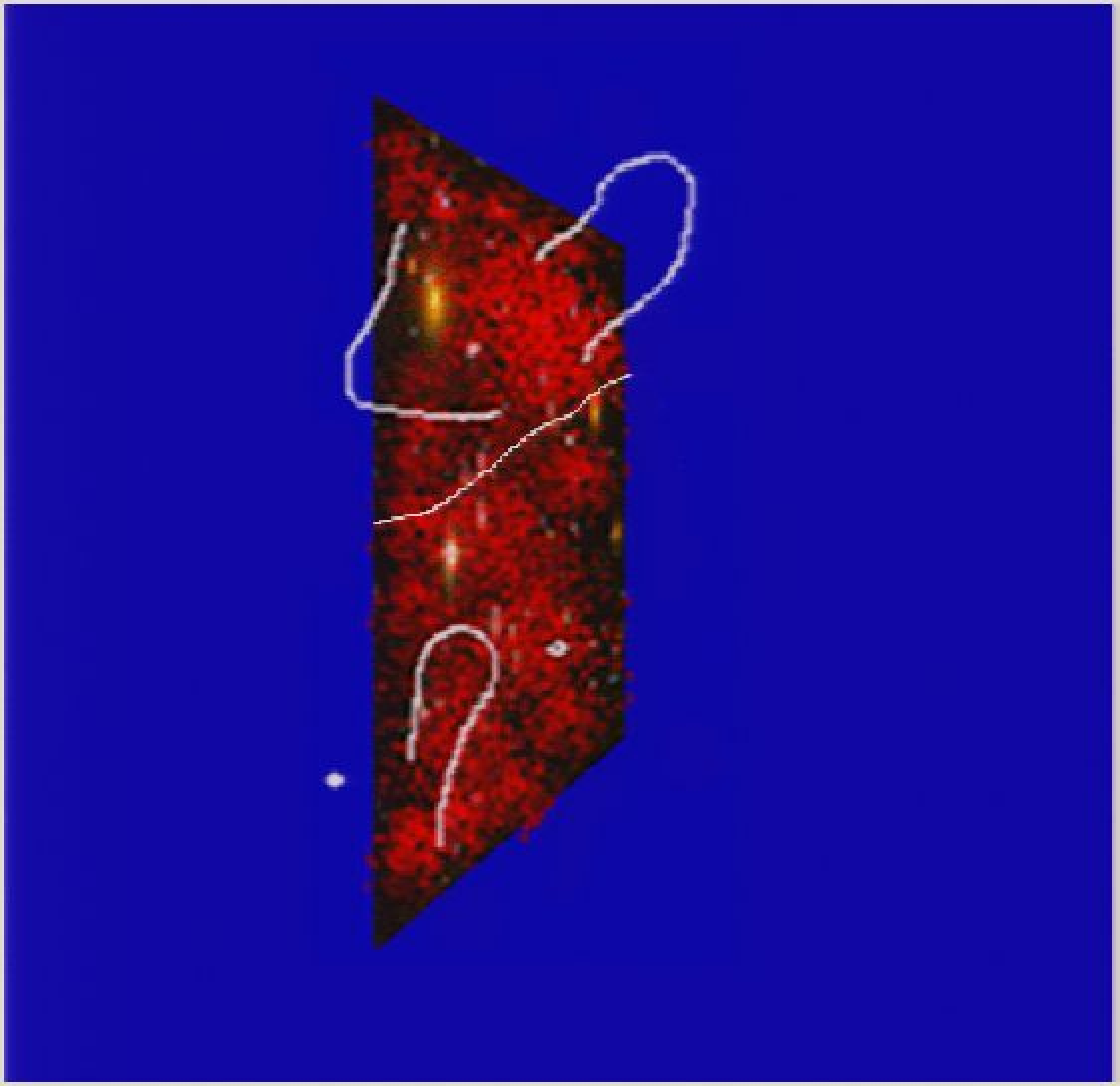


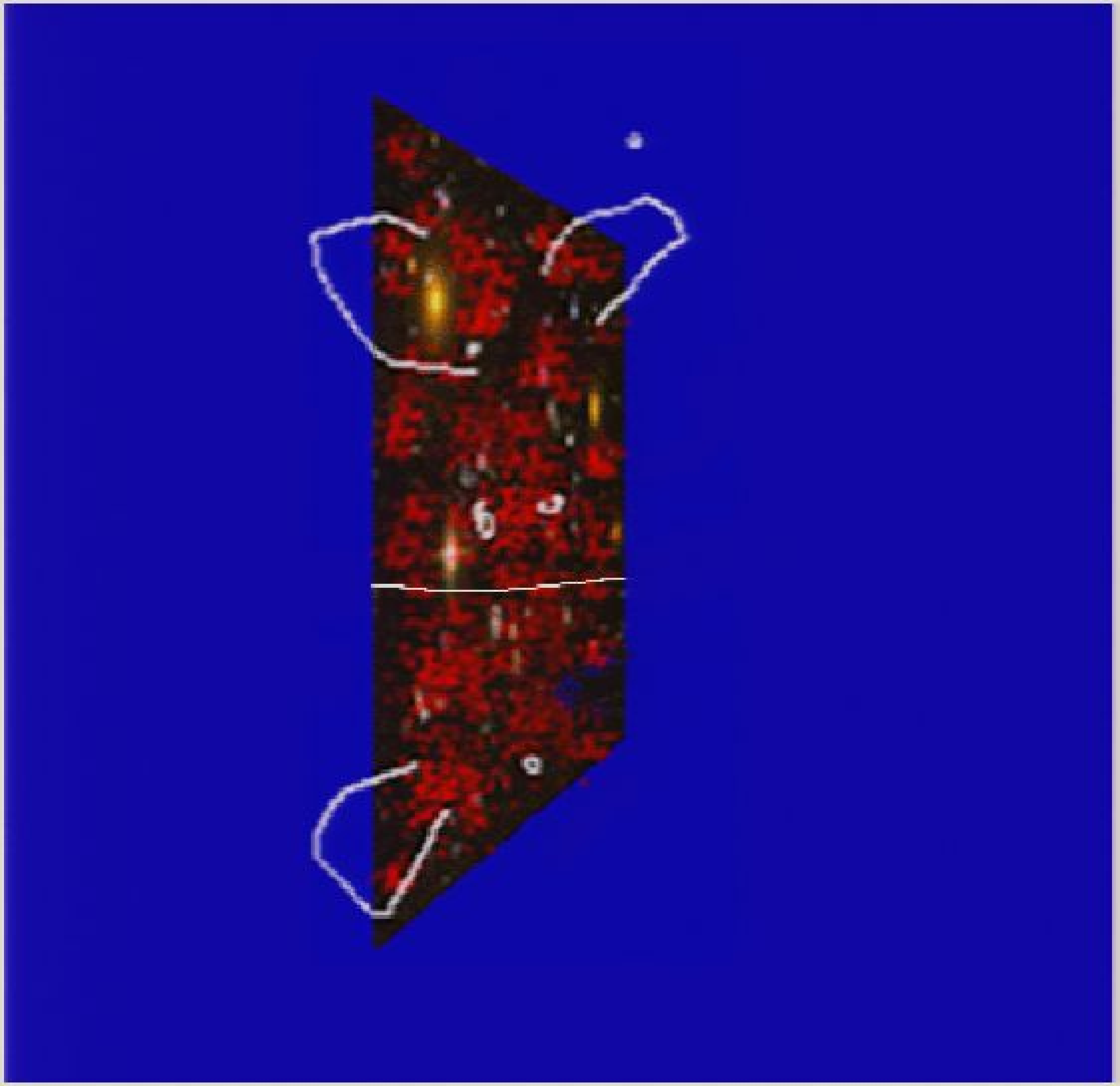


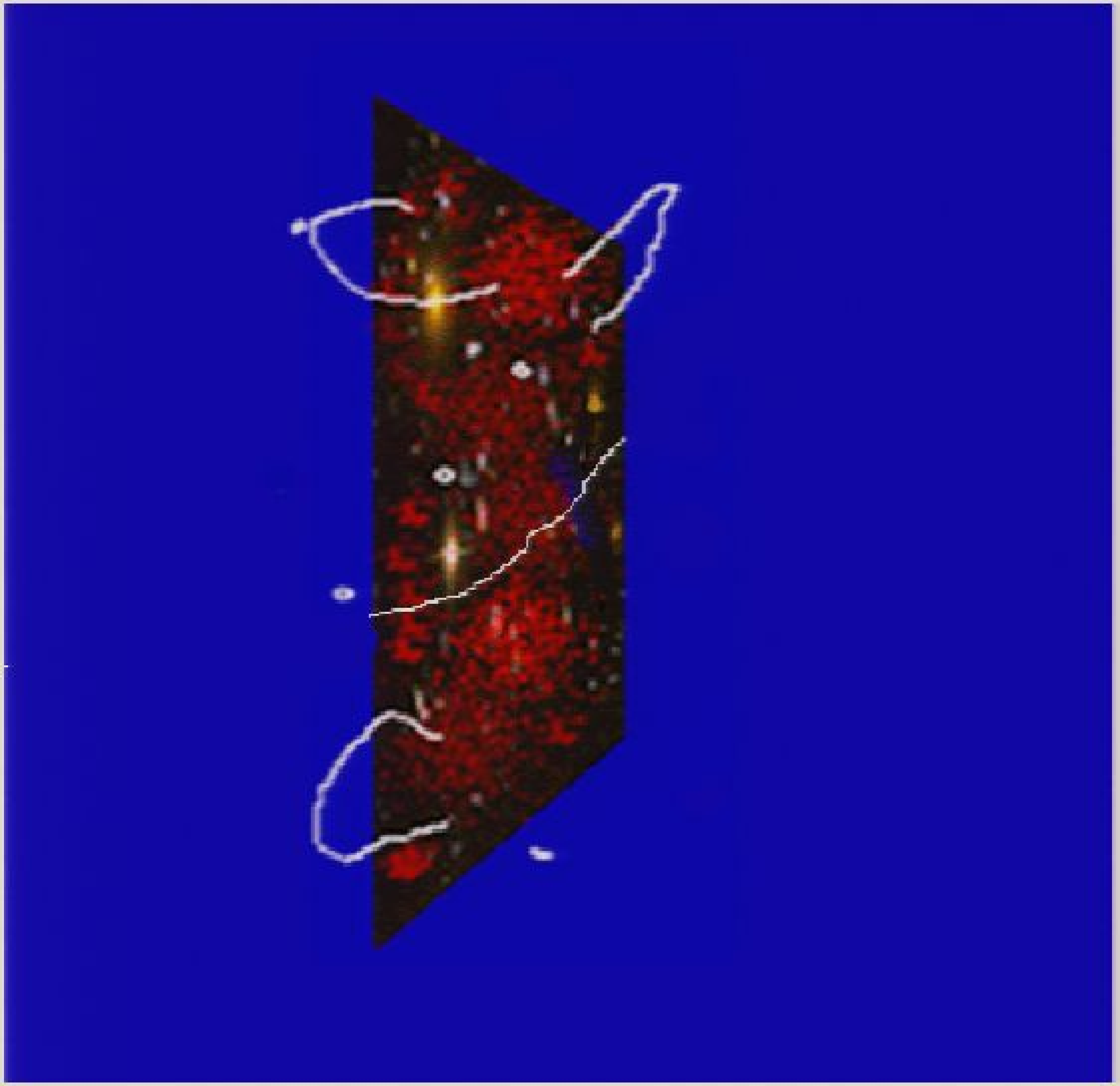










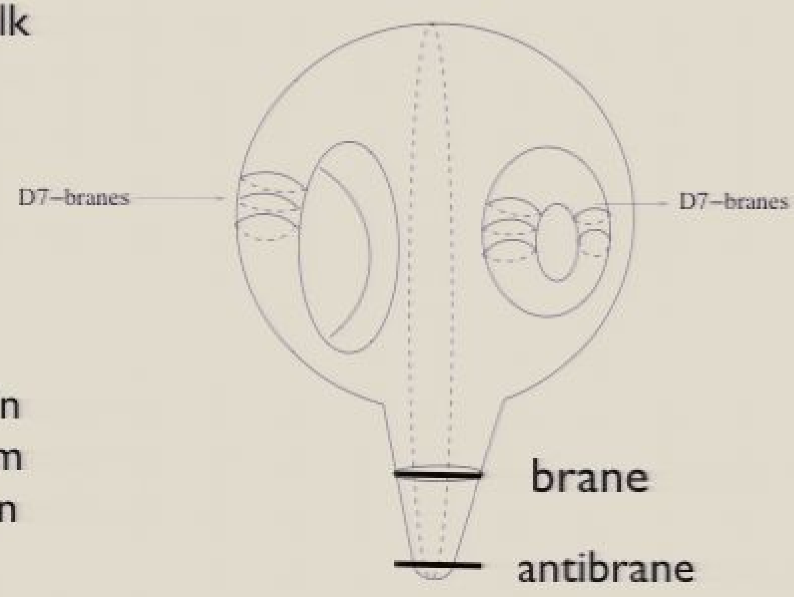


Warped Brane Inflation

- Warped Geometry is a method to flatten the potential between brane and anti-brane. As in Randall-Sundrum, this is achieved with the help of warp factor.

- There are localized regions in the bulk of the Calabi-Yau compactification which are highly warped. These regions are called the throats. Usually there are many of them.

- By putting the brane and anti-brane in these throats the force between them becomes weaker and enough inflation can be obtained.
  (KKLMMT: hep-th/0308055)



- In the presence of warped geometry, the potential is:

$$V = V_K + V_A + V_{D\bar{D}} = \frac{1}{2}\beta H^2 \phi^2 + 2T_3 h_A^4 (1 - \frac{1}{N_A}\frac{\phi_A^4}{\phi^4})$$

- In the absence of VK the slow-roll conditions can be satisfied easily.

- However, one can not neglect the effect of volume modulus.

$$\beta \sim 1 \qquad \eta \sim 1$$

- In this case the slow-roll condition is violated.

- It was argued in KKLMMT that in general a fine-tuning of 0.01 is required to allow for slow-roll conditions.

Cosmic Strings in Brane Inflation

- At the end of brane inflation cosmic strings are copiously produced S. Sarangi and H. Tye, hep-th/0204074.

- They can be detected via lensing, their effects on CMB or by gravitational wave bursts.

- The most important quantity in cosmic strings observations is their tension in term of Planck mass, $G\mu$. Recent constraints from WMAP puts the upper bound:

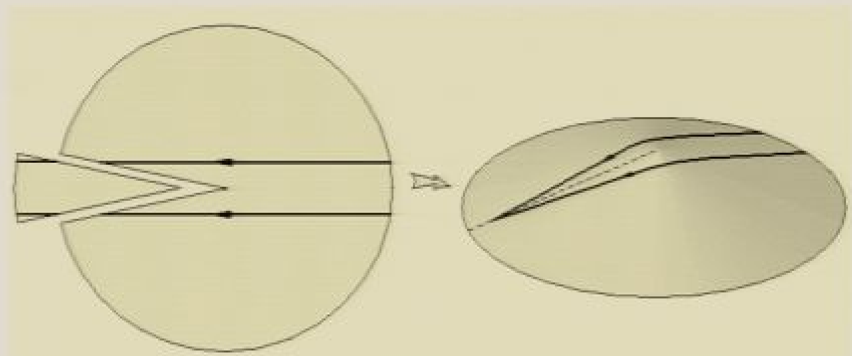
$$G\mu \leq 3 \times 10^{-7}$$

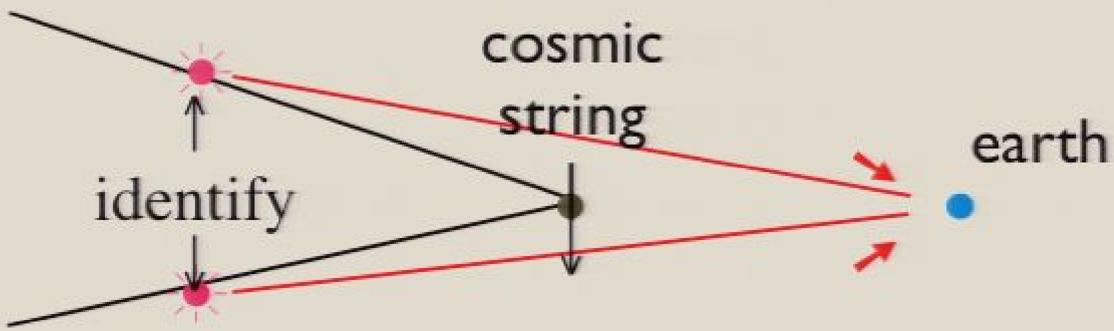
- In KKLMMT, they neglected the effect of V_k, the contribution from volume modulus. This is equivalent to $\beta = 0$.

- In this case they obtained $G\mu = 4 \times 10^{-10}$.

Lensing by Cosmic Strings

- A cosmic string produces a deficit angle in nearby space.





Cosmic Strings Tension

H. F. and H. Tye, hep-th/0501099

The slow roll analysis in the presence of β

$$\eta = M_P^2 \frac{V''}{V} = \frac{\beta}{3} - \frac{20}{N_A} \frac{{M_P}^2 \phi_A^4}{\phi^6}$$

Slow-roll ends when $\eta \sim -1$ which gives

$$\phi_f^6 = \frac{1}{(1+\beta/3)} \left(\frac{20}{N_A} M_P^2 \phi_A^4 \right)$$

The original value of inflaton field is $\phi_i^6 = \frac{24 N_e}{N_A} M_P^2 \phi_A^4 \, \Omega(\beta)$

where

$$\Omega(\beta) \simeq \frac{e^{2\beta N_e} - 1}{2\beta N_e} .$$

The COBE normalization:
$$\delta_H \equiv \frac{1}{\sqrt{75}\pi}\frac{1}{M_P^3}\frac{V^{\frac{3}{2}}}{V'} = \left(\frac{2^{11}}{3\times 5^6\times\pi^4}\right)^{\frac{1}{6}} N_e^{\frac{5}{6}}\left(\frac{T_3}{M_P^4}h_A^4\right)^{\frac{1}{3}} f(\beta)^{-\frac{2}{3}}$$

where

$$f(\beta) \simeq \left[\frac{2\beta N_e}{e^{2\beta N_e}-1}\right]^{5/4} e^{3\beta N_e}$$

The cosmic string tension:
$$G\mu = \left(\frac{3\times 5^6\times\pi^2}{2^{21}}\right)^{1/4} g_s^{-1/2}\,\delta_H{}^{3/2}\,N_e^{-5/4}\,f(\beta) = G\mu_0\,f(\beta)$$

The scalar spectrum index:
$$n_s - 1 \simeq 2\eta - 6\epsilon \simeq \frac{2\beta}{3} - \frac{5}{3N_e}\frac{1}{\Omega(\beta)}$$

The constraints on β

WMAP I:

$$n_s \leq 1.28 \quad \rightarrow \quad \beta \leq .4$$

$$r \leq .89 \quad \rightarrow \quad \beta \leq .22$$

WMAP I & 2dFGRS & Lyman alpha :

$$n_s \leq 1.086 \quad \rightarrow \quad \beta \leq 1/7$$

Cosmic strings : $$G\mu \leq 5 \times 10^{-7} \quad \rightarrow \quad \beta \leq 1/7$$

WMAP III : $$n_s \leq 1 \quad \rightarrow \quad \beta \sim 2 \times 10^{-2}$$

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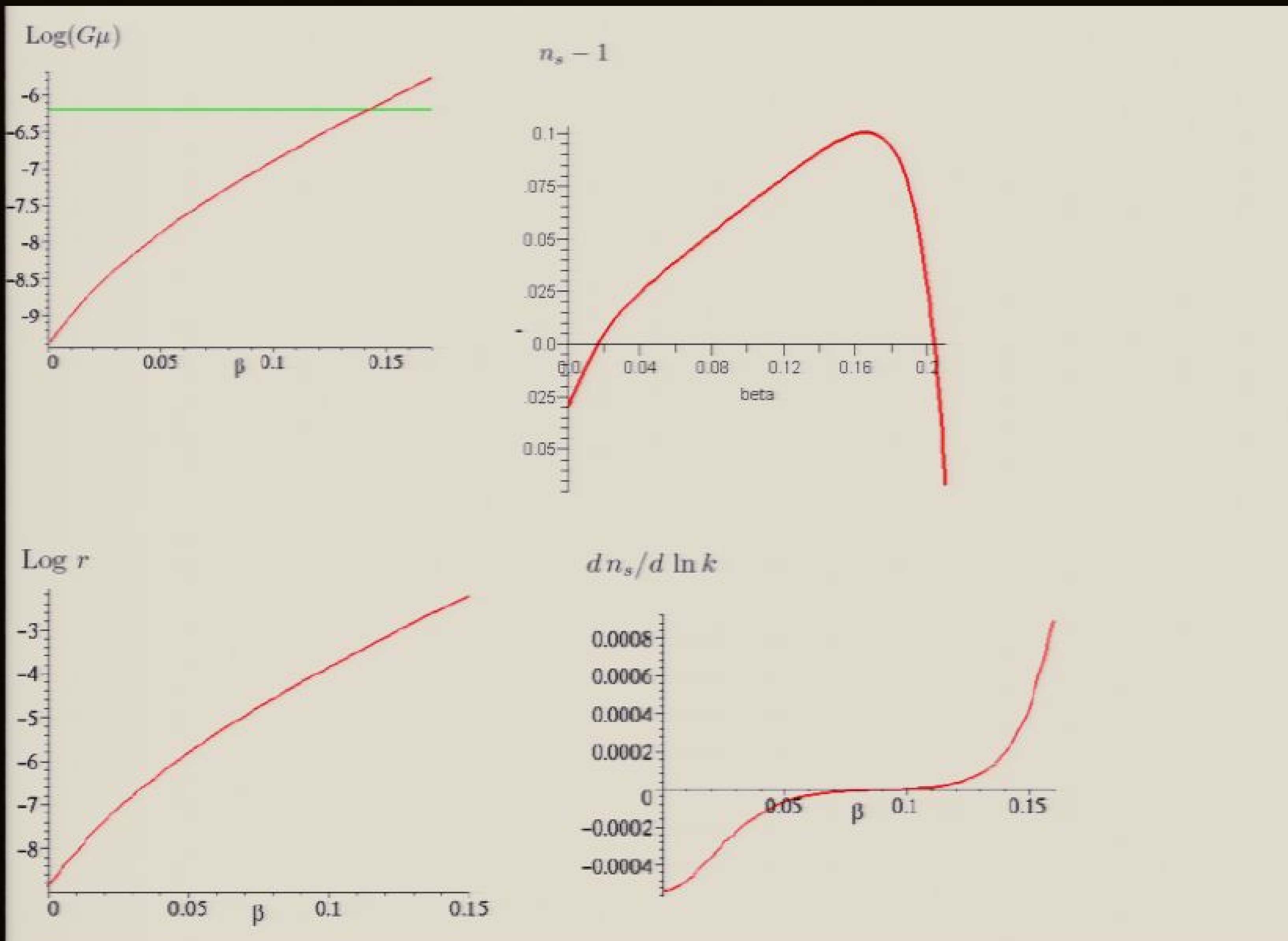

Log(Gμ)
-6
-6.5
-7
-7.5
-8
-8.5
-9
0
0.05
β
0.1
0.15
$n_s - 1$
0.1
.075
0.05
.025
0.0
.025
0.05
0.04
0.08
0.12
0.16
beta
Log r
-3
-4
-5
-6
-7
-8
0
0.05
β
0.1
0.15
$d\,n_s/d\ln k$
0.0008
0.0006
0.0004
0.0002
0
−0.0002
−0.0004
0.05
β
0.1
0.15

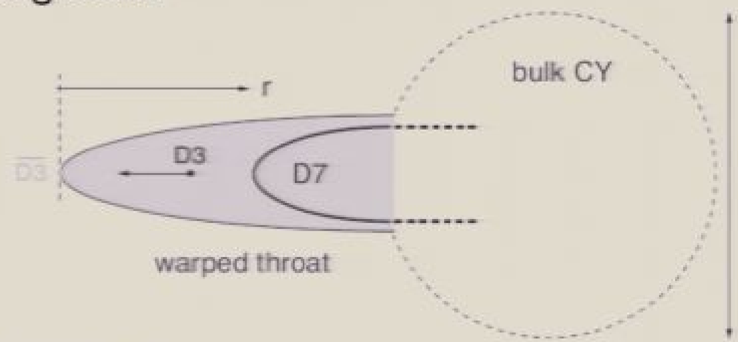
dS vacua without $\overline{\text{D3}}$-brane

hep-th/0610320
C. Burgess, J. Cline, K. Dasgupta and H.F.

The background is similar to Dymarsky-Klebanov-Seiberg , hep-th/0511254 with a resolved conifold. One needs also to take into account the back-reaction effects of D3 and D7-branes into account.

Ouyangn(hep-th/0303024) has considered the effect of wrapped D7-branes on Klebanov-Tsetlin background:

$$e^{-\Phi} = \frac{1}{g_s} - \frac{N_{D7}}{2\pi} \log\left(\frac{r^{3/2}}{\mu}\sin\frac{\theta_1}{2}\,\sin\frac{\theta_1}{2}\right)$$



$$\delta V_O = T_3\left[\sqrt{g}(e^{-\Phi} + \delta e^{-\Phi}) - C_{0123}\right] = T_3\, h^{-1}\delta e^{-\Phi}$$

$$\delta V_O = -\frac{\delta N(\epsilon)}{2\pi}\,\frac{T_3\xi_0^4}{R^2}\left(\frac{r}{r_0}\right)^4 \log\left(\frac{r^{3/2}}{\mu}\sin\frac{\theta_1}{2}\sin\frac{\theta_1}{2}\right) + \mathcal{O}(\epsilon^2)$$

Baumann et al has considered the effects of D3-branes to the background

hep-th/0607050

$$W = W_0 + A(w_i)e^{-a\rho} \qquad A(w_i) = A_0\left(1 - \frac{\prod_{i=1}^4 w_i^{p_i}}{\mu^P}\right)^{1/N_{D7}}$$

The total potential is V = V_{KKLT} + δV_F + δV_O

$$\delta V_F = V_1 \sin^2 \tfrac{1}{2}\theta + V_2 \sin^4 \tfrac{1}{2}\theta$$

$$\delta V_O = V_O \log\left(\frac{r^{3/2}}{\mu}\sin^2 \tfrac{1}{2}\theta\right) \; + \; \mathcal{O}(\epsilon^2)$$

$$V_O = -\frac{\delta N(\epsilon)}{2\pi}\frac{T_3\,\xi_0^4}{R^2}\left(\frac{r}{r_0}\right)^4$$

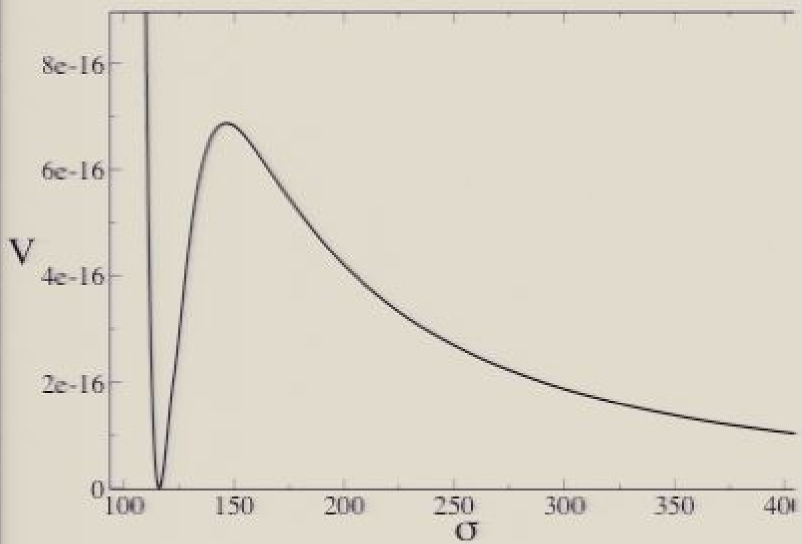
$$V_1 = \frac{\kappa_4^2\,A_0^2\,r\,e^{-2a\sigma}}{3\,\mu^2\,c\,R^2}\left(3 - a\,\mu\,c\,\sqrt{r}\cos\tfrac{1}{2}\tilde{\psi}\,\left(9 + 4\,a\,\sigma + 6\tfrac{W_0}{A}e^{a\sigma}\right)\right)$$

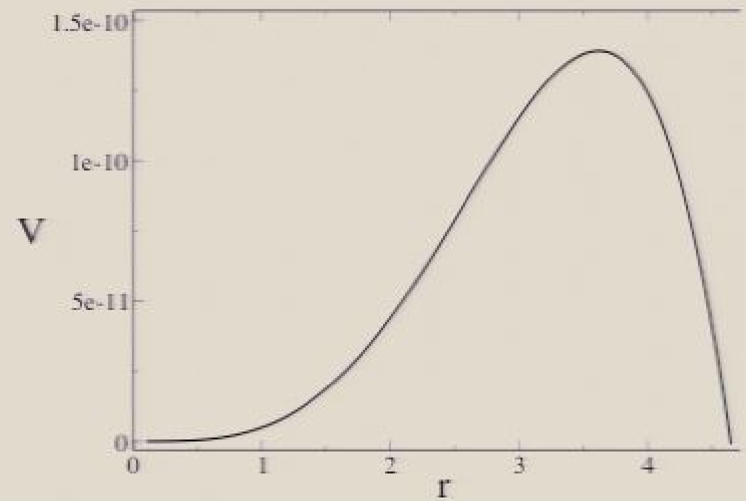
$$V_2 = \frac{\kappa_4^2 A_0^2\,r\,e^{-2a\sigma}}{12\,\mu^2\,c\,R^2}\left(-3 + a\,c\,r^2\,(12 + 8\,a\,\sigma)\right)$$

Finding the stable solution for polar coordinates $\sin^2\left(\frac{1}{2}\theta\right) = -\frac{V_O}{V_1} = \frac{|V_O|}{V_1}$

The potential is

$$V(r) = |V_O|\left[1 - \frac{|V_O|}{V_1}\log\left(\frac{r^{3/2}}{\mu}\right)\right] + V_{KKLT}$$





$A_0 = 1,\ a = 0.1,\ W_0 = -10^{-4}, \quad r_0 = 0.1$

$\delta N(\epsilon)\xi_0^4 T_3 = 7.3 \times 10^{-11}$

Baumann et al has considered the effects of D3-branes to the background

hep-th/0607050

$$W = W_0 + A(w_i)e^{-a\rho} \qquad A(w_i) = A_0\left(1 - \frac{\prod_{i=1}^4 w_i^{p_i}}{\mu^P}\right)^{1/N_{D7}}$$

The total potential is V = $V_{KKLT} + \delta V_F + \delta V_O$

$$\delta V_F = V_1 \sin^2 \tfrac{1}{2}\theta + V_2 \sin^4 \tfrac{1}{2}\theta$$

$$\delta V_O = V_O \log\left(\frac{r^{3/2}}{\mu} \sin^2 \tfrac{1}{2}\theta\right) \; + \; \mathcal{O}(\epsilon^2)$$

$$V_O = -\frac{\delta N(\epsilon)}{2\pi} \frac{T_3 \xi_0^4}{R^2} \left(\frac{r}{r_0}\right)^4$$

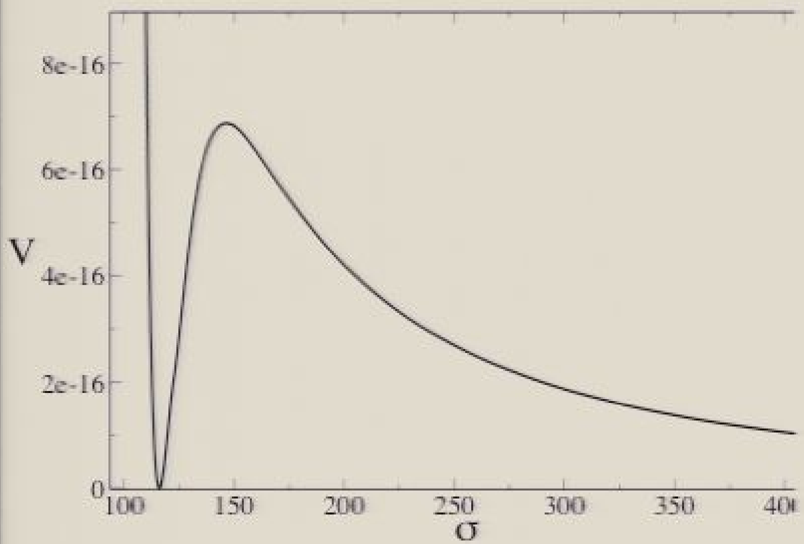
$$V_1 = \frac{\kappa_4^2 A_0^2 \, r \, e^{-2a\sigma}}{3\,\mu^2\, c\, R^2} \left(3 - a\,\mu\, c\,\sqrt{r}\cos\tfrac{1}{2}\tilde{\psi}\,\left(9 + 4\,a\,\sigma + 6\tfrac{W_0}{A}e^{a\sigma}\right)\right)$$

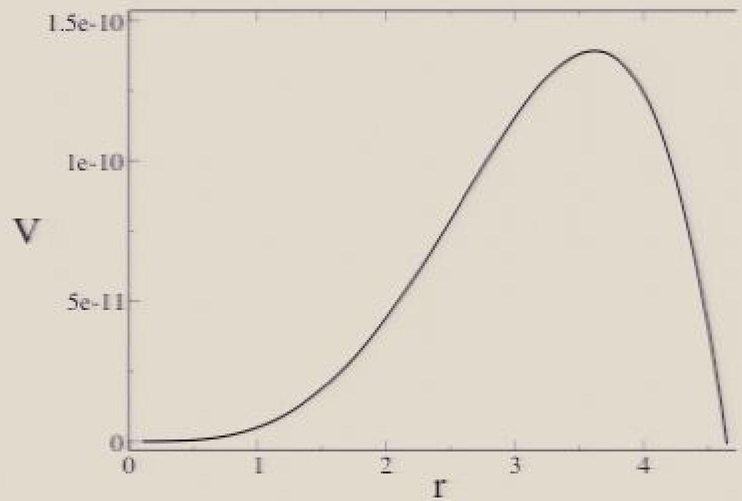
$$V_2 = \frac{\kappa_4^2 A_0^2 \, r \, e^{-2a\sigma}}{12\,\mu^2\, c\, R^2} \left(-3 + a\, c\, r^2\,(12 + 8\,a\,\sigma)\right)$$

Finding the stable solution for polar coordinates $\sin^2\left(\frac{1}{2}\theta\right) = -\frac{V_O}{V_1} = \frac{|V_O|}{V_1}$

The potential is

$$V(r) = |V_O|\left[1 - \frac{|V_O|}{V_1}\log\left(\frac{r^{3/2}}{\mu}\right)\right] + V_{KKLT}$$





$A_0 = 1,\ a = 0.1,\ W_0 = -10^{-4}, \quad r_0 = 0.1.$

$$\delta N(\epsilon)\xi_0^4 T_3 = 7.3 \times 10^{-11}$$

Conclusion

- All observations strongly support the inflationary scenario. However, the origin of inflaton filed is not known from a fundamental theory point of view.
- The brane&anti-brane inflation is an interesting realization of inflation from string theory.
- Cosmic strings are produced at the end of brane inflation. If they are detected, it would be a unique chance to test string theory. Their spectrum is highly non-trivial.
- The back-reaction effects may have important consequences. One may achieve dS vacua without adding anti-brnaes that break susy explicitly.