Title: Tachyon Mediated Non-Gaussianity

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Abstract: I will discuss the various sources of non-Gaussianity (NG) in a class of multi-field models of inflation. I will show that there is both an intrinsic and a local contribution to the NG although they both have the same shape. It is also possible in this class of models that the dominant part to the 3-pt function comes from loop diagrams. These models are of the hybrid type and while they occur naturally in string theory, the conditions for the NG to be important are not generic.

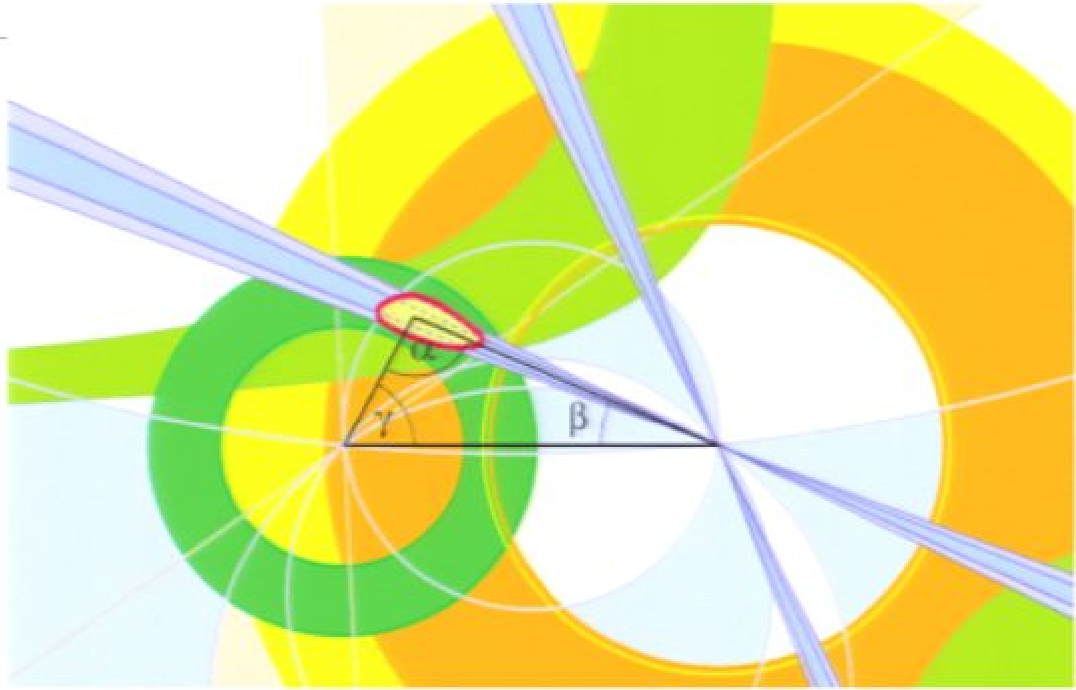
Outline

- General motivation to string cosmology/string phenomenology
- Multi-field effects in hybrid inflation
- Tachyon mediated density perturbations with non-Gaussianity
- D-term inflation as an example

Electroweak Precision Test

10^{19} Gev — Planck, M_p

10^{15} Gev — GUT, inflation



TeV — LHC, Dark Matter

80 GeV — W boson

↓

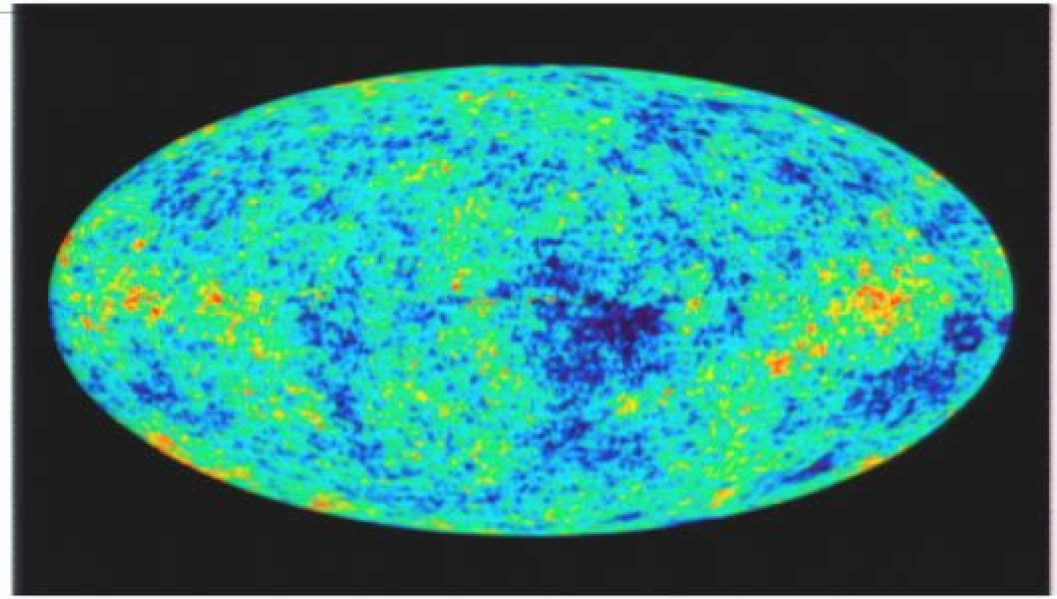
10^{-3} ev — Dark Energy (CC)

We have learned things about TeV scale (e.g. FCNC)

Planck Ceiling

10^{19} Gev — Planck, M_p

10^{15} Gev — GUT, inflation



TeV — LHC, Dark Matter

Cosmological Precision Test?

80 GeV — W boson

10^{-3} ev — Dark Energy (CC)

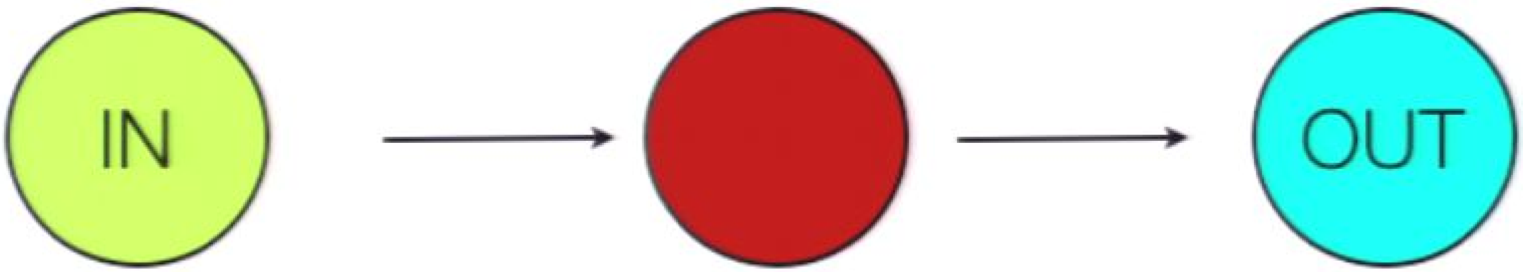
Use cosmology to learn about quantum gravity.

- Inflation and alternatives are very high scale phenomena that are now being probed by cosmological observations. Quantum gravity (Planckian) corrections could be important.
- Stringy signature?? Can we reproduce any inflation models?? What are we learning from string theory??
- Look for UV sensitive quantities in the data: non-Gaussianity, Tensor modes, special properties of cosmic strings....

Here: multi-field set-up to generate NG, tricky to obtain in string theory (most current models do not have it)

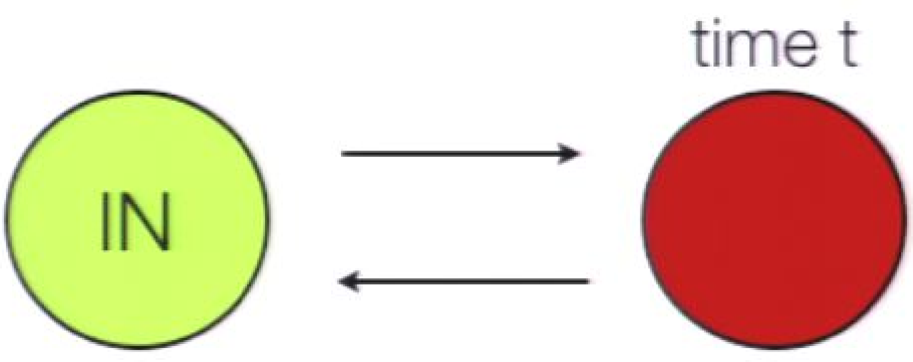
c.f. Erickcek, Shandera

Use particle physics/string theory thinking to learn about cosmology



- Time independent scattering amplitude
- What is it that we are computing in cosmology?

Expectation values... IN-IN formalism, Keldysh-Schwinger



Weinberg

loop calculations
EFT for inflation

Summary and Results

Cosmological Signal, hints of NG in the CMB data with local shape

WMAP5

$$-9 < f_{NL} < 111$$

Komatsu et al
Yadav and Wandelt

Propose a method to generate this signal that utilize the tachyon at the end of brane inflation

cosmo lesson

loop dominated 3-pt function

string lesson

Not generic in string theory models, e.g. that works D-term inflation with cosmic strings

Start with a smooth patch

dark energy
Modeled by a
scalar field

Λ

$$l \sim \frac{1}{\Lambda^{1/4}}$$

$$l \sim [10^{-25} cm, 10^{-29} cm]$$

many models smaller than that

bound from data

Inflate!

Our horizon, anything outside that circle is unobservable unless it comes back in

Quantum fluctuations
(perturbations of the metric)
are amplified and grow

In single field model, the perturbation amplitude
remains constant once the wavelength grows bigger
than the horizon

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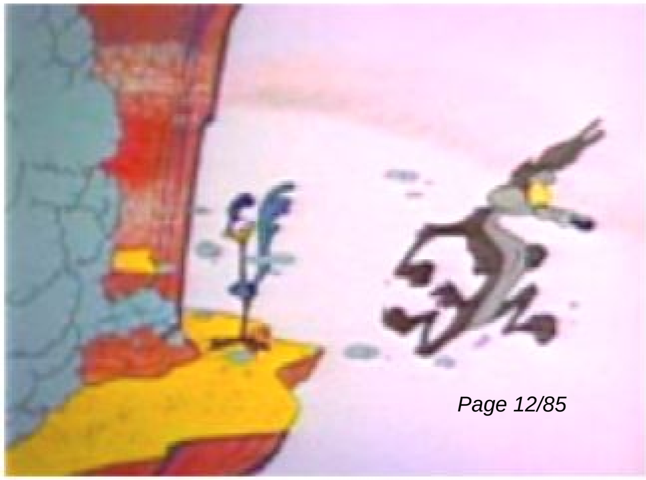
In single field model, the perturbation amplitude remains constant once the wavelength grows bigger than the horizon

Brane Inflation, a lab to study planck physics and early universe.

- Inflaton is an open string mode, position or deformation of branes.
- Gives a geometric interpretation of inflation
- Inflation often ends when the brane annihilate or recombine

“Graceful Exit”



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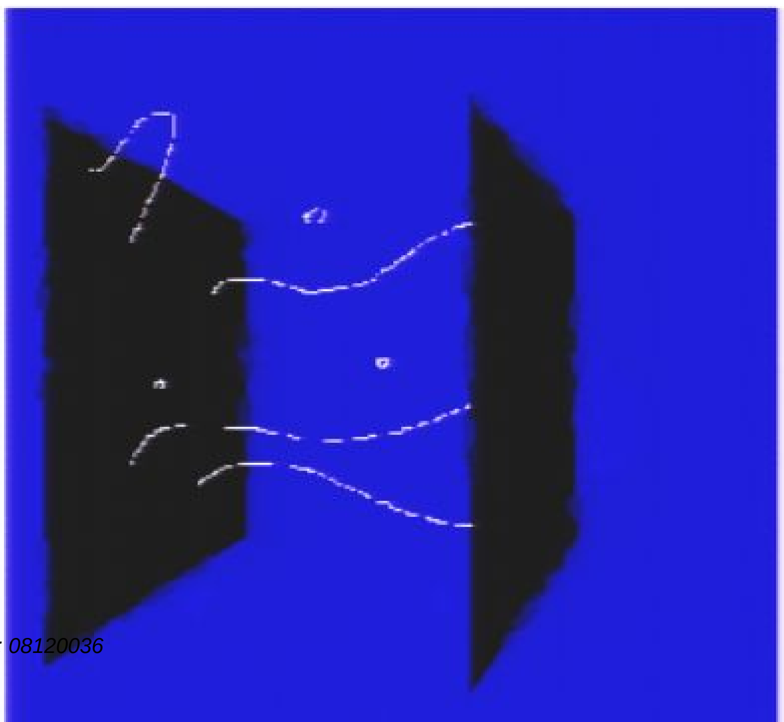

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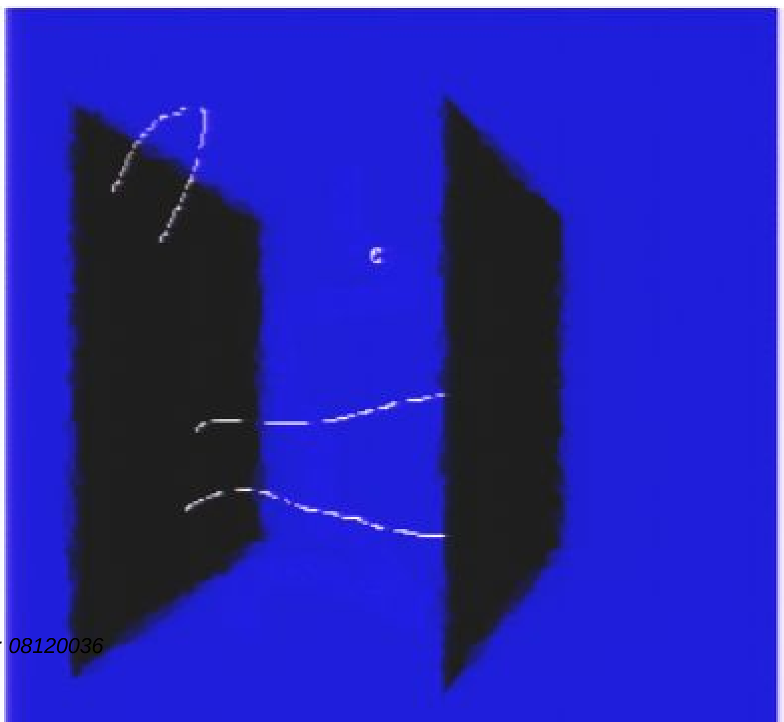

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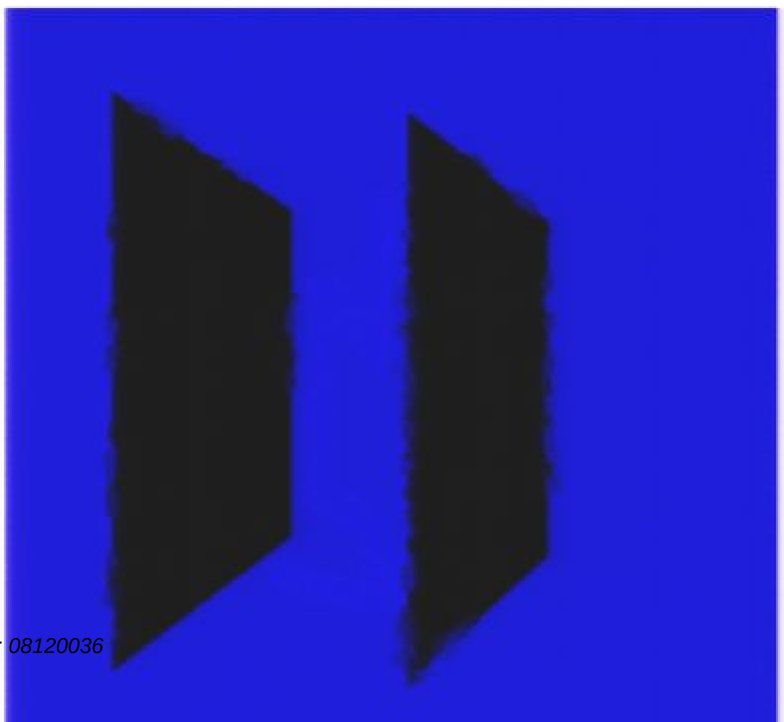

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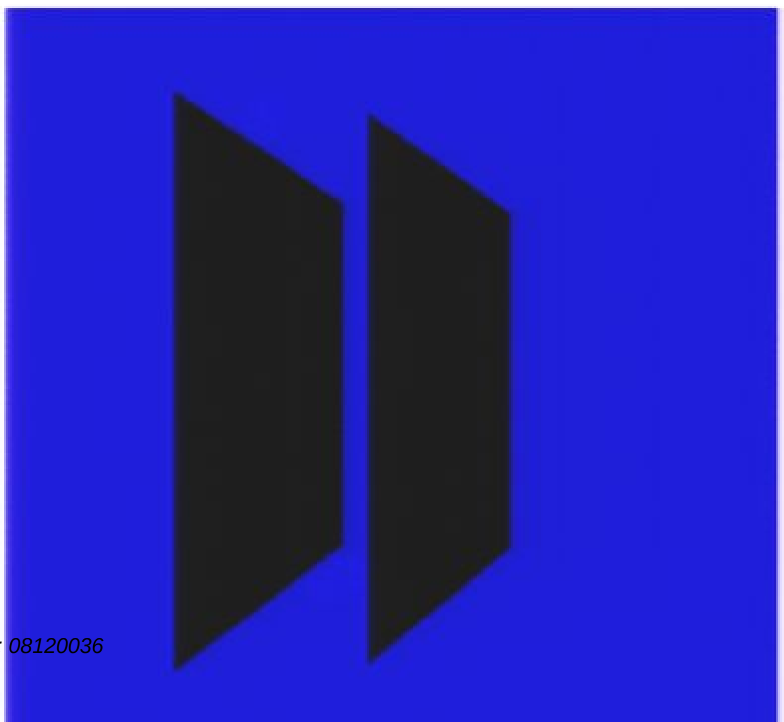

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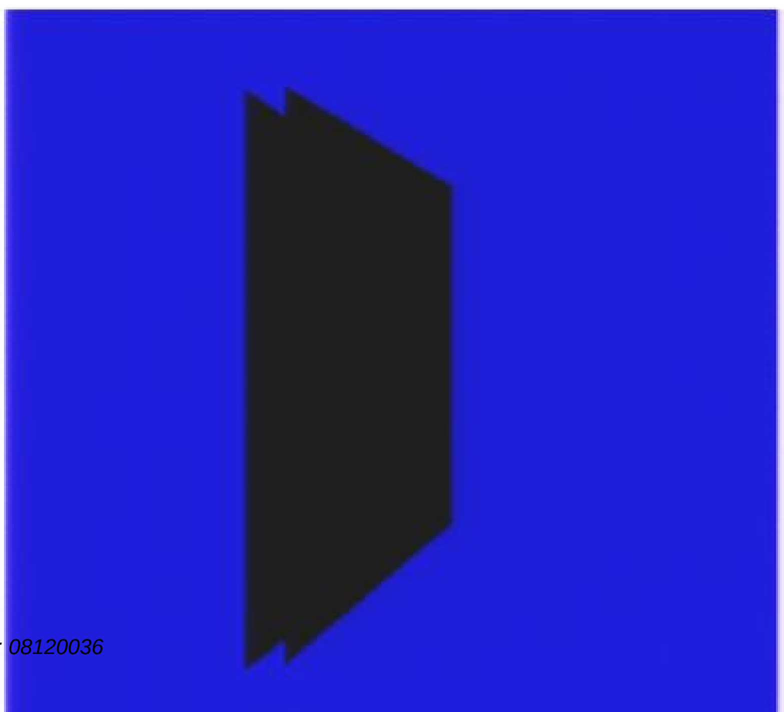

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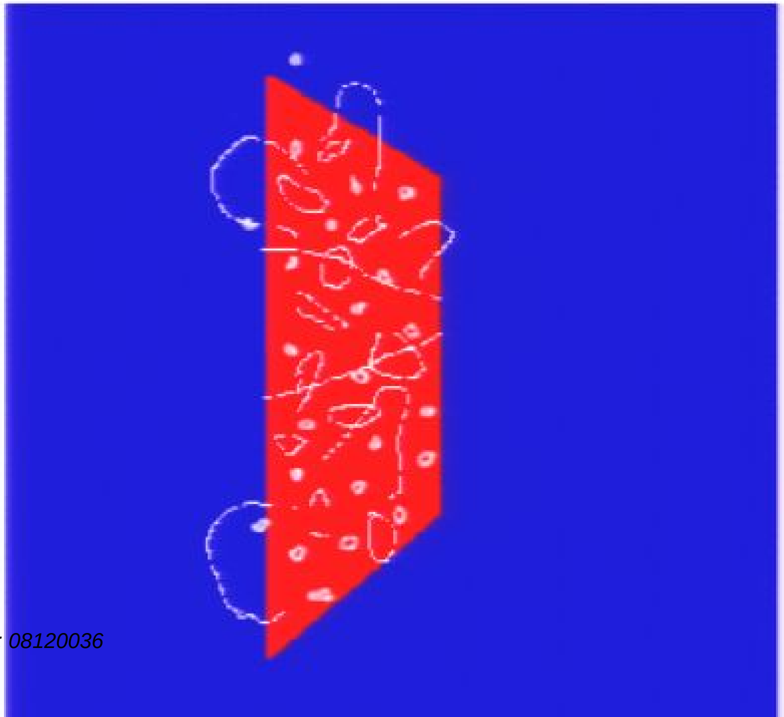

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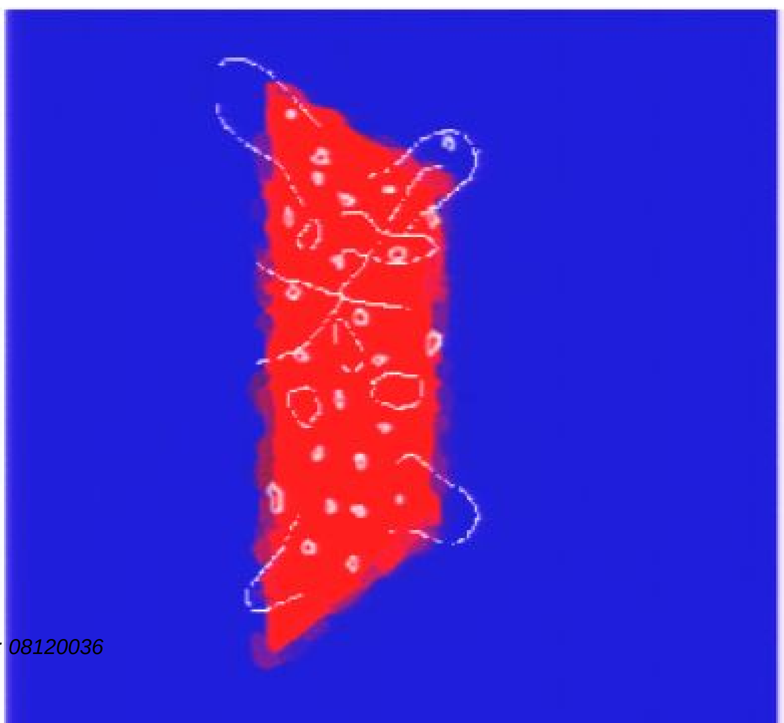

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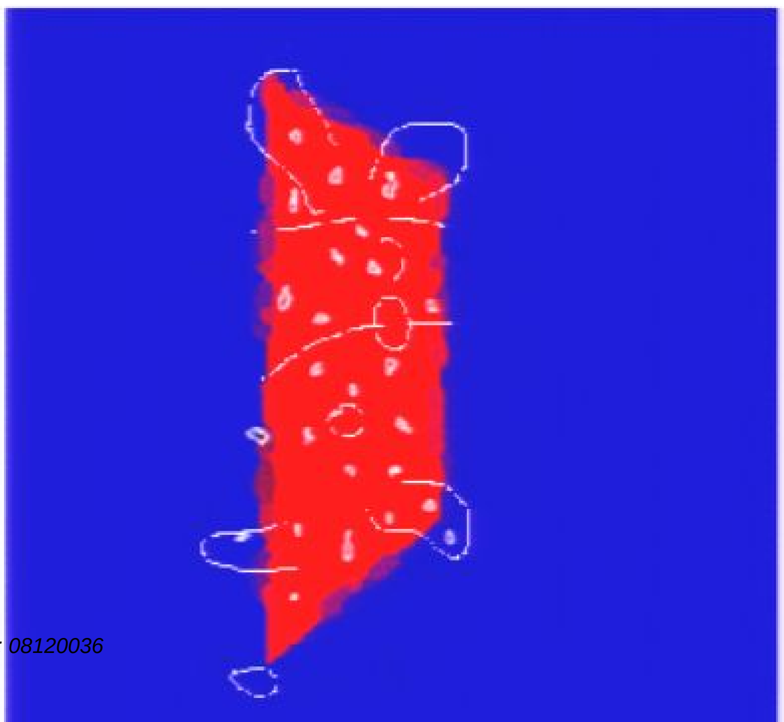

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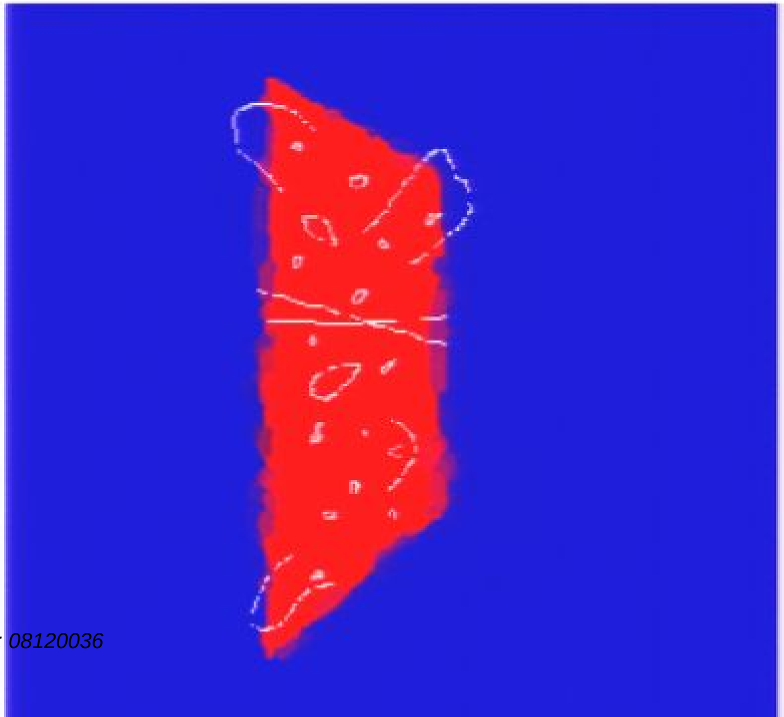

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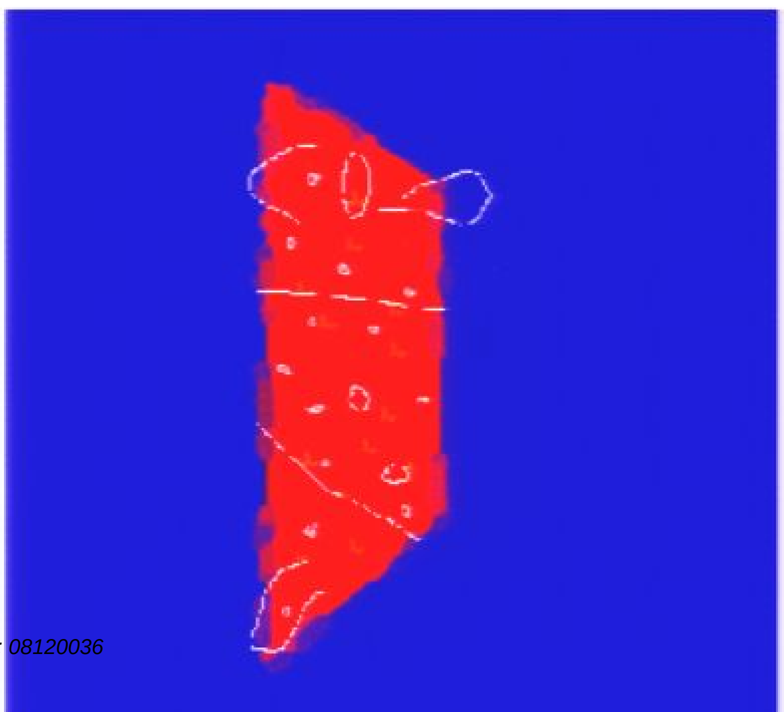

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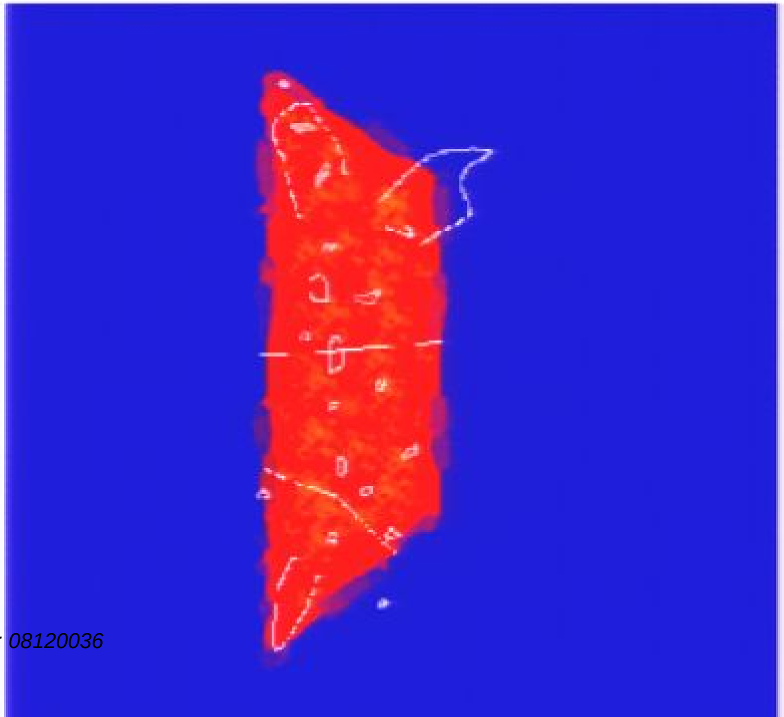

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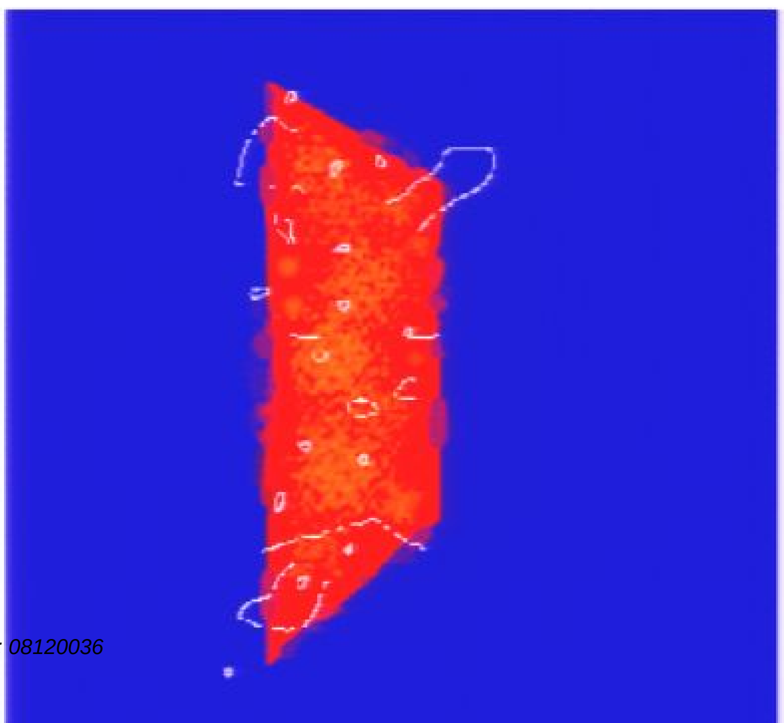

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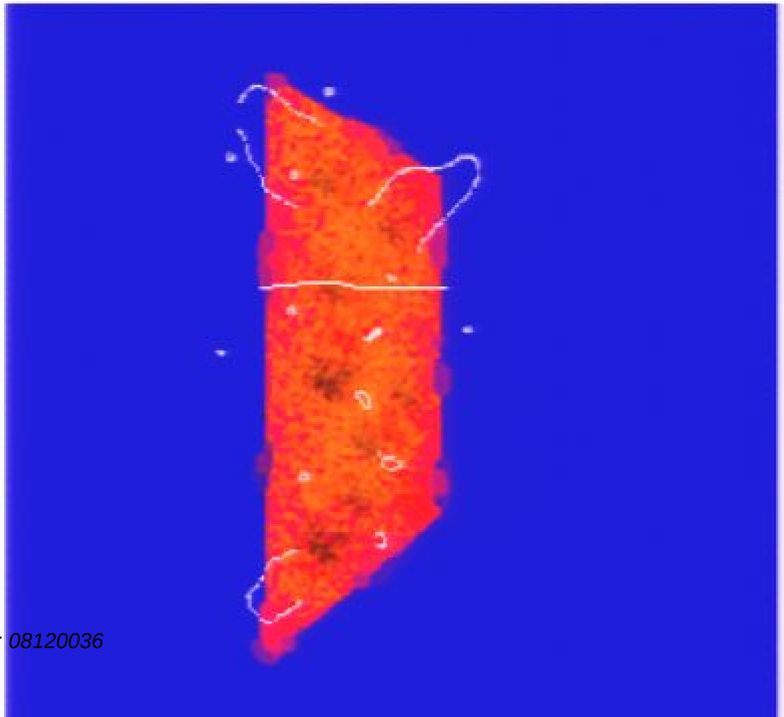

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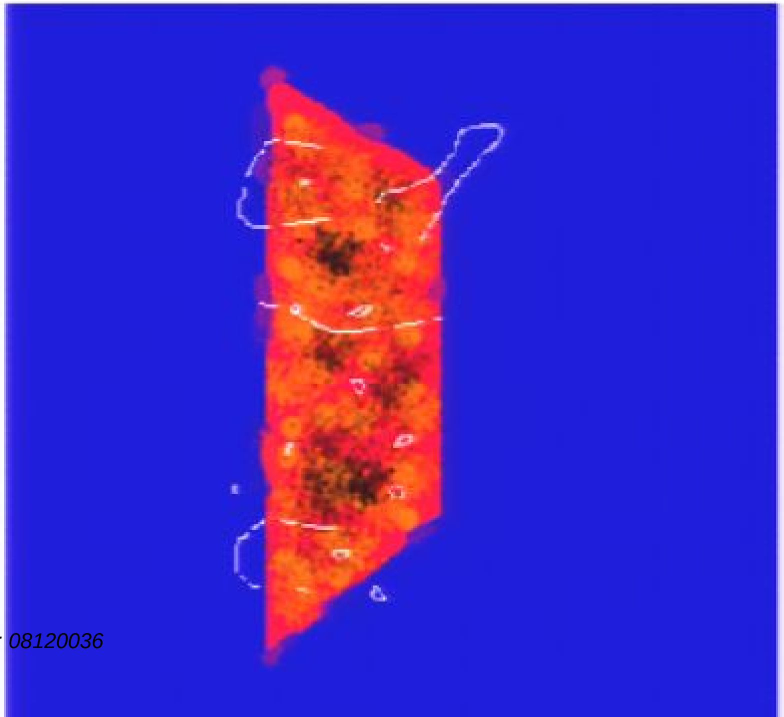

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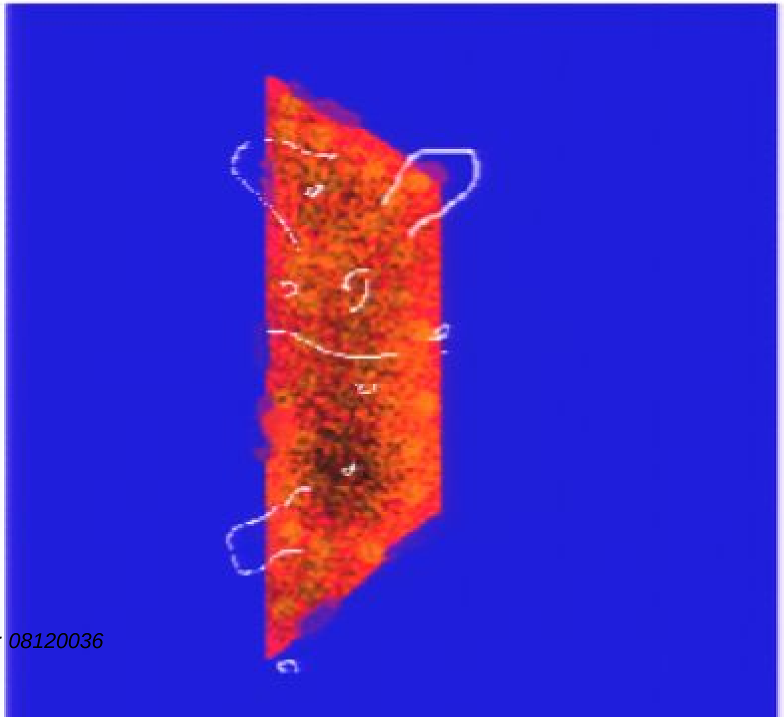

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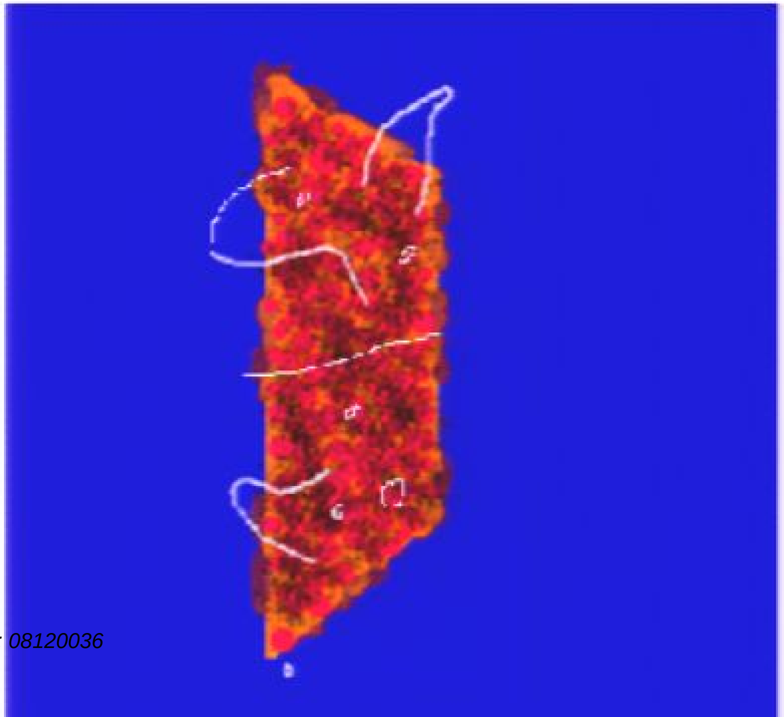

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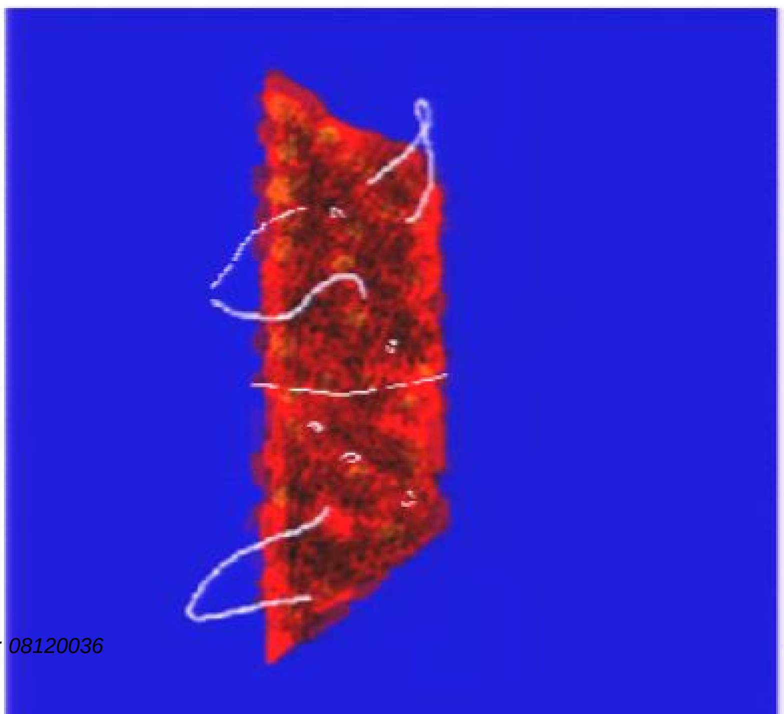

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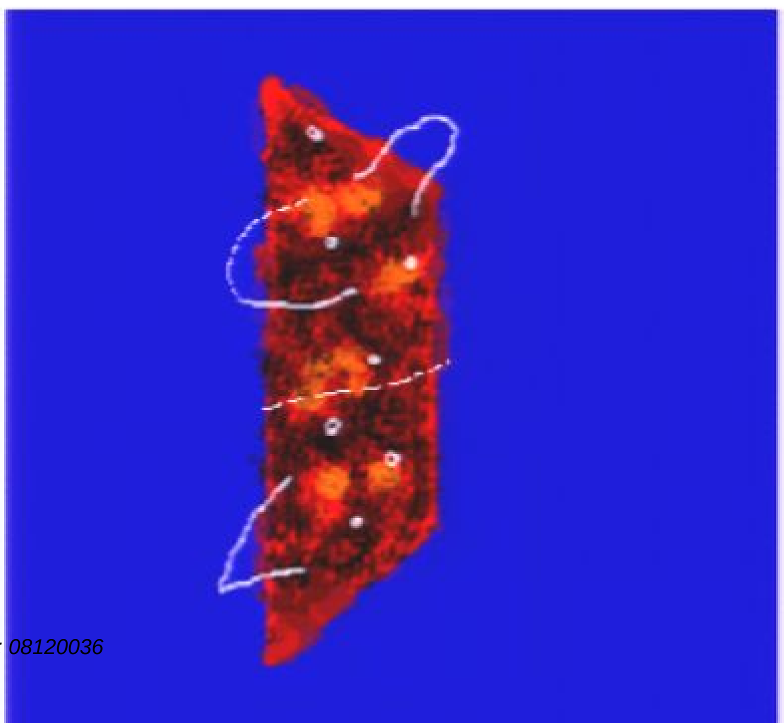

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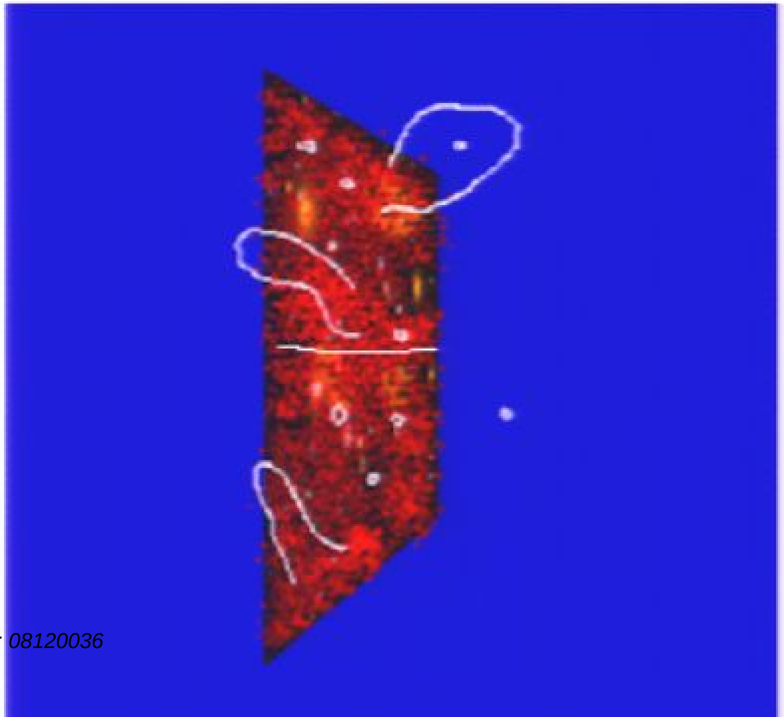

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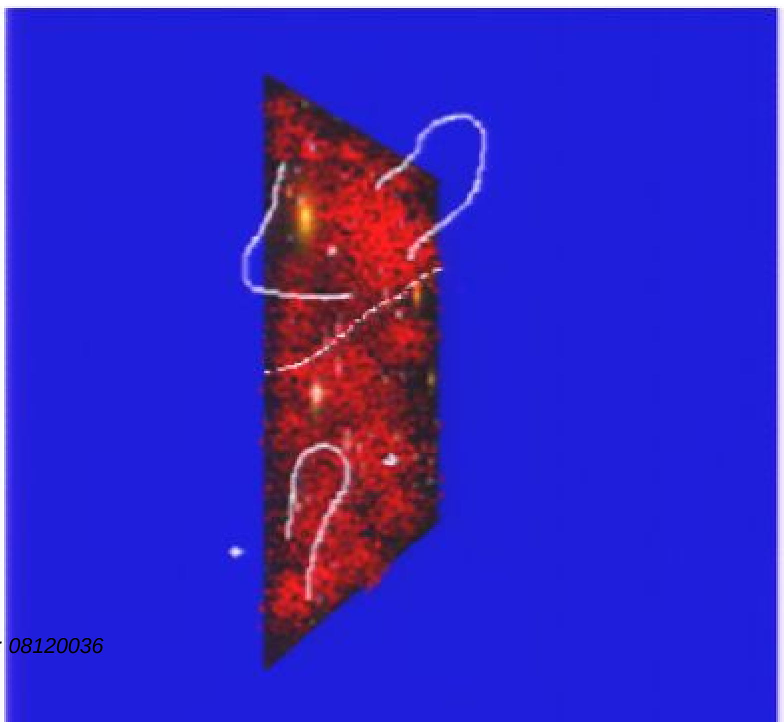

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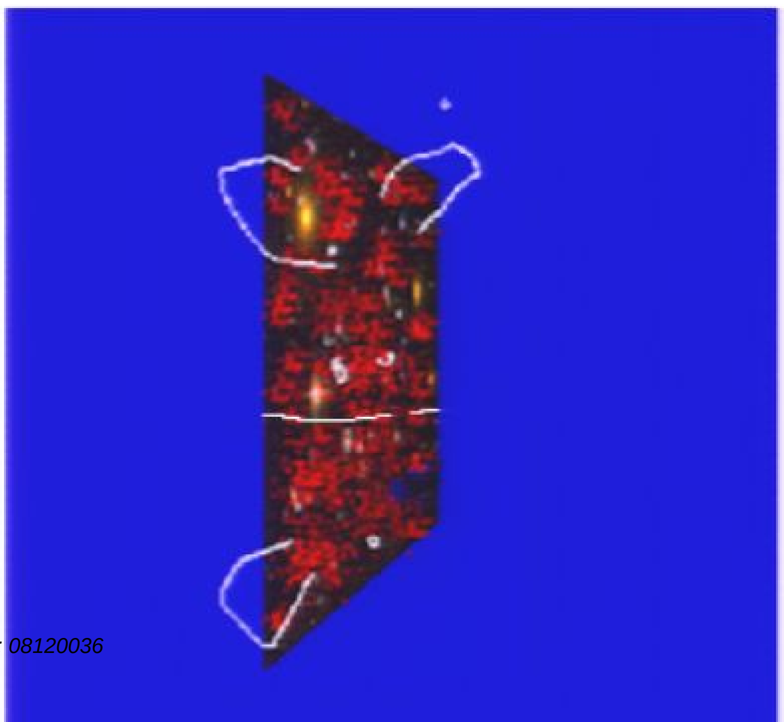

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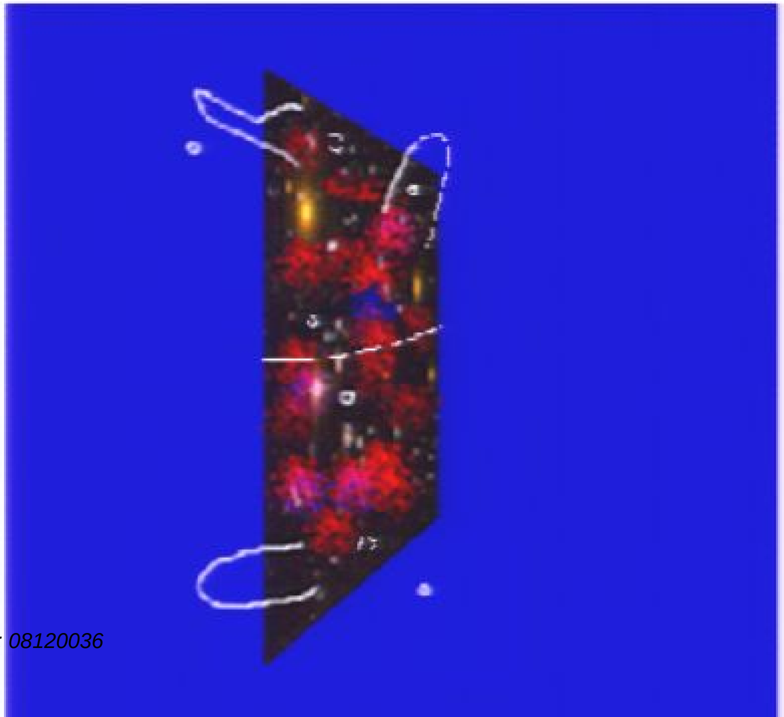

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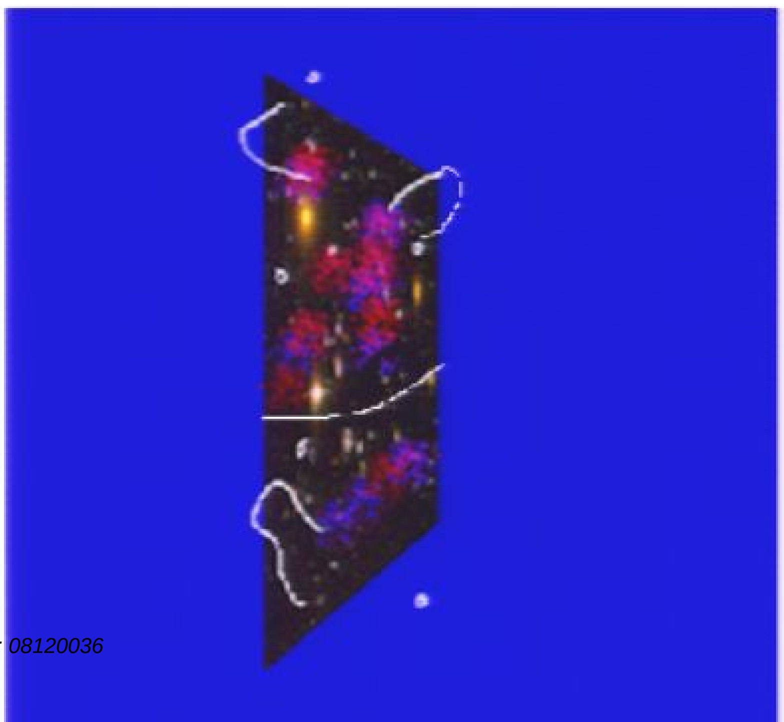

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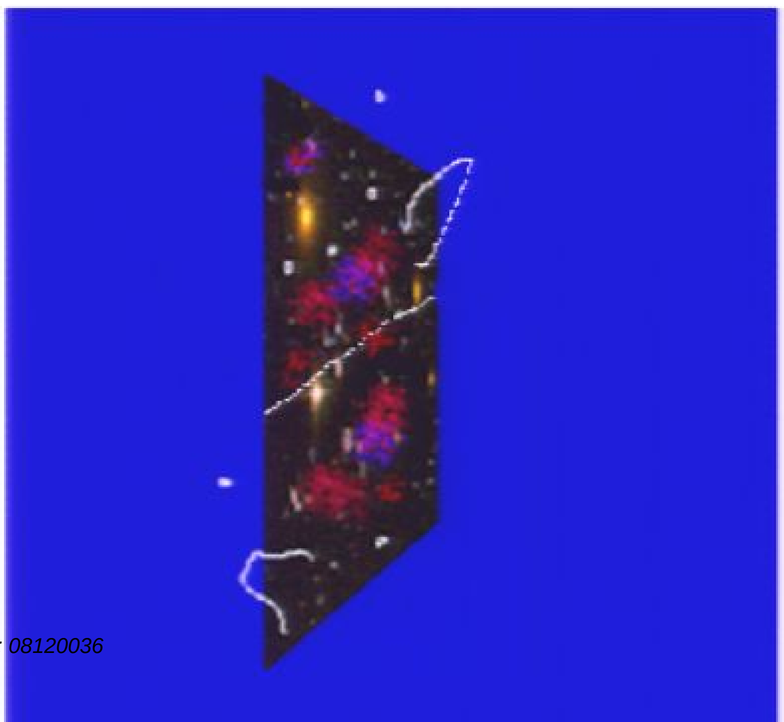

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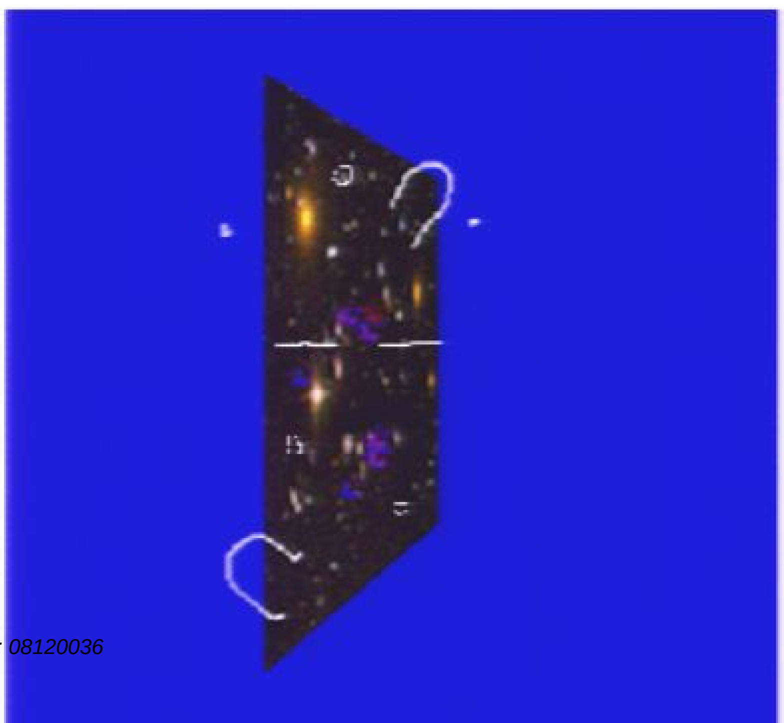

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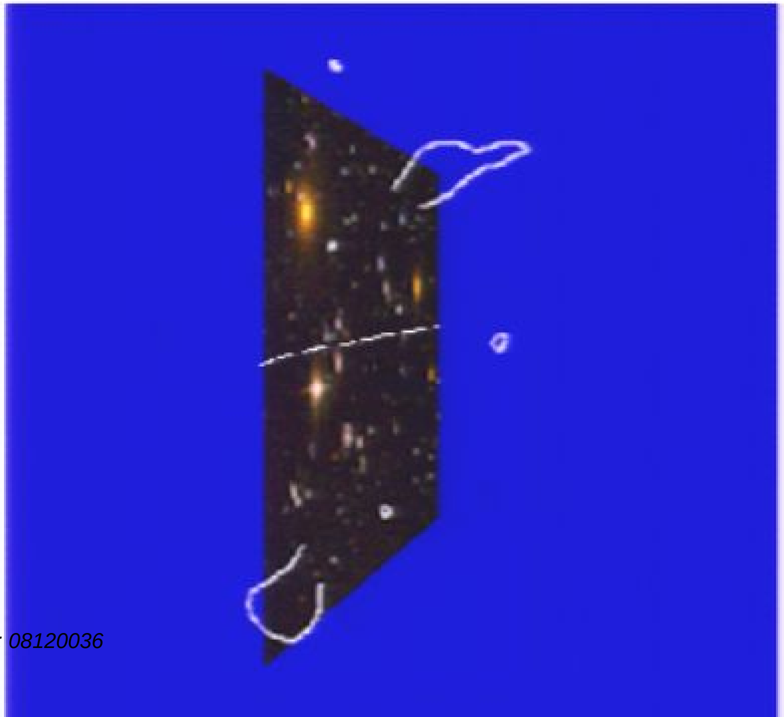

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Tachyon Condensation

- Brane annihilation and tachyon condensation is a stringy phenomena (although it has an effective field theory description)

Sen

- Special consequences for reheating.

- Leads to metastable codimension 2 defects (cosmic strings) with special properties.

CMP
L.L. Tye

- In some models, one can also generate density perturbations (with a non-Gaussian spectrum).

Going beyond with Multi-field, A Quick History

- In multi-field inflation, curvature (ζ) is NOT necessarily constant after horizon exit.

Bernardeau & Uzan
Bernardeau, Kofman, Uzan
Weinberg

- In general, one needs to integrate over the whole inflationary trajectory to get all contributions but in many systems, the effects all come from a special event in time simplifying the analysis.

Linde & Mukhanov
Lyth & Wands
Moroi & Takahashi

  - Curvaton: a new field starts dominating the energy density well after the end of inflation.

Buchbinder, Khoury & Ovrut

  - Modulated Reheating: Reheating starts everywhere in sync, but the final temperature is modulated.

Dvali, Gruzinov & Zaldarriaga

  - Modulated End: The onset of reheating is modulated but then proceed everywhere the same.

Lyth

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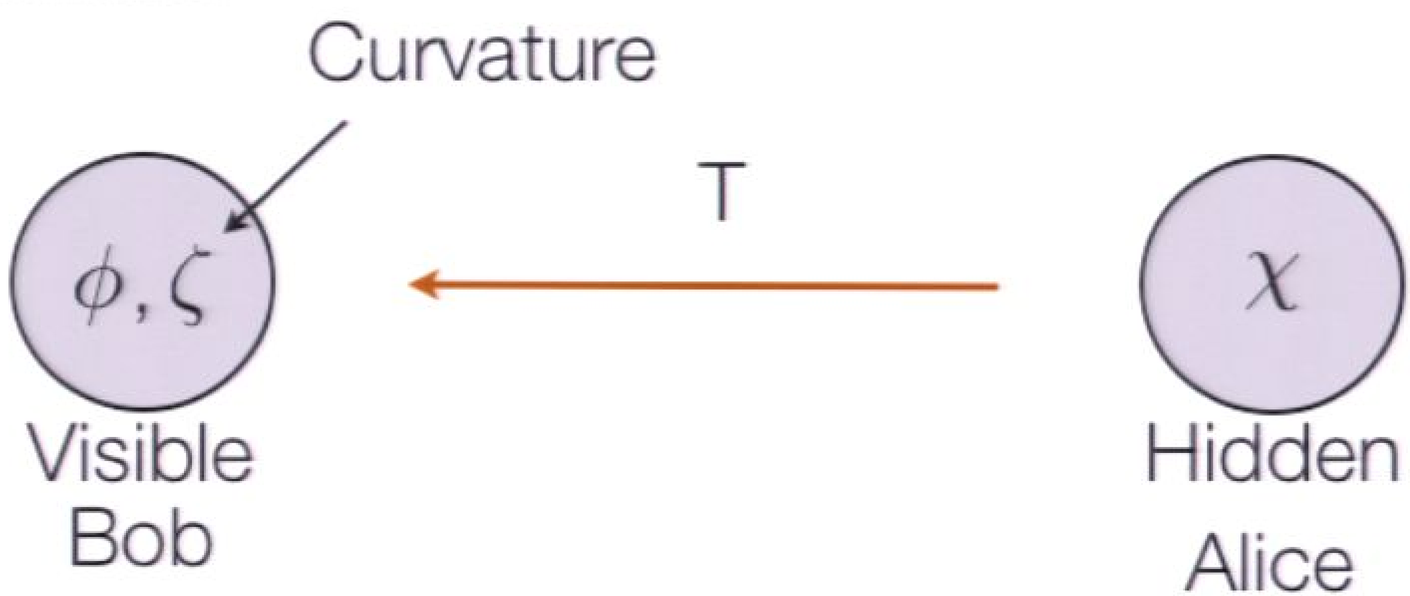
Lyth

Tachyon Mediated Density Perturbations

- In Hybrid inflation



We are not generating
density perturbations from the tachyon.
(assume that contribution from tachyon
preheating for example are small)

Basic Idea

- Couple Hybrid inflation (2 fields) to an extra field. (Here Tachyon = Waterfall field)

$$V \quad = \quad V_{\rm inf}(\phi) + V_{\rm hid}(\chi) + V_{\rm mess}(\phi, \chi, T)]$$

- There is no direct coupling between ϕ and χ. They couple only through the T which is very massive during inflation.

- Consider a solution with background values $\phi(t), \chi = 0, T = 0$ and assume that the potential energy is dominated by the inflaton potential

$$H^2(\phi) \approx \frac{V_{inf}(\phi)}{3M_p^2}$$

- Inflation ends at a critical value of the inflaton for which the mass of the tachyon is zero.

$$m_T^2 = f(\phi, \chi) = 0 \longrightarrow \phi_c(\chi)$$

Basic Idea 2

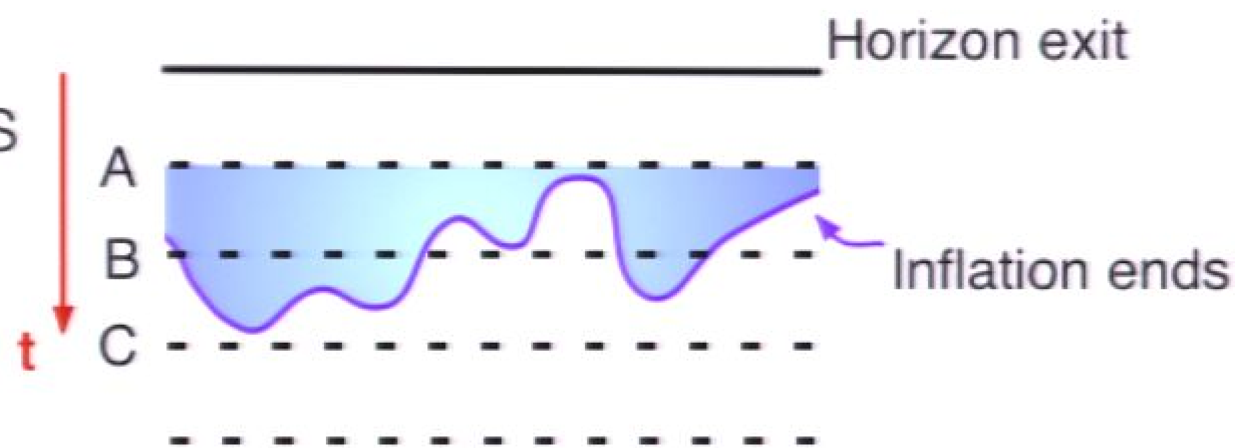
- We consider an inflating solution where we inflate for N efolds

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

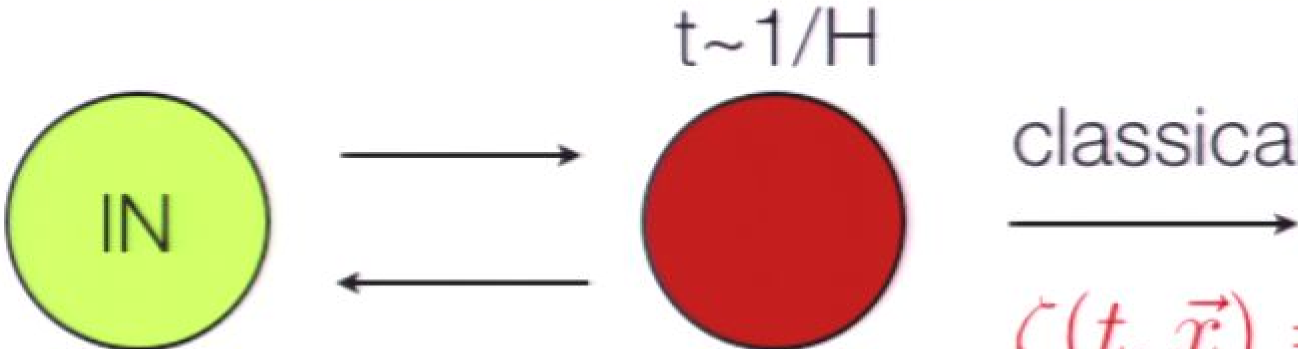
curvature perturbation

$$a(t_f) \sim a(t_*) e^{N_e}$$

Curvature perturbations can be seen as a perturbations in the number of efolds



Delta N formalism



$$\zeta(t, \vec{x}) = \delta N(t, \vec{x})$$

Sasaki & Stewart

- Given a perturbation at horizon crossing, this formalism account for the classical evolution.

- Often use for multi-fields, this formula does not correctly account for anything that happens inside the horizon (before horizon crossing)

$$N = \int_{\phi_*}^{\phi_c} \frac{H}{\dot{\phi}} d\phi \qquad \zeta = \delta N = -\frac{H}{\dot{\phi}}\delta\phi\Big|_*$$

For single field

From field perturbations to curvature.

$$N = \int_{\phi_*}^{\phi_c} \frac{H}{\dot{\phi}} d\phi$$

$\phi_c(\chi)$

The new field only change the end of inflation

* = horizon exit

$$\delta N = -\frac{H}{\dot{\phi}}\delta\phi\Big|_* + \frac{H}{\dot{\phi}}\frac{\partial \phi_c}{\partial \chi}\delta\chi\Big|_{\phi_c} + \frac{1}{2}\frac{H}{\dot{\phi}}\frac{\partial^2 \phi_c}{\partial \chi^2}\left(\delta\chi^2 - < \delta\chi^2 >\right)\Big|_{\phi_c} + \cdots$$

Usual contribution

Note sign difference

"transfer function" $\gamma \equiv \frac{\partial \phi_c}{\partial \chi}\Big|_{\phi_c}$

The 2-pt

- χ fluctuating, but with no interaction to the inflaton and its large energy density, so it is a pure entropy mode up to the end of inflation.

- "transfer" entropy to curvature at the end.

At horizon crossing

$$\delta\phi = \delta\chi \sim \frac{H}{2\pi}$$

We need to evaluate the new contribution at the end of inflation, it will be damped by mass term

$$\delta\chi(t_f) \sim \frac{H_*}{2\pi}\kappa$$

$$\kappa \sim e^{-\eta_\chi N_e}$$

$\eta_\chi \sim 0.01$

$N_e \sim 55$

$\kappa \sim 0.6$

The 2-pt function

$$\mathcal{P}_2^\zeta = \frac{H_*^2}{8\pi^2 M_{pl}^2}\left(\frac{1}{\epsilon_*} + \frac{\gamma^2\kappa^2}{\epsilon_f}\right)$$

most models must have $\gamma < 1$

- In most models, the potential is steeper at the end than at horizon exit (could argue it is unnatural to have it the other way around)

In D3 brane inflation, inflation ends with a tachyon. Coulombic potential is too steep while the DBI regime does better. Most recent analysis found no effects.

Lyth & Riotto
L.L. & Shandera
Chen, Gong, Shiu

counter example: hilltop potential which flattens out at the end

Alabidi and Lyth

From field perturbations to curvature.

$\phi_c(\chi)$

$$N = \int_{\phi_*}^{\phi_c} \frac{H}{\dot\phi} d\phi$$

The new field only change the end of inflation

* = horizon exit

$$\delta N = -\frac{H}{\dot\phi}\delta\phi\Big|_* + \frac{H}{\dot\phi}\frac{\partial\phi_c}{\partial\chi}\delta\chi\Big|_{\phi_c} + \frac{1}{2}\frac{H}{\dot\phi}\frac{\partial^2\phi_c}{\partial\chi^2}\left(\delta\chi^2 - <\delta\chi^2>\right)\Big|_{\phi_c} + \cdots$$

Usual contribution

Note sign difference

"transfer function" $\gamma \equiv \frac{\partial\phi_c}{\partial\chi}\Big|_{\phi_c}$

The 2-pt function

$$\mathcal{P}_2^{\zeta} = \frac{H_*^2}{8\pi^2 M_{pl}^2}\left(\frac{1}{\epsilon_*} + \frac{\gamma^2\kappa^2}{\epsilon_f}\right)$$

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Non-Gaussianity in the CMB

- Gaussianity is a consequence of the slow-rolling conditions (from which the inflaton behaves like a free field).

- Detectable NG can be generated by going beyond the standard single field slow-roll approximation.

  - non-standard kinetic term (e.g. DBI)

    Silverstein & Tong
    cf Shandera's talk

  - Multi-fields (this talk, present a string theory motivated D-term inflation with NG from multi-fields)

WMAP5

$$-9 < f_{NL} < 111$$

$$\zeta(\vec{x},t) = \zeta_{Gauss} + \frac{3}{5} f_{NL}(\zeta^2_{Gauss} - <\zeta^2_{Gauss}>)$$

Komatsu et al

The intrinsic contribution to f_{NL}

In most model the contribution to the 2-pt will be negligible but the 3-pt function can be significant.

Because, the hidden field is NOT the inflaton, its potential can be steeper and it can be strongly interacting.

$$\langle \zeta_{\rm int}^3 \rangle = \left(\frac{H}{\dot{\phi}} \right)^3 \gamma^3 \langle \delta\chi^3 \rangle \Big|_f$$

the inflaton contribution is small (proportional to epsilon)

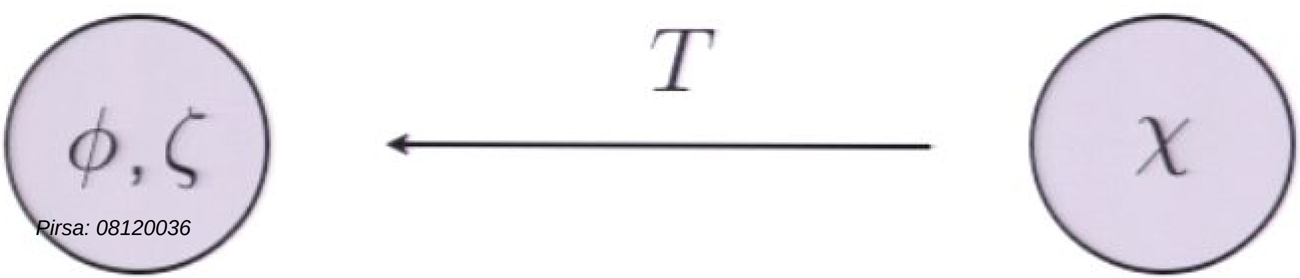
The intrinsic contribution to f$_{NL}$

$$< \delta\zeta^3 > \quad \longleftarrow \quad < \delta\chi^3 >$$

$$f_{NL}^{\rm int} \sim \frac{N_e M_p \gamma^3 \kappa^6}{H^2} \frac{\epsilon_*^2}{\epsilon_f^{3/2}} V_{,\chi\chi\chi} \quad \longleftarrow \quad F(\vec{k}_1, \vec{k}_2, \vec{k}_3) \sim -N_e H^2 V_{,\chi\chi\chi} \kappa^6 \frac{\sum k_i^3}{\prod k_i^3}$$

local shape

Falk, Rangarajan, Srednicki, '93
Zaldarriaga
Lyth, Malik Seery
Bernardeau, Brunier
Barnaby, Cline
Dutta, Kumar and L.L.



The intrinsic contribution to fNL

Contribution grows with the number of efolds

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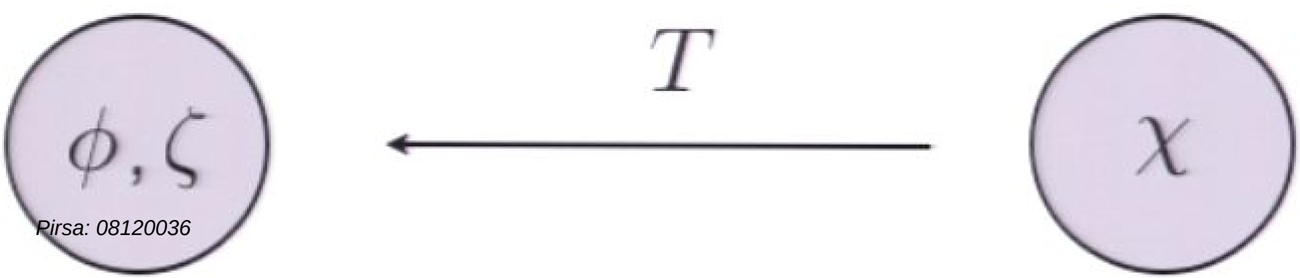

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Ratio of epsilons is bad

local shape

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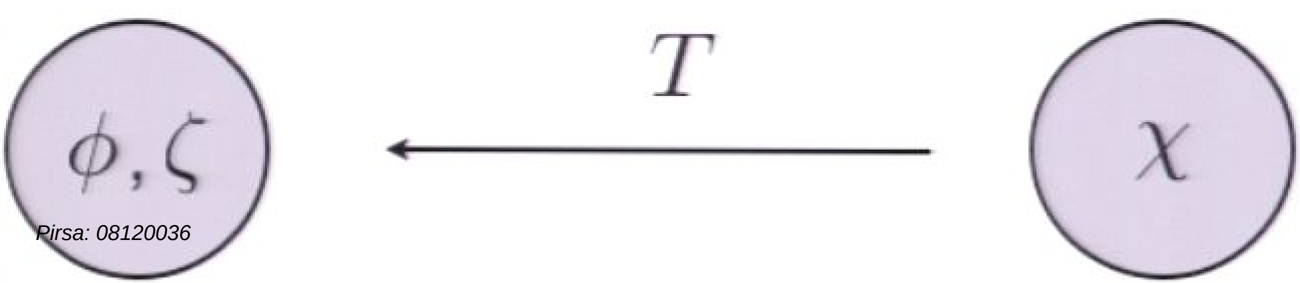

The Non-linear Contribution

- From the non-linear piece in the delta N, we will get a non-zero 3-pt curvature even for gaussian χ

$$\delta N = -\frac{H}{\dot{\phi}}\delta\phi\Big|_* + \frac{H}{\dot{\phi}}\frac{\partial\phi_c}{\partial\chi}\delta\chi\Big|_{\phi_c} + \frac{1}{2}\frac{H}{\dot{\phi}}\frac{\partial^2\phi_c}{\partial\chi^2}\left(\delta\chi^2 - <\delta\chi^2>\right)\Big|_{\phi_c} + \cdots$$

The ratio of these two contributions

$$\beta \equiv \left|\frac{f_{NL}^{\rm int}}{f_{NL}^{\rm loc}}\right| = \frac{1}{3}\frac{\gamma}{\gamma_{,\chi}}\frac{V_{,\chi\chi\chi}}{H^2}N_e\kappa \xrightarrow{\gamma \sim \chi} \beta \sim \eta_\chi N_e \kappa^2$$

This is always smaller than 1
but one can still have a significant fraction
of NG in intrinsic

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$$f_{NL}^{\rm loc} \sim -\frac{\partial\gamma}{\partial\chi}\gamma^2\kappa^4 M_p \frac{\epsilon_*^2}{\epsilon_f^{3/2}}$$

The ratio of these two contributions

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This is always smaller than 1
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Loops dominance?

$$\zeta_k = N'\delta\phi_k - N'\gamma\delta\chi_k - \frac{1}{2}N'\gamma'\int\frac{d^3k'}{(2\pi)^3}\delta\chi_{k-k'}\delta\chi_{k'}$$

$$\langle\zeta_k^2\rangle \quad \supset \quad N'^2\gamma'\gamma(2\pi)^3\delta^3(\sum_i \vec{k}_i)f_3\int\frac{d^3k'}{(2\pi)^3}f(k_1,k_2,k')$$

$$\frac{\ln kL}{k^3}$$

Weinberg

Seery

We found points in parameter space where loops are important

$$\gamma'' \sim 0 \qquad \gamma' \gg \gamma$$

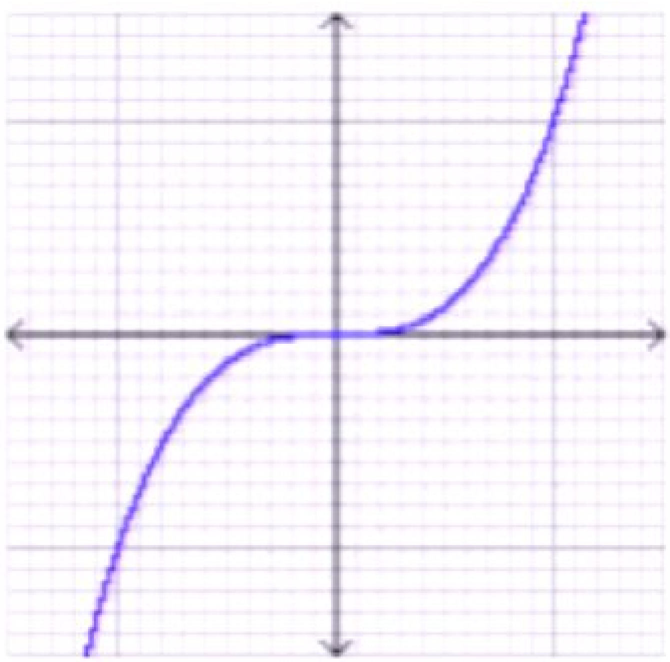
Perturbative analysis still looks good

Can we find a model... in string theory?

Brane inflation

- Can these effects be important in brane inflation? Lyth & Riotto

- We can have light fields from approximate isometries of the geometry: angular coordinate. They couple to the tachyon.



Baumann et al.

Hoi and Cline

potential is tuned to be flat in small region and steep everywhere else

so in general no effect

Chen, Gong, Shiu

Argue that the potential flattens out again but found that for this specific model (a.k.a D7 embedding), there is no isometries at the tip and no light fields

D-term Inflation

- Susy breaking is dominated by D-terms. For N U(1) gauge group + non abelian piece, we get

Gauge coupling
Functions of moduli

$$V_D \sim \sum_{j=1}^{N} g_j^2 \left(\sum_i q_{i,j} |\chi_i|^2 - \xi_j \right)^2 + V_{NA} \,,$$

+ planck suppressed terms

Charged matter, light open string mode

Fayet-Illiopoulos term (function of the string moduli)

Minimal D-term model

- Assume three fields, a neutral scalar S and two charged fields $\phi_{\pm}$ with charges +1, -1 under a U(1)

$$K(\phi, S) = \phi_-^2 + \phi_+^2 + S^2$$

$$W(\phi, S) = \lambda S \phi_+ \phi_-$$

$$V = \lambda^2((\phi_+\phi_-)^2 + (\phi_+ S)^2 + (\phi_- S)^2) + \frac{g^2}{2}(\phi_+^2 - \phi_-^2 + \xi)^2 + O(M_p^{-n})$$

F-term D-term

$$m_{\phi_\pm}^2 = \lambda^2 S^2 \pm g^2 \xi$$

If $|S| > S_C = \frac{g\sqrt{2\xi}}{\lambda}$

$$\phi_{\pm} = 0$$

Binetruy, Dvali
Halyo

Hybrid inflation

$$V = \frac{g^2 \xi^2}{2}$$

Coleman-Weinberg (approximate)

U(1) Produce cosmic strings!!

2 regimes

- Large S, $n_s \sim 0.98$ $\quad \xi \sim 10^{-5} M_p^2$

$$G\mu \sim 10^{-5}$$

- S close to S_c, $n_s \sim 1$ $\quad \xi < 10^{-7} M_p^2$

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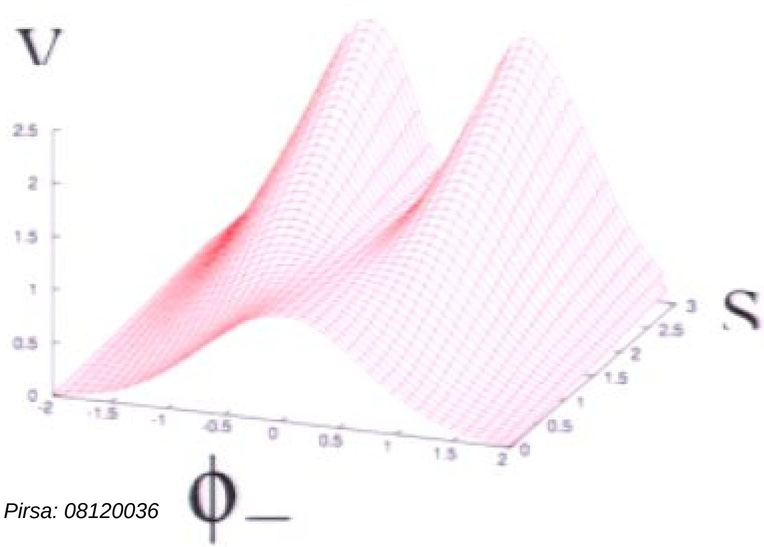

Hybrid inflation

$$V_{eff} = \frac{g^2\xi^2}{2}\left(1 + \frac{Cg^2}{8\pi^2}\ln\frac{\lambda^2 S^2}{\Lambda^2}\right)$$

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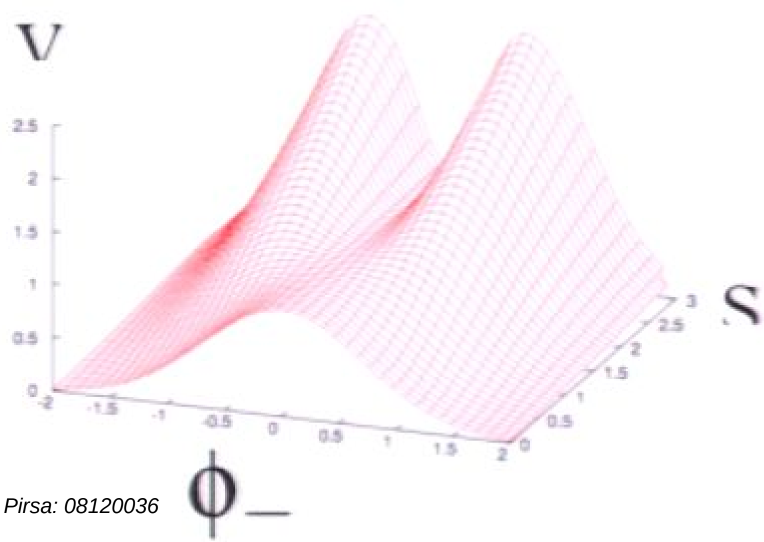

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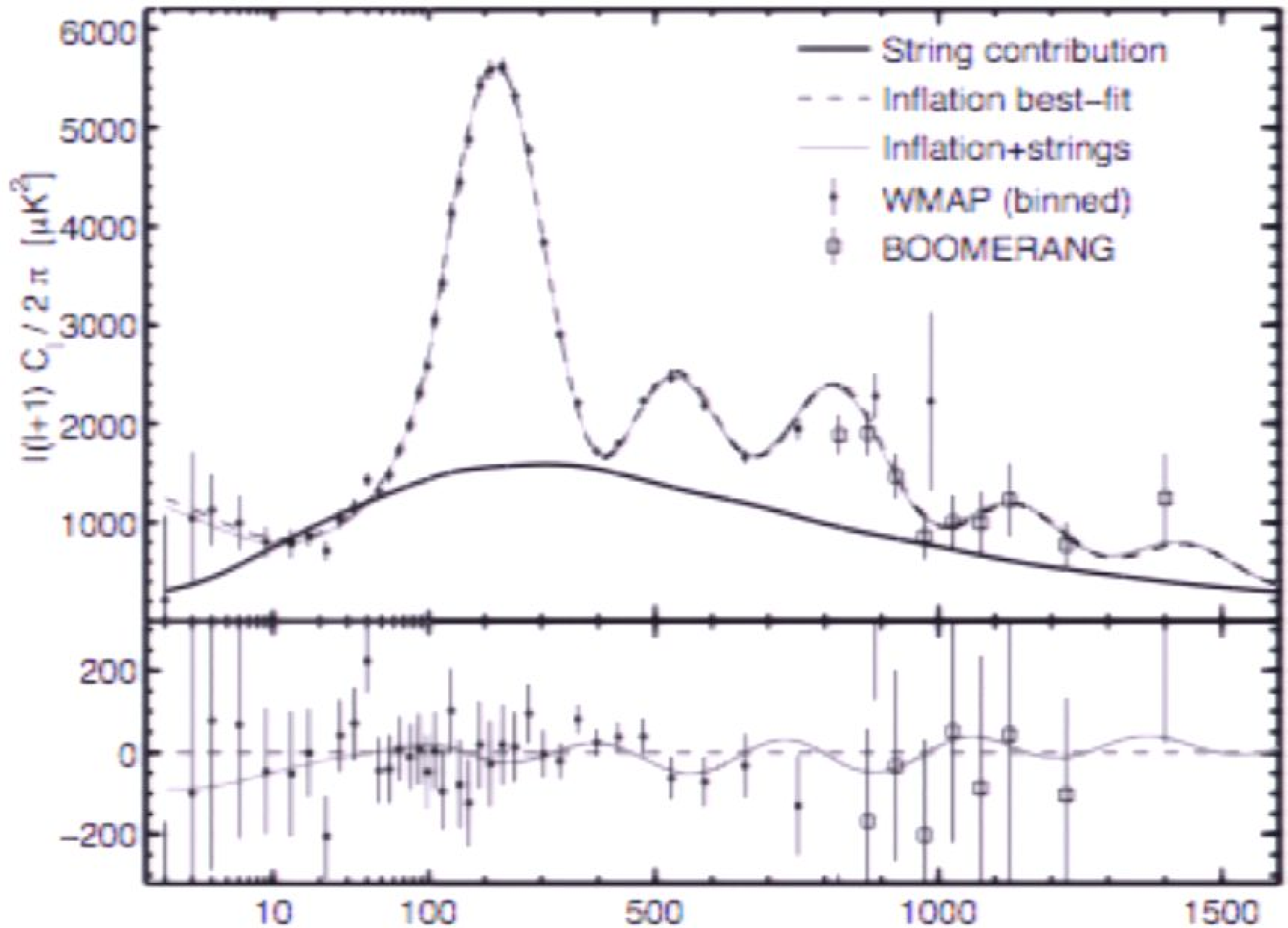

Battye, Garbrecht, Moss
Bevis, Hindmarsh, Kunz, Urestilla

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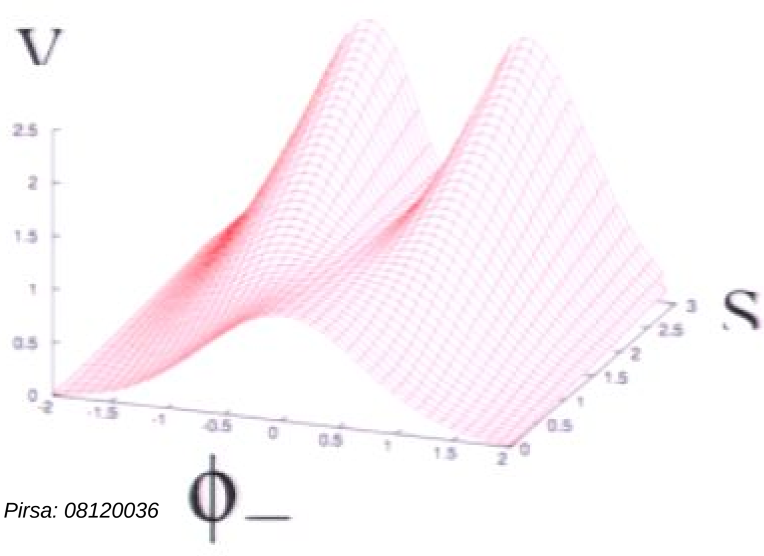

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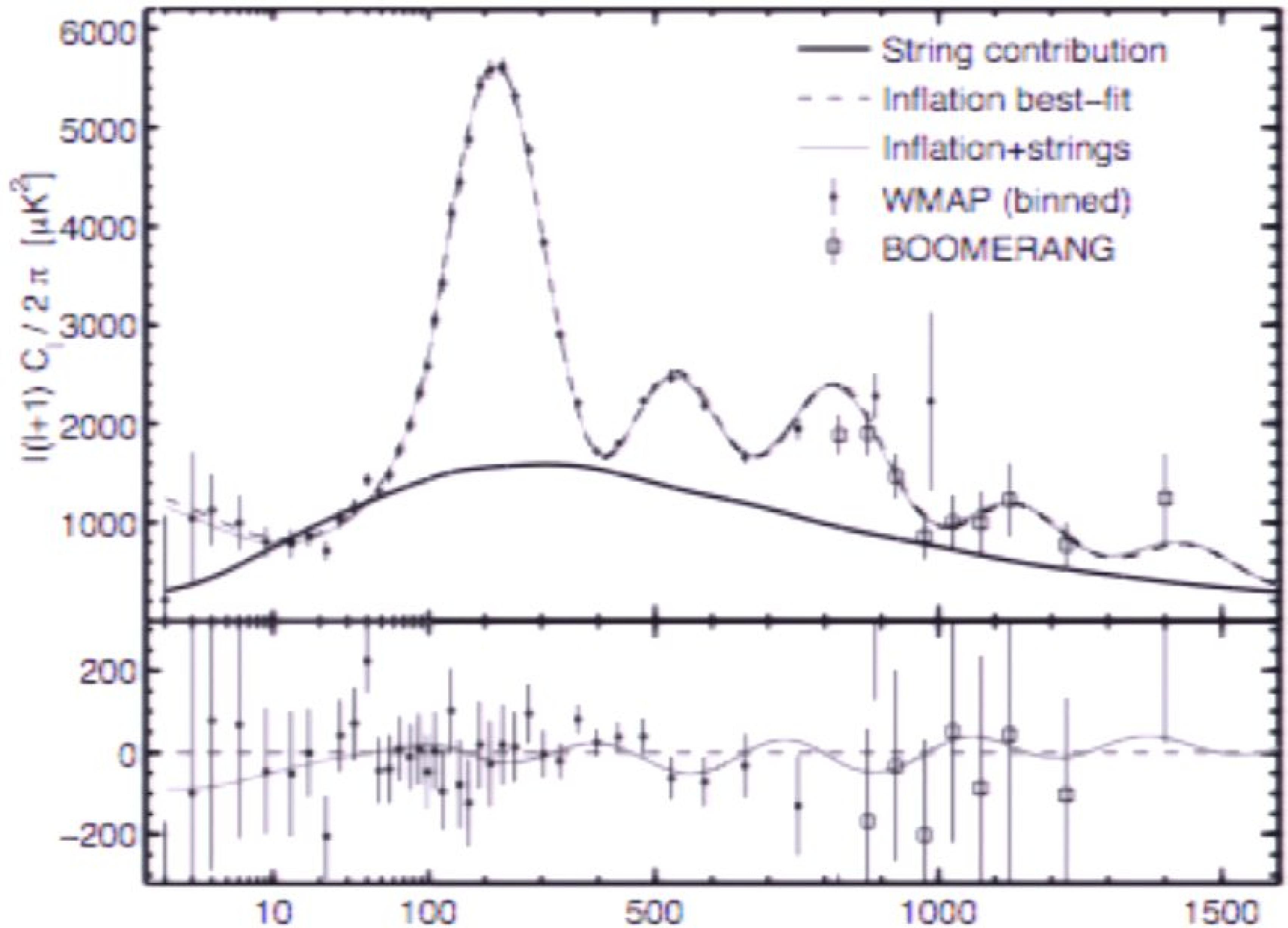

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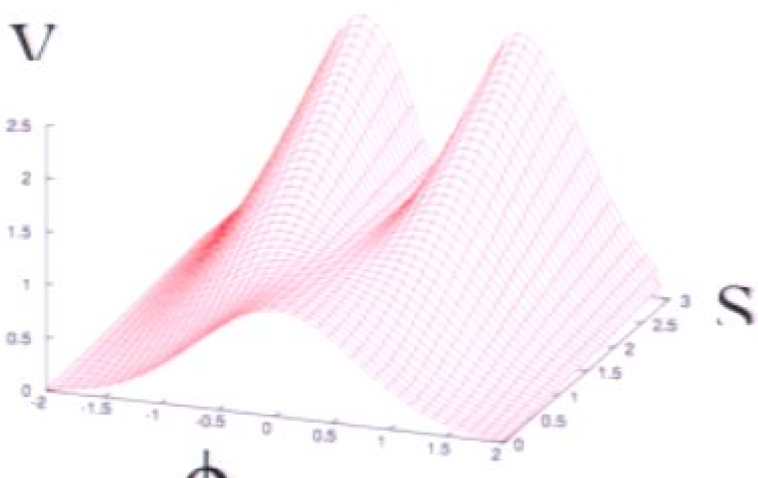

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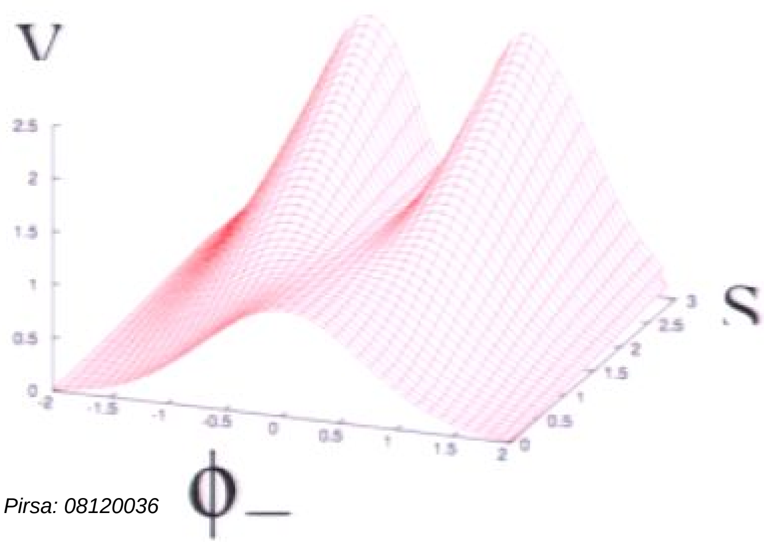

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IBM-flation

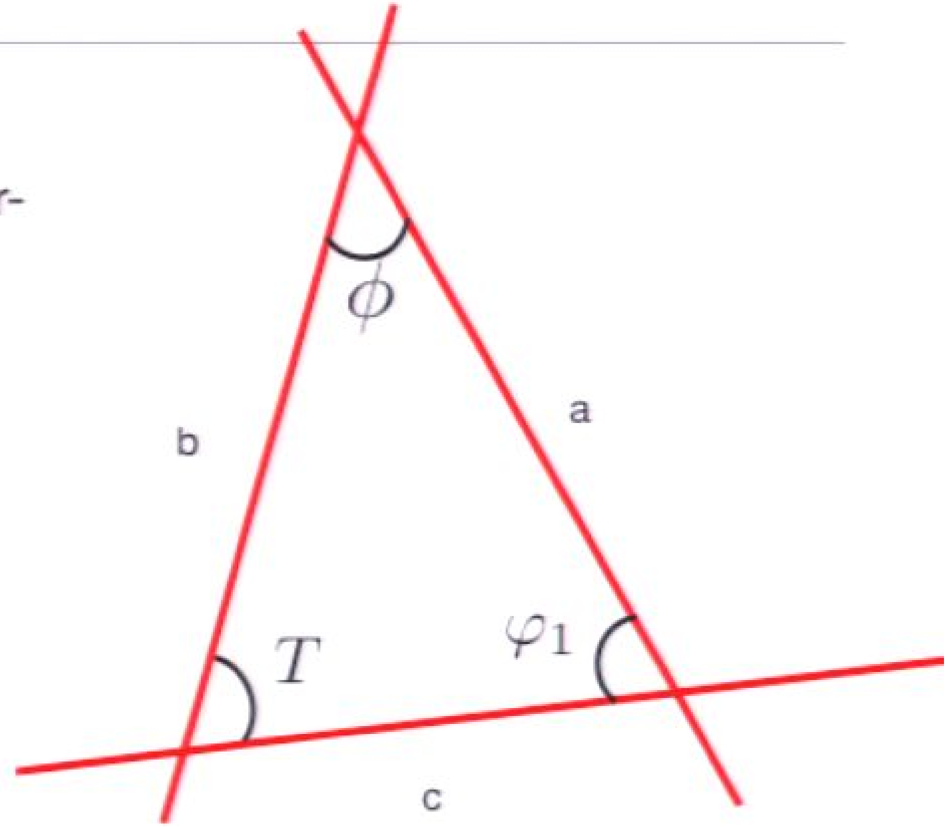
- Can realize D-term inflation, using open string between branes (strings are in vector-like rep)

- Using gauge invariance one can “brane engineered” flat direction by forbidding dimension 6 operators for example.

- and large NG mediated by the tachyon

- can get a regime with $n_s \sim 1$

- cosmic strings



$$W = \lambda \phi T \varphi_1 + \lambda_{NG} \chi T \varphi_2$$

Dutta, Kumar, L.L

D3D7

Haack, Kallosh, Krause,

Burgess, Cline, Postma

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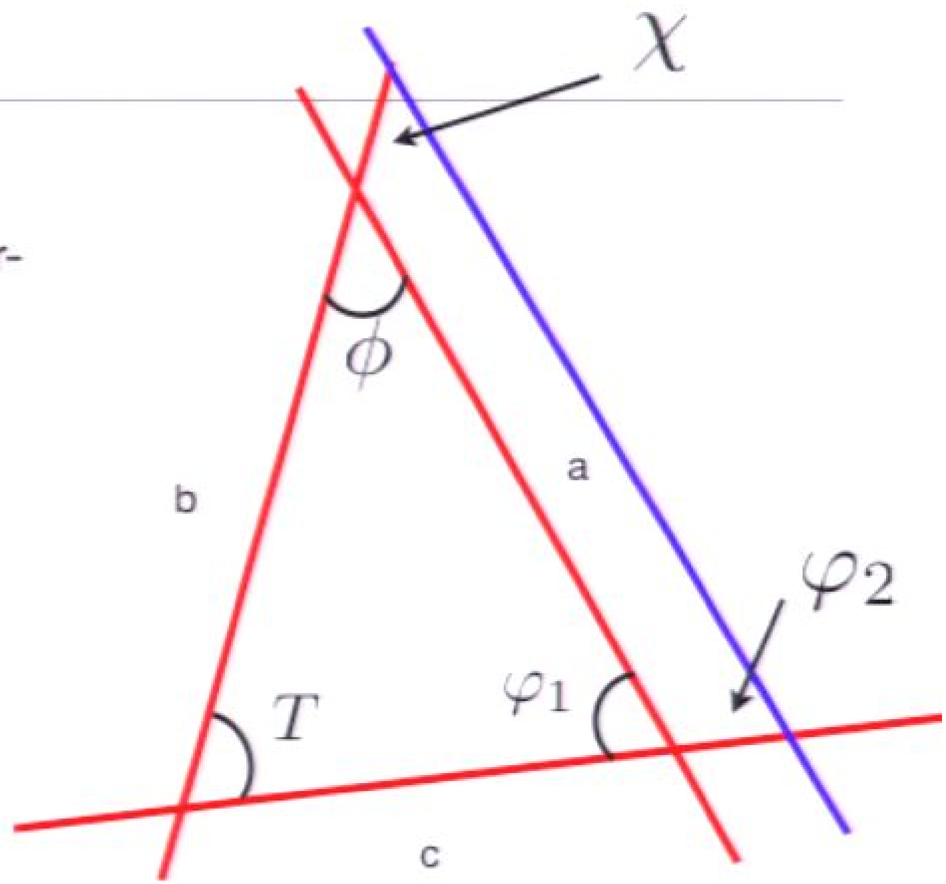

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D3D7 Haack, Kallosh, Krause, Burgess, Cline, Postma

Detailed example

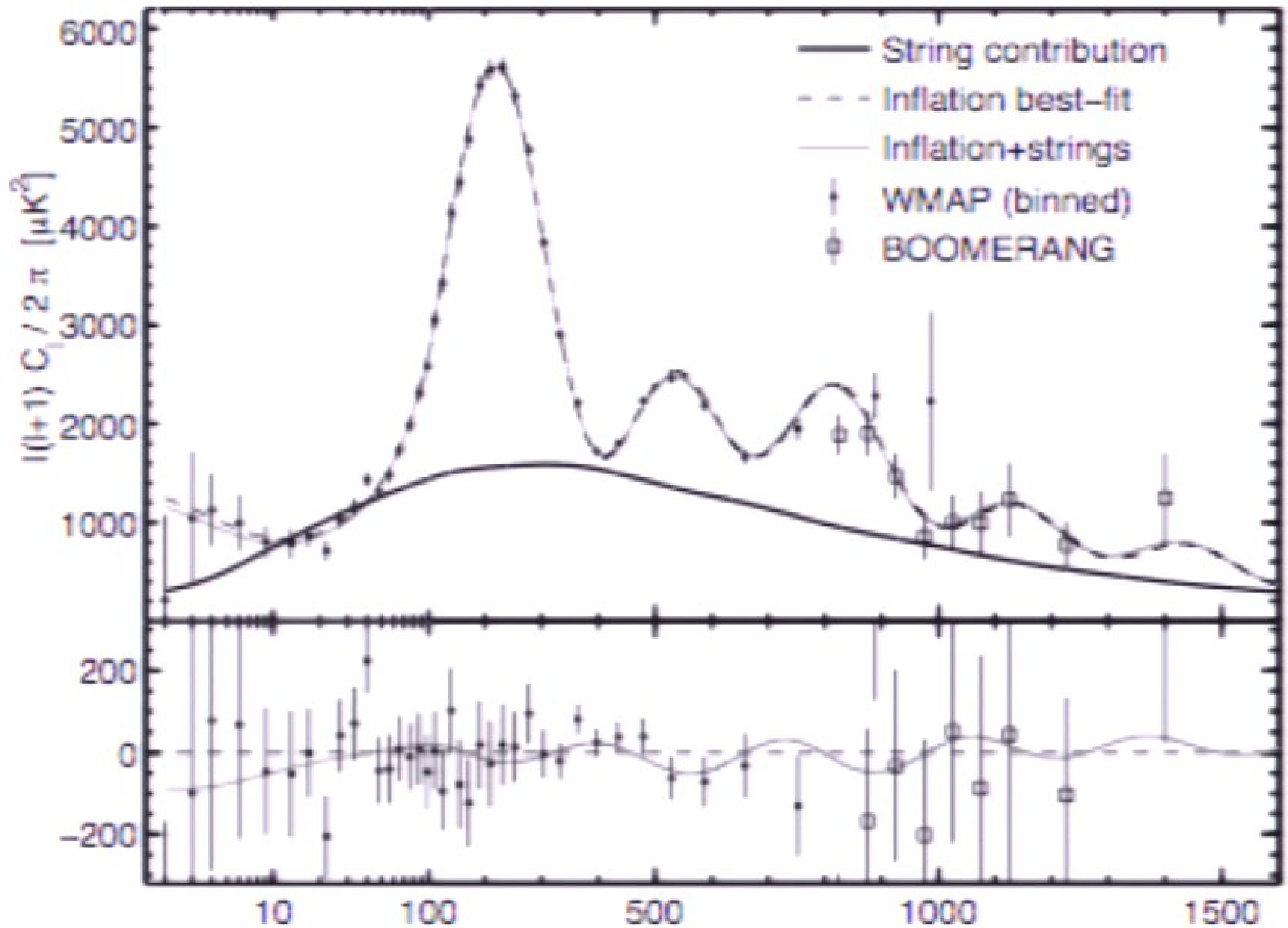
- The tachyon mass depends on both ϕ and χ

$$m_T^2 = -g^2\xi + \lambda^2\phi^2 + (\lambda_{NG}^2 - qg_2^2)\chi^2$$

$\gamma \approx \chi$ so the non-linear contribution dominate

a point in parameter space

$$f_{NL}^{\text{int}} \sim -8\ , \quad n_s \sim 1.002\ ,$$
$$f_{NL}^{\text{loc}} \sim 45\ , \quad G\mu \sim 7 \times 10^{-7}\ .$$



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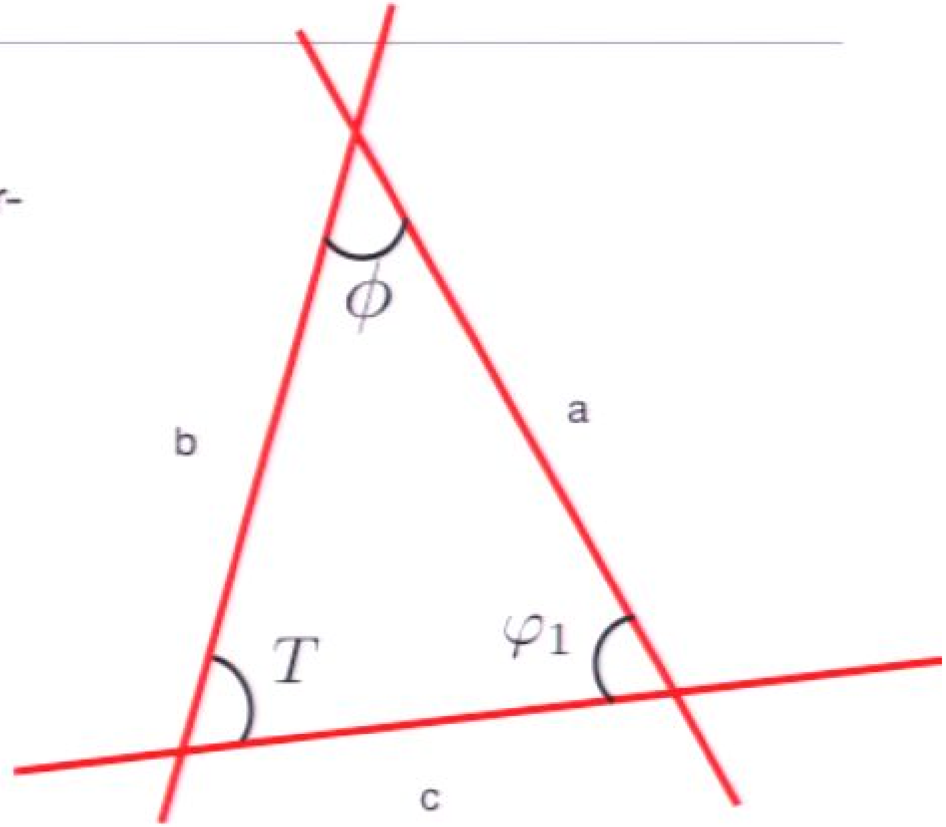

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Conclusion

- One can generate observable NG at the end of hybrid inflation with a rich structure.
- Many models fail because the potential is too steep at the end. D-term inflation in the regime of flat spectrum with cosmic strings can lead to observable NG.
- The NG has the local shape and both signs can be obtained.
- One can write a string theory motivated model with such features but it needs more detailed study.
- Further questions: Loop effects? NG from the cosmic strings?

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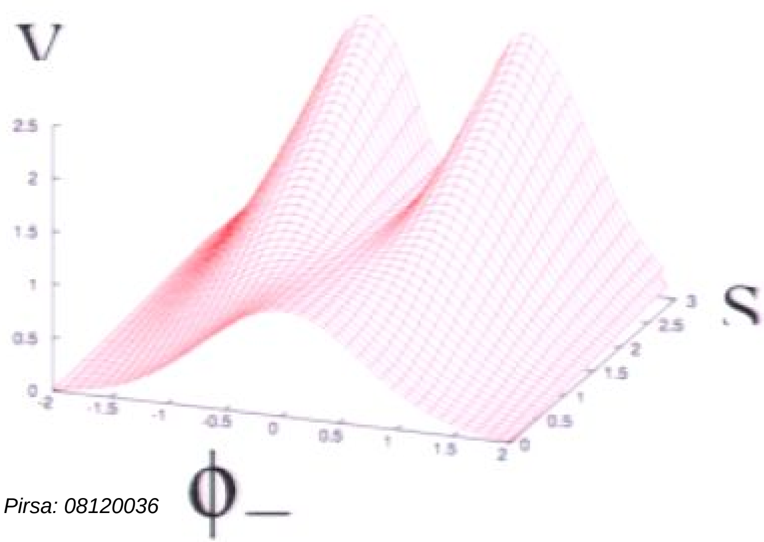

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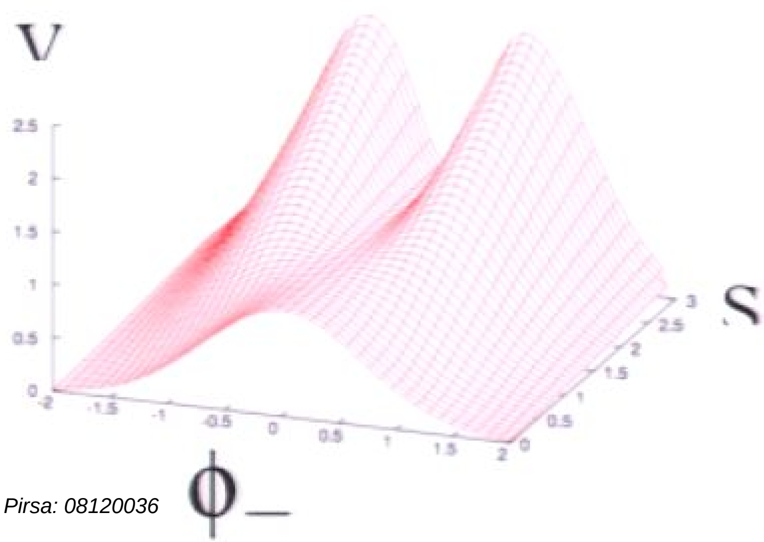

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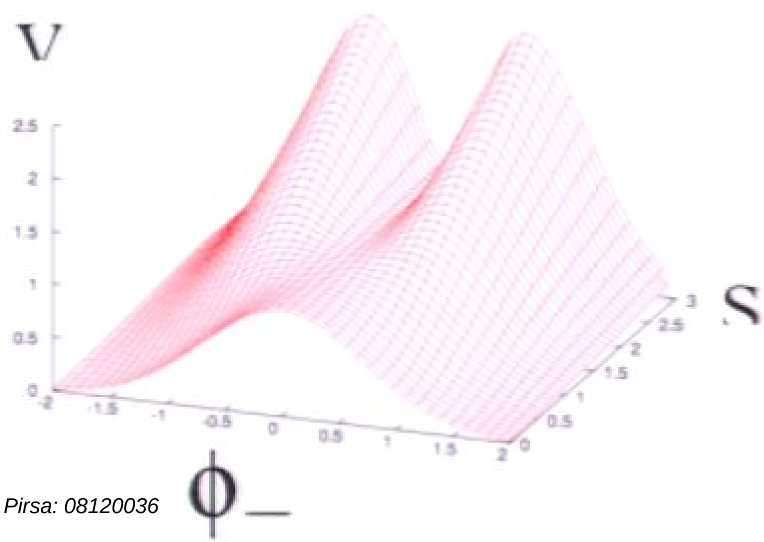

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