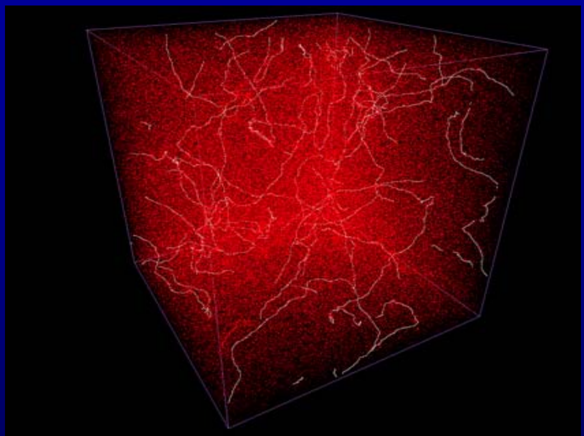
production of topological defects at the end of inflation



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outline

- motivation / introduction
  - hybdrid inflation
  - topological defects – cosmic strings
    - o formation
    - o evolution
    - o predictions on cmb
- inflation within supersymmetric grand unified theories

cosmic strings / cosmic superstrings

- inflation within braneworld cosmologies
- compatibility between predictions and data
- conclusions

motivation

the inflationary scenario is with no doubt extremely succesful

however

inflation is still a paradigm in search of a model

↓

high energy physics

search for an inflationary model inspired from a fundamental theory

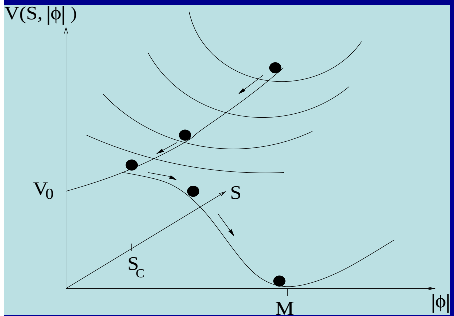
and test its predictions against current data

astrophysics

hybrid inflation

chaotic inflation [1] : elegant but needs fine tuning

hybrid inflation [2] : based on eisntein's gravity but driven by a false vacuum



the inflaton field rolls while another scalar field remains trapped in false vacuum

false vacuum unstable when inflaton field much smaller than a critical value and there is a phase transition to the true vacuum which signals the end of inflation

the phase transition may lead to topological defects formation [3]

non-supersymmetric grand unified theories

supersymmetric grand unified theories

[1] linde 1983

[2] linde 1991, 1994

[3] jeannerot 1997; kofman & linde 1997; linde & riotto 1997; lyrh & riotto 1999; contaldi, hindmarsh & magueijo 1999; battye & weller 2000

topological defect formation and harmless defects

the universe cools, undergoes phase transitions which may leave behind topological defects which are false vacuum remnants [1]

ssb: $G \longrightarrow H$, with $H \subset G$ by the condensation of a Higgs field ϕ

defect formation during ssb depends on the homotopy group $\pi_k(G/H)$ of the false vacuum $\mathcal{M} = G/H$ if $:\pi_k(G/H) \neq I$ then $(2-k)-$ dim defects appear

examples :

$$\mathrm{SO}(3) \to \mathrm{O}(2) \quad ; \quad \pi_1(\mathrm{SO}(3)/\mathrm{O}(2)) \simeq Z_2$$ ⟹ strings

$$\mathrm{SU}(2) \to \mathrm{U}(1) \quad ; \quad \pi_1(\mathrm{U}(1)) \neq I$$ ⟹ monopoles

[1] kibble 1976

harmless & cosmologically interesting defects: local cosmic strings & global defects

the scalar field energy density scales like $\rho_{\rm TD} \propto 1/(at^2) \Longrightarrow \rho_{\rm TD}/\rho \sim 8\pi G T_c^2$

monopoles $(k=2)$ or domain walls $(k=0)$ are incompatible with our universe

textures $(k=3)$ are irrelevant [1]: $\rho_{\rm textures}/\rho$ decreases rapidly with t

cosmic strings

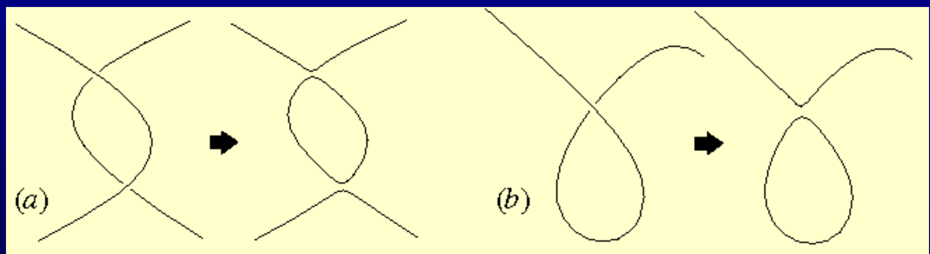
$$\mathcal{L} = \bar{\mathcal{D}}_\mu \phi \mathcal{D}^\mu \phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\lambda}{4}(|\phi|^2 - \phi_0^2)^2$$

abelian higgs model

the model obeys local U(1) symmetry which is broken in the low-temperature regime by any choice of vacuum $|\phi| = \phi_0$

nambu-goto effective action: $S_0[x^\mu] = -\mu \int \sqrt{-\gamma}\, d^2\zeta$

e.o.m. : $\ddot{\mathbf{x}} + 2\left(\frac{\dot a}{a}\right)\dot{\mathbf{x}}(1-\dot{\mathbf{x}}^2) = \left(\frac{1}{\epsilon}\right)\left(\frac{\mathbf{x}'}{\epsilon}\right)'$ in a f.l.r.w.



[2,3]

[1] turok 1989

[2] shellard 1988; moriarty, myers & rebbi 1988; laguna matzner 1990

[3] achucarro & de putter 2006

cosmic string network evolution

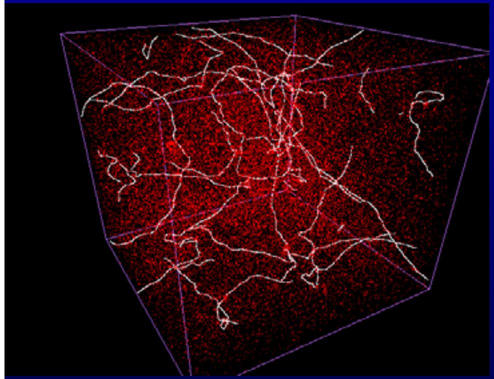
long strings enter the *scaling* regime and the network is characterised by a single length scale, the interstring distance ξ which grows with the horizon[1]

early numerical simulations[2] revealed dynamical processes at scales $\ll \xi$

3-scale model[3]: interstring separation ξ, curvature scale $\bar{\xi}$, wiggliness ζ

some of its aspects have been tested[4] numerically in a flat spacetime

recent simulations[5] have shown the existence of a scaling evolution for string loops down to the hundredth of the horizon time
this result does not rely on gravitational back reaction effect and it is due just to string intecommuting mechanism



[1] kibble 1985

[2] bennett & bouchet 1988; sakellariadou & vilenkin 1990

[3] austin, copeland & kibble 1993

[4] vincent, hindmarsh & sakellariadou 1997

[5] ringeval, sakellariadou & bouchet 2005; martins & shellard 2005; vanchurin, olum & vilenkin 2005

cosmic strings as seeds of structure formation

$$\mathcal{D}X = \mathcal{S}$$

for given initial conditions, this eq. can be solved by means of a green's function:

$$X_j(\eta_0, \mathbf{k}) = \int_{\eta_{\rm in}}^{\eta_0} \mathcal{G}_{jm}(\eta_0, \eta, \mathbf{k})$$

we want to compute quadratic expectation values of the form:

$$\langle X_j(\eta_0, \mathbf{k}) X_l^\star(\eta_0, \mathbf{k}') \rangle =$$

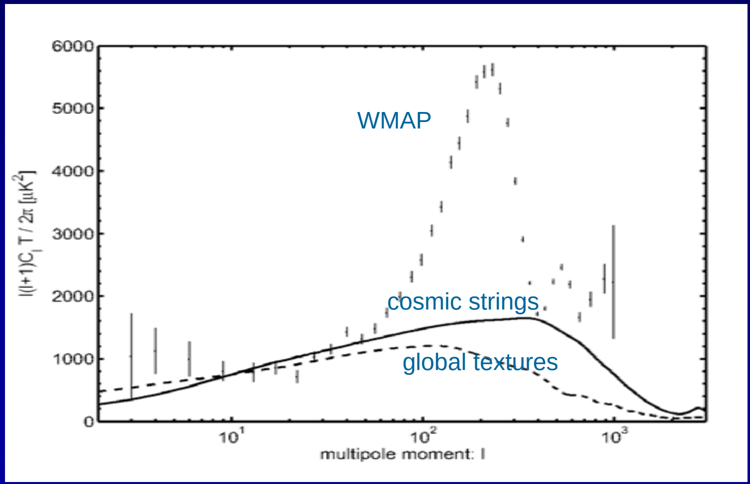
$$\int_{\eta_{\rm in}}^{\eta_0} {\rm d}\eta \mathcal{G}_{jm}(\eta, \mathbf{k}) \int_{\eta_{\rm in}}^{\eta_0} {\rm d}\eta' \mathcal{G}_{ln}^\star(\eta', \mathbf{k}') \times \underbrace{\langle \mathcal{S}_m(\eta, \mathbf{k}) \mathcal{S}_n^\star(\eta', \mathbf{k}') \rangle}$$

unequal time 2-pt correlators [1]

heavy numerical simulations !

[1] hindmarsh 1995

cmb power spectrum from cosmic strings using field evolution simulation [1] of the Abelian Higgs model



[1]

a roughly constant slope at low multipoles, rising up to a single peak at $\ell \approx 400$, with decay at small scales

$\ell = 10$ WMAP normalisation [1] →

$$G\mu = 2 \times 10^{-6}$$

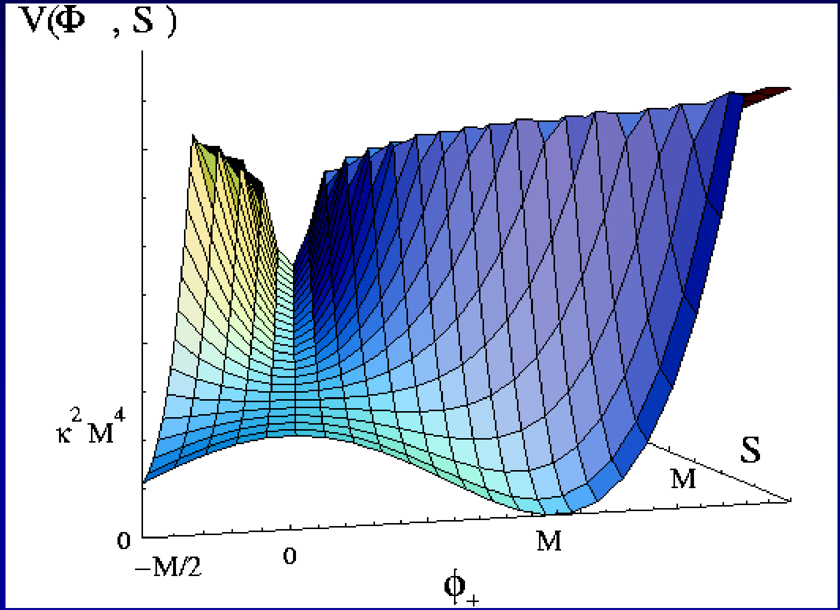
$$\mu \sim T_{\rm crit}^2$$

[1] bevis, hindmarsh, kunz & urrestilla 2006

inflation in N=1 supersymmetric grand unified theories

F-term hybrid inflation

$$W^{\rm F}_{\rm infl} = \kappa S(\Phi_+\Phi_- - M^2)$$



$$G_{\rm GUT} \xrightarrow{M_{\rm GUT}} H_1 \xrightarrow[\Phi_+\Phi_-]{M_{\rm infl}} H_2 \longrightarrow G_{\rm GM}$$

$$V = |F_{\Phi_+}|^2 + |F_{\Phi_-}|^2 + |F_S|^2 + \frac{1}{2}\sum_a g_a^2 D_a^2$$

$$F_{\Phi_i} \equiv \left|\frac{\partial W}{\partial \Phi_i}\right|_{\theta=0} \qquad D_a = \bar{\phi}_i (T_a)^i{}_j \phi^j + \xi_a$$

compute one-loop radiative corrections to the scalar potential V along the inflationary valley, using the coleman-weinberg expression compute [1] one-loop radiative corrections to the scalar potential V along the inflationary valley, using the coleman-weinberg expression

$$V_{\rm eff}^{\rm F}(|S|) = \kappa^2 M^4 \Big\{ 1 + \frac{\kappa^2 \mathcal{N}}{32\pi^2} \times \Big[2\ln\frac{|S|^2\kappa^2}{\Lambda^2} + (z+1)^2 \ln(1+z^{-1}) + (z-1)^2 \ln(1-z^{-1}) \Big] \Big\}$$

$$z = |S|^2/M^2$$

$\mathcal{N}$: dimensionality of the representations to which ϕ_+, ϕ_- belong

$\mathcal{N} = \mathbf{126}$ for SO(10) $\mathcal{N} = \mathbf{27}$ or $\mathbf{351}$ for E_6

Λ : renormalisation scale

[1] dvali, shafi, schaefer 1994

lazarides 2001

rocher & sakellariadou 2005

remark :

in general, F-term inflation suffers from the *hubble-induced mass* problem

sugra corrections induce contributions of the order unity to the slow roll parameter

any scalar field gets mass of the order of the expansion rate during inflation

for minimal kähler potential this problem is lifted by cancellation of the problematic mass terms

D-term hybrid inflation in supergravity

superpotential [1]

$$W^{\rm D}_{\rm infl} = \lambda S \Phi_+ \Phi_-$$

$$G_{\rm GUT} \times U(1) \xrightarrow{M_{\rm GUT}} H \times U(1) \xrightarrow[\Phi_+\Phi_-]{M_{\rm infl}} H \longrightarrow G_{\rm GM}$$

$\mathcal{L}_{\rm sugra}$ depends on $K(\Phi_i, \bar\Phi_i); W(\Phi_i); f_{ab}(\Phi_i)$

it depends on the combination $G(\Phi_i, \bar\Phi_i) = \frac{K(\Phi_i,\bar\Phi_i)}{M_{\rm Pl}^2} + \ln \frac{|W(\Phi_i)|^2}{M_{\rm Pl}^6}$

ill-defined [2] formulation at W=0

D-term inflation: W=0 at unstable de sitter (and in absolute minkowski) vacuum

supergravity constructed [2] from superconformal theory

[1] halyo 1996 ; binetruy & dvali 1996

[2] binetruy, dvali, kallosh & van proyen 2004

under $\mathrm{U}(1)$ gauge transformations in the directions in which there are constant fayet-iliopoulos terms, the superpotential must transform as[1]

$$\delta_\alpha W = -\, i \frac{g\xi_\alpha}{M_{\rm Pl}^2} W(\phi)$$

in sugra with constant fayet-iliopoulos terms, the charge assignements for the superfields is non-vanishing, and it should be such that the superpotential transforms under[1] local R-symmetry:

$$q(S) = -\frac{\xi}{M_{\rm Pl}^2}\rho_S \;\; ; \;\; q(\Phi_\pm) = \pm 1 - \frac{\xi}{M_{\rm Pl}^2}\rho_\pm$$

$$\sum_{i=S,\Phi_\pm} \rho_i = 1$$

to avoid η -problem : $\rho_S = 0$

[1] binetruy, dvali, kallosh & van proyen 2004

how generic is cosmic strings formation within supersymmetric grand unified theories[1]

$$G_{GUT} \rightarrow \ \dots \ \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times Z_2$$

SM

subgroup of $U(1)_{B-L}$

consider simple lie groups with:

rank(SU(3) x SU(2) x U(1)) = 4 → $8 \geq$ Rank(G) ≥ 4 → $n \geq 4$

complex fermionic representations (to keep the nature of EW interactions)

anomaly free fermionic representation

~~SU(5)~~, ~~SU(6)~~, ~~SU(7)~~, SU(8), SU(9) SO(10), SO(14), E6

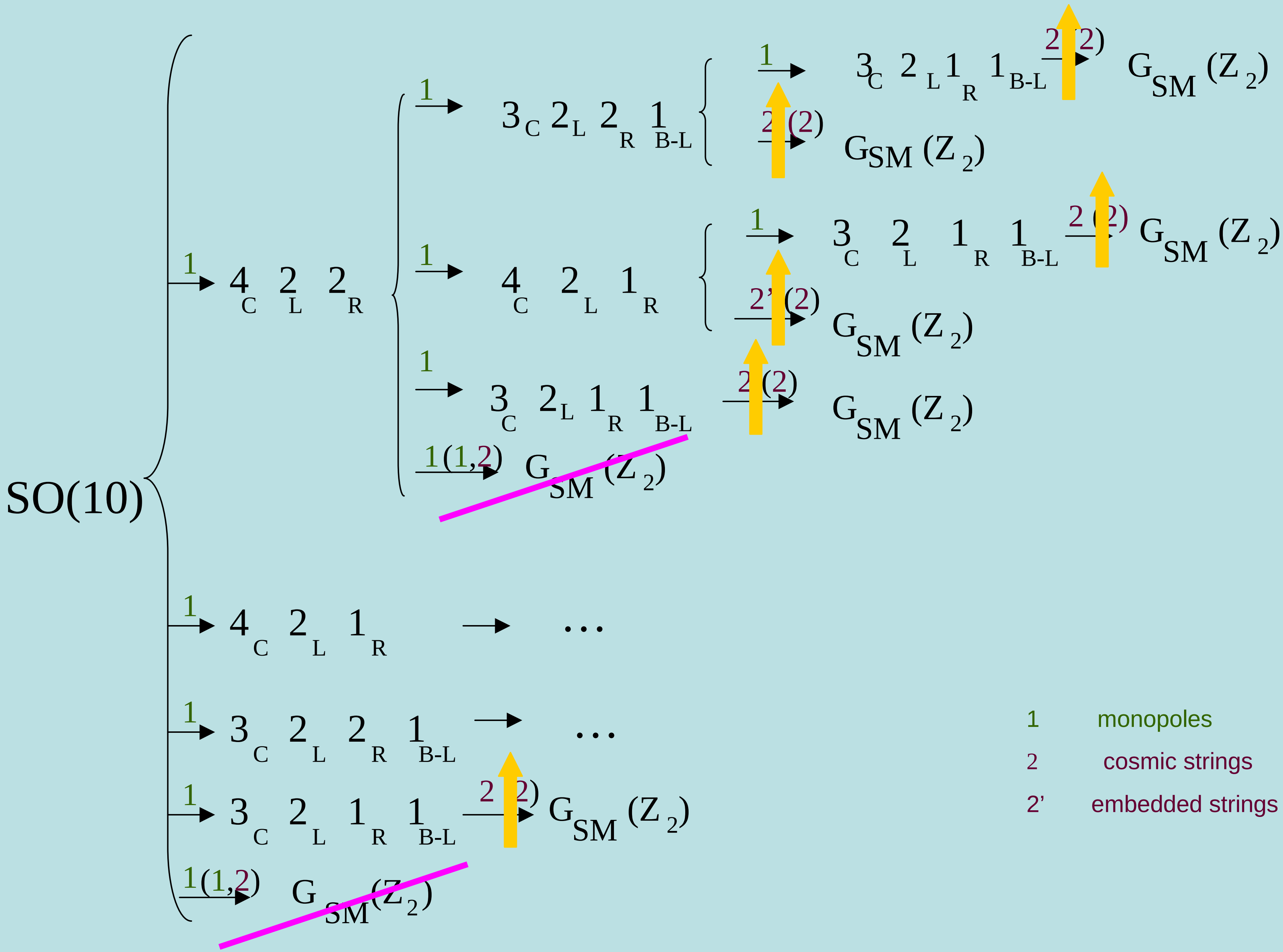
SU(5): stable monopoles

minimal SU(6) and minimal SU(7) do not contain $U(1)_{\rm B-L}$

- neutrinos get masses via the see-saw mechanism
- baryogenesis via leptogenesis : (i) <u>non-thermal leptogenesis</u>: $U(1)_{B-L} \subset G_{GUT}$ and B-L at the end/after inflation

  (ii) <u>thermal leptogenesis</u>: B-L independently of inflation; if B-L before inflation: $T_{B-L} \sim M_{\nu_R} < T_{\rm reheating} < T_{\rm gravitino\ limit}$
- solve the shortcomings of the big bang model via supersymmetric hybrid inflation

[1] jeannerot, rocher & sakellariadou 2003


SO(10)
1 → $4_C\ 2_L\ 2_R$
1 → $3_C\ 2_L\ 2_R\ 1_{B-L}$
1 → $3_C\ 2_L\ 1_R\ 1_{B-L}$ 2 (2) → $G_{SM}\ (Z_2)$
2 (2) → $G_{SM}\ (Z_2)$
1 → $4_C\ 2_L\ 1_R$
1 → $3_C\ 2_L\ 1_R\ 1_{B-L}$ 2 (2) → $G_{SM}\ (Z_2)$
2' (2) → $G_{SM}\ (Z_2)$
1 → $3_C\ 2_L\ 1_R\ 1_{B-L}$ 2 (2) → $G_{SM}\ (Z_2)$
1(1,2) → $G_{SM}\ (Z_2)$
1 → $4_C\ 2_L\ 1_R$ → …
1 → $3_C\ 2_L\ 2_R\ 1_{B-L}$ → …
1 → $3_C\ 2_L\ 1_R\ 1_{B-L}$ 2 (2) → $G_{SM}\ (Z_2)$
1(1,2) → $G_{SM}\ (Z_2)$
1 monopoles
2 cosmic strings
2' embedded strings

E_6

non-thermal leptogenesis and Z_2 : 100% string formation

thermal leptogenesis and Z_2 : $\sim 98\%$ string formation

thermal leptogenesis without Z_2 : $\sim 80\%$ string formation

within supersymmetric grand unified theories, cosmic strings formation is generic at the end of F-term hybrid inflation, in ssb schemes from the $G_{\rm GUT}$ down to the $G_{\rm SM}$

F-term strings

standard D-term inflation ends *always* with cosmic strings formation

D-term strings

simplest D-term inflation in sugra:

the constant fayet-iliopoulos term gets compensated by a single complex scalar field

⇒ the D-term strings are topologically stable

$$\pi_1(\mathcal{M}) \neq I \qquad \mathcal{M}: \text{ vacuum manifold of broken } U(1) \text{ symmetry}$$

there are models with D-term strings unstable[1]

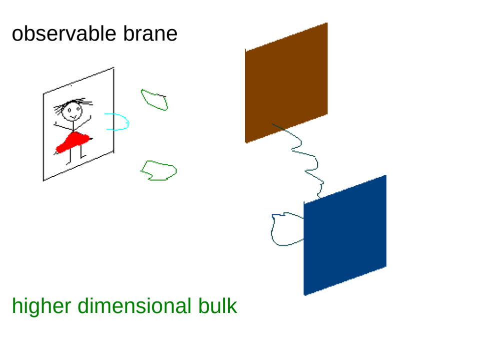
- introduce additional matter multiplets (so as to obtain a non-trivial global symmetry), leading to a simply connected vacuum manifold and the production of semi-local strings
- embed D-term inflation into some model with large gauge symmetry, leading to topologically unstable strings

[1] urrestilla, achucarro & davis 2004

binetruy, dvali, kallosh & &van proeyen 2004

cosmic superstring formation in braneworld cosmological models

brane inflation is caused by the attraction, and subsequent annihilation of a D-brane and a D-anti-brane



examples: $D3/\bar{D}3$ [1] $D3/D7$ [2]

$Dp - \bar{D}p$ brane inflation in IIB string theory:

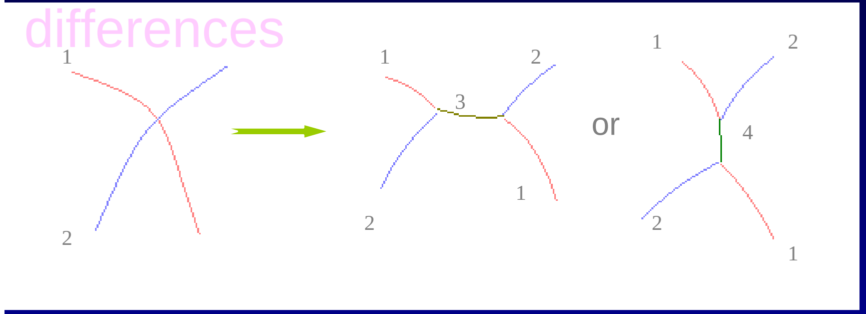
as the branes approach, the open string modes between the branes develop a tachyon; brane inflation ends by a phase transition mediated by open string tachyons

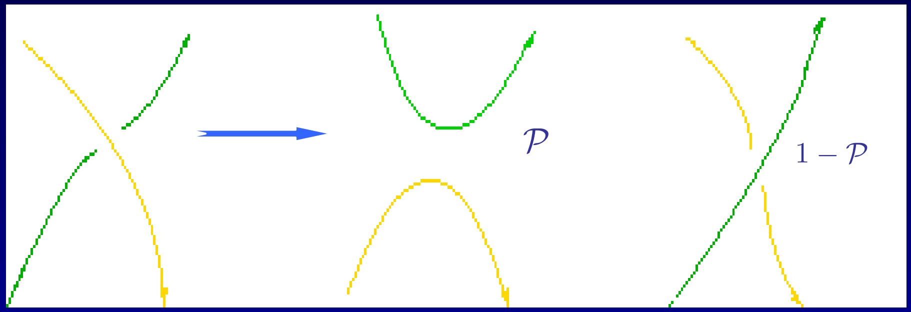
brane annihilation leads to lower dimensional branes with D3 and D1-branes favoured [3]; depending on the model, F-strings can also arise [4] and sometimes axionic local strings [5]

D-strings have been identified in the low-energy sugra with the D-term strings [6]

[1] kachru, kallosh ,linde, maldacena, mcallister & trivedi 2003
[2] dasgupta, herdeiro, hiano & kallosh 2002
[3] majumdar & davis 2002; durrer, kunz & sakellariadou 2005
[4] copeland, myers & polchinski 2004
[5] davis, binetruy & davis 2005
[6] dvali, kallosh & van proeyen 2004

the cosmic superstrings have many features in common with cosmic strings formed in a cosmological phase transition, but there is also a number of differences [1] [1]





the network reaches a scaling limit [2, 3]

$$\xi(t) \simeq \sqrt{\mathcal{P}} t$$ [2]

- FF-strings: $10^{-3} \leq \mathcal{P} \leq 1$
- DD-strings: $0.1 \leq \mathcal{P} \leq 1$
- FD-strings: $0 \leq \mathcal{P} \leq 1$

in r.d.e.[2] : $$\frac{\rho_{\rm strings}}{\rho_{\rm total}} = \frac{32\pi}{3} \frac{G\mu}{\mathcal{P}}$$

⇨ observational consequences [4]

[1] jackson, jones & polchinski 2004

[2] sakellariadou 2005

[3] copeland &shaffin 2005

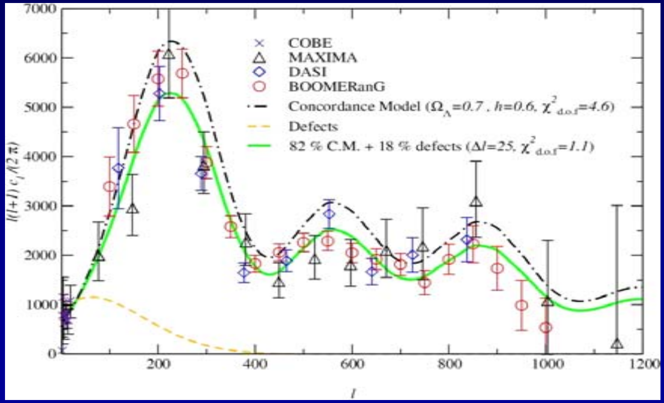
tye, wasserman & wyman 2005

hindmarsh & shaffin 2006

[4] e.g., damour & vilenkin 2005

<u>mixed models</u>: anisotropies in the cmb are induced both by quantum fluctuations of the inflaton and topological defects, created at the end of inflation

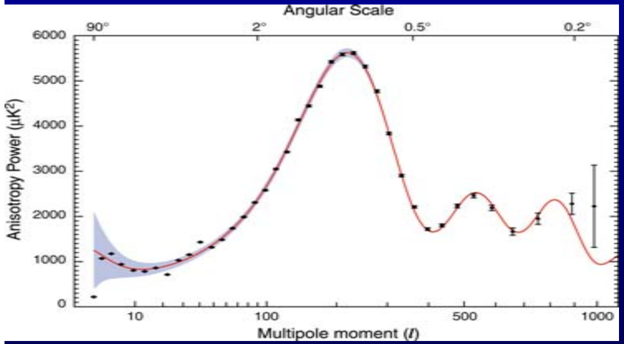
$$C_\ell = \alpha C_\ell^{\rm infl} + (1-\alpha) C_\ell^{\rm cs}$$



[1]

taking into account more recent cmb data:

the upper bound on the fraction of primordial fluctuations sourced by cosmic strings is [2] 14% and for D-term inflation considering WMAP3 data [3] 7%-11% ⇒ $G\mu < 2.7 \times 10^{-7}$



[4]

[1] bouchet, riazuelo, peter & sakellariadou 2001

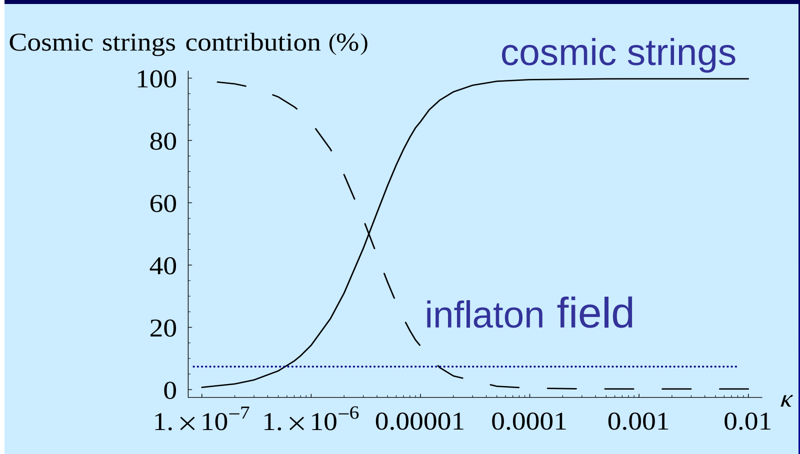
[2] pogosian, wyman & wasserman 2004; wyman, pogosian & wasserman 2005

[3] fraisse 2006

[4] spergel et al 2006

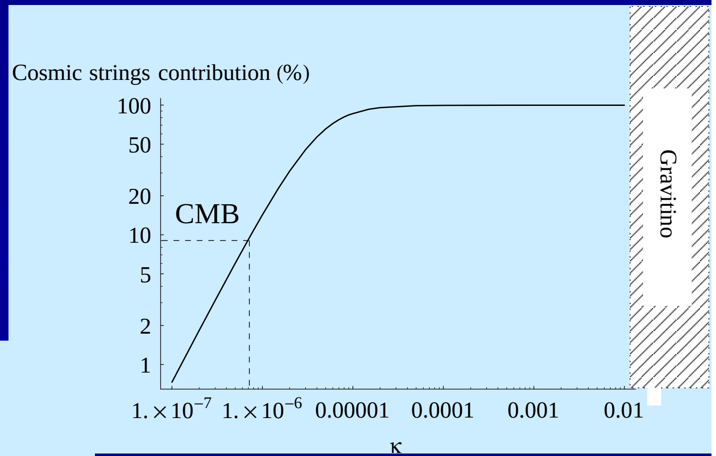
compatibility between predictions and constraints imposed from data

F-term hybrid inflation



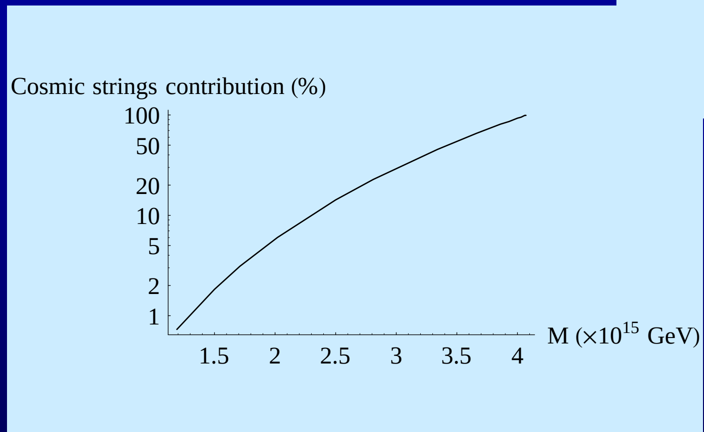
$\kappa \leq 7 \times 10^{-7}$ [1]

$\kappa \leq 8 \times 10^{-3}$ [1,2]



$G\mu < 2 \times 10^{-7}$

$M \leq 2 \times 10^{15} \mathrm{GeV}$

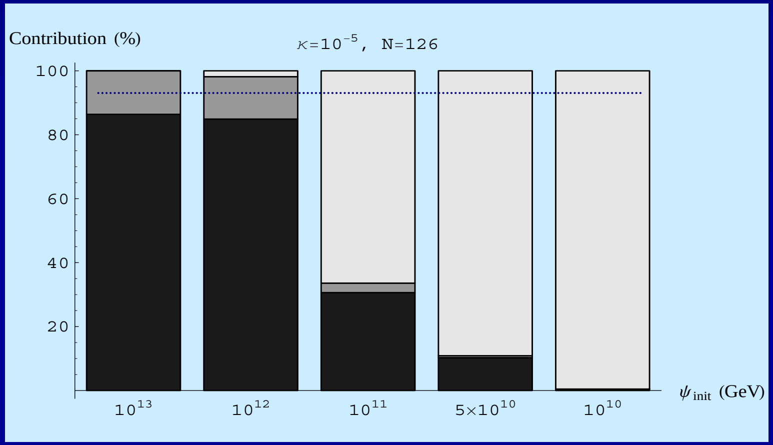


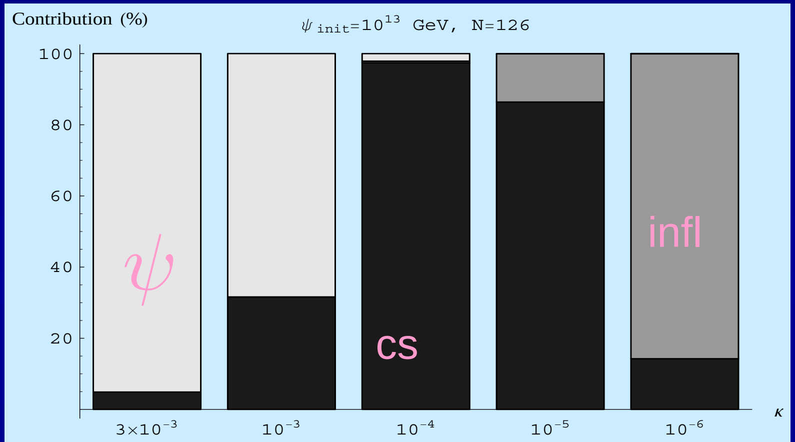
[1] rocher & sakellariadou 2005

[2] in agreement with: kallosh & linde 2003

curvaton mechanism:

$$\psi_{\rm init} \leq 5 \times 10^{13} \left(\frac{\kappa}{10^{-2}}\right) {\rm GeV}$$ [1]





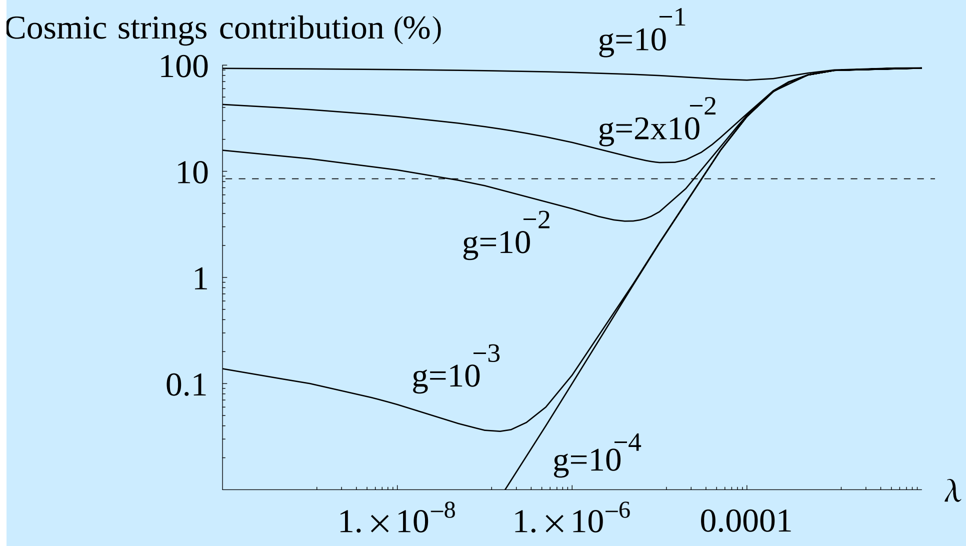
[1] rocher & sakellariadou 2005

D-term hybrid inflation

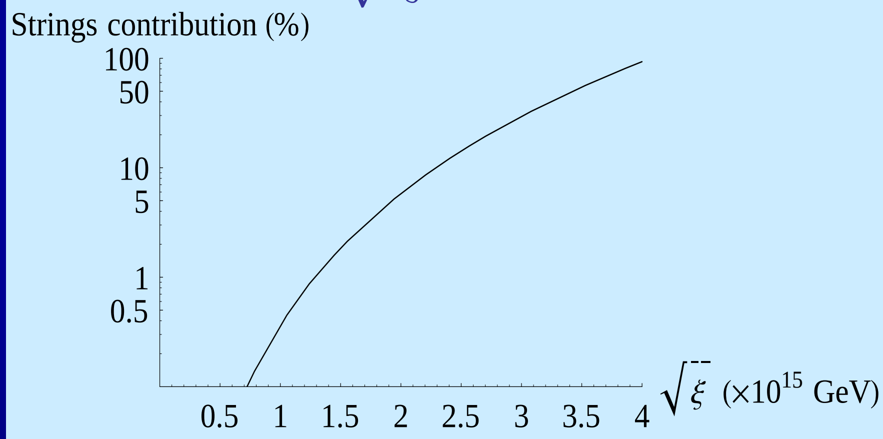
- minimal sugra (minimal kähler potential and minimal kinetic function)

$$K = |S|^2 + |\Phi_+|^2 + |\Phi_-|^2$$

[1] [1]



$$\sqrt{\xi} \leq 2 \times 10^{15}\mathrm{GeV}$$



for $g \leq 0.02 : \lambda \leq 3 \times 10^{-5}$ [1,2]

sugra imposes [1] also lower bound on λ

[1] rocher & sakellariadou 2005

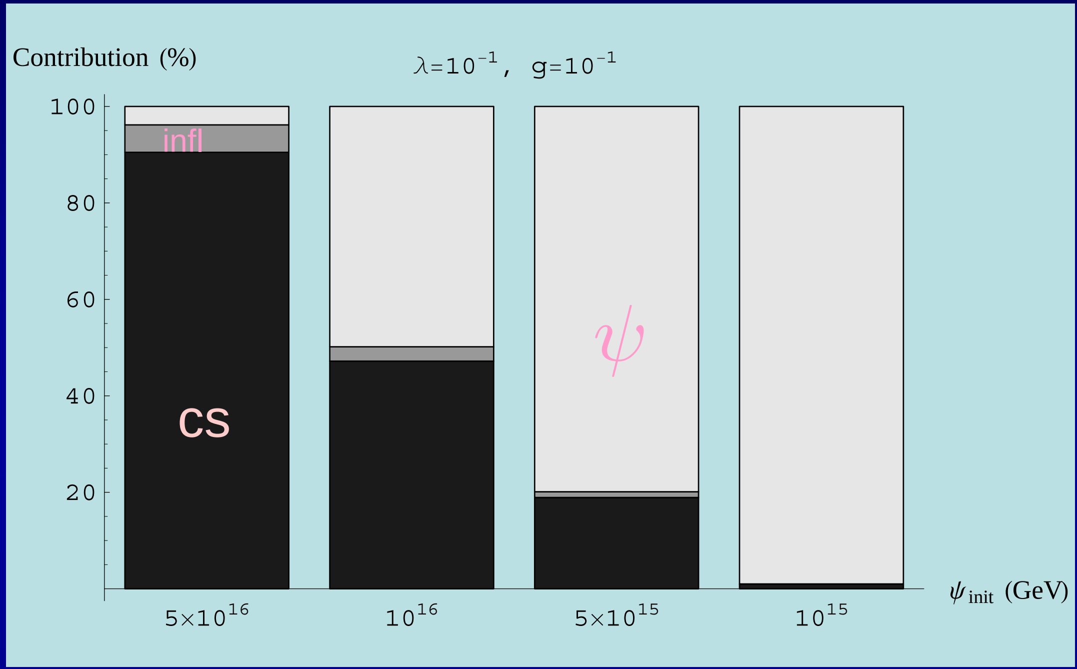
[2] in agreement with: endo, kawasaki & moroi 2003

consider a curvaton mechanism:

$$\psi_{\rm init} \leq 3 \times 10^{14} \left(\frac{g}{10^{-2}}\right) {\rm GeV}$$

for $\lambda \in [10^{-1}, 10^{-4}]$

for smaller values of λ, the curvaton mechanism is not necessary



[1]

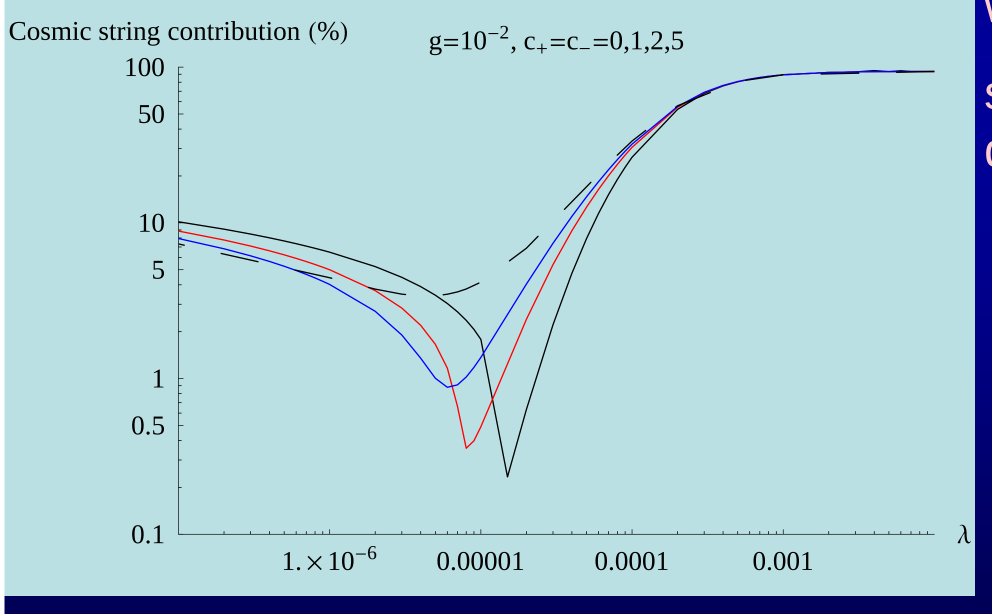
[1] rocher & sakellariadou 2005

- higher order terms[1]

$$K = |S|^2 + |\Phi_+|^2 + |\Phi_-|^2 + f_+\left(\frac{|S|^2}{M_{\rm Pl}^2}\right)|\Phi_+|^2 + f_-\left(\frac{|S|^2}{M_{\rm Pl}^2}\right)|\Phi_-|^2$$

$$f_\pm\left(\frac{|S|^2}{M_{\rm PL}^2}\right) = c_\pm\frac{|S|^2}{M_{\rm Pl}^2}$$

it was claimed that the contribution of strings gets really suppressed[1]



we disagree ![2]

strings have a high contribution to the cmb data unless the couplings are small[2]

$$[3\times10^{-8} - 2\times10^{-7}] \leq \lambda \leq [2.5\times10^{-5} - 5.3\times10^{-5}]$$ [2]

[1] seto & yokoyama 2006
[2] rocher & sakellariadou 2006

- keep all corrections up to the order $M_{\rm Pl}^{-2}$ [1]

$$K = |S|^2 + |\Phi_+|^2 + |\Phi_-|^2 + f_+\left(\frac{|S|^2}{M_{\rm Pl}^2}\right)|\Phi_+|^2 + f_-\left(\frac{|S|^2}{M_{\rm Pl}^2}\right)|\Phi_-|^2 + b\frac{|S|^4}{M_{\rm Pl}^{-2}}$$

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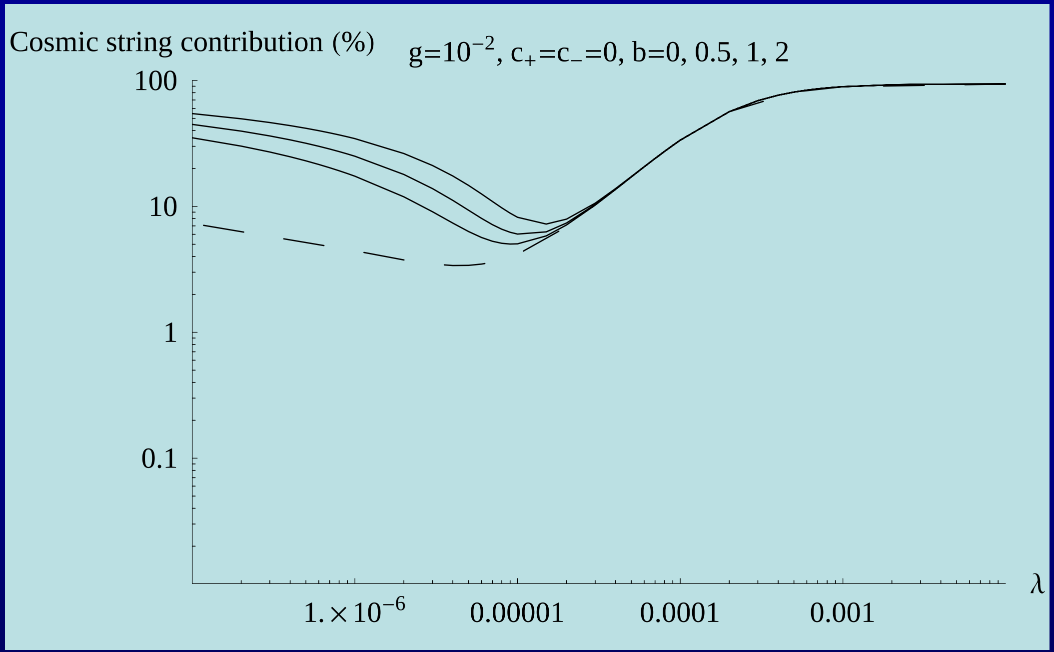


[1] rocher & sakellariadou 2006

- inflation with shift symmetry

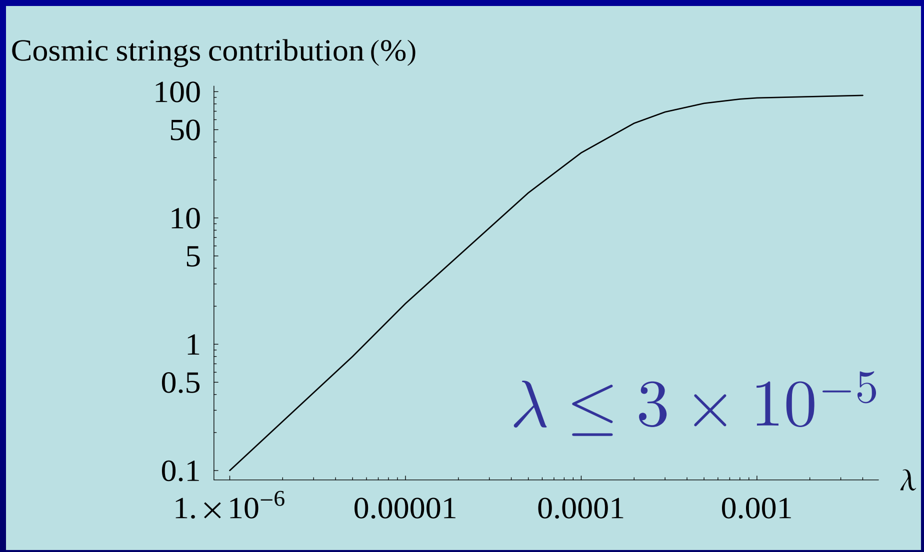
$$K = \frac{1}{2}(S+\bar{S})^2 + |\phi_+|^2 + |\phi_-|^2$$

$$S = \eta + i\phi_0$$

V as in D-term infl ation within SUSY

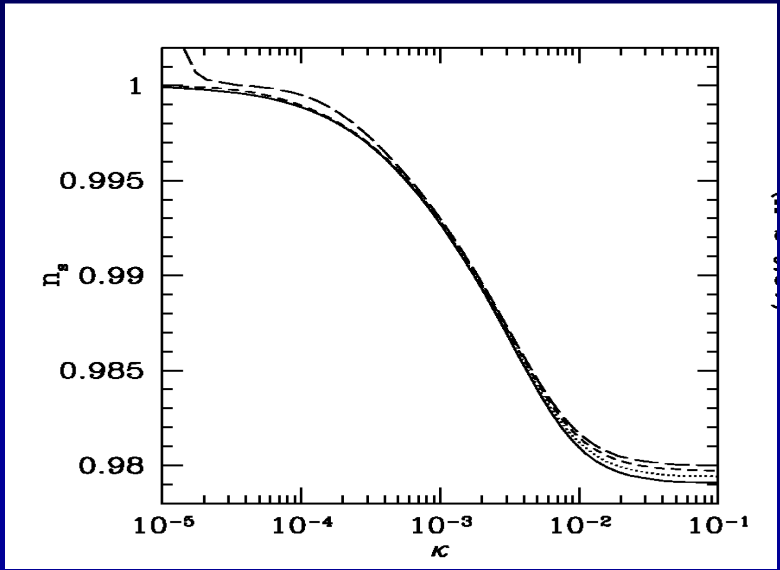
V as in the minimal SUGRA

[1]



[1] rocher & sakellariadou 2005,2006

spectral index for various values of g, in the context of minimal sugra [1]



[1]

cosmic strings contributing aroud 5% to the CMB on large scales, can increase the preferred value of spectral index

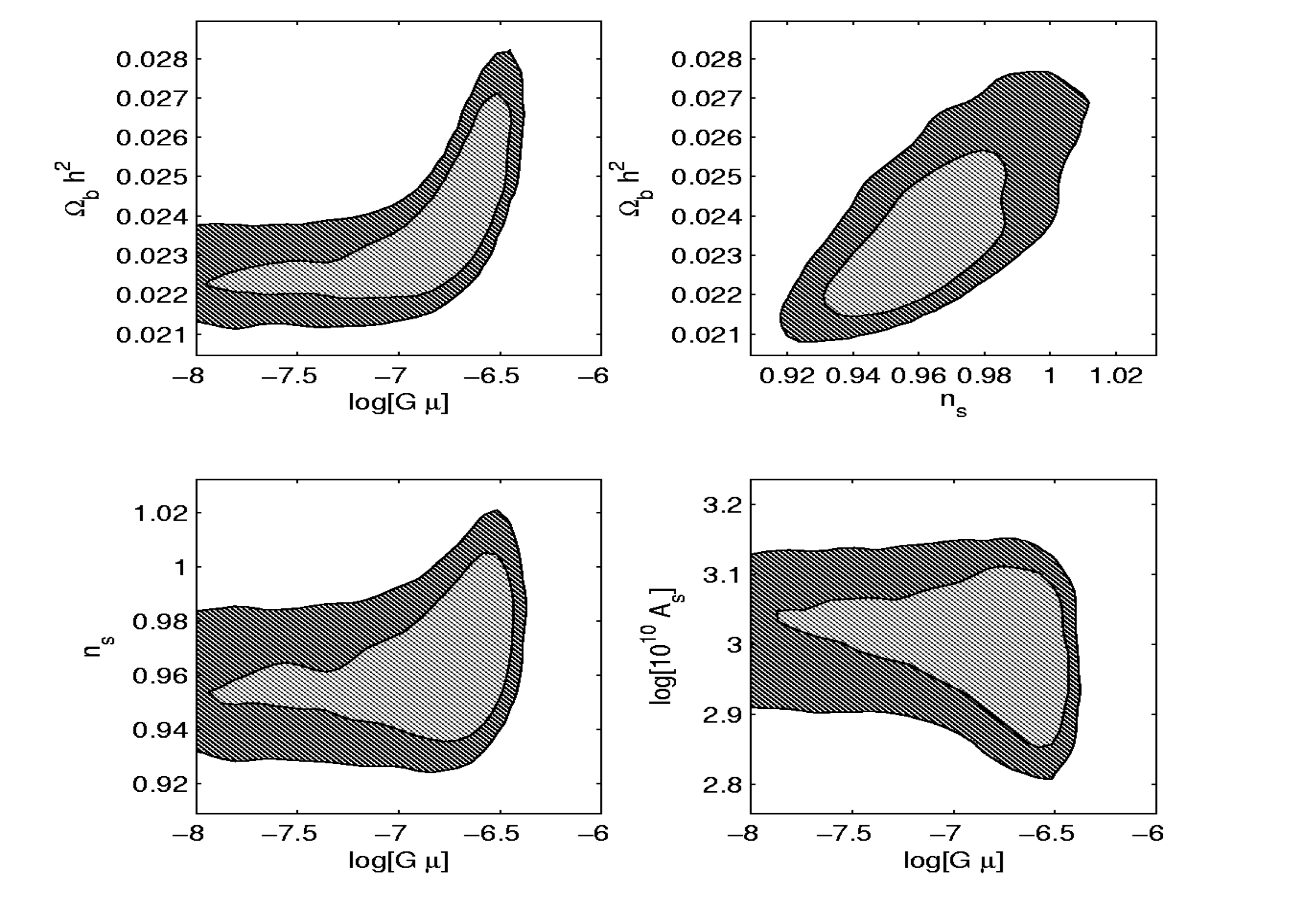
this can be applied to hybrid inflation models which predict $n_{\rm s} \geq 0.98$ in tension with WMAP3 data

WMAP: $n_{\rm s} = 0.951^{+0.015}_{-0.019}$

[1] battye, garbrecht & moss 2006

7 parameter fit to the CMB data, for minimal F-term hybrid inflation in sugra [1]

[1]



the contours are the 68% and 95% CL

[1] battye, garbrecht & moss 2006

conclusions

cosmic strings/superstrings form generically at the end of hybrid inflation within supersymmetric grand unified theories, or at the end of brane inflation within braneworld cosmological models inspired by string/M-theory

⇓

even though cosmic strings can not play a dominant role in structure formation, due to the cmb constraints, one has to consider them as a sub-dominant partner with tensions of the order of $G\mu \leq 10^{-6} - 10^{-7}$