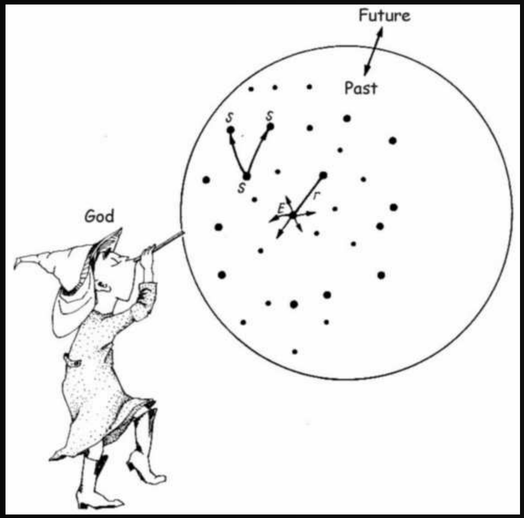
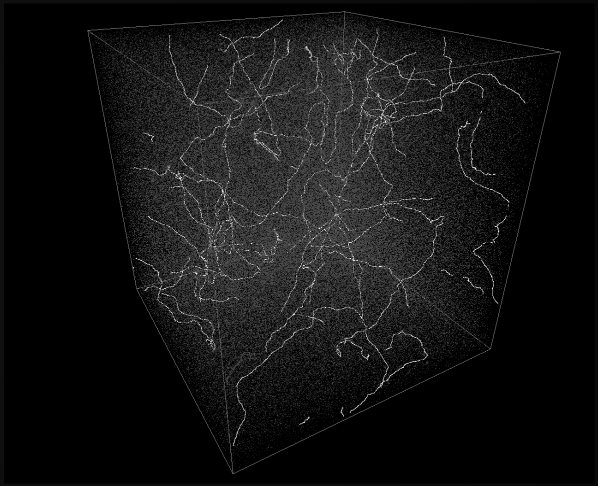
the reconciliation of cosmological inflation with cosmic strings





mairi sakellariadou
king's college, london

cosmological inflation and topological defects have been considerd for a long time, either in disagreement or in competition

however, on the one hand we need inflation, while on the other hand cosmic strings and string-like objects were formed in the early universe

⇩

one has to find ways that both can coexist

aim of my talk: how to reconcile inflation with cosmic strings

outline

- big bang model (successes & shortcomings)
- cosmological inflation
- topological defects (cosmic strings)
- cmb and constraints on strings
- genericity of cosmic strings and cosmic superstrings
- observational constraints
- conclusions

the hot big bang model

basic ingredient: general relativity and the choice of a metric

FLRW cosmological model --- the hot big bang model

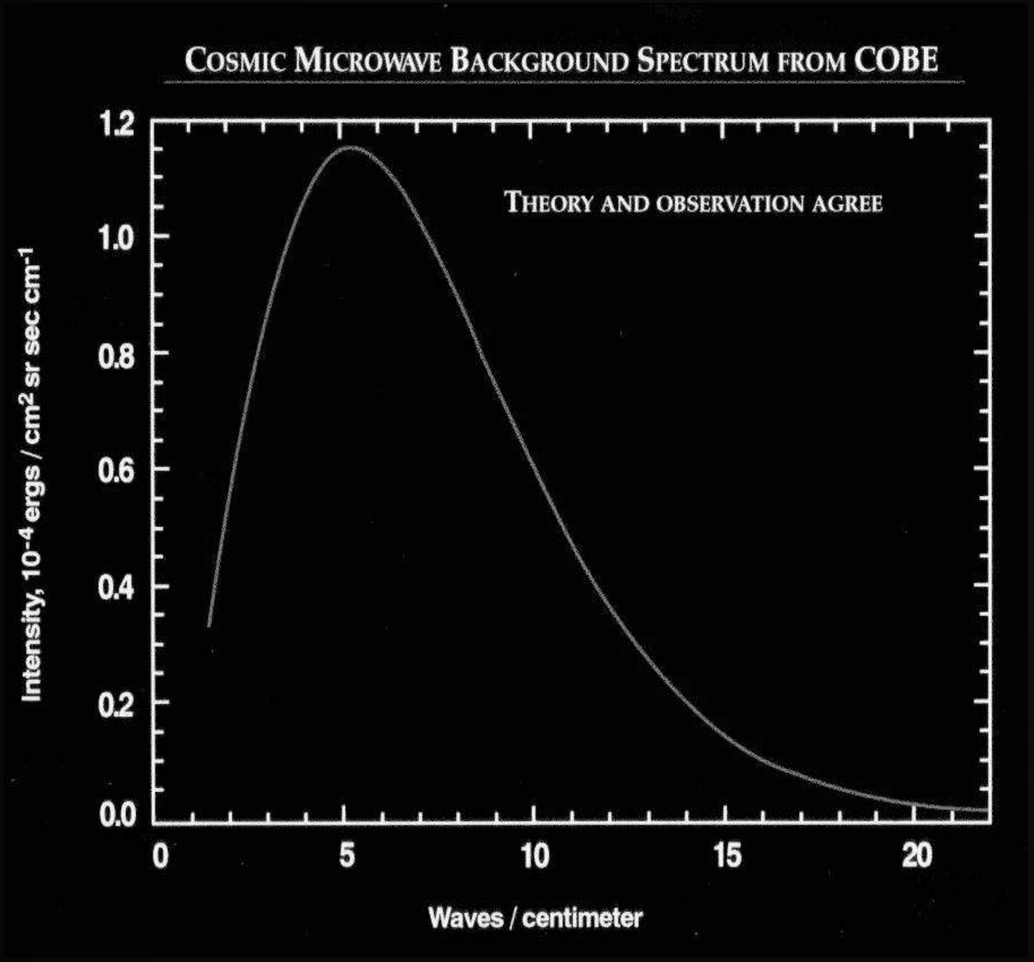
cornerstone of FLRW model: high degree of symmetry of FLRW metric;
there is only one dynamical variable $a(t)$

$$\begin{aligned} ds^2 &= -\,dt^2 + a^2(t)\gamma_{ij}dxdx^j \\ &= -\,a^2(\eta)d\eta^2 + a^2(\eta)\gamma_{ij}dxdx^j \end{aligned}$$

γ_{ij} the metric of a space with constant curvature

so successful ⟹ standard cosmology

the high degree of symmetry of the metric, originally a theorist's simplification, is now an evidence thanks to the remarkable uniformity of temperature of the cosmic microwave background (cmb) measured by COBE-DMR (1992) cmb radiation : perfect black body spectrum of cosmic photons



$$T_\gamma = 2.728 \pm 0.004\mathrm{K}$$

gamov (1946)

penzias & wilson (1965)

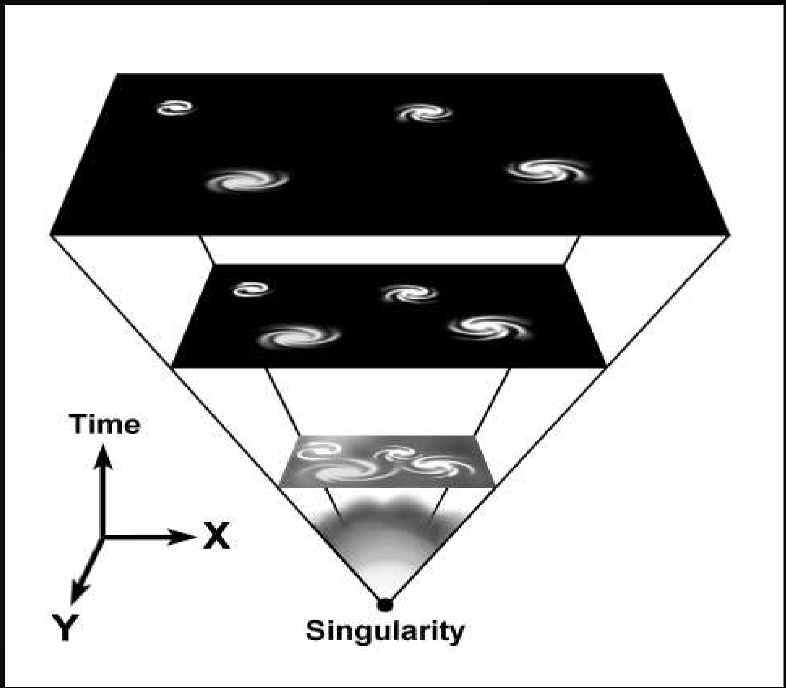
the cmb photons have not only a very thermal spectrum, but they are also distributed very isotropically

isotropy of 3K cmb:

a relic of the plasma of baryons, electrons and radiation at times before protons and electrons combined to form hydrogen

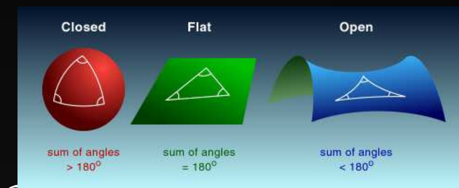
four pillars of the standard hot big bang model

- expansion of the universe
- origin of the cosmic background radiation
- synthesis of light elements
- formation of galaxies and large scale structure



but …

shortcomings of the standard hot big bang model

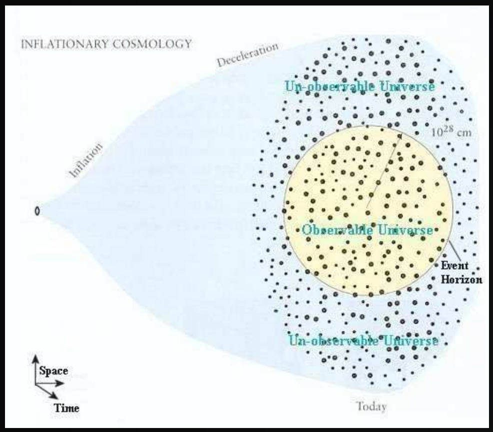


- horizon problem — consider an infinite (open or flat) universe; why all the causally disconnected regions of the infinite universe start their expansion simultaneously (at t=0)?
- flatness problem — why is our universe so flat?
- exotic relics — GUTs predict the existence of superheavy stable particles carrying magnetic charge (magnetic monopoles), with a typical mass 16 orders of magnitude bigger than the mass of proton; in this case the mean density of matter would be about 15 orders of magnitude higher than its present value
- homogeneity problem — why is the universe extremely homogeneous in very large scales? on the scale of 10^{10} l.y. the distribution of matter departs from perfect homogeneity by less than a part in a thousand
- density fluctuations — what is the origin of the important inhomogeneities in small scales, leading to the observed structure formation?
- cosmological constant
- singularity problem — what happened before the big bang?

solution ?

inflation

era of repulsive gravity $\ddot{a} > 0$



the scale factor of the universe changed more than 10^{40} in 10^{-32} sec

at that time, the universe was less than 1 cm

acceleration equation $$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

$$\Longleftrightarrow \quad 3p < -\rho$$

the fluid dominating the matter content of the universe must have $p < 0$

scalar field -- inflaton

guth (1981); linde (1981)

during inflation the energy density & pressure are dominated by a scalar field ϕ with

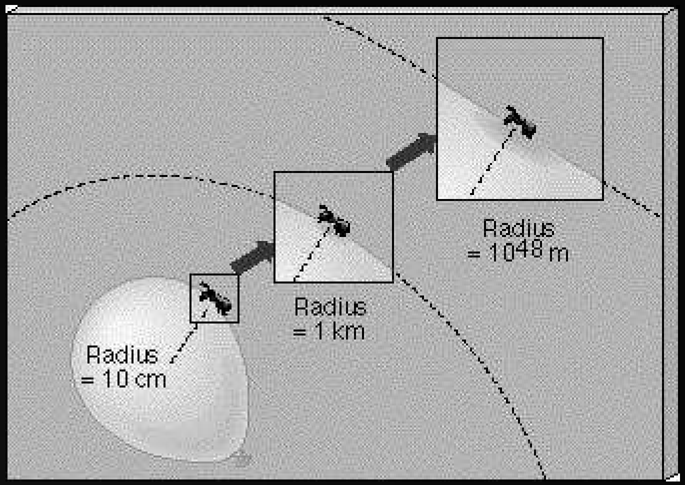
$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi) \qquad p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

if $V(\phi) \gg \dot{\phi}^2$ one obtains $p \simeq -\rho$ ➡ $p < 0$

energy conservation: $\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + p) = 0$ ➡ ρ is constant

friedmann eq. $\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$ ➡ $a(t) \propto e^{\mathrm{const.}\ t}$

this rapid expansion flattened space and also allowed regions already in communication to become spread over vast regions, thus explaining the high degree of uniformity seen today



after inflation, vast amounts of energy were released, that reheated the universe and eventually condensed into all the matter seen today

although inflation produces a broadly uniform universe, it also predicts a fairly specific amount of irregularity—about the amount needed to serve as seeds for the gravitational clustering that led to the formation of galaxies 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

- topological defects

the universe has steadily cooled down since the planck time ⟹ spontaneous breaking of symmetries (ssb) must have occurred

ssb may lead to the creation of topological defects, such as domain walls, cosmic strings, monopoles, or textures, which are false vacuum remnants

kibble (1976)

ssb: G ⟶ H , with $\mathrm{H} \subset \mathrm{G}$ by the condensation of a Higgs field ϕ

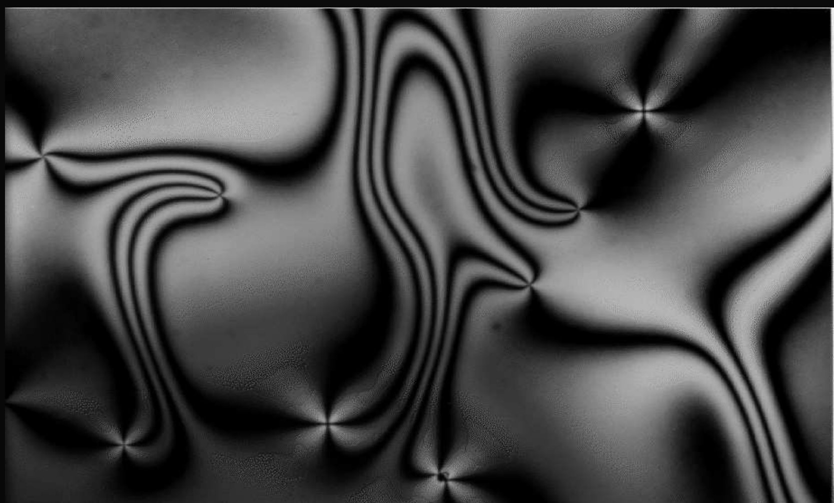
defect formation during SSB depends on the homotopy groups $\pi_k(G/H)$ of the vacuum maniford $\mathcal{M} = G/H$:

if $\pi_k(G/H) \neq I$ then $(2-k)$ –dim defects appear

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

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

cobe normalisation: $T_{\mathrm{c}}^2/m_{\mathrm{Pl}}^2 \sim 10^{-5}$ $\Longrightarrow$ GUT scale cosmic strings liquid crystals exhibit an array of topological defects:



point defects in nematic liquid crystal

domain walls connecting point defects
in nematic liquid crystal

defects can also been found in biochemistry, notably in the process of protein folding analogue: the time of the day

in principle, at any time of the day, we could choose any possible value from the whole range of possibilities from 00:00 to 23:59; there is a circle of possibilities

to avoid problems we do not use a separate time convention from the rest of the country;

worldwide however different countries use different time zones

the time zones correspond to a spontaneous breakdown of a continuous symmetry; vortices appear which are the north and south poles

around each pole the time zone changes by a full 24 hours around any closed path that encircles a pole

the time zone is not well defined at the pole itself; the symmetry is therefore restored there

early universe: cosmic strings

the abelian higgs model : consider a complex scalar field ϕ with lagrangian density

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

field strength tensor

$$V(\phi) = \frac{1}{4}\lambda[\bar{\phi}\phi - \phi_0^2]^2$$

+tive constants

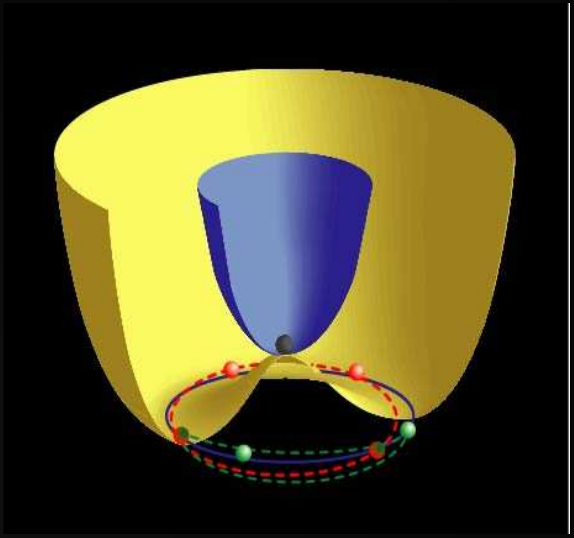
$$F_{\mu\nu} = \vartheta_\mu A_\nu - \vartheta_\nu A_\mu$$

$$\mathcal{D}_\mu = \vartheta_\mu - ieA_\mu$$

covariant derivative

gauge coupling constant

gauge field



the minima of V lie on a circle of fixed radius $|\phi| = \phi_0$ ⇒ symmetry is spontaneously broken & field ϕ acquires a nonzero VEV

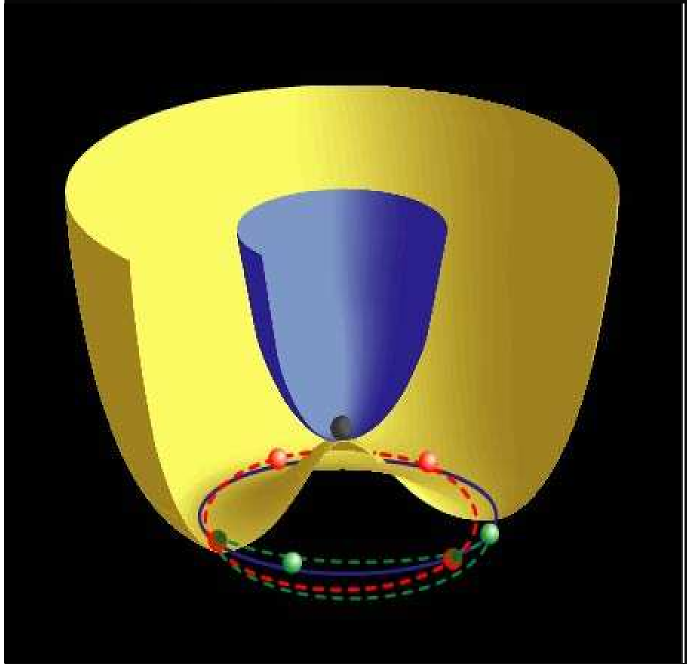
$$< 0|\phi|0 >= \phi_0 e^{i\theta}$$

the vacuum |0> is not invariant under phase transformation

the model is invariant under the group **U(1)** of local gauge transformations

$$\phi(x) \longrightarrow e^{i\alpha(x)}\phi(x) \qquad A_\mu(x) \longrightarrow A_\mu(x) + \frac{1}{e}\vartheta_\mu \alpha(x)$$

a real single-valued function



going around a closed path L in plysical space, the phase θ of the higgs field ϕ develops a nontrivial winding, $\Delta\theta = 2\pi$

this closed path can be shrunk continuously to a point, only if the field ϕ is lifted to the top of its potential where it takes the value $\phi = 0$

within a closed path for which the total change of the phase of the higgs field ϕ is 2π, a string is trapped

a string must be either a closed loop or an infinitely long (no ends) string, since otherwise one could deform the closed path L and avoid to cross a string the abelian-higgs model is the simplest model which admits string solutions, the nielsen-olesen vortex lines

width of the string $\delta \sim \frac{1}{T_{\rm crit}}$

string linear mass density $\mu \sim T_{\rm crit}^{\,2}$

far from the string core the energy density vanishes exponentially

the string internal structure is meaningless when we deal with scales much larger than the string width

for a straight string along the z-axis, the effective energy-momentum is:

$$T^{\mu}{}_{\nu} = \mu\delta(x)\delta(y){\rm diag}(1,0,0,1)$$

cosmic string dynamics

the world history of a string is expressed by a 2-dim surface in the 4-dim spacetime

$$x^\mu = x^\mu(\zeta^a) \;\; ; \;\; a = 0, 1$$

worldsheet coord: ζ^0 timelike ; $\zeta^1 \equiv \sigma$ spacelike

the string eqs of motion in the limit of a zero thickness string, are derived from the goto-nambu effective action :

$$S_0[x^\mu] = -\,\mu \int \underbrace{\sqrt{-\,\gamma}\, d^2\zeta}$$

surface area swept out by the string in spacetime

γ : the determinant of the 2-dim worldsheet metric γ_{ab}

$$\gamma = \det(\gamma_{ab}) = \tfrac{1}{2}\epsilon^{ac}\epsilon^{bd}\gamma_{ab}\gamma_{cd} \qquad \gamma_{ab} = g_{\mu\nu}x^\mu_{,a}x^\nu_{,b}$$

cosmic strings in a FLRW metric:

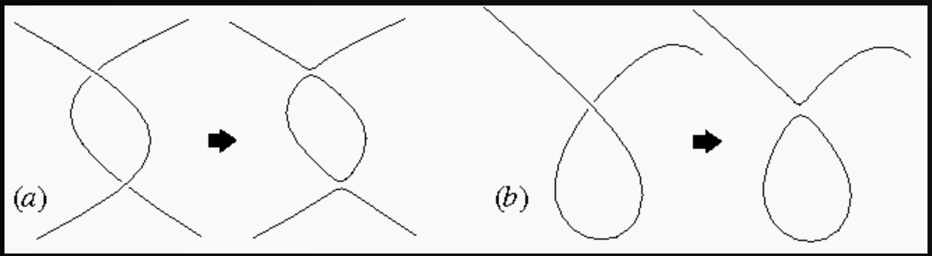
$$\ddot{\mathbf{x}} + 2\left(\frac{\dot{a}}{a}\right)\dot{\mathbf{x}}(1-\dot{\mathbf{x}}^2) = \left(\frac{1}{\epsilon}\right)\left(\frac{\mathbf{x}'}{\epsilon}\right)'$$

$$\epsilon \equiv \sqrt{\mathbf{x}'^2/(1-\dot{\mathbf{x}}^2)}$$

ζ^0: conformal time

string energy per unit σ

$$\dot{\mathbf{x}} \cdot \mathbf{x}' = 0$$



$$\mathcal{P} = 1$$ [1]

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

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]

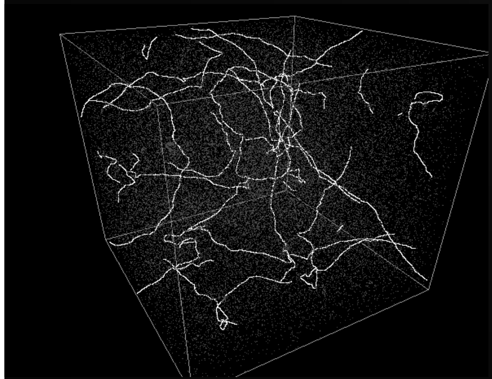
early numerical simulations[2] revealed dynamical processes at scales $\ll \xi$

3-scale model[3]: interstring separation ξ, curvature scale, 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

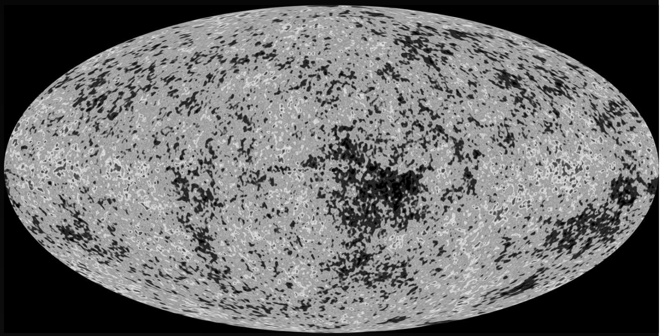
[2] bennett & bouchet 1988; sakellariadou & vilenkin 1990

[3] austin, copeland & kibble 1993

[4] vincent, hindmarsh & sakellariadou 1997

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

cosmic microwave background



recombination:

at $T \approx 3000\mathrm{K}$ electrons and protons formed neutral hydrogen

earlier, free electrons acted as glue between the photons and baryons through thomson and coulomb scattering

the cosmological plasma was a tightly coupled photon-baryon fluid

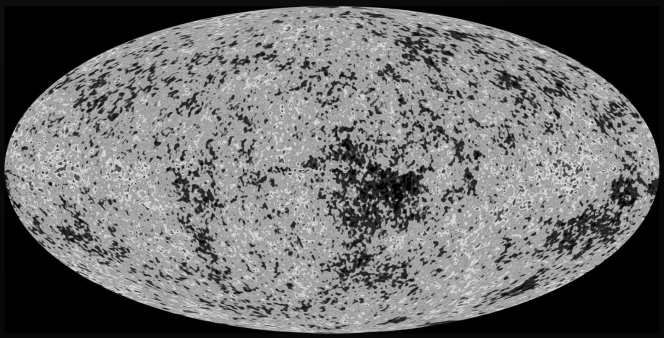
after recombination, the universe becomes transparent for cmb photons, and they move along geodesics of the perturbed friedmann geometry the remarkable uniformity of the cmb indicates that at the epoch of last scattering for the CMB ($\sim 200,000$ yr after the bang, $T \simeq 0.26$ eV $\simeq 3000$ K) the universe was to a high degree of precision (10^{-5}) isotropic and homogeneous

- at very large scales $(\gg 100\text{Mpc} \simeq 10^{21}\text{km})$: the universe is smooth
- at small scales : the universe is very lumpy

$$\left(\frac{\delta\rho}{\rho}\right)_{\rm dec} = \text{const.} \times \left(\frac{\delta T}{T}\right) \preceq \mathcal{O}(10^{-2} - 10^{-3})$$

It depends upon the nature of density perturbations $\mathcal{O}(10 - 100)$

the universe at decoupling was very smooth and today is very lumpy



how did this happen ?

in the 1980's and 1990's, cosmologists had the following picture in mind:

small, primeval density inhomogeneities grew via gravitational instability into the large inhomogeneities we observe today

at this point we add more ingredients (scalar fields) to the cosmological model; this is where high energy physics enters the picture

to construct a detailed scenario of structure formation one needs to know the initial conditions for that epoch: total amount of non-relativistic matter; composition of the universe; spectrum & type of primeval density perturbations

theoretical models of structure formation

- inflationary model:

  quantum fluctuations are amplified during inflation and produce

  adiabatic (curvature), gaussian, nearly scale invariant fluctuations

  fluctuations in the local value of the spatial curvature

  $$|\delta_k|^2 \propto k^{-3}$$

- cosmic strings trigger isocurvature (isothermal), non-gaussian and scale invariant fluctuations

  fluctuations in the form of the local equation of state

$\mathcal{D}X = \mathcal{S}$ for given initial conditions, this eq. can be solved by means of a green's function:

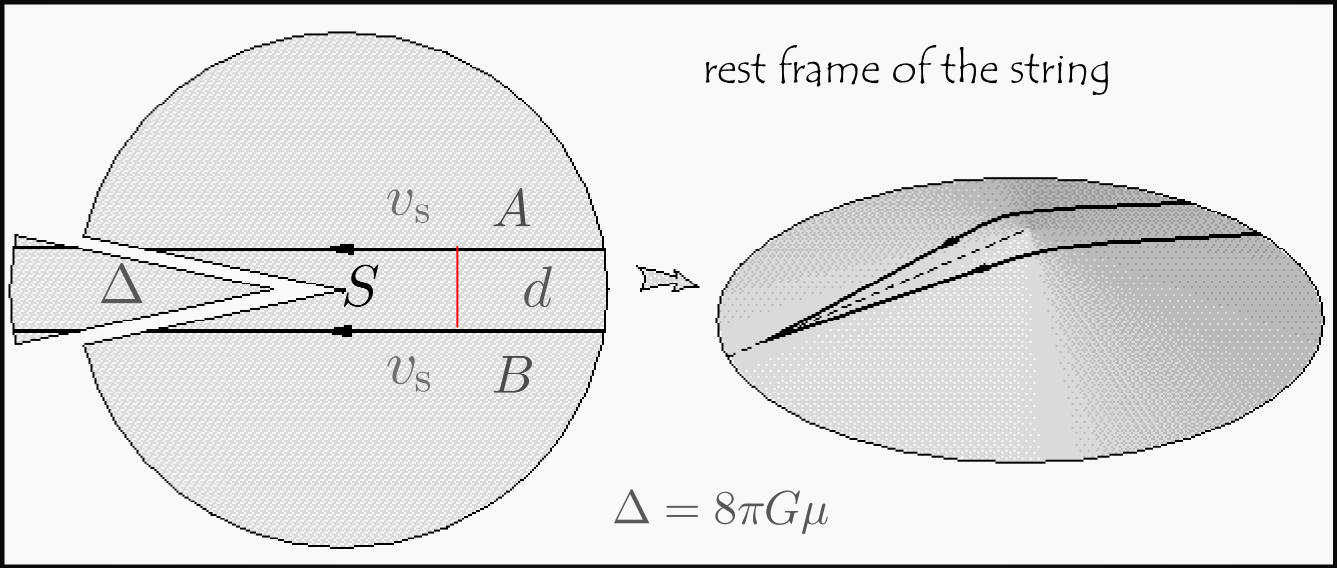
$$X_j(\eta_0, \mathbf{k}) = \int_{\eta_{\rm in}}^{\eta_0} \mathcal{G}_{jm}(\eta_0, \eta, \mathbf{k}) \mathcal{S}_m(\eta, \mathbf{k})$$

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
heavy numerical simulations !

the kaiser-stebbins effect: discontinuity in the cmb temperature due to a moving string between the observer and the cmb



rest frame of particles:

if particle A emits photons at frequency ω and B receives them, as soon as the string has passed, B observes a doppler shift due to their relative motion with velocity $u = \delta\omega/\omega = \gamma v_s \Delta$

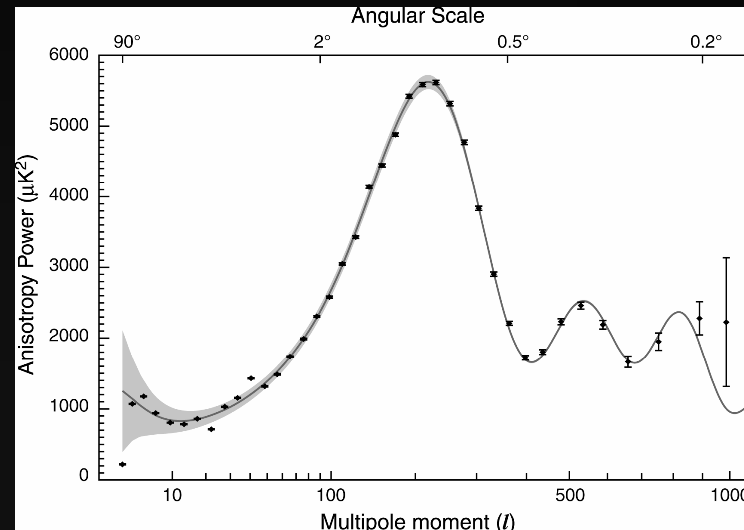
$$\langle \frac{\Delta T}{T_0}(\hat{n}_1)\frac{\Delta T}{T_0}(\hat{n}_2)\rangle = \frac{1}{4\pi}\sum_\ell (2\ell+1)C_\ell P_\ell(\hat{n}_1\cdot\hat{n}_2)\ \mathcal{W}_\ell^2$$

1st peak at $\ell = 220.7 \pm 0.7$

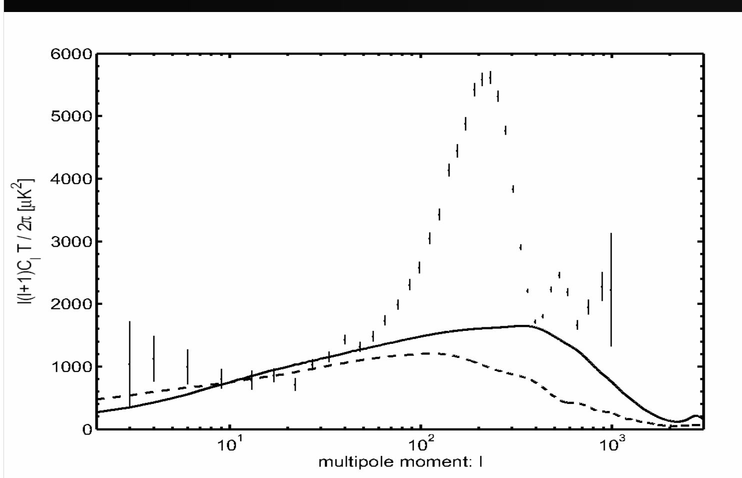
with amplitude $74.7 \pm 0.5\mu\mathrm{K}$

2nd peak at $\ell = 531.3 \pm 3.5$

with amplitude $48.8 \pm 0.9\mu\mathrm{K}$



hinshaw et al 2006



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

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

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

bevis, hindmarsh, kunz & urrestilla 2006 topological defects are ruled out as the unique source of the cmb anisotropies

durrer, gangui & sakellariadou 1996
durrer, kunz, lineawever & sakellariadou 1997
allen et al 1997
contaldi, hindmarsh & magueijo 1999

⇓

what are the implications for the high energy physics model upon which the cosmological scenario is based?

- how generic is cosmic strings formation ?
- which is the role of cosmic strings, if any ?
- which is a natural inflationary scenario (a paradigm in search of a model) ?

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

$G_{GUT} \rightarrow \ldots \rightarrow \underbrace{SU(3)_C \times SU(2)_L \times U(1)_Y}_{SM} \times Z_2$

Z_2: 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

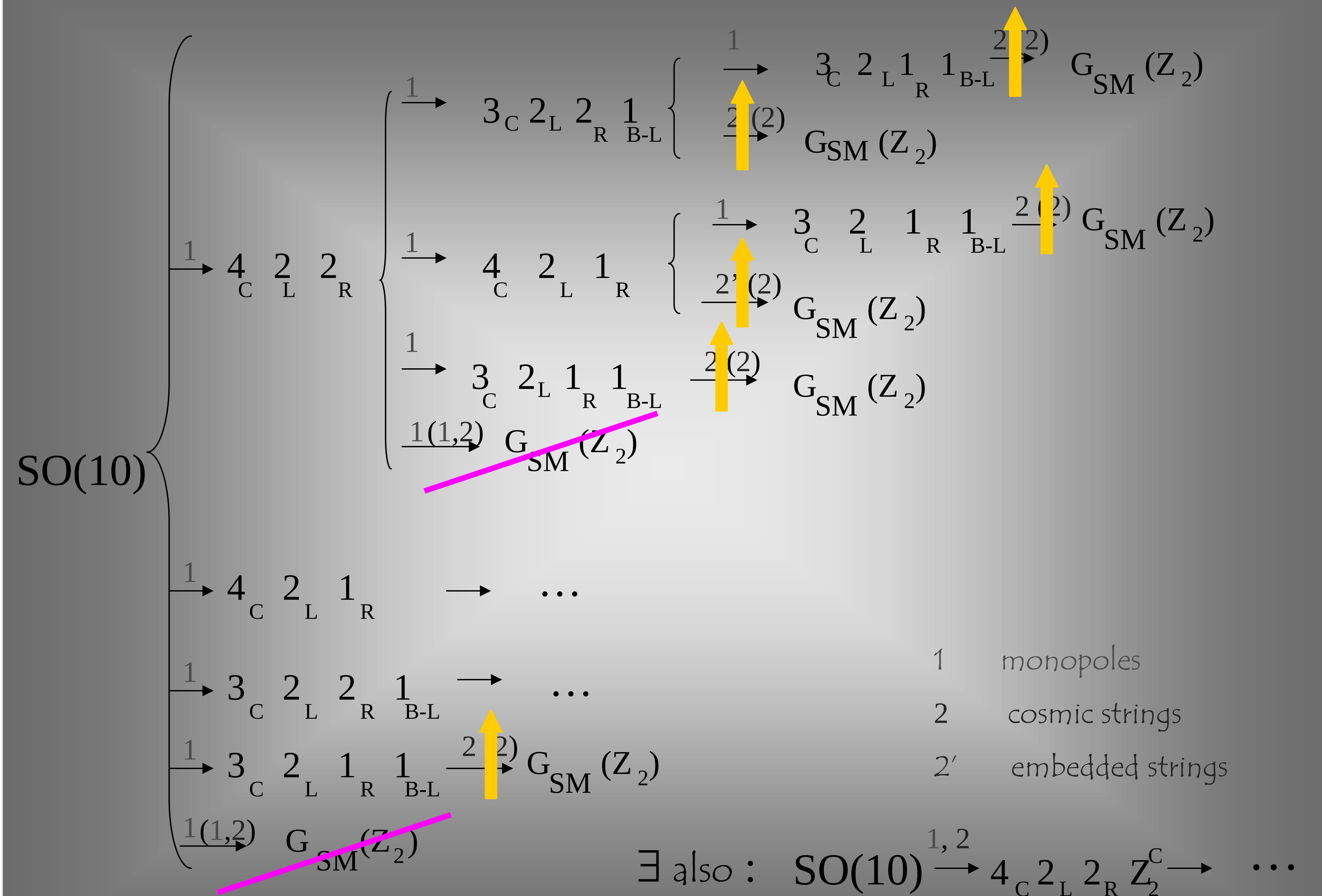
~~SU(5)~~, ~~SU(6)~~, ~~SU(7)~~, SU(8), SU(9) SO(10), SO(14), E6

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) non-thermal leptogenesis: $U(1)_{B-L} \subset G_{GUT}$ and $\not{B}\text{-}L$ at the end/after inflation (ii) thermal leptogenesis: $\not{B}\text{-}L$ independently of inflation; if $\not{B}\text{-}L$ before inflation: $T_{\not{B}-L} \sim M_{\nu_{\rm R}} < T_{\rm reheating} < T_{\rm gravitino\ limit}$
- 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
∃ also : SO(10) 1, 2 → 4_C 2_L 2_R Z_2^C → …

E_6

non-thermal leptogenesis and Z_2 : 100% string formation

thermal leptogenesis and Z_2 : ~ 98% string formation

thermal leptogenesis without Z_2 : ~ 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 $G_{\rm SM}$

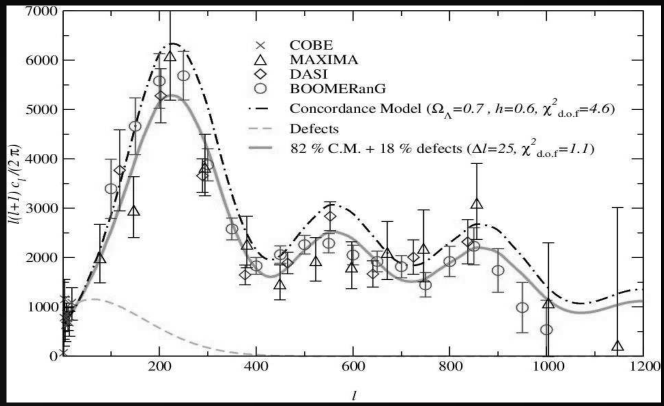
F-term strings

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

D-term strings

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

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

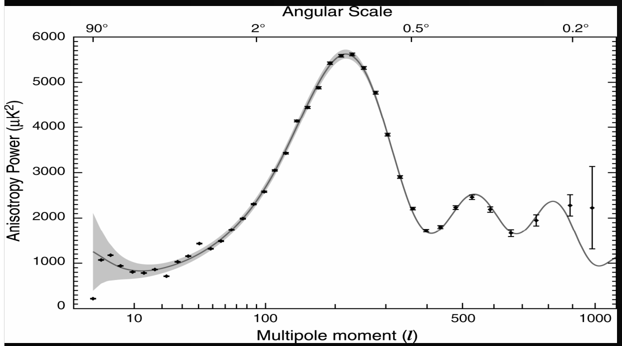


[1]

taking into account more recent cmb data:

the upper bound on the fraction of primordial fluctuations sourced by cosmic strings is **10%**[2]

$$G\mu \leq 1.8(2.7)\times 10^{-7}$$



[3]

[1] bouchet, riazuelo, peter & sakellariadou 2001

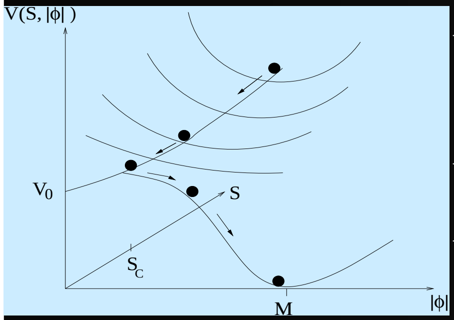
[2] pogosian, wyman & wasserman 2004; wyman, pogosian & wasserman 2005

[3] spergel et al 2006

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

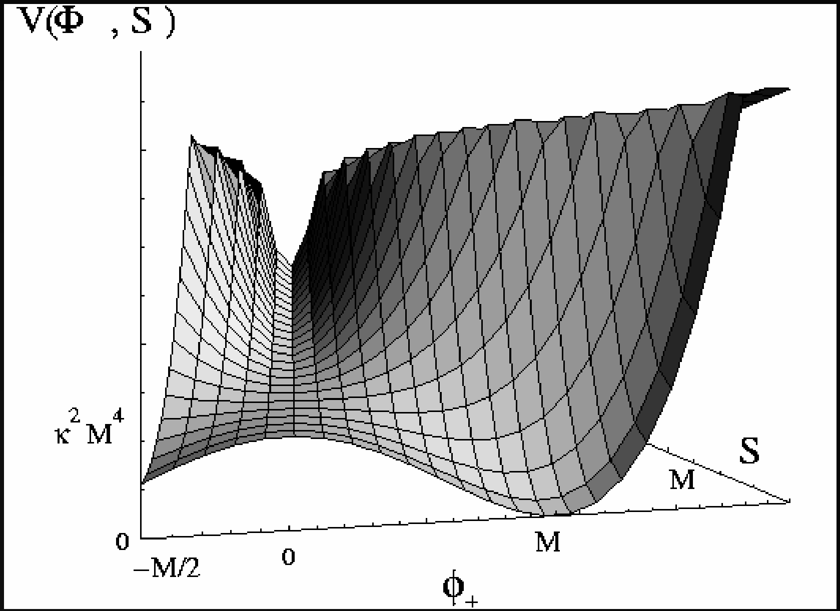
[1] linde 1983

[2] linde 1991, 1994

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

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 quadrupole temperature anisotropy:

$$\left[\left(\frac{\delta T}{T}\right)^{\mathrm{Q-tot}}\right]^2 = \left[\left(\frac{\delta T}{T}\right)^{\mathrm{Q-inf}}\right]^2 + \left[\left(\frac{\delta T}{T}\right)^{\mathrm{Q-cs}}\right]^2$$

$$\Uparrow$$

$$\left[\left(\frac{\delta T}{T}\right)^{\mathrm{Q-S}}\right]^2 + \left[\left(\frac{\delta T}{T}\right)^{\mathrm{Q-T}}\right]^2$$

scalar   tensor

sachs-wolfe effect

inflation

$$\left(\frac{\delta T}{T}\right)^{\mathrm{Q-S}} = \frac{1}{4\sqrt{45}\pi M_{\mathrm{Pl}}^3}\frac{V^{3/2}}{V'}$$

$$\left(\frac{\delta T}{T}\right)^{\mathrm{Q-T}} \sim \frac{0.77}{8\pi}\ \frac{V^{1/2}}{M_{\mathrm{Pl}}^2}$$

$$\left(\frac{\delta T}{T}\right)^{\mathrm{Q-cs}} \sim (9-10)G\mu \quad \text{with} \quad \mu = 2\pi\langle\varphi\rangle^2$$

cosmic strings

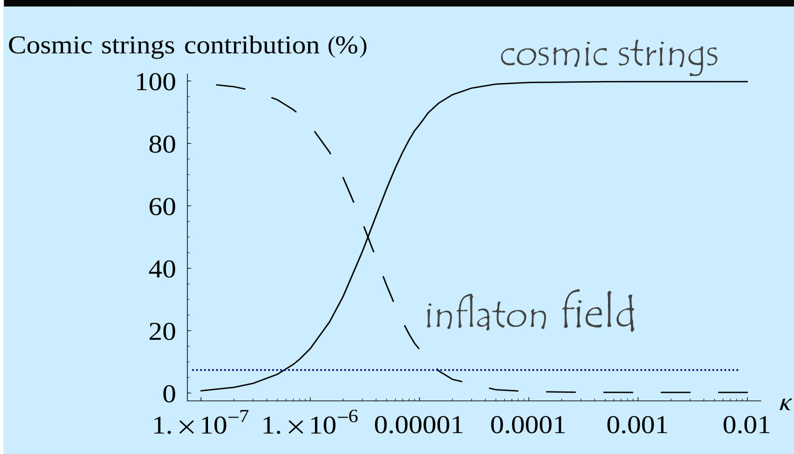
$$\sim \frac{9}{4}\left(\frac{M}{M_{\mathrm{Pl}}}\right)^2$$

landriau & shellard (2004)

normalize the total quadrupole temepature anisotropy to the cobe measurements 6.3×10^{-6}

compatibility between predictions and constraints imposed from data

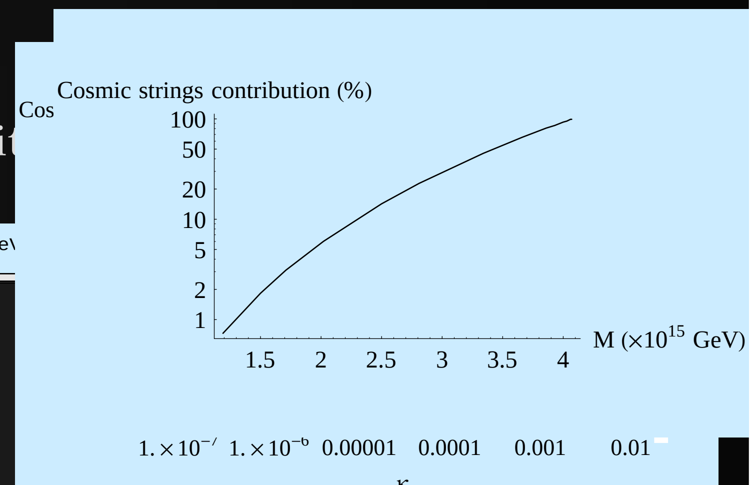
F-term hybrid inflation

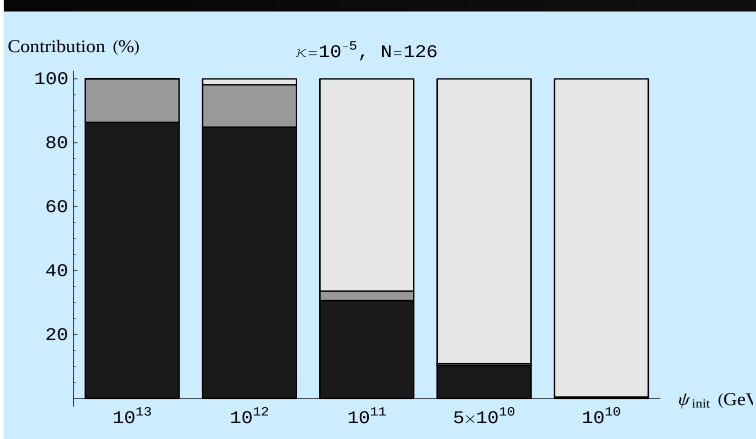


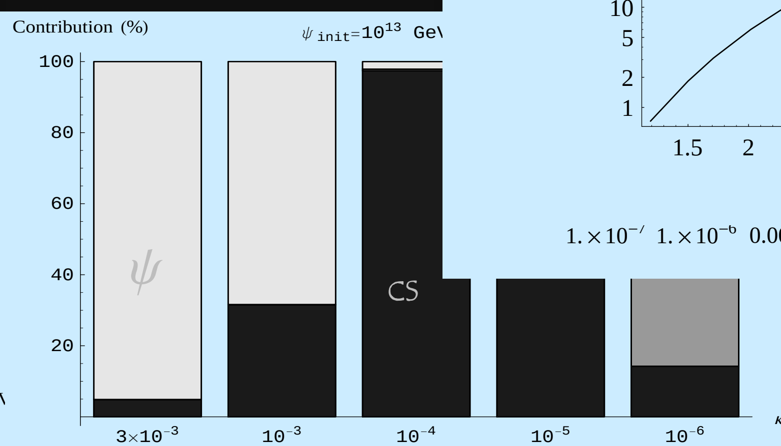
[1]

$\kappa \leq 7 \times 10^{-7}$ [1,2]

$\psi_{\rm init}$







[1] rocher & sakellariadou 2005

[2] in agreement with: kallosh & linde 2003

D-term hybrid inflation in supergravity

superpotential[1]

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

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

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

it depends on the combination $G(\Phi_i, \bar{\Phi}_i) = \frac{K(\Phi_i, \bar{\Phi}_i)}{M^2_{\mathrm{Pl}}} + \ln \frac{|W(\Phi_i)|^2}{M^6_{\mathrm{Pl}}}$

ill-defined[2] formulation at W=0

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

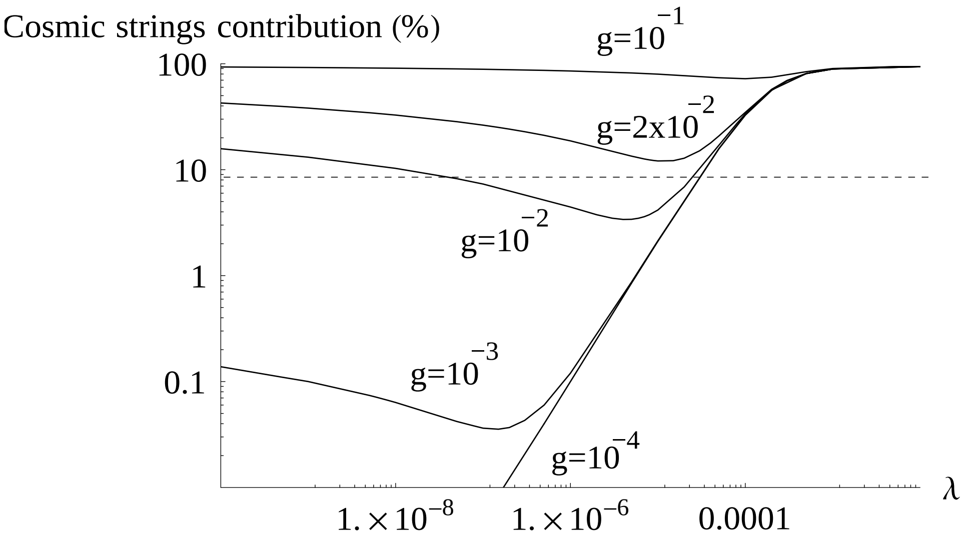
supergravity constructed[2] from superconformal theory

[1] halyo 1996 ; binetruy & dvali 1996
[2] binetruy, dvali, kallosh & van proyen 2004

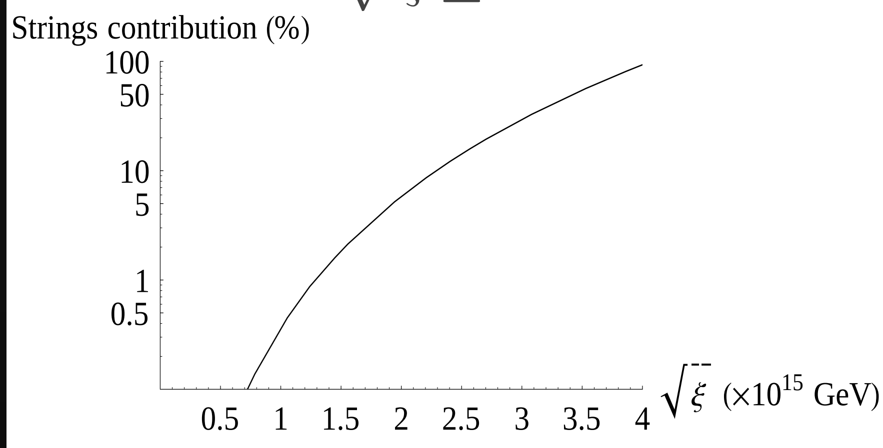
D-term hybrid inflation

minimal sugra (minimal kahler potential and minimal kinetic function)

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



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



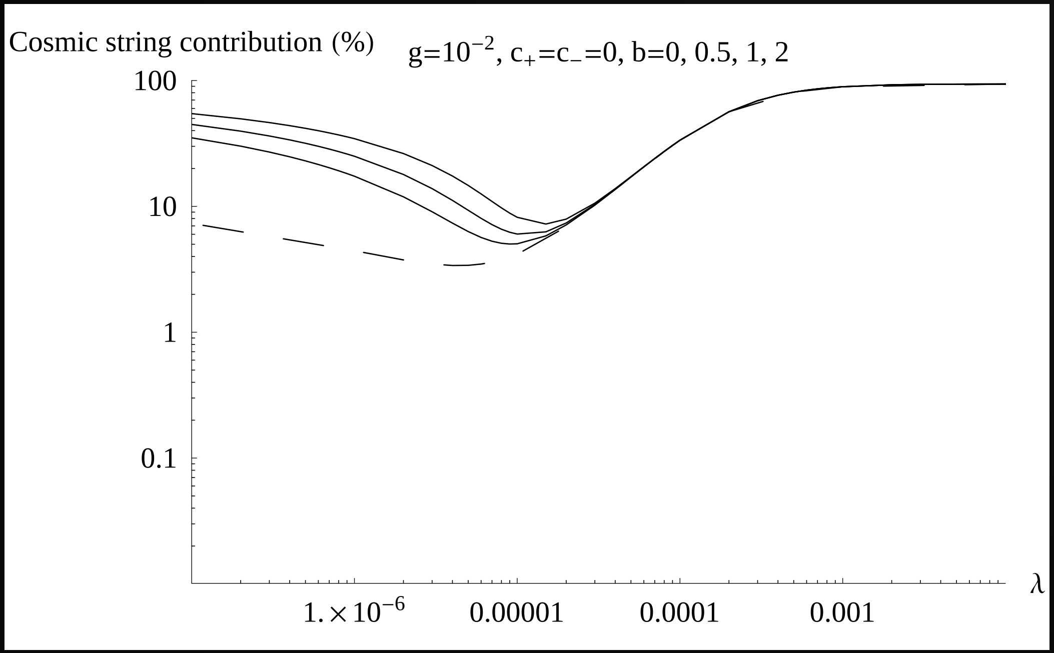
for $g \leq 0.02 : \lambda \leq 3 \times 10^{-5}$ [1,2]

rocher & sakellariadou 2005

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

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

strings have a high contribution to the cmb data unless the couplings are small [1]



[1] rocher & sakellariadou 2006

- inflation with shift symmetry

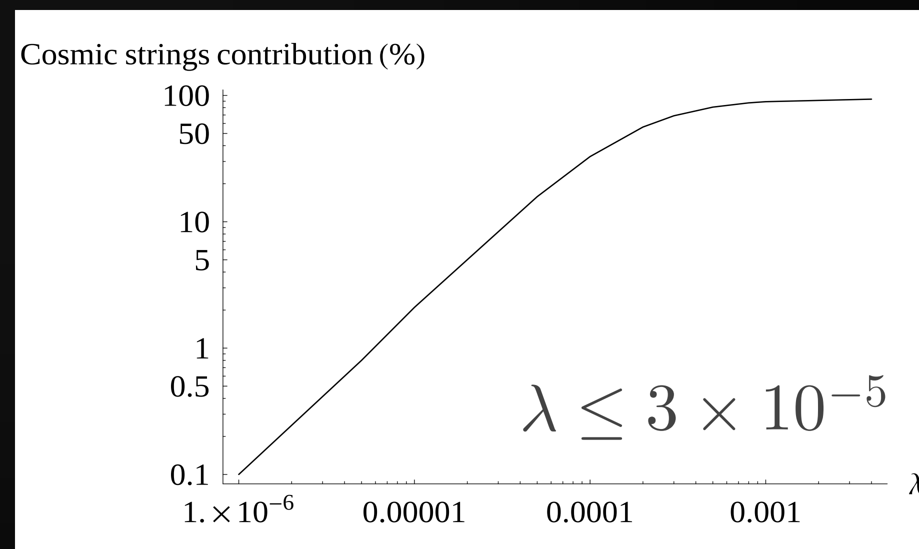
$$K = \frac{1}{2}(S + \bar{S})^2 + |\phi_+|^2 + |\phi_-|^2$$

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

V as in D-term infl ation within SUSY

V as in the minimal SUGRA

1



1

rocher & sakellariadou 2005,20065

cosmic strings in string theory

old picture: in the context of perturbative string theory, the high tension of fundamental strings (close to the Planck scale) ruled them out as cosmic string candidates

reasons:

- they would produce cmb inhomogeneities far larger than observed these strings could not have been produced after inflation since the scale of their tension exceeds the upper bound on the energy scale of the inflationary vacuum; any strings produced earlier would have been diluted before observation

- there were identified instabilities, which would prevent long strings from surviving on cosmic time scales

witten 1985

new picture: in string theory there are fundamental (**F**) strings and dirichlet (**D**) branes of all dimensions

to obtain the **SM** of strong and **EW** interactions with weak gauge coupling constant, we adopt the brane world picture

shiu & tye 1998; kakushadze & tye 1999

IIB string theory (it has odd-dimensional **D**-branes):

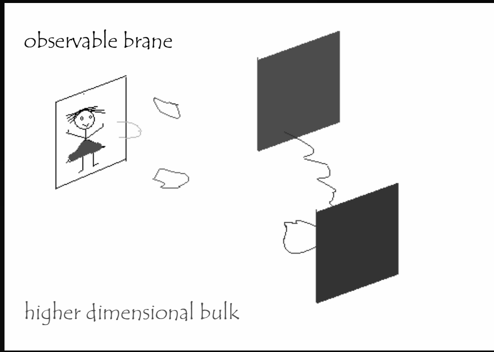
for a **D1**-brane: $$\mu_{\rm D} = \frac{\mu_{\rm F}}{g_{\rm s}}$$

within the braneworld framework: $$\underbrace{5\times 10^{-7}}_{\text{WMAP data}} \geq G\mu \geq \underbrace{4\times 10^{-10}}_{\text{fine-tuning}}$$

firouzjahi & tye 2005

⇒ in models with large compact dimensions, cosmic superstrings of macroscopic length are not ruled out

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:

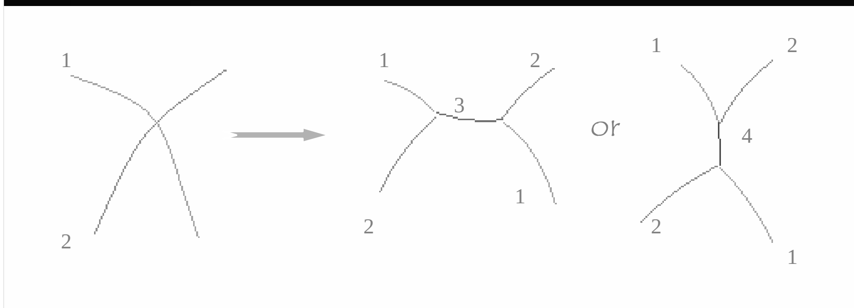
as the branes approach, the open string modes between the branes develop a tachyon

brane inflation ends by a phase transition mediated by open string tachyons

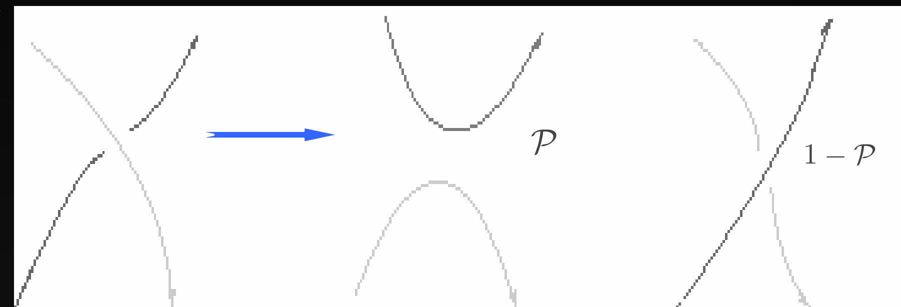
brane annihilation leads to lower dimensional branes with D3 and D1-branes favoured [3]
depending on the model, F-strings can also arise [4] and sometimes axionic local strings [5]

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

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

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 $G\mu \leq (\mathrm{a\ \ few})10^{-7}$

however …

observational constraints

assume that gravitational radiation is indeed the dominant mode of energy dissipation from a string network strings

then, using pulsar timing observations one can place limits on the existence of an isotropic stochastic gravitational background due to cosmic strings

the upper limit on th energy density per unit logarithmic frequency interval is

$$\Omega_g^{\rm cs}(1/8{\rm yr})h^2 \leq 1.9 \times 10^{-8}$$

$$\Longrightarrow \quad G\mu \leq 1.5 \times 10^{-8}$$

jenet et al 2006

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

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

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