Scaling of non-topological cosmic string networks

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COSMO 07, 21 Aug 07

AA, P. Salmi, J. Urrestilla PRD07 astro-ph/0512487

Cosmic defects (in particular, **strings**) can form in the early Universe after phase transitions and after hybrid inflation

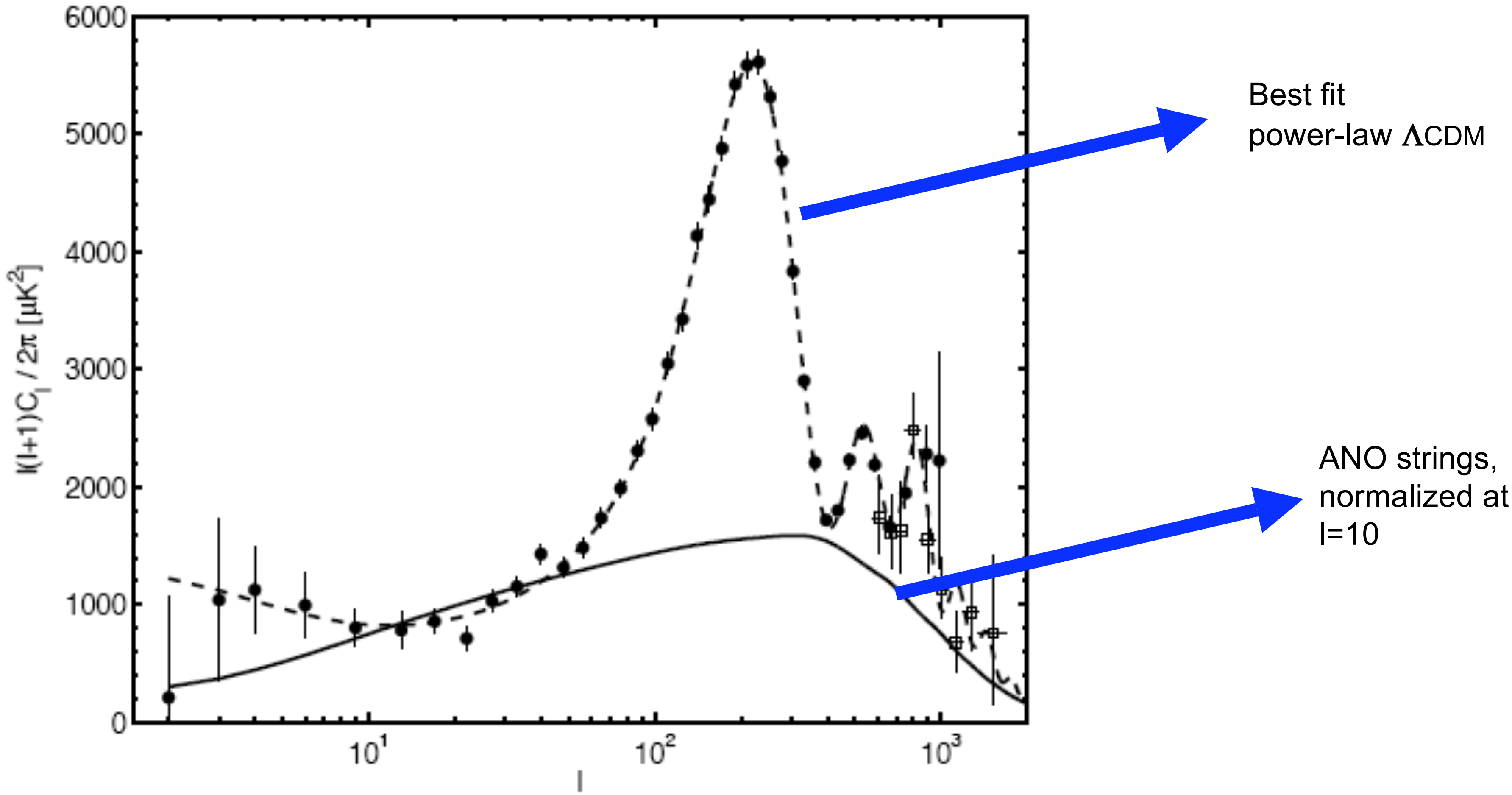
(GUT- , D-, F-, brane-)

Scaling network with L ~ t has energy density ~$1/t^2$, remains a constant small fraction of the dominant form of energy (matter/rad) and can leave a detectable imprint.

CMB (gravitational radiation? Cosmic rays?) enough to rule out or contrain **specific** inflation models and/or parameter ranges **even now**.

Jeannerot and Postma 05
Rocher Sakellariadou 04,05
Fraisse 05,06
Battye, Garbrecht and Moss 06

Bevis, Hindmarsh, Kunz, Urrestilla (2007)

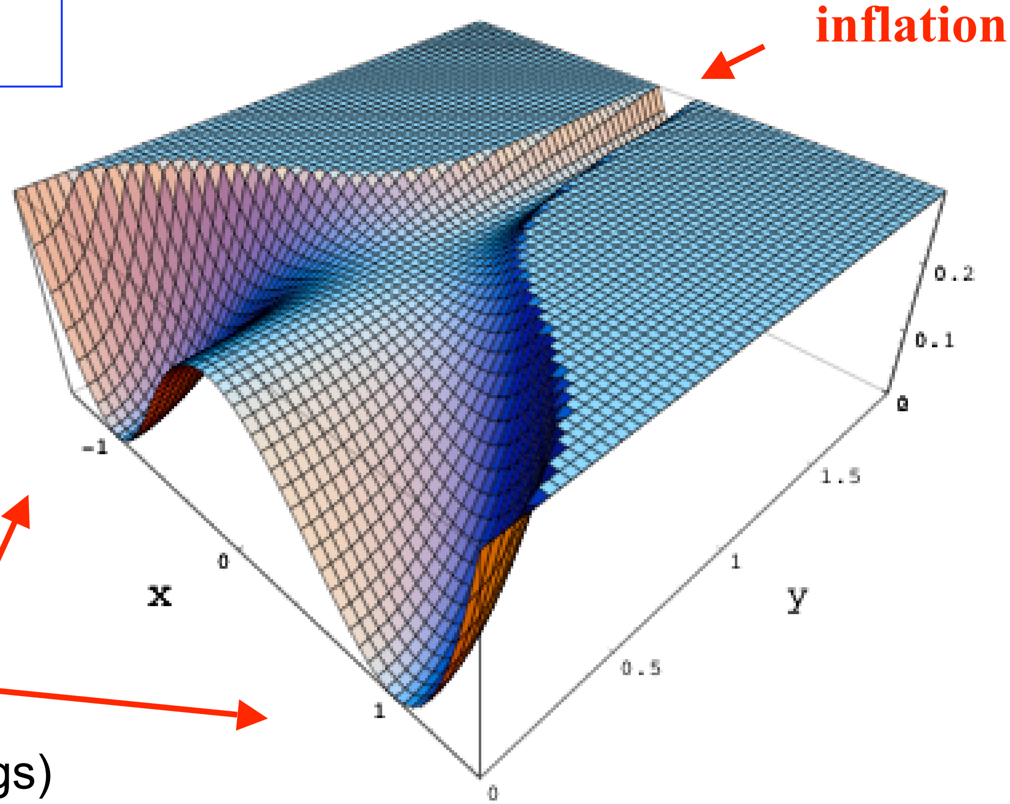


Allowed fraction in defects ~ 10% (strings) - 13% (global)

Maximum $G\mu$ ~ 10^{-7} - 10^{-6} (slightly better for global defects)

Wyman, Pogosian, Wasserman 05, Bevis, Hindmarsh, Kunz 04

STRING FORMATION AFTER HYBRID INFLATION



(Typically local strings)

A generic hybrid inflation potential

Adapted from R. Kallosh

Battye, Garbrecht and Moss 06

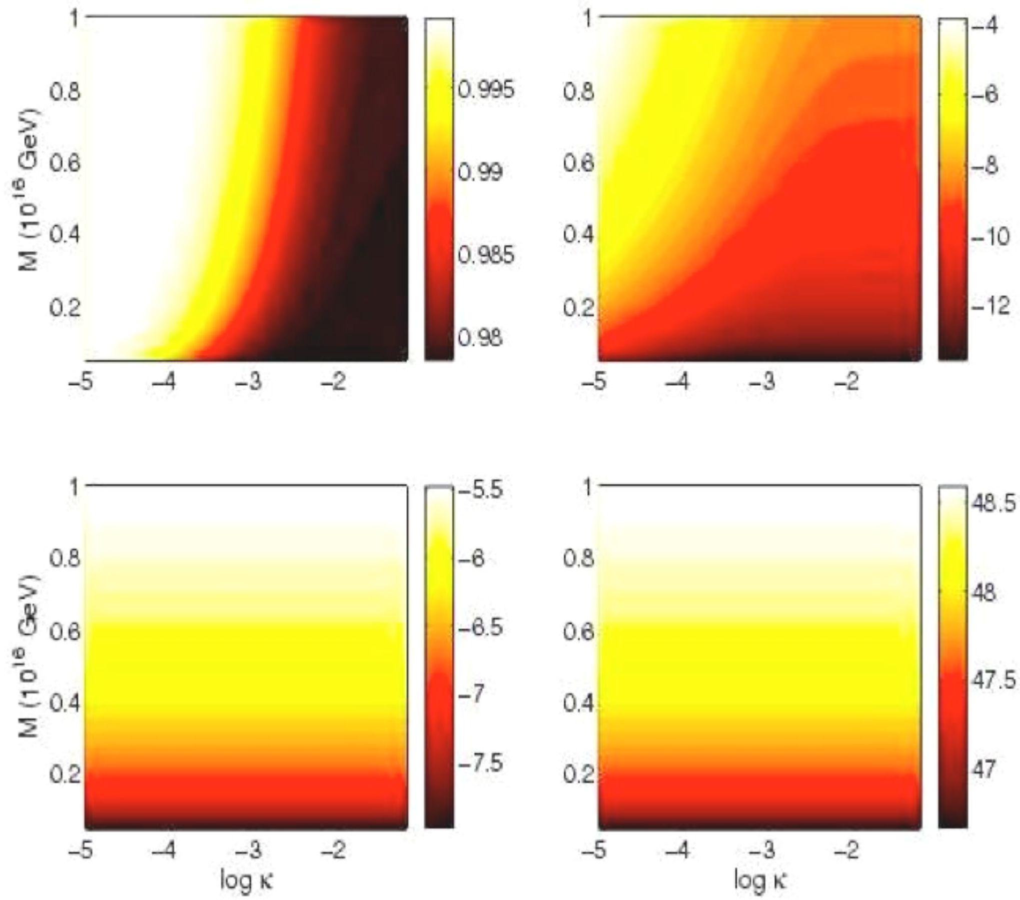


FIG. 4: The computed values of n_s (top-left), $\log P_{\mathcal{R}}$ (top-right), $\log G\mu$ (bottom-left) and N_e (bottom-right) as a function of D-term model parameters κ and $M_{\rm FI}$ for $g = 10^{-3}$, $T_{\rm R} = 10^9\,$GeV and $s = S$.

An example of cosmic strings after supersymmetric hybrid inflation: (D-term inflation)

$$V = \frac{g^2}{2}\left\{\frac{1}{4}\left[|\phi_+|^2 - |\phi_-|^2 - \omega^2\right]^2 + \left|\phi_+\phi_-\right|^2 + \phi_0{}^2\left[|\phi_+|^2 + |\phi_-|^2\right]\right\}$$

- If $\phi_0 > \omega/2$,

$$\phi_\pm = 0, \qquad \text{any } \phi_0 \qquad V = \frac{g^2\omega^2}{8}$$

Flat direction: Inflation

- If $\phi_0 < \omega/2$,

$$|\phi_+| = \omega, \qquad \phi_0 = \phi_- = 0, \qquad V = 0 \qquad \text{(global minimum)}$$

Kibble mechanism: Nielsen - Olesen strings

A way out? D-term inflation with two hypermultiplets

$$V = \frac{g^2}{2}\Big\{\frac{1}{4}\left[|\phi_+|^2 + |\widehat{\phi}_+|^2 - |\phi_-|^2 - |\widehat{\phi}_-|^2 - \omega^2\right]^2 +$$

$$\left|\phi_+\phi_- - \widehat{\phi}_+\widehat{\phi}_-\right|^2 + {\phi_0}^2\left[|\phi_+|^2 + |\widehat{\phi}_+|^2 + |\phi_-|^2 + |\widehat{\phi}_-|^2\right]\Big\}$$

- If $\phi_0 > \omega/2$,

$\phi_\pm = \widehat{\phi}_\pm = 0,$ any ϕ_0 $V = \frac{g^2\omega^2}{8}$

Flat direction: Inflation

- If $\phi_0 < \omega/2$,

$|\phi_+|^2 + |\widehat{\phi}_+|^2 = \omega^2,$ $\phi_0 = \phi_- = \widehat{\phi}_- = 0,$ $V = 0$

Semilocal strings in the Bogomolnyi limit

Many models of hybrid inflation that produce topological abelian strings can be extended to models that produce **semilocal** cosmic strings

F-term, D-term inflation models   in SUSY and supergravity

Urrestilla, A.A., Davis 2003

D-brane inflation models in Superstrings

D3/D7 Dasgupta, Hsu, Kallosh, Linde, Zagermann 2004
Chen et al 05
Dasgupta, Firouzjahi, Gwyn 07

whose properties are quite **different** from the topological case:

if unstable, the strings don't form
if stable, they form a network - with properties intermediate between **global defects** and **topological strings**

A.A., Salmi, Urrestilla, this talk

in BPS case: confirmed by explicit CMB calculation

Urrestilla's talk

(Urrestilla, Bevis, Kunz, Liddle, Hindmarsh, arXiv: 07xx)

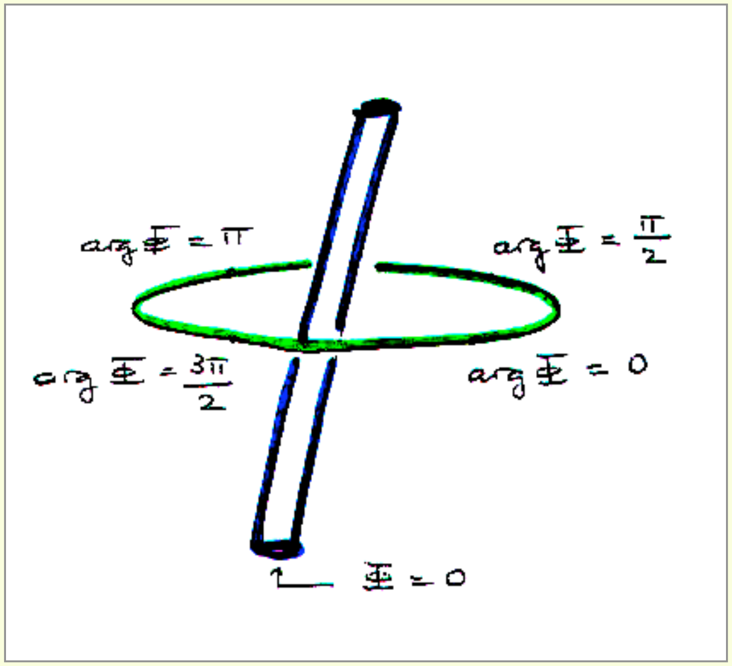
Semilocal strings

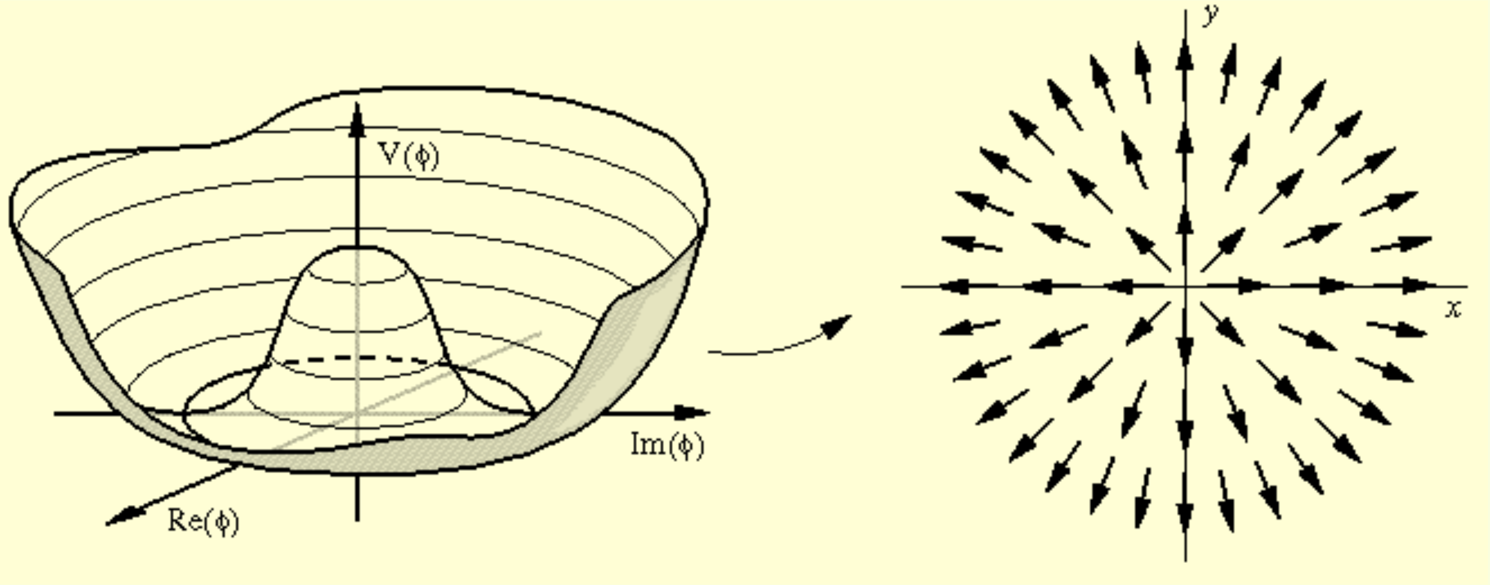
=

a non-topological version of Abrikosov-Nielsen-Olesen

Vachaspati, AA 91, Hindmarsh 92

Abrikosov-Nielsen-Olesen strings





Semilocal strings

Several charged scalars coupled equally to U(1) gauge field (e.g. SU(2) multiplets)

Mix **global** and **local (gauge)** symmetries

Non-topological **quantized magnetic flux**

$m_v < m_s$	**unstable**	**superconducting solutions Forgacs, Rouillon, Volkov 05,06**
$m_v = m_s$	magnetic "tubes" of arbitrary radius	
$m_v > m_s$	**stable (fixed radius)**	

m_v = vector mass, m_s = scalar mass

A.A., T.Vachaspati, Phys. Reports '00

Semilocal strings

$$S = \int d^4x \left[|D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\lambda}{2} (|\phi_1|^2 + |\phi_2|^2 - \eta^2)^2 \right]$$

$$D_\mu \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = (\partial_\mu + i\, g\, A_\mu) \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu.$$

$\phi_2 = 0$ abelian Higgs model

embedded ANO strings

Only relevant parameter is

$$\beta = \frac{m_s^2}{m_v^2} = \frac{\lambda}{g^2}$$

(distinguishes type-I from type-II)

Semilocal strings

$$S = \int d^4x \left[|D_\mu \phi_1|^2 + |D_\mu \phi_2|^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\lambda}{2} (|\phi_1|^2 + |\phi_2|^2 - \eta^2)^2 \right]$$

$$D_\mu \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = (\partial_\mu + i\, g\, A_\mu) \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu .$$

- Symmetry: $SU(2)$ global $\times$ $U(1)$ local $/Z_2$
- Vacuum manifold is S^3, $|\phi_1|^2 + |\phi_2|^2 = \eta^2$ (simply connected)
- Magnetic flux is still quantised in units of $2\pi/g$.

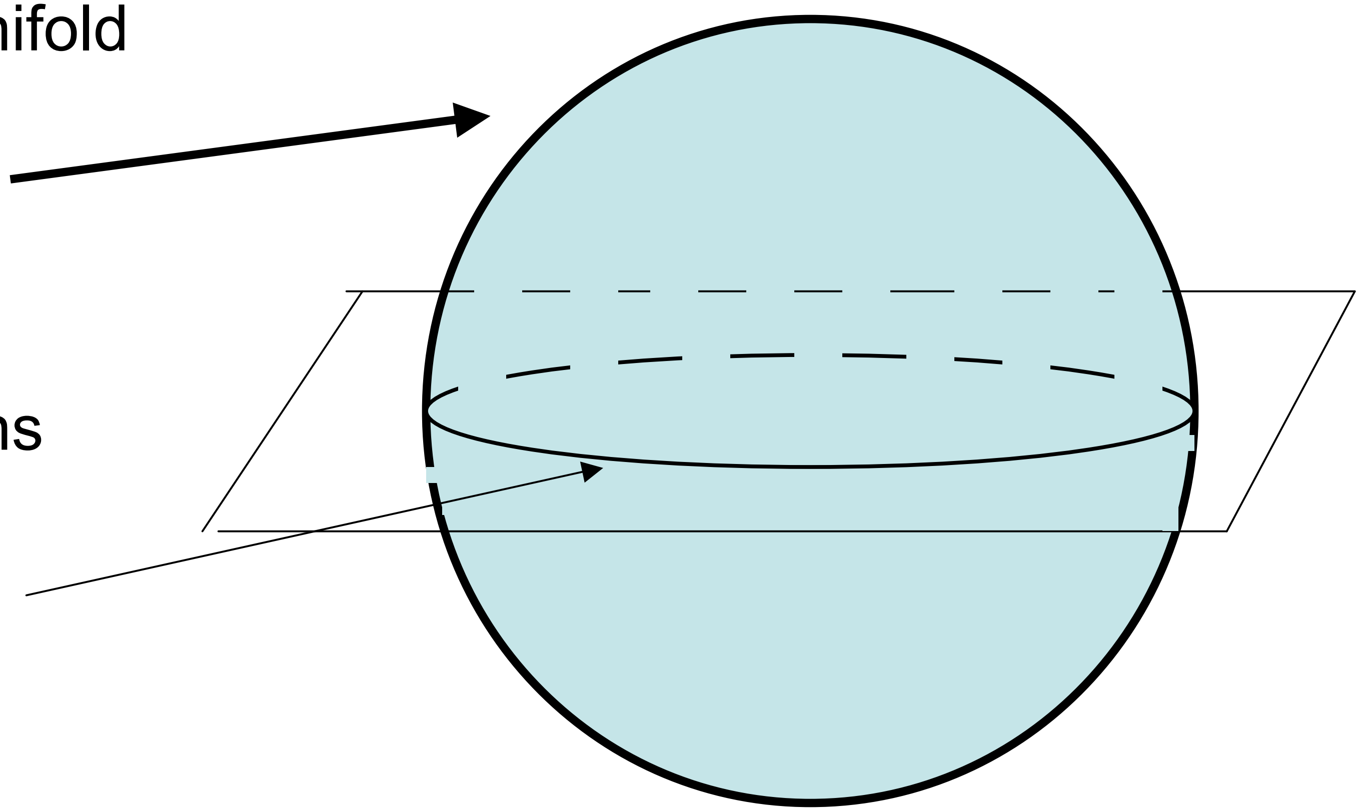
Semilocal model:

vacuum manifold

S^3

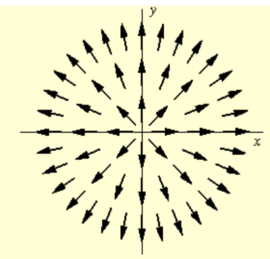
finite energy configurations

S^1



In unstable case, an embedded ANO string

$\phi_2 = 0$

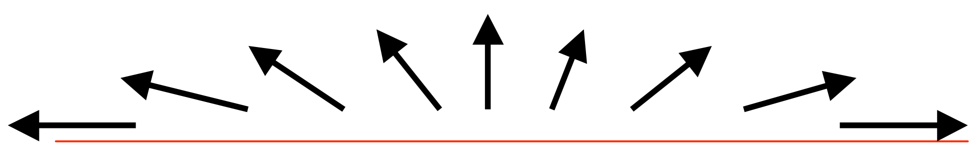


top view

side view

becomes a texture ("skyrmion")

$\phi_2 \neq 0$

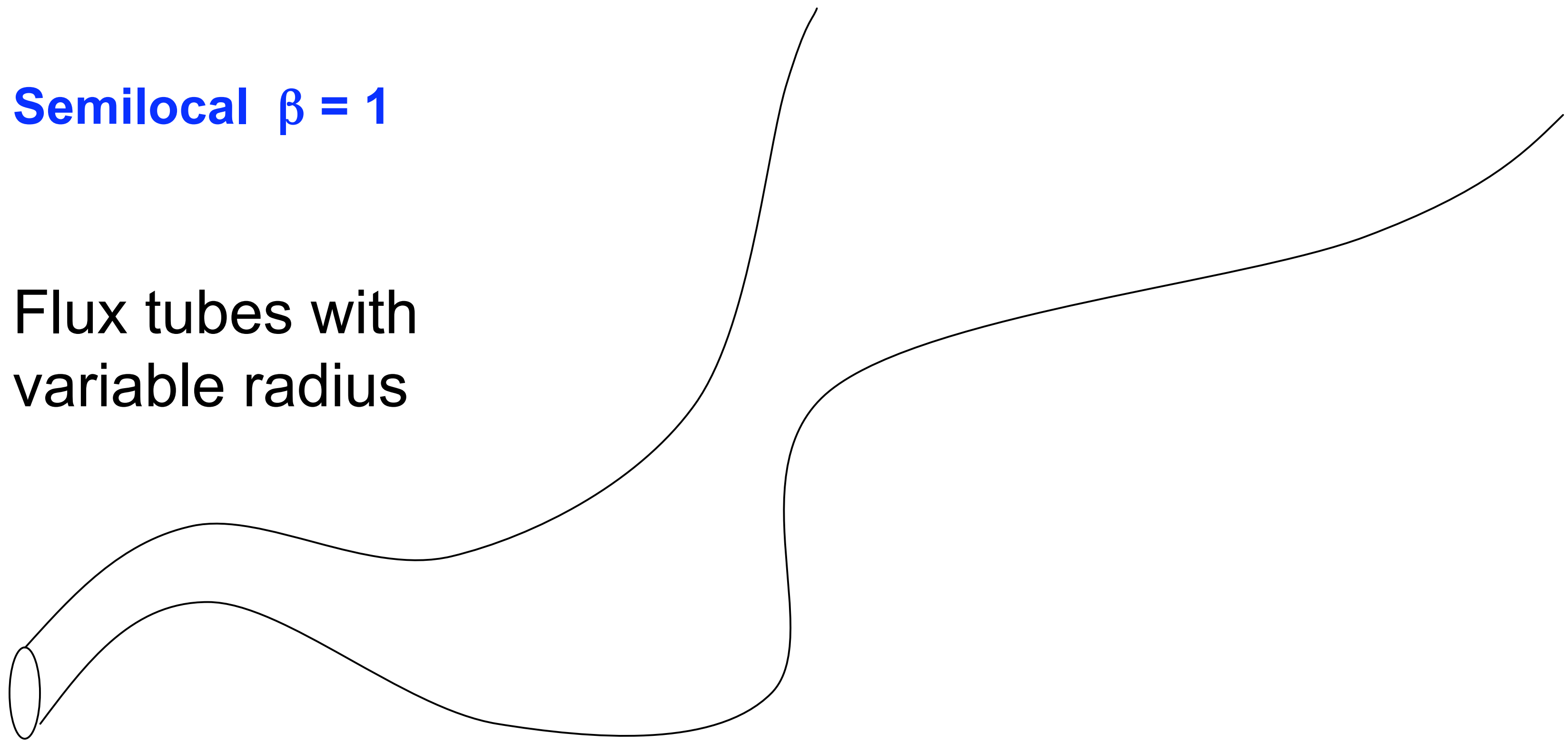


β = 1:zero mode

Hindmarsh 92

Semilocal $\beta = 1$

Flux tubes with
variable radius



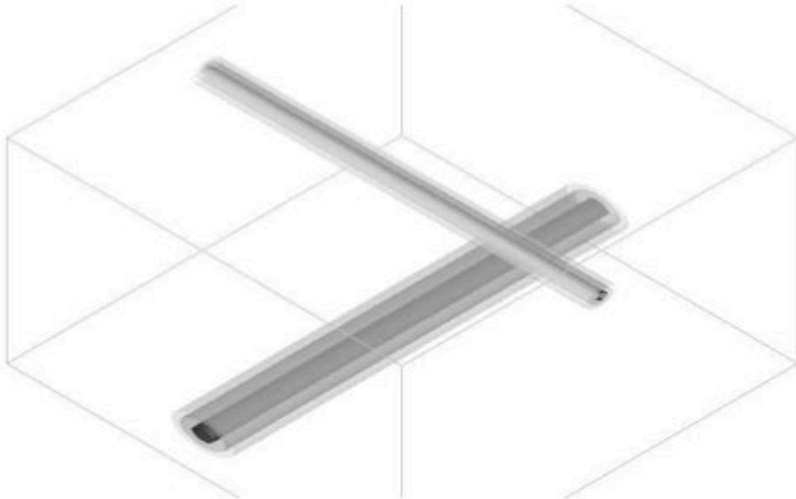
BPS semilocal strings,

Vachaspati, A.A. 91; Hindmarsh 92
Leese 94
Laguna, Natchu, Matzner, Vachaspati 06

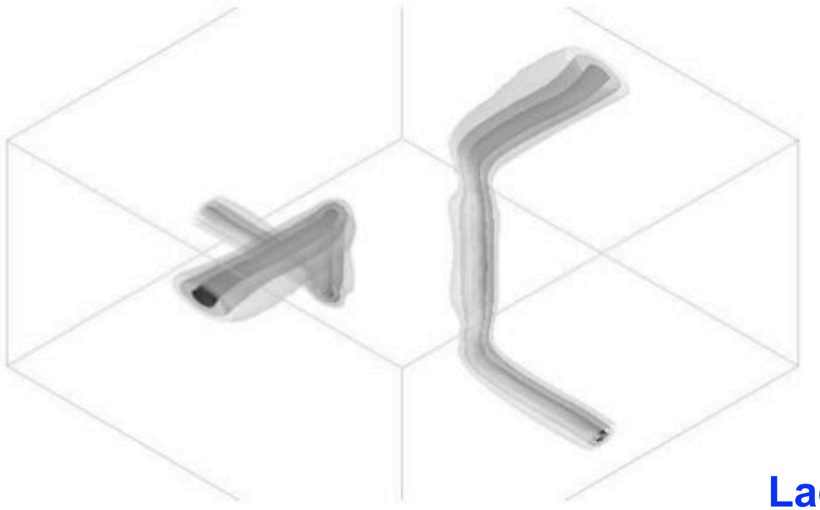
also
e.g. BPS axionic D-term strings (s-strings)

Blanco-Pillado, Dvali, Redi 2005
A.A., Sousa 2005

Semilocal $\beta = 1$



(a) Initial configuration

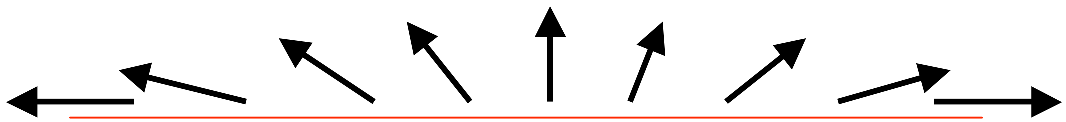


(b) Late configuration

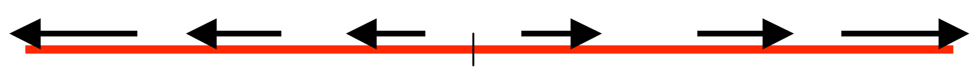
Skyrmions revert to ANO at the point of intercommutation

Laguna, Natchu, Matzner, Vachaspati, PRL06
Leese, Samols 94

In stable case, a texture (“skyrmion”)



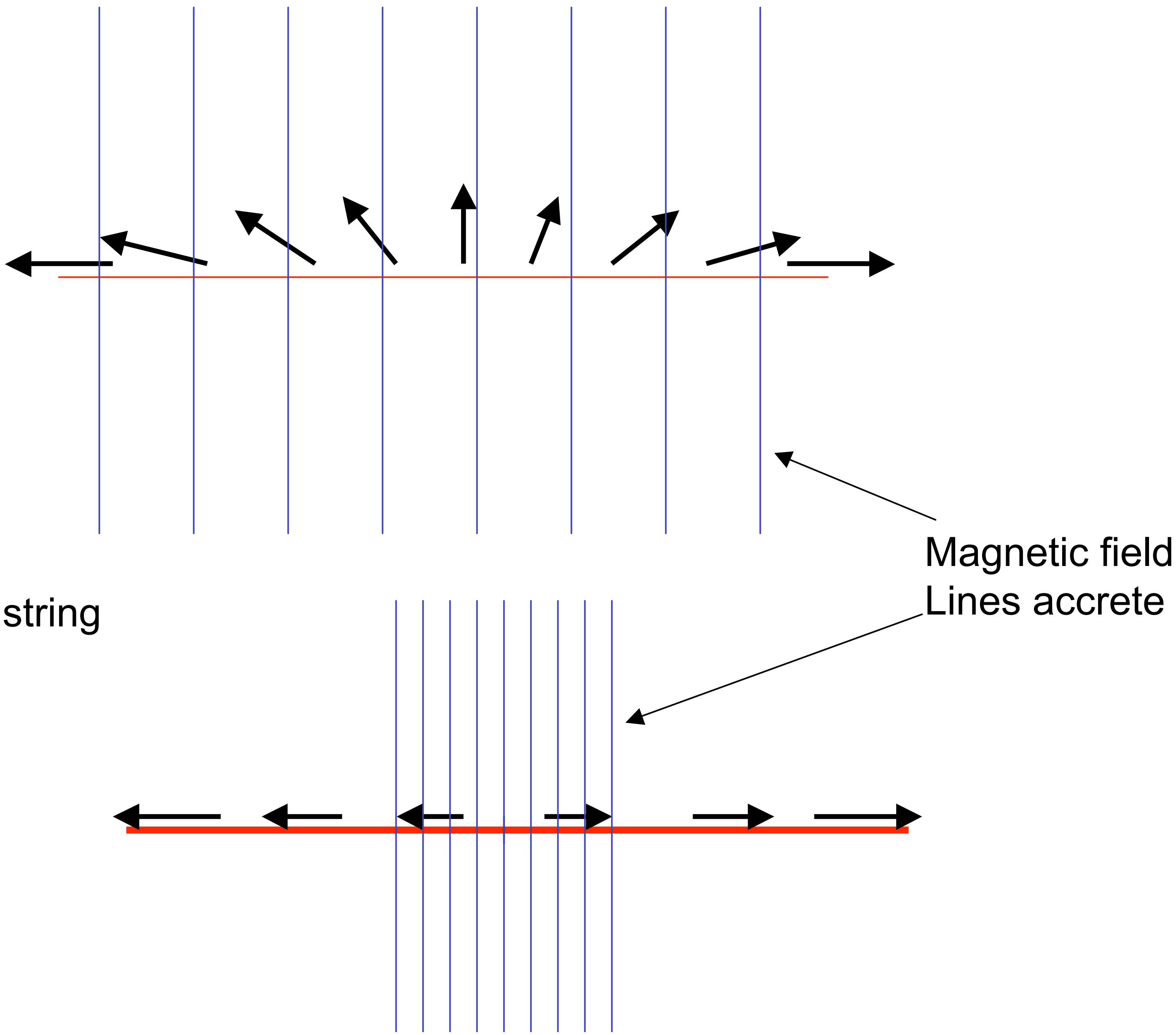
becomes a string



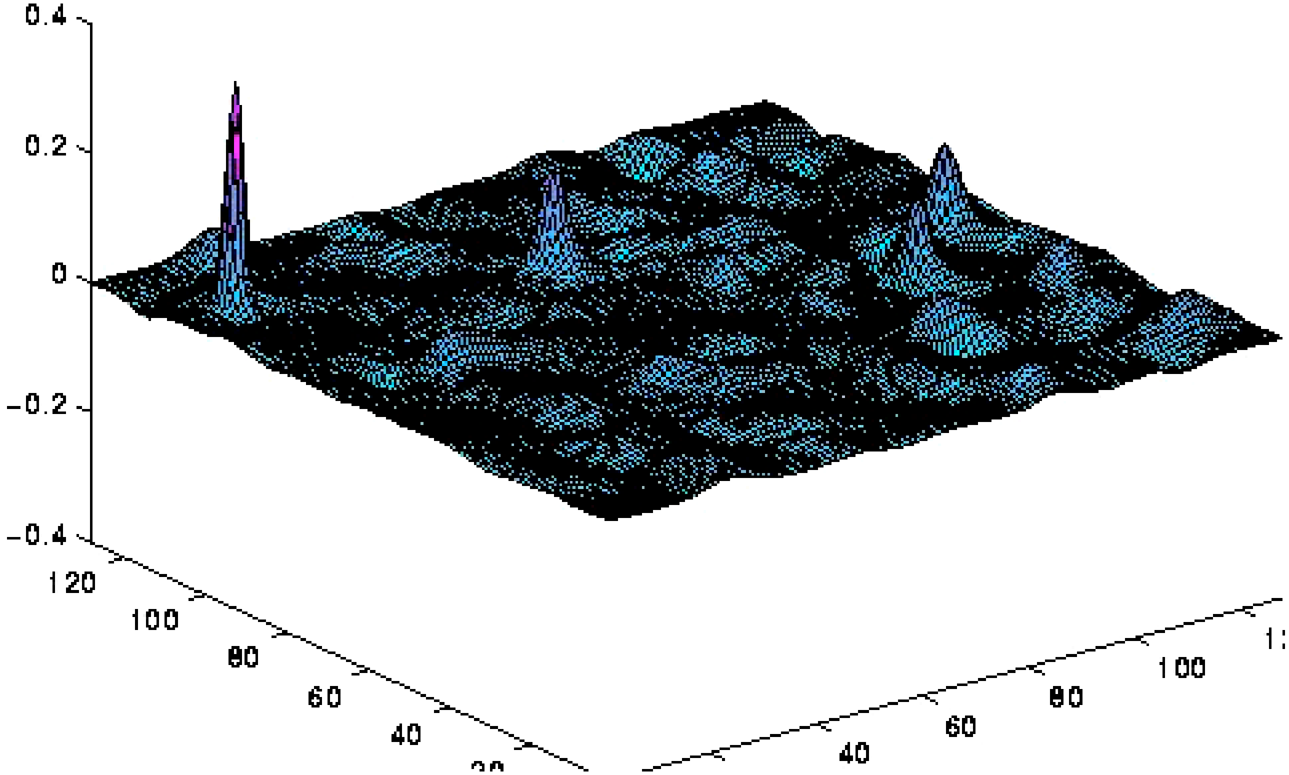
Benson and Bucher 93

A texture

Becomes a string



Accretion of magnetic flux into strings, stable regime, 2D



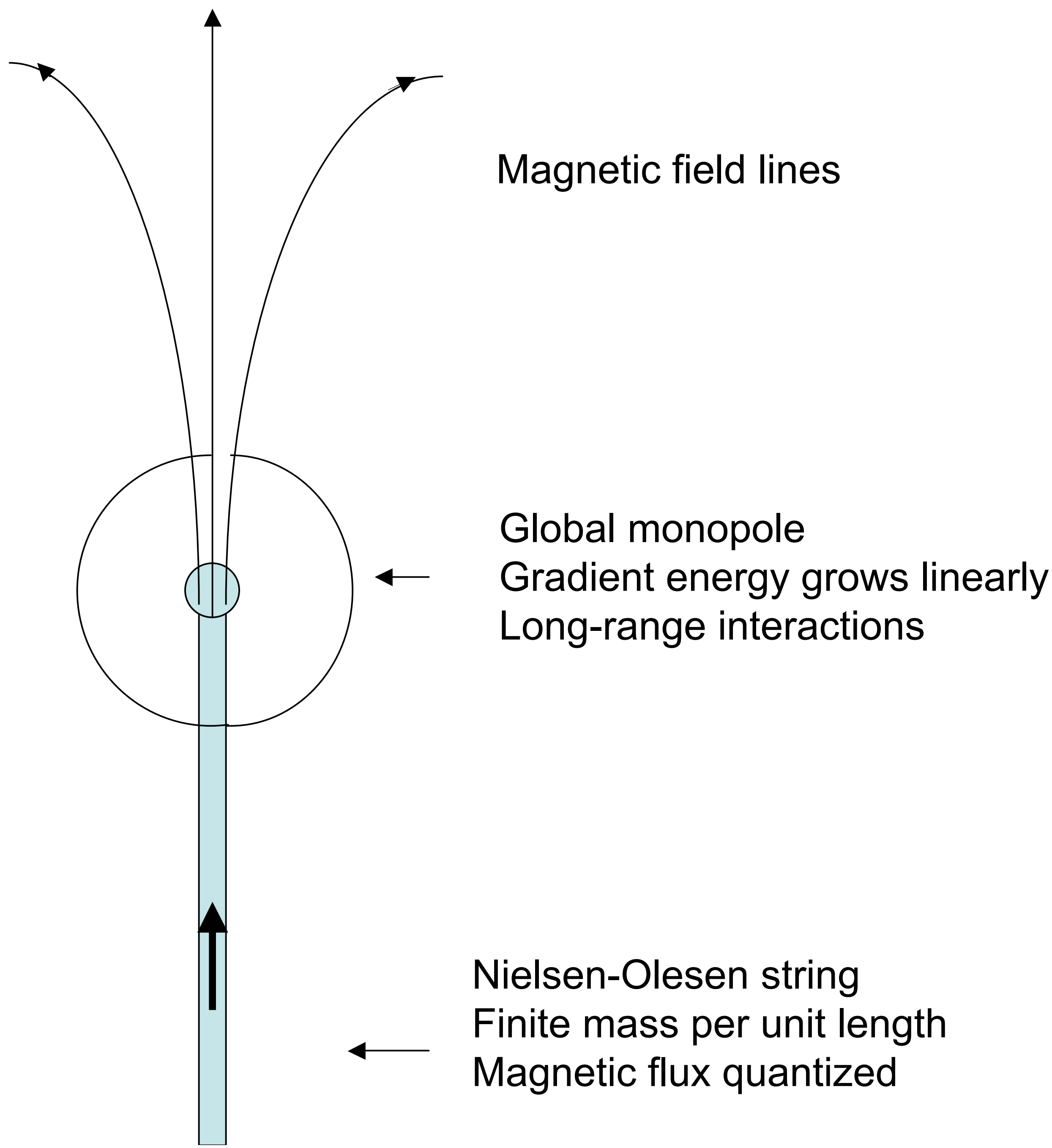
Type-I vortices stable

$$\beta = \frac{m_s^2}{m_v^2} < 1$$

Exactly like ANO
but can have **segments** with open ends.

The ends are “global monopoles” with long-range interactions

No Nambu-Goto approximation

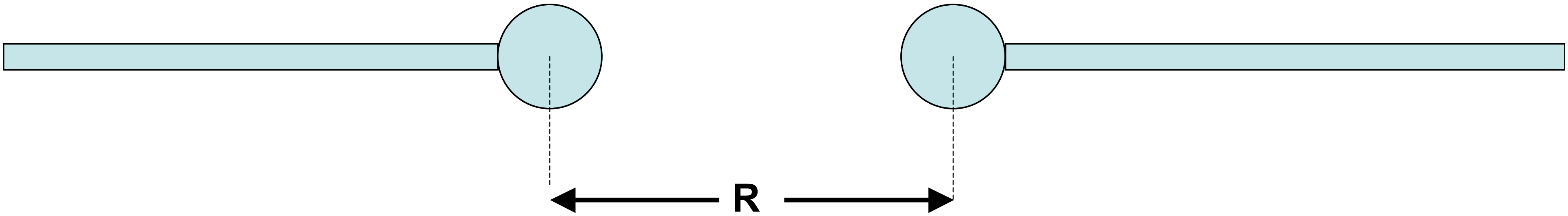

Magnetic field lines
Global monopole
Gradient energy grows linearly
Long-range interactions
Nielsen-Olesen string
Finite mass per unit length
Magnetic flux quantized

Semilocal strings segments can grow!

- to join other nearby segments
- to form closed loops

Hindmarsh 92

Compare



with

Difference in energy:

$\rho \geq 1$

$\nu(1)=1$ monot. incr.

$$\Delta E \approx 2E_c + 2\pi\rho\eta^2 R - 2\pi\nu(\beta)\eta^2 R$$

2 x monopole - string

β < 1 min. at R = 0 expect that **string grows**

A straight string does **not** break into monopole-antimonopole pairs

No exponential suppression of long strings

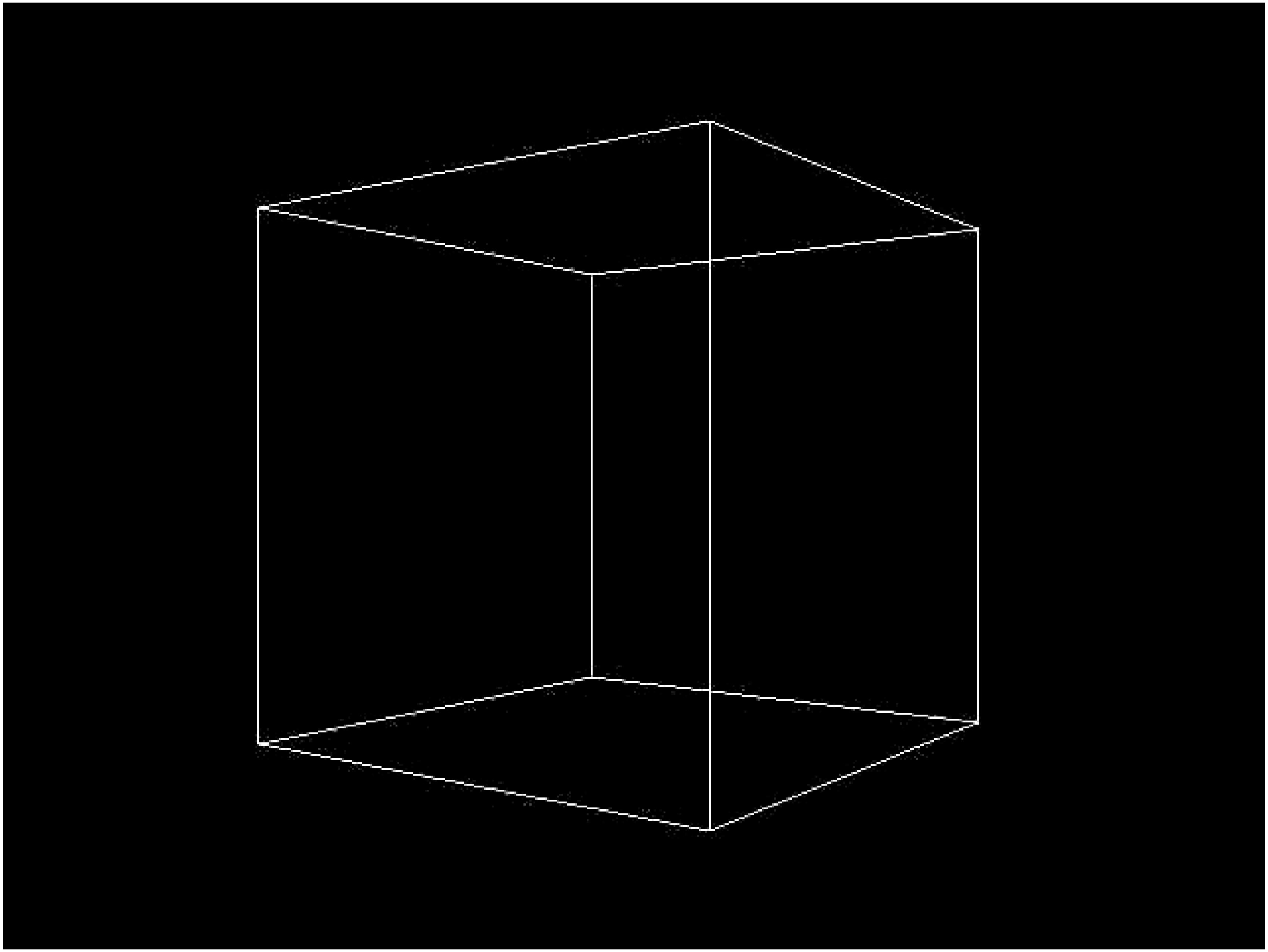
different from light (magnetic) monopoles connected by strings

A simulation of semilocal string network evolution

No expansion

256^3 lattice, periodic boundary conditions

A.A., Borrill, Liddle 99



Cosmic strings show (linear) scaling behaviour

Global defects also

Semilocal strings, when they are stable, have properties that are intermediate - do they also scale?

Cosmic strings show (linear) scaling behaviour

Thin defect approximation: Nambu-Goto

Global defects also

Thin defect approximation: sigma model

Semilocal strings, when they are stable, have properties that are intermediate - do they also scale?

No thin defect approximation…
(VOS?)

Numerical simulations

A.A., P. Salmi, J. Urrestilla PRD 07

Rescale length by inverse vector mass

512^3 lattice
lattice spacing Dx=1, dt=0.2

periodic boundary conditions

Flat space simulation (no expansion)

Random initial configuration,

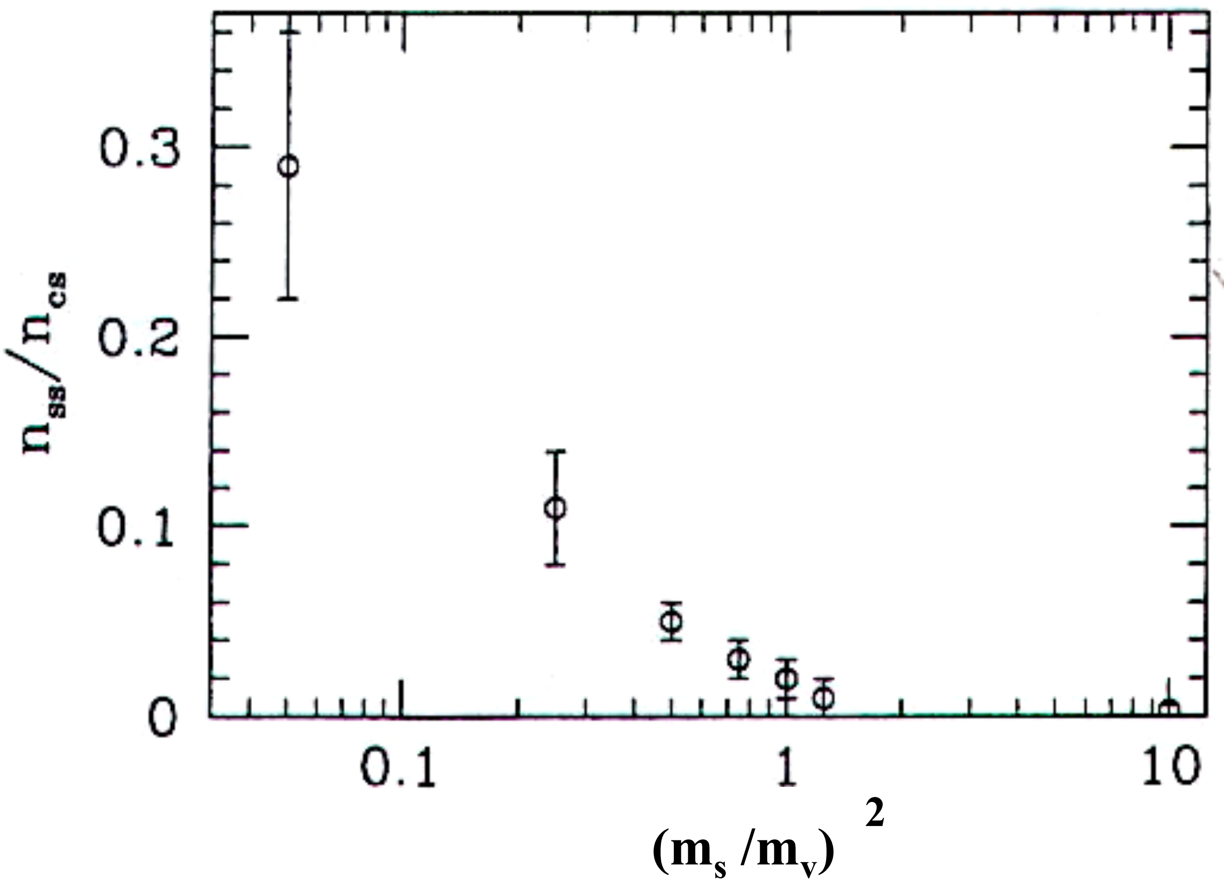
zero field, random velocity, smooth 20 times
(initial correlation length ~ 40 lattice points)

Add dissipation - several values, from 0.05 to 0.2, also 1/t dissipation

Analyze network evolution for different values of stability parameter β

Measure magnetic field.
Any point with 25% of theoretical value counted as "in a string".
Discard blobs.
Monitor $n(l,t)$ and $\xi(t) = (\text{Volume/length})^{1/2}$

Network less dense than for topological NO strings
Defect density increases with smaller β

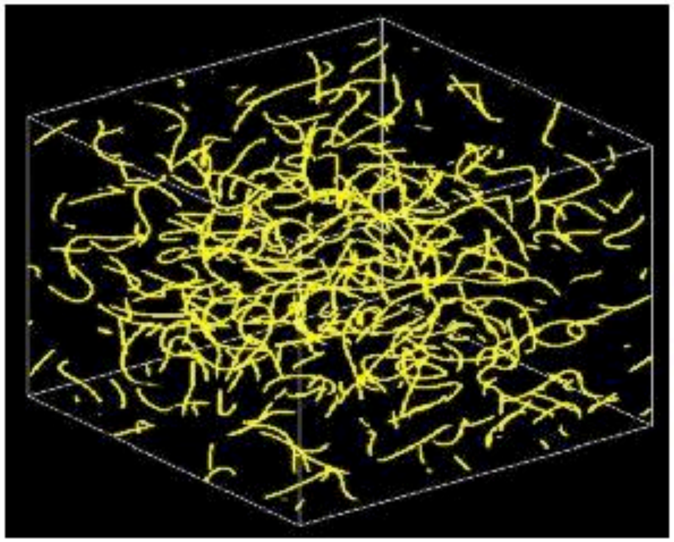


The ratio of lengths of semilocal and cosmic strings.

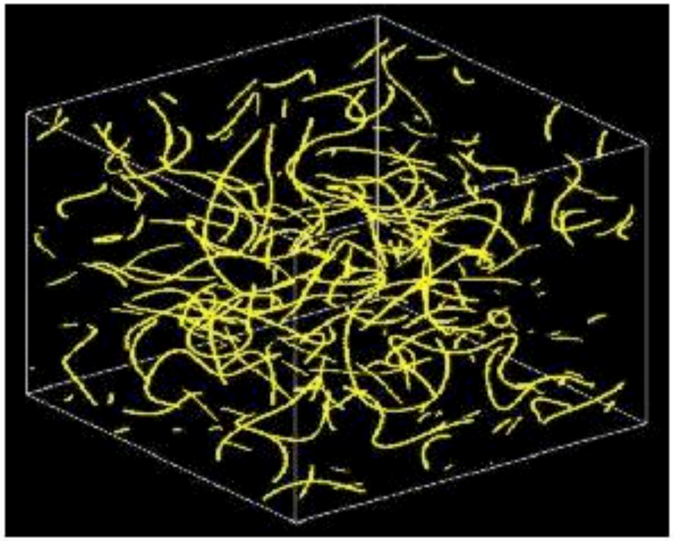
A.A., Borrill, Liddle 99

β = 0.04

time = 150

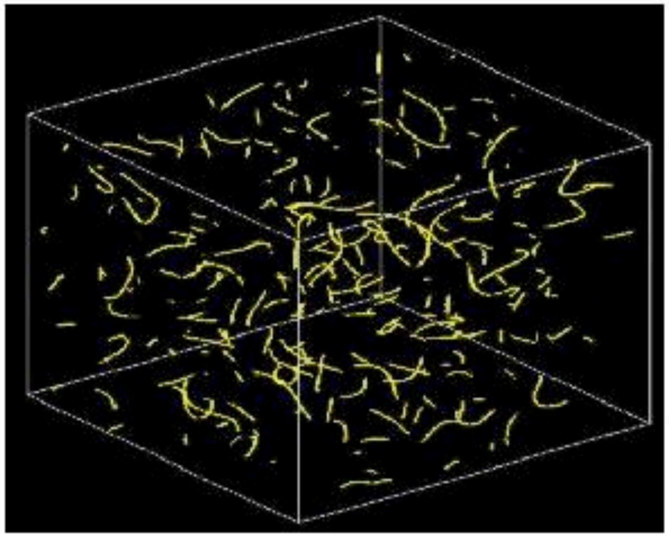


time = 300

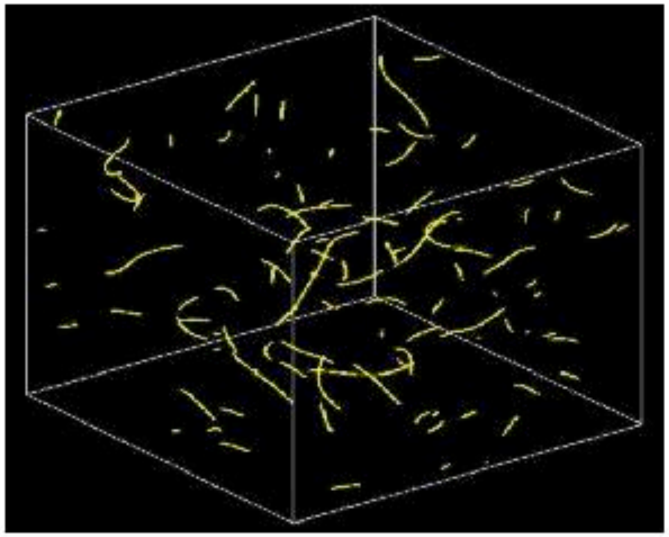


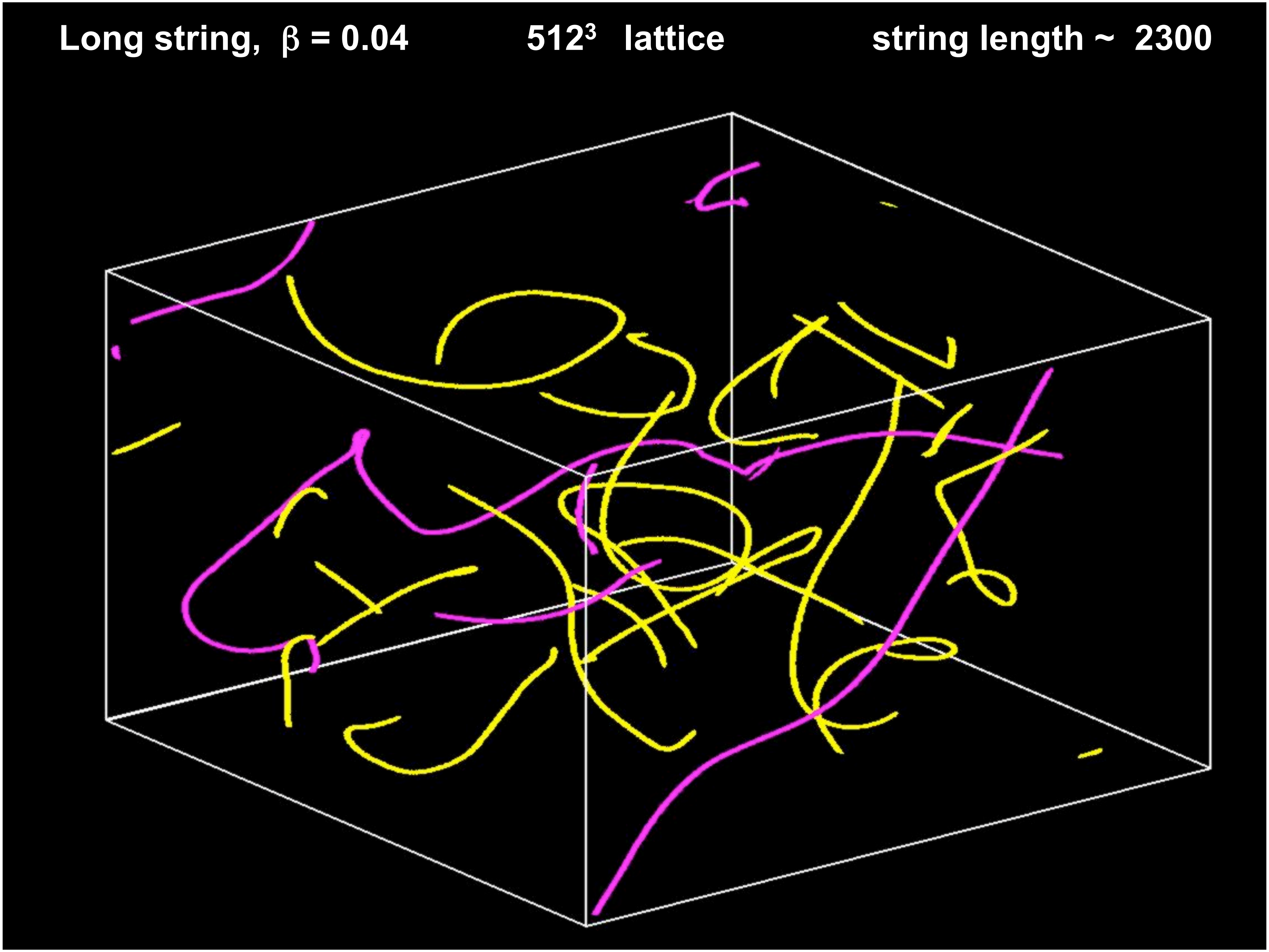
$\beta = 0.36$

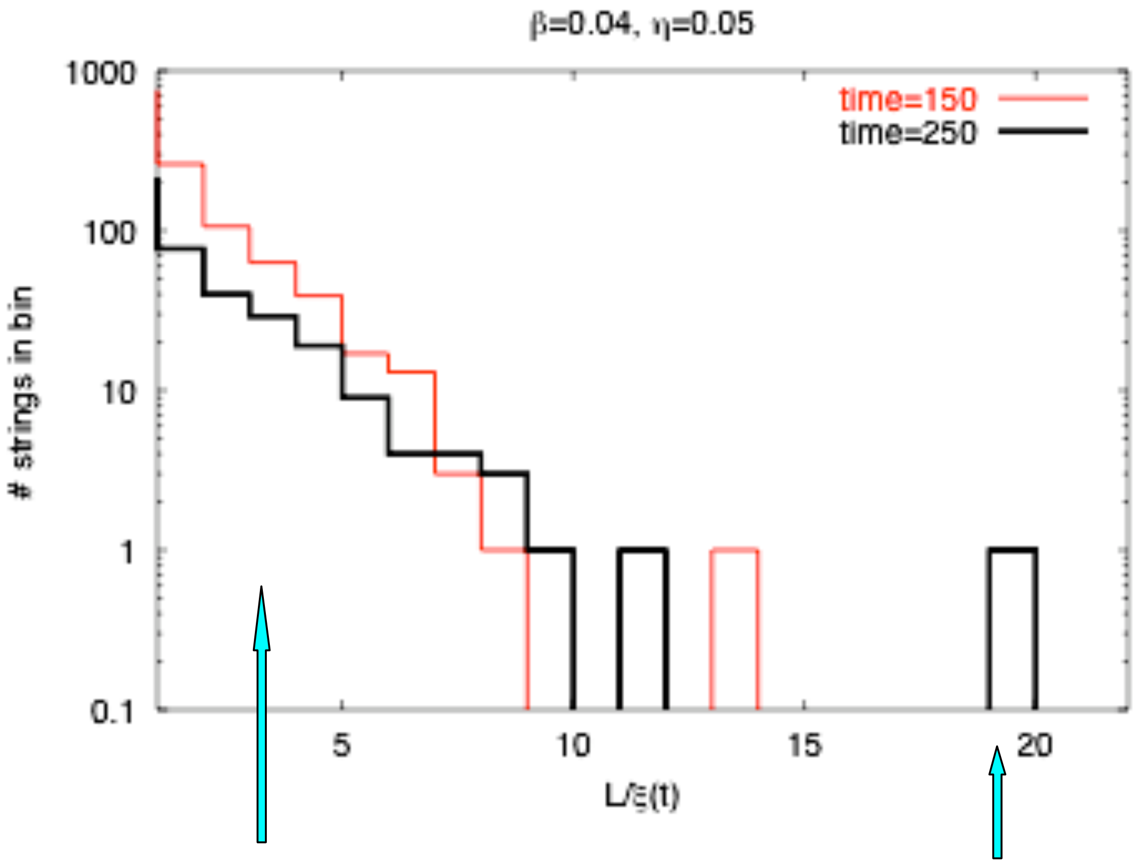
time = 150



time = 300



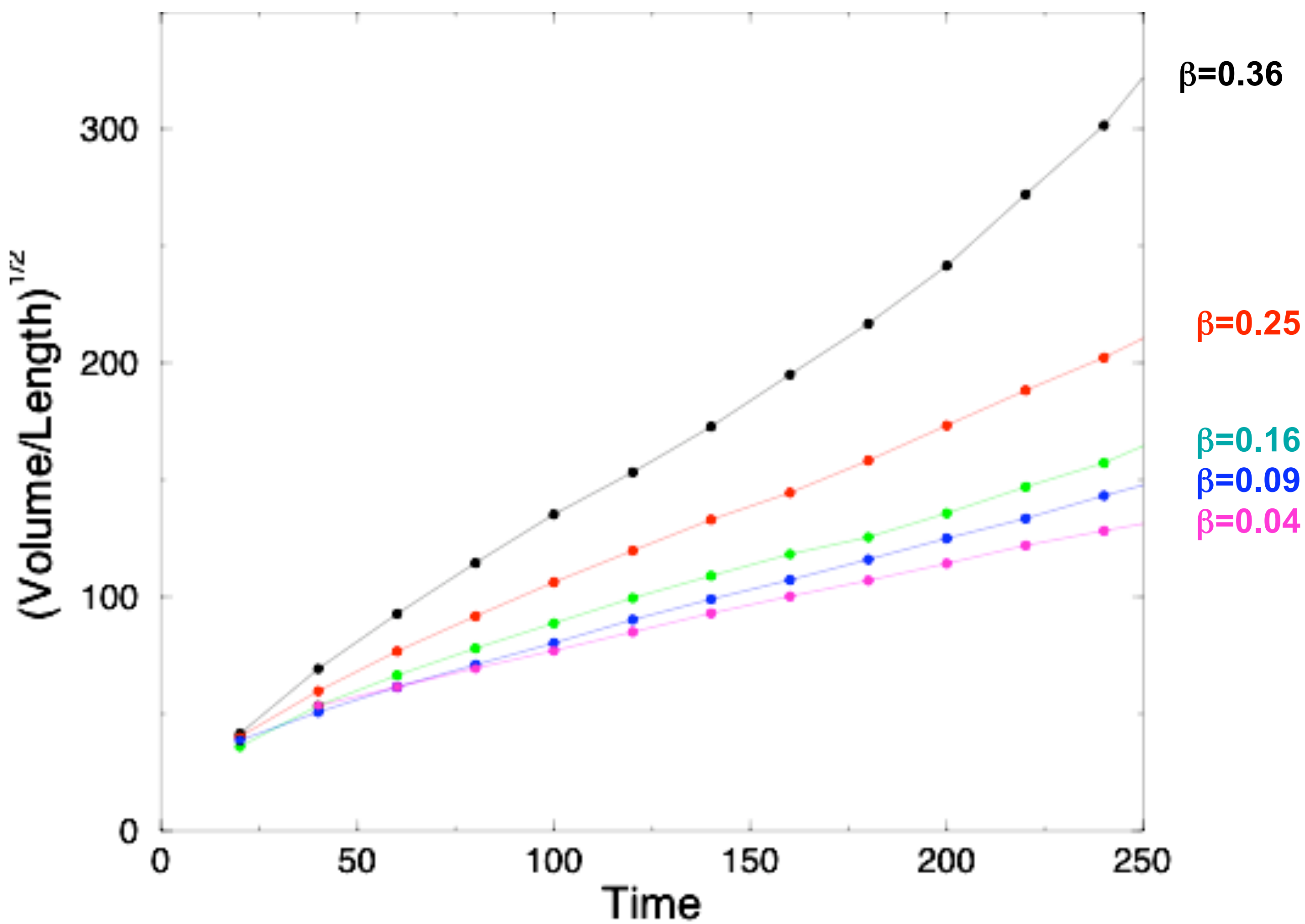

Long string, β = 0.04
512³ lattice
string length ~ 2300



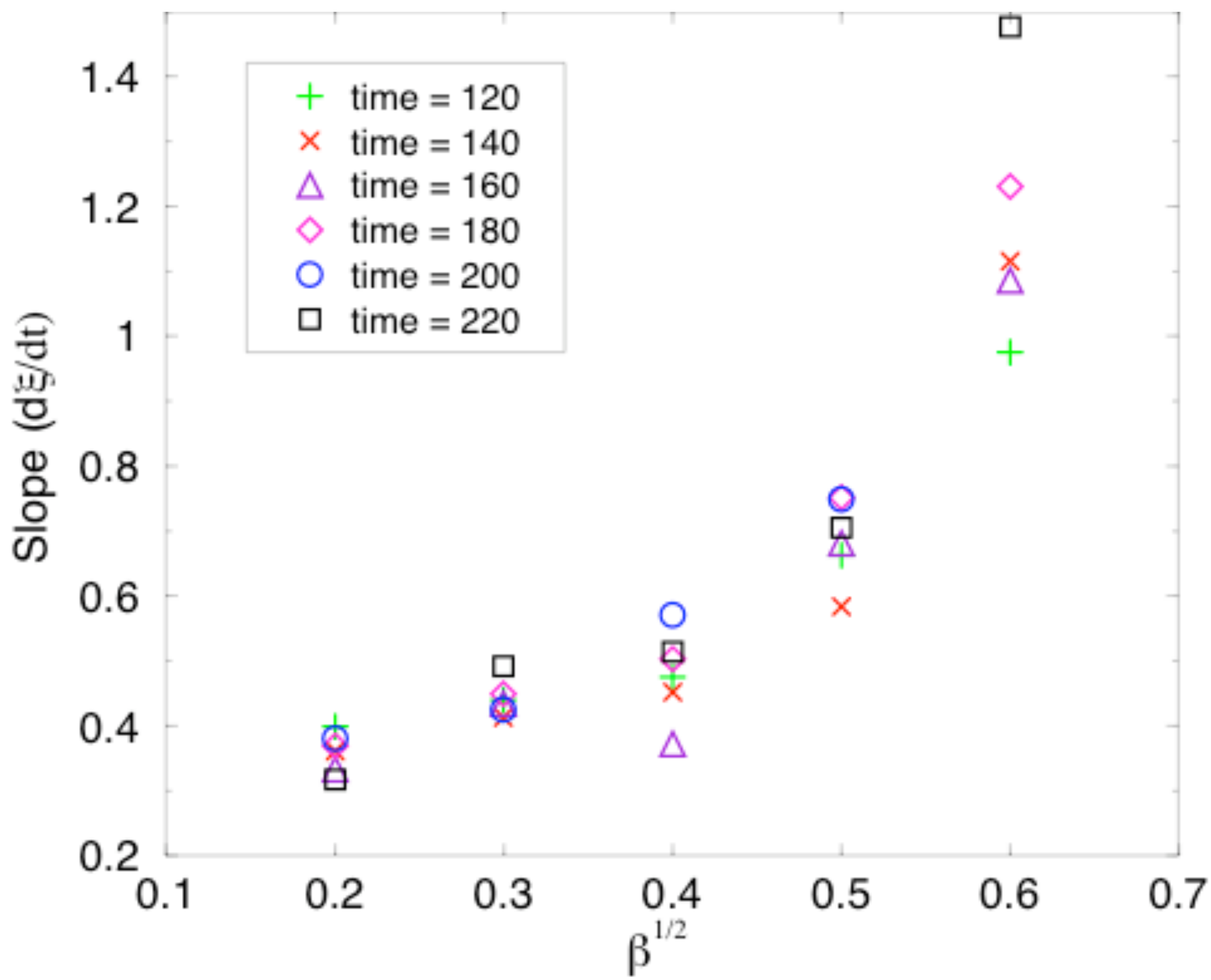
Exponential distribution of short segments

Long strings

Scaling ?



β=0.36
β=0.25
β=0.16
β=0.09
β=0.04
(Volume/Length)^1/2
300
200
100
0
0
50
100
150
200
250
Time



time = 120
time = 140
time = 160
time = 180
time = 200
time = 220
Slope (dξ/dt)
β^1/2
0.2
0.4
0.6
0.8
1
1.2
1.4
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Results

- Initially: exponential distribution of segments
- Small segments disappear, mean length increases

- Closed loops very rare (they behave like usual ANO loops)
- No intercommutations observed

- No long string unless very deep in stable regime (very low β)
- Evidence of extremely long string for $\beta = 0.04$

  qualitative change, two populations

- Consistent with linear scaling

- Energy mostly in scalar gradients
- Network behaviour like global monopoles connected by (very light) strings plus some “infinite” ANO string

Summary

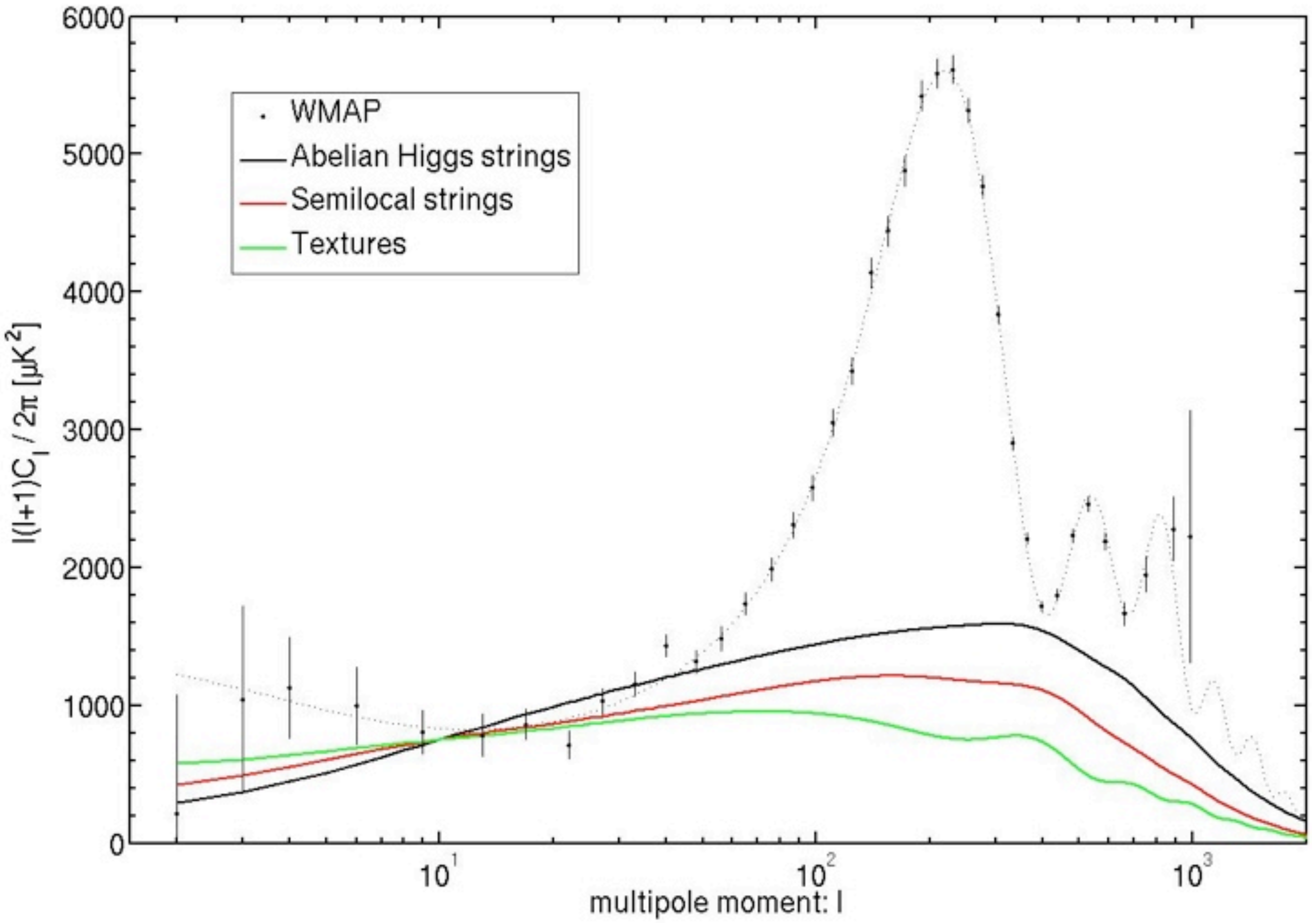
It is not unlikely that nature has chosen a model of inflation with (cosmic) strings attached.

Their expected imprints (on CMB, LSS, GW, lensing…) can be used to constrain the underlying microphysics.

Many models with topological strings are easily extended to semilocal models

Semilocal strings produce a scaling network that is qualitatively different from topological strings. Global defect features may ease tension with data in marginal cases.

Temperature power spectra in BPS case
(PRELIMINARY - courtesy J. Urrestilla)



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

$G\mu_{10} = 5 \times 10^{-6}$

$G\mu_{10} = 7 \times 10^{-6}$

Abelian Higgs strings: Bevis, Hindmarsh, Kunz, Urrestilla (2006)

Semilocal: Urrestilla, Bevis, Hindmarsh, Kunz, Liddle (in preparation)

Textures: Bevis, Hindmarsh, Kunz (2004)