Cosmic Strings
from
Supersymmetric Flat Directions

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Based on work done in collaboration with

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Motivation

- New $U(1)$ gauge symmetries arise in many new physics models:
  - grand unified theories
  - D-brane constructions
  - superstring theory compactifications
- Supersymmetry is motivated by:
  - the gauge hierarchy problem
  - grand unification
  - cosmological observations (dark matter, baryon asymmetry, . . .)
  - superstring theory
- What are the cosmological consequences if these possibilities are realized in nature?

$\longrightarrow$ supersymmetric cosmic strings

Ingredients:

Cosmic Strings

and

Supersymmetry

Cosmic Strings

- Cosmic strings are non-trivial field configurations that can arise in theories containing scalar fields. [Nielsen+Olesen '73]

- Cosmic strings can be formed when a $U(1)$ (gauge) symmetry is spontaneously broken in the early universe.

- Some cosmic string signatures:
  - large-scale structure formation
  - gravitational lensing
  - gravity waves

- *Cosmic superstrings* can also arise from superstring theory. [Jones,Stoica,Tye '02; Dvali+Vilekin '03; Copeland,Myers,Polchinski '03]

  $(p, q) \quad \Rightarrow \quad p$ fundamental F strings and q $D1$ branes

A Simple Cosmic String - Part 1

- Abelian Higgs model with a complex scalar φ, and a $U(1)$ gauge field A_μ:

$$\mathcal{L} \supset |(\partial_\mu - igA_\mu)\,\varphi|^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\lambda}{4}(|\varphi|^2 - v^2)^2$$

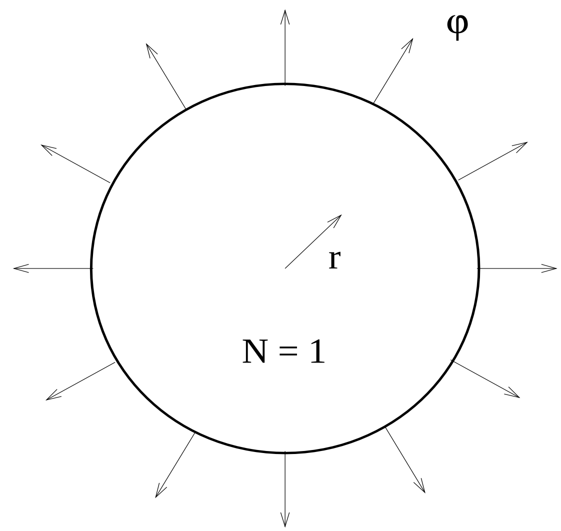
- Symmetry breaking vacuum: $\langle|\varphi|\rangle = v, \quad A_\mu = 0$.

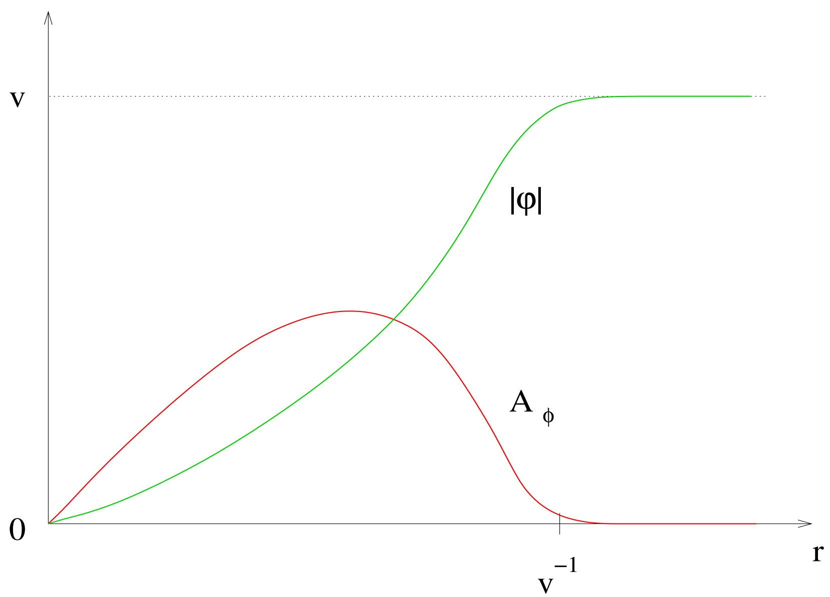
- This theory also has cosmic string configurations labelled by $N \in \mathbb{Z}^{>}$:

$$\begin{aligned} \varphi(r,\phi,z) &= v\,f(r)\,e^{iN\phi}, \quad \text{with} \quad f(r) \to \begin{cases} 1 & ; \quad r \to \infty \\ 0 & ; \quad r \to 0 \end{cases} \\ A_\phi(r,\phi,z) &= \frac{N}{gr}a(r), \quad \text{with} \quad a(r) \to \begin{cases} 1 & ; \quad r \to \infty \\ r^2 & ; \quad r \to 0 \end{cases} \end{aligned}$$

- This configuration has finite energy per length for nice $f(r)$ and $a(r)$.
  $\to$ *cosmic string with winding number* N.

$N = 1: \quad \varphi = v\, f(r)\, e^{i\phi} \quad , \;\; A_\mu \rightarrow A_\phi(r)$





A Simple Cosmic String - Part 2

- This cosmic string configuration is stable on account of topology,

$$\Pi_1(S^1) = \mathbb{Z}$$

An infinite energy cost is required to change the winding number N.

- The properties of the string are set by the scale of spontaneous symmetry breaking $v = \langle|\varphi|\rangle$:

$$\text{String Width} \;:\; w \simeq v^{-1}$$
$$\text{String Tension} \;:\; \mu \simeq v^2$$

- Usually only the $N = 1$ mode is stable.
- This example is typical of *ordinary* cosmic strings.

Supersymmetry (SUSY)

- Supersymmetry is a well-motivated possibility for new physics.

- Quantum corrections can destabilize the gauge hierarchy:

  $$M_W \sim 100\,\mathrm{GeV} \ll M_{\mathrm{Pl}} \sim 10^{18}\,\mathrm{GeV}$$

  With SUSY, the dangerous quantum corrections cancel out.

- This feature makes SUSY theories a natural setting for the scalar fields that make up cosmic strings.

- The cancellations due to SUSY can also give rise to directions in the scalar potential that are extremely *flat*.

A Simple SUSY Flat Direction

- Sample SUSY flat-direction potential:

$$V_{eff}(\varphi) = -m^2|\varphi|^2 + \frac{\lambda}{M^{2n}}|\varphi|^{4+2n},$$

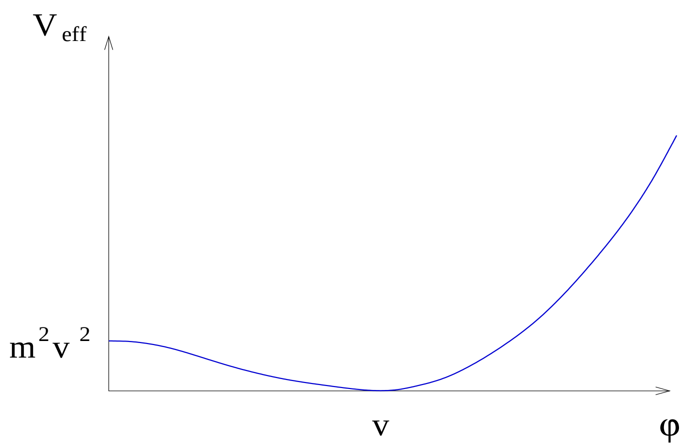
  with $m \ll M$, $n > 0$.

- Supersymmetry allows for $m \ll M$.

- The vacuum value of $|\varphi|$ is

$$v := \langle|\varphi|\rangle \simeq (mM^n)^{1/(n+1)}.$$

  Note that $m \ll v \ll M$.



- We have in mind $m \sim 10^3$ GeV, $M \sim M_{\rm Pl} \simeq 2.4 \times 10^{18}$ GeV.

Flat-Direction Strings

String Solutions

- We look for classical field solutions of the form

$$\begin{aligned} \varphi(r,\phi) &= v\, f(r)\, e^{iN\phi}, \\ A_\phi(r) &= \frac{N}{gr}\,\tilde{a}(r), \end{aligned}$$

with the boundary conditions

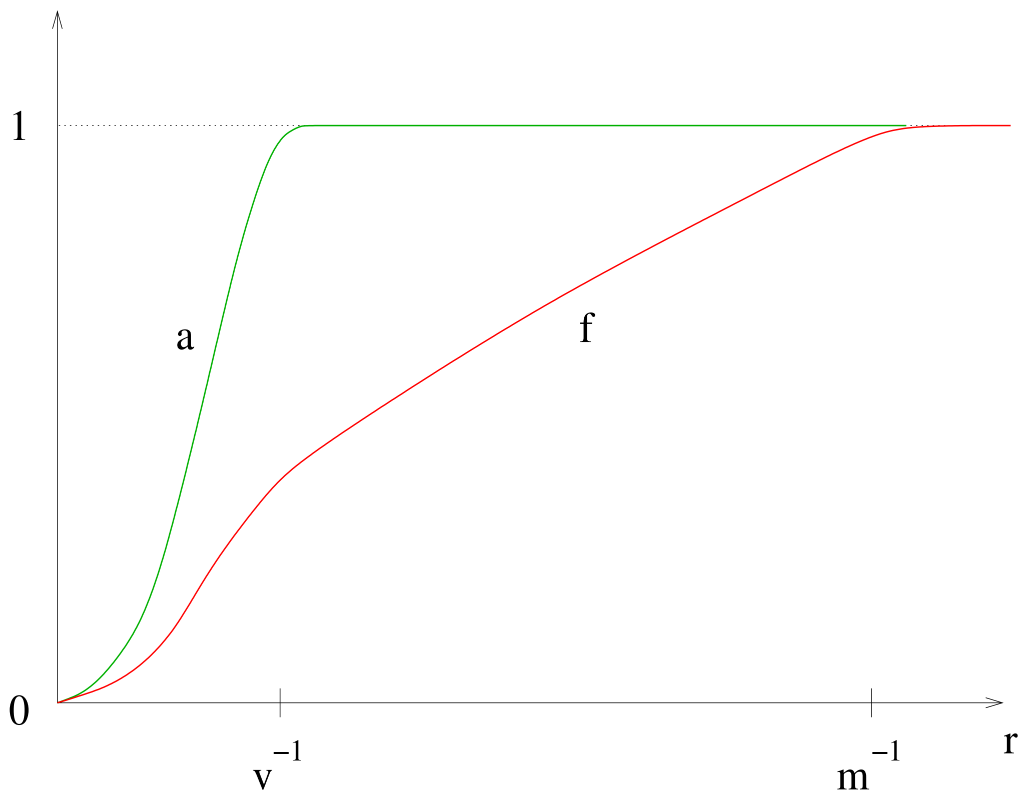
$$\begin{aligned} f(r),\ \tilde{a}(r) &\rightarrow 1 \quad \text{as} \quad r \rightarrow \infty, \\ f(r),\ \tilde{a}(r) &\rightarrow 0 \quad \text{as} \quad r \rightarrow 0. \end{aligned}$$

- N is a positive integer.

- We solve the equations of motion approximately and refine them using variational methods.

- The profile $\tilde{a}(r)$ has a width of v^{-1}.
- The profile $f(r)$ has width m^{-1}.

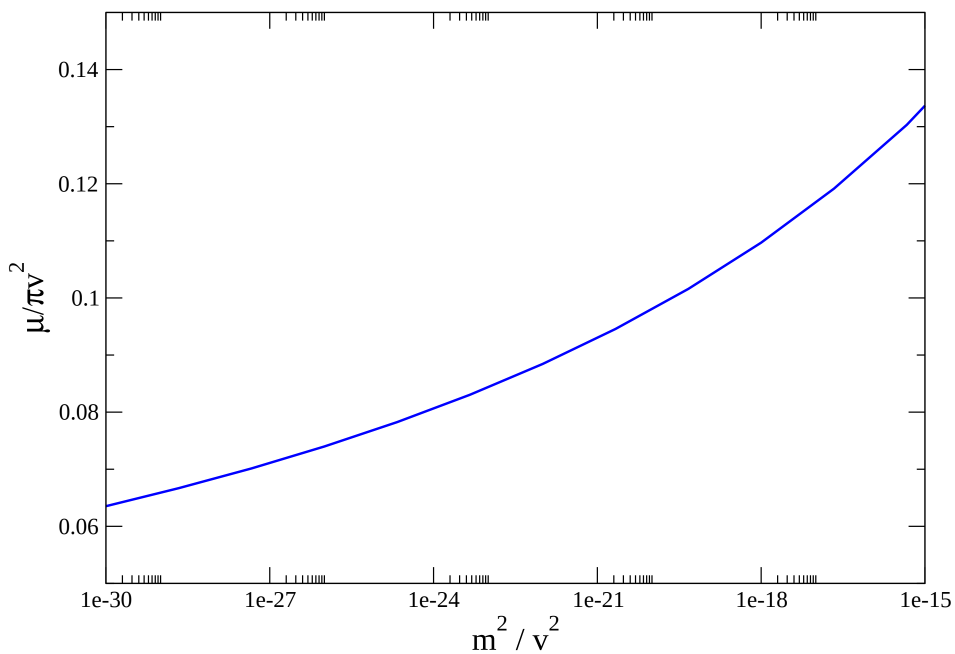
  $\rightarrow$ corresponds to the flat direction



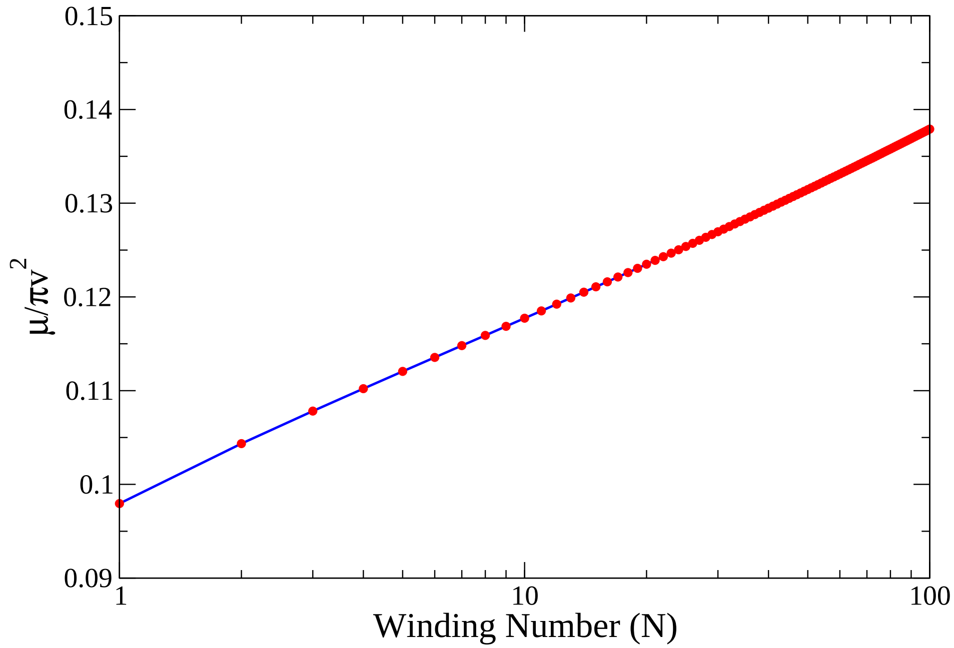
String Tensions

- Tension $= \mu =$ energy per unit length
- Flat direction strings have tensions $\mu \sim v^2$ (like ordinary strings).
- To a good approximation,

$$\mu_1 \simeq \frac{4\pi^2 v^2}{\log(v^2/m^2)}.$$



- The tension μ_N increases very slowly with the winding number N:



- We find

$$\mu_N \simeq \mu_1 \left[1 + \frac{3}{\ln(v^2/m^2)} \ln N\right].$$

$\Rightarrow$ $\mu_{N+M} < \mu_N + \mu_M$

$\Rightarrow$ higher ($N > 1$) winding modes are energetically stable.

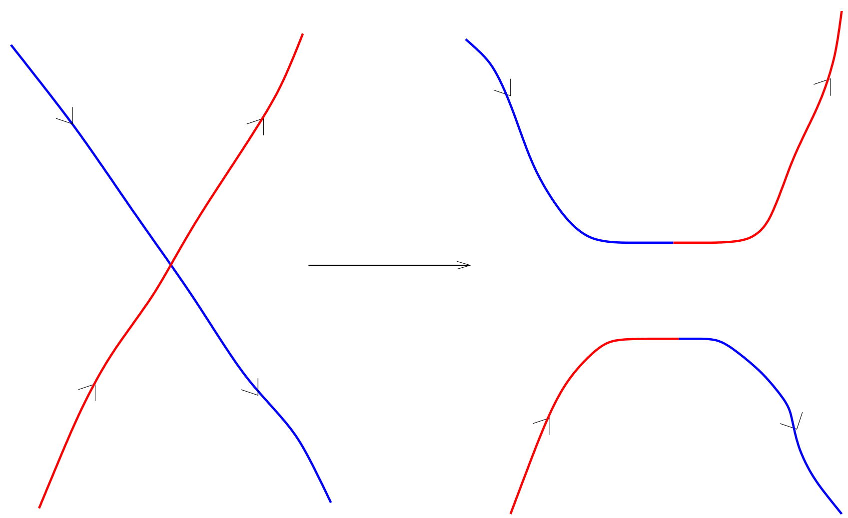
String Interactions

String Interactions: Intercommutation

- When a pair of ordinary strings intersect they can:

  1. pass through each other

  2. intercommute (reconnect)

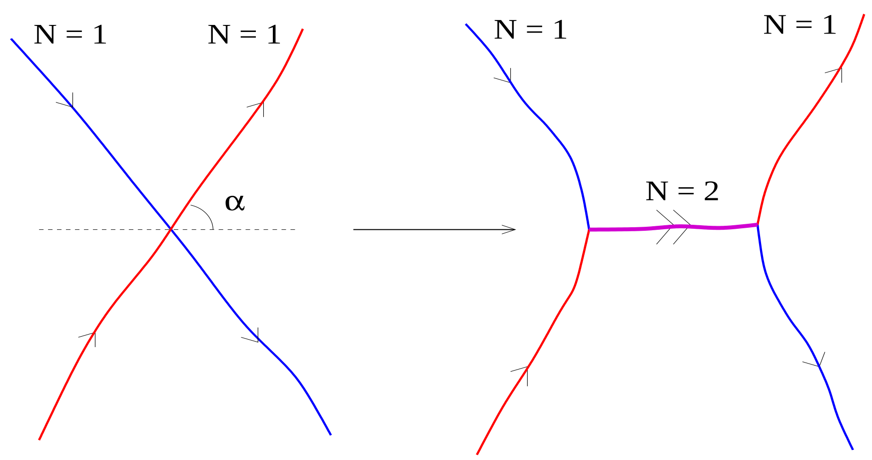


- Flat strings also intercommute.

String Interactions: Zippering

- Flat-direction strings have a qualitatively new interaction mode because they have stable higher winding states.

- Two $N = 1$ strings can form a new segment with $N = 2$:

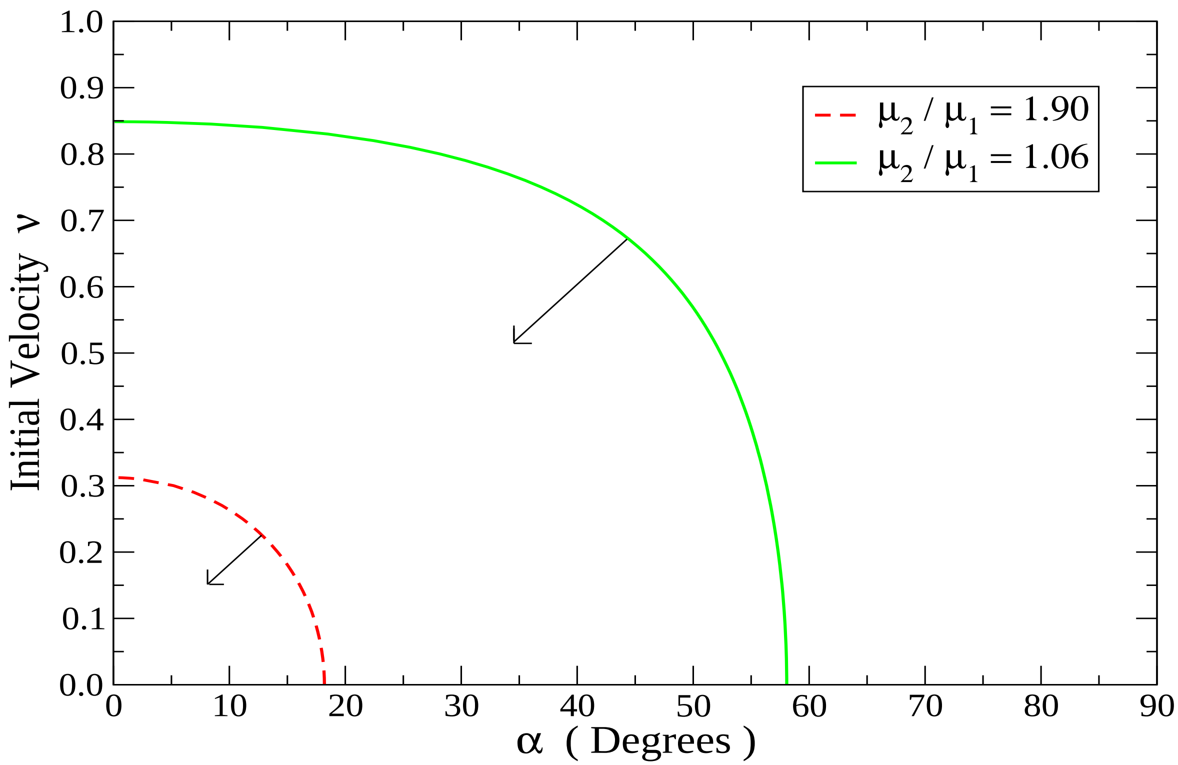


$\longrightarrow$ Zippering

- More generally, topology allows $N + M \to |N \pm M|$.

- Cosmic superstrings are also able to form zippers.

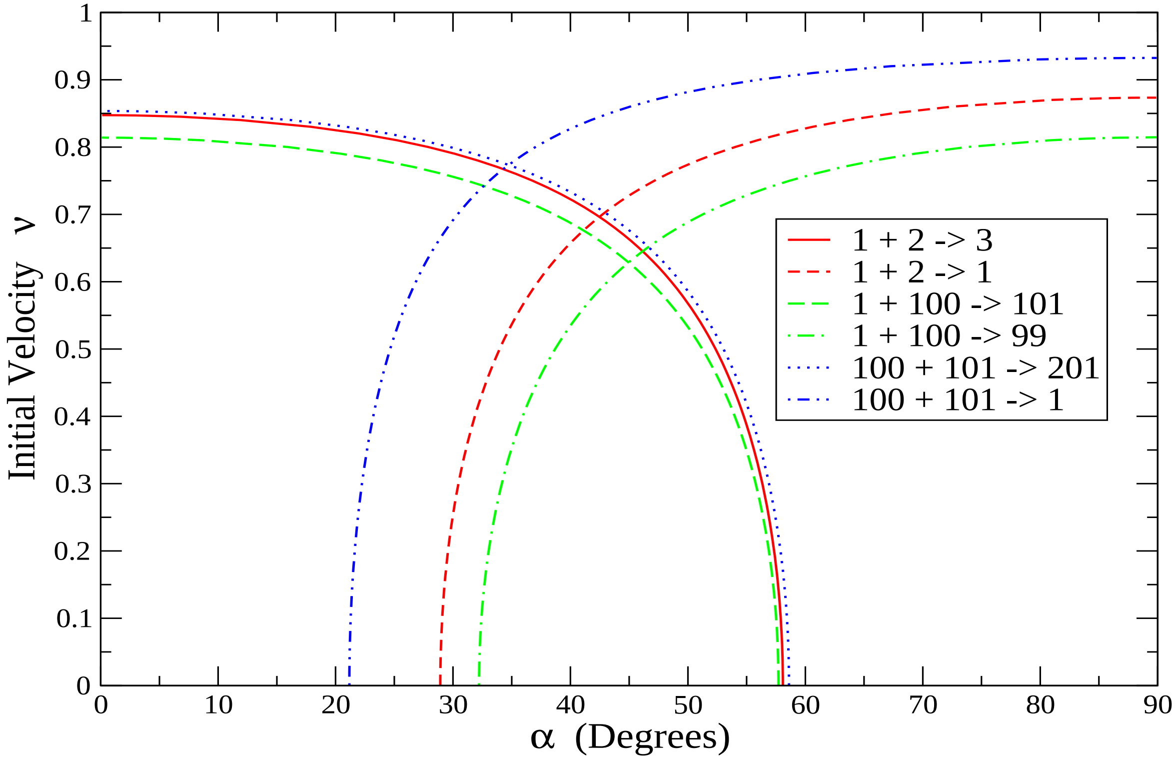
- $1 + 1 \to 2$
- Zippering is only kinematically allowed for $\mu_2 < 2\,\mu_1$.



- Initial velocities $\nu \simeq 0.6$ are typical in the early universe.

- For ordinary strings, $\mu_2 \simeq 2\,\mu_1$, and zippering is unlikely.

- $N + M \to |N \pm M|$ is also possible.
- (Intercommutation corresponds to $N + N \to 0$.)



- We assume that zippering occurs whenever it is kinematically allowed.

Comparison with Ordinary Strings

- Ordinary strings depend on a single dimensionful quantity v.
  - String Tension: $\mu \sim v^2$
  - String Width: $w \sim v^{-1}$
  - $\mu_2 \simeq 2\,\mu_1$, and zippering is unlikely.
- Flat strings depend on two dimensionful quantities, $m \ll v$.
  - String Tension: $\mu \sim v^2$
  - String Width: $w \sim m^{-1} \;\gg\; v^{-1}$
  - $\mu_2 < 2\,\mu_1$, and zippering is often possible.
- Cosmic superstrings are also able to zipper.

String Networks
in the
Early Universe

Cosmic String Scaling

- Scale factor: $a(t) \propto \frac{1}{T(t)}$.
- The energy density of *non-interacting* strings scales as

$$\rho_{string} \propto a^{-2}(t).$$

- This is a problem?

$$\rho_{matter} \propto a^{-3}(t),$$
$$\rho_{radiation} \propto a^{-4}(t).$$

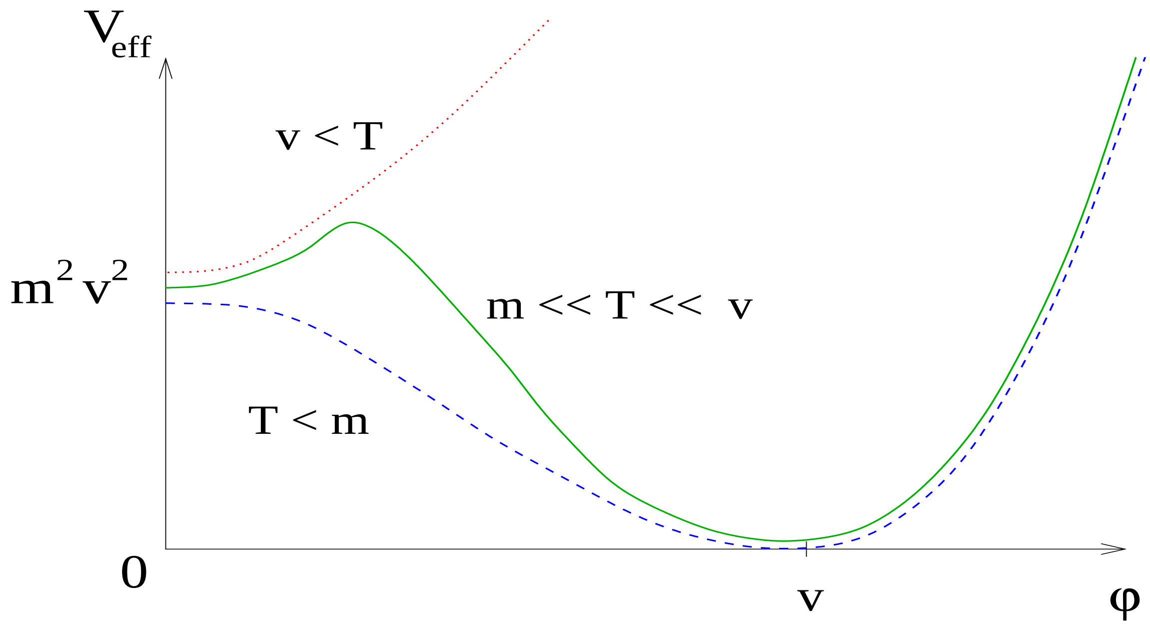
- However, strings form loops by intercommutation, which decay away.
- Cosmic strings track the background matter or radiation density

$$\rho_{string} \simeq G\mu \left(\rho_{matter} + \rho_{radiation}\right)$$

$\longrightarrow$ cosmic string scaling

Flat String Formation

- Flat strings are formed after a brief period of thermal inflation: [Lyth+Stewart '95]
  - Thermal corrections trap the flat direction scalar at the origin.
  - The excess vacuum energy drives inflation until $T \sim m$.
  - When the $T \lesssim m$, the scalar rolls down the potential and oscillates.



- Number of e-foldings of thermal inflation: $N_e \simeq \frac{1}{2}\log(v^2/m^2)$.

- The oscillating scalar decays at time $t = \Gamma^{-1}$ with

$$\Gamma = \gamma \frac{m^3}{v^2}$$

- These decays reheat the universe to

$$\begin{aligned} T_{RH} &\simeq g_*^{-1/4}(M_{\mathrm{Pl}}\Gamma)^{1/2} \\ &\simeq 100\,\mathrm{MeV}\left(\frac{g_*}{10}\right)^{-1/4}\left(\frac{\gamma}{0.1}\right)^{1/2}\left(\frac{v}{10^{14}\,\mathrm{GeV}}\right)^{-1}\left(\frac{m}{10^3\,\mathrm{GeV}}\right)^{3/2} \end{aligned}$$

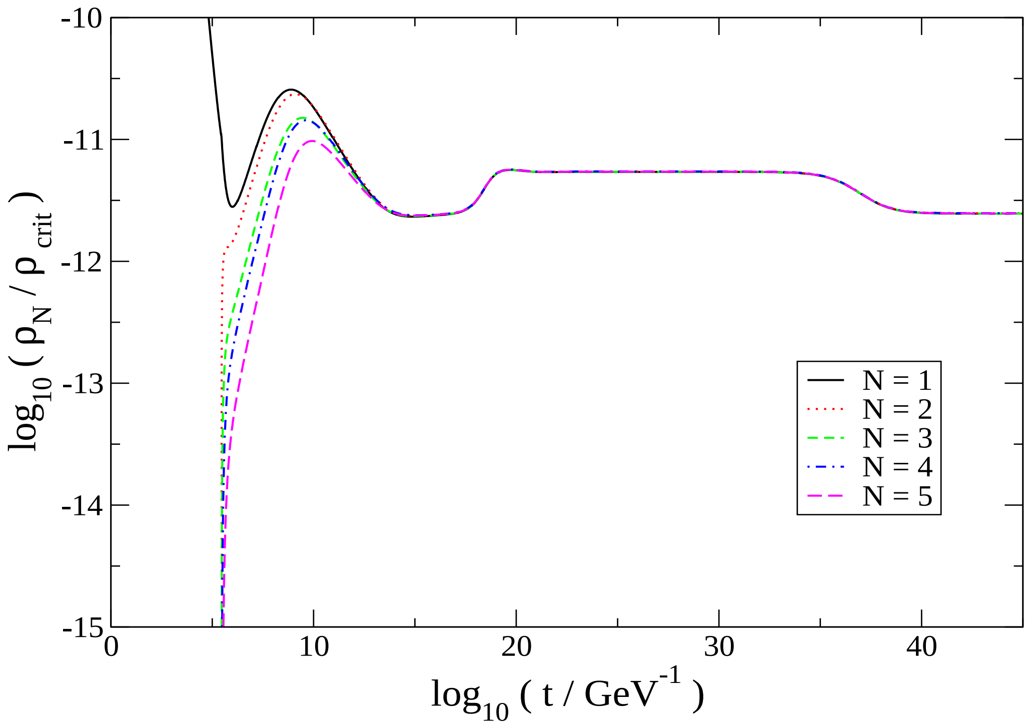
- Nucleosynthesis requires $T_{RH} > 5\,\mathrm{MeV}$. [Hannested '05]

- Flat-direction strings are formed at $T \simeq m$.

- Ordinary cosmic strings are formed at $T \simeq v$.

Scaling of Flat Strings

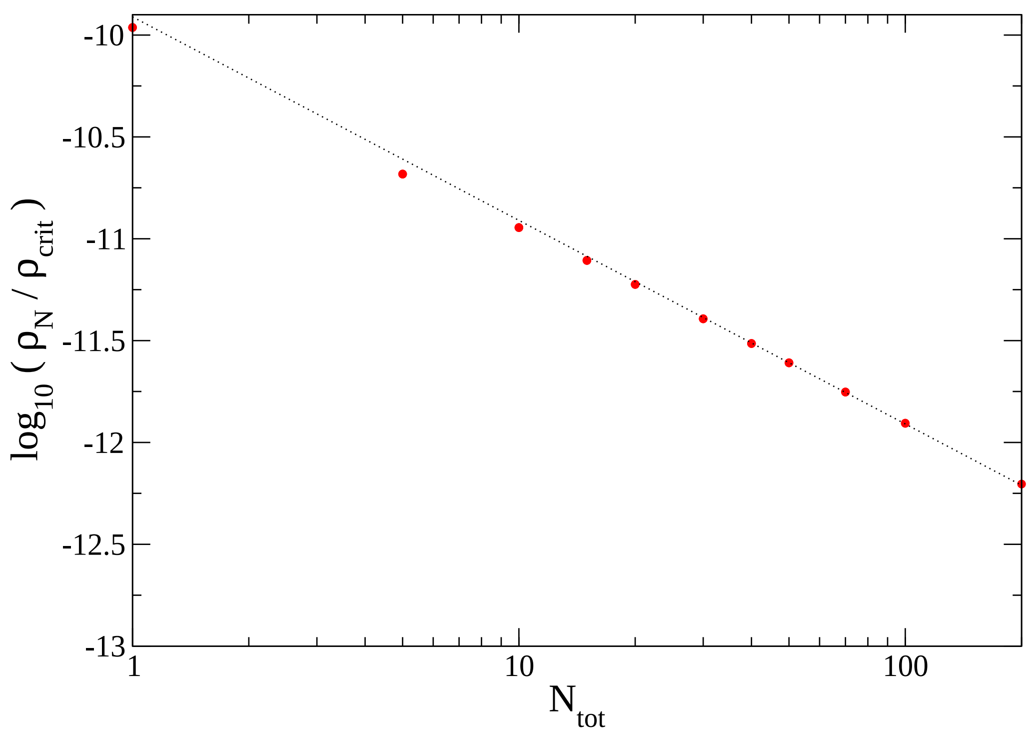
- Flat strings can zipper in addition to intercommuting.
- We study their evolution with a simple model by Tye, Wyman, and Wasserman. [TWW '05]
- They form a scaling network with many different types of string.
- Many string varieties approach an equal scaling density:



- The density of each string species is inversely proportional to the total number of strings types that are scaling,

$$\rho_N \simeq \frac{1}{N_{tot}} \rho_{tot} \simeq \frac{1}{N_{tot}} G\mu \left(\rho_{matter} + \rho_{radiation}\right)$$

- The flat cosmic string density is spread out among many species, each with a nearly equal tension.



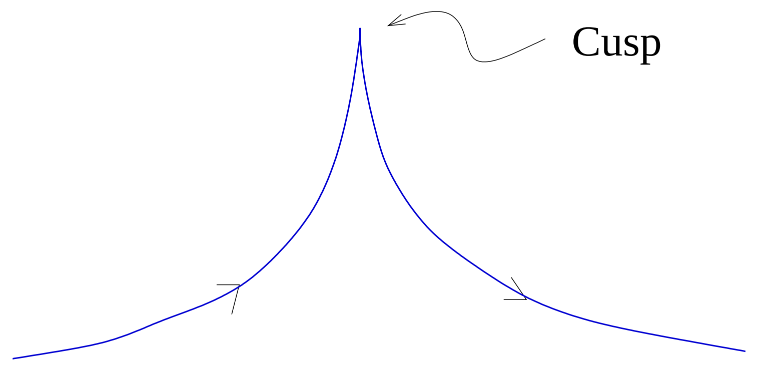
Cosmological String Signatures

Ordinary Cosmic String Signatures

- Most cosmic string signatures are characterized by $G\mu \simeq \left(\frac{v}{\sqrt{8\pi}\,M_{\rm Pl}}\right)^2$.
- Long strings:
  - String wakes can seed large scale structure.
    CMB $\Rightarrow G\mu \lesssim 10^{-7}$
    [Pogosian,Wyman,Wasserman '06,Fraisse '06]
  - Light passing by a string is gravitationally lensed. [Vilenkin '81]
- String loops:
  - Loops are not topologically stable.
  - They oscillate and emit gravity waves.
    Pulsar timing measurements $\Rightarrow G\mu \lesssim 10^{-7}-10^{-10}$
    [DePies+Hogan '07]
- Flat direction strings have additional signatures.

String Cusps and Particle Creation

- String loops frequently form cusps as they oscillate.



- In each cusp event, a length of string ℓ_c is annihilated

$$\ell_c = \sqrt{w\ell},$$

where w is the string width and ℓ is the loop length.
[Blanco-Pillado+Olum '98]

- String annihilation in cusps leads to particle creation.

  This is expected to be the dominant source of particles.

  [Srednicki+Theisen '87, Brandenberger '87]

- The rate of energy loss from a loop to gravitational radiation is

$$P_{grav} \simeq G\mu^2$$

- The rate of energy loss from a loop to particles by cusping is

$$P_{cusp} \simeq \mu \left(\frac{w}{\ell}\right)^{1/2},$$

where ℓ is the loop length. [Blanco-Pillado+Olum '98]

- Flat strings are much wider than ordinary strings,

$$w_{flat} \sim m^{-1} \gg v^{-1} \sim w_{ordinary}.$$

$\Rightarrow$ particle creation is enhanced for flat strings

- Particle creation dominates over gravitational radiation for loops smaller than

$$\ell < \ell_{=} \simeq w \left(\frac{1}{G\mu}\right)^2.$$

Flat String Loop Signatures

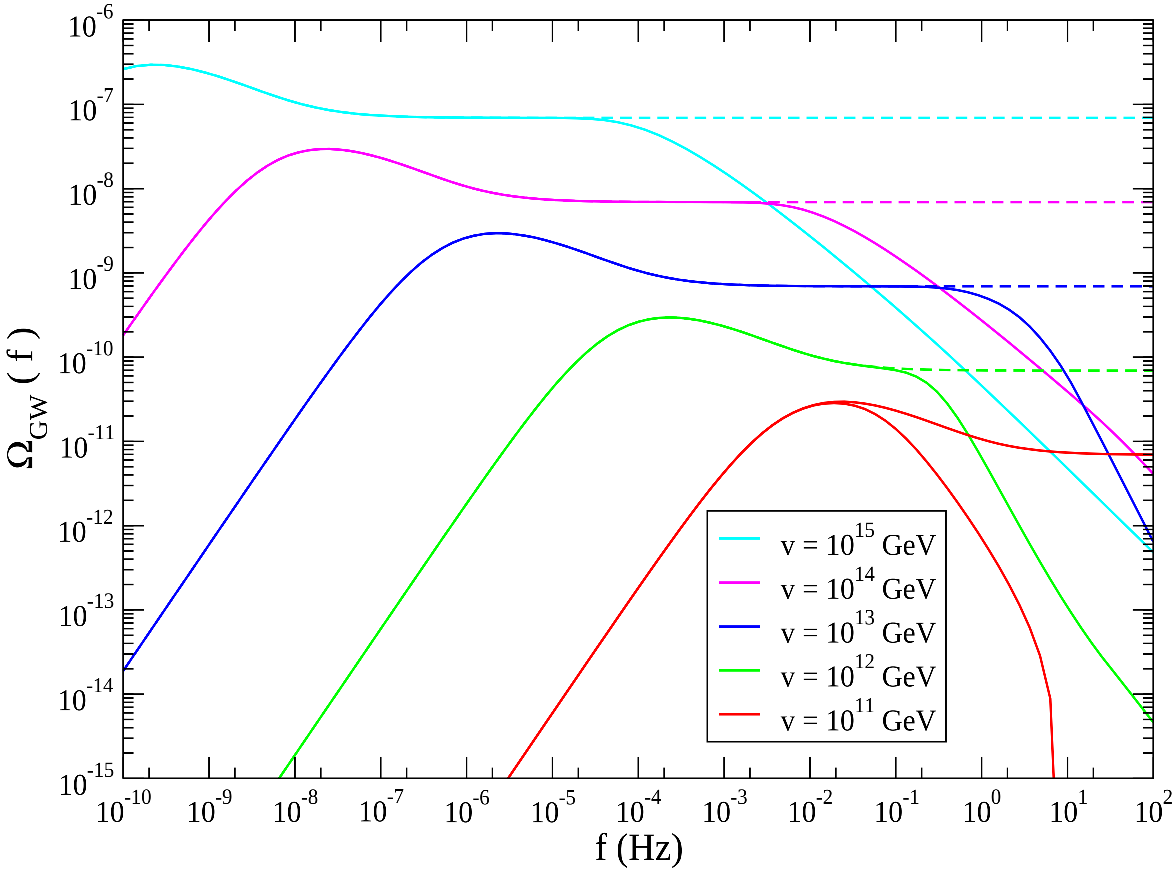
- Enhanced particle creation leads to new signatures:
  - dark matter
  - modifications to nucleosynthesis and the CMB blackbody
  - cosmic rays
- The nature of the signatures depends on the typical intial loop size.
- Large initial loops, $\ell_i(t_i) \simeq 0.1\, t_i$: [Ringeval *et al.* '05;Olum+Vanchurin '06]

  $\rightarrow$ loops lose most of their energy to gravitational radiation.
- Small initial loops, $\ell_i(t_i) \ll G\mu\, t_i$: [Siemens+Olum '01; Polchinski *et al.* '06]

  $\rightarrow$ loops lose most of their energy to particle creation
- This is a topic of current debate, even for ordinary strings.
  We therefore consider both large and small initial loop sizes.

Gravitational Wave (GW) Signatures

- The GW spectrum from flat strings is suppressed.
- This suppression is very strong for small initial loop sizes.
- For large initial loops ($\ell_i(t) = (0.1)\,t$) the GW spectrum is



Particle Creation Signatures

- These are important for small initial loops ($\ell_i(t) \ll t$).
  - Dark matter:
    some of the decay products can be dark matter.
  - Nucleosynthesis:
    late decays modify light element abundances.
    $\Rightarrow G\mu \lesssim 10^{-12}$
  - CMB blackbody:
    late-time photon production modifies the CMB frequency spectrum.
    $\Rightarrow G\mu \lesssim 10^{-11}$ (COBE/FIRAS)
  - Cosmic rays: energetic decay products can make up cosmic rays.
    $\Rightarrow G\mu \lesssim 10^{-11}$ (EGRET)
- These signatures are all very enhanced due to the large width of flat-direction cosmic strings.
- (We have assumed $m = 10^3\,\text{GeV}$ and small loops for these bounds.)

Dark Matter from Flat-Direction Strings

- If the dark matter (DM) is made up of massive particles, these particles can be created as decay products from cusps.

- The amount of dark matter created in this way depends on how the string fields couple to the dark matter fields.

- For very small loops that decay entirely by cusp annihilation,

$$\Omega_{DM}^{strings} \simeq 30\,\epsilon_1 \left(\frac{\gamma}{0.1}\right)^{1/2} \left(\frac{v}{10^{14}\,\mathrm{GeV}}\right) \left(\frac{m}{10^{3}\,\mathrm{GeV}}\right)^{3/2},$$

  where ϵ_1 is the branching fraction into DM.

- DM can also be generating during reheating after thermal inflation.

Constraints from Nucleosynthesis

- Nuclear reactions at $T \lesssim 1\,\mathrm{MeV}$ in early universe can account for the primordial light element abundances.

- Energy released after this time can ruin this prediction.

- For very small loops that decay entirely by cusp annihilation,

$$\frac{\Delta E}{S}(t > 100\,s) \simeq (10^{-12}\,\mathrm{GeV})\left(\frac{G\mu}{2 \times 10^{-11}}\right).$$

  where S is the entropy in a volume a^3.

- Recent estimates constrain $\Delta E/S \lesssim 10^{-12}$–$10^{-14}\,\mathrm{GeV}$.
  [Kawasaki,Kohri,Moroi '04]

Constraints from the CMB Blackbody Spectrum

- The cosmic microwave background (CMB) frequency spectrum is perfectly fit by a blackbody spectrum. [COBE/FIRAS '96]

- Photons produced after t_{dC}, when double Compton scattering ceases, will distort the blackbody spectrum. [Hu+Silk '93]

- COBE/FIRAS implies $\Delta\rho_\gamma/\rho_\gamma \lesssim 7 \times 10^{-5}$.

- For very small loops that decay entirely by cusp annihilation,

$$\frac{\Delta\rho_\gamma}{\rho_\gamma} \simeq (8 \times 10^{-5}) \left(\frac{G\mu}{2 \times 10^{-11}} \right) .$$

Gravitational Lensing

- Angular Deflection $\propto G\mu$.
- The tension μ can be determined by observing several galaxies lensed by the same cosmic string.
  [Oguri+Takahashi '05]
- In this way we might hope to observe flat strings with *different* tensions.

$$\mu_N \simeq \mu_1 \left[1 + \frac{3}{\ln(v^2/m^2)}\right] \ln N.$$

- Cosmic superstrings can also form multi-tension string networks.
  [Tye,Wyman,Wasserman '05]

$$\mu_{(p,q)} \propto \sqrt{g_s^2\, p^2 + q^2}$$

- In practice, it will be difficult to distinguish between these different types of cosmic strings. [Gasparini *et al.* '07]

Summary

- Cosmic strings from symmetry breaking along a supersymmetric flat direction are qualitatively different from ordinary cosmic strings.
  - Flat strings are wide: $w \simeq m^{-1} \gg v^{-1}$.
  - Higher winding modes are very stable: $\mu_N \simeq \mu_1 \left[1 + \frac{3}{\ln(v^2/m^2)}\right] \ln N$.
- Higher winding modes can form dynamically by zippering.
  - Zippering occurs in the early universe.
  - The scaling string network contains many string types.
- Particle creation by cusp annihilation is enhanced.
  - Gravitational wave signatures are suppressed.
  - New string signatures are possible:
    dark matter, CMB distortions, cosmic rays.

Extra Slides

A Simple SUSY Flat Direction

- SUSY $U(1)$ gauge theory with chiral superfields φ_a and φ_{-b}:

$$
\begin{aligned}
W &= \frac{\lambda}{M^{a+b-3}} \varphi_a^b \varphi_{-b}^a + \dots \qquad \rightarrow \qquad V_F = \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 \\
V_D &= \frac{g^2}{2} (a|\varphi_a|^2 - b|\varphi_{-b}|^2)^2 \\
V_{soft} &= -m_a^2 |\varphi_a|^2 - m_b^2 |\varphi_{-b}|^2 - \left(\frac{A}{M^{a+b-3}} \varphi_a^b \varphi_{-b}^a + h.c. \right) + \dots
\end{aligned}
$$

- The full potential is minimized with

$$
\begin{aligned}
\varphi_a &= \sqrt{\frac{b}{a+b}} v \\
\varphi_{-b} &= \sqrt{\frac{a}{a+b}} v
\end{aligned}
$$

where

$$
v \simeq \left(m M^{a+b-3} \right)^{1/(a+b-2)}, \qquad m \sim A \sim \sqrt{m_i^2}.
$$

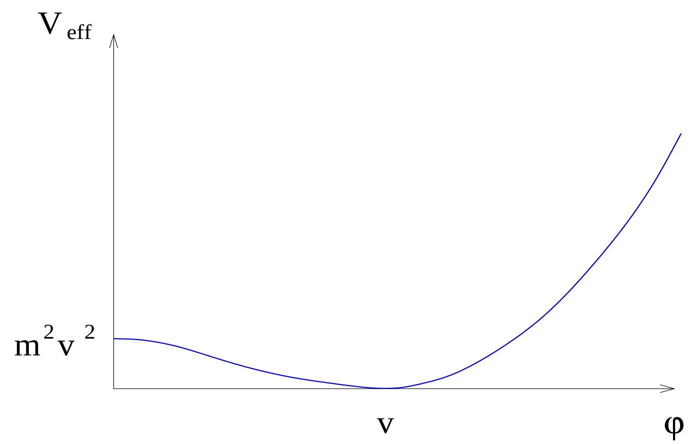
- We have in mind

$$m \sim 10^3\,\text{GeV}, \qquad M \sim M_{\text{Pl}} \simeq 2.4 \times 10^{18}\,\text{GeV}.$$

$\Rightarrow m \ll v \ll M$ for $a + b > 3$

- The direction $\varphi_a = \sqrt{\frac{b}{a}}\varphi_{-b}$ is *D-flat*; $V_D = 0$.

- This direction is destabilized by the soft masses at the origin, and restabilized by the superpotential away from the origin.



- SUSY prevents quantum corrections from pushing $m \to M$.

Initial Loop Sizes

- The spectrum of small fluctuations on cosmic strings is not fully understood, and neither is the typical initial loop size.
- In the scaling regime, the loop size is usually written as

$$\ell_i(t) = \alpha\, t,$$

where t is the cosmic time.

- Estimates:
  - Standard Lore: $\alpha \simeq G\mu$
  - Recent Simulations: $\alpha = 0.01 - 0.1$
    [Ringeval *et al.* '05;Olum+Vanchurin '06]
  - Recent Analytics: $\alpha \simeq (G\mu)^{1+2\chi}$, $\chi > 0$
    [Siemens+Olum '01; Polchinski+Rocha '06; Dubath,Polchinski,Rocha '07]
- We therefore consider both large and small initial loop sizes.