



Exotic Acceleration Mechanisms

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8/11/2008



Outline

- Introduction.
- A Disclaimer
- Topological Defects (I'll focus on these)
 - Overview
 - Classification and Formation
 - Dynamics
 - Examples - cusps, superconducting strings, cosmic necklaces
- Superheavy Dark Matter (Briefly)
 - Generation - Preheating
 - Annihilations and Decays
- Lorentz Violations (Even more briefly)
- Summary and Conclusions



Disclaimer

- I am not a cosmic ray physicist!
- I don't write papers on this topic!
- I really am not a cosmic ray expert in any way!
- Honestly!

But ...

- My particular topic isn't really about cosmic rays.
- It is really about the types of beyond the standard model physics, (both particle physics and cosmology) that can give rise to tremendously high particles in today's universe.
- I do know a bit about that.
- Hopefully!



Main Point

We seek extremely high energy particles in today's universe

There are really two broad ways in which one can imagine getting these

- **Astrophysics:** Interacting matter in today's universe conspires to accelerate particles to high velocities.
- **Cosmology:** Here there is a problem - the universe cools! No simple equilibrium process leads to high energy particles being produced cosmologically in today's universe.
- To get around this need to somehow “preserve” some of the early, high-energy universe, and then persuade it to give up its energy as highly-accelerated particles today.. (Top Down mechanisms)



Plan

You've been hearing a lot about cosmic rays and other cosmic messengers from a great variety of astrophysical sources.

Nevertheless there is a difficulty in using astrophysical accelerators to accelerate particles to energies

$$E \geq 10^{21} \text{ eV}$$

This further raises the possibility that new physics beyond the standard model may be responsible for the highest energy cosmic rays and other phenomena.

I'll survey some proposals, focusing on the physics behind the generation and how it fits into particle physics and cosmology models.

Note that if one of these were to turn out to be correct, then not only would we have an exotic explanation for these high-energy phenomena, but we would also have direct astrophysical input to complement those coming from colliders and cosmology.



Main Principle

As we've noted, we'd like a way to generate particles with energies $> 10^{21}$ eV

In all these proposals, high energy particles (such as UHECR primaries) are produced as the decay products of some superheavy particles X with mass $m_X > 10^{12}$ GeV.

The relevant primary particles may be

- produced in the early universe, but metastable, decaying today.
- produced in the early universe, stable, but annihilating today.
- produced today (or recently) by exotic structures produced in the early universe.

The point is to identify ways to preserve a portion of the high-energy early universe, either in the form of superheavy particles, or through a region of false vacuum protected by topology (for example) from early times.

So let's get on with it!



Topological Defects - General

Let's just jump straight in with some examples. We'll start off with global defects, since they are simpler. Consider the Lagrangian

$$L = \frac{1}{2}(\partial_\mu\phi_i)\partial^\mu\phi_i - V(\phi_i) \quad i = 1, \dots, N$$

with

$$V(\phi) = \lambda(\phi_i\phi_i - v^2)^2$$

Theory is spontaneously broken: the Lagrangian is invariant under $O(N)$ but the vacua are where

$$\langle |\phi|^2 \rangle = v^2$$

So any vacuum configuration is invariant only under $O(N-1)$ - an $N-1$ sphere.

Doing perturbation theory around any such vacuum will yield the perturbative spectrum, the Goldstone mode, etc.

But consider not doing perturbation theory.

Example I: Domain Walls

Example: $N=1$

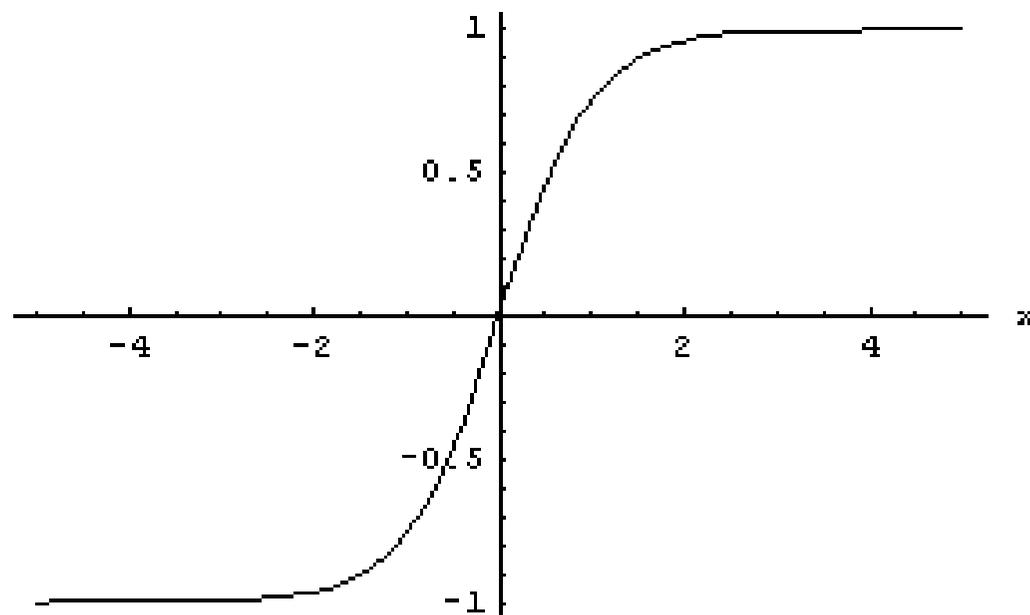
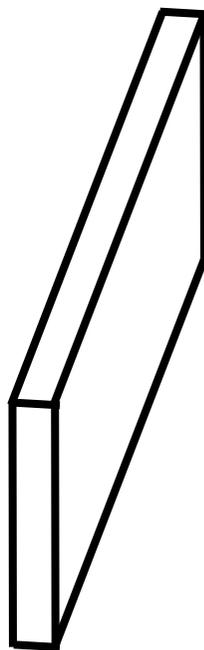
Vacuum consists of two distinct points $\langle \phi \rangle = \pm v$

Topologically disconnected!

Choose boundary conditions $\langle \phi \rangle \longrightarrow \pm v$ as $z \longrightarrow \pm \infty$

Then a continuous field configuration cannot be in vacuum everywhere

- it will be out of vacuum in some region of space
- in this case the vacuum field configuration is a *domain wall* which can't relax to a trivial vacuum without infinite energy.



Example II: Cosmic Strings

Example: $N=2$

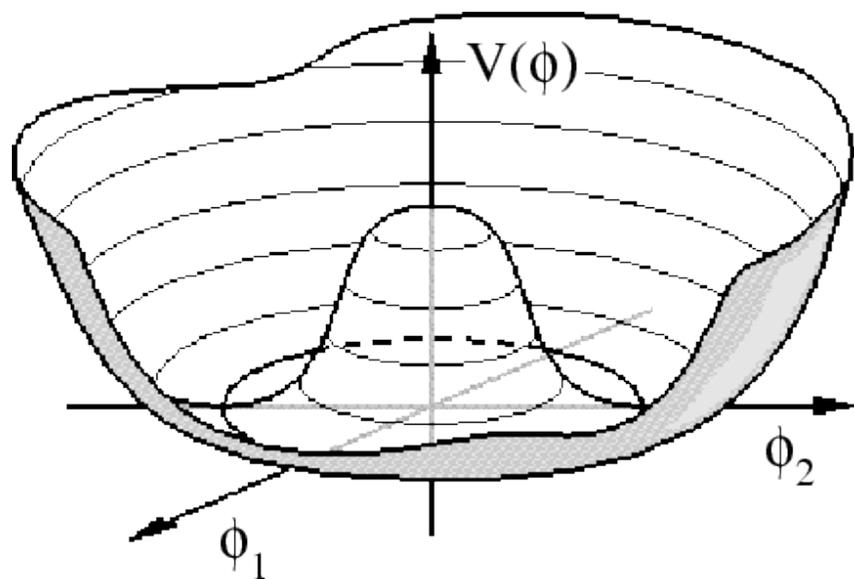
Vacuum consists of a circle $\langle \phi \rangle = v e^{i\alpha}$

Topologically connected, but not simply connected!

Choose boundary conditions $\langle \phi \rangle \longrightarrow v e^{in\theta}$ as $(r, \theta) \longrightarrow \pm(\infty, \theta)$

Then a continuous field configuration cannot be in vacuum everywhere

- it will be out of vacuum in some region of space
- in this case the vacuum field configuration is a *cosmic string* which can't relax to a trivial vacuum without infinite energy.



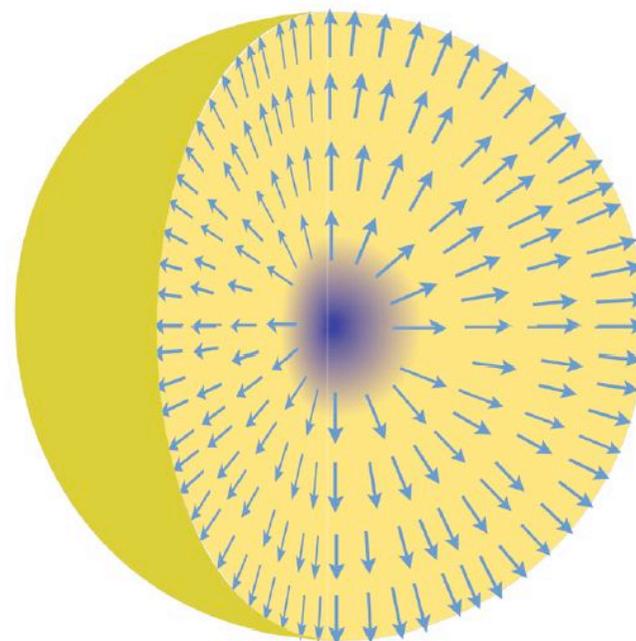
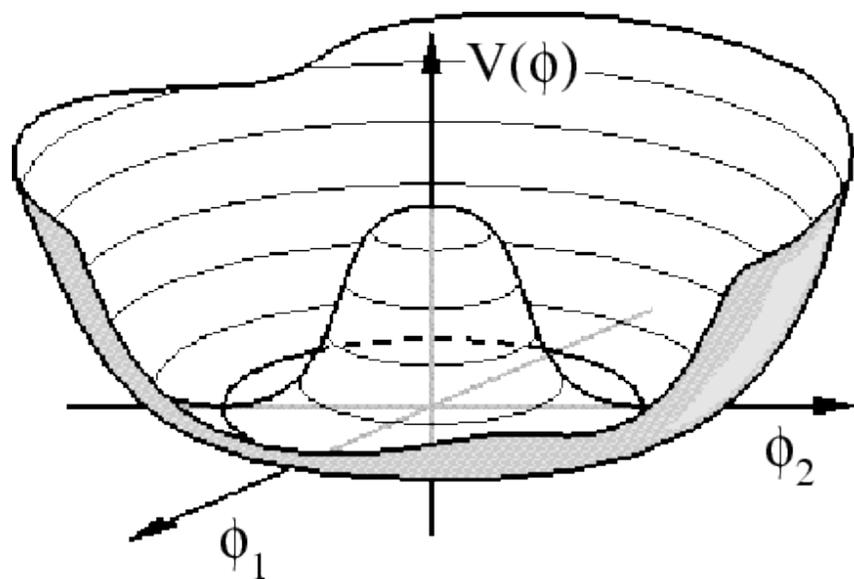
Example III: Magnetic Monopoles

Example: $N=3$

Vacuum consists of a 2-sphere

More complicated topological structure!

- Then a continuous field configuration cannot be in vacuum everywhere
- it will be out of vacuum in some region of space
 - in this case the vacuum field configuration is a *magnetic monopole* which can't relax to a trivial vacuum without infinite energy.



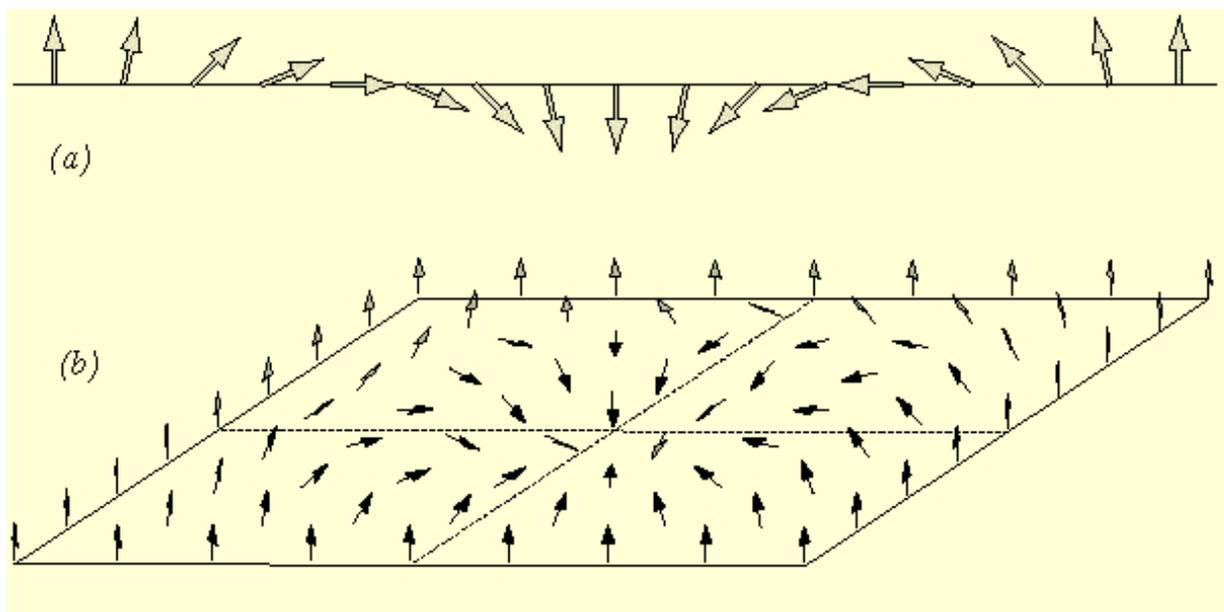
Example IV: Texture (Global)

Example: $N=4$

Vacuum consists of a 3-sphere

More complicated topological structure!

- Then a continuous field configuration cannot be in vacuum everywhere
- it will be out of vacuum in some region of space
 - in this case the vacuum field configuration is a *cosmic texture* which consists entirely of gradient energy, and can unwind, releasing energy.



[DAMTP]



Topological Defects - Formal

Suppose have a theory with a symmetry group G (local or global), spontaneously broken to a subgroup H

$$G \longrightarrow H$$

The *vacuum manifold* (the space of minimum energy configurations) is the set of left cosets of H in G

$$M \equiv G/H$$

We're interested in the topological properties of this space. In particular, we would like to know whether there exist any nontrivial *homotopy groups*.

The n th homotopy group classifies maps from S^n to M

$\pi_{d-p-1}(M) \neq 1$ implies dimension p defects in $(d+1)$ spacetime dimensions.

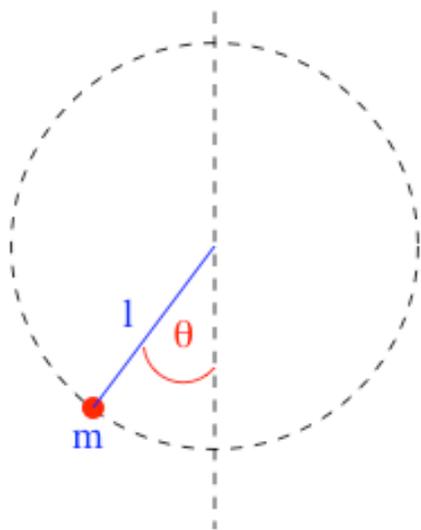
$d=3$: $\pi_0(M) \neq 1$ $p=2$: Domain walls

$\pi_1(M) \neq 1$ $p=1$: Cosmic strings

$\pi_2(M) \neq 1$ $p=0$: Magnetic monopoles

An Analogy

A simple pendulum



$$L = \frac{1}{2}ml^2\dot{\theta}^2 - mgl(1 - \cos\theta)$$

Vacua:

$$\theta_n = 2\pi n \quad n \in \mathbb{Z}$$

New Definitions

$$\chi \equiv \frac{\theta}{2} \quad \omega \equiv \frac{g}{l} \quad \alpha \equiv \frac{\hbar\omega}{4mgl} \ll 1$$

Schrödinger Equation

$$\frac{\hbar\omega}{2} \left[-\alpha \frac{d^2}{d\chi^2} + \frac{1}{\alpha} \sin^2 \chi \right] \psi_n(\chi) = E_n \psi_n(\chi)$$

Perturbative Approach
(expand about a minimum)

$$\sin^2 \chi = \chi^2 - \frac{\chi^4}{3} + \dots$$

Keep only first term:
Harmonic Oscillator!

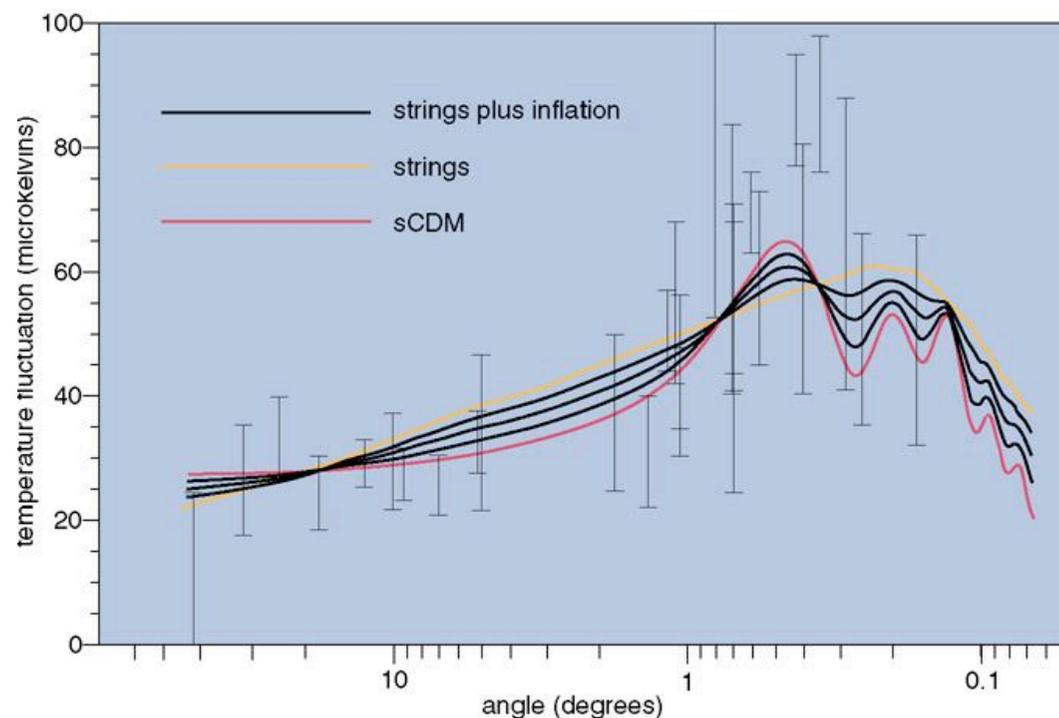
Great for doing collider physics, but
misses some important structure!



Some History

Topological defects have been discussed in connection with almost all cosmological phenomena:

- Inflation
- Structure formation
- Baryogenesis
- Dark matter
- Cosmic acceleration
- Primordial magnetic fields
- ...



[Contaldi et al.]

We know that they cannot be responsible for all of these (in particular structure formation). However, they generically occur in field theories, and in many ways it would be surprising if they didn't exist in the universe!

Focus on Cosmic Strings

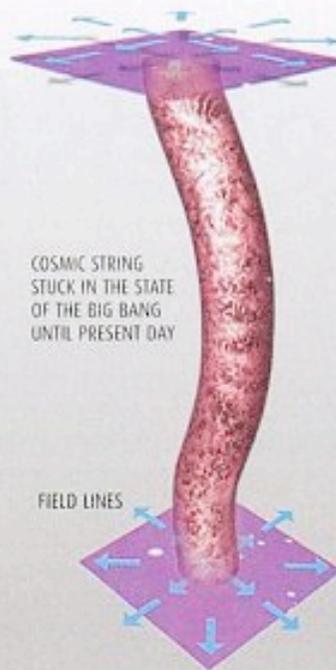
There are actually a number of ways in which these can be created.

Here, I'll focus on the first one, which is best understood (and requires less extrapolation than the others).

THREE WAYS TO MAKE COSMIC STRING

Most theories of the early universe describe how some form of cosmic strings came into existence

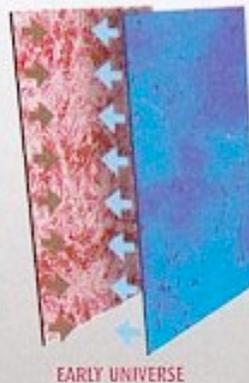
1. AN ANCIENT FORCE FIELD FREEZES



2. A MINUSCULE SUPERSTRING INFLATES



3. BRANES COLLIDE



COLLISION LEAVES BEHIND OUR UNIVERSE THREADED WITH COSMIC STRING





The Abelian Higgs Model

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

Look for static finite energy solutions with cosmic string boundary conditions:

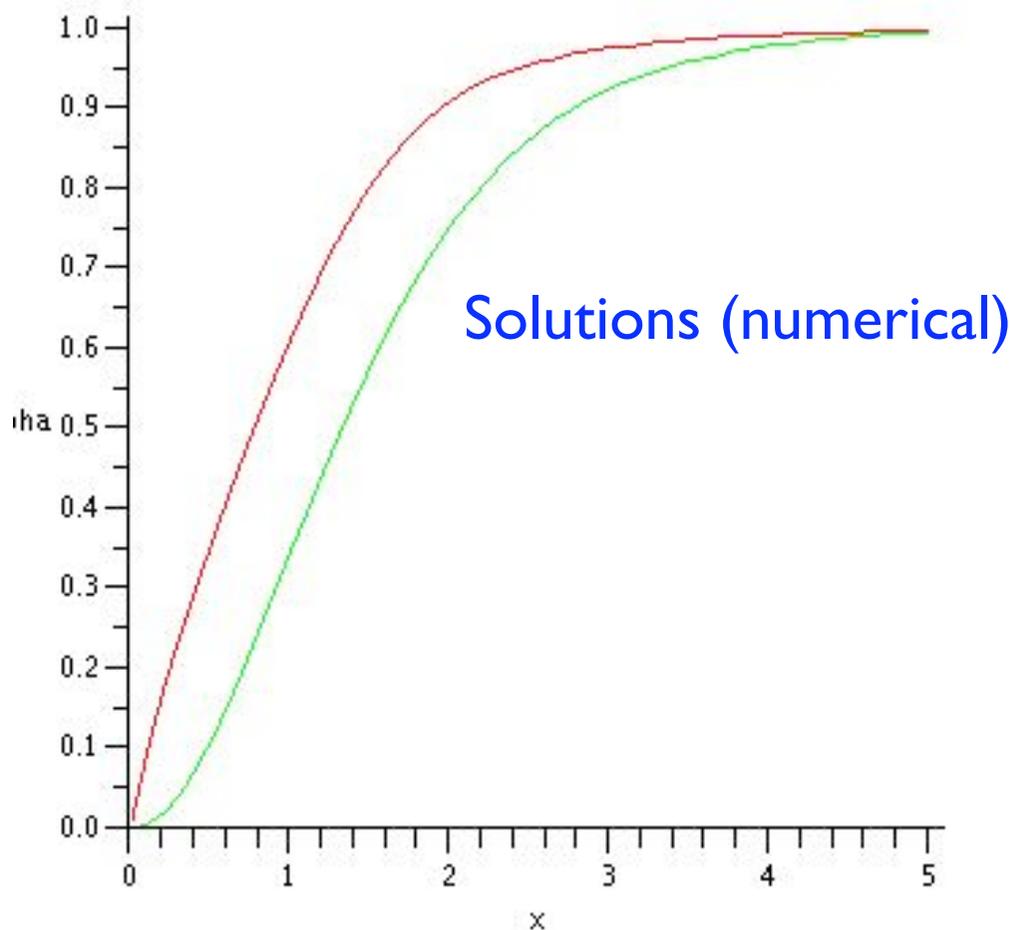
$$\phi(r, \theta) = v f(r) e^{i\theta}$$

$$A_\mu = \frac{g(r)}{e} \partial_\mu \theta$$



$$-f'' - \frac{f'}{r} + \frac{g^2 f}{r^2} + \frac{\lambda v^2}{2} f(f^2 - 1) = 0$$

$$-g'' + \frac{g'}{r} + \frac{2e^2 v^2 f^2 g}{\lambda} = 0$$

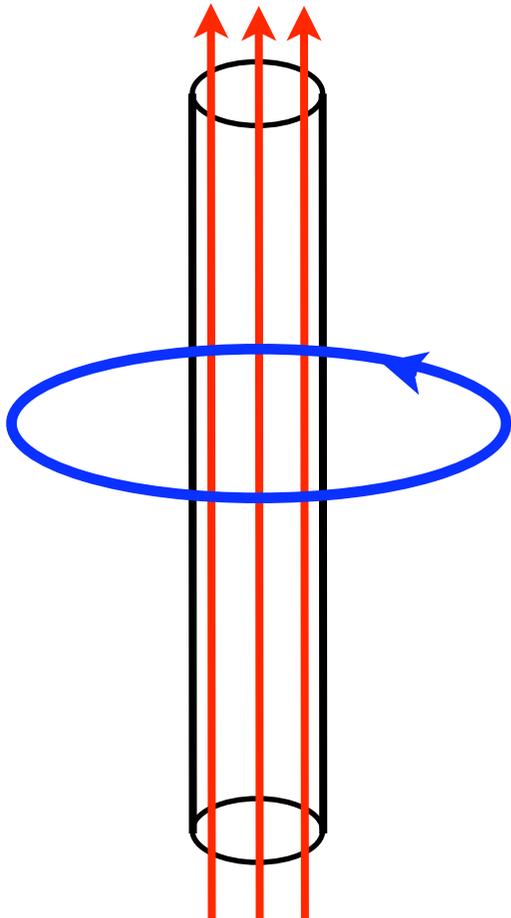


Energy (mass) per unit length $\mu \sim v^2$

Magnetic core, width $\sim (ev)^{-1}$

Carrying total magnetic flux

$$\Phi = \oint_{r=\infty} A_\mu dx^\mu = -\frac{2\pi}{e}$$



Core consists of false vacuum
 - a small part of the early, high energy universe, preserved against decay by topology



Formation of Strings

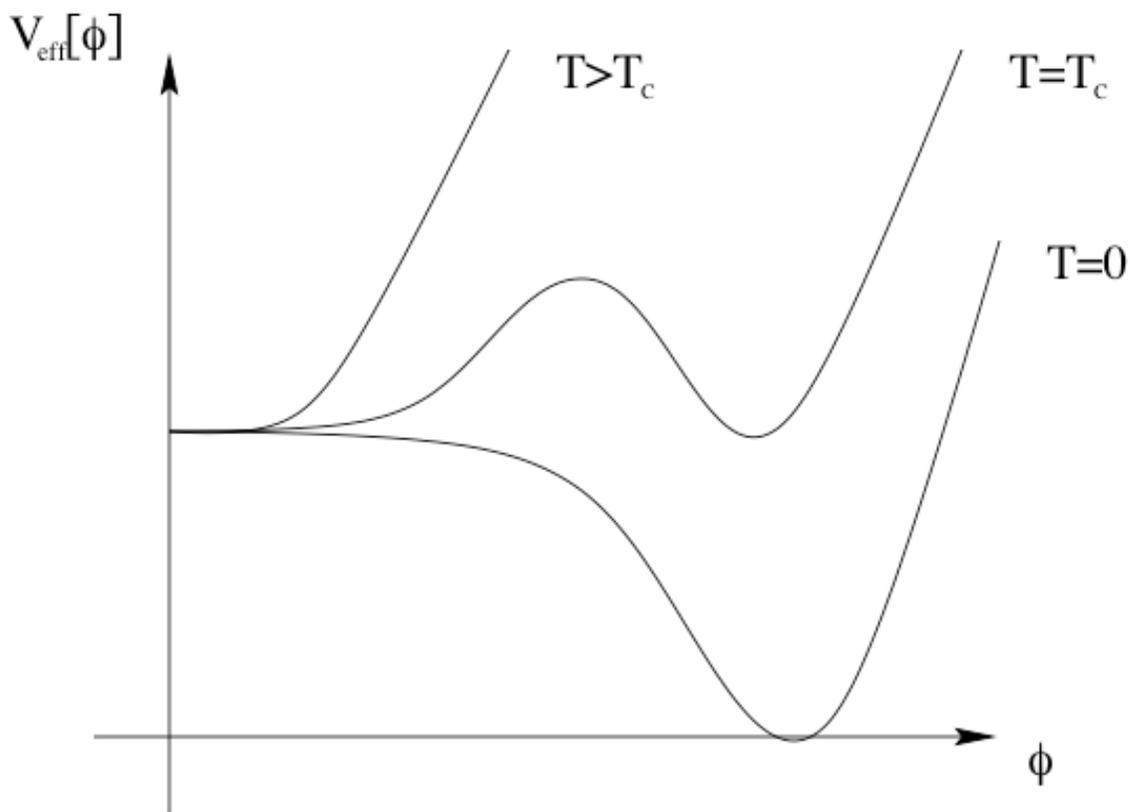
At high temperatures, finite temperature effective potential takes form

$$V(\phi) \rightarrow V(\phi) + CT^2\phi^2 + \dots$$

Critical temperature $T_c^2 = \frac{\lambda}{2C}v^2$

giving

$$V(\phi) = \frac{\lambda}{4}(\phi^*\phi) + \frac{\lambda}{2}v^2 \left(\frac{T^2}{T_c^2} - 1 \right) \phi^*\phi + \frac{\lambda}{4}v^2$$



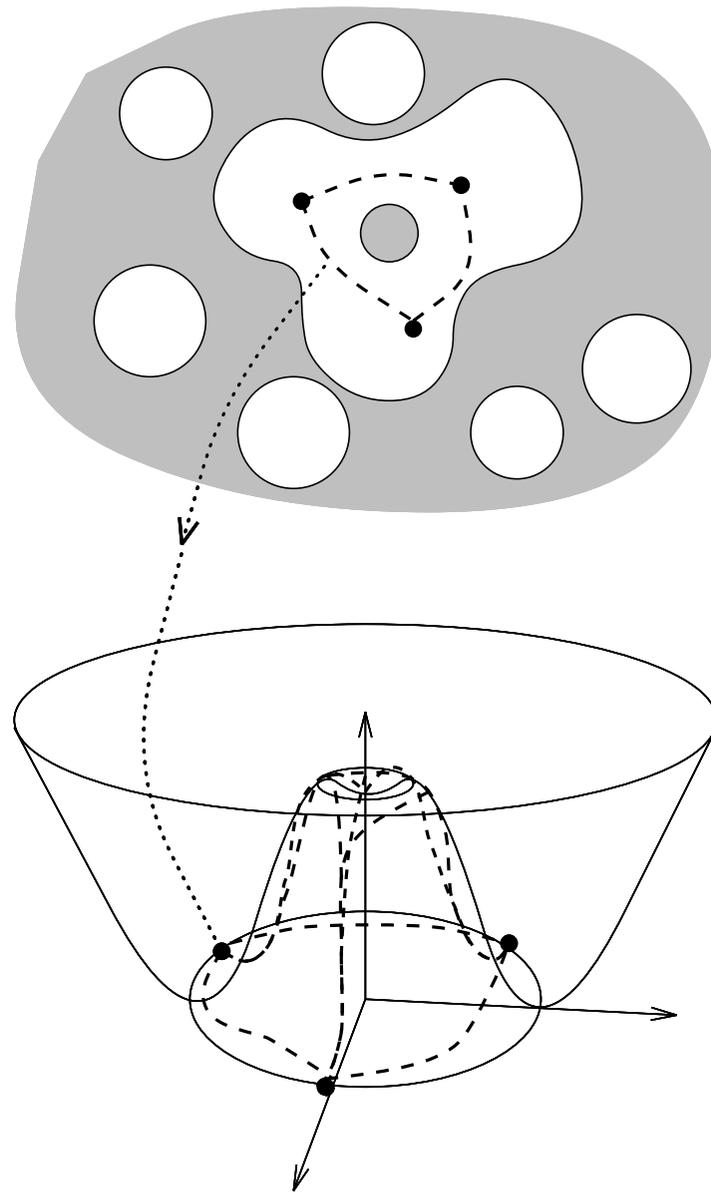
Potential minimized by

$$\langle \phi \rangle = 0 \quad T < T_c$$

$$\langle \phi \rangle^2 = v^2 \left(1 - \frac{T^2}{T_c^2} \right) \quad T > T_c$$



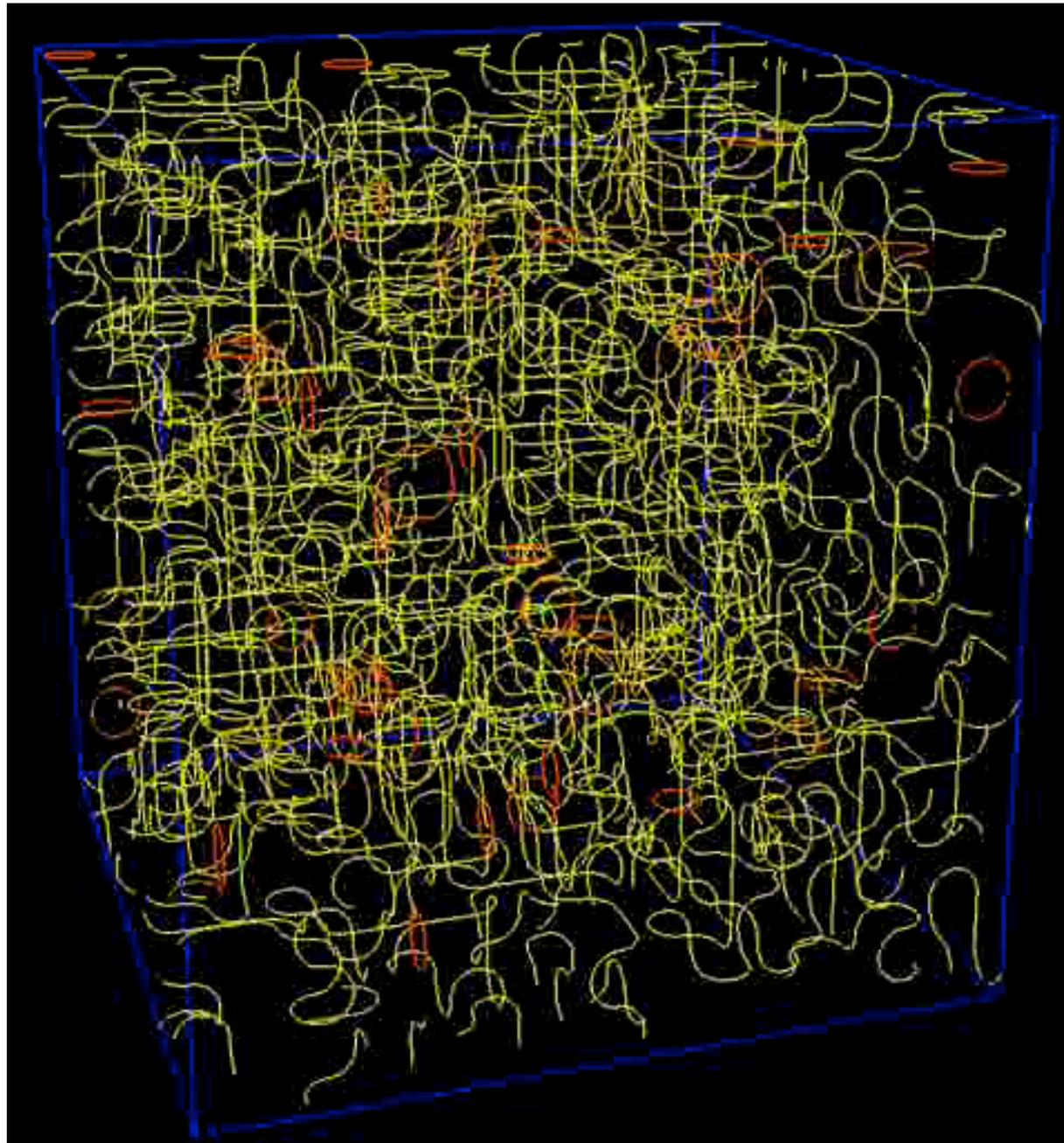
... in causally Disconnected Regions



[Hindmarsh & Kibble]



Evolution of Strings



[Martins & Shellard]

Dramatic Events on Strings

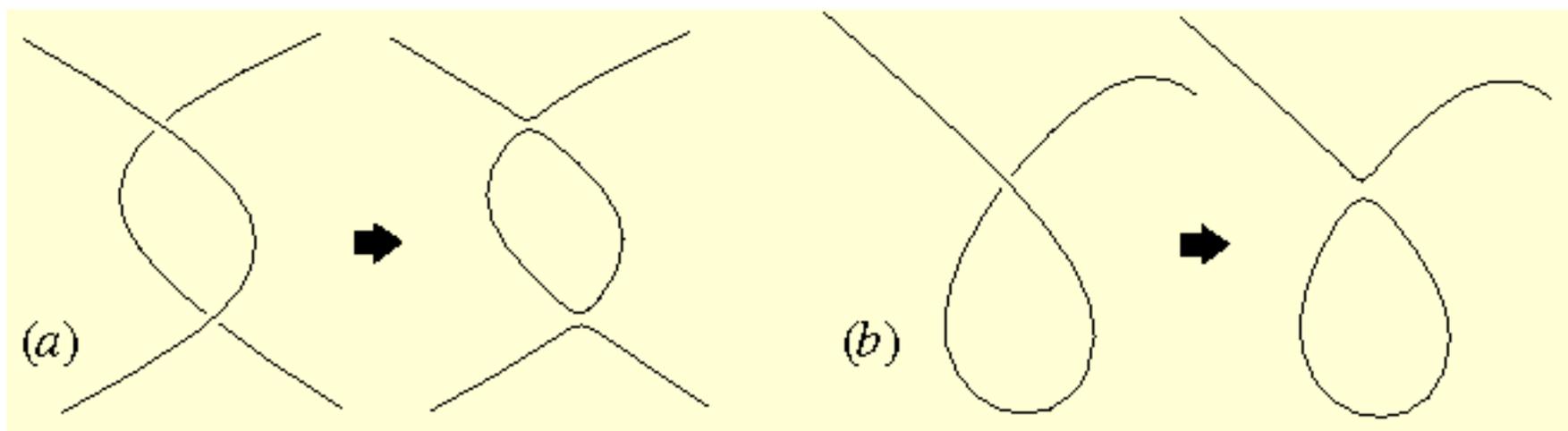
Describe dynamics of strings by effective action - Nambu-Goto action

- position of string is where Higgs has zeros
- string sweeps out a worldsheet in time, with induced metric γ_{ab}
- action extremizes area of this

$$S = -\mu \int d^2\sigma \sqrt{-\gamma}$$

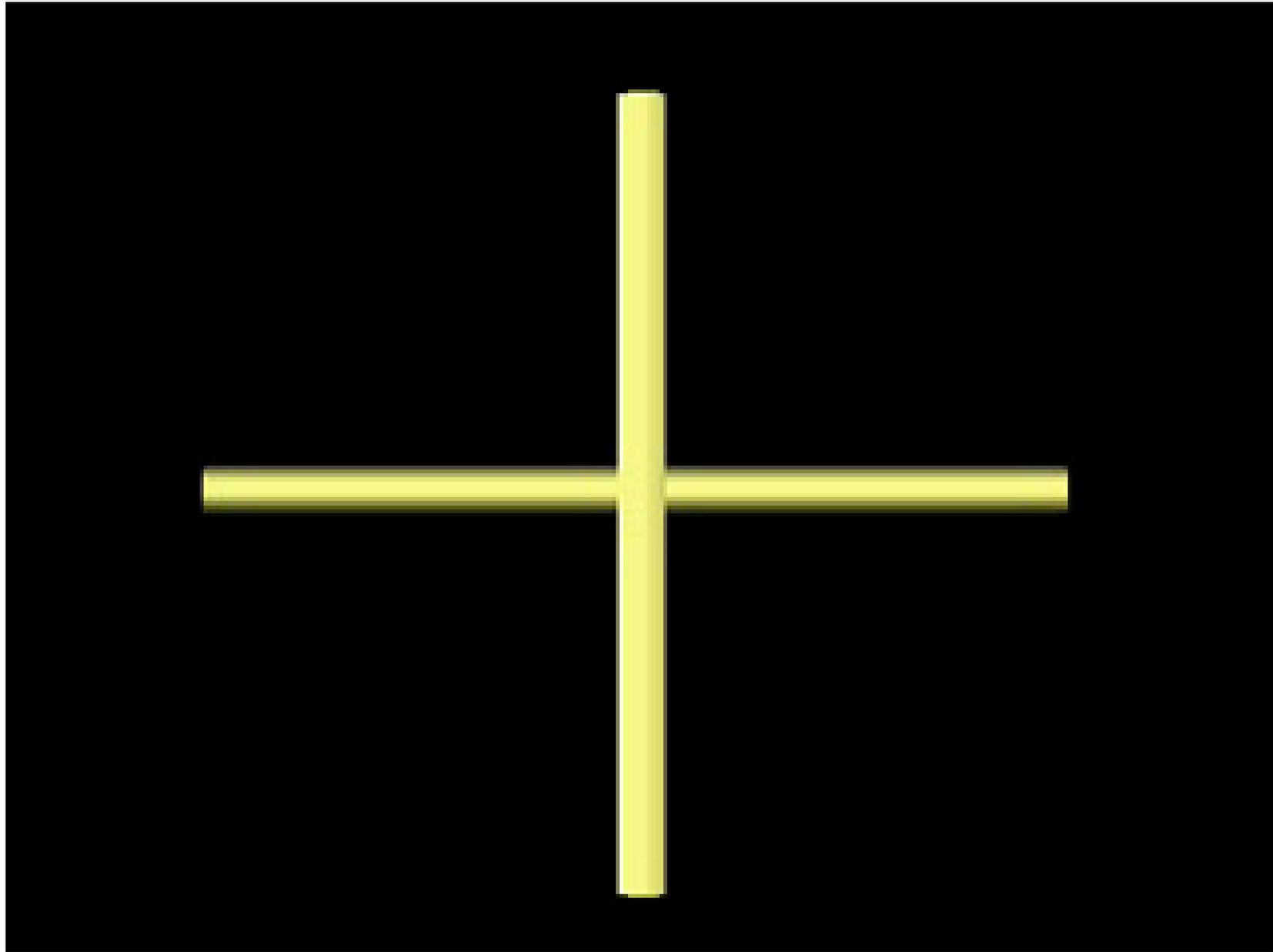
There exist exact solutions - left and right moving modes

- allows for “generic” occurrence of *cusps*
- string moves at speed of light there (in this simplified limit)
- don't *have to* occur, but generic interactions will generate them





Intercommutation and Cusps



[\[http://www.damtp.cam.ac.uk/user/gr/public/movies/cs_reconn.mpg\]](http://www.damtp.cam.ac.uk/user/gr/public/movies/cs_reconn.mpg)



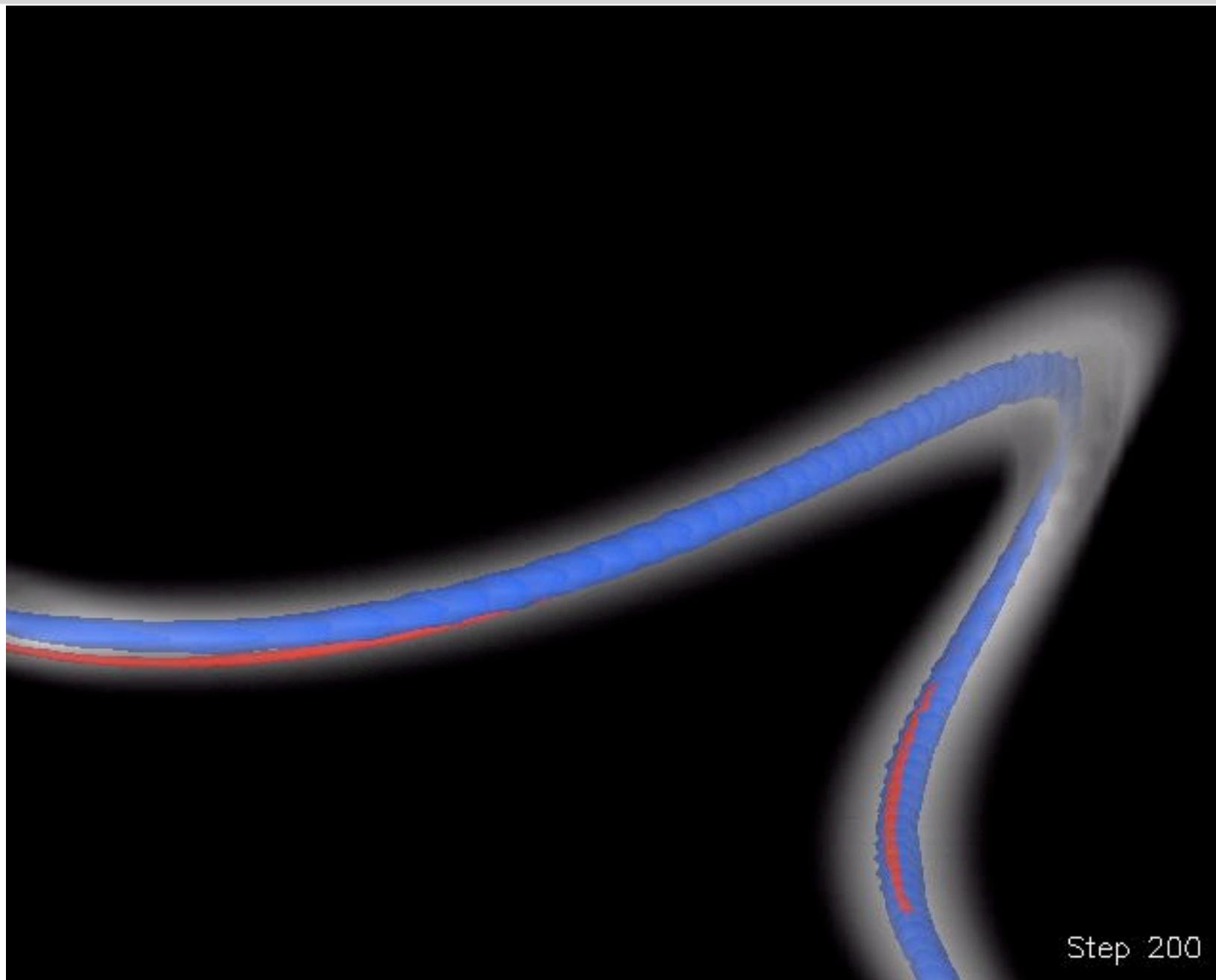
Realistic Dynamics of Cusps

Of course, string doesn't really reach speed of light.

- Nambu-Goto action breaks down there
- Backreaction from finite thickness of string
- Microphysical forces counteract cusp formation with particle emission
- Region of false vacuum, unsupported by any winding, being expelled from the network at high (but less than c) speed.



Particle Emission & Acceleration



Step 200

[Thanks to Ken Olum]



A Word on Superconducting Strings

In many situations, cosmic strings can carry supercurrents.

Charge carriers can be bosons, fermions, or even vectors

It is simple to write down models, but all we need here is the general idea.

- Seed currents are generated as loops are threaded by cosmic or galactic magnetic fields.
- Thereafter, currents build as loops shrink under tension.
- Three possibilities:
 - Loop shrinks and unwinds before either a stabilization current or a critical current is reached.
 - Loop shrinks until the force due to the current is enough to balance the tension. This leads to *vortons*!
 - Loop shrinks and current becomes critical (reaching Higgs VEV or higher). Particles then preferentially are emitted from the string at high energies.



Cosmic Necklaces I

Monopoles alone (actually in bound states with antimonopoles) have been proposed as candidates for superheavy dark matter (later), but are highly constrained.

An interesting hybrid is the idea of cosmic necklaces.

Consider a symmetry breaking scheme (G is semi-simple):

$$G \xrightarrow{\eta_m} H \times U(1) \xrightarrow{\eta_s} H \times Z_2$$

- At first breaking, monopoles form
- At second one, each monopole gets connected by two strings





Cosmic Necklaces II

Dynamics controlled mostly by parameter

$$r \equiv \frac{m}{\mu d}$$

String mass/unit length \rightarrow μ \leftarrow Distance between monopoles

m \leftarrow Monopole mass

- Strings contract due to gravitational radiation
- Monopoles annihilate, producing superheavy particles
- These then fragment into high energy particles

For $\eta_m \gg \eta_s \sim 100 \text{ GeV}$ lifetime can be comparable to age of universe

Rate of X-particle production estimated as $\dot{n}_X \sim \frac{r^2 \mu}{t^3 M_X}$

Can provide a (subdominant) component of ultra-high energy cosmic ray spectrum



Super-heavy dark matter model

With Auger results - excellent example of the astro/cosmo/particle interplay - rules out (as a candidate for UHECR)!

General idea:

- Particles with mass 10^{12-14} GeV
- Created in early Universe.
- Lifetime comparable to age of universe
- Can decay today and produce UHECR

[V.Berezinsky, M.Kachelriess and A.Vilenkin;
V.Kuzmin and V.Rubakov , (1997)]

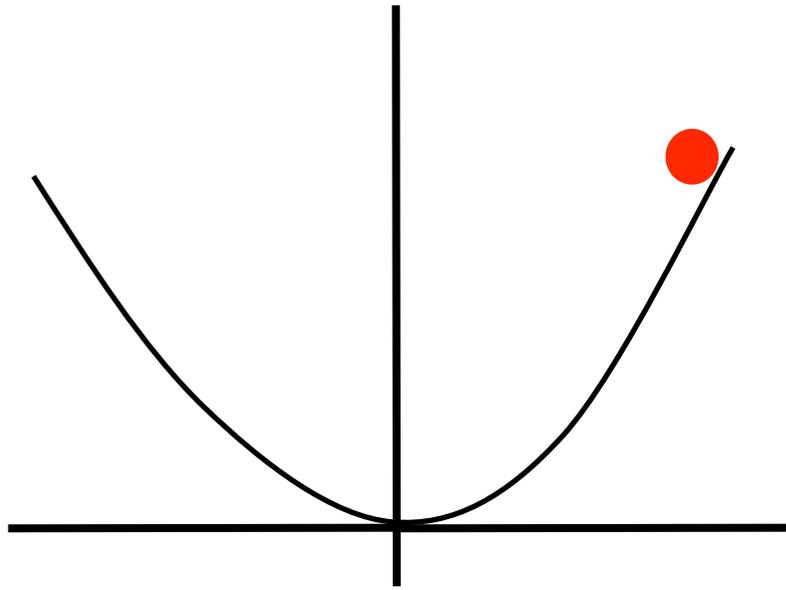
Production possibilities

- Preheating
- Non-adiabatic transition to radiation domination
- ...

Aim is to non-thermally produce the particles, and then ensure that they never thermalize



A Reminder about Inflation



$$\rho_\phi \approx V(\phi) \approx \text{constant}$$

$$H^2 \equiv \left(\frac{\dot{a}}{a} \right)^2 \propto \rho$$

$$\frac{\ddot{a}}{a} \propto -(\rho + 3p)$$

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

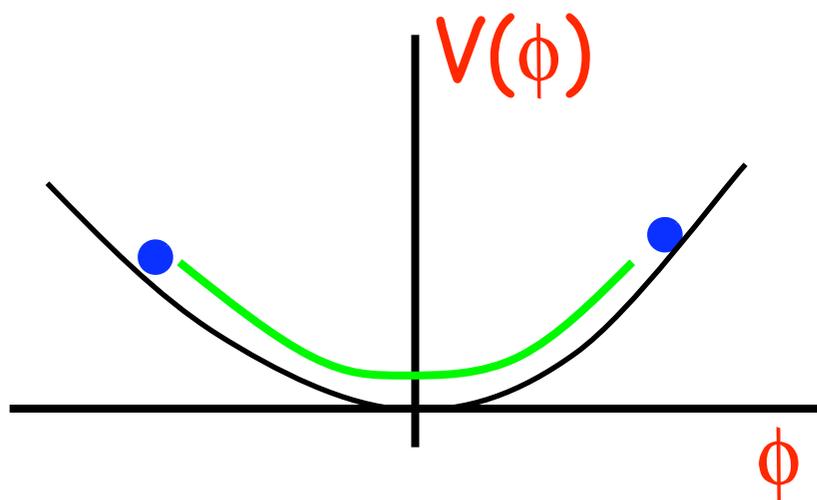
$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\nabla\phi)^2 + V(\phi)$$

- Get quasi-exponential expansion - solves horizon and flatness problems
- Completely dilutes the universe of any particles or energy other than that in the inflaton
- Need to regenerate the particle content of the universe - *reheating*.

[There may be new surprises here, as we understand origin of inflation better]

Preheating after Inflation

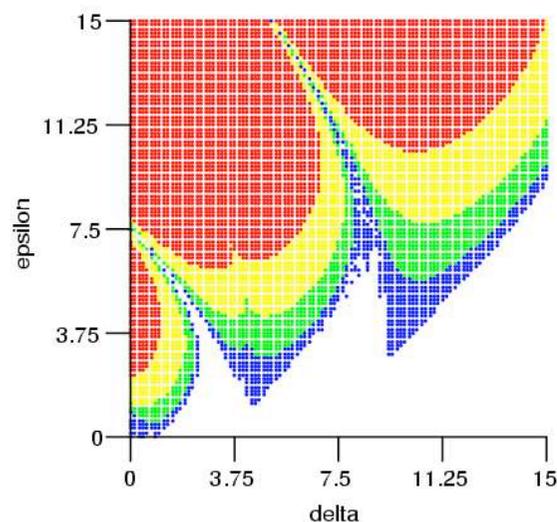
- Instead of perturbative reheating can have *parametric resonance*
- Non-thermal production of particles
- Can generate particles w/ mass up to 100 times the inflaton mass



- Naturally out of equilibrium
- Somewhat model dependent (depends on some of the details of the inflaton couplings to regular matter.)

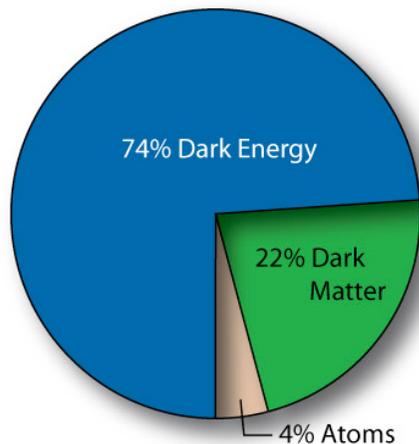
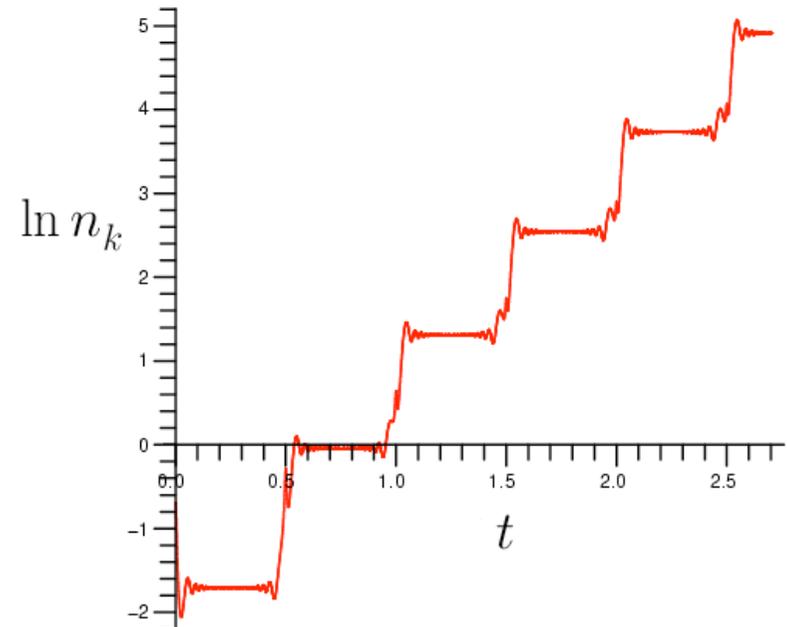
$$\ddot{X}_k + \omega_k^2 X_k = 0$$

$$X_k'' + [A(k) - 2q \cos(2z)]X_k = 0$$



Possible consequence of Preheating

- So at the end of inflation can generate superheavy particles, with masses higher than the reheating temperature.
- Can be a bad thing! Can re-introduce unwanted relics (monopoles, moduli, ...)
- Can be a good thing - could generate baryon asymmetry, magnetic fields, ...
- ... or could give rise to the right kind of long-lived relics
- Could be dark matter $\Omega_X h^2 \approx 1$ if



$$m_X \sim m_\phi \sim 10^{13} \text{ GeV}$$

[V.Kuzmin and I.Tkachev, hep-ph/9802304, hep-ph/9809547;
Chung, Kolb and Riotto, hep-ph/9802238, hep-ph/9805473, hep-ph/9809453]



Self-interacting Dark Matter

- One possibility (natural for dark matter): SHDM particles are stable.
- Can ignore the possibility of SHDM decays, but there is the possibility that SHDM can interact (annihilate), with itself.
- UHECRs may be secondary particles from such annihilations.

Signatures

- No GZK cutoff
- Galactic anisotropy

- Main signature: UHECR are photons.
- Galactic contribution dominates due to larger density and due to GZK cutoff:

$$\frac{\rho_G}{\rho_U} = \left(\frac{R_U}{R_G} \right)^3 \frac{M_G}{M_U} \propto 10^5$$

But! • SHDM also produces a signature in gamma-rays.

- Number of gamma-rays at 10^{19} eV was already bounded by data from AGASA

And now (see Angela's talk), Auger rules these out as UHECR sources.

$$\frac{N_\gamma}{N_p} < 0.3$$



Lorentz Invariance Violation

- Lorentz Invariance: Symmetry of Special Relativity
 - Physical phenomena the same for all inertially moving observers.
 - So spacetime looks the same at all length scales.
 - Energy and momentum are Lorentz transformed, but *dispersion relation* is invariant

$$E^2 = m^2 c^4 + p^2 c^2$$

What happens if we violate this (and what does it have to do with UHECRs)?

- Some quantum gravity theories, e.g., contain a fundamental length scale
- Implies speed of light should be energy dependent.
 - e.g. spacetime might be granular (spacetime quanta).
 - As in some condensed matter systems, granularity of the medium may give rise to energy-dependent dispersion relation.
 - Long wavelength modes travel at c , but modes with wavelength short enough to be sensitive to the microscopic structure of medium may not.

[Luis Valcárcel]



Modified Dispersion Relations

An example

$$E^2 = p^2 + m^2 + \eta \left(\frac{E}{E_{Pl}} \right)^n p^2 + \mathcal{O} \left(\frac{E^{n+3}}{E_{Pl}^{n+1}} \right)$$


Modification due to Planck-scale departures from Lorentz invariance

- Simple
- Natural first step in phenomenology of Planck-scale departures from Lorentz invariant expression
- Inspired by
 - Spacetime foam
 - Loop Quantum Gravity
 - Noncommutative spacetimes
 - Critical and noncritical String Theory
 - Canonical Quantum Gravity

[Luis Valcárcel]



Threshold effects

- Combine modified dispersion relation with unmodified laws of energy-momentum conservation
- Changes the threshold condition of some processes
 - Photopion production in the GZK cutoff effect
- Even a very small violation of Lorentz invariance can shift the threshold energy for protons significantly upward (for negative eta)
- This should change the expected GZK cutoff for the observed cosmic-ray spectrum in an observably large way.
- One sample approach (AEMNS): clear prediction that there should be an upward shift of the GZK threshold.
- Another approach (GPMP): One expects roughly one half of the UHE protons to evade the GZK cutoff, so the cutoff would still be violated but in a softer way than in the case of the AEMNS test theory.



Caveats

- Ad Hoc assumptions: Assume all of standard physics except boost invariance.
 - rotation symmetry
 - electromagnetic gauge invariance
 - additivity of energy and momentum for multi-particle systems
 - energy-momentum conservation in particle interactions.

[Luis Valcárcel]



Conclusions

- Physics beyond the standard model provides a range of ways in which high energy particles can be created and then accelerated to high speeds.
- I've provided several examples of this
 - Cosmic strings
 - Superconducting strings
 - Cosmic Necklaces
 - Superheavy Dark Matter
 - Violations of Lorentz Invariance
- Some of these may explain some of the highest energy cosmic rays.
- However, for me, the most interesting point is that high energy particles in today's universe provide a probe of beyond the standard model physics, complementary to those provided by colliders and cosmology.

Thank you