Title: Cosmic Strings from Supersymmetric Flat Directions

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Abstract: Cosmic strings are non-trivial configurations of scalar (and vector) fields that are stable on account of a topological conservation law.
They can be formed in the early universe as it cools after the Big Bang.
The scalar fields required to form cosmic strings arise naturally if Nature is supersymmetric at high energies. A common feature of supersymmetric theories are directions in the scalar potential that are extremely flat. Combining these two ingredients, the cosmic strings associated with supersymmetric flat directions are qualitatively different from ordinary cosmic strings.
In particular, flat-direction strings have very stable higher-winding modes, and are very wide relative to the scale of their energy density.
These novel features have important implications for the formation and evolution of a network of flat-direction cosmic strings in the early universe. They also affect the observational signatures of the strings, which include gravity waves, dark matter, and modifications to the nuclear abundances and the blackbody spectrum of the microwave background radiation

Cosmic Strings
from
Supersymmetric Flat Directions

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Based work done in collaboration with

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Ingredients:

Cosmic Strings

and

Supersymmetry

Particles, Fields, and Cosmic Strings

- Relativity + Quantum Mechanics → Quantum Field Theory

  Fields ↔ Particles

- Cosmic strings are special field configurations that can arise in theories containing scalar fields. [Nielsen+Olesen '73]
- Cosmic strings can be formed in the early universe.
- 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]

A Simple Cosmic String - Part 1

- Consider a theory with a complex scalar φ,

$$\mathcal{L} \supset |\partial_\mu \varphi|^2 - \frac{\lambda}{4}(|\varphi|^2 - v^2)^2 + \ldots$$

- This theory is $U(1)$ symmetric: $\varphi \to e^{i\alpha}\varphi$.
- The vacuum state breaks the symmetry: $\langle \varphi \rangle = v$.

→ *spontaneous symmetry breaking*

- Special axially symmetric field configuration:

$$\varphi(r,\phi,z) = v\, f(r)\, e^{iN\phi}, \quad \text{with} \quad N \in \mathbb{Z}^{>}, \ \ f(r) \to \begin{cases} 1\,; & r \to \infty \\ 0\,; & r \to 0 \end{cases} .$$

- This configuration has finite energy for nice $f(r)$ (and a gauge field).

→ *cosmic string with winding number* N.

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 $v = \langle \varphi \rangle$:

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

- Usually only the $N = 1$ mode is stable.

- This example is typical of *ordinary* cosmic strings.

*Natural units: $\hbar = c = k_B = 1 \Rightarrow L \sim t \sim M^{-1} \sim T^{-1}$

Cosmic Strings in the Early Universe

- Cosmic strings can be formed in the early universe.
- At high temperatures (T):

$$V_{eff}(\varphi) \simeq \frac{\lambda^2}{16\pi^2} T^2 |\varphi|^2 + \frac{\lambda}{4}(|\varphi|^2 - v^2)^2$$

  The $U(1)$ symmetry is restored when $T \gg v$.

- The $U(1)$ symmetry is eventually broken as the universe cools.
- Cosmic strings are formed in this phase transition.

Supersymmetry

- Supersymmetry is a well-motivated possibility for new physics at high energies.
- It is an extension of the Poincaré symmetries of spacetime:

$$\begin{aligned} \text{spin} &\leftrightarrow \text{spin} + 1/2 \\ \text{bosons} &\leftrightarrow \text{fermions} \end{aligned}$$

- Supersymmetry is also a natural setting for scalar fields.
- A common feature in supersymmetric theories are *flat directions* in the potential for the scalar fields.
- We study the cosmic strings associated with spontaneous (gauge) symmetry breaking along a supersymmetric flat direction.

Properties of Flat-Direction Strings

String Profiles

- Sample flat-direction effective potential:

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

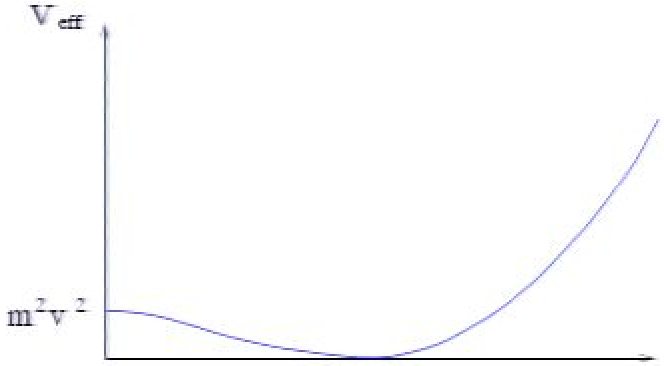
  with $m \ll M$, $n > 0$.

- Supersymmetry allows for $m \ll M$ and prevents quantum corrections from generating $n = 0$ terms.

- The vacuum value of φ is

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

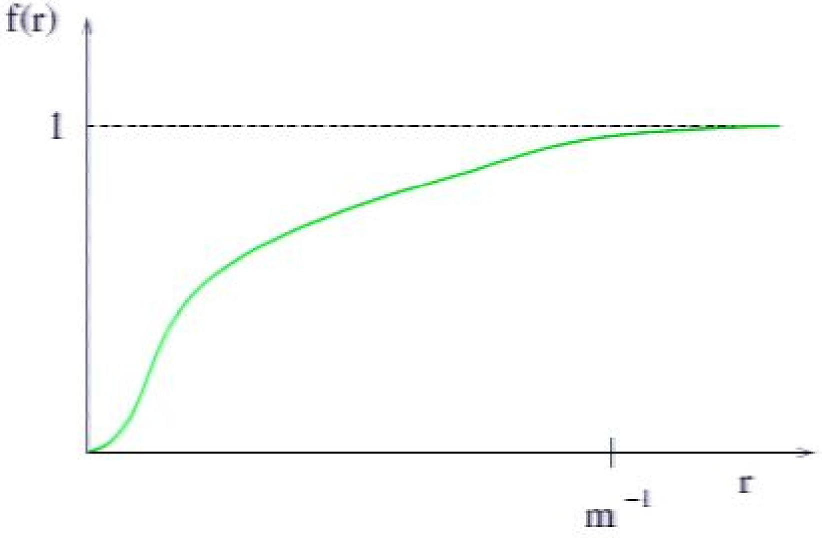
  Note that $m \ll v \ll M$.



- We look for string solutions of the form

$$\varphi(r,\phi,z) = v\, f(r)\, e^{iN\phi}, \quad \text{with} \quad N \in \mathbb{Z}^{>}, \quad f(r) \to \begin{cases} 1\,; & r \to \infty \\ 0\,; & r \to 0 \end{cases} .$$

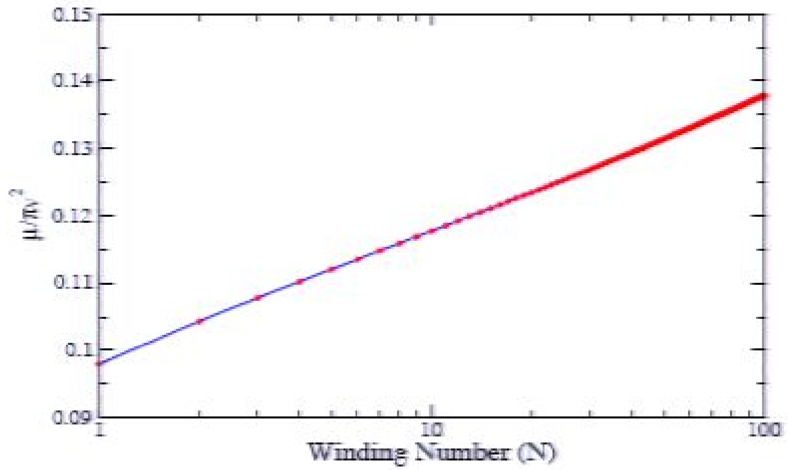
- Profile $f(r)$ from variationally minimizing the energy per length μ_N:



- Flat direction strings have width $w \sim m^{-1}$.
- Ordinary cosmic strings have width $w \sim v^{-1} \ll m^{-1}$.

String Tensions

- Flat direction strings have tensions $\mu \sim v^2$ (like ordinary strings).
- μ_N increases very slowly with the winding number N:



- To a good approximation

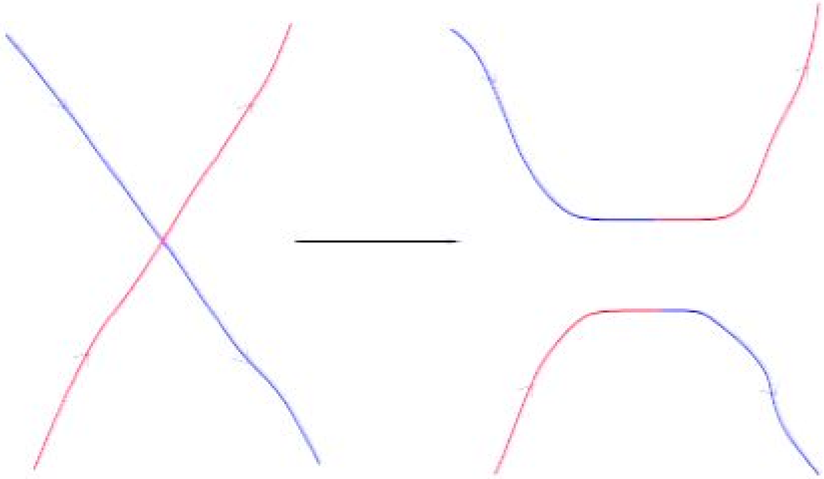
$$\mu_N = \mu_1 \left[1 + \frac{3}{\ln(v^2/m^2)} \ln N \right].$$

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

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

String Interactions: Intercommutation

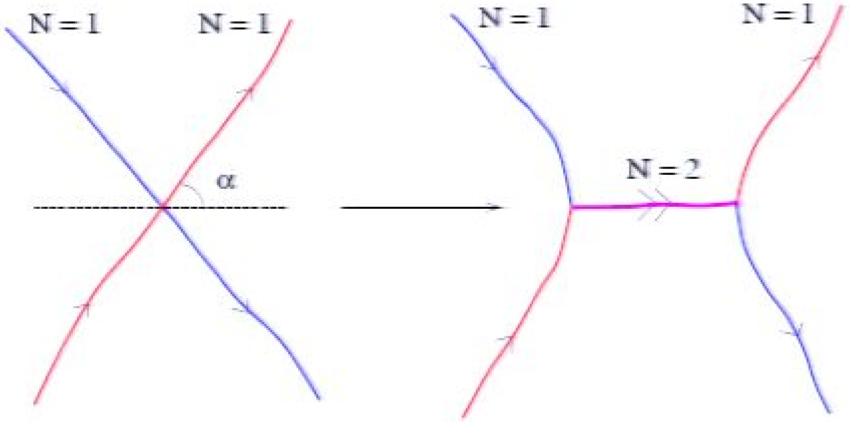
- When a pair of ordinary strings intersect they can:
  1. pass through each other
  2. intercommute (reconnect)



- 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 $N = 2$:



$\rightarrow$ Zippering

- More generally, $N + M \rightarrow |N \pm M|$.
- Cosmic superstrings are also able to form zippers.

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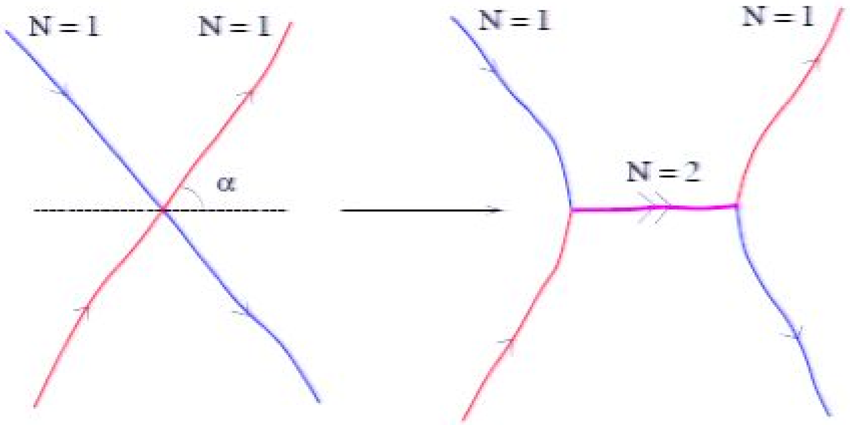

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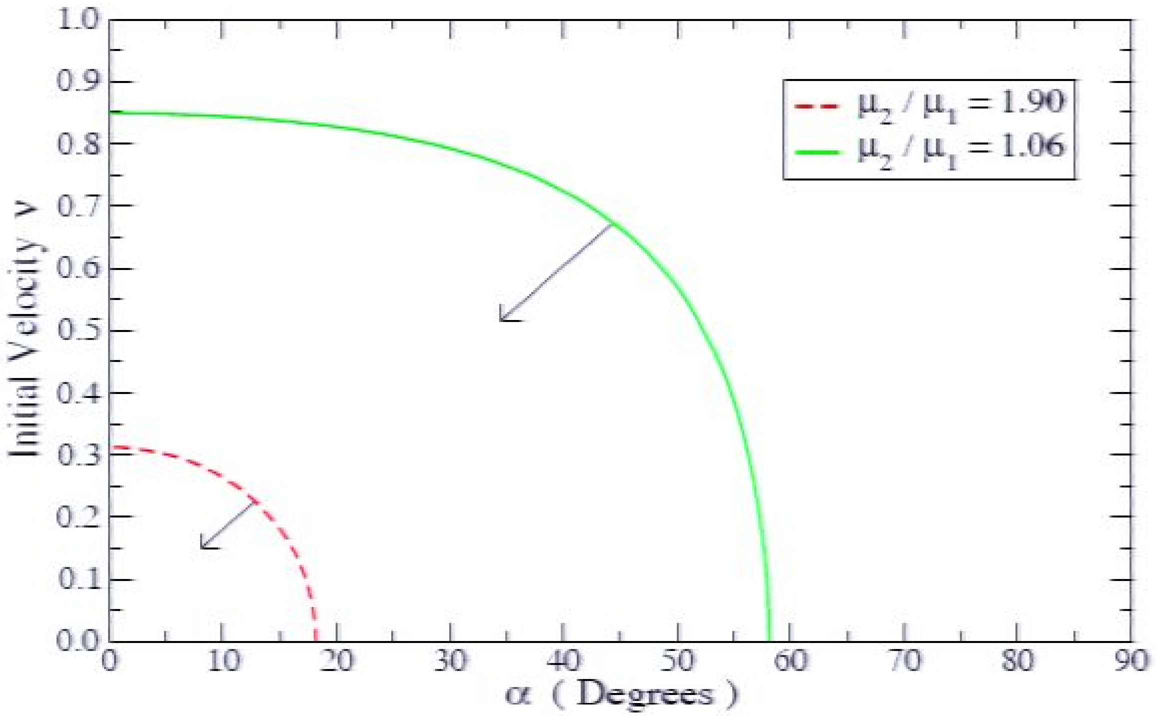
- Zippering is only kinematically allowed for $\mu_2 < 2\,\mu_1$.



- 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.

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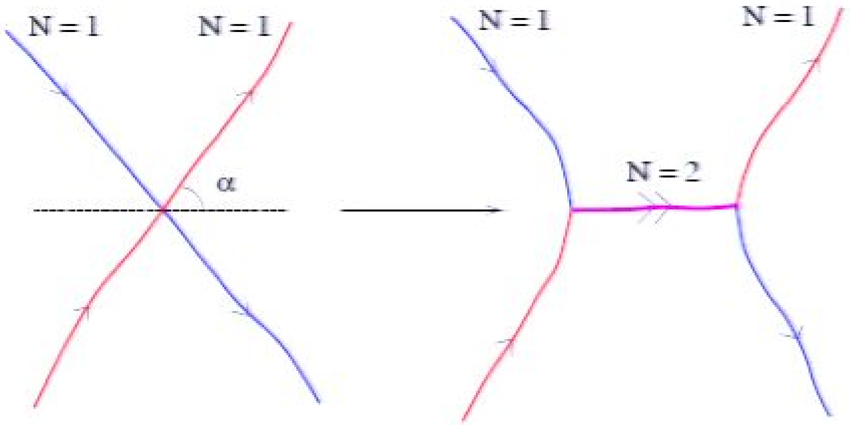

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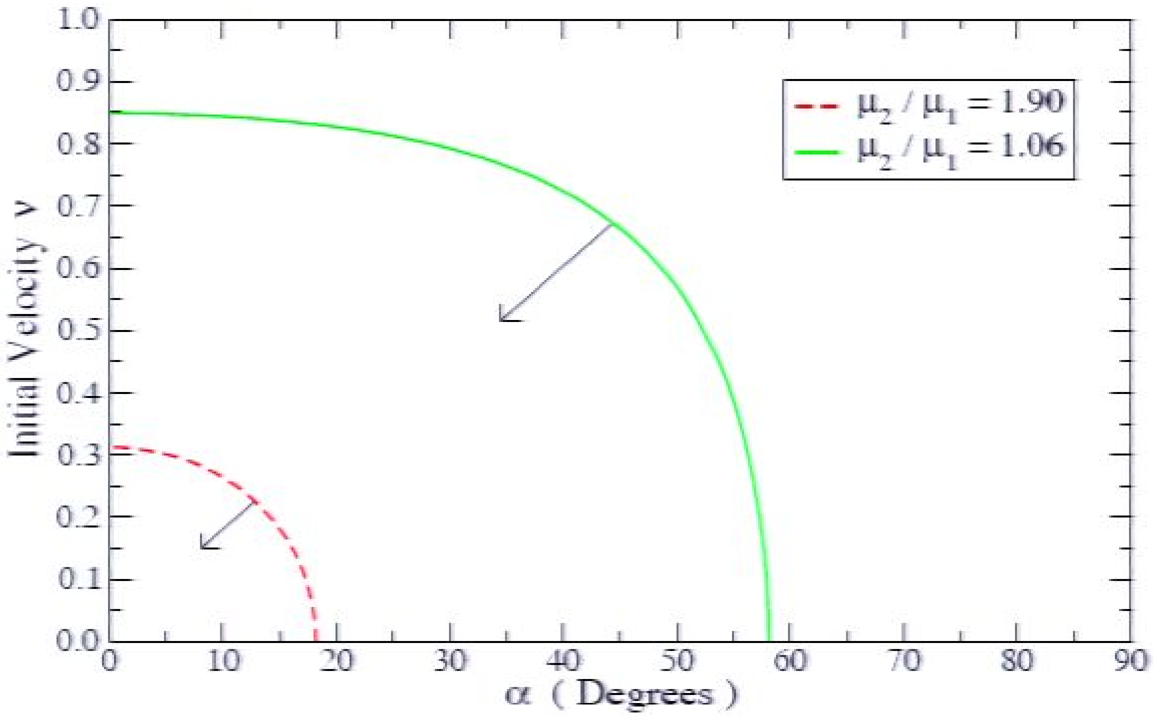

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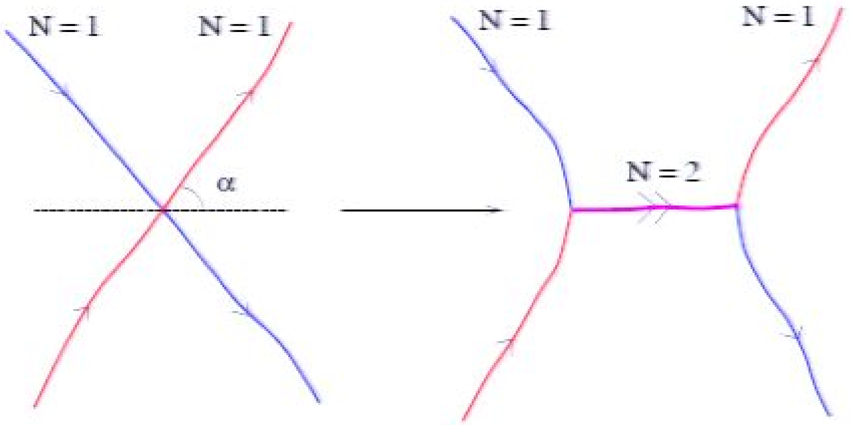

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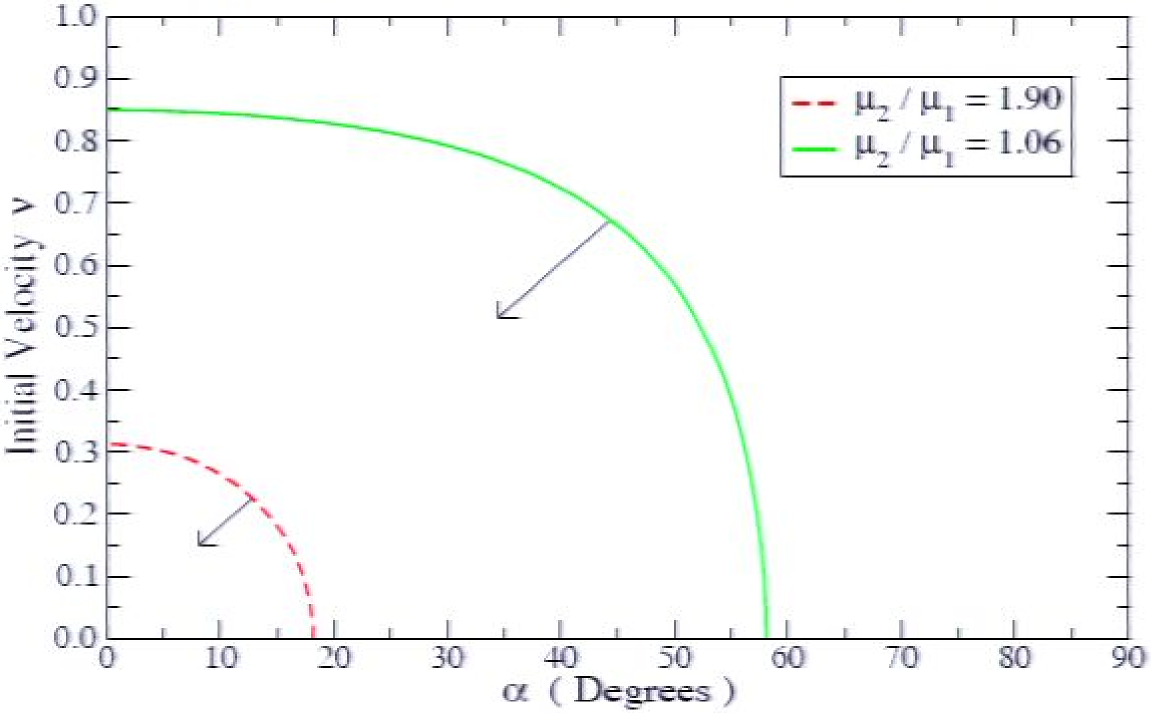

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Comparison with Ordinary Strings

- 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 and Cosmology

Cosmic String Scaling

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

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

- This could be a problem:

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

Cosmic strings could come to dominate the universe?

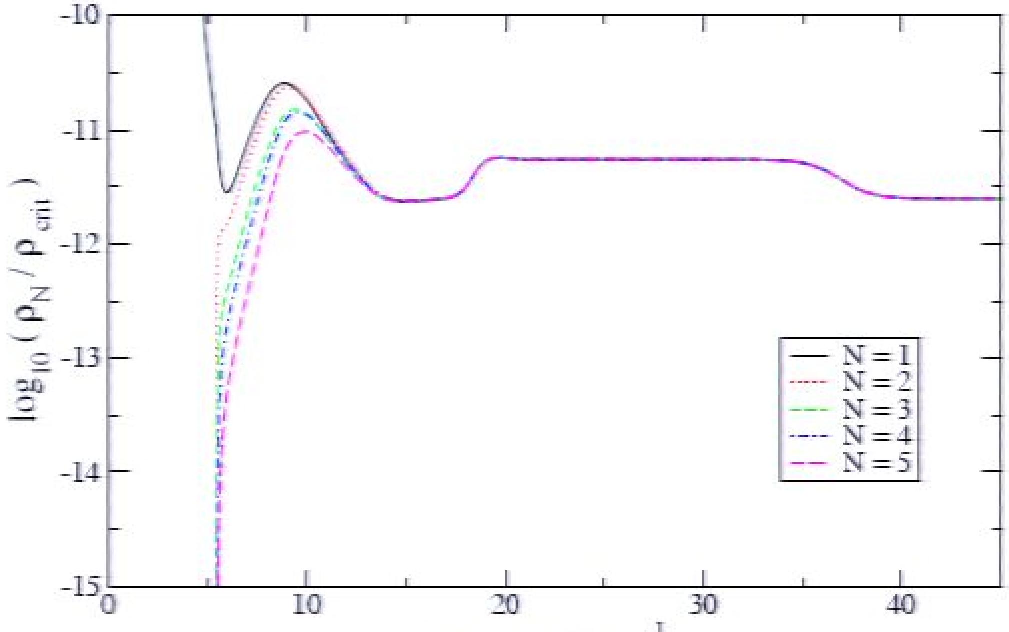
- However, strings form loops by intercommutation, which decay away.
- Cosmic strings track the background matter or radiation density

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

→ cosmic string scaling

Scaling of Flat Strings

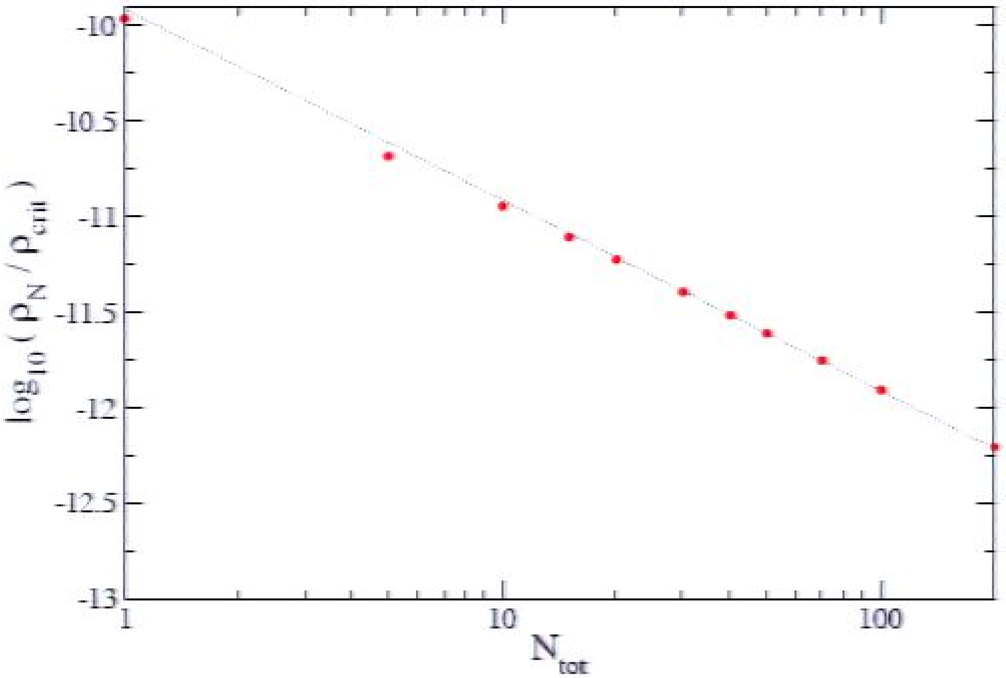
- Flat strings can zipper in addition to intercommuting.
- They form a network with many different types of string.
- We study their evolution with a simple model by Tye, Wyman, and Wasserman. [TWW '05]
- Many string varieties approach an equal scaling density:



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

$$\rho_N \simeq \frac{1}{N_{tot}} \rho_{tot}.$$

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

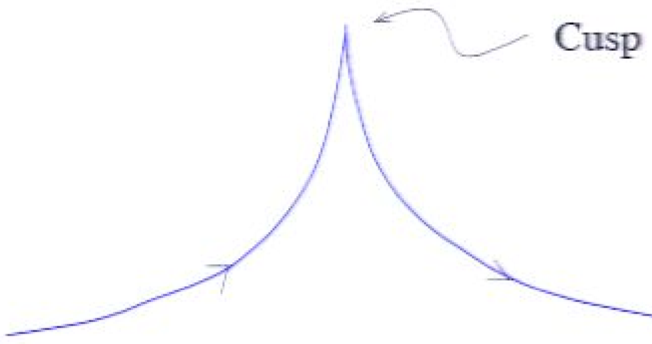


Ordinary Cosmic String Signatures

- Most cosmic string signatures are characterized by $G\mu \simeq \left(\frac{v}{M_{\mathrm{Pl}}}\right)^2$.
- Long strings:
  - Long strings create wakes that can seed large scale structure. CMB measurements $\Rightarrow G\mu \lesssim 10^{-7}$ [Pogosian,Wyman,Wasserman '06,Fraisse '06]
  - Light passing by a string is bent: gravitational lensing [Vilenkin '81]
- String loops:
  - Loops are not topologically stable.
  - They oscillate, emit gravity waves, and decay away. Pulsar timing measurements $\Rightarrow G\mu \lesssim 10^{-7}\text{–}10^{-10}$ [DePies+Hogan '07]

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 particle creation 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,

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

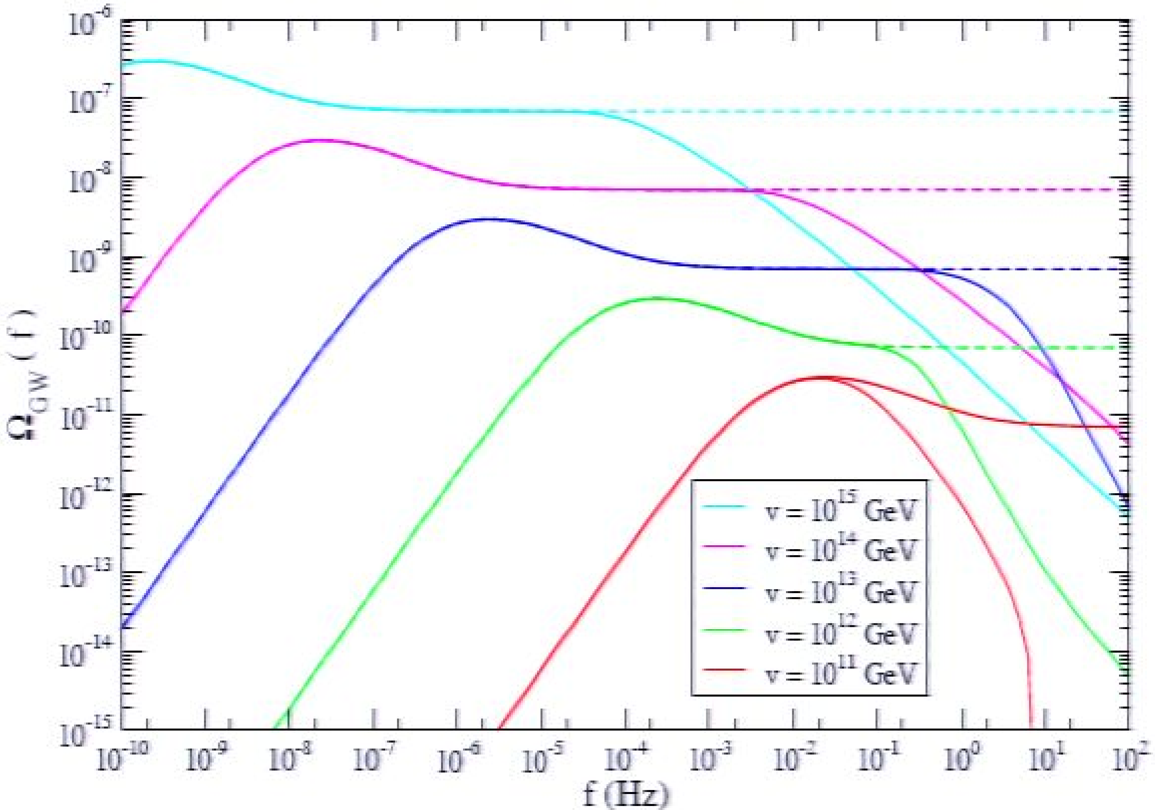
  ⇒ particle creation is enhanced for flat strings!

- Particle creation dominates over gravitational radiation for loops smaller than

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

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 $m = 10^3\,\mathrm{GeV}$ and small loops for these bounds.)

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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.

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Initial Loop Sizes

- The spectrum of small fluctuations on cosmic strings is not fully understood, and neither is the typical initial loop size.

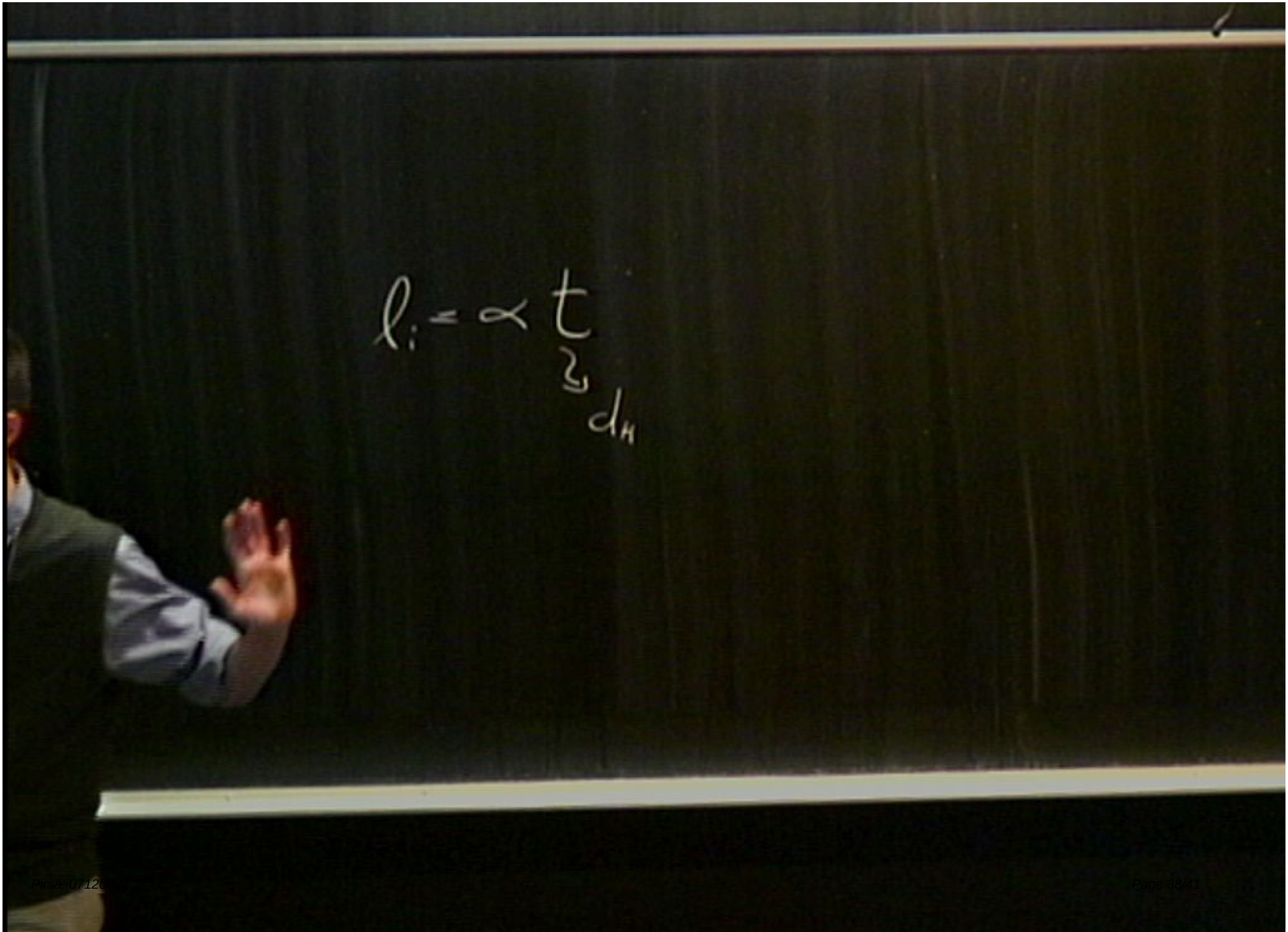
- In the scaling regime, the loop size is usually written as

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

  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]

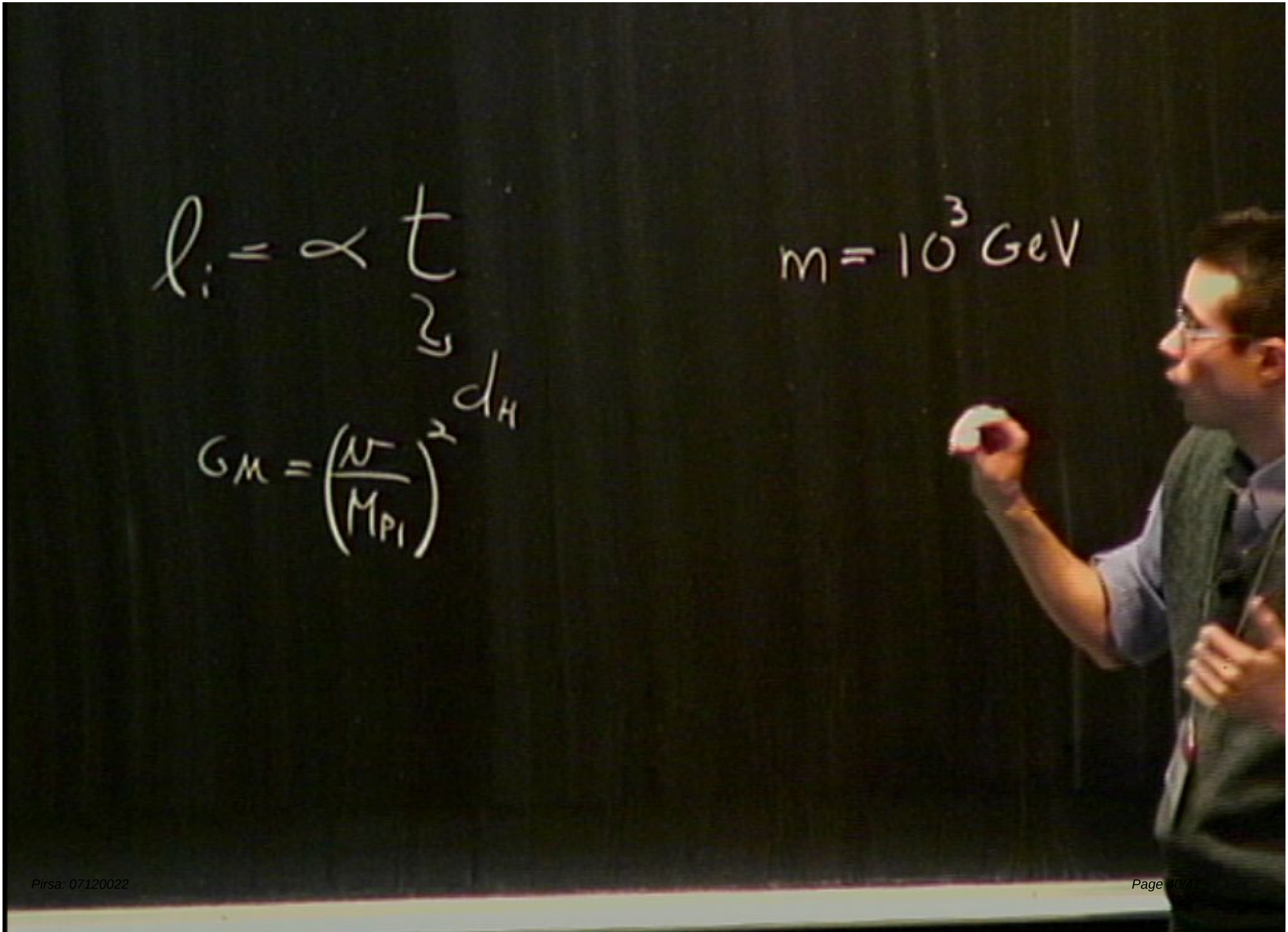
- We therefore consider both large and small initial loop sizes.



$$\ell_i = \alpha t \gtrsim d_H$$

$$l_i = \alpha\, t \rightsquigarrow d_H$$

$$G\mu = \left(\frac{\mu}{M_{Pl}}\right)^2$$



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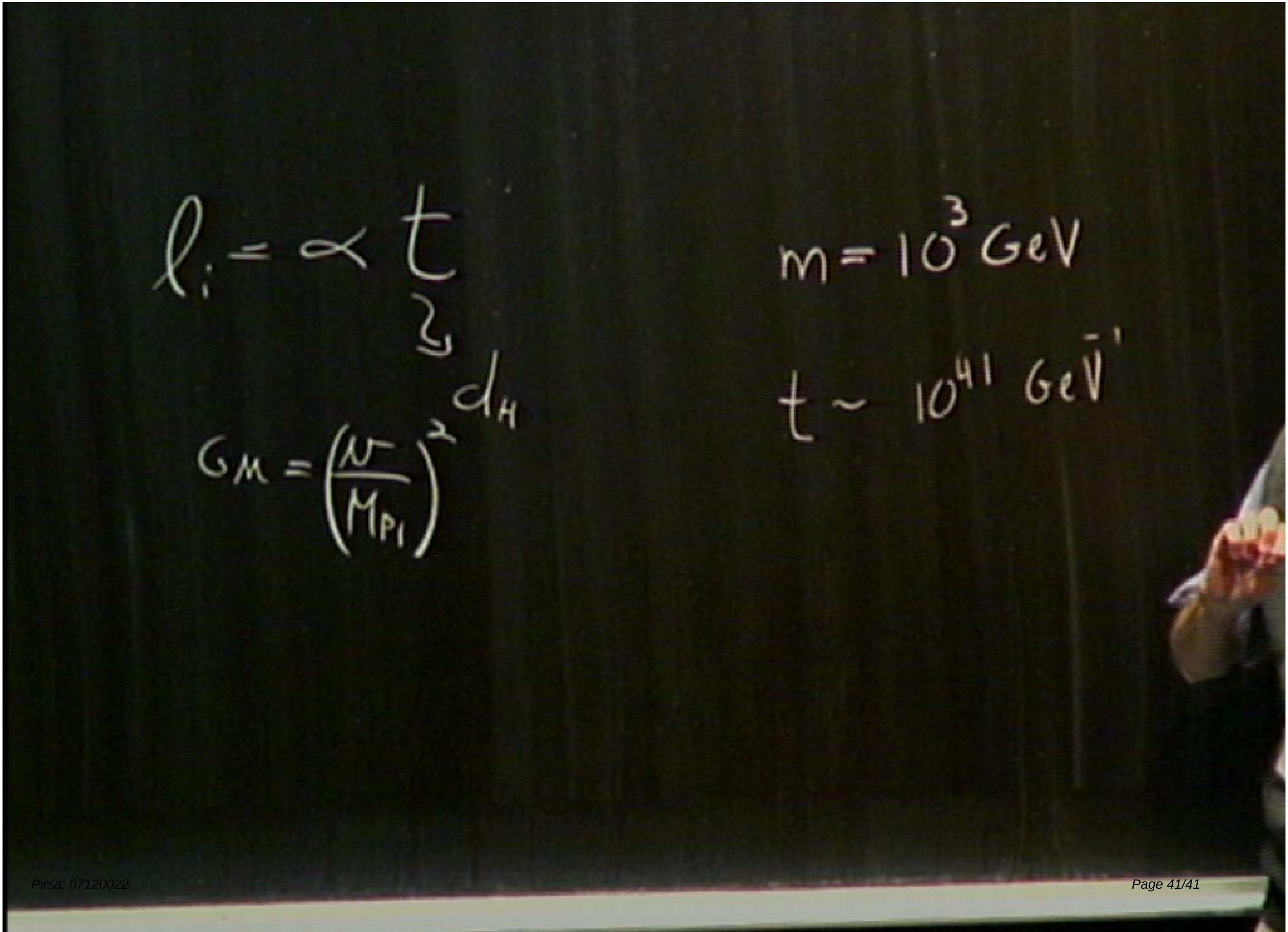
$$m = 10^3 \text{ GeV}$$



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$$t \sim 10^{41} \text{ GeV}^{-1}$$