Collisions of Cosmic F- and D- Strings

Nicholas Jones

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with Jackson & Polchinski [th/0405229]

(NJ, Stoica, Tye [th/0203163], [th/0303269])

Field Theory Cosmic String Interactions

- Cosmic Strings from vortices formed at some phase transition (e.g. some hybrid inflation models).

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- Inter-vortex reconnection probability is essentially 1 (numerically; Matzner).

String Pair Interactions and the Network

- Naively, cosmic string network density scales like a^{-2}
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- For a probability of interaction P, the interacting network density scales like $\rho \sim \tau / P$ (simulations; losses to loop formation).
- $P < 1$, enhancement of cosmic string effects & observables.

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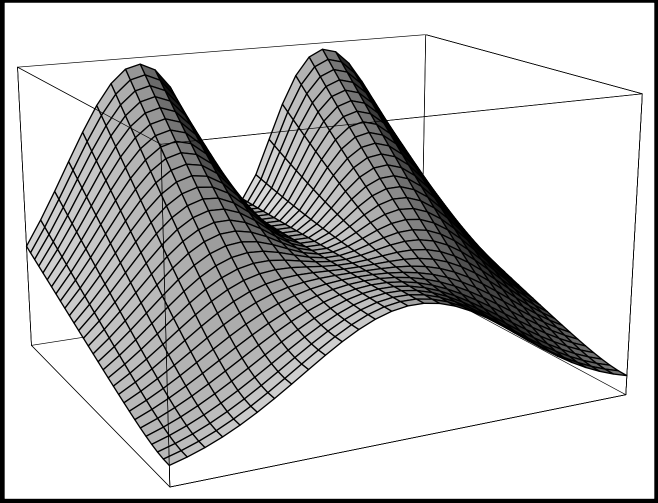

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- Irrespective of details (warping, compactification ...), the brane collision ending inflation is hybrid inflation.
- Inflation ends when the complex tachyon rolls.
- Post inflation, string-like defects (only) are formed; no monopoles or domain walls (NJ, Stoica, Tye; Sarangi, Tye).

String Types and Stability

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- (p,q)-strings stable in KKLMMT when no branes are in the inflationary throat (p,q relatively prime, $|p| < M/2$).
- General brane inflation (non-stabilised) models can have long-lived F-, D- and (p,q)-strings.

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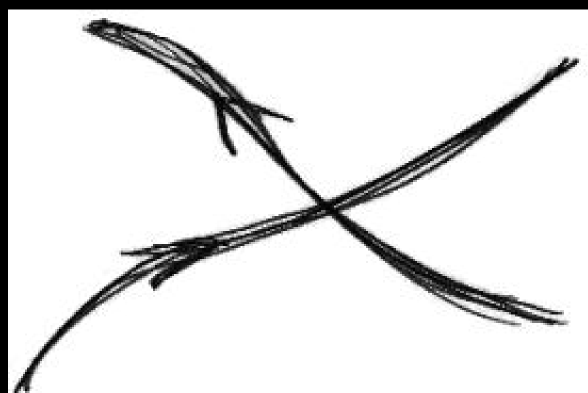
- Results: $P_{FF} \sim 10^{-2} \leftrightarrow 1$; $P_{DD} \sim 0.1 \leftrightarrow 1$.

String Interaction Types



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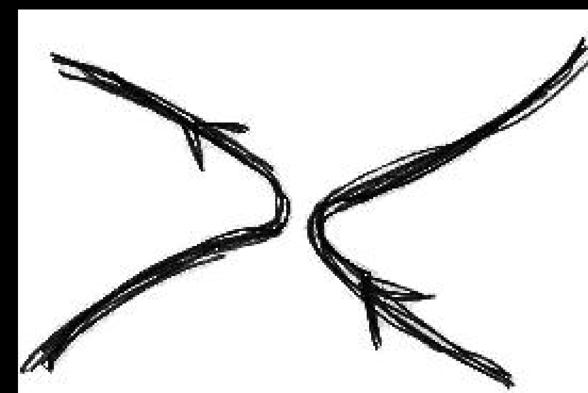
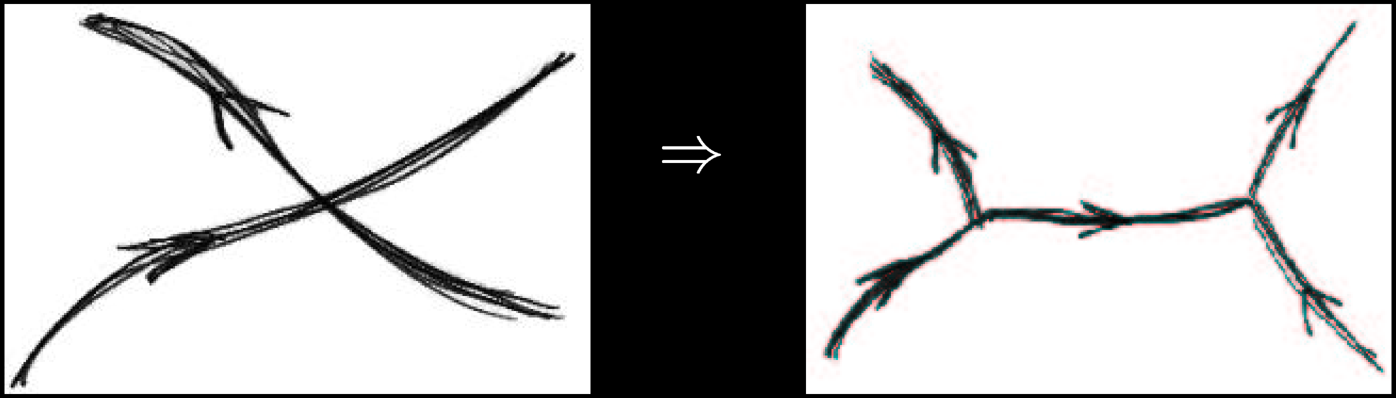


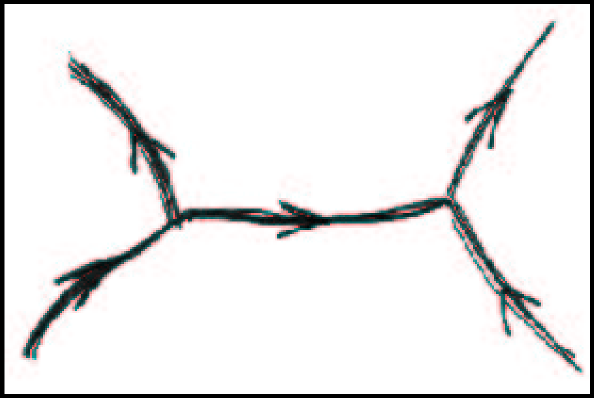
F+F or D+D reconnection.

String Interaction Types



$(p, q) + (p', q')$ connection.

String Interaction Types



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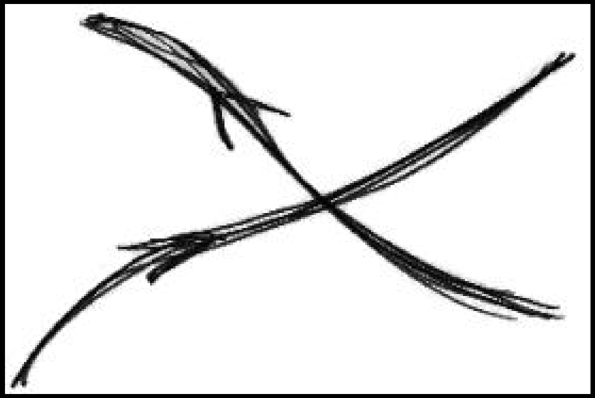

$(p, q) + (p', q')$ disconnection.

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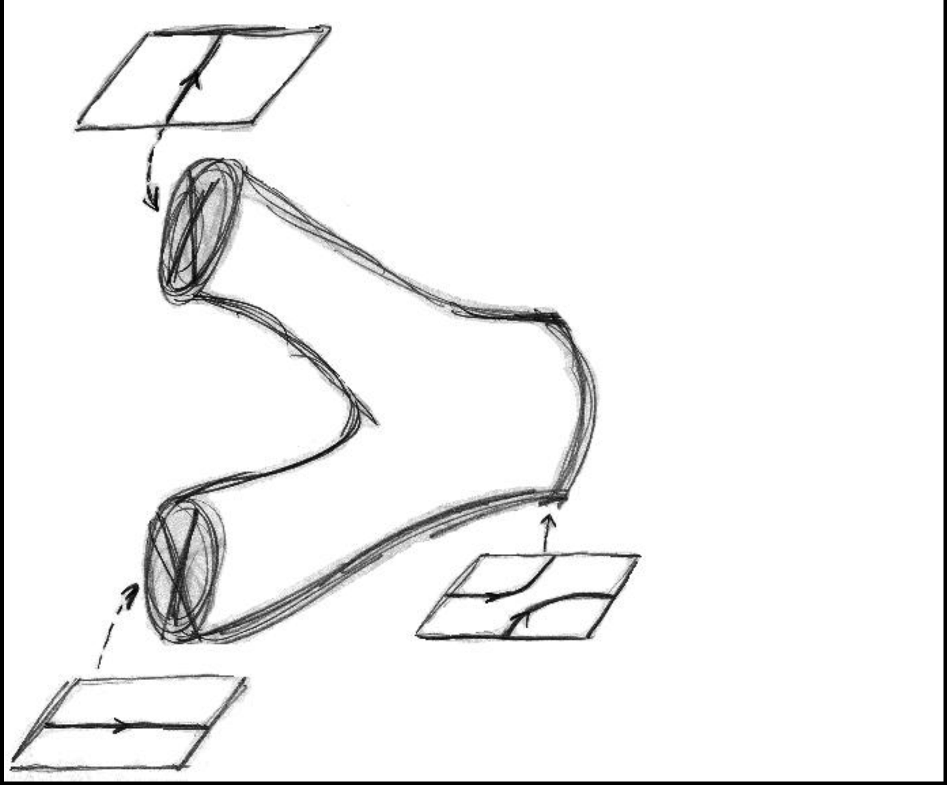
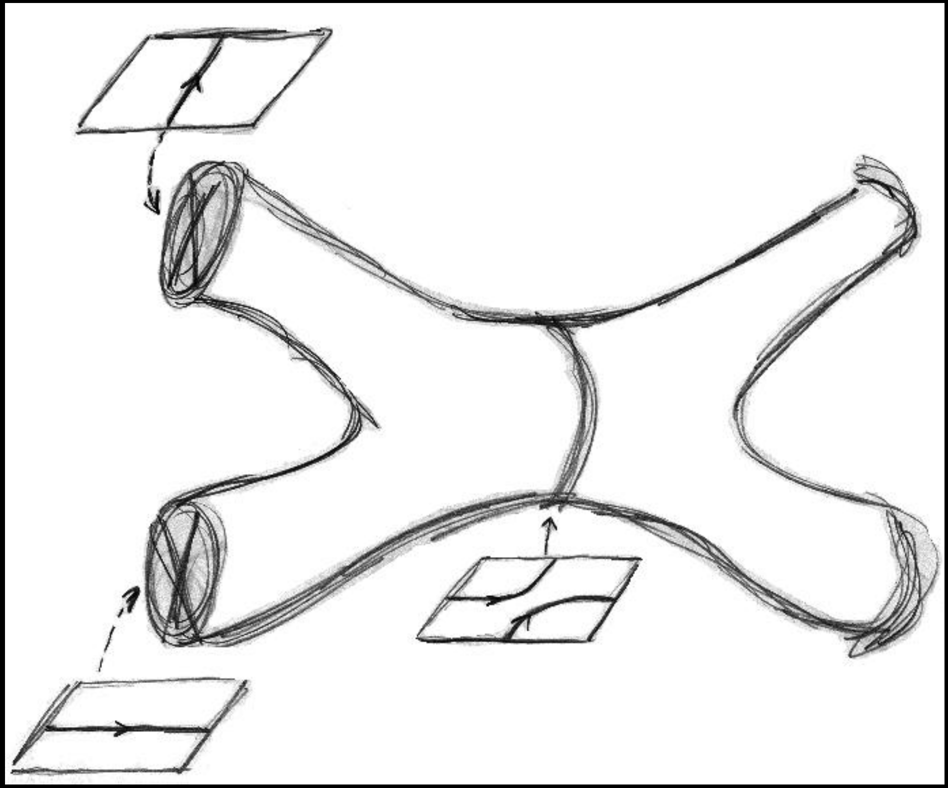
- Account for warping by effective confining potential.
  - Quantum fluctuations of string position give an effective volume of compactification.
  - Valid if geometry varying slowly on string scale.

F-F Interaction



Compactify 2D of 4D spacetime directions on torus and use wound closed strings (Polchinski, 1988).

F-F Interaction



Use unitarity to sum over all final states and macroscopic string limit (Polchinksi 1988).

F-F Interaction

$$A = \left\langle \mathcal{V}_1^{(0,0)} \mathcal{V}_2^{(0,0)} \mathcal{V}_3^{(-1,-1)} \mathcal{V}_4^{(-1,-1)} \right\rangle$$

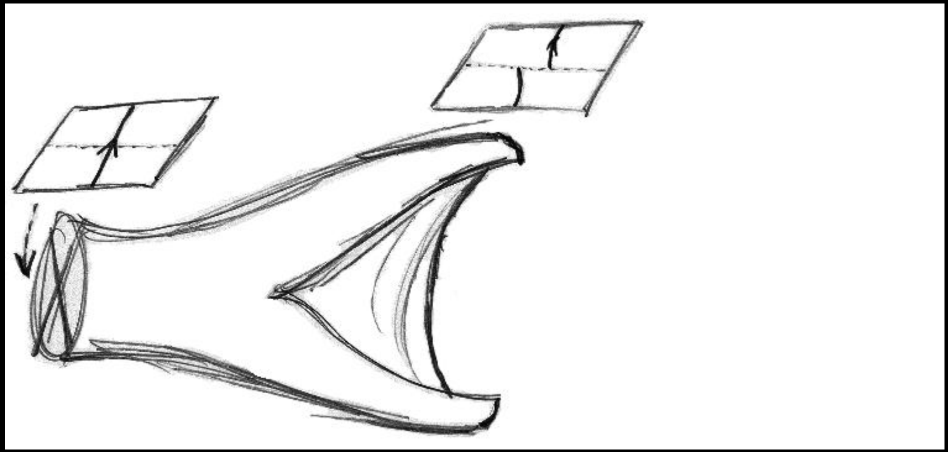
$$= (2\pi)^2 \delta^{(2)}(\textstyle\sum_i p_i) \frac{N_{\mathbb{S}^2} \kappa^4}{(2\pi)^4 V^2} \left(\frac{\alpha'}{2} p_{L1} \cdot p_{L2} \right)^2$$

$$\int d^2 z_4 |z_4|^{\alpha' p_{L1} \cdot p_{L4}} |1 - z_4|^{\alpha' p_{L2} \cdot p_{L4}}$$

$$\to -\frac{4\kappa^2}{V\alpha'} \frac{\Gamma\big(-\frac{\alpha'}{4}s\big)\,\Gamma\big(-\frac{\alpha'}{4}t\big)\,\Gamma\big(-\frac{\alpha'}{4}u\big)}{\Gamma\big(1+\frac{\alpha'}{4}s\big)\,\Gamma\big(1+\frac{\alpha'}{4}t\big)\,\Gamma\big(1+\frac{\alpha'}{4}u\big)},$$

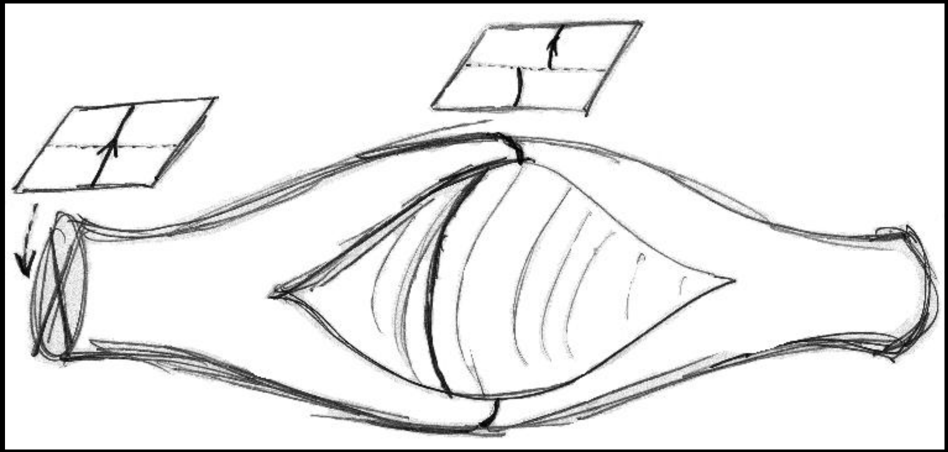
$$P = \frac{g_s^2}{V_\perp} (2\pi^2\alpha')^3 \frac{\big(1 - \cos\theta\sqrt{1-v^2}\big)^2}{\sin\theta\; v\sqrt{1-v^2}}.$$

F-(p, q) Interaction



Interaction of a wound closed string with a boundary; add Dirichlet boundary conditions, Chan-Paton factors & constant electric flux.

F-(p, q) Interaction



Unitarity etc...

$$\langle X^\mu(z_1)\tilde{X}^\nu(\bar{z}_2)\rangle = -\frac{\alpha'}{2}G^{\mu\nu}\ln(z_1-\bar{z}_2), \qquad \langle \psi^\mu(z_1)\tilde{\psi}^\nu(\bar{z}_2)\rangle = \frac{G^{\mu\nu}}{z_1-\bar{z}_2},$$

$$G^{\mu\nu} = \begin{pmatrix} -\frac{1+f^2}{1-f^2} & -\frac{2f}{1-f^2} & 0 \\ \frac{2f}{1-f^2} & \frac{1+f^2}{1-f^2} & 0 \\ 0 & 0 & -\mathbb{1} \end{pmatrix}.$$

(Callan, Lovelace, Nappi, Yost; Seiberg, Witten; . . .)

F-(p,q) Interaction

$$A = \left\langle \mathcal{V}_2^{(0,0)} \mathcal{V}_4^{(-1,-1)} \right\rangle$$

$$= N_{\mathbb{D}^2} \frac{\kappa^2 \sigma 2^{-2\sigma}}{(2\pi)^2 V} \int_0^1 dx\, (1-x)^{-1-\alpha' t/2} (1+x)^{1+2\sigma+\alpha' t/2} x^{-1-\sigma}$$

$$= -N_{\mathbb{D}^2} \frac{\kappa^2}{(2\pi)^2 V} \frac{\Gamma(-\frac{\alpha'}{4} t)\Gamma(1-\sigma)}{\Gamma(-\frac{\alpha'}{4} t - \sigma)},$$

$$P = \frac{g_s}{V_\perp} (2\pi^2 \alpha')^3 \frac{q^2 v^2 + \left(g_s p - \cos\theta \sqrt{1-v^2} \sqrt{g_s^2 p^2 + q^2} \right)^2}{\sin\theta\; v\sqrt{1-v^2} \sqrt{g_s^2 p^2 + q^2}}.$$

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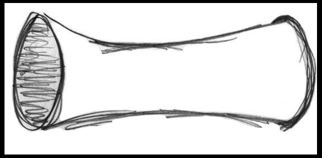
- Similar for (p, q)-(p', q') interaction.

D-D Interaction: Pair Production



$$= -\frac{i}{2}\int_0^\infty \frac{dt}{t} e^{-ty^2/2\pi\alpha'} \left[\eta^6(it)\,\Theta_1\big(i\frac{\theta t}{\pi}\big|it\big)\Theta_1\big(\epsilon t\big|it\big)\right]^{-1}$$

$$\times \left\{\sum_{k=2}^{4}(-1)^{k-1}\Theta_k\big(0\big|it\big)^2\Theta_k\big(i\frac{\theta t}{\pi}\big|it\big)\Theta_k\big(\epsilon t\big|it\big)\right\}.$$

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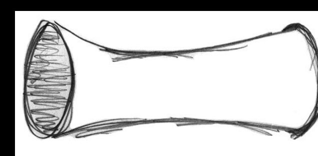
- Total inelastic probability (Schwinger; Bachas), or the probability of producing *at least one* pair of F-strings is

$$1 - \exp\left(-2\,\mathrm{Im}\right.$$



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$$= 1 - \frac{\prod_{\mathrm{fermions},i}(1 - x_i)}{\prod_{\mathrm{bosons},j}(1 + x_j)}, \qquad x = e^{-2\pi\alpha' m^2/\epsilon}.$$

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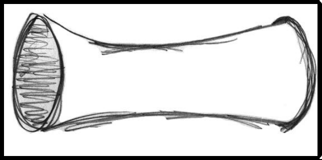
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- Since $\tau_F/\tau_D = g_s$, a single pair of F-strings will not cause connection.

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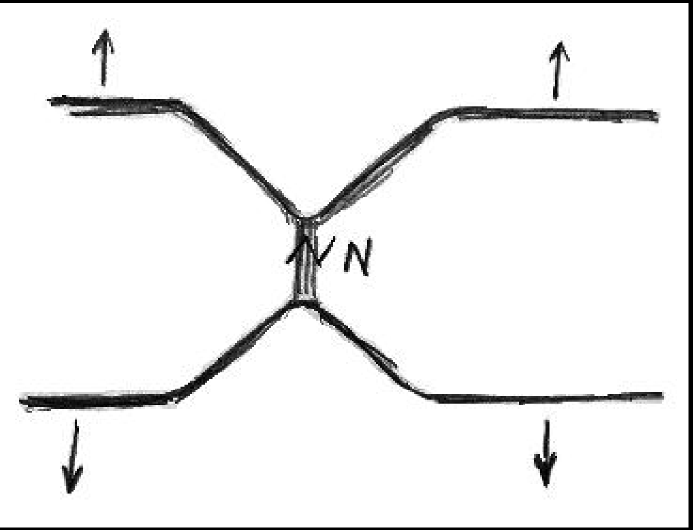

- If few F pairs are produced, the D-strings continue but kink, stretching the F’s. F’s eventually annihilate.

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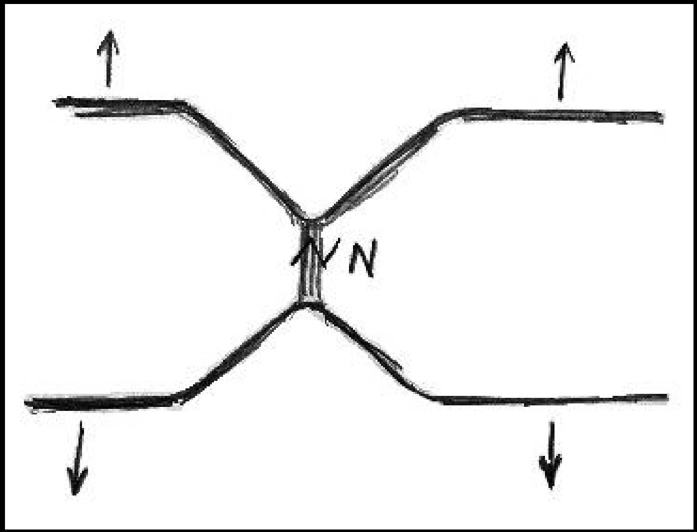

- If few F pairs are produced, the D-strings continue but kink, stretching the F's. F's eventually annihilate.
- If many F pairs are produced, their total tension is sufficient to stick the D-strings together; tachyon rolls and D's reconnect (Hashimoto, Taylor; Hashimoto, Nagaoka).

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- At most cosmic velocities, only tachyon and massless fermions are important.
- Then, 4 fermionic strings always are produced, so need at least $[\frac{1}{g_s}\sinh(\pi\epsilon/2) - 4]$ tachyonic strings.
- Probability is

$$P \sim \exp\left([4 - \frac{1}{g_s}\sinh(\pi\epsilon/2)]e^{-\theta/\epsilon}\right) .$$

Compactification Effects

- Metric and dilaton depend on compact coords, Y^i:
$ds^2 = H^{-\frac{1}{2}}(Y)\eta_{\mu\nu}dX^\mu dX^\nu + H^{\frac{1}{2}}(Y)g_{ij}(Y)dY^i dY^j$.

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- Fluctuations of position about a minimum are

$$\langle Y^i Y^i \rangle = \frac{\alpha'}{2\tau_{p,q}(0)} \ln\left[1 + \frac{\tau_{p,q}(0)}{2\pi\alpha'^2 H^{\frac{1}{2}}(0) V_{,ii}(0)}\right].$$

Fluctuations: F-Strings

- F-F wavefunction overlap:

$$\left(\frac{1}{V_\perp}\right)_{FF} \sim \left(\prod_{i=1}^{6} \ln\left[1 + \frac{\tau_{p,q}(0)}{2\pi\alpha'^2 H^{\frac{1}{2}}(0) V_{,ii}(0)}\right]\right)^{-\frac{1}{2}} .$$

Fluctuations: F- & D-Strings

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- F-D can have separated minima if dilaton depends on Y^i.
- $\Rightarrow$ supression of wavefunction overlap volume:

$$\left(\frac{1}{V_\perp}\right)_{FD} \propto \left(\frac{1}{V_\perp}\right)_{FF} \times \exp\left(-\sum_i \frac{Y_D^i Y_D^i}{\alpha' \ln[\ldots]_i}\right).$$

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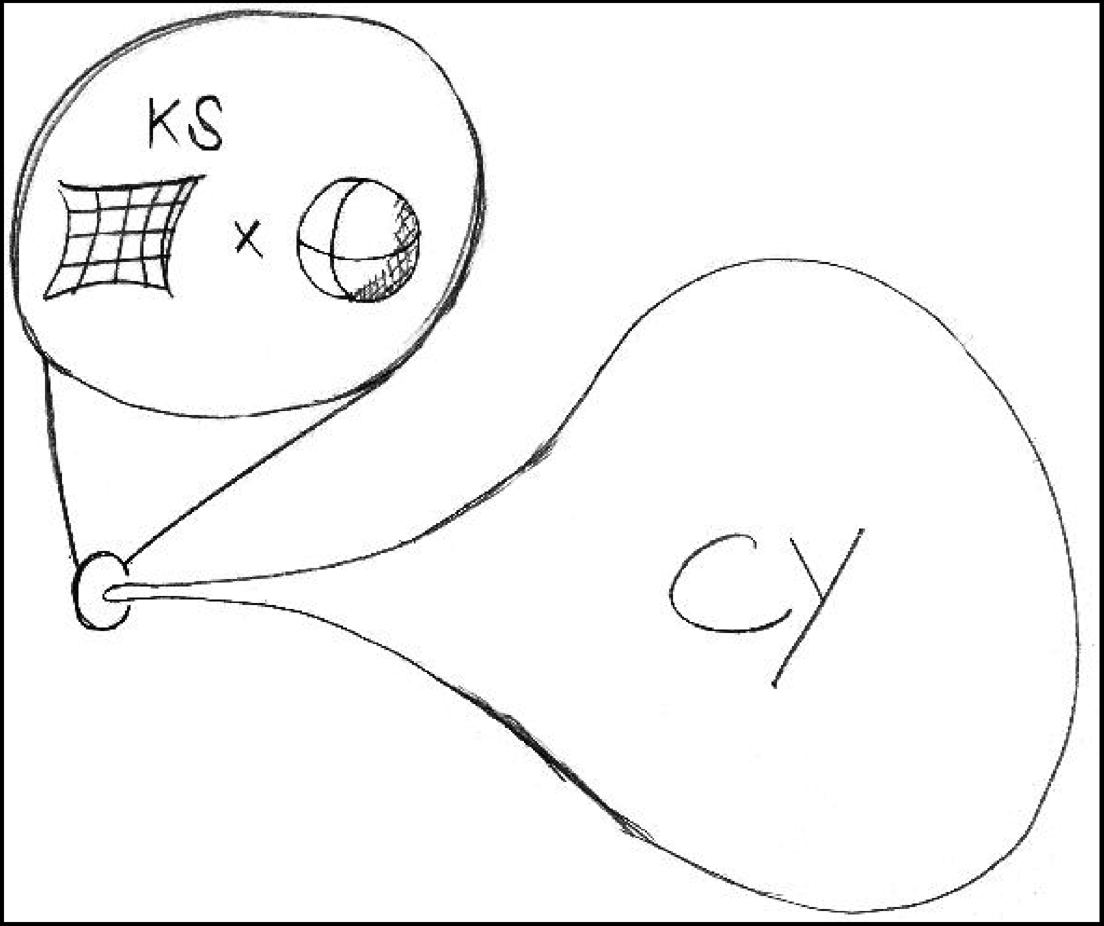
- Reconnection probability supressed by

$$\exp\left(- \frac{1}{2\pi \tau_{p,q}(0) \epsilon} \sum_i \ln[\ldots]_i \right) .$$

Fluctuations in KKLMMT Model



Vol$(\mathbb{S}^3) \sim (g_s M)^{3/2}$.

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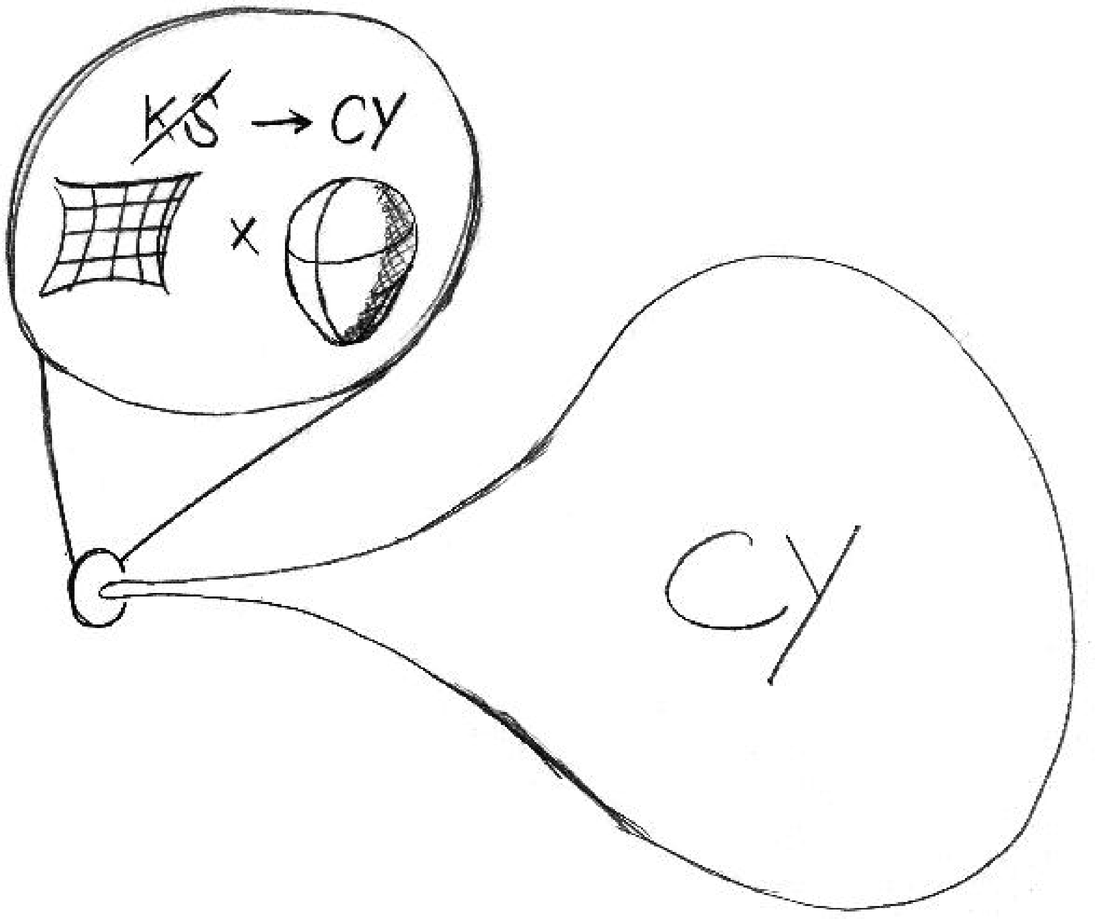

Assume CY curvature has effect $\mathcal{O}(H^{-\frac{1}{2}})$ on the throat geometry.

Fluctuations in KKLMMT Model

Two cases:

- Fluctuations are localised on $\mathbb{S}^3$:

$$\left\langle Y^i Y^i \right\rangle \sim \frac{3}{4} g_s \ln H(0) \alpha'.$$

Fluctuations in KKLMMT Model

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- Fluctuations fill the $\mathbb{S}^3$:

$$\langle Y^i Y^i \rangle \sim g_s M \alpha' .$$

Results: KKLMMT

- FF reconnection:

$$P_{FF} = \text{Max}\left[\frac{1.5 g_s^2}{\ln^{3/2}(1+g_s M)}, \frac{100 g_s^{1/2}}{M^{3/2}\ln^{3/2}(1+g_s M)}\right].$$

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- $M \simeq 20$, $P_{FF} \sim 0.25$,
  $M \simeq 100$, $P_{FF} \sim 0.01$.

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- Require $M > 12$, g_s can range between 1 and the G.U.T. value $1/20$.
- $M \simeq 20$, $P_{FF} \sim 0.25$,
  $M \simeq 100$, $P_{FF} \sim 0.01$.
- F-(p,q) connection probability increased by $1/g_s$ (if localised at same Y^i).

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- DD reconnection:

$$P_{DD} \simeq \exp\left(-\frac{1}{g_s}\sinh(\pi\epsilon/2)e^{-\theta/\epsilon+Y^2/2\pi\alpha'\epsilon}\right),$$

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- Supression is angle dependent; tachyon production is limited when $\theta < Y^2/2\pi\alpha'$.
- $P_{DD} \sim 0.1 \leftrightarrow 1$.

Detection and Bounds: P & τ

- Model Tensions:
  $10^{-10} \lesssim G\tau \lesssim 10^{-9}$ (KKLMMT).
  $10^{-11} \lesssim G\tau \lesssim 10^{-6}$ (General Brane Inflation).

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- Cosmic Microwave Background: sensitive to τ^2/P.
  $G\tau \lesssim 7 \times 10^{-7}$.

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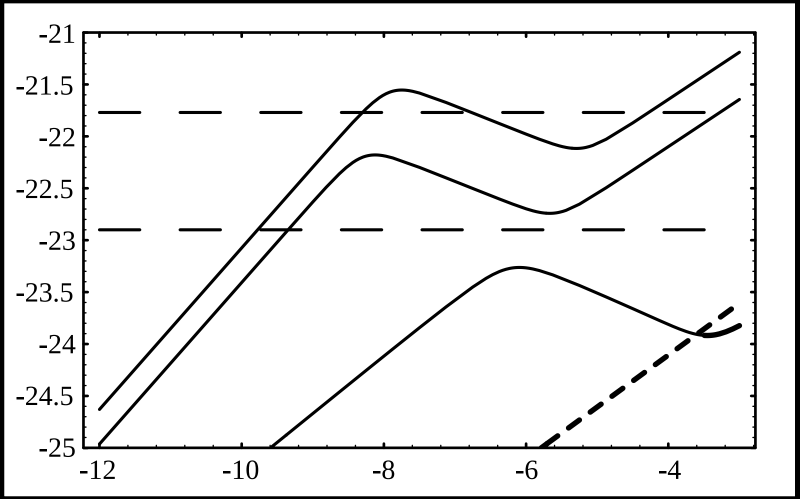
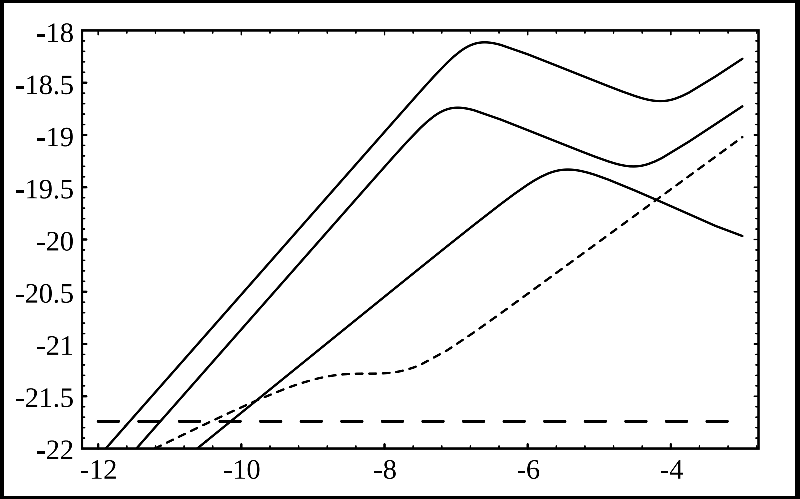
- Lensing: sensitive to τ.

Summary

- $P_{FF} \sim 10^{-2} \leftrightarrow 1$.
- $P_{DD} \sim 0.1 \leftrightarrow 1$.
- In most cases distinguishable from gauge theory strings; enhanced densities at a given tension.
- (p, q)-string networks can be very different from scaling solutions; interesting or disasterous?

Observation: Gravitational Waves

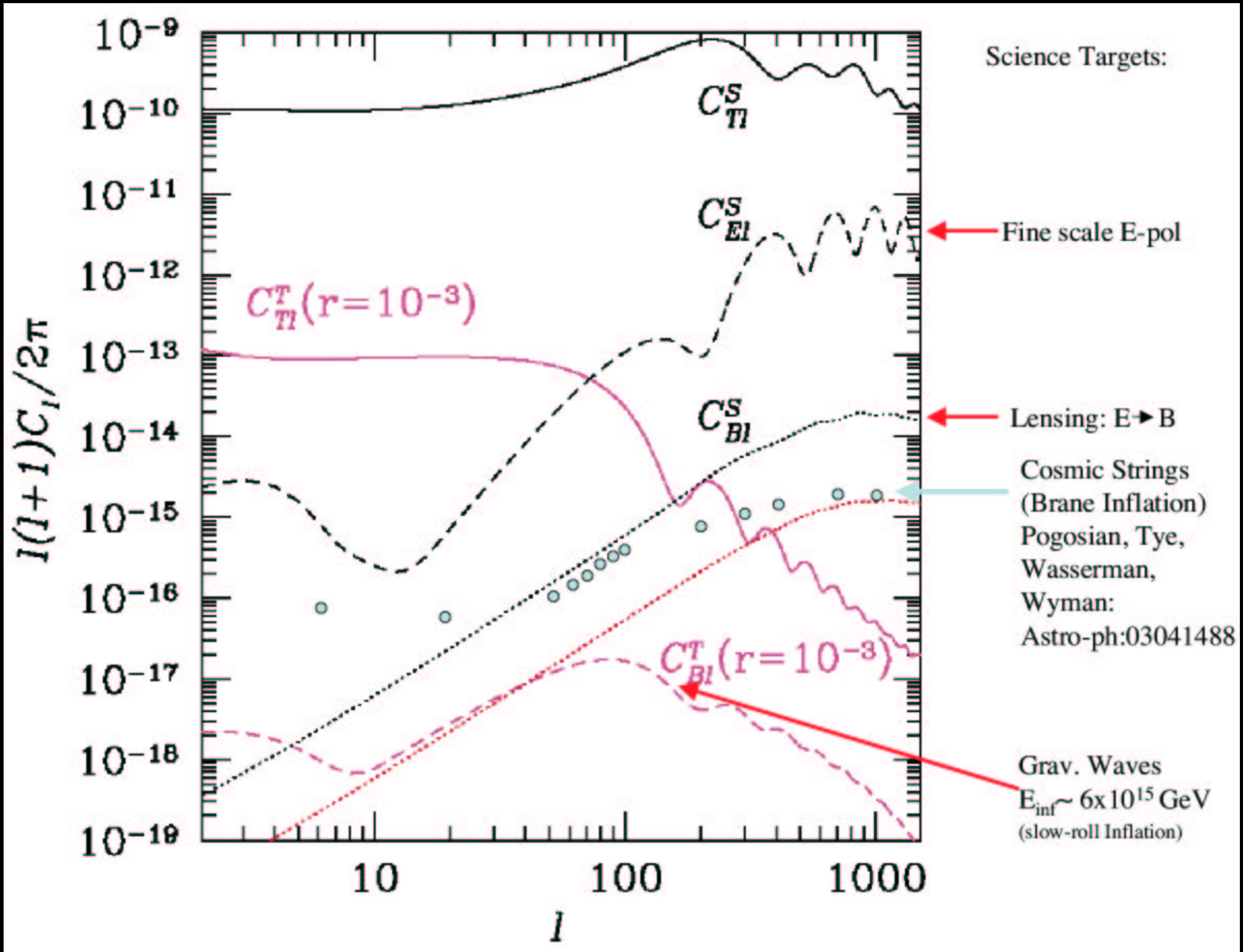




(Damour, Vilenkin [gr-qc/0104026])

- GW burst sensitive to τ only, to first order.
- Burst frequency sensitive to network density & therefore P.

Observation: CMB



(Winstein)