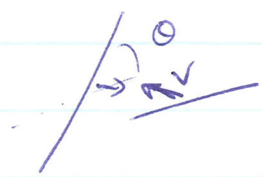
POLCHINSKI LECTURES - PART 3

1. $P \sim 1$, solitons in typical gauge theories
2. $P \sim g_s^2$, fund. strings ← dual in KS throat
3. $P \sim \frac{1}{N}$, electric flux tubes ←

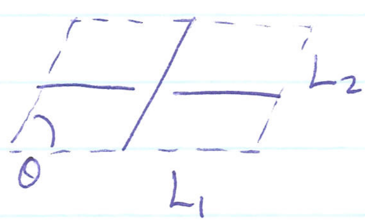
Dual but not the same, since we live ~~in~~ at some specific point of parameter space.

Fund. strings give a definite prediction for

$P(v, \theta)$



How to do calc? Don't have vert. op. for ∞ strings but do for winding strings, so put them on a torus:



~ Virasoro-Shapiro amplitude

Total interaction (imaginary part of 2→2 forward [tree] amplitude). $L_1, L_2 \to \infty$ limit is smooth →

$$\to g_s^2 \frac{V_{min}}{V_\perp} f(\theta, v)$$

($V_{min} \to (4\pi^2\alpha')^3$)

$$f(\theta,v) \to \frac{(1-\cos\theta\sqrt{1-v^2})^2}{8\sin\theta\, v\sqrt{1-v^2}}$$

$V_\perp \sim V_{compact}$? <u>No</u>: compact fluctuations of string are massive, pruned.

$$\langle y^2 \rangle = \frac{\alpha'}{2} \ln(m^2\alpha')$$

↑ massive world-sheet field

only logarithmic in mass

$$\frac{1}{V_\perp} \sim \langle \delta^6(Y_1 - Y_2) \rangle = \int \frac{d^6k}{(2\pi)^6} \langle e^{ik\cdot(y_1-y_2)} \rangle$$

$$\langle e^{ik\cdot(y_1-y_2)} \rangle \to e^{-\frac{k^2}{2}(\langle y_1^2\rangle + \langle y_2^2 \rangle)}$$

$$= \frac{(2\pi)^3}{V_{min}(\ln m^2\alpha')^3}$$

KS throat: S_3 at the bottom helps, log roughly offsets $(2\pi)^3$

D-strings: $\sim e^{-1/g_s}$ for $g_s \ll 1$, but $> P_{FF}$ for "typical" g.

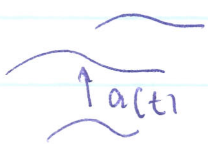
Phenomenology of Cosmic Strings –

$$ds^2 = -dt^2 + a^2(t)\, dx \cdot dx$$

$a \sim t^{1/2}$ $t < 10^{5.5}$ yr

$\sim t^{2/3}$ $t > {}^{5.5}$ yr.

<u>If</u> the string network just expanded uniformly,



$\rho_{string} \propto a^{-2}(t)$ (dilutes in 2 of 3 dimension)

↑

$w = -\frac{1}{3}$

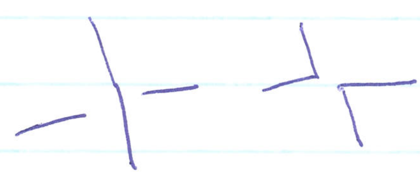
If this were true then over time

$\rho_{string} > \rho_{matter} \ (\sim a^{-3}(t))$

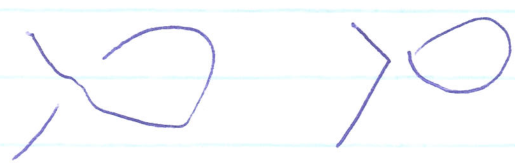
$\rho_{radiation} \ (\sim a^{-4}(t))$

But this is not what happens –

- redshifting inside horizon.
- long string reconnection



feedback ↓ ↑ makes kinks

- 

loops break off and decay

Feedback: More Long Strings

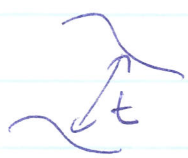
→ More LS Reconnection

→ More Kinks

→ More Loops

→ Less Long String

~~Agrees with simulations~~: Rate equations suggest



$$\rho \sim \frac{\mu}{t^2}$$

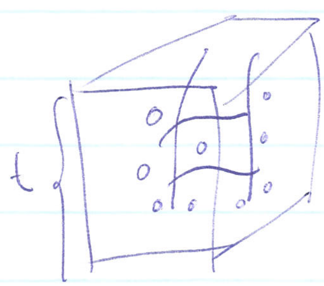
Agrees w/ simulations.

Notation: in FRW $\rho_{\text{total}} = \frac{3H^2}{8\pi G} \sim \frac{1}{t^2 G}$

So $\frac{\rho_{\text{string}}}{\rho_{\text{matter}}} \sim 60\, G\mu$ (matter dom)

$\frac{\rho_{\text{string}}}{\rho_{\text{rad}}} \sim 400\, G\mu$ (radiation dom)

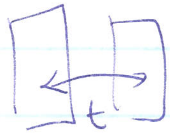
__not__ __dark__ __matter__

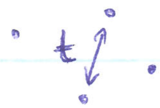


~4 long strings (matter)

~12 long strings (radiation)

cf 2-branes, 0-branes

• DW:  $\rho \propto \frac{1}{t}$ dominates

• Particles:  Causality limits $\rho \propto \frac{1}{t^3}$, but this is not attained: ~~cant~~ unlike strings + walls, particles can't find each other after a certain period of time.

$\rho \propto a^{-3}$ (comes to dominate radiation density)

"magnetic monopole problem" $\Rightarrow$ ~~itself~~ inflation

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For strings want to know:

- What are current bounds and possible future sensitivity?
- How precisely can we measure P and look for non-standard network behavior?

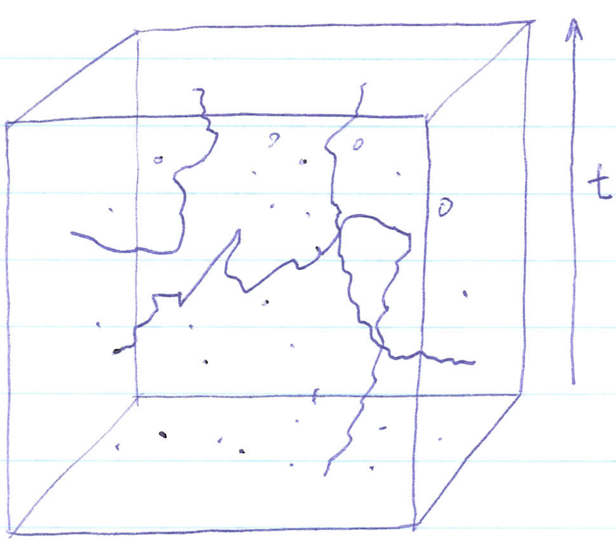
Will focus on strings with gravitational interactions only. Signatures:

- effect on CMB
- lensing
- grav. waves: LIGO/LISA
  Pulsars

Important parameter: $G\mu$:

- string tension in Planck units
- typical metric perturbation produced by string
  (so we are not close to producing black holes)

brane inflation models: $10^{-11} \lesssim G\mu \lesssim 10^{-6}$
↑ current bound



long string sep. at
"scaling": ~~all props~~ mean
string distribution, scaled to t, is the same at all times.

$\bar{v}^2 \sim 0.4c$

- Gross properties well-understood
- Short distance structure ~~not~~ on long strings not well-characterized

- Size of loops a total mystery.

Estimates of ~~log~~ loop size:

$0.1t$

$10^{-4}t$

$50G\mu t$?

$(50G\mu)^{5/2}t$

$\sqrt{\alpha'}$

} simulations disagree but loop size usually near UV limit of simulation.

- A few facts:

$\bar{v}^2 \sim 0.4$ (virial theorem: for closed loops of ∞ random walks in flat spacetime, $\bar{v}^2 = \frac{1}{2}$. Here it is reduced by the expansion of the universe).

(Classic: $\partial_+ X^\mu \cdot \partial_+ X_\mu$
$= \partial_- X^\mu \cdot \partial_- X_\mu$
$= 0 \quad t = \tau$)

- μ scales out of Nambu action,
- grav self-interaction negligible ($G\mu \ll v^2$)

- grav radiation suppressed by $G\mu$

Goals for remaining lecture:

- discuss signatures + uncertainties
- analytic model of network properties

Note: scaling of long string density ρ_∞ with P:

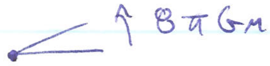
naive estimate: $\rho_\infty \propto \frac{1}{P}$ (so rate of long string intercommutation remains constant).

Numerical: less sensitive:

$$\frac{\partial \ln \rho_\infty}{\partial \ln P} \sim -0.2 \quad (P \sim 1)$$
$$-0.6 \quad (P \ll 1)$$

(tentative explanation: strings intersect several times as they cross, due to short distance structure).

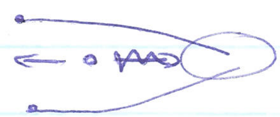
• structure formation + CMB: scaling property of network ⇒ strings produce scale invariant perturbations.



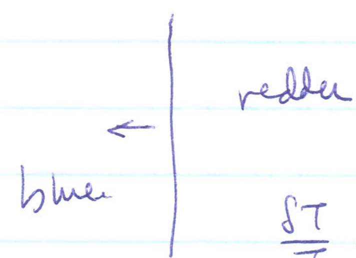
How does cosmic geometry seed galaxies?

#1 Wiggles → Newtonian force

#2 Wakes

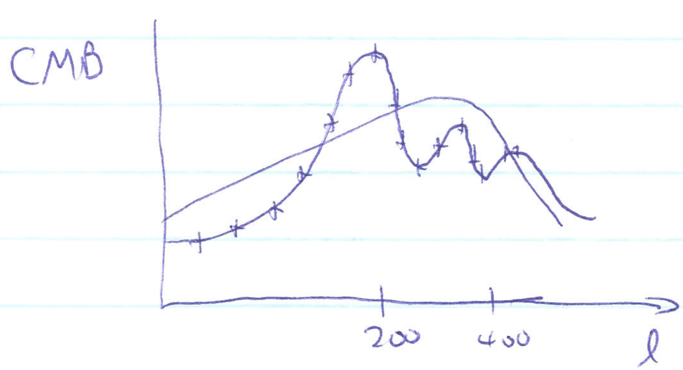


Additional effect on CMB



$$\frac{\delta T}{T} \sim 8\pi G\mu \frac{v}{\sqrt{1-v^2}}.$$

$G\mu \sim 10^{-5.5}$ would give right magnitude for galaxies + CMB, but wrong pattern



Reason: inflationary pert. form before scale leaves horizon; oscillations begin (with common phase)