What's New in String Theory?

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Lots of course, including the following:

- Flux compactifications *[Kachru-Kallosh- Linde-Trivedi]*: a huge enough number to solve cosm. const. problem?
- Light cosmic strings *[Copeland-Myers-Polchinski]*: suggested by flux compactifications, may be observable.
- Light strings in preheating *[Gubser]*: a natural but stringy mechanism of reheating.
- String-inspired modification of CDM *[Gubser-Peebles]*: scalar-mediated forces might alter structure formation.

Mainstream of thought on particle phenomenology is still driven by low-energy SUSY and by GUTs.

Flux compactifications

The Good News: Now we can stabilize all moduli of certain Calabi-Yau constructions, break supersymmetry, and get a small cosmological constant.

The Bad News: The constructions are complicated, and small Λ is achieved with a shot-gun approach which may limit predictivity.

Compactification on a CY_3 takes us from 10-dim to 4-dim. The CY_3 has *moduli*:

Complex structure:	$\Omega = dz^1 \wedge dz^2 \wedge dz^3$	(locally)
Kahler/ size:	$\rho = \text{axion} + iR^4/g_s\alpha'^2$	(assumed unique)
coupling:	$\tau = \text{axion} + i/g_s$	(unique)

(1)

A priori these are all massless. After SUSY breaking, size tends to run to ∞: decompactification.

1) Well-established *flux superpotential* can stabilize Ω and τ:

$$W_{\text{tree}} = \int G_3 \wedge \Omega \qquad G_3 = F_3 - \tau H_3 \,. \tag{2}$$

Choice of G_3 roughly amounts to wrapping 5-branes and then letting them "dissolve" into flux.

2) Instantons or gaugino condensation on other wrapped branes can stabilize ρ:

$$W = W_{\text{tree}} + A e^{ia\rho} \,, \tag{3}$$

where second term is due to $\langle \lambda\lambda \rangle \sim e^{-8\pi^2/g_{YM}^2 N}$, with $\rho = \frac{\theta}{2\pi} + \frac{4\pi}{g_{YM}^2}$.

But the result of 1) and 2) is unbroken SUSY and $\Lambda_0 < 0$.

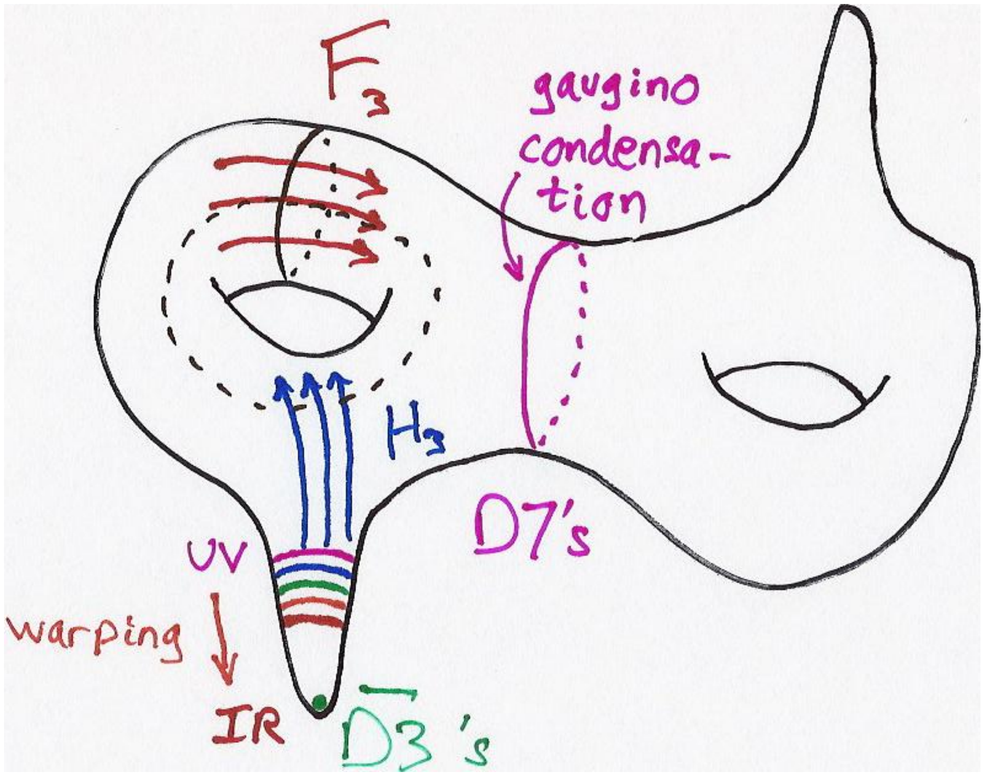
3) Anti-D3-branes can break SUSY and raise Λ:

$$\Lambda = \Lambda_0 + \frac{N_{\overline{D3}} e^{4A}}{(\text{Im}\,\rho)^3} \,, \tag{4}$$

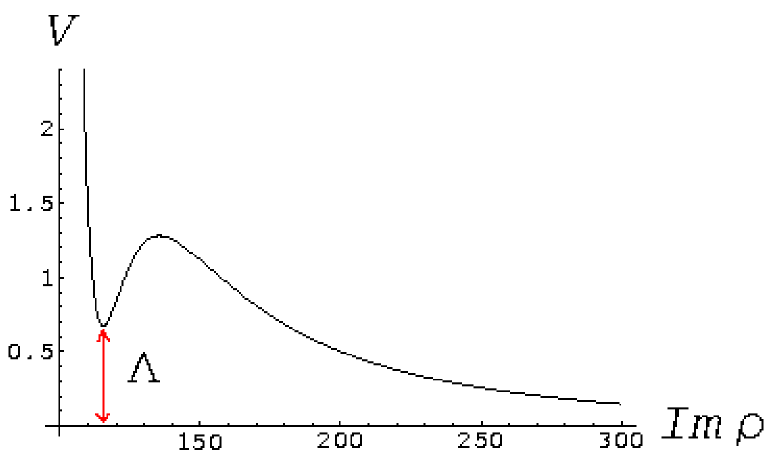
where the *warp factor* e^A can vary over the CY_3:

$$ds^2 = e^{2A}(-dt^2 + d\vec{x}^2) + e^{-2A} ds^2_{CY_3} \,. \tag{5}$$

End picture is complex:



But potential for $\mathrm{Im}\,\rho$ is rather nice:



and the key point is that we have *huge but discrete* freedom in choosing $G_3 \in H^3(CY_3, \mathbf{Z})$: we can easily try 10^{100} choices if $\dim H^3 = 100$. So small Λ can be arranged. This is the "shotgun" approach.

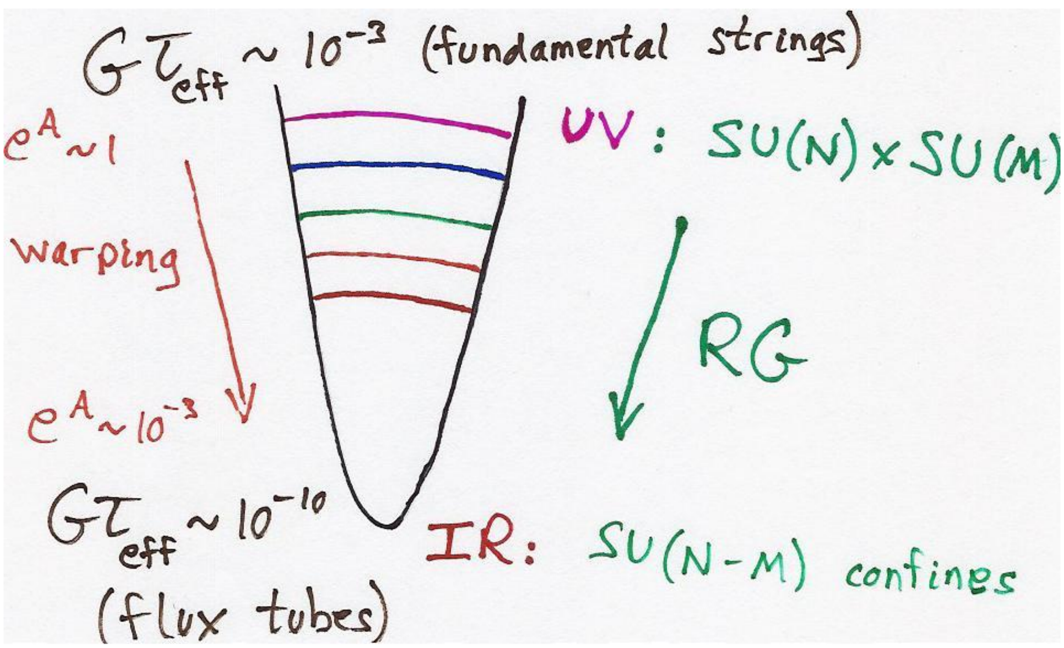
Light cosmic strings

An old objection to fundamental strings as cosmic strings is

$$\begin{aligned} G\tau &\gtrsim 10^{-3} \qquad \text{for fundamental strings} \\ G\tau &\lesssim 10^{-5} \qquad \text{for cosmic strings}, \end{aligned} \tag{6}$$

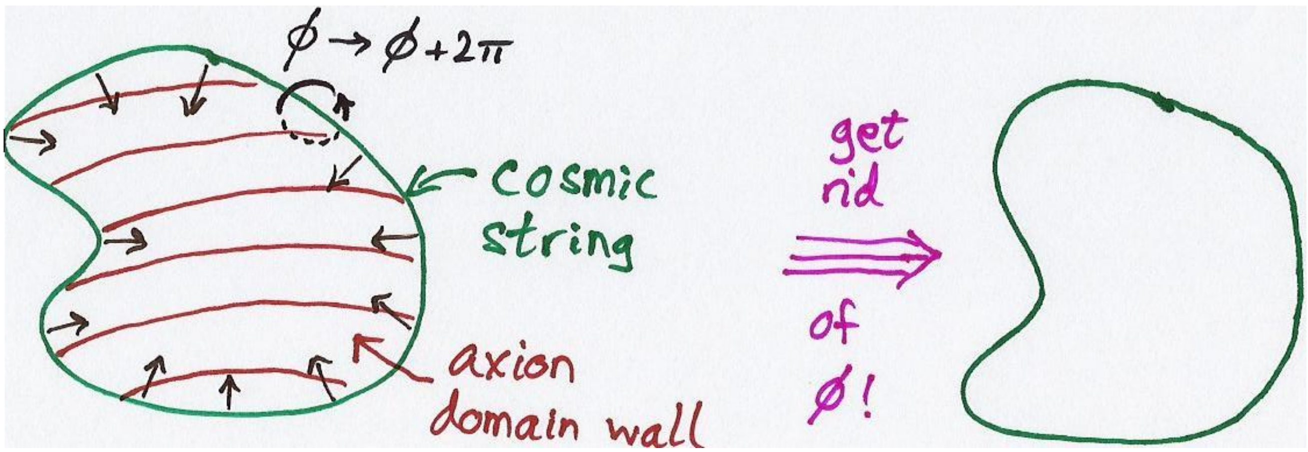
where the second inequality comes from anisotropies in the CMB.

This can be solved in the flux compactification picture thanks to severe warping:

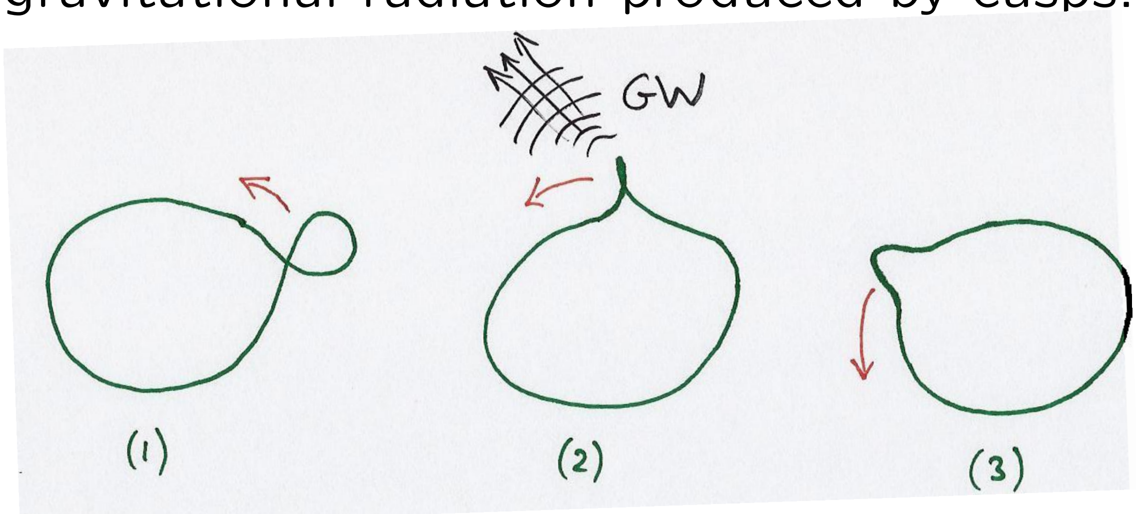


This is not a fine-tuning: dual to a $SU(N)\times SU(M)$ gauge theory which confines at a scale $\ll M_{Pl}$: the cosmic strings in question are basically the flux tubes of this gauge theory.

A further objection based on axionic domain walls is removed by a further feature of flux compactifications: orientifold planes based on a $\mathbf{Z}_2$ which projects away the axion.



A signal for such strings could come from bursts of gravitational radiation produced by cusps:



and LIGO might see this signal for $G\tau \gtrsim 10^{-11}$.

Light strings in preheating

We typically think of creating cosmic strings through the Kibble mechanism (i.e. in a phase transition). What about quantum production of individual vibrational modes?

The on-shell constraint $L_0|\psi_{\text{phys}}\rangle = 0$ amounts approximately to

$$\ddot{\chi} + \omega^2 \chi = 0\,, \tag{7}$$

where

$$\omega^2 = k^2 + m^2 \qquad m^2 = N/\alpha'\,. \tag{8}$$

If α' varies with time, so does ω^2, and positive frequency modes for (7) evolve into a mix of positive and negative frequency: *string creation*.

- How might $\tau = 1/2\pi\alpha'$ vary after inflation?

- Most useful answer is for strings in 4-dim coming from wrapped branes in 10-dim.

Consider D3-branes wrapped on an S^2 whose complexified volume is

$$\varphi \propto \int_{S^2} (B_2 + iJ_2) \qquad \text{(a Kahler modulus).} \tag{9}$$

If S^2 shrinks we have light strings in 4-dim. Starting from

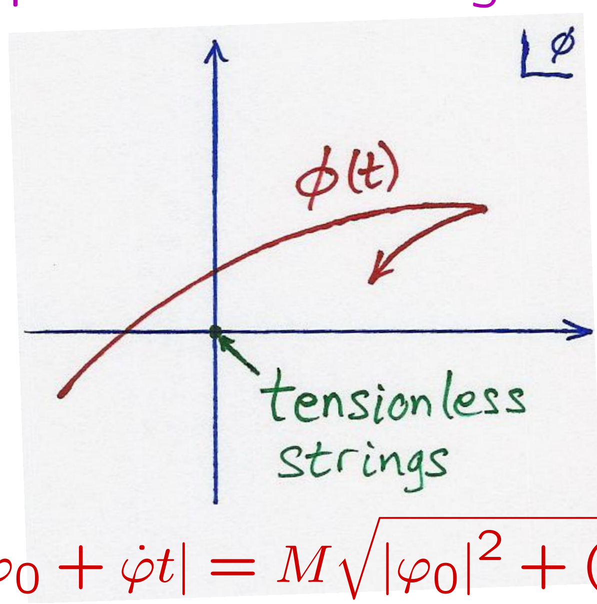
$$S_{D3} = -\tau_{D3} \int d^4\xi \sqrt{G_{\mu\nu} + B_{\mu\nu}} + \dots , \tag{10}$$

with $\tau_{D3} \sim 1/(\alpha'^2 g_s)$, obtain

$$\tau_{\text{eff}} \approx M|\varphi| \qquad \text{with} \qquad M \sim \frac{M_{\text{Pl},4}}{g_s} , \tag{11}$$

where φ has been rescaled to be canonically normalized. (11) is typical for light strings.

String creation after inflation might proceed via a "fly-by" of a point where strings are tensionless:



$$\tau_{\text{eff}} \approx M|\varphi_0 + \dot{\varphi} t| = M\sqrt{|\varphi_0|^2 + (|\dot{\varphi}|t)^2} . \tag{12}$$

To estimate string creation, use a steepest descent trick:

$$\omega^2 \approx m^2 \propto \tau_{\rm eff} = 0 \quad \text{for } t = -i\mu = -i|\varphi_0|/|\dot\varphi|$$

$$|\beta|^2 \approx e^{-\pi\mu\omega(0)} \,. \tag{13}$$

To get the total number of strings produced, we sum over the Hagedorn spectrum:

$$\frac{dN}{dE} \propto E^\gamma e^{E/T_H} \,, \qquad T_H = \frac{1}{2\pi\sqrt{\alpha' c_\perp/6}} \,, \tag{14}$$

$$N_{\rm tot} = \int_0^\infty dE \, \frac{dN}{dE} |\beta|^2 = \int^\infty e^{E/T_H} e^{-\pi\mu\omega(0)} \,. \tag{15}$$

String production is

$$\begin{array}{ll} \text{exponentially suppressed if} & T_H > \dfrac{1}{\pi\mu} \\ \text{exponentially enhanced if} & \dfrac{1}{\pi\mu} > T_H \,. \end{array} \tag{16}$$

The borderline case is when

$$(M\phi_0)^{3/2} \equiv \tau_{\rm min}^{3/2} = M\dot\varphi \sim M M_{\rm Pl,4} m_{\rm inflaton} \,. \tag{17}$$

Assuming $\dot\varphi \sim M_{\rm Pl,4} m_{\rm inflaton}$ is reasonable for oscillations of amplitude $M_{\rm Pl,4}$ and frequency $m_{\rm inflaton}$.

Further estimating

$$\left.\begin{array}{r} M \sim 10 M_{\mathrm{Pl},4} \\ m_{\mathrm{inflaton}} \sim 10^{-5} M_{\mathrm{Pl},4} \end{array}\right\} \implies \sqrt{\tau_{\mathrm{min}}} \lesssim \frac{M_{\mathrm{Pl},4}}{20} \quad (18)$$

in order for strings to be copiously produced right after inflation.

Comparison to *preheating* (coherent production of bosons through parametric resonance driven by inflaton oscillations):

- Causes an even more sudden reheating of the universe.
- Less contrived: (18) is not implausible, and tensionless strings occur on codimension two loci in moduli space.
- Similarly unconstrained by current observations.

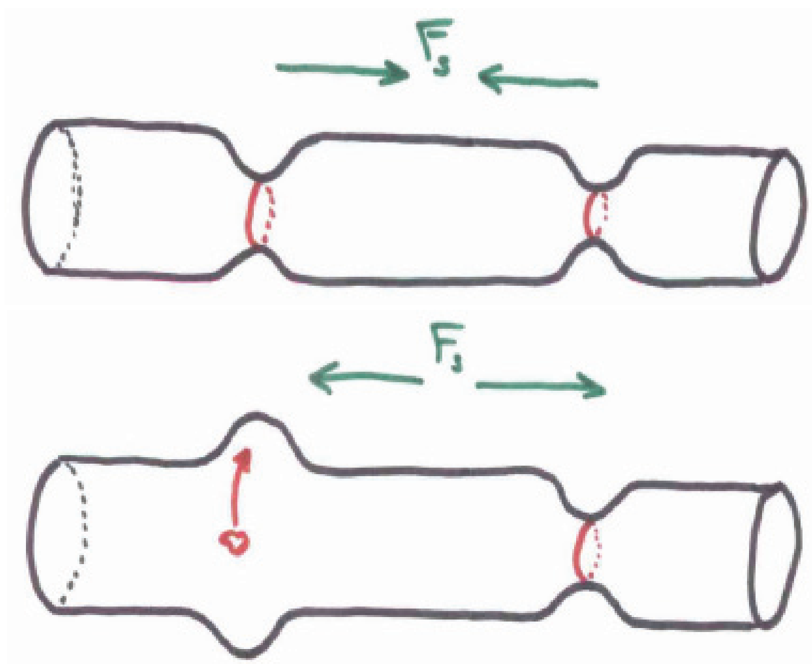
Speculate that decay of these strings would cause non-gaussian spectrum of gravitational waves, but I don't have an estimate for LIGO.

String-inspired modication of CDM

Strings and preheating relied upon rolling scalars at 10^{13} GeV: no conflict with Flux compactifications.

But the next set of ideas hinges on *very light* scalars: if we have to work so hard to get rid of them, why not use them?

Scalar-mediated forces cause like particles to attract and unlike particles to repel. Consider for example strings winding or moving around a compact S^1:

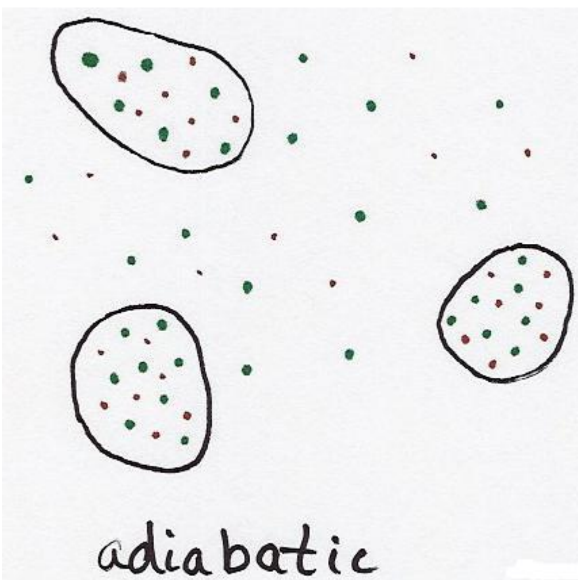


If these forces are comparable to gravity, structure formation might happen differently than in the CDM model.

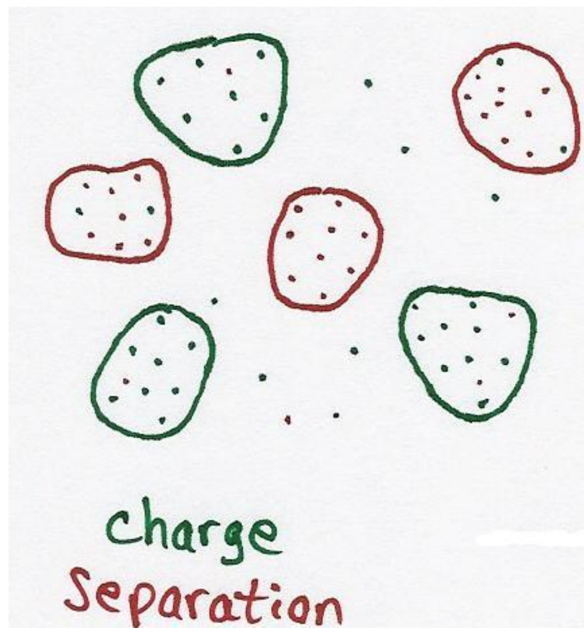
In general, assume several species of dark matter particles with force law

$$F_{pq} = \beta_{pq} \frac{G m_p m_q}{r^2} \tag{19}$$

between particles of species p and q. Gauge contributions to β_{pq} don't change structure formation (Debye screening), but scalars do:



vs



• Adiabatic mode grows as $t^{2/3}$: good match with observations.

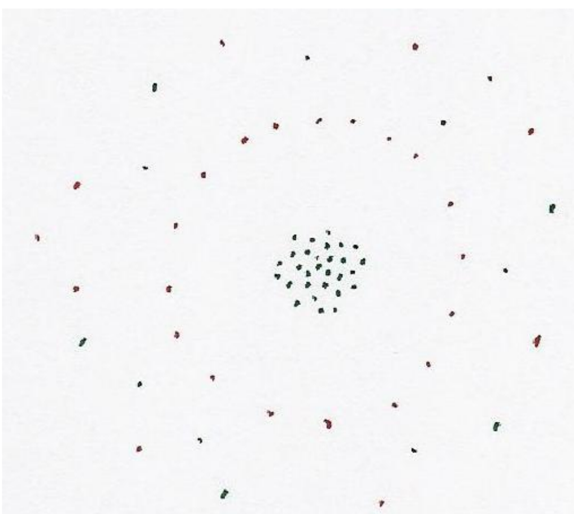
• Separation mode grows faster if $\beta_{12} < 0$: i.e. if scalar forces are stronger than gravity.

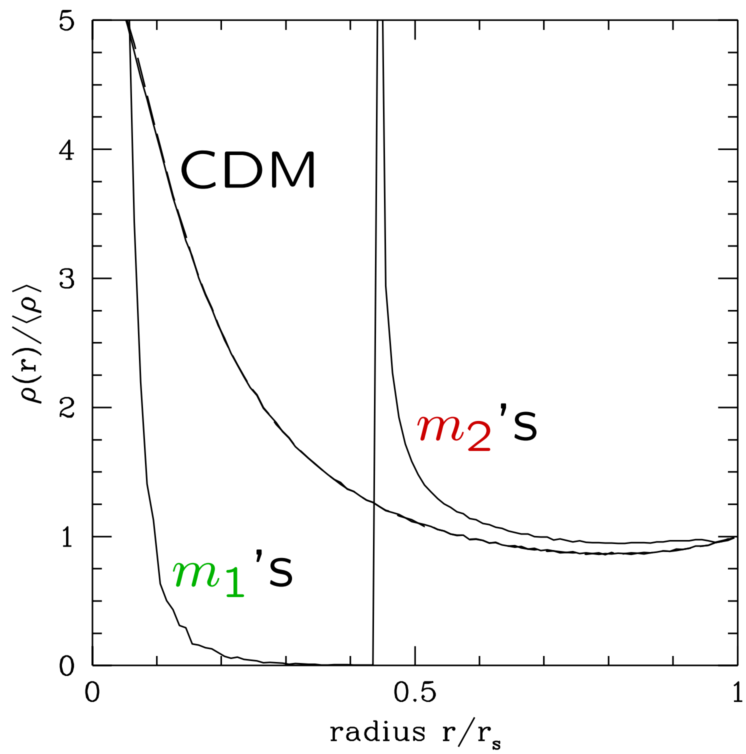
• *Naive* string theory computation gives $\beta_{12} = -1$.

• String theory sits near the border of an observable effect for the linearized regime.

Can allow rather strong scalar forces if they're screened at a scale r_s comparable to galaxies.

Such forces may ameliorate some problems with CDM. For example, if $m_1 \ll m_2$, get an intriguing phenomenon of light vs. heavy halos in bound structures.





Central object is bound by scalar forces, and is much smaller than CDM predicts.

This may be a way of suppressing dwarf galaxies but leaving enough small dense objects to explain recent anomalies in lensing around quasars.

Summary

- One theme in recent string theory developments has been connection with cosmology.

- Moduli (massless scalars) continue to fascinate, either as heroes or villains.

- Hoping for signals at LIGO, or successes in structure formation.

- With many powerful theoretical tools in hand, still need to focus on the simple and robust features of string theory.

References

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[Gubser-Peebles] S. S. Gubser and P. J. E. Peebles, forthcoming.