Beyond Perturbation Theory

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Academic Training Lectures

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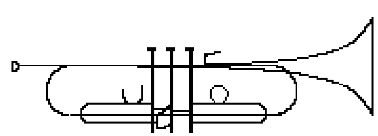


This Section's Goal

To see how to go beyond perturbation theory:

- to better understand what happens to strings
- to understand non-perturbative phenomena
- to see how D-branes help us do this

To set the scene for:

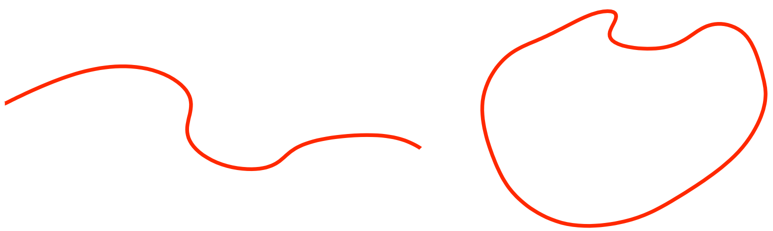
- various special topics
- various current events....

What Should We Expect?

We'd like to go beyond perturbation theory. What should we expect?

Basically, the unexpected.

Yes, all bets are off:



We lose control of the basic degrees of freedom, the strings. Spectrum could be completely different

Don't have any right to expect theory to even be in same target space any more (since strings are also maybe supposed to control spacetime non-perturbatively)

Don't have any right to expect theory to even be a string theory any more

What Should We Expect?

We don't have control over a "string field theory" formulation of the theory.

We don't even know if that's generally applicable.

Given what happens with field theory non-perturbatively, its not clear that string field theory would help anyway.

So with that all in mind, lets proceed.

A Small Window

We have a small window: D-branes

What do we know?

They are solitons in the theory:

Tension: $$\tau_p = \frac{(2\pi)^{-p}\alpha'^{-\frac{p+1}{2}}}{g_s}$$ (So very heavy at weak coupling)

The collective coordinates (massless excitations) are just a gauge theory on the world-volume

They are BPS saturated states: $$\tau_p = \frac{\mu_p}{g_s}$$

Most stable objects. Their spectrum is exact: Not corrected by loops.

So what? Well, maybe we can watch them as the string coupling gets large. Maybe we can recognize where they get to.

The Type I Theory at Strong Coupling

This theory has two D-brane types: D1- and D5-

Look at D1-brane   It is a closed string which couples to $C^{(2)}$

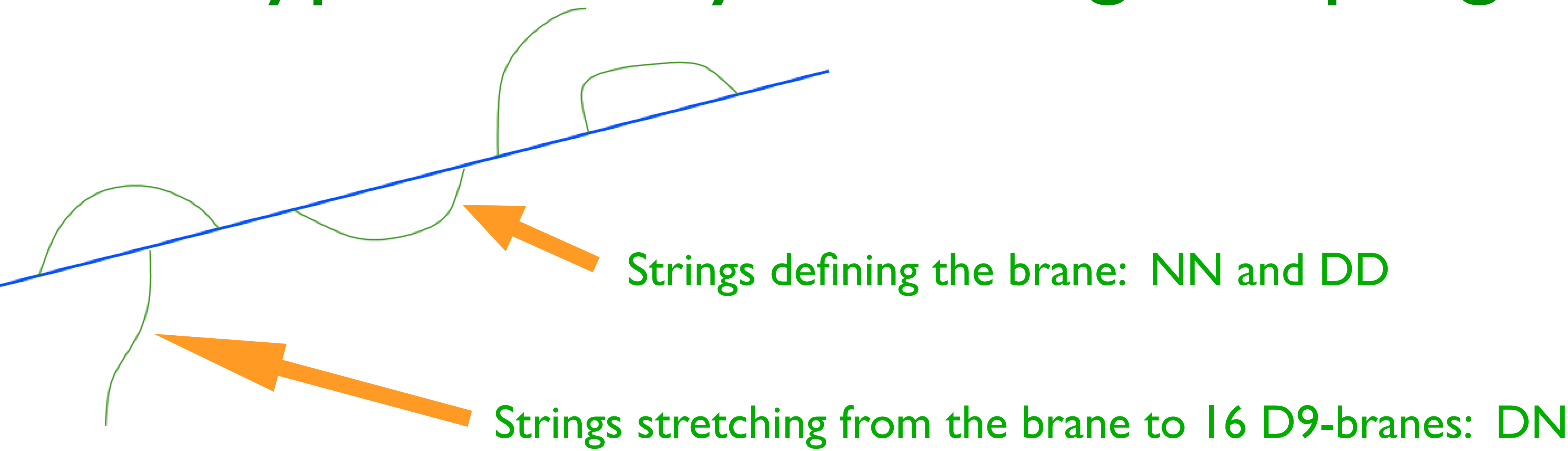
Tension: $\tau_p = \frac{(2\pi)^{-p}\alpha'^{-\frac{p+1}{2}}}{g_s} \longrightarrow \tau_1 = \frac{1}{2\pi\alpha' g_s}$

What is its spectrum of massless excitations?

Well:

	x^0	x^1	x^2	x^3	x^4	x^5	x^6	x^7	x^8	x^9
D9	—	—	—	—	—	—	—	—	—	—
D1	—	—	•	•	•	•	•	•	•	•

The Type I Theory at Strong Coupling



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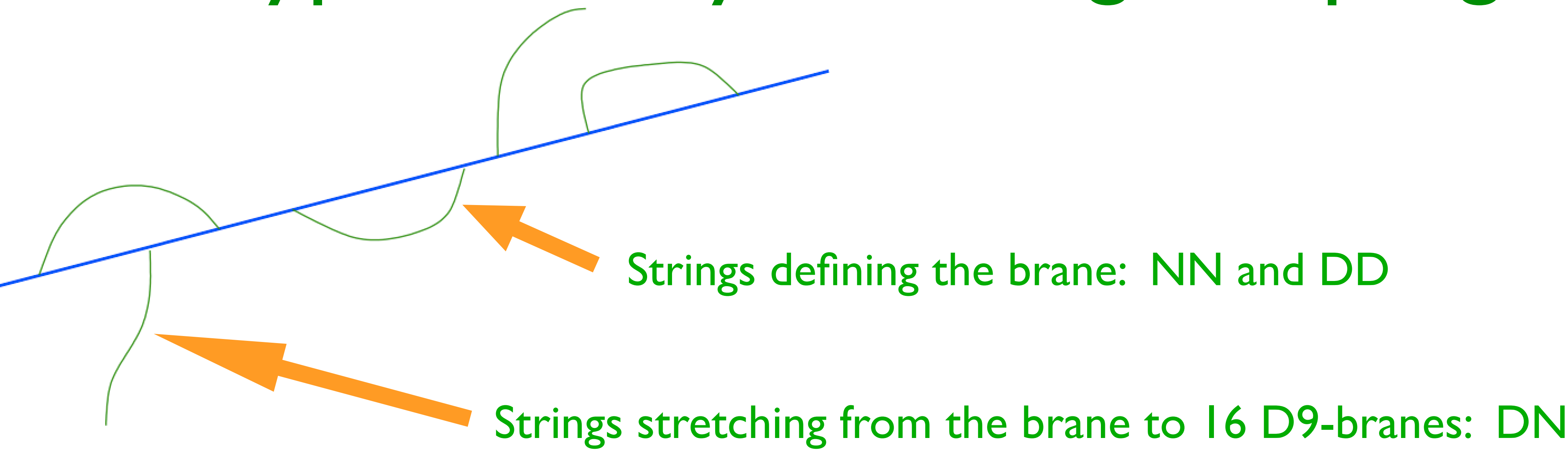

Resulting 1+1 dimensional world-volume theory contains:

A U(1) gauge field gets projected out by orientifold	NN
8 scalars	DD
8 right moving fermions transforming as an 8 of SO(8)	DD
32 left moving fermions, singlet of SO(8), fundamental of SO(32)	DN, from D9 branes and their images

The Type I Theory at Strong Coupling

This tells you it's moving in ten dimensions

This tells you it's got N=1 D=10 supersymmetry

This tells you it's got left-moving SO(32) current algebra

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This is the spectrum of an SO(32) heterotic string!

The Type I Theory at Strong Coupling

So if we follow this string at large string coupling, it becomes the lightest object.

Its massless excitations will dominate the spectrum. But those excitations are of the SO(32) heterotic string. So.....

The type I SO(32) string theory becomes the SO(32) heterotic string theory at strong coupling!!

Further evidence?

The Type I Theory at Strong Coupling

Supergravity:

$$S_{\mathrm{I}} = \frac{1}{2\kappa_0^2}\int d^{10}x(-G)^{1/2}\left\{e^{-2\Phi}\left[R+4(\nabla\phi)^2\right] - \frac{1}{12}(\widetilde{G}^{(3)})^2 - \frac{\alpha'}{8}e^{-\Phi}\mathrm{Tr}(F^{(2)})^2\right\}$$

$$S_{\mathrm{H}} = \frac{1}{2\kappa_0^2}\int d^{10}x(-G)^{1/2}e^{-2\Phi}\left\{R+4(\nabla\phi)^2 - \frac{1}{12}(\widetilde{H}^{(3)})^2 - \frac{\alpha'}{8}\mathrm{Tr}(F^{(2)})^2\right\}$$

The Type I Theory at Strong Coupling

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These are very different. Note the R-R couplings vs the NS-NS as already remarked upon.

but....

The Type I Theory at Strong Coupling

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$$\begin{aligned} G_{\mu\nu}(\text{type I}) &= e^{-\Phi}G_{\mu\nu}(\text{heterotic}) \\ \Phi(\text{type I}) &= -\Phi(\text{heterotic}) \\ \widetilde{G}^{(3)}(\text{type I}) &= \widetilde{H}^{(3)}(\text{heterotic}) \\ A_\mu(\text{type I}) &= A_\mu(\text{heterotic}) \end{aligned}$$

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This implies several important things, e.g:

$$g_s(\text{heterotic}) = g_s^{-1}(\text{Type I})$$

$$g_s^{-1}\ell_s^2(\text{heterotic}) = \ell_s^2(\text{Type I})$$

Can we deduce anything with this?

The Type I Theory at Strong Coupling

$$\tau_1 = \frac{1}{2\pi\alpha' g_s} \qquad \longrightarrow \qquad \tau_H = \frac{1}{2\pi\alpha'}$$

measured in Type I units — measured in Heterotic units

The D1-brane really does turn into the fundamental heterotic string!

$$\tau_5 = \frac{1}{(2\pi\alpha')^5 g_s} \qquad \longrightarrow \qquad \tau_H = \frac{1}{(2\pi\alpha')^5 g_s^2}$$

The D5-brane turns into the heterotic string's NS5-brane soliton

$$g_s\,(\text{heteroti}c) = g_s^{-1}\,(\text{Type I})$$

$$g_s^{-1}\ell_s^2(\text{heterotic}) = \ell_s^2(\text{Type I})$$

What Have We Learned?

We saw an open (and unoriented) string theory rearrange its degrees of freedom into an oriented closed string

This is remarkable and an impressive demonstration of what can happen at strong coupling.

Witten, '95, Witten+Polchinski, '95

But there's more...

The Type IIA Theory at Strong Coupling

This theory has four D-brane types: D0-, D2- and D4- and D6

Look at D0-brane It is a particle which couples to $C^{(1)}$

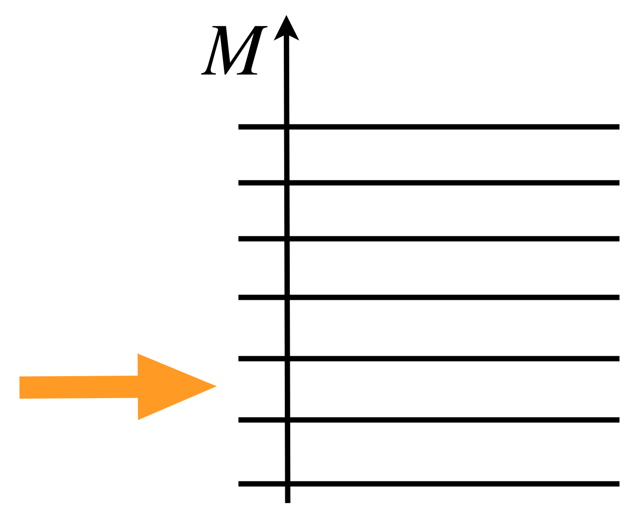
Tension: $$\tau_p = \frac{(2\pi)^{-p}\alpha'^{-\frac{p+1}{2}}}{g_s} \longrightarrow \tau_0 = \frac{1}{\alpha'^{1/2} g_s}$$

These are BPS particles. There's a whole spectrum of particles made by forming (threshold) bound states of these.

For N of them: $$\tau_0^{(N)} = \frac{N}{\alpha'^{1/2} g_s}$$

So there's a whole tower of states:

Spacing $$\frac{1}{\alpha'^{1/2} g_s}$$



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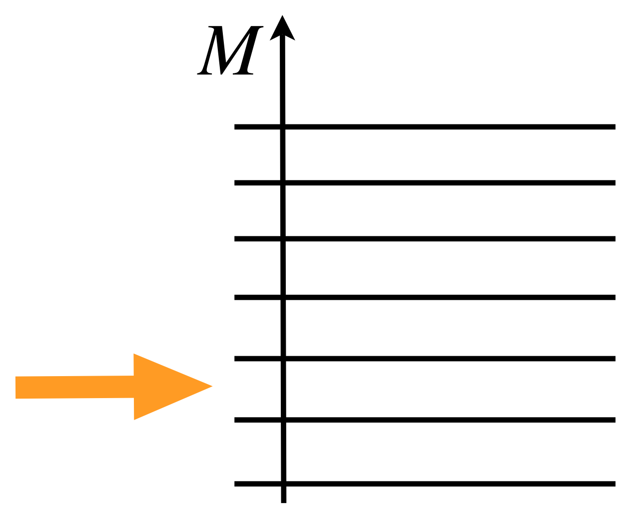

So what happens at strong coupling?

The Type IIA Theory at Strong Coupling

On the journey to strong coupling the spacing drops to zero....

....get a continuum of states.

How to make sense of this?

Hard, unless make radical step:

Spectrum looks like that of a Kaluza-Klein theory!

If take gravity theory and place it on a circle or radius R, get a gauge field from the components of metric on circle....

...and get a tower of states with masses $M=N/R$

As you decompactify (send R large), you get a continuum back, corresponding to the momenta in the extra dimension.

This is exactly what we are seeing here! So.....

What Have We Learned?

The Type IIA string theory at strong coupling becomes supergravity in 11 dimensions!

$$G^{(11)}_{MN} dx^M dx^N = e^{-\frac{2}{3}\Phi} G^{(10)}_{\mu\nu} dx^\mu dx^\nu + e^{\frac{4}{3}\Phi} (dx^{10} + A_\mu dx^\mu)^2$$

This is another remarkable and an impressive demonstration of what can happen at strong coupling:

The dimension of the physics can change!

Witten, '95

(Can also see the D2-brane become an M2-brane, and the D4 and NS5-branes become the M5-brane. The D6 becomes pure geometry -Taub-NUT) Townsend, '95

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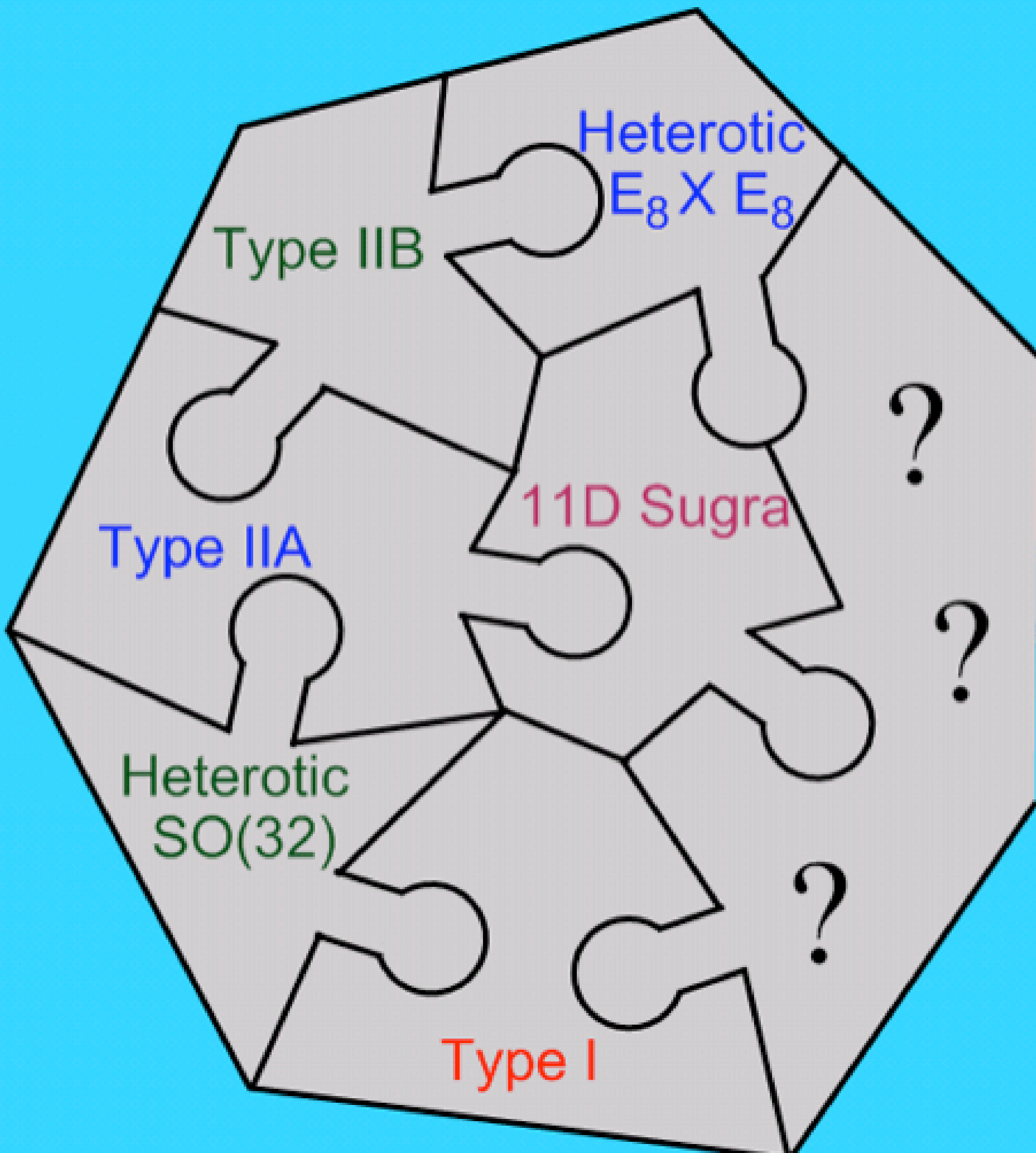
Several other remarkable dualities link all the string theories together. Clearly, staying in perturbation theory for all of pre-1995 missed a remarkable story....

The various theories all fit together into a larger picture.



What is the full "M-Theory" ?

Witten '95 Hull-Townsend '94.....

What Have We Learned?

The story of string theory is just the beginning!

Working with one particular string for phenomenological reasons was clearly premature. There are several new ways of constructing low energy models.

The new post 1995 technology for constructing low energy models shows a vast range of possibilities for finding vacua quite close to the Standard Model.

Still no sign if there are is a non-perturbative selection principle....

Where Do We Go From Here?

The field is divided, but perhaps healthily so:

Some continue to look for better understanding of string/M-theory (perhaps there is a mechanism/principle to select a unique vacuum)

Some now assume there is no principle, and have begun simply surveying the "landscape" of vacua, looking at distributions of vacua which have certain desirable characteristics.

Some have declared that since there must be a reason "why" we're in this vacuum, if there's no stringy principle to select them, there must be an Anthropic reason.

It's probably *way* to early to tell, but:

At least one simply thinks that there's no compelling reason that string/M-theory must have no uncomputable parameters. Perhaps that's always true for any theory. We must always leave something for the next generation of thinkers. It's how science has always proceeded.