D-MATTER

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WITH

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hep-ph/0311228

Motivation :

WELL STUDIED PARTICLE-LIKE STATES

zero modes ← SM matter 0

KK tower ← effect of extra. D. $\frac{n}{R} \sim n M_c$

winding states ← non-local stringy states $\frac{nR}{\alpha'} \sim n \frac{M_s^2}{M_c}$

string resonances ← stringy excitations $\sqrt{n} M_s$

Monopoles ('t Hooft - Polyakov) ← topological defects from SSB $\frac{\langle \phi \rangle}{g_{YM}}$

D-matter

NEW TYPE OF PARTICLE - LIKE STATES

NON-PERT. OBJ. in string theory.

D-brane (WELL-KNOWN PROPERTIES & APPLICATIONS)

- NON-PERT. obj.

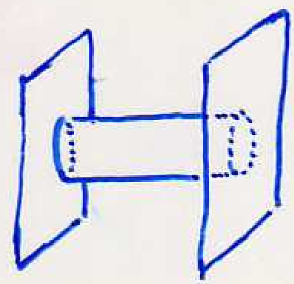
  - Open strings can end

    ↳ matter and gauge fields

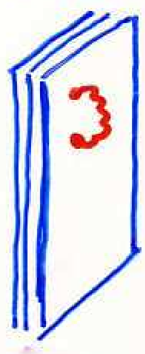
    $$\int \frac{1}{g_s} F^2 \rightarrow g_s \propto g_{YM}^2$$

  - potential sources of RR fields $C_{\mu_1 \cdots \mu_p}$

  - tension $\tau \propto \frac{M_s}{g_s}$



- Model building (D-brane as backgrounds)



Dp $(\underbrace{t, x_1, x_2, x_3}_{\text{OUR WORLD}}, \underbrace{x_4 \cdots x_p}_{\text{compact. e.g. orbifold}})$

orientifold
braneworld
intersecting D-branes
⋮

2.

D-matter (D-BRANES AS PARTICLES)

- Dp if $p \le 6$. compactify <u>all</u> spatial dim. of the world volume.

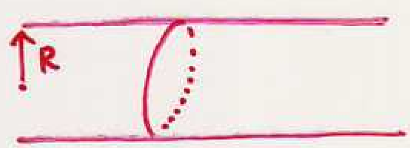
$\downarrow$ $\Rightarrow$ compact obj behaves like a particle

world-line

$$m_D \sim \frac{M_s^{p+1} V_p}{g_s} \sim \frac{M_s}{g_s}$$

e.g. D-particle (D0-brane)

e.g. D-string (D1-brane)



$$m_D \sim \frac{M_s^2 R}{g_s}$$

D-branes as excitations

3.

Properties of D-matter

- Mass

$$M_D = \frac{M_s^{p+1} V_p}{g_s} \sim \frac{M_s^{p+1} R_D^p}{g_s} \qquad \frac{1}{R_D} \le M_s \rightarrow M_D \gtrsim \frac{M_s}{g_s}$$

$$M_{Pl}^2 = \frac{M_s^8 V_6}{g_s^2} \sim M_s^8 R_D^p R^{6-p} \Big/ g_s^2$$

$$\hookrightarrow \frac{M_D}{M_{Pl}} \sim \frac{1}{(M_s \cdot R)^{3-p/2}} \rightarrow M_D \ll M_{Pl} \text{ if } \begin{matrix} p<6 \\ M_s R \gg 1 \end{matrix}$$

*: Gauge field living on Dp-brane

$$M_s^{p-3} \frac{1}{g_s} \int F^2 \, dx^{p+1} \rightarrow \frac{1}{g_{YM}^2} = \frac{V_{p-3}}{g_s} M_s^{p-3}$$

$$M_{Pl}^2 = \frac{1}{g_{YM}^2} \frac{V_6}{V_{p-3}} \underset{\uparrow}{M_s^{11-p}}$$

low string scale possible

- Mass of D-matter is not constrained to be close to the Planck scale.

- Comparing with heterotic scenario

- Type I – heterotic duality Polchinski & Witten, '96

$$\frac{1}{g_I} \leftrightarrow g_h$$

D0 particle $\leftrightarrow$ 1st string resonance $\propto M_s$

D1 string $\leftrightarrow$ fundamental string

- However

$$\frac{1}{g_{YM}^2} = \frac{1}{g_s^2} V_6 M_s^6$$

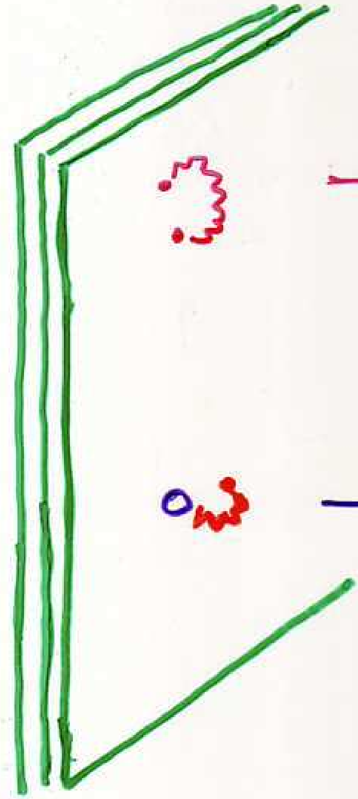
$$\rightarrow \quad M_p^2 = M_s^2 / g_{YM}^2$$

$$\mathcal{L}_{grav} \supset \frac{m_s^8}{g_s^2} \int \sqrt{g}\, R\, dx^{10}$$

$$\mathcal{L}_{YM} \supset \frac{m_s^6}{g_s^2} \int F^2\, dx^{10}$$

$$g_s = g_{YM}$$

5.



$\longrightarrow$ C_{pp}; A^{μ}, Φ, f ....

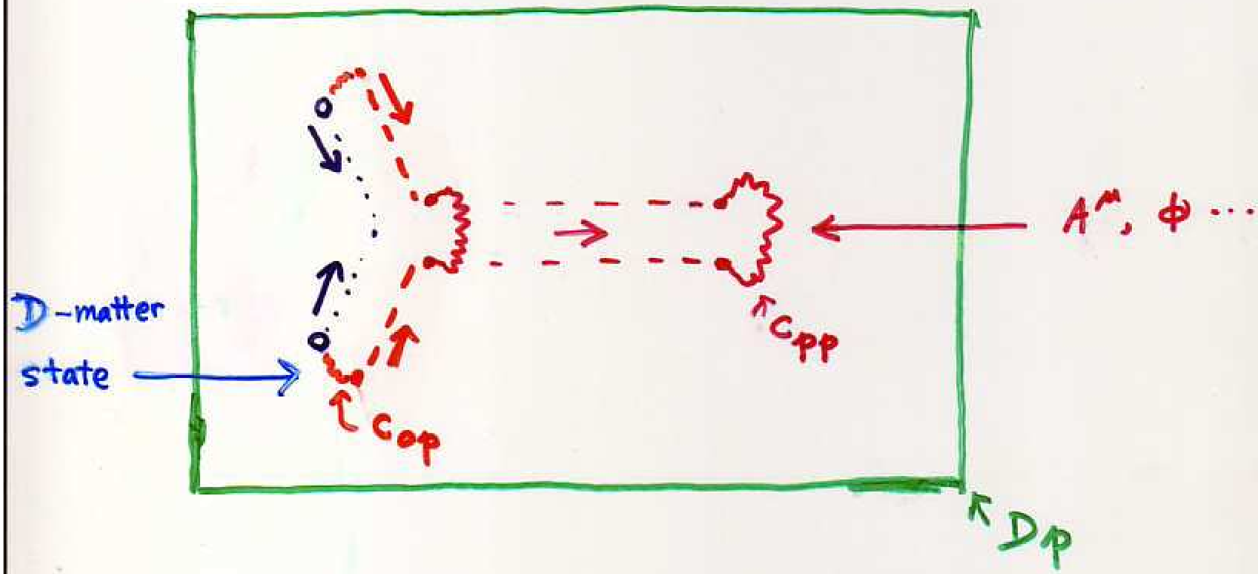
$\longrightarrow$ D-matter state charge under $U(N)_p$

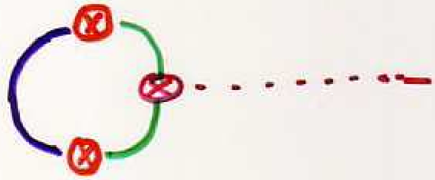
(fill super-multiplet)

Dp

D-matter interactions

"brane-in-brane"





Gallot et.al. 2000

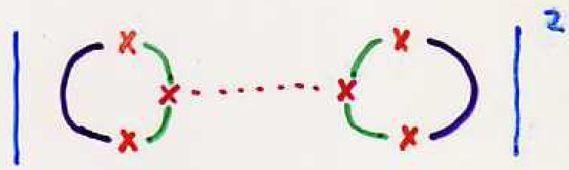
$$\rightarrow C_{pp} C_{op} C_{op} \rightarrow \begin{cases} g_{YM}\, \bar{D} \gamma^\mu A_\mu D \\ y\, \bar{D} D \phi \end{cases}$$

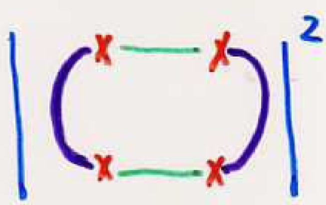
Power counting: $g_s^{\frac{n_c}{4} - \chi} = g_s^{1/2}$

$$\rightarrow g_{YM} \sim Y \sim g_s^{1/2}$$

- Comparing with monopoles

	't Hooft - Polyakov monopole	D-matter
mass	$\frac{\langle\phi\rangle}{g_{YM}} \sim \frac{M_X}{g_{YM}^2}$	$\frac{M_s}{g_s} \sim \frac{M_s}{g_{YM}^2}$
$(\text{size})^{-1}$	$\lambda\langle\phi\rangle$ $g_{YM}\langle\phi\rangle$	$g_s^{\lambda} M_s$ $\begin{cases} \lambda = \frac{1}{3} & \text{brane-probe} \\ \lambda = 0 & \text{string-probe} \end{cases}$
interaction (IR)	$\propto \mu_m \quad \mu_m = \frac{n}{g_{YM}}$	$\propto g_{YM}$ $\uparrow\uparrow\uparrow\uparrow$

$\sigma(D\bar{D} \to D\bar{D}) \propto$ 



7.

More Carefully

"Form-factor"

$$C_{op'}\, C_{op'}\, C_{p'p'} \propto g_s^{\frac{1}{2}}\, F(s,t,\alpha') + g_s\, G(s,t,\alpha')$$

$$+ \cdots$$

→ depending on momentum exchange q

corrections $\propto q/M_s$ could be important

→ for production / annihilation

$$s \gtrsim 4 M_s^2$$

→ F, G fully calculabe for pert. string states

$q \to 0 \qquad F \to 1$

$s \to \infty \qquad \cdots\ e^{-\alpha' s}$

A full string theory calculation of product/annihilation (all α' corrections...) impossible.

- pert. string states: Vertex operator, CFT (world-sheet formulation)
- D-brane are not part of pert. spectrum.

  Waiting for string field theory ....

- Some insights/estimates from duality

Type-I $D0$ $\leftrightarrow$ excited strings (heterotic)

$\uparrow$ pert. states.

Tree-level Four-point Amplitude (all in -1/2 picture):

$$A_4 \sim C_0 \hat{N}^4 < c\bar{c}V_1^{-1/2}(z_1,\bar{z}_1)V_2^{-1/2}(z_2,\bar{z}_2)c\bar{c}V_3^{-1/2}(z_3,\bar{z}_3)c\bar{c}V_4^{-1/2}(z_4,\bar{z}_4) >$$

where $C_0 = (2\pi)^{-4}\alpha'^{-5}g_h^{-2}$ and $\hat{N} = 8\pi^{5/2}\alpha'^2 g_h$. Hence $A_4 \sim g_h^2 \sim g_{YM}^2$.

Vertex operators of first excited string states:

$$V^{-1/2}(z,\bar{z}) = e^{-\phi(z)/2} e_\mu u_\alpha i\partial_z X^\mu \theta^\alpha(z) e^{ik\cdot X(z,\bar{z})} C_K e^{i\frac{K}{\sqrt{2\alpha}}\cdot\tilde{X}(\bar{z})}$$

$$V^{-1/2}(z,\bar{z}) = e^{-\phi(z)/2} e_\mu u_\alpha i\partial_z \psi^\mu \theta'^\alpha(z) e^{ik\cdot X(z,\bar{z})} C_K e^{i\frac{K}{\sqrt{2\alpha}}\cdot\tilde{X}(\bar{z})}$$

where $k^2 = -4/\alpha'$ and $K^2 = 4$.

Vertex operators of massless states:

$$V^{-1/2}(z,\bar{z}) = e^{-\phi(z)/2} u_\alpha \theta^\alpha(z) e^{ik\cdot X(z,\bar{z})} \mathcal{O}(\bar{z})$$

with $k^2 = 0$, $\mathcal{O}(\bar{z}) = \bar{\partial}\tilde{X}^I(\bar{z})$ for Cartan generators, and $\mathcal{O}(\bar{z}) = C_K e^{i\frac{K}{\sqrt{2\alpha}}\tilde{X}(\bar{z})}$ with $K^2 = 2$ for the remaining 480 generators. Consider

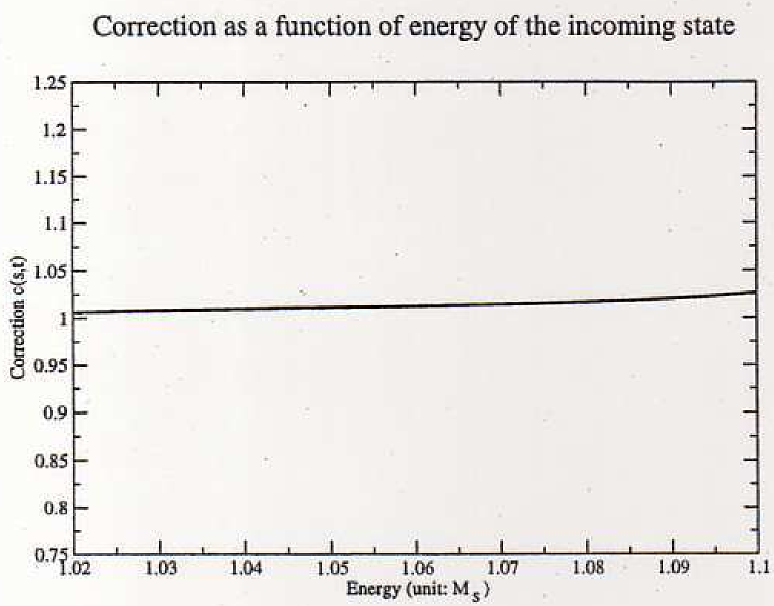
$$\begin{aligned}
k_1 &= (E, 0, ...0, k) \\
k_2 &= (E, 0, ...0, -k) \\
k_3 &= (-E, 0, ... -E\cos\theta, -E\sin\theta) \\
k_4 &= (-E, 0, ...E\cos\theta, E\sin\theta). \\
K_1 &= -K_2 = (+\frac{1}{2}, ..., +\frac{1}{2}), \\
K_3 &= -K_4 = (0, ...0, +1, 0, ..., 0, +1, 0, ...).
\end{aligned}$$

$$\mathcal{A} \quad \propto \quad 2\pi \times \frac{\Gamma(\alpha' s/4 + \alpha' u/4 - 2)\Gamma(-\alpha' s/4)\Gamma(1-\alpha' u/4)}{\Gamma(\alpha' u/4 - 3)\Gamma(\alpha' s/4 + 2)\Gamma(1 - \alpha' s/4 - \alpha' u/4)}$$

The four-point amplitude takes the form:

$$\mathcal{A}_4 = \frac{f(u,t)}{s} + g(s,t,u,\alpha')$$

Comparing the stringy corrections $g(s,t,u,\alpha')$ to the usual s-channel gauge boson exchange in field theory.



The corrections are of the same order as the field theory result.

Stability of D-matter and CDM

- Other candidates of CDM

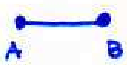
LSP of MSSM with R-parity

$P_R = (-1)^{3(B-L)+2s}$ $\quad\quad$ $\lambda LLE + \lambda' LQD + \mu LH \cdots$

superpartners -1 under P_R → stable LSP

Weakly coupled LSP → Ω_{CDM}

LKP



S^1/Z_2 $\quad\quad$ Z_2' $\quad$ $A \leftrightarrow B$ $\quad$ $\mathcal{L}_A = \mathcal{L}_B$ → symm.

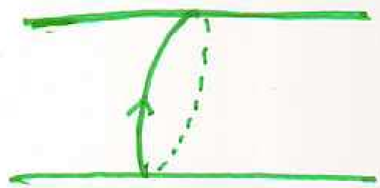
$n=1$ KK states (-1) under Z_2'
→ stable!

LBP "baryon" number Z_3

⋮

LDP

LWP ?



- Winding state as stable CDM candidate?

Stability $\longleftrightarrow$ Winding # conservation

$\updownarrow$ T-dual

momentum conservation

- realistic orbifold usually break winding # conservation

$Z_2 \qquad z \to -z$

$Z_3 \qquad z \to e^{i\frac{2\pi}{3}} z$

No invariant 1-cycle (dz)

- Stability of LDP

→ BPS

Conserved RR charge $\sim n$

$n=1$ state stable

example: D0 brane in IIA

→ NON-BPS w/ conserved charge

conserved charge under twisted RR field

↑

orbifold fix point

→ NON-BPS without conserved charge

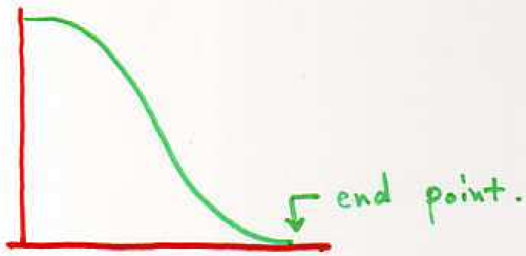
No conserved charge

Orientifold / comp. project out the tachyon mode.

Stable D-particle (D0) of Type I

- D-brane decay and tachyon

  unstable D-brane $\Leftrightarrow$ tachyon in open string spectrum



- Possible end-points of tachyon Vac.

  - Vac. w/ closed strings

  - lower dimensional stable D-branes

D0 from D1 + $\overline{\text{D1}}$ system.

D1 + $\overline{\text{D1}}$

NS sector

$|0\rangle$ ↑ Scalar $\xrightarrow{GSO}$ $|0\rangle$ ↑ $M^2 = -\frac{1}{\alpha'} + \frac{L^2}{(2\pi\alpha')^2}$

$\psi^\mu |0\rangle$

↑

gauge boson + scalar

→ unstable

→ No gauge symm (continuous)

→ discrete $Z_2 \times Z_2$. tachyon charge $\pm(1, -1)$

↓ disconnect Vac.

⇒ Kink tachyon cannot unwind.

End point of D1 + $\overline{\text{D1}}$ is a stable $\widehat{\text{D0}}$

Formally, stable D-branes ↔ K-theory

Type I: D1 D5.

D(-1), D0, D7, D8

Prospect of explaining Ω_{CDM} (estimates).

high scale: $M_s \sim 10^{11-12}$ GeV

Wimpzillas! D. Chung, E. Kolb. '97, '98

e.g. production during reheating

$$\Omega_{CDM} \sim M_D^2 \langle \sigma v \rangle \left(\frac{g_*}{200}\right)^{-3/2} \left(\frac{10^3\, T_{RH}}{M_D}\right)^7$$

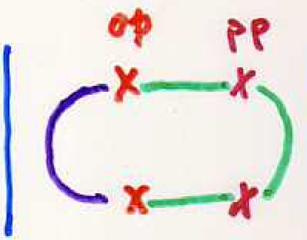
$$\langle \sigma v \rangle \sim \alpha_{YM} M_D^{-2}$$

IF $T_{RH} \sim 10^9$ GeV, $\Omega_{CDM} \sim 0.1$

Low scale: $M_s \sim$ TeV $\qquad M_D \sim \frac{M_s}{g_{YM}^2}$

like a usual wimp

$$\Omega_{CDM} \sim \frac{3 \times 10^{-6}}{\alpha_{YM}^2} \left(\frac{M_D}{100\ \text{GeV}}\right)^2$$

$\sigma(D\bar{D} \to \underset{pp}{\cdots}) \propto \Big|$  $\Big|^2$

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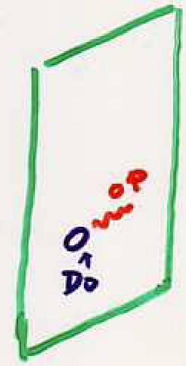
Mass splittings in D-matter tower

- D-matter states

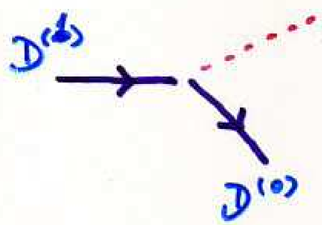


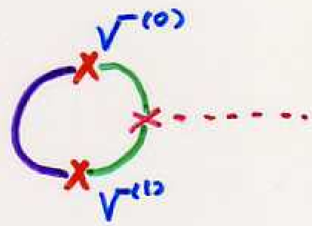
$$|D^{(i)}\rangle = |D_0\rangle \otimes |V_{op}^{(i)}\rangle$$

Ground state $|D^{(0)}\rangle = |D_0\rangle \otimes |V_{op}^{(0)}\rangle$

1st excited state $|D^{(1)}\rangle = |D_0\rangle \otimes |V_{op}^{(1)}\rangle$

$\vdots$





- Mass splittings

"bare" state + resonances

$$m^2_{D^{(n)}} = \frac{M_S^2}{g_S^2} + n M_S^2 \qquad \left(L_0^{D_0} + L_0^{(op)} |D^{(i)}\rangle = 0 \right)$$

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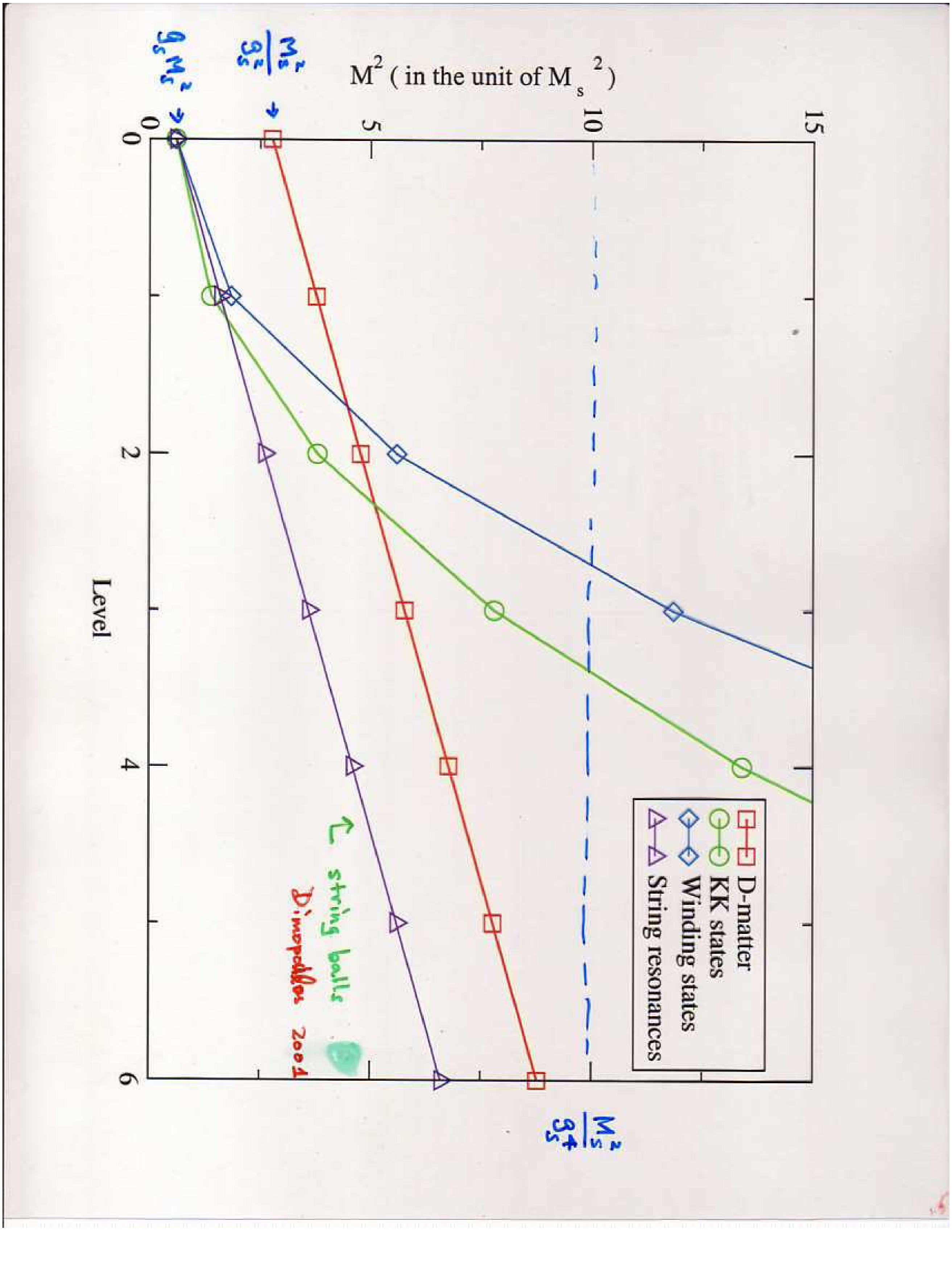
M^2 (in the unit of M_s^2)
Level
D-matter
KK states
Winding states
String resonances
string balls
Dimopoulos 2001
0
5
10
15
0
2
4
6

Comments on other relevant properties.

- Additional information on geometry of the internal manifold.

  - KK and winding modes

    $\uparrow$ KK: $\Box$; $\uparrow$ winding: 1-cycle

    Limited info on internal geometry

    Rabadan, Shiu 2003

  - $$m_D = \frac{m_s}{g_s}\left(m_s^n V_n\right)$$

    $\uparrow$ n-cycle

- Extra stable D-brane states & brane inflation.

  $$D_p\ \overline{D_p} \rightarrow D_{p'} \qquad (p-p') \bmod 2 = 0 \leftarrow \text{BPS}$$

  only cosmic strings are formed.

  Not true for non-BPS.

Conclusions.

- D-matter are interesting & important states to study.
  - distinct mass dep. on the scales & couplings $\sim \frac{M_s}{g_s}$
  - Perturbative couplings $\propto g_s^{1/2} \sim g_{YM}$
  - generically exist.
- Two generic pheno. features
  - CDM
  - distinct mass splittings

→ Future directions
  - Classification of stable D-branes in a "realistic" model
  - Better understandings of interactions.

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